Investigating Cluster Astrophysics and Cosmology with Cross-Correlation of Thermal Sunyaev-Zel'dovich Effect and Weak Lensing

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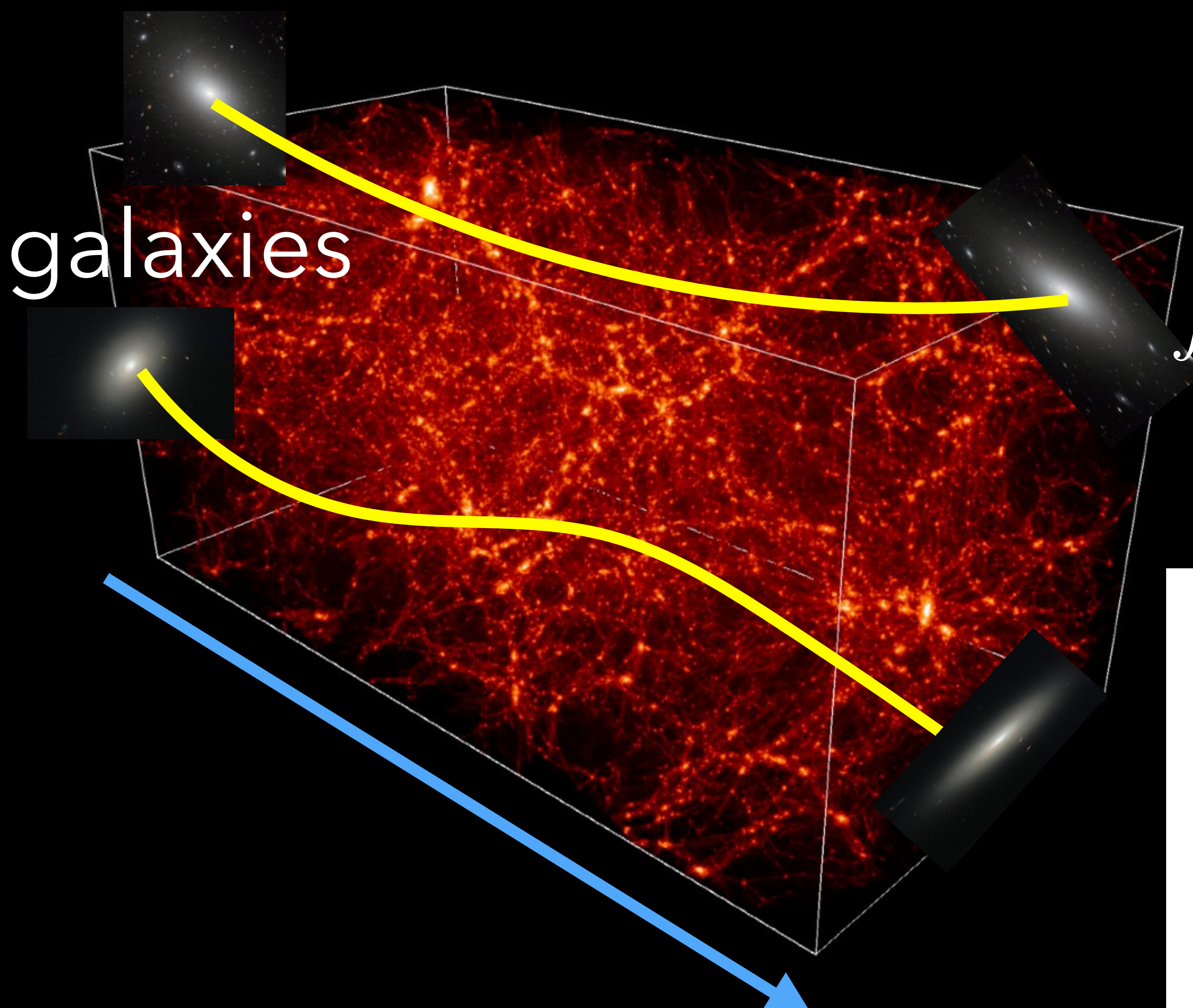
Based on ArXiv:1706.08972

Contents

Weak Lensing: Cosmic Shear

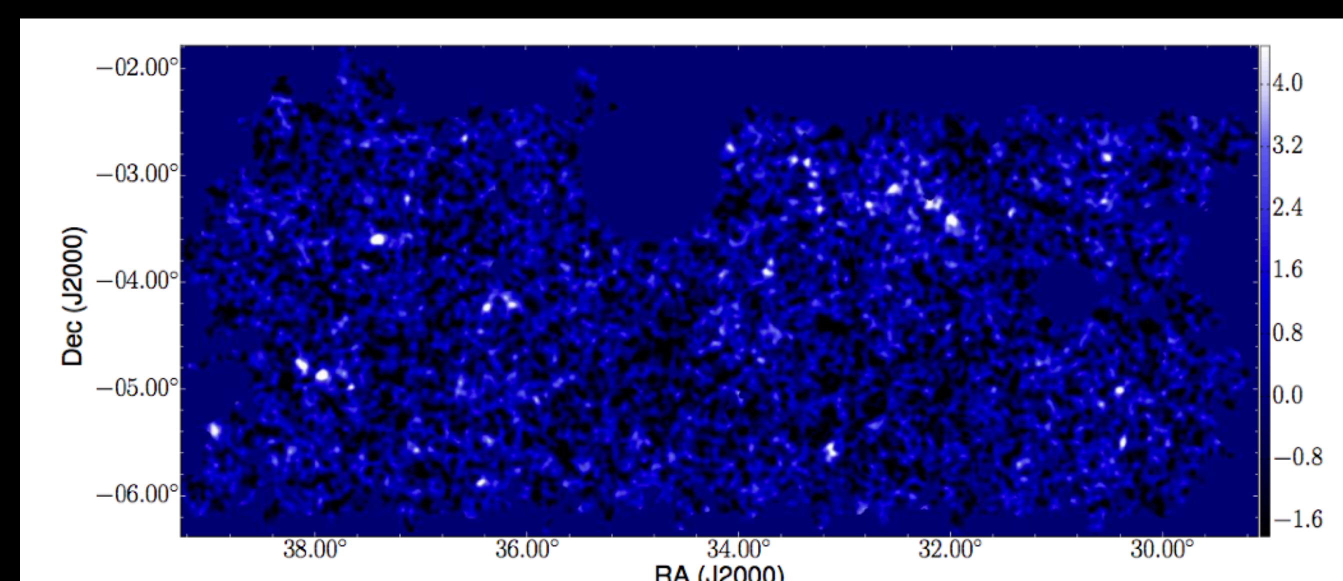
'Cosmic Shear': Gravitational lensing by large-scale structure.

