Galaxy Clusters: Cosmology, Astrophysics, and the Need for Multi-Probe Observations

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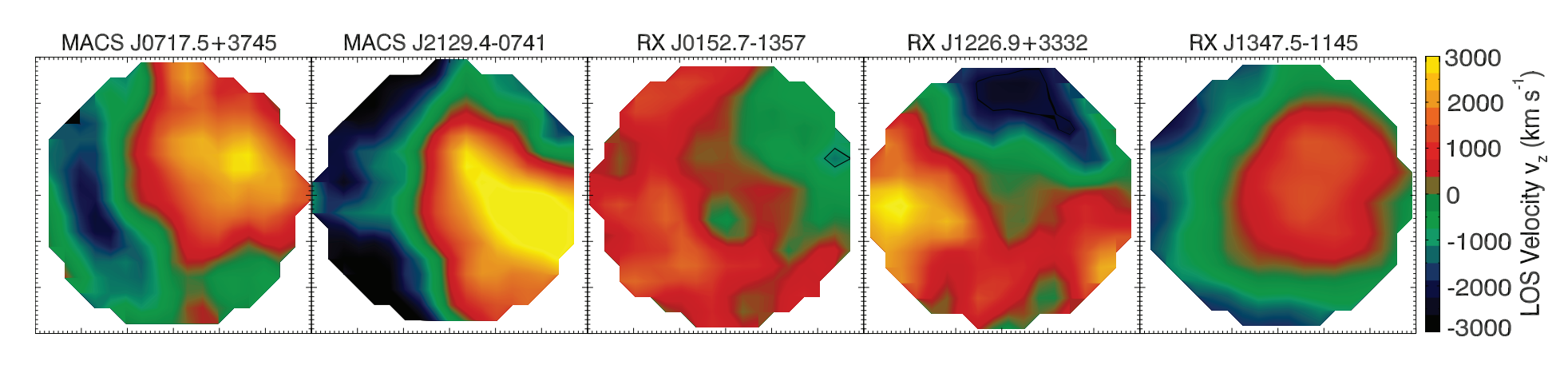
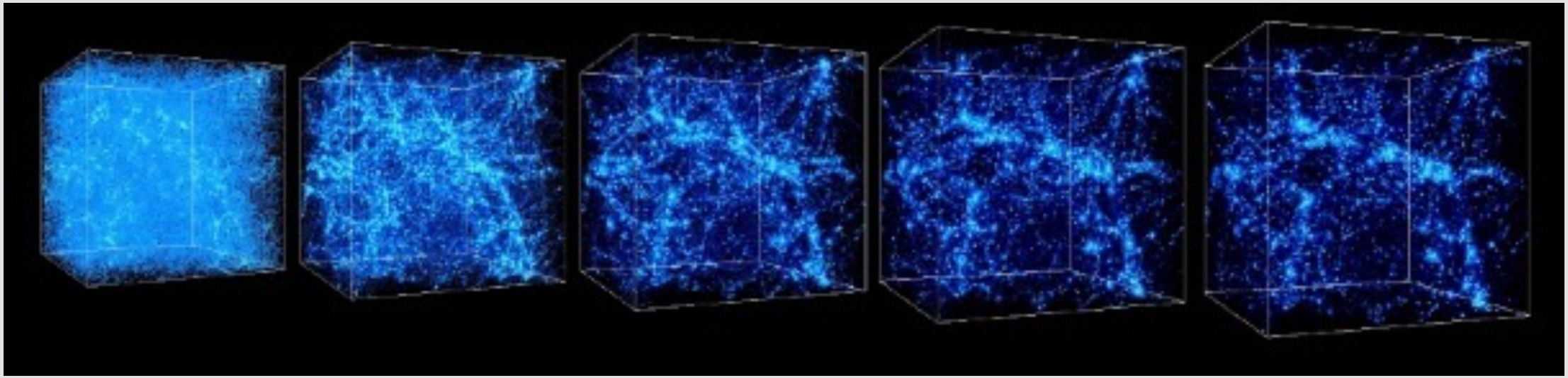


General Outline

- What are galaxy clusters and how do they form?
- How do we observe galaxy clusters?
- Highlights of some recent results from our group based on galaxy clusters

History of Structure Formation in the Universe

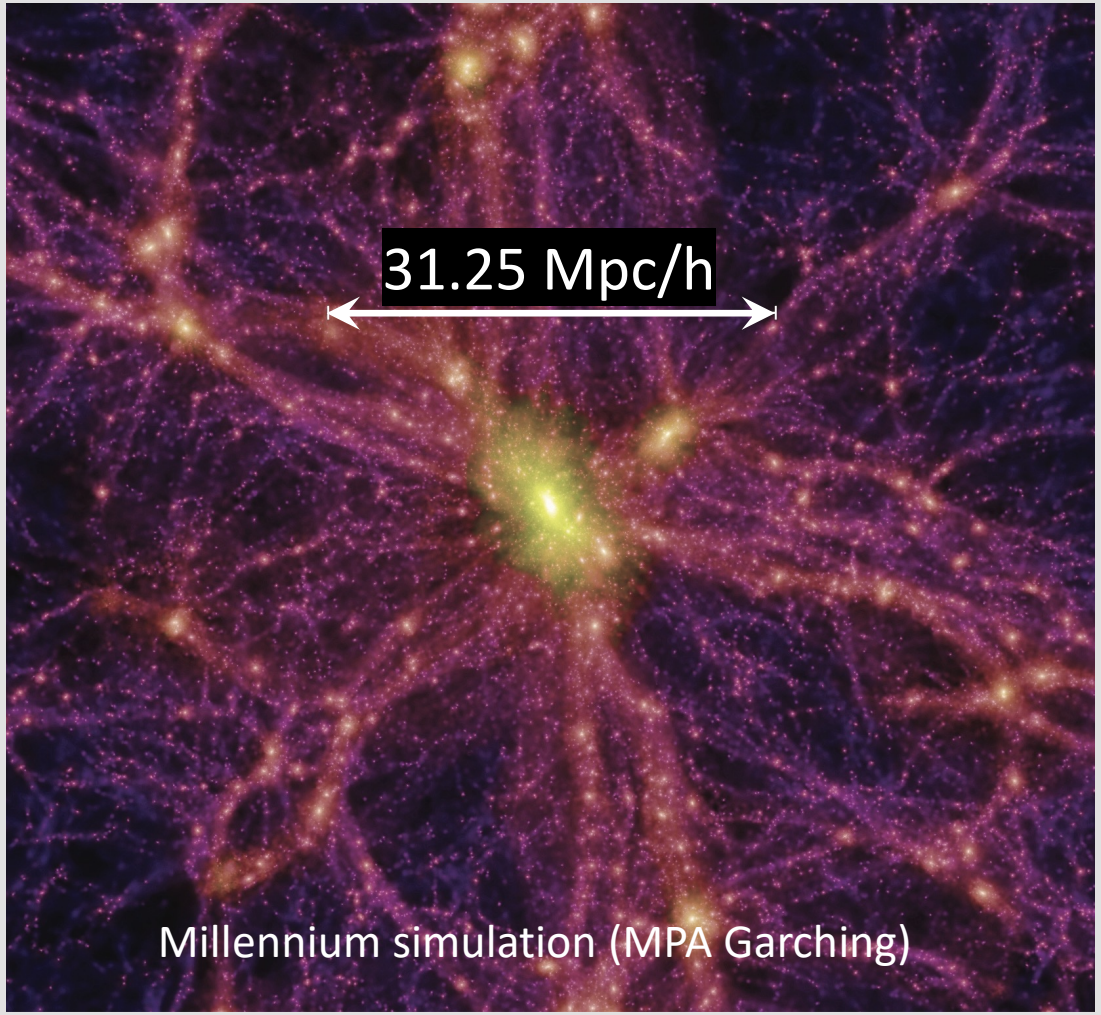
- The early universe was nearly homogeneous and isotropic
- Via gravity, slight overdensities accreted nearby material and grew non-linearly as the universe evolved
- Bound Objects, like stars and galaxies, eventually formed
- These objects continue to grow, with galaxy clusters (~ 1000 galaxies) representing the largest structures in the current universe



Simulations from z = 10 to z = 0 (KICP – University of Chicago)

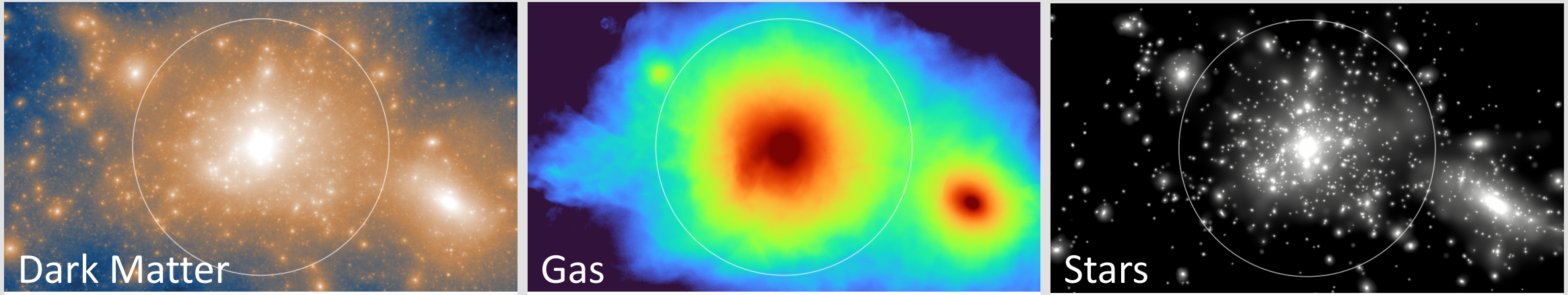
History of Structure Formation in the Universe

- Matter collapses into a web of filaments
- Largest objects form at nodes in the web
- Accretion of new material occurs mainly along filaments
- Growth occurs from both diffuse material and major mergers (in roughly equal ratios for galaxy clusters)



What Are Galaxy Clusters?

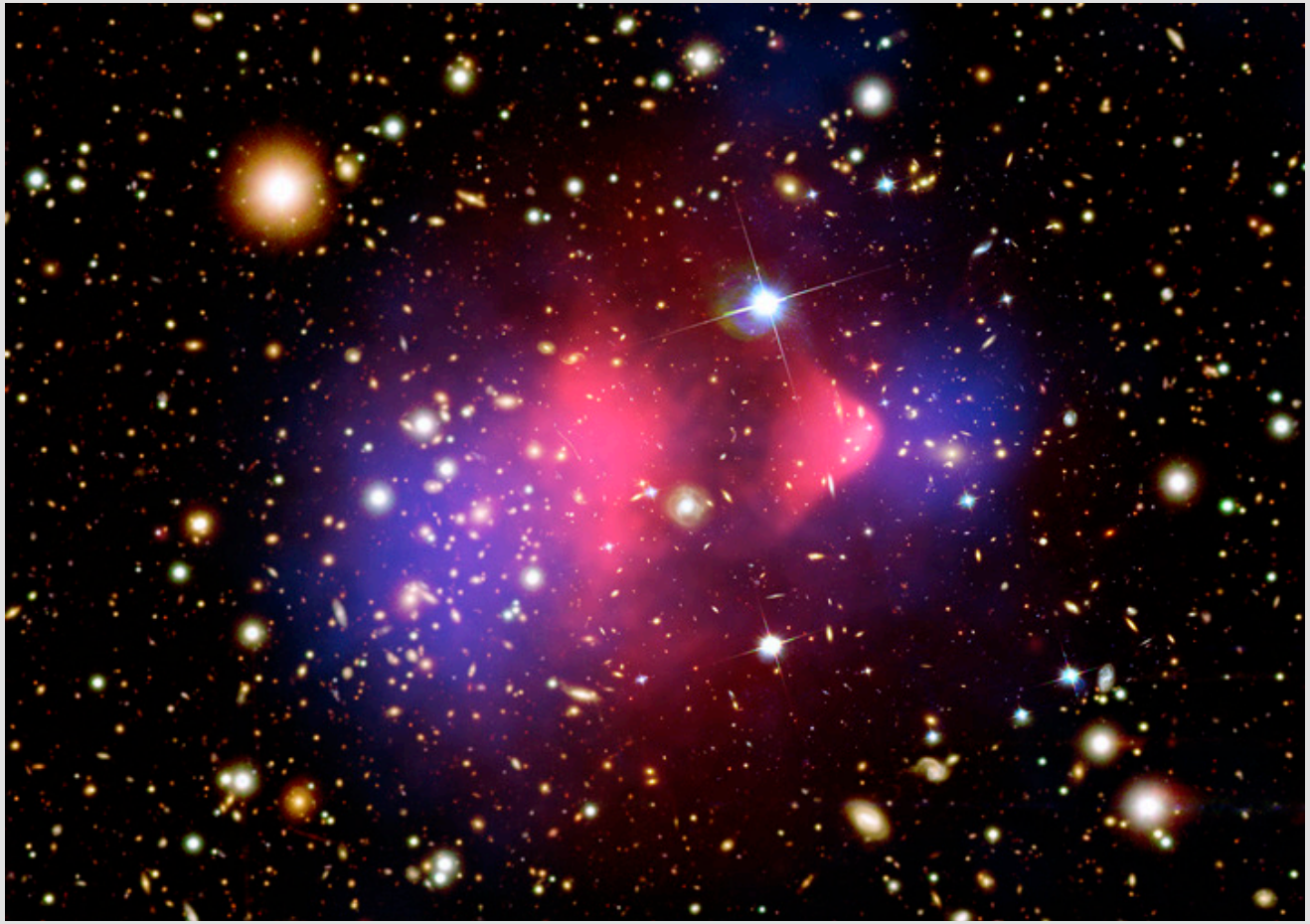
- Composition well matched to the universe as a whole (i.e., approximately 85% dark matter and 15% baryons)
- Very few of the baryons are in stars (~10%)
- Most of the baryons are in a diffuse 10^8 Kelvin ionized gas (intra-cluster medium or ICM)



Simulation of dark matter, gas, and stellar density (Illustris TNG, Nelson+2023)

Why Should We Study Galaxy Clusters?

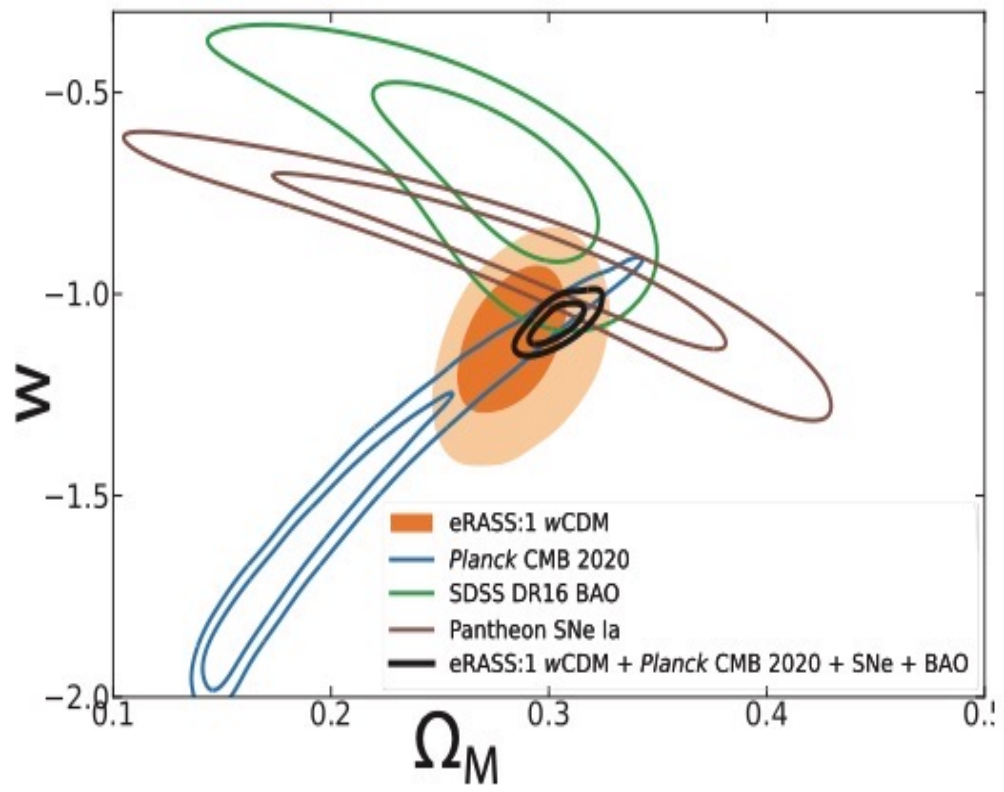
- They allow us to probe a wide range of astrophysics related to structure formation
- For example, merger induced shocks in the ICM are sensitive to a range of plasma physics (e.g., electron-ion equilibration, diffusion)
- Mergers can also probe the properties of dark matter - Bullet Cluster, Baby Bullet, etc.



The Bullet Cluster provides compelling evidence for dark matter with a small self-interaction cross section (Markevitch+, Clowe+)

Why Should We Study Galaxy Clusters?

