Charting the metallicity evolution history of the Universe

Abstracts Booklet

Adam Carnall

Edinburgh University

The stellar metallicities of massive galaxies at cosmic noon

The majority of stars in the present-day Universe reside in massive galaxies, primarily formed during the first six billion years prior to z = 1. Detailed studies of the processes that shaped these galaxies are critical for our overall understanding of galaxy evolution. However, observing their formation and quenching in progress at z > 1 presents huge challenges. I will discuss current and future efforts to constrain the stellar metallicities of massive quiescent galaxies at z > 1, including the technical considerations for robustly measuring stellar metallicities via full spectral fitting. In particular, I will discuss results from the VANDELS survey and subsequent KMOS follow-up in the rest-frame optical. Combined, these provide high-SNR rest-frame UV-optical continuum spectroscopy for a mass-complete sample of massive quiescent galaxies at z > 1 for the first time, allowing studies of the stellar mass-stellar metallicity relation to be extended to these redshifts (arXiv:2108.13430). I will also discuss efforts to study interrelations between stellar mass, size and stellar metallicity at 0.6 < z < 1.3 using data from the LEGA-C and VANDELS surveys (arXiv:2201.10576). Finally, I will discuss the upcoming 200-night Multi-Object Optical and Near-Infrared Spectrograph (MOONS) extragalactic GTO program MOONRISE. Starting in 2023, MOONRISE will provide huge statistical samples of high-SNR spectra at z > 1 that will revolutionise the study of chemical enrichment at high redshift.

Adam Schaefer

Max Planck Institute for Astrophysics

Exploring the local scaling relations for N/O with MaNGA

In this talk I will present, for the first time, the relationship between the local properties of galaxies on kpc scales, such as the star formation rate and stellar mass surface densities and the N/O in galaxies. Using data from 792765 high signal-to-noise ratio star-forming spaxels in SDSS-IV MaNGA, we find that the N/O ratio is sensitive to both stellar mass surface density and star formation rate surface density. Interestingly, we find that the local N/O scaling relations also depend on the total galaxy stellar mass at fixed stellar mass surface density as well as the galaxy size at fixed stellar mass. We find that more compact galaxies are more nitrogen rich, even when the local galaxy properties are controlled for. We show that ∼50% of the variance of N/O is explained by the total stellar mass and galaxy size. Thus, the evolution of nitrogen that we measure in galaxies will be sensitive to the sample of galaxies from which it is derived. This result casts doubt on the universal applicability of nitrogen-based strong-line metallicity indicators and hints at varying evolutionary processes for galaxies with different morphologies.

Alessandro Marconi

Department of Physics and Astronomy, University of Florence

A new approach to photoionization modelling: towards percent accuracy in reproducing observed emission lines and the physical properties of the ionised medium

Emission lines from photo-ionized nebulae have always been used to study the physical properties of the emitting media and the characteristics of the ionizing sources.
Over the past decades, several attempts have been made to reproduce the observed emission lines using photoionization models with several degree of complexity but, in most cases, these models fail to simultaneously reproduce all the emission lines fluxes from different excitation stages. I will present an approach to photoionization modelling based on emission from multiple clouds whose properties, at variance with previous models, are not assumed but determined by observations. I will show how these models are able to reproduce all emission lines from many different kinds of sources (HII regions, Planetary nebulae, star forming and active galaxies) down to a few percent accuracy. I will discuss the implications for our knowledge of the physical properties of the photo-ionised gas, compare our results with those from the well known line ratio diagnostics of electron temperature and density, and present the application of our models to metallicity measurements in galaxies.

Alex Cameron

University of Oxford

How many metals do galaxies lose to outflows? New constraints from the DUVET survey

A basic prediction of the baryon cycle is that gas expelled as outflows is metal-enriched compared to the inflowing gas that fuels star formation.
The outflow metal loading factor, defined as the ratio between the outflow metallicity and that of the ISM, is a critical input for galaxy evolution models. However, this quantity remains almost completely unconstrained from observations. This is in part due to the faintness of the observational tracers required. But also, the conditions in outflowing ionised gas are poorly understood meaning the interpretation of emission line ratios is dominated by systematics. Futhermore, measurements of total outflow rate, which underpins total metal loss, often suffer from lack of spatial resolution and uncertainties of outflow covering fraction.

I will present the latest results from the DUVET survey. Our deep Keck/KCWI data have afforded unique constraints on the metallicity of outflows in low-z starburst galaxies using the direct Te-method.
I will present a comparison of these measurements to GLACIER, a novel hydrosim featuring non-equilibrium metal chemistry coupled to on-the-fly radiative transfer. These results provide powerful new insights into interpretation of outflows that were not possible with traditional photoionization codes. I will also present a novel constraint on the covering fraction and time-variability of outflows from our observation of spatially-resolved mass outflow rates along an outflow filament in an edge-on galaxy.

Aliza Beverage

UC Berkeley

The Chemical Enrichment and Assembly Histories of Massive Quiescent Galaxies over Cosmic Time with JWST and Keck

The existence of a population of massive quiescent galaxies beyond z~2 has spurred questions about how they form so rapidly and why they quench so early. Chemical properties of this population provide crucial insights into solving these puzzles. Unfortunately, characterizing their chemical compositions has proven difficult due to their already faint stellar continua and the redshifting of key absorption features into the NIR. New ultra-deep spectroscopic surveys, along with advancements in full spectrum modeling, are beginning to open a new window into studying this population. In this presentation, I will introduce the Heavy Metal survey, which has taken the deepest rest-frame optical spectra (~3600-5400 Angstom) for a sample of 20 massive quiescent galaxies at z=1.4 - 2.1 with Keck. I will also present our approved Cycle 1 JWST program, which will obtain additional ultra-deep spectra for 16 massive quiescent galaxies at z=1.0 - 2.5. By targeting a range of Balmer and metal absorption lines, these programs will enable the measurement of elemental abundances and stellar population properties using full spectrum modeling. By comparing the results from z~2 to those of massive quiescent galaxies in the LEGA-C survey at z~0.7 and in SDSS at z~0, I will discuss implications for chemical enrichment and star formation quenching across cosmic time.

Andrea Pallottini

Scuola Normale Superiore

Unveiling the Interstellar Medium of galaxies in the Epoch of Reionization.

The characterization of primeval galaxies is a key question of modern astrophysics. Optical surveys are exquisite tools to search for galaxies in the Epoch of Reionization (EoR). Their interstellar medium can be probed via spectroscopy, in particular by exploiting the unprecedented capabilities of ALMA. Observations can be combined with detailed models to achieve a solid theoretical understanding. This can be done by exploiting cosmological zoom-in simulations of galaxies in the EoR that are able to follow their radiative, hydrodynamical, and chemical evolution, with particular attention to their metal and dust content; by precisely computing the emerging line and continuum emission, we can properly compare our models to the most recent observations. This allows us to draw novel conclusions on the study of primeval galaxies and prepare for the advent of the JSWT era.

Andrea Saccardi

GEPI, Observatoire de Paris, Université PSL, CNRS

Chemical signatures of the first stars in high-redshift gaseous absorbers

The first stars were born from chemically pristine gas. They were likely massive and thus they rapidly exploded as supernovae, enriching the surrounding gas with heavy elements. In the Local Group, the chemical signatures of the first stars were identified among low-mass, long-lived, very metal-poor ([Fe/H]<-2) stars, characterized by a high abundance of carbon over iron ([C/Fe]>+0.7). Conversely, a similar carbon excess was not found in dense neutral gas traced by QSO absorption systems.
In this talk I will report the results of a work (A. Saccardi, S. Salvadori, V. D'Odorico et al. in prep) on the signatures of first stars at z=3-4. Through the analysis of the spectra of QSO lines of sight, we detected 9 very metal-poor, carbon-enhanced systems, at redshift z~3-4. These absorption systems reveal an overabundance with respect to Fe of all the analyzed chemical elements such as C, O, Mg, Al, and Si, which allows us to exclude contamination by the wind of a companion star. The distribution of the relative abundances with respect to [Fe/H] perfectly matches those of the local very metal-poor stars.
Consequently, these absorbers, likely imprinted by the chemical yields of the first stars, suggest that the signature of the first stars survives in optically thick, relatively diffuse absorbers, not sufficiently dense to sustain star formation and hence, not dominated by the chemical products of normal stars.

Anna Rita Gallazzi

INAF-Arcetri Astrophysical Observatory

The evolution of stellar metallicities at intermediate redshift from deep spectroscopic surveys

The metal abundances of galaxy stellar populations, together with stellar ages, constitute a fossil record of galaxies' SFHs and can inform about the build-up of the massive quiescent population in the local Universe. The so-called archaeological approach has been extensively adopted at z=0 and, until recently, it has been carried out in a complementary but parallel way to direct look-back studies of the demographics of galaxy populations at different redshifts. The LEGA-C deep spectroscopic survey has provided, for the first time, spectra of the required stellar continuum quality and for statistically representative samples at intermediate redshifts (0.6<z<1) that finally allow a joint archaeological and look-back approach.
In this talk I will present the diagnostic power of the LEGA-C spectra and I will discuss our efforts to constrain stellar ages and metallicities from absorption features and spectral fitting, with attention to the systematics affecting these estimates. I will present the first results on the mass-metallicity relation of quiescent and star-forming galaxies, in connection with their z=0 equivalent, derived in a homogeneous way. I will then highlight prospects from the upcoming WEAVE-StePS and 4MOST-StePS surveys.

