New Kid on the Block: Kinematic Sunyaev-Zel'dovich Effect

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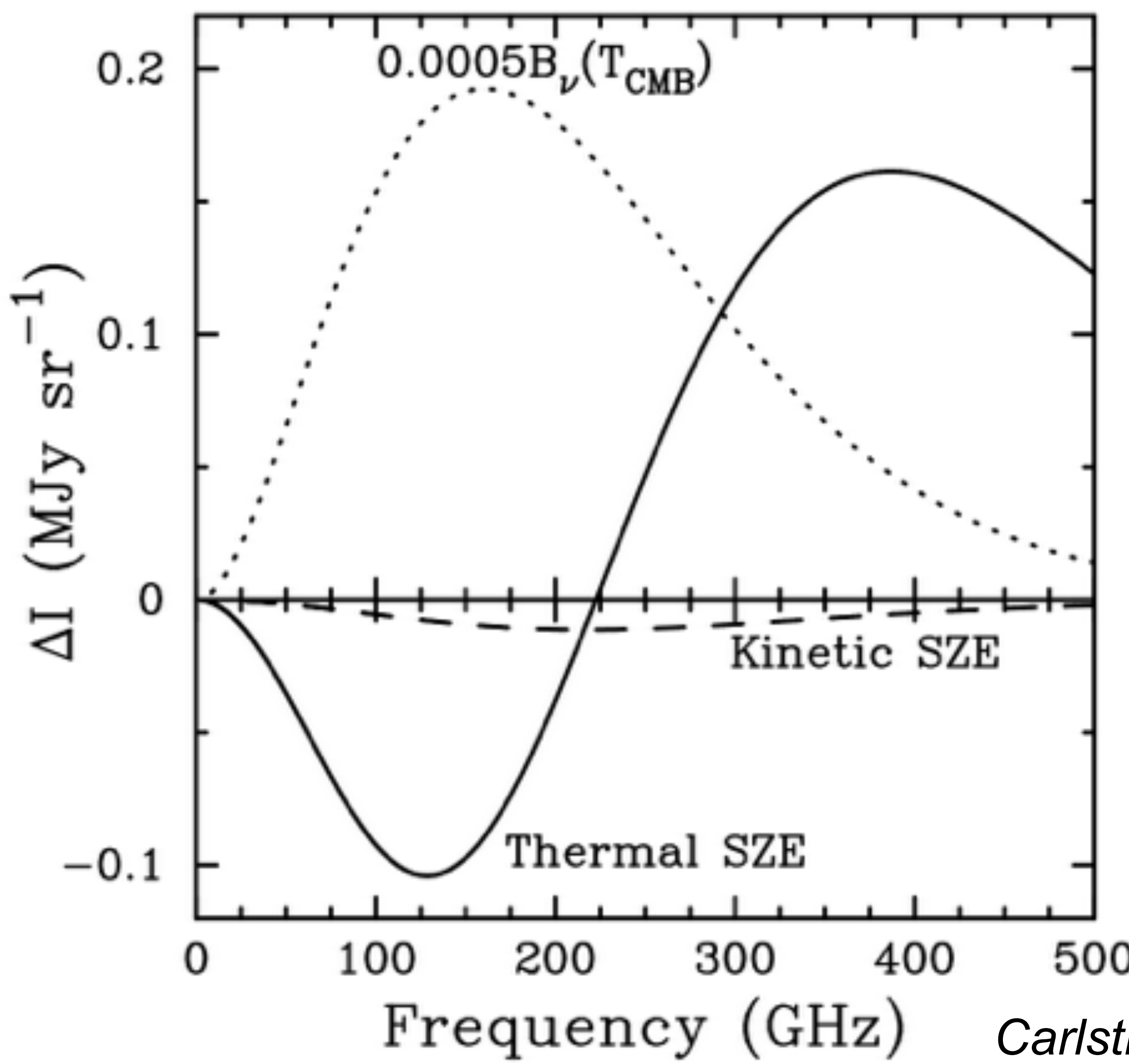
The kinematic Sunyaev-Zel'dovich (kSZ) effect

- **kSZ effect:** inverse Compton scattering of CMB photons with free electrons moving with high bulk velocities: $\left(\frac{\Delta T}{T_{\rm CMB}}\right)_{\rm kSZ} = \sigma_T \int dl n_e(l) \frac{v_{\rm los}}{c} = \tau \frac{v_{\rm los}}{c}$



Carlstrom+02

- same spectral shape as the primary CMB (i.e. blackbody)
—> challenging to measure for individual objects!

The pairwise kSZ effect

Pairwise kSZ signal:

- CMB pattern caused by the kSZ effect + pairwise motion of clusters (improve statistics by summing over many cluster pairs):

$$\frac{\Delta T_{\rm pkSZ}}{T_{\rm CMB}}(r,z) = \bar{\tau}_{\rm eff}\frac{v_{12}(r,z)}{c}$$

optical depth (astrophysics) — pairwise velocity (cosmology)

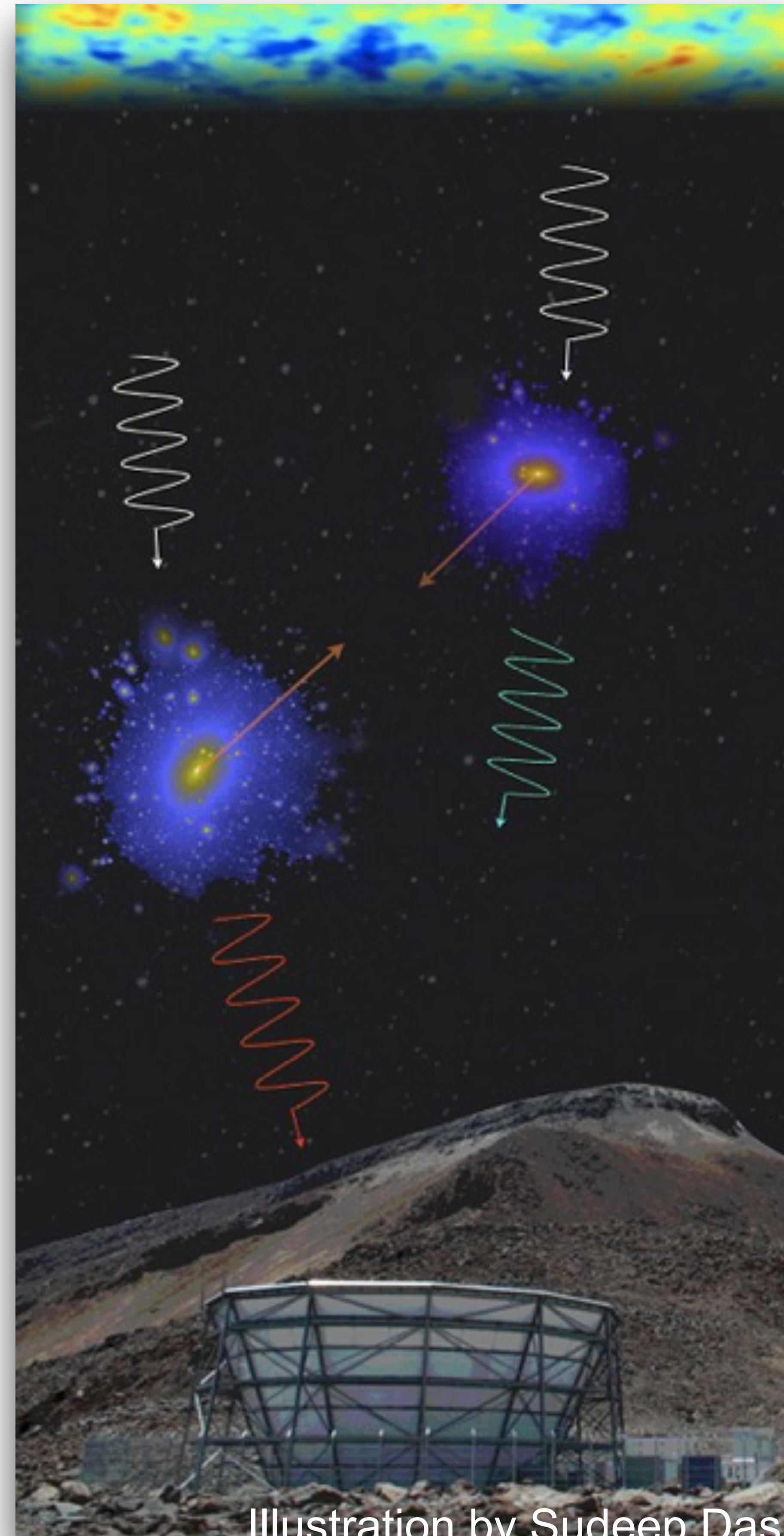
- at large scales:

