Galaxy Clusters at the Edge: Temperature, Entropy Structure, & Gas Dynamics at the Virial Radius

Jack Burns and Sam Skillman

Center for Astrophysics and Space Astronomy

University of Colorado at Boulder

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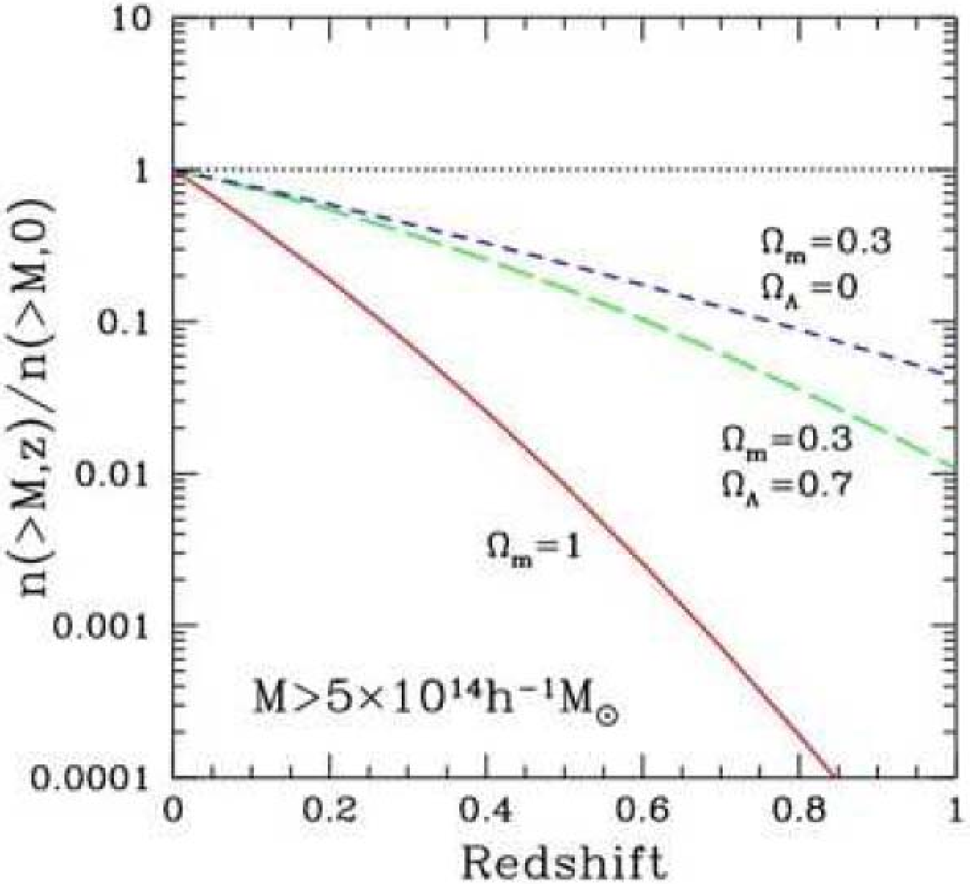
Are Clusters Accurate Probes of Cosmological Parameters?

Cluster Mass Function



Borgani (2004)

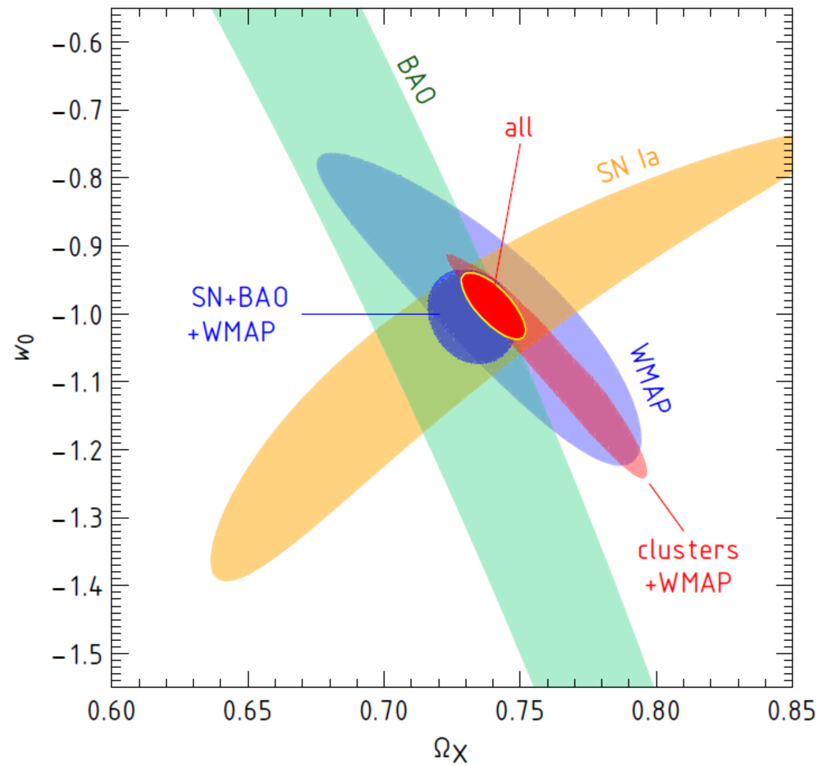


FIG. 10.— Dark energy constraints in flat universe from combination of all cosmological datasets. We find $w_0 = -0.991 \pm 0.045$ (± 0.04 systematic) and $\Omega_X = 0.740 \pm 0.012$, see Table 2 and § 8.3.

Vikhlinin et al. 2009, ApJ, 692, 1060

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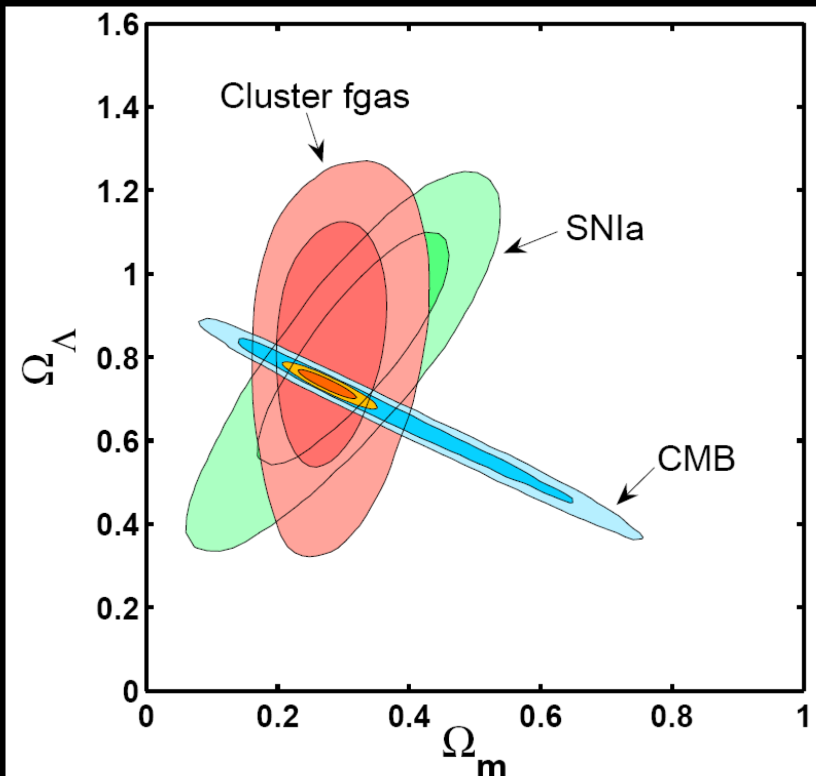
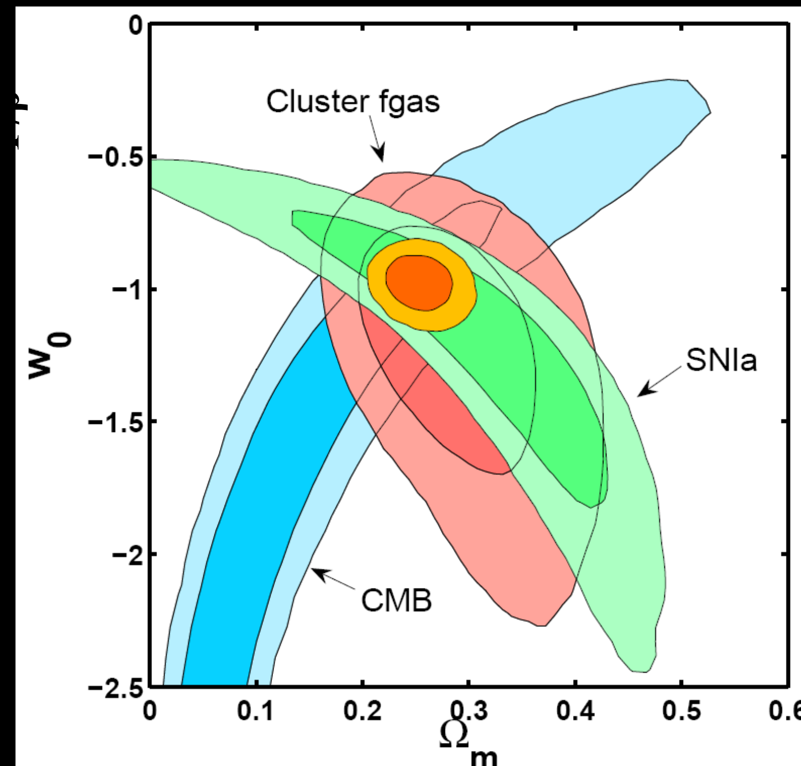
Cluster Gas Fraction





- Baryon fraction (f_{gas}) in X-ray clusters is potentially powerful tool as shown above (Allen et al. 2008, MNRAS, 383, 879).
- Angular diameter distance (depends on Dark Energy model) $d_A \sim f_{gas}^2$ (assume f_{gas} is constant and ICM is in hydrostatic equilibrium).

