Illuminating the Dark Ages

Quasars and Galaxies in the Reionization Epoch

TALK AND POSTER ABSTRACTS
June 27 – July 1, 2016

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Monday, June 27

The most distant quasars

Quasars in the epoch of reionization

Eduardo Banados

Carnegie Observatories, USA

Luminous high-redshift quasars (z>6) provide direct probes of the growth of supermassive black holes and their host galaxies at the epoch of cosmic reionization. Numerous studies have established a sample of ∼70 quasars at 5.5<z<7.1. These studies demonstrated the existence of massive black holes less than a Gyr after the Big Bang and indicated that the end of reionization occurred at z∼6. These findings suggest that fundamental changes are happening in the intergalactic medium at 6<z<7. The discovery and characterization of a statistically significant sample of quasars in this redshift range is crucial to further study this important era in the history of the universe. I will present the progress on building such a statistical sample over the last 3 years. In particular, I will focus on the results coming from the Pan-STARRS1 survey, which has doubled the number of quasars known in the first Gyr of the universe. The quasar sample spans a factor of ∼20 in luminosity and shows a diverse range of properties, including a number of weak-line and radio-loud quasars. I will also discuss the future directions for high-redshift quasar searches, highlight some of the surprises revealed by our current quasar sample as well as our initial follow up studies, which are the first steps towards a statistical characterization of the high-redshift quasar population.

The Final SDSS High-Redshift Quasar Sample: 52 Quasars at z > 5.7 Since 2000

Linhua Jiang

Peking University, China

We will present a complete sample of the SDSS quasars at z > 5.7. The sample consists of 52 quasars found in the SDSS main survey area (>10,000 deg^2), the SDSS Stripe 82 field (∼300 deg^2), and the SDSS overlap regions (with more than one imagings scans over ∼4000 deg^2). These quasars span a redshift range of 5.7 < z < 6.4 and a magnitude range of 18 mag < z_AB < 22 mag (or a luminosity range of -29 mag < M_1450 < -25 mag). We will present some basic properties of these quasars, and the quasar luminosity function (QLF) at z ∼ 6. The QLF derived from the sample is consistent with the previous SDSS and CFHQS results, with a steep bright-end slope. We will estimate the quasar contribution to cosmic reionization based on the combination of this sample and recent fainter quasar samples. We will also briefly introduce our near-future plan with this sample, including a large near-IR spectroscopic survey using Gemini/GNIRS. This sample will have a legacy value on studies of high-redshift quasars, early supermassive black holes and their co-evolution with host galaxies, and cosmic reionization.

A Sample of Eight New Quasars from the Dark Energy Survey

Sophie Reed

University of Cambridge, United Kingdom

We present the results from the first year of our search for z $>$ 6 quasars using photometric data from the Dark Energy Survey (DES) combined with the VISTA Hemisphere Survey (VHS) and the Wide-Field Infrared Survey Explorer (WISE). We use the photometric data from these surveys combined with a series of quasar models to generate a probabilistically ranked candidate list. Astrophysical contaminants are removed using derived brown dwarf colours. This sample includes eight new objects with $6.0 < z < 6.5$ and magnitudes $20.1 < z\,[AB] < 20.8$ selected from 1523 degrees squared and we rediscovered two previously known objects in the field. The photometric ranking method reduces the need for strict colour cuts by removing astrophysical contaminants and down weighting junk objects. Combined with automatic removal of the main types of non-astrophysical contaminant the method allows large data sets to be processed without human intervention and without being overrun by false candidates. This also allows more unusual objects to be found that would have been missed by previous surveys. The number of objects found in this area is consistent with current predictions from the luminosity function. This method is applicable to higher redshift selection and can be used to recover a confirmed $z = 6.75$ object found with the DES data. Over the next three years DES will provide a large sample of quasars bright enough to be used in detailed studies of the intergalactic medium at the end of reionization.

The Pan-STARRS1 search for the highest-redshift quasars

Chiara Mazzucchelli

Max Planck Institute for Astronomy, Germany

Quasars are among the most powerful non-transient extragalactic sources: due to their high intrinsic luminosities, they are ideal probes of the universe at z>6, i.e., ∼1 Gyr after the Big Bang. Through the first and second internal Pan-STARRS1 Survey Data Release, we undertook a large search for high redshift quasars. The resulting sample almost doubled the number of z > 5.6 quasars and, spanning a factor of ∼40 in the quasar UV luminosity, allows for a new statistical approach to the high redshift quasars population. In particular, we discovered 6 of the 12 known quasars at z>6.5 (within ∼815Myr from the Big Bang). I will present the last updates on these discoveries: our selection method, the properties of these sources (e.g. masses of the black holes, near ionization zones). Our campaigns revealed diverse properties in the phenomenology of these z>6.5 objects, including a quasar harboured in an extended Lyman alpha halo, and a quasar with a z∼6 damped Lyman alpha system along its line of sight.

Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs)

Yoshiki Matsuoka

National Astronomical Observatory of Japan, Japan

We present the recent results from the SHELLQs (Subaru High-z Exploration of Low-Luminosity Quasars; arXiv:1603.02281) project, a new spectroscopic survey for low-luminosity quasars at $z > 6$. By exploiting the exquisite imaging data produced by the Subaru Hyper Suprime-Cam survey, we aim to probe quasar luminosities down to M1450 $\sim$ -22 mag, i.e., below the classical threshold between quasars and Seyfert galaxies, over 1400 deg2. The candidate selection is performed by combining several photometric approaches including a Bayesian probabilistic algorithm. We have carried out spectroscopic follow-up observations since 2015 Fall, and discovered 30 new quasars and bright galaxies at $5.7 < z < 6.9$ so far. This result indicate that we are starting to see the steep rise of the luminosity function of $z \sim 6$ galaxies, compared to that of quasars, at magnitudes fainter than M1450 $\sim$ -22 mag or z(AB) $\sim$ 24 mag. Follow-up studies of the discovered objects as well as further survey observations are ongoing.

Galaxies in the Epoch of Reionization

Galaxy Build-up at Cosmic Dawn: Insights from Deep HST and Spitzer/IRAC Observations

Pascal Oesch

Yale University / Geneva Observatory, USA / Switzerland

Thanks to the revolutionary capabilities of the Hubble Space Telescope we have made enormous progress in our exploration of the early universe over the last two decades. Hubble allowed us to push the observational frontier back to z∼10-11, only ∼400 Myr after the Big Bang. To date, we have identified ∼1000 likely galaxies at z>6, with up to 20 credible candidates at z∼9-11, one of which is even spectroscopically confirmed at z∼11. These unprecedented samples allow us to directly track the build-up of galaxies in the heart of the cosmic reionization epoch, providing an increasingly more complete picture. For instance, in combination with deep data from the Spitzer Space Telescope we can now even probe the evolution of the stellar mass density over 96% of cosmic history. In this talk I will provide an overview of recent observational progress coming from very deep HST and Spitzer/IRAC observations as well as from ground-based imaging and spectroscopy to study the first generations of galaxies. In particular, I will present recent results on the build-up of the galaxy UV luminosity functions, the cosmic SFR densities, as well as stellar mass densities out to z∼10, and I will highlight the exciting possibilities that are just ahead of us based on several major upcoming and planned telescopes.

The Galaxy Luminosity Function at z=6-10

Hsiao-Wen Chen

The University of Chicago, USA

I will present a new analysis of the galaxy luminosity function at z=6-10 that incorporates the full redshift likelihood function for uncertainty estimates. I'll show that while previous analyses based on dropout techniques includes considerations of interlopers from low-z galaxies, there is a non-negligible fraction of high-z galaxies that have been misidentified as low-z objects and therefore excluded from these papers. Our new measurements explicitly account for these missed galaxies.

Unveiling the nature of the brightest Lyman-alpha emitters in the epoch of re-ionisation

Jorryt Matthee

Leiden Observatory, The Netherlands

I will present recent results from our wide-field narrow-band survey to search for galaxies through their Lyman-alpha emission line at z>5. We have found that luminous Lya emitters are much more common than previously thought, with implications for re-ionisation. Our best studied galaxy, COSMOS Redshift 7 (CR7), has spectroscopic evidence for a very hot source (10^5 K) in an extremely low metallicity gas (Z< $3x10^{-3}$ Zsun), which has sparked a lot of theoretical investigations into its nature. I will update on the ongoing follow-up of CR7 with ALMA and HST and I will also update on our spectroscopic follow-up campaign of similar candidates at z=5.7 and z=6.6, which will answer whether there are more CR7-like objects.

