CAMELS Simulations
A Strategic Approach to Precision Cosmology and Galaxy Astrophysics

Daisuke Nagai

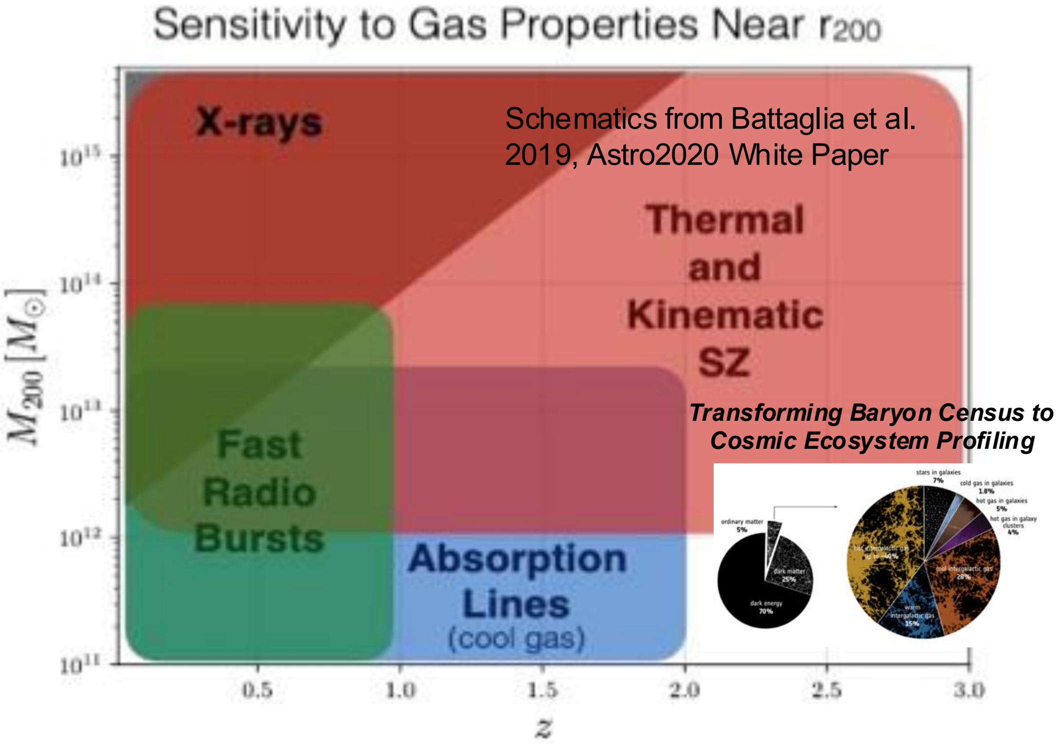
Yale University

on behalf of the CAMELS collaboration

mmUniverse workshop @ Chicago

June 24, 2025

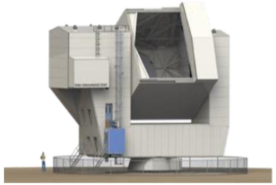
Cosmology & Galaxy Astrophysics in the Era of Multi-λ Surveys



Schematics from Battaglia et al. 2019, Astro2020 White Paper

Transforming Baryon Census to Cosmic Ecosystem Profiling

Simons Obs



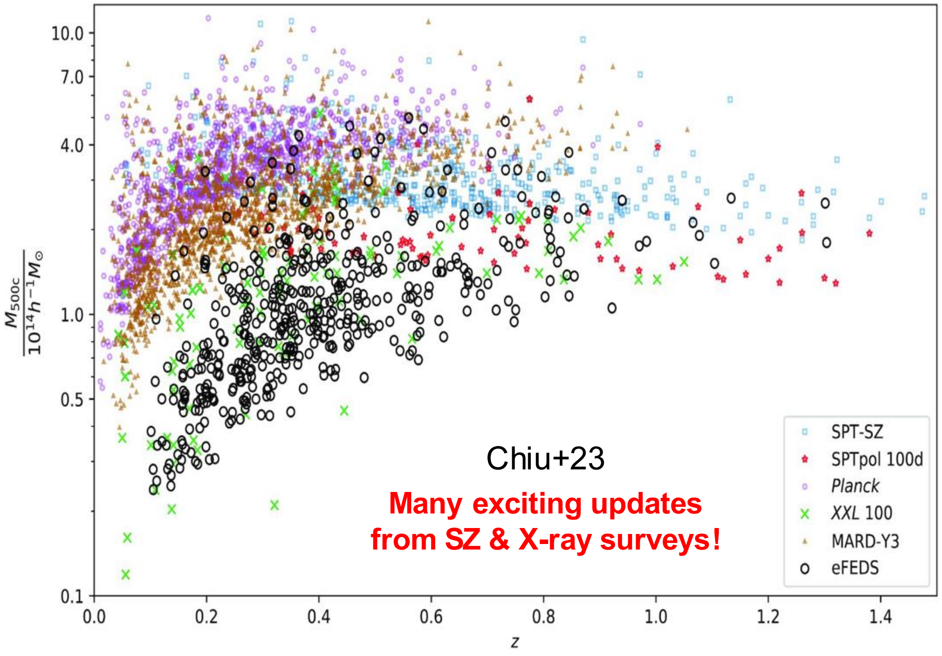
Rubin

DSA

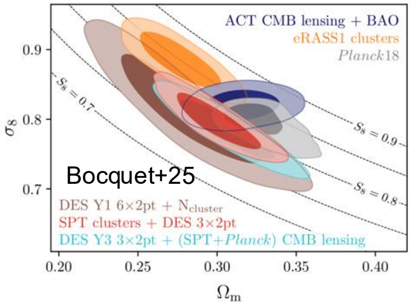
We are entering the golden age of multi-λ surveys!

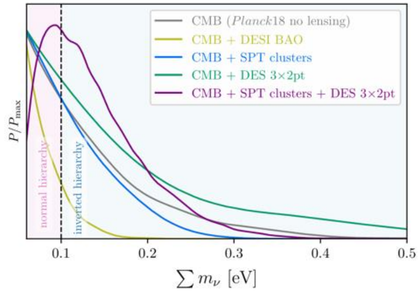
Understanding **Diffuse Gas in Cosmic Ecosystem** is essential for maximizing the scientific returns of these surveys.

Cluster Cosmology in the Stage IV & eROSITA Era

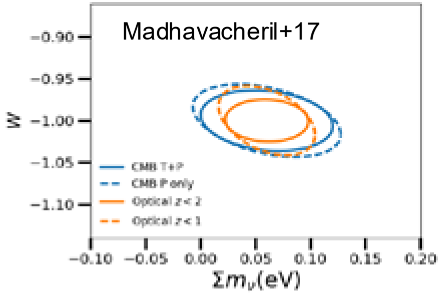


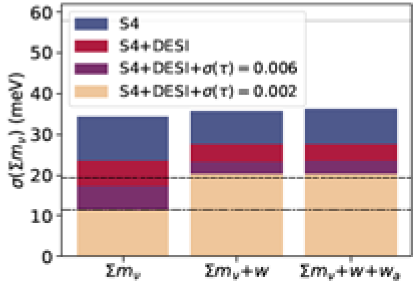
Today





Future

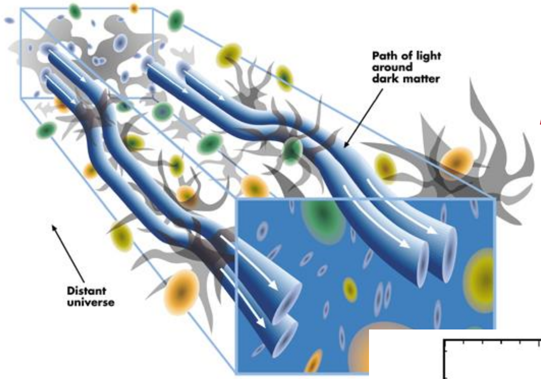




Galaxy Clusters & Groups are powerful cosmological probes

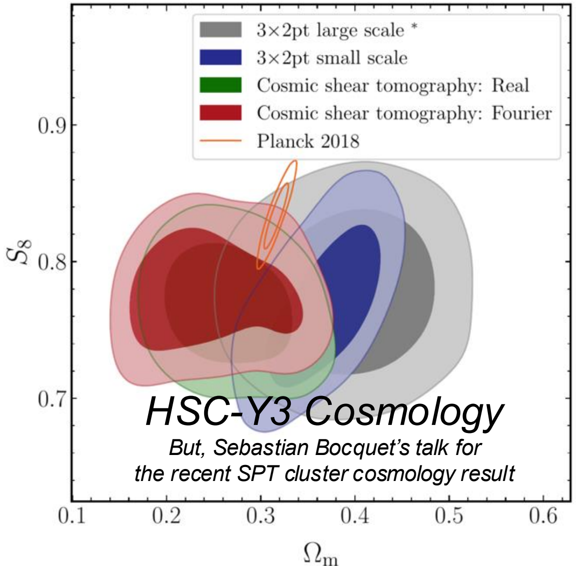
Systematic Floor: ICM physics *(aka baryonic effects)*

Cosmic Shear & S8 tension

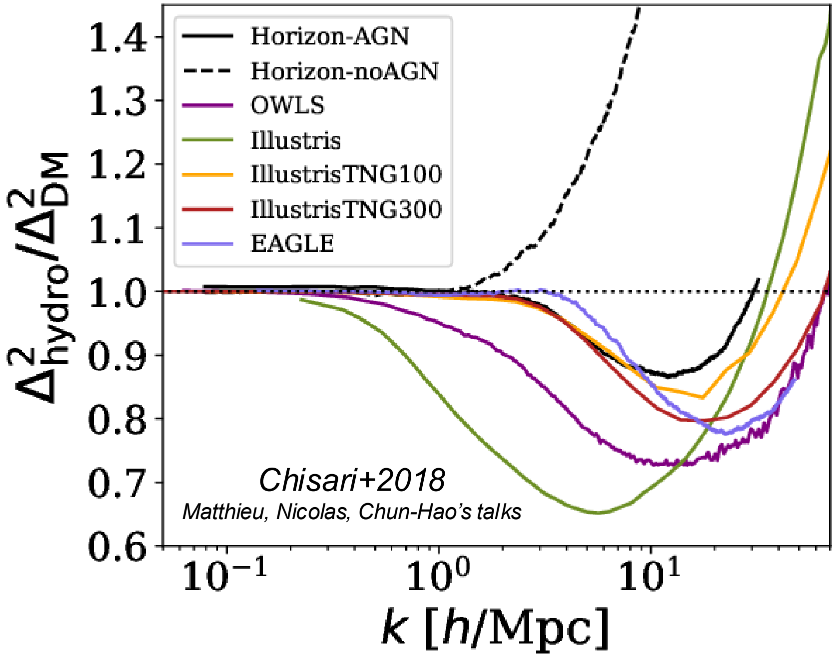


IntraGroup Medium (IGrM) are dominant baryons in groups.
IGrM profiles are essential for the current S8 tension!

