2022 Spring Symposium

Galaxy Clusters 2022:
Challenging Our Cosmological Perspectives

April 25–29, 2022 | 10:00 AM - 4:30 PM EDT | VIRTUAL
Galaxy clusters are the densest galaxy environments in the Universe and provide us with important insights into many fundamental astrophysical processes. They are essential laboratories for studying gravity, dark matter, cosmology, interactions between galaxies, the intracluster gas and stars, and the cycling of baryons into and out of galaxies.

Recent multi-wavelength observations have enabled significant progress in our understanding of cluster formation and evolution, delivering more complete samples of clusters and finding ever more distant clusters and protoclusters. However, this is only the starting point. There will be an explosion of multi-wavelength data from the existing and upcoming cluster programs from facilities such as eROSITA, ALMA, ACT, SPT, the Dark Energy Survey, Subaru's HSC-SSP, Euclid, Rubin Observatory's LSST, SPHEREx, the Roman Space Telescope, and the Simons Observatory. Wide-area multi-object spectroscopic surveys are providing extensive redshift coverage of clusters out to $z = 0.5$ and beyond, enabling new lines of research. JWST will further revolutionize our ability to obtain deep spectroscopy and near-infrared data to probe the properties of distant cluster galaxies in unprecedented detail. All of these observations will need to be interpreted with a new, richer generation of more precise simulations of cluster assembly in ever larger volumes.

This symposium will provide a forum for researchers to discuss recent results and future perspectives in the study of galaxy clusters. Topics to be discussed include cluster cosmology, cluster surveys and detection, cluster mass estimation, gravitational lensing and analyses of cluster substructures, environment-driven galaxy evolution, baryon cycling, connections to large-scale structure, results from new large-scale simulations, and the challenges of analyzing cluster data across many wavelengths and over a large span of cosmic time.
Local Organizing Committee Members
  Dan Coe
  Harry Ferguson
  Ray Lucas
  Mireia Montes
  Michelle Ntampaka
  Marc Postman

Science Organizing Committee Members
  Esra Bulbul (MPE)
  Megan Donahue (MSU)
  Yen-Ting Lin (ASIAA)
  Toby Marriage (JHU)
  Mireia Montes (Chair, STScI)
  Priyamvada Natarajan (Yale)
  Michelle Ntampaka (STScI)
  Marc Postman (STScI)
AGENDA
### CLUSTERS 2022: Challenging Our Cosmological Perspectives Symposium Schedule

**MONDAY, APRIL 25**

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<th>Time (EDT)</th>
<th>Talk Title</th>
<th>Speaker</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>9:00 - 9:30 AM</td>
<td>GatherTown Social</td>
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<tr>
<td>9:30 - 10:00 AM</td>
<td>Welcome and Meeting Logistics</td>
<td>Ken Sembach, Mireia Montes</td>
<td>Space Telescope Science Institute</td>
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<tr>
<td>10:00 - 10:25 AM</td>
<td>One survey to find them all, and in the darkness study them. In LCDM where dark energy and dark matter lie</td>
<td>Yen-Ting Lin</td>
<td>ASIAA</td>
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<tr>
<td>10:25 - 10:40 AM</td>
<td>Untangling the Positive and Negative Impacts of AGN Feedback in Galaxy Clusters</td>
<td>Yu Qiu</td>
<td>Kavli Institute for Astronomy and Astrophysics</td>
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<tr>
<td>10:40 - 10:55 AM</td>
<td>Physical Properties of More than One Thousand Brightest Cluster Galaxies Detected from the CFHTLS</td>
<td>Aline Chu</td>
<td>Institut d’Astrophysique de Paris</td>
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<tr>
<td>10:55 - 11:05 AM</td>
<td>Break</td>
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<tr>
<td>11:05 - 11:30 AM</td>
<td>Cosmological simulations for galaxy evolution in clusters</td>
<td>Annalisa Pillepich</td>
<td>Max Planck Institute for Astronomy</td>
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<tr>
<td>11:30 - 11:45 AM</td>
<td>Satellite Quenching was not Important for z~1 Clusters: Most Quenching Occurred during Infall</td>
<td>Stephane Werner</td>
<td>University of Nottingham</td>
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<tr>
<td>11:45 - 12:00 PM</td>
<td>The Intracluster Light Fraction across Cosmic Time</td>
<td>Yolanda Jiménez-Teja</td>
<td>Instituto de Astrofísica de Andalucía</td>
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<tr>
<td>12:00 - 1:00 PM</td>
<td>Lunch</td>
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<tr>
<td>1:00 - 1:25 PM</td>
<td>Success and failures of cosmological and hydrodynamical simulations of galaxy clusters.</td>
<td>Elena Rasia</td>
<td>INAF-Trieste</td>
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<tr>
<td>1:25 - 1:40 PM</td>
<td>The Chemical Evolution of Galaxy Clusters: Dissecting the Iron Mass Budget of the Intracluster Medium</td>
<td>Ang Liu</td>
<td>Max Planck Institute for Extraterrestrial Physics</td>
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<tr>
<td>1:40 - 1:55 PM</td>
<td>Localizing Accretion Shocks in Galaxy Cluster Outskirts with UV Absorption Spectroscopy</td>
<td>Priscilla Holguin Luna</td>
<td>New Mexico State University</td>
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<tr>
<td>1:55 - 2:05 PM</td>
<td>Break</td>
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<tr>
<td>2:05 - 2:30 PM</td>
<td>ICM in Galaxy Clusters from observations</td>
<td>Vittorio Ghirardini</td>
<td>Max Planck Institute for Extraterrestrial Physics</td>
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<tr>
<td>2:30 - 2:45 PM</td>
<td>Testing the Limits of AGN Feedback in the Most Rapidly Star Forming Central Cluster Galaxies</td>
<td>Michael Calzadilla</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>2:45 - 3:00 PM</td>
<td>Molecular Gas Flows in Active Galaxies and the Potential Impact of Radio-Mechanical Feedback</td>
<td>Prathamesh Tamhane</td>
<td>University of Waterloo</td>
</tr>
<tr>
<td>3:10 - 4:10 PM</td>
<td>Discussion session 1</td>
<td>Discussion leaders: Megan Donahue (MSU), Grant Tremblay (CfA), Mark Voit (MSU)</td>
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# CLUSTERS 2022: Challenging Our Cosmological Perspectives Symposium Schedule

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<td><em>GatherTown Social</em></td>
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<tr>
<td>10:00 - 10:15 AM</td>
<td>Measuring Sloshing, Merging and Feedback Velocities in the Galaxy Clusters</td>
<td>Efrain Gatuzz</td>
<td>Max Plank Institute for Extraterrestrial Physics</td>
</tr>
<tr>
<td>10:15 - 10:30 AM</td>
<td>The Density Profile and Boundary of Galaxy Clusters and Its Implications on Star Formation Quenching in Satellite Galaxies</td>
<td>Tae-hyeon Shin</td>
<td>Stony Brook University</td>
</tr>
<tr>
<td>10:30 - 10:45 AM</td>
<td>Constraining ICM Thermodynamics and Feedback with Thermal and Kinematic SZ Effects</td>
<td>Stefania Amodeo</td>
<td>Strasbourg Observatory</td>
</tr>
<tr>
<td>10:45 - 11:10 AM</td>
<td>Optical surveys of clusters of galaxies</td>
<td>Masamune Oguri</td>
<td>University of Tokyo</td>
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<tr>
<td>11:10 - 11:20 AM</td>
<td><em>Break</em></td>
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<tr>
<td>11:20 - 11:45 AM</td>
<td>The ZFIRE Survey: Environment Matters at z ~ 2</td>
<td>Kim-Vy Tran</td>
<td>University of New South Wales</td>
</tr>
<tr>
<td>11:45 - 12:00 PM</td>
<td>Getting the Most from ICM Selected Cluster Catalogs: The Important Role of Optical Confirmation</td>
<td>Matthias Klein</td>
<td>Ludwig-Maximilians University, Munich</td>
</tr>
<tr>
<td>12:00 - 1:00 PM</td>
<td><em>Lunch</em></td>
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<tr>
<td>1:00 - 1:25 PM</td>
<td>Tracing Baryons in Clusters of Galaxies with eROSITA</td>
<td>Esra Bulbul</td>
<td>Max Planck Institute for Extraterrestrial Physics</td>
</tr>
<tr>
<td>1:25 - 1:50 PM</td>
<td>Sunyaev-Zel'dovich (SZ) Surveys of Galaxy Clusters</td>
<td>Brad Benson</td>
<td>University of Chicago</td>
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<tr>
<td>1:50 - 2:00 PM</td>
<td><em>Break</em></td>
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<tr>
<td>2:00 - 2:30 PM</td>
<td>Surveys of Clusters of Galaxies: Astrophysical Insights</td>
<td>Michael Strauss</td>
<td>Princeton University</td>
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<tr>
<td>2:30 - 2:45 PM</td>
<td>X-ray Properties of HSC Weak Lensing Peaks in the eFEDS Footprint</td>
<td>Miriam E. Ramos-Ceja</td>
<td>Max Planck Institute for Extraterrestrial Physics</td>
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<tr>
<td>2:45 - 3:00 PM</td>
<td>The Universal Density Profile and the Core-excised Luminosity in Clusters Up to z=1.13</td>
<td>Gabriel W Pratt</td>
<td>CEA Saclay</td>
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<tr>
<td>9:00 - 10:00 AM</td>
<td><strong>Discussion Session 2</strong></td>
<td>Discussion leaders: Arif Babul (U. Victoria), Alexey Vikhlinin (CfA), Anja von der Linden (Stony Brook University)</td>
<td></td>
</tr>
<tr>
<td>10:00 - 10:30 AM</td>
<td>Clusters as astrophysical laboratories</td>
<td>Priya Natarajan</td>
<td>Yale University</td>
</tr>
<tr>
<td>10:30 - 10:55 AM</td>
<td>Probing Dark Matter Structure with Combined Strong and Weak Lensing from Space</td>
<td>Keiichi Umetsu</td>
<td>ASIAA</td>
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<tr>
<td>10:55 - 11:05 AM</td>
<td><strong>Break</strong></td>
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<tr>
<td>11:05 - 11:20 AM</td>
<td>DES Cluster Mass Calibration via SPT-3G CMB Lensing</td>
<td>Behzad Ansarinejad</td>
<td>University of Melbourne</td>
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<tr>
<td>11:20 - 11:35 AM</td>
<td>Shape and Connectivity of Clusters: Impact on Gas Distribution</td>
<td>Celine Gouin</td>
<td>Korean Institute for Advanced Study</td>
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<tr>
<td>11:35 - 11:50 AM</td>
<td>Early Results of the LoVoCCS Survey</td>
<td>Shenming Fu</td>
<td>NOIRLab</td>
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<tr>
<td>12:00 - 1:00 PM</td>
<td><strong>Lunch</strong></td>
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<tr>
<td>1:00 - 1:25 PM</td>
<td>Outer Galaxy Mass Traces Halo Mass with Scatter Comparable to Richness and Reduced Projection Effects</td>
<td>Alexie Leauthaud</td>
<td>UC Santa Cruz</td>
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<tr>
<td>1:25 - 1:40 PM</td>
<td>Cosmology with Multiple Halo Sparsities</td>
<td>Amandine Le Brun</td>
<td>LUTH, Paris Observatory, PSL University</td>
</tr>
<tr>
<td>1:40 - 1:55 PM</td>
<td>Probing the Inner Density Profile of Galaxy Clusters with Strong Lensing and MUSE Spectroscopy</td>
<td>Catherine Cerny</td>
<td>Durham University</td>
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<tr>
<td>1:55 - 2:05 PM</td>
<td><strong>Break</strong></td>
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<tr>
<td>2:05 - 2:20 PM</td>
<td>Weak Lensing Mass Estimates of the Most Distant Clusters in the SPT-SZ Survey</td>
<td>Hannah Zohren</td>
<td>Argelander Institute for Astronomy</td>
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<tr>
<td>2:20 - 2:35 PM</td>
<td>Evolution of Shocks and Splashback Boundaries in Cluster Outskirts</td>
<td>Congyao Zhang</td>
<td>The University of Chicago</td>
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<tr>
<td>2:35 - 2:50 PM</td>
<td>CLUMP-3D: Constraining Three-Dimensional Models of the Gas and Dark Matter in Galaxy Clusters Using Multi-Probe Data</td>
<td>Jack Sayers</td>
<td>California Institute of Technology</td>
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<tr>
<td>3:00 - 3:30 PM</td>
<td><strong>GatherTown Social</strong></td>
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## CLUSTERS 2022: Challenging Our Cosmological Perspectives Symposium Schedule