Probing Early Galaxies with the Hubble, Subaru, and ALMA Legacy Data

Masami Ouchi

The University of Tokyo, Japan

I show the recent observational progresses of star-forming galaxies at a redshift up to $z \sim 10$. In conjunction with gravitational lensing magnifications, deep HST observations obtain first density estimates of UV-continuum radiation given by young massive stars, and reveal that the star-formation rate density (SFRD) continuously decreases from $z \sim 2-3$ to $z \sim 10$. This decrease of SFRD gave the tension between the CMB Thomson scattering optical depth, tau_e, and the estimates of ionizing photon production rates, but the tension is now significantly eased, due to the small tau_e estimates from the recent Planck data. The SFRD decrease towards high-z should be explained by the combination of the cosmic structure formation and radiative cooling+feedback effects in a halo. To decouple the contribution of the cosmic structure formation from the SFRD decrease, the stellar-to-halo mass ratios (SHMRs) of high-z galaxies are derived by intensive clustering analyses with HST and Subaru survey data. The SHMR-halo mass (M_h) relation shows a clear decrease from $z \sim 0$ to 4, and a significant increase from $z \sim 4$ to 7 at $M_h = 10^{11}\ M_{\rm sun}$. Although the SHMR decrease at $z = 0-4$ is explained by the recent numerical and semi-analytical models, no physical models, made so far, can reproduce the SHMR increase at $z = 4-7$. In the HST data, the effective radius of galaxies monotonically decreases from $z \sim 0$ to 10, while the clumpy galaxy fraction peaks at $z \sim 2$ that follows the trend of SFRD evolution on the Madau-Lilly plot. The complementary ALMA data are useful to uncover the physical properties of these star-forming galaxies. I also discuss the recent ALMA deep survey results in this talk.

The prevalence of CIII] emission before the Dark Ages

Michael Maseda

Leiden Observatory, The Netherlands

While large samples of z>6 galaxies have been constructed using deep optical and near-IR imaging using the Lyman-break technique, relatively few of those candidates have been confirmed spectroscopically. Much of the difficulty is caused by the increasingly neutral intergalactic medium at these redshifts, which would attenuate the Lyman-alpha emission that is relied upon for confirmation. Some authors have posited that other, relatively strong emission lines can be used to confirm redshifts at z>6, namely semi-forbidden CIII] 1907,1909. While observed in a small sample of lensed galaxies at high-z, it is not understood exactly what controls the strength of CIII] emission. Here we combine extremely deep optical spectroscopy with MUSE and near-IR spectroscopy from 3D-HST in the UDF to systematically obtain the largest sample yet of (unlensed) $1.4 < z < 3.8$ CIII] emitters. We investigate the prevalence of CIII] emission with properties such as M*, sSFR, and UV luminosity. These results allow us to make predictions about the emission line-spectra of atypicala galaxies observed in the Epoch of Reionization with JWST, helping us to optimize future spectroscopic surveys.

Tuesday, June 28

Ionizing radiation from galaxies and reionization

Probing the end of the reionization epoch with spectroscopic observations of high-z galaxies.

Laura Pentericci

INAF-Osservatorio Astronomico di Roma, Italy

We have just entered an exciting era when cosmic microwave background observations can be directly compared to observations of the first galaxies. The interaction between the first galaxies and the intergalactic medium has major effects on one of the primary probes of the reionization epoch, Lyalpha emitting galaxies. The Lyalpha line can be easily suppressed by neutral gas, making its observed strength a sensitive gauge of the final stage of the reionization epoch, the so-called cosmic dawn. I will present the latest results on the redshift 6 to 7 universe, with particular emphasis on CANDELSz7 a recently completed ESO Large Programme that has obtained nearly 200 spectra of galaxies selected around the reionization epoch in three of the CANDELS fields. I will present the demographics of Lyalpha emission and its implications for the reionization process.

I will also discuss the physical and morphological properties of these high redshift galaxies derived from the combination of spectroscopy and photometry and their evolution with time.

Faint Galaxies as Drivers of Cosmic Reionization: New Constraints on both their Volume Density and Lyman-Continuum Production Efficiency from the latest Frontier Fields Data

Rychard Bouwens

Leiden University, The Netherlands

Galaxies represent one of the preferred candidate sources to drive the reionization of the universe. Even as gains are made in mapping the galaxy UV luminosity density to z>6, significant uncertainties remain regarding the conversion to the implied ionizing emissivity. The relevant unknowns are the Lyman-continuum (LyC) photon production efficiency xi_*ion* and the escape fraction f_*esc*. In this presentation, I explain how we can obtain direct measurements of the LyC photon production efficiency based on the inferred Halpha fluxes inferred from IRAC observations for z=4-5 galaxies. In parallel with this discussion, I also describe new constraints we can obtain on the volume density of ultra-faint z=5-9 sources by combining the power of lensing amplification with deep integrations from the Hubble Frontier Fields program. In describing constraints from the Frontier Fields program, I will describe in detail the probable systematic uncertainties and including a full account of those uncertainties in our estimates of the volume density of ultra-faint sources.

Relationship between Reddening, Gas Covering Fraction, and the Escape of Ionizing Radiation at High Redshift

Naveen Reddy

University of California, Riverside, United States

We use a large sample of 933 spectroscopically confirmed LBGs at z$\sim$3 to measure the shape of the far-UV attenuation curve, and establish an empirical relationship between UV reddening, HI covering fraction, and ionizing escape fraction at high-z. We derive a dust curve that implies a lower attenuation in the far-UV for a given E(B-V) than those obtained with standard attenuation curves. The UV composite spectra can be well modeled by assuming our new attenuation curve, a high covering fraction of HI, and absorption from the H2 Lyman-Werner bands with small ($<$20%) covering fraction. The high covering fraction of outflowing optically-thick HI indicated by the composite spectra implies that photoelectric absorption, rather than dust attenuation, dominates the depletion of LyC photons. By modeling the spectra as the combination of an unattenuated stellar spectrum including nebular continuum emission with one that is absorbed by HI and reddened by a line-of-sight extinction, we derive an empirical relationship between E(B-V) and HI covering fraction. With direct measurements of the LyC flux, our model connecting the gas covering and ionizing escape fractions can be used to independently constrain the intrinsic LyC-to-UV flux density ratio and assess the mechanisms by which ionizing radiation escapes galaxies.

The Lyman continuum escape fraction of z∼3 star forming galaxies with LBC/LBT in the COSMOS and CANDELS fields

Andrea Grazian

INAF-Osservatorio Astronomico di Roma, Italy

The Reionization of the Universe is one of the most important and hottest topics of the present day astrophysical research. The most plausible candidates for the reionization process are star-forming galaxies, which according to the predictions of the majority of the theoretical and semi-analytical models should dominate the HI ionizing background at z>3. We have used deep U-band imaging by LBC/LBT in the COSMOS, CANDELS GOODS-NORTH, GOODS-SOUTH, and EGS fields in order to estimate the Lyman continuum escape fraction of 74 star forming galaxies at z∼3 down to faint magnitude limits (L=0.2L*). We have measured a stringent upper limit (<2%) for the escape fraction of HI ionizing photons from bright galaxies (L>L*), while for the faint population (L=0.2L*) the limit to the escape fraction is <10%. We have computed their contribution to the observed UV background at z∼3 and we have found that it is difficult to keep the Universe ionized at z∼3 only with star-forming galaxies. We compare our results with recent achievements on the Lyman continuum escape fraction of high-z galaxies and AGNs in the literature and discuss future prospects to shed light on the Dark Ages.

Observational constraints on the origin and effects of ionizing radiation

Michael Rauch

Carnegie Observatories, USA

Galactic starlight is thought to have re-ionized the universe, but known types of galaxies (outside of those hosting AGN) tend to be highly opaque to ionizing radiation. The precise origin and the escape mechanism(s) of the ionizing photons have not been identified so far. The production and escape of ionizing radiation is likely to be associated with unusual stellar populations or gaseous emission features. Recently, a combination of spectroscopic observations of disturbed Lyman alpha emitting halos with deep space-based imaging of their extragalactic continuum emission has allowed us to shed light on such environments conducive to the escape ionizing photons. I shall describe a case where ionizing radiation, escaping from a z$\sim$3 galaxy, induces fluorescent Lyman alpha and 2-photon continuum emission in its environment. In other cases, significant amounts of ionizing photons appear to be produced by young stars forming outside of their galaxies in gaseous galactic contrails.

