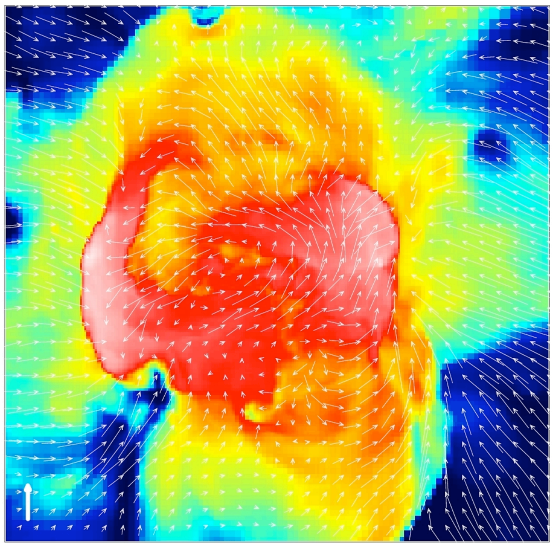
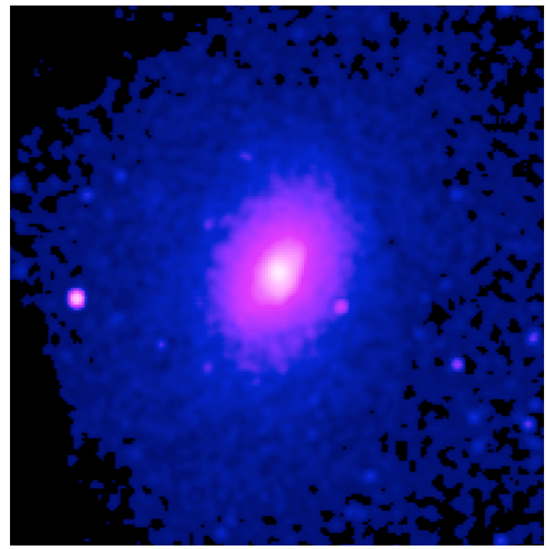
Thermodynamics of Galaxy Clusters and Beyond





