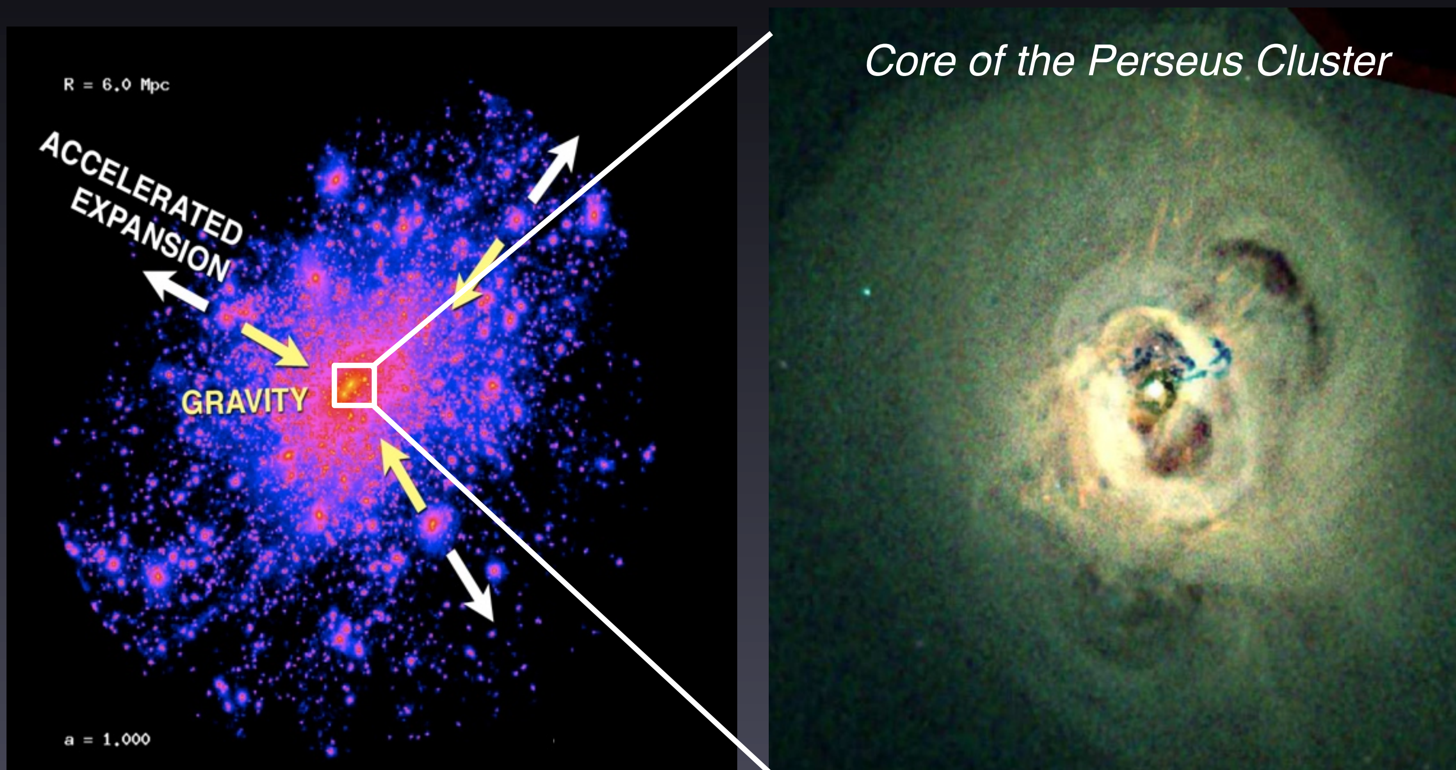
Galaxy Clusters in the Era of Precision Cosmology



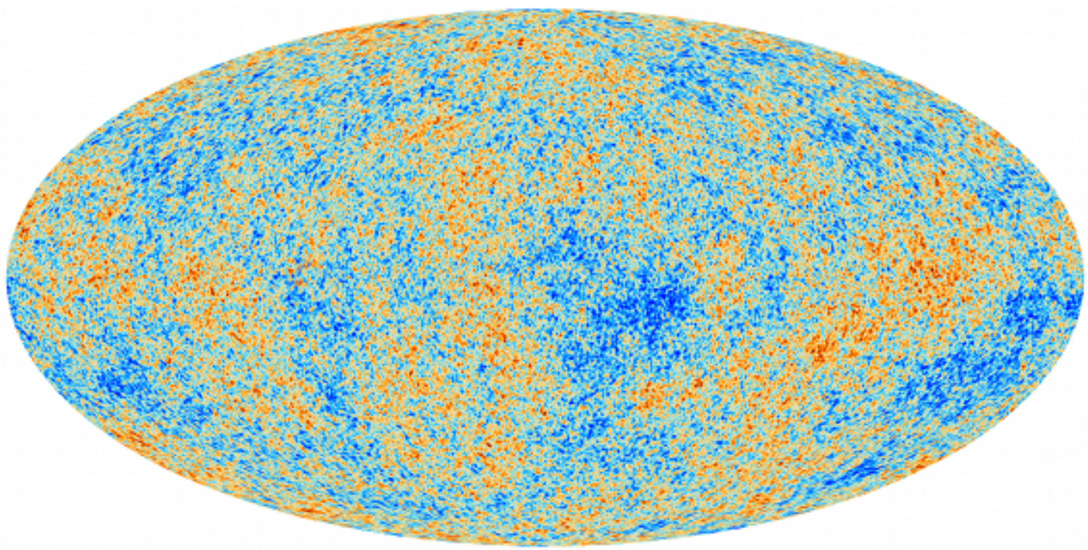
Daisuke Nagai

Yale University

SSL Colloquium, Berkeley

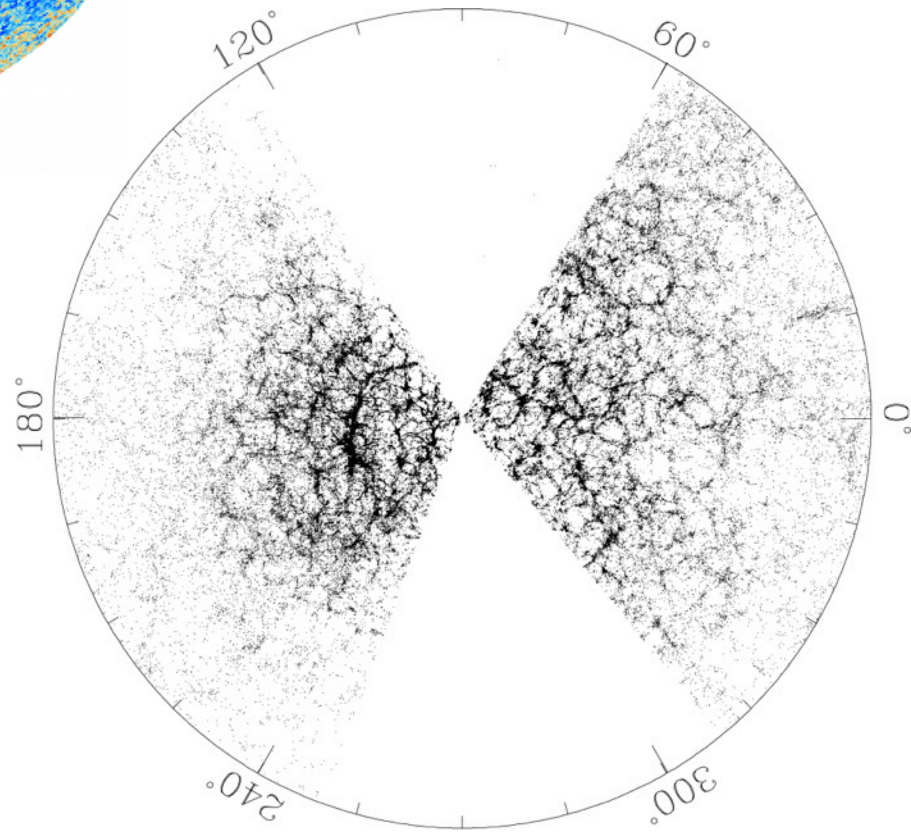
December 13th, 2013

Large-scale structure in the Universe



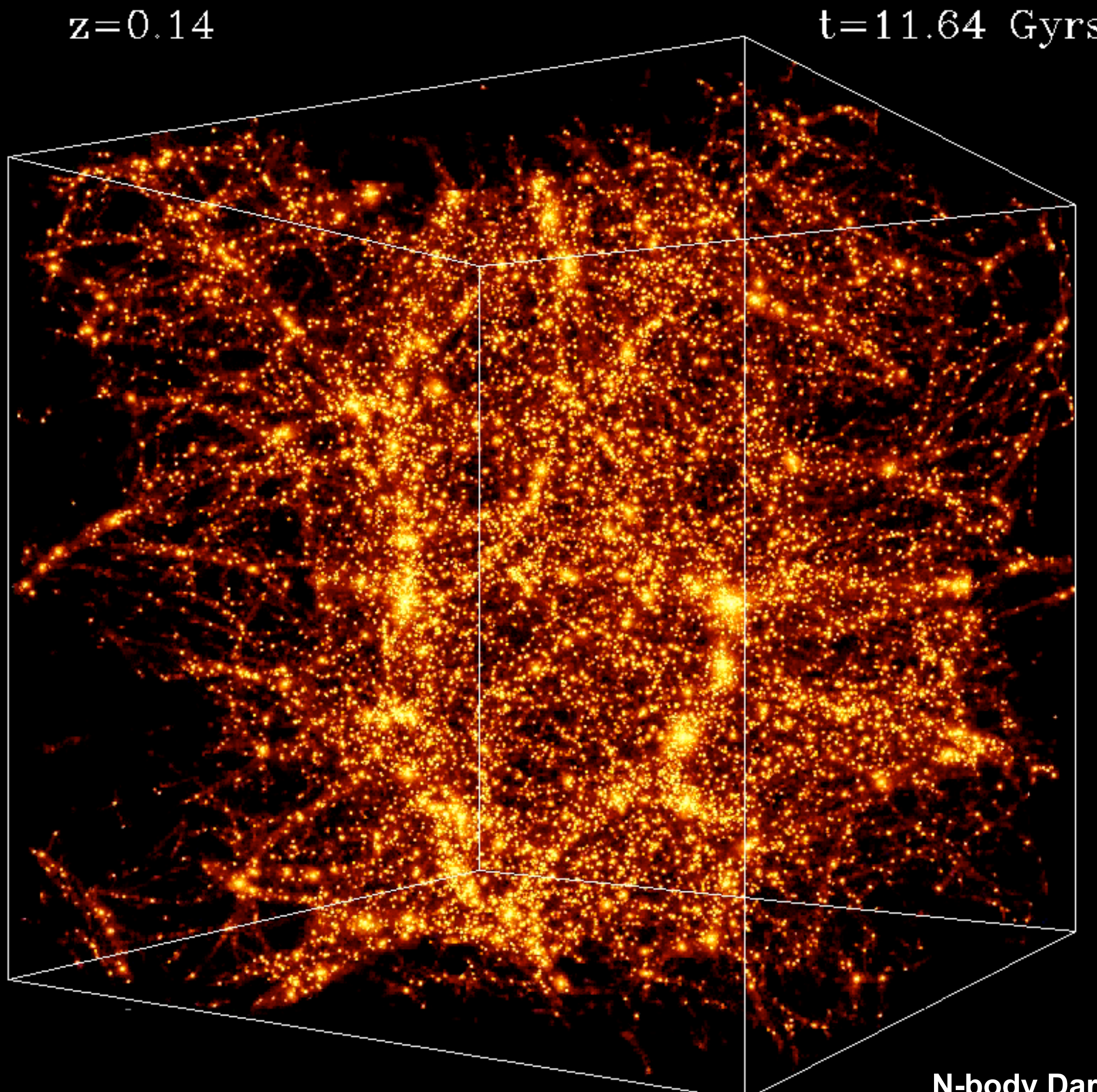
Planck (microwave)
Early Universe
$\delta\rho/\rho \sim 10^{-5}$

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



Simulating Structure Formation in the Universe

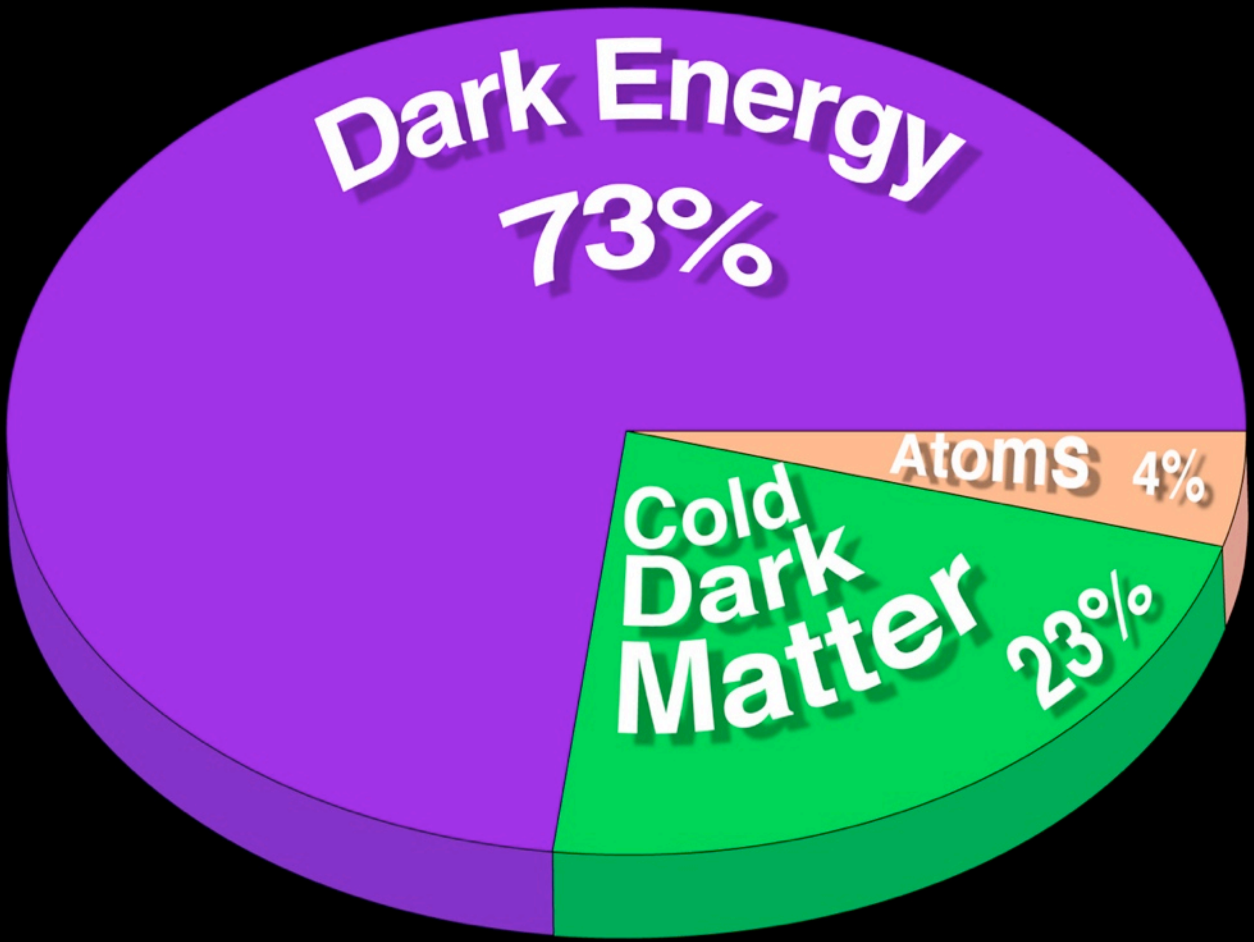
Color = Mass Density Distribution of Dark Matter in the Universe



Box size = 100 Mpc (comoving)

N-body Darm Mater simulation with Adaptive Refinement Tree (ART) code

Dark Energy & Dark Matter



What are dark energy & dark matter?
How does the structure form in the Universe?

Probes of Dark Energy and Dark Matter

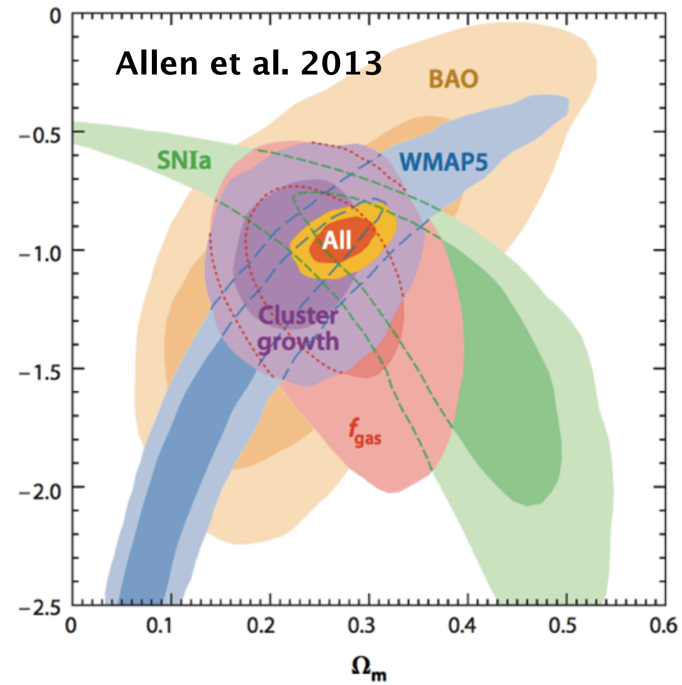
- **Dark Matter**
  - Direct Detection (CDMS, LHC, LUX, Axion-searches)
  - Indirect Astrophysical Probes (Fermi)

- **Dark Energy**
  - Supernova Ia
  - Baryon Acoustic Oscillations
  - Clusters of Galaxies
  - Weak Lensing

Important to have both geometric (SNe, BAO) and growth of structure (clusters, WL) measurements!!

Dark Energy Task Force (2006)

Cosmic Complementarity



Dark Energy energy-density of the universe in units of the critical density

Dark Matter energy-density of the universe in units of the critical density

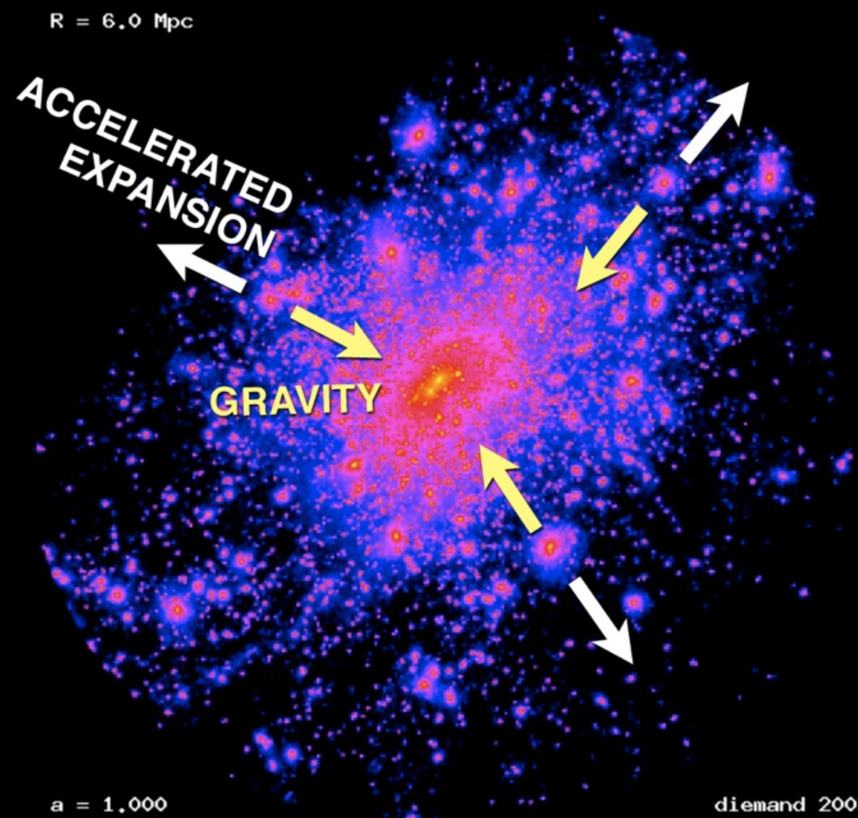
Cluster Cosmology since 1930s

Fritz Zwicky
1898–1974

In 1933, Zwicky used the dynamics of galaxies in Coma cluster to infer the existence of dark matter.