unbiased tracer of dark matter.



convergence

$$\kappa(\boldsymbol{\theta}) = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \Omega_{\mathrm{m0}} \times \int_0^{\chi_{\mathrm{s}}} d\chi \underbrace{\frac{f_K(\chi_{\mathrm{s}}-\chi) f_K(\chi)}{f_K(\chi_{\mathrm{s}}) a(\chi)}}_{\text{position kernel}} \underbrace{\delta[f_K(\chi)\boldsymbol{\theta}, \chi]}_{\text{density}}$$



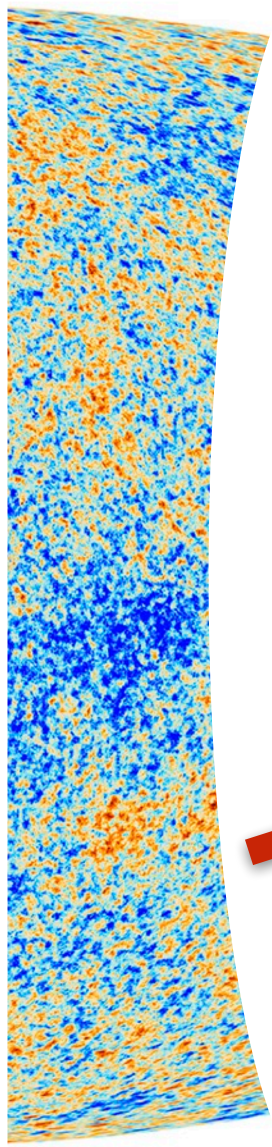
Convergence map from HSC (Oguri+, 2017)

Thermal Sunyaev-Zel'dovich Effect

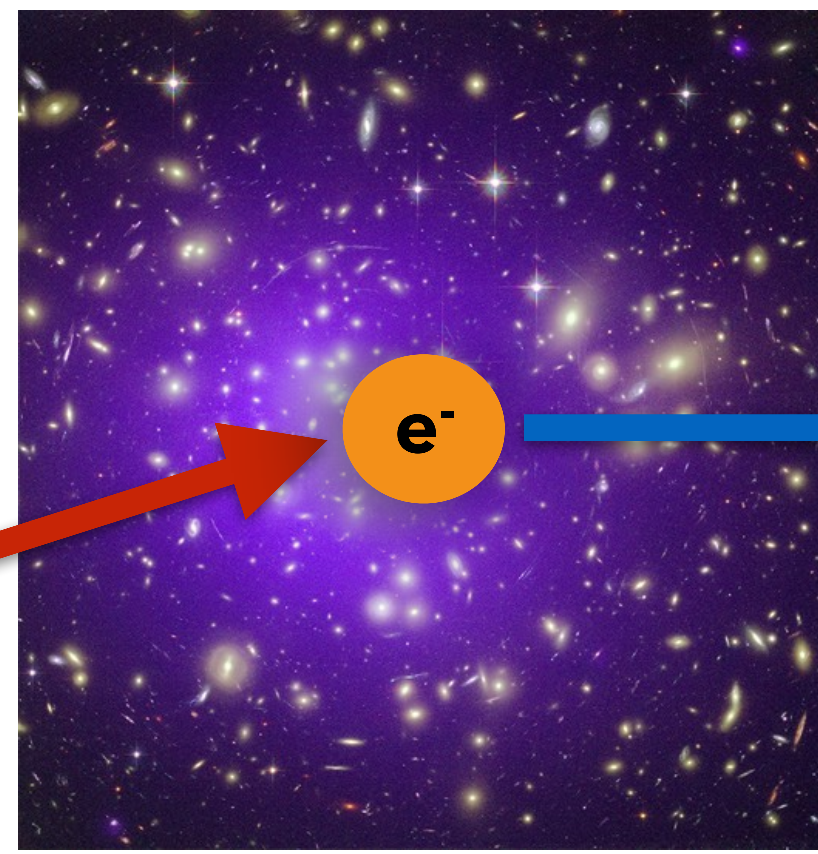
CMB z ~ 1300

Hot gas (galaxy cluster) z ~ 3 - 0

Observer z = 0



CMB photon



Variation of T

$$\frac{\Delta T}{T} = y\left(x\frac{e^x+1}{e^x-1} - 4\right), \; x = \frac{h\nu}{kT}$$

