Abstract Booklet

MASSIVE BLACK HOLES ACROSS COSMIC TIME

8-12 SEPTEMBER 2025

Organised and hosted by the Kavli Institute for Cosmology, Cambridge

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Xiaohui Fan (University of Arizona)
Jenny Greene (Princeton University)
Sophie Koudmani (Herts/KICC)
Roberto Maiolino (KICC, co-chair)
Chris Moore (KICC/IoA/DAMPT)
Priyamvada Natarajan (Yale University)
Debora Sijacki (KICC)
Hannah Übler (MPE, co-chair)

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09:30 - 09:40 • Welcome

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Unraveling the Quasar Broad-Emission Line Region

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Emma Weller and Linhua Jiang

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Quantifying the Uncertainties of Massive Black Hole
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BH FEEDBACK (OBS)

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Outflow Coupling Efficiency in AGN Host Galaxies Across Cosmic Time: Insights from IFU Surveys

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Modelling the Mergers of Supermassive Black Holes and their Gravitational Wave Emission in Cosmological Simulations

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Tracking On-The-Fly Massive Black Hole Binary Evolution and Coalescence in Galaxy Simulations: RAMCOAL

15:00 - 15:20 • Laura Blecha | **pg 80**
Constraining Low-Frequency Gravitational-Wave Source Populations with Cosmological Simulations

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Topics:
BH Mass Measurements
TDEs
Dual / Merging BHs
BH Seeding and Early Growth
MBHs in the Early Universe (QSOs)
MBHs in the Early Universe (AGN)
BH Demographics (obs)
BH Feedback (sims)
BH Feedback (obs)
GWs

JONELLE WALSH • REVIEW TALK

The Dynamical Detection of Supermassive Black Holes in Nearby Galaxies

Over the past 30 years it has become increasingly clear that supermassive black holes are essential components of galaxies, as demonstrated by the correlations connecting black hole masses and host galaxy properties. Although about 150 dynamical black hole mass measurements have been made to date, the local black hole mass census is highly incomplete. Gaining a more complete picture of black hole demographics and a deeper understanding of the mechanisms that drive black hole - galaxy co-evolution requires the measurement of black holes in a wider range of galaxies with diverse evolutionary histories. I will discuss several programs aimed at taking this necessary step, including the stellar and gas-dynamical methods used for black hole mass measurements, and the observational and modeling advances that have made the work possible.

NOTES

JENS THOMAS

Ultra Massive Black Holes in the Local Universe and Beyond

It is well known that almost every galaxy hosts a supermassive black hole (SMBH) at its center. Classical scaling relations like the one between SMBH mass and host galaxy velocity dispersion or host galaxy total stellar mass are well established up to black hole masses of 10^{10} M⊙. However, little is known about the so-called ultramassive black holes (UMBHs), i.e. black holes with masses above 10^{10} M⊙. Only a handfull of UMBHs have been detected dynamically in the local universe. I'll discuss first results from our ongoing observational search for UMBHs in very massive galaxies with depleted cores. Using our latest orbit-based triaxial dynamical models, we find that UMBH masses scale with the size of the depleted-core region of the host galaxy. They are offset from the relation between black-hole mass and galaxy velocity dispersion established for less massive elliptical galaxies. This provides further evidence that the most massive black holes grow by mergers at late evolutionary stages. I will also discuss our recently started study of the redshift evolution of the most massive black holes using high-resolution EUCLID data.

NOTES

KIRK LONG

Unraveling the Quasar Broad-Emission Line Region

Broad emission lines are an observational hallmark of AGN that imply the presence of a supermassive black hole. This broadening, in conjunction with a radial distance measurement, allow us to measure the masses of supermassive black holes. But to obtain the most precise masses and understand the true nature of the broad-line region requires a degree of modeling.

Two popular models of the BLR imagine the emitting gas as either a distribution of puffed up clouds or a thin disk with strong velocity gradients, which could give rise to winds/outflows. In this talk we will first show fits of thin disk-wind models to interferometric GRAVITY data in 3C 273, demonstrating that multiple models can fit real BLR data. We will then discuss modeling of reverberation mapping data obtained via the AGN STORM project in NGC 5548, and how these data products -- in particular delay profile measurements -- imply that current models of the BLR cannot adequately explain all the observations. In particular, the observed delay and line profiles in NGC 5548 seem to imply multiple populations of broad line emitting gas with different geometries and kinematics, and we will discuss ongoing efforts to alleviate this tension with multi-component BLR models. We will also briefly show a promising deep learning technique for the deconvolution of reverberation mapping data to obtain 2D velocity-delay maps, which can help in discriminating between which types of models best represent the BLR.

The goal of this talk is to demonstrate that through these approaches we can better constrain the true nature of the BLR, what physics can plausibly exist there, and how our choice of model systematically influences our measurements of high level properties such as SMBH mass.

NOTES

NABANITA DAS

A Stellar Dynamical Mass for the Central Black Hole in MCG-06-30-15

Given the many different techniques currently in use for directly constraining black hole mass (M_{BH}), a comparison of M_{BH} measurements from multiple techniques applied to the same galaxy allows us to identify and investigate possible sources of bias associated with each. This may in turn influence our understanding of black hole and galaxy coevolution across cosmological timescales. In this talk, I shall present the first stellar dynamical mass of the central black hole in the nearby Seyfert galaxy MCG-06-30-15 using the Schwarzschild orbit superposition method. MCG-06-30-15 is only the fourth galaxy in which we can compare M_{BH} from stellar dynamical modeling with that from reverberation mapping. We obtained spatially resolved K-band nuclear stellar spectra for this galaxy with SINFONI on the VLT. We extracted the bulk stellar kinematics using Gauss-Hermite (GH) parameterization. A multi-component surface brightness profile of the galaxy was determined from a medium-V HST image. We applied the Schwarzschild method to fit the line-of-sight velocity distributions using the open-source code FORSTAND, which allows exploration of the 3D galaxy shape. Our best-fit models indicate a M_{BH} within (2.5-7.0)X10^7 $M_\odot$, and a stellar mass-to-light ratio, M/L= (2.6-3.7) $M_\odot$/ $L_\odot$. Our constraint on M_{BH} is ~10 times larger than the reported mass from reverberation mapping, and agrees with the upper limit of mass from stellar dynamical modeling determined by implementing the Jeans Anisotropic Method. However, our best-fit M_{BH} may be systematically biased high due to the counter-rotating disk in the nucleus of MCG-06-30-15 and the inability of the GH parameterization to fully describe such a complicated set of stellar kinematics. In addition, dynamical M_{BH} depends heavily on the assumed distance, which is not yet accurately constrained for this galaxy, but is currently under investigation.

NOTES

ECKHARD STURM • REVIEW TALK

Measuring Supermassive Black Hole Masses Across Cosmic Times with Interferometric Spectro-Astrometry and Reverberation Mapping Techniques

Measuring the masses of supermassive black holes (SMBHs) plays a key role in our understanding of black hole growth and galaxy-BH co-evolution over cosmic time. For a long time, the only available method for measuring black hole masses in large surveys and out to high redshift was based on reverberation mapping (RM). Past RM programs on local AGN established a size-luminosity relation between the radius of the Broad Line Region (BLR) and BH luminosity (RBLR ~Lα) which allows black hole mass estimates from a single AGN spectrum. However, applicability of these local scaling relations to high redshifts is uncertain, and recent velocity-resolved RM studies are starting to indicate a variety of BLR geometries and a previously unknown dependence on the Eddington ratio. A few years ago, a new technique, spectro-astrometry with the GRAVITY interferometer at the ESO/VLTI, started to provide a new, highly complementary and direct probe of the BLR spatial and velocity structure which can independently test and break degeneracies in these studies. I will briefly review recent advances in measuring masses of super-massive black holes with both techniques, discuss their respective pros and cons, and outline the potential of combined studies.

NOTES

RAHMA ALFARSY

The Feasibility of Stacked Reverberation Mapping with DESI

Reverberation mapping has been a cornerstone technique for probing quasars, measuring the time lag between variations in continuum emission and their echoes from the broad line region. This method has enabled the resolution of the broad line region and the calculation of supermassive black hole (SMBH) masses. However, traditional observational programs are costly and selective, limiting the volume and diversity of quasar samples.

With the advent of large spectroscopic surveys, stacked reverberation mapping has been proposed to leverage extensive quasar samples instead of relying on high-cadence observations. In this presentation, we outline a pipeline developed to test the feasibility of stacked reverberation mapping using data from the Dark Energy Spectroscopic Instrument (DESI). We present promising results from mock data, highlighting how various observational factors influence the reliability of this method. Finally, we apply the pipeline to year 3 DESI data, containing 2.3 million SMBHs, and show these techniques can potentially be used to extend the BH mass calibration pipeline up to redshifts of 4.7.

NOTES

SARA ROSBOROUGH

Modeling the Reverberation Response of Multiple Broad Emission Lines in Active Galactic Nuclei

Gas clouds are deep within the potential well of an active supermassive black hole (SMBH) emit photoionization lines Doppler-broadened by several 1,000 km/s. Measuring the size and velocity dispersion of this broad line region (BLR) provides a way to infer the mass of the SMBH. However, the distances to most active galactic nuclei (AGN) make spatially resolving the BLR very challenging, and much of its structure and dynamics are uncertain. The variable continuum emission of an AGN produces corresponding responses in the broad lines that are modulated by light travel-time delays. The response is described by the transfer function, which contains information on the physical properties, structure, and kinematics of the BLR. The reverberation mapping technique, a time-series analysis of the driving light continuum curve and time-delayed response of the broad lines, can recover some of this information. We will present a new forward-modeling tool, the Broad Emission Line MApping Code (BELMAC), that simulates the velocity-resolved reverberation response of the BLR to an observed input light curve, given the bolometric luminosity and spectral energy distribution of the AGN. It is the first reverberation mapping code to incorporate photoionization models to enable modeling of ultra-violet, optical, and near infrared broad lines. It is a unique tool for interpreting the BLR reverberation and single-epoch spectroscopy data from intensive time-domain campaigns as well as large-scale surveys.

NOTES

VADIM RUSAKOV
Electron-Scattered Broad Lines at High Redshift

The James Webb Space Telescope has revealed a large number of galaxies with broad hydrogen lines in the early universe. Unlike most known AGN, these broad-line systems lack characteristic X-ray or radio emission, as well as optical variability. Together with frequent Balmer absorption features in these systems, the evidence suggests that they have high column densities of neutral absorbing gas with a high covering fraction. In this work, we provide new insights into the nebular properties of these objects by investigating different mechanisms of line broadening. By using highest-quality spectra of bright objects and stacking the spectra of fainter systems, we find strong evidence that the line widths are dominated by electron-scattering in the presence of high-column-density ionised gas. This supports the idea that the high-redshift AGN are embedded into Compton-thick gas, which likely absorbs some of the low-energy X-rays. The finding further implies that the systems are likely not over-massive for their host galaxies, as found in recent studies.