Annalisa De Cia

University of Geneva

The chemical enrichment of the neutral ISM throughout cosmic time

The ISM chemical composition is key for the evolution of stars and galaxies throughout cosmic time. The metal content of the neutral gas in galaxies can be probed in great detail with absorption-line spectroscopy of stars in the Local Group, or distant quasars and gamma-ray bursts (GRBs). However, the presence of dust dramatically alters the observed metal abundances, because of the depletion of dust into dust grains. I developed a technique to characterise dust depletion, based on the relative abundances, because different metals deplete into dust at different rates. This was key for a deeper understanding of the chemical content of the neutral ISM. My three main discoveries are: 1) Large metallicity variations in the neutral ISM in the Galaxy, which was hitherto assumed chemically uniform. This suggests the accretion and inefficient mixing of pristine gas on the Galactic disk. 2) The cosmic chemical evolution of the neutral ISM. After taking dust corrections into account, the evolution of the neutral ISM metallicity shows three times more metals than previously estimated. This leads to the fact that the neutral ISM carries the majority of metals at high z. 3) Peculiar metal content in early galaxies. A strong overabundance of aluminium (and possibly a hyper enhancement of α-elements) is observed in the two GRBs at $z = 6$ with quality spectra available so far, suggesting that very massive stars may play an important role for the chemical enrichment of the early Universe.

Bethan James

STScI

Exploring Star-formation & Inhomogeneity in Pristine Environments: IFU studies of metal-poor dwarf galaxies

Understanding the interplay between metallicity and star-formation (SF), both spatially within a system and globally with redshift, are of paramount importance for understanding galaxy formation and evolution. Nearby metal-poor dwarf galaxies offer the opportunity to tackle both these aspects: their chemically-young environments are akin to those at high-z and their close proximity provides insight into these processes on <100 pc scales. In this talk I will present a series of IFU-based results that illustrate our new detailed insight into the spatially resolved chemical properties and SF activity within low-metallicity dwarfs. For example, while most dwarf galaxies are thought to be chemically homogeneous, chemical abundance maps of BCDs often reveal inhomogeneities and enrichment on <100 pc scales suggesting rapid cooling of ejecta or mixing on long timescales. In-turn, such variations in metal content and temperature can affect the progression of SF. In particular, I will focus on recent VLT/MUSE observations of blue diffuse dwarf galaxies, where SF is actively ongoing in extremely metal poor HII regions scattered amongst highly diffuse gas - i.e., environments strongly reminiscent of primordial galaxies. This study additionally highlights the role of multi-phase hydrodynamical simulations in interpreting abundance variations and demonstrates that the methods used in the assessment of chemical inhomogeneities can be subject to bias.

Casey Papovich

Texas A&M University

The Evolution of Gas-Phase Metallicity and Ionization from Hubble/ Spectroscopy

Infrared slitless spectroscopy from the Hubble Space Telescope (HST) has become a mainstream method to study distant galaxies. I will discuss constraints using such data to study distant galaxies based on a large HST program (from the CLEAR [CANDELS Lyman-alpha Emission At Reionization] survey). CLEAR uses >120 orbits of HST to target roughly 100 square arcminutes in the GOODS-North and -South fields using slitless spectroscopy covering 0.85 to 1.65 micron. The CLEAR data cover important spectral features of galaxies, including rest-frame optical emission lines (such as [OII], H-beta, [OIII], H-alpha+[NII]) for galaxies at redshifts z~1-3. I will discuss constraints on the evolution of galaxy gas-phase metallicities and ionization parameters derived from these data using the MAPPINGS V models (from Kewley et al. 2019) We find both strong evolution in galaxy metallicities and the ionization parameter with redshift. We observe trends between these parameters and the galaxy specific SFRs: galaxies with higher H-beta equivalent width have higher ionization parameter, even at fixed stellar mass and metallicity. I will discuss the implications this has for galaxy formation and predictions for future surveys at higher redshift from JWST.

Celine Peroux

ESO

The Cosmic Baryon & Metal Cycles

These are incredibly exciting times for extra-galactic astrophysics; above all for studies of galaxy formation and growth of structure. New observatories and advanced simulations are revolutionising our understanding of the cycling of matter into, through, and out of galaxies. In this talk I will provide an overview of the normal matter in collapsed structures, their chemical make-up and dust content. I will present fresh clues of the cosmic evolution of cold gas; revisit the 20-year old "missing metals problem" and introduce new calculations of the dust content of the Universe up to early times. Together, these results provide an increasingly accurate description of the baryon and metal cycles which play many crucial roles in transforming the bare pristine Universe left after the Big Bang into the rich and diverse Universe in which we live today.

Ciro Pappalardo

Institute of Astrophysics and Space Sciences

Mean stellar metallicity of galaxies in spectral synthesis methods: a quantitative test using different approaches

In this work, we investigate the reliability of spectral synthesis methods in the estimation of the mean stellar age and metallicity, addressing the question of which signal-to-noise ratios (S/N) are needed to determine these quantities and how these depend on the tool used to model the spectra.

To address this problem we used realistically simulated spectra containing stellar and nebular emissions, reproducing the evolution of a galaxy for a constant and exponentially declining star formation history (SFH). The spectra have been degraded to different S/N and analysed with three different spectral synthesis codes: FADO, STECKMAP, and STARLIGHT assuming similar fitting set-ups and the same spectral bases.

Considering a continuous SFH all the tools have difficulties recovering the metallicity evolution at S/N<20. For exponentially decreasing SFHs the results for mean metallicities are more homogeneous than in the continuous case. The solutions are more unstable at log(t/yr) ~ 7, with FADO and STARLIGHT showing a peak of ~0.2 dexes at ~200 Myr in mean stellar metallicities, resulting from the poor coverage of the spectral basis at those ages.

Our results indicate that phases of high specific star formation rate (sSFR) in galaxies require analysis tools that do not neglect the nebular continuum emission in the fitting process, since purely stellar models would have strong problems in the estimation of metallicity history, even in presence of high S/N spectra.

Connor Hayden-Pawson

Kavli Institute for Cosmology, Cambridge

The KLEVER survey: Insights into galaxy evolution using the N/O ratio

The different production mechanisms and delayed enrichment timescales of nitrogen compared to oxygen make the N/O ratio a time-sensitive probe of different evolutionary stages of galaxies. Furthermore, comparisons with properties such as metallicity, stellar mass and SFR can give insights into the impact of gas inflows and outflows. Here, we investigate galaxy evolution through probing the gas-phase N/O ratio in star forming galaxies across cosmic time. We focus on spatially resolved observations of ~40 galaxies at $1.2<z<2.5$, obtained in the framework of the KMOS Lensed Emission Lines and VElocity Review (KLEVER) Survey, for which we could robustly measure both O/H and N/O using independent emission line diagnostics. Comparing the global properties of these galaxies with those from local SDSS galaxies, we find no strong evolution in the N/O-O/H relation with redshift, a result that when considered alongside the existence of a fundamental metallicity relation (FMR), suggests that the FMR may be driven in part by variations in galaxy age, star formation history and star formation efficiency. We then extend our analysis to a spatially resolved scale, finding N/O gradients that are flatter at high redshift than in local MaNGA galaxies. This result is similar to that found when studying O/H gradients, suggesting strong feedback mechanisms are effectively mixing the ISM at high redshift, but also that nitrogen production at high-redshift may be dominated by massive stars.

Conor Byrne

University of Warwick

The Dependence of Synthetic Spectra on Alpha-Enhancement in Young, Binary Stellar Populations

The non-uniform chemical evolution of the Universe has laid bare a shortcoming in the modelling of young stellar populations at high redshift. These populations are typically enhanced in alpha elements relative to a Solar composition. This challenges most stellar population models, which are Solar-scaled. Here I present initial models calculated using the Binary Populations and Spectral Synthesis (BPASS) framework that include alpha-enhanced stellar spectra, matched on total metallicity mass fraction with Solar-scaled stellar evolution models. This study focuses primarily on the impact on the integrated light of young stellar populations, including those with large binary star fractions. We examine the effects that changes in [alpha/Fe] make to broadband spectral features (e.g. ionising flux production) as well as more specific features, such as line indices. Although individual ultraviolet stellar absorption lines are relatively insensitive to particular abundance ratios, it is determined that a combination of UV line indices may enable a simultaneous measurement of total metallicity mass fraction and [alpha/Fe] in young, star-forming stellar populations. For stellar populations older than 1 Gyr, alpha-enhanced models are found to be bluer than their Solar-scaled counterparts, in agreement with previous work. These models are made available to the community with the aim of assisting interpretation of observations of high-redshift galaxies with the James Webb Space Telescope.

Daichi Kashino

Nagoya University

The stellar mass versus stellar metallicity relation at cosmic noon and implications for the evolution of the [O/Fe] abundance ratio

We present the relationship between stellar mass and stellar metallicity, i.e., the MZ* relation, for 1336 star-forming galaxies at 1.6 < z < 3.0 from the zCOMSOS-deep survey. We utilized a full spectral fitting with the BPASS stellar population synthetic spectra to measure the stellar metallicities that reflect mainly the iron abundance. The inferred metallicities are in a range of -1.5 <~log(Z*/Zsun) <~ -0.3, showing a tight positive correlation with stellar mass. Comparing the local MZ* relation, we found a significant redshift evolution between z~0 and z~2.2 with the latter showing ~0.8 lower Z* at a given M*. Furthermore, comparing the gas-phase MZ relation, we constrained the O/Fe-enhancement and found a intriguing link between the galactic archeology and high-z galaxy evolution: the evolution of the location in the O/Fe vs. Fe/H plane occupied by local and high-z galaxies are in good agreement with the sequence of the Galactic stars. We discuss the interpretation of the observed results by using a simple chemical evolution model in which the delayed time of iron enrichment due to type-Ia supernovae is accounted for.