- They are a sensitive probe of cosmology, and are particularly useful in breaking parameter degeneracies in other probes (e.g., CMB)
- "Classical" cluster cosmology is based on abundance measurements (i.e., N(M,z))
- Many other options (e.g., f_{gas}, H_0, clustering of clusters, cosmological velocity field)



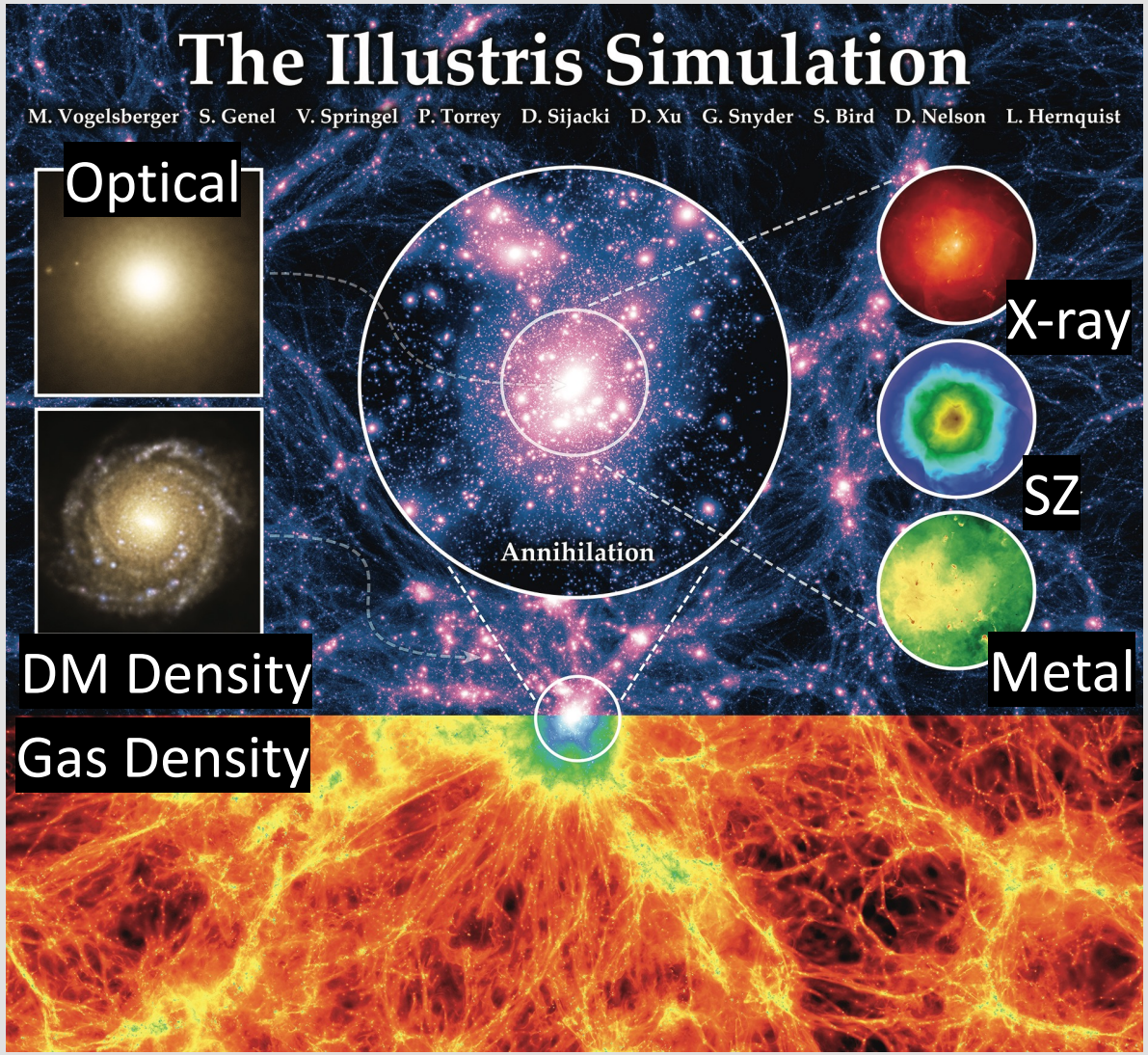
eROSITA Cluster constraints on dark energy equation of state (w) and matter density (Ω_m) – Ghirardini+2024

Quick Notes on Jargon/Terminology

- Masses are generally quoted within spherical apertures based on an average enclosed overdensity Δ
  - Common values for Δ are 2500, 500, and 200 times the critical density of the universe (200 is approximately the virial radius)
  - Sometimes also defined relative to matter density (e.g., "200m")
  - The radius corresponding to this sphere is also commonly used (e.g., "R_{500}")
- Simple models based on spherical tophats and gravity result in "self-similar" scalings that are approximately obeyed
  - For example, $P_{500} \sim (M_{500})^{2/3}\, E(z)^{8/3}$, where $H(z) = H_0 E(z)$
- Typical values for massive galaxy clusters are:
  - $M_{500} \sim 10^{15}\, M_\odot$; $R_{500} \sim 1$ Mpc; $T_{500} \sim 10$ keV (10^8 K)

How Do We Observe Galaxy Clusters?

- Optical/UV/IR
  - Cluster-member galaxy luminosities, velocities
  - Gravitational lensing
- X-ray
  - Direct emission from ICM
- Submm/mm
  - CMB scattering with ICM
- Radio
  - Relativistic electrons in magnetic fields

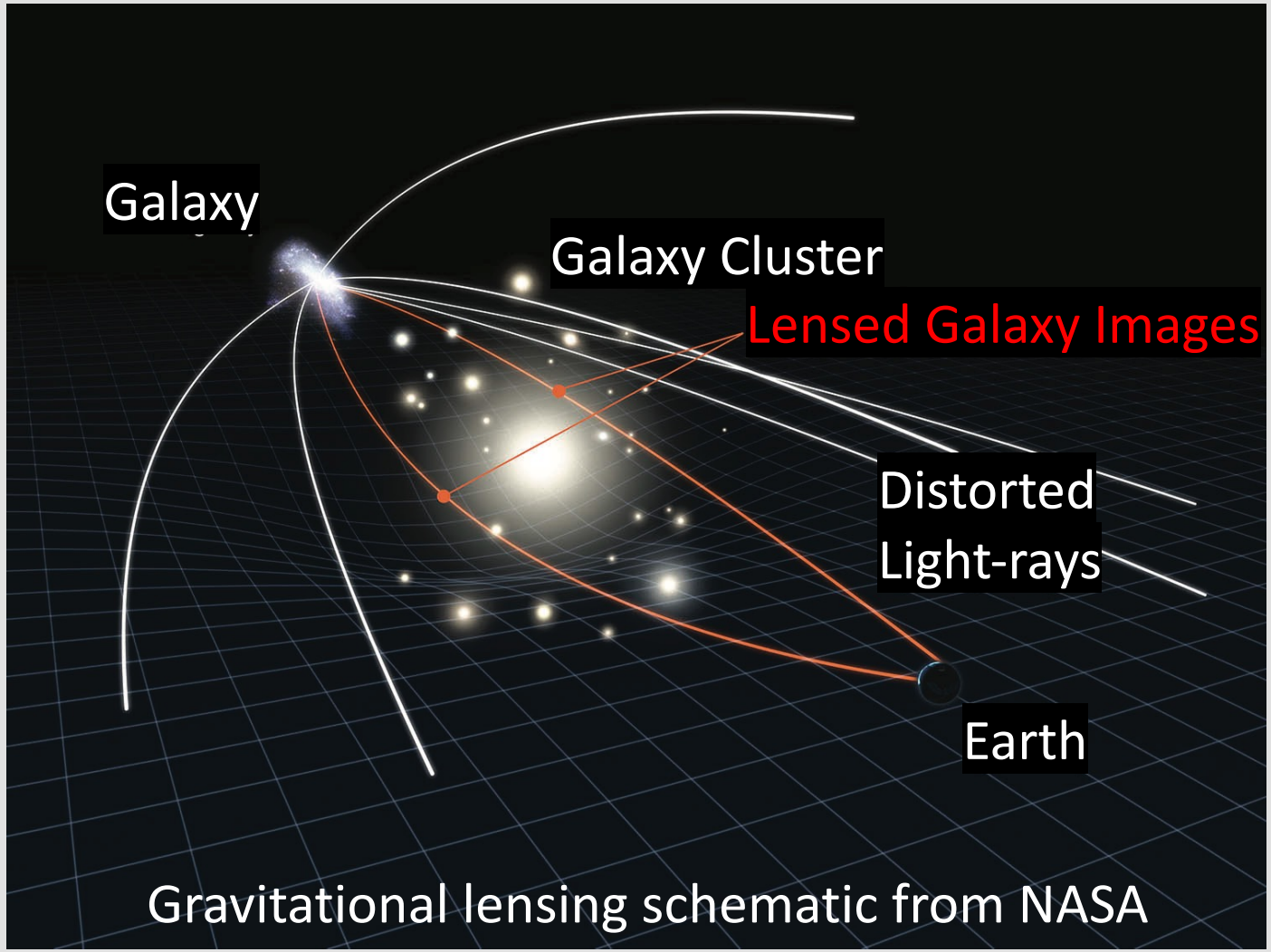


OUVIR Image of a Galaxy Cluster

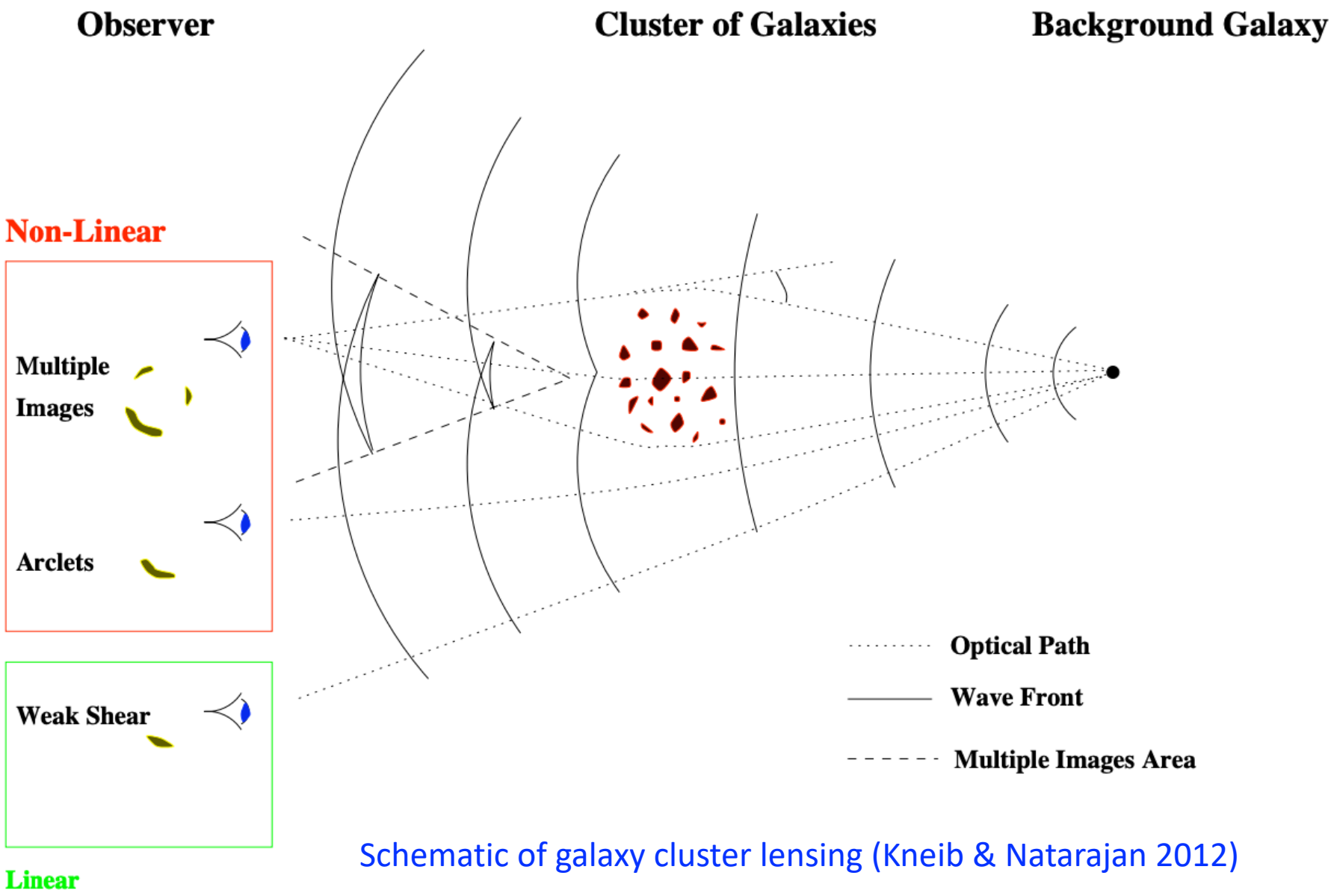
- Galaxy clusters are mainly filled with old elliptical galaxies
  - Yellowish in this Hubble Image
- Centrally located brightest cluster galaxy (BCG) that is a massive elliptical
- Classical optical detection works by counting the number of member galaxies (i.e., richness, N_{gal})

Gravitational Lensing

- The galaxy cluster's mass distorts space-time
- It thus acts as a lens on background objects (e.g., galaxies)
- By measuring the distortions and magnifications of the background galaxies we can determine the mass distribution of the cluster



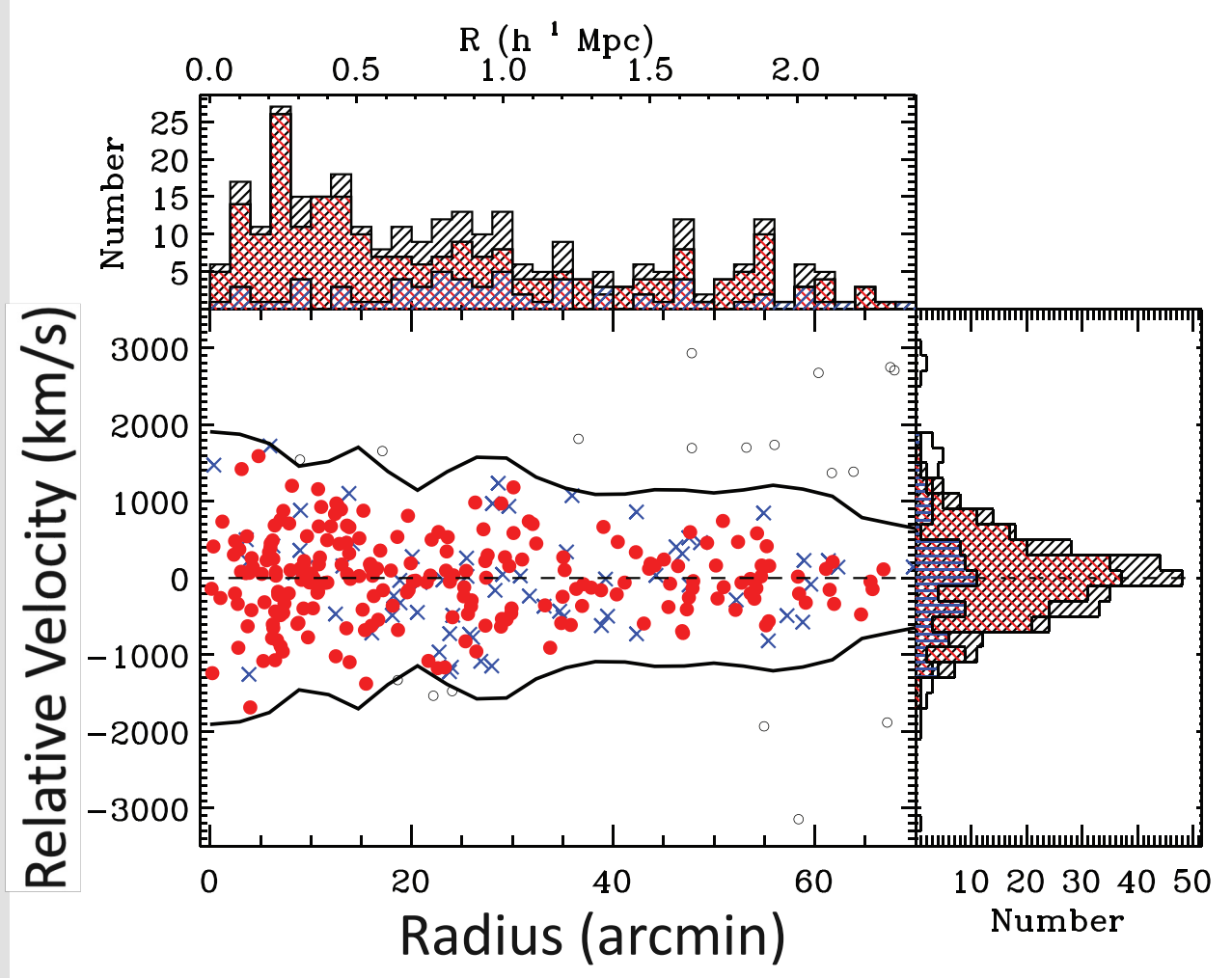
Gravitational lensing schematic from NASA



Schematic of galaxy cluster lensing (Kneib & Natarajan 2012)

Cluster-Member Velocity Measurements

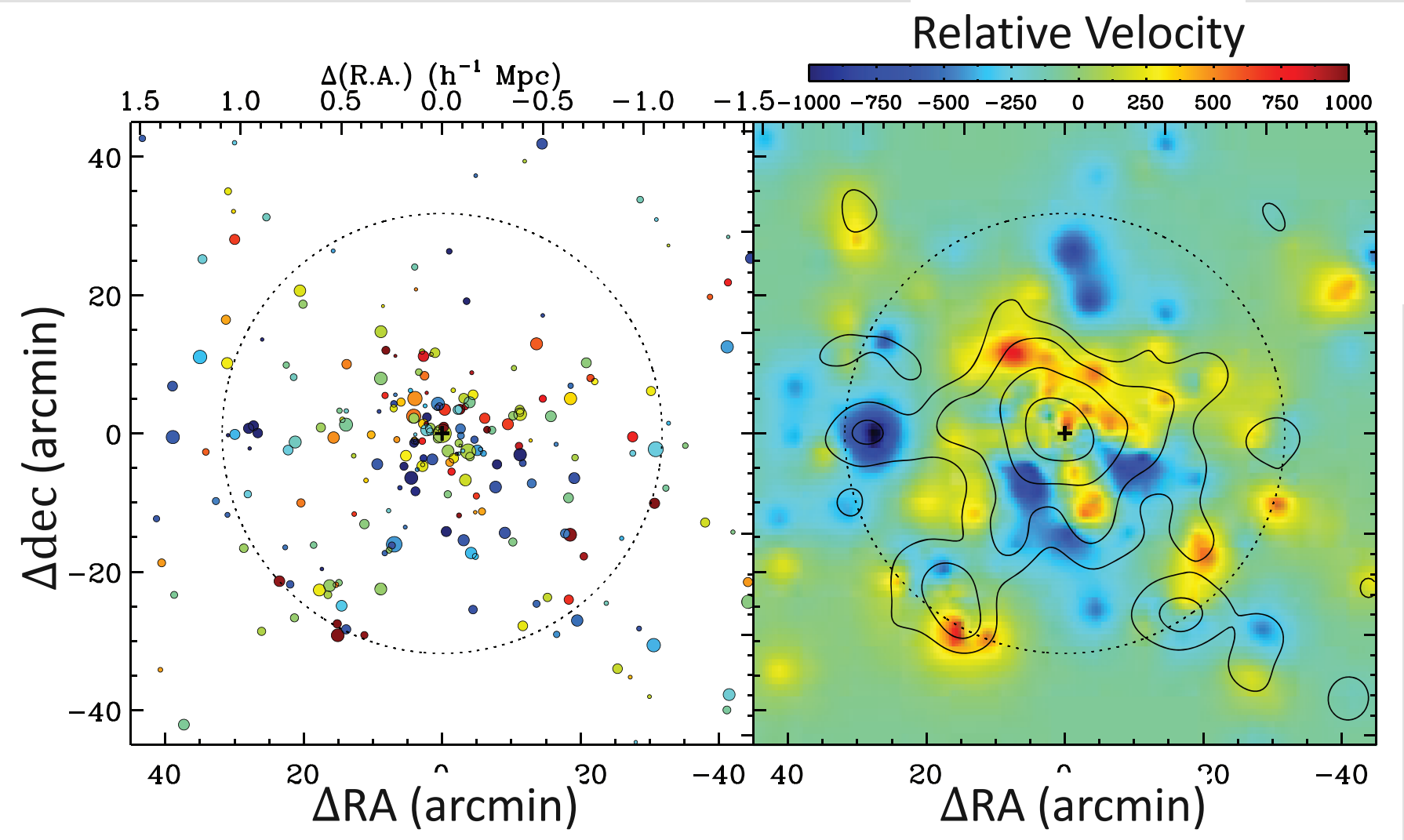
- Spectroscopically measure emission and/or absorption lines to obtain redshifts of member galaxies
- Can then compute velocities relative to the average redshift
- Estimate total galaxy cluster mass from velocity distribution



