Cosmology with Galaxy Clusters
Future Prospects & Challenges

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Cluster Workshop @ Tokyo University of Science
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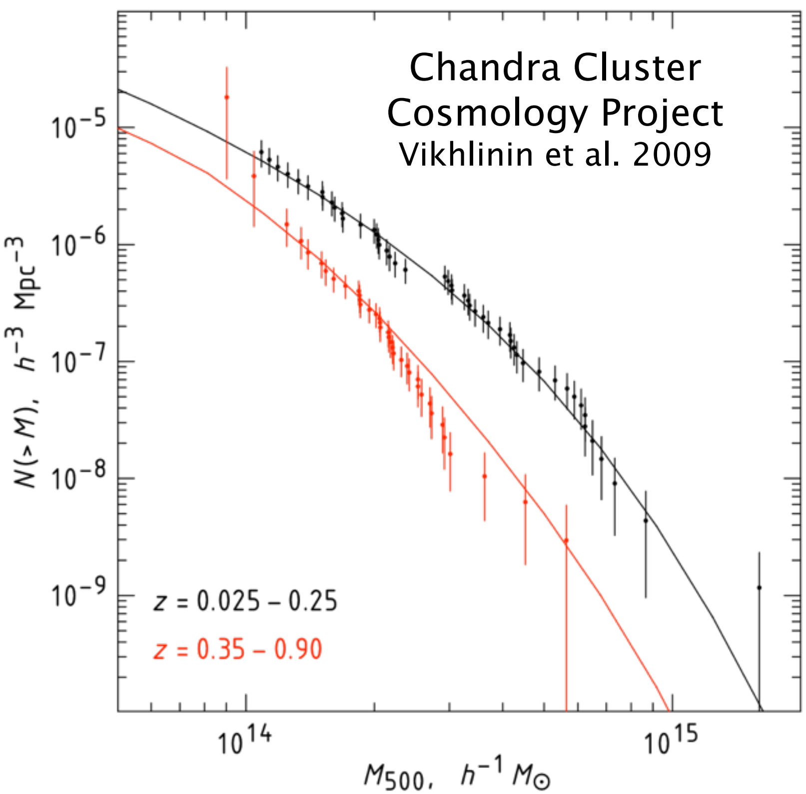
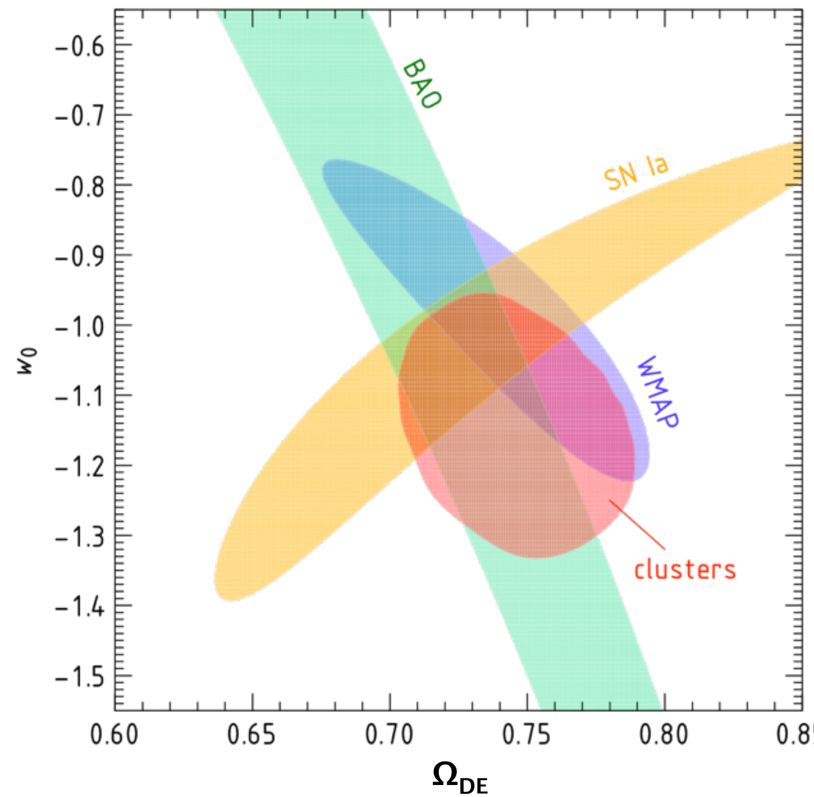
Era of Precision Cluster Cosmology

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





$$\sigma_8=0.813(\Omega_M/0.25)^{-0.47}\pm0.013(\mathrm{stat})\pm\mathbf{0.024(sys)}$$
$$w_0=-0.991\pm0.045(\mathrm{stat})\pm\mathbf{0.039(sys)}$$
$$\Omega_{DE}=0.740\pm0.012$$

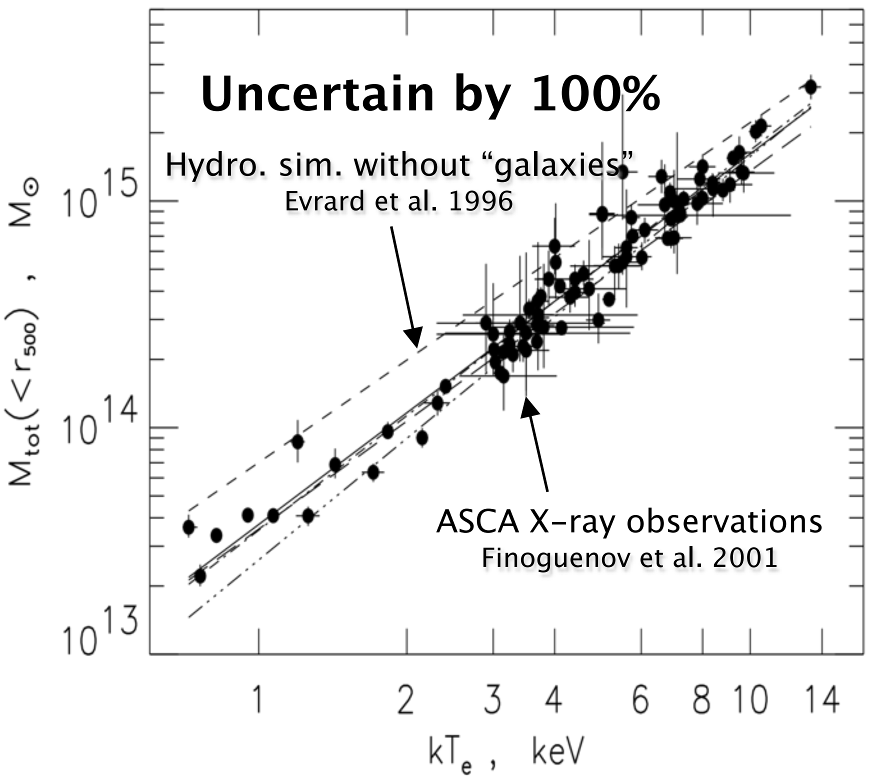
Systematics uncertainty in cluster mass measurements.

Recent Advances and Future Challenges for Cluster Cosmology

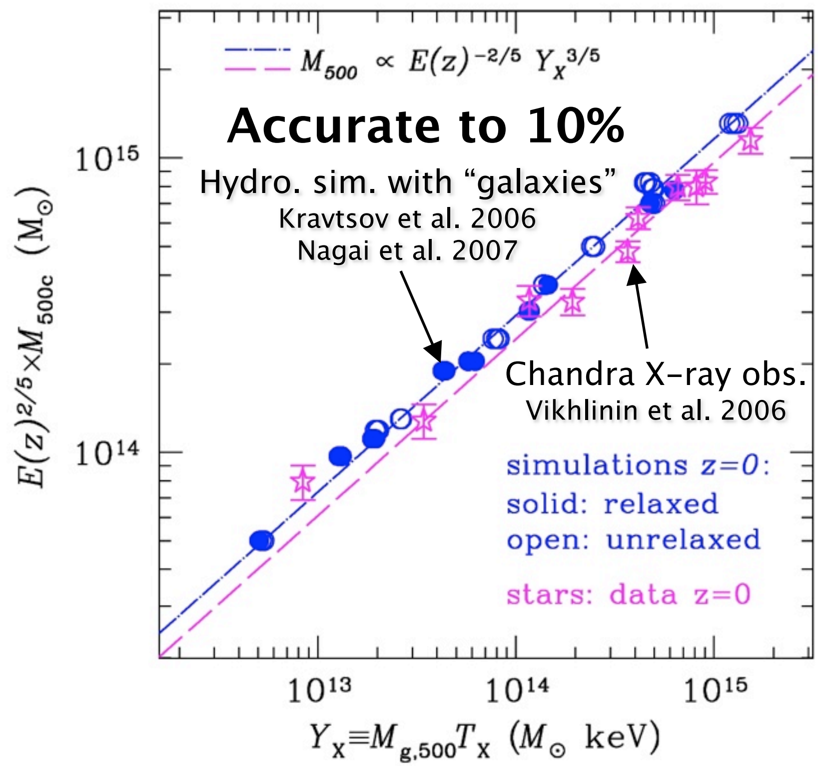
Dark Energy Task Force (2006)

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.

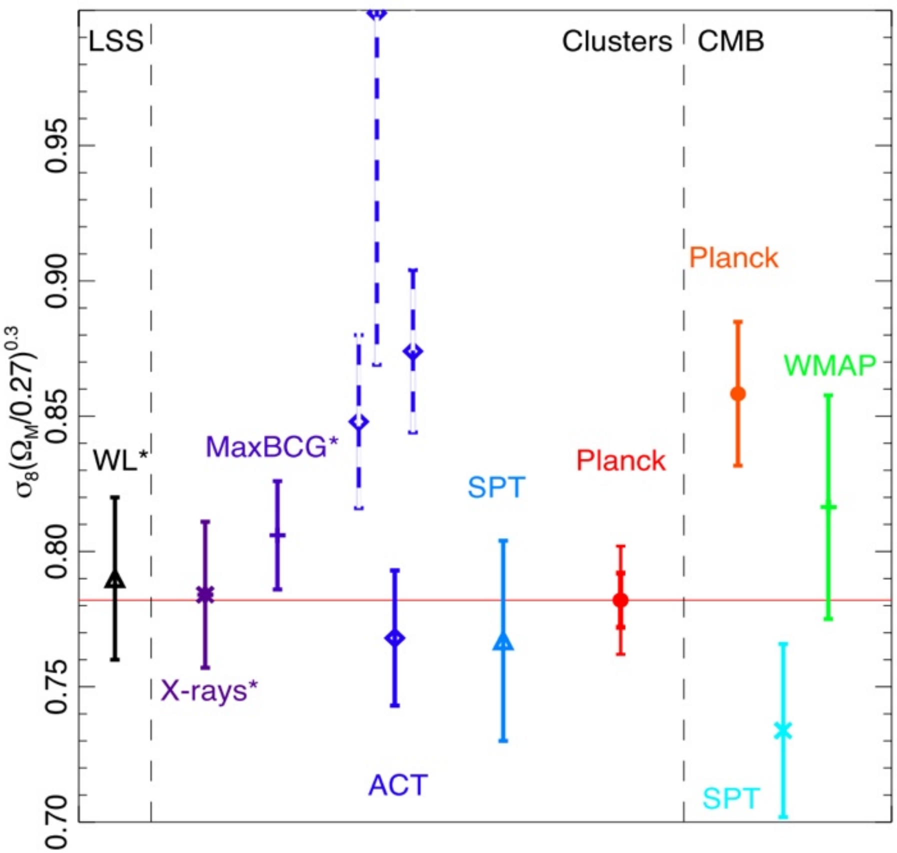
Before



Now



Cosmology in the Planck Era
Clusters vs. CMB



Planck 2013, Paper XX

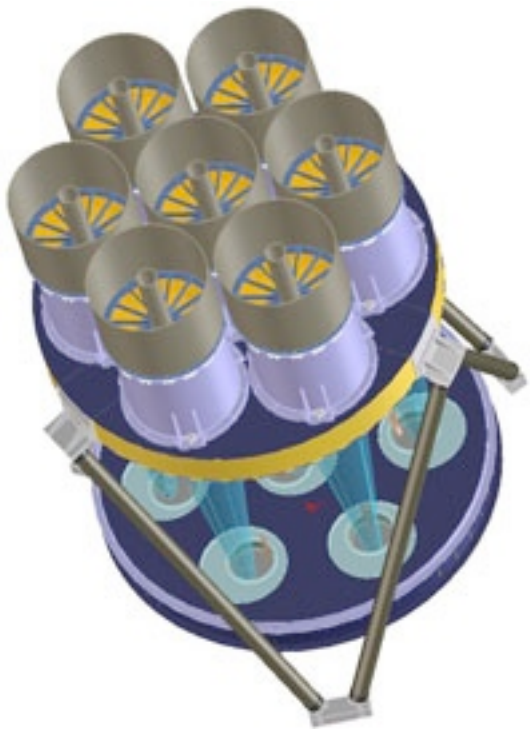
Possible Solutions

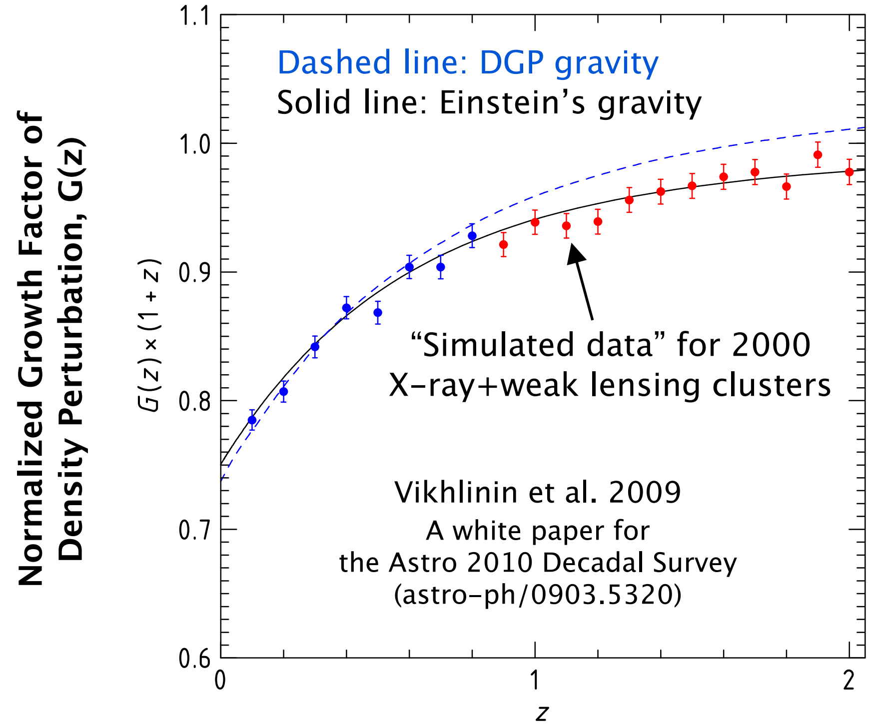
- cluster scaling relations are off by ~45% - mass calibration?
- Planck CMB results may be biased - issue with 217GHz data (Spergel et al. on astro-ph this month)
- sum of the neutrino masses is ~0.2-0.25eV
- a combination of bias in cluster scaling relations, Planck CMB constraints, and non-zero neutrino masses

Planck cosmological constraints from SZ cluster counts and CMB are in tension!