Dyna Ibrahim

University of Hertfordshire

The evolution of mass-metallicity relation with various supernova feedback in cosmological simulations

The metallicity of galaxies gives a strong constraint on galaxy formation and evolution. The formation of stars in galaxies is highly impacted by the metal production and the energy released by supernova explosions as it suppresses star formation by generating outflows and evaporating star-forming clouds. This energy is known as supernova feedback. In order to understand its impact, we compare different feedback methods and parameters by ejecting energy in thermal, kinetic, stochastic and mechanical forms. We implement these different schemes in a cosmological simulation based on our version of Gadget code including the latest supernova yields. For each scheme, we predict the evolution of stellar and gas-phase metallicity, and we analyse the feedback impact in terms of Mass-Metallicity relation where we find, for example, that the kinetic feedback gives a systematically lower metallicity. Next, compared to observational data, such as the James Web Space Telescope (JWST), we will constrain the feedback method and discuss the chemical enrichment from the first stars in the early universe.

Emma Curtis Lake

University of Hertfordshire

Tracing metallicities in obscured AGN over cosmic time with BEAGLE-AGN

We learn so much by tracing the chemical evolution in different regions of the ISM within galaxies. The abundances of different elements in HII regions is well studied but those of the narrow-line region (NLR) gas in AGN, less so. Significant progress has been made in the last few years, culminating with a new T_e based empirical calibration by Dors+21. However, this still doesn't address the varying contribution of the star-forming regions to the emission line properties in AGN spectra. I will present the integration of the Feltre+ 2016 NLR emission models into BEAGLE (Chevallard & Charlot 2016), a Bayesian spectral and SED fitting code. This allows us to perform simultaneous HII and NLR fits. This tool will enable us to find obscured AGN to high redshifts where the star-forming locus in the BPT shifts towards the AGN cloud at z~2 (Steidel+14), and low-metallicity AGN occupy similar regions (e.g. Feltre+16) while also determining the gas properties of the NLR and HII regions. To test the models and fitting technique we fit to a) BEAGLE-simulated galaxies with range of AGN contribution to the line fluxes and b) a sample of X-ray selected Type-II AGN with SDSS DR7 spectra, as well as measuring HeII for a large sample of SDSS DR7 spectra, as well as measuring HeII for a large sample of SDSS AGN to determine their ionisation state. I will present these studies as well as prospects for identifying and measuring NLR metallicities of high redshift AGN with JWST.

Evan D. Skillman

University of Minnesota

The End of the Instantaneous Recycling Approximation for Oxygen

The instantaneous recycling approximation (IRA) has been widely used to describe the chemical evolution of oxygen. This is based on the relatively fast time scale for the production and release of oxygen from massive stars (3 - 40 Myr). However, there is a second timescale, and that is the time for the oxygen to become observable (i.e., in the emission line spectra of the ISM). Measurements of oxygen abundances in HII regions in star forming dwarf and spiral galaxies show a high degree or regularity as a function of radius. This argues strongly against in situ pollution (as represented in the IRA) and is best understood as the newly synthesized oxygen being released into the hot phase of the ISM where it is well mixed before cooling sufficiently to be observed.

Fergus Cullen

University of Edinburgh

Iron and oxygen abundances in star-forming galaxies at z=3.5

A number of recent results in the literature have demonstrated that it is possible to derive robust stellar iron abundances (Fe/H) from ultra-deep rest-frame FUV spectra of star-forming galaxies at high redshift. In combination with oxygen abundances (O/H) derived using standard rest-frame optical emission line techniques, this has enabled an investigation of the O/Fe abundance ratio in high-redshift galaxies.

In this talk I will present a joint rest-frame FUV+optical spectroscopic analysis of galaxies from the VANDELS survey, aimed at measuring the O/Fe abundance ratio in star-forming galaxies at z=3.5. Our results indicate that both Fe/H and O/H show the same scaling with galaxy stellar mass, with a difference in normalisation indicating super-solar O/Fe abundance ratios (i.e., α-enhancement), with (O/Fe) ~ 2.5 × (O/Fe)_solar. I will discuss how these results are in excellent agreement with the O/Fe abundances ratios observed for old (10 - 12 Gyr) stars observed at large scale heights within the Milky Way (i.e, thick disk, halo), representing an interesting link between local and high-redshift stellar populations, and a pleasing consistency between independent constraints on α-enhancement in the early Universe.

Fontanot Fabio

INAF - OATs

The evolution of the mass-metallicity relations in the GAEA Semi-Analytic model

In my talk, I will discuss the evolution of the mass-metallicity relations (MZRs) as predicted by the GAlaxy Evolution and Assembly (GAEA) semi-analytic model. Out team contrast these results with recent and updated observational results, that allows us to expand the accessible redshift range up to z~3.5, and consider, at the same time, the evolution of both the stellar and the gas-phase MZRs. Our results show that GAEA is able to reproduce the observed evolution of the z<3.5 gas-phase MZR and z<0.7 stellar MZR. Furthermore, we also focus on the the so-called fundamental metallicity relation (FMR) between gas-phase metallicity, stellar mass and star formation rate (SFR); we find that the gas-phase FMR in GAEA is already in place at z~5 and it shows almost no evolution at lower redshift. Moreover, GAEA predicts the existence of a well-defined stellar FMR, that is, however, characterized by a relevant redshift evolution. We also report additional unsolved tensions between model and data: the overall normalization of the predicted MZR agrees with observations only within 0.1 dex, with the largest discrepancies at z~3.5 where models tend to overpredict observed metallicities. Moreover, the slope of the predicted MZR at fixed SFR is too steep below a few Msun/yr. Finally, I will present model predictions for the evolution of the MZRs at higher redshifts, that would be useful in the context of future surveys, like those that will be performed with JWST.

Francesca Matteucci

Trieste University

Chemical evolution models

I will describe the main ingredients necessary to build analytical and numerical chemical evolution models, and discuss how we can reconstruct the history of star formation in galaxies by means of chemical abundances. The time-delay interpretation of the [X/Fe] vs. [Fe/H] diagrams for different star formation histories will be discussed. In the era of large spectroscopic surveys our knowledge of the evolution of the Milky Way is rapidly improving, therefore I will first discuss some important facts about the evolution of the different components of our Galaxy, such as the possible interpretations of the dichotomy in the [alpha/Fe] ratios in the thick and thin disk stars. Then, I will present some models for dwarf and elliptical galaxies and finally, on the basis of the previous chemical models, some considerations on the cosmic metal and dust enrichment will be discussed.

Francesco Belfiore

INAF- Arcetri Astrophysical Observatory

The ionisation sources of diffuse ionised gas (DIG) in local galaxies

About half of the ionising photons produced by young stars leak from HII regions and contribute to powering the DIG. The optical line ratios observed in the DIG, however, are inconsistent with the expectations from such a simple scenario. Several additional sources of harder ionising photons have been invoked in the literature, but a comprehensive model for the ionisation of the DIG has remained elusive. In this talk I will use integral field spectroscopy from the PHANGS–MUSE survey, which resolves the interstellar medium at ~50 pc resolution, to study both the spatial and spectral signatures of the DIG. We find that the DIG results from a superposition of two components, an energetically dominant contribution from young stars and a more diffuse background of harder ionising photons from old stars. In particular, evolved stars make a small contribution to the energy budget of the DIG (2% on galaxy-integrated scales), but their harder spectra are necessary to explain the observed line ratios. Our unified framework bridges observations of the Milky Way DIG with LI(N)ER-like emission observed in nearby galaxy bulges and will inform future DIG corrections for metallicity calibrations at low and high redshift.

Francois Mernier

European Space Agency (ESA)

An X-ray view of chemical enrichment in galaxy groups and clusters

An essential component of the cycle of metals in our Universe comes from the hot, X-ray emitting gas pervading clusters and groups of galaxies. Not only this intracluster medium accounts for 70-90% of the baryonic content of these systems; it is also rich in metals (typically from N to Ni) whose abundances can be robustly constrained via X-ray spectroscopy. Here, we will briefly review the latest progress and knowledge acquired through X-ray observations of clusters and groups, particularly thanks to the capabilities of the XMM-Newton, Chandra, and Suzaku missions. We will see how the chemical composition of the intracluster medium, along with the spatial distribution of its abundances, point toward a scenario where the bulk of metals were synthesized, diffused out of galaxies and thoroughly mixed at Mpc scales early on ($z > 2$-3), before clusters and groups began to assemble.
Last but not least, we will discuss recent work on the abundance spatial distribution and the chemical composition of the hot, X-ray emitting halo of the elliptical galaxy NGC1404, with the aim to connect the chemical history of galaxies with that of the largest scale structures of our Universe.