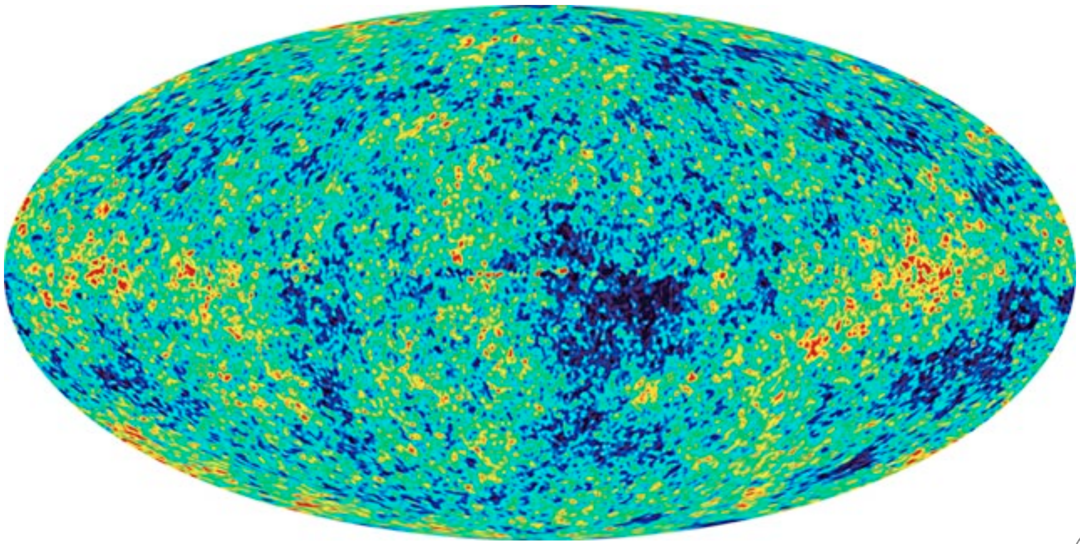
Daisuke Nagai

Yale University

TAC seminar @ UC Berkeley

April 13th, 2009

Large-scale structure in the Universe

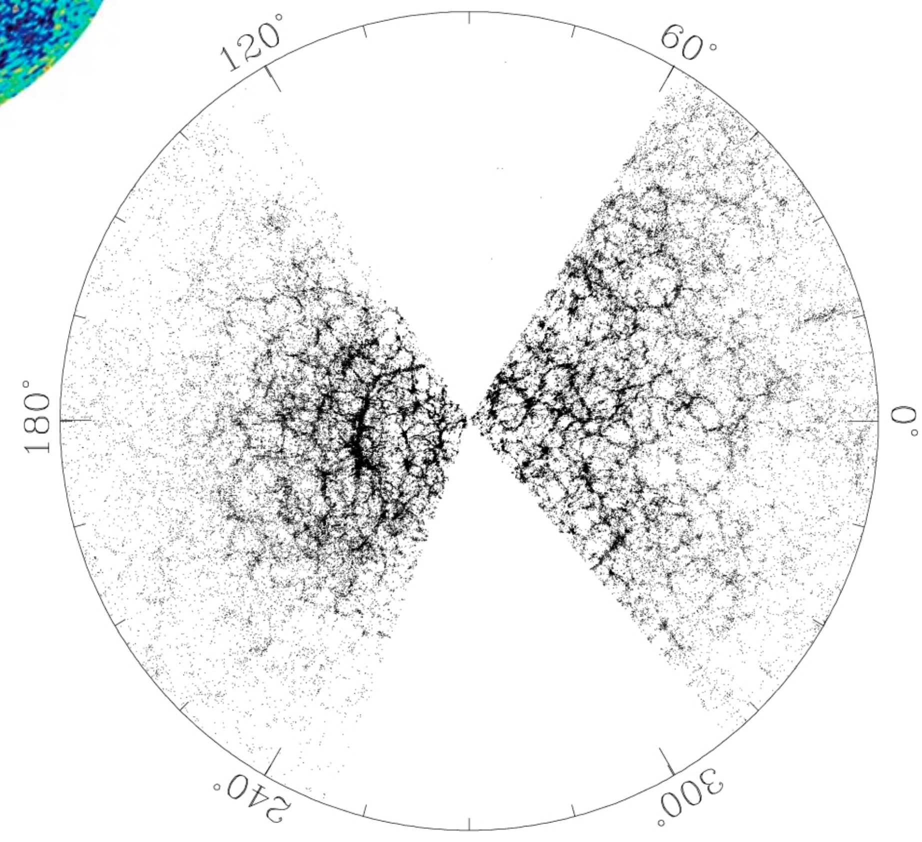


WMAP (microwave)
Early Universe
$\delta\rho/\rho \sim 10^{-5}$

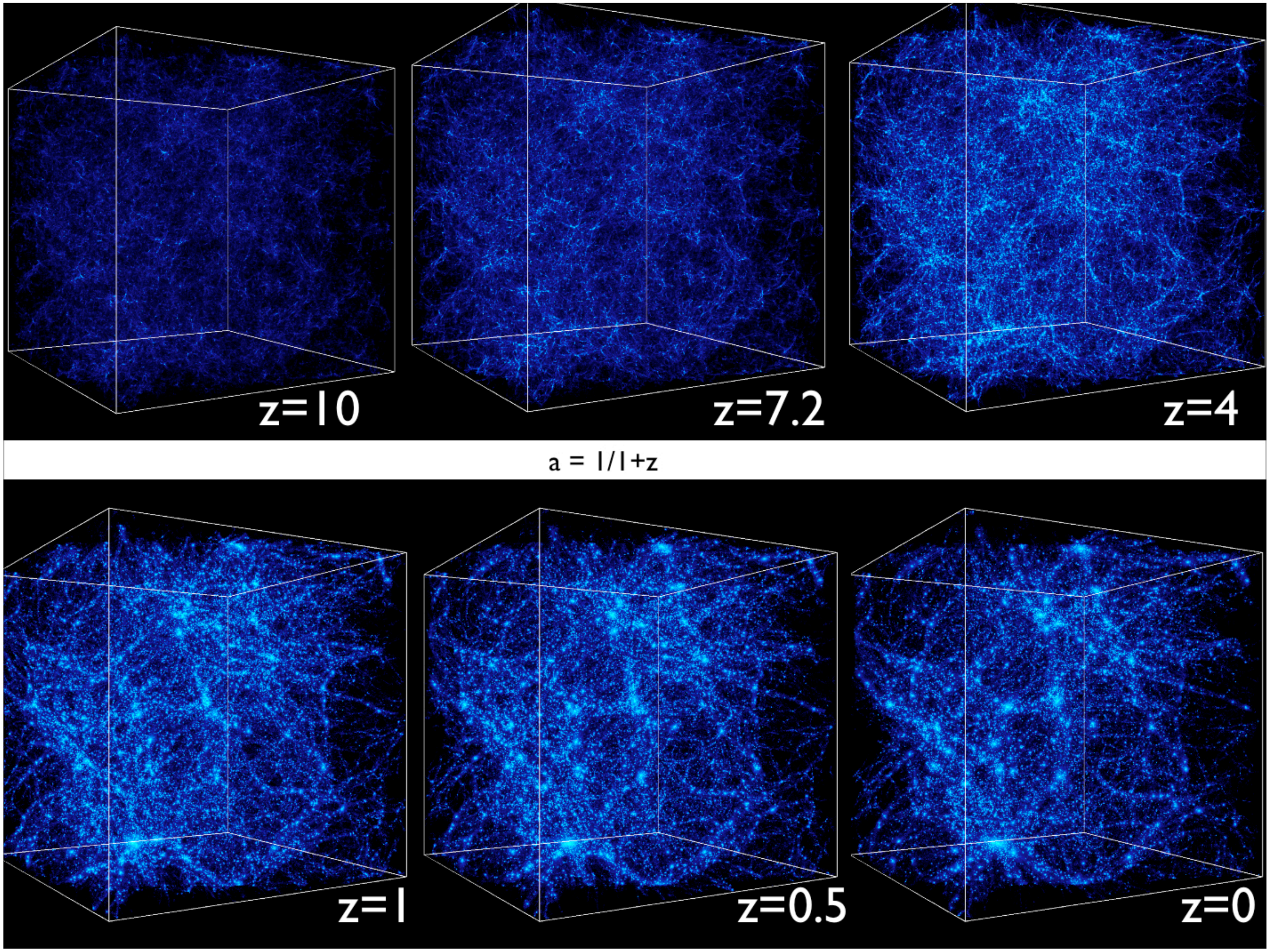
Courtesy of WMAP team

SDSS (optical)
Today
$\delta\rho/\rho >> 1$

Blanton et al. 2003

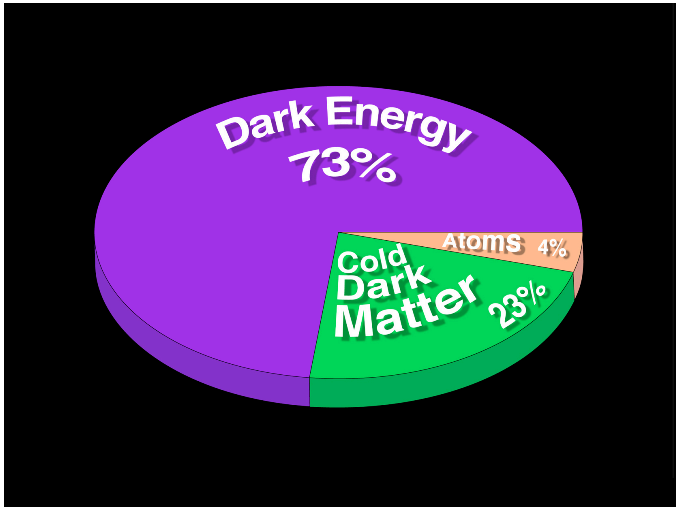


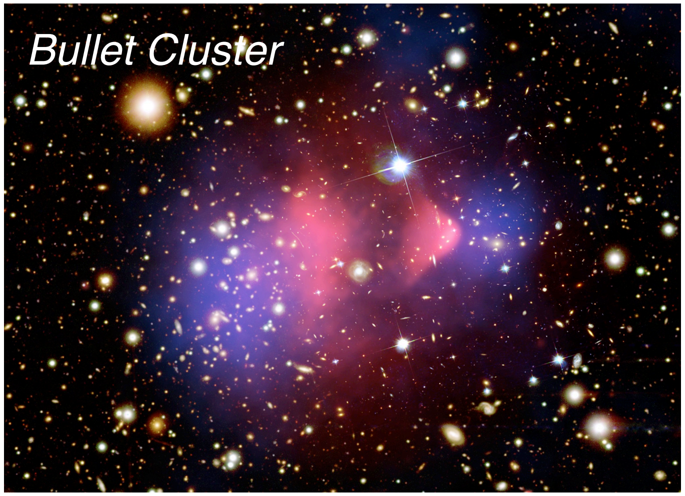
Formation of the large-scale structure in the Universe

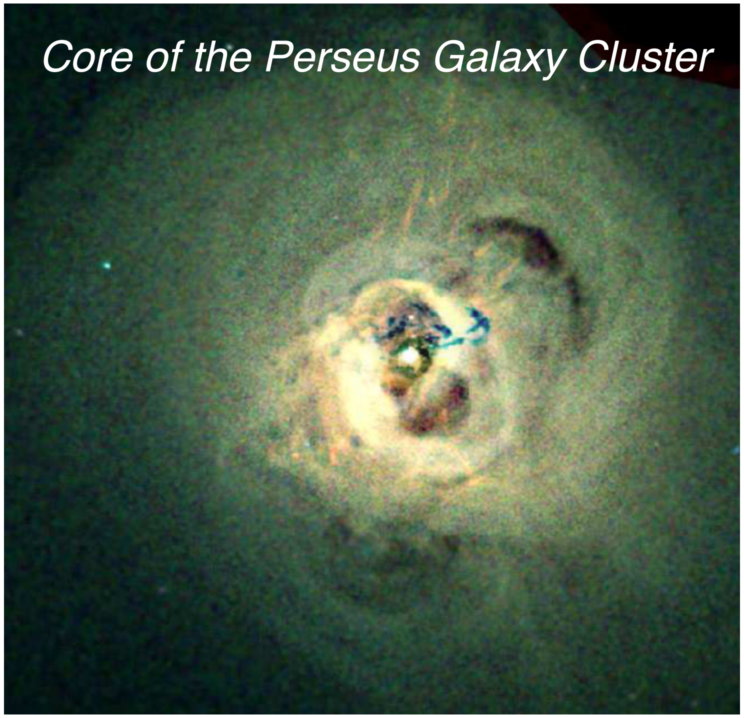


Cosmology and Astrophysics with Galaxy Clusters

Clusters of galaxies provide important insights into the nature of dark energy and dark matter.







The most massive galaxies and black holes in the universe form and evolve in cores of galaxy clusters.

Cosmology and Astrophysics with Galaxy Clusters

- The majority of baryons in clusters are in the form of hot, X-ray emitting intracluster plasma.

- Understanding thermodynamics (e.g., heating and cooling) of the intracluster plasma is important for the use of galaxy clusters as cosmological probes as well as understanding the physics of the most massive galaxies and black holes.

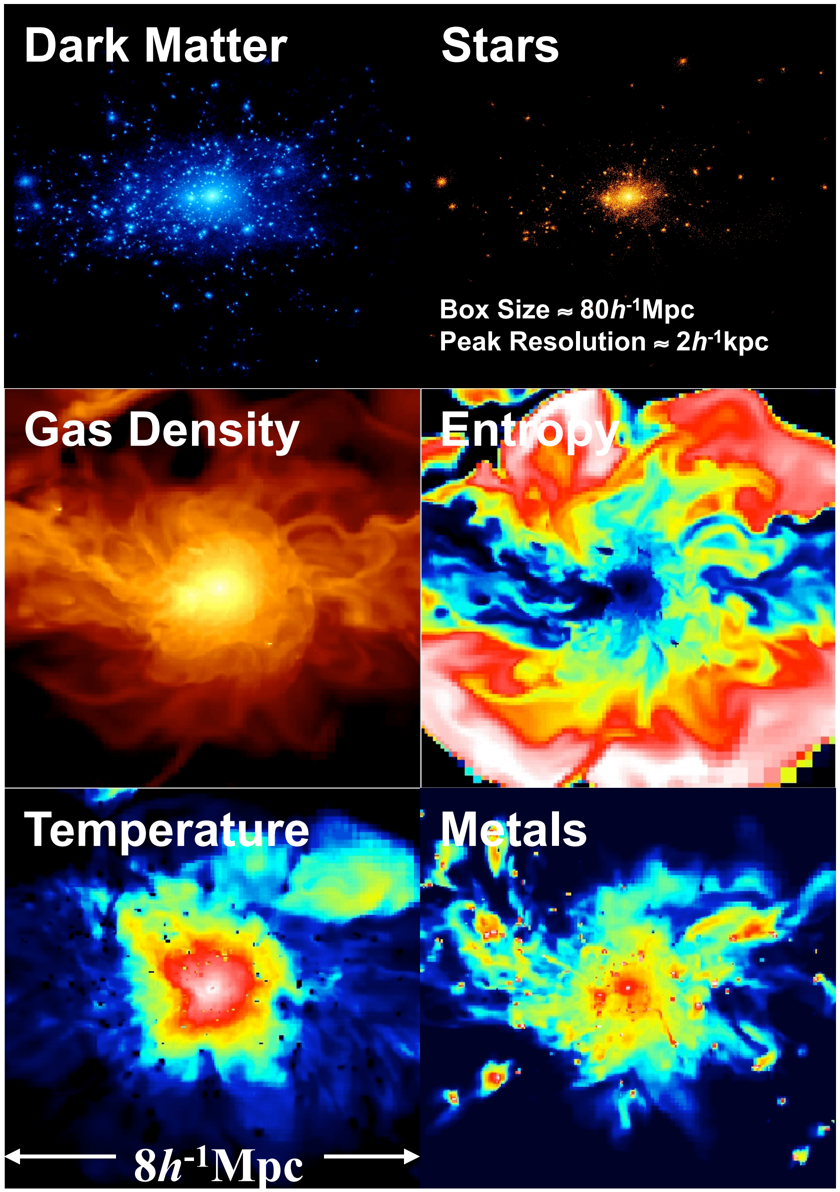
- **Main Challenges for Cluster Cosmology**: understanding cluster gas physics (e.g., gas cooling and heating by energy feedback) and calibrate the relationship between X-ray and SZE observables and mass (Δ=500).

$$\boxed{\begin{array}{l} T_{gas} \propto GM_\Delta / R_\Delta \propto M_\Delta^{2/3} \\ SZ\ flux \propto \int P_{gas}\, dl\, d\Omega \propto f_{gas} M_\Delta^{5/3} \end{array}}$$

$$M_\Delta \equiv (4\pi/3)\, R_\Delta^3\, \Delta\, \rho_{crit}(z)$$

How does galaxy formation physics affect global cluster properties?
How do current simulations compare with observations?
How well cluster observables correlate with mass?