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



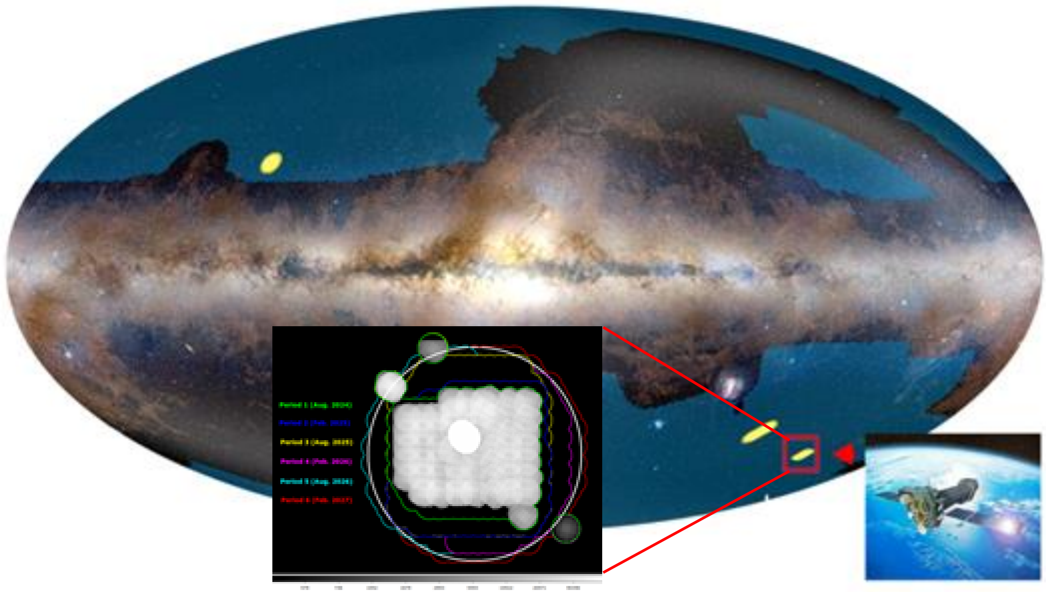
HSC-Y3 Cosmology
But, Sebastian Bocquet's talk for the recent SPT cluster cosmology result



Chisari+2018
Matthieu, Nicolas, Chun-Hao's talks

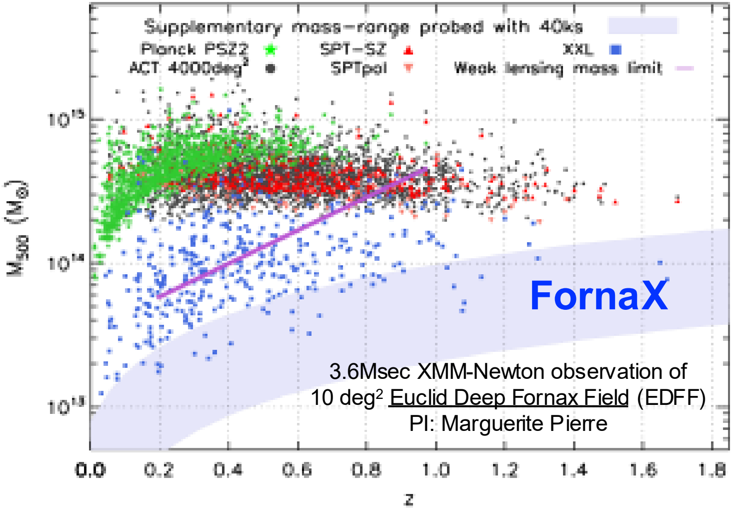
Baryonic effects (due to galactic feedback) cause baryons to spread and drag dark matter, causing the suppression of the matter power spectrum on large scales (k<30 h/Mpc).

Constraining IGrM over Cosmic Time



FornaX

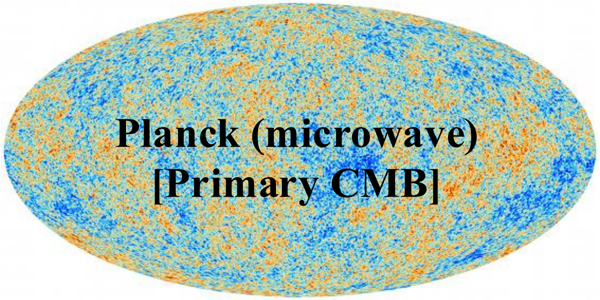
2024 – Heritage Programme – 2034

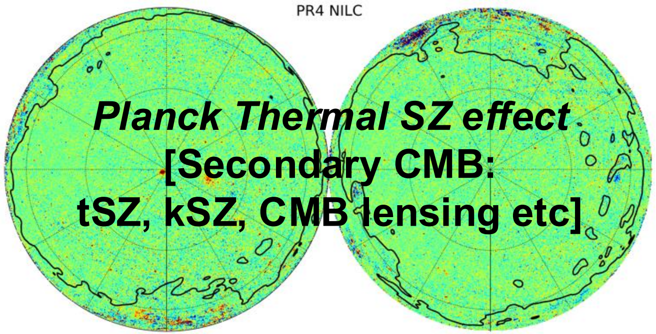


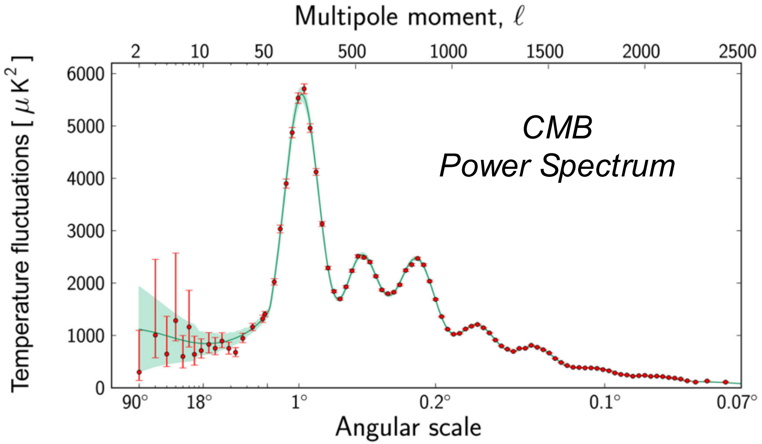
FornaX will detect groups down to 10^{13} $M_{\odot}$ to z=1.8, complementary to the wider but shallower eRASS
Goal: constrain baryonic feedback in groups across cosmic time!

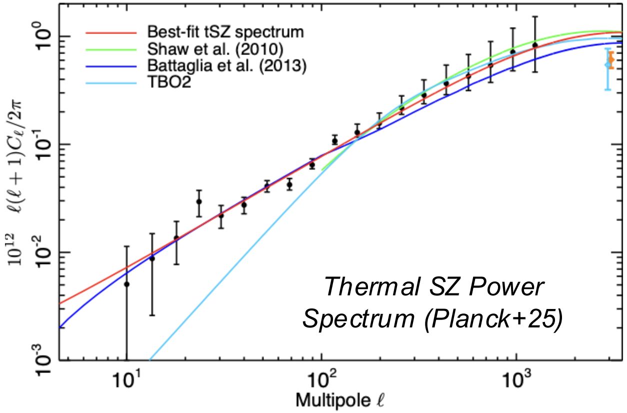
Constraining ICM & IGrM with SZ Power Spectrum

