Cosmology and Astrophysics with Galaxy Clusters
Recent Advances and Future Challenges

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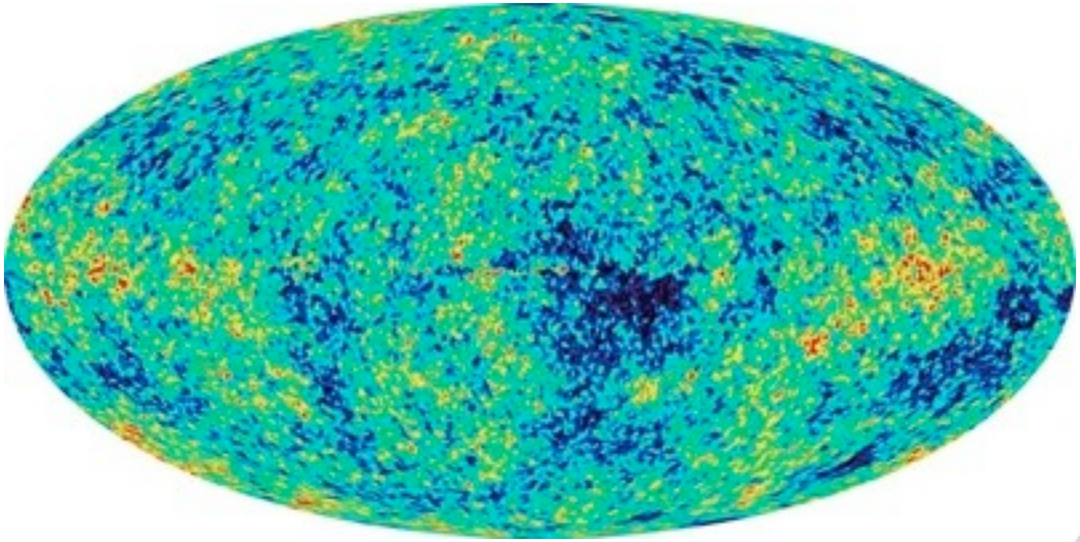
Yale University

IPMU, July 15th, 2010

Large-scale structure in the Universe

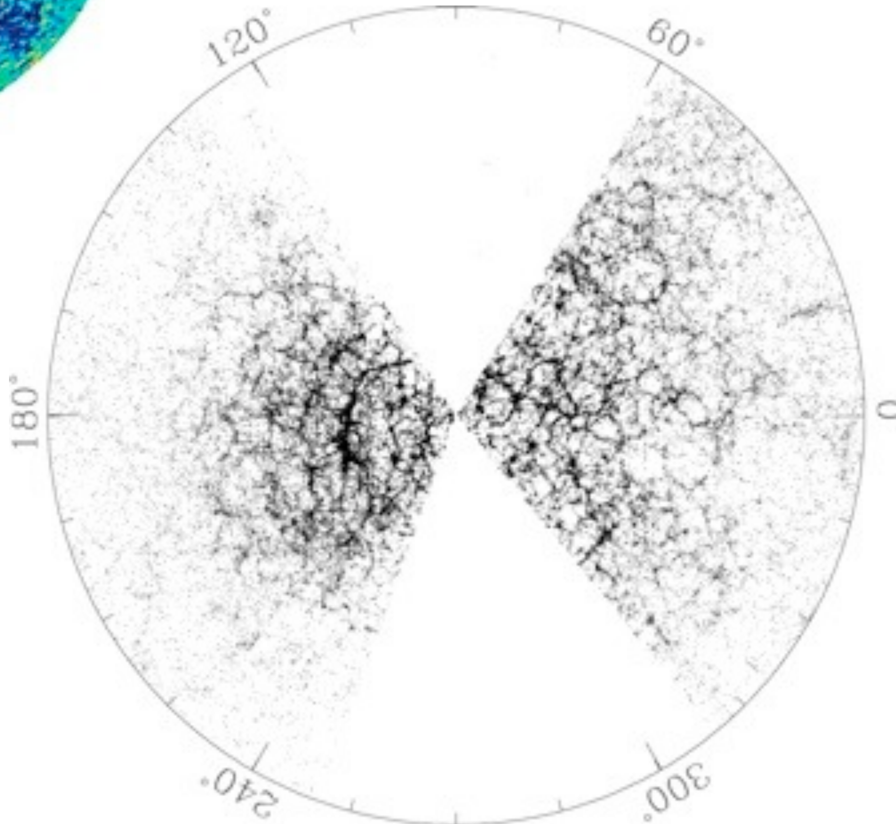


WMAP (microwave)
Early Universe
$\delta\rho/\rho \sim 10^{-5}$

Courtesy of WMAP team

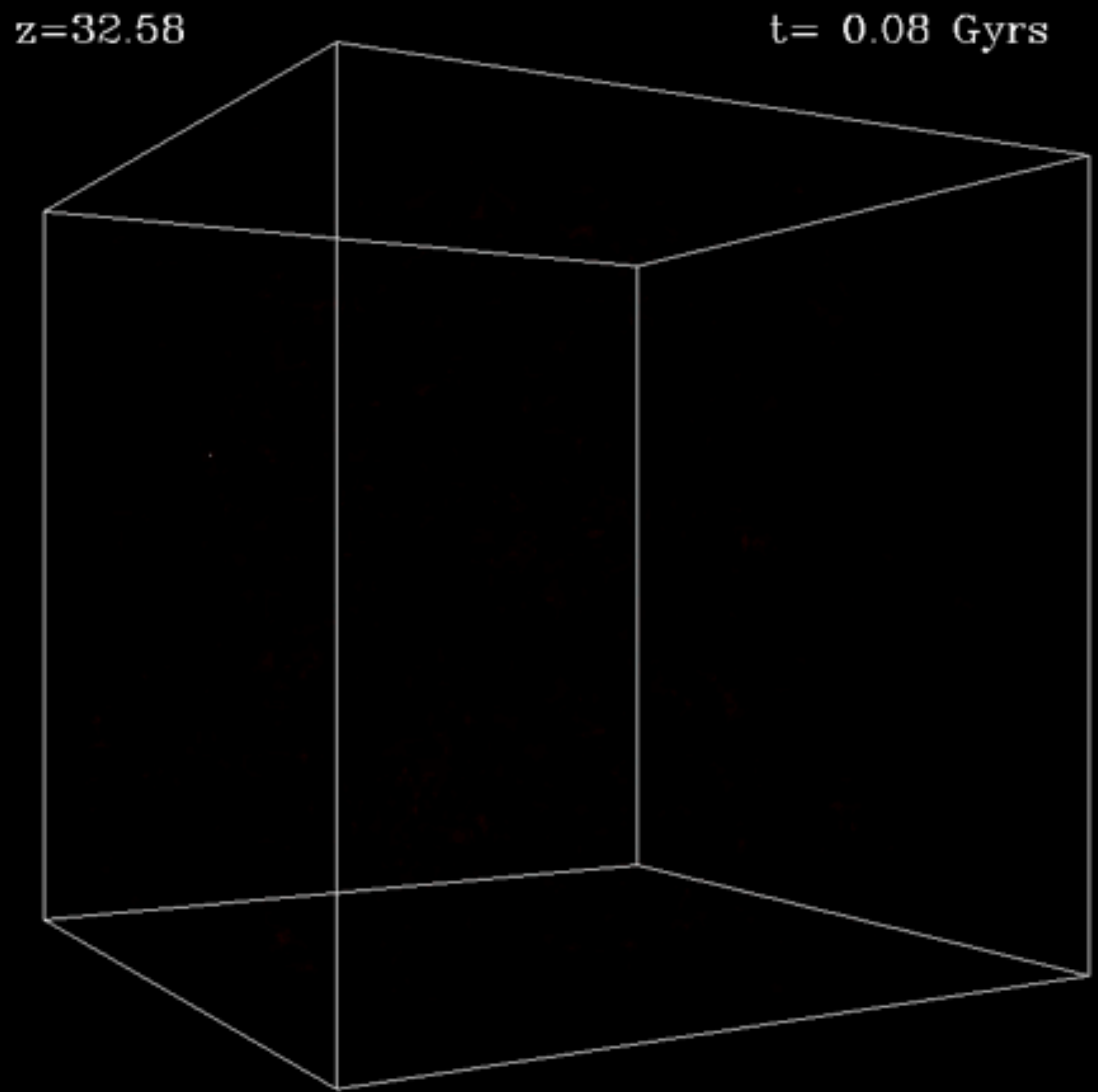
SDSS (optical)
Today
$\delta\rho/\rho >> 1$

Blanton et al. 2003

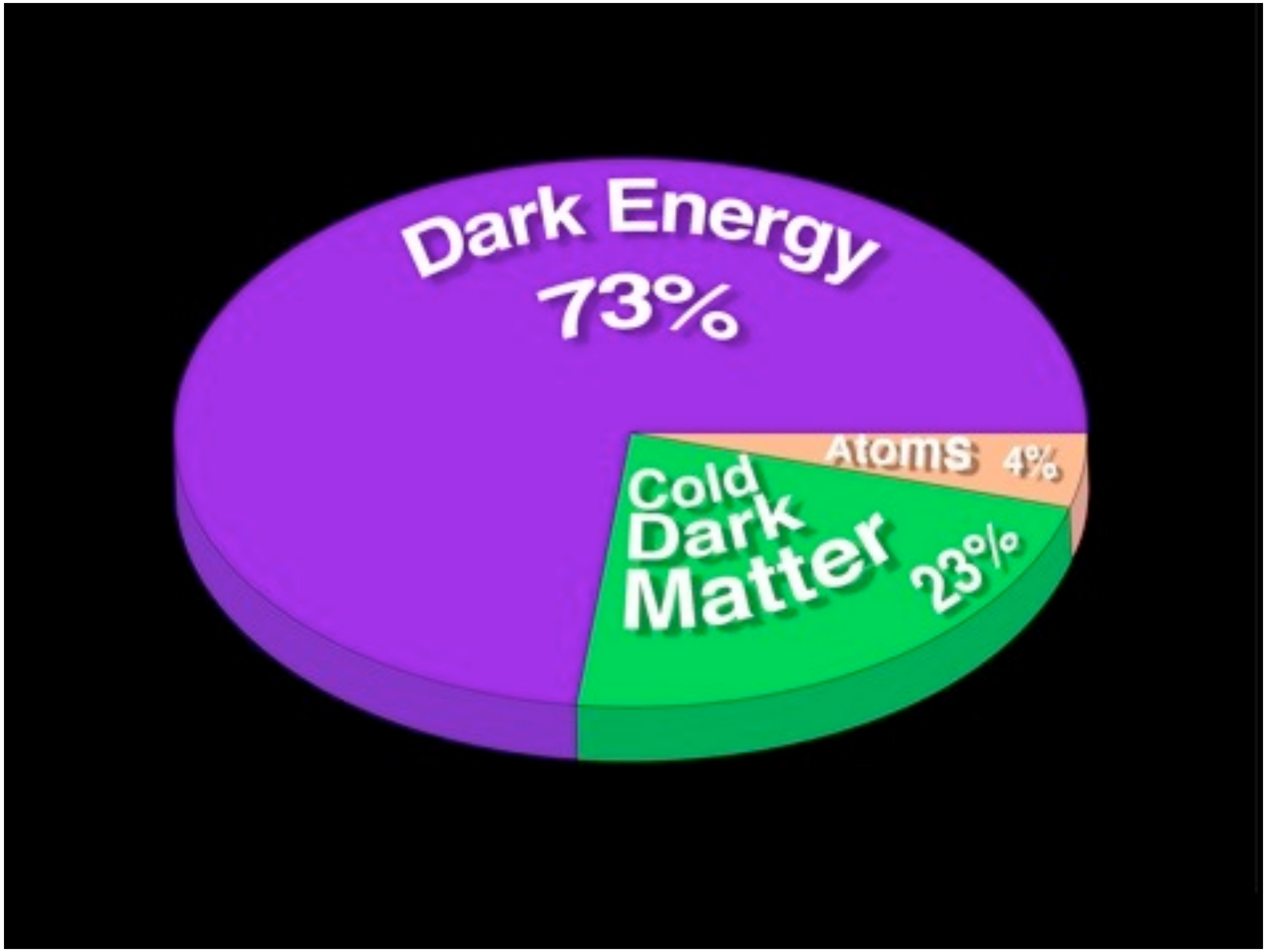


Simulating Structure Formation of the Universe

Simulating Structure Formation of the Universe



Dark Energy and Dark Matter



But, energy and matter of unknown origin govern the structure formation and expansion history of our Universe!!

Probes of Dark Energy and Dark Matter

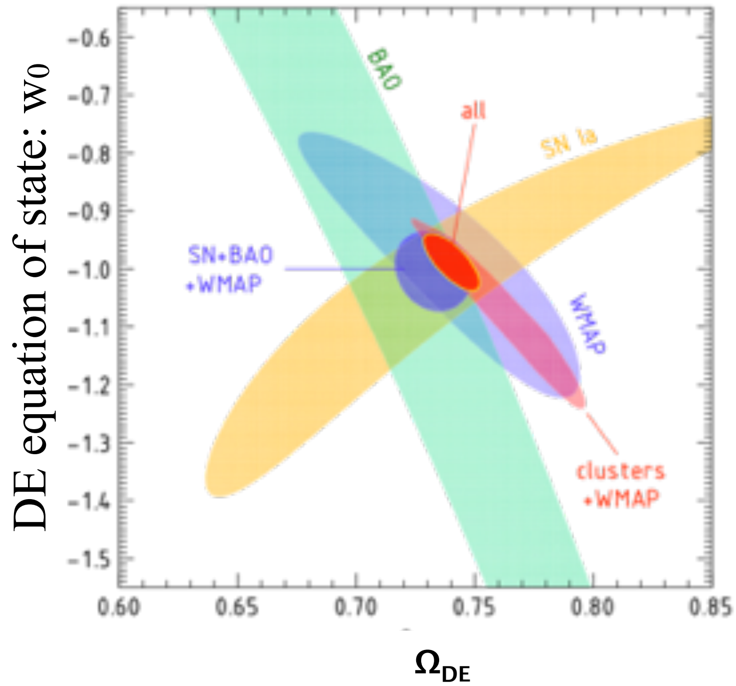
- **Dark Matter**
  - **Direct Detection (e.g., LHC, CDMS)**
  - **Indirect Astrophysical Probes (e.g., Fermi)**

- **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
(astro-ph/0609591)

