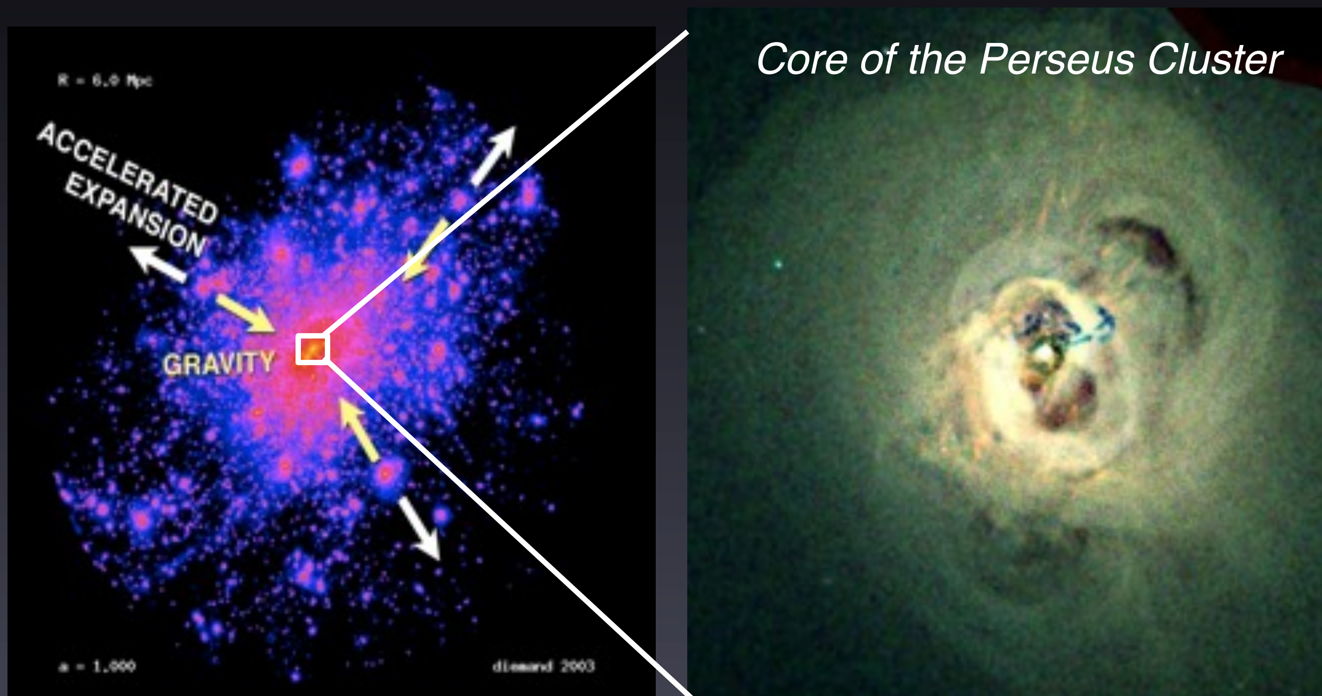
Simulating the Cosmic Melting Pot in the Virialization Regions of Galaxy Clusters

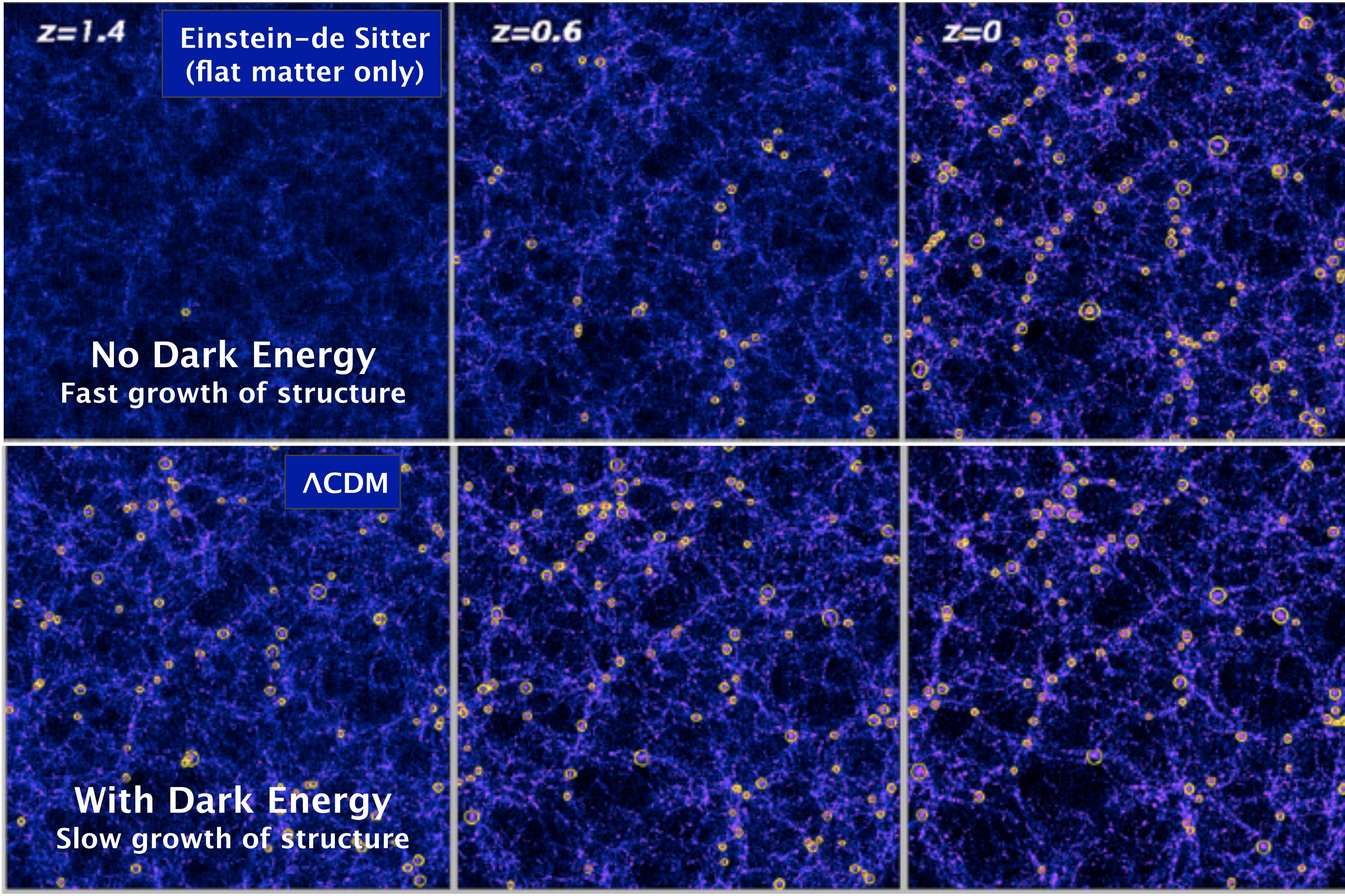


Daisuke Nagai

Yale University

July 12th, 2011 @ Chandra Cluster workshop

Accurate Determination of Mass Function and Clustering of Dark Matter halos with N-body simulations



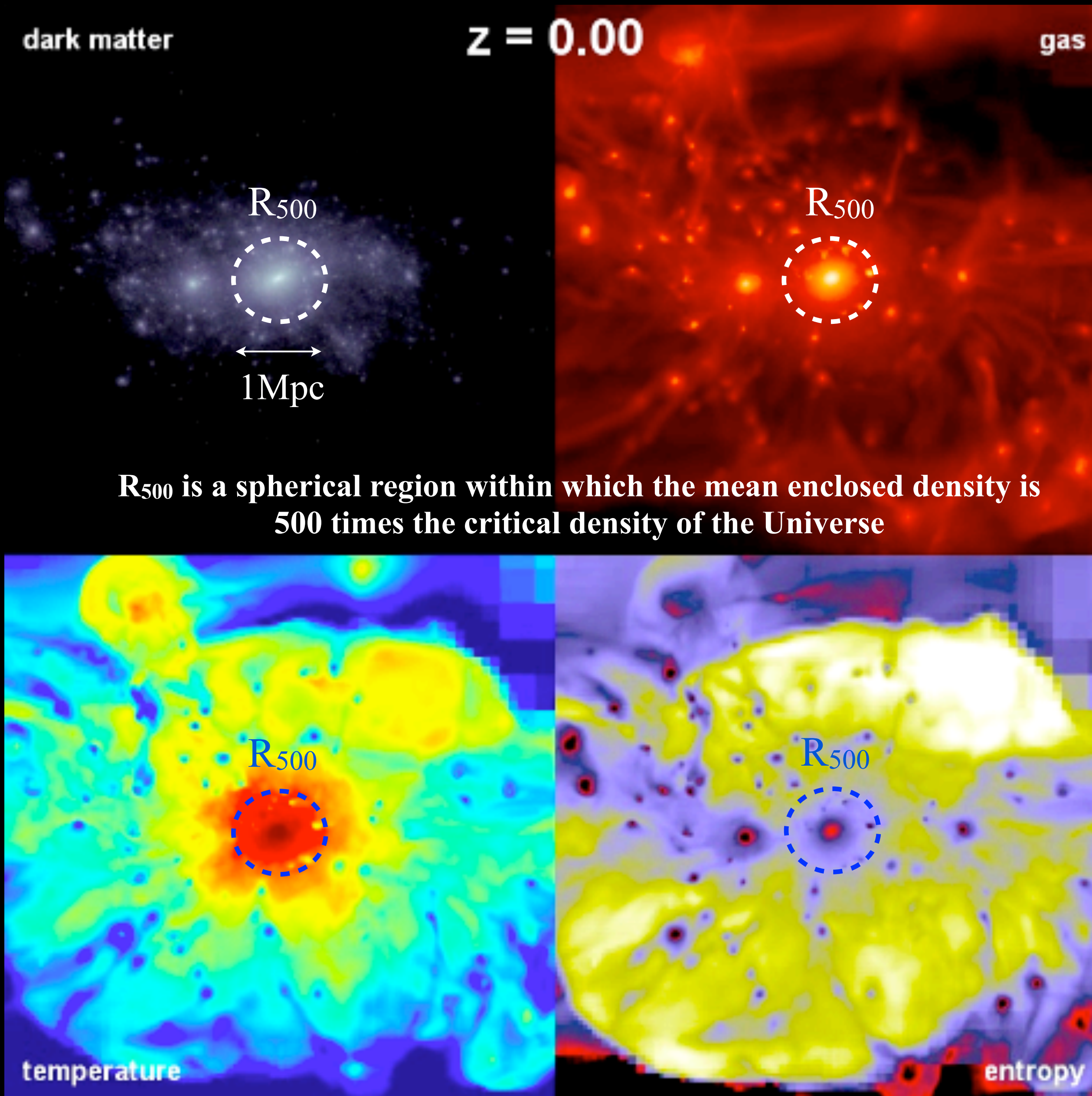
Hydrodynamical Simulations of Galaxy Clusters