NOTES

FRANCESCO D’EUGENIO

Dense Gas Absorbers Around Little Red Dot AGN

JWST has uncovered a new population of low-luminosity broad-line AGN characterised by blue rest-frame UV slopes and red rest-frame optical continuum. Many of these dust-obscured sources exhibit prominent Balmer breaks, attributed to bound-free hydrogen absorption from the n=2 level. Notably, at least 10% of these ‘Little Red Dot’ AGN display Balmer breaks—an order of magnitude higher than the ~1% observed in large spectroscopic surveys at z~0.

I will demonstrate that strong Balmer breaks are linked to n=2 absorption features in Hα and Hβ, with high equivalent widths indicating that the absorbing gas resides between the broad-line region and the observer. The broad absorption profiles suggest both a high covering fraction and turbulent gas motion (~120 km/s).

The kinematics of this absorbing gas point to two possible scenarios: a rotating disk or a stalling outflow, potentially driven by accretion at high Eddington rates. These findings offer new insights into the structure and evolution of AGN obscuration, as well as the role of turbulent gas in regulating black hole growth.

NOTES

SUVI GEZARI • REVIEW TALK

Searching for the Tidal Disruption of Stars from Massive Black Holes Over Cosmic Time

The tidal disruption of a star that wanders too close to a central black hole is a unique probe of quiescent supermassive black holes lurking in the nuclei of galaxies. Over the last 5 years, we have demonstrated the ability to discover and spectroscopically classify large samples of tidal disruption events (TDEs) in the optical from the Zwicky Transient Facility (ZTF) Northern Sky Survey, with systematic high-energy follow-up with Swift and XMM-Newton. One of the most exciting applications of TDEs is the ability to probe intermediate mass black holes (IMBHs) that are expected to reside in dwarf galaxies, with demographics that encode the seeding mechanism of massive black holes in the Early Universe. I will present our strategy in the next decade for searching for TDEs across the black hole mass function, and over cosmic time, by extending our sensitivity to TDEs to lower central black hole masses and higher redshifts, by exploiting the discovery power of the next generation of wide-field time domain surveys, including Rubin, Roman, ULTRASAT, and UVEX.

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MITCHELL KARMEN

A Candidate High-z tidal Disruption Event at $z \gtrsim 7$ in COSMOS-Web: the First Photometric Search with JWST

I predict the rates of tidal disruption rates (TDEs) across a number of upcoming surveys, and show that they will be observed from the local universe all the way to z~10 through the use of the Rubin observatory, the Roman Space Telescope, and the JWST. I argue that, given what we have learned from JWST observations of galaxies at high redshifts, the TDE rate at z>4 should be enhanced by a factor of as high as 100. To test this, we developed a novel methodology for identifying high-redshift TDEs in deep surveys through color and morphology selection criteria- without the use of time domain information- and applied it to the COSMOS-Web survey. We discover a high redshift TDE candidate, at redshift $7.2 \lessapprox z \lessapprox 8.0$ which, if validated, confirms the enhancement of the high-redshift TDE rate of at least an order of magnitude. This work is the first demonstration of a method for identifying TDE candidates without time-domain information, and can be applied to find the dozens of z > 4 TDEs that will be present in the Roman Wide Area Survey, providing a new tool for studying otherwise dormant SMBHs in the early universe.

NOTES

OR GRAUR

Mapping the Inner Parsec of Supermassive Black Holes with Tidal Disruption Events

Tidal disruption events (TDEs) offer an innovative way to map the properties of the interstellar medium (ISM) in the vicinity (<1 pc) of supermassive black holes (SMBHs). A TDE occurs when a star crosses the tidal radius of an SMBH and is disrupted by the black hole's gravitational field. As a result, half of the mass of the TDE falls into the black hole to create a transient accretion disk. During this process, a bright flare is emitted, which peaks in X-rays and hard UV. Over the last few years, my group has provided strong evidence that this high-energy radiation ionizes the ISM surrounding the SMBH to produce the high-ionization iron lines (also called "coronal lines") observed in rare, extreme coronal-line emitting galaxies (ECLEs). In this talk, I will present the evidence linking ECLEs to TDEs and show how we have already begun to use this link to map the properties of the ISM within 1 pc of the SMBH. With this method, we can probe the properties of the ISM around both active and quiescent SMBHs to shed new light on how active galactic nuclei turn on and off again.

NOTES

FILIPPO MANNUCCI

Merging and SMBH Growth

SMBHs grow through two main channels: accretion and merging. While the role of accretion is relatively well understood, the impact of merging remains highly debated, together with the impact of merging on AGN activity. Dual AGN, which occur when two SMBHs exist within a single merging host galaxy at kiloparsec separations, offer unique insights into both SMBH growth and galaxy merger processes. Current models of galaxy/SMBH co-evolution make specific predictions about these systems, including their frequency (dual fraction), black hole mass distribution, and separation distribution. However, these predictions remain totally untested. Understanding this population is also crucial for predicting GW event rates and backgrounds detectable by LISA and Pulsar Timing Arrays.

I will present an extensive observational project designed to detect and characterize a large sample of dual AGN at sub-arcsecond separations. The project employs a selection method based on Gaia and Euclid data, complemented by observations from multiple space-based and ground-based facilities, including VLT/MUSE, VLT/ERIS, Keck, LBT, HST, VLA, LOFAR, and JWST. I will discuss our findings regarding the dual fraction and black hole mass distribution, comparing these results with predictions from current galaxy formation and galaxy/SMBH co-evolution models."

NOTES

HANNAH ÜBLER

BlackTHUNDER and Multiple AGN at z>5 with NIRSpec

JWST has discovered an unexpected ubiquity of massive, active black holes at high redshift. Understanding their formation and the properties of their host galaxies is an ongoing endeavour. I will present first results from BlackTHUNDER, a JWST/NIRSpec-IFS Large Program to study broad-line AGN and their immediate surroundings during the first billion years of cosmic history. Specifically, I will discuss the discovery of a triple AGN system at z~5, in context with other confirmed and candidate dual AGN at high redshift. Our results indicate that multiple massive black holes may be common in galaxies in the early Universe, and highlight the important role of IFU observations for their discovery and characterisation.

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SANDRA ZAMORA

Black Holes in the Early Universe: a High-z Double AGN and its Overdense Environment from NIRSpec JWST Observations

Distant quasars (QSOs) are considered key actors in the evolution of the early Universe. High-redshift merging systems, containing two or more supermassive black holes surrounded by close companions, tidal bridges, and tails on kiloparsec scales, represent an expected phenomenon, as evidenced by the first spatially resolved spectroscopic observations from the James Webb Space Telescope (JWST). The study of these gas-rich systems provides crucial insights for constraining key components of galaxy evolution models, enhancing our understanding of galaxy growth and the feedback effects of active galactic nuclei (AGN) throughout the history of the Universe.

In this work, I will present the merging system BR1202-0725 formed by a QSO and a submillimetre galaxy (SMG) with evidence of a heavily dust obscured black hole at its center. Together, they form one of the most distant close pairs of AGN known to date. Moreover, this merger is one of the most overdense fields known in the early universe, also formed by the three Lyα emitters. Through JWST observations, I will discuss the properties of the QSO, the SMG's BH, and the fast outflowing ionised gas found in this galaxy. Furthermore, we characterised the interstellar medium, the physical and ionising mechanisms and the kinematics of the merger. Finally, we investigated the environment of the system and we found four new galaxies. Then, this overdense system includes at least ten galaxies in a field of view of only 980 kpc2.

NOTES

RAFFAELLA SCHNEIDER • REVIEW TALK

Black Holes at Cosmic Dawn: Seeding and Early Growth in the Young Universe

The formation and rapid growth of black holes during the cosmic dawn represent one of the most intriguing puzzles in astrophysics. In this talk, I will summarise the current understanding of black hole seeding mechanisms in the early universe, including the nature of initial seed black holes and their environments. I will explore the physical processes driving their early accretion phases that enable the emergence of supermassive black holes observed at high redshifts, and how these influence the formation of the first galaxies. I will highlight ongoing challenges and future prospects for probing early black hole growth. Importantly, future gravitational wave observatories will enable direct detection of early black hole mergers, offering vital constraints on seed masses and growth rates. These upcoming observations will complement electromagnetic studies, providing new insights into black hole evolution in the young universe.

NOTES

ANTTI RANTALA

Formation of Supermassive Black Hole Seeds in Dense, Clustered Stellar Environments

Observations by the James Webb Space Telescope (JWST) and solar mass resolution hydrodynamical simulations indicate that high-redshift star formation was dense, clumpy, and clustered. I examine the consequences of such an environment for the collisional formation of seeds for supermassive black holes (SMBHs) at low metallicities. With up to 5 million stars in evolving single, binary, and triple systems, the clustered models run with my modern GPU-accelerated N-body code BIFROST are the largest post-Newtonian star cluster simulations to date. The simulation results highlight the importance of low metallicity, stellar multiplicity, stellar collisions, tidal disruption events, and gravitational wave-driven black hole mergers in the SMBH seed formation process. Individual SMBH seeds of 10,000 solar masses acquire up to ~50% of their mass in black hole mergers within 10 Myr of their formation. I highlight the characteristic gravitational wave (GW) fingerprint of SMBH seed formation during hierarchical star cluster assembly: an equal-mass GW merger in the mass range of 1,000-10,000 solar masses. Finally, I discuss the implications of detailed SMBH seed formation models for the currently used SMBH seeding sub-resolution prescriptions in cosmological simulations.

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ELIA CENCI

Modelling of Direct-Collapse Black Hole Seeds in Large-Scale Cosmological Simulations

The formation and growth of massive black holes (MBHs) at high redshift remain a key challenge in modern astrophysics. Observations of quasars at $z > 6$ indicate the presence of MBHs with masses exceeding ~ 1e9 $M_\odot$, yet the processes responsible for their early assembly are highly debated. Direct-collapse black holes (DCBHs) are among the most promising candidates to seed the high-redshift over-massive black holes that were recently discovered with the James Webb Space Telescope (JWST). We introduce a novel cosmological hydrodynamical high-resolution simulation framework that models DCBH seed formation and growth within evolving galactic environments. A new self-consistent treatment of local Lyman-Werner flux from nearby star-forming halos is employed, alongside criteria for gas density, metallicity, and inflow rates, ensuring realistic conditions for seed formation. We explore how variations in environmental and astrophysical conditions affect the initial mass function and spatial distribution of DCBH seeds, and compare to available data from JWST. We also discuss our results in the context of gravitational wave detection from high-redshift black holes with the upcoming Laser Interferometer Space Antenna (LISA).