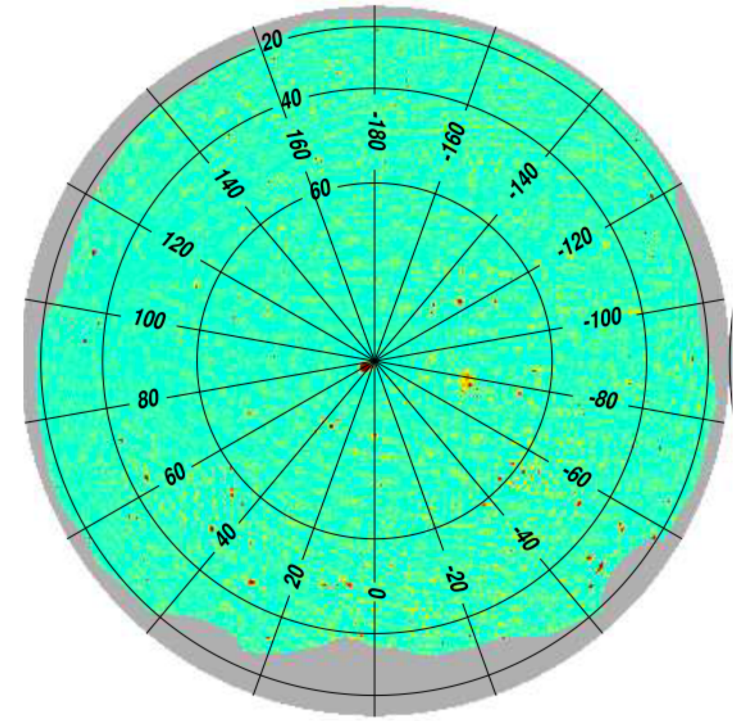
Compton-y

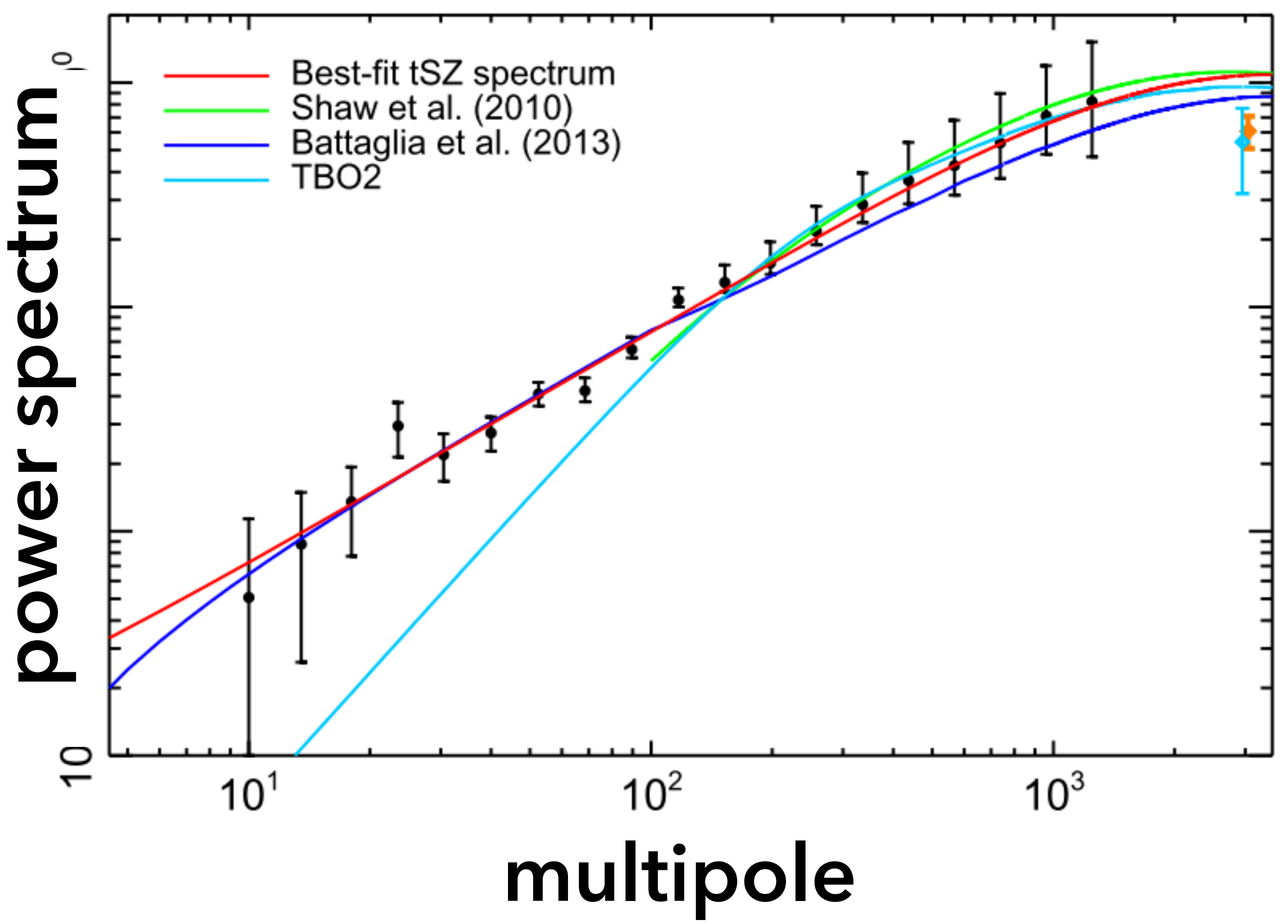
$$y = \frac{\sigma_T k_B}{m_e c^2}\int n_e T_e dl$$

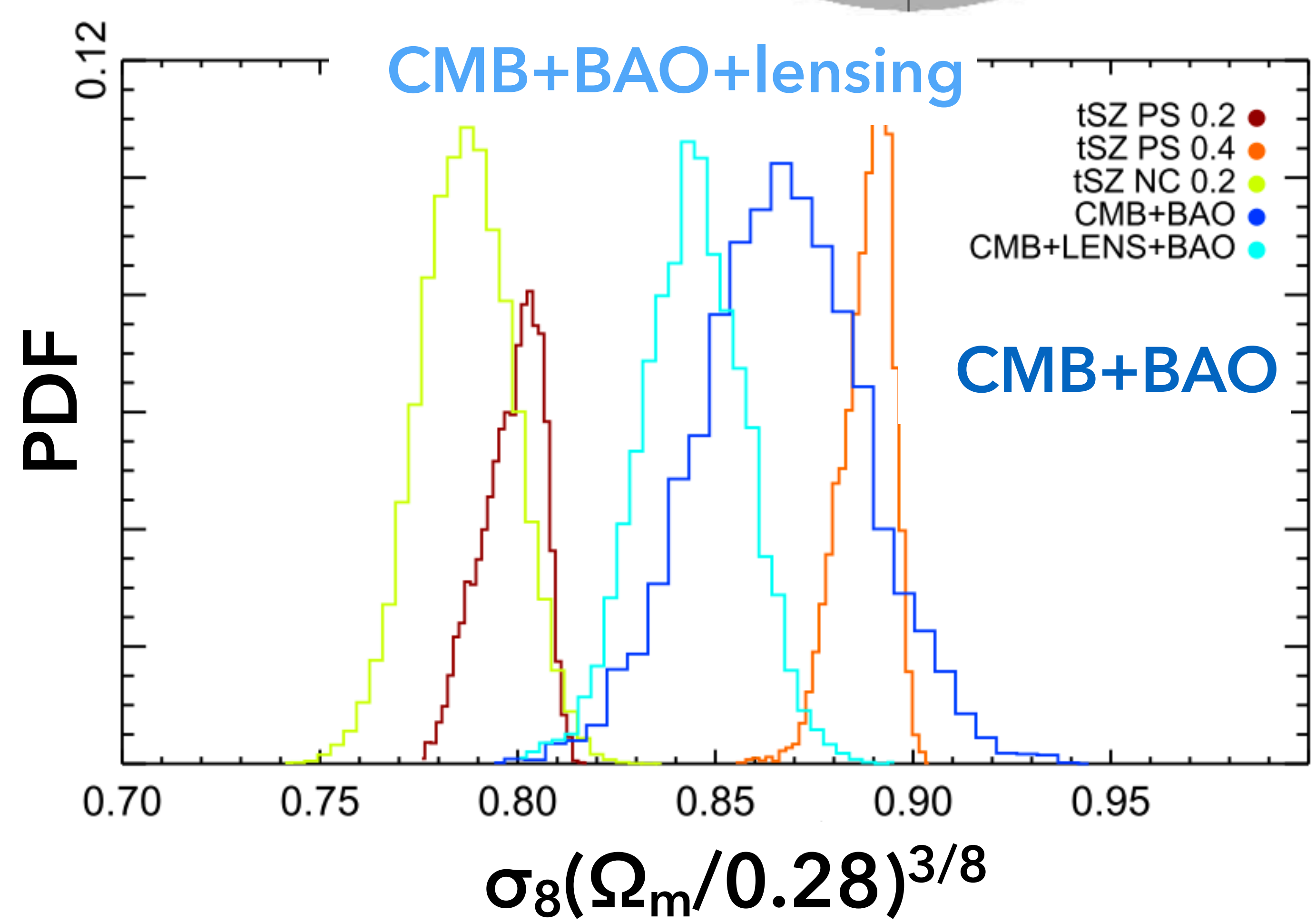
Sunyaev and Zel'dovich (1972, 1980)