$$v_{12} \sim \xi_{v\delta} \sim f\sigma_8^2$$

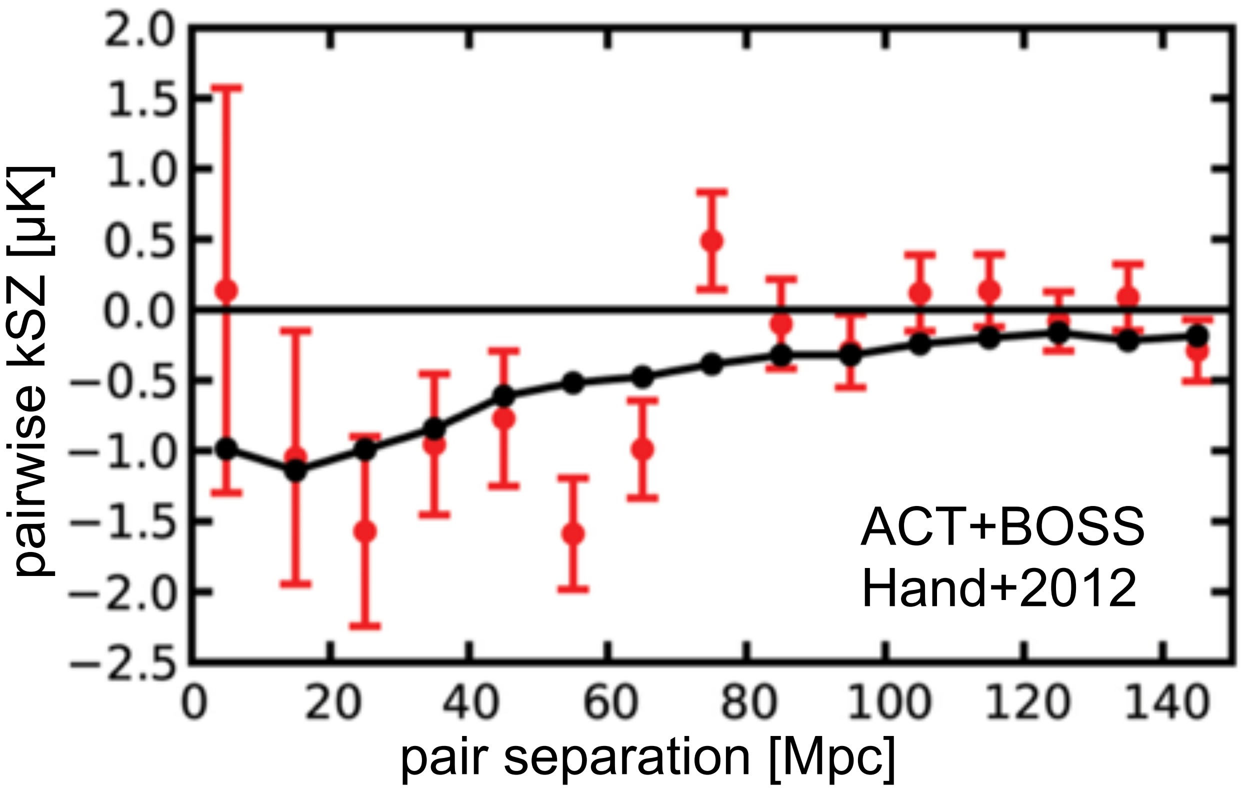
growth function

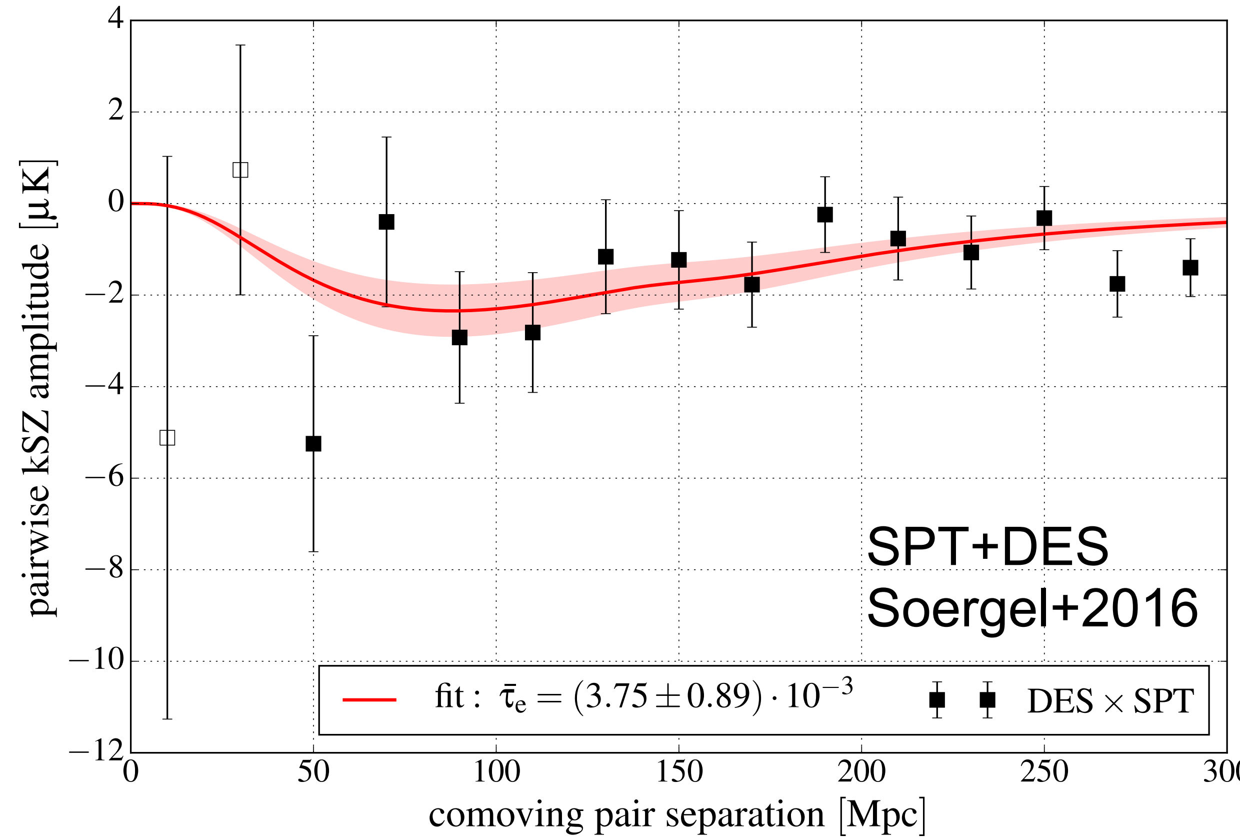
- therefore the signal is of fundamental cosmological interest:

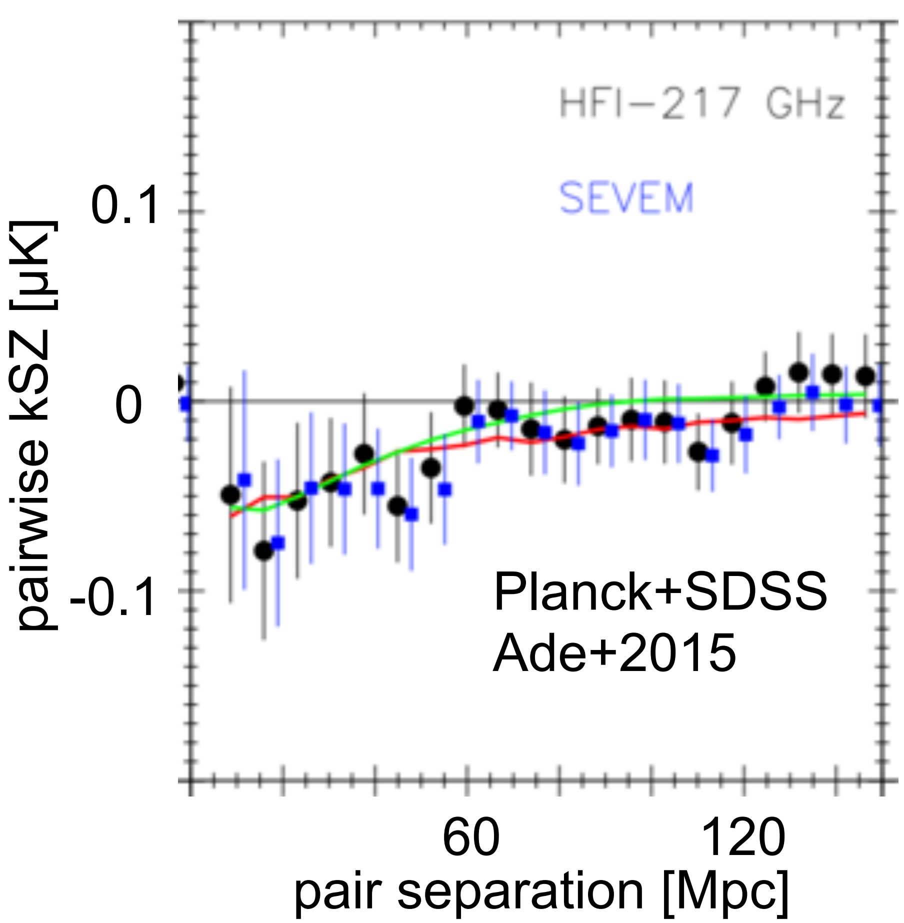
$$\Delta T_{\rm pkSZ} \sim \bar{\tau}_{\rm eff} f \sigma_8^2$$

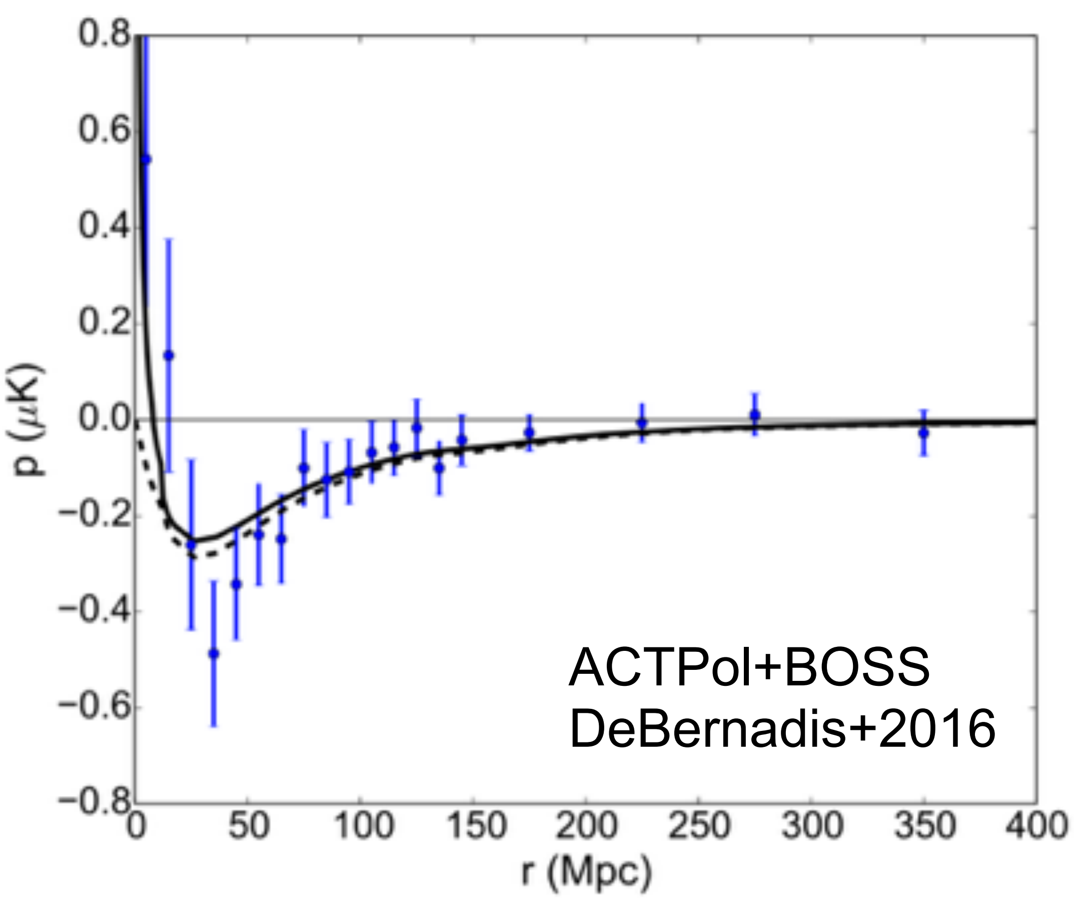


Previous pairwise kSZ measurements









Pairwise kSZ measurements in the future

data scenario	method	predicted S/N	Reference
SPT-3G × DES	pairwise kSZ	$\sim 18-30$	Keisler & Schmidt (2013)
Adv.ACTPol × DESI	pairwise kSZ	$\sim 20-57$	Flender et al. (2016)
Adv.ACTPol × SPHEREx	pairwise kSZ	~ 55	Doré et al. (2016)
Adv.ACTPol × WISE	projected kSZ	~ 120	Ferraro et al. (2016)
Adv.ACTPol × DESI	pairwise kSZ power spectrum	~ 30	Sugiyama et al. (2016)
CMB StageIV × DESI	pairwise kSZ power spectrum	$\sim 50-100$	Sugiyama et al. (2016)