In 2005, the Bullet Cluster "proved" the existence of dark matter.

Recently, the Growth of Galaxy Clusters as probes of dark energy.



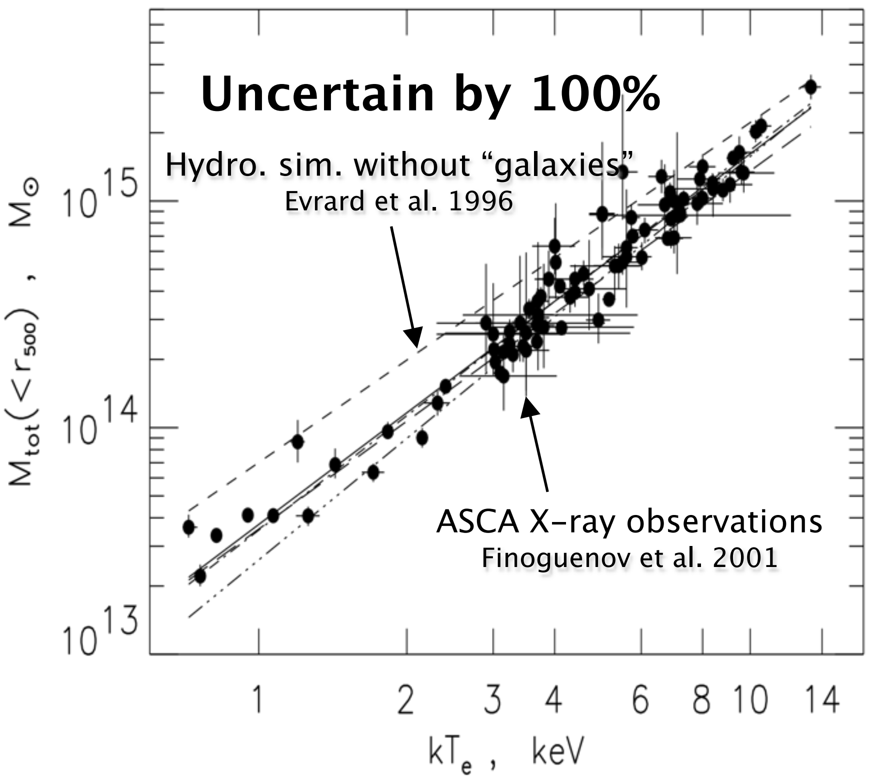
Optical: Rozo+08
X-ray: Allen+04,08; Vikhlinin+09, Mantz+10
Microwave: Benson+13 (SPT), Hasselfield+13 (ACT), Planck+13

Recent Advances and Future Challenges for Cluster Cosmology

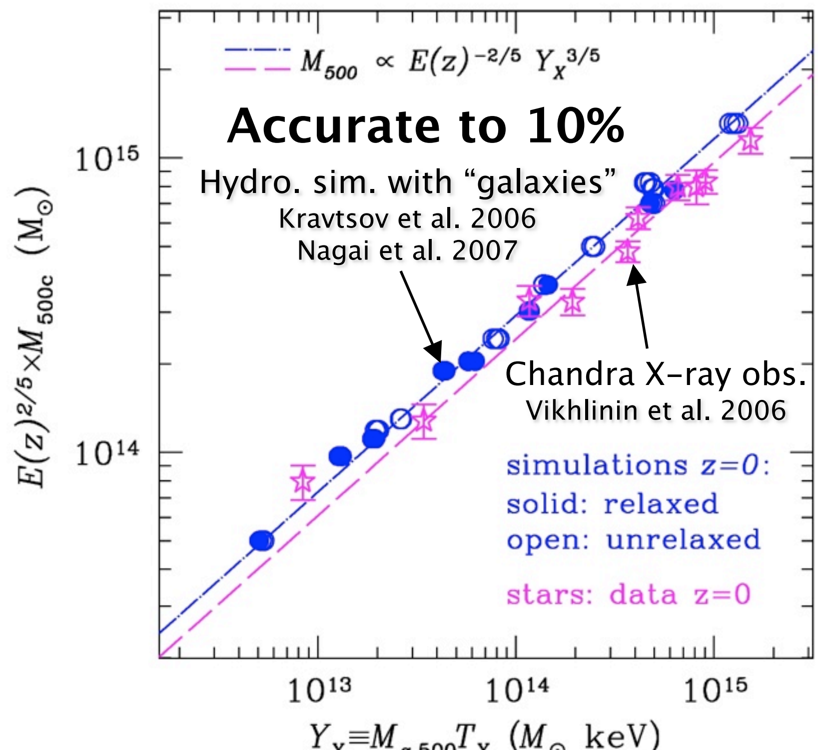
Dark Energy Task Force (2006)

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

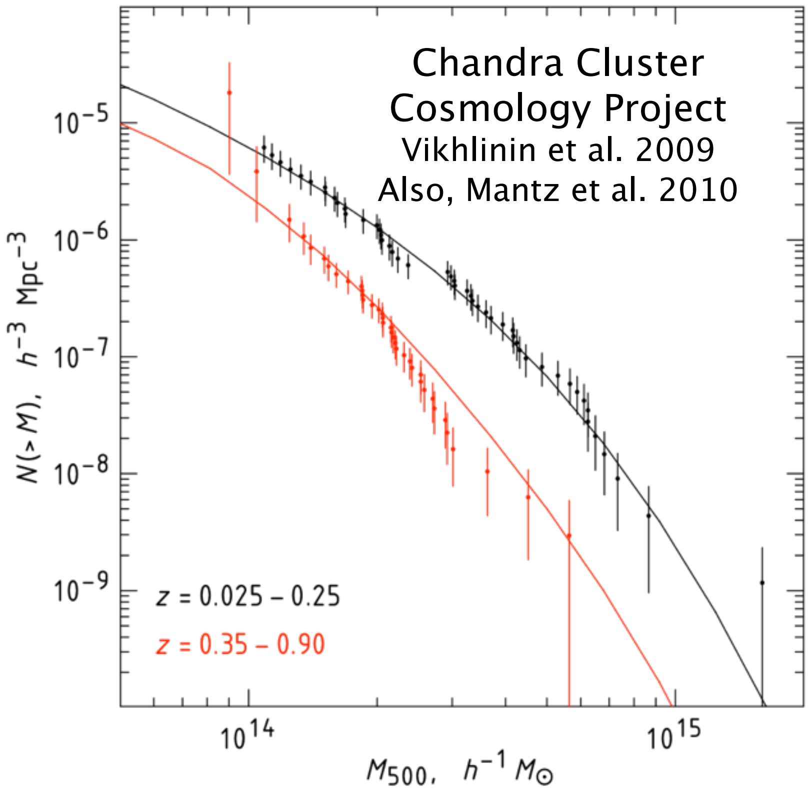


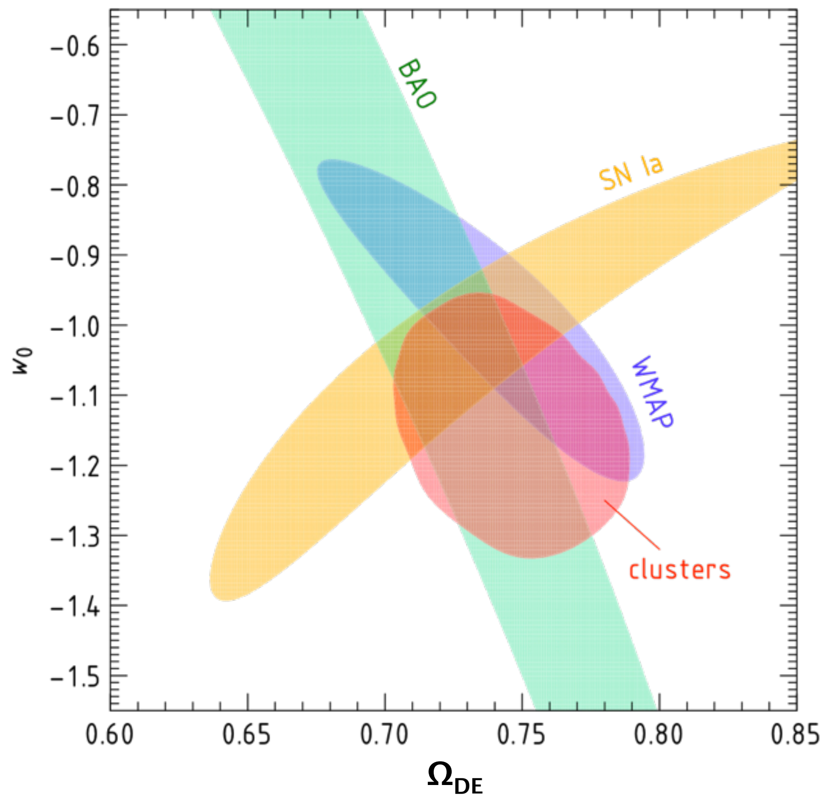
Now



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





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

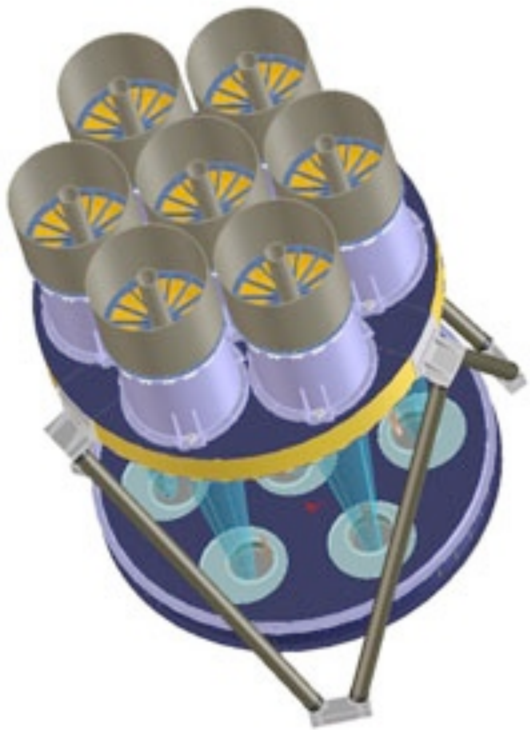
$w_0 = -0.991 \pm 0.045(\text{stat}) \pm \mathbf{0.039(sys)}$

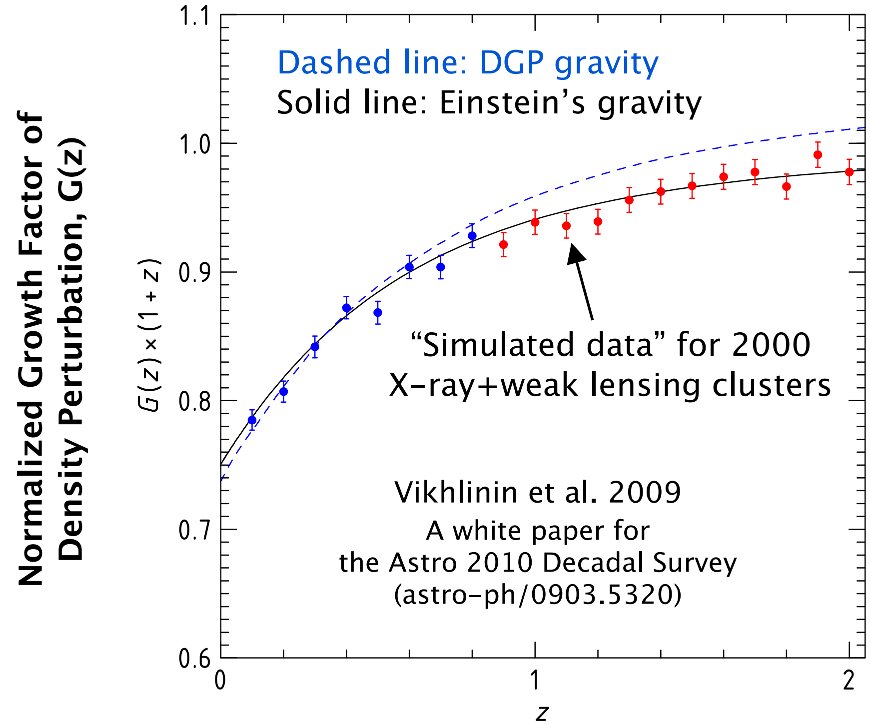
$\Omega_{DE} = 0.740 \pm 0.012$

Systematics uncertainty in cluster mass measurements.

Dark Energy Space Mission of 2010s

eROSITA (scheduled launch in 2016)



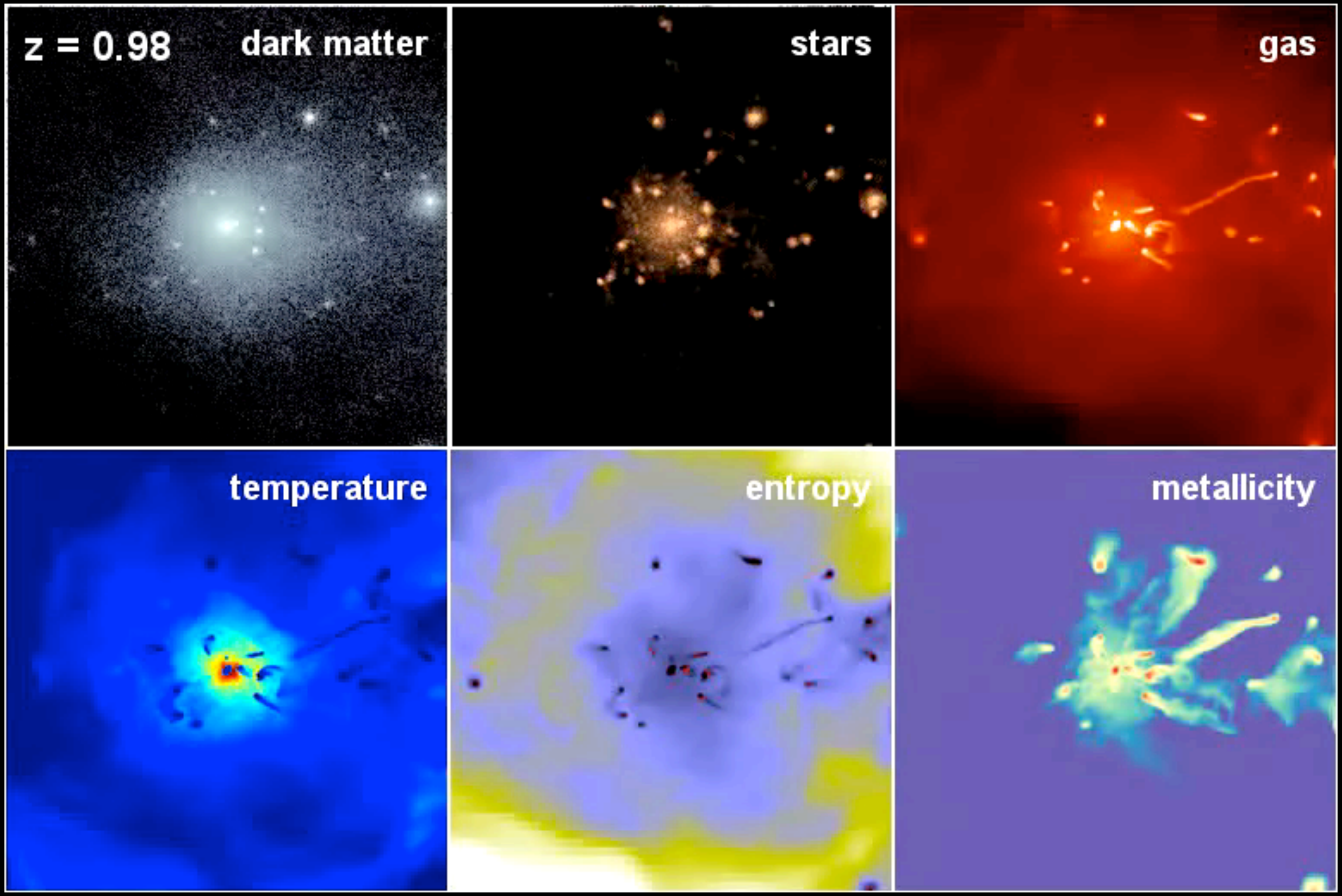


All-sky survey for 4yrs + targeted obs.
Science Goals: Study the LSS and Dark Energy
>100,000 clusters up to z~1.5
A_{eff}~1500 cm^2 @ 1.5keV; Θ_{eff}~25-40 arcsec

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

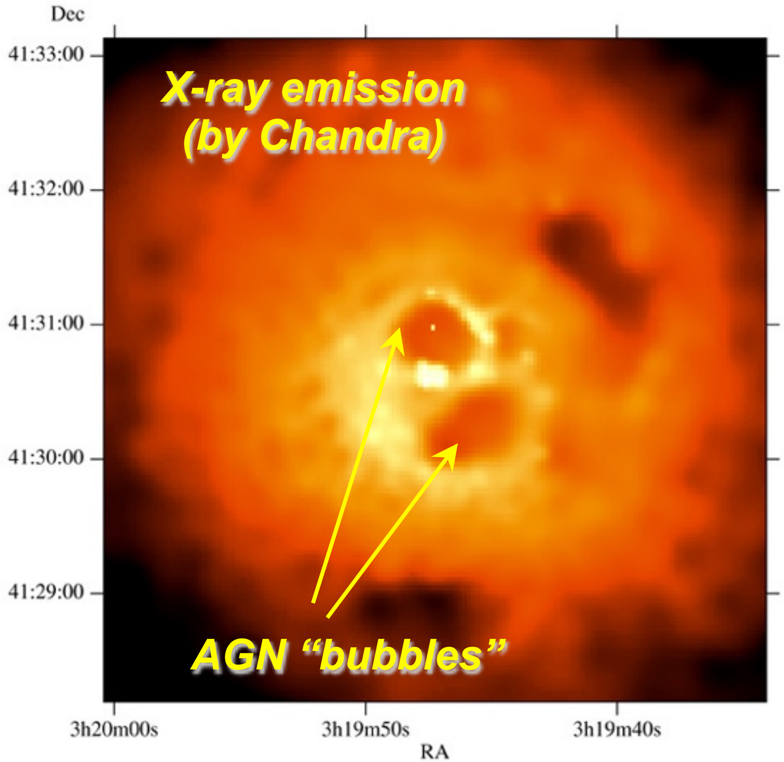


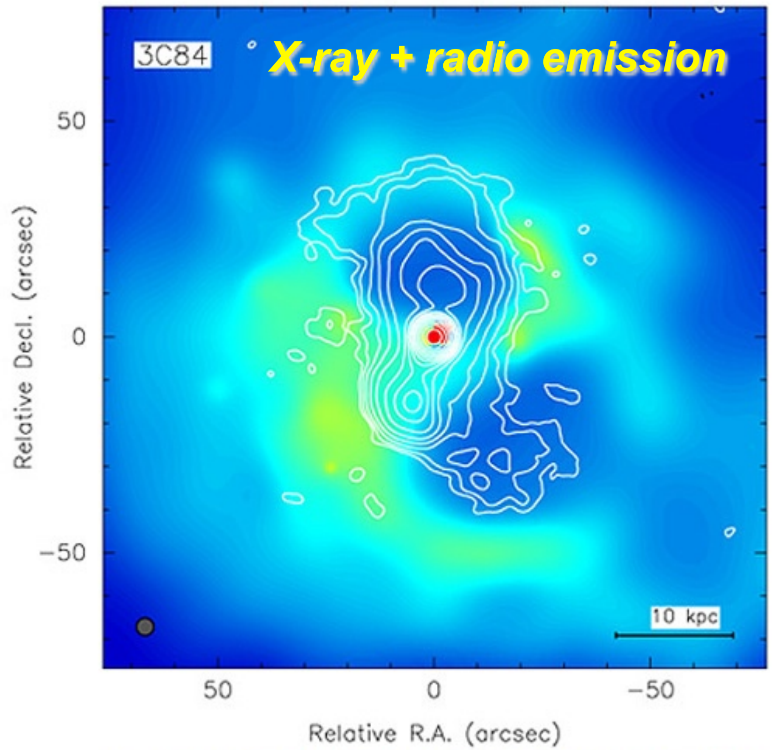
Modern cosmological hydro simulations include the effects of baryons (i.e., gas cooling, star formation, heating by SNe/AGN, metal enrichment and transport). But, also remember limitations - e.g., a single fluid approximation!

