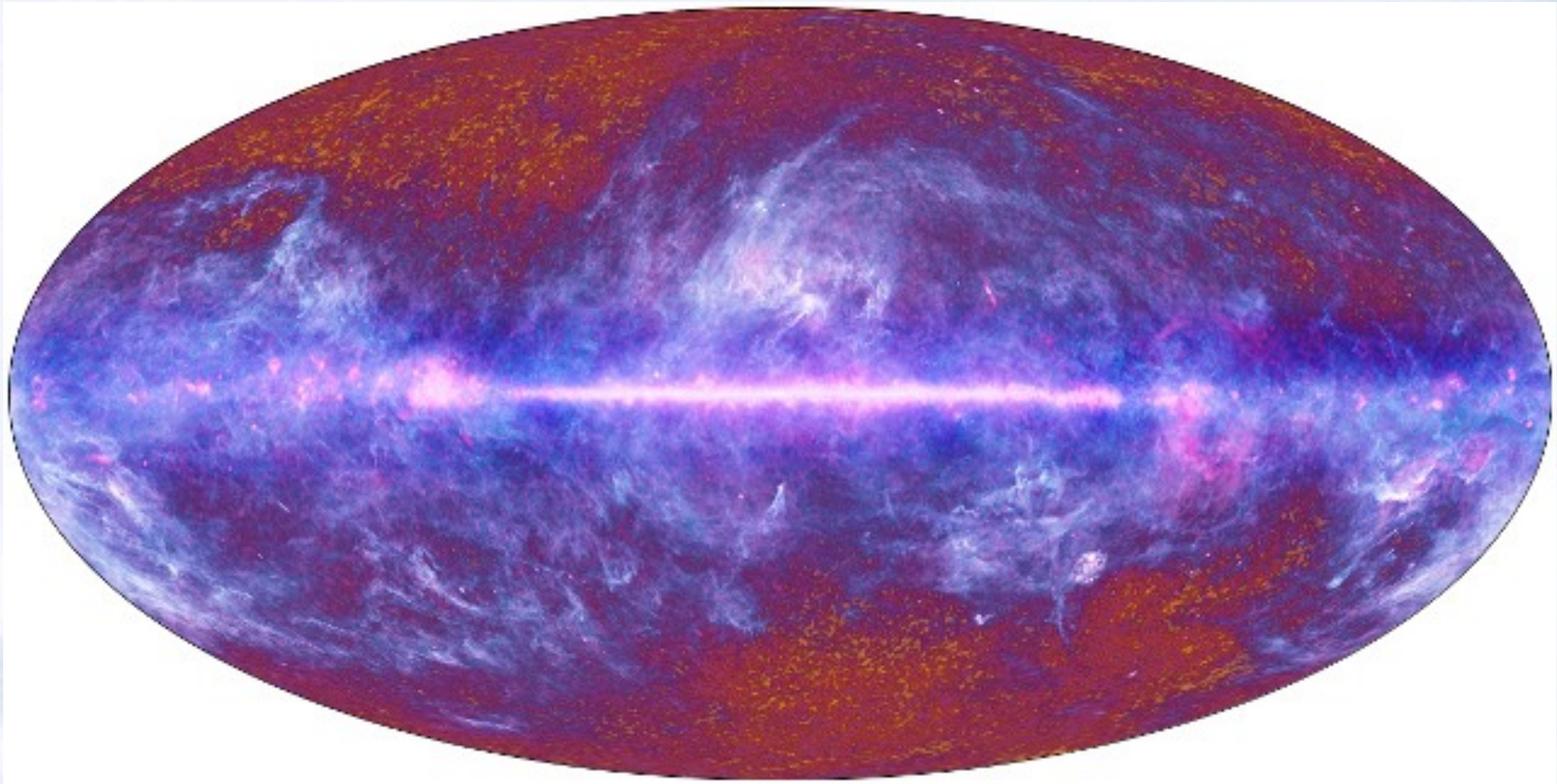
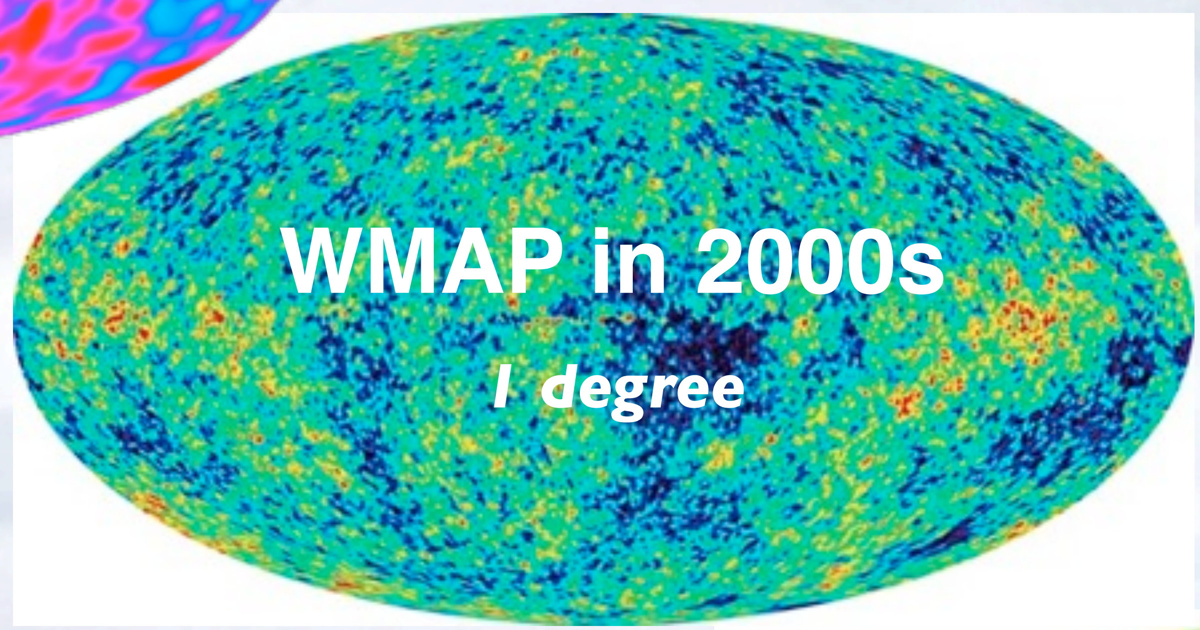
The SZ Power Spectrum:
New Crossroads of Cosmology & Astrophysics