In the second half of the talk I will report on first results from an ultra-deep 2- dimensional spectroscopic attempt to spatially resolve individual Lyman alpha halos at z$\sim$5.8 - 6.5. Theoretical arguments suggest that the increasing shielding by the surrounding IGM (when looking back in time) will alter the shape and surface brightness profile of the surviving Lyman alpha halos in ways that may be used to learn more about the geometry and topology of the increasingly neutral IGM, and infer the reason for the rapid disappearance of Lyman alpha emitting galaxies beyond redshift 6.

Exploring reionisation with Lyman-alpha absorption

James Bolton

University of Nottingham, United Kingdom

I will briefly review existing observational constraints on the reionisation era from quasar absorption lines, before going on to discuss new developments arising from observations of Lyman-alpha absorption in the spectra of bright quasars at z>5 and the abundance of Lyman-alpha emitting galaxies approaching z=7. These measurements may be used to test existing theoretical models for reionisation, and can yield insight into the timing of reionisation as well the nature of the first sources of light in the early Universe.

The Lya-LyC Connection: Evidence for an Enhanced Contribution of UV-faint Galaxies to Cosmic Reionization

Mark Dijkstra

University of Oslo, Norway

The escape of ionizing Lyman Continuum (LyC) photons requires low column densities of atomic hydrogen, which also promote escape of Lya. We use a suite of 2500 Lya Monte-Carlo simulations through models of dusty, clumpy interstellar media from Gronke & Dijkstra (2016), and correlat e the escape fractions of Lya (f_a) and ionizing radiation ($f_{\rm ion}$). We find that $f_{\rm ion}$ and f_a are correlated, with galaxies with low f_a having a low $f_{\rm ion}$, while galaxies with high f_a have a large spread in $f_{\rm ion}$. We argue that there is increasing observational evidence that Lya escapes more easily from UV-faint galaxies. The correlation between $f_{\rm ion}$ and f_a then implies that UV-faint galaxies contribute more to the ionizing background than implied by the faint-end slope of the UV-luminosity function, which directly affects cosmic reionization.

Cosmic reionization: sources and constraints

Pratika Dayal

Kapteyn Astronomical Institute, The Netherlands

I will show that state-of-the-art simulations that include a detailed treatment of the transition from metal-free to metal enriched stellar populations point to a scenario where the bulk (50%) of hydrogen ionizing photons is produced by objects populating the faint-end of the UV luminosity function (M_UV<-16), which JWST will resolve up to z = 7.3. I will show the constraints on the ionization state of the intergalactic medium, obtained using a combination of Lyman Alpha Emitter and Lyman break Galaxy data. I will show how the 21cm-galaxy correlation, detectable through a combination of SKA and Subaru data, will be a powerful probe of the reionization topology. I will end by showing the implications of early galaxy formation for reionization in both cold and warm Dark Matter cosmologies.

Constraining reionization with Lyman-alpha emitters, the Lyman-alpha forest and the CMB

Ewald Puchwein

Institute of Astronomy / KICC, Cambridge, United Kingdom

We use a combination of cosmological hydrodynamical simulations and semi-numerical methods to illuminate the reionization history of the IGM. We confront our models with the latest observational constraints on the statistics of Lyman-alpha emitting galaxies and their redshift evolution. Furthermore, we compare to the opacity of the high-redshift Lyman-alpha forest and to the latest measurements of the Thomson scattering optical depth towards the CMB. To match the data we need a late and not too extended reionization.

The UV background and the IGM

AGNs in the CANDELS/GOODS fields: looking for high-z ionizing sources

Emanuele Giallongo

INAF - Rome Observatory, Italy

The process of cosmic reionization remains one of the most important and puzzling problems for cosmology and the identification of the source populations emitting enough UV radiation to reionize the Universe is still an open issue. Besides star forming galaxies, AGNs could give an important contribution to the reionization depending on their abundance at low luminosities (M1500>-23) and very high redshift (z>4) We present results in the CANDELS/GOODS fields based on deep NIR (UV rest-frame) selection of candidates having weak X-ray detection in 7Msec Chandra images in GOODS south. We also include in the analysis the shallower GOODS north field. We discuss implications and caveats for the estimate of the AGN contribution to the reionization at z>4.

Do Quasars Dominate the UV Background at z>4?

Gabor Worseck

MPIA, Germany

Due to the steeply declining space density of bright quasars at z>3 it is widely believed that galaxies reionized the hydrogen in the Universe. However, due to the significantly uncertain faint end of the quasar luminosity function (e.g. Glikman et al. 2011 and Giallongo et al. 2015 vs. Masters et al. 2012 and McGreer et al. 2013), it is unclear whether faint quasars significantly contributed to the z>4 UV background and to reionization. At z=5 current estimates of the quasar emissivity disagree by a surprisingly large factor of 10. We present results of a Monte Carlo Markov Chain analysis of recalibrated quasar luminosity functions to assess the quasar emissivity and the quasar contribution to the UV background. In the near future, dedicated spectroscopic surveys will ultimately determine the contribution of faint 4<z<6 quasars to the ionizing budget.

New Models of the UV-Background in Cosmological Hydrodynamical Simulations: Implications for IGM and galaxy formation observations

Jose Onorbe

Max Planck Institute for Astronomy, Germany

How the first luminous sources reionized diffuse baryons in the intergalactic medium (IGM) is one of the most fundamental open questions in cosmology. Even after reionization is complete, its vestiges persist in the IGM to much later times. The ultraviolet background (UVB) governs the ionization state of intergalactic gas and plays a key role in its thermal evolution. In current state of the art cosmological hydrodynamical simulations the UVB is commonly implemented as a uniform and isotropic set of photoionization and photoheating rates provided by UVB models (e.g. Faucher-Giguere et al. 2009, Haardt & Madau 2012). I will show that simulations using these UVB models ionize and heat the Universe much earlier than they should and what constraints from the Cosmic Microwave Background indicate. I will also discuss the implications of the this problem in the study of the properties of the intergalactic medium and in the formation and evolution of galaxies. I will present a new method that I have developed to solve this problem and that allows to build consistent UVB models with different ionization and thermal histories. I will use a grid of simulations that incorporate these recent models to interpret a new set of observations using high resolution quasar spectrum done by our group, as the $1.6<z<3.4$ 1D flux power spectrum and the $2<z<3.4$ intergalactic medium pressure smoothing scale.

Constraints on the IGM neutral fraction at z=7 from the reconstructed Ly-alpha emission line profile of ULASJ1120+0641

Bradley Greig

Scuola Normale Superiore, Italy

The uncertainty in the intrinsic Lyman-alpha emission profile from high-z quasars is degenerate with a putative imprint from the IGM neutral hydrogen, complicating interpretation during the EoR. Accessing this intrinsic profile is crucial for studies of DLAs, the QSO proximity effect or the IGM damping wing. Using a Bayesian approach, we develop an MCMC analysis framework to reconstruct the intrinsic Lyman-alpha emission line by constructing a covariance matrix of emission lines observed in a large low-z sample of SDSS QSOs. Utilising this approach, we have performed a preliminary redward IGM damping wing analysis of QSO ULASJ1120+0641 and found significant evidence that the universe is partially neutral at z$\sim$7.

The next frontier of high-z Massive Galaxies and Quasars

Tiziana DiMatteo

Carnegie Mellon University, Pittsburgh, USA

I will discuss recent progress in cosmological hydrodynamic simulations of galaxy formation at unprecedented volumes and resolution. I will focus on predictions for the first quasars and their host galaxies and their contribution to reionization from the BlueTides simulation. BlueTides is a uniquely large volume and high resolution simulation of the high redshift universe: with 0.7 trillion particles in a volume half a gigaparsec on a side. This is the first simulation large enough to resolve the relevant scales relevant to the formation of the first large galaxies and quasars. These massive objects at high redshifts will be investigated with the next generation telescopes (Euclid, JWST and WFIRST).

Large scale opacity fluctuations in the Lyman-alpha forest: evidence for QSOs dominating the ionising UV background at z∼5.5-6 ?