Primary vs. Secondary CMB







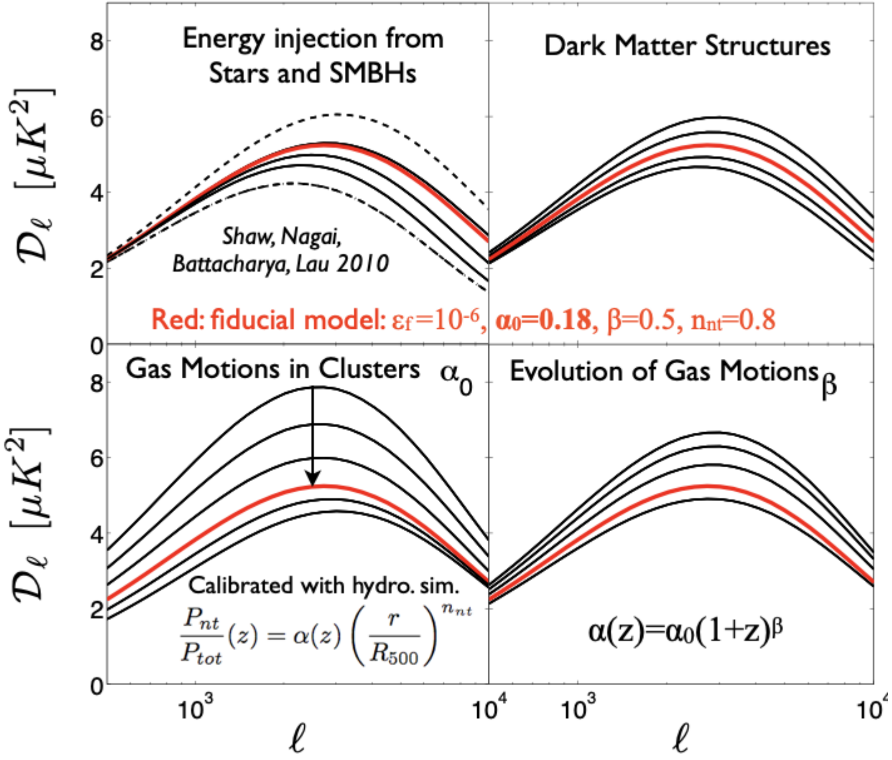


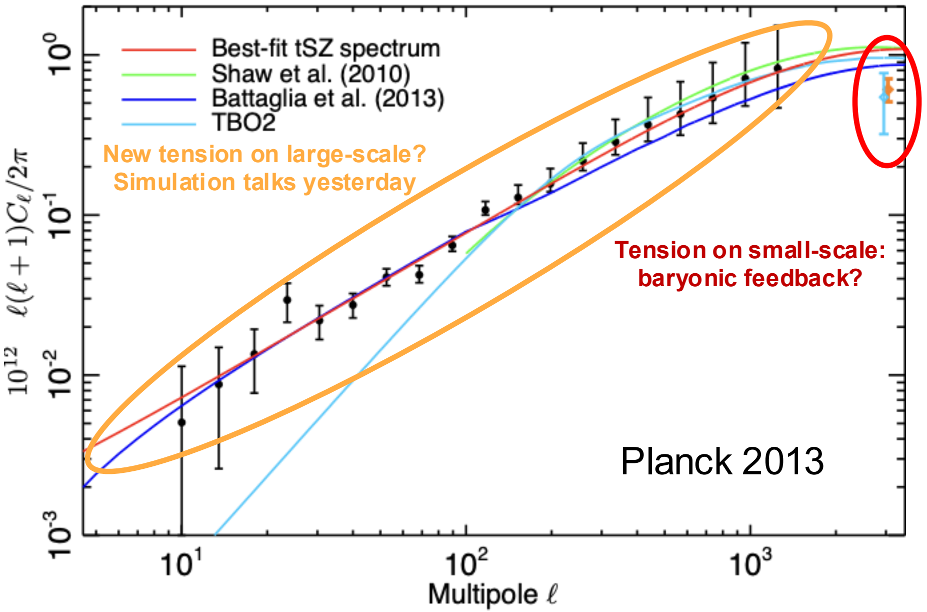
Complementary approach for constraining cosmology & astrophysics via field-level inference.

Higher-Order Statistics, Cross-Correlations, Simulation-Based Inference (SBI) etc.

Deconstructing 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





Possible explanations & next steps:

- Differences in non-thermal pressure in different sims?
- Is Psz = Px? (e.g., clumping, ellipticity, X-ray calibration etc.)
- CMB foreground modeling? (e.g., DSFGs)
- Check X-ray Power spectrum? (Erwin Lau's talk on Thursday)

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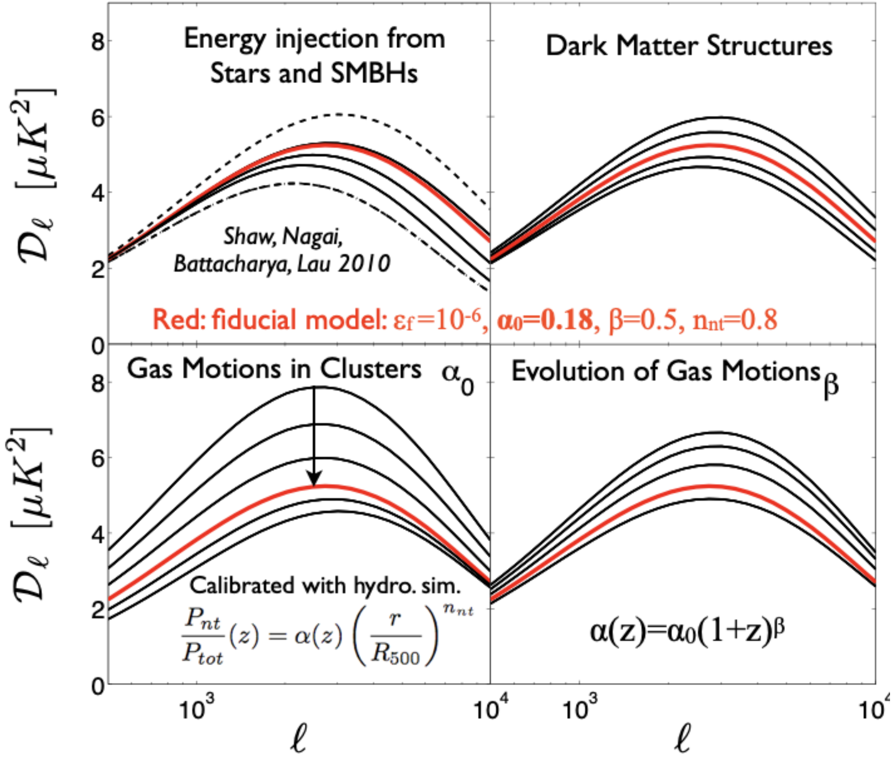

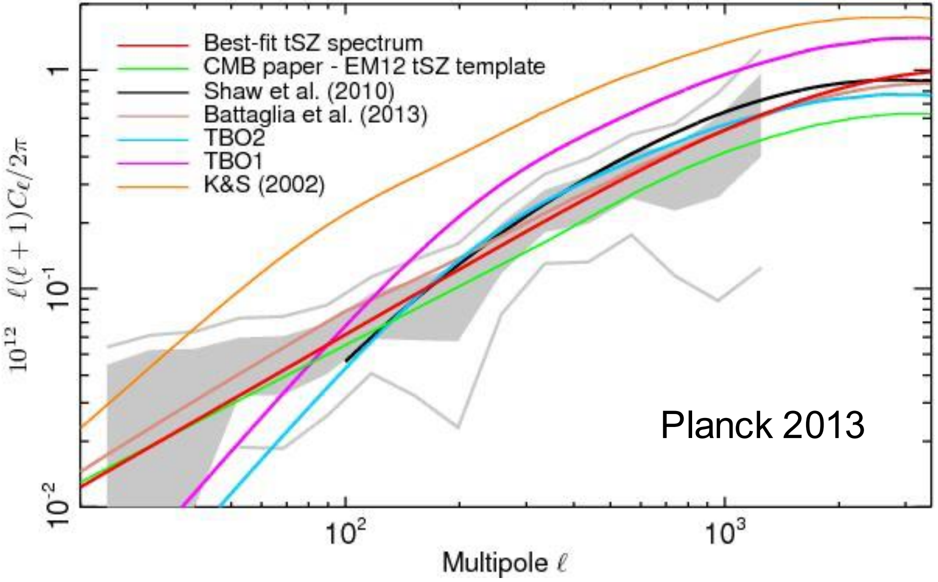

Possible explanations & next steps:

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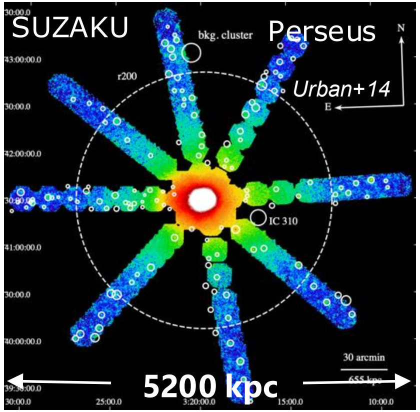
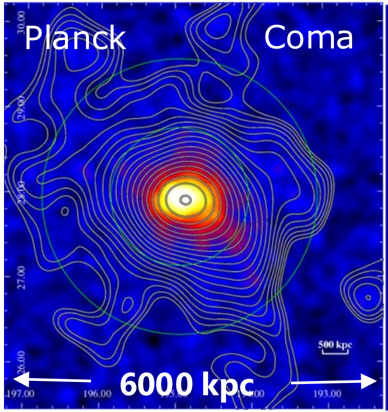
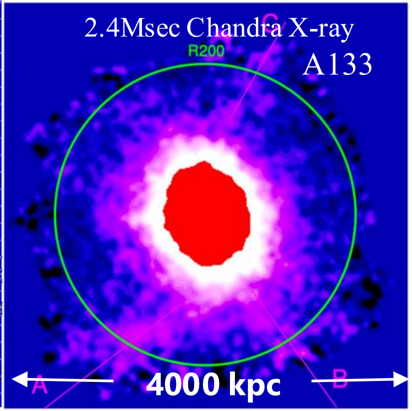
Circum-Galactic Medium (CGM)

