**Title:** Cosmology in the Era of Multi-Wavelength Surveys

**Speakers:** Daisuke Nagai

**Collection/Series:** Cosmology and Gravitation

**Subject:** Cosmology

**Date:** November 12, 2024 - 11:00 AM

**URL:** https://pirsa.org/24110059

**Abstract:**

We are entering the golden age of multi-wavelength astronomical surveys. In the 2020s, a plethora of surveys (such as Euclid, eROSITA, Rubin-LSST, Simons Observatory, and CMB-S4) are underway or planned to provide unprecedented insights into cosmology and astrophysics. In this talk, I will discuss the significant scientific opportunities and challenges that arise in the era of big data, highlighting recent advances in computational modeling and the roles of artificial intelligence and machine learning.

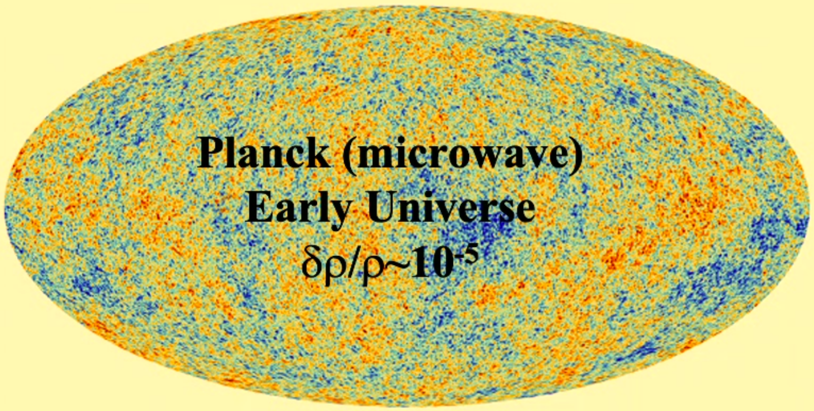
# Cosmology in the Era of Multi-Wavelength Surveys

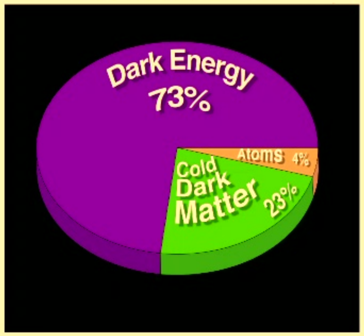
**Daisuke Nagai**
Yale University

Cosmology Seminar
Perimeter Institute
November 12, 2024

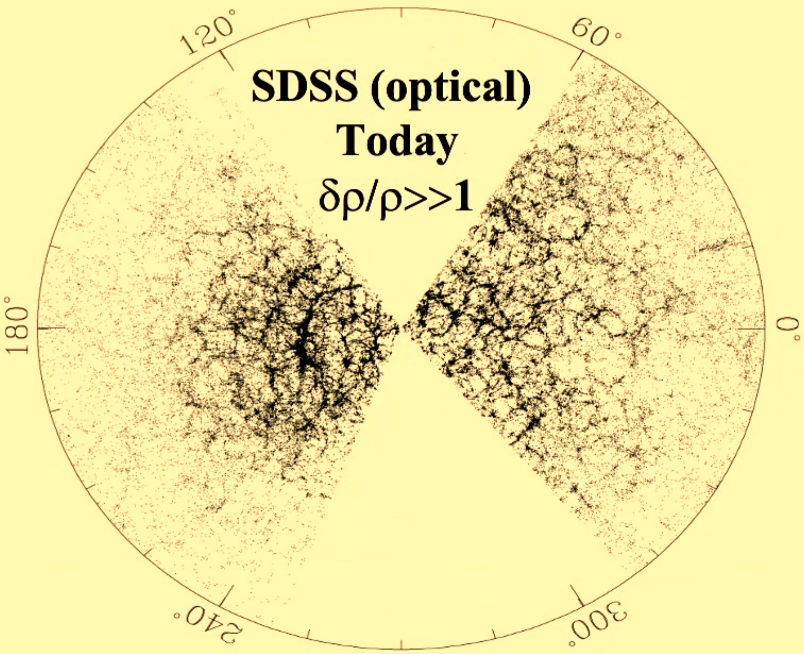
# Cosmology: from large to small scales

## The Universe as a Laboratory for Fundamental Physics

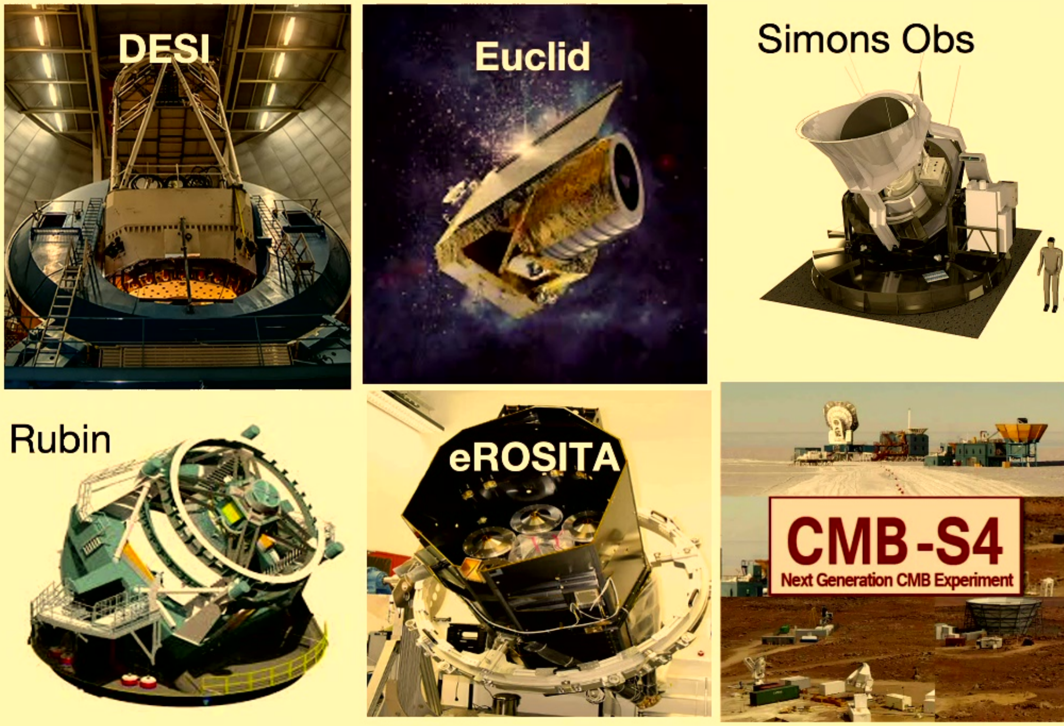


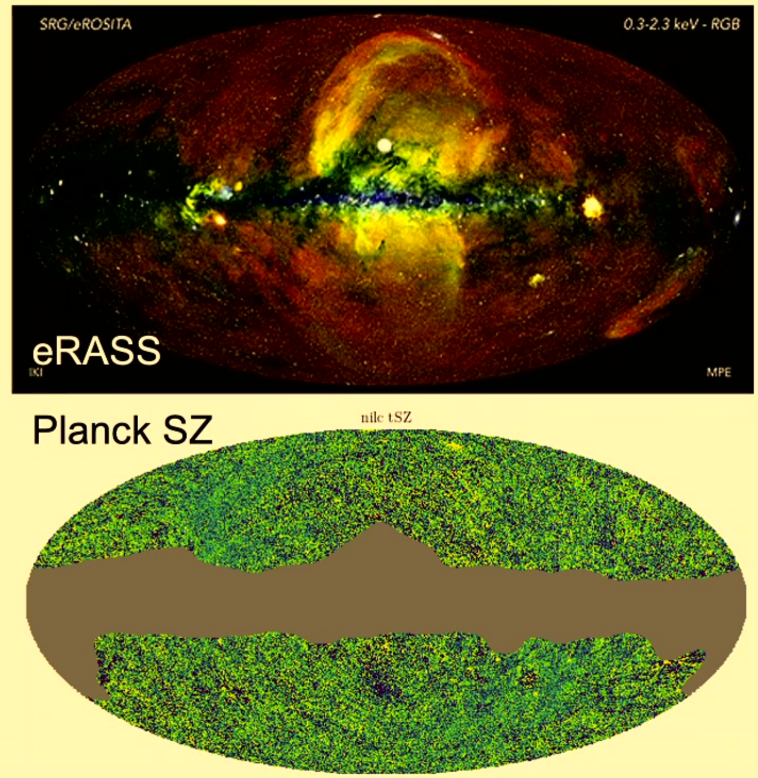




*What are dark energy & dark matter?*
*How does the structure form in the Universe?*



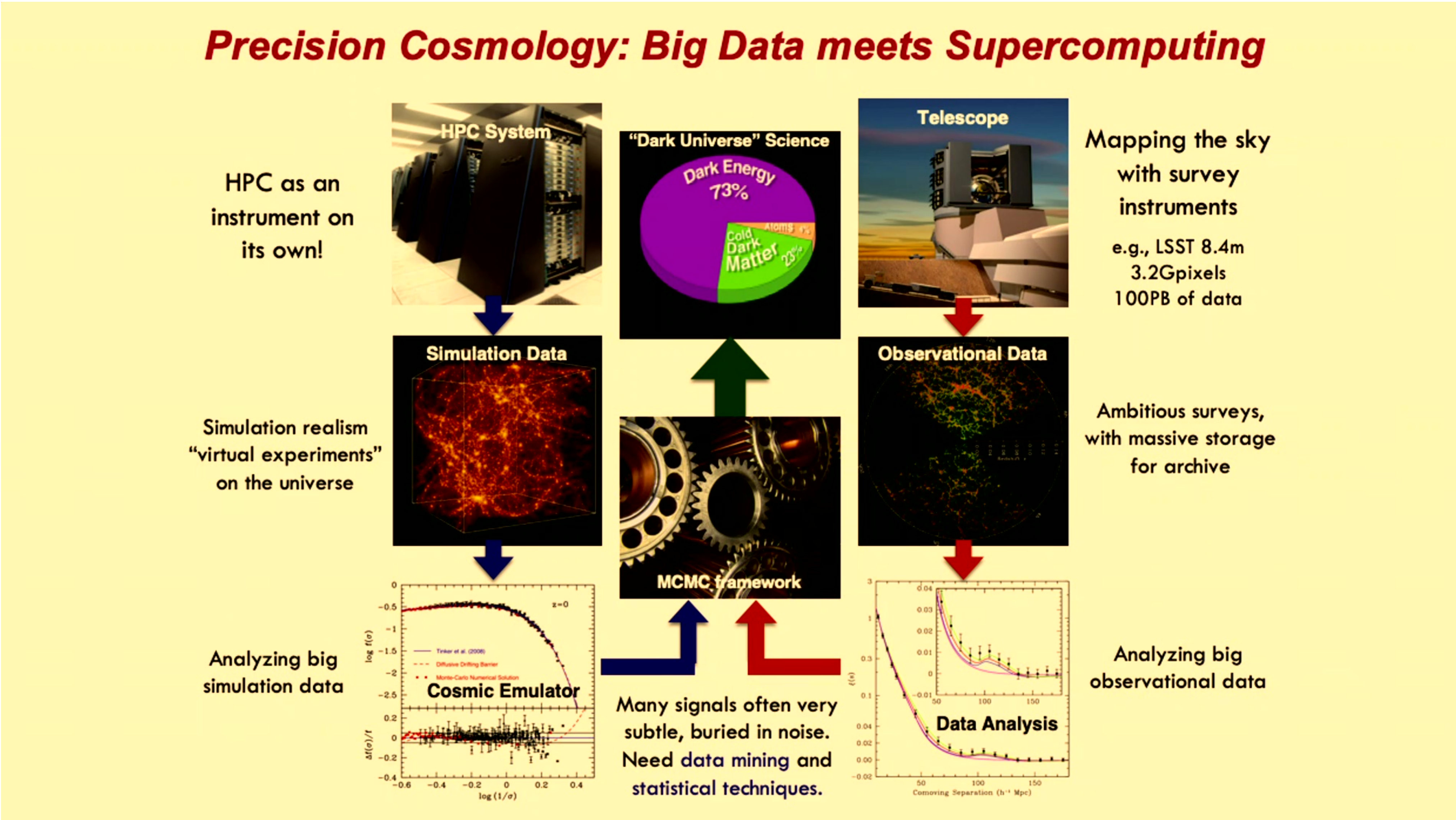
# *Cosmology in the Era of Multi-Wavelength Surveys: from large to small scales*



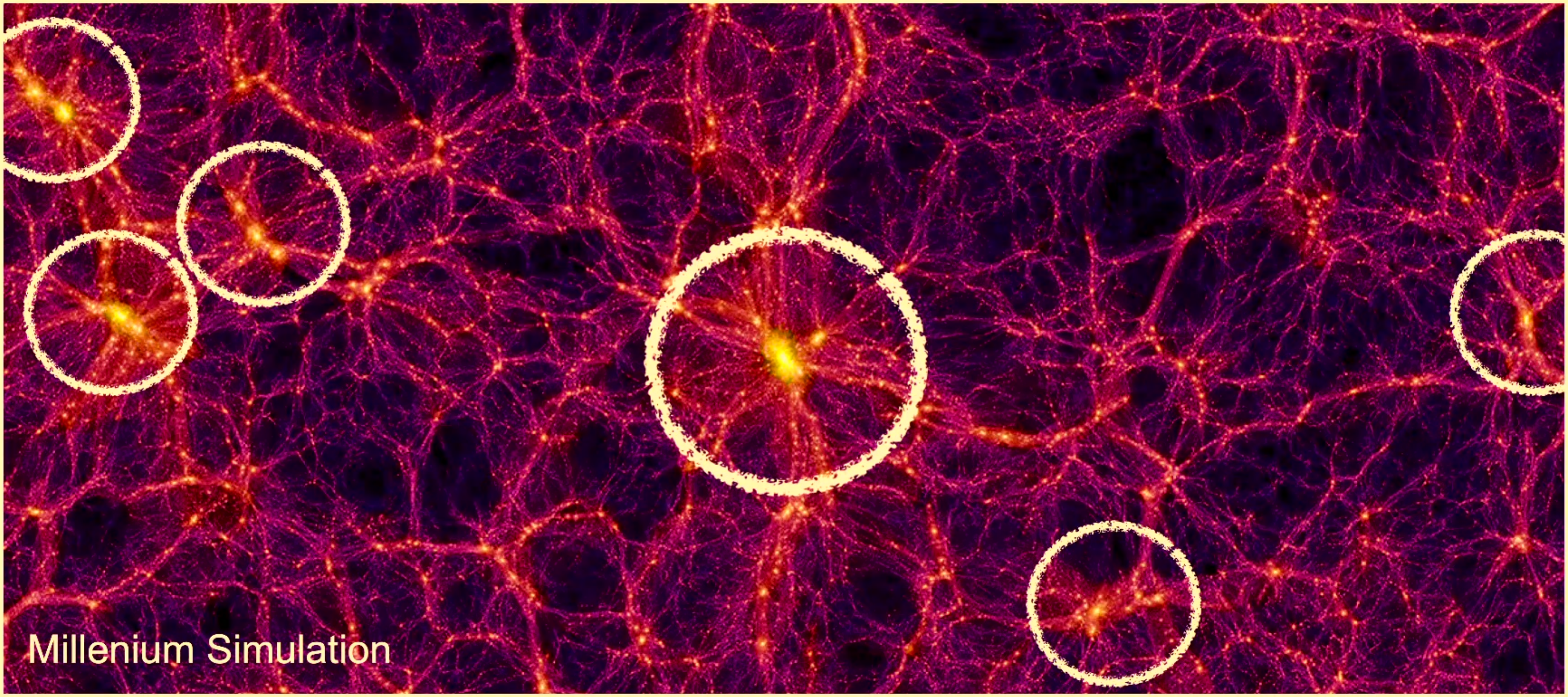




*Cosmic Visions 2016 Report from DOE:*

"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!**

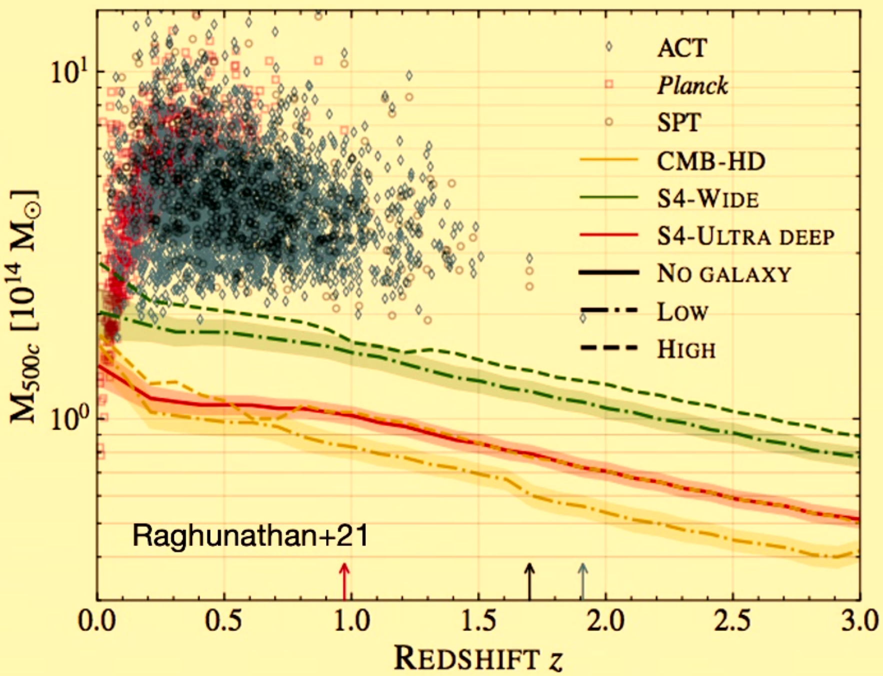

Precision Cosmology: Big Data meets Supercomputing
HPC as an instrument on its own!
HPC System
"Dark Universe" Science
Dark Energy 73%
Cold Dark Matter 23%
Atoms 4%
Telescope
Mapping the sky with survey instruments
e.g., LSST 8.4m
3.2Gpixels
100PB of data
Simulation Data
Observational Data
Simulation realism "virtual experiments" on the universe
Ambitious surveys, with massive storage for archive
MCMC framework
Analyzing big simulation data
Cosmic Emulator
Many signals often very subtle, buried in noise. Need data mining and statistical techniques.
Data Analysis
Analyzing big observational data

# Cosmology: from Galaxy Clusters to Groups, Galaxies and Cosmic Web

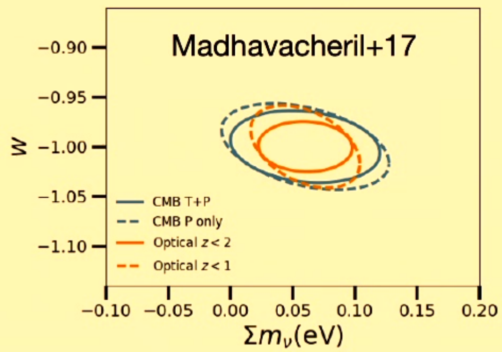


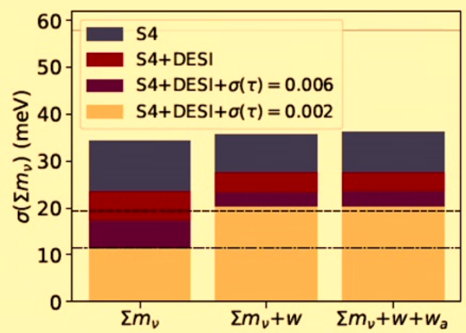

Galaxy clusters are the largest virialized objects in the Universe today, forming through mergers and mass accretion from the cosmic-web. Their formation and evolution are governed by dark matter and dark energy.

