Title: Review Talk

Speakers: Daisuke Nagai

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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Halo-Gas Connection for Precision Cosmology

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Cosmic Ecosystems
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July 29, 2025

Astrophysics as a Foundation to Precision Cosmology

Cosmological observables are now sensitive to baryonic physics

Interpreting LSS, lensing, and CMB data requires credible feedback models

Astrophysical uncertainties must be constrained to avoid biasing cosmology

The model should be made as simple as possible, but not simpler!

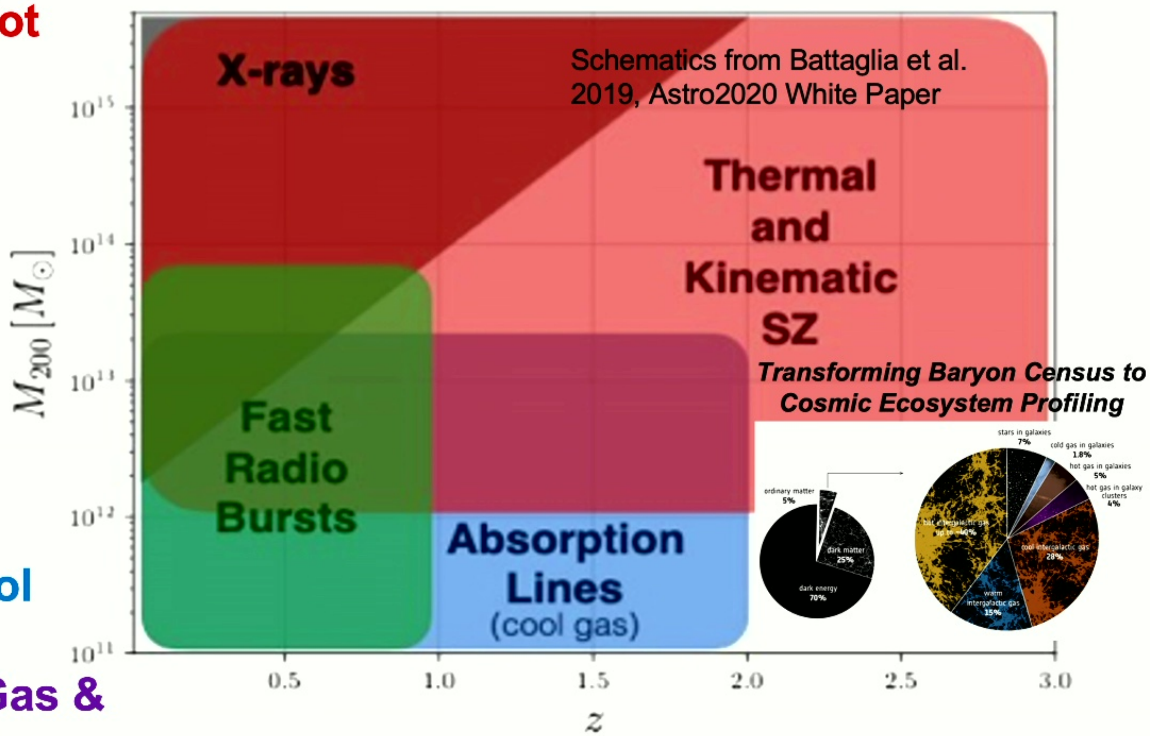
Halo-Gas Connection in the Era of Multi-λ Surveys

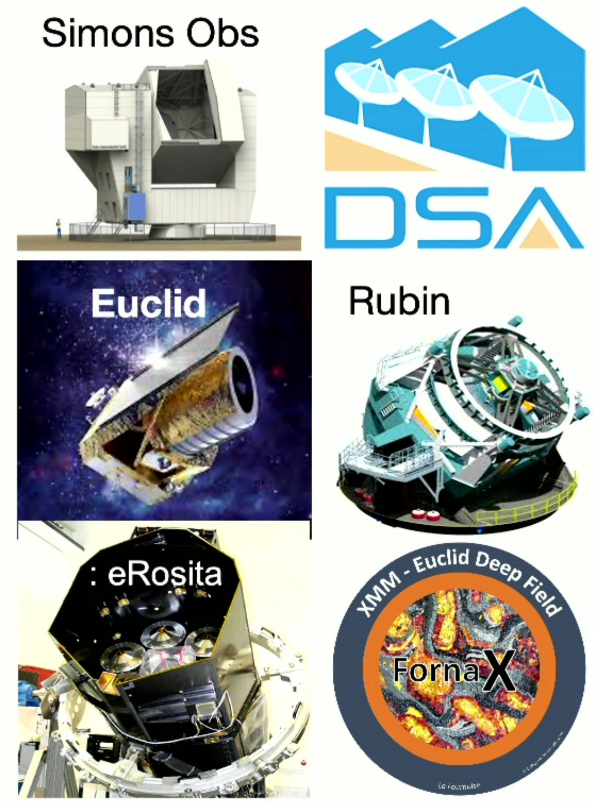
Hot

Cool

Cold Gas & Stars

Sensitivity to Gas Properties Near r_{200}

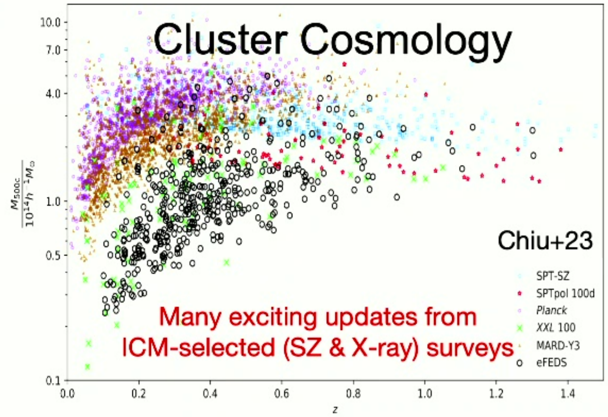


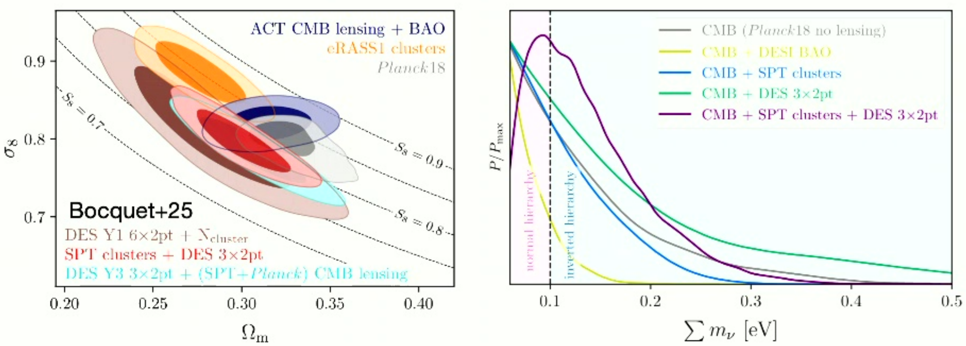


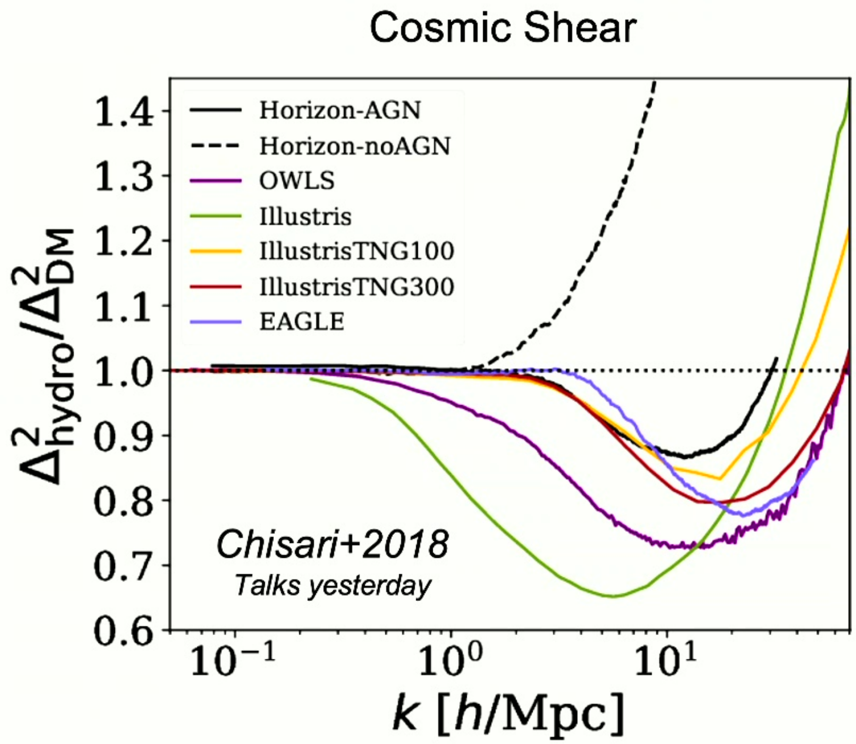
We are entering the golden age of multi-λ surveys!

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

S8 Tension in Cluster Cosmology vs. Cosmic Shear





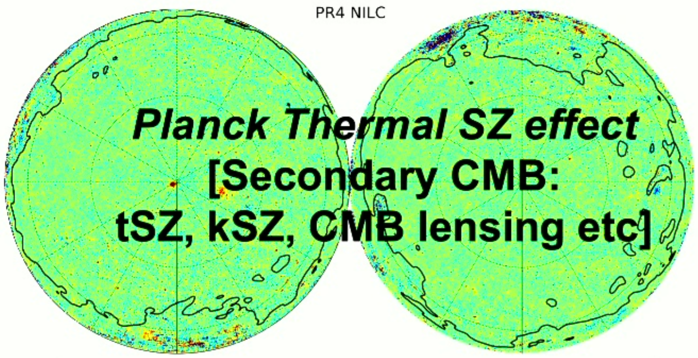


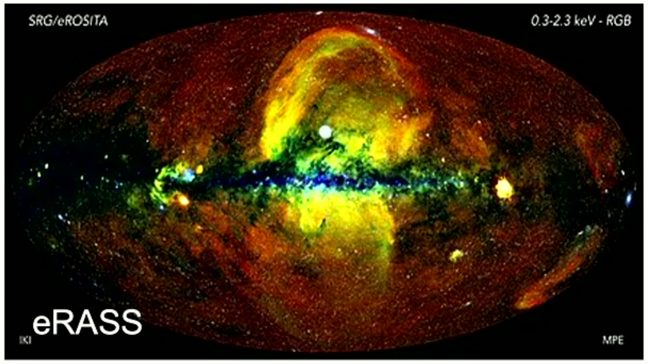
Clusters/Groups are powerful cosmological/astrophysical probes

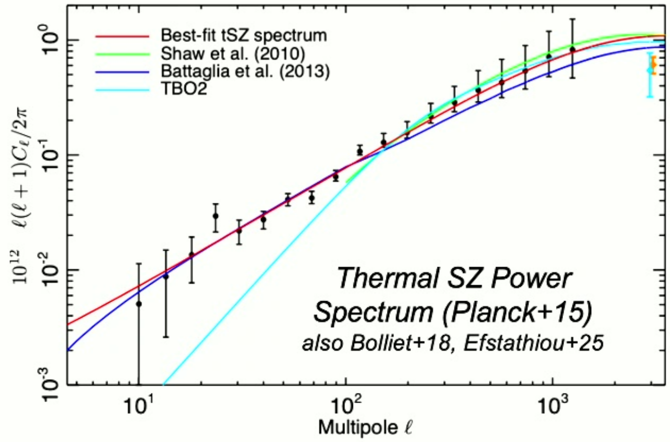
Systematic Floor: ICM/CGM astrophysics

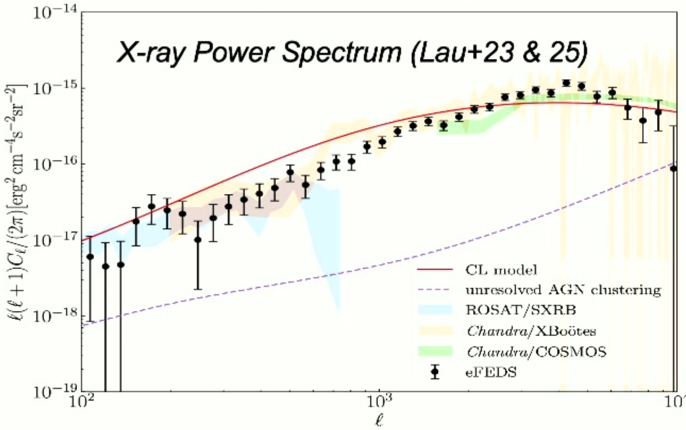
*including **the scatter in gas profiles & selection functions***

Strengthening Cluster Cosmology with X-ray & SZ Power Spectra







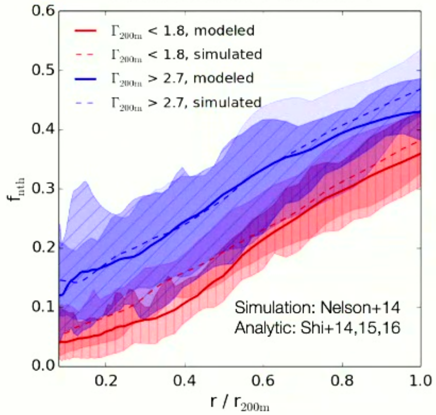


Complementary approach for constraining cosmology & astrophysics via field-level inference.
Higher-Order Statistics, Cross-Correlations, Simulation-Based Inference (SBI) etc.