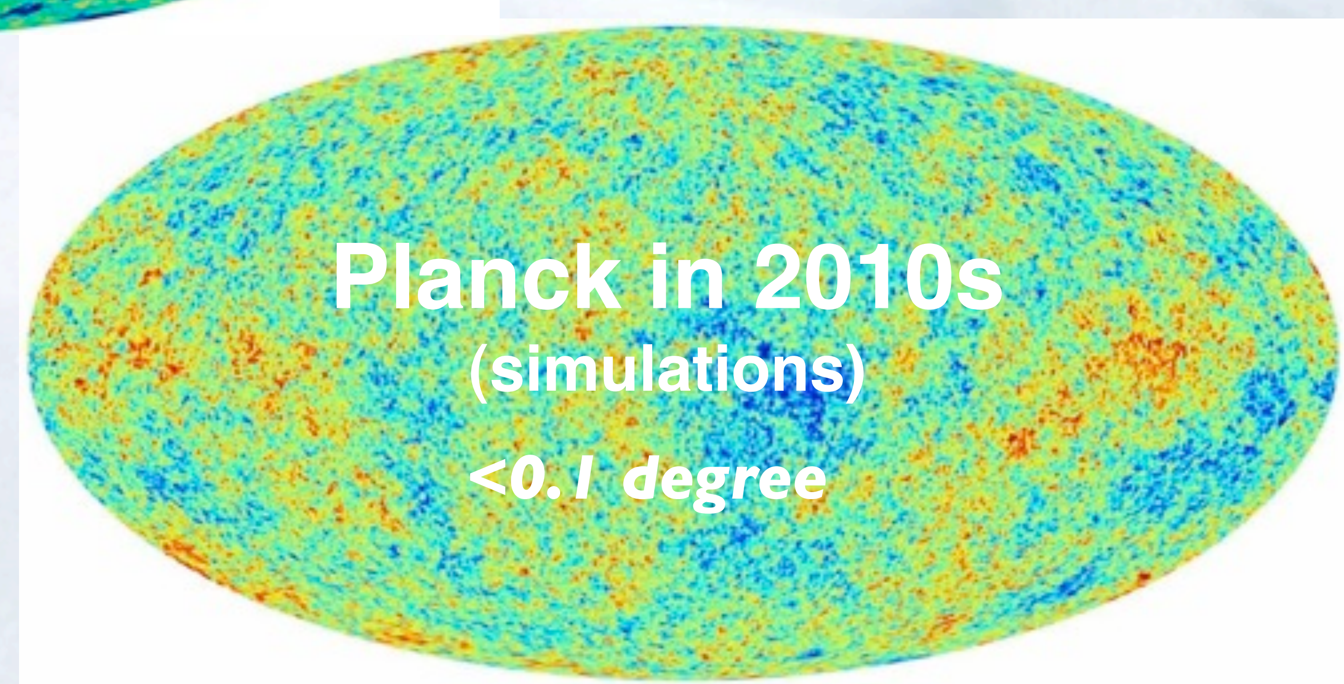


Daisuke Nagai
Yale University

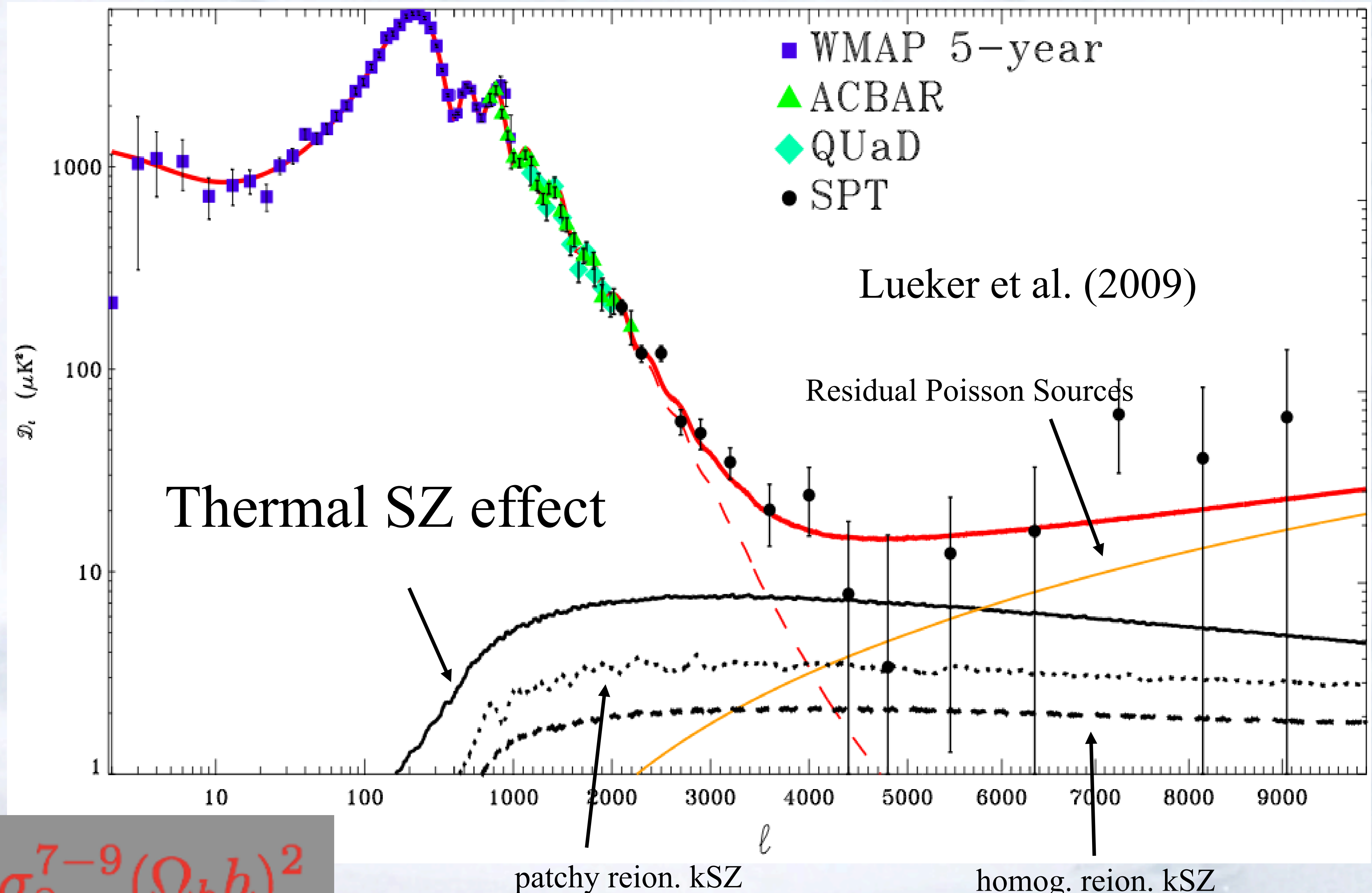
KITP, Santa Barbara
March 18, 2011

New Frontier in CMB research
toward smaller scales & higher sensitivities





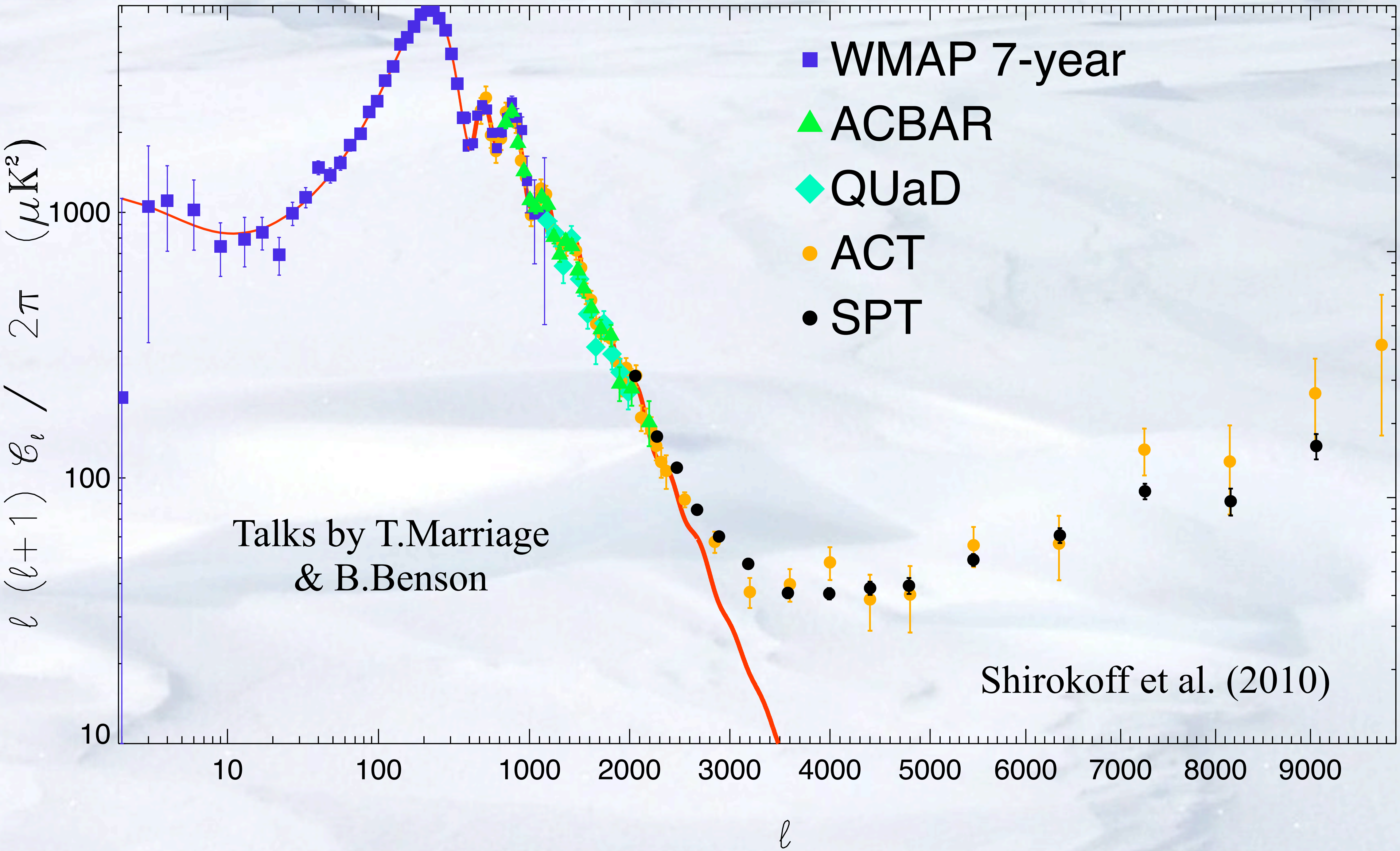
Measurements of the SZ power spectrum



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

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

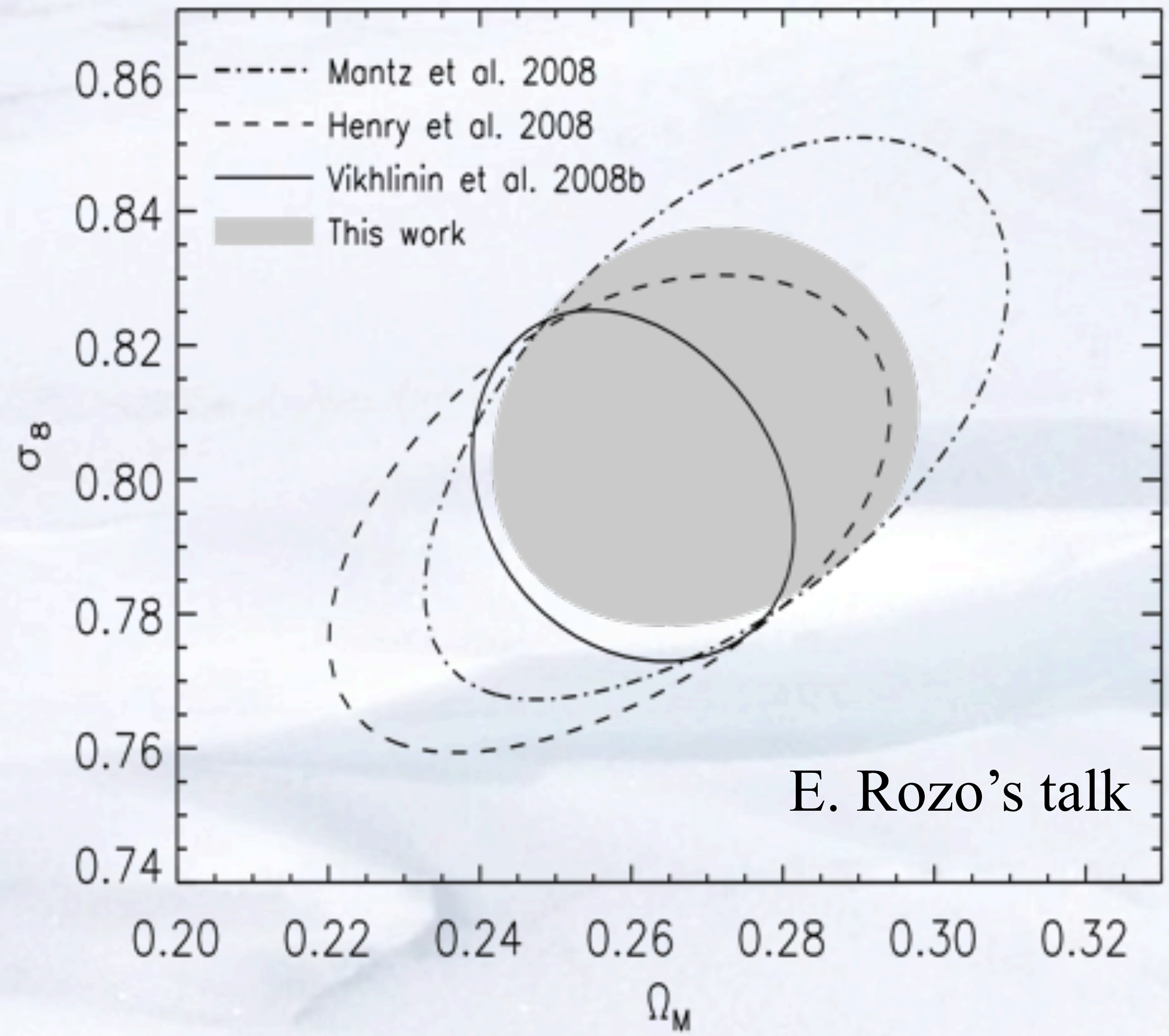
Measurements of the SZ power spectrum



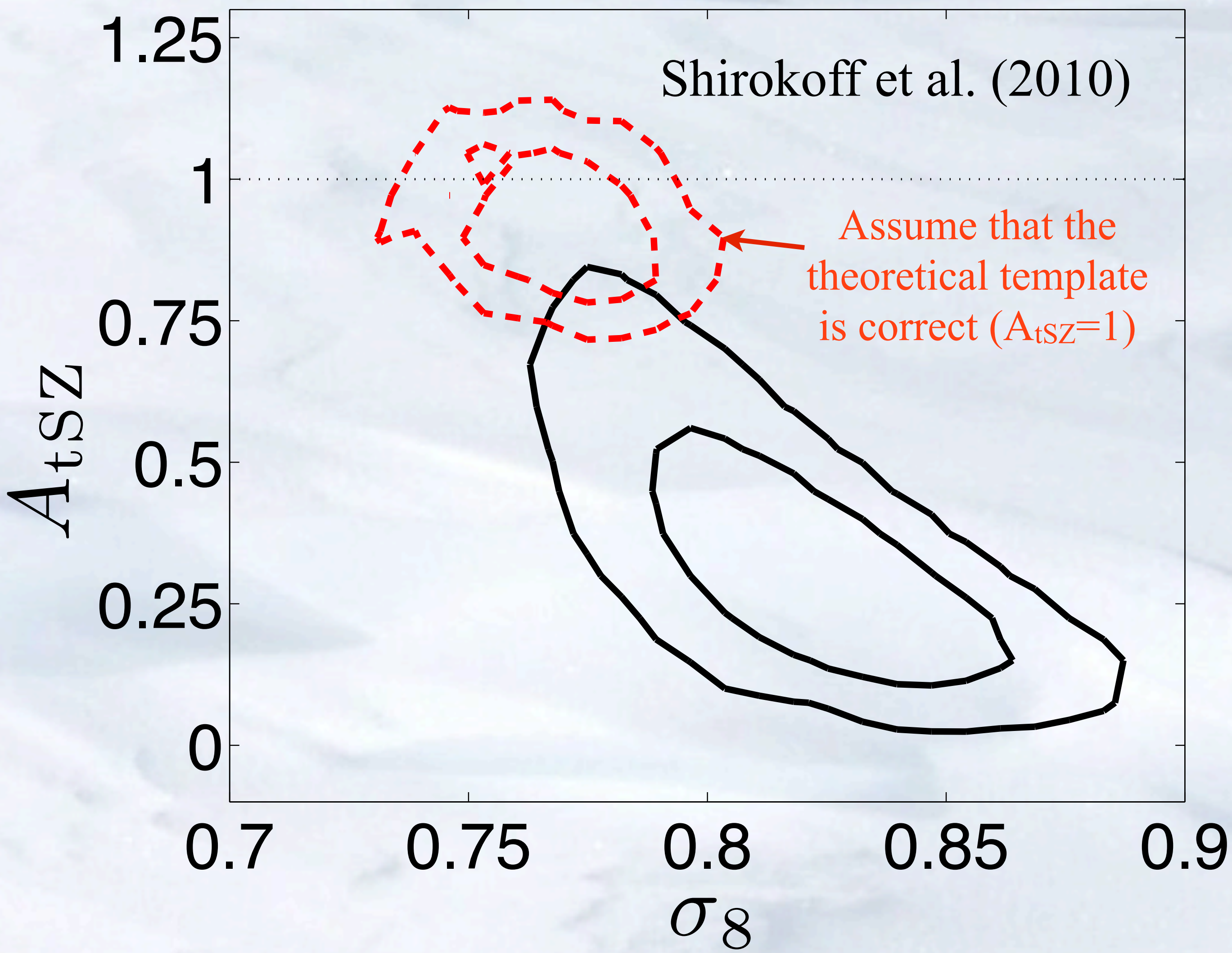
Amplitude of SZ power spectrum has very sensitive dependence on matter power spectrum normalization, σ_8

Tension in σ_8 measurements

Cluster Abundance



SZ power spectrum



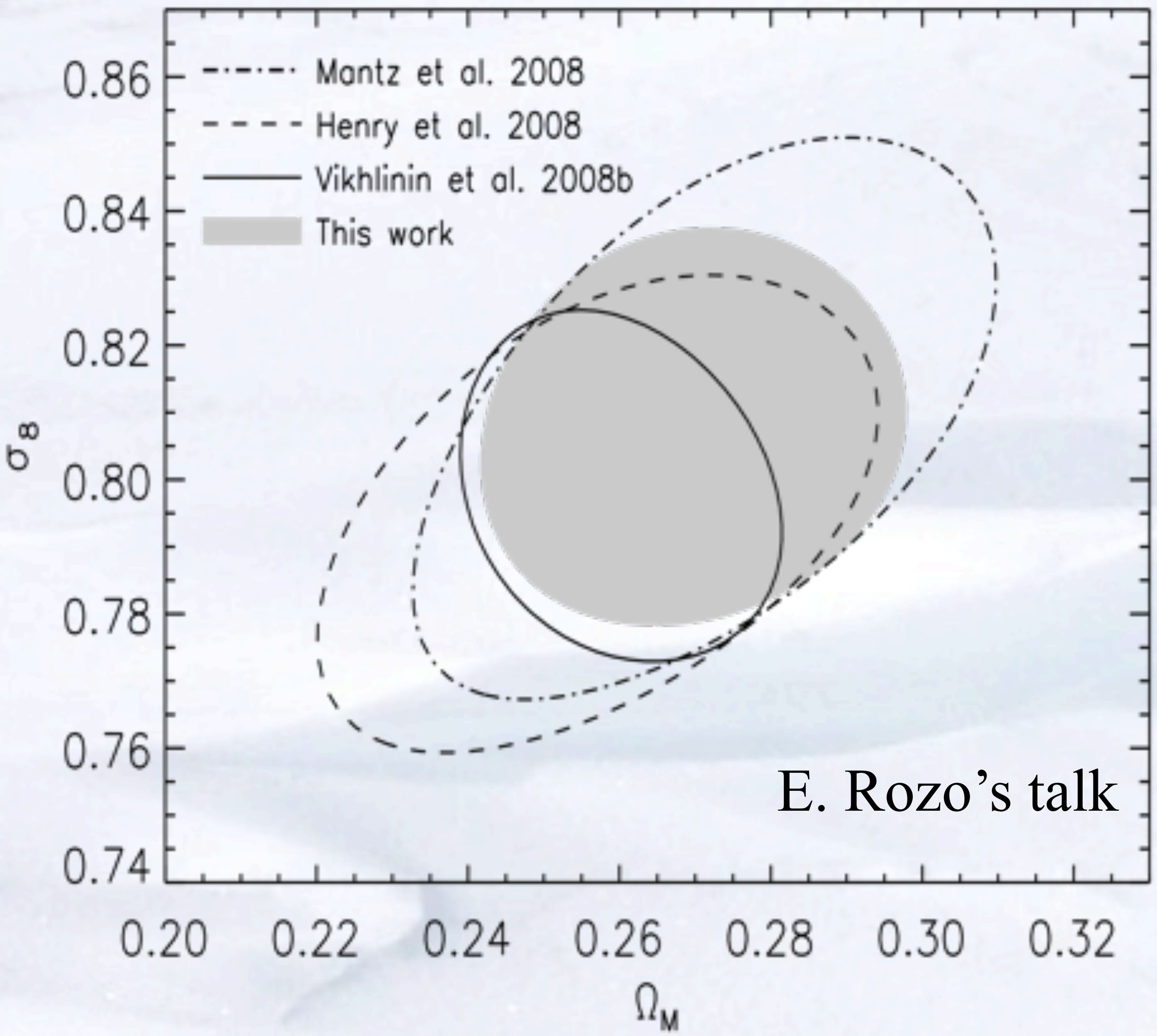
$\sigma_8 = 0.80 \pm 0.02$

$\sigma_8 = 0.771 \pm 0.013$

In tension at a few σ level?