Jonathan Chardin

Institute of Astronomy (IOA) and Kavli Institute for Cosmology Cambridge (KICC), United Kingdom

Lyman-alpha forest data probing the post-reionization Universe shows large opacity fluctuations over large (50 cMpc/h) scales. We explore here the idea that a significant contribution of QSOs leads to large UV background fluctuations at the tail-end of reionization. Using a hybrid approach utilizing the large volume Millennium simulation to model the spatial distribution of QSOs combined with smaller scale radiative transfer simulation, we produce realictic mock absorption spectra that account for large-scale UV fluctuations due to QSOs. With a range of assumptions for the shape and normalisation of the QSO luminosity function, we find that a significant contribution of ionising photons from QSOs can explain the large reported opacity fluctuations on large scales. However, even with a plausible extrapolation of our results accounting for physical effects not yet included in our simulations the inferred QSO luminosity function is only marginally consistent with current measurements of the space density of QSOs at this redshift. Our simulations also marginally reproduce the very long (110 Mpc/h) high opacity absorption trough observed in ULAS J0148+0600, perhaps suggesting an even later end of reionization than assumed in our currently favoured model. Large QSO surveys as well as targeted searches for the predicted strong (transverse) QSO proximity effect should allow to determine the relative contribution of UV fluctuations due to QSOs compared to recent suggestion invoking temperature or mean free path fluctuations to be primarily responsible for the observed large scale opacity fluctuations.

What are the last Gunn-Peterson troughs in the Lyman-alpha forest?

Frederick Davies

MPIA, Germany

The transmission of UV photons through the Lyman-alpha forest proves that most of the hydrogen in the universe has been highly ionized for at least the last ∼12.5 billion years of cosmic time. At the earliest epochs probed by observations, z>6, the Lyman-alpha forest rapidly becomes extremely opaque, suggesting that we are probing the final stages of the reionization epoch. However, opaque troughs on >50 Mpc scales — apparently unexplained by cosmological structure formation alone — appear to exist as late as $z \sim 5.5$, long after reionization is thought to be over. I will discuss my theoretical modeling to understand the nature of these regions, competing models which make a completely opposite prediction, and observational tests which may be able to distinguish between the two scenarios.

Wednesday, June 29

The Reionization Epoch

Cosmic Reionization After Planck: Progress and Challenges

Piero Madau

University of California Santa Cruz

The reionization of the all-pervading intergalactic medium marks a turning point in the history of structure formation in the Universe. The details of this process reflect the nature of the first astrophysical sources of radiation and heating as well as the early thermodynamics of cosmic baryons, and continue to be the subject of considerable observational and theoretical efforts. In this talk I will survey key aspects of reionization-era phenomenology and review recent challenges in our understanding of cosmic dawn.

Cosmological simulation of the Reionization with EMMA: successes and difficulties

Dominique Aubert

Observatoire Astronomique de Strasbourg

During the last 4 years, we developed in Strasbourg a new GPU-driven AMR cosmological simulation code named EMMA, able to track the the physics of radiative transfer in addition to the usual hydrodynamics. As such, we have been using it to study the physics of galaxy formation during the epoch of Reionization. In my contribution, I aim at presenting the features of this new tool and the results of our first investigations. In particular we looked at how standard diagnostics of these epochs (reionization history, luminosity functions, cosmic star formation rates, magnitude mass relations,.) depend on the details of the physics modeling. The latter include numerical effects (mass resolution, simulated volume, spatial resolution) as well as physical assumptions such as the stellar population models used to assign luminosities to simulated source. The variations on the standard diagnostics can be quite significant: I will demonstrate that a proper simulation of the reionization epoch and the formation of the first galaxies remains quite a challenge and should impact our ability to interpret observations from such numerical products.

New light on hydrogen and helium reionization in a cosmological volume

Marius Berge Eide

Max Planck Institute of Astrophysics, Germany

We shed some new light on the processes that could have driven the epoch of reionization and reheating. We have run a suite of simulations where cosmological outputs from the MassiveBlack-II hydrodynamical simulation were piped into the radiative transfer program CRASH. We have covered the evolution in a 100 cMpc/h simulation volume from redshift z=20 to z=5.5. We have investigated the effects of different reionization and reheating sources. We have also explored the reionization history of helium, which can impose additional constraints on the physical processes governing the epoch. I will give a qualitative and quantitative overview of our findings.

Simulations of the epoch of reionization

Joop Schaye

Leiden Observatory, Netherlands

I will present models of the epoch of reionization, including both radiation-hydro dynamical simulations and models based on the EAGLE hydrodynamical simulation.

Introducing the Aurora reionization simulations

Alireza Rahmati

University of Zurich, Switzerland

I will talk about the Aurora project, a set of spatially adaptive radiation-hydrodynamical cosmological simulations which are designed to study different aspect of the coevolution of galaxies and the intergalactic medium during the epoch of reionization. The simulations are calibrated to reproduce both the observed high-redshift properties of galaxies and the timing of the reionization consistent with the most recent constraints from the Planck experiment. I will talk about the unique design of the simulations and show some of our first results (mainly based on arXiv:1603.00034).

Exploiting 21cm-LAE synergies: constraints on reionization

Anne Hutter

Swinburne University of Technology, Australia

We investigate the environment of ionizing sources and the diffusion of the ionized regions in the cosmic web during the epoch of reionization by using our model for high-redshift galaxies and the IGM (Hutter et al. 2014), which combines a smoothed particle hydrodynamics cosmological simulation (Gadget-2), a dust attenuation model and radiative transfer simulations (pCRASH). For this purpose we calculate the cross correlations between the 21cm brightness temperature and galaxies with visible Lyman-alpha emission (LAEs), as well as between the 21cm signal and the underlying galaxy population. For both galaxy samples, we find that the cross correlations trace the growth of the ionized regions, i.e. the 21cm emission from neutral regions is found at increasing distances from the sources, and the corresponding anti-correlation signal on super-ionized scales shifts to larger radii as reionization proceeds. Faint field galaxies are not able to ionize their surrounding sufficiently which introduces a correlation signal on smaller scales, while LAEs lie in the most overdense and ionized regions where the significantly suppressed 21cm signal causes the cross correlation signal to vanish. From the ionization histories in knots, filaments, sheets and voids we find our simulations to follow an inside-out scenario, wherein the ionization fronts propagate from over- to underdense regions. With the 21cm signal being significantly lower (even lower for LAEs) in regions containing galaxies than in regions lacking galaxies, the corresponding difference in the 21cm brightness temperature in over densities and voids provides an "observable" for reionization topology.

Reionization by Starbursts

Mahavir Sharma

ICC, Durham University, UK

We study the reionization of the Universe by galaxies and identify the fossils of these early starburst galaxies in the present day Universe using the cosmological hydrodynamical simulation EAGLE. There is a strong empirical evidence that the supernovae explosions can puncture a galaxy to facilitate the escape of ionizing radiation. We use this idea to calculate the escape fraction of ionizing photons and its evolution with redshift, which we find to be adequate to explain the existing data on the ionised fraction of hydrogen in the Universe and the HI photoionization rate. We find that the brighter of the galaxies at high redshift play a prominent role in reionization. Half of the required ionising photons are in fact emitted by the galaxies within the current detection limits of the HST.

Thursday, June 30

Black hole formation

The early (feedback-regulated) growth of supermassive black holes

Martin Haehnelt

Institute of Astronomy, Cambridge

Supermassive black holes with masses of several billion solar masses are already in place at $z \sim 6$–7. I will discuss models and numerical simulations of the (early) growth of supermassive black holes and their environment with an emphasis on:

- the feeding of supermassive black holes from the cosmic web
- the role of AGN feedback in driving outflows into the inter-/circumgalactic medium and regulating the growth of supermassive black holes and the star formation in massive galaxies

From seed to supermassive: growing black holes at high redshift

Ricarda Beckmann

University of Oxford, United Kingdom

The growth of supermassive black holes (SMBHs) powering quasars at redshift z=6 and above is still poorly understood. Efforts so far have either concentrated on black hole (BH) seed formation mechanisms, or approximated the SMBHs using massive seeds in low resolution simulations. The work presented here will bridge the gap, following the growth of a SMBH from its origins as a stellar mass seed at high redshift, to its massive representation at redshift z=6. The growth of this object is studied using a hydrodynamical Adaptive Mesh Refinement resimulation at extremely high resolution that allows the gas to be tracked over many orders of magnitude, and offers new insights into the accretion patterns of high redshift black holes.