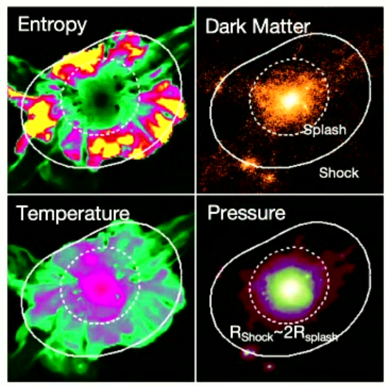
The Recipe of the Halo-Gas Model

Insights from Omega500 Hydro-Cosmo Simulations

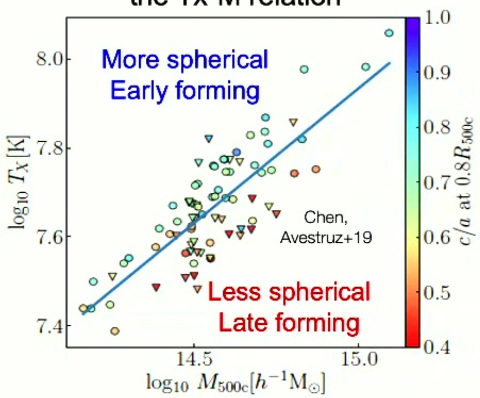
Nonthermal Pressure



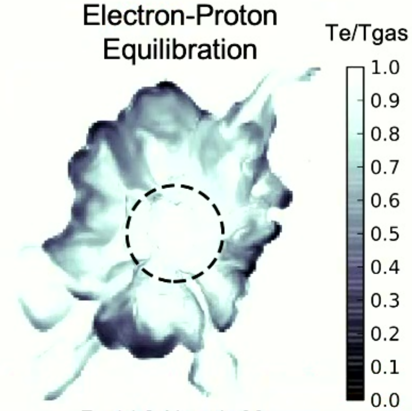
Shock vs. Splackback



Impact of Gas Shapes on the Tx-M relation



Electron-Proton Equilibration



Rudd & Nagai+09
also Avestruz+15

✦Cluster Outskirts

Gas Accretion & Non-equilibrium phenomena

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

Key Parameters
Mass & MAH

Walker et al. 2019 for a review

✦Cluster Cores

Heating, Cooling & Plasma physics

1. Baryonic feedback (AGN+SNe)
2. Dynamical Heating, Gas sloshing
3. Thermal Conduction, Magnetic Field, He sedimentation

Still very uncertain, but
core-excied Yx & Ysz can help!

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

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

Non-thermal pressure fraction profiles (Nelson+14; see also Lau+09,13, Shi+15, Green+20)

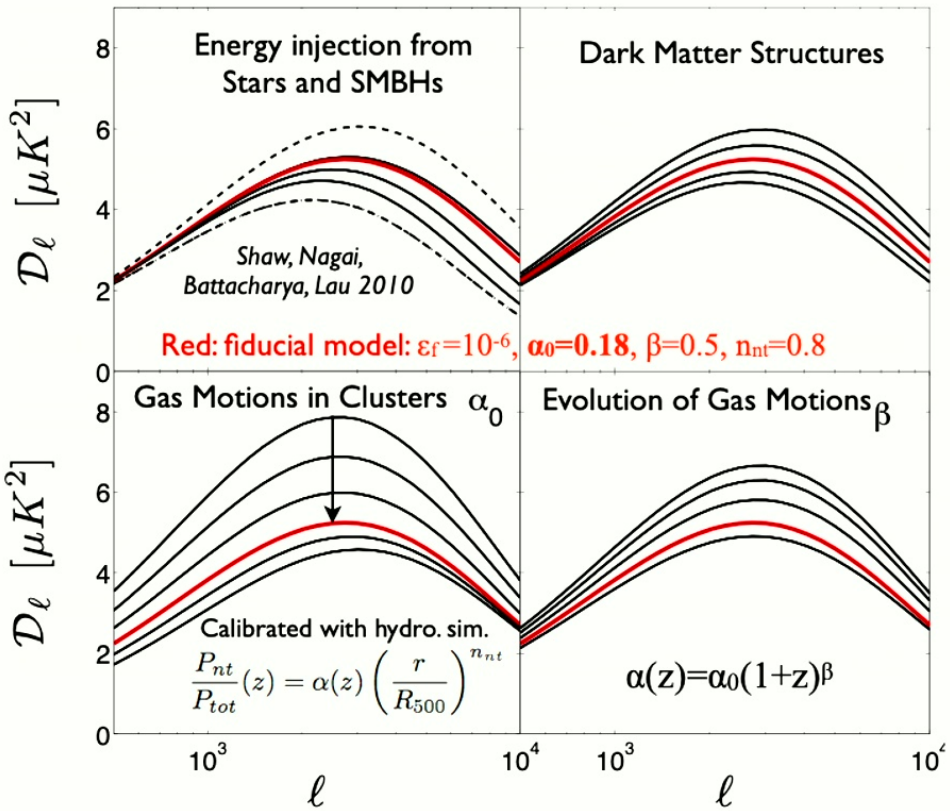
$$\frac{P_{\rm rand}}{P_{\rm total}}(r) = 1 - A \left\{ 1 + \exp\left[- \left(\frac{r/r_{200m}}{B} \right)^\gamma \right] \right\}$$

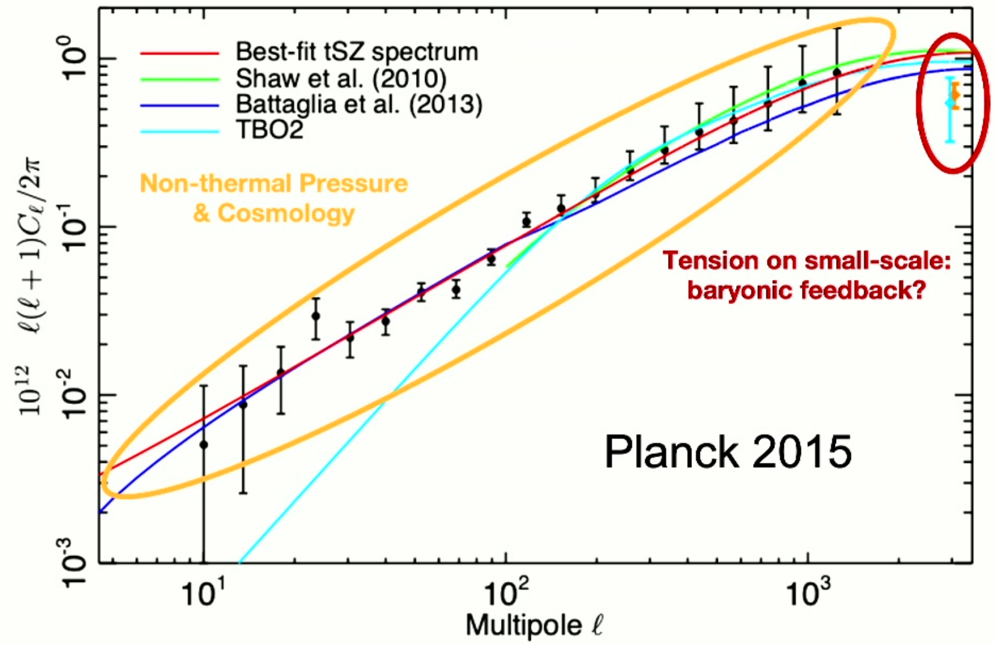
Outer pressure boundaries of gas accretion shock: $R_{sh} = 2 R_{sp}$

5 key astrophysics parameters

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

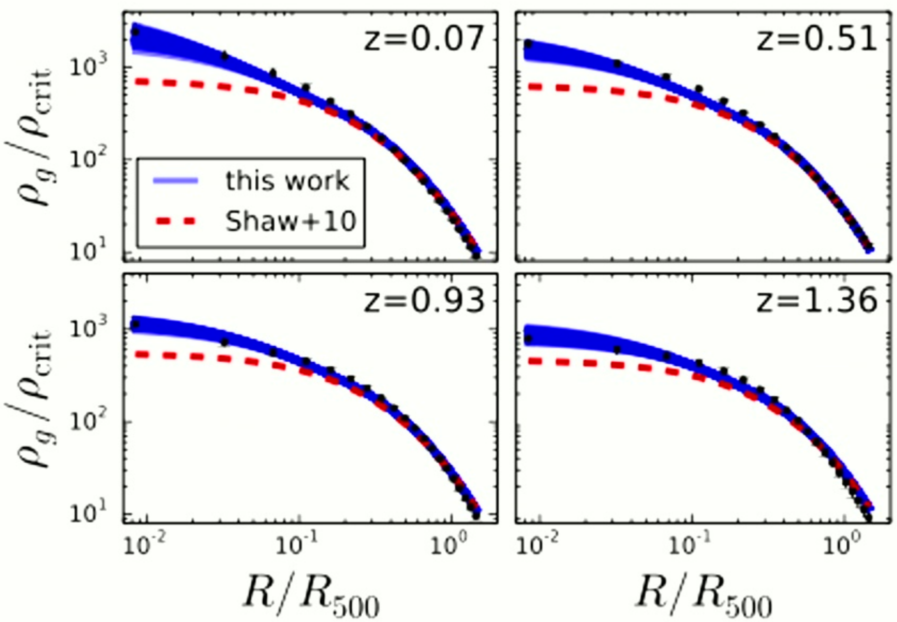




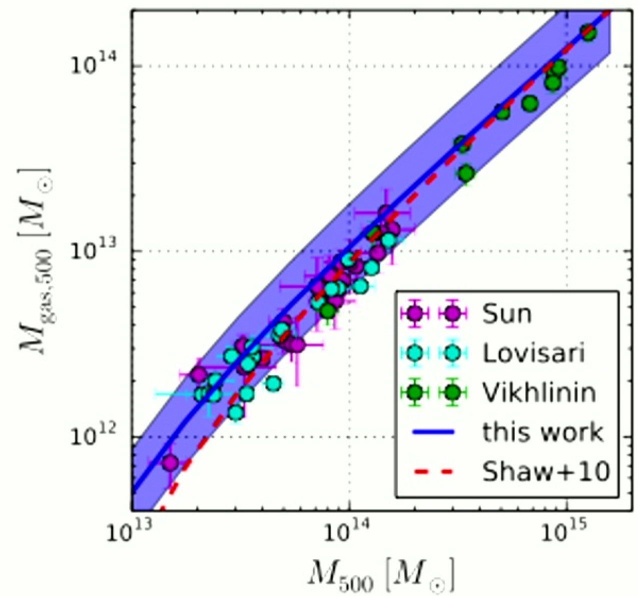
Planck measurements of the SZ power spectrum can constrain cluster astrophysics

Nonthermal Pressure at low-*l*
Baryonic feedback at high-*l*

Constraining BP Model with X-ray Clusters & Groups



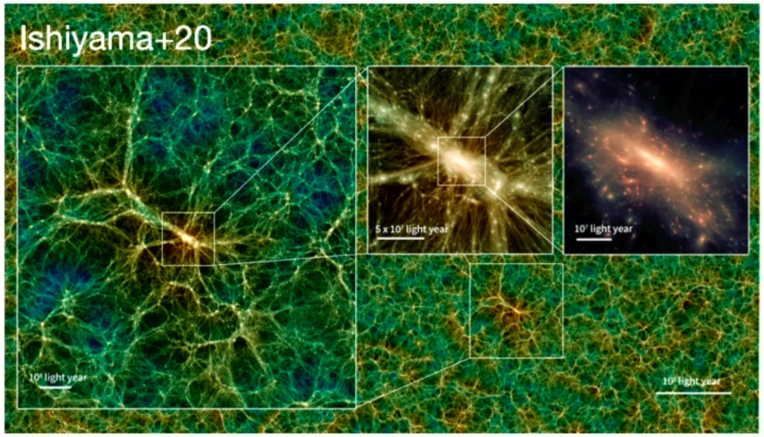
McDonald+13,17:
X-ray measurements of **gas density profiles**



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

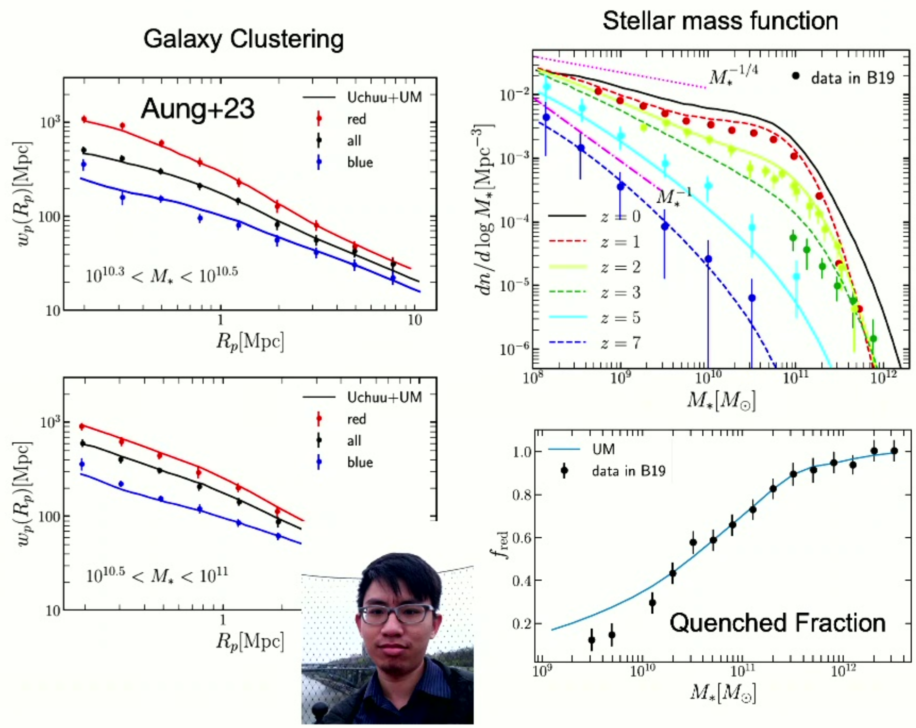
Baryon Pasting gas model describes X-ray observations (density profiles and gas mass) well
Flender, Nagai, McDonald+17