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JOHN REGAN

Modelling Massive Black Hole Formation and Growth in the Early Universe

The formation pathways of Massive Black Holes remains unknown. Both the so-called light seed pathway (M_{init} <~ 1000 M⊙) and the heavy seed pathway (M_{init} >~ 1000 M⊙) appear both to be still in play with both suffering hurdles to either efficient growth or efficient formation.

In this talk I will introduce the SEEDZ suite of simulations. These simulations, run with the Arepo2 code, aim to probe the formation and growth of both light and heavy seeds simultaneously within a high-resolution and high-redshift setting. In addition to massive black formation the simulations contain detailed prescriptions for PopIII and PoII star formation and feedback. The goal of these simulations is to connect with recent JWST measurements which show the formation of over-massive black holes, a higher than anticipated number density of massive black holes as well as unusual chemical abundances in high-z galaxies.

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AKLANT BHOWMICK

BRAHMA Simulations: Unveiling the First Seeds of Supermassive Black Holes Using Cosmological Hydrodynamic Simulations

Deciphering the first "seeds" of supermassive black holes (BH) is a key science goal for current facilities such as the James Webb Space Telescope (JWST) and upcoming facilities like the Laser Interferometer Space Antenna (LISA) gravitational wave observatory. Most popular candidates include "light" seeds as Population III stellar remnants (~1e2 solar masses), "medium-weighted" seeds as merger remnants of stellar and BH collisions in dense nuclear star clusters (~1e3-1e4 solar masses), and "heavy seeds" formed out of direct collapse of gas (~1e4-1e6 solar masses). However, most cosmological simulations employ very simplistic seeding prescriptions due to their inability to explicitly resolve the seed masses and the formation processes. I will talk about our new suite of BRAHMA cosmological simulations that implement a novel set of physically motivated BH seeding prescriptions that rely on a wide range of gas properties, including high gas density, low gas metallicity, strong Lyman Werner radiation, low gas angular momentum, and rich halo environment. To model low mass seeds in larger simulation volumes, we have developed a novel stochastic seed model that can faithfully represent the descendants of seeds that are ~10-100 times below the simulation resolution. Using our new seed models, we have carried out one of the largest systematic studies for quantifying the impact of BH seeding, on BH populations across cosmic time. I'll talk about the key signatures of our seed models and the impact of BH dynamics over a wide range of BH observables such as the BH merger rates detectable by LISA, high-z stellar mass vs BH mass relations probed by JWST, and the local BH occupation fractions in dwarf galaxies.

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LEWIS PROLE

Simulating High Redshift Star & Black Hole Formation

TBC

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CAROLINE NAGIB

Seeing the Invisible: Developing the First Comprehensive Simulation of Direct-Collapse Black Hole Formation

The origin of supermassive black holes (SMBHs) embedded in the centers of massive galaxies remains one of the key questions in astrophysics because they can provide clues to the birth of their host galaxies. Direct-collapse black holes (DCBHs), remnants of supermassive stars (SMSs) with masses around 10,000 solar masses, are of special interest because they are ideal seed candidates for the formation of SMBHs. We present a high-resolution, radiation hydrodynamical simulation using the adaptive mesh refinement code Enzo that models the collapse of a turbulent, primordial gas cloud and the ensuing star formation, including SMSs, and stellar feedback that includes Lyman-Werner and ionizing radiation feedback. This preliminary simulation serves as a precursor to a suite of radiation hydrodynamical simulations that will follow the formation and evolution of DCBHs and the surrounding nuclear star cluster within the first galaxies, encompassing nearly all relevant physical processes. We will analyze DCBH evolution, providing predictions for multi-messenger astrophysics and the James Webb Space Telescope. Our results provide insights into how the properties of the cloud evolve as it forms nearly 100,000 solar masses of stars within a free-fall time with the most massive star having 127 solar masses.

NOTES

EDUARDO BAÑADOS • REVIEW TALK

Review on Quasars in the Early Universe

Quasars are among the most powerful and luminous objects in the Universe. As such, they can be found and studied in detail far back into the epoch of reionisation at redshifts z>6. These luminous quasars are ideal laboratories to study the build-up of the first massive galaxies and black holes and the onset of small- and large-scale structures in the early Universe. I will review our "pre-JWST" knowledge of the physical properties of the most distant quasars (black holes, host galaxies, and their environment). Additionally, I will highlight recent JWST results, which are rapidly changing the landscape.

NOTES

DAMING YANG

Euclid: A Gold Mine of z > 7 Quasars

Luminous high-z quasars provide direct probes of the buildup of supermassive black holes, the primeval massive galaxies hosting them, and the intergalactic medium during the epoch of reionization. Despite its extraordinary capabilities, a significant challenge remains: the lack of quasar samples at redshift larger than 7. The Euclid space telescope offers a promising avenue to enrich our quasar samples at redshifts around 7 and to explore the unknown regime at z>7.5. The key to finding these quasar samples among the countless sources in the deep, wide Euclid survey is to select and confirm the candidates much more effectively.

In this talk, I will introduce the first-year result of the Euclid high-z quasar search and the methodology used to select the candidates. Our candidate selection method is grounded in Bayesian probability and density estimation with extreme deconvolution. In the density estimation, we incorporate a new generative model for quasar spectra, which is based on a new compilation of low redshift NIR quasar spectra, and integrate the photometric data from WISE and radio survey to boost the efficiency. The subsequent task involves rapid follow-up confirmations using large, ground-based telescopes, for which we have developed a simulation tool to minimize required exposure times and refine observational strategies. So far, three follow-up observation programs on Keck and Magellan are finished, delivering more than 20 new high-z quasars, including 8 at z>7 and one record-breaking discovery at z~7.7. In this talk, I will present the preliminary results and show the lessons we have learnt so far.

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LUCA ZAPPACOSTA

Probing the First Quasars During Reionization: Unprecedented X-ray Insights into Their Nature and Growth

Shedding light on the nuclear properties of $z \geq 6$ quasars (QSO) powered by supermassive black holes (SMBHs) with masses >1e9 Msun is fundamental to understand their rapid formation. To this aim we are probing the innermost QSO regions, as close as possible to the growing SMBH, through X-ray emission, which provides a direct window down to few tens of gravitational radii from the QSO central engine.

Leveraging our ~700 hours XMM-Newton Heritage program, HYPERION, we are conducting an unprecedented systematic X-ray investigation of 18 luminous QSOs at $z>6$, which experienced the most rapid SMBH growth during their assembly. Our findings strikingly reveal a new regime for the nuclear properties of these first QSOs: their X-ray continuum slopes (Γ) are significantly steeper than similar QSOs at $z<6$.

We present our extensive search for possible correlations between Γ and other key physical properties related to accretion, ejection, and SMBH growth in these QSOs. We find:
(i) A significant correlation between Γ and the velocity of AGN-driven ionized winds.
(ii) An indication that QSOs with steeper Γ are those that underwent the most rapid SMBH growth.

We interpret these findings as evidence that these early QSOs have predominantly accreted at or above the super-Eddington rate throughout their formation history.

Finally we will: (i) present new results from our recent XMM-Newton Large program, which significantly expands our investigation to a larger sample of ~30 QSOs including sources with faster and slower SMBH growth than probed so far; (ii) discuss the implications of our results for the detectability of $z>6$ X-ray faint AGN recently discovered by JWST, as well as the prospects of future surveys with next-generation X-ray observatories.

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JULIEN WOLF

The First Giant Reionization-Era Quasar Jet Revealed with JWST/NIRSpec IFU

Quasars , active galactic nuclei (AGN) in their peak luminous phase, signpost the growth of the most massive supermassive black holes (SMBHs; $>10^9$ M⊙) over cosmic time. The discovery of quasars within the first billion years of the Universe ($z > 5.6$) raises important questions about black hole formation and evolution channels: How did these gargantuan SMBHs accrete so much mass on such short timescales? Understanding the early symbiotic growth of SMBHs and their host galaxies is crucial.

Relativistic jets are thought to play a key regulatory role in SMBH-host co-evolution by modulating gas reservoirs on circumgalactic medium (CGM) scales. By heating, expelling, or compressing gas, they can disrupt cooling flows and influence star formation rates. However, while giant radio jets (10–100 kpc) are common at $z < 3$, they remain elusive at $z > 5$, hindering our understanding of their role in early cosmic history.

In this talk, I present high-resolution JWST NIRSpec/IFU observations of the quasar P352–15 at z=5.83, which hosts the largest known radio jet (only ~1.6 kpc) from this era. Our data reveal an extended ionized gas structure (>20 kpc) aligned with the jet, detected through [OIII]5007 kinematic maps, showing a striking velocity gradient ($\Delta v \approx \pm 500$ km/s). Analysis of the IFU cube indicates that jet-driven outflows are impacting nearby star formation. Remarkably, the influence on the ambient gas is observed on scales ten times larger than the radio jet itself, even extending beyond the IFU's field of view.

These findings provide the first empirical constraints on kinetic feedback and jet–gas interactions on CGM scales in the first billion years of the universe. I will discuss how quenching of radio emission by the cosmic microwave background may clarify the spatial disparity between gas distribution and radio structure. Could this suggest a hidden population of large jets at high redshift, detectable not through radio frequencies but via their gas interactions?

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ROMAIN MEYER

Discovery of Two z~6.5 Post-Quasar Galaxies in Large Ionised Bubbles

JWST is shining a new light on early supermassive black holes and their co-evolution with their host galaxy. On the one hand, the surprising number of AGN at high-redshift is reawakening the debate surrounding the contribution of AGN to cosmic hydrogen reionisation. On the other hand, JWST is discovering a population of over-massive black holes that could be the progenitors of luminous z>6 quasars and shine a light on early galaxy BH co-evolution. In this talk, I will present the discovery of two overmassive black holes (>1/10 BH-to-stellar mass) from NIRSpec IFU observations of two luminous z~6.5 galaxies. The broad Balmer lines (Ha+Hb) indicate BH masses rivalling that of luminous quasars (>10^8 $M_\odot$). The two host galaxies (COLA1 and NEPLA4) were previously known for displaying double-peaked Lyman-alpha emission, indicating the presence of a large ionised bubble around them. The ionised bubble has likely been created by the most recent quasar phase of the AGN, which can thus be constrain to have ended < 1 Myr ago. The galaxies' star-formation history indicates that 90% of the stellar mass formed in a recent <20 Myr burst, providing definitive evidence for early SMBH growing faster than their host galaxy and even delaying their growth. In summary, these are two unique laboratories to study quasar host galaxies at a time when the quasar is inactive, opening new perspectives for early BH-galaxy co-evolution studies, and provide evidence that AGN contribute to reionisation on local scales.