N-body+Gasdynamics with Adaptive Refinement Tree (ART) code

Box size ~ 100 Mpc
Spatial resolution ~ a few kpc

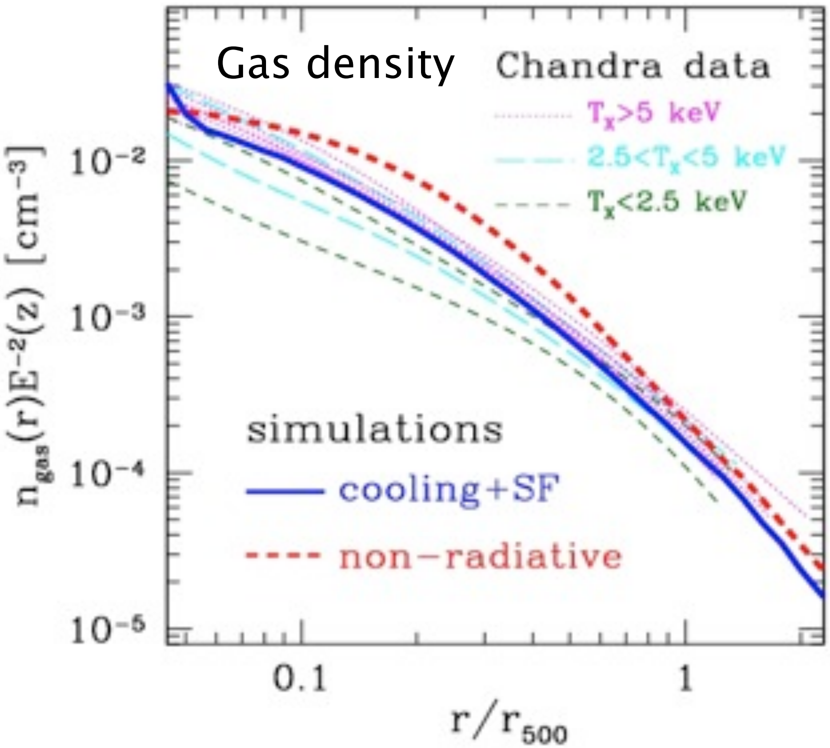
Modern cosmological hydro simulations include the effects of baryons (i.e., gas cooling, star formation, heating by SNe/AGN, metal enrichment and transport)

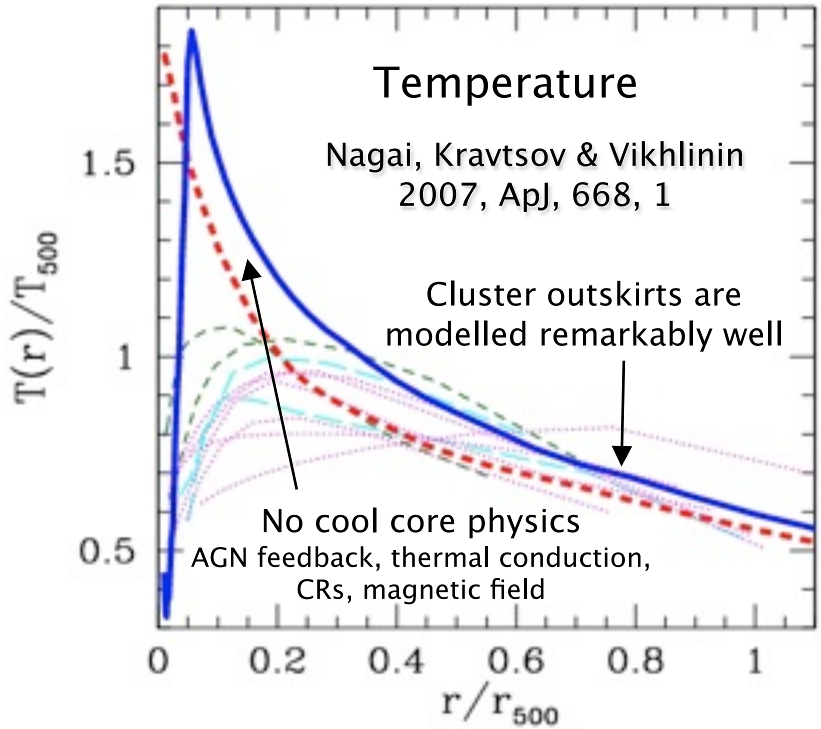
But, also remember the limitations - e.g., a single fluid approximation!



R_{500} is a spherical region within which the mean enclosed density is 500 times the critical density of the Universe

Radial profiles of X-ray emitting ICM
Simulations vs. Chandra X-ray Observations





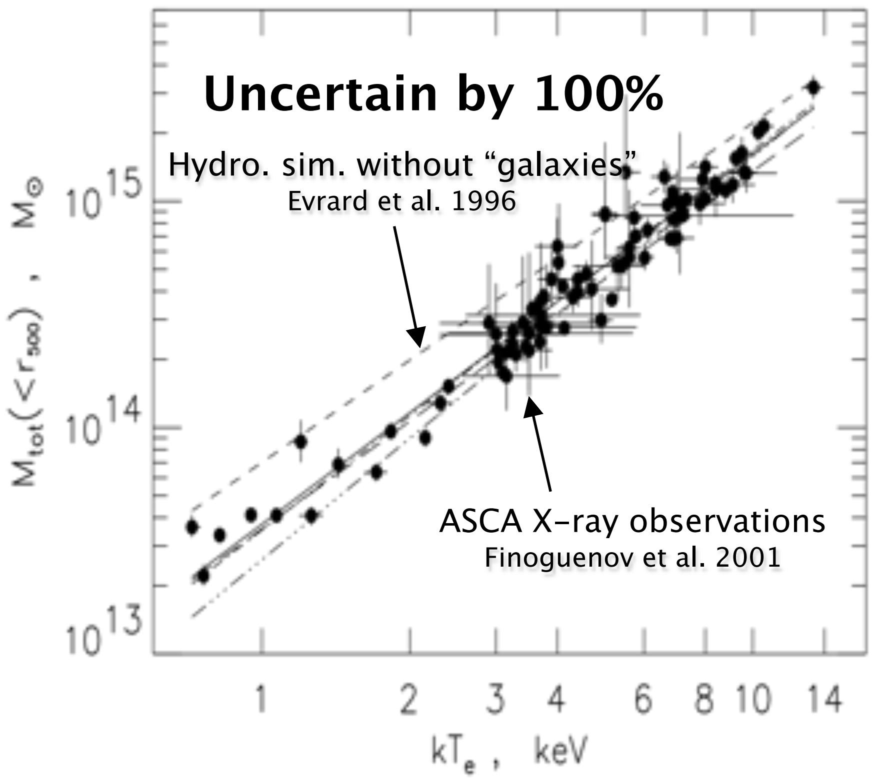
Modern hydrodynamical cluster simulations reproduce observed ICM profiles outside cluster cores ($r>0.15 \times r_{500}$).