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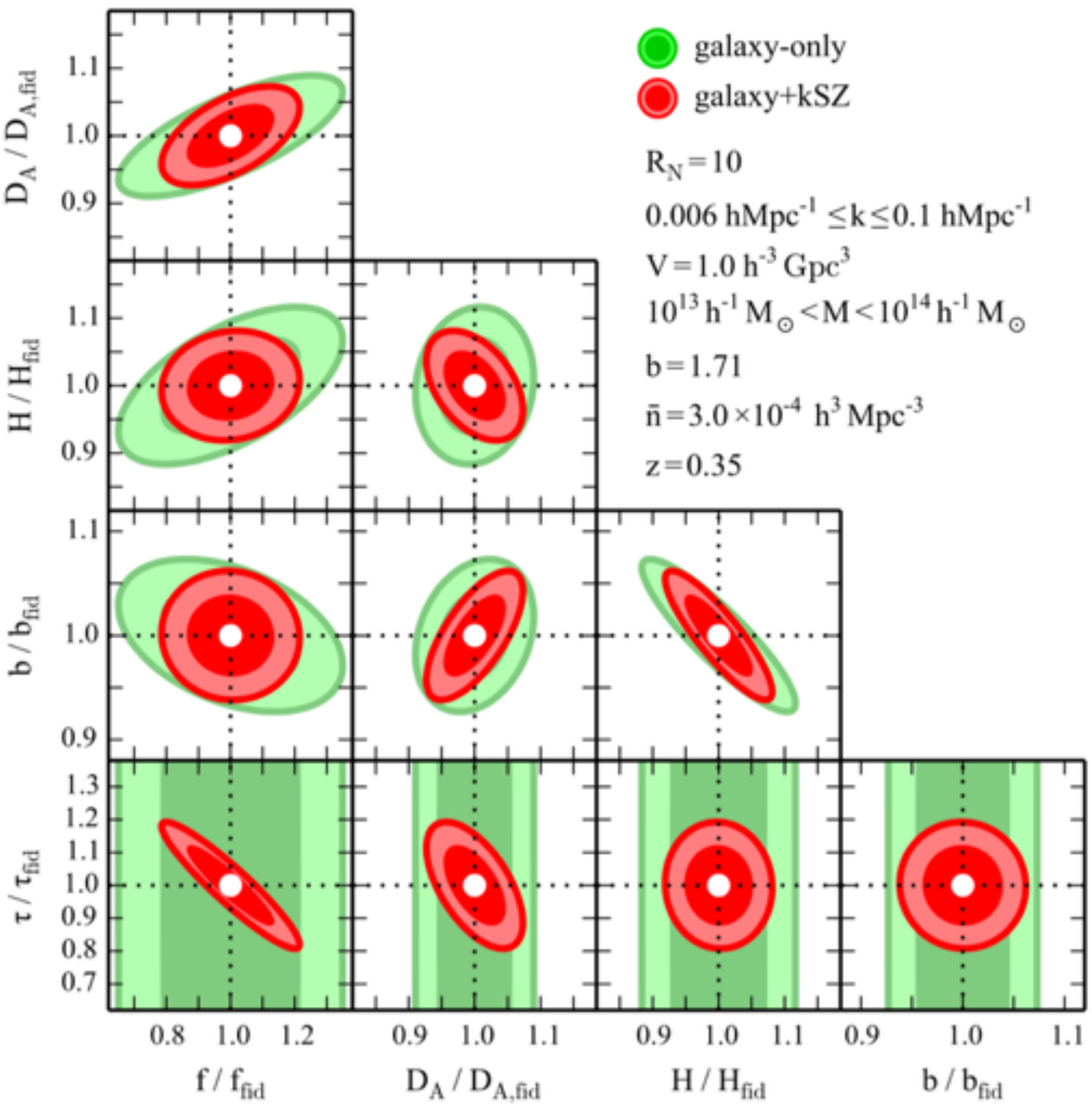
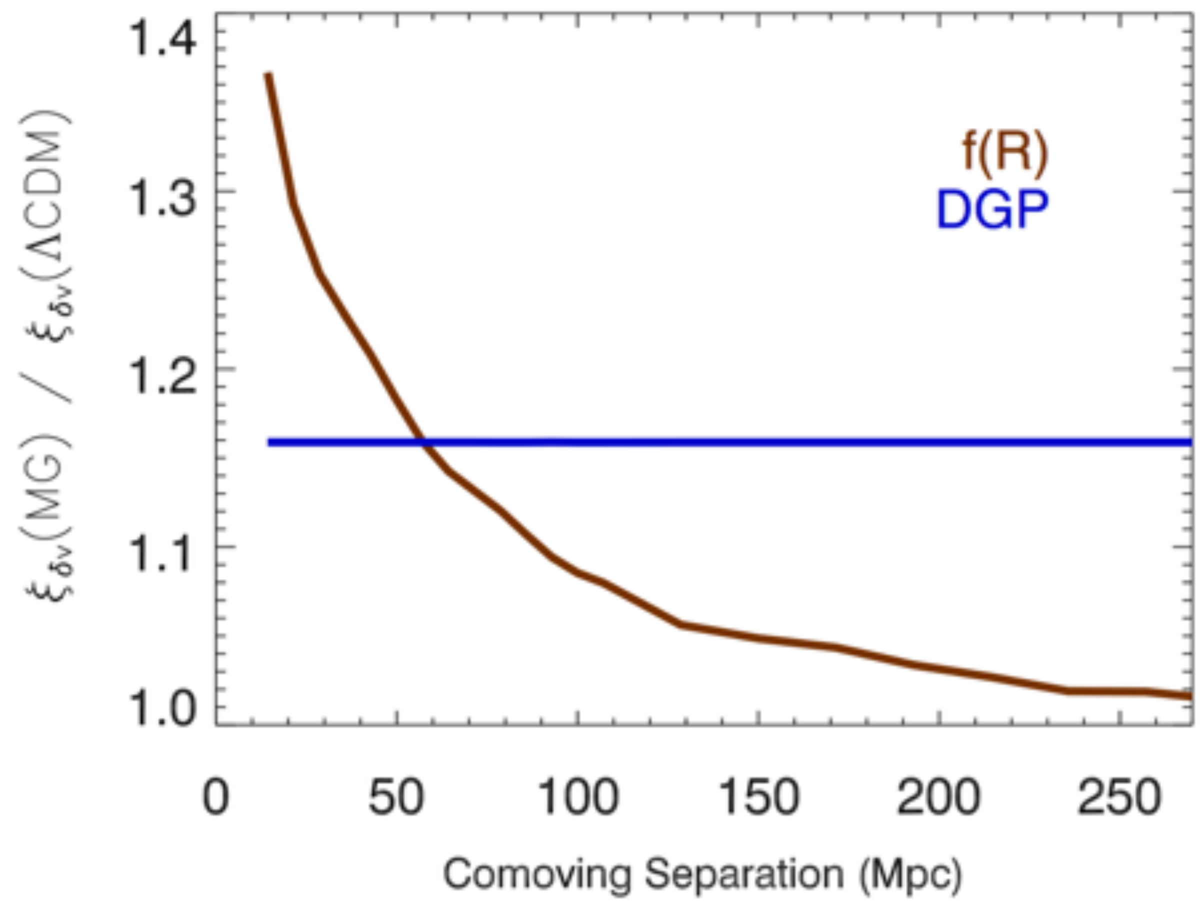
Adv.ACT			Ferraro et al. (2016)
Adv.AC			Sugiyama et al. (2016)
CMB Sta			Sugiyama et al. (2016)

Will Kinematic Sunyaev-Zel'dovich Measurements Enhance the Science Return from Galaxy Redshift Surveys?

Abstract. Yes. Future CMB experiments such as Advanced ACTPol and CMB-S4 should achieve measurements with S/N of > 0.1 for the typical galaxies in redshift surveys. These measurements will provide complementary measurements of the growth rate of large scale structure f and the expansion rate of the Universe H to galaxy clustering measurements. This paper emphasizes that there is significant information in the anisotropy of the relative pairwise kSZ measurements. We expand the relative pairwise kSZ power spectrum in Legendre polynomials and consider up to its octopole. Assuming that the noise in the filtered maps is uncorrelated between the positions of galaxies in the survey, we derive a simple analytic form for the power spectrum covariance of the relative pairwise kSZ temperature in redshift space. While many previous studies have assumed optimistically that the optical depth of the galaxies τ_T in the survey is known, we marginalize over τ_T, to compute constraints on the growth rate f and the expansion rate H. For realistic sure parameters, we find that combining kSZ and galaxy redshift survey data reduces the marginalized 1-σ errors on H and f by $\sim$ 50-70% compared to the galaxy-only analysis.

