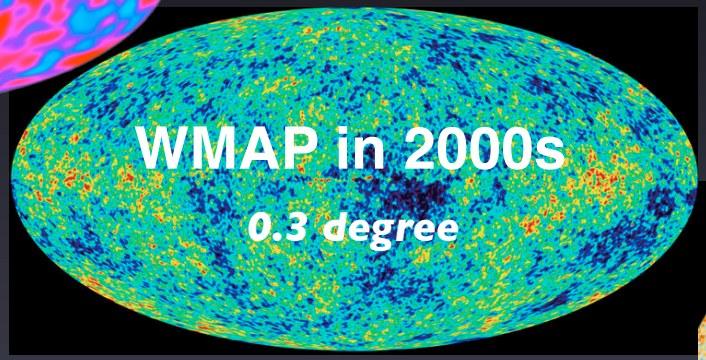
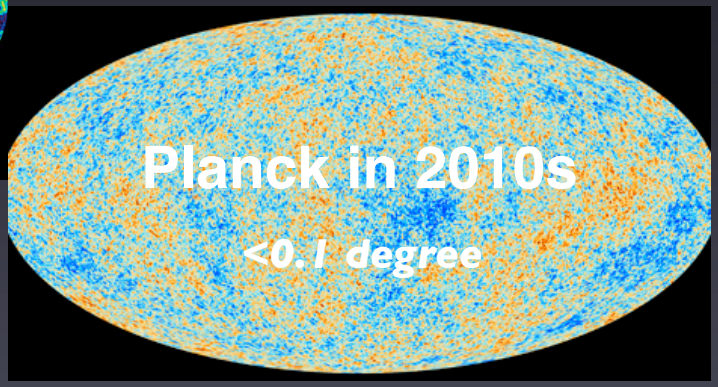
SZ Science in the Planck Era

Insights from Simulations





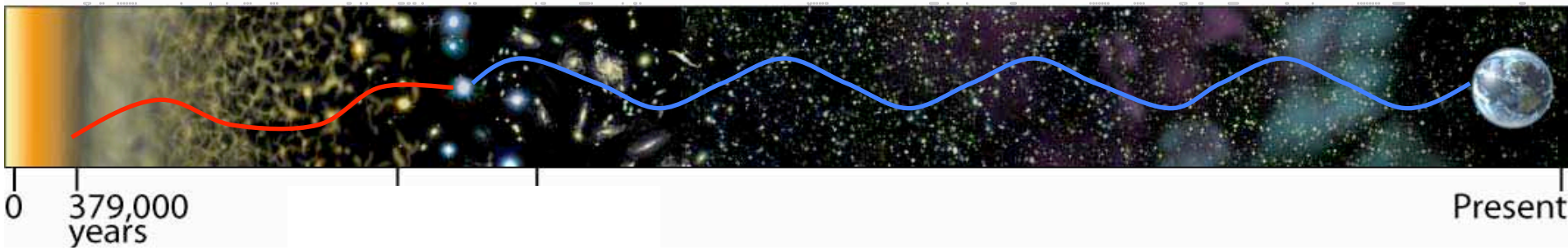
Daisuke Nagai

Yale University

Planck Meeting, Noordwijk, Netherland

April 4, 2013

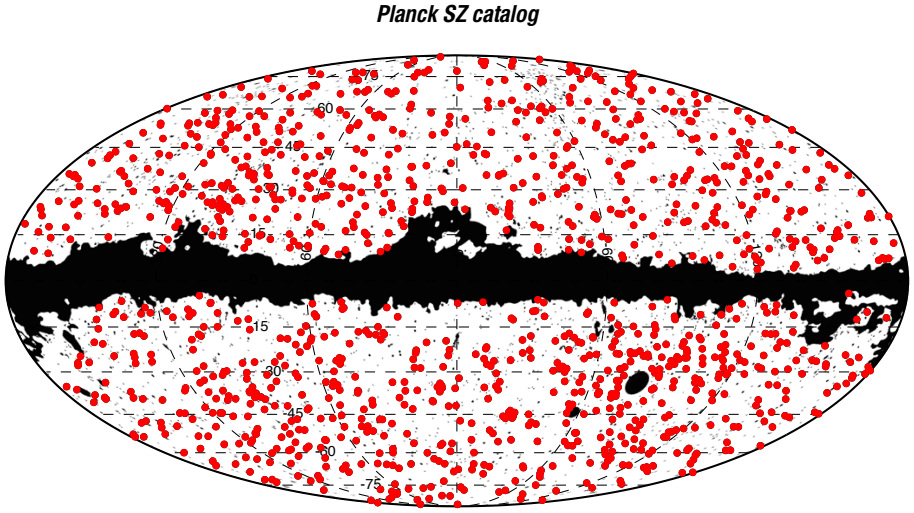
Sunyaev-Zel'dovich Effect



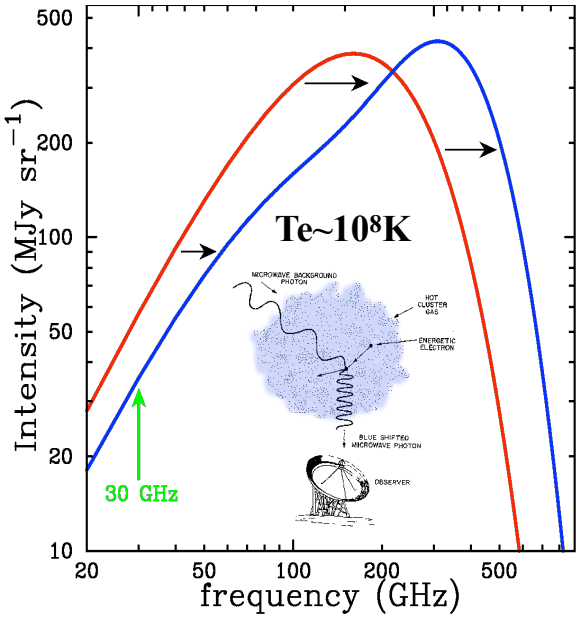
CMB photons provide a backlight for structure in the universe.

1-2% of CMB photons traversing galaxy clusters are inverse Compton scattered to higher energy

