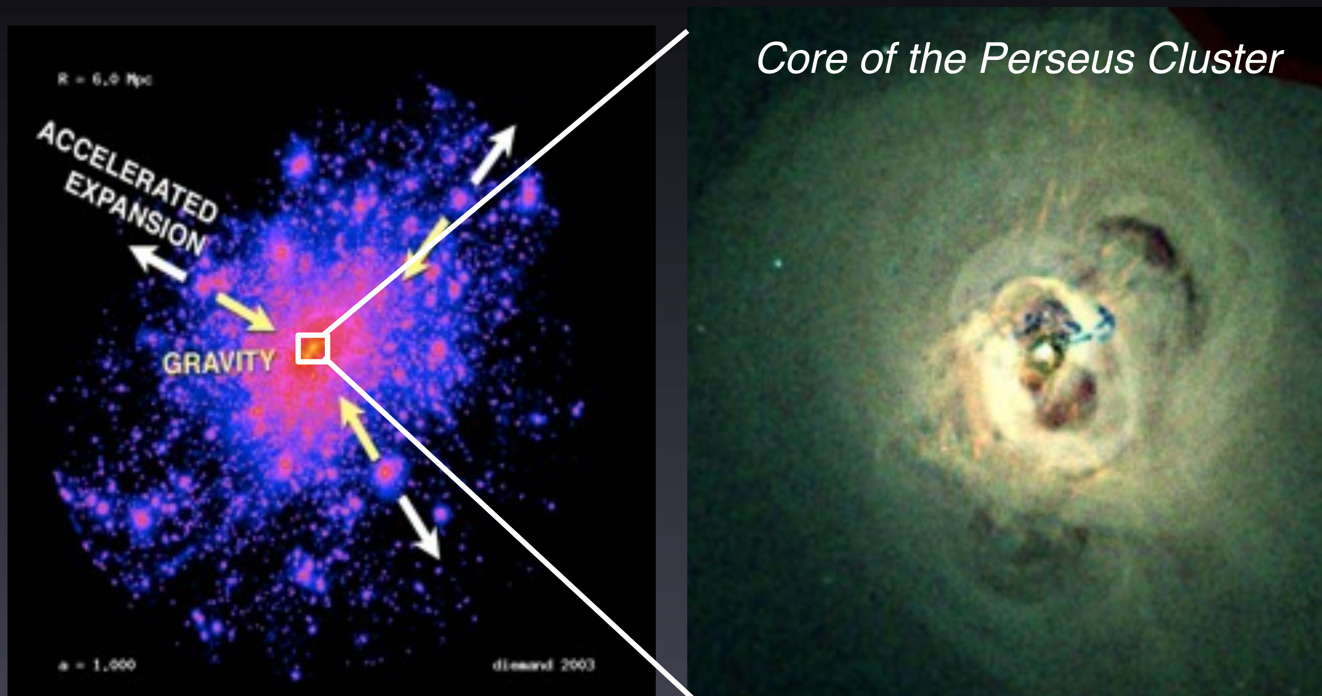
Non-equilibrium Phenomena in the Outskirts of Galaxy Clusters



Daisuke Nagai

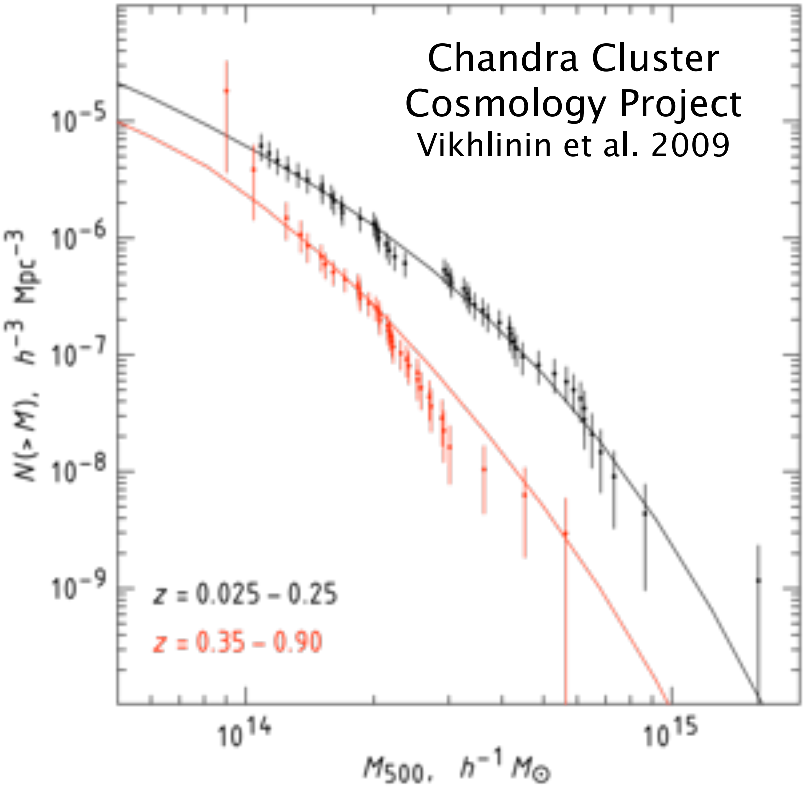
Yale University

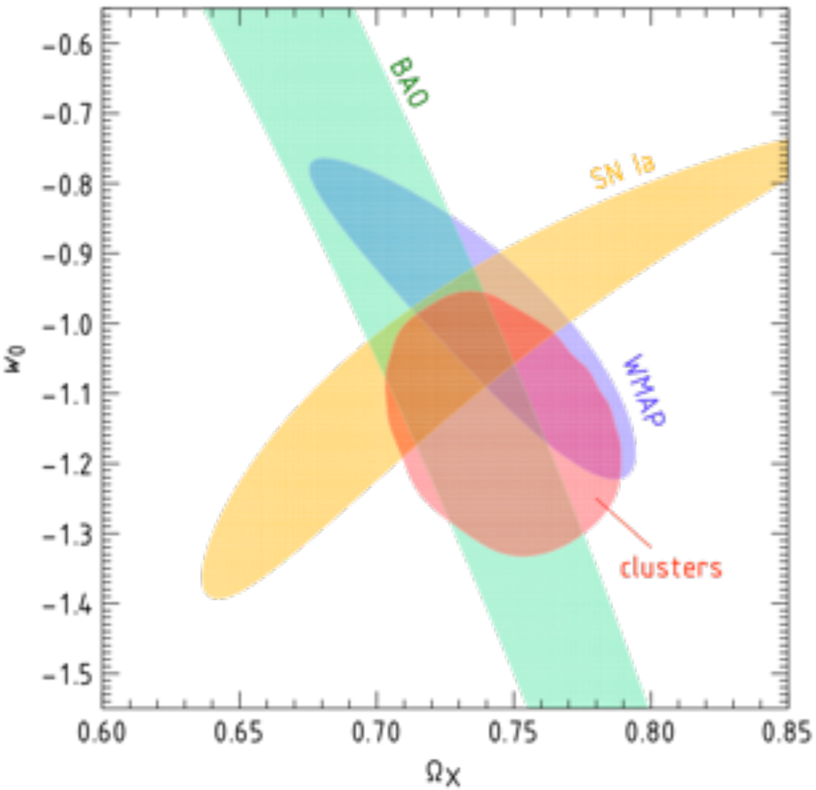
ICM workshop, Ann Arbor

August 31, 2012

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





$$\sigma_8 = 0.813(\Omega_M/0.25)^{-0.47} \pm 0.013(\text{stat}) \pm \mathbf{0.024(sys)}$$

$$w_0 = -0.991 \pm 0.045(\text{stat}) \pm \mathbf{0.039(sys)}$$

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

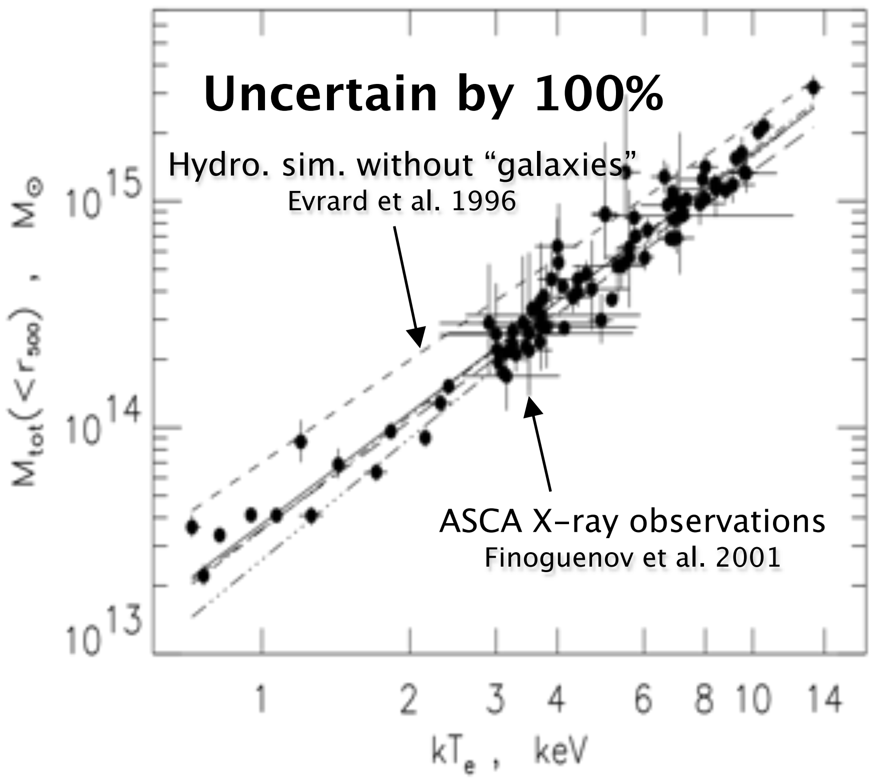
Systematics, Systematics, Systematics!!

Recent Advances and Future Challenges for Cluster Cosmology

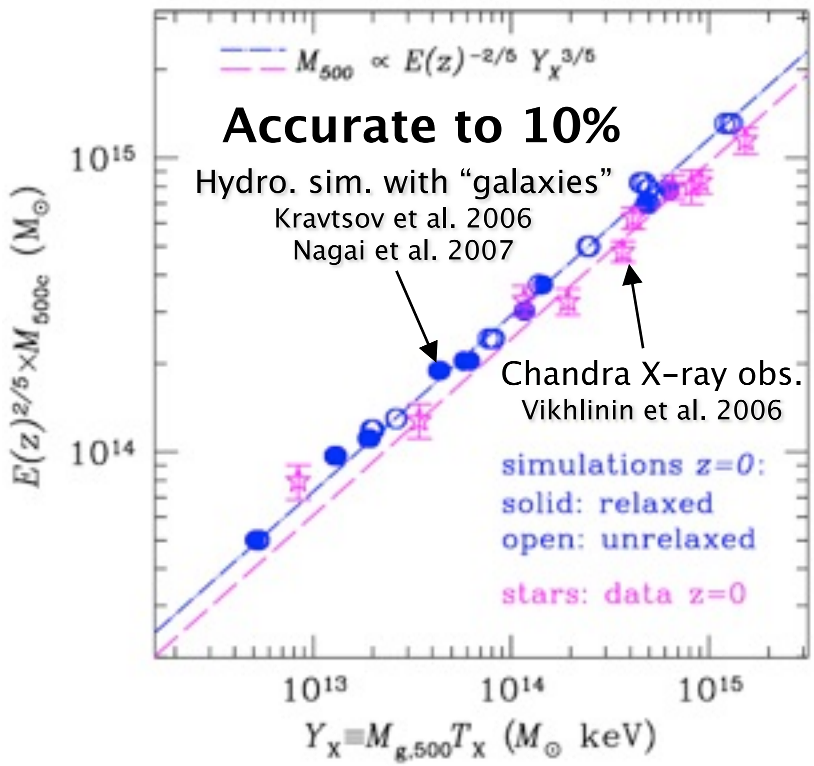
Dark Energy Task Force (2006)