Galaxy velocities in Abell 2107 (Song+2012)

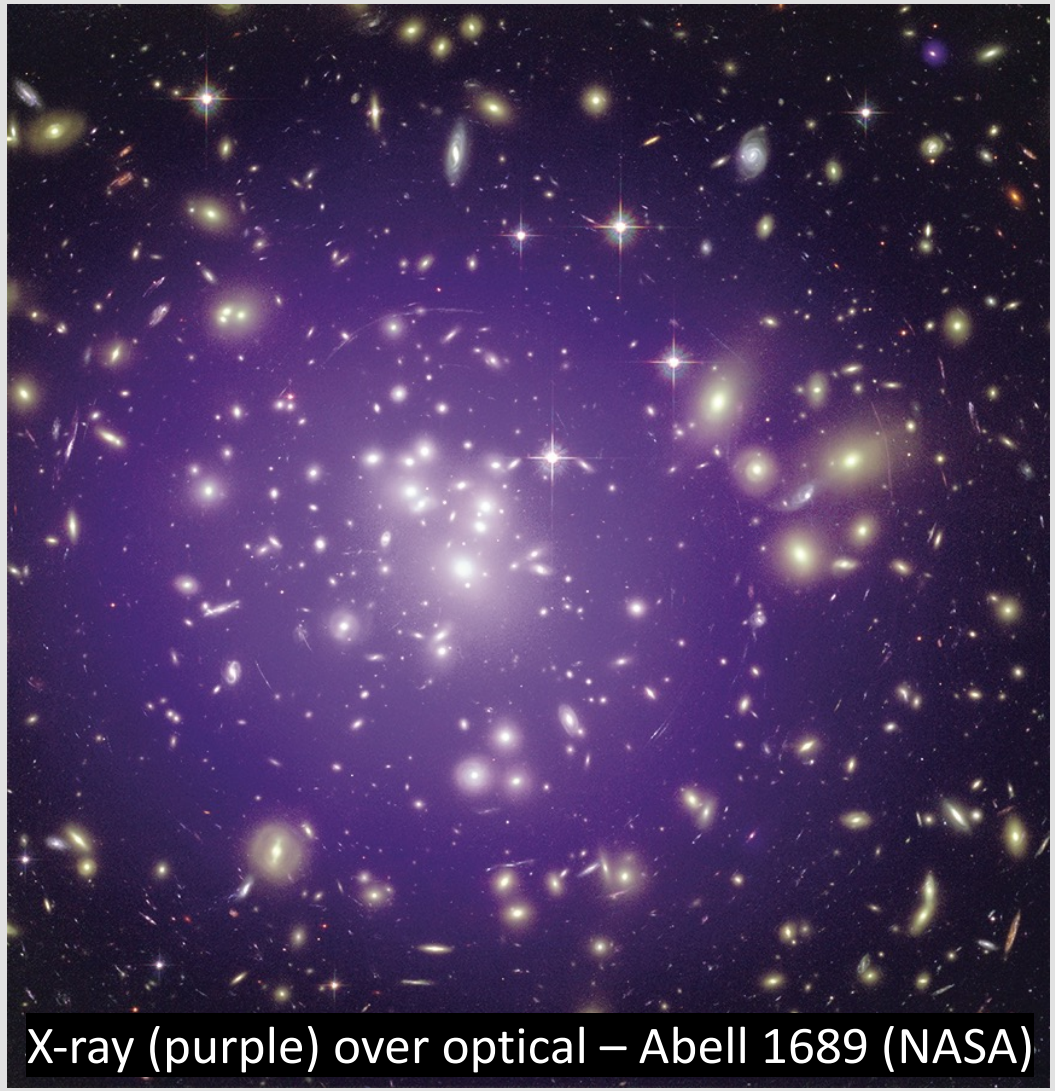
Cluster-Member Velocity Measurements

- Also 2-D map of line of sight (LOS) velocity structure
  - Tracing dark matter
- Example from Song+2012 for Abell 2107



X-ray Images of Galaxy Clusters

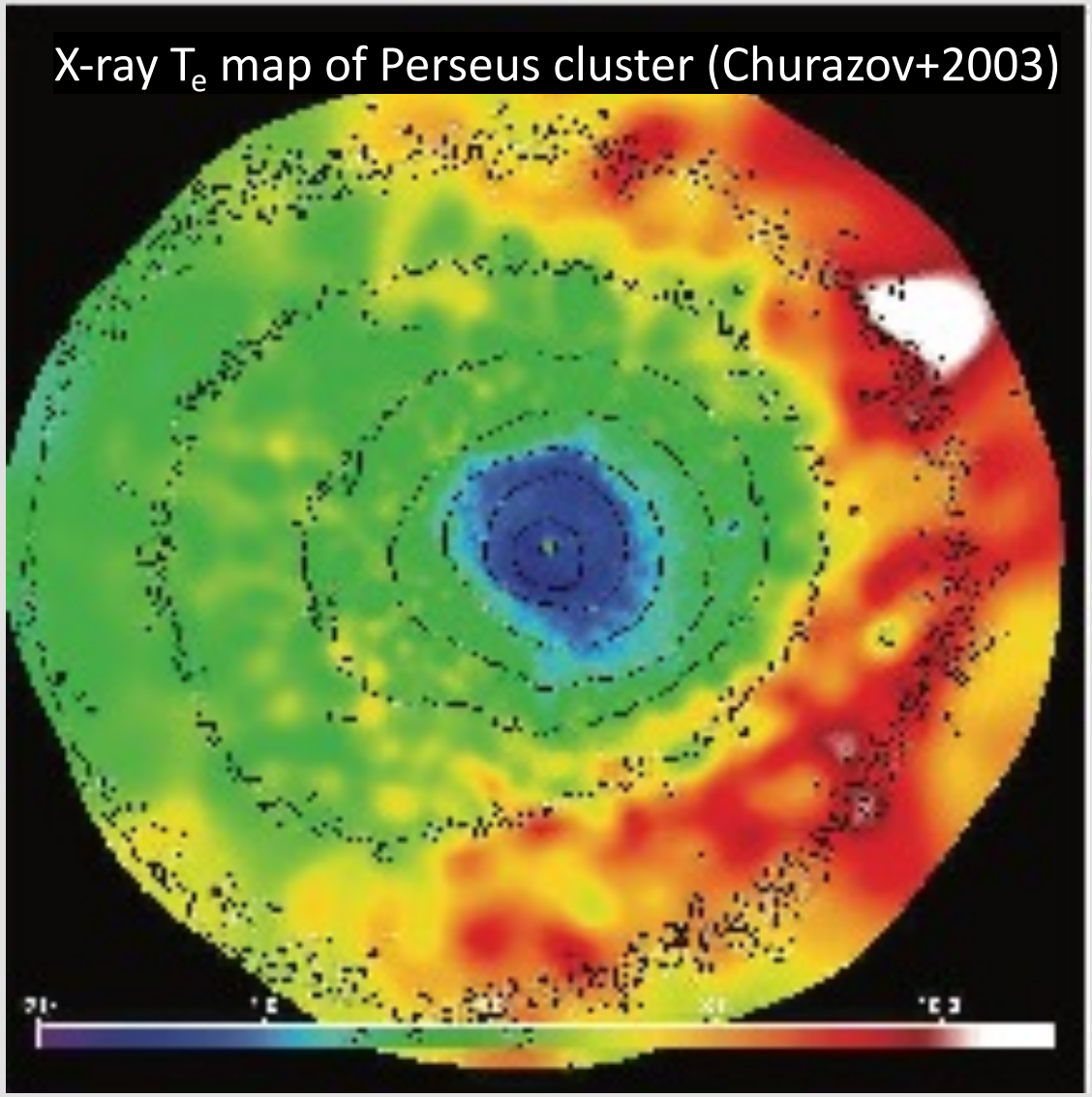
- ICM directly emits thermal bremsstrahlung
  - Electron accelerated by an ion
- X-ray brightness is therefore proportional to $n_e \times n_i \sim n_e^2$
- The spectral shape of the X-ray signal can be used to measure temperature T_e
  - X-ray luminosity well established for survey detection (*ROSAT, eROSITA*)
  - Also for detailed studies (*Chandra, XMM*)



X-ray (purple) over optical – Abell 1689 (NASA)

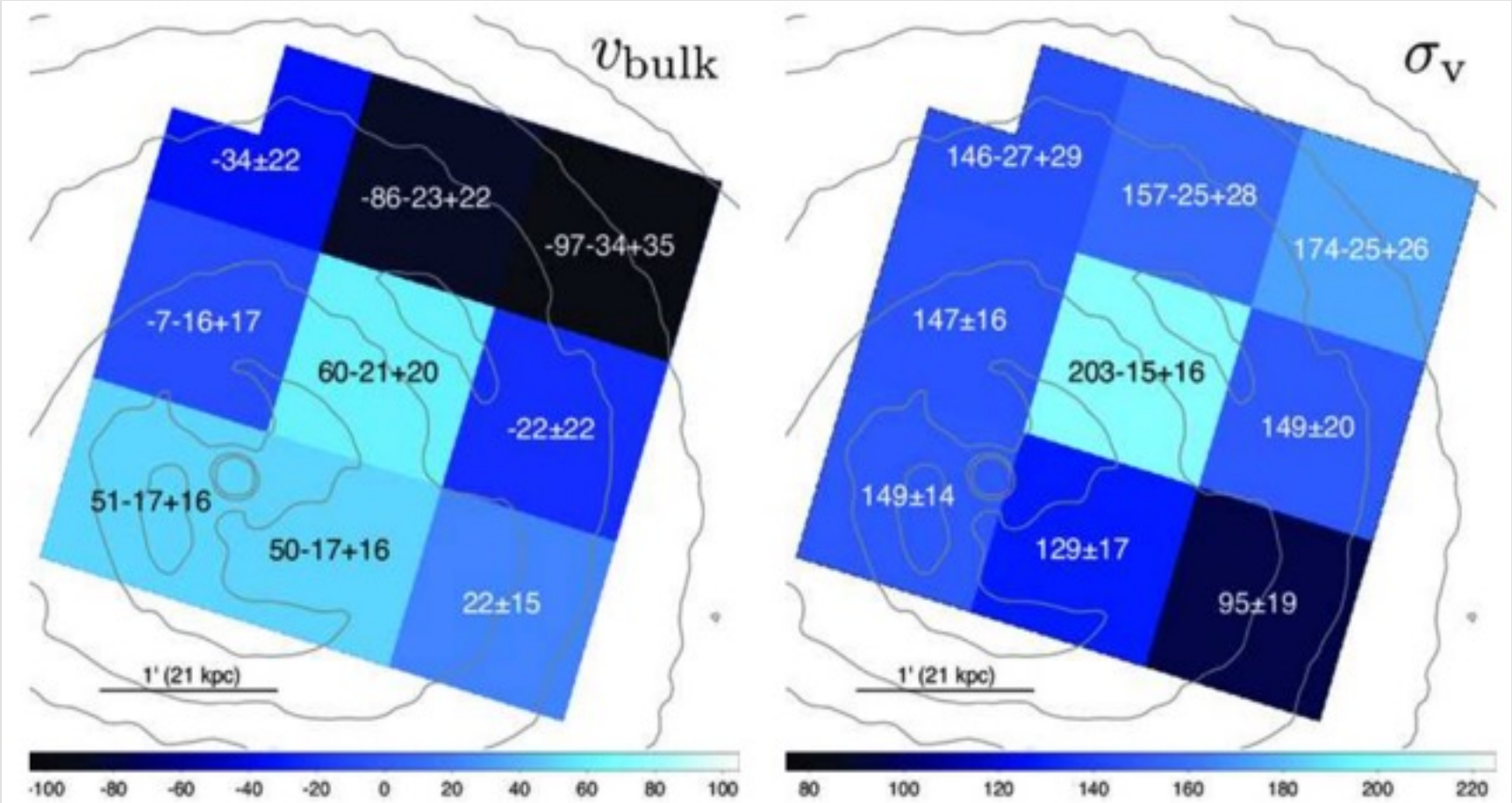
X-ray ICM Thermodynamics

- X-rays fully constrain ICM thermodynamics
  - n_e via surface brightness
  - T_e via spectroscopy
- Can therefore derive other characteristics of the ICM
  - Pressure
  - Entropy
  - Hydrostatic equilibrium (HSE) mass



X-ray ICM Velocity Measurements

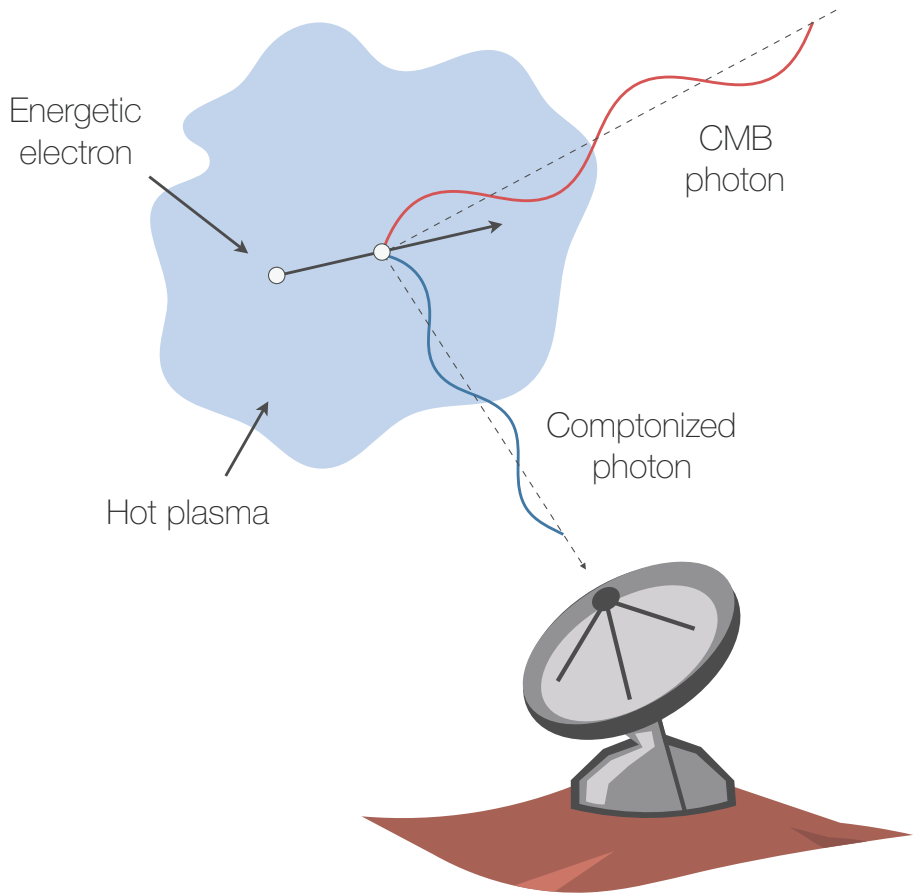
- X-ray spectroscopy -> redshifts (v), line broadening (σ_v)
- One cluster observed with *Hitomi*, waiting for *XRISM*, *Athena*, *Lynx*



ICM velocity (left) and dispersion (right) for Perseus cluster (Hitomi Collaboration 2018)

Sunyaev-Zel'dovich Effects

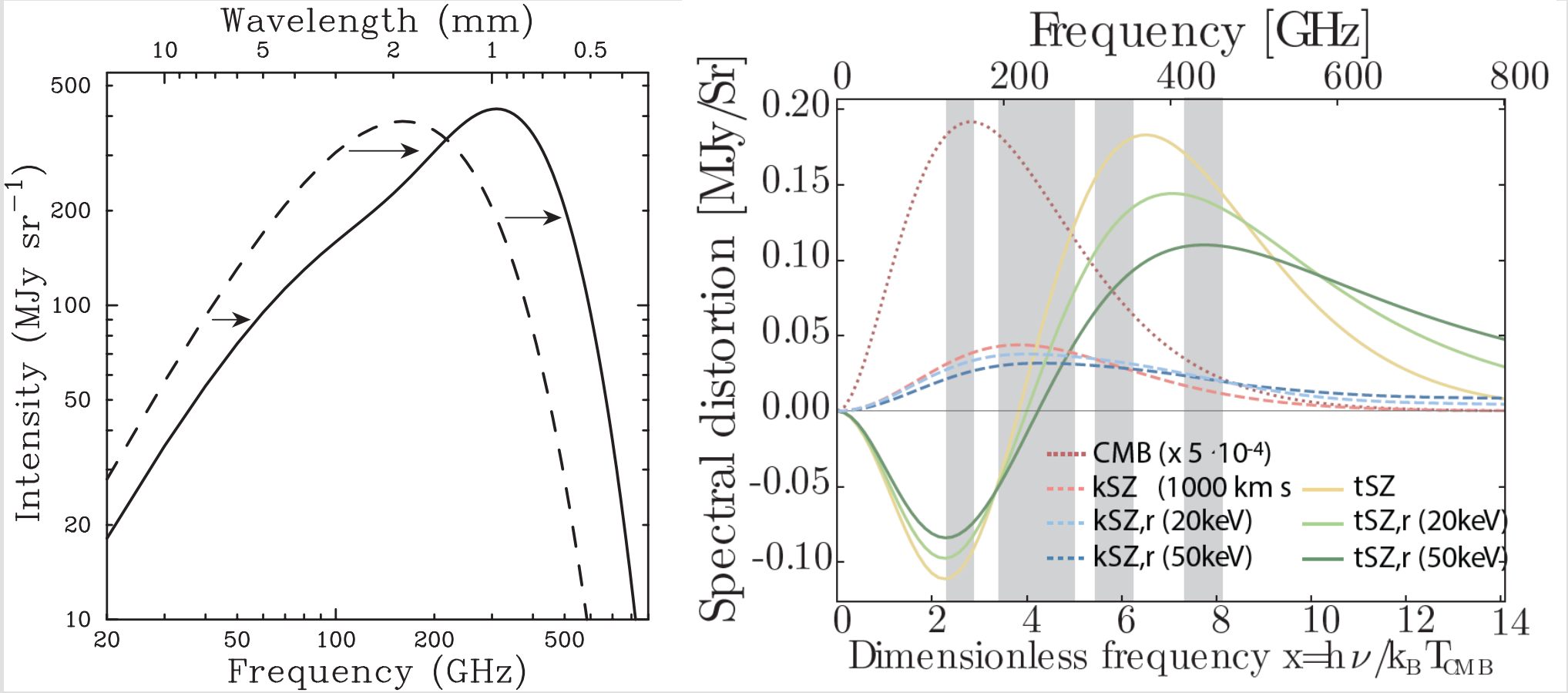
- Cosmic microwave background (CMB) photons scatter with ICM electrons
  - Described by Sunyaev-Zel'dovich effects (SZE)
- Thermal SZE (tSZE)
  - Compton scattering of CMB photons with hot ICM electrons
  - Used to detect clusters in large surveys (*Planck, ACT, SPT*)
- Kinematic SZE (kSZE)
  - Doppler shift due to LOS velocity of ICM electrons