High-Resolution Cluster Simulations



N-body+Gasdynamics with ART code

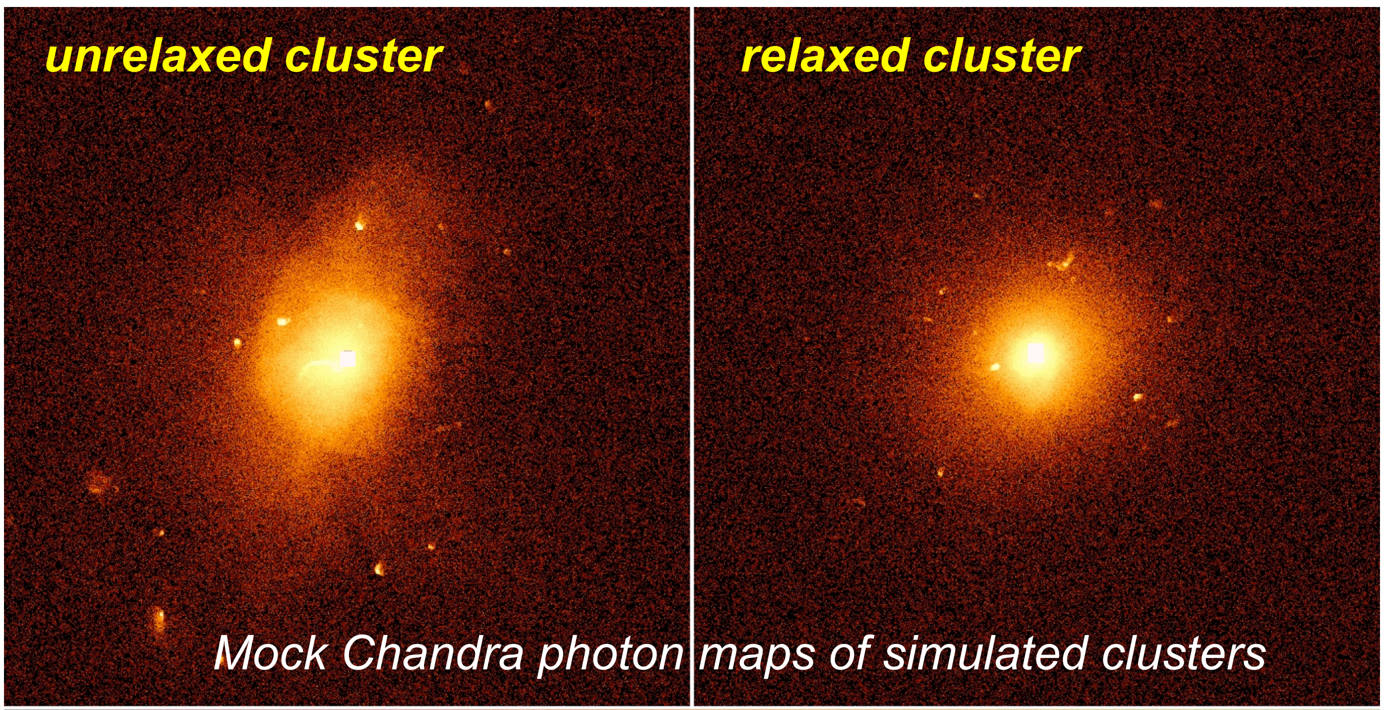
- **Collisionless dynamics** of DM and stars
- **Gasdynamics:** Eulerian Adaptive Mesh Refinement
- **Radiative cooling and heating of gas:** metallicity dependent net cooling/heating rates
- **Star Formation** using the Kennicutt (1998) recipe
- **Thermal stellar feedback**
- **Metal enrichment** by SNII/Ia
- **No AGN feedback, thermal conduction, cosmic-rays, magnetic field & physical viscosity**

Cluster Samples

- **High-resolution allows us to actually simulate clusters of galaxies**
- **Effects of galaxy formation on the ICM**
  - **Sample of 16 clusters in ΛCDM model**
  - **Two sets of runs with cooling & SF (CSF) and with non-radiative gasdynamics**
  - **Comparison with Chandra X-ray observations of nearby, relaxed clusters (Vikhlinin et al. 2006)**

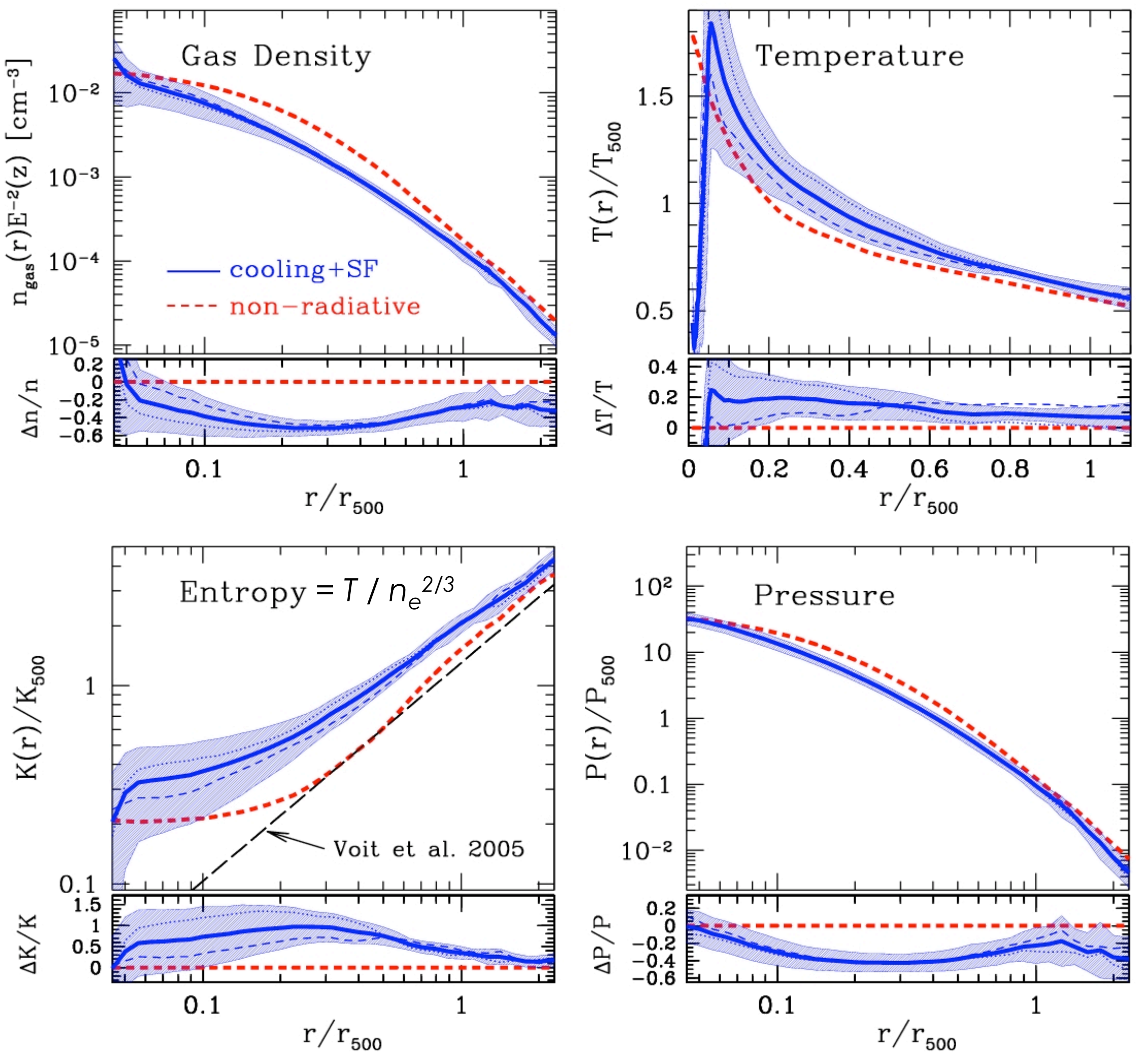
Testing Chandra measurements
with mock observations of simulated clusters

- generate "Chandra data" for clusters from cosmological simulations
- reduce with real data analysis pipeline
  - **gas mass accurate to ~3%, temperatures are accurate to <~10%**
  - **but, hydrostatic mass is biased low by ~10% due to turbulence**



Nagai, Vikhlinin & Kravtsov 2007, ApJ, 655, 98

Intracluster Gas Profiles:
Effects of gas cooling and star formation



cluster-centric r in units of r500

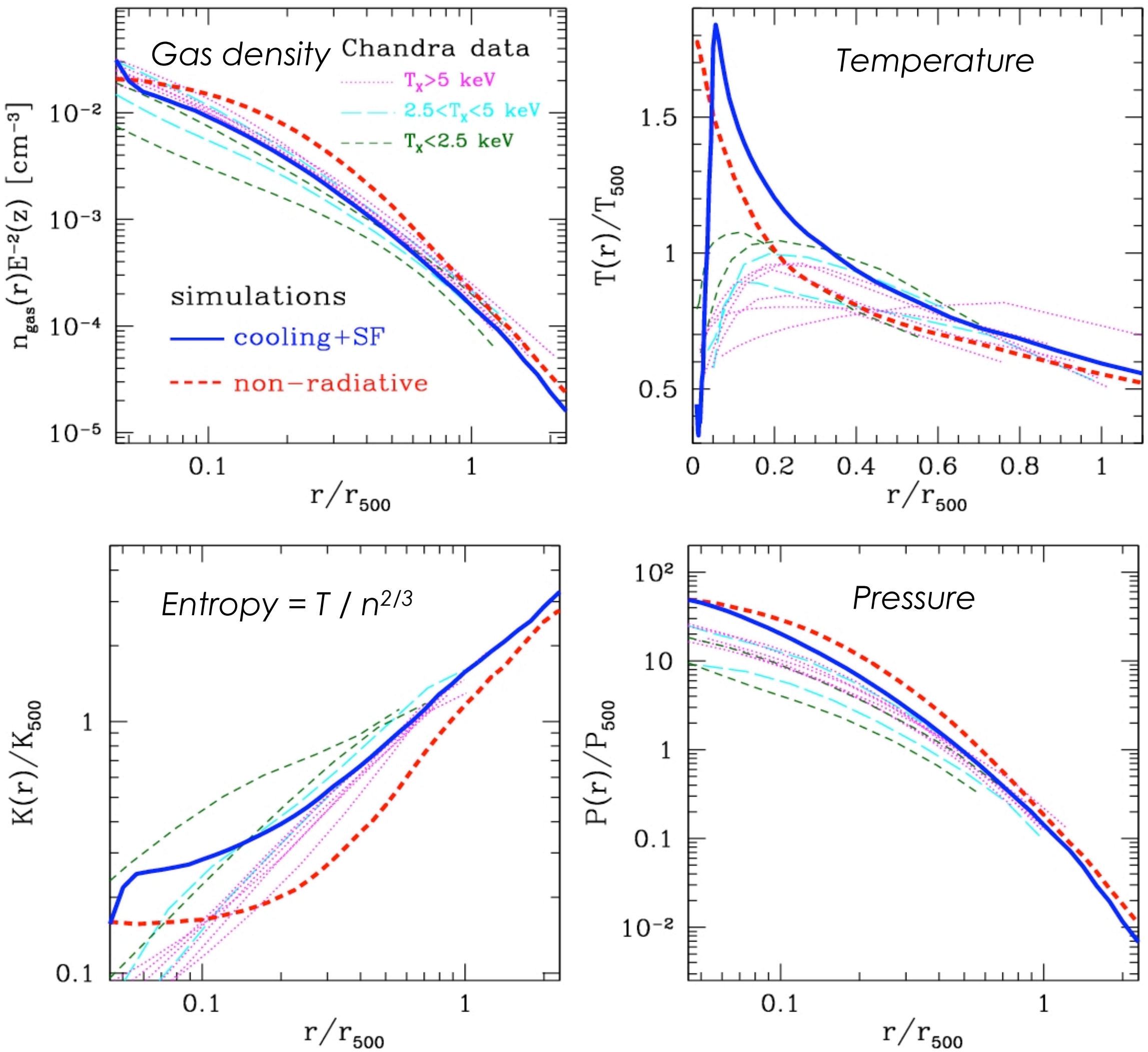
red line:
mean profile for relaxed clusters in non-radiative ("adiabatic") simulations