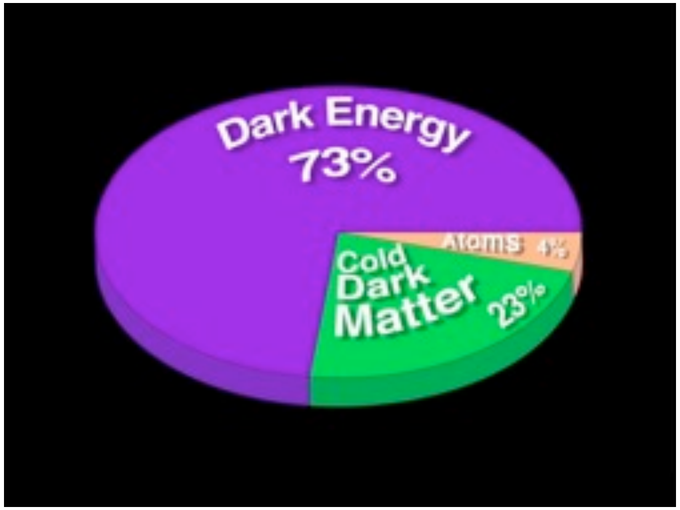
Cosmic Complimentarity

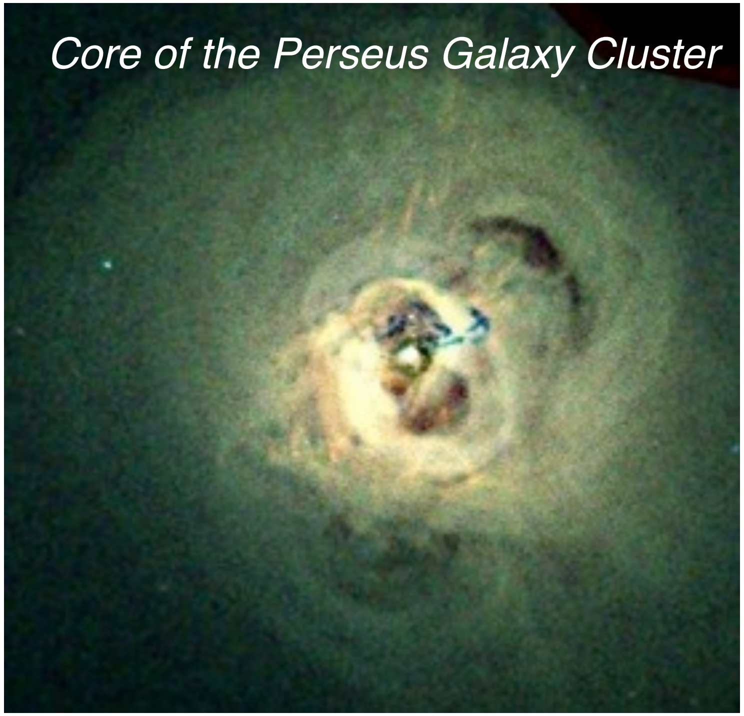


DE energy-density of the universe in units of the critical density

Galaxy Clusters: The Crossroads of Cosmology and Astrophysics

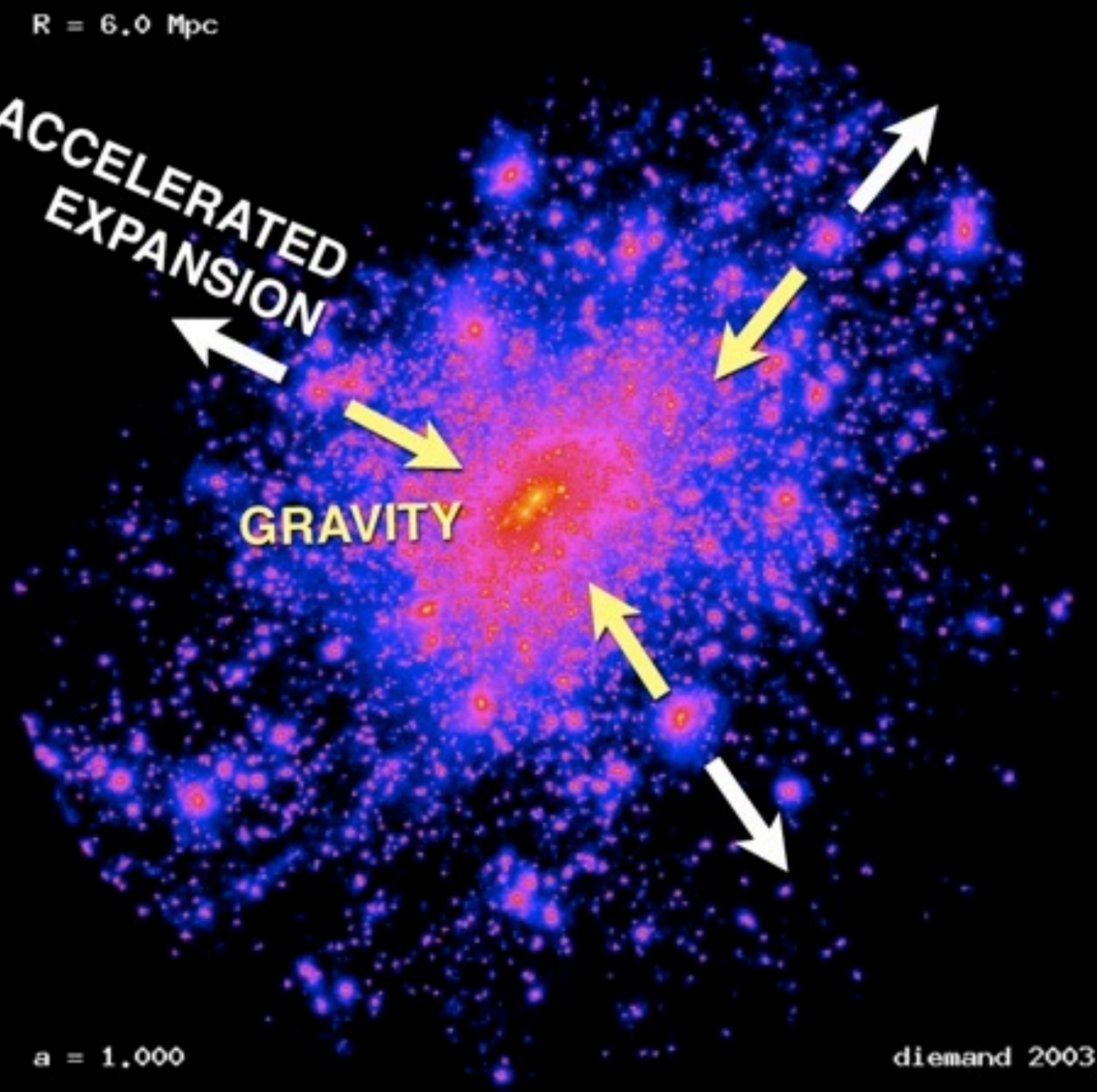
Clusters of galaxies provide important insights into the nature of dark energy and dark matter.



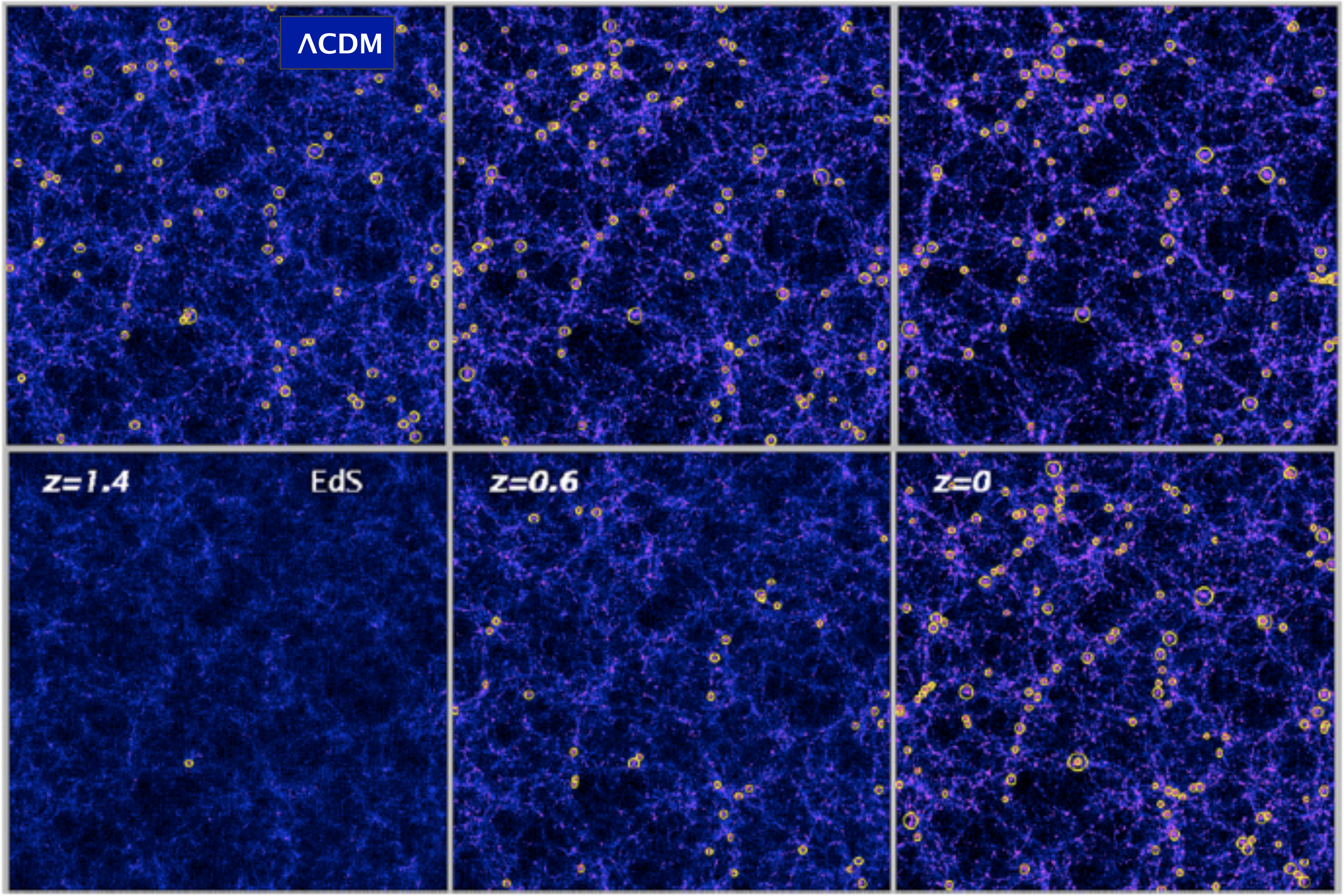


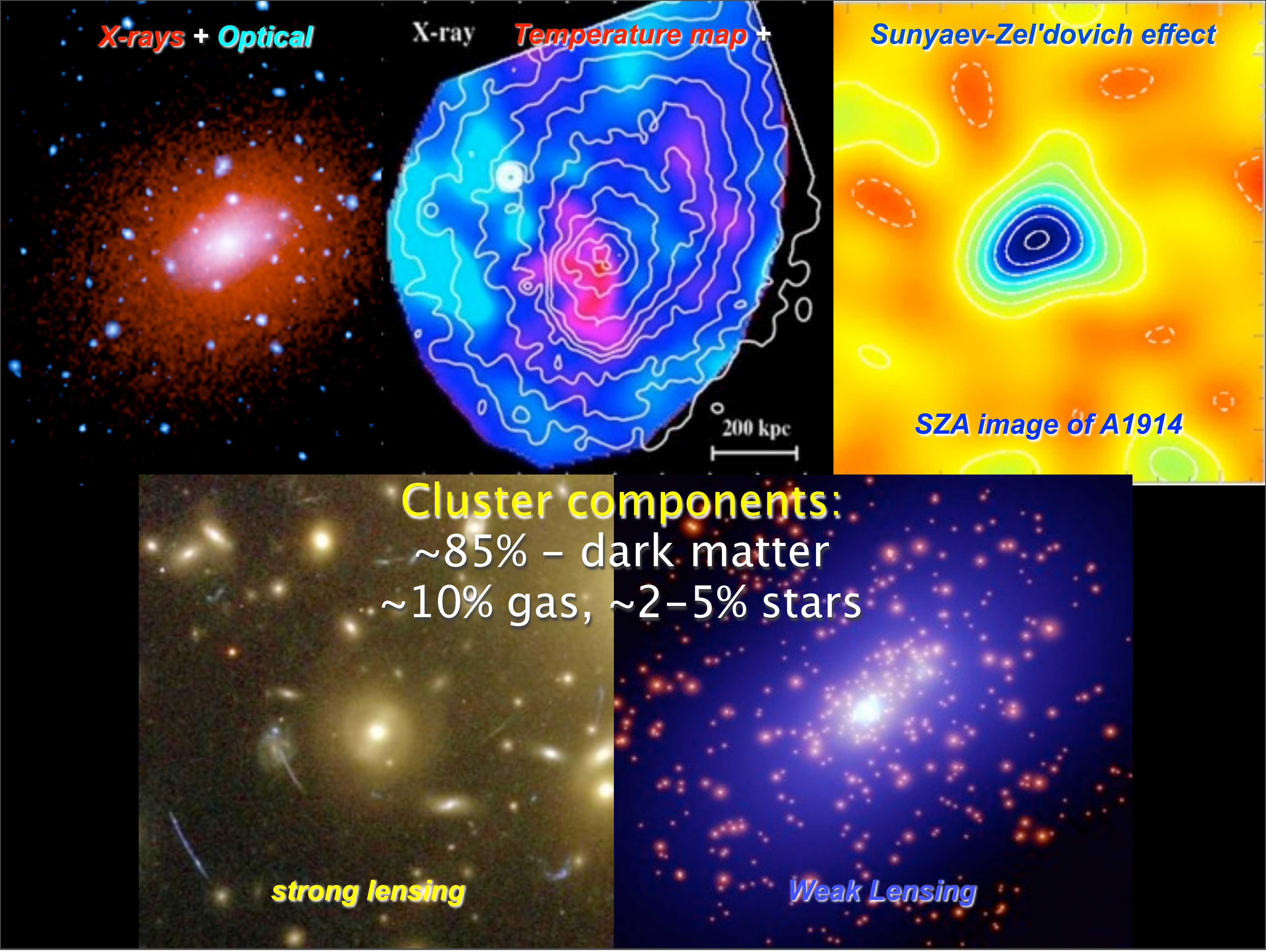
The most massive galaxies and black holes in the universe form and evolve in cores of galaxy clusters.

Studying dark energy using the structure formation as a probe



Evolution of massive clusters in the LCDM model (W_M=0.3) and the Einstein-de Sitter model (W_M=1.0)





Friday, July 16, 2010

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.

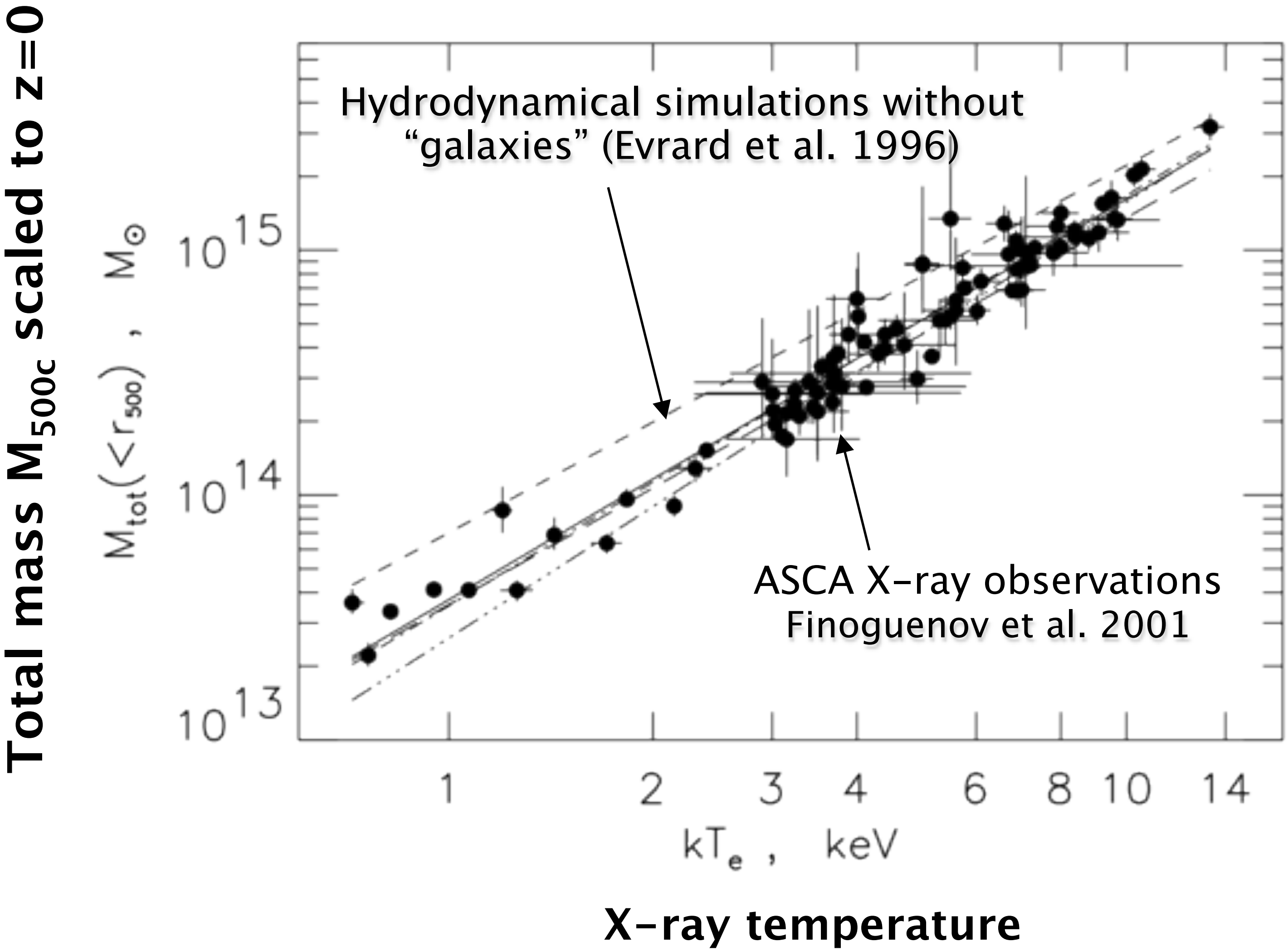
- **Observable-mass relations**: understanding cluster physics (e.g., gas cooling and star formation) and calibrate the relationship between observables and cluster mass (Δ=500).

$$T_{gas} \propto GM_\Delta / R_\Delta \propto M_\Delta^{2/3}$$

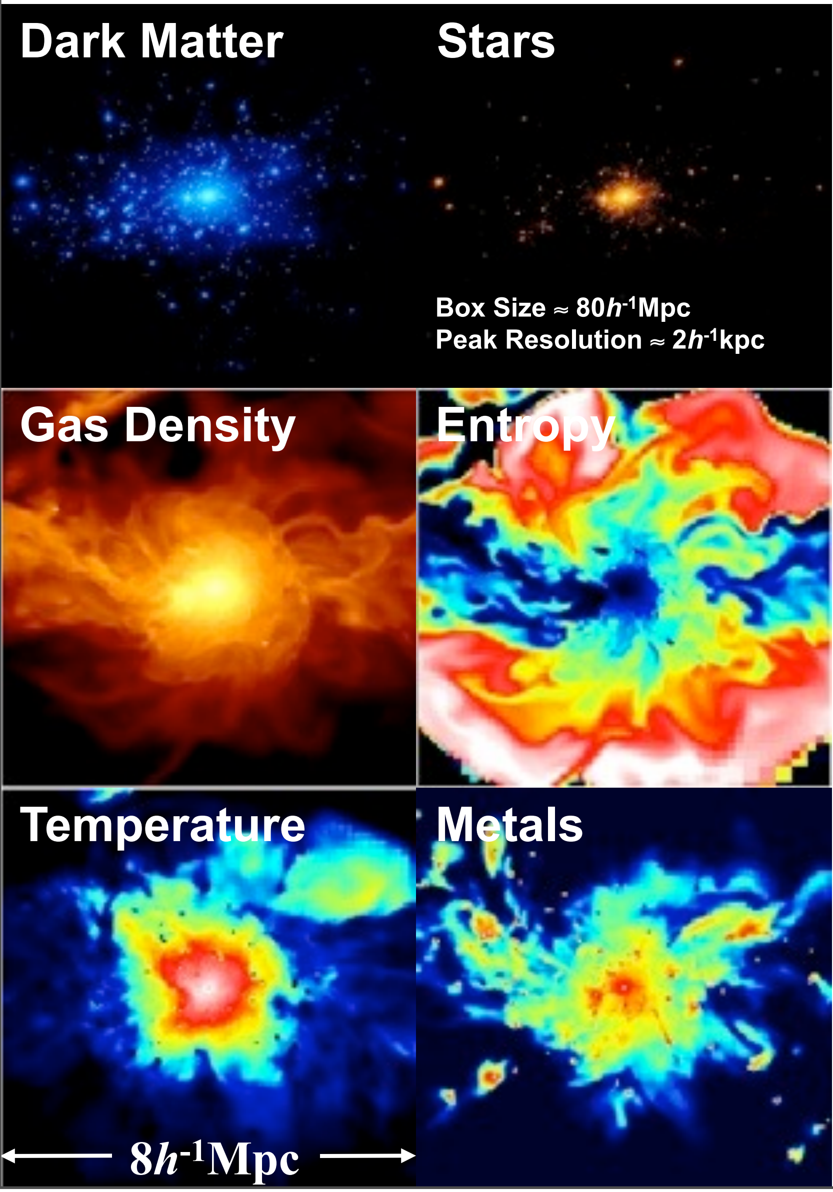
$$SZ\ flux \propto \int P_{gas}\, dl\, d\Omega \propto f_{gas} M_\Delta^{5/3}$$

$$M_\Delta \equiv (4\pi/3)\, R_\Delta^3\, \Delta\, \rho_{crit}(z)$$

Mass – ICM temperature relation until several years ago..



