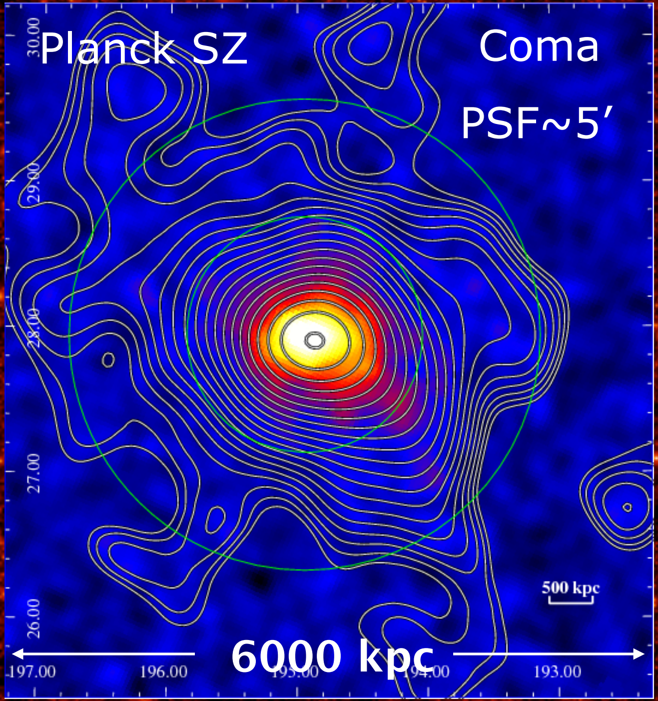
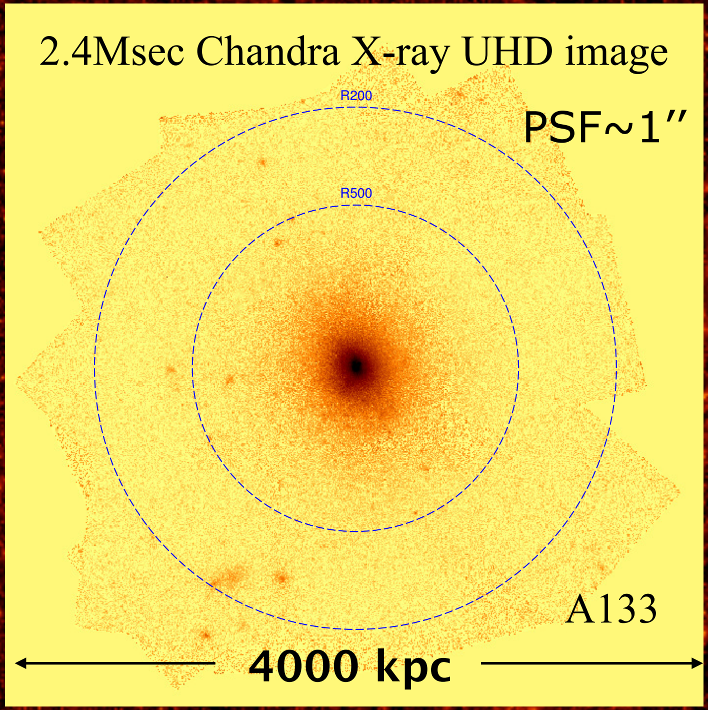
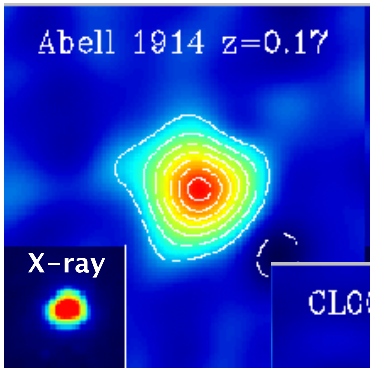
Probing Physics of Galaxy Cluster Outskirts with High-Resolution SZE Spectral Imaging





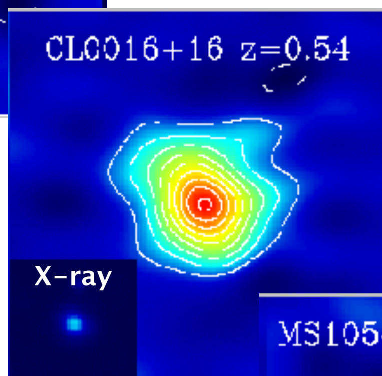
Daisuke Nagai
Yale University
NICA2 @ Grenobles
June 4, 2019

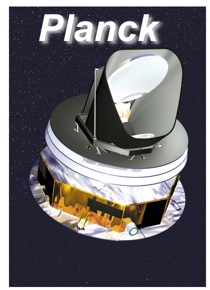
High-Resolution SZE Frontier #1: Cosmology & Astrophysics with tSZ + kSZ

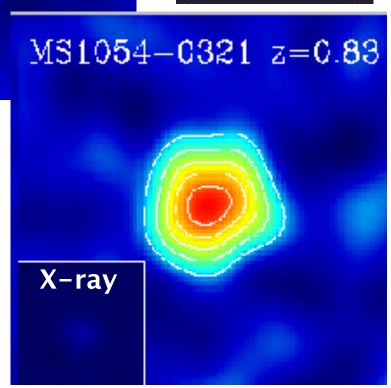


SZE is independent of redshift
tSZ is a robust mass proxy

Thousands of clusters have been found by ACT, SPT, and Planck recently





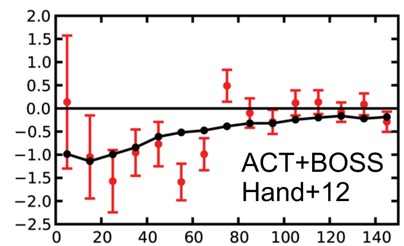


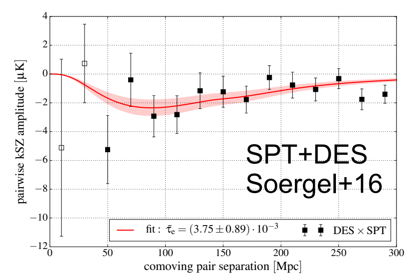
kSZ is a new probe of missing baryons + cosmology

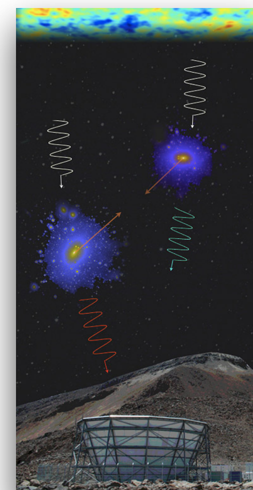
$$\frac{\Delta T_{\rm pkSZ}}{T_{\rm CMB}}(r,z) = \bar{\tau}_{\rm eff}\frac{v_{12}(r,z)}{c}$$

optical depth (astrophysics)

pairwise velocity (cosmology)







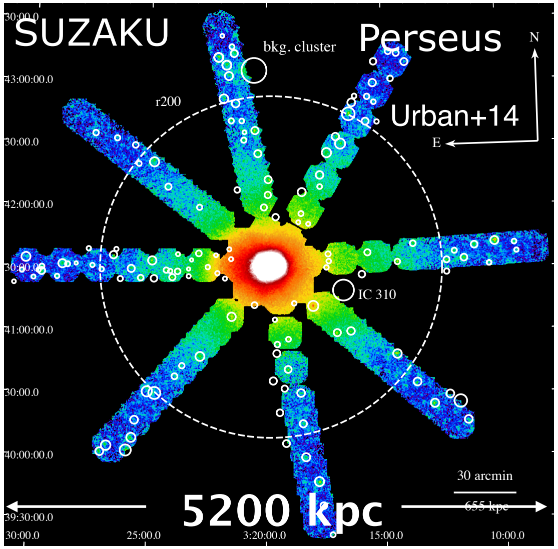
Key Observables: Gas Pressure + Density Profiles

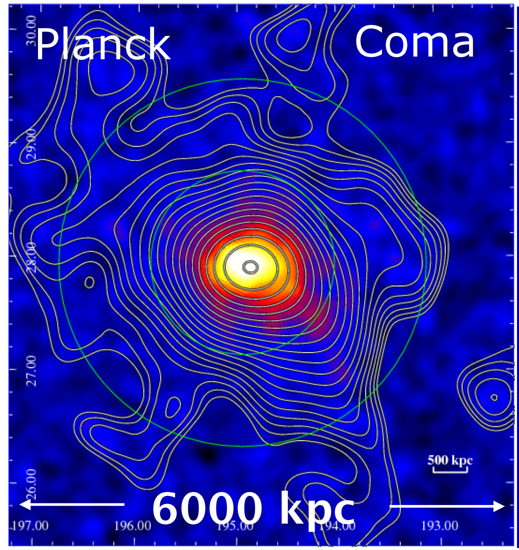
Challenges: Mass Calibration + Selection Function

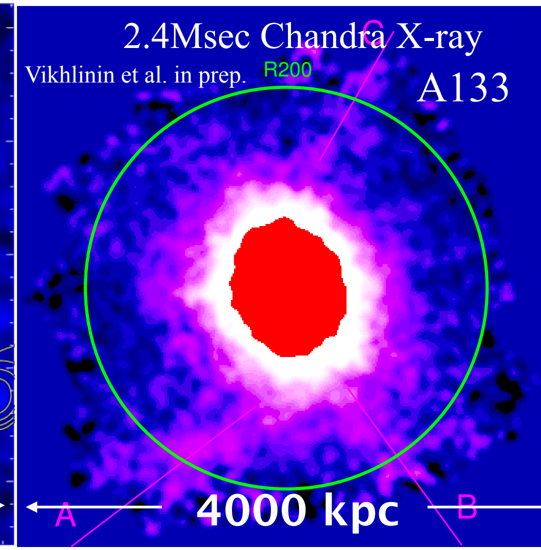
Mroczkowski et al. 2019, Space Science Review

