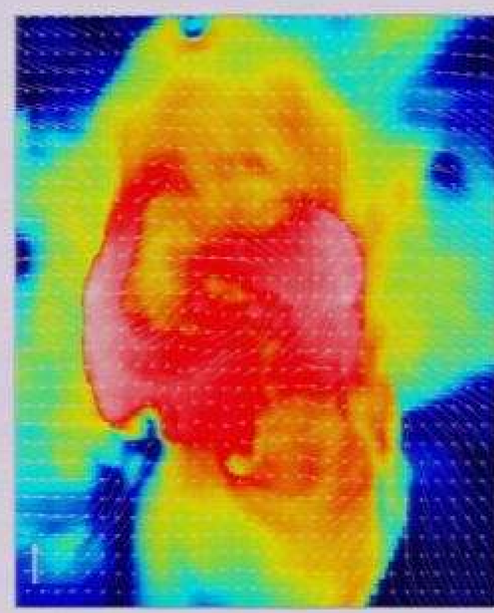
Title: Thermodynamics of Galaxy Clusters and Beyond

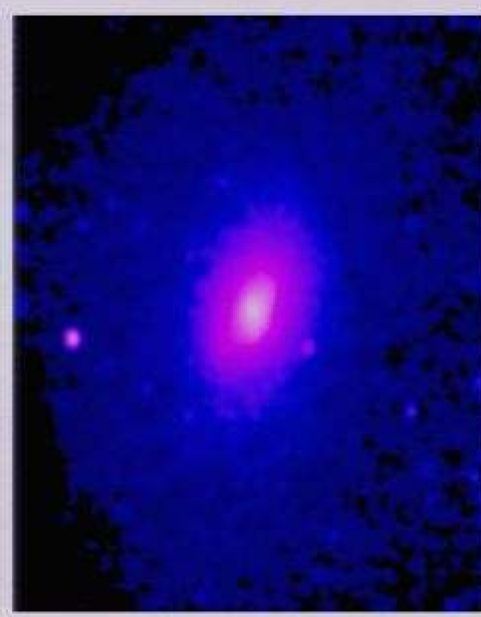
Date: Apr 27, 2009 04:45 PM

URL: http://pirsa.org/09040037

Abstract: Clusters of galaxies are unique probes of cosmology and astrophysics, promising to provide new insights into both the nature of dark energy and dark matter and the physics of galaxy formation. One of the key challenges facing this approach lies in our understanding of cluster physics and their impact on cluster structure and evolution. In this talk, I will present numerical simulations of galaxy clusters and their comparisons to recent Chandra X-ray observations, with focus on thermodynamics of intracluster plasma. Numerical simulations including gas cooling and star formation reproduce global properties of the intracluster medium (ICM) and observable-mass relations with an accuracy of ~10%. I will further show that non-thermal processes, such as turbulence, cosmic-rays, and ICM plasma physics, will become important for understanding the remaining systematic uncertainty in the cluster mass estimate and cosmological constraints derived using galaxy clusters.

Thermodynamics of Galaxy Clusters and Beyond





Daisuke Nagai

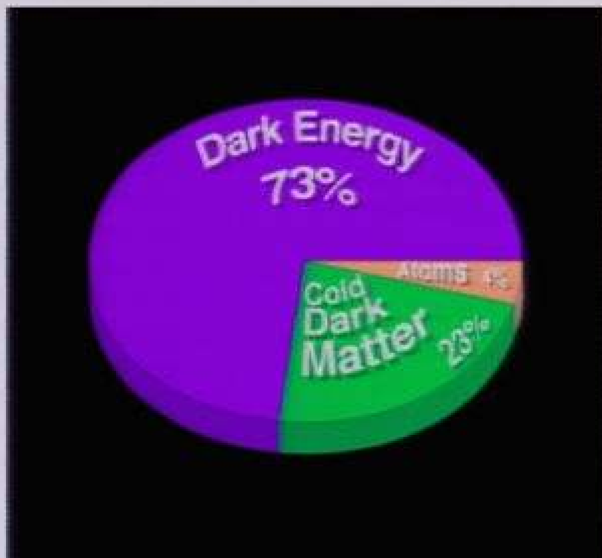
Yale University

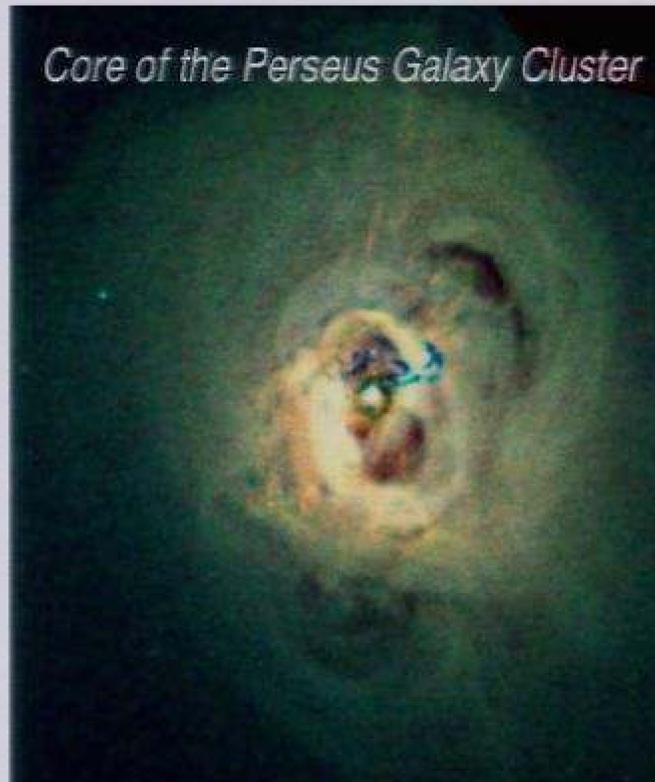
Perimeter Institute

April 27th 2009

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.

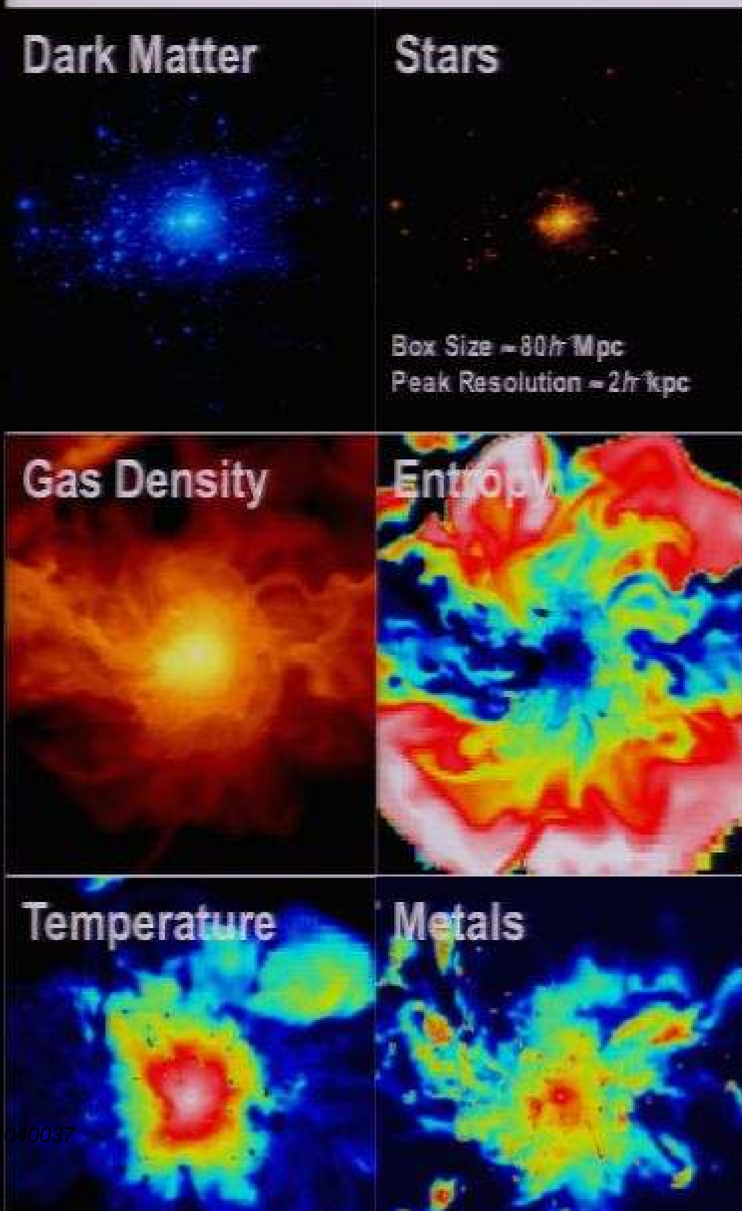
- **Main Challenges for Cluster Cosmology**: understanding cluster gas physics (e.g., gas cooling and heating by energy feedback) and calibrate the relationship between X-ray and SZE observables and mass (Δ=500).

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

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

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

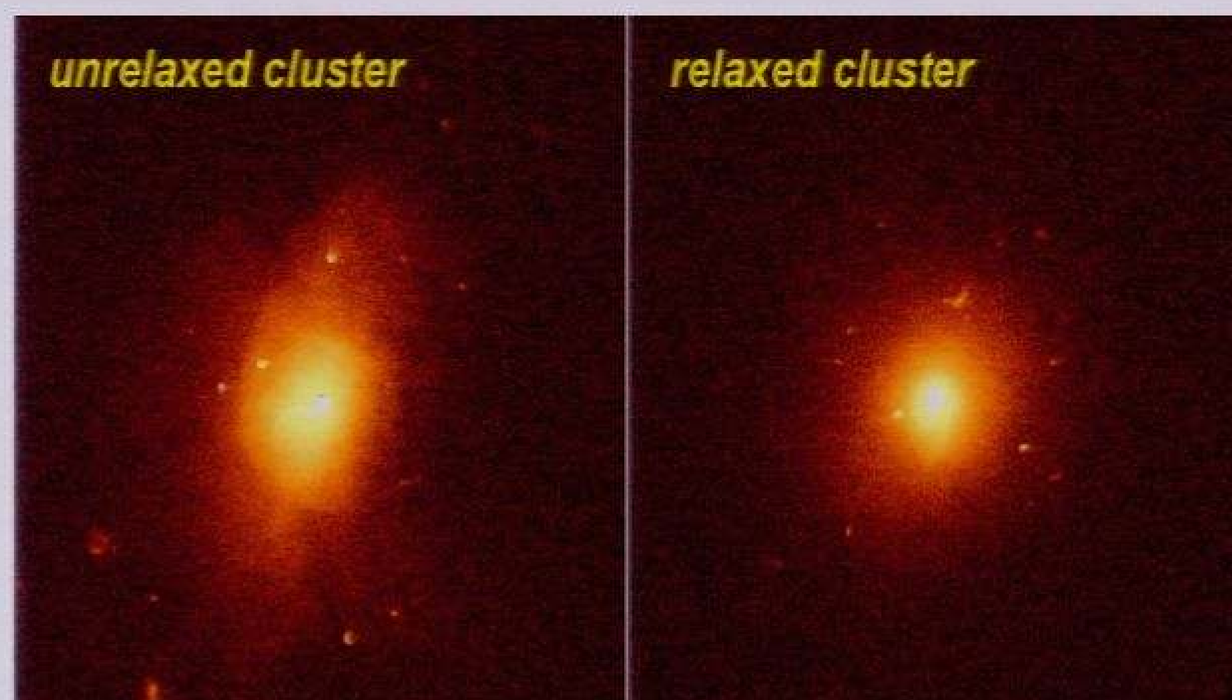
- **Collisionless dynamics** of DM and stars
- **Gasdynamics**: Eulerian Adaptive Mesh Refinement
- **Radiative cooling and heating of gas**: metallicity dependent net cooling/heating rates
- **Star Formation** using the Kennicutt (1998) recipe
- **Thermal stellar feedback**
- **Metal enrichment** by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

Cluster Samples

- **High-resolution allows us to actually simulate clusters <u>of galaxies</u>**
- **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

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**



Mock Chandra photon maps of simulated clusters

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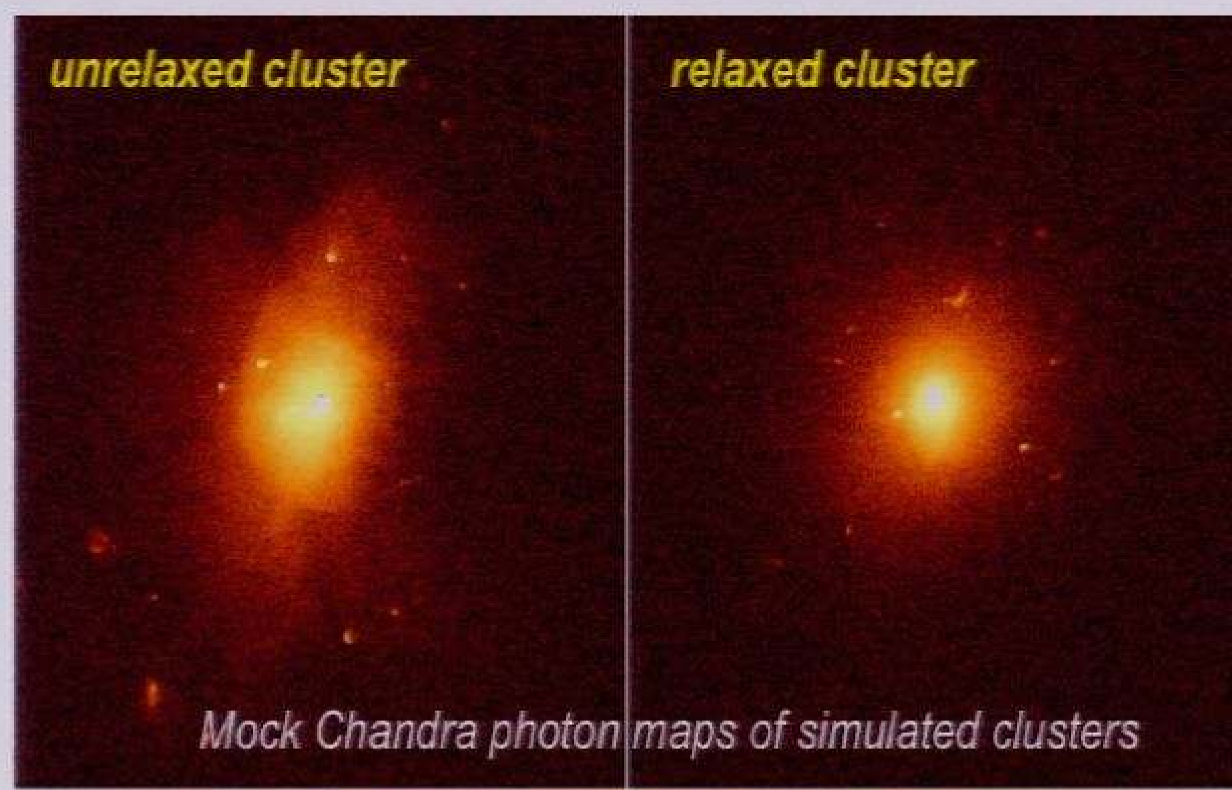
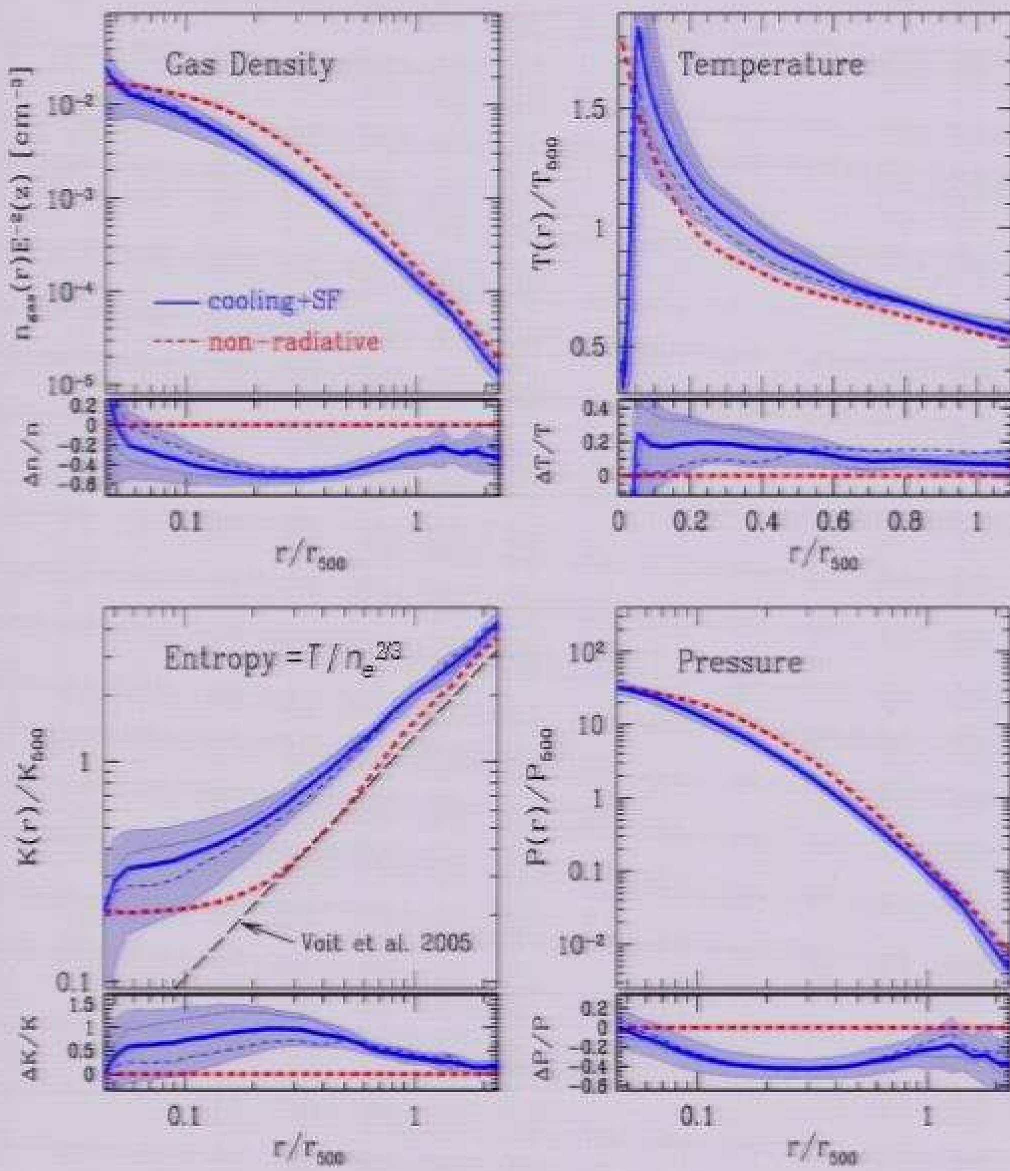


