Views on the multi-phase interstellar medium in galaxies

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ALMA MATER STUDIORUM - GIORGIO PRODI LECTURE HALL

Background image: NASA, ESA, CSA, and STScI

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I. Local galaxies

Dust and gas in the nuclear and circumnuclear regions of nearby Seyfert galaxies as revealed by JWST/MIRI

Almudena Alonso-Herrero

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In this talk I will present the first results from two JWST Cycle 1 programs awarded to the Galactic Activity, Torus, and Outflow Survey (GATOS). We used both the imaging and integral field unit (MRS) observing modes of MIRI to study the properties of the dust as well as the ionized and warm molecular gas in nearby Seyfert galaxies with resolutions of tens of parsecs. The MIRI imaging observations display extended emission on nuclear and circumnuclear scales and allow to investigate the origin and possible heating mechanisms of the detected dust emission. The MIRI-MRS program targets Seyfert galaxies with similar AGN bolometric luminosities but with optical ionized gas mass outflow rates differing by two orders of magnitude. I will discuss the properties of the ionized gas outflows derived from mid-infrared high excitation lines, which are less subject to extinction than optical observations. The molecular hydrogen transitions observed with MRS allow to trace the warm phase of the molecular outflows. We also characterized the polycyclic aromatic hydrocarbon (PAHs) properties on nuclear and circumnuclear scales, including regions potentially affected by the ionized gas outflows. Finally, I will show that these new JWST/MIRI observations also revealed the presence of water ice in the most obscured nuclei in our sample demonstrating the need to include the molecular content (water, PAHs, and amorphous hydrocarbons) in the next generation of torus models.

On the origin and evolution of cold gas in galactic outflows

Francesco Bollati

Leibniz Institute for Astrophysics Potsdam, Germany

Galactic outflows are fundamental in shaping the evolution of galaxies, their star formation history and the baryon cycle throughout cosmic time. However, reconciling the complex, multi-phase nature of outflows with both cosmological hydrodynamical simulations and observational data presents a significant challenge. On the computational side, it is currently infeasible to directly simulate galactic scales together with the sub-pc scales of cold dense clouds. Yet, understanding the impact of these clouds and their interplay with the hot volume filling phase is crucial for understanding the role of outflows in galaxy evolution. Here I introduce a novel model implemented in the `AREPO` code that effectively tracks the interactions between the unresolved cold phase and the hot phase in a sub-grid fashion. These interactions are informed by high-resolution simulations of cloud crushing dynamics. Subsequently, I present a suite of simulations aimed at addressing (i) the origin and evolution of cold gas within galactic outflows, (ii) their dependence on the underlying feedback mechanism and environmental factors, and (iii) the respective contributions of hot and cold phases to mass and energy loading within outflows. Finally, I compare such results with recent observational data.

The multi-phase structure ISM shaped by the baryon cycle in nearby galaxies

Mélanie Chevance

Heidelberg University, Germany

Galaxies are in constant evolution, under the influence of the gas-star matter cycle within them. However, the exact physical mechanisms driving this multi-scale cycle remain elusive, due to a lack of observational constraints. By combining high-resolution, multi-wavelength observations from a broad range of galactic environments, I will present how we can characterise for the first time the successive steps of this cycle, from the assembly of dense gas clouds from the diffuse interstellar medium, to the successive collapse, star formation and dispersal by stellar feedback redistributing matter and energy back into the diffuse medium. I will show that molecular clouds are rapidly destroyed by pre-supernova stellar feedback (within 1-5 Myr), which drastically limit their star formation efficiency to 2 to 10%, depending on the galactic environment. The vast majority of momentum and energy emitted by the young stellar populations escapes the parent cloud, affecting galaxies on large scales. This comprehensive analysis sheds new light on the matter cycle within galaxies, revealing its underlying processes and quantitative characteristics. I will conclude by showing how these measurements provide critical constrains to improve the description of the unresolved processes of star formation and feedback in galaxy formation and evolution simulations.

What is the most fundamental scaling relation for predicting star formation?

Sara Ellison

University of Victoria, Canada

The surface density of star formation rate, measured on kpc-scales, correlates stringly with both the surface density of molecular gas (i.e. the Schmidt-Kennicutt relation) and the surface density of stellar mass (i.e. the star forming main sequence). However, neither of these emipircal scaling relations offers a theoretical framework for the formation of stars, and both show considerable galaxy-to-galaxy variation. Are they therefore 'fundamental' scaling relations? In contrast, the pressure-regulated feedback modulated (PRFM) theory of star formation posits that the pressure in the galactic interstellar medium is balanced by feedback from star formation and therefore predicts a tight correlation between star formation rate and dynamical equilibrium pressure. Indeed, previous surveys that measure gas and star formation in normal star-forming galaxies on ∼kpc scales have found excellent agreement with PRFM model predictions. However, the PRFM theory has yet to be tested in a diverse sample of galaxies that includes both starburst and quenching galaxies. The extended ALMA-MaNGA QUEnching and STar formation (ALMaQUEST) sample, which includes mergers, starbursts and green valley galaxies, offers the ideal opportunity to more fully test the PRFM model. In this talk I will assess the performance of the various star formation scaling relations, in a quest to identify whether any of them is truly 'fundamental'.

Dissecting the mid-infrared heart of M83 with JWST

Svea Hernandez

Space Telescope Science Institute, Maryland, USA

Molecular gas is a critical ingredient in the recipe of star formation (SF) in galaxies. To fully understand the processes that govern SF, it is essential to accurately measure and characterize the distribution of H_2 in star-forming environments. Since H_2 is a weak rotational emitter, the molecular gas content in galaxies is typically inferred using indirect tracers such as the CO $(1-0)$ transition. However, CO provides a partial census of the total H_2 mass, particularly in regions with large quantities of CO-dark gas. A few years ago, an HST/FUV spectroscopic study proposed that the starburst region in the nearby galaxy, M83, would be an ideal environment to host CO-dark gas. We have begun exploiting the unprecedented capabilities of JWST in the MIR, using the MIRI/MRS, performing a study of the warm H_2 gas in the heart of this face-on spiral galaxy. Our initial results indicate that a large fraction of the total molecular gas mass in the core of M83 is contained in the warm H_2 component, hidden to the CO tracer. We are now performing a more in-depth, detailed analysis probing the distribution of this gas on spatial scales $\sim$5 pc, uncovering the effect recently-formed massive stars, observed with HST/COS, have on the reservoirs of molecular gas and star formation. It is imperative that we understand the fueling star-formation history through cosmic time, and the unmatched synergy of HST and JWST is allowing us to do exactly that.

Key signatures of molecular gas: linking dense gas and star formation across a diverse set of environments

María Jesús Jiménez Donaire

Observatorio Astronómico Nacional – Instituto Geográfico Nacional (OAN-IGN), Spain

Spectroscopic tracers of molecular and dense gas offer the best way to study the cold, immediately star-forming gas. I will overview the main results from our large EMPIRE and ALMA related surveys, providing maps of high density gas tracers (e.g. HCN, HCO^+, HNC) systematically across nearby galaxy disks. Our results show that the star formation efficiency in the dense gas varies systematically in all galactic disks, and provide support for a context-dependent role of density, where the dense gas fraction follows interstellar pressure but star formation only takes place in local over-density regions. Our ability to translate extragalactic emission from commonly used high density tracers such as HCN into a dense gas mass, however, is still uncertain, since a large fraction of their luminosity arises from low-density regions. Building up on this work, I will present new IRAM and ALMA observing efforts capturing the emission from challenging, density selective molecules such as N_2H^+. Our work shows a strong correlation between N_2H^+ and commonly used dense gas tracers like HCN at sub-kpc and kpc scales. I will discuss these findings in the context of recent Galactic work, as well as those processes that participate in our interpretation of the dense gas emissivity, ultimately forming stars.

Molecular gas conditions and CO line excitation in nearby galaxies with AMISS

Ryan Keenan

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The CO $(1-0)$ line has been carefully calibrated as a tracer of molecular gas mass. However, recent studies often favor higher-J CO transitions which are brighter and accessible for redshift ranges where CO $(1-0)$ is not. These lines are not perfect analogues for CO $(1-0)$, owing to their more stringent excitation conditions, and must be calibrated for use as molecular gas tracers. Conversely, observations of multiple CO lines in a single target can constrain additional gas properties beyond mass. I will present the Arizona Molecular ISM Survey with the SMT (AMISS), a multi-CO line survey of $z < 0.05$ galaxies conducted with the CO $(1-0)$, CO $(2-1)$ and CO $(3-2)$ lines. The project targeted a representative sample of $10^9 M_\odot < M_* < 10^{11.5} M_\odot$ galaxies. The final survey includes CO $(2-1)$ spectra of 176 galaxies and CO $(3-2)$ spectra for a subset of 45 supplemented by new and archival CO $(1-0)$ spectra for all targets. I will present the results of our study of CO luminosity ratios, showing that CO $(2-1)$ and CO $(3-2)$ are systematically fainter relative to CO $(1-0)$ in galaxies with less star formation activity. These results provide a reference for comparison to ongoing high-redshift gas excitation studies with ALMA, as well as a tool for converting between CO lines in studies of nearby galaxies.

CN as a tool for dense gas studies in star-forming galaxies

Blake Ledger

McMaster University, Hamilton, Canada

I will present recent work focusing on the cyanide radical, CN, as an added tool to study dense gas and star formation in nearby star-forming galaxies and U/LIRGs. We have used archival ALMA data to show that the CN $(1-0)$/CO $(1-0)$ intensity ratio varies between and within individual galaxies on 0.1–1 kiloparsec scales. CN/CO tends to be higher in the more extreme ULIRGs compared to LIRGs and normal star-forming galaxies, higher in galaxy centres compared to their disks, and correlates with global infrared and hard X-ray luminosities. The correlations become stronger when considering the location of peak hard X-ray or peak gas surface density. Additionally, we have measured a nearly constant CN/HCN line intensity ratio using the CN $(1-0)$ and HCN $(1-0)$ lines, with no correlation with molecular gas surface density and only a weak correlation with star formation rate surface density and star formation efficiency. Our results imply that CN, like HCN, can be used as a tracer of dense gas mass and dense gas fraction in nearby galaxies.

The contribution of gravity, rotation and pressure to the observed structure of gas disks

Sharon Meidt

Ghent University, Belgium

The structure of molecular gas disks is a key record of the processes responsible for its organization across a range of spatial scales: thermal and mechanical feedback from star formation carve bubbles and shells on small scales (tens of pc) and, as a result of galactic processes on larger (kpc) scales, gas disks exhibit the global spiral features definitive of the galaxy as a whole. In the intermediate (hundreds of pc) regime – near the cloud scale – our picture of structure formation contains a variety of channels, all devised at least partially to compensate for the fact that gas on these scales is often observed to be locally Toomre (gravitationally) stable. In this talk I will discuss a new, straightforward avenue of structure formation mediated by gravity and rotation that is possible outside the regime where the Toomre criterion applies. This new process is described by extending the Lin-Shu framework to the regime of 'open spirals', well outside the conventional 'tight-winding' limit. Forming filaments and spiral structures are predicted to have properties set by the local disk conditions and arrange themselves on scales nearer to the Jeans length than the Toomre length. In gas disks, this makes them consistent with the highly regular, remarkably long filamentary features newly revealed by JWST across the neutral gas disks of nearby galaxies. I will discuss the implications of this new channel of structure formation, highlighting turbulence driving near the 100 pc scale, the interplay with Q regulation and violent disk instability at earlier cosmic time, and the critical role it plays in offseting the rapid destruction of small scale structure by feedback.

Are GMCs real? Searching for a virialized scale in NGC 253

Elias Oakes

University of Connecticut, Storrs, USA

Giant Molecular Clouds (GMCs) are widely thought to set the initial conditions for star formation. However, the hierarchical and complex nature of the interstellar medium (ISM) makes drawing contours to define individual GMCs a fraught enterprise. The somewhat arbitrary nature of structure identification raises the question of whether GMCs are physically motivated, well-defined entities. In this work, I will describe the search for a characteristic size scale at which the molecular ISM becomes preferentially gravitationally bound. I will present new high-resolution ALMA observations, which map ^{12}CO $(2-1)$ at $0.3'' \sim 5$ pc spatial resolution over 1.4 kpc^2 in the disk of NGC 253. Using dendrograms, we have conducted a scale-free, hierarchical decomposition of these data to recover over 2400 structures on scales from the size of our field to the resolution limit. We estimate the gravitational boundedness of each structure using the virial parameter. By comparing this value against structure sizes and other physical properties, we have carried out a comprehensive search for a preferred scale at which bound structures emerge. Ultimately, we find a wide range of virial parameters at all size scales and no clear trend with size, pointing to a lack of emergent scale for cloud-like structures. These findings suggest that the GMC paradigm is incomplete and emphasize the need for structure-agnostic approaches to characterize the molecular ISM.

MICONIC: an unprecedented view of the nuclear and circumnuclear ISM of nearby iconic galaxies by JWST MIRI-MRS

Lara Pantoni

Ghent University, Belgium

I will present new insights into the properties of the multi-phase ISM in the nuclear and circum-nuclear regions of three peculiar galaxies, i.e. Mrk 231 (*Alonso Herrero et al. submitted to A&A*), Arp 220 (*van der Werf et al, in prep.*) and Centaurus A (*Pantoni et al. in prep., Guillard et al. in prep.*), observed by the Mid-Infrared Spectrometer (MRS) of JWST MIRI. These galaxies are part of the GTO program termed Mid-Infrared Characterization of Nearby Iconic galaxy Centers (MICONIC) of the MIRI European Consortium, along with NGG 6240, SBS0335-052 and the areas surrounding Sgr A*. Thanks to the high angular resolution and spectral resolving power of MIRI-MRS, observing between 4.9 to 27.9 μm, we got unprecedented rich and detailed spectra that we used to identify and model the ionized gas emission lines, the molecular hydrogen rotational transitions and the PAH emission lines across the MIRI-MRS fields of view (up to $\sim$10 arcsec), covering the galaxy nuclear and circum-nuclear regions. By computing intensity line ratios, studying the gas kinematics, and fitting the spectral line profiles we were able to provide an in-depth analysis of the local properties of the ISM and to distinguish between the contribution from star formation and nuclear activity up to scales $\lesssim$100 pc.

Unveiling the nature of spiral arms in PHANGS galaxies

Miguel Querejeta

Observatorio Astronómico Nacional – Instituto Geográfico Nacional, Spain

Spiral arms are some of the most spectacular features in disc galaxies, also prominent in our own Milky Way. It has been argued that star formation should proceed more efficiently in spiral arms as a result of gas compression. Yet, observational studies have so far yielded contradictory results, limited by the scarcity of high-resolution maps of molecular gas in nearby galaxies and the difficulty of such measurements in the Milky Way. The PHANGS survey, mapping molecular gas and star formation at $\sim$100 pc scales across dozens of nearby spirals, opens up the exciting possibility of shedding light on this long-standing question. We show that the strongest stellar spiral arms tend to pile up more gas, resulting in higher star formation rates, but without significantly increasing the star formation efficiency in general. Only locally, for outstandingly large stellar contrasts, do we find a trend for a noticeable boost in the efficiency at which gas converts into stars. We also quantify offsets between tracers of the gravitational potential, molecular gas and star formation, which allow us to determine which spirals are associated with density waves.

Structure and porosity of the multiphase ISM: insights from resolved and unresolved galaxies

Lise Ramambason

Heidelberg University, Germany

Nearby galaxies observed at high spatial resolution with JWST, ALMA, and MUSE, allow us to tackle fundamental questions related to the impact of young stars on their surrounding interstellar medium (ISM), from the cloud scales to the galactic scales: How far can ionizing photons travel, and which physical mechanisms favor their escape from H II regions? How do such processes shape the ISM and impact galactic evolution? I will first present constraints on the timescales and physical mechanisms associated with the baryon cycle of 30 galaxies from the PHANGS-JWST survey, including their dust-embedded phase of star-formation (SF). We find that the embedded phase is typically short (< 5 Myr) and insensitive to variations of global parameters. Remarkably, this phase is drastically reduced – or even absent – in environments with high SF rate surface density and hosting numerous density-bounded H II regions, from where ionizing photons can leak out. Our results indicate that the intrinsic properties and the distribution of the ISM around ionizing sources strongly impact the early feedback phase. While the latter information is not directly accessible in unresolved observations, I will show how multi-component models can be used to probe the ISM structure and porosity to UV photons, even when no spatial information is present. Finally, I will discuss the complementarity of resolved and unresolved approaches, especially to calibrate the modeling tools needed for high-redshift studies.