# Cluster Cosmology in the Stage IV Era

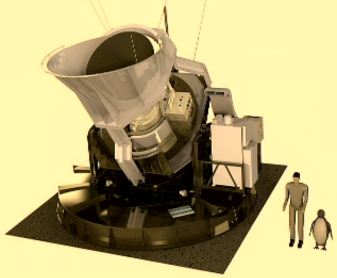



**CMB-S4+optical**



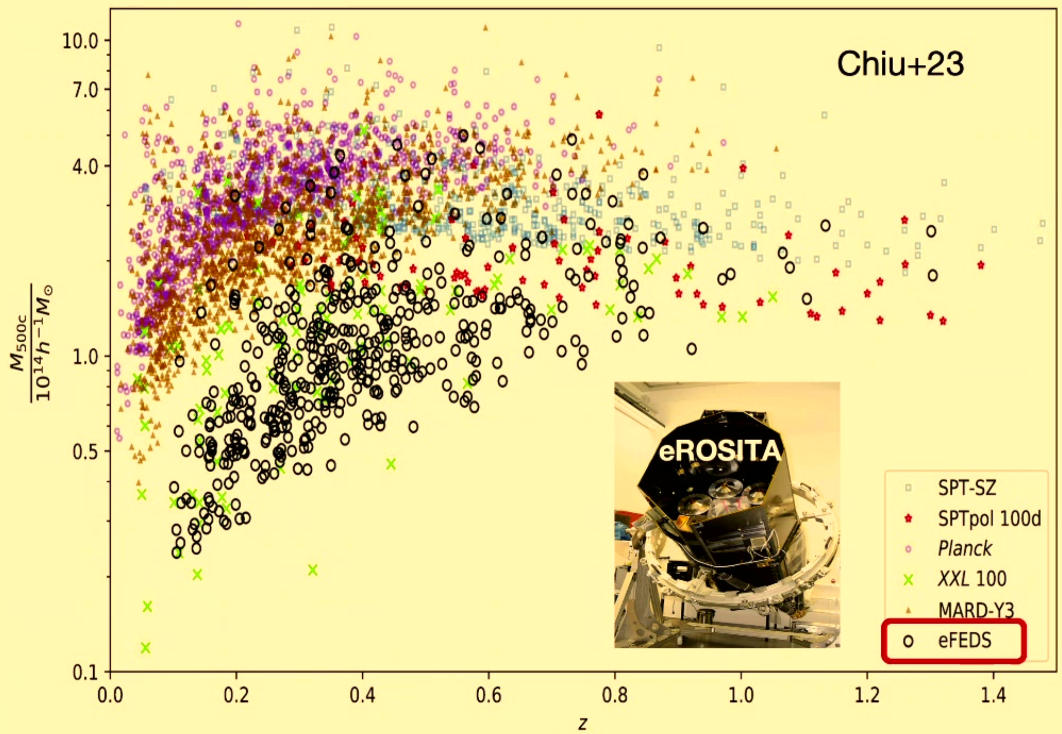

Simons Obs



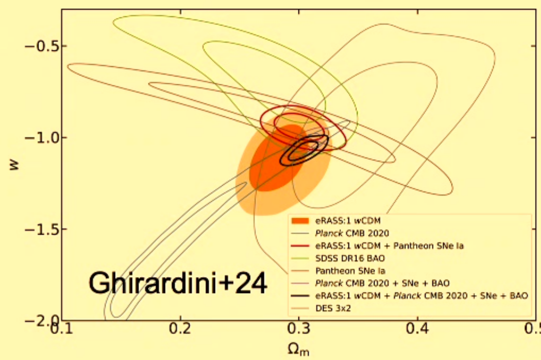

*Galaxy Clusters are potentially powerful cosmological probes*

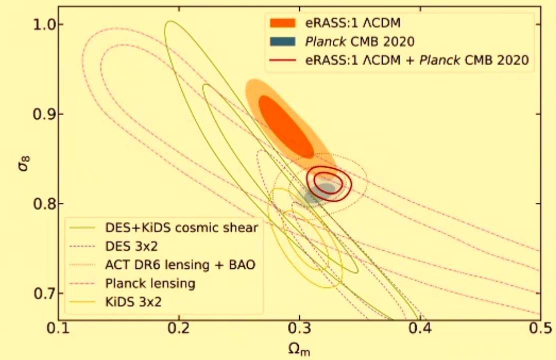
***Major Uncertainties: ICM physics & modeling!!***

# Cosmology with Galaxy Groups in the eROSITA era




**eRASS1**

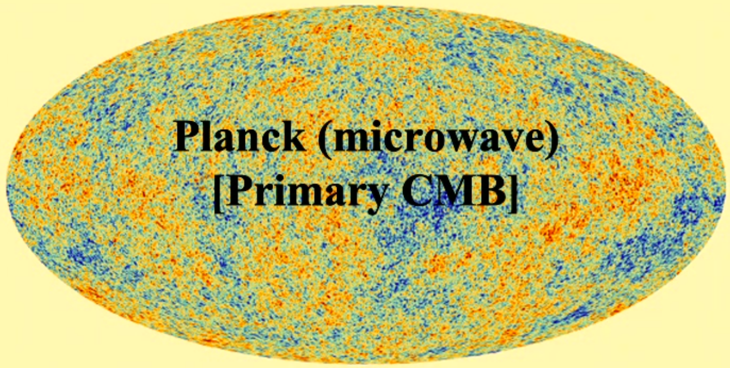


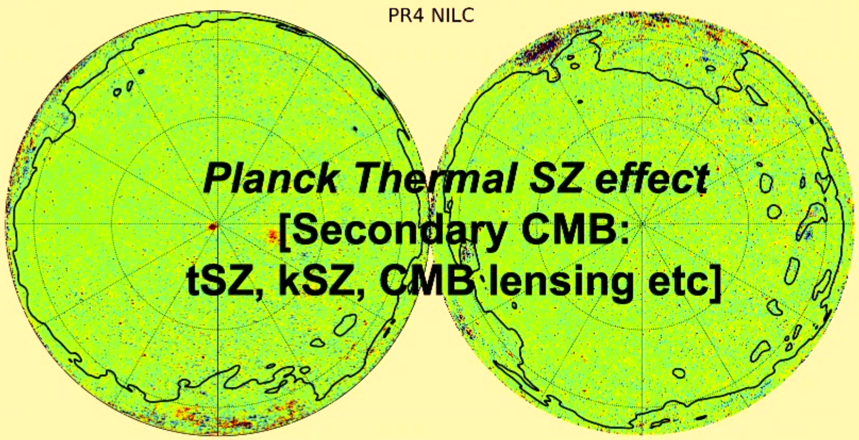



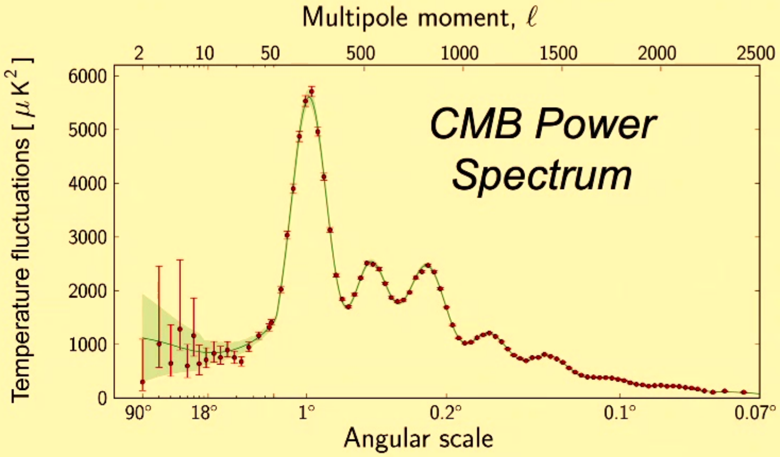

*Galaxy Groups are potentially powerful cosmological probes*

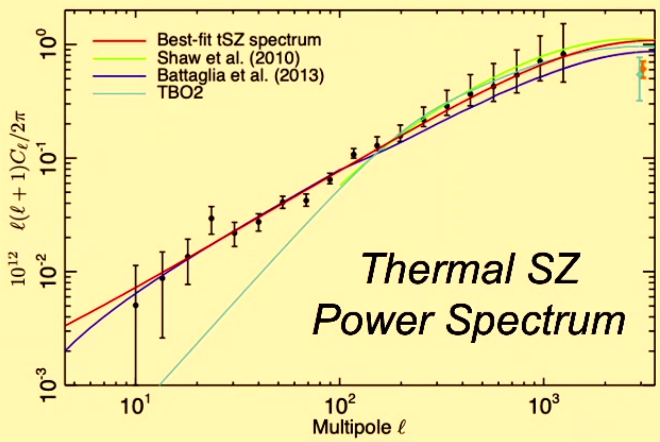
***Major Uncertainties: Baryonic Feedback Effects on the IntraGroup Medium (IGrM) profiles!!***

# Map-level analysis with Simulation-Based Inference (without Halo Mass): Primary vs. Secondary CMB

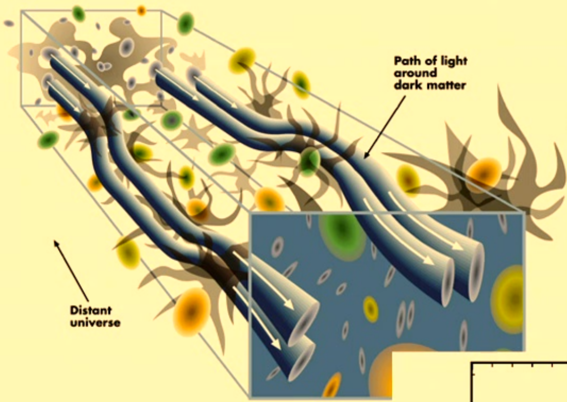


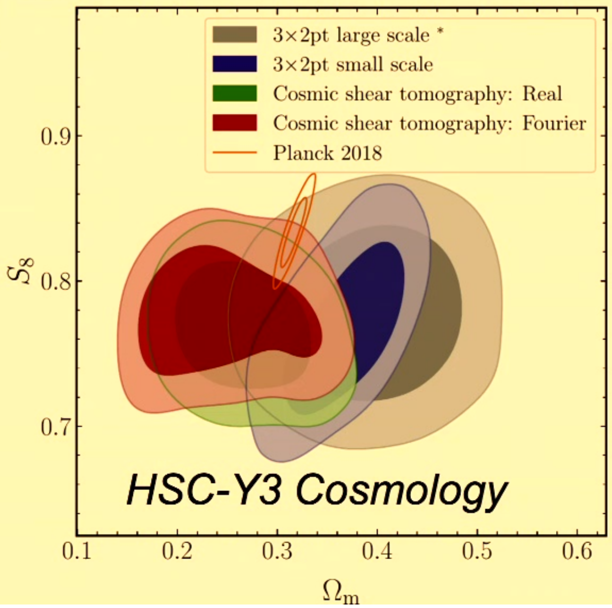
# Cosmic Shear & S8 tension

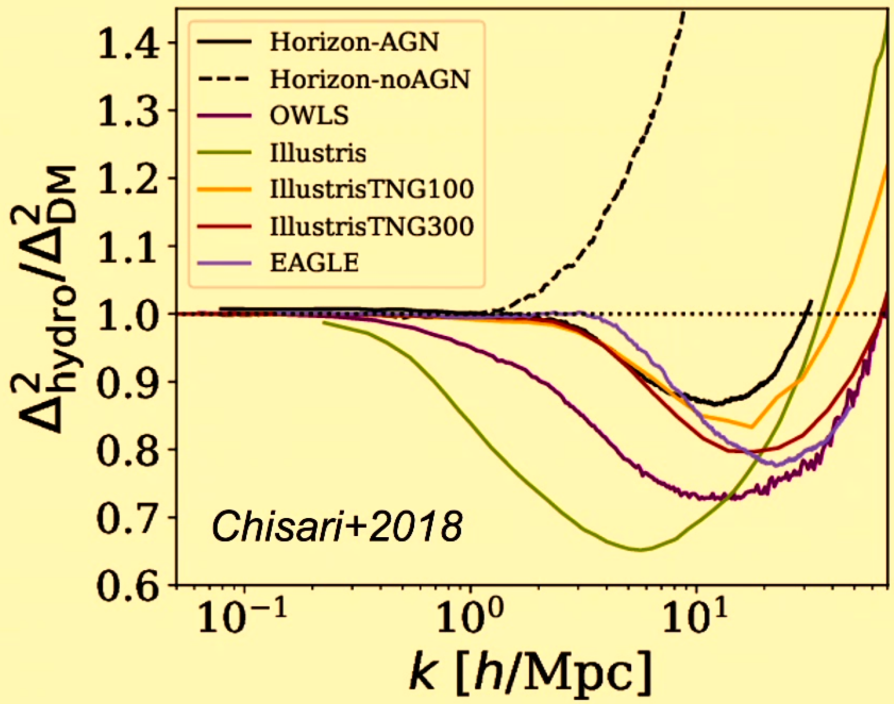



*IntraGroup Medium (IGrM) are dominant baryons in groups.*

***IGrM profiles are essential for the current S8 tension!***

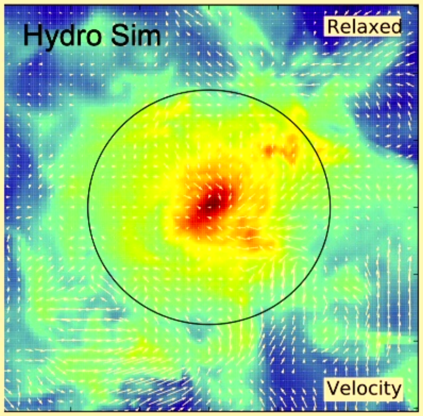
$$S_8 \equiv \sigma_8 \sqrt{\Omega_\mathrm{m}/0.3}$$

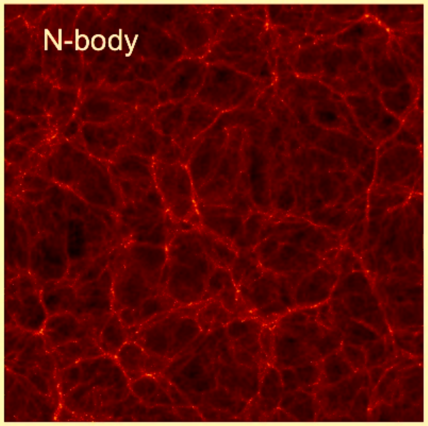




**Baryonic effects** (due to galactic feedback) cause baryons to spread and drag dark matter, causing the suppression of the matter power spectrum on large scales (k<30 h/Mpc).

