A Roadmap for Cluster Cosmology

Toward Precision Cosmology & Astrophysics in the Era of Multi-Wavelength Cosmological Surveys

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On behalf of the BP collaboration

Yale University

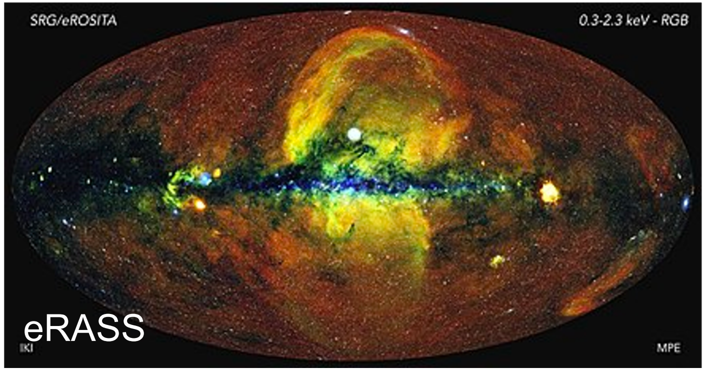
Cluster Cosmology Workshop @ Trieste

July 4, 2023

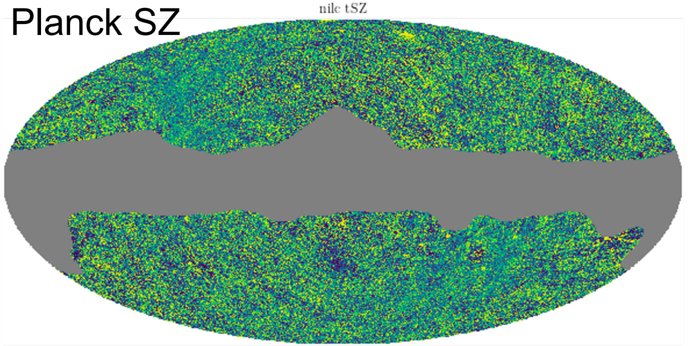
A New Era of Multi-Wavelength Cluster Surveys

Simons Obs

Rubin



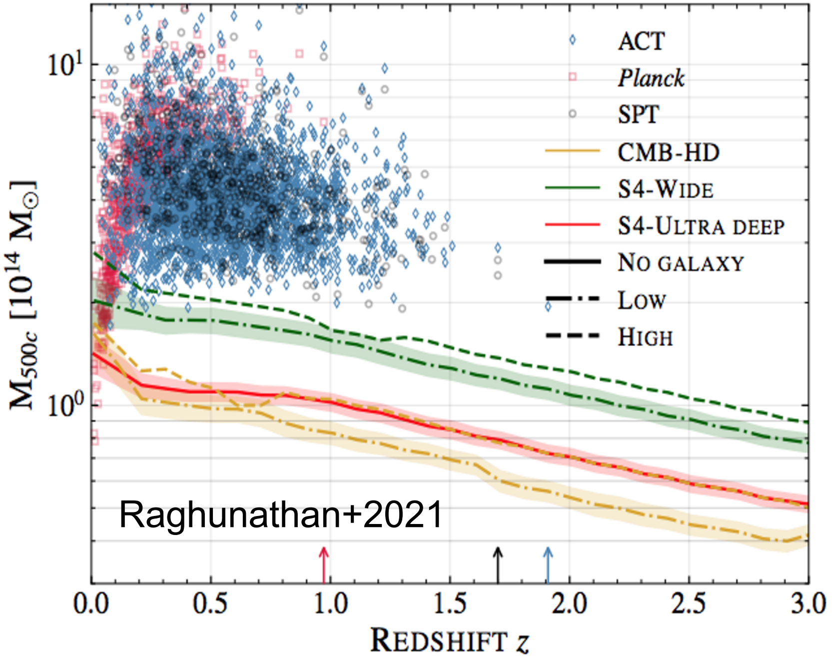
Planck SZ



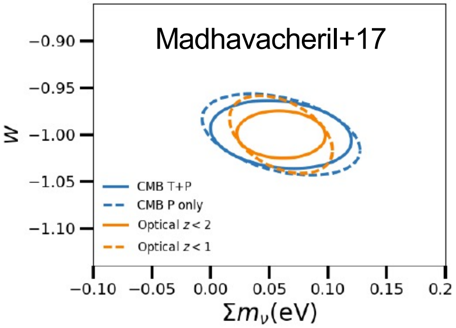
Cosmic Visions 2016 Report from DOE:

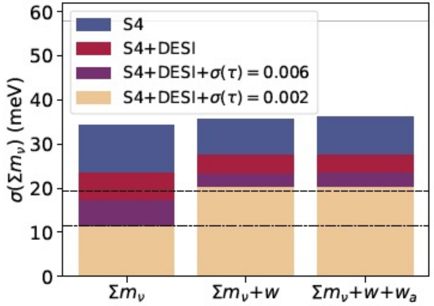
"The number of massive galaxy clusters could emerge as the most powerful cosmological probe *if* the masses of the clusters can be accurately measured." **Understanding Cluster Astrophysics is the Key!**

Cluster Cosmology in the Stage IV Era

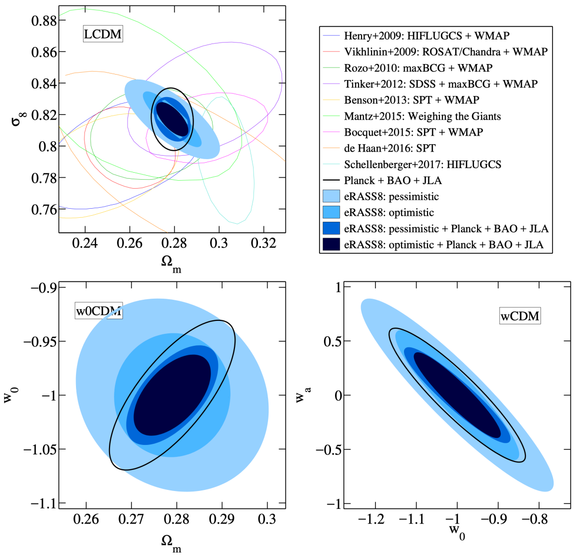


CMB-S4+optical





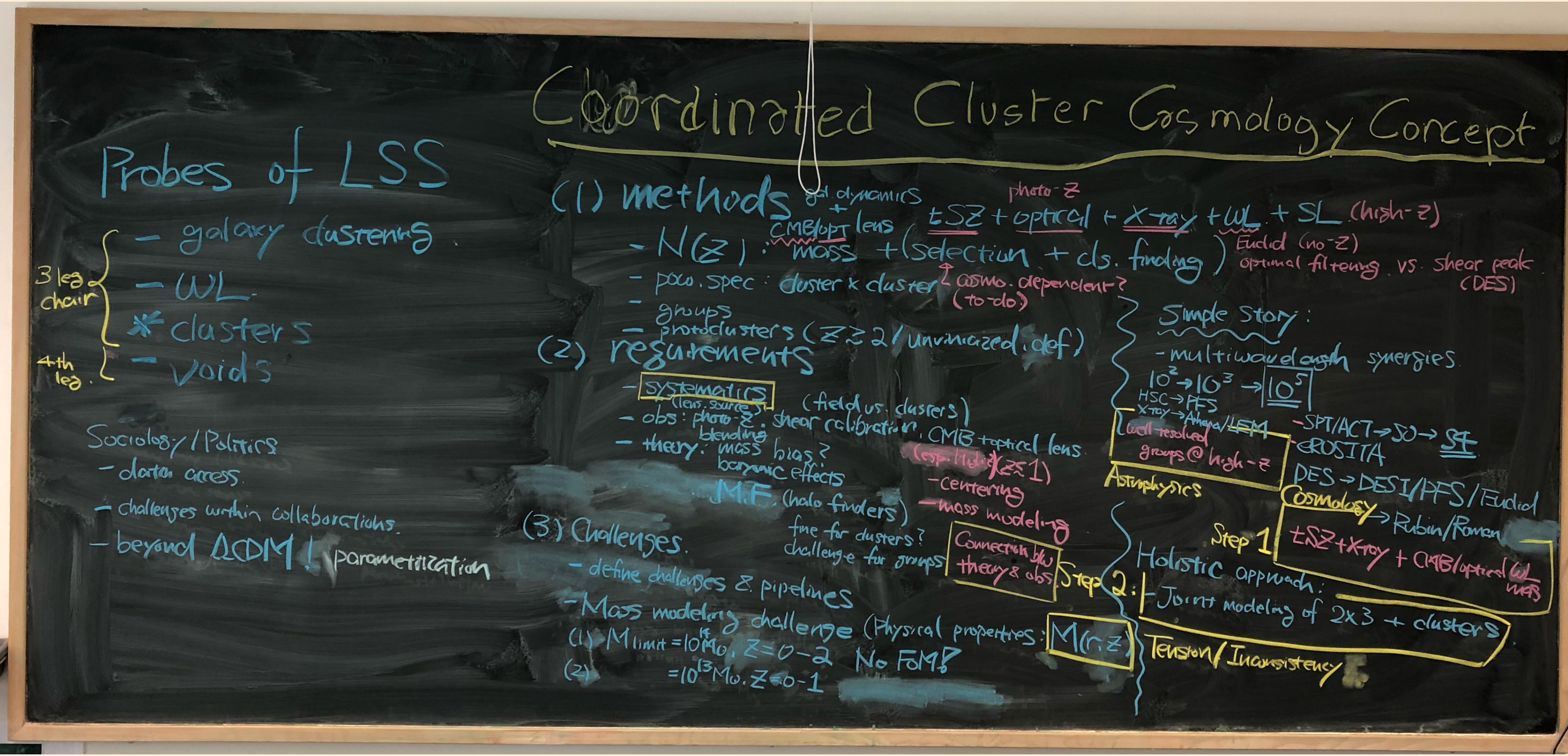
eROSITA



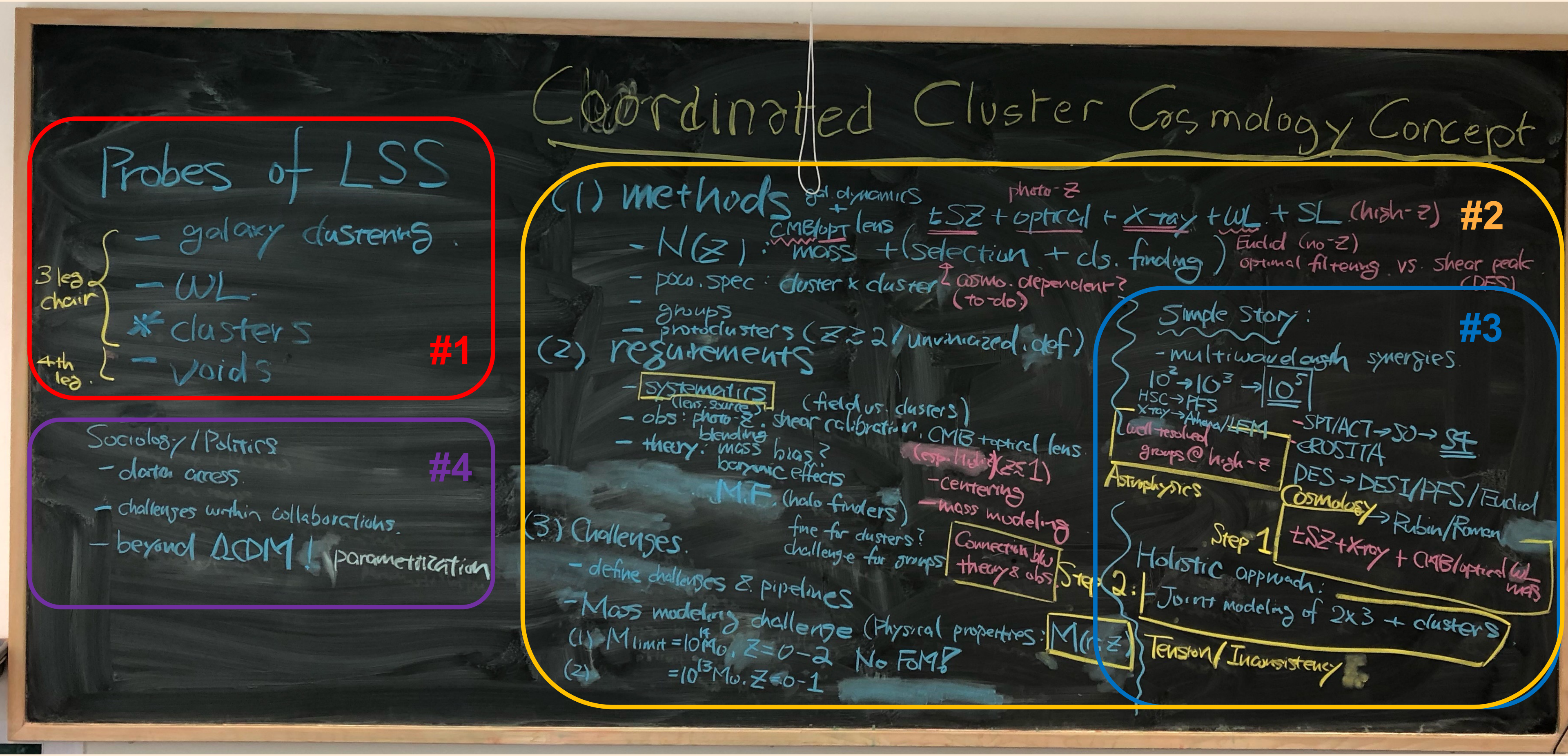
Pillepich+18

Galaxy Clusters are potentially powerful cosmological probes

Systematics, Sysmatics, Syatematics!



MIAPP workshop, 2022



MIAPP workshop, 2022

Probes of LSS

- galaxy clustering.
- WL.
* clusters
- voids

3 leg chair

4th leg.

Coordinated Cluster Cosmology Concept

(1) methods

photo-z

gal. dynamics + CMB/opt lens

tSZ + optical + X-ray + WL + SL (high-z)

Euclid (no-z)

optimal filtering vs. shear peak (DES)

- N(z) : mass + (selection + cls. finding)
  - ↑ cosmo. dependent? (to-do)
- pow. spec : cluster x cluster
- groups
- protoclusters ($z \gtrsim 2$ / unvirialized. def)

(2) requirements

- $\boxed{\text{systematics}}$ (lens, source) (field vs. clusters)
- obs : photo-z, shear calibration, CMB + optical lens
  - blending
  - (esp. high-z) ($z \gtrsim 1$)
  - centering
  - mass modeling
- theory : mass bias?
  - baryonic effects
  - M.F. (halo finders)
  - fine for clusters?
  - challenge for groups

$\boxed{\text{Connection b/w theory \& obs.}}$

(3) Challenges.

- define challenges & pipelines
- Mass modeling challenge (Physical properties: $\boxed{M(r,z)}$)

(1) $M_{limit} = 10^{14} M_\odot$, $z = 0-2$ No FoM!