Formation of supermassive black holes via direct collapse

Muhammad Latif

Institut d'Astrophysique de Paris , France

Observations of quasars at z>6 suggest the presence of supermassive black holes (SMBHs) of a few billion solar masses. The formation of such objects within a few hundred million years after the Big Bang presents a challenge for our understanding of early structure formation. The direct collapse model is emerged as the most promising way to assemble high redshift quasars as it provides massive seeds of about 10^5 M_sol. In this talk, I will discuss what are the typical masses of direct collapse black holes (DCBHs)? How abundant they are? I will show that for realistic conditions number density of DCBHs drops few orders of magnitude below the observed abundance of quasars at z=6 and makes their sites extremely rare. I will also present ideas both from semi-analytical models and numerical simulations which may help in boosting the abundance of massive black hole seeds. Furthermore, I will present results from three dimensional cosmological radiative transfer simulations showing the impact of AGN feedback in the growth of massive black holes and during the assembly of first galaxies

Quasar Outflows at $z \gtrsim 6$ in Zoomed Cosmological Hydrodynamical Simulations

Paramita Barai

Scuola Normale Superiore di Pisa, Italy

I will present results from zoom-in cosmological hydrodynamical simulations to probe z>=6 quasar outflows in the early universe. Quasars are observed to host supermassive black holes (SMBH) at their centers even at high-redshifts ($z = 6 - 7$). Accretion of gas onto the SMBHs and resulting energy feedback generates powerful outflows, which are also observed. We perform zoom-in cosmological hydrodynamical simulations of high-z massive galaxies, which are typical host galaxies of quasars. Our simulations employ the 3D TreePM-SPH code GADGET-3, and include metal cooling, star formation, chemical enrichment, supernova feedback, AGN accretion and feedback. We analyze the simulation output in post-processing to study the growth of the first SMBHs and their co-evolution with galaxies. The simulated BHs start as seeds of mass 10^5 Msun, grow by gas accretion and mergers, and simultaneously eject feedback energy affecting their host galaxies. When the BHs become supermassive (mass $\gtrsim 10^8 - 10^9$ Msun), we find strong outflows being generated. We quantify the impact of quasar outflows on the host galaxy; especially the effects on star formation in terms of negative or positive feedback.

The first black holes and AGN

Marta Volonteri

Institut d'Astrophysique de Paris, France

At z>6 we currently detect very luminous quasars powered by black holes with masses of billions of solar masses. These black holes and quasars are likely the tip of the iceberg, with an underlying population composed of "normal" black holes in "normal" galaxies. I will discuss some aspects of the cosmic evolution of black holes, from their formation to their growth and how different physical processes shape the relation between black holes and galaxies in the first few billion years of the Universe.

How Supermassive Black Holes Form by $z > 7$: Synthetic Observables in the NIR, Ly-a and 21 cm

Dan Whalen

Institute of Cosmology and Gravitation, University of Portsmouth

About 50 supermassive black holes (SMBHs) have now been found at $z > 6$, including a 12 billion solar mass candidate at $z = 6.3$ and a 2 billion solar mass object at $z = 7.1$. The discovery of these high redshift quasars severely challenged current paradigms of early structure formation, but new simulations have now shown that they can be understood to be direct collapse black holes (DCBHs) at the nexus of heavy, cold accretion flows that drive their rapid growth. We have developed radiation hydrodynamical models of SMBH birth and evolution in cosmological environments that now account for the masses of the $z = 7.1$ and 6.3 quasars whose H II regions can be post processed to produce their NIR and Ly-a luminosities and their footprint at 21 cm. I will discuss these synthetic observables and the prospects for detection of $6 < z < 15$ quasars by JWST, the E-ELT, Euclid and WFIRST.

Black Holes Seeds: A Local Perspective

Jenny Greene

Princeton University

I will summarize our work to understand the low-mass end of the supermassive black hole mass function in the local universe, and highlight outstanding challenges. I will then present new work focused on extending our census to z 0.5 using deep X-ray fields. I will end with future prospects, including the power of JWST, LSST, and thirty-meter class telescopes, to truly uncover the distribution of black hole mass in low-mass halos.

High redshift quasars: host galaxies and environment

High-redshift quasars in current and future wide-field surveys

Manda Banerji

Institute of Astronomy, Cambridge, UK

I will summarize the status of both ongoing and upcoming wide-field surveys (in particular at optical and infrared wavelengths) and prospects for finding high-redshift quasars at the epoch of reionization from within these datasets.

Implications for the early growth of supermassive black holes from the KiDS+VIKING survey

Gijs Verdoes Kleijn

Kapteyn Astronomical Institute, Netherlands

We present the results from the sample of QSOs at $5.7 < z < 7$ that we have built up combining ESO's Kilo Degree Survey and the VISTA Kilo-Degree Infrared Galaxy survey. The 9-band u through Ks photometry from the combined surveys goes up to $\sim$2 mag deeper than SDSS, UKIDSS and Pan-STARRS1. They survey is nearing completion for i through K. We focus on the implications for early growth of supermassive black holes based on the KiDS+VIKING harvest and follow-up observations.

Gas and star formation in the quasar host galaxies at z∼6

Ran Wang

Kavli Institute for Astronomy and Astrophysics, Peking University, China

The large millimeter and radio telescopes, such as ALMA, NOEMA, and the JVLA, provide us the best opportunity to study the formation of the first supermassive black holes (SMBHs) and galaxies at the earliest epoch. In particular, huge amount of dust and molecular gas were detected in about 30% of the luminous quasars at z∼6, which suggests an early phase of SMBH-galaxy evolution with massive star formation. We have been carrying out a systematic survey of the star formation and ISM properties in the host galaxies of z∼6 quasars using millimeter dust continuum, molecular CO, and [C II] line emission. Our ALMA observations of the millimeter bright quasar at z∼6 have resolved the [C II] line emission from the quasar host galaxies on 1∼2 kpc scales. The observations allow us to study the gas kinematics and the star forming activity in the young quasar hosts into details. Molecular CO line emission was detected in the millimeter bright quasars at z∼6. The JVLA observations of the CO (2-1) line at 0.6" resolution has constrained the source size to a few kpc, which is comparable to that of the [C II] and dust continuum emission. The ratios between the CO (6-5) and (2-1) lines are consistent with a highly-excited molecular gas component similar to that find in the z=6.42 quasar SDSS J1148+5251. These observations set key constraints on the early growth of the first SMBH-galaxy systems at epoch of the cosmic reionization.

ALMA observations of z>6.5 quasar hosts: forming massive galaxies in the epoch of reionisation

Bram Venemans

MPIA, Germany

Luminous quasars at high redshift are powered by supermassive black holes. These massive black holes are thought to be located in the progenitors of the massive early type galaxies we see in the local Universe. Therefore, studying the host galaxies of the most distant quasars enables us to study the formation of massive galaxies in the early Universe. Recently, using wide field infrared surveys, we successfully discovered various quasars at z>6.5 with a central black hole of $> 10^5$ solar mass. While at (observed) optical and near-infrared wavelengths the central point sources outshine the host galaxies of these bright quasars, observations in the millimetre can constrain the gas and dust content of these galaxies. In this talk I will present ALMA and NOEMA observations of the host galaxies of z>6.5 quasars. The host galaxies show a range of properties in both line and dust continuum emission. I will discuss our results and the implications for massive galaxy formation at high redshift and our understanding of the relation between the black hole mass and the bulge mass of galaxies.

The birth of the giants: dust and gas in QSO host galaxies at z∼6

Roberto Decarli

MPIA, Germany

Despite residing in a <1 Gyr old universe, QSOs at z∼6 appeared as relatively evolved systems in terms of mass of the central black hole, structure of the broad line region, metallicity, gas and dust content in their host galaxies. The rapid growth of these systems is supported by massive reservoirs of cold, dense gas that feed the black hole accretion and drive the intense star formation (100-1000 Msun/yr). We started various observational campaigns aimed at constraining the physics of the interstellar medium in these systems. Molecular lines, such as CO, water, OH reveal the properties of the dense component of the ISM. Fine structure lines and optical observations (in particular of Ly-a) trace the ionized phase. Dust extinction at rest-frame optical and UV wavelengths (sampled by optical, NIR observations and our dedicated Spitzer program) and continuum emission at mm and sub-mm wavelengths expose the interplay between the ISM and the formation of new stars. The results of these efforts shed light of the formation of the first massive galaxies in the universe.