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DALE KOCEVSKI • REVIEW TALK

What Little Red Dots Reveal about Black Hole Growth in the Early Universe

TBC

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XIHAN JI

A Non-Stellar Origin For Balmer Breaks In Broad-Line Little Red Dots Discovered by JWST

Recent observations from JWST have revealed an abundant population of active galactic nuclei (AGN) and the so-called "Little Red Dot" (LRD) galaxies at $2 < z < 11$, which are characterized by their V-shaped UV-to-optical continua with strong Balmer breaks. The physical nature of these LRDs is unclear, and the cause of their peculiar spectral shape is debated. We present the analysis of NIRSpec-MSA data and new NIRSpec-IFU data from the BlackTHUNDER JWST Large Programme of a lensed LRD at $z = 7.04$. The spectra confirm the presence of a smooth Balmer break and a broad H-beta tracing the Broad Line Region (BLR) of an AGN. The small dispersion of the H-beta narrow component indicates a small dynamical mass of the host galaxy that is less than 10% of the stellar mass inferred from the Balmer break, implying the optical continuum cannot be dominated by stellar light. We show that the Balmer break can be well described by an AGN continuum absorbed by very dense ($n_H \sim 1e10$ cm^{-3}) and nearly dust-free gas along our line of sight (possibly gas in the BLR or its surrounding). Meanwhile, the same gas is expected to produce H-beta absorption, which is at a level consistent with a tentative detection (3σ) in the high-resolution spectrum. We further show that such a non-stellar origin of the Balmer break may apply to other broad-line LRDs, which would greatly alleviate the issue of extremely high stellar mass densities inferred in the case of a stellar interpretation of the Balmer break.

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ALBERTO TORRALBA

Dissecting Little Red Dots: Spatially Resolved Spectroscopy of Faint Broad-Line AGN

The most recent JWST observations have revealed a population of red compact objects at $z>4$. Many of these objects, dubbed "Little Red Dots" (LRDs), exhibit broad components in their Balmer lines (i.e., Hα, Hβ), indicative of AGN activity. Their high abundance and low mass promises to reveal new insights in the first stages of SMBH growth and the co-evolution with galaxies. However, classical AGN+stellar models struggle to accurately reproduce the SEDs of these objects, leaving the true nature of their emitted light unresolved. One of the most surprising features is that many LRDs show Balmer absorption features, which may indicate the presence of extremely dense neutral gas along the line of sight, though the origin of this gas remains unclear.

In this talk, we present the first results from the JWST Cycle 3 GO program #5664 (PI Matthee), which aims to analyze the spatially resolved emission of five LRDs at $z\sim5$, selected based on their broad Hα emission, using NIRSpec IFU spectroscopy. Through high-resolution grating spectroscopy we can study in detail the Balmer absorption present in these objects, correlate it with the general shape of the SED and characterize the gas dynamics and prevalence of outflows.

NOTES

AKOS BOGDAN

Detecting the Earliest Supermassive Black Holes with Chandra and JWST

Although supermassive black holes (BHs) are widely observed in both the nearby and distant universe, their origin remains debated, with two viable formation scenarios. In the light seed model, BHs originate from the collapse of massive stars, while in the heavy seed model, they form from the collapse of pristine, massive gas clouds. Detecting BHs in the high-redshift universe offers the clearest method to probe the origin of the first BHs. Based on ultra-deep Chandra X-ray observations, we detected two X-ray-luminous massive BHs in JWST-identified, gravitationally lensed galaxies at z=10.07 and z=10.15. The mass of the BHs is in the range of 10^7-10^8 $M_\odot$, amounting to approximately 20-40% of the stellar mass of their host galaxies. The high BH mass and the exceedingly large BH-to-galaxy stellar mass ratio, less than 500 Myrs after the Big Bang, suggest that the BHs residing in these galaxies originate from heavy seeds.

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DAVID SETTON

Even “Goldilocks” Dust Temperatures Struggle to Reconcile Implied Reddening with IR Limits in The Most Luminous LRDs

Highly luminous broad Halpha emission and red rest-optical SEDs are the hallmark of compact, JWST-discovered Little Red Dots, implying that they are powered by some combination of highly attenuated dusty starbursts or active galactic nuclei. However, the lack of any appreciable FIR emission has proved difficult to reconcile with the implied attenuated luminosity in these models. We utilize deep new ALMA imaging, new and existing JWST/MIRI imaging and archival Herschel imaging of the two brightest Little Red Dots (z=3.1 and z=4.47) in the rest-optical to place the strongest constraints on the IR luminosity in Little Red Dots to date. The detections at lambda_rest=1-4 micron imply flat slopes in the rest-IR, ruling out any significant energy contribution from hot (T>500 K) dust. Similarly, the FIR non-detections imply that there cannot be any appreciable cold (T<75 K) dust component. Together, these constraints essentially rule out the possibility of these LRDs being highly reddened starbursts; not only is there no room in the FIR SED for the reprocessed attenuated light, the systems are also not detected in [CII], implying a non-star forming origin for the highly luminous Halpha. Composite galaxy+AGN models where the IR luminosity is dominated by the reprocessed light from an attenuated standard AGN disk are also difficult to reconcile with our strict IR luminosity limits. We conclude that it is unlikely that LRDs are highly dust-reddened intrinsically blue sources with IR SEDs that conspire to avoid current observing facilities; instead, we propose that these systems may indeed be intrinsically redder than most models assume, alleviating the need for strong attenuation.

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JIANWEI LYU

A Comprehensive Study of MIRIidentified High-z AGN Population

The James Webb Space Telescope (JWST) has unveiled a significant population of active galactic nuclei (AGN) in the early Universe, including broad-line sources among little red dots (LRDs) and narrow-line AGN candidates identified through the rest-frame UV high-ionization lines. However, current selection methods based on NIRCam color and NIRSpec/NIRCam-WFSS spectroscopy are subject to biases, hindering a complete census of the AGN population. Leveraging the MIRI data from the SMILES and JADES programs in the GOODS-S field, we have identified ~50 AGN candidates at redshifts z = 4–8.5 through their hot dust emission with a considerable of the sample have spectroscopic data from NIRSpec and NIRCam/WFSS. We construct the first bolometric luminosity function for AGNs at z > 4, encompassing both obscured and unobscured populations and compare the AGN statistics with those derived from LRDs and NIRSpec-identified samples. In addition, we will discuss the X-ray, radio, and variability characteristics of these AGNs, as well as the properties of their host galaxies. Our findings provide new insights into the demographics and evolution of AGNs in the early Universe, highlighting the critical role of mid-infrared observations in overcoming selection biases inherent in other methods.

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JUNYA ARITA

The Clustering Signature of JWST AGNs: A Missing Link in Quasar Evolution?

WST has discovered many faint AGNs at high-z by detecting their broad Balmer lines. However, their high number density, lack of X-ray detection, and overly high black hole masses with respect to their host stellar masses suggest that they are a distinct population from general type-1 quasars. Here, we present clustering analysis of 27 low-luminosity broad-line AGNs discovered by JWST at $5<z<6$ based on cross-correlation analysis with 679 photometrically-selected galaxies to characterize their host halo masses. The correlation analysis shows that the halo mass of JWST AGNs is $\log (M_{halo}/h^{-1} M_\odot) \sim 11.5$, which is ~1 dex smaller than that of luminous type-1 quasars. This halo mass is predicted to grow to $10^{12-13}\ h^{-1} M_\odot$ at $z<3$, which is comparable to that of a more luminous quasar at the same epoch. Therefore, it is implied that JWST AGNs are in a transition phase into quasars. For further discussion about the difference between JWST AGNs and type-1 quasars, their environment is important. We will also present the low-luminosity quasar environment traced by Lyman alpha emitters, which will be useful to compare the environment of JWST AGNs and that of quasars.

NOTES

ERINI LAMBRIDES

Un-Obscuring Obscuration: Characterizing Representative AGN Growth in the Early Universe

First results from JWST have raised more questions than answers on the prevalence, growth, and impact of growing SMBHs at z>4. Recent studies purport extreme over-abundances of early AGN alongside the estimated extreme masses of their black holes. We are potentially on the brink of a paradigm shift in early BH evolution -- but to robustly test and potentially break accepted paradigms, we need to go beyond single wavelength regime approaches. I will first highlight some of our recent work that finds most of the serendipitously discovered z > 4 broad-line AGN observed with JWST may be super-Eddington accretors. We find models of super-Eddington accretion can self-consistently explain the lack of X-ray, UV line, & rest-NIR flux exhibited in these sources – implying rampant BH growth in the early Universe. I will discuss how this sample, which includes some of the ''Little Red Dots'' are not heavily obscured. I will highlight our selection method of the most truly obscured early AGN via deep radio and JWST imaging in the COSMOS-Web field. I will present our full preliminary sample of the highest-redshift (z>4) obscured radio AGN with incoming JWST spectroscopy. We find a significant over-abundance of high-z radio sources relative to previous studies,and link these results to the high-z AGN candidates solely identified with JWST.

NOTES

MARTA VOLONTERI • REVIEW TALK

Modeling Massive Black Holes Across Cosmic Time

The formation and evolution of massive black holes and their interplay with host galaxies is a complex (astro)physical problem, in part because of the different physical and time-scales involved, in part because of the various physical processes at play. Over the last ~2 decades different theoretical approaches have been developed to model and understand massive black hole evolution. After a brief historical perspective, I will discuss how physical processes shape the demographics of massive black holes and their relation with galaxies in models, and the importance of selection effects when comparing theory with observations.

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MARTIN BOURNE

Simulating SMBHs: from Event Horizon to the Cosmic Web

Processes, from accretion and feedback production close to the black hole (BH) event horizon out to galactic scales on which feedback acts, span a vast dynamic range that is currently unfeasible to capture entirely in simulations. However, recent developments in numerical techniques mean that we are closer than ever to spanning the gap. I will present our latest results simulations performed with the moving-mesh code AREPO that leverage super-Lagrangian refinement (SLR) to enhance resolution around the BH, as well as novel models for accretion and high-resolution jet and wind launching that afford new opportunities to study BH physics and the multi-scale nature of feedback.