Recent Advances at the Crossroads of Cluster Astrophysics & Cosmology

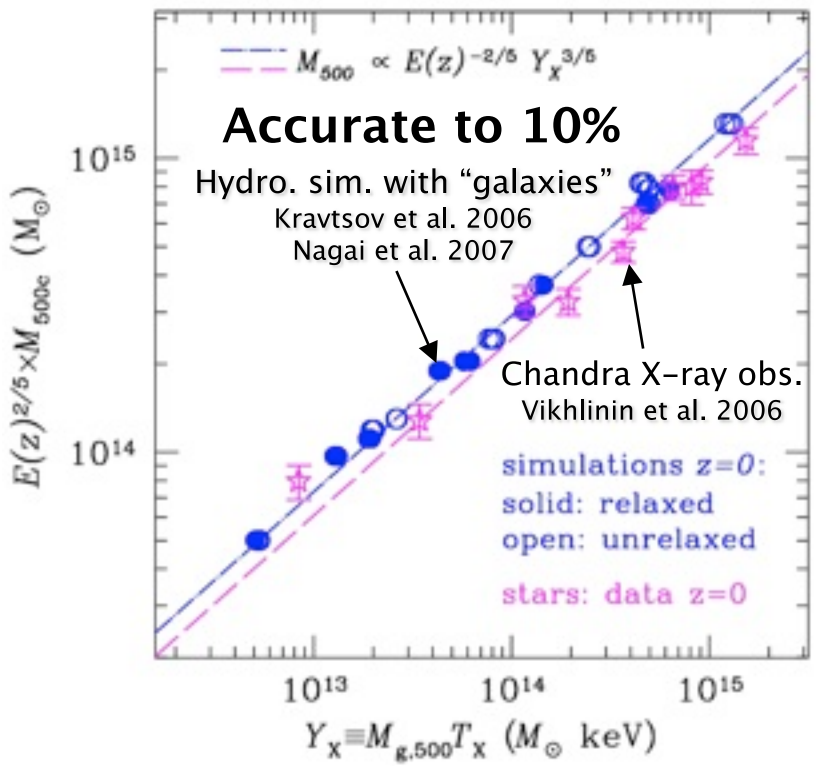
Dark Energy Task Force (2006)

The **CL** technique has the statistical potential to exceed the BAO and SN techniques but at present has 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.

Before

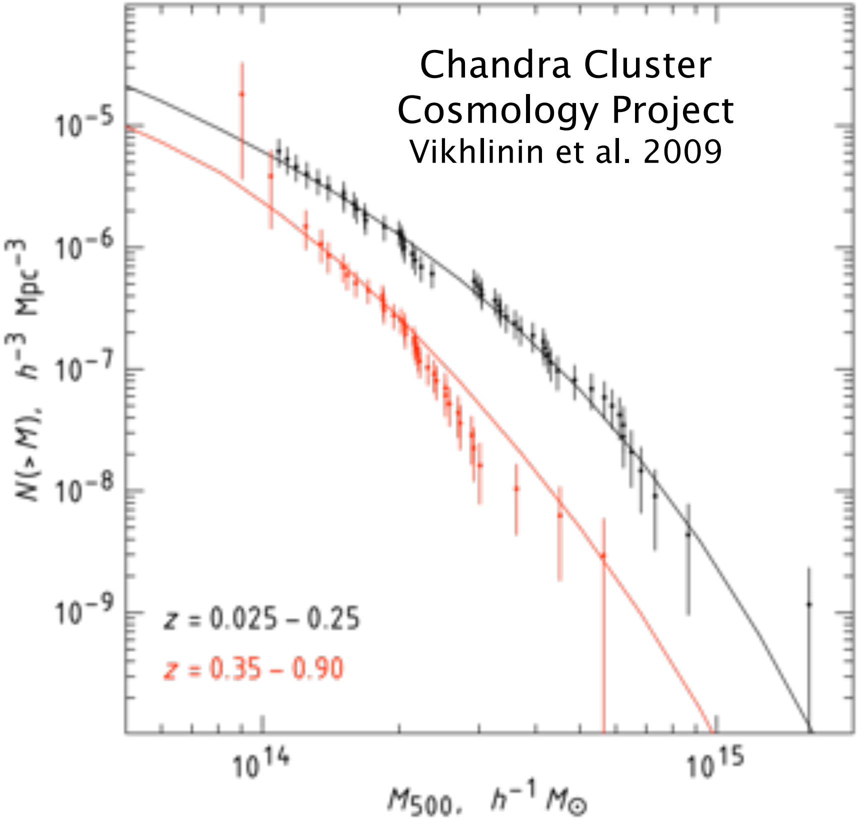


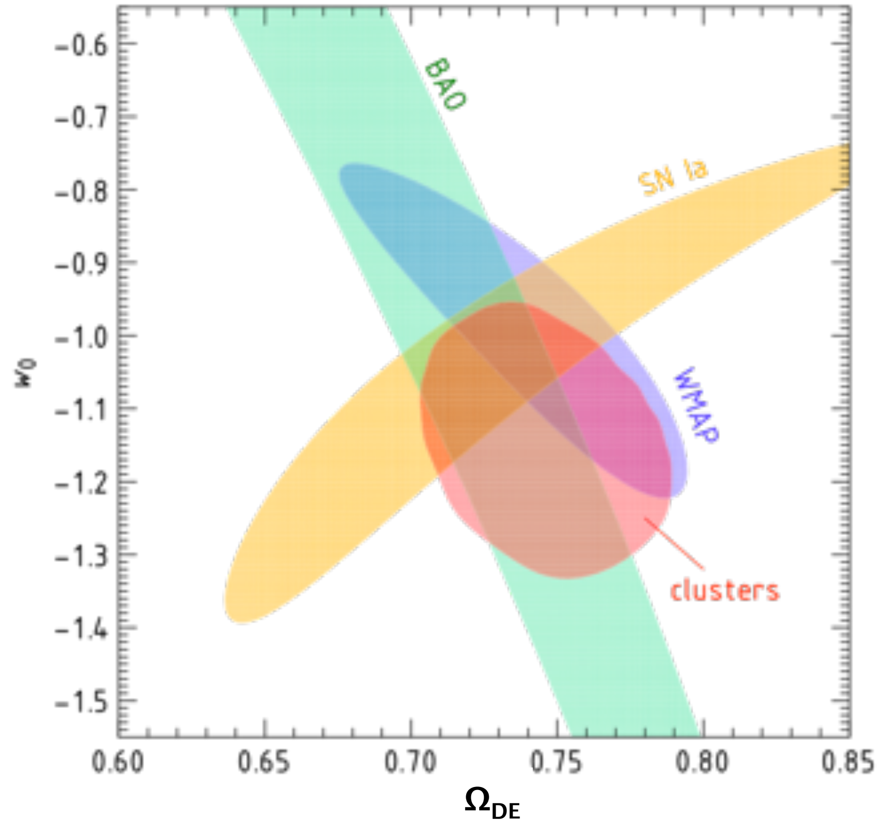
Now



Era of Precision Cluster Cosmology

Local (z<0.1) sample of 49 clusters + 37 high-z clusters
from the 400d X-ray selected cluster sample





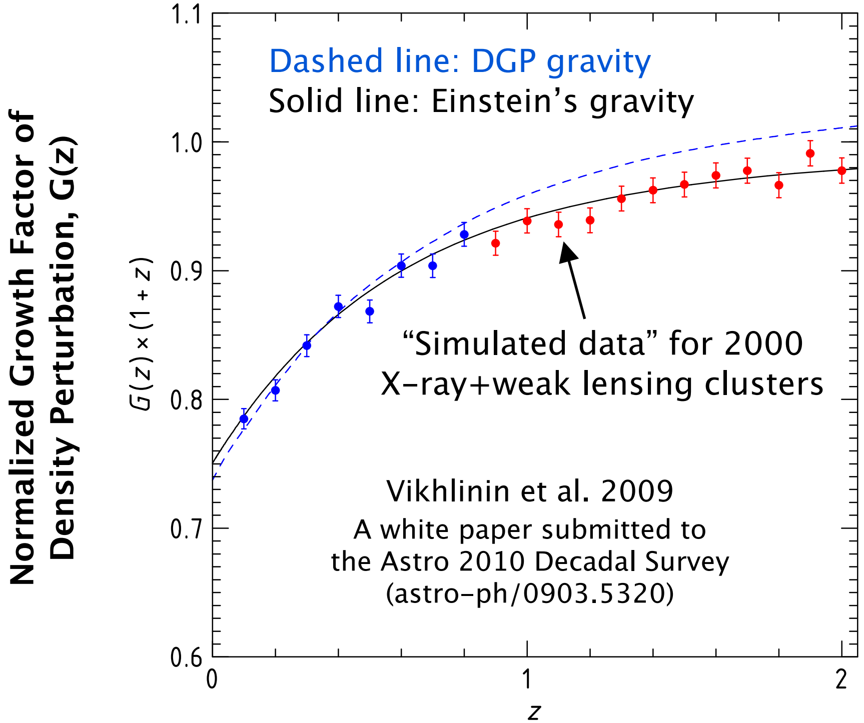
$\sigma_8 = 0.813(\Omega_M/0.25)^{-0.47} \pm 0.013$

$w_0 = -0.99 \pm 0.045$

$\Omega_{DE} = 0.740 \pm 0.012$

Testing non-GR theories of the Cosmic Acceleration with Next Generation X-ray surveys