blue band:
mean profile for relaxed clusters in simulations with cooling and star formation
width = rms scatter

dotted line : Tx < 3keV
dashed line : Tx > 3keV

Nagai, Kravtsov, Vikhlinin 2007, ApJ, 668, 1

Intracluster Gas Profiles: Comparison with observations



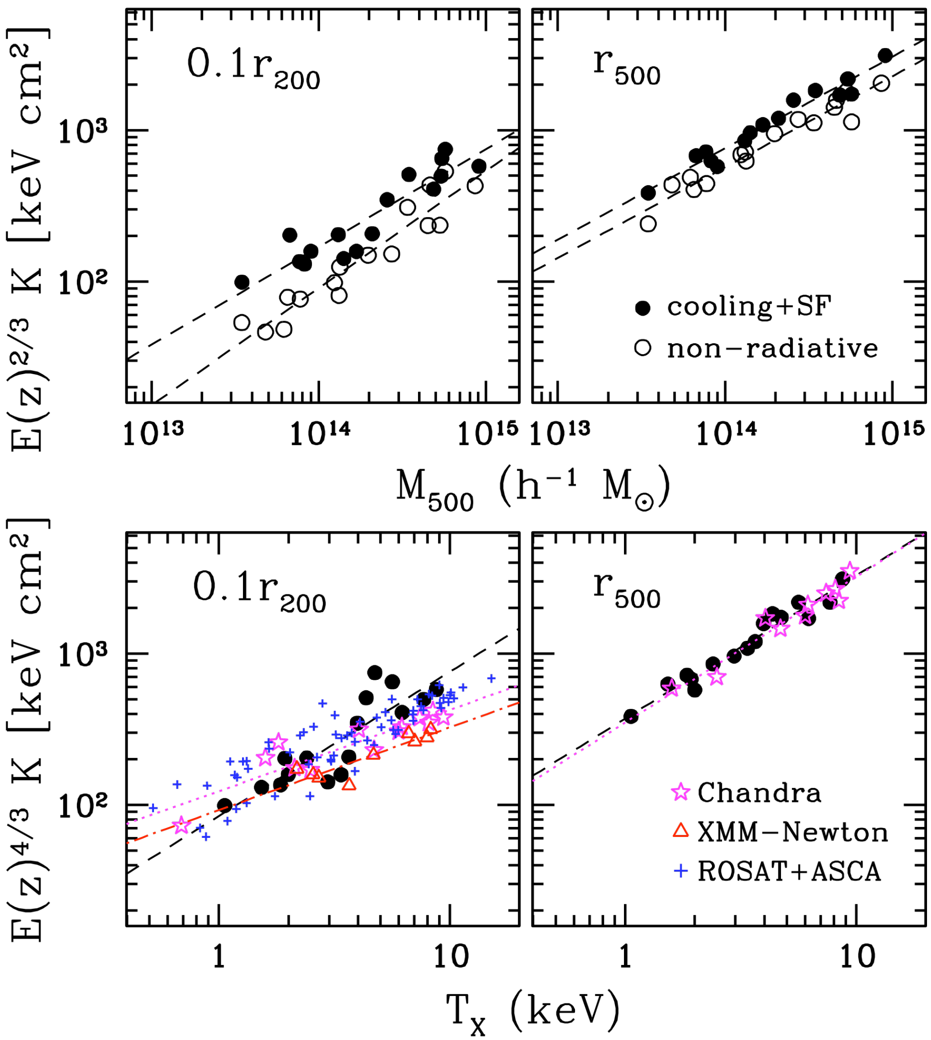
cluster-centric r in units of r500

red line:
mean profile for relaxed clusters in non-radiative ("adiabatic") simulations

blue band:
mean profile for relaxed clusters in simulations with cooling and star formation
width = rms scatter

Thin dashed lines: profiles of Chandra observations of nearby, relaxed clusters of different temperature

Entropy scaling with cluster mass & Tx



mean temperature of the ICM

Simulations with cooling+SF reproduce both the amplitude and scaling with temperature (i.e., mass) exhibited by observed clusters at r>0.1 r_{200}, but not in the core

Solid black pts: CSF simulations

Open black pts: non-radiative sim.

magenta pts: Chandra data
Vikhlinin et al. 2006

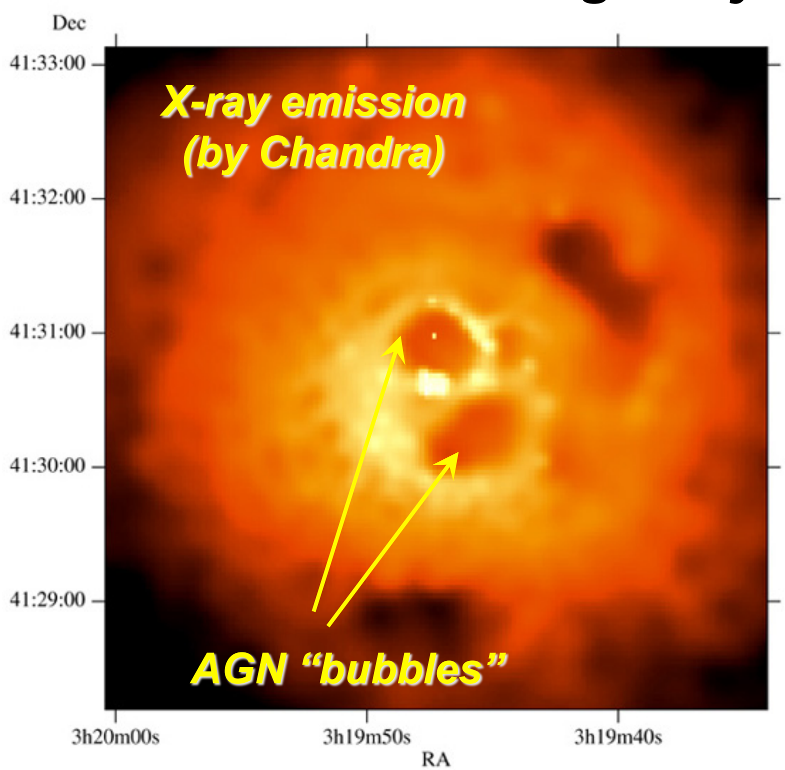
red pts: XMM-Newton data
Pratt et al. 2006

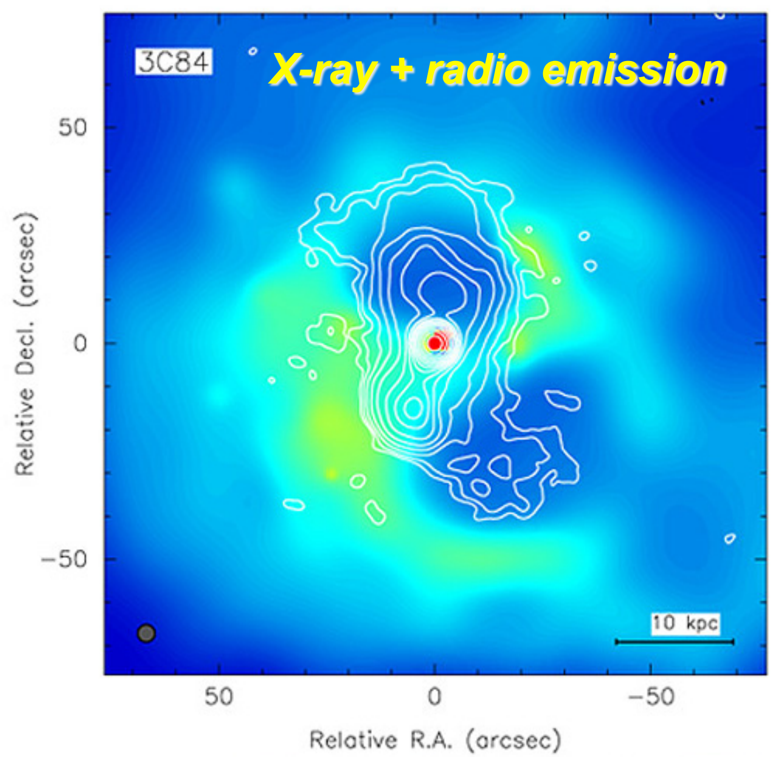
blue pts: ROSAT+ASCA data
Ponman et al. 2003

Nagai, Kravtsov, Vikhlinin 2007, ApJ, 668, 1

additional physical processes affect properties of intracluster gas in cores

example: heating by Active Galactic Nuclei of the central cluster galaxy in the Perseus cluster