Tension in σ_8 measurements

Cluster Abundance



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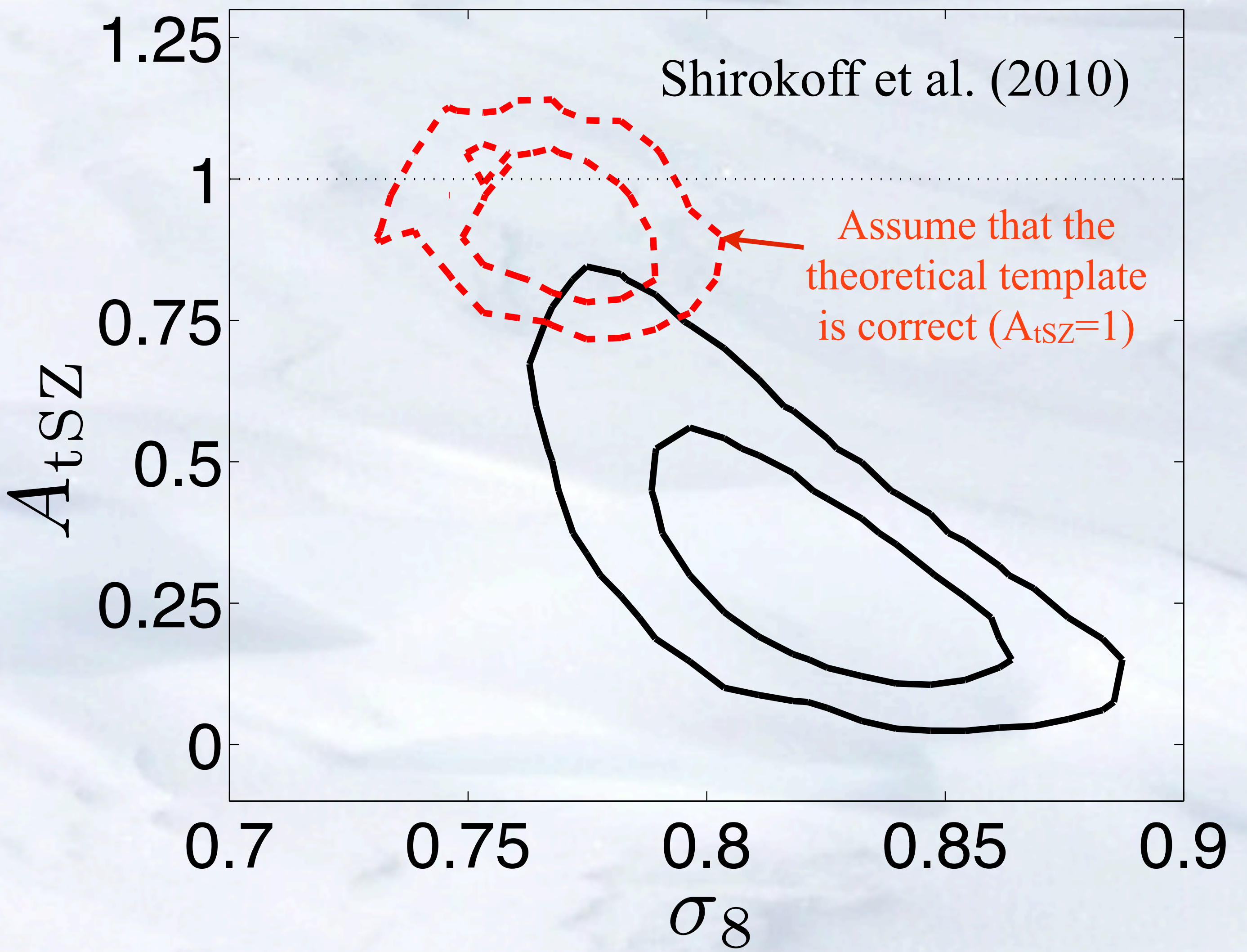
SZ power spectrum



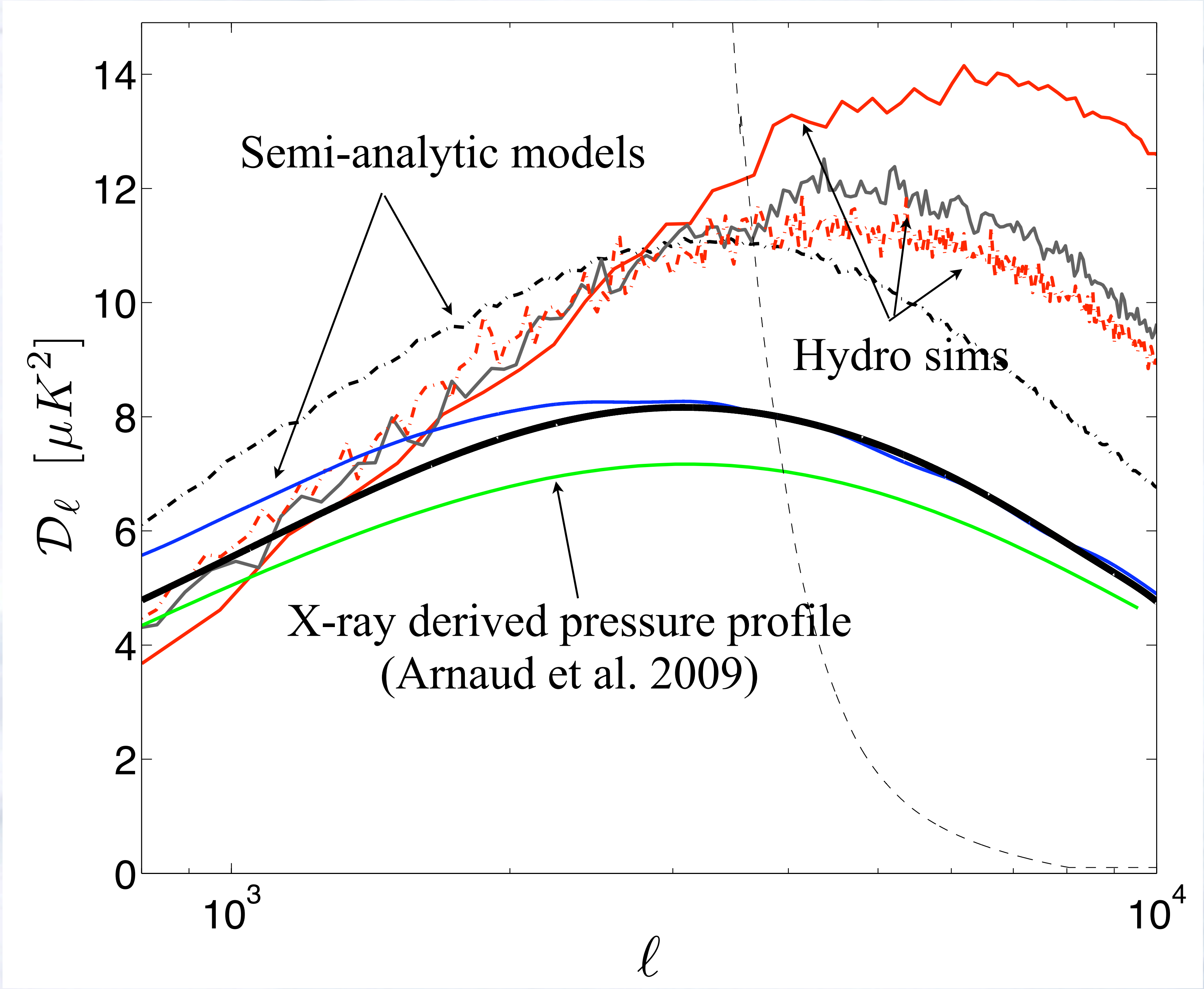
$\sigma_8 = 0.771 \pm 0.013$

I argue that the current SZ template is overpredicting the amplitude by 50-100%

Missing Key Physics: Gas Motions in Outskirts of Groups and Clusters

L. Shaw, D. Nagai, S. Bhattacharya, E. Lau, 2010, 725, 1452 (in December 2010 issue)

Astrophysical Uncertainty in the SZ power spectrum

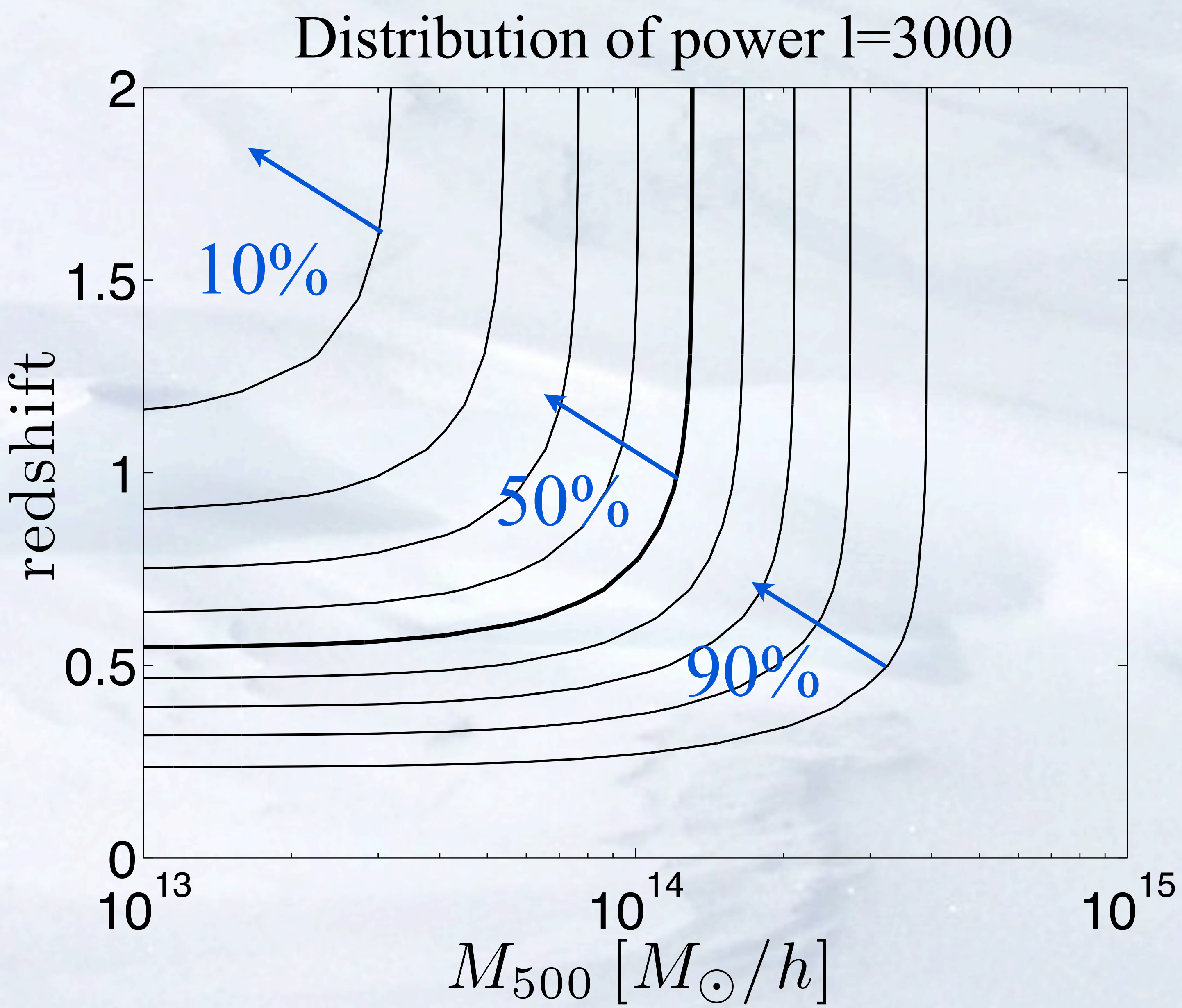


Current SZ theoretical template is uncertain by 100% due to poorly understood cluster astrophysics at high-z!!