# Opportunities, Challenges & New Frontiers
## Computational x Physical x Data-Driven Modeling




### Opportunities
- We are entering the golden age of data-driven cosmology, with large datasets from simulations & observations
- New frontiers: cosmology with small-scale, non-linear structures (e.g., galaxies, clusters, cosmic web)

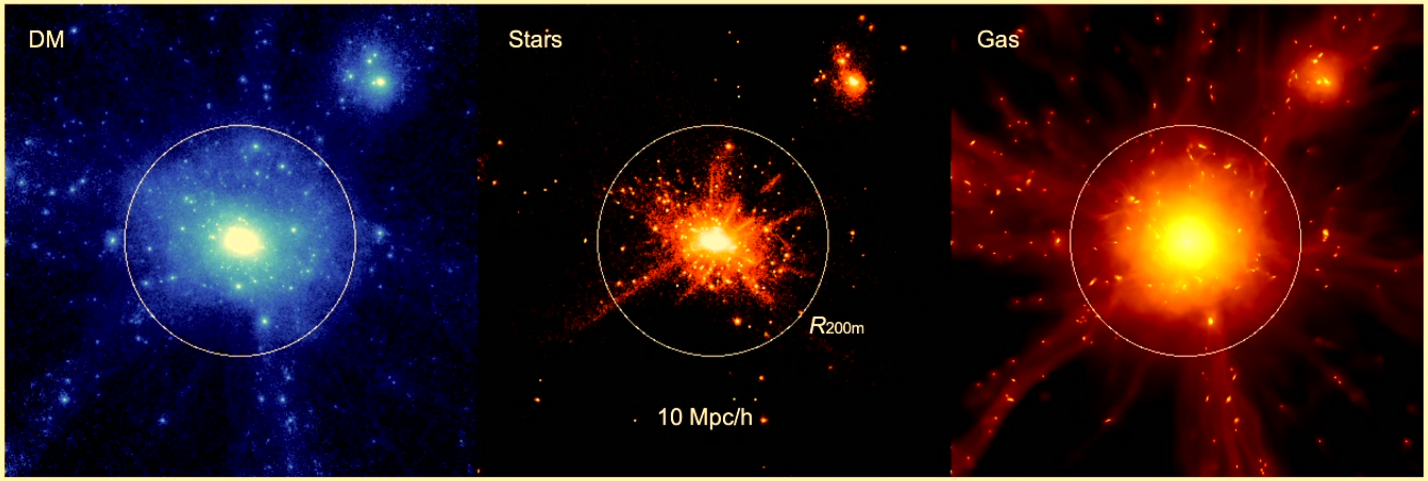
### Challenges
- Baryonic Effects on Gas & Dark Matter Halo Profiles
- Large Multi-$\lambda$ maps for a range of cosmology & astrophysics

### New Frontiers
1. **Computational:** *hydro. cosmo. simulations*
2. **Modeling:** *a physical, computationally efficient model*
3. **Machine Learning:** a new tool *for analyzing big data from both sims. & obs.*
4. **Low-noise + High-resolution:** CGM & baryonic effects

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





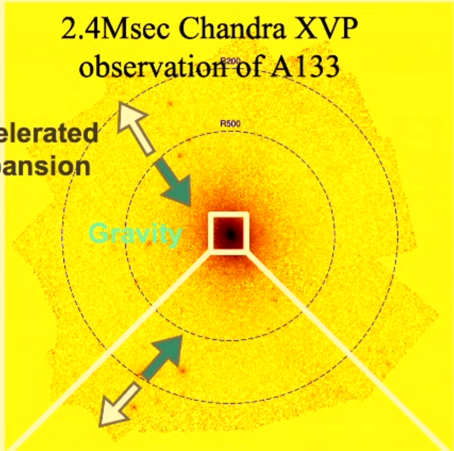
Erwin Lau


Camille Avestruz


Kaylea Nelson

- 500$h^{-1}$ 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.

# 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. Splashback & Shock Radii
3. Non-equilibrium electrons
4. Gas clumping/inhomogeneities
5. Filamentary gas streams

***Tractable***

***Key Parameters Mass & MAH***

Walker et al. 2019 for a recent review

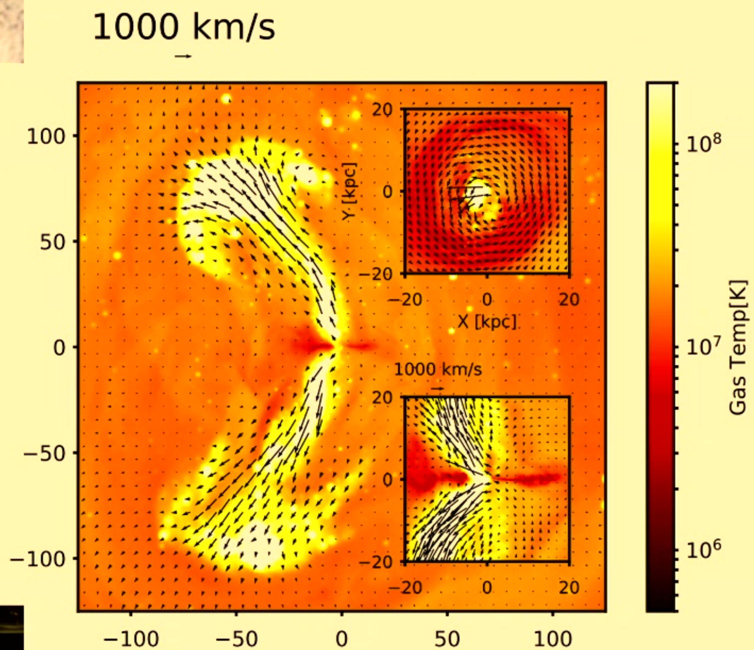
## ✦Cluster Cores

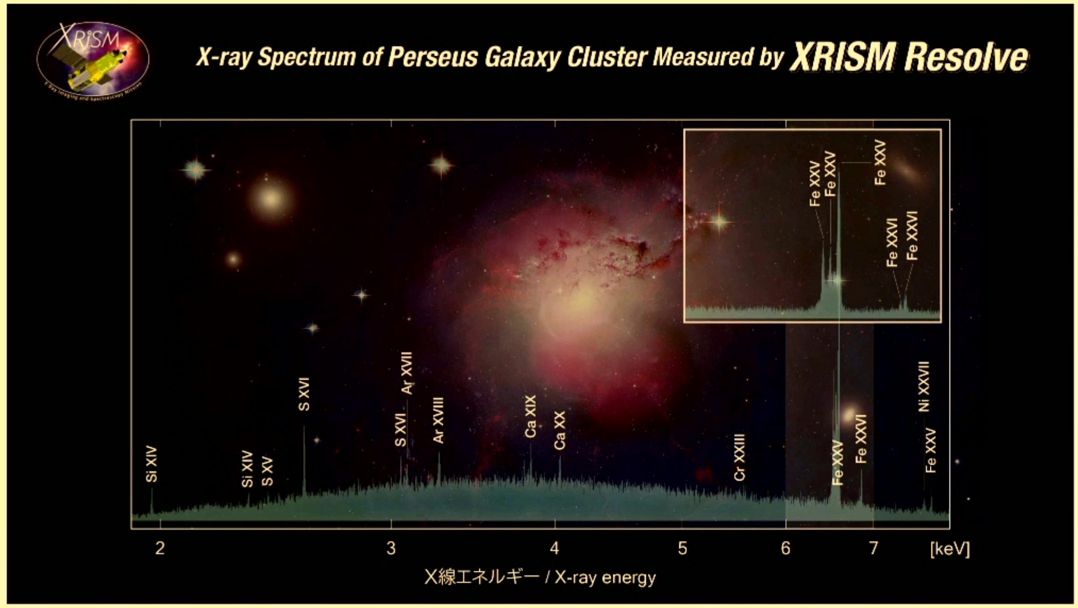
Heating, Cooling & Plasma physics

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)***

# Probing Gas Motion with XRISM
## AGN feedback vs. Mergers




RomulusC cosmo hydro simulation
$M_{500c} \sim 1.5 \times 10^{14}$ Msun
Spatial Resolution ~ 250 pc
Chadayammuri, Tremmel, Nagai et al.2021
Lau et al. 2017

XRISM spectra of the Perseus cluster probes the motions of X-ray emitting plasma driven by AGN feedback and mergers
JAXA Press Release: March 4, 2024

# Non-thermal Pressure
# Analytical Model vs. Hydro Simulations

Shi & Komatsu 2014 (analytical model)

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

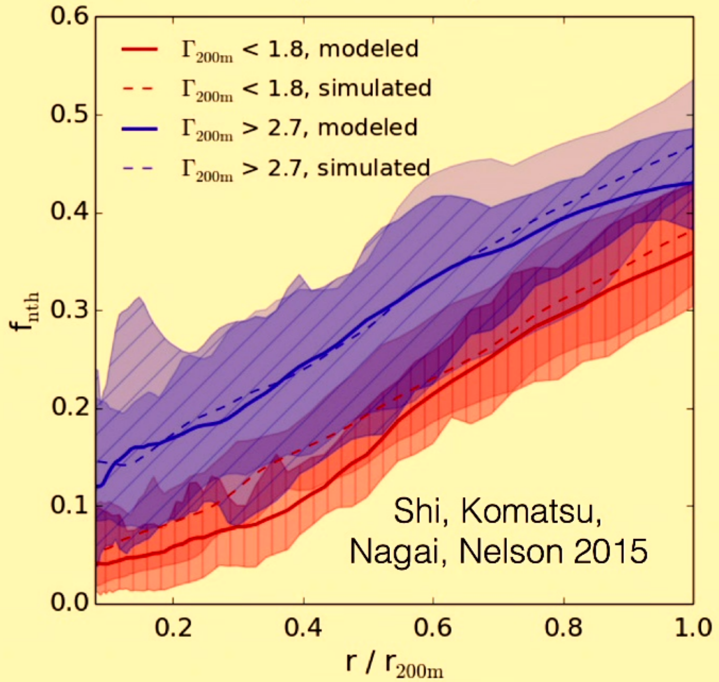
- Time Change in Turbulence Energy per unit mass
- Dissipation of Turbulence
- Generation of Turbulence sourced by mass accretion

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

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

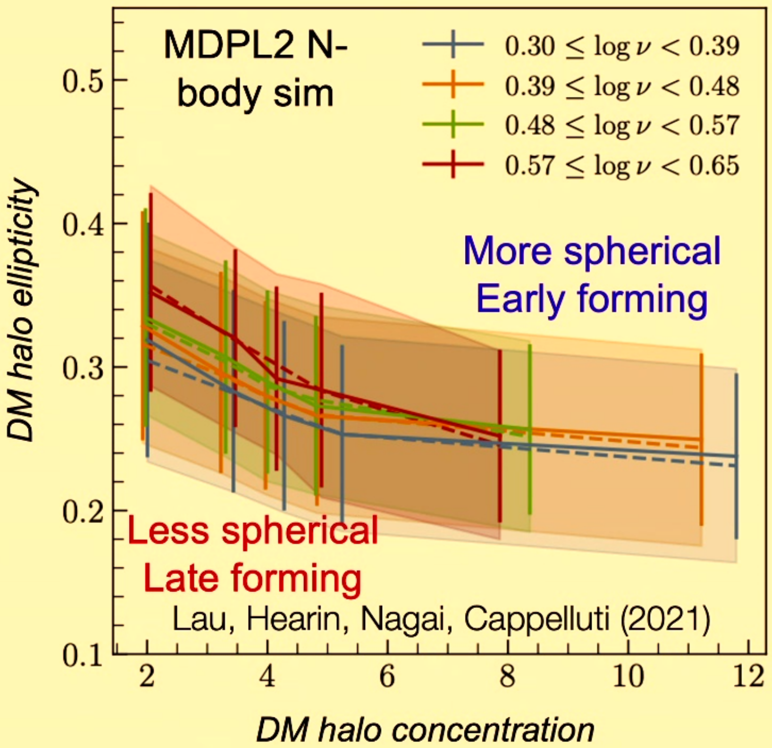
Impact of Non-thermal pressure on tSZ effects
Green, Aung, Nagai, van den Bosch 2020

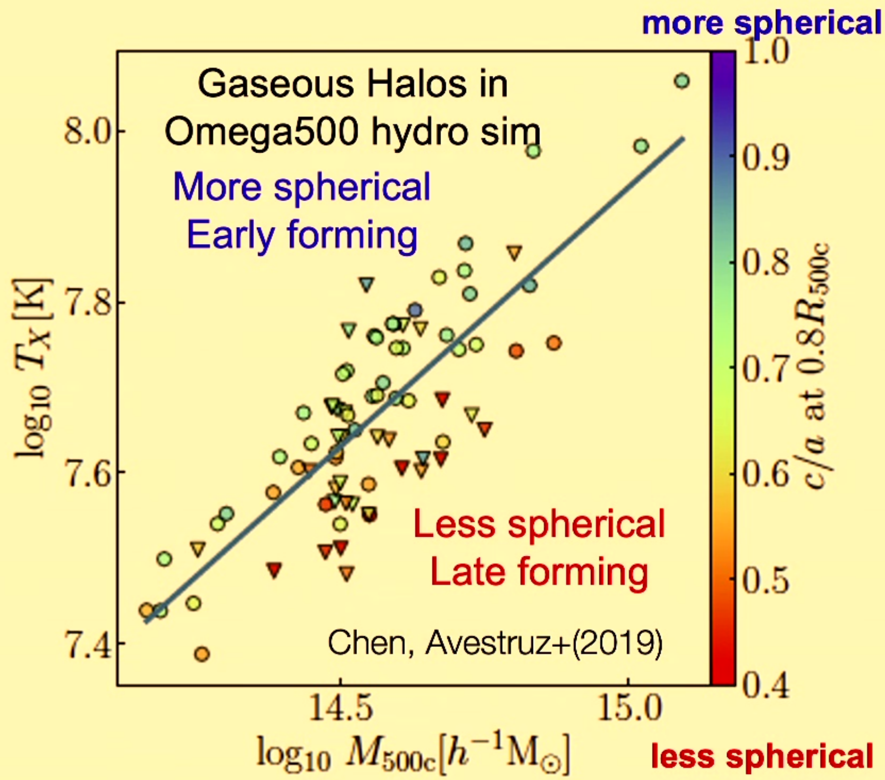
Comparison to the Omega 500 simulation (Nelson+14)




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

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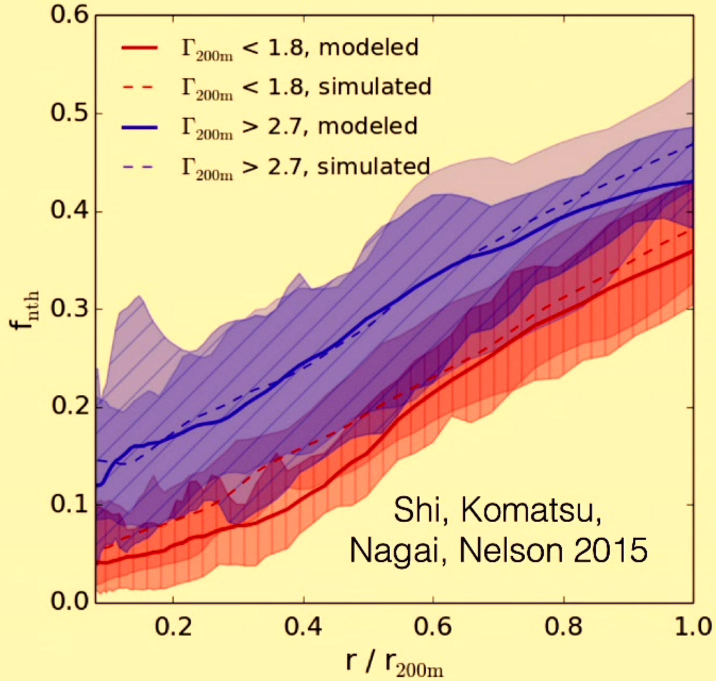


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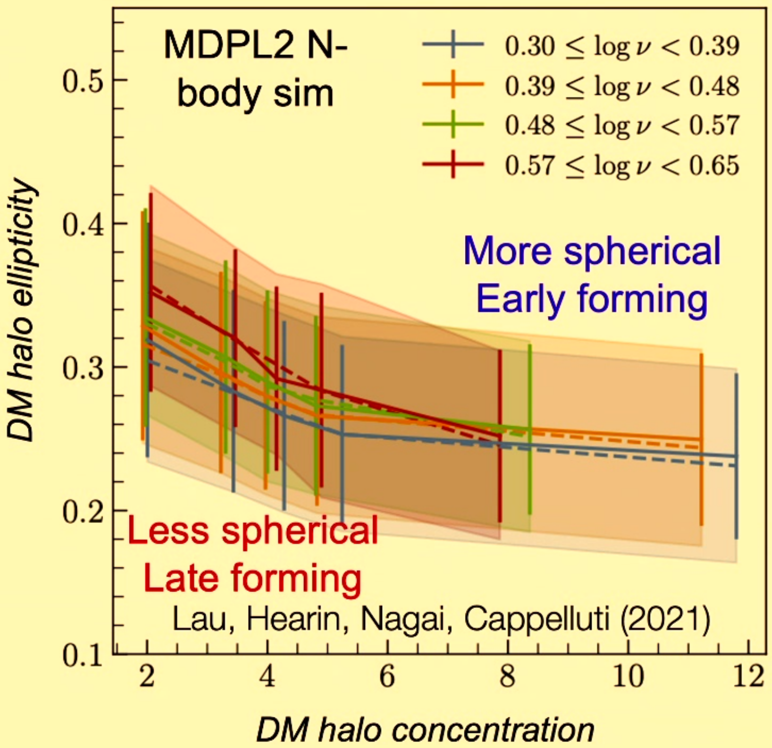