Simulation performed by the Yale BulldogM HPC cluster

AGN Feedback in Galaxy Clusters

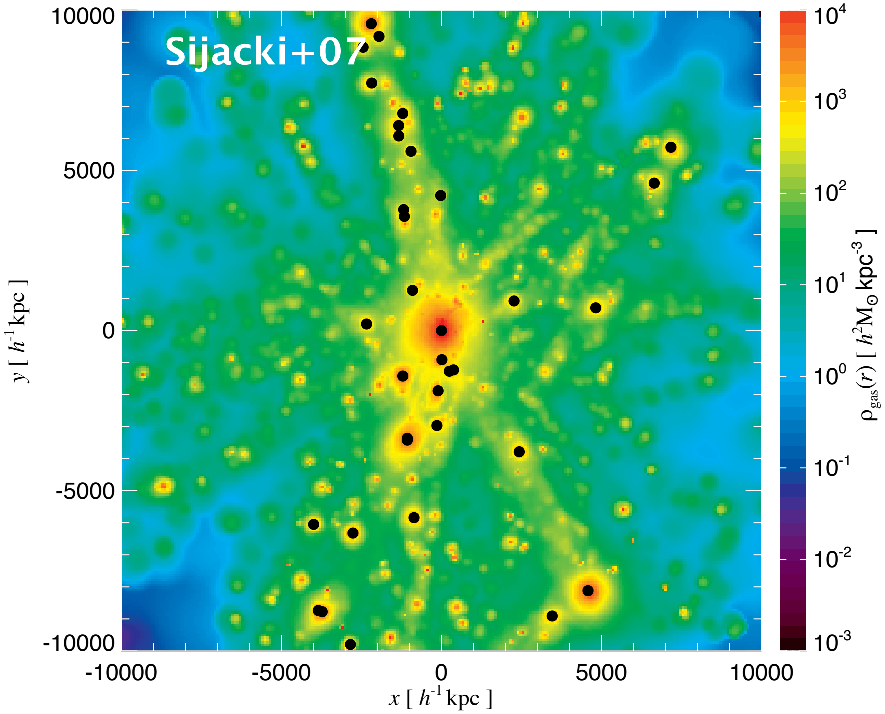
Heating by Active Galactic Nuclei of the central cluster galaxy in the Perseus cluster



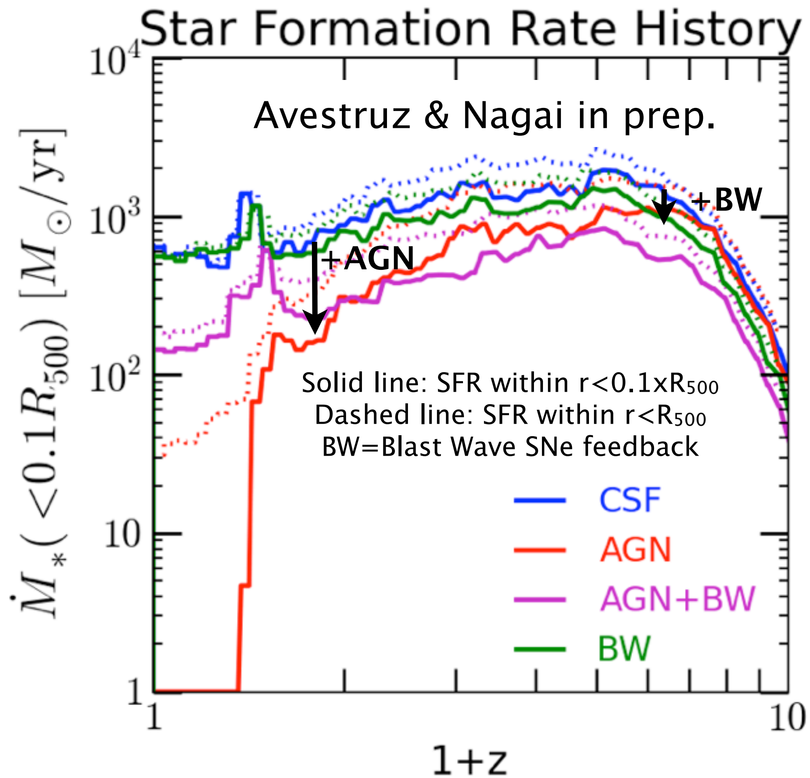


these effects, however, appear to be confined to the core
=> *outer regions of clusters can be used to reliably estimate their total masses*

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



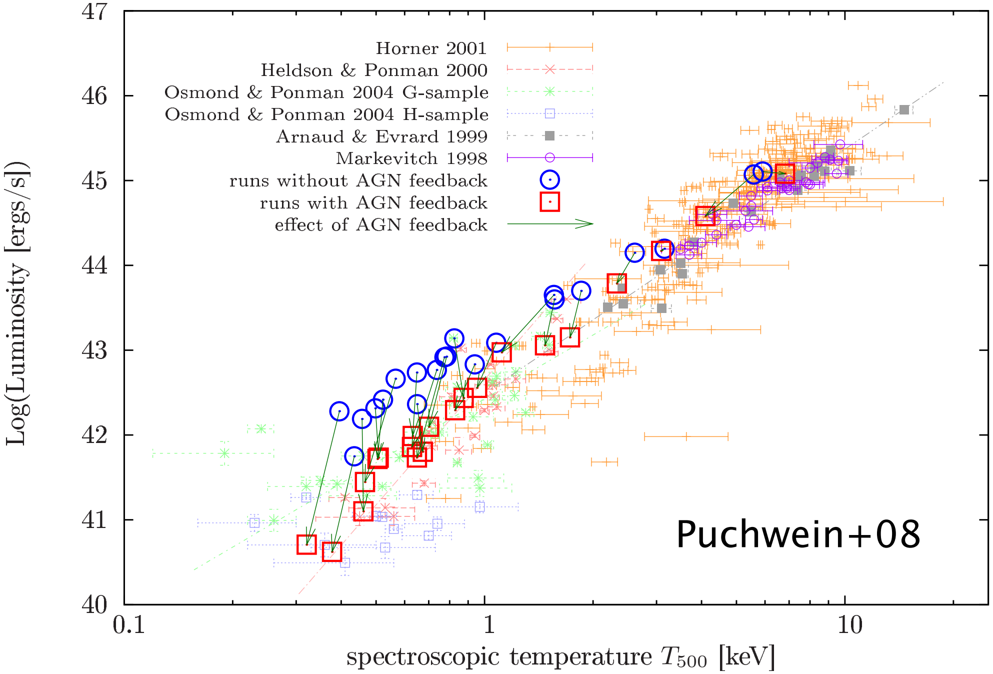
Cluster Simulations with thermal AGN feedback
Virgo-size cluster with $M_{500}=2\times10^{14}$Msun/h
Box size=80Mpc/h, Peak resolution=2.5kpc/h;
mass resolution=2×10^8Msun/h

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

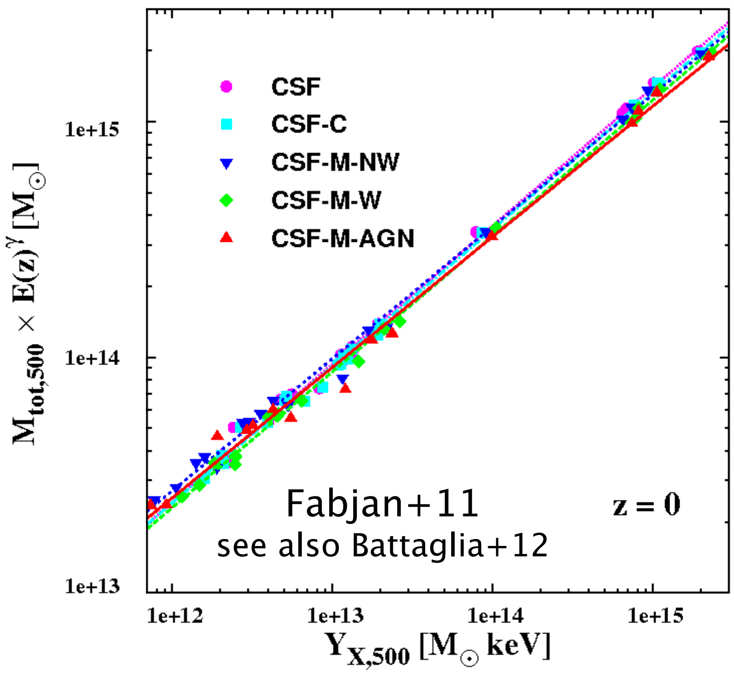
e.g., Sijacki+06,07, 08; Booth & Schaye 09, 11; Dubois+10,12

Missing Cluster Astrophysics #1
Impact of AGN feedback on Cluster Scaling Relations

L_X–T_X relation
sensitive to cluster cores

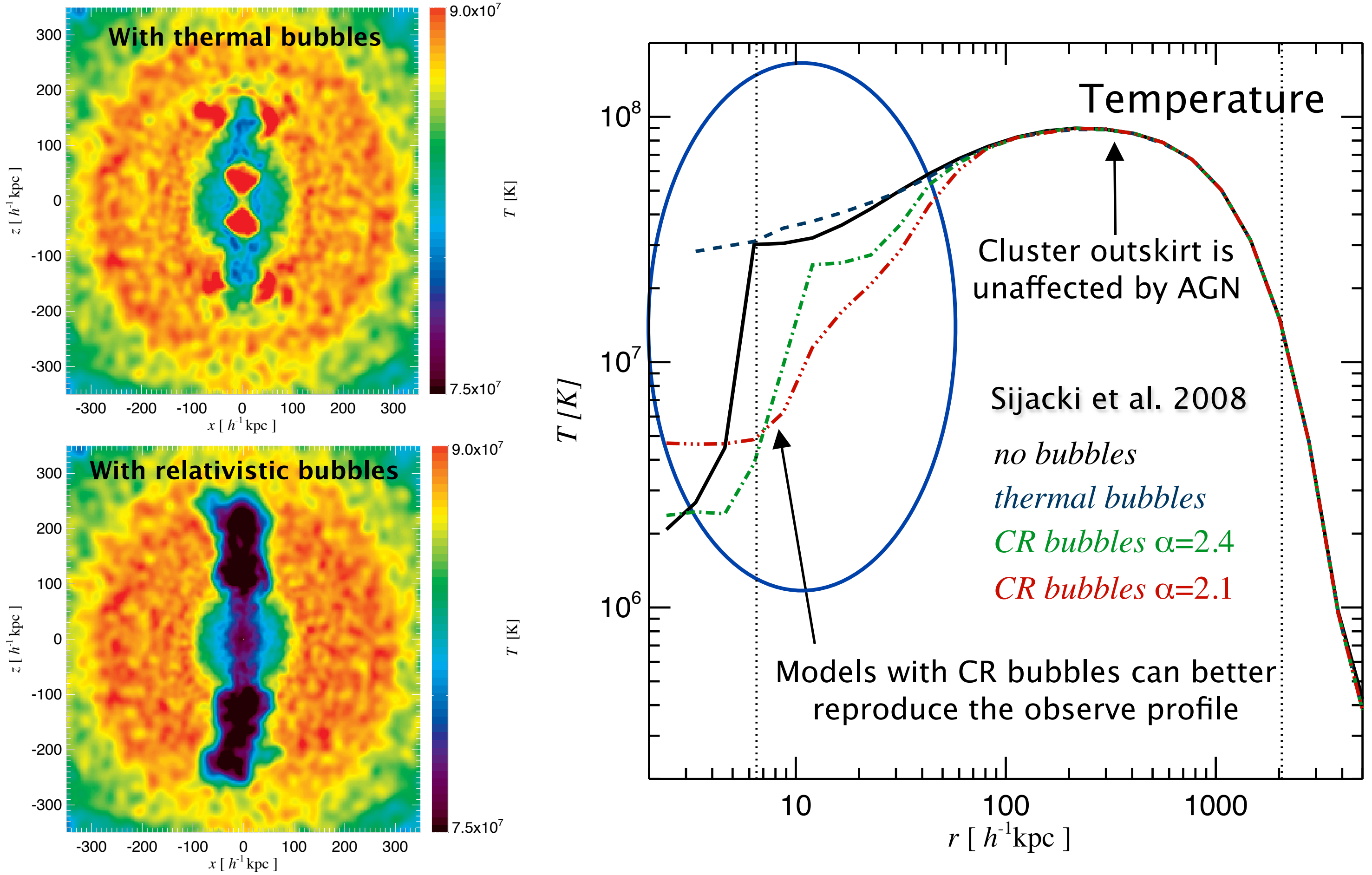


Y_X–M relation
not so sensitive to cluster cores



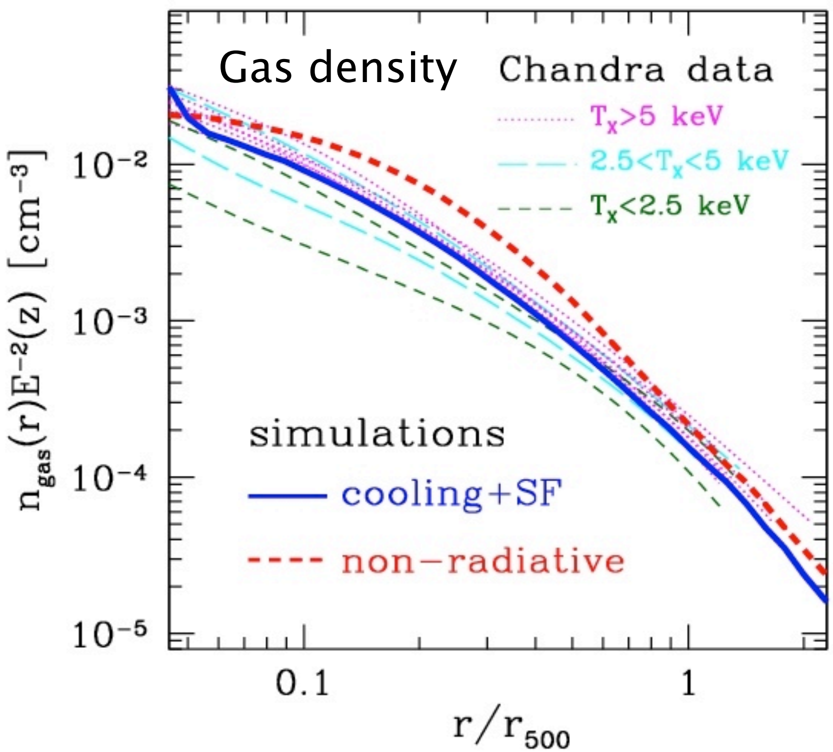
AGN feedback helps reproduce the observed Lx-Tx relation, but has little effect on the Yx-M relation.

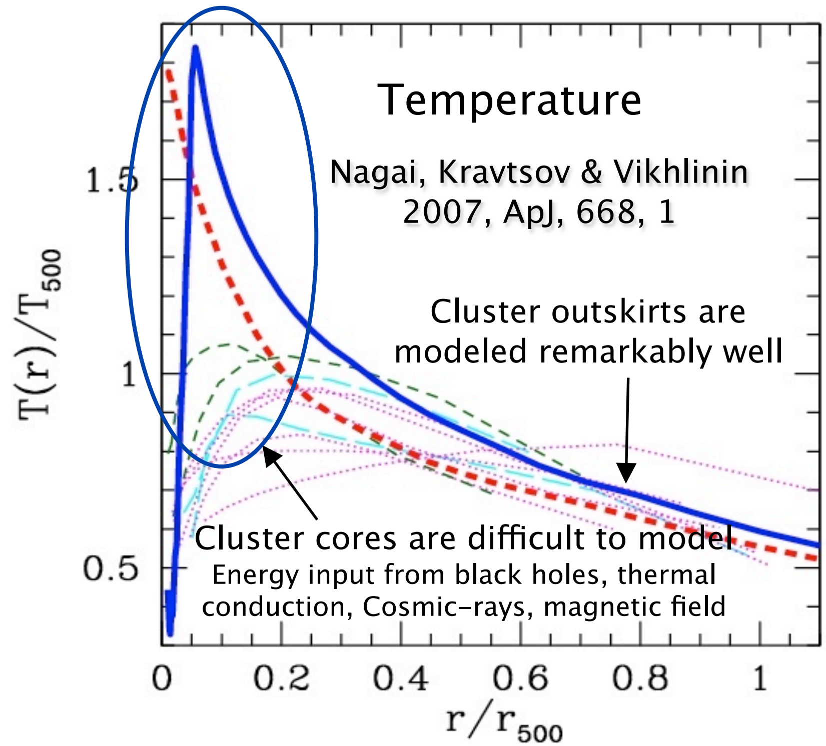
Missing Cluster Astrophysics #1
AGN feedback in Cluster Cores



The question is not whether AGN feedback is important, rather how its energy is transferred to heat the surrounding ICM.

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

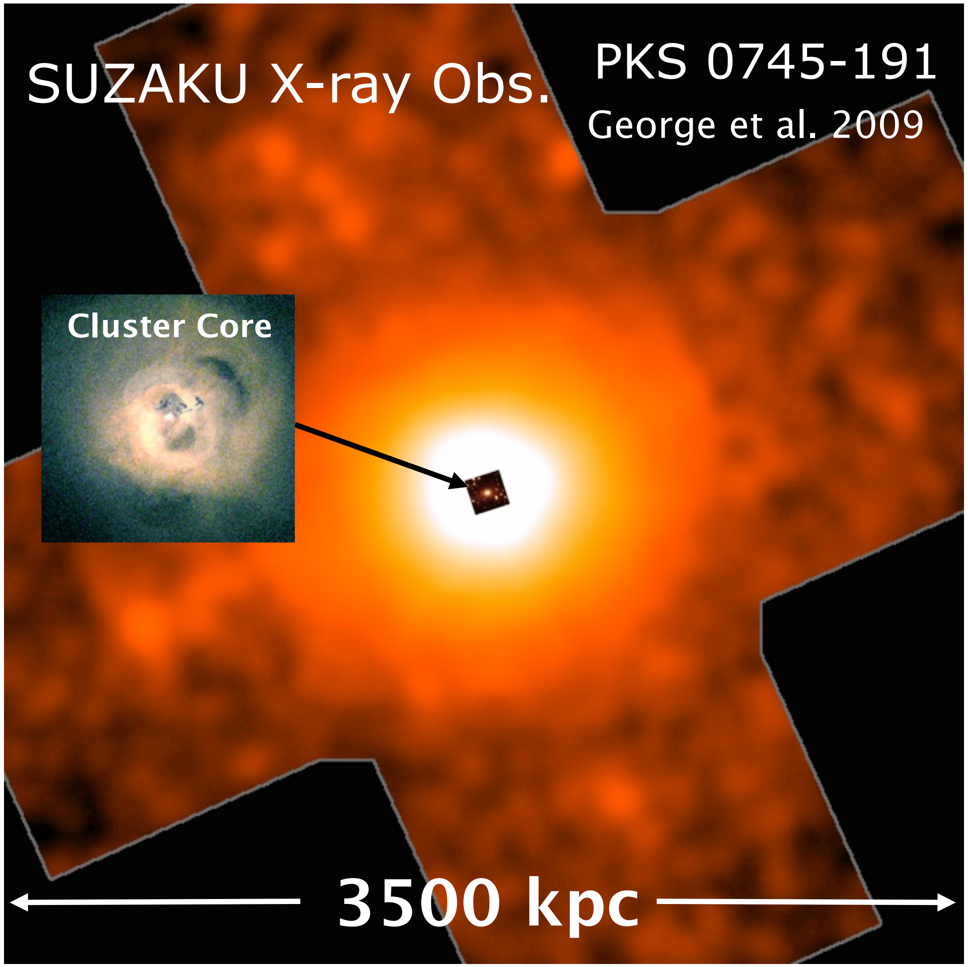


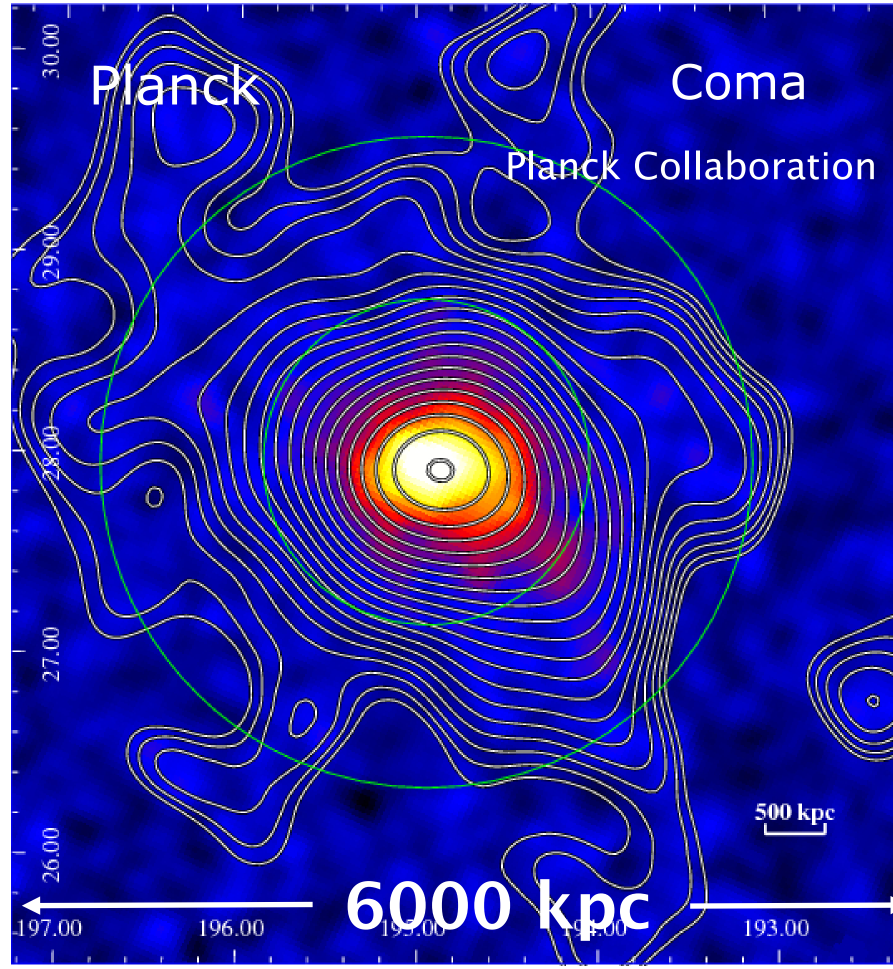


Modern hydrodynamical cluster simulations reproduce observed gas density and temperature profiles outside cluster cores ($0.15<r/r_{500}<1$)

Outskirts could be used to measure the cluster mass accurately.