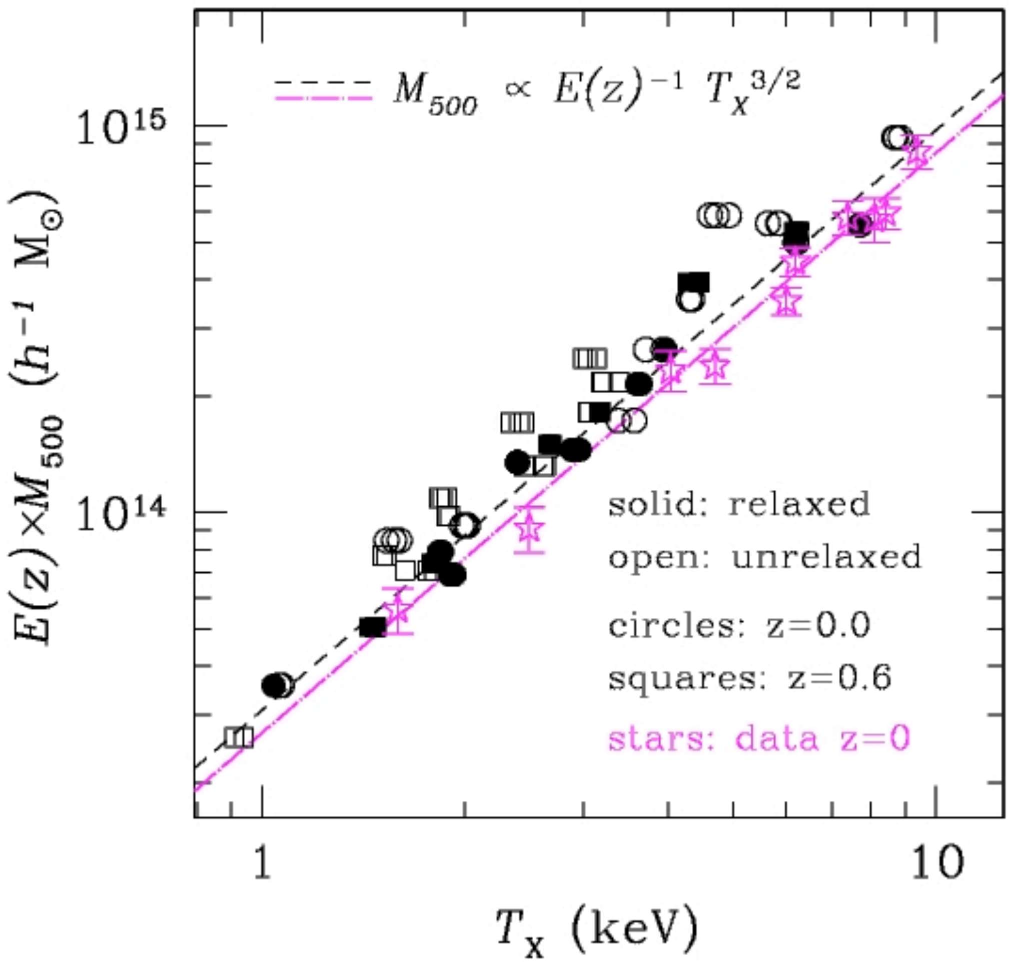




these effects, however, appear to be confined to the core
=> <u>outer regions of clusters can be used to reliably estimate their total masses</u>

Mass – ICM temperature relation

Total mass M_{500c} scaled to z=0



X-ray spectral temperature
excluding cluster cores ($r<0.15 x r_{500c}$)

~10% agreement in the amplitude between observed and model M-Tx relation -- improvements are in both sim. and obs.

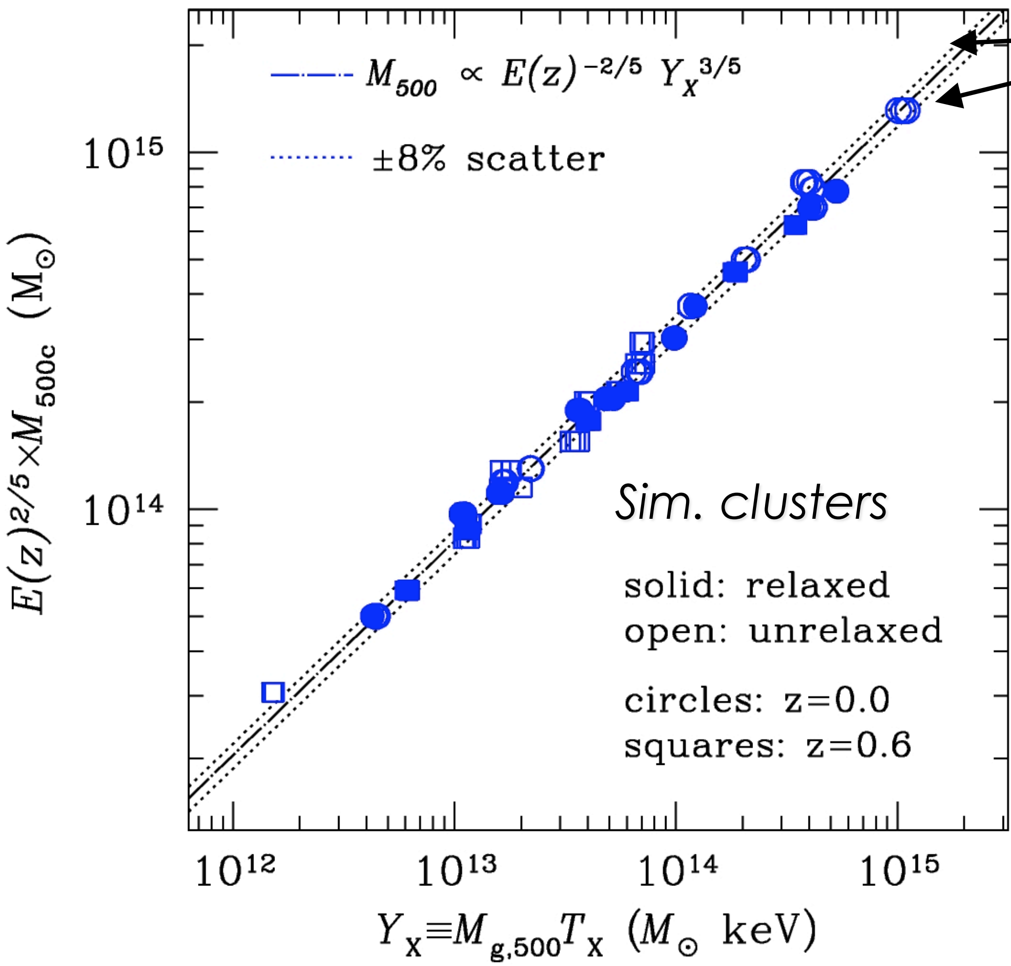
Scatter in M-Tx is ~20% in mass at a given Tx - the scatter is primarily driven by unrelaxed systems

Unrelaxed systems have systematically lower Tx

black pts: Simulated clusters with cooling+SF

magenta pts: Chandra data
Vikhlinin et al. 2006 ApJ, 640, 691

Mass – Yx relation
a new X-ray mass proxy



M_{500c} scaled to z=0

X-ray "pressure" = gas mass x temperature

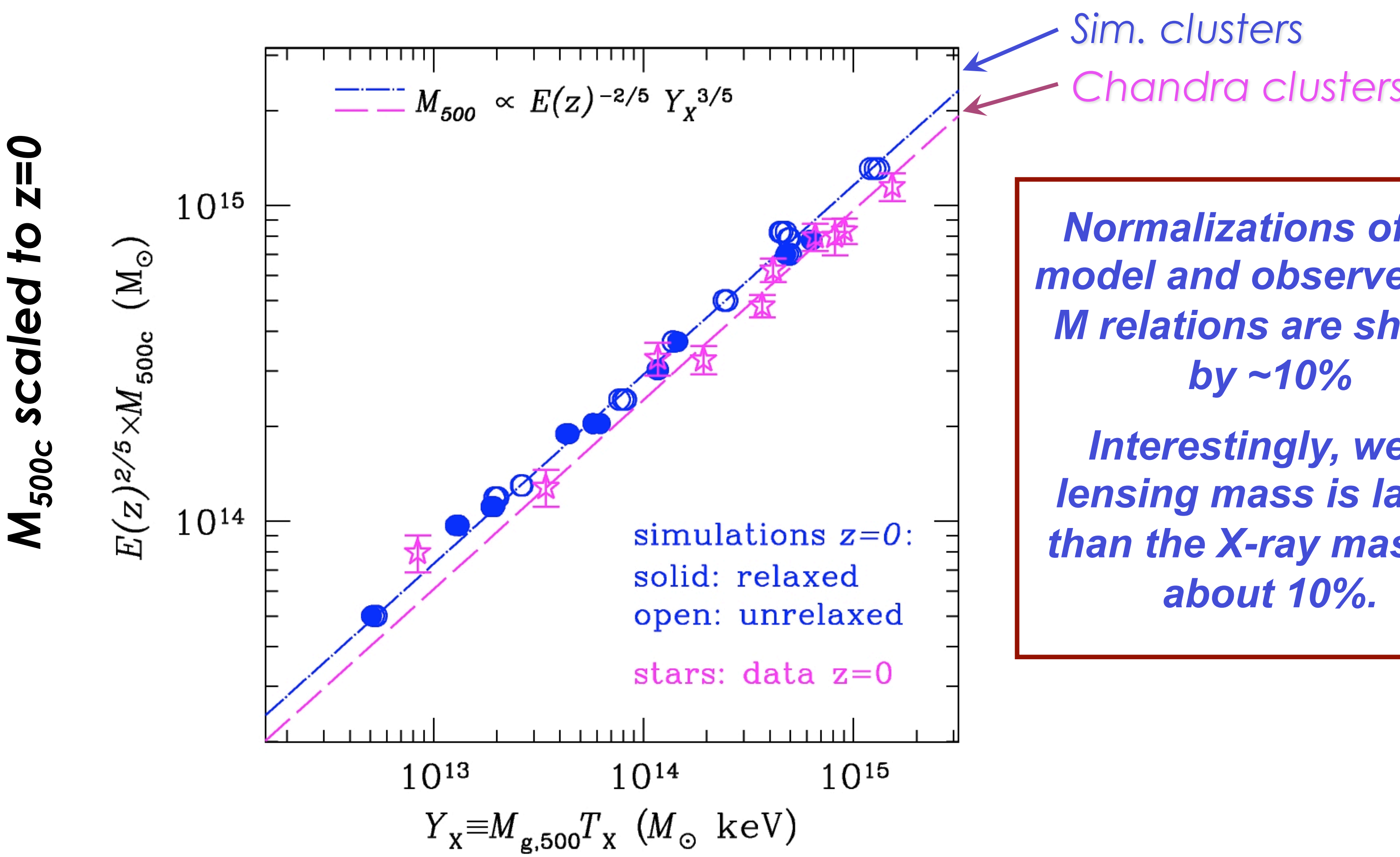
Dotted lines show 8% deviation from the mean

Yx is an excellent mass proxy!

scatter in Yx-M is ~8% for both relaxed & unrelaxed systems and for low- & high-z