High-Resolution SZE Frontier #2:
from ICM to CGM/IGM

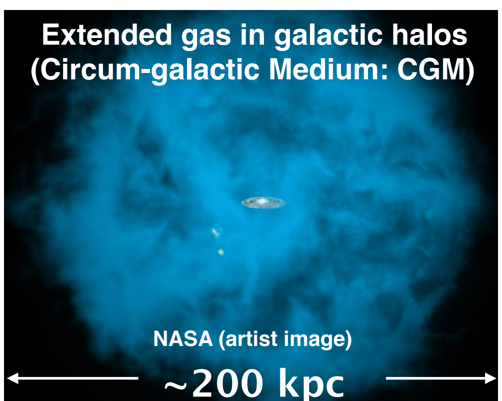
Galaxy Clusters

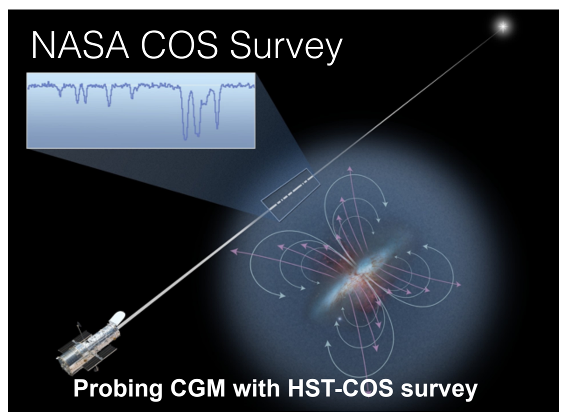


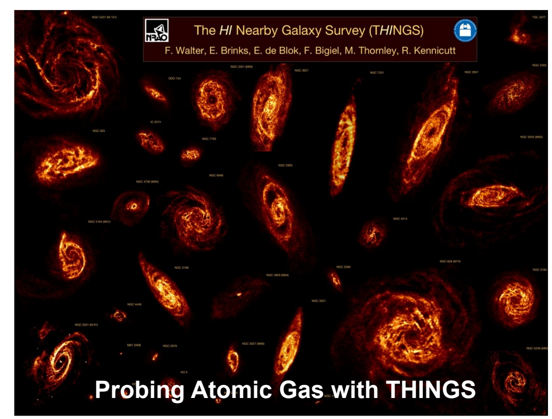




Galaxies

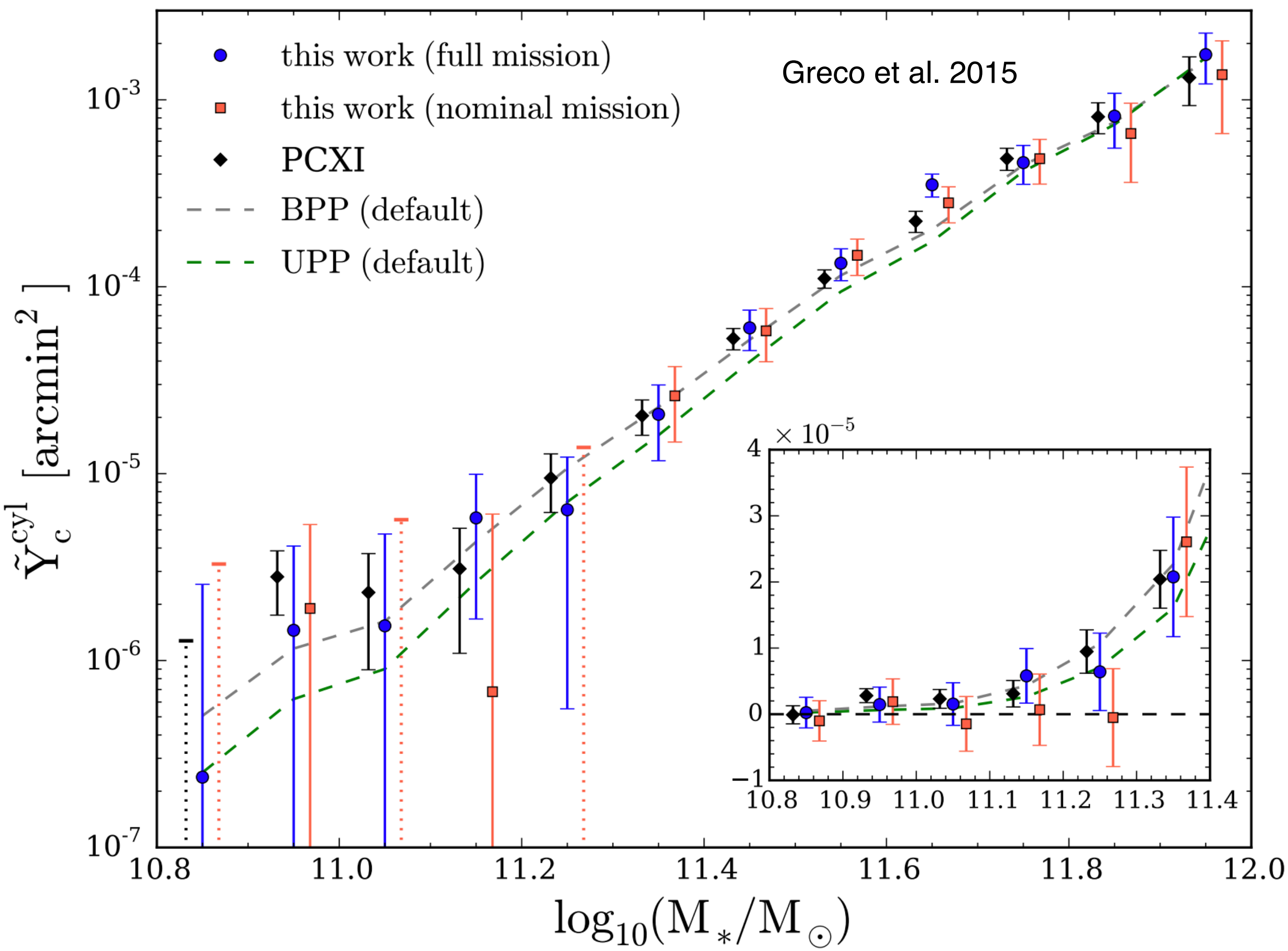






Most baryons are in gaseous form across all halo masses. Galaxy clusters are powerful platforms for studying the physics of gas in halo outskirts.

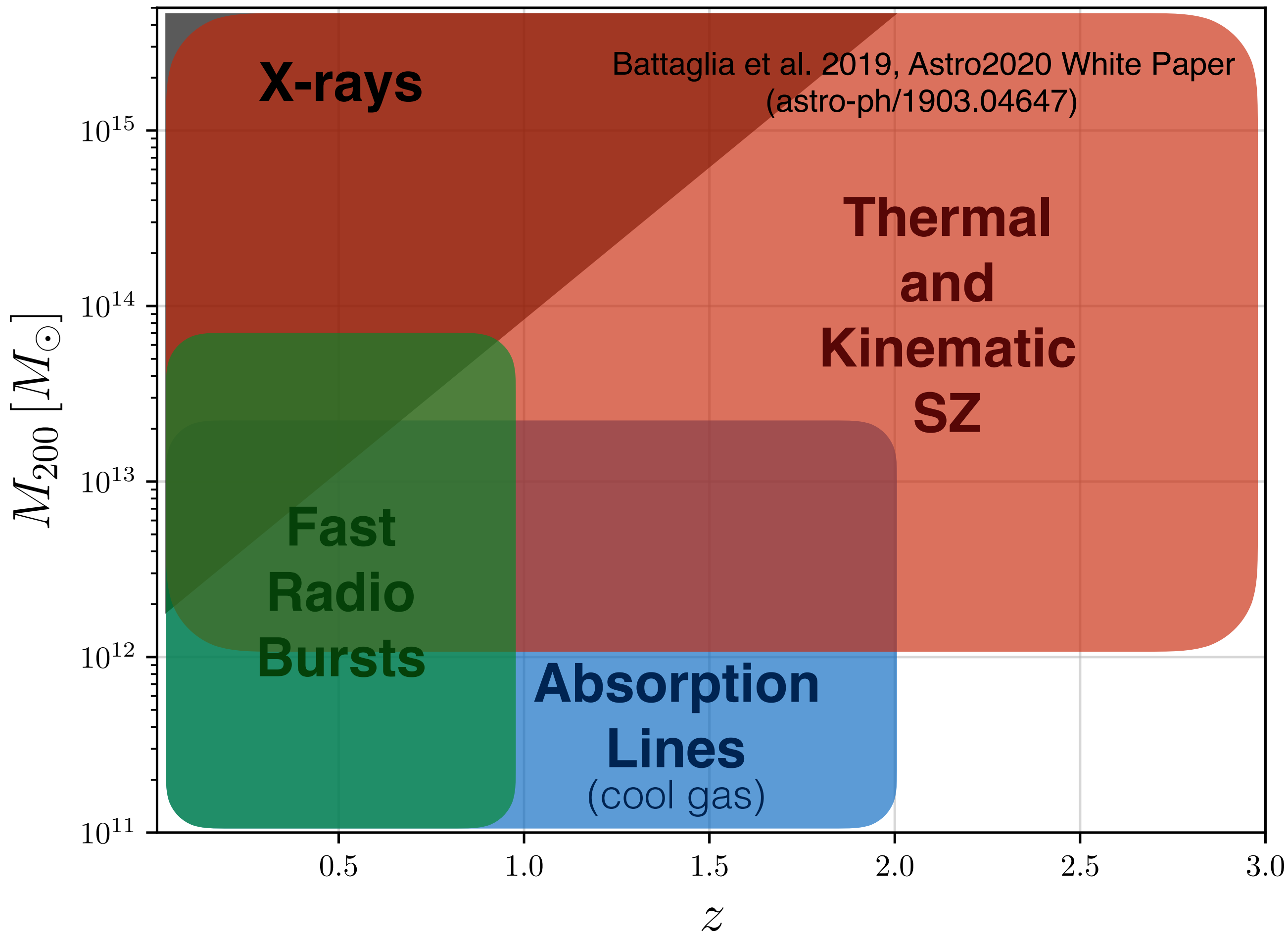
Today: Stacked SZ measurements



Detection of warm-hot gas down to $M_* \sim 10^{10.8} M_\odot$
with stacked Planck measurements of LBGs

Future: Stacked SZ measurements

Sensitivity to Gas Properties Near r_{200}

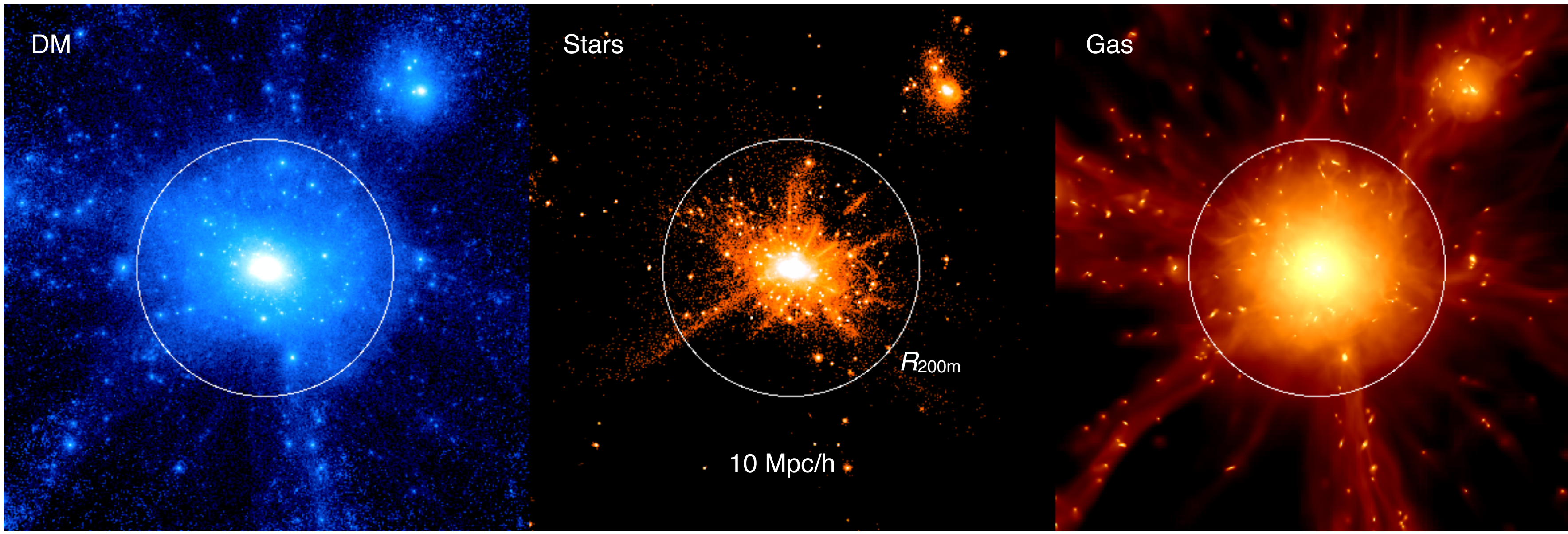


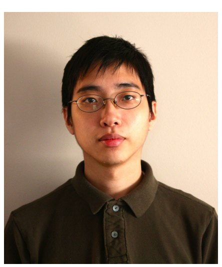
Stacked tSZ and kSZ measurements provide unique constraints on warm-hot gas in CGM and ICM, especially at high-z