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

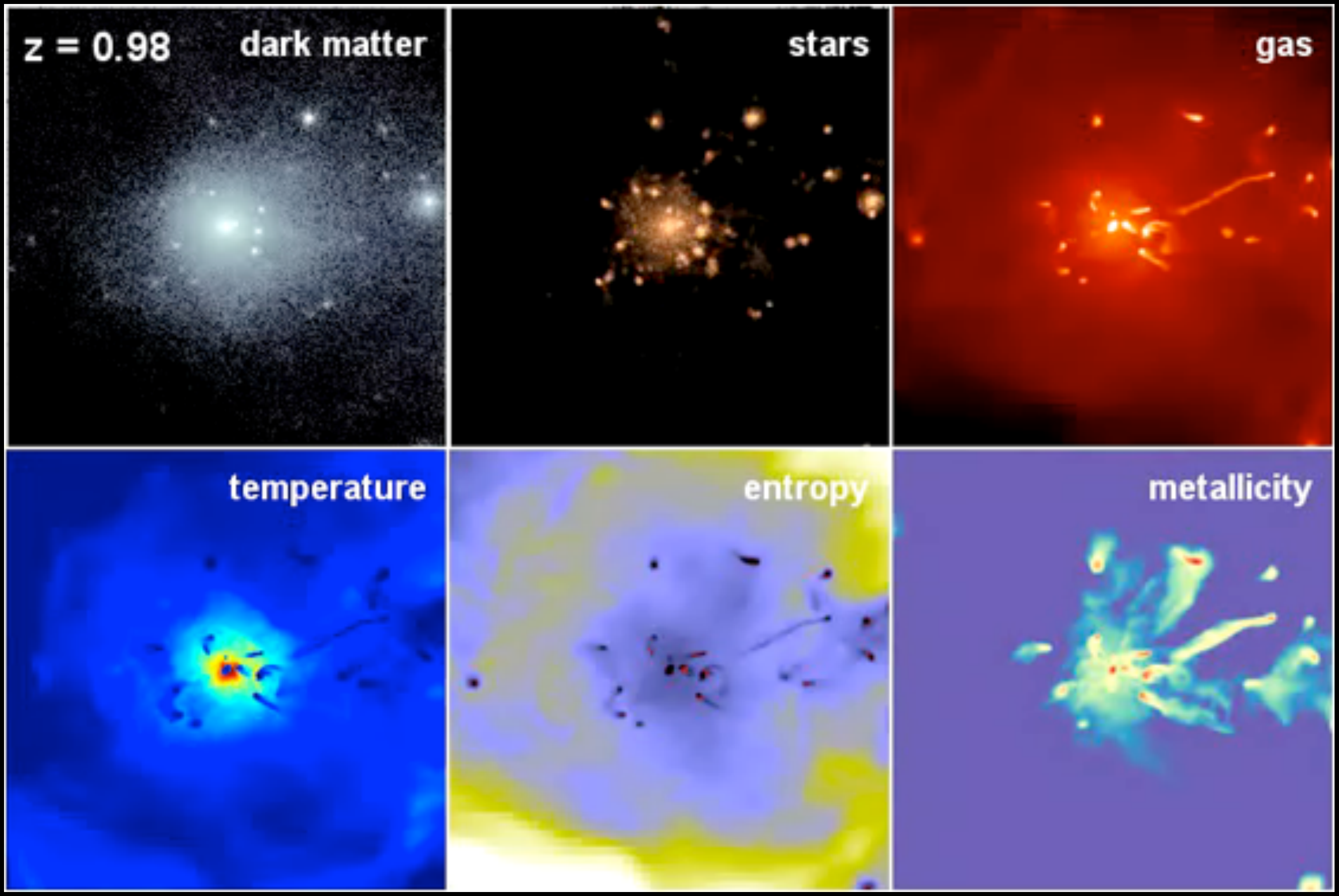


Now



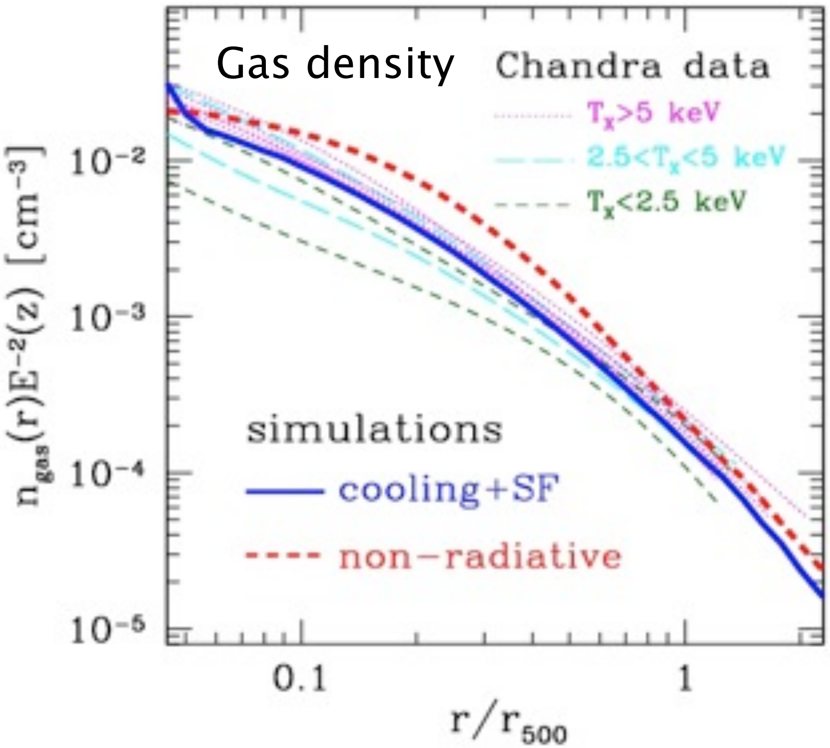
Simulations of Galaxy Cluster Formation

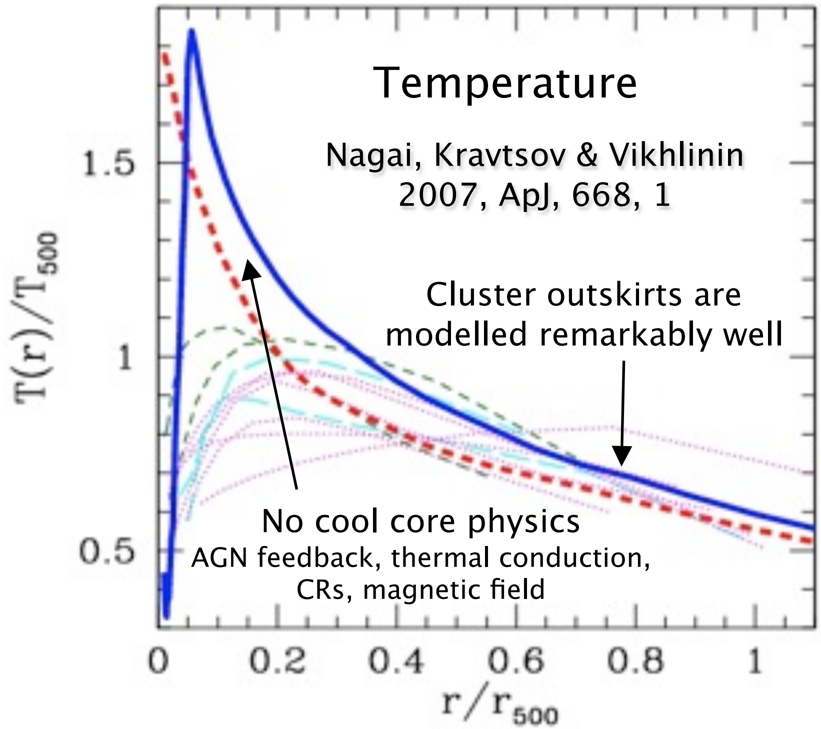
N-body+Gasdynamics with Adaptive Refinement Tree (ART) code
Region shown ~2/h Mpc; Spatial resolution ~ a few kpc



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!

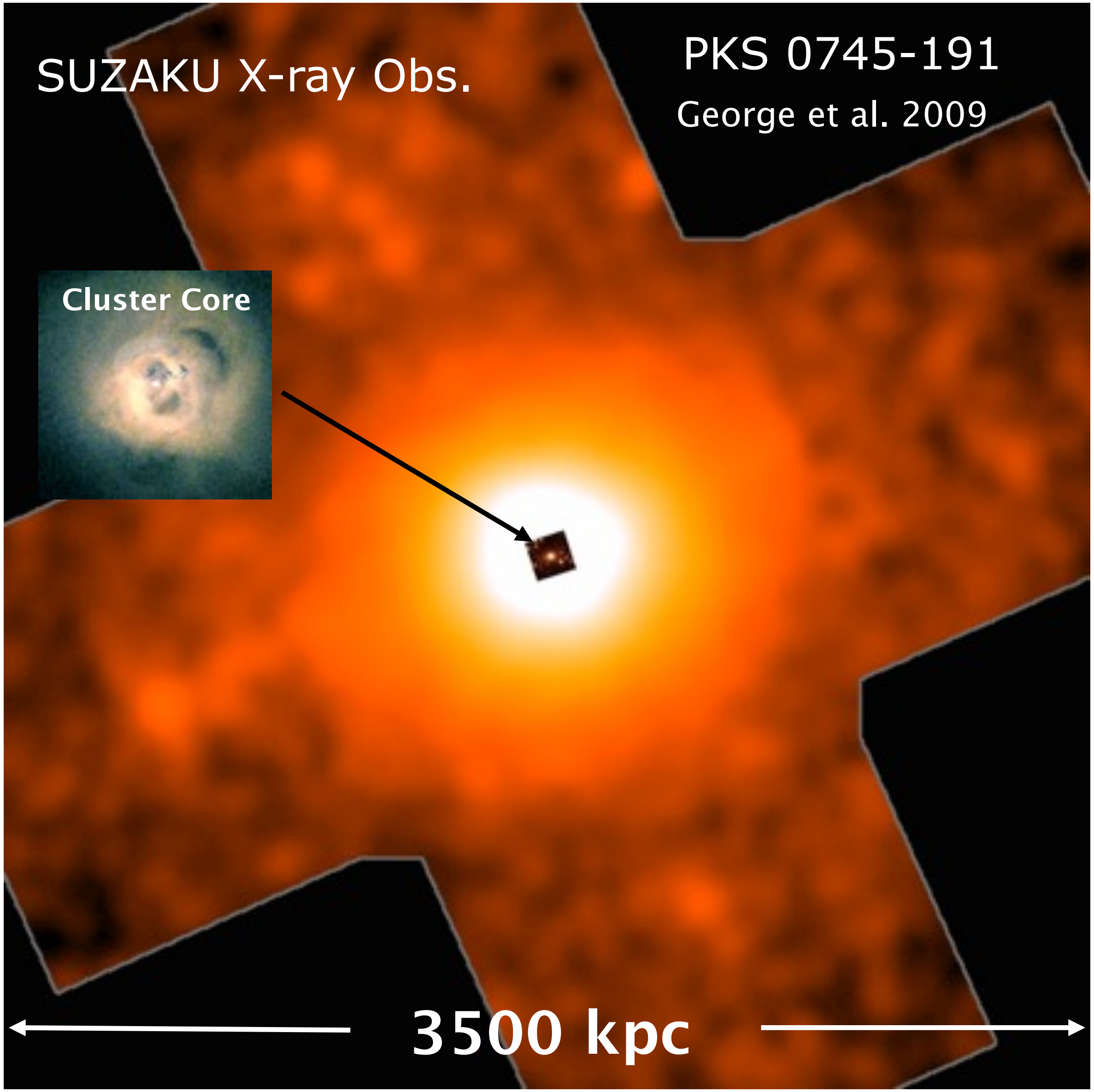
Radial profiles of X-ray emitting ICM
Simulations vs. Chandra X-ray Observations





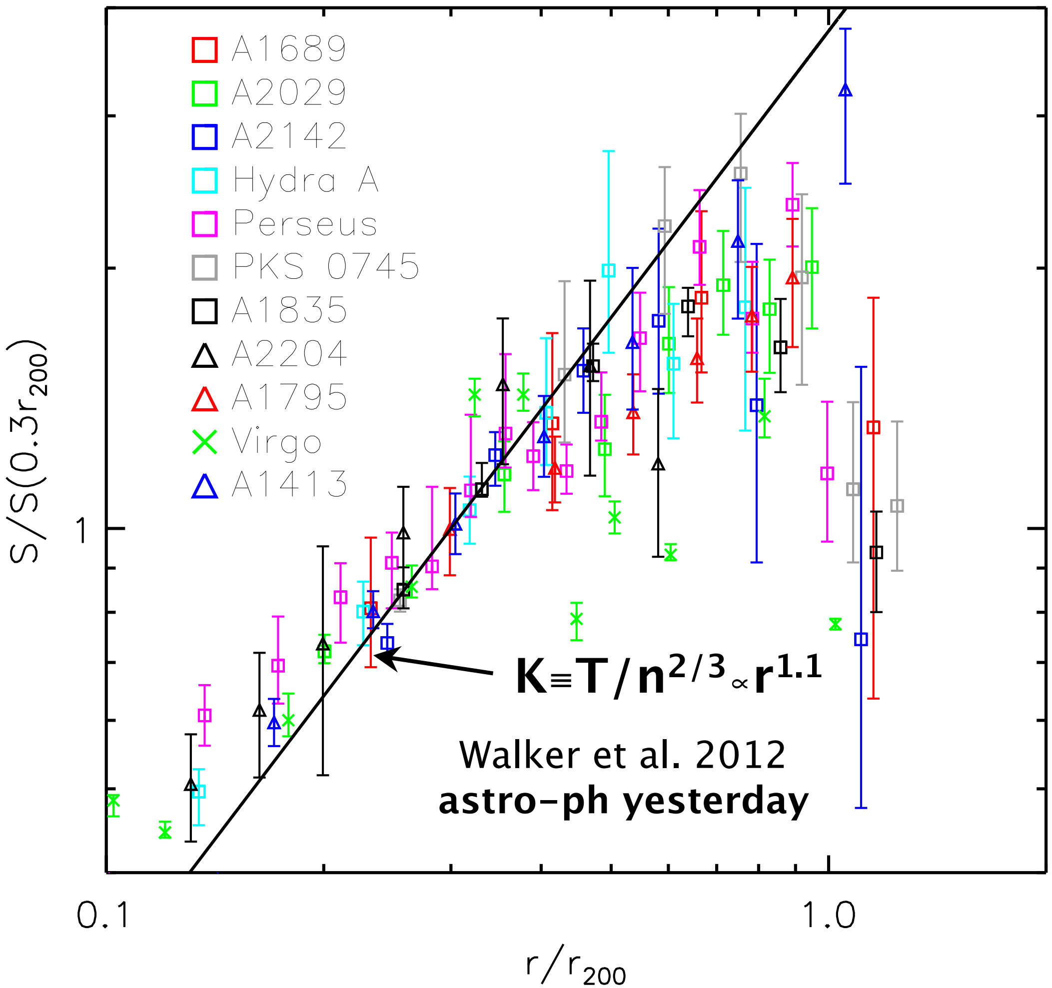
Modern hydrodynamical cluster simulations reproduce observed ICM profiles outside cluster cores ($0.15<r/r_{500}<1$).

Suzaku X-ray measurements of cluster outskirts



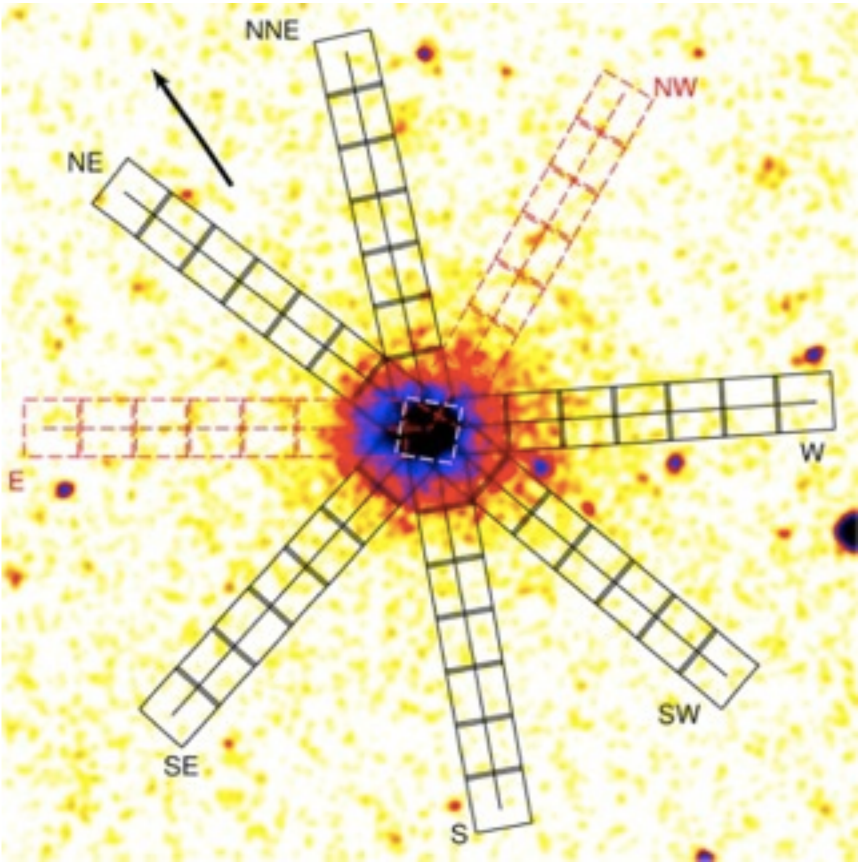
Entropy Profiles in Cluster Outskirts

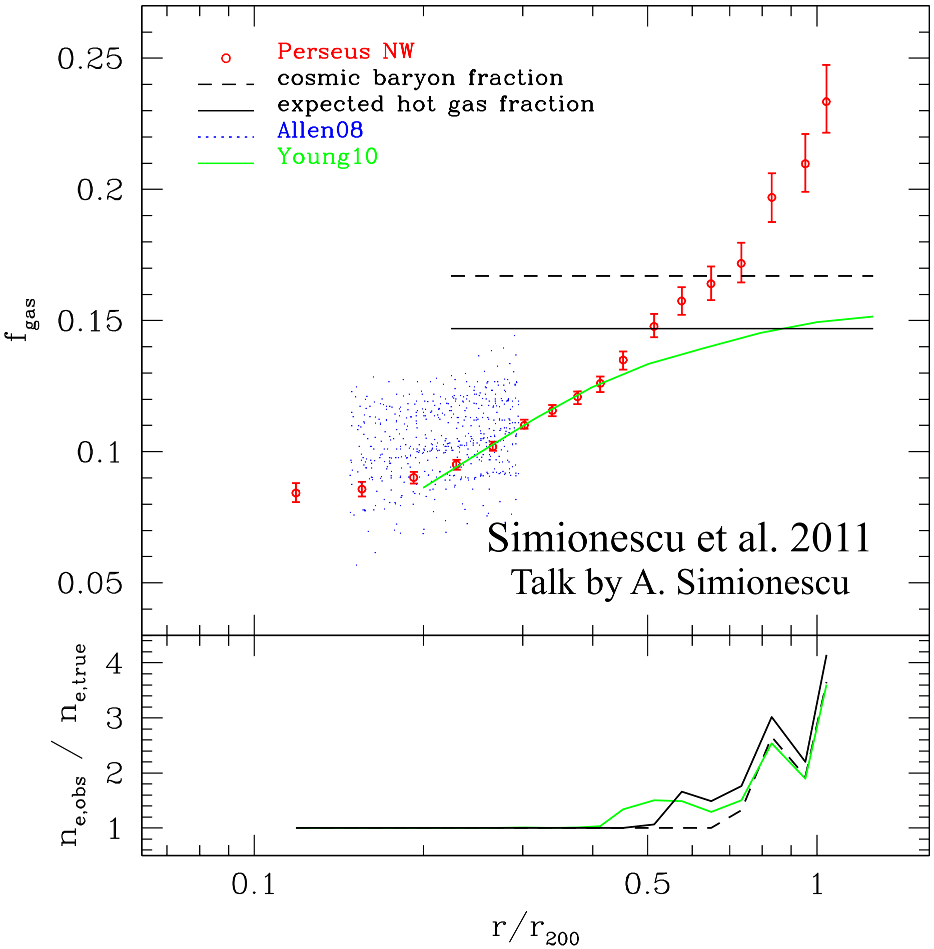
Sample of 11 relaxed clusters at z<0.25



The observed entropy profiles are inconsistent with the prediction of hydrodynamical cluster simulations.