New Laboratory for Baryonic Feedback & Cosmological Tension

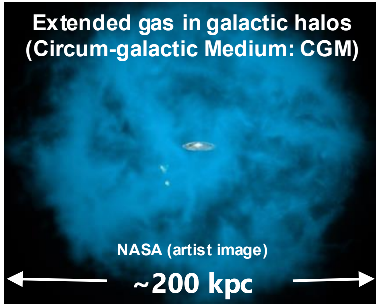
Galaxy Clusters

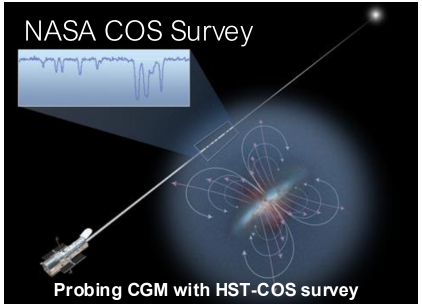


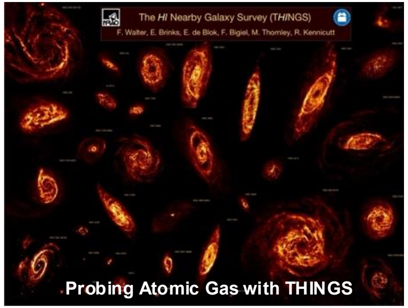




Galaxies

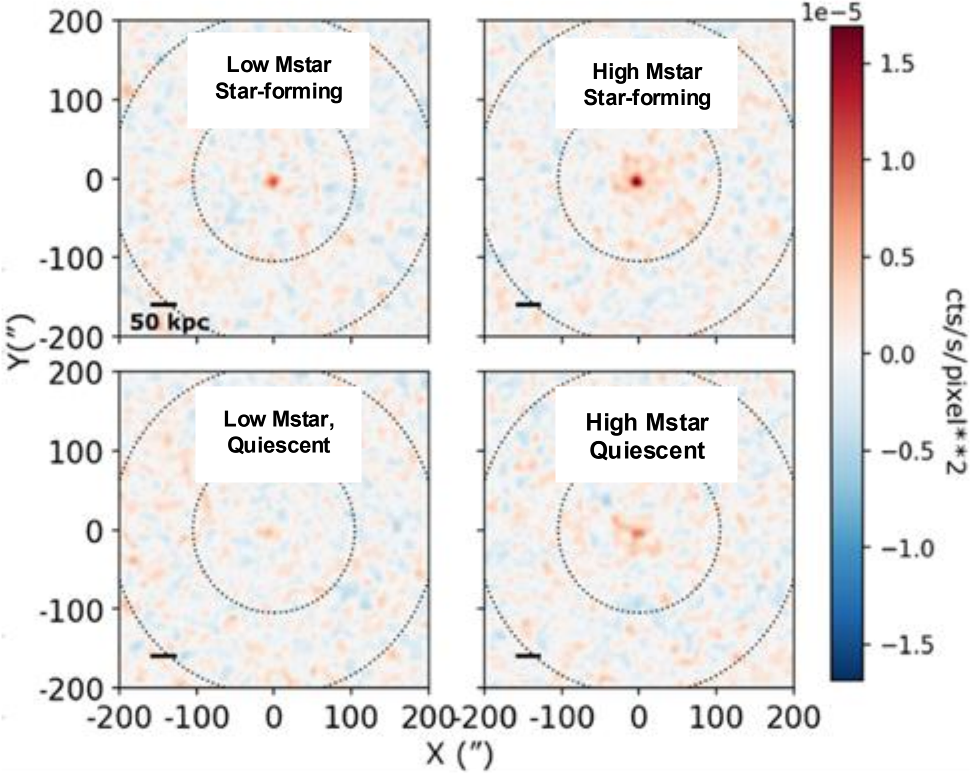




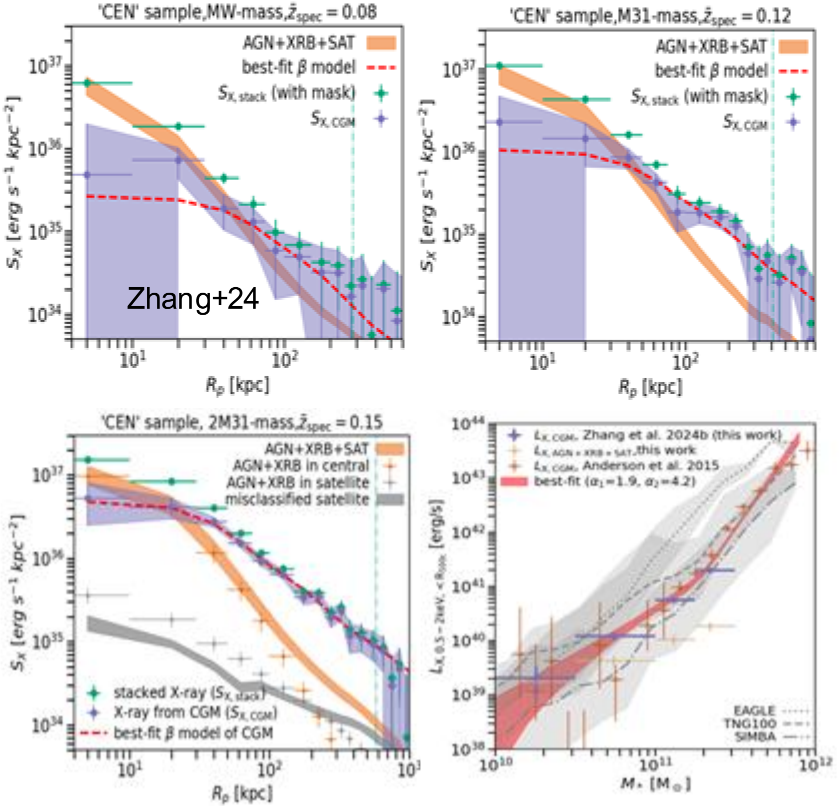


Transforming Baryon Census into Cosmic Ecosystem Profiling!

Stacked X-ray measurements of CGM with eROSITA All Sky Survey (eRASS)

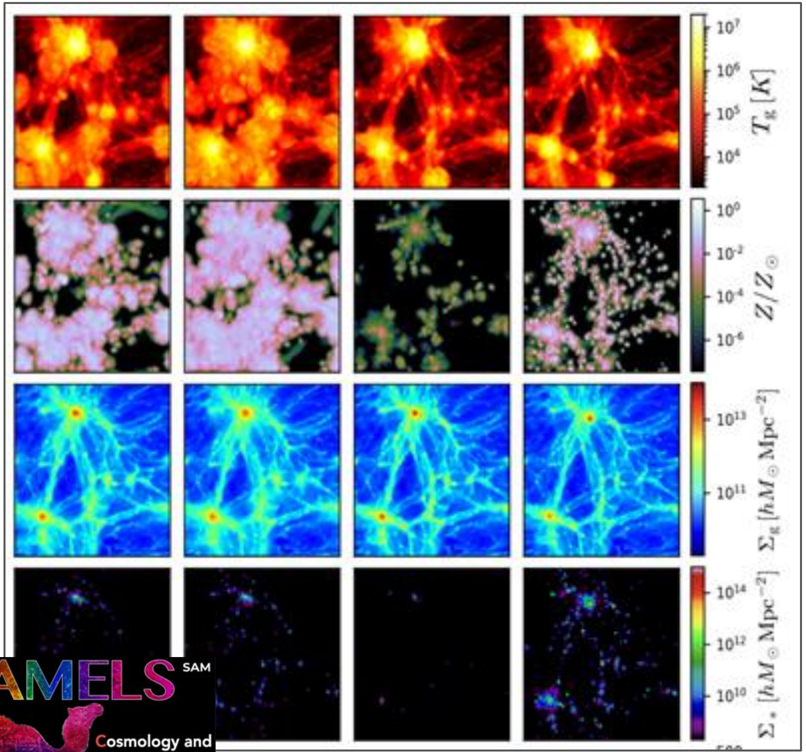


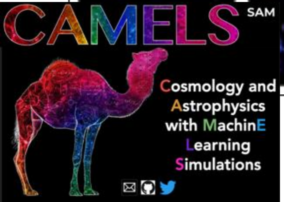
Chadayammuri+22, Comparat+22
Lau+25 for interpretation with CAMELS



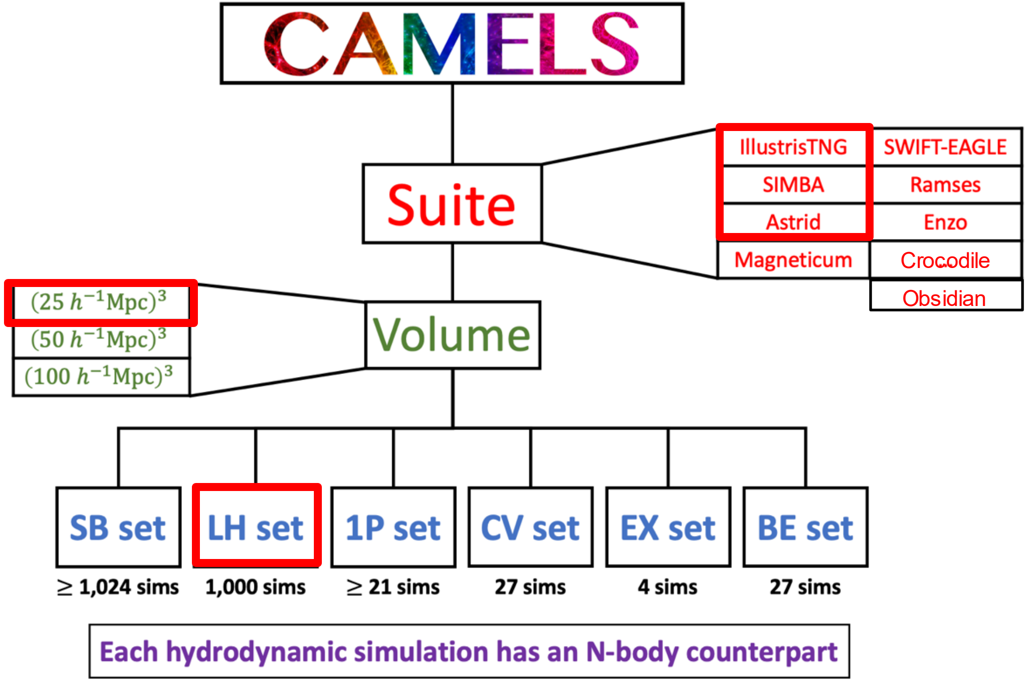
Tension between eRASS measurements & simulations

CAMELS: Cosmology & Astrophysics with Machine Learning Simulations





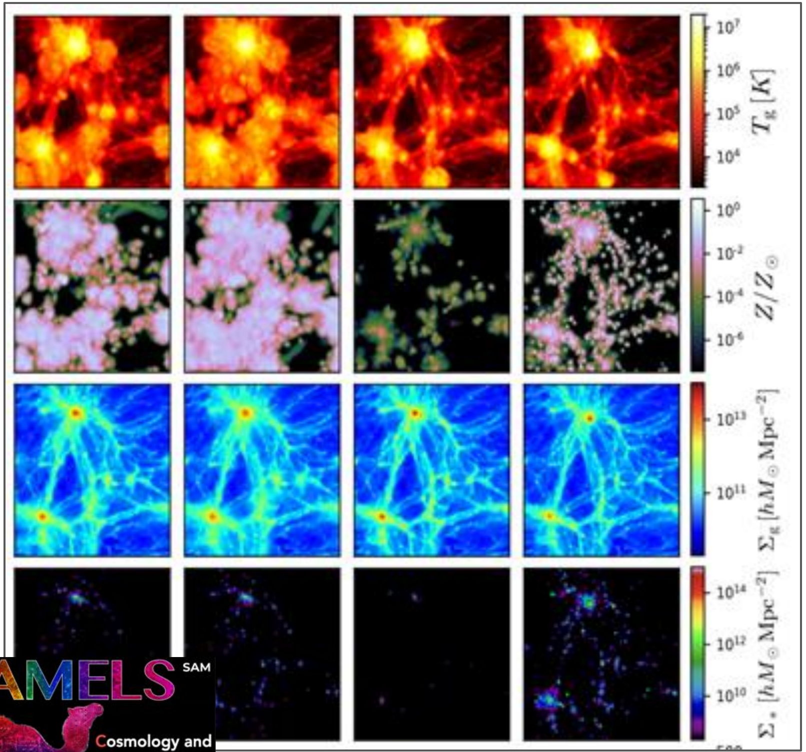
A series of CAMELS papers (including public data release in 2022)