Omega 500 Simulation Project

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

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




Erwin Lau

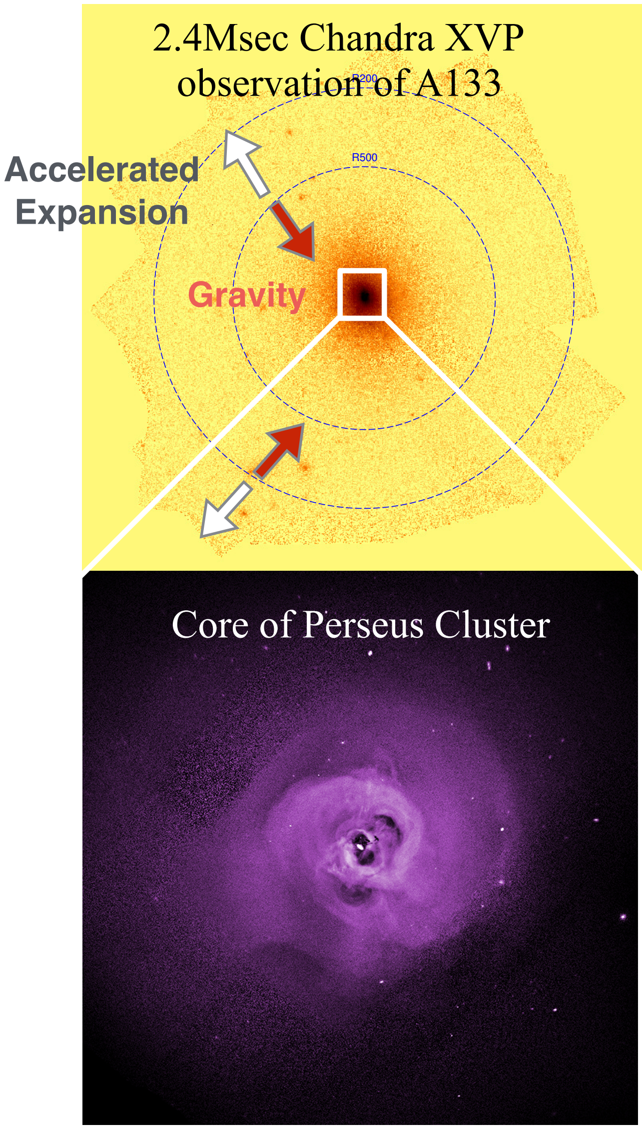

Camille Avestruz


Kaylea Nelson


Han Aung

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

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



✦Cluster Outskirts

Gas Accretion & Non-equilibrium phenomena

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

Tractable

Key Parameters Mass & MAH

Walker et al. 2019, Space Science Review

✦Cluster Cores

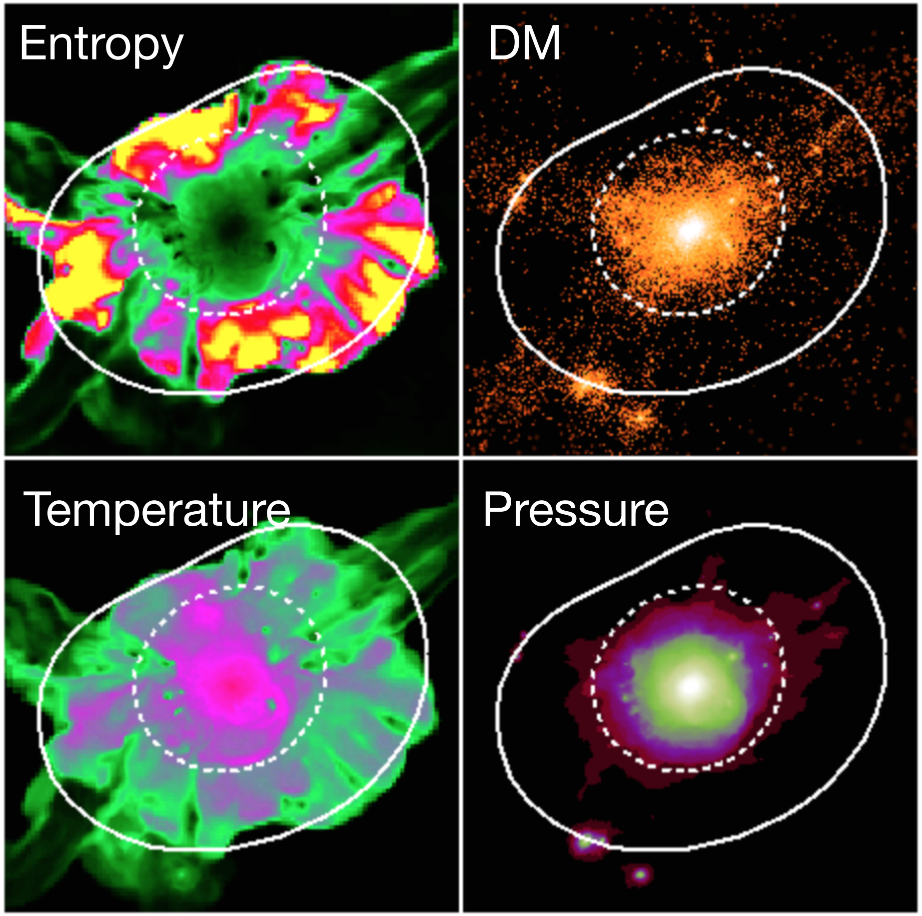
Heating, Cooling & Plasma physics

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

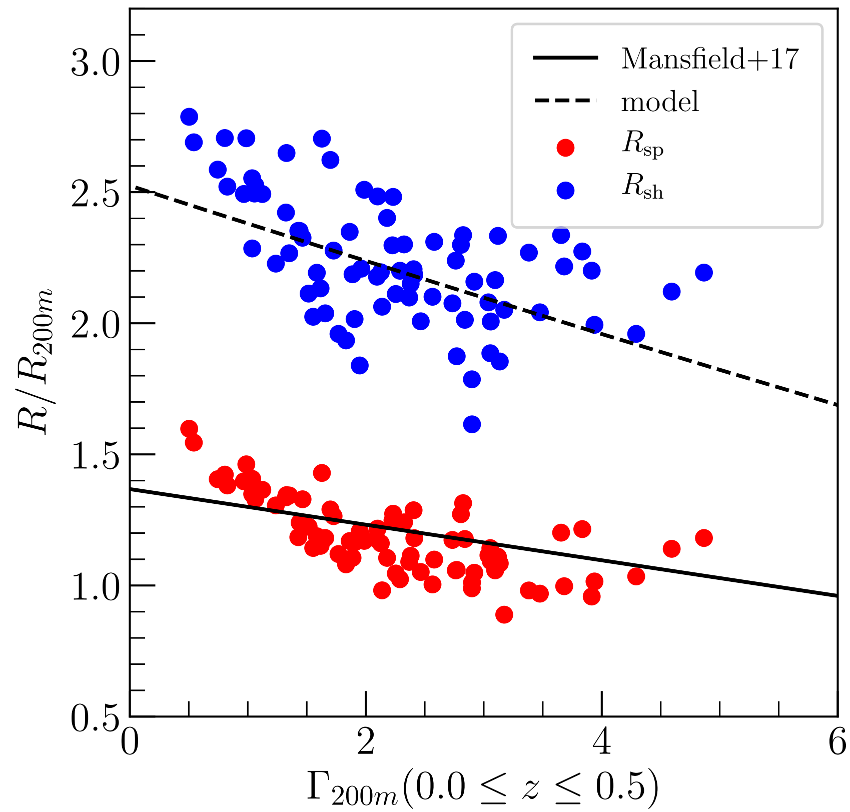
Outstanding Challenge - especially critical for X-ray surveys (e.g., eROSITA)

Physics of Cluster Outskirts #1
Splash vs. Shock Radii

DM splashback computed using SHELLFISH (Mansfield+17)



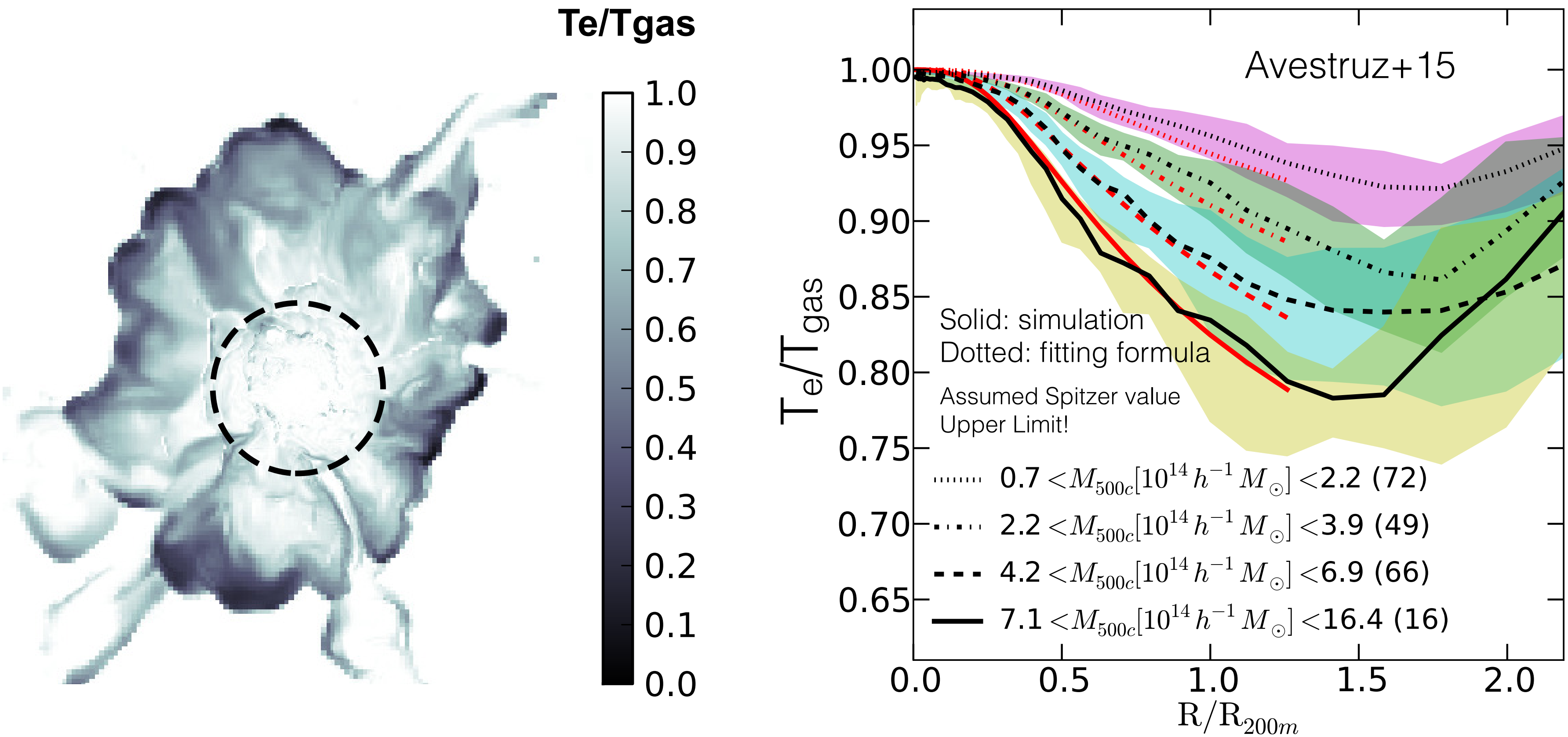
Aung et al. in prep.



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

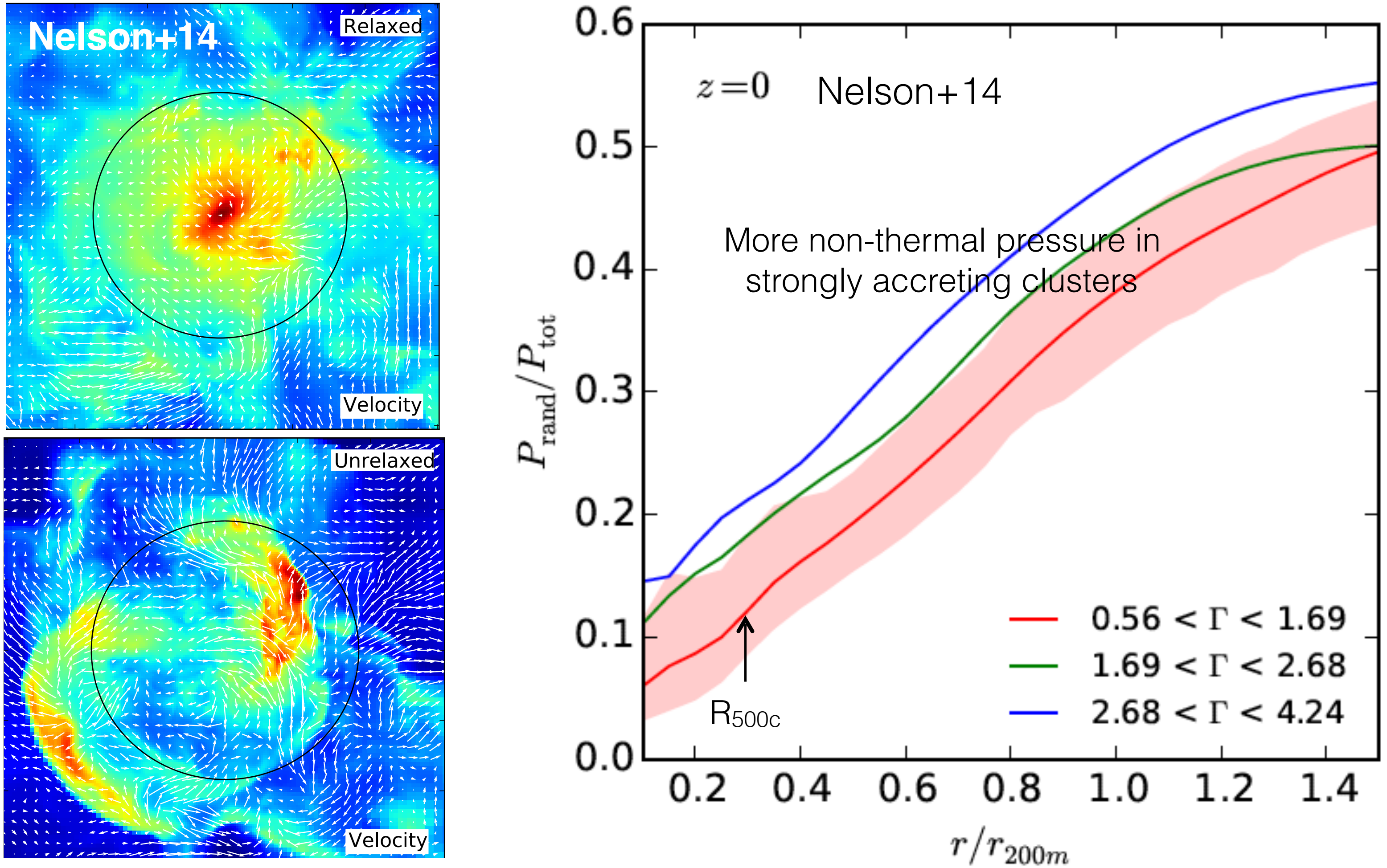
Physics of Cluster Outskirts #2

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.