What the Dark Energy Task Force said about Galaxy Clusters:

Galaxy clusters have "the statistical potential to exceed the baryon acoustic oscillations and supernovae techniques but at present have the largest *systematic errors*. Its eventual accuracy is currently very difficult to predict and its ultimate utility as a dark energy technique can only be determined through the development of techniques that control systematics due to *non-linear astrophysical processes*."

What are the systematics?

- **Gastrophysics**
  - Cooling
  - Heating/feedback from SN and AGNs
- **Cluster dynamics** (hydrostatic equilibrium?)
  - Mergers
  - Turbulence & bulk flows ("sloshing")
- **Nonthermal component of ICM**
  - Cosmic rays (possibly ~10% of total pressure)
  - Magnetic fields (~1-3 μG)
- **Cluster sample selection effects**
  - Use of cool core clusters
  - Non-statistically complete samples

=> Use numerical simulations to model and correct for these biases and errors.

Potential to use Cluster Mass Function for cosmology is challenging because mass is not a directly observable quantity. Instead, we measure:

- X-ray luminosity or X-ray temperature.
- Sunyaev-Zeldovich Effect ($Y \sim \int nT\, dl$).
- Weak lensing shear.

Hydrostatic Equilibrium

$$\nabla\Phi = -\frac{\nabla P}{\rho}$$

Applying Gauss' Law to the above:

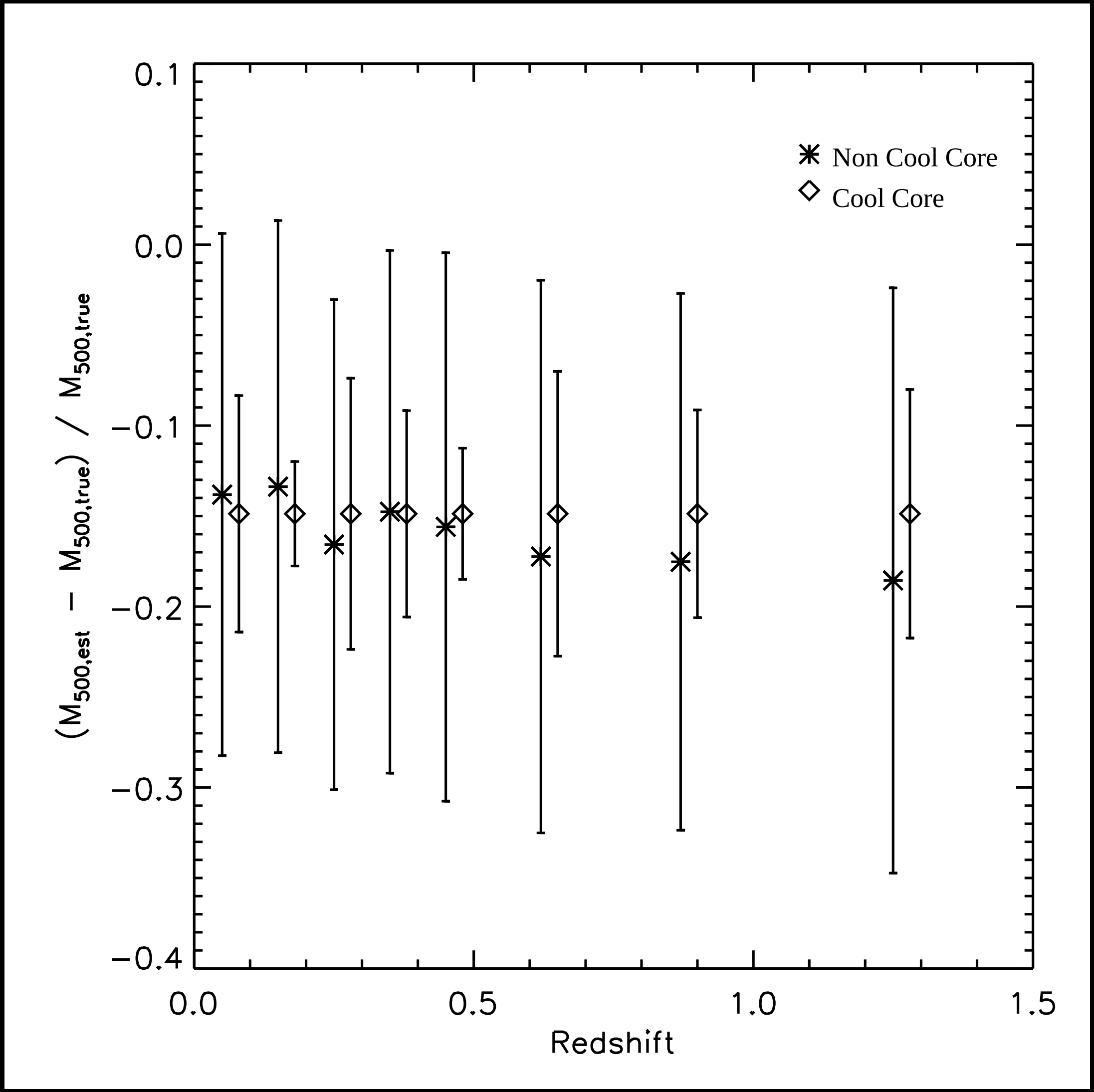
$$M(<r) = \frac{1}{4\pi G}\int -\frac{\nabla P}{\rho} dA$$

If cluster is spherical & P = nkT, then,

$$M(<r) = -\frac{r^2 k}{\rho G \mu m_p}\left[T\frac{d\rho}{dr} + \rho\frac{dT}{dr}\right]$$

=>Need to measure T, ρ and their gradients

Are CC clusters in Hydrostatic Equilibrium?