On small scales, this includes detailed modelling of binary BHs in gas-rich circumbinary discs. Thanks to SLR, we capture gas streams and minidiscs around individual BHs that contribute to torquing the binary. We additionally track BH spin evolution using our sub-grid accretion disc models, enabling predictions for spin alignment timescales and implications for recoil velocities and gravitational wave detectability by the future LISA mission.

On large scales, simulations of realistic galaxies and clusters incorporate high-resolution jets and winds injected close to the BH that propagate to and influence large scales. These unveil in unprecedented detail how AGN feedback and environment (including cluster weather and magnetic fields) interact and shape galaxy, group and cluster properties. By considering these intertwined factors, we can gain valuable insights into the nature of AGN feedback in realistic environments. I will conclude by discussing several key open questions and outlining future directions for research in this field.

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STEPHEN WILKINS

The FLARES View of Early AGN

A key question in our understanding of super-massive black holes (SMBHs) and active galactic nuclei (AGN) is how they first formed and how they subsequently impacted their hosts. This is one of the objectives of the First Light And Reionisation Epoch Simulations (FLARES), a novel suite of hydrodynamical cosmological zoom simulations. The FLARES strategy allows us to simulate much larger effective volumes than possible with traditional periodic box methods, making it ideal to study the formation and evolution of AGN in the distant Universe.

In this talk I will introduce insights from the first iteration of FLARES (FLARES-EAGLE). I will begin by exploring predictions for the physical properties of SMBHs, and their hosts. I will also discuss the impact of SMBHs on their hosts using insights gained through matched simulations entirely without AGN feedback, or other modelling changes.

Finally, I will introduce a new AGN emission model, combining disc, BLR, NLR, and torus components, incorporated into the open-source synthesizer synthetic observations pipeline. When coupled with FLARES or other simulations, this allows us to predict the rest-frame X-ray to far-IR emission, including line emission. This enables us to make direct comparison with observational surveys, avoiding the need for complex and poorly motivated completeness corrections.

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ALESSANDRO TRINCA

Shedding Light On The Early Rise Of Massive Black Holes with LISA and JWST

The advent of JWST has revolutionized our understanding of the high-redshift Universe, enabling the exploration of Active Galactic Nuclei (AGN) in unprecedented detail and extending observations to fainter and more distant objects. Early JWST campaigns uncovered an ubiquitous population of AGNs at z~5, with several extreme candidates identified up to z>10. Many of these AGNs are powered by black holes (BHs) that appear overmassive relative to their host galaxies, showing BH-to-stellar mass ratios orders of magnitude higher than those predicted by local scaling relations. This poses a significant challenge to current theoretical models of early galaxy evolution.

To investigate this emerging population of massive BHs, we combine the statistical power of the Cosmic Archaeology Tool, a semi-analytical model designed to reconstruct the co-evolution of the first galaxies and AGNs within a full cosmological framework, with the predictive capabilities of high-resolution hydrodynamical simulations of early BH growth. This enables us to explore different possible BH evolutionary pathways against JWST-detected AGNs to test whether their properties can already shed some light on the early rise of massive BHs. An early BH growth dominated by short, efficient phases of super-Eddington accretion, driven by the frequent dynamical interactions characterizing the first galaxies, might not only explain their overmassiveness but also provide a natural mechanism to realign these systems with the local population at later times.

However, the true nature of their initial seeds will be fully disclosed only with the next generation of gravitational wave (GW) telescopes. Therefore, we also explore how different formation and growth channels for BH seeds might influence the rates of merger events detectable by the Laser Interferometer Space Antenna (LISA), with the goal of probing the potential of future GW detectors to complement electromagnetic observations, offering a deeper understanding of the nature of the first BH seeds and their dominant growth mechanisms in the early Universe.

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RICARDA BECKMANN

The Evolving Spin of Massive Black Holes Across Cosmic Time

Astrophysical black holes are described by only two properties: their mass and their spin. While the black hole mass evolution has been the subject of many detailed studies, the spin of black holes is still comparatively little understood. Black hole spin shapes the long-term evolution of both the black hole and the galaxy, as it has important consequences for the mass growth efficiency of the black hole and the amount of energy that the host galaxy of the black hole is subject to. Spin evolves through gas accretion and through black hole - black hole mergers. In this talk, I will share insights into the long-term spin evolution of massive black holes as their host galaxies form and evolve, modelled on-the-fly using the NewHorizon simulation.

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MICHAELA HIRSCHMANN

The Art of Modelling Broad-Line and Narrow-Line Emission of AGN in Simulated, High-Redshift Galaxies

First JWST results revealed a growing population of faint, low-mass AGN at early cosmic epochs. However, identifying AGN, especially type-2, and estimating properties such as accretion rates and Eddington ratios for both type-1 and type-2 AGN from high-redshift galaxy spectra remains challenging. To address these issues, we developed novel, comprehensive grids of thousands of AGN photo-ionization models, covering both broad-line and narrow-line emission, considering the most recent incident AGN ionizing spectra, dependent on BH mass and Eddington ratio. These model grids are integrated into simulated galaxies from our new high-resolution, high-redshift cosmological zoom simulations (including updated models for BH accretion and winds) as well as the SantaCruz SAM and IllustrisTNG, making geometrical assumptions on the viewing angle to include broad emission lines and continuum emission. We revisit optical and UV emission-line diagnostics for both type-1 and type-2 AGN, presenting new criteria for identifying type-2 AGN, and novel tracers for BH accretion rates, Eddington-ratios, BH accretion-to-star formation rate ratios and gas metallicities in the vicinity of the BH. Comparisons with type-1 and type-2 AGN from JWST (applying the same selection criteria in simulations) indicate that simulations tend to underestimate type-2 AGN fractions and type-1 AGN number densities, likely due to insufficient gas accretion onto BHs at high redshift in current models. Finally, we outline future applications to JWST data and prospects for refining BH models in simulations.

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ALESSANDRO MARCONI

Probing Black Hole-Galaxy Co-Evolution with HOMERUN: From Broad-Line Regions to Ionized Outflows

We present HOMERUN, a cutting-edge photoionization modeling framework designed to accurately characterize the physical properties of ionized gas in active galactic nuclei across a wide wavelength range. HOMERUN enables us to simultaneously reproduce within 10% many emission lines in the spectra of photoionized nebulae, facilitating precise determinations of their metallicity, average density, and ionization parameter.

HOMERUN's unique approach allows for high-fidelity determinations of the BLR metallicity, revealing supersolar values ranging from 1 to 3 solar – significantly lower than previous estimates based on previous photoionization models. Furthermore, our refined estimates of BLR sizes, derived from emission-line modeling, provide a crucial new test of the radius-luminosity relation, clarifying discrepancies raised by recent near-infrared interferometric measurements. This allows for more secure determinations of black hole masses through virial relations.

Beyond the BLR, HOMERUN can model NLR emission from the ultraviolet to mid-infrared regimes, enabling the determination of gas metallicity in AGN-dominated spectra—a challenging task so far. This allows us to test how AGN host galaxies compare to well-known metallicity scaling relations. Furthermore, recent results from our VLT/MAGNUM and JWST/MIRACLE programs, demonstrate how HOMERUN can further aid in measuring ionized gas masses of the outflowing gas. These measurements are pivotal for constraining outflow energetics—a key component in understanding AGN-driven feedback and its role in shaping galaxy evolution.

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SOPHIE KOUDMANI

A Multi-Scale Exploration of Supermassive Black Holes in the Early Universe

Major progress has been made by JWST in uncovering early supermassive black holes, pushing to much lower luminosities and higher redshifts. Intriguingly, this includes a sample of overmassive black holes (compared to the local scaling relations) which may have a significant impact on the baryon cycle of their host galaxies. I will present a novel set of large volume cosmological simulations testing different seed masses and AGN accretion prescriptions, with a special focus on the evolution of early black holes. The efficiency of high-redshift black hole growth heavily depends on the seeding and accretion models assumed, with the widely employed Bondi accretion model suppressing the growth of light seeds. This demonstrates the importance of incorporating as realistic black hole accretion and feedback models as possible and I will present some first results from cosmological zoom-in simulations based on a novel accretion-disc-based AGN model derived from GR(R)MHD simulations with a focus on breaking the degeneracies between black hole activity and seeding.

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ANDREA MERLONI • REVIEW TALK

Black Holes Demographics: Constraints from X-ray and Radio Surveys

TBC

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RAGADEEPIKA PUCHA

Tripling the Census of Dwarf AGN Candidates Using DESI Early Data

The coevolution of galaxies and their central black holes is commonly explored via scaling relations and by examining the impact of AGN feedback on various galaxy properties. While this interdependence is well-studied in massive galaxies, its extension to low-mass galaxies remains unclear. The DESI (Dark Energy Spectroscopic Instrument) survey offers a unique opportunity for this investigation, with deeper spectra, higher spectral resolution, and a larger sample of targets extending to fainter magnitudes compared to prior spectroscopic surveys. In this talk, I will present results from early DESI data, where we identified ~2,500 AGN candidates in ~115,000 low-redshift ($z \leq 0.45$) dwarf galaxies ($\log M^*/M_\odot \leq 9.5$) using optical emission line diagnostics. This represents the largest sample of dwarf AGN candidates to date, more than tripling the existing census and providing a robust statistical sample for probing feedback mechanisms in dwarf galaxies. I will discuss our black hole mass estimates using single-epoch virial techniques and the extension of M_{BH} - M^* scaling relation down to $\log (M^*/M_\odot) \sim 8.5$. Additionally, we investigated the energetics of both AGN and stellar feedback in these systems by analyzing [OIII] outflows, where available. I will compare the two feedback processes and discuss how they depend on various stellar properties such as stellar mass, star formation rate, specific star formation rate, etc. Our results place important constraints on the role of AGN feedback in regulating star formation in dwarf galaxies and offer new insights into galaxy-black hole co-evolution at the low-mass end of the galaxy mass function.

NOTES

JAN SCHOLTZ

Role of AGN in Galaxy Evolution in z~3-11 with Deep NIRSpec Spectroscopy

With the recent discovery of quiescent galaxies at z>3, identifying typical moderate AGNs at high redshift became more important than ever, as they are necessary to explain the ever-growing population of high-z quiescent galaxies. As typical selection techniques such as X-ray and radio observations are not sensitive enough to detect typical AGN population at high redshifts (z>3), we need to rely on optical and UV emission lines, not accessible to astronomers at these redshifts until the launch of JWST. However, typical selection techniques using optical emission lines (such as BPT diagram), fail to reliably select AGN due to low metallicities of galaxies at high redshift, hence the need to revisit AGN selection. In this talk, I will present the results from the JWST Advanced Galactic Survey (JADES) and its deep NIRSpec/MSA observations of ~6000 galaxies between z~3-11. I will describe the selection of AGN host galaxies at high-z using these emission lines, to reliably distinguish between star-forming and AGN host galaxies. Using this unique state-of-the-art dataset, I will present the first characterisation of moderate luminosity AGN, and its impact on their hosts, including the first evidence of cumulative AGN feedback in a z=3 quiescent galaxy. Lastly, I will present the analysis of deep JWST/NIRSpec observations of GSz-11.2, a candidate for the most distant black hole up to date and its constraints on seeding the first black holes in the Universe.

