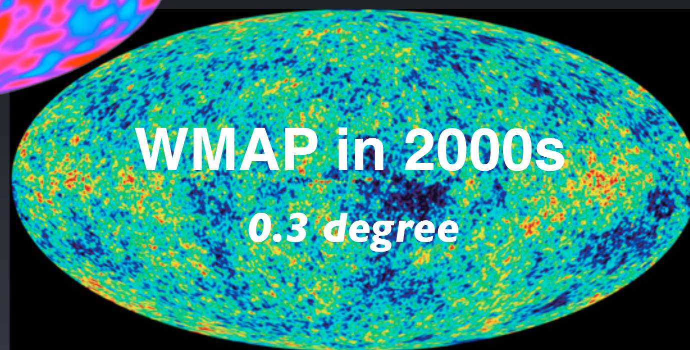
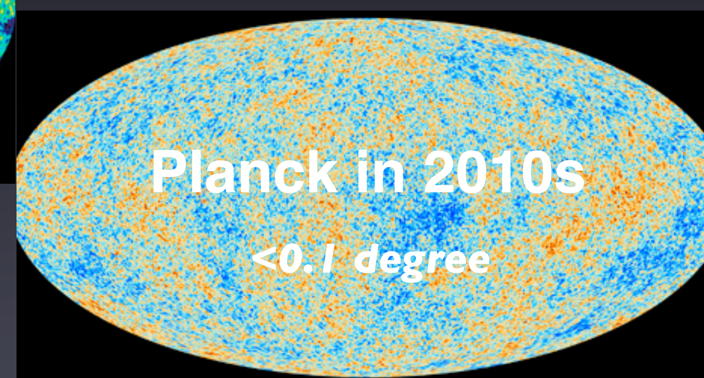
SZ Science in the Planck Era
Insights from Cosmological Simulations

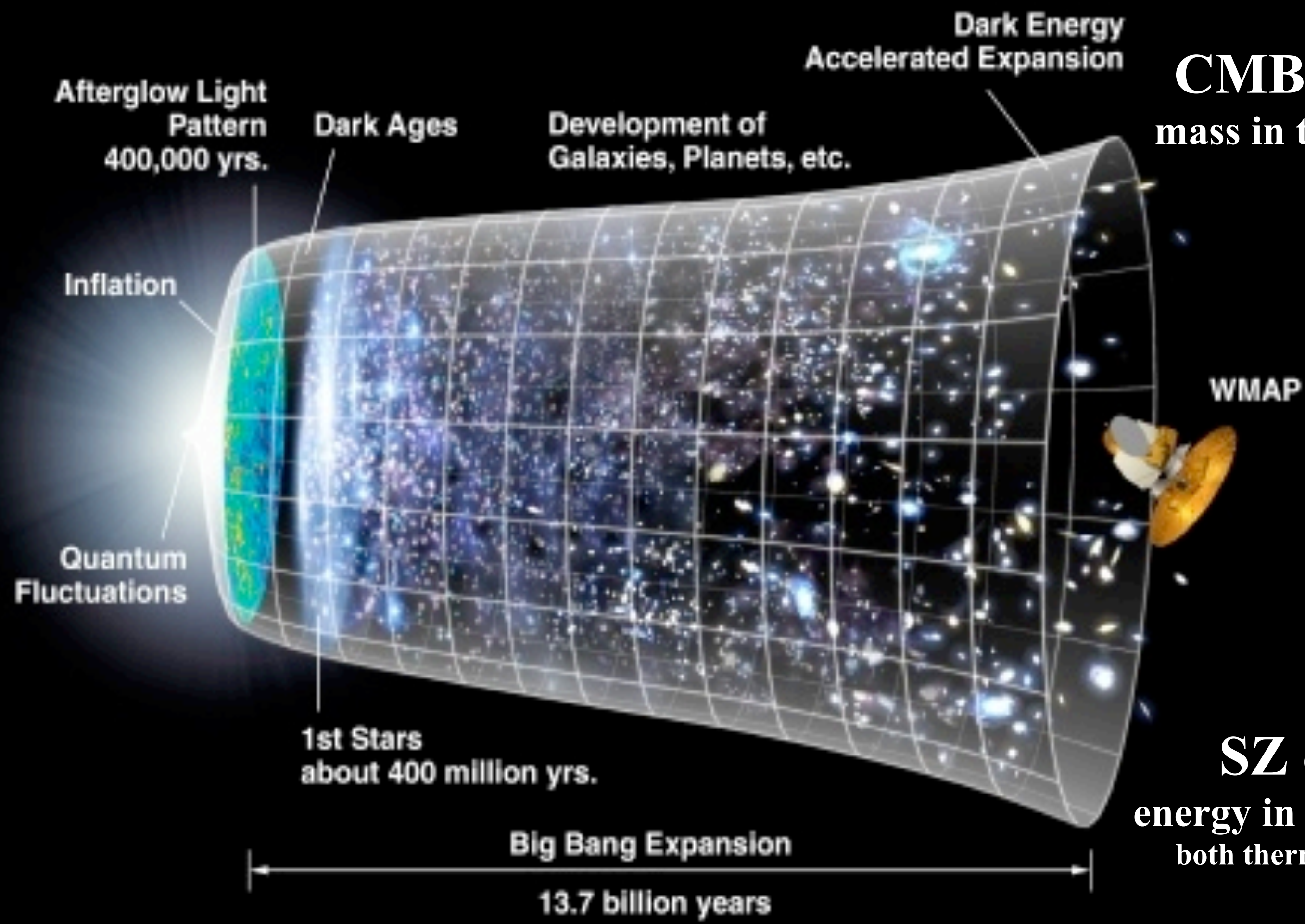




Daisuke Nagai
Yale University
New Light in Cosmology from the CMB
ICTP, Trieste
July 31, 2013

Secondary CMB Anisotropy

Using the CMB as backlight

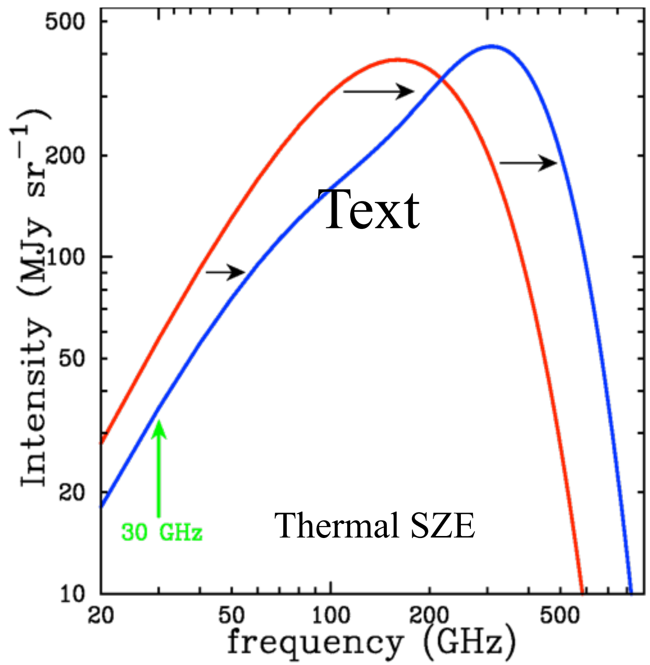


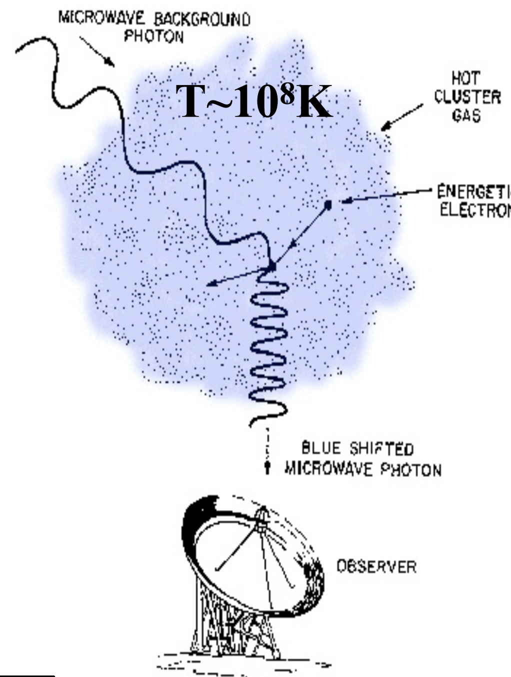
CMB lensing
mass in the universe

SZ effect
energy in the universe
both thermal & kinetic

Sunyaev-Zeldovich Effect

CMB photons provide a backlight for structure in the universe.



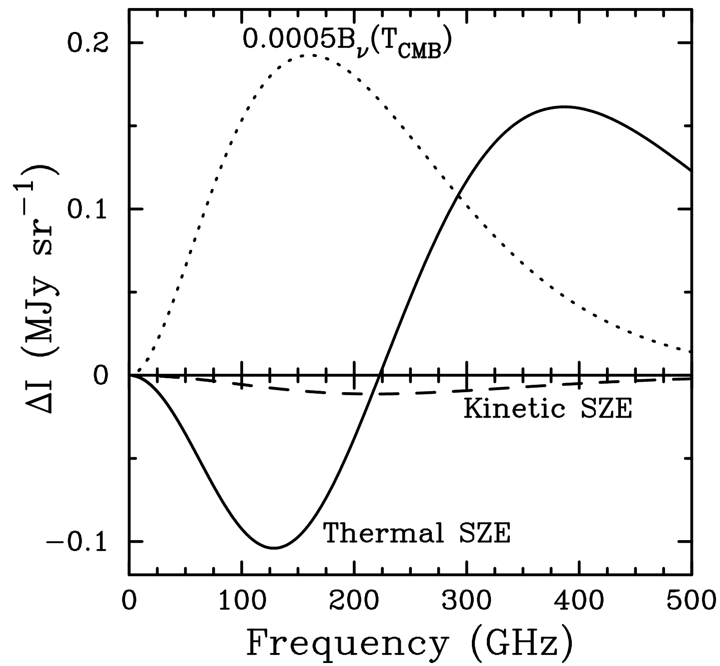


$$\boxed{\frac{\Delta T_{cmb}}{T_{cmb}} \equiv f_\nu(x) y = \left(\frac{k_B \sigma_T}{m_e c^2}\right) \int n_e(l) T_e(l) dl}$$

Sunyaev & Zeldovich 1970, 1972; also Birkinshaw 1999 for a review

Sunyaev-Zeldovich Effect

CMB photons provide a backlight for structure in the universe.



- **Thermal SZ effect:** 1-2% of CMB photons traversing galaxy clusters are inverse Compton scattered to higher energy
- **Kinetic Effect:** the effect due to a cluster gas moving with respect to the CMB - Talk by Arthur Kosowsky
- **Surface Brightness of the effect independent of redshift**

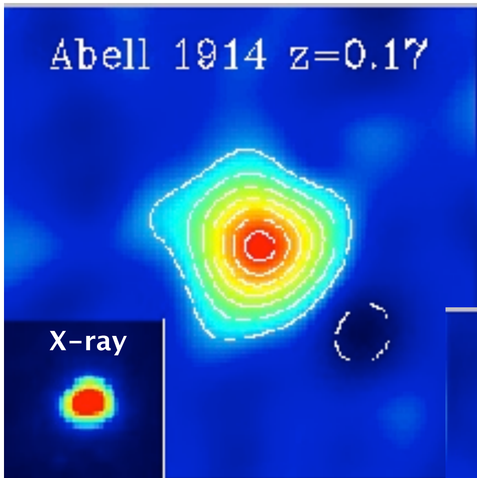
$$\boxed{\frac{\Delta T_{cmb}}{T_{cmb}} \equiv f_\nu(x)y = \left(\frac{k_B\sigma_T}{m_c c^2}\right)\int n_e(l)T_c(l)dl}$$

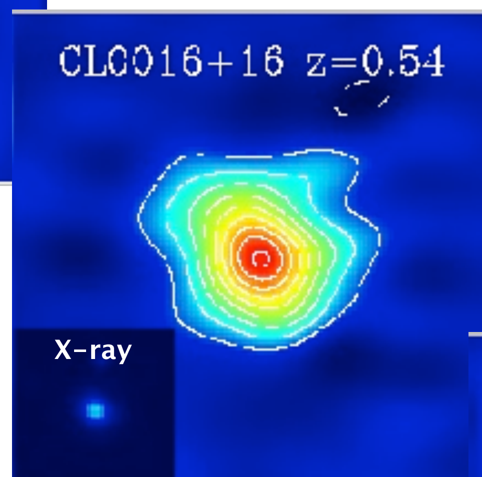
Sunyaev & Zeldovich 1970, 1972; also Birkinshaw 1999 for a review