Dark Energy Space Mission of 2010s

eROSITA in X-ray (scheduled launch in 2016?)
DES, HSC, LSST in optical





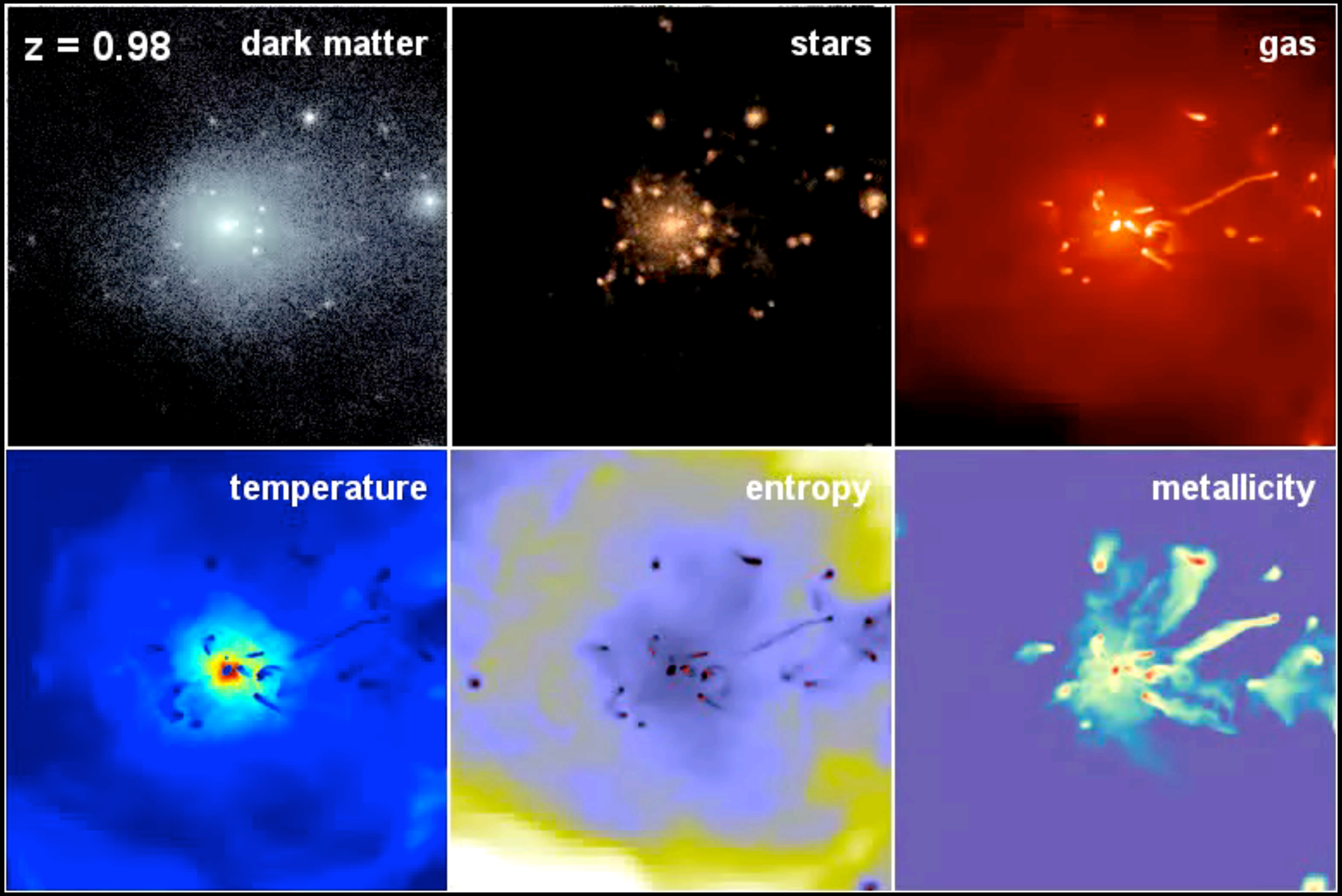
All-sky survey for 4yrs + targeted obs.
Science Goals: Study the LSS and Dark Energy
>100,000 clusters up to z~1.5
A_{eff}~1500 cm^2 @ 1.5keV; Θ_{eff}~25-40 arcsec

Need to measure the cluster mass with a few % accuracy!!

Cosmological Simulations of Galaxy Cluster Formation

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

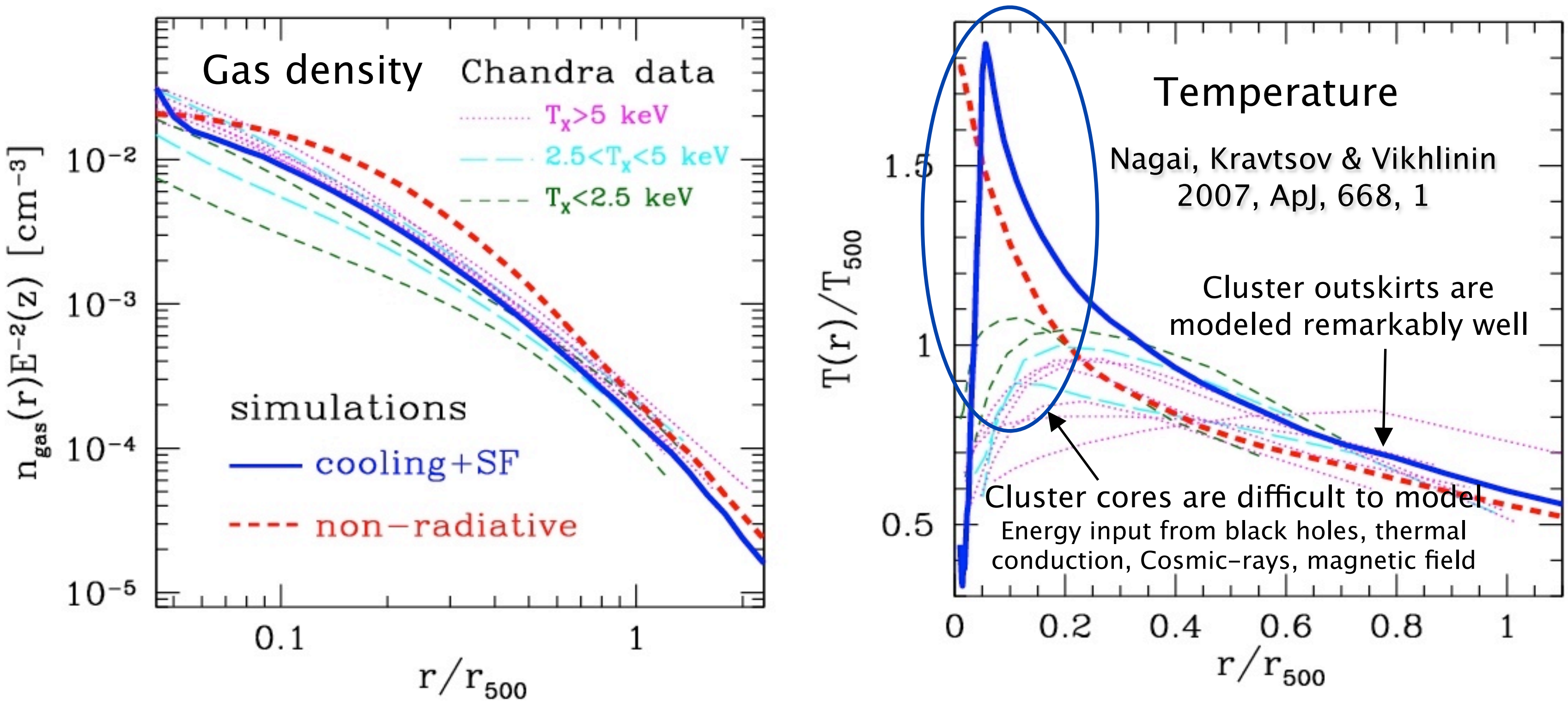
Box size ~ 80/h Mpc; Region shown ~ 2/h Mpc; Spatial resolution ~ a few kpc



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 limitations - e.g., a single fluid approximation!

Simulation performed by the Yale BulldogM HPC cluster

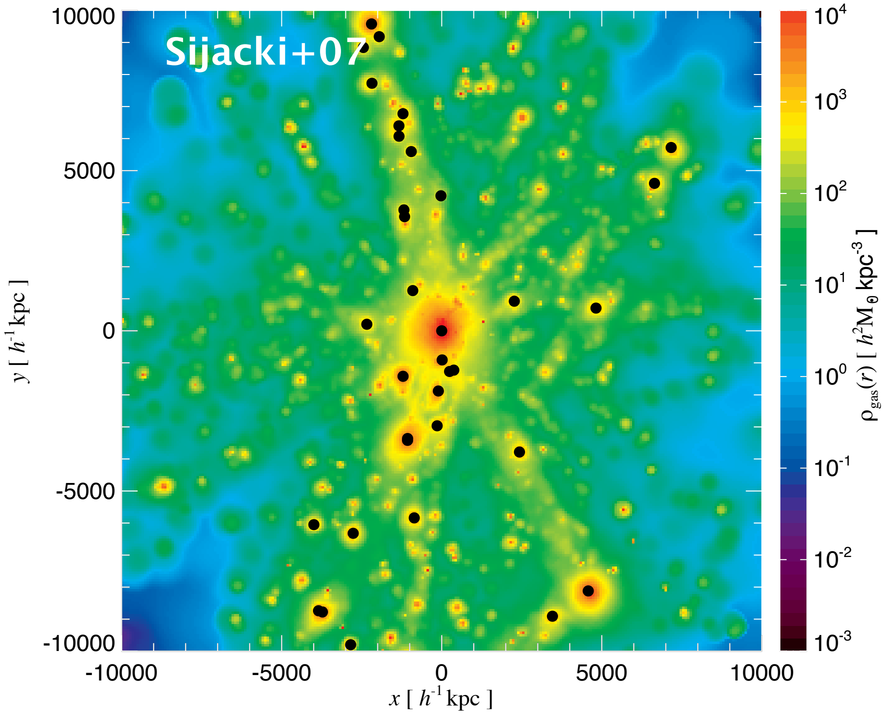
X-ray emitting, hot gas in clusters
Simulations vs. Chandra X-ray Observations



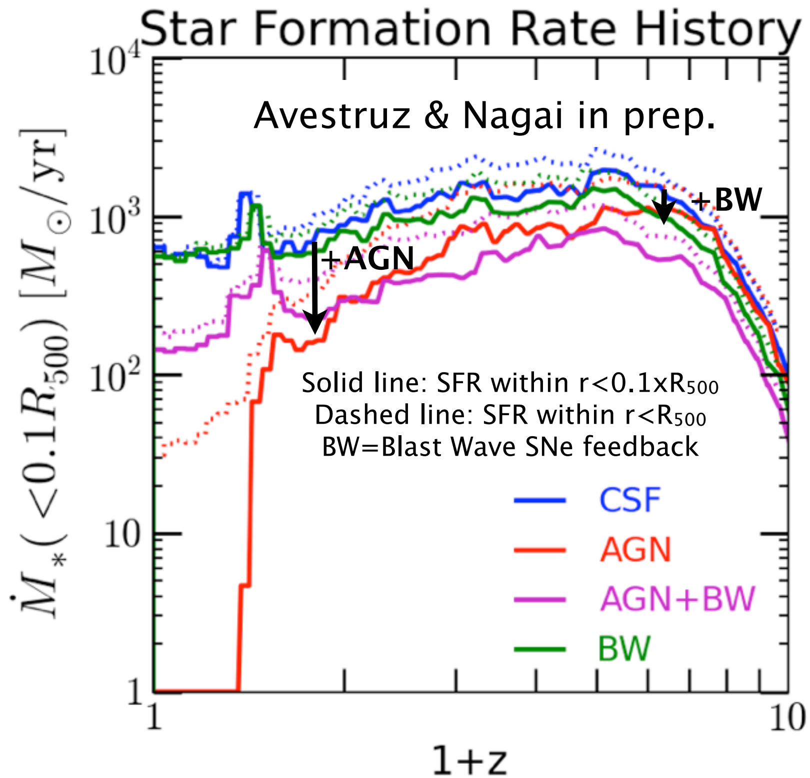
Modern hydrodynamical cluster simulations reproduce observed gas density and temperature profiles outside cluster cores ($0.15<r/r_{500}<1$)

Outskirts could be used to measure the cluster mass accurately.

Missing Cluster Astrophysics #1
AGN feedback in Cluster Cores



Subgrid modeling of BHs
(1) Seeding & Merging
(2) Gas Accretion: Bondi-like prescription
(3) Energy Injection: Thermal vs. Mechanical