Kinetic effect for cluster moving with respect to CMB



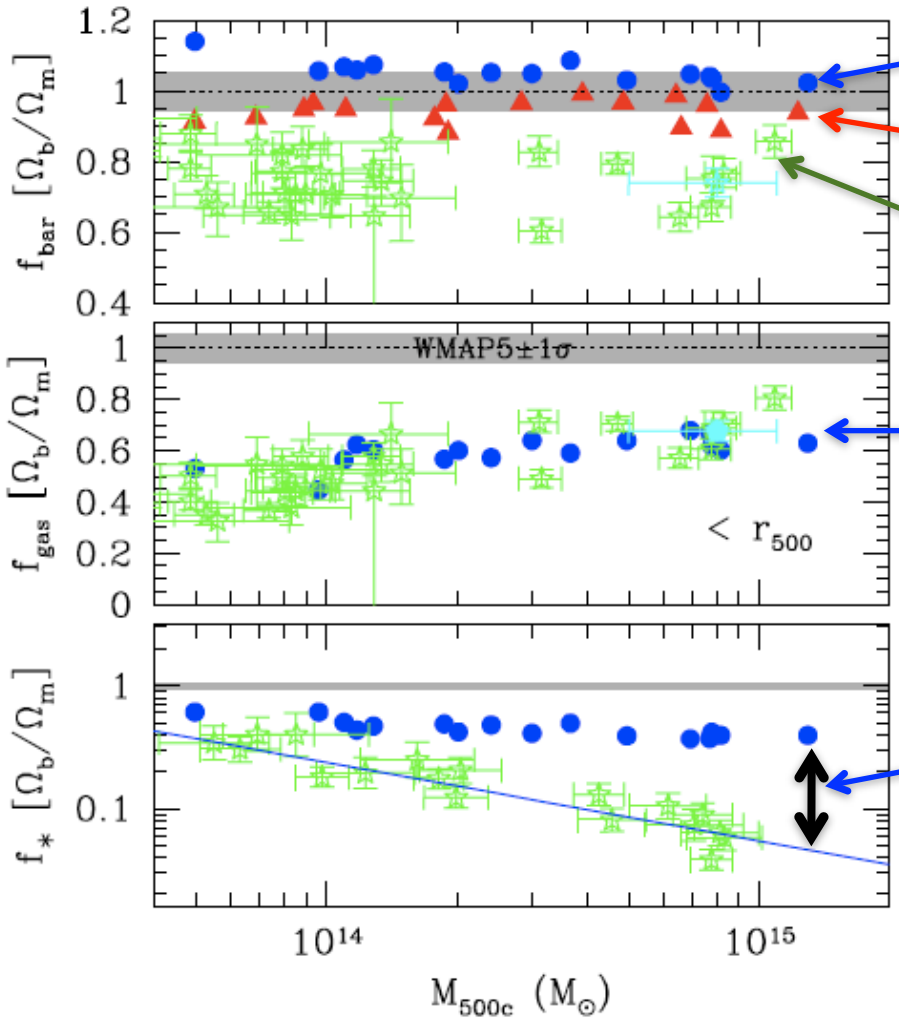
Planck 2013, Papers I, XX, XXIX



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

Surface Brightness of the effect independent of redshift

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

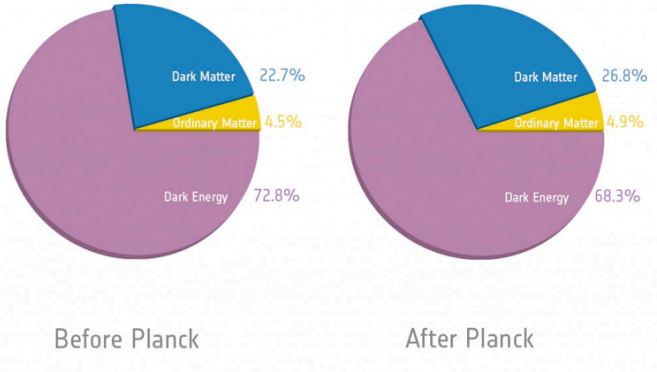
Baryon fraction enclosed within R_{500} is 75–85% of the cosmic baryon fraction.

Effects of changing the cosmology from WMAP to Planck

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

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

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



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

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

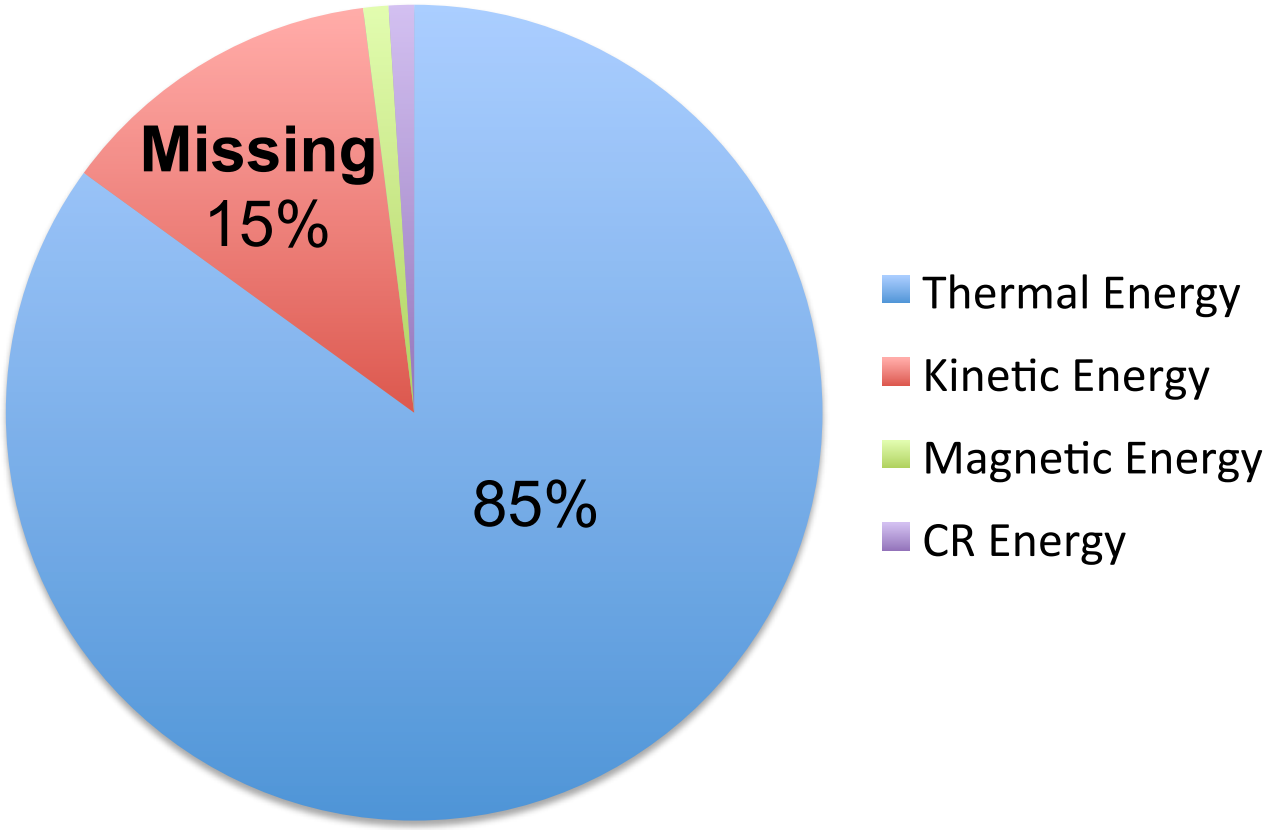
$$h_{\rm WMAP} = 0.703 \pm 0.014$$
$$h_{\rm Planck} = 0.673 \pm 0.012$$

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

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

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%

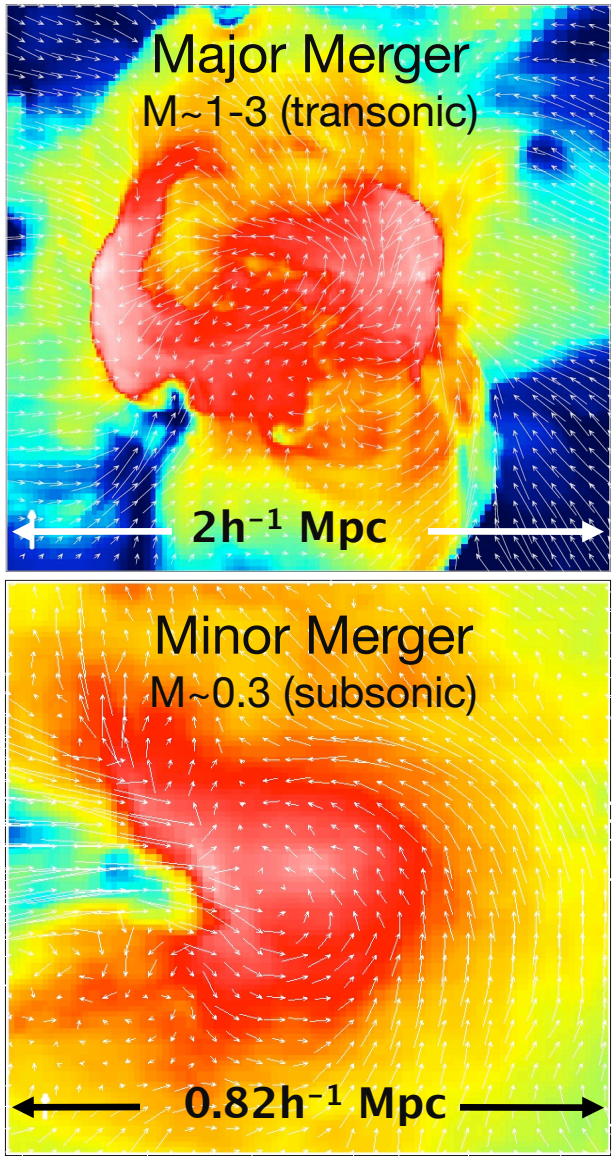
Missing Energy Problem in Galaxy Clusters



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 fraction are estimated from radio, hard X-ray, and gamma-ray observations of clusters.