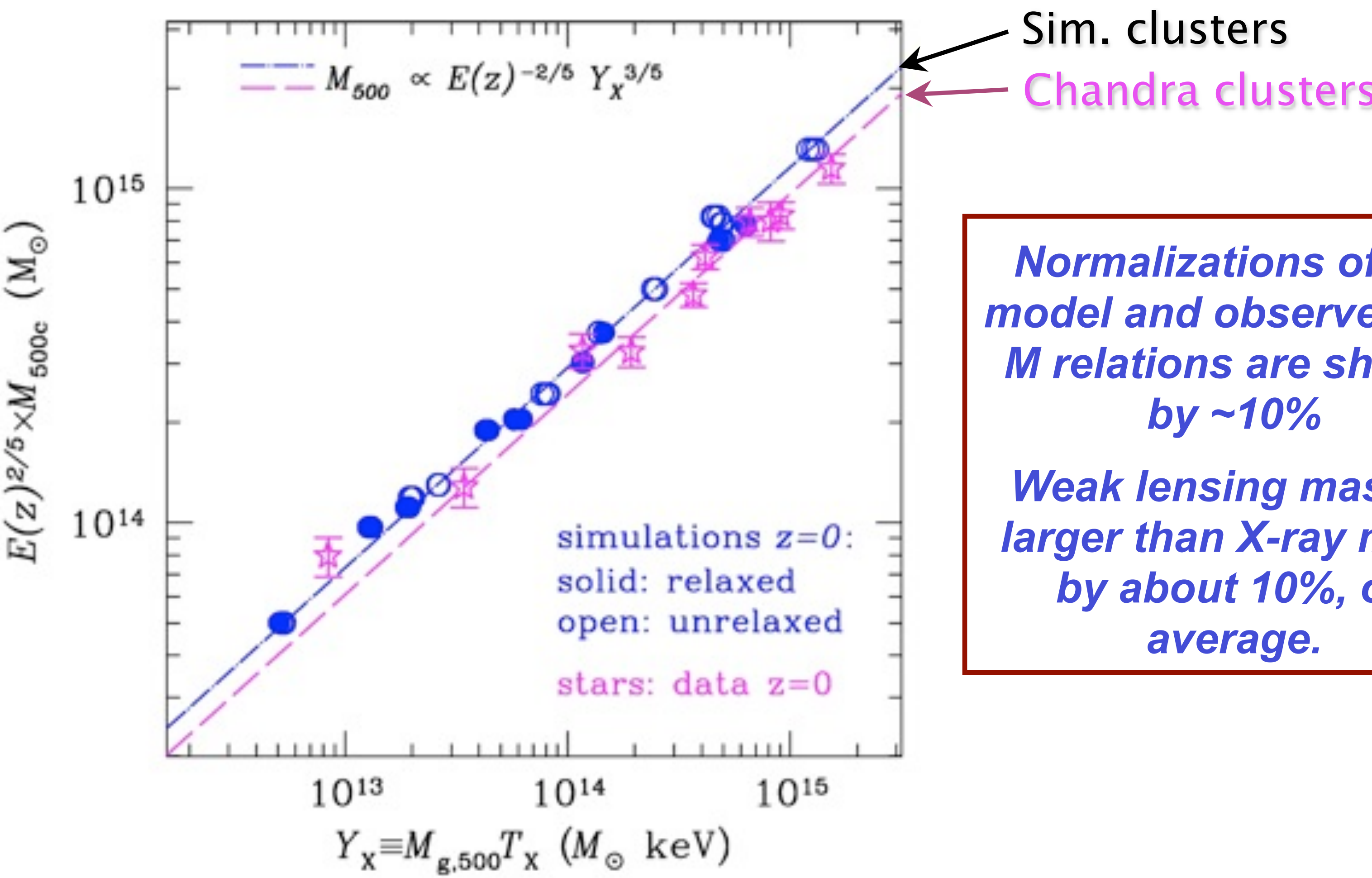
eROSITA (scheduled launch in 2013)



All-sky survey for 4yrs + targeted obs.
Science Goals: Study the LSS and Dark Energy
~100,000 clusters up to z~1.3
A_{eff}~1500 cm^2 @ 1.5keV; Θ_{eff}~25-40 arcsec

Main Challenge

Calibration of Observable-Mass relations



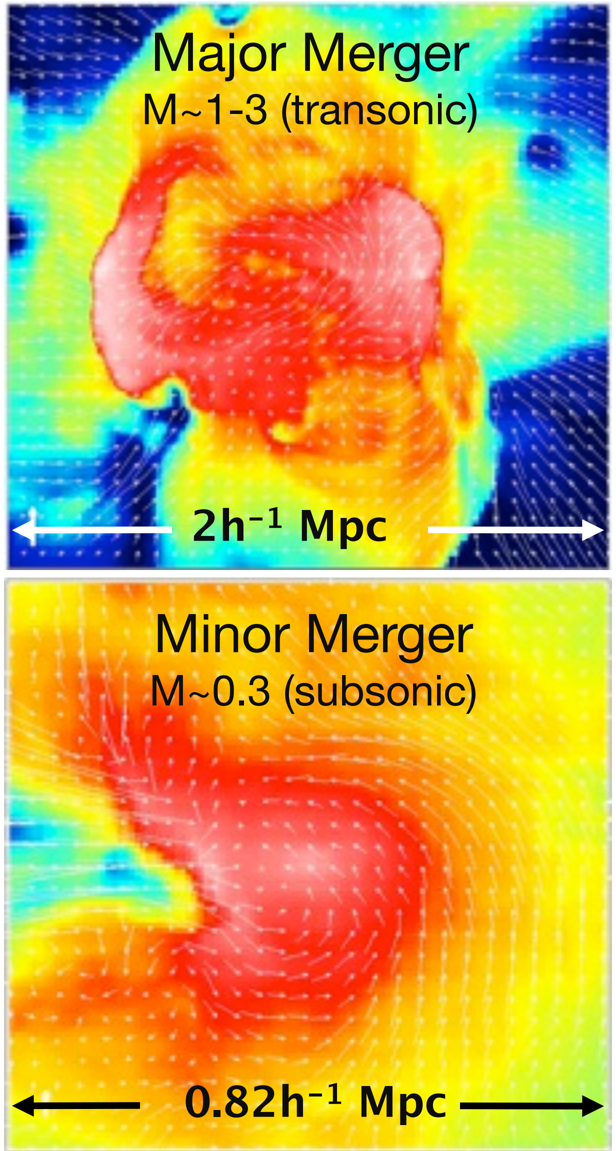
Normalizations of the model and observed Yx-M relations are shifted by ~10%

Weak lensing mass is larger than X-ray mass by about 10%, on average.

X-ray "pressure" = Yx = gas mass x temperature measured excluding cluster core regions

The Physics of Cluster Outskirts is the key!!

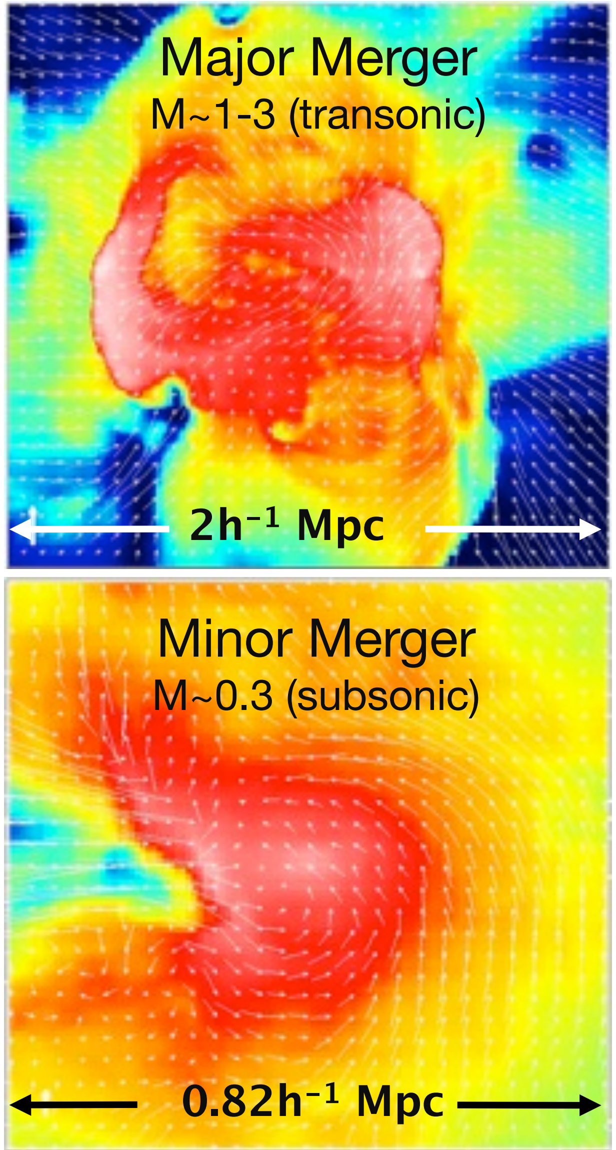
Missing Cluster Astrophysics #1
Gas Motions in Clusters