### THURSDAY, APRIL 28

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<tr>
<td>10:00 - 10:25 AM</td>
<td>Cosmology with X-ray cluster samples</td>
<td>Alexis Finoguenov</td>
<td>University of Helsinki</td>
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<tr>
<td>10:25 - 10:40 AM</td>
<td>A New GalWeight-Derived SDSS Galaxy Cluster Catalog and Cosmological Constraints on ( \Omega_m ) and ( \sigma_8 )</td>
<td>Mohamed Elhashash</td>
<td>Chiba University</td>
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<tr>
<td>10:40 - 10:55 AM</td>
<td>The Euclid Galaxy Cluster Cosmological Pipeline</td>
<td>Barbara Sartoris</td>
<td>USM-LMU</td>
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<tr>
<td>10:55 - 11:05 AM</td>
<td><strong>Break</strong></td>
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<tr>
<td>11:05 - 11:30 AM</td>
<td>Cosmology with Galaxy Clusters: impact of systematics</td>
<td>Laura Salvati</td>
<td>U. Paris-Saclay/INAF-Trieste</td>
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<tr>
<td>11:30 - 11:45 AM</td>
<td>Cosmological Constraints from Galaxy Cluster Statistics in KIDS</td>
<td>Giorgio Lesci</td>
<td>Università di Bologna</td>
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<tr>
<td>11:45 - 12:00 PM</td>
<td>Retrieving Cosmological Information from Clusters and Hot Diffuse Gas</td>
<td>Marian Douspis</td>
<td>IAS (Orsay)</td>
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<tr>
<td>12:00 - 1:00 PM</td>
<td><strong>Lunch</strong></td>
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<tr>
<td>1:00 - 1:25 PM</td>
<td>Enabling cluster cosmology with CMB lensing</td>
<td>Mathew Madhavacheril</td>
<td>Perimeter Institute</td>
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<tr>
<td>1:25 - 1:40 PM</td>
<td>Galaxy Cluster Strong Lensing Cosmography: Cosmological Constraints from Precise Mass Models</td>
<td>Gabriel Bartosch Caminha</td>
<td>Max Planck Institute for Astrophysics</td>
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<tr>
<td>1:40 - 1:55 PM</td>
<td>Cosmology with Weak Lensing Shear-selected Clusters in the Hyper Suprime-Cam Survey</td>
<td>Kai-Feng Chen</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>1:55 - 2:05 PM</td>
<td><strong>Break</strong></td>
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<tr>
<td>2:05 - 2:30 PM</td>
<td>Weak Lensing of Galaxy Clusters as a tool for Cosmological Studies: Perspectives from the past 30 years and Future Prospects</td>
<td>Ian Dell’Antonio</td>
<td>Brown University</td>
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<tr>
<td>2:30 - 2:45 PM</td>
<td>Constraining Cluster Astrophysics and Cosmology with X-ray Angular Power Spectrum - Results from eFEDS and Prospects for eRASS</td>
<td>Erwin Lau</td>
<td>Smithsonian Astrophysical Observatory</td>
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<tr>
<td>2:45 - 3:00 PM</td>
<td>Multi-probe Cluster Cosmology Analyses with Photometric Surveys</td>
<td>Chun-Hao To</td>
<td>The Ohio State University</td>
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<tr>
<td>9:30 - 10:00 AM</td>
<td>Deep learning-based galaxy cluster recognition.</td>
<td>Maggie Lieu</td>
<td>University of Nottingham</td>
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<tr>
<td>10:00 - 10:25 AM</td>
<td>Machine Learning within THE THREE HUNDRED Simulation Project</td>
<td>Daniel de Andres</td>
<td>Autonomous University of Madrid</td>
</tr>
<tr>
<td>10:25 - 10:40 AM</td>
<td>Analysis of Constrained Simulations of the Coma Cluster and of Its Surrounding Cosmic Web</td>
<td>Nicola Malavasi</td>
<td>Ludwig-Maximilians University</td>
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<td>10:55 - 11:05 AM</td>
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<tr>
<td>11:05 - 11:30 AM</td>
<td>Simulations of the Hot and Dynamic ICM of Galaxy Clusters</td>
<td>John Zuhone</td>
<td>Center for Astrophysics/ Harvard</td>
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<tr>
<td>11:30 - 11:45 AM</td>
<td>The 300 Project: The New Simba Clusters</td>
<td>Weiguang Cui</td>
<td>IfA, University of Edinburgh</td>
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<tr>
<td>11:45 - 12:00 PM</td>
<td>A New Generation of High-precision Strong Lensing Models of Galaxy Clusters: Applications in the JWST Era</td>
<td>Pietro Bergamini</td>
<td>Università degli Studi di Milano</td>
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<tr>
<td>12:00 - 1:00 PM</td>
<td>Lunch</td>
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<tr>
<td>1:00 - 1:25 PM</td>
<td>Trustworthy Machine Learning for Data-Driven Discovery</td>
<td>Michelle Ntampaka</td>
<td>Space Telescope Science Institute</td>
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<tr>
<td>1:25 - 1:40 PM</td>
<td>Velocity Dispersion of Brightest Cluster Galaxies in Cosmological Simulations</td>
<td>Ilaria Marini</td>
<td>University of Trieste</td>
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<td>1:55 - 2:05 PM</td>
<td>Break</td>
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<tr>
<td>2:05 - 2:30 PM</td>
<td>Hidden Signals in Population Diversity of Galaxy Clusters</td>
<td>Arya Farahi</td>
<td>U. Texas, Austin</td>
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<tr>
<td>2:30 - 2:45 PM</td>
<td>A Dynamics-based Model for Cluster Halos</td>
<td>Benedikt Diemer</td>
<td>University of Maryland</td>
</tr>
<tr>
<td>2:45 - 3:00 PM</td>
<td>A Galaxy Cluster Finder for eROSITA Using Deep Neural Networks</td>
<td>Brianna Galgano</td>
<td>Johns Hopkins University</td>
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<tr>
<td>3:10 - 4:10 PM</td>
<td>Discussion Session 3</td>
<td>Discussion leaders: Gus Evrard (U Michigan), Daniel Gruen (LMU), Neelima Sehgal (Stonybrook)</td>
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In this talk I present measurements of the stacked cluster mass for the DES Y3 redMaPPer sample, using the lensing of SPT-3G CMB temperature and polarization maps, observed in the first two years of the survey. The high S/N, resolution and sky coverage of the SPT-3G data enables us to obtain the most precise CMB-lensing cluster mass constraints to date. Upon combining the temperature and polarization measurements, we expect to measure the stacked mass of the sample with a precision of ~6.5%. Thanks to the high S/N of the data, for the first time, we are also able to use this technique to examine the presence of any redshift or richness-dependent biases in the DES RedMapper cluster catalog, as well as in the optical weak lensing analysis of this sample. After dividing the sample into three redshift or richness bins, we anticipate an ~11% constraint on the stacked cluster mass per bin using the combined temperature and polarization measurements. These measurements enable us to further test if weak lensing systematics or cluster contamination (at low richness) was the main contributing factor to the lower-than-expected $\Omega_m$ constraint obtained in the DES Y1 weak lensing and cluster counts analysis. Furthermore, the information provided by our measurements can be integrated into the cosmological analysis of the DES Y3 sample to improve the constraining power of this dataset.
Constraining ICM Thermodynamics and Feedback with Thermal and Kinematic SZ Effects
Stefania Amodeo
Strasbourg Observatory

The thermodynamic properties of the ionized baryons in galaxies, groups, and clusters encode the effects of the assembly history and feedback processes that shape galaxy and cluster formation. These properties can be studied through the thermal and kinematic Sunyaev-Zel’dovich (SZ) effects imprinted on high resolution maps of the cosmic microwave background (CMB), measured for individual clusters or from stacking analyses. I will show a preview of the constraints on the intracluster medium (ICM) parameters obtained from a detailed analysis of the SZ spectrum of individual clusters, using multi-band observations of the Atacama Cosmology Telescope (ACT), Planck and Herschel. I will also present recent SZ cross-correlation measurements from the ACT DR5 and Planck, from which we achieve high signal-to-noise measurements of the electron density, temperature and pressure distribution around the CMASS galaxy groups (Amodeo et al. 2021, Schaan et al. 2021). I will discuss our constraints on the feedback and the non-thermal pressure support, as well as the effect of including baryons in the modeling of galaxy-galaxy lensing measurements. These measurements provide novel tests of current and future hydrodynamical simulations with sub-grid physics models. I will outline the rapid growth of SZ cross-correlation measurements expected over the next decade with upcoming CMB experiments, like Simons Observatory and CMB-S4, and large-scale structure surveys like DESI, the Rubin Observatory or Euclid.