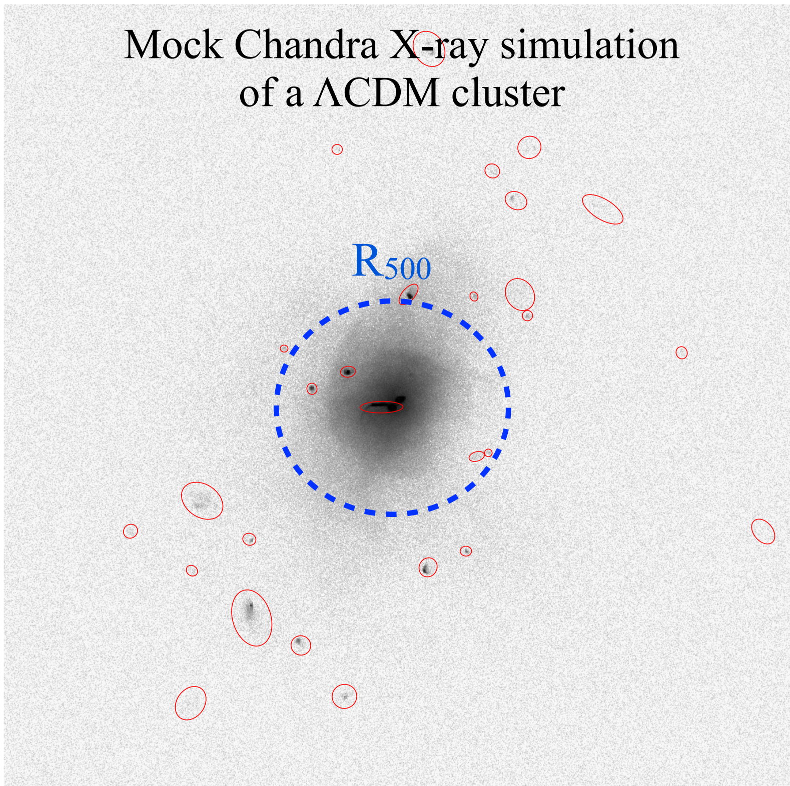
Suzaku Observations of Perseus

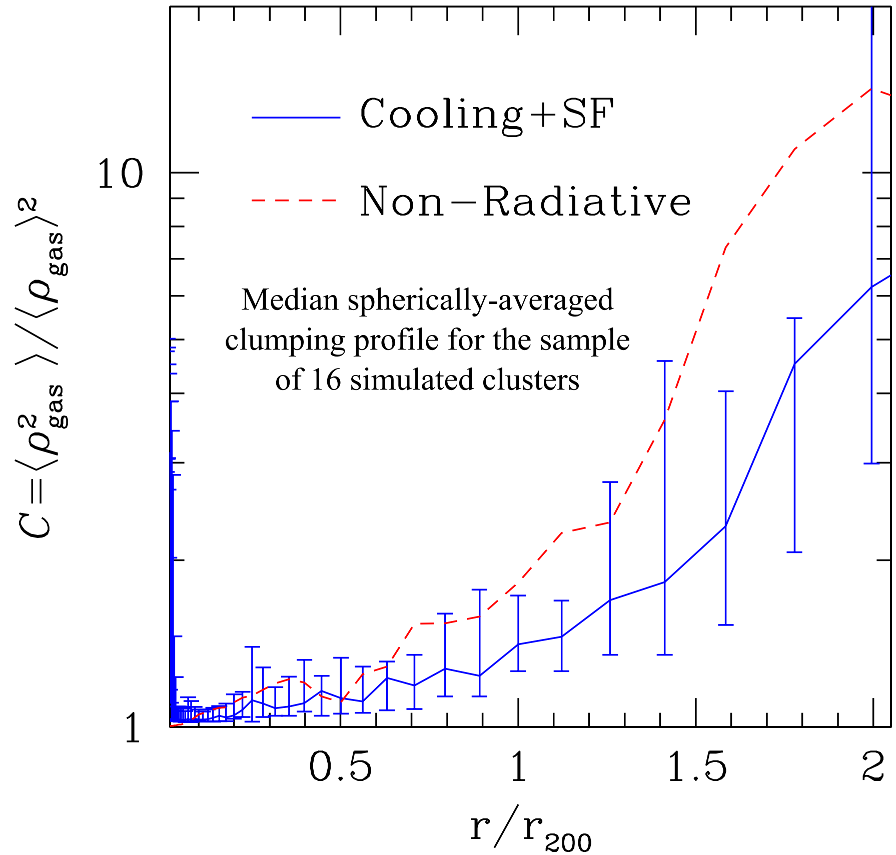




Observed gas density is overestimated by a factor of ~2.5-3 at r~R_{200}.
The mean X-ray surface brightness is enhanced by a factor of 5-9
(the square of the density overestimation).

Missing Cluster Astrophysics #1
Cluster outskirts are very clumpy

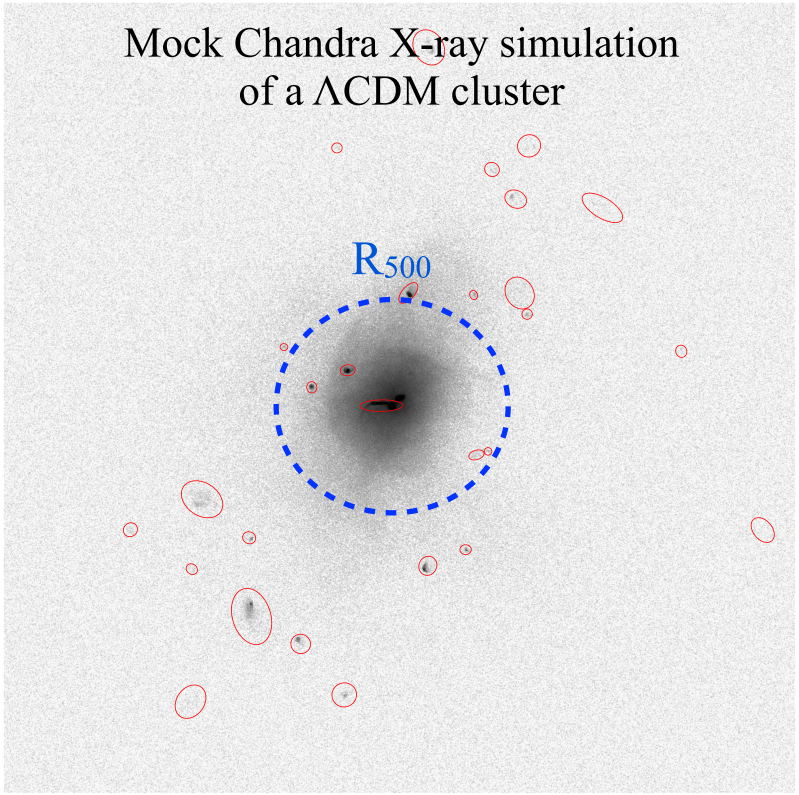


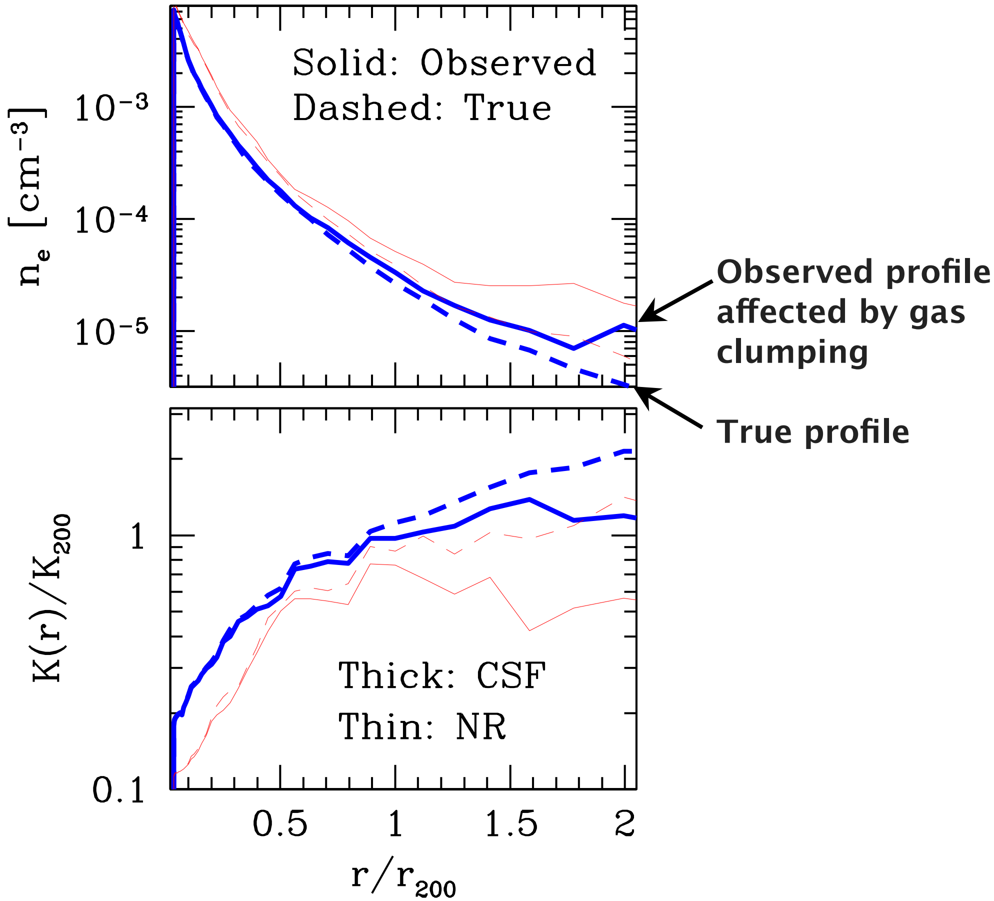


Hydrodynamical cluster simulations also predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}$) arise from small groups accreting along filaments

D. Nagai & E. Lau 2011 (astro-ph/1103.0280)

Missing Cluster Astrophysics #1
Cluster outskirts are very clumpy



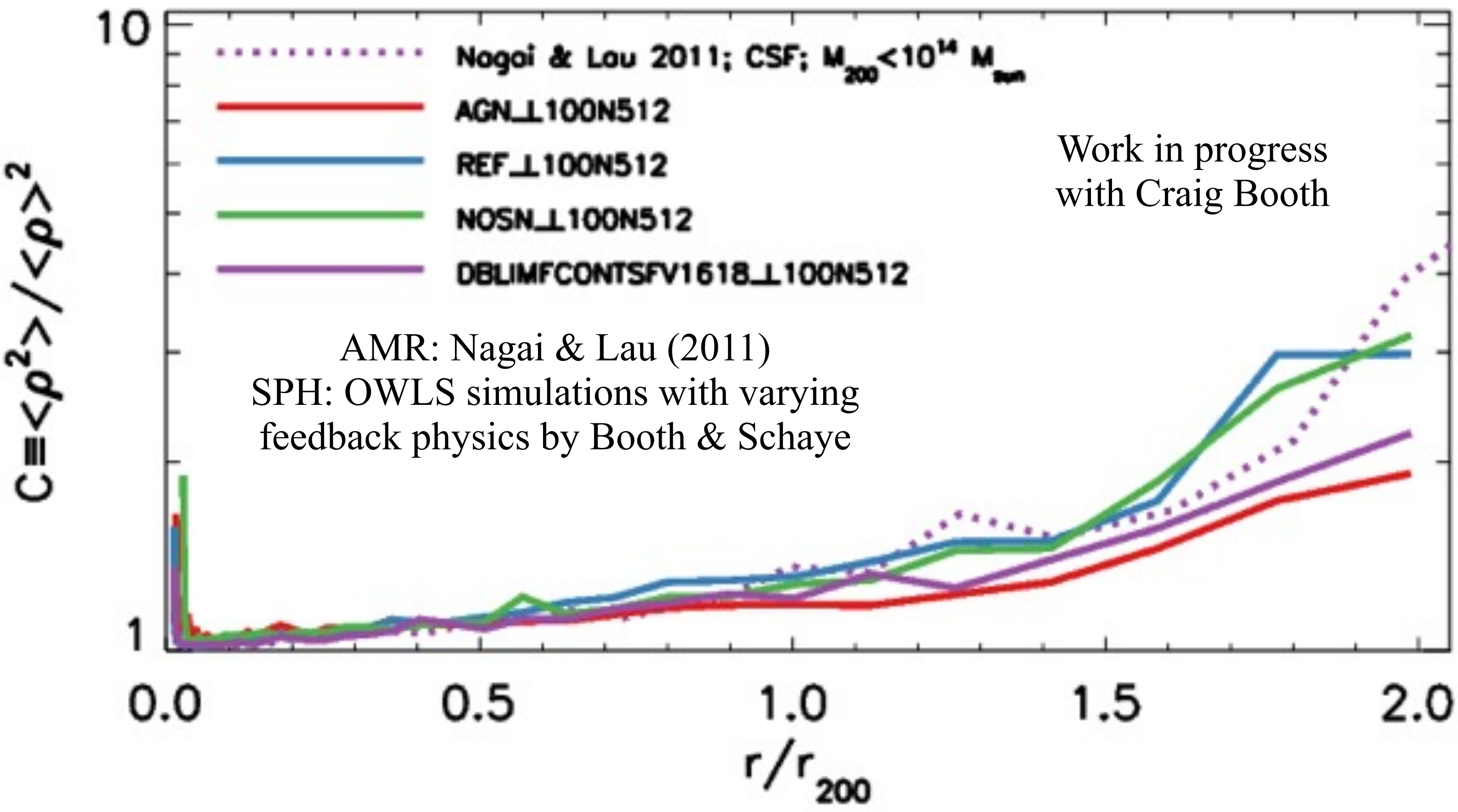


Hydrodynamical cluster simulations predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}$) arise from infalling groups from the filaments

D. Nagai & E. Lau 2011 (astro-ph/1103.0280)

Effect of Feedback on Gas Clumping

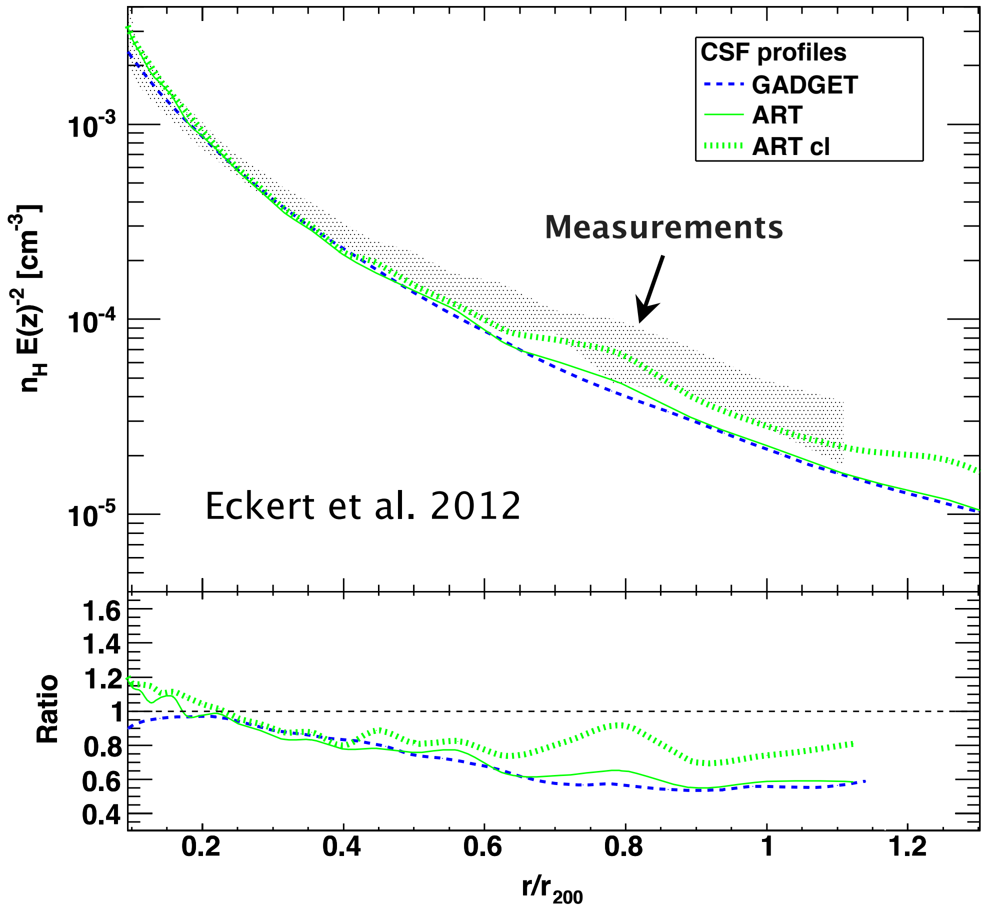
AMR+SPH simulation comparison



Feedback suppresses gas clumping somewhat,
but does not erase gas clumps entirely.