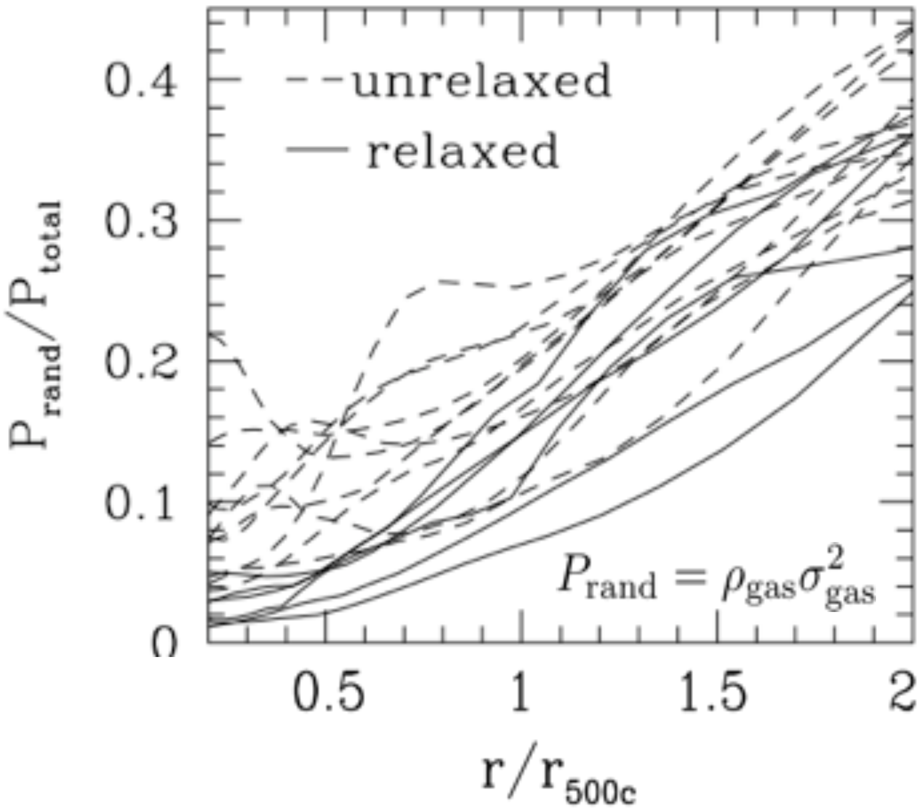
- Gas (bulk+turbulent) motions are predicted to be ubiquitous in the ICM
- Drivers of gas motions
  - Accretion/Mergers (on large scales)
  - Energy injection from SNe/AGN (in cluster cores)
- Implications
  - Hydrostatic mass modeling
  - X-ray/SZE observable-mass relations
  - ICM temperature and entropy profiles
  - SZ power spectrum
  - Metal distribution (e.g., by mixing)
  - Particle acceleration

Observationally, we know very little about the nature of gas motions in clusters!!

Non-thermal Pressure in Cluster Outskirts



Gas motions due to incomplete virialization are ubiquitous in ΛCDM clusters

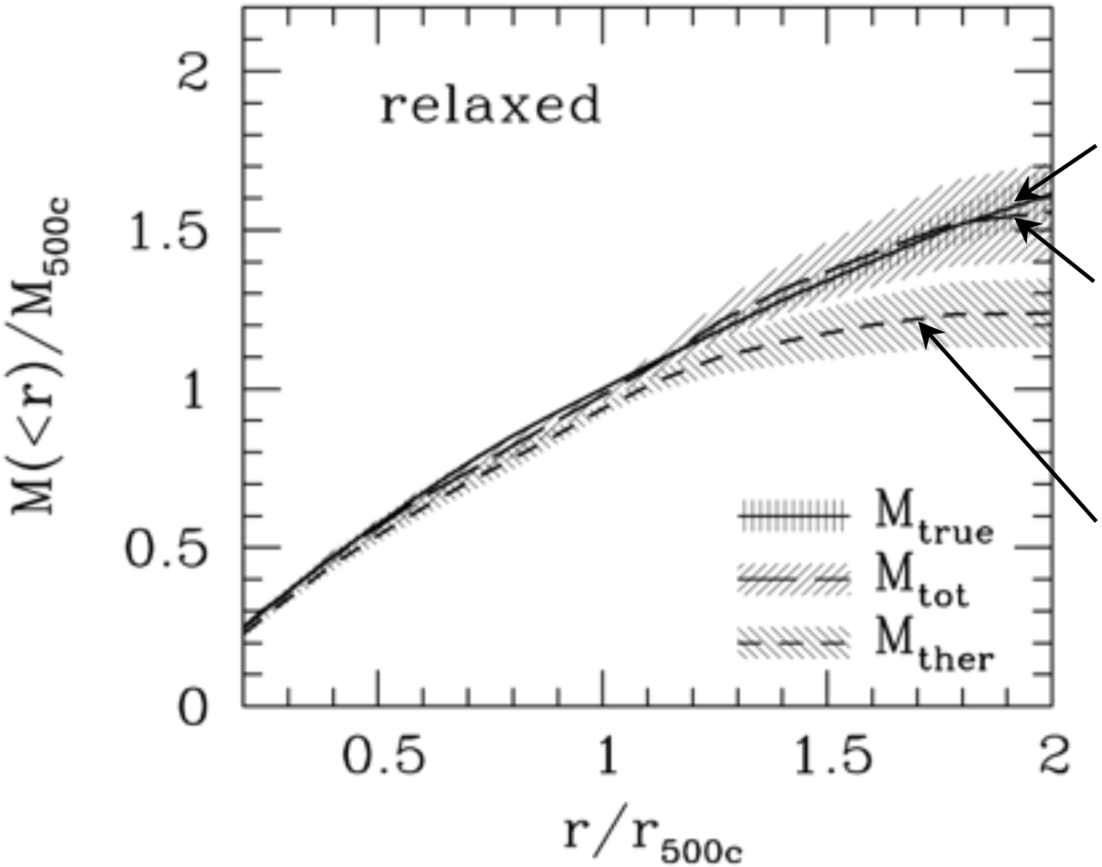


cluster-centric radius in units of r_{500c}

Lau, Kravtsov, Nagai 2009, ApJ, 705, 1129

Bias in the Hydrostatic Mass

$$M_{tot}(<r) = \frac{-r}{G\rho_{gas}}\left(\frac{dP_{therm}}{dr} + \frac{dP_{rand}}{dr}\right)$$



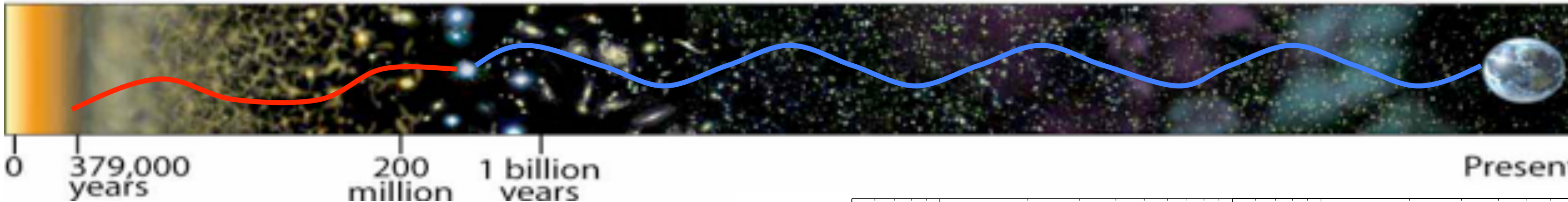
True mass profile in simulations

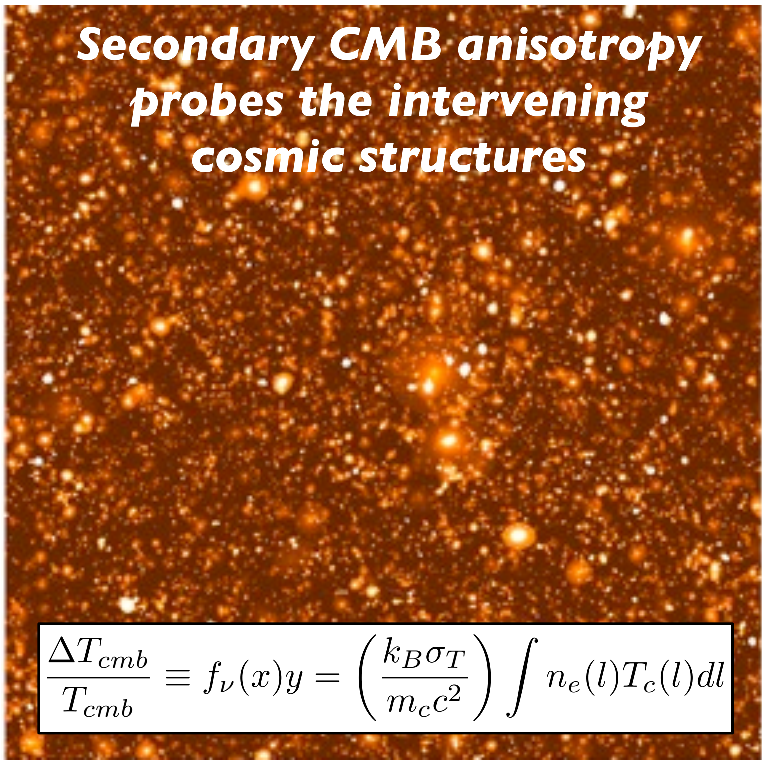
Mass profile from hydrostatic equilibrium taking into account turbulent pressure