Fuyan Bian

ESO, Chile

Gas-Phase Metallicity Measurements in High-Redshift Galaxies in the JWST Era

The gas-phase metallicity calibrations highly depend on the physical conditions of the ionized interstellar medium (ISM). The widely used empirical metallicity calibrations based on the local HII regions may not be suitable for high-redshift galaxies, due to the strong evolution of the physical conditions of the ionized ISM. In this talk, I will present a sample of local galaxies selected by matching their optical diagnostic line ratios to those in z=2 galaxies. These galaxies closely resemble the ionized ISM conditions in galaxies at z=2, including high ionization parameters and high electron densities. Our new empirical metallicity calibrations based on these local analogues provide the most robust metallicity measurements at z=2-3. In the JWST era, we will extend such an approach to galaxies at even higher redshift. I will build up robust empirical metallicity calibrations and other ionized gas diagnostic methods for galaxies at $4<z<7$. This method, together with the future JWST spectra, will paint a comprehensive picture of the evolution of gas-phase metallicity and physical conditions of the ionized gas over cosmic time.

Hanna Parul

University of Alabama

Imprints of bursty star formation on the abundance patterns in FIRE-2 Milky Way-like galaxies

Milky Way-mass galaxies in cosmological simulations and observational data demonstrate two different modes of star formation. At high redshifts star formation occurs in a series of short and intense bursts, while at low redshifts star formation proceeds at a steady rate. For the case of 11 Milky Way-like galaxies from the FIRE-2 simulation we analysed how the mode of star formation affects metallicity and alpha-elements abundance. We found that stars formed during the bursty regime are distributed in the shape of a "sideways chevron" on the [Fe/H] - [O/Fe] plane and that the scatter of [O/Fe] at a given age is higher when a galaxy is in the bursty regime. That means that the evolution of [O/Fe] scatter with age for high metallicity stars provides an estimate of the end of the bursty phase. We applied our method to real Milky Way data from the GALAH survey and the Second APOKASC Catalog and estimated that the transition to steady star formation in the Milky Way happened 8 Gyrs ago.

Harley Katz

University of Oxford

Metallicity diagnostics in high-redshift galaxies enriched by Pop III and Pop II stars

Measuring the evolution of the gas-phase metallicity across time requires precise models for how observed emission lines can be translated into metal abundances. Various methods such as Te-based, recombination line, collisional line, etc. approaches have been applied to galaxies at nearly all redshifts; however, uncertainties persist due to calibration errors, non-solar abundance ratios, and unknown ionization correction fractions. Correcting for these uncertainties and understanding the adequacy of published calibrations at z>6 requires detailed physical models of the ISM in the early Universe. For this reason, we have developed the new RAMSES-RTZ code that directly couples non-equilibrium metal chemistry to the local inhomogeneous and fluctuating radiation field of galaxies, allowing us, for the first time, to test whether known metallicity calibrations can be applied during the epoch of reionization. Using a state-of-the-art suite of simulations of galaxy formation at z>6, I will discuss the accuracy of various metallicity calibrations on galaxies that have been enriched by both Pop II and Pop III stars and highlight the physics governing whether metallicity calibrations can be applied. Furthermore, when existing models break down, I will present new models that can be exploited with upcoming JWST data.

Irene Shivaei

University of Arizona

First constraints on the properties of dust grains as a function of gas metallicity at Cosmic Noon

Dust plays a key role in the physics and chemistry of the ISM. In this talk, I will give an overview of multi-wavelength studies using ALMA, Keck, and VLT on the properties of dust grains as a function of gas metallicity at Cosmic Noon, z~1-3: 1) using rest-frame optical spectra of MOSFIRE/Keck and rest-frame UV spectra of MUSE/VLT, I study the shape of the attenuation curve of galaxies at z~2 as a function of metallicity. Specifically, I will show our results on how the slope of the UV attenuation curve, originated from absorption by small dust grains, is steeper at low metallicities, while the UV 2175A absorption bump, assumed to originate from PAH dust grains, is stronger at high metallicities. This work will be extended to z>5 using JWST/NIRCam data (JADES GTO program); 2) using deep ALMA continuum observations of 27 galaxies at z~2 with robust metallicities from MOSFIRE/Keck (MOSDEF survey), I constrain the shape of the dust SED as a function of metallicity, for the first time beyond the local Universe. I will show that the IR SED is warmer and wider at sub-solar metallicities, which has direct implications for reionization-era studies, where metallicities are often sub solar. Using JWST/MIRI and NIRSpec (US MIRI GTO), I will extend this work to study the variations of mid-IR dust emission with metallicity at z~2. These studies demonstrate the power of multi-wavelength studies to constrain the chemical composition and size distribution of dust grains at high redshifts.

Joris Witstok

Kavli Institute for Cosmology, University of Cambridge

Assessing the sources of reionization: a spectroscopic case study of a 30× lensed galaxy at $z \sim 5$ with Lyα, C IV, Mg II, and [Ne III]

I will present a detailed spectroscopic analysis of a galaxy at $z \simeq 4.88$ that is, by chance, magnified ~30× by gravitational lensing. Only three sources at $z \sim 5$ are known with such high magnification. This particular source has been shown to exhibit widespread, high equivalent width CIV λ1549 Å emission, implying it is a unique example of a metal-poor galaxy with a hard radiation field, likely representing the galaxy population responsible for cosmic reionization. Using UV nebular line ratio diagnostics, VLT/X-shooter observations rule out strong AGN activity, indicating a stellar origin of the hard radiation field instead. I will present a new detection of [NeIII] λ3870 Å and use the [NeIII]/[OII] line ratio to constrain the ionization parameter and gas-phase metallicity. This makes it one of the most distant systems for which the metallicity has been measured through optical line ratios. Closely related to the commonly used [OIII]/[OII] ratio, our [NeIII]/[OII] measurement shows this source is similar to local 'Green Pea' galaxies and LyC leakers. It furthermore suggests this galaxy is more metal poor than expected from the fundamental metallicity relation, possibly as a consequence of excess gas accretion diluting the metallicity. In conclusion, this strongly lensed galaxy, observed just 300 Myr after reionization ends, enables testing of observational diagnostics proposed to constrain the physical properties of distant galaxies in the JWST/ELT era.

Karl Glazebrook

Swinburne University of Technology

Stellar chemical abundances in stars in $z>1$ galaxies

The abundances of individual elements is very difficult to measure in stellar populations at $z>1$ and only a handful of galaxies have been measured. We present new deep optical and near-infrared spectra of two lensed low mass quiescent early type galaxies at $1<z<1.5$. Recently discovered in the DECALS and DES surveys, these unique lenses are very bright and permit SNR>50 rest frame optical spectroscopy. This SNR regime permits abundances of individual elements in stellar populations to be measured from absorption lines, allowing more precise distinction of different epochs of star-formation. The alpha abundance and metallicity measures are several times more precise than previous $z>1$ observations and this is the first time the low stellar mass galaxy regime has been probed. We interpret the abundance patterns in terms of models for elliptical galaxy formation.

Kathryn Grasha

Australian National University

The Chemical Evolution of Spiral Galaxies from Start of Cosmic Dawn to Today

The spatial distribution of oxygen in the interstellar medium of galaxies is key to understanding how efficiently metals that are created in the hearts of massive stars are mixed and redistributed across the galaxy. I present a study of 6 nearby spiral galaxies using the 3D optical data obtained in the TYPHOON Program. We use HIIPhot to identify the HII regions within the galaxy based on the surface brightness of the H-alpha luminosity and measure the radial variations of the HII region oxygen abundance. We recover a flattening to the negative radial gradient in several of the galaxies at large galactocentric radius, suggesting that we have sufficient resolution and sensitivity to detect the metallicity floor, which may be set by direct accretion of gas from the cosmic web. The measured metallicity floor informs on the chemical enrichment of the galaxy and the outflow of metals to the outer regions of the disk from the enriched inner region of the galaxy disk through radial flows. I will present comparisons with hydrodynamical simulations to shed light on the dynamical local enrichment of the oxygen enrichment in these galaxies and the implications for galaxy evolution studies with the next generation of observatories including the upcoming James Webb Space Telescope.

Kathryn Kreckel

Zentrum für Astronomie der Universität Heidelberg

A PHANGS view towards abundance variations across nearby galaxies

Gas-phase metallicities track the growth of stellar mass and the pollution from massive stars into the interstellar medium (ISM), providing a unique tracer of galaxy evolution. With new VLT/MUSE optical integral field spectroscopy, the PHANGS team now has a wealth of emission line maps that trace different ionization sources and physical conditions at the 50pc spatial scales needed to isolate individual ionized regions (e.g. HII regions, supernova remnants, planetary nebulae) from surrounding diffuse ionized gas. I will present our most recent results measuring the gas phase oxygen abundances for 24,000 HII regions across 19 galaxies in the PHANGS-MUSE survey. We move beyond simple radial gradients to search for signatures of azimuthal abundance variations. Regions with enhanced abundances have high ionization parameter and are associated with younger star clusters and higher molecular gas densities, indicating a correlation between recent star formation and locally enriched material. We further place quantitative constraints on the mixing scale within the ISM. We find correlations between metallicity variations, gas turbulence and SFR, driven principally by dilution rather than pollution, demonstrating the role of mixing in regulating the ISM.