Hydrodynamic Simulations of Galaxy Clusters



N-body+Gasdynamics with ART code

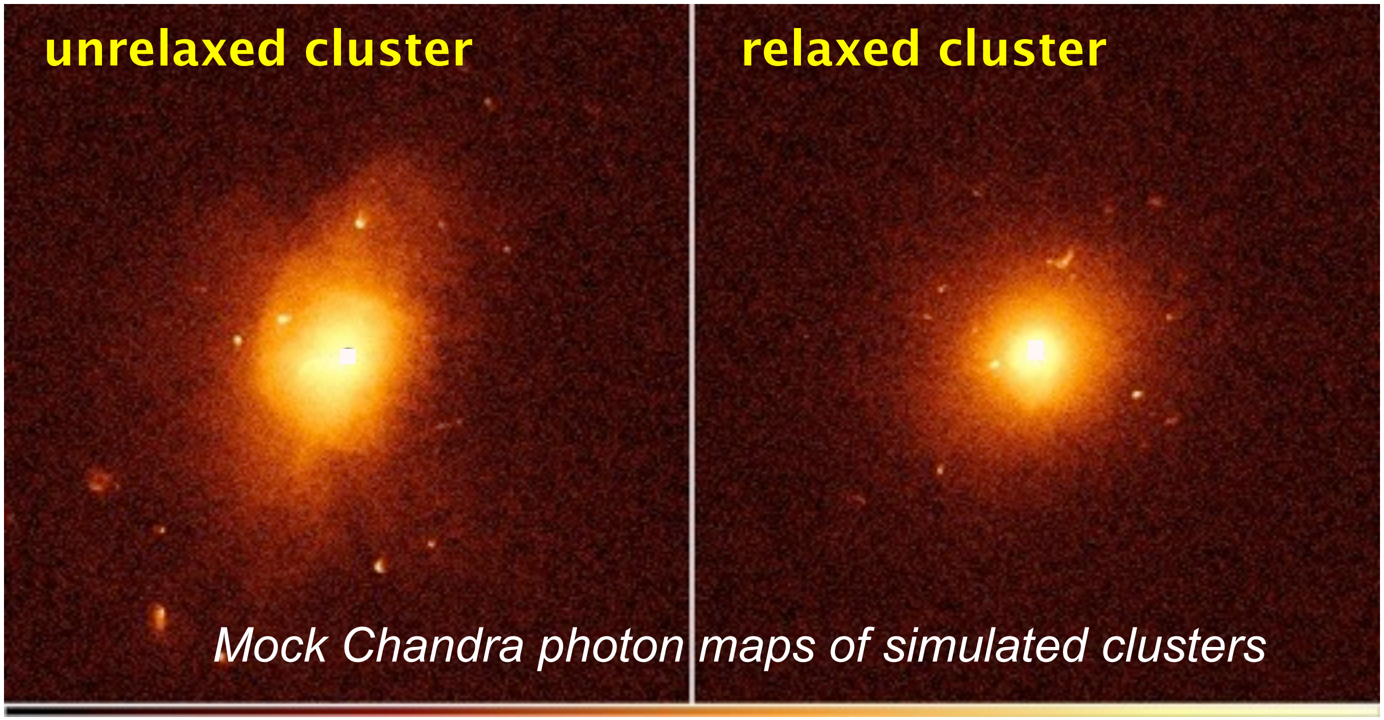
- **Collisionless dynamics** of DM and stars
- **Gasdynamics**: Eulerian Adaptive Mesh Refinement
- **Radiative cooling and heating of gas**: metallicity dependent net cooling/heating rates
- **Star Formation** using Kennicutt (1998) recipe
- **Thermal stellar feedback**
- **Metal enrichment** by SNII/Ia
- **No AGN feedback, thermal conduction, B-field, cosmic-rays, hydro. approximation**

Cluster Samples

- **High-resolution allows us to actually simulate clusters of galaxies**
- **Effects of galaxy formation on the ICM**
  - Sample of 16 clusters in ΛCDM model
  - Two sets of runs with cooling & SF (CSF) and with non-radiative gasdynamics
  - Comparison with Chandra X-ray observations of nearby, relaxed clusters (Vikhlinin et al. 2006)

Testing Chandra measurements with mock observations of simulated clusters

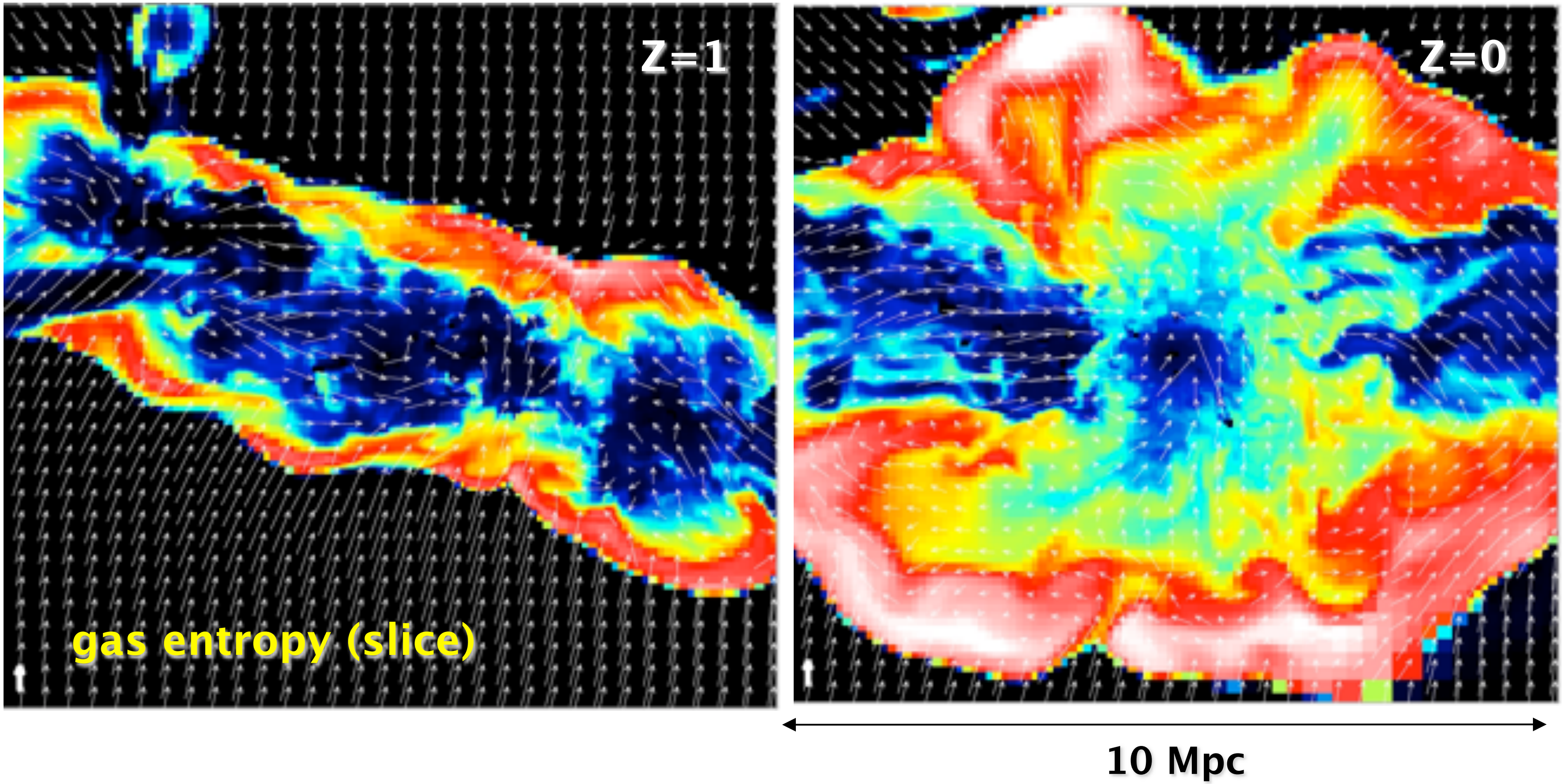
- generate "Chandra data" for clusters from cosmological simulations
- reduce with real data analysis pipeline
  - **gas mass accurate to ~3%, temperatures are accurate to <~10%**
  - **but, hydrostatic mass is biased low by ~10% due to turbulence**



Mock Chandra photon maps of simulated clusters

Nagai, Vikhlinin & Kravtsov 2007, ApJ, 655, 98

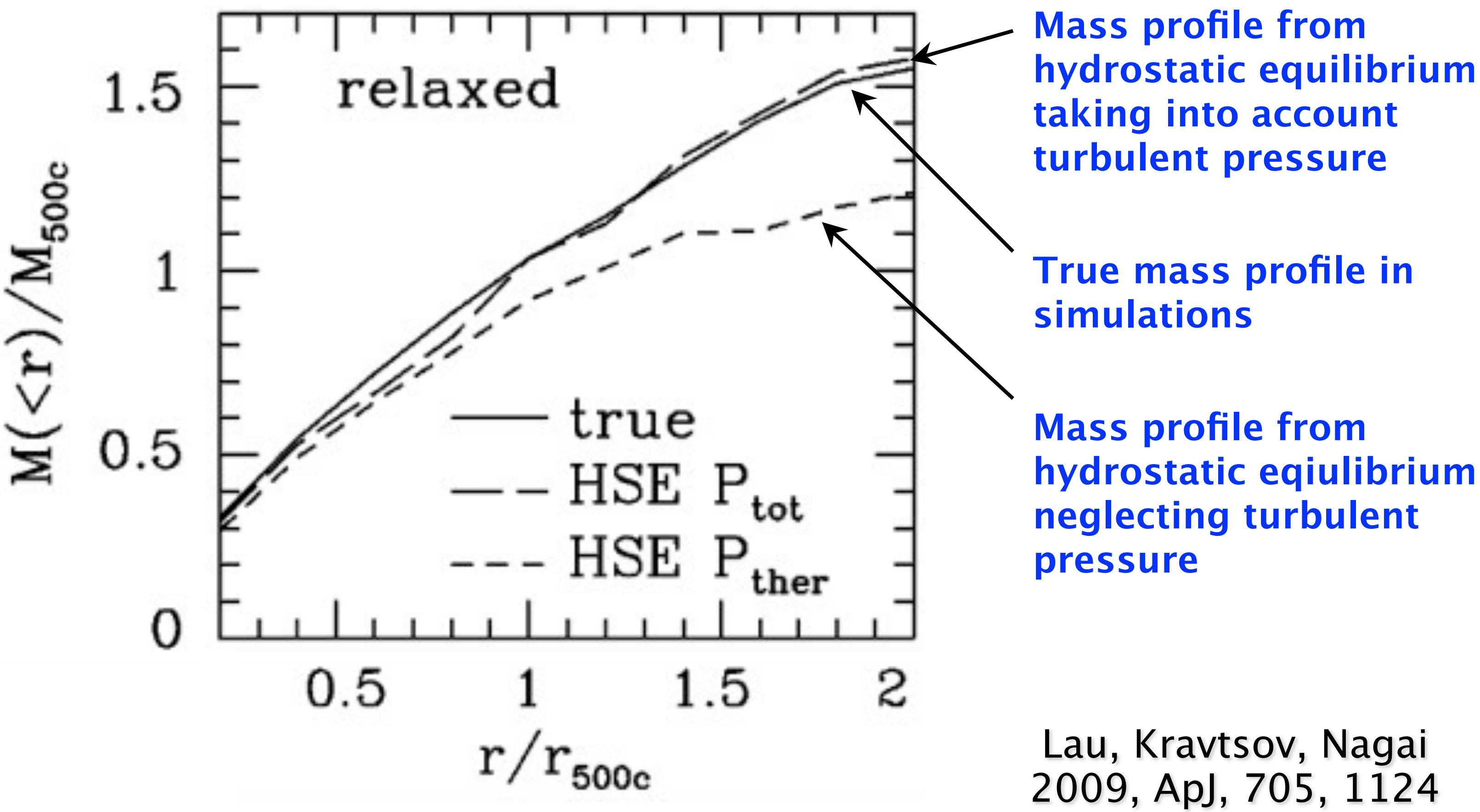
Accretion, Mergers → Shocks, Turbulence



Norman & Bryan 1999, Nagai, Kravtsov & Kosowsky 2003
Sunyaev, Norman & Bryan 2003; Rasia et al. 2004, 2006;
Dolag et al. 2005; Nagai et al. 2007; Lau et al. 2009

Effect of turbulent gas motions on mass measurements

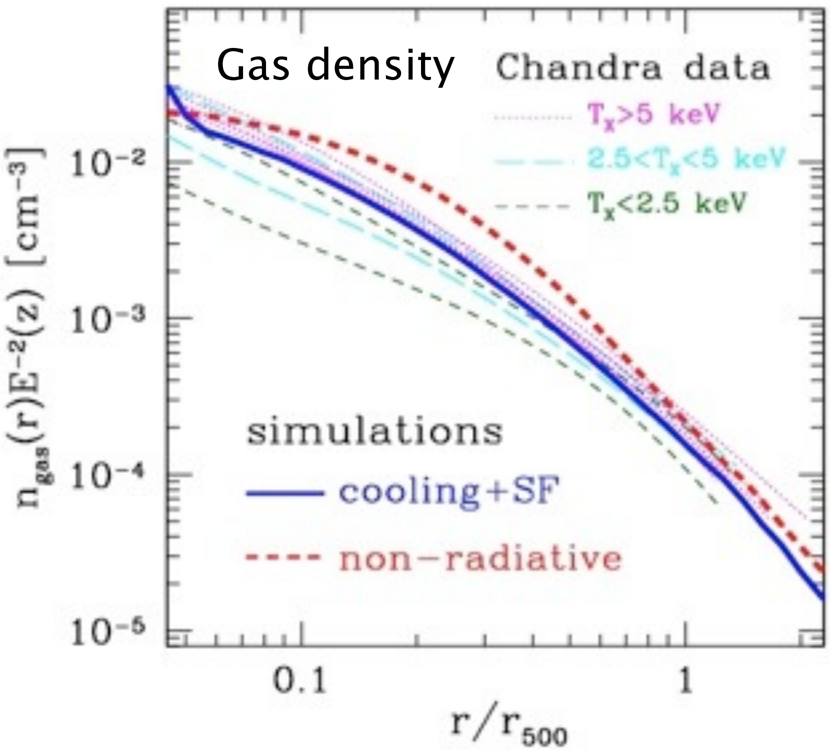
$$M_{\rm tot}(<r) = \frac{-r^2}{G\rho}\left(\frac{dP_{\rm ther}}{dr} + \frac{dP_{\rm turb}}{dr}\right)$$