DUVET: How star formation-driven outflows regulate star formation

Bronwyn Reichardt Chu

Durham University, UK

Outflowing gas driven by star formation plays a critical role regulating star formation and contributing to the baryon cycle. However the details of this stellar feedback process are still unclear, particularly in starbursting environments. To better constrain feedback models, high resolution IFU observations are needed to spatially resolve star formation-driven outflow properties and link these to co-located galaxy properties. I will present results from the DUVET survey of starbursting galaxies observed using the IFU KCWI. We measure outflows in 10 face-on galaxies with $\sim$1000 lines of sight of individual outflow measurements at 500 pc resolution. Using our observations, we are able to discriminate between widely used models of the launching mechanism of the outflow. We derive much needed scaling relations for the relationship between star formation and outflow properties across a range of star-forming environments, and compare these to simulations. We compare to observations from NOEMA, and connect the outflows with location in the resolved Kennicutt-Schmidt relation to find that starburst regions remove more gas via the outflow than they convert into stars. This directly measures how outflows regulate star formation and contribute to the baryon cycle. DUVET's unprecedented sample of resolved outflows provides a new perspective to make ground-breaking constraints on how stellar feedback regulates star formation and contributes to the baryon cycle.

Environmental dependance of GMC evolution and star formation in nearby galaxies

Andrea Romanelli

Institut für Theoretische Astrophysik, Universität Heidelberg, Germany

With the advent of revolutionary telescopes such as JWST and ALMA, observations now allow us to study the baryon cycle of nearby galaxies with unprecedented spatial resolution and sensitivity. Numerical and observational studies reveal that the properties of molecular gas and star formation are regulated by local galactic environment, GMC properties vary between galaxies and with galactocentric radius. However, definitive observational constraints on how the local environment regulates star formation are still lacking. For this, we need a systematic characterisation of the evolutionary sequence from the gas clouds to star formation, and to the disruption of the parent clouds by stellar feedback, in a broad range of well defined environments. I will present the results of applying a rigorous statistical method to CO and Hα maps to a sample of nearby galaxies from the PHANGS survey, to measure cloud lifetimes, feedback timescales, clouds separation scales and star formation efficiency, as a function of local environment. I will show that the durations of the cloud lifetime and of the feedback phase, as well as the star formation efficiency are statistically indistinguishable between the arm and inter-arm regions of spiral galaxies, suggesting that spiral arms do not trigger or favour star formation in galaxies. I will further demonstrate how other galaxy-wide properties do influence the sequence of cloud collapse, star formation and feedback. These measurements provide critical constrains to improve our understanding of how gas structure and properties regulate star formation in galaxies.

The primary role of star-formation-driven outflows on the baryon cycle of nearby dwarf galaxies

Michael Romano

National Centre for Nuclear Research, Otwock, Poland

Feedback from stars and active galactic nuclei is one of the most important processes steering the baryon cycle in galaxies, i.e. the set of complex phenomena driving the interplay between gas, dust, and star formation in their interstellar medium (ISM). Such a feedback could be strong enough to produce galactic-scale outflows able to sweep the gas out of the galaxies, drastically shaping their evolution. We investigated the impact of star-formation-driven outflows in local, low-metallicity dwarf galaxies drawn from the Dwarf Galaxy Survey. We made use of Herschel observations to detect atomic outflowing gas in the high-velocity wings of [C II] 158 μm emission line profiles. We found that outflows are ubiquitous in these galaxies, with an average outflow efficiency of the order of unity, at odds with predictions from state-of-the-art chemical evolution models. We estimated that $\sim$40% of the gas entrained by the outflows can be expelled from the ISM, significantly enriching the surrounding circumgalactic medium. We indeed found evidence of extended atomic gas and dust reservoirs around these galaxies and compared them with those observed by ALMA in the early Universe, pointing out their possible common origin. These results highlight the key role of stellar feedback in the baryon cycle of low-mass sources, and are crucial for calibrating cosmological simulations attempting to reproduce the processes ruling the evolution of these galaxies across cosmic time.

The origin of cold gas in nearby early-type galaxies

Ilaria Ruffa

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INAF – Istituto di Radioastronomia, Bologna, Italy

Local massive early-type galaxies (ETGs) have been historically believed to be mostly devoid of their gaseous reservoirs. However, over the past decade and thanks in particular to the advent of ALMA, significant amounts of cold gas have been observed in their nuclear regions. How this gas (re-)forms in ETGs and how it migrates from scales of several kpc to few hundreds of pc (where molecular gas is usually concentrated) is still hotly debated: it may be either internally re-generated (through stellar mass loss or hot halo cooling) or externally accreted (through interactions or minor mergers). Evidence is mounting that the large-scale environment plays a role in determining the dominant mechanism for the cold gas supply in ETGs. The many details of these processes, however, are still poorly understood. We are carrying out the first systematic, multi-component, multi-scale study of the cold gas origin in a volume-limited ($z < 0.05$) sample of ∼130 ETGs located in different environments and characterised by different types of nuclear activities (i.e. both active and quiescent). In this talk, I will present the first results obtained in this framework by combining high-resolution ALMA CO observations with deep HI data from MeerKAT and optical photometry from the VLT survey telescope (VST). I will also discuss how crucial is the multi-wavelength information to shed light on this issue and ultimately understand which mechanism(s) regulate the life-cycle of cold gas in nearby ETGs.

A high resolution view of the interstellar medium and star formation in nearby galaxies with JWST

Karin Sandstrom

University of California, San Diego, USA

JWST observations of nearby galaxies reveal the physics of the interstellar medium and star formation in stunning detail, particularly in combination with high resolution mapping of the cold ISM by ALMA. I will review results from recent observations of nearby galaxies, showcasing embedded star clusters, pervasive filamentary structure in the cold ISM, and a multitude of bubbles and shells throughout galaxies. These observations provide key insights into the life cycle of small dust grains, the structure of the cold ISM, the relationship between mid-IR emission, gas, and star formation, and the impact of stellar feedback on molecular cloud lifetimes and star formation efficiency.

Galactic thermometers: probing the radial gradient of dust temperature in local spiral galaxies

Vidhi Ritesh Tailor

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Although dust constitutes a small percentage (∼1%) of the interstellar medium (ISM) mass it affects galaxy properties in different and non-negligible ways. Understanding the properties of dust and its connections with other ISM components (e.g. cold gas) and main galaxy properties are therefore of particular importance for the formation and evolution of galaxies. I present the analysis of the spatial variation of dust temperature in a sample of 18 nearby, face-on, spiral, resolved galaxies from the DustPedia sample. The heating mechanisms of dust within galaxies are complex, influenced by both the energy output of recent episodes of star formations and the interstellar radiation field originating from older stellar populations. While the traditional approach of studying global properties struggles to discern between these heating mechanisms, radial profiles of dust properties offer a unique diagnostic avenue for comprehending the processes underlying dust heating. By combining dust temperature profiles with other resolved galaxy properties such as dust mass surface density, stellar mass surface density, and SFR surface density, we aim to understand the factors that influence dust heating.

Re-evaluating star formation efficiencies in nearby galaxies with a new $\alpha_{\rm CO}$ prescription

Yu-Hsuan (Eltha) Teng

University of California San Diego & University of Maryland, USA

Star formation in galaxies is governed by the amount of molecular gas and the efficiency that gas is converted into stars. However, assessing the amount of molecular gas relies on the CO-to-H_2 conversion factor ($\alpha_{\rm CO}$), which is known to vary with molecular gas conditions like density, temperature, and dynamical state – the same conditions that also alter star formation efficiency. The variation of $\alpha_{\rm CO}$, particularly in galaxy centers where $\alpha_{\rm CO}$ can drop by an order of magnitude, has caused major uncertainties in current molecular gas and star formation efficiency (SFE) measurements. To breakthrough such limitations, we leveraged ALMA multi-band CO isotopologue observations that have led us to (i) measure cloud-scale gas properties and $\alpha_{\rm CO}$, (ii) identify the physical drivers and observational tracers for $\alpha_{\rm CO}$ variations, and eventually (iii) construct a new $\alpha_{\rm CO}$ prescription for star-forming galaxies. By re-evaluating SFE across the PHANGS-ALMA sample with our new prescription, we found unprecedented trends suggesting that higher star formation rates in barred galaxy centers are mainly due to an enhanced SFE, rather than a substantially increased amount of molecular gas.

II. Cosmic noon

The cold ISM of gas-rich galaxies through cosmic time

Leindert Boogaard
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Leiden Observatory, Netherlands

Cold molecular gas is the fuel for star formation and to understand the build-up of galaxies over cosmic time, characterizing the interplay between the gaseous and stellar content inside galaxies is fundamental. Galaxies during the peak of cosmic star formation at cosmic noon ($z = 1 - 3$) and beyond are found to have order-of-magnitude higher gas fractions than their local counterparts. Yet, the impact of these large gas fractions on the typical conditions in the cold interstellar medium of the galaxies is still poorly understood. We present new ALMA multi-frequency observations of CO, [C I] and dust continuum of gas-rich galaxies at cosmic noon in the Hubble Ultra Deep Field from ASPECS. We analyze these data using novel radiative transfer models of the turbulent ISM, to provide constraints on the evolution of the typical gas mass and excitation conditions in the star-forming galaxies. Using JWST/MIRI, we study their rest-frame near-infrared morphology, which shows that a smoother and more centrally concentrated stellar structure is already in place in these massive star-forming galaxies, compared to their more clumpy rest-frame UV/optical morphology. We discuss the implications of these results on the cold gas mass fractions of galaxies and the evolution of the molecular gas content of galaxies through cosmic time. Finally, we present deep NOEMA measurements of cosmic molecular gas density at $z = 1-6$ in the Hubble Deep Field North, that provides independent constraints on the field-to-field variance in the cosmic molecular gas density.

Ionized gas emission in quiescent galaxies at Cosmic Noon with JWST

Letizia Bugiani
University of Bologna

The study of massive, quiescent galaxies at high redshift is crucial for understanding many physical processes driving galaxy evolution. The presence of a large population of such galaxies already in place at $z \sim 2$ poses the questions of how they formed and what mechanisms hide behind the quenching of their star formation. We analyze ionized gas emission lines in deep rest-frame optical spectra of 22 quiescent galaxies at $1.7 < z < 3.5$ observed by JWST NIRSpec in the COSMOS field, in order to derive information about the underlying sources of ionization and thus constrain the quenching mechanism. Emission lines are detected with SNR > 3 in 73% of the spectra, indicating the presence

of continued ionizing sources in this passive population, while, based on the Hα flux, the majority of the sample is indeed found to be quiescent. Galaxies with multiple detected emission lines make up more than half (54%) of the sample. There is no detected X-ray or radio activity for these galaxies: however, 8 galaxies are classified as AGN hosts by their emission line ratios. Additionally, 4 of the 8 AGN show broad and asymmetric line profiles, indicating the presence of powerful ionized gas outflows with typical velocities of $\sim$1000 km/s, which can only be due to AGN feedback. The general picture emerging from this study is that massive quiescent galaxies at Cosmic Noon harbour a significant fraction of never-before-detected AGN. The detection of ionized gas outflows in a subset of galaxies in the sample is an even more direct evidence of AGN feedback in action. Our results are consistent with a direct link between quenching of star-formation in massive quiescent galaxies and AGN feedback in the form of gas ejection at high velocities.

Do AGN-driven outflows quench star-formation in massive $z \sim 2$ galaxies?

Rebecca Davies

Swinburne University of Technology, Melbourne, Australia

AGN-driven outflows are thought to play a key role in quenching massive galaxies, but it has long been debated whether they eject enough gas to have a significant impact on star-formation. JWST has enabled us for the first time to trace the bulk of the mass in AGN-driven outflows at cosmic noon using NaD absorption which probes neutral-atomic gas. Using deep JWST/NIRSpec observations of 113 galaxies from the mass-complete Blue Jay survey, we show that neutral gas outflows are widespread in massive $z \sim 2$ AGN host galaxies. There is no significant difference in outflow incidence between the star-forming and quenching populations, but outflows from quenching galaxies have much larger mass-loading factors (ranging from 4–360). Outflows are commonly found in galaxies that experienced a recent rapid decline in star-formation activity but are rarely seen in galaxies that quenched gradually, suggesting a link between violent ejection of cold gas and rapid quenching. A case study of the post-starburst galaxy COSMOS-11142 additionally confirms the hypothesis that AGN-driven outflows contain significantly more neutral gas than ionized gas. Our findings suggest that AGN-driven ejection of cool gas may be a dominant mechanism for rapid star formation quenching at $z \sim 2$.

Star clusters shaping the morphology and tracing the ISM of galaxies out to the reionization epoch

Miroslava Dessauges-Zavadsky

University of Geneva, Switzerland

The HST observations have revealed that more than 60% of star-forming galaxies at cosmic noon have peculiar morphologies characterised by UV-bright clumps. Such morphologies have now been found to be ubiquitous in many galaxies out to the cosmic reionisation epoch thanks to the new JWST observations. When combined with the strong gravitational lensing by foreground massive galaxy clusters, we are able to resolve these clumps down to tens of parsecs and derive their physical properties. We find that they are young, massive ($10^5 - 10^8 M_\odot$), and dense star clusters complexes, significantly contributing to the recent star formation of the host galaxy and the build-up of its stellar mass. We explore the physical properties of these stellar clumps throughout the redshifts, and we find their star formation rate densities, together with their stellar mass densities (but at a more moderate level), increase with redshift. We associate this increase to the overall evolution of the host galaxy ISM conditions, which are more turbulent, rich in molecular cold gas, denser, with a higher stellar radiation field and higher disk hydrostatic pressure in the early times. Moreover, we link these star cluster complexes with molecular gas clouds detected with ALMA, and estimate the star formation efficiency to be ∼30% at $z = 1$. This is an important finding showing the possible increase of the star-formation efficiency toward higher redshifts, as such an increase could be one possible explanation to the problem of the numerous UV-luminous galaxies detected with JWST toward the epoch of reionisation. Globally, we demonstrate that multi-wavelength observations of high-redshift lensed galaxies start probing the star-formation cycle from the collapse of molecular clouds to the formation of stars in clustered star-forming regions at <100 pc scales.

Sub-kpc molecular gas morphology of 5 main-sequence galaxies at $z \sim 4.5$ revealed by ALMA

Toby Devereaux

University of Padova, Italy

The evolution of primordial low mass galaxies towards the more mature massive galaxies that we see at cosmic noon is shaped by the combination of gas accretion and mergers. However, there currently exists much uncertainty over the contribution of each of these processes to the overall evolution of galaxies. Previous characterisations of the morphology of galaxies in the molecular gas phase has been limited by the coarse resolution of previous observations. In this talk we present new high-resolution ALMA [C II] observations to analyse three $z \sim 4.5$ redshift main sequence galaxy systems (constituent of 5 galaxies) at resolutions of up to $0.15''$, which enable us to investigate the morphology and kinematics on kpc-scales and understand the interplay between stars, dust and molecular gas with unprecedented detail. Through this unique window, we gain insights into the molecular gas of main sequence galaxies undergoing mass assembly in the early Universe. We will show how ALMA data reveals more complex morpho-kinematic properties. We find significant evidence of mergers – with all systems showing evidence of major or minor

mergers (even though the majority were not previously identified to be mergers). We also tentatively detect star-formation powered outflows which appear to be fuelling diffuse gas regions and enriching the circumgalactic medium. We also show interaction-induced clumps, showing the profound effect that mergers have on the molecular gas and star formation in galaxies.

A three-phase ISM model for the largest cosmological simulations

Benedikt Diemer

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In the largest cosmological simulations of galaxy formation (such as IllustrisTNG, EAGLE, or SIMBA), star-forming clouds cannot be resolved. The SFR, stellar feedback, and the gas phases of the ISM are thus determined by sub-grid models. While the current state-of-the-art models succeed in reproducing the basic properties of low-redshift galaxies, they are missing key physical mechanisms and generally cannot predict most observables, for example the molecular distributions observed by ALMA. We are developing a new class of model that explicitly includes previously neglected physics, namely the warm-cold phase distinction, low-temperature cooling/heating rates, and turbulence. Before ever evaluating the model in simulations, we are guided by the spatially resolved observations of the ISM that are now available thanks to ALMA and other observatories. I will give an update on our efforts, and I hope to connect with observers to determine the most constraining observations that we should forward-model.