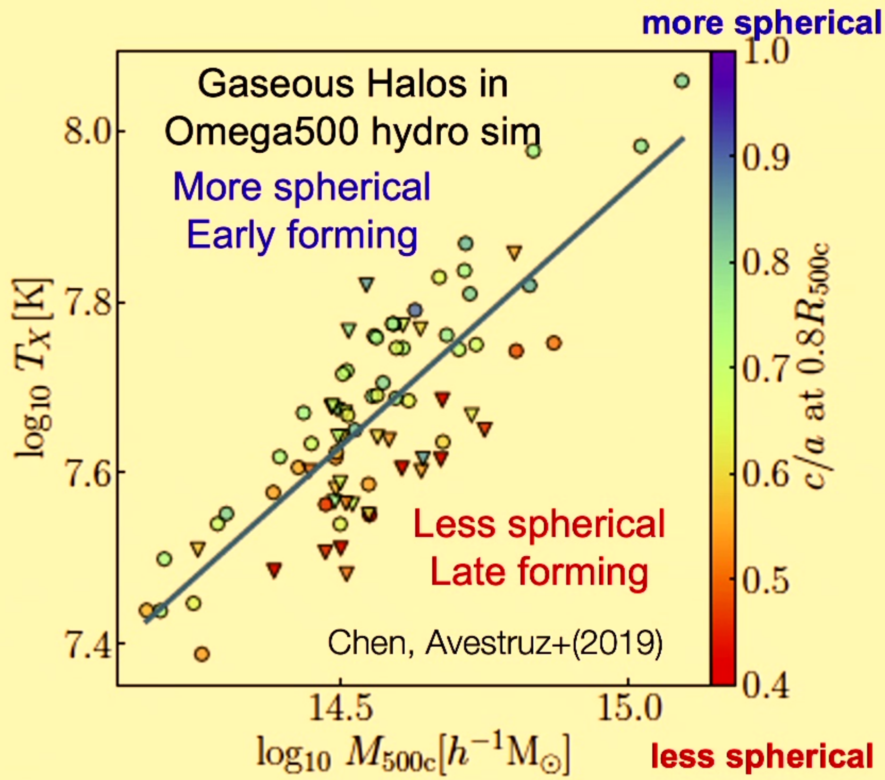


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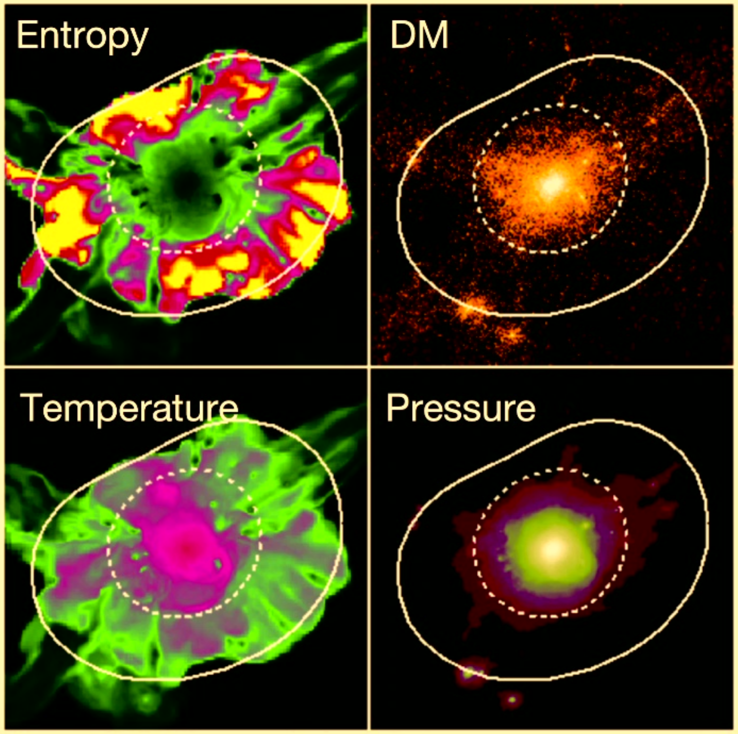
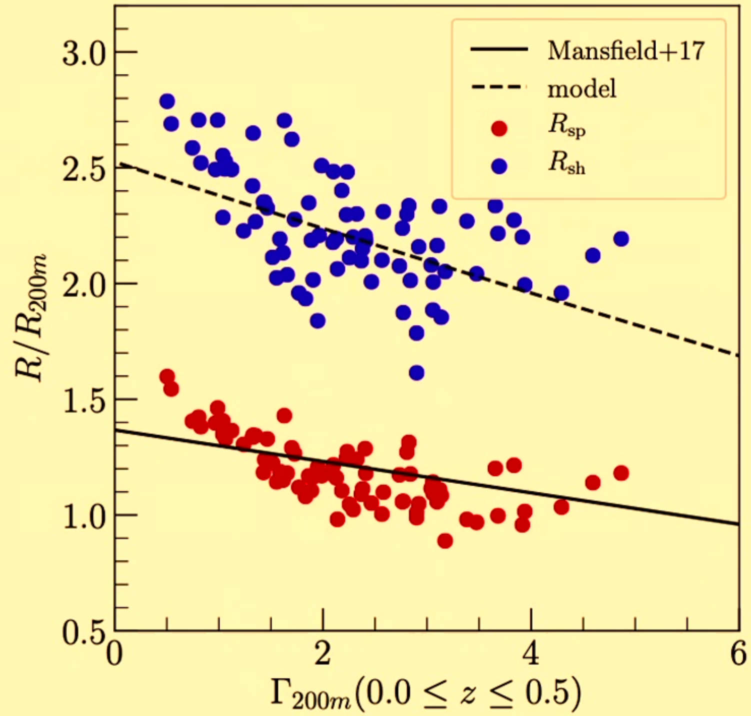
# Splashback vs. Accretion Shock Radii

DM splashback computed using SHELLFISH (Mansfield+17)

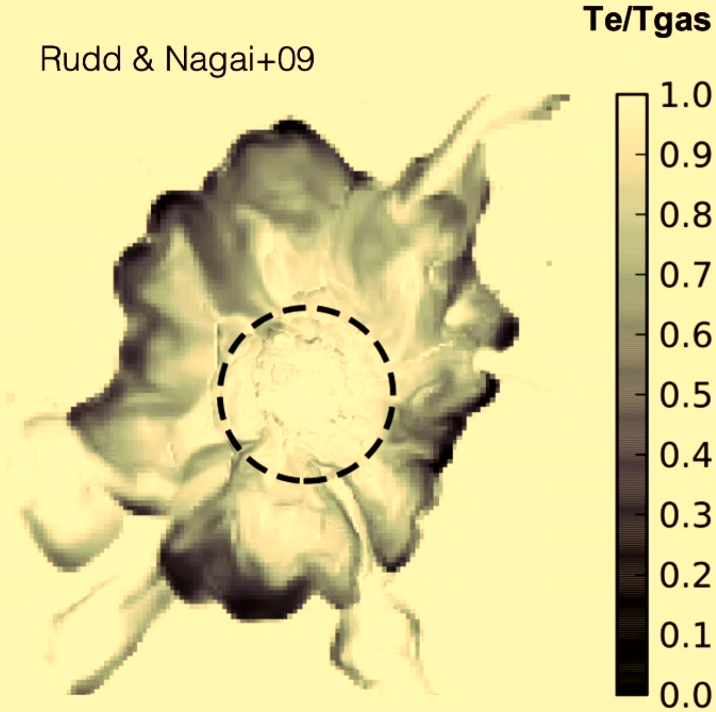


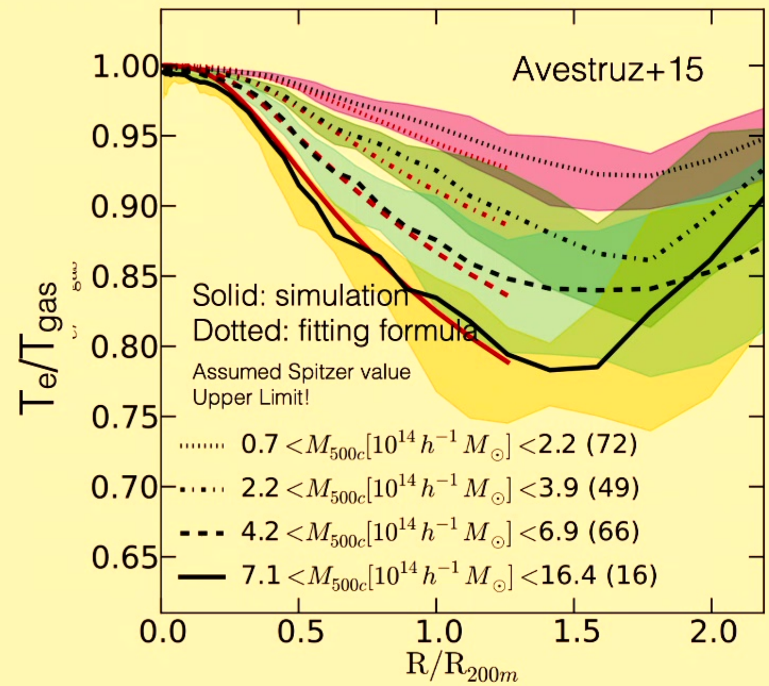

Aung, Nagai, Lau 2020




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

# Plasma Physics in Cluster Outskirts
## electron-proton equilibration




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

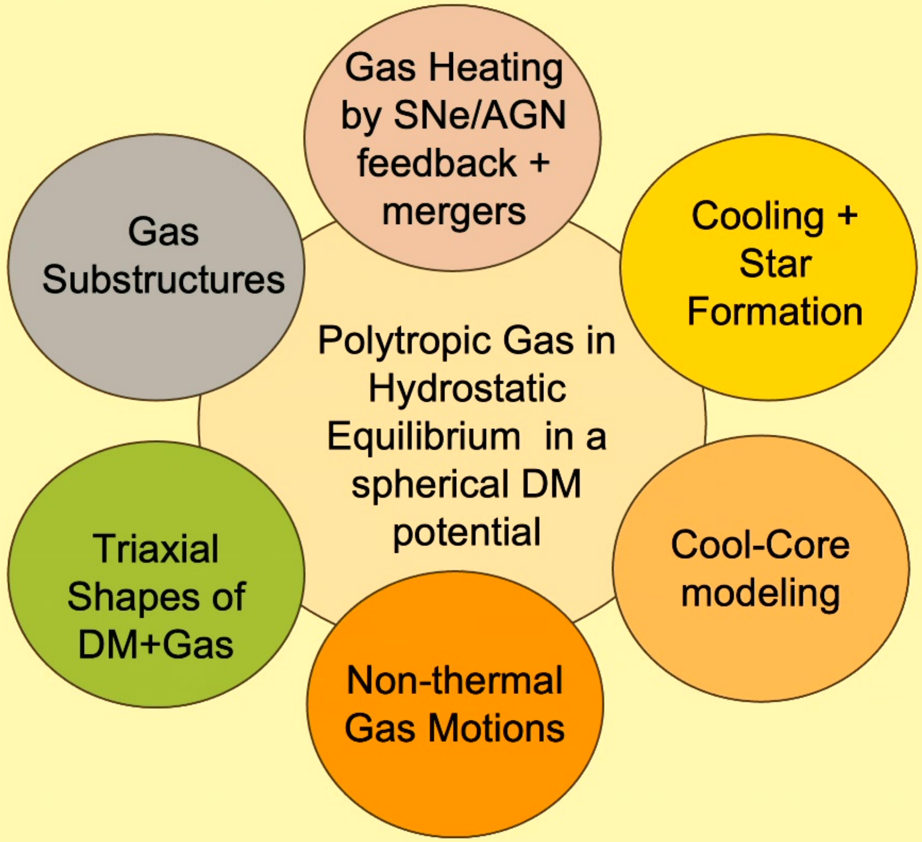
# Baryon Pasting Project

**Gas profiles**

*Pressure, Temperature, Density, X-ray emissivity*

**Scaling Relations**

Mass-observable (*Lx, Tx, Mgas, Ysz, Yx vs.* $M_{Lens}$, $M_{HSE}$)




**Lightcone Maps**

*SZ, X-ray, FRB, lensing*

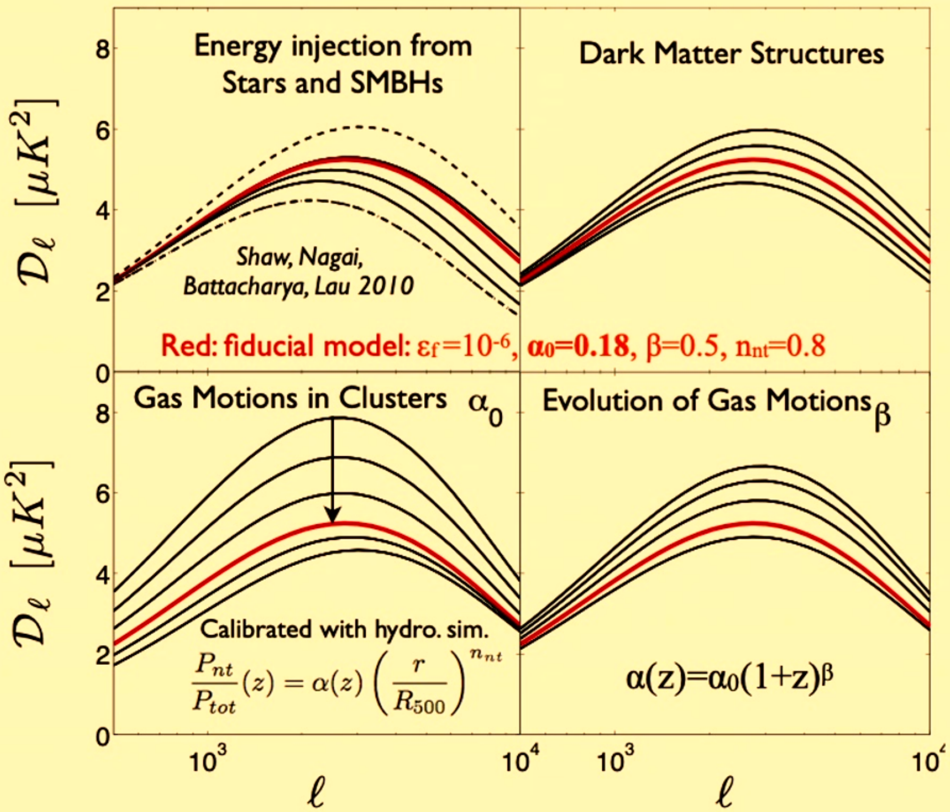
**Correlation Statistics**

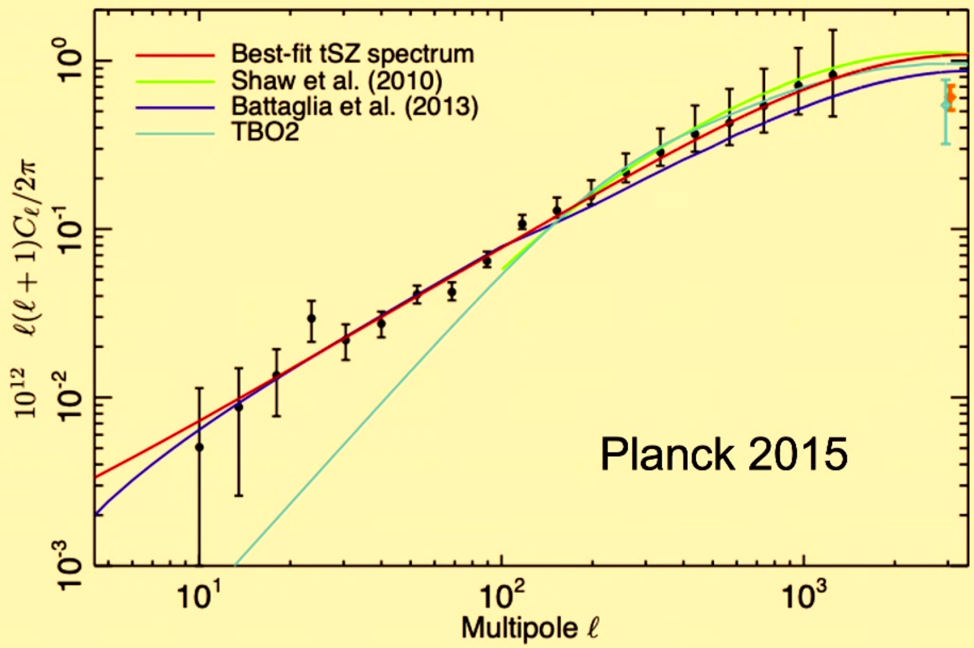
*Auto- & cross-correlations of SZ, X-ray, Gal, Lensing*

NASA ATP23-0154

# BP Modeling of tSZ Power Spectrum

Thermal SZ power spectrum contains significant contributions from outskirts of low mass ($M<3x10^{14}$ Msun), high-z (z>1) groups at l<5000




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

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# BP Gas Model

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)

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

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

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

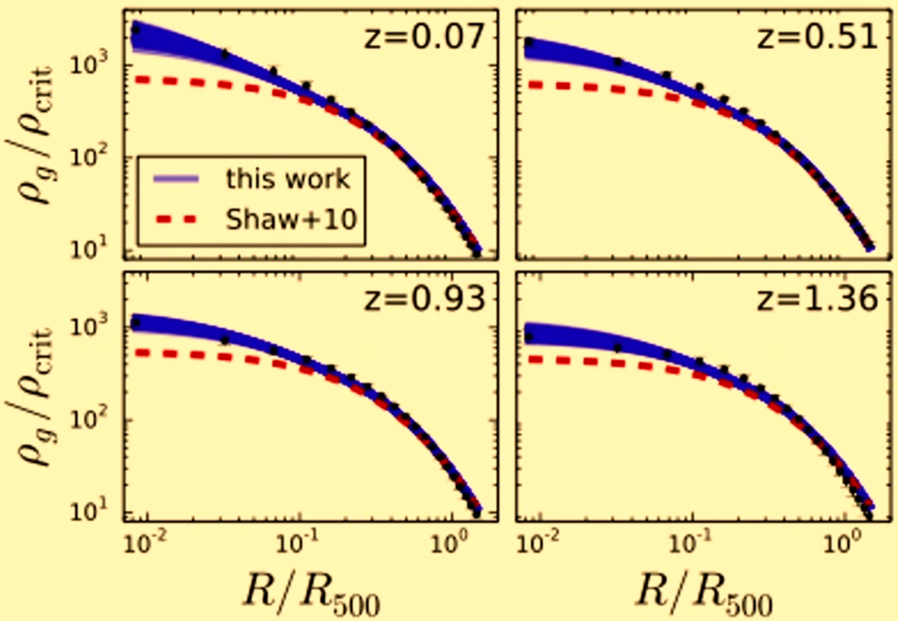
Dynamical heating from DM and energy feedback from AGN and SNe

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

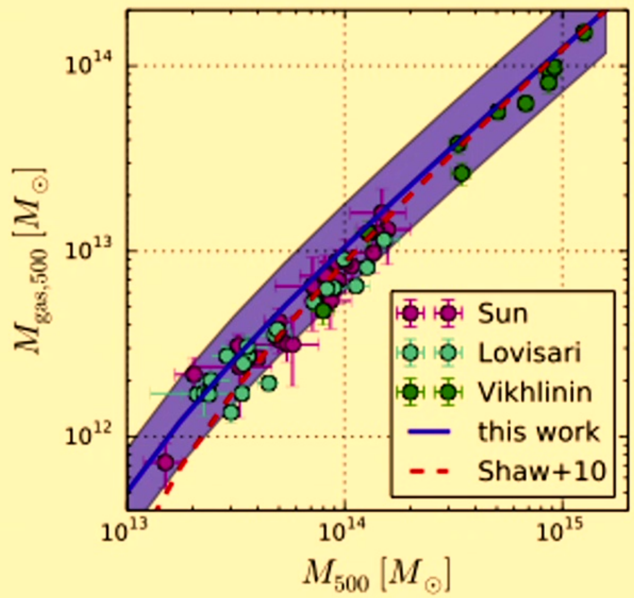
Model of merger-induced non-thermal pressure fraction (Nelson+14; see also Lau+09,13, Green+20)