Astrophysical Uncertainty in the SZ power spectrum

Where does the tSZ power come from?

- High-z groups are poorly studied observationally.
- Impact of star-formation, AGN, SNe, difficult to evaluate.
- Additional important effects not incorporated in semi-analytic models (e.g. gas motions in clusters)



Thermal SZ power spectrum contains significant contributions from outskirts of low mass ($M<2\times10^{14}$ Msun), high-z ($z>0.6$) groups at l~3000-5000

Predicting the SZ power spectrum

- Analytic calculations
  - take 'universal' mass function (e.g. Tinker et al. 08)
  - assume spherical gas pressure profiles (e.g. Komatsu and Seljak 02)
  - approximately capture cluster physics, but important for parameter estimation (need to vary both cosmology + cluster physics)

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

Cosmology — $\frac{\mathrm{d}V}{\mathrm{d}z}$, $\frac{\mathrm{d}n(M,z)}{\mathrm{d}M}$

Astrophysics — $|y_l(M,z)|^2$
electron pressure profile

- Numerical simulations
  - don't need to 'assume profiles'
  - follow detailed hydrodynamical evolution of gas in clusters (+ star-formation, AGN, bulk+turbulent gas motions...)
  - need both large simulation boxes and high-resolution to resolve relevant sub-grid cluster physics. **Prohibitably expensive!!**

Toward realistic cluster gas model

- Dark Matter Halos - NFW density profiles

$$c(M,z) = 7.85 A_C \left(\frac{M_{vir}}{2 \times 10^{12}\, h^{-1} M_{\odot}} \right)^{-0.081} (1+z)^{-0.71}$$

Duffy et al. 2008
$A_C = 1$

- Gas resides in hydrostatic equilibrium in dark matter halos

$$\frac{dP_{tot}(r)}{dr} = -\rho_g(r) \frac{d\Phi(r)}{dr}$$

- Polytropic equation of state for the ICM: $P_{tot}=P_0(\rho_{gas}/\rho_0)^{\Gamma}$ with $\Gamma=1.2$ and $P_{tot}(r)=P_{therm}(r)+P_{nt}(r)$

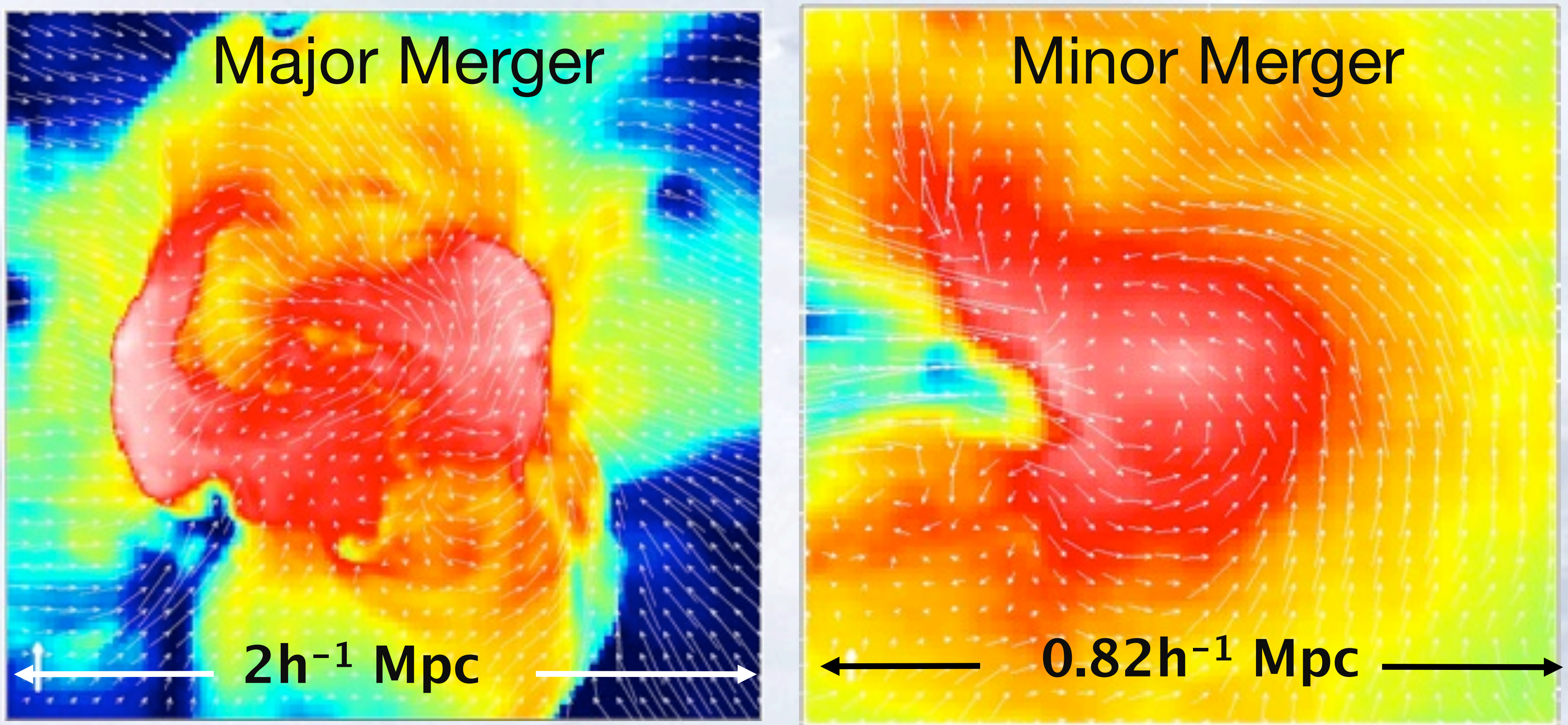
- Assume that some fraction of the gas has radiatively cooled and formed stars. Adopt the observed stellar mass fraction (Giodini et al. 2010).

c.f., Ostriker et al. 2005; Bode & Ostriker et al. 2007

Cluster Astrophysics

$$E_{g,f} = E_{g,i} + \epsilon_{\rm DM}|E_{DM}| + \epsilon_{\rm f} M_* c^2 + \Delta E_p$$

- Energy feedback from Supernovae/AGN: $\varepsilon_f \sim 10^{-6}$-$10^{-5}$
- Dynamical heating by mergers: $\varepsilon_{DM} \sim 0.05$
- Non-thermal pressure due to gas motions in galaxy clusters



Gas motions due to incomplete virialization are ubiquitous in ΛCDM clusters

Cluster Astrophysics

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- Energy feedback from Supernovae/AGN: $\varepsilon_f \sim 10^{-6}$-$10^{-5}$
- Dynamical heating by mergers: $\varepsilon_{DM} \sim 0.05$
- Non-thermal pressure support: α_0, β, n_{nt}

$$\frac{P_{nt}}{P_{tot}}(z) = \alpha(z)\left(\frac{r}{R_{500}}\right)^{n_{nt}}$$

where $\alpha(z)=\alpha_0(1+z)^\beta$

Calibrate with hydro simulations:

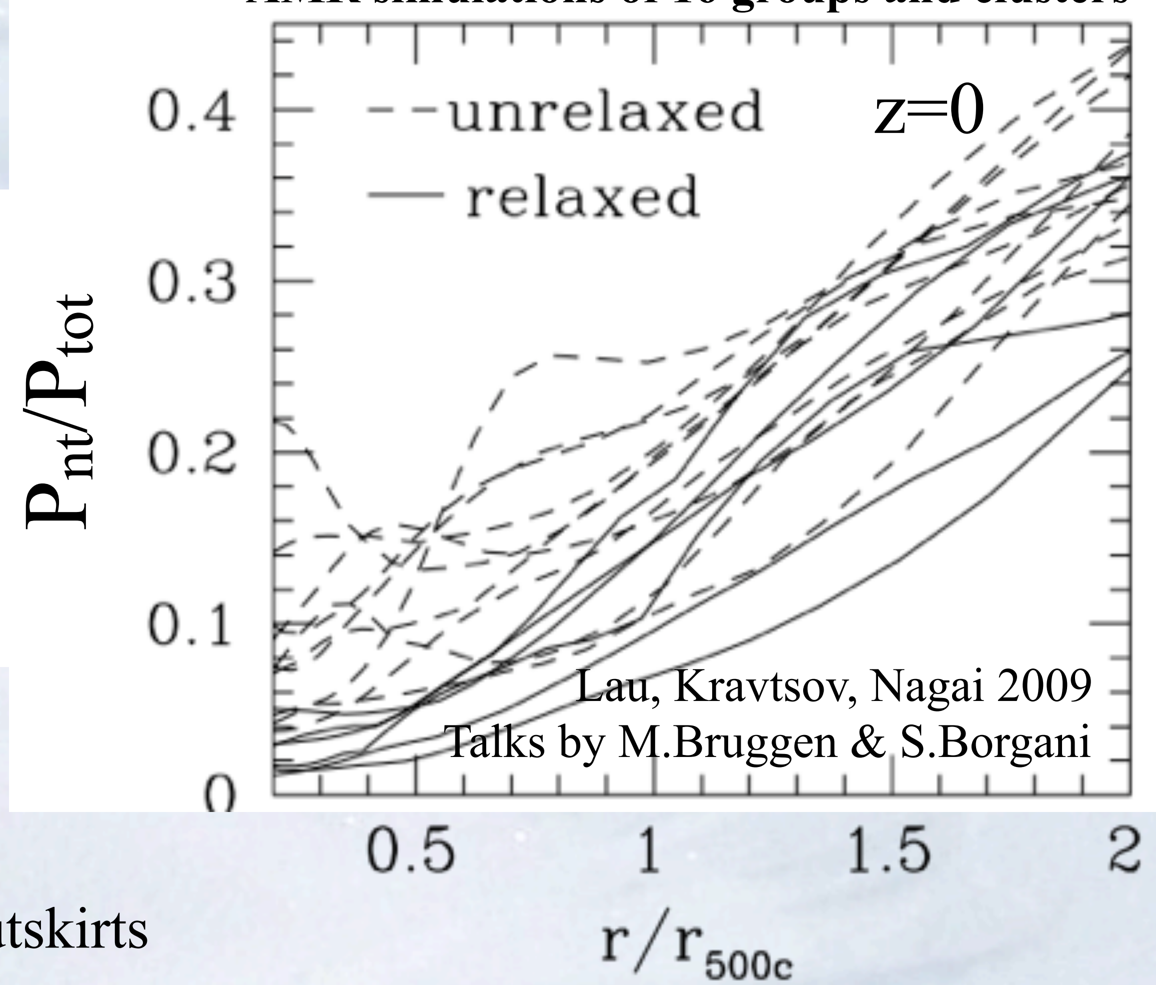
$\alpha_0=0.18$, $\beta=0.5$, $n_{nt}=0.8$

18% at R_{500} at z=0

enhanced at high-z

enhanced toward outskirts

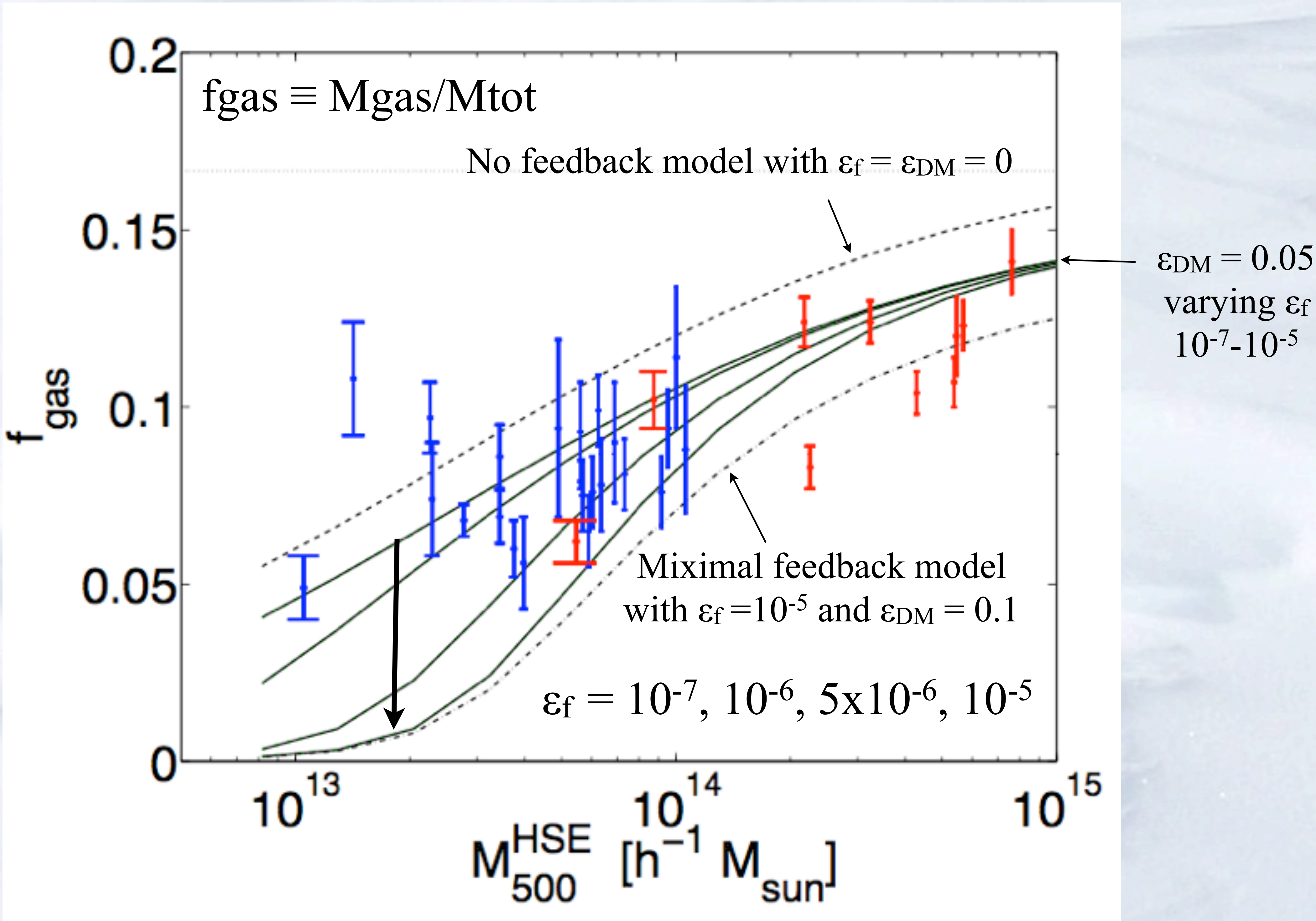
AMR simulations of 16 groups and clusters