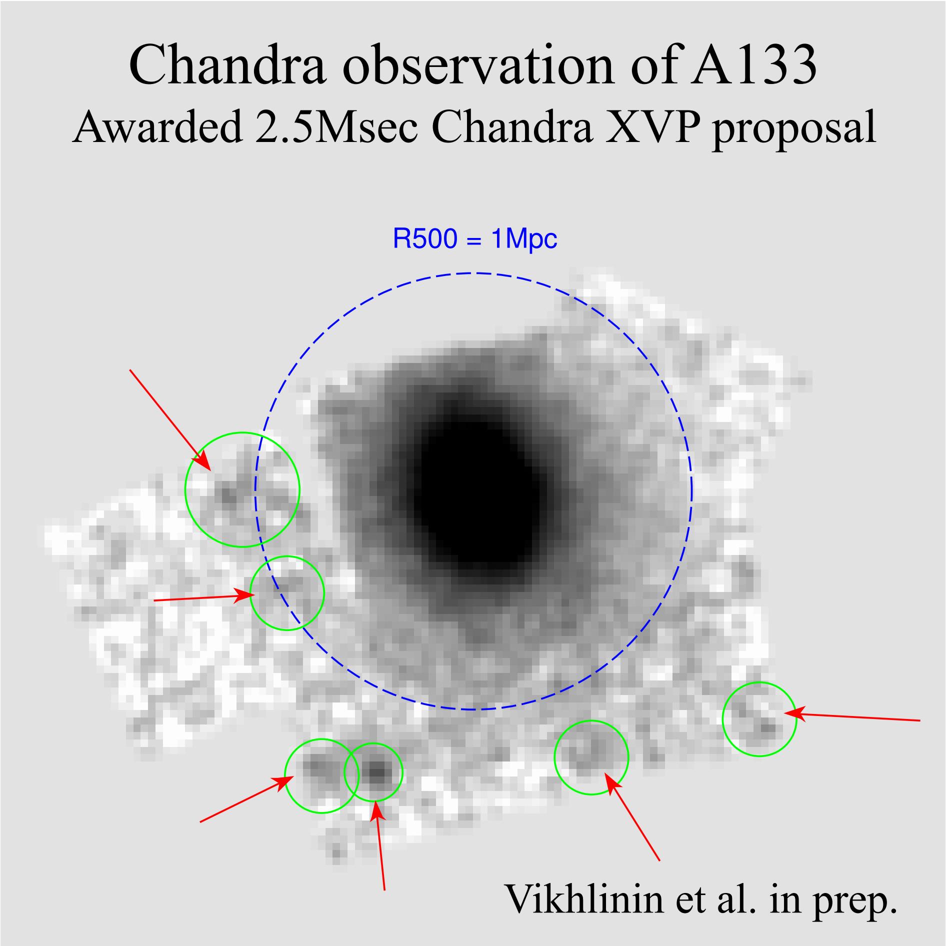
ROSAT Measurements of Cluster Outskirts

X-ray stacking analysis of 31 massive galaxy clusters



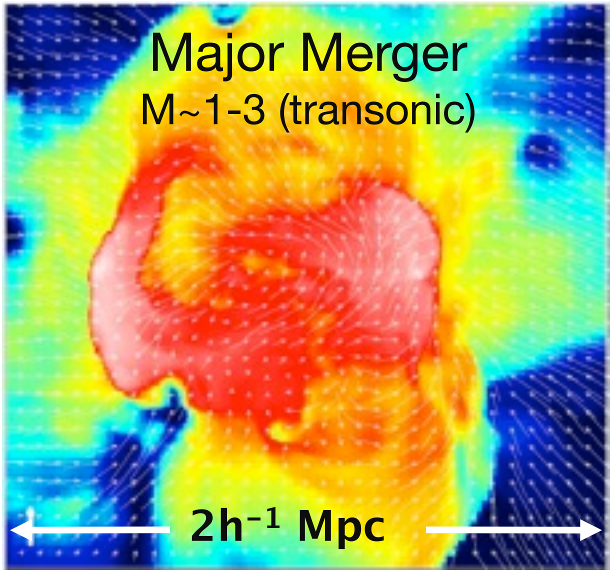
Simulations under-predict the observed gas density in cluster outskirts.
Gas clumping can help explain the observed gas distribution.

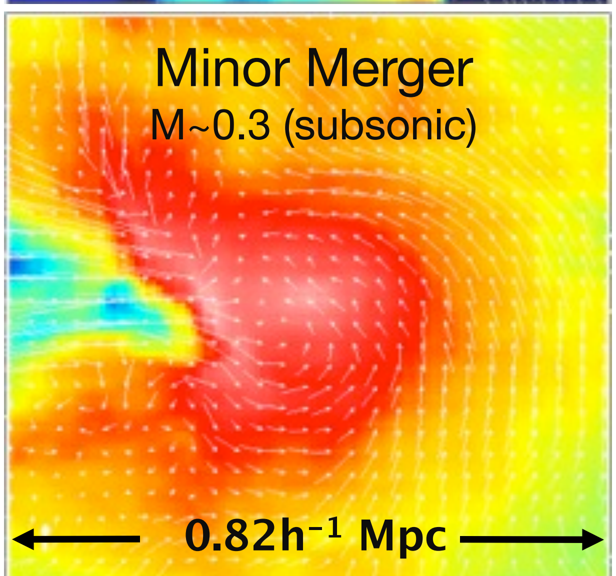
Evidence for Gas Clumping in Cluster Outskirts



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 #2
Gas Motions in Clusters

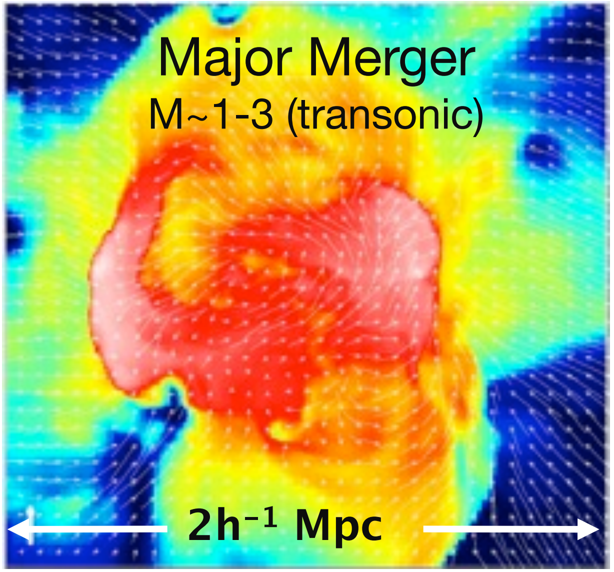


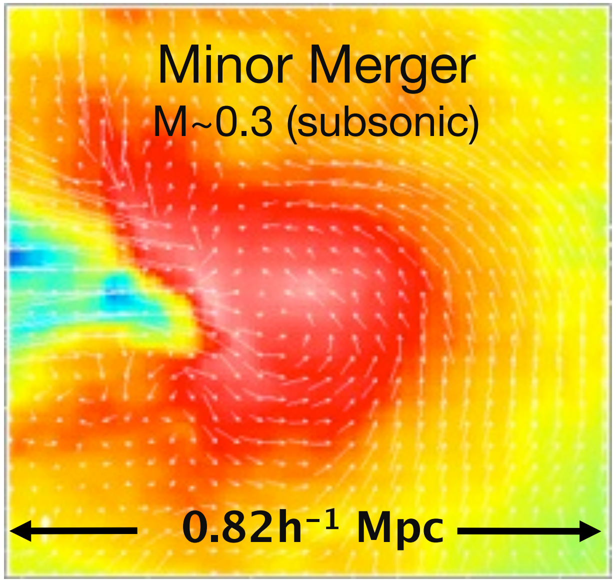


- Gas (bulk+turbulent) motions are predicted to be ubiquitous in the ICM
- Drivers of gas motions
  - Accretion/Mergers (on large scales)
  - Energy injection from SNe/AGN (in cluster cores)
  - Plasma Instabilities
- Implications
  - Hydrostatic mass modeling
  - X-ray/SZE observable-mass relations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

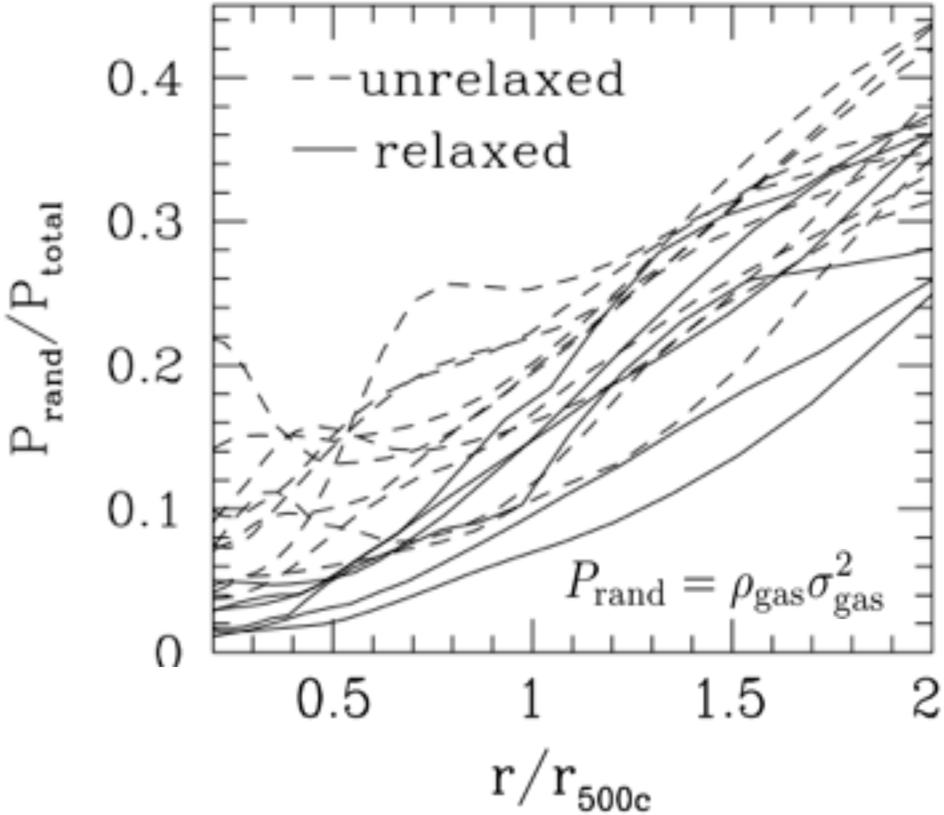
Observationally, we know very little about the nature of gas motions in clusters!!

Missing Cluster Astrophysics #2
Gas Motions in Clusters





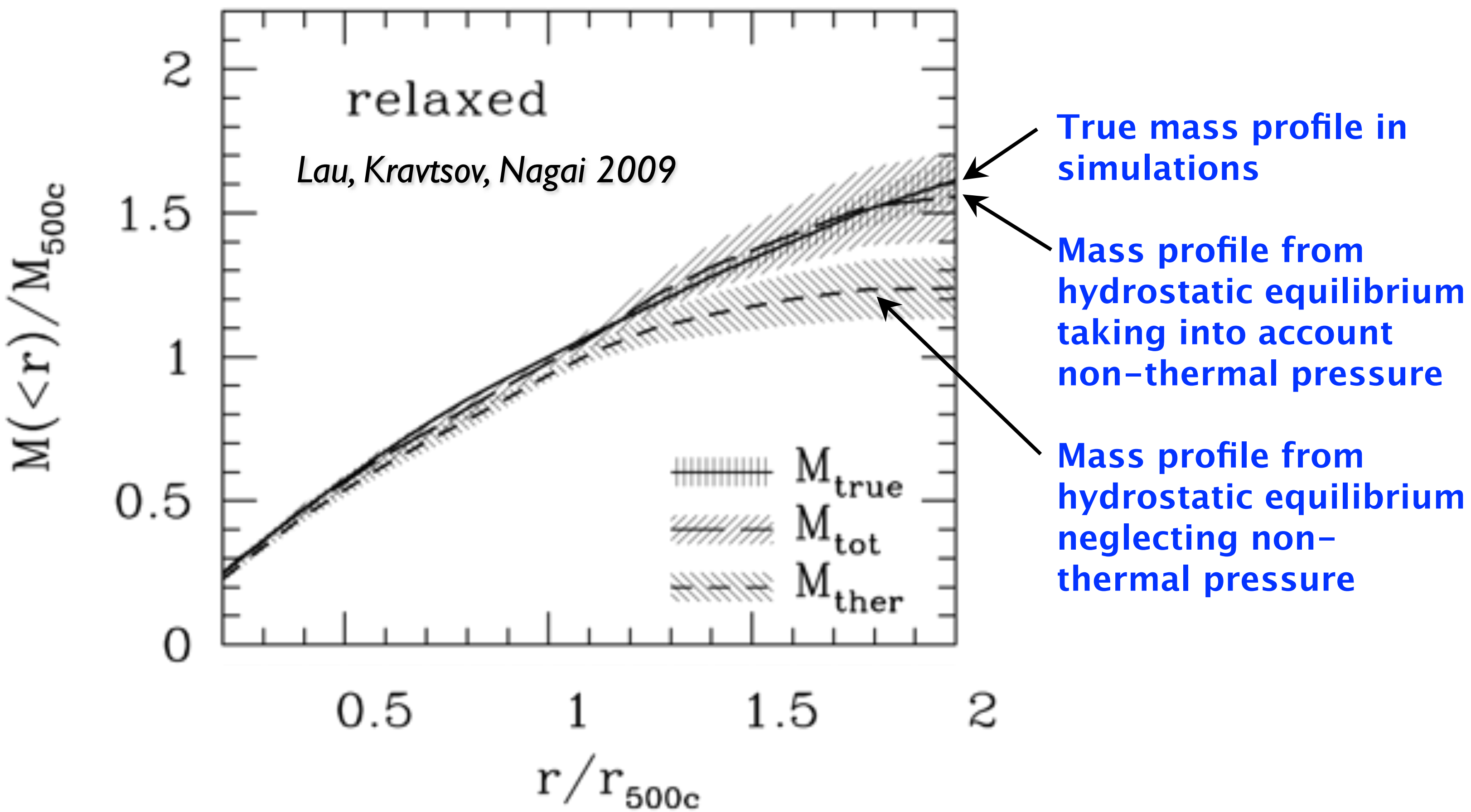
Hydrodynamical simulations predict the ratio of kinetic energy in turbulent gas motions to thermal energy content of galaxy clusters in ΛCDM models



Lau, Kravtsov, Nagai 2009
Also Dolag+05, Vazza+09, Battaglia+11, Nelson+12

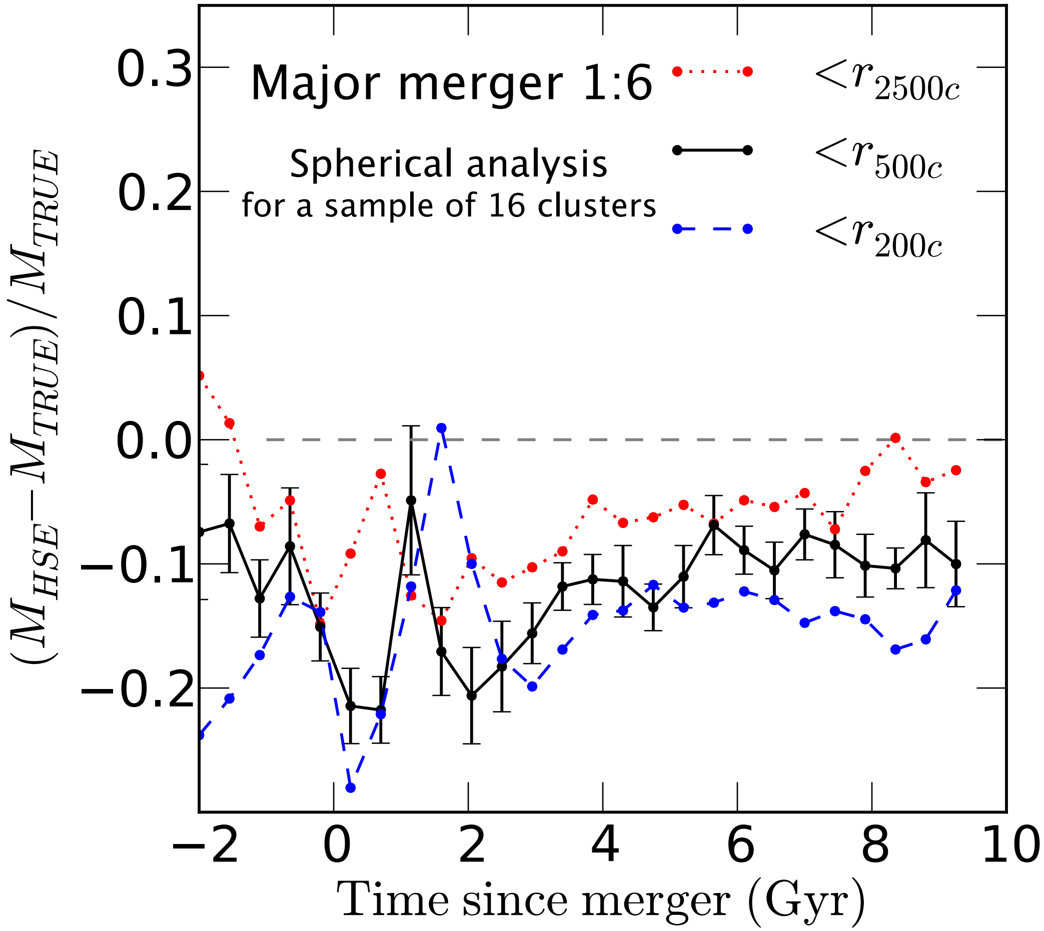
Turbulent Gas Flow is a dominant source of systematic bias in X-ray cluster mass estimates

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



Non-thermal pressure due to turbulent gas flows introduces bias in the hydrostatic cluster mass estimate at a level of 10% at R_{500}