Physics of Cluster Outskirts #3
Non-thermal Pressure



Non-thermal pressure due to bulk and turbulent gas motions affects the thermodynamic properties of the cluster outskirts

Physics of Cluster Outskirts #3
Analytic Model of Non-thermal Pressure

Shi & Komatsu 2014 (analytical model)

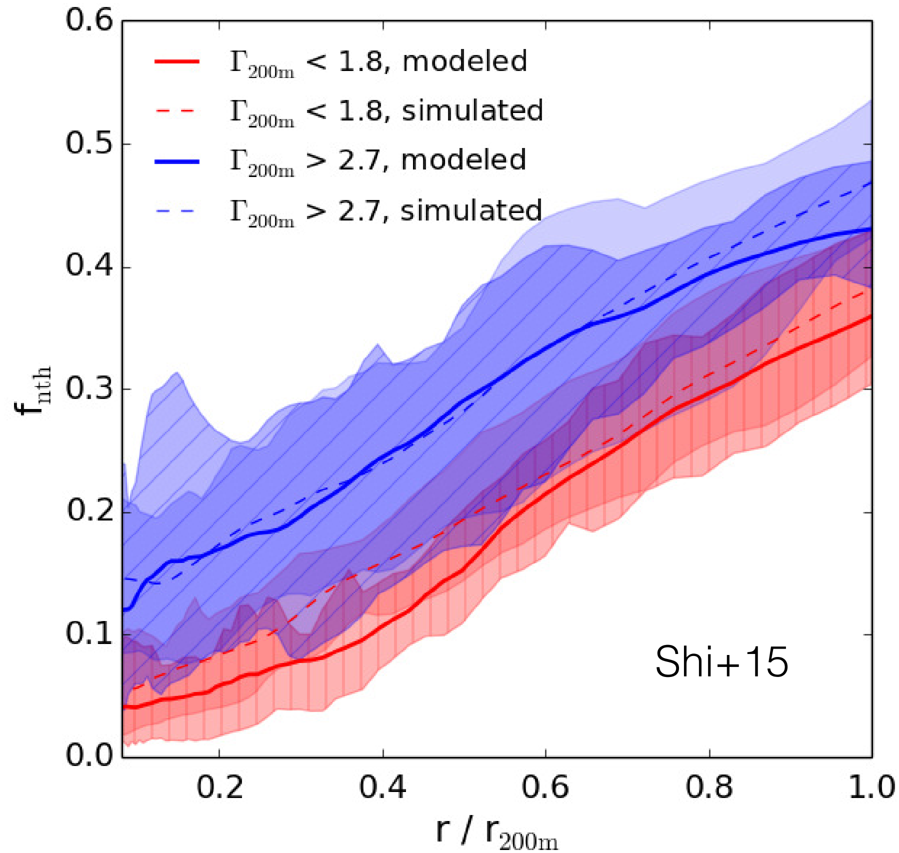
$$\frac{d\sigma^2_{\rm nth}}{dt} = -\frac{\sigma^2_{\rm nth}}{t_{\rm d}} + \eta \frac{d\sigma^2_{\rm tot}}{dt}$$

- 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

Comparison to the Omega 500 simulation (Nelson+14)



Analytic model can match the results of hydro. sims. remarkably well, **but not directly observed**

"Averaged Gas Dynamics": Modified Jeans Equation

- Previous works used Jeans equation + thermal pressure to characterize *collisional* gas dynamics in galaxy clusters (e.g., Rasia+04, Lau+09, Suto+13)
- Inviscid collisional gas follows the Euler Equation:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{\nabla P}{\rho} = -\nabla \Phi$$

- Observations measure gas properties averaged over some finite region (e.g., spherical shell) where gas motions can be uncorrelated
- Performing **spatial average** of the Euler Equation leads to a Jeans-like equation plus thermal pressure:

$$\frac{\partial \langle \mathbf{v} \rangle}{\partial t} + (\langle \mathbf{v} \rangle \cdot \nabla)\langle \mathbf{v} \rangle + \frac{1}{\langle \rho \rangle}\nabla \langle \rho \rangle \sigma^2 + \frac{1}{\langle \rho \rangle}\nabla \langle P \rangle = -\nabla \langle \Phi \rangle$$

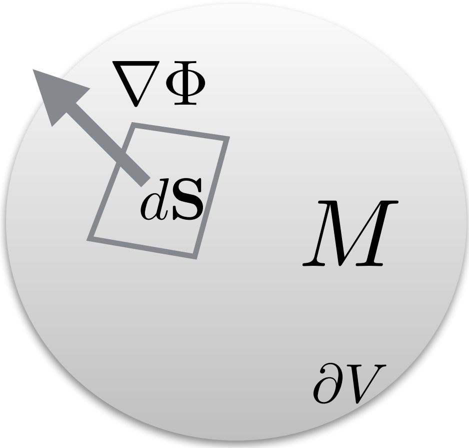
Acceleration ***Bulk flow*** ***Random motions*** ***Thermal pressure*** ***Potential***

Lau, Nagai, Nelson 2013, ApJ, 777, 151

Weighing Cluster Mass with Averaged Gas Quantities

- Measuring mass with Gauss' Law:

$$M = \frac{1}{4\pi G} \oint_{\partial V} \nabla\Phi \cdot d\mathbf{S}$$



- Combined with modified Jeans Equation:

$$M = \frac{-r^2}{G\langle\rho\rangle}\nabla_r\langle P\rangle + \frac{-r^2}{G\langle\rho\rangle}\nabla_r\langle\rho\rangle\sigma^2 + \frac{-r^2}{G}(\langle\mathbf{v}\rangle\cdot\nabla)\langle v_r\rangle + \frac{-r^2}{G}\frac{\partial\langle v_r\rangle}{\partial t}$$

M_{HSE} M_{rand} M_{bulk} M_{accel}

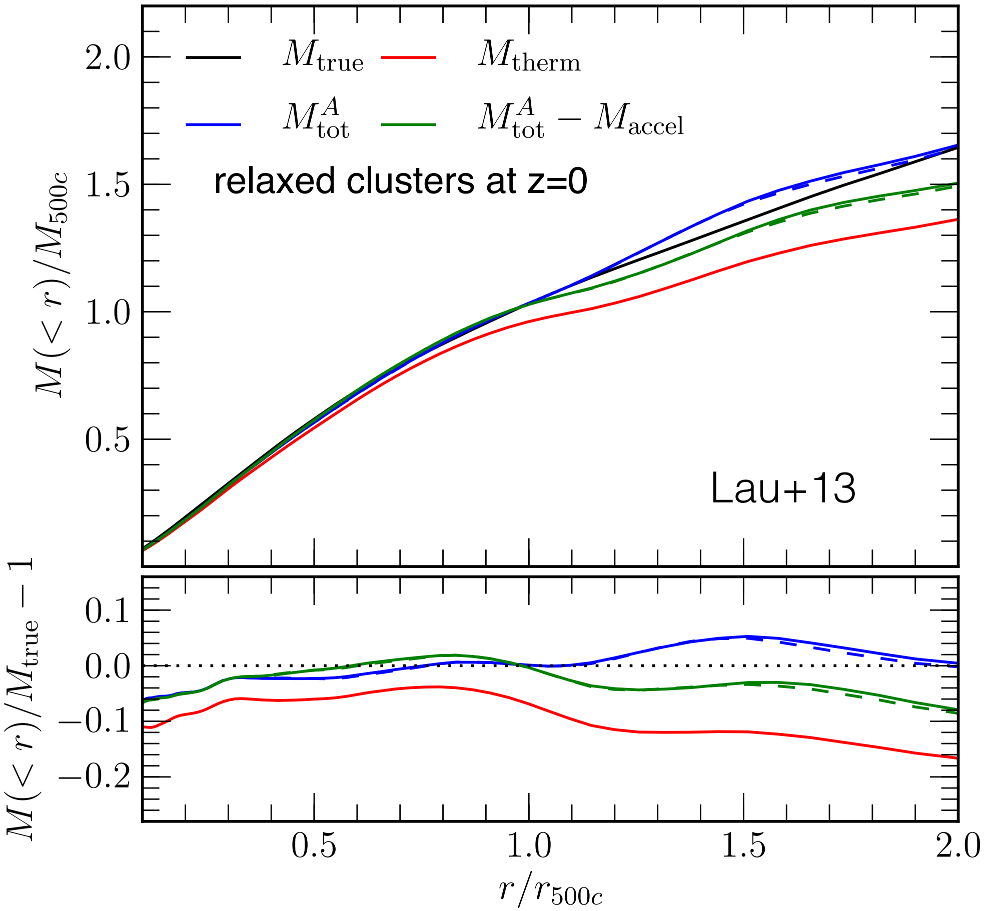
Lau, Nagai, Nelson 2013, ApJ, 777, 151

Hydrostatic Mass Bias

$$M = M_{\rm therm} + M_{\rm rand} + M_{\rm bulk} + M_{\rm accel}$$

HSE mass bias

unmeasurable



Unmeasurable mass bias term due to gas acceleration introduces < 1% bias at < R_{500c} (Suto+13, Nelson+14) for ***relaxed*** clusters, but causes significant scatter in **unrelaxed** clusters (Nelson+14)

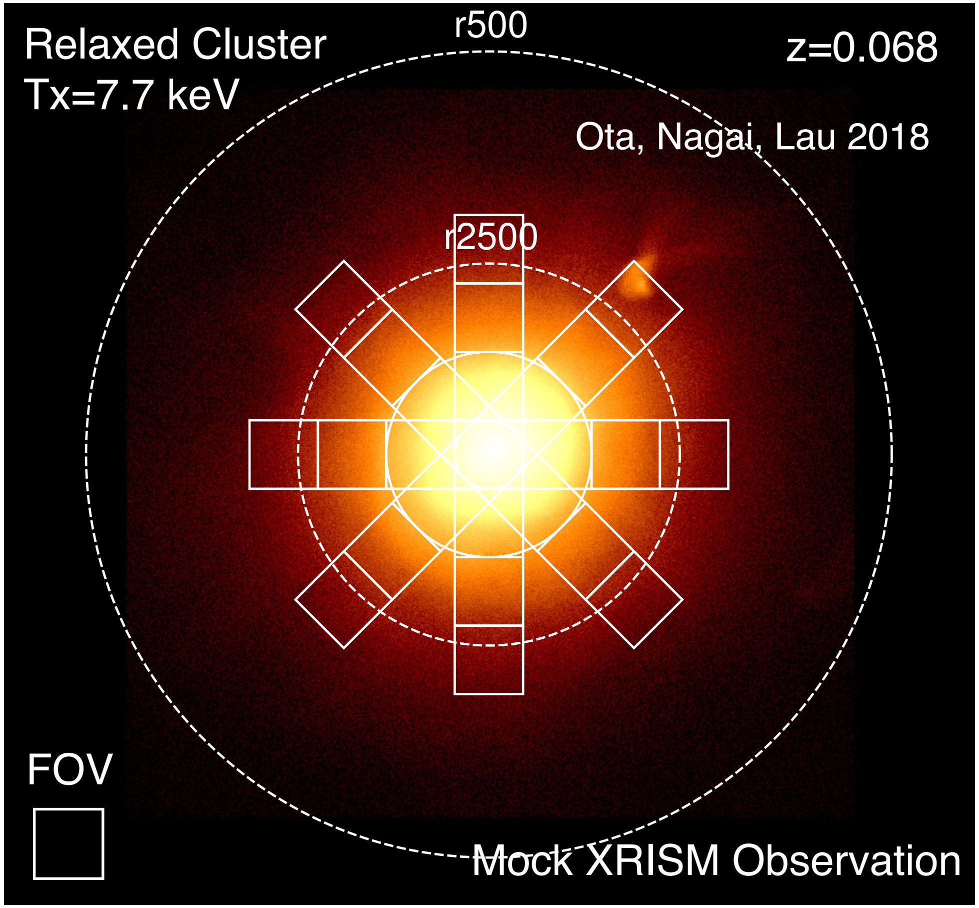
Black: True mass

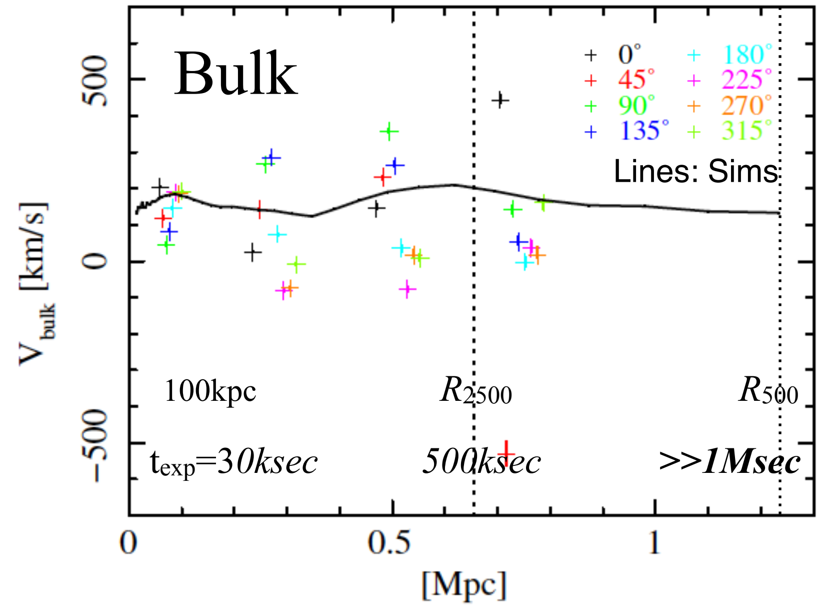
Red: Thermal pressure only

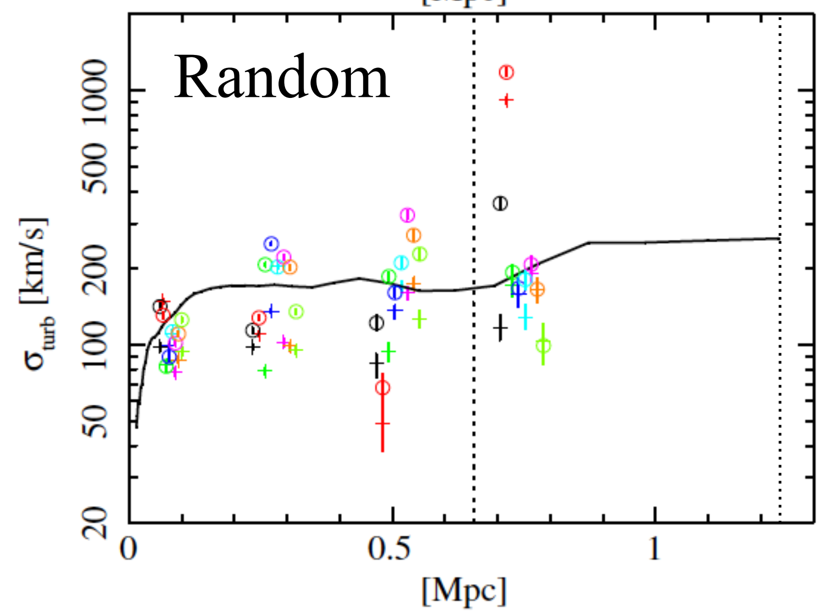
Green: Thermal pressure + Bulk and random gas motions