tSZ by Planck

- The all-sky thermal Sunyaev-Zel'dovich effect has already been measured by Planck.
  The power spectrum of Compton-y can place a **tight constraint on σ_8.**
  (c.f. Komatsu and Seljak, 2002).







Planck Col. (2015)

Cross-Correlation of tSZ and WL

- **Astrophysics and Cosmology with WL and tSZ**
  Power spectra of WL and tSZ give us information of the large-scale structure in the Universe and are very useful to constrain cosmological models. However, **the combination of them (cross-correlation) provides us with additional and independent information.**
  Furthermore, tSZ directly reflects gas distribution. We can obtain implications on **cluster astrophysics** as well.

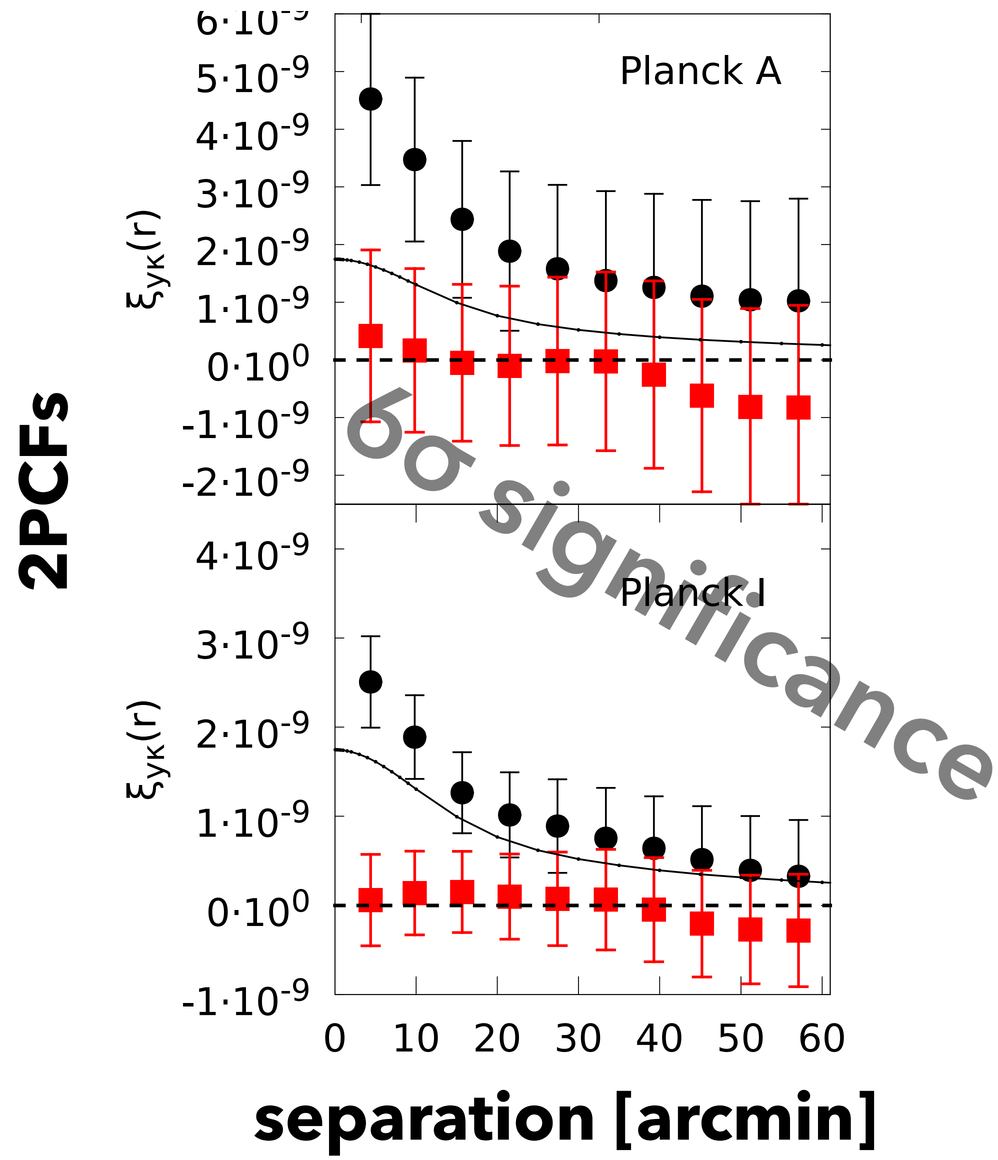
- **From the observational aspect**
  Cross-correlation does not suffer from noise auto-correlation in the assumption that noises of different observables are uncorrelated.