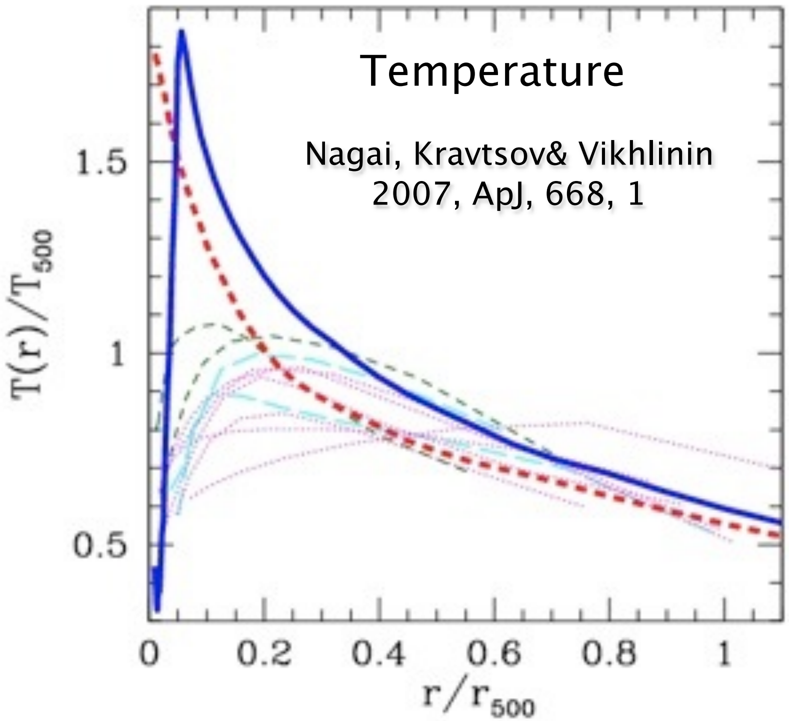


cluster-centric radius in units of r_{500c}

Lau, Kravtsov, Nagai
2009, ApJ, 705, 1124

Intracluster Gas Profiles
Simulations vs. Chandra X-ray observations

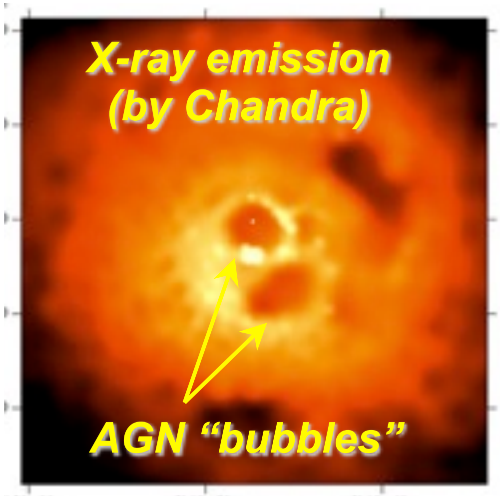


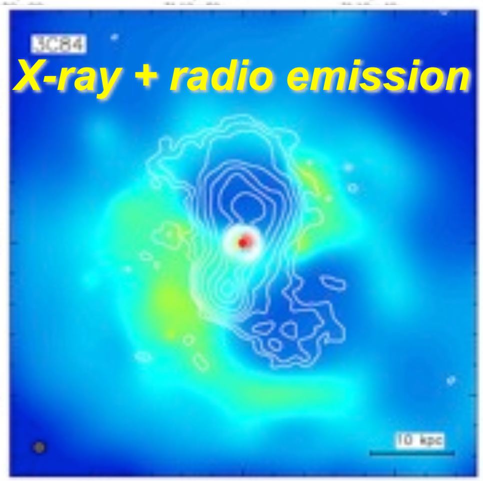


cluster-centric r in units of r500

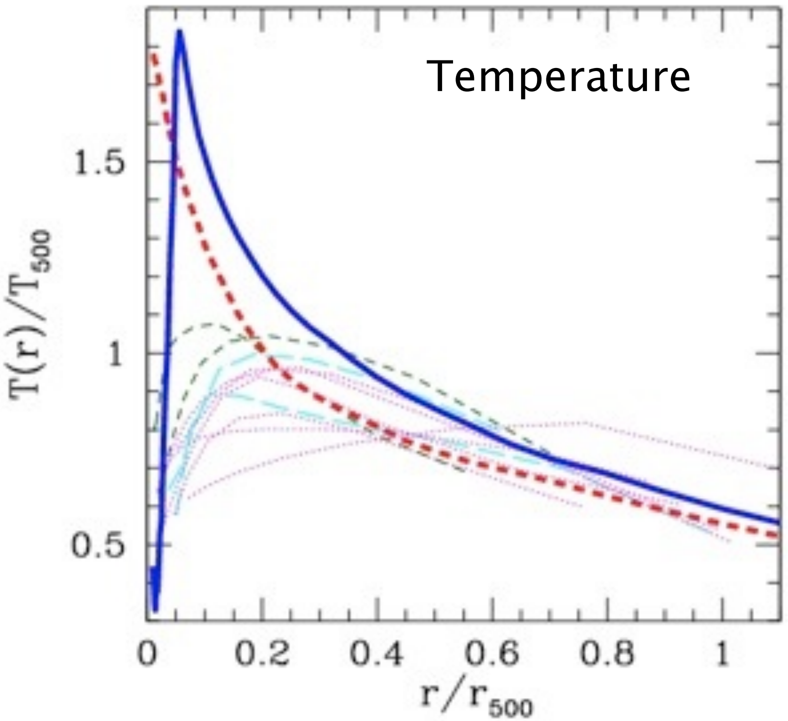
Modern hydrodynamical cluster simulations reproduce observed ICM profiles outside cluster cores ($r>0.15 \times r_{500}$).

Most uncertainties in cluster cores





example: heating by Active Galactic Nuclei of the central cluster galaxy



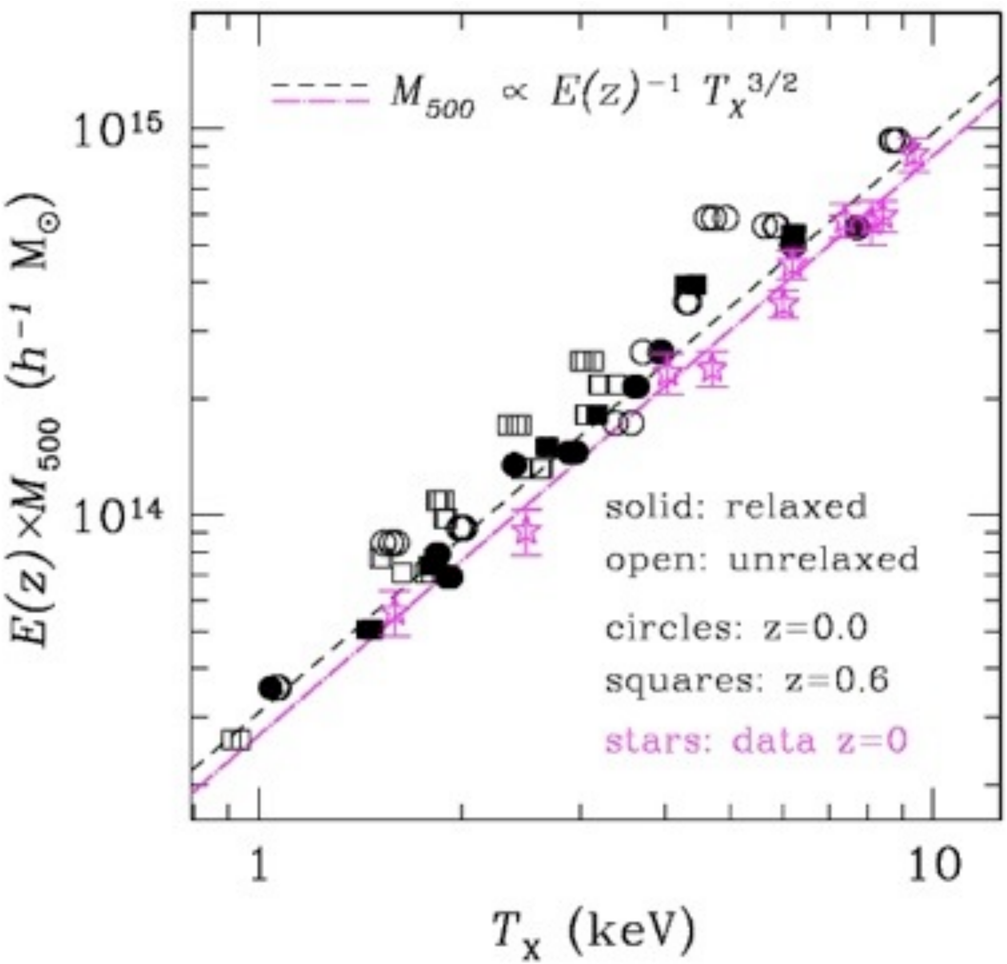
cluster-centric raidus in units of r500

outer regions of clusters can be used to reliably estimate their total masses

Mass – ICM temperature relation

Advances in both simulations and observations

Total mass M_{500c} scaled to z=0



X-ray spectral temperature
excluding cluster cores ($r<0.15 x r_{500c}$)

~10% agreement in the amplitude between observed and model M-Tx relation -- improvements are in both sim. and obs.

Scatter in M-Tx is ~20% in mass at a given Tx - the scatter is primarily driven by unrelaxed systems

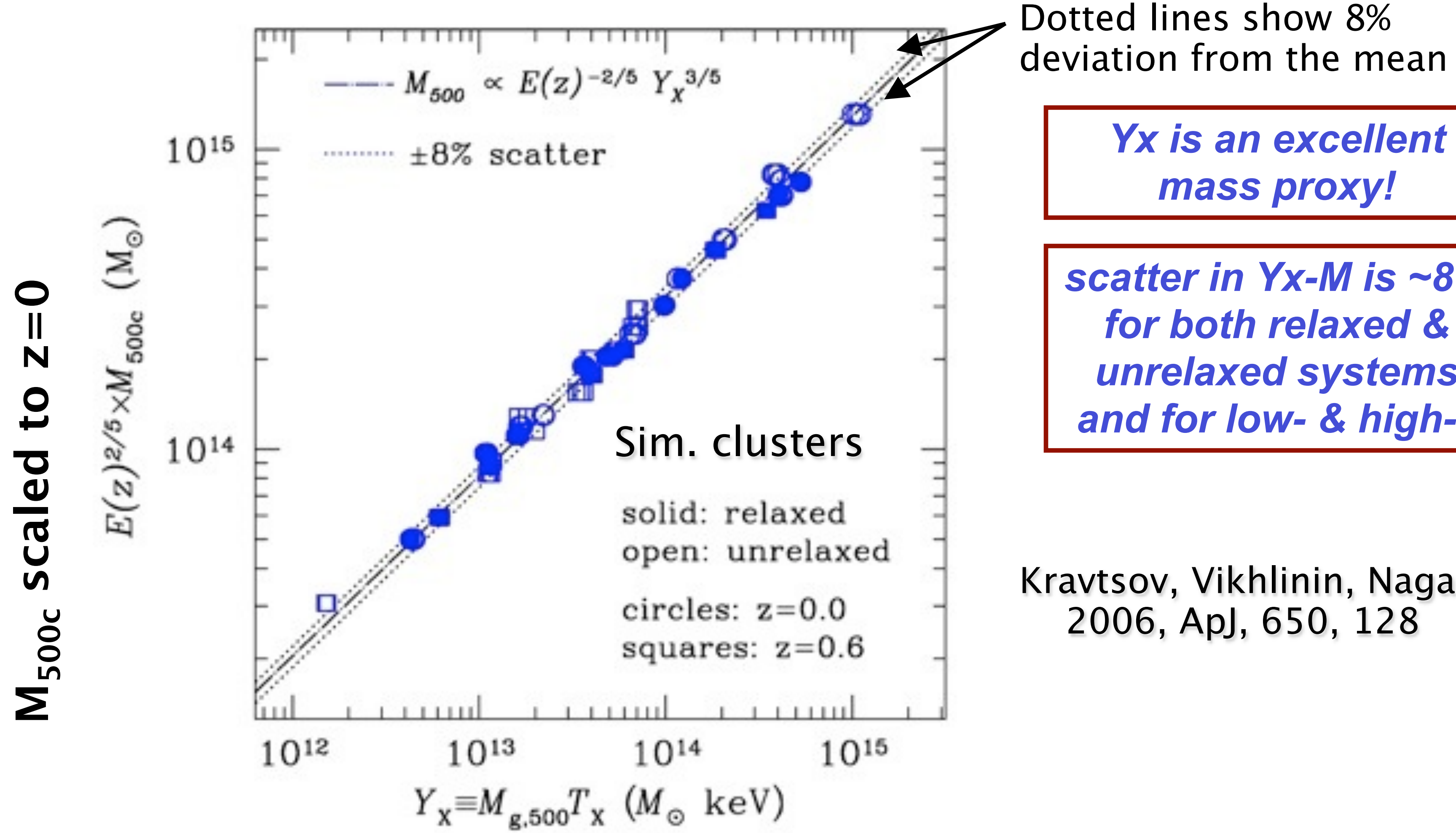
Unrelaxed systems have systematically lower Tx

black pts: Simulated clusters with cooling+SF

magenta pts: Chandra data Vikhlinin et al. 2006 ApJ, 640, 691

Mass – Yx relation

The most robust mass proxy



Yx is an excellent mass proxy!

scatter in Yx-M is ~8% for both relaxed & unrelaxed systems and for low- & high-z

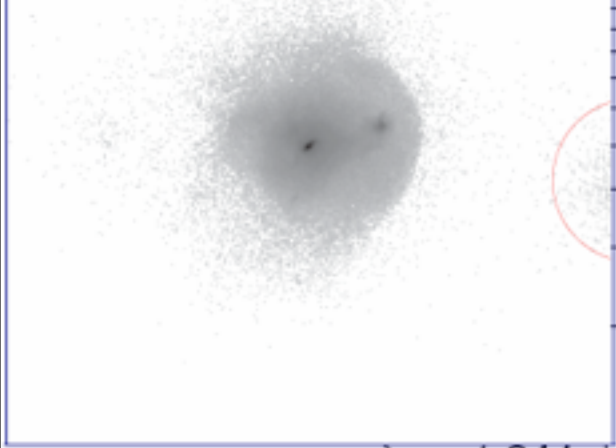
Kravtsov, Vikhlinin, Nagai 2006, ApJ, 650, 128

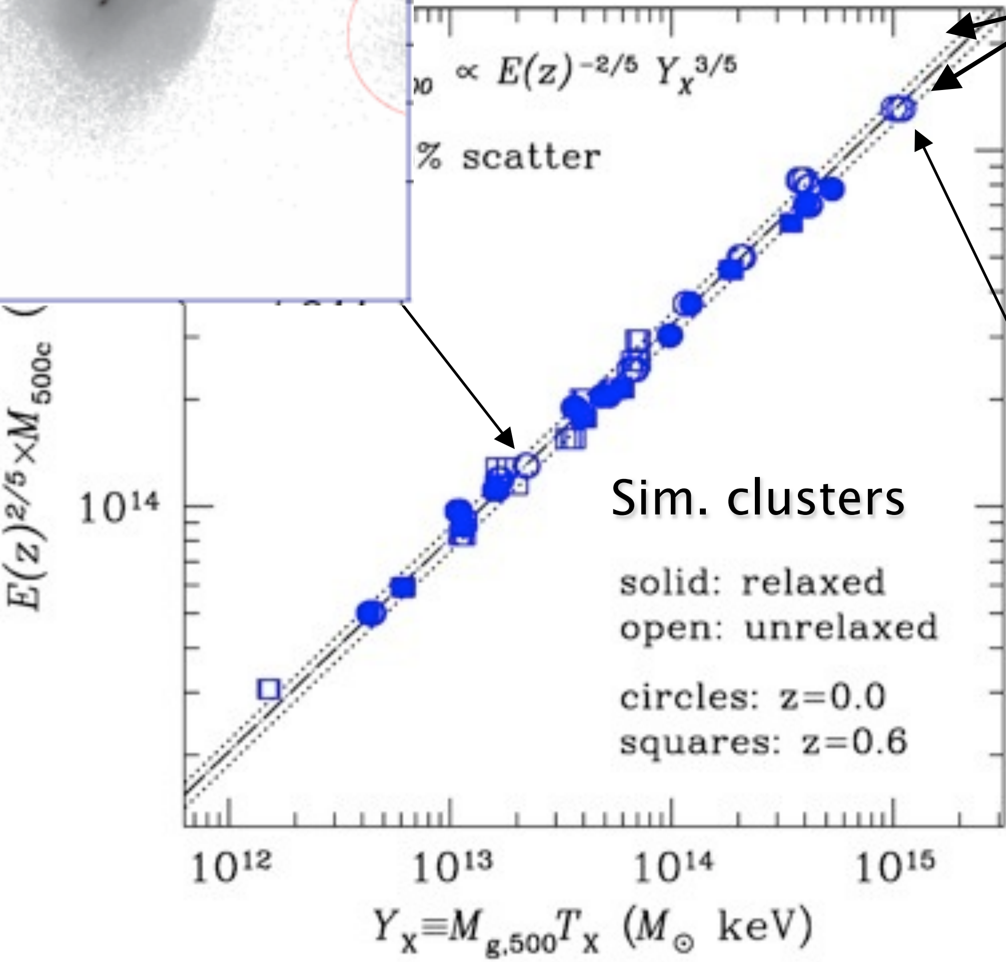
X-ray "pressure" = Yx = gas mass x temperature measured excluding core region

Mass – Yx relation

The most robust mass proxy

Mock Chandra X-ray maps of merging simulated clusters



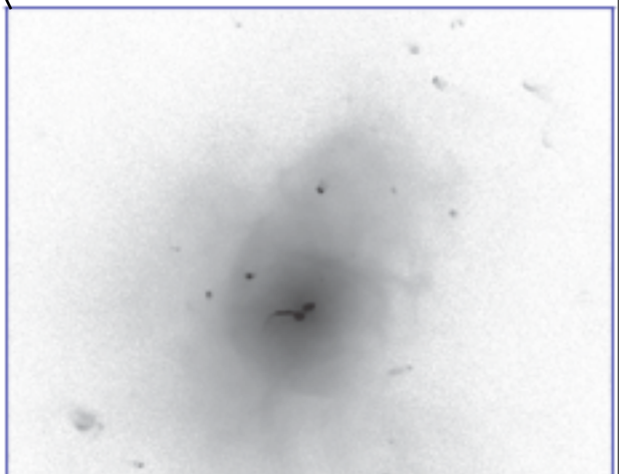


M_{500c} scaled to z=0

Dotted lines show 8% deviation from the mean

Yx is an excellent mass proxy!