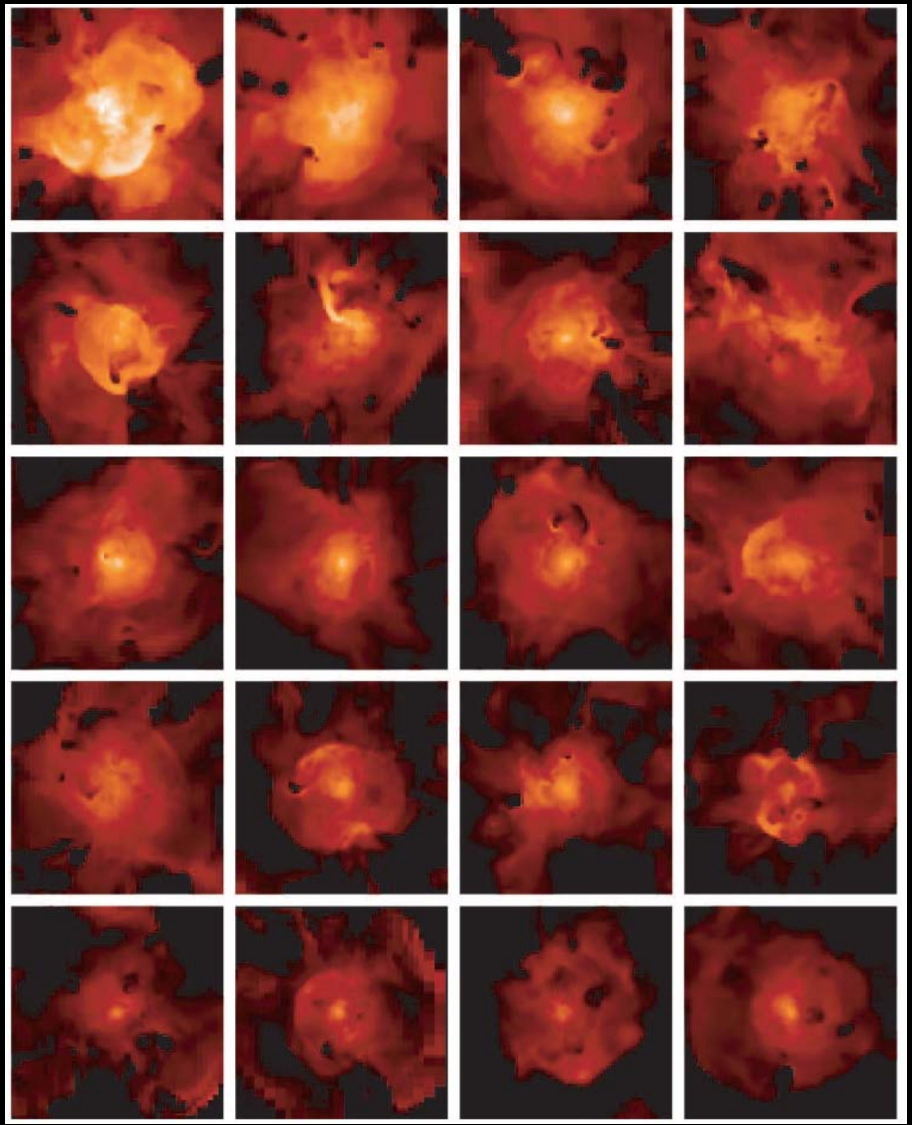


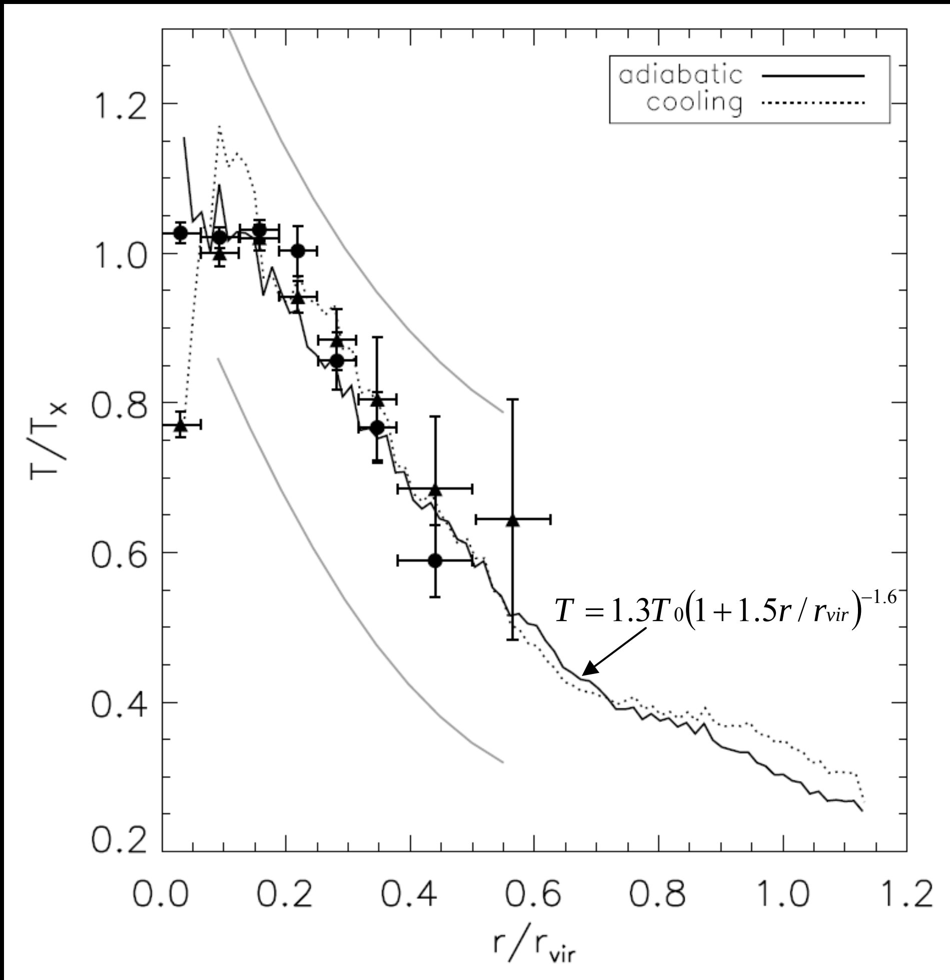
- Burns *et al*. 2008.
- Jeltema, Hallman, Burns & Motl, 2008, ApJ, 681, 167.
- Our results are consistent with X-ray to Lensing mass ratios from Mahdavi *et al*. 2008, MNRAS, 384, 1567.

CC clusters are biased low by ~15%, just like NCC clusters. Kinetic energy of bulk gas motions contributes ~10% of total energy.

A Universal Temperature Profile for Galaxy Clusters?