Blue: Full recovery including gas

Probing Non-thermal Pressure & HSE mass bias of Galaxy Clusters with X-ray Spectroscopy



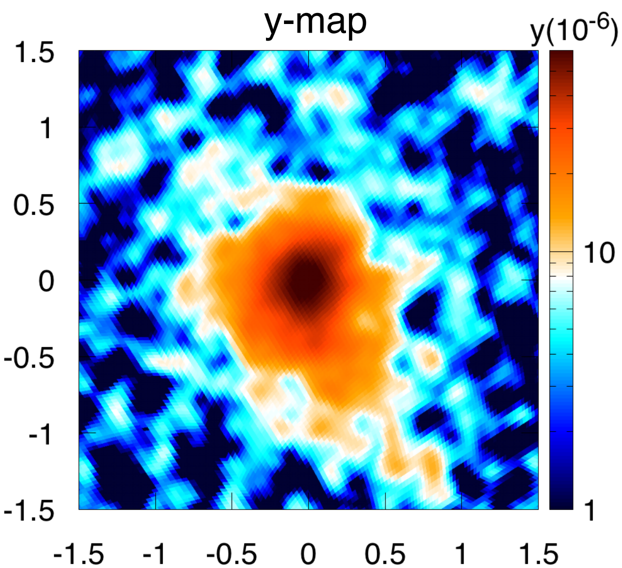


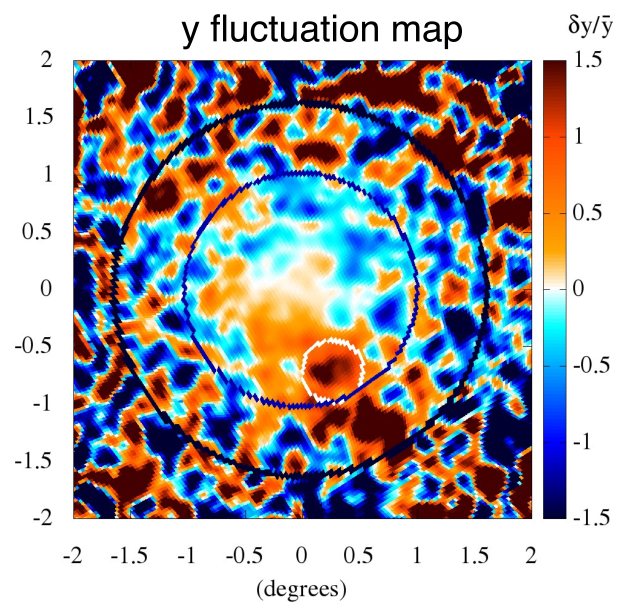


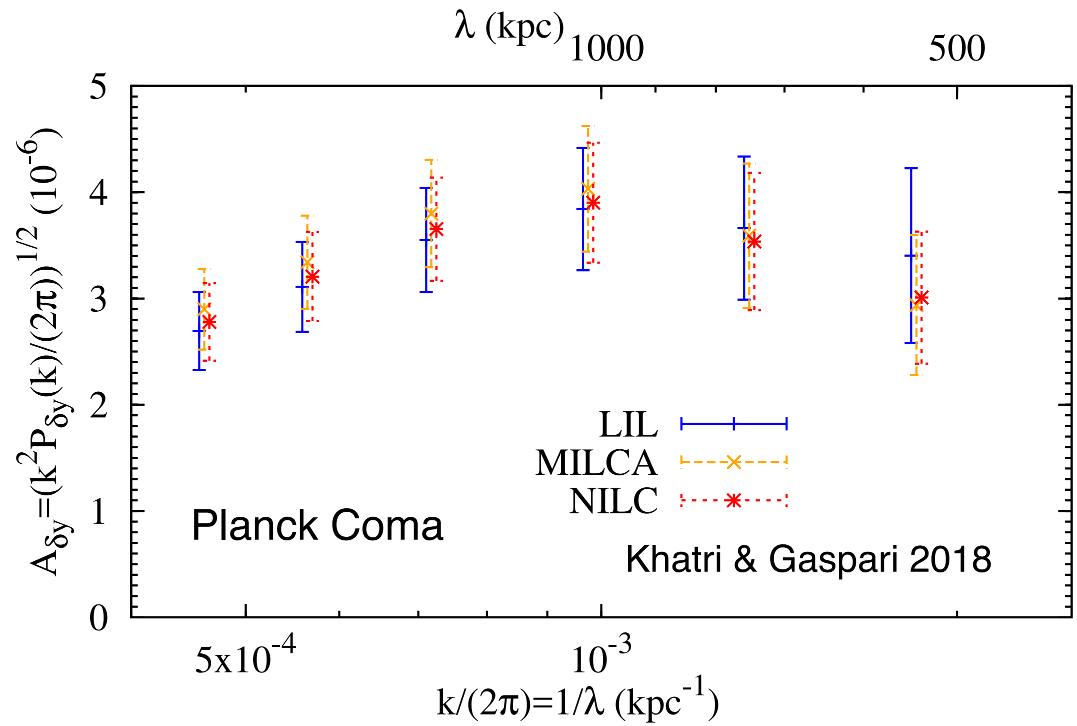
XRISM, Athena and Lynx can measure the non-thermal pressure and hydrostatic mass bias, **but only out to R_{2500} of massive clusters at z~0**

Bulbul et al. 2019, Astro2020 White Paper (astro-ph/1903.06356)
c.f. Simionescu et al. 2019, Space Science Review

High-resolution SZ probe of Non-thermal Pressure in Cluster Outskirts



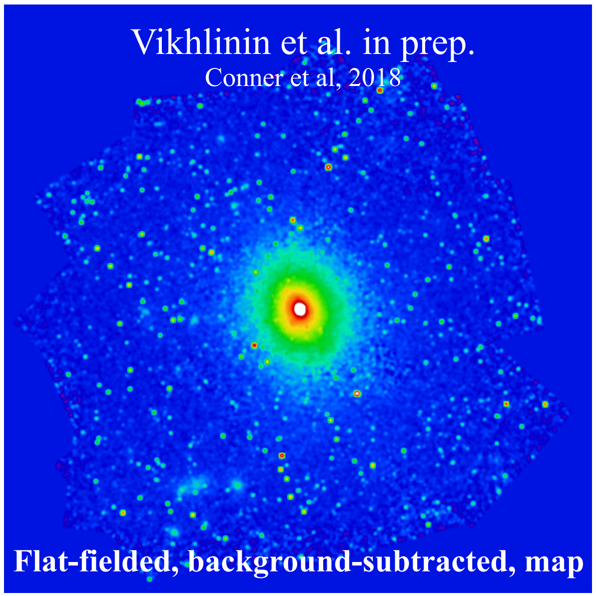


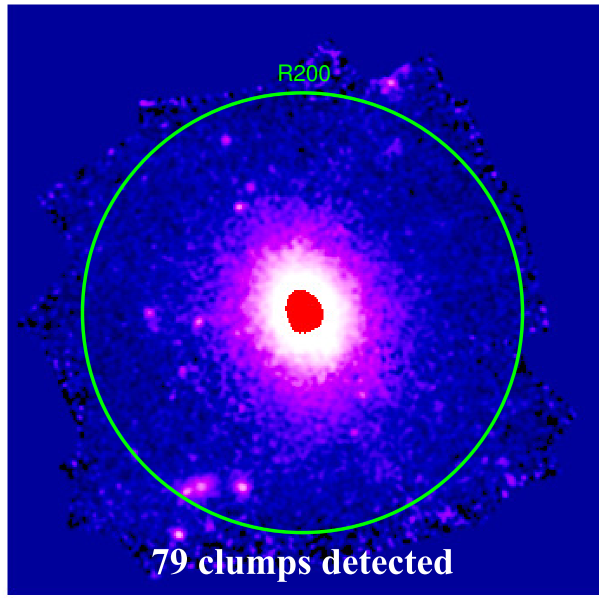


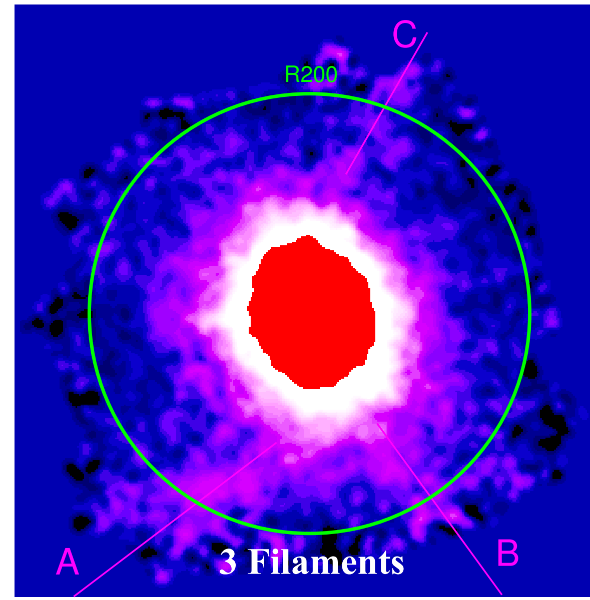
High-resolution SZ spectral imaging has the potential to provide unique measurements of the non-thermal pressure in the outskirts of high-z clusters

Testing the Model Predictions with Ultra-deep, High-resolution X-ray Observations

2.4Msec Chandra XVP observation of the outskirt of A133







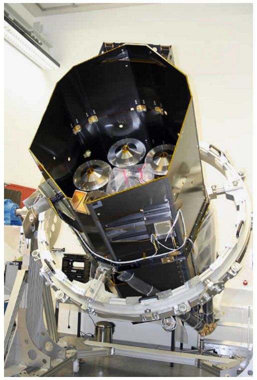
A transition of the smooth state in the virialized region to a clumpy intergalactic medium in the infall region outside of $r \approx R_{500c}$

High-angular resolution (<1”) is critical

Walker et al. 2019, Astro2020 Decadal White Paper (astro-ph/1903.04550)

Cluster Cosmology in 2020s

X-ray



eRosita

Microwave

Optical

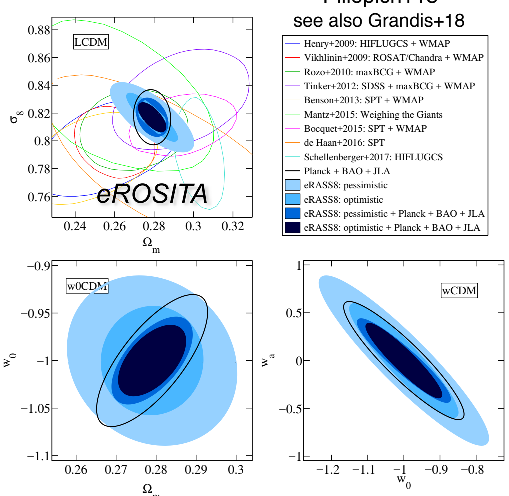
Golden Era: >100,000 clusters & groups in multiple bands; huge statistical power!

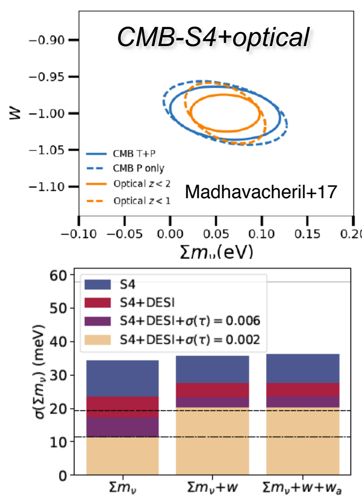
Challenge: <1% mass calibration in order to maximize the scientific return

Problem: Hydro cosmo sims are still prohibitively expensive for covering the vast parameter space of astrophysics & cosmology

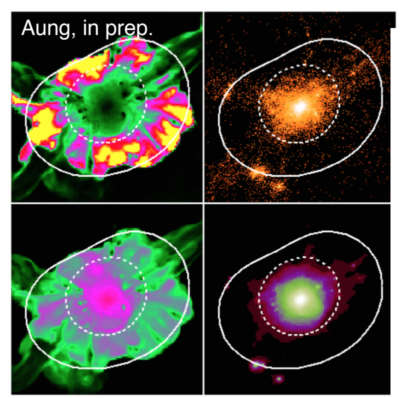
Solution: Computationally efficient, physically-motivated model of baryons (gas+stars) - need a new framework!