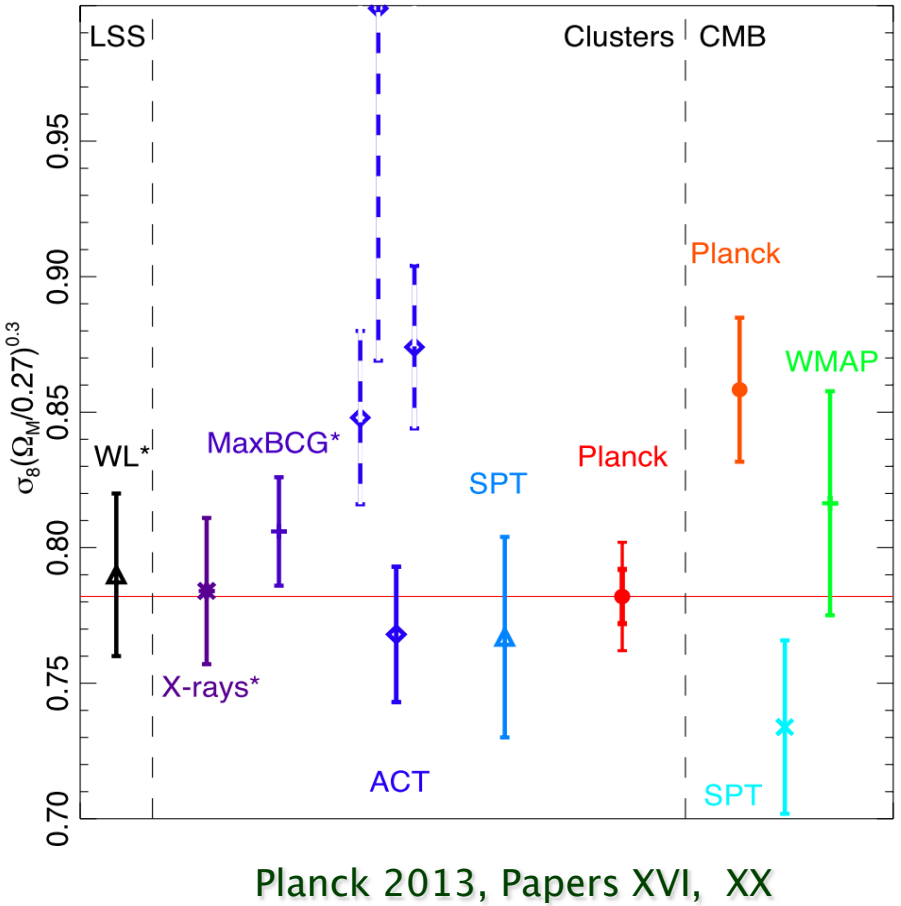
Missing Cluster Astrophysics #1
Gas Motions in Clusters



- 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)
  - 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!!

Planck cosmological constraints from CMB are in tension with cluster abundances



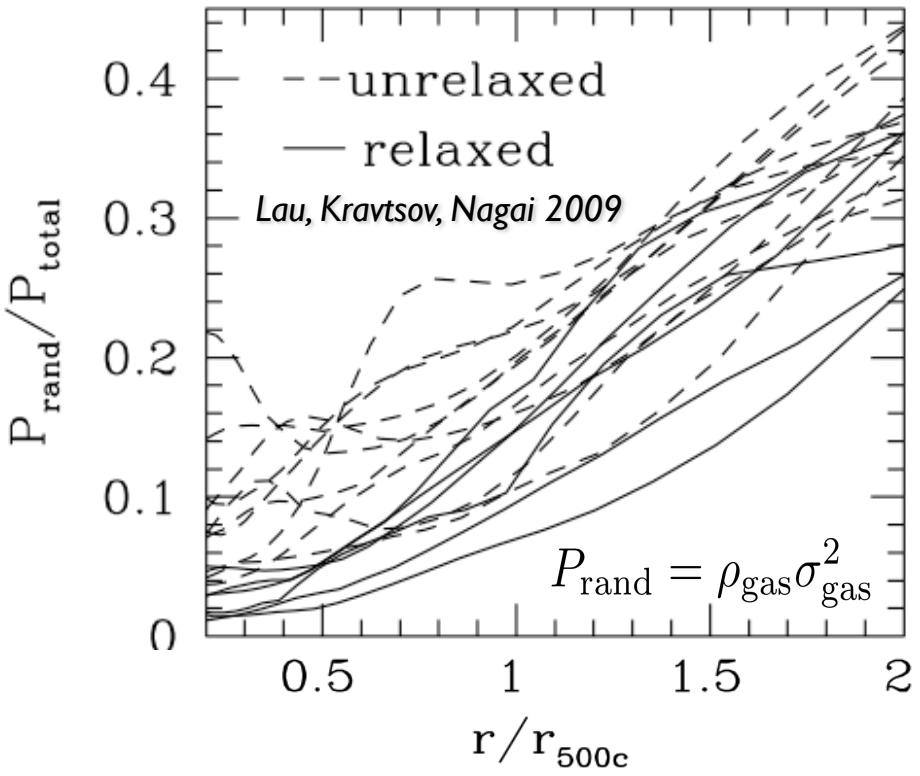
Planck 2013, Papers XVI, XX

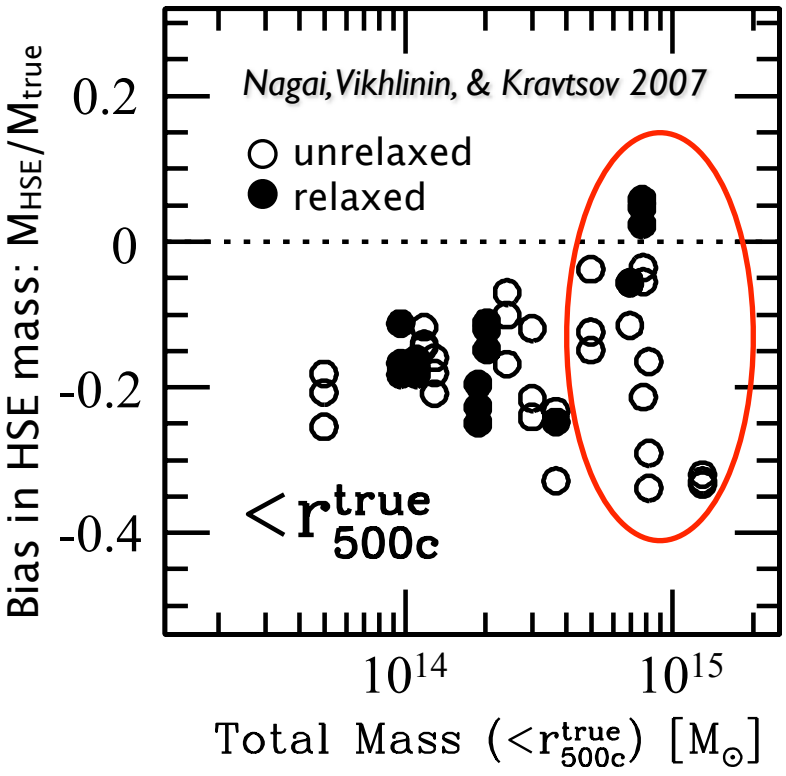
Possible Solutions

- cluster scaling relations are off by ~45%
- 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