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COLIN BURKE

Constraints on the Local Black Hole Occupation Fraction

The fraction of dwarf galaxies hosting central, intermediate-mass black holes (IMBHs) at low redshifts is an important observational probe of black hole seeding at high redshift. Detections of nuclear accretion signatures in dwarf galaxies provides strong evidence for the presence of these IMBHs. In this talk, I will describe a new Bayesian method to infer the black hole occupation fraction and Eddington ratio distribution function. Our approach accounts for non-detections, incompleteness, and contamination from star-forming-related emission. We apply this model to galaxies with X-ray data from the Chandra Source Catalog at distances <50 Mpc, radio data from the VLA Sky Survey at <50 Mpc, and optical variability data from the Palomar Transient Factory at z<0.055. We find a black hole occupation fraction of at least 90 percent at stellar masses of 10^8 $M_\odot$ and at least 39 percent at 10^7 $M_\odot$ (95\% confidence intervals). I will show the resulting black hole mass function. These constraints on the IMBH population have implications for the Laser Interferometer Space Antenna (LISA) mission and for cosmological models of black hole seeding and growth. We also constrain the extremely low luminosity end of the AGN luminosity functions at z=0. Our AGN luminosity functions are broadly consistent with an extrapolation of the shallow slope of the AGN luminosity functions from previous work.

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GIOVANNI MAZZOLARI

AGN Under the Eye of JWST: New Selection Techniques and Physical Properties

In this talk, I will present key results on the selection of high-redshift AGN and their peculiar properties. Specifically, I will introduce three new narrow-line AGN diagnostic diagrams, leveraging the [OIII]4363 auroral line, which has been detected in several JWST spectra. These diagnostics effectively differentiate much of the AGN population from Star-Forming Galaxies (SFGs) and have proven capable of selecting AGN at z>6, where traditional narrow-line AGN (NLAGN) diagnostic diagrams fail due to the different conditions of AGN host galaxies.

For the first time, I applied these new AGN diagnostics in the spectroscopic selection of NLAGN among the ~ 300 publicly available medium-resolution spectra of the CEERS survey, identifying 52 NLAGN up to z~9. I conducted a detailed multiwavelength analysis of these sources, and I will present the main findings. Notably, given the availability of deep X-ray observations for this field, I investigated the X-ray properties of the selected NLAGN. I found that all but four NLAGN are undetected in the deep X-ray image, as well as all the high-redshift BLAGN previously selected in the literature from the same survey. Even stacking the undetected sources did not result in a detection, revealing an X-ray weakness of 1-2 dex compared to what is expected based on their bolometric luminosities.

Lastly, I will present the radio analysis of ~20 broad-line AGN selected with JWST showing indications of radio weakness. Investigating the radio emission of these sources is crucial for distinguishing between the heavily obscured AGN scenario and intrinsic X-ray weakness as the cause of the observed X-ray deficiency in these sources.

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MASAFUSA ONOUE

Probing the Demographics of Supermassive Black Holes and Their Host Galaxies at z=6

One of the highlights of early JWST observations is the detection of stellar emission from quasar host galaxies at high redshift, which was previously only possible down to z=2. Direct constraints on the stellar contents of the hosts now allow us to investigate how the early growth history of supermassive black holes (SMBHs) relates to that of their host galaxies over cosmic time. In this talk, we present our NIRCam imaging and NIRSpec Fixed-Slit observations of 12 intermediate-luminosity quasars at z=6, originally discovered by the Subaru Hyper Suprime-Cam Subaru Strategic Program. These quasars, with bolometric luminosities log L_bol [/(erg s-1)]= 46-47, fall in between the most luminous quasars and much fainter JWST-detected AGN, thus bridging the luminosity gap. Through our imaging decomposition analysis of the NIRCam images, we detected spatially extended host galaxy emission in the majority of the sample, with inferred stellar masses of log $M_* / M_\odot \sim 10.5$. The high success rate is due to the relatively high contrast of host emission compared to quasar light in our targets. Surprisingly, two of the brightest hosts exhibit stellar absorption lines in the NIRSpec rest-optical spectra. One of them, J2236+0032, even shows a clear photometric break at the Balmer limit and a lack of spatially extended H-alpha emission. A dedicated analysis reveals that their sizes are relatively compact among our sample (effective radius 0.6-1 kpc), and their stellar populations have ages of a few hundred Myr, transitioning into a quiescent phase. We further discuss these stellar properties in the context of their dynamical properties revealed by our ALMA observations of the same sample. We conclude by discussing the observed BH-to-stellar mass ratios, which are less extreme than those for other high-redshift quasars and JWST AGN.

NOTES

IGNACIO DEL MORAL-CASTRO

Dual AGN in Galaxy Mergers: Unveiling Black Hole Growth and Feedback

Galaxy mergers play a crucial role in the growth of supermassive black holes (SMBHs) and the evolution of their host galaxies. A natural consequence of this process is the formation of dual AGN, where both SMBHs accrete simultaneously at nuclear separations <10 kpc. These events represent a transient yet transformative stage, characterized by rapid SMBH accretion, intense star formation, and powerful feedback effects. Despite extensive searches, the fraction of dual AGN remains poorly constrained due to observational challenges such as obscuration and spatial resolution limitations.

In this talk, I will present a novel approach to identifying and characterizing dual AGN using high-spatial-resolution multiwavelength data. Specifically, I will discuss results from our ongoing studies combining narrow field mode (NFM) MUSE optical Integral Field Unit (IFU) spectroscopy and ALMA observations for dual AGN at z<0.1 with nuclear separations <1 kpc. These studies allow us to understand the complex connection between black hole growth and galaxy evolution, shedding light on inflow and outflow kinematics, merger-driven star formation, and the impact of AGN feedback.

Finally, I will introduce our MUSE Legacy Survey of Luminous Nearby Dual AGN in Mergers, a groundbreaking volume-limited survey. This program enables the first systematic study of AGN in mergers across a broad range of separations and luminosities (and hence black hole accretion rates). Covering a wide range of merger stages is essential for rigorously testing theoretical models in terms of SMBH mass, AGN activity, host gas content, morphology, and merger mass ratios. It will be the most comprehensive dataset to date, establishing a critical benchmark for understanding the role of galaxy mergers in SMBH–galaxy coevolution and the assembly of massive galaxies over cosmic time, providing key observational constraints for interpreting dual AGN populations at higher redshifts with JWST.

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SOPHIA GERIS

Exploring the Presence of Accreting Black Holes in the Early Universe via JWST Stacking

Observations of massive black holes in the early universe are revolutionising our understanding of galaxy evolution across cosmic time with cutting edge surveys like JADES, CEERS and many others. Their unprecedented depth has uncovered a population of both type 1 and 2 AGN at high redshifts (out to $z \sim 11$), through deep NIRSpec MSA spectroscopy. However, standard emission line diagnostics such as BPT or VO87 are insensitive to AGN at $z>3$ due to the decrease in metallicity of galaxies and lack of detection of high ionisation lines such as He IIλ4686Å, [Ne V] λ3427Å , etc, which are too faint to detect in individual observations. In this talk, I will present our effort to expand these diagnostics through stacking of thousands of galaxies in the JADES survey at $z>3$, in order to detect these faint lines and investigate the presence of any subtle broad lines around Hα indicating AGN activity. I will further discuss the evolution of the narrow line diagnostics with redshift and its effect on the selection of type-2 AGN. I will present BPT and SII- and OI-VO87 diagrams of the stacked spectra, revealing spectral features that may have been hidden in previously studied diagrams of the individual spectra. These stacks of JADES spectra have allowed an evaluation of the high redshift AGN census and have provided novel insights into the average emission line properties of high redshift galaxies.

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TIAGO COSTA • REVIEW TALK

AGN Feedback: Mechanisms, Modes, Models & Misconceptions

I will start by revisiting the original arguments laid out for the need of AGN feedback in the light of today's theoretical understanding of galaxy evolution. I will describe advances in our grasp of the various physical mechanisms through which such feedback comes about, including momentum- and energy-driving, jets, winds and radiation pressure and how they might couple the properties of supermassive black holes to those of their host galaxies. I will illustrate how these early ideas have been reshaped by new sophisticated cosmological simulations and the increasingly detailed models of AGN feedback that have emerged over the last decade. Backed by results from these simulations and new observations of AGN outflows, I will (i) make the case for "energy-driven" winds as the main AGN feedback mechanism, (ii) revisit the division of AGN feedback into radio- and quasar "modes" and (iii) illustrate how AGN feedback operates over a range of timescales, with the window for rapid "blow-out" episodes as the chief star formation suppressant narrowing. An updated catalogue of predicted imprints of AGN activity on galaxy and black hole properties will be presented, with emphasis placed on newly-unveiled feedback effects, such as the impact of AGN on galaxy morphology, and the state of the interstellar- and circum-galactic media. Finally, I will reflect on the progress made in the last decade in constraining theory with observations, discussing the pitfalls of this exercise and highlighting the new questions about the role of AGN in galaxy evolution this work has begun to generate.

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NICHOLAS CHOUSTIKOV

The Impact of Radiation-and MHD-Coupled Blandford-Znajek Jets on the ISMs of High-Redshift Galaxies

Ever since the advent of JWST, novel observational results have been pointing to the likely presence of a large number of massive black holes at high-redshift. Many of these have been identified by their unique spectroscopic signatures, such as broad Balmer lines as well as the appearance of high-ionization state lines in star-forming galaxies, or the intriguing UV-optical continuum of little red dots. While the masses inferred by these diagnostics suggest the need for exciting novel physics such as super-Eddington accretion, it is first vital to understand the effect that AGN feedback and radiation has on the state of the ISM. This is especially true in the extreme, merger-rich, and high-density regime inhabited by high-redshift galaxies. Once charted, this understanding will allow us to trace these properties through to the direct observables that JWST is measuring.