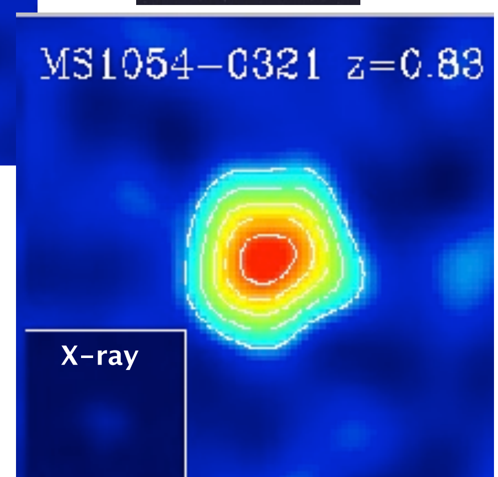
Cosmology with Sunyaev-Zeldovich Effect

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

SZE is independent of redshift with a robust mass proxy

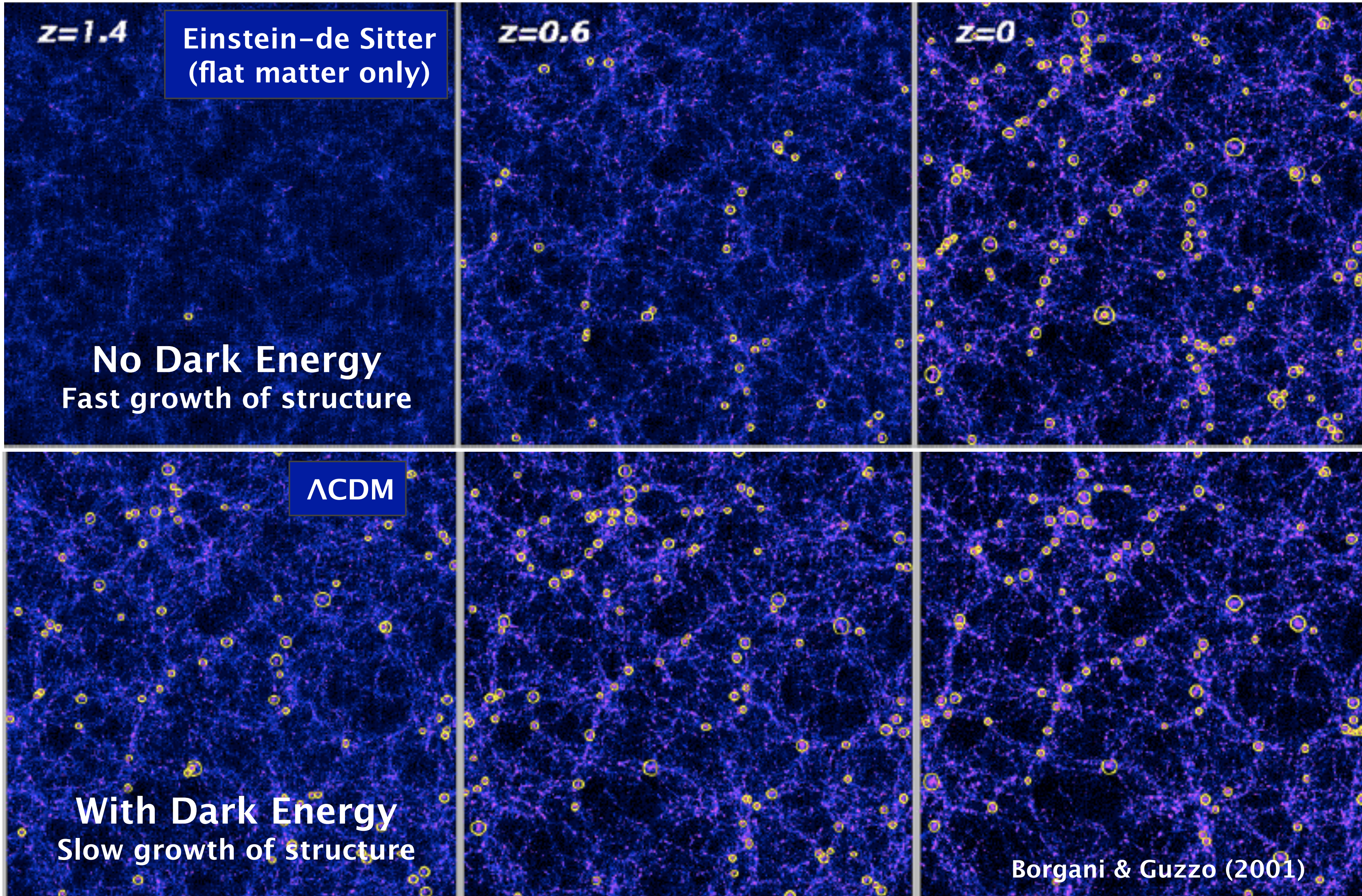






Carlstrom, Holder, Reese 2002 for a review

Probing Dark Energy with Galaxy Clusters

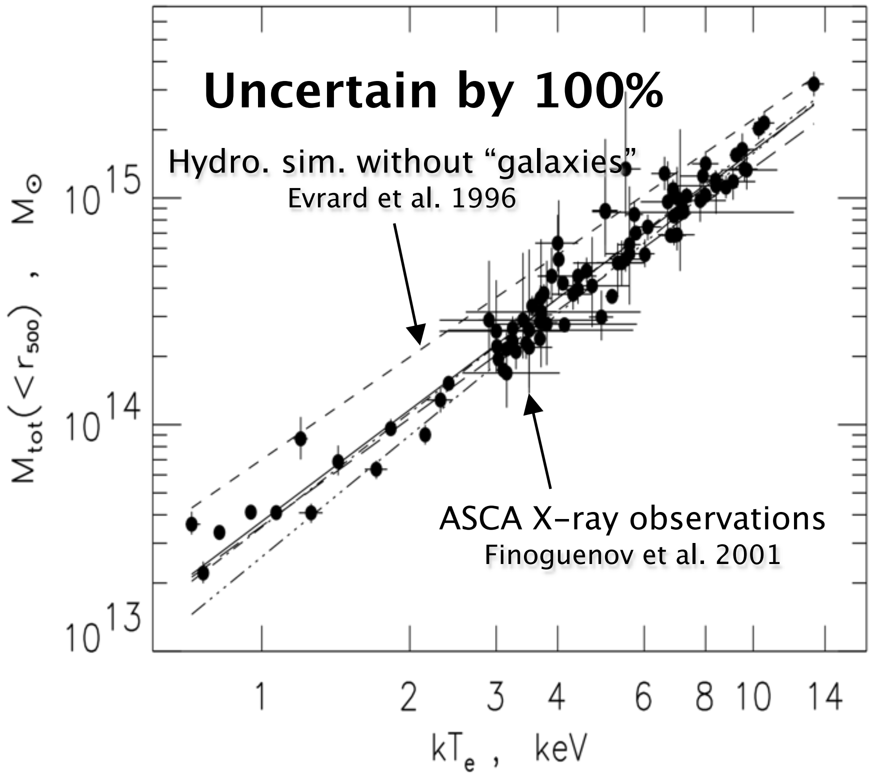


Challenges & Recent Advances in Cluster Cosmology

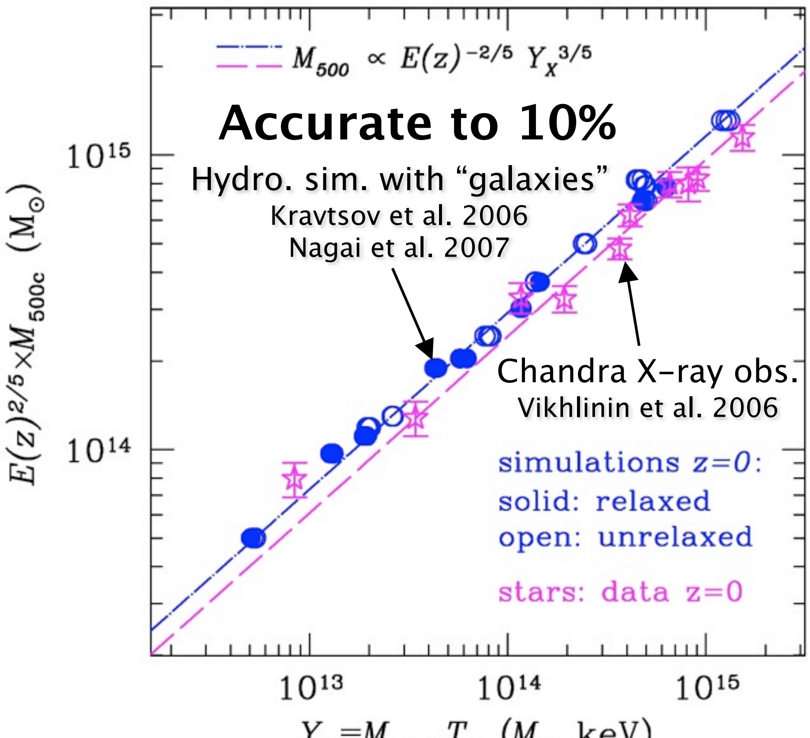
Dark Energy Task Force (2006)

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



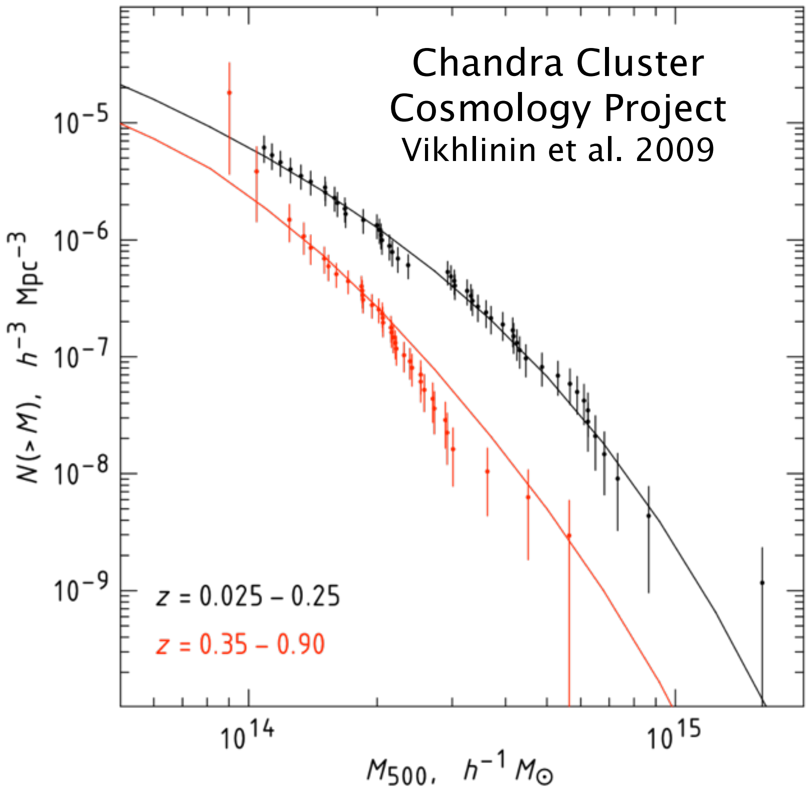
Now

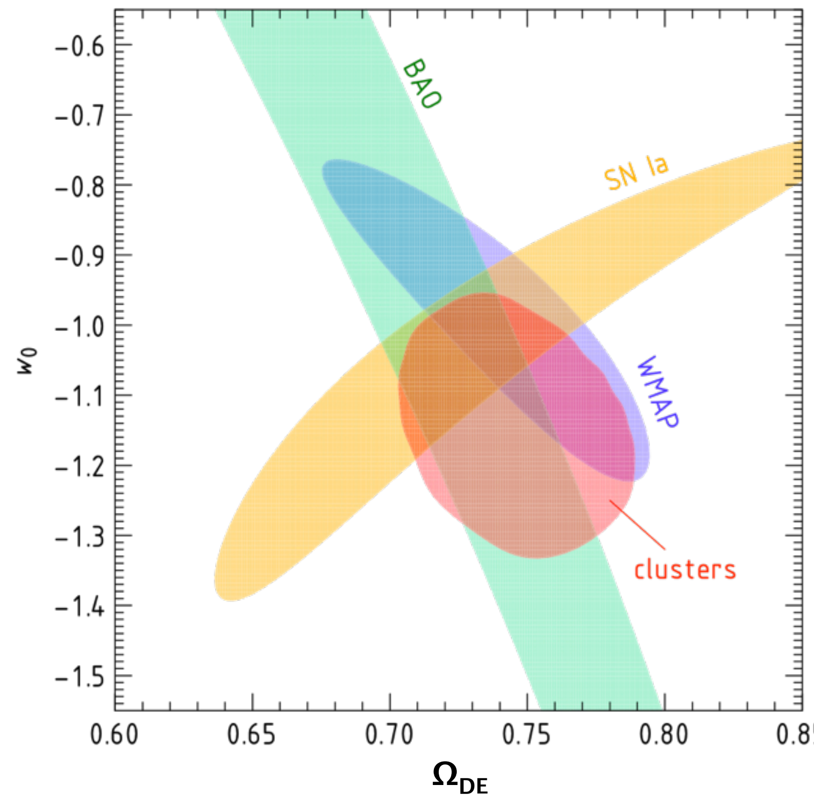


excluding cluster cores ($r<0.15r_{500}$)

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



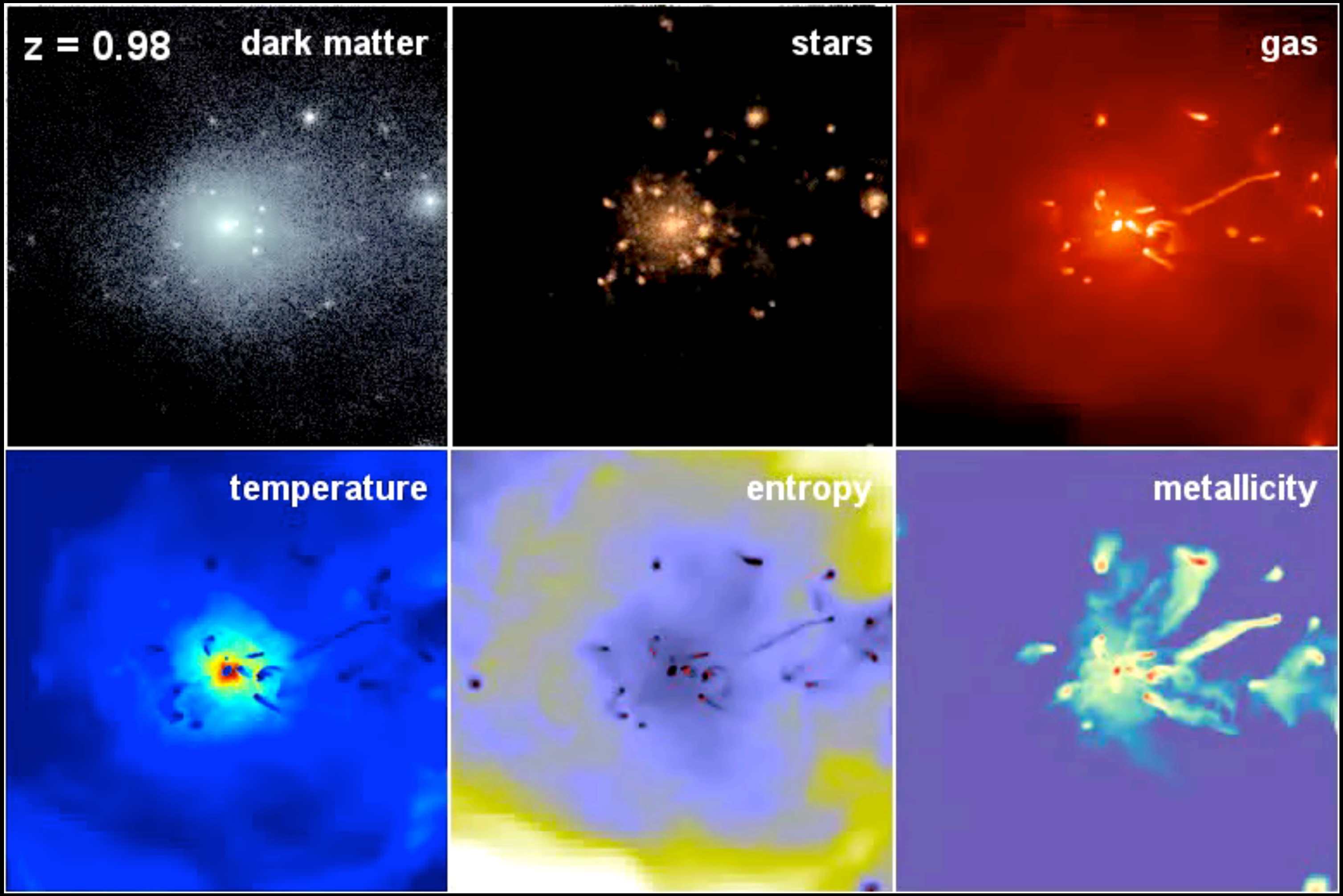


$\sigma_8=0.813(\Omega_M/0.25)^{-0.47}\pm0.013(\text{stat})\pm\mathbf{0.024(sys)}$
$w_0=-0.991\pm0.045(\text{stat})\pm\mathbf{0.039(sys)}$
$\Omega_{DE}=0.740\pm0.012$

Systematics, Systematics, Systematics..