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

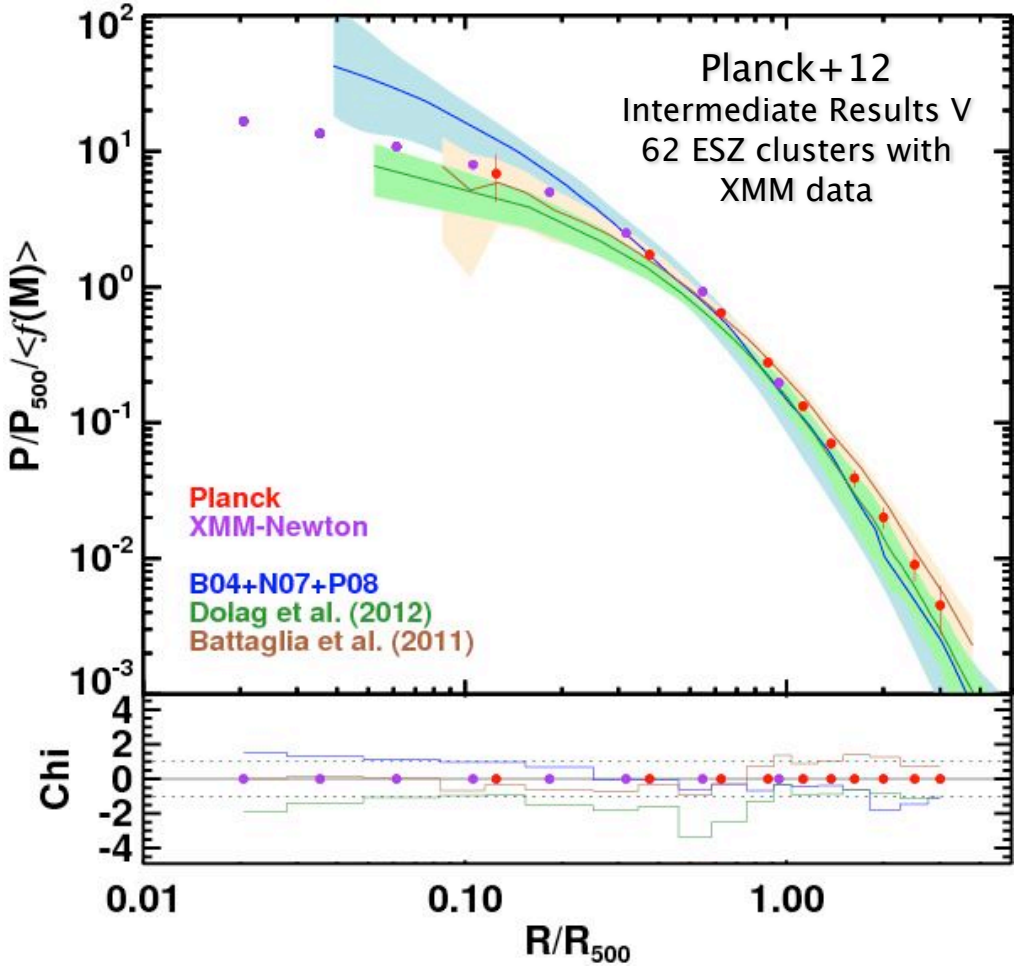




Non-thermal pressure due to gas motions introduces bias in the hydrostatic mass estimate at a level of 0-35% at R_{500}. The mass bias is larger for disturbed clusters.

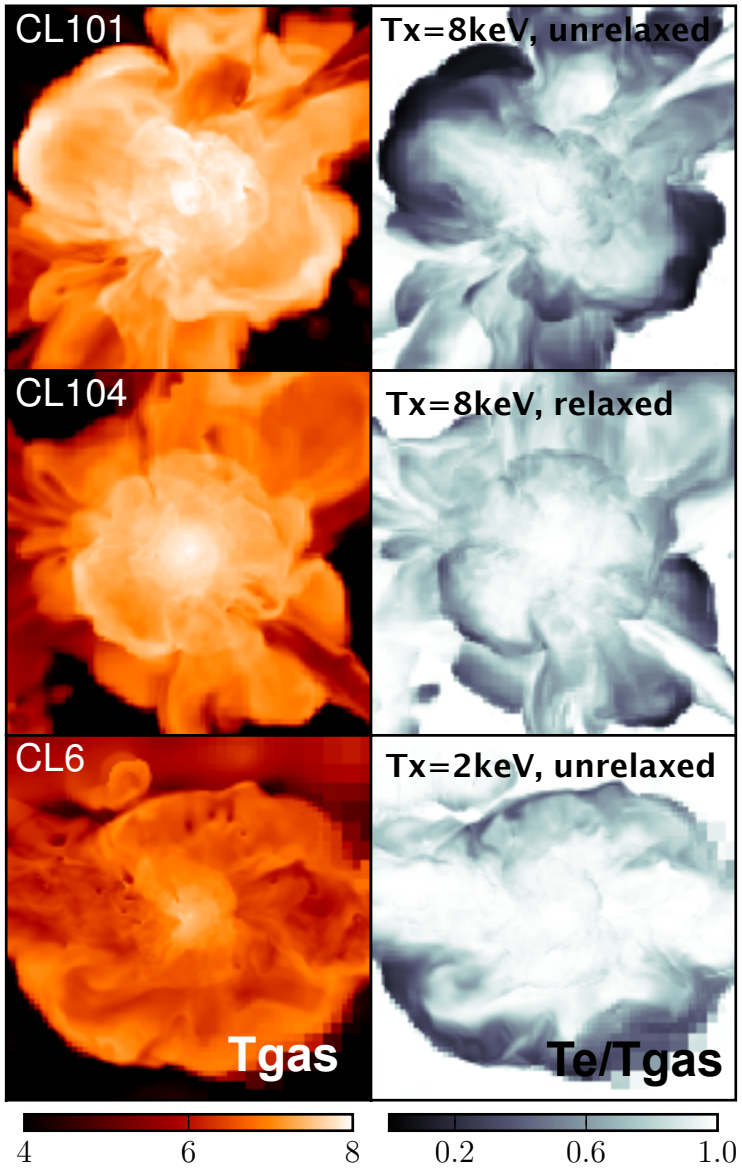
Also Dolag+05, Rasia+06, Vazza+09, Battaglia+11, Nelson+12

Universal Pressure profile of Galaxy Clusters
Simulations vs. Observations

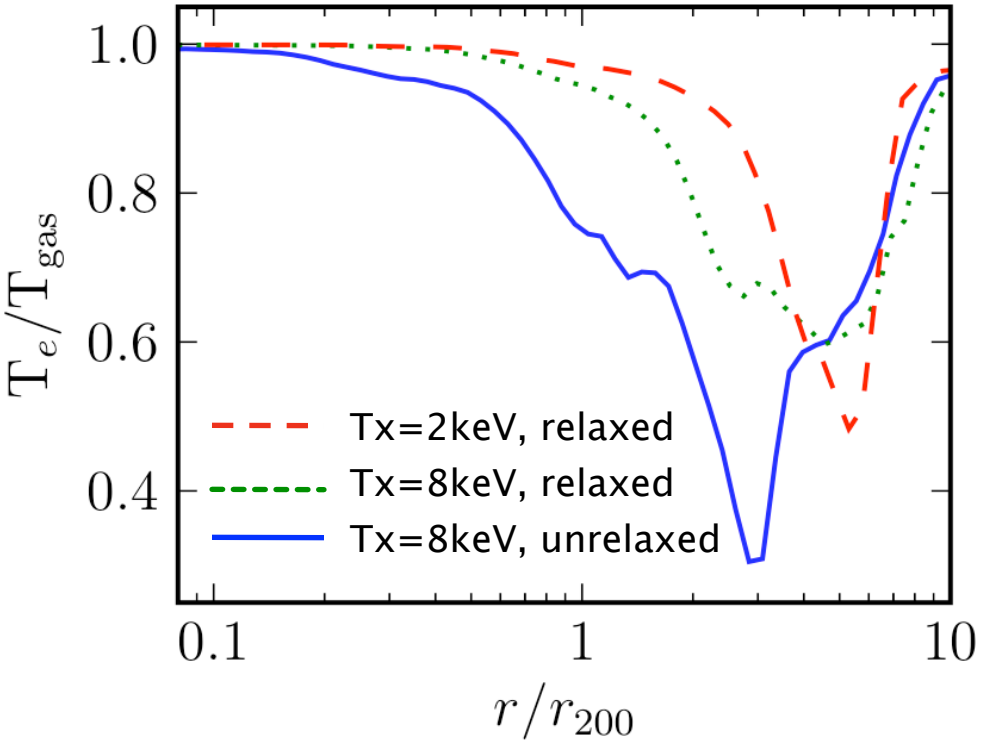


Non-thermal pressure due to gas motions steepens the pressure profile in the outskirts of massive galaxy clusters.