(2) $= 10^{13} M_\odot$, $z = 0-1$

Simple Story :

- multiwavelength synergies
  - $10^2 \to 10^3 \to \boxed{10^5}$
  - HSC → PFS
  - X-ray → Athena/LEM
  - SPT/ACT → SO → S4
  - eROSITA
  - DES → DESI/PFS/Euclid → Rubin/Roman

$\boxed{\text{well-resolved groups @ high-z}}$ Astrophysics

$\boxed{\text{tSZ + X-ray + CMB/optical WL mass}}$ Cosmology Step 1

Step 2 : Holistic approach :

- $\boxed{\text{Joint modeling of 2x3 + clusters}}$ Tension/Inconsistency

Simple Story:

- multiwavelength synergies

$10^2 \rightarrow 10^3 \rightarrow \boxed{10^5}$

HSC → PFS

X-ray → Athena/LEM

well-resolved groups @ high-z

Astrophysics

- SPT/ACT → SO → S4
- eROSITA

DES → DESI/PFS/Euclid → Rubin/Roman

Cosmology

Step 1: tSZ + X-ray + CMB/optical WL mass

Holistic approach:

2: - Joint modeling of 2x3 + clusters

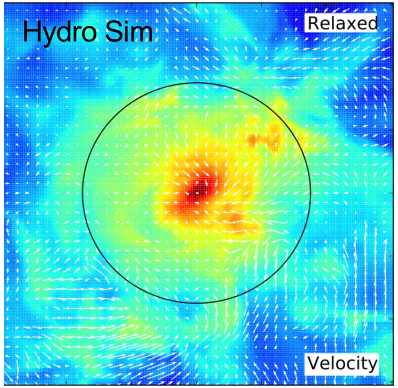
Tension/Inconsistency

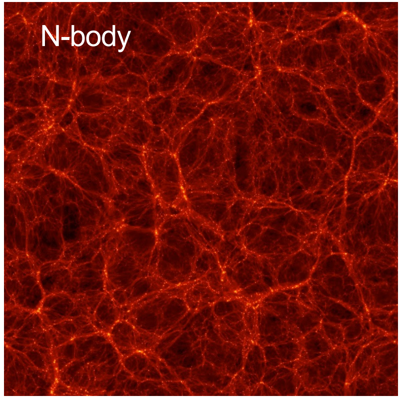
z)

Sociology / Politics

- data access.
- challenges within collaborations.
- beyond ΛCDM! parametrization

Opportunities, Challenges & New Frontiers
Computational + Analytical + Data-Driven Modeling





Opportunities
Maximize the scientific returns of multi-wavelength surveys by using non-linear structure formation physics (e.g., clusters, lensing, galaxy clustering)

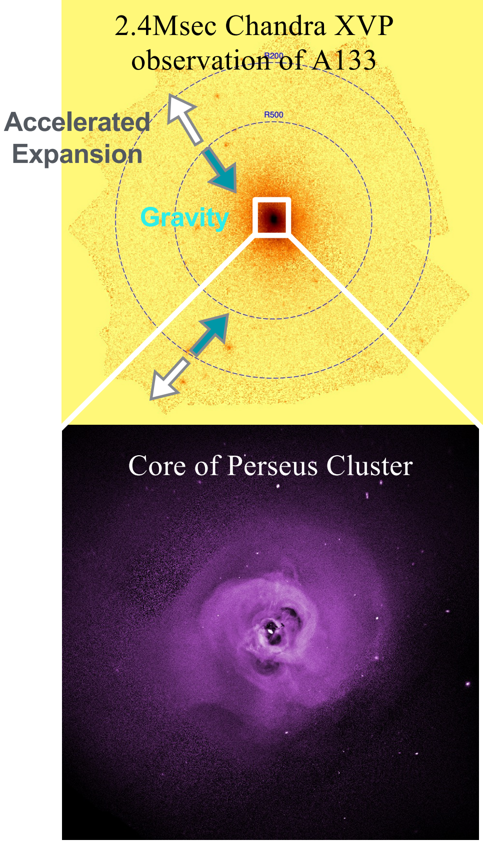
Challenges:
- Big Data Challenge
- Multi-scale, Multi-physics Problem
- DM Halo-Galaxy-Gas Connection
- Roles of Hydro Sim, SAMs, ML for cosmo/astro inference

New Frontiers
1. **Computational Frontier:** use *hydrodynamical cosmological simulations* of galaxy cluster formation to gain physical insights into cluster astrophysics
2. **Modeling Frontier:** Develop *a physically-motivated, computationally efficient model* for modeling multi-properties of galaxies, clusters, and cosmic web
3. **Machine Learning Frontier:** use *machine learning* techniques to detect and exploit small signals in noisy and complex data

Computational Frontier

use hydrodynamical cosmological simulations of galaxy cluster formation to gain physical insights into cluster astrophysics

The Physics of Galaxy Cluster Outskirts vs. Cores
Lessons from Hydro Simulations



✦Cluster Outskirts

Gas Accretion & Non-equilibrium phenomena

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

Tractable

Key Parameters
Mass & MAH

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

Outstanding Challenge - especially critical for X-ray surveys (e.g., eROSITA)

Non-thermal Pressure
Analytical Model vs. Hydro Simulations

Shi & Komatsu 2014 (analytical model)

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

Time Change in Turbulence Energy per unit mass

Dissipation of Turbulence

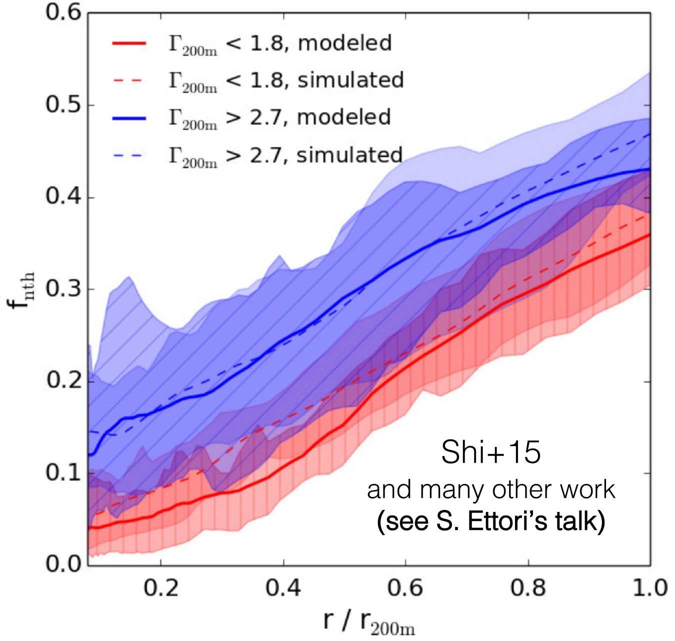
Generation of Turbulence sourced by mass accretion

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

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

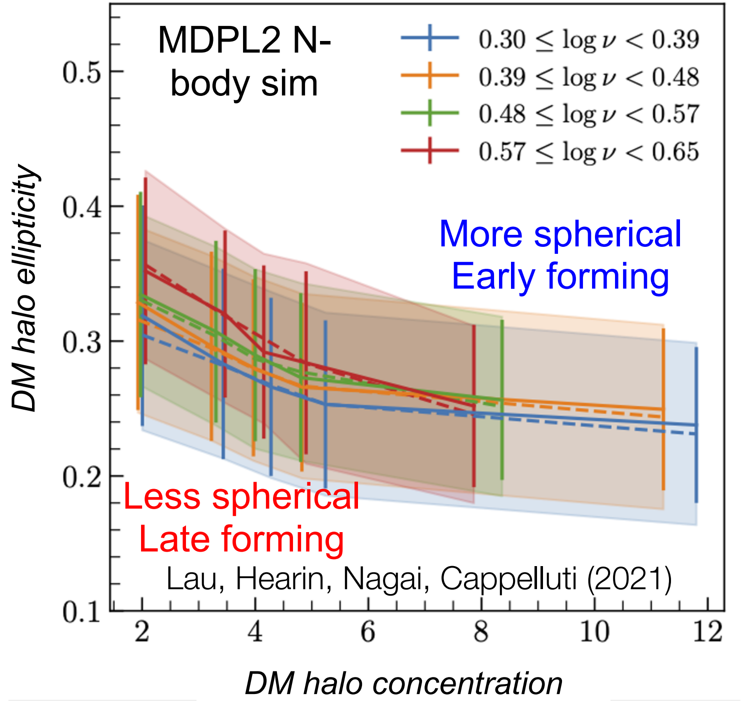
Impact of Non-thermal pressure on tSZ effects
Green, Aung, Nagai, van den Bosch 2020

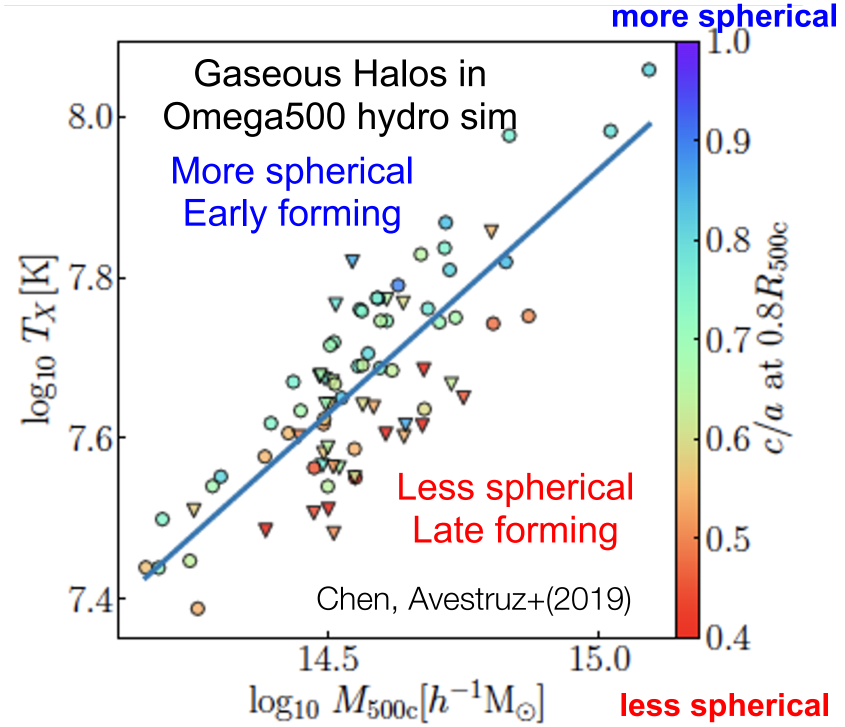
Comparison to the Omega 500 simulation
(Nelson+14)



Analytic model can match the results of hydrodynamical simulations remarkably well

Halo & Gas Shape and Formation History





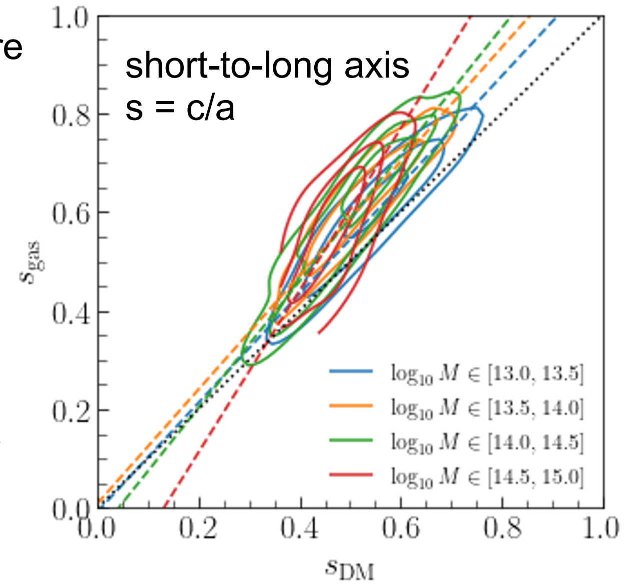
- DM halo & gas shapes depend on its formation history: early-forming/higher concentration halos are more spherical
- Systematic scatter in observable scaling relation driven by halo formation history

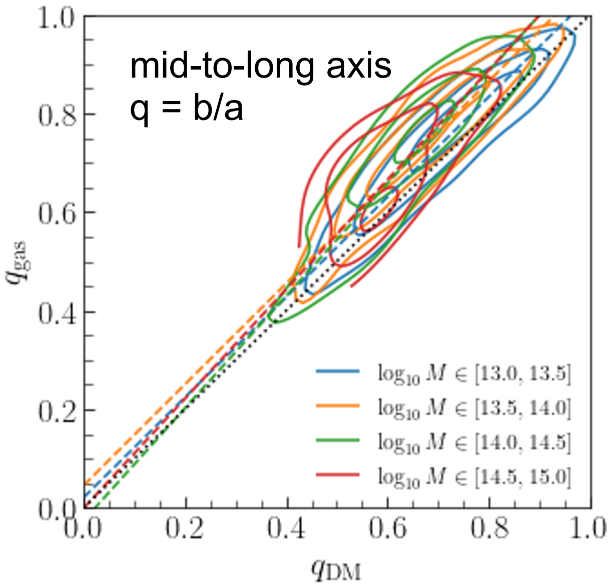
DM and Gas Halo Shapes

Calibrate relations between DM halo shape & gas shape using ML methods with Illustris-TNG300 hydro simulations (Lau, Nagai, et al. in prep)

s~ 1: more spherical

s~ 0: less spherical





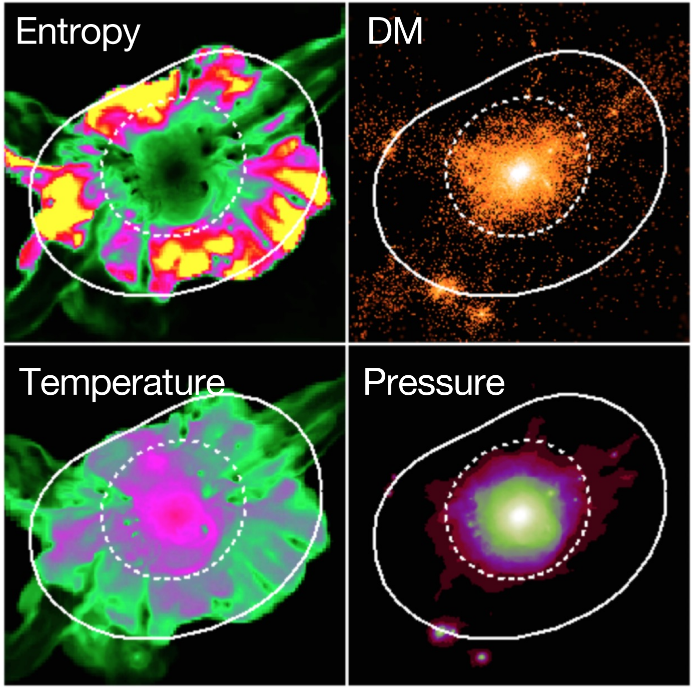
q~ 1: more spherical

q~ 0: less spherical

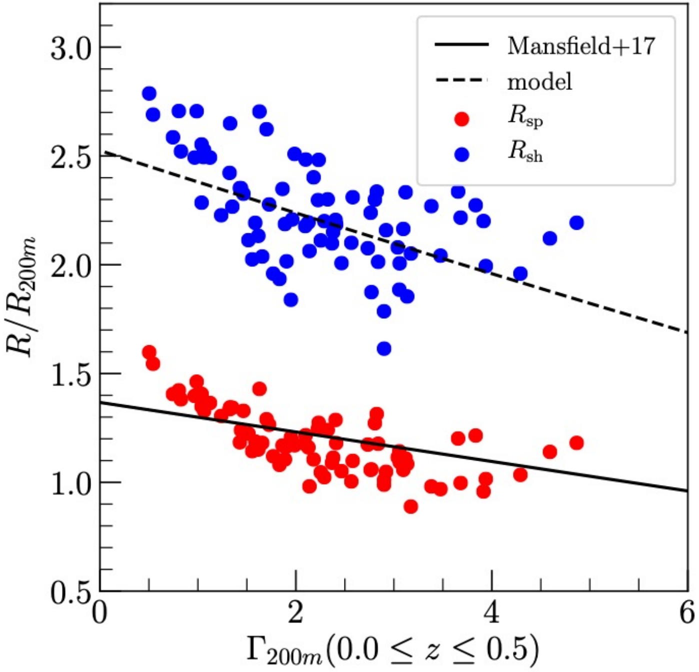
Gas shape is triaxial, but more spherical than DM

Splashback vs. Accretion Shock Radii

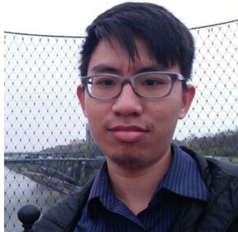
DM splashback computed using SHELLFISH (Mansfield+17)



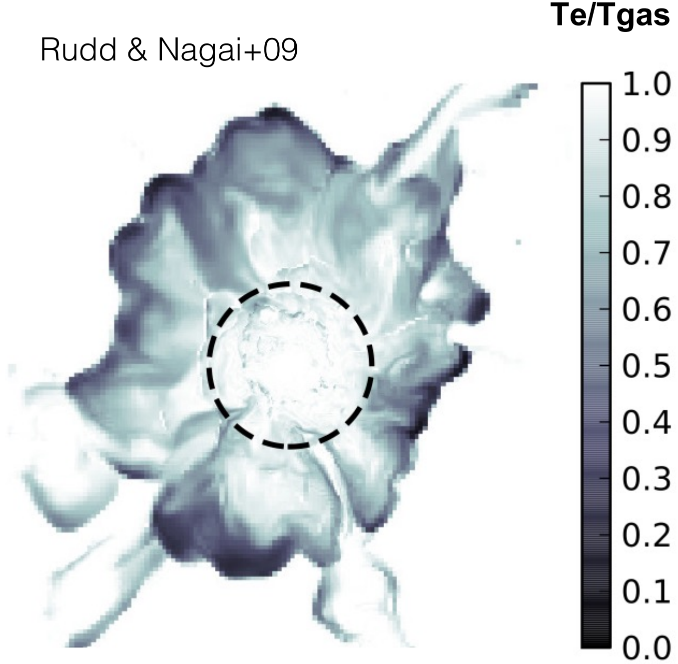
Aung, Nagai, Lau 2021

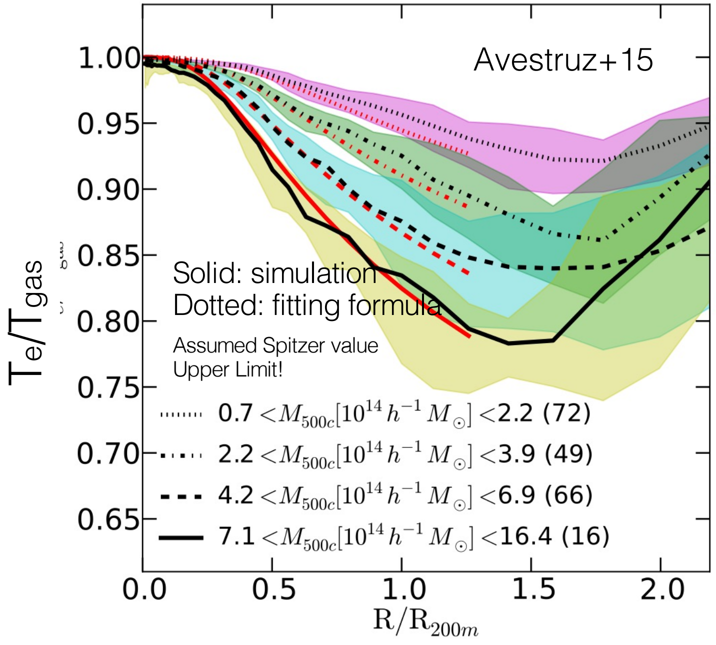


Accretion shock radius is ~2 times larger than the Splashback radius, making the hot gas extend beyond the splashback radius.