To this end, I will present a novel sub-grid black-hole/AGN model for high-resolution cosmological radiation magnetohydrodynamical galaxy formation simulations which feature live non-equilibrium chemical evolution. This model focuses on the evolution of a thin alpha-disc, which self-consistently drives the formation of a Blandford-Znajek jet, itself completely coupled to the black hole's local magnetic and radiation environment. Specifically, disc properties, accretion rates, and jet powers are all determined by the magnetic properties of accreted gas. In turn, each of these will also drive the production and release of radiation which is captured by on-the-fly radiative transfer. Along with discussing the model, I will present first results from zoom simulations, investigating the production of ionization cones and narrow line regions around the AGN at high-redshift, discussing the impacts on diagnostic tests such as line ratio diagrams.

NOTES

FRANCESCO BOLLATI

The Impact of AGN Feedback and Spin on the Evolution of Massive Black Hole Binaries

AGN feedback is a key regulator of massive black hole (MBH) growth and evolution, yet its impact on MBH binaries remains poorly understood. I present a numerical model of AGN radiative feedback that incorporates the often-overlooked but crucial effects of black hole spin. Spin significantly alters the intensity and anisotropy of AGN emission, affecting the coupling of radiation-driven AGN winds to the surrounding environment and influencing MBH accretion and dynamics. Using a suite of 3D simulations, I explore the (sub-)parsec scale evolution of MBH binaries embedded in circumbinary disks (CBDs), focusing on (i) how AGN feedback reshapes CBD structure and regulates the MBHs growth, (ii) the impact of spin-dependent AGN feedback on MBH migration and merger timescales, and (iii) the co-evolution of MBH masses and spins, which plays a crucial role in setting recoil kicks and determining MBH occupation fractions across cosmic time. These results provide new insights into the small-scale environments of merging MBHs, linking AGN-driven feedback to the long-term evolution of the MBH population.

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DANIEL ANGLÉS-ALCÁZAR

Investigating Black Hole Accretion and Feedback Self-Regulation in Seyfert Galaxies using the FIRE-3 Cosmological Hydrodynamic Simulations

Recent observations of Seyfert galaxies in the local Universe show an intriguing connection between Active Galactic Nuclei (AGN) luminosity and a deficit of molecular gas on ~50 pc scales, the plausible imprint of AGN feedback impacting galactic nuclei. Motivated by these findings, we investigate the relationship between black hole accretion, AGN feedback, and nuclear gas reservoir in high-resolution cosmological hydrodynamic simulations from the Feedback In Realistic Environments (FIRE) project. Our simulations implement FIRE-3 multi-phase interstellar medium physics and multi-component black hole accretion and feedback. Focusing on the late-time evolution of four Milky Way-mass galaxies, we show that they experience repeated AGN fueling and feedback episodes with a range of X-ray luminosities and nuclear gas surface densities similar to observed Seyfert galaxies. AGN winds interact with the ISM and escape preferentially through low-density channels along the polar direction after opening a central cavity on ~10–500 pc scales. Higher luminosity AGN are more common in simulated galaxies during fueling-dominated phases, with centrally-peaked gas density profiles, but also occur in feedback-dominated phases when the accretion disk reservoir can power a luminous AGN while black hole feedback evacuates gas from the nuclear region. The prevalence of central cavities in higher luminosity Seyfert galaxies provides strong constraints on the characteristic time and spatial scales of AGN feedback self-regulation. We discuss the limitations of current state-of-the-art subgrid models and the prospects of new hyper-refinement simulations that can self-consistently model AGN fueling and feedback at sub-pc resolution.

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LUCAS TORTORA

Radiative Feedback of Super-Eddington QSOs at High Redshift in the JWST Era

The discovery of gargantuan black holes (BHs) with masses in excess of 10^9 Msun at z >~ 6, confirmed by JWST observations, suggests extremely rapid BH growth and significant energy input into their host galaxies in the early Universe. As observations continue to probe these objects at higher and higher redshifts, developing a robust theoretical framework for their formation and impact is crucial. In our work, we use high-resolution zoom-in simulations of a massive protocluster at z ~ 6, employing both the fiducial FABLE galaxy formation model and a set of modifications to allow earlier seeding and super-Eddington accretion. These simulations have been shown to reproduce the most extreme QSOs known in the early Universe. We post-process the simulations to generate mock observations of key physical properties and compare our predictions with the latest JWST data. Specifically, we perform full radiative transfer calculations with a novel and accurate ray-tracing code to assess the effects of the QSO radiation field on the environment during super-Eddington accretion phases.

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EUN-JIN SHIN

Modeling Black Hole Accretion Through an α-disc with a Resolved Interstellar Medium in Dwarf Galaxies

While there is a mounting observational evidence that feedback from intermediate mass black holes (IMBHs) may be important in shaping the properties of dwarf galaxies both at high redshifts and in the local Universe, our theoretical understanding of how these black holes grow in mass is largely incomplete. To address this issue, here we perform high-resolution simulations of an isolated dwarf galaxy with a virial mass of 10^{10} M⊙ harbouring a 10^4 M⊙ IMBH at its centre. The dwarf galaxy is embedded within a circumgalactic medium (CGM) and to simulate a realistic interstellar medium (ISM), we incorporate explicit sampling of stars from the IMF, photo-ionization feedback, and the modeling of H_{II} regions. Additionally, we account for photoelectric heating from a spatially varying far-ultraviolet field and include supernova feedback. Our simulation setups consider dwarf galaxy models both with and without nuclear star clusters (NSCs), spanning a range of effective radii. Furthermore, our approach employs a sub-grid Shakura-Sunyaev accretion disc model to accurately simulate the evolution of BH mass and spin.

Using super-Lagrangian refinement techniques, we resolve spatial scales up to 0.01 pc, resolving the self-gravitating radius of the accretion disc, which allows us to accurately measure the mass and angular momentum transfer to the IMBH. We find that the gravitational potential of the NSC captures the ISM gas and forms a circumnuclear disk (CND) with a radius of 7 pc, while simultaneously, gravitational torques from the NSC effectively reduce its angular momentum on parsec to subparsec scale, circularizing it onto the α accretion disc and promoting IMBH accretion. We further investigate star formation and the stellar IMF in the vicinity of the IMBH. In the innermost regions (<0.5 pc), star formation is highly suppressed. However, at distances of approximately 1-7pc from the center, the gas remains locally susceptible to fragmentation, leading to the formation of massive, young stars. The feedback from these stars has the potential to completely disperse the CND and cut off the gas supply to the IMBH. Interestingly, despite a supernova rate of 0.7 Myr^{-1}, the dense CNDs persist, sustaining BH accretion stably for over 140 Myr. Our study demonstrates the complexity of IMBH accretion once the resolved ISM is taken into account and paves the way to next-generation studies where feedback processes from IMBH itself will be considered.

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RAINER WEINBERGER

Quantifying the Uncertainties of Massive Black Hole Models in Cosmological Galaxy Formation Simulations

Massive black holes (MBHs) are an essential ingredient of modern cosmological galaxy formation simulations. Feedback powered by MBHs proves to be essential to reproduce the low star formation rates of quiescent elliptical galaxies and the intra-cluster medium properties of cool-core galaxy clusters. While many cosmological simulations have managed to come up with models to produce realistic simulated galaxy populations, their models differ substantially in the MBH modeling and consequently in the black hole growth history. In this talk, I will present a series of cosmological simulations varying the MBH related models, notably the accretion model, feedback prescription and seeding criteria and discuss the uncertainties in these models once they are recalibrated to key observational constrains. I will show the key role of AGN feedback not just for galaxy evolution, but also for MBH growth, while even drastic changes in the accretion formula only have moderate impacts on supermassive black holes. The high redshift growth of potential intermediate mass black holes, however, is dramatically changed depending on accretion model. Finally, I will discuss the implications of these findings for future electromagnetic and gravitational wave detections of IMBHs.

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CRISTINA RAMOS-ALMEIDA • REVIEW TALK

Observational Signatures of Feedback from Massive Black Holes

TBC

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MANDA BANERJI

Evidence for Depleted Gas Reservoirs in a Large Sample of ~40 UV-Luminous Type 1 Quasars at z=2

I will present ALMA CO observations of warm molecular gas in a large, statistical sample of ~40 high-redshift UV-luminous quasars at cosmic noon (z~1-3). All quasars have full rest-UV to optical spectral coverage allowing us to study correlations between the molecular gas content and outflows in the quasar broad-line region (BLR; e.g. CIV) and narrow-line region (NLR; e.g. [OIII]).

We find that, regardless of accretion or outflow properties, UV-luminous quasars exhibit depleted molecular gas reservoirs compared to the main-sequence of star-forming galaxies at these redshifts. We find tentative evidence that quasars with strong BLR winds have higher gas fractions and no difference in molecular gas properties between broad absorption line (BAL) and non-BAL quasars. The gas fractions in UV-bright quasars are on average lower than those seen in obscured quasar populations at similar redshifts and luminosities. Our results support an evolutionary scenario in which UV-luminous quasars represent a late stage in massive galaxy evolution, following the clearing of molecular gas by strong outflows in earlier, dust-obscured phases.

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DARSHAN KAKKAD

Outflow Coupling Efficiency in AGN Host Galaxies Across Cosmic Time: Insights From IFU Surveys

TBC

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CHRISTINA EILERS

Using Lyman-Alpha Tomography to Map Ionized Bubbles around Luminous Quasars

The ultraviolet radiation of luminous high-redshift quasars within the Epoch of Reionization carves out large bubbles of highly ionized intergalactic gas in the quasars' environments, making the otherwise opaque Lyman-alpha forest highly transparent at redshifts near the quasar. I will present the first results from the JWST MASQUERADE program, which leverages some of the deepest NIRSpec/MSA observations to date of galaxies in the background and environment of luminous quasars at $z>6$ to tomographically map the quasars' ionized bubbles. The extents of these bubbles provide model-independent constraints on the quasars' ages based on the light travel time, enabling new insights on the puzzle of the early growth of supermassive black holes. Simultaneously, the quasars' highly ionized regions provide a unique laboratory to study the intrinsic ionizing properties and unattenuated line profiles of high-redshift galaxies without absorption by the neutral intergalactic medium to reveal the elusive protagonists that reionize the universe.

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MATILDE BRAZZINI

A Tale of Emission and Absorption: Decoding Black-Hole Driven Outflows In z>5 Quasars Through Multiple Tracers

Outflows from active galactic nuclei are invoked as the principal feedback process regulating the co-evolution of supermassive black holes and their host galaxies. However, their complex, multi-phase and multi-scale nature demands a comprehensive approach that integrates multiple tracers to fully uncover their physical properties. Connecting these different outflow features remains a major challenge in Astrophysics. In this presentation, I will provide a complete characterization of outflows in a sample of high-redshift quasars, by exploiting the combined power of both emission and absorption diagnostics. Focusing on the z=5–7 redshift range, my intent is to unravel the early feedback mechanisms shaping the (post-) Reionization Universe, where these processes are expected to be particularly intense and efficient. In order to achieve this, I will analyze state-of-the-art samples of quasar spectra at these early cosmic epochs, integrating observations from X-Shooter and ALMA. I will address the complex relation between diverse outflow tracers, and investigate their driving mechanisms. In particular, I will focus on the link between nuclear winds, traced through asymmetric and blue-shifted profiles of UV emission lines, and strong absorption features, either broad and narrow, that appear to be ubiquitous in quasar spectra: how confidently can we assert whether these processes are, or are not, manifestations of the same phenomenon?