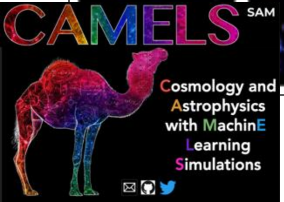


Latin Hypercube (LH) sets for TNG, SIMBA, Astrid

Box size = 25 Mpc/h; Resolution: $10^7_{\odot}$; 2 kpc

CAMELS Simulation Variations

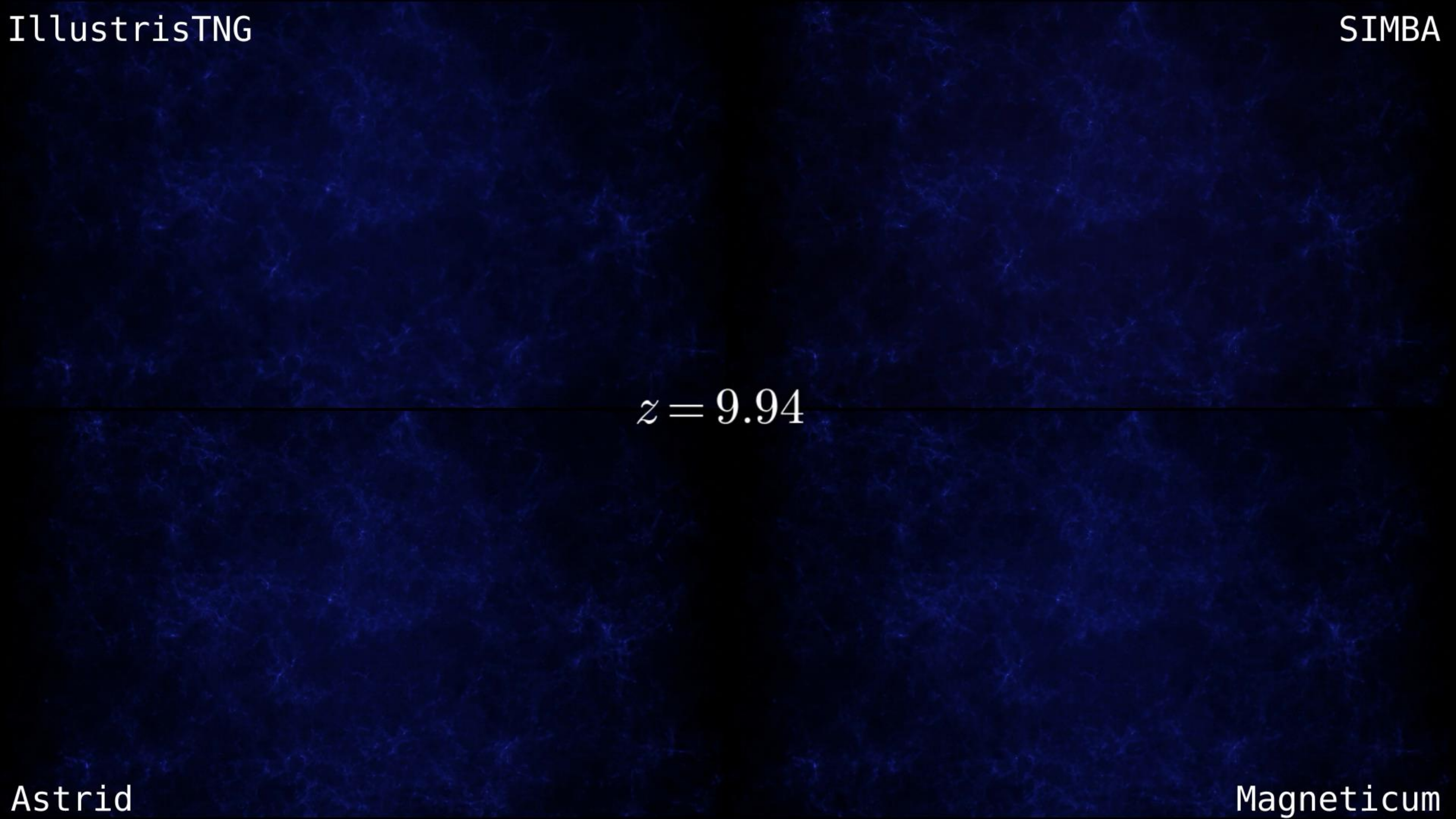




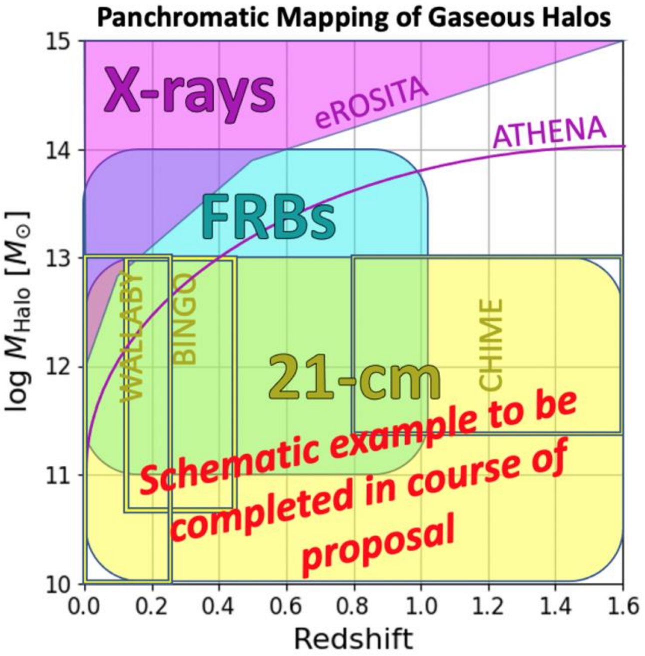
A series of CAMELS papers (including public data release in 2022)

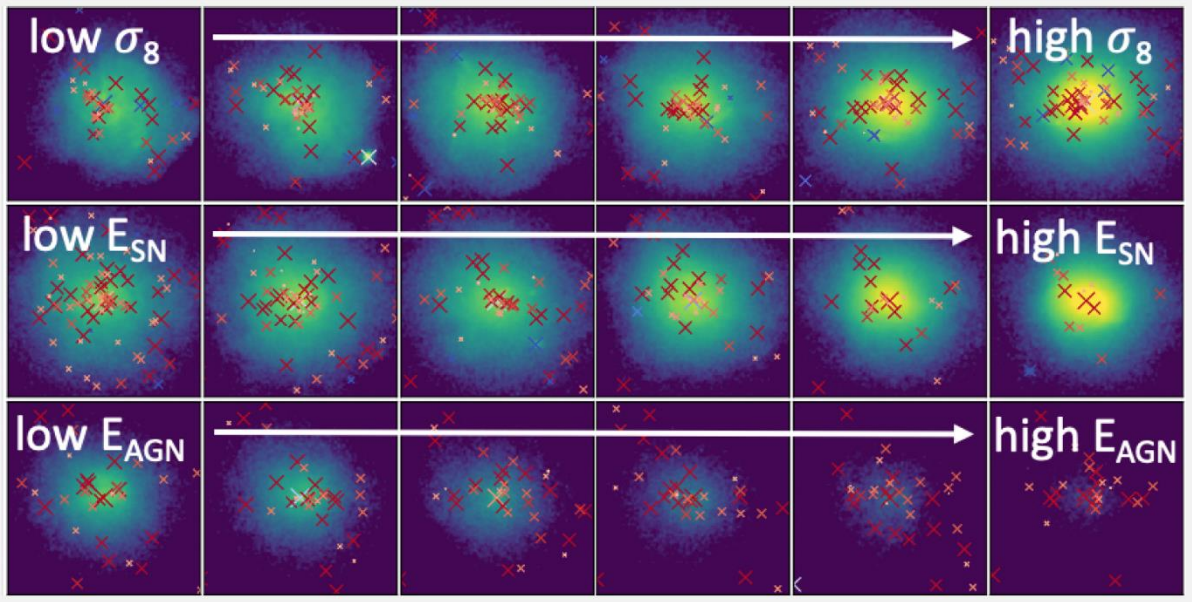
Parameter	Value Range	Physical meaning
SN1	[0.25, 4]	SN energy output per SFR (IllustrisTNG, Astrid) Mass loading factor (SIMBA)
SN2	[0.5, 2]	SN wind speed
AGN1	[0.25, 4]	Kinetic AGN feedback energy (IllustrisTNG, Astrid) AGN jet momentum flux (SIMBA)
AGN2	[0.5, 2] [0.25,4] (for Astrid)	AGN 'Burstiness' (IllustrisTNG) Jet speed (SIMBA) Thermal AGN feedback energy (Astrid)
Ω_m	[0.1, 0.5]	Matter density
σ_8	[0.6, 1.0]	Matter fluctuation

Note: the same parameter has a different meaning in different subgrid models.