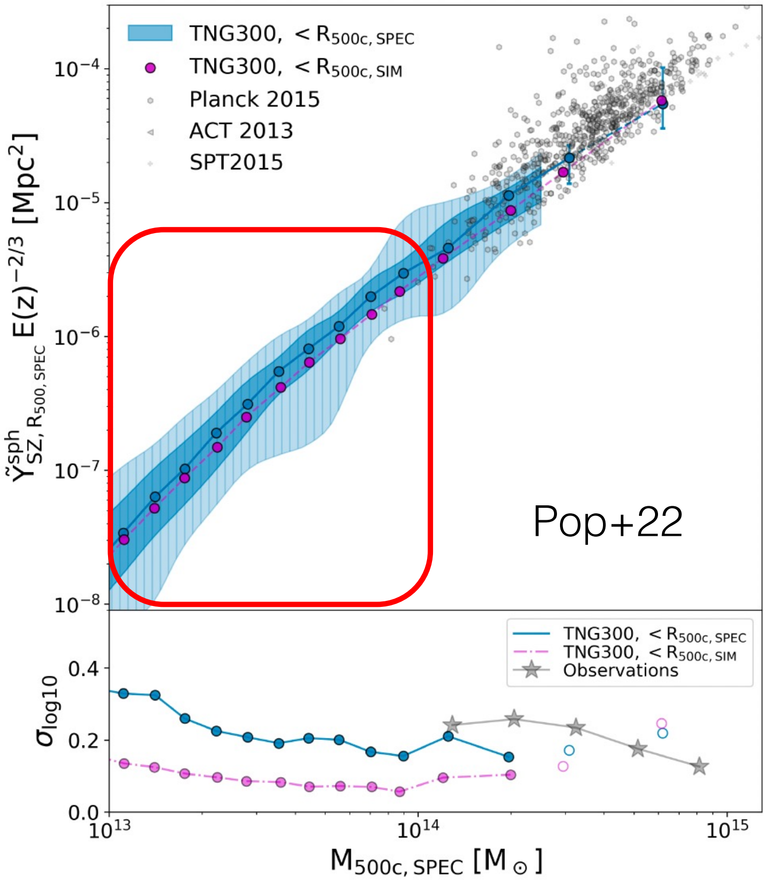
Electron-Proton Equilibration in Cluster Outskirts





In the outskirts of galaxy clusters, the collision rate of electrons and protons becomes longer than the age of the universe.

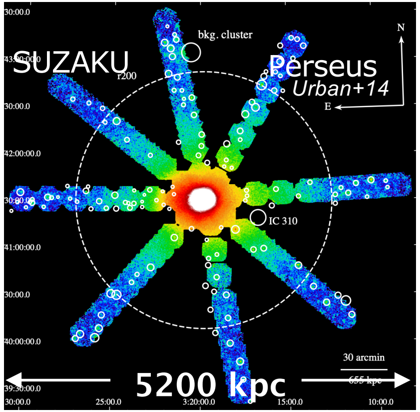
AGN feedback in Groups

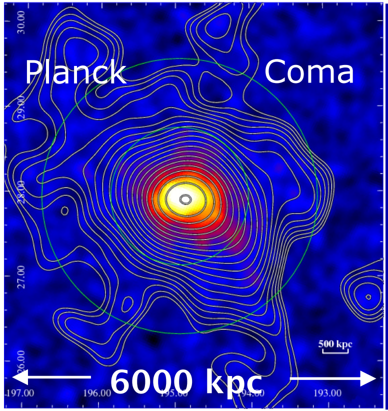


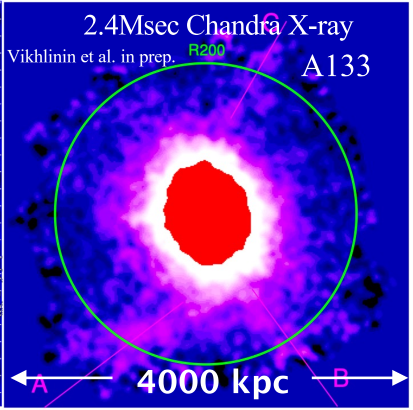
AGN feedback may cause a break in the Y-M relation on low-mass groups, by lowering gas fraction via stochastic energy injection by jets and winds

New Frontier: Astrophysics & Cosmology with CGM

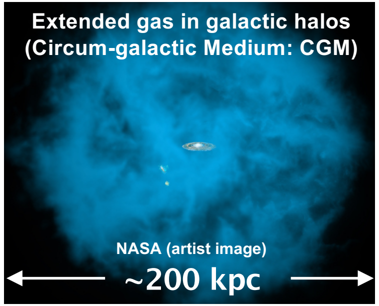
Galaxy Clusters

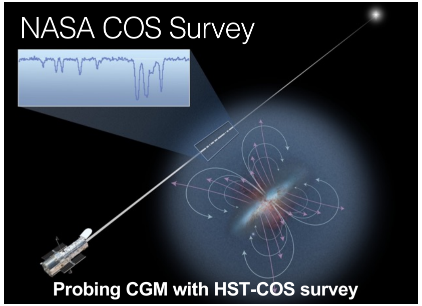


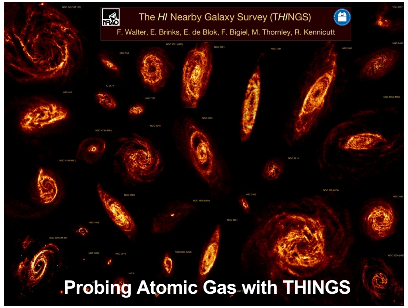




Galaxies

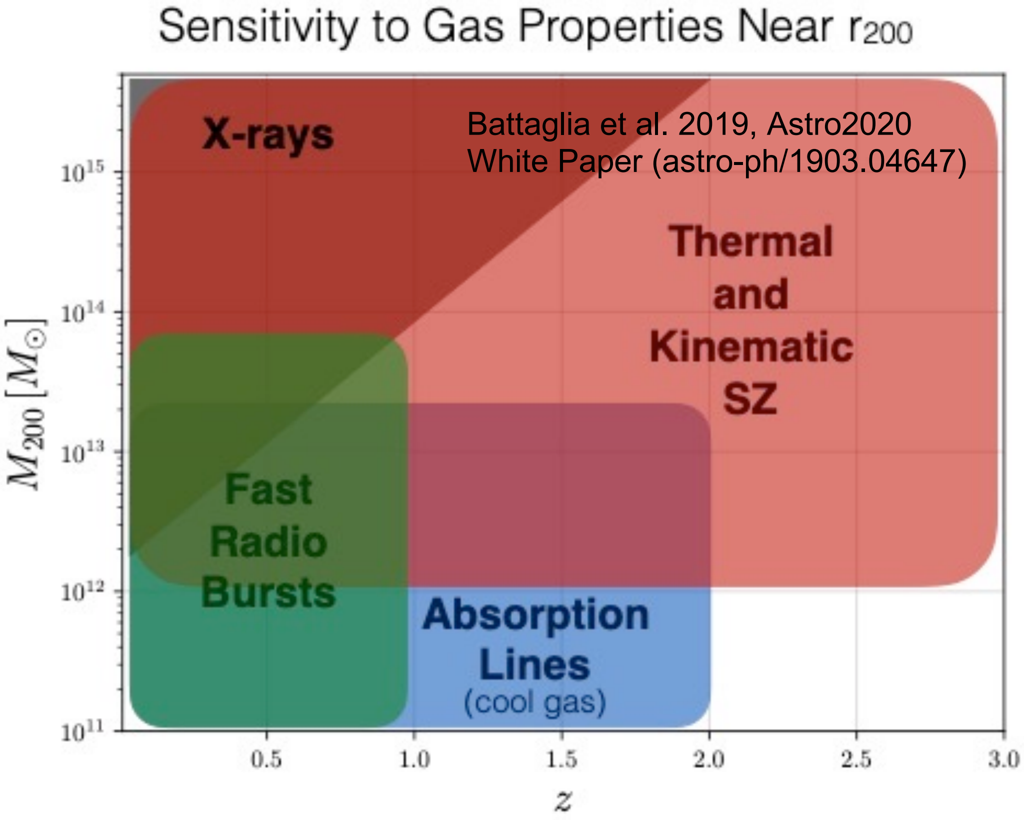






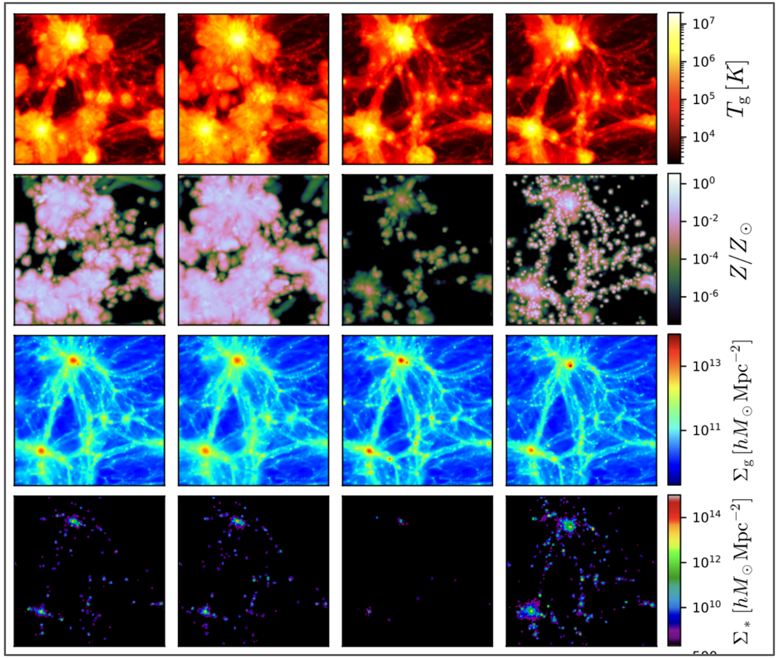
Most baryons are in gaseous form *across all halo masses.* Current-surveys are probing gas in galaxies and galaxy clusters.

New Frontier: CGM as a Laboratory for Galaxy Formation PHysics



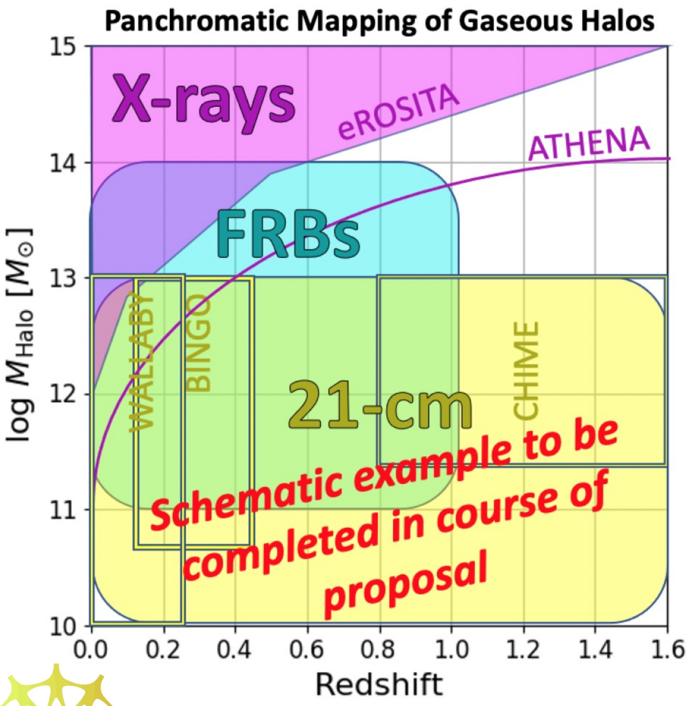
Battaglia et al. 2019, Astro2020 White Paper (astro-ph/1903.04647)

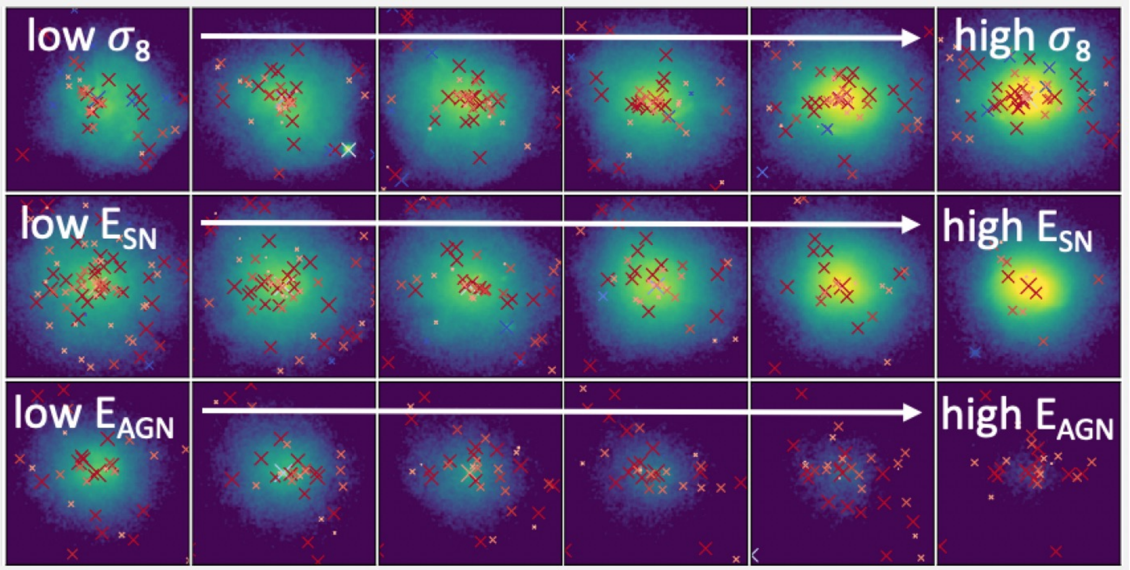
Cosmology and Astrophysics with Machine Learning Simulations (CAMELS)



A series of CAMELS papers (including public data release in 2022)

A Data-Driven Approach to the Multi-Wavelength Circumgalactic Revolution





NSF AST 2206055

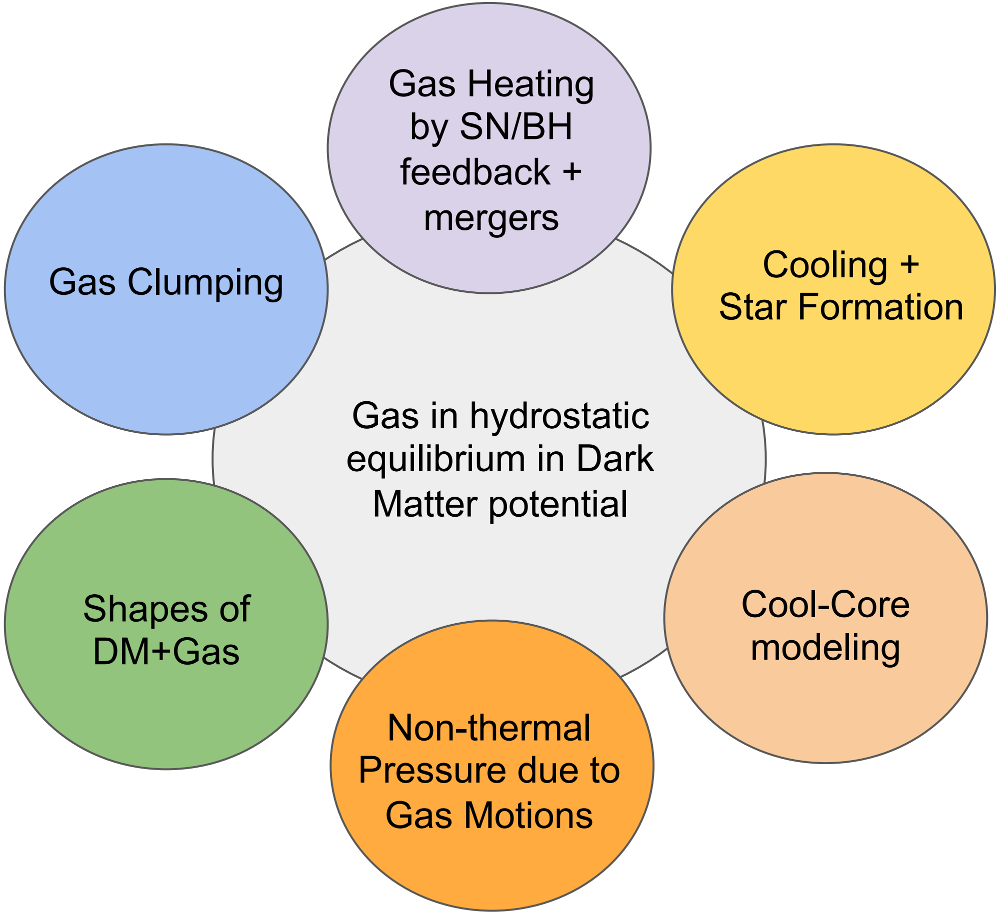
X-ray mock maps with galaxies in red stars

Constraining Feedback Physics using CAMELS & multi-wavelength observations of CGM => extensible to groups!