Mock Chandra photon maps of simulated clusters

Intracluster Gas Profiles:
Effects of gas cooling and star formation



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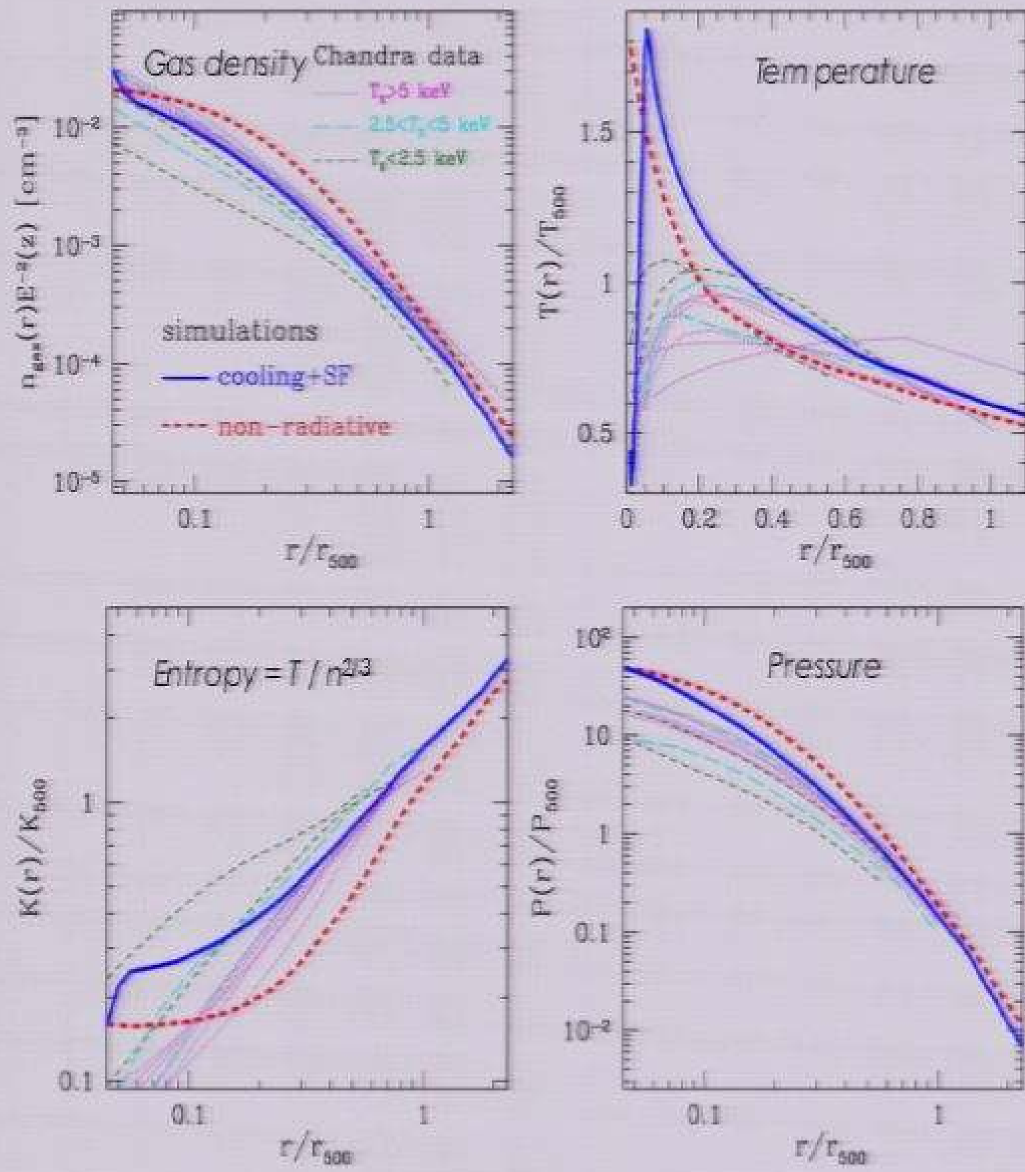
mean profile for relaxed clusters in non-radiative ("adiabatic") simulations

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



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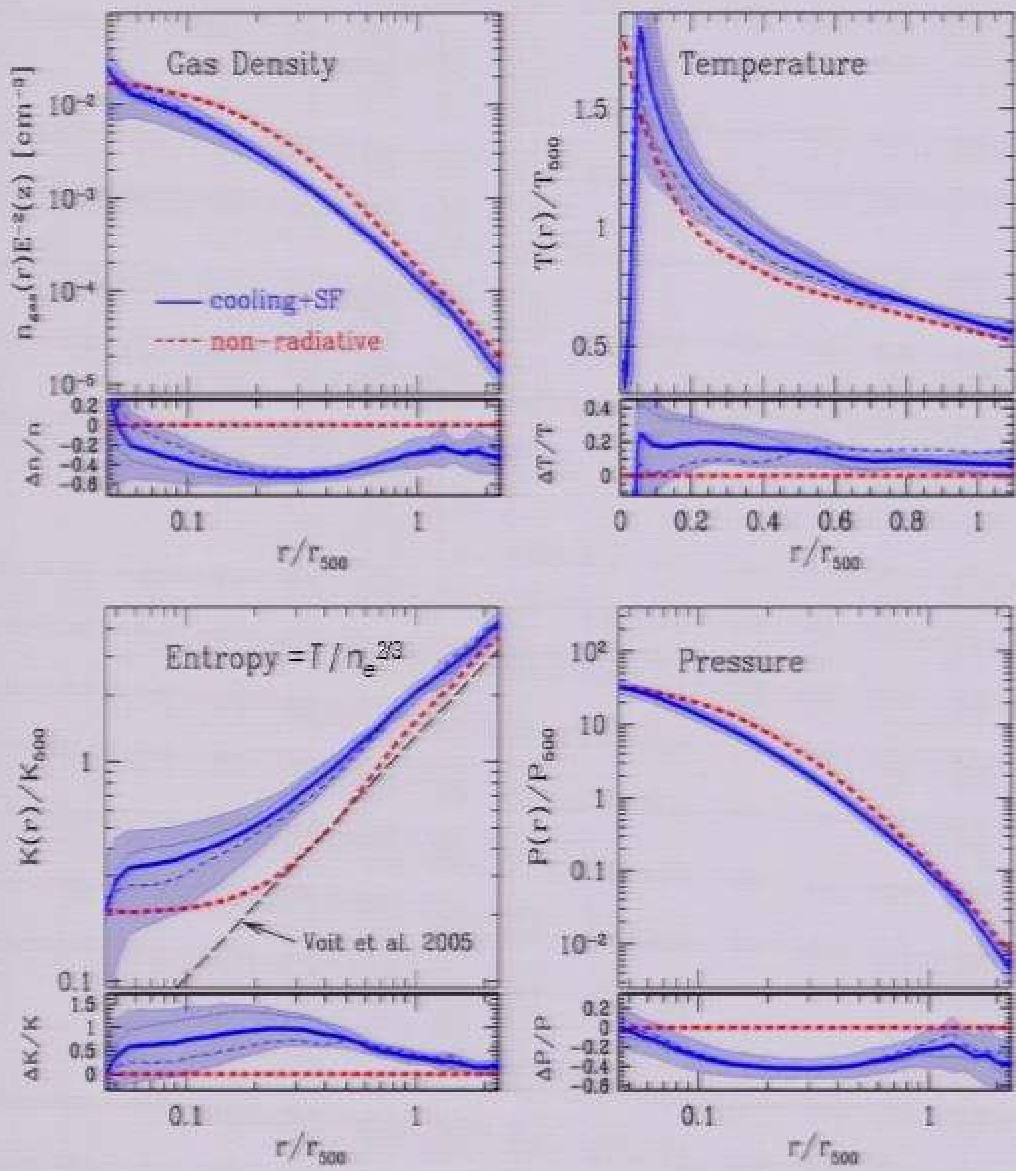

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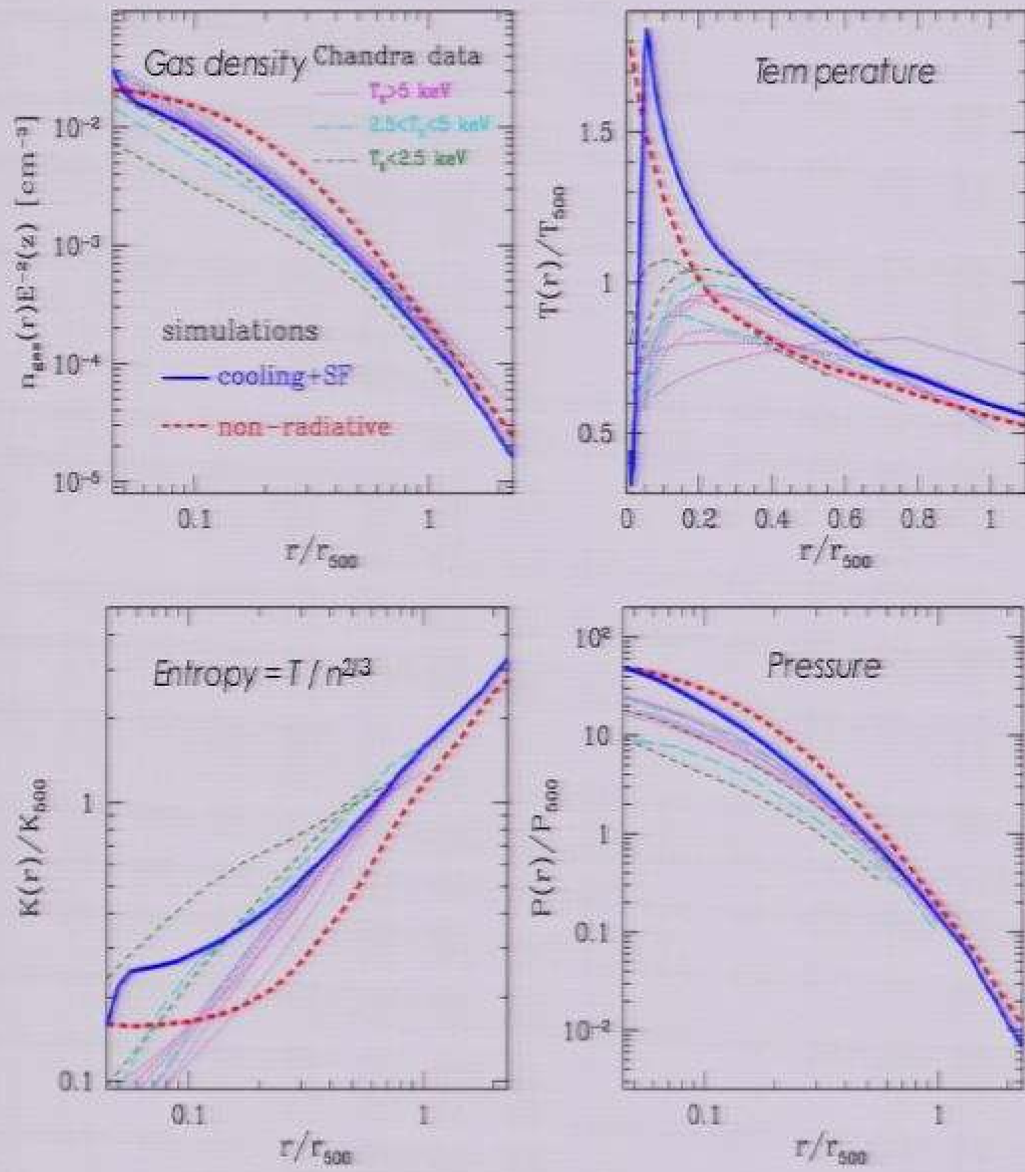

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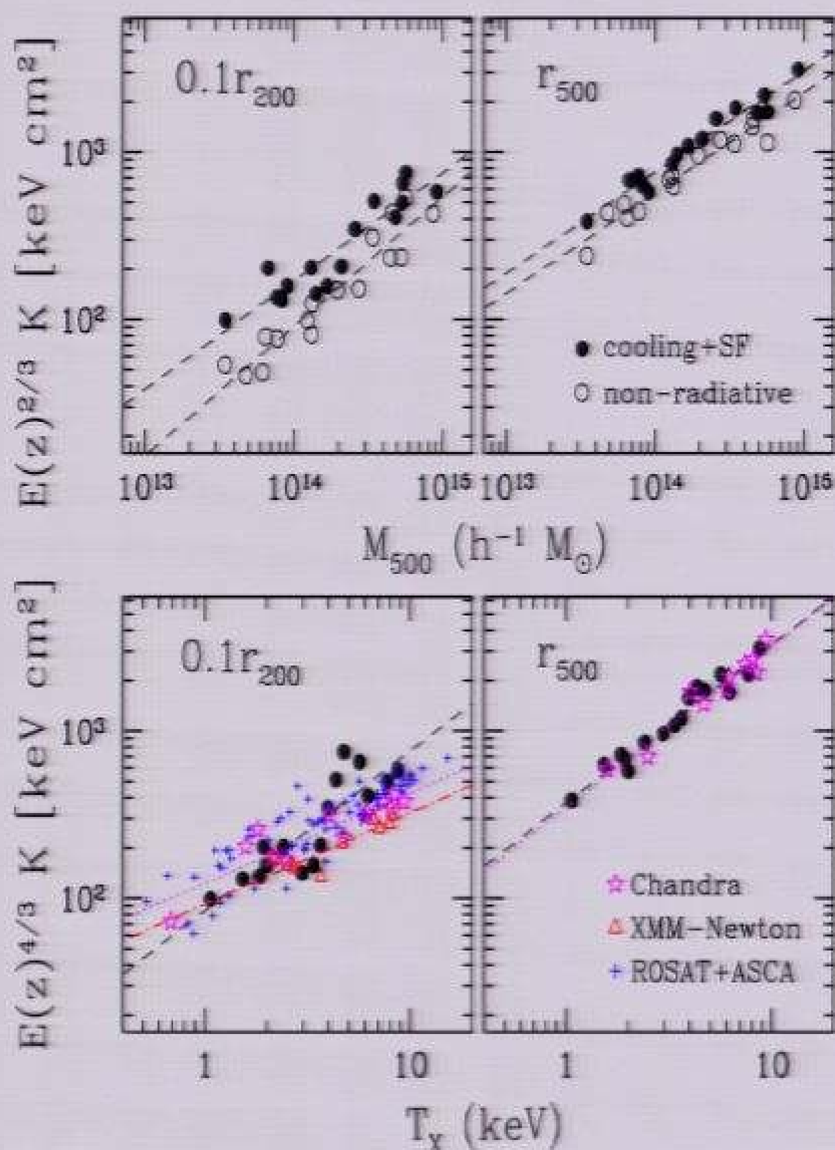
Entropy scaling with cluster mass & Tx



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

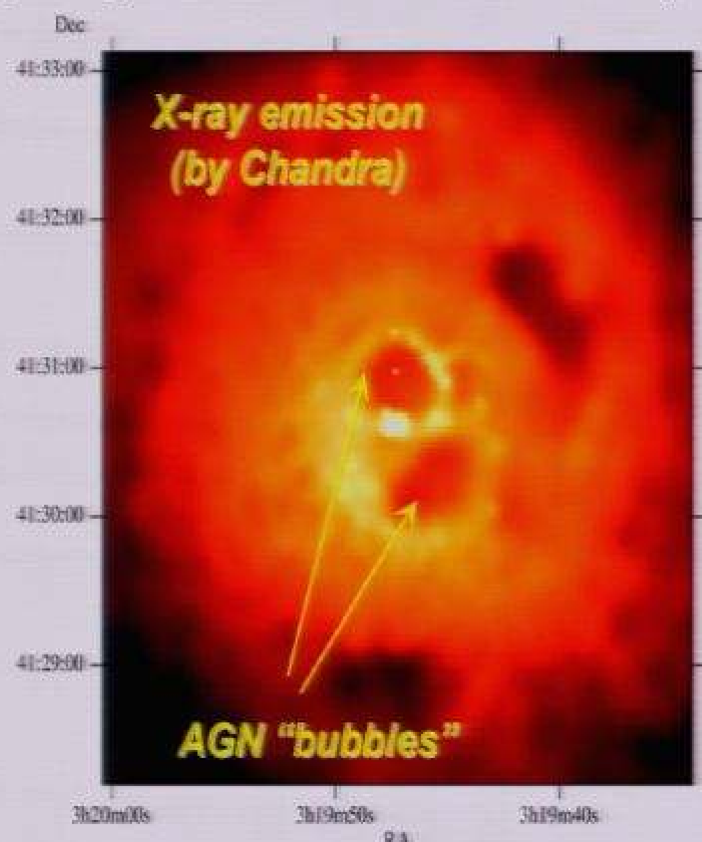
red pts: XMM-Newton data
Pratt et al. 2006

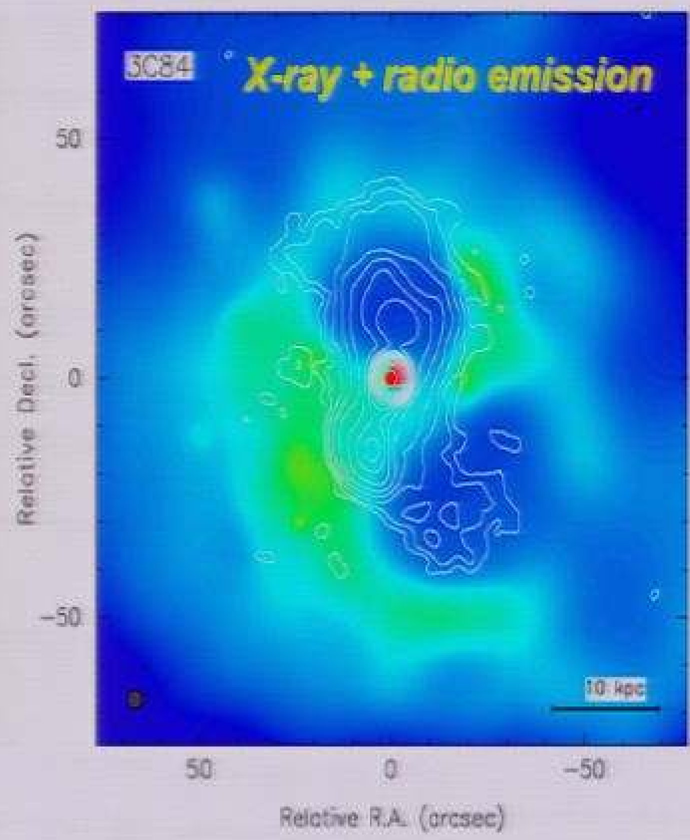
blue pts: ROSAT+ASCA data
Ponman et al. 2003

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 (Talks by A. Babul, P. Bode, & P. Oh)



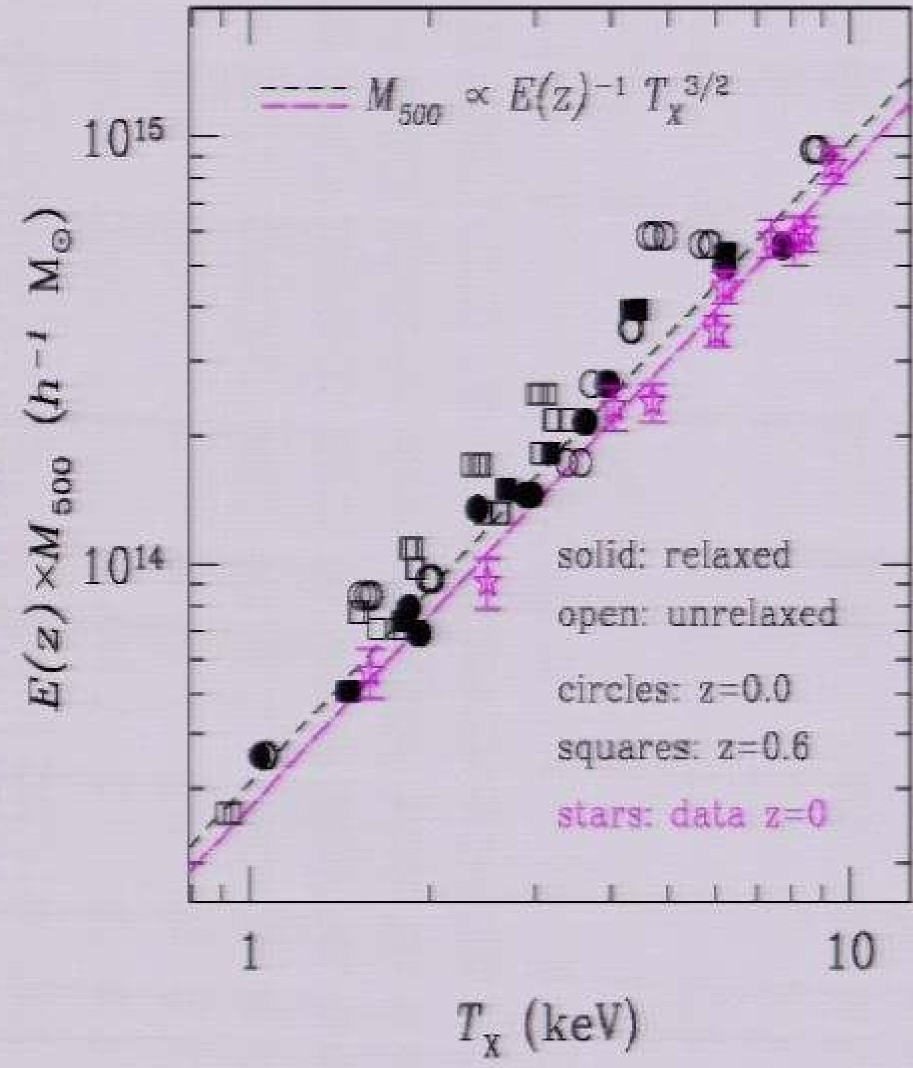


these effects, however, appear to be confined to the core

=> *outer regions of clusters can be used to reliably*

Mass – ICM temperature relation

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



X-ray spectral temperature

excluding cluster cores ($r<0.15 \times r_{500}$)