Kevin Bundy

UC Santa Cruz

The Impact of Halo-Driven Assembly on the Enrichment of Spatially-Resolved Stellar Populations

I will begin with a review of key insights on stellar metallicity profiles from MaNGA's resolved spectroscopy of 10,010 nearby galaxies. The large sample size has enabled us to study subtle trends in stellar chemical enrichment across a range of galaxy properties and environments. A careful look at biases from spectral fitting codes and profile definitions motivates the need for data-driven confirmation and early-type samples. I will then focus on our work using MaNGA-inferred stellar chemistry as a probe of early-type galaxy assembly. Differing outer metallicity profiles provide evidence for late-time accretion in massive galaxy outskirts. When we look at the inner profiles of central galaxies, we find enrichment histories that, at fixed halo mass, reveal a surprising secondary dependence on stellar mass. Halos that host galaxies with more stars seem to have experienced accelerated formation and assembly, leading to older and more alpha-enhanced populations today. Finally, passive satellite galaxies also feature older and more enriched populations compared to similar-mass centrals. In agreement with recent work on SDSS-I samples, this result strengthens with proximity to the halo center, evidence that environmental quenching impacts aggregate stellar populations.

Kristen McQuinn

Rutgers University

GLOW: Galaxies Losing Oxygen via Winds

The metallicities of galaxies scale with stellar mass. Theoretical notions have long held that, in addition to lower star formation rates and efficiencies, the low metallicities of dwarf galaxies reflect their increasing inability to retain metals. This is seen in cosmological simulations where feedback-driven galactic winds transport metals from galaxy disks to large distances, with a steep inverse dependence on the amount of metals lost with galaxy mass. We are quantitatively testing this framework of stellar feedback and metal loss by actually tracking the metals in real galaxies in the GLOW program. Using data from the HST, VLA, Spitzer, and ground-based observatories, we are measuring the production, distribution, and retention of metals in the stars, ISM, and CGM in a large sample of low-mass, nearby galaxies over the critical mass range where metal loss is predicted to change the most but has yet to be investigated (10^6 ~ 10^9 Msun), for a full accounting of metals. In this talk, I will present first results in determining the metal retention fraction in dwarfs from the GLOW program.

Laura Sommovigo

Scuola Normale Superiore

The unexpected guest: dust in EoR galaxies

ALMA observations have revealed the presence of large amounts of dust in the first generations of galaxies in the Universe. However, the dust temperature Td remains mostly unconstrained due to the few available FIR continuum data. This introduces large uncertainties in the derived dust masses, infrared luminosities, and obscured fraction of star formation of z>5 galaxies.

We use a recently-developed method to constrain Td using a single continuum data point at 158 microns by combining it with the overlying CII emission. This allows us to shed light on the infrared emission properties of the high-z galaxies targeted in recent ALMA large programs, such as ALPINE and REBELS.

We find that the dust temperature increases at a higher redshift, with a larger scatter than observed in the local Universe. We produce a physical model that motivates this increasing Td-redshift trend with the decrease of the total gas depletion time at early epochs. We also explain the measured Td scatter at a given redshift with metallicity and UV optical depth variations in individual sources.

A higher Td has several testable implications. For instance, it alleviates the problem of the uncomfortably large dust masses deduced from observations of some EoR galaxies. We find that except few outliers, the newly-derived dust masses in ALPINE and REBELS galaxies are consistent with the latest Supenovae dust productions constraints.

Livia Vallini

Scuola Normale Superiore, Pisa

High [O III]/[C II] surface brightness ratios trace metal enriched starburst galaxies

Shedding light on the unfolding of galaxy evolution is a challenging task that requires a deep understanding of physical, chemical, and radiative processes occurring on a huge range of scales, from the IGM to sub-kpc scales in the ISM of galaxies. The advent of ALMA revolutionised the study of the ISM at early epochs, enabling the detection of [CII] 158µm, [OIII] 88µm in normal galaxies at z>6 at unprecedented spatial and spectral resolution.

In this talk I will present a novel model able to disentangle the impact of the gas metallicity, deviations from the Kennicutt-Schmidt relation (parametrised with the burstiness parameter, k) and variations in the gas density on the observed [O III]88 µm/[C II]158 µm surface brightness ratios in galaxies at z=6-9. I will discuss possible biases in the measured ratios by comparing the data with zoom-in cosmological simulations and then use a Markov Chain Monte Carlo algorithm to derive the best-fitting values of (k, Z, n). I will show that high [OIII]/[CII] ratios are caused by the starburst phase experienced by the sources which, in turn, have a significantly enriched ISM (Z = 0.2-0.5 Zsun) and are characterised by dense, n=300 cm-3, gas. This lends further support to the starburst scenario in which a rapid enrichment of the interstellar medium is expected.

Logan Jones

Space Telescope Science Institute

Open SESAME: Stellar Metallicities Revealed from Integrated-light UV Spectroscopy

The abundance of metals has a critical influence on the astrophysics of stars and gas, shaping how galaxies evolve with time. However, extragalactic metallicity studies focus primarily on the neutral and ionized gas, which may give a biased view of the chemical evolution of galaxies. Here we present measurements of the stellar metallicities of young star clusters in a sample of 12 nearby star-forming galaxies using UV spectra from HST/COS. The galaxy sample ranges from the massive, super-solar metallicity M83 to the extremely metal-poor dwarfs IZw18 and DDO68. We also discuss these new stellar measurements in the context of published results for the neutral and ionized gas. Examining the quantitative relationship between the metallicities of these three components will illuminate how metals are recycled in galaxies as a function of environment and global properties, which is important for interpreting upcoming JWST and ELT observations of high-redshift galaxies. We also present, for the first time, the Python software SESAME - a Markhov chain Monte Carlo tool for Simultaneous Estimates of Star-cluster Age, Metallicity, and Extinction, which we used to derive the stellar properties in our sample.

Mariska Kriek

Leiden Observatory

The Cosmic Evolution of Stellar Metallicity

The chemical compositions of quiescent galaxies enable a unique view into their formation histories. In particular, their metallicity evolution can be used to constrain their past chemical enrichment and assembly histories. Furthermore, the evolution in their elemental abundances and ratios yield insights into their star formation histories and the processes responsible for quenching star formation in these galaxies. However, measuring chemical compositions of quiescent galaxies beyond z=0.5 is very challenging, as such measurements rely on faint stellar absorption lines shifted to near-IR wavelengths. In this talk, I will discuss recent progress to measure stellar metallicities and elemental abundances in quiescent galaxies from z=0.5 out to z=2.5 and what we have learned from these observations regarding the formation histories of galaxies. I will also discuss future prospects with JWST and other upcoming facilities.

Martyna Chruslinska

Max-Planck Institute for Astrophysics

Birth metallicity of stars over the cosmic history

We develop a framework to empirically characterise the metallicity-dependent cosmic star formation history.
To build our observation-based model, we assemble and combine a large set of literature results describing the properties of star forming galaxies.
In a series of papers, we quantify the uncertainty of our result due to factors such as: the ambiguous absolute metallicity scale and metallicity evolution at high redshift, poorly constrained properties of the low mass/faint galaxies,
IMF variations or contribution of starbursts.
We compare our results with the predictions of cosmological simulations.

We further demonstrate that the metallicity-dependent cosmic star formation history is a crucial ingredient in population modelling of gravitational wave sources.
Current uncertainty of this quantity severely limits our ability to use gravitational wave observations to constrain the origin of the detected sources (thereby hampering the achievement of main science goals of gravitational wave astrophysics).
At the same time, our results indicate that gravitational waves are a promising (and complementary to electromagnetic observations) tool to study (multi-element) chemical evolution of galaxies across the cosmic history.

Matilde Mingozzi

Space Telescope Science Institute

Exploring UV diagnostics of the interstellar medium in local high-z analogs

Rest-frame UV spectra play a key role in the understanding of massive stellar populations, chemical evolution, feedback processes, and reionization. Indeed, in the upcoming JWST era, the UV spectroscopic frontier will be pushed to higher redshifts than ever before, to finally reveal the first galaxies in the distant Universe. In this context, the COS Legacy Archive Spectroscopic SurveY (CLASSY) provides the first high-quality, high-resolution and broad-wavelength range catalogue of 45 local star-forming high-z analogues in the rest-frame UV (1150 −2000 Å), including very low-metallicity dwarf galaxies such as Izw18 and SBS-0335-052W. CLASSY provides the ideal FUV atlas with which we can tailor a complete UV diagnostic toolkit to investigate the interstellar medium (ISM) properties (i.e., extinction, density, temperature, metallicity, ionization parameter, source of ionization). In this talk I will present such a toolkit, obtained from the main emission lines of CLASSY spectra excluding Lya (i.e., N IV] λλ1483,87, C IV λλ1548,51, He IIλ1640, O III]λλ1661,6, Si III] λλ1882,93, C III] λλ1907,9). I will also discuss how our UV toolkit compares to well-known optical diagnostics. In particular, I will focus on the differences between the gas-phase metallicity derived from the direct method and UV calibrations proposed from photoionization models. Overall, CLASSY provides us with an extremely powerful tool to understand the ISM conditions of the earliest galaxies.

Meghana Killi

The Cosmic DAWn Center, University of Copenhagen

[OIII] 52um, [NII] 122um at z > 7; Novel Metallicity Constraint in the Reionization Epoch

The gas-phase metallicity of a galaxy measures the extent of its evolution. Constraining this property in the epoch of reionization (redshift, $z > 6$) can thus provide insight into how and when the earliest galaxies formed and evolved. However, barring a few quasar hosts, we currently do not have metallicity estimates for normal galaxies at these redshifts.