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

# BP Modeling of X-ray Clusters & Groups



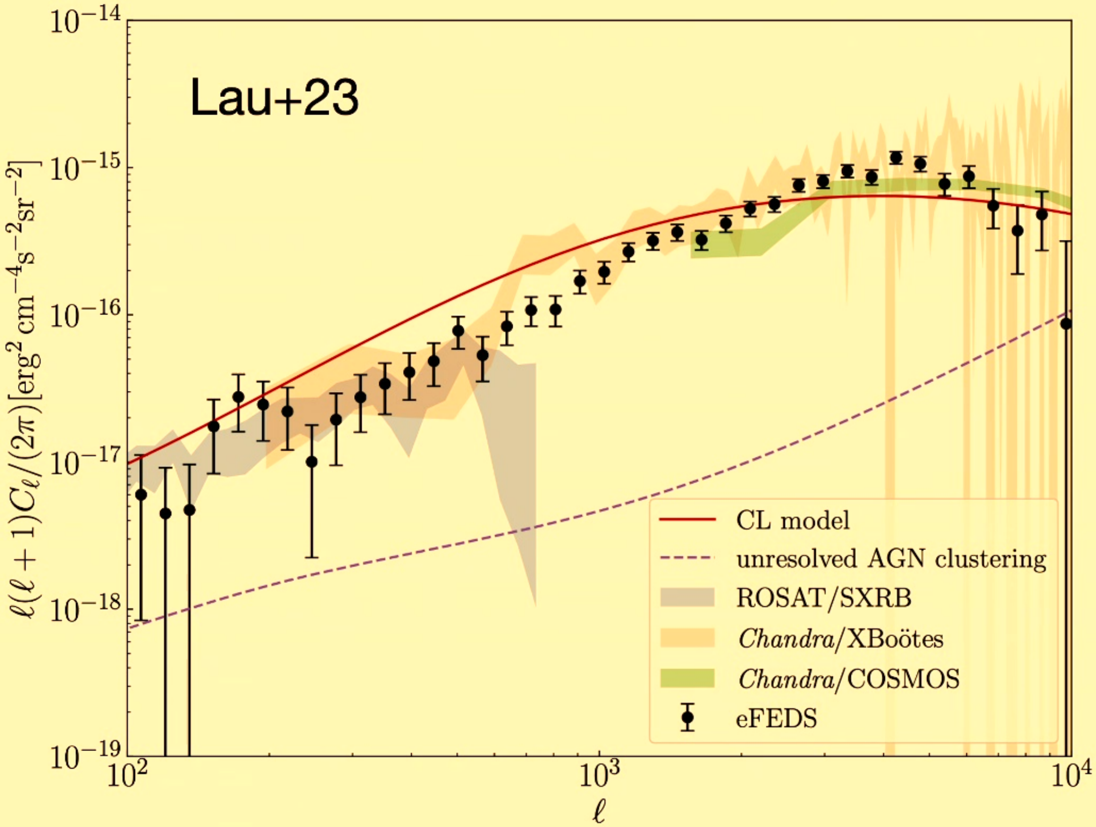

McDonald+13,17:
X-ray measurements of **gas density profiles**




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)

# X-ray power spectrum of eFEDS field




- Large-scales ($\ell < 2000$, $\vartheta > 0.2^o$ ) - consistent than with ROSAT and slightly lower than the *Chandra* calibrated BP model.
- Small-scales ($\ell > 2000$, $\vartheta < 0.2^o$ ) - agrees with BP model and *Chandra*/COSMOS
- Expected eROSITA All Sky Survey (eRASS4)+Chandra cosmological constraint 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

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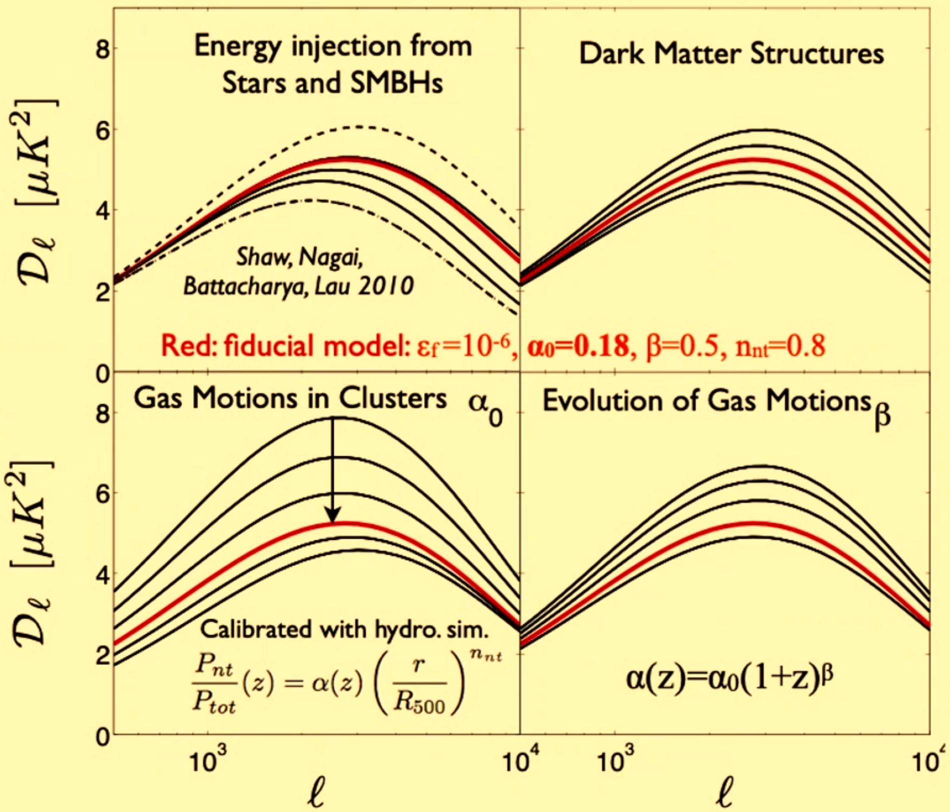


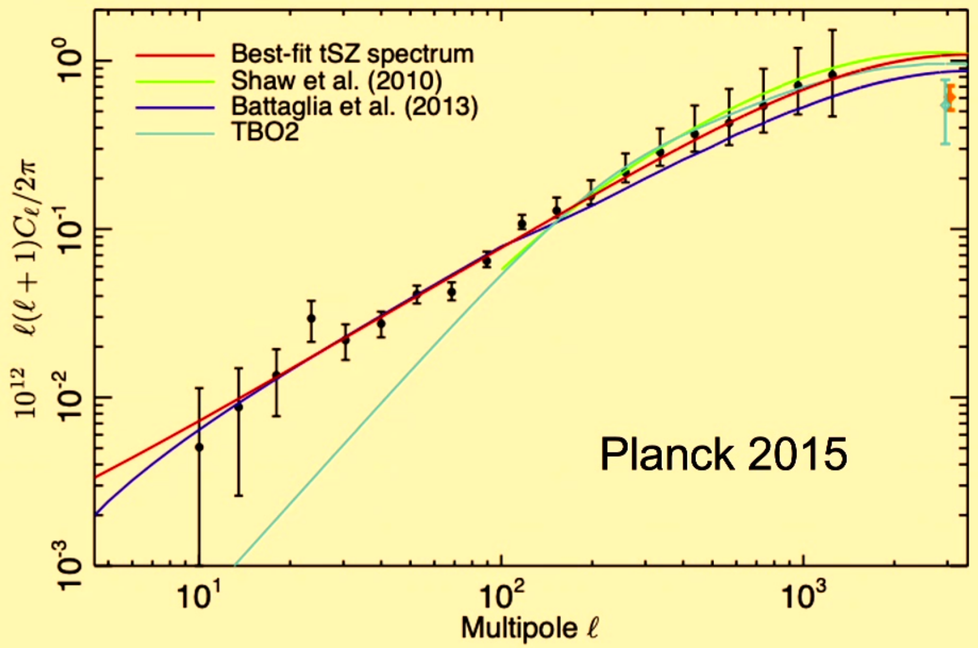


Planck measurements of the SZ power spectrum can constrain cluster astrophysics (especially non-thermal pressure)

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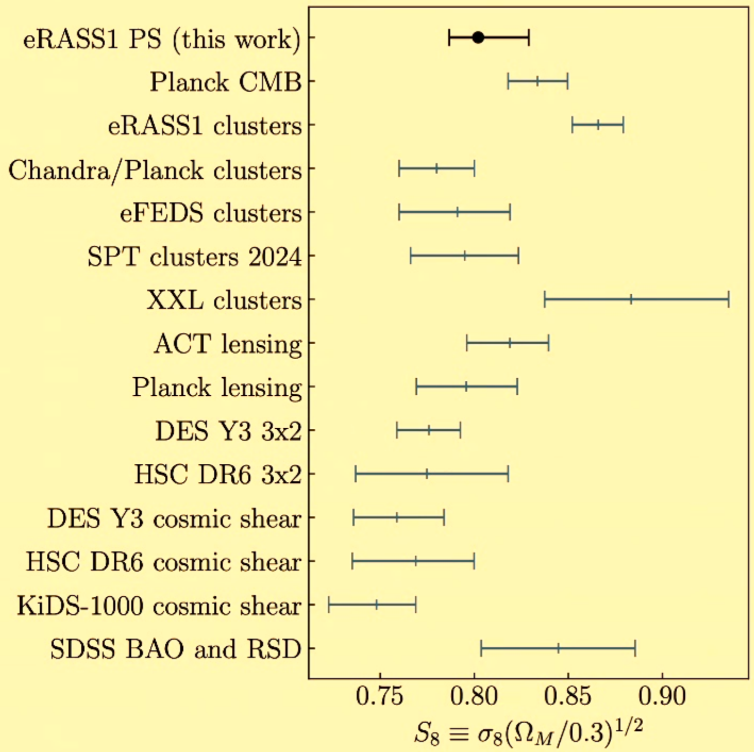
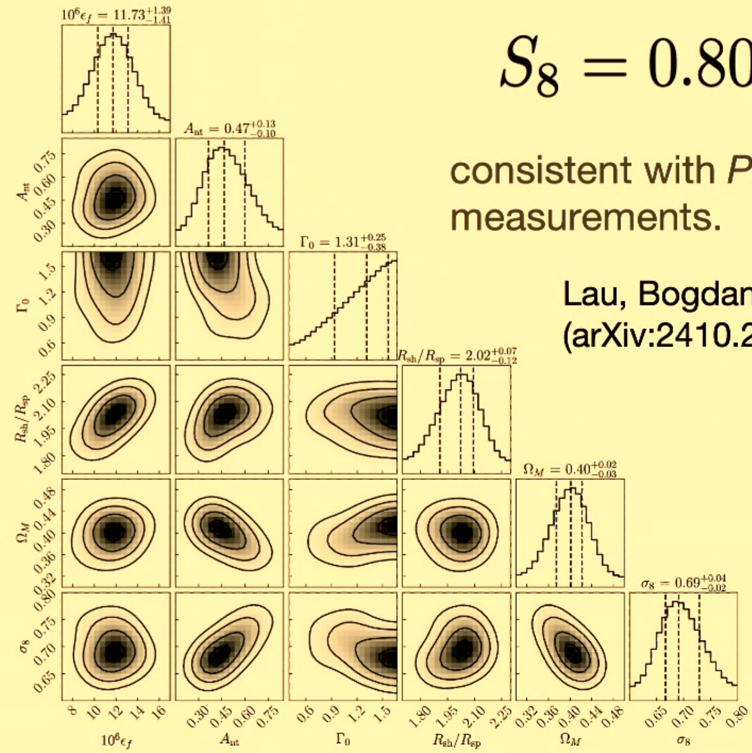
# Cosmology & Astrophysics with eRASS1 Power Spectrum



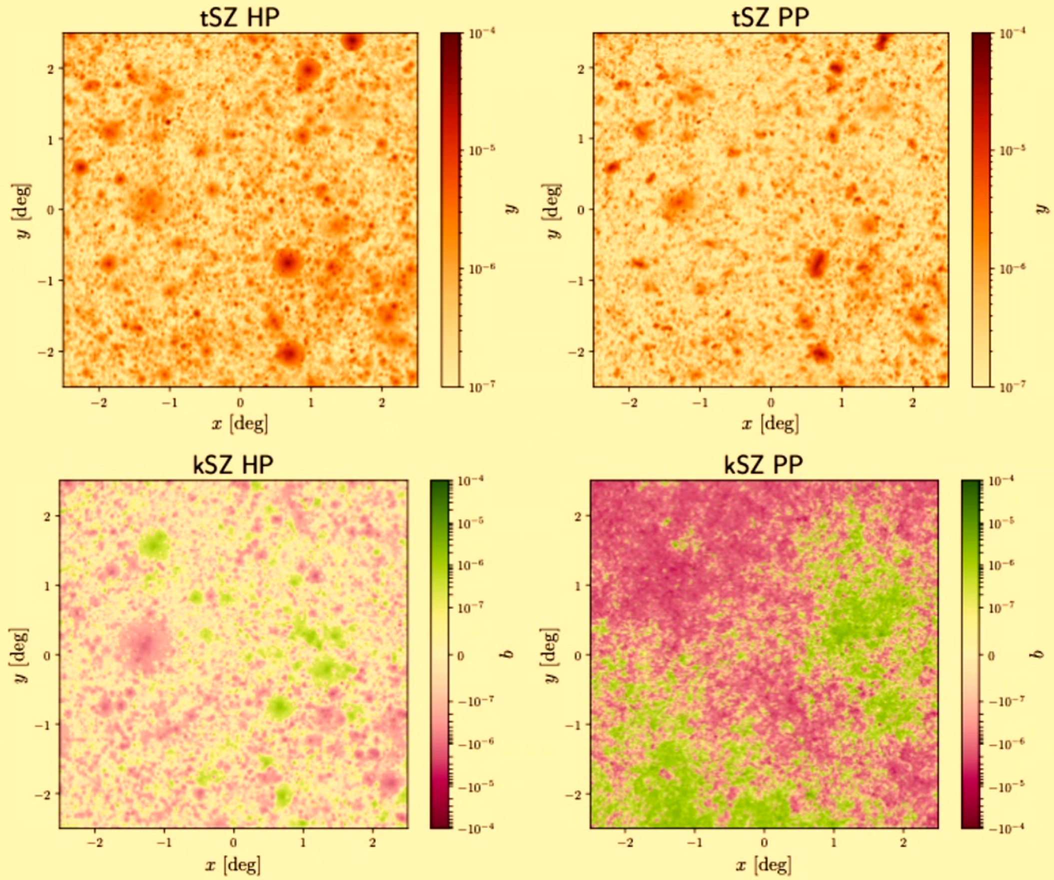
$$S_8 = 0.80^{+0.02}_{-0.01}$$

consistent with *Planck* CMB measurements.

Lau, Bogdan, DN et al. (arXiv:2410.22397)

eRASS1 X-ray power spectrum provides the first constraints on cosmology (S8) and astrophysics (feedback + non-thermal pressure support) of galaxy groups