Cosmology with the pairwise kSZ signal





Sugiyama+16:
improved constraints on H, D_A, f
by adding kSZ information

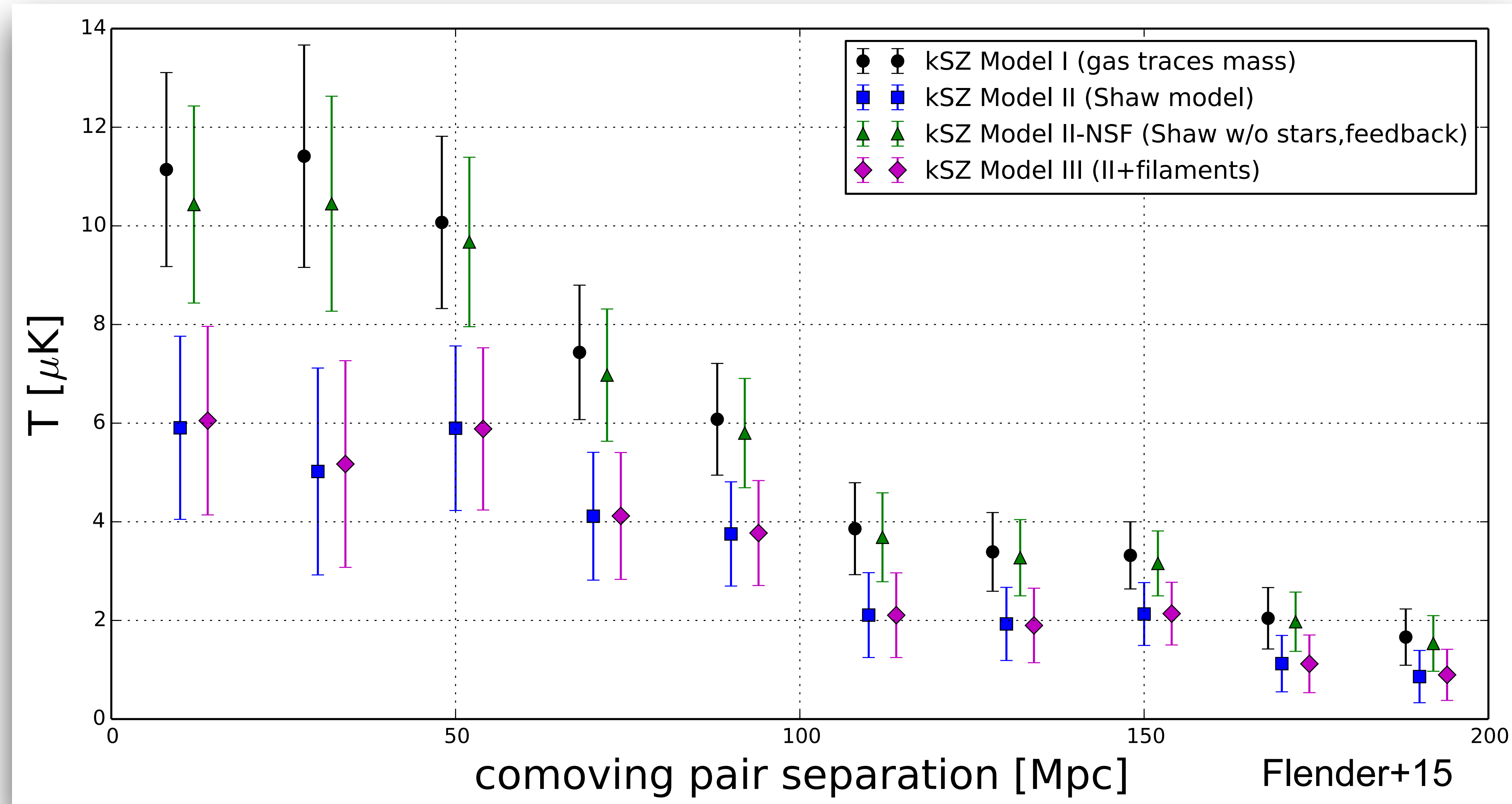
Keisler & Schmidt 2013:
dependence of $\xi_{\delta v}$ on the gravity model

External prior of the optical depth (τ) to better than 20% can be a big help!

But, do we understand the ICM physics well enough?

without feedback

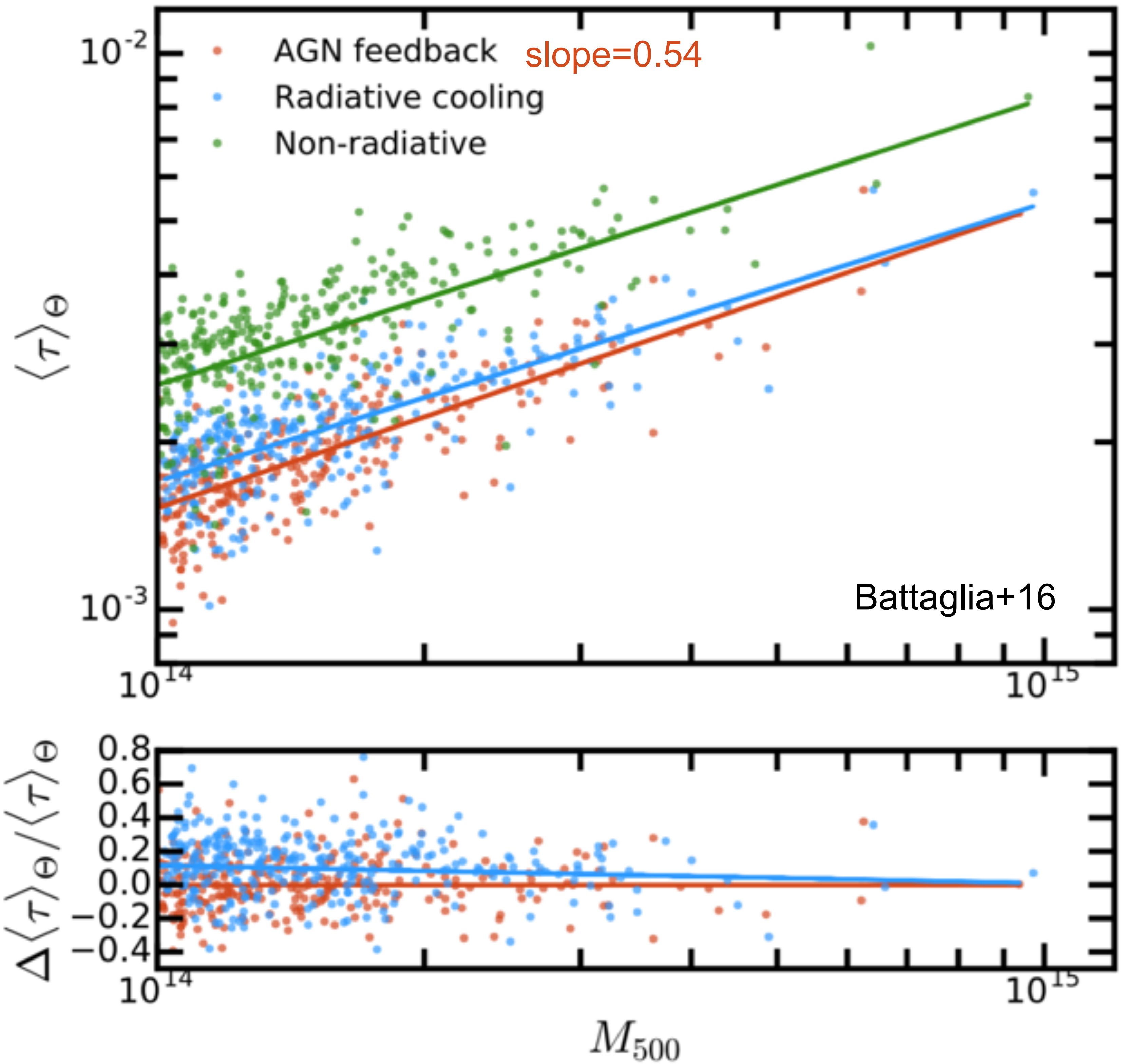
with feedback



- Factor of ~2 difference due to the ICM physics (Flender+15; also Battaglia+16)
- In order to do 'kSZ cosmology' we need external constraints on the amplitude, which is controlled by the **optical depth profile**!

Hydrodynamical Simulations - Battaglia 2016

average τ within 1.3’ aperture



Factor of ~2 discrepancy among different runs… Can we do better?

Methodology: modeling the kSZ signals

Answer: Yes.

- **Approach #1:** Hydrodynamical Simulations
  - follow detailed hydrodynamical evolution of gas in clusters

    (+ gas cooling, star-formation, AGN, bulk+turbulent gas motions…)
  - Pro: don't need to 'assume gas profiles'
  - Con: need both large simulation boxes and high-resolution to resolve relevant sub-grid cluster physics. **Still prohibitably expensive!**

(e.g., Hallman+07, Battaglia+10,16, Le Brun+15)

- **Approach #2:** N-body simulations + semi-analytic gas model
  - DM only N-body simulations are becoming cheaper and feasible - no need to assume the mass function and/or velocity statistics
  - Con: assume gas pressure profiles (e.g. Komatsu & Seljuk+02; Shaw+10)
  - Pro: approximately capture essential ICM physics + computationally efficient - important for parameter estimation where we need to vary both cosmology + cluster astrophysics

(e.g., Shaw+10, Trac+11)

Semi-analytic model of the ICM - Shaw Model

A simple parameterized model, calibrated to observations and including cosmological scaling (Ostriker+05, Bode & Ostriker+06, Shaw+10)

(1) Gas resides in hydrostatic equilibrium in NFW dark matter halos with polytropic equation of state (EoS):

$$\frac{dP_{tot}(r)}{dr} = -\rho_g(r)\frac{d\Phi(r)}{dr} \qquad P_{tot} \propto \rho_g^{\Gamma}$$

(2) Assume some gas has radiatively cooled + formed stars. Stellar mass fraction constrained by observed relations (e.g., Giodini+09, Leauthaud+11, Budzynski+13)

$$F_*(M_{500}) = f_* \times \left(\frac{M_{500}}{3\times10^{14}\,M_\odot}\right)^{-S_*}$$

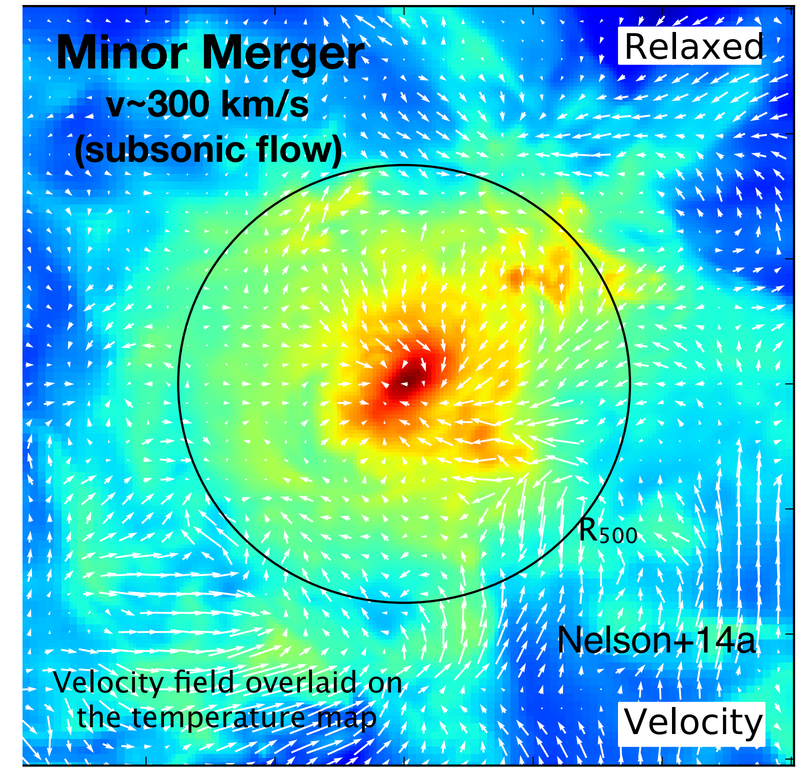
(3) Include simple parameterization for dynamical heating and energy feedback from stars and AGN; i.e., assume feedback energy proportional to stellar mass

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

calibrated by comparing to X-ray obs.