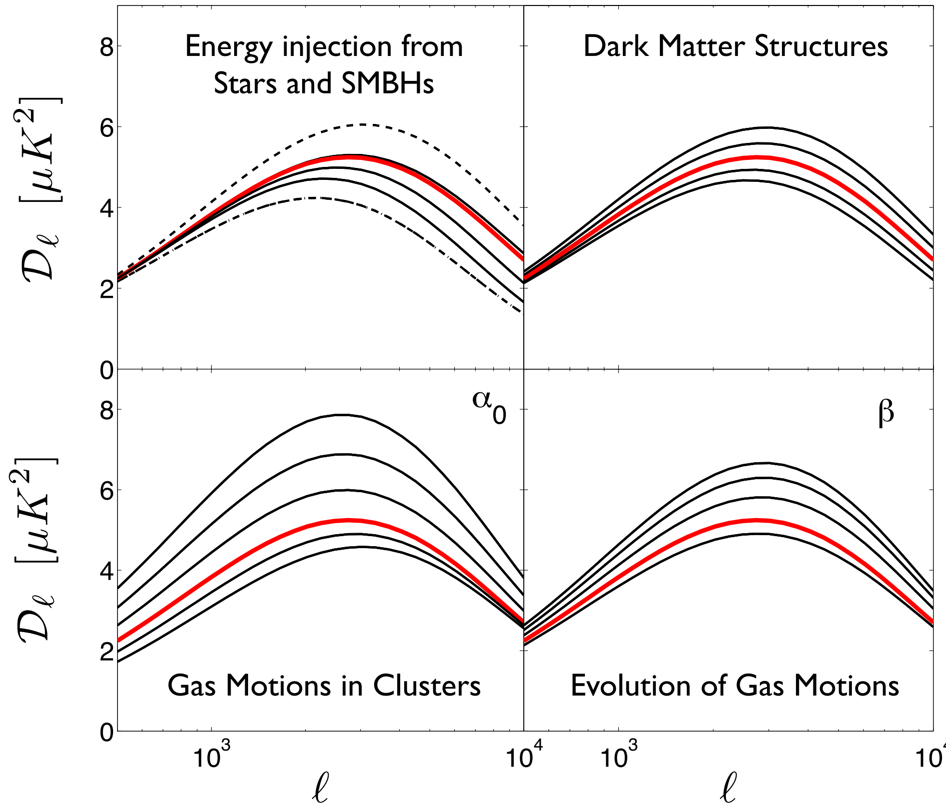
Mass profile from hydrostatic equilibrium neglecting turbulent pressure

Lau, Kravtsov, Nagai 2009, ApJ, 705, 1129

Astrophysical Uncertainty in SZ power spectrum



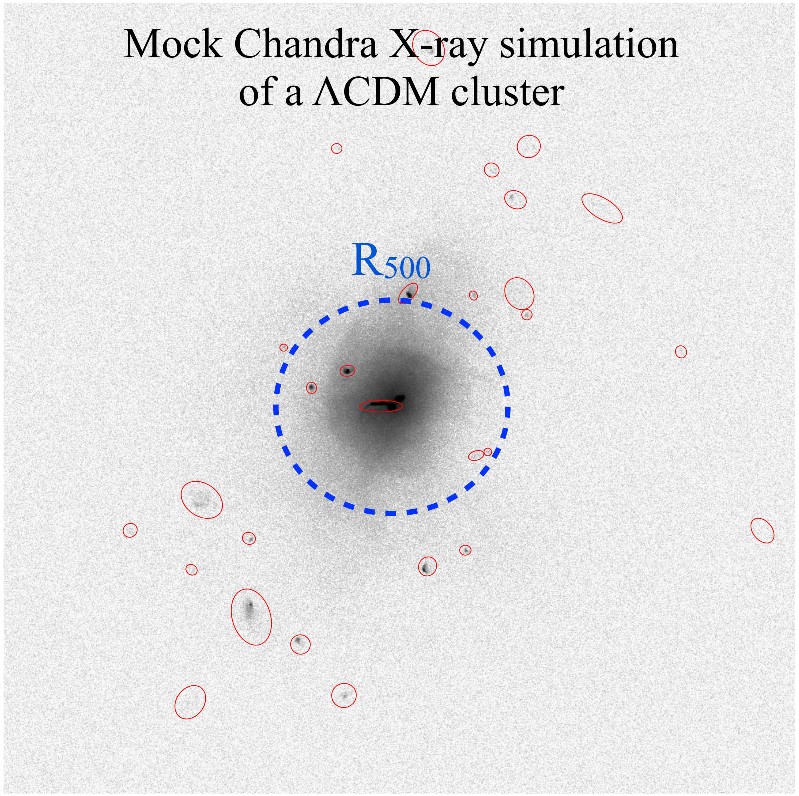


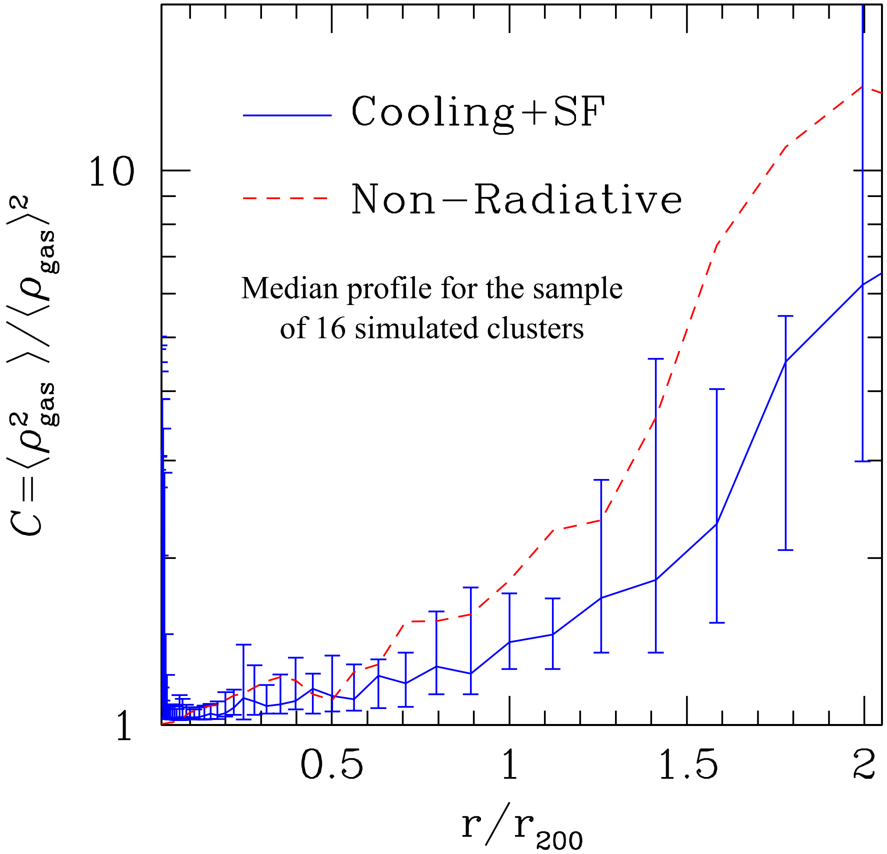


Non-thermal pressure due to gas motions is the dominant uncertainty for interpreting the recent SZ power spectrum measurements by ACT, Planck, and SPT.