# Baryon Pasting Algorithm
## Halo vs. Particle-based methods




Time / map

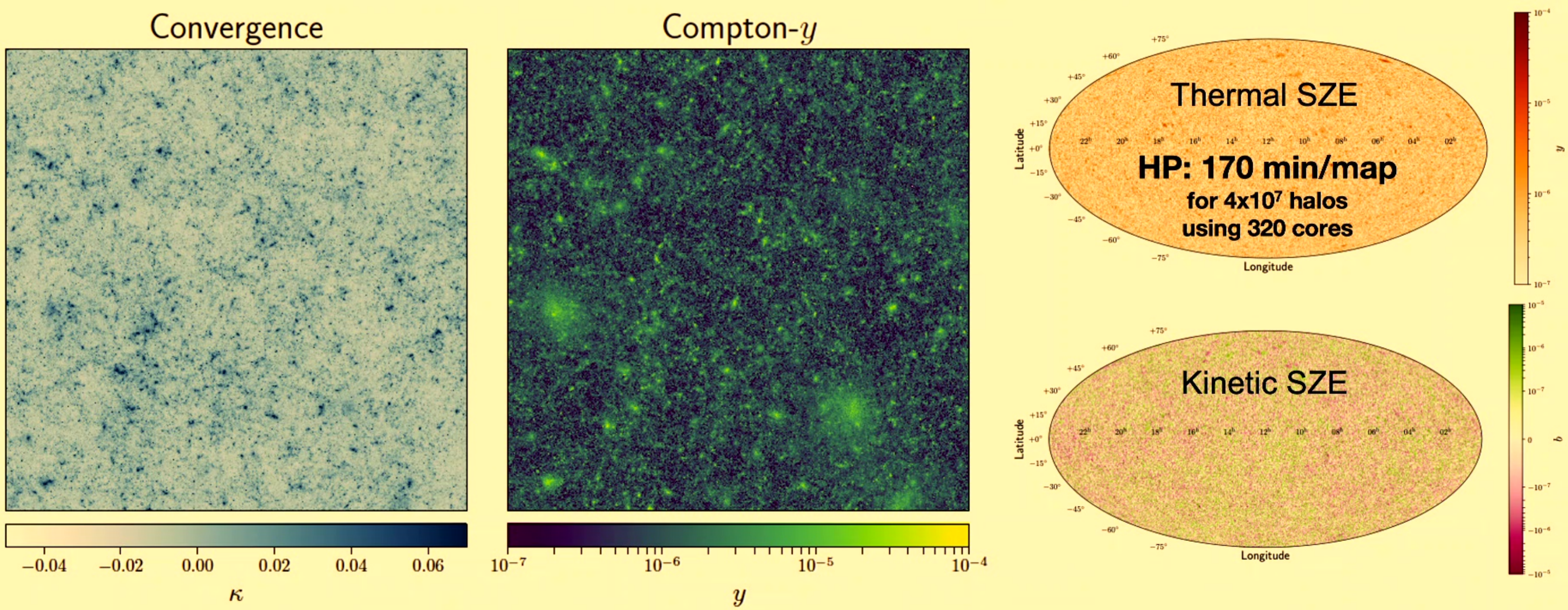
HP: 1.5 min
PP: 69 min

for $5 \times 10^5$ halos
using 224 cores

Osato & Nagai 2023

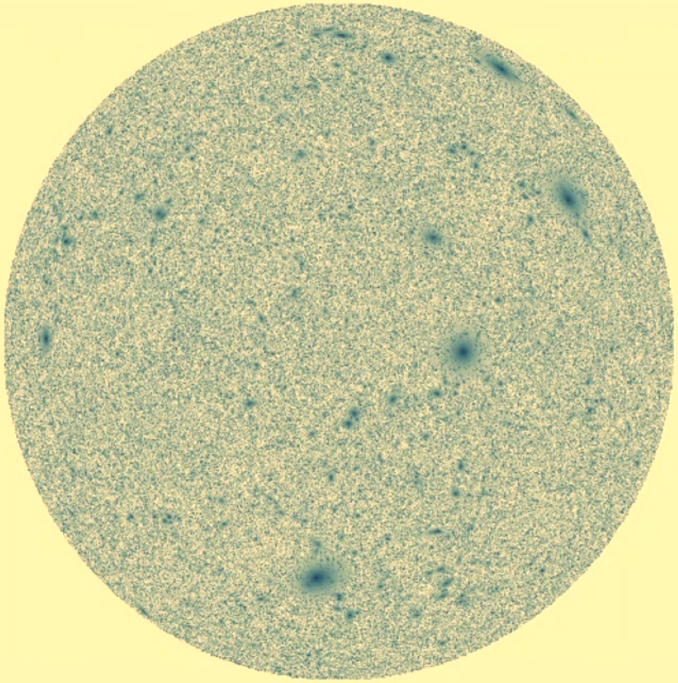
# All-Sky BP SZ Maps

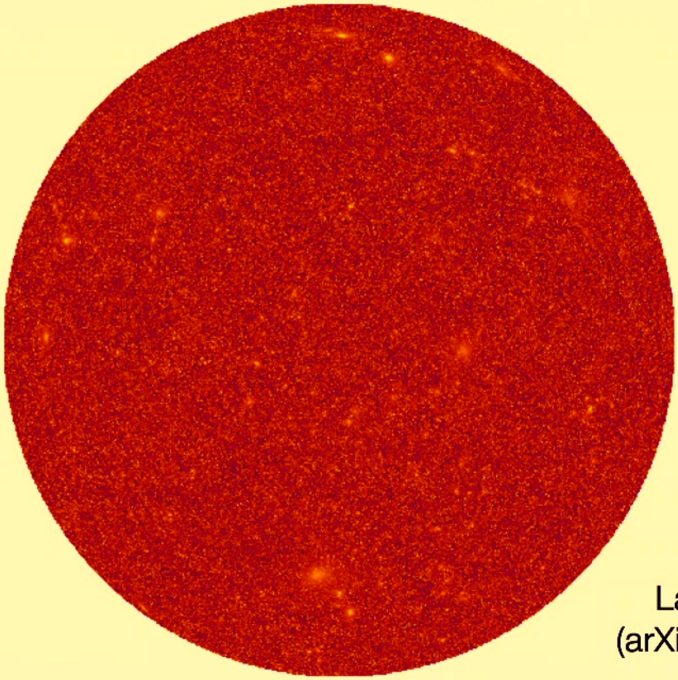
108 full-sky lightcone simulations of CMB lensing (Takahashi+17) and tSZ (Osato & Nagai+23) maps




Next Step: Baryonification + Cosmic-Web + tSZ/kSZ/FRB/X-ray x WL/galaxy cross-correlation

# BP-Uchuu Half-Sky Maps



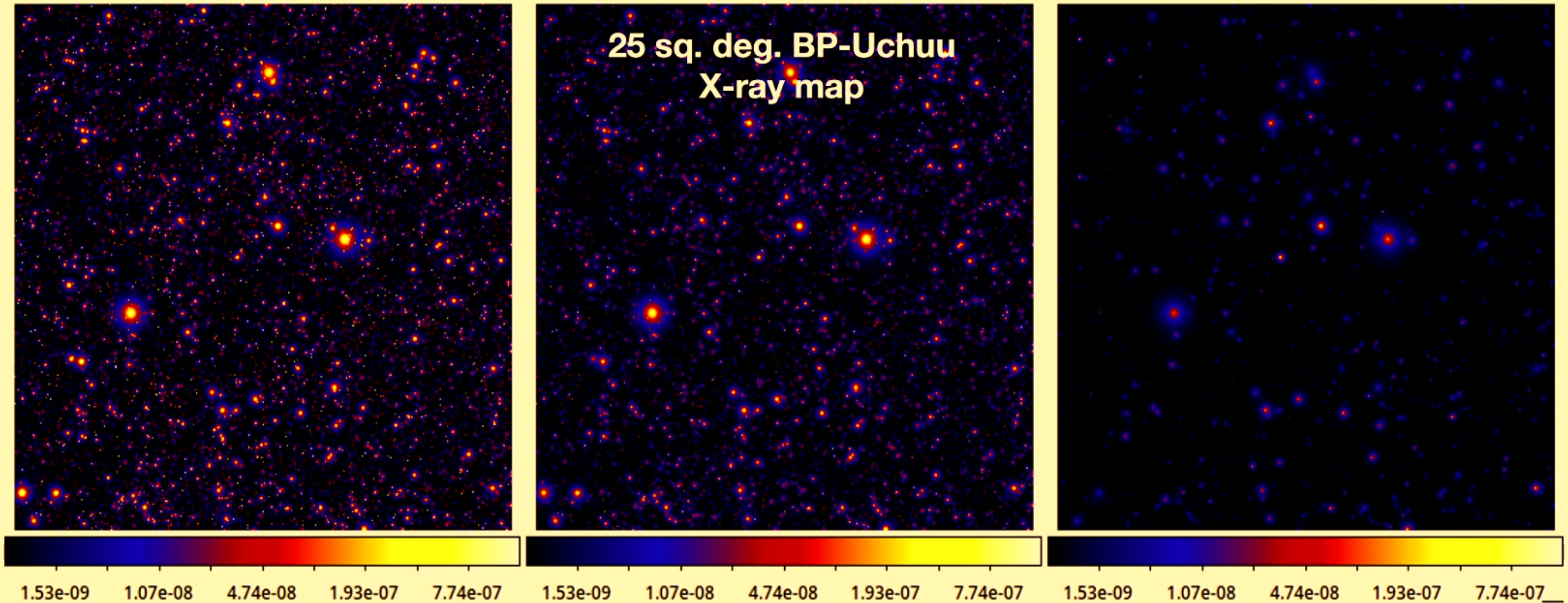

Lau, DN et al.
(arXiv:2411.00108)

Paste X-ray and tSZ on Uchuu DM half-sky halo lightcone with 75 million halos with $M_{500c} > 10^{13}\ M_\odot$ from 0<z<2.

Forward model observed scatter: intrinsic + extrinsic scatters using 3 sets of maps; (a) spherical halo without intrinsic scatter, (b) spherical halo with intrinsic scatter, and (c) triaxial halos with intrinsic scatter.

# Forward Modeling X-ray Selection Function

*Increasing feedback*

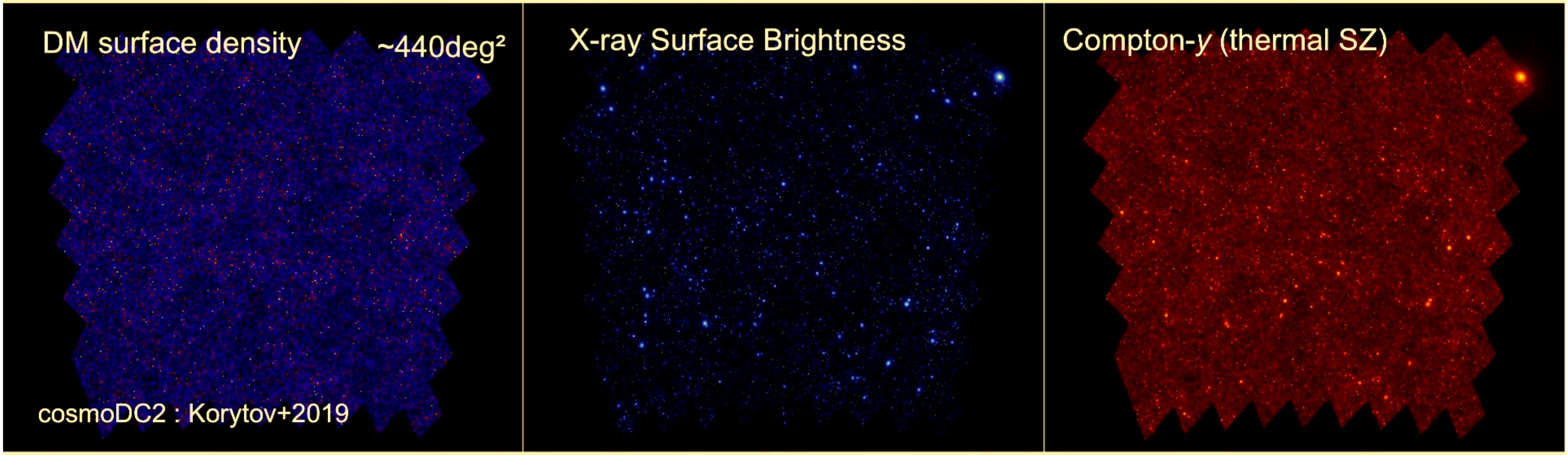



Forward model effects of feedback, morphology, and cosmic variance on X-ray flux measurements and cluster selection with **BP X-ray maps**.

Increasing feedback decreases X-ray fluxes of halos and impacts the selection function!

Lau, DN et al.
(arXiv:2411.00108)

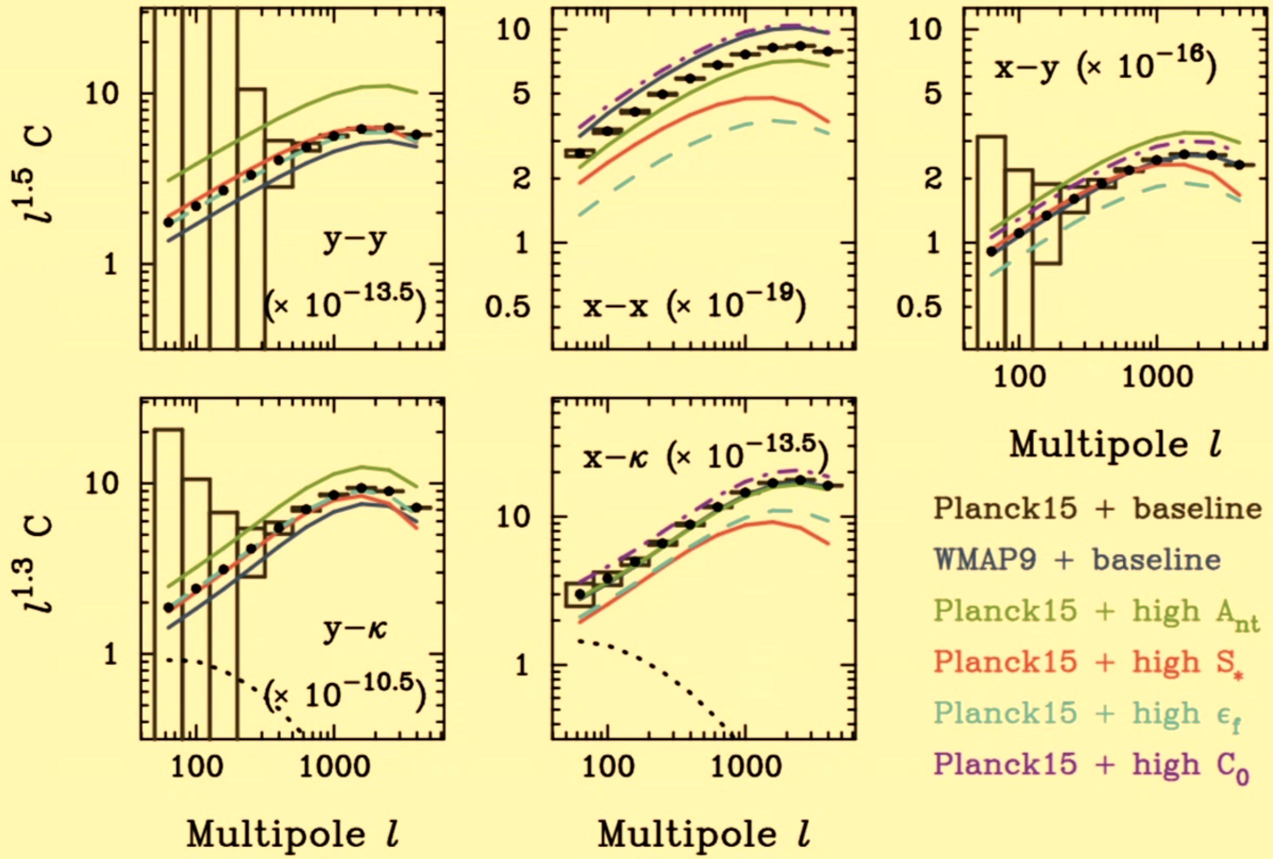
# Baryon Pasted Multi-wavelength Maps




- 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 in the Halo-Model Framework

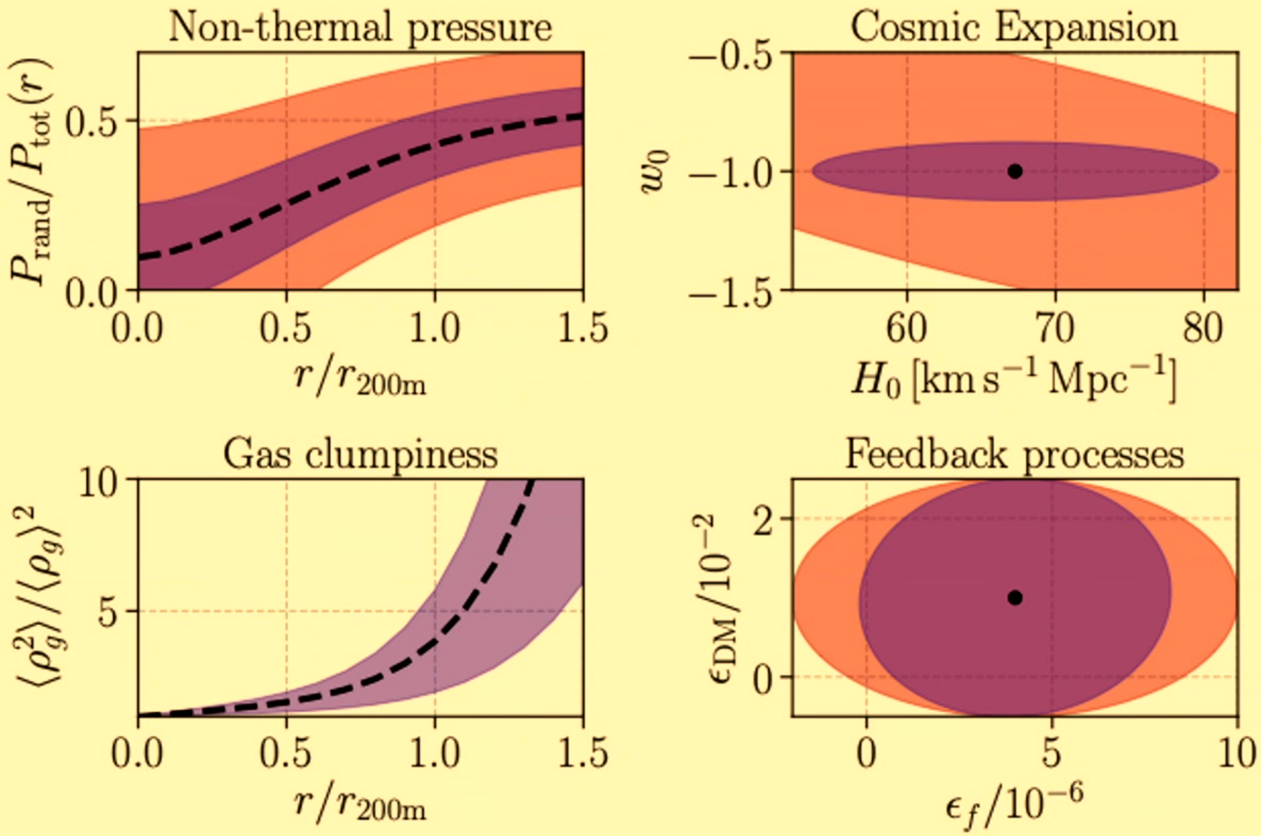
## Fast Computation of Auto- & Cross-Spectra




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

Shirasaki, Lau & Nagai (2020)

# Cosmological & Astrophysics Inference from Multi-$\lambda$ Surveys



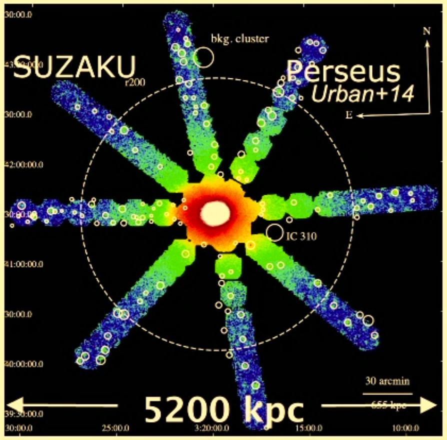

**Microwave+Optical+X-ray**

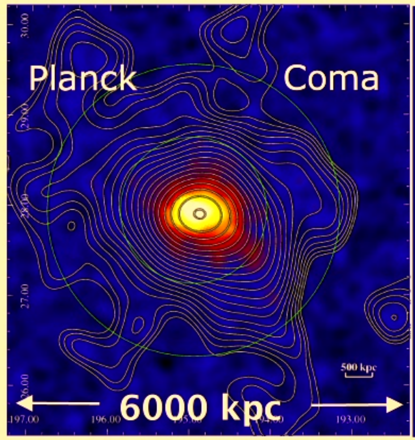
Measuring the **angular power spectra** in X-ray (eROSITA, microwave (CMB-S4), and optical (Rubin) lead to improved constraints on cosmology and astrophysics