~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

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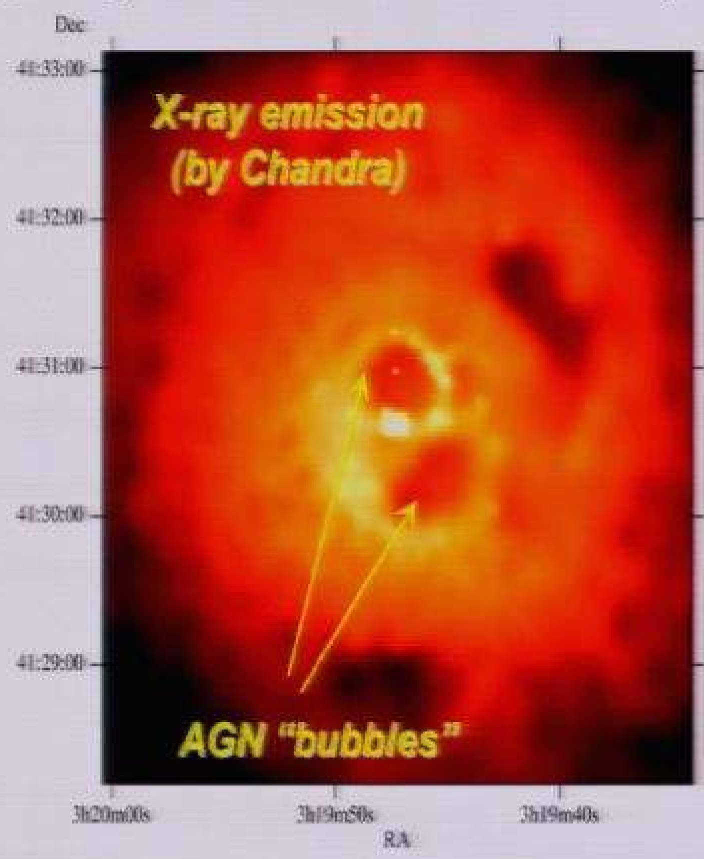

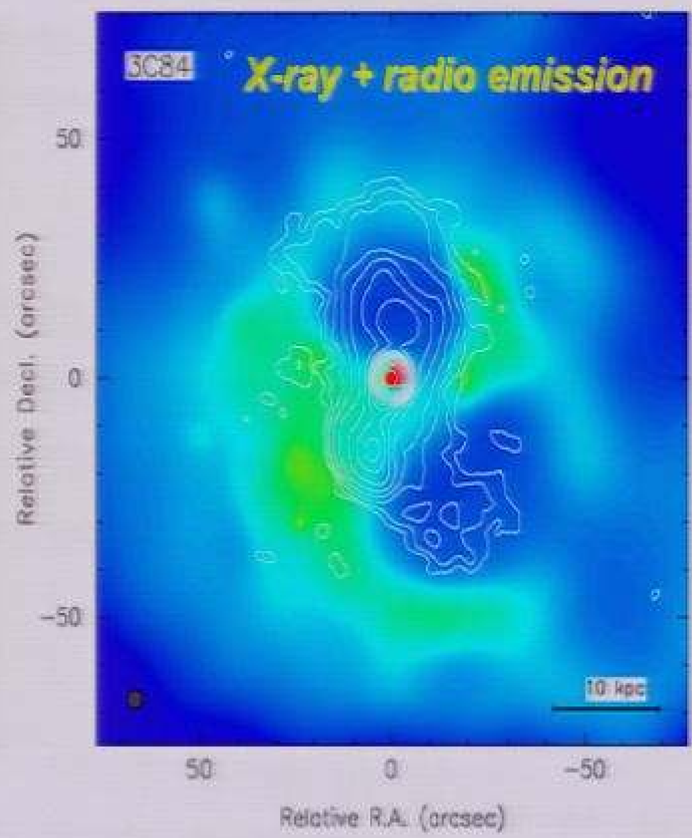

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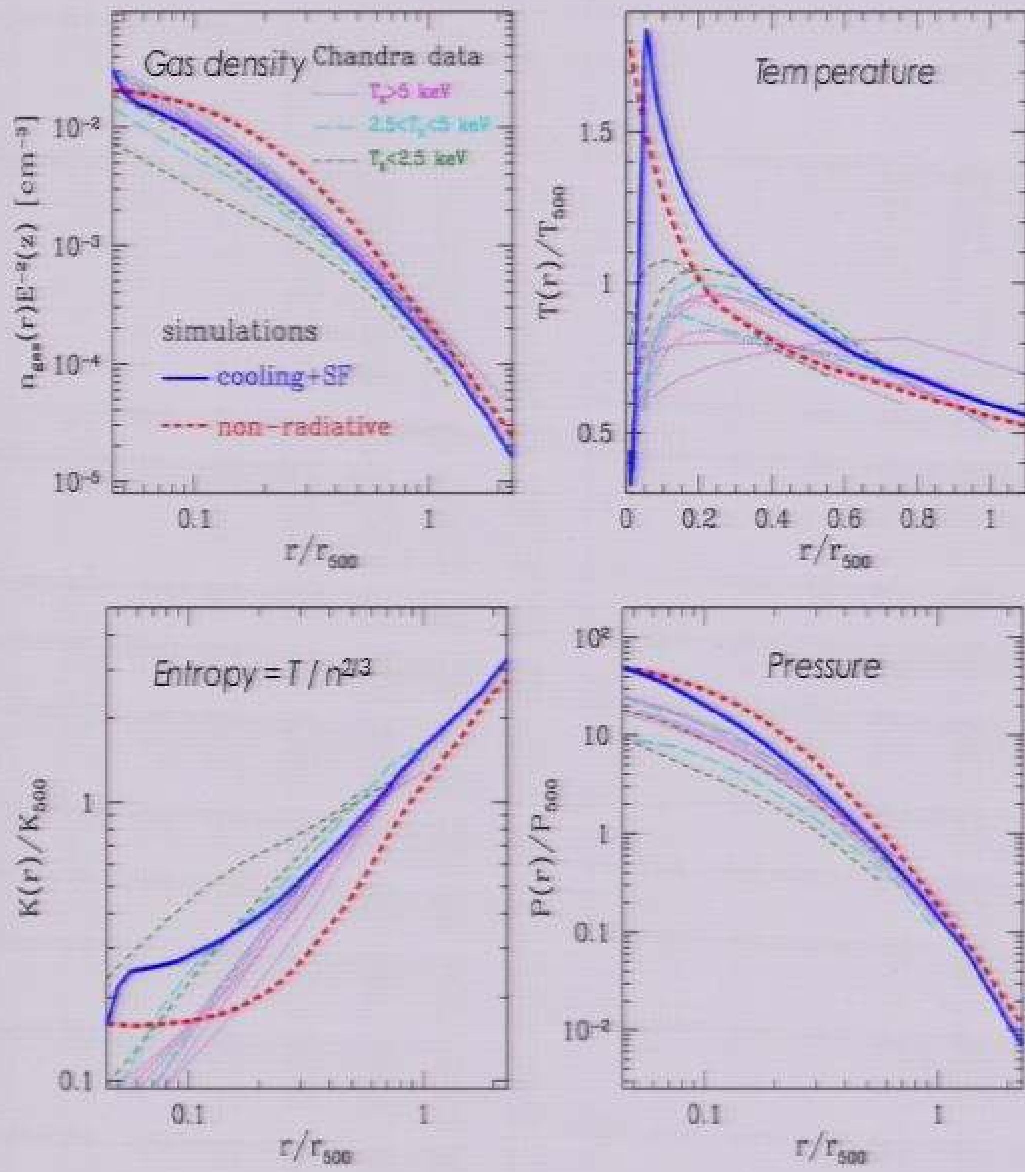
=> <u>outer regions of clusters can be used to reliably estimate their total masses</u>

Intracluster Gas Profiles:
Comparison with observations



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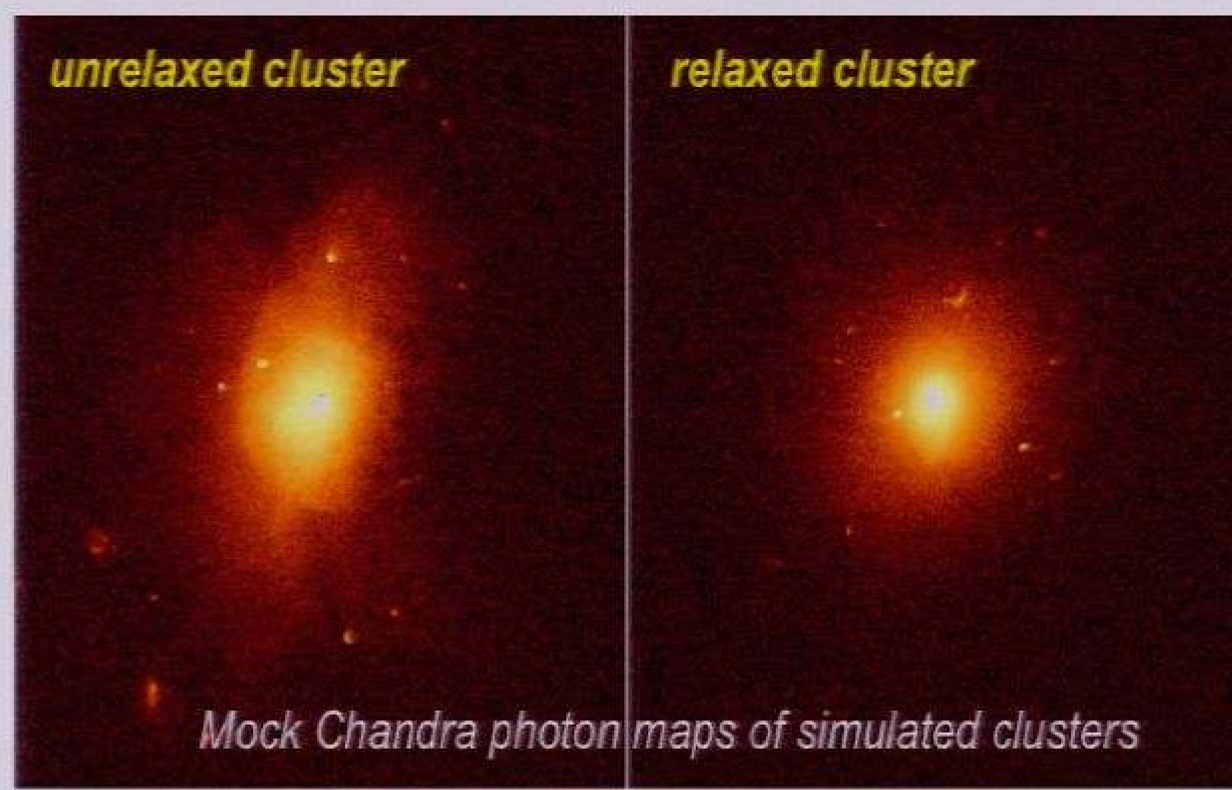

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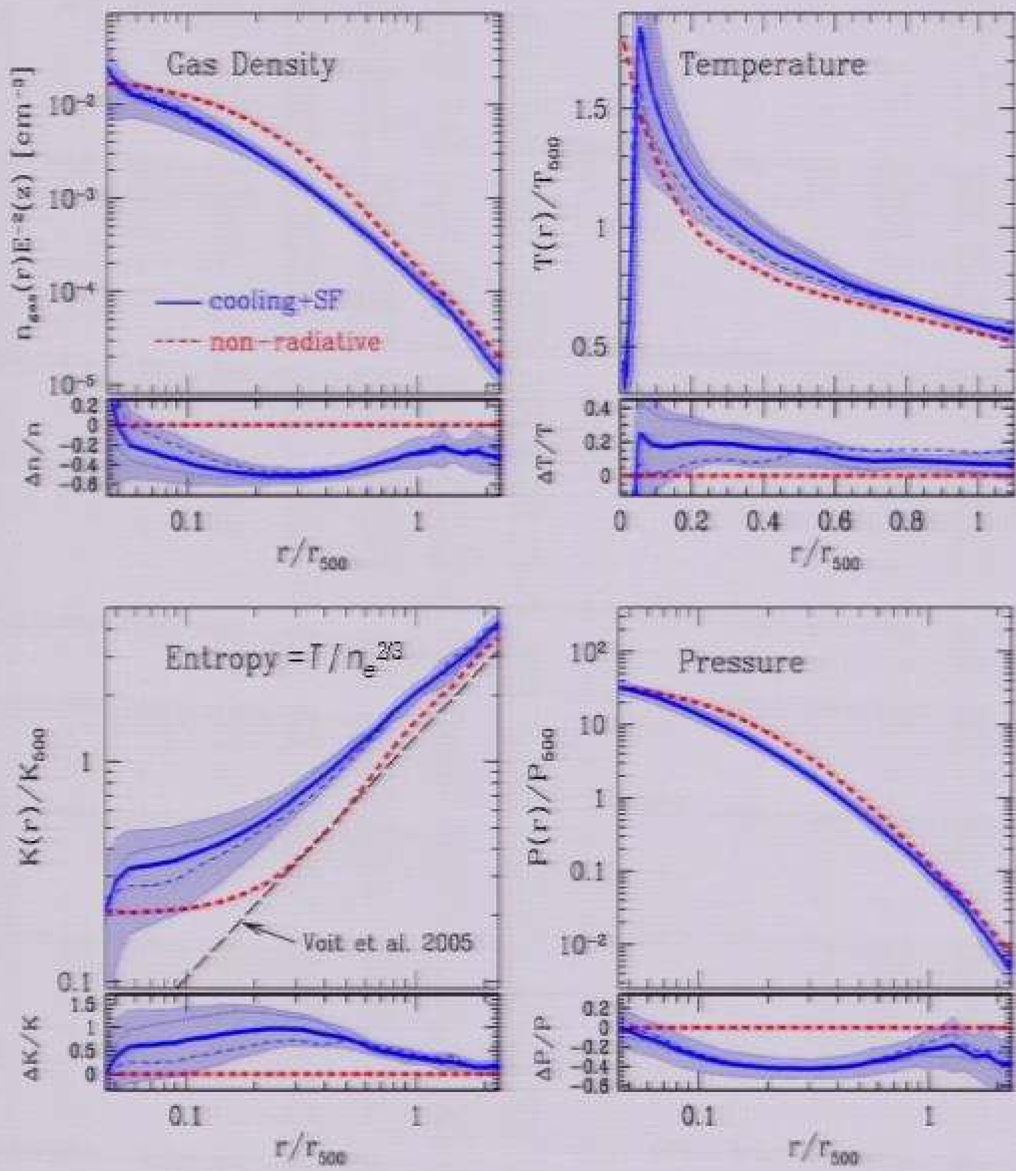

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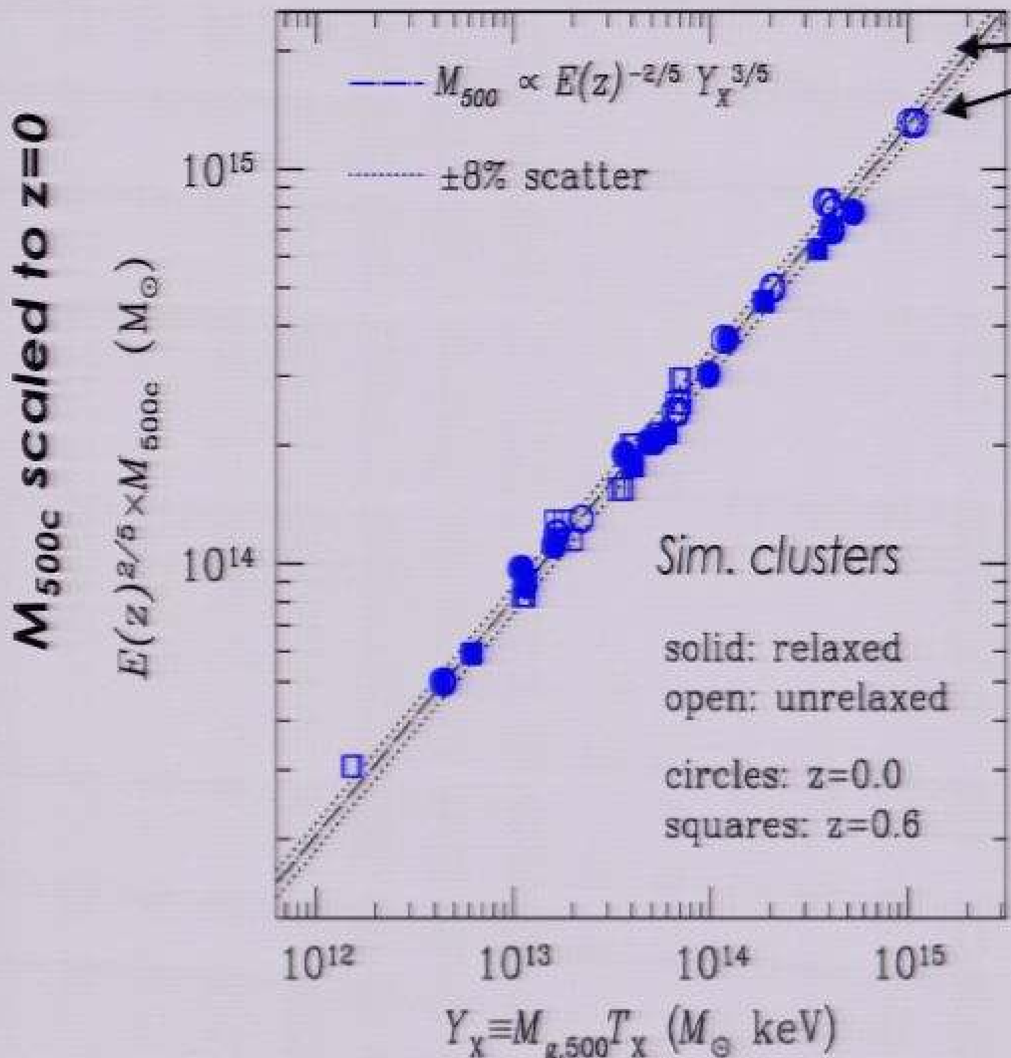
Mass – Yx relation

a new X-ray mass proxy



Dotted lines show 8% deviation from the mean

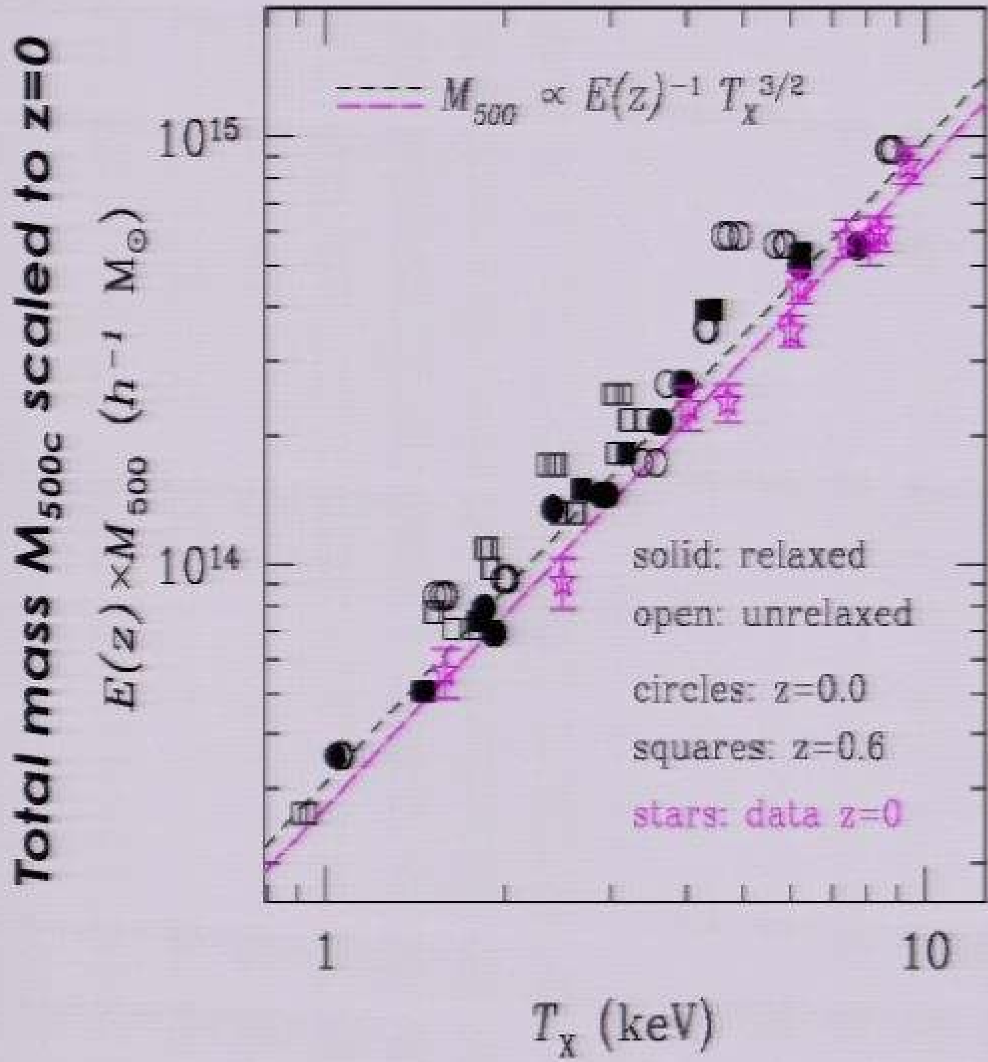
Yx is an excellent mass proxy!