Missing Cluster Astrophysics #2
Non-equilibrium Electrons

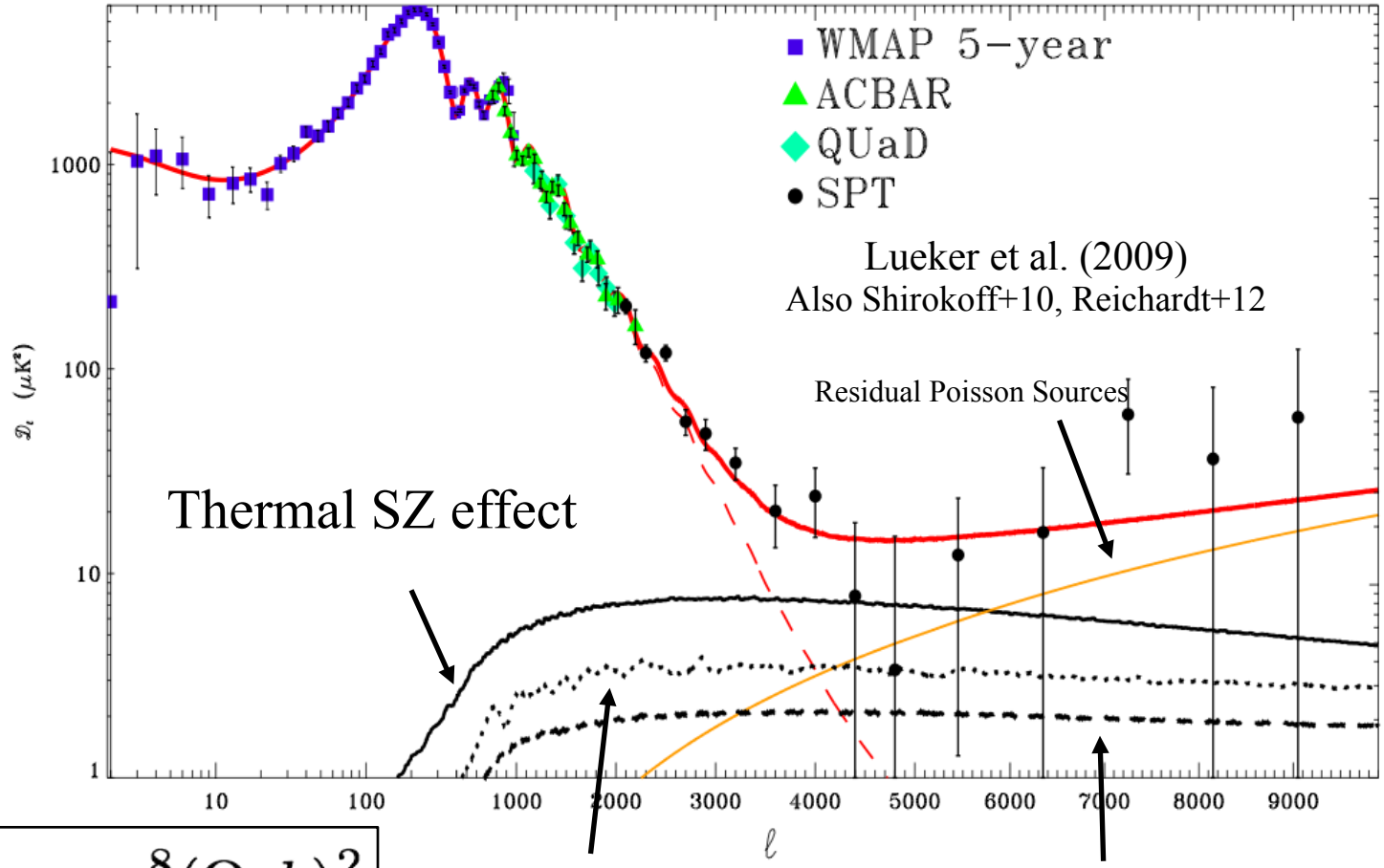


Electron temperature is lower than gas (or ion) temperature in the outskirt of dynamically active clusters



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

Measurements of the SZ power spectrum

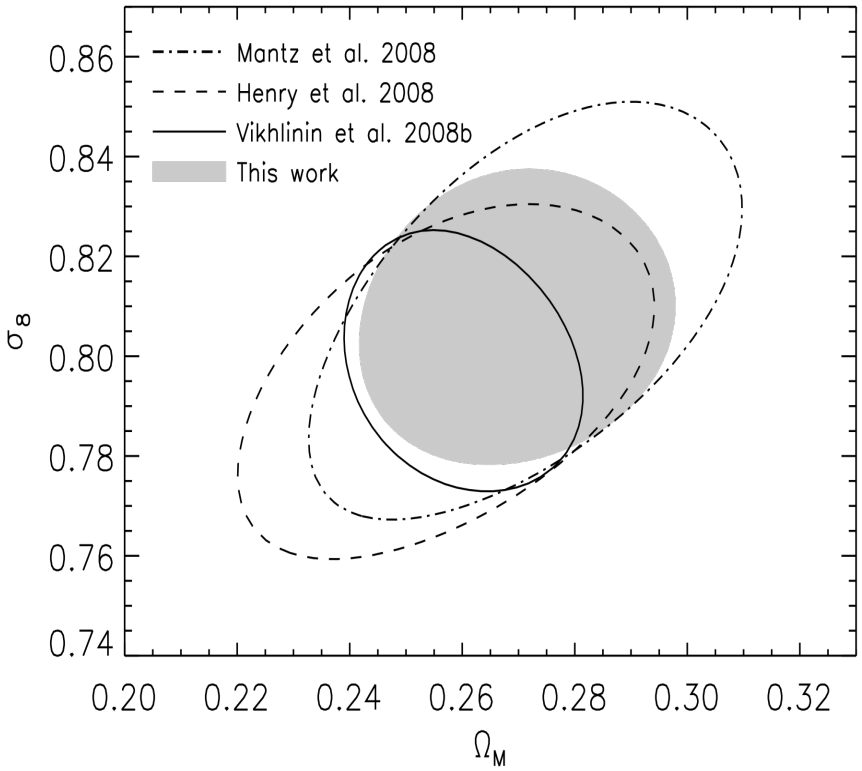


$$C_{\ell,\mathrm{tSZ}} \propto \sigma_8^8 (\Omega_b h)^2$$

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..

