The Physics of Galaxy Cluster Outskirts

Daisuke Nagai

Yale University

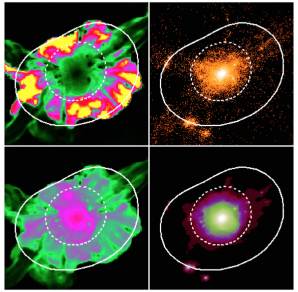
ICM workshop, Copenhagen

Aug 15, 2022

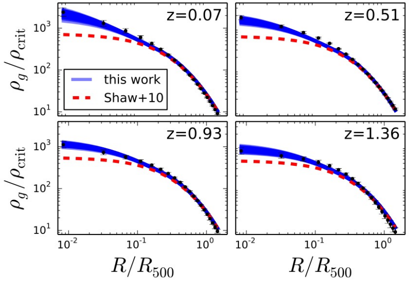
Modeling Challenges in the Era of Multi-wavelength Cluster Surveys

X-ray *Microwave* *Optical*

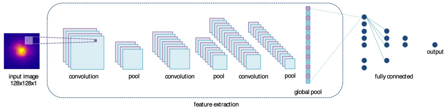
Computer Simulation



Analytical Modeling



Machine Learning



Opportunity

Cosmology with Multi-Wavelength Observations of Dark Matter Halos (including clusters, groups & galaxies)

Challenge

Develop a physically-motivated and computationally efficient model for forward-modeling the **DM halo-gas-galaxy connection** (e.g., scatter, covariance, selection function etc) for cosmological inference with large cosmological surveys

Frontiers

1. **Computational:** gain physical insights from *hydrodynamical cosmological simulations*
2. **Modeling:** develop of *a physically-motivated, computationally efficient model*
3. **Data-Driven:** extract more from large simulation & observational data using *machine learning*

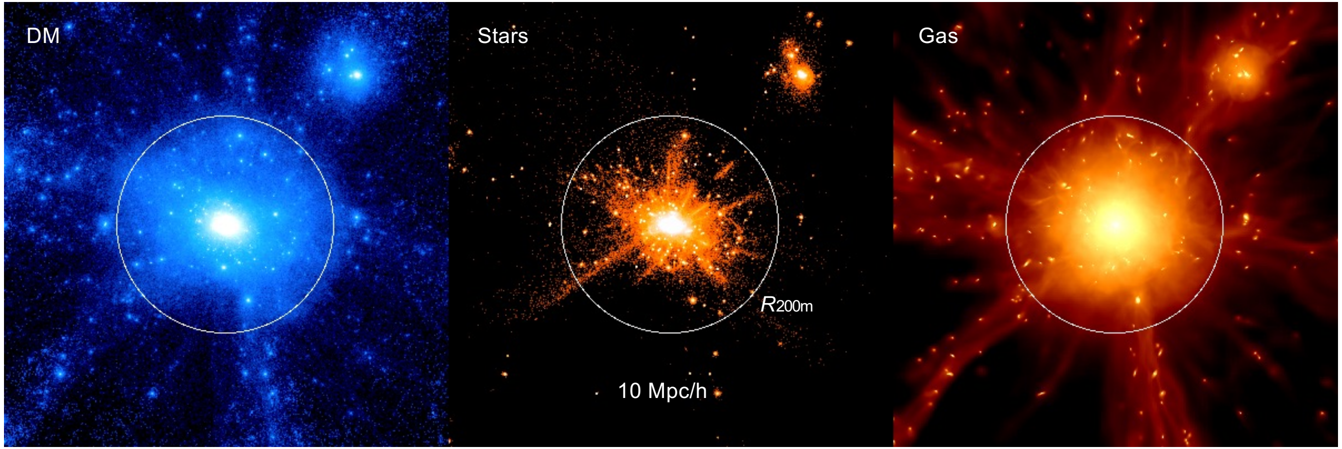
Computational Frontier

gain physical insights on the non-linear structure formation using hydrodynamical cosmological simulations

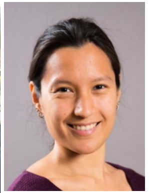
Omega 500 Simulation Project

High-Resolution *N*-body+Gasdynamics Cosmological Simulation with Adaptive Refinement Tree (ART) code on Yale's OMEGA HPC Cluster

Box size = $500h^{-1}$ Mpc, DM particle mass ≈ $10^9 h^{-1} M_\odot$, Peak Spatial Resolution ≈ $3.8\ h^{-1}$ kpc



Kaylea Nelson



Camille Avestruz

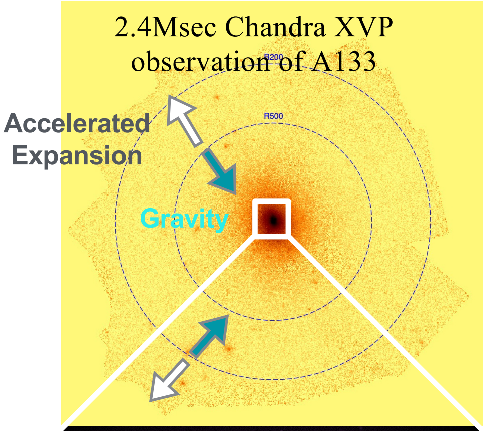
Erwin Lau

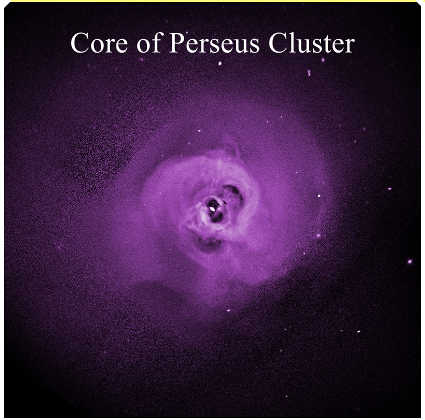
Han Aung

- $500h^{-1}$ Mpc zoom-in cosmological hydrodynamical simulations of 65 galaxy clusters with $M_{500c} > 3\times10^{14}\ h^{-1}\ M_\odot$ in WMAP5 cosmology (Nelson et al. 2014)
- Three runs: (1) simple non-radiative gas physics, (2) +galaxy formation physics, (3) +AGN feedback physics.

ICM Physics

Insights from Hydro Simulations





✦Cluster Outskirts

Gas Accretion & Non-equilibrium phenomena

1. Gas clumping/inhomogeneities
2. Non-thermal pressure due to gas motions
3. Shapes of DM halo & gas
4. Splashback & Shock Radii
5. Non-equilibrium electrons
6. Filamentary gas streams

Tractable

Key Parameters
Mass & MAH/Mergers

Walker et al. 2019 for a recent review

✦Cluster Cores

Heating, Cooling & Plasma physics

1. AGN feedback (Mechanical/CR heating)
2. Dynamical Heating, Gas sloshing
3. Thermal Conduction, Magnetic Field, He sedimentation

Great science targets for ongoing and planned X-ray missions
(e.g., eROSITA & LEM) - Talks by Analisa, Dylan, Nhut, Maxim, and more!

Non-thermal Pressure
Analytical Model vs. Hydro Simulations

Shi & Komatsu 2014 (analytical model)

$$\frac{d\sigma^2_{\rm nth}}{dt} = -\frac{\sigma^2_{\rm nth}}{t_{\rm d}} + \eta \frac{d\sigma^2_{\rm tot}}{dt}$$

Time Change in Turbulence Energy per unit mass

Dissipation of Turbulence

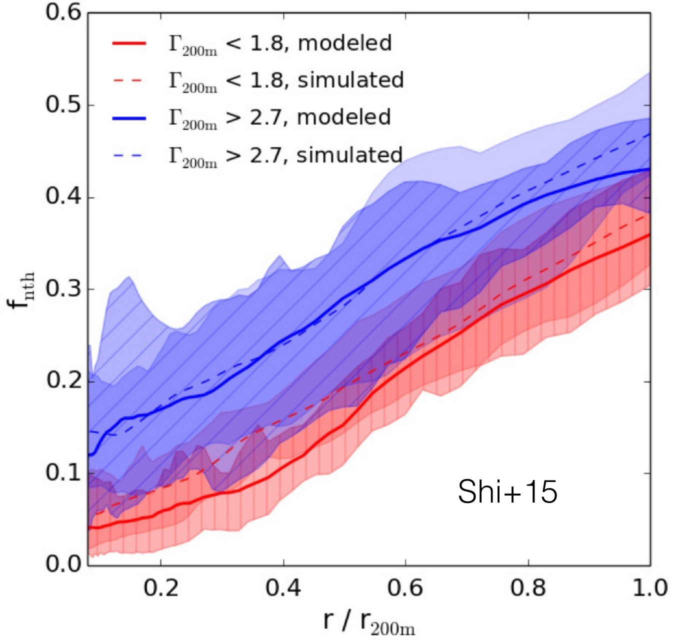
Generation of Turbulence sourced by mass accretion