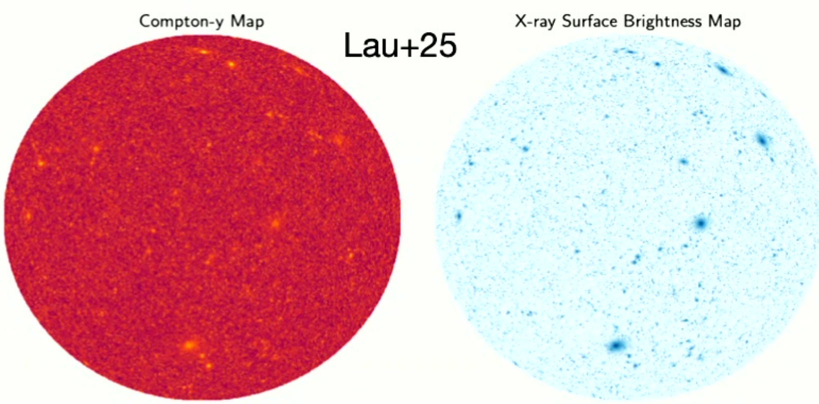
Baryon Pasted Uchuu Half-Sky Lightcone Maps



The Uchuu-universe machine data set: galaxies in and around clusters

Han Aung[1,2★] Daisuke Nagai[1] Anatoly Klypin[3] Peter Behroozi[4] Mohamed H. Abdullah[5,6] Tomoaki Ishiyama[5] Francisco Prada[7] Enrique Pérez[7] Javier López Cacheiro[8] and José Ruedas[7]

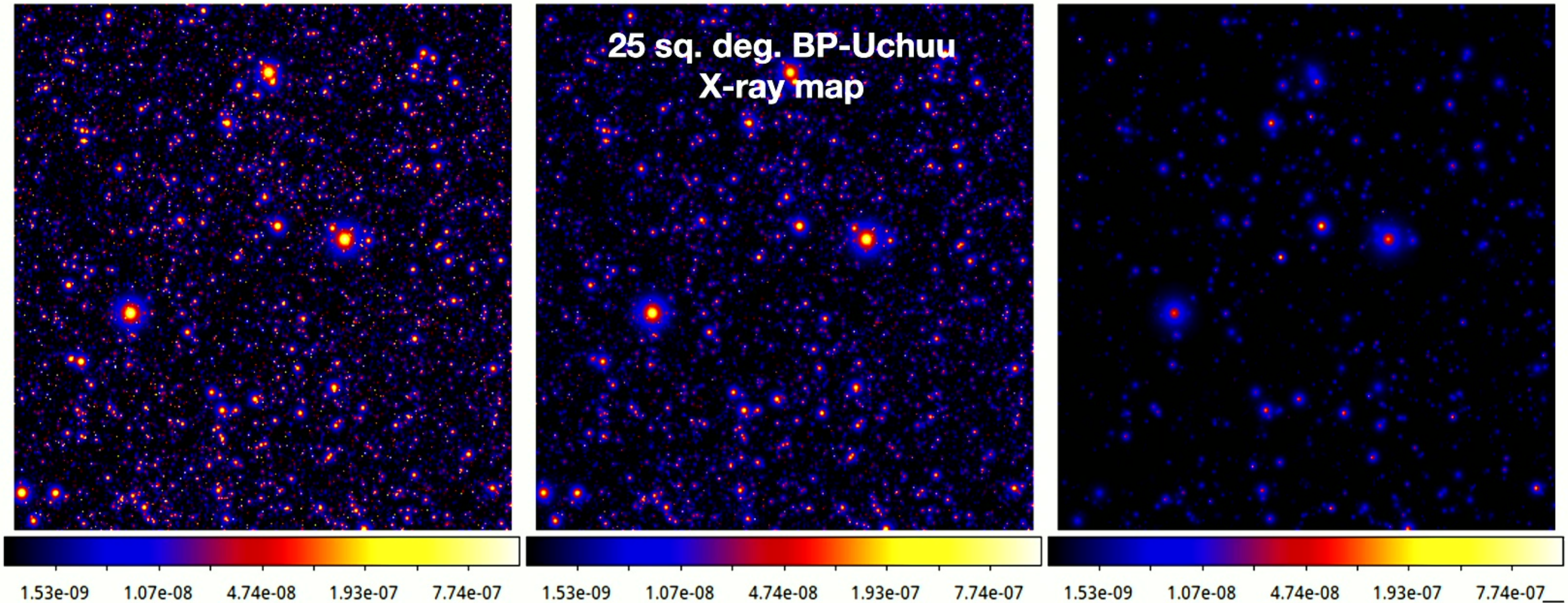




Multi-λ mock maps with half-sky lightcone from the *Uchuu N*-body simulation (2.1 Gpc) with 75 million halos with M_{500c} > 10^{13} Msun from z = [0,2]

Forward Modeling X-ray Selection Function

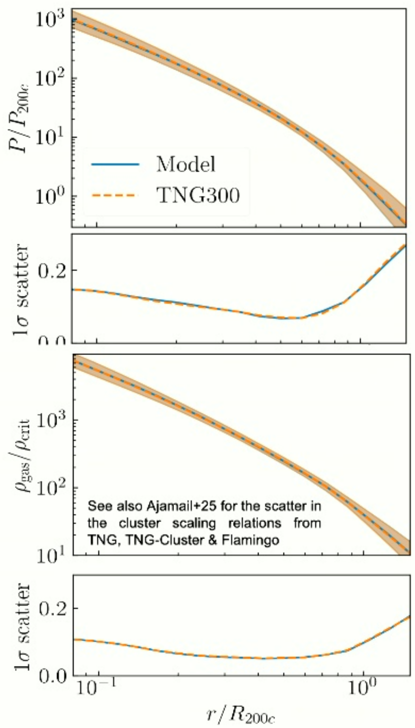
Increasing feedback



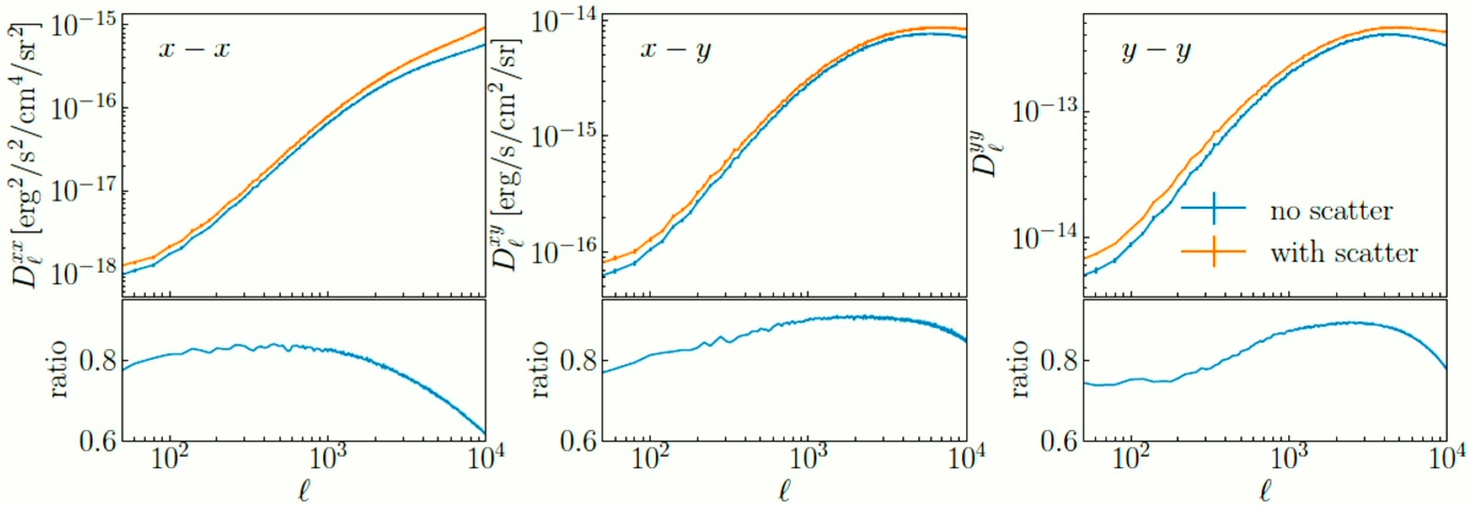
Forward model effects of feedback, morphology, and cosmic variance on X-ray flux measurements and cluster selection with **BP X-ray maps**.

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

Impact of Intrinsic Scatter in Gas Profiles on X-ray and SZ Power & Cross Spectra



Modeling **Intrinsic scatter** due to internal halo properties (pressure and gas density profiles) due to feedback, substructures, and merger histories using TNG300 simulations.

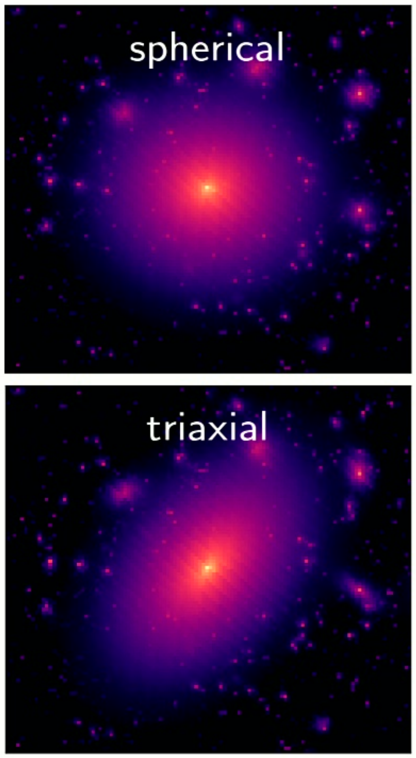


Intrinsic scatter in density and pressure profiles -> **more fluctuations** in X-ray SB and Compton-y from halo to halo-> **increases the fluctuation power across scales**.

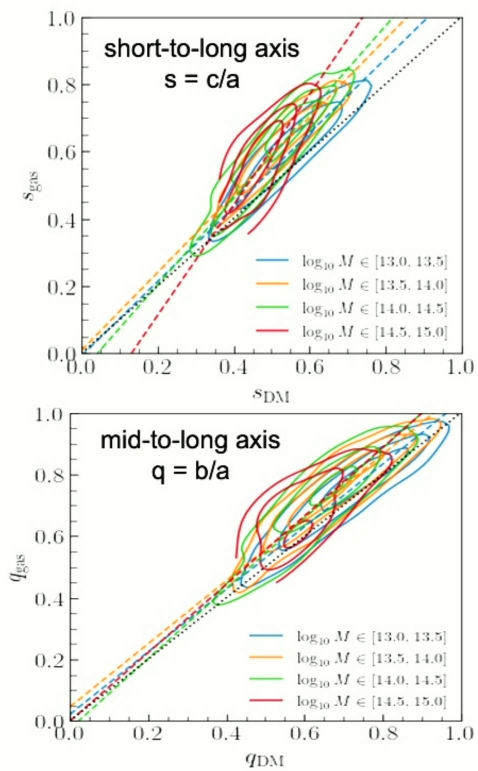
Scatter in ICM profiles increases angular power by 10%-40%.

Beyond Spherical Cows: Orientation Bias due to Triaxial Gas Halos

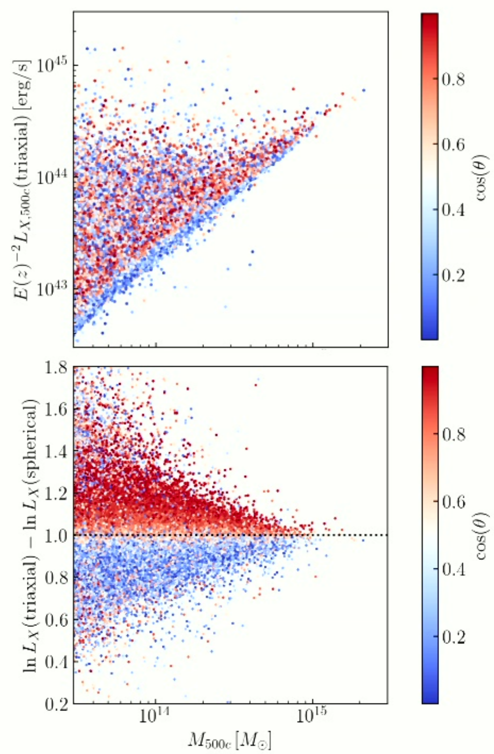
X-ray maps of the same halo triaxial vs spherical



Gas shape is more spherical than DM shape in clusters and groups in TNG300 simulations



Impact of the “extrinsic scatter” on the total scatter (intrinsic+extrinsic) of the Lx-M500 relation