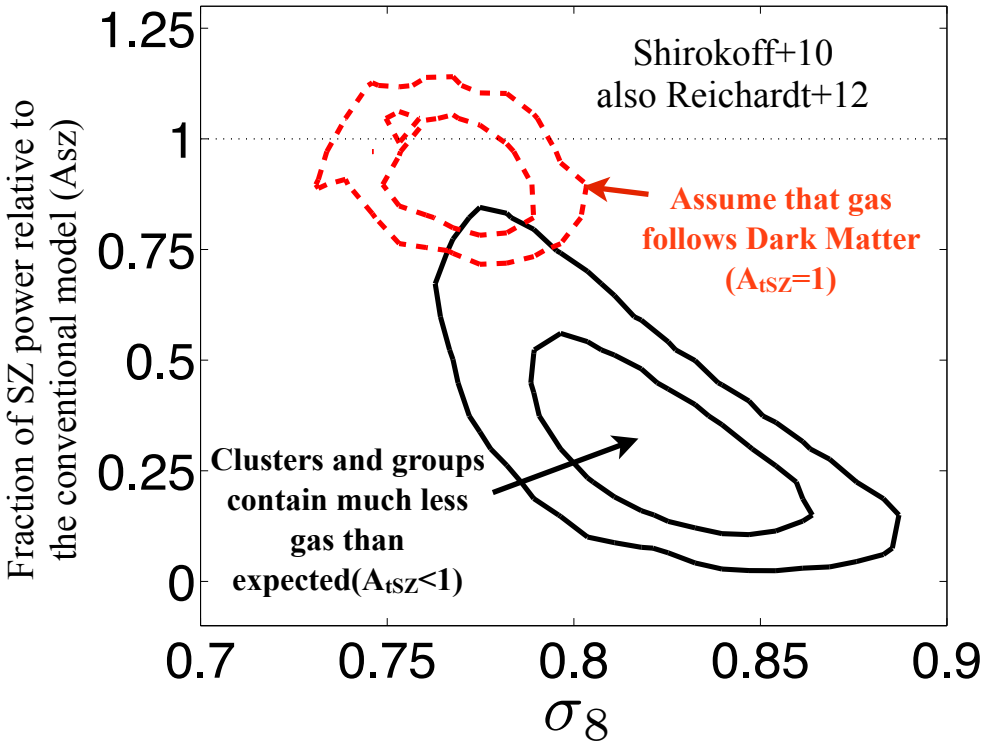
Tension in σ_8 measurements

Cluster Abundance



$\sigma_8 = 0.80 \pm 0.02$

SZ power spectrum



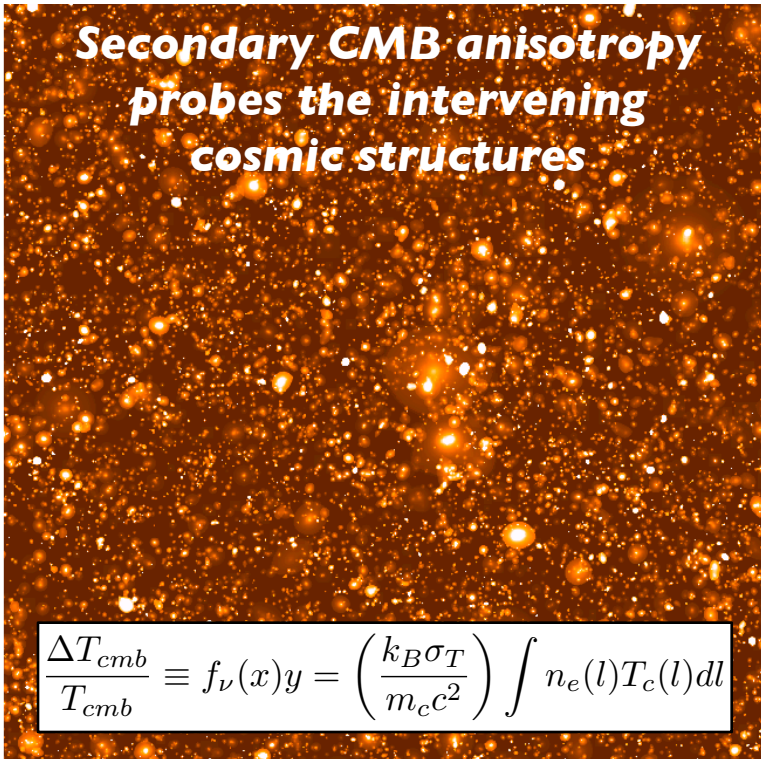
$\sigma_8 = 0.767 \pm 0.009$

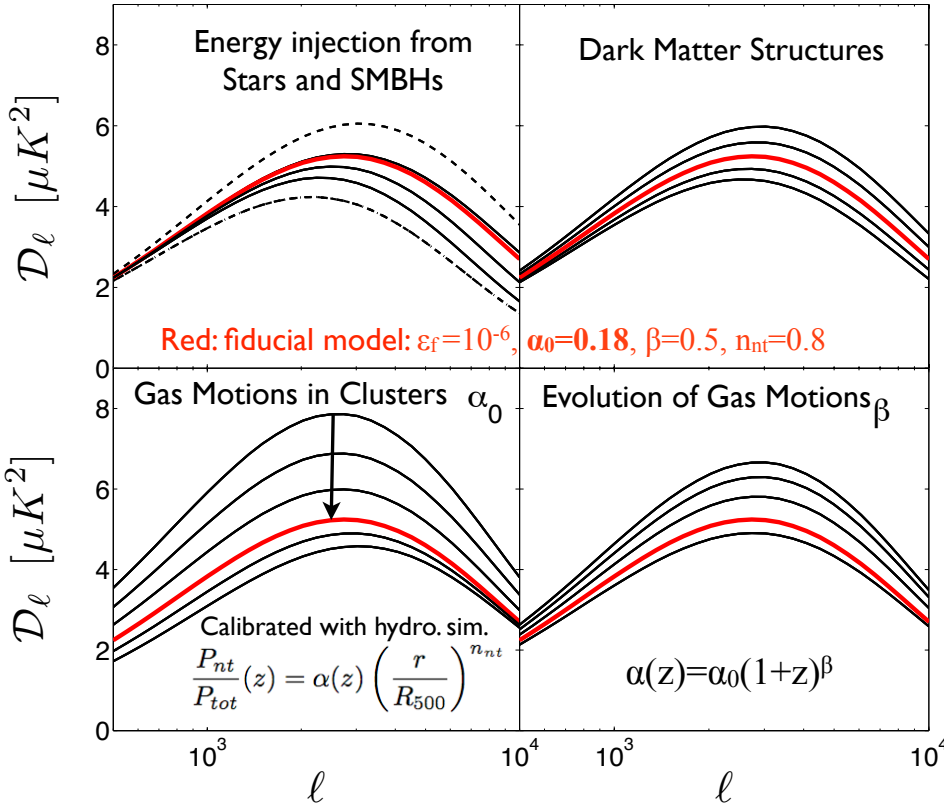
In tension at a few σ level

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 $l<5000$

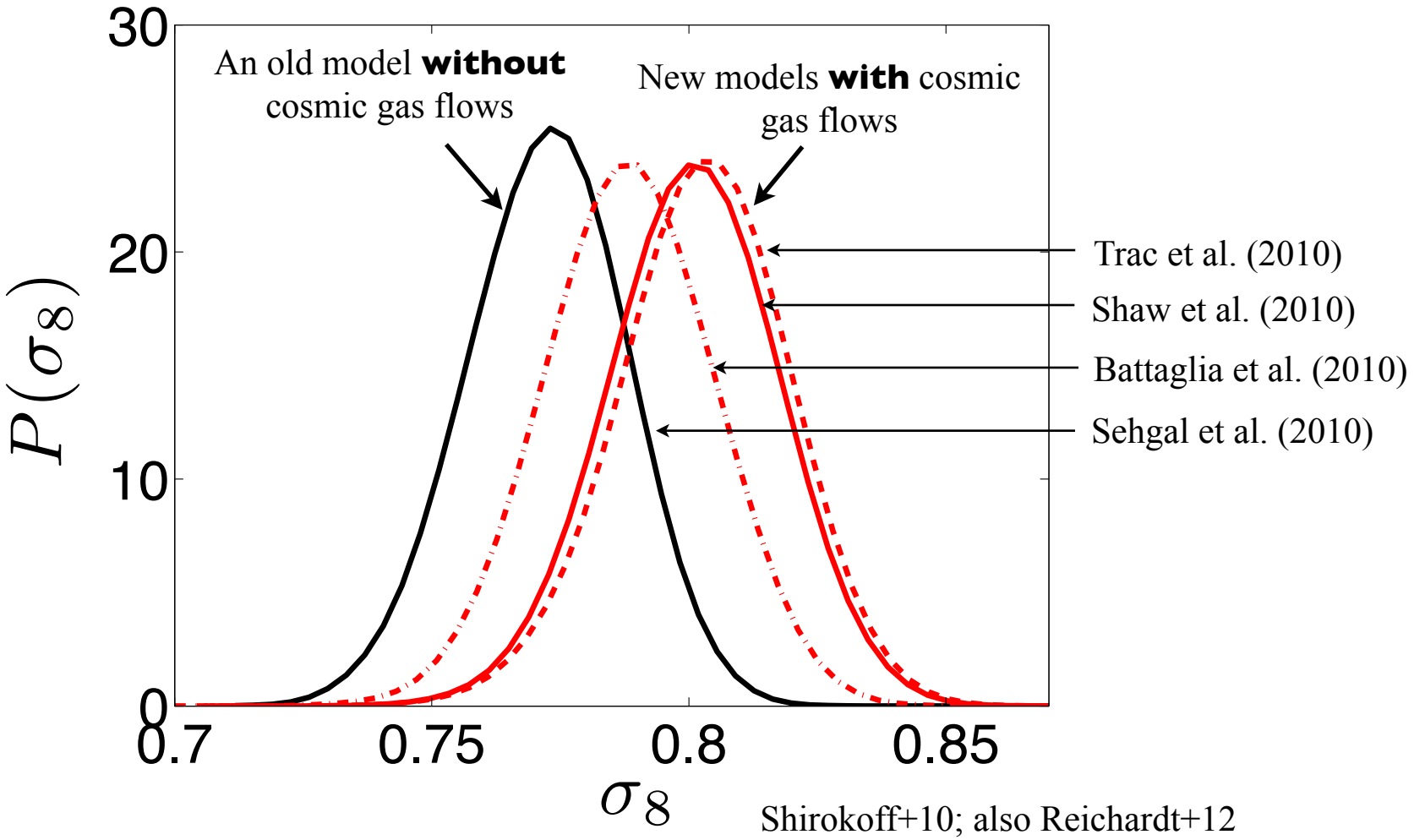




Non-thermal pressure support due to gas motions in clusters is a dominant source of systematic uncertainty.

Shaw, Nagai, Bhattacharya, Lau, 2010, ApJ, 725, 1452 (Also talk by Nick Battaglia)

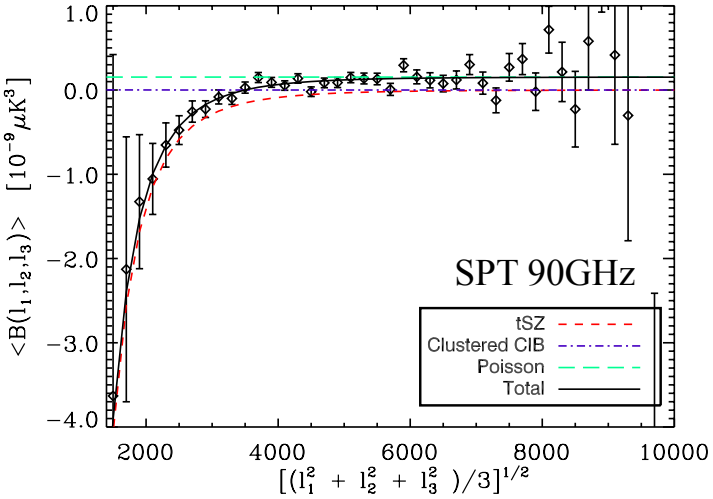
Cosmic Gas Flows alleviate the tension in cosmological constraints