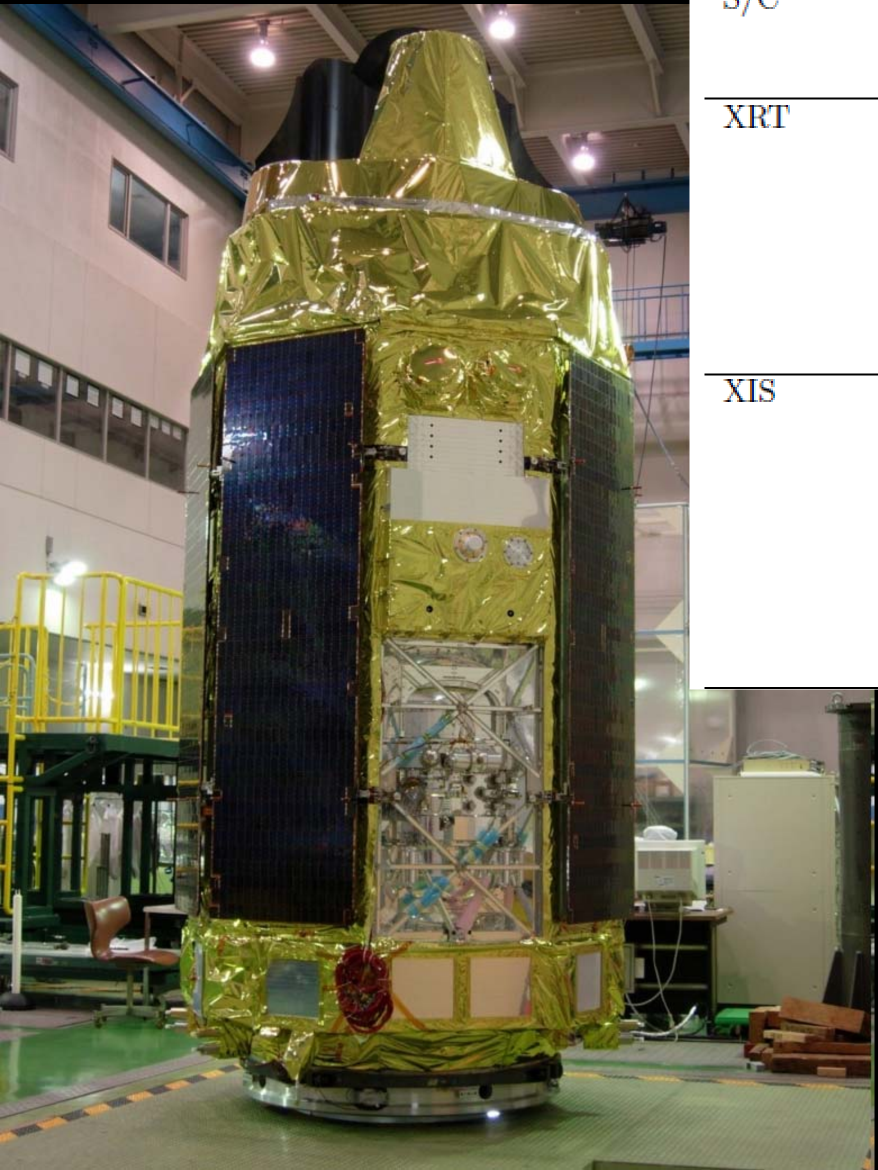
Loken et al. 2002, ApJ, 579, 571





ΛCDM AMR Cosmology Simulations compared to X-ray observations from BeppoSAX

Suzaku is a game-changer for measuring cluster temperatures

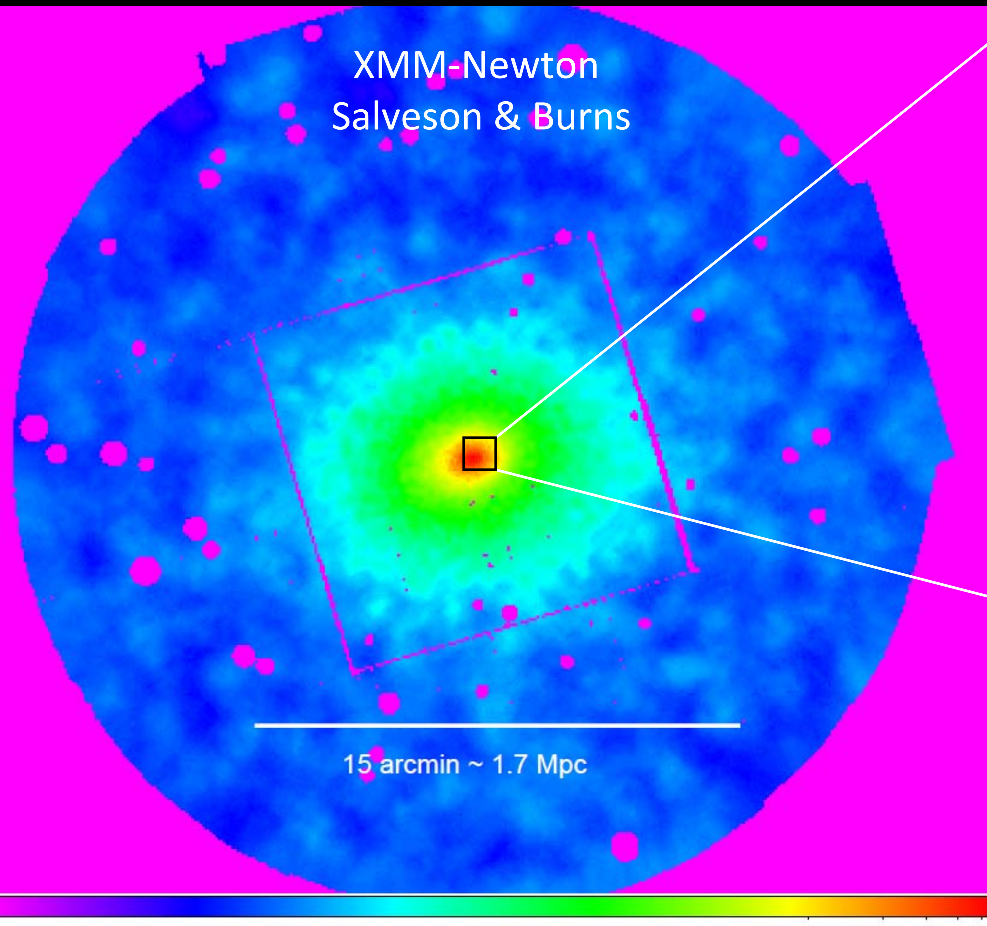


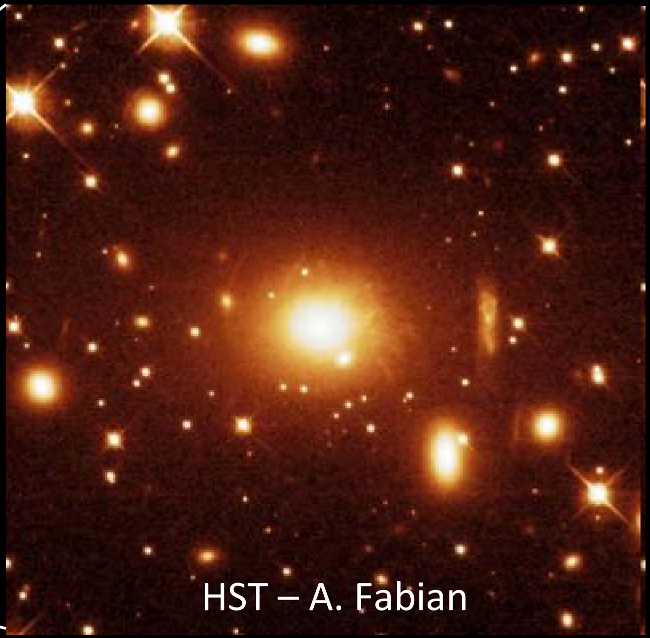
S/C	Orbit apogee	568 km
	Orbital period	96 minutes
	Observing efficiency	$\sim 45\%$
XRT	Focal length	4.75 m
	Field of view	$17'$ at 1.5 keV
		$13'$ at 8 keV
	Plate scale	0.724 arcmin/mm
	Effective area	440 cm^2 at 1.5 keV
		250 cm^2 at 8 keV
	Angular resolution	$2'$ (HPD)
XIS	Field of view	$17.8' \times 17.8'$
	Bandpass	0.2–12 keV
	Pixel grid	1024×1024
	Pixel size	$24\,\mu m \times 24\,\mu m$
	Energy resolution	~ 130 eV at 6 keV
	Effective area	340 cm^2 (FI), 390 cm^2 (BI) at 1.5 keV
	(incl XRT-I)	150 cm^2 (FI), 100 cm^2 (BI) at 8 keV
	Time resolution	8 s (Normal mode), 7.8 ms (P-Sum mode)

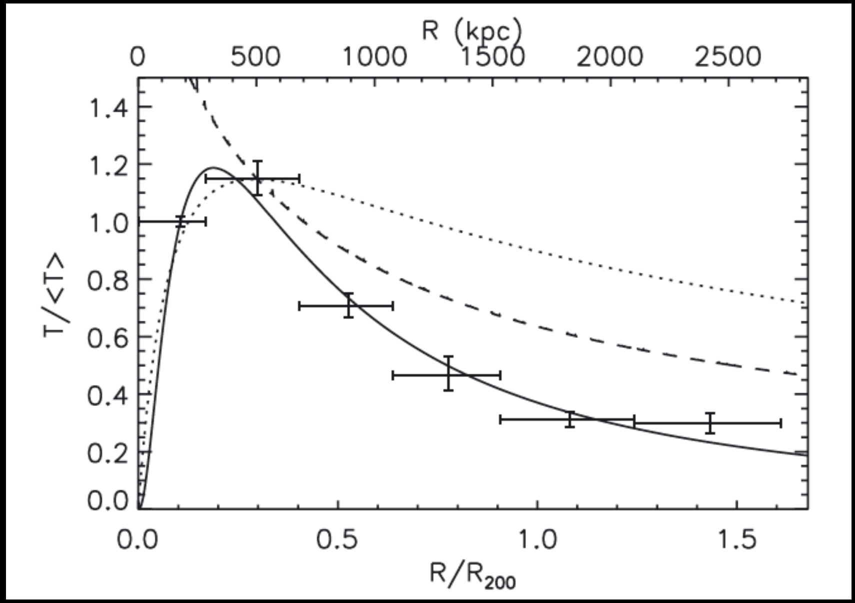
Low and stable backgrounds!

X-ray Observations of PKS 0745-191

$z=0.103$, $M_{200}=6.4\times10^{14}\ M_{\odot}$, $T\approx7$ keV , $r_{200} = 1.7\ h_{70}^{-1}$ Mpc





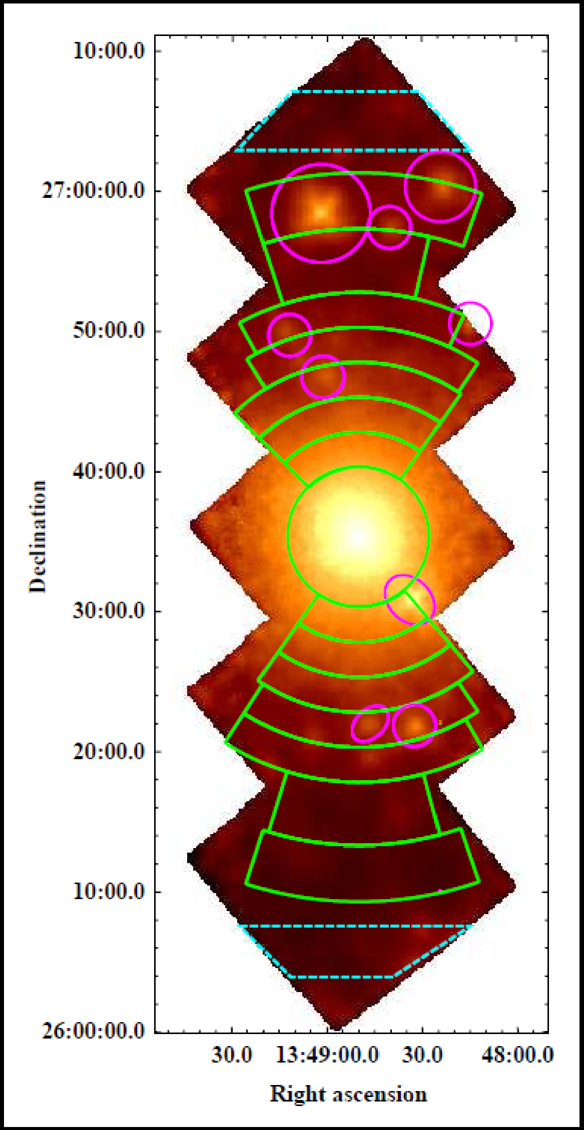


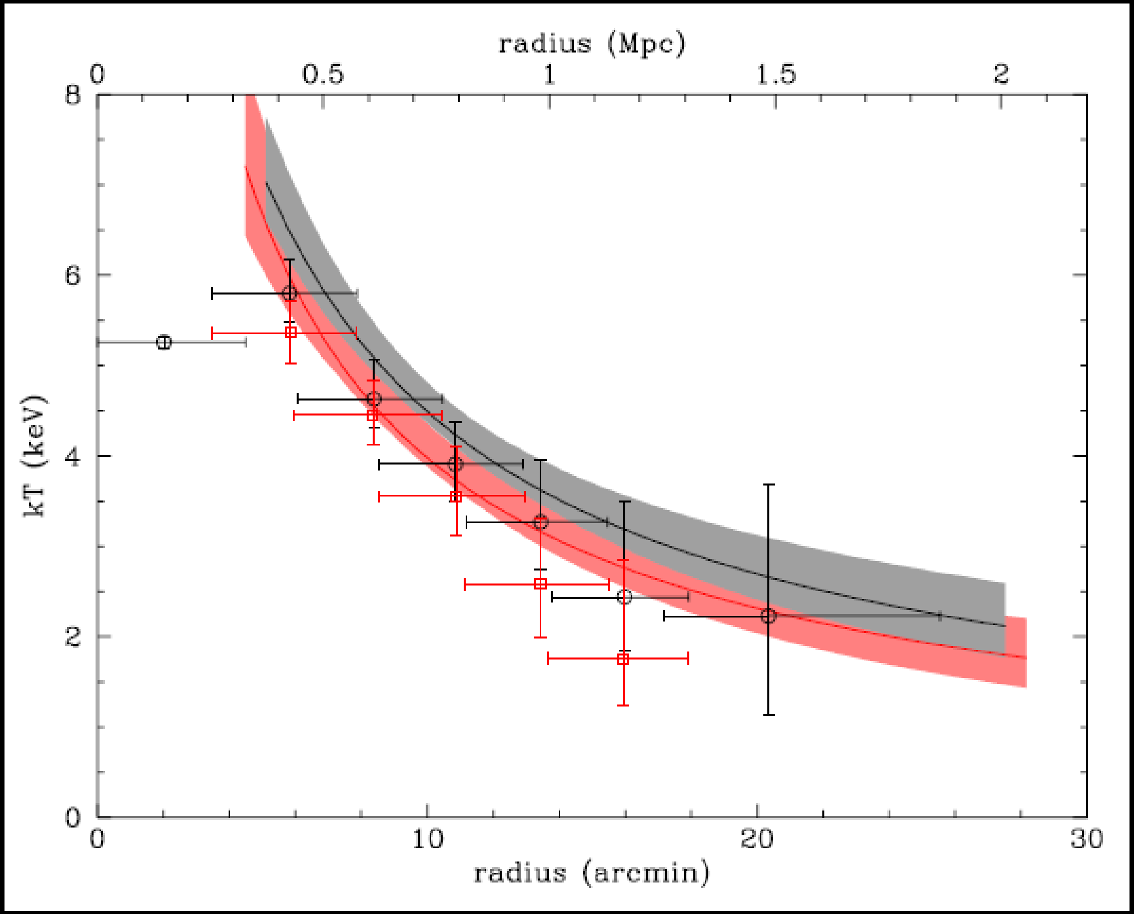
Suzaku X-ray Observations

George et al., 2009, MNRAS, 395, 657

Suzaku Observations of Abell 1795

z=0.063, M_{200}=8.6x10^{14} $M_{\odot}$, T=5.3 keV , r_{200} = 1.9 h_{70}^{-1} Mpc