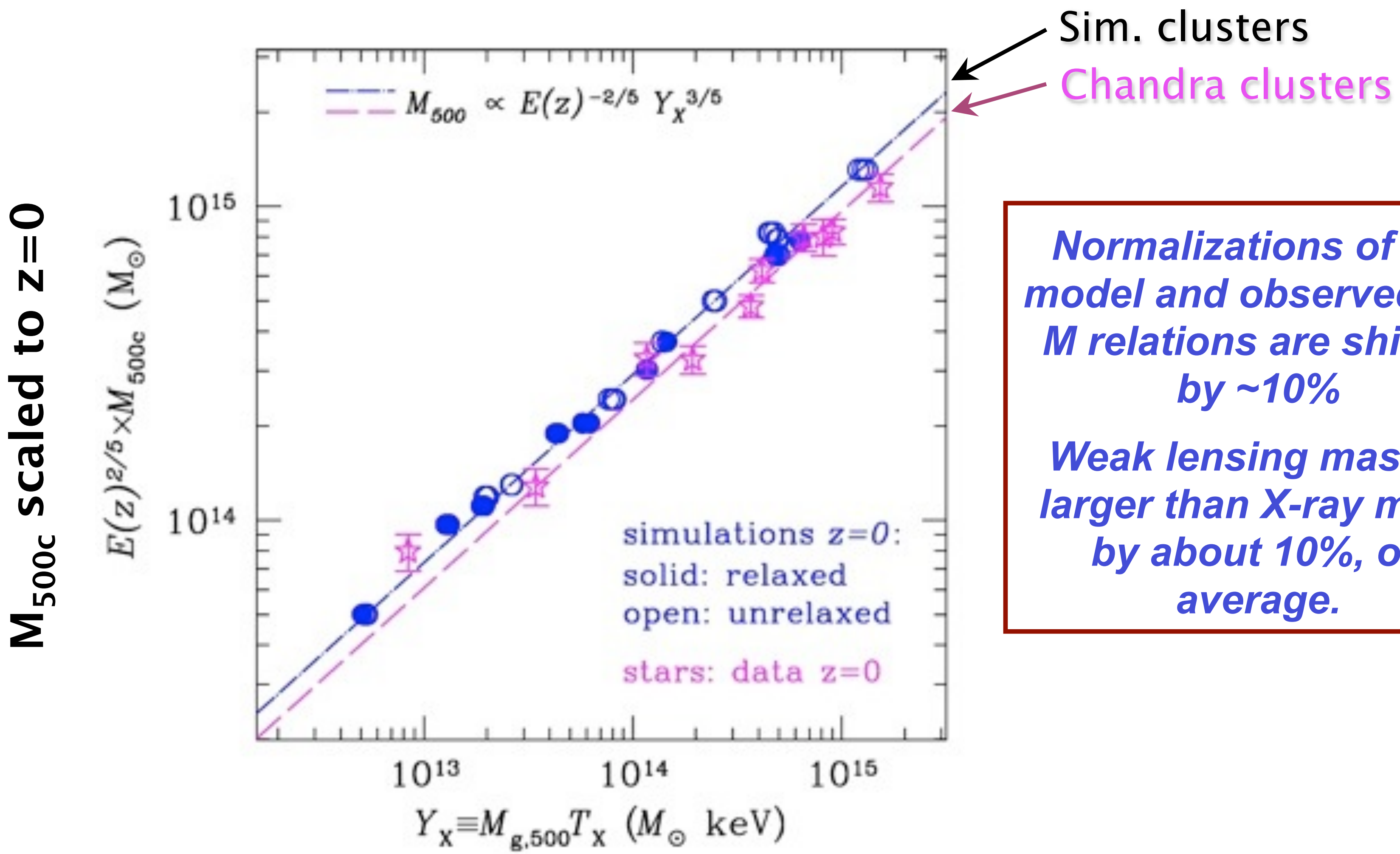
scatter in Yx-M is ~8% for both relaxed & unrelaxed systems and for low- & high-z



Kravtsov, Vikhlinin, Nagai 2006, ApJ, 650, 128

X-ray "pressure" = Yx = gas mass x temperature measured excluding core region

Main Challenge
Mass Estimate of Galaxy Clusters



Normalizations of the model and observed Yx-M relations are shifted by ~10%

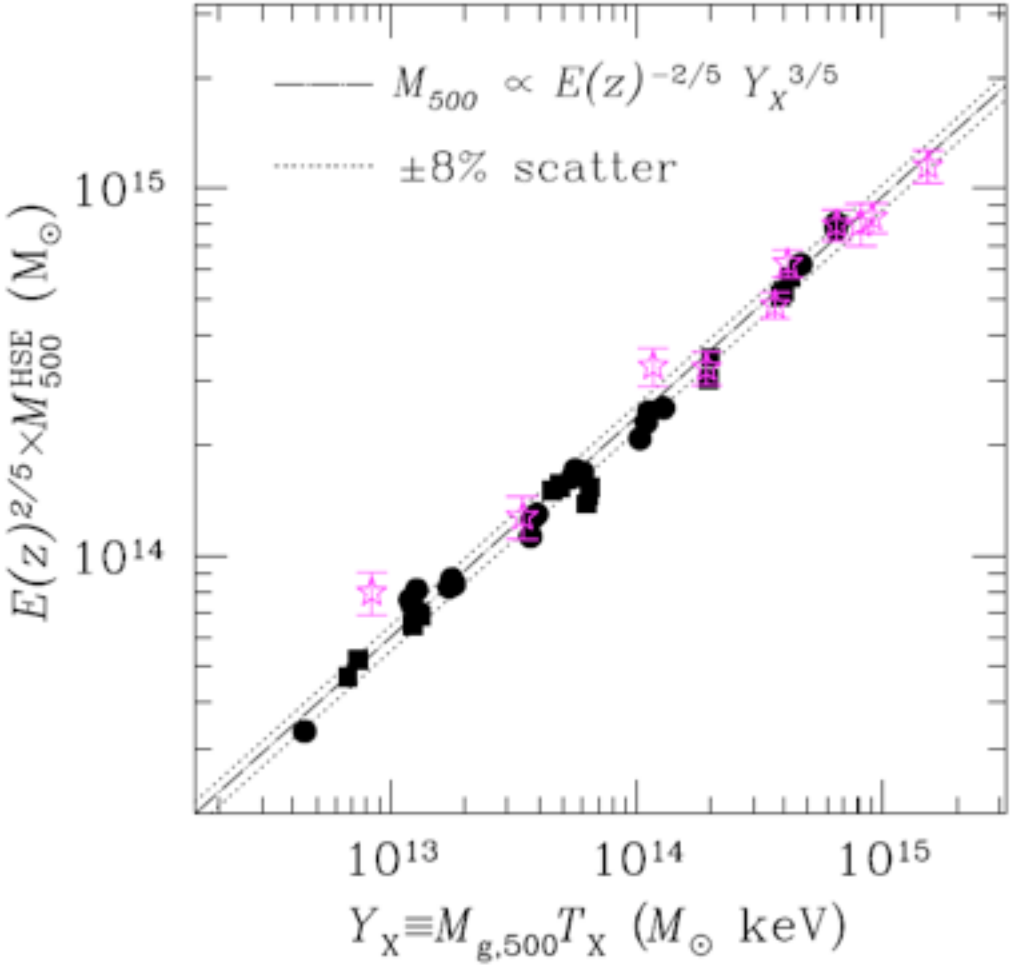
Weak lensing mass is larger than X-ray mass by about 10%, on average.

Need to calibrate observable-mass relation and its evolution to a few percent!

Mass – Yx relation

using mass derived from the hydrostatic equilibrium analysis both in observations and simulations

Hydrostatic mass M_{500c}

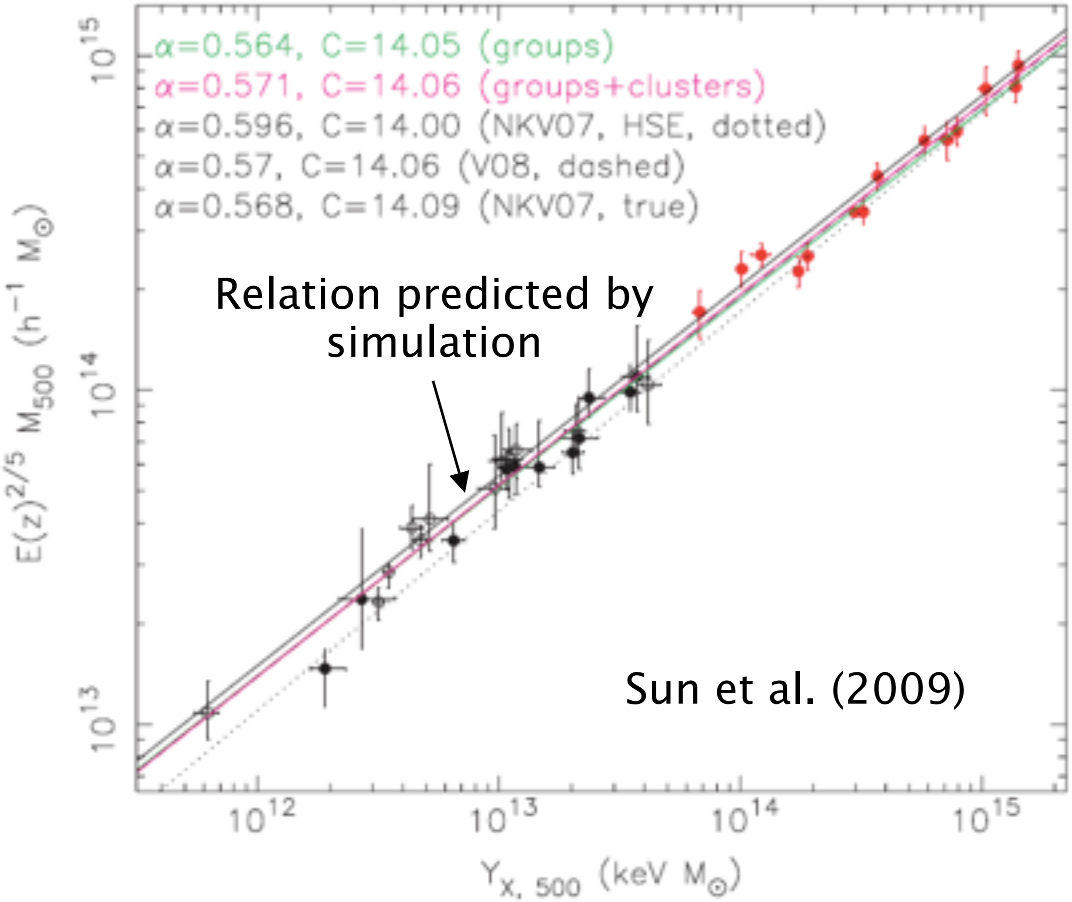


X-ray "pressure" = gas mass x temperature

Nagai, Kravtsov, Vikhlinin 2007

Observed Yx-M_{500} relation

Yx is measured directly using Chandra observations

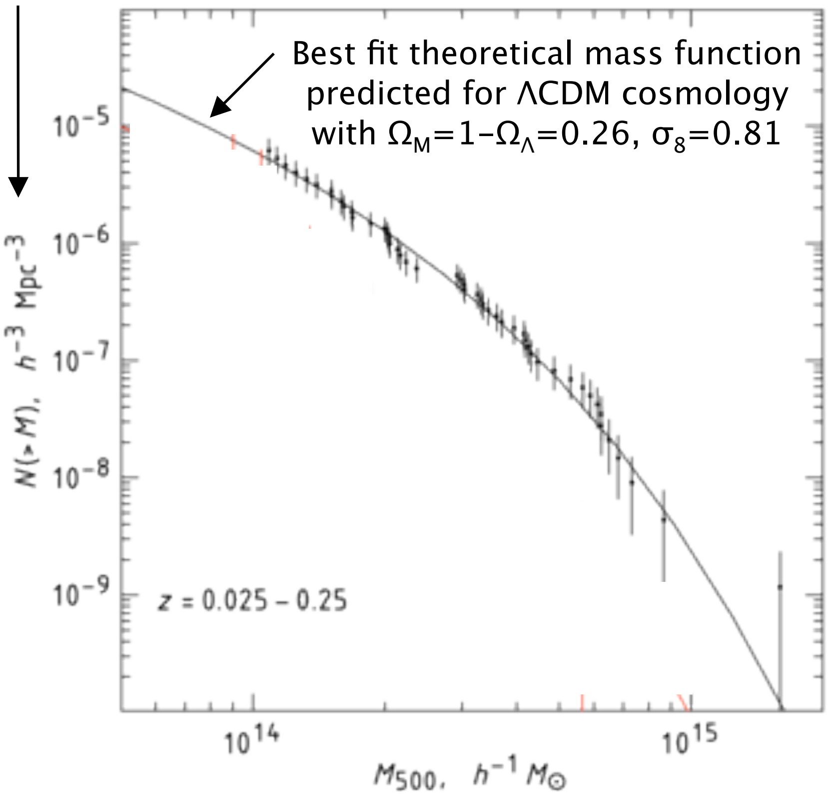


The slope is consistent with simulations.
~10% offset in normalization between
simulations and observations

Accurate constraints on σ_8 and Ω_M

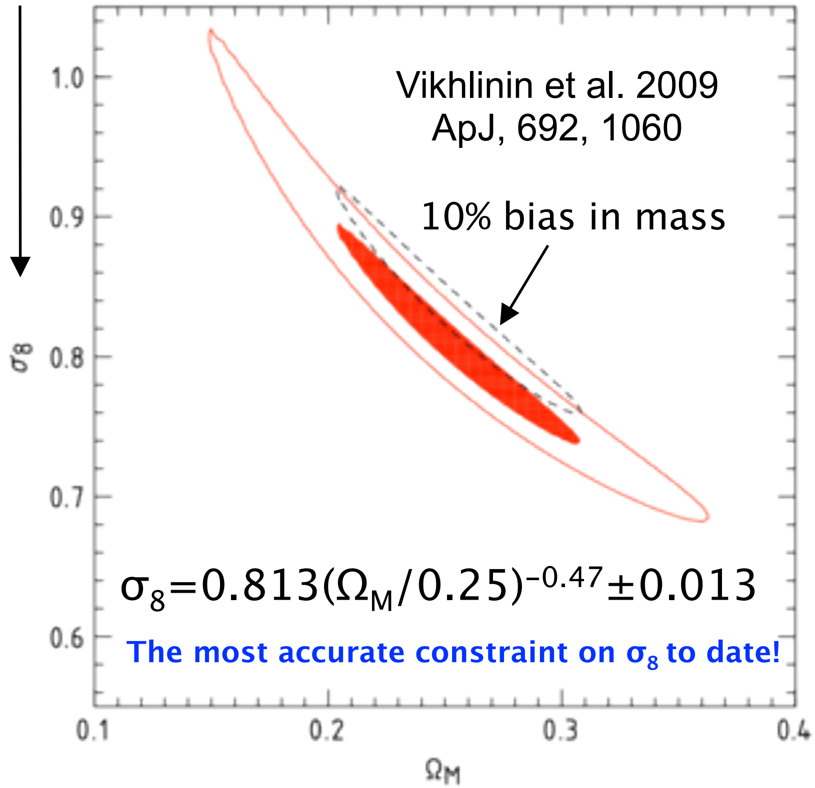
Using the local (z<0.1) sample of 49 X-ray selected clusters