To obtain a novel metallicity constraint at $z > 6$, we study the gravitationally lensed $z = 7.133$ galaxy, A1689-zD1.

We detect, for the first time at $z > 6$, the far-infrared fine-structure emission lines of doubly-ionized oxygen [OIII] at 52 micrometers (um) and singly-ionized nitrogen [NII] at 122um. We combine these with previous measurements of singly-ionized carbon [CII] at 158um and [OIII] at 88um to derive a constraint on the metallicity, following the methodology of Rigopolou et al 2018 and Harikane et al 2020.

Our current results indicate that the metallicity of A1689-zD1 may be as high as solar metallicity, making it an evolved system with star-formation older than 250 Myr. This will push the beginnings of galaxy formation to $z > 10$.

Moreover, despite the relatively large dust mass in this galaxy, the dust-to-metals ratio is lower than expected at this metallicity, hinting that dust formation efficiency may drop in galaxies beyond $z \sim 7$.

Thus, our study of metallicity based on far-infrared emission lines can help constrain the timeline of formation and evolution of the first galaxies.

Mirko Curti

Kavli Institute for Cosmology, University of Cambridge

A 'KLEVER' view on the metallicity properties of high-redshift galaxies

I will present an overview on the ISM and chemical abundance properties in $1.2 < z < 2.5$ galaxies as probed by the 'KLEVER' Survey, a Large Programme exploiting KMOS multi-band (YJ, H and K), near-IR integral-field spectroscopy to map multiple optical rest-frame emission lines (from [O II]3727 to [S III]9530) in a sample of ~200 sources.
I will discuss the properties and evolution of chemical abundances gradients, and the presence of metallicity scaling relations on resolved scales at high-z.
I will also discuss the physical drivers responsible for the observed evolution in the emission-line diagnostic diagrams, and assess whether what is observed at z~2 can be predicted by means of machine learning techniques extensively trained and tested on local galaxies. Finally, I will discuss forthcoming perspectives on studying the chemical evolution of high-redshift galaxies in light of the advent of new generation, cutting-edge near-infrared spectrographs (e.g., JWST/NIRSpec and VLT/MOONS), and I will present (subject to JWST/Cycle 1 scheduling and timescales) some of the very first observations and results on the metallicity properties of $4<z<9$ galaxies as probed by the JWST/NIRSpec GTO 'JADES' Survey.

Mitchell Revalski

Space Telescope Science Institute

Measuring the Mass-Metallicity Relation of Low Mass Galaxies at Redshifts 1-2

We present measurements of the mass-metallicity relationship (MZR) for low mass galaxies at z ≈ 1-2 in the MUSE Ultra Deep Field (MUDF). This unique region hosts two quasars at z ≈ 3.22 that are physically separated by only 500 kpc, providing a stereoscopic view of gas and galaxies in emission and absorption. Utilizing the deepest Hubble Space Telescope (HST) grism survey ever conducted, we find that the MZR continues to decrease monotonically down to log(M/Msun) ≈ 8, without evidence of a turnover. This result is enabled by our extremely deep, multi-wavelength observations of this field, including 90 orbits of HST Wide Field Camera 3 (WFC3) grism spectroscopy and imaging in the near-infrared, and 150 hours of Multi Unit Spectroscopic Explorer (MUSE) integral field spectroscopy in the optical, which provide spectroscopic and photometric coverage of ~1,500 galaxies between z ≈ 0-5. In combination with high resolution Ultraviolet and Visual Echelle Spectrograph (UVES) spectroscopy of the quasar pair, we are able to probe the CGM of individual galaxies along two sightlines. We will also discuss initial investigations aimed at comparing the metallicities of galaxies observed in emission with the metal content of the IGM and CGM that is observed in absorption as a function of impact parameter and environment.

Molly Peeples

STScI/JHU

Metals in galaxies and the CGM: a retrospective, insights from the FOGGIE simulations, and a look to the future

Realistic cosmological hydrodynamic simulations offer a useful tool for interpreting complex observations. In this talk, I will give an overview of some of the history, and challenges, with observing metals in the circumgalactic medium. I will then introduce the FOGGIE (Figuring Out Gas & Galaxies In Enzo) simulations, where with a very highly spatially resolved CGM and high temporal resolution, we are able to follow in detail the effects of gas kinematics on the co-evolution of galaxies and the CGM. I will show how the realization that our static observations of metals in and out of galaxies are but small snapshots of a complex dynamic medium presents interesting challenges for the next decade of deciphering how metals flow in and around galaxies.

Nicolas Lehner

University of Notre Dame

The evolution of the metallicity of the IGM/Galaxy interface over the last 12 billion years

Our modern understanding of galaxy evolution relies on understanding the exchange of matter between galaxies and the intergalactic medium (IGM) to explain a broad range of observable galaxy properties. The competition between mass gain (via accretion) and loss (via outflows) plays out in the interface between the IGM and galaxies. The metallicity of the IGM/Galaxy interface gas is one of the key diagnostics to characterize since it directly informs us on the level of enrichment of the gas around galaxies and hence its origins.
I will discuss new results stemming from the KODIAQ-Z and COS CGM Compendium (CCC) programs that uses COS and Kec HIRES observations to infer properties of the IGM/Galaxy interface gas from $z \sim 3.7$ to $z \sim 0.1$, i.e., over a period of nearly 12 billion years. I will show there is evidence for very low metallicity CGM gas well below the lowest metallicities of galaxies at any redshifts. Pristine gas (<0.01% solar metallicity) is, however, found only at high redshift. I will discuss the striking features of the metallicity evolution of the IGM/Galaxy interface and will confront those to findings from recent cosmological simulations.

Patricia B. Tissera

Institute of Astrophysics, Pontificia Universidad Catolica de Chile

Metallicity gradients as fingerprints of galaxy evolution

The evolution of chemical abundances in galaxies provides crucial information to study how they formed and evolved.
Results in the Local Universe show that on average, star-forming gas-phase in galaxies have negative metallicity gradients and that flat and inverted positive gradients could be associated with galaxy interactions. As a function of redshift, the trend is not clear enough yet, although there is a significant fraction of inverted metallicity gradients.
In serie of papers using the EAGLE simulations, we studied the metallicity gradients at z=0 and the processes that might affect them and the azimuthal metallicity distribution such as mergers, SN and AGN feedback and gas inflows. We extended the analysis as a function of redshift, focusing on the impact of mergers in triggering strong positive or negative gradientes. We found galaxies with negative metallicity gradients more frequent in disc-dominated galaxies, which also determine a relation with size. Galaxies with positive gradients departure from this relation and show systematic differences to be associated with recent mergers or starbursts. In this talk I will summarise the latest results, obtained from the EAGLE project, on the evolution of the metallicity gradients as a function of stellar mass, galaxy size and star formation efficiency up to z~2.5 and on the impact of the environment by analysing the metallicity gradients of galaxies in voids and filaments.

Paul Torrey

University of Florida

An overview of the cosmic evolution of gas-phase metallicity in the IllustrisTNG Simulation Suite

The IllustrisTNG simulation suite includes a galaxy formation physics model that regulates the growth of galaxies to reasonably match observations. In doing so, feedback is required which significantly redistributes the gas phase metals both within galactic haloes, and beyond. In this talk, I will provide an overview of the IllustrisTNG simulation suite metallicity predictions. I will specifically focus on the drivers behind the evolution of the mass-metallicity relation, the emergence and extent of metallicity gradients, and the impact of the baryon cycle as realized in IllustrisTNG on metal distributions within the galactic halo.

Qi Li

Max Planck Institute for Astrophysics

Modeling dust mass and grain-size distributions evolution across cosmic time

Dust plays a crucial role in the physics of the ISM, and cycle of metals between galaxies and CGM. In this work, we investigate the evolution of dust content using a dust evolution model combined with state-of-the-art cosmological hydrodynamical simulations. In this model, dust grains form in stellar ejecta, grow via the accretion of metals and are destroyed by sputtering in the hot halos and shocks of supernovae. The model additionally tracks the grain size distributions which evolve through grain growth, aforementioned destructive processes and grain-grain collisional processes including shattering and coagulation. Using the simulations, I will present the dust-gas scaling relations and grain size distributions of galaxies across cosmic time. I will discuss the physics driving the evolution of the dust mass and grain size distributions, and the impact on extinction.

Raffaella Schneider

University of Rome Sapienza

Blue or red? Charting the assembly of the first galaxies

In the past few years, impressive progress has been made in understanding the physical properties of the earliest galaxies, and specifically of
those possibly responsible for the reionization of the Universe. Rest frame UV observations with HST have told us that going to higher redshift,
these early galaxies appear to be very blue and to host very young and metal poor stellar populations.
However, recent observing campaigns have started to reveal a much more nuanced and complex situation.
The detection of significant amounts of dust, inferred by its
thermal emission with ALMA, supports a picture where galaxy formation was well under way in the pre-reionization era and these
galaxies not only had time to significantly enrich their interstellar medium, but also to produce significant amounts of dust.
Measurements of dust obscuration in $z \approx 7$ galaxies by the REBELS survey show that a substantial fraction of star formation
is obscured even at that time. The early data release by JWST has started to revolutionize the field by revealing a
diversity of galaxy properties at these early cosmic epochs, some of which showing very blue UV colors while others being
very red and chatacterized by unexpectedly important dust content.
In this talk, I will attempt to provide some indications on the diversity of physical properties of the first galaxies expected by theoretical models
and on the current (limited) understanding of dust enrichment at very early cosmic epochs.