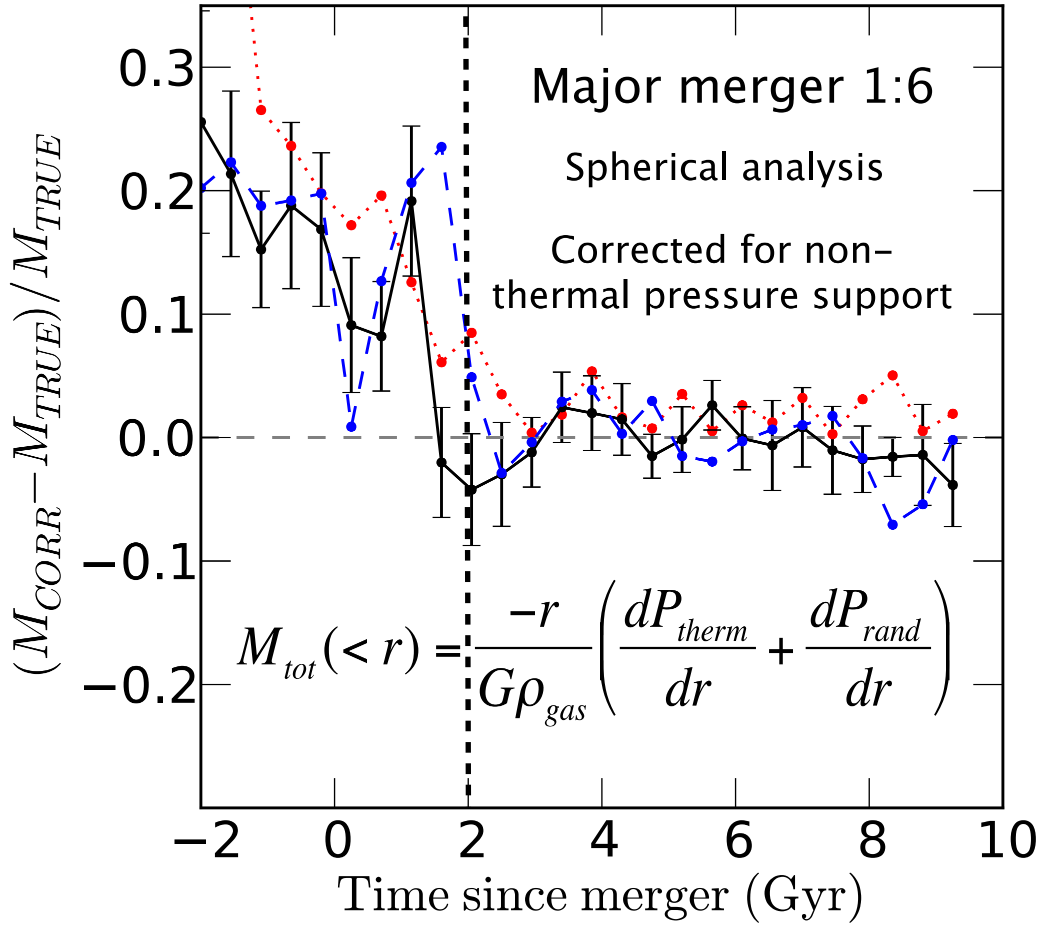
Evolution of the Hydrostatic Mass Bias



The HSE mass bias is larger in cluster outskirts. Major mergers are catastrophic events, but minor mergers are also important.

Nelson, Rudd, Shaw, & Nagai, 2012, ApJ, 751, 121

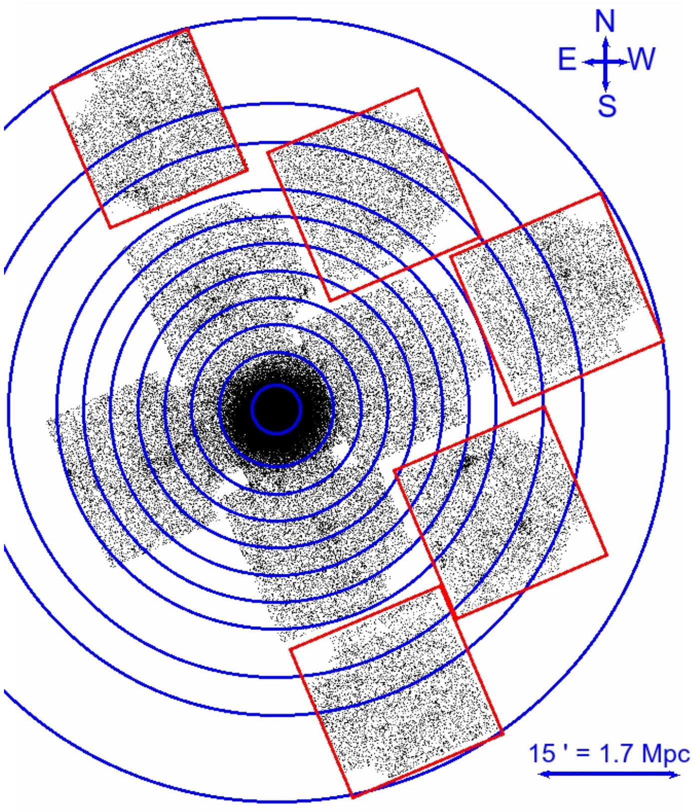
Evolution of the Hydrostatic Mass Bias



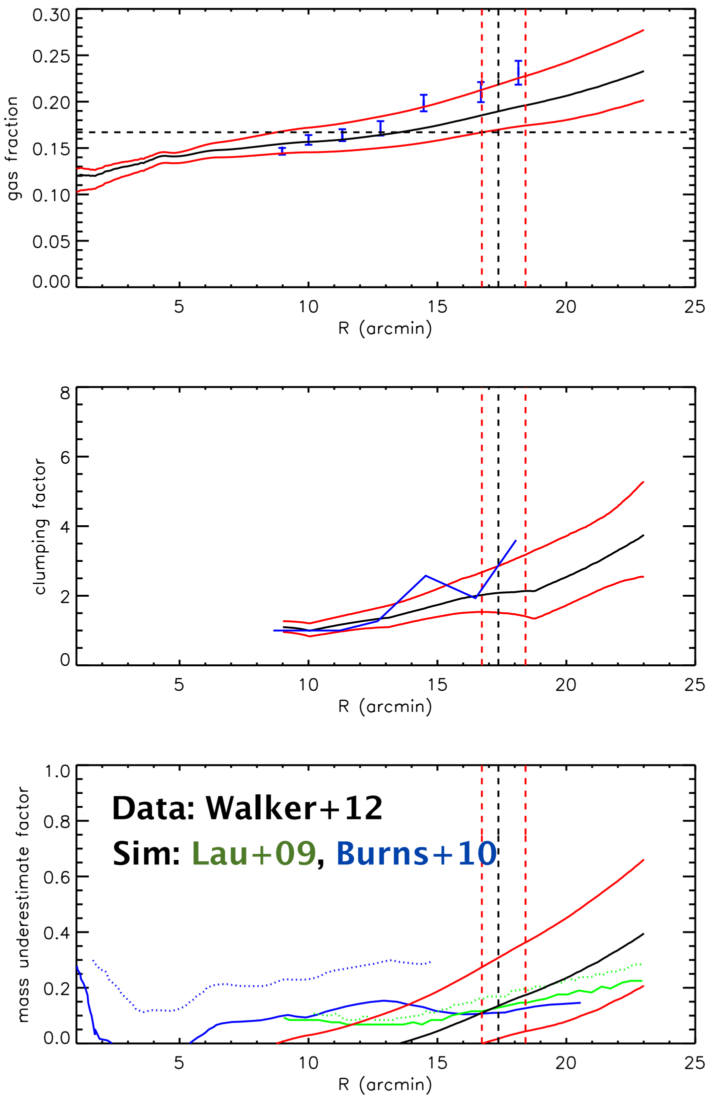
Hydrostatic mass bias is correctable in principles..
Care needed for systems undergoing major mergers.

Nelson, Rudd, Shaw, & Nagai, 2012, ApJ, 751, 121

Suzaku Observations of PKS 0745-191

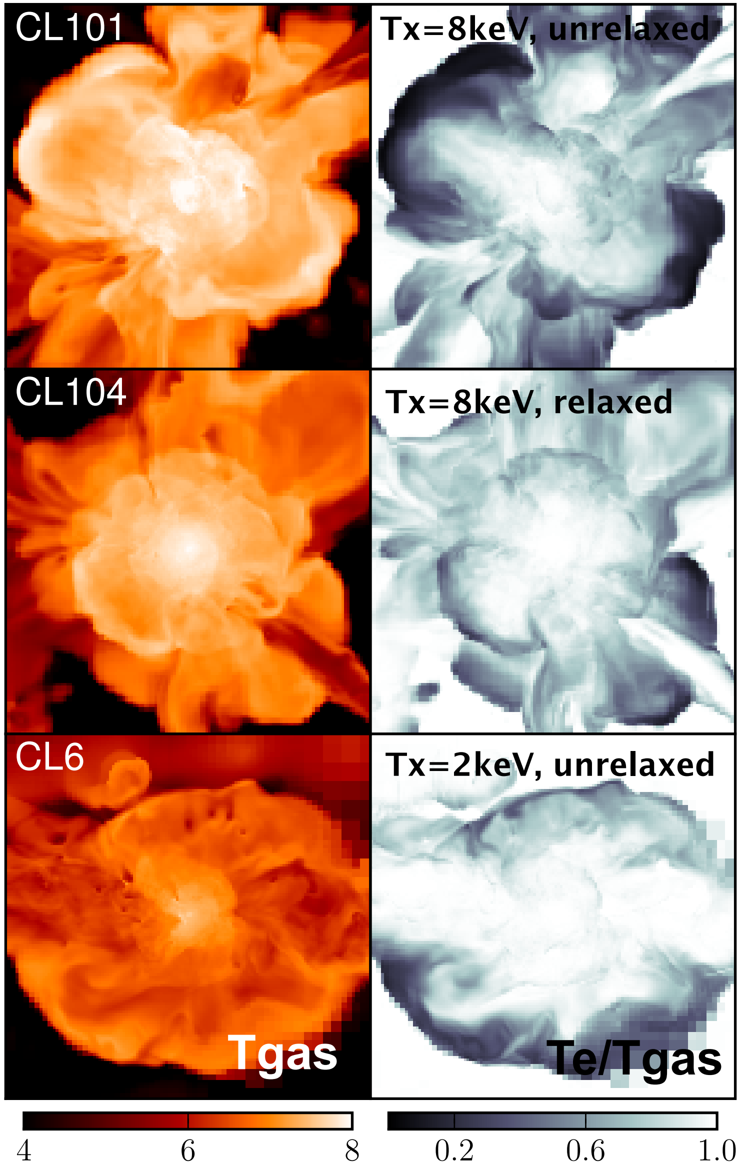


Walker et al. 2012
astro-ph/1205.2276

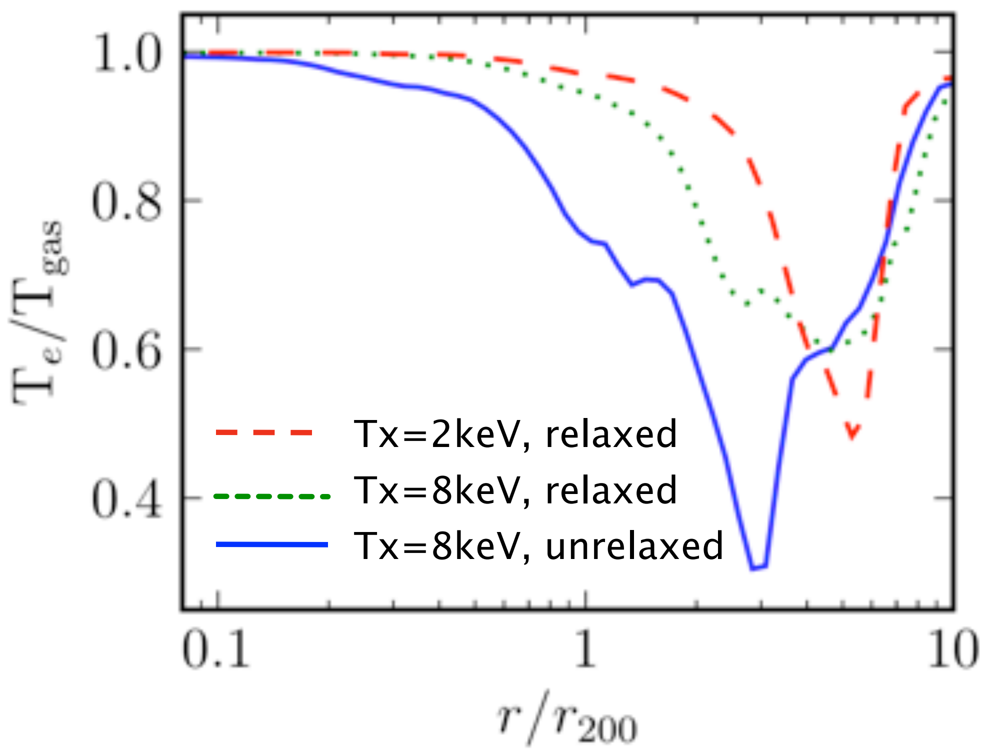


Azimuthally averaged gas density is over-estimated by a factor of ~2 at R_{200}
OR non-thermal pressure causes the underestimate of HSE mass by ~15%.

Missing Cluster Astrophysics #3
Non-equilibrium Electrons



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

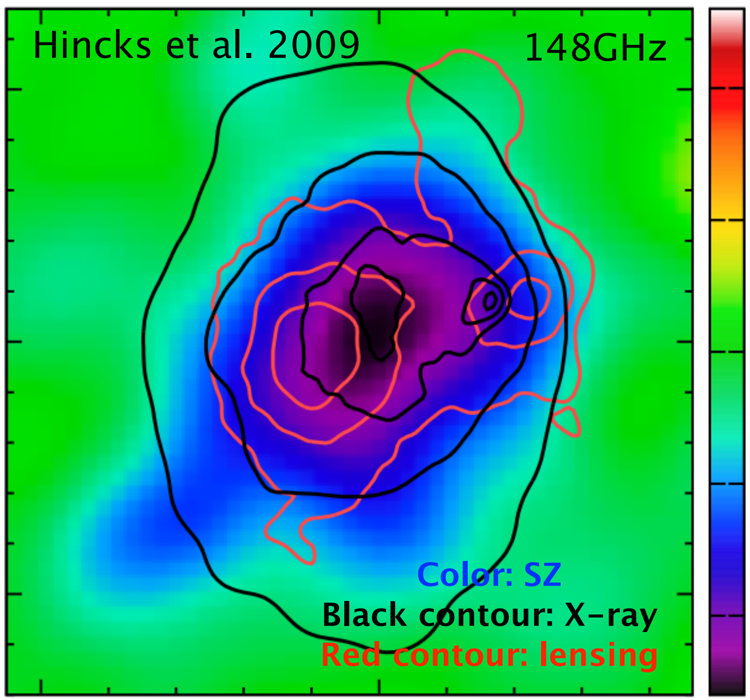


Rudd & Nagai, 2009
Spitzer 1962, Chuzhoy & Loeb 2004, Akahori & Yoshikawa 2010

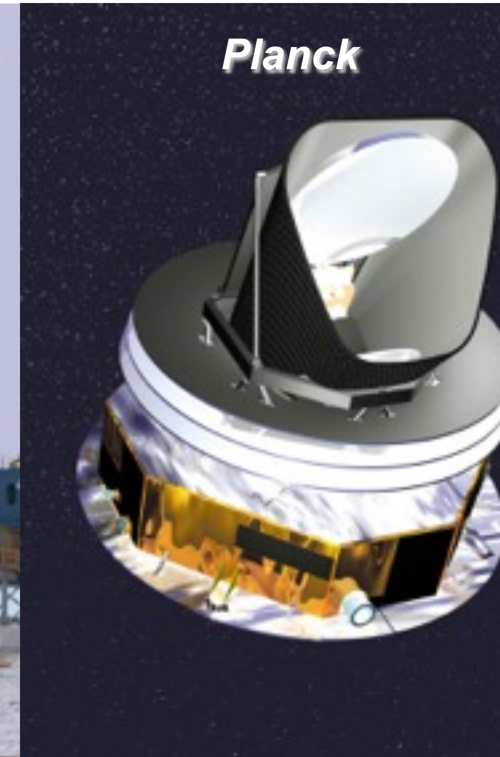
Cosmology with Sunyaev-Zel'dovich Effect

Ongoing SZE cluster surveys will produce large statistical samples, including AMI, AMiBA, APEX, SZA to ACT, Planck, and SPT