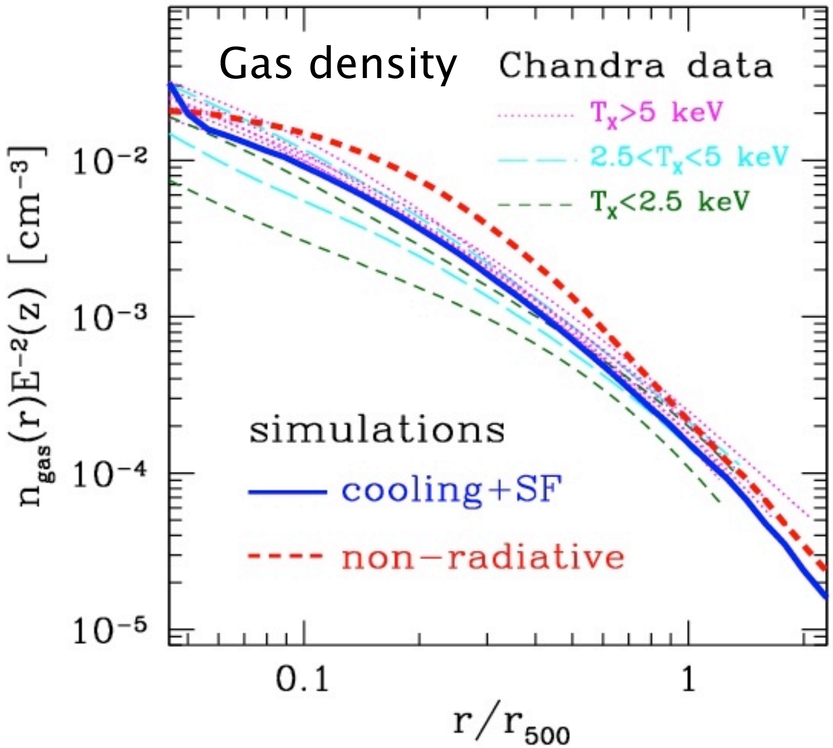
Cosmological Simulations of Galaxy Cluster Formation

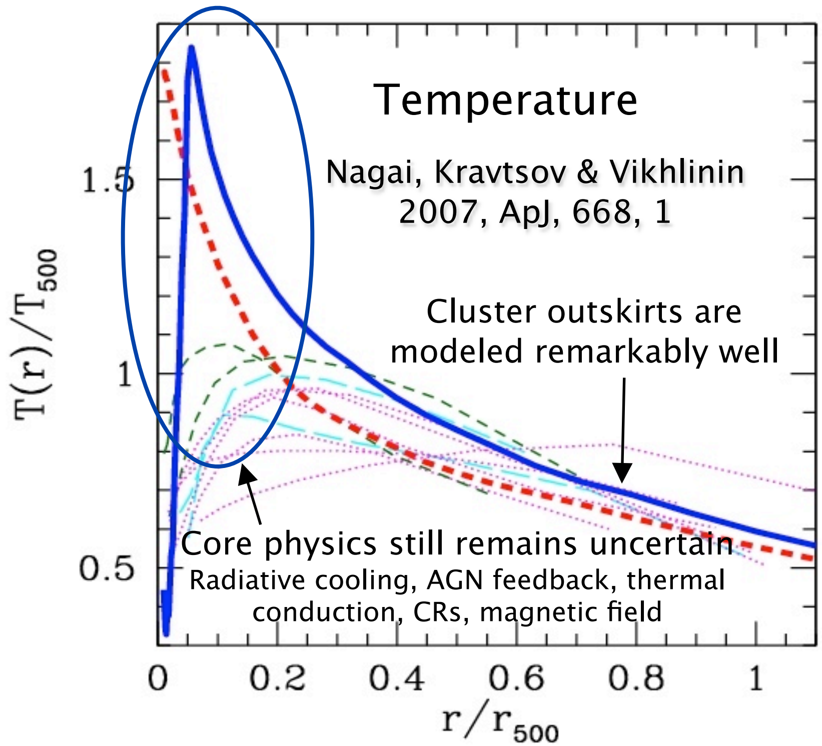
N-body+Gasdynamics with Adaptive Refinement Tree (ART) code
Box size ~ 80/h Mpc; Region shown ~ 2/h Mpc; Spatial resolution ~ a few kpc



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!

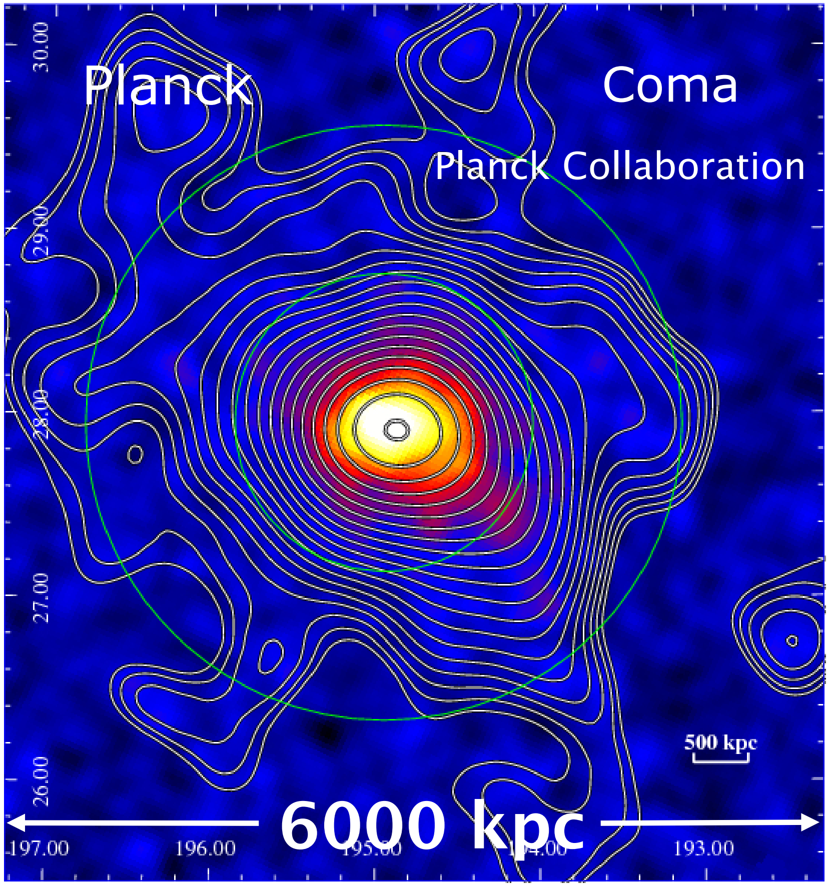
Radial profiles of X-ray emitting ICM
Simulations vs. Chandra X-ray Observations

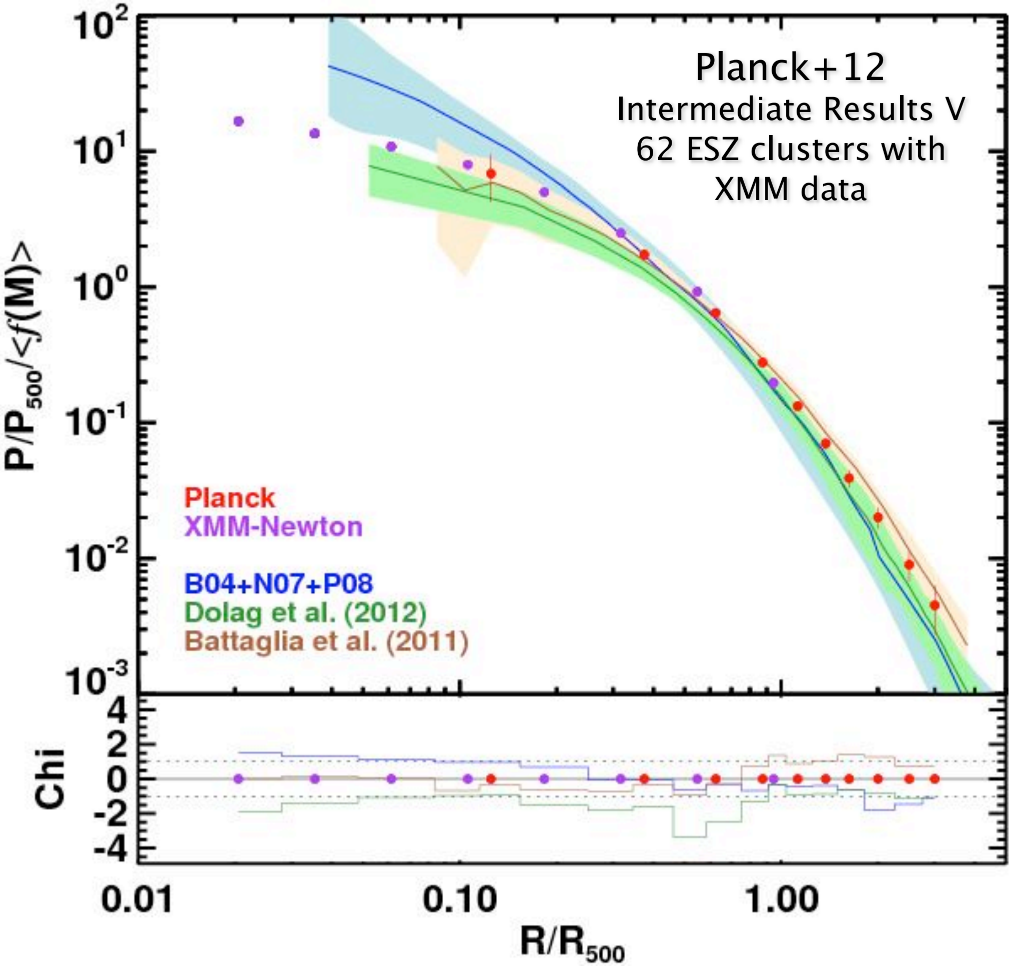




Modern hydrodynamical cluster simulations reproduce observed ICM profiles outside cluster cores ($0.15<r/r_{500}<1$).

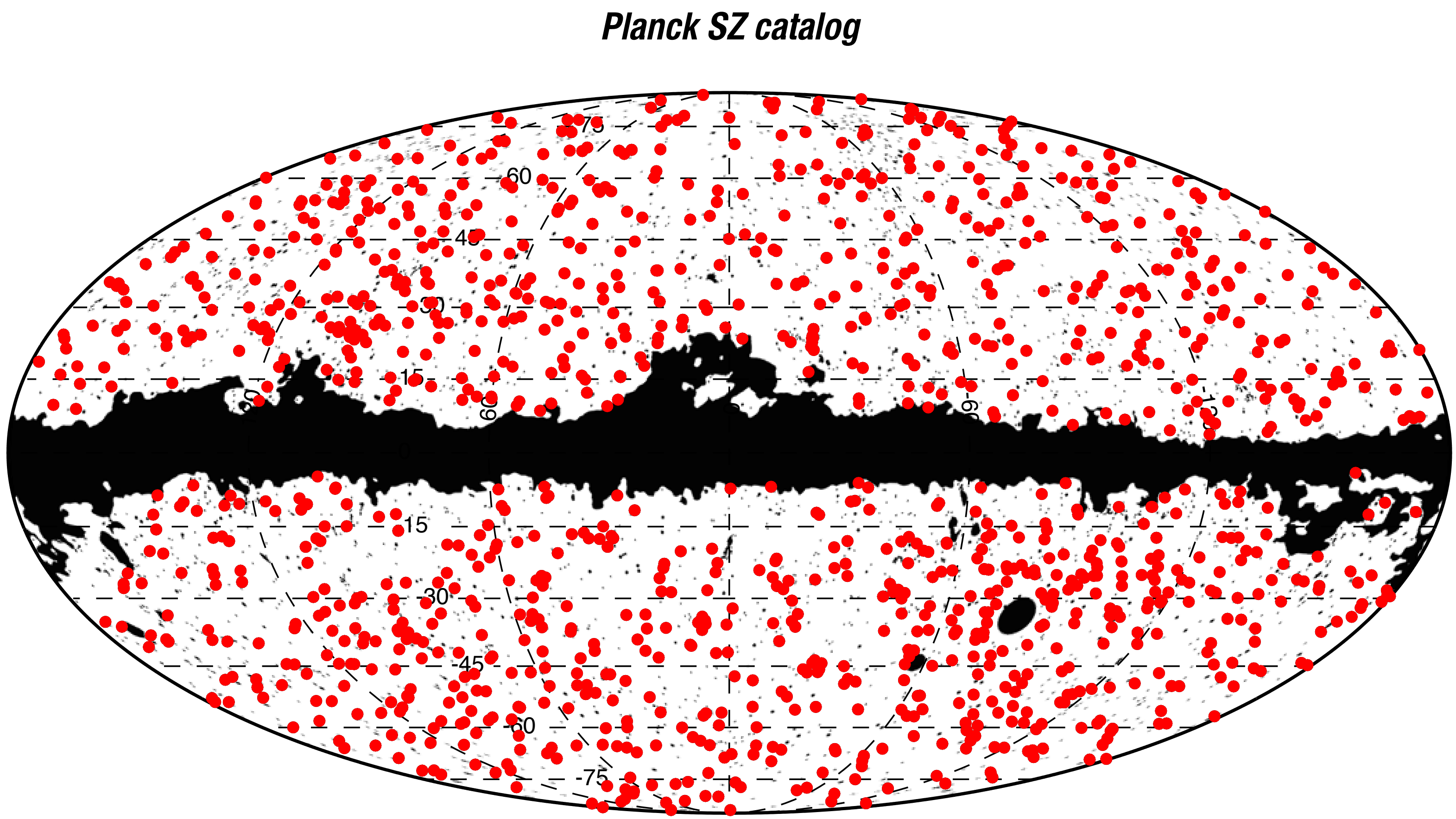
Universal Pressure profile of Galaxy Clusters
Simulations vs. Observations





Stacked Planck measurements of the gas pressure profiles are consistent with the results of hydrodynamical simulations out to $r=3R_{500}$!