Kravtsov, Vikhlinin, Nagai 2006, ApJ, 650, 128

Mass – Yx relation
comparison with observations

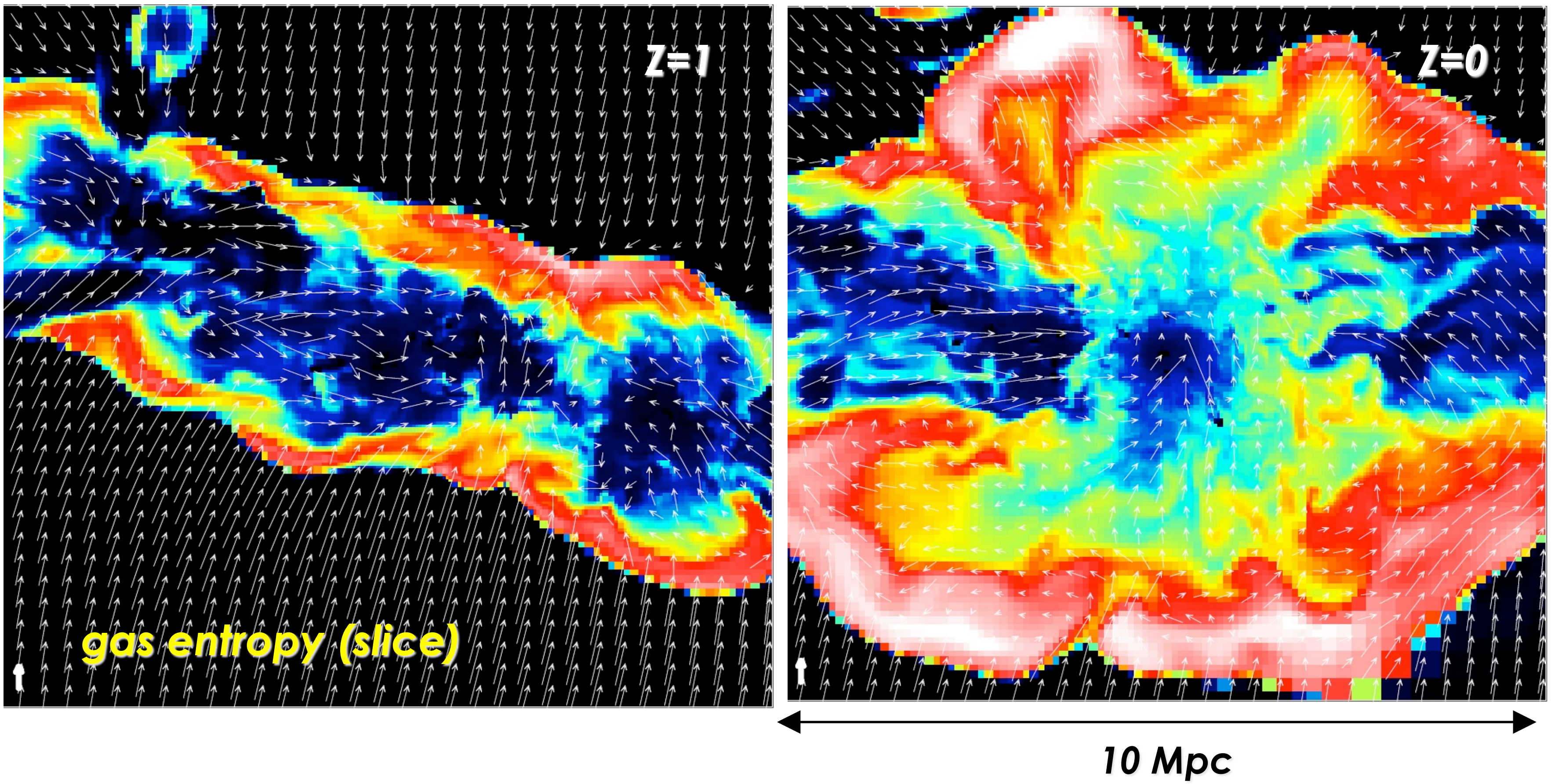


X-ray "pressure" = gas mass x temperature

Normalizations of the model and observed Yx-M relations are shifted by ~10%

Interestingly, weak lensing mass is larger than the X-ray mass by about 10%.

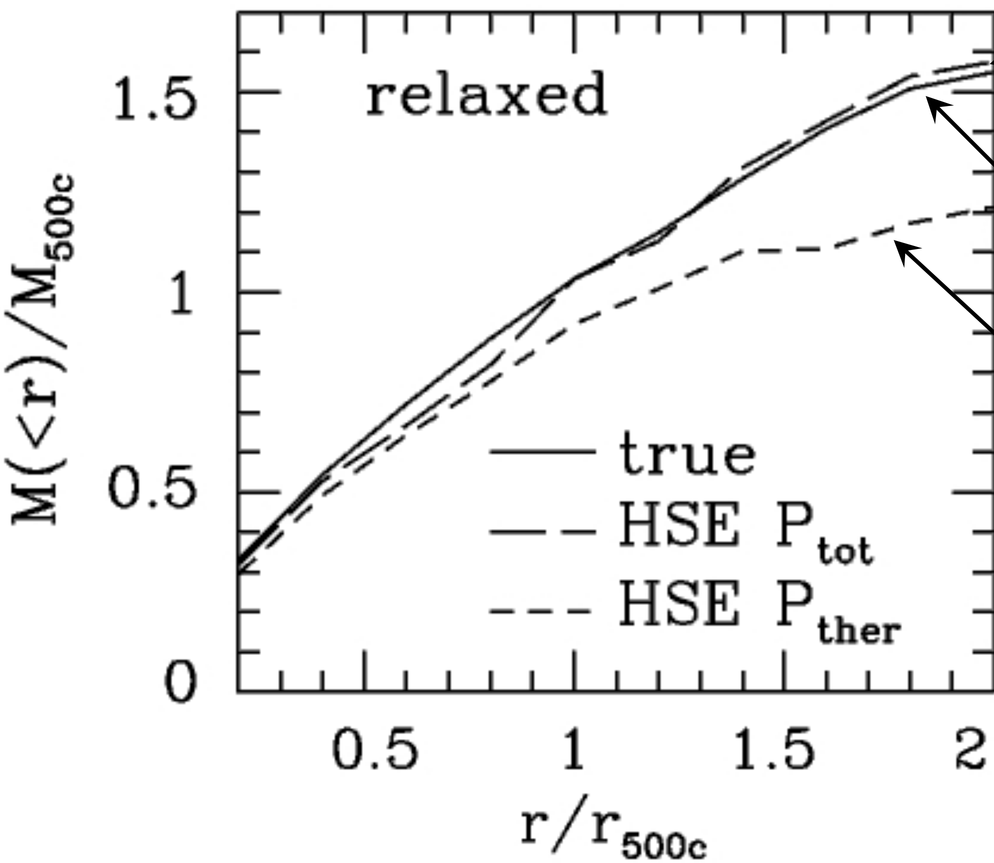
Accretion, Mergers
→ Shocks, Turbulence



Norman & Bryan 1999, Nagai, Kravtsov & Kosowsky 2003
Sunyaev, Norman & Bryan 2003; Rasia et al. 2004, 2006;
Dolag et al. 2005; Nagai et al. 2007; Lau et al. 2009

Effect of turbulent gas motions on mass measurements

$$M_{\rm tot}(<r) = \frac{-r^2}{G\rho}\left(\frac{dP_{\rm ther}}{dr} + \frac{dP_{\rm turb}}{dr}\right)$$



Mass profile from hydrostatic equilibrium taking into account turbulent pressure

True mass profile in simulations

Mass profile from hydrostatic eqiulibrium neglecting turbulent pressure

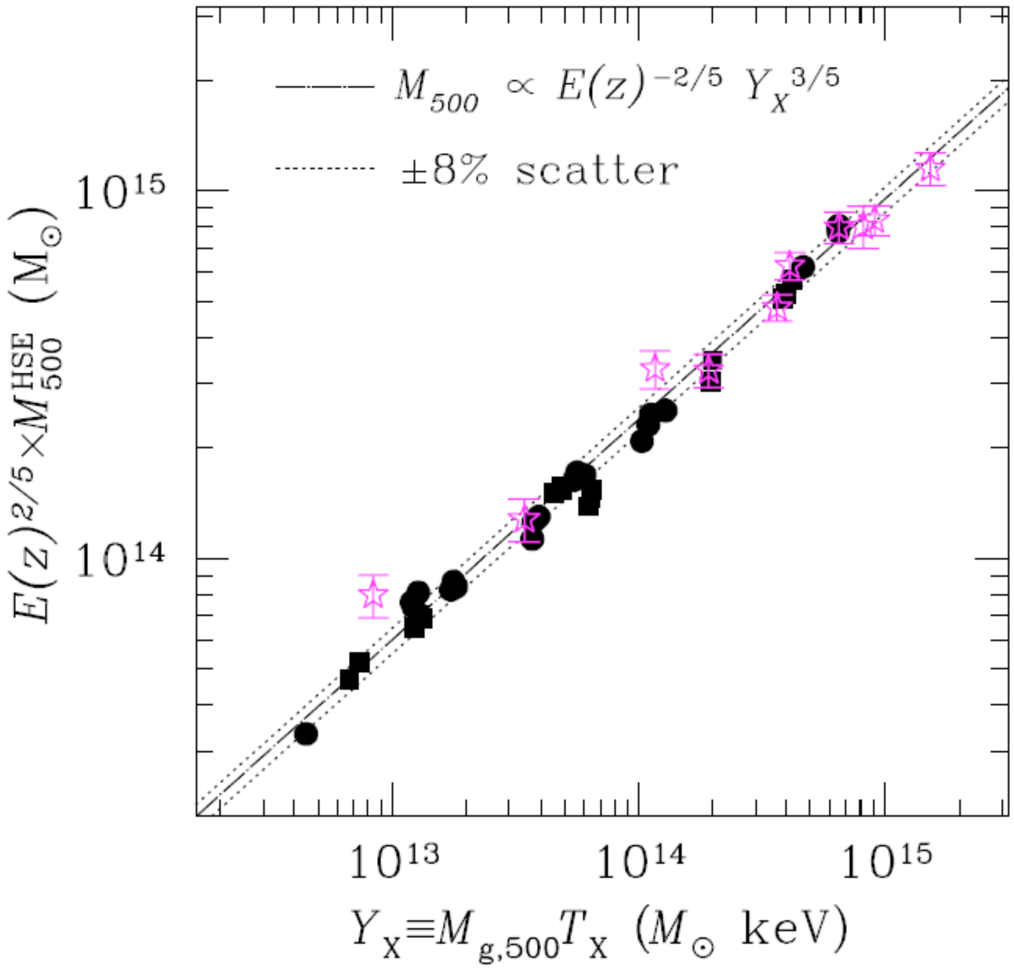
Lau, Kravtsov, Nagai 2009
astro-ph/0903.4895

cluster-centric radius in units of r_{500c}

Mass – Yx relation

using mass derived from the hydrostatic equilibrium analysis both in observations and simulations