Large scale galaxy overdensities around z∼6 QSOs

Roberto Gilli

INAF - Osservatorio Astronomico di Bologna, Italy

Most cosmological simulations predict that the billion solar mass black holes powering QSOs at z∼6 formed and grew within the most overdense regions of the Universe at that time. However, the search for galaxy overdensities within a few hundreds kpcs from z∼6 QSOs did not produce conclusive results so far.

I will report on the detection of significant large scale (<4 physical Mpcs) overdensities of Lyman Break Galaxy (LBG) candidates around four SDSS QSOs at z∼6. LBG candidates were selected as bright (zAB < 25) i-band dropouts using optical imaging with the Large Binocular Camera (25' x 25') at the Large Binocular telescope, complemented by near-IR observations with WIRCAM/CFHT on the same sky areas. Spectroscopic follow-up observations are ongoing, for which I will present preliminary results. Finally, I will discuss future developments of the project, including a 500ks Chandra Large Program that has been granted to one of our fields.

Chasing LyAlpha Haloes at z>6

Emanuele Paolo Farina

MPIA, Germany

Luminous quasars have been detected well into the epoch of reionization, probing the existence of super-massive black holes (SMBH) less than a Gyr after the Big Bang, and setting strong constraints on the the first crucial phases of the build-up of SMBHs and their host galaxies. To form a SMBH in such a short time scale, the first quasars need to be embedded in abundant cold gas reservoirs able to continuously feed the growth of the first black holes. This key ingredient of the galaxy formation could be mapped at z>6 through the detection of an extended and diffuse LyAlpha emission that appears when the cold gas is fluorescently illuminated by the emission of a bright quasar and/or by the UV-photons generated by an intense star formation event. I will present our efforts to directly observe this feature and thus to probe the environment where supermassive black holes can form in the early Universe.

Friday, July 1

IGM enrichment

Metals in Absorption at the Conclusion of Reionization

Emma Ryan-Weber

Swinburne University, Australia

The metallicity, hydrogen neutral fraction, topology and spectral shape of the ionizing flux in the intergalactic (IGM) and circumgalactic medium at z 6 sets the initial conditions from which modern day galaxies form and evolve. Metals absorption lines observed in the spectra of background z(em)>6 quasars can be used to measure these quantities. I will talk about our search for metals in absorption at the highest observable redshifts. I will present new results on the evolution of the cosmological mass density of triply ionized Carbon, Omega(CIV), and singly ionized Magnesium, Omega(MgII) out to redshift 6.2. In addition, I will present work on the relationship between CIV absorbers and their galaxy environments at z$\sim$6. We find that - in contrast to UV-bright galaxies at $z \sim 2-3$ - metals are likely to have been injected into the IGM prior to the conclusion of reionization or are associated with dwarf galaxies fainter than current detection limits.

Metal Enrichment during Reionisation using the redshift 7 quasar ULAS J1120+0641

Sarah Bosman

Institute of Astronomy, Cambridge and Kavli Institute for Cosmology, Cambridge, United Kingdom

I will present constraints on early galaxy formation and evolution models from intervening metal absorption lines towards the highest redshift quasar, ULAS J1120+0641. Using a deep (27h) X-SHOOTER spectrum of the object, we found a rich sightline containing 6 intervening systems over $5.5 < z < 7$, allowing us to measure the number densities of C IV, C II and Mg II up to redshift 7. Our finding are generally consistent with a softening of the UVB in addition to ongoing metal enrichment at high redshift. We however find a significant and intriguing overdensity of weak Mg II systems at $z>5.5$ compared to lower redshifts, as well as unusual absorption profiles in one of the associated absorbers to the quasar. The implications of these results will be discussed.

Testing the effect of feedback on the high-redshift IGM with metal-line absorbers

Laura Keating

Institute of Astronomy, Cambridge, UK

I will present models of low- and high-ionization metal-line absorbers (O I, C II and C IV) during the end of the reionization epoch, at z $\sim$ 6. Using four cosmological hydrodynamical simulations with different feedback schemes (including the Illustris simulation), I will discuss how the overall incidence rate and equivalent width distribution of metal-line absorbers varies with the galactic wind scheme. I will show that the O I and C II absorbers are reasonably insensitive to the wind feedback scheme, but that all models struggle to reproduce observations of C IV which is probing overdensities close to the mean at z $\sim$ 6. This suggests that the metals in the simulations are not being transported out into the IGM efficiently enough. I will also show that the situation is improved but not resolved if we choose a harder and/or (locally) increased UV background.

The intergalactic medium at high redshifts and its implications for the epoch of reionization

Anna-Christina Eilers

Max-Planck Institute for Astronomy, Germany

The epoch of hydrogen reionization is an important phase in the evolution of our universe. The details of this process affect the formation of the first stars, galaxies and AGN as well as the large-scale structure of our universe. The imprint of Ly-alpha absorption lines observed in spectra of distant quasars, has become an important tool for constraining the intergalactic medium (IGM) at these high redshifts and thus reveals information about the reionization process. We compiled a new data set of 37 high redshift quasar spectra of moderate resolution and reduced these spectra in a coherent and homogeneous way. The spectra cover a redshift range of $5.8<z<6.5$ and contain spectra of several new and unpublished objects. The analysis of this rich data set enables new insights into the epoch of reionization. We analyse the evolution of the Ly-alpha, Ly-beta and Ly-gamma optical depths with redshift, which sets constraints on the onset and duration of the reionization process. We aim to constrain the evolution of the neutral gas fraction of the intergalactic medium surrounding the quasars by determining the sizes of their proximity zones. We measure statistical properties, such as the probability distribution function of the transmitted flux in the Ly-alpha forest as well as in the Ly-beta forest. The comparison between the two probability distribution functions reveals information about the morphology and strength of the ionizing UV background radiation field.

Spectroscopic Studies of Galaxies in the Reionization Era

Richard Ellis

ESO, Germany

Spectroscopy is a highly valuable tool for addressing outstanding questions in understanding the role that galaxies play in driving cosmic reionization. I will review recent progress in the use of Lyman alpha emission as a probe of the neutrality of the intergalactic medium, rest-frame UV metal lines as indicators of the ionizing spectrum and various diagnostics of the escape fraction of ionizing photons. With the approaching launch of JWST, these diagnostics collectively offer an important route to progress.

Studying the dark ages with WFIRST

Sangeeta Malhotra

Arizona State University, USA

The WFIRST mission will be a 2.4m space telescope with a wide-field near-infrared camera, covering 0.28 square degrees with spatial resolution and sensitivity comparable to HST's, and with both multi band imaging and slitless spectroscopy. WFIRST has tremendous potential for studying the epoch of Cosmic Dawn - the period encompassing the formation of the first galaxies and quasars, and their impact on the surrounding universe through cosmological reionization. WFIRST will yield imaging and spectroscopic data for thousands of galaxies at high redshifts to answer many questions about cosmic dawn. These include determining the epoch, pace and homogeniety of reionization by quantifying the luminosity function of Lyman-alpha galaxies as well as their clustering. WFIRST will also characterize the sources responsible for reionization - quasars as well as galaxies.

Poster Abstracts

Hunting Direct Collapse Black Holes in HUDF

Bhaskar Agarwal

Yale University, USA

Direct Collapse Black Holes (DCBH) present an elegant solution to the first quasar problem of assembling a supermassive black hole within the first billion years of our Universe's evolution. However, they have eluded observations thus far, with the hope of JWST doing the required task. I will outline recent work in the field of determining the critical flux required for direct collapse, demonstrating the need for a new framework of reaction rates to determine if a pristine atomic cooling halo can undergo DCBH formation. Furthermore, I will outline a pipeline to hunt them in the HUDF where the SED (thus SFH history) of an object is used to construct a Lyman-Werner history of the system. Using conservative estimates of metal pollution and mass accretion histories, we can then conclude if a system is likely to have caused DCBH at some point in its past, in its local neighbourhood. The pipeline has already been applied to the recently observed Ly-alpha emitter CR7 at z=6.6, resulting in a 63% probability of it hosting a DCBH.