Semi-analytic model of the ICM - Shaw Model

(4) Hydrodynamical simulations predict significant bulk/turbulent motions in ICM outside cluster cores



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

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

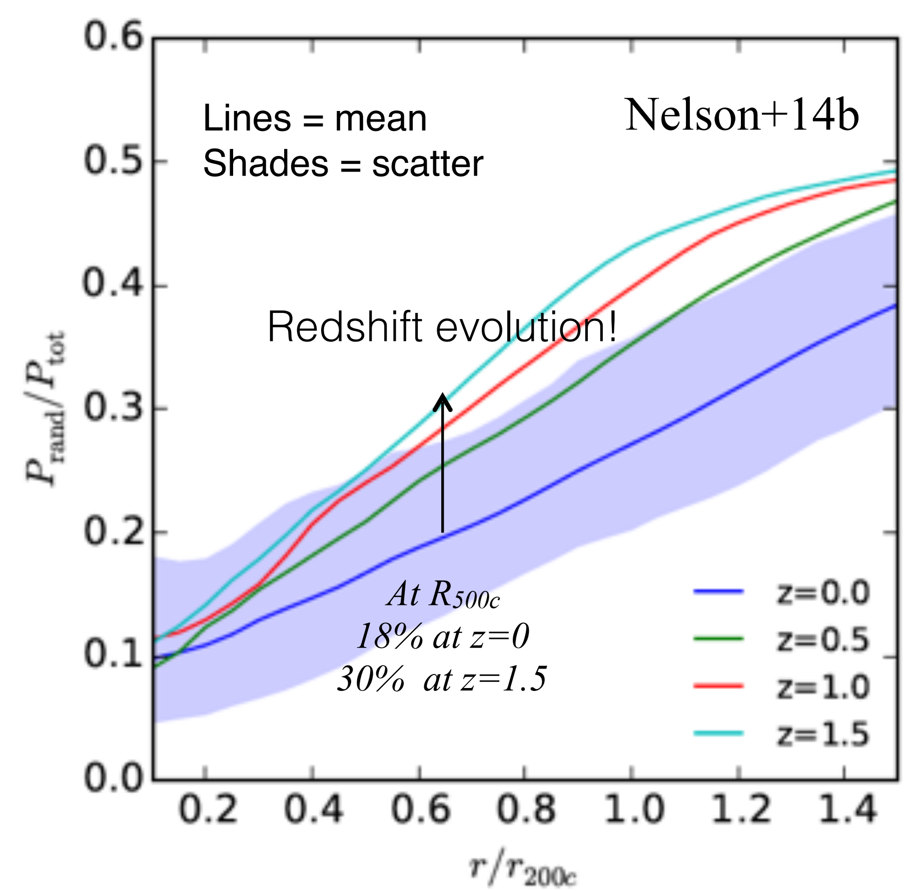
calibrate params with hydro sims

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

18% at R_{500} and z = 0

P_{nt} enhanced at high z, and at larger radii

Omega 500 simulations of galaxy clusters

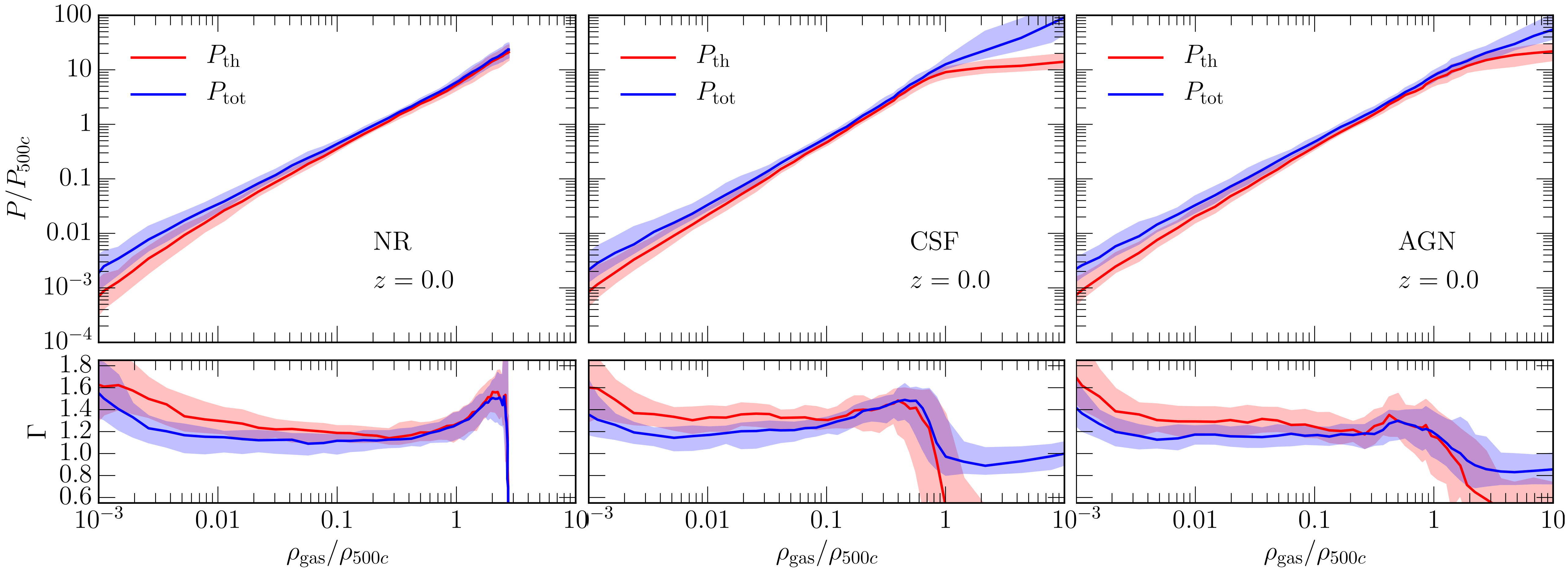


Major source of astrophysical uncertainty in the ICM modeling (Shaw+10, see also Lau+09, Battaglia+11, Nelson+14, Shi+14)

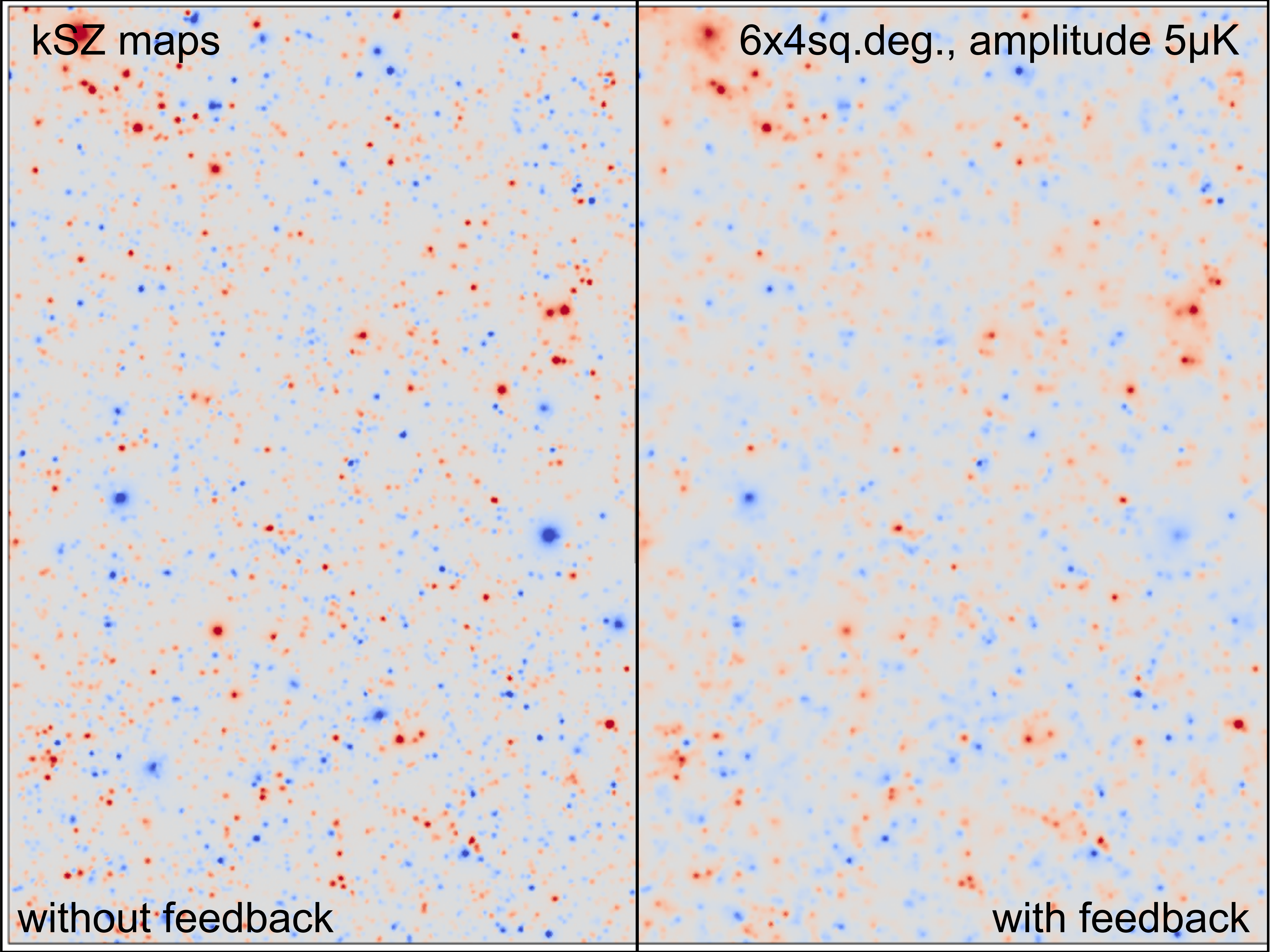
Semi-analytic model of the ICM - Extended Shaw Model

（5）**PROBLEM:** the simple polytropic model breaks down in cool cores.