IllustrisTNG
SIMBA
$z = 9.94$
Astrid
Magneticum

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



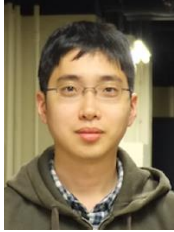


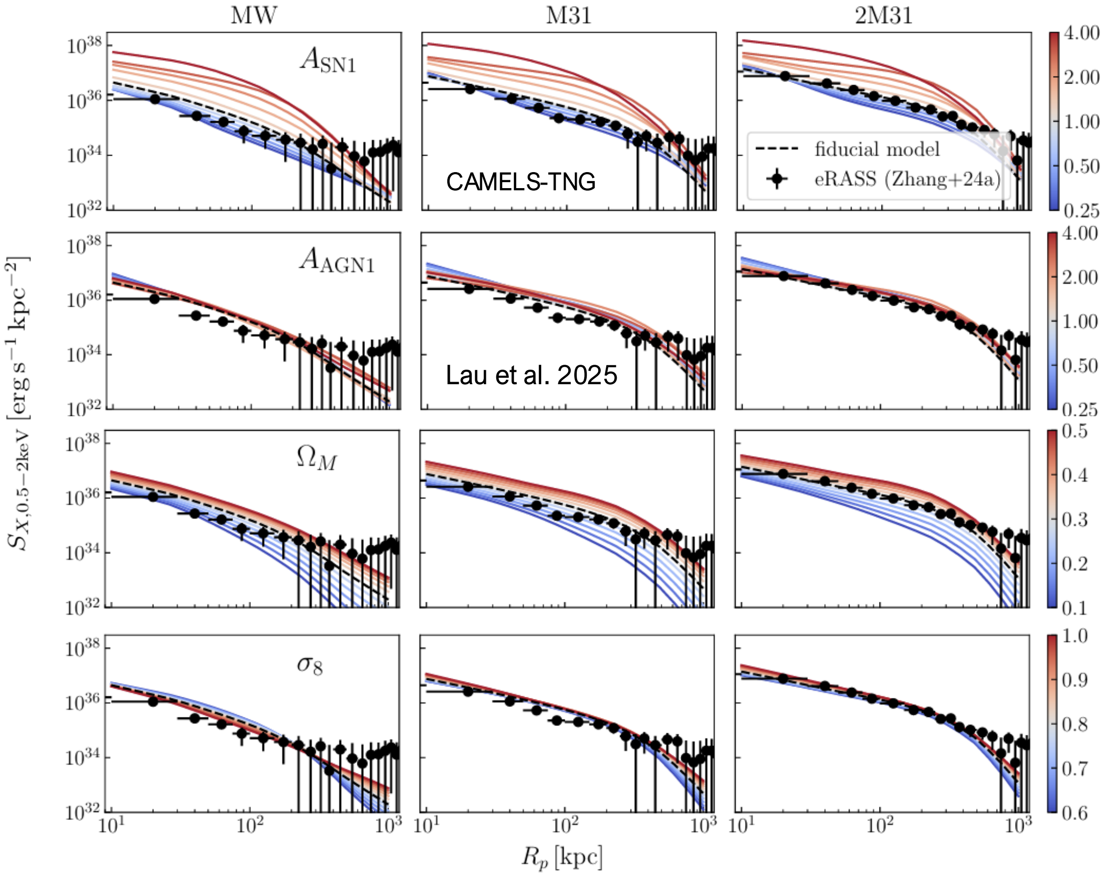
NSF AST 2206055

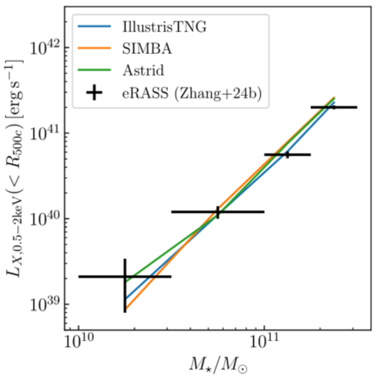
D. Nagai (PI: Yale) & B. Oppenheimer (Co-I: U. Colorado)

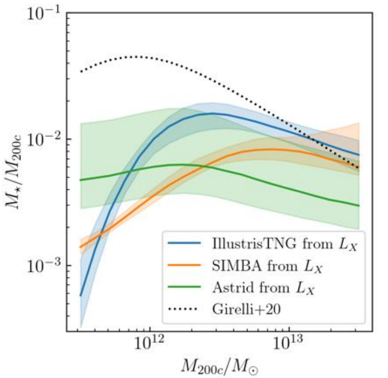
Goal: emulating multi-λ surveys for a range of cosmology and galaxy astrophysics

X-raying CAMELS: Constraining Baryonic Feedback in CGM with CAMELS & eRASS data



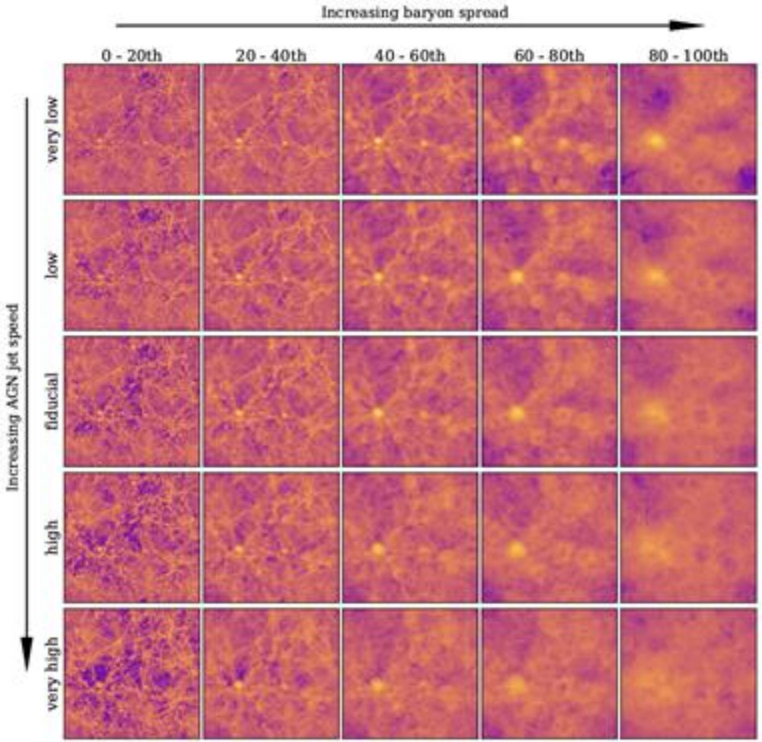




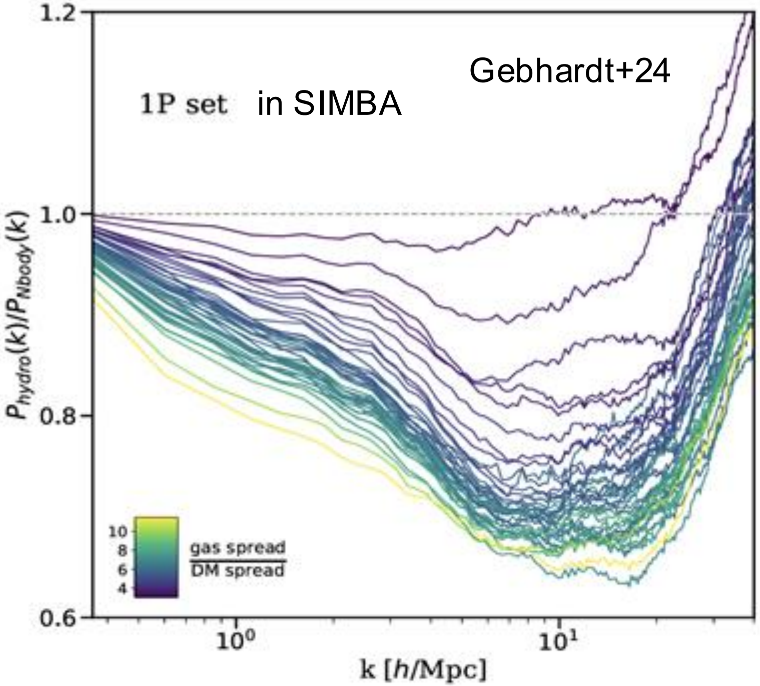


- **Tension:** the best-fit X-ray CGM model prefers enhanced feedback models, but is inconsistent with the observed stellar fraction
- **Implications**: (1) systematics in eRASS stacked measurements or (2) inadequacy in feedback models in cosmological simulations
- **Next Steps:** (1) cross-check stacked SZ data and (2) larger CAMEL box for more groups

Impact of “Baryon Spread” on Matter Clustering in CAMELS



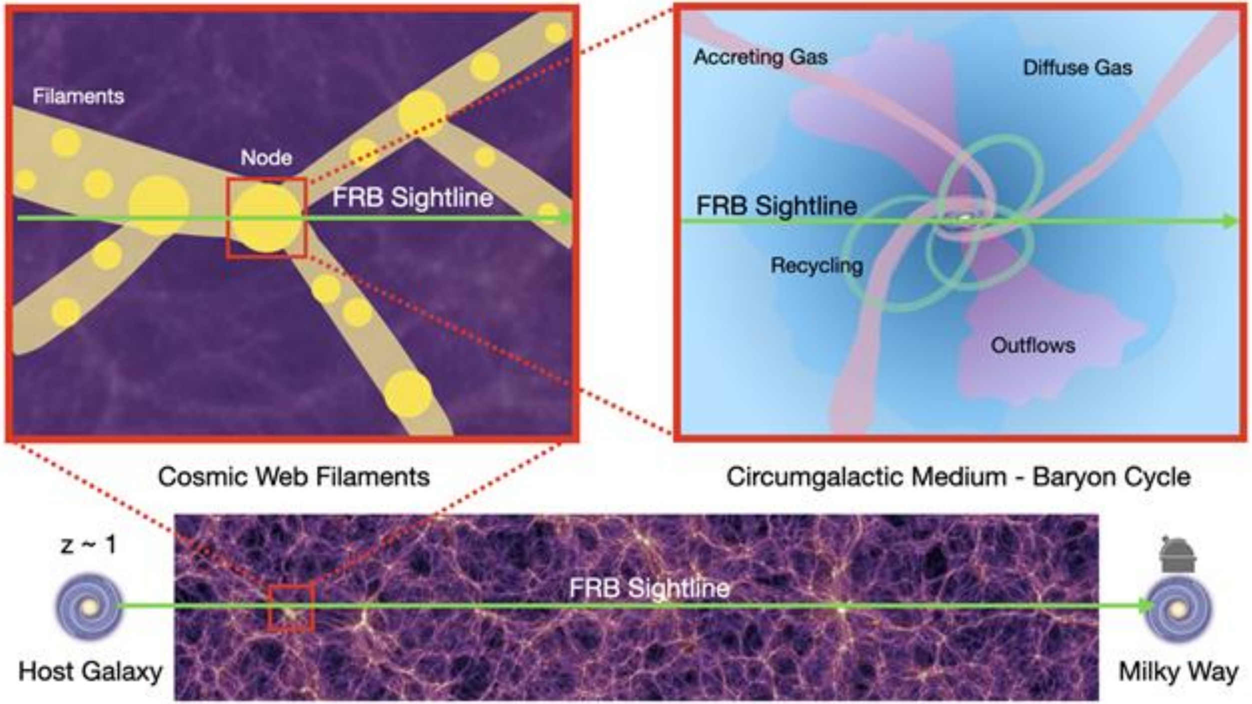
Impact of AGN jet speed (A_{SN2}) in SIMBA



The “baryon spread” metric is a good predictor of the global impact of feedback on the large-scale distribution of matter.

But, the “baryon spread” is not observable..