Galaxy Cluster Strong Lensing Cosmography: Cosmological Constraints from Precise Mass Models
Gabriel Bartosch Caminha
Max Planck Institute for Astrophysics

Galaxy cluster strong lensing has numerous applications in cosmology. Thanks to the wealth of multi-wavelength observations of clusters using state-of-the-art observatories, such as the Hubble Space Telescope and the Very Large Telescope, this field provides significant contributions to the understanding of our Universe. One of the main points still to be fully understood is the nature of the components that drives the evolution of the Universe, such as Dark Matter and Energy. This issue motivates further tests on the ΛCDM model, both at small and large scales, and they play an essential role in the concept and design of cosmological observations and programs.
Sunyaev-Zel’dovich (SZ) Surveys of Galaxy Clusters
Bradford Benson
Fermilab, University of Chicago

I will give an overview of Sunyaev-Zel’dovich (SZ) cluster surveys. Since the first SZ-discovered cluster in 2008, there are now over 5,000 SZ-selected clusters reported in the literature. Ongoing surveys from AdvACT and SPT-3G promise to deliver samples with several thousand additional clusters in the next few years, with the future CMB-S4 experiment expected to find over 100,000 clusters. These data sets promise to deliver unique samples of massive clusters at $z > 1$, including proto-clusters detected at $z > 4$ from their mm-wave emission, which enable SZ surveys to effectively trace the entire history of cluster formation. Therefore SZ cluster samples provide unique data sets to understand cluster astrophysics and cosmology, particularly at the highest-redshifts. The resultant astrophysical and cosmological constraints will be most powerful when including multi-wavelength data from overlapping X-ray and optical surveys, which will help to characterize the cluster selection and mass calibration, and enable a wide range of additional science. I will summarize recent results, upcoming challenges, and projected future constraints from SZ cluster surveys.
Galaxy clusters are important astrophysical laboratories to study the nature of Dark Matter, whose physical properties are still unknown. In particular, a detailed investigation of the mass distribution of cluster halos, by dissecting the DM and baryonic components, can provide stringent tests of the Cold Dark Matter paradigm of structure formation. Over the last decade, strong gravitational lensing has become the most powerful technique to study the total mass distribution of the inner region of galaxy clusters from the central brightest cluster galaxy down to about a third of their virial radius. This remarkable progress in cluster lens modelling has been mainly possible thanks to dedicated extensive imaging and spectroscopic surveys, carried out in the core of a sizeable sample of massive galaxy clusters. In particular, by combining the multiband imaging capabilities of the Hubble Space Telescope with the Very Large Telescope VIMOS and MUSE spectroscopic data, we have moved from lens models counting just a few tens of multiple images with photometric redshifts to a new generation of high-precision strong lensing models exploiting several hundreds of spectroscopically confirmed multiple images and cluster member galaxies. An even larger growth (from hundreds to possibly thousands of multiple images) is expected in the next future, when several clusters will be observed with the JWST and the ELT telescopes. In this context, I will present our state-of-the-art strong lensing models, that incorporate the stellar kinematic information of a significant fraction of cluster galaxies and the hot-gas mass distribution of the clusters, and that can reproduce the observed positions of hundreds of multiple images with a typical accuracy of only 0.4″. As an example, I will show our latest lens model of the galaxy cluster MACS J0416.1-2403, counting 235 spectroscopically confirmed multiple images (the largest set currently available). Other than to robustly characterize the mass distribution of the clusters, our models will provide accurate and precise magnification maps that are key to studying the intrinsic physical properties of faint high-redshift (z > 6) sources that are magnified by the clusters and will soon be observed by the JWST telescope. These objects are the progenitors of the galaxies in the local Universe and may have an important role in the re-ionization process of the Universe. I will also present a new online tool, soon to be publicly available, that through a simple graphical interface will allow astronomers (even lensing non-experts) to take full advantage of the predictive and statistical results of our models for their research, both on the lens clusters and lensed sources.
Tracing Baryons in Clusters of Galaxies with eROSITA
Esra Bulbul
Max Planck Institute For Extraterrestrial Physics

Clusters of galaxies trace the highest peaks in the cosmic density field and offer an independent and powerful probe of the growth of structure. The final eROSITA All-Sky Survey catalog with more than 100,000 clusters will map the large-scale structure and put us on the verge of a breakthrough in precision measurements of the cosmological parameters. The performance verification survey eFEDS, at the depth of the final All-Sky Survey, has provided a sneak preview of rich cluster science that will be achieved by eROSITA. I will review the eFEDS results on cluster science published in the early A&A Special Issue. I will also present initial results on the properties of clusters of galaxies detected in the first All-Sky survey.

Testing the Limits of AGN Feedback in the Most Rapidly Star Forming Central Cluster Galaxies
Michael Calzadilla
Massachusetts Institute of Technology

For years we have grappled with the “cooling flow problem” in galaxy clusters, where the massive reserves of hot (10^7 K) gas in the intracluster medium (ICM) have been universally observed to form stars with an efficiency of only 1-10%. Feedback from accreting active galactic nuclei (AGN) has been identified as the likely heating source capable of suppressing runaway cooling by up to two orders of magnitude. However, with the recent discovery of the Phoenix cluster exhibiting the only known pure cooling flow, the thermostat of AGN feedback appears to be broken in this and a few other highly accreting systems. In this study, we use new, deep Hubble Space Telescope observations to map out massive, intricate [OII] emission line nebulae in exquisite detail in a handful of the most rapidly star forming central cluster galaxies in the Universe. From these maps of cool (10^4 K) gas we can measure accurate star formation rates (SFRs), which we use together with systems from the literature spanning several orders of magnitude in ICM cooling rates (dM/dt, as measured from Chandra X-ray data) to determine the efficiency with which the ICM cools. We find a steeper than unity relationship between SFR and dM/dt, indicating perhaps a saturation point for AGN feedback in the strongest cooling systems (i.e. dM/dt > 1000 Msun/yr), where feedback from the central AGN is being overwhelmed by the prodigious deposition of cooling material. We also use the maximum extent of cool gas as measured from our [OII] maps along with Halpha measurements from the literature and compare these to features in the ICM to weigh in on the hotly-debated issue of identifying what criteria best predict the onset of thermal instability in the ICM.
Probing the Inner Density Profile of Galaxy Clusters with Strong Lensing and MUSE Spectroscopy
Catherine Cerny
Durham University

Galaxy clusters play a key role in studying the distribution of dark matter throughout the universe. However, the shape of dark matter density profiles in the inner region of galaxy clusters is currently a source of tension between observational models and cold dark matter (CDM) numerical simulations. While CDM simulations predict mass profiles that follow a steep power law, where the density increases in a 'cusp' in the inner region of the cluster, observations suggest that the profile instead flattens out, forming a constant density 'core' in the center. From an observational perspective, resolving the 'core-cusp' problem will require robust models of the mass distribution for many different clusters in order to examine the structure that leads to core-like density profiles. In this talk, I will discuss the use of strong gravitational lensing to create parametric models of the mass distribution for four different galaxy clusters. Each cluster is home to at least one radial arc, which is a unique physical feature that allows for more sensitive measurements of the inner mass profile from strong lensing. I will additionally discuss using MUSE spectroscopy to measure the 2-D velocity dispersion of the BCG, which I use to subtract the baryonic mass component from the inner profile. With these models in hand, I will discuss the shape of the resulting density profiles and comment on the potential for a statistical survey of roughly one hundred and fifty more clusters with MUSE spectroscopy to reveal trends in the shape of the modelled density profiles.

Cosmology with Weak Lensing Shear-selected Clusters in the Hyper Suprime-Cam Survey
Kai-Feng Chen
Massachusetts Institute of Technology

We present the first cosmological constraints based on a sample of hundreds of galaxy clusters selected in a 510 deg^2 weak-lensing mass map constructed with the latest shear catalogue from the Hyper Suprime-Cam Subaru Strategic Program. This is the largest sample of shear-selected clusters ever used in constraining cosmology. The uniqueness of this study is that the cluster sample is selected purely based on gravitational lensing and is nearly independent of any baryonic assumptions. Our cosmological constraints are derived from forward modeling the cluster number counts as a function of the observed weak-lensing signal-to-noise ratio, in which we carefully account for the complex selection function by using realistic simulations. Our results open a new route for cluster cosmology and will pave a way for future deep-and-wide lensing surveys such as those observed by the Vera Rubin Observatory and the Euclid space telescope.
Physical Properties of More than One Thousand Brightest Cluster Galaxies Detected from the CFHTLS
Aline Chu
Institut d'Astrophysique de Paris

Located at the intersection of cosmic filaments in the large scale structures, galaxy clusters present in their center, at the bottom of the cluster potential well, a supermassive galaxy which is also most often the brightest galaxy of the cluster. This galaxy is referred to as the Brightest Cluster Galaxy (BCG). Understanding how BCGs were formed and how they evolve can help us to understand how the clusters which host them were formed. BCGs are the result of billions of years of successive cluster mergers which can leave an imprint on the galaxy. Studies have shown that clusters are preferentially aligned in the cosmic web, along the filaments which connect them. BCGs were also found to share this same tendency with their host clusters, contrary to other cluster galaxies which were shown to have random orientations. There is still, though, a lot of controversy as to whether or not these galaxies are still evolving today, as authors find conflicting results on the growth of BCGs with redshift. For the purpose of this study, we analyzed a sample of 1371 BCGs detected from the CFHTLS up to z = 0.7, and modeled their 2-D luminosity profiles. We also quantify, in a preliminary work, the impact of the intracluster light in such studies. Our results show that neither the sizes or luminosities of BCGs evolve with redshift since z = 0.7. This indicates that BCGs were most likely formed at an earlier epoch. We also show that the major axis of the triaxial structure of BCGs tends to align with that of their host cluster. This alignment agrees with the general idea that BCGs form at the same time as clusters by accreting matter along the filaments of the cosmic web.

The 300 Project: The New Simba Clusters
Weiguang Cui
IfA, University of Edinburgh

I will introduce the 300 Galaxy Project (https://the300-project.org/) with its new Simba run in this talk. Targeting at zoomed-in simulations of galaxy clusters with a very large sample (324 clusters with M_200>~6X10^{14} Msun/h), the 300 project provides varieties of analogues resulting from several semi-analytical models to hydrodynamic simulations with different baryon models. This new Simba run based on the successful Simba simulation (Dave et al. 2019) shows good agreements with observational results. I will show how Simba thinks the cluster, especially its brightest central galaxy, is formed with this set of galaxy clusters, and how Simba predicts the M_bh and M*/sigma relation at cluster scale.
Machine Learning within THE THREE HUNDRED Simulation Project
Daniel de Andres
Autonomous University of Madrid

THE THREE HUNDRED (The300) project aims at collecting one of the largest set of hydrodynamical simulations of massive galaxy clusters. Since massive clusters are very scarce, the zooming technique is used to individually resimulate spherical regions around the 324 most massive objects found in the MULTIDARK, 1 giga-parsec volume N-body only simulation. From the results of these simulations we train a machine learning algorithm to find a mapping between dark matter halo properties derived by Rockstar halo finder and baryon properties, such as gas mass, stellar mass and the Compton Y parameter within $R_{500}$ obtained from the hydrodynamical simulations. By doing so, we successfully populate the whole MultiDark cluster-size halos with baryonic properties similar to those from the THREEHUNDRED hydro simulations. We also prove that the trained models can also be applied to other N-body simulations even when the mass resolution is a factor 8 lower than the one used for training. Therefore, we can use these machine learning models to populate halos in much larger computational volumes so they can be used to produce mock light cone observations of full sky Xray surveys like e-ROSITA. We have collected a catalogue of almost 200,000 mock SZ maps from The300 simulations with the same angular resolution and noise as the clusters observed by the Planck satellite. We then applied deep learning techniques to compute the mass of the real full-sky Planck maps by training our algorithms on the simulated mock images. We show that the deep learning mass estimate is compatible with the Planck mass derived by applying SZ scaling relation within a 20\% bias, which is the expected bias assuming the hypothesis of hydrostatic equilibrium holds. The advantage of deep learning methods is that they do not rely on any assumption on the gas profiles to derive masses. The only requirement is that the training set is accurate enough to reproduce the physical and observing conditions of the objects of interest.

Weak Lensing of Galaxy Clusters as a tool for Cosmological Studies: Perspectives from the Past 30 Years and Future Prospects
Ian Dell’Antonio
Brown University

Ever since the first weak lensing detections of galaxy clusters through their weak gravitational lensing, their potential value for cosmology has been recognized. I will review the successes that have been achieved and the challenges that have arisen in past studies, and the prospects for clusters to play a key role in future cosmological surveys such as the Vera Rubin Observatory’s LSST, EUCLID, and the Nancy Grace Roman Telescope High Latitude Core Community Survey.
A Dynamics-based Model for Cluster Halos
Benedikt Diemer
University of Maryland

The dark matter density profiles of cluster halos carry signatures of their mass, dynamical state, and even of the nature of dark matter. Some of the most interesting signals reside at large radii (around the virial radius and beyond), which have recently become observationally accessible via satellite distributions and weak lensing. However, to harness the rapid progress promised by future instruments such as VRO/LSST and Roman, we need to significantly upgrade our theoretical understanding of the expected signals. One key roadblock has been the superposition of orbiting and infalling dark matter particles in simulations, which obscures the true shape of the orbiting (1-halo) term near the cluster edge. Based on a novel algorithm to split simulated halos into their dynamical components, I will introduce an accurate, more physical fitting function for profiles out to large radii. I will show how the best-fit parameters are related to the halo properties of interest, providing a practical framework for deriving cluster properties such as the mass accretion rate from profile observations.

Retrieving Cosmological Information from Clusters and Hot Diffuse Gas
Marian Douspis
IAS (Orsay)

Planck and SPT experiments have observed galaxy clusters using their SZ signature but were also able to produce maps of the full hot gas distribution in the sky (including clusters and more diffuse components). I will show how to use the SZ signature at small scales in these two experiments to retrieve both cosmological parameters and cluster scaling relations. Using machine learning to compute efficiently the SZ angular power spectrum, I will show the constraints obtained using SPT CMB observations combined with the latest Planck observed SZ spectrum and compare them with constraints obtained with cluster number counts. I will discuss how such analysis could shed light on the sigma8 tension observed between CMB and clusters.
Galaxy clusters are uniquely powerful tools for constraining cosmological parameters. I will present GalWeight, a new and powerful toolkit for ingesting large spectroscopic datasets, identifying cluster locations, assigning membership, and calculating dynamical parameters including cluster mass, velocity dispersion, concentration, size, and richness. GalWeight has been applied to the Sloan Digital Sky Survey spectroscopic dataset to create “GalWCat19”, a publicly available catalog of 1800 clusters. By analyzing GalWCat19, we derive cosmological constraints on the matter density $\Omega_m$ and the amplitude of mass fluctuations $\sigma_8$. Our constraints on $\Omega_m$ and $\sigma_8$ are consistent and very competitive with those obtained from non-cluster abundance cosmological probes such as cosmic microwave background, baryonic acoustic oscillation (BAO), and supernovae. Spectroscopic observations are not always available. I will also present an assessment of the mass richness relation as a cosmological tool. I will end by discussing prospects for applying GalWeight on ongoing and upcoming spectroscopic galaxy surveys, including GCLASS, VIPERs, DESI, and SPHEREx at high redshifts.
Hidden Signals in Population Diversity of Galaxy Clusters  
Arya Farahi  
University of Texas at Austin

Cosmological and astrophysical constraints through population statistics of individual halos hinge on developing a better understanding of the relation between cluster observables and their host halo mass. Past studies have shown considerable diversity in the formation time and accretion history of halos. Additionally, their baryonic properties are altered due to stochastic energy and momentum feedback processes. These processes produce diversity in observable properties of halos that are reflected in the correlated scatter about the halo mass—cluster observable relation. Directly measuring these correlated scatters is currently limited by averaging and stacking methods. Though intuitive and easy to implement, these methods suffer from loss of information. I will present our recent works on retrieving and exploiting this information.

First, I will introduce a population-based framework that enables us to unpack and build upon the information contained in the correlated observables. As a case study, I will illustrate the impact of the formation time on observable properties of clusters as well as the process to extract this information from observational data. By employing our population-based framework, I will demonstrate that while the existing observational data agree with simulation-based predictions, there are predictions that have not been confirmed yet. Finally, I will identify rising methodological opportunities and challenges to achieve the unmet need in detecting these hidden signals from growing observational data. I will present our recent work on developing a set of novel data analysis tools that enable population studies with multi-wavelength data collected by deep and wide surveys, such as Rubin, Roman, eROSITA, Simons Observatory, and CMB-S4.

Cosmology with X-ray Cluster Samples  
Alexis Finoguenov  
Helsinki University

Formation of dark matter halos is sensitive to the expansion rate of the Universe and to the growth of structures under gravitational collapse. Virialization of halos heats the gaseous intra-cluster medium to high temperatures, leading to copious emission of photons at X-ray wavelengths. We summarize the progress of X-ray surveys in determining cosmology using galaxy clusters. We review recent cosmological results based on cluster volume abundance, clustering, standard candles, extreme object statistics, and present relevant theoretical considerations. We discuss clusters as gravitation theory probes and present an outlook on future developments.
Early Results of the LoVoCCS Survey
Shenming Fu
NOIRLab

We present the results of the first set of galaxy clusters in the LoVoCCS survey. LoVoCCS is an NSF’s NOIRLab survey program that uses the Dark Energy Camera (DECam) to map the dark matter distribution and galaxy population in 107 nearby (0.03 < z < 0.12) X-ray luminous (LX500 > 10^{44} \text{ erg/s}) galaxy clusters that are not obscured by the Milky Way. The survey will reach Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) Year 1–2 depth and will conclude around 2023, which is coincident with the beginning of the LSST science operations, and will serve as a zeroth-year template for the LSST time-domain studies in these cluster fields. We process the data using the LSST Science Pipelines (LSP) software and analyze the results using our own pipeline scripts. In each galaxy cluster, we study the lensing signal and compare the peaks of the lensing mass map, member galaxy flux distribution, and X-ray emission. The deep LoVoCCS imaging enables the studies of low-surface-brightness features and jellyfish galaxies as well.

A Galaxy Cluster Finder for eROSITA Using Deep Neural Networks
Brianna Galgano
Johns Hopkins University

Galaxy clusters are used as a reliable cosmological tool to constrain the amount (Omega_m) and distribution (sigma_8) of matter in the Universe. The precision of these cosmological parameters relies on our ability to accurately measure cluster masses and the abundance of galaxy clusters in surveys. Galaxy clusters can be observed through emissions from their intracluster medium (ICM), which consist of hot plasma gas (10^7-10^8 \text{ K}, 1-10s \text{ keV}) that is luminous in X-ray. However, there is difficulty in observing lower mass (<10^{14} \text{ Msolar}) galaxy clusters due to their faint X-ray emission. The eROSITA mission, an X-ray survey, will provide a precedent to observe low-mass galaxy clusters on all-sky scales. I will present a deep neural networks (DNN), a type of supervised machine learning model, to detect galaxy clusters via their faint ICM emission. The model is trained on artificial X-ray observations of galaxy clusters from a hydrodynamical simulation, Magneticum. DNNs are advantageous to use as cluster finders because they are more flexible than non-A.I., traditional cluster finders and can extract subtle features from images. The use of simulated data also enables us to train the model to differentiate clusters from other X-ray sources, such as active galactic nuclei (AGN). I have created a DNN that can detect simulated ICM and AGN sources under ideal conditions. Current work involves incorporating realistic instrumental effects to our simulated X-ray images to increase the applicability of our cluster finder to future data releases from the eROSITA survey. Applying our data-driven model to observations over the next few years has the potential to produce more accurate and complete cluster all-sky catalogs, allowing us to put more precise constraints on the matter density (Omega_m) and matter distribution (sigma_8) of the Universe.
Measuring Sloshing, Merging and Feedback Velocities in the Galaxy Clusters
Efrain Gatuzz
Max Planck Institute for Extraterrestrial Physics

The intracluster medium (ICM) velocity structure is important to understand cluster physics for several reasons: it affects the cluster mass estimates, help to constrain AGN feedback models, can probe the viscosity of the gas, regulate the transport of metals within the ICM and directly measure the sloshing of gas in cold fronts. However, there are few direct measurements of the ICM velocity structure, despite its importance for understanding cluster physics. In this talk I will present the analysis of long exposure XMM-Newton X-ray observations of the Virgo, Coma, Perseus, Ophiuchus and Centaurus galaxy clusters. We applied a novel technique which consist of using background X-ray lines seen in the spectra of the XMM-Newton EPIC-pn detector to calibrate the absolute energy scale of the detector to obtain velocity measurements with unprecedented accuracy down to 100 km/s. Using this technique, we have found signatures for AGN outflows and/or gas sloshing in our galaxy clusters sample.

ICM in Galaxy Clusters from Observations
Vittorio Ghirardini
Max Planck Institute Mpe

Galaxy clusters are among the largest virialized structures in the Universe, which form, according to the hierarchical structure formation scenario, at the nodes of the cosmic web, and grow from primordial density fluctuation to form the massive structure we observe today. The pristine primordial gas falls from the cosmic web filaments into the clusters deep dark matter potential well, and is progressively heated up to tens of millions of Kelvin, and at this high temperature the majority of the baryons end up in the form of fully ionized plasma, the intracluster medium (ICM), and only a small fraction (3-5%) end up in the cold gas phase. The ICM produces X-rays via bremsstrahlung radiation and line emission. Therefore X-ray observations of galaxy clusters enable in-depth information about the ICM thermodynamic properties. Furthermore, cosmic microwave background (CMB) photons are scattered by the ICM baryons, causing a spectral shift in the CMB spectrum, the so-called thermal Sunyaev-Zeldovich (SZ) effect. I will present the recent progress of the last decade in the studies on the ICM, focusing on recent results on the studies of the thermodynamic properties of the ICM and their evolution with cosmic time, both for individual clusters or for cluster samples, using either SZ or X-ray experiments to select clusters in the first place.
Matter distribution around clusters is highly anisotropic from their being the nodes of the cosmic web. Clusters' shape and the number of filaments they are connected to, i.e., their connectivity, should reflect the level of anisotropy in the matter distribution and must be, in principle, related to their physical properties. In this presentation, I will first present the influence of the dynamical state and the formation history on both the shape and local connectivity of about 415 clusters of galaxies from the hydrodynamical simulation IllustrisTNG at z=0. We found that the mass of clusters mainly influences the geometry of the matter distribution: massive halos are significantly more elliptical, and more connected to the cosmic web than low-mass ones. Beyond the mass-driven effect, ellipticity and connectivity appear to trace different dynamical states, and this is the sign of different accretion histories. Secondly, I will present the statistical exploration of gas distribution (hot and warm phases) around the same simulated galaxy cluster sample. Azimuthal asymmetries of matter are direct related to the geometry of the cluster density field, and appear as a promising probe to assess their physical and dynamical properties. Azimuthal signature of different gas phases differ depending on cluster centric distance and host halo mass. Warm gas phase is dominant outside galaxy clusters and follows dark matter distribution by tracing the cosmic filamentary patterns.

In this talk, I will discuss how we use modern deep learning models to infer galaxy cluster masses with high precision, reliable uncertainty, and computational efficiency. I will describe our work in using Convolutional Neural Networks (CNNs) to mitigate systematics in the virial scaling relation to produce dynamical mass estimates of galaxy clusters, using projected galaxies, with remarkably low scatter and reliable Bayesian uncertainties. I will describe how we've validated these methods on real observational systems like the Coma, CLASH, and HeCS clusters. Lastly, I will mention results from our ongoing work on combining multi-wavelength observables to produce fully informed observational probes of cluster dark matter.
Galaxy cluster halos play host to multiphase gas that is essential for the study of halo gas physics and galaxy evolution, containing clues as to how these environments have transformed over time. While accretion shocks are uniformly predicted in formation models of the intracluster medium, their location (1-5 times the virial radius - r200) varies from model to model. The location of these accretion shocks have important implications for infalling galaxies and gas physics in cluster outskirts, such as the quenching of satellite galaxies. I am carrying out a study to detect these accretion shocks with a novel application of QSO absorption line spectroscopy. Using a statistical sample of HST/COS-observed quasar sightlines that probe the outskirts of >30 foreground, optically selected galaxy clusters, I have mapped diffuse H I and O VI absorption as a function of projected clustocentric distance from within r200 to 5 r200. We can statistically localize an accretion shock by comparing the number of absorbers detected within the intracluster medium to that of the ambient intergalactic medium (IGM) density (measured from random sightlines). My results for H I reveal consistency with the ambient IGM density in clusters’ far outskirts, a sudden peak between 2 - 3 r200, consistent with the accretion shock location in some models, and a decline to the IGM density within r200. This suggests a scenario where H I arises from infalling gas that is heated by the accretion shock front, and these gas clouds are ionized to a greater degree than photoionization in the IGM. Once the gas is exceedingly shock-heated, the neutral fraction plummets, causing a depression in H I following the shock front. In contrast, the O VI is enhanced above the ambient IGM density in the far outskirts and falls to the IGM density by 3-4 r200 with an indication of a slight enhancement around 1-2 r200. Thus, O VI is preferentially detected in the far outskirts. This study sheds new light not only on the formation of these massive structures but also the potential presence of the warm-hot intergalactic medium.
The intracluster light (ICL) is a diffuse, extended emission of the clusters of galaxies composed of stars bound by the cluster's potential that, however, do not belong to any galaxy in particular. Simulations predict a burst in the formation of ICL at $z<0.5$, mainly driven by minor and major mergers. However, several works detect a significant amount of ICL already set up at $z\sim1$, likely originating from mergers with the BCG. We show the results of measuring the ICL fraction (defined as the ratio between the ICL and the total flux of the cluster) in several optical and infrared broadband filters -using data from the Hubble Space Telescope, collected by CLASH, FF, and RELICS programs- and its evolution with cosmic time depending on the dynamical stage of the systems. Our sample spans the redshift interval $0.1<z<0.97$, and the clusters' dynamical stage is well defined using several other indicators that include X-ray morphology of the gas, detection of substructures, or presence of radio haloes and relics. Apart from a burst in the ICL fraction, we can also observe a distinctive signature that merging events imprint on the ICL fractions measured at specific wavelengths: merging clusters show enhanced ICL fractions in the wavelengths corresponding to younger and/or lower metallicity stars, indicating that these could be stars that were ripped off the galaxies outskirts during the merger. However, this signature differs from high redshift ($z>0.8$) to intermediate redshift ($z<0.5$) clusters. Contrarily, relaxed clusters show nearly constant ICL fractions independently of the wavelength, indicative of passive evolution where the dynamical friction of galaxy members would be the primary mechanism to feed the ICL.
Getting the Most from ICM Selected Cluster Catalogs: The Important Role of Optical Confirmation
Matthias Klein
Ludwig-Maximilians University Munich

Deep, multiband optical surveys—when combined with X-ray or SZE cluster surveys—offer much more than cluster photometric redshifts or even cluster weak lensing mass constraints. Surveys like DES, KiDS, HSC, and Legacy now and Rubin+Euclid later offer the information needed to control the contamination of the final cluster catalog. In practice, the optical richness of an ICM selected cluster encodes the probability that it is a real physical system as opposed to a random superposition of an X-ray or SZE noise fluctuation with an unassociated optical system. This additional information allows for much larger and deeper ICM selected cluster samples to be extracted from a given SZE or X-ray survey. We employ this statistical information in our MCMF code to greatly extend the Planck and SPT SZE surveys and on the eROSITA eFEDS to increase the sample purity. In case of the Planck catalog the systematic confirmation with MCMF resulted in a cluster catalog that triples the number of the previous known Planck clusters over the same footprint by maintaining a sample purity of 90%. With a similar purity threshold we obtained a new SPT-SZ catalog with >50% more clusters and doubling the number of high-z (z>0.8) clusters found in that survey. On the example of our work on eFEDS and SPT-SZ we will further show sample purity and the impact of optical confirmation on completeness can be traced to support future cosmological studies with those or similar samples.
The eROSITA Final Equatorial Depth Survey (eFEDS) is one of the first data products of the eROSITA surveys. It covers a sky area of 140 square degrees with depth equivalent to the final eROSITA all-sky survey. It represents the largest continuous X-ray fields to-date, except the ROSAT all sky survey. Compared to the ROSAT data, the eFEDS field has much higher angular resolution and sensitivity, making it one of the premier data set for measuring the angular power spectrum of X-ray sources. Models and simulations show that the angular power spectrum of galaxy clusters and groups can potentially provide competitive and complementary constraints on cluster cosmology and astrophysics, to traditional probes like cluster abundances.

In this work, we measure the X-ray angular power spectrum of galaxy clusters and groups in the eFEDS field. We show that the measured power spectrum of the eFEDS field is consistent with the predictions of cluster gas halo model calibrated from previous X-ray observations of galaxy clusters. With the eFEDS data, we provide first constraints on the level of non-thermal pressure fraction and feedback efficiency from supernovae and active galactic nuclei in clusters with the X-ray angular power spectrum. Using Fisher Forecast based on the eFEDS results, we show that the X-ray angular power spectrum from the upcoming eROSITA All Sky Survey (eRASS) data will provide competitive and complementary constraints on both astrophysical and cosmological parameters compared to abundance and stacking measurements. Specifically, it will constrain Omega_Matter and sigma_8 to within 5%, marginalized over astrophysical uncertainties.
Internal Dark Matter Structure of the Most Massive Galaxy Clusters since Redshift 1
Amandine Le Brun
LUTh, Paris Observatory, PSL University

The evolution of the dark matter profiles of high-mass galaxy clusters from $z \sim 1$ to the present day remains poorly constrained and is a powerful test of the LambdaCDM model. Such a test requires systematic confrontations of observations of a representative sample of the Universe's most massive clusters, preferably in several redshift bins, with tailor-made numerical simulations. To date, there exist no cosmological numerical simulations with the exceptionally large volume (required to simulate the rarest, most massive clusters) and the resolution (required to resolve their structure) necessary to undertake such a project. We will present the first results from a simulation campaign aimed at producing large cosmological simulations that are 1 Gpc/ h on a side and have a medium mass and spatial resolution. They are being complemented with very-high resolution zoom simulations which are progressively including the non-gravitational physics of galaxy formation such as star formation, supernova and AGN feedback. The simulations are produced using the AMR code RAMSES. The first results are based on a subset of the systems, consisting of the 25 most massive galaxy clusters at each redshift ($z=1, 0.8, 0.6$ and $0$) to study the evolution of their internal structure, finding that their dark matter profiles within $r_{500}$ are strikingly similar from $z \sim 1$ to the present day, exhibiting a low dispersion of $0.15$ dex, and showing little evolution with redshift in the radial logarithmic slope and scatter. They have the running power law shape typical of the NFW-type profiles, but their inner structure shows no signs of converging to an asymptotic slope. This suggests that this type of profile is already in place at $z > 1$ in the highest-mass haloes in the Universe, and that it remains exceptionally robust to merging activity.

Outer Galaxy Mass Traces Halo Mass with Scatter Comparable to Richness and Reduced Projection Effects
Alexie Leauthaud
University of California, Santa Cruz

I will present new results from Huang et al 2022 that use data from the Hyper Suprime Cam Survey (HSC) and gravitational lensing to show that the light from central galaxies is a much better tracer of halo mass than previously recognized. I will present four key results. First, custom measurements of outer light outperform “Cmodel” magnitudes as tracers of halo mass. Second, galaxy outer light correlates better with halo mass than galaxy inner light. Third, the outer light measured from 50 to 150 kpc has scatter comparable to richness based halo finders. Fourth, the shape of the lensing profile suggests that clusters selected according to galaxy outer light may have reduced selection effects compared to richness based methods. Finally, I will conclude with a discussion on how these results might be used to improve optical cluster finding algorithms.
Cosmological Constraints from Galaxy Cluster Statistics in KiDS
Giorgio Lesci
Università di Bologna

Breaking the degeneracies between the galaxy cluster mass-observable relation and cosmological parameters is one of the crucial quests in the current cosmological studies. This is possible by performing joint analyses of mass measurements and cosmological probes such as cluster abundance and clustering, as a function of redshift and mass proxy. I will present the cosmological analyses carried out by our group on KiDS data, based on the detections of galaxy clusters performed through the use of the cluster finder code AMICO (Adaptive Matched Identifier of Clustered Objects). AMICO was also selected as one of the two cluster detection codes to be used on the Euclid photometric galaxy catalogue, and it provides accurate estimates of sample purity and completeness thanks to the application of the novel algorithm SinFoniA (Selection Function extrActor). By means of new state-of-the-art cosmological analyses, we performed weak-lensing mass calibrations and we derived robust constraints on the main cosmological parameters ($\Omega_m$, $\sigma_8$, and $S_8$) from cluster counts, clustering and also from the 2-halo term of cluster stacked profiles.

Deep Learning-Based Galaxy Cluster Recognition
Maggie Lieu
University of Nottingham

Object recognition has been a ubiquitous task throughout the history of computer vision, but only with recent developments in deep learning have we been able to see significant improvements in performance. The robustness and reproducibility that we can achieve with machine learning, combined with the huge number of expected cluster detections in upcoming surveys, makes for an attractive case to integrate such methods into our pipelines. In this talk, I will provide a concise overview of what we have achieved and what we will be able to achieve with machine learning in the context of galaxy cluster recognition.
SuMIRe: One Survey to Find Them All and in the Darkness Dstudy Them in $\Lambda$CDM Where DE & DM Lie
Yen-Ting Lin
ASIAA

With its unprecedented combination of areal coverage, imaging quality and depth, the Subaru Hyper Suprime-Cam (HSC) survey has enabled a whole new avenue in studying clusters, from infancy (proto-clusters), adolescence (intense star formation at cosmic noon), to maturity (low redshift clusters dominated by quiescent galaxies). In addition to the traditional red-sequence cluster detection, the HSC data also enables one to find clusters as mass peaks (via weak lensing) and concentrations of emission line galaxies (via narrow-band data). I will review the lessons learned on the formation and evolution of galaxy populations in clusters, from the HSC observations from z~4 to z~0.3, paying particular attention to the evolution of brightest cluster galaxies.

The Chemical Evolution of Galaxy Clusters: Dissecting the Iron Mass Budget of the Intracluster Medium
Ang Liu
Max Planck Institute for Extraterrestrial Physics

I will present our recent results in the chemical evolution of galaxy clusters. We dissect the iron mass budget of the intracluster medium into different components according to their spatial distribution: an iron peak centered at the BCG, a wider and flatter iron plateau, and a small-scale central iron drop. We study the properties of these components in a sample of clusters with Chandra data, and explore the link between their properties and physical processes in different scales, from early star forming activities to AGN feedback. Thanks to the angular resolution of Chandra data, we are able to trace the increase in the size of the iron peak, which, however, does not grow significantly in mass in the redshift range [0, 1]. This behavior is consistent with an early production of the bulk of the metals in ICM, and a slow diffusion process possibly driven by the mechanical-mode feedback from the central galaxy. On the other hand, the iron plateau includes the majority of the iron mass and shows almost no evolution. Our results indicate that a comprehensive understanding of the spatial distribution of metals in the ICM is crucial to study the chemical evolution of galaxy clusters.
Enabling Cluster Cosmology with CMB Lensing
Mathew Madhavacheril
Perimeter Institute

Formation of dark matter halos is sensitive to the expansion rate of the Universe and to the growth of structures under gravitational collapse. Virialization of halos heats the gaseous intra-cluster medium to high temperatures, leading to copious emission of photons at X-ray wavelengths. We summarize the progress of X-ray surveys in determining cosmology using galaxy clusters. We review recent cosmological results based on cluster volume abundance, clustering, standard candles, extreme object statistics, and present relevant theoretical considerations. We discuss clusters as gravitation theory probes and present an outlook on future developments.

Analysis of Constrained Simulations of the Coma Cluster and of Its Surrounding Cosmic Web
Nicola Malavasi
Ludwig-Maximilians University

The cosmic web is a complex network of structures that fills the Universe, composed of galaxy clusters at the nodes, connected among them by filaments and separated by large voids. Filaments are elongated, one-dimensional structures which are much more elusive than clusters due to their lower density. The advent of wide-area large-scale spectroscopic galaxy surveys has allowed us to start investigating the properties of the filaments (and of the cosmic web in general) and to understand their nature. In particular, how filaments connect to clusters and how these connections impact cluster evolution is a hot topic in astrophysics. The average connectivity (number of connected filaments) of a few observed and simulated cluster samples has been measured and it has been demonstrated that it scales with cluster mass. Filaments connecting to clusters have also been detected in the gas phase, either as bridges of matter connecting pairs of clusters or as the tip of gas structures visible at large radii from the cluster center in X-ray observations. In Malavasi et al. 2020, we applied a cosmic web detection algorithm (DisPerSE) to the Sloan Digital Sky Survey (SDSS) to detect the filaments of the cosmic web from the galaxy distribution. We then looked at the position of the Coma cluster of galaxies and we detected three secure filaments connecting to the cluster. This discovery led to the developing of a further investigation based on constrained numerical simulations. This kind of simulations allow to reproduce in detail a portion of the nearby Universe, recreating observed clusters including Coma. We are currently performing an analysis of these simulations, aimed at reproducing the observed distribution of the filaments connected to Coma with the aim of studying their evolution throughout cosmic history and determining the impact of matter accretion channeled through these structures on the evolution of the Coma cluster. In this talk I will review the results of Malavasi et al. 2020 and introduce the results we obtained with the study of our constrained numerical simulations.
Brightest cluster galaxies (BCGs) are a peculiar family of objects: being the most luminous (and most massive) galaxies in the Universe, they are often located at the bottom of the gravitational potential of galaxy clusters. Because of their privileged position, their properties are severely influenced by, and in turn heavily affect, the extreme environmental conditions of galaxy cluster centers, making them attractive targets to benchmark models of galaxy formation. Using the DIANOGA hydrodynamical zoom-in cosmological simulation set of galaxy clusters, we analyze the dynamics traced by the stars belonging to the BCG and their surrounding diffuse component, forming the intracluster light (ICL), and compare them to the dynamics traced by dark matter and galaxies identified in the simulations. We compute scaling relations between velocity dispersion of the BCGs and clusters with the corresponding BCG stellar masses and total collapsed cluster mass, to find in general a good agreement with the most recent observational results. We find these relations to not significantly change up to redshift z=1, in line with a relatively slow accretion of the BCG stellar mass at late times. We weight the impact on the observed velocity dispersion when dynamically excluding the ICL, with the use of machine learning techniques. We also examine the main features of the velocity dispersion profiles, as traced by stars, dark matter, and galaxies. Our results confirm that simulations can correctly describe the dynamics of BCGs and their surrounding stellar envelope, as determined by the past star-formation and assembly histories of the most massive galaxies of the Universe.

In this talk, I will discuss the power and promise of clusters as astrophysical laboratories for testing the cold dark matter (CDM) paradigm. I will present results from mapping dark matter spatially with lensing observations from HST data; comparison with CDM simulations to stress-test this model, dealing with understanding the redistribution of DM in clusters in the inner density profiles and from tidal stripping; small scale constraints on DM, and new metrics for comparison of lens model inferences with simulations.
Astronomy is entering an era of data-driven science, due in part to modern machine learning techniques that enable powerful new data analysis methods. This is a shift in our scientific approach, and requires us to ask an important question: Can we trust the black box? In this talk, I will highlight opportunities and challenges for creating trustworthy ML to interpret galaxy cluster observations. I will show examples of how machine learning can be used, not just as a tool for getting “better” results at the expense of understanding, but also as a partner that can point us toward physical discovery.

Optical Surveys of Clusters of Galaxies
Masamune Oguri
Chiba University

Recent progress of wide-field multi-band imaging surveys allow us to construct large samples of clusters of galaxies out to redshift of 1 and beyond. In addition, we can identify clusters of galaxies in those surveys directly from weak lensing by identifying peaks in weak lensing mass maps. These weak lensing shear-selected clusters shed new light on the physical state of baryon in clusters. In this talk I will review the current state of the art of cluster finding in optical surveys and highlight some important results from those cluster samples.
Cosmological Simulations for Galaxy Evolution in Clusters
Annalisa Pillepich
MPIA, Heidelberg

I will give an overview of the scope and limitations of current cosmological hydrodynamical simulations of galaxy clusters, with a special focus on those that can resolve well the galaxies therein. I will then present exciting and recent results from such theoretical models, particularly in relation to observational findings, and discuss both the predicted fate of the massive central galaxies and that of the satellites. For example, have we yet understood what quenches massive satellite galaxies (> $10^{10.5}$-11 solar masses) in dense cluster-like environments? According to the IllustrisTNG simulations, massive satellites in clusters are quenched to first degree by their own AGN feedback and not by environmental processes.

The Universal Density Profile and the Core-excised Luminosity in Clusters Up to z=1.13
Gabriel W. Pratt
CEA Saclay

We investigate the regularity of galaxy gas cluster density profiles and the link to the relation between core-excised luminosity, L_{Xc}, and mass from the Yx proxy, M_{Yx}, for 93 objects selected through their Sunyaev-Zeldovich effect (SZE) signal. The sample spans a mass range of $M = [0.5 - 20] \times 10^{14}$ Msun, and lies at redshifts $0.05 < z < 1.13$. Using XMM-Newton observations, we derive an average ICM density profile for the SZE-selected systems and determine its scaling with mass and redshift. This average profile exhibits an evolution that is slightly stronger than self-similar, and a significant dependence on mass. Deviations from this average scaling with radius indicate different evolution for the core regions as compared to the bulk. We measure the radial variation of the intrinsic scatter in scaled density profiles and show that the scatter evolves slightly with redshift. We examine the evolution of the core properties over time for both scaled and unscaled density, which both suggest the presence of a majority population that is stable over time, and a minority population with higher central density. The relation between core-excised luminosity L_{Xc} and mass is extremely tight, with a measured logarithmic intrinsic scatter of 0.13. Using extensive simulations we investigate the impact of selection effects, intrinsic scatter, and covariance between quantities on this relation. The slope is insensitive to selection and intrinsic scatter between quantities; however, the scatter is very dependent on covariance between L_{Xc} and Yx. Accounting for our use of the Yx proxy to determine the mass, we estimate an upper limit to the logarithmic intrinsic scatter with respect to the true mass of 0.22. Our results are consistent with the overall conclusion that the ICM bulk evolves approximately self-similarly, with the core regions evolving separately. They indicate a systematic variation of the gas content with mass. They also suggest that the core-excised X-ray luminosity L_{Xc}, has a tight and well-understood relation to the underlying mass.
Untangling the Positive and Negative Impacts of AGN Feedback in Galaxy Clusters
Yu Qiu
Kavli Institute for Astronomy and Astrophysics

Outflows driven by active galactic nuclei (AGN) are an important channel for accreting supermassive black holes (SMBHs) to interact with their host galaxies and clusters. Properties of the outflows are however poorly constrained due to the lack of kinetically resolved data of the hot plasma that permeates the intracluster space. In order to untangle the various impacts of AGN feedback in galaxy clusters, we use simulations to study the evolution of the multiphase outflows and the long-term thermal balance of the intracluster medium (ICM). (1) By modeling both M87 and Perseus, and comparing the simulated thermal profiles with the X-ray observations of these two systems, we demonstrate that the outflow-to-accretion mass-loading factor can be constrained between 200-500. This parameter corresponds to a bulk flow speed between 4000-7000 km/s at around 1 kpc, and a thermalized outflow temperature between 1e8.7-1e9 K. Our results indicate that the dominant outflow speeds in giant elliptical galaxies and clusters are much lower than in the close vicinity of the SMBH, signaling an efficient coupling with and deceleration by the surrounding medium on length scales below 1 kpc. (2) On the other hand, for the low-energy component of the multiphase outflow, we demonstrate that cold gas can continuously fragment out of the radiatively cooling plasma, forming elongated filamentary structures extending tens of kiloparsecs. For a range of physically relevant temperature and velocity configurations, a ring of cold gas perpendicular to the direction of motion forms in the outflow. This naturally explains the formation of the blue loop of star-forming region in the Perseus cluster. The positive feedback mechanism can therefore be used to constrain the energetics of past AGN outbursts. Our simulation studies strongly suggest that AGNs in the centers of galaxy clusters tightly control both the thermal balance of the hot ICM and the scattered star formation activity in giant elliptical galaxies, and shed light on the complex interactions between SMBHs and their hosts mediated by the multiphase AGN-driven outflows.
X-ray Properties of HSC Weak Lensing Peaks in the eFEDS Footprint
Miriam E. Ramos-Ceja
Max Planck Institute for Extraterrestrial Physics

The eFEDS survey is a proof-of-concept mini-survey designed to demonstrate the survey science capabilities of eROSITA onboard SRG. It covers an area of 140 square degrees and more than 500 galaxy clusters have been detected out to a redshift of 1.3. The HSC-SSP S19A data release covers around 510 square degrees, containing approximately 36 million galaxies. This galaxy catalogue is used to construct a sample of more than 180 shear-selected galaxy clusters. The common area to both surveys covers about 90 square degrees, making it an ideal region to investigate the wavelength selection effects in the identification of galaxy clusters. In this talk, we aim to present and discuss the X-ray properties of shear-selected clusters in comparison with X-ray detected cluster samples. Our results show that the luminosity-mass relation of both samples is similar, and the distribution of the cluster dynamical properties of both samples is also indistinguishable. We find that there is no significant population of X-ray underluminous clusters, indicating that X-ray selected cluster samples are complete and can be used as an accurate cosmological probe.

Success and Failures of Cosmological and Hydrodynamical Simulations of Galaxy Clusters
Elena Rasia
INAF-OATS

Zoom-in simulations of galaxy clusters nowadays achieve a decent dynamical-scale coverage, including both the large-scale-structure gravitational field influence and the small-scales astrophysical processes such as stellar evolution and feedback, BH accretion, and AGN heating. The implemented subgrid models have been able to finally reproduce several key observational results related to cluster members and the intra-cluster medium. Nevertheless, it is still difficult to simultaneously reproduce all features observed in X-ray and optical wavelengths. In this talk I will review some of our recent comparisons performed against Chandra, XMM-Newton, and HST data.
Galaxy Clusters are a powerful cosmological probe, being able to track the evolution of large scale structure in the latest Universe. In the last decade, different experiments have detected clusters in X-rays, mm and optical-near IR wavelengths, providing catalogs of hundreds of well-characterised objects. Ongoing and future surveys are planned to release catalogs of thousands of clusters to be used for the cosmological analysis. It is therefore timely to nail down the possible sources of systematic uncertainties that might impact the accuracy and precision of the inferred cosmological parameters.

From current analyses, the cluster mass calibration stands out as the dominant source of systematics. I will review the basic ingredients used to build the theoretical mass-observable relations and calibrate them, and discuss the biases that these assumptions might introduce in the estimation of the cosmological parameters. I will focus in particular on the analysis of clusters detected through the thermal Sunyaev-Zeldovich effect.

The large statistics provided by future surveys will likely bring out new sources of systematics with non-negligible impact. I will discuss the importance of the characterisation of the other ingredients needed for the cluster cosmological analysis, namely the calibration of the mass function and selection function, showing also results of forecasts analyses.

On behalf of the Euclid consortium, I will present the official pipeline developed to constrain the cosmological parameters by using Galaxy Cluster as probes. I will present the two official Euclid cluster detection algorithms. The first cluster finder is PzWav. It is based on the wavelet method that searches for overdensities in the galaxy field and uses the information of the full probability redshift distribution. The second algorithm follows a completely different approach: it is an Adaptive Matched Identifier of Clustered Objects (AMICO) that takes advantage of the known statistical properties of the field galaxies and of the galaxy clusters to fully exploit the survey data and provide a complete and pure cluster catalogue.
I will present recent results from our triaxial modeling of the CLASH clusters using X-ray, SZ, and strong and weak lensing data. We find a distribution of three-dimensional shape parameters, quantified by the major and intermediate axial ratios and the concentration, consistent with the predictions of lambda-CDM. However, there are hints of more extreme major axial ratios, potentially suggesting later formation times and/or that baryonic processes are not effective in producing rounder shapes. In addition, the line of sight inclination angles are consistent with a random distribution, indicating that the CLASH selection based on round X-ray morphology is not strongly biased in this regard. Furthermore, our triaxial fits significantly reduce possible projection biases in recovering the non-thermal pressure fraction from direct measurements of the thermal pressure and total mass. In good agreement with Hitomi observations of Perseus, we find very little non-thermal pressure in the core region, suggesting that AGN feedback and other relevant processes heat the ICM in a relatively gentle manner. At larger radii, the measured non-thermal pressure fraction rises, as expected from simulations due to accretion. Also in agreement with simulations, we find significant cluster-to-cluster scatter in the non-thermal pressure fraction. We are now applying this triaxial modeling formalism to the much larger CHEX-MATE sample of galaxy clusters, and I will describe our expected results from those data.
Infalling matter around dark matter halos forms a sharp drop in the halos' density profile around the first orbital apocenters, which demarcates the physical boundary of dark matter halos, separating the infall stream from the multi-streaming, virialized region. This boundary, called "splashback radius", is known for its tight correlation with the halos' mass accretion history, therefore could be used to constrain the halo formation in the LCDM cosmology. In order to do such analysis, it is important to accurately measure the splashback radii and validate it against theoretical expectations. In this talk, the measurements of the splashback radii as well as the measurements of the WL and galaxy density profiles around SZ-selected clusters will be discussed. The results show that 1) the location of the splashback feature around the SZ clusters agrees well with that in N-body simulations, as opposed to the case for optically detected clusters. Also, Interestingly, 2) the shapes of galaxy density profile and WL profile around the SZ clusters agree well with each other, implying that the galaxies closely trace dark matter from large scales (~10-20 Mpc/h) down to very small scale (~0.3-0.5 MPc/h), given the selection in this analysis. In addition, it is known that infalling galaxies experience star formation quenching due to the extreme cluster environment (e.g. RAM pressure, strangulation). It is one of the key ingredients for understanding the evolution of galaxy clusters in cosmological time. It will be shown in this talk that the splashback radius and the galaxy density profile split on galaxy color could be used to constrain the timescale of star formation quenching of infalling galaxies. Using the same set of the SZ-selected clusters, we will show 3) how these measurements can quantitatively constrain the timescales for satellite galaxies to be quenched due to the cluster environment.
Surveys of Clusters of Galaxies: Astrophysical Insights
Michael Strauss
Princeton University

Surveys of Clusters of Galaxies: Astrophysical Insights Clusters may be identified and selected in a wide variety of ways: from optical photometric surveys, from galaxy redshift surveys, from X-ray maps, from CMB observations of the Sunyaev-Zel'dovich effect, and from gravitational weak lensing. Each of these techniques focuses on a different aspect of cluster physics, meaning that cluster samples selected in different ways often only have modest overlap with one another. Catalogs of clusters are used for a broad range of different science: as a probe of large-scale structure, as a test of cosmological models, as a laboratory to study galaxy evolution, as a platform for investigating the interaction of galaxies and the inter-cluster medium, to name a few. I will summarize various cluster survey techniques, emphasize what scientific questions each is best suited to address, and look forward to the next generation of surveys.

Molecular Gas Flows in Active Galaxies and the Potential Impact of Radio-Mechanical Feedback
Prathamesh Tamhane
University of Waterloo

We present an analysis of molecular gas flows in 14 cluster galaxies centered in cooling hot atmospheres (BCGs) experiencing radio-mechanical feedback. The BCGs contain $10^9$–$10^{11}$ Msol of molecular gas, much of which is being thrust outward by radio jets and lobes. We compared their molecular flows and radio jet powers to molecular outflows in 45 active galaxies in the local Universe to understand the relative efficacy of radio-mechanical, quasar, and starburst feedback over a range of active galaxy types. Molecular flows powered by radio-mechanical feedback in BCGs are $\sim$10–1000 times larger in extent compared to contemporary galaxies hosting quasar nuclei and starbursts. Radio-mechanical feedback yields lower flow velocities but higher momenta compared to quasar nuclei, as the molecular gas flows in BCGs are usually $\sim$10–100 times more massive. The product of the molecular gas mass and lifting altitude divided by the lifting power (AGN, starburst power) — a parameter referred to as the lifting factor—exceeds starbursts and quasars by two to three orders of magnitude, respectively. Therefore, when active, radio-mechanical feedback is generally more effective at lifting gas in galaxies compared to quasars and starbursts. The kinetic energy flux of molecular clouds generally lies below and often substantially below a few percent of the driving power (AGN, Starburst). The ratio of SFR to total molecular gas mass in BCGs lies between five and ten times below the Seyfert and starburst galaxies. We find, tentatively, that radio-mechanical feedback can suppress star formation relative to other active galaxies. Our results indicate that radio-mechanical feedback effectively suppresses star formation by regulating cooling atmospheres and by lifting molecular clouds out of galaxies.
The large-scale structure of the universe can be measured by multiple cosmological probes in photometric surveys, including cluster abundances and positions, galaxy positions, and weak gravitational lensing shear. Combining all these cosmological probes is important for current and future surveys to provide precise and accurate measurements of the cosmic structure. In this talk, I will introduce a framework to combine cluster abundances and all possible large-scale auto/cross correlations between clusters, galaxies, and weak lensing shear. I will first present the application of this framework on the first-year observation of the Dark Energy Survey (DESY1; To, Krause et al. 2021a&b). We find that this approach yields competitive cosmological constraints while being robust against several cluster specific systematics, such as projection/selection effects. I will then discuss on-going works of preparing for the upcoming DESY6 analysis, including improvements of cluster simulations for analyses validation, and developments of a novel sampling scheme that reduces the computational cost of the analysis by more than a factor 50. This talk will be concluded by discussing the prospects of this multi-probe cluster cosmology framework in the Rubin Observatory's LSST and CMB-S4 era.

The ZFIRE Survey: Environment Matters at z≈2
Vy Tran
University of South Wales

Multi-object near-IR spectroscopy opened up the z≈2 universe, an epoch when even massive galaxies in clusters are still forming a significant fraction of their stars. Using surveys that couple deep spectroscopy with space-based observations, we can now pinpoint when cluster galaxies begin to diverge from their field counterparts to separate evolution driven by galaxy mass from that of environment. The ZFIRE survey extends established scaling relations at z≈0 to cluster and field galaxies at z≈2 to track galaxy growth over the last 10 billion years. By comparing our observations to predictions from the IllustrisTNG cosmological simulation, we are able to "press rewind" and "fast forward" to quantify the interplay between multi-phase gas, star formation, and chemical enrichment in cluster galaxies. I summarize highlights from our ZFIRE survey (main take-away -- it's mostly about the gas) and introduce the AGEL survey, a pathfinder for Euclid and LSST for using gravitational lenses to find galaxy groups and clusters.
Probing Dark Matter Structure with Combined Strong and Weak Lensing from Space
Keiichi Umetsu
ASIAA

In this talk I will discuss prospects for studying the dark matter halo structure in galaxy clusters and constraining the nature of dark matter from combined strong and weak lensing, using wide-field imaging observations from space missions, such as the Roman Space Telescope. In particular, I will discuss the possibility of using the radial acceleration relation (RAR) in galaxy clusters to constrain the self-interacting dark matter cross section from strong-and-weak lensing and X-ray observations. I will present results obtained from the CLASH lensing and X-ray data sets in combination with the BAHAMAS.

Satellite Quenching was not Important for z~1 Clusters: Most Quenching Occurred during Infall
Stephane Werner
University of Nottingham

We quantify the relative importance of environmental quenching versus pre-processing in $z\sim1$ clusters by analysing the infalling galaxy population in the outskirts of 15 galaxy clusters at $0.8<z<1.4$ drawn from the GOGREEN and GCLASS surveys. We find significant differences between the infalling galaxies and a control sample; in particular, an excess of massive quiescent galaxies in the infalling region. These massive infalling galaxies likely reside in larger dark matter haloes than similar-mass control galaxies because they have twice as many satellite galaxies. Furthermore, these satellite galaxies are distributed in an NFW profile with a larger scale radius compared to the satellites of the control galaxies. Based on these findings, we conclude that it may not be appropriate to use \lq field\rq\ galaxies as a substitute for infalling pre-cluster galaxies when calculating the efficiency and mass dependency of environmental quenching in high redshift clusters. By comparing the quiescent fraction of infalling galaxies at $1<R/v<3$ to the cluster sample ($R/v<1$) we find that almost all quiescent galaxies with masses $>10^{11}$\Msun\ were quenched prior to infall, whilst up to half of lower mass galaxies were environmentally quenched after passing the virial radius. This means most of the massive quiescent galaxies in $z\sim1$ clusters were self-quenched or pre-processed prior to infall.
Radio-mode of AGN feedback has been widely accepted as a promising heating mechanism of the intracluster medium (ICM). High-resolution X-ray observations show that the mechanical energy released inside the bubbles of relativistic plasma is sufficient to balance the radiative cooling losses in cluster cores. However, through what specific way(s) the bubble energy is transferred to the ICM is still under debate. In this talk, I will introduce an attractive possibility – excitation of internal gravity waves by the long-term interaction between intact bubbles and stratified atmospheres. These waves propagate horizontally and downwards from the rising bubbles, spreading their energy over large volumes of the ICM. We numerically demonstrate this picture in the framework of our rigid-bubble model and find that the terminal velocities of the flattened bubbles are small enough so that they can efficiently drive internal waves. If our findings are scaled to the conditions of the Perseus cluster, the expected bubble’s terminal velocity is \( \sim 100-200 \) km/s near the cluster cores, which is in broad agreement with direct measurements by the Hitomi satellite. Meanwhile, our simulations show that buoyantly rising bubbles play an important role in shaping the \( \sim 10-100 \) kpc long ionized/molecular filaments (e.g., Ha and CO) in cluster cores. The gas is dragged up by the eddies in the bubble’s wake and radially stretched during the propagation, which is expected to have high radial velocities, i.e., by a factor of \( \sim 2-3 \) higher than the bubble’s rise velocity. Our model explains both the shape and amplitude of the filaments’ velocity structure function measured in nearby clusters.
Weak Lensing Mass Estimates of the Most Distant Clusters in the SPT-SZ Survey
Hannah Zohren
Argelander Institute for Astronomy

In my talk, I will present a Hubble Space Telescope HST weak gravitational lensing study of nine distant and massive galaxy clusters with redshifts $1.0 < z < 1.7$ ($z_{\text{median}} = 1.4$) and SZ detection significance $> 6.0$ from the South Pole Telescope Sunyaev Zel'dovich (SPT-SZ) Survey. I will demonstrate how we measure weak lensing galaxy shapes in HST/ACS F606W and F814W images and use additional observations from HST/WFC3 in F110W and VLT/FORS2 in U_HIGH to preferentially select background galaxies at $z > 1.8$, achieving a high purity. We combine recent redshift estimates from the CANDELS/3D-HST and HUDF fields to infer an improved estimate of the source redshift distribution and measure weak lensing masses by fitting the tangential reduced shear profiles with spherical NFW models. I will then present our constraints on the scaling relation between the unbiased SZ detection significance and the cluster mass for the SPT-SZ Survey. Combining our weak lensing mass constraints with results obtained by previous studies for lower redshift clusters, we extend the calibration of the scaling relation out to higher redshifts. In particular, we find that the mass scale inferred from our highest redshift bin $1.2 < z < 1.7$ is fully consistent with the constraints derived at lower redshifts. Thus, our results agree with previous findings, indicating that the cluster mass scale derived from the weak lensing data is lower than the mass scale expected in a Planck Lambda-CDM cosmology given the SPT-SZ cluster number counts.

Simulations of the Hot and Dynamic ICM of Galaxy Clusters
John ZuHone
Smithsonian Astrophysical Observatory

The hot plasma in clusters of galaxies, the ICM, makes up the bulk of the baryonic material of the cluster and is evidenced by X-ray observations and the Sunyaev-Zeldovich effect at mm wavelengths. Radio observations provide a window onto the cosmic ray component of the cluster gas, which is strongly linked to the thermal plasma. For these reasons, the ICM presents our most detailed window on the energetics and dynamics of clusters as a whole, which can be explored in detail by simulations. I will showcase a number of recent results from simulations of galaxy clusters, both in idealized merger simulations and from cosmological simulations, with a focus on comparisons to observations using mocks and the power of machine learning techniques to provide new ways of making the connections between theory and observation.
2022 Spring Symposium

Galaxy Clusters 2022: Challenging Our Cosmological Perspectives

POSTERS
Time-delay Cosmography with Cluster Strong Lensing
Ana Acebron, Università degli Studi di Milano

How to Improve the Measurements and Interpretation of the Intracluster Light in Galaxy Groups?
Syeda Lammin Ahad, Leiden Observatory

Gas Rich or Poor? Stacking Reveals a Significant Molecular Gas Deficiency in Cluster Galaxies
Stacey Alberts, University of Arizona

Differences in the Physical Properties of Satellite Galaxies Belonging to Relaxed and Disturbed Clusters
Franklin Aldas, Universidad de La Serena

Exploring Imprints of Wavelike Dark Matter in Galaxy Clusters through Gravitational Lensing
Amruth Alfred, University of Hong Kong

New Cosmological Constraints from Cluster Catalogs
Yuba Amoura, University of Waterloo

Cool Circumgalactic Gas in Galaxy Clusters: Connecting the DESI Legacy Imaging Survey and SDSS DR16 Mg II Absorbers
Abhijeet Anand, Max Planck Institute for Astrophysics

Clusters of Low Surface Brightness: Impact on Scaling Relations and Survey Completeness
Stefano Andreon, INAF-OA Brera, Italy

The Environmental Dependency of Galaxy Evolution in and around Galaxy Clusters
Mohammadreza Ayromlou, Heidelberg University

Galaxy Evolution in the Cosmic Web at z>1.5
Michael Balogh, University of Waterloo

The MAGPI Survey
Andrew Battisti, Australian National University

Red Dragon: A Redshift-Evolving Gaussian Mixture Model for Galaxies
William K. Black, University of Michigan

The South Pole Telescope Strong Lensing Cluster Sample: Constraints on the Mass-Concentration relation of Galaxy Clusters
Lindsey Bleem, Argonne National Laboratory

Galaxy Cluster Simulations with a Spectral Cosmic Ray Model
Ludwig Böss, Ludwig-Maximilians-University Munich

XSORTER: X-ray Survey Of meRging clusTErs in Redmapper
Faik Bouhrik, California Northstate University/University of California Davis

Don't Forget to Stir: KHI in MHD Simulations of Merging Galaxy Clusters
Urmila Chadayammuri, Smithsonian Observatory

Uncovering Massive Galaxy Protoclusters in the Early z=4-7 Universe with the South Pole Telescope
Scott Chapman, UBC

The Frequency of Large Molecular Gas Reservoirs in Dense Environments
Zhengyi Chen, Instituto de Astrofísica de Canarias (IAC)

The First Weak-lensing Mass Calibration of Galaxy Clusters in the eROSITA Final Equatorial-Depth Survey (eFEDS) with the Hyper Suprime-Cam Subaru Strategic Program Survey
I-Non Chiu, Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tung University (SJTU)
Morpho-kinematics of MACS J0416.1-2403 dwarf galaxies  
Bianca-Lulia Ciocan, University of Vienna, Department of Astrophysics

Forward Modelling the Cosmological Large Scale Structure Seen in the X-ray by eROSITA  
Johan Comparat, MPE

Galaxy Cluster Mergers in Simulations and their Impact on the Stellar Component of BCGs  
Ana Contreras Santos, Universidad Autónoma de Madrid

Galaxy Clusters Behind the Magellanic Clouds  
Jessica Craig, Keele University

Brightest Cluster Galaxies Are Statistically Special From z=0.3 to z=1.0  
Roohi Dalal, Princeton University

Clusters' Far-reaching Influence of Narrow-angle Tail Radio Galaxies  
Kellie de Vos, University of Nottingham

Relativistic Corrections to Galaxy Cluster Hydrostatic Masses of Galaxy Clusters of Galaxy Clusters  
Shantanu Desai, IIT Hyderabad

How Environment Defines the HI Content of Galaxies  
Boris Deshev, Astronomical Institute, Czech Academy of Sciences

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