Pillepich+18
see also Grandis+18

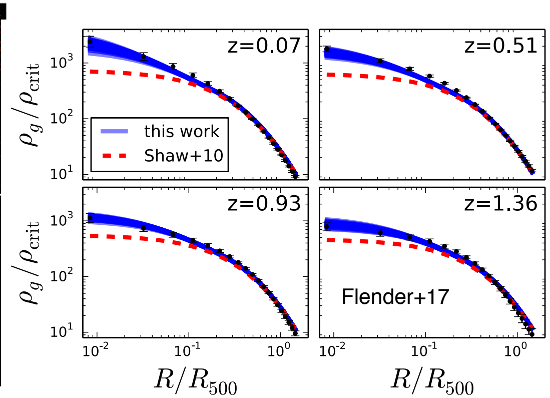




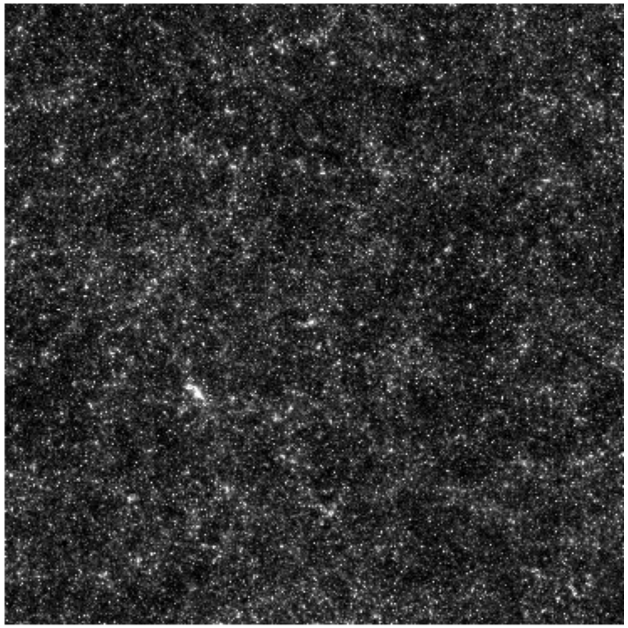
Hydro Sims



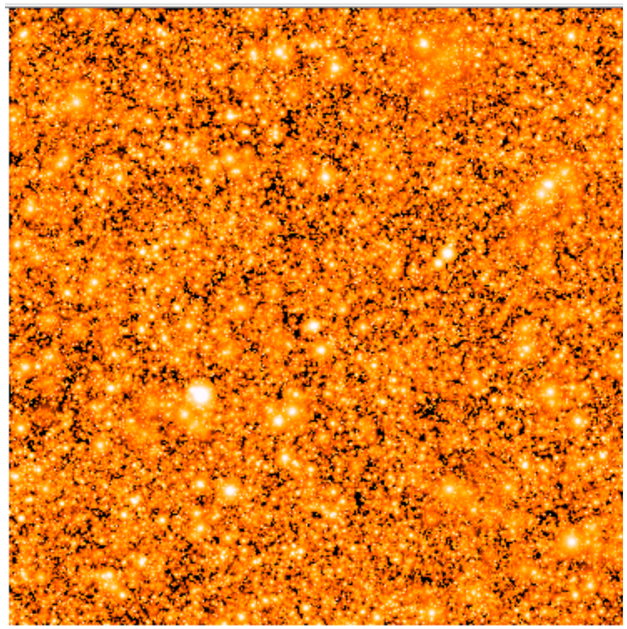
Analytic Model



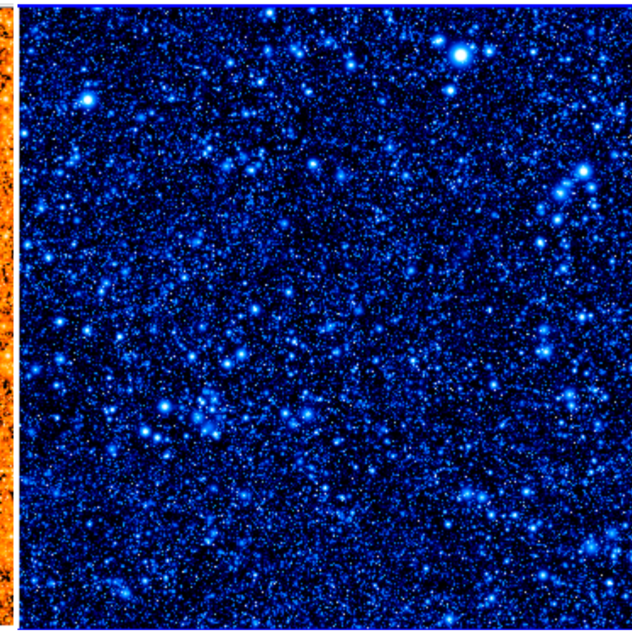
Physics-Based Approach
Baryon Pasting Project



Lensing



Compton-y

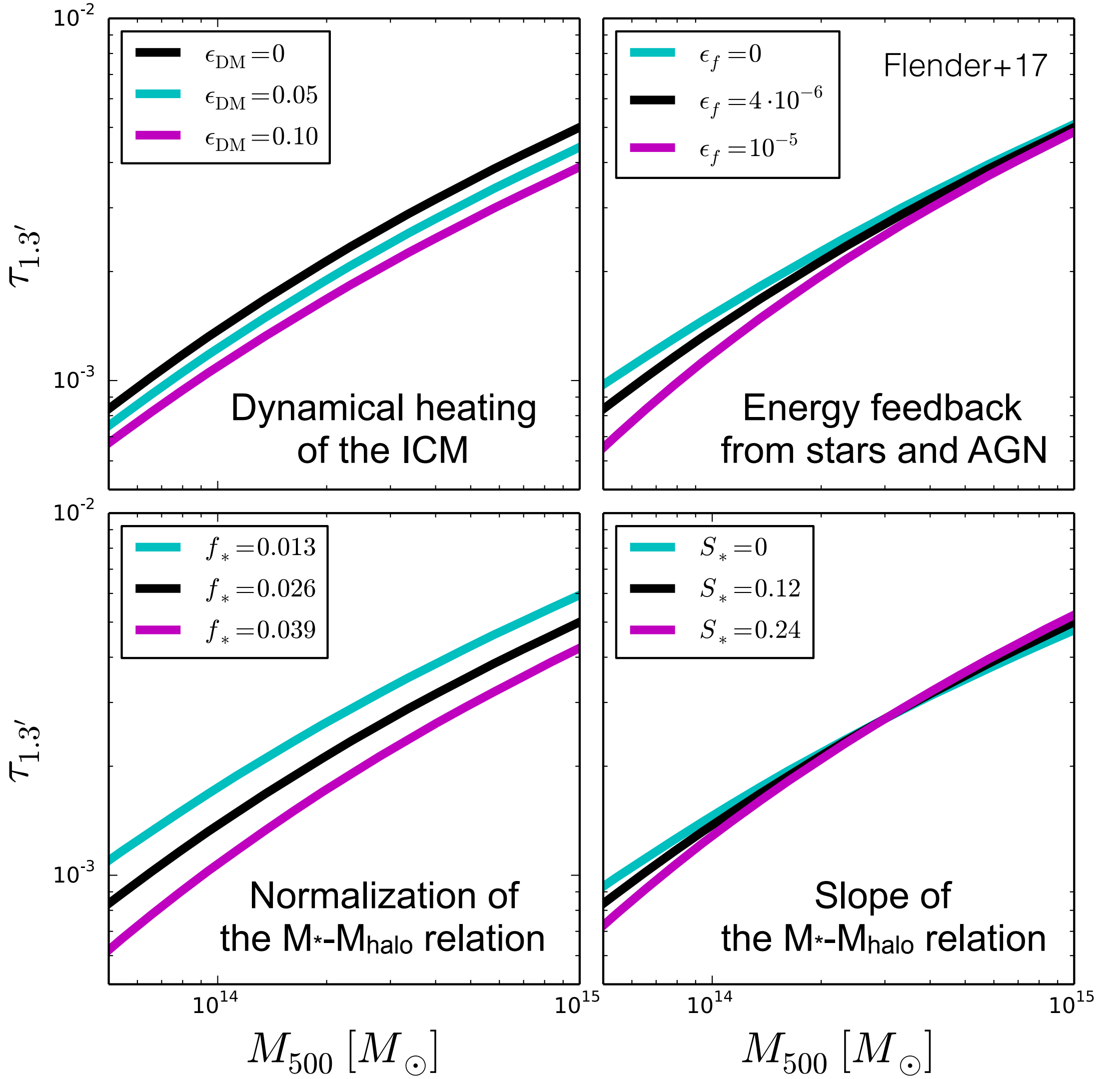


X-ray surface brightness

- Analytic model of gas (Ostriker+05; Shaw+10; Flender+17; Osato+18) + stars (Behroozi+18) for creating multi-wavelength light-cone mocks (halo model or N-body sims)
- Goals: (1) cluster mass + scaling relations, (2) selection function, (3) cross-correlations, (4) cosmology

Baryon Pasters team: H. Aung, C. Avestruz, G. Evrard, A. Farahi, S. Green, A. Hearin, H.J. Huang, E. Lau, R. Makiya, P. Mansfield, H. Miyatake, D. Nagai, B. Nord, K. Osato, M. Shirasaki

How to Maximize SZ Science from CMB-HD survey?



Problem: Hydro sim. still prohibitively expensive for analyzing large CMB+LSS datasets and modeling baryonic effects & cosmology

Solution: Computationally efficient, physically-motivated **analytic model of the ICM/CGM**

(1) Gas resides in HSE in DM halos with the polytropic EoS

(2) Assume some gas has radiatively cooled + formed stars. Stellar mass fraction constrained by observed relations.

(3) Energy feedback from stars and AGN (e.g., assume feedback energy proportional to stellar mass) and dynamical heating

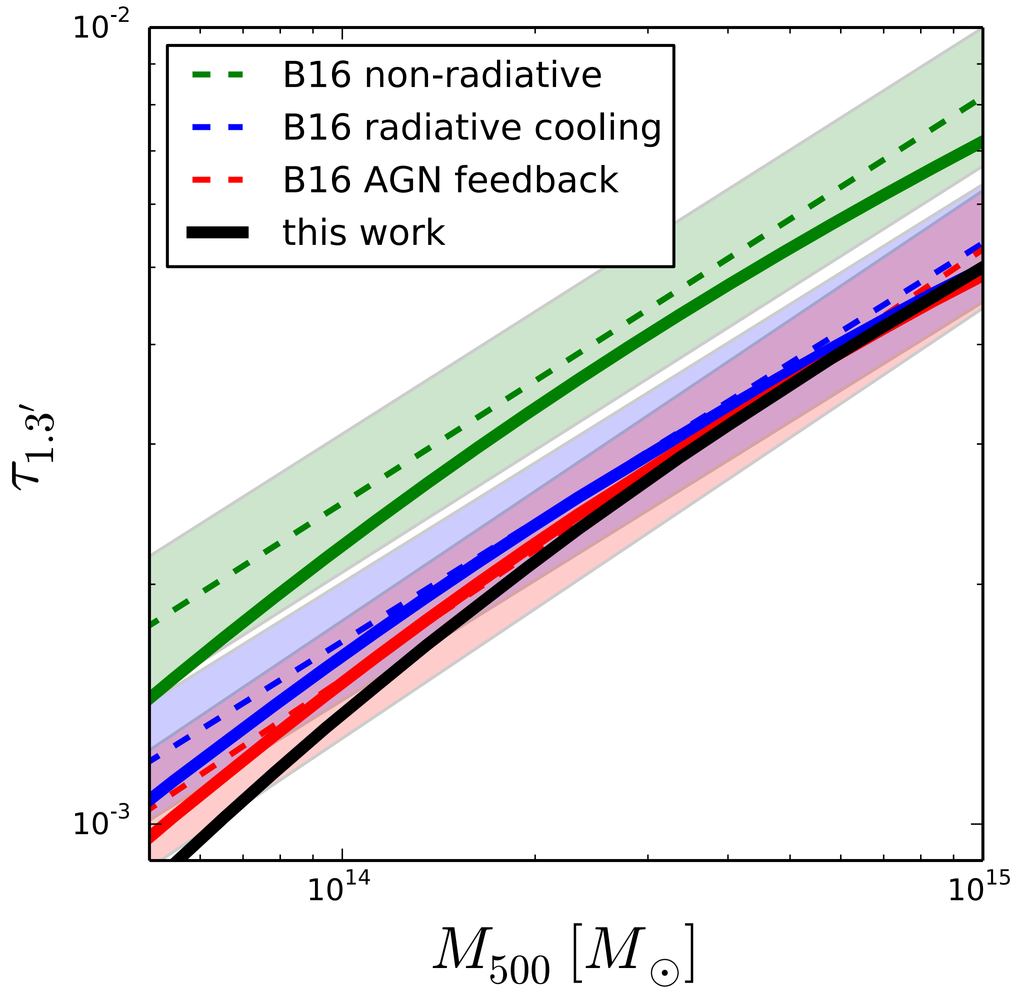
(4) Non-thermal pressure from random and bulk gas motions