Ramona Augustin

Space Telescope Science Institute

The metal distribution in circum-galactic gas structures: combining IFU observations with high resolution simulations

Gas flows in and out of galaxies are typically probed by quasar absorption lines which are usually limited to a single sightline through the halo, giving no information on the structure of the gas probed in absorption. First studies using lensed, multiple or extended background objects have shown that there can be significant variation of absorber strengths on relatively small (~kpc and less) scales, hinting at an inhomogeneous clumpy circum-galactic medium. I am going to present our ongoing efforts of combining observational IFU data of lensed quasars with high spatial resolution cosmological simulations in order to study the small-scale structure and metal distribution of the CGM. For a pilot study I was granted MUSE data of a lensed quasar field, and I will show the results of our non-targeted "blind" search for intermediate absorbers and their metal line variations over kpc scales. To learn more about the underlying physical structure of the gas probed in the CGM and its metal distribution, I am using FOGGIE's highly resolved cosmological simulations to extract and analyse the clumps and filaments in galactic halos and I will report on the current state of our efforts to mock and interpret observables from these simulations.

Rebecca Davies

Swinburne University of Technology

XQR-30: Probing the Enrichment of the CGM by Outflows at z > 5.3

Measurements of the metal content of the circumgalactic medium (CGM) from the era of the first galaxies to the present day are key to understanding how metals are redistributed by outflows over cosmic time. Spectra of small numbers of background z~6 quasars have revealed intervening CIV absorbers tracing enriched gas deposited into the CGM of z >~ 5.3 galaxies by stellar outflows. However, larger samples are required to robustly quantify the distribution of absorber properties and track the chemical evolution history of the CGM. I will present exciting new results from the ESO large program XQR-30 which has quadrupled the number of high S/N z~6 quasar spectra, enabling much more precise measurements of the properties of CIV absorbers at z >~ 5.3. I will compare our measurements to predictions from simple enrichment models as well as state-of-the-art cosmological simulations, and discuss implications for the formation redshifts of the first galaxies and the properties of stellar feedback at high redshift.

Robert Yates

University of Surrey

Constraining galaxy evolution by combining the cosmic metal density, SFR density, and dust mass density of the Universe

The cosmic metal density (ZD) and cosmic star formation rate density (SFRD) are both key diagnostics for understanding galaxy evolution. Combined, their evolution encodes the relative significance of all the main physical processes driving galaxy evolution, from gas cooling, through to star formation and supernova-driven galactic outflows. Consequently, these cosmological-scale diagnostics can be used to provide rigorous constraints on galaxy evolution models.

In this talk, I will present recent work comparing the latest observations of the cosmic ZD and SFRD from z = 6 to 0 with that seen in three cosmological galaxy evolution simulations: EAGLE, L-GALAXIES 2020, and TNG100 (Yates et al. 2021b). I will show how there is an apparent tension between the observed ZD and SFRD, highlighted by the fact that none of the simulations is able to reproduce them both simultaneously. This apparent tension allows us to rule-out some of the physics models implemented into these simualtions, and also points to two possible issues with observational data: either (a) the true SFRD at z~3 is greater than inferred from FUV observations, or (b) high-redshift DLA samples have a host galaxy mass distribution that is shifted high compared to the overall galaxy population.

I will also supplement this study with a brand new analysis of the cosmic dust mass density (DD) of the Universe, as seen in observations and the L-Galaxies 2020 simulation (Yates et al., in prep.). This complimentary analysis allows us further constrain galaxy evolution models, by taking account of the significant amount of dust production that is believed to occur at high redshift, leading to up to 35% of the true cosmic SFRD being obscured by dust at z~5.

Finally, I will contrast this cosmological-scale analysis with the evolution of dust and metallicity radial profiles in Milky Way Analogue galaxies (Yates et al. 2021a; Yates et al., in prep.). This complimentary study, which includes a comparison to the latest (selection-bias-corrected) stellar metallicity data from APOGEE, provides a strong orthogonal constraint to the cosmic analysis described above.

Roland Szakacs

European Southern Observatory

The VISTA/4MOST 4HI-Q Survey: A Machine Learning Approach

One of the most valuable tools for studying the evolution of metals in the Circumgalactic medium (CGM) of galaxies is the study of absorption line systems detected in background quasar spectra. Due to the sensitivity of the observations being independent of redshift, it allows the probing of low column density CGM gas even at high redshifts. One of the upcoming surveys exploiting this advantage is the VISTA/4MOST community survey 4HI-Q. This 2.8-Million-fibre-hour project will be equivalent to the latest release of the SDSS quasar catalogue (~1 million quasar spectra), at 10 times the SDSS spectral resolution. The primary goal of the survey is to measure the radial profile, covering fraction and optical depth of the neutral hydrogen and metals in the CGM of foreground galaxies. Given the vast number of spectra, we use machine learning to detect metal absorbers including MgII (λ2796, λ2803). Using TNG50 from the IllustrisTNG project, we create realistic MgII absorption spectra and inject them into quasar mock spectra including Lyman-alpha forests. In preparation for the 4HI-Q survey, we use this dataset to train a neural network to efficiently and accurately detect MgII absorption lines within quasar sightlines. In this talk I will introduce our upcoming 4MOST community survey 4HI-Q and demonstrate that machine learning is a viable alternative to traditional methods for the detection of large sample of absorption systems which will ultimately probe the CGM metal distribution.

Ryan Sanders

University of California, Davis

The cosmic evolution of galaxy gas-phase metallicity: progress, challenges, and a bright future

I will review our knowledge of the gas-phase metallicity of galaxies and its evolution over cosmic time, emphasizing progress at the current frontier of the high redshift universe. I will present the latest observational constraints on metallicity scaling relations including the mass-metallicity relation and the fundamental metallicity relation, and their evolution with redshift. I will discuss the current challenges we face with the tools and methods used to both derive gas-phase metallicities and interpret these results. These techniques include strong-line calibrations, photoionization modeling, and the use of chemical evolution models and comparisons to numerical simulations of galaxy formation. Finally, I will outline how new and upcoming observational facilities that will transform our view of the chemical abundances of galaxies near and far. JWST and ELTs promise to greatly advance our progress in addressing these challenges, while pushing galaxy metallicity measurements to unprecedented regimes in redshift, mass, and spatial resolution. These new observations (some of which will be a reality by the time of the workshop) will shape our understanding of the chemical enrichment and formation of the first generations of galaxies.

Shuang Zhou

University of Nottingham

Investigating the chemical evolution of galaxies through semi-analytical spectral fitting

We develop a novel semi-analytic spectral fitting approach to quantify the star-formation histories (SFHs) and chemical enrichment histories (ChEHs) of individual galaxies. We construct simple yet general chemical evolution models that account for gas inflow and outflow processes as well as star formation. These models are fitted directly to galaxies' absorption-line spectra, while their emission lines are used to constrain current gas phase metallicity and star formation rate. We apply this method to spiral galaxies selected from the SDSS-IV MaNGA survey. By fitting the co-added absorption-line spectra for each galaxy, and using the emission-line constraints on present-day metallicity and star formation, we reconstruct both the SFHs and the ChEHs for all objects in the sample. We obtain archaeological measures of derived correlations such as the mass--metallicity relation at any redshift, which compare favourably with direct observations. We find that both the SFHs and ChEHs have strong mass dependence: massive galaxies accumulate their stellar masses and become enriched earlier. This mass dependence causes the observed flattening of the mass--metallicity relation at lower redshifts. Moreover, we are able to determine that more massive galaxies have earlier gas infall times and shorter infall time-scales, and that the early chemical enrichment of low-mass galaxies is suppressed by strong outflows, while outflows are not very significant in massive galaxies.

Simon Weng

ESO/University of Sydney

Connecting galaxy and HI absorber metallicities in the CGM

Gas in the circumgalactic medium can be probed to low column densities using sightlines towards bright quasars. However, it is only with the recent advent of powerful integral field spectrographs such as the Multi-Unit Spectroscopic Explorer (MUSE) that has allowed us to draw clearer connections between the gas detected in absorption and the physical properties of surrounding galaxies. The MUSE-ALMA Halos survey combines MUSE, ALMA and HST data with high-resolution UV spectroscopy of HI Lyman-α absorbers to study the baryon cycle in galaxies at redshift $0.3 < z < 1.0$. In total, we find ~80 galaxies within 1000 km/s of our 32 HI absorbers, with impact parameters ranging from < 10 kpc up to 250 kpc. With this unique sample, we can connect the metallicity of our HI absorbers with the metallicity of nearby galaxies. I will present initial results from our 19 MUSE fields, focusing on the metallicity gradients calculated using absorber-galaxy systems and how the metallicity of galaxies depends on absorber properties.