L. Shaw, D. Nagai, S. Bhattacharya, E. Lau, 2010, ApJ, 725, 1452

Missing Cluster Astrophysics #2
Cluster outskirts are very clumpy

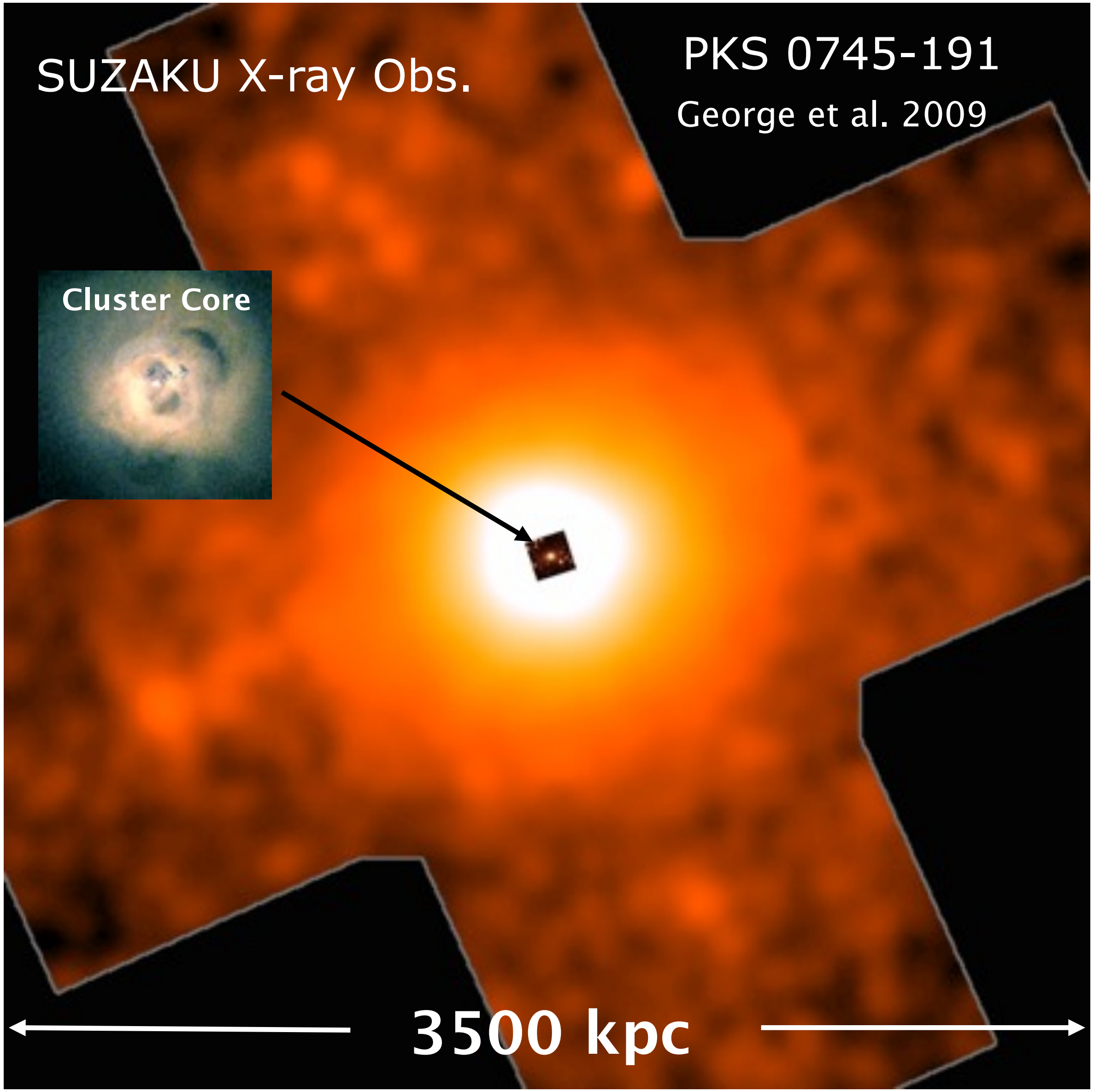




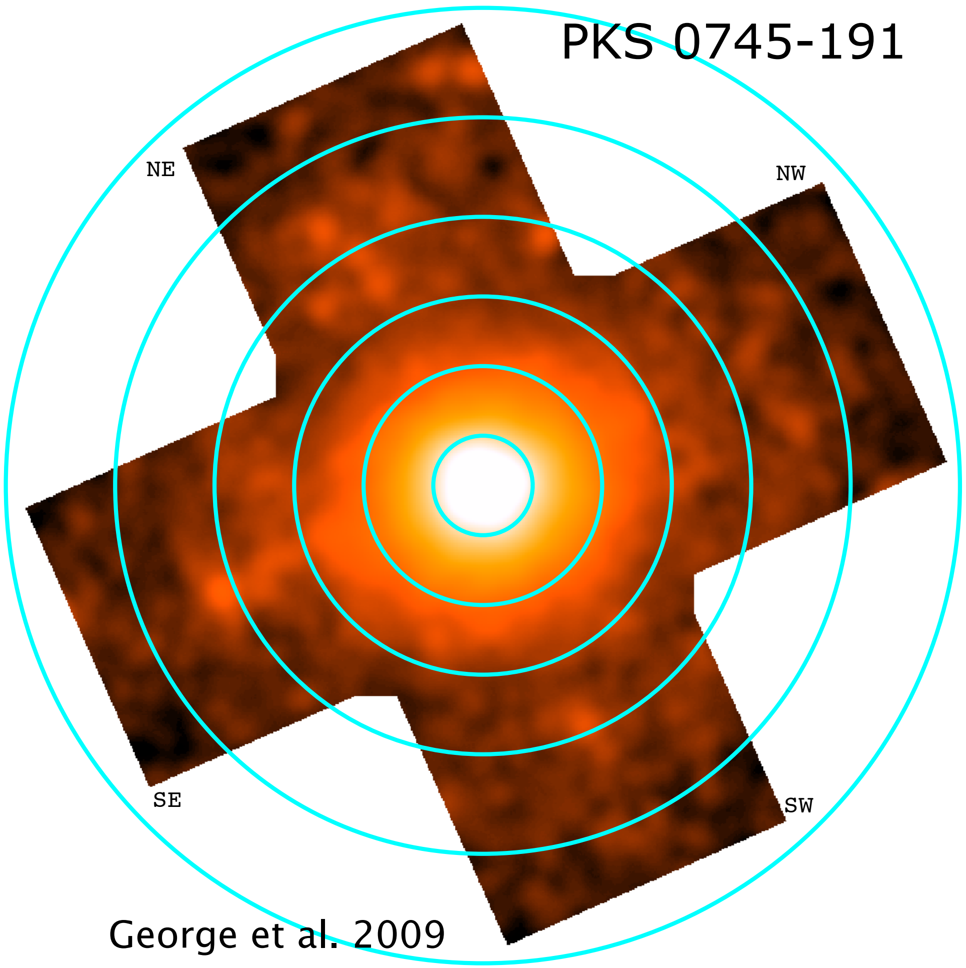
Hydrodynamical cluster simulations predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}$) arise from infalling groups from the filaments

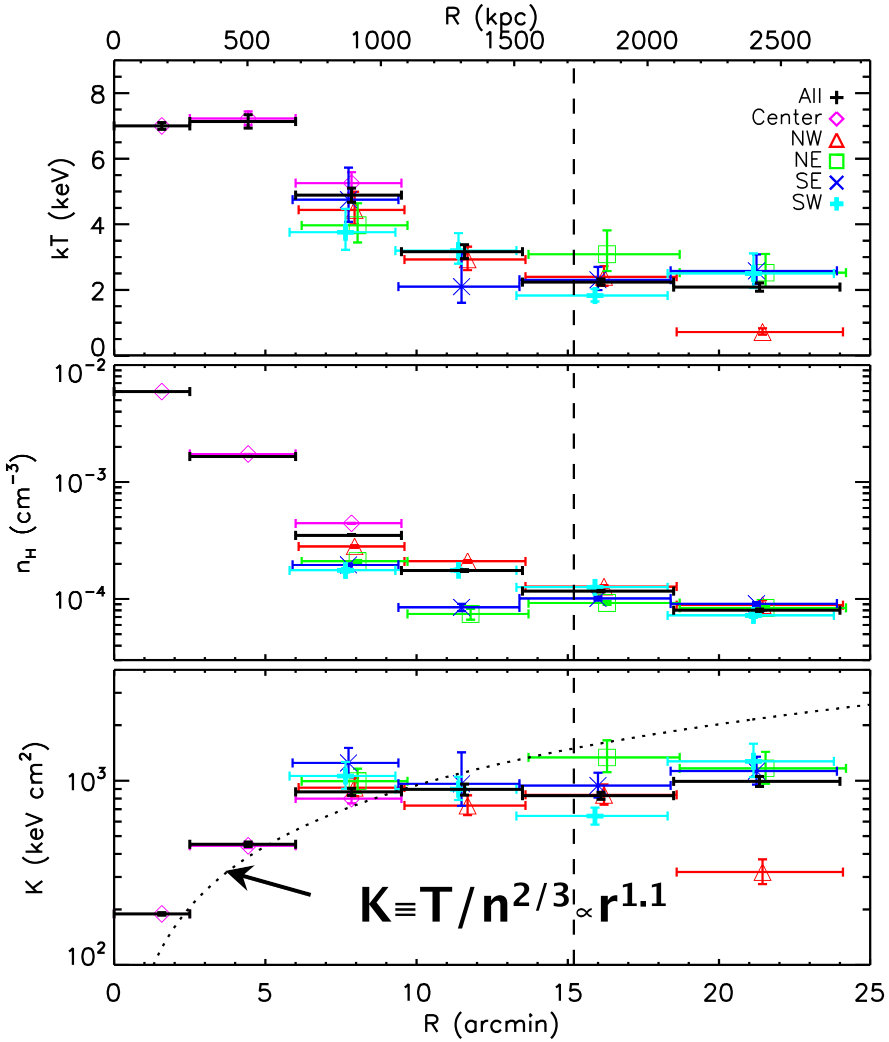
D. Nagai & E. Lau, 2011, ApJ, 731, 10 (astro-ph/1103.0280)