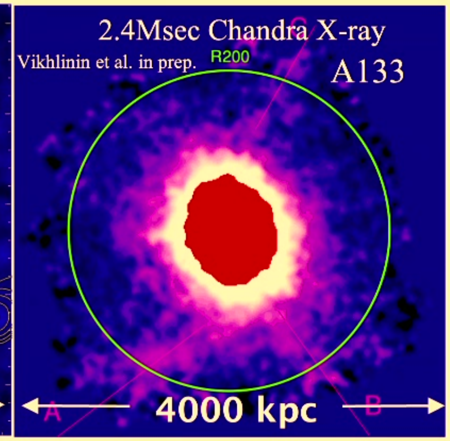
Shirasaki, Lau & Nagai (2020)

# *Cosmology & Astrophysics with CGM*

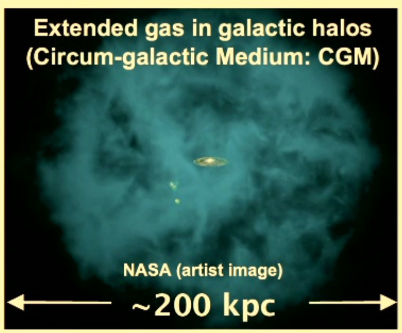
Galaxy Clusters

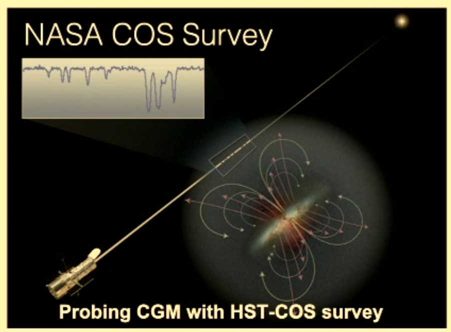


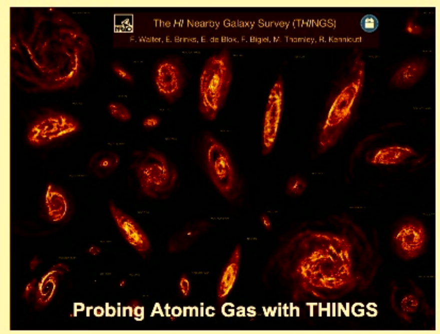




Galaxies

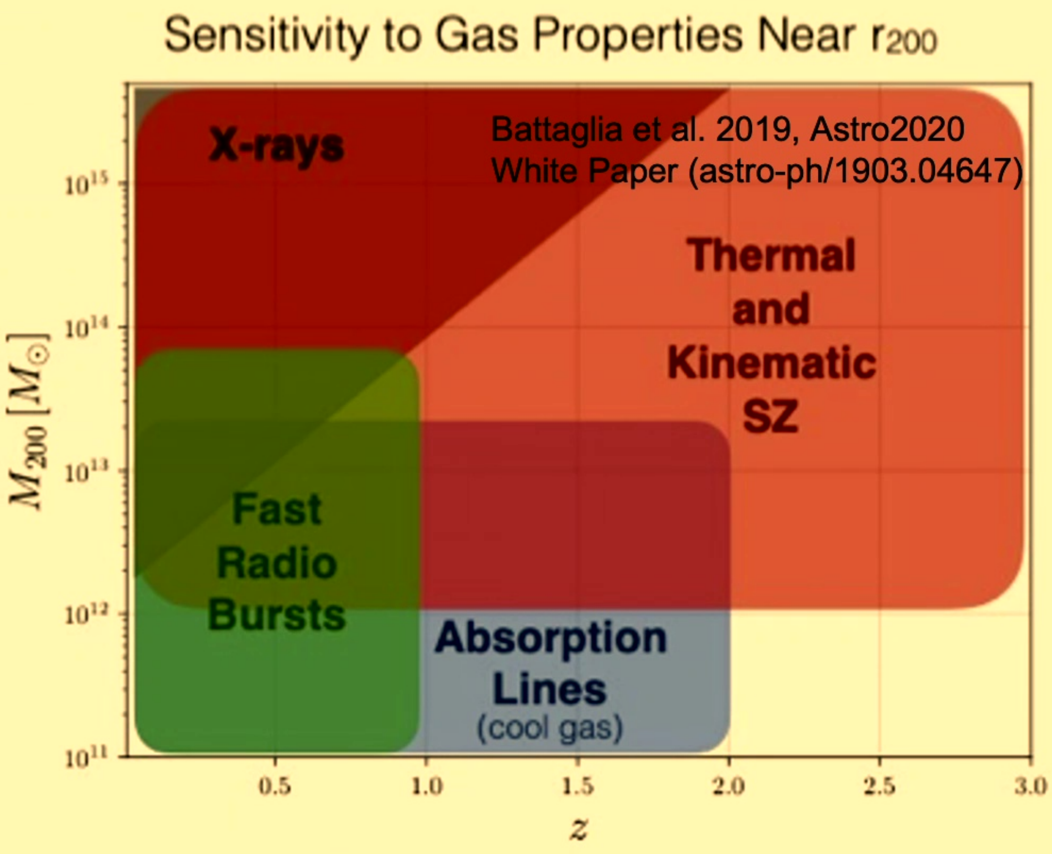


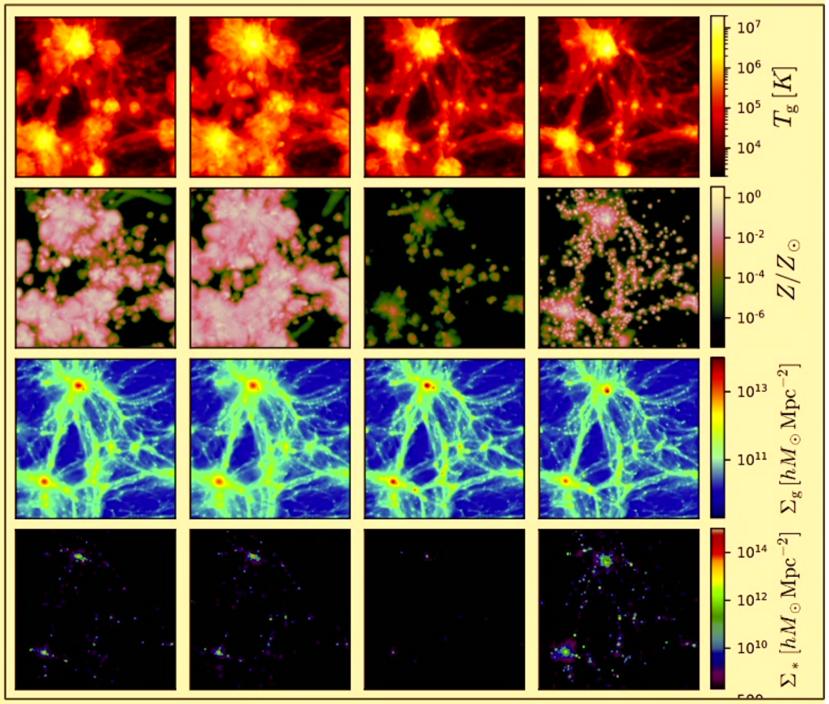




Most baryons are in gaseous form *across all halo masses.* Current-surveys are probing gas in galaxies and galaxy clusters.

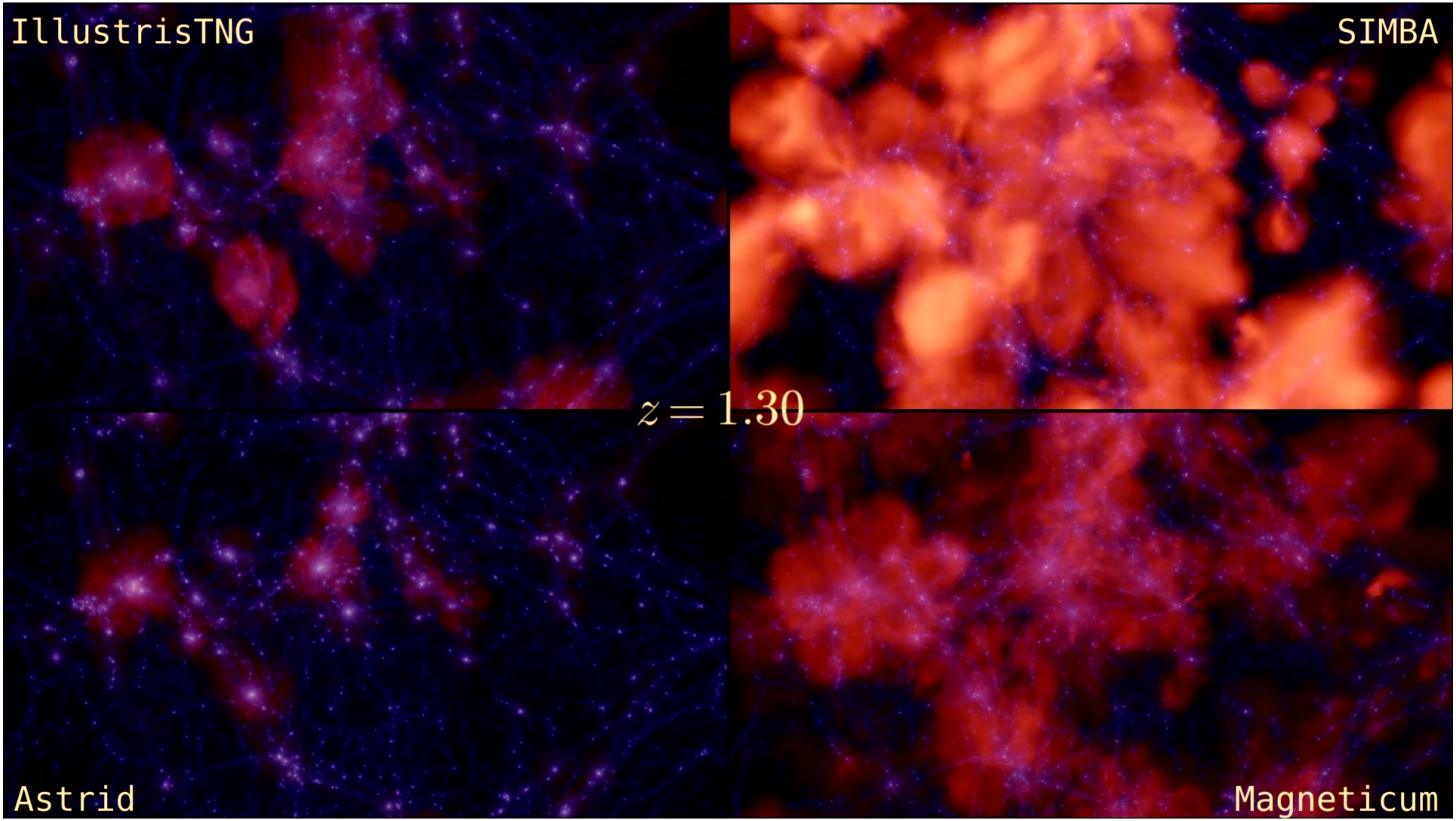
# Cosmology & Astrophysics with CGM
## Observations & Simulations



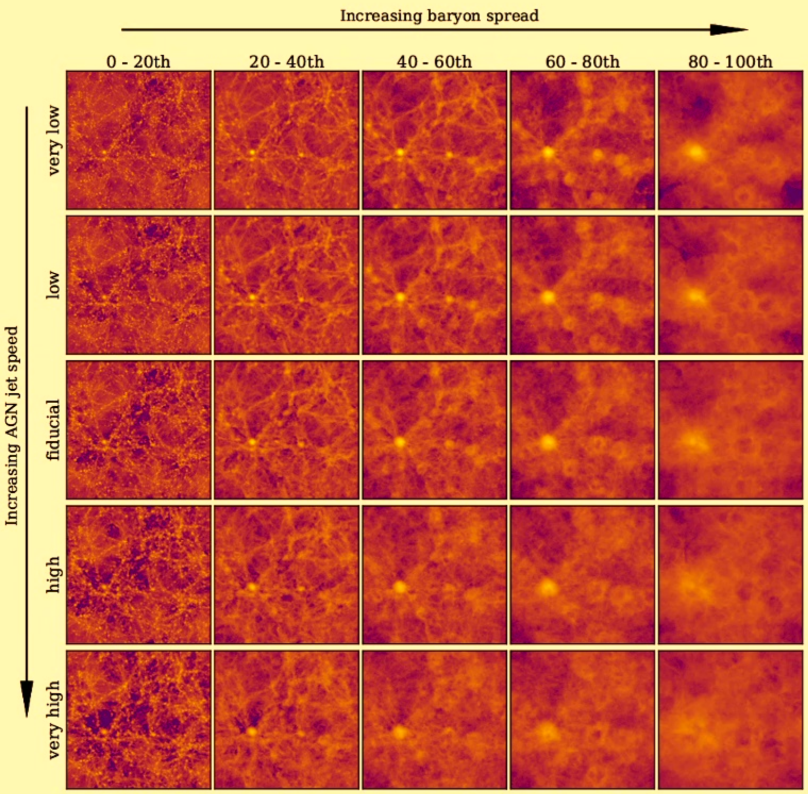

Cosmology and Astrophysics with Machine Learning Simulations (CAMELS)



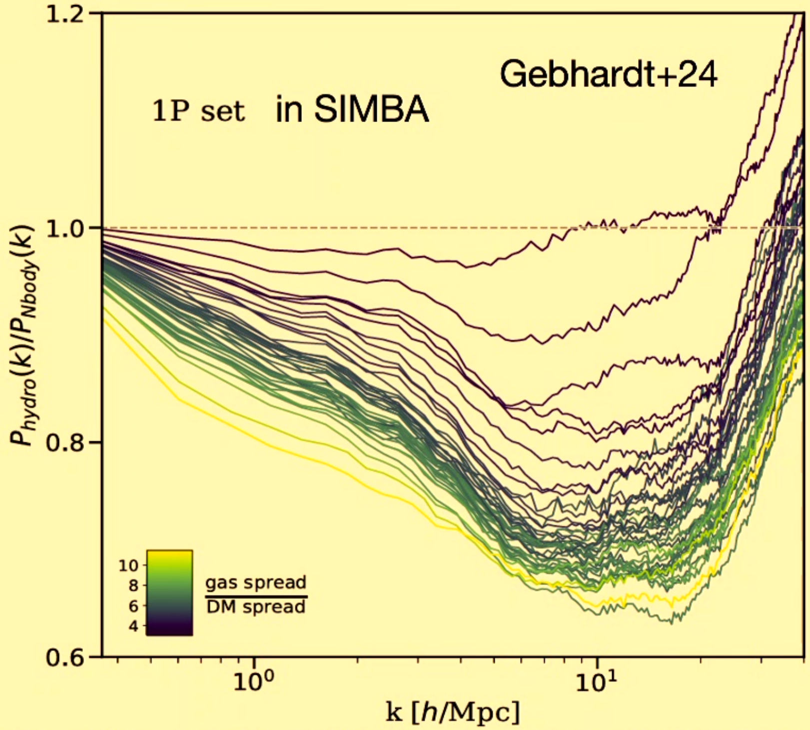
A series of CAMELS papers (including public data release in 2022)


IllustrisTNG
SIMBA
$z = 1.30$
Astrid
Magneticum

# Impact of "Baryon Spread" on Matter Clustering in CAMELS




Impact of AGN jet speed ($A_{SN2}$) in SIMBA

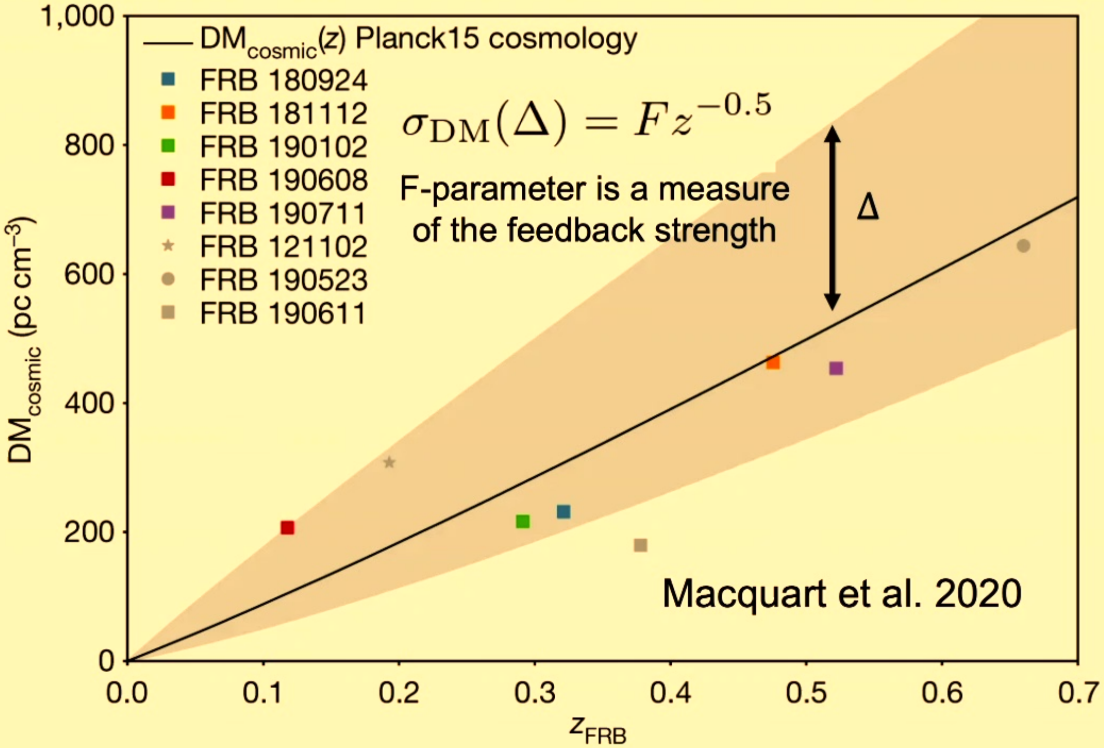



The "baryonic spread" metric is a good predictor of the global impact of feedback on the large-scale distribution of matter.