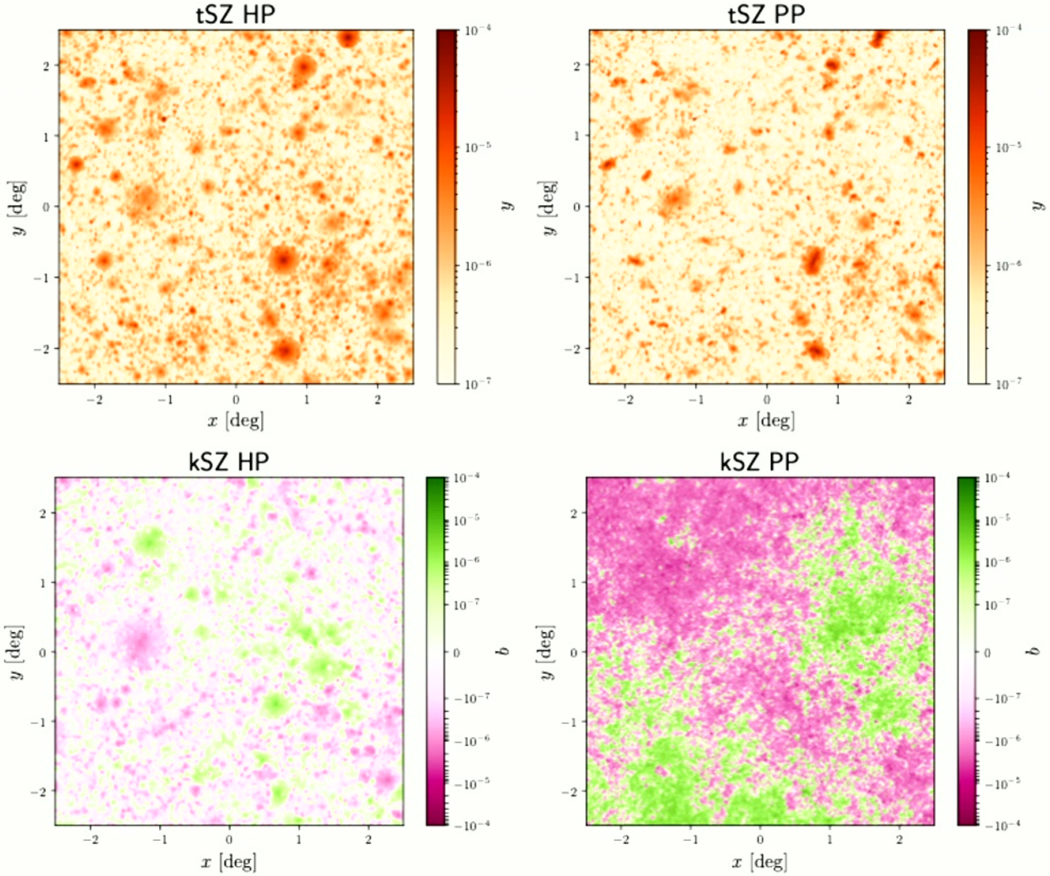


1σ Scatter in $\ln L_X$(map type)$-\ln L_X$(sph) for Halos $z < 0.5$ in Different Halo Mass Bins, With and Without the Core ($r < 0.2\,R_{500c}$) Excised

map type	$\log_{10}(M_{500c}/M_\odot)$ [13.5, 14.0]	[14.0, 14.5]	[14.5, 15.0]
Without core excision			
tri	0.09	0.08	0.08
sph+var	0.29	0.22	0.20
tri+var	0.31	0.24	0.22
With core excision			
tri	0.12	0.09	0.07
sph+var	0.22	0.15	0.11
tri+var	0.26	0.19	0.15

Extrinsic scatter due to ***projection effects and triaxiality*** accounts for **half** of the total scatter (intrinsic+extrinsic) of the core-excised X-ray luminosity-halo mass scaling relation.

Beyond Halo Model
Halo vs. Particle-based methods



Modeling the cosmic web (especially gaseous filaments) is crucial for kSZ & FRB!

Time / map

HP: 1.5 min
PP: 69 min

for 5x10^5 halos using 224 cores

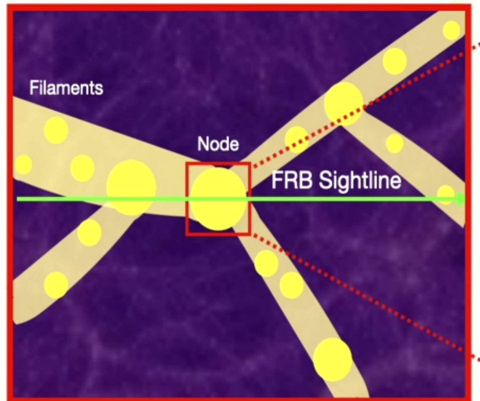
Next Step: Halo+Filament gas model

Halo + Filament Model

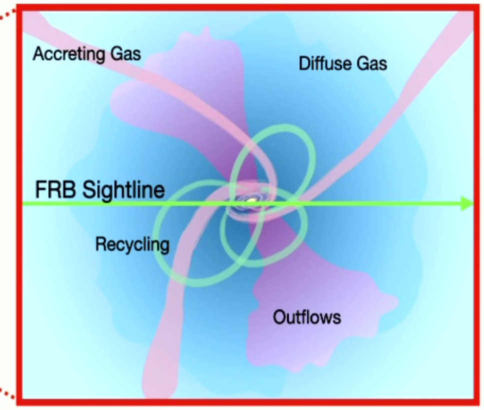
Goal: develop a halo+filament model for baryon pasting

- The Halo model has been remarkably successful for modeling large, multi-λ surveys.
- But, need a halo+filament model for kSZ & FRB!
- The key quantity for defining filaments is **the mass per unit length, Λ**.
- Analytical self-similar model of filaments reproduces the filament properties in TNG300!
- Caveats: rich structures of realistic filaments beyond a simple cylindrical model.

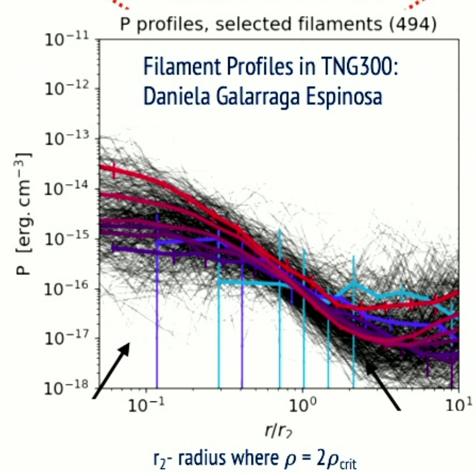
Next Steps: derive observational constraints on the halo+filament model using SZ, X-ray and FRB surveys

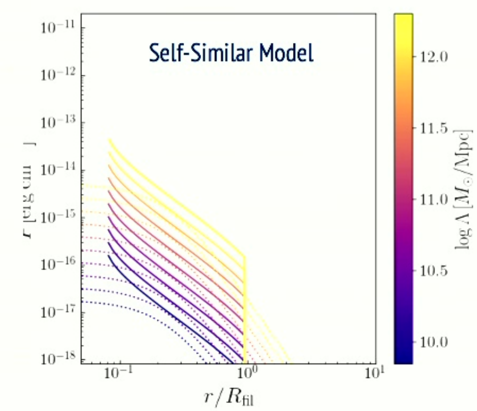


Cosmic Web Filaments



Circumgalactic Medium - Baryon Cycle





AGN Feeding & Feedback

Most cosmological simulations use (spherically symmetric) **Bondi Accretion**:

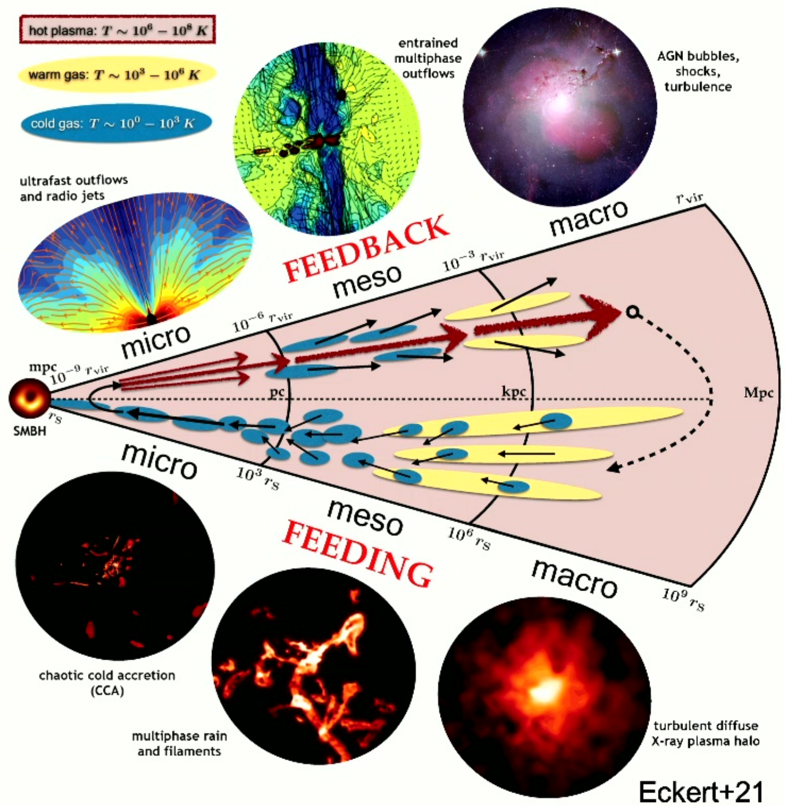
$$\dot{M}_{\rm BH} = \dot{M}_{\rm Bondi} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho}{c_s^2}$$

Allows to efficiently infer black hole growth rate for gas flows at a characteristic scale of the Bondi radius, typically 5-5000 pc from SMBHs.

Caveats & Challenges:

- **Spherical symmetry assumption does not necessarily hold** in a galactic context.
- Bondi accretion makes it **very difficult** to grow light seeds or reproduce bright AGN in dwarfs
- Modeling the multi-scale nature of SMBH evolution requires **(at least) 14 orders of magnitude!**

A schematic of the self-regulation loop necessary to fully link feeding and feedback processes over nine orders of magnitude in space (and time).

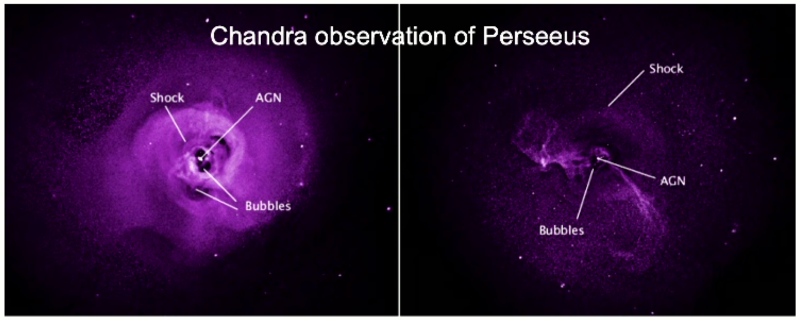


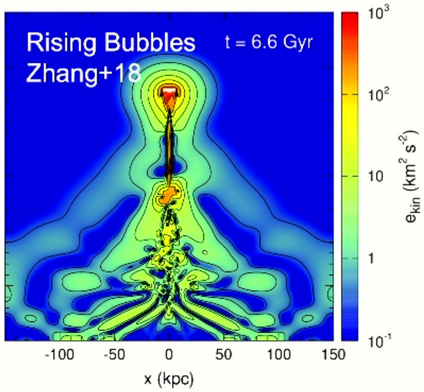
Eckert+21
Gaspari & Sadowski+19

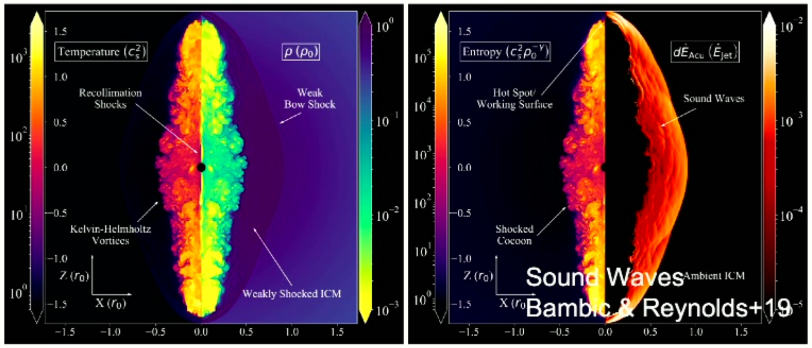
Modeling Mechanical Feedback Models in Idealized Simulations

Key: High-coupling efficiency of the generated energy with the gas

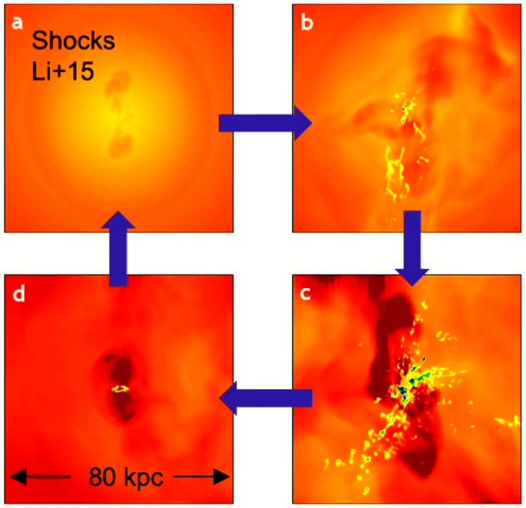
- Buoyantly Rising Bubbles
- Sound waves
- Strong shocks
- Winds, outflows of thermal plasma, and mixing
- Heating by Cosmic Rays + Streaming