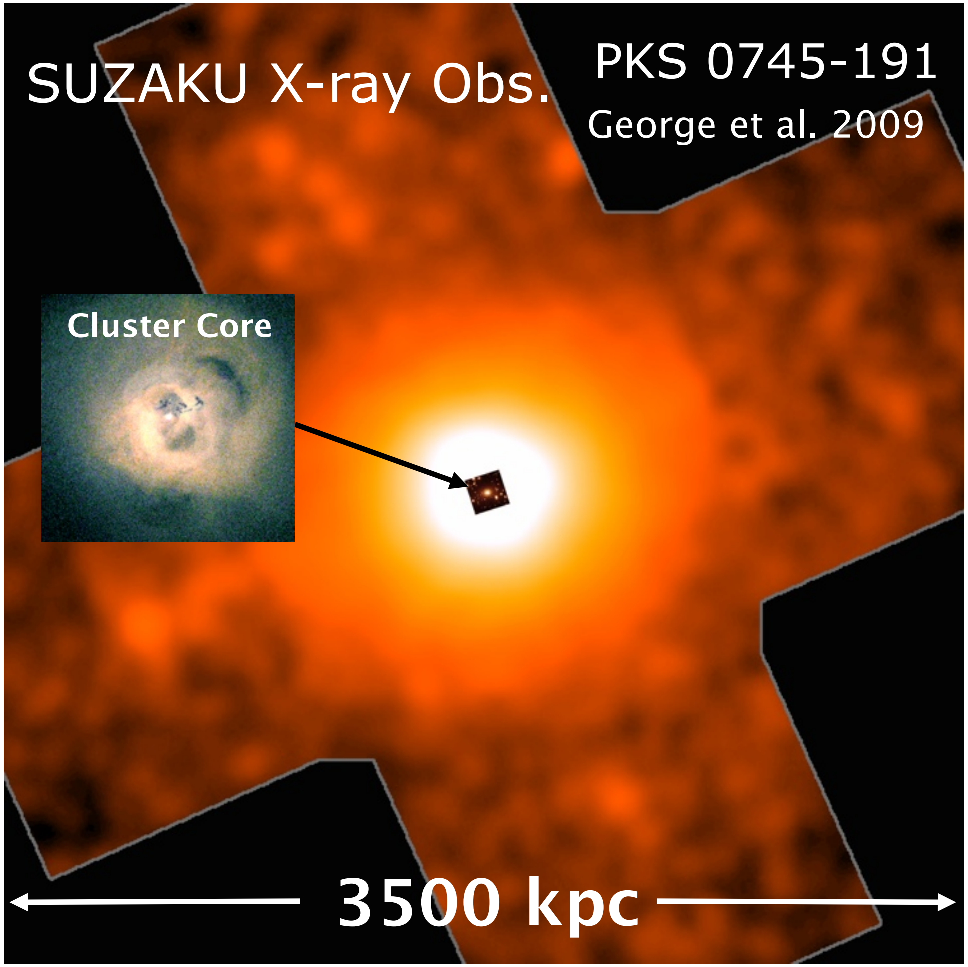


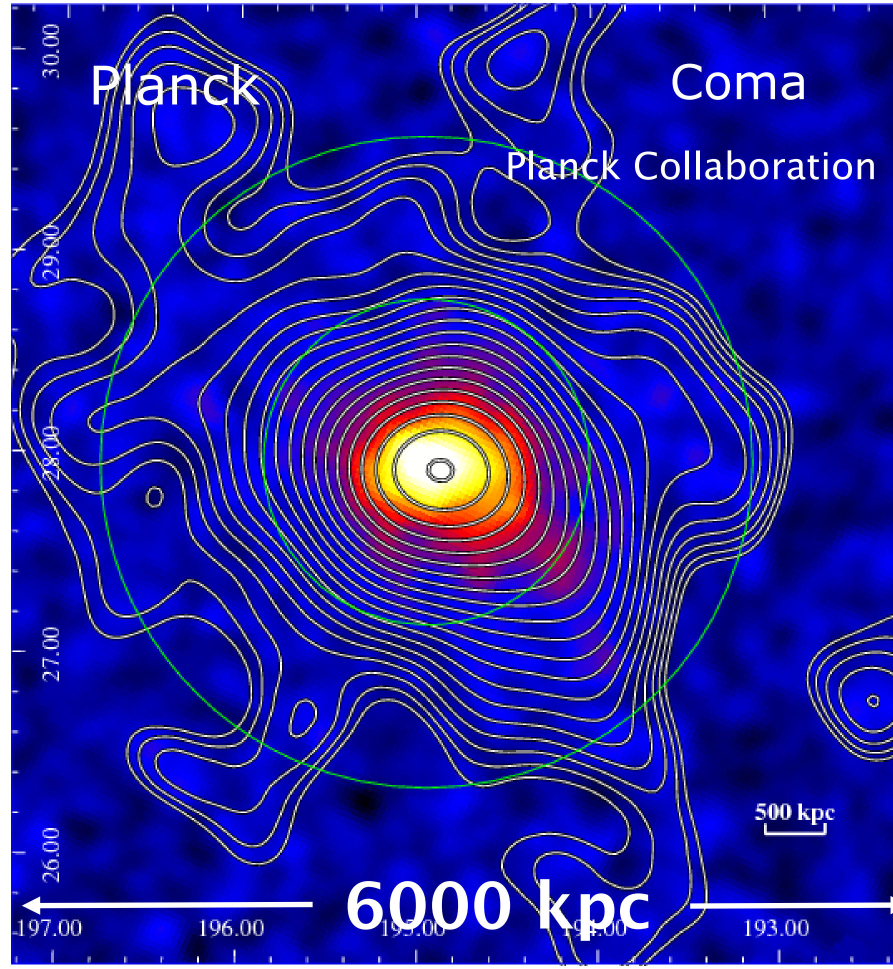
Cluster Simulations with thermal AGN feedback
Virgo-size cluster with $M_{500}=2\times10^{14}$Msun/h
Box size=80Mpc/h, Peak resolution=2.5kpc/h;
mass resolution=2×10^{8}Msun/h

AGN feedback is important for mitigating the "overcooling problem" and reproducing the mass and colors of cluster galaxies.

e.g., Sijacki+06,07, 08; Booth & Schaye 09, 11; Dubois+10,12 - Talk by Fujita-san

X-ray+SZ measurements of cluster outskirts

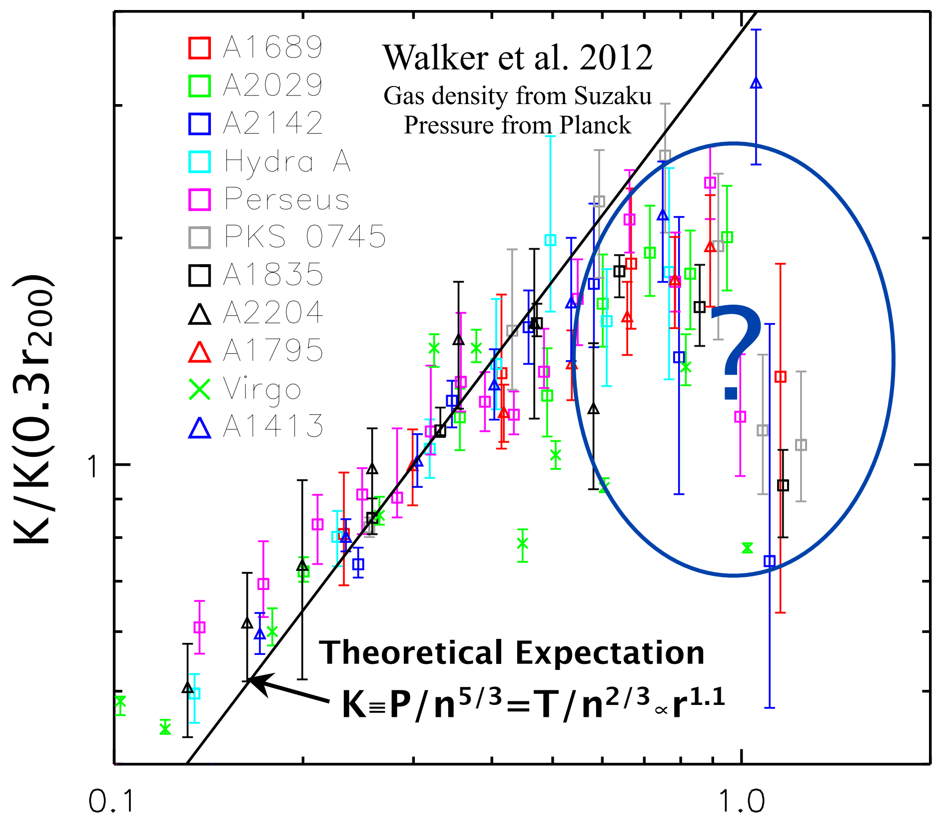




Recent X-ray and microwave observations have detected the hot gas in the outskirts of galaxy clusters

Suzaku+Planck measurements of cluster outskirts

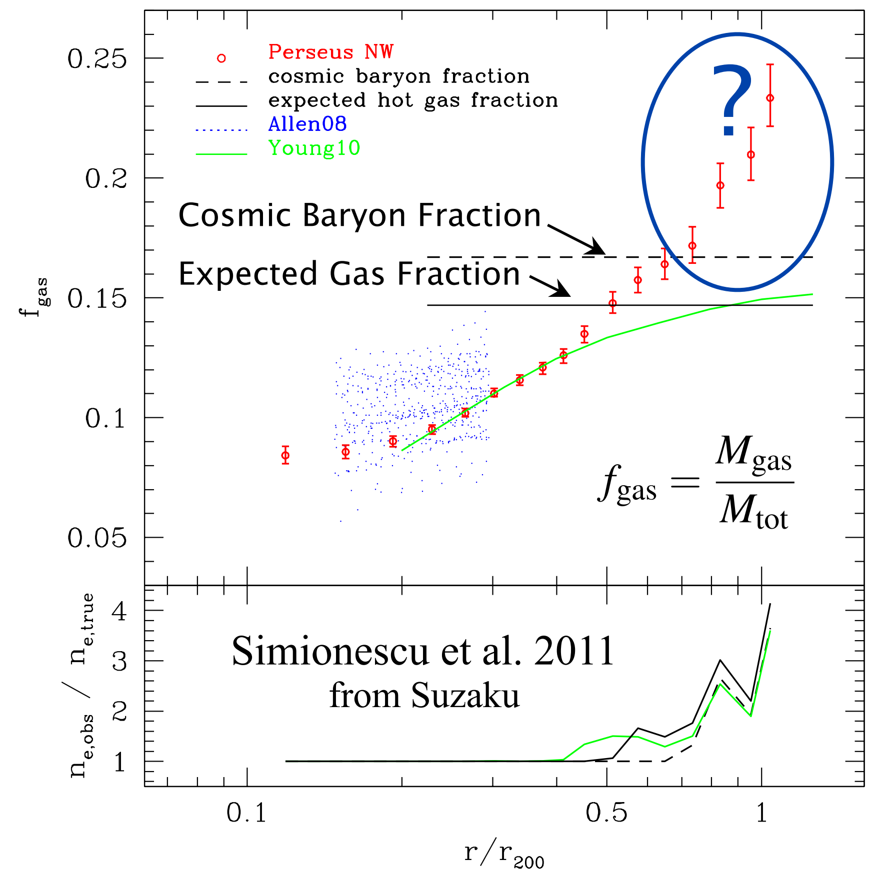
Entropy profiles of 11 nearby relaxed clusters



$s = \log K$
specific entropy

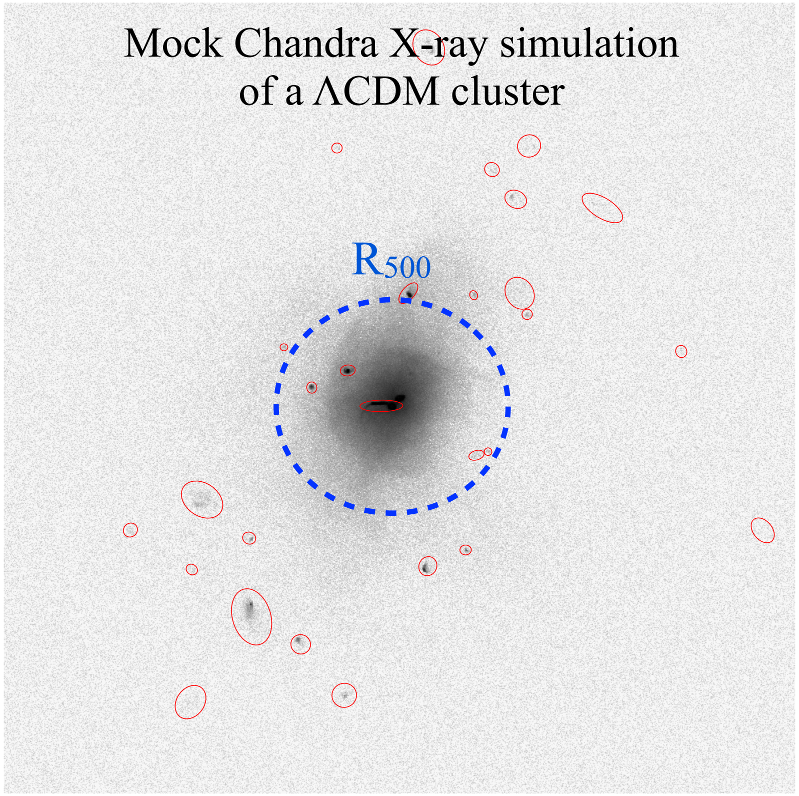
$P = K\rho^{5/3}$
for monoatomic gas

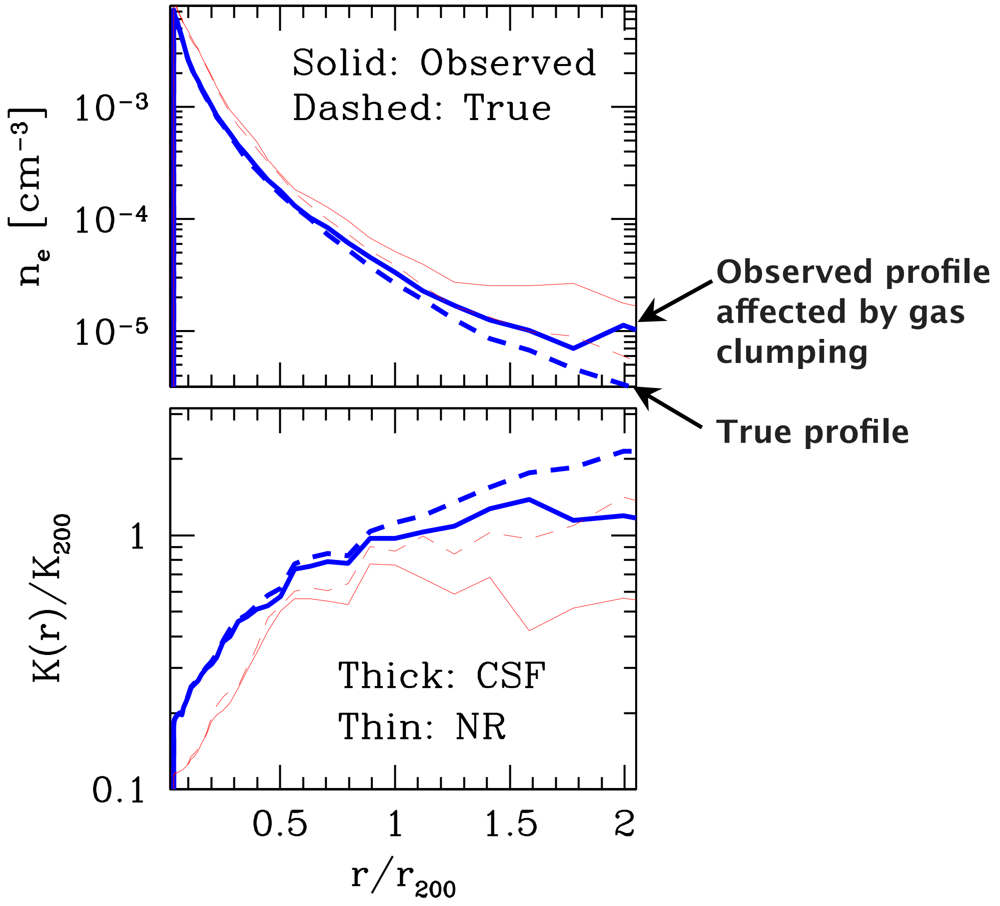
Gas fraction profile in Perseus cluster



PUZZLES: Observed entropy and gas fraction profiles are strongly inconsistent with theoretical expectations