(5) Cool-core with a broken polytropic model

Ostriker+05, Bode & Ostriker+06, Shaw+10, Flender+17

Testing the Analytic Model of the ICM with Hydro Simulations

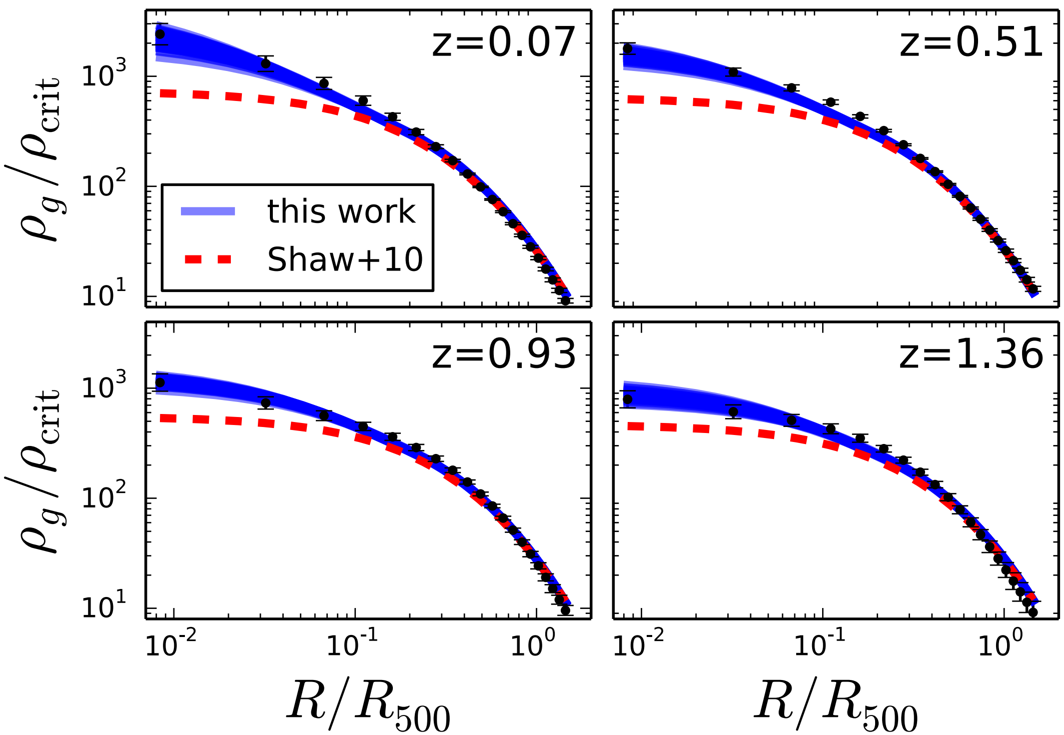
average τ within 1.3' aperture



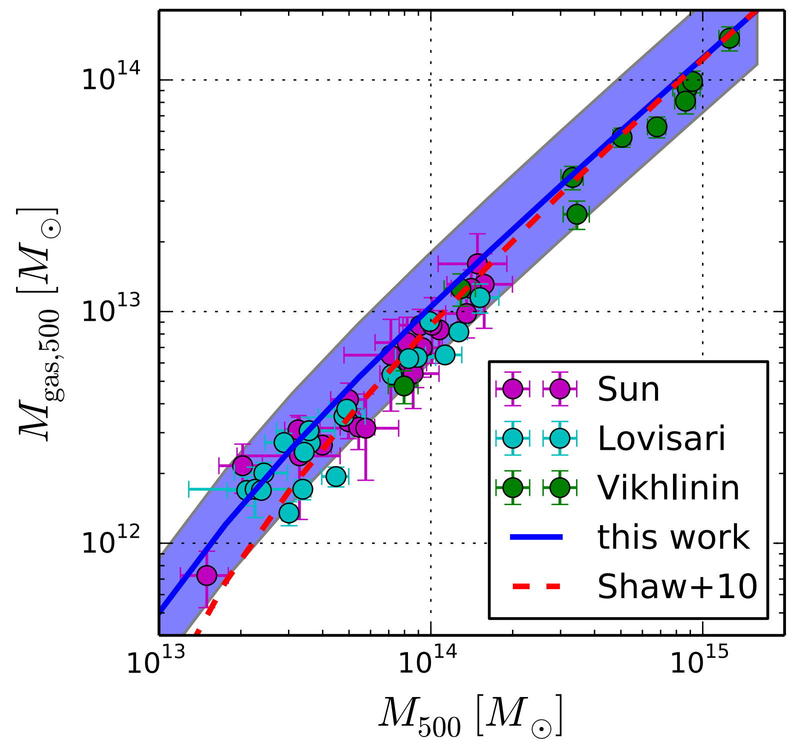
Analytic model can reproduce the results of hydro simulations by Battaglia+16 (see also Soergel+17)

Calibrating the Analytic Model of the ICM with X-ray observations

Gas density profile from extended Shaw Model from Flender+17

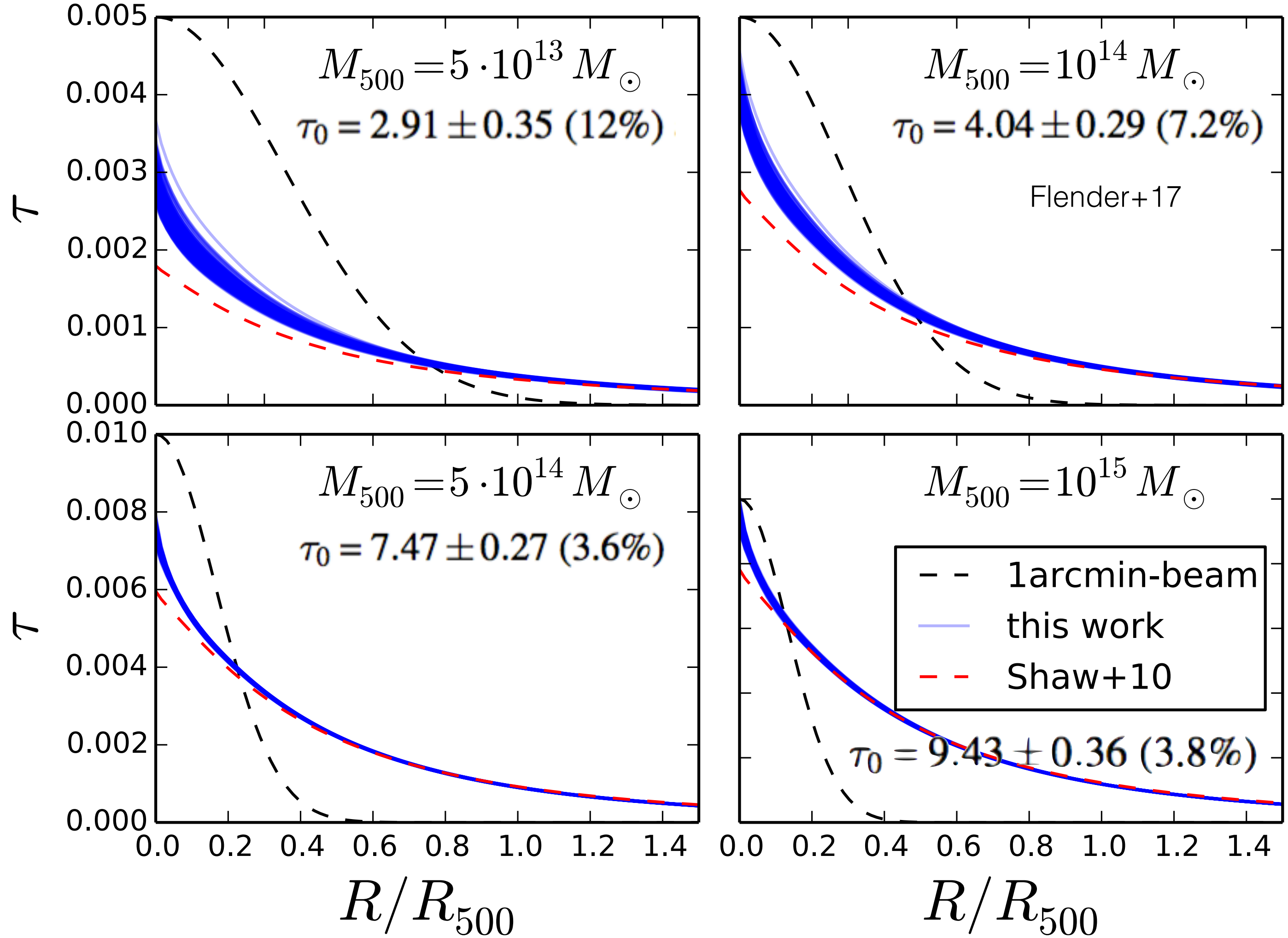


McDonald+13:
Chandra measurements of gas density profiles of SPT-selected clusters



Vikhlinin+06, Sun+09, Lovisari+15: measurements of the M_{gas}-M relation

X-ray constraints on the Optical Depth of Groups & Clusters

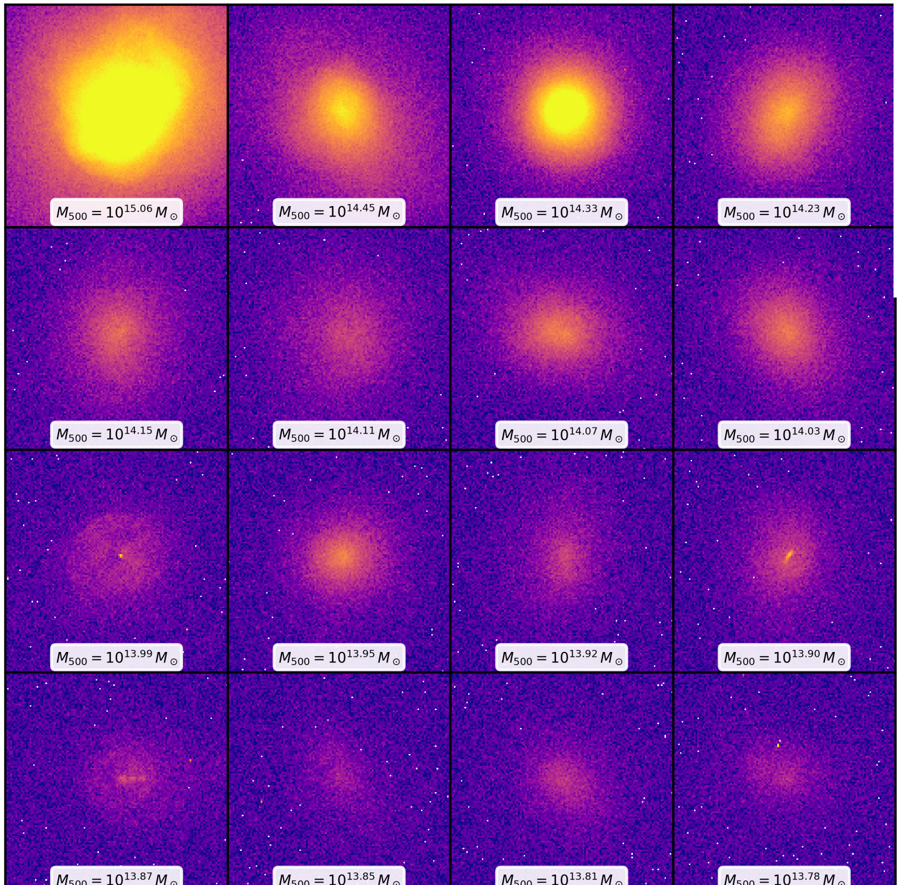


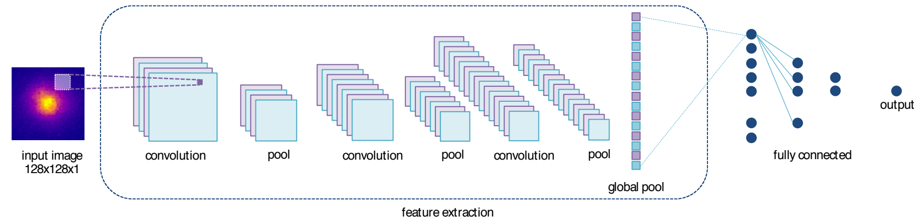
X-ray data can constrain the optical depth of groups and clusters at the level of 10%,
but missing constraints on CGM at high-z!