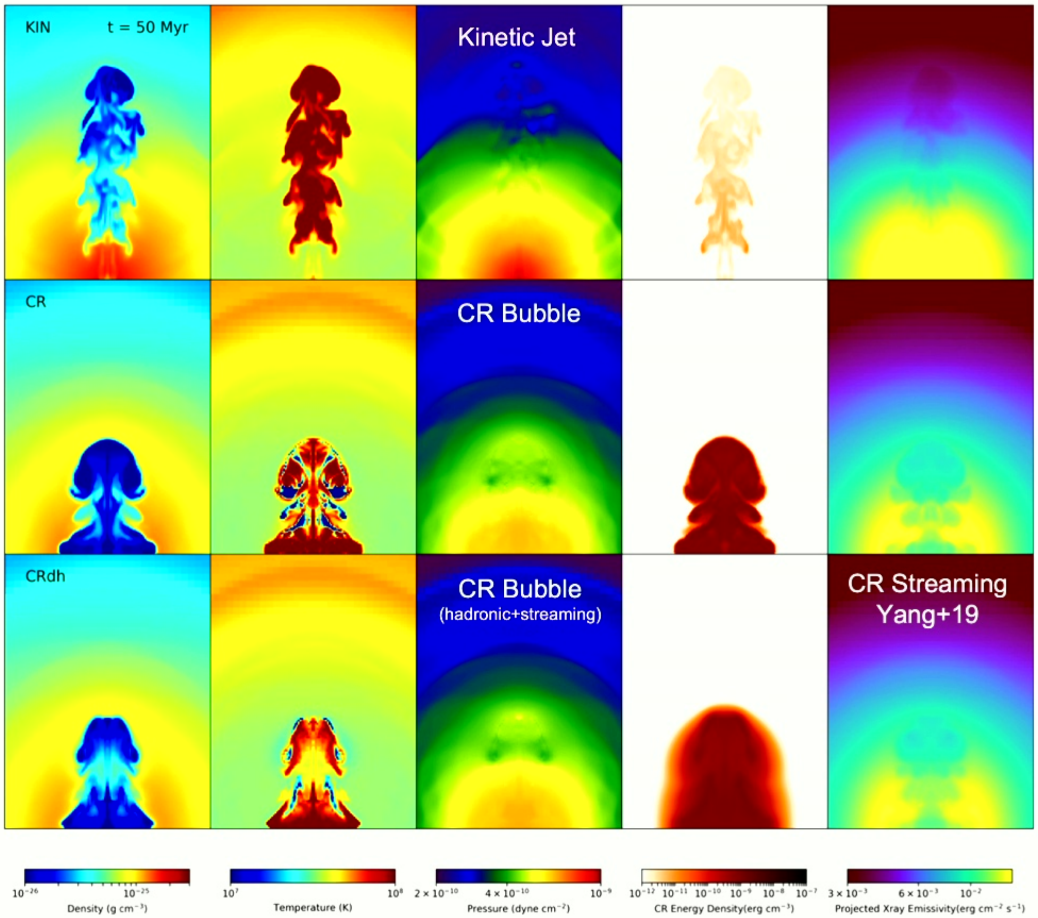


Borne & Yang+23 for a recent review



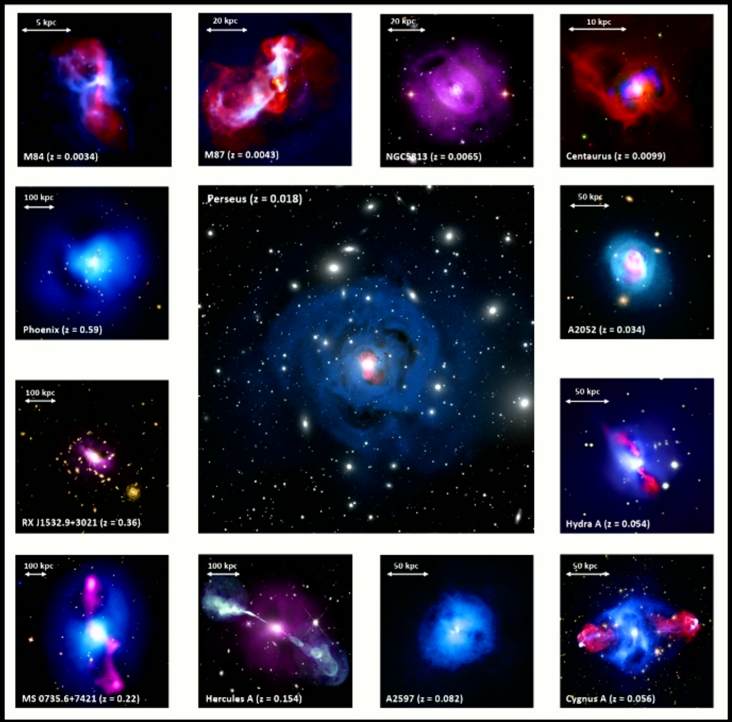
The Case of Cosmic Ray (CR) Bubbles + Streaming

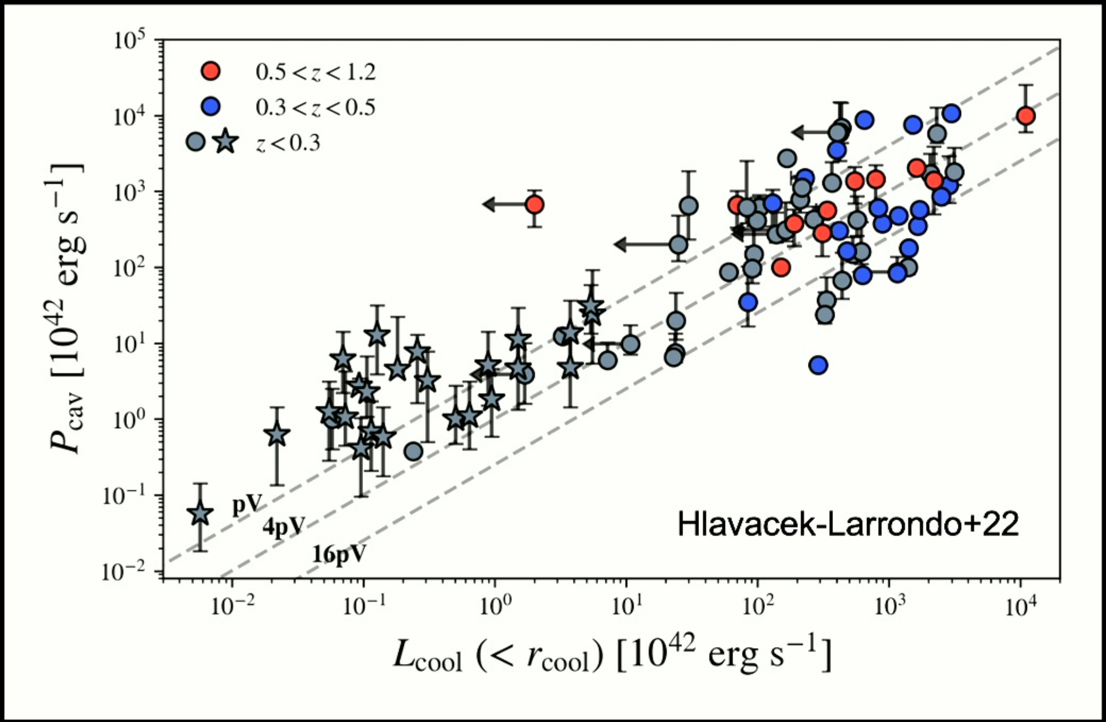
Self-regulation & Episodic AGN activity



- Kinetic-jet-inflated bubbles tend to be more elongated, whereas fatter bubbles observed in the Perseus cluster are more easily produced by CR-dominated jets.
- CR bubbles can drive a more significant expansion of the hot ICM due to buoyancy and larger cross-sections => suppress radiative cooling => longer time to feed SMBH => more episodic AGN activity.
- Heating by CR jets is less efficient => episodes of cold-gas formation during the bubble formation => this condensed multiphase gas triggers the AGN via Cold Caotic Accretion (CCA).
- CR streaming further enhances the formation of cool gas ($T<10^5$ Kelvin) and may play a significant role in self-regulation.

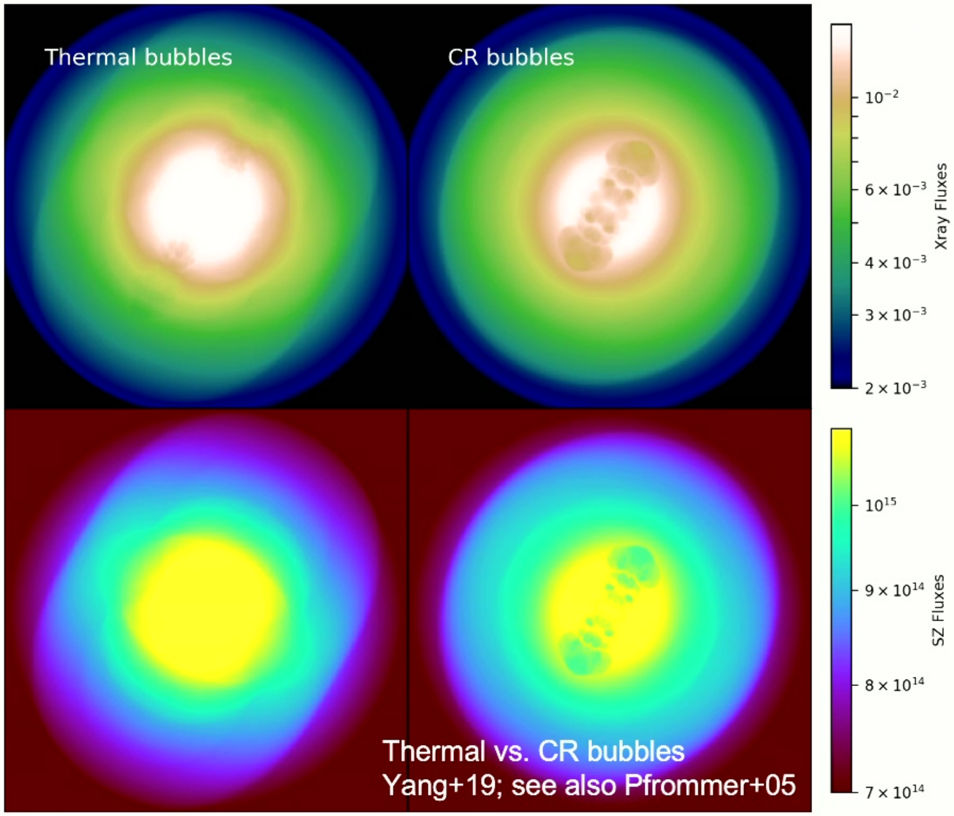
Observational Evidence of AGN Feedback in Clusters & Groups

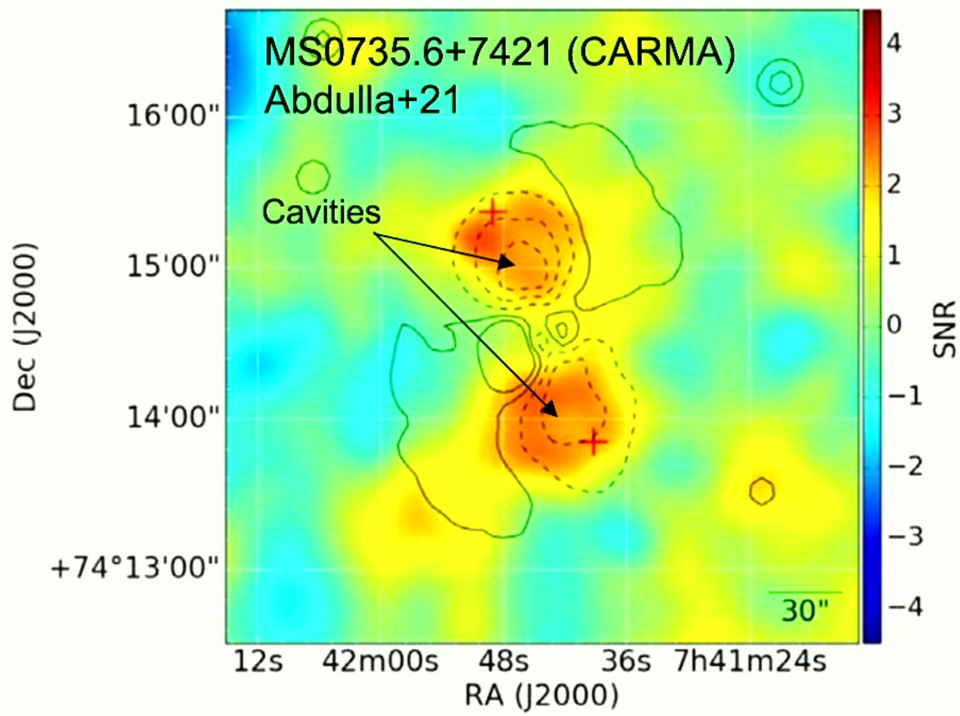




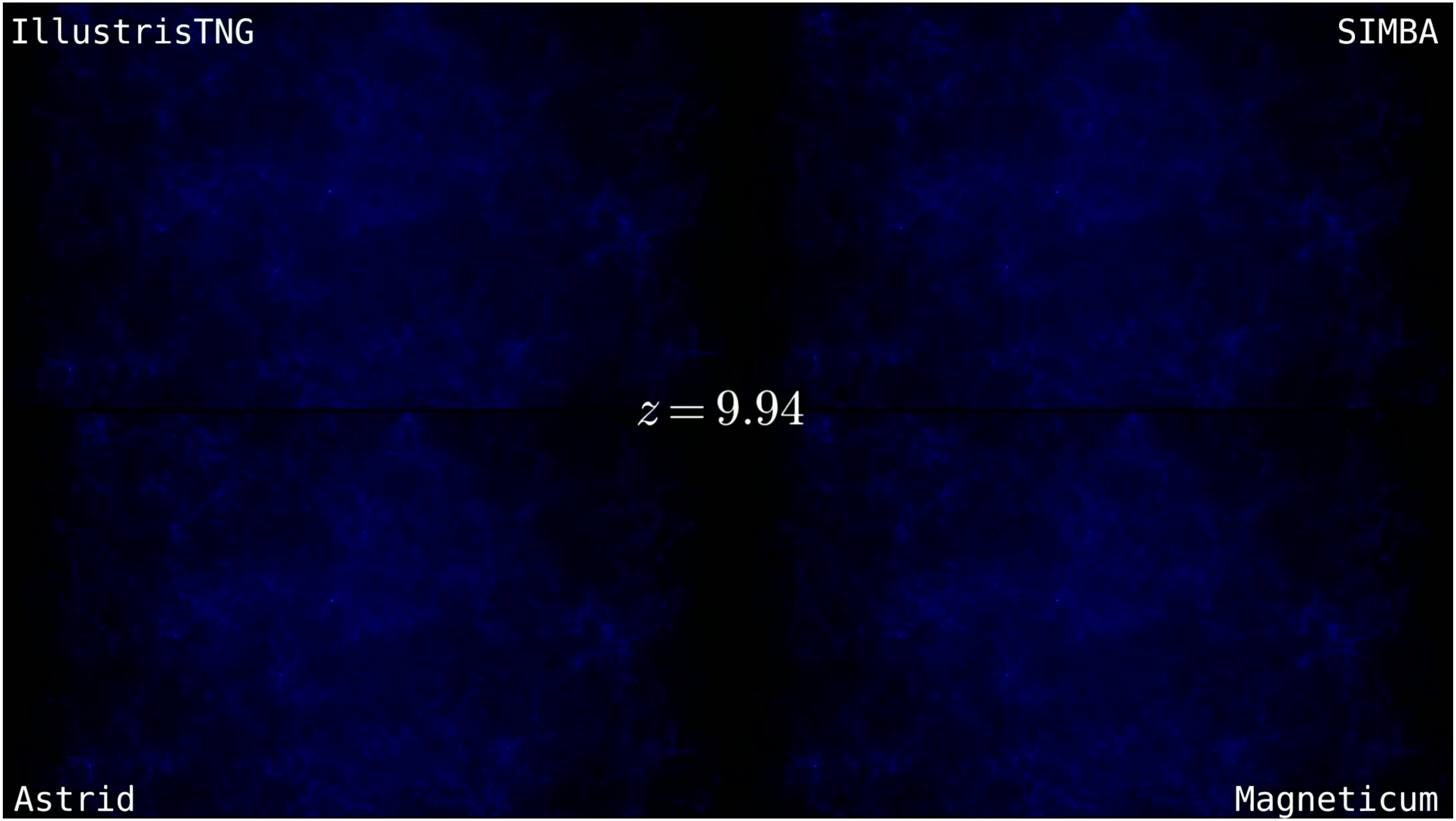
AGN feedback energy in Radio Bubbles is enough to offset cooling in cluster cores