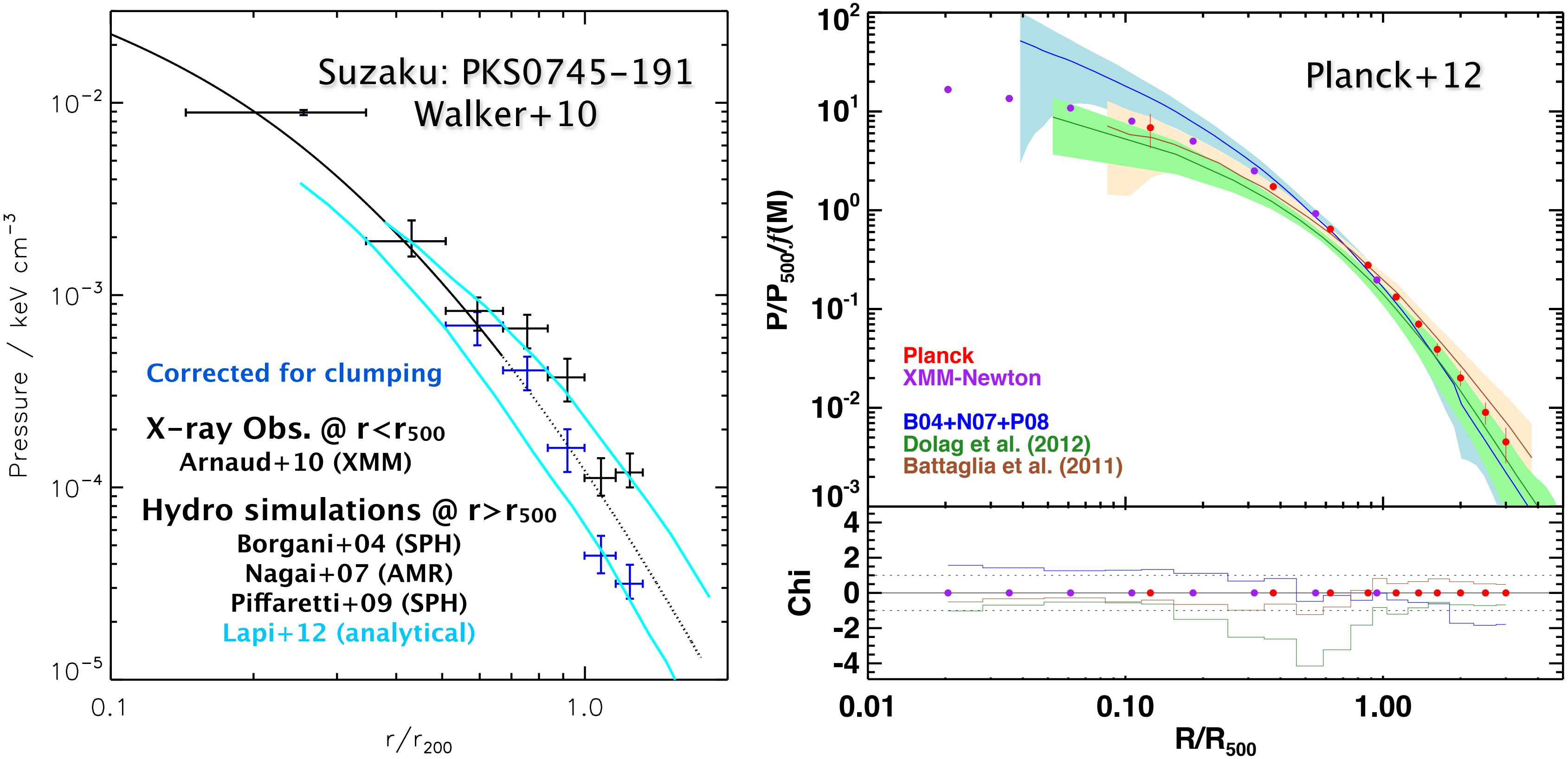
SZE is an excellent probe of cluster outskirts!!



The Bullet Cluster observed by Atacama Cosmology Telescope

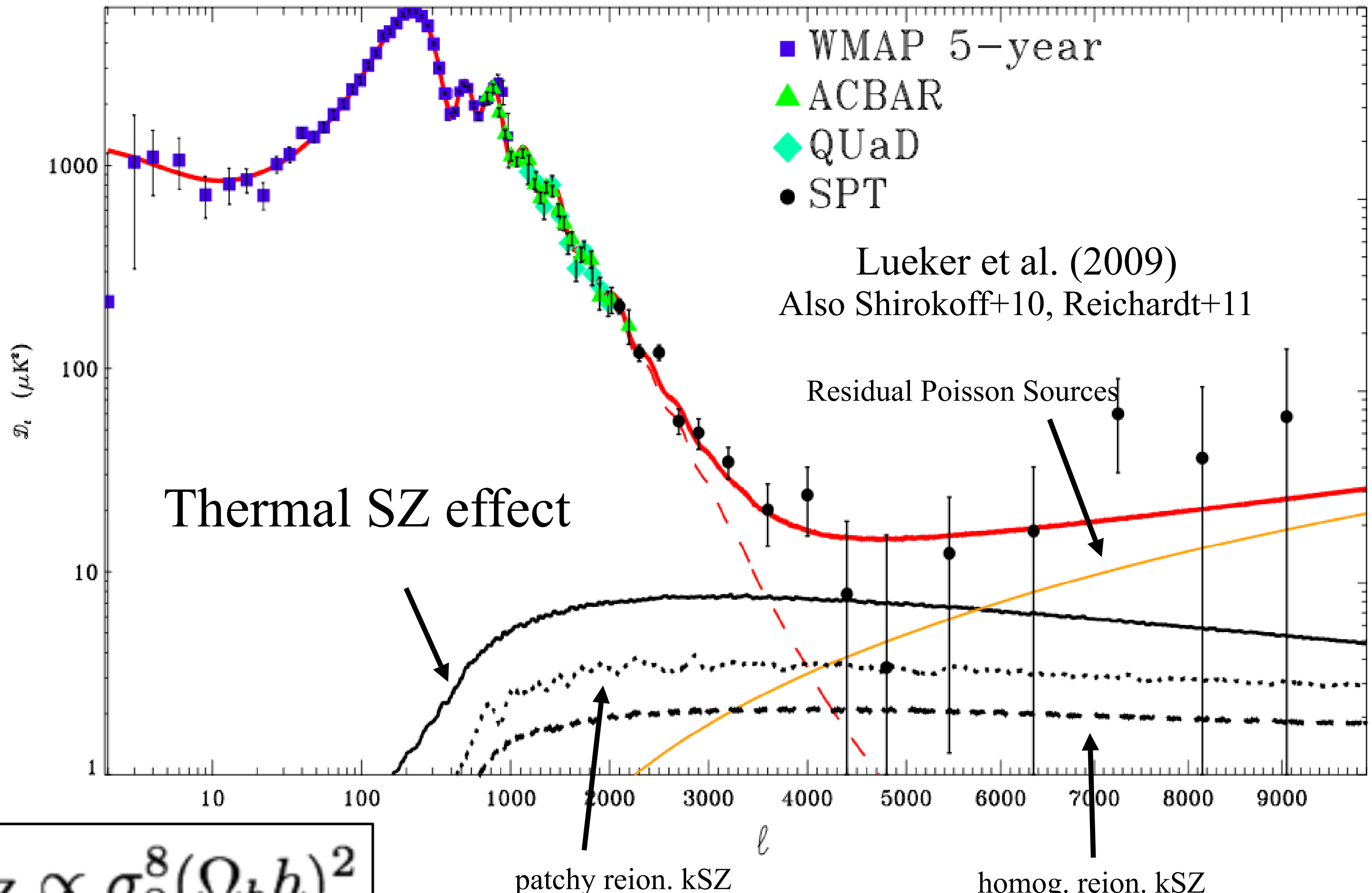


SZ+X-ray observations of Cluster Outskirts



SZ observations provide complementary views of cluster outskirts;
i.e., SZ signal is less sensitive to gas clumping, but affected by non-thermal pressure.

Measurements of the SZ power spectrum

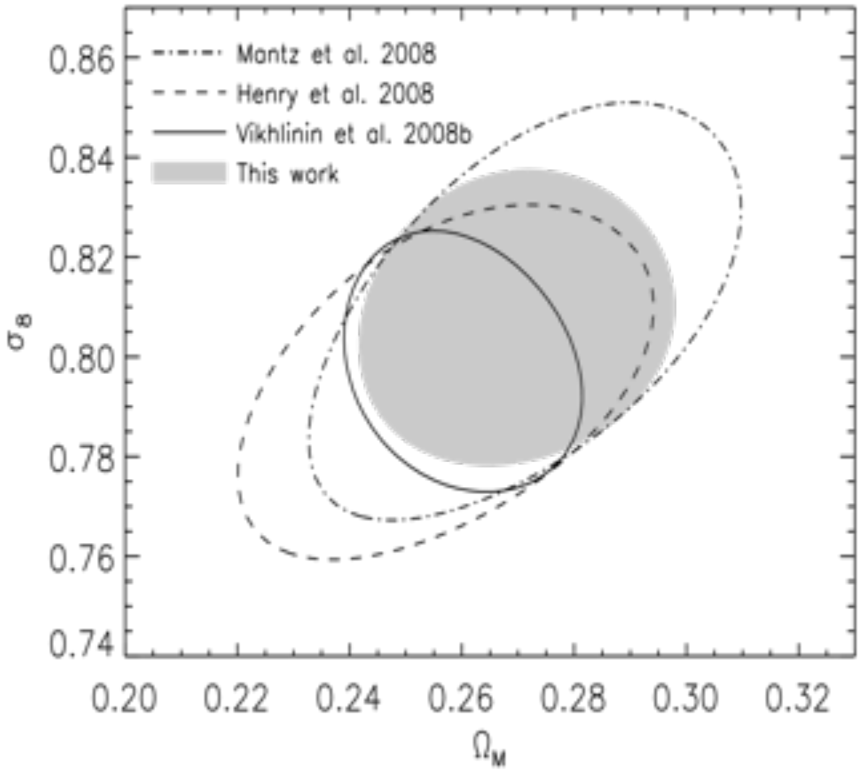


$$C_{\ell,\mathrm{tSZ}} \propto \sigma_8^8 (\Omega_b h)^2$$

The SZ power spectrum is sensitive to **the outskirts of low-mass groups at high-z**.
But, the measured SZ power was only half of what's predicted..

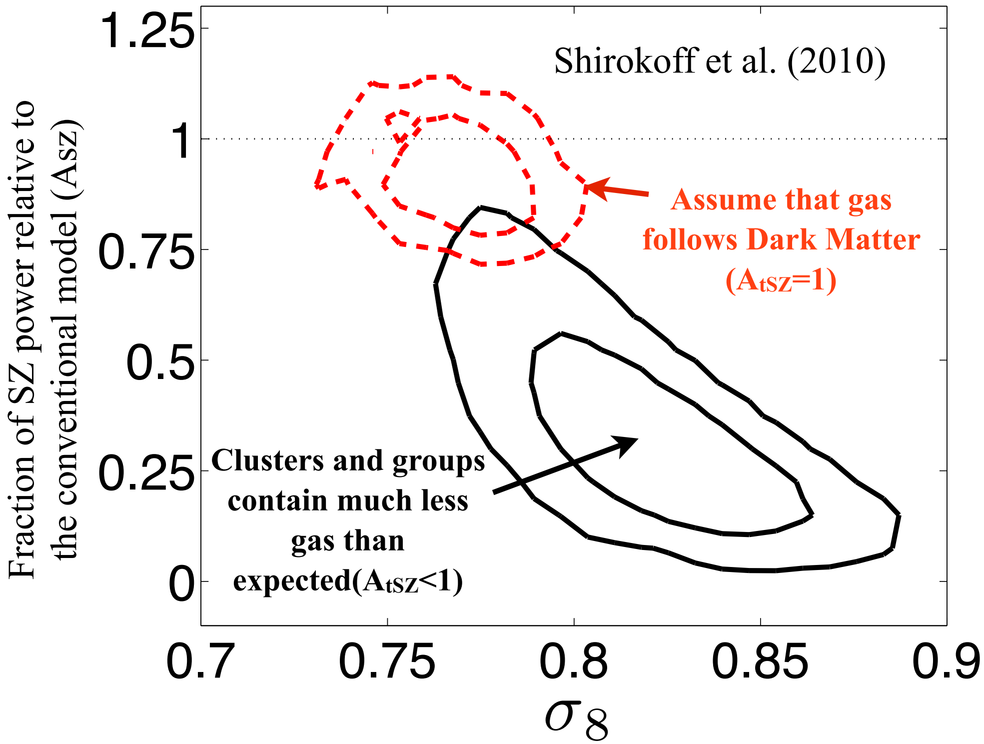
Tension in σ_8 measurements

Cluster Abundance



$\sigma_8 = 0.80 \pm 0.02$

SZ power spectrum

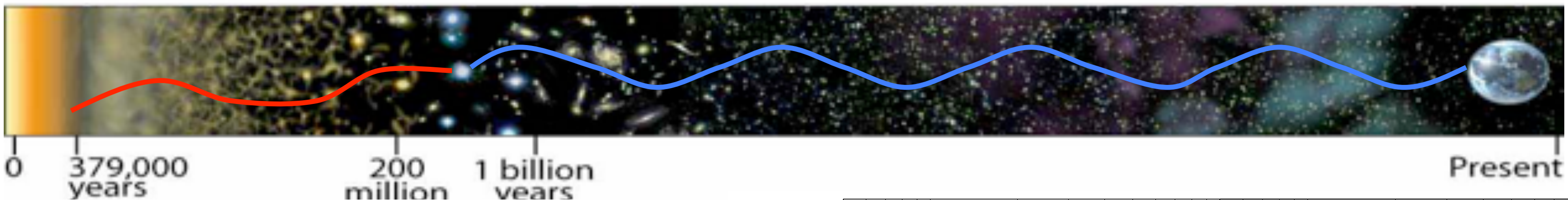


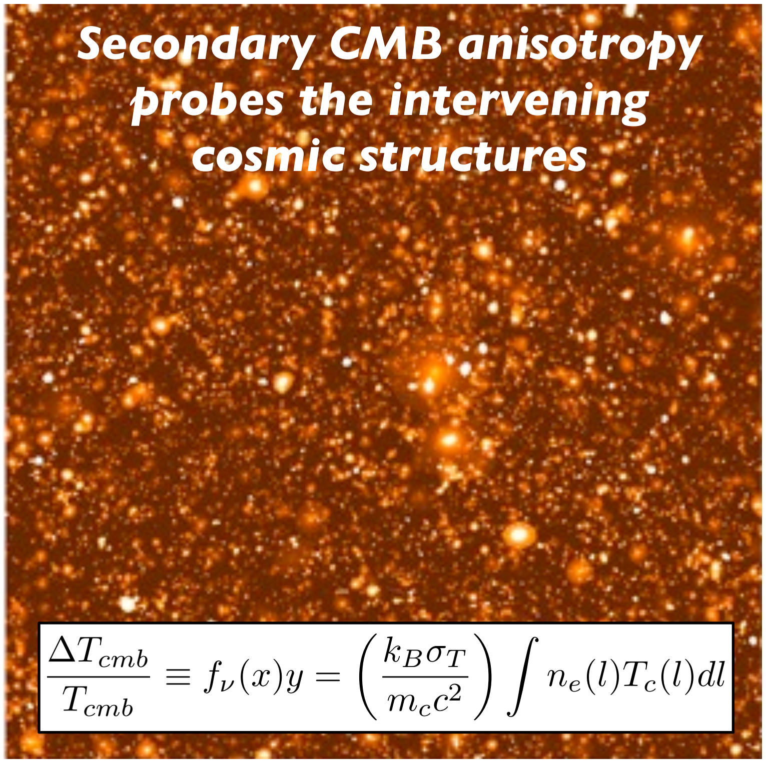
$\sigma_8 = 0.771 \pm 0.013$

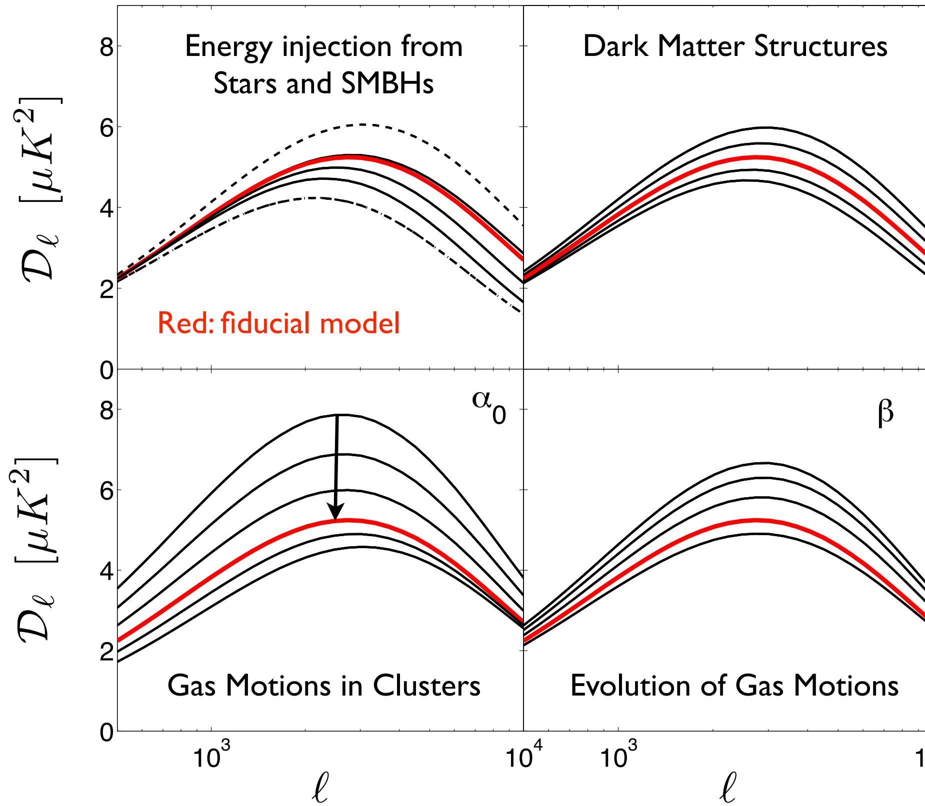
In tension at a few σ level

The measured thermal SZ power is much less than expected..