Modeling Frontier

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

Baryon Pasting Project



Goals

Maximize the scientific returns of multi-wavelength surveys of galaxy clusters and LSS via Cross-Survey Cross-Correlation Cosmology (CSC3)

Challenges

- Halo-Gas Connection: modeling of SZ and X-ray profiles of ICM and CGM
- Baryonification: 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

BP Gas Model: 2005-2017

A physically-motivated parameterized model of gas in DM halos:

Polytropic equation of state in cluster cores and outskirts (Ostriker+05; Shaw+10, Flender+17)

$$P_{tot} = \boxed{P_{th}} + \boxed{P_{nt}} \propto \rho_g^{\Gamma} \qquad \Gamma(r,z) = \begin{cases} 1.2 & (r/r_{500} > 0.2) \\ \boxed{\tilde{\Gamma}(1+z)^{\gamma} \quad (\text{otherwise})} \end{cases}$$

Star formation: stellar mass fraction (e.g., Giodini+09, Leauthaud+11, Budzynski+13)

$$\boxed{\frac{M_*}{M_{500}} = f_* \left(\frac{M_{500}}{3 \times 10^{14} M_\odot} \right)^{-S_*}}$$

Dynamical heating from DM and energy feedback from AGN and SNe

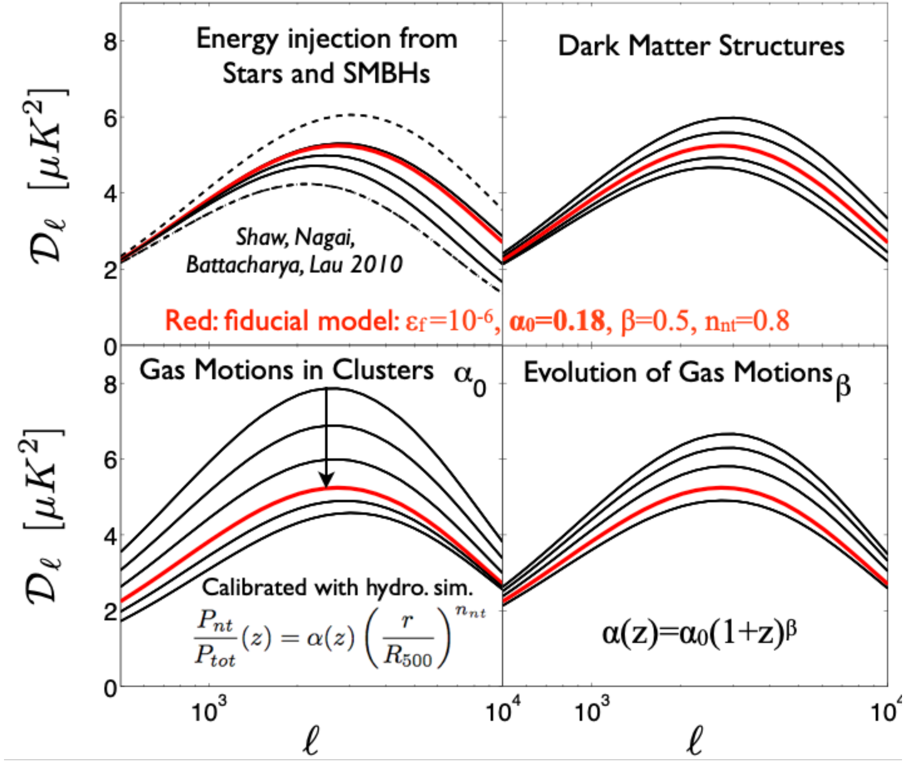
$$\boxed{E_{g,f} = E_{g,i} + \epsilon_{\rm DM} |E_{\rm DM}| + \epsilon_f M_* c^2 + \Delta E_p}$$

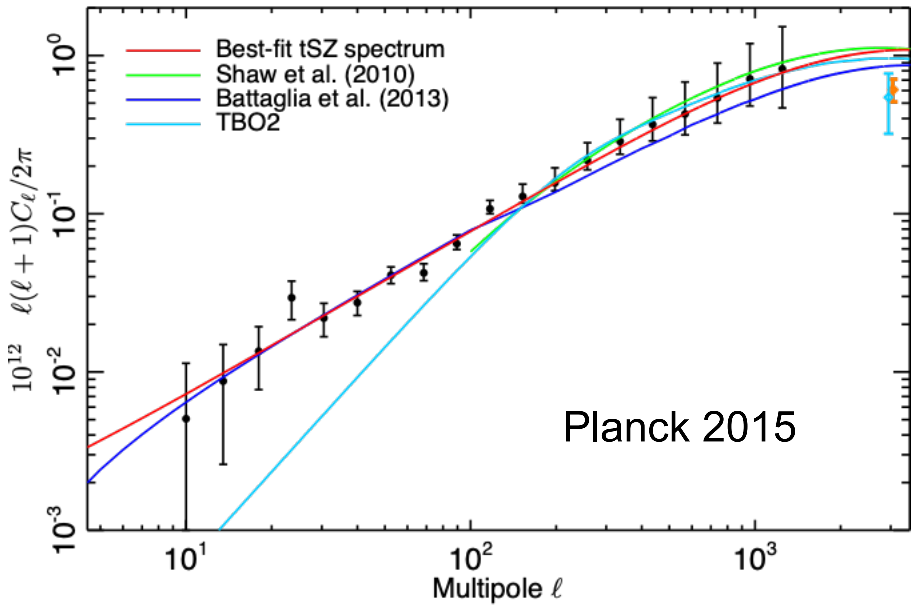
Model of merger-induced non-thermal pressure fraction (Nelson+14; see also Lau+09,13, Green+20)

$$\boxed{\frac{P_{\rm rand}}{P_{\rm total}}(r) = 1 - A \left\{ 1 + \exp\left[- \left(\frac{r/r_{200m}}{B} \right)^{\gamma} \right] \right\}}$$

BP Modeling of tSZ Power Spectrum

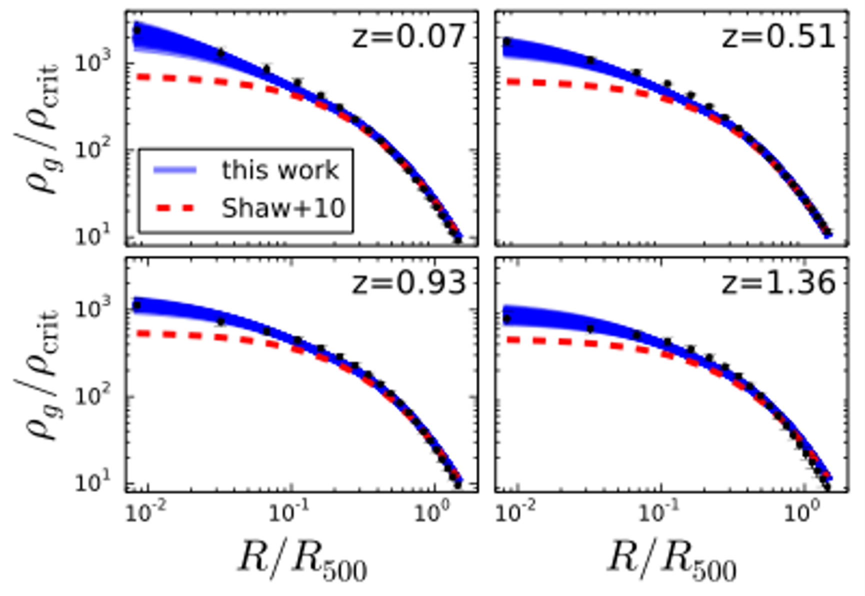
Thermal SZ power spectrum contains significant contributions from outskirts of low mass ($M<3\times10^{14}$ Msun), high-z ($z>1$) groups at $l<5000$



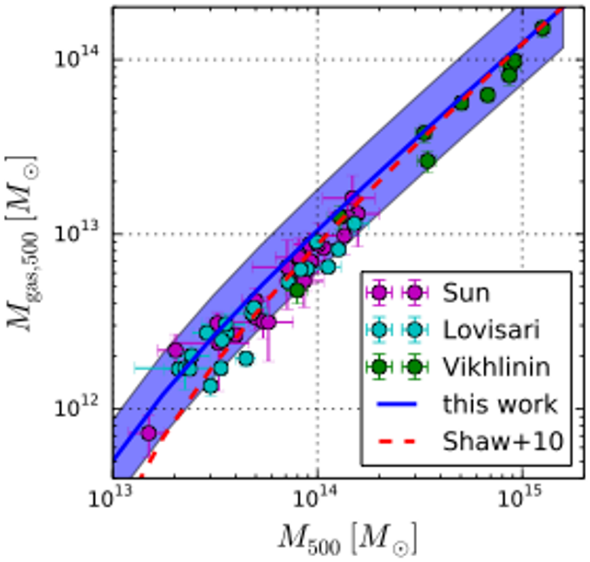


Planck measurements of the SZ power spectrum can constrain cluster astrophysics (especially non-thermal pressure)

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)