Dark progenitors and massive descendants: an ALMA/JWST perspective on radio-selected NIRdark galaxies

Fabrizio Gentile

University of Bologna, Italy

Since the first (sub)mm observations, it has been clear that the cosmic census of high-z galaxies based on deep optical/NIR surveys is quite far from being complete. The ‘darkest galaxies’, in which significant amounts of dust absorb the stellar emission, are missed by these surveys, even though their contribution to the cosmic Star Formation Rate Density and to the evolution of massive galaxies is thought to be significantly high. In this talk, I will present a significant population of these sources: the so-called Radio-Selected NIRdark galaxies, defined as radio-detected sources lacking a counterpart at optical/NIR wavelengths. Being the radio emission a good tracer of star formation, the RS-NIRdark galaxies could represent a significant population of Dusty Star Forming Galaxies. In this talk, I will present our first characterization of these sources as a population of highly dust-obscured ($A_V = 4$), massive ($M_* = 10^{11} M_\odot$) and star-bursting (SFR $= 500 M_\odot$/yr) galaxies *(Talia et al. 2021, Enia et al. 2022, Behiri et al. 2023, Gentile et al. 2024)*. Then, thanks to our first ALMA follow-up for a pilot sample of these sources, I’ll show our first results concerning their spectroscopic redshifts, molecular gas content, and ISM kinematics *(Gentile et al. 2024)*. Finally, thanks to the first JWST follow-up, I’ll present our first results concerning their stellar population, morphology, and environment *(Gentile et al. 2024, in prep)*. Combining all these results, I will present our forecasts for the possible evolutionary path of these sources as likely progenitors of the most massive galaxies in our Universe.

The nature and fate of the most obscured high-z galaxies

Carlotta Gruppioni

INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Italy

The early assembly of the most massive galaxies, and their contribution to the SFR density of the universe is currently one of the main challenges for galaxy formation models. Recently, a population of massive red sources already in place at $z > 2-3$ have been discovered, and called HST-dark, because missed by optical/UV search but detected at MIR and often in the mm. Their characterisation remains uncertain, due to limited information available, and to different selection techniques. JWST is now allowing us to investigate the nature of HST-dark galaxies, and to reveal new populations of early massive galaxies. One of these, the 'Little Red Dots' (LRDs), showing compact sizes, red spectra at $> 2\mu$m and blue/flat ones at $> 2\mu$m, are likely associated to the presence of an obscured AGN. I discuss the main properties of HST-dark galaxies, compared to those of JWST NIR-dark and LRDs. For those ALMA detected, I estimate the molecular gas mass and depletion times, showing that they are likely on the way to quenching their SF. For ALMA HST-dark and LRDs, there is a consensus on the presence of large amounts of dust, posing the problem of high-z dust production. To constrain dust properties and obscured SF at high-z we need to observe in the FIR. I will present the NASA PRobe far-Infrared Mission for Astrophysics (PRIMA), a FIR (25–235 μm) observatory operating in the 2030s in spectroscopy and imaging, that will allow us a leap forward in our knowledge of the high-z obscured universe.

Theoretical understanding of dust evolution across cosmic time

Hiroyuki Hirashita

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We introduce theoretical perspectives for the dust evolution across cosmic time based on our studies. One of the unique aspects of our theoretical modeling is that we calculate the evolution of not only the total dust amount but also the grain size distribution in galaxies. The grain size distribution is particularly important for radiative processes in galaxies since it determines the wavelength dependence of dust extinction (or the extinction curve) and emission. We first explain basic dust evolution processes and our theoretical models. We then review our implementation of the models in cosmological galaxy evolution calculations to understand how dust evolves in the history of the Universe. We also present some studies that focused on high-redshift galaxies. We finally mention recent developments of radiative transfer calculations that enable us to directly compare our models with observations.

Understanding the role of clumps in bulge formation using ALMA and JWST

Boris Sindhu Kalita

University of Tokyo, Japan

In the study of galaxy evolution, we are yet to understand the significance of the 'clumpiness' observed in high-redshift galaxies, primarily investigated in rest-frame UV. I will be presenting our work on galaxy clumps, that exploits JWST/NIRCam, HST/ACS, and high-resolution ALMA continuum imaging. By utilising the CEERS and FMOS JWST+HST databases to access rest-frame UV, optical, and near-IR data from galaxies within the $z = 1 - 2$ range, we achieve precise and resolved estimations of their stellar mass distributions. We find that the previously identified UV clumps in galaxies from this epoch constitute components of underlying, more abundant 'stellar clumps', detectable up to rest-frame near-IR wavelengths. We find these structures to have sufficient mass to drive gas to galaxy cores via gravitational torques, also supported by radial property gradients. Additionally, star formation in the galaxy bulge exhibits correlations with the total mass of clumps, further substantiating this scenario. High-resolution ALMA sub-mm continuum observations in the FMOS sample enable these measurements, allowing the spatial separation of core and disk star formation. Moreover, the net stellar mass of bulges show strong correlations with clump masses. This further links bulge formation and stellar clumps. Lastly, I will also show evidence of the bulge stabilising the gas in the disk, inhibiting further clump formation and driving morphological quenching across the galaxy.

Blowing dusty bubbles into the CGM: the contribution of dust-enshrouded starbursts to the baryon cycle

Patrick Kamieneski

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Maximal starbursts form stars at a sufficient rate to disrupt the collapse of molecular clouds through stellar feedback. Capturing their prevalence is critical to understanding the quenching of star formation after Cosmic Noon. Dusty star-forming galaxies (DSFGs) are considered the best candidates, as they are optically thick not just to UV radiation from massive stars, but even to dust-reprocessed IR light. This creates significant radiation pressure, capable of ejecting dust and gas from the plane of the disk and into the circumgalactic medium (CGM). To better understand this, we focus on some of the most luminous known DSFGs. Our sample of 30 gravitationally-lensed objects includes hyperluminous IR galaxies with SFRs $\sim$300–3000 $M_\odot$/yr. Using $0.1''$–resolution ALMA observations, and taking advantage of lensing magnification, we aim to identify $\sim$100 pc-scale regions forming stars at super-Eddington rates, from where galactic winds are likely to be launched. Such measurements are nearly impossible without lensing, as they would require $\sim$10 milliarcsec resolution. JWST is now adding valuable insight to this picture, peering through the thick shrouds of dust and allowing for spatially-resolved SED fitting of DSFGs on similar scales. Through NIRCam, we find widespread distributions of star formation, but also a significant presence of dust in front of more quiescent regions. This may be further evidence of our proposed scenario of dust being transported into the intervening CGM.

Sub-kiloparsec study of the ISM and star formation in starbursts at $z = 1.5$

Zhaoxuan Liu

Kavli Institute for the physics and mathematics of the Universe, University of Tokyo, Japan

We present observations and analysis of three starbursts at $z \sim 1.5$ revealed by high-resolution ($0.04-0.3''$) ALMA observations and JWST NIRCam/MIRI observations. The molecular line CO $J = 5-4$ provides gas kinematics for confirming the presence of rotating disks and additional components, while the FIR continuum gives an assessment of the dust/gas content on scales of $\sim 0.3-3$ kpc. The high resolution NIRCam data in multiple filters complements the relationships between different components within the starbursts by revealing the spatially resolved stellar distribution and dust attenuation while MIRI infers the PAH distribution. Exquisite imaging with NIRCam, MIRI and ALMA reveals diverse structures including highly obscured starbursting cores, unobscured tidal tails, clumps, and even normal spiral features at redder wavelengths *(Liu et al. arXiv:2311.14809)*. The latter is challenging whether a major merger is a requirement to trigger a starburst whereas a minor merger or gas-rich disk instability may be as effective. Regarding the ISM gas, all systems exhibit characteristics of being dusty, gas rich, and centrally concentrated. Within the central region, all exhibit heightened starburst activity, given the associated stellar mass, which is attributed to both high gas fractions and shorter depletion time. Furthermore, spatially resolved IR8 map discloses a PAH deficit in the central starburst core due to the PAH destruction by the intense star forming activity. These observations demonstrate the importance of spatially resolved studies on gas and stars for compact distant starbursts.

Witnessing the assembly of galaxies in a massive node of the Cosmic Web at $z \sim 3$

Antonio Pensabene

University of Milano–Bicocca, Italy

Galaxies form and evolve within the densest structures of the Universe where they are fed by filamentary inflows of gas from the Cosmic Web. However, the processes regulating how galaxies accrete their gas from the large-scale structure and how this affects their gas content are still largely unknown. A recent VLT/MUSE survey around a $z \sim 3$ quasar provided us with one of the first images of contiguous cosmic web filaments on Mpc-scales converging into a node containing a large concentration of galaxies and AGN. This represents a ideal laboratory to investigate the role of large-scale environment on the assembly of galaxies and AGN activity at high-z. In this talk, I will present ALMA follow-up observations targeting CO emission lines as well as mm-dust continuum in galaxies toward this massive node of the Cosmic Web. We obtained a complete census of dusty, gas-rich star-forming galaxies embedded in this gigantic structure revealing a huge overdensity (> 10–100) of galaxies, some of which remain undetected in the rest-frame optical/UV, including a closely-separated quasar companion. We revealed the presence of a massive ($> 5 \cdot 10^{12} M_{\odot}$) protocluster core in the node of the Cosmic Web. Here, we studied the galaxy cold-gas morphology and kinematics and discovered rotationally-supported disks. Our findings show that galaxies in dense regions at $z \sim 3$ are more massive and

significantly richer in molecular gas and dust than galaxies in fields, hence enabling a faster and accelerated assembly. I will discuss how these observations, in conjunction with our multiwavelength data from NIR to X-rays, shed light on the formation of galaxies within one of the densest regions of the Universe at $z \sim 3$.

Dust at Cosmic Noon with JWST and ALMA

Irene Shivaei

Centro de Astrobiología, CSIC-INTA, Spain

A crucial component of the baryonic matter in galaxies is the ISM consisting of gas and solid-phase metals called dust. Dust determines how galaxies look from UV to IR, how the ISM behaves, and the very process of star formation. We are now at the beginning of an exciting journey with the unprecedented IR capabilities, high sensitivity, and high angular resolution of JWST/MIRI compared to its predecessors such as Spitzer. For the first time, we are able to not only detect warm dust emission in individual typical galaxies across masses and star formation rates (SFRs) at cosmic noon, but also resolve the dust-obscured SFR $z \sim 1-2$. In this talk, I will show our recent results on the mid-IR dust emission of galaxies at cosmic noon ($z \sim 1-3$) from our GTO multi-band MIRI survey, SMILES, in HUDF. SMILES is the largest MIRI survey that covers all bands of MIRI from 5 to 25 μm, providing a unique opportunity to identify obscured AGN emission and extend our reach to star-forming galaxies with stellar masses an order of magnitude lower than ever observed before. I will show how the PAH mass fraction and obscured star formation fraction evolve from $z \sim 0$ (local studies) to $\sim$2 (SMILES). Additionally, owing to the wealth of deep ALMA data in HUDF, such as the ASPECS survey, I will present our results on the tight and universal correlation between the PAH emission (SMILES) and CO emission (ASPECS), marking a new base for the studies of dust and gas at cosmic noon.

A MUSE+ALMA+JWST view into a strongly-lensed Lyman Alpha Halo at $z = 3$

Manuel Solimano

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Spatially extended halos of H I Lyman Alpha (Lyα) emission are a common trait of star-forming galaxies, especially at $z \gtrsim 2$ when both star formation rates and the fraction of neutral hydrogen were higher. These so-called Lyα halos (LAHs) carry valuable information about the circumgalactic medium (CGM) and the associated processes that regulate galaxy growth. Yet LAHs remain mysterious, since complex radiative transfer distorts the line profile and morphology. Moreover, several competing theoretical scenarios are able to produce extended Lyα emission. In this contribution, we present one of the most detailed views yet of a LAH at $z = 3$, thanks to the combined power of gravitational lensing and state-of-the-art facilities such as HST, VLT/MUSE, ALMA and JWST. The target is a $\sim$20 kpc LAH hosting a pair of interacting UV-bright galaxies, which are highly magnified by a foreground cluster, allowing us to probe into sub-kpc scales. In previous work, we revealed spatial variations of the Lyα profile and a coherent outflow signal. Now, we analyze ALMA [C II] data and observe a compact [C II] distribution, with no evidence of kinematic coupling between the interstellar medium and the CGM traced by Lyα. Furthermore, JWST's early-release TEMPLATES program provided NIRCam, MIRI and NIRspec data on this benchmark system. We explore this exquisite dataset to address the outstanding questions: what powers the LAH? What drives the bulk outflow motion?

Testing ISM models using ALMA-observed CO excitation of $z = 2-4$ dusty star-forming galaxies

Dominic Taylor

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Molecular gas plays a key role in galaxy evolution, providing the raw fuel for star formation. Observations have shown that the molecular gas fraction in galaxies evolves strongly with redshift, increasing up to $\sim$50% for massive galaxies at high redshift ($z \sim 2$). Submillimetre galaxies (SMGs) found at high redshifts have high star-formation rates and dust masses similar to local ultra-luminous infrared galaxies (ULIRGs) and are therefore ideal candidates for investigating star-formation in the early Universe. The carbon monoxide (^{12}CO) emission is commonly used as a powerful diagnostic of the properties of the molecular hydrogen. Furthermore, the diversity of the spectral line energy distributions (SLEDs) of CO is expected to reflect the gas density and temperature of the interstellar medium, which in turn is related to the properties of the star-forming regions. Recent findings from hydrodynamical simulations have suggested that the shapes of CO SLEDs should strongly correlate with the galaxy-averaged star-formation rate surface densities. To test these predictions, I will present the results using observations of $z \sim 2-4$ luminous, dusty, star-forming galaxies from the Atacama Large Millimeter/submillimeter Array (ALMA) measuring the CO emission in multiple J transitions, as-well-as searching for further empirical correlations between the molecular gas properties and other observables such as the local interstellar radiation field.

Painting galaxies growth and death at cosmic noon (and beyond)

Francesco Valentino

European Southern Observatory (ESO)

In contemporary observational astronomy, the synergy of powerful telescopes probing the entire electromagnetic spectrum is pivotal in uncovering the true nature of celestial objects. With the advent of JWST, the enhanced capabilities of ALMA, and ever-growing data archives, astronomers now have formidable tools to create a complete portrait of how galaxies assemble, grow, and eventually transition to a quiescent phase. In this seminar, I will address several open questions in modern galaxy evolution and present promising avenues for understanding what the interstellar medium can reveal about how galaxies collect cold gas, transform it into stars, and how feedback processes regulate and eventually halt star formation around the cosmic noon epoch – and beyond.

CH^+ (1–0) in $z \sim 2-6$ starburst galaxies: probes of extended reservoirs of multi-phasic turbulent gas

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Submillimetre-selected galaxies at redshifts $z \sim 2-6$ are among the most intensely star forming galaxies in the universe. The way they accrete their gas to form stars at such high rates is still a controversial issue. We have detected the CH^+ $(1-0)$ line in emission and/or in absorption in all the gravitationally lensed starburst galaxies observed so far with ALMA in this redshift range (*Falgarone et al. 2017, Vidal-García et al. in prep.*). The highly endothermic formation of CH^+ and the extremely short lifetime of its $J = 1$ level make this line a unique tracer of dissipation of mechanical energy, seen in emission in very dense gas and in absorption in diffuse gas. The absorption lines observed in this sample reveal the intermittent dissipation in massive turbulent reservoirs of diffuse molecular gas extending far out of the galaxies. The emission lines detected with widths up to a few thousands of km/s, arise in myriad molecular shocks powered by the feedback of star formation (*Godard et al. 2019, Lehmann et al. 2020,2021*) and, in one case, an active galactic nucleus (*Vidal-García et al. 2021*). The CH^+ $(1-0)$ lines therefore probe the sites of prodigious energy releases in the CGM of these starburst galaxies. Mechanical energy is stored in turbulent motions of molecular gas before being radiated away and lost. These turbulent reservoirs therefore act as extended buffers of mass and energy over timescales of a few tens to 100 Myr. Finally, we will present the detection rates of inflows and outflows in the galaxies of the sample by means of the CH^+ $(1-0)$ absorption lines.