Missing Cluster Astrophysics #2
Cluster outskirts are very clumpy

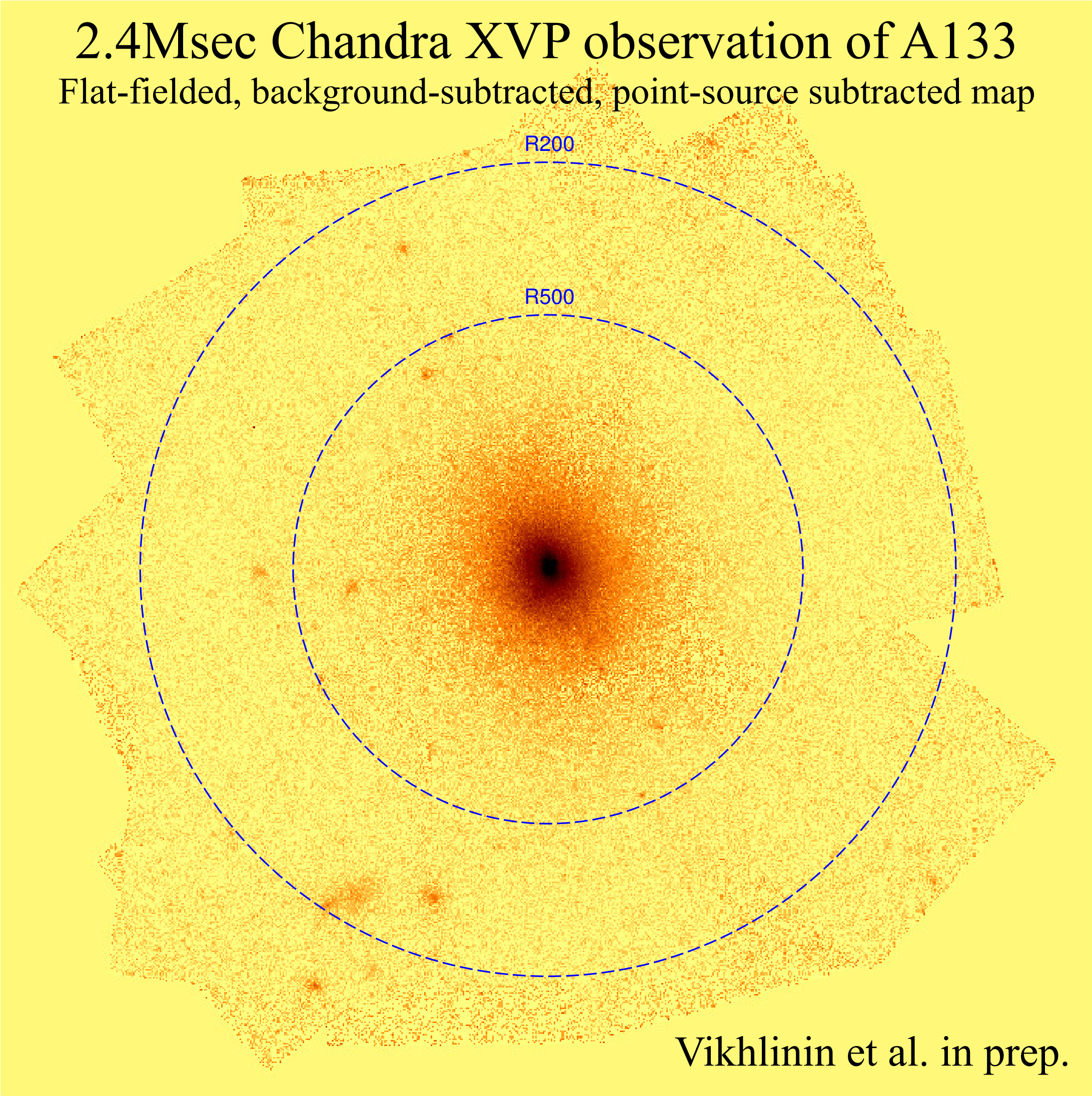




Hydrodynamical simulations predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}=0.7r_{200}$) arise from infalling groups from the filaments

Nagai & Lau 2011; Zhuravleva et al. 2013

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 $r \approx R_{500}$

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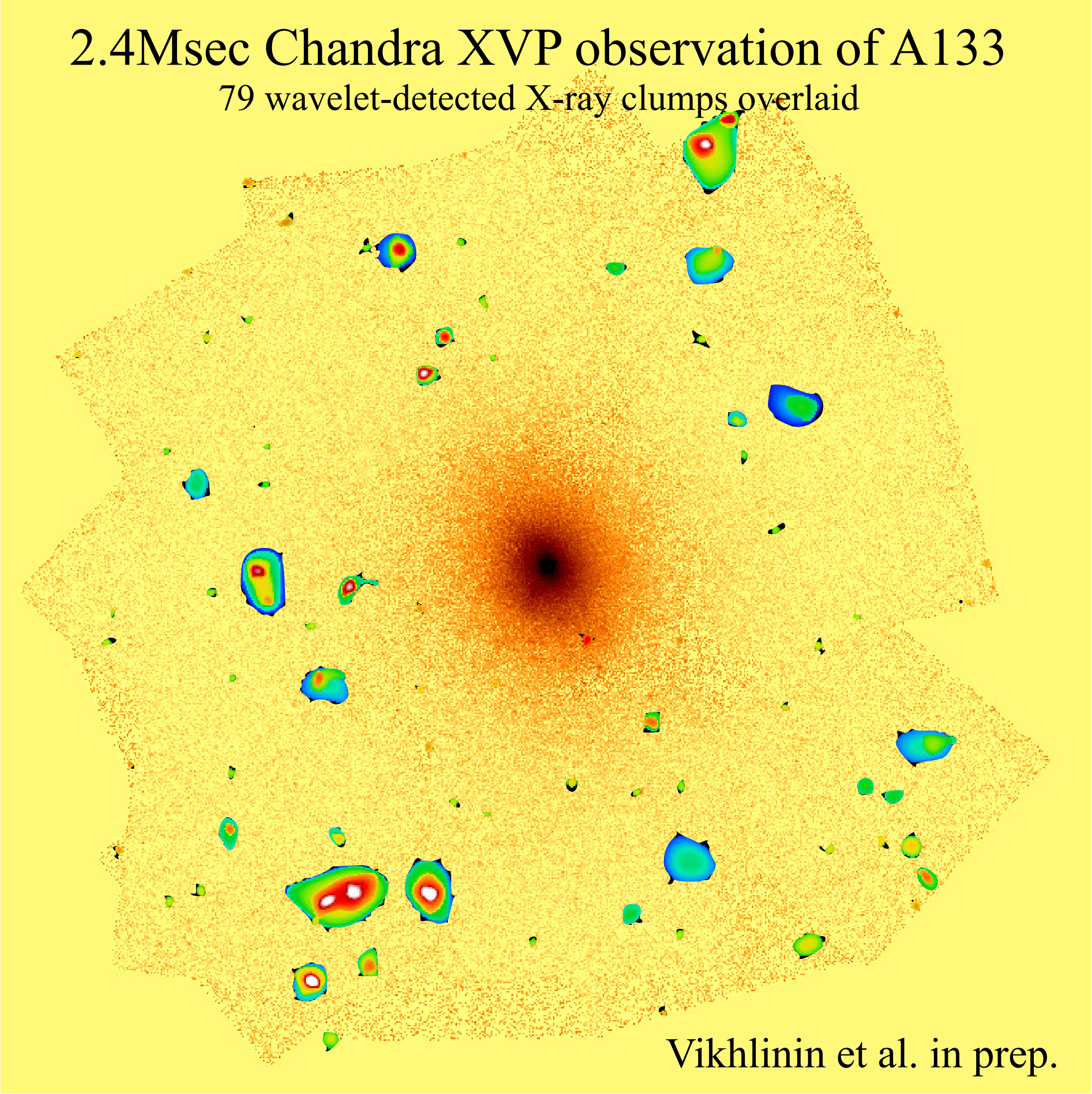

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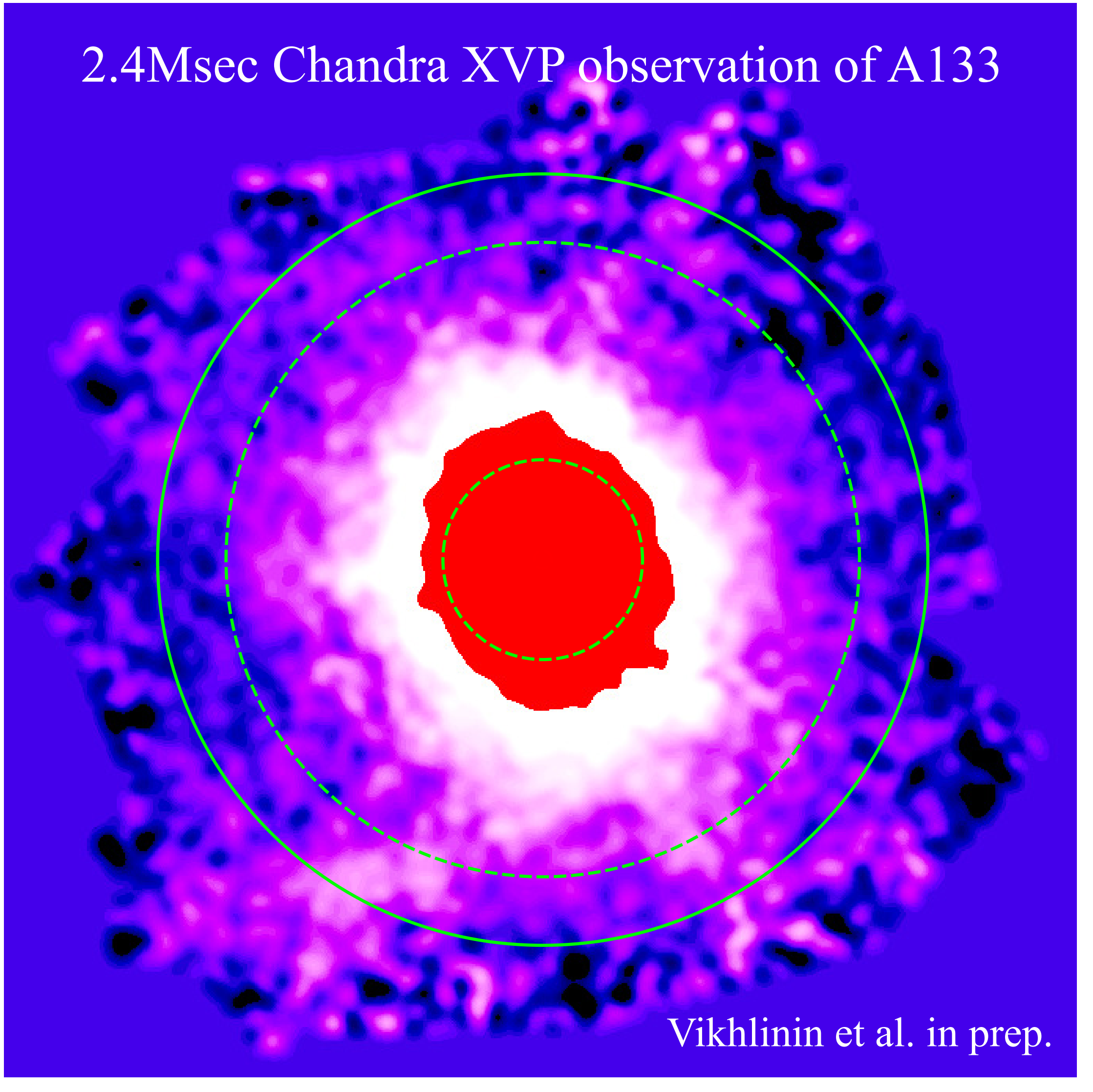
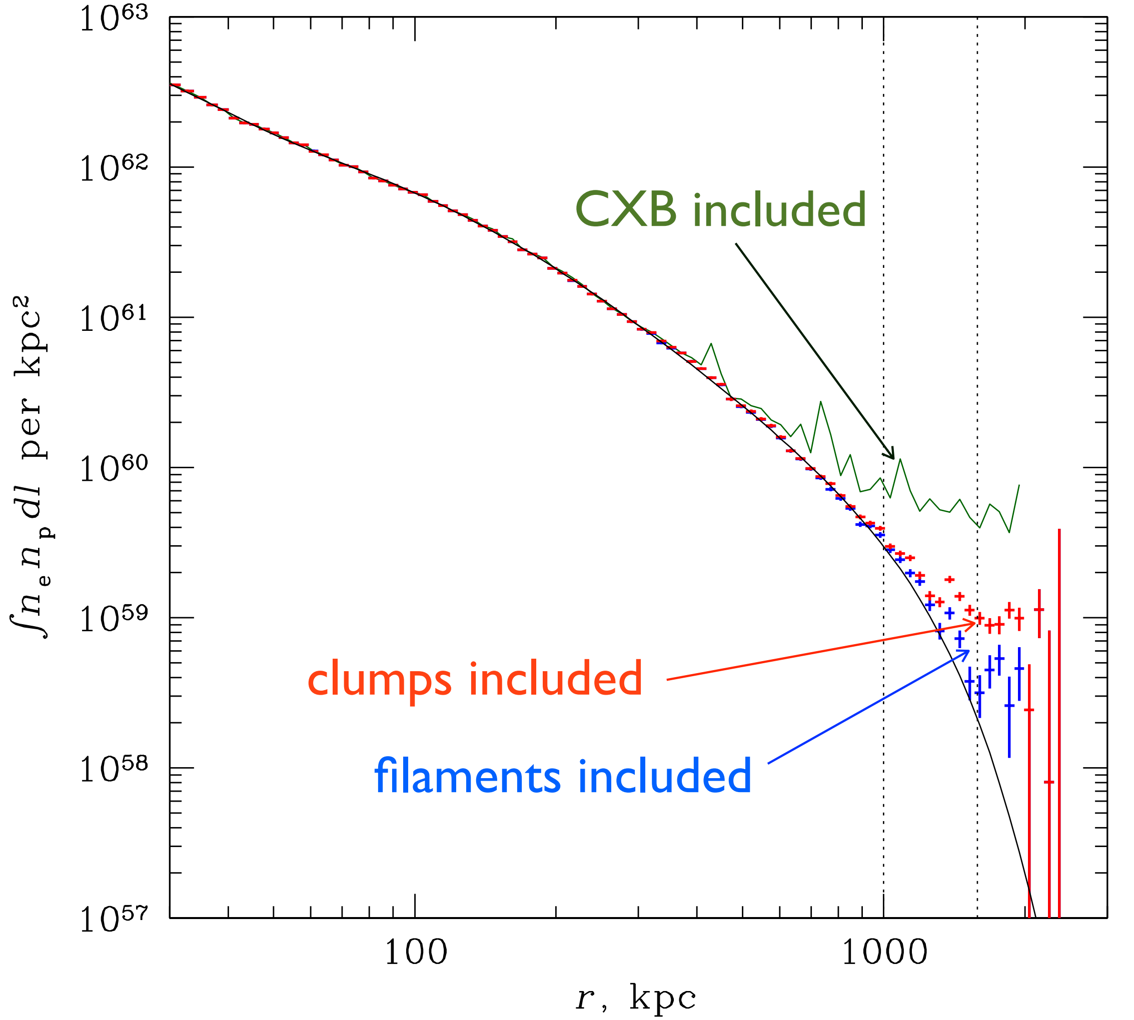
Filamentary Morphology in Cluster Outskirts



Heavily smoothed image with all point sources & detected small-scale extended clumps removed, showing the azimuthally symmetric to filamentary morphology outside R_{500}.