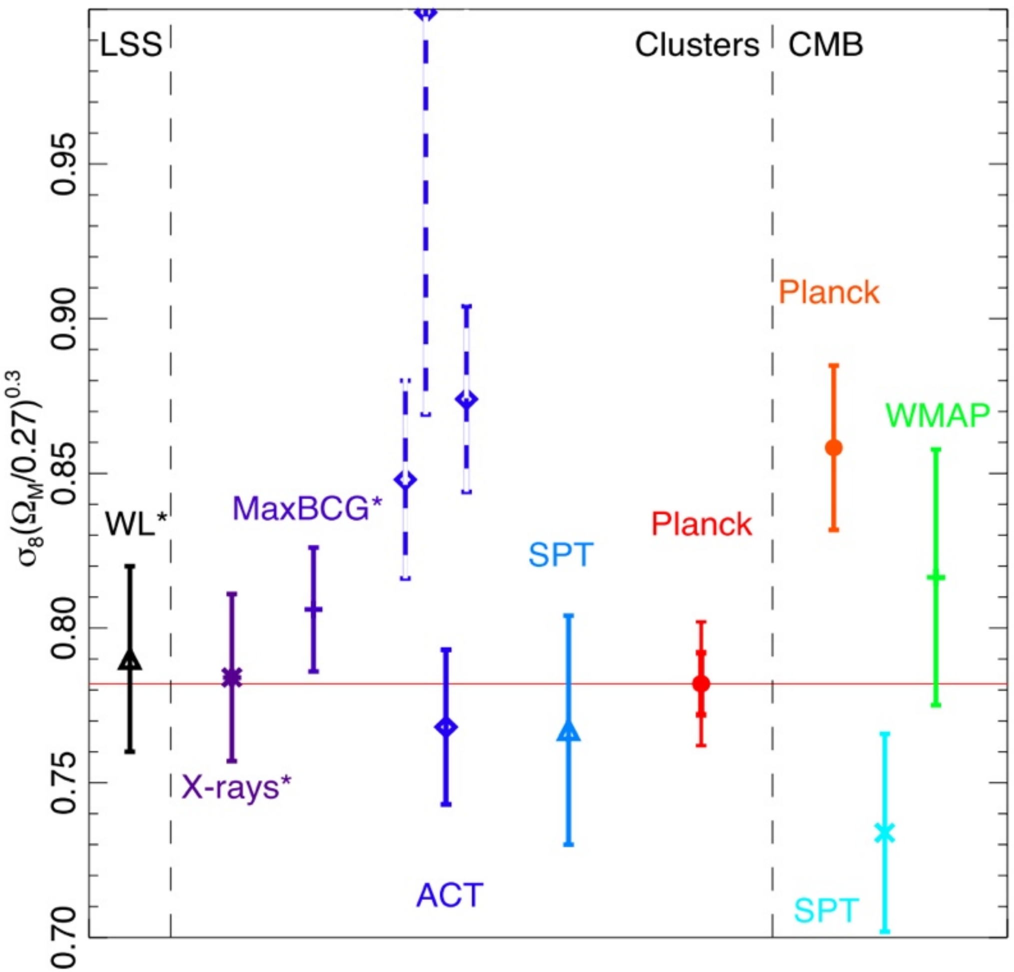
Planck SZ catalog



Planck 2013, Papers XXIX

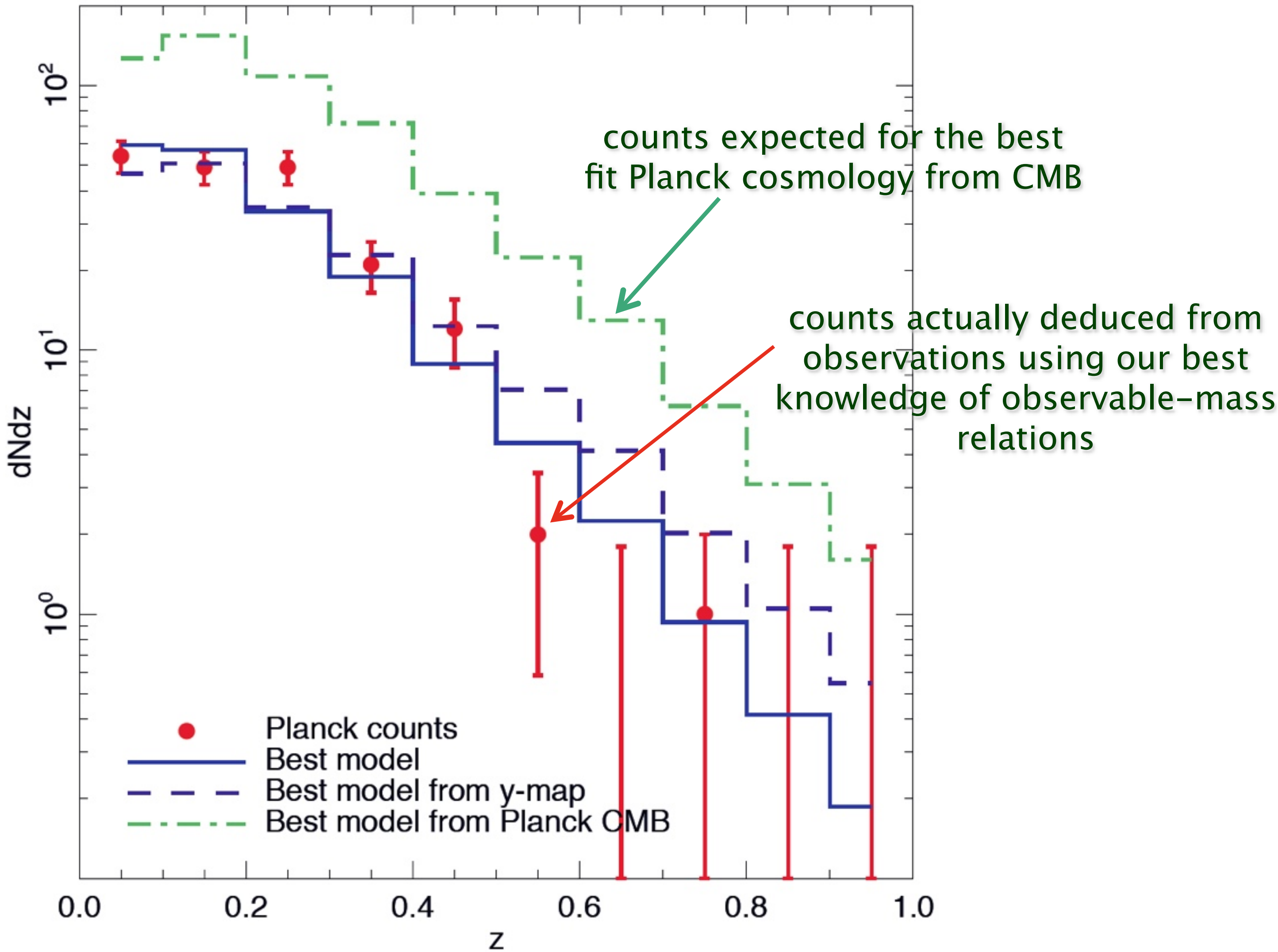
Planck SZ source catalog from the first 15.5 months
1227 entries
861 confirmed clusters
683 previously known clusters; 178 new clusters
366 cluster candidates

Planck cosmological constraints from CMB are in tension with cluster abundances



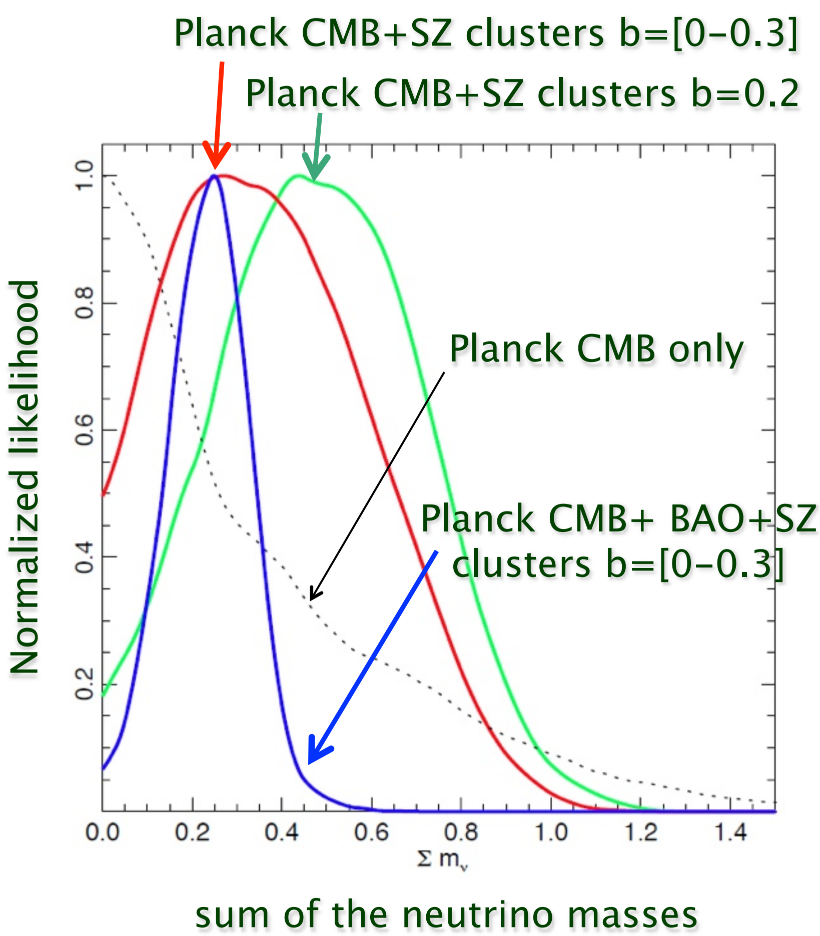
Planck 2013, Papers XX

For best fit Planck cosmology, ~3 times more clusters than expected than deduced from observations



Planck 2013, Paper XX

Possible Solutions



Planck 2013, Paper XX

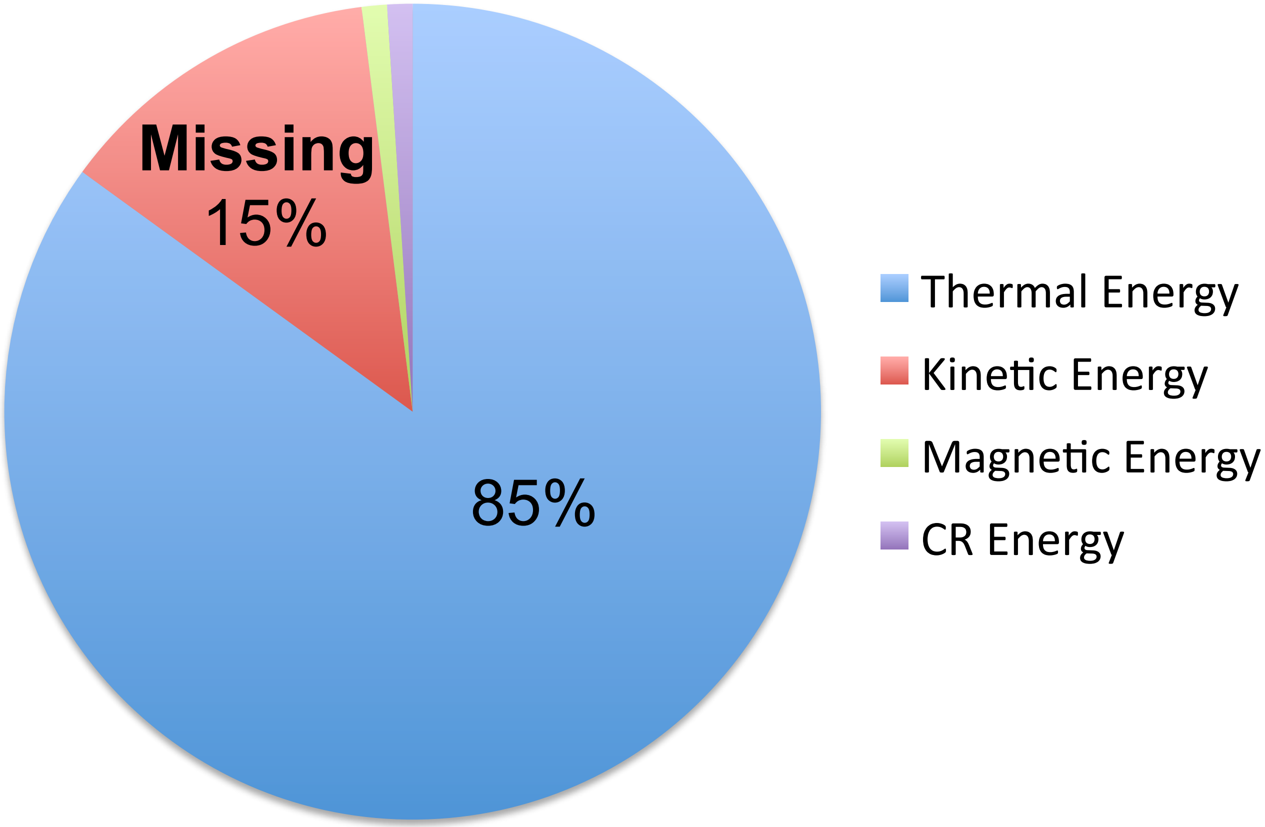
- cluster scaling relations are off by ~40-45%

$$b \equiv (M_{HSE}\text{-}M_{true})/M_{true} \text{ at } r = R_{500}$$

M_{HSE} are derived using the Yx-M_{HSE} calibrated with XMM-Newton

- Planck CMB results may be biased
- 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

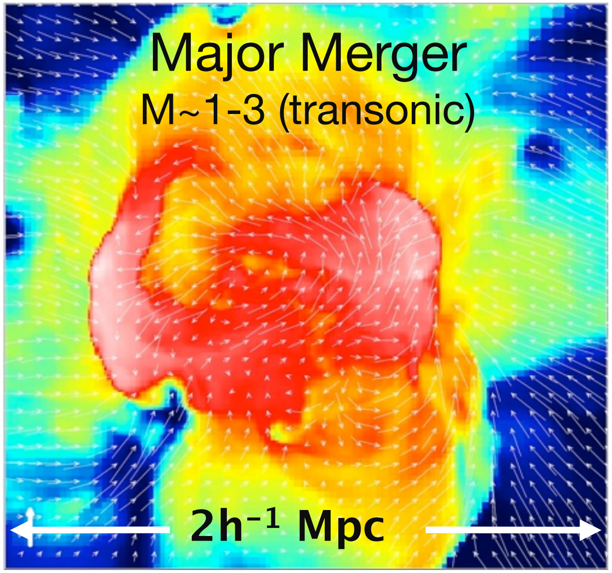
Missing Energy Problem in Galaxy Clusters

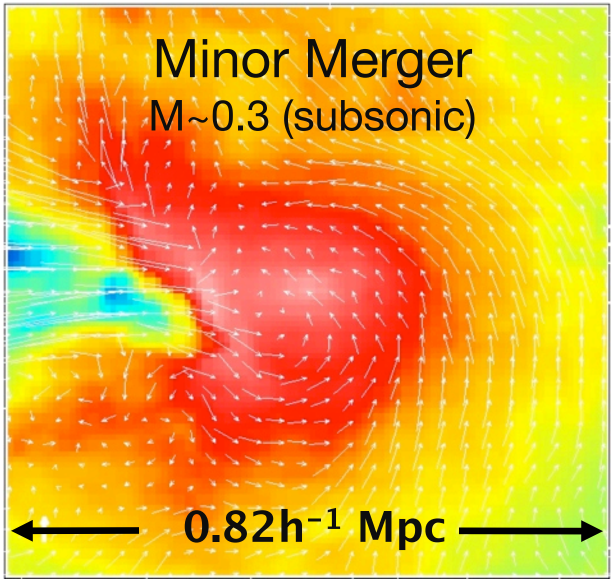


The "average" kinetic energy fraction within the virial radius ($r<R_{vir}=2xR_{500}$) for a typical simulated galaxy cluster forming in the LCDM model. Also, some observational constraints from the Chandra/XMM-Newton surface brightness fluctuations in cluster core regions.