Revealing the onset of star formation by studying high-redshift clumpy galaxies with ALMA

Anita Zanella

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Star-forming galaxies at $z \sim 2-4$ seem to be more gas-rich than local galaxies and to have gravitationally-unstable interstellar medium. Simulations predict that such conditions allow the formation of massive star-forming regions, dubbed 'clumps', 100 times larger and more massive than local star-forming regions. While clumps have been extensively studied at UV and optical wavelengths, their molecular gas and dust reservoirs have hardly been observed and are still poorly constrained. We tackled these open questions by investigating the [C II] and dust morphology of a $z \sim 3.4$ lensed galaxy hosting four clumps detected in the UV continuum. We conducted ALMA observations probing scales down to ∼300 pc and detected three [C II] clumps, while we do not detect the dust continuum. We used the [C II] luminosity as a tracer of molecular gas, as recently suggested by severeal observational and theoretical studies, to estimate the star formation efficiency of clumps and investigate their location in the Schmidt-Kennicutt plane. This revealed that clumps span a range of SFE, likely depending on their evolutionary phase (early formation vs more evolved ages). These observations suggest that multi-wavelength observations ranging from the UV to the FIR are key to understand the onset of star formation and the role of clumps in galaxy evolution. I will conclude the presentation by discussing future prospects and developments.

III. Active Galactic Nuclei

Formation of filaments/feathers in disc galaxies: Is self-gravity enough?

Raghav Arora

Universität Hamburg, Germany

Dense filaments/feathers are kpc scale dusty features found in nearby main sequence disc galaxies. Visible as dust-attenuated features in HST and recently seen in emission maps of JWST/MIRI images in unprecedented detail. They are known to harbor embedded star forming regions, giving us insight into early stages of star formation and are expected to play an important role in molecular cloud formation as well. We explore the origin of these galactic filaments via the action of a global gravitational instability. Using 3D high resolution numerical simulations of isolated disc galaxies, we demonstrate that self-gravity alone is able to form galactic filaments without the need for spiral lanes, magnetic fields or feedback from stars. Their morphological properties, as well as their timescales of formation are found to vary with the thermodynamical and rotational properties of the disc. This is characterised by the dimensionless ratio v_c/c_s (ratio of the saturated circular velocity to the sound speed) of the galaxy. We also quantify the spacing of the filaments using a 2D Fourier transform and compare them with JWST and HST observations of nearby galaxies and find them to be in good agreement.

A 3D view on the local gravitational instability in cold gas discs of star-forming galaxies at redshift $0 < z < 5$

Cecilia Bacchini

DARK – University of Copenhagen, Denmark

Local gravitational instability (LGI) is considered key for regulating star formation and gas turbulence in galaxies, especially at high redshift. Instability criteria usually assume infinitesimally-thin discs or approximations to include the stabilising effect of the gas disc thickness. I will present a new 3D instability criterion for rotating gas discs that are vertically stratified in an external potential. Thus, LGI can be studied both in and above the galaxy midplane in a rigorous and self-consistent way. The criterion is applied to 44 star-forming galaxies, including H I and CO nearby discs, and ^{13}CO and [C II] discs at $1 \lesssim z \lesssim 5$ observed with ALMA. The sample is representative of main sequence galaxies at $z \approx 0$ and includes massive star-forming and starburst galaxies at $1 \lesssim z \lesssim 5$. Using the 3D approach, there are less unstable discs than using the criterion for infinitesimally-thin discs. No unstable disc is found at $0 \lesssim z \lesssim 2$, while ≈60% of the

systems at $4 \lesssim z \lesssim 5$ are locally unstable. However, a relatively small fraction of the total gas (≈30%) is potentially unstable. These results disfavour LGI as the main driver of star formation and turbulence in nearby star-forming galaxies. LGI likely becomes important at high redshift, but the input by other mechanisms seems required in a significant portion of the disc. This work highlights the importance of comparing nearby and high-z galaxies. Thanks to ALMA and JWST, this approach can be used to study LGI in larger samples at high redshift.

Relaxation timescales of stellar-gas misalignments in the EAGLE simulation

Maximilian Baker

Cardiff University, UK

Mergers and accretion events are a key element of the baryon cycle, and have strong impacts on the distribution, kinematics and mixing of gas in galaxies. Major mergers are well studied in this regard, but gas-rich minor mergers and cold gas accretion are much less well constrained. A key probe of these external gas accretion events are kinematic misalignments between the stellar and the cold gas components. These misalignments are predicted to be short-lived (lifetimes ∼100 Myr), apart from in the presence of continued external accretion. However, such relaxation timescales are unable to explain the distribution of misalignments observed in $30-40\%$ of early-type galaxies (ETGs). In this talk, I am going to present the results obtained by using the cosmological hydrodynamical simulation EAGLE to investigate the stellar-gas misalignment relaxation timescales over a large, representative galaxy population (approximately 5 600 galaxies) from present day to $z = 1$. We find good agreement with existing observational results from SAMI/MaNGA and mm-interferometers (such as ALMA), with $39 \pm 5\%$ of ETGs showing significant misalignments at $z = 0$. The misalignments coincide with mergers only ∼16% of the time, with median relaxation timescales of ∼300 Myr and only 6% of misalignments lasting longer than 1 Gyr. The use of EAGLE and future cosmological simulations allows us to constrain the physical processes extending the relaxation times, shedding light on the gas accretion processes that fuel star formation and AGN activity in massive galaxies.

Galactic coronae in Milky Way-like galaxies: the role of stellar feedback in gas accretion

Filippo Barbani

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Star-forming galaxies like the Milky Way are surrounded by a hot and diffuse gaseous halo at the virial temperature, the galactic corona. This component strongly influences their evolution: while the inflow of coronal gas could potentially sustain star formation with new material, galactic fountain flows driven by supernova activity eject gas from the disc back to the corona. In this context stellar feedback plays a major role. Although it is generally considered to act mainly against star formation, it is speculated that it could also promote the formation of new stars since it mediates the interaction between the star-forming disc and the corona. However, notwithstanding its crucial importance for galaxy evolution, the balance between the positive and negative nature of stellar feedback is still not well understood. In this talk, I will present results from N-body hydrodynamical simulations of isolated Milky Way-like galaxies, aimed at studying the presence of positive feedback generated by the interaction between the disc and the corona. I made use of the moving-mesh code `Arepo` in conjunction with the `SMUGGLE` model, an explicit interstellar medium and stellar feedback model that includes key stellar feedback channels such as energy and momentum injection from stellar winds and from supernovae. I found that the gas accreted from the corona is the primary fuel for the formation of new stars, helping in maintaining a nearly constant cold gas mass in the galactic disc. Stellar feedback generates a gas circulation between the disc and the corona by ejecting different gas phases that are eventually re-accreted onto the disc. This circulation of cold gas and its mixing with the corona causes the formation of a gas phase at intermediate temperatures at the disc-corona interface that enhances the cooling of the hot corona and its subsequent accretion onto the disc, thus sustaining star formation. Therefore, this process acts as a positive feedback mechanism and has a direct impact on the formation of new stars in the disc, with major implications for galaxy evolution.

The magnetic field structure of the central region of the starburst galaxy NGC 253

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Observations of polarized light at far-IR and sub-millimeter emitted by magnetically-aligned dust grains can be used to map the orientation of the B-fields in the plane of the sky in the cold regions of the interstellar medium such as molecular clouds, where the star formation takes place. We present the analysis of ALMA polarization observations in band 4 ($\sim$140 GHz) and 7 ($\sim$350 GHz) of the central regions of the galaxy NGC 253, a very well studied nearby starburst galaxy. This galaxy's central area exhibits a complex structure characterized by 14 dense clumps of molecular gas, likely hosting young super starclusters. The intense feedback from the starburst region manifests as various structures in the molecular gas, including bubbles, streams, and a prominent multiphase outflow at scales exceeding kiloparsecs. We obtained a detailed parsec-scale map of magnetic field structures in the galaxy, exploring their relationship with the outflow and super starclusters. The findings suggest a significant role of magnetic fields in the collimation of the outflow, and highlight a correlation between polarization structures and the presence of super starclusters. This investigation contributes valuable insights into the interplay between magnetic fields, molecular outflows, and star formation in nearby galaxies.

Excitation or efficiency: a multi-line analysis of dense gas tracers across the Antennae

Ashley Bemis

University of Waterloo, Canada

As extreme systems, galaxy mergers are important testbeds for constraining star formation models and the baryon cycle. The Antennae, the nearest gas-rich major merger, is of particular importance as it is well studied with interesting variations in the star formation efficiency of dense gas (SFE_{dense}) at sub-kpc scales. L_{HCN}/L_{CO} appears to be enhanced in the nuclei relative to the overlap, indicating a higher dense gas fraction (f_{dense}), while multiple SFR indicators are suppressed relative to L_{HCN} in the nuclei indicating a lower SFE_{dense}. Additionally, L_{HCN} is enhanced relative to L_{HCO^+} in NGC 4038, but not elsewhere in the Antennae. This indicates that the conversion of molecular line luminosities to dense gas masses may be different than typically assumed. We present the first multi-J radiative transfer modeling of dense gas tracers at sub-kpc scales across the Antennae to constrain the physical conditions of the gas exciting HCN and HCO^+ using data from ALMA and the SMA. This includes the $J = 1-0, 3-2$, and $4-3$ lines of HCN and HCO^+ in NGC 4038 and SGMCs in the overlap region. We combine this with data of the CN and HNC $J = 1 - 0$ transitions to explore potential chemical variations in dense gas tracers at these scales. Finally, these results are compared against the predictions of turbulent star formation models to assess if we are observing true variations in SFE_{dense} and f_{dense}, or if the emissivity of HCN is enhanced in the nuclei due to physical conditions of the gas.

The molecular view of AGN feedback at cosmic noon: do AGN gas-deplete their hosts?

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Active galactic nuclei (AGN) are thought to play a key role in shaping the buildup of galaxies. If AGN influence galaxy growth, then they will reasonably impact the molecular gas reservoir first, and star formation (SF) as a consequence. Literature results concerning the gas content of high-z AGN hosts often focused on high-luminosity AGN ($L_{bol} > 10^{46}$ erg/s), i.e. good candidates for driving outflows. The SUPER and KASHz surveys are complementary projects that aim at assessing AGN feedback in samples of unbiased, X-ray-selected AGN at cosmic noon. The SUPER project recently found that significant CO depletion is present only in the most massive host galaxies ($M_* > 10^{11}\,M_\odot$), demonstrating the importance of using unbiased samples representative of the AGN population at cosmic noon. I will present our comparative study of the total molecular gas content, as traced by CO, of a sizable sample of cosmic noon AGN, obtained by merging SUPER and KASHz AGN with targeted or archival ALMA observations, and a control sample of matched non-AGN galaxies. Applying the Bayesian framework developed by the SUPER project, we find that AGN at cosmic noon are significantly CO depleted for fixed FIR luminosity compared to non-AGN galaxies. Moreover, AGN and non-AGN show a significantly different gas fraction distribution, with AGN shifted and skewed to lower values, consistent with negative AGN feedback effects. Lastly, I will report on the comparison between our observational results and the predictions of cosmological simulations.

Unveiling cosmic cold gas: insights from ALMACAL survey

Victoria Bollo

European Southern Observatory (ESO)

A full understanding of galaxy evolution requires a complete description of the role of cold gas as the primary fuel for star formation. The amount of cold gas in galaxies and how efficiently it is converted into stars determine many galaxy properties. Observations of molecular gas, particularly through CO emission, are directly linked to star formation over cosmic time *(Carilli & Walter 2013, Tacconi et al. 2020).* While ALMA has made significant progress in this field, the limited scales of previous surveys and the potential effects of cosmic variance have constrained the accuracy of cosmic gas mass density measurements. Here, I will introduce the ALMA calibrator dataset (ALMACAL), a large untargeted survey that covers 1064 calibrator fields across the southern sky. Encompassing over 1000 square arcseconds and accumulating over 2000 hours of integration time, ALMCAL surpasses previous surveys in volume by at least ten times (Zwaan et al. 2022). I will outline the methods used to process and image a subset of the highest-quality data from this extensive survey. Initial findings will include the CO luminosity function based on ALMA Bands 3 and 6 detections. I will discuss the significance of these results in revealing the critical role of cold gas within the baryon cycle of galaxies.

Failed AGN feedback? Molecular reservoirs are not severely affected by extreme AGN ionized-wind in ULIRGs

Xiaoyang Chen

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Large-scale outflows are generally considered as a possible evidence that active galactic nuclei (AGNs) can severely affect their host galaxies. Recently several ultraluminous IR galaxy (ULIRG) selected from AKARI FIR catalog was found to have galaxy-scale [O III] 5007Å outflows with extremely high energy-ejection rates compared to active galaxies at $z < 2$. However, the latest ALMA follow-ups of these galaxies reveal that the molecular reservoirs are not severely affected by the fast ionized AGN wind. The velocity of the molecular outflow is slower by one order of magnitude than that of ionized-wind, indicating that the outflowing molecular gas could not escape from the gravitational potential of these galaxies. The finding suggests that the feedback effect on star-forming clouds in hosts could be limited even with extremely fast and powerful AGN ionized-outflows, which is consistent with the vigorous starbursts in the galaxies, i.e. with SFR of $1000\,M_{\odot}/\mathrm{yr}$.

The ISM of the most luminous obscured quasar revealed by ALMA and JWST

Tanio Diaz Santos

Institute of Astrophysics – FORTH, Greece

In this talk I will present results obtained from ALMA and JWST observations of the most luminous obscured quasar known, WISEJ W2246-0526, with a bolometric luminosity of $\sim 3.5 \cdot 10^{14} L_{\odot}$, located at $z \sim 4.6$. The hot, dust-obscured quasar and its host are surrounded by at least three companion galaxies, which also show dusty tidal streamers connecting them with the central host, thus suggesting they in the process of being accreted. New, very deep ($> 12^h$ on-source) ALMA observations of the [C II] emission line reveal extremely complex kinematics in the multiple-merger system. For instance, one of the previously identified dusty companions is now resolved spatially and kinematically into several sub-components, indicating that this is, in itself, a merger of three galaxies likely interacting with each other while simultaneously infalling towards the quasar host. We also identify a radial gradient of increasing gas turbulence outwards from the central quasar reaching velocity dispersion up to 1000 km/s (FWHM) whose origing is still unknown. In addition, WISEJ W2246-0526 was observed by JWST last year. A 6-tile NIRSpec/IFU 3D map of the entire merger system, targeting Hα, [N II], [O II] and Hβ, was obtained, together with a MIRI/MRS pointing towards the central quasar and host probing the hot, dust continuum emission. Results from these observations will also be presented.

The manifold ways of AGN feedback on the molecular gas: X-ray dominated regions and outflows

Federico Esposito

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The molecular phase of the interstellar medium (ISM) plays a central role in the evolution of galaxies: it feeds star formation and black hole accretion. At the same time, stars and AGN excite the gas through radiative and mechanic feedback, which can be studied by modelling the carbon monoxide (CO) luminosities and velocities, respectively. The CO spectral line energy distribution (SLED), in particular, can be used to trace the X-ray dominated regions (XDR) due to the AGN. In this context, we developed a new physically-motivated model for estimating it in AGN-host galaxies. It takes into account the internal density structure of giant molecular clouds (GMCs), the radiative transfer of photo-dissociation regions (PDRs) and XDRs, and the mass distribution of GMCs within galaxies. The model can fit observed CO SLEDs by finding the best CO-to-H_2 conversion factor and obscuring column density. I will show the results from testing it for a sample of local Seyferts. For the nearby Seyfert NGC 5506, I will also show evidence of a molecular gas nuclear depletion, likely due to the action of AGN feedback. Using high angular resolution observations, we modelled the complex kinematics of molecular and ionized gas to separate the wind component from the rotating disk. We found a difference of a factor of 40 between the mass outflow rate of cold and hot gas. By comparing the radiative and mechanic processes, I will present a comprehensive scenario of AGN feedback in local active galaxies.

The ALMA view of the gas cycle in nearby AGN

Santiago García-Burillo

Observatorio Astronómico Nacional – Instituto Geográfico Nacional (OAN-IGN), Spain

The availability of high-resolution ($< 10 - 100\,\mathrm{pc}$) images of the distribution and kinematics of molecular gas in the circumnuclear disks of nearby AGN is key to decipher the mechanisms regulating the feeding and feedback cycle of nuclear activity in galaxies. These observations have started to be accessible for an increasing number of targets thanks to the advent of ALMA. We describe how detailed studies conducted by our group have underlined the potential pivotal role of radio jets and AGN winds in launching molecular outflows in a number of AGN. We have also searched for the 'relic' imprint left by AGN feedback on the radial distribution of molecular gas using high-resolution ALMA images from > 70 nearby AGN in 3 CO lines obtained in the context of the NUGA, GATOS, WISDOM, PHANGS and LLAMA projects. Using different prescriptions for the normalised distribution of molecular gas we find evidence of enhanced nuclear-scale molecular gas deficits in the most extreme AGN. We also detect molecular outflows in the sources that show the most extreme nuclear-scale gas deficits. This suggests that AGN feedback can be 'caught in the act' more frequently among the higher luminosity and/or higher Eddington ratio sources. We discuss possible avenues to validate this evolutionary scenario using numerical simulations of the feeding and feedback cycle in galaxy disks.