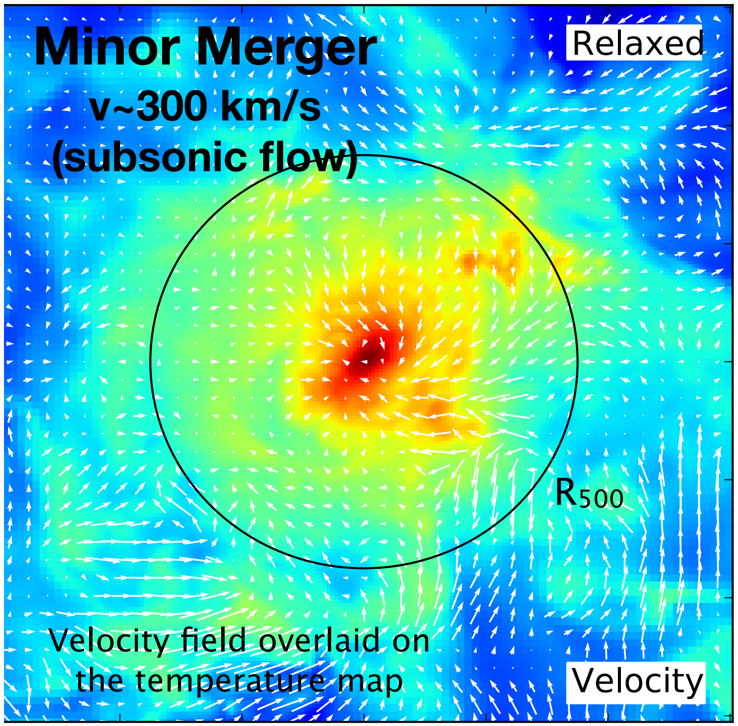
Evidence for Gas Clumping in Cluster Outskirts

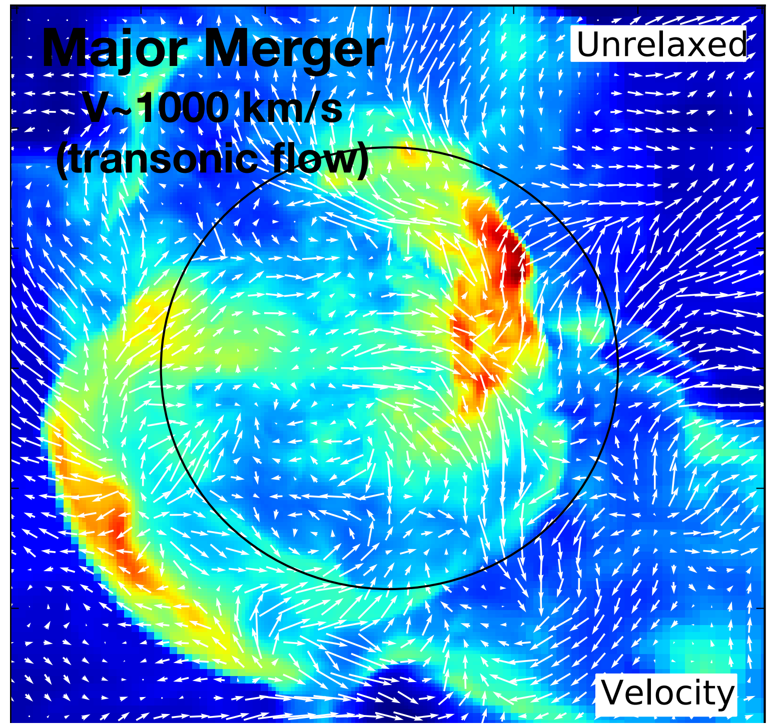


Superb angular resolution and sensitivities of Chandra are critical for studying the outskirts of galaxy clusters.

Missing Cluster Astrophysics #3
Merger-Induced Gas Motions in Clusters

Nelson, Lau, Nagai, Rudd, Yu 2013 (astro-ph/1308.6589)
Large (>80) sample of simulated galaxy clusters with M_{500}>3x10^{14}Msun/h
(also Rasia+06, Nagai+07, Lau+09, Nelson+12, Suto+13, Lau+13; Talk by Daichi Suto)

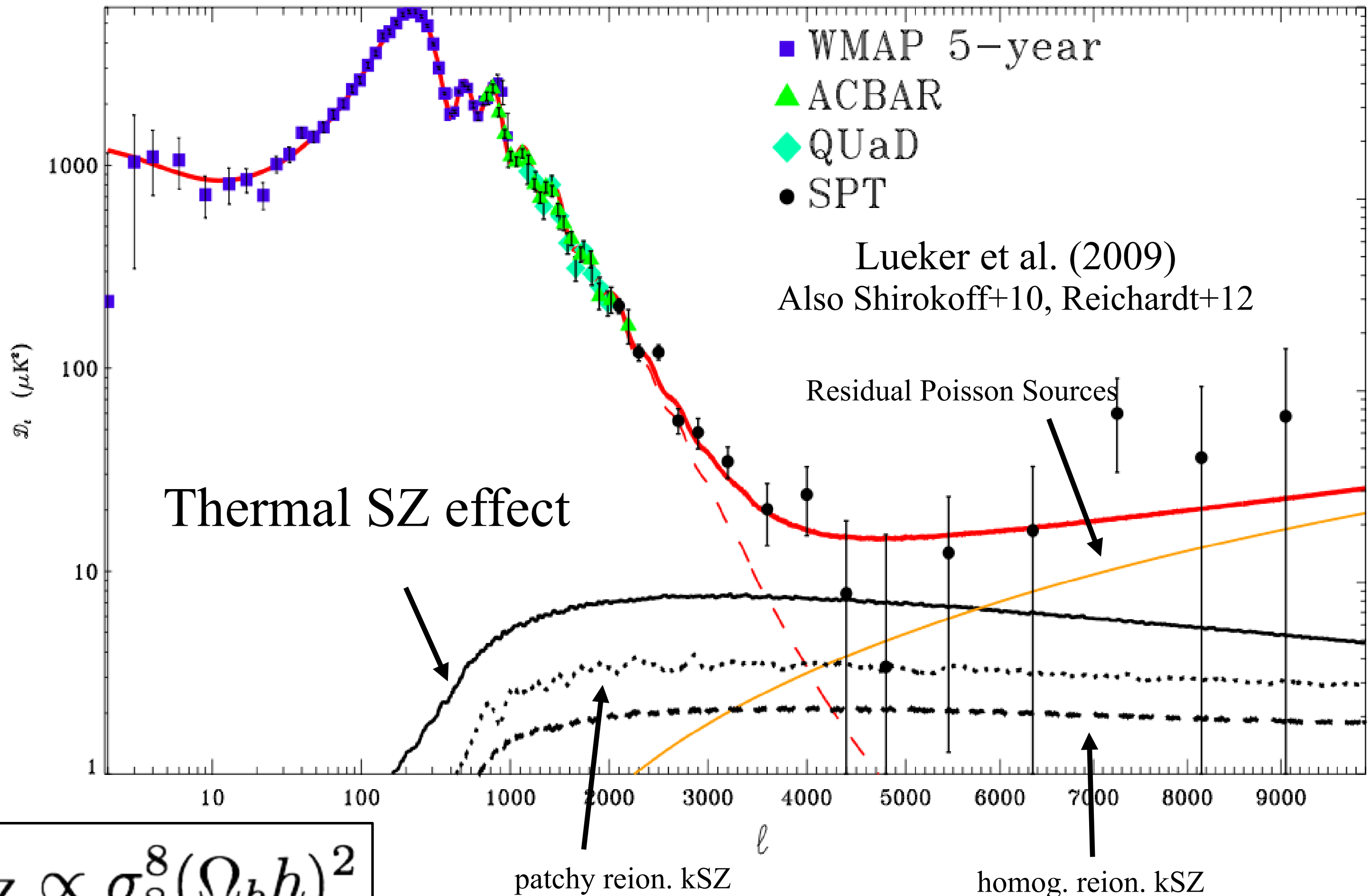




Hydrodynamical simulations predict turbulent gas motions in clusters, and they introduce biases in the hydrostatic cluster mass estimates at the level of ~20%.

Observationally, we know very little about turbulence in clusters..

Measurements of the SZ power spectrum



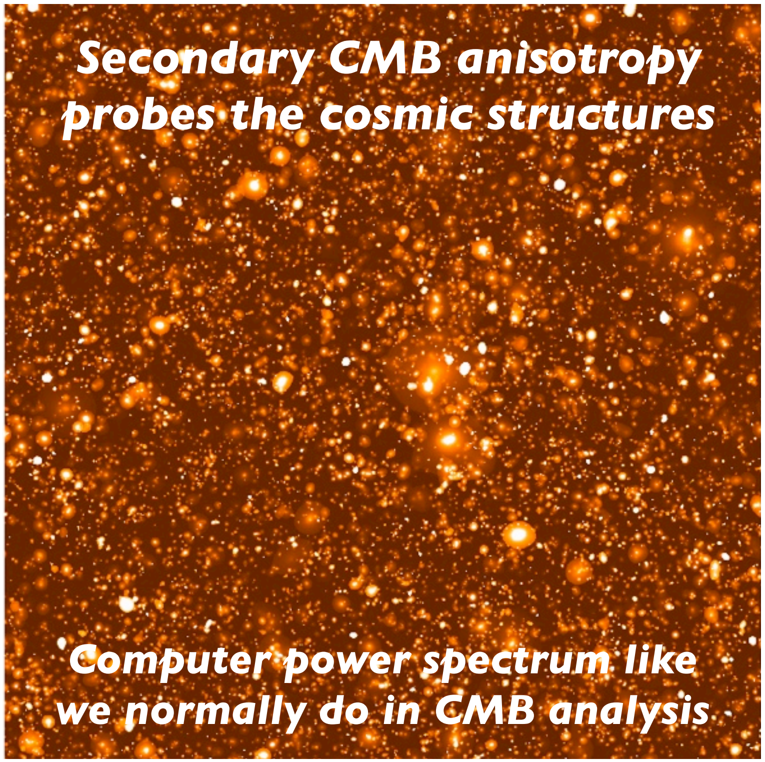
$$C_{\ell,\mathrm{tSZ}} \propto \sigma_8^8 (\Omega_b h)^2$$

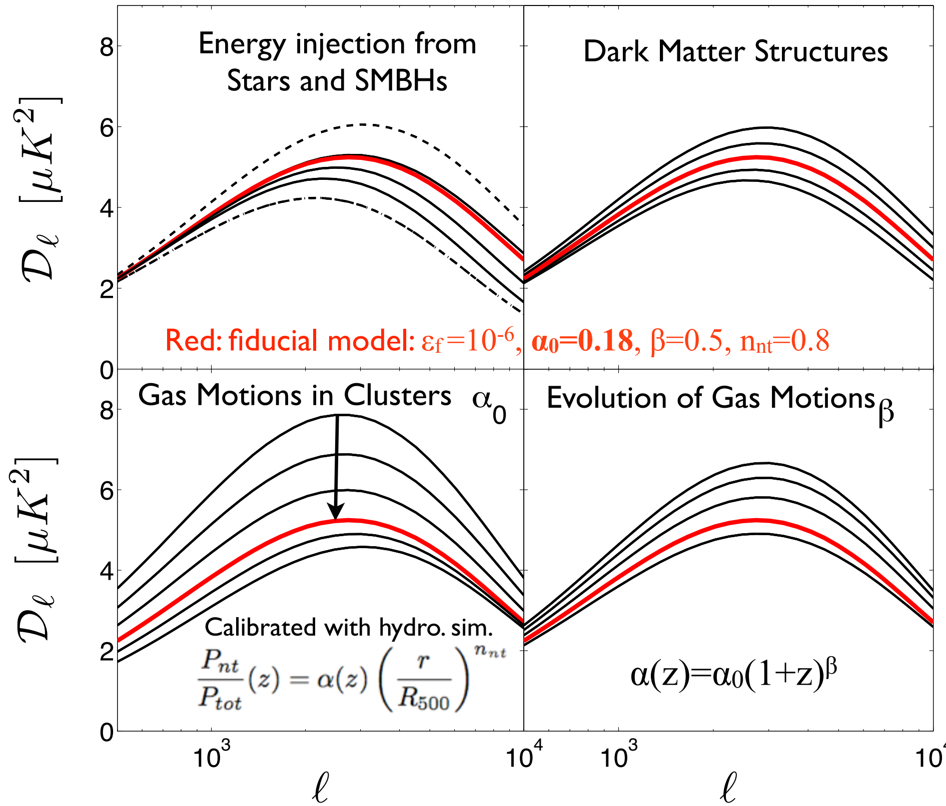
The SZ power spectrum also contains information about galaxy clusters.

PUZZLE: But, the measured SZ power was only half of what was predicted..

Astrophysical Uncertainty in the SZ power spectrum

Thermal SZ power spectrum contains significant contributions from outskirts of low mass ($M<3\times10^{14}$ Msun), high-z ($z>1$) groups at $l<5000$

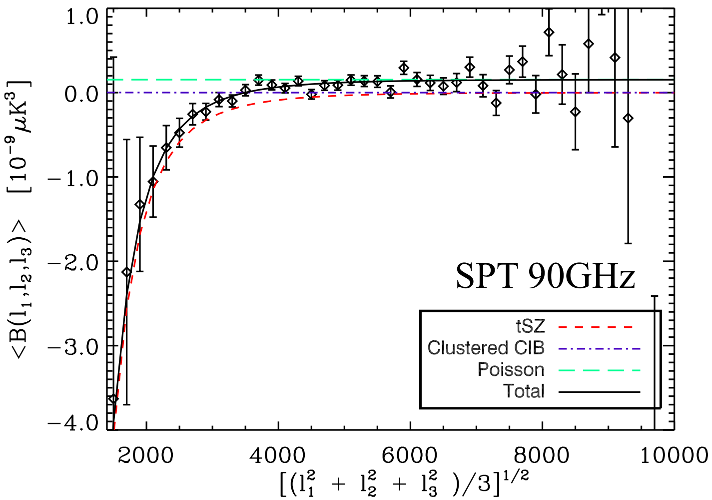


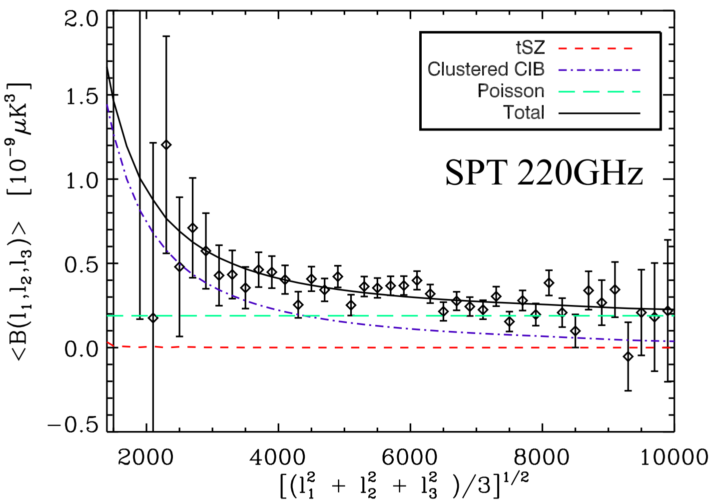


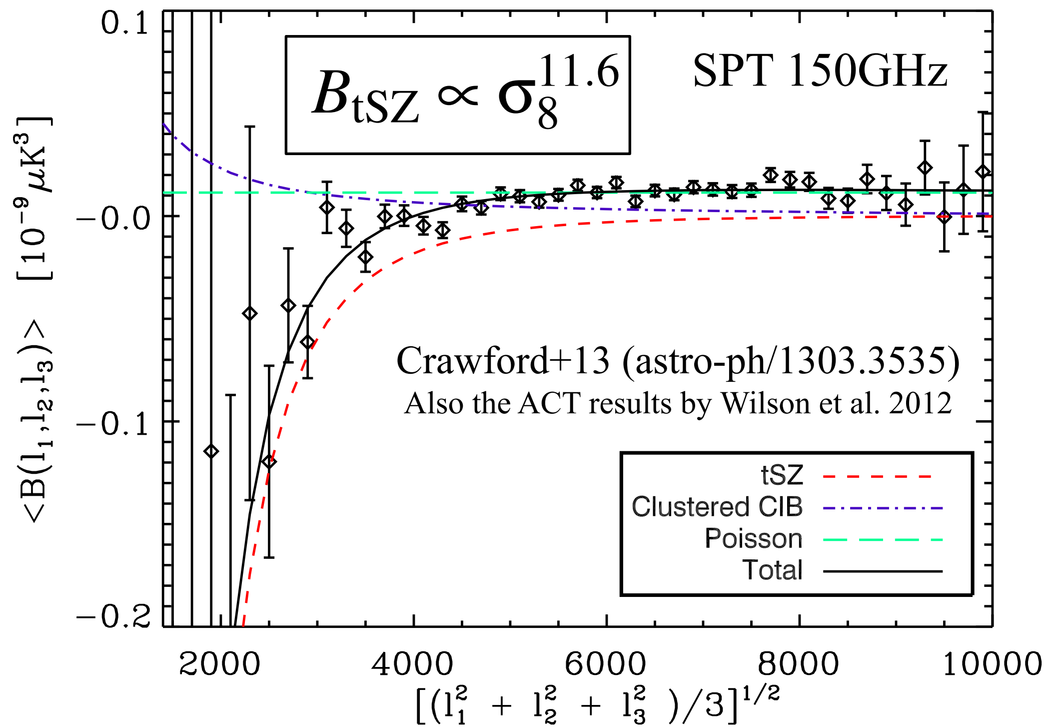
Non-thermal pressure support due to gas motions in clusters is a dominant source of systematic uncertainty.