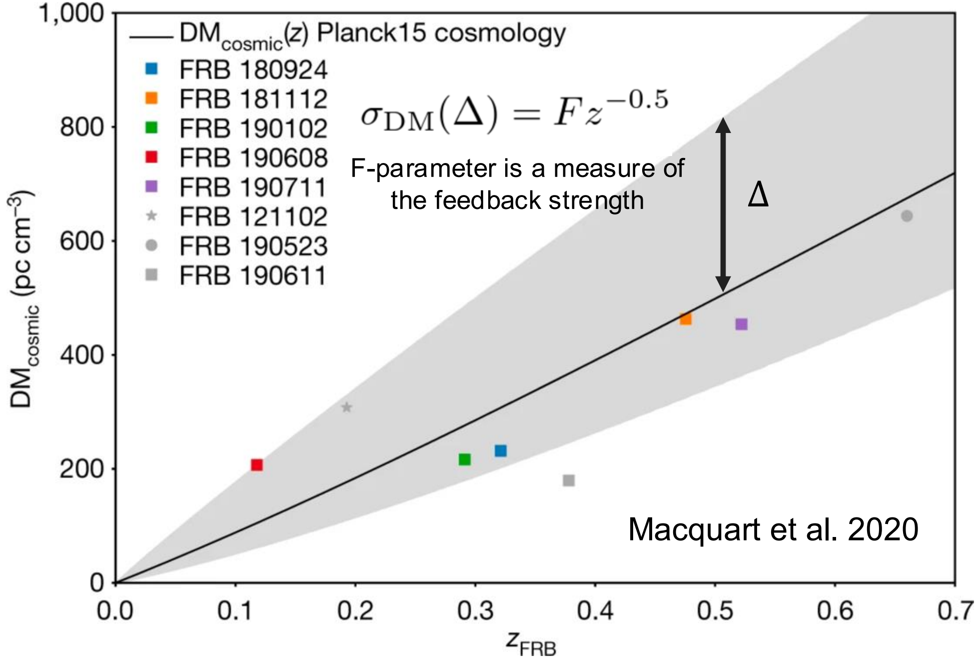
Probing Baryonic Feedback & Cosmological Tension with Fast Radio Bursts (FRB)



$$DM_{\mathrm{obs}} = \int_0^z n_e dl = DM_{\mathrm{Host}} + DM_{\mathrm{Filament}} + DM_{\mathrm{IGM}} + DM_{\mathrm{CGM}} + DM_{\mathrm{MW,Halo}} + DM_{\mathrm{MW,ISM}}$$

Probing Baryonic Feedback 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

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

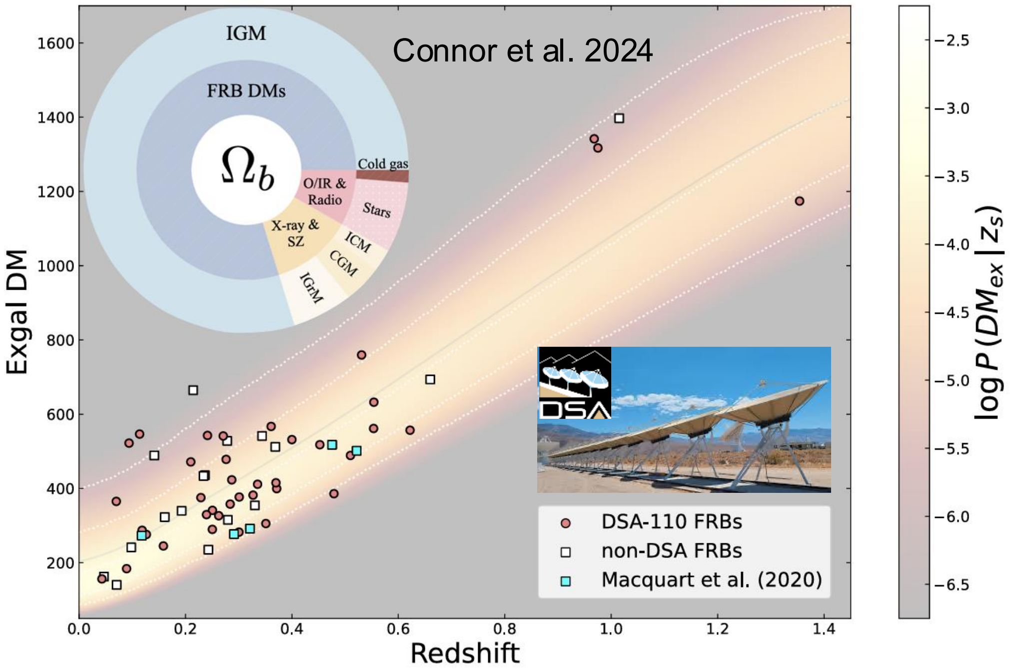
And is made up of several components

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

Here, we focus on

$$\boxed{\mathrm{DM_{cosmic}} = \mathrm{DM_{IGM}} + \mathrm{DM_{CGM}}}$$

Probing Baryonic Feedback using FRB



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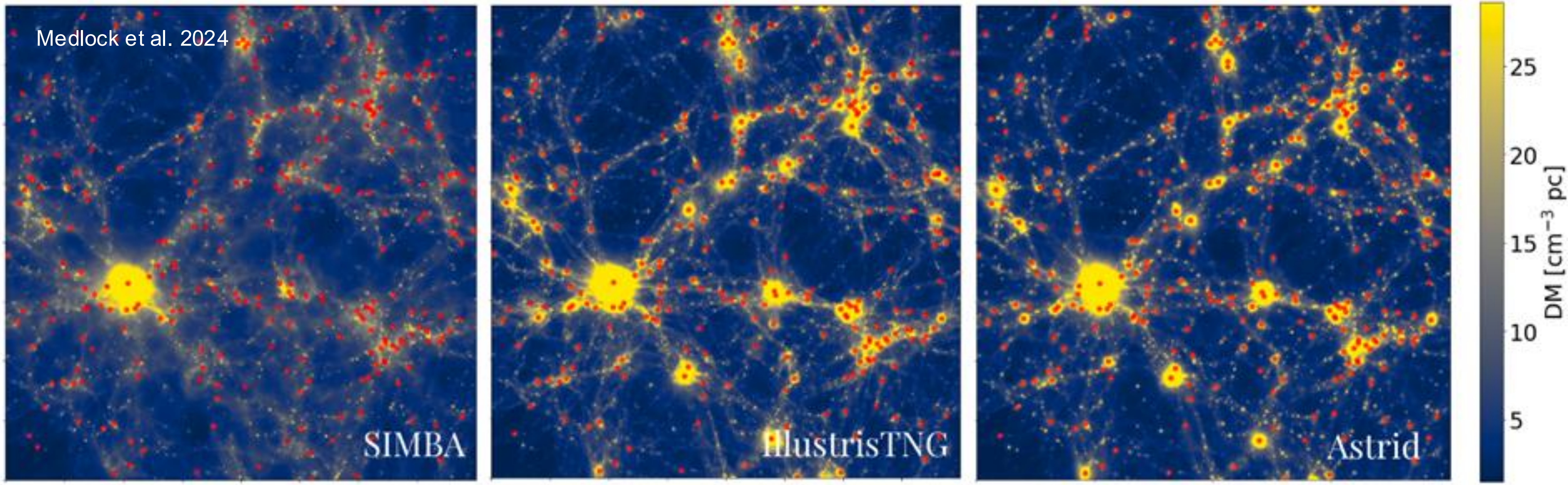
Here, we focus on

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

Probing Baryonic Feedback with FRB
Insights from CAMELS

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

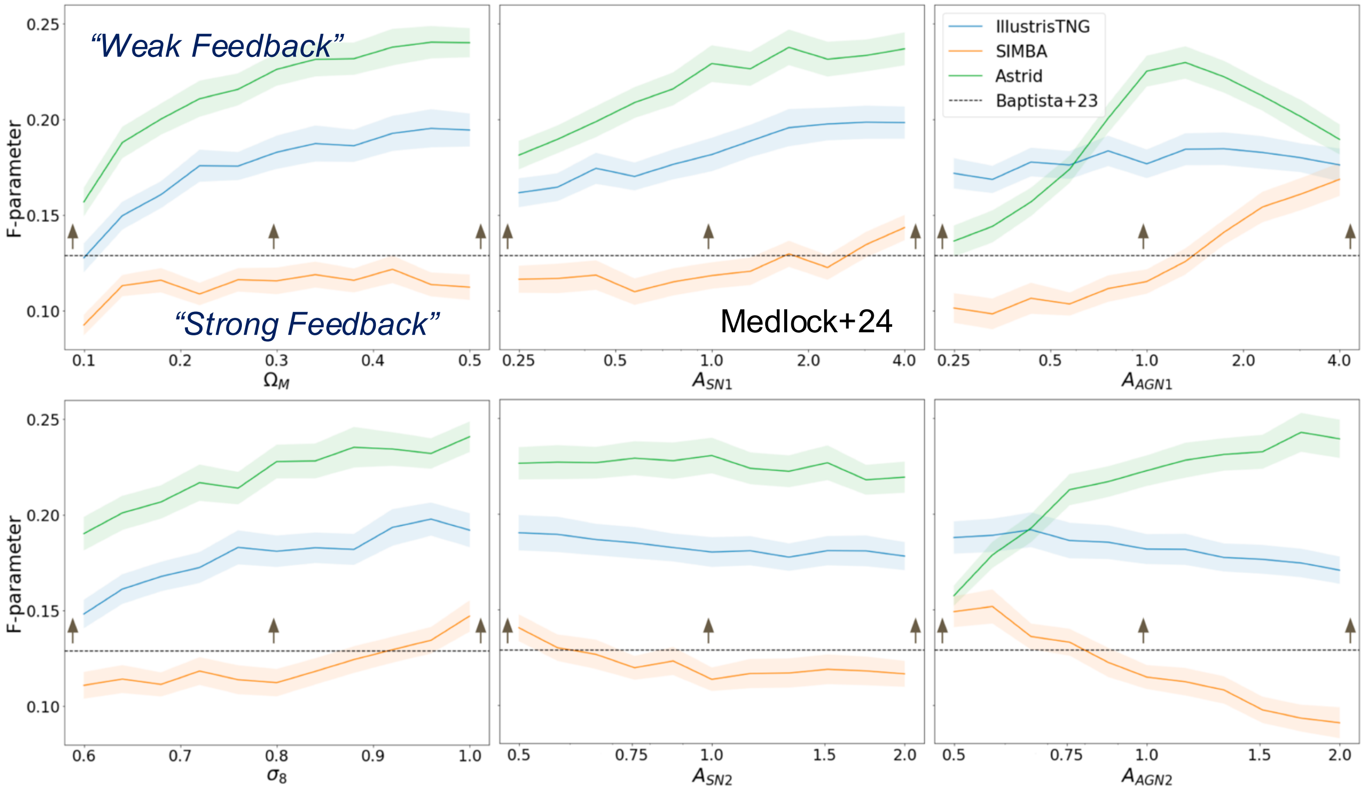


Centers of top 300 most massive halos marked with red dots. From right to left, we observe increasing uniformity and more “baryon spreading” in electron density (Medlock et al. 2024)