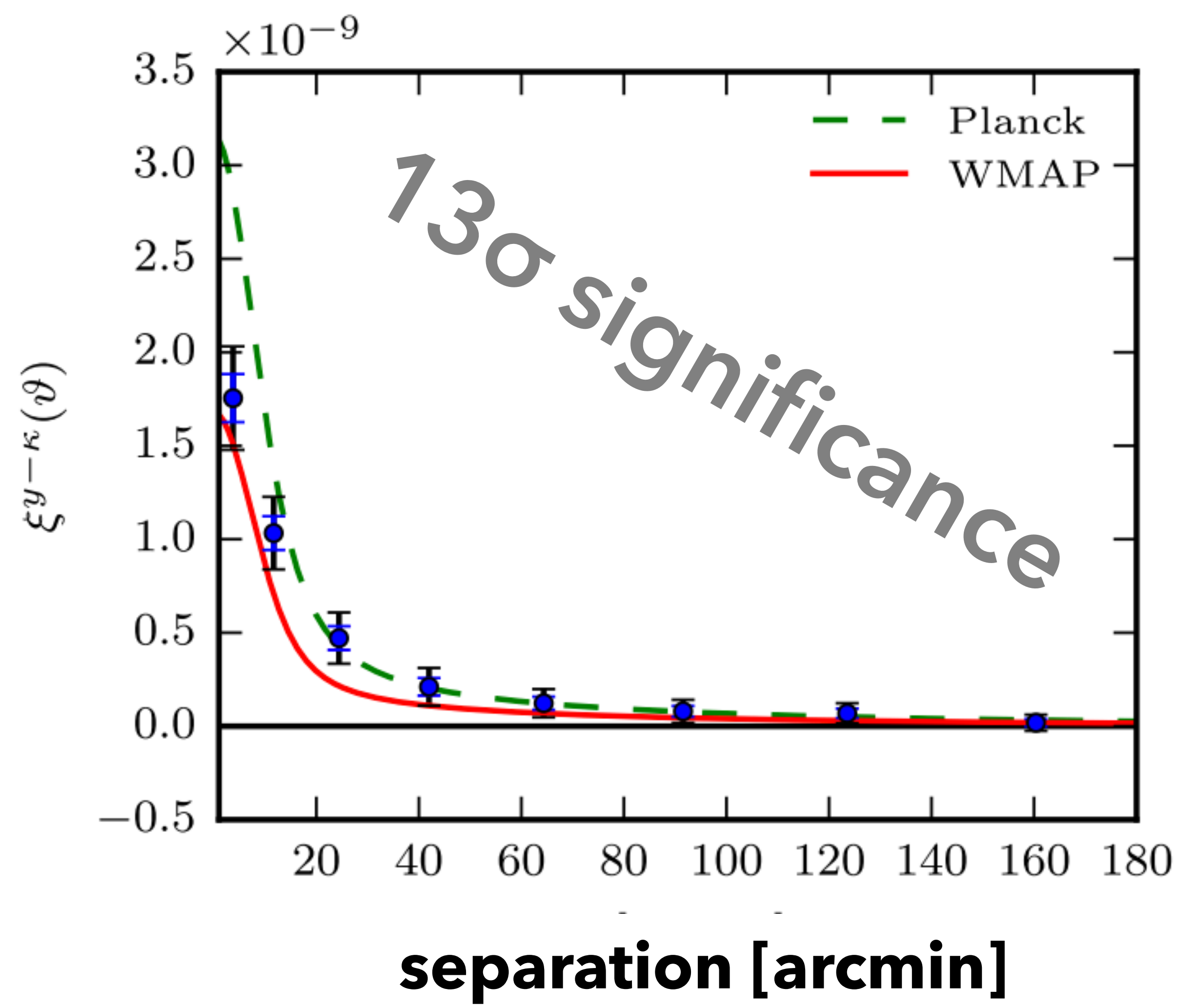
$$\langle A_{\mathrm{obs}} B_{\mathrm{obs}} \rangle = \langle AB \rangle, \;\; A_{\mathrm{obs}} = A + N_A, \;\; B_{\mathrm{obs}} = B + N_B$$

Measurements of Cross-Correlation

✦Several groups have already reported the detection of the cross-correlation.

- CFHTLenS x Planck (Van Waerbeke+, 2014)
- RCSLenS x Planck (Hojjati+, 2016)





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1. Weak Lensing, thermal Sunyaev-Zel’dovich Effect
   and cross-correlations

2. Construction of Model and Covariance

3. Results: Implications to Cluster Astrophysics
   and Cosmology

4. Summary

Models

✦First, let us consider the model of the signal.

- **Theoretical prediction of auto- and cross-power spectra**

  Spectra can be decomposed into two terms based on halo model.

well calibrated by N-body sim.

Tinker et al. (2008, 2010)

$$C_\ell^{y\kappa} = C_\ell^{y\kappa(1\mathrm{h})} + C_\ell^{y\kappa(2\mathrm{h})},$$

$$C_\ell^{y\kappa(1\mathrm{h})} = \int_0^{z_\mathrm{dec}} dz\, \frac{d^2V}{dz d\Omega} \int_{M_\mathrm{min}}^{M_\mathrm{max}} dM\, \underline{\frac{dn}{dM}}\, \underline{y_\ell(M,z)}\kappa_\ell(M,z),$$

$$C_\ell^{y\kappa(2\mathrm{h})} = \int_0^{z_\mathrm{dec}} dz\, \frac{d^2V}{dz d\Omega} P_\mathrm{m}(k=\ell/d_A, z)$$

$$\times \int_{M_\mathrm{min}}^{M_\mathrm{max}} dM\, \underline{\frac{dn}{dM} b(M,z)}\kappa_\ell(M,z)$$

$$\times \int_{M_\mathrm{min}}^{M_\mathrm{max}} dM\, \underline{\frac{dn}{dM} b(M,z)}\, \underline{y_\ell(M,z)}.$$

Fourier transform of Compton-y of halo

➡We need pressure profile of halo.

Analytic Model of Gas Profiles

✦We employ the analytic gas density/pressure profile model of individual halo, which is proposed by Shaw+ (2010) and improved by Flender+ (2017).
The model contain six free parameters,
each of which describes a physical process
(e.g., SNe/AGN feedback, non-thermal pressure).

‣ **Basic ideas**

DM density follows NFW profile. $\rho_{\rm DM} = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

Gas profile is determined from Euler eq. with polytope relation.