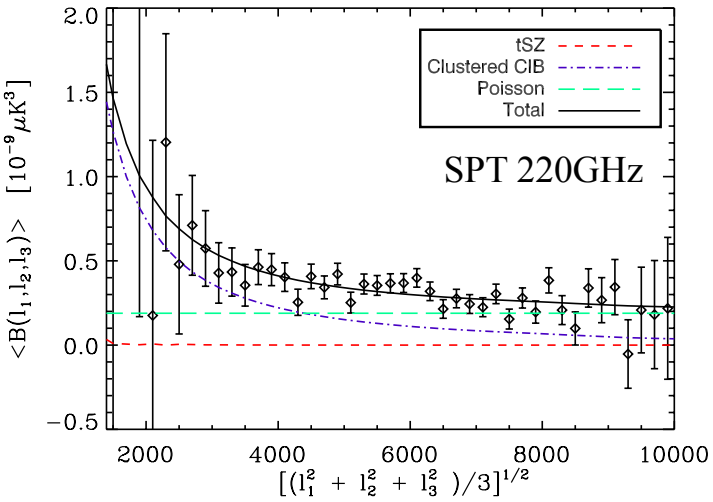


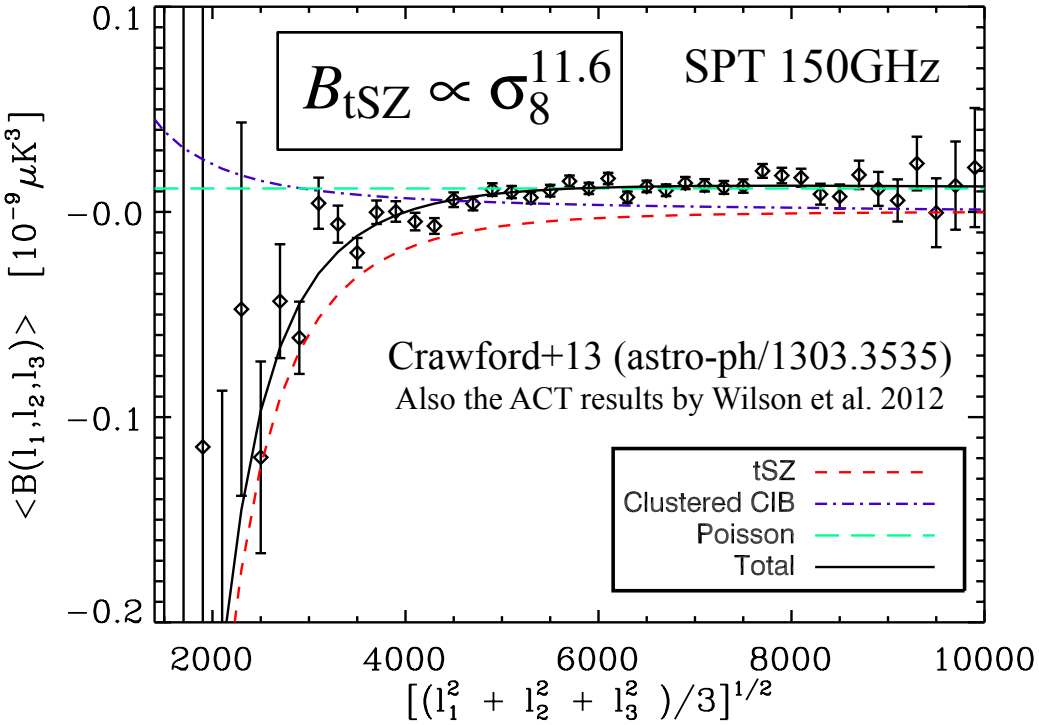
Shirokoff+10; also Reichardt+12

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

The SZ bispectrum measurements







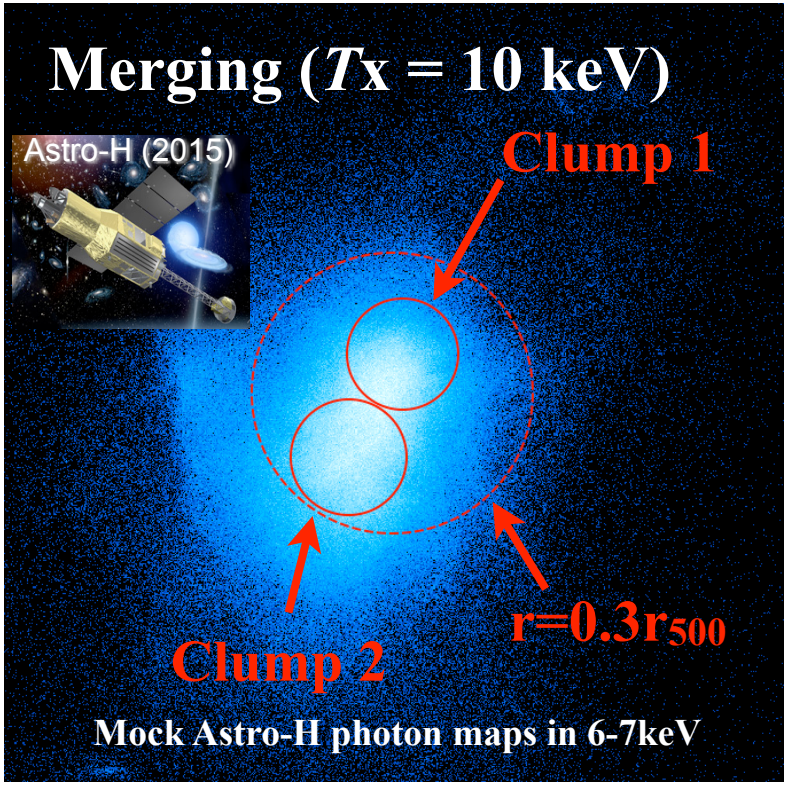
$\sigma_8 = 0.786 \pm 0.031$

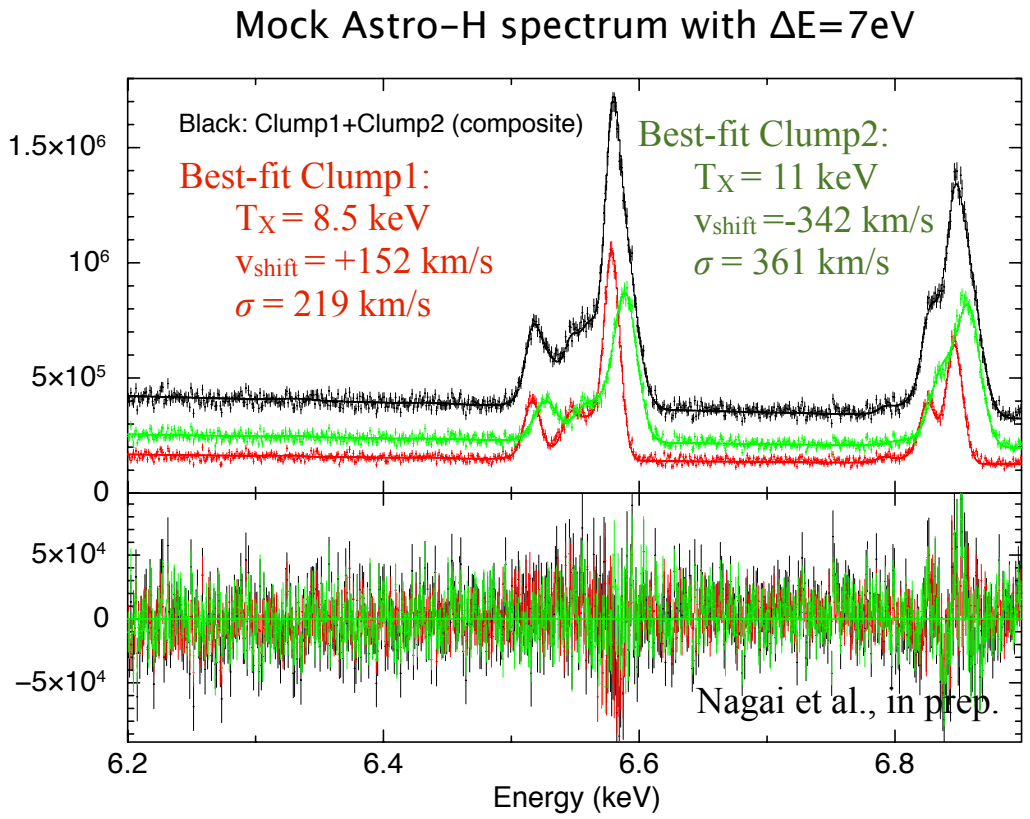
using a template with gas motions

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)