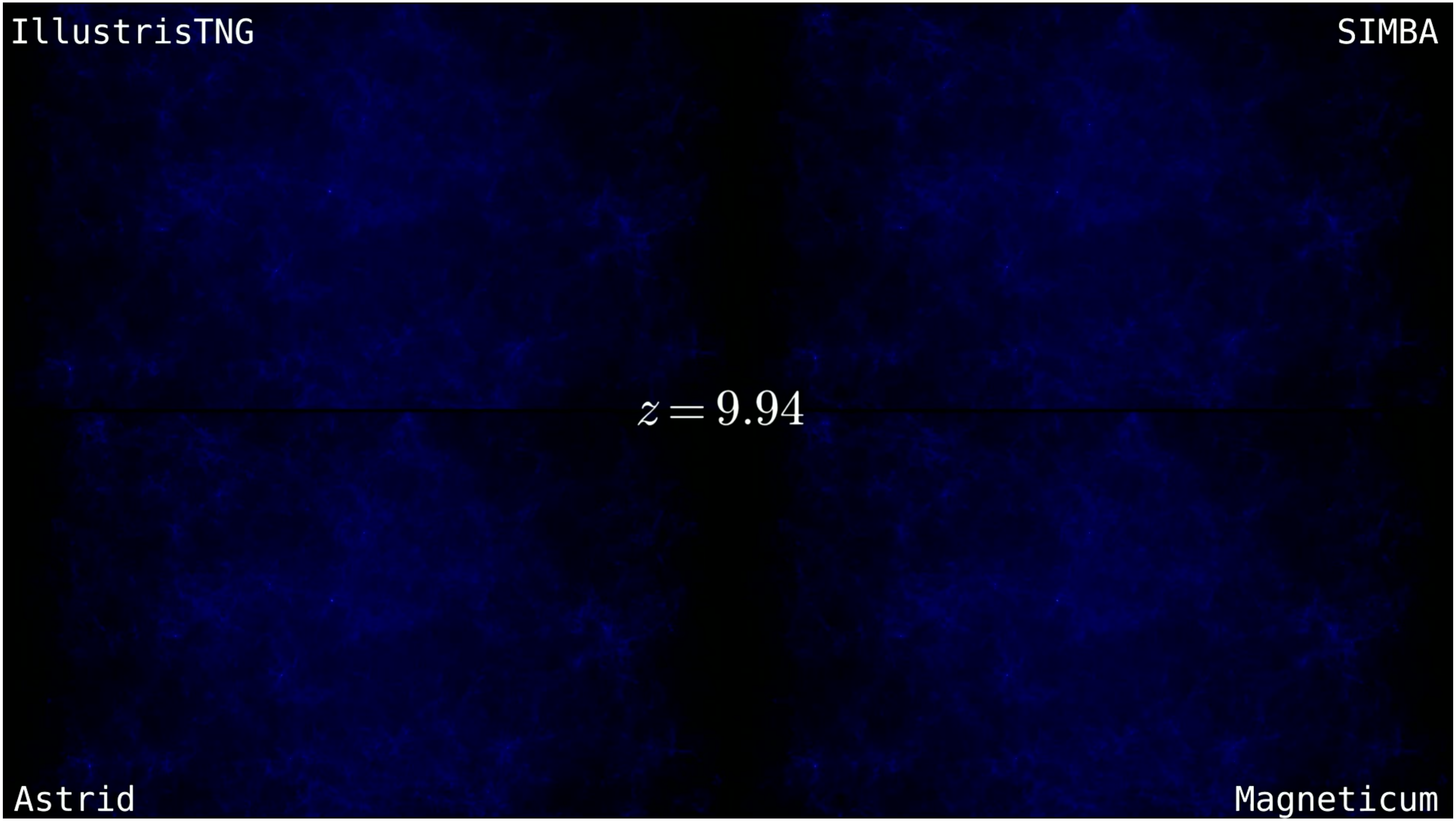
Constraining the Composition of Radio Bubbles with High-Resolution SZ Imaging





"Cavities (in dotted lines) have very little SZ-contributing material, suggesting that they are either supported by very diffuse thermal plasma with temperature in excess of hundreds of keV, or are not supported thermally."

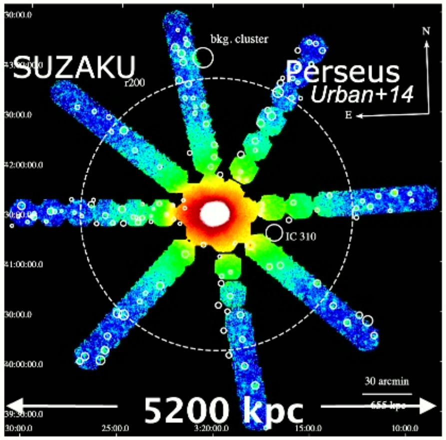

IllustrisTNG
SIMBA
$z = 9.94$
Astrid
Magneticum

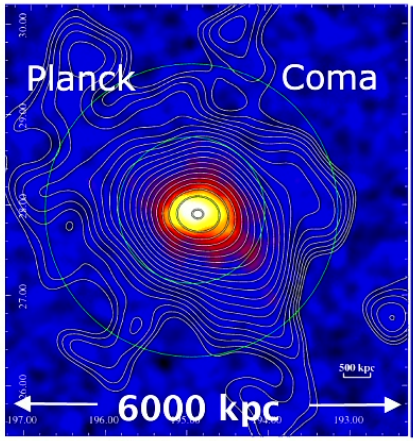

IllustrisTNG
SIMBA
$z = 9.94$
Astrid
Magneticum

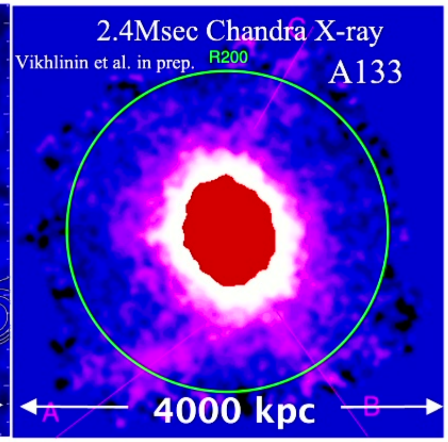
Circum-Galactic Medium (CGM)

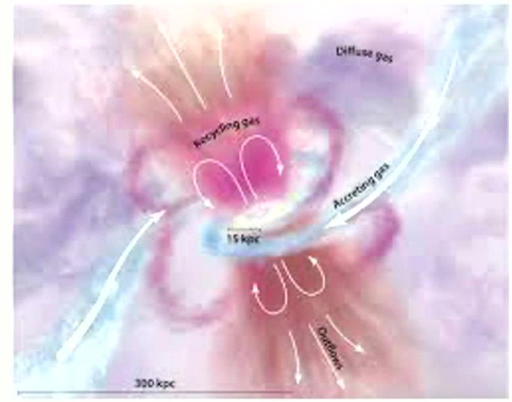
New Laboratory for Baryonic Feedback & Cosmological Tension

Galaxy Clusters

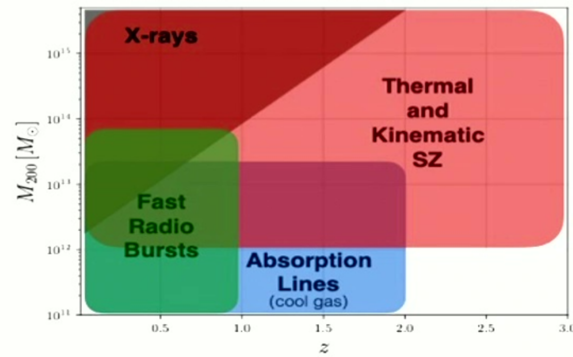




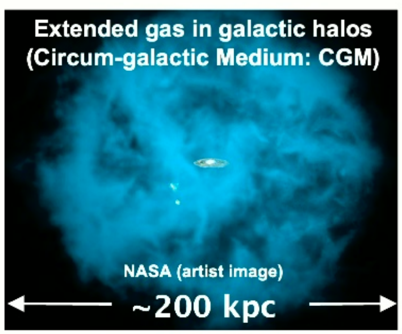


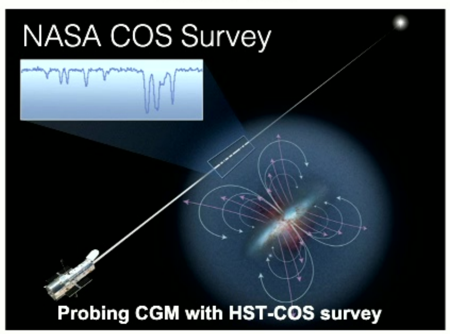


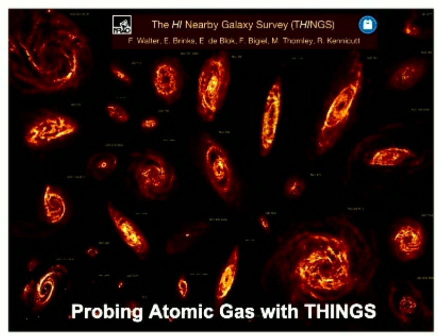
Sensitivity to Gas Properties Near r_{200}