Constraints on the Gas Parameters

AGN feedback

dynamical friction heating

breaking point

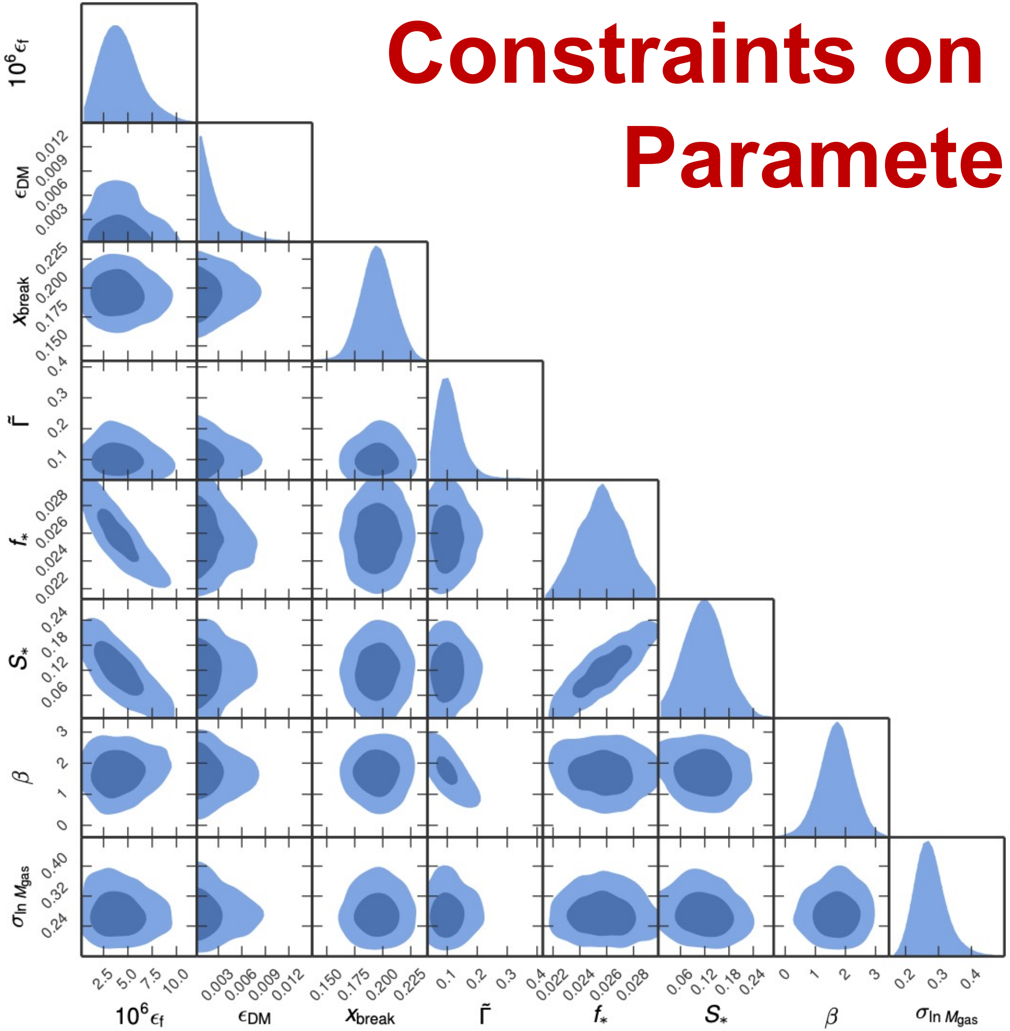
broken polytropic exponent

stellar fraction

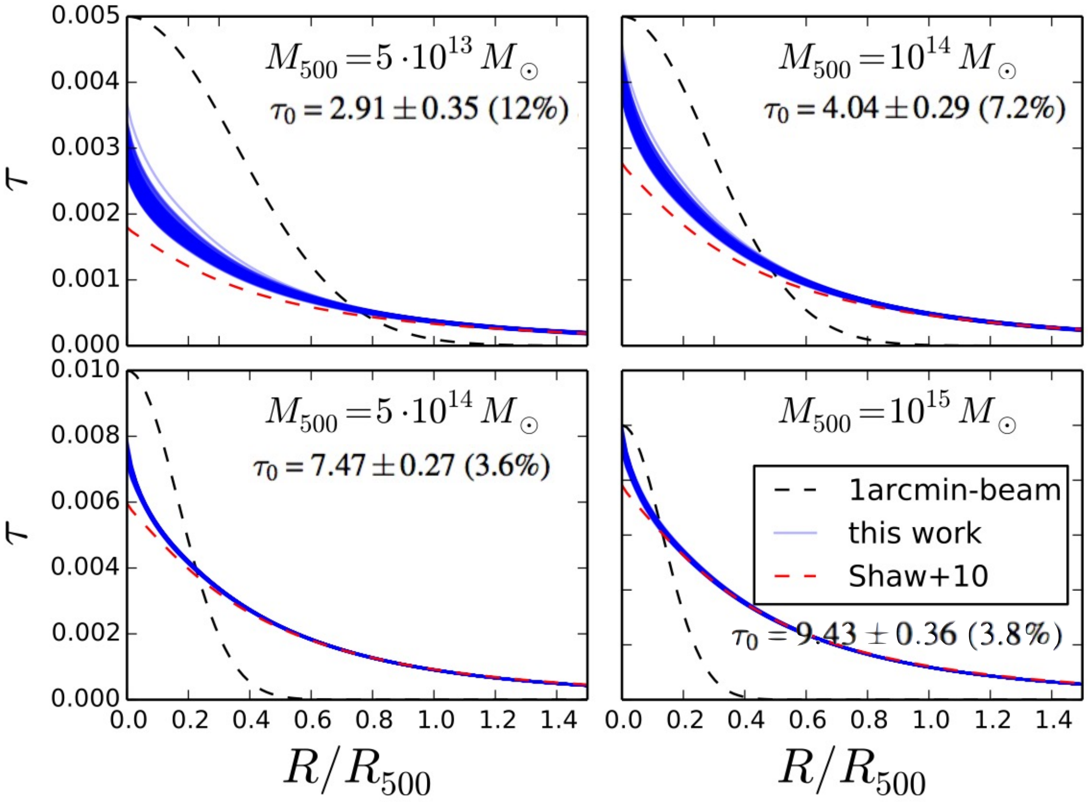
slope in stellar model

z-evolution of cooling

scatter in M_{gas}-M

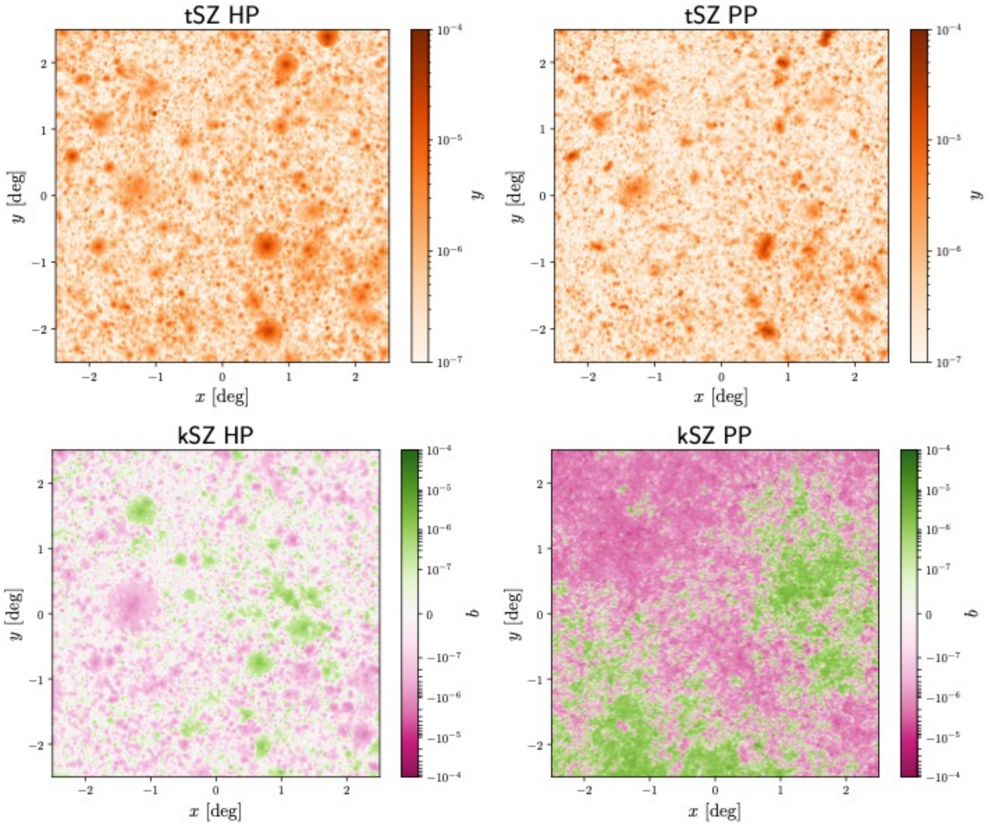


Constraining the Optical Depth of Galaxy Groups and Clusters



Better than 12% constraints on the τ profile!

Baryon Pasting Algorithm
Halo vs. Particle-based methods



Time / map

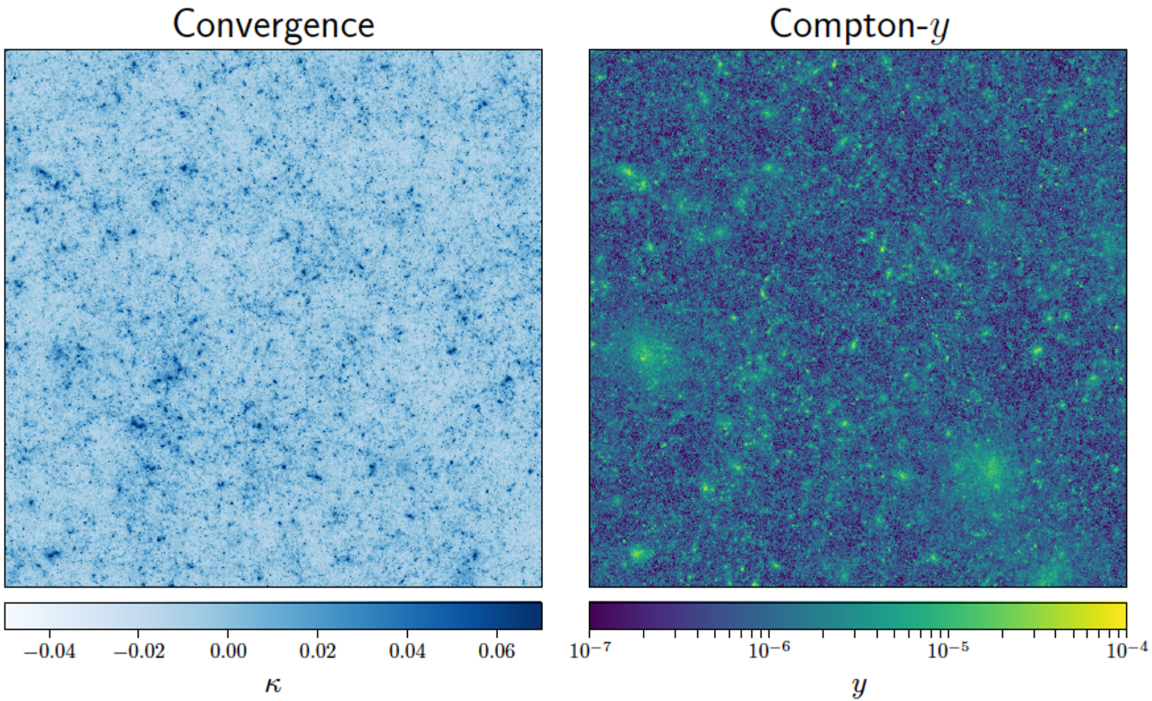
HP: 1.5 min
PP: 69 min

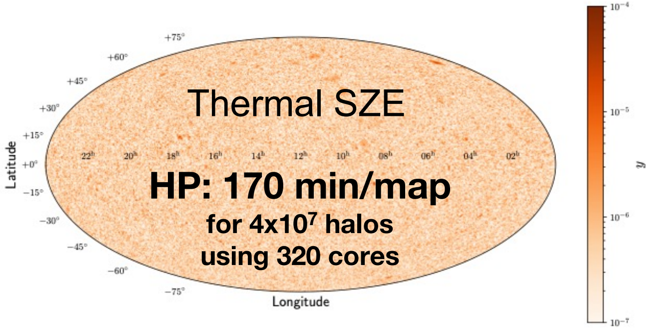
for 5×10^5 halos
using 224 cores

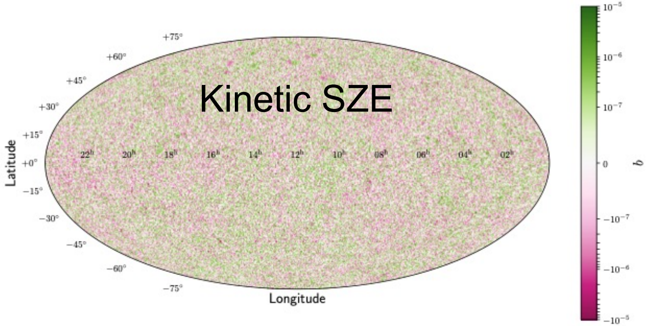
Osato & Nagai 2023
(astro-ph/2201.02632)

All-Sky BP SZ Maps

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

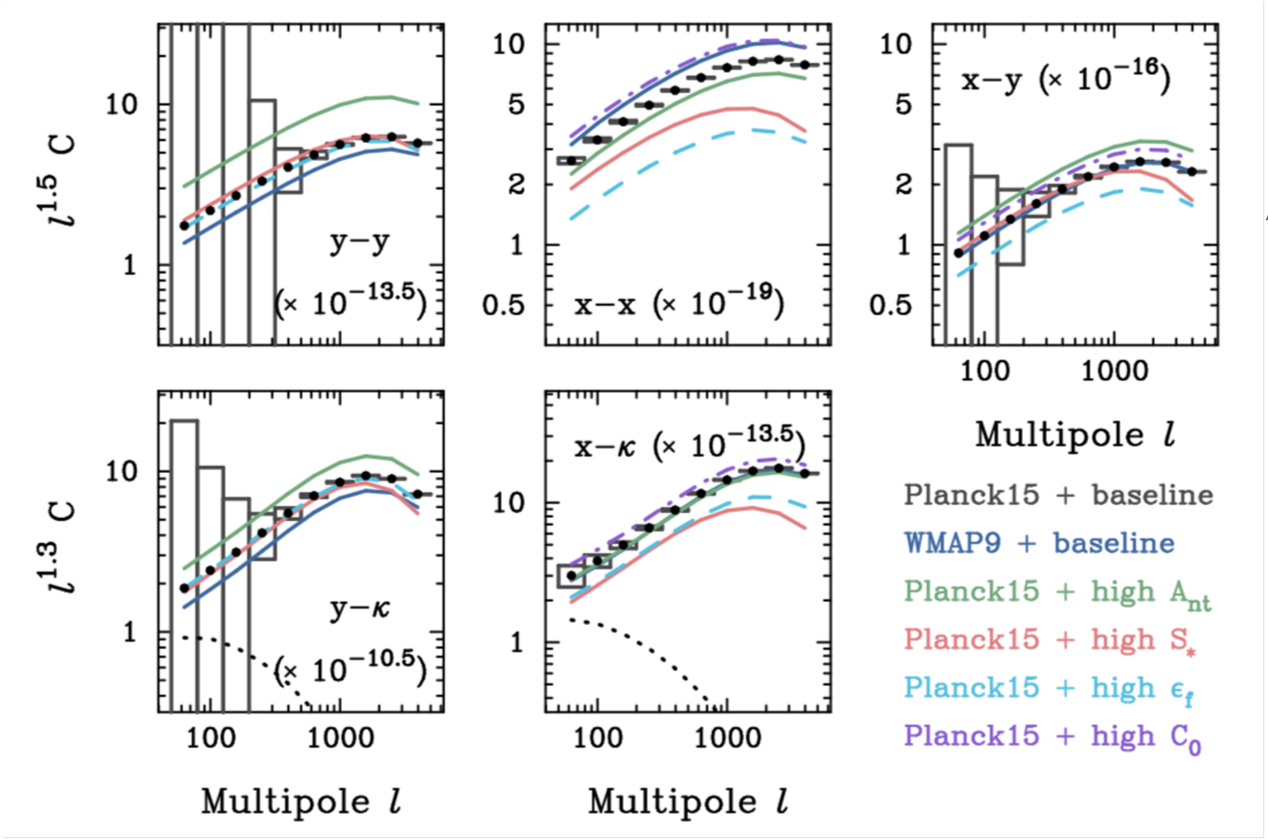






Next Step: Baryonification + tSZ x WL cross-correlation

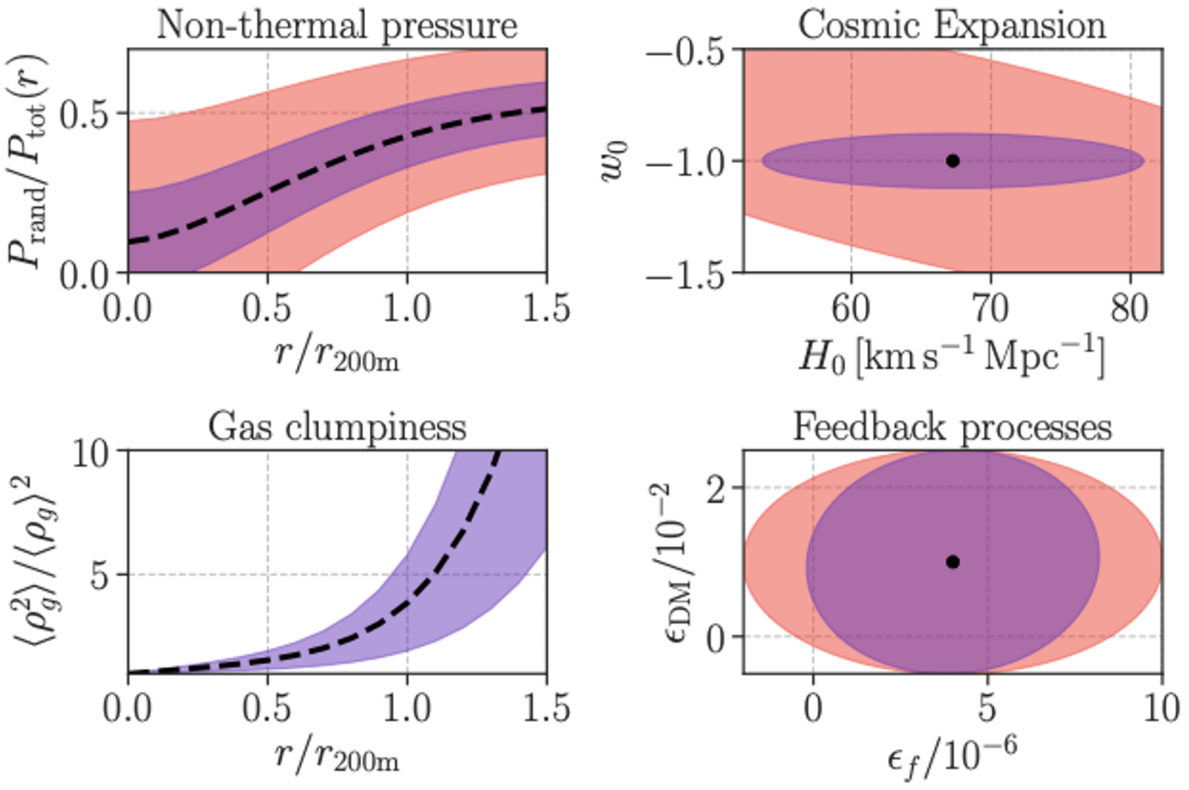
Cosmology & Astrophysics with Cross-Survey Cross-Correlation Cosmology (CSC3)



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

Shirasaki, Lau & Nagai (2020)

Cosmology & Astrophysics with Cross-Survey Cross-Correlation Cosmology (CSC3)

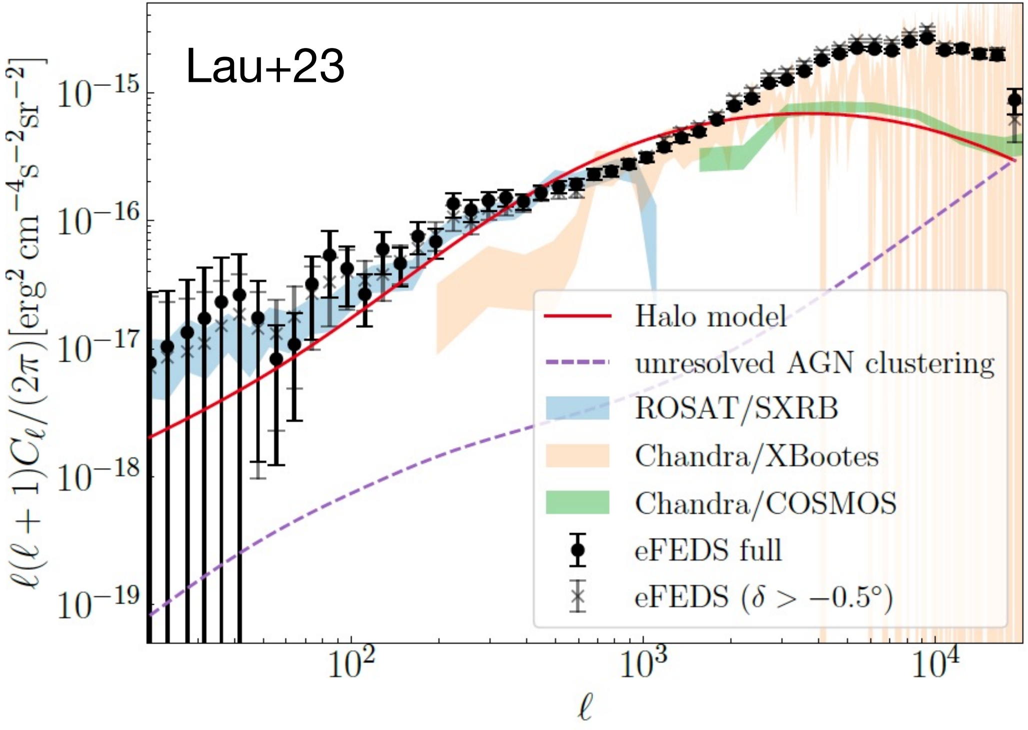


Microwave+Optical+X-ray

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)