Number density of clusters with masses $>M_{500}$



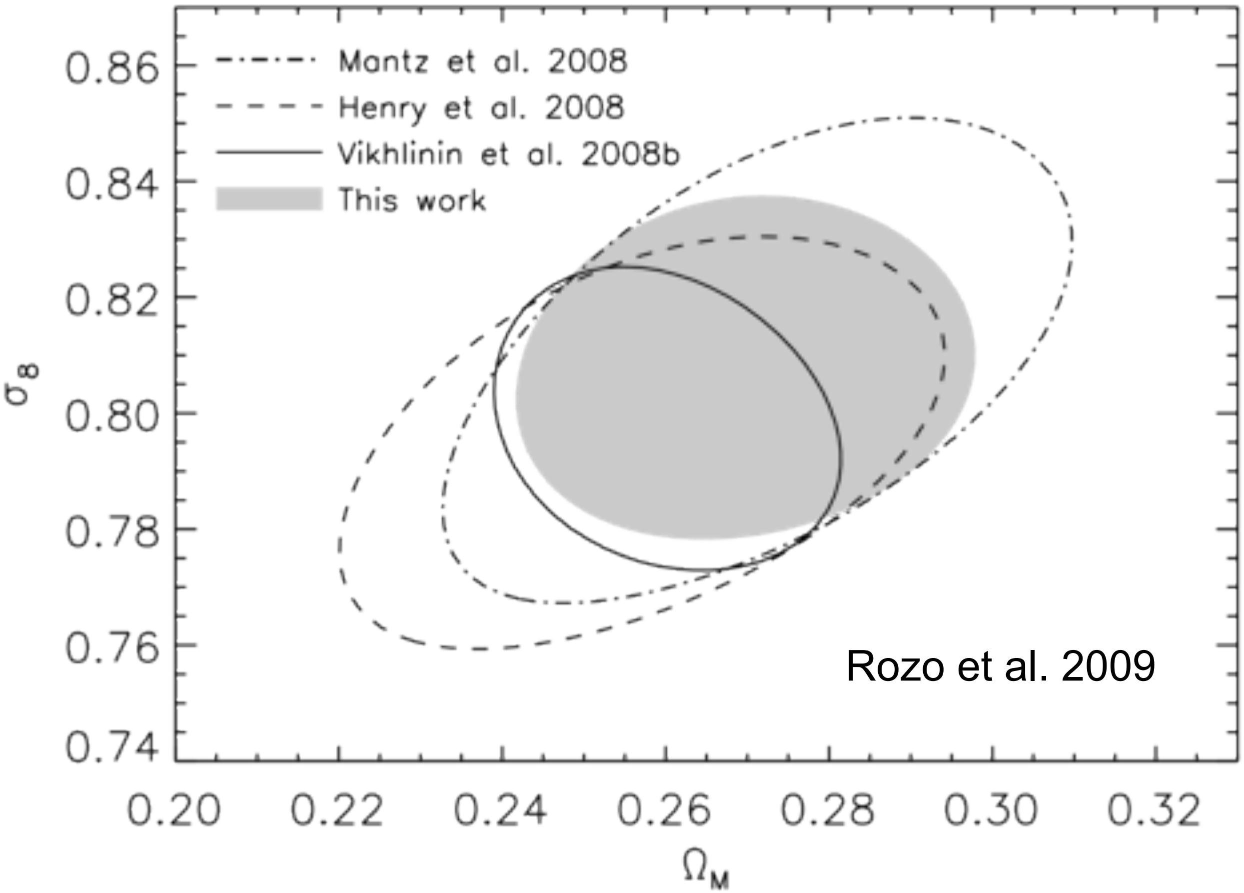
Mass within radius enclosing overdensity of 500 times the critical density $\rho_{crit}(z)$

Density fluctuations amplitude at 8/h Mpc scale



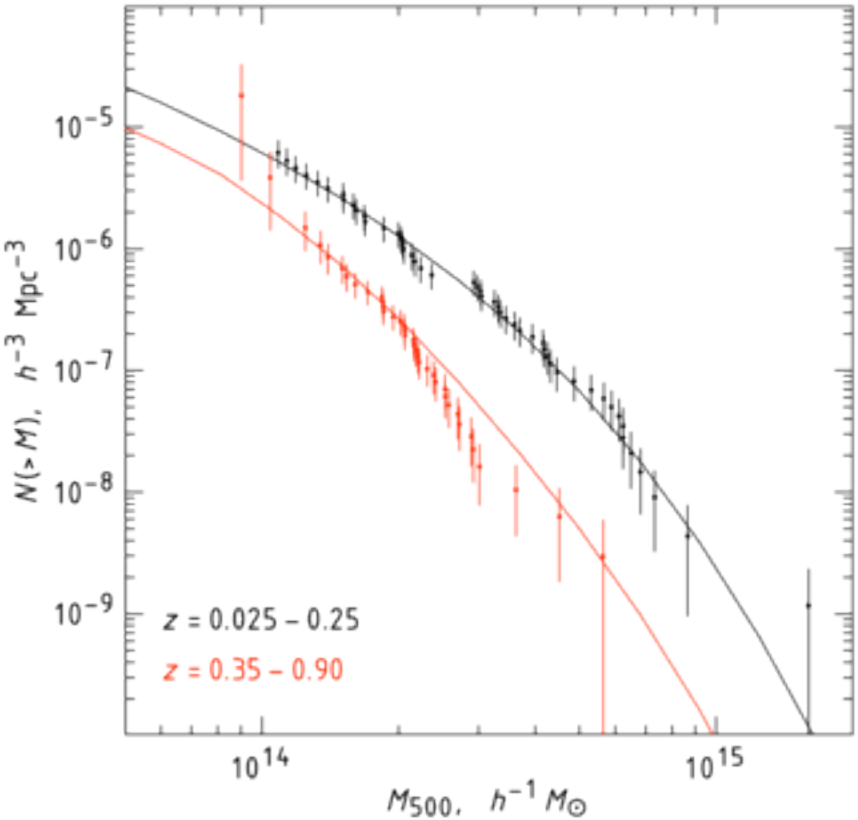
The mean mass density of the universe in units of the critical density

Consistent constraints from other X-ray and optical cluster studies

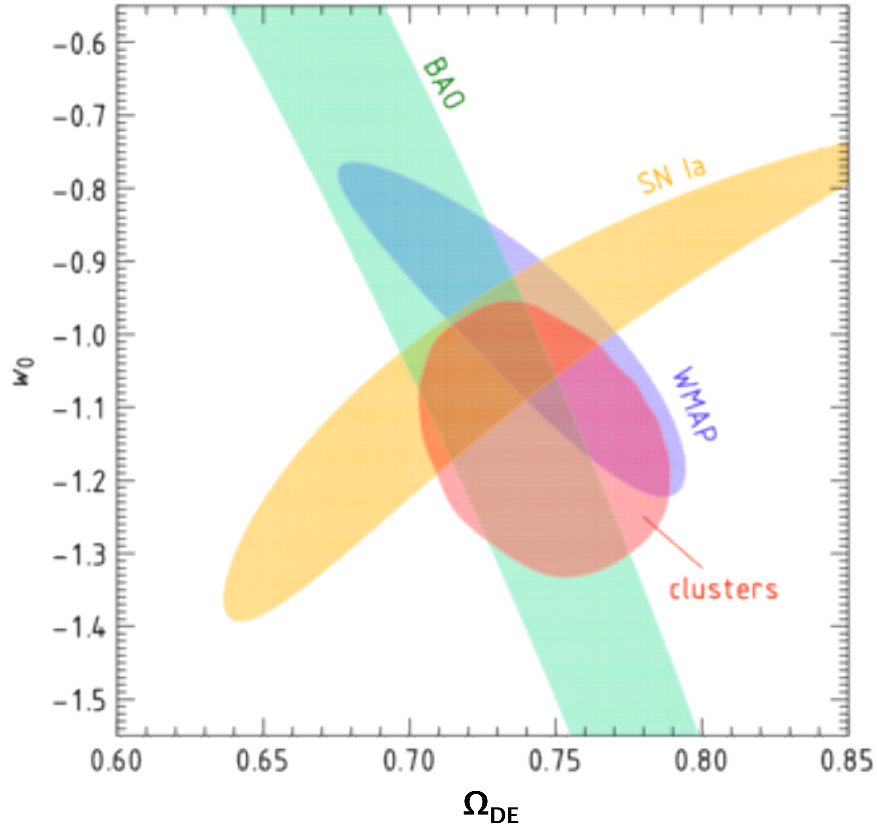


Complementary constraints on w-Ω_X from the evolution of cluster abundance

Local ($z<0.1$) sample of 49 clusters + 37 high-z clusters from the 400d X-ray selected cluster sample (http://hea-www.harvard.edu/400d/)



Mass within radius enclosing overdensity of 500 times the critical density $\rho_{crit}(z)$

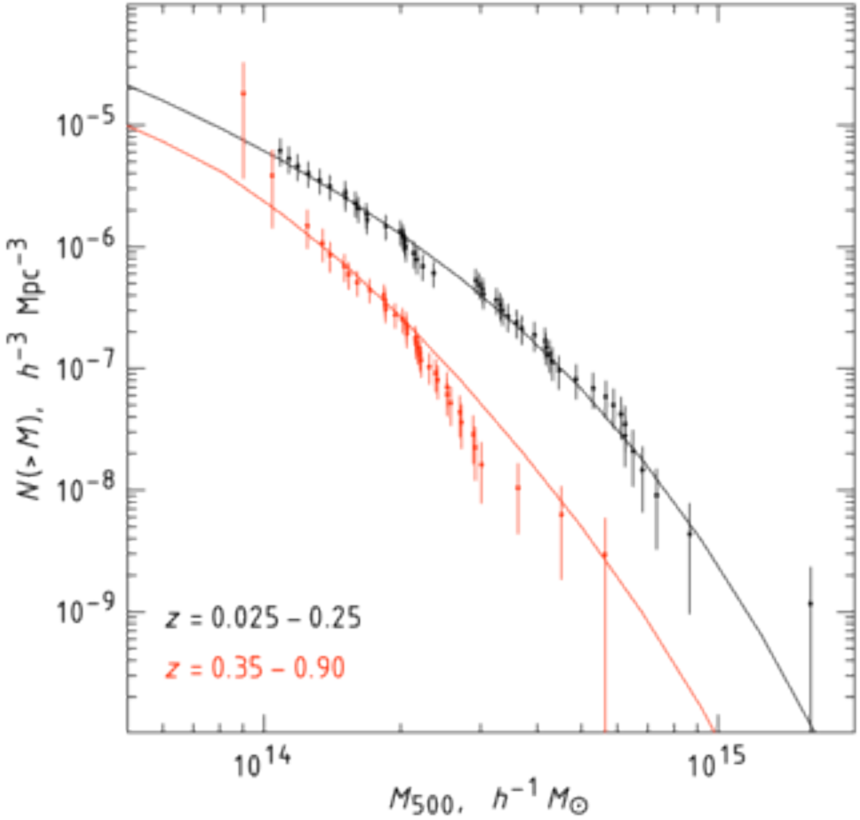


Contribution of dark energy to the energy-density of the universe in units of the critical density

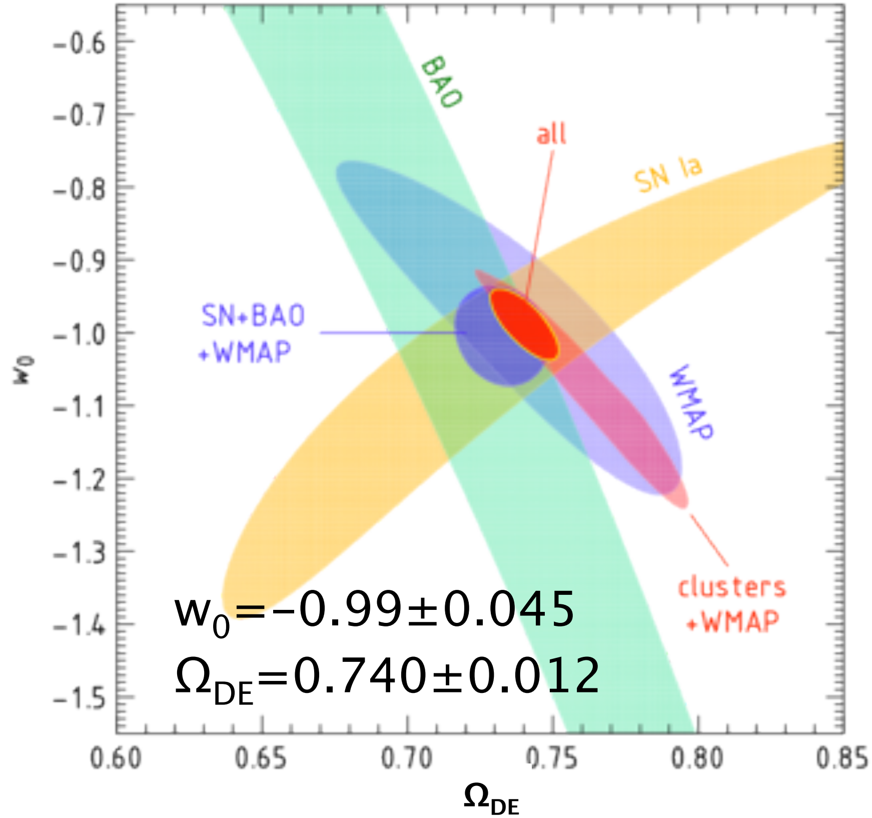
Equation of state of dark energy: $p=w_0\rho$

Complementary constraints on w_0-Ω_X from the evolution of cluster abundance

Local ($z<0.1$) sample of 49 clusters + 37 high-z clusters from the 400d X-ray selected cluster sample (http://hea-www.harvard.edu/400d/)



Mass within radius enclosing overdensity of 500 times the critical density $\rho_{crit}(z)$

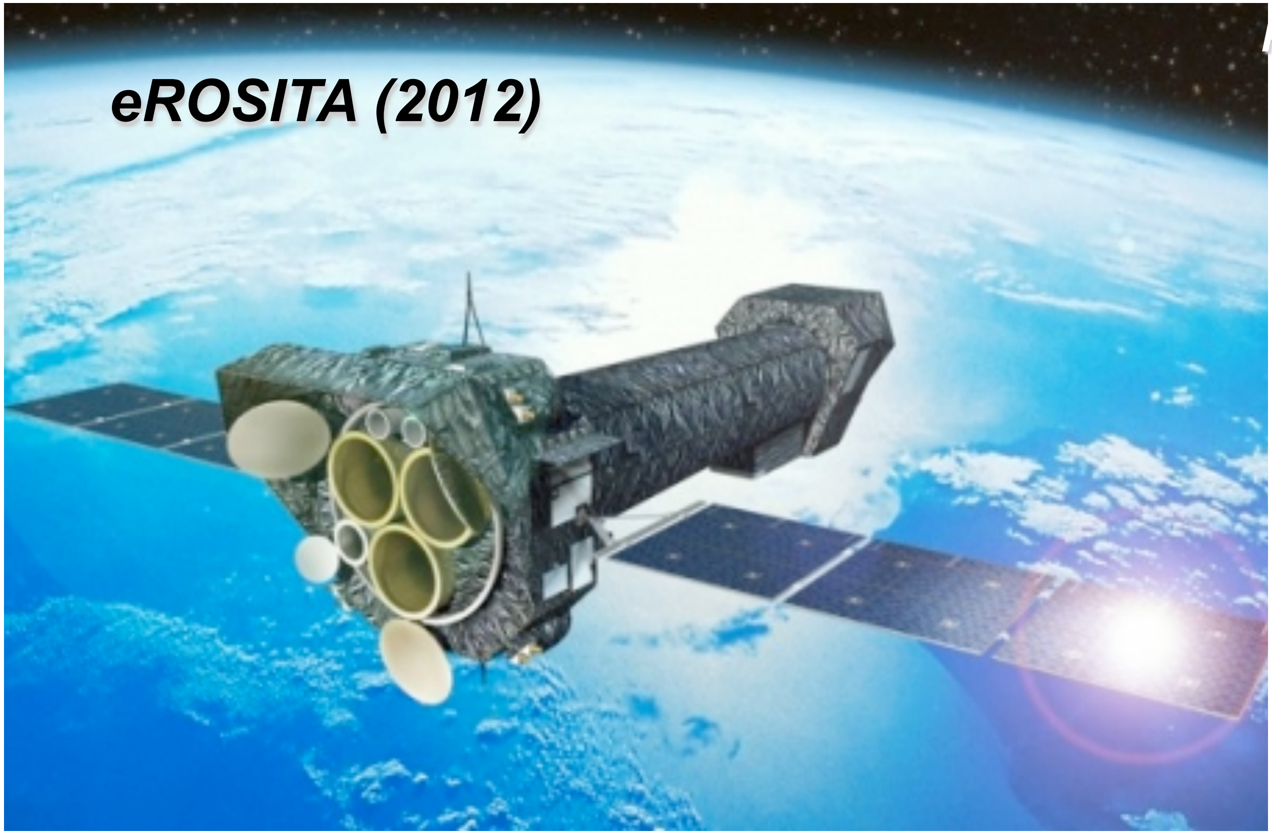


Contribution of dark energy to the energy-density of the universe in units of the critical density