X-ray+SZ measurements of cluster outskirts

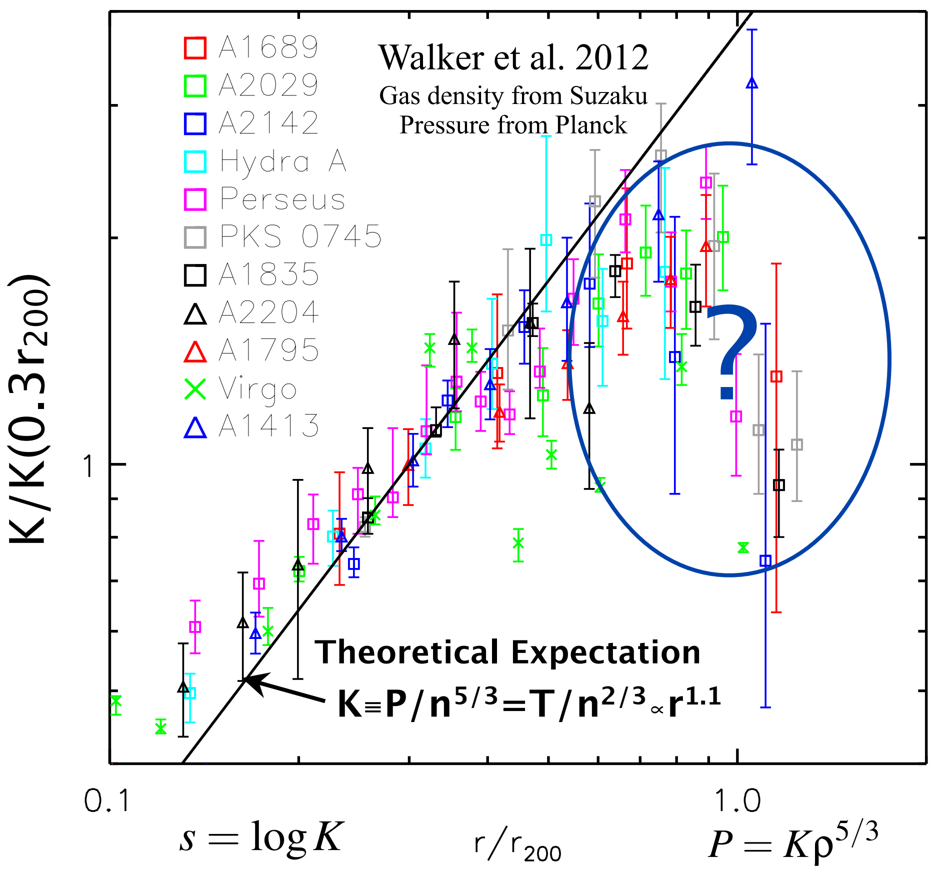




Recent X-ray and microwave observations have detected the hot gas in the outskirts of galaxy clusters

Suzaku+Planck measurements of cluster outskirts

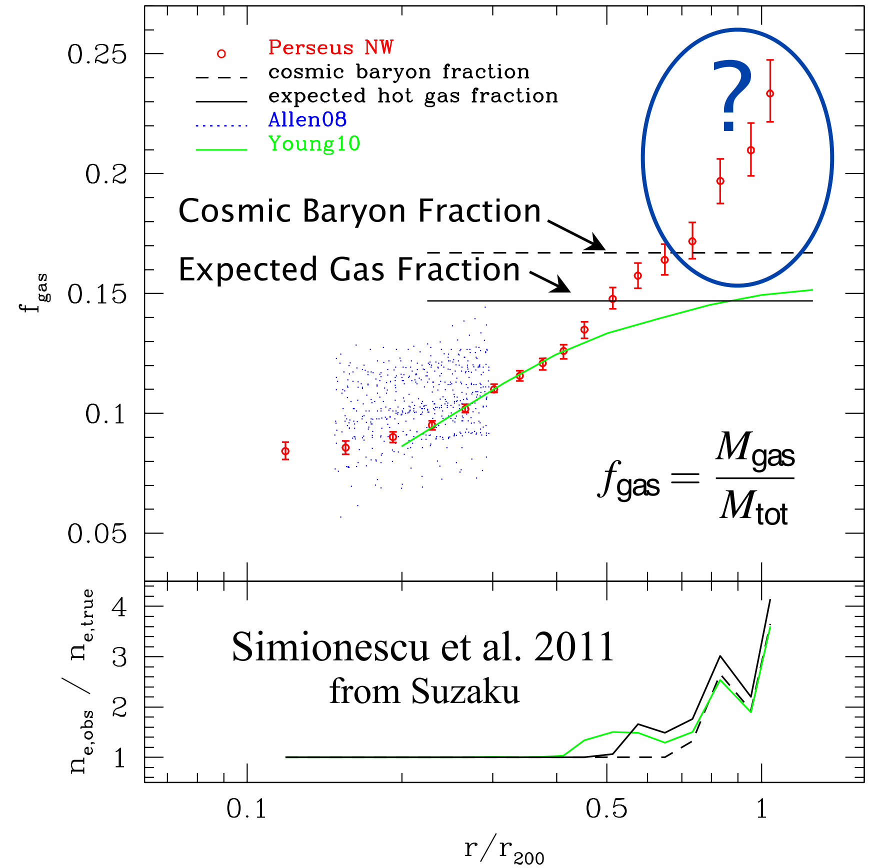
Entropy profiles of 11 nearby relaxed clusters



$s = \log K$
specific entropy

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

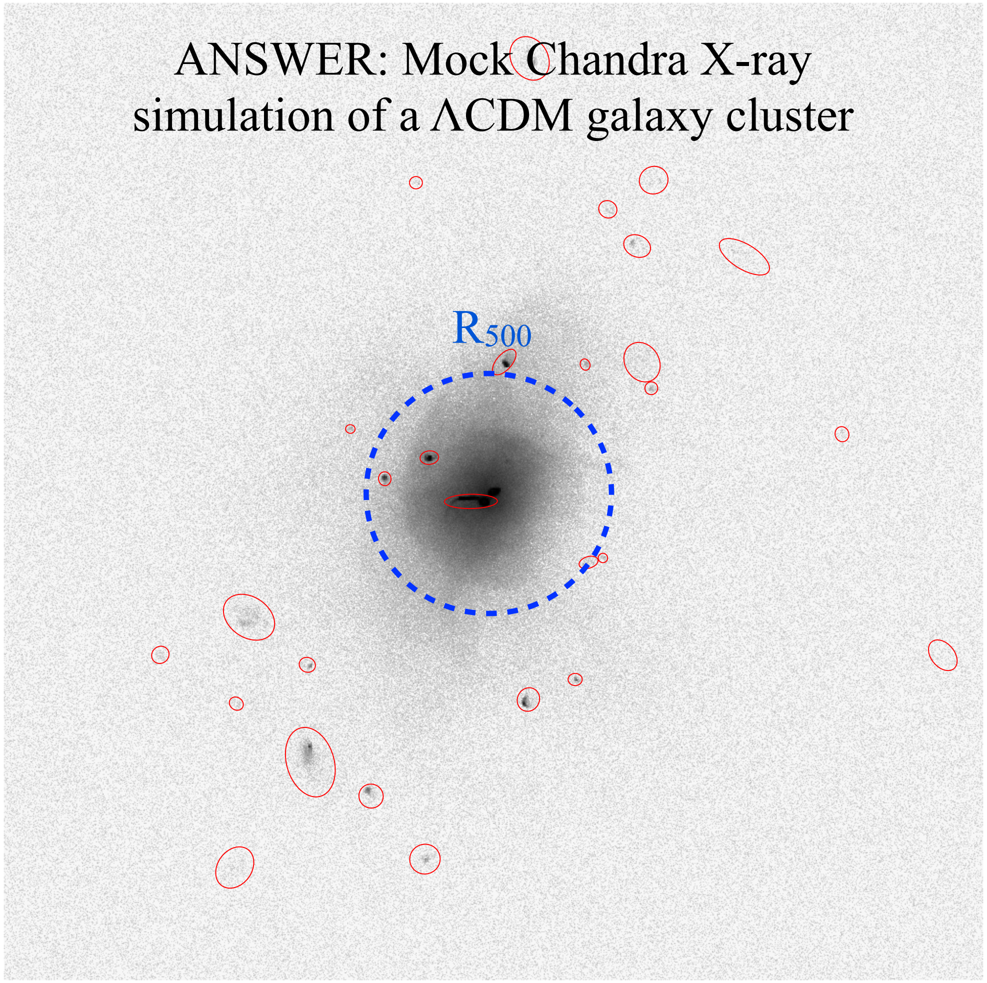
Gas fraction profile in Perseus cluster



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

Missing Cluster Astrophysics #2

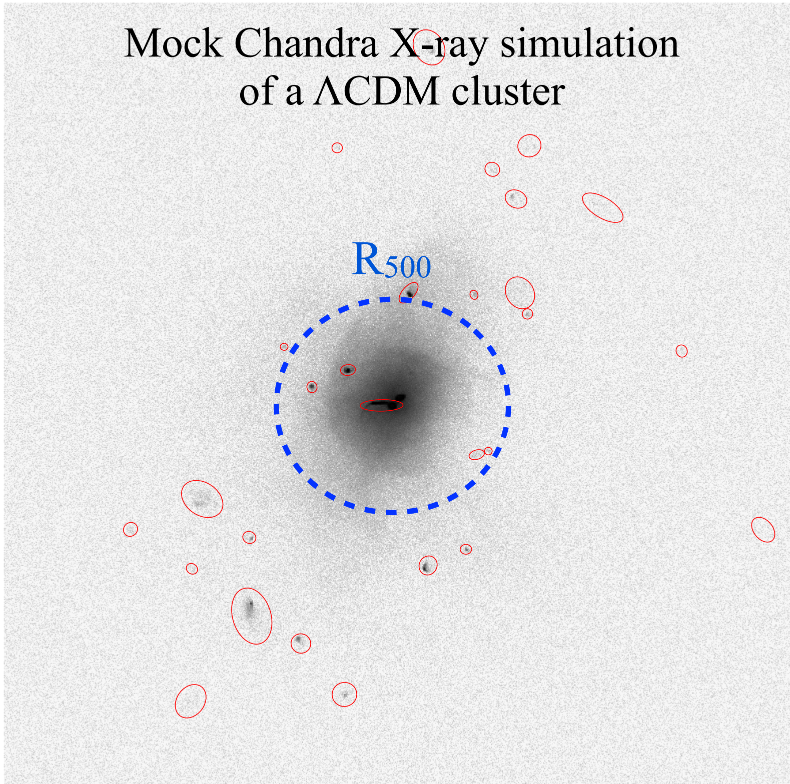
Cluster outskirts are very clumpy

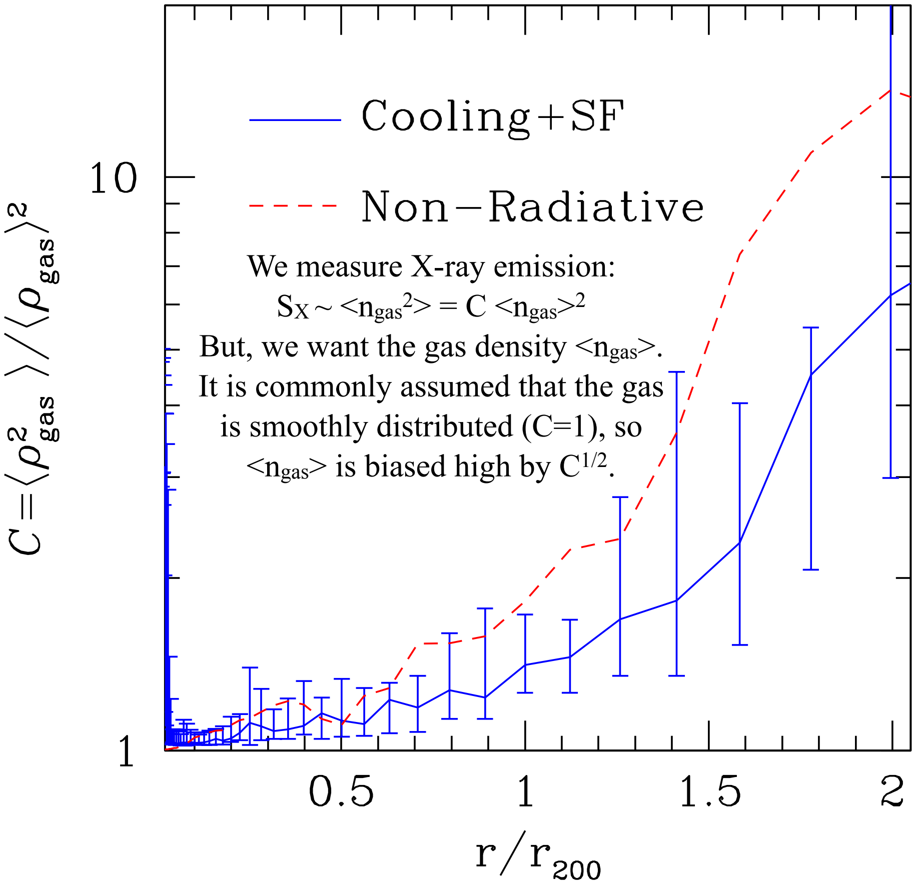


Hydrodynamical simulations predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}=0.7r_{200}$) arise from small groups accreting along filaments

Nagai & Lau 2011; Zhuravleva et al. 2013

Missing Cluster Astrophysics #2
Cluster outskirts are very clumpy

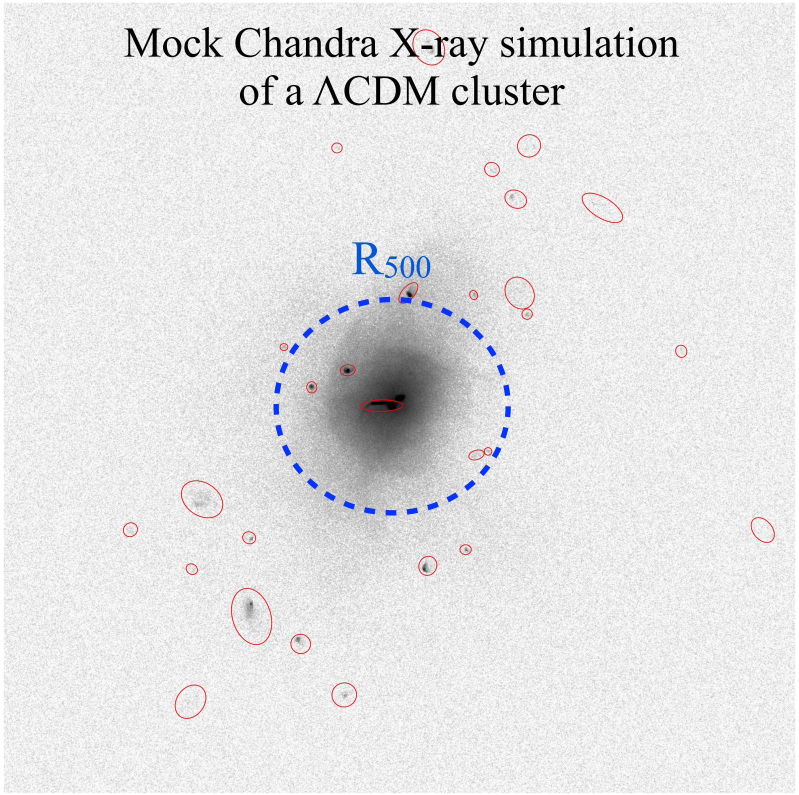


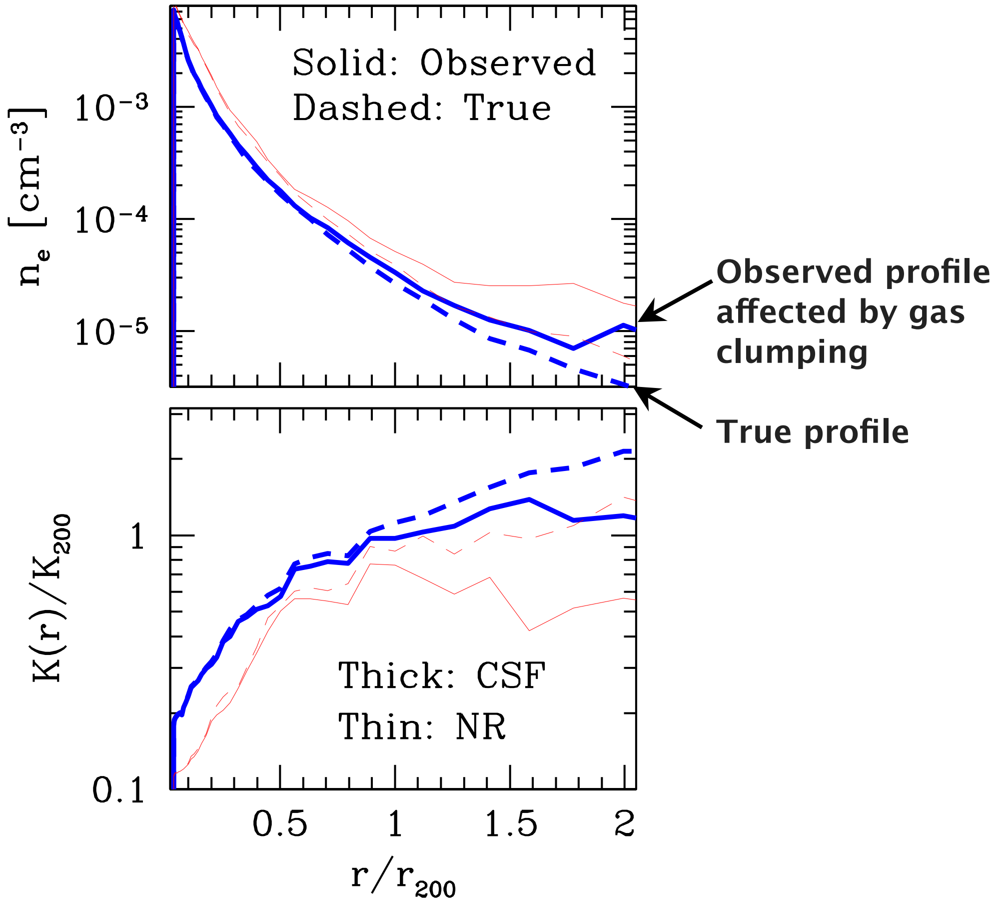


Hydrodynamical simulations predict that most of the X-ray emissions from cluster outskirts ($r > r_{500} = 0.7 r_{200}$) arise from small groups accreting along filaments