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

hydro. sim. suggests Γ~1.2

To determine the normalization,

stellar and AGN feedback

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

Energy of gas

dynamical friction between gas and DM

work by gas expansion

Gas Profile Model

✦Non-thermal pressure

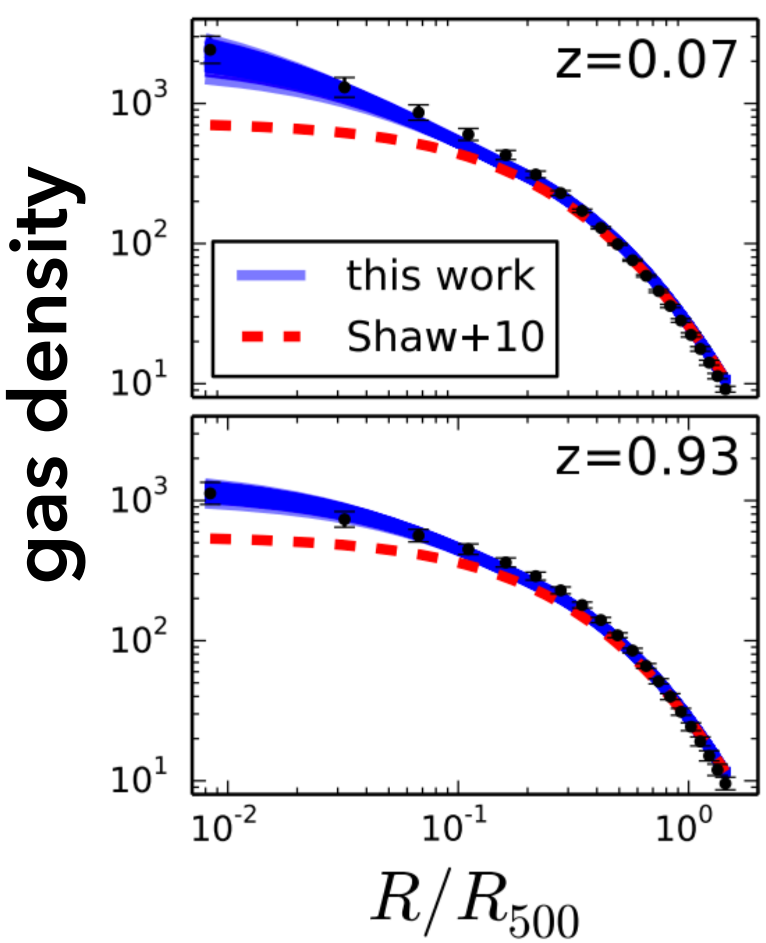
Turbulent motion also can support the self-gravity of the halo.

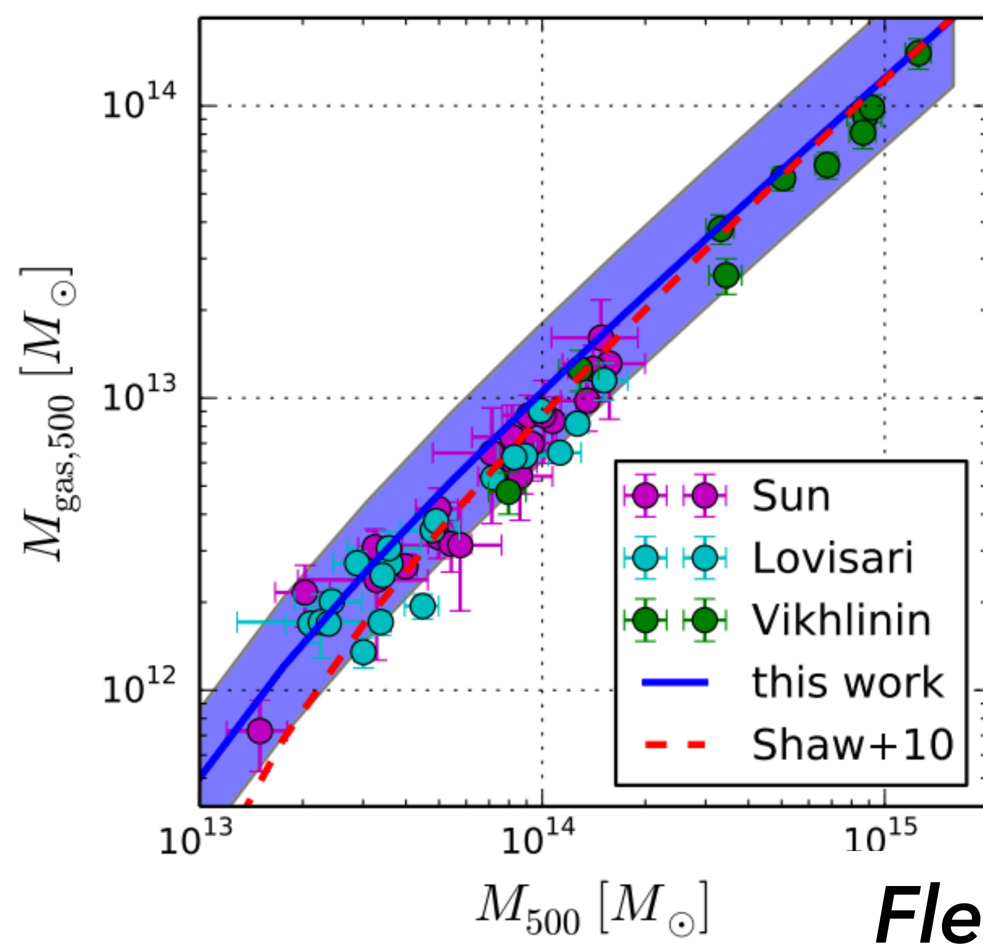
This effect is parametrized as,

$$\frac{P_{\rm nth}}{P_{\rm tot}}(r) = \alpha(1+z)^{\beta}\left(\frac{r}{R_{500}}\right)^{0.8}$$

Note: only thermal pressure contributes as tSZ.

- Free parameters are calibrated by gas density and gas fraction of X-ray clusters. We fix parameters other than alpha.