Hydrostatic mass M_{500c}

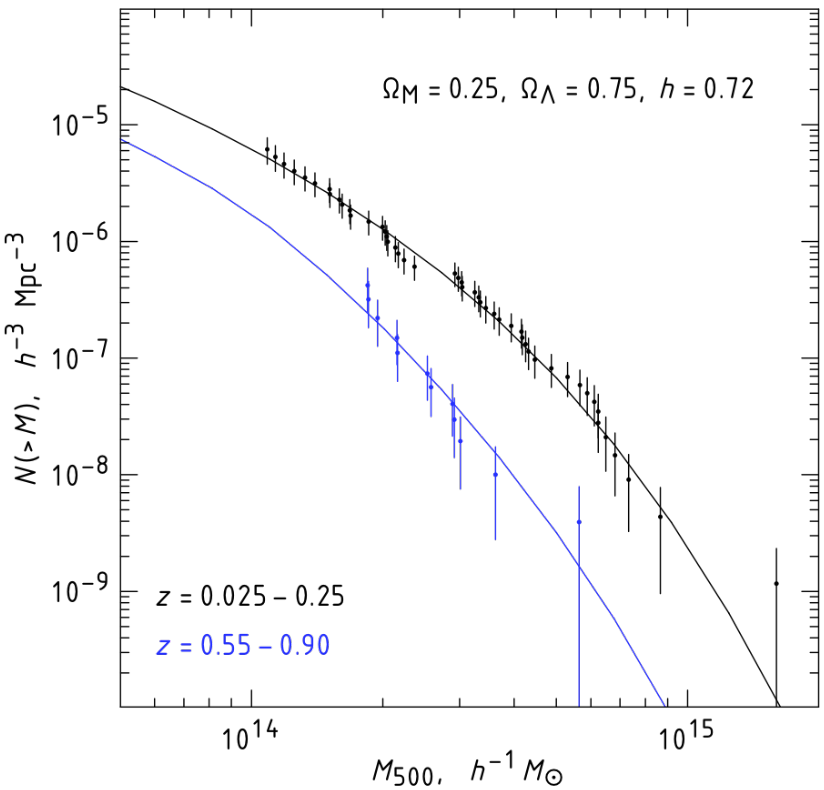


X-ray "pressure" = gas mass x temperature

Dark energy constraints from the evolution of cluster mass function

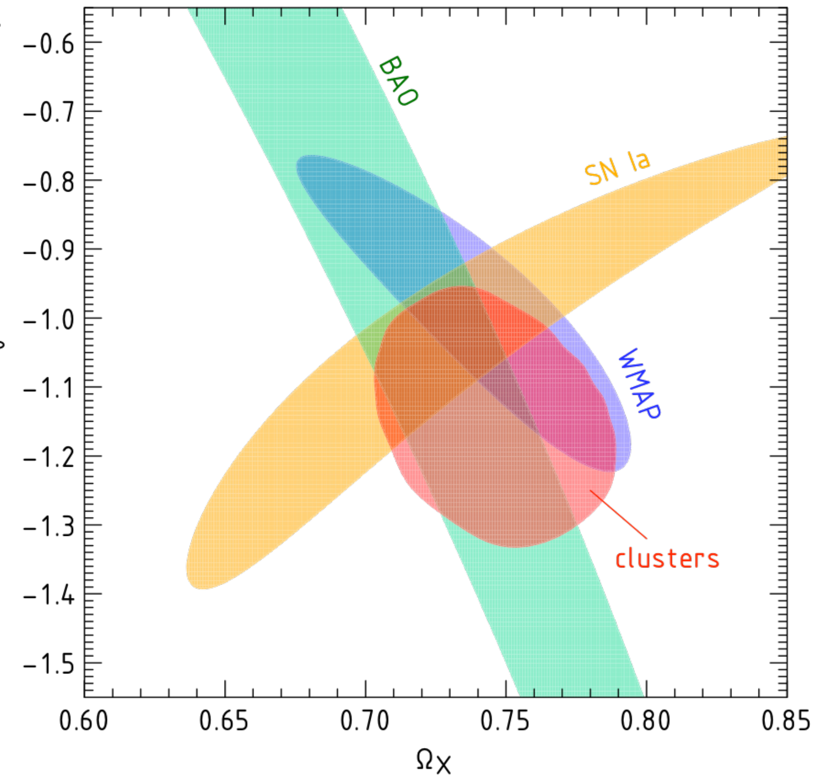
The 400 sq. deg. X-ray cluster survey (Vikhlinin et al. 2009)
Talk by A. Vikhlinin next month

Cumulative abundance (>M)



M_{500} **–** total mass within radius enclosing overdensity of 500 x $\rho_{\mathbf{crit}}$

Dark energy equation of state, w_0

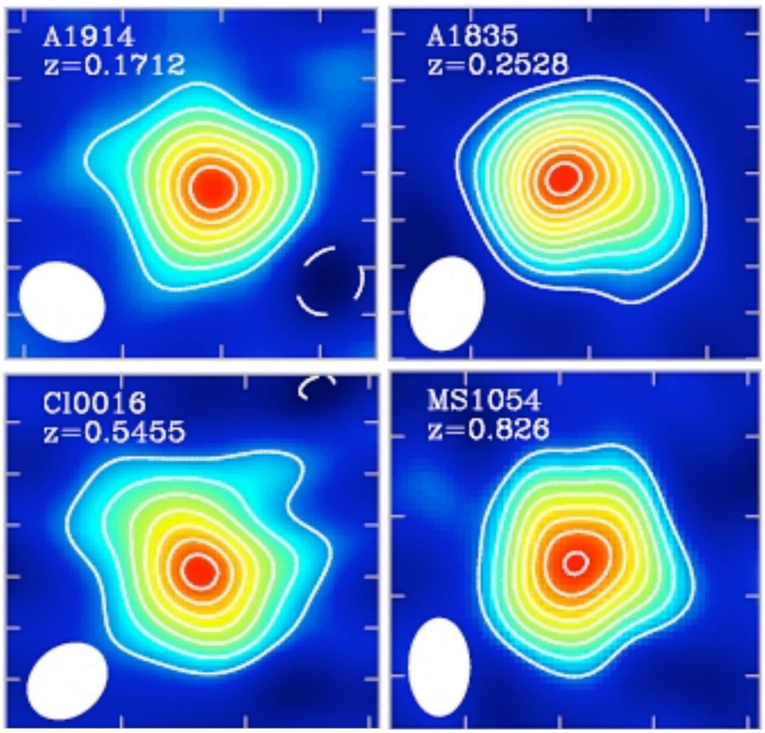


Dark energy density, Ω_X

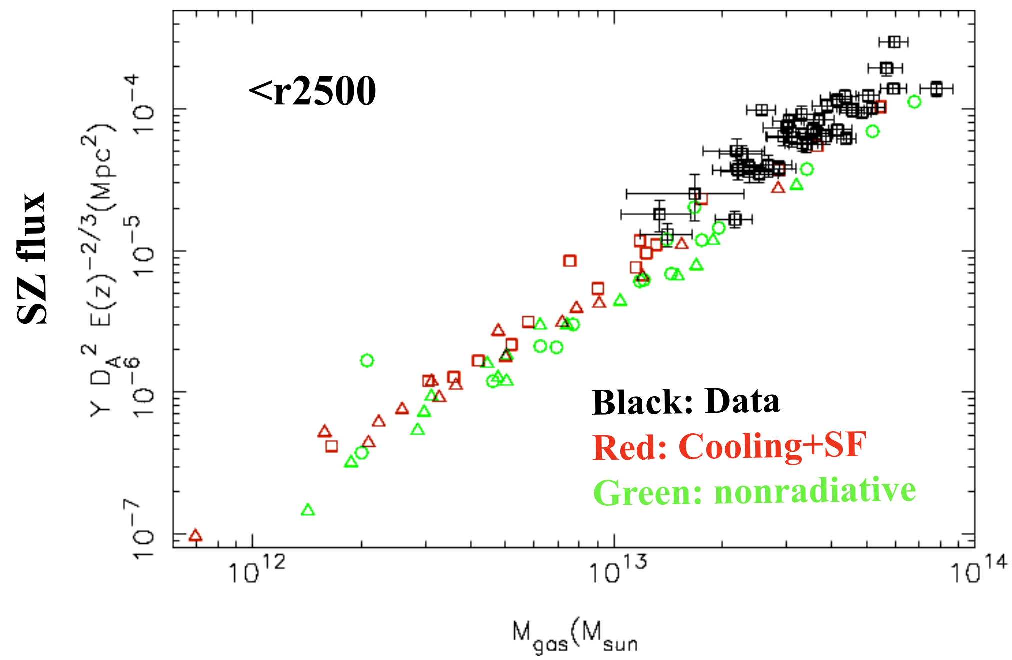
Cosmology with Sunyaev-Zel'dovich Effect

Upcoming SZE cluster surveys will produce large statistical samples (e.g., from AMI, AMiBA, APEX, SZA to ACT, Planck, and SPT)