Nagai & Lau 2011; Zhuravleva et al. 2013

Gas Clumping introduce biased in the ICM profiles derived from X-ray observations

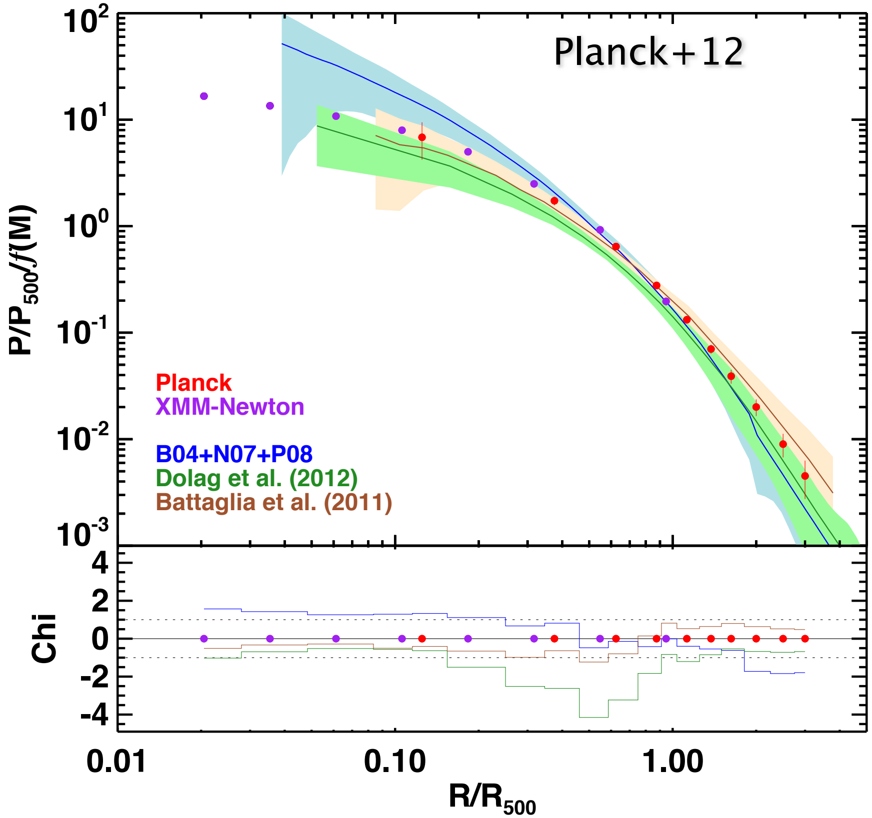


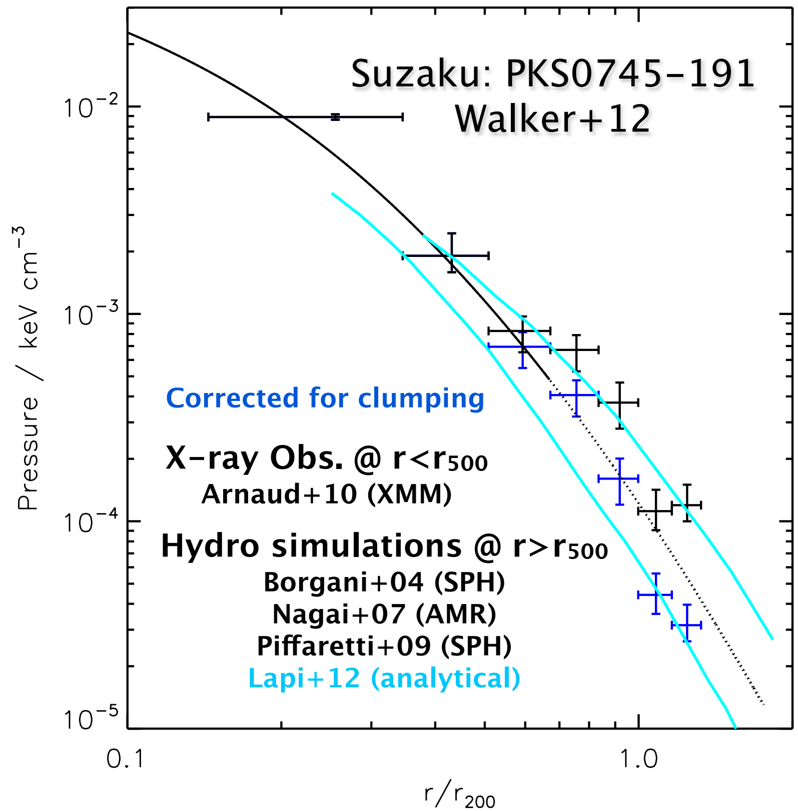


Hydrodynamical simulations predict that most of the X-ray emissions from cluster outskirts ($r>r_{500}=0.7r_{200}$) arise from infalling groups from the filaments

Nagai & Lau 2011; Zhuravleva et al. 2013

SZ+X-ray Observations of Pressure Profiles in Cluster Outskirts

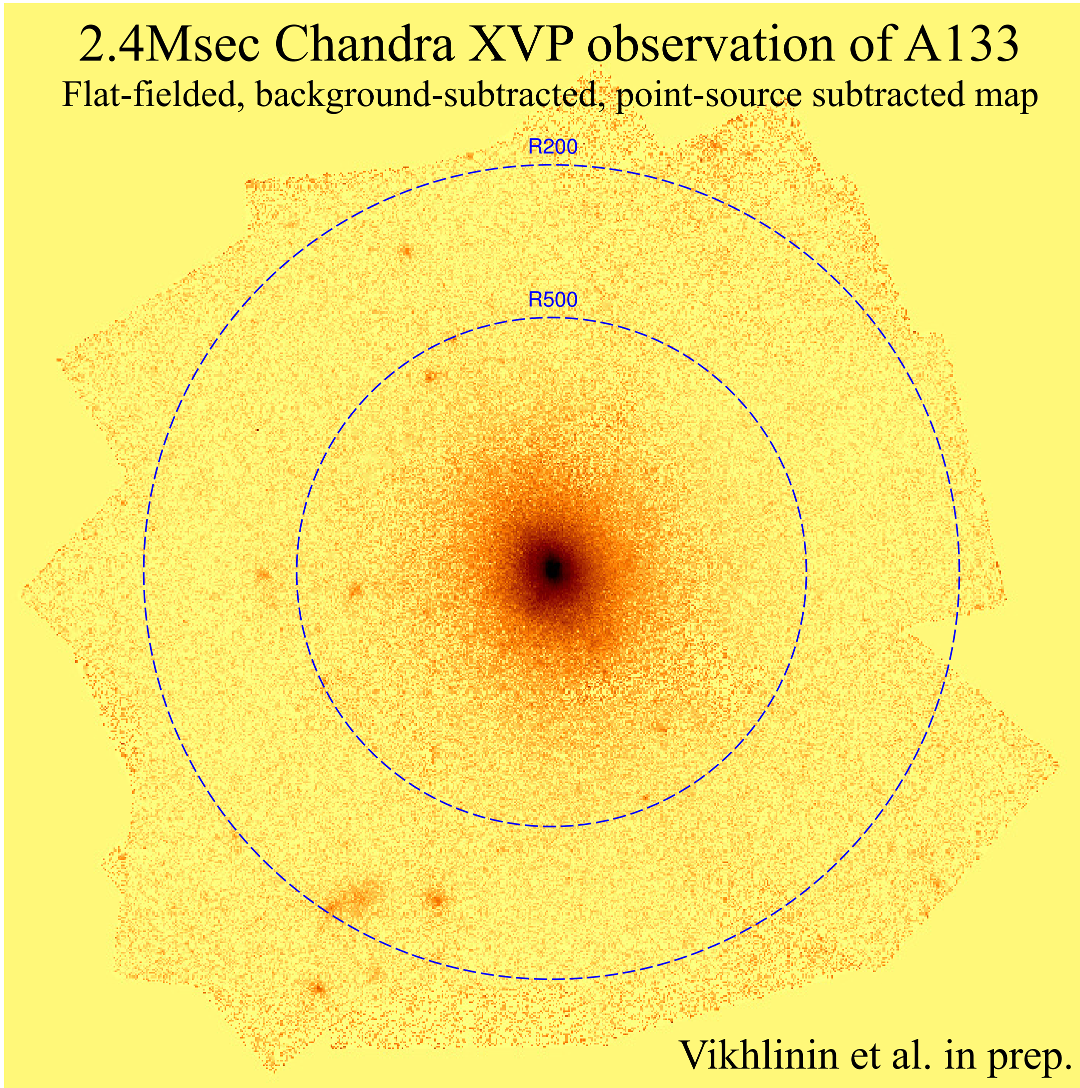




SZ and X-ray observations provide complementary views of cluster outskirts;
i.e., SZ signal is less sensitive to gas clumping, but affected by non-thermal pressure, while both SZ and X-ray signals are susceptible to non-thermal pressure or non-equilibrium electrons.

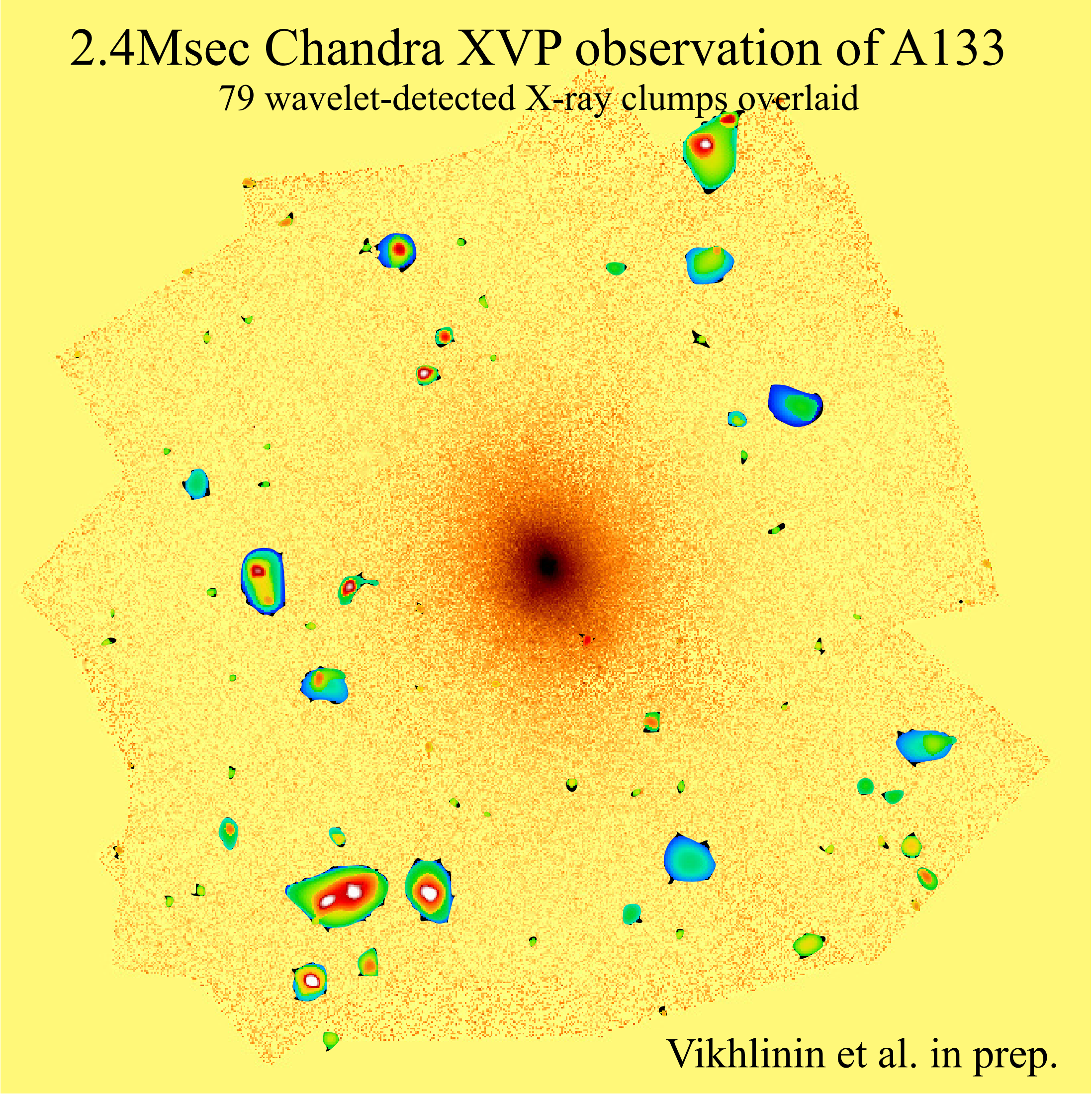
also Eckert et al. 2013a,b

Evidence for Gas Clumping in Cluster Outskirts



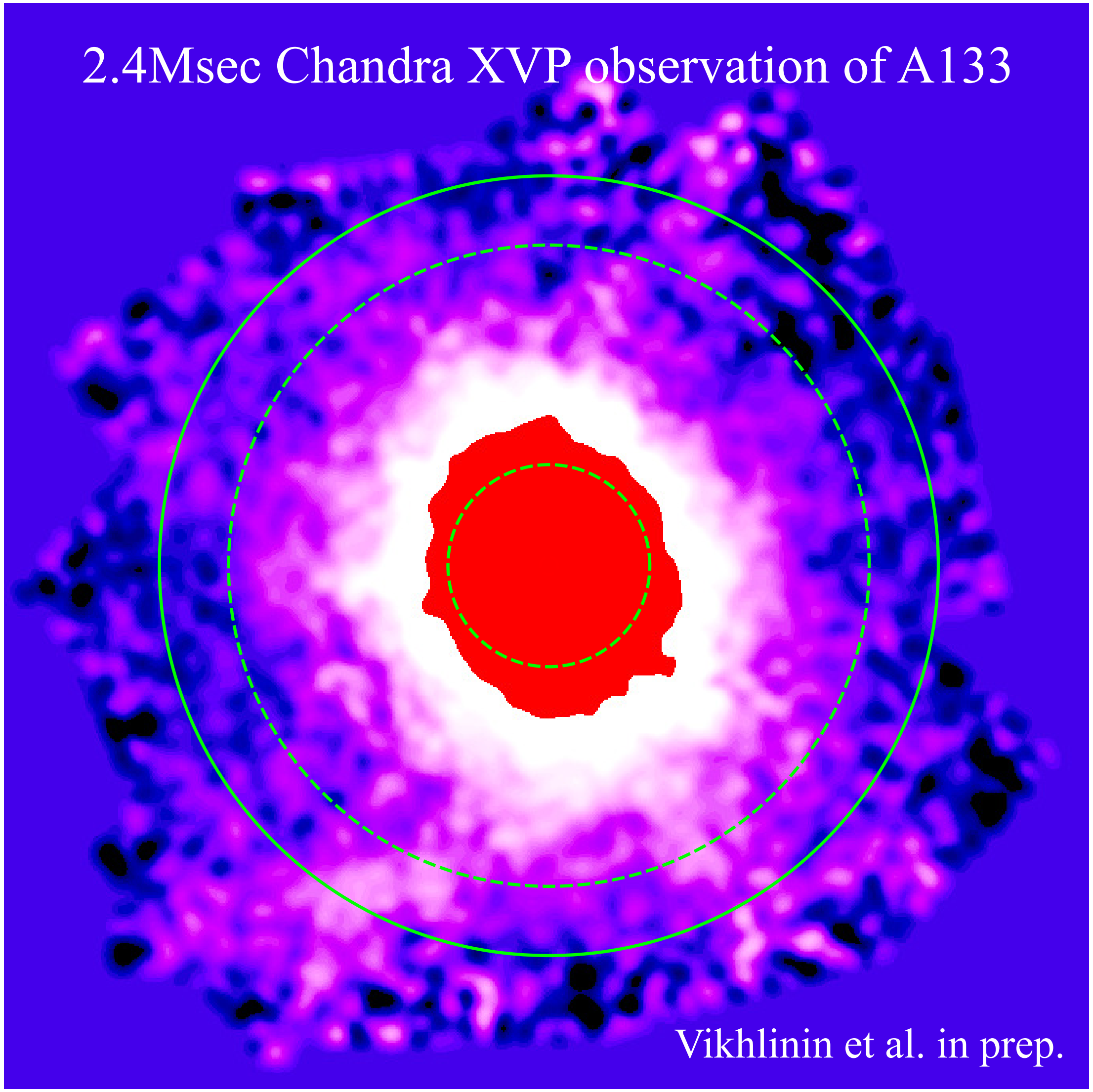
A transition of the smooth state in the virialized region to a clumpy intergalactic medium in the infall region outside of $r \approx R_{500}$

Evidence for Gas Clumping in Cluster Outskirts



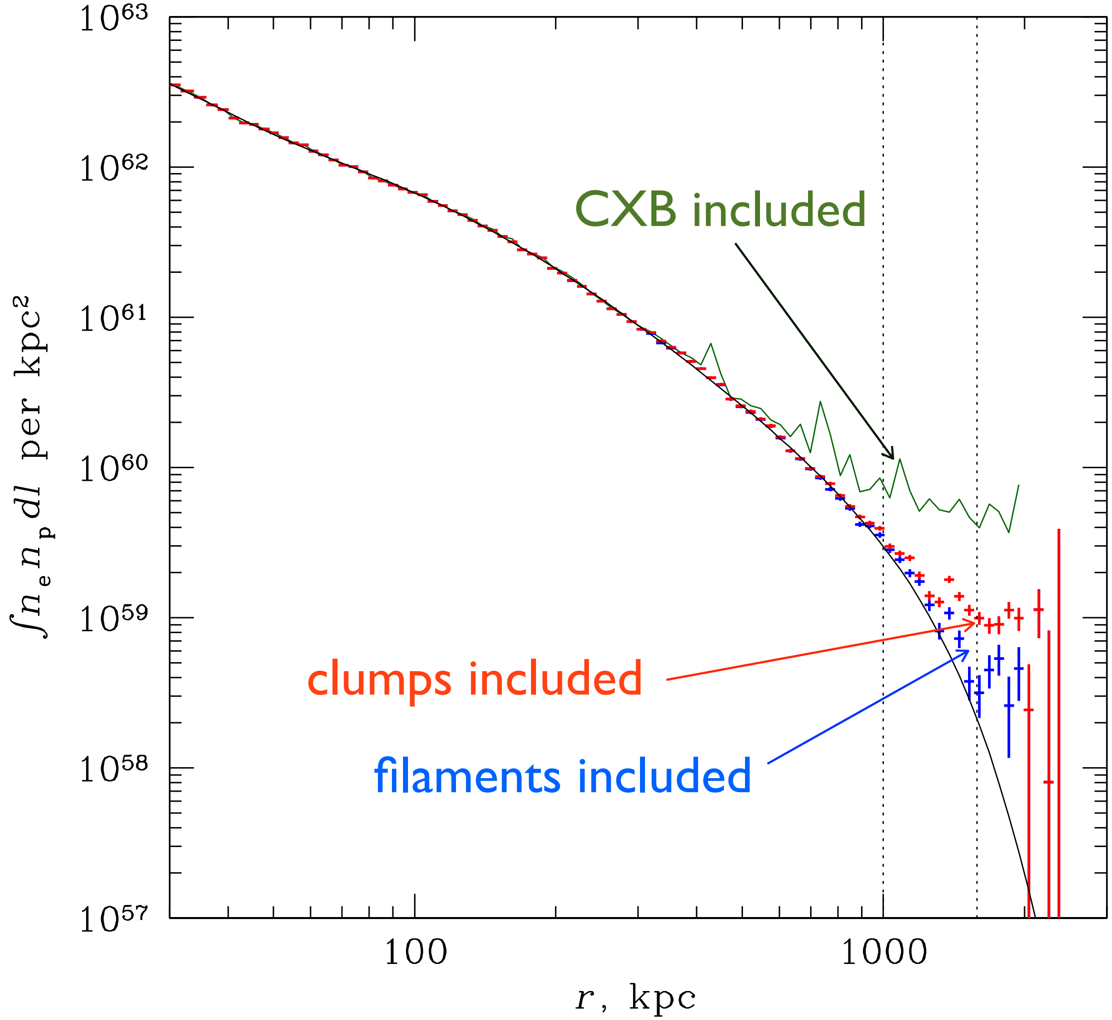
A transition of the smooth state in the virialized region to a clumpy intergalactic medium in the infall region outside of $r \approx R_{500}$

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}.