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

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

X-ray "pressure" = gas mass x temperature

Mass – ICM temperature relation



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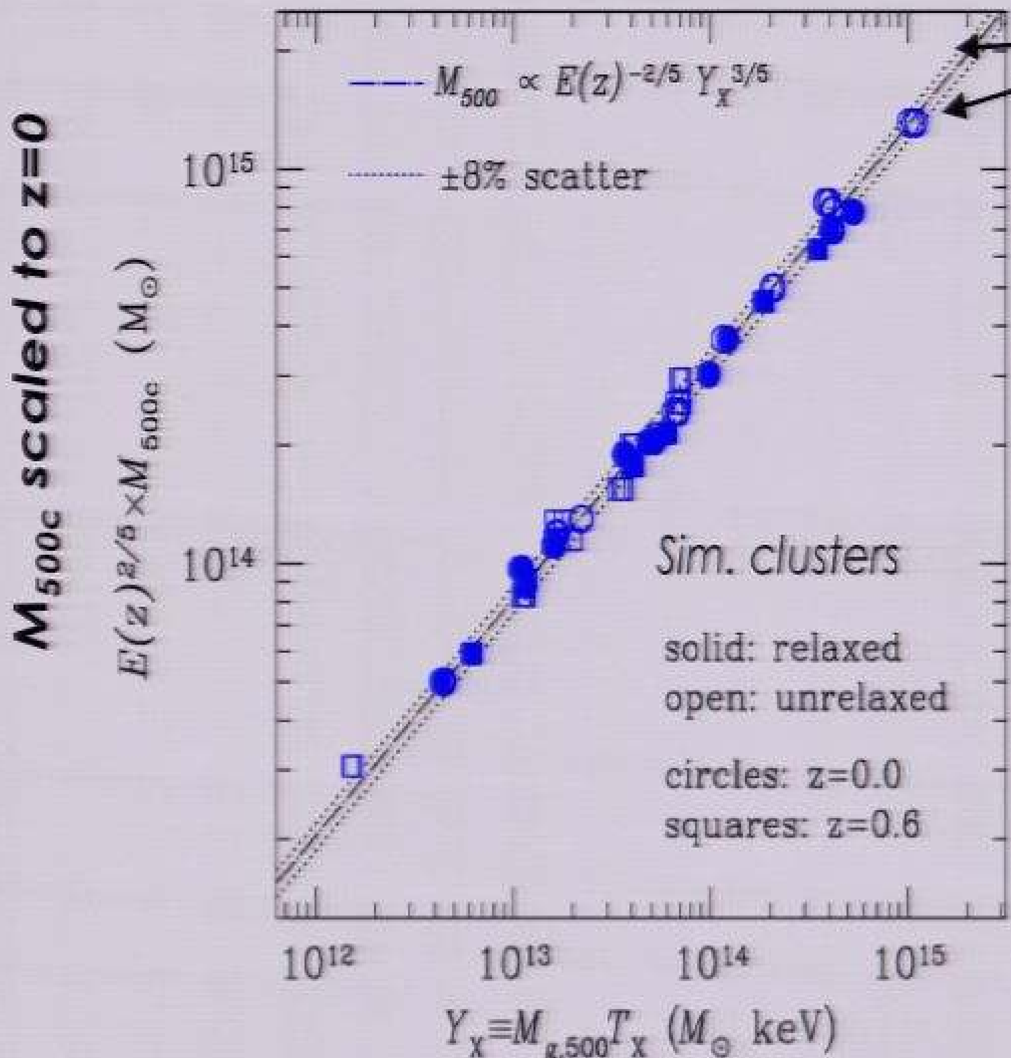

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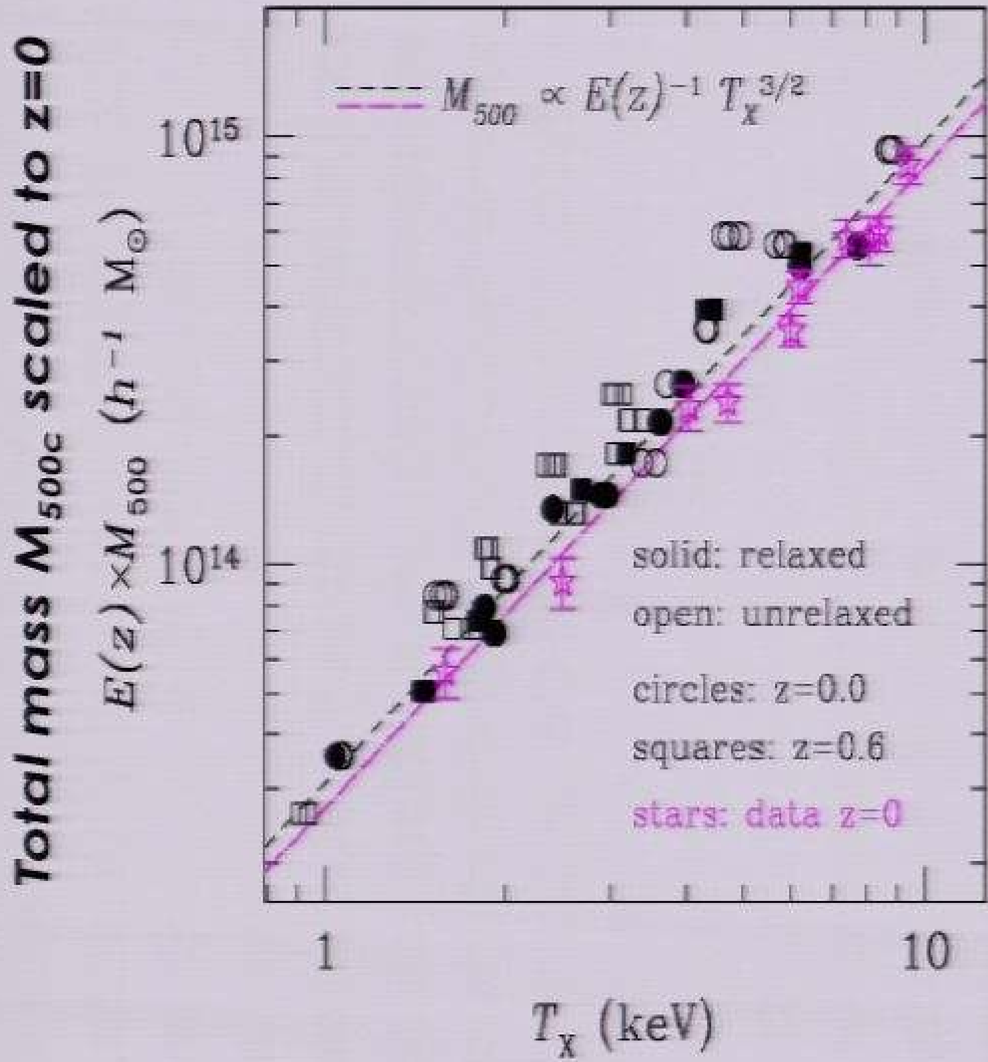

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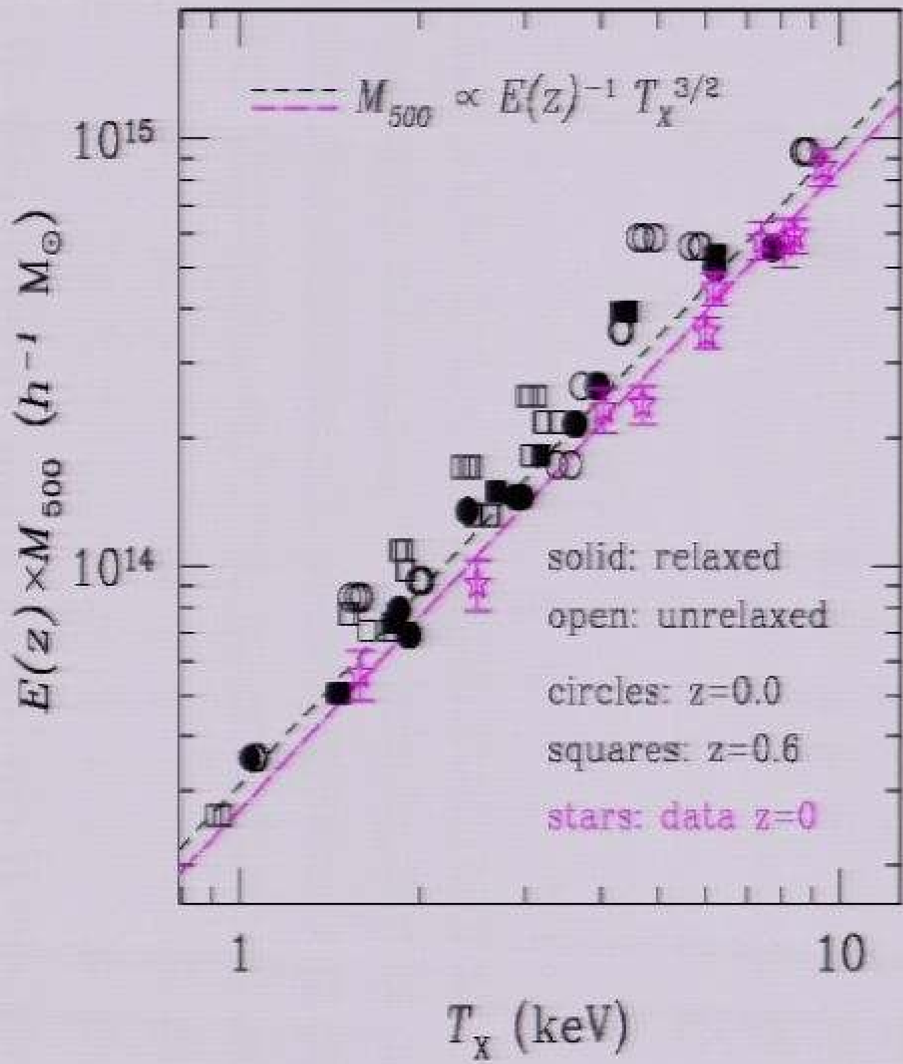

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a new X-ray mass proxy

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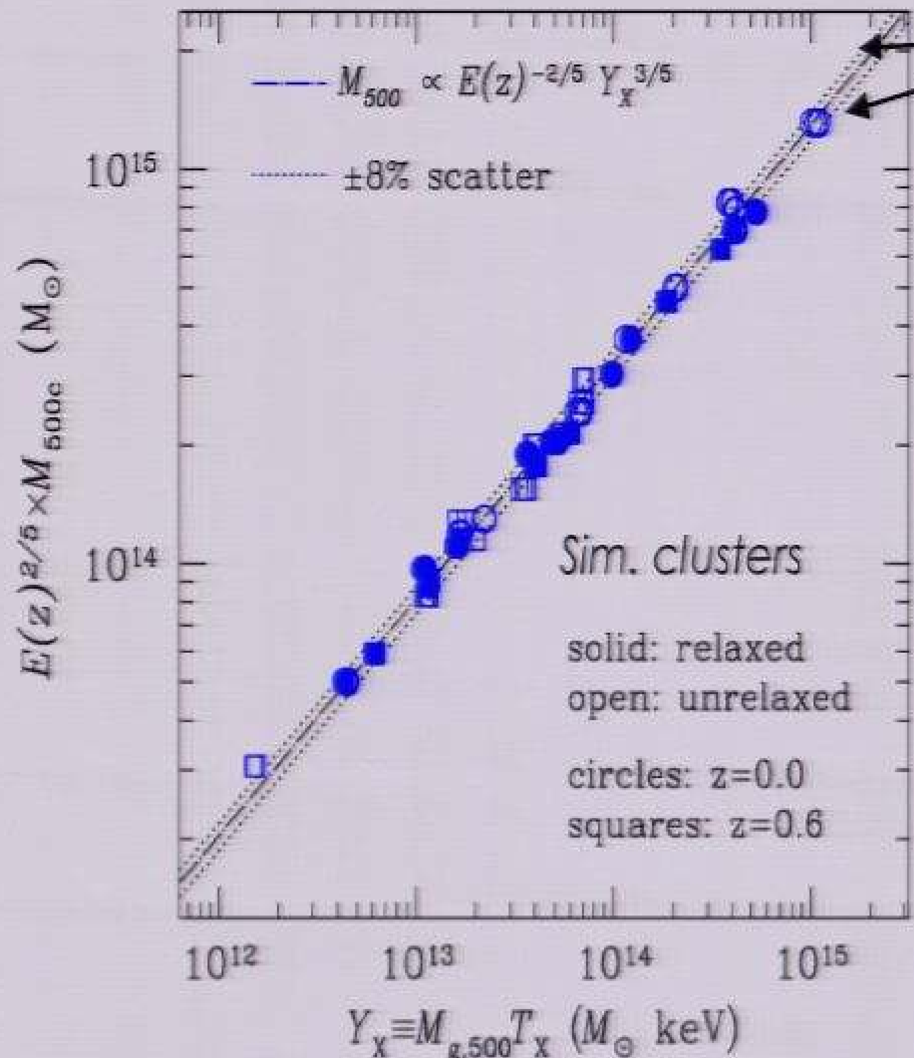

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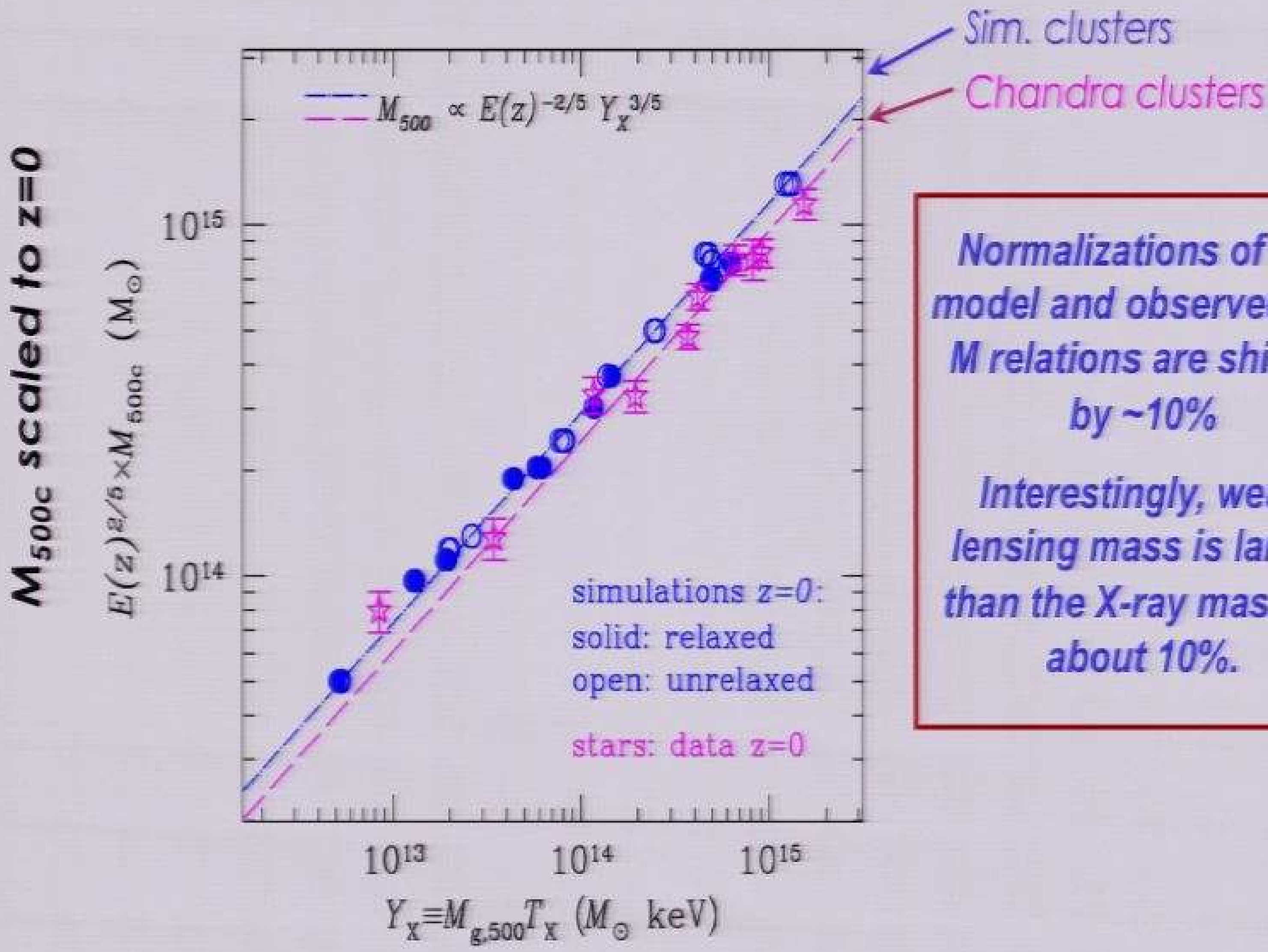
X-ray "pressure" = gas mass x temperature

Mass – Yx relation

comparison with observations



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%.