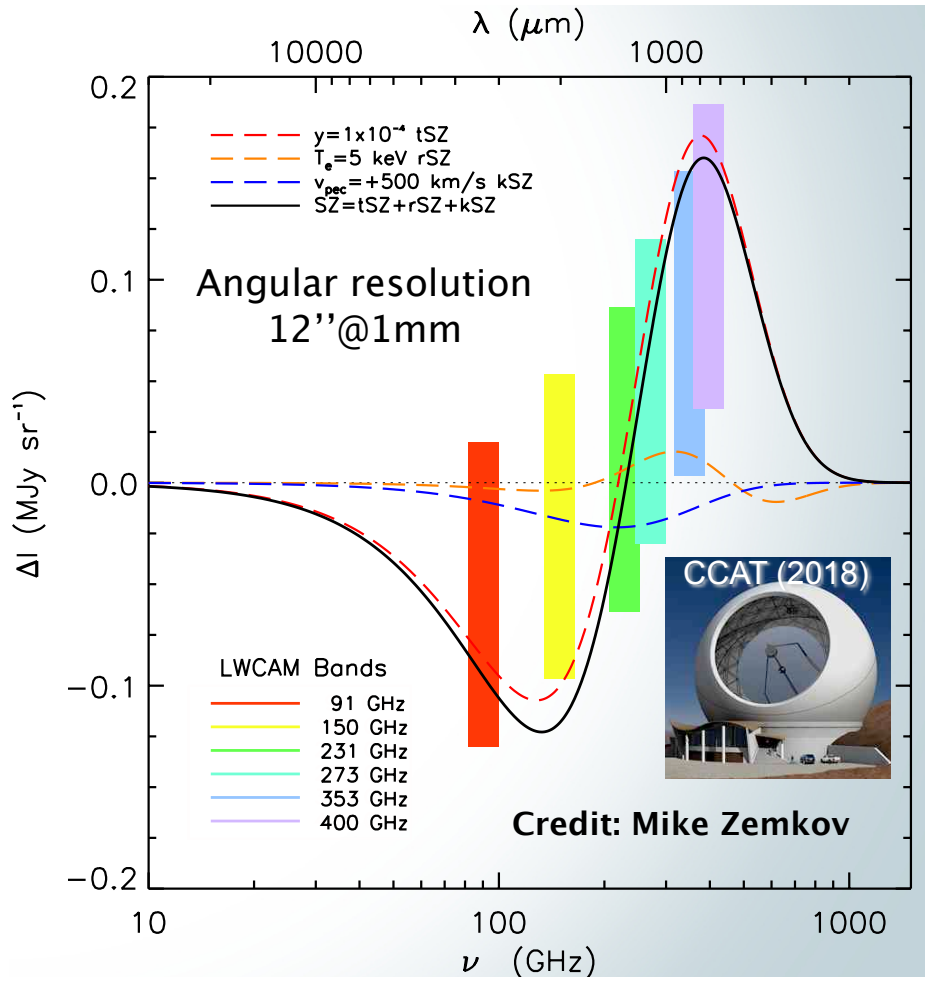
Probing Gas Motions in Galaxy Clusters with Astro-H X-ray mission



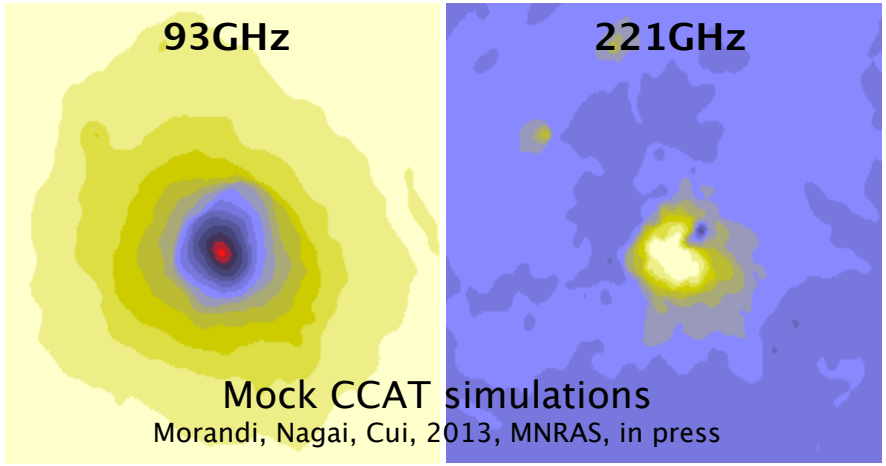


Astro-H will measure peculiar velocity and turbulent gas flows in massive galaxy clusters via shifting and broadening of Fe line.

High-Resolution SZ studies of Individual Clusters with CCAT

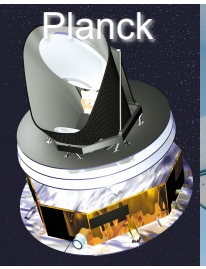


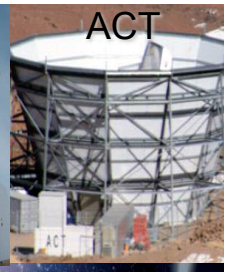
- ***Thermodynamic structure of the ICM***
  - ***Temperature profile via SZ relativistic corrections (independently from X-ray)***
  - ***Inhomogeneities in the ICM (gas clumping)***
- ***Non-thermal pressure in clusters***
  - ***Bulk vs. Turbulent motions via kSZ substructure***

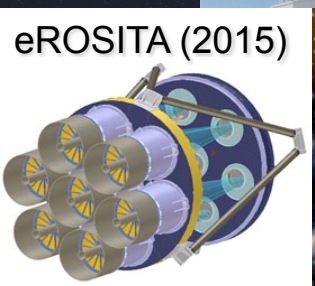


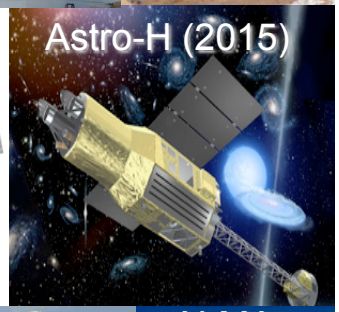
High-resolution, multifrequency SZE observations are unique probes of thermodynamic and velocity structures of the ICM.

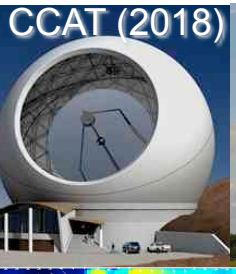
New Frontiers: SZ Science in the Planck Era

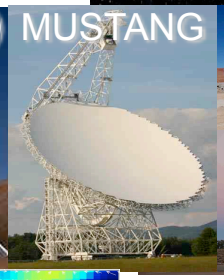


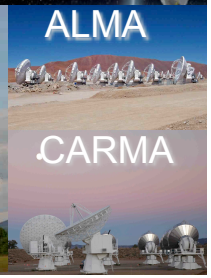


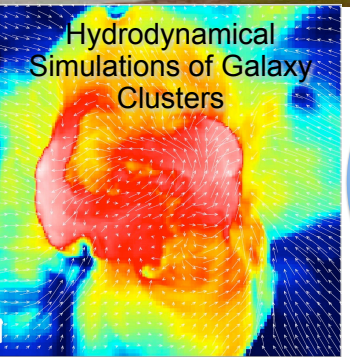






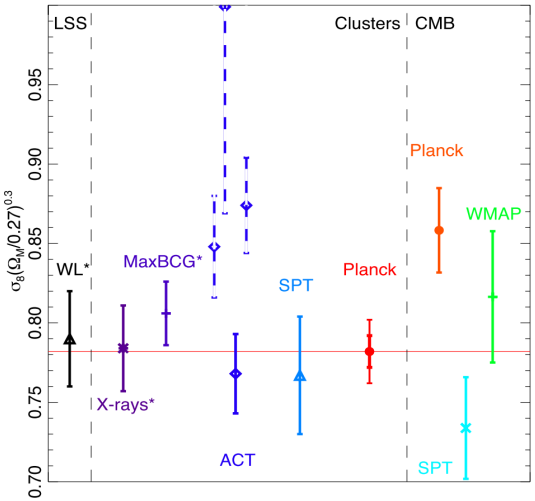






- ***SZ studies of galaxy clusters are new crossroads of cosmology and astrophysics***
  - ***Missing Baryon Problem in Clusters***
    - ★ *New Planck cosmology (partly) helps resolve the missing baryon problem*
  - ***Missing Energy Problem in Clusters***
    - ★ *Bias in cluster mass & scaling relations*
    - ★ *Interpretation of SZ power & bispectra*

Planck Cosmological Constraints from CMB vs. Cluster counts



SZ power & bispectra