Shaw, Nagai, Bhattacharya, Lau, 2010, ApJ, 725, 1452

The SZ bispectrum measurements







$\sigma_8 = 0.786 \pm 0.031$

using a template with gas motions

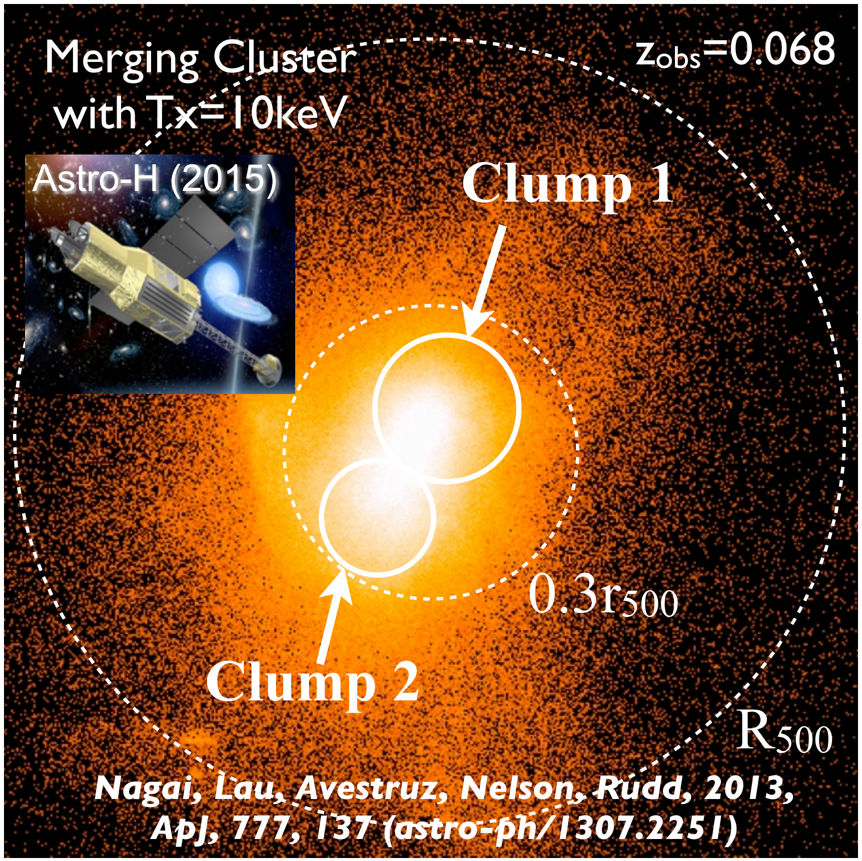
The SZ bispectrum is sensitive to **the outskirts of massive clusters at intermediate redshift (z~0.3-0.5)**. Insensitive to the kSZ signal & less sensitive to gastrophysics than the power spectrum.

Bhattacharya, Nagai, Shaw, Crawford, & Holder, 2012, ApJ, 760, 5

also Hill & Sherwin 2013

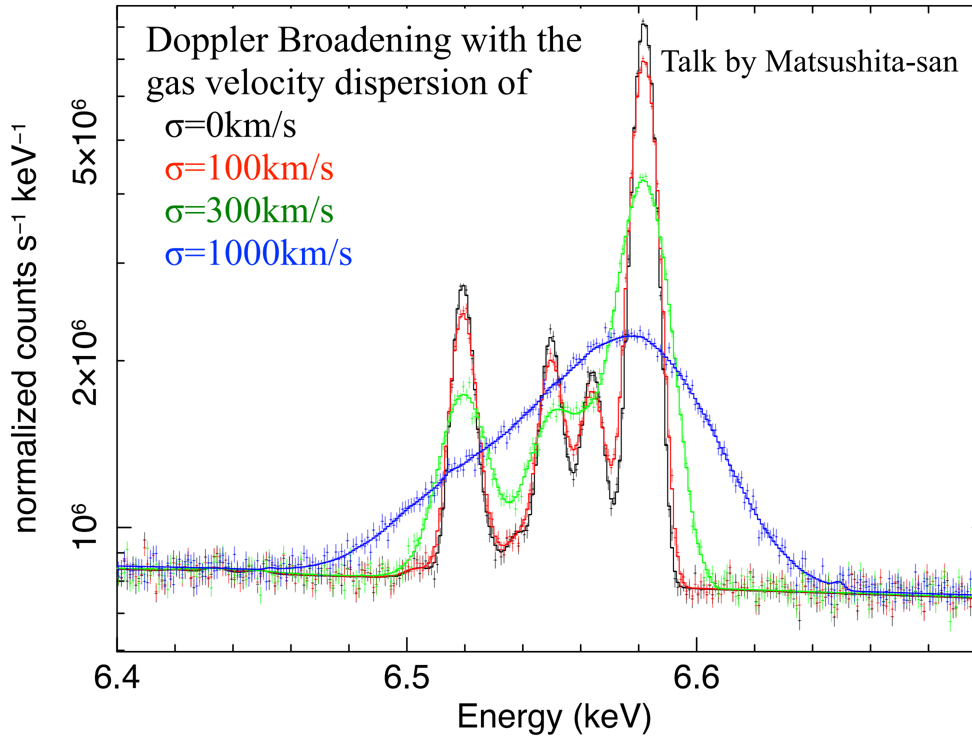
Probing Gas Motions in Galaxy Clusters with Astro-H X-ray mission

Predicting what Astro-H will see.



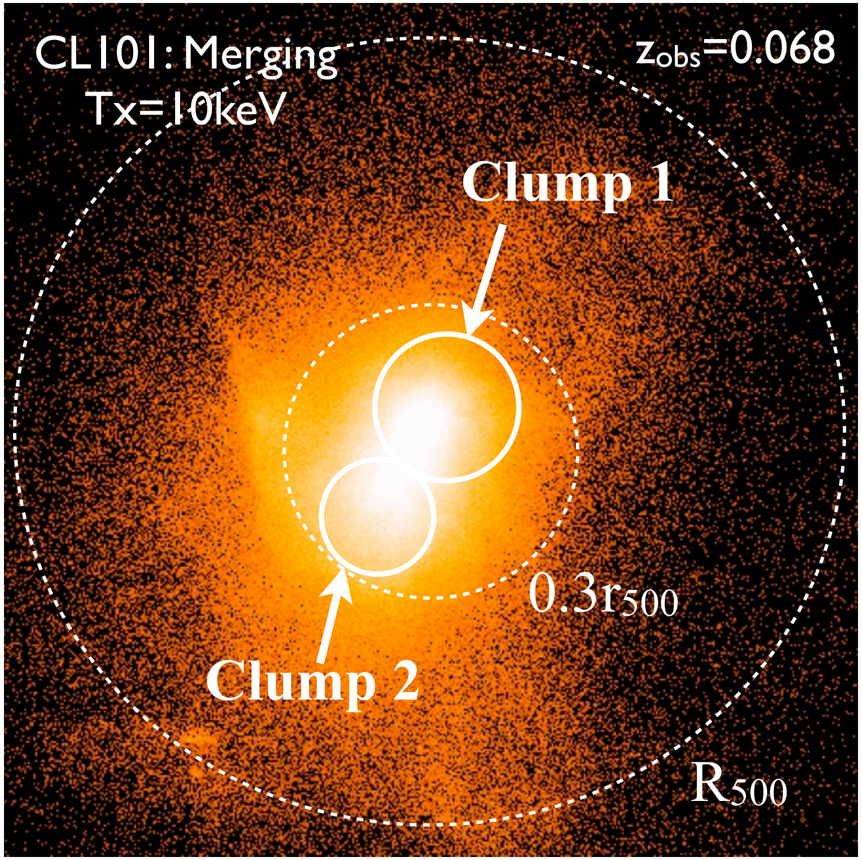
Measuring turbulent gas velocities with the Doppler Broadening of Fe lines

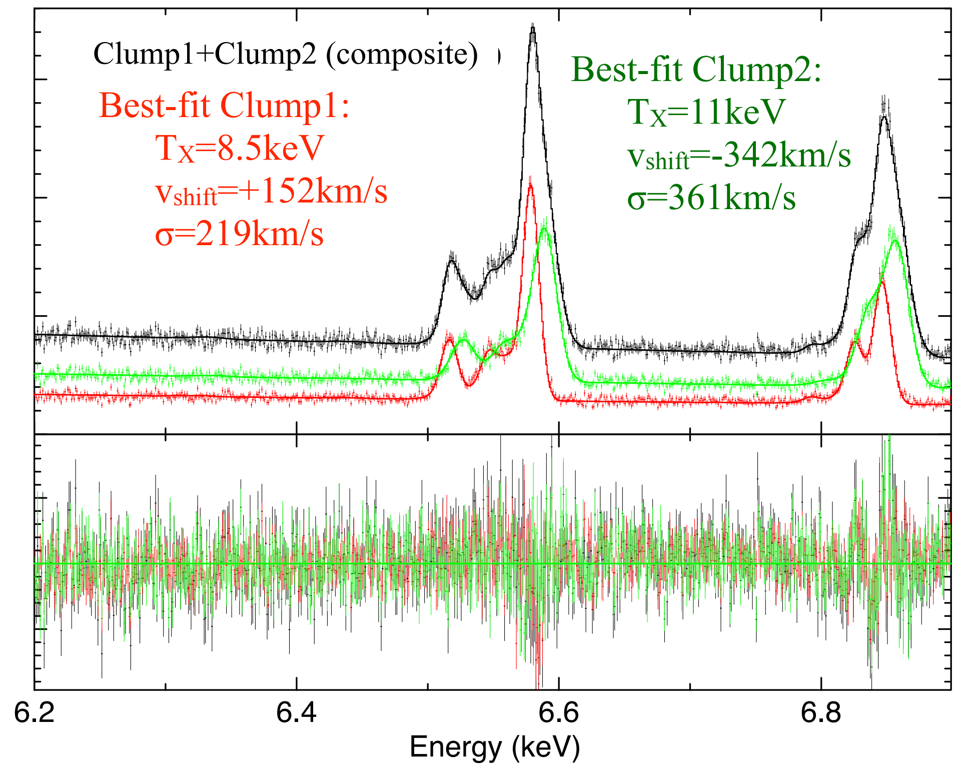
T=10.0 keV z=0.018 ΔE =7eV



Astro-H will measure peculiar velocity and turbulent gas flows in the inner regions of nearby, massive galaxy clusters via shifting and broadening of Fe line.

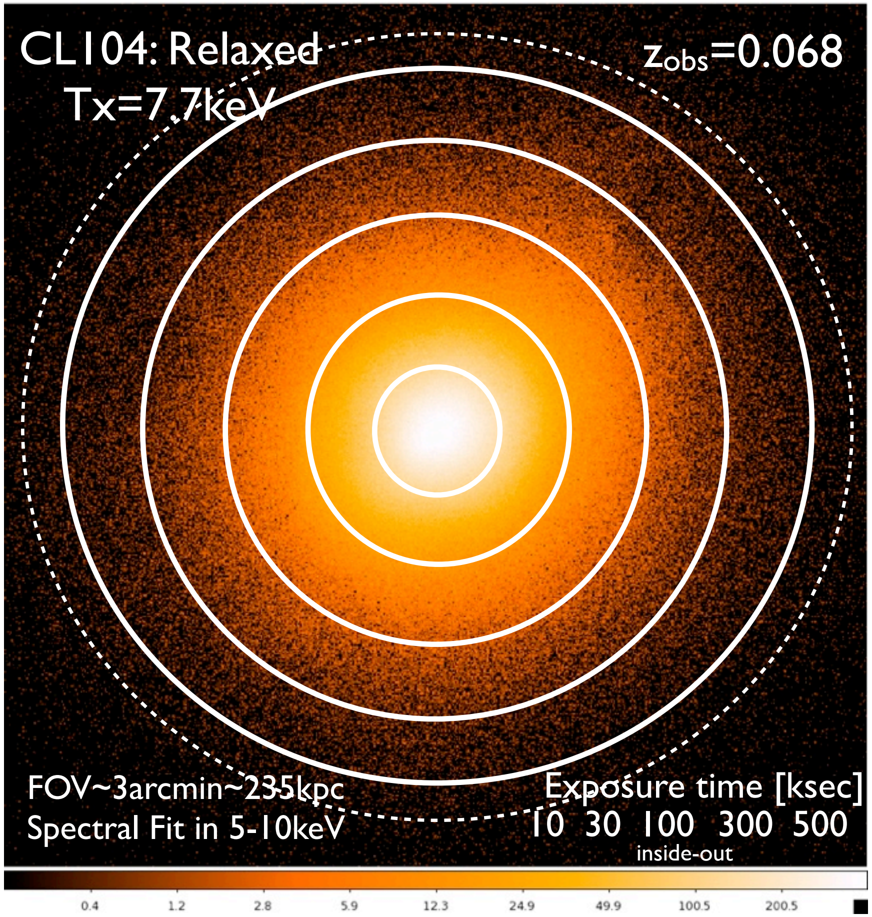
Probing Dynamics and Substructures of Merging Clusters with Astro-H