Magnetic and CR energy fractions are constrained to be very small from radio, hard X-ray, and gamma-ray observations of clusters.

Missing Cluster Astrophysics
Gas Motions in Clusters



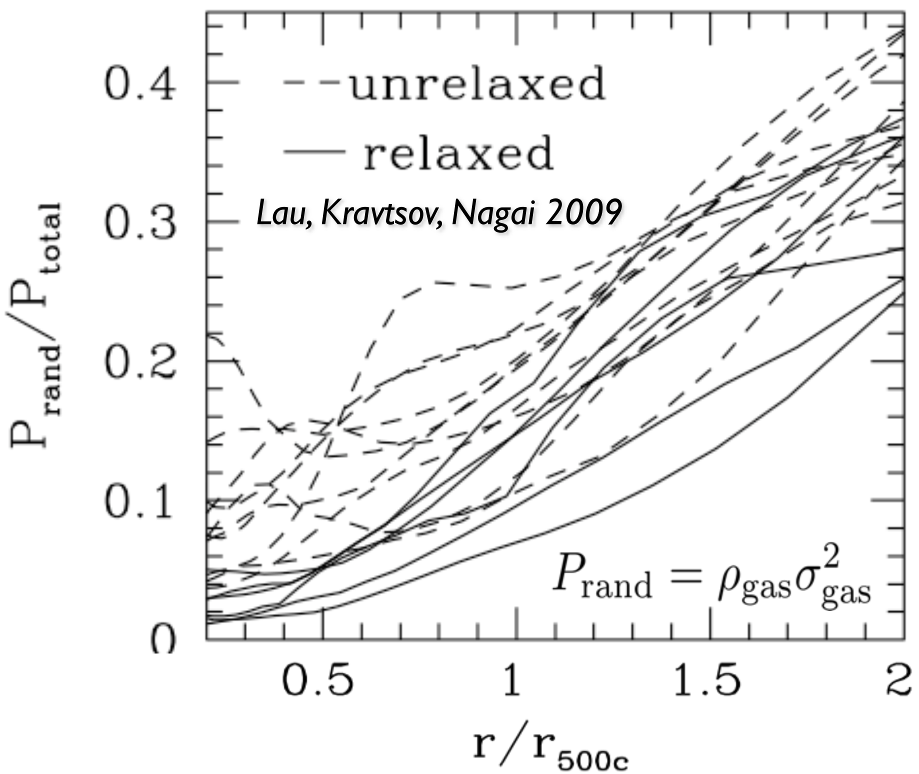


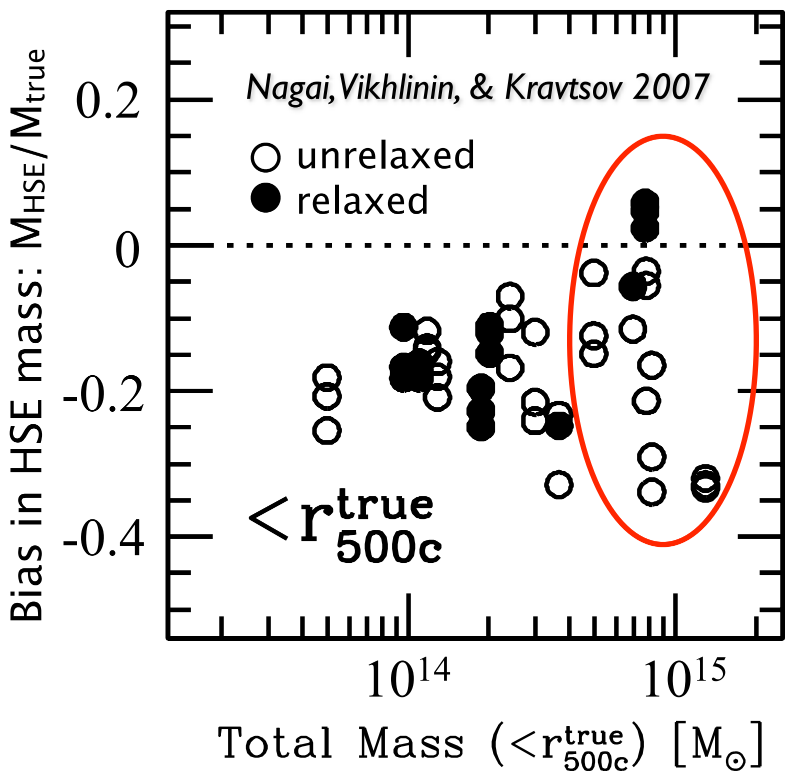
- Gas (bulk+turbulent) motions are predicted to be ubiquitous in the ICM
- Drivers of gas motions
  - Accretion/Mergers (on large scales)
  - Energy injection from SNe/AGN (in cluster cores)
  - Plasma instabilities
- Broad Implications
  - **SZ pressure profiles**
  - **Hydrostatic mass modeling**
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

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

Gas motions is one of the dominant sources of systematic bias in SZ/X-ray cluster mass estimates

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

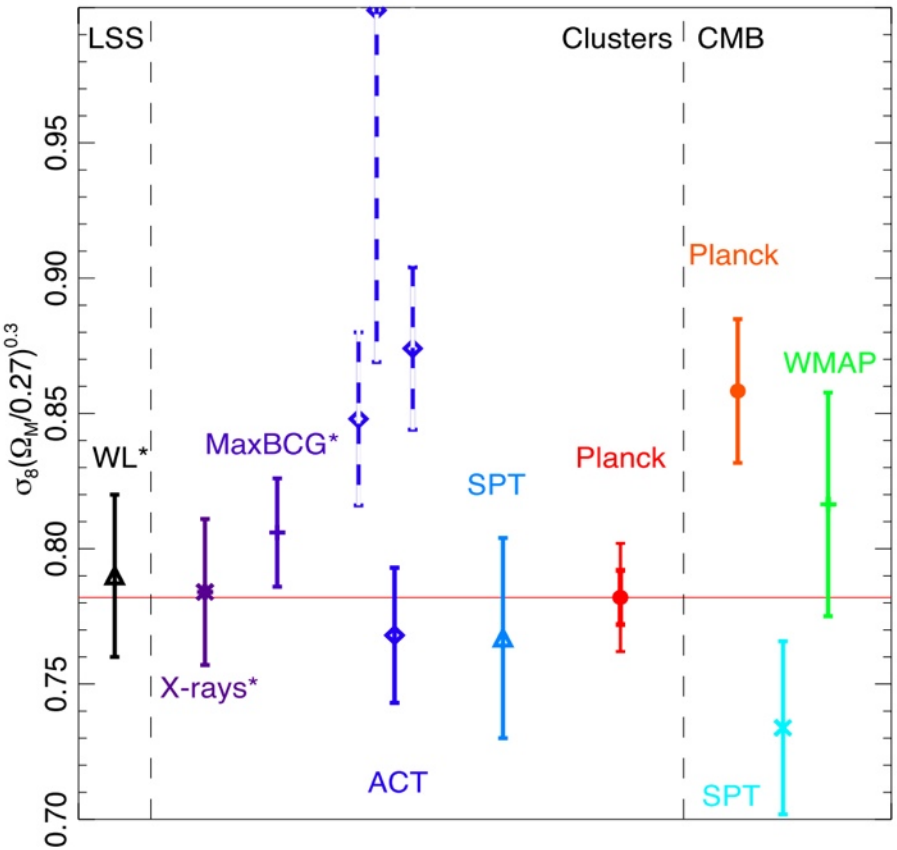




Non-thermal pressure due to gas motions introduces bias in the hydrostatic mass estimate at a level of 0-35% at R_{500}. The mass bias is larger for disturbed clusters.

Also Dolag+05, Rasia+06, Vazza+09, Battaglia+11, Nelson+12, Lau+13

Planck cosmological constraints from CMB are in tension with cluster abundances

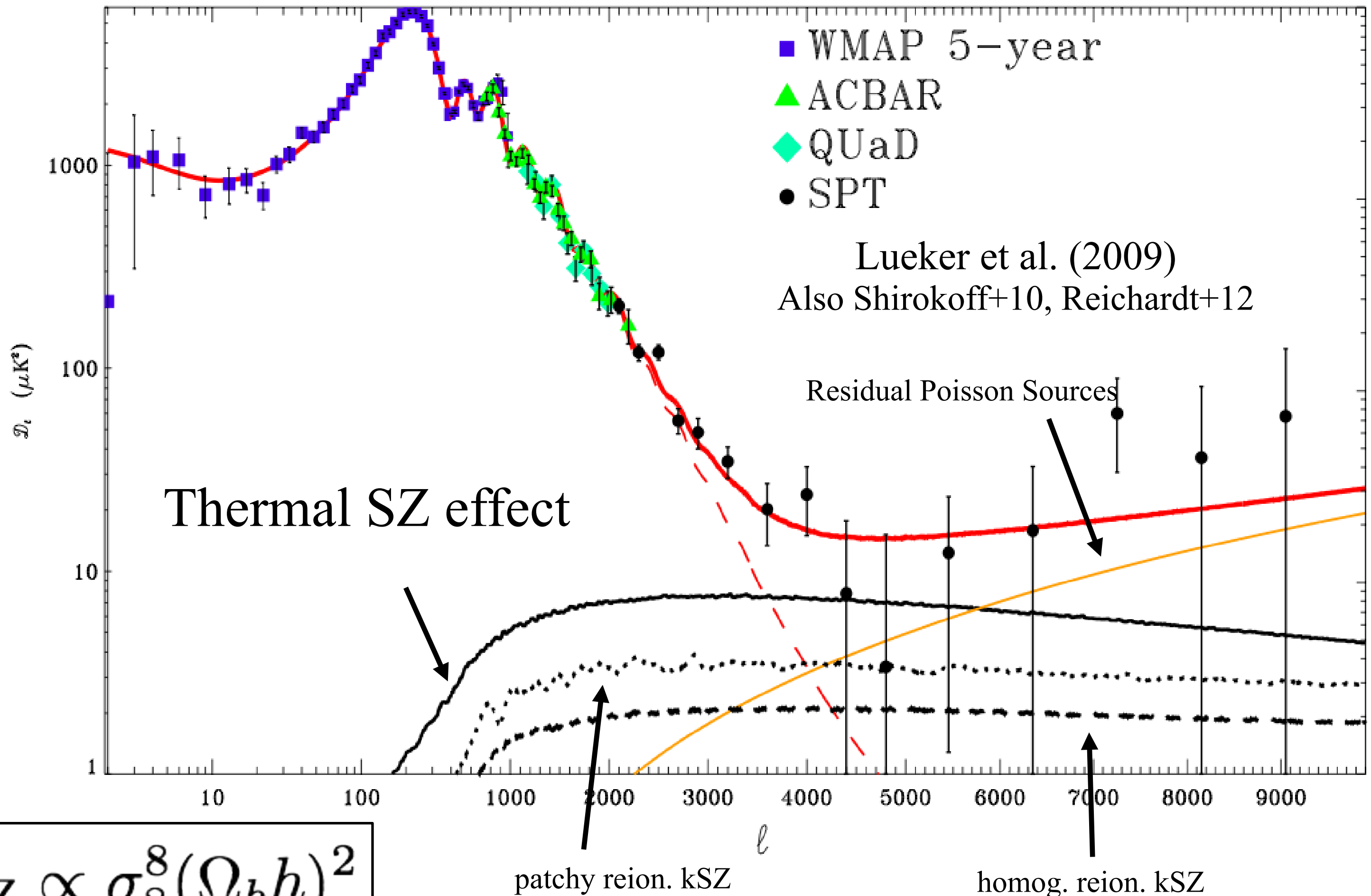


Planck 2013, Papers XX

Possible Solutions

- cluster scaling relations are off by ~45% - **VERY UNLIKELY**
- Planck CMB results may be biased
- 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

Measurements of the SZ power spectrum



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

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..

Predicting the SZ power spectrum

- Analytical calculations (e.g., Komatsu & Seljak 2002; Shaw et al. 2010)
  - take ‘universal’ mass function (e.g., Tinker et al. 2008)
  - assume spherical gas pressure profiles without substructures
  - approximately capture cluster physics, but important for parameter estimation (need to vary both cosmology + cluster physics)
  - gas (bulk+turbulent) motions are predicted to be ubiquitous in the ICM

$$\boxed{C_l = g_\nu^2 \int_0^{z_{max}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \int_0^{M_{max}} \mathrm{d}M \frac{\mathrm{d}n(M,z)}{\mathrm{d}M} |y_l(M,z)|^2}$$

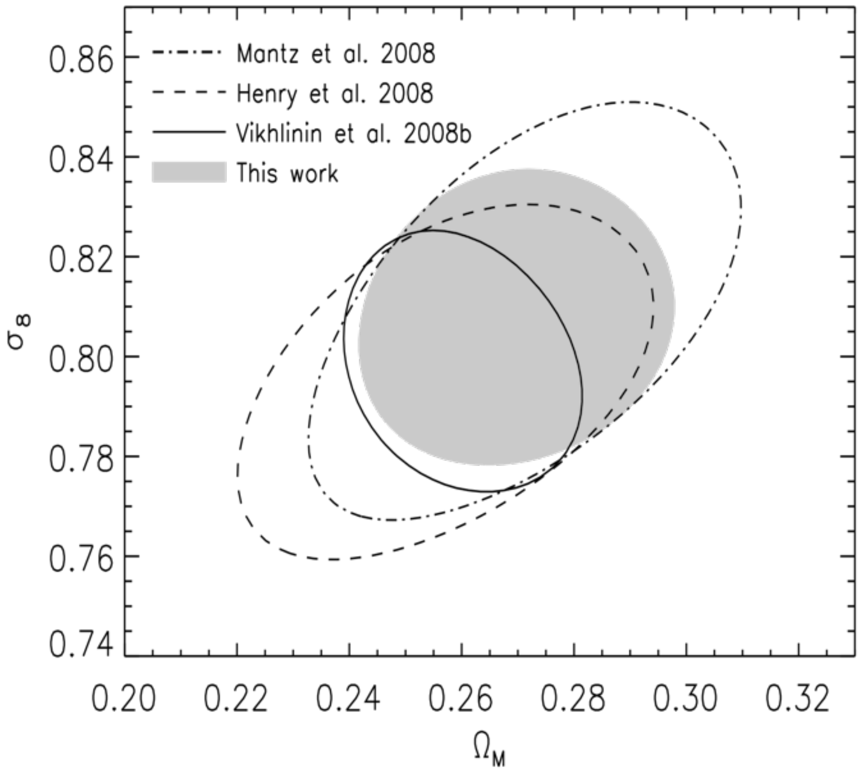
Cosmology

Astrophysics
electron pressure profile

- Hydrodynamical Simulations (e.g., Battaglia et al. 2010)
  - don’t need to ‘assume profiles’
  - follow detailed hydrodynamical evolution of gas in clusters (e.g., gas cooling, star formation, AGN, bulk+turbulent gas flows etc.)
  - need both large simulation boxes and high-resolution to resolve relevant sub-grid cluster physics. **Prohibitably expensive!!**

