# Snowmass2021 Letter of Interest:
# Cosmology from Multi-Wavelength Observations of Clusters of Galaxies

## Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CompF2) Theoretical Calculations and Simulation

**Contact Information:** Submitter Name/Institution: Lindsey Bleem (Argonne National Laboratory)
Contact Email: lbleem@anl.gov

**Authors:** Lindsey Bleem (Argonne National Laboratory), Camille Avestruz (University of Michigan), Yuanyuan Zhang (Fermilab)

## Abstract:

Clusters of galaxies have proven to be powerful probes of dark energy and dark matter and are expected play a significant role in future cosmic experiments. An outstanding opportunity in the studies of clusters is the cross-analysis of multi-wavelength observations collected by multiple surveys. We propose that this opportunity should be given serious consideration in the future with efforts to ensure close collaboration between the diverse experimental collaborations and simulation efforts as well as support for dedicated and open-access resources to facilitate this work.

# Overview

Clusters of galaxies—the largest gravitationally-bound systems in the universe—are prominent tracers of cosmic structure. The abundance and spatial distribution of these massive systems are highly sensitive to the physical laws and phenomena that govern its growth. Clusters particularly place sensitive constraints on Dark Energy parameters, the sum of the masses of the neutrino species, primordial non-Gaussianity, and the density of dark matter (See e.g., (1) for a recent review) . The potential for cluster samples to constrain cosmology has long been recognized and, indeed, for some cosmological models, clusters have the potential to be the *most* constraining probe (2). However, such constraints are currently limited by systematic error control. The next decade offers an unprecedented confluence of expansive new multi-wavelength cosmic surveys and new computational and simulation capabilities which, if fully leveraged, will allow for the requisite control of these errors and will enable us to maximize the potential of these extreme systems to probe the composition and physical laws of the universe.

# Advances

The primary steps of cluster-based cosmological analyses are cluster identification and the connection of galaxy cluster observables to the mass of the systems. Both of these steps are subject to systematic bias from astrophysical or observational sources. As clusters are multi-component systems and traced by numerous signatures (e.g., from overdensities of galaxies at optical and infrared wavelengths, hot gas detectable at X-ray and millimeter wavelengths, and as significant mass peaks in lensing data), employing data from all available telescopes will enable analyses that are not susceptible to any single set of astrophysical systematics or observational biases. The upcoming surveys are numerous, each offering distinct advantages. These include:

- **Vera Rubin Observatory's Legacy Survey of Space and Time (LSST)** and **Euclid**: The upcoming (2022) LSST (3) and ESA/Euclid mission (4) will provide deep observations of the sky at optical through infrared wavelengths. In addition to compiling large samples of clusters identified via galaxy overdensities, these surveys will provide critical weak lensing mass calibration and redshift information for cluster samples selected in other surveys.
- **CMB-S4**: Commencing operations in the late 2020s, CMB-S4 (5) will be unprecedented wide-area millimeter survey over $\sim 70\%$ of the sky. Over 100,000 galaxy clusters are expected to be detected in the arcminute-scale survey data via the thermal Sunyaev Zel'dovich effect (**?** ) to produce an approximately mass-limited catalog of clusters out to the epoch of cluster formation (6). Additionally, the gravitational lensing maps reconstructed from the cosmic microwave background (CMB) survey data will unique mass calibration measurements for the highest redshift systems.
- **eROSITA/Athena**: The eROSITA (7) and ESA/Athena mission (with NASA involvement) represent the next generation of X-ray surveys. The ongoing all sky eROSITA mission is expected to find discover ∼100,000 galaxy clusters (primarily at lower redshifts) in a way that is highly complimentary to the optical and SZ surveys. Athena's (scheduled for launch in 2031) unprecedented sensitivity will allow detection of galaxy clusters and groups to $z \sim 2$ in a modest wide-area survey as well as extensive targeted characterization of clusters detected at other wavelengths (8).
- **Dark Energy Spectroscopic Instrument (DESI)** + Future Spectroscopic Surveys: Wide area spectroscopic surveys such as DESI (9) are also a critical piece for mitigating systematic biases in next generation cluster analyses as large spectroscopic samples are crucial for calibrating photometric redshifts for both the cluster samples themselves as well as those of the source galaxies used in weak lensing mass calibration. Spectroscopic surveys are also important for quantifying the contamination to optical cluster samples from line-of-site structure.

In parallel to the significant advancement in observational capabilities we are seeing similar revolution in the computational and simulation tools used to model these systems and provide the cosmological predictions.