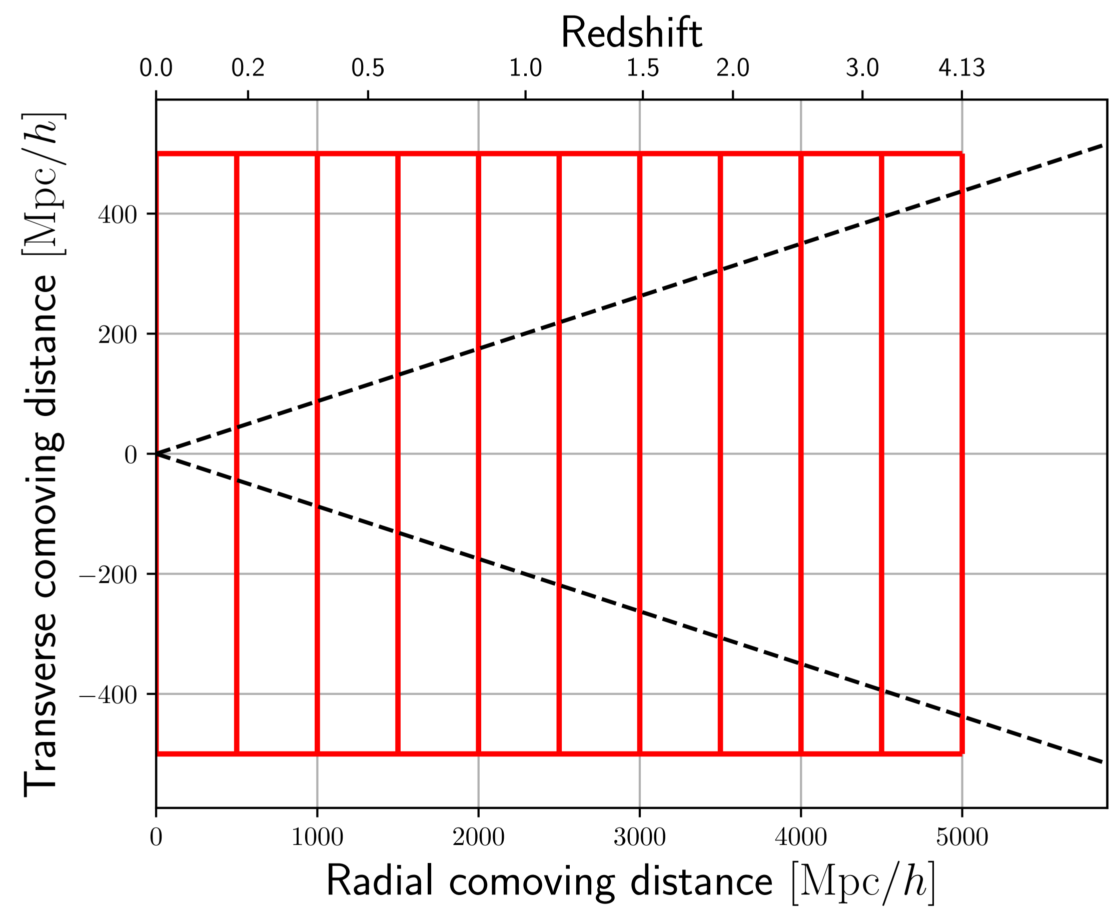
Flender+ (2017)

Covariance Estimation

✦**Let us move on covariance matrix estimation.**

- **Simulations**

  In order to estimate covariance matrix, we employ **N-body simulations.**
  Box size: (1 Gpc/h)^3
  \# of particles: 2048^3
  Cosmology: Planck 2015
  The snapshots cover up to z=4.13.