Schematic of the SZ effect (Mroczkowski+2018)

Sunyaev-Zel'dovich Effects

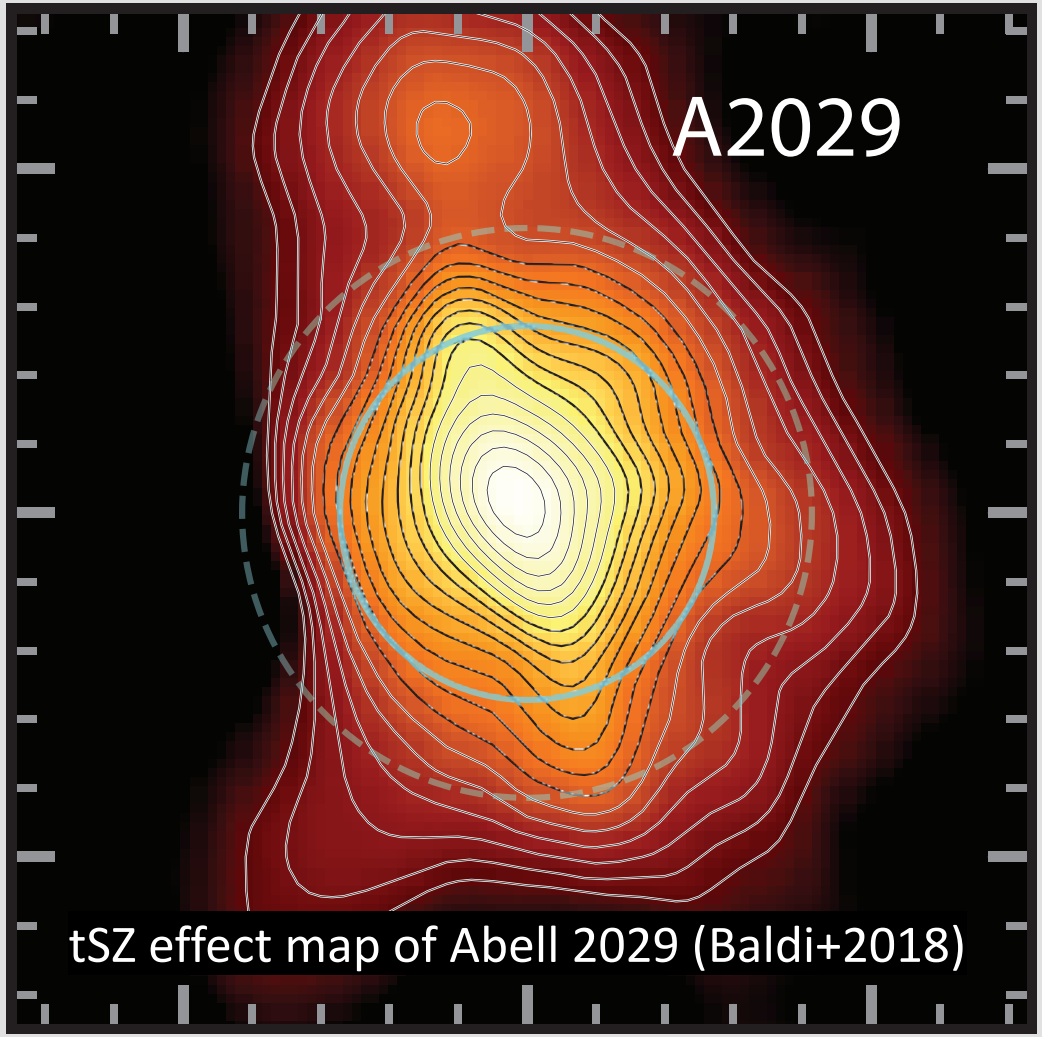
- ICM electron v/c ~ 0.01, and so there are also non-negligible relativistic corrections to the SZ effects (rSZE)



Thermal SZ shift (Carlstrom+2002) and net distortion of CMB (Mroczkowski+2018)

Thermal Sunyaev-Zel'dovich Effect

- The energy transfer per scattering is proportional to temperature T_e
- The number of scattering events is proportional to n_e
- The tSZ effect is thus proportional to P_e
  - tSZ map is LOS integrated pressure
  - Recall that X-ray brightness is LOS integrated density squared

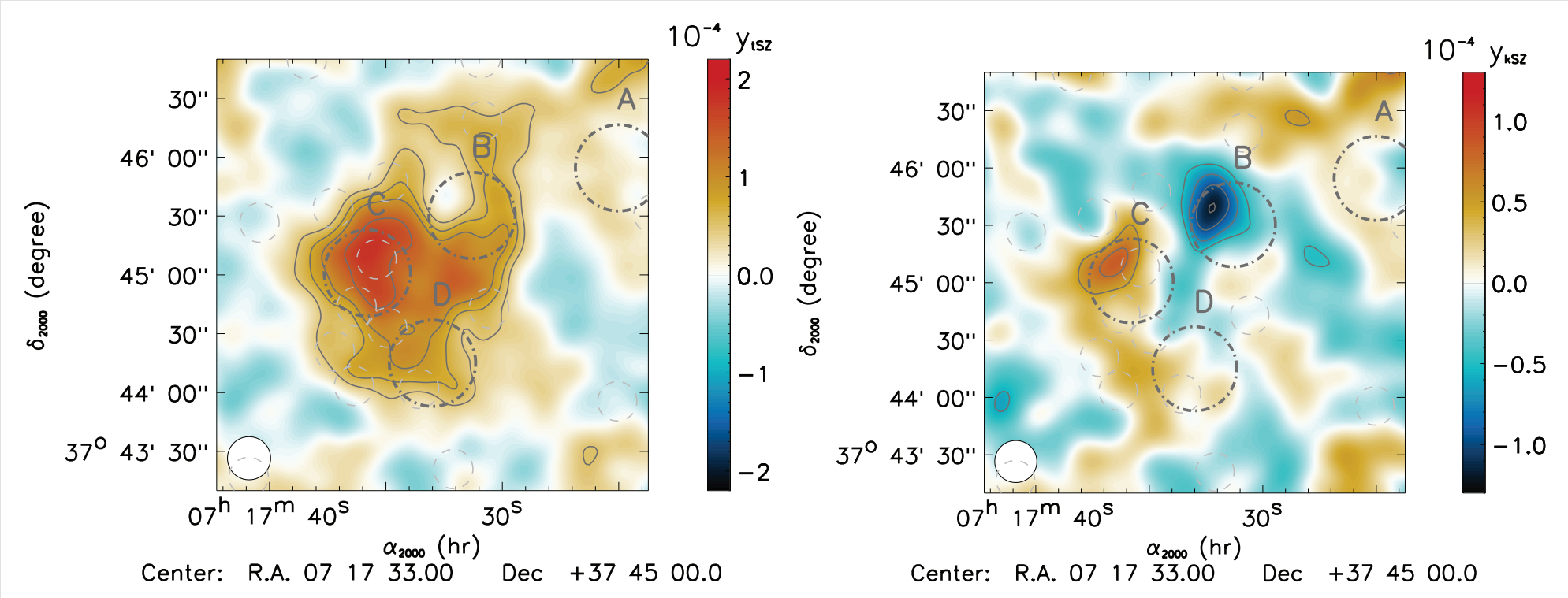


tSZ effect map of Abell 2029 (Baldi+2018)

Kinematic Sunyaev-Zel'dovich Effect

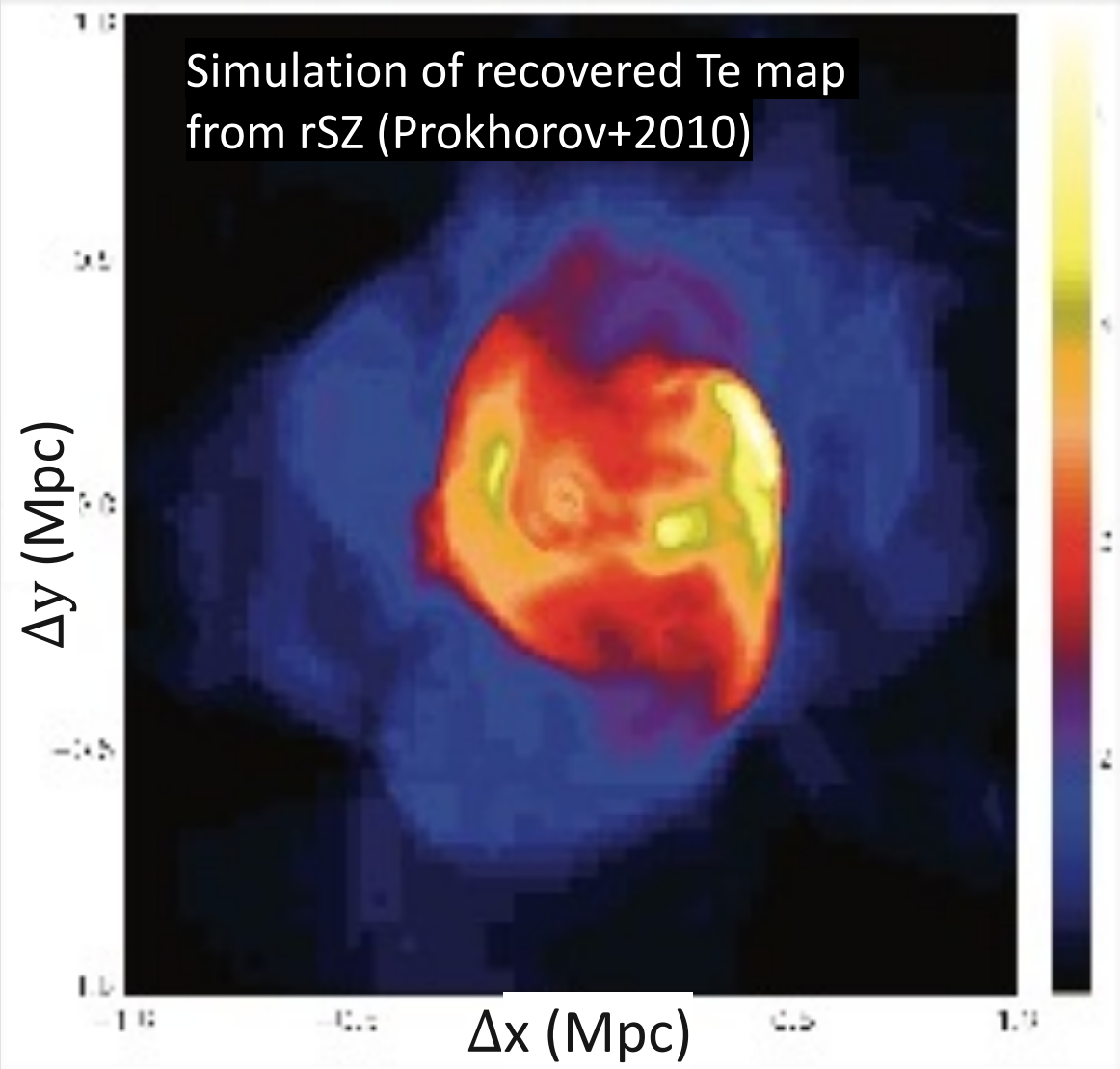
- Doppler shift per scattering proportional to v
- Total scatterings proportional to n_e
- Total kSZE thus proportional to momentum
  - Need independent constraint on n_e to obtain v
- Handful of low significance detections to date

tSZE map (left) and kSZE map (right) of MACS J0717.5 (Adam+2017)



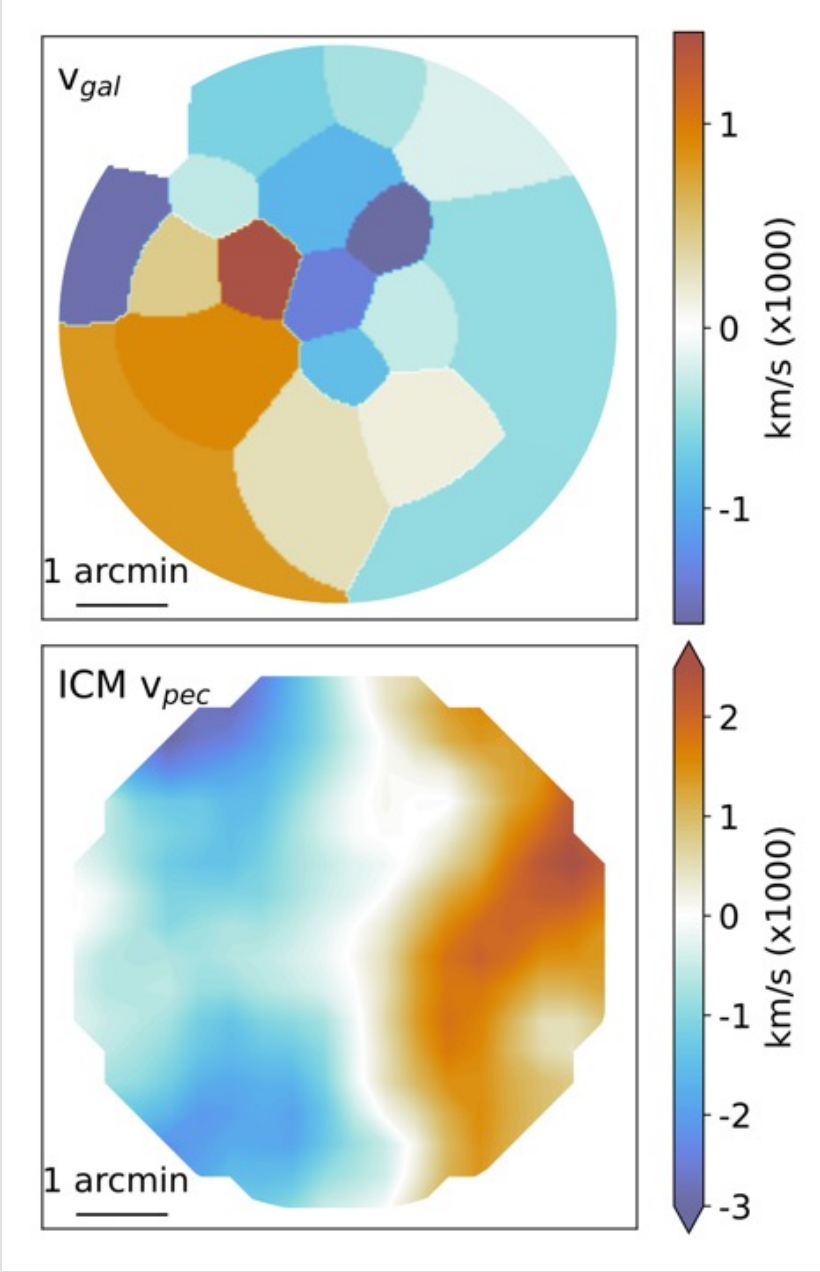
Relativistic Sunyaev-Zel'dovich Effect

- tSZE alone does not fully constrain ICM thermodynamics
- Need to also measure relativistic correction (rSZE) to constrain T_e
- Only marginal hints of detection to date



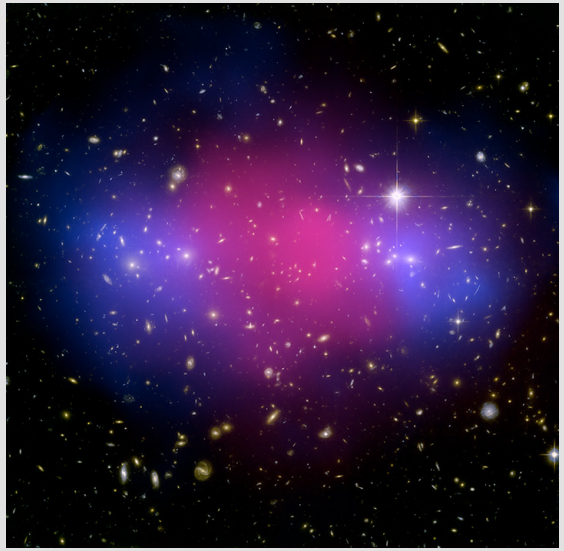
Galaxy Cluster Mergers (Silich+2024)

- Combining multi-probe data to study a sample of 8 mergers
  - Gas positions (X-ray SB, X-ray T, tSZE)
  - Gas velocity (kSZE)
  - Dark matter positions (lensing)
  - Dark matter velocity (galaxy spectra)
- First time gas velocity has been used for such studies
- We discovered a decoupling of the gas and dark matter velocities in MACS J0018.5+1626
  - Analogous to the positional decoupling found in previous studies