Exploring the role of outflows driven by active galactic nuclei in the baryon cycle up to redshift ~1

Chiara Circosta

European Space Agency (ESA)

Feedback from active galactic nuclei (AGN) is thought to be key in shaping the life-cycle of galaxies. AGN inject a significant amount of energy into the surrounding interstellar medium and launch gaseous winds. They are therefore able to potentially regulate future star formation in their hosts. AGN feedback is a necessary ingredient of theoretical models of galaxy evolution, although proving its role observationally remains a challenge. Moreover, large spectroscopic surveys are needed to characterize AGN outflows in a systematic fashion across cosmic time. The Dark Energy Spectroscopic Instrument (DESI) survey is collecting hundreds of thousands of spectra over a large area of the sky, therefore providing an unprecedented sample of targets to investigate diagnostics of galaxy-wide scale ionized outflows such as [O III] up to redshift ~1. In this talk, I will present recent work aimed at building a statistical understanding of AGN feedback across the galaxy population. In particular, this dataset enabled an ideal avenue to characterize: (i) the occurrence of outflows in AGN as a function of redshift, AGN/host galaxy properties (e.g. AGN luminosity, black hole mass, stellar mass), and AGN types, (ii) scaling relations between outflow and AGN/galaxy physical parameters, for a cosmic epoch ($z = 0 - 1$) overall unexplored so far with such large statistics.

Mapping molecular gas in super spiral galaxies

Romane Cologni

Faculté des Sciences et d'Ingénierie – Sorbonne Université, Paris, France

The population of galaxies in the high-mass range ($M > 10^{11} M_{\odot}$) is almost entirely represented by quenched early-type galaxies. Except for 6% of the most luminous galaxies observed by *Ogle et al. (2016, 2019)* at redshift $z < 0.3$, that are indeed massive super spiral galaxies (SSG). These objets are of great interest because they question our knowledge on galaxy evolution and challenge mass-quenching scenarios. They have preserved their rotation-supported disc shape as well as a standard to high star formation rate (SFR) throughout their growth process, although we know growth can severely affect both these aspects, either by disrupting the gas and stellar dynamics (mergers, collisions) or by depriving the galaxy of its gas content (RAM pressure stripping, tidal effects, AGN feedback). As such, SSGs constitute a relevant population to study failed quenching in galaxies. Learning more about their star forming gas content is necessary to better understand star formation in such objects. In this poster, I will present preliminary results from molecular gas observations (NOEMA/IRAM) of 10 SSGs at redshift ranging $z \sim [0.01, 0.25]$, which allowed us to map the distribution of the cold gas reservoir and measure the star formation efficiency.

Extraplanar gas in nearby galaxies

Mikhail de Villiers

University of Cape Town, South Africa / South African Astronomical Observatory

The flow of gas into and out of galaxies is a key factor in understanding how galaxies maintain their star formation, or how they turn into gas-poor low star formation rate galaxies. Deep H I observations of galaxies reveal the presence of copious amounts of H I in their galactic haloes. MHONGOOSE is an H I Nearby Galaxies Legacy Survey of MeerKAT probing the H I in and around local disk galaxies with an unprecedented combination of high spatial resolution and sensitivity. Combining deep H I data from MHONGOOSE with high resolution spectroscopic data from SALT allows for the detection an analysis of extraplanar gas in both its neutral atomic as well as its ionised state. Here we present results on analysis done using the full-depth MHONGOOSE cubes through the means of tilted-ring modelling and Gaussian decomposition to quantify the dynamics of the galaxy. This is supplemented with results from spectroscopic SALT data to probe the ionised gas associated with the galaxy. This work exhibits how the combination of radio data achieved at both a high sensitivity and high resolution can be combined with high-resolution long-slit spectroscopy.

Does the fundamental metallicity relation evolve with redshift?

Alex Garcia

University of Virginia, Charlottesville, USA

Understanding the intricate relationship between stellar feedback and a galaxy's metal content is essential for unraveling the complexities of the baryon cycle. The fundamental metallicity relation (FMR), a three-parameter correlation between stellar mass, gas-phase metallicity, and star formation rate, serves as a valuable tool for tracing the evolution of galactic gas dynamics across cosmic epochs. Surprisingly, previous studies indicate no redshift-dependence in the FMR up to $z \sim 2.5$. However, recent observations from JWST challenge this view, suggesting evolution of the FMR in the early universe. In this presentation, I propose a novel framework to reconcile these discrepancies and shed light on the evolving nature of the FMR. I corroborate the JWST findings, identifying clear evidence of FMR evolution in the cosmological simulations Illustris, IllustrisTNG, and EAGLE. Additionally, I find a remarkable sensitivity of the FMR to variations in stellar feedback implementation between the different simulation models. I further predict that simulations incorporating burstier stellar feedback, such as FIRE, should have a much weaker FMR. These findings underscore the significance of the high-redshift FMR as a sensitive probe for delineating the underlying physics governing galaxy formation in the early universe.

SLICK-LIM: an AI-assisted model for forecasting (molecular) line intensity mapping experiments

Karolina Garcia

National Center for Supercomputing Applications, University of Illinois, USA

Accurate predictions for molecular line intensity mapping (LIM) experiments require exact thermo-radiative-chemical equilibrium calculations in molecular clouds of bona-fide hydrodynamic simulations while covering cosmological scales. I will show the first such model, which was built using `SLICK` (the Scalable Line Intensity Computation Kit, `https://arxiv.org/abs/2311.01508`) – a python package developed by us that combines realistic and ML-predicted CO, [C I], and [C II] luminosities to generate entire light cones. I will show its methodology and application to SIMBA and IllustrisTNG, along with the first predictions for LIM experiments based on exact luminosity calculations. Finally, I will mention the many projects SLICK has been getting applied to, ranging from dark CO studies and luminosity profiles, to tests on [C I] as a molecular gas tracer and studies on the impact of AGNs on measured luminosities.

The role of dynamical equilibrium pressure in elevated molecular gas ratios and star formation of cluster galaxies

Taavishi Jindel

McMaster University, Hamilton, Canada

The environment of a galaxy influences its gas and star formation properties via the evolutionary mechanisms, such as ram pressure stripping and tidal stripping, the galaxy experiences. In particular, the molecular to atomic gas ratio and dynamical equilibrium pressure are key parameters for understanding star formation in galaxies. I use 1.2 kpc data for galaxies in the Virgo Cluster from the VERTICO survey and for field galaxies from the HERACLES survey to study the spatially resolved relationship between molecular gas ratios and star formation properties (e.g. star formation rate, molecular gas depletion time) in galaxies as a function of dynamical equilibrium pressure. I find that cluster galaxies have higher molecular gas ratios at a given dynamical equilibrium pressure than field galaxies. Within both samples there is strong galaxy to galaxy variation in the relationship driven by the gas content of the galaxy. To gain a better understanding of the roles that cluster pressure and ram pressure stripping play in the elevated molecuar gas ratios of cluster galaxies, I explore how the H I-deficiency, cluster pressure, and the extent of ram pressure stripping the galaxies experience impact the relationship.

The interstellar medium properties in the most radio-loud quasars at $z > 6$

Yana Khusanova

Max Planck Institute for Astronomy, Heidelberg, Germany

The first Gyr since the Big Bang is a period of rapid supermassive black hole (SMBH) growth. It is thought that active SMBH (AGN) profoundly affect their host galaxies' star formation and interstellar medium (ISM). Quasar host galaxies at high redshift ($z > 6$) can provide clues on the role of AGN in the earliest stages of galaxy evolution. Most quasars (∼90%) are radio-quiet and only a few have relativistic jets. Little is known about the host galaxies of radio-loud quasars at $z > 6$. In this talk, I will present multi-line analysis of the two brightest $z > 6$ radio-loud quasars in [C II], FIR, radio, and X-ray. These are currently the only radio-loud quasars at $z > 6$ in which [C I] emission line and CO spectral line energy distribution (with CO transitions from CO $(5-4)$ to CO $(10-9)$) have been observed. With this suite of observations, we can determine the role of AGN in the ISM excitation, and the contribution of synchrotron emission from the jet to the IR luminosity. I will discuss the differences between the observed ISM properties in the radio-loud and radio-quiet quasar host galaxies at the highest accessible redshifts.

The dynamical impact of cosmic rays in Milky Way-like galaxies

Karin Kjellgren

Heidelberg University, Germany

The Milky Way, with its distinctive observational features, is a unique laboratory to constrain physical parameters and test various theories of galaxy evolution ranging from star formation, to the formation of gaseous structures and galactic outflows. A particularly important ingredient in the interstellar medium for the vertical structure of the gas, outflows and fountain flows are cosmic rays (CRs), which reveal their impact via gamma rays. We perform high-resolution magnetohydrodynamical simulations of the Milky Way, in which we follow individual massive stars and include self-consistent stellar feedback such as SNe and CRs, dynamically coupled to the MHD equations. We model the multi-phase interstellar medium using a non-equilibrium chemical network that includes hydrogen and carbon species, allowing us to take into account the relevant cooling and heating processes and compare the simulations to observations. We will present how thermal and CR feedback affect the structure of the galaxy and the gas dynamics. We show how the inclusion of CRs change the structure and thermal phase of outflows and fountain flows in different regions of the galaxy, from the Galactic Center to the solar circle and beyond. Finally, we back up our simulations with accurate gamma ray maps both in the solar vicinity as well as for the global galaxy, which is compared to observations of the gamma-ray sky.

Does star formation drive increased molecular gas turbulence in galaxy centres?

Jennifer Laing

McMaster University, Hamilton, Canada

Recent work by the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) collaboration found higher molecular gas surface densities and velocity dispersions in barred galaxies compared to unbarred galaxies. The observed increase in line width may be due to turbulence caused by streaming motions along the bar, which is expected to cause a build up of gas and star formation in the central region. In this work, I explore bar turbulence in molecular gas using published high resolution ($\sim$100 pc) measurements of CO $(2-1)$ from the PHANGS-ALMA survey. I compare the molecular gas surface density, velocity dispersion, and star formation rate, in the centres of barred and unbarred galaxies. All three quantities are found to be enhanced in barred galaxy centres. I further investigate ways a rapidly rising rotation curve could contribute to enhancements of these properties on the scale of molecular clouds.

A NIRSpec/IFU view of a quasar-galaxy merger at cosmic dawn

Federica Loiacono

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Quasars are among the most active sources emerging in the early universe ($z > 6$). Their host galaxies have stellar masses and star formation rates orders of magnitude higher than what is observed in typical galaxies at the same redshifts. Investigating these sources is thus necessary if we want to unveil how the first massive galaxies formed. Here we present the rest-frame optical spectrum of a $z = 6.23$ quasar obtained with JWST/NIRSpec IFU. The spectrum shows the quasar emission with exquisite quality (S/N $\sim 100-400$ per spectral element). As shown by previous ALMA and HST data, the quasar presents two companion galaxies and lies within a prominent Lyman α halo. This makes this source a perfect target to investigate several aspects, such as, the black hole properties, the quasar-host and companion galaxies, and the environment. Specifically, the NIRSpec data provide us with: accurate estimates of the black hole mass and the Eddington ratio, study of AGN feedback via ionized outflows. A map of the ionized gas in the host galaxy and companion sources, showing a complex velocity structure, which enables a detailed study of the dynamics within this system, A chart of the photoionization conditions in the gas, which enables shedding light on the physics of the interstellar medium (metallicity, hardness of the ionization field, powering source, etc), A map of the halo seen in Hα, which reveals resonance scattering as the main mechanism powering the Lyman α halo. These data offer a deep insight into the assembly and early growth of the first massive galaxies and black holes.

Low-luminosity AGN Feedback: the ISM impact by the ADAF/radio-jet in M58

Iván E. López

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We delve into the effects of LLAGN feedback through an in-depth study of Messier 58. This galaxy hosts a radio-loud AGN, with evidence of advection-dominated accretion flows (ADAF) at its center. Spitzer spectral maps reveal a luminous, warm H_2 disk at the galaxy center. Higher resolution Gemini NIRI imaging, ALMA CO $(2-1)$, and HST multiband imagery expose in-situ shocks within the inner 2.6 kpc, suggesting radio-jet-driven outflows. The temperature of the inner disk is higher than the temperature observed in the spiral arms, where stars are forming. We determine that the star formation is suppressed in the inner disk, while the PAH is not destroyed, as in more luminous AGN. Forbidden line ratios from ionized gas indicated shock heating by low-velocity shocks, suggesting that the gas emissions are excited by shocks and turbulence driven by the radio jet and outflows. M58 will be observed during this summer with JWST NIRSpec and MIRI, revealing this feedback's impact at a 10 pc scale, which shows unprecedented clarity on AGN influence on star formation processes and potential ionized outflows, linking their origins to ADAF-driven winds or jet-induced shock interactions. Eight other massive, nearby galaxies show luminous H_2 structures with a radio-loud AGN, suggesting that radio-jet feedback is a key driver of the observed H_2 emission and the disruption of the ISM.

Galaxy-black hole interplay in high-redshift active galactic nuclei: the impact of super-Eddington accretion

Alessandro Lupi

University of Insubria, Varese, Italy

The observations of high redshift quasars up to $z \sim 7$ tell us that massive black holes (MBHs) were already in place, with masses well above $10^9 M_\odot$, when the Universe was less than 1 Gyr old. Recent observations by JWST have also shown that MBHs are ubiquitous above $z = 6$, and are typically overmassive compared to their galaxy host. According to the currently accepted framework, MBHs gain most of their mass via radiatively efficient accretion, hence we expect they to form early in the Universe as smaller seeds. However, explaining how these MBHs formed and grew so rapidly is particularly challenging in this scenario, and requires an accurate description of the physical processes at play. In particular, numerical simulations suggest a particularly intricate interplay between black holes (BHs) and their host, with a stunted early growth due to the strong impact of stellar feedback on the accreting gas, followed by an extremely efficient accretion phase, and finally by a self-regulated phase dominated by BH feedback. After discussing the relative importance of these phases on the evolution of the BH and the galaxy interstellar medium (ISM), I will present some recent results which highlight for the first time the relevance of super-Eddington accretion phases in high-redshift quasar hosts, both for the central BH and the galaxy host. I will also discuss how our understanding of the galaxy-BH (co)-evolution at these early times is strongly affected by the accretion regime, and the impact it has on the BH mass observational estimates.

From momentum to energy driven: the first proof of accelerating AGN outflows

Cosimo Marconcini

University of Florence, Italy

Super massive black holes at the centre of galaxies experience an active phase of matter accretion via pc-scale accretion disks. As a consequence of accretion and to conserve angular momentum, energetic multi-phase winds are produced, pushing the ambient gas up to the galaxy outskirt. Models predict the key role of these winds in shaping galaxy evolution, regulate star formation and metals distribution over kpc scales. Nonetheless, it is still unclear what is the mechanism accelerating such outflows and how energy can be exchanged between the wind and the galaxy Inter Stellar Medium. I will present a detailed analysis of the wind kinematical properties in a sample of nearby active galaxies observed which finds evidence, for the first time, of the predicted transition from the momentum to the energy driven regime at the critical radius of ∼1 kpc. In particular, I will show that all these outflows are characterized by constant radial velocities followed by a rapid acceleration starting from ∼1 kpc from the nucleus, as predicted by theoretical models and hydrodynamical simulations of AGN outflows. I will motivate how these results are crucial to understand the origin of these winds, their powering mechanism and the energy exchange with the ambient medium. Finally, this results confirm and motivate the key role of outflows in shaping the galaxy properties and evolution, as a manifestation of AGN feedback.