Implications for the HSE mass bias
Shi, Komatsu, Nagai, Lau 2016

Turbulence evolution in the density stratified medium
Shi, Nagai, Lau 2018

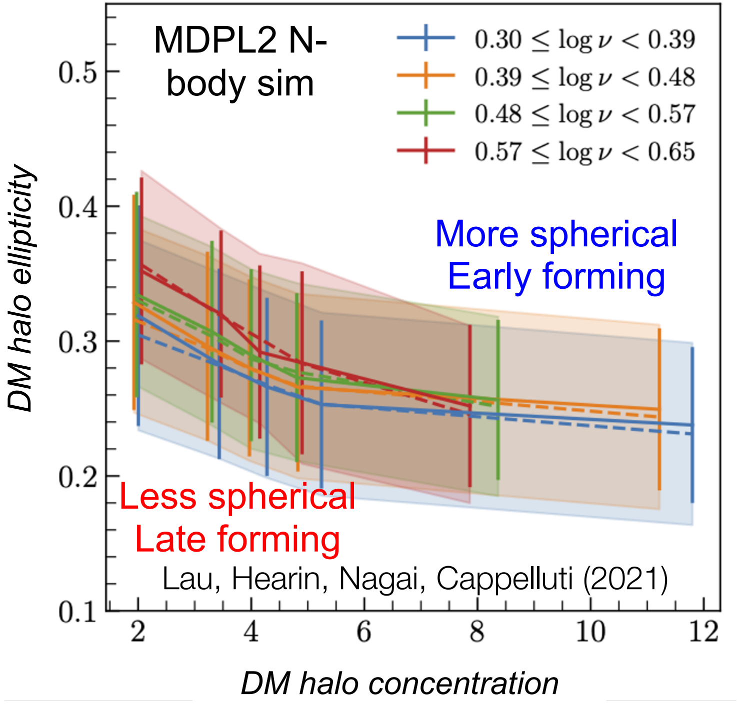
Impact of Non-thermal pressure on tSZ effects
Green, Aung, Nagai, van den Bosch 2020

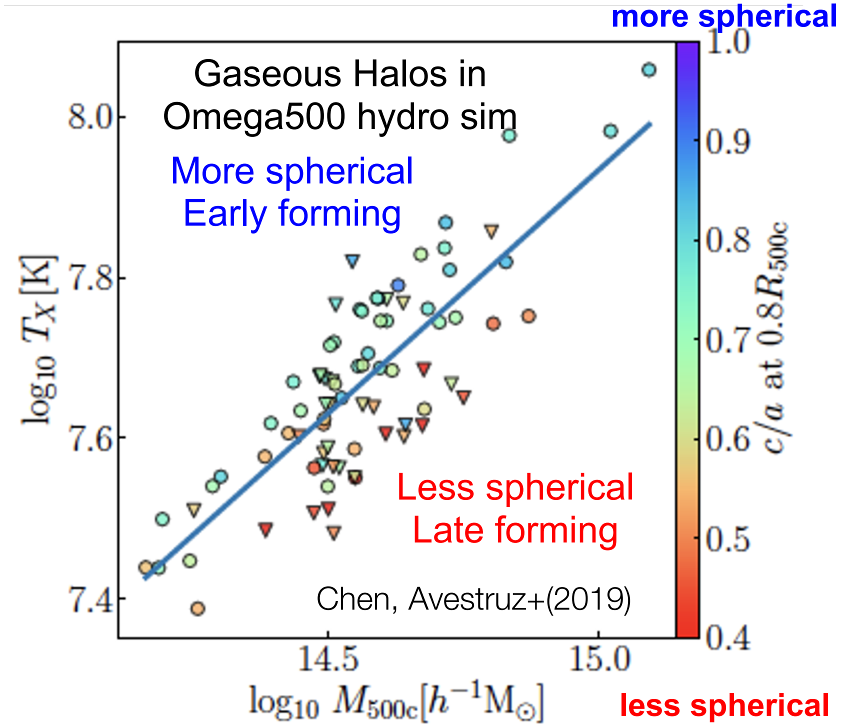
Comparison to the Omega 500 simulation (Nelson+14)



Semi-analytic model can match the results of hydrodynamical simulations remarkably well

Halo & Gas Shape and Formation History

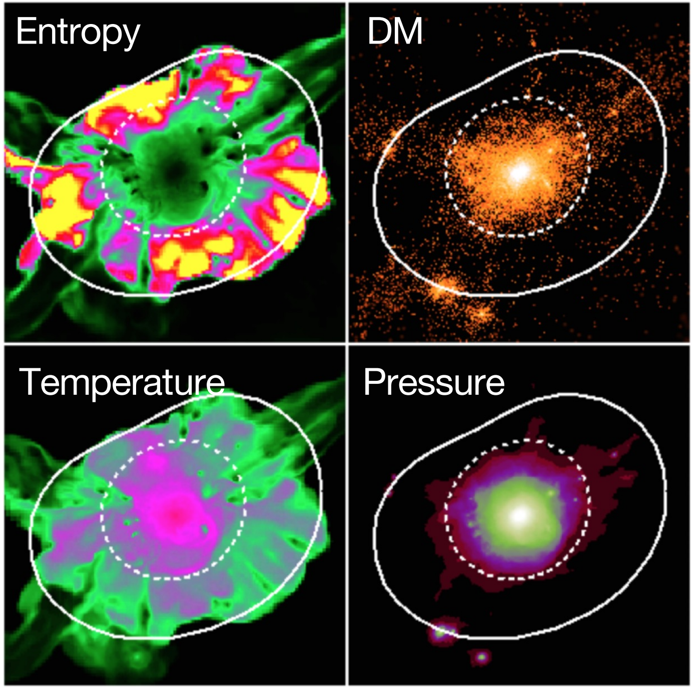




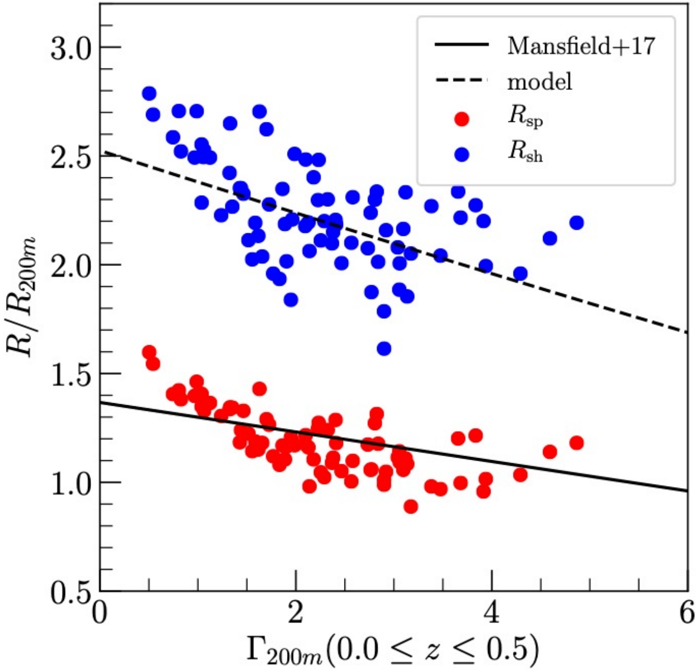
- DM halo & gas shapes depend on its formation history: early-forming/higher concentration halos are more spherical
- Systematic scatter in observable scaling relation driven by halo formation history

Splashback vs. Accretion Shock Radii

DM splashback computed using SHELLFISH (Mansfield+17)

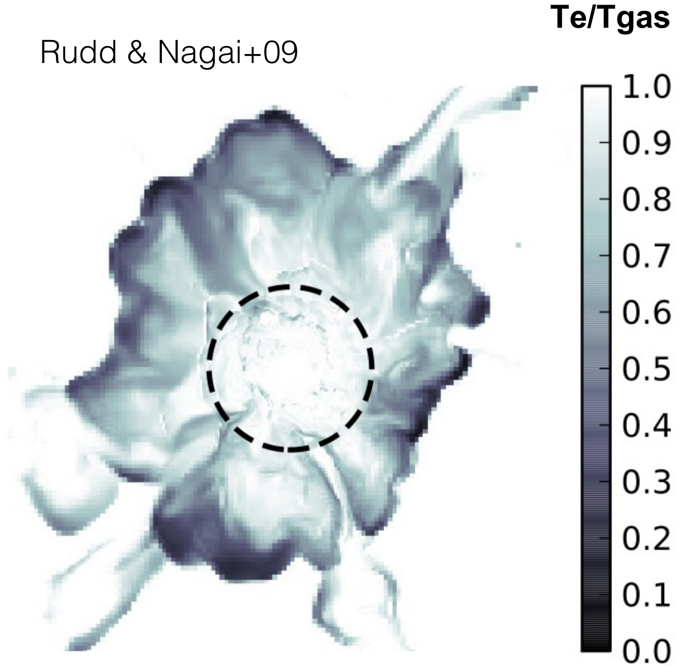


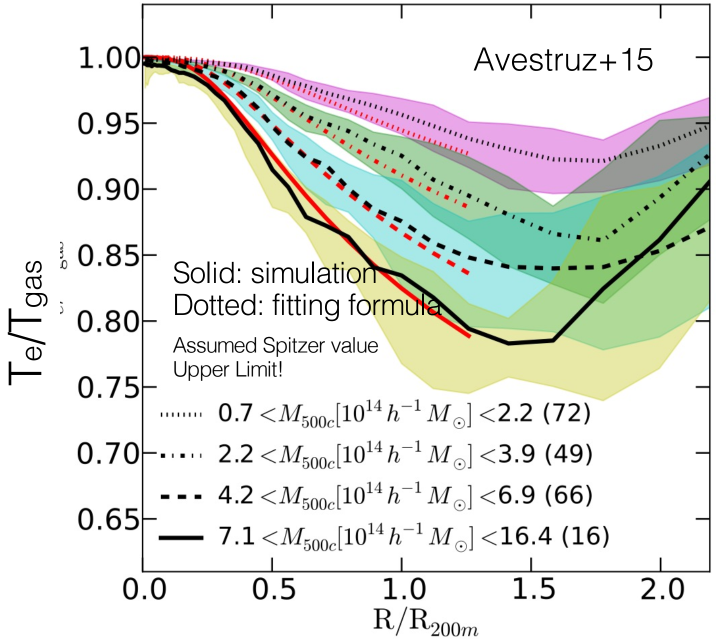
Aung, Nagai, Lau 2020



Accretion shock radius is ~2 times larger than the Splashback radius, making the hot gas extend beyond the splashback radius.