The baryon fraction in halos is also a good metric.

# Probing Feedback in CGM using FRB

The Macquart relation




Fast Radio Burts (FRBs) are great cosmological probes as they are direct tracers of ionized baryons along each sightline as the signal traverses through the intervening medium.

**Dispersion Measure** is given by

$$DM = \int_0^d \frac{n_e(l)}{1+z} dl$$

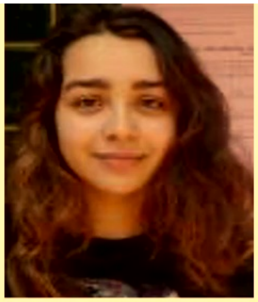
And is made up of several components

$$DM_{obs} = DM_{MW} + DM_{IGM} + DM_{CGM} + \frac{DM_{Host}}{1+z}$$

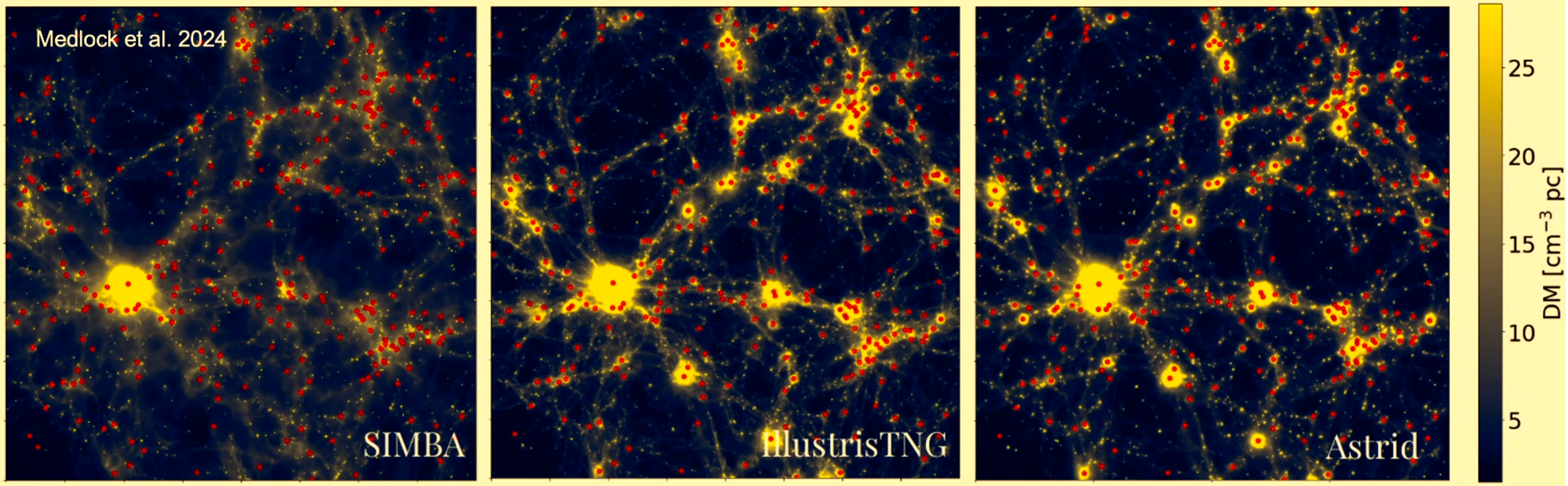
Here, we focus on

$$DM_{cosmic} = DM_{IGM} + DM_{CGM}$$

# Probing Feedback in CGM using FRB



Dispersion measure maps over a single box at z = 0.05 for fiducial subgrid models

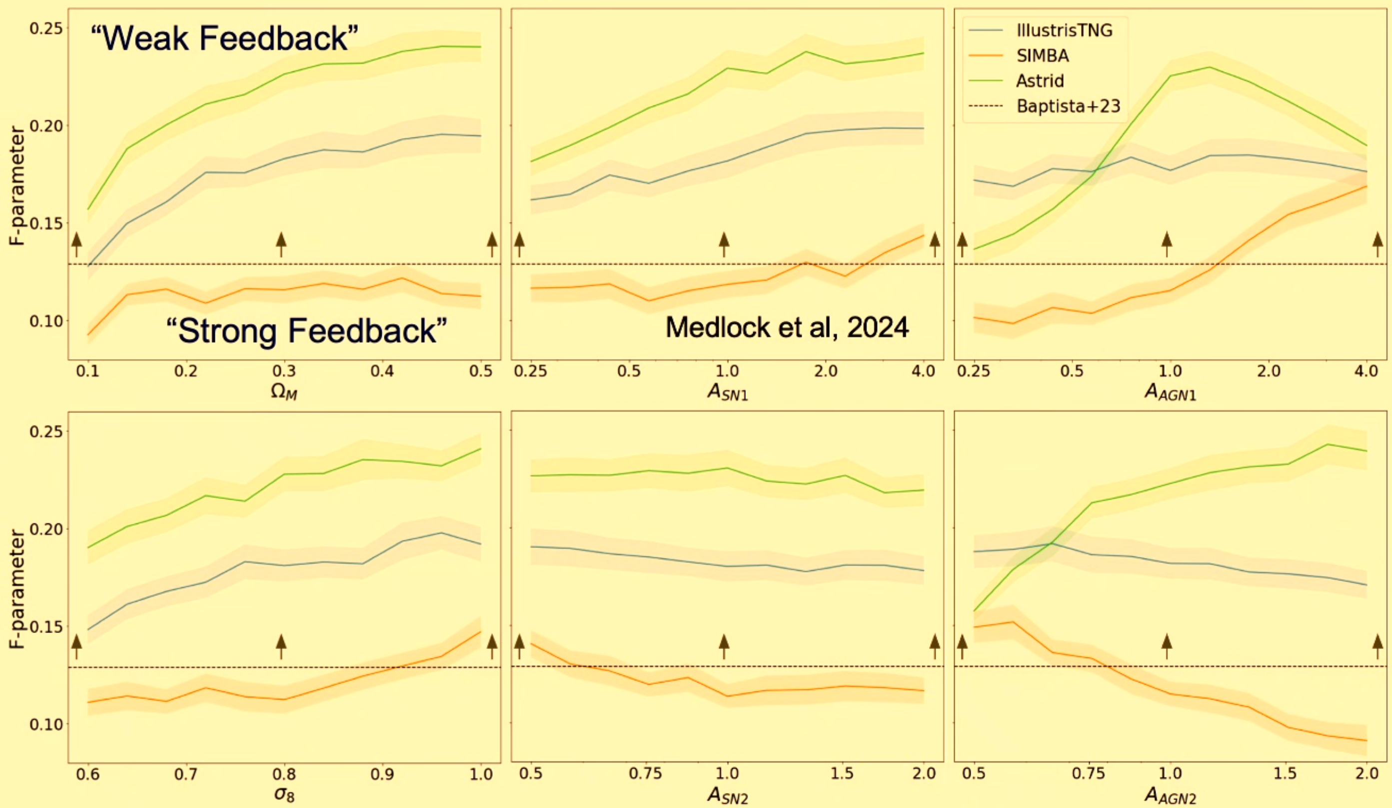



Centers of top 300 most massive halos marked with red dots. From left to right, we observe decreasing uniformity/increasing spread in electron density (Medlock et al. 2024, ApJ, 967, 15)

# F-parameters in CAMELS

F measurements for the 1P set for TNG, SIMBA, and Astrid.

Observational lower limit at (99.7% confidence) from 78 FRBs (21 with redshifts)
(Baptista et al., 2o23)




See also Medlock, Neufeld et al. (arXiv: 2410.16361) on
"Quantifying Baryonic Feedback in CAMELS simulations"

# FRB-based Baryonic Effect Correction Model

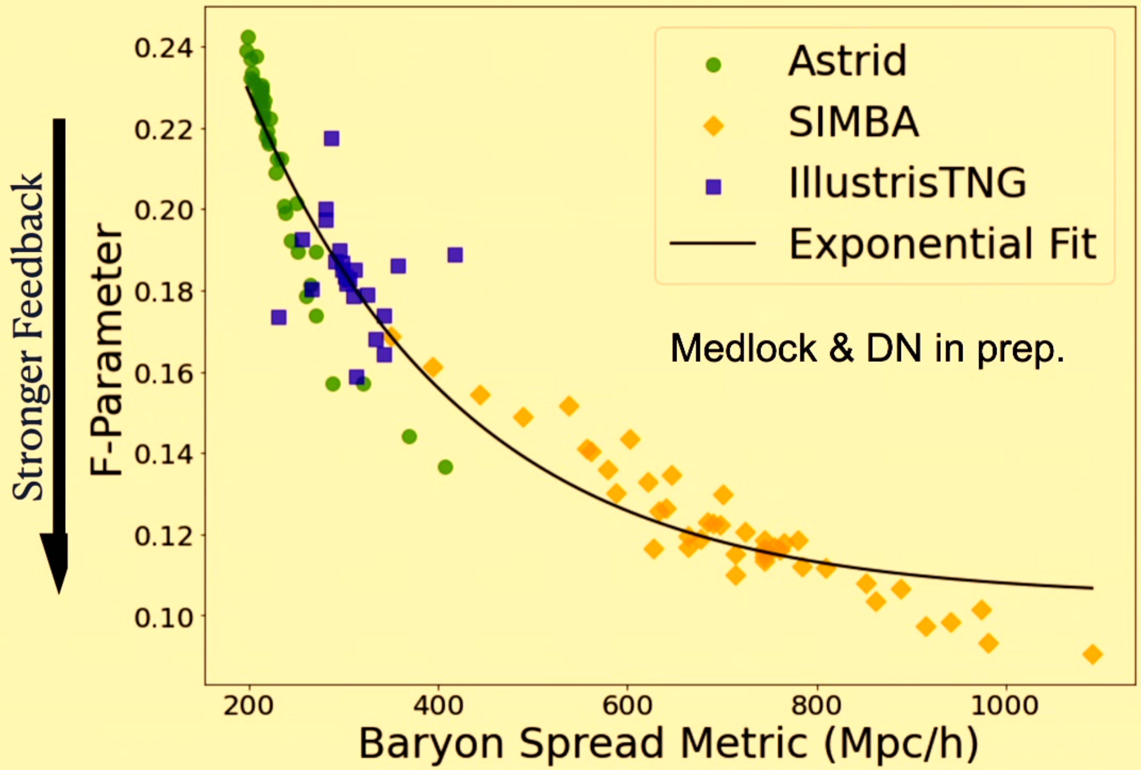
**Preliminary Results:**

Strong correlation between *S* and *F*, independent of sub grid model

**Exponential Decay Fit:**

$$F = 0.299 \cdot e^{-0.004 \cdot S} + 0.104$$

FRBs and the F-parameter are a robust observational probe for baryonic spread



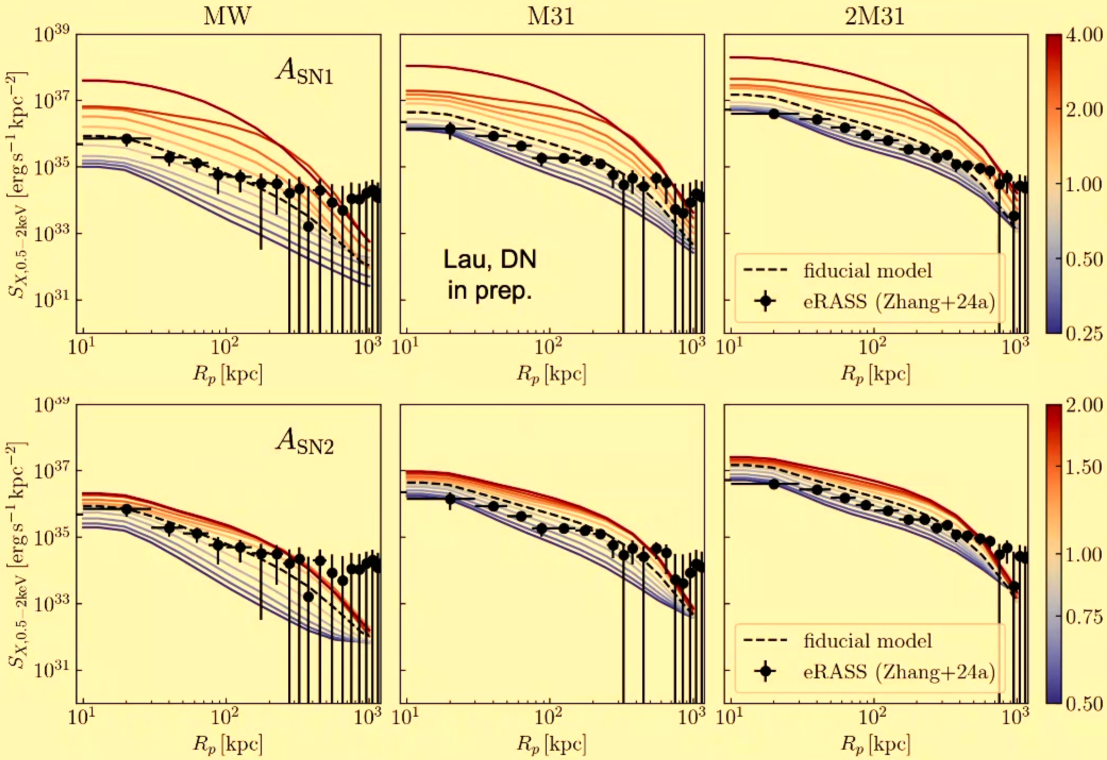

**FRB is a powerful probe of the baryonic effects on the matter power spectrum.**

**This universal relation is independent of the details of subgrid physics of galaxy formation!!**

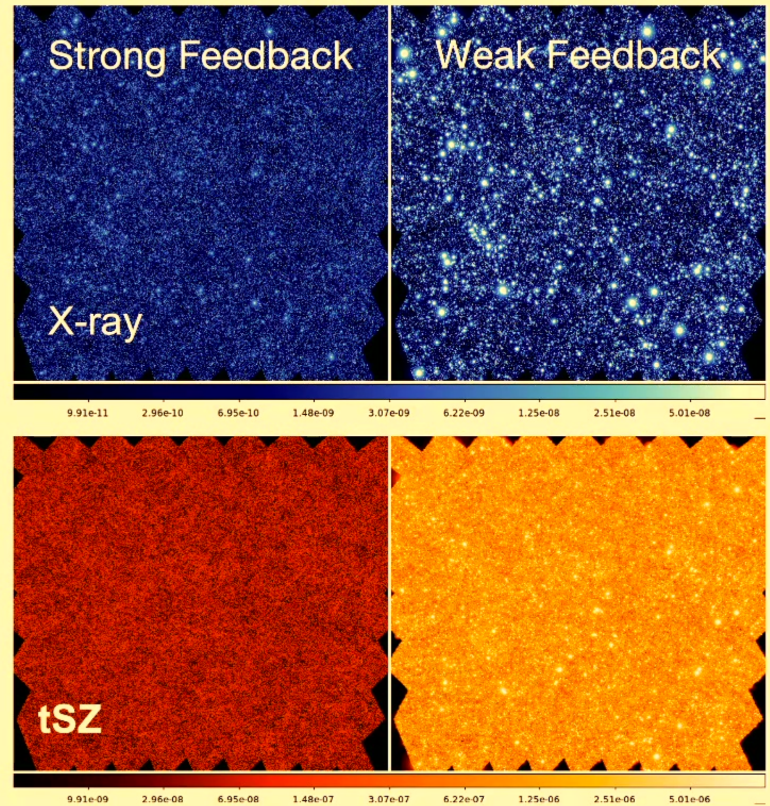
**Similar relation holds for the baryon fraction enclosed.**

# Probing Feedback with X-ray & SZ surveys

## Baryon Pasting with X-ray+SZ CAMELS profile emulator




### BP maps with varying feedback physics

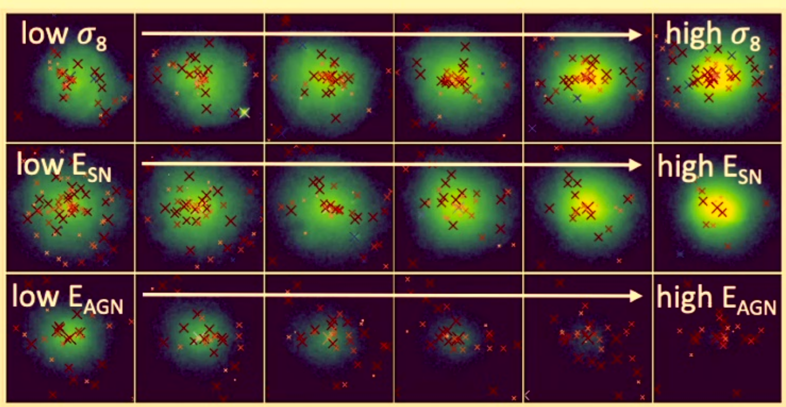



- Constrain CGM and Group feedback physics with eRASS.
- CAMELS+BP Maps: enables **simulation-based inference**.

# Cosmology in the Era of multi-$\lambda$ Surveys

*X-ray* *Microwave* *Optical*


*Emulating the Universe with CAMELS*




## Opportunities

- We are entering the golden age of data-driven cosmology, with large datasets from simulations & observations
- New frontiers: cosmology with small-scale, non-linear structures (e.g., galaxies, clusters, cosmic web)

## Challenges

- Baryonic Effects on Gas & Dark Matter Halo Profiles
- Large Multi-$\lambda$ maps for a range of cosmology & astrophysics

## New Frontiers

1. **Computational:** *hydro. cosmo. simulations*
2. **Modeling:** a *physical, computationally efficient model*
3. **Machine Learning:** *for big data from both sims. & obs.*
4. **Low-noise + High-resolution:** CGM & baryonic effects

**Cosmic Ecosystems Workshop at PI**
**July 28-Aug 1, 2025 (hosted by Selim!)**