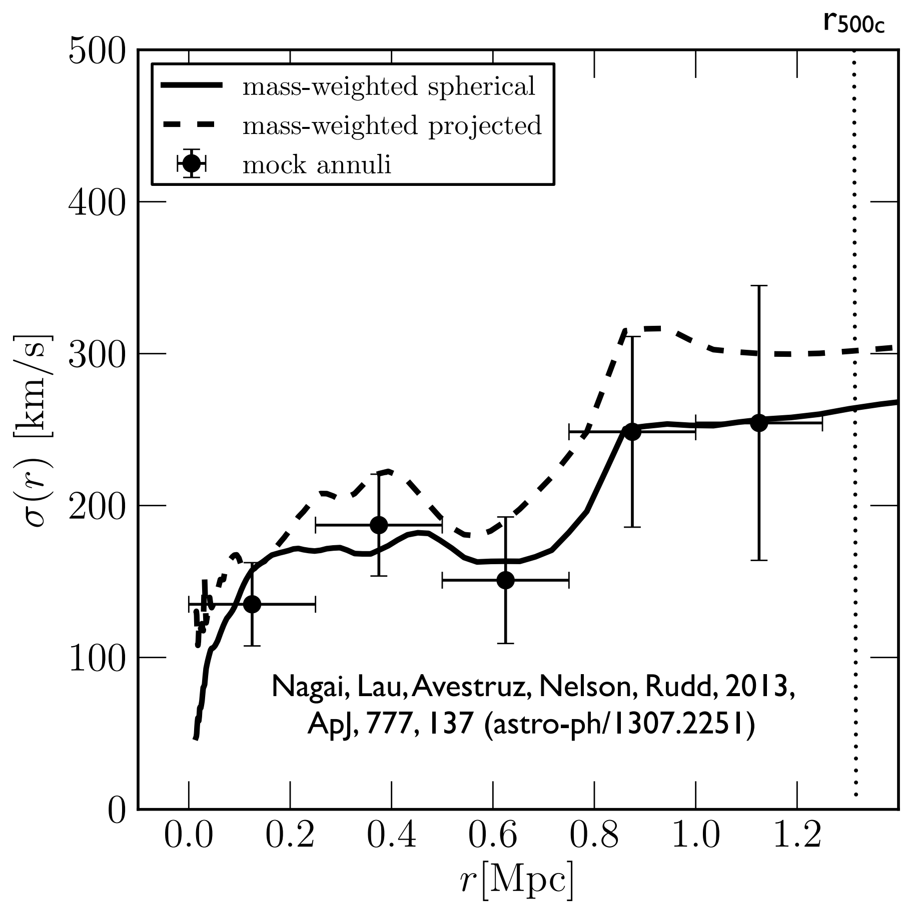




Multiple components are required for the merging cluster.
Astro-H spectra can reveal substructures in velocity space.

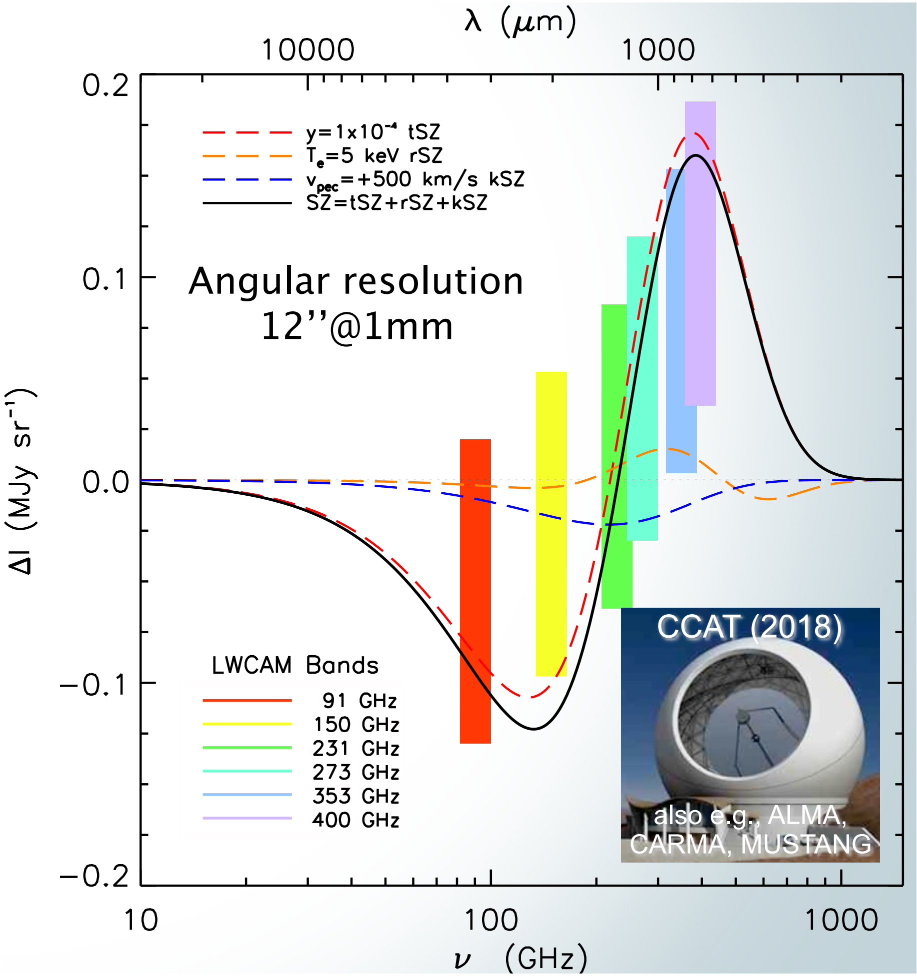
Probing Gas Motions in Galaxy Clusters with deep Astro-H observation



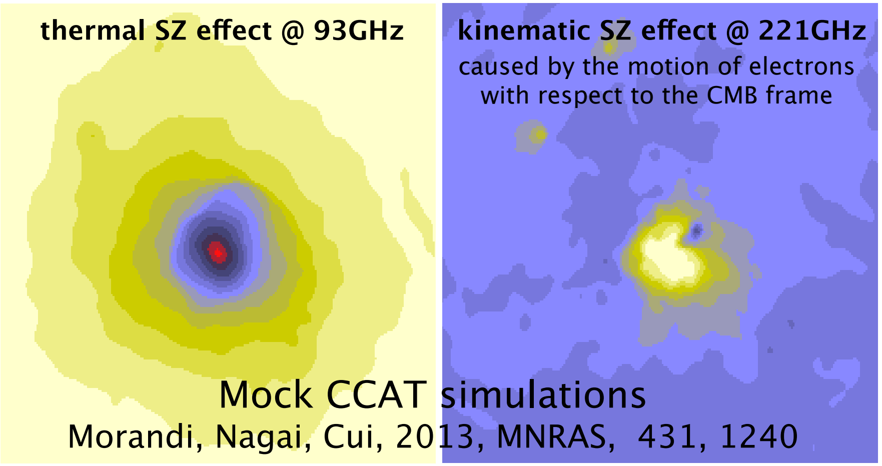


Deep Astro-H observations can map out the gas velocity profile out to R_{500}.

High-Resolution SZ studies of Individual Clusters with the next-generation radio telescopes

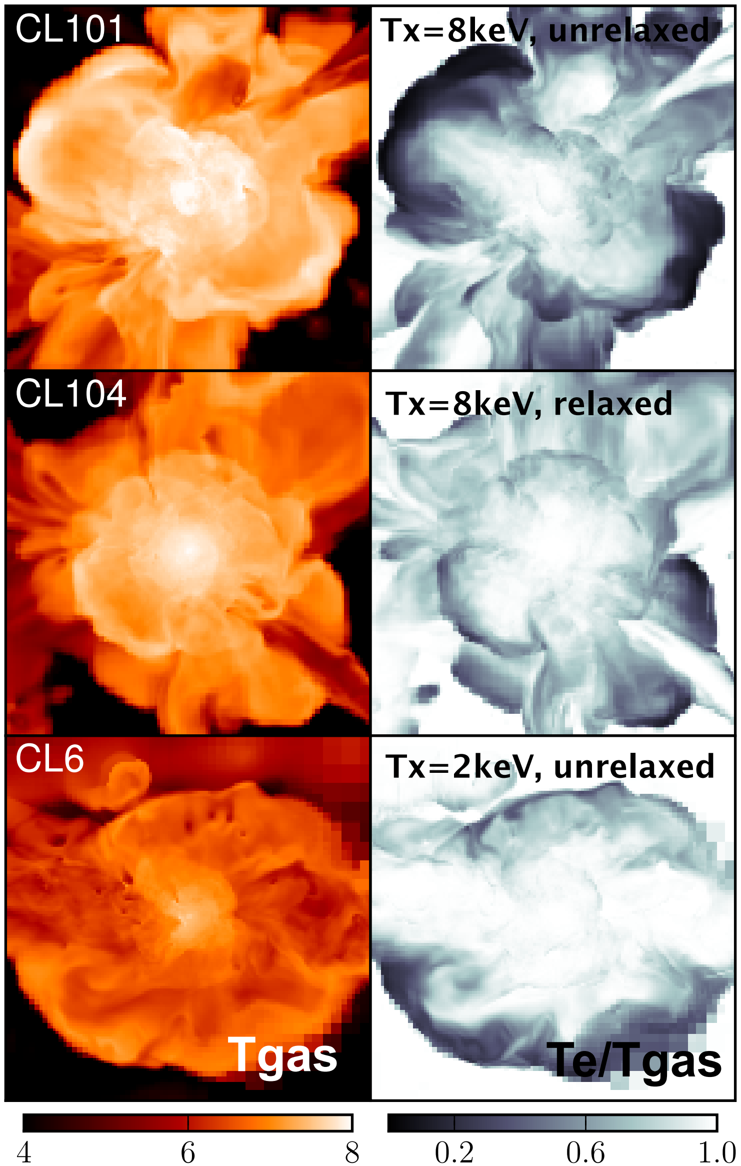


- **_Thermodynamic structure of the ICM_**
  - **_Temperature profile via SZ relativistic corrections (independently from X-ray)_**
  - **_Inhomogeneities in the ICM (gas clumping)_**
- **_Non-thermal pressure in clusters_**
  - **_Bulk vs. Turbulent motions via kSZ substructure_**

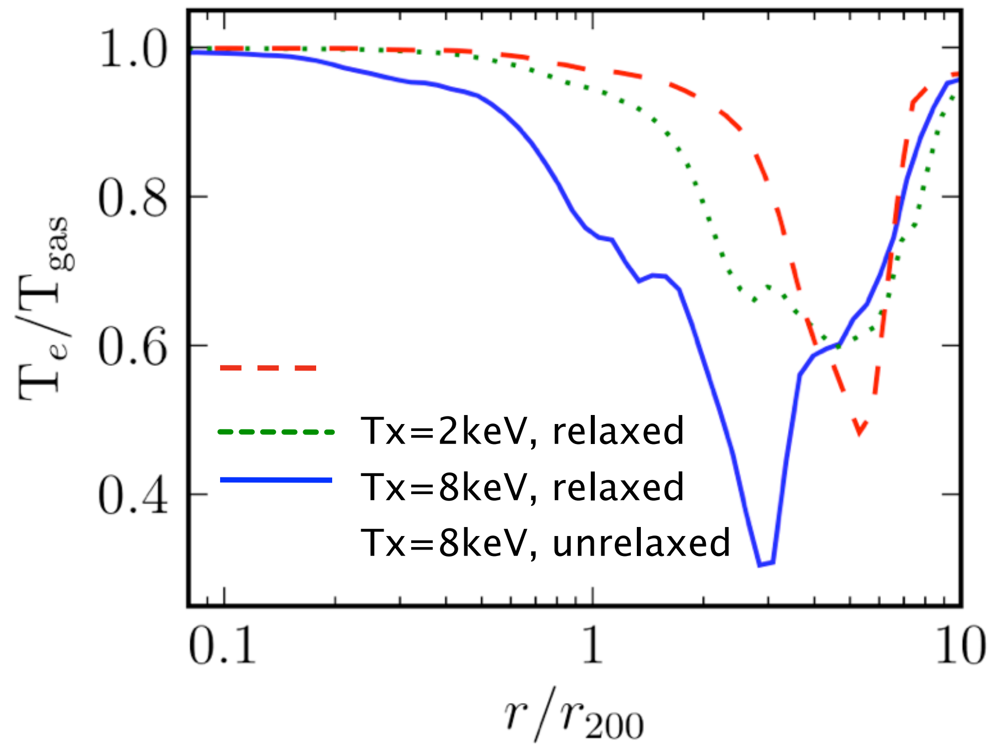


High-resolution, multifrequency SZE observations are sensitive to thermodynamic and velocity structures of the hot gas in the outskirts of galaxy clusters.

Missing Cluster Astrophysics #4
Plasma Physics in Cluster Outskirts



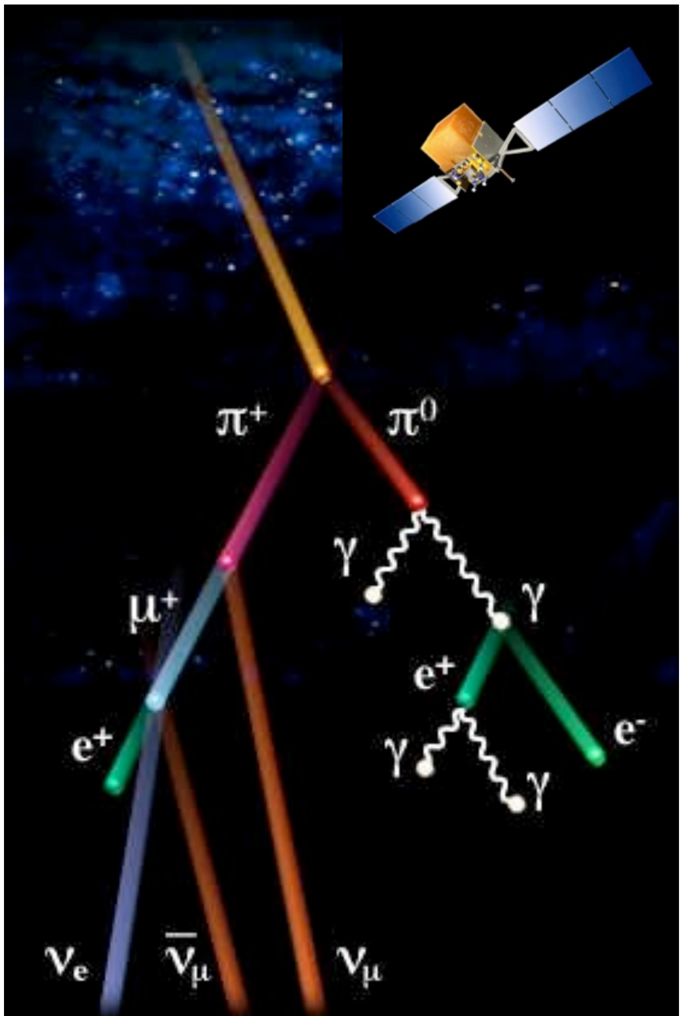
In the outskirts of galaxy clusters, the collision rate of electrons and protons becomes longer than the age of the universe.