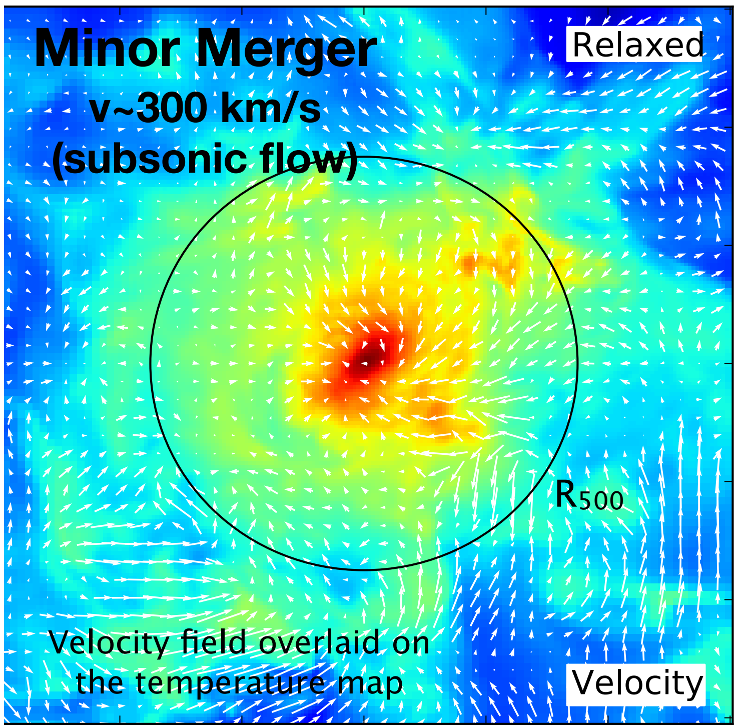
Evidence for Gas Clumping in Cluster Outskirts

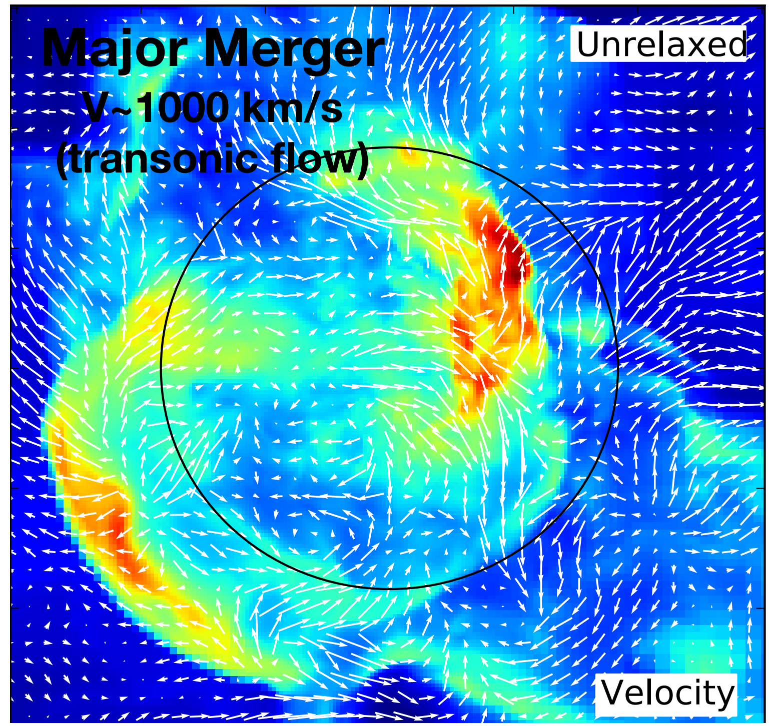


Superb angular resolution and sensitivities of Chandra are critical for studying the outskirts of galaxy clusters.

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

Nelson, Lau, Nagai, Rudd, Yu 2013 (astro-ph/1308.6589)
Kaylea Nelson's Ph.D. thesis work based on the large (>80) sample of simulated galaxy clusters using the Yale OMEGA HPC cluster (also Nagai+07, Lau+09, Nelson+12, Lau+13)





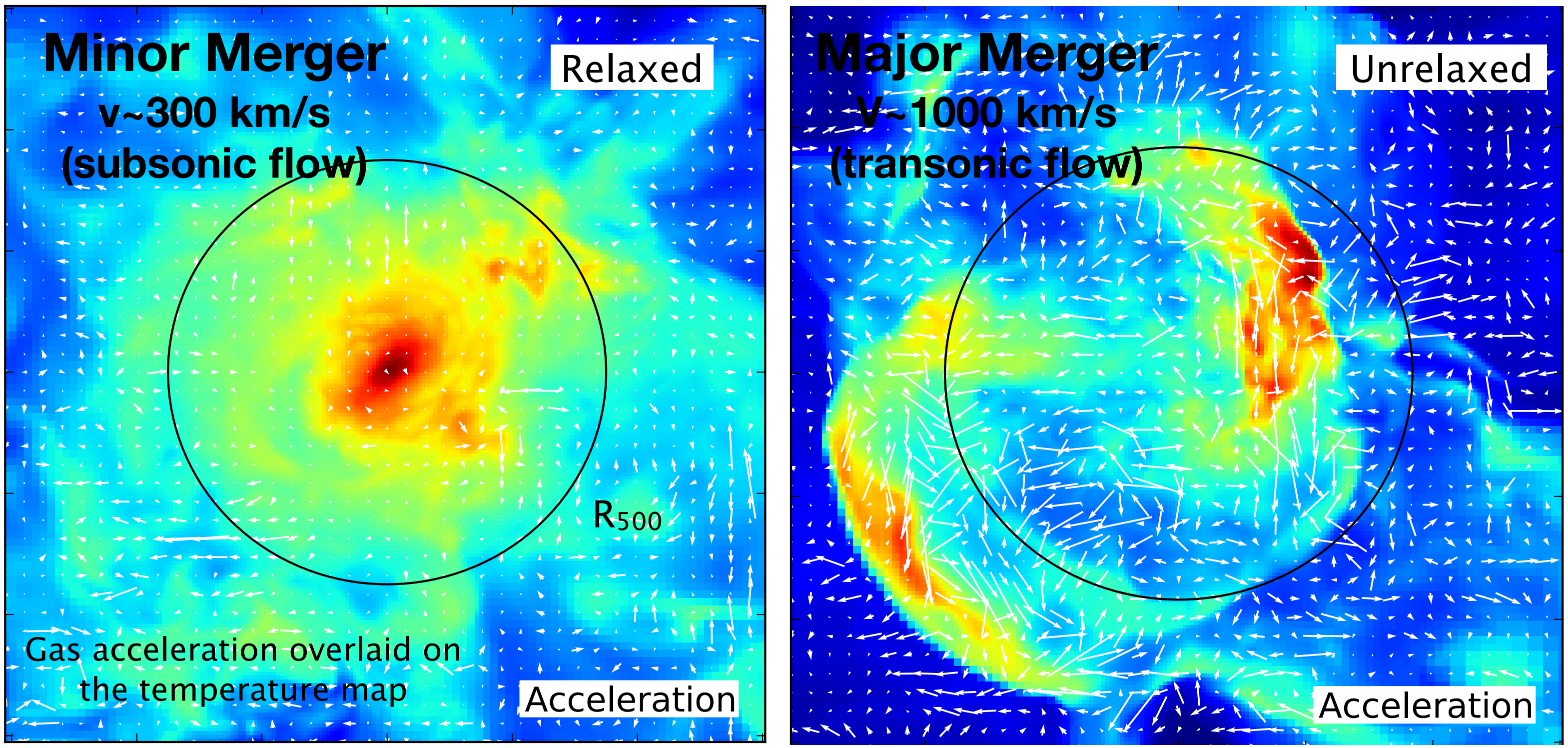
Hydrodynamical simulations predict turbulent gas motions in clusters, and they introduce biases in the hydrostatic cluster mass estimates at the level of ~20%.

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

Missing Cluster Astrophysics #3
Gas Acceleration in Cluster Outskirts

Nelson, Lau, Nagai, Rudd, Yu 2013 (astro-ph/1308.6589)

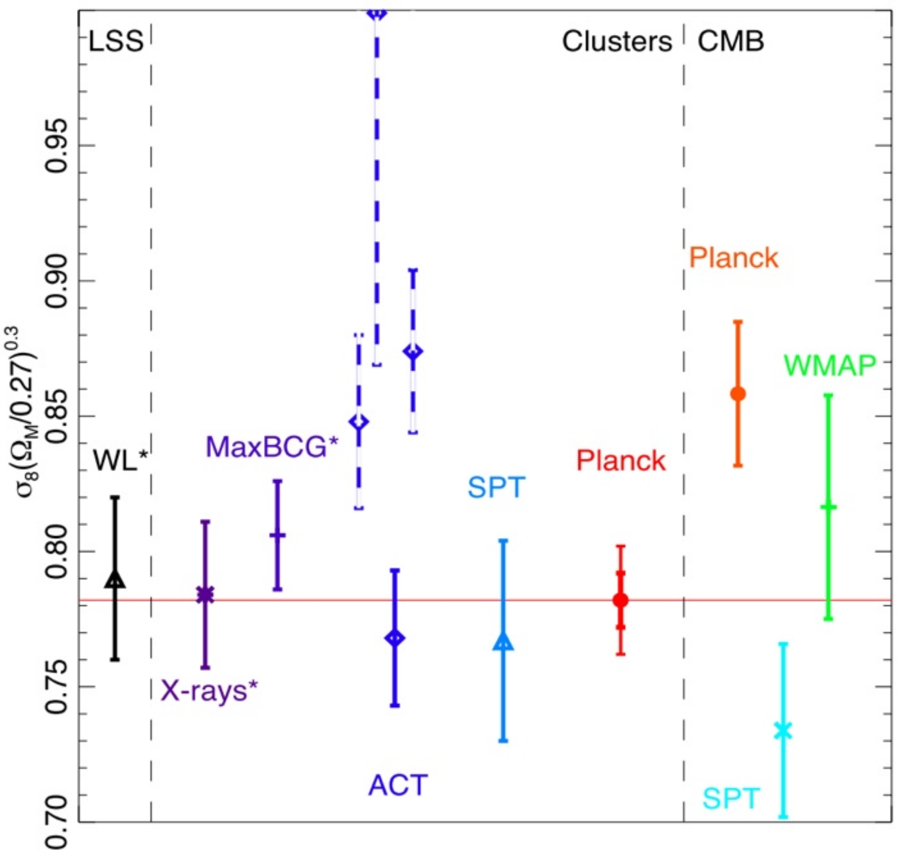
Kaylea Nelson's Ph.D. thesis work based on the large (>80) sample of simulated galaxy clusters using the Yale OMEGA HPC cluster (also Suto+12, Lau+13)



Gas acceleration is also significant in the virialization regions in cluster outskirts.

Gas acceleration introduces an irreducible error to cluster mass estimate.

Cosmology in the Planck Era
Clusters vs. CMB



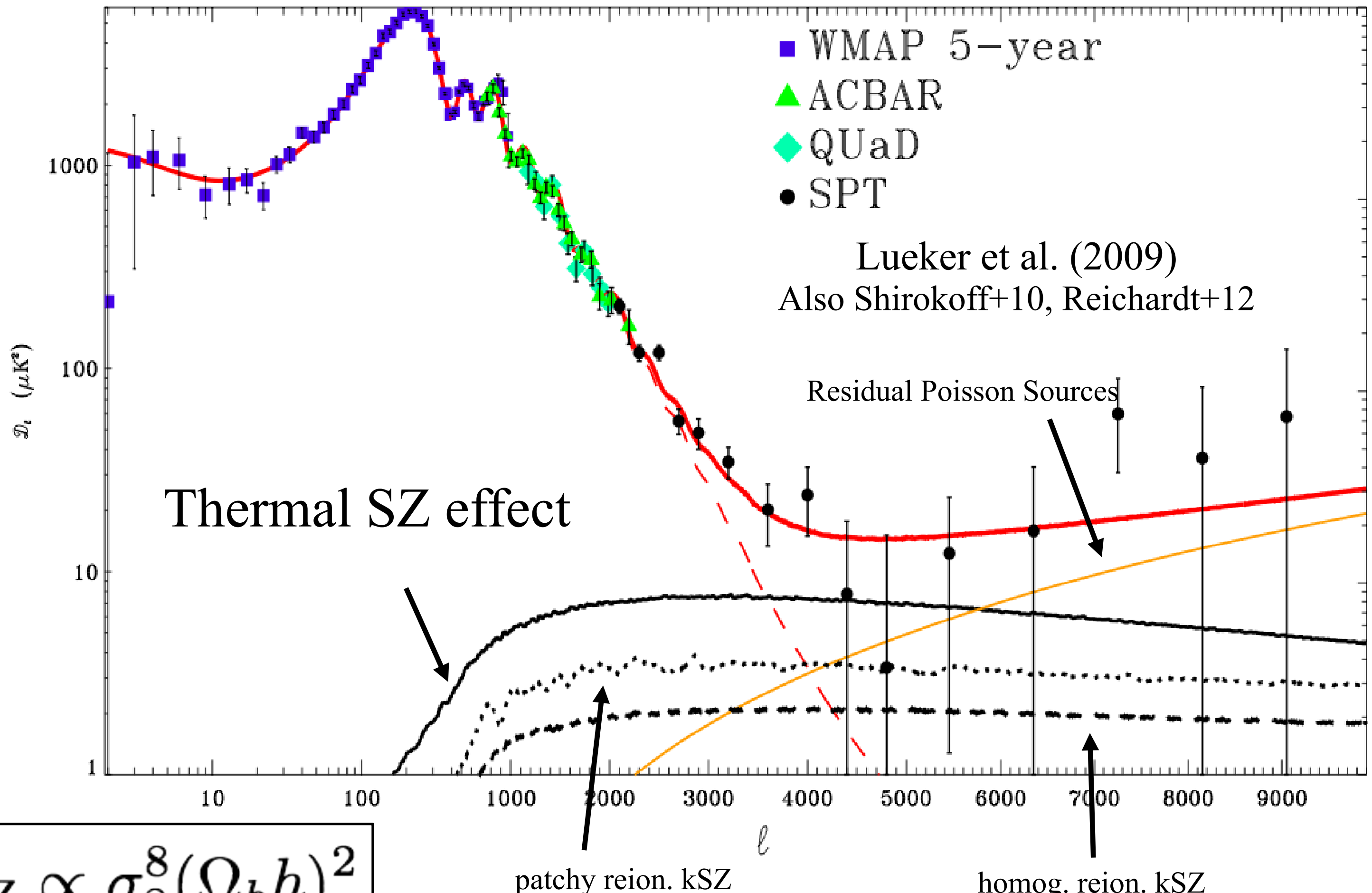
Planck 2013, Paper XX

Possible Solutions

- cluster scaling relations are off by ~45% - *very unlikely*
- Planck CMB results may be biased - issue with 217GHz data (Spergel et al. on astro-ph yesterday)
- 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!

Measurements of the SZ power spectrum



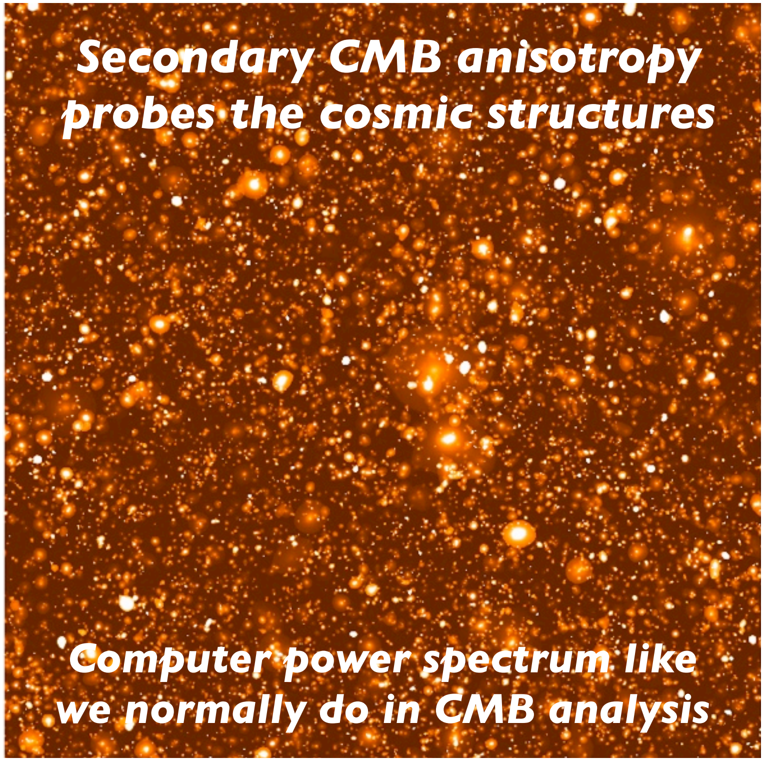
$$C_{\ell,\mathrm{tSZ}} \propto \sigma_8^8 (\Omega_b h)^2$$

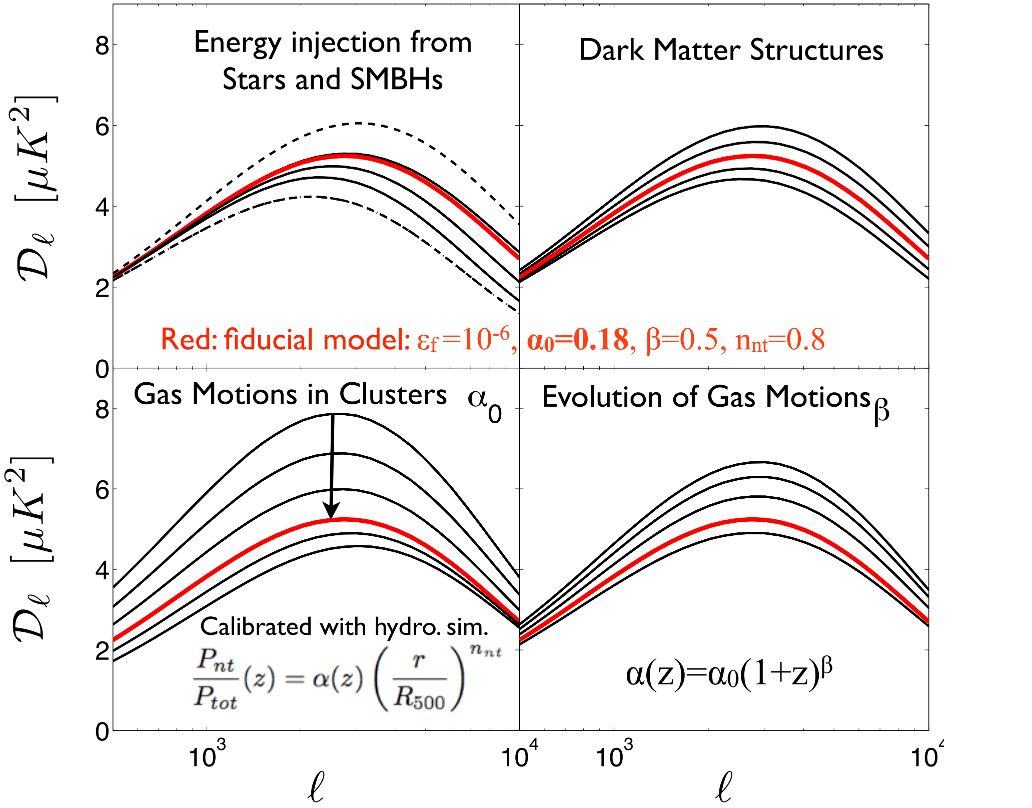
The SZ power spectrum also contains information about galaxy clusters.