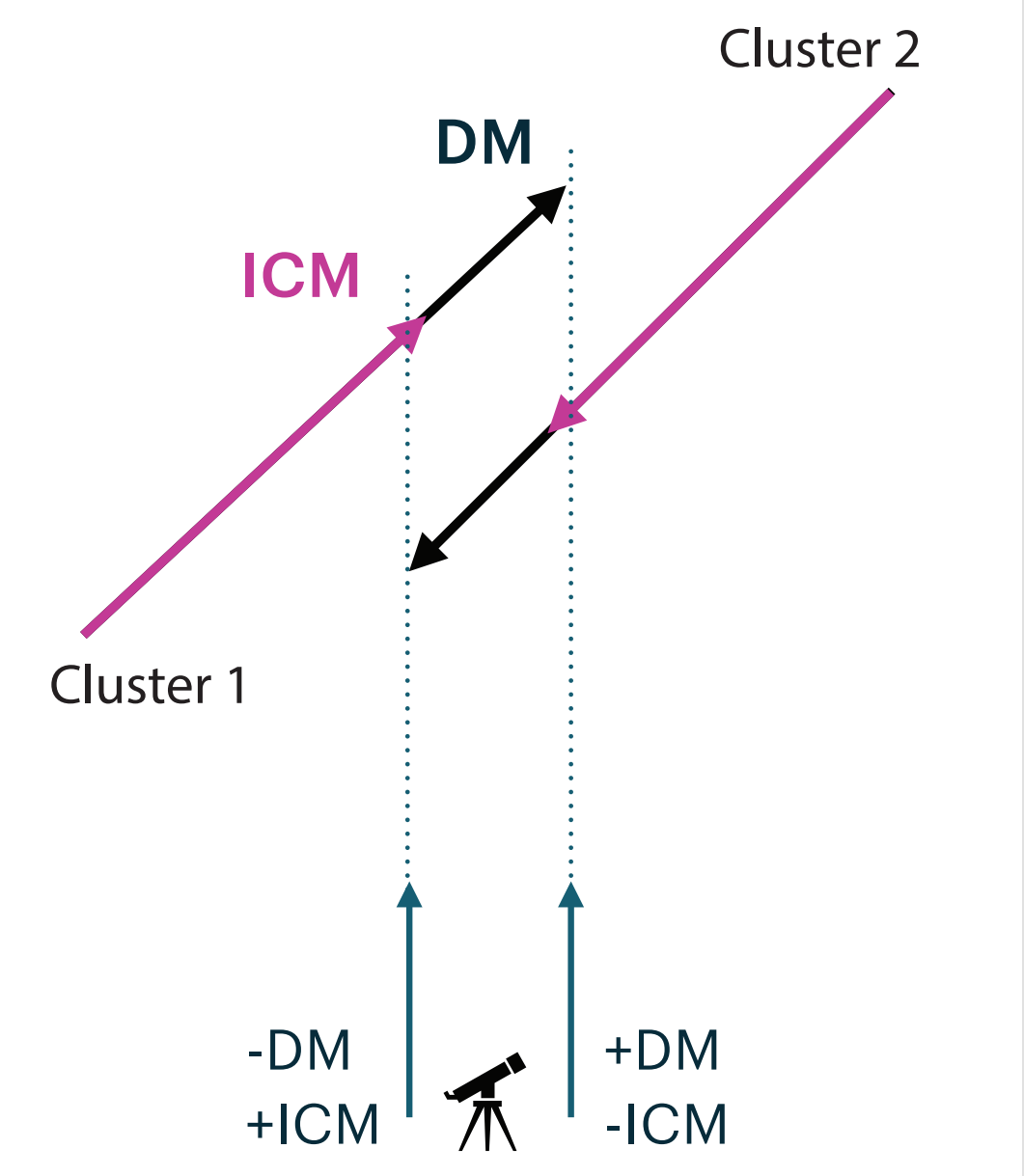
Far right: dark matter and gas velocity for MACS J0018.5+1626 (Silich+2024)

Right: positional decoupling of gas (pink) and dark matter (blue) in MACS J0025.4-1222 (Bradač+2008)



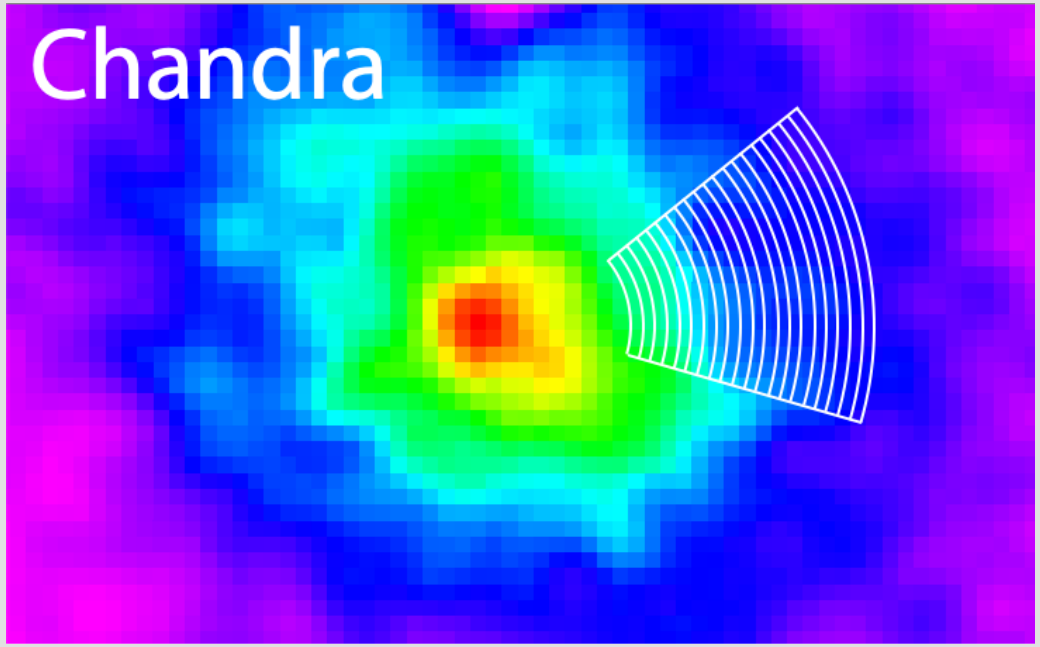
Galaxy Cluster Mergers (Silich+2024)

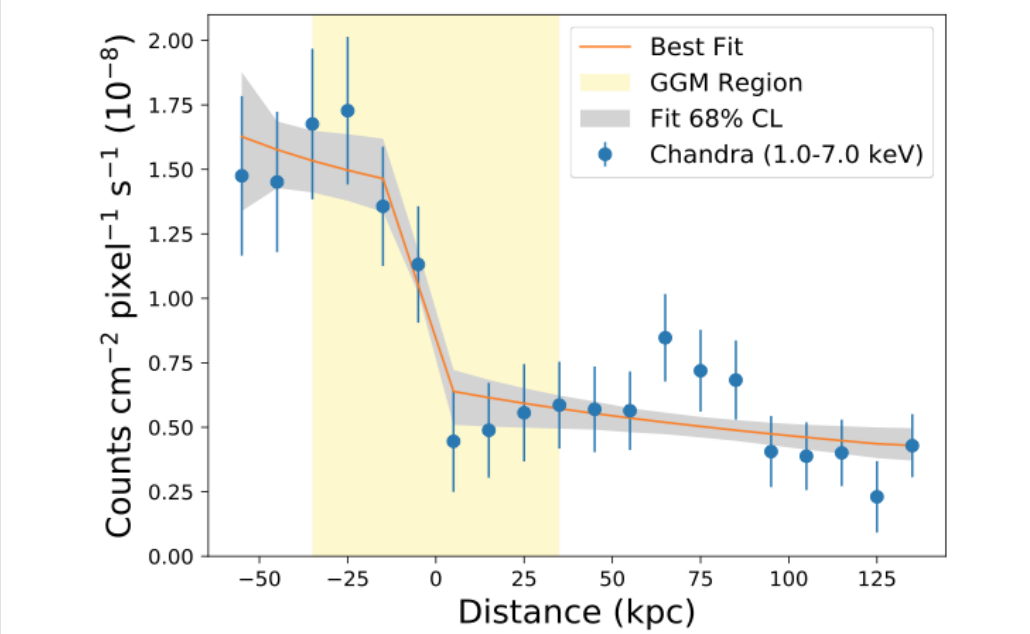
- How does this decoupling occur?
- ICM is collisional, and so it is slowed down during the merger relative to the dark matter
- From simulations - with the right combination of viewing angles, geometry, and epoch the decoupling can be observed
  - Velocity aligned close to line of sight, but not perfectly
  - Epoch near pericenter
- Rare - only seen in 1/8 clusters



Galaxy Cluster Mergers (Silich+2024)

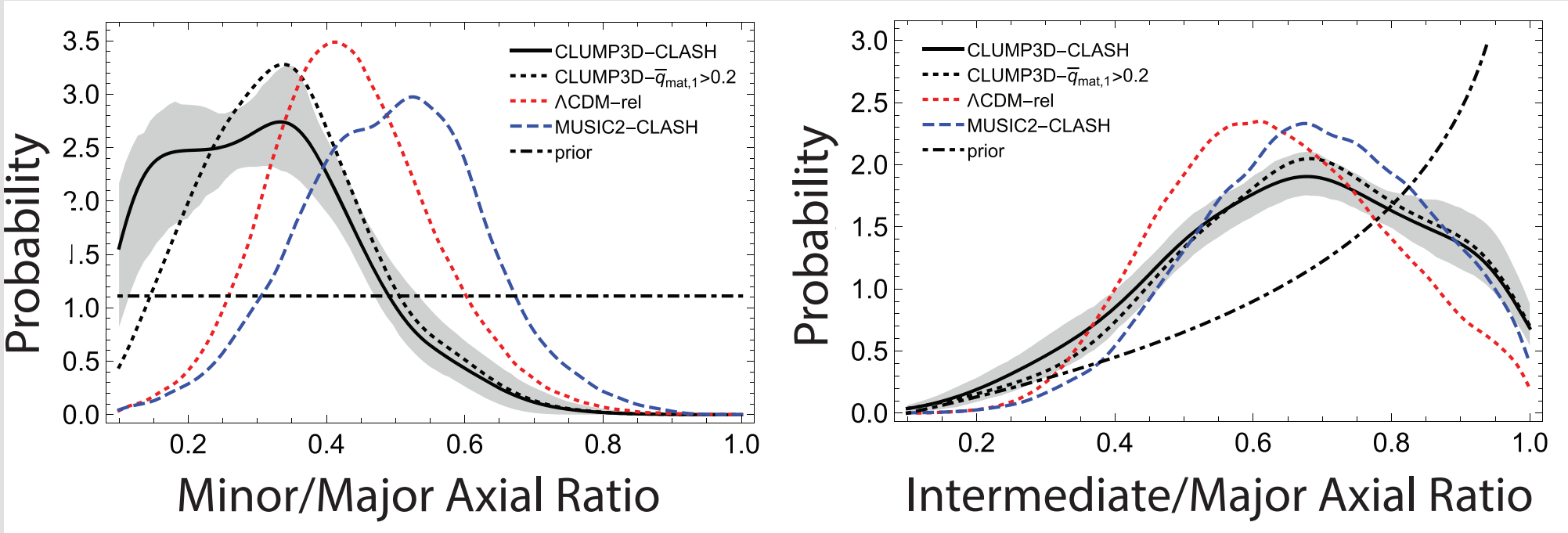
- From our analysis the geometry of MACS J0018.5 is well constrained
  - 0-60 Myr post-pericenter
  - Inclined 27-40 degrees from LOS
  - Impact parameter <250 kpc
  - Mass ratio of 1.5-3.0
  - Velocity of 1700-3000 km/s
- Still some mysteries
  - Potential shock to the WNW in *Chandra* would require much smaller inclination angles (<10 degrees from LOS)
- New data will soon be coming to better understand this unique system





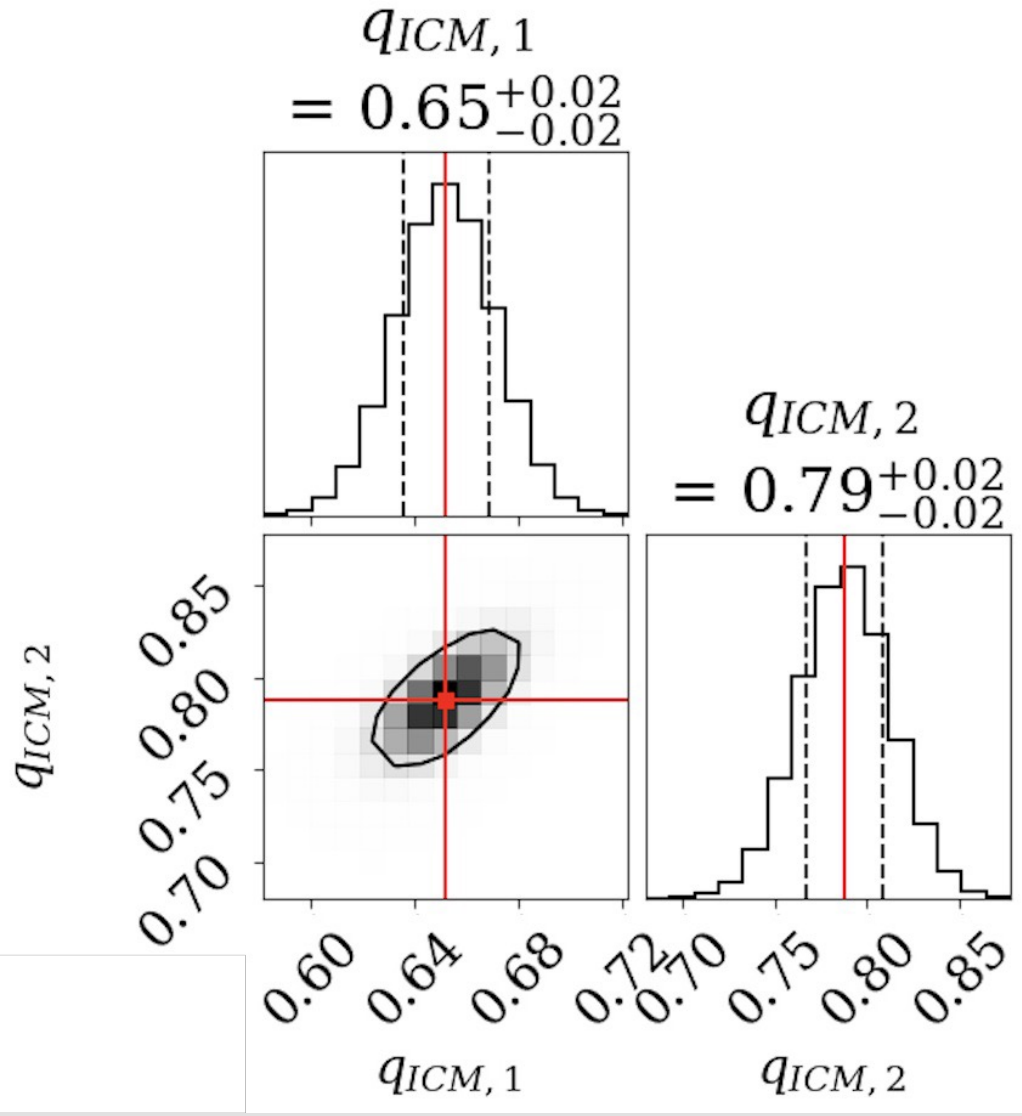
CLASH Triaxial Shapes (Sereno+2018)

- SZ brightness ~ $n_e T_e \Delta l$, X-ray brightness ~ $n_e^2 \Delta l$
  - Can constrain cluster LOS length $\Delta l \sim SZ^2 / (XR \times T_e^2)$ – POS given by 2D imaging
- Assume ICM and total mass co-aligned, fit 3-D triaxial shape to total mass
  - Sensitive to gravity/cosmology (e.g., self interacting dark matter makes clusters rounder and more recent formation time makes clusters more elongated)
- Hints of tension in minor/major axial ratio, but modest significance ($\sim 2\sigma$)



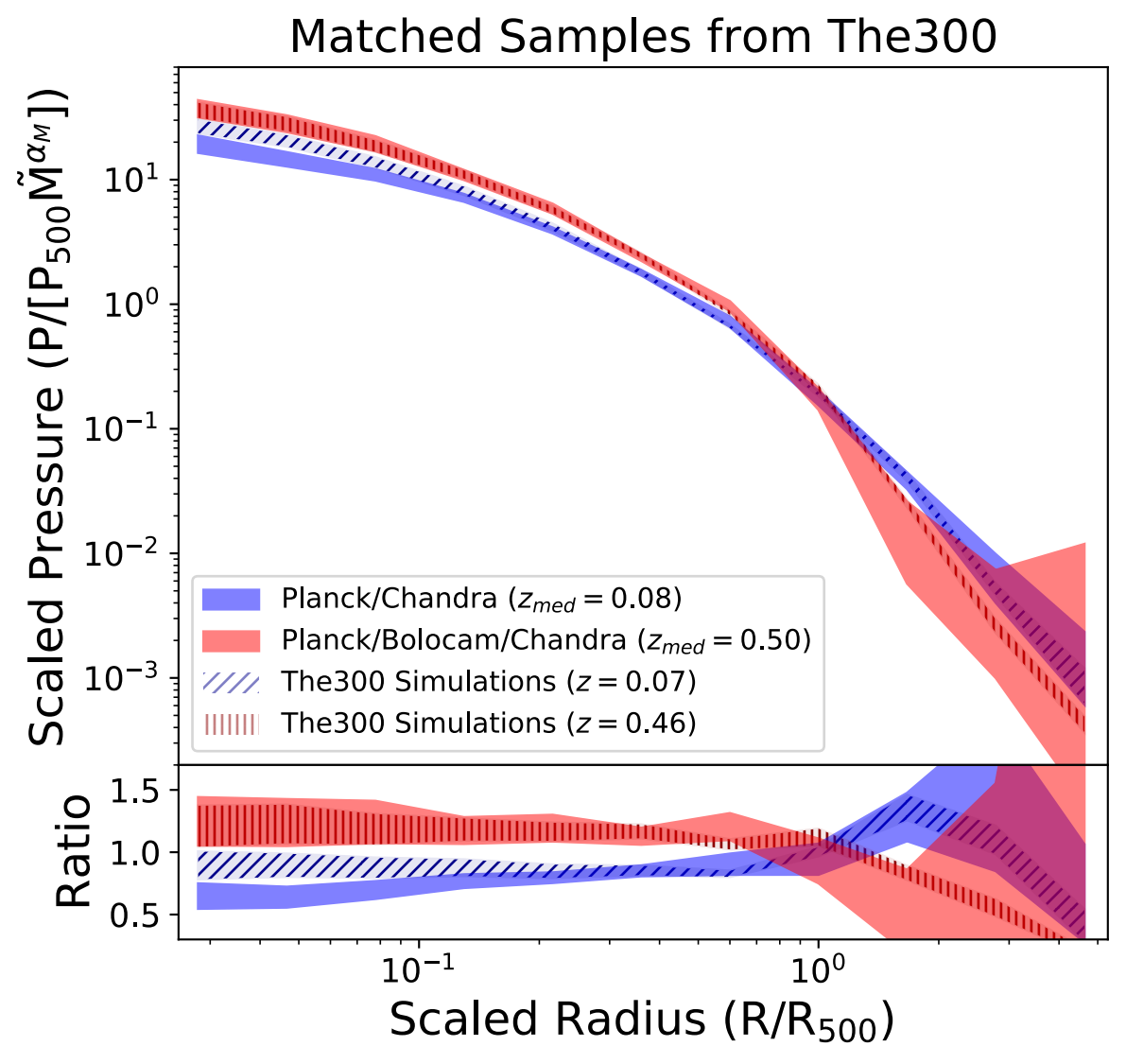
CHEX-MATE Triaxial Shapes (Kim+2024)