Astrophysical Uncertainty in SZ power spectrum



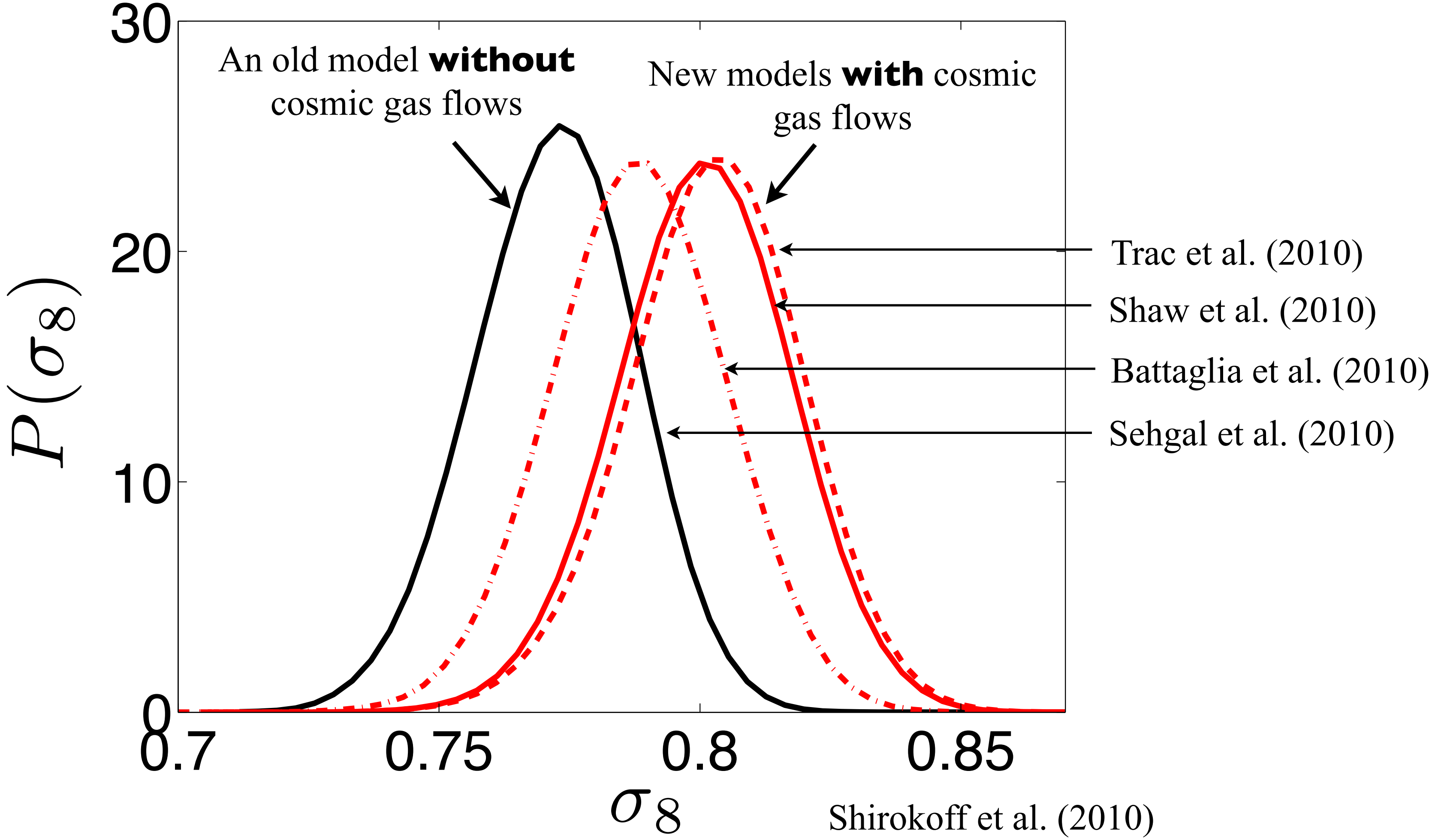




Non-thermal pressure due to gas motions is the dominant uncertainty for interpreting the recent SZ power spectrum measurements by ACT, Planck, and SPT.

Shaw et al. 2010; also Battaglia+10, Trac+11, Bode+12

Cosmic Gas Flows alleviate the tension in cosmological constraints

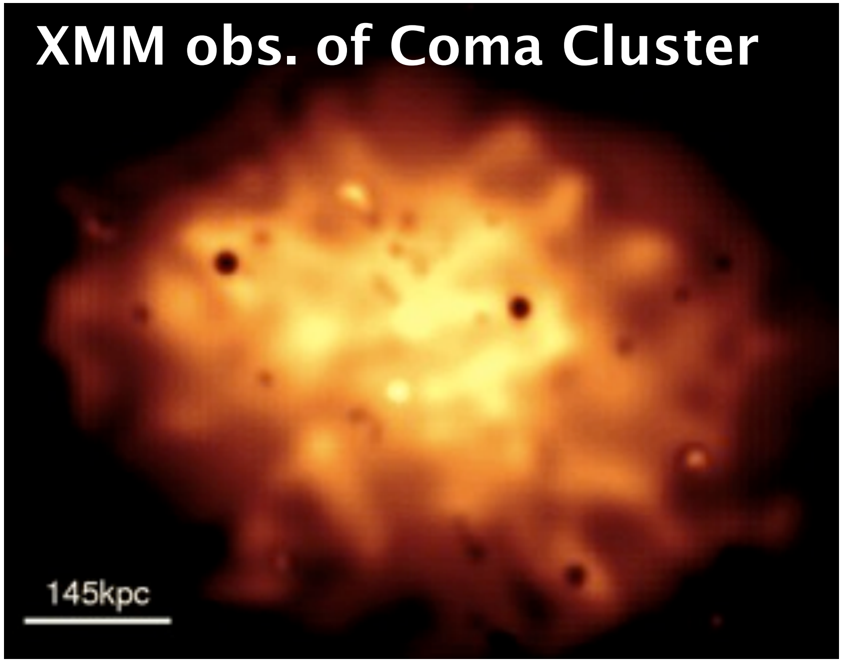


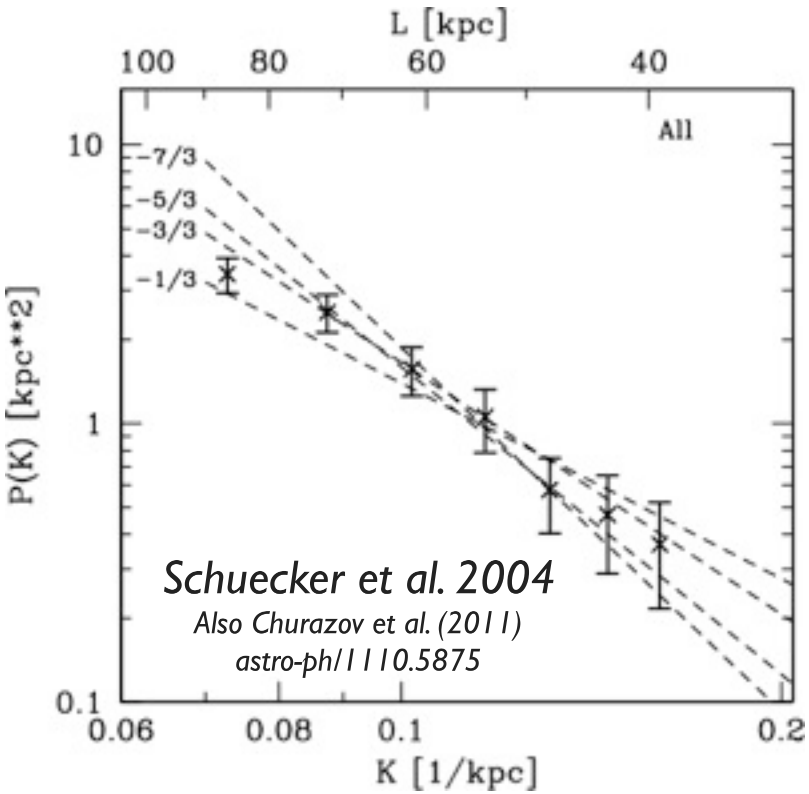
Shirokoff et al. (2010)

New SZ model with cosmic gas flows yields results consistent with the cluster abundance measurements: σ_8=0.8

Observational Probes of Cosmic Gas Flows

- Pressure fluctuations (Chandra/XMM X-ray space observatories)
- Doppler broadening of Fe line (Astro-H X-ray space observatory)
- High-resolution SZE imaging (ALMA/CARMA/CCAT/MUSTANG ground-based radio telescopes)





Schuecker et al. 2004

Also Churazov et al. (2011) astro-ph/1110.5875

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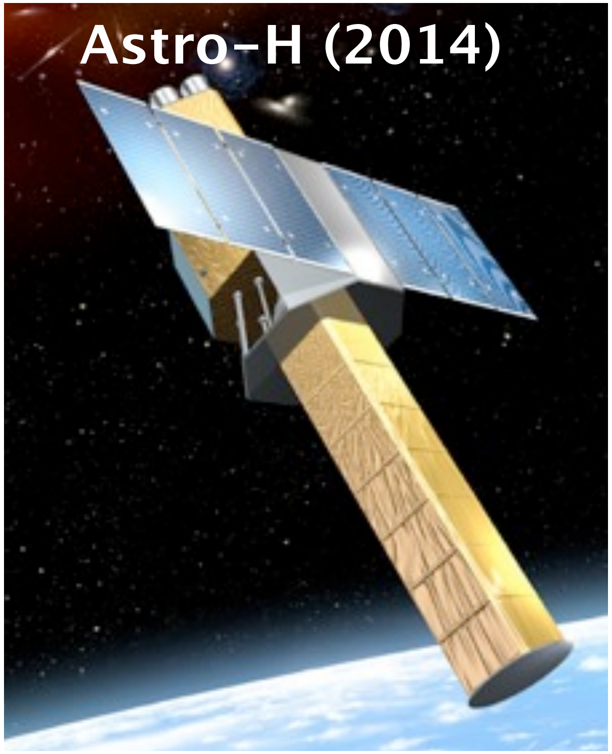
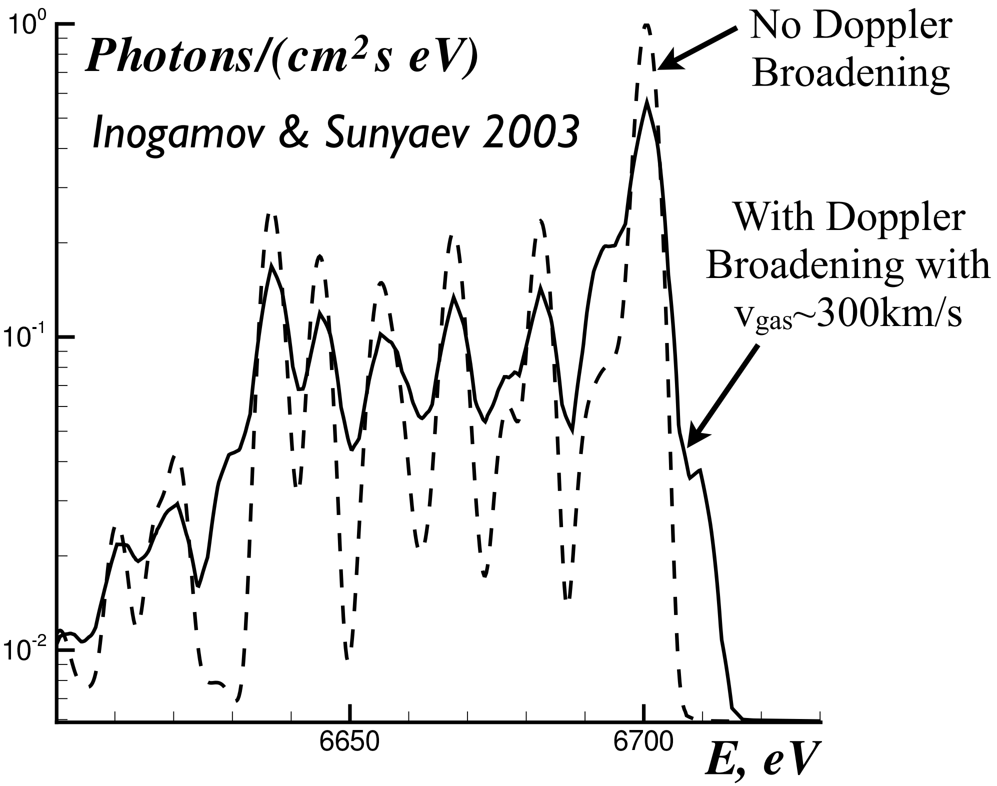
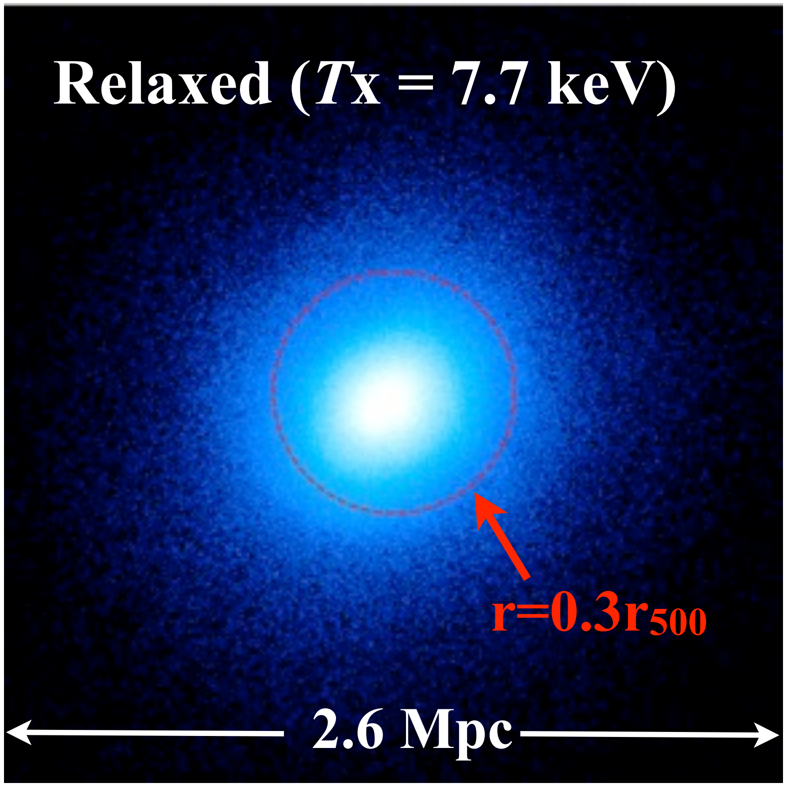