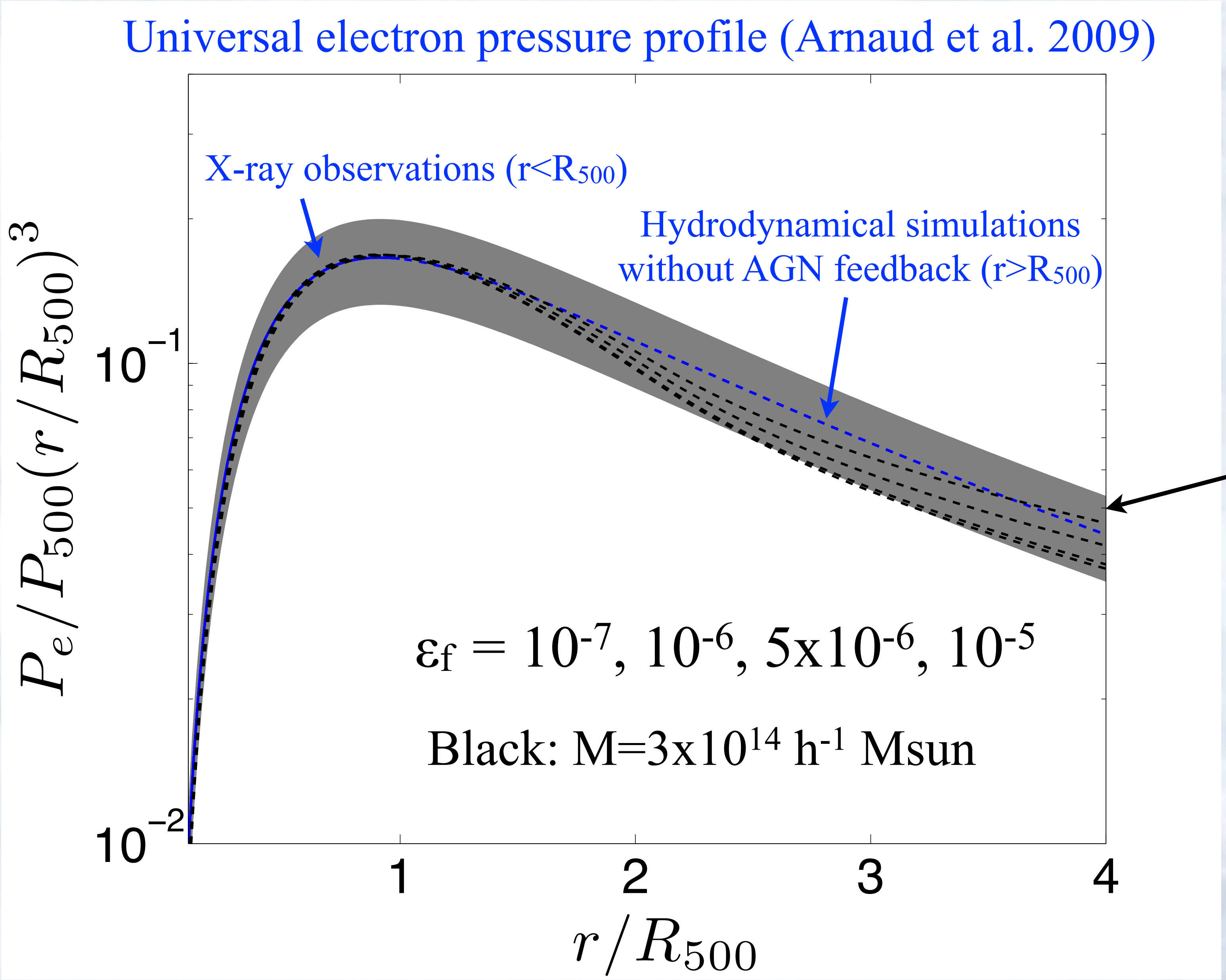
Astrophysical Parameters

	fiducial	min.	max.
energy feedback (ε_f)	10^{-6}	0	10^{-5}
dynamical heating (ε_{DM})	0.05	0	0.1
non-thermal amplitude (α_0)	0.18	0	0.3
non-thermal z-evolution (β)	0.5	-1	1
c_{DM}-M relation (A_C)	1.0 Duffy et al. 2008	0.8	1.2

Matching to fgas-M observations at z~0

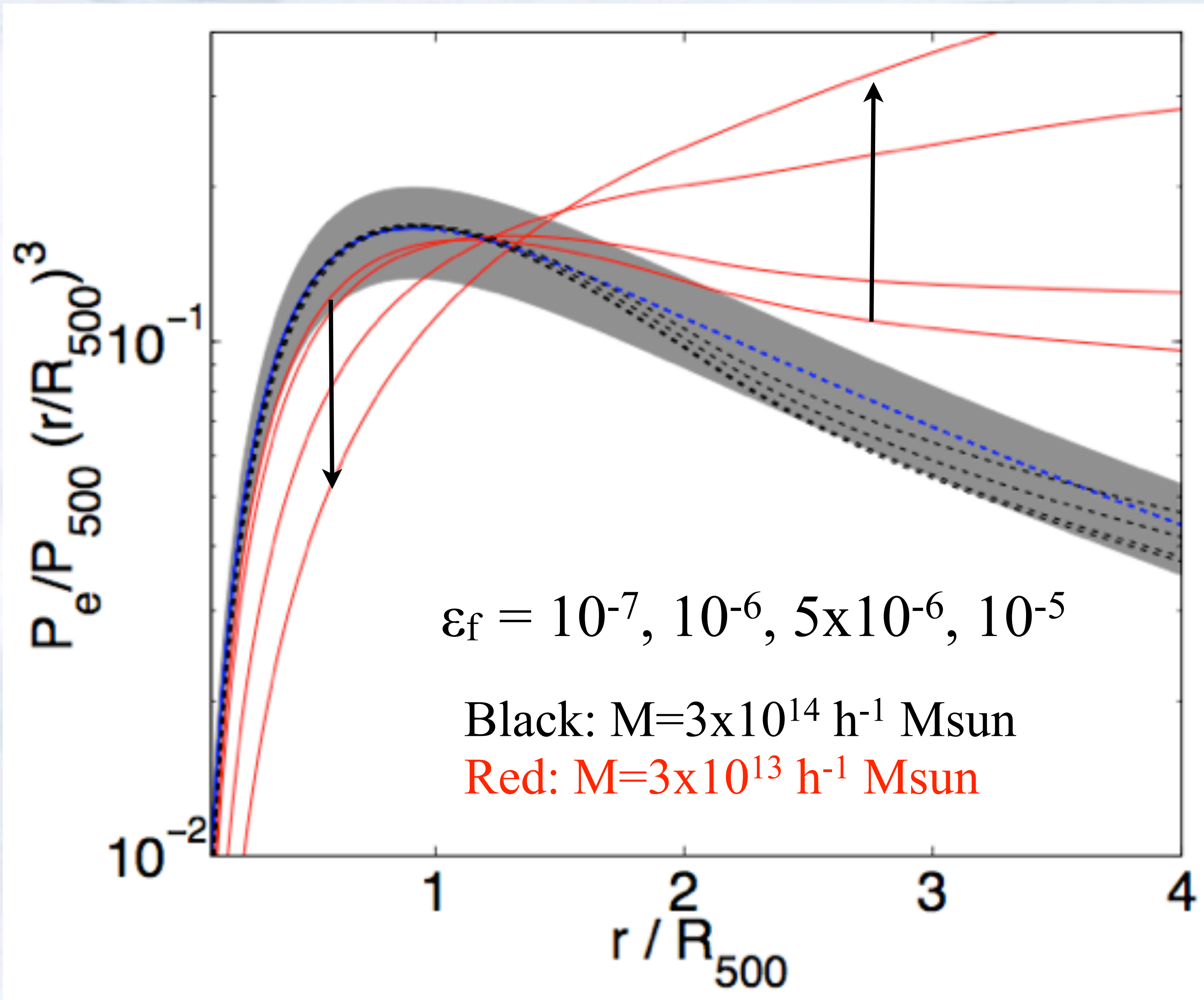


Impact of Energy Feedback on Pressure Profiles



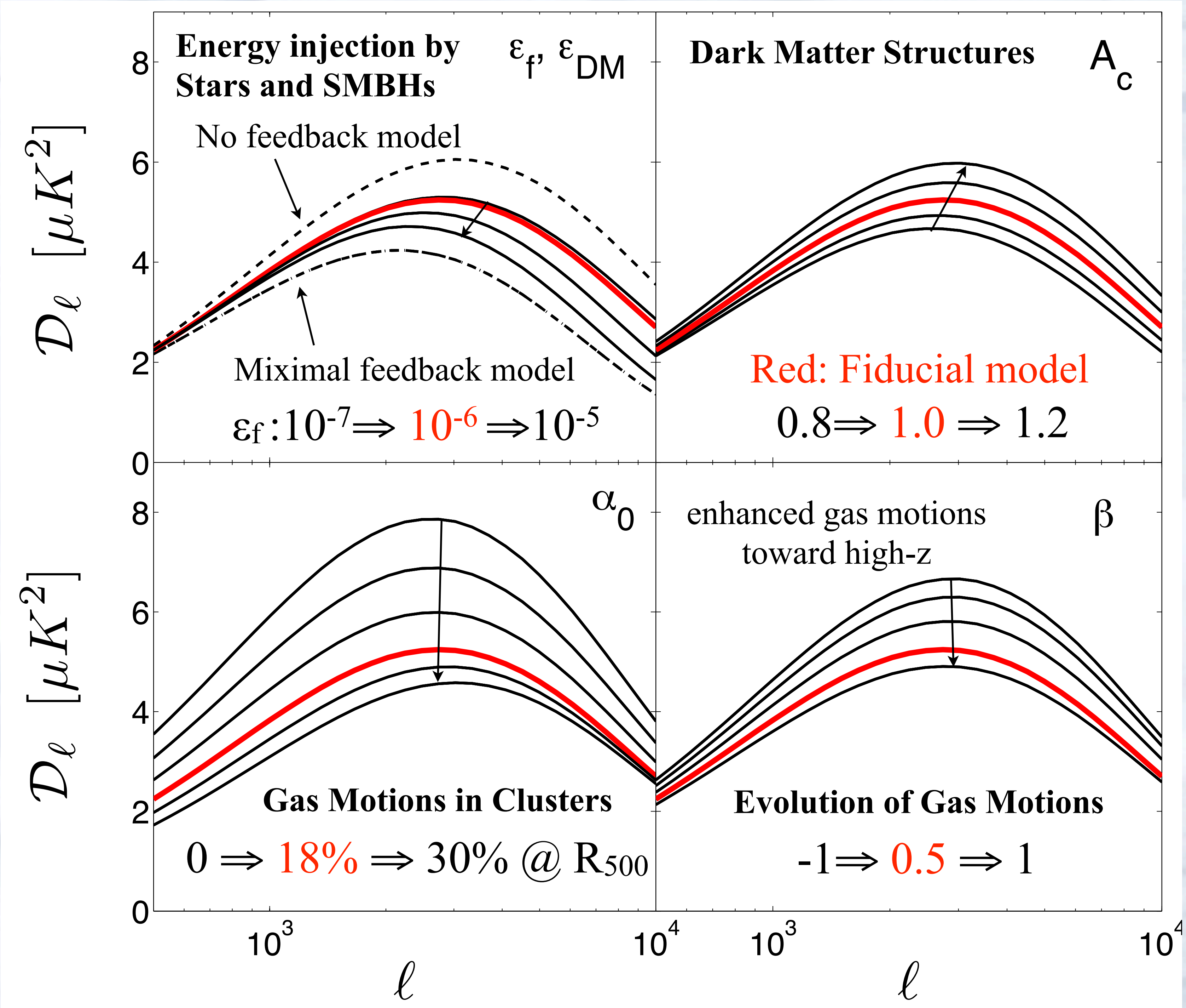
Energy feedback does NOT significantly modify the electron pressure profiles of massive clusters.