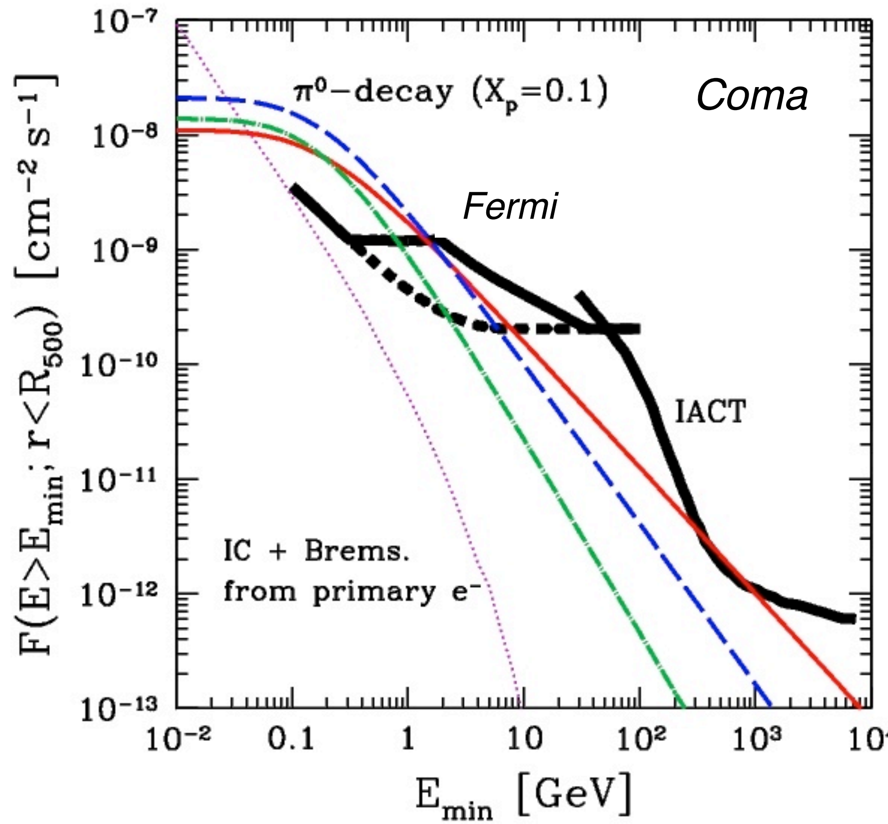
Rudd & Nagai, 2009
Spitzer 1962, Takizawa 1999, Chuzhoy & Loeb 2004, Akahori & Yoshikawa 2010 - Talk by Yoshikawa-san

Missing Cluster Astrophysics #5
Non-thermal pressure by cosmic-rays

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



Fermi provides stringent constraints (<1%) on the cosmic-ray protons in nearby, rich clusters



Ando & Nagai 2008

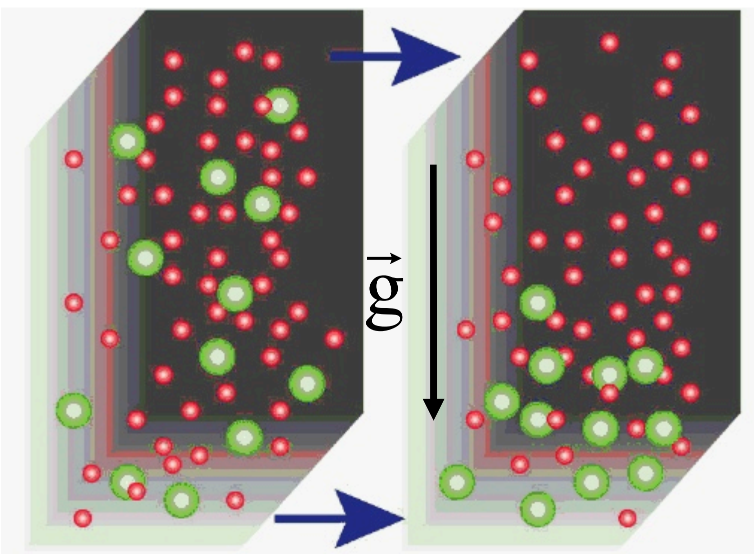
also Pfrommer+08; Jeltema+09; Pinske+11, Zandanel & Ando+13

Missing Cluster Astrophysics #6
He sedimentation in Galaxy Clusters

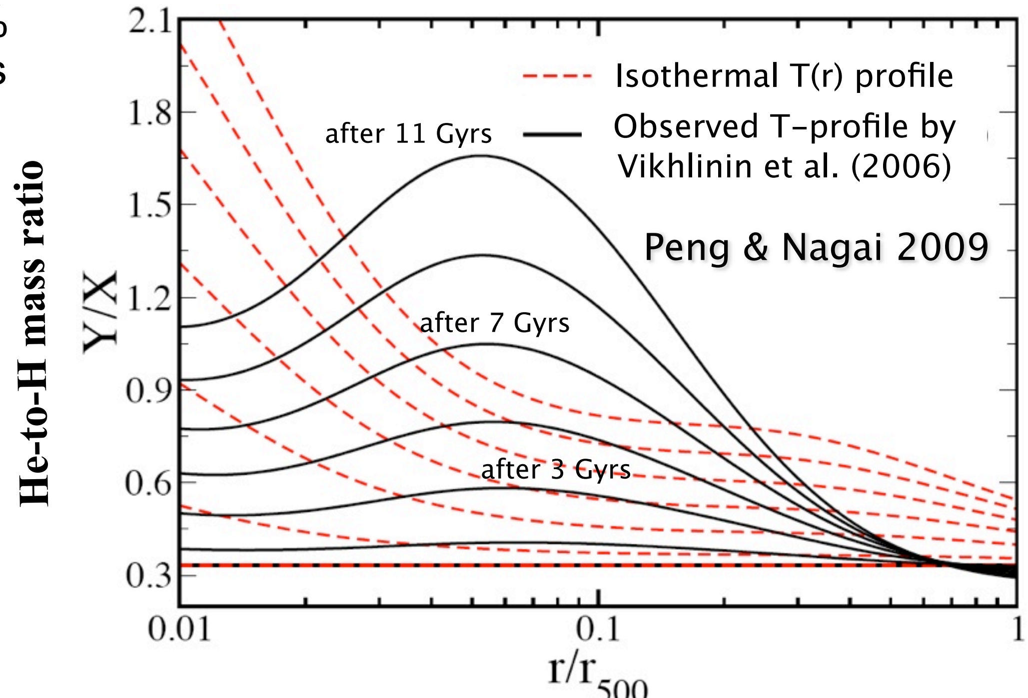
$$M_{\rm tot}(<r) = \frac{-r^2}{G\rho}\frac{dP_{\rm ther}}{dr} \propto \frac{1}{\mu} = \frac{8+3(Y/X)}{4+4(Y/X)}$$

$$\rho_{\rm gas} \propto n_{\rm p} + 4n_{\rm He} \propto \left(\frac{4+4(Y/X)}{4+2(Y/X)}\right)^{1/2}$$

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 massive relaxed galaxy clusters at several percent level within the virialized regions of clusters ($r<R_{500}$).

also Abramopoulos1981, Gilfanov & Sunyaev1984, Qin & Wu2000, Chuzhoy & Nusser2003, Chuzhoy & Loeb 2004, Ettori & Fabian 2006

Missing Cluster Astrophysics #6
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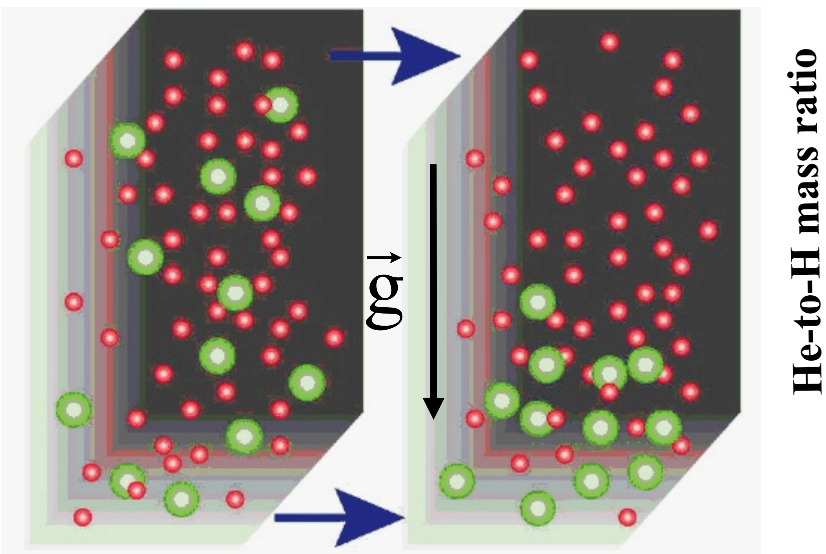
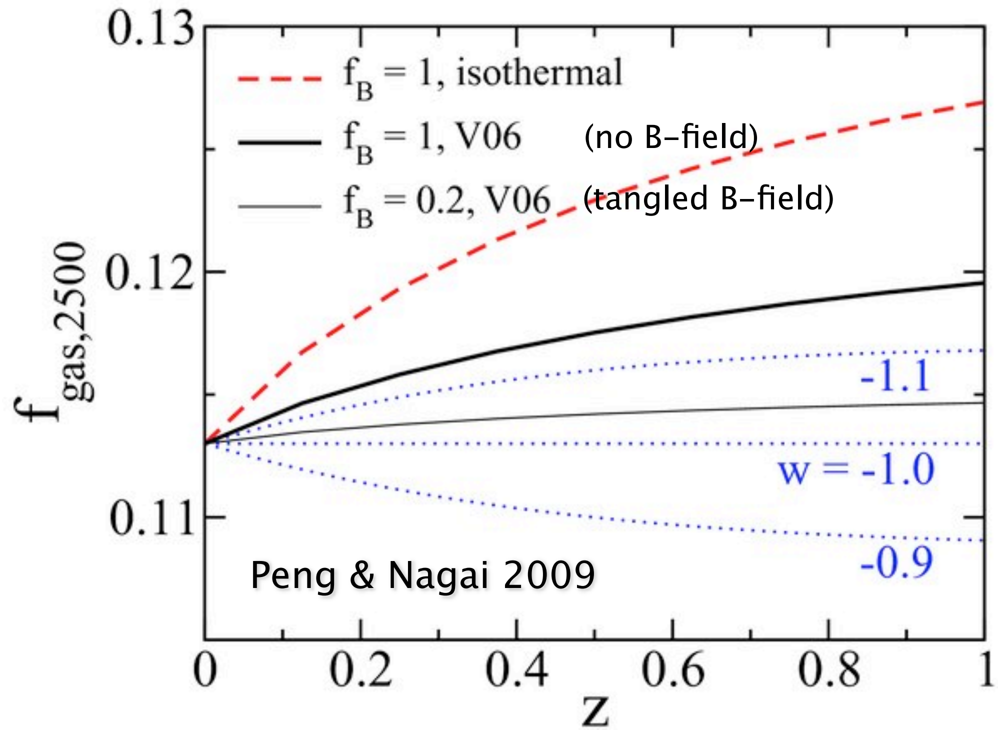
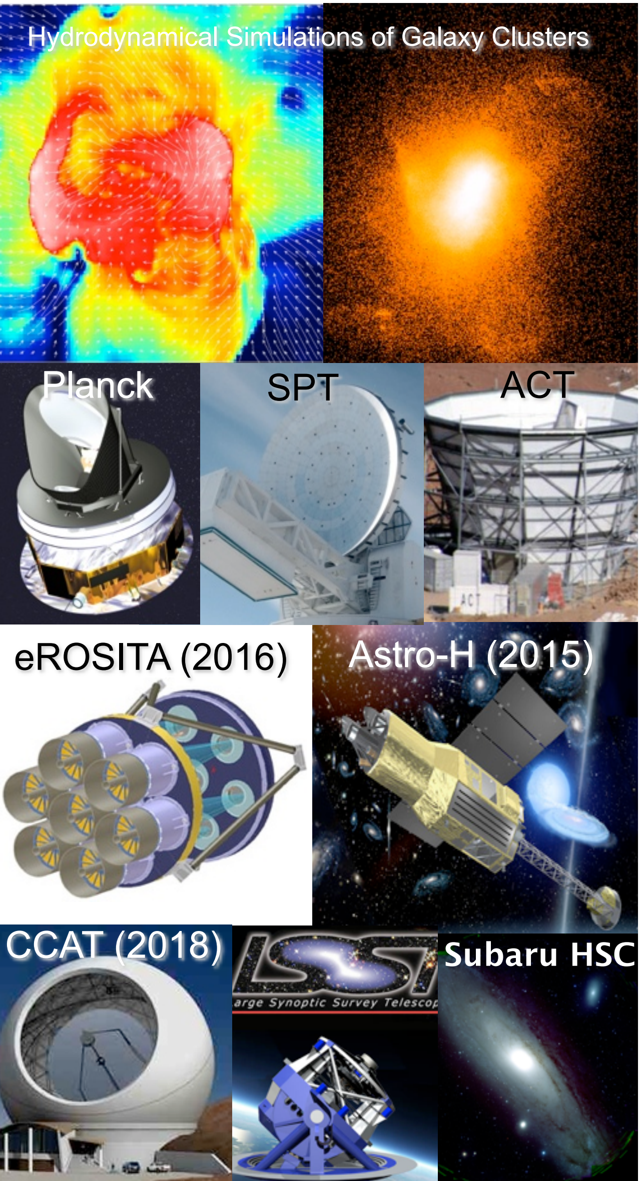


Solving the diffusion equations for the fully ionized H-He plasma in the NFW potential



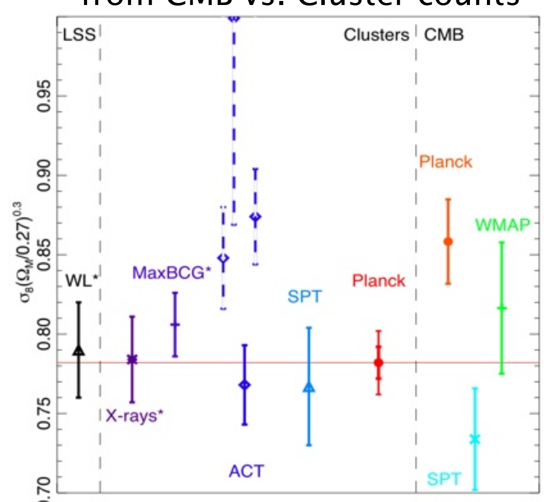
The effect of He sedimentation is degenerate with the effect of the equation of state of dark energy, w. The cluster-based cosmological constraints aiming to measure w to better than 5% (at $r \sim R_{2500}$) must take this effect into account or go to cluster outskirts ($r \sim R_{500}$).

Galaxy Clusters in the Era of Precision Cosmology



- **Cosmology & Fundamental Physics**
  - *Cluster counts: mass calibration!!*
  - *Power spectra & bispectra: complementary*
- **Cluster Astrophysics**
  - *Turbulent & bulk gas motions in outskirts*
  - *Substructures/inhomogeneities in outskirts*
  - *AGN feedback in cluster cores*
  - *Plasma Physics: cosmic-ray, magnetic field, non-equilibrium electrons, He sedimentation*

Planck Cosmological Constraints from CMB vs. Cluster counts



Searching for Missing Energy