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

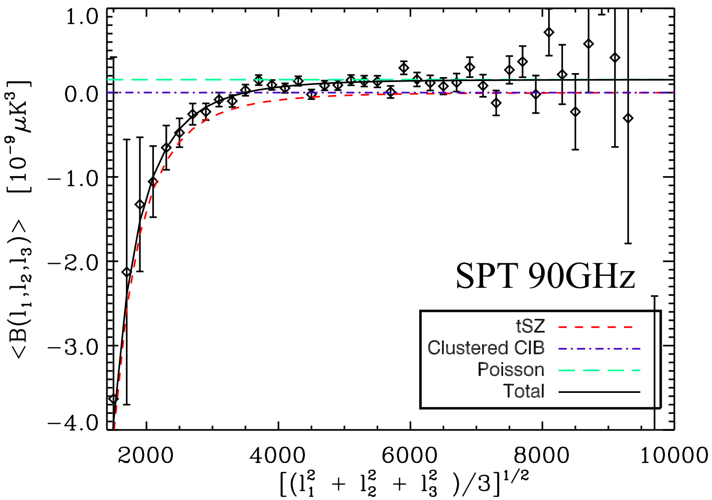


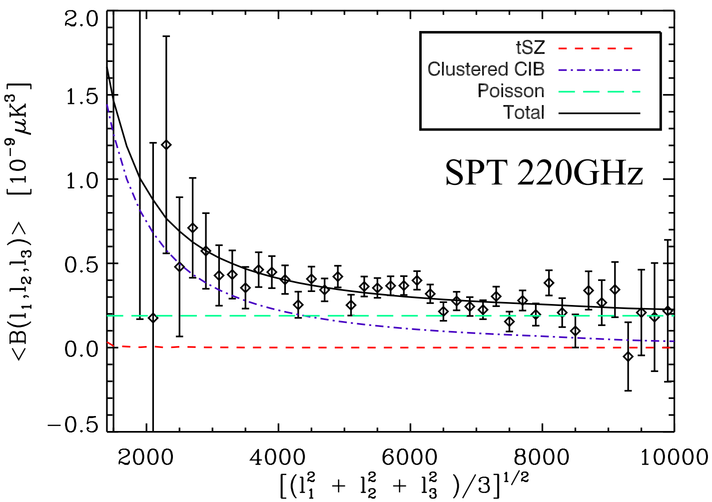


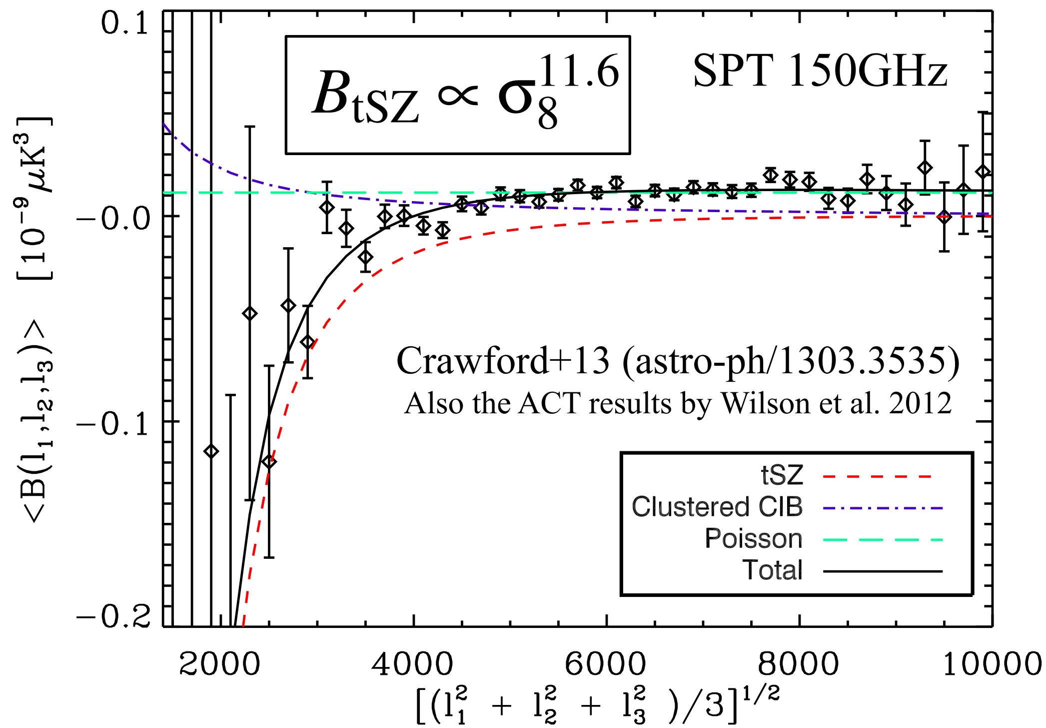
Non-thermal pressure support due to gas motions in clusters is a dominant source of systematic uncertainty.

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

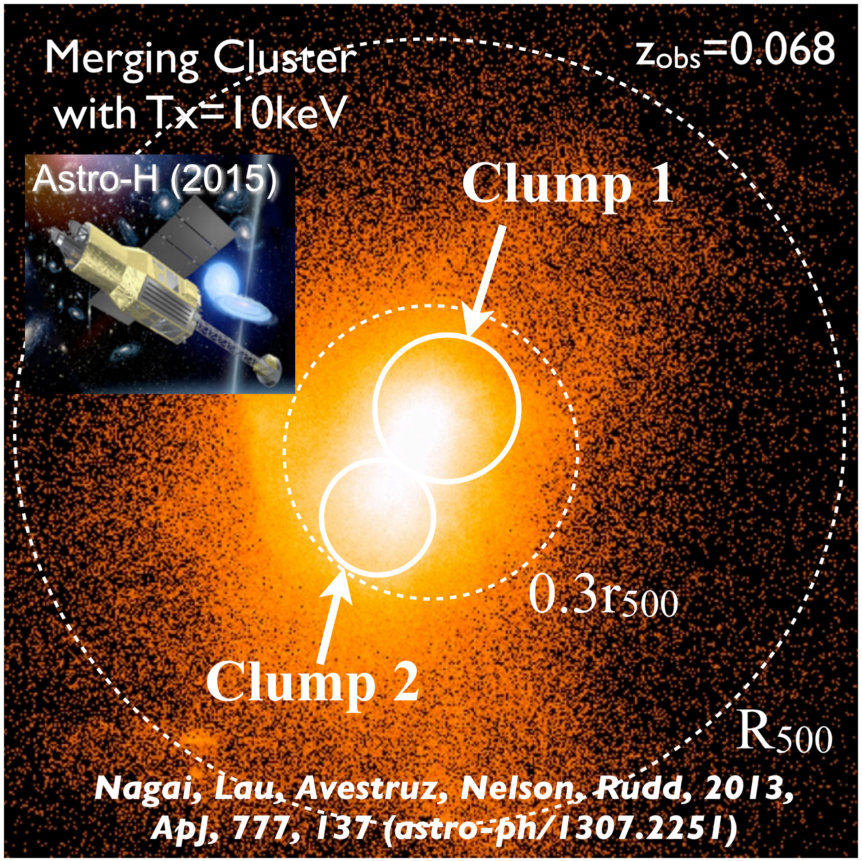
The SZ bispectrum is sensitive to **the outskirts of massive clusters at intermediate redshift (z~0.3-0.5)**. Insensitive to the kSZ signal & less sensitive to gastrophysics than the power spectrum.

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

also Hill & Sherwin 2013

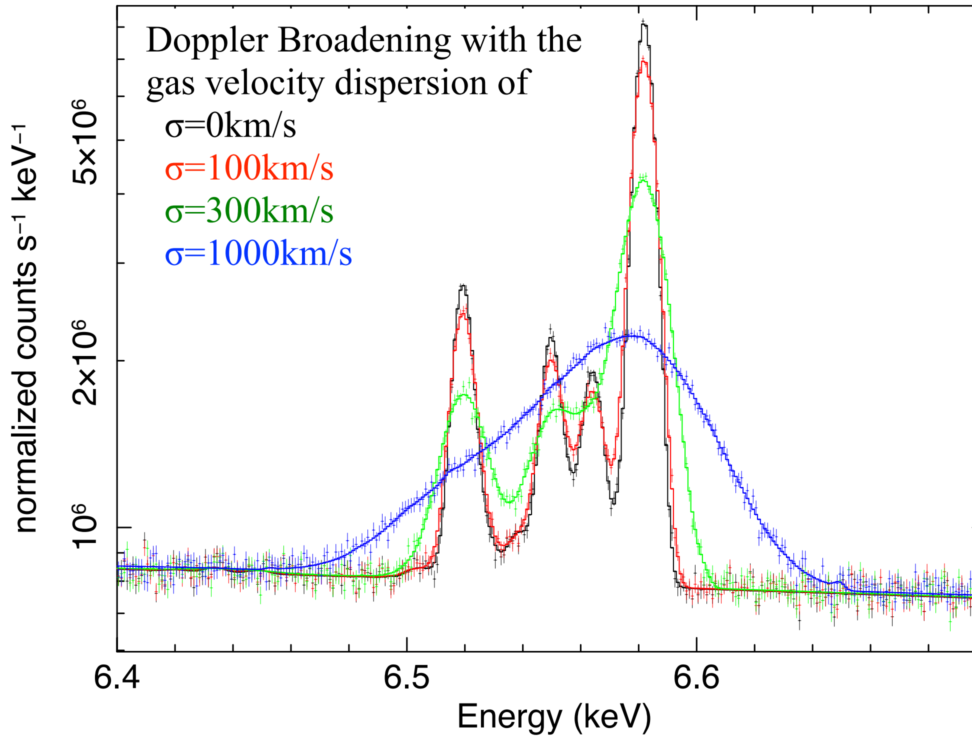
Probing Gas Motions in Galaxy Clusters with Astro-H X-ray mission

Predicting what Astro-H will see.



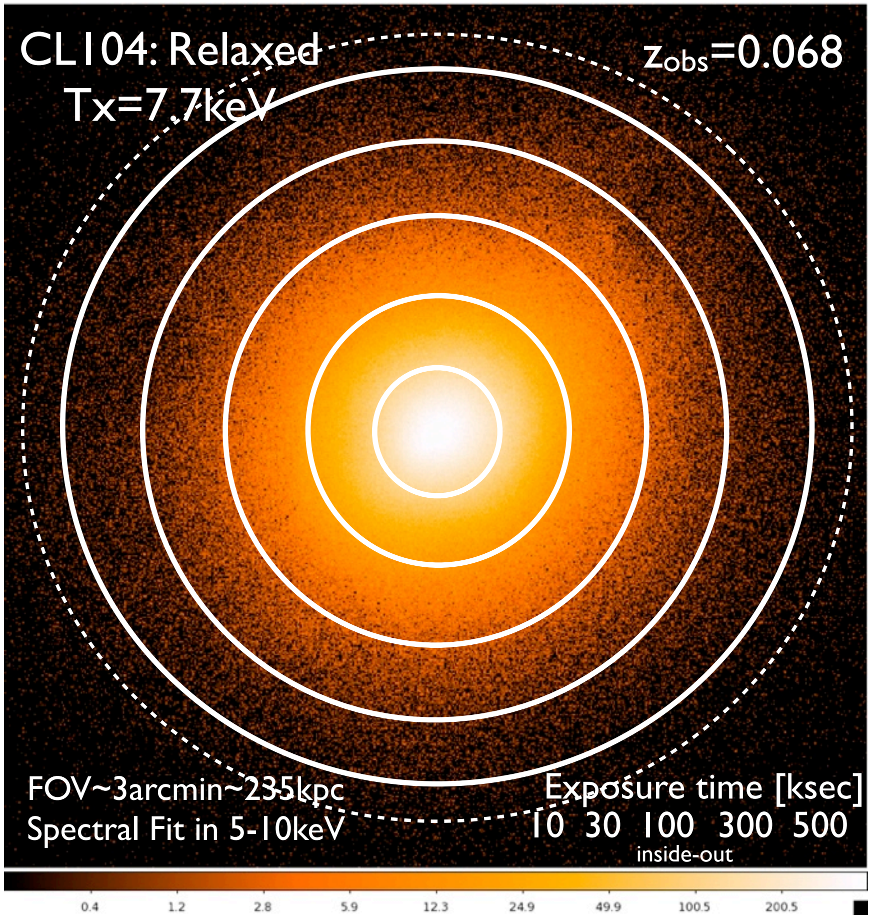
Measuring turbulent gas velocities with the Doppler Broadening of Fe lines

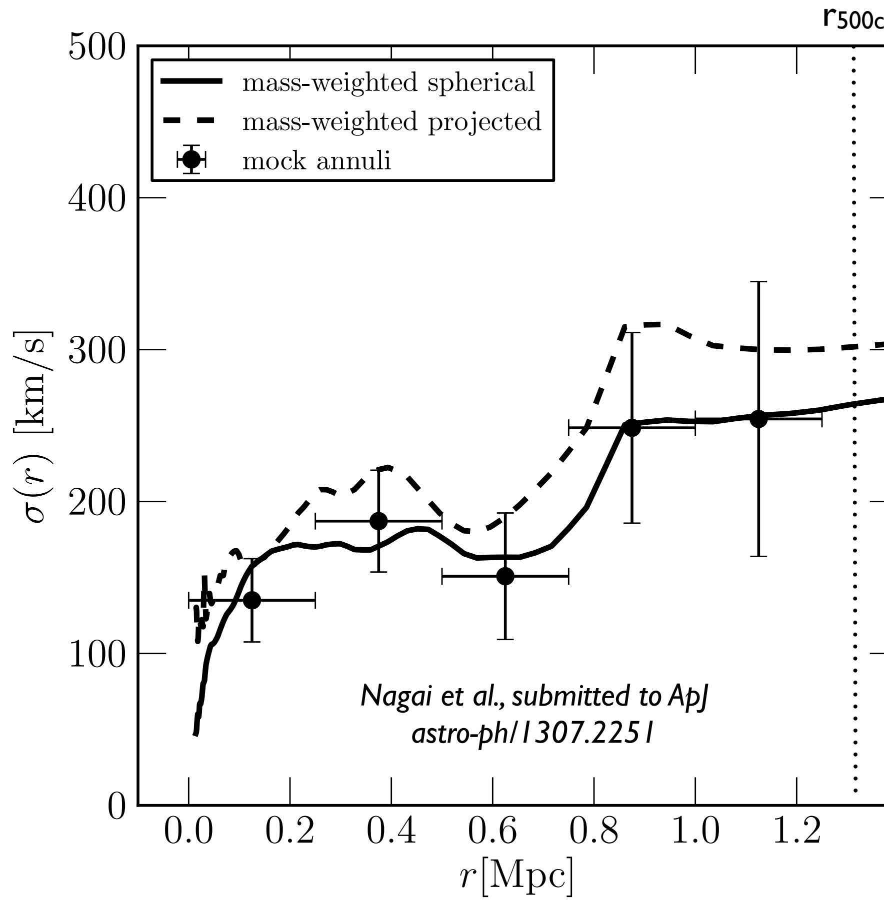
T=10.0 keV z=0.018 ΔE =7eV



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.

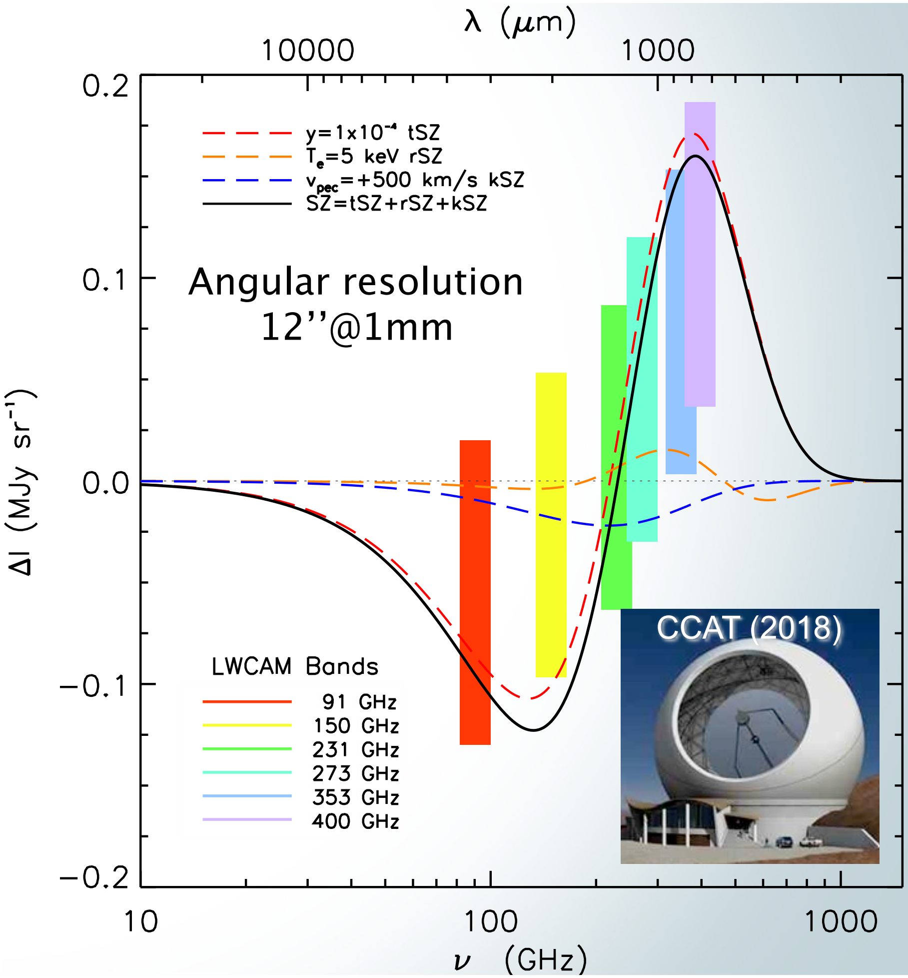
Probing Gas Motions in Galaxy Clusters with deep Astro-H observation



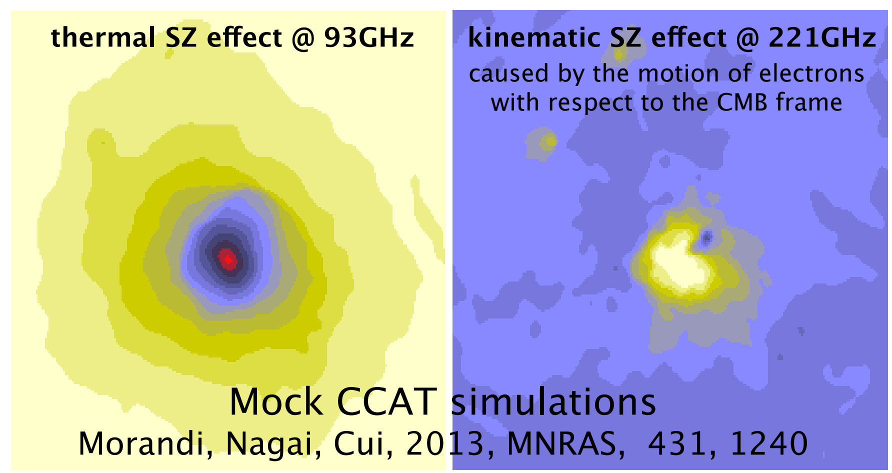


Deep Astro-H observations can map out the gas velocity profile out to R_{500}.