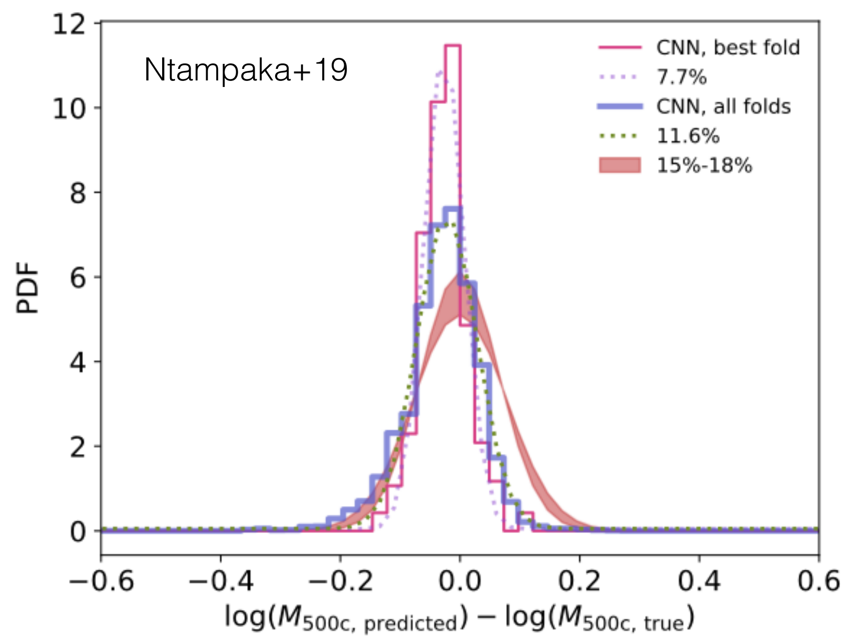
Data-Driven Approach

X-ray Cluster Mass Estimates

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

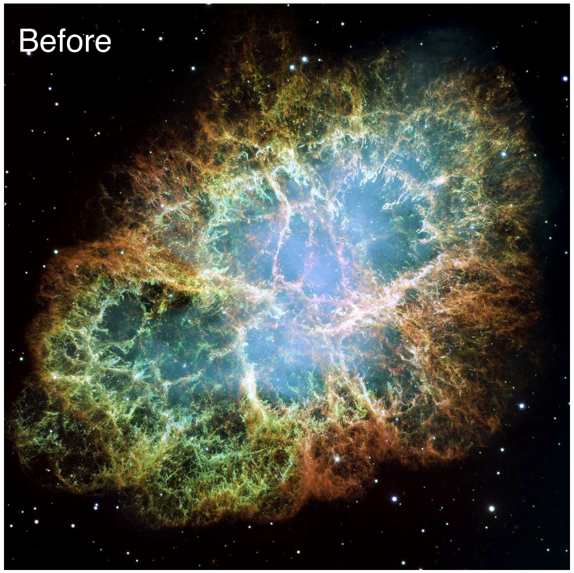


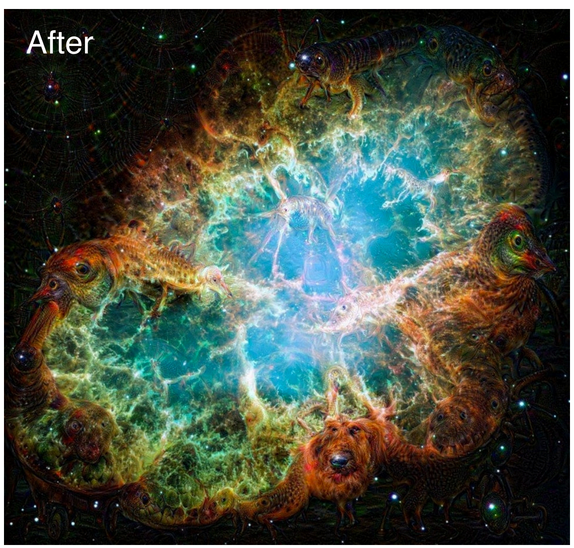




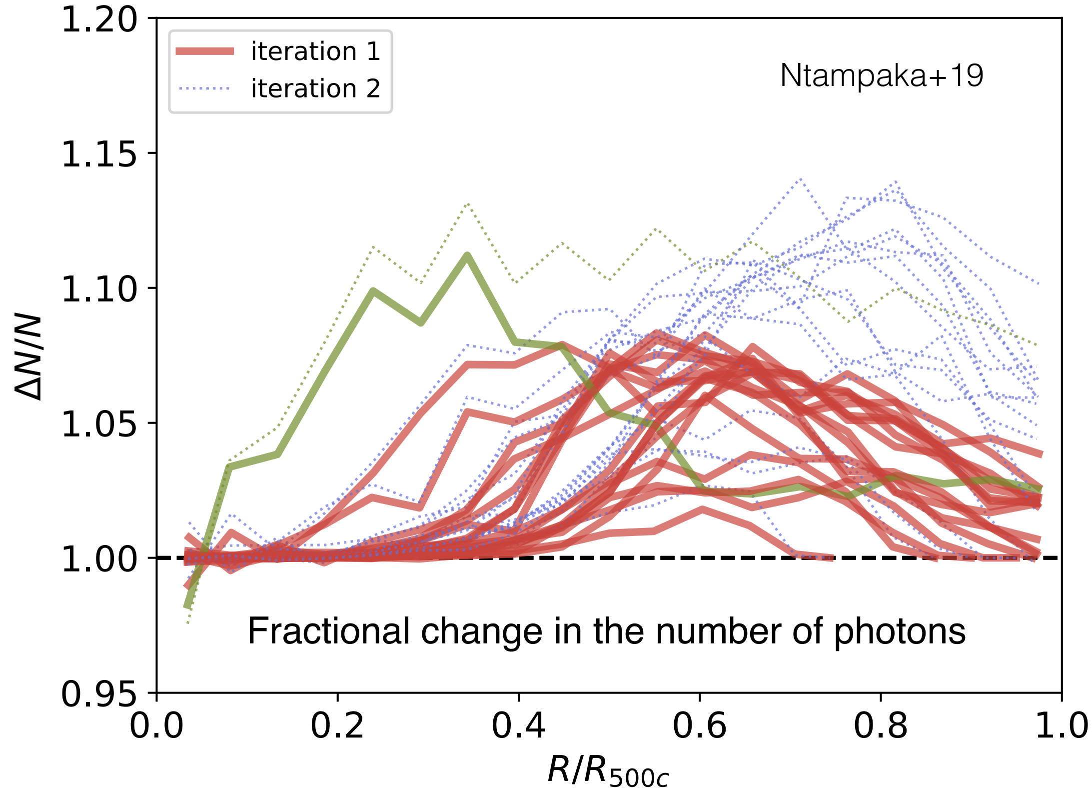
The ML-based X-ray cluster mass has a small scatter of 8-12%, which is a significant improvement from 15-18% scatter based on the core-excised X-ray luminosity - the current market standard.

Beyond the Black Box: Interpreting the model with Deep Dream





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

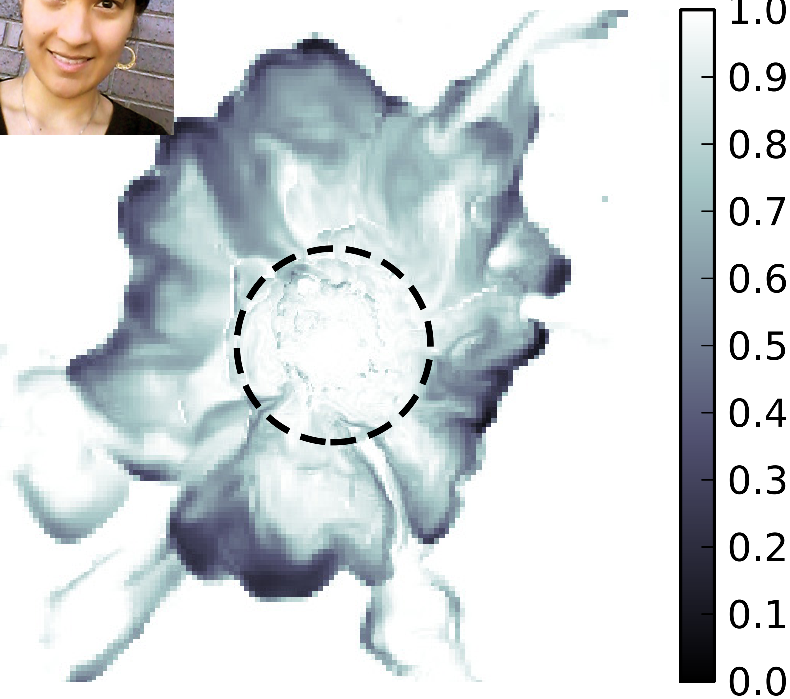


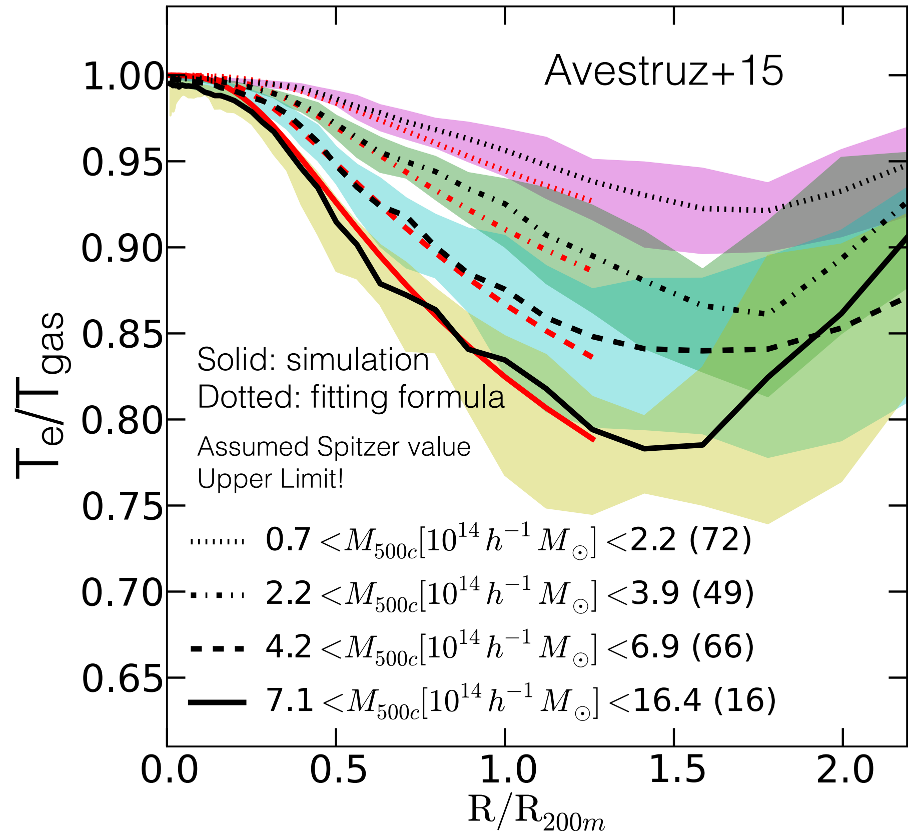
CNN has learned to excise core, which are known to have large scatter with mass.

Perhaps, ML can also teach us about astrophysics of cluster outskirts in hydro sims (Walker+19 for a recent review)

Beyond Hydrodynamics

Electron-Proton Equilibration in Cluster Outskirts





In the outskirts of galaxy clusters, the collision rate of electrons and protons becomes longer than the age of the universe. Pressure profile measurements in cluster outskirts will be critical!

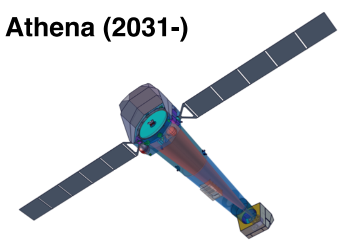
Cluster Cosmology & Astrophysics
Simulation + Observation + Theory Connection

Observational Frontier

2020s will be a Golden Age of Cluster Surveys

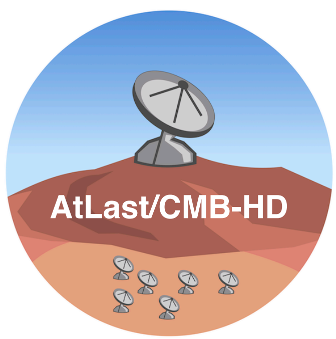
High-Resolution, Low-Noise Frontier is critical in 2020+

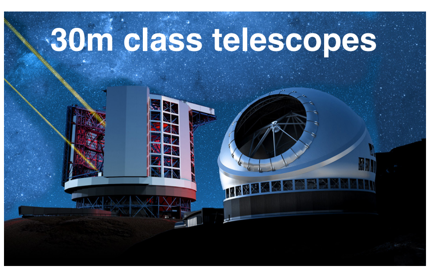
Map out DM+gas+stars in clusters + galaxies + cosmic web



CMB-S4

Next Generation CMB Experiment



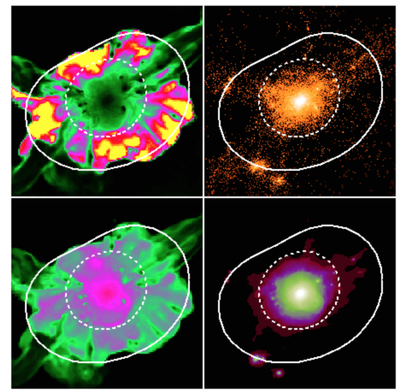


Theoretical Frontier

Physics-based + Data-driven approaches

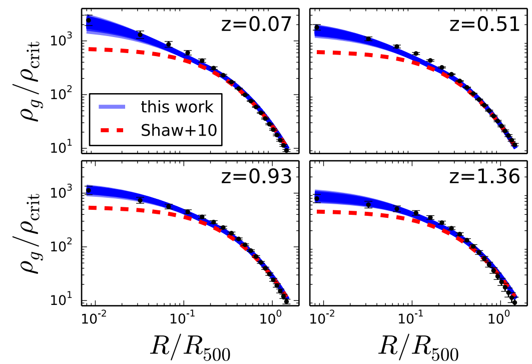
Simulations

Cosmological Hydro + Plasma effects

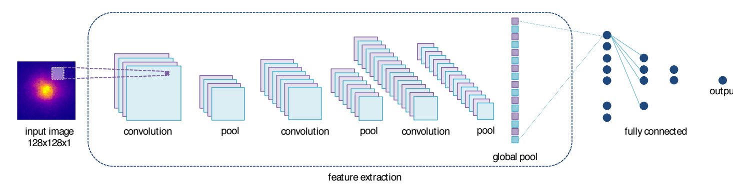


Analytic Model

Baryon Pasting Project



Machine Learning



Sciences

Cluster Cosmology with X-ray+SZE+Lensing

Physics of ICM/CGM/IGM + Missing Baryons

Galaxies+Gas+DM Halo Connections