Equation of state of dark energy: $p=w_0\rho$

Next-generation X-ray mission

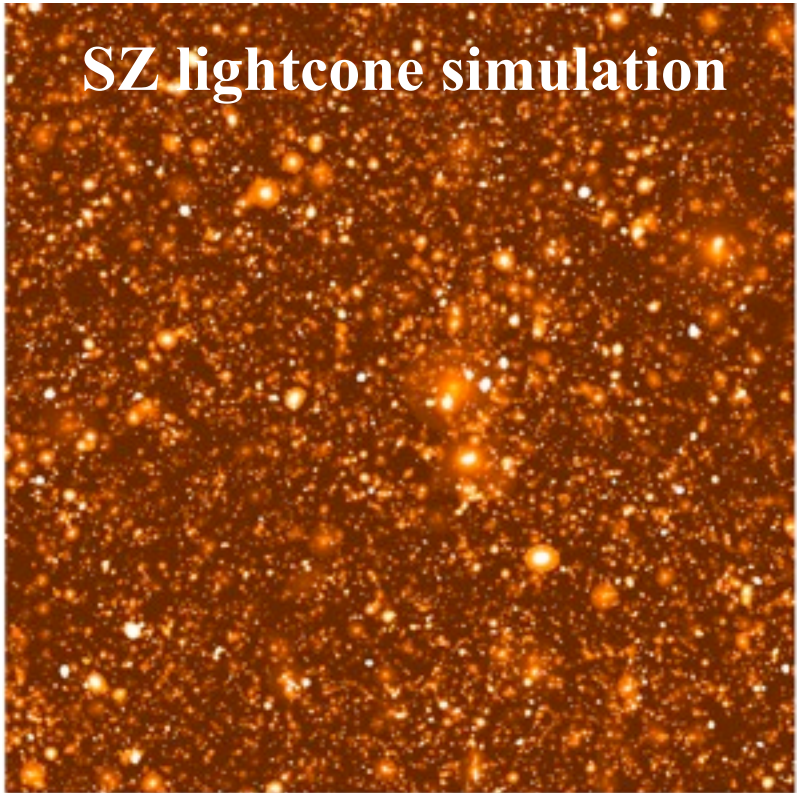
Planck



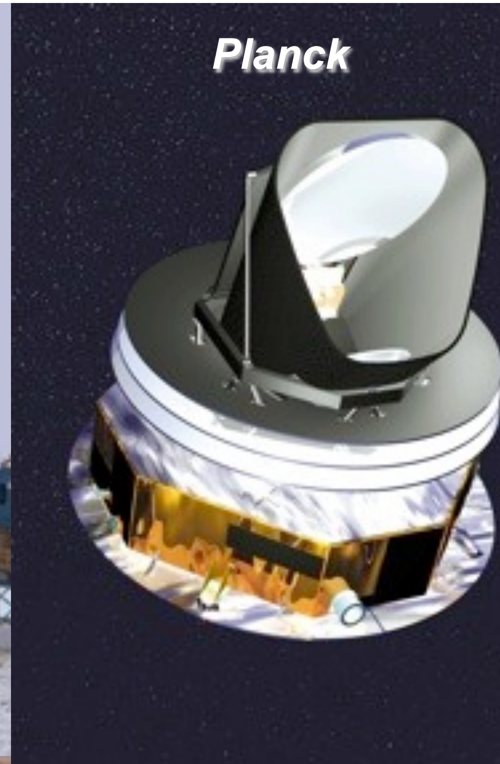
All-sky survey for 4yrs + targeted obs.
Science Goals: Study the LSS and Dark Energy
50-100,000 clusters up to z~1.3
A_{eff}~1500 cm^2 @ 1.5keV; Θ_{eff}~25-40 arcsec

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



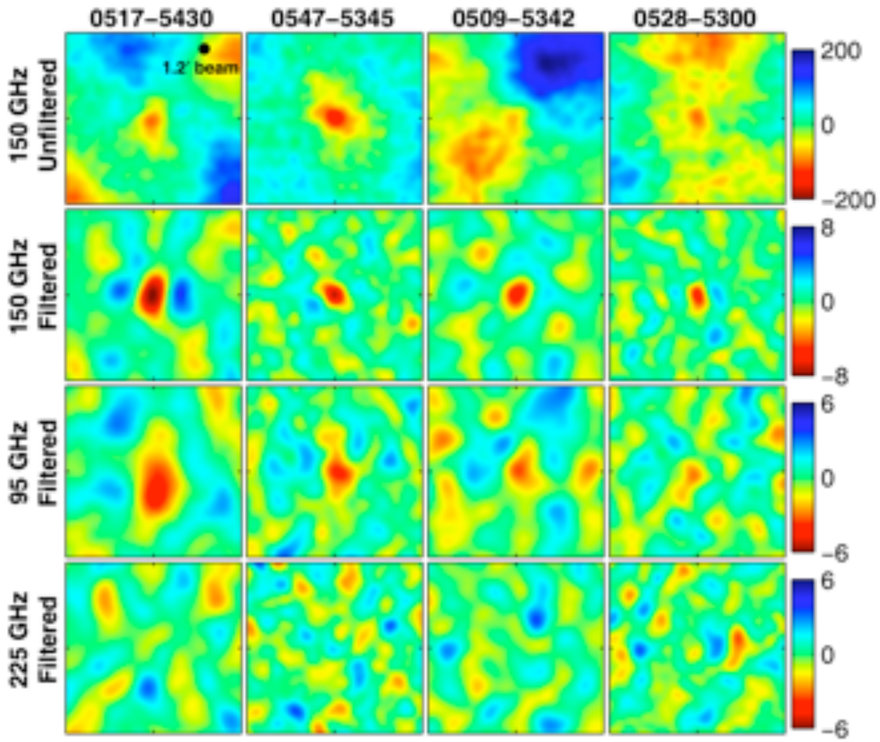
10 degree



Cosmology with Sunyaev-Zel'dovich Effect

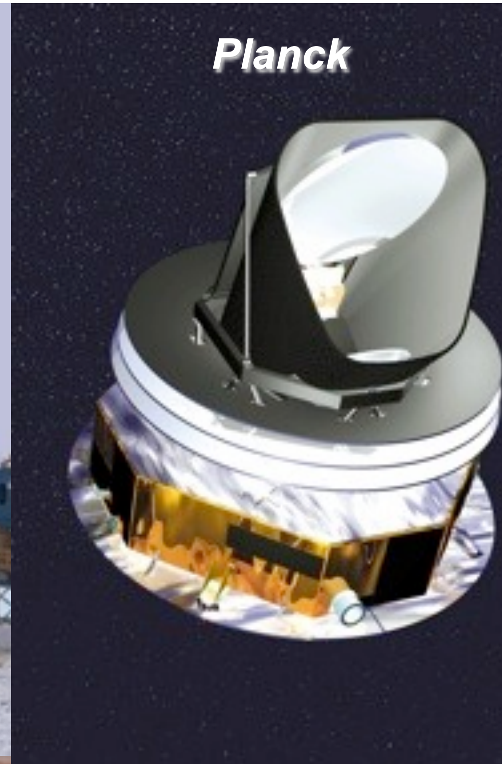
Ongoing SZE cluster surveys will produce large statistical samples, including AMI, AMiBA, APEX, SZA to ACT, Planck, and SPT

SZE is independent of redshift



Galaxy Clusters discovered with the SPT

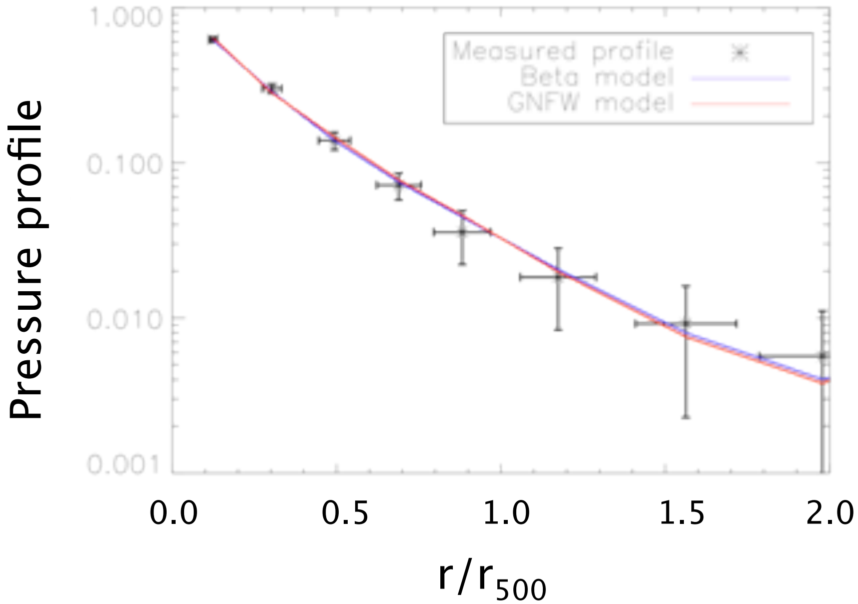
Staniszewski et al. 2008



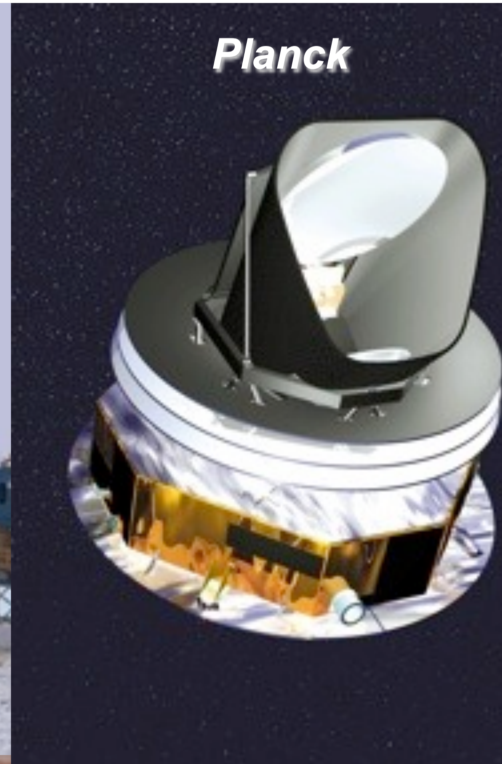
Cosmology with Sunyaev-Zel'dovich Effect

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

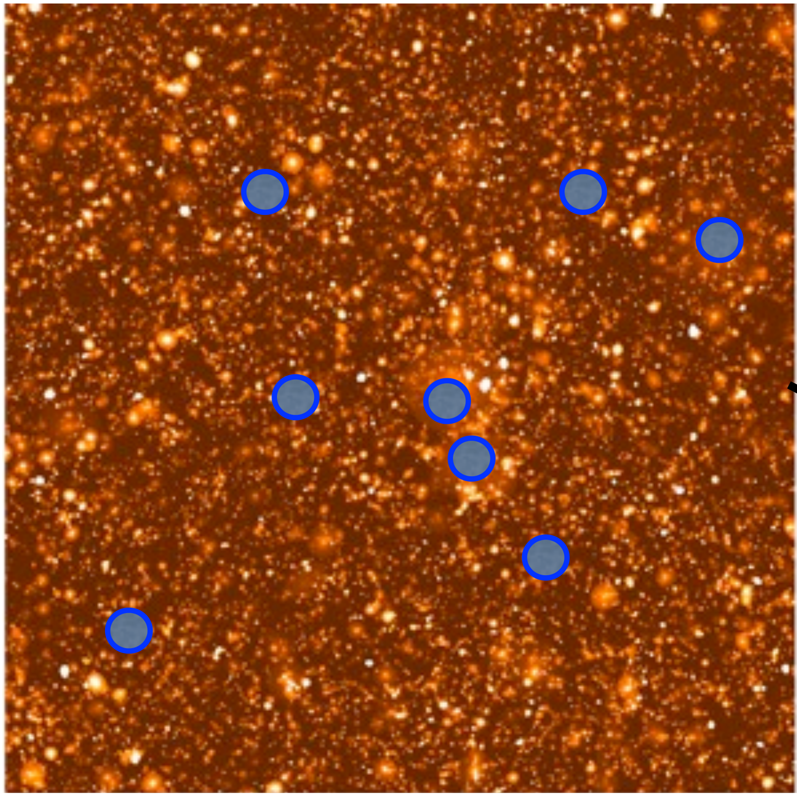
SPT measurements of cluster gas out to virial radius!



Plagge et al. 2009
astro-ph/0911.2444

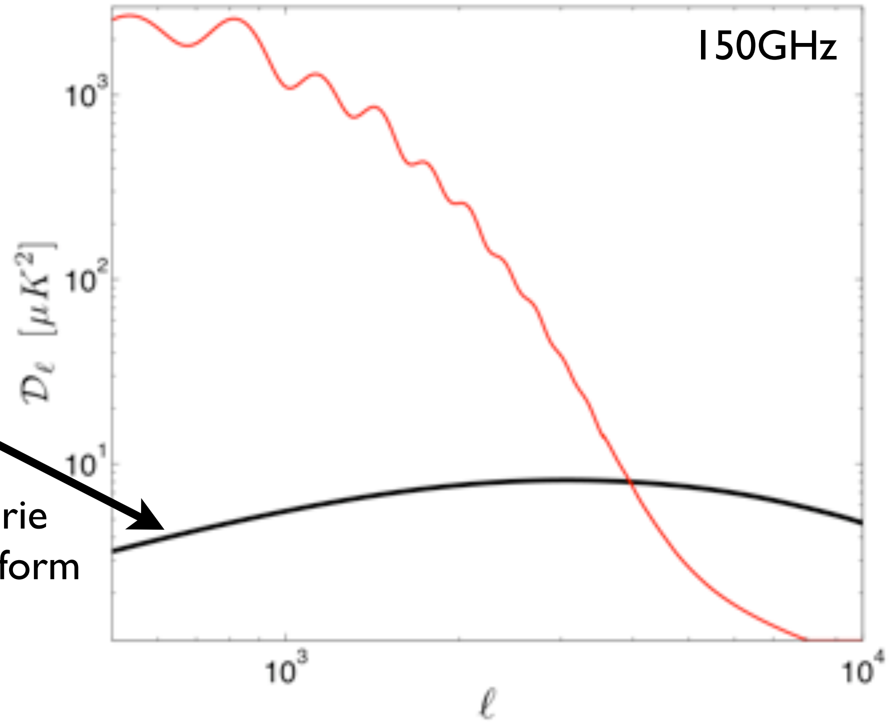


Statistical detection of SZE by searching for anisotropy power at small angular scales