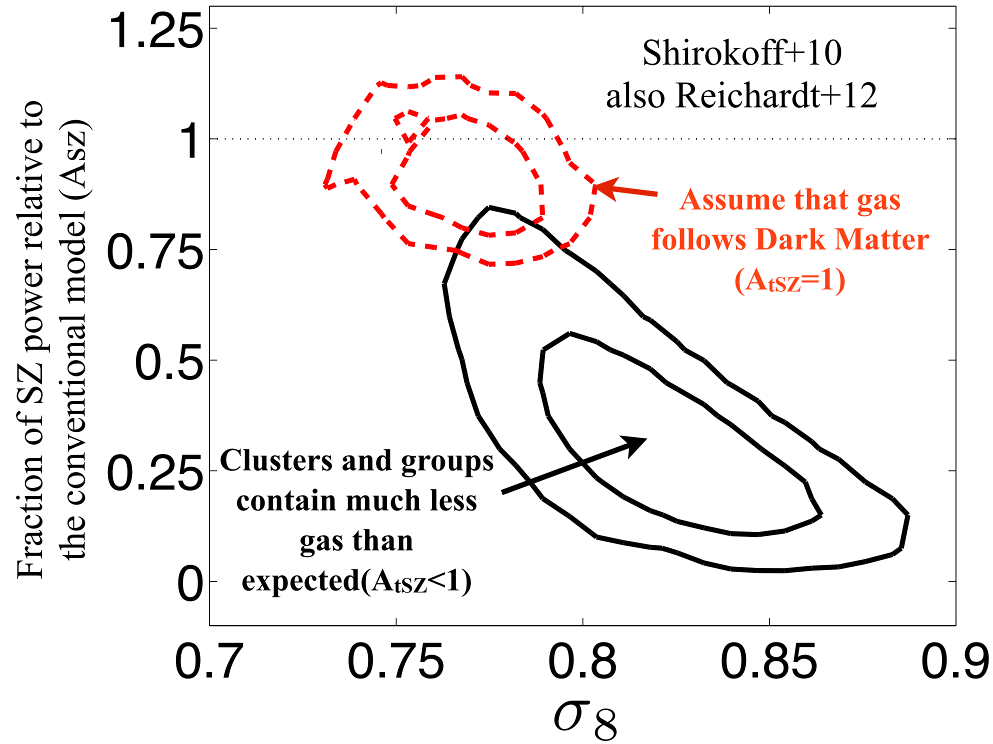
Tension in σ_8 measurements

Cluster Abundance



$\sigma_8 = 0.80 \pm 0.02$

SZ power spectrum



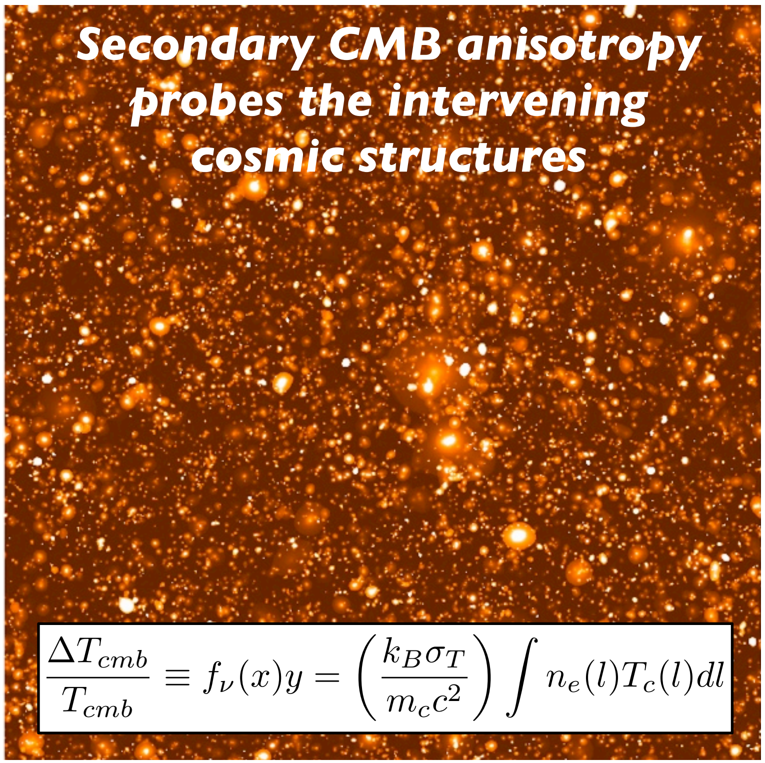
$\sigma_8 = 0.767 \pm 0.009$

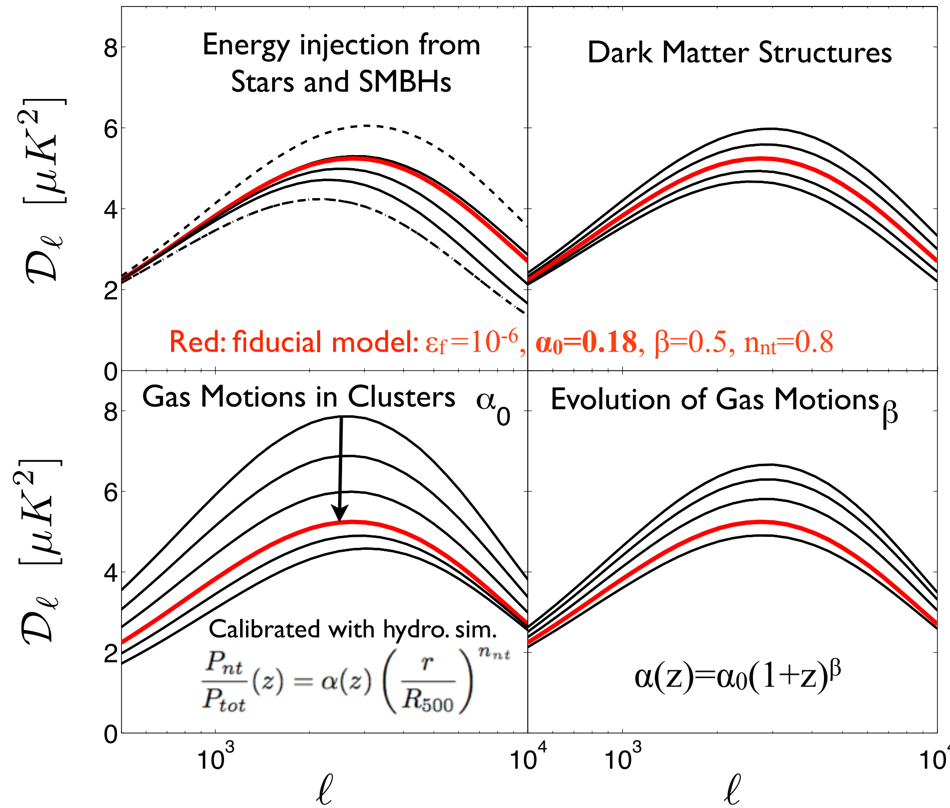
In tension at a few σ level

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

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

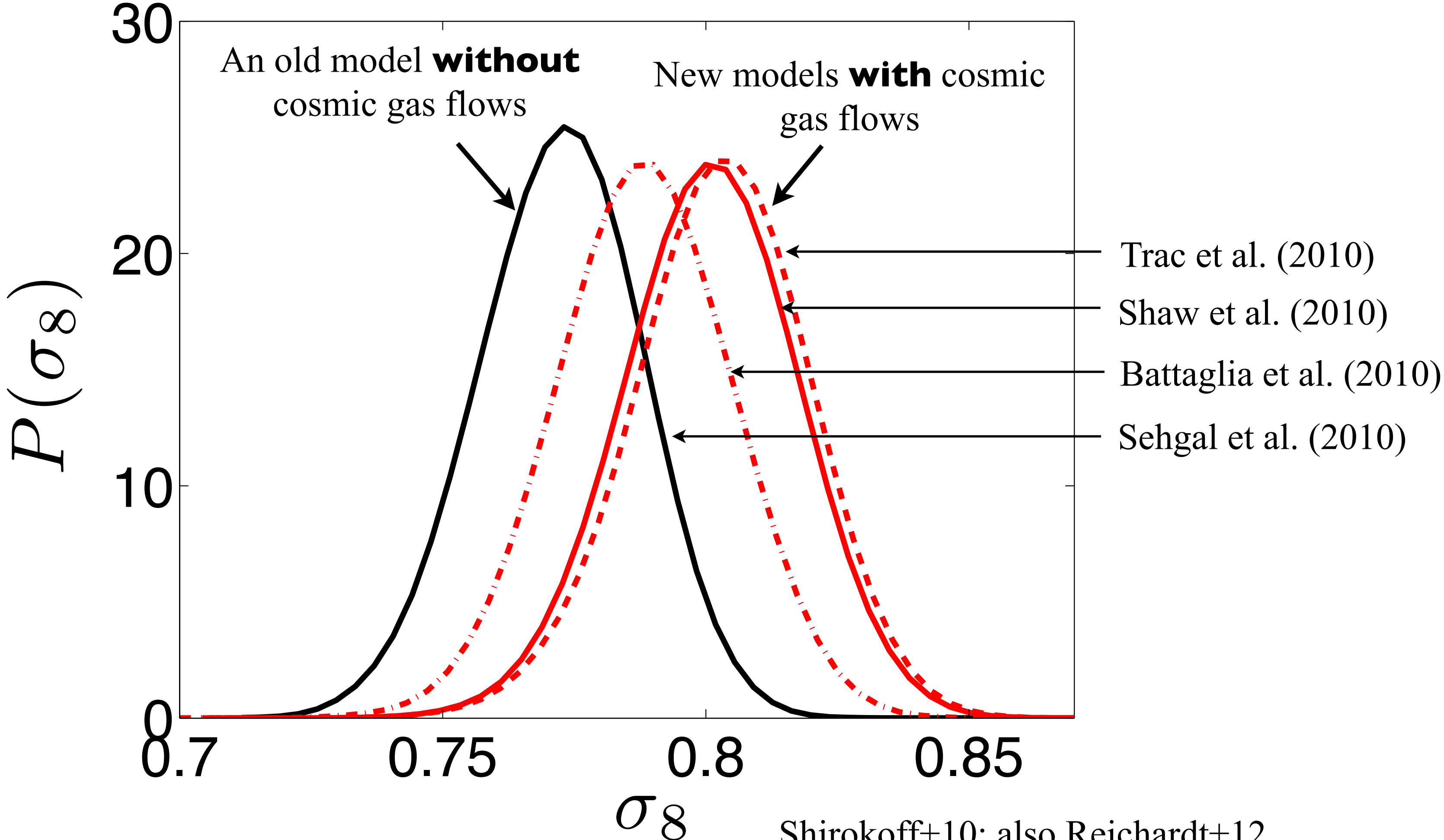




Non-thermal pressure support due to gas motions in clusters is a dominant source of systematic uncertainty.

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

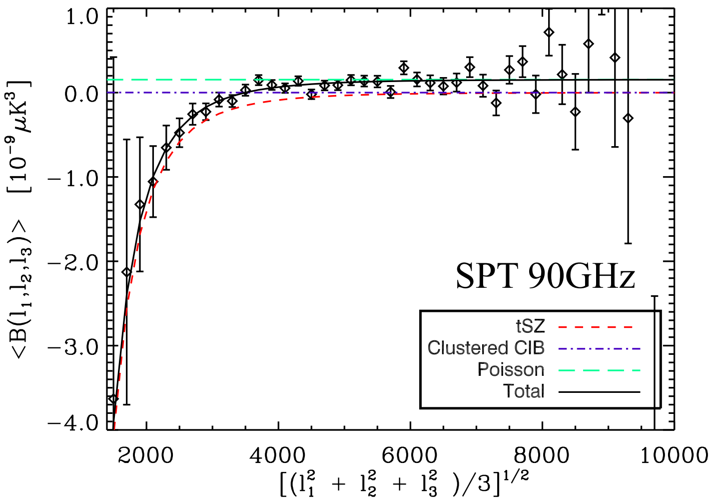
Cosmic Gas Flows alleviate the tension in cosmological constraints