X-ray "pressure" = gas mass x temperature

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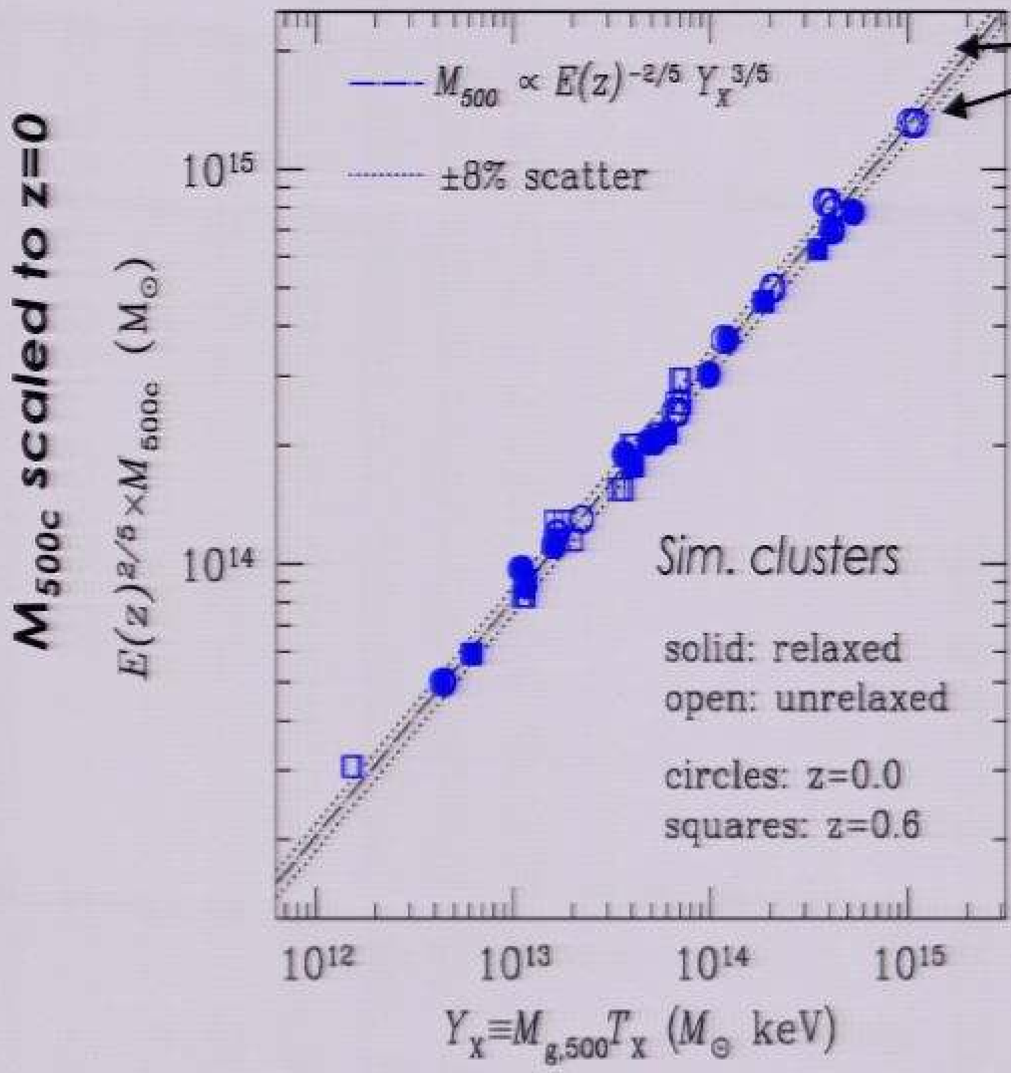

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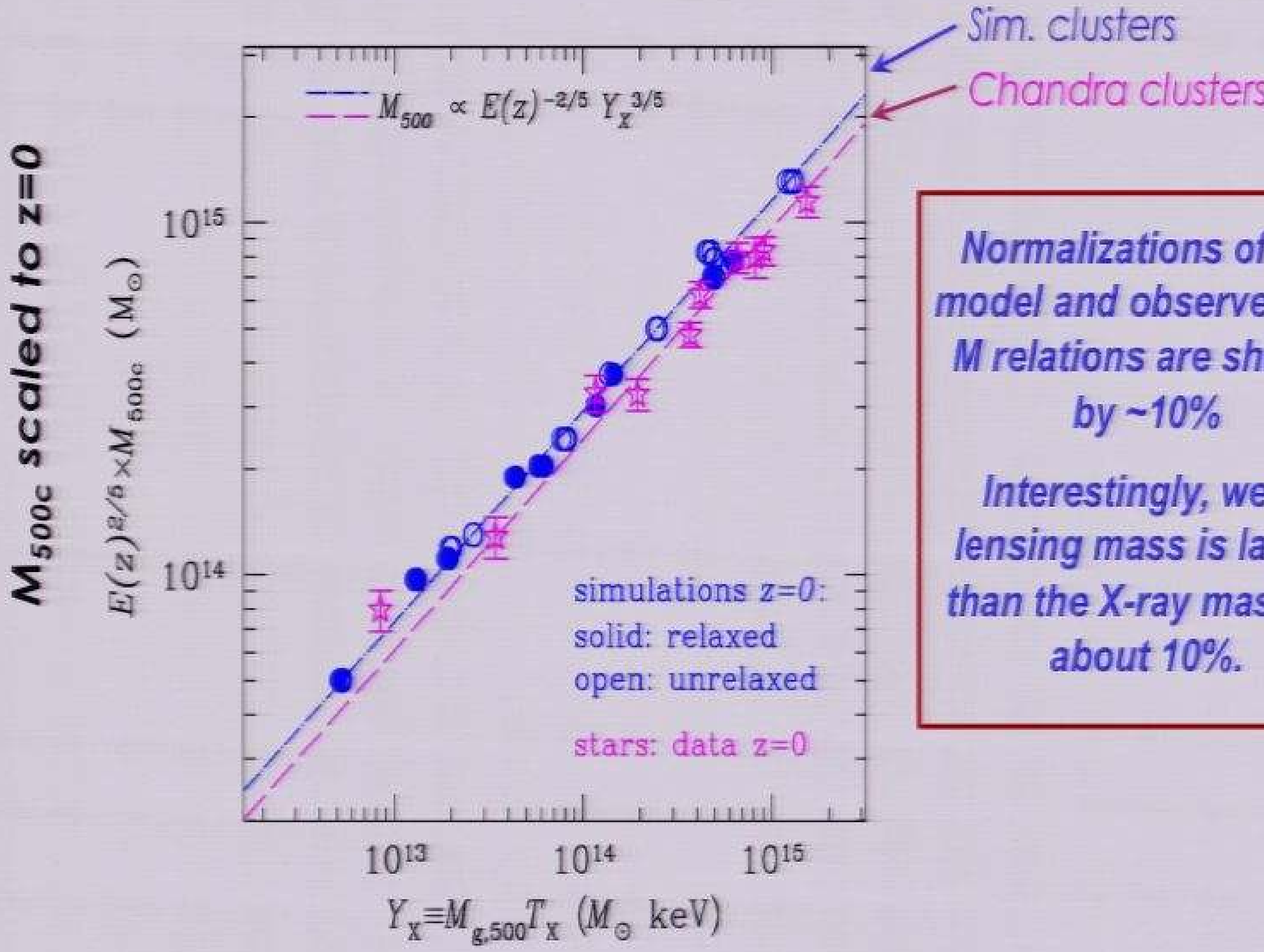

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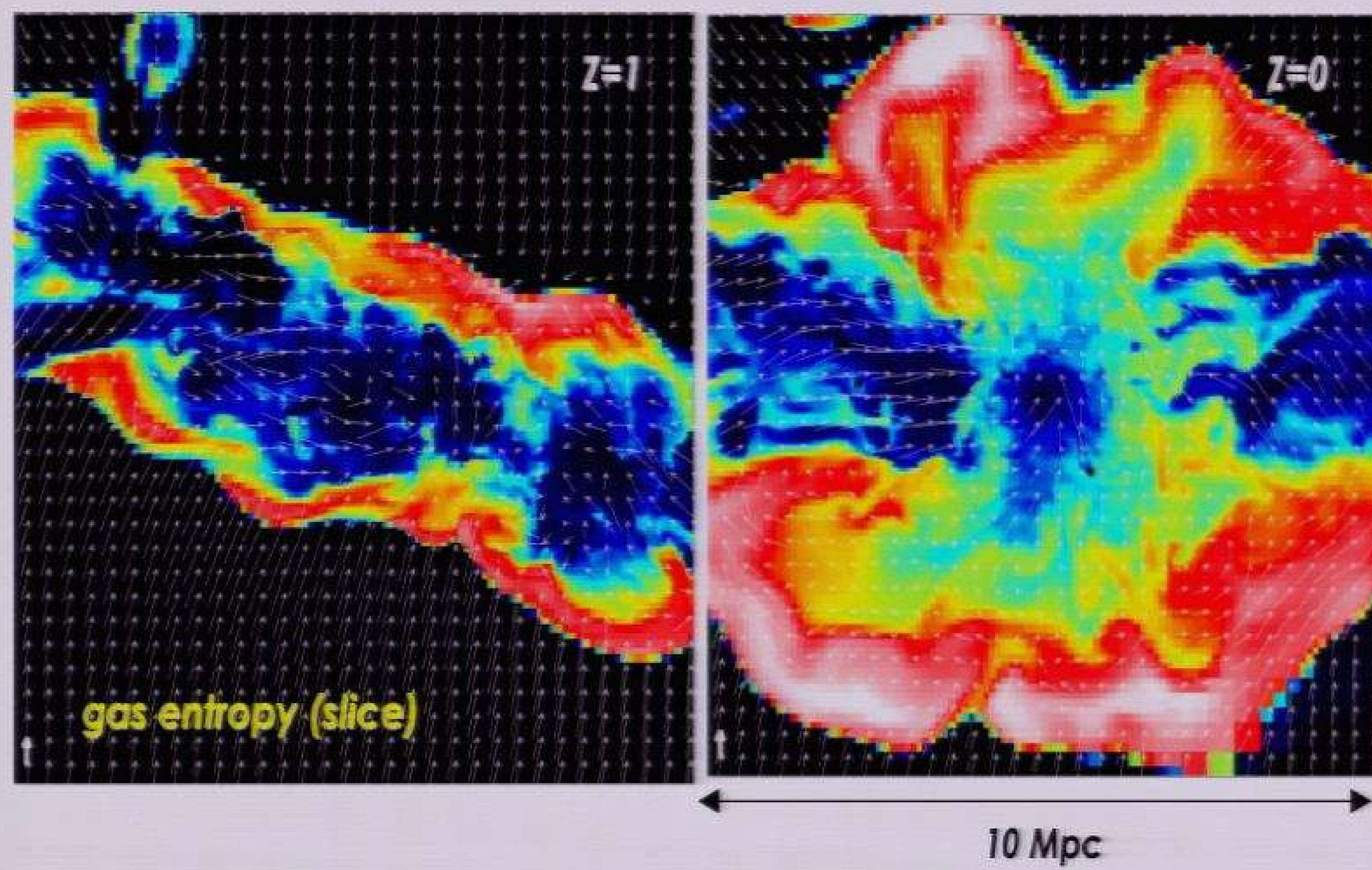
Accretion, Mergers
→ Shocks, Turbulence



Norman & Bryan 1999, Nagai, Kravtsov & Kosowsky 2003
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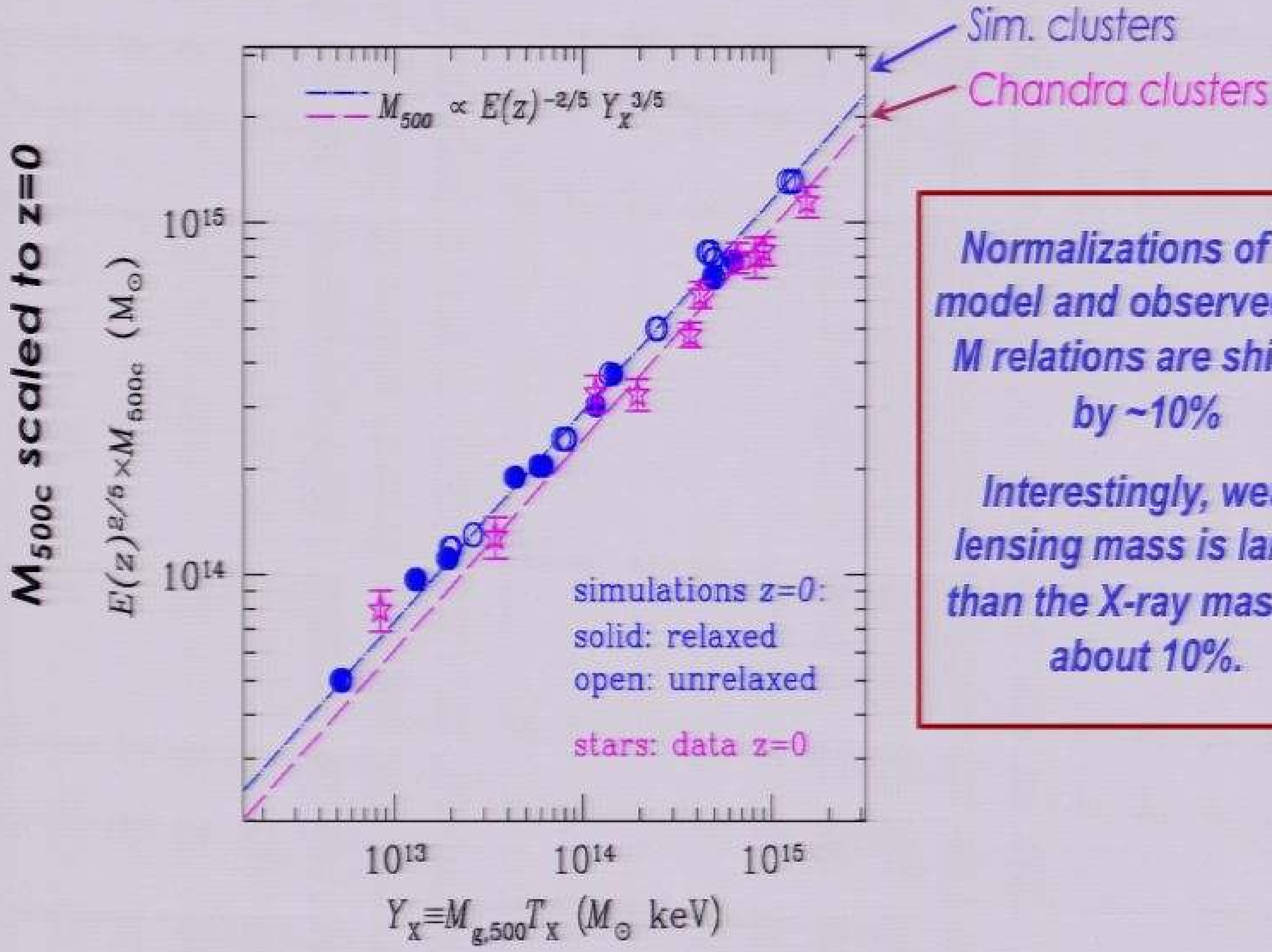

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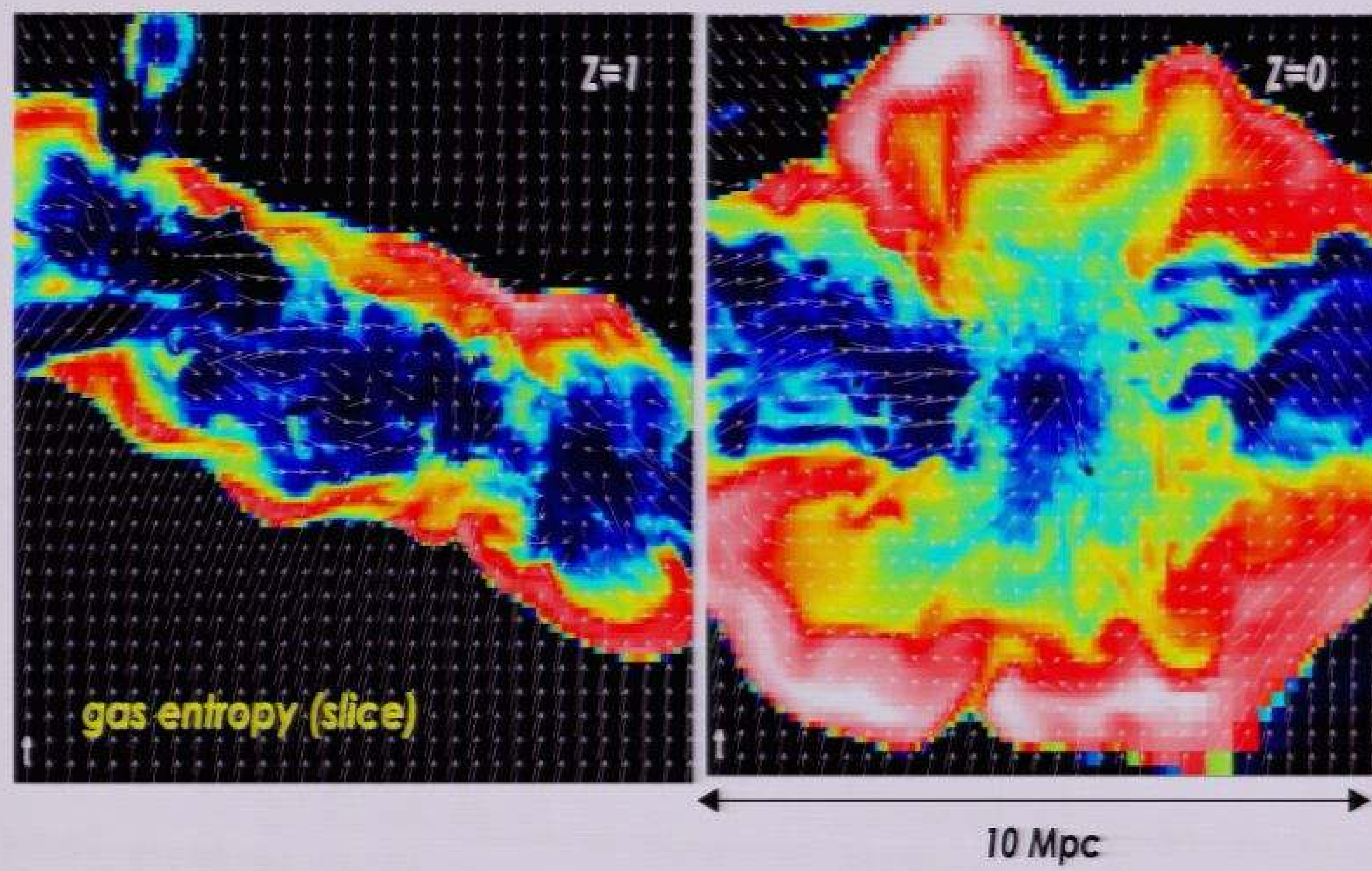

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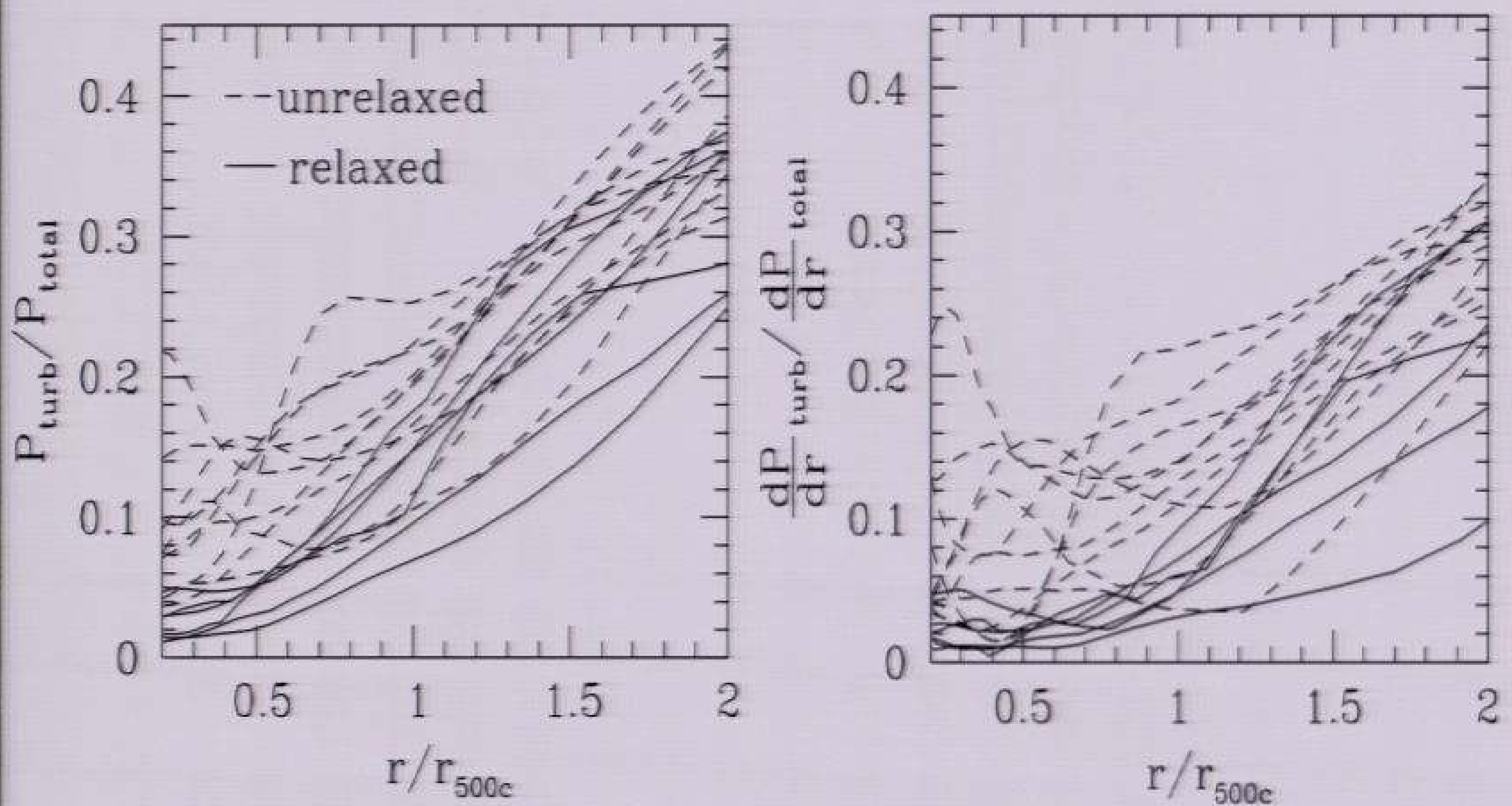
Effect of random gas motions on mass measurements