Beyond Hydrodynamics: Electron-Proton Equilibration in Cluster Outskirts



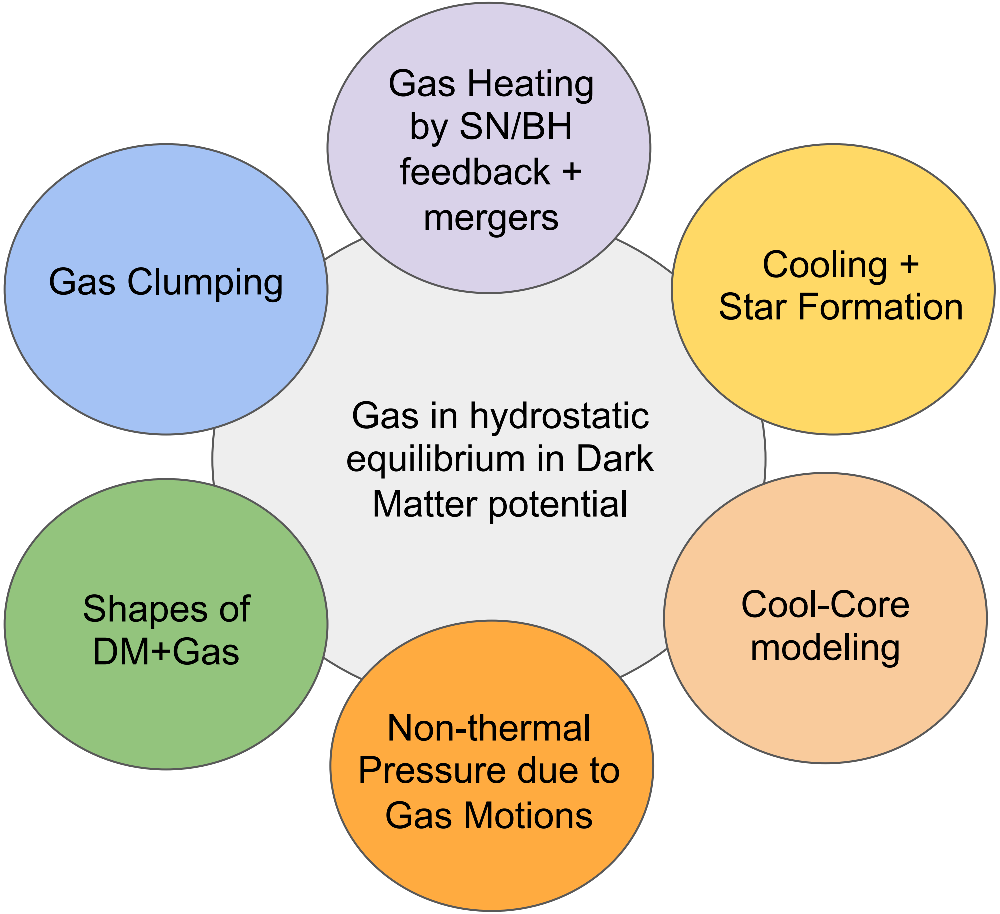


In the outskirts of galaxy clusters, the collision rate of electrons and protons becomes longer than the age of the universe (see Anbajagane+22 for the recent SPT detection)

Modeling Frontier

develop a physically-motivated, computationally efficient model for modeling multi-properties of galaxies, groups, and clusters

Baryon Pasting Project



Goals

Maximize the scientific returns of multi-wavelength surveys of galaxy clusters and LSS via Multi-wavelength Astronomical Surveys

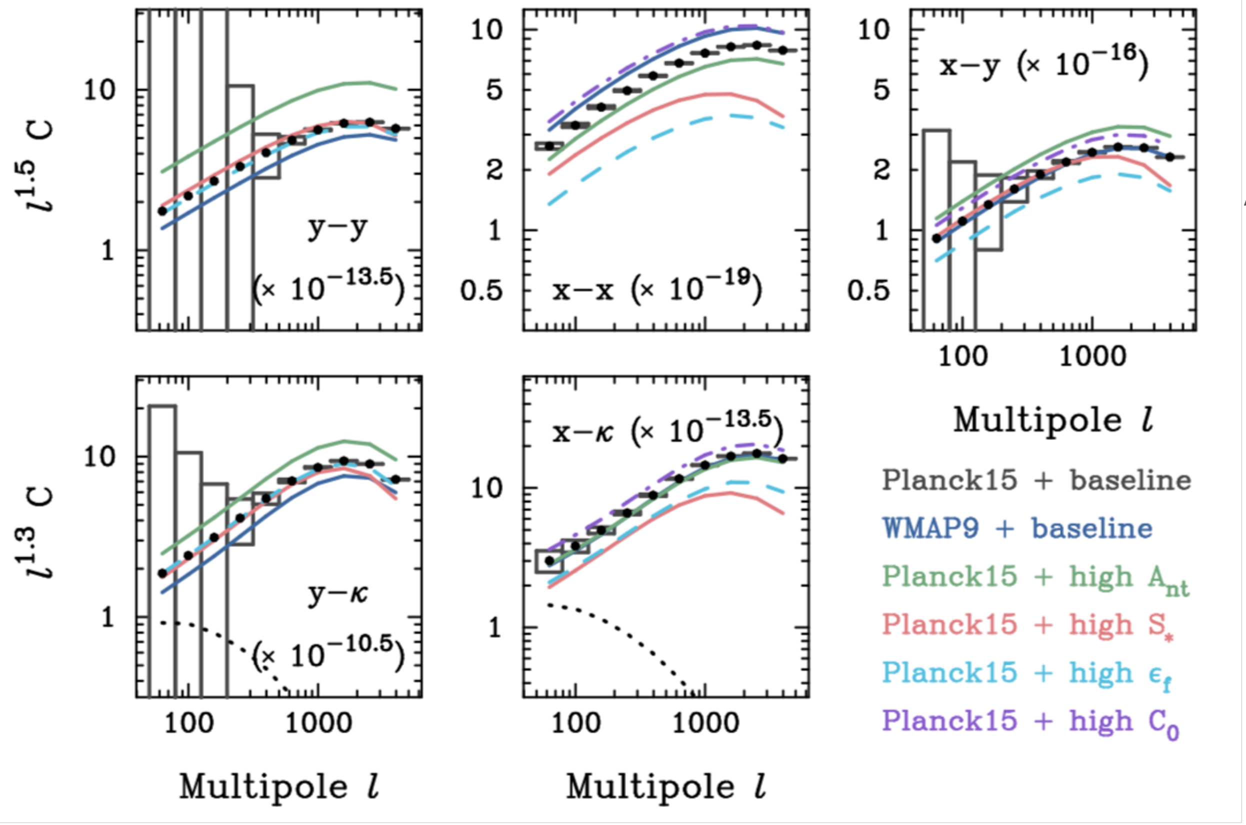
Challenges

- Halo-Gas Connection: modeling of SZ and X-ray profiles of ICM and CGM
- Baryonic effects: constraining baryonic effects with WL x SZ cross-correlations

Solution

Develop a **simple, physically-motivated computationally efficient method** for modeling multi-properties of clusters, groups, and galaxies