- CLASH had 20 clusters – we now have 118 clusters with CHEX-MATE
- Much better quality X-ray data
- Demonstration paper with one cluster illustrating precise constraints on axial ratios
  - Now working on extension to full CHEX-MATE sample
- Definitively test of the modest tension found in CLASH
  - Constrain SIDM cross section to $\pm$ 0.15 $cm^2\ g^{-1}$



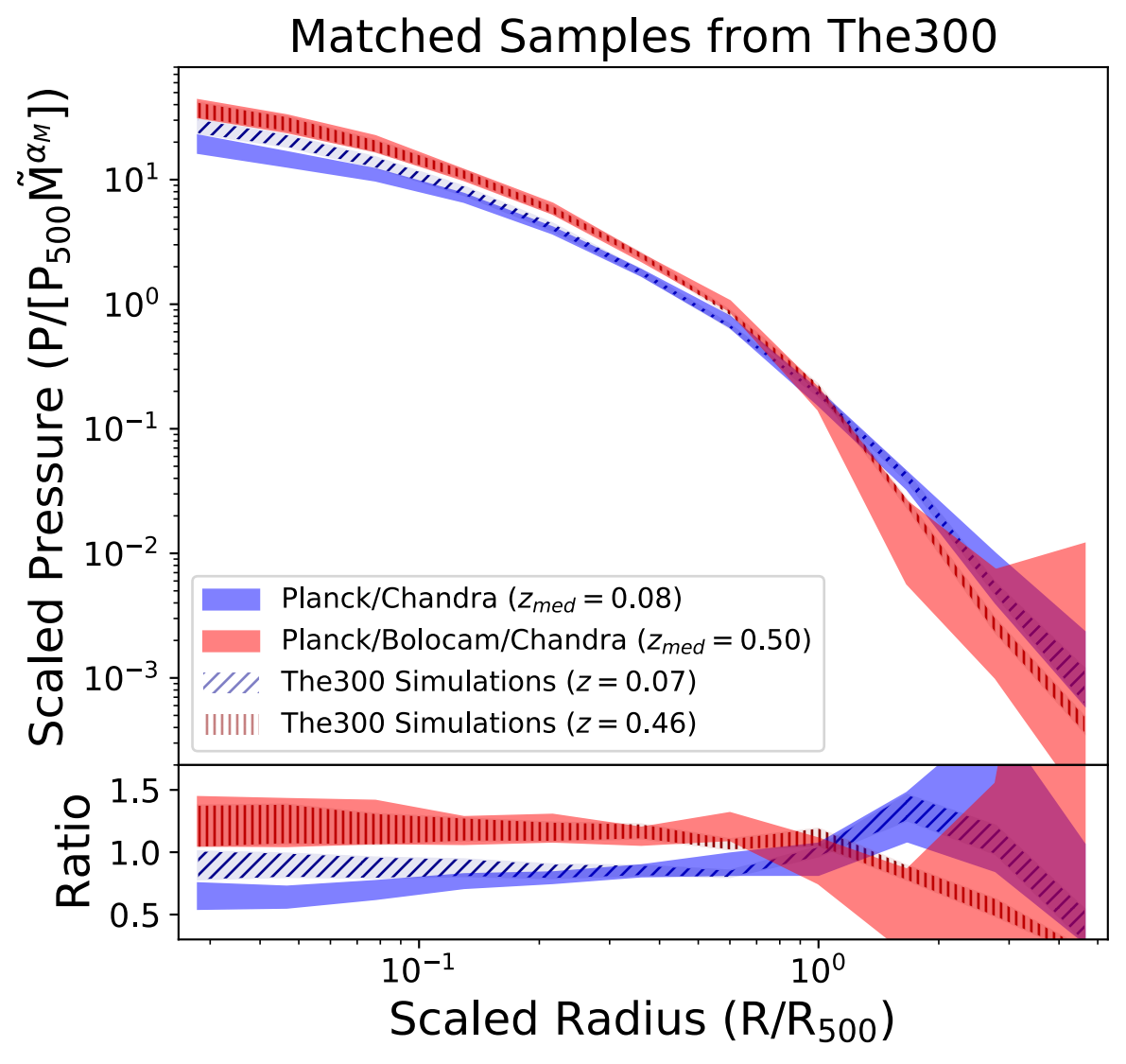
ICM Pressure Profile Shapes (Sayers+2023)

- Influenced by a range of processes, such as:
  - AGN feedback -> larger fractional impact in low mass systems resulting in flatter profiles at both small and large radii
  - Accreting clumps and non-thermal motions -> increase with redshift resulting in steeper profiles at large radii



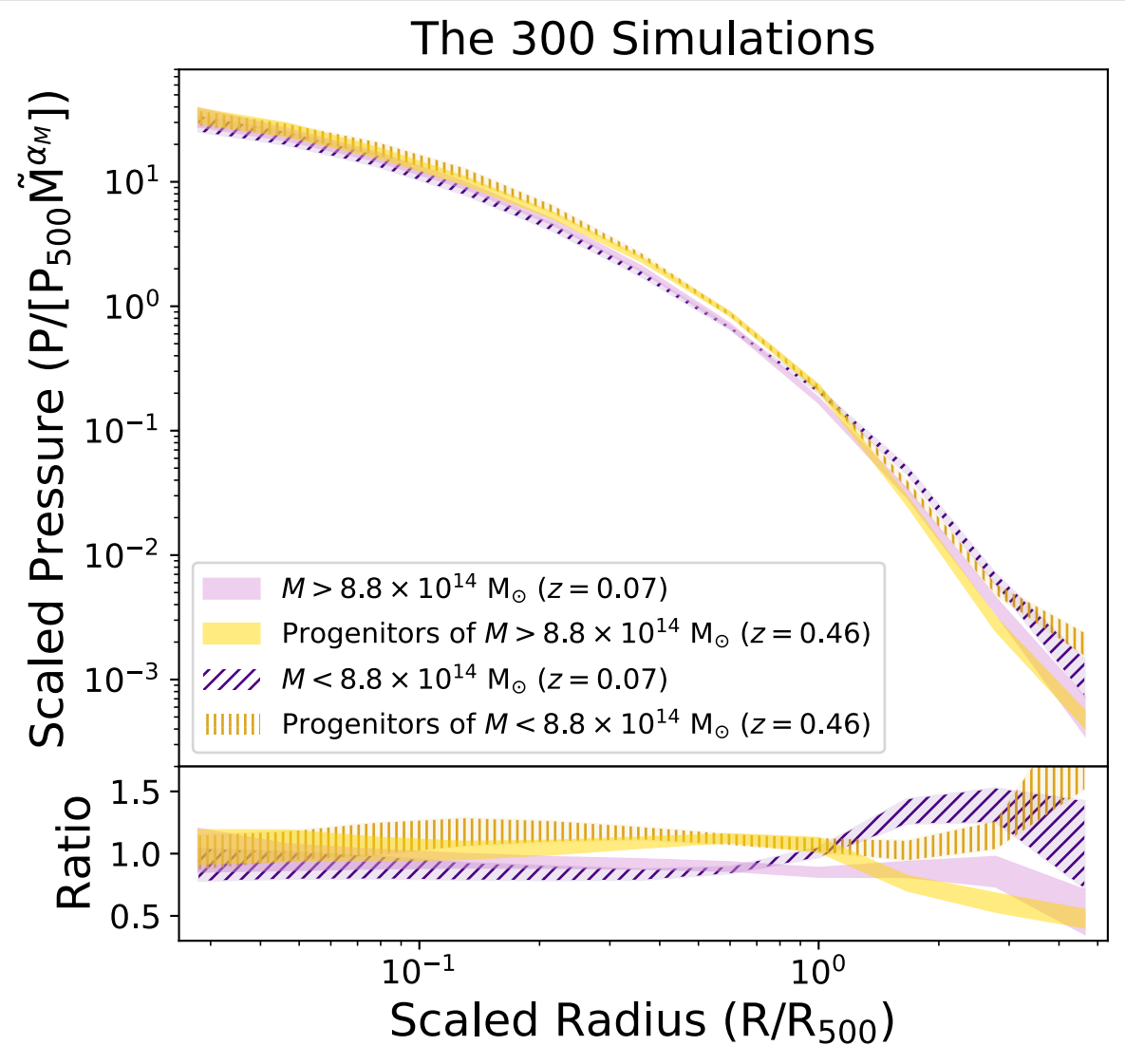
ICM Pressure Profile Shapes (Sayers+2023)

- We defined two representative samples in narrow redshift bins, one at z ~ 0.05 and one at z ~ 0.50
  - Search for mass-dependent trends within each sample and evolution between samples
- At $\lesssim 1.0R_{500}$ higher redshift sample has higher pressure
- At $1.0R_{500}$-$3.0R_{500}$ lower redshift sample has higher pressure
- Good agreement with The 300 simulations



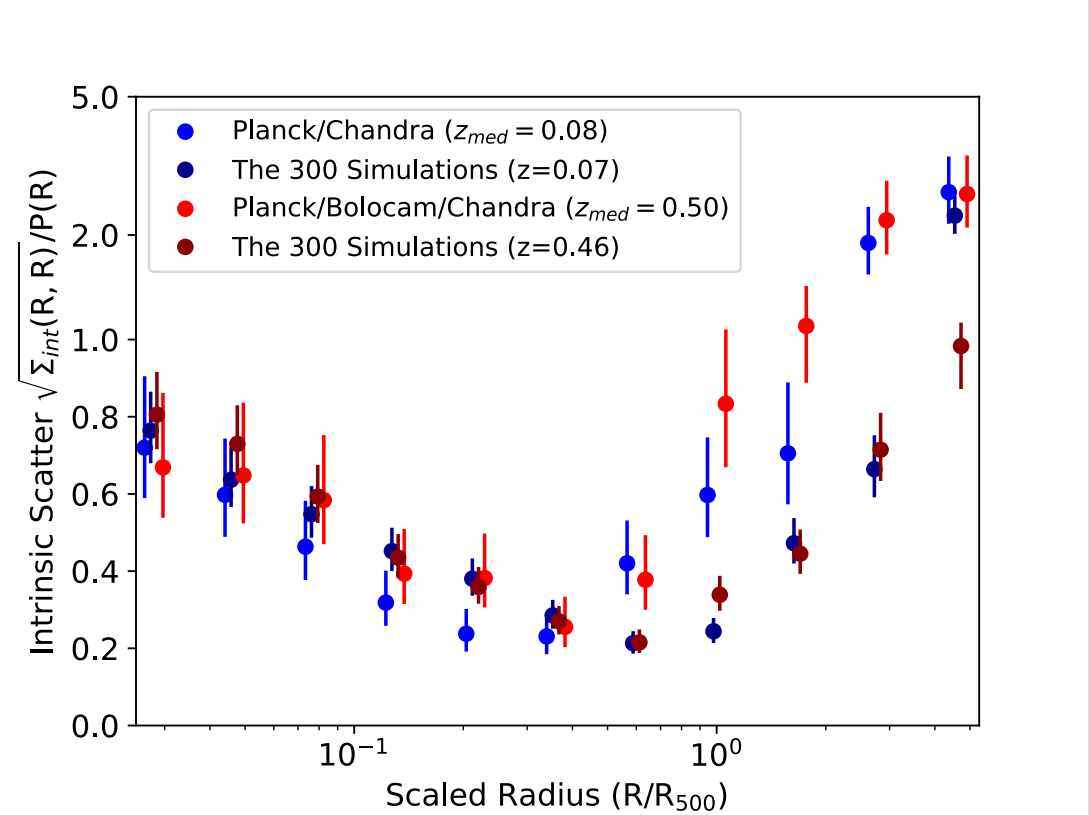
ICM Pressure Profile Shapes (Sayers+2023)

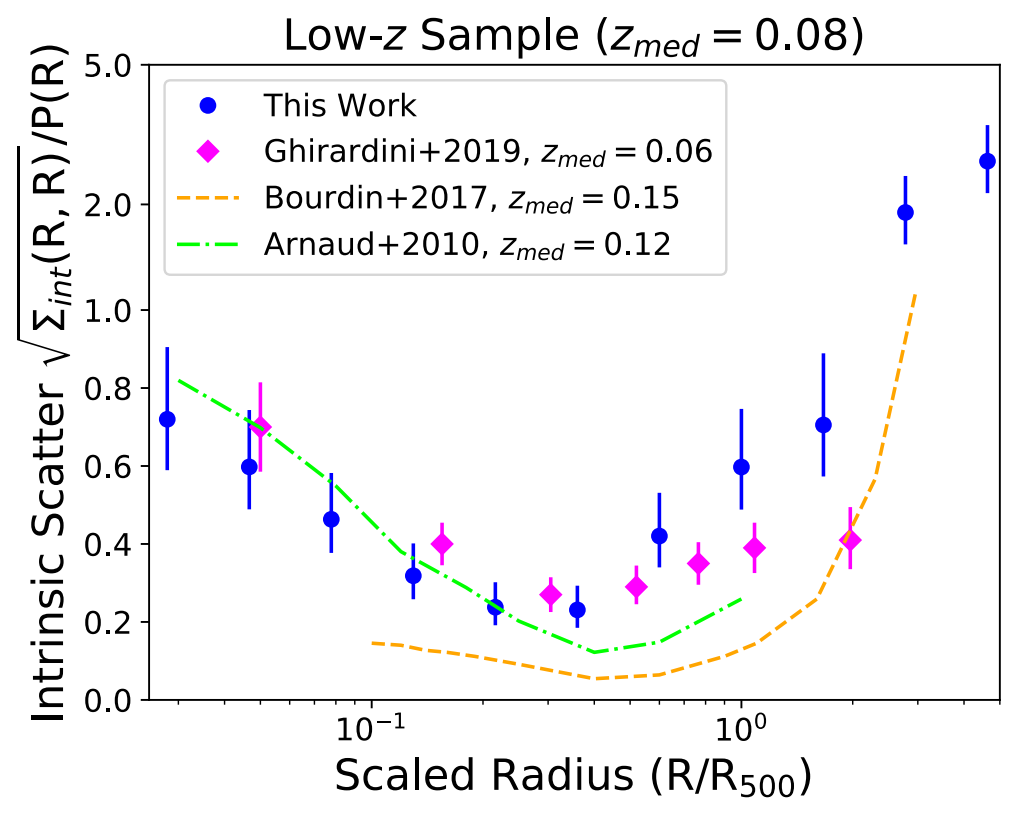
- Define matched samples from "The 300" simulations
  - Match redshift with snapshot
  - Match mass cluster-by-cluster
  - Adjust sample to match overall fraction of relaxed/disturbed
- Use simulations to isolate what's causing the difference between observed samples
  - $< 0.2R_{500}$: dynamical state
  - $0.2R_{500}$-$1.0R_{500}$: redshift (i.e., evolution)
  - $1.0R_{500}$-$3.0R_{500}$: mass+redshift



ICM Pressure Profile Shapes (Sayers+2023)

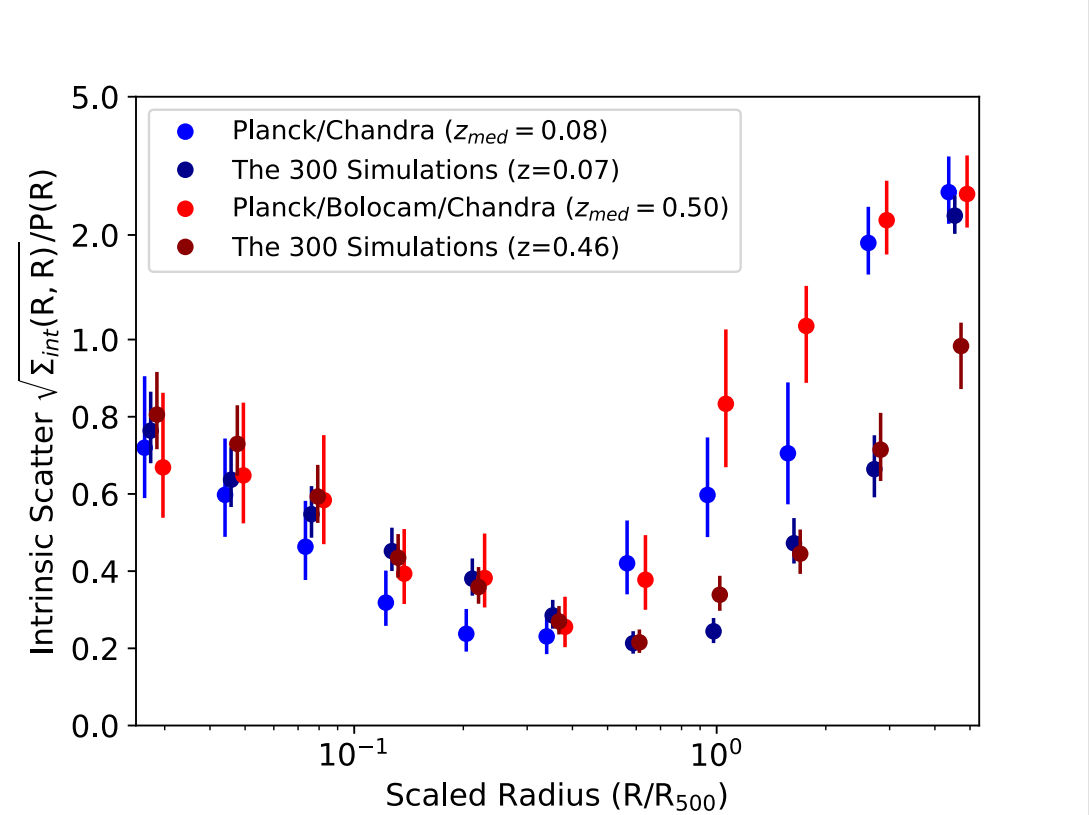
- Also predictions for the intrinsic scatter as a function of radius
  - Increases at small radii due to feedback, disruption of core during mergers
  - Increases at large radii due to differences in accretion history