Galaxies

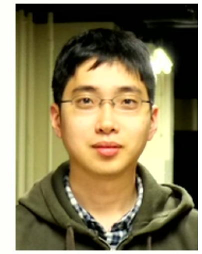


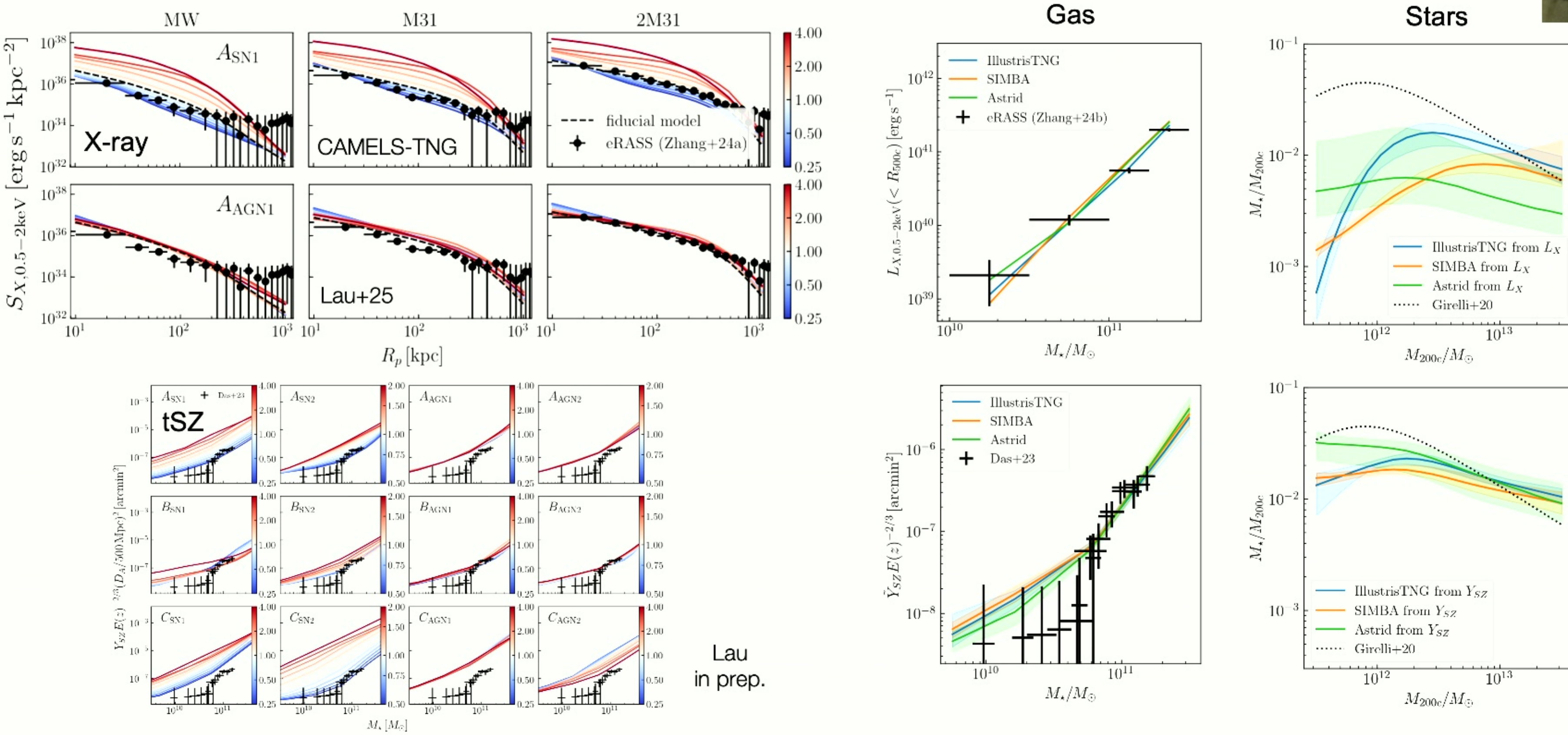




CGM as a laboratory for probing Baryonic Feedback & Cosmological Tension

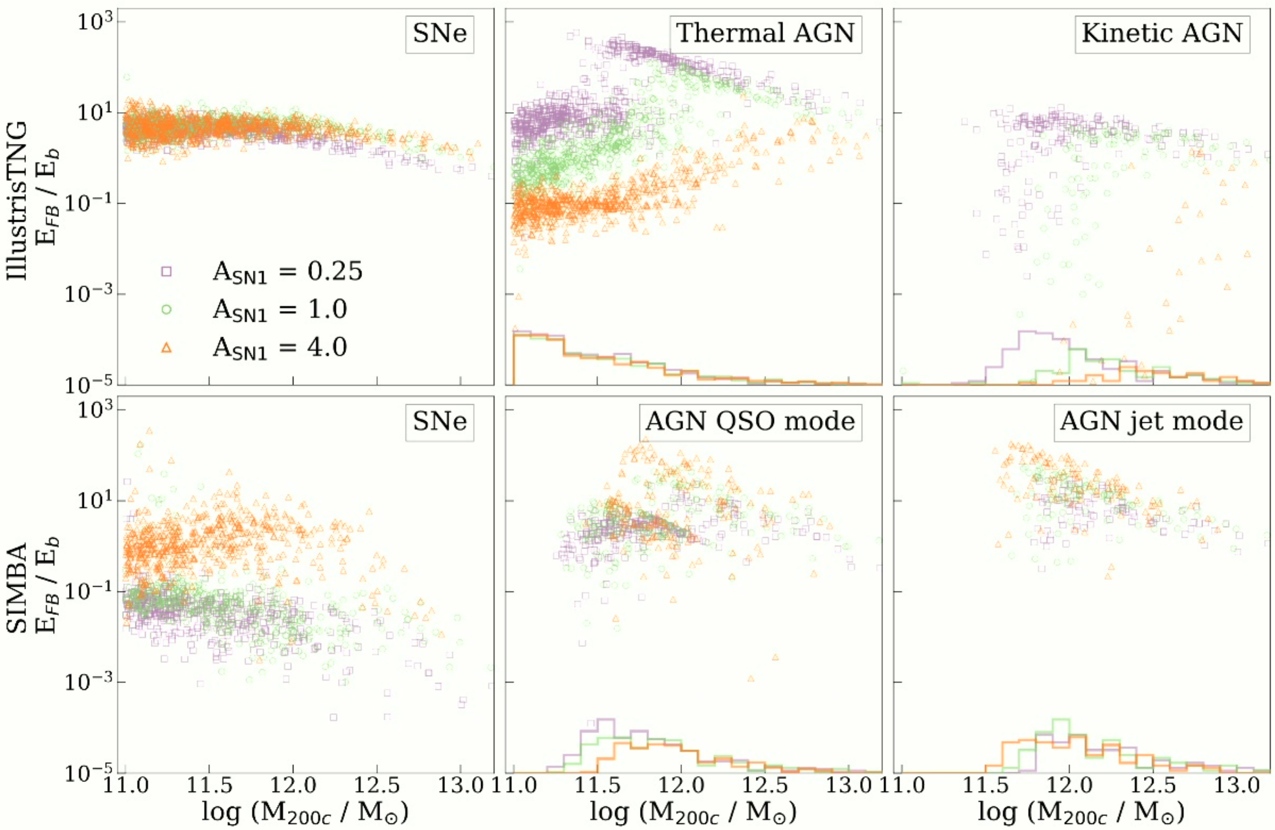
Constraining Baryonic Feedback with stacked eROSITA and tSZ observations





X-ray and tSZ observations provide a critical systematic check for constraining baryonic feedback in CGM

How SNe & AGN feedback work in CAMELS?



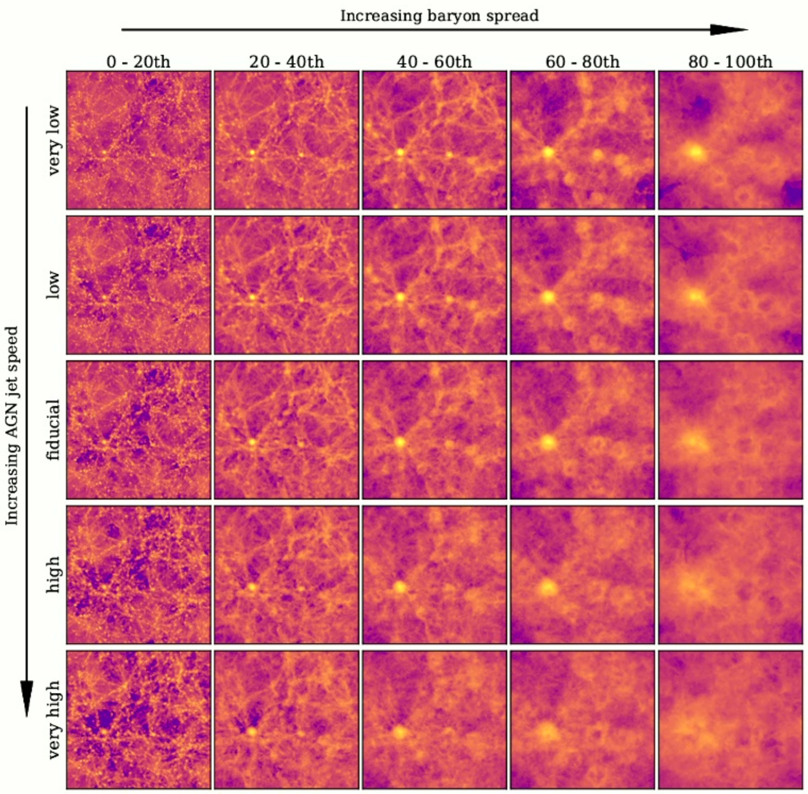
It's not just the amount of SNe/AGN energy, but how their energy couples to the gas.
AGN and SNe feedback are also highly degenerate and model-dependent.

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

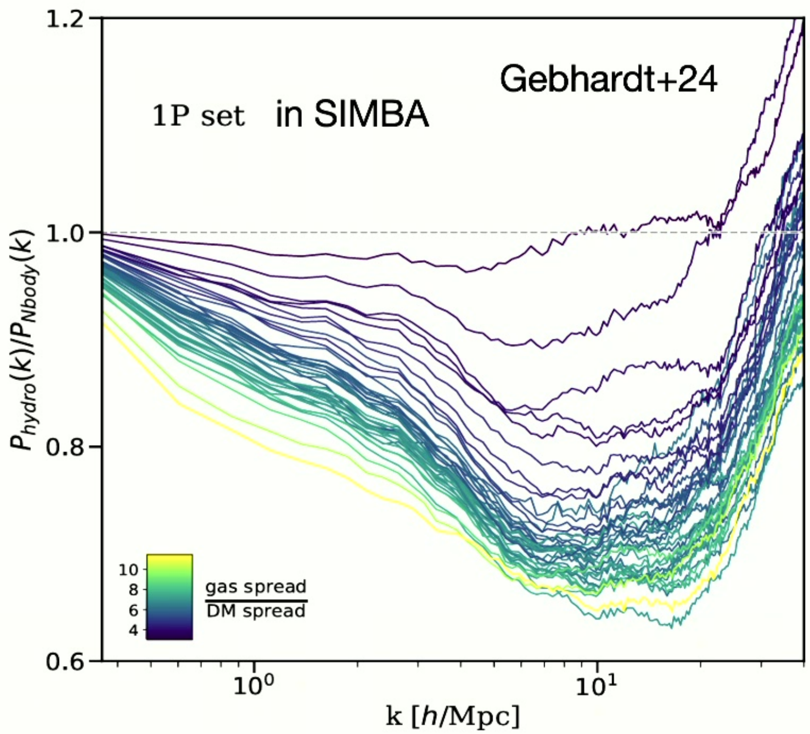
TNG has more cumulative feedback, but SIMBA is more efficient in pushing baryons to a further distance.

Medlock & Neufeld+24
(arXiv: 2410.16361)

Impact of "Baryon Spread" on Matter Clustering in CAMELS



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

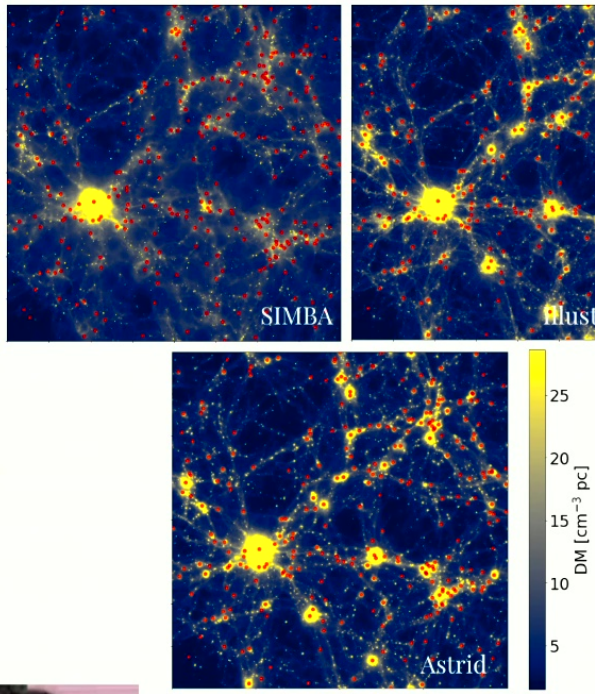


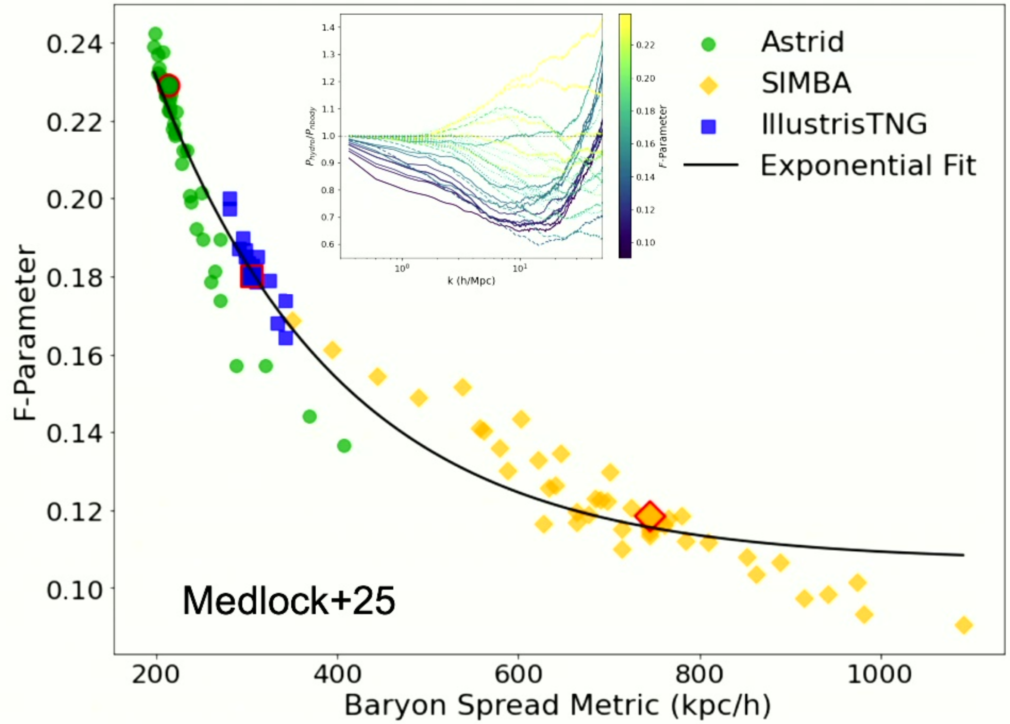
The "baryon spread" metric is a good predictor of the global impact of feedback on the large-scale distribution of matter.

But, the "baryon spread" is not observable..