Suzaku X-ray measurements of cluster outskirts



Suzaku X-ray measurements of cluster outskirts

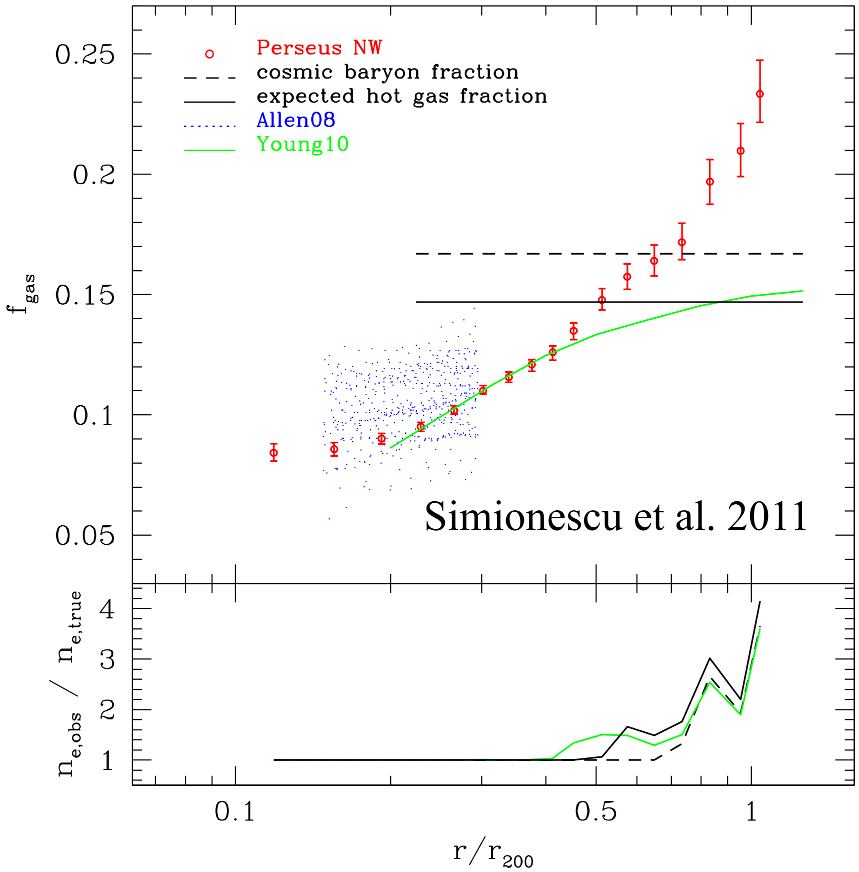


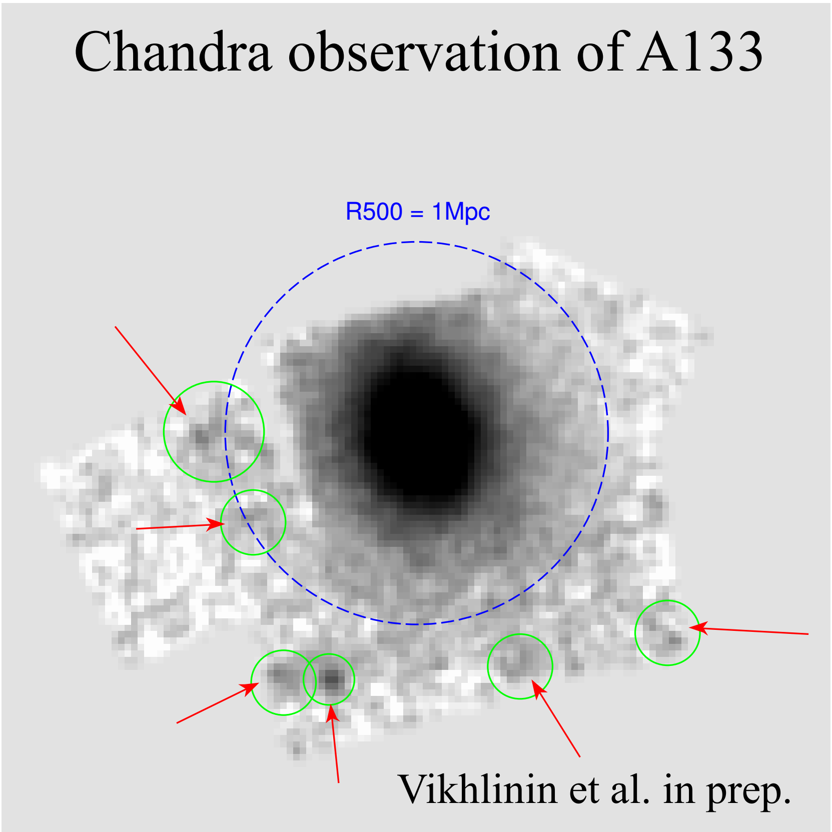


The observed entropy profile is inconsistent with the prediction of hydrodynamical cluster simulations.

Evidence for Gas Clumping in Cluster Outskirts

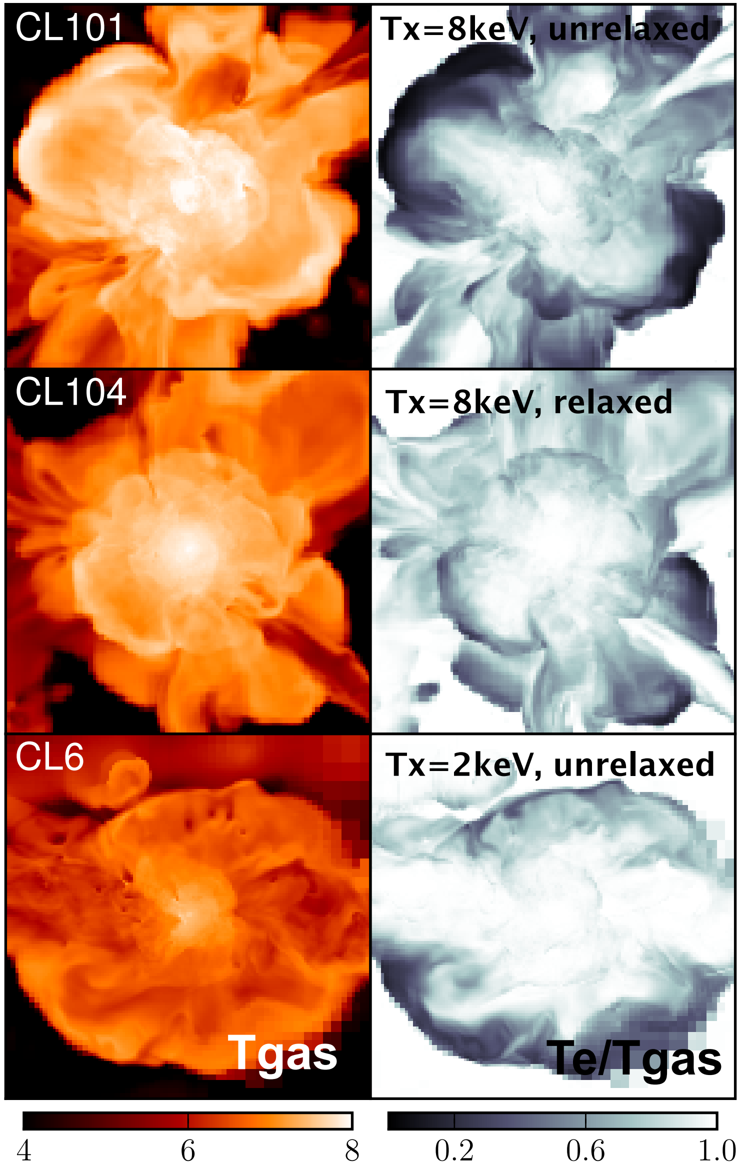
Suzaku observation of Perseus



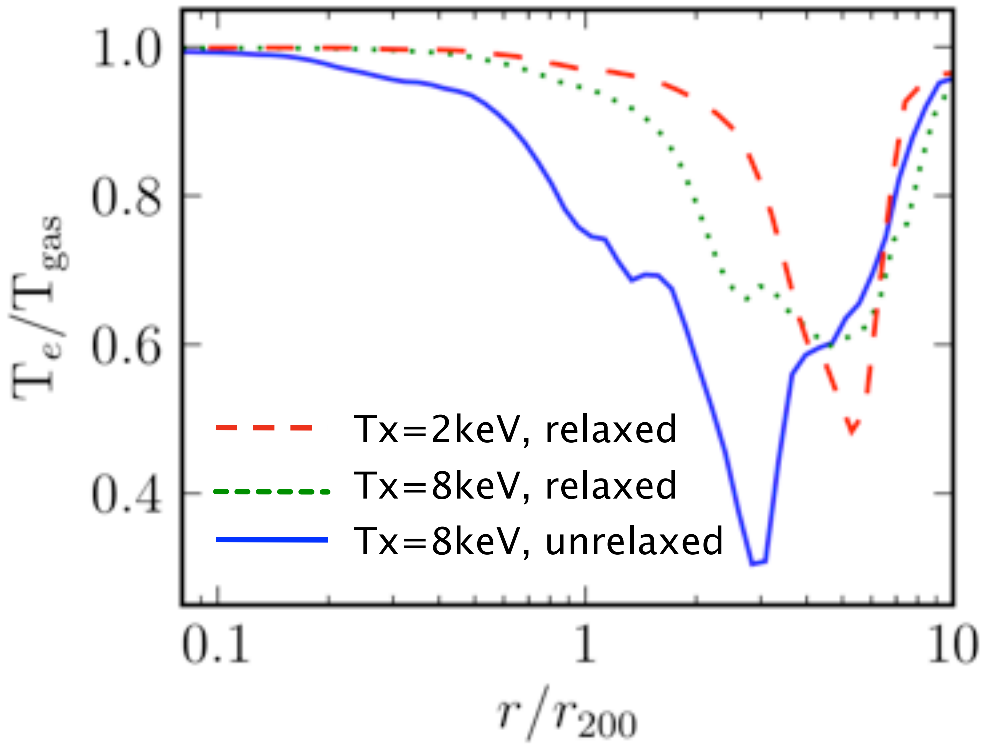


A transition of the smooth state in the virialized region to a clumpy intergalactic medium in the infall region outside of $r \approx R_{500}$

Missing Cluster Astrophysics #3
Non-equilibrium Electrons



Electron temperature is lower than gas (or ion) temperature in the outskirt of dynamically active clusters



Rudd & Nagai, 2009

Chuzhoy & Loeb 2004, Akahori & Yoshikawa 2010, Wong et al. 2010, also talk by Helen Russell

New Frontier: Exploration of the Virialization Regions of Galaxy Clusters

- **Cluster outskirt is a new territory for studying the physics of cluster formation**
  - ***Important for understanding thermodynamic and chemical evolution of clusters***
    - ★ *Cluster outskirts are turbulent and clumpy filled with non-equilibrium electrons*
  - ***Critical for cluster-based cosmological tests***
    - ★ *Calibration of observable-mass relations*
    - ★ *Interpretation of SZ power spectrum*

eROSITA (2013)