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

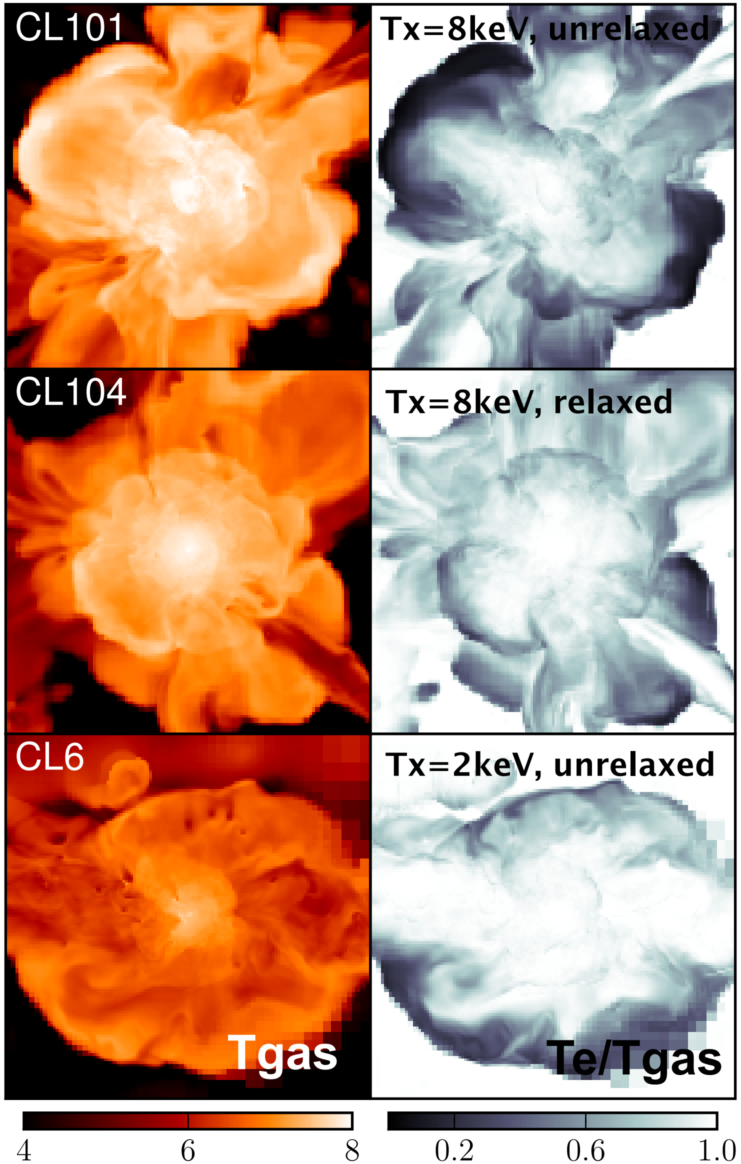


- ***Thermodynamic structure of the ICM***
  - ***Temperature profile via SZ relativistic corrections (independently from X-ray)***
  - ***Inhomogeneities in the ICM (gas clumping)***
- ***Non-thermal pressure in clusters***
  - ***Bulk vs. Turbulent motions via kSZ substructure***

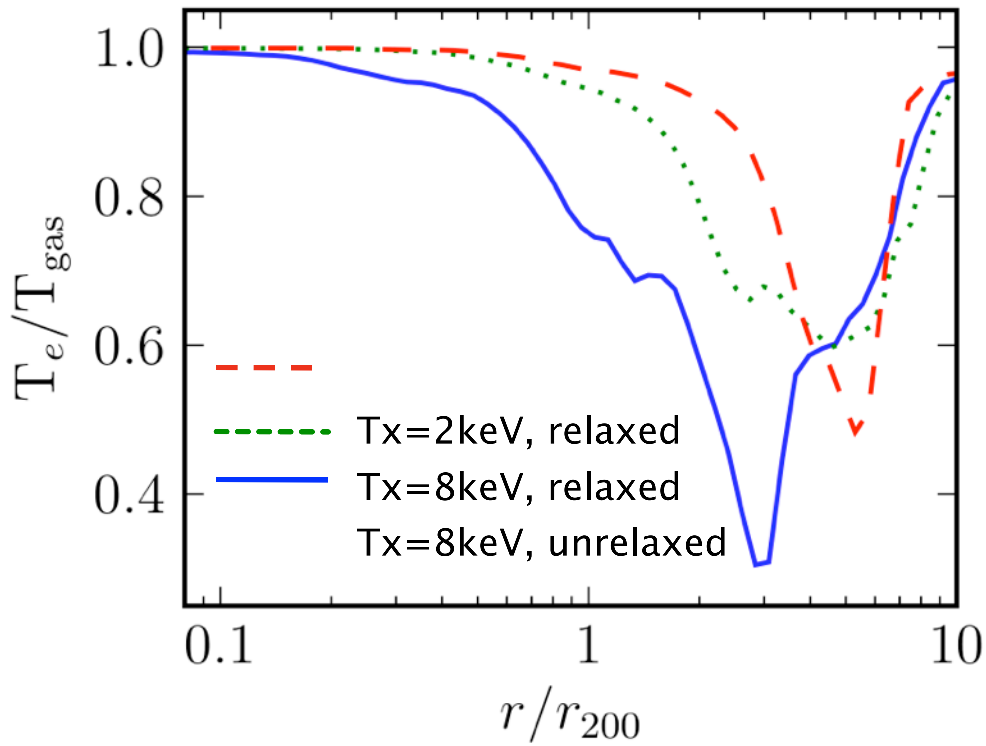


High-resolution, multifrequency SZE observations are sensitive to thermodynamic and velocity structures of the hot gas in the outskirts of galaxy clusters.

Missing Cluster Astrophysics #4
Plasma Physics in Cluster Outskirts



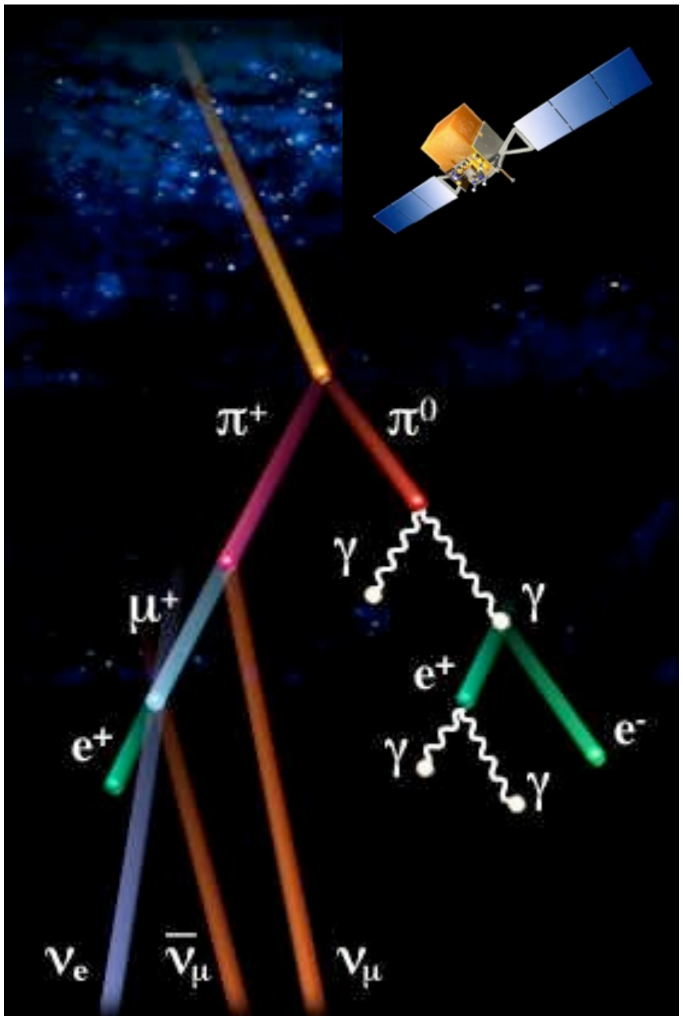
In the outskirts of galaxy clusters, the collision rate of electrons and protons becomes longer than the age of the universe.



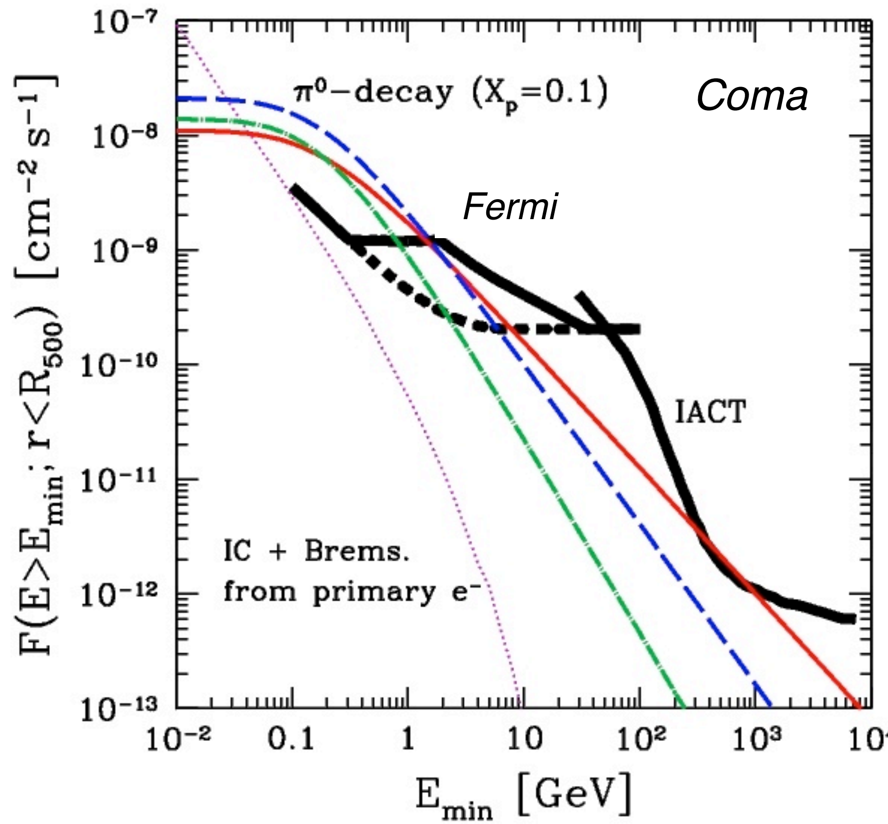
Rudd & Nagai, 2009, ApJ, 701, 16
Spitzer 1962, Chuzhoy & Loeb 2004,
Akahori & Yoshikawa 2010

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

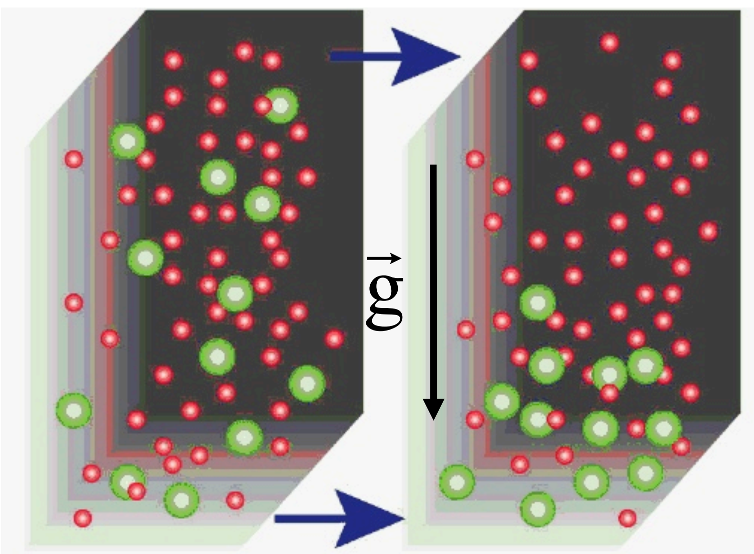
also Pfrommer+08; Jeltema+09; Pinske+11

Missing Cluster Astrophysics #6
He sedimentation in Galaxy Clusters

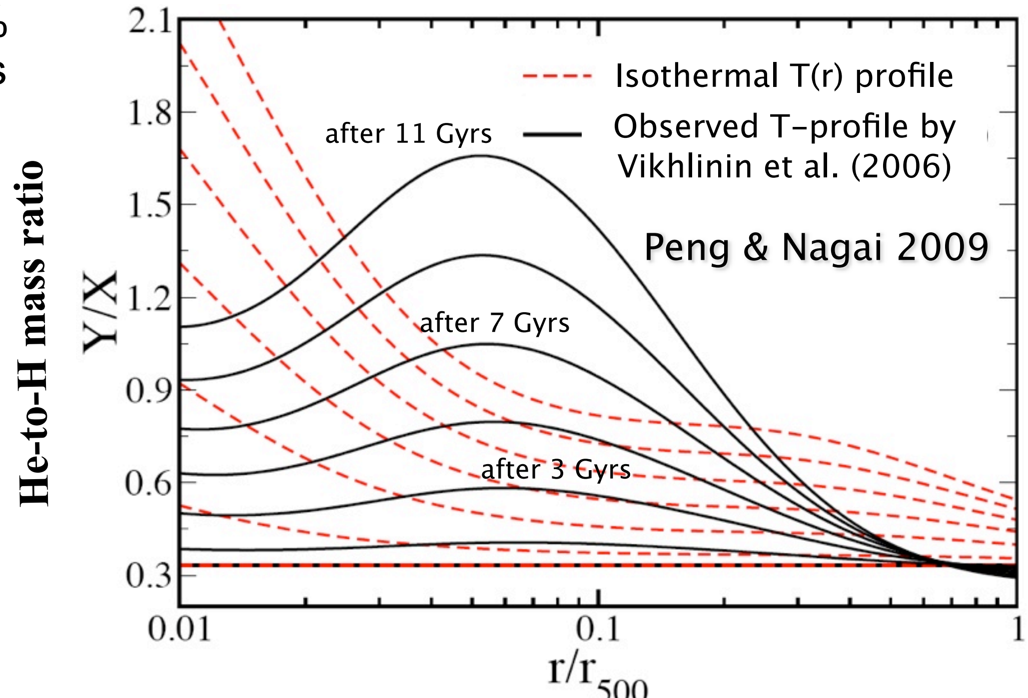
$$M_{\rm tot}(<r) = \frac{-r^2}{G\rho}\frac{dP_{\rm ther}}{dr} \propto \frac{1}{\mu} = \frac{8+3(Y/X)}{4+4(Y/X)}$$

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

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 ($r<R_{500}$).

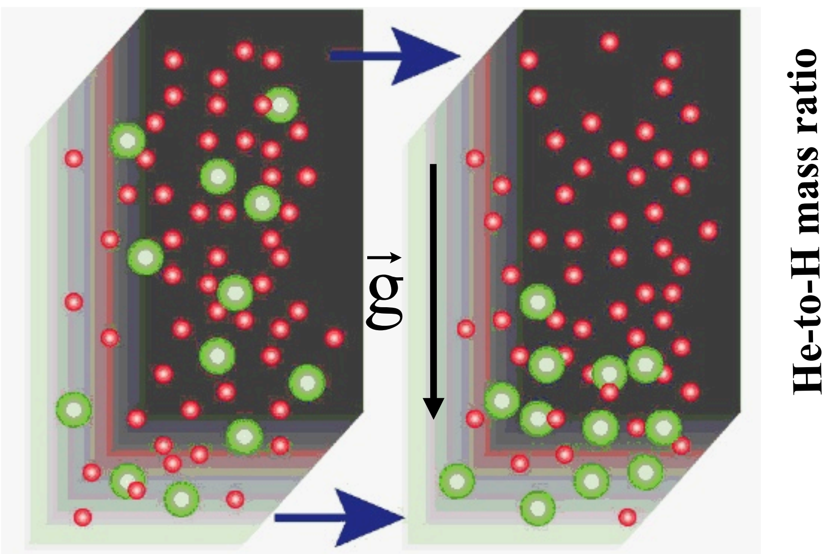
also Abramopoulos1981, Gilfanov & Sunyaev1984, Qin & Wu2000, Chuzhoy & Nusser2003, Chuzhoy & Loeb 2004, Ettori & Fabian 2006

Missing Cluster Astrophysics #6
He sedimentation in Galaxy Clusters

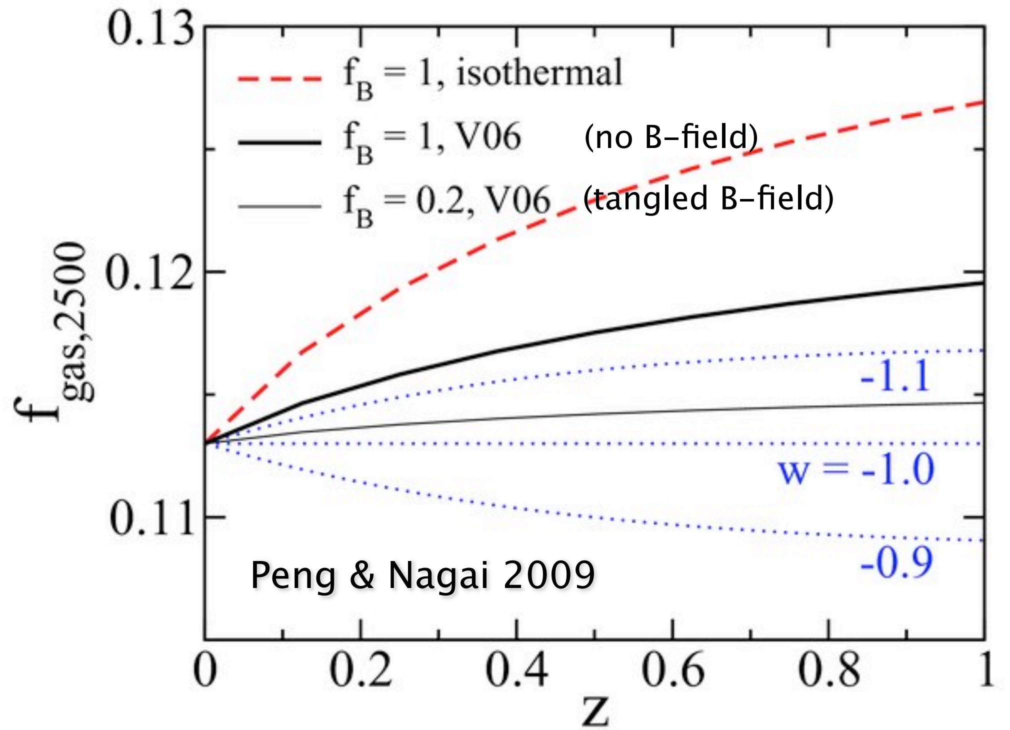
$$M_{\rm tot}(<r) = \frac{-r^2}{G\rho}\frac{dP_{\rm ther}}{dr} \propto \frac{1}{\mu} = \frac{8+3(Y/X)}{4+4(Y/X)}$$

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

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

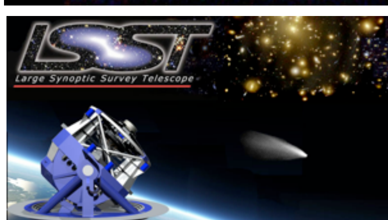


Solving the diffusion equations for the fully ionized H-He plasma in the NFW potential



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 ($r \sim R_{500}$).

New Science Opportunities



DARK ENERGY SURVEY

Big Questions

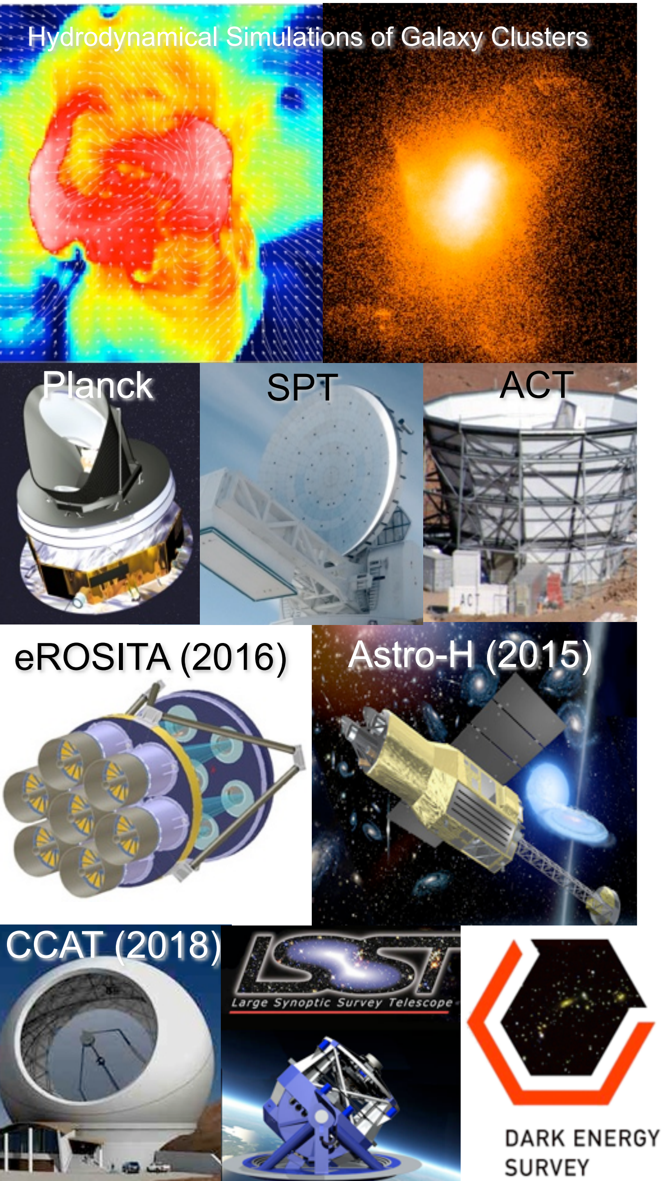
What are dark energy & dark matter?

How do galaxies form and evolve?

Big Challenge

The physics of baryons (galaxy formation)?

Galaxy Clusters in the Era of Precision Cosmology



- **Galaxy Clusters are powerful probes of cosmology & astrophysics**
  - ***Fundamental Physics of the Cosmos***
    - ★ *What are Dark Energy & Dark Matter?*
    - ★ *Does the Einstein's theory of gravitation hold on large-scales?*
  - ***Structure Formation of the Universe***
    - ★ *What is the physics of baryons?*
    - ★ *How do galaxies form and evolve?*

Planck Cosmological Constraints from CMB vs. Cluster counts