X-ray power spectrum of eFEDS field

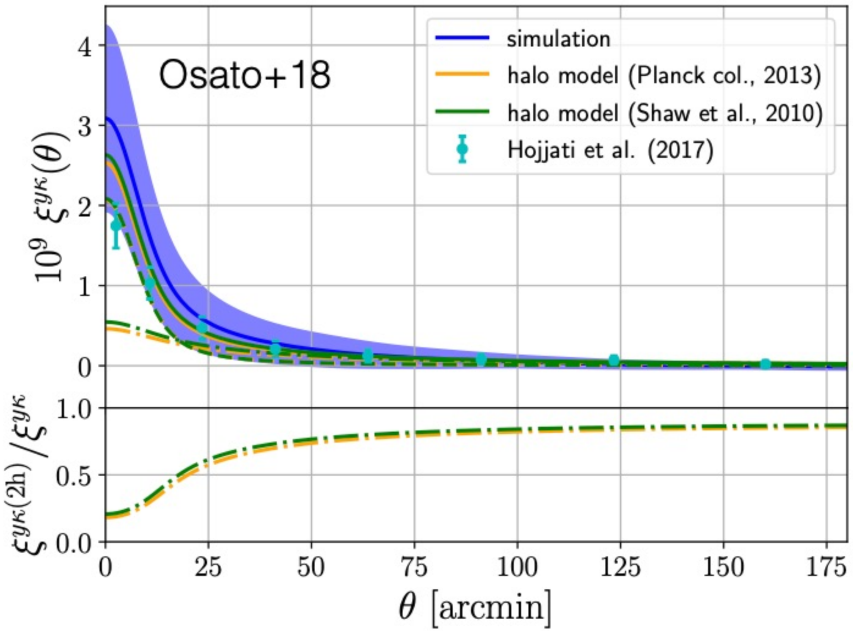


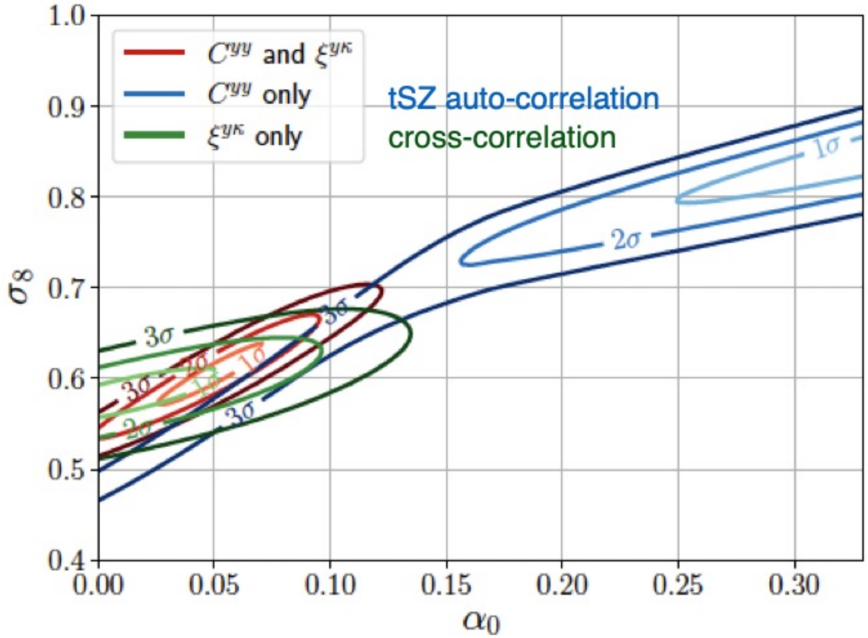
- Large-scales (ℓ < 2000, ϑ > 0.2°) - Consistent with ROSAT and the *Chandra* calibrated BP model.
- Small-scales (ℓ > 2000, ϑ < 0.2°) - Large differences between BP model and *Chandra*/COSMOS
- Expected eROSITA All Sky Survey (eRASS1) cosmological constraint using only large angular scales (ℓ < 2000)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

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

Lau, Bogdan, Chadayammuri, Nagai, Kraft, Cappelluti 2023

Cross-Correlation: tSZ x Lensing





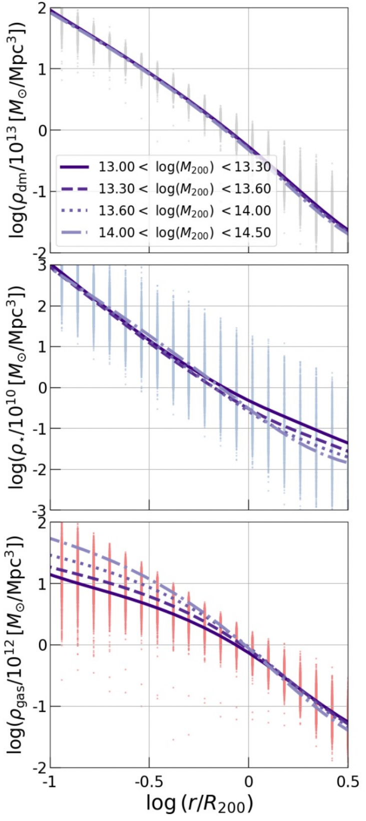
Non-thermal pressure at r=R500c

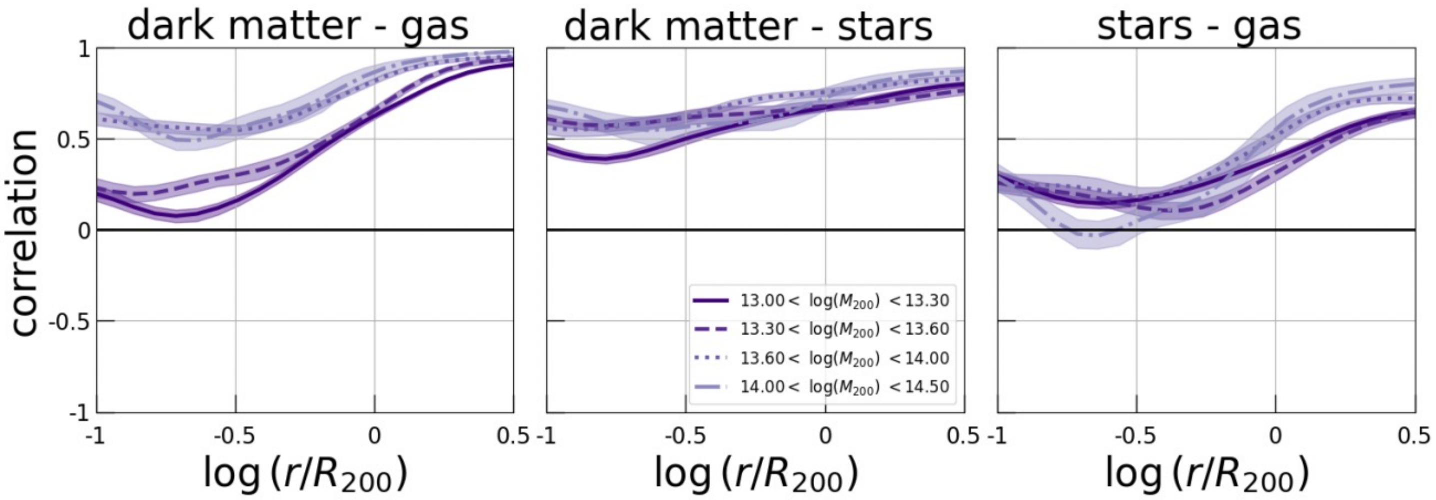
Cross-correlation of Planck and RCSLens data shows tensions with the Planck tSZ power spectrum result, indicating ICM physics in low-mass clusters at z>0.2 and/or possible systematics in SZ/lensing measurements.

e.g., van Waerbeke+14, Hill & Spergel+14, Hojjati+17, Makiya+18, Osato+20, Pandey+21

Towards Forward-Modeling Covariances

Correlated Structures of Dark Matter, Gas & Stellar Profiles

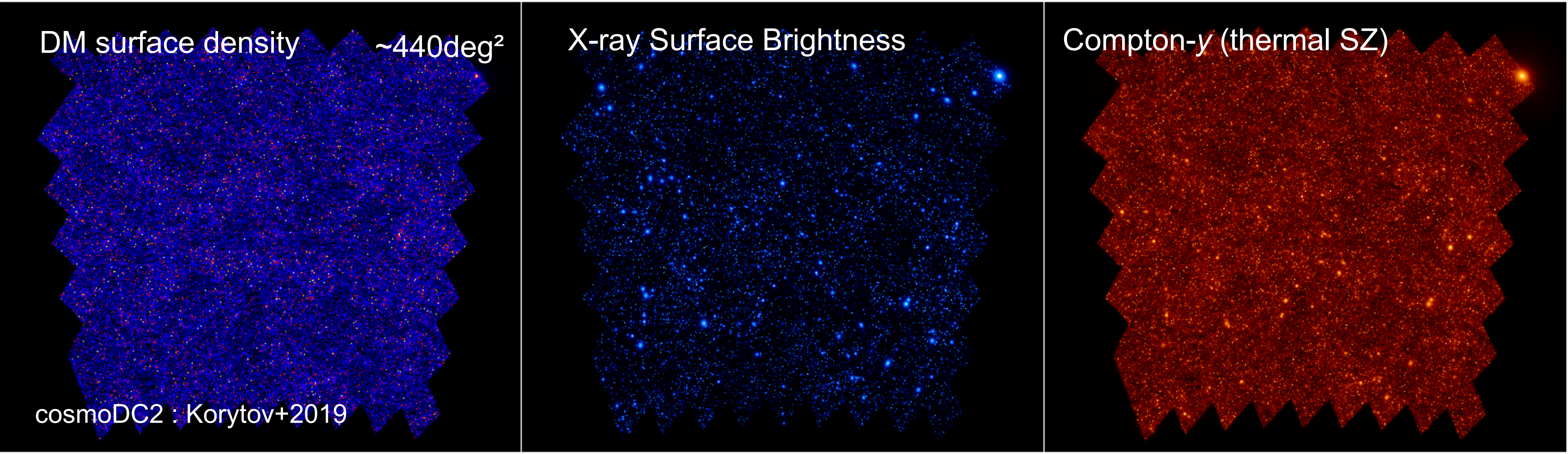




- Correlations between scatter of DM, stars, and gas density profiles in Illustris-TNG300 simulations is scale dependent and can potentially be used as a probe of astrophysics.
- These covariance matrices are a source of systematics in cluster mass calibration.

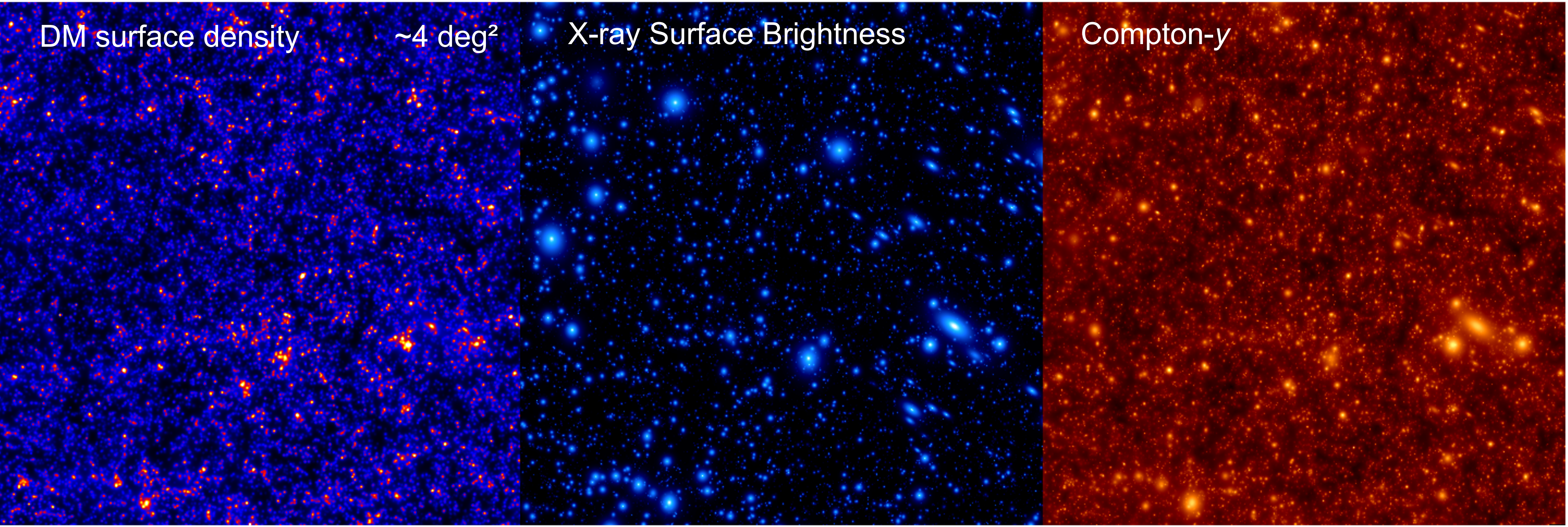
Farahi, Nagai, Anbajagane, 2022

Baryon Pasted (BP) Multi-wavelength Maps



- We generate realistic maps in X-ray and microwave, using the cosmoDC2 halo lightcone generated from large-scale *N*-body simulations
- Explore impact of astrophysics by varying parameters in the gas model

BP x cosmoDC2 maps (Zoomed-in)



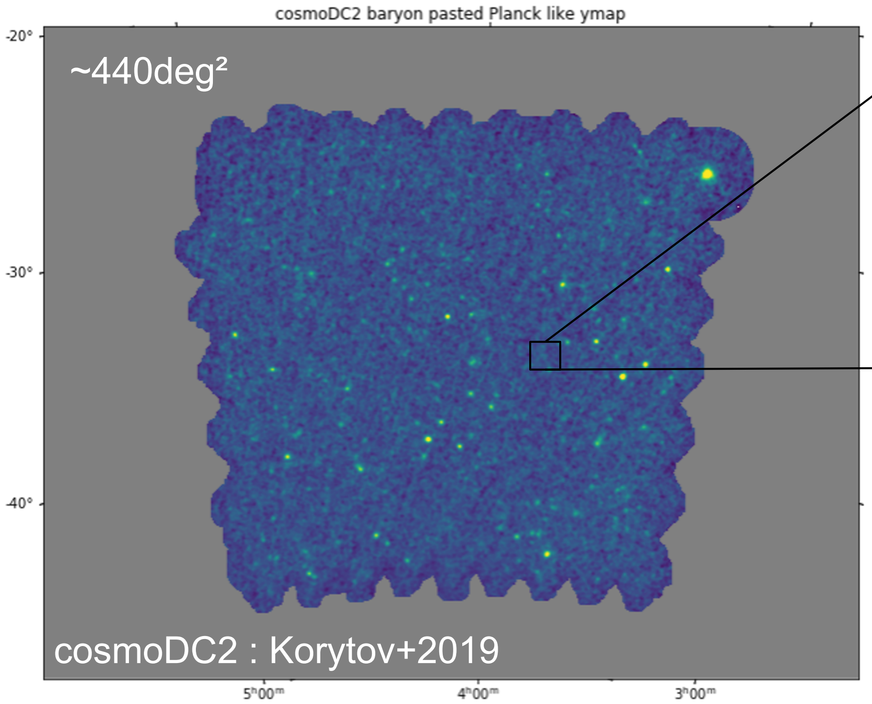
With Baryon Pasting we can:

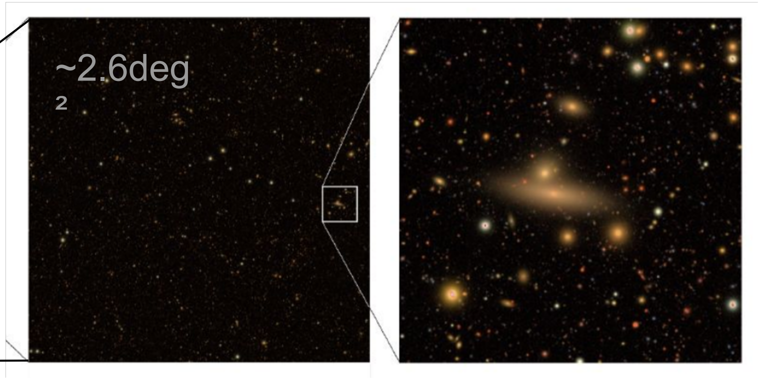
- explore astrophysical systematics by varying parameters in the gas model
- forward-model halo & gas shape, projection effects, instrumental responses with BP-generated maps