Among my initial findings is the discovery of a correlation between ionized winds observed in emission and in both broad and narrow absorption, suggesting that, while the physical mechanisms powering the two outflow phenomena may differ, a strong correlation exists between them. Further investigation promises deeper insights into these feedback mechanisms and their role in shaping the Universe, from distant and remote cosmic epochs to the cosmos as we observe today.

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HELEN RUSSELL

Quasar Feedback in Massive Galaxies

The impact of quasar feedback on galaxy and cluster hot atmospheres is still largely unknown. This is principally due to a lack of low-redshift analogues for which we can spatially resolve the quasar's immediate environment. I will present results from a new large Chandra program on H1821+643, which is the nearest quasar hosted by a central cluster galaxy. The hot atmosphere of this massive galaxy captures the energy output by the quasar, in the form of intense radiation and radio jets. Using detailed simulations to subtract the quasar light, I show that, within 10 kpc of the quasar, the gas temperature drops precipitously to <0.4keV and the density increases by over an order of magnitude. The radiative cooling time of the gas falls to only 12 +/- 1Myr, below the free fall time, and we resolve the sonic radius of a cooling flow. The quasar is photoionizing and Compton cooling the surrounding gas on kpc scales and the enhanced gas cooling of 3000 solar masses per year can easily supply the required accretion rate and the observed high star formation rate. Looking to the future, I will also discuss the future of high spatial resolution X-ray observations with the AXIS observatory, which was recently selected by NASA for phase A development. AXIS will reveal the seeds of supermassive black holes, the subsequent rise of stellar and black hole feedback as drivers of galaxy evolution, and the nature of explosive transients.

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ANDREW CHAEL

Black Hole Mass and Spin from Horizon-Scale Images

The Event Horizon Telescope (EHT) is a Very-Long-Baseline Interferometry (VLBI) network of millimeter-wavelength radio telescopes that spans the globe from Greenland to the South Pole. The EHT has imaged event-horizon scale structure in two low-luminosity AGN (LLAGN); in the giant elliptical galaxy M87, and in the Galactic Center black hole Sgr A*. In this talk, I will discuss how black hole masses and spins can be measured with horizon-scale observations from the EHT and future VLBI observatories. The size of the horizon-scale image in both M87* and Sgr A* is a direct probe of the black hole mass, with the EHT image of M87* indicating a 6.5 billion solar mass BH. I will show how analytic models and General Relativistic Magnetohydrodynamic (GRMHD) simulations of black hole accretion reveal the precise relationship between black hole mass and image size, and how ongoing multi-epoch and multi-frequency observations with the EHT will lead to more precise black hole mass measurements in M87. Furthermore, polarized EHT images probe near-horizon magnetic fields and strongly suggest that the accretion disks in both M87* and Sgr A* are magnetically arrested. I will show how polarized images on multiple scales can be used to probe energy outflow from the black hole and allow for precise measurements of black hole spin. Finally, I will briefly discuss how the proposed Black Hole Explorer (BHEX) space VLBI mission will open a new window for constraining the BH mass, spin, and jet launching mechanism in a larger sample of LLAGN and extragalactic jet sources at horizon-scale resolution.

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AVISHAI DEKEL

Growth of Massive Black Holes in FFB Galaxies at Cosmic Dawn

Excessively bright galaxies, as observed by JWST at cosmic dawn, are explained by a physical model, which predicts high star-formation efficiency due to feedback-free starbursts (FFB) in thousands of star clusters within compact galactic disks. I will discuss how the FFB scenario may provide a natural setting for black hole (BH) growth. The multi-stage process involves the formation of intermediate-mass seed BHs by sped-up core collapse in the young, rotat- ing FFB star-clusters, followed by their dynamical-friction-driven migration to the galaxy disk centers, and ending with the growth of super-massive BHs (SMBH) by mergers that overcome the bottleneck introduced by gravitational-wave recoils. The resultant SMBHs, with high BH- to-stellar mass ratios and low AGN activity, are consistent with the observed population at z=4-7. The key for efficient BH growth in the different stages of the scenario is cold, compact, rotating, FFB disk configurations at cosmic dawn. I will discuss how this scenario predicts massive quiescent galaxies at z~4-7, and a large population of high-z globular clusters, as indicated by JWST observations.

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ALBERTO SESANA - REVIEW TALK

Learning about Massive Black Holes with Gravitational Waves

While ground based interferometers continue to amass detections of merging stellar binaries, the scientific community is also looking into expanding our capability to detect gravitational waves (GWs) at lower frequencies, where massive black hole binaries (MBHBs) are expected to be the loudest sources. In particular, the milliHz and nanoHz frequency bands are targeted by the spaceborne Laser Interferometer Space Antenna (LISA) and by pulsar timing arrays (PTAs) respectively. I will describe the potential of LISA and PTAs to unveil the cosmic population of MBHBs. I will discuss the recent PTA results and their implications and describe the scientific prospects of LISA.

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STEPHANIE BUTTIGIEG

Fact or FABLE: Predictions for SMBH Merger Rates from Cosmological Simulations

The co-evolution of massive black holes and their host galaxies is well established within ΛCDM cosmology. The repeated mergers, accretion, and feedback that conspire to regulate this process can be studied in large-scale cosmological simulations, such as Illustris, FABLE, MillenniumTNG and Flamingo. These simulations resolve key galaxy formation processes at ~kpc scales, but are plagued with numerical inaccuracies at the smaller scales of black holes. This scale discrepancy presents significant challenges for investigating black hole properties and generating testable predictions, e.g. for future JWST, Gaia, LISA and IPTA observations of isolated and binary black holes. In this talk I will discuss the black hole population in FABLE. Our results show that the numerical treatment of black holes in cosmological simulations leads to a misleading picture, even at the well-resolved large scale of galaxies. In particular, a large fraction of black holes coalesce well before their host galaxies merge and thus require extra delays on the order of a few Gyrs. These delays, governed by the dynamical timescale of the merging host galaxies, occur before and in addition to any delays arising from unresolved 'sub-grid' physics describing BH hardening mechanisms on parsec scales. This effect has profound implications for the black hole merger rates predicted from these large-scale cosmological simulations as well as for the multi-messenger predictions, once black hole growth during these dynamical galaxy merger delays is accounted for.

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PETER JOHANSSON

Modelling the Mergers of Supermassive Black Holes and their Gravitational Wave Emission in Cosmological Simulations

Traditional numerical simulations employing gravitational softening are unable to resolve the small-scale dynamics and gravitational wave emission from supermassive black hole binaries. Instead, the parsec-scale dynamics is typically modelled by post-processing the simulations using either semi-analytic methods based on orbit-averaged equations or resimulating the core regions of the merged galaxies using a separate N-body code.

An alternative is to use a hybrid approach, such as the KETJU code, recently developed in our group. The KETJU code includes algorithmically regularised regions around every supermassive black hole (SMBH) and post-Newtonian terms in the equations of motion of the SMBHs. This approach allows for simultaneously following global galactic-scale dynamical and astrophysical processes while accurately solving the dynamics of SMBHs at sub-parsec scales and directly calculating the expected gravitational wave signal. We demonstrate how the KETJU code can be used to resolve the dynamics and mergers of supermassive black holes down to sub-parsec scales in cosmological simulations.

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YOHAN DUBOIS

Tracking On-The-Fly Massive Black Hole Binary Evolution and Coalescence in Galaxy Simulations: RAMCOAL

Gravitational wave (GW) emission from massive black hole binary (MBHB) coalescence plays a crucial role in shaping black hole evolution and influencing galactic dynamics. We present RAMCOAL, a novel sub-grid model integrated into the RAMSES code that simulates MBHB orbital evolution within hydrodynamical galaxy simulations. RAMCOAL accounts for key physical processes such as stellar and gaseous dynamical friction, stellar scattering, circumbinary disk interactions, and GW emission at scales below the simulation resolution. By tracking MBHB dynamics in real time using local quantities, RAMCOAL enables accurate predictions of GW signals, black hole merger rates, and electromagnetic counterparts. We validate the model across isolated and merging galaxy setups, demonstrating its robustness across different resolutions and environments. Additionally, we also investigate the effects of GW recoil following MBH mergers by performing high-resolution cosmological simulations that self-consistently evolve MBH spins and masses. Comparing simulations with and without GW recoil, we find that recoil significantly influences MBH growth, merger rates, and MBH-galaxy correlations. Recoiling MBHs can escape their host galaxies, remain as wandering MBHs, or dynamically interact with their surroundings, depending on the recoil velocity relative to the escape speed.

Our findings emphasize the necessity of incorporating both MBHB orbital evolution and GW recoil into cosmological models to achieve a more comprehensive understanding of MBH assembly, GW backgrounds, and their observational signatures.

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LAURA BLECHA

Constraining Low-Frequency Gravitational-Wave Source Populations with Cosmological Simulations

The strong evidence for a stochastic, low-frequency gravitational wave (GW) background presented by pulsar timing arrays (PTAs) represents a breakthrough in our view of massive black hole (MBH) binary evolution. This signal, consistent with theoretical predictions for a cosmic MBH binary population, provides the first compelling evidence that these systems successfully overcome the final parsec problem and merge. The upcoming Laser Interferometer Space Antenna (LISA) will be able to detect lower-mass MBH mergers out to z ~ 20, thereby probing the poorly understood origins of MBHs, and JWST is also opening a new window into this regime as it uncovers high-redshift accreting MBH candidates at a rapid pace. These groundbreaking discoveries must be accompanied by robust theoretical models in order to disentangle various MBH seeding and growth channels using GW and EM observations. I will describe our recent work to model MBH formation, growth, and dynamics in galactic-scale and cosmological hydrodynamics simulations, including a novel prescription for representing the descendants of low-mass MBH seeds in large-volume simulations, as well as models for binary and triple dynamics. I will discuss the implications for our understanding of MBH evolution across cosmic time in this new era of low-frequency GW astrophysics.

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Massive Black Holes across Cosmic Time
at the Kavli Institute for Cosmology, Cambridge
https://sites.google.com/cam.ac.uk/mbh2025