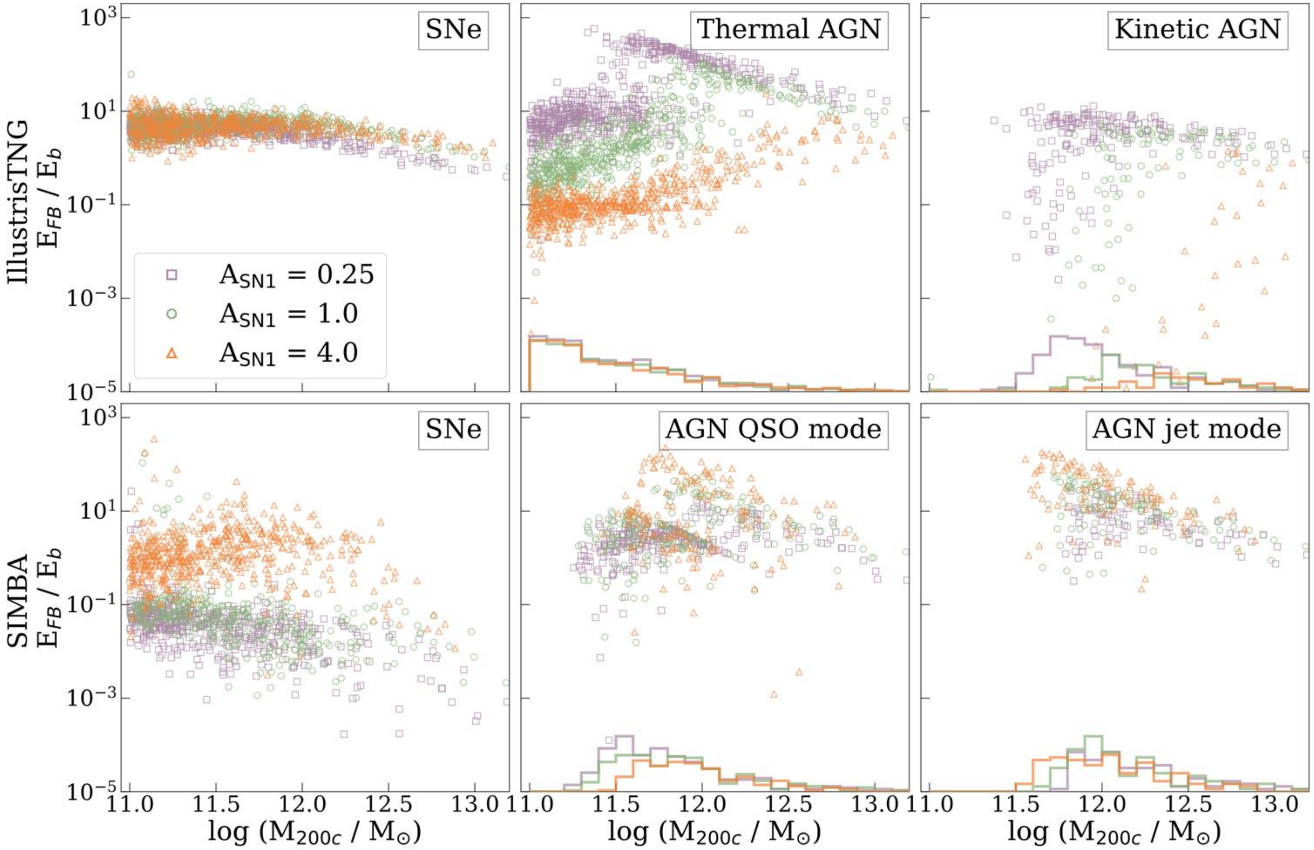
Measuring F-parameter with CAMELS

F measurements for the 1P set for TNG, SIMBA, & Astrid

Observational lower limit at (99.7% confidence) from 78 FRBs (21 with redshifts) (Baptista+23)



Quantifying Feedback Energetics in CAMELS



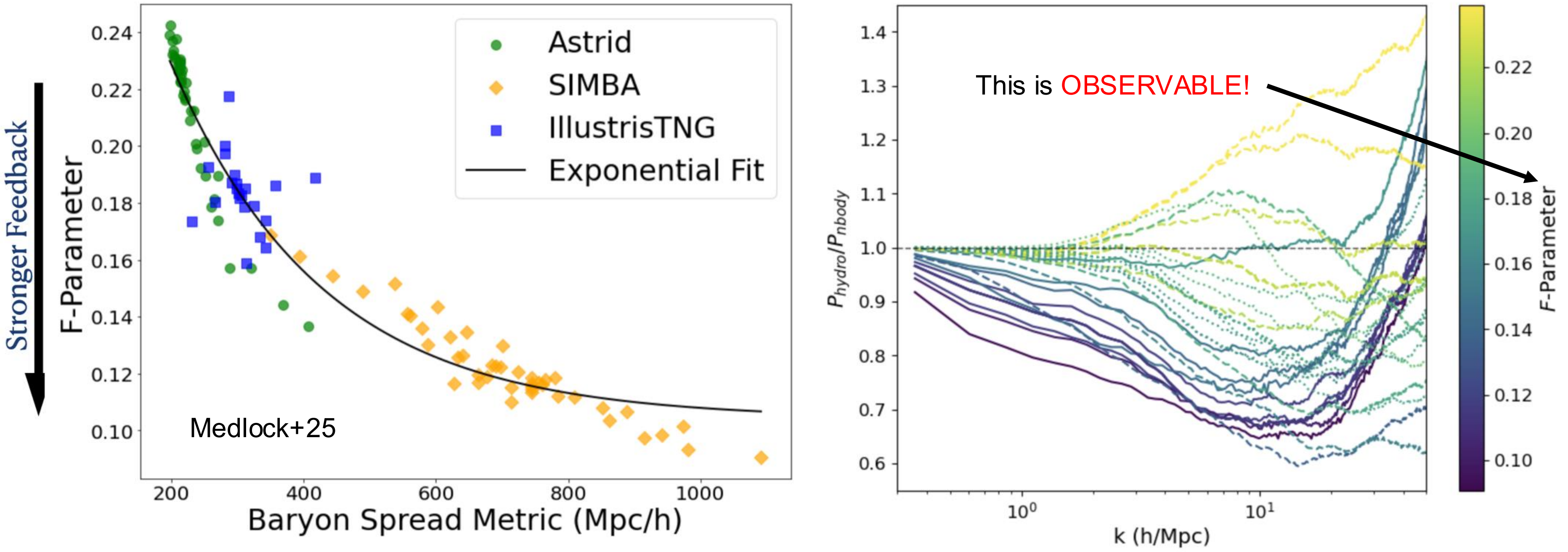
Coupling between SN and AGN feedback

In TNG, increasing ASN1 suppresses BH growth and total feedback energy.

TNG has more cumulative feedback, but SIMBA is more efficient in pushing baryons to greater distances.

Medlock & Neufeld et al. 2024

FRB-based Baryonic Effect Correction Model



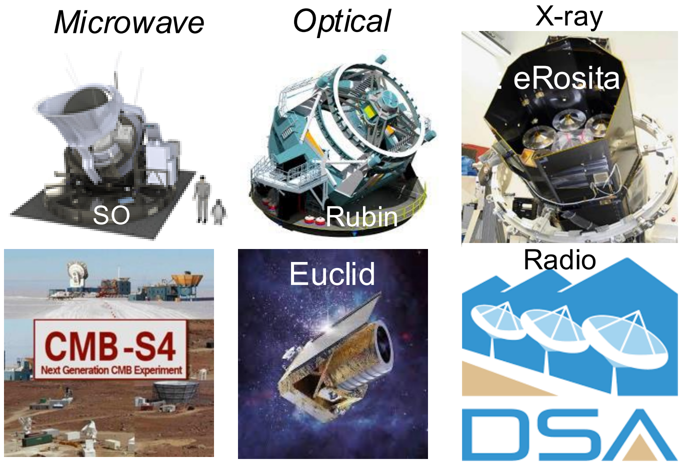
FRB is a powerful probe of the baryonic effects on the matter power spectrum.

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

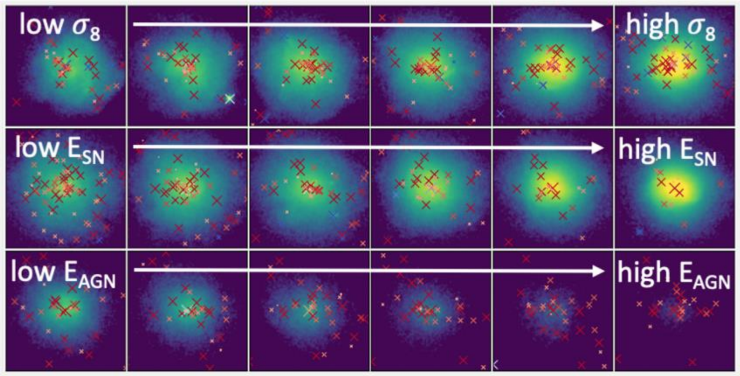
A similar relation holds for the enclosed baryon fraction – interesting to explore with SZ & X-ray surveys

See also Sharma+25 for the limitation of the F-parameter

Redefining Cosmic Exploration with CAMELS in the Era of Multi-λ surveys



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-λ maps for a range of cosmology & astrophysics

New Frontiers

1. Computational: *larger CAMELS boxes (clusters+cosmic web)*
2. Machine Learning: *interpretable & explainable AI/ML for big data from both sims. & obs.*
3. Modeling: ***forward-modeling multi-λ surveys** with CAMELS*
4. Low-noise + High-resolution: CGM & baryonic effects