AGN feedback to low-mass galaxy formation at z∼5

Satoshi Kikuta

National Astronomical Observatory of Japan, Japan

While feedback from active galactic nuclei (AGNs) is now considered to be an essential ingredient of the process of galaxy formation, the importance of AGN feedback to surrounding other galaxies is observationally unclear, although theoretically often expected to be at work especially to low-mass ones by heating the gas. To test whether QSO's radiative feedback is indeed strong enough to suppress the formation of neighboring low-mass galaxies, we have conducted a deep and wide field imaging observation with the Suprime-Cam on the Subaru telescope and searched for Lyman alpha emitters (LAEs) around QSOs at z∼4.86 by using a narrow band filter. We compared the shape of luminosity functions of LAEs in the proximity of QSOs (the zone strongly affected by QSO's UV radiation) and in the blank fields where the influence of QSO radiation is negligible to find no clear difference even in the faintest luminosity bin where the feedback effect is expected to become the strongest. Our results suggests that i) the QSO radiative feedback does not affect LAE formation because LAEs have already formed before QSOs turned on and/or duration of the QSO phase is too short, ii) we have to go deeper to witness feedback at work, or iii) the size of the QSO proximity is too large or too small compared to S-Cam FoV.

Physical properties of the ultra-faint galaxies that likely reionized the universe

Daniel Lam

Leiden Observatory, The Netherlands

Ultra-faint galaxies in the early universe z=10 to z=6 have been thought to play a key role in driving the reionization of the universe. With gravitational lensing from galaxy clusters, we can gain unprecedented leverage to observe ultra-faint galaxies in the early universe, particularly in combination with the deep HST and Spitzer/IRAC data available from a number of recent visionary programs (CLASH, Frontier Fields, SURFSa UP). In this presentation, I describe the constraints we can set on the physical properties of ultra-faint galaxies seen in these data sets, including an exciting lensed galaxy at z$\sim$11 (Coe+2013), and contrast the observed properties with brighter L* galaxies seen at the same epochs. In deriving these constraints, I will briefly discuss how we overcome several key challenges for this enterprise, namely, the broad PSF in the Spitzer/IRAC and substantial intracluster light, both of which require careful modeling to ensure the accurate removal of foreground light.

CGM Carbon Absorption at High Redshifts

Daniel Miller

MIT, United States

We have increased the CIV statistics at high-redshift by systematically searching for CIV absorption lines in the spectra of about thirty high-redshift (z $>\sim$ 6) QSOs. The spectra were obtained with the FIRE spectrograph on the Magellan Baade telescope, and we identified over 40 CIV systems over a path covering $4.3 < z < 7.0$. We present initial results from the survey including equivalent width frequency distributions, line densities, and their evolutions.

Inferring the IGM thermal history during reionisation with the Lyman-alpha forest power spectrum at redshift z=5

Fahad Nasir

Dept. of Physics and Astronomy, University of Nottingham., United Kingdom

We use cosmological hydrodynamical simulations of Lyman-alpha forest at z=5 to examine the feasibility of constraining the integrated thermal history at z>5 using the 1D flux power spectrum. We demonstrate the energy deposited per proton at the mean background density at z<12 correlates with the gas density power spectrum at overdensities Delta<10 on scales where pressure smoothing is mostly dominant. A Markov Chain Monte Carlo analysis indicates that the energy deposited per proton may be measured with a statistical uncertainty of about 20 per cent at z=5, with a redshift path length and signal-to-noise per pixel comparable to existing data. We conservatively estimate that current systematic uncertainties are similar, such that available data alone will allow for a measurement with a total uncertainty of about 30 per cent. This corresponds to distinguishing between reionisation scenarios with similar instantaneous temperatures at z=5, but an energy deposited per proton that varies by 2-3 eV over the redshift interval 5<z<12. Higher precision measurements are possible if systematic uncertainties associated with continuum placement can be minimised in combination with improved signal-to-noise and an increase in the available path length. Utilising measurements of the power spectrum on small scales, this approach also jointly constrains the normalisation and slope of the temperature-density relation at z=5.

Galaxy Environment around Multiple QSO Systems Probed by Subaru/HSC

Masafusa Onoue

Sokendai / National Astronomical Observatory of Japan, Japan

Under the hierarchical galaxy evolution scenario, it is widely accepted that a quasar is likely to emerge in a rich environment where a number of gas-rich galaxies cluster and interact with each other within a massive dark matter halo. However, while it is natural to expect that a quasar would be a good tracer of such a massive structure and indeed it has been used as a probe of proto-clusters, the picture derived from observational studies of quasar environment is far from clear even at highest ($z\sim6$) redshift (e.g., Kim+09, Simpson+14). From semi-analytical approaches, some papers suggest that the host halo mass of quasars are less massive than those of radio galaxies (e.g., Orsi+15), which could explain the high fraction of radio-loud galaxies residing in proto-clusters (Venemans+07). At intermediate redshift, the quasar clustering analysis show that the clustering strength of quasar two-point correlation function increases toward $z\sim5$, but it is also suggested that this trend is only for most luminous quasars (Shen+07, Eftekharzadeh+15).

We have started a program to study galaxy clustering around quasars with the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey, which is the first 1000 deg^2 class survey with an 8m telescope. In particular, we focus on the environment of extremely rare systems, multiple quasar systems in which two or more quasars are physically associated with each other inside the same massive halo. This project takes full advantage of the HSC-SSP, which is able to offer a large sample of quasar multiples ($\sim$100 pairs at $z>3$) thanks to its wide coverage with sufficient depth to find surrounding galaxies. From the first internal data release ($\sim$80 deg^2), we have extracted a few quasar pair fields at $z>3$ from which we found a prominent overdense

region around a close pair. In the presentation, we show general overview of this study and also some preliminary results derived from the latest HSC data set.

Metal enrichment by the first galaxies.

Andrea Pallottini

Cavendish Laboratory, University of Cambridge, UK

Galaxy formation is regulated by the competition between gas infall from the intergalalactic medium and supernova/AGN outflows. The circumgalactic medium is the interface that bears the signatures of the feedback of the infall/outflow processes. Using state-of-the-art simulations, we have modelled metal enrichment by the first galaxies.

In this talk I will discuss the main outcome of our study, clarifying the interplay between galaxies and their surrounding environment. These predictions are compared to current observational data using synthetic quasar spectra and far infrared emission models, allowing to draw key conclusions on the physics of galaxy formation and cosmic enrichment.

Cosmological mass transport on galactic nuclei

Joaquin Prieto

Astronomy Department, U. de Chile, Chile

By using AMR cosmological hydrodynamic N-body zoom-in simulations, with the RAMSES code, we studied the mass transport processes onto galactic nuclei from high redshift up to z$\sim$6. Due to the large dynamical range of the simulations we were able to study the mass accretion process on scales from $\sim$50 kpc to $\sim$pc. The SMBHs are modelled as a sink particles at the center of our galaxies, which allowed us to quantify the BH growth in relation with the mass transport processes associated to three different angular momentum fluxes: i) Reynolds stress, ii) gravitational stress and iii) viscous stress. Such a quantification allowed us to identify the main mass transport process as a function of the scales of the problem. Wefound that in simulations that include radiative cooling and SNe feedback, the SMBH grows at the Eddington limit most of the time. The disk momentum flux is dominated by the Reynolds stress transporting mass at a rate of $\sim$1-10 Msun/yr. This level of SMBHs accretion rates found in our cosmological simulation, are needed in all models of SMBH growth attempted to explain the formation of redshift 6-7 quasars.

Influence of sterile neutrino dark matter on the process of reionization

Anton Rudakovskyi

Bogolyubov Institute of Theoretical Physics, Kiev, Ukraine; Taras Shevchenko National University of Kyiv;, Ukraine

A hypothesis of dark matter particles requires an extension of Standard Model of particle physics. Recent reports of a weak unidentified emission line at $\sim$3.5 keV found in spectra of several dark matter-dominated objects may give a clue to resolve this long-standing problem. One of the best physically motivated dark matter particle candidate able to produce such a line is sterile neutrino. Previous works show that the sterile neutrino dark matter with parameters consisting with the measurements ofthe new line should affect the formation of cosmic structure. In this work, we concentrate on the influence of initial velocities for such a dark matter that lead to suppression of power spectra at small scales, to the process of reionization. We found that the influence of initial velocities of sterile neutrino dark matter particles is comparable with conservatively estimated existing uncertainties of other reionization model parameters, and that more detailed treatment of the process of reionization will be essential for reconstruction of the nature of $\sim$3.5 keV line dark matter candidate.