SZ Effect directly probes the integrated pressure



Sample of 38 BIMA/OVRO SZE+Chandra X-ray clusters at 0.14<z<0.89

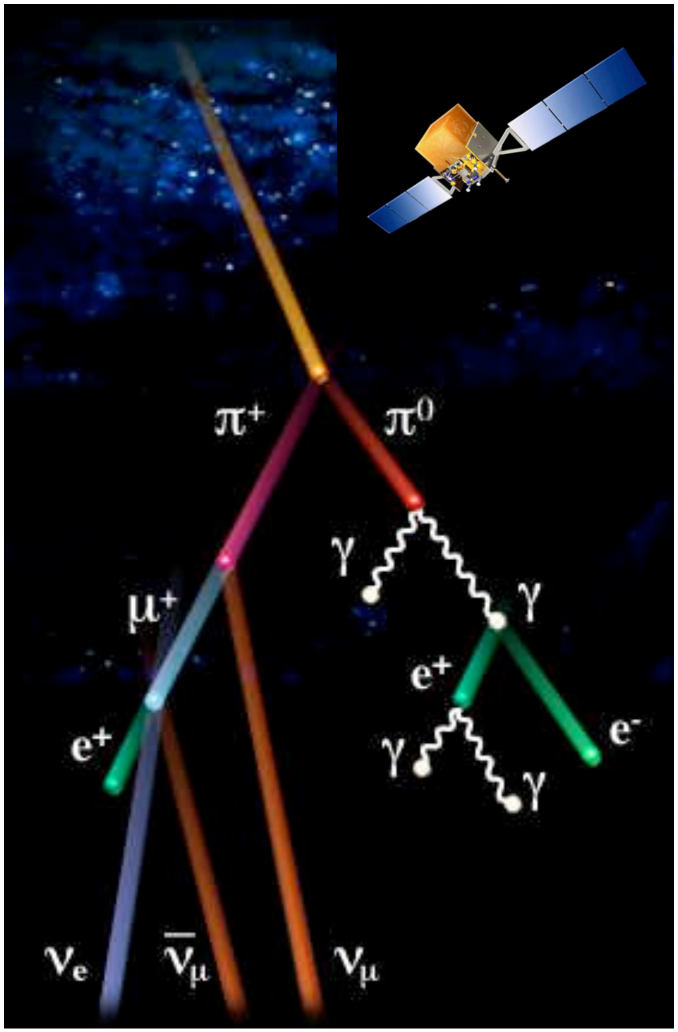


Gas mass within r2500

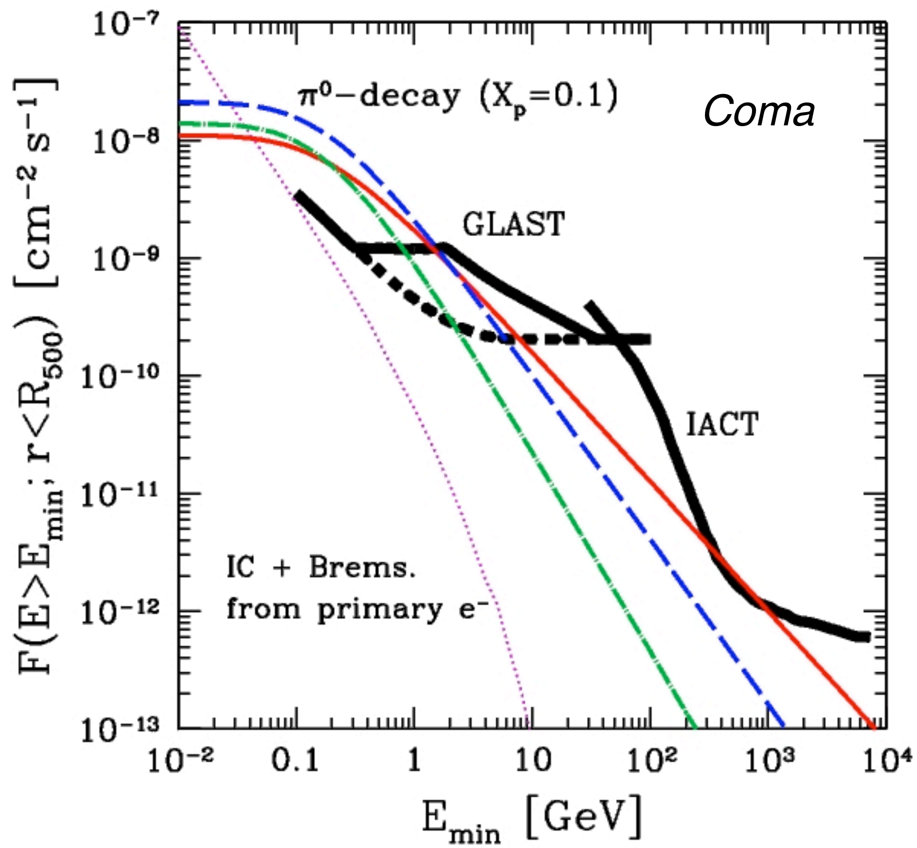
Simulations: *Nagai 2006, also Motl et al. 2005, Hallman et al. 2007*
Data: *Bonamente, Joy, LaRoque, Carlstrom, Nagai, Marrone 2008*
Also talk by D. Marrone on recent results from SZA.

Probing cosmic-rays pressure with Fermi

$$M_{\rm tot}(<r) = \frac{-r^2}{G\rho}\left(\frac{dP_{\rm ther}}{dr} + \frac{dP_{\rm turb}}{dr} + \frac{dP_{\rm cr}}{dr}\right)$$



Fermi will provide stringent constraints (~1%) on the cosmic-ray protons in nearby, rich clusters

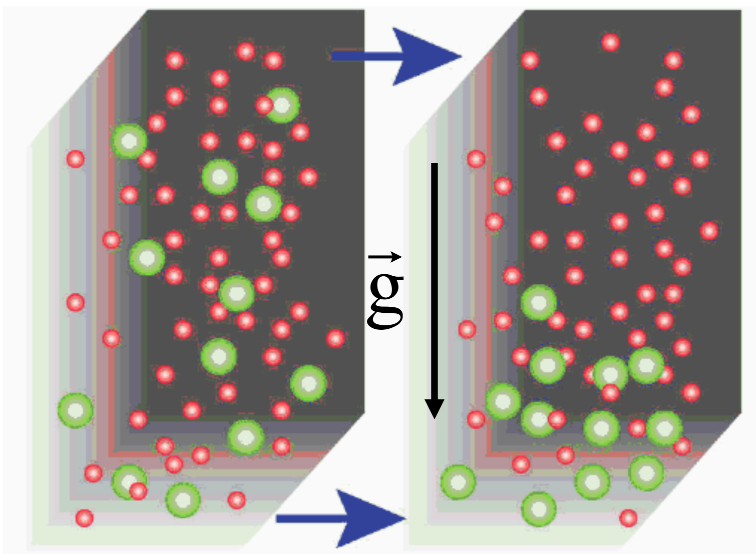


Ando & Nagai 2008; also Pfrommer et al. 2008; Jeltema et al. 2008

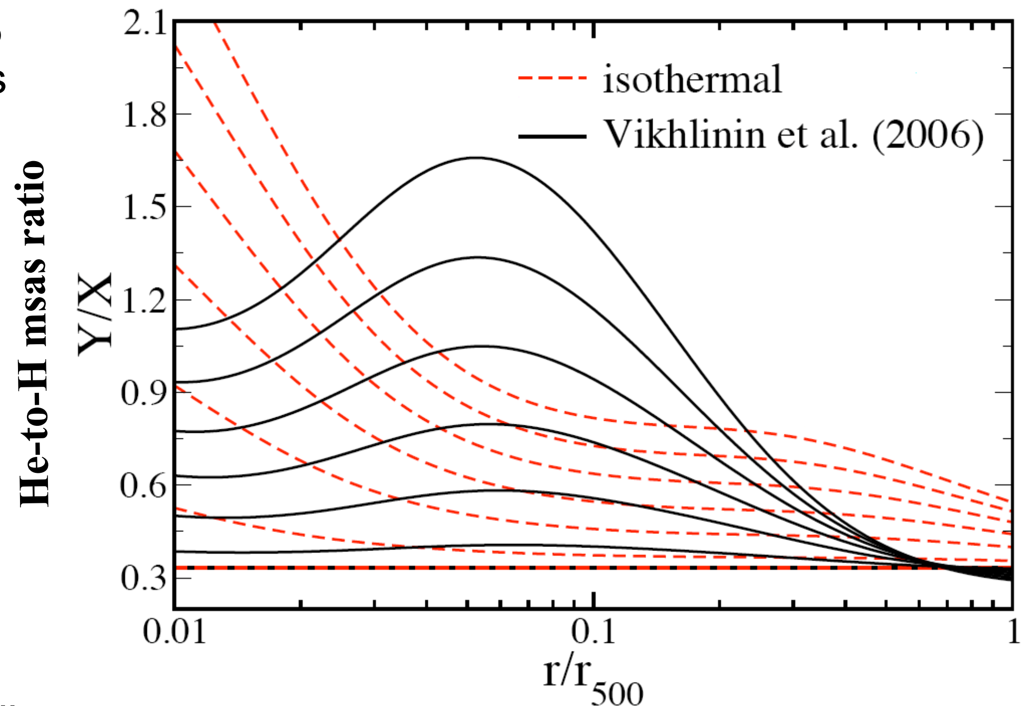
He sedimentation in X-ray Clusters

$$M_{\rm tot}(<r) = \frac{-r^2}{G\rho}\frac{dP_{\rm ther}}{dr} \propto \frac{1}{\mu} = \frac{8+3(Y/X)}{4+4(Y/X)}$$

Intracluster plasma consists of ~75% hydrogen and ~25% helium by mass



Solving the diffusion equations for the fully ionized H-He plasma in the NFW potential



cluster-centric radius in units of r_{500}

He sedimentation can introduce systematic uncertainty in X-ray measurements of galaxy clusters at the level of <5-10%.

Peng & Nagai 2008; also Chuzhoy & Loeb 1998

Summary

- *Successes*
  - **Modern cosmological cluster simulations with cooling+SF reproduce observed thermodynamic properties of real clusters outside cores.**
  - **Observable-mass relations of simulated clusters and recent X-ray observations agree to about 10%.**
  - **Robust, low-scatter mass proxies (Yx and Ysz) are accessible for *both* X-ray and SZE cluster surveys.**
- *Problems & Challenges*
  - ***But, there is a remaining offset of ~10% between simulations and observations. Likely, due to non-thermal pressure components (e.g., turbulence, cosmic-rays, ICM plasma physics).***
  - ***Also, cluster cores are not well-reproduced in simulations.***
- *Future Prospect*
  - **Upcoming cluster surveys will produce large statistical samples of clusters (X-ray: eROSITA; SZE: ACT, AMI, APEX, Planck, SPT, SZA)**
  - **Further advances in numerical simulations are also underway**
    - Larger sample of simulated clusters to study the scatter
    - Detailed understanding of cluster gas physics (e.g., AGN feedback, turbulence, cosmic-rays, ICM plasma physics)