Sirio Belli

Università di Bologna

Understanding Stellar Chemical Abundances at Cosmic Noon

Deep ground-based observations have recently enabled the first measurements of stellar chemical abundances in massive quiescent galaxies at z~2. JWST will soon deliver more precise measurements for larger samples, thus producing a substantial step forward in this field. However, it is still unclear how to use stellar abundance measurements to constrain the formation of massive galaxies. In order to understand this link, we analyzed the stellar abundances of Fe and Mg in massive galaxies at z~2 from the IllustrisTNG cosmological hydrodynamical simulations. We found that the global abundance measured for each galaxy is strongly affected by the presence of steep gradients, which are mostly set by variations in the star formation efficiency. Accounting for these gradients is crucial for a meaningful interpretation of the measurements. Moreover, the TNG model makes clear predictions regarding the trend between stellar abundances, masses, and radii of massive galaxies at high redshift. We will test these predictions using JWST observations from the Blue Jay survey, a Cycle-1 program that will provide continuum spectra of unprecedented quality for massive galaxies at z~2.

Stefano Carniani

Scuola Normale Superiore of Pisa

Evidence for large-scale metal enrichment due to AGN feedback

Evidence for large-scale metal enrichment due to AGN feedback
Theoretical models suggest that the energy inflated by AGNs into the surrounding environment drives the bulk motion of the gas at speeds of hundreds of km/s on galactic scales. Such fast-outflowing gas might have a huge impact - feedback - on galaxy evolution. Indeed, AGN feedback is thought to be an important mechanism regulating the gas-phase metallicity of massive galaxies, capable of transporting heavy elements into the circum-galactic medium. I will present ALMA [CII] observations revealing metal-rich extended (up to 10-20 kpc) gas in a sample of z~6 AGN-host galaxies. I will show that such extended emission is likely associated with AGN-driven outflows as also expected by current simulations. Finally, I will discuss that the extension and morphology of [CII] emission provide new clues for understanding the physical origin of the metal-rich extended gas in early galaxies.

Susanna Diana Vergani

CNRS - Paris Observatory

Probing chemical enrichment at high-resdhift with LGRBs: dissecting a galaxy at z=6.3

Thanks to their exceptional brightness, the afterglows of long gamma-ray bursts (LGRBs) can be used as powerful extragalactic background sources to unveil the properties of the ISM (such as neutral hydrogen, dust content, metallicity, kinematics) of their host galaxies, through the detection of the absorption lines of the host gas in the optical/near-infrared afterglow spectra of LGRBs. The association of LGRBs with massive stars makes them especially suitable to investigate galaxies up to the early Universe.
In this talk, I will show that LGRBs are unique tools to probe the chemical enrichment of galaxies and its evolution up to the highest redshift, and I will present the results of the analysis of the afterglow spectrum of GRB210905A, for which the X-shooter data allowed us to determine the detailed properties of a z=6.3 galaxy. We measured the galaxy metallicity, abundances, dust depletion and dust-to metal ratio, as well as the total (gas+dust) metallicity. We disentangled several gas components and performed the same analysis also component-by-component. From the analysis of the abundance pattern, we found evidence for alpha-element enhancement, and, in some components, of aluminium overabundance and oxygen under-abundance. I will draw possible interpretations of such peculiar patterns. I will present also the results of the HST observations of the galaxy, planned for Spring 2022.

Themiya Nanayakkara

Swinburne University of Technology

The mysterious case of Iron in XMPs

Recent studies of the two lowest metallicity galaxies in the local Universe has shown Fe/O values similar to our sun. These galaxies are at 1.6% and 2% solar metallicity, respectively and have very young stellar populations. Therefore, their Fe enhancements are expected to be driven by non-traditional supernovae enrichments mechanisms including bright hypernovae and pair instability supernovae. Such mechanisms require stars up to and exceeding 100 solar masses to be present in these systems.
In my talk I will present results from our recent Keck/KCWI campaign to spatially map the metallicity and element abundances of these galaxies. By probing how gas phase Fe enhancement correlate with SFR and other galaxy observables, I will comment on whether proposed supernovae enrichments mechanisms carry the answer and implications there of for first galaxies in the Universe in the era of JWST.

Tobias Looser

Kavli Institute for Cosmology, University of Cambridge

Investigating young metal-poor stellar populations with full spectral fitting

Gas accretion from the CGM is critical to understanding galaxy evolution and particularly galaxy quenching, because it provides the fuel for star-formation. But gas accretion is difficult to measure in the local Universe, because accretion rates are low.

We developed a new methodology to reconstruct reliable non-parametric Star Formation Histories (SFHs) from full spectral fitting using the penalized pixel fitting code pPXF (Cappellari, 2017), and by adopting a bootstrapping re-sampling scheme in combination with weight regularization. This enables us to extend the observability of gas accretion by "integrating" over lookback time.

Our analysis of MaNGA SDSS indicates the existence of young metal-poor populations (YMPP) in galaxies with high sSFR, likely tracing the recent accretion of young metal-poor gas. Our spatially resolved analysis also shows both, central and extended YMPP.

These results suggest that our methodology is well suited to study outside-in versus inside-out quenching in combination with quenching timescales derived from our non-parametric SFHs.

I will present a statistical analysis of the YMPP and spatially resolved quenching in 10'000 MaNGA SDSS galaxies as a function of host galaxy characteristics like stellar mass, star-formation state, and central/satellite classification.

Finally, depending on data availability, I may be able to present first results on galaxy quenching at high redshift from first data of the JWST NIRSpec

Valentina D'Odorico

INAF - Osservatorio Astronomico di Trieste / SNS Pisa

The quest for metals in the IGM/CGM from the epoch of Reionization to cosmic noon

Chemical elements heavier than helium - dubbed metals in astrophysics – are formed by stars in galaxies and then spread in the diffuse gas by stellar winds, SN explosions and AGN winds. Metals in the diffuse gas at high redshift are chased and studied mainly with quasar absorption spectra. In this talk, I will explain which fundamental questions in astrophysics and cosmology we would like to answer with these studies, I will present new results based on state-of-the-art observations and describe what are the future perspectives for this field of research.

Vladan Markov

Scuola Normale Superiore

Characterizing the ISM properties of high-redshift galaxies using observations of carbon lines and models

During the Epoch of Reionization, the first galaxies played a key role in the complete reionization of the Universe by z ∼ 6 and in the metal enrichment of the intergalactic medium. Characterizing the internal properties of early galaxies, namely the physical conditions of their interstellar medium (ISM) is fundamental in our understanding of galaxy evolution. In order to constrain the ISM properties of high-z star-forming galaxies, we exploit observations of two carbon lines CIII] λ1909 and [CII] 158μm of a sample of galaxies at 2 < z < 7.5 and theoretical models (Markov et al., submitted). By combining the emission from two lines, which trace different gas phases of the ISM, we constrain the gas metallicity, gas density, and the burstiness parameter ks. This latter parameter quantifies the deviation from the Kennicutt-Schmidt (KS)
law. We show that the majority of early galaxies are in a starburst phase, suggesting that the whole KS relation might be shifted upwards at early times. Moreover, all high-z sources show subsolar metallicity. Extreme ISM conditions in early galaxies also explain the [CII] deficiency in the [CII]-SFR diagram reported in the literature for high-z galaxies. Finally, we also
find that gas density estimates correlate with the [CII] deficiency i.e. low-density high-z systems have lower [CII] surface brightness, in agreement with theoretical predictions.

Yuichi Harikane

University of Tokyo

Observations of Metal Enrichment and ISM Properties in Early Galaxies

Understanding the physical properties of galaxies in the early universe is a frontier in modern astronomy. Recent observations using large telescopes such as ALMA, VLT, Keck, NOEMA, and Subaru reveal many interesting aspects of metal enrichment and properties of the interstellar medium (ISM) in high redshift galaxies. In this talk, I will review these results including peculiar ISM properties of z>6 galaxies inferred from ALMA [OIII] and [CII] lines, gas-phase and stellar metallicities and their difference in massive high redshift galaxies, and recent detections of metal/dust emission up to z∼11. In addition, I will discuss prospects (and hopefully early results) of the JWST observations including our approved GO program to understand metal contents in early galaxies.

Yuma Sugahara

Waseda University

Bridging Optical and Far-Infrared Emission-Line Diagrams of Galaxies from Local to the Epoch of Reionization

We would like to present redshift evolution of ISM properties predicted from photoionization modeling of galaxy populations at z~0, 2, and >6.
We aim to bridge optical ([OIII]5007/Hb and [NII]6585/Ha (BPT)) and FIR ([OIII]88um/SFR and [CII]158um/SFR) emission-line diagrams using photoionization models.
Our photoionization models employ three free nebular parameters of the ionization parameter (U), hydrogen density (nH), and gaseous metallicity (Zgas).
Our models predict that the galaxy distributions evolve along redshift on all the diagrams; e.g., [OIII]/Hb and [OIII]88/[CII]158 ratios continuously decreases from z > 6 to 0.
Specifically, our models predict that the z > 6 galaxies exhibit ~0.5 dex higher U than low-z galaxies at a given Zgas and show flat distributions on the BPT diagram at log[OIII]/Hb = 0.5--0.8.
We find that some of the z > 6 galaxies exhibit high [OIII]88/SFR ratios in the FIR diagram. To explain these high ratios at z > 6, our photoionization models require a low stellar-to-gaseous metallicity ratio (Z*/Zgas) or bursty/increasing star-formation history, the latter of which is consistent with results of previous SED fitting.
While low Z*/Zgas is suggested by previous rest-UV observations, our modeling indicates the necessity of it from FIR observations ([OIII]88/SFR).
As a case study, we would like to additionally present an N/O constraint on a Lyman-break galaxy at z = 7.15 using ALMA [NII]122 observations along with our photoionization models.