AGN emission lines in high-redshift galaxies

Theulé Patrice

Labotatoire d'Astrophysique de Marseille (CNRS–LAM), France

Black holes activity has a strong influence on the star-formation activity of galaxies over cosmic times and the co-evolution of galaxies and black holes is important, especially in the Early Universe. Black holes accretion disk in Active Galactic Nuclei (AGN) radiate from gamma-rays to radio and induces a response from the surrounding interstellar medium (ISM). The resulting emission, both in its continuum and in its emission spectrum, (i) gives us important information on black holes physics, such as the black hole mass and the accretion rate, (ii) it contaminates the star-forming galaxies emission and needs to be removed to evaluate the fraction of AGN and to retrieve the galaxy evolution parameters, such as the star formation rate and the stellar mass. To model the panchromatic emission of galaxies hosting AGNs we implemented a dedicated module in the `CIGALE` (Code Investigating GALaxy Emission, `https://cigale.lam.fr/`, *Boquien et al. 2019*). Using the `CLOUDY` photoionization code (`https://www.nublado.org`) we modeled AGNs atomic and molecular emission lines (from X ray to radio), both in the narrow line regions and in the broad line regions (*Groves et al. 2004, Spinoglio et al. 2021*) to generate a library of synthetic spectra templates. This work is benchmarked on existing samples from previous works (*Mountrichas et al. 2023*).

Galaxy assembly with JWST/NIRSpec IFS (GA-NIFS): the close environment of AGN at $z \sim 3-7$

Michele Perna

Centro de Astrobiología (CAB), CSIC-INTA, Spain

The JWST/NIRSpec GTO programme 'Galaxy Assembly with NIRSpec IFS' (GA-NIFS) is an ambitious project aimed at characterising the internal structure and close environment of > 50 distant galaxies and active galactic nuclei (AGN) at $z = 2 - 11$. I will present an overview of the very first results obtained for a GA-NIFS subsample of AGN at $3 < z < 7$ (e.g. *Perna et al. 2023*). The discussion will include an analysis of the prevalence of galaxy-AGN and dual AGN configurations within the relatively small NIRSpec field-of-view ($3'' \times 3''$, corresponding to a projected distance ∼20 kpc from the primary AGN). I'll report the serendipitous discovery of a triple AGN and four dual AGN. These results suggest that multiple AGN can be more common than expected from the most recent cosmological simulations. I will also present an overview of the analysis required to optimise the AGN-host decomposition taking into account the NIRSpec PSF under-sampling effects (wiggles).

AGN feeding and feedback from parsec to kiloparsec scales

Cristina Ramos Almeida

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In the last 10-15 years, our view of the circumnuclear material around Active Galactic Nuclei (AGN) has been revolutionised by a combination of observations and simulations. In particular, high angular resolution (sub-)mm and infrared observations from ground- and space-based observatories have been crucial to peer into the innermost region of AGN and study its geometry and composition, and how it is connected to the central engine (feeding) and the host galaxy (feedback). In this talk I will summarise recent observational results showing that the circumnuclear material of AGN is complex and highly dynamic, varying with periods of nuclear activity, AGN luminosity and Eddington ratio. I will also give a broad overview of observational approaches aimed at identifying the physical processes that couple AGN energy to the multi-phase gas, and at finding evidence that AGN influence galaxy evolution.

Testing the impact of outflows in the molecular gas content of nearby X-ray AGN

Alejandra Rojas

Pontificia Universidad Católica, Chile

An open question in extragalactic astronomy is what is the extent to which the Active Galactic Nuclei (AGN) affect the evolution of their host galaxies. Proper characterization of the AGN influence becomes necessary for cosmological hydrodynamical simulations that invoke feedback from these AGN to realistically simulate galaxy growth and evolution. AGN-driven outflows are frequently detected in low-redshift and high-redshift galaxies across a wide range in luminosity and multiple gas phases. However, most of the samples considered by these studies are incomplete as often only bright AGN are considered and the samples are biased against absorption in the optical/soft X-ray band. In this study, we present recent MUSE and ALMA CO $(2-1)$ observations of nearby hard X-ray selected AGN. The AGN sample covers a large range in bolometric luminosity, black hole mass, Eddington ratio and obscuration and therefore, allows us to perform an unbiased statistical study of outflows and their impact on host galaxies. We find kpc-scale ionized outflow signals in all galaxies and substantial amounts of molecular gas in their central sub-pc regions distributed in a compact disk or ring-like structure. We will show if the presence of AGN results in a negative or positive feedback. We will conclude by presenting relations between the AGN luminosity, outflow power with molecular gas content and star formation rate of the host galaxy determined using ancillary multi-wavelength data and advanced SED models.

Multi-phase outflows in local Type II quasars

Giovanna Speranza

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Active galactic nuclei (AGN) have an indisputable role in the evolution of their galaxies through the continuous exchange of energy and matter. To fully characterize AGN impact on the surrounding environment, it is worth observing outflows of gas in different phases. Despite the importance of this multi-phase characterization, integral field studies have been mostly focused on a single outflow phase. I will present detailed results for the Type II quasar (QSO2) J0945+1737, in which we detect high-velocity wings associated with outflows in its near-infrared spectrum, where low-ionization (Paα, Brδ), high-ionization ([Si VI]) and molecular (H_2) emission lines are present. The ionized outflow has a mass rate of 51 $M_\odot$/yr and it is oriented close to the radio PA, suggesting that jets perturb the ionized gas even in radio-quiet AGNs as J0945+1737. Furthermore, I will present analogous results for ionized and molecular outflows detected in a sample of five QSO2s, observed with GTC/MEGARA and ALMA. For the whole sample, we find that the molecular outflows carry more mass than their ionized counterparts, but both phases show much lower outflow mass rates than what expected from observational scaling relations. This highlights the importance of having good constraints, as outflow densities and radii, which have a huge impact in the outflow properties. Providing these multi-wavelength results, we aim to present a more comprehensive view on the AGN feedback process in the local Universe.

Illuminating the Dark Ages: luminous quasars and their massive host galaxies in the reionization epoch

Fabian Walter

Max Planck Institute for Astronomy, Heidelberg, Germany

Quasars are the brightest, non-transient objects observed at the highest redshifts ($z > 7$) which makes them unique probes of the evolution of black holes, massive galaxies and the intergalactic medium. The density of high redshift quasars puts powerful constraints on the mechanisms that are required to seed and grow supermassive, $> 10^9$ solar mass black holes less than a Gyr after the Big Bang. Observations in the (sub)millimeter can constrain the gas and dust content, star formation rate and masses of the galaxies hosting these luminous quasars. I will present the results of various multi-wavelength follow-up programmes of the most distant quasars currently known, focusing on our recent ALMA observations of quasar host galaxies at $z \sim 7$ and discuss the implications of the findings on massive galaxy formation, the black hole – galaxy co-evolution and cosmic reionization.

The spatially resolved star formation law in nearby AGN host galaxies

Maria Vittoria Zanchettin

International School for Advanced Studies (SISSA), Trieste, Italy

In this talk I will discuss the correlation between gas content and star formation activity in nearby active galactic nuclei (AGN) host galaxies. This relation plays a pivotal role in galaxy evolution and determines the efficiency with which galaxies convert their gas reservoirs into stars. This study aims at investigating how the gas and star formation properties change across the galaxy and understanding whether the activity of the central super massive black hole (SMBH) plays a role. I will provide a detailed spatially resolved analysis of the interstellar medium properties by combining JWST/MIRI imaging with the F770W filter, with CO $(2-1)$ and the underlying 1.3 mm dust continuum data from ALMA, along with VLA radio continuum observations. I will focus on the correlation between the 7.7 μm polycyclic aromatic hydrocarbon emission, the star formation rate and the cold molecular gas. We derived the correlation between the star formation rate and the cold molecular gas mass surface densities, commonly referred to as the Kennicutt-Schmidt star formation law, and the depletion time, which is the time needed to exhaust the molecular gas reservoir. I will illustrate the application of this approach to a sample of local hard-X-ray selected Seyfert galaxies, including NGC 7469. Furthermore, I will compare these results with spatially resolved studies on non active galaxies.

IV. High redshift

[C II]–selected sample of extremely high SFR sources in the $z > 6$ Universe: first results from the new CISTERN program

Rychard Bouwens

Leiden University, Netherlands

One of the most significant surprises in the first year of observations with JWST is the number of luminous and seemingly massive galaxies in the very high-redshift universe. As search efforts with JWST proceed, it is essential to also make use of surveys in the far-IR to identify very massive galaxies in the early universe obscured by dust. One such survey program – CISTERN – has just started with ALMA in cycle 10 and systematically targets ~ 200 of the brightest QSOs+galaxies known in the $z > 6$ universe and searches their neighborhoods for especially high SFR galaxies using the dust-insensitive [C II] line. Already ∼50% of the highest SFR galaxies at $z > 6$ have been identified this way, but the samples are small. By significantly expanding the number of bright sources targeted with ALMA, CISTERN expects to triple existing samples of high-SFR galaxies at $z > 6$. Thanks to the large sample size, pure SFR selection, and insensitivity to dust (superior even to JWST), it will serve as a key $z \gtrsim 6$ reference sample. Observations from this program will commence in March 2024 and finish in early May. In my presentation, I will share some of the early results being obtained from this program, contrasting the demographics and likely ISM characteristics of our ∼75 source [C II]-selected samples from ALMA with parallel efforts with JWST to identify very high SFR sources at $z \sim 6 - 7$.

Dust and metal evolution from $z = 4$ to $z = 12$ with the `CIGALE` code and JWST photo+spectrometric data

Denis Burgarella

Aix-Marseille Université, Marseille, France

We use a brand new version of the `CIGALE` code to simultaneously model JWST photometric+spectroscopic data, and study the co-evolution of dust and metals over Cosmic times. A parent sample of 173 is extracted from the CEERS data with NIRSpec observation. All of them with safe and confirmed spectroscopic redshifts from $z = 4.0$ to $z = 12.4$. We add to this sample the galaxy identified at $z = 12.3$ with NIRSpec and MIRI spectroscopic data. After testing the validity of the measurements (line fluxes, equivalent widths, metallicity measurements, etc) of a sub-sample by comparing it with published papers that use more traditional methods, we check the spectra to flag potential

AGNs. Finally, we build diagnostic diagrams, e.g. SFR vs M_*, IRX vs β, M_* vs Z and compare them to published works (observations and models) at lower (and at similar) redshifts to assess any evolution of the galaxy dust/metal characteristics from 0.3 Myrs to 1.6 Myrs after the Big Bang. This approach also allows to measure the slope of the dust attenuation law, and to identify objects in the studied sample that feature an ultraviolet bump at 217.5 nm, in the dust attenuation law. Finally, we use this information to build consistent physical models, and try and constrain the formation of the first dust grains in the Universe.

A comprehensive redshift survey of the brightest Herschel galaxies

Pierre Cox

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The Herschel surveys have enabled the detection of numerous dusty luminous submillimeter galaxies (SMGs) in the early universe. Follow-up observations of these sources are essential to determine their nature and the physical properties of their interstellar medium, reliable measurements of their redshifts are therefore crucial to explore the molecular and atomic gas of these objects. We will here present the results of a Large Program, using NOEMA, aimed at a comprehensive 3 and 2 mm spectroscopic redshift survey of a large (∼135 sources) sample of the brightest ($S_{500\,\mu m} > 80\,\mathrm{mJy}$) SMGs selected from the Herschel H-ATLAS and HerMES surveys, which probe the peak of cosmic evolution ($2 < z < 4$). The results highlight the nature of the sources, lenses and the rare hyperluminous galaxies, as well as, in some cases, their multiplicity. We will describe the main results of the survey as well as complementary data, in particular, with NOEMA, ALMA and the HST, addressing aspects of feedback activity in selected sources and outline future prospects.

The ISM and dust properties of (post-)reionization galaxies probed by ALMA and JWST

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For obtaining a complete picture of galaxies, multi-wavelength observations are crucial to observe their stars, gas, dust, and chemical composition. With Hubble, JWST, and ALMA operating at the same time, we find ourselves in an era where we can jointly observe the UV, optical and infrared light of high redshift galaxies to describe their ISM properties in detail. I will present first results from two new programs, which take advantage of imaging and spectroscopy from HST, JWST, and ALMA. The main goal of the ALPINE-CRISTAL JWST program is to combine high-resolution sub-mm observations with JWST/IFU spectroscopy to study the chemical compositions and dynamic properties of the ISM of $z = 4-6$ galaxies as well as possible contributions and feedback from AGN. CHAMPS is a 1.2 mm ALMA large program synergistic to JWST NIRCam and MIRI imaging to search for the most dust-obscured sources during the Epoch of Reionization.

Galaxy Evolution during the cosmic reionization: new insights from ALMA and JWST

Yoshinobu Fudamoto

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The ALMA and JWST observations are dramatically transforming our understanding of galaxy formation, particularly at high redshifts. Their unprecedented high-spatial resolution and sensitivity covering the panchromatic wavelength range allow us to access to multi-phase processes shaping the galactic ecosystem – such as star formation activities, gas inflows/outflows as well as interactions between galaxies. In recent observing cycles, ALMA and JWST observations have provided essential insights into the early galaxy growth, building reference samples of bright star-forming galaxies at $z > 7$. Also, recent observations of these telescopes identified an extreme over-density of galaxies at $z > 7$ which shows an enhanced dust production in very gas rich galaxy mergers. These observations enabled to study the rapid assembly of massive galaxies under extreme conditions in the early universe in great details. In this talk, I will present the latest results from our ALMA observations of star-forming galaxies at $z > 7$, combined with complementary JWST observations. Our findings reveal properties of multiple phases of interstellar medium (ISM) which is rapidly forming stars, and uncover the complex structures of galaxy interactions within over-dense environments. In the first part of the talk will focus on our analysis of ionized and neutral ISM properties through multiple far-infrared emission lines. In the second part, I will discuss our high-resolution ALMA observations of the core of the galaxy over-density at $z \sim 8$, which provide new insights into galaxy formation within the extreme environments. These results would pave the way for future comprehensive studies with JWST and ALMA, which is essential to understand galaxy evolution during cosmic reionization.

Porous neutral gas nature of interstellar medium in a Lyman Break galaxy at redshift $z = 8.312$

Masato Hagimoto

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The ionization structure of interstellar medium (ISM) in galaxies at the epoch of reionization (EoR) gives us a hint to understand what types of galaxies mainly contribute to reionization. Recent ALMA observations toward relatively massive galaxies at $z > 6$ have revealed high [O III] 88 μm-to-[C II] 158 μm luminosity ratios in UV-luminous normal star-forming galaxies, including Lyman Break galaxies (LBGs) and Lyman-alpha emitters. Previous studies have predicted a high ionizing photon escape fraction for those galaxies with such high ratios (e.g., *Katz et al. 2022, Ura et al. 2023*). However, few works have investigated the neutral gas porosity in individual galaxies at EoR. Then, we construct the photoionization model where the covering fraction of neutral gas (covPDR) is taken into account. Here, we present the detailed analysis of one of the highest-z LBGs with high [O III] 88 μm-to-[C II] 158 μm luminosity ratios and detection of dust continuum, MACS0416_Y1 at $z = 8.312$ (hereafter Y1). The best-fit model shows a covPDR of ~30%, indicating that ~70% of the ionized gas region is exposed to intercloud space. We confirm that our conclusion does not change even if we change some fixed parameters, such as the carbon-to-oxygen abundance ratio. This result suggests that galaxies similar to Y1 could contribute to the cosmic reionization. Finally, we found that the estimated size of the modeled H II region is similar to that of local compact H II regions, suggesting bursty star formation in Y1.

Dynamically cold disks in the early Universe: myth or reality?

Mahsa Kohandel

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The existence of dynamically cold disks (DCDs), characterized by significant rotation support, in high redshift galaxies remains a subject of intense debate. I will address the intriguing question of whether dynamically cold disks are indeed prevalent during the early cosmic epochs or if they represent exceptional cases. Leveraging the power of zoom-in cosmological simulations, I will present SERRA suite predictions specifically tailored for the synergy between the JWST and ALMA to investigate these elusive structures at $z > 4$. The JWST-ALMA synergy holds promise for studying DCDs. JWST's high-resolution near-infrared imaging and spectroscopic capabilities enable the exploration of stellar populations and the kinematics of ionised gas within these disks, particularly through the observation of the Hα emission line. On the other hand, ALMA's exceptional sensitivity and resolution enable tracing cold gas content and the investigation of the kinematics of high redshift galaxies through CO and [C II] emission lines. During the talk, I will address the existence of dynamically cold disks both during the EoR ($z > 6$) and at cosmic high noon ($4 < z < 6$). These predictions will be supported by the analysis of synthetic hyperspectral datacubes for the far-infrared [C II] and nebular Hα emission lines. Emphasis will be placed on the importance of detailed ISM and emission lines modelling to effectively bridge sophisticated galaxy simulations with JWST/ALMA observations.