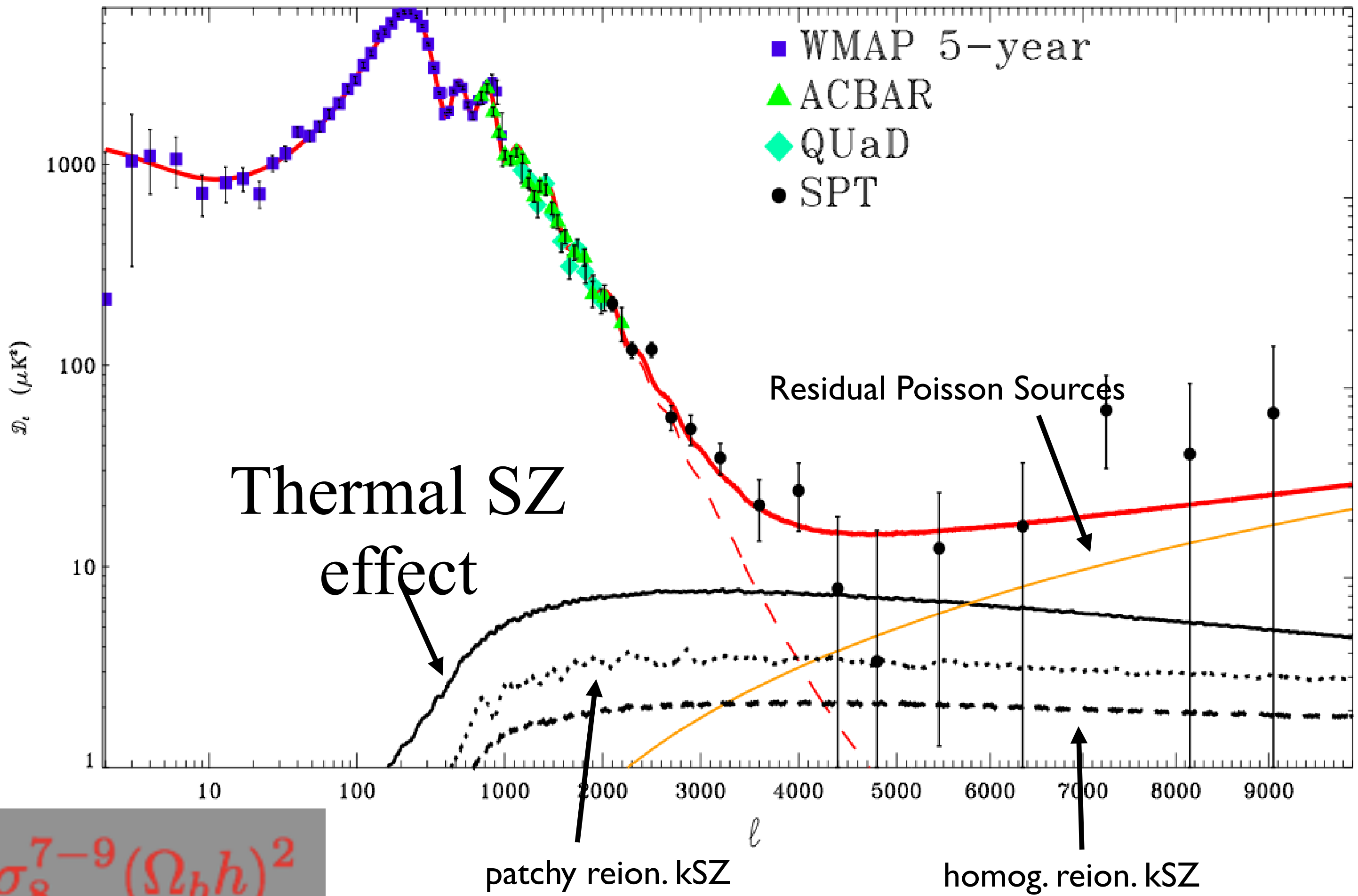
10 degree

Fourie
Transform



$$D_l = l\,(l+1)\ C_l\ /\ 2\ \pi$$

Measurements of SZ power spectrum

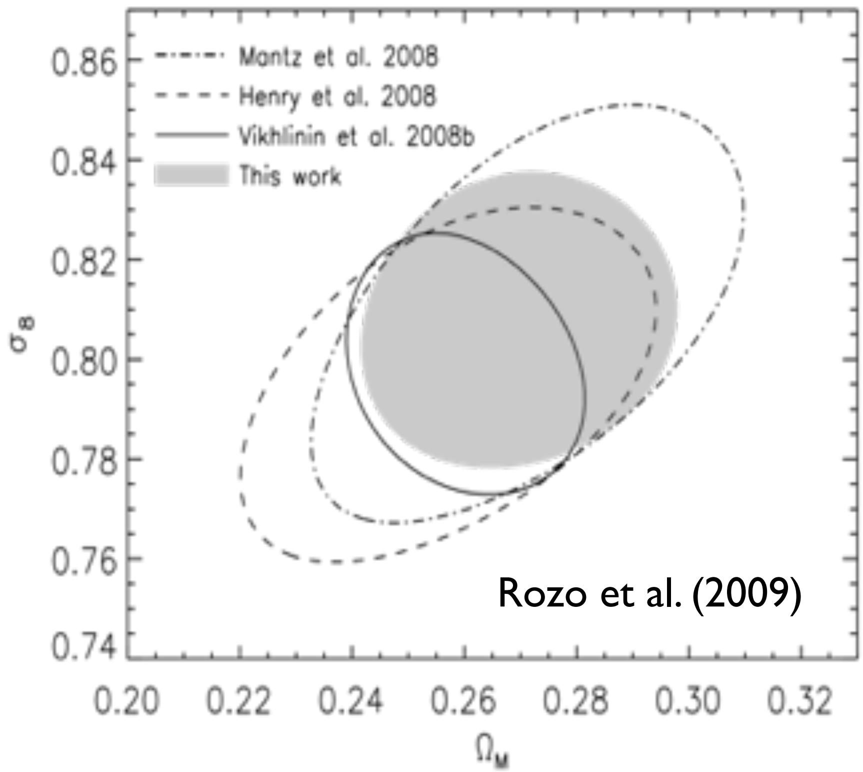


$$C_\ell \propto \sigma_8^{7-9}(\Omega_b h)^2$$

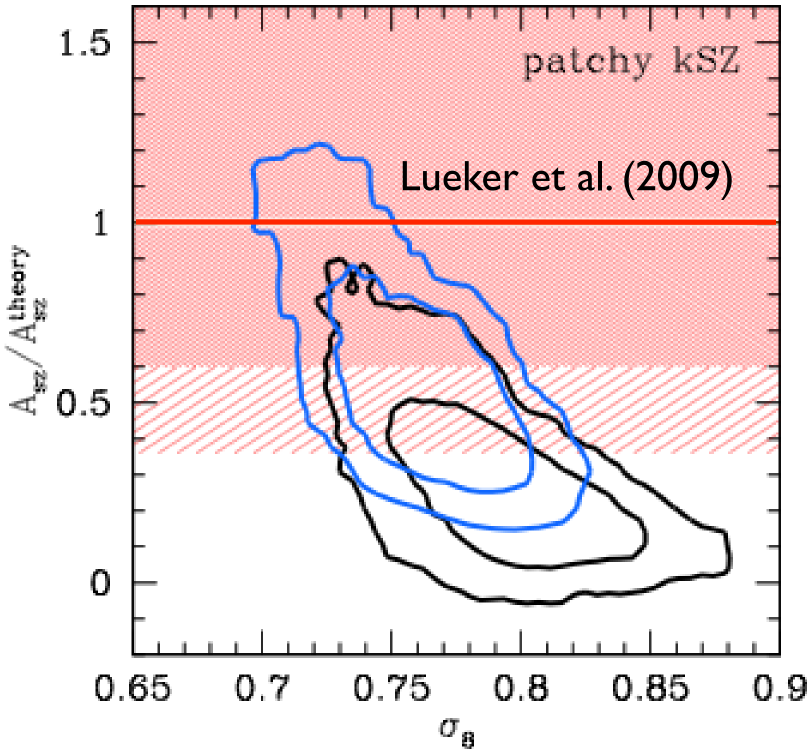
Amplitude of SZ power spectrum has very sensitive dependence on matter power spectrum normalization, σ_8

Tension in σ_8 measurements

Cluster Abundance



SZ power spectrum



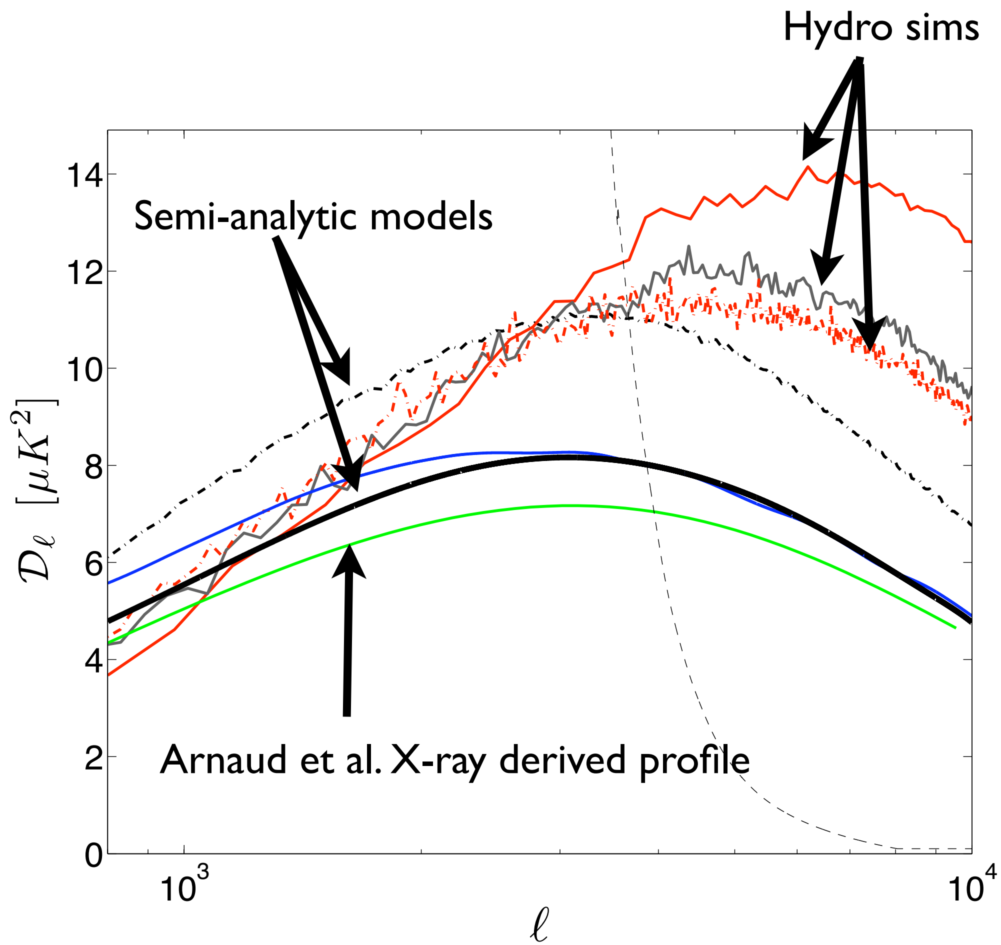
$\sigma_8 = 0.80 \pm 0.02$

$\sigma_8 = 0.746 \pm 0.017$

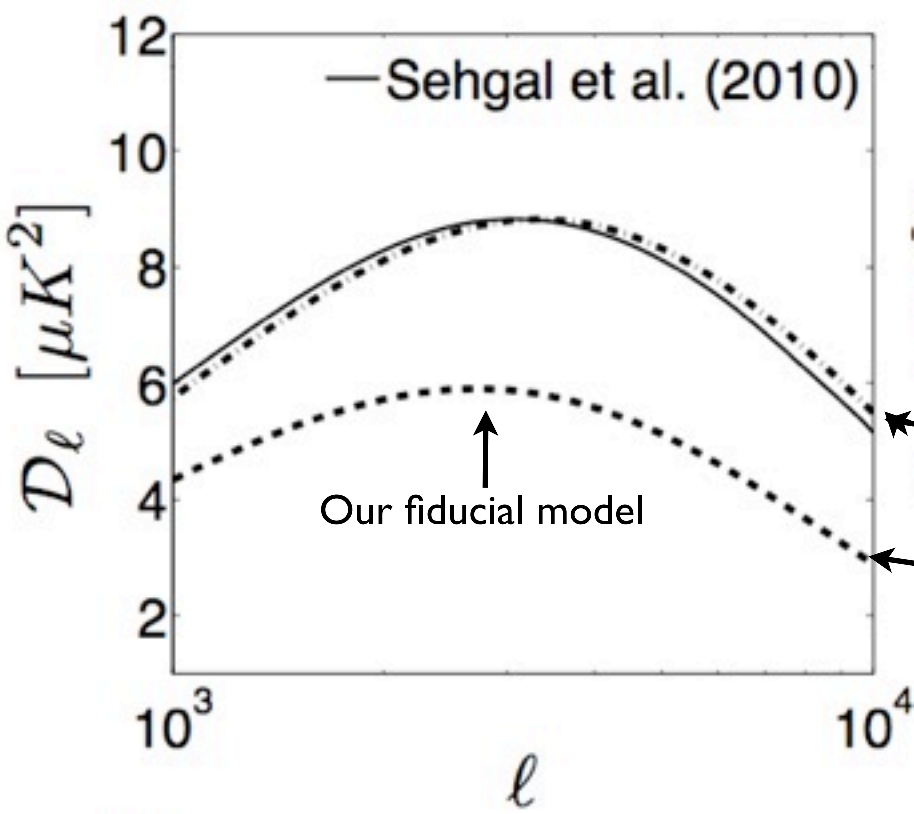
In tension at 3σ level!

Gastrophysical Uncertainty

- Thermal SZ power spectrum contains significant contribution from outskirts of low mass ($M<3x10^{14}$ Msun), high-z (z>1) groups at l~3000
- However, high-redshift groups are poorly studied observationally.
- Impact of star-formation, AGN, SNe, difficult to evaluate.
- Additional effects not incorporated in semi-analytic models (e.g. bulk and turbulent motions)



Impact of Cluster Physics on the SZ power spectrum



Non-thermal pressure causes reduction of power by 50-60% at all scales.

No non-thermal pressure. This is a template used in current SPT and ACT analyses

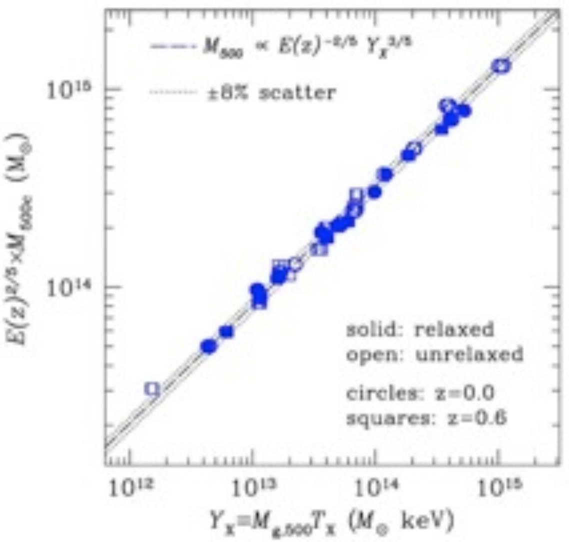
Our new model with non-thermal pressure profile

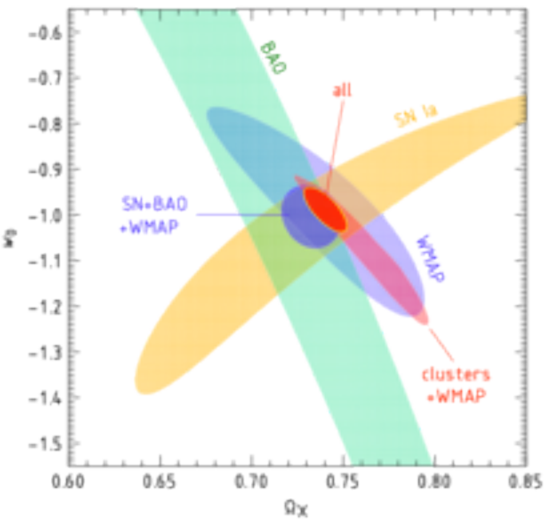
Current SZ template is overpredicting the amplitude by 50-100%!!

Missing Physics: Gas Motions and Energy Feedback in Groups and Clusters

L. Shaw, DN, S. Bhattacharya, E. Lau, astro-ph/1006.1945 (last month!)

Recent Advances & Current Status





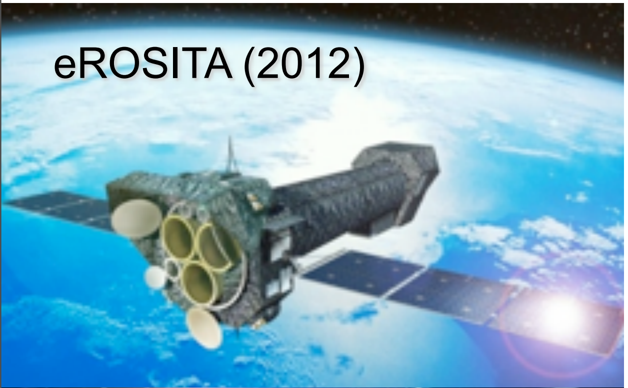
- *Outside the cores intracluster medium exhibits tight scaling relations between observable quantities and total gravitating mass, consistent with predictions of the simplest self-similar models*

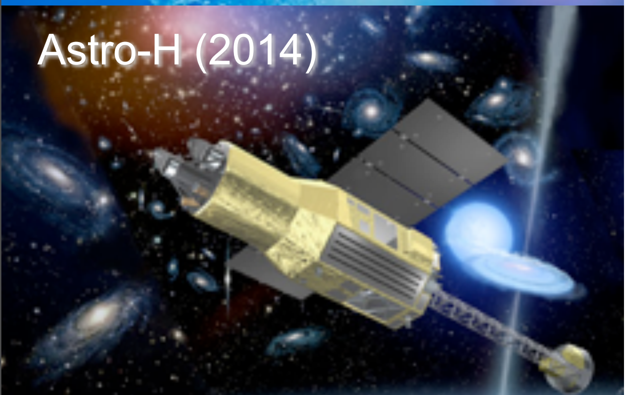
- *The tight relations between observables and cluster mass allow us to use evolution of cluster abundance to derive constraints on spectrum normalization, mean matter density, and the expansion history of the universe and dark energy.*

- *Current cluster samples provide independent confirmation of accelerating expansion of the universe at z<1 and complement other cosmological probes to tighten constraints on* w_0 *and* Ω_{DE}

$$\sigma_8 = 0.813(\Omega_M/0.25)^{-0.47} \pm 0.013$$
$$w_0 = -0.99 \pm 0.045$$
$$\Omega_{DE} = 0.740 \pm 0.012$$

Future Challenges & Prospects





- ***Main Challenges***
  - ***Calibrate observable-mass relation and its evolution to ~1-3%***
  - ***Mass function and spatial clustering (bias) must be calibrated to 1-2%***

- ***Future Prospects***
  - ***Upcoming cluster surveys will produce large statistical samples of galaxy clusters***
    - X-ray: *Astro-H, eROSITA, IXO*
    - SZE: *ACT, Planck, SPT*
    - *Optical: DES, LSST, HSC, SDSS, SuMIRe*
  - **Further advances in numerical simulations are also underway**
    - Large cosmological simulations with baryons
    - Detailed understanding of cluster gas physics (e.g., AGN feedback, turbulence, cosmic-rays, ICM plasma physics)