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: forward-modeling cluster scaling relations, cluster finders, selection functions, multi-wavelength cross-correlations





Critical features:

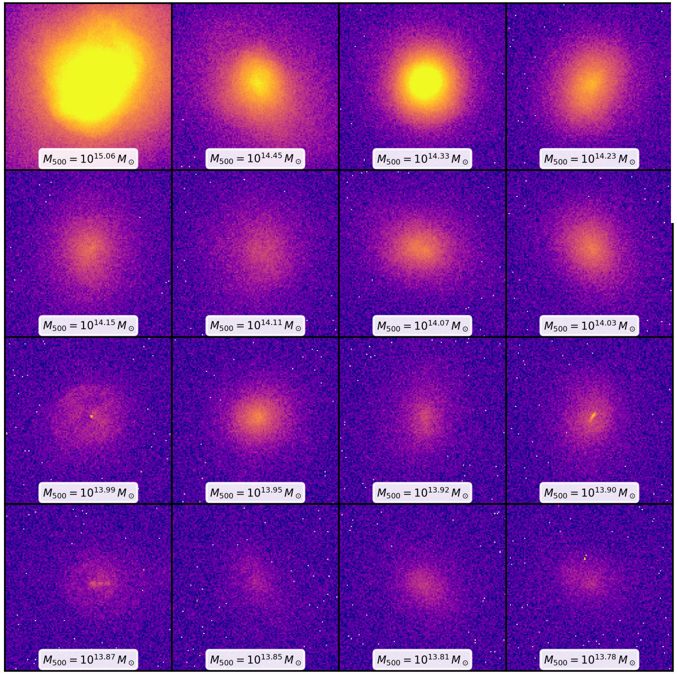
- Gas & Halo shapes & Miscentering
- Intrinsic & extrinsic scatter & orientation bias
- Scatter & covariance in DM-gas-star profiles
- Dependence on halo assembly history
- A unified model of DM halo-gas-galaxies

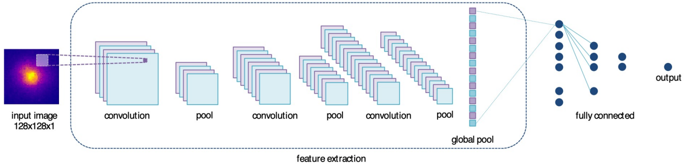
Machine Learning Frontier

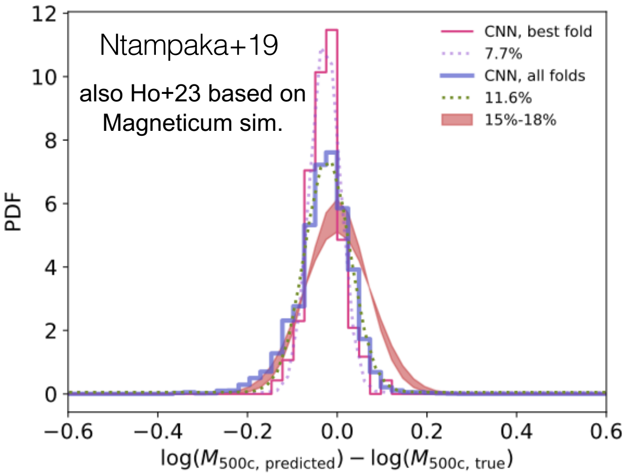
use machine learning technique to detect and exploit small signals in noisy and complex data

Precision Cluster Cosmology with Interpretable Machine Learning

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

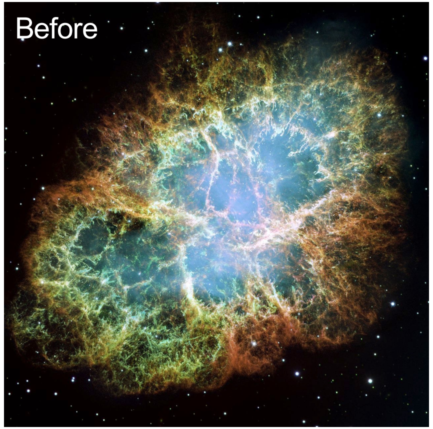


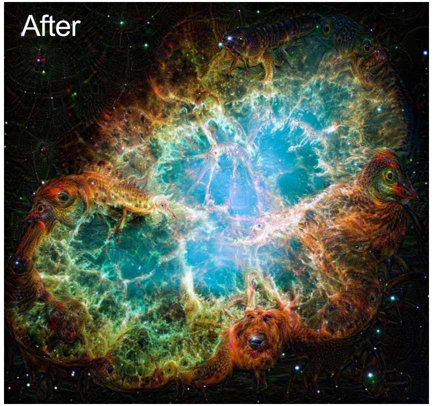




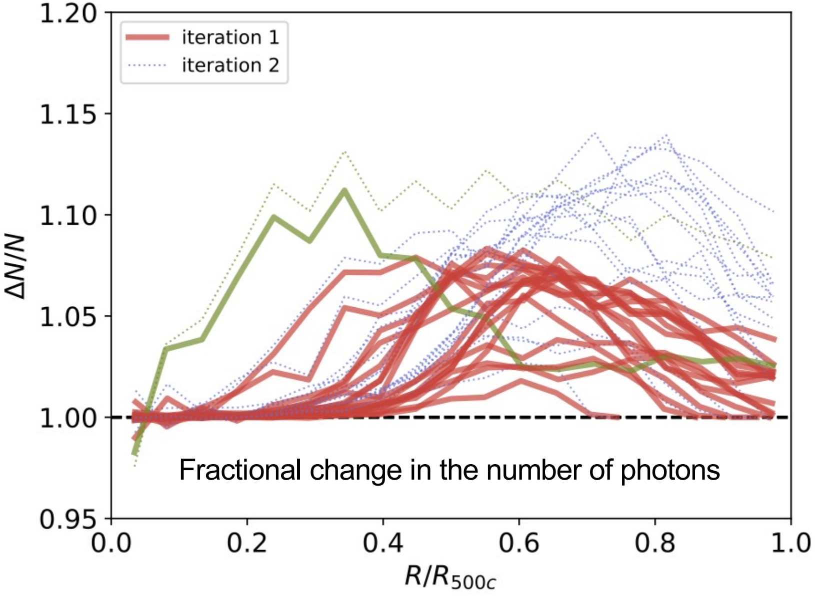
The ML-based X-ray cluster mass has a small scatter of 8-12%, which is a significant improvement from 15-18% scatter based on the core-excised X-ray luminosity - the current market standard.

Beyond the Black Box: Interpreting the model with Deep Dream



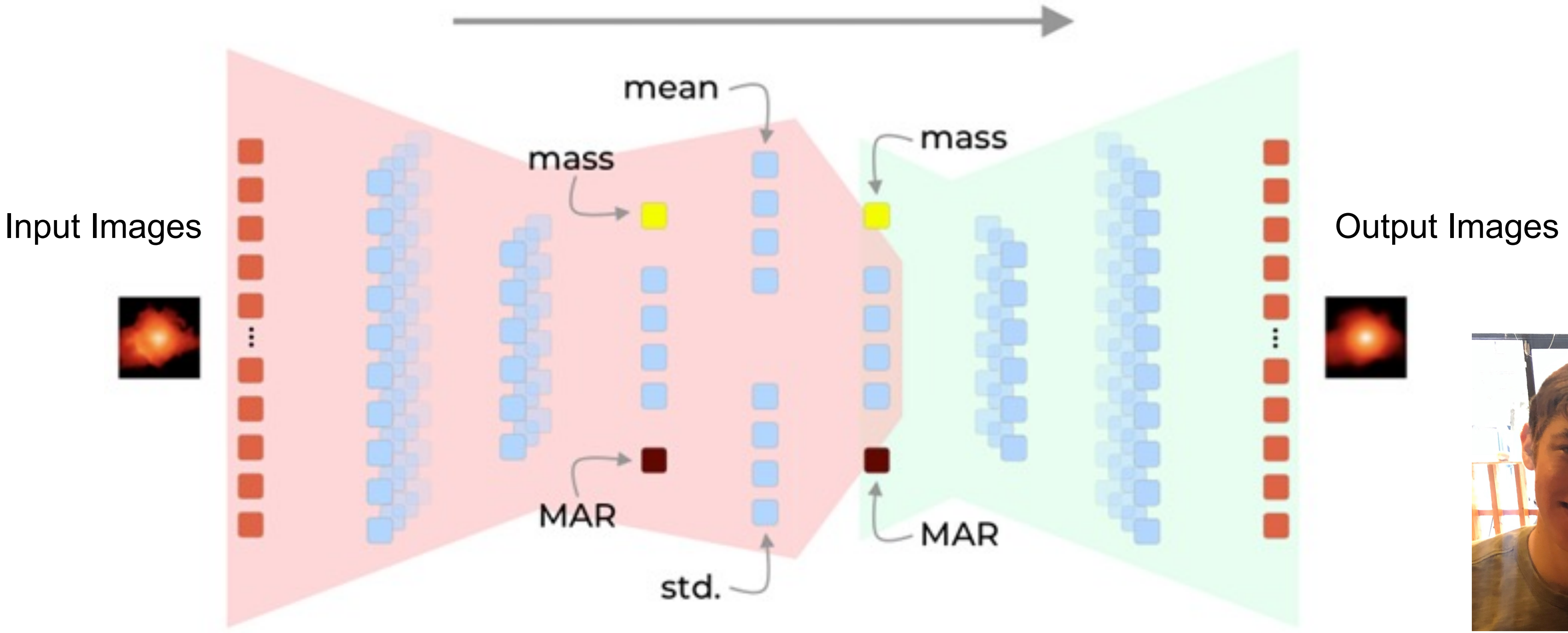


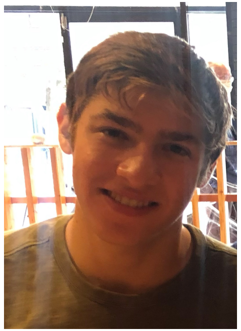
Ask: What changes in the input cluster image will result in a mass change of this image?



Good News: CNN has learned to excise core, which are known to have large scatter with mass and more!

Emulating SZ Images using Auto-Encoder

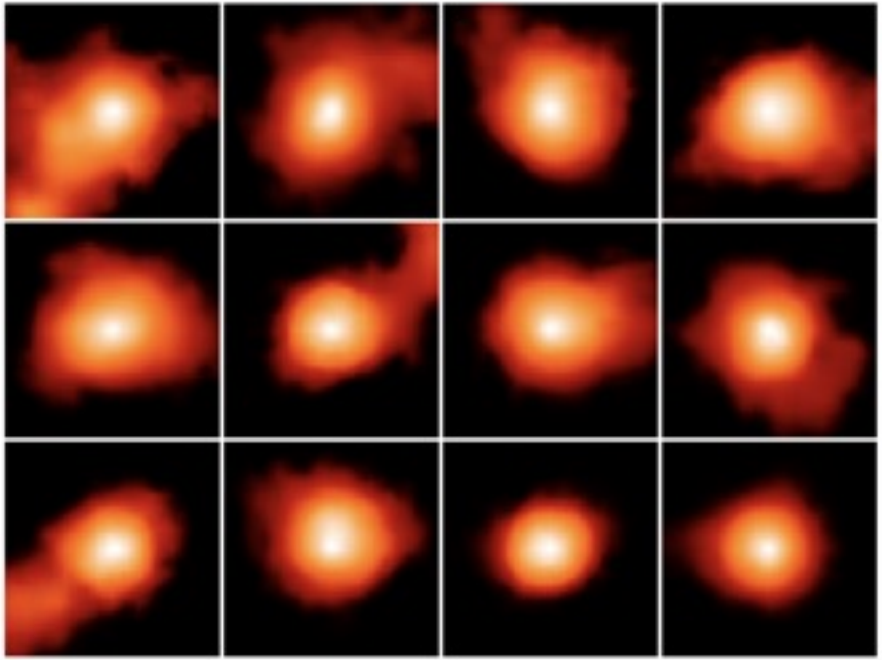


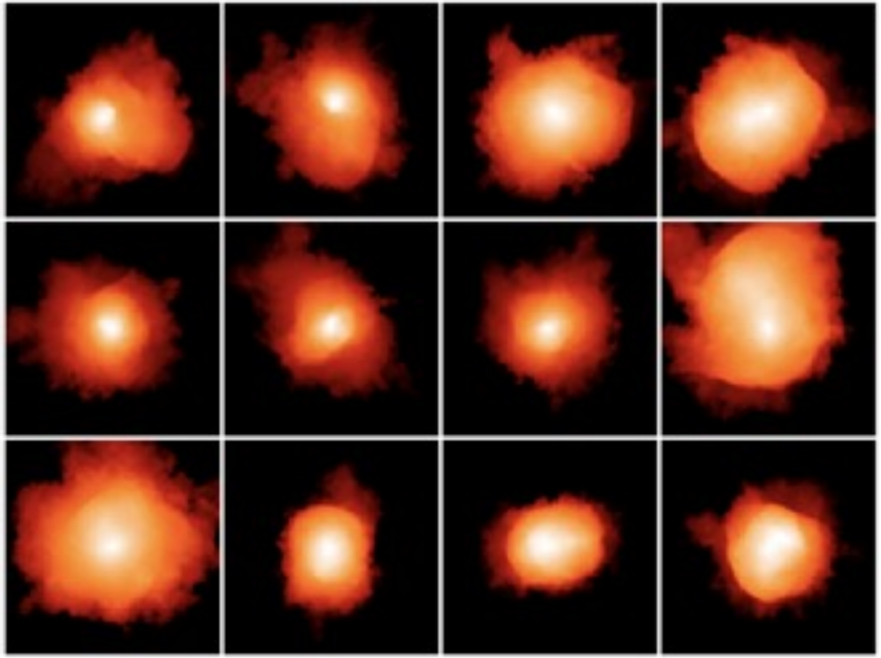

Tibor Rothschild

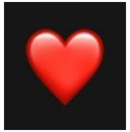
Rothschild+22

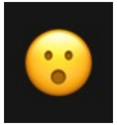
Question: Original vs. Generated Images?

Which images are generated by auto-encoders?









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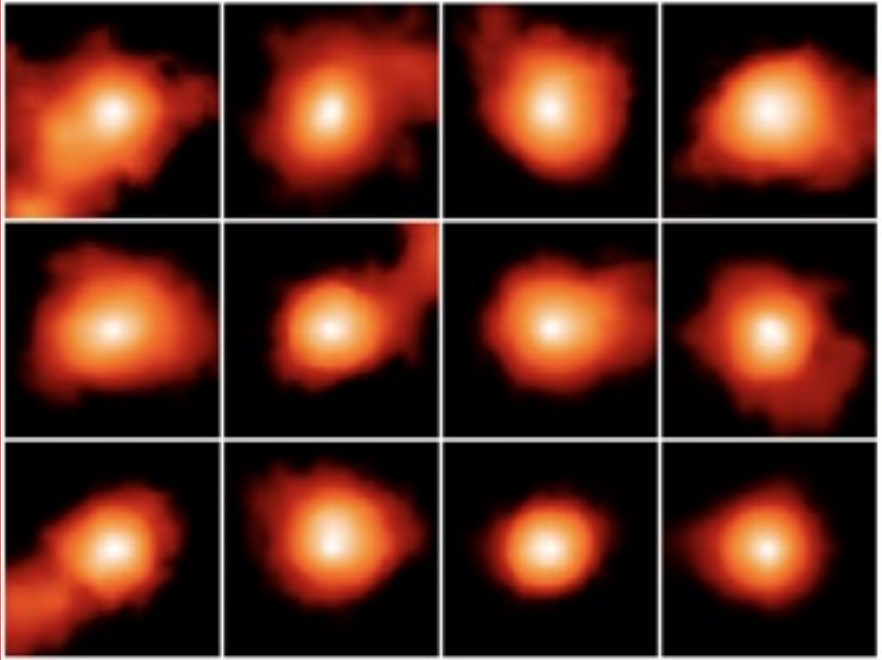
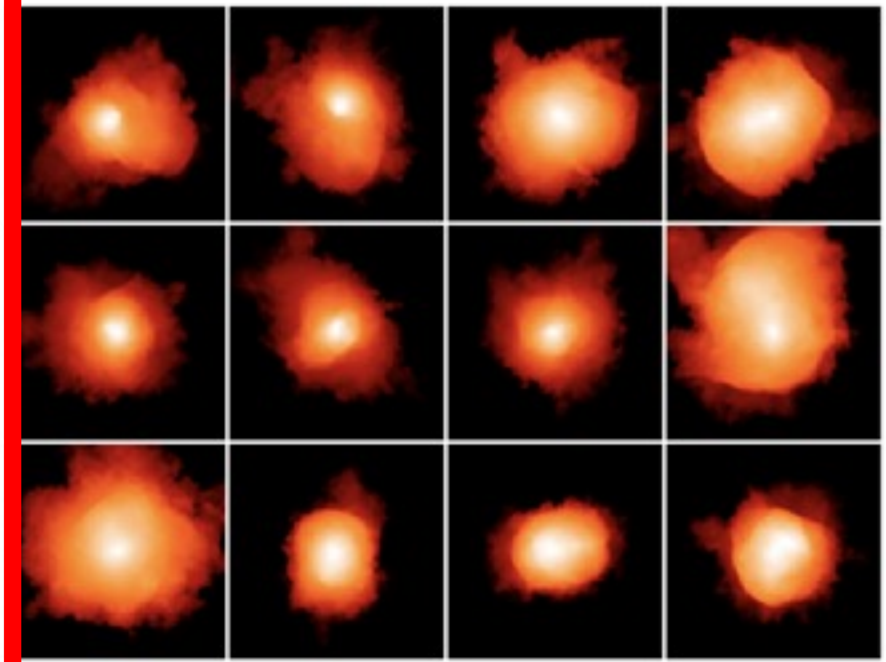
Answers: Original vs. Generate Images?