Exploiting the synergy between integrated galaxy spectra and complex ISM models

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Spectroscopic diagnostics of galaxies hold tremendous diagnostic power, yet we do not know how to fully interpret the integrated galaxy spectra by accounting for and modelling the complex mechanisms that produce the observed emission arising from the multi-phase ISM. Integral field spectroscopy illustrates well the variations of metallicity, ionization, as well as the potential presence of compact objects, and this even at high redshifts. As we accumulate very high-z observations with JWST and ALMA, which inevitably show the same complexity as in nearby galaxies, it becomes urgent to design a modelling framework to derive robust and reliable physical parameters describing galaxy evolution. In this talk I will present recent developments and applications of the `MULTIGRIS` probabilistic framework (*Lebouteiller et al. 2022, Ramambason et al. 2022, 2024)* which accounts for statistical distributions of primary physical parameters (density, incident radiation field etc.) through a combination of 1D models. After describing some biases and caveats related to the single 1D model hypothesis, I will show results from a volume-limited galaxy survey observed in optical lines. One of the most interesting results shows that the metallicity dispersion within star-forming galaxies that is needed to explain the observed emission lines is a strong function of the chemical evolutionary state. I will then show ongoing works focusing on low-mass galaxies with significant AGN contribution.

Probing the physical conditions of the interstellar and circumgalactic medium in the early Universe

Jianan Li

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In the Early Universe, the luminous QSO and the active star formation in the host galaxy lead to the ejection of a large amount of energy into the interstellar medium (ISM) and circumgalactic medium (CGM). This makes them ideal targets to investigate the interplay between the star-formation/AGN feedback and the ISM/CGM properties. In this talk, I will present our recent NOEMA observations of CO and water emission lines, and the underlying dust continuum in two quasars at cosmic dawn. Notably, among all published CO SLEDs of quasars at $z \sim 6$, the two systems reveal the highest and the lowest CO levels of excitation, respectively. Our radiative transfer modeling of the CO SLED suggests that the molecular gas heated by AGN could be a plausible origin for the highest CO excitation. In addition, we obtain the first well-sampled CO SLED (from transitions from $2-1$ to $10-9$) of a radio-loud quasar at $z \sim 6$, whose CO SLED is best explained by a single photo-dissociation region (PDR) model. The diversity of the CO SLEDs reveals the complexities in gas conditions and excitation mechanisms at their early evolutionary stage. I will also introduce our recent ALMA and ACA observations of atomic carbon [C I] $(1-0)$ and dust continuum in a sample of 10 Enormous Lyα Nebulae hosted by ultra-luminous Type I QSOs at $z = 2.2 - 2.5$, as part of the SUrvey of Protocluster ELANe Revealing CO/CI in the Lyα Detected CGM (SUPERCOLD-CGM). We detect [C I] $(1-0)$ and dust in all 10 QSOs and 40% of companion galaxies in the fields. We find that the QSOs and companion galaxies tend to have higher gas densities and intenser radiation fields compared to Luminous Infrared galaxies and high-z main sequence galaxies, while a slightly higher density and intenser radiation is found in the QSOs compared to the companions. After tapering our data to a lower resolution, the [C I] $(1-0)$ flux increases for nine QSOs, hinting at the possibility of [C I] $(1-0)$ in the circum-galactic medium (CGM). However, the [C I] $(1-0)$ sensitivity is too low to confirm this for individual targets, except for one QSO, where a tentative (2.7σ) CGM detection reveals a molecular mass of $(1.0-2.8)\times10^{10}$ within $5''$ (40 kpc). Our study highlights the utility of the CO SLED in uncovering the ISM properties in these young quasar-starburst systems at the highest redshift and the importance of ALMA+ACA in studying the physical conditions of the ISM and CGM in the Early Universe.

Pushing ALMA to the limit: 140 pc resolution [C II] and continuum observations of a $z = 6.6$ quasar-galaxy merger

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Both observational evidence and theoretical arguments support the idea that Supermassive Black Holes (SMBHs) play a fundamental role in the evolution of galaxies. Observations of $z > 6$ luminous quasars in the FIR regime thus probe the first steps of the galaxy-SMBH coevolution in the first billion years of the Universe. ALMA/NOEMA studies of $z > 6$ quasars accreting at nearly Eddington rate have shown that they are hosted by massive, highly star-forming galaxies, in agreement with theoretical predictions. However, these recent studies did not have the resolution to go beyond global properties and study the resolved ISM of the host galaxies. I will present hyper-resolution (140 pc, $\sim$0.026″) ALMA observations of the [C II] 158 μm and cold dust continuum emission of a $z = 6.6$ quasar-galaxy merger system (J0305-3150). The highly resolved observations reveal strikingly different morphologies in the dust and [C II] emission: the dust is compact (< 2 kpc) with several 84–200 pc clumps, whereas the [C II] emission is smooth and extended (up to 10 kpc). Analysis in the UV– and image plane reveals that dust and [C II] are not emitted in the same location: dust continuum originates on physical scales $< 1.2''$ consistent with the size of photo-dissociation regions, whereas [C II] is emitted in regions with much larger sizes ($> 1.2'' - 10''$). The extended [C II] kinematics are not aligned with that of the small-scale [C II] emission, suggesting that the extended [C II] emission/halo traces diffuse gas tidally-stripped during the ongoing quasar-galaxy merger. The unprecedented resolution of our observations enable us to study the '[C II] deficit' or [C II]/FIR ratio at 200 pc scales, showing that this 'deficit' is not affected by the central AGN and instead follows the far-infrared surface brightness as in $z \sim 0$ ULIRGS. Finally, the spatially resolved depletion timescale suggests that star-formation is being quenched inside-out, mostly due to the intense star-formation activity but with a non-negligible contribution from the quasar accretion of gas in the inner 200 pc. In summary, these observations provide important lessons for the analysis of maximally extended ALMA data, exemplify the fundamental physical difference between [C II] and dust emitting regions, and probe the delicate balance between quenching and gas replenishment via mergers in a high-redshift quasar host galaxy.

Dust-obscured star formation of the UV-selected galaxies at high-z

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National Astronomical Observatory of Japan (NAOJ)

We present the recent study about the dust continuum emissions of UV-selected star-forming galaxies at $z \sim 5$ and $z \sim 6$. The datasets are mainly composed of two ALMA programs, the ALMA Cycle 8 large program CRISTAL for $z \sim 5$ and the multi-band observation program SERENADE for $z \sim 6$. By utilizing the combination of the identification of high-z galaxies with optical telescopes and the follow-up observations with

ALMA, we measured the statistical properties of the spectroscopically-confirmed UV-selected galaxies at $z = 4 - 6.5$. At $z \sim 5$, our constraints on M_*–$f_{\rm obs}$ relation support that the obscured fraction at the range of $M_* < 10^{10} M_\odot$ does not show clear evolution from $z = 0 - 2.5$, but may decrease at the range of $M_* > 10^{10} M_\odot$. For an individual view, the spread from an average M_*–$f_{\rm obs}$ relation ($\Delta f_{\rm obs}$) shows a possible correlation with the compactness of SF region and the spatial offset between UV and dust continuum. Typical dust continuum sizes are ~ 1.5 kpc, and appear to be about two times more extended than the UV continuum. At $z \sim 6$, our results show a lower IRX value by ~ 1 dex at βUV$\sim$0, and support the shallow IRX-βUV relation suggesting a good agreement with the metal-poor nature of the high-z galaxies. We also constrain average dust temperature ($T_{\rm dust}$) at $z \sim 6$ and test whether the redshift evolution of $T_{\rm dust}$ can be explained by the combination of the analytical models and some observational constraints on the metallicity and gas depletion timescale.

High-precision SFR mapping of the nearby galaxy NGC 1068 using ALMA 100 GHz continuum and HST Paα line

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Ionized gas plays a crucial role in the study of galaxy evolution as the star formation in galaxies. Star formation rate (SFR) can be derived from ionized gas, and there are several difficulties in extracting pure components originating from star formation. Astronomers have traditionally addressed these uncertain parameters by assuming classical and textbook values. However, some parameters (e.g. T_e, $A_{\rm V}$) have a critical impact on deriving SFR. We present an SFR for the entire molecular gas disk of the nearby galaxy NGC 1068, based on our new high-sensitivity ALMA 100 GHz continuum data at 55 pc ($= 0.8''$) resolution in combination with the HST Paα line data. The main goal is to exploit the synergy between free-free continuum (FFC) and Paα for deriving reliable SFR for NGC 1068. This specific combination of ionized gas tracers allows us to derive and map accurate SFR distributions by obtaining electron temperature. In addition, we subtract the contamination by AGN and DIG from ionized gas when deriving the SFR. As a result, the total SFR obtained by cross-calibrating FFC and Paα is $\sim 3.2 M_\odot$/yr for the DIG-corrected case and $\sim 9.1 M_\odot$/yr for the DIG-uncorrected case. This result indicates a significant contamination to SFR measurement by DIG. Our SFR was derived from the first physically motivated measurement in this galaxy, and that offers more precise insights into understanding galaxy evolution.

Probing dust across cosmic time: early epoch insights with the James Webb Space Telescope

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Cosmic dust provides key information on the evolution of the interstellar medium (ISM) of galaxies. The advent of the James Webb Space Telescope (JWST) marks a turning point to understand the role of these pivotal particles in the framework of galaxy evolution. With its unparalleled capabilities, JWST has recently revealed the presence of 2175Å dust feature in galaxies up to $z \sim 7$ (JWST Advanced Deep Extragalactic Survey, JADES). Such a feature, well known up to redshift of 3, indicates the possible presence of carbonaceous grains at these early epochs. Furthermore, the large observed values of $H\alpha/H\beta$, indicative of large dust extinction, and strong oxygen lines, point at a fast enrichment of metals in their ISM. In this talk, I will present our ongoing investigation aimed at constraining the dust build-up in JADES galaxies by modelling their spectra consistently with dust evolution in their ISM. Through such a study, it has been possible to shed light regarding the dust enrichment processes due to different stellar sources (massive vs low and intermediate-massive stars), initial mass function of stars and star formation history.

Star formation suppression and SNe feedback enhancement due to photoelectric heating by dust

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Photoelectric heating (PEH) of gas by electrons ejected from dust-grain surfaces is the primary heating mechanism in the cold neutral medium (CNM) and diffuse atomic hydrogen (H I) regions. Theoretical studies of PEH found that PEH is capable of reducing the star formation rate in dwarf galaxies due to the reduction in the gas density. We expect this effect to be amplified in more massive, Milky Way-like galaxies since more massive galaxies harbour larger dust reservoirs. Indeed, studying hydrodynamical simulations of Milky Way-like galaxies, we found that PEH affects the abundance and distribution of the different ISM components (H I, H_2, metals and dust) and the thermal phases of the ISM. This results in the suppression of the formation of high-density regions (gaseous clumps) which consequently suppresses the star formation activity. This suppression is seen across the entire range of gas fractions, star-formation recipes, dust models, and PEH efficiencies investigated by our code. However, it has a strong correlation with the gas fraction and PEH efficiency. The reduction of the gas density makes the gas prone to SNe feedback, and as such galaxy models with PEH show higher gas outflow rates and have higher loading factors, indicative of enhanced SNe feedback efficiency. The gas loaded into the halo is recycled back to the disk in a much longer time scale compared to the case where PEH is absent.

Energized clouds in the Galactic bar

Juergen Ott

National Radio Astronomy Observatory, USA

Multiphase outflows in a main sequence galaxy at $z \sim 5.5$

Eleonora Parlanti

Scuola Normale Superiore di Pisa, Italy

Outflows play a crucial role in galaxy evolution, shaping the galaxy mass function at the high and low mass end by expelling and heating the gas in the galaxy and suppressing star formation. Low-z studies suggest that outflows are multiphase, and the majority of the mass expelled by winds is in the molecular or neutral phase. Despite the large efforts, only few neutral outflows have been observed at $z > 5$. With the advent of JWST we can observe the rest-frame optical emission line from high redshift galaxies, expand our search for ionized outflows up to the early Universe and compare them with the few observations of neutral outflows from ALMA. I will present the JWST IFU high ($R \sim 2700$) and low ($R \sim 100$) spectral resolution observation of HZ4, a main sequence, star-forming galaxy at $z = 5.5$, which is the highest redshift star forming galaxy with a neutral outflow traced by the broad [C II] emission. R2700 data unveil the ionized outflow through the detection of a broad component in the [O III] and Hα emission lines. The outflow is launched by a region hosting a burst of star formation, the mass outflow rate of the ionized phase is comparable with the neutral one. These two phases are expelling from the star forming clump the same amount of gas that is converted into stars. R100 data allow us to study the stellar population and address the role of the outflows in regulating star formation. ALMA and JWST synergy enables a comprehensive look at multiphase outflows in the early Universe.

Comprehensive view of far-infrared fine structure lines: new answers & new questions

Bo Peng

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The far-infrared fine structure lines (FIR FSLs) are powerful tools in both identifying high redshift galaxies and studying the physical condition of interstellar medium (ISM). However, many gaps remain in the study of FIR FSL, especially between the study of FIR FSLs and the optical strong lines, and between the local and high redshift galaxies, which limits our capability in systematically comparing and combining multi-wavelength observations from powerful facilities like ALMA and JWST. In this talk, I will present a comprehensive catalog including most of the global FIR FSL data of both low- and high-z galaxies collected from the literature covering a large range of galaxy types, with rich ancillary optical and mid-infrared data. Based on this comprehensive catalog, I will give a renewed view of the empirical FIR FSL relations, and demonstrate the canonical factors behind these lines aided by the photoionization models. I will highlight the new

results enabled by combining the multi-wavelength data, including the identification of [O III] 88 μm contribution from AGN, the coherence between all the neutral and ionized gas emission in both FIR and optical, the dichotomy between the ionized & neutral gas and the dust that results in 'line deficit' of, not only [C II], but all the lines including Hα, as well as the consequent crisis of the star formation rate measurement in dusty galaxies and the quest for an updated view of ISM.

ALMA and JWST observations of SXDF-NB1006-2 at $z = 7.2$

Yi Ren

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In the past decade, ALMA observations have detected and investigated dozens of galaxies at $z \gtrsim 6$ with FIR emission lines. After entering the era of JWST, NIR photometric and spectroscopic follow-up observations of ALMA-detected distant galaxies are key to understanding their stellar, ISM and morphological properties in a more detailed and comprehensive way. As the target of this study, SXDF-NB1006-2 is the first galaxy at $z > 6$ that was detected with [O III] 88 μm emission by using ALMA. In this presentation, we will report the follow-up ALMA observations targeting [O III] 88 μm, 52 μm, and [C II] 158 μm of this galaxy, and the JWST NIRCam and NIRSpec observations which are part of RIOJA (Reionization and the ISM/Stellar Origins with JWST and ALMA) project. We will also discuss the ISM, stellar and morphological properties obtained from the study of multi wavelength observations.

The coevolution of star formation and SMBH accretion: from Cosmic Noon to the Epoch of Reionization

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High-z luminous quasars are ideal laboratories to investigate the co-evolution of supermassive black hole (SMBH) accretion and star formation (SF) across cosmic time, as well as to reveal evidences of the SMBH feedback regulating the host-galaxy assembly. Even with the advent of JWST, mm observations remains a viable tool to probe the properties of luminous quasars host-galaxies, in particular the properties of the molecular and dust phases of the interstellar medium (ISM). Here, I will present the ISM properties of the host galaxies of luminous quasars from the Epoch of Reionization (EoR, $z \gtrsim 6$) to Cosmic Noon (CN, $z \sim 2 - 4$). I will present new and archival ALMA/NOEMA observations of luminous quasars (25 objects at CN and 12 at the EoR), which reveal the presence of copious amounts of dust ($> 10^8 M_\odot$), and SFR up to 1000-3000 $M_\odot$/yr. Luminous quasars represent the peak population of bright SMBHs, which track the regimes of the highest star formation efficiency across cosmic time, when compared with star forming galaxies at similar epochs. Thanks to the high-angular resolution provided by ALMA/NOEMA and recent JWST observations, we show that high-z LQSOs pinpoint the high-density sites where giant galaxies assemble. Both the high number of close (few kpc) companion galaxies detected, and the promising evidences for extended ($\gtrsim$ 10 kpc) C II emission for two quasars at the EoR, support the scenario where mergers play a major role in the build-up of the final host-galaxy.