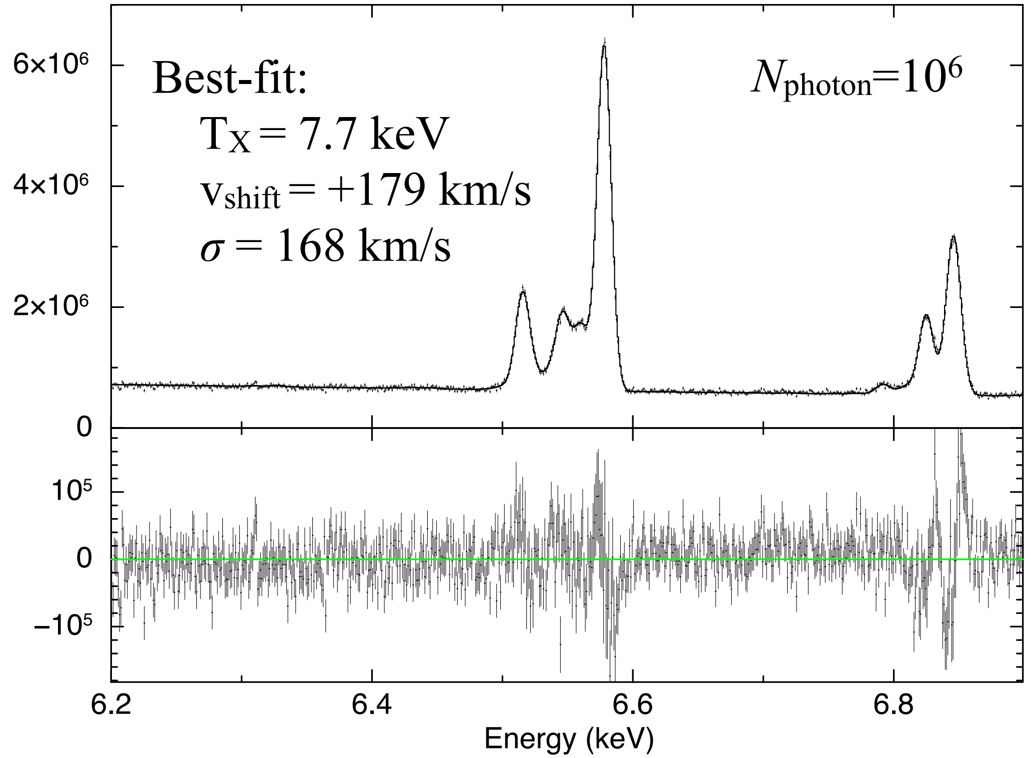
Doppler Broadening of Iron line => Motions of Gas in Clusters

Mock Astro-H Simulations of ΛCDM Clusters

Photon map in 6-7keV at z=0.018



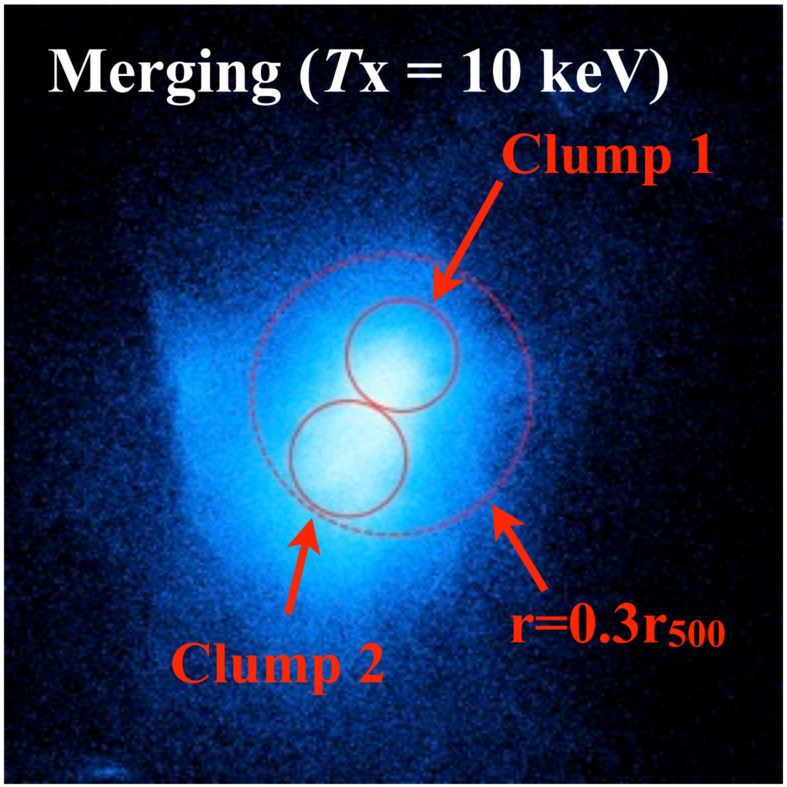
Work in progress



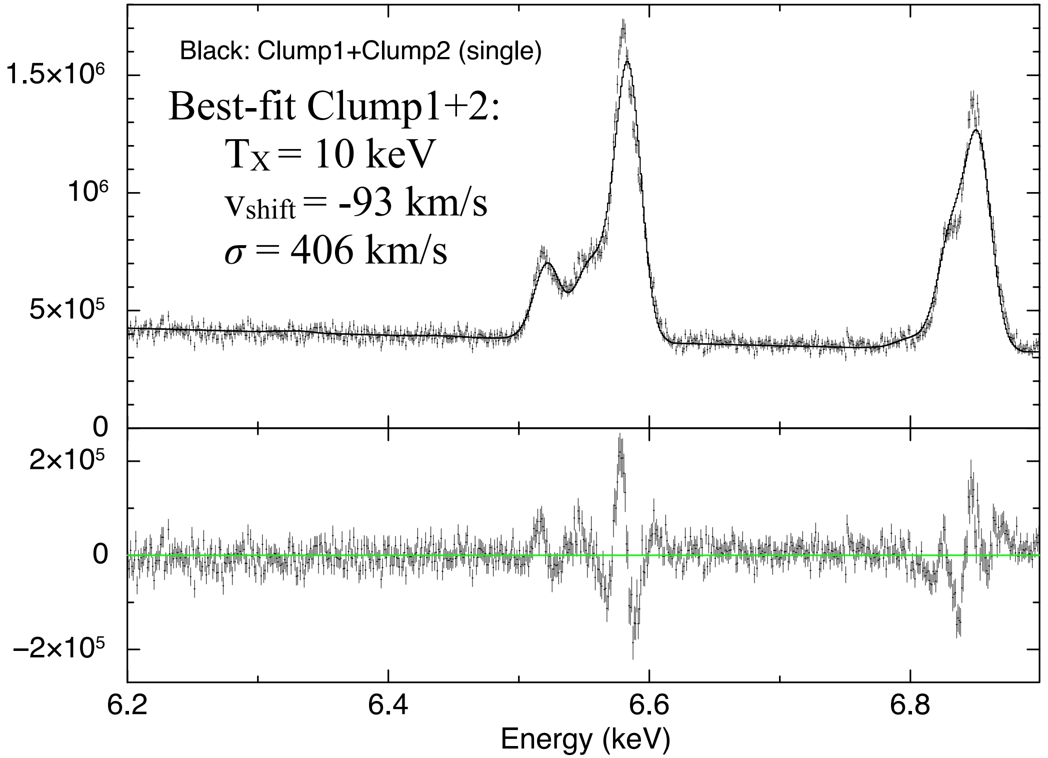
Single component fit works well for the relaxed cluster (including the inhomogeneous gas density, temperature, and velocity structures in ΛCDM simulated clusters)

Mock Astro-H Simulations of ΛCDM Clusters

Photon map in 6-7keV at z=0.018



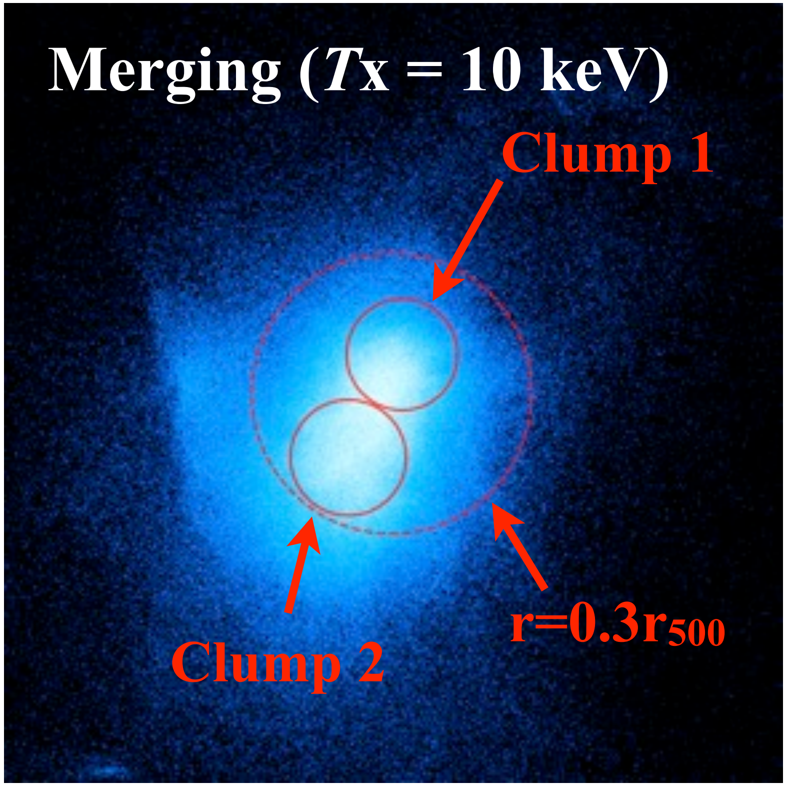
Work in progress



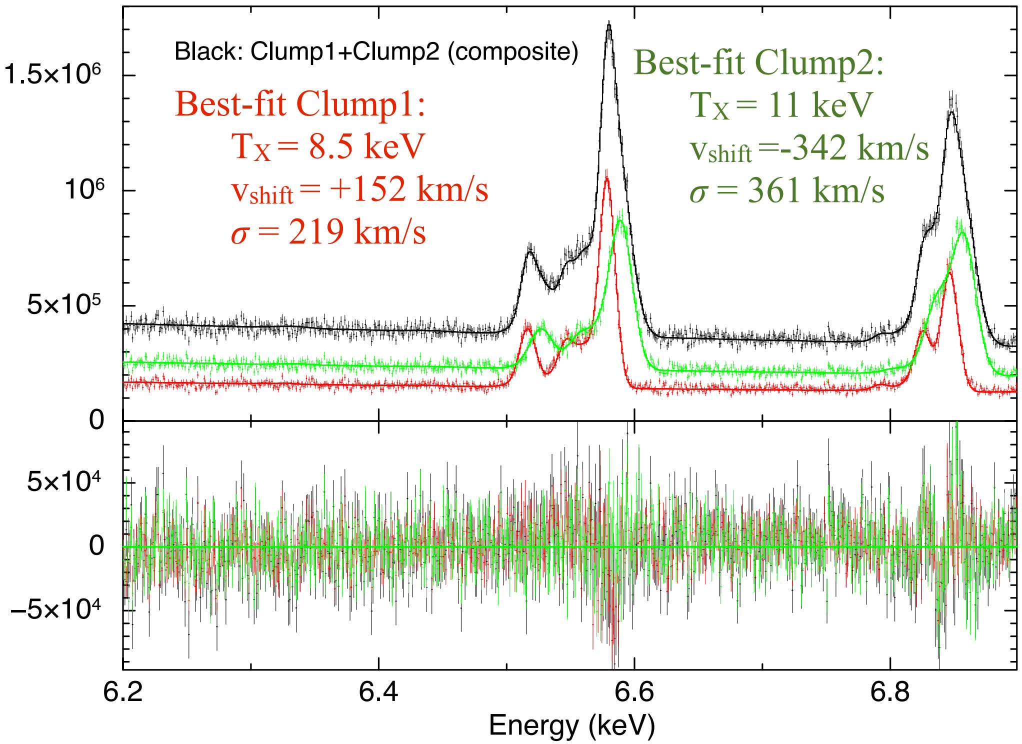
Single component fit does NOT work well for the merging cluster...

Mock Astro-H Simulations of ΛCDM Clusters

Photon map in 6-7keV at z=0.018



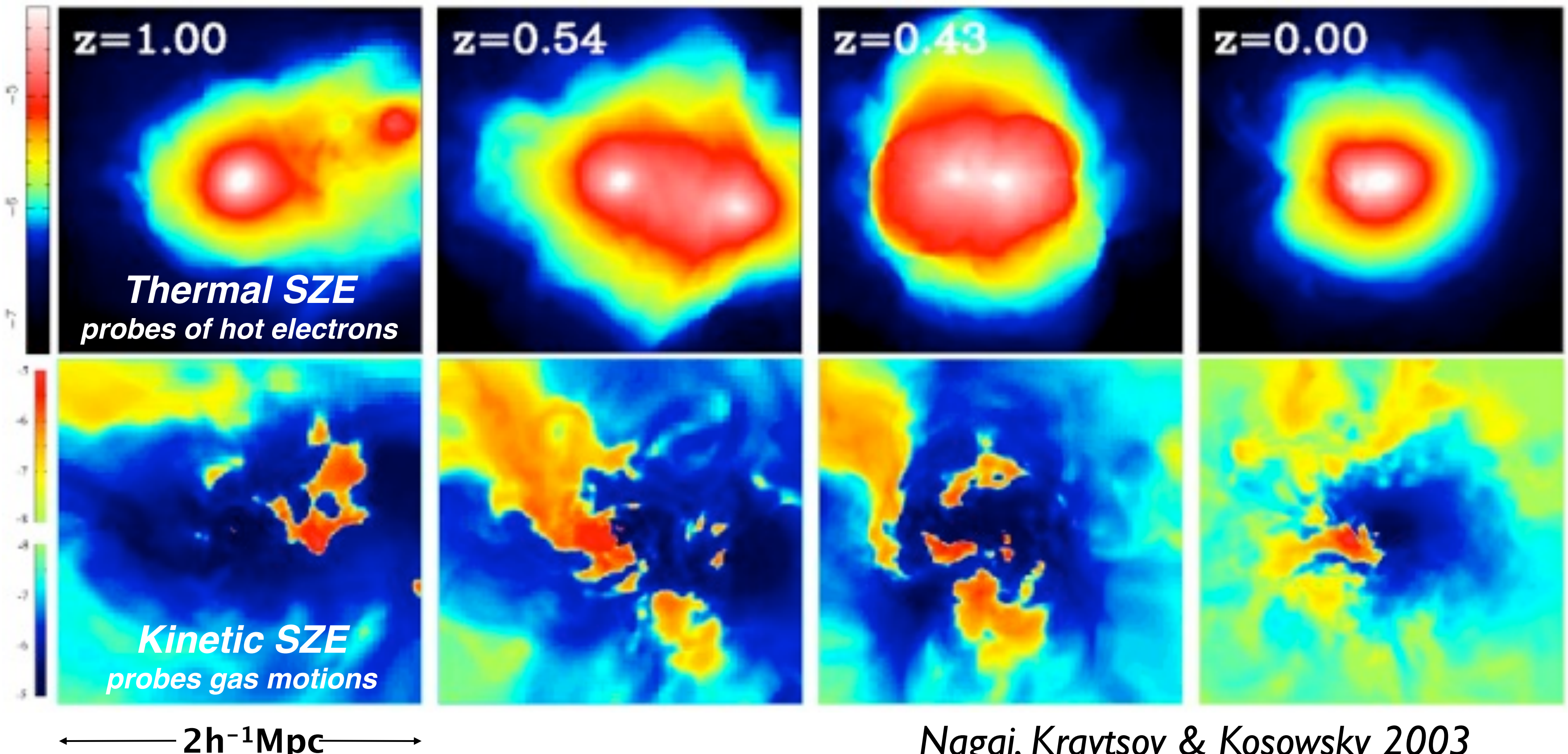
Work in progress



Astro-H spectrum can reveal merging substructures in velocity space

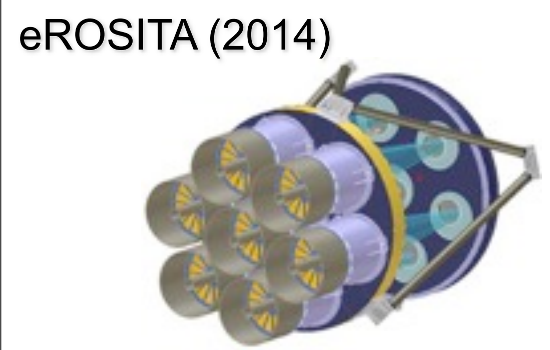
Observational Probes of Cosmic Gas Flows

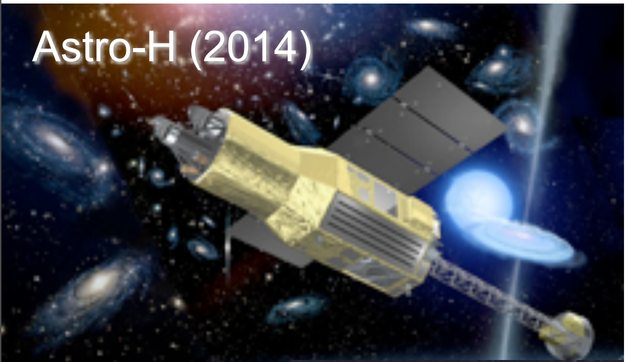
- Pressure fluctuations (Chandra/XMM X-ray space observatories)
- Doppler broadening of Fe line (Astro-H X-ray space observatory)
- High-resolution SZE imaging (ALMA/CARMA/CCAT/MUSTANG ground-based radio telescopes)



Nagai, Kravtsov & Kosowsky 2003

New Frontier: Exploration of the Virialization Regions of Galaxy Clusters





- ***Cluster outskirt is a new territory for studying 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 surveys*