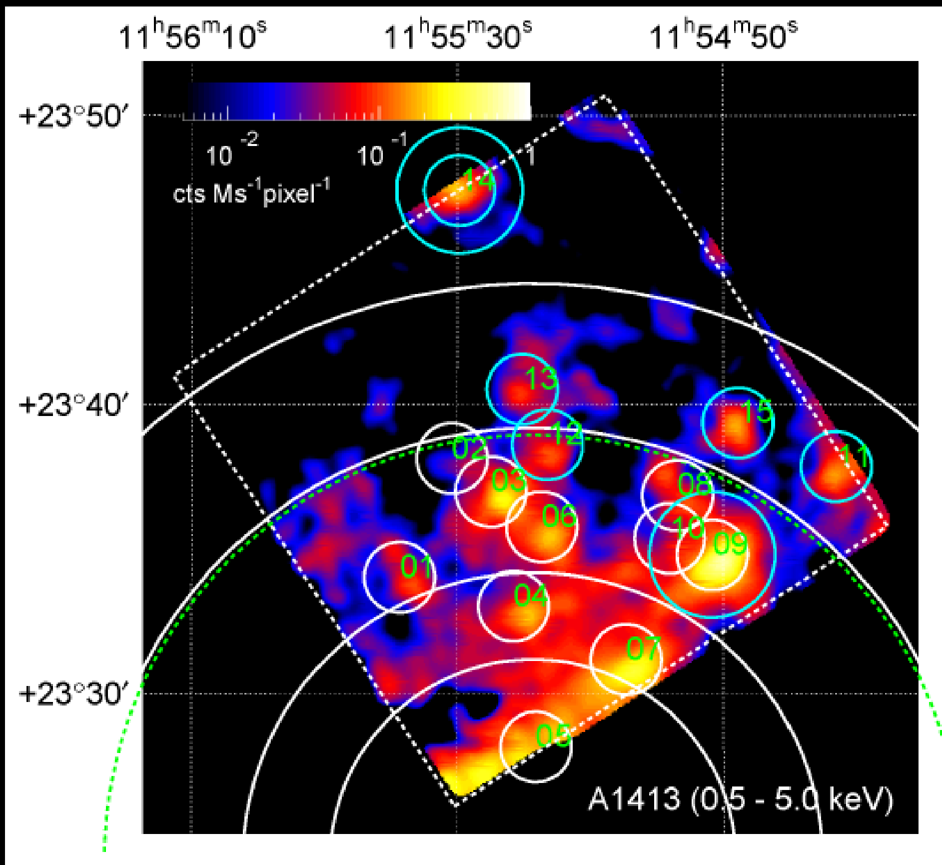


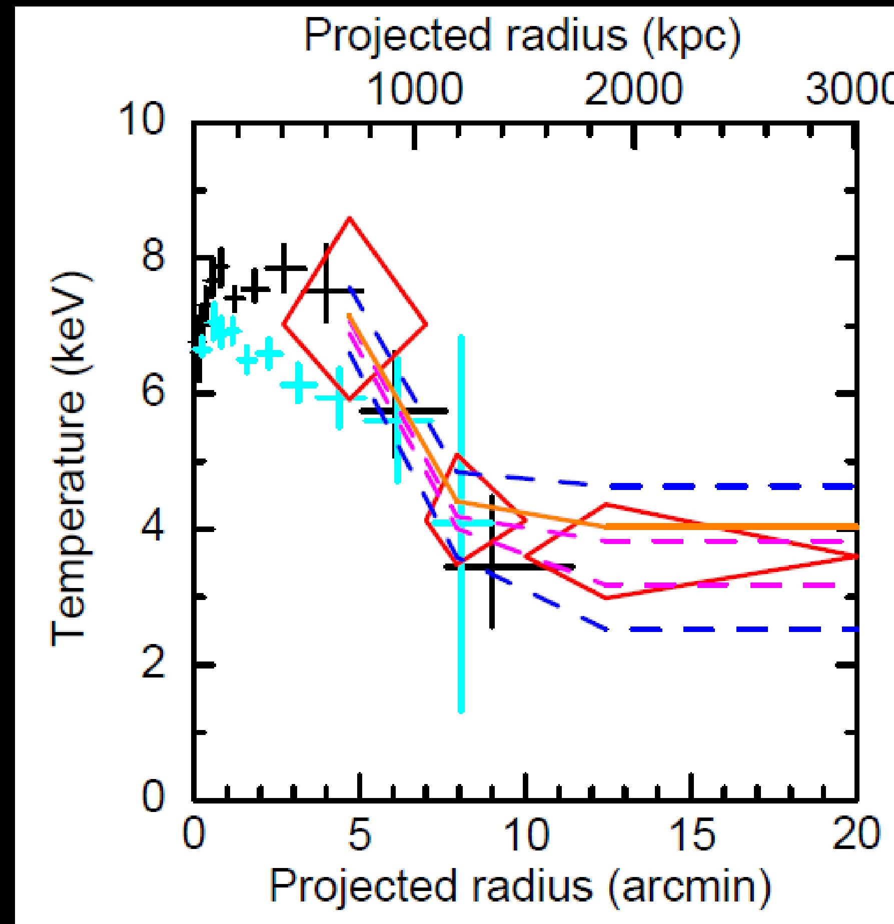


Bautz et al. 2009, PASJ, 61, 1117

Suzaku Observations of Abell 1413

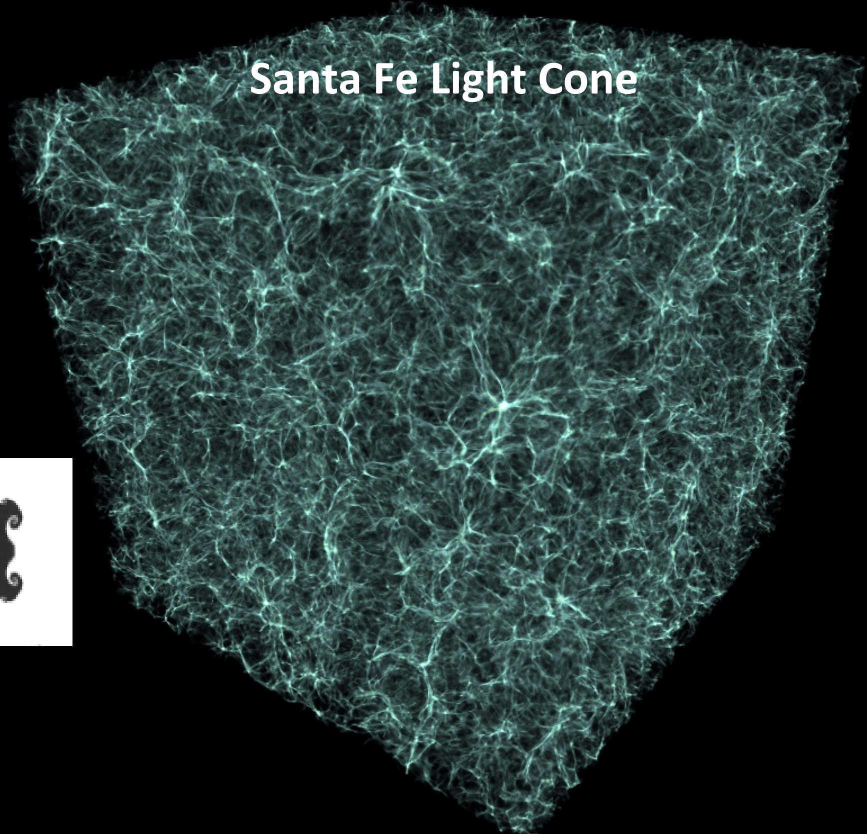
$z=0.143$, $M_{500}=7.8\times10^{14}\ M_{\odot}$, $T=7.4$ keV , $r_{200} = 2.2\ h_{70}^{-1}$ Mpc





Hoshino et al. 2010, ArXiv 1001.5133, PASJ (in press).

Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution



Hallman et al., 2007, ApJ, 671, 27.