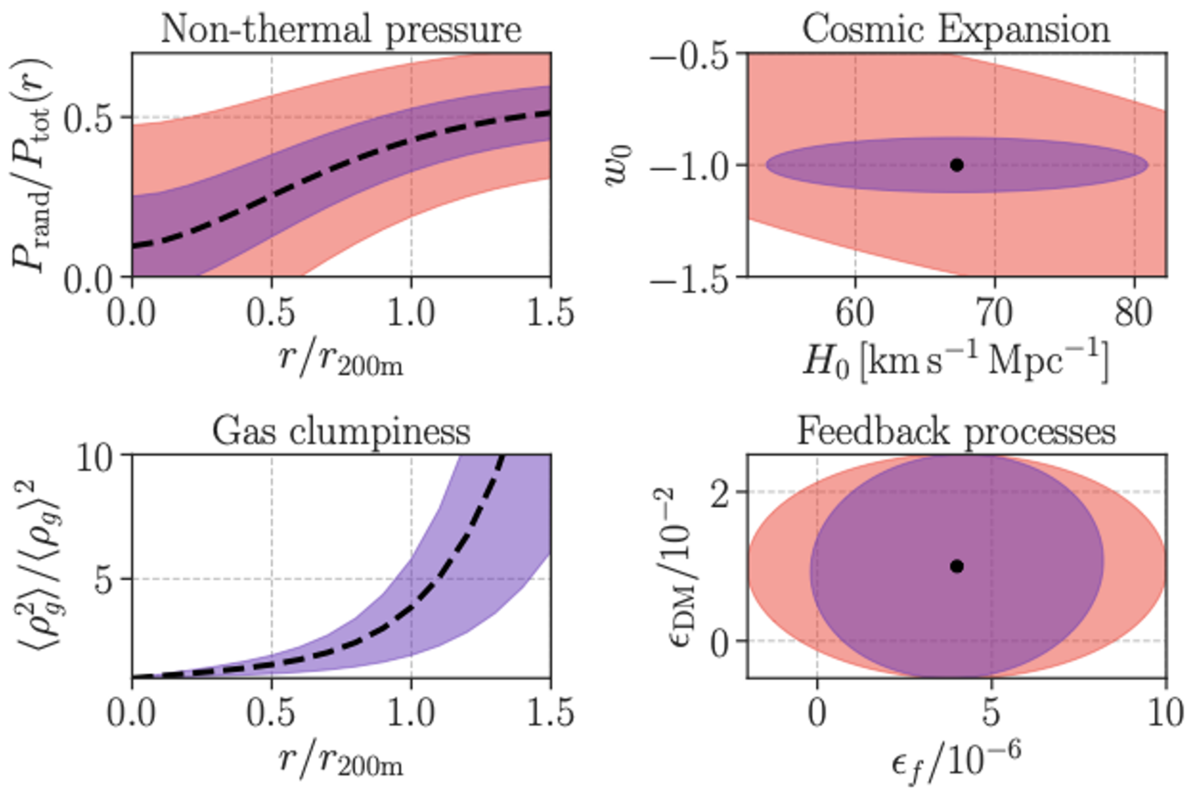
Probing Cosmology & Astrophysics with Multi-wavelength surveys



Auto- and cross-power spectra measurements are sensitive to the lensing bias, non-thermal pressure, feedback and gas clumping.

Shirasaki, Lau & Nagai (2020)

Probing Cosmology & Astrophysics with Multi-wavelength Surveys

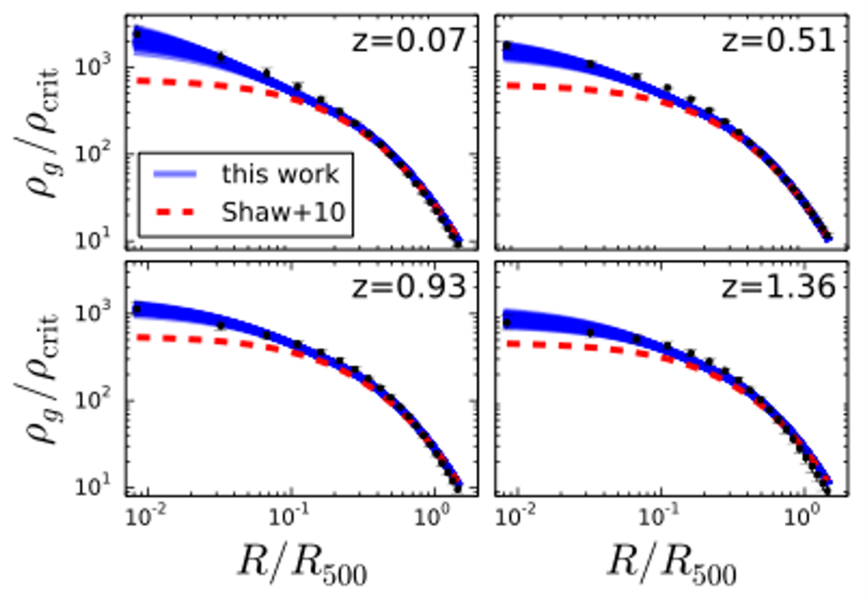


Microwave+Optical+X-ray

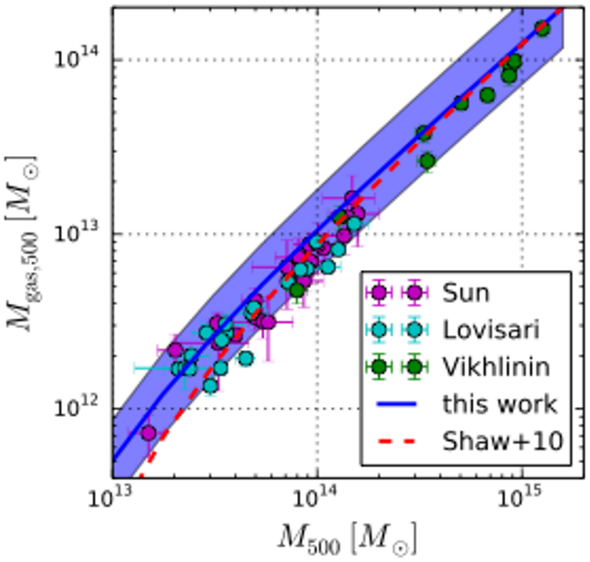
Measuring the **angular power spectra** in X-ray (eROSITA, microwave (CMB-S4), and optical (Rubin) lead to improved constraints on cosmology and astrophysics

Shirasaki, Lau & Nagai (2020)

BP Modeling of X-ray Clusters & Groups



McDonald+13,17:
X-ray measurements of **gas density profiles**

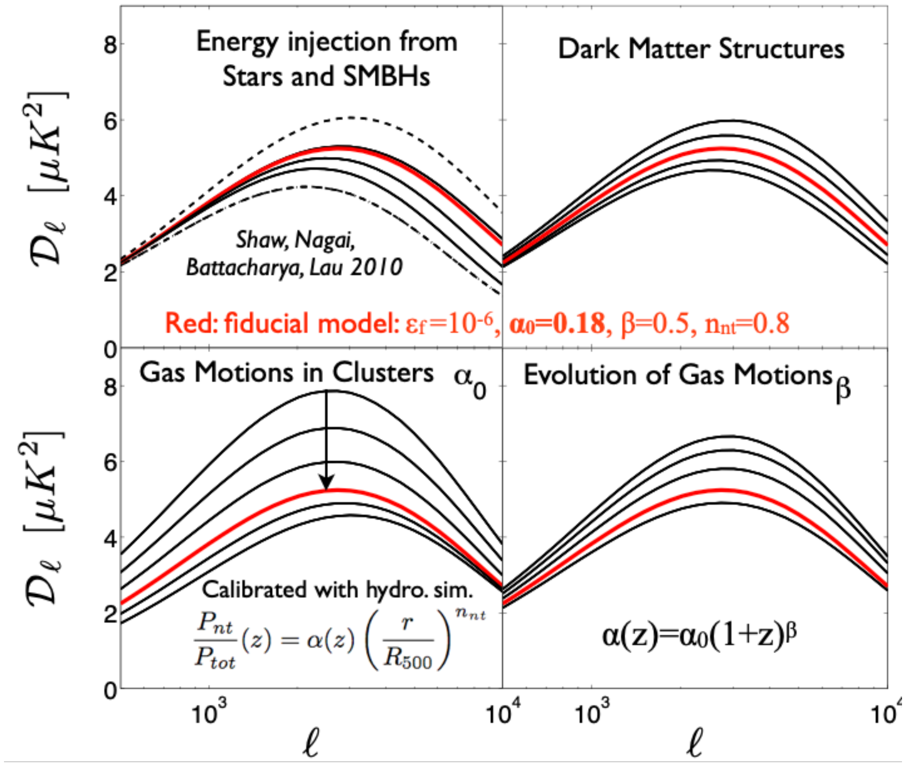


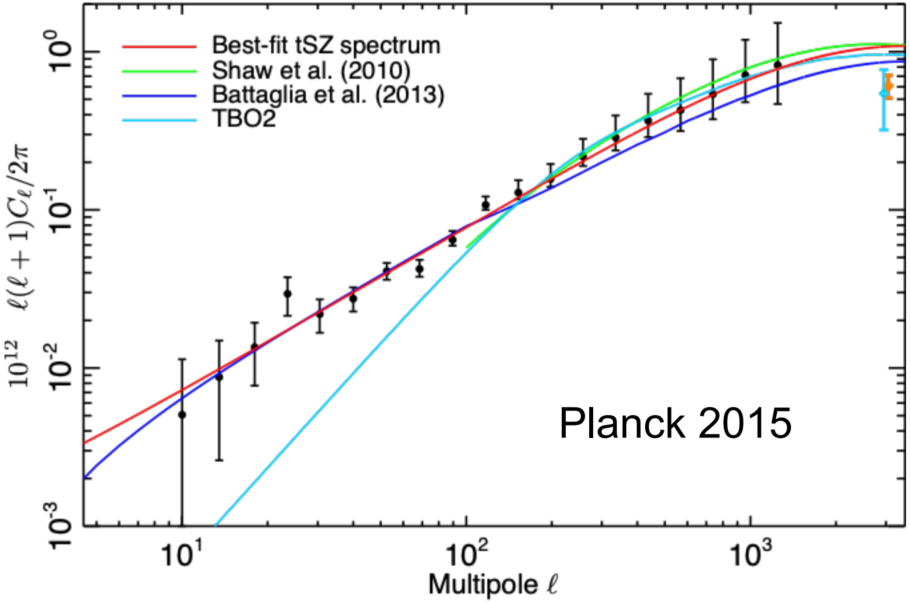
Vikhlinin+06, Sun+09, Lovisari+15:
measurements of the **relation between mass of gas and total mass** (DM+gas+stars)