Generated images by the auto-encoder



Original images from hydro sims



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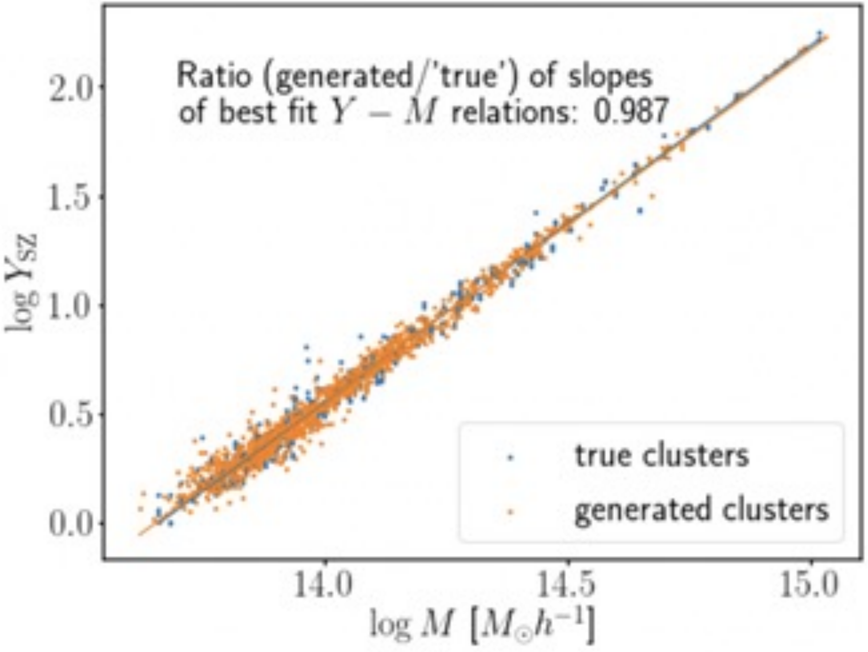
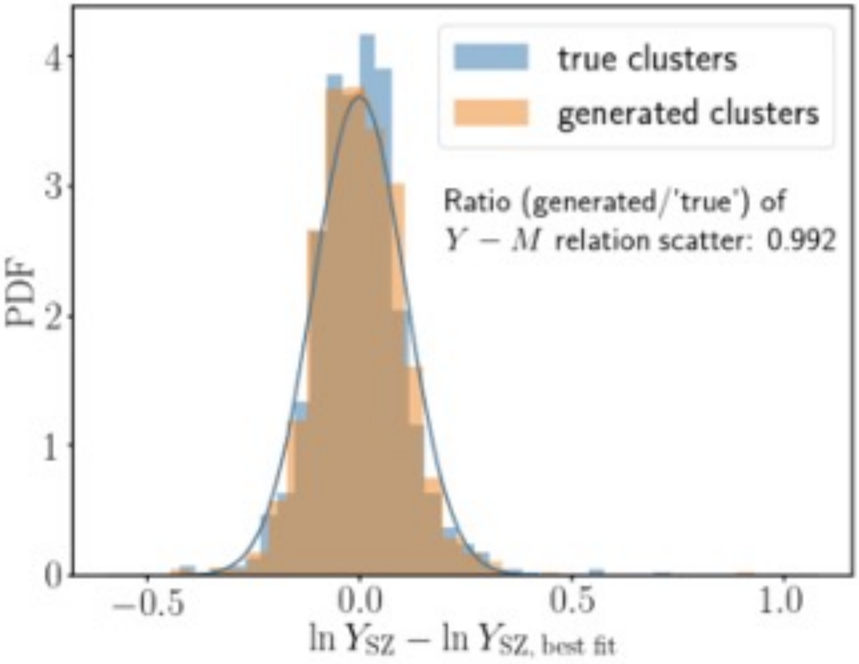
Reproducing the Scatter in tSZ scaling relation





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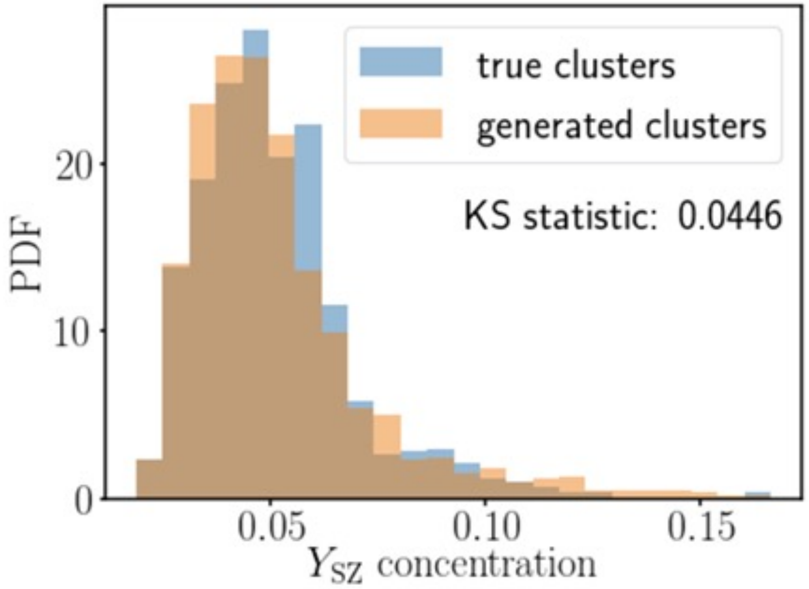
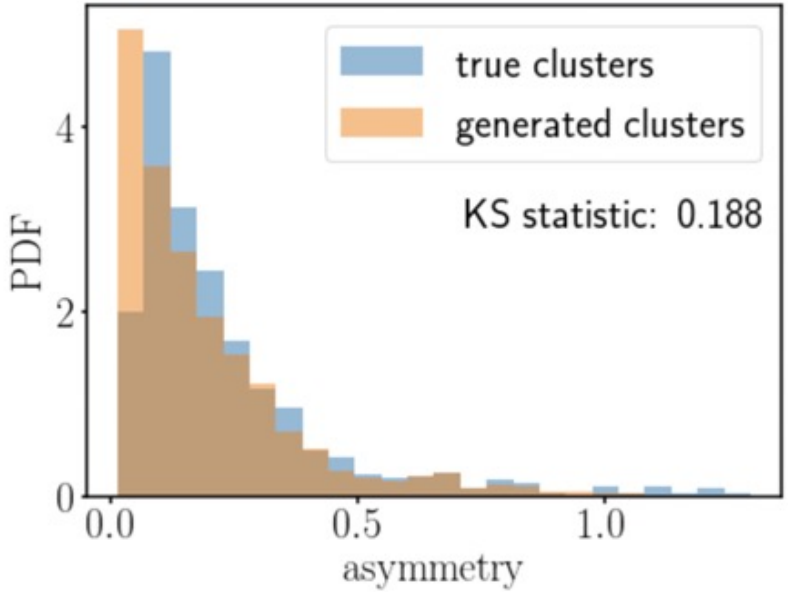
Reproducing Morphological Properties





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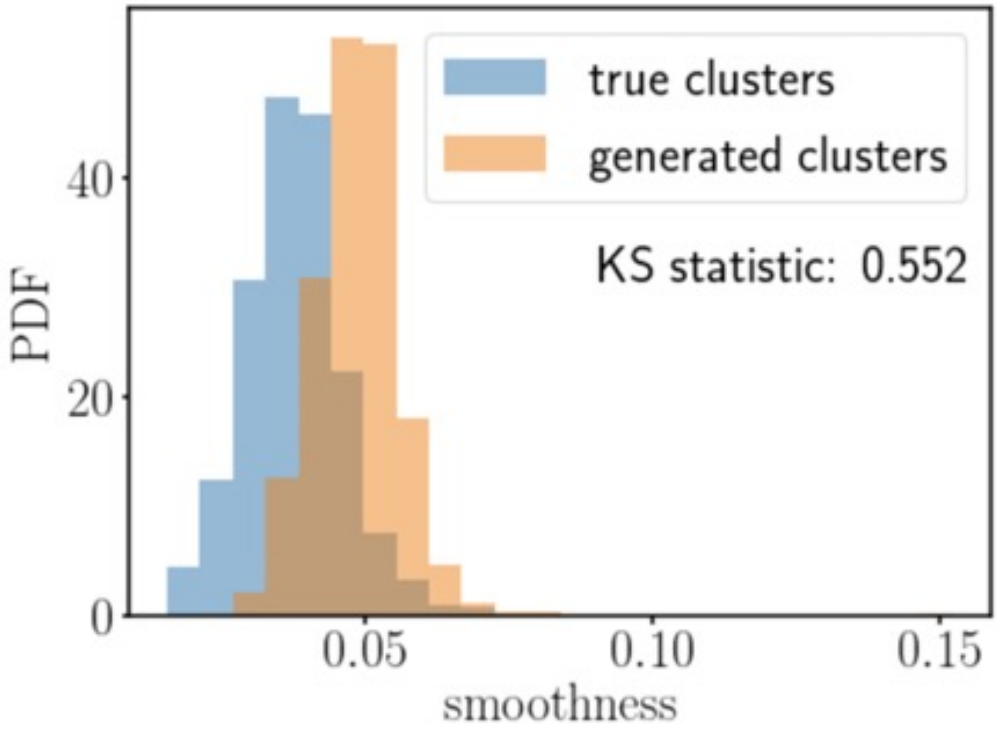
Reproducing Morphological Properties



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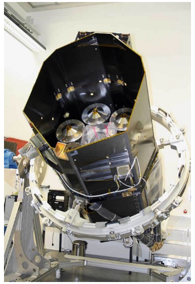
Baryon Pasting Project:

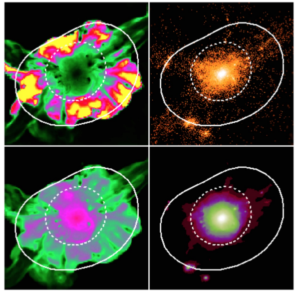
Precision Cosmology & Astrophysics in the Era of Multi-Wavelength Surveys

X-ray *Microwave* *Optical*

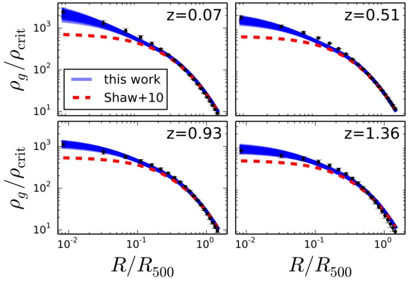


eRosita

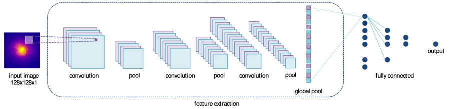
Computer Simulation



Analytical Modeling



Machine Learning



Opportunities

Maximize the scientific returns of multi-wavelength surveys (e.g., galaxies, clusters, cosmic web)

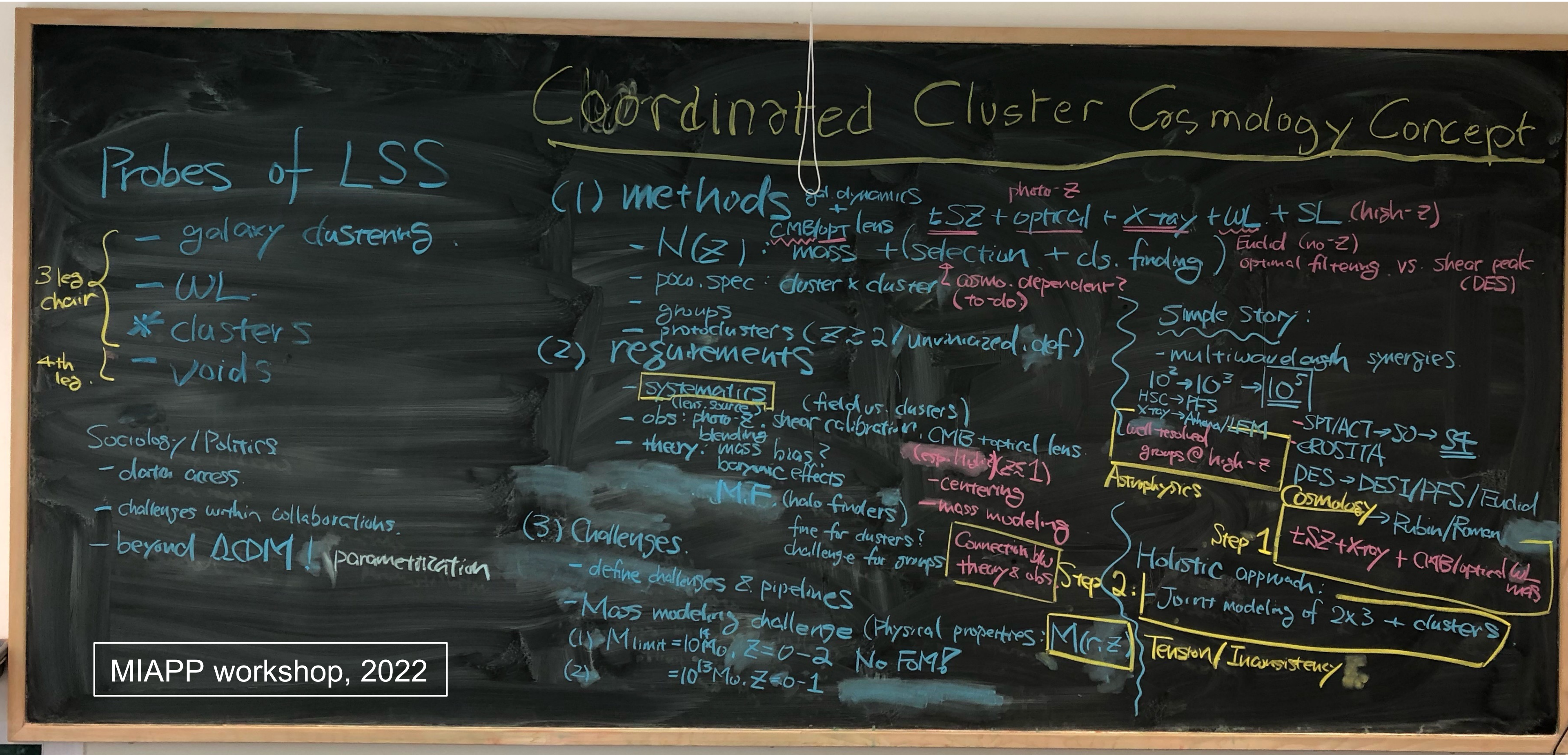
Challenges

- DM Halo-Gas-Galaxy Connection
- Multi-scale, Multi-physics Problem
- Big Data Challenge
- Roles of Hydro Sim, SAMs, ML for cosmo/astro inference

New Frontiers

1. **Computational Frontier:** *hydro. cosmo. simulations*
2. **Machine Learning Frontier:** *machine learning*
3. **Modeling Frontier:** *a physically-motivated, computationally efficient model*

A Roadmap for Cluster Cosmology



MIAPP workshop, 2022