First Galaxies and Cosmology

Martin Sahlen

University of Oxford, Sweden

We investigate how first-galaxy distributions from future surveys can help constrain modified gravity, dark energy, inflation, and dark matter; and characterise the degeneracy between such physics and the reionisation history. For example, current observations of the cosmic microwave background (CMB) and large-scale structure (LSS) show tentative indications of a deviation from General Relativity (GR) on large scales or different densities. A modification of gravity also improves consistency between the reionisation optical depth currently determined from the CMB and from the first-galaxy luminosity function. We further consider how combination with other LSS data 'for free' (e.g. voids) in the same surveys can tighten model constraints.

Constraining the quasar lifetime using the HeII transverse proximity effect

Tobias Schmidt

Max Planck Institute for Astronomy, Germany

The quasar lifetime is a key ingredient for quasar demographics, relevant in the context of SMBH mass assembly and might distinguish between different models of AGN activity. The helium transverse proximity effect is a unique way to directly measure this quantity. In contrast to hydrogen reionization, the sources of helium reionization are bright quasars at $z \sim 3$ and directly accessible to observations. I will present results from our dedicated optical survey which is designed to yield a full census of the foreground quasar population around all 25 available helium sightlines with science grade Far-UV spectra. While the HST/COS FUV spectra reflect the helium ionization state, the foreground quasar population gives information of about the HeII ionizing radiation along the sightlines. Combining both does not only give unique insights into the process of helium reionization but also hints about the quasar opening angle and allows to constrain the episodic quasar lifetime. From our large statistical sample of foreground quasars we infer a lower limit of 25 Myr, indicating that the episodic quasar lifetime is probably long and possibly comparable to the Salpeter timescale. This in consequence means that SMBHs might accumulate a substantial fraction of their mass during luminous quasar phases.

SMBH growth parameters in the early Universe of Millennium and Millennium-II simulations

Majda Smole

Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia

We make black hole (BH) merger trees from Millennium and Millennium-II simulations to find under what conditions 10^5Msun SMBH can form by redshift z=7. In order to exploit both: large box size in the Millennium simulation; and large mass resolution in the Millennium-II simulation, we develop a method to combine these two simulations together, and use the Millennium-II merger trees to predict the BH seeds to be used in the Millennium merger trees. We run multiple semi-analytical simulations where SMBHs grow through mergers and episodes of gas accretion triggered by major mergers. As a constraint, we use observed BH mass function at redshift z=6. We find that in the light of the recent observations of moderate super-Eddington accretion, low-mass seeds (100Msun) could be the progenitors of high-redshift SMBHs (z$\sim$7), as long as the accretion during the accretion episodes is moderately super-Eddington, where f_Edd=3.7 is the effective Eddington ratio averaged over 50 Myr. This paper has been published in MNRAS.

The Near Infrared Signatures of the First Quasars

Marco Surace

Institute of Cosmology and Gravitation, University of Portsmouth

About 50 quasars have now been discovered at $z > 6$, including a 2 billion solar mass black hole (BH) at z = 7.1 and a 12 billion solar mass BH at z = 6.3. The origins of these high redshift supermassive black holes (SMBHs) are likely direct collapse black holes forming in pristine, atomically cooled halos at $z \sim 15-20$. The contribution of this early population of quasars to cosmological reionization will soon be probed by observatories such as JWST, WFIRST, and ELT. We have performed cosmological simulations that follow for the first time the birth and evolution of the $z > 6$ quasars with X-ray transport that produces H II regions that can be post-processed to obtain realistic synthetic observables for $5 < z < 15$ SMBHs. We have used these simulations to model the NIR continuum emission of the first quasars and we will discuss their properties and prospects for detection by NIR observatories in the coming decade.

Local remnants of reionisation

Tom Theuns

ICC, Durham University, United Kingdom

I will elaborate on the model of reionization from the Eagle simulations presented by Sharma, with particular attention to how remnants of reionisers are distributed in the Milky Way today, and how you might recognise them as such.

Heavily obscured AGN: an ideal laboratory to study the early coevolution of galaxies and black holes

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Understanding the evolution of AGN is a crucial challenge in astrophysics, especially at high redshifts. At present, a few thousands luminous unobscured AGN have been observed in the distant Universe, whereas only a limited number of obscured AGN are currently known, although these are thought to be intrinsically more abundant than unobscured ones. Disclosing the high-redshift obscured AGN population is necessary to constrain the whole history of super-massive black holes and the coevolution with their host galaxies. These hosts often show up as submillimeter galaxies, which trace the most active phase in the lifetime of massive systems, being characterized by a high production of stars and very fast consumption of gas. We will present a multiwavelength analysis of a sample of six $z > 2.5$ X-ray selected AGN in the Chandra Deep Field-South (CDF-S) which are classified as Type 2 and have detections in the far-IR/submm bands. This study includes X-ray spectral analysis (using the 7Ms Chandra data) to derive the absorbing column density and the AGN intrinsic luminosity, and spectral energy distribution (SED) fitting to estimate stellar mass, star-formation rate and AGN bolometric luminosity. By comparing the column density associated with the gas with that measured from the X-ray data, it is possible to understand whether the ISM in the host galaxy may be able to produce a substantial part of the observed nuclear obscuration.

A new measurement of the Lyman-alpha forest small scale power spectrum

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The line-of-sight power spectrum (P_F(k)) of the Ly-α forest has proven to be a valuable tool for doing cosmological observations. It also not only allows to constrain cosmological parameters, but enables us to measure the thermal state of the IGM at redshifts z>2. While at large scales (k<0.02 s/km) P_F(k) has been accurately measured using the large number ($10^3 - 10^5$) of quasar sightlines from SDSS and BOSS, there are much less spectra available at smaller scales (larger k). Prior power spectrum measurements from high-resolution data only used less than ∼10 quasar (QSO) spectra in our redshift range about 10 years ago whereas several hundred became available in the meantime. We therefore performed a new measurement using 75 quasar sightlines with 1.8<z<3.4 significantly improving the precision of the small-scale P_F(k). Using this additional precision on small scales combined with the BOSS measurements on large scales will enable us to accurately constrain the thermal cutoff scale of the IGM set by a combination of temperature broadening of Ly-α forest lines, and 'Jeans' smoothing due to baryonic pressure support. Using these additional constraints should allow us to observe the changes in thermal properties during the end phase HeII-reionization as predicted by radiative transfer simulations.

Galaxy Overdensity Around the Most Massive Black Hole at the Reionization Epoch

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Billion solar mass black holes (BHs) within quasars at $z > 6$ are thought to reside in large-scale galaxy overdensity regions, progenitors of the most currently massive clusters. Recently, we discovered the first ten billion solar mass BH at $z > 6$ within the ultra-luminous qua sar J0100+2802 at $z = 6.30$. It is the most luminous objects known at $z > 5$, powered by a BH compa rable to the most massive BHs found in the local universe. Our deep HST/ACS and LBT/LBC images reveal a signifiant overdensity of i-dropout galaxy candidates at $> 3.5\sigma$ level compared to blank fields that extend up to 410Mpc physical scale.

The bright end of the quasar luminosity function at $z \sim 5$

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We want to present a new determination of the bright end of the quasar luminosity function (QLF) at $z \sim 5$. We do a luminous $z \sim 5$ quasar survey by using SDSS-WISE optical and near-infrared colors. Combined our 45 new quasars with previously known quasars that satisfy our selections, we construct the largest uniform luminous $z \sim 5$ quasar sample to date, with 99 quasars in the range $4.7 < z < 5.4$ and $-29 < M1450 < -26.8$, within the SDSS footprint. We use a modified 1/Va method including flux limit correction to derive a binned QLF, and we model the parametric QLF using maximum likelihood estimation. With the faint-end slope of the QLF fixed as $\alpha = -2.03$ from previous deeper samples, the best fit of our QLF gives a flatter bright end slope $\beta = -3.55$ and a fainter break magnitude $M1450 = -26.95$ than previous studies at similar redshift. Combined with previous work at lower and higher redshifts, our result is consistent with a luminosity evolution and density evolution (LEDE) model, but prefers a steeper slope of $\log\phi(z)$ evolution and a slower break magnitude evolution. Using the best fit QLF, the contribution of quasars to the ionizing background at $z \sim 5$ is found to be 18%–45% with a clumping factor C of 2–5. Our sample suggests an evolution of radio loud fraction with optical luminosity but no obvious evolution with redshift.