Impact of Energy Feedback on Pressure Profiles



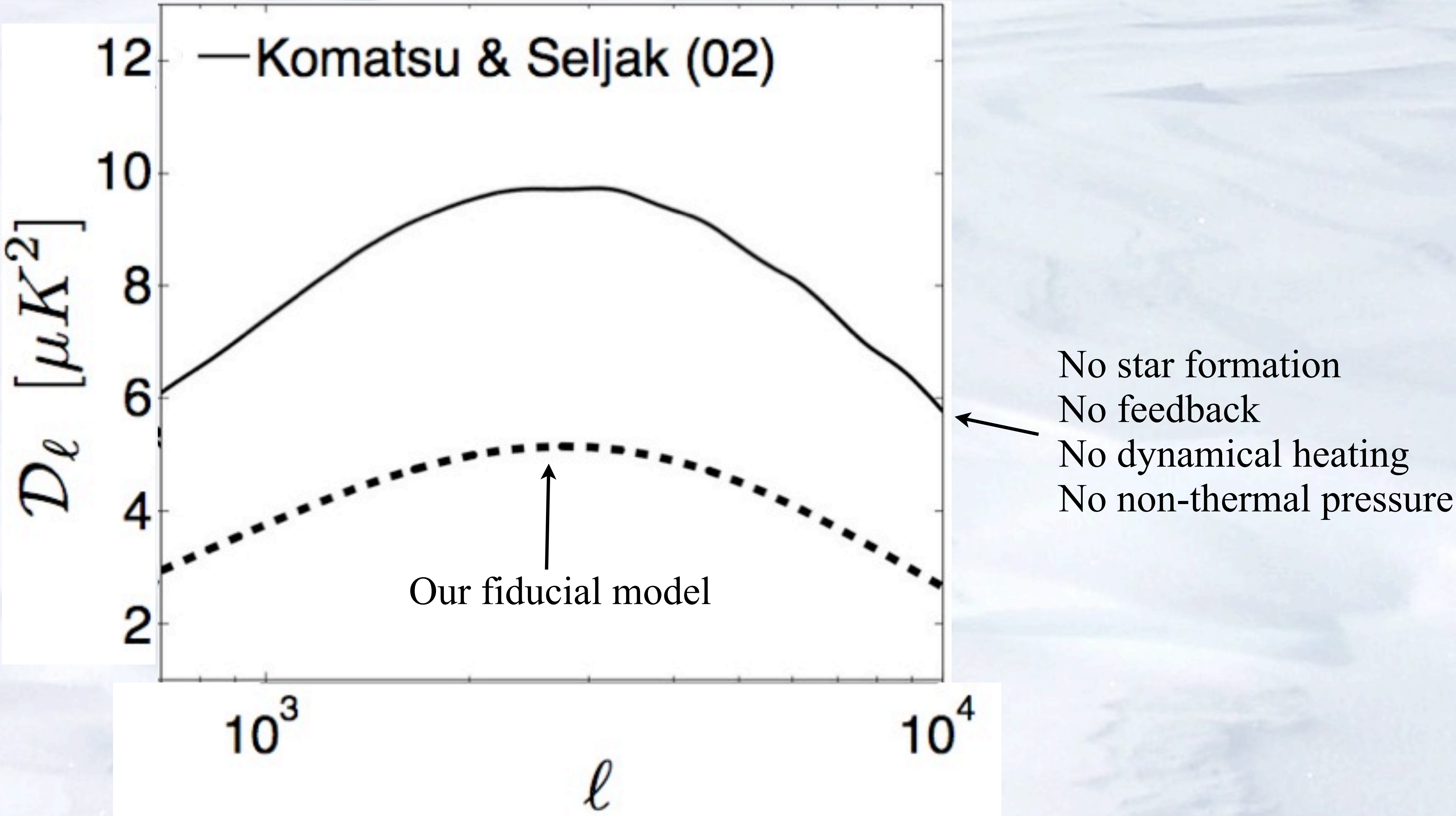
But, significant impact on groups!

Astrophysical Uncertainty in the SZ power spectrum



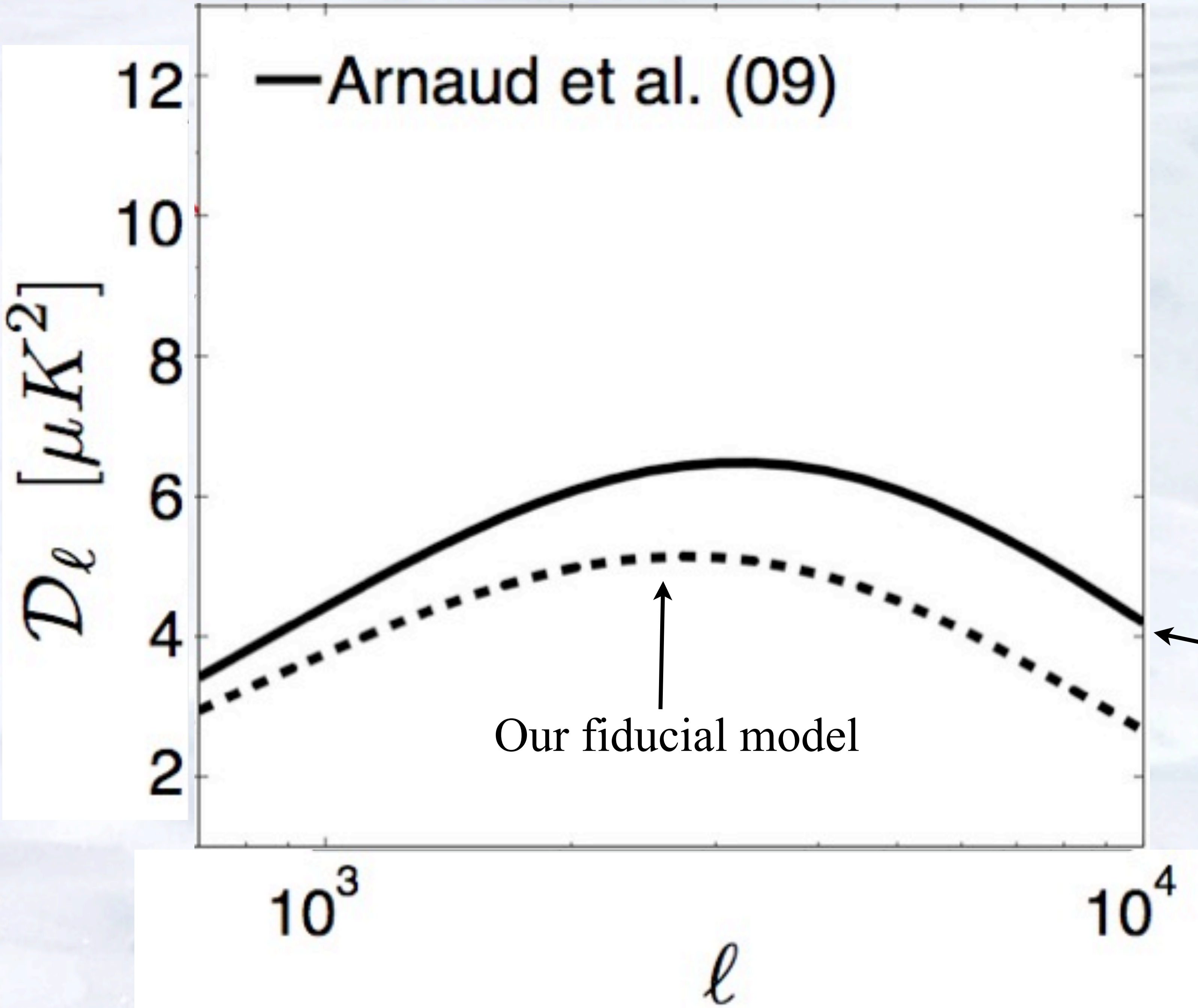
Current SZ theoretical template is uncertain by 100%
due to poorly understood cluster astrophysics at high-z!!

Comparison to Komatsu & Seljak (2002)



KS02 model predicts larger power by a factor of 2 at all scales, compared to our model.

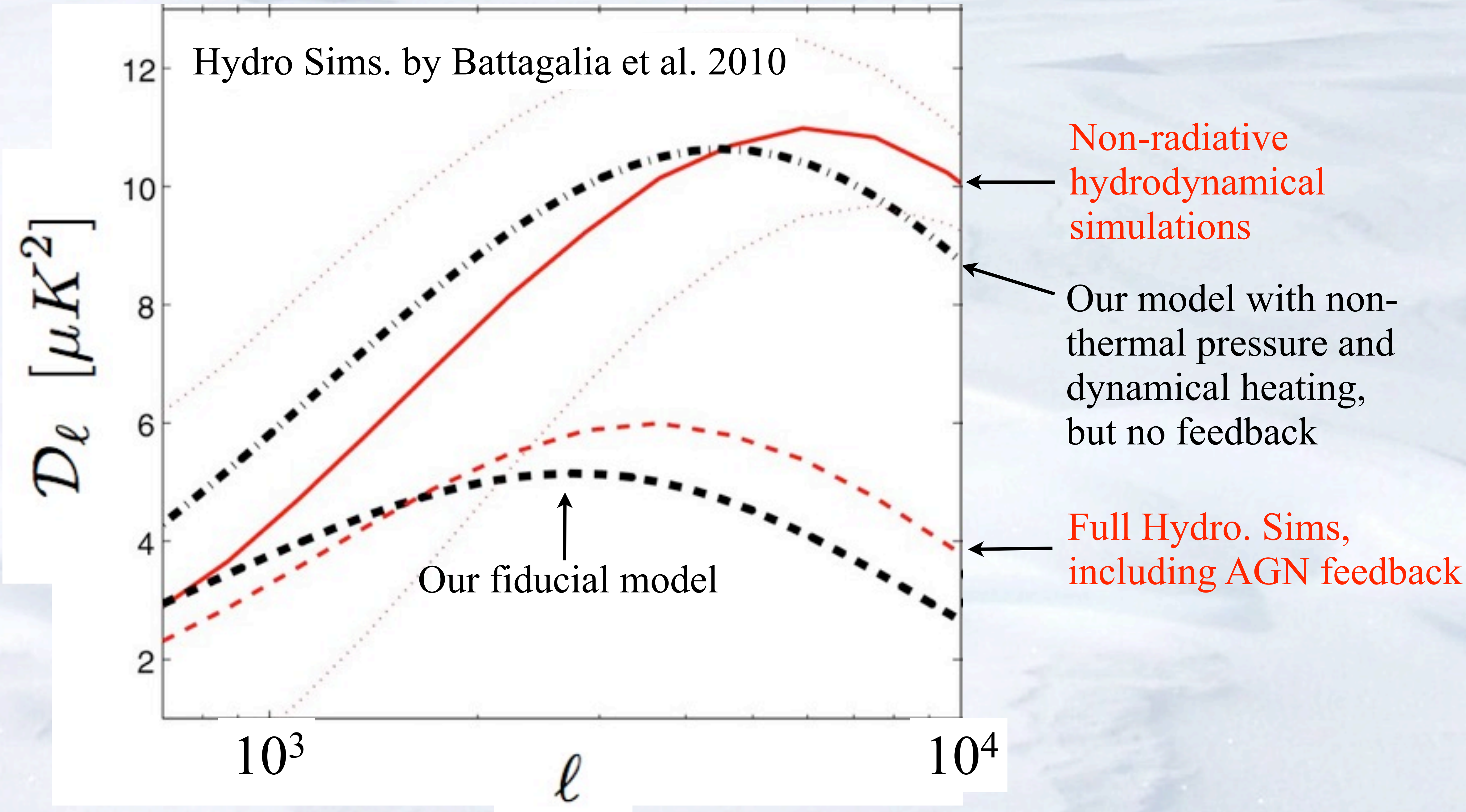
Comparison to the universal pressure profile



Calibrated based on X-ray observations of massive, low-z clusters at $r<r_{500}$ and hydro simulations at $r>r_{500}$. Assuming self-similar evolution.