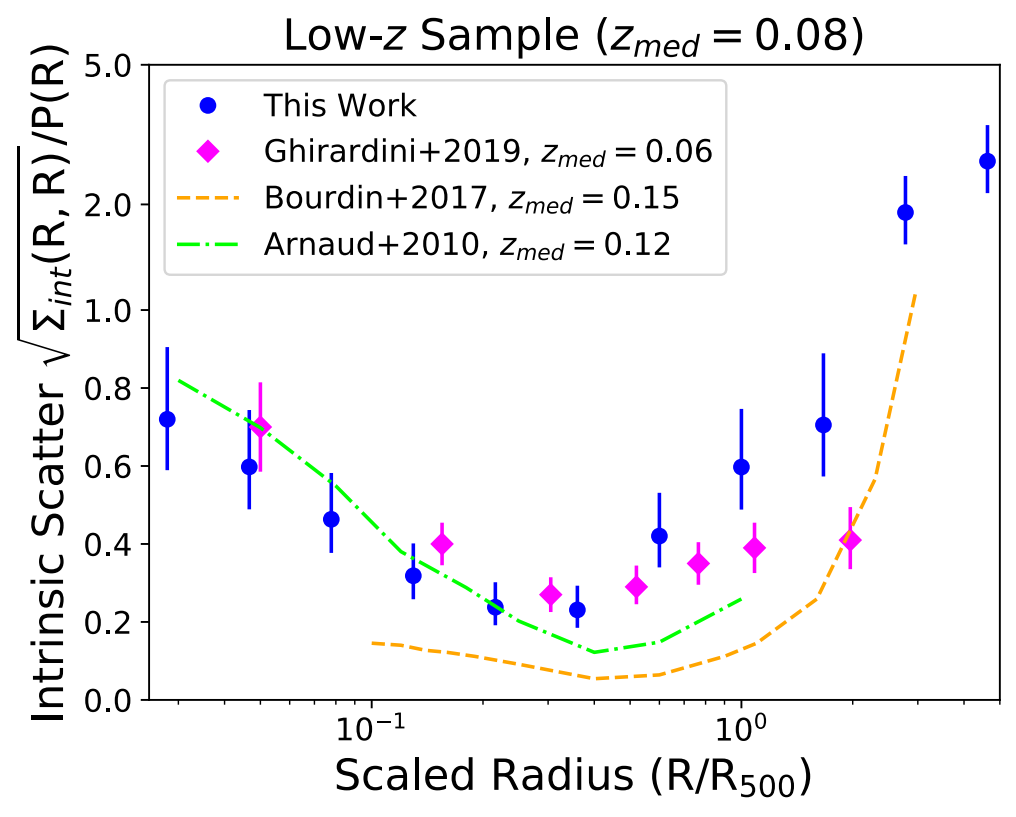




ICM Pressure Profile Shapes (Sayers+2023)

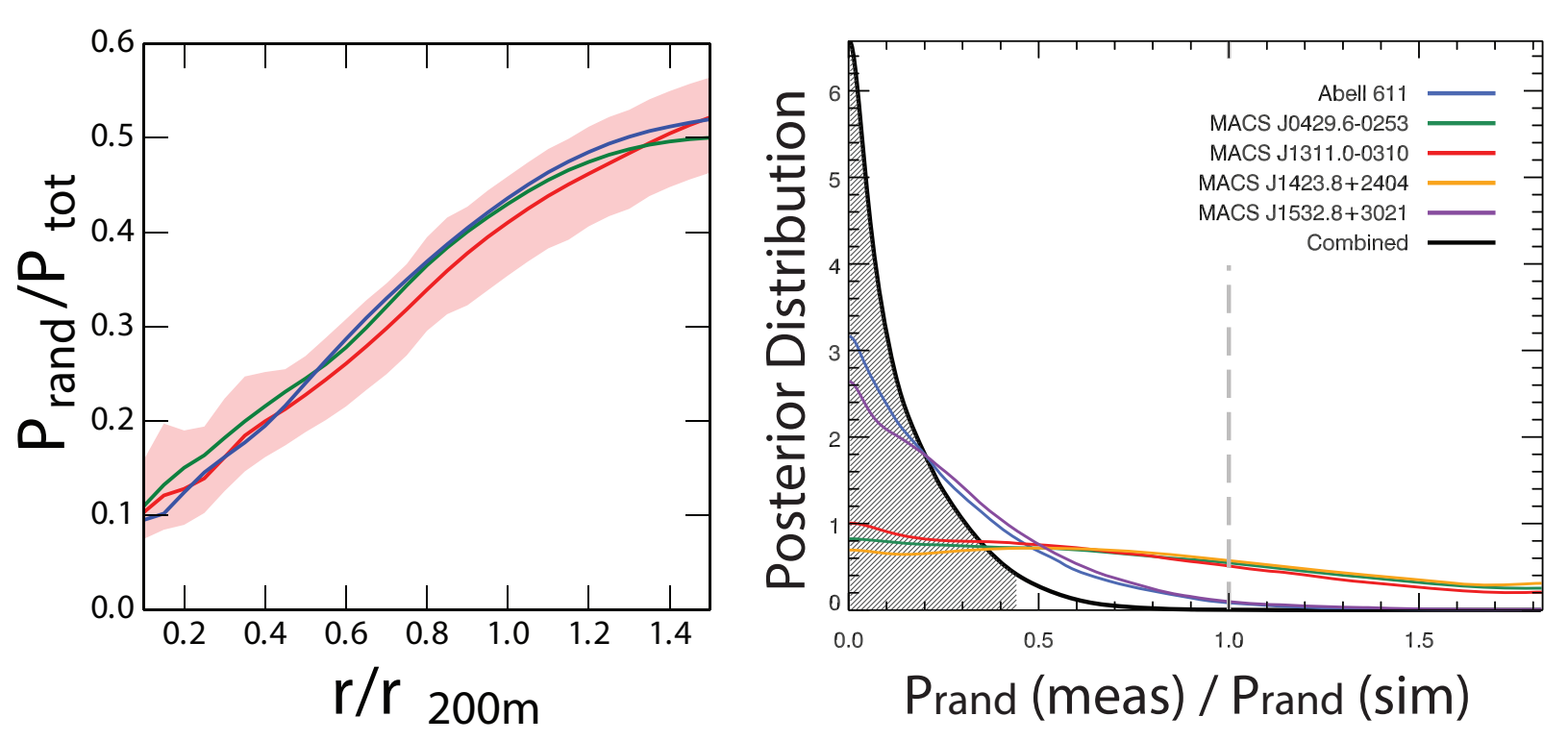
- Good qualitative agreement with predictions/previous observations
- Hints of higher than expected scatter at large radius
  - Perhaps indicates more diversity in accretion histories?





Non-Thermal Motions in the ICM

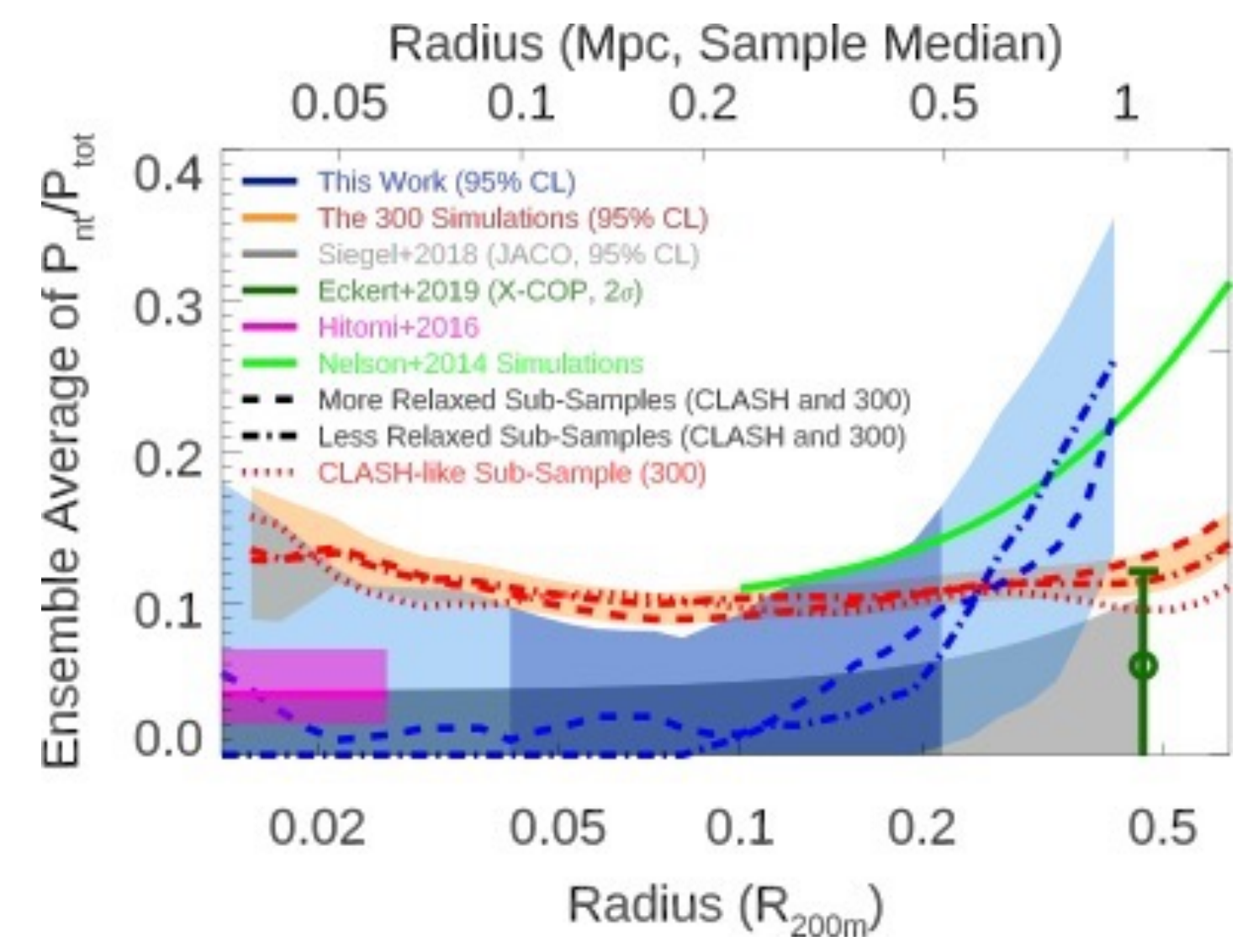
- Infalling material is thermalized via cascading series of shocks
  - This process is thought to be relatively inefficient
- Processes such AGN outbursts, core sloshing, etc. can produce non-thermal motions near the core
- HSE bias is due to non-thermal motions -> implications for mass calibration



Predicted non-thermal pressure fraction (Nelson+2014) and our first measurement (Siegel+2018)

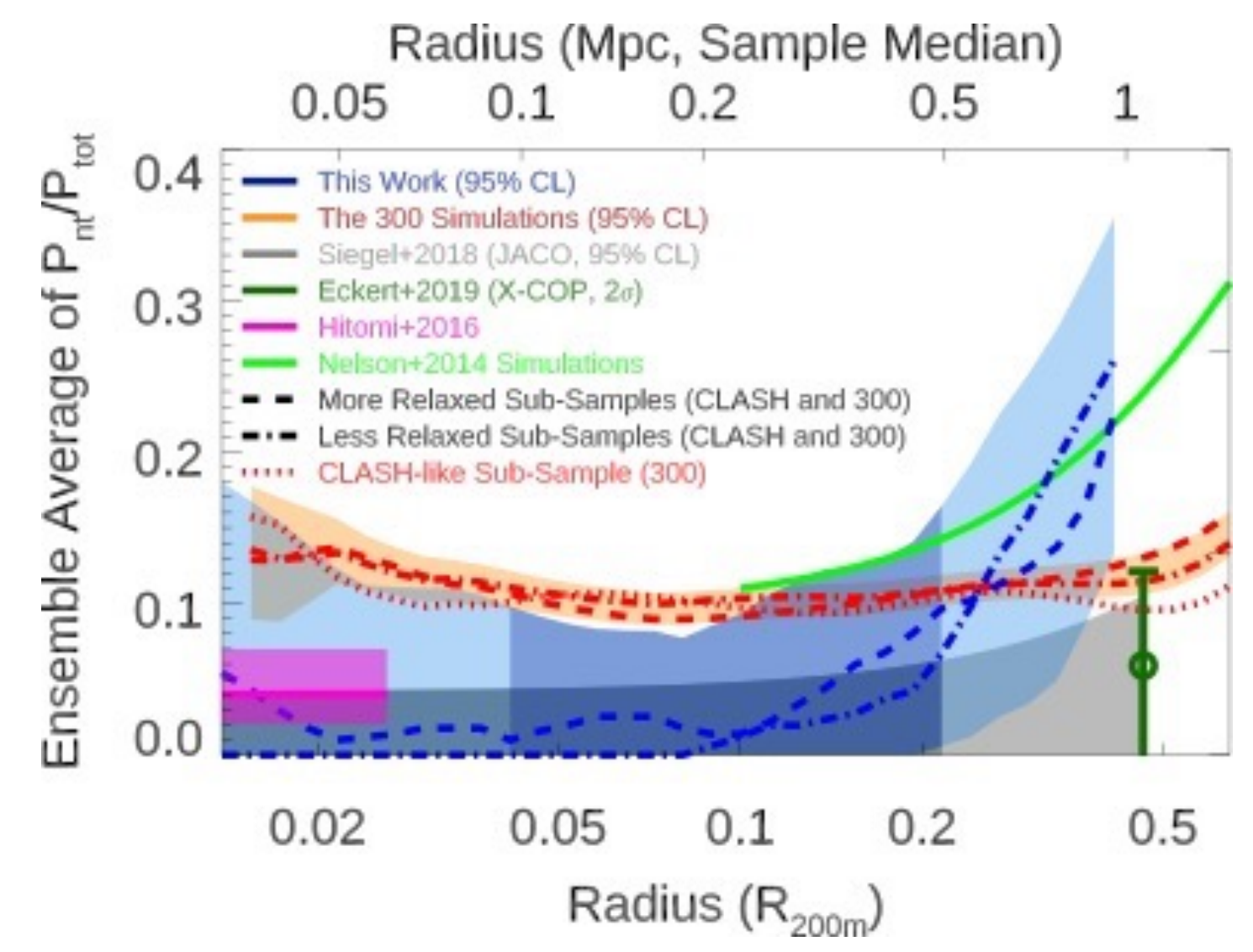
Non-Thermal Motions in the ICM (Sayers+2021)

- Our measurement compares thermal pressure (X-ray+SZ) to total pressure required to offset gravity (lensing)
- Lensing is very sensitive to projection, LOS elongation degenerate with non-thermal pressure
  - Use triaxial modeling plus larger sample to significantly improve results compared to Siegel+2018



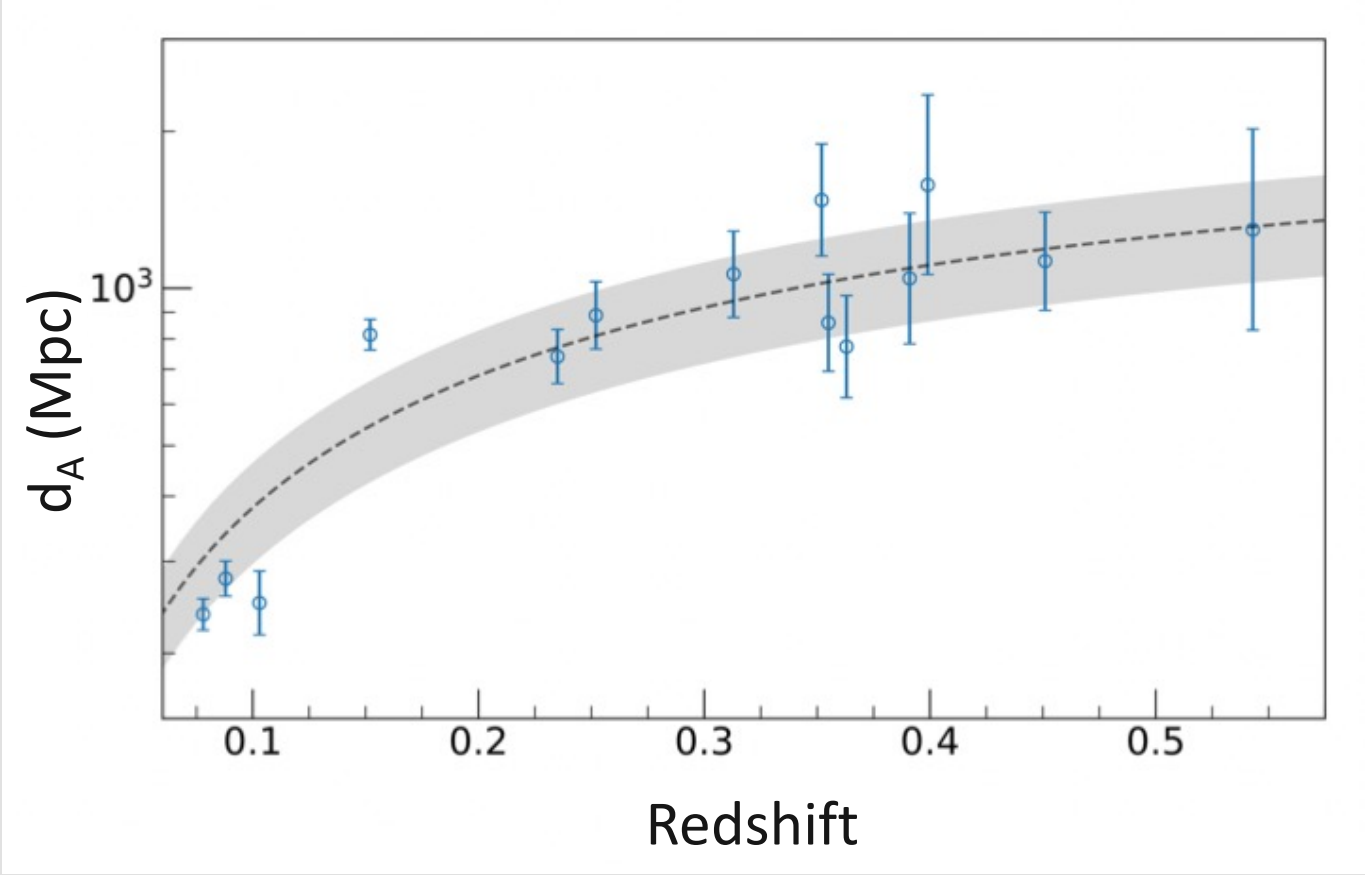
Non-Thermal Motions in the ICM (Sayers+2021)