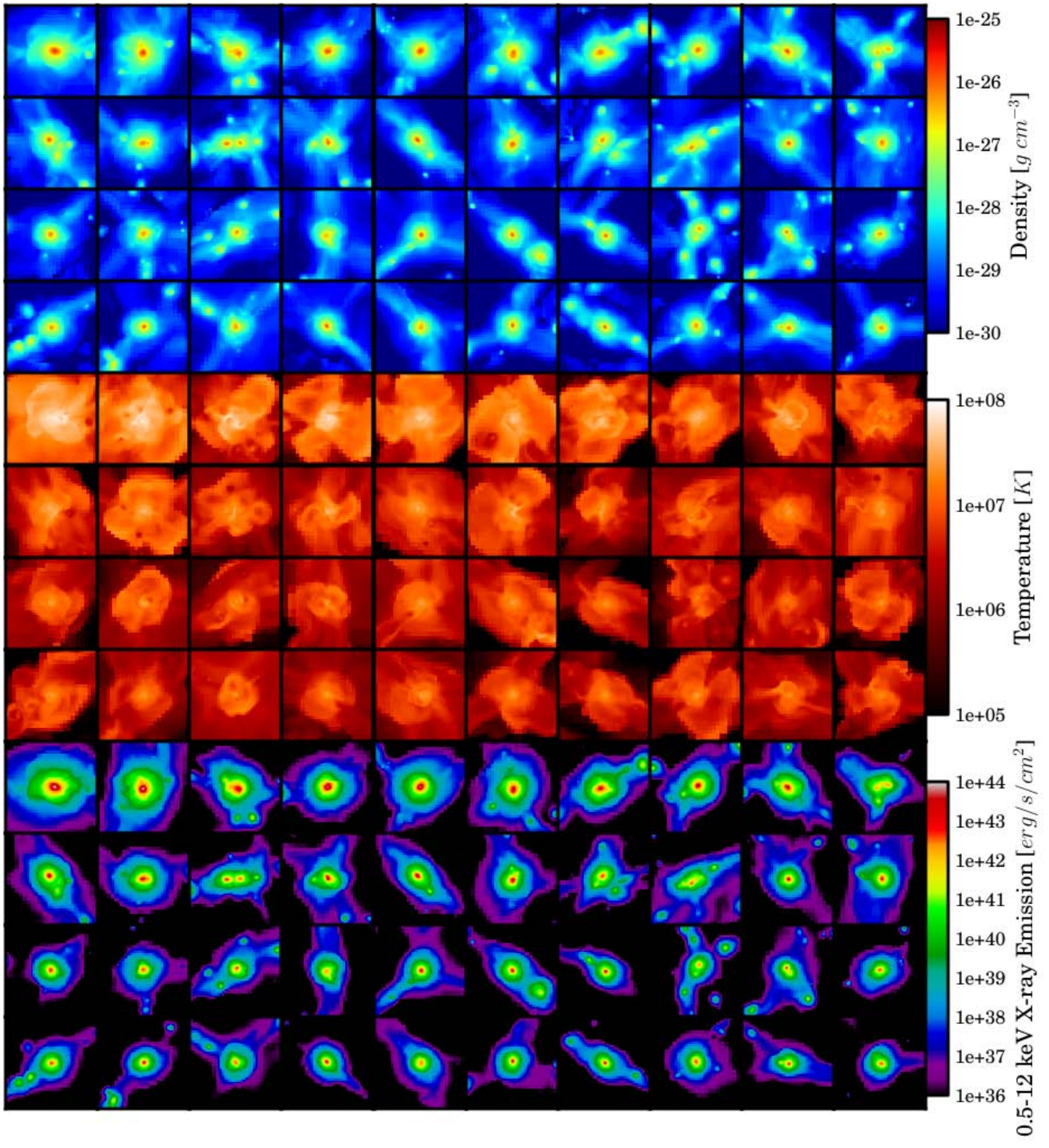
Enzo (e.g., O'Shea et al. 2004, http://lca.ucsd.edu/portal/software/enzo)

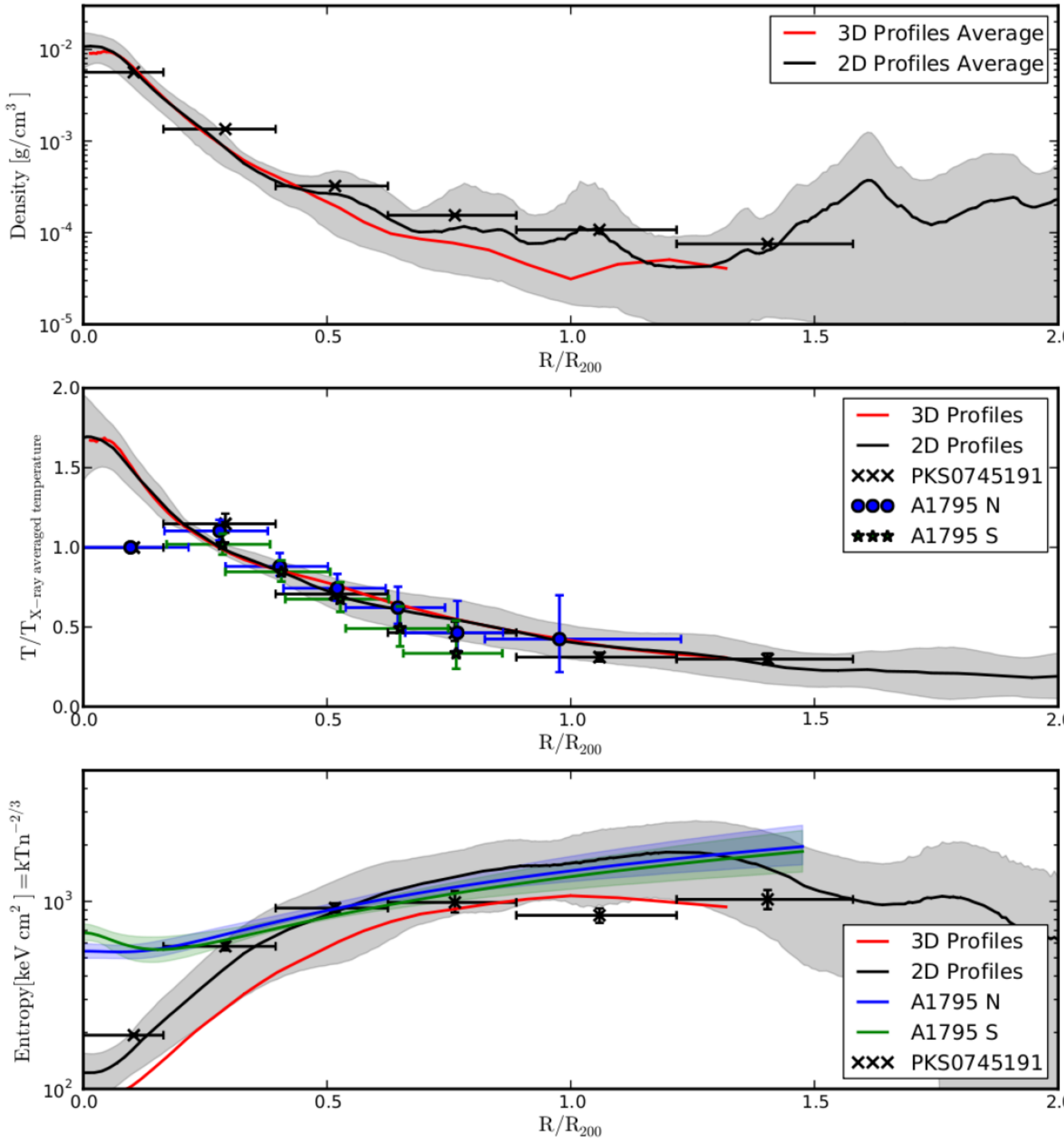
- ΛCDM with $\Omega_m = 0.27$, $\Omega_b = 0.04$, $\Omega_\Lambda = 0.73$, $h = 0.7$, and $\sigma_8 = 0.9$.
- AMR achieves 15.6 h^{-1} kpc resolution in dense regions.
- $(128\ h^{-1}\ \mathrm{Mpc})^3$, 5 levels of refinement => 80 clusters with $>10^{14}\ M_\odot$ for $z = 0$.
- Dark matter mass resolution is $3.1\times10^9\ h^{-1}\ M_\odot$.
- Adiabatic gas physics.