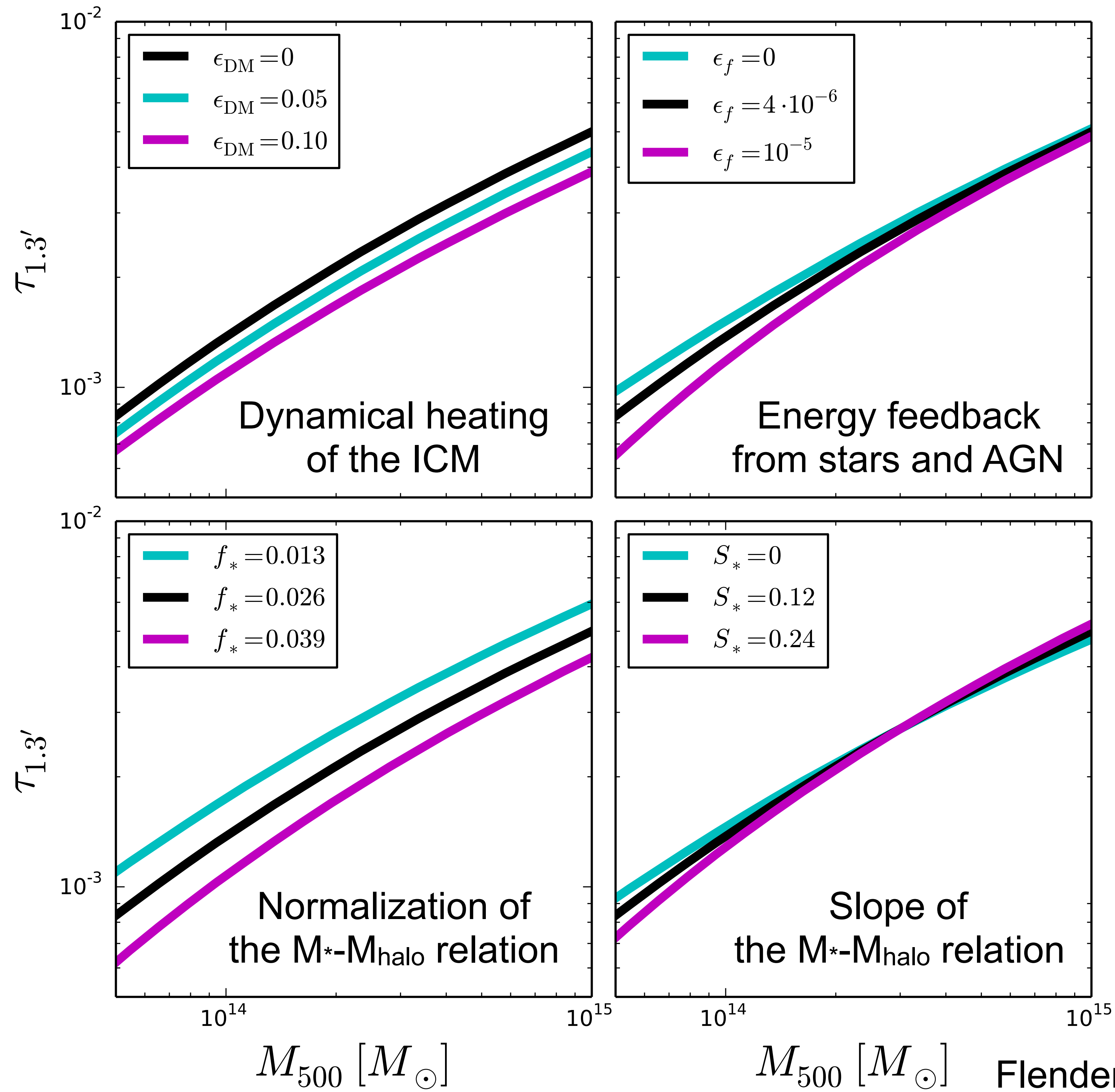
Polytropic equation of state for the ICM: $P_{tot}=P_0(\rho_{gas}/\rho_0)^{\Gamma}$
with Γ~1.2 and $P_{tot}(r)=P_{therm}(r)+P_{nt}(r)$, except in cluster core



The extended Shaw model with a breaking polytope (with $\Gamma'(z)=\tilde{\Gamma}(1+z)^{\beta}$ at $x=r/r_{500c}<x_{break}$) can model the entire ICM from cores to outskirts.