- We find lower than expected non-thermal pressure near core
  - Implies that AGN outbursts and other relevant processes heat the ICM in a "gentle" manner
- "Hints" of expected increase at large R
  - Limited by *Chandra*
  - CHEX-MATE *XMM* data are much better
  - Will be able to probe to ~ R_{200m} (Gavidia+)



Hubble Parameter (Wan+2021)

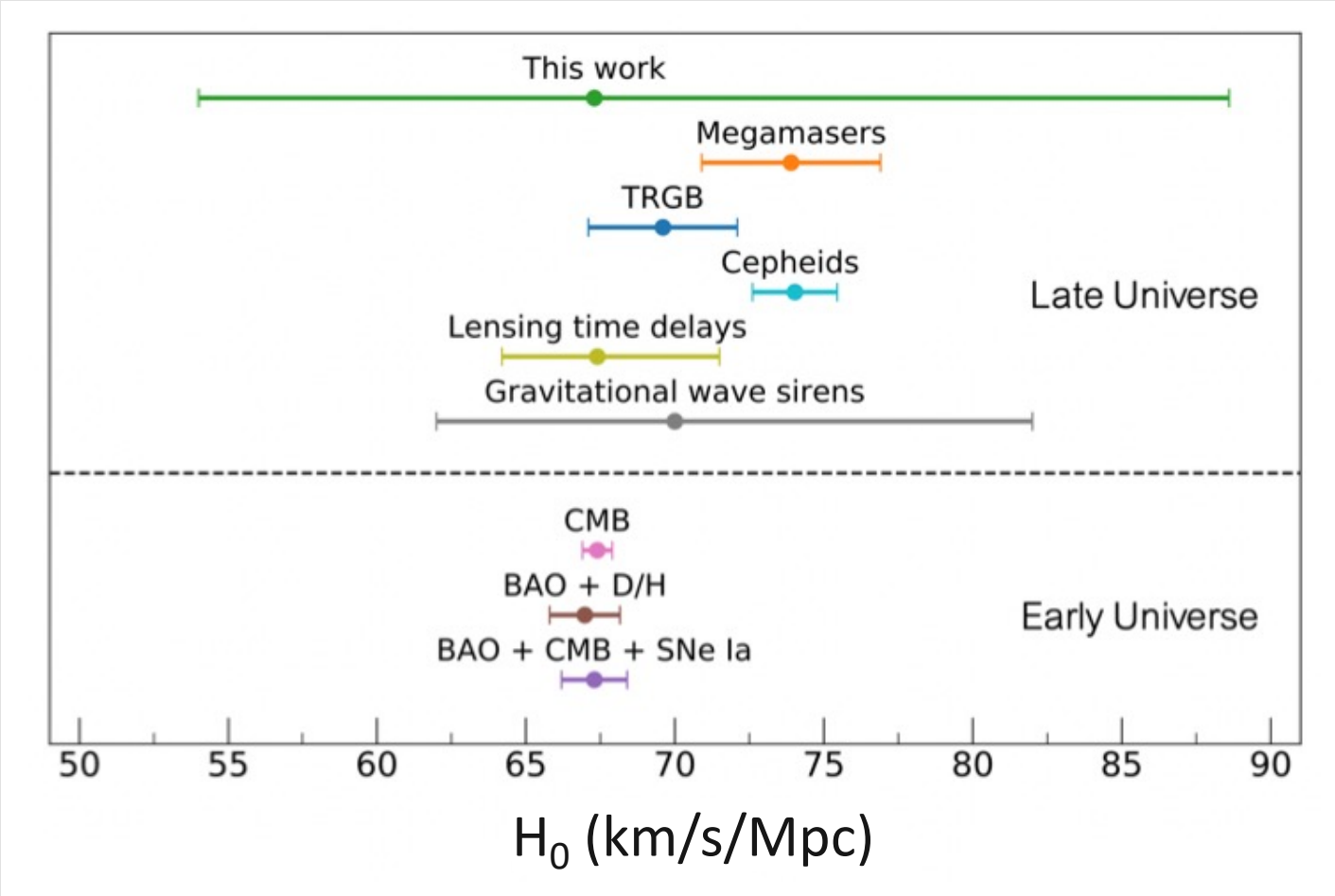
- As in triaxial analysis, the ratio of SZ/X-ray can be used to measure the LOS size of the galaxy cluster (in physical units, e.g., Mpc)
- Assuming random orientations, the LOS size will on average match the POS size (i.e., angle on the sky)
- Can thus determine $d_A(z)$ and constrain H_0
- Defined a sample of 14 highly relaxed galaxy clusters



Black dashed: 0.7,0.7,0.3 ΛCDM; grey band: 68% region

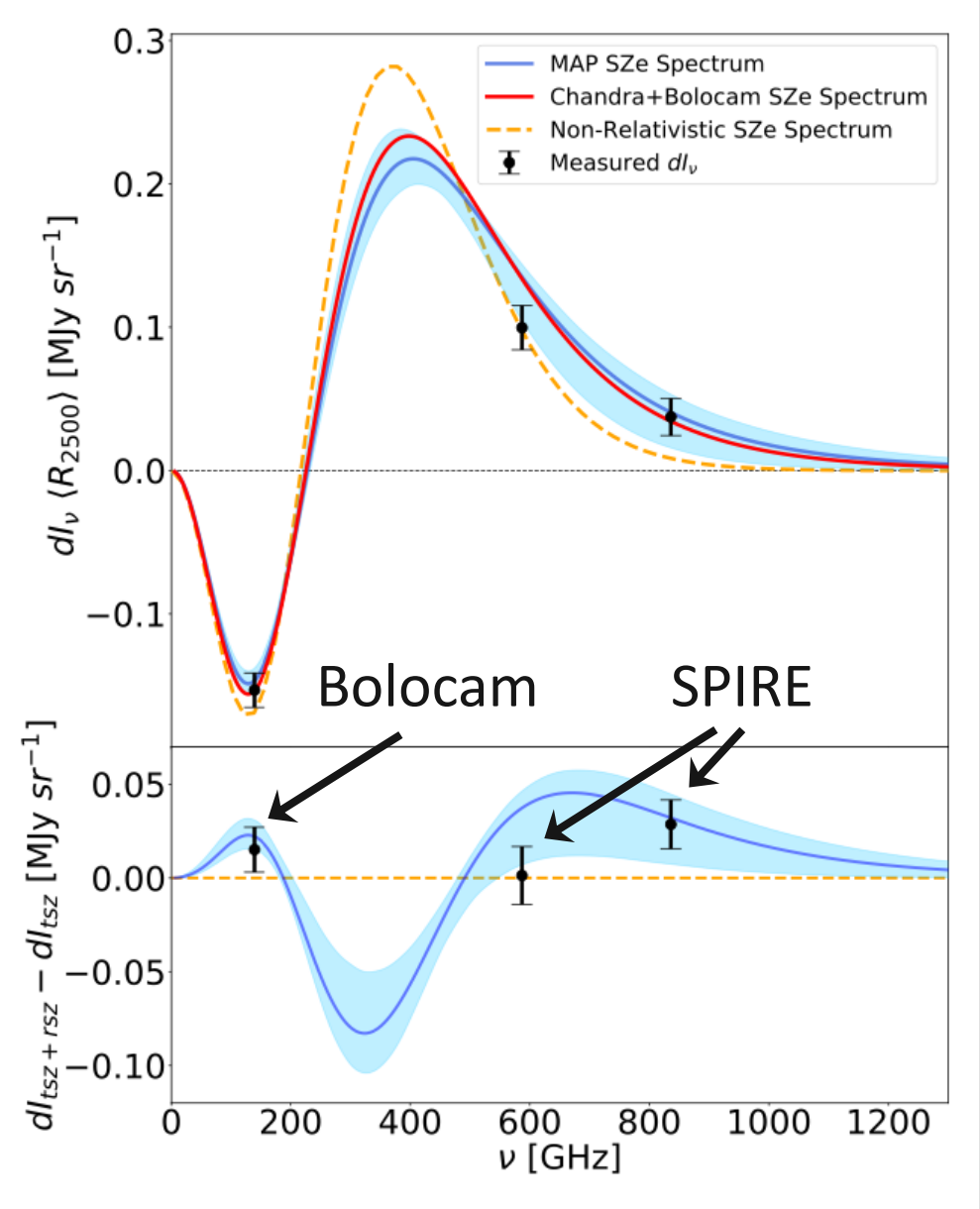
Hubble Parameter (Wan+2021)

- Obtain a value of H_0 = $67.3^{+21.3}_{-13.3}$ km/s/Mpc
  - Limited entirely by uncertainties related to X-ray T_e calibration (assumed to be 13% based on external mass calibration –> 26% uncertainty on H_0)
- Without this calibration uncertainty, find $72.3^{+7.6}_{-7.6}$ km/s/Mpc
- Percent-level H_0 possible with ~ 1000 clusters and better X-ray calibration



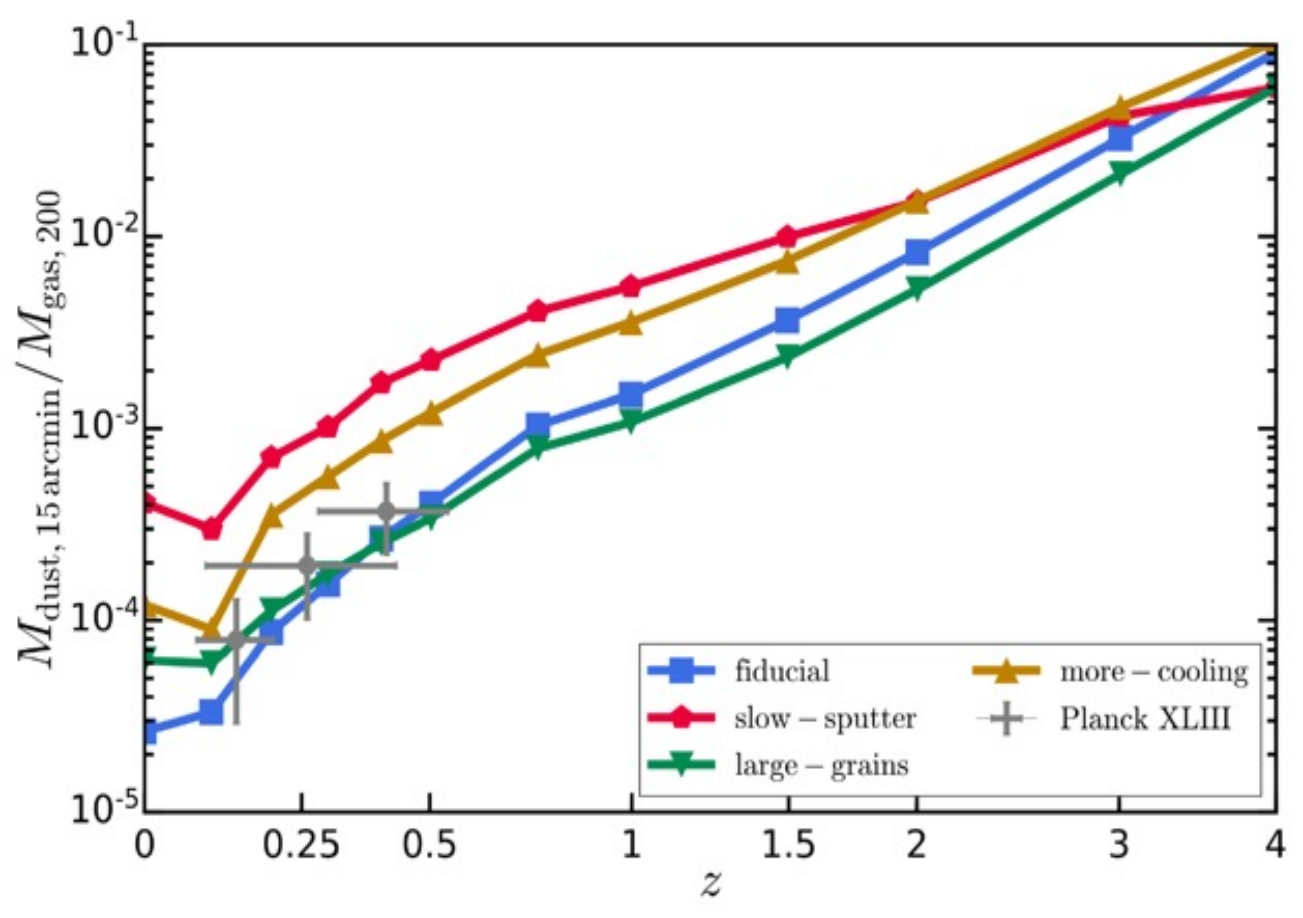
rSZE (Butler+2022)

- High frequency measurements of the SZ spectrum are sensitive to relativistic SZE
- Use *Herschel*-SPIRE in combination with ground-based Bolocam
- Initial demonstration of analysis for RX J1347.5
  - Have data for an additional 40 clusters ready to analyze
- Potential to improve Te calibration for H_0 measurement



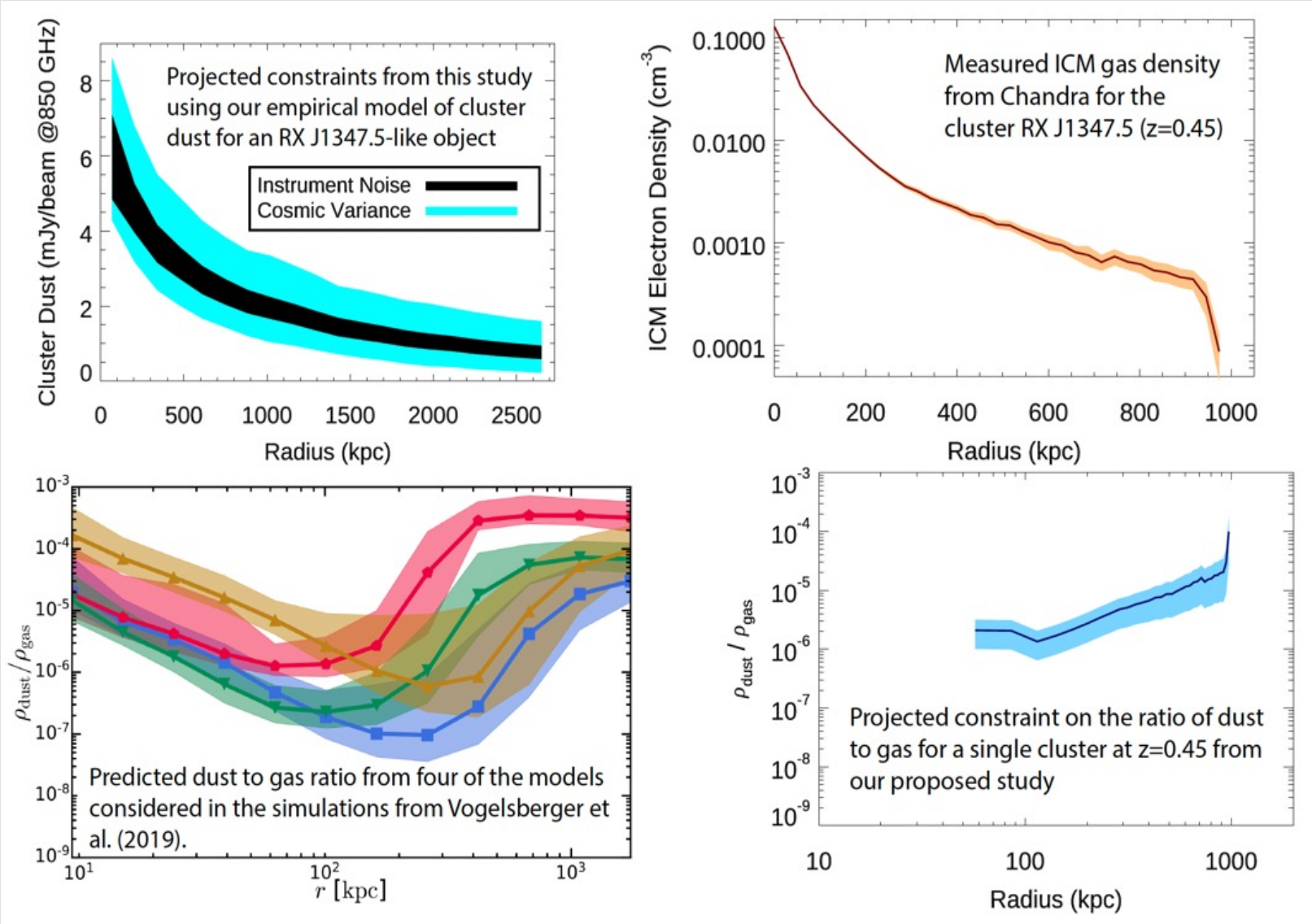
Dust in the Cluster Environment

- Thermal sputtering by the ICM is thought to quickly destroy dust
- Difficult to simulate, and existing constraints from Planck are not that constraining
- Instead of measuring Te via the rSZE, we can do so using *Chandra*
  - We thus remove SZ contamination to allow for accurate dust measurement



Various Dust models compared to Planck (Vogelsberger+2019)

Dust in the Cluster Environment



Summary

- Galaxy clusters are useful probes of both cosmology and astrophysics
- There are many ways to observe clusters (optical, X-ray, SZ, etc.)
- Most novel studies require combining multiple probes
- Our group works on a range of these multi-probe studies
  - Characterizing the geometry of cluster mergers
  - Probing the triaxial shapes of clusters
  - Understanding how ICM gas thermodynamics are influenced by physical processes related to AGN feedback and accretion
  - Probing the non-thermal signatures of these same processes
  - An independent probe of the Hubble Parameter
  - How do dust and the ICM interact?