Linking gas, dust and star formation: probing the baryonic cycle in early galaxies with the ALPINE survey

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The early growth phase of the Universe ($4 < z < 6$) marks a pivotal transition between the primordial galactic formation and the onset of the peak of cosmic star formation rate density. Understanding the interplay between gas, dust, and star formation during this phase is critical for deciphering the mechanisms that regulate galactic evolution across cosmic history. In this work, we make use of chemical evolution models to probe the baryonic evolution of $z \sim 5$ main-sequence star-forming galaxies as part of the ALMA Large Program ALPINE. We utilize panchromatic observations to perform spectral energy distribution fitting for these galaxies, employing both Chabrier and top-heavy initial mass functions (IMFs) to derive the physical parameters (i.e. stellar mass, star formation rate and dust mass). Our models successfully reproduce the gas and dust content in most of these primordial galaxies, indicating dust production primarily through Type II supernovae and gas/dust removal via galactic outflows and moderate inflow of primordial gas. Furthermore, a subset of these galaxies displays rapid dust build-up in shorter timescales ($\sim$20 Myr – 100 Myr), which is partially reconcilable with a top-heavy IMF. These findings, coupled with upcoming studies driven by James Webb Space Telescope observations, bridge the gap between observations and models, shedding new light on dust production mechanisms in the early universe.

Unveiling the origins of the molecular gas reservoirs in quenched galaxies

Ethan Savitch

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Observations of galaxies across the universe reveal a persistent bimodality, characterized by star-forming blue spiral galaxies, and quenched red elliptical galaxies. Traditionally, the latter population of quenched ‘red and dead’ galaxies are believed to be devoid of molecular hydrogen gas, essential for star formation. However, recent observations by the ALMA interferometer have challenged this notion, showing quenched galaxies harboring significant reservoirs of molecular gas. In our study, we use the SIMBA cosmological simulation to investigate the mechanisms that allow quenched galaxies to retain molecular gas. In total our study will investigate four hypotheses, two physical and two observational.

Dynamics of circumgalactic medium and the interaction with the Galactic disk: towards understanding Galactic star formation history

Izumi Seno

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The star formation rate in our Galaxy has been maintained at several $M_{\odot}$/yr for about 10^{10} yr. However, if star formation continues at the current rate, the current amount of gas in the galactic disk should be depleted in less than 10^9 yr. Recently, large amounts of metal-enriched gas, exceeding $10^{10} M_{\odot}$, have been observed in the halo. From these observations, it is expected that the gas supply and circulation between the disk and the halo is responsible for long-sustained star formation. The gas transport mechanism from the disk to the halo has been re-examined by *Shimoda & Inutsuka 2022*. Their detailed theoretical calculations have shown that cosmic ray heating suppresses radiative cooling, allowing the gas to be transported out of the disk over 100 kpc. However, there is still a need to further investigate of the gas supply mechanism from the halo to the disk, including the condensation process in the halo and the infall process from the halo to the disk. In this study, we analyze the thermal state of the halo gas in detail to examine the gas supply processes. We have performed a linear stability analysis of the gas condensation in the halo and the gas infall from the halo to the disk, considering thermal instability, gravitational dynamics, and the effect of cosmic rays. We also discuss whether the gas condensing in the halo and infalling onto the disk may correspond to a high- or intermediate-velocity cloud, whose origin is still under debate.

Heating of warm gas in a luminous quasar at $z = 6$

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We demonstrate that high-resolution observations of high-J CO line and dust continuum emission are a promising way to identify dust-obscured quasars at $z > 6$. In the central region of luminous quasars, X-ray photons from an AGN can heat the surrounding gas to several hundred K. However, warm gas in quasars has not been directly probed due to a lack of resolution. We present results from ALMA 130 pc ($0.022''$) resolution observations of dust continuum and CO $J = 13-12$ and $J = 14-13$ line emission in a luminous quasar at $z = 6.0$. The high-resolution data reveal the existence of a compact disk component with an effective radius of 266 pc, which is likely to be a scaled-up version of a circumnuclear disk (CND) in nearby AGNs. We furthermore obtained CO Spectral Line Energy Distributions (SLEDs) with four CO emission lines ($J_{up} = 6,\ 8,\ 13,\ 14$) at 460 pc ($0.08''$) resolution. In the central region ($R < 230$ pc), the CO SLED and dust SED are consistent with an XDR model with a large gas column density of $\log N_{\mathrm{H}} = 25$, suggesting that it is classified as a dust-obscured quasar in the radial direction of the disk. On the other hand, even in the outer extended region ($R > 230 - 700$ pc) where X-rays are attenuated by gas, the CO SLED still indicates that the gas is highly excited. Given the signature of galaxy-scale outflows from ALMA observations of ionized carbon lines, the interaction between the outflows and the gas could be responsible for the CO excitation in the extended region.

Resolving the kinematics of galaxies at the first billion years

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The study of the kinematics of galaxies from the end of the Epoch of Reionization provides insights into the early history of gas assembly. Despite the tremendous progress in early galaxy studies done with ALMA prior barely resolved observations were not suited for dynamical classification. With the new spatially resolved [C II] ALMA observations, we present detailed kinematic and morphological maps of the cool gas in two of the most FIR bright and gas-rich star-forming galaxies, one being a dusty starburst galaxy with SFR $> 1500\,M_{\odot}$/yr and another a main-sequence normal galaxy, from the end of the Epoch of Reionization, at $z \sim 5.7$. The new observations reveal previously unresolved complex galaxy kinematics and morphology, indicating recent and/or ongoing merging activity. Being also part of the protocluster, these galaxies are shedding light on the link between star formation and the environment when the Universe was around one billion years old.

Unveiling the dust-obscured activity of the Universe through cosmic time: the view from the ALMA A3COSMOS Survey

Alberto Traina

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One of the major unknowns concerning the evolutionary history of the Universe is how galaxies form and on what timescales they build up their baryonic mass over time. In order to tackle this topic, much effort has been put in building large samples of galaxies at different redshifts, aiming at reconstructing their evolutionary history at different epochs. To study the dust-obscured activity of galaxies, the ALMA interferometer is without doubt the most performing facility available nowadays, to hunt for dusty star forming galaxies. However, because of the small FoV of the interferometer, the large quantity of sources needed for statistical significant studies is not reachable by ALMA deep surveys. Only recently, thanks to the A3COSMOS project, it has been possible to perform, for the first time, statistical studies of ALMA selected galaxies, from the archive. This has allowed us to derive the main statistical properties characterizing galaxy evolution across cosmic time. In particular, in this talk, I will present the latest results on the IR-LF and the evolution of the dust-obscured SFRD at $0.5 < z < 6.0$, using the latest version of A3COSMOS survey. I will also discuss the contribution of the IR and UV SFRDs to the total, as well as their comparison with state-of-the-art simulations and semi-analytical models. Finally, I will show our results on the evolution of the dust content in galaxies, with cosmic times, by deriving the dust mass density from the A3COSMOS survey.

Illuminating the CO–Dark Reservoir

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Stars form in giant clouds comprised of molecular H_2 gas and yet we have not quantified the amount of molecular gas there is in the Universe. H_2 requires gas at temperatures of 500 K to excite the first quadrupole emission which makes it difficult to observe with traditional measuring techniques and disposes inhospitable conditions for star formation. Historically, we've used carbon monoxide (CO) rotational transition lines as a tracer molecule. Despite its accessibility, CO is easily destroyed by ultraviolet radiation and cosmic rays this way leaving a fraction of the molecular gas unaccounted for through the conventional techniques, namely 'CO-dark'. Using cosmological simulations, coupled with thermal, radiative, and chemical equilibrium models for the interstellar medium, we will develop the first ever theoretical model for the fraction of molecular gas across the cosmic time that is currently invisible via traditional CO surveys, and quantify how this gas may be observable.

Zoom-in on the first galaxies: how to bridge theory and observations at the cosmic dawn

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Galaxy evolution is a complex, multi-scale process involving the interplay of various physical mechanisms, including gravity, gas dynamics, radiation, star formation, feedback from stars and active galactic nuclei, and the influence of dark matter. To understand how the first galaxies formed and evolved during cosmic dawn, simulations must cover an enormous dynamic range — from sub-parsecs to megaparsecs — to capture all relevant physical processes. In this talk, I will review the state of the art in the field by highlighting the successes and challenges in developing increasingly precise simulations able to reproduce ALMA and JWST observations. I will specifically focus on advances in the implementation of feedback processes, interstellar medium physics, and radiative transfer. Finally, I will showcase how the synergy between simulations and exquisite observations can help us characterize the internal properties of the earliest sources that formed in the Universe.

Modeling the neutral gas heating in low metallicity galaxies

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Star formation in galaxies is regulated by purely dynamical processes as well as thermal processes. While the neutral atomic gas heating is dominated by the photoelectric effect on small dust grains around Milky Way metallicity, the lower dust-to-gas mass ratio together with the higher occurence and luminosity of X-ray sources in metal-poor galaxies suggest that other heating mechanisms may dominate. We will present a modeling study of the Dwarf Galaxy Survey, which comprises nearby star-forming galaxies down to 1/35 solar metallicity, observed spectroscopically in the IR range. We use a multi-phase photoionization and photodissociation grid to associate cooling lines with specific heating mechanisms such as the photoelectric effect, ionization by cosmic rays, and photoionization by UV and X-ray photons. Specifically, we use a combination of 1D models parametrized as statistical distributions within a probabilistic framework. Our results show that the photoelectric effect heating becomes negligible below 1/10 metallicity and that X-rays provide significant heating, with an inferred X-ray luminosity that is in good agreement with direct observations. These results offer an interesting prospective to better understand the heating mechanisms and, more generally the star-formation properties, in both local galaxies and early galaxies. Our next steps will be to exploit the wealth of JWST tracers in similar galaxies, especially high-ionization lines.

Gas-phase metallicity gradients in early galaxies at $z \sim 6-8$

Giacomo Venturi

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Gas-phase metallicity, and its spatial distribution, hold the signature of the processes that shape the build-up and evolution of galaxies in the Universe. Different radial profiles of metallicity can be interpreted in terms of either inside-out galaxy growth, intense stellar feedback, galaxy mergers, or (re-)accretion of chemically enriched or pristine gas. Different theoretical predictions exist for gas metallicity gradients at high z. However, until the advent of JWST, metallicity gradients could be probed only up to $z \sim 2-4$, with conflicting results. I will present gas-phase metallicity gradients in three systems at $z \sim 6-8$, when the Universe was only < 1 Gyr old and the galaxy assembly was vigorously taking place. By making use of JWST NIRSpec integral field spectroscopic observations, we mapped the ionised gas in several rest-frame optical emission line diagnostics (e.g. [O II], Hβ, [O III], Hα). We find generally flat radial gradients of gas metallicity, which are consistent with these sources being experiencing galaxy-scale gas mixing, induced by frequent mergers and/or stellar feedback. These results extend out to $z \sim 8$ the regime in which metallicity gradients are explored, providing a critical reference to inform models of galaxy evolution.

A self-consistent model linking [C II] line emission to nebular lines in ALPINE galaxies

Enrico Veraldi

University of Bologna, Italy

In this talk I will present a new physically motivated model able to link the [C II] emission from photodissociation regions (PDRs), to the optical and UV lines tracing ionized gas phase in high-z galaxies extracted from the ALPINE sample. The model combines a set of tailored `CLOUDY` photoionization simulations with an analytical approach able to link the H II region and PDRs physical conditions to the impinging radiation from star formation traced by UV and IR continuum. In particular, the model takes into account three physical properties characterising the gas: the hydrogen number density (n), the ionization parameter (U) and the gas metallicity (Z). I will show that the slope of the correlation between UV and optical emission lines (i.e. C III], [O III], [N II], Hα) and the star formation rate (SFR) is a valuable tool to get information on the ISM physical parameters. Finally, I will focus on the strong impact of UV binaries, and highlight how their presence can balance the effect of star formation quenching in the predictions.

CRISTAL: A survey of gas, dust, and stars in star-forming galaxies when the Universe was ~1 billion years old

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We present the CRISTAL survey, which encompasses [C II] and dust-continuum ALMA data for 25 dusty star-forming galaxies (SFG) at $z \sim 4-6$. CRISTAL mainly focuses in producing a census of the gas, dust, and stars to perform a systematic analysis on galaxy kinematics, outflows, morphology, among others. The exquisite kpc-scale resolution of the data reveals the complex structure of sources at high-z as never seen before. In this talk I will present a general overview of the key results from the survey, which includes the analysis of kinematics, morphology and physical conditions of normal galaxies when the Universe was only 1 Gyr old. So far, CRISTAL have shown that galaxy interactions (e.g. merging events) are very frequent at high-z. For instance, in this talk I will review the interacting nature of the star-forming galaxy HZ10 (CRISTAL–22), which has a dusty bridge-like structure between the two main components. In addition, I will focus on the study of the physical conditions of the interstellar medium in HZ10. Performing SED fitting using kpc-scale resolution ALMA Band 7 plus new ALMA Band 9 observations continuum data, we derive high precision dust temperature estimations for the more dusty component affected by severe UV-obscured (with evidence of AGN activity). Upcoming CRISTAL studies will analyze the kinematics and the IRX-βUV relation in more detail, increasing the probed environments with extreme physical conditions of the dust at high-z.

First quenched galaxies from the perspective of semi-analytic model

Lizhi Xie

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JWST has discovered many quiescent galaxies that raise the fundamental questions on when and how these galaxies became quenched. In this talk I will present what we learn from the latest version of the Galaxy Evolution and Assembly (GAEA) theoretical model. The latest version has been greatly improved by combining effort on AGN feedback and environmental effects. The model now provides nice agreements with observational measurements up to $z \sim 3-4$, and a turn-over of the number densities of quenched galaxies at low stellar masses that is in qualitative agreement with current observational estimates. Making use of this model we find that in a simulated box of 685 Mpc on a side, the first quenched massive, Milky Way mass, and low mass galaxies appear at $z \sim 4.5$, $z \sim 6.2$, and before $z = 7$. Most quenched galaxies identified at early redshifts remain quenched for more than 1 Gyrs. Independently of galaxy stellar mass, the dominant quenching mechanism at high redshift is the accretion disk feedback (quasar winds) from a central massive black hole, which is triggered by mergers in massive and Milky Way mass galaxies, and by disk instabilities in low-mass galaxies. Environmental stripping becomes increasing more important at lower redshift.

Molecular Excitation in Two Optically Faint Quasars at $z \sim 6$

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We present NOrthern Extended Millimeter Array observations of CO (8 – 7), (9 – 8), and (10 – 9) lines, as well as the underlying continuum for two optically faint quasars: SDSS J2054-0005 at $z = 6.0389$ and SDSS J0129-0035 at $z = 5.7788$. Both quasars were previously detected in CO (2 – 1) and (6 – 5) transitions, making them potential candidates for studying the CO Spectral Line Energy Distribution (SLED) of optically faint quasars at $z \sim 6$. We fit the continuum detections with graybody thermal dust models, and the best estimates for dust masses and total-infrared luminosities are $M_{\rm dust} \sim 1.5 \cdot 10^8 M_\odot$ and $L_{\rm TIR} = 6.1 \cdot 10^{12} L_\odot$ for J2054-0005 and $M_{\rm dust} \sim 3.3 \cdot 10^8 M_\odot$ and $L_{\rm TIR} = 7.1 \cdot 10^{12} L_\odot$ for J0129-0035. Utilizing the radiative transfer code `CLOUDY`, we fit the CO SLED with two heating mechanisms, including the photo-dissociation region (PDR) and X-ray-dominated region (XDR) for both objects. The CO SLEDs of both objects can be fitted by either a dense PDR component with an extremely strong far-ultraviolet radiation field (gas density $n_{\rm H} \sim 6$ and field strength $G \geq 6$) or a two-component model including a PDR and an XDR. However, the line ratios, including TIR and previous C II and C I measurements, argue against a very high PDR radiation field strength of $G \geq 6$. Thus, the results prefer the PDR+XDR origin of the CO SLED. It is likely that the excitation of the high-J CO lines in both objects is dominated by the central AGN. We then check the CO (9 – 8)-to-(6 – 5) line luminosity ratio r_{96} for all $z \sim 6$ quasars with available CO SLEDs and find that there are no clear correlations between r_{96} and both TIR and the AGN luminosities. This further demonstrates the complexity of the CO excitation powered by both the AGN and nuclear star formation in these young quasar host galaxies.