FRB-based Baryonic Effect Correction Model

Medlock+24





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

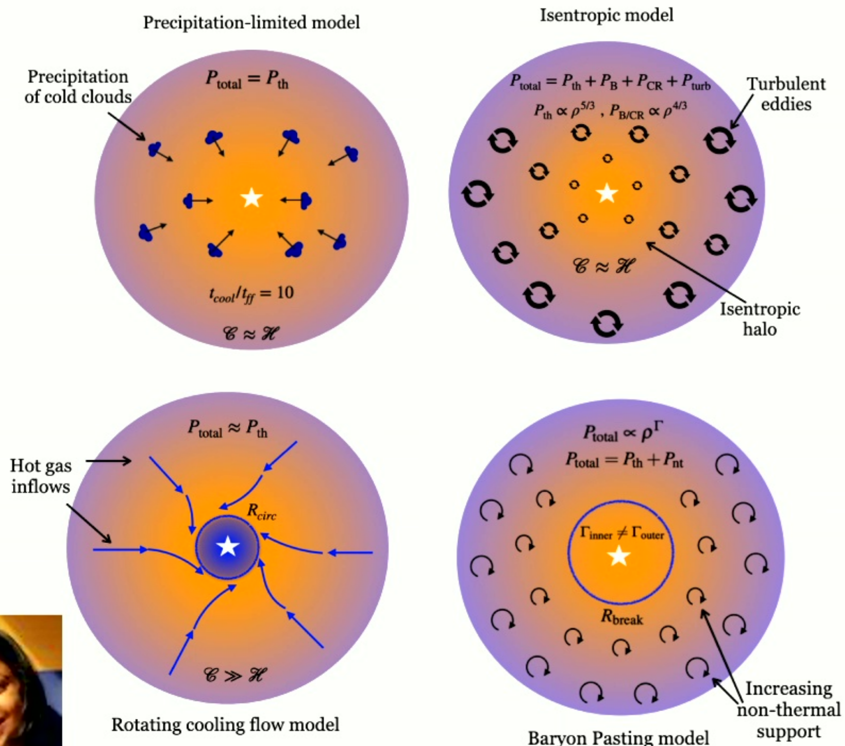
This universal relation is independent of the details of subgrid physics of galaxy formation!!

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

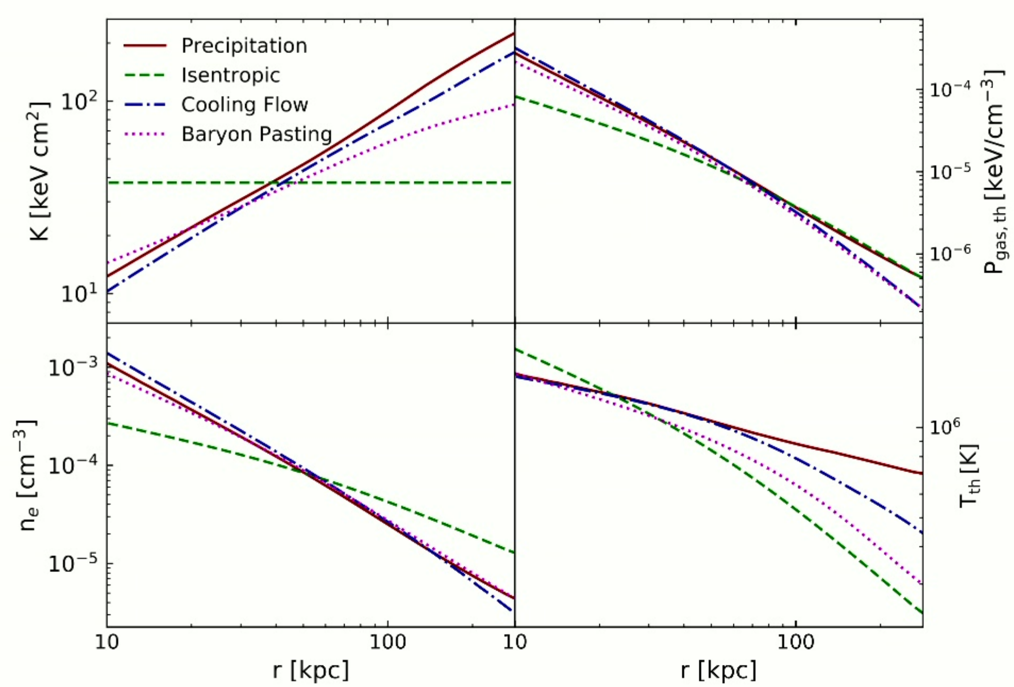
Stay tuned for FRB talks on Friday

Challenges for SBI: Interpretablity & Explainability

CGM Model Comparison Project



Thermodynamic Profiles of Warm-Hot CGM in Milky Way-like Galaxies

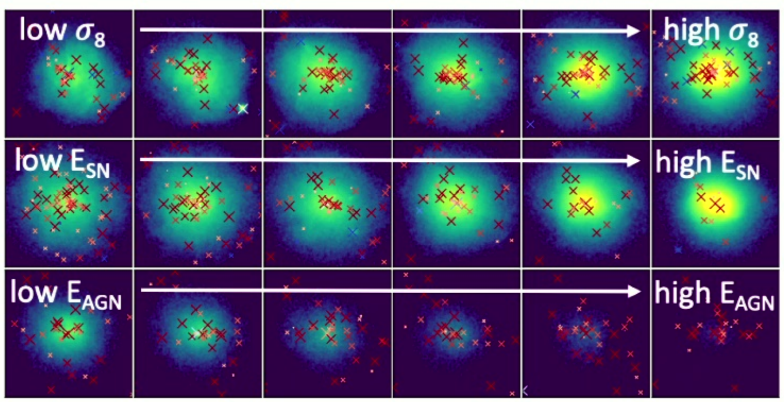


Singh, Lau, Faerman, Stern, Nagai 2024

Talks by Mark Voit, Jonathan Stern, Claude-André Faucher-Giguére & Yakov Faerman

Harnessing Diffuse Gas in Cosmic Ecosystems for Precision Cosmology & Galaxy Astrophysics

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)

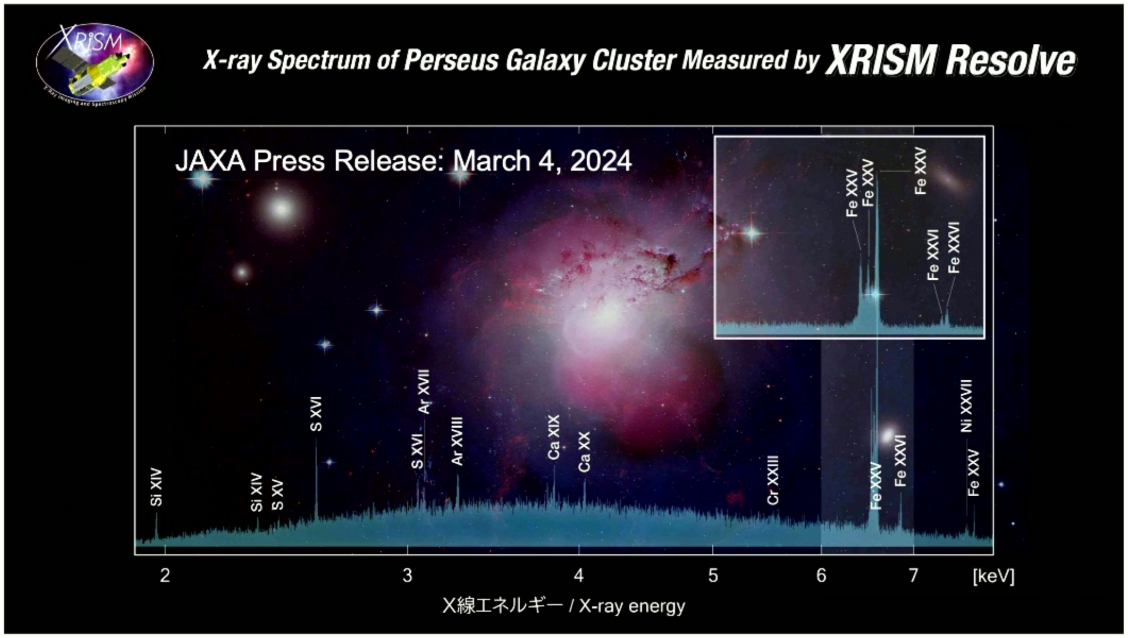
Challenges

- Precision Modeling of **Diffuse Gas in Cosmic Ecosystems (DGCE)** and the **Halo-Gas-Galaxy Connection**
- Large Multi-λ maps for a range of cosmology & astrophysics

Future Prospects

1. ***Larger CAMELS boxes*** *(clusters + cosmic web) for SBI*
2. ***Baryon Pasting*** *to elucidate the ICM/CGM astrophysics and inference from large multi-λ surveys*
3. ***Halo-Filament model*** for forward-modeling **kSZ & FRB**
4. **CGM model comparison** for explainability &interpretability

Probing Gas Kinematics in Galaxy Clusters with High-Resolution X-ray Spectroscopy

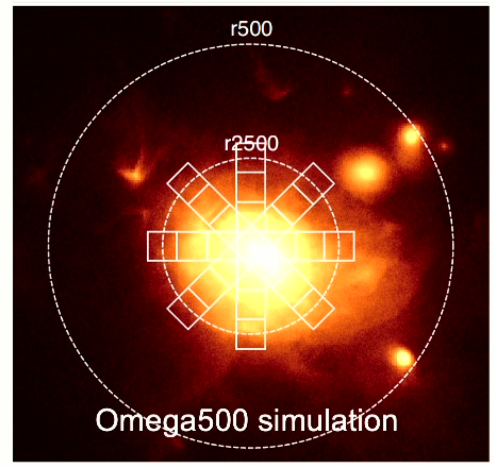


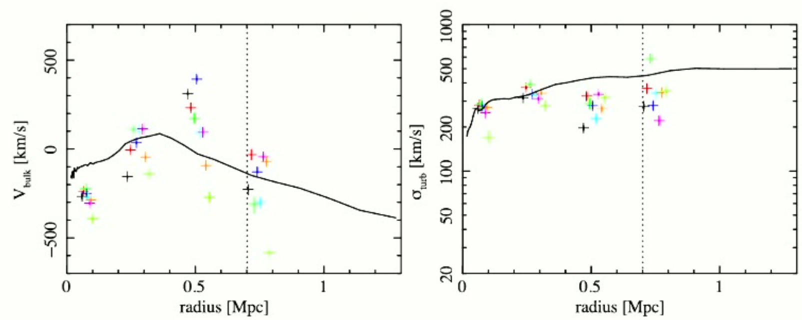
XRISM spectra of the Perseus cluster revealed "lower-than-expected" gas motions of order ~100km/s

Talk by Irina on Thursday

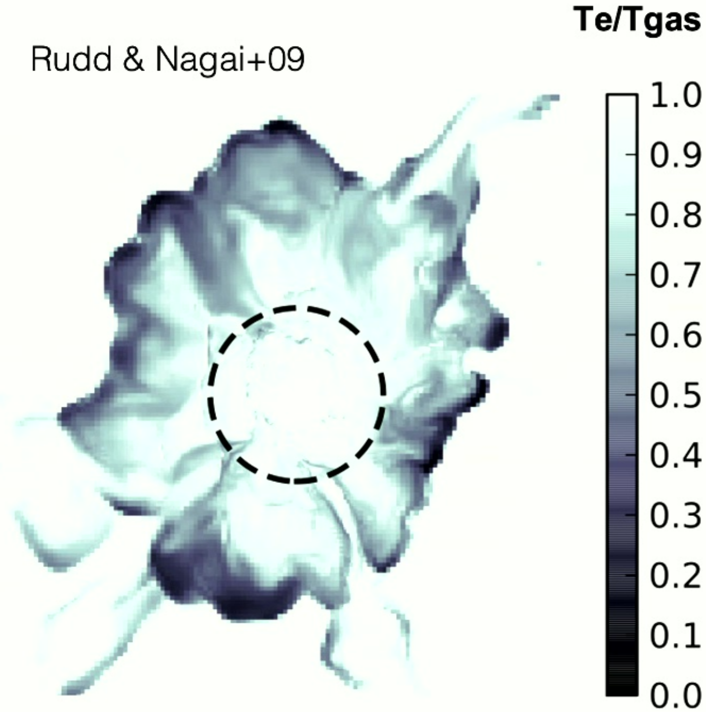
Ota, Nagai, Lau 2018

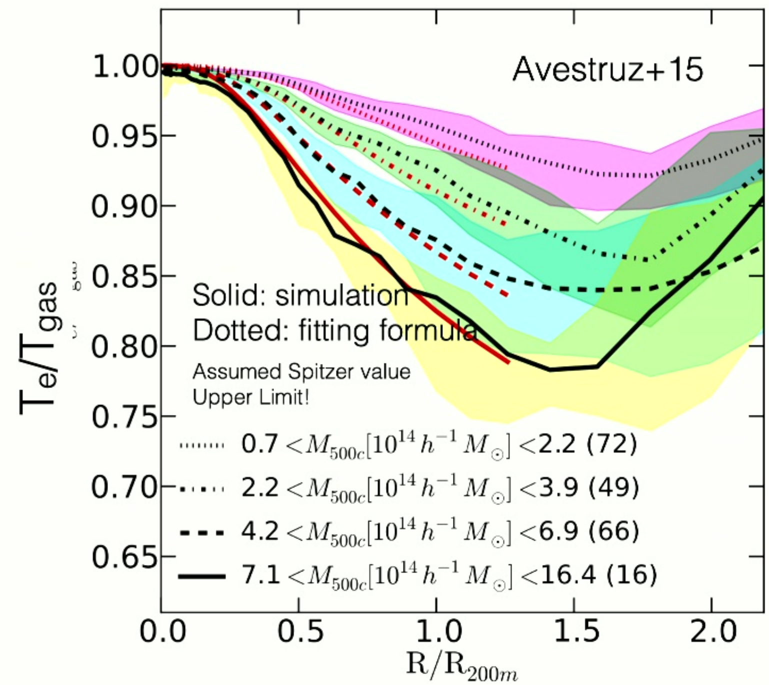
See also Lau et al. 2017





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.

Halo + Filament Model

Goal: develop a halo+filament model for baryon pasting

- The Halo model has been remarkably successful for modeling large, multi-λ surveys.
- But, need a halo+filament model for kSZ & FRB!
- The key quantity for defining filaments is **the mass per unit length, Λ**.
- Analytical self-similar model of filaments reproduces the filament properties in TNG300!
- Caveats: rich structures of realistic filaments beyond a simple cylindrical model.

Next Steps: derive observational constraints on the halo+filament model using SZ, X-ray and FRB surveys