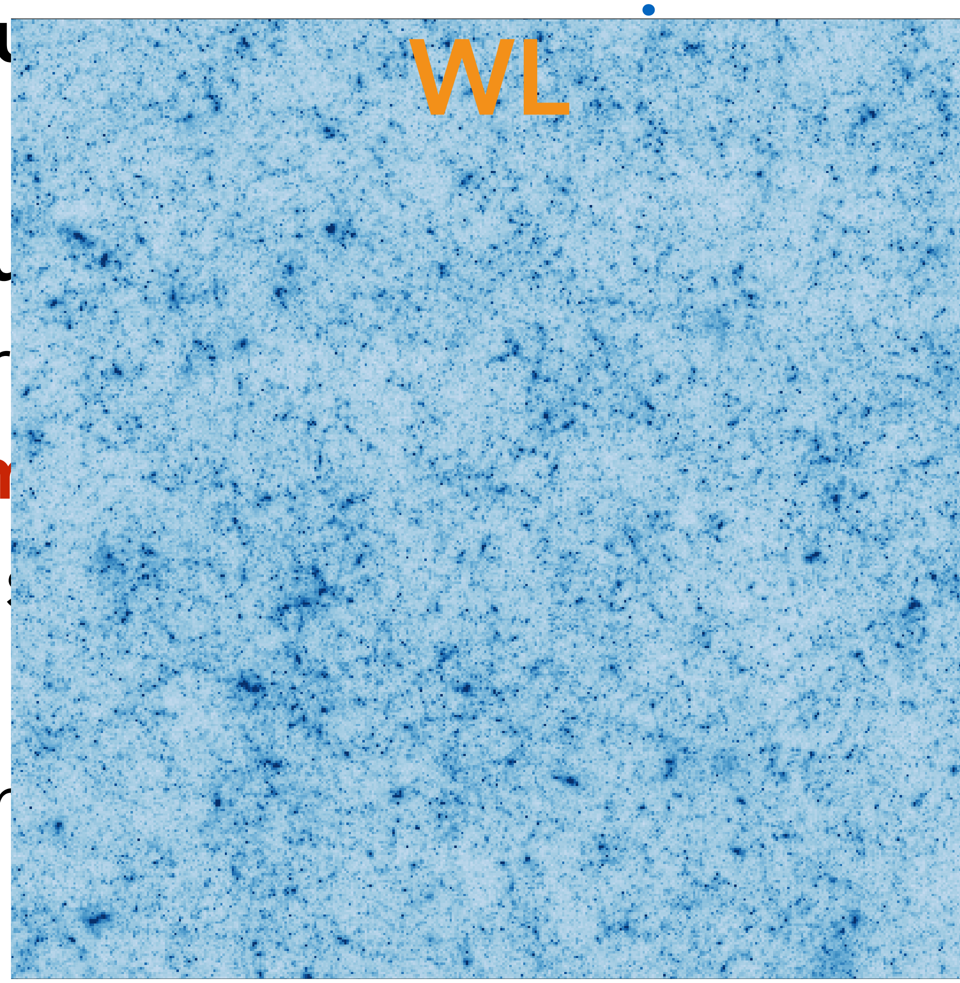


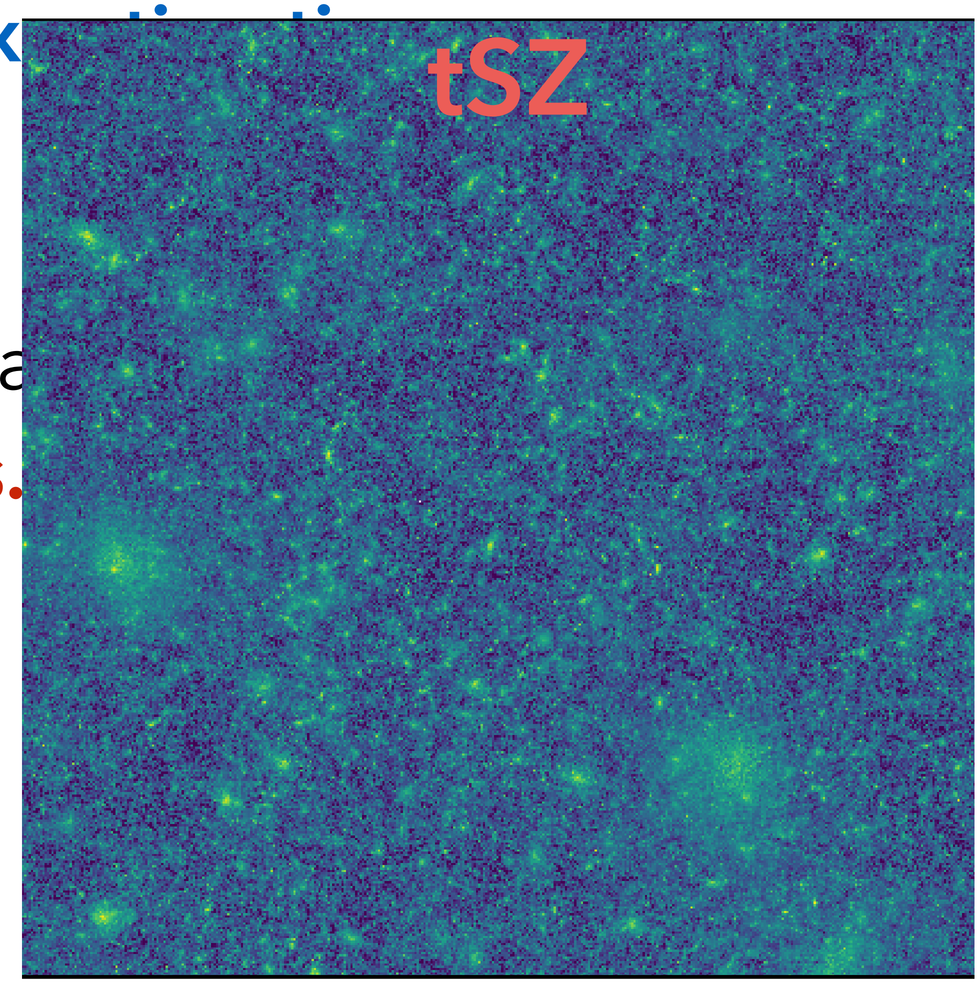
- **Mock observations**

  WL: Multiple plane method (White & Hu, 2000)
  tSZ: First, we find halos with Rockstar (Behroozi+, 2013).
  For each halo, we solve the analytic model, and assign thermal pressure to the member particles.

Covariance Estimation

✦L et u … trix …





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- **Mock observations**

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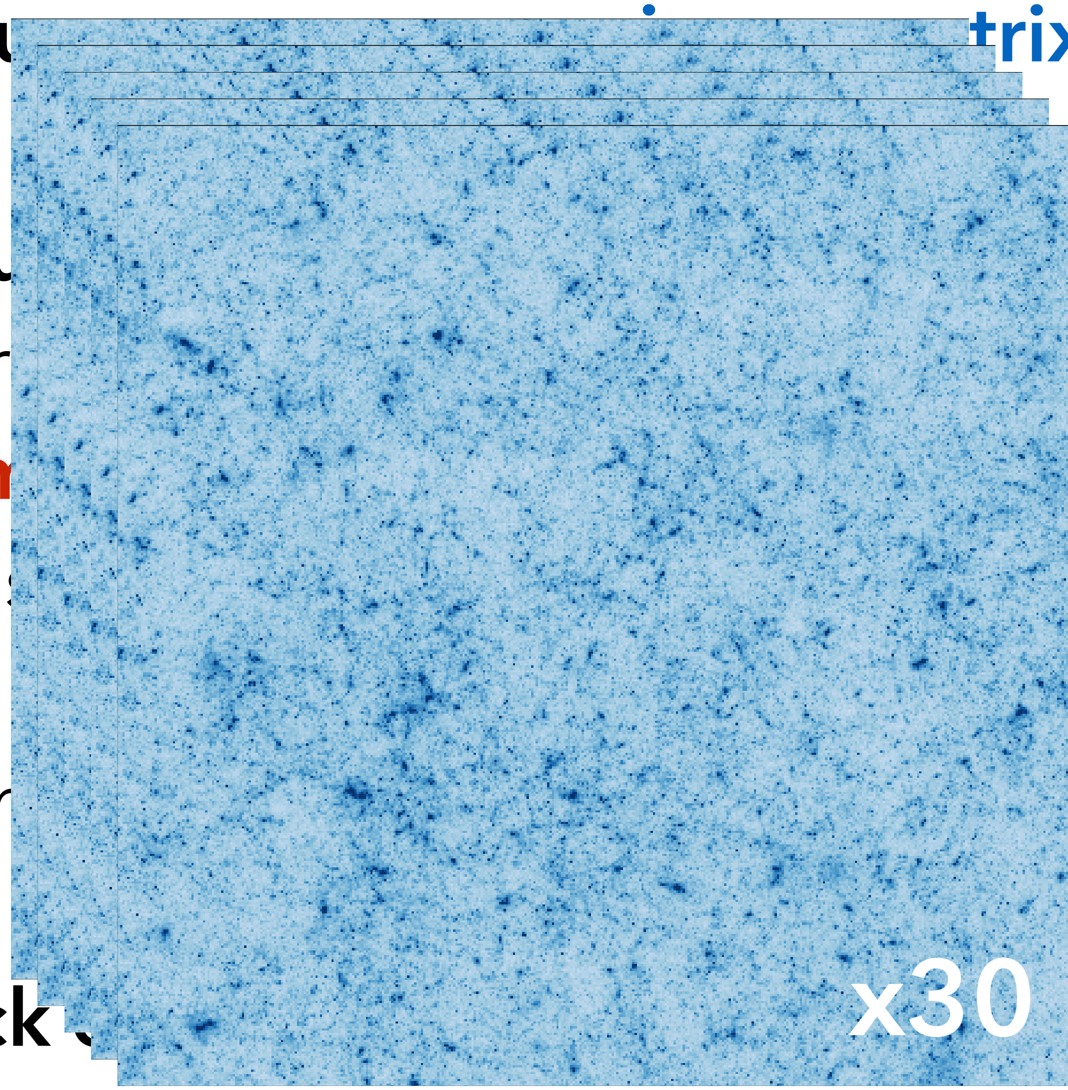