Baryon Pasting gas model describes X-ray observations (density profiles and gas mass) well
(Flender, Nagai, McDonald+17)

BP Modeling of tSZ Power Spectrum

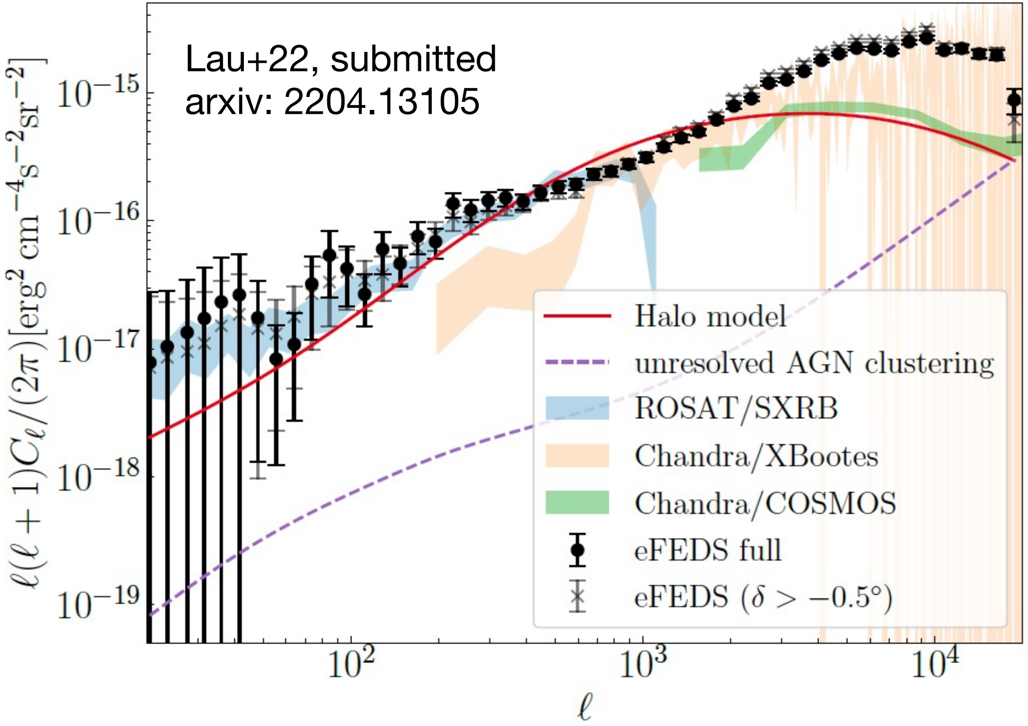
Thermal SZ power spectrum contains significant contributions from outskirts of low mass ($M<3\times10^{14}$ Msun), high-z (z>1) groups at l<5000





Planck measurements of the SZ power spectrum can constrain cluster astrophysics (especially non-thermal pressure)

X-ray power spectrum of eFEDS field

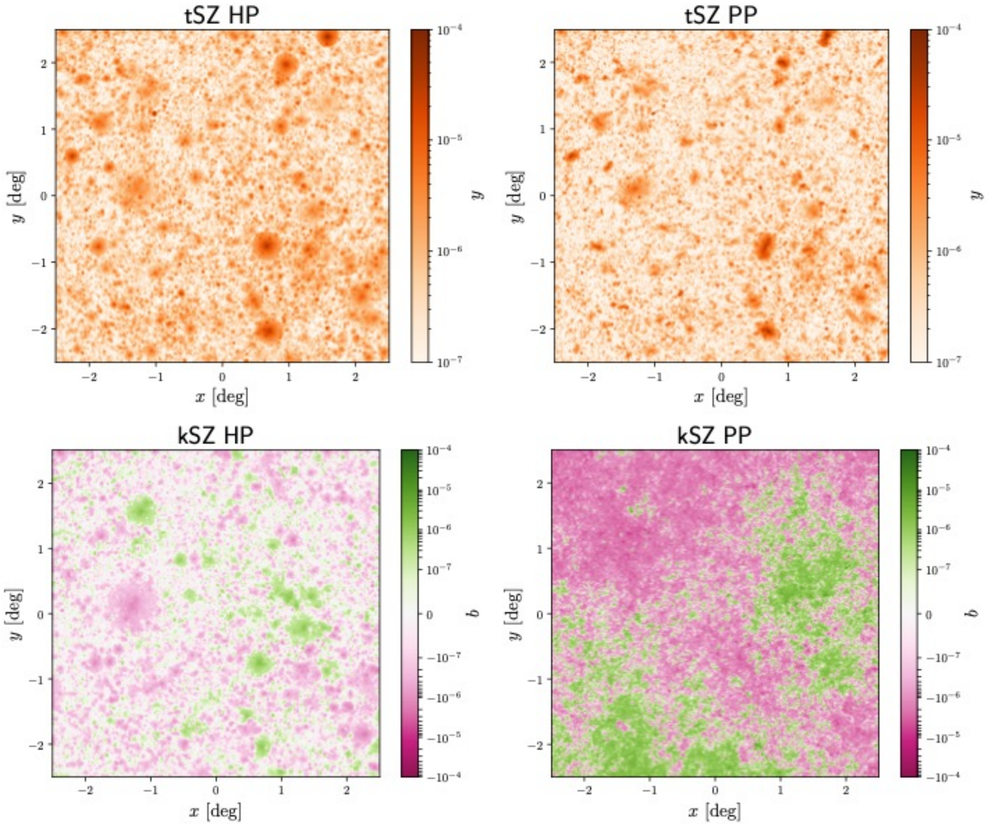


- Large-scales (ℓ < 2000, ϑ > 0.2°) - Consistent with ROSAT and the *Chandra* calibrated BP model.
- Small-scales (ℓ > 2000, ϑ < 0.2°) - Large differences between BP model and *Chandra*/COSMOS
- Expected eROSITA All Sky Survey (eRASS1) cosmological constraint using only large angular scales (ℓ < 2000) - marginalized over astrophysics parameters:

$$\Delta\Omega_M/\Omega_M \sim 5\%$$
$$\Delta\sigma_8/\sigma_8 \sim 4\%$$

Lau, Bogdan, Chadayammuri, Nagai, Kraft, Cappelluti 2022 (under review): astro-ph/2204.13105