kSZ maps
6x4sq.deg., amplitude 5μK
without feedback
with feedback

Impact of ICM physics on τ of galaxy clusters

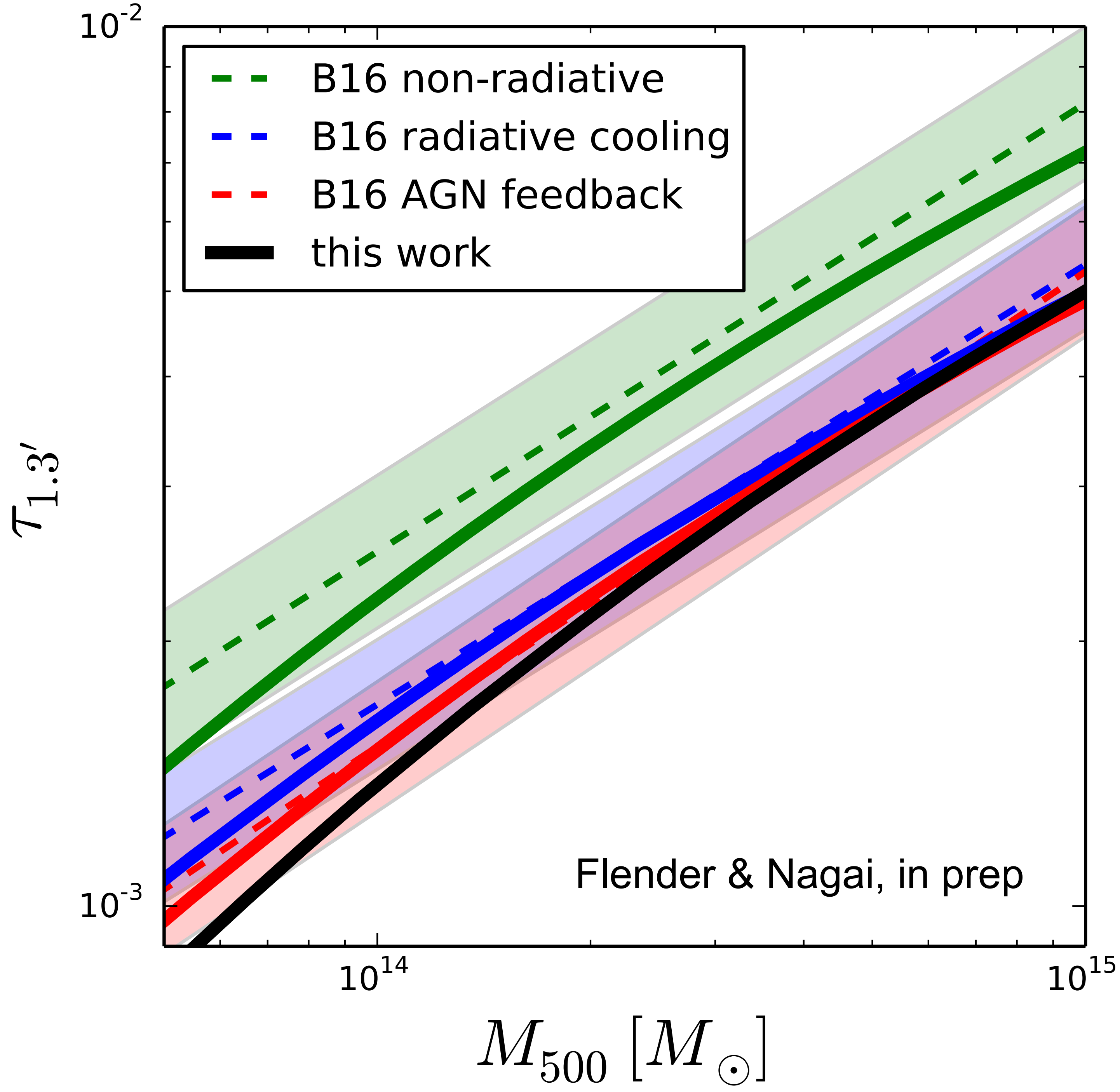


Flender & Nagai, in prep

Our model is computationally efficient and suitable for parameter estimation

Semi-Analytic model vs. Hydro Simulations: Comparison with Battaglia 2016

average τ within 1.3’ aperture

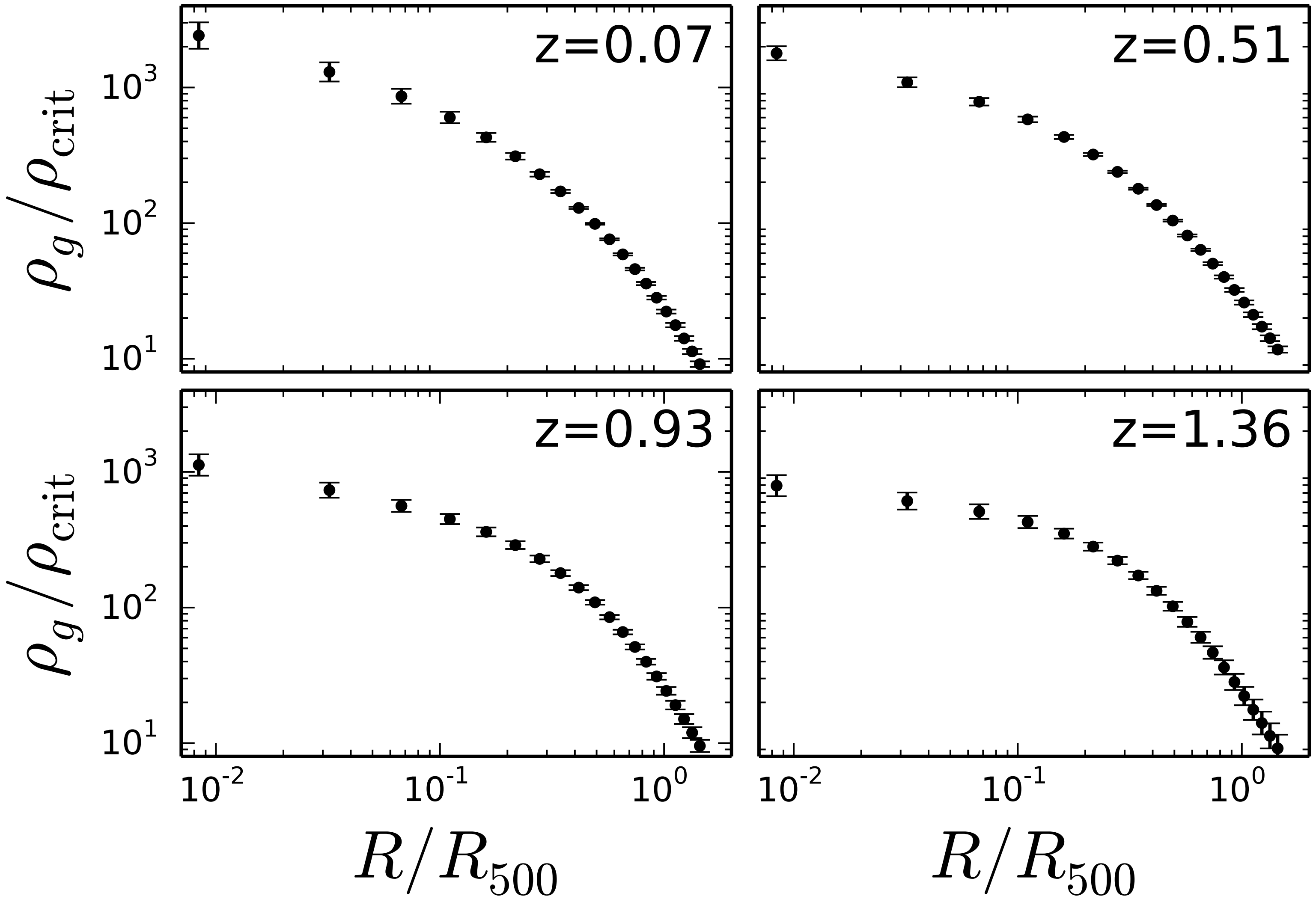


Our semi-analytic model can reproduce the results of hydro simulations

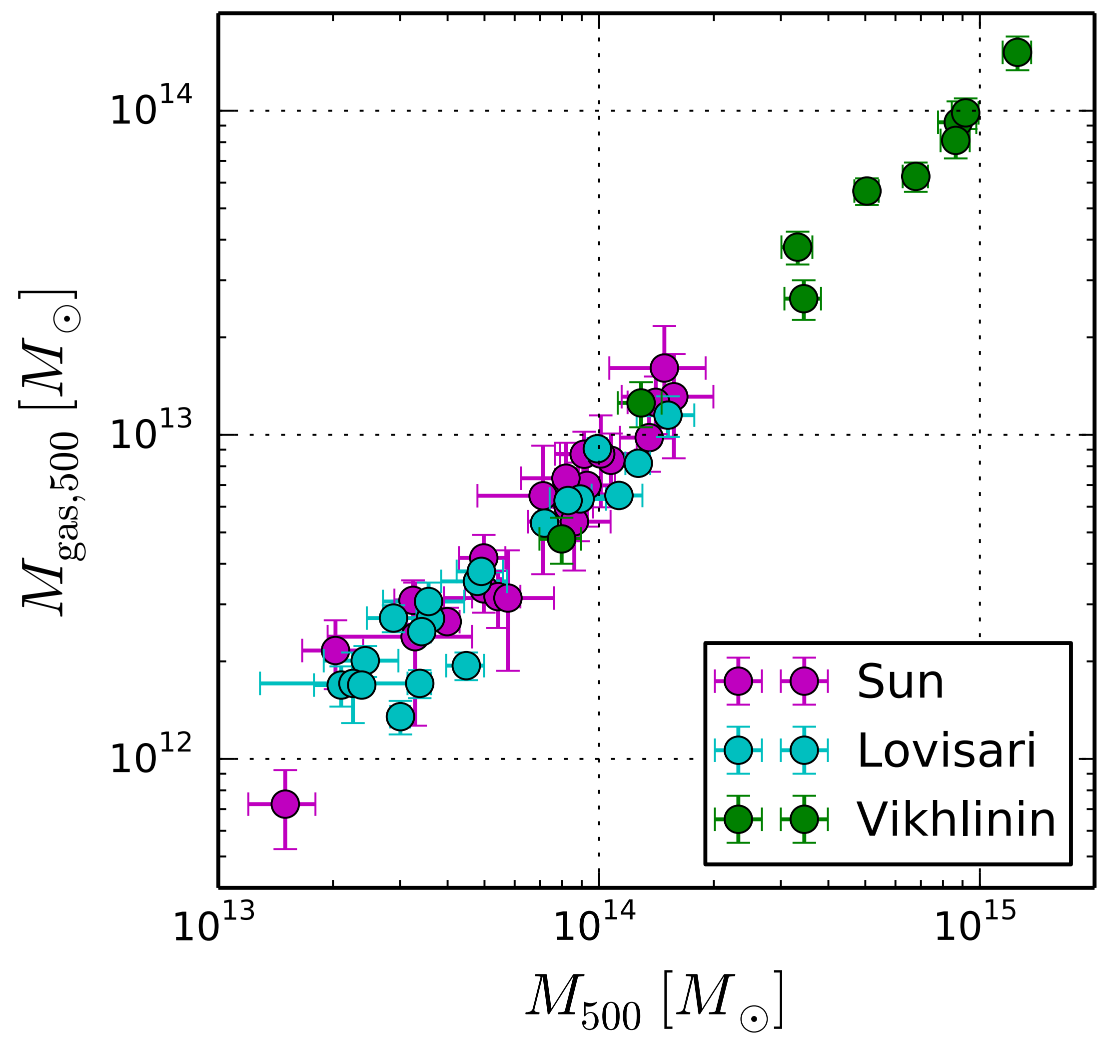
Important: In recent years, we've learned a lot about the ICM from a plethora of new X-ray and SZ data… So, the ICM physics is not that uncertain anymore, right?

Question: How well can we constrain the astrophysical uncertainty in the optical depth of galaxy clusters using current observations (and hence use the kSZ effect to do cosmology)?

X-ray observations of galaxy clusters

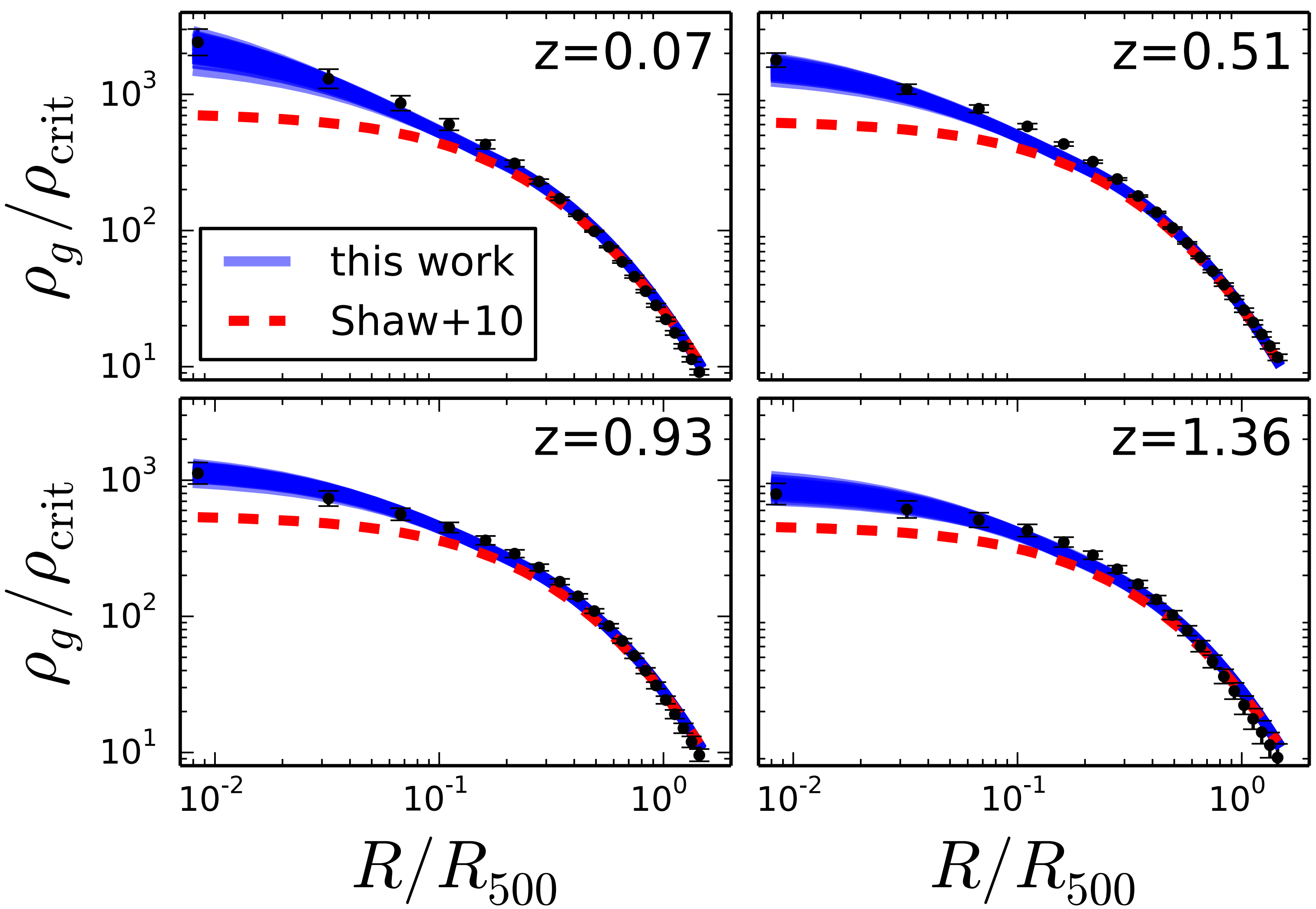


McDonald+2013:
Chandra measurements of gas density profiles
of SPT-selected clusters



Vikhlinin+06, Sun+09, Lovisari+15:
measurements of the M_{gas}-M relation

Improved modeling of gas density profiles with X-ray data + semi-analytic model



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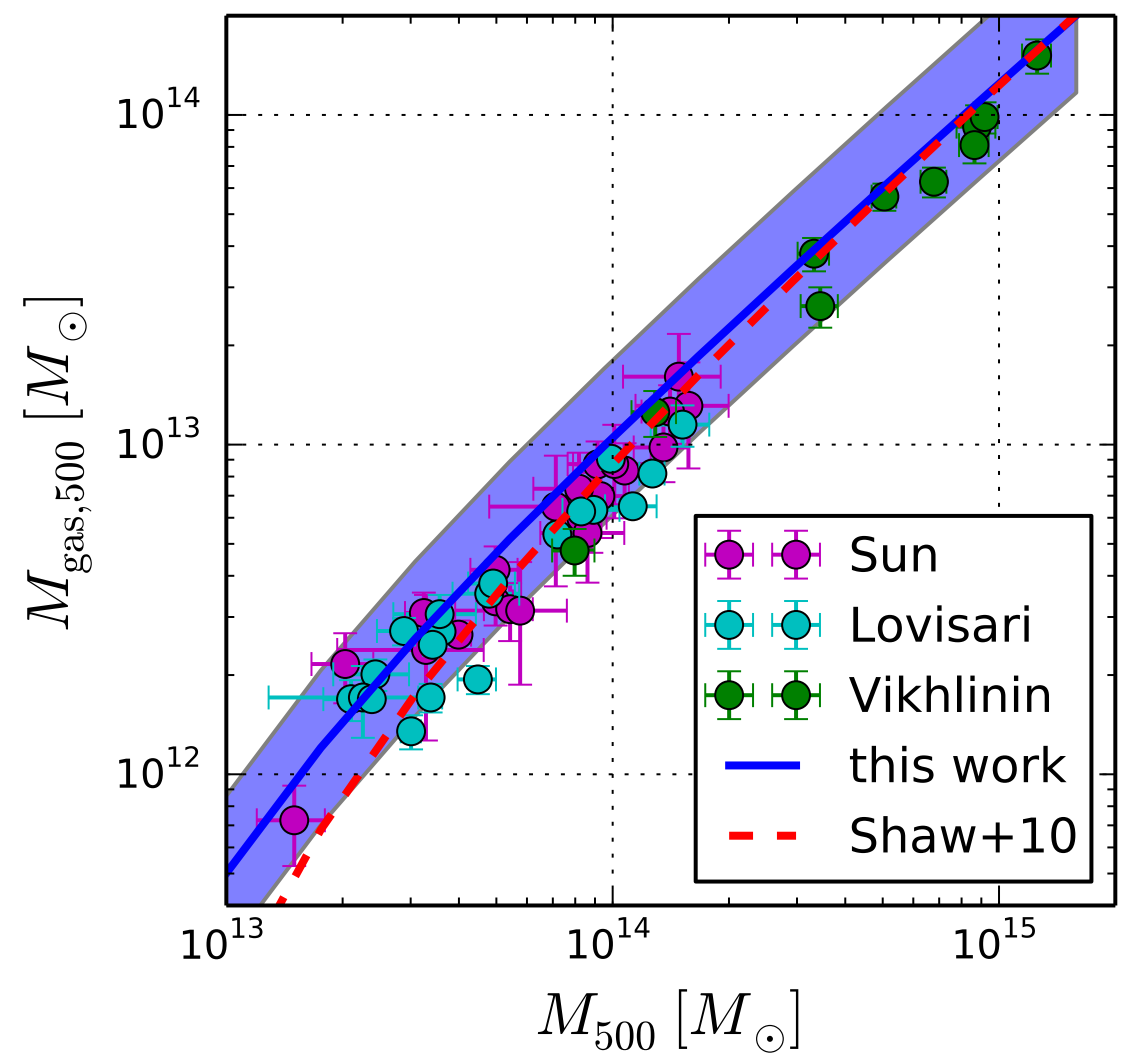