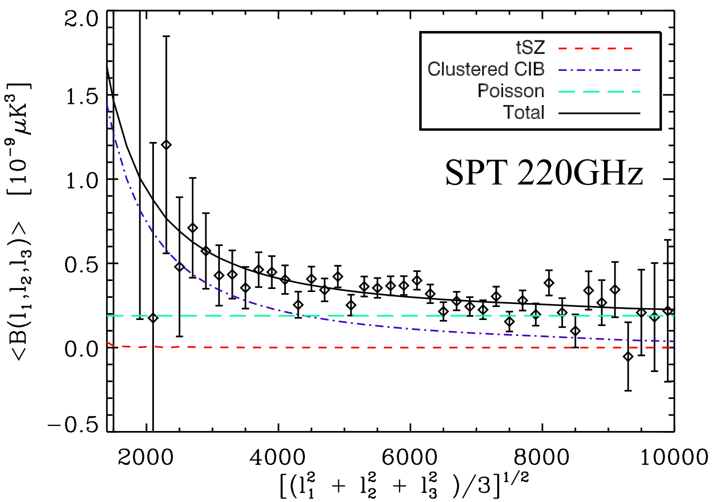


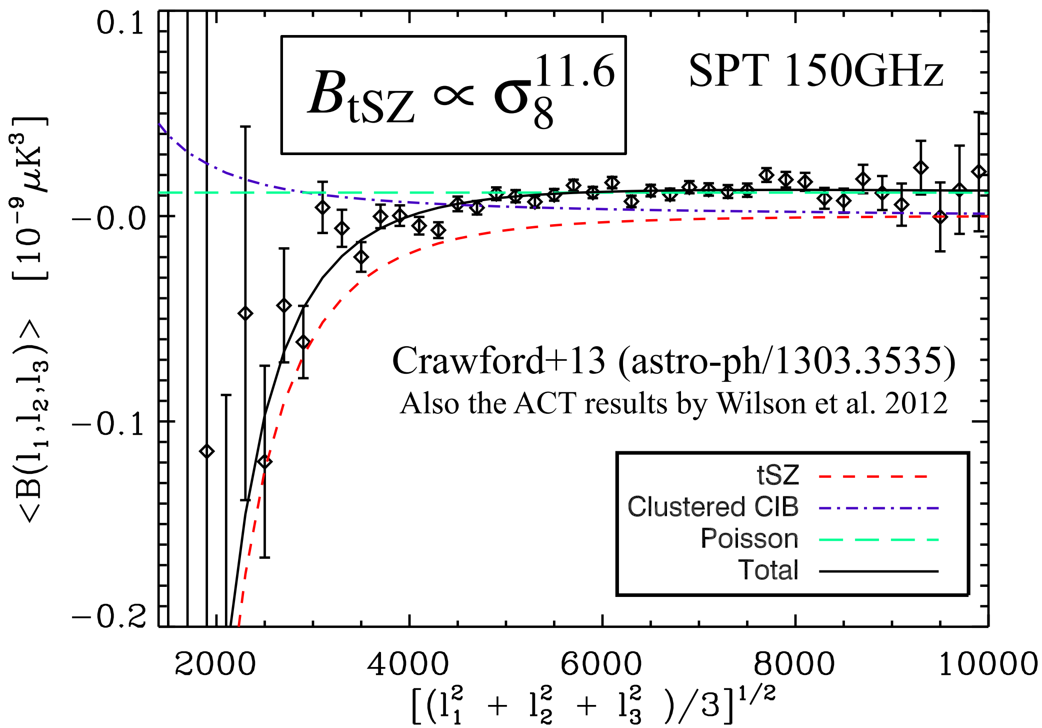
Shirokoff+10; also Reichardt+12

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

The SZ bispectrum measurements







$\sigma_8 = 0.786 \pm 0.031$

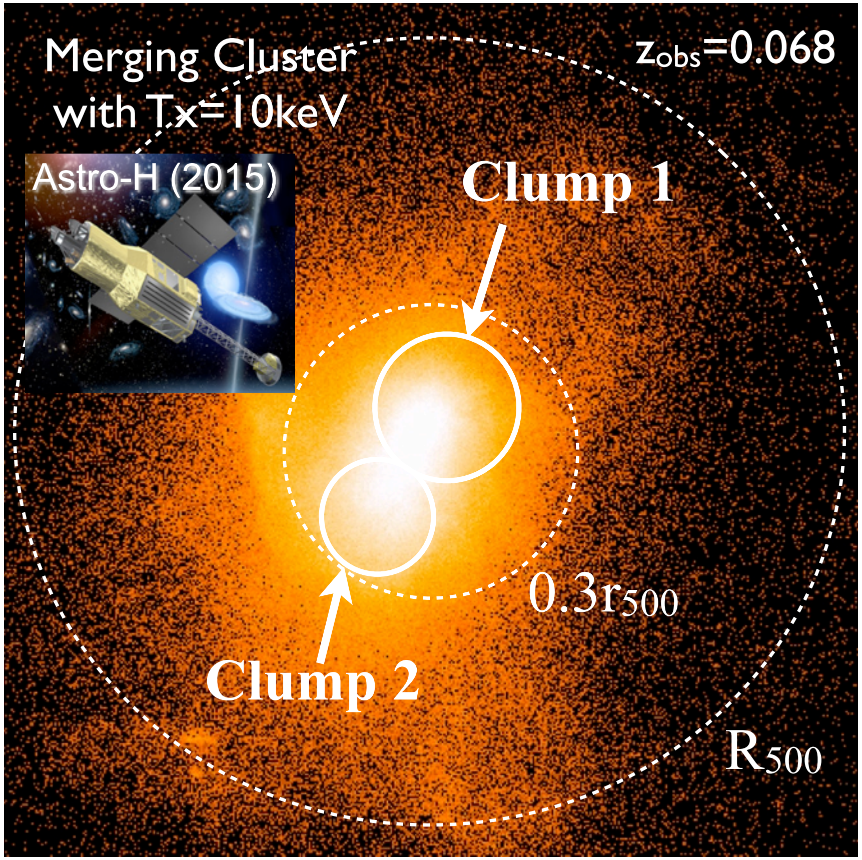
using a template with gas motions

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 astrophysical uncertainties than the SZ power spectrum.

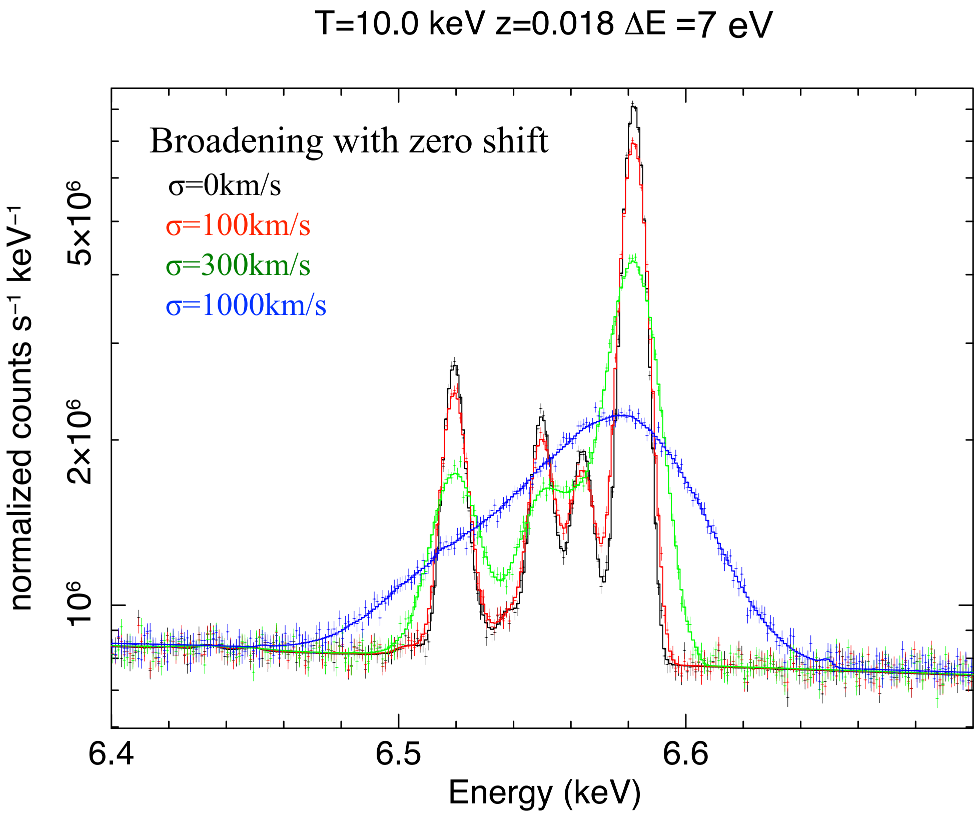
Bhattacharya, Nagai, Shaw, Crawford, & Holder, 2012, ApJ, 760, 5 (also Hill & Sherwin 2013)

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

Mock Astro-H photon maps in 6-7keV



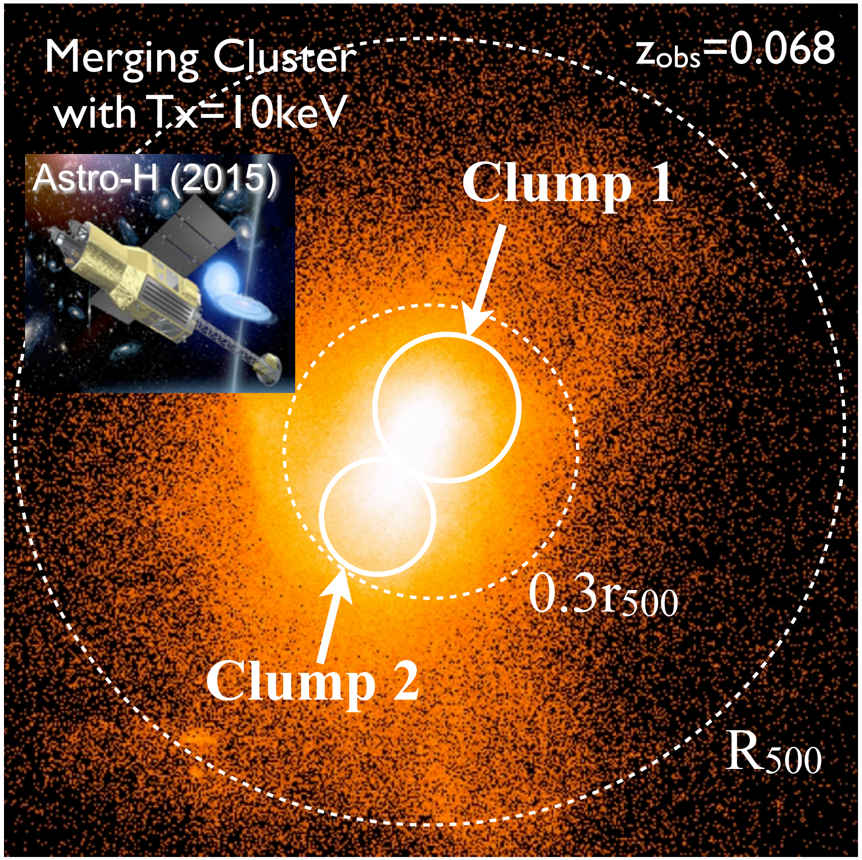
Doppler Broadening of Fe lines

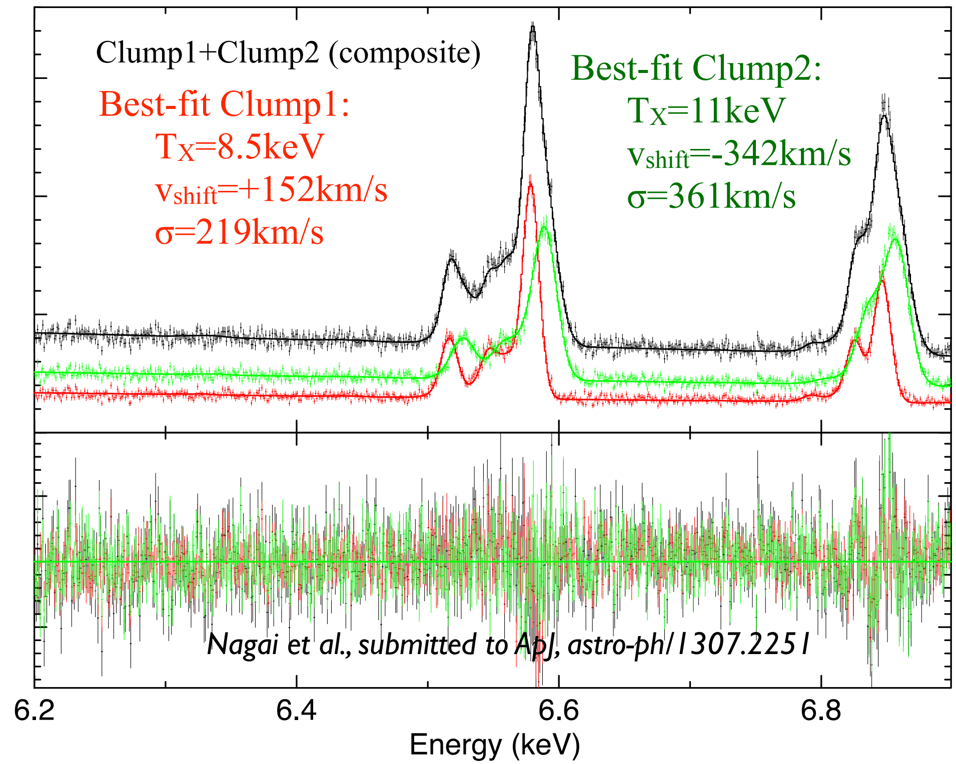


Astro-H will measure peculiar velocity and turbulent gas flows in massive galaxy clusters via shifting and broadening of Fe line.

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

Mock Astro-H photon maps in 6-7keV





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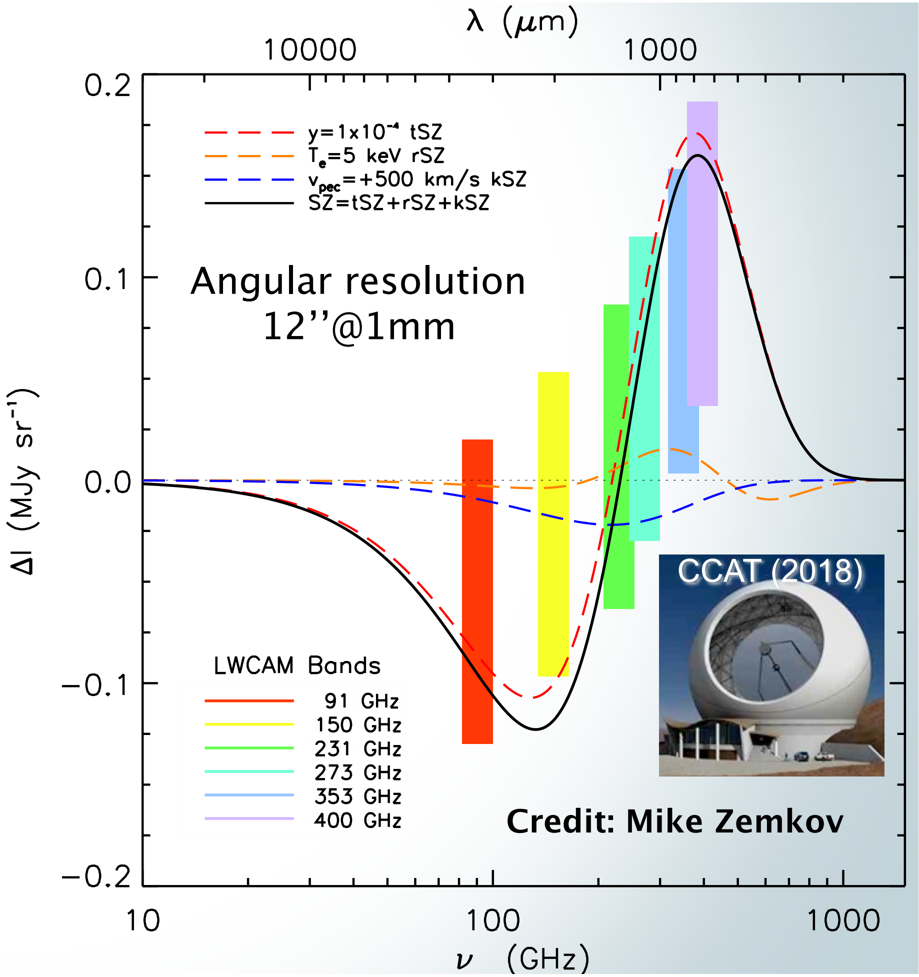
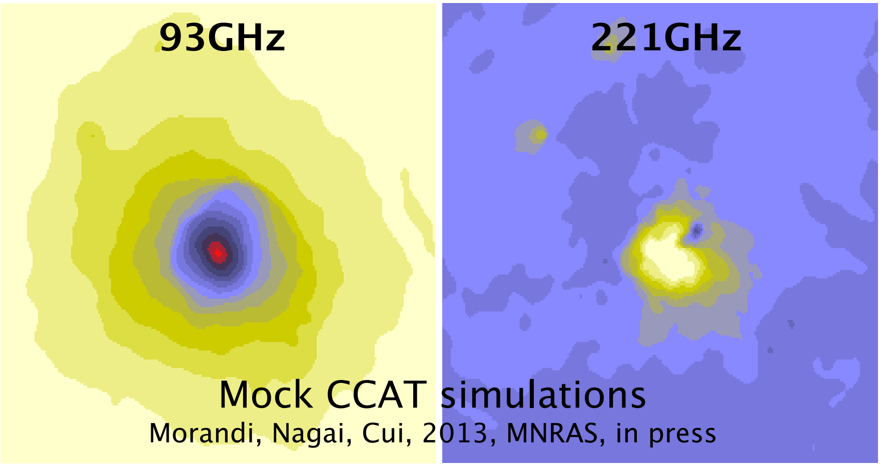
High-Resolution SZ studies of Individual Clusters with CCAT