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



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

Lau, Kravtsov, Nagai 2009, astro-ph/0903.4895

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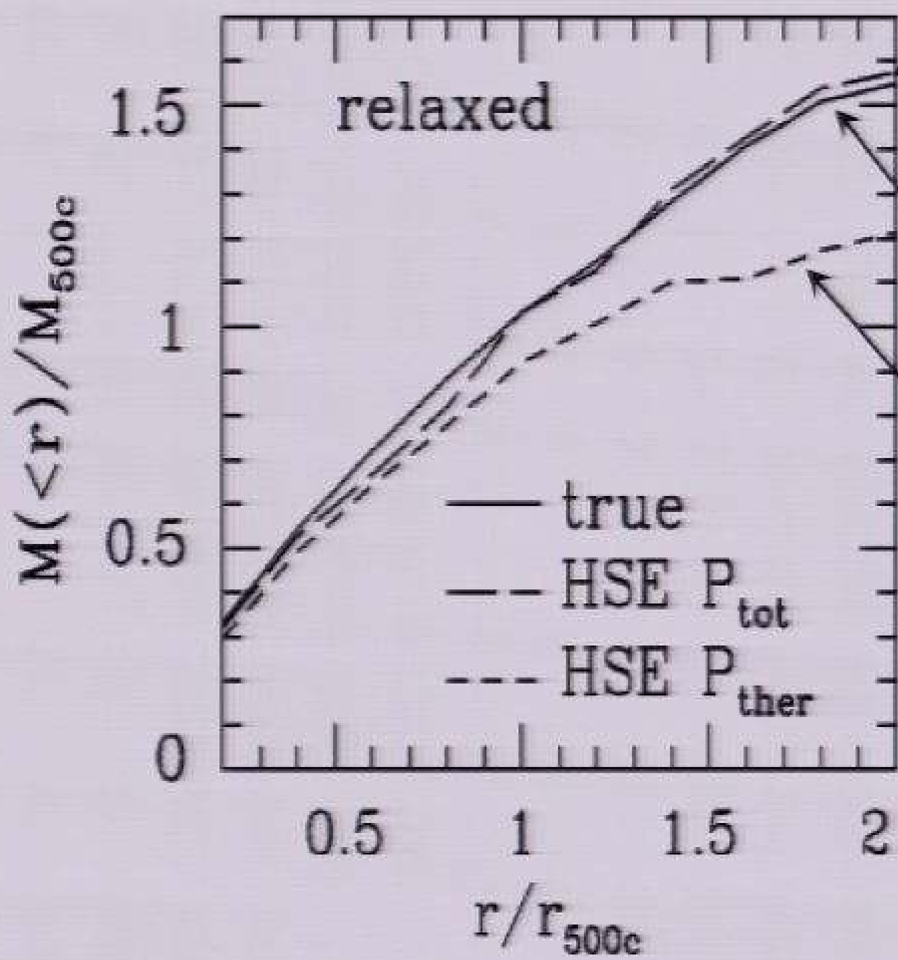


Mass profile from hydrostatic equilibrium taking into account turbulent pressure

True mass profile in simulations

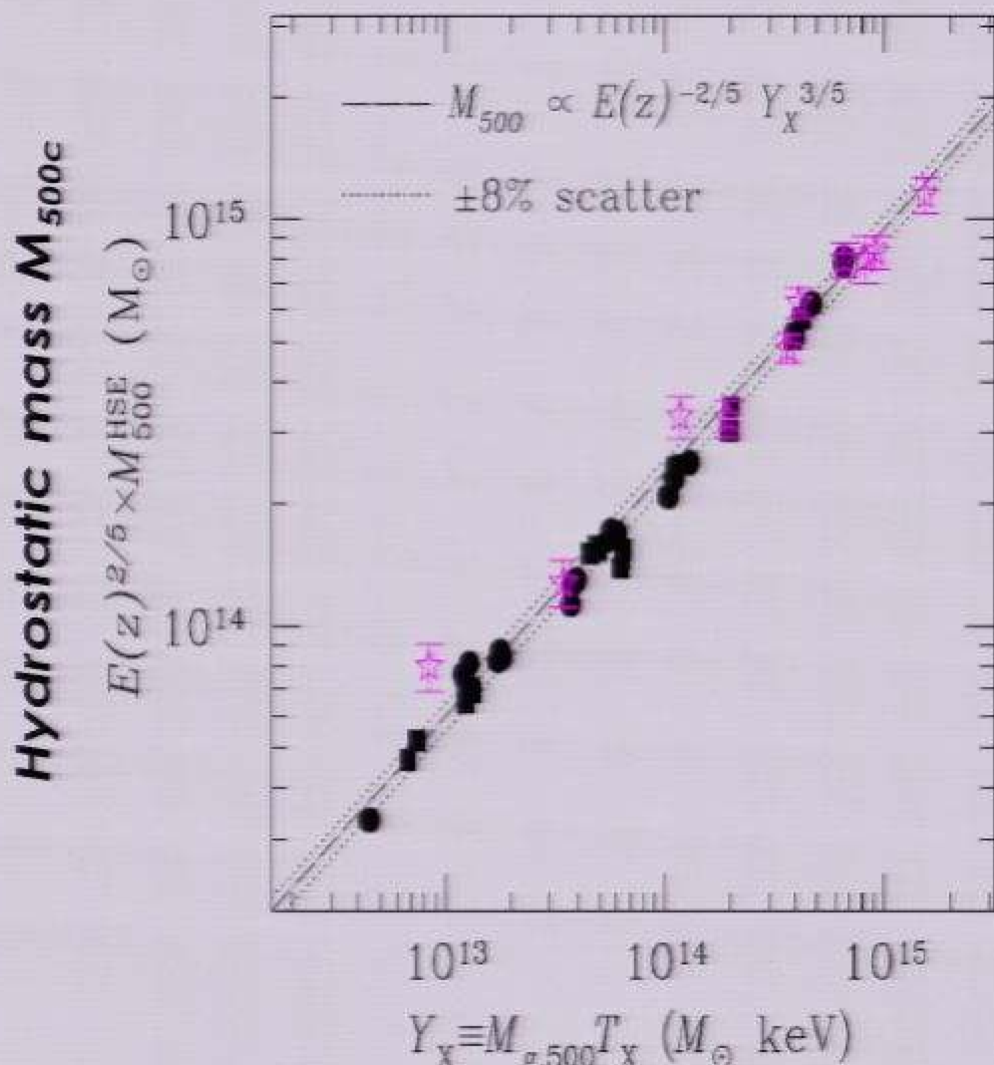
Mass profile from hydrostatic eqiulibrium neglecting turbulent pressure

Lau, Kravtsov, Nagai 2009
astro-ph/0903.4895

cluster-centric radius in units of r...

Mass – Yx relation

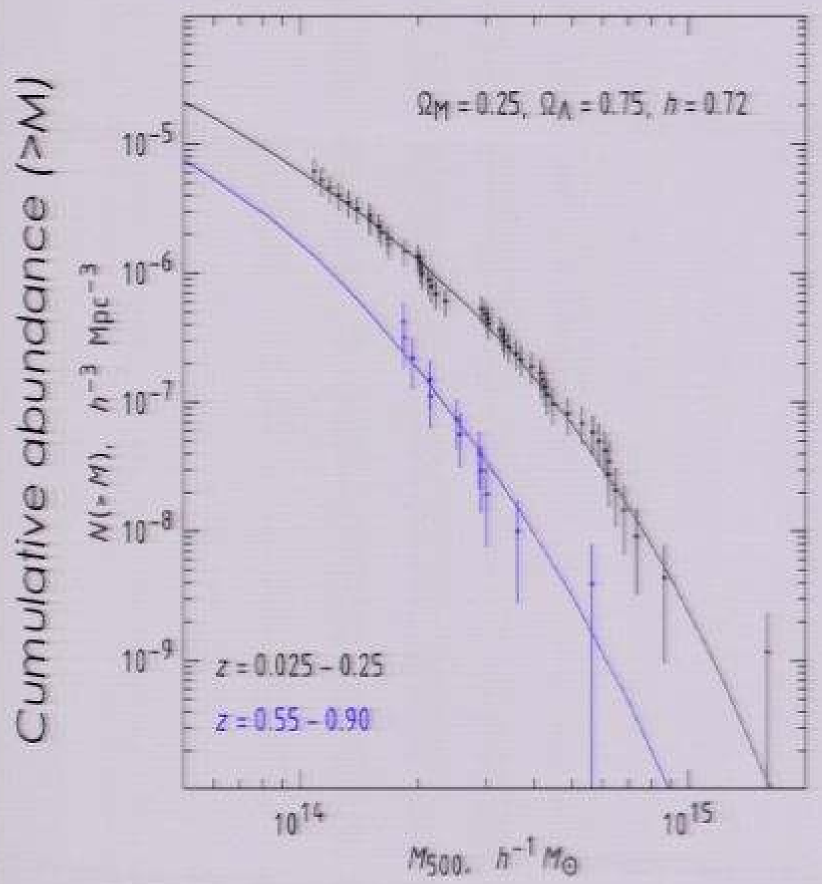
using mass derived from the hydrostatic equilibrium analysis both in observations and simulations



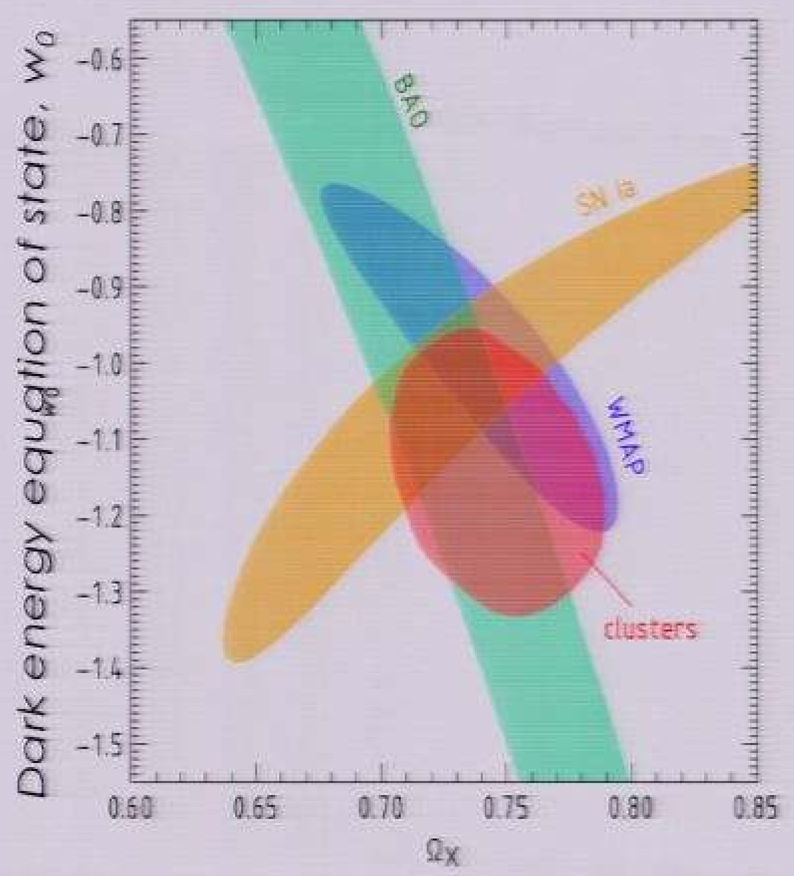
X-ray "pressure" = gas mass x temperature

Dark energy constraints from the evolution of cluster mass function

The 400 sq. deg. X-ray cluster survey (Vikhlinin et al. 2009)
Also talk by M. Hilton for the XMM cluster survey



M_{500} – total mass within radius enclosing overdensity of 500 x ρ_{crit}

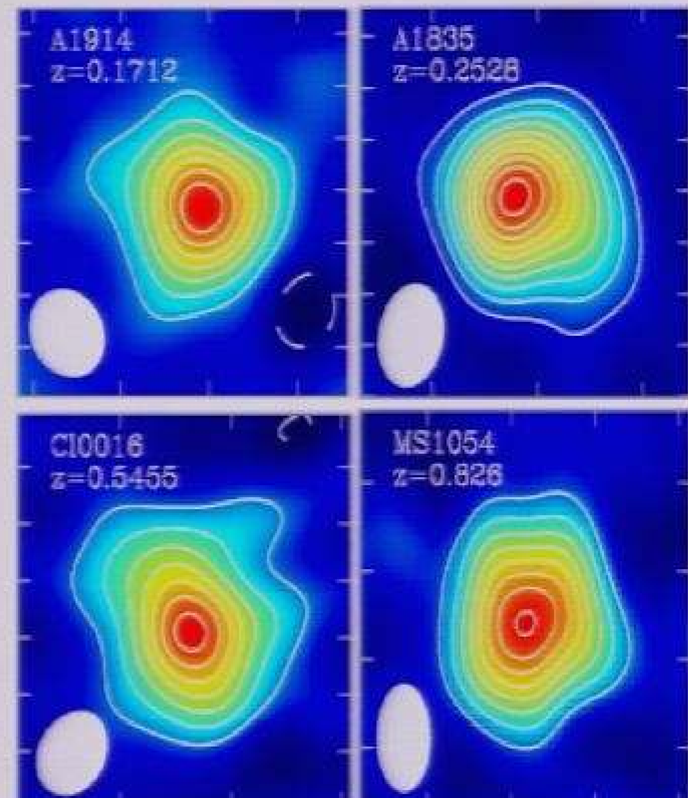


Dark energy density, Ω_X

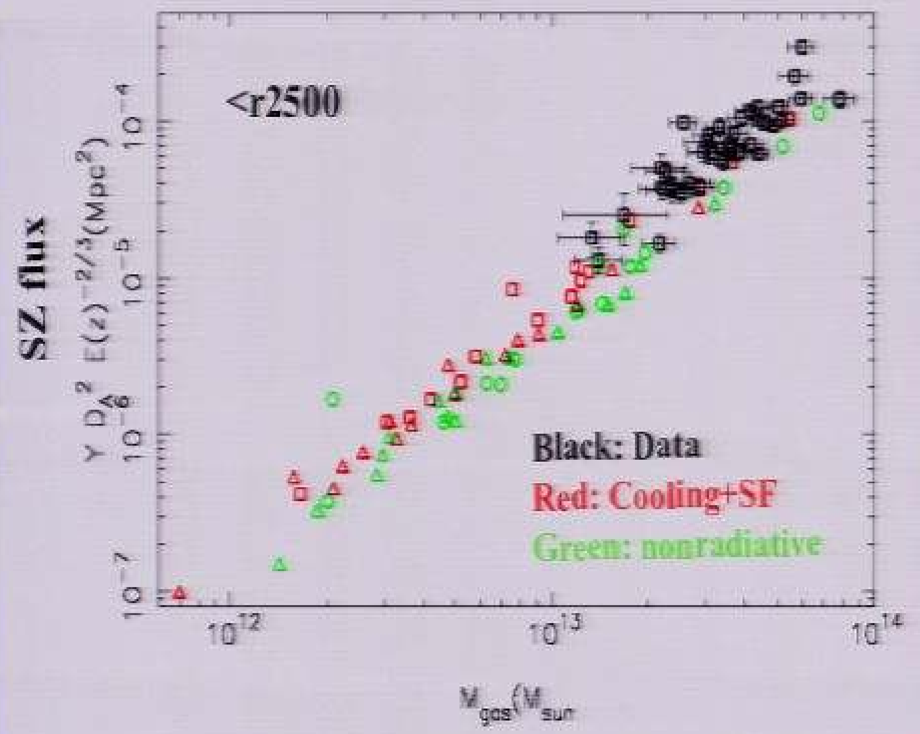
Cosmology with Sunyaev-Zel'dovich Effect

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



Simulations: Nagai 2006, also Motl et al. 2005, Hallman et al. 2007

Data: Bonamente, Joy, LaRoque, Carlstrom, Nagai, Marrone 2008

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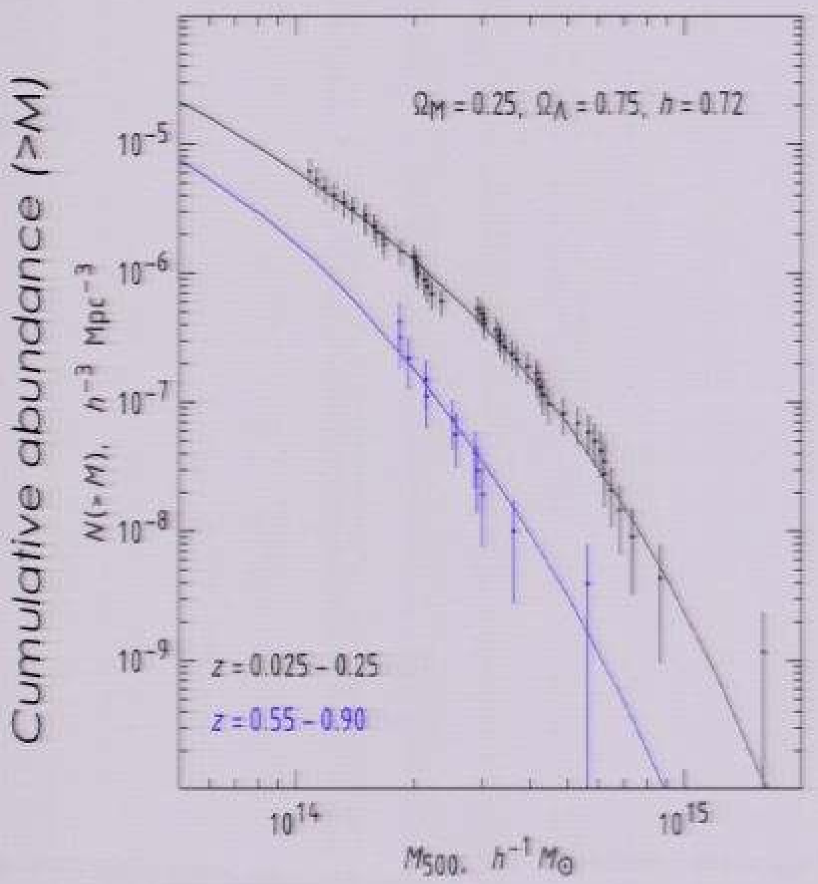

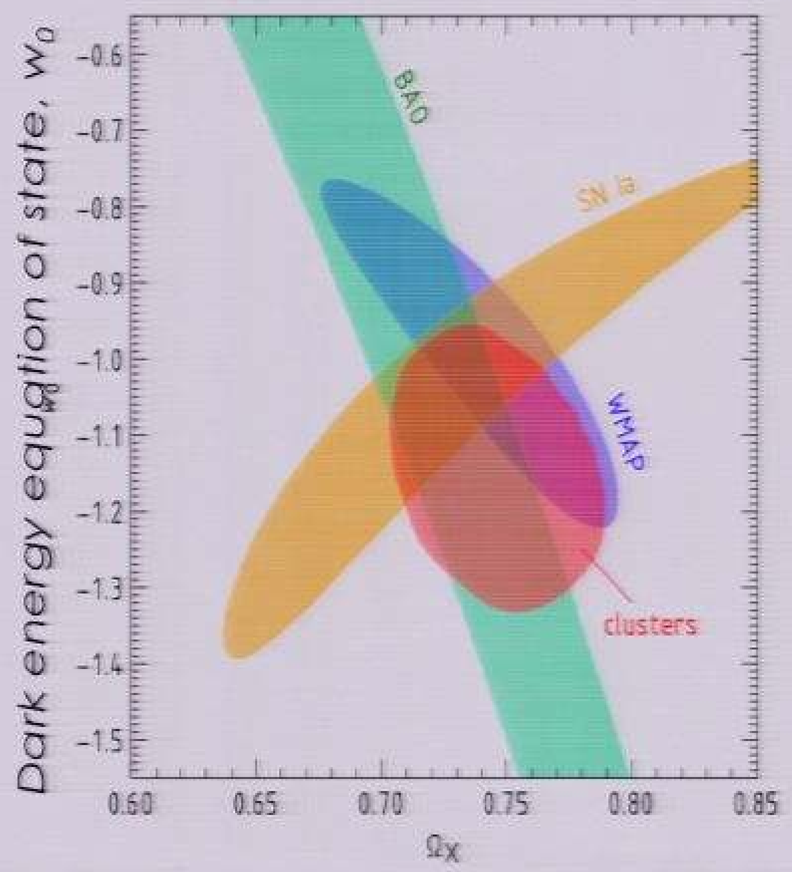

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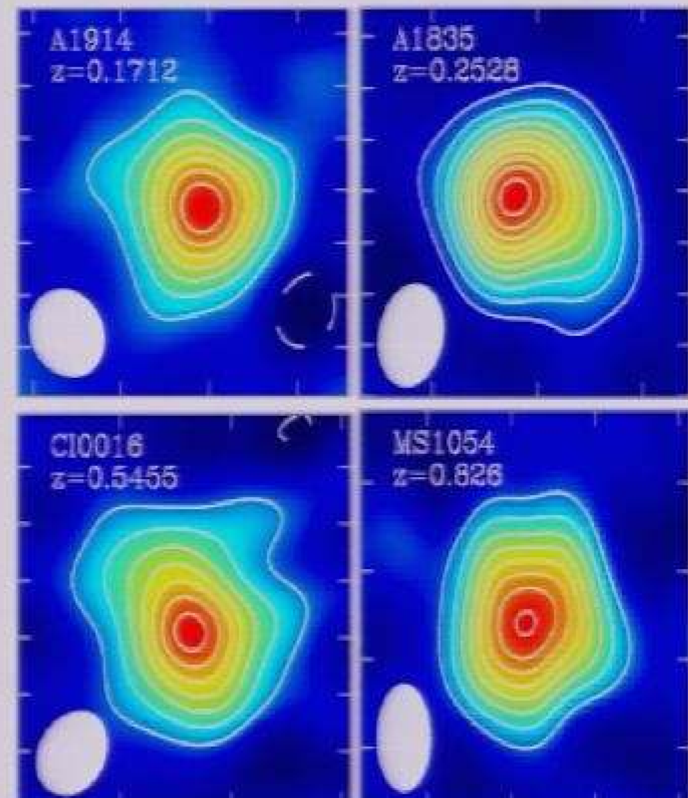
Dark energy density, Ω_x