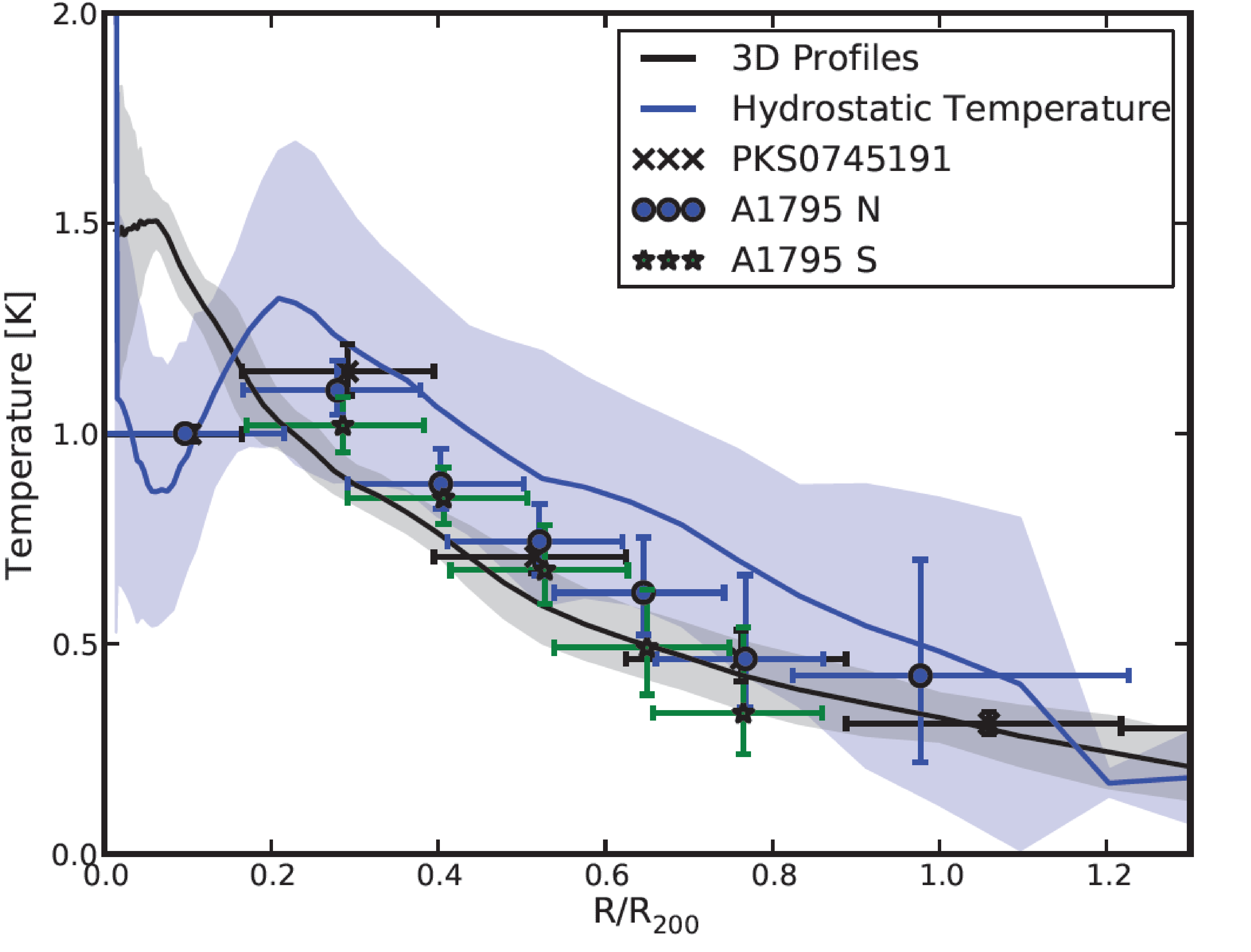
z = 0

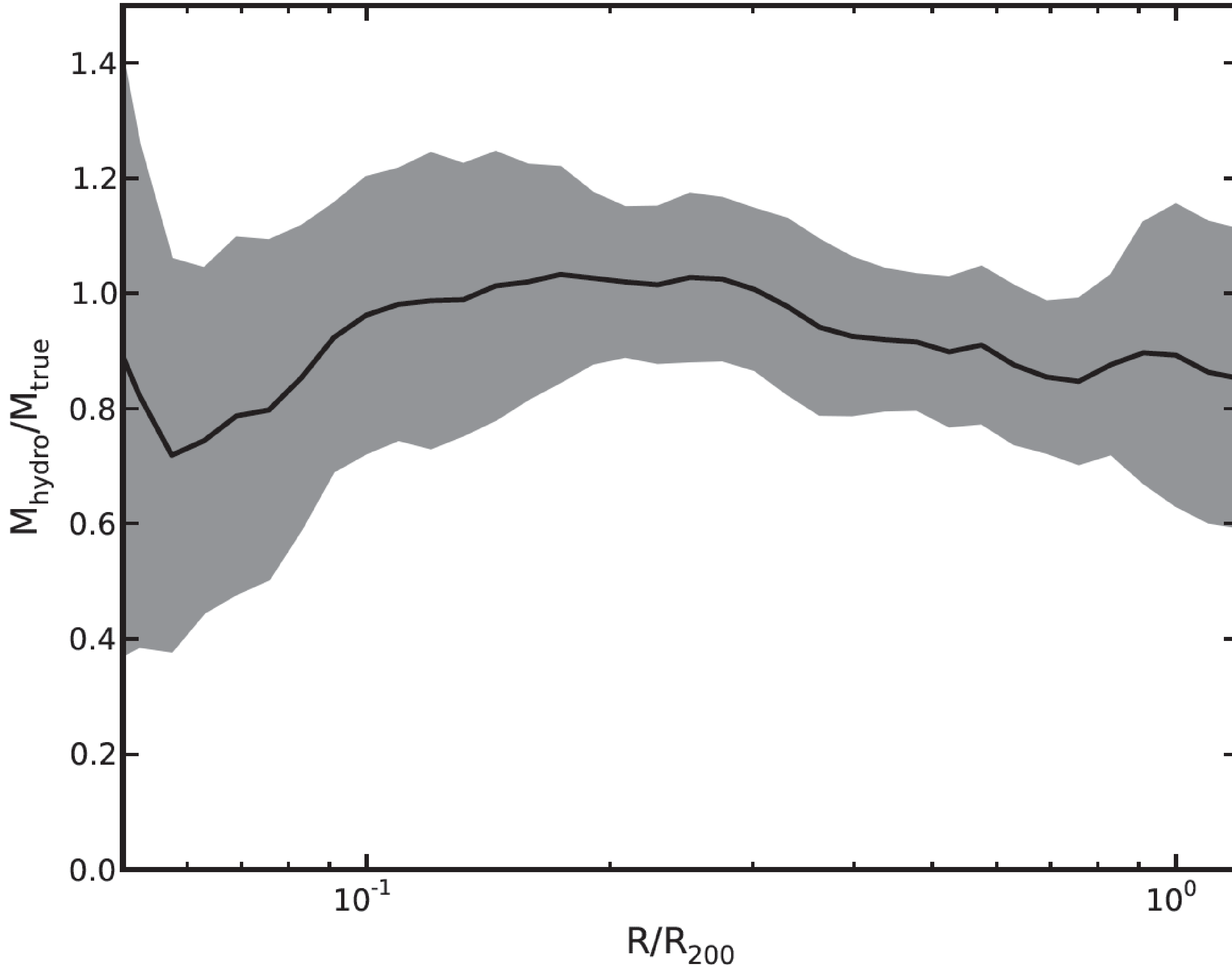
Mass = 1.7-10 × 10^{14} $M_{\odot}$

T = 1.4-4.4 keV



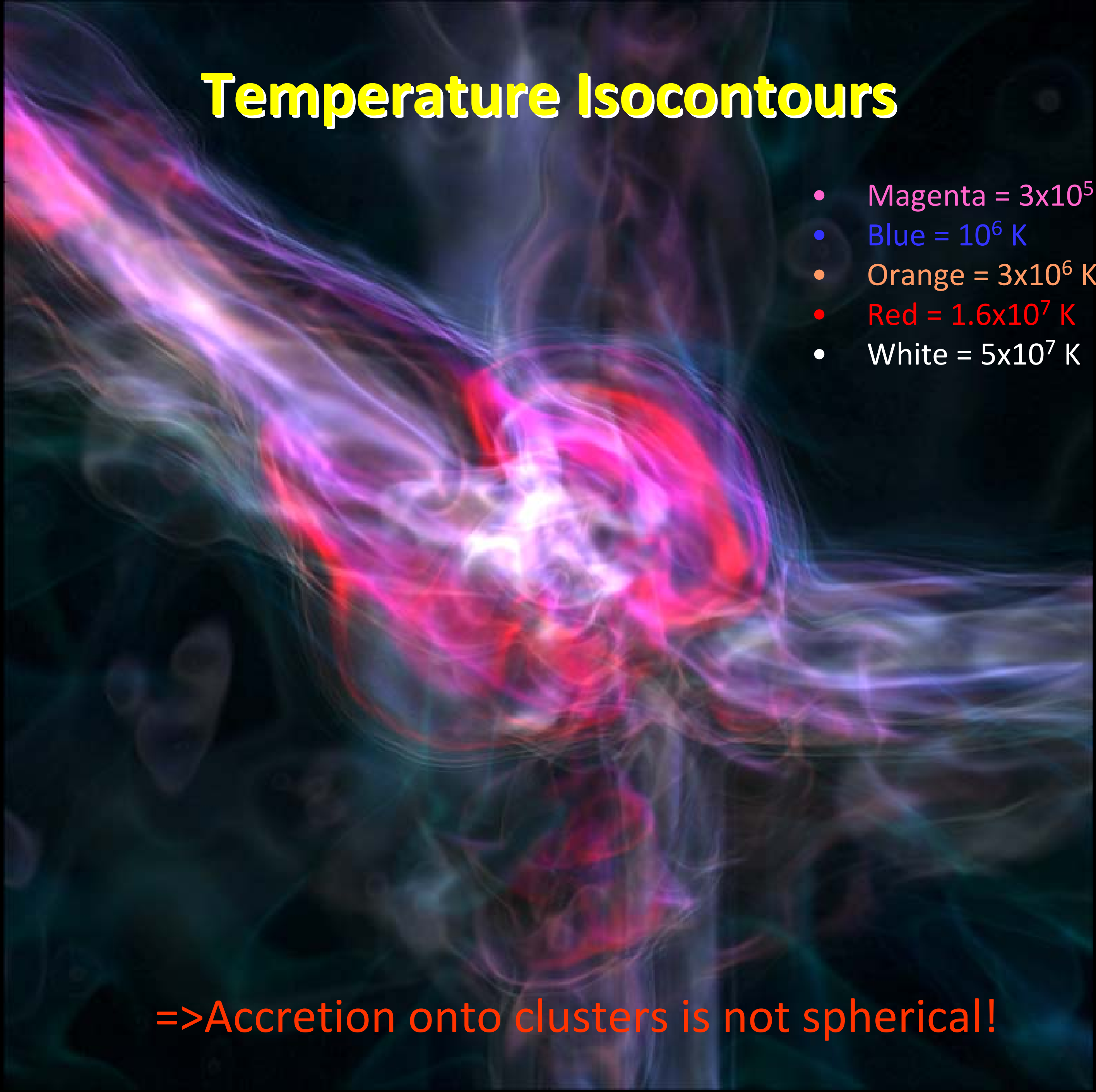

3D Profiles Average
2D Profiles Average
Density [g/cm^3]
R/R$_{200}$
3D Profiles
2D Profiles
PKS0745191
A1795 N
A1795 S
T/T$_{\mathrm{X-ray\ averaged\ temperature}}$
R/R$_{200}$
Entropy[keV cm^2] =kTn$^{-2/3}$
R/R$_{200}$