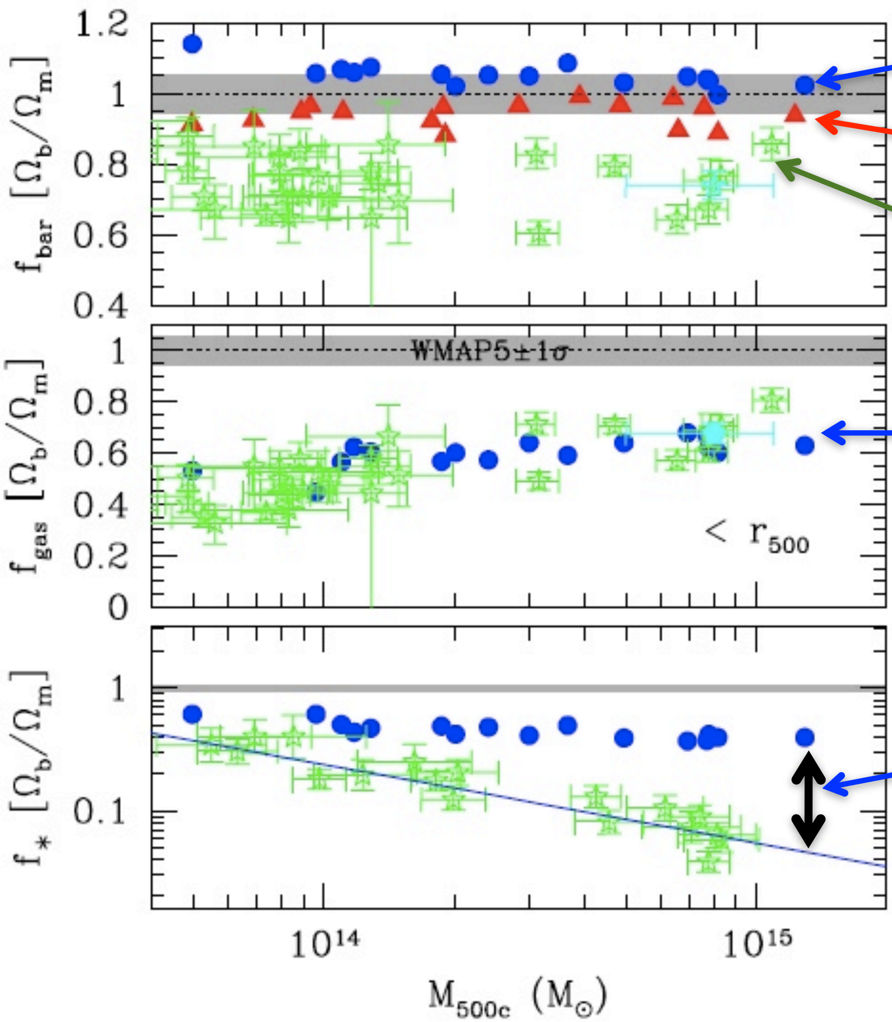


- **Thermodynamic structure of the ICM**
  - *Temperature profile via SZ relativistic corrections (independently from X-ray)*
  - *Inhomogeneities in the ICM (gas clumping)*
- **Non-thermal pressure in clusters**
  - *Bulk vs. Turbulent motions via kSZ substructure*



High-resolution, multifrequency SZE observations are unique probes of thermodynamic and velocity structures of the ICM.

Missing Baryon Problem in Galaxy Clusters before Planck



Cluster simulations with galaxy formation (without AGN)

Cluster simulations without galaxy formation

Chandra X-ray data

Surprising agreement in gas fractions at expense of overproduction of stars

Large discrepancies at high cluster mass end

Kravtsov et al. Astro2010 decadal survey white paper (astro-ph/0903.0388)

Missing Baryon Problem in Groups and Clusters

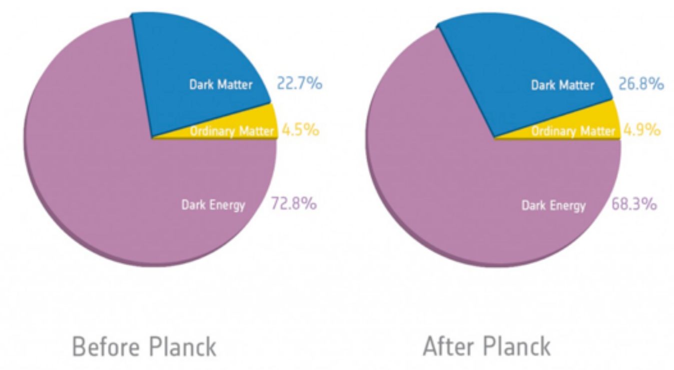
Baryon fraction enclosed within R_{500} is 75–85% of the cosmic baryon fraction.

Effects of changing the cosmology from WMAP to Planck

WMAP: $\Omega_{\rm b}/\Omega_{\rm m} = 0.1667 \pm 0.006$

Planck: $\Omega_{\rm b}/\Omega_{\rm m} = 0.1553 \pm 0.0029$

$$\frac{f_{\rm b,WMAP}}{f_{\rm b,Planck}} \approx 1.073$$



$$M_{\rm gas} \propto h^{-2.5}$$
$$M_{*} \propto h^{-2}$$
$$M_{500} \propto h^{-1}$$

$$f_{\rm gas} \propto h^{-1.5}$$
$$f_{*} \propto h^{-1}$$

$$h_{\rm WMAP} = 0.703 \pm 0.014$$
$$h_{\rm Planck} = 0.673 \pm 0.012$$

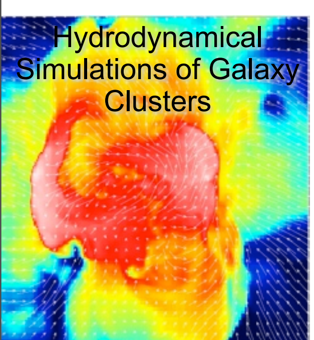
$$\left(\frac{h_{\rm Planck}}{h_{\rm WMAP}}\right)^{-1.5} \approx 1.068$$

$$\left(\frac{h_{\rm Planck}}{h_{\rm WMAP}}\right)^{-1} \approx 1.045$$

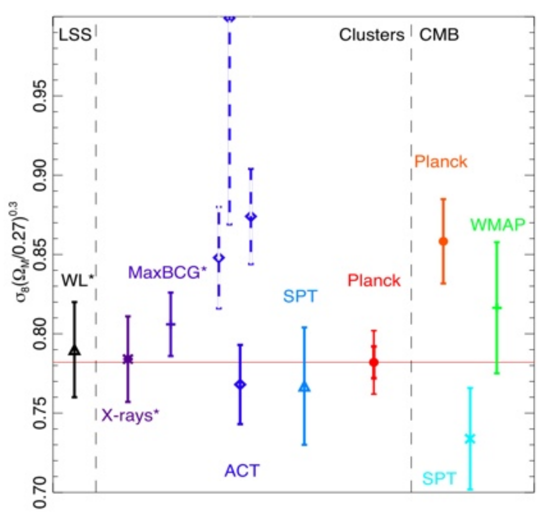
the net effect of switching from WMAP to Planck cosmology is to increase normalized gas fractions by 15% and increase normalized stellar fractions by 12% the baryon fraction is increased by ~15%

New Frontiers: SZ Science in the Planck Era

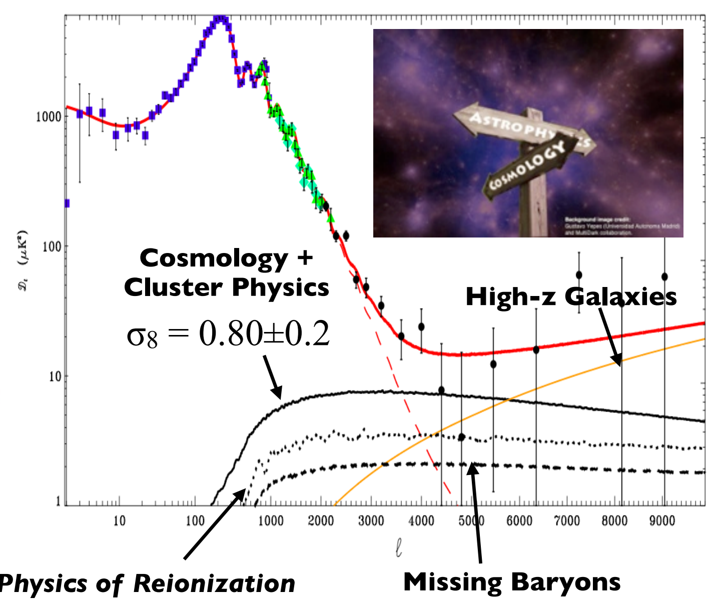
- **SZ observations are crossroads of cosmology & astrophysics**
  - ***Cosmology***
    - *Cluster counts from SZ+X-ray+optical surveys and SZ power+bispectra are in agreement.*
  - ***Astrophysics***
    - *Missing Baryon & Energy Problems in Clusters*
    - *Physics of Reionization*



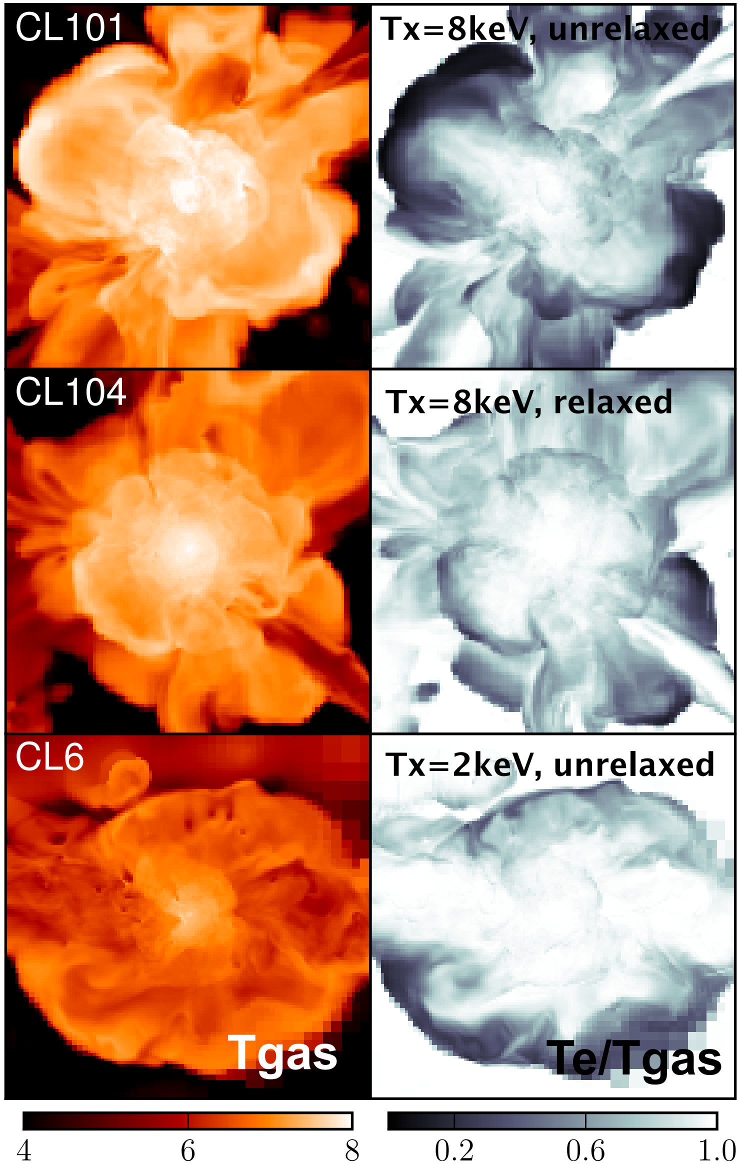
Planck Cosmological Constraints from CMB vs. Cluster counts



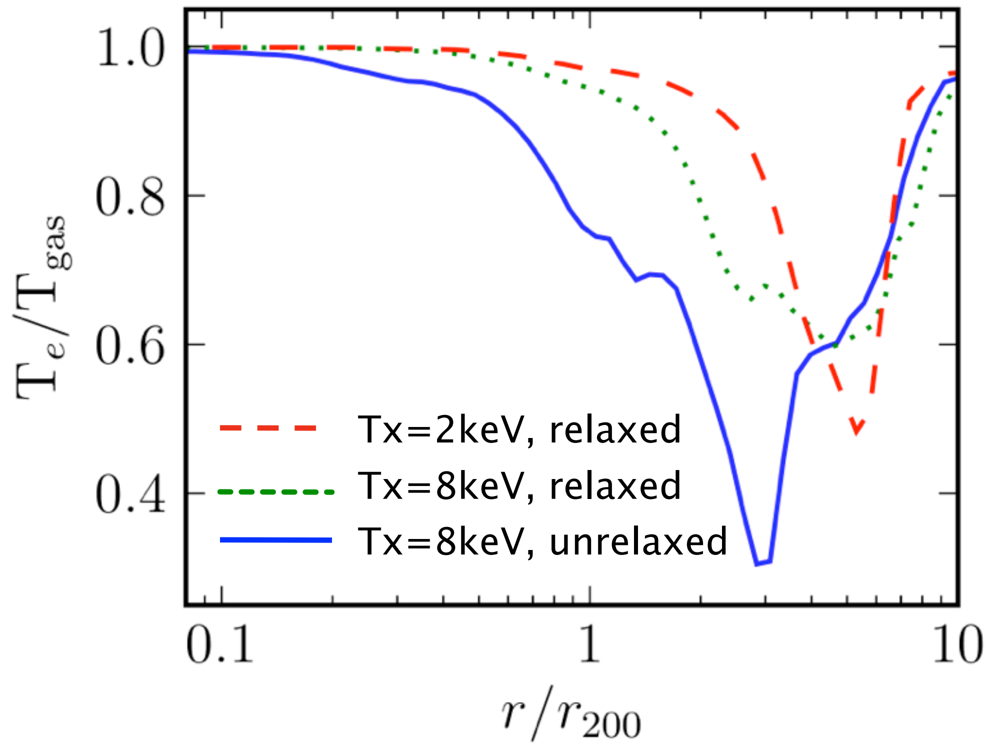
SZ power & bispectra



Missing Cluster Astrophysics #2
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