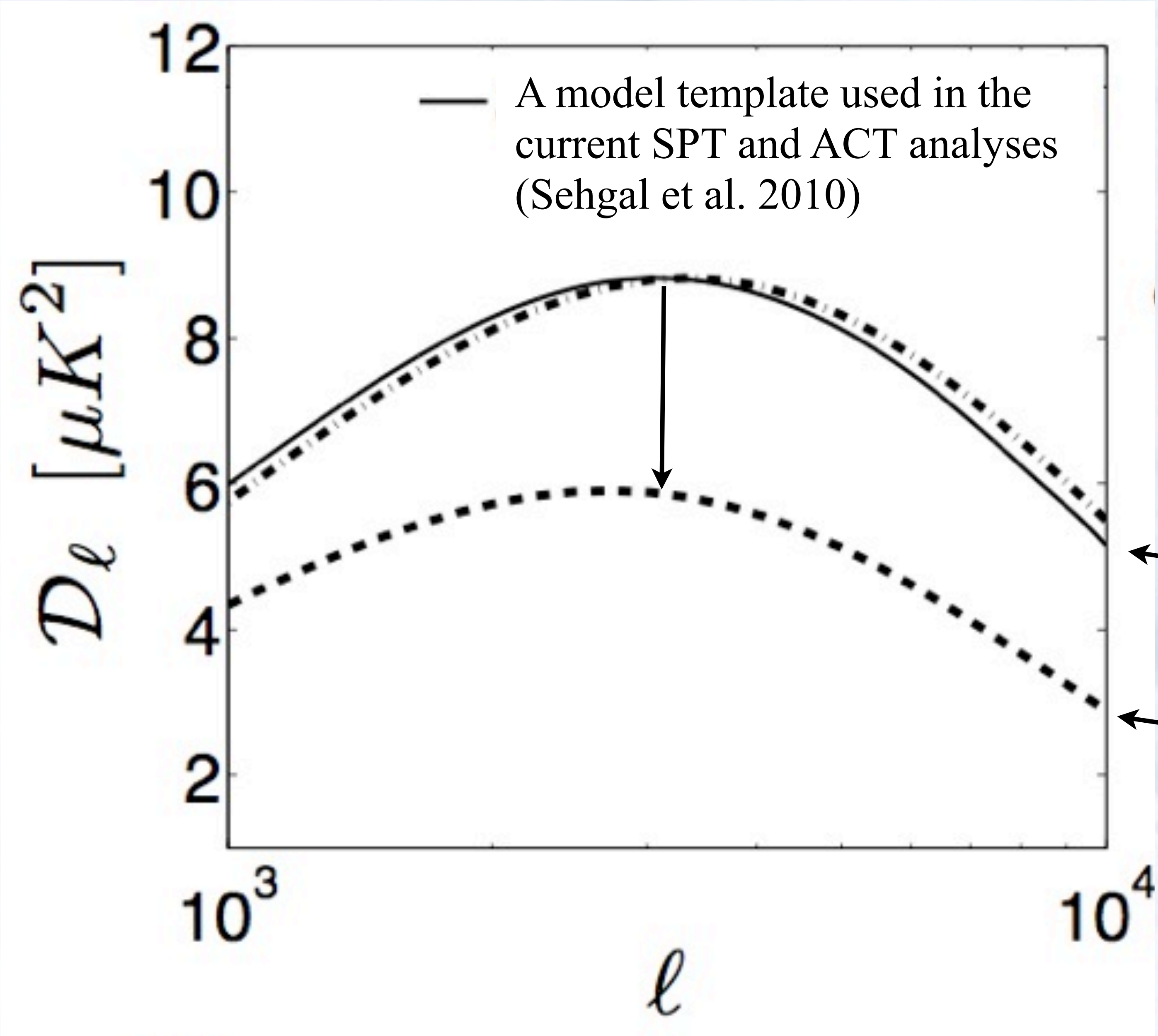
The predicted power spectra match at large scales, but our model is slightly below that of the A09 profile at small scales due to enhanced non-thermal pressure at high-z.

Comparison to hydrodynamical simulations



The overall amplitude is in reasonable agreement, but our model predicts less power at small scales (l > 4000) compared to the simulation, likely due to substructures.

Missing Astrophysics
Impact of Gas Motions on the SZ power spectrum



Non-thermal pressure by gas motions due to incomplete virialization causes reduction of power by 60% at all scales.

Additional contributions possible from CRs (C.Pfrommer's talk) and MTI instability (I.Parrish's talk)

A old model **without** non-thermal pressure

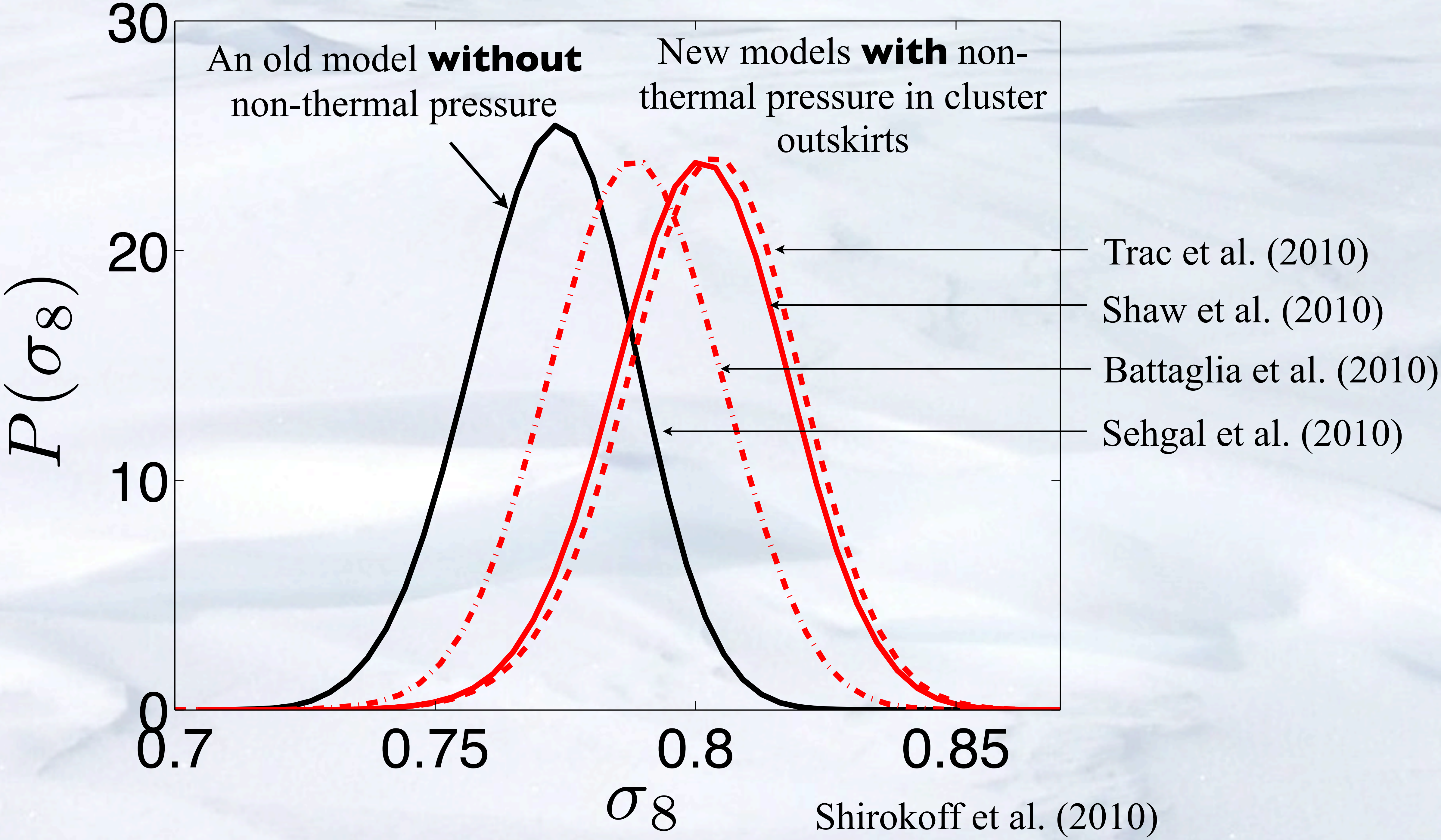
Our new model **with** non-thermal pressure due to gas motions

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

Missing Physics: Gas Motions in the Outskirts of Groups and Clusters

L. Shaw, D. Nagai, S. Bhattacharya, E. Lau, 2010, 725, 1452 (in December 2010 issue)

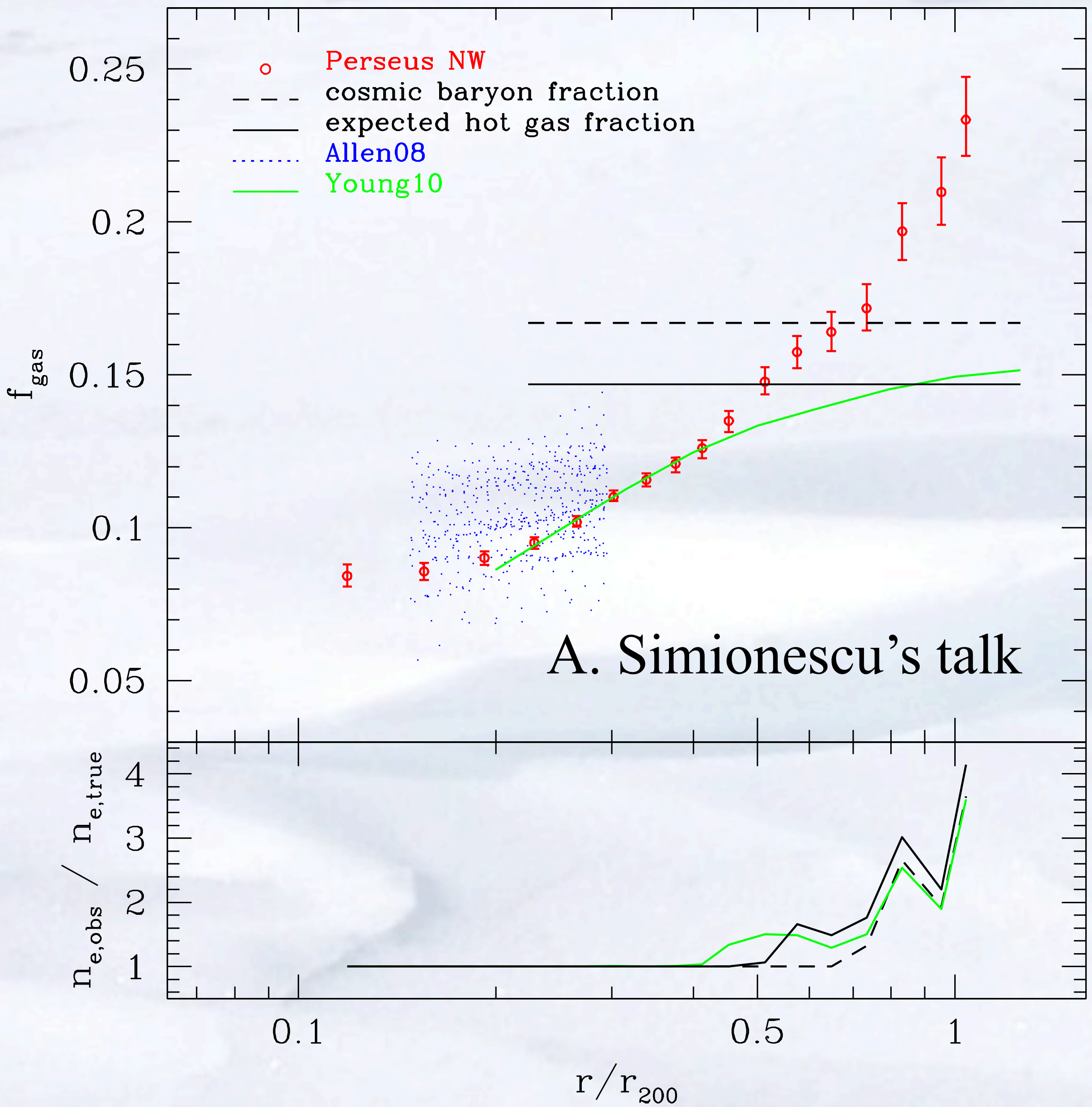
Improved Constraints on σ_8

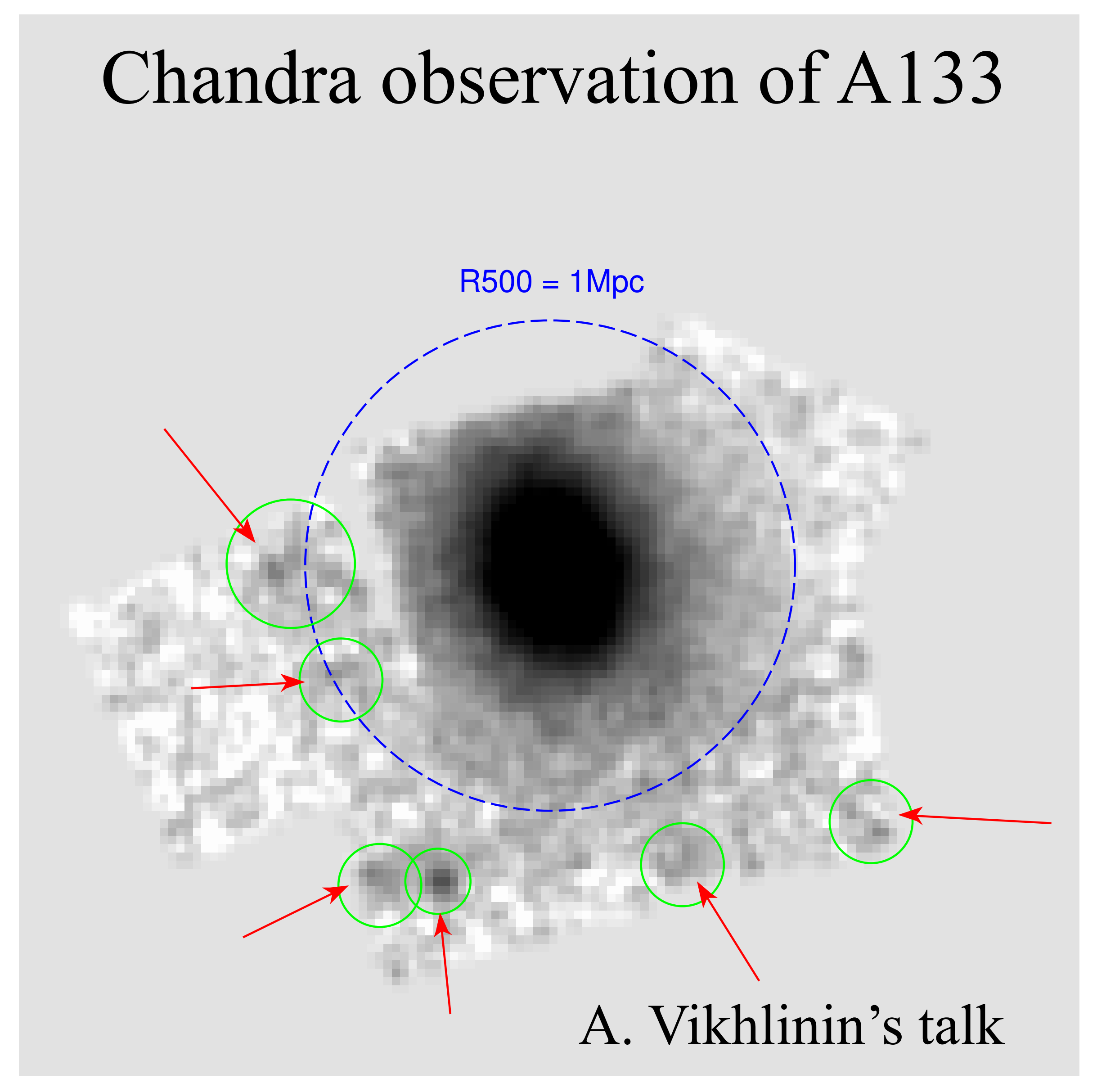


New SZ template yields results consistent with the cluster abundance measurements: σ_8=0.8