Baryon Pasting Algorithm
Halo vs. Particle-based methods



Time / map

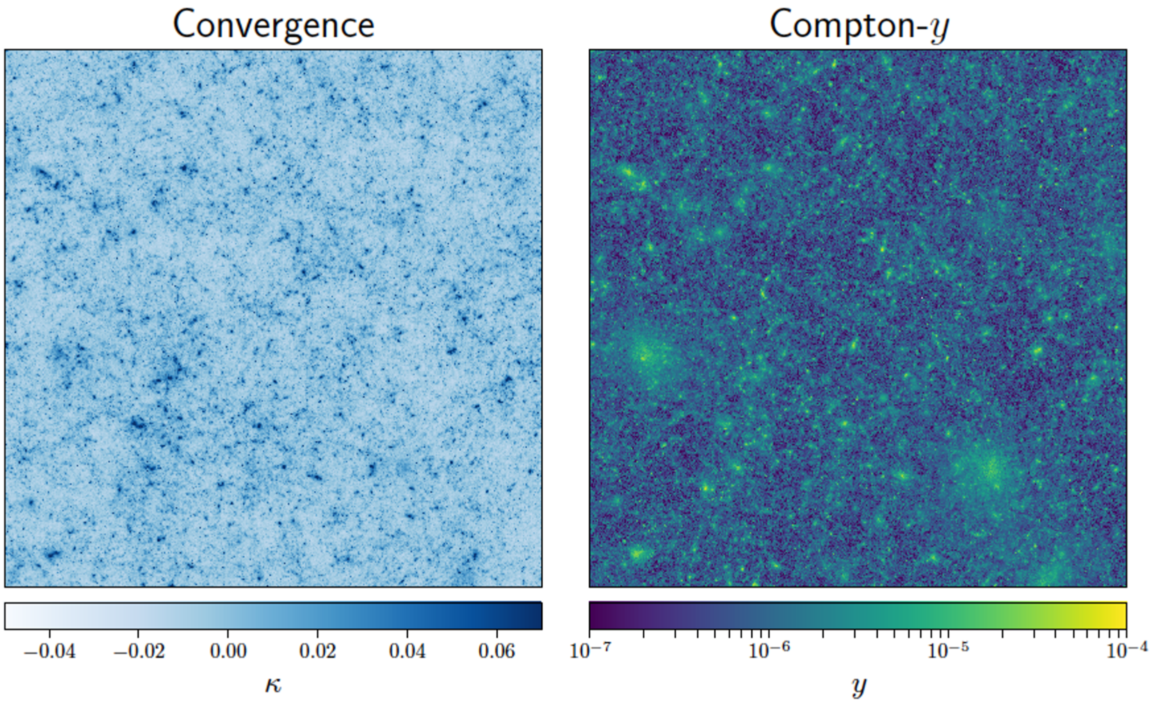
HP: 1.5 min
PP: 69 min

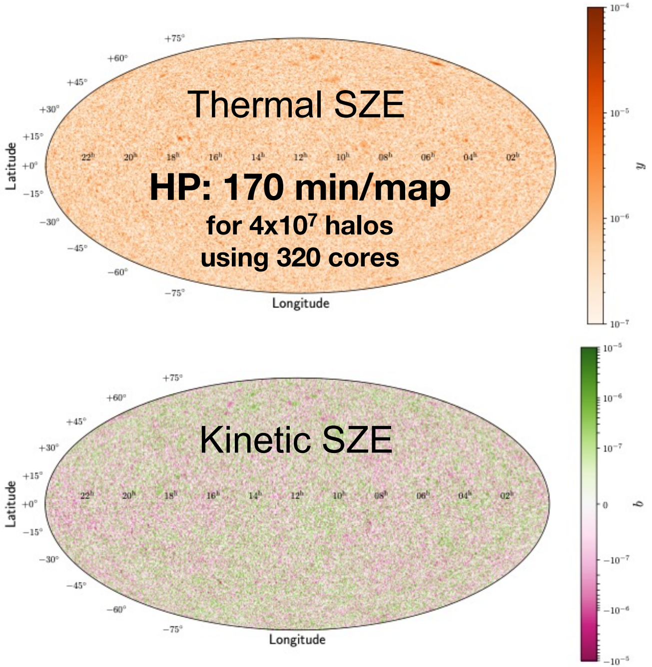
for 5×10^5 halos
using 224 cores

Osato & Nagai 2022
(astro-ph/2201.02632)

All-Sky BP SZ Maps

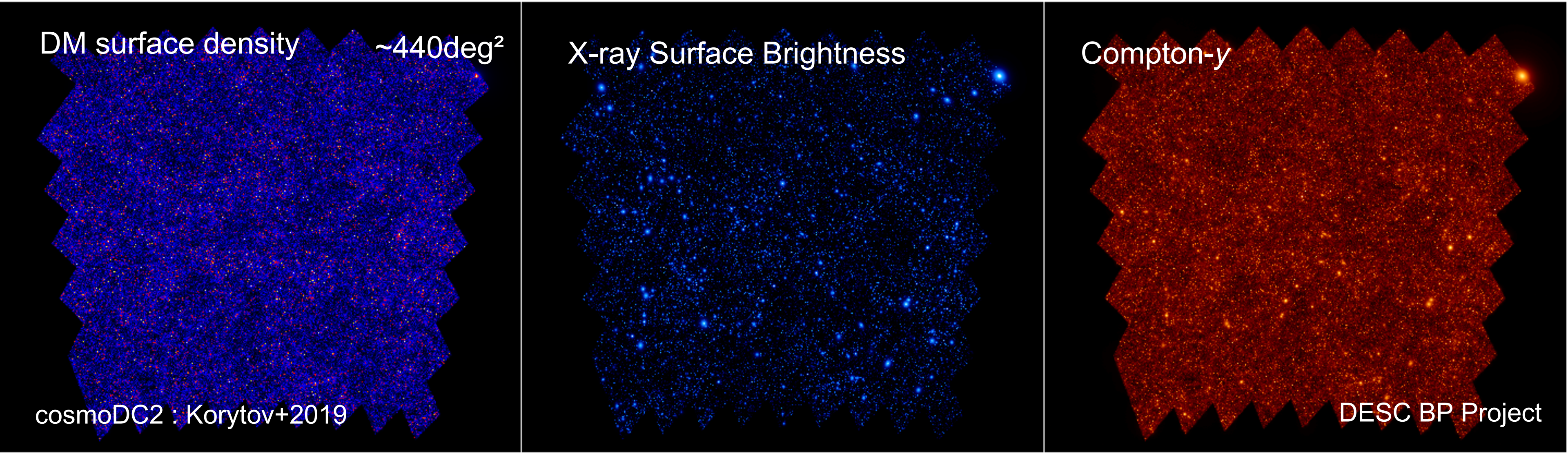
108 full-sky lightcone simulations of CMB lensing (Takahashi+17) and tSZ (Osato & Nagai+22) maps





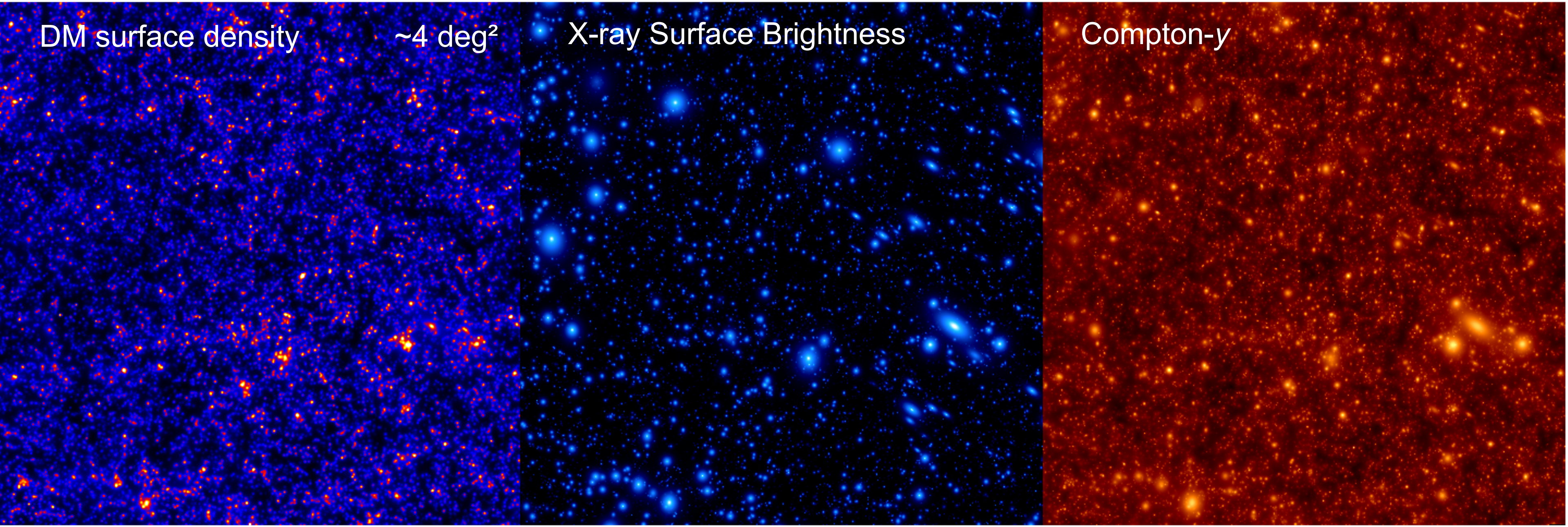
Next Step: Baryonification + tSZ x WL cross-correlation

Baryon Pasted (BP) Multi-wavelength Maps



Halo-based painting: lensing, X-ray surface brightness, & compton y-maps of cosmoDC2 lightcones and Dark Quest simulations with and without aspherical DM halos and mis-centering

BP x cosmoDC2 maps (Zoomed-in)



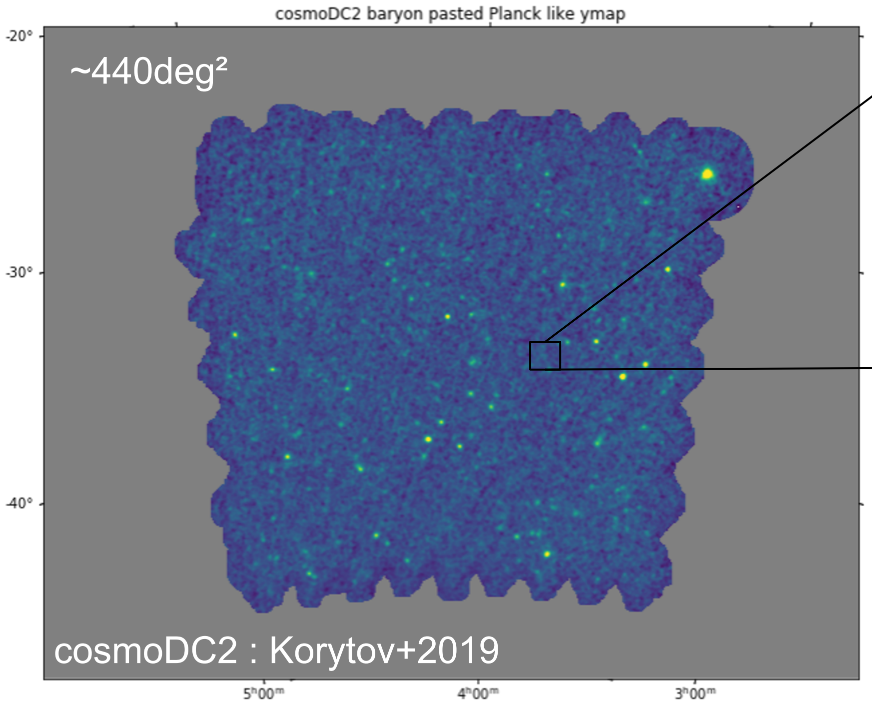
With Baryon Pasting we can:

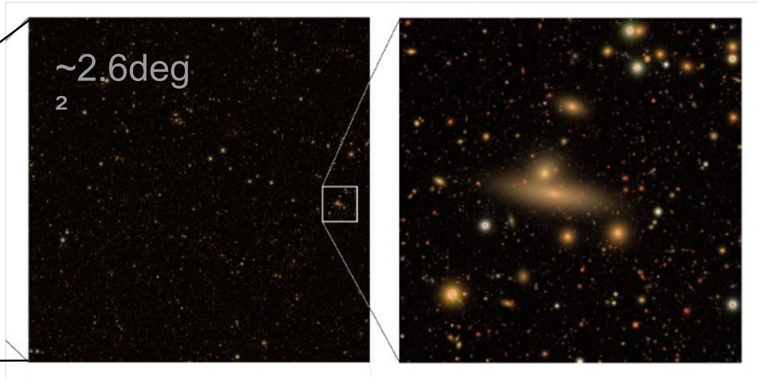
- explore astrophysical systematics by varying parameters in the gas model
- capture projection effects, instrumental responses with BP-generated maps

BP DESC Project

Goal : produce and analyse X-ray and SZ sky-maps corresponding to DESC sims with galaxy catalogs (redMAPPER) with cosmoDC2, and eventually SkySim5000, lightcone simulations

Science Applications: cluster scaling relations, cluster finders, selection functions, multi-wavelength cross-correlations



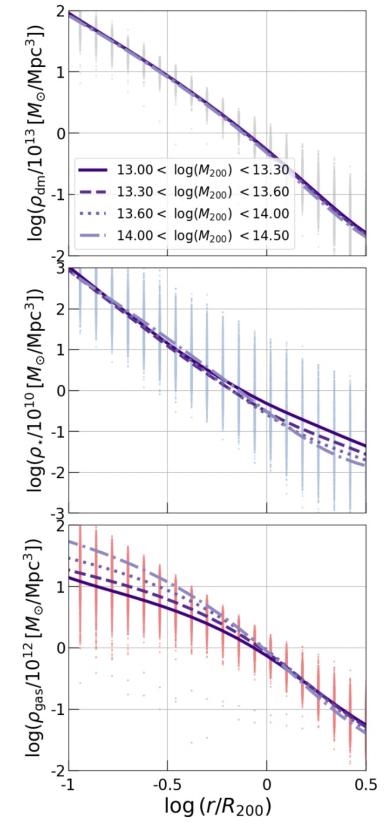


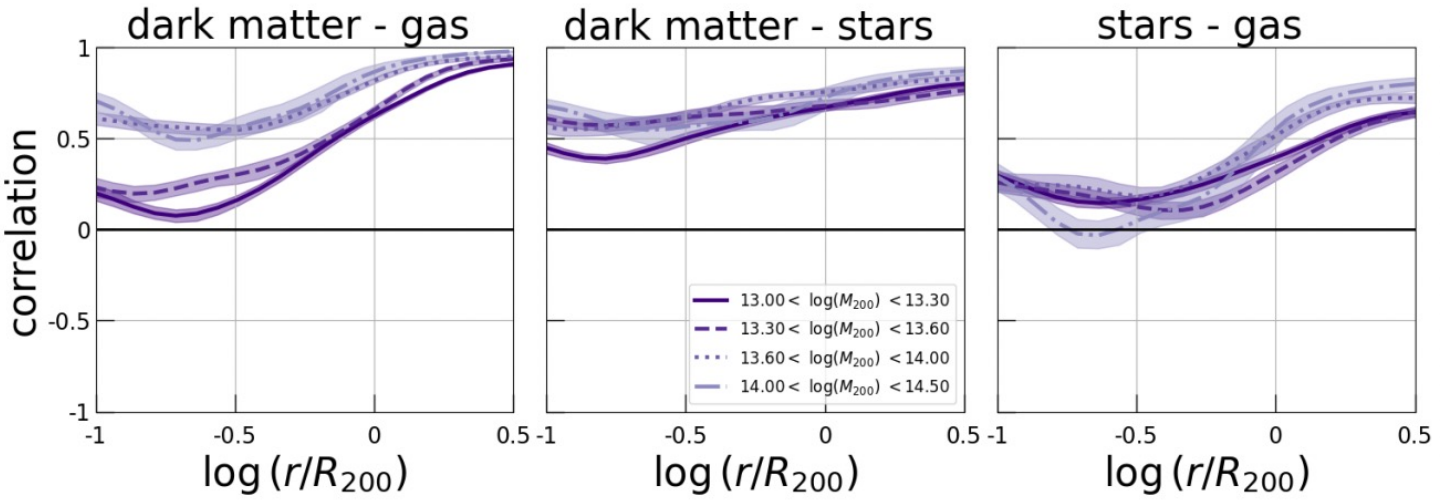
Upcoming features in progress:

- Scatter & covariance in gas profiles
- Dependence on halo assembly history
- Particle-based painting for diffuse gas (incl. kSZ)
- Unified model of DM halo-gas-galaxies

Towards Forward-Modeling Covariances

Correlated Structures of Dark Matter, Gas & Stellar Profiles





- Correlations between scatter of DM, stars, and gas density profiles in Illustris-TNG300 simulations is scale dependent and can potentially be used as a probe of astrophysics.
- These covariance matrices are a source of systematics in cluster mass calibration.

Farahi, Nagai, Anbajagane, 2022, ApJ, 933, 48

Galactic Atmospheres

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CONTENTS

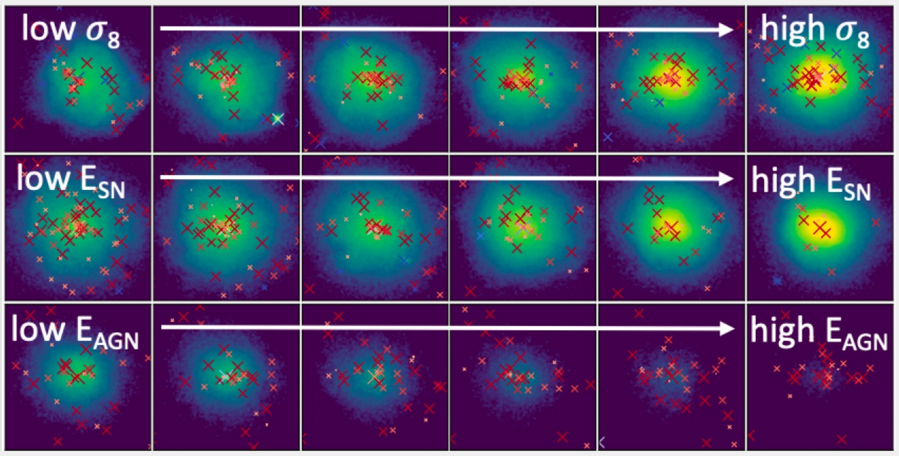
Galactic Gaseous Halos: Mini-Clusters Disrupted by Feedback

Hot gaseous halos around galaxies are mainly the realm of theoretical exploration which will soon change.

by Priyanka Singh, Daisuke Nagai, Benjamin D. Oppenheimer, Erwin Lau, Naomi Gluck, and Isabel Medlock

Goals: Study the variation of X-ray properties and galaxies using **CAMELS** - a suite 4,233 cosmological simulations: 2,049 N-body and 2,184 MHD with TNG and SIMBA subgrid model (Public Data Release in Jan 2022: Villaescusa-Navarro et al. 2022)

Right-panel figure: CAMELS variations on cosmological and astrophysical parameters of X-ray luminosity and galaxies in the same group sized halos.