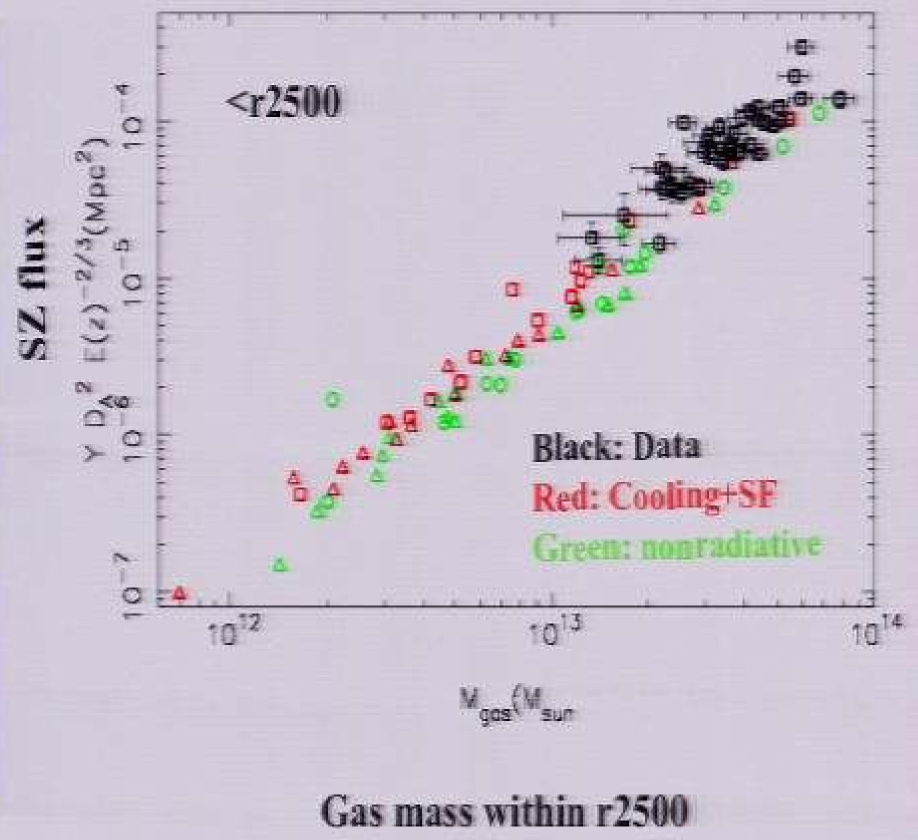
Cosmology with Sunyaev-Zel'dovich Effect

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



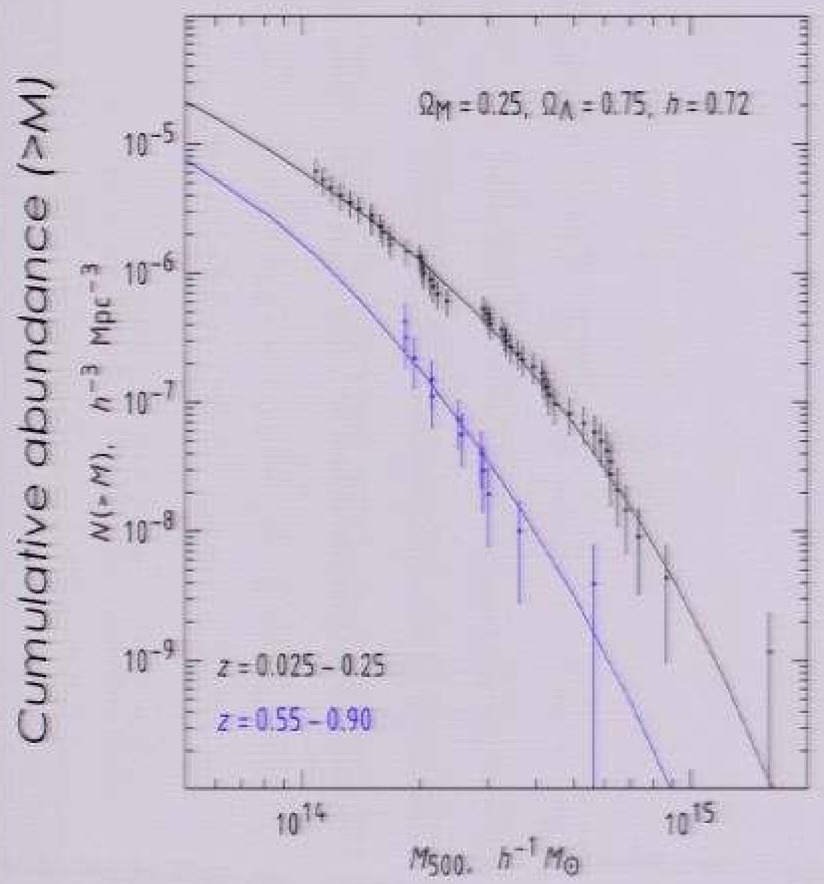
Sample of 38 BIMA/OVRO SZE+Chandra X-ray clusters at 0.14<z<0.89

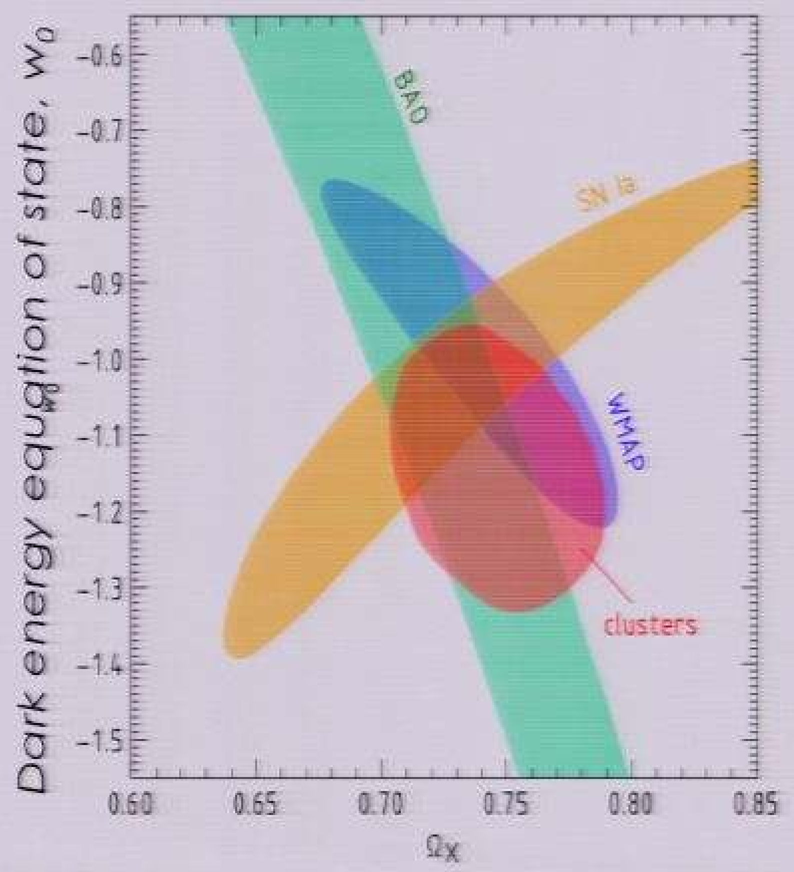


Simulations: Nagai 2006, also Motl et al. 2005, Hallman et al. 2007
Data: Bonamente, Joy, LaRoque, Carlstrom, Nagai, Marrone 2008

Dark energy constraints from the evolution of cluster mass function

The 400 sq. deg. X-ray cluster survey (Vikhlinin et al. 2009)
Also talk by M. Hilton for the XMM cluster survey





M_{500} – total mass within radius enclosing overdensity of 500 x ρ_{crit}

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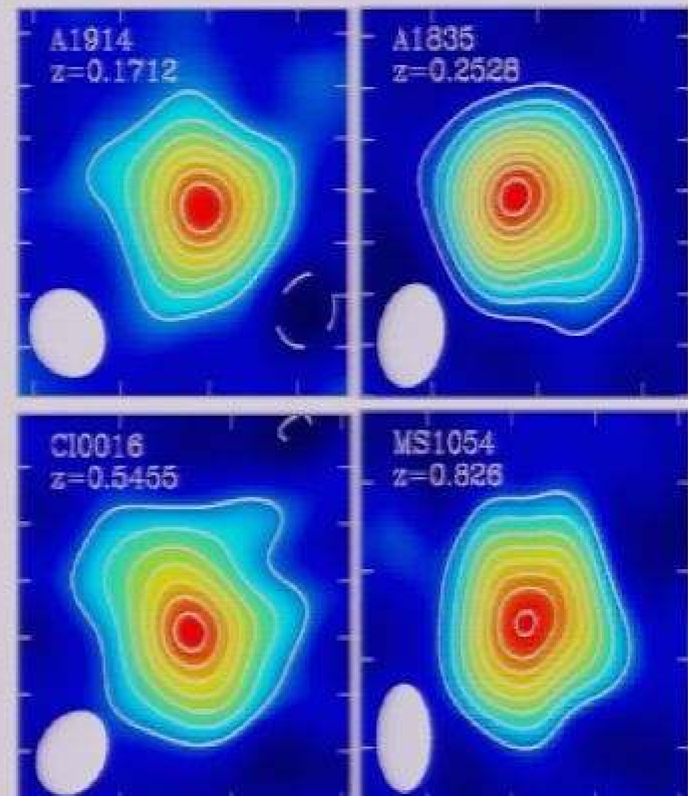

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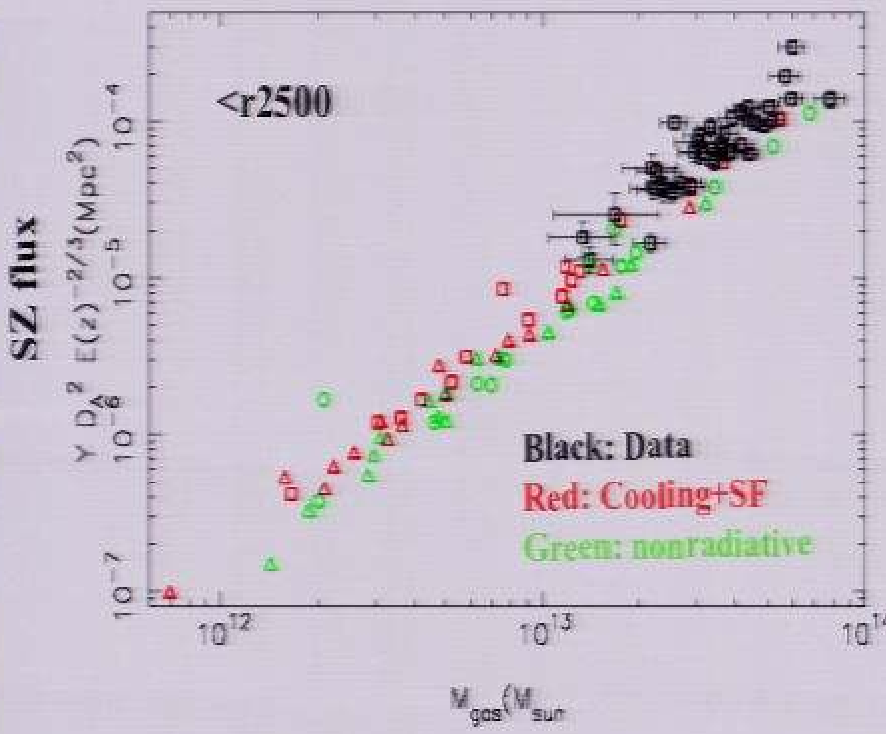

Gas mass within r2500

Simulations: Nagai 2006, also Motl et al. 2005, Hallman et al. 2007

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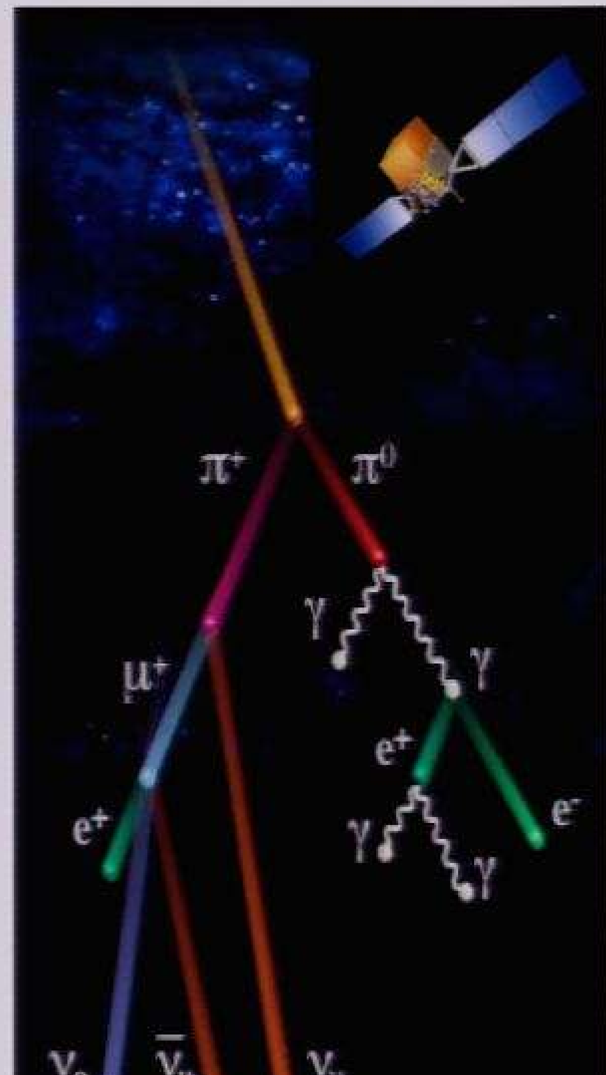
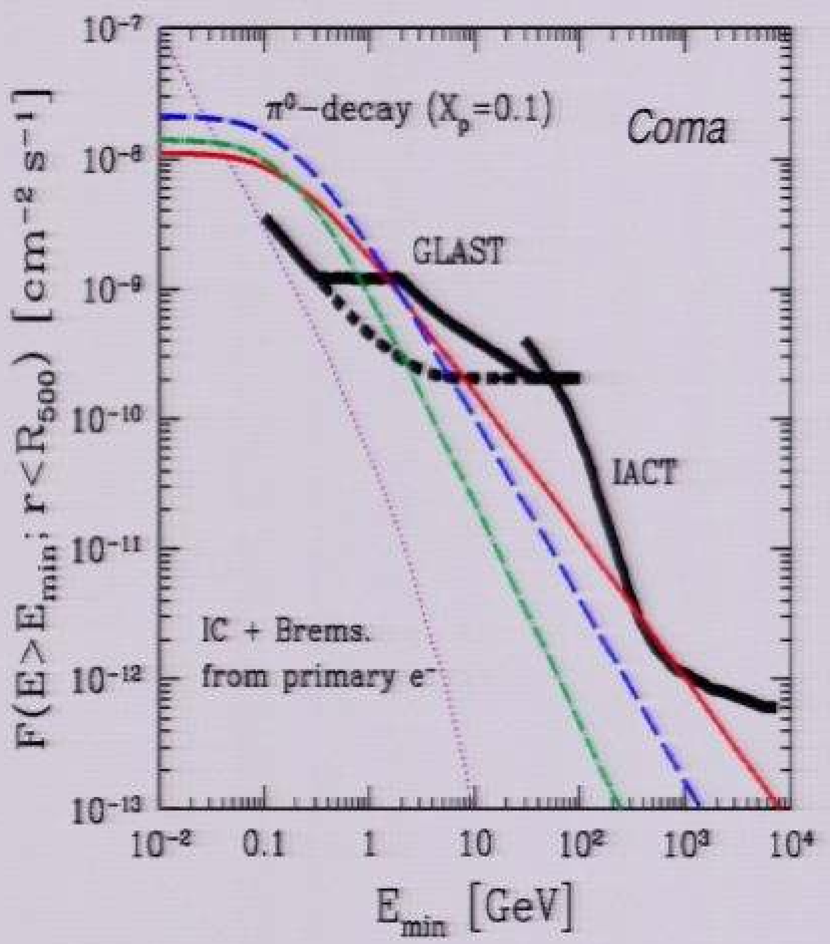
Probing cosmic-rays pressure with Fermi

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



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



Ando & Nagai 2008; also

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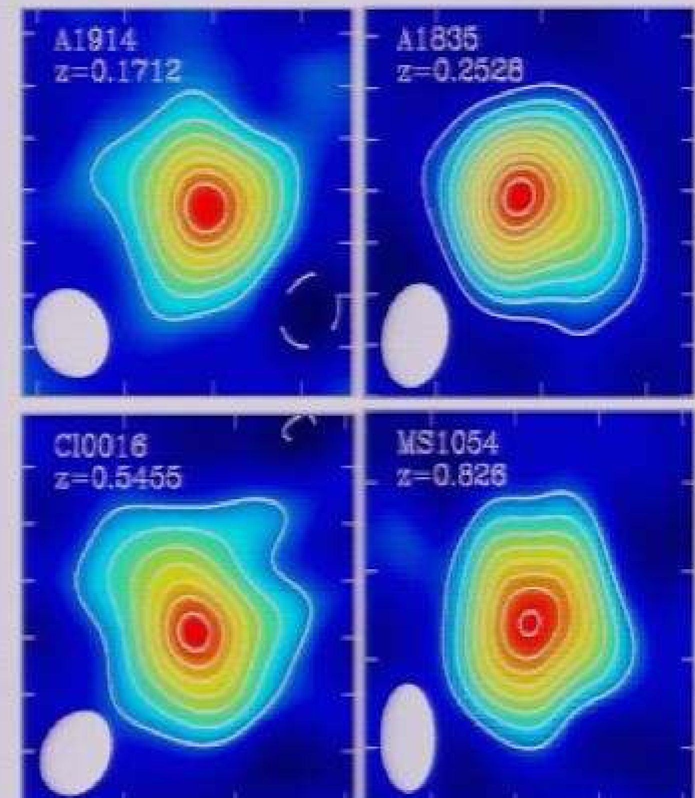

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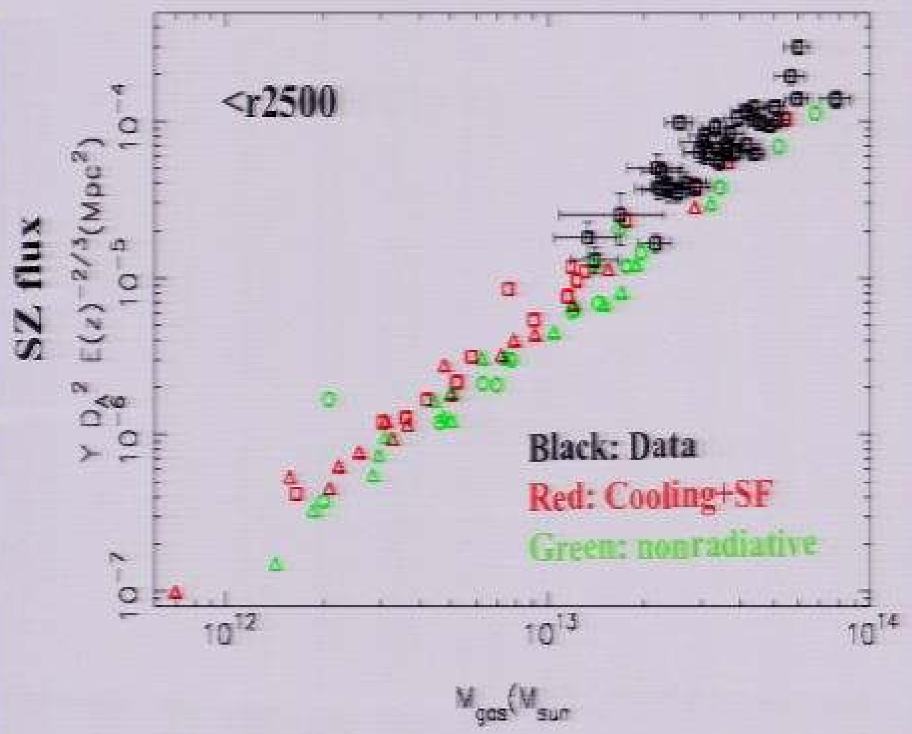