Evidence for Gas Clumping in Cluster Outskirts

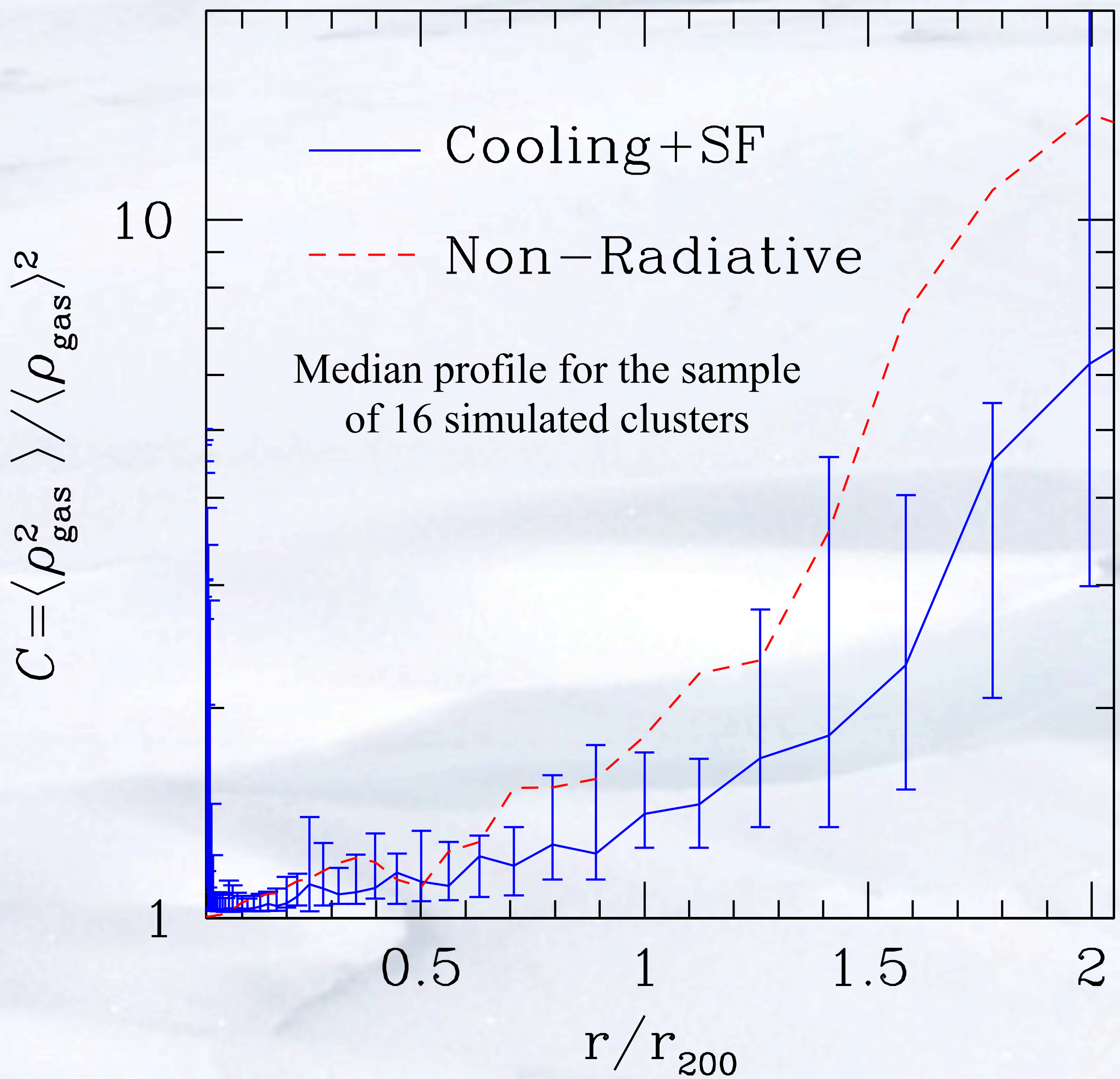
Suzaku observation of Perseus

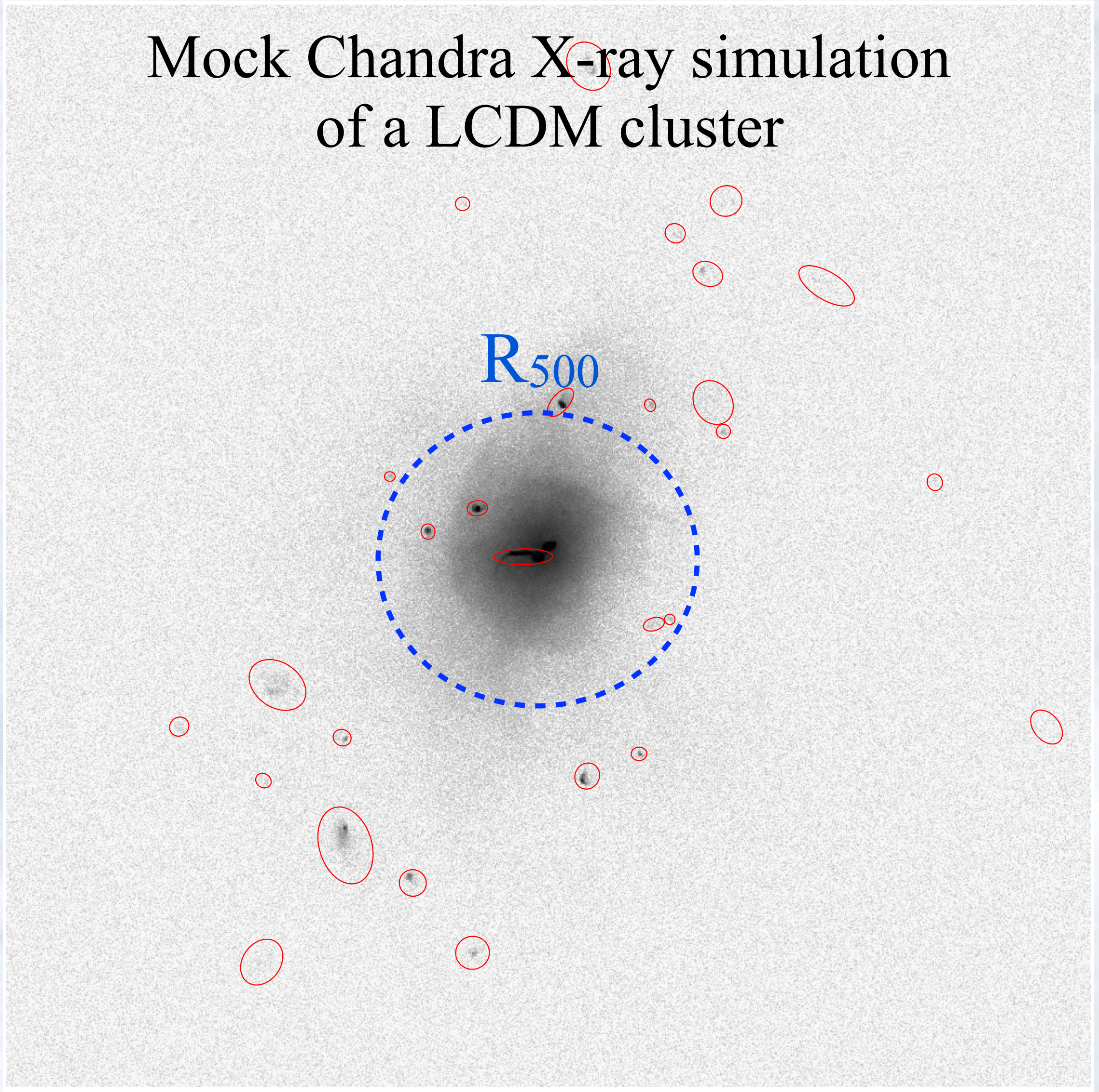




A transition of the smooth state in the virialized region to a clumpy intergalactic medium in the infall region outside of $r \approx R_{500}$

Gas Clumping in the Outskirts of ΛCDM Clusters

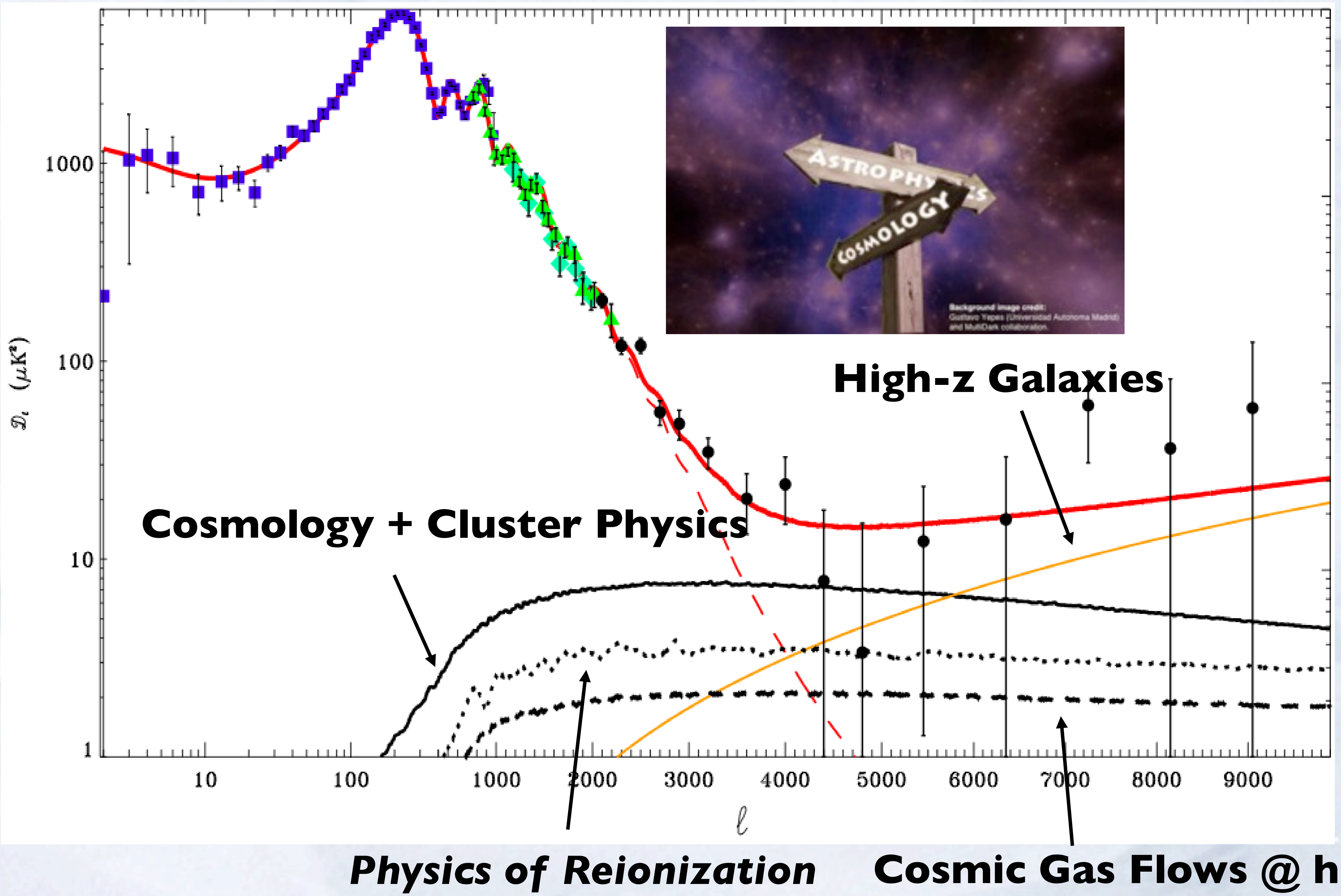




Cluster outskirts are clumpy with large cluster-to-cluster variations.
The clump distribution is also highly anisotropic.

D. Nagai & E. Lau, 2011, accepted for publication in ApJ Letters
astro-ph/1103.0280

New Crossroads of Cosmology & Astrophysics



The SZ power spectrum promises to be a new gold mine of cosmology & astrophysics!