3D Profiles
Hydrostatic Temperature
PKS0745191
A1795 N
A1795 S
Temperature [K]
R/R_{200}
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2



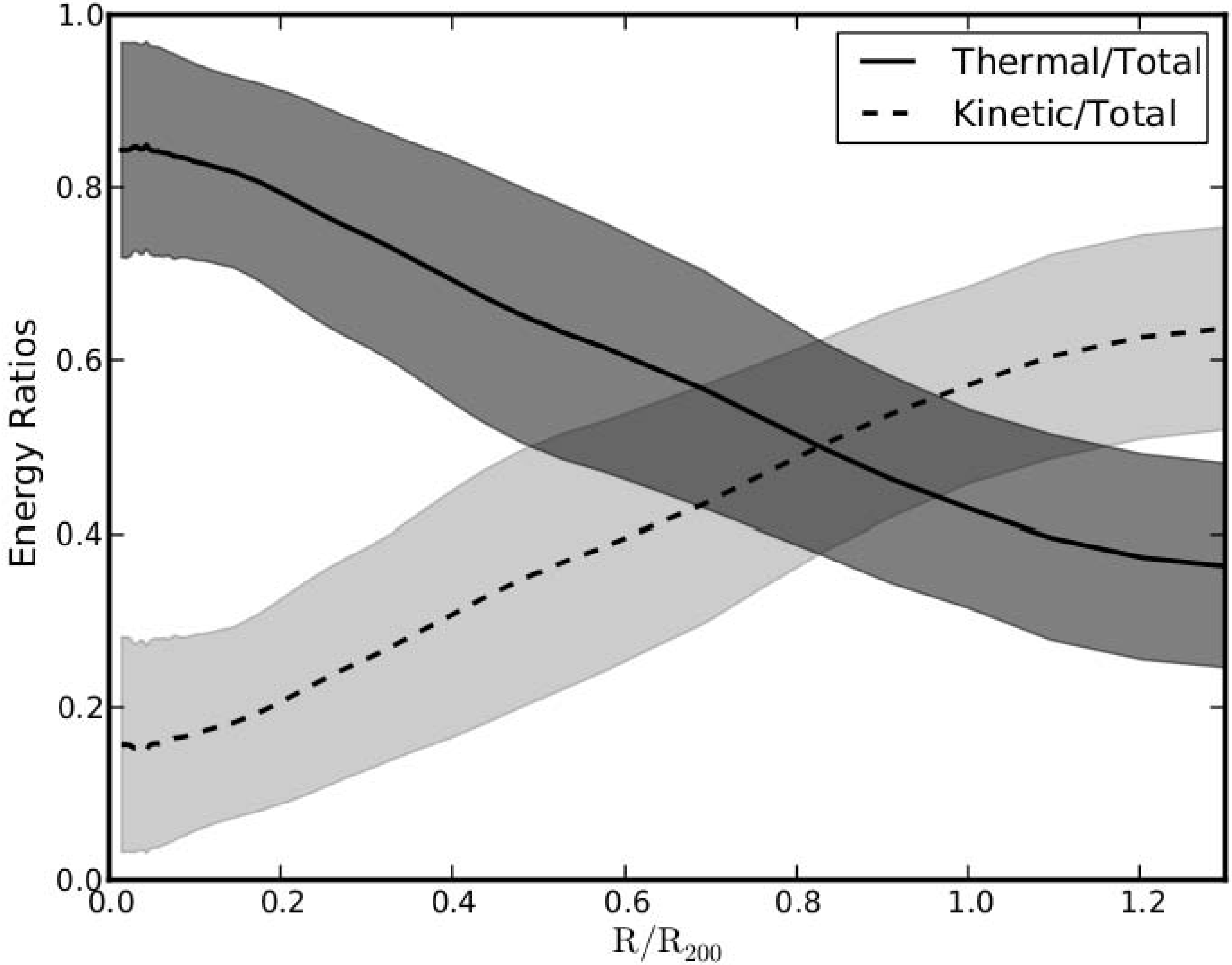
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
M_{hydro}/M_{true}
10^{-1}
10^{0}
R/R_{200}

Temperature Isocontours



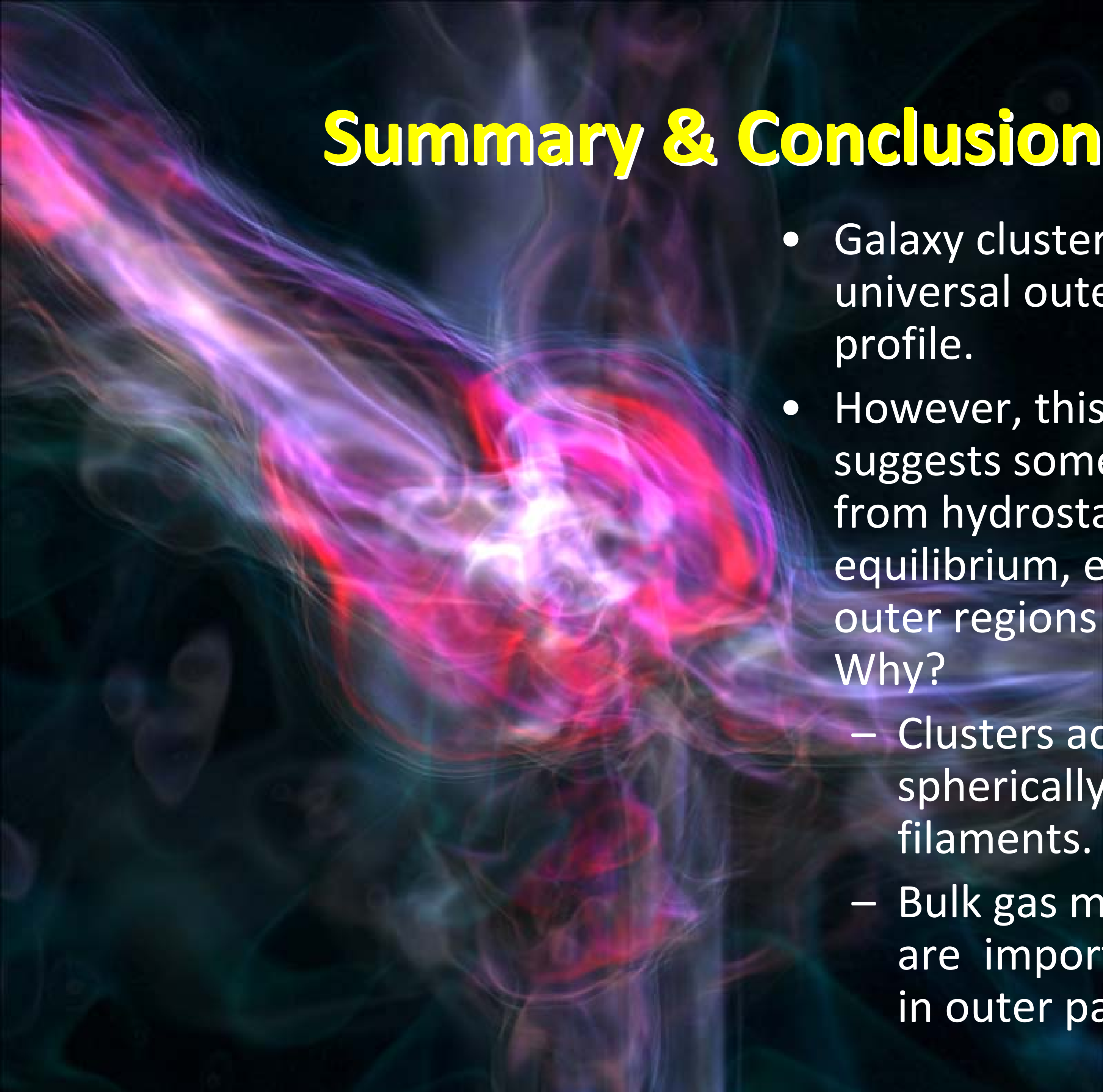
- Magenta = 3×10^5 K
- Blue = 10^6 K
- Orange = 3×10^6 K
- Red = 1.6×10^7 K
- White = 5×10^7 K

=>Accretion onto clusters is not spherical!



Thermal/Total
Kinetic/Total
Energy Ratios
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
R/R_{200}

Summary & Conclusions



- Galaxy clusters exhibit a universal outer temperature profile.
- However, this T profile suggests some deviation from hydrostatic equilibrium, especially in the outer regions of clusters. Why?
  - Clusters accrete gas non-spherically via linear filaments.
  - Bulk gas motions in ICM are important, especially in outer parts of cluster.