Vikhlinin+06, Sun+09, Lovisari+15: measurements of the M_{gas}-M relation

Constraints on the ICM physics parameters

AGN feedback

dynamical friction heating

breaking point

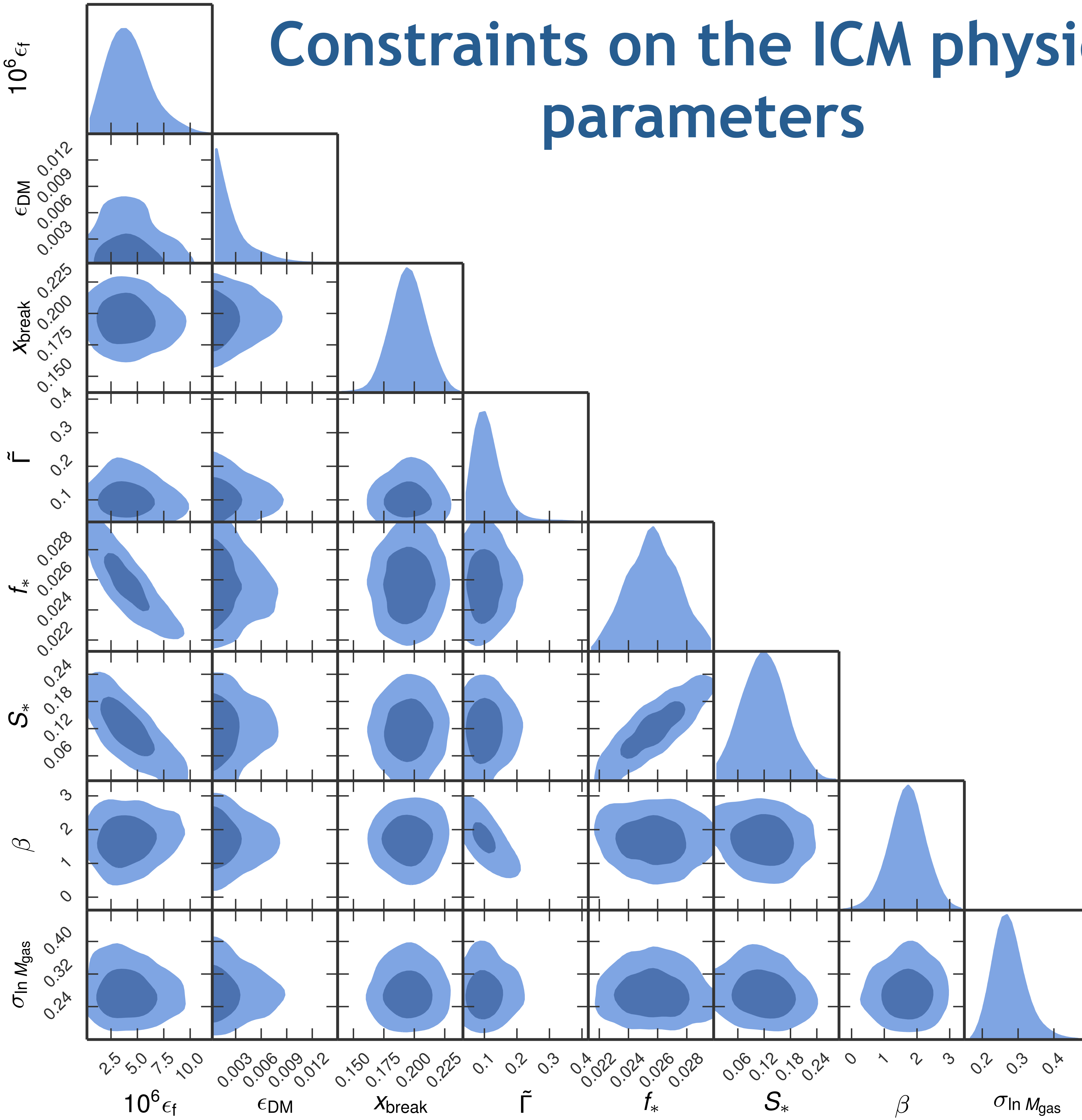
broken polytropic exponent

stellar fraction

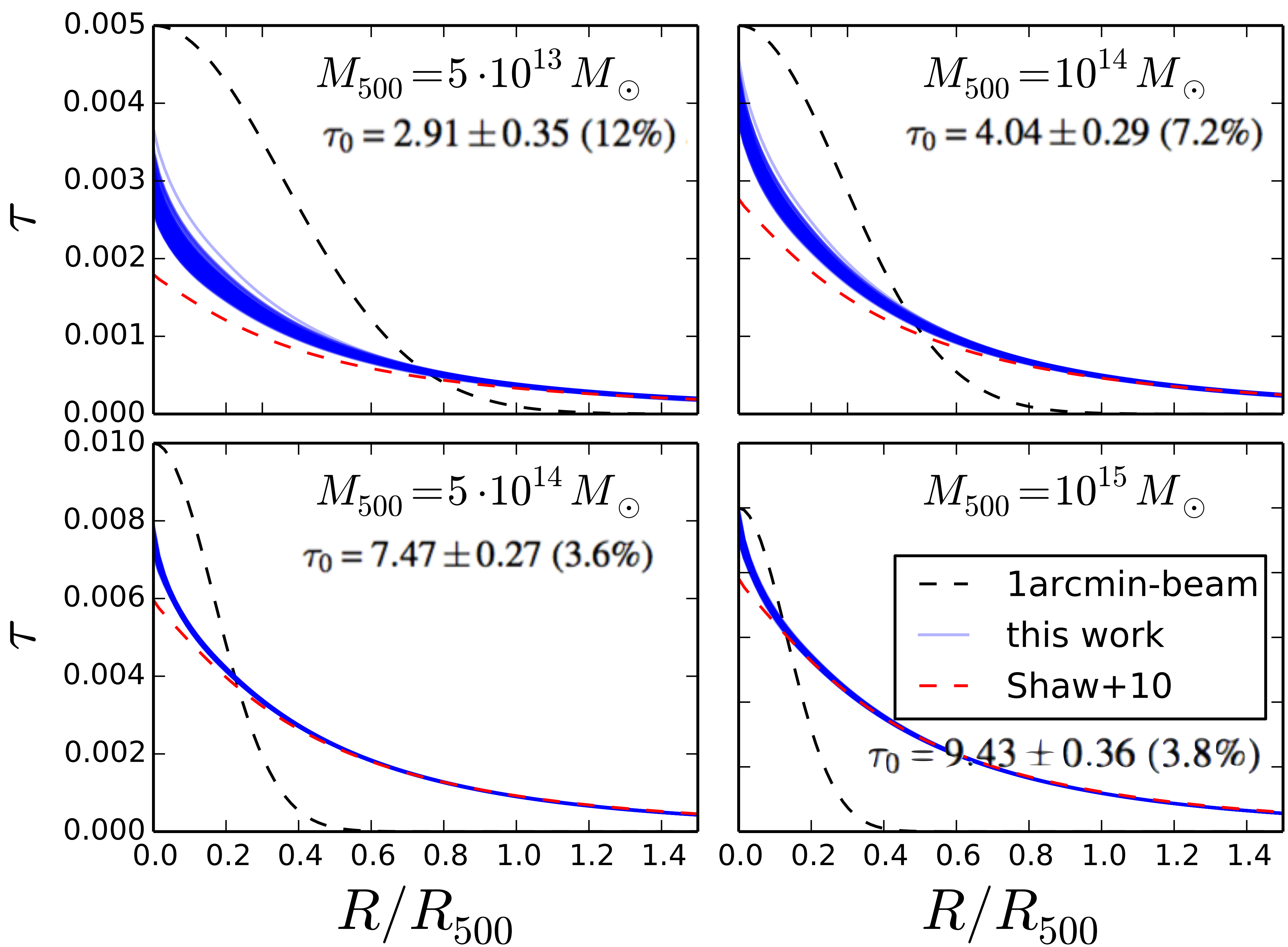
slope in stellar model

z-evolution of cooling

scatter in Mgas-M



Better than 12% constraints on the τ profile



kSZ effect is A New Kid on the Block: New Crossroad of Cosmology & ICM physics

- kSZ effect has emerged as a new (and powerful) probe of cosmology and fundamental physics. But, the power of kSZ cosmology is currently limited by an uncertainty in the optical depth of galaxy clusters.
- In this work, we (1) presented a new model (*extended Shaw model*) of the ICM that takes into account star-formation, feedback, non-thermal pressure *and cooling* and (2) calibrated the model using the state-of-the-art X-ray/SZ data.
- Our semi-analytic model is computationally efficient and can reproduce the results of the recent hydro simulations by Battaglia+16, and our best-fit model agrees well with the result of hydro sim with AGN feedback.
- Our observationally calibrated model predicts that the **τ profile to better than 12% modeling uncertainty** - considerably better than a factor of 2 uncertainty discussed in the recent literature.
- The prior on τ from our model can be implemented into future analyses of the pairwise kSZ signal and help shed insights into the nature of dark energy and modified gravity.

Further advances in our understanding of the ICM physics (focus of this workshop) will teach us more about both astrophysics and cosmology!