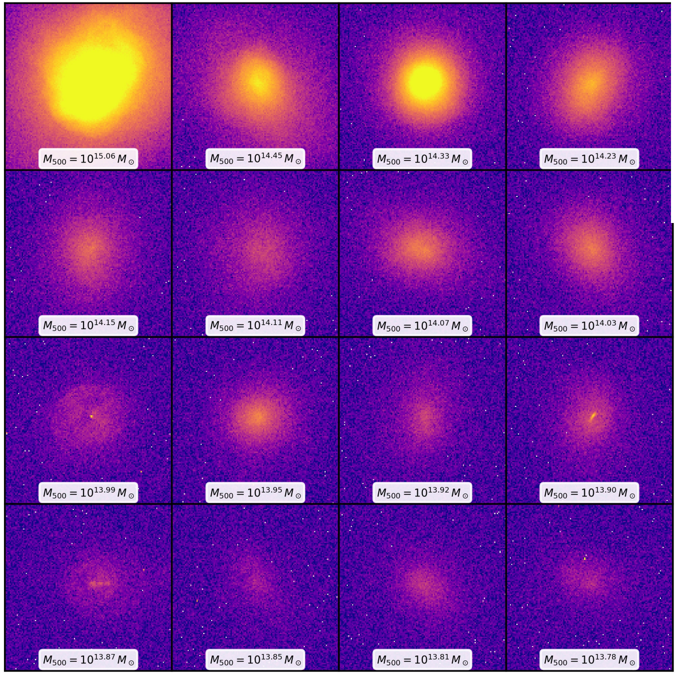
Supported by the NSF-AST Grant 2206055

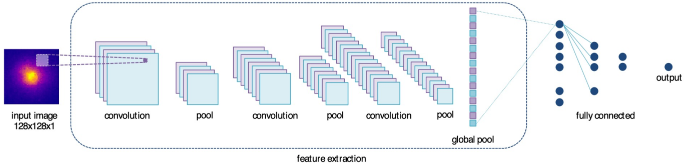
Machine Learning Frontier

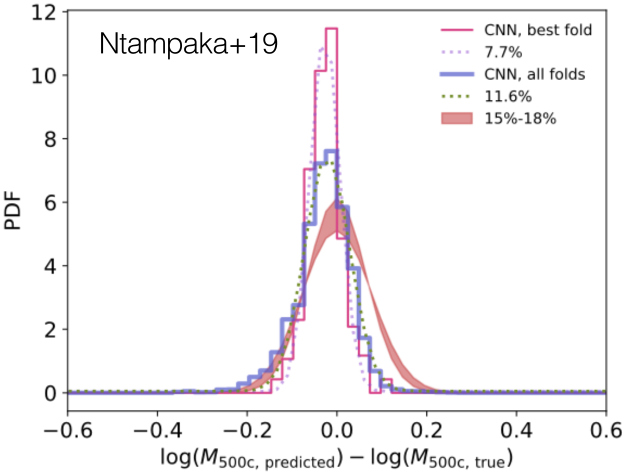
discover new features in large simulation datasets and model large observational dataset using machine learning

A Deep Learning Approach for Weighting the Giants

Mock X-ray images of 329 clusters with $M_{500c} \geq 10^{13.6}$Msun, augmented with many viewing angles of each cluster from the Illustris TNG-300 simulation



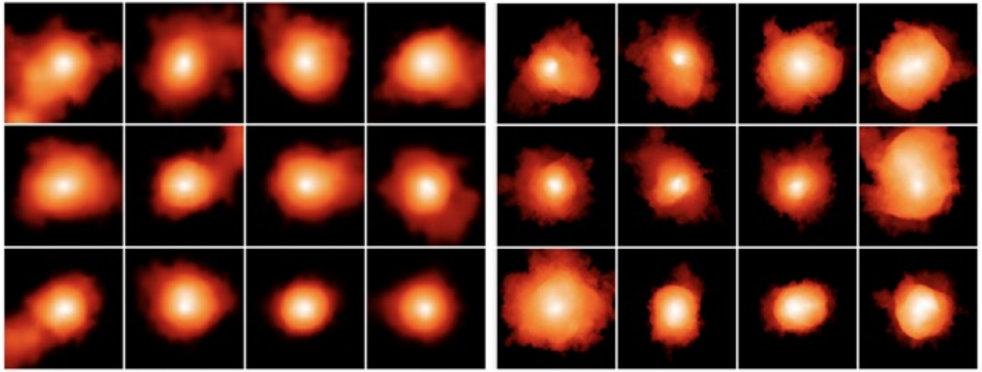


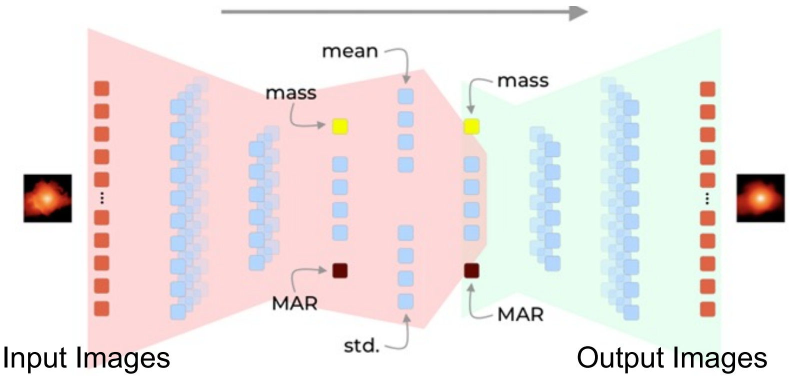


The ML-based X-ray cluster mass has a small scatter of 8-12%, which is a significant improvement from 15-18% scatter based on the core-excised X-ray luminosity - the current market standard.

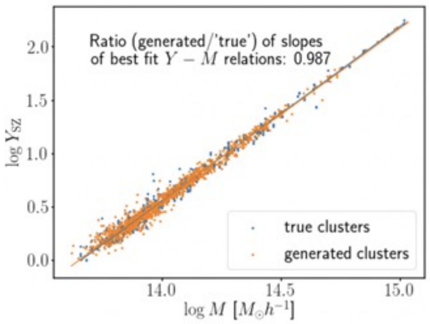
Emulating SZ Images using Auto-Encoder

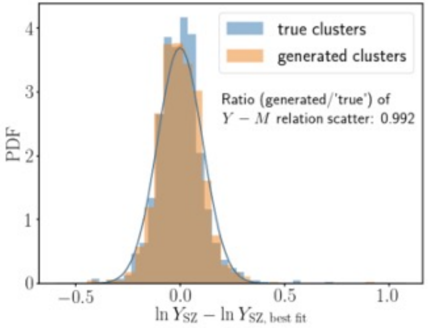
Generated images by the auto-encoder | Original images from TNG-300



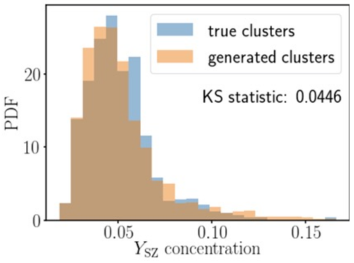


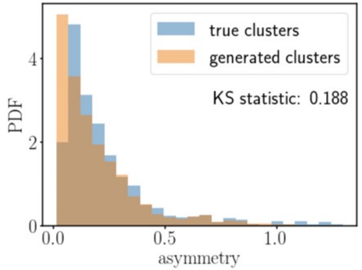
Reproducing Ysz-M relation & scatter





Reproducing Ysz concentration & asymmetry





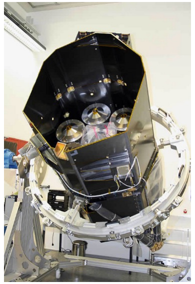
Imperfection: Smoothness

Tibor Rothschild

Rothschild, Nagai, Aung, Green, Ntampaka, ZuHone 2022, MNRAS, 513, 333

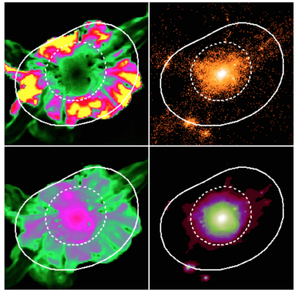
Towards Precision Modeling of ICM Physics

X-ray *Microwave* *Optical*

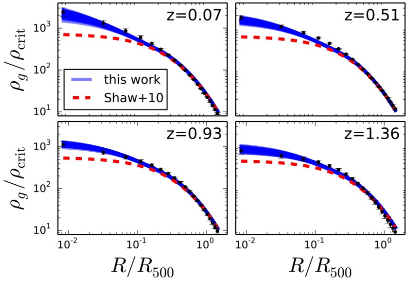


eRosita

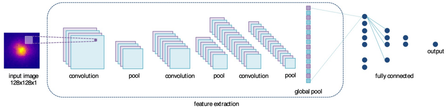
Computer Simulation



Analytical Modeling



Machine Learning



Opportunity

Multi-wavelength cosmological surveys promise to constrain the warm-hot gas in galaxies, groups, and clusters using X-ray, SZ effects, and galaxies.

New Tools

1. **Computational:** gain physical insights into *SZ astrophysics* from *hydrodynamical cosmological simulations*
2. **Modeling:** develop of *a physically-motivated, computationally efficient model of pressure and gas density profiles for WL-SZ cross-correlations*
3. **Data-Driven:** extract more from large simulation & observational data using *machine learning*

Outstanding Challenges

1. **Cluster Astrophysics:** feedback, non-thermal pressure, gas shape, accretion shock, & plasma effects
2. **SZ+X-ray profile modeling:** Halo-Gas connection, Covariance, Beyond profile with generative model