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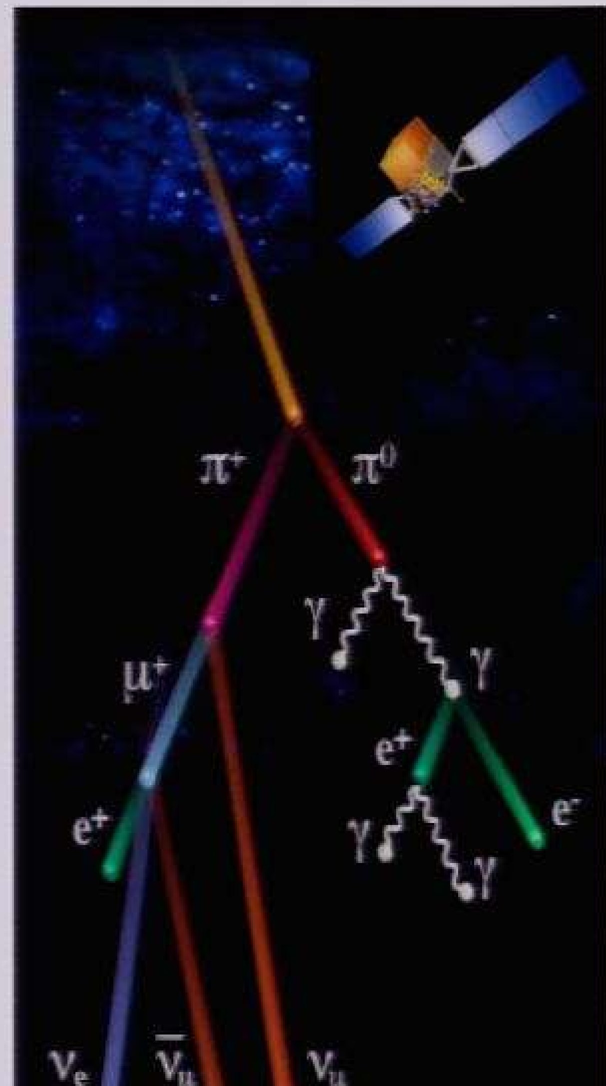

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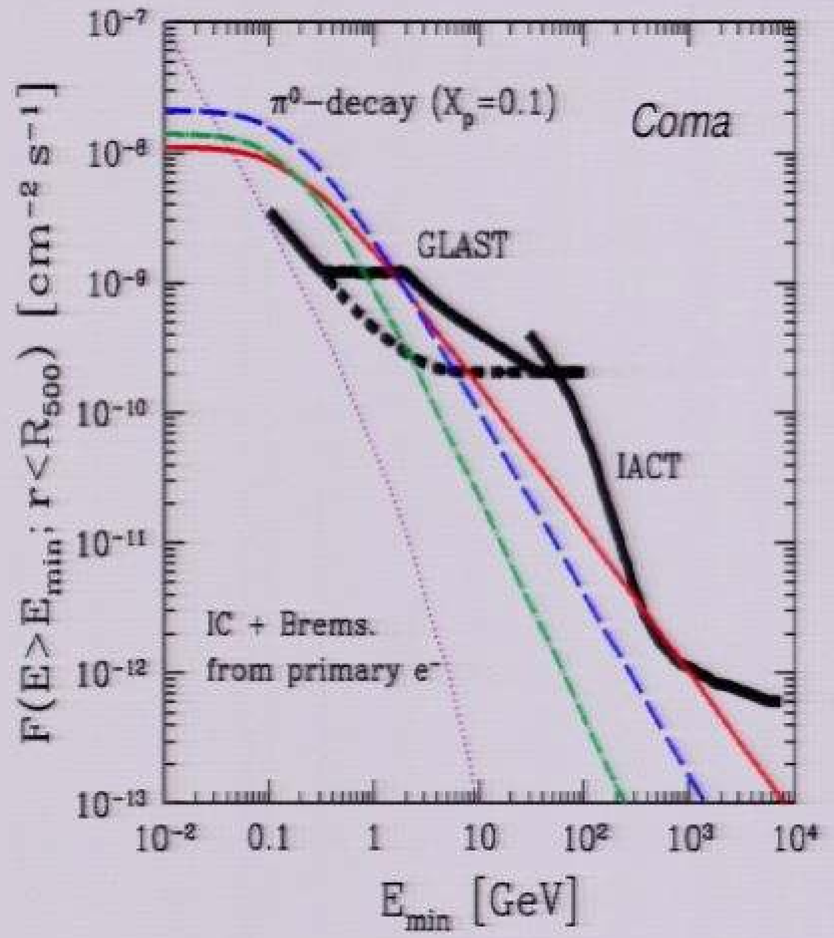

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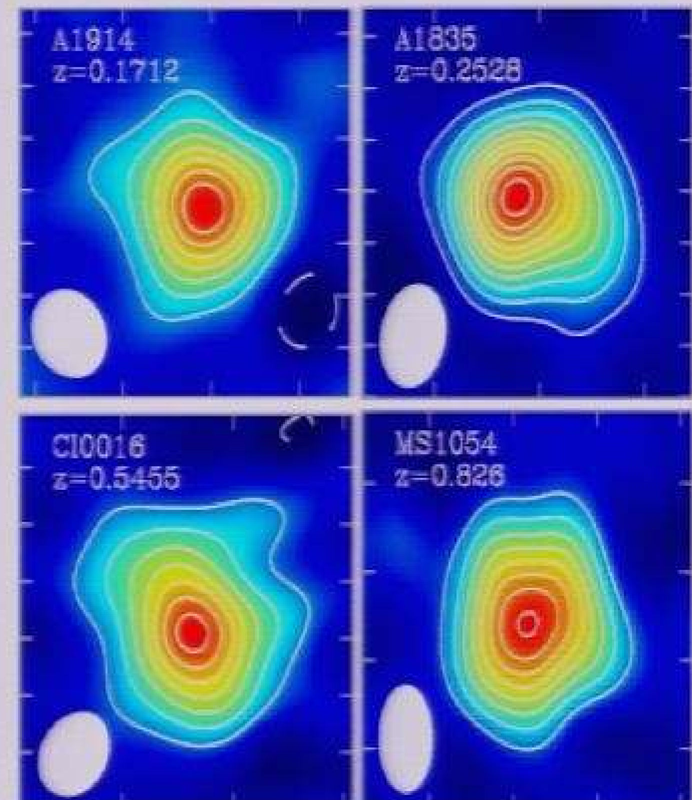

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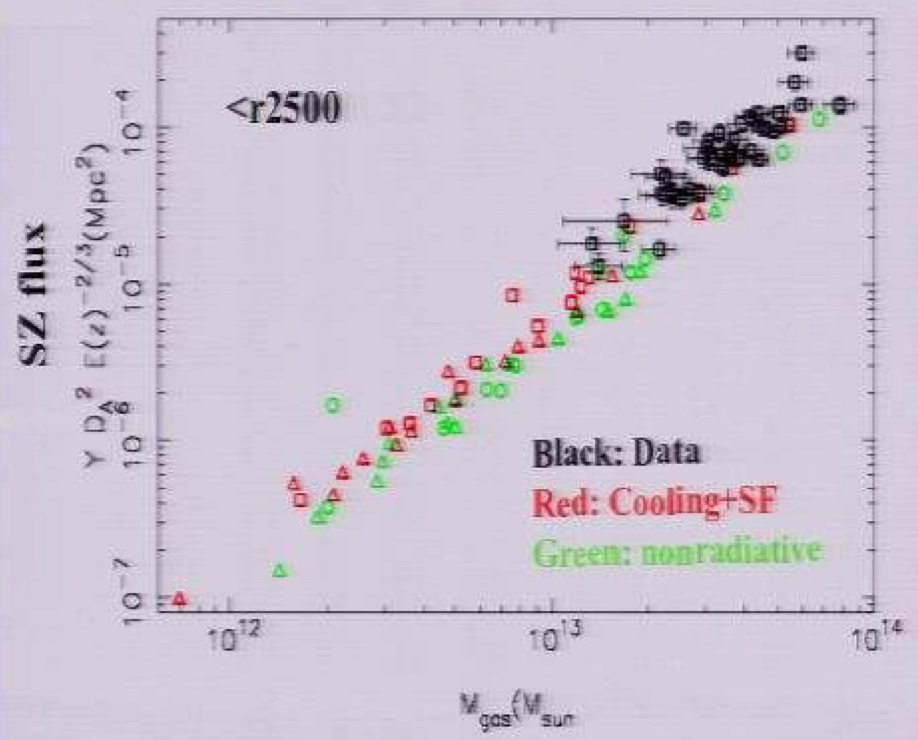

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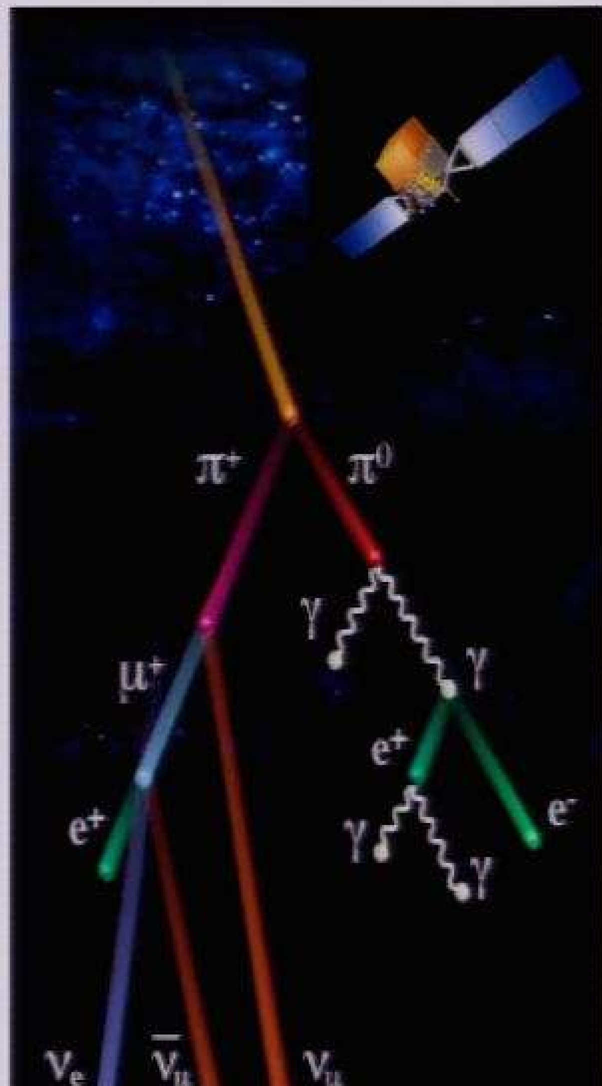

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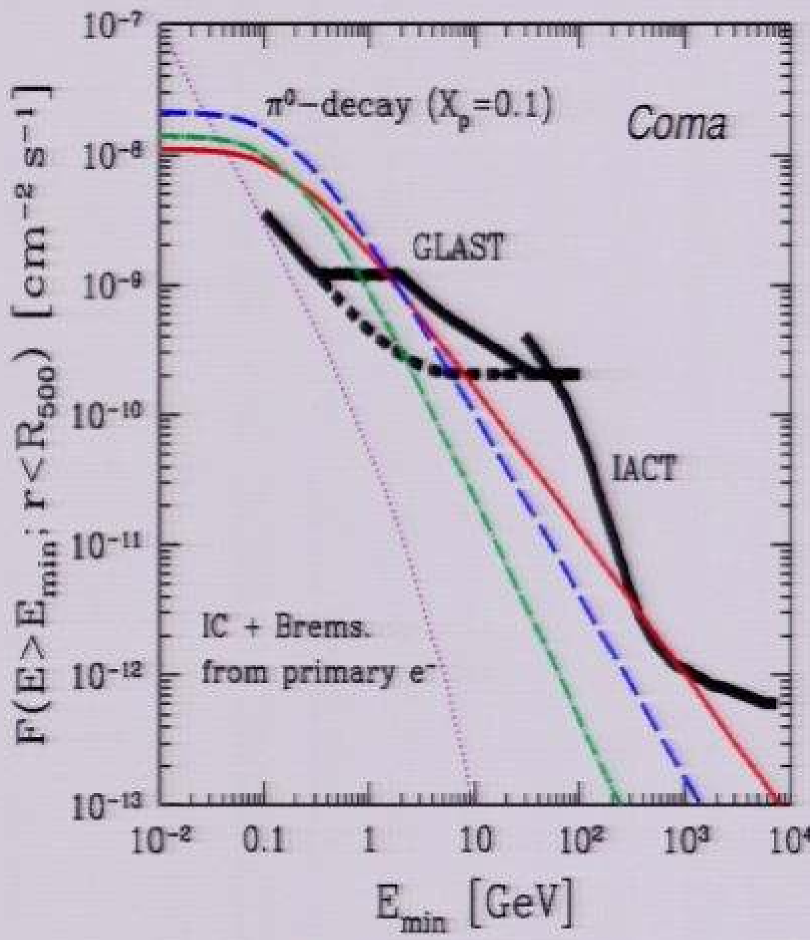
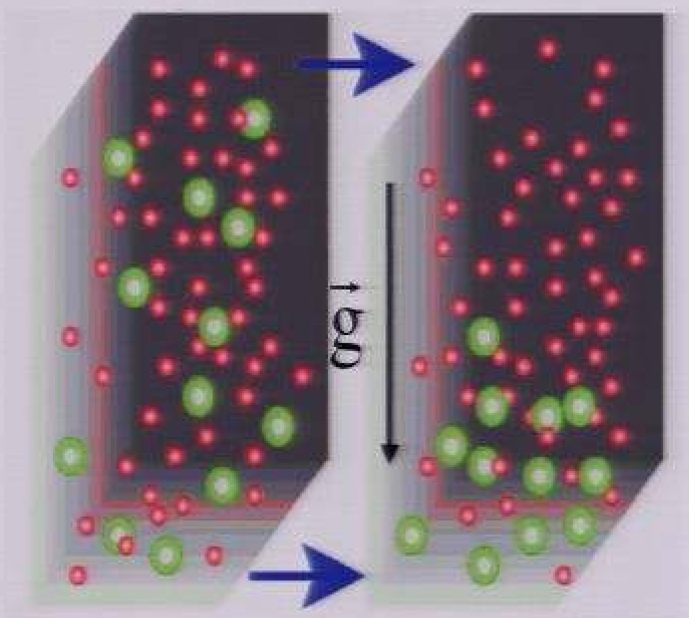


Ando & Nagai 2008; also

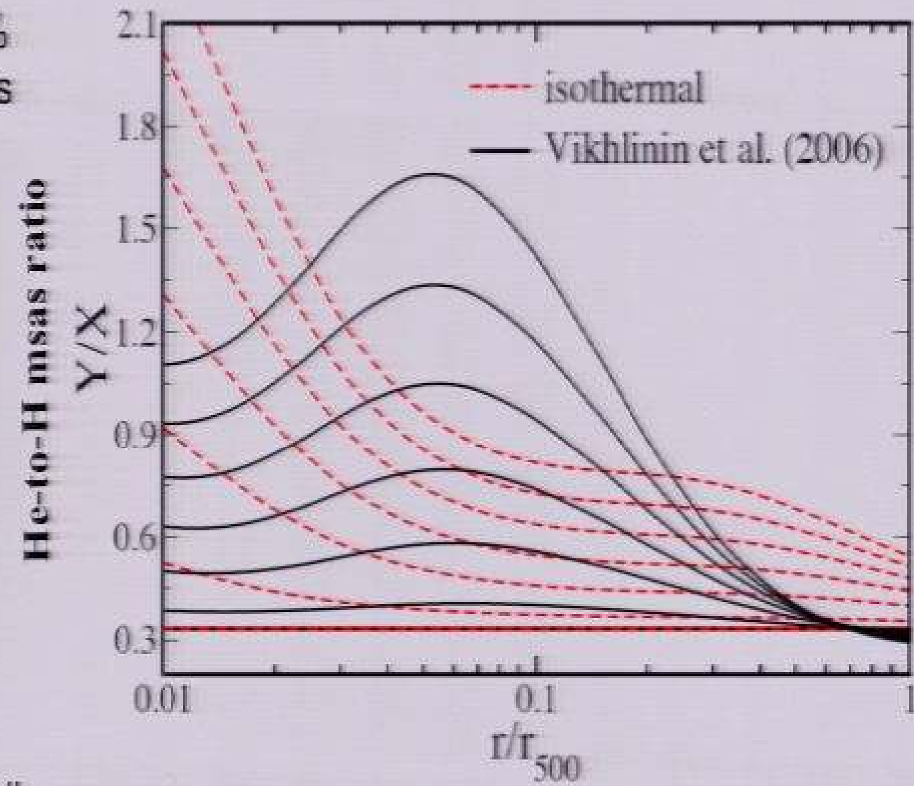
He sedimentation in X-ray Clusters

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

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

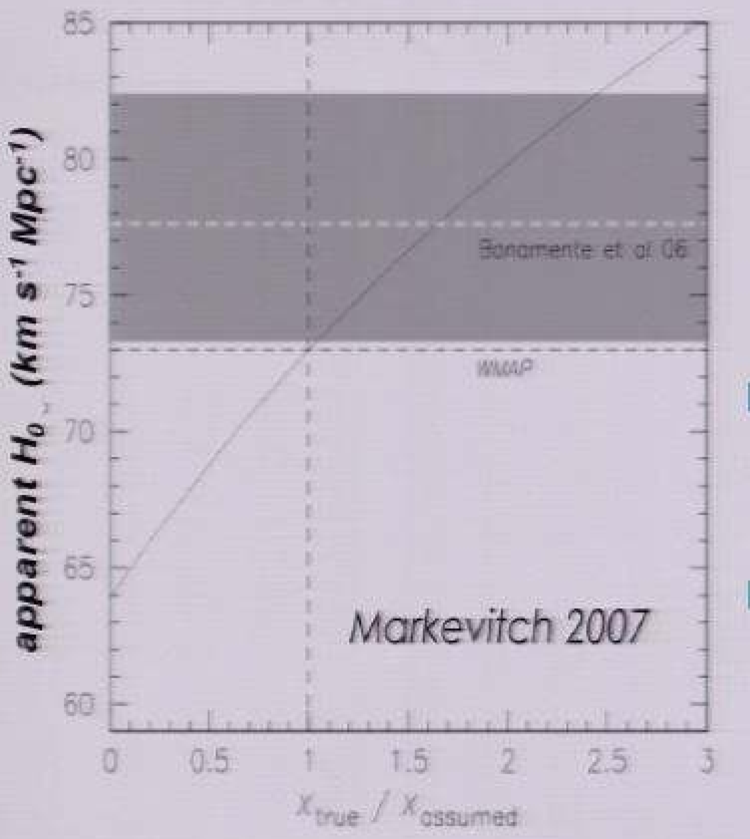


cluster-centric radius in units of r_{500}

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

Bias in X-ray + SZE derived Hubble parameter

H_0 measurements at $r = r_{2500}$



Enhancement in He-to-H number density ratio relative to the primordial value

- **X-ray + SZE-derived Hubble parameter**

$$\begin{cases} S_X \propto n_e^2 d_A \left(\dfrac{1+4x}{1+2x}\right) \\ y_{SZE} \propto n_e T_e d_A \end{cases} \Rightarrow d_A \propto \frac{y_{SZE}^2}{S_X T_e^2}\left(\frac{1+4x}{1+2x}\right)$$

- **Our model predicts an overestimate of the X-ray+SZE H_0 ($\propto d_A^{-1}$) by about 5%.**

- **This can explain the offset seen in the latest X-ray+SZE-derived H_0=77.6±4.5 km s^{-1} Mpc^{-1} (Bonamente et al. 2007) relative to H_0=73 km s^{-1} Mpc^{-1} of the WMAP and/or Hubble Key projects.**

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)