**Hydrodynamical simulations** are increasingly able to self-consistently follow astrophysical processes, bridging the gap between cosmological simulations that employ coarse sub-grid model approaches with idealized simulations that are able to resolve the smaller-scale physics relevant to galaxy formation processes. A multi-wavelength approach to cluster-based cosmology will require simulations that can capture both the global diversity of galaxy cluster populations (emphasizing the need for large volume boxes) and the effects of astrophysical processes on the intracluster medium and stellar populations in and around galaxy clusters (emphasizing the need for self-consistent models).

Cluster cosmology requires high precision. Analysis pipelines have therefore evolved to increasing complexity in order to account for astrophysical effects on cosmological observables (10). As a result, emerging performance-improving technologies such as deep machine learning methods (11) and GPU computing (12) are becoming essential. Finally, validation for such analysis pipelines require data from large volume cosmological simulations with models that incorporate baryonic physics processes (13).

# Opportunities

Key to the success of this future expansive cluster cosmology effort is close collaboration between observers, simulators, and analysts. On the observational front this will require extensive calibration across experiments and collaborations as well as the tighter integration of simulation efforts with the suite of multi-wavelength surveys.

Cross-experiment analyses of galaxy clusters will also require dedicated computing and software infrastructure. To enable collaboration, the platforms for such infrastructure need to be open and accessible to all participating scientific communities. Guidelines for contribution and quality assurance also need to be collaboratively developed and mutually agreed upon by all communities.[1]

[1] https://openastronomy.org/

## References


[1] S. W. Allen, A. E. Evrard and A. B. Mantz, *Cosmological Parameters from Observations of Galaxy Clusters*, **49** (2011) 409 [1103.4829].

[2] S. Dodelson, K. Heitmann, C. Hirata, K. Honscheid, A. Roodman, U. Seljak et al., *Cosmic Visions Dark Energy: Science*, *arXiv e-prints* (2016) arXiv:1604.07626 [1604.07626].

[3] LSST Science Collaboration, P. A. Abell, J. Allison, S. F. Anderson, J. R. Andrew, J. R. P. Angel et al., *LSST Science Book, Version 2.0*, *arXiv e-prints* (2009) arXiv:0912.0201 [0912.0201].

[4] R. Laureijs, J. Amiaux, S. Arduini, J. L. Auguères, J. Brinchmann, R. Cole et al., *Euclid Definition Study Report*, *arXiv e-prints* (2011) arXiv:1110.3193 [1110.3193].

[5] K. N. Abazajian, P. Adshead, Z. Ahmed, S. W. Allen, D. Alonso, K. S. Arnold et al., *CMB-S4 Science Book, First Edition*, *arXiv e-prints* (2016) arXiv:1610.02743 [1610.02743].

[6] K. Abazajian, G. Addison, P. Adshead, Z. Ahmed, S. W. Allen, D. Alonso et al., *CMB-S4 Science Case, Reference Design, and Project Plan*, *arXiv e-prints* (2019) arXiv:1907.04473 [1907.04473].

[7] A. Pillepich, C. Porciani and T. H. Reiprich, *The X-ray cluster survey with eRosita: forecasts for cosmology, cluster physics and primordial non-Gaussianity*, **422** (2012) 44 [1111.6587].

[8] K. Nandra, D. Barret, X. Barcons, A. Fabian, J.-W. den Herder, L. Piro et al., *The Hot and Energetic Universe: A White Paper presenting the science theme motivating the Athena+ mission*, *arXiv e-prints* (2013) arXiv:1306.2307 [1306.2307].

[9] M. Levi, L. E. Allen, A. Raichoor, C. Baltay, S. BenZvi, F. Beutler et al., *The Dark Energy Spectroscopic Instrument (DESI)*, in , vol. 51, p. 57, Sept., 2019, 1907.10688.

[10] T. M. C. Abbott, M. Aguena, A. Alarcon, S. Allam, S. Allen, J. Annis et al., *Dark Energy Survey Year 1 Results: Cosmological constraints from cluster abundances and weak lensing*, **102** (2020) 023509.

[11] M. Ntampaka, C. Avestruz, S. Boada, J. Caldeira, J. Cisewski-Kehe, R. Di Stefano et al., *The Role of Machine Learning in the Next Decade of Cosmology*, **51** (2019) 14 [1902.10159].

[12] K. Heitmann, N. Frontiere, C. Sewell, S. Habib, A. Pope, H. Finkel et al., *The Q Continuum Simulation: Harnessing the Power of GPU Accelerated Supercomputers*, **219** (2015) 34 [1411.3396].

[13] N. E. Chisari, A. J. Mead, S. Joudaki, P. G. Ferreira, A. Schneider, J. Mohr et al., *Modelling baryonic feedback for survey cosmology*, *The Open Journal of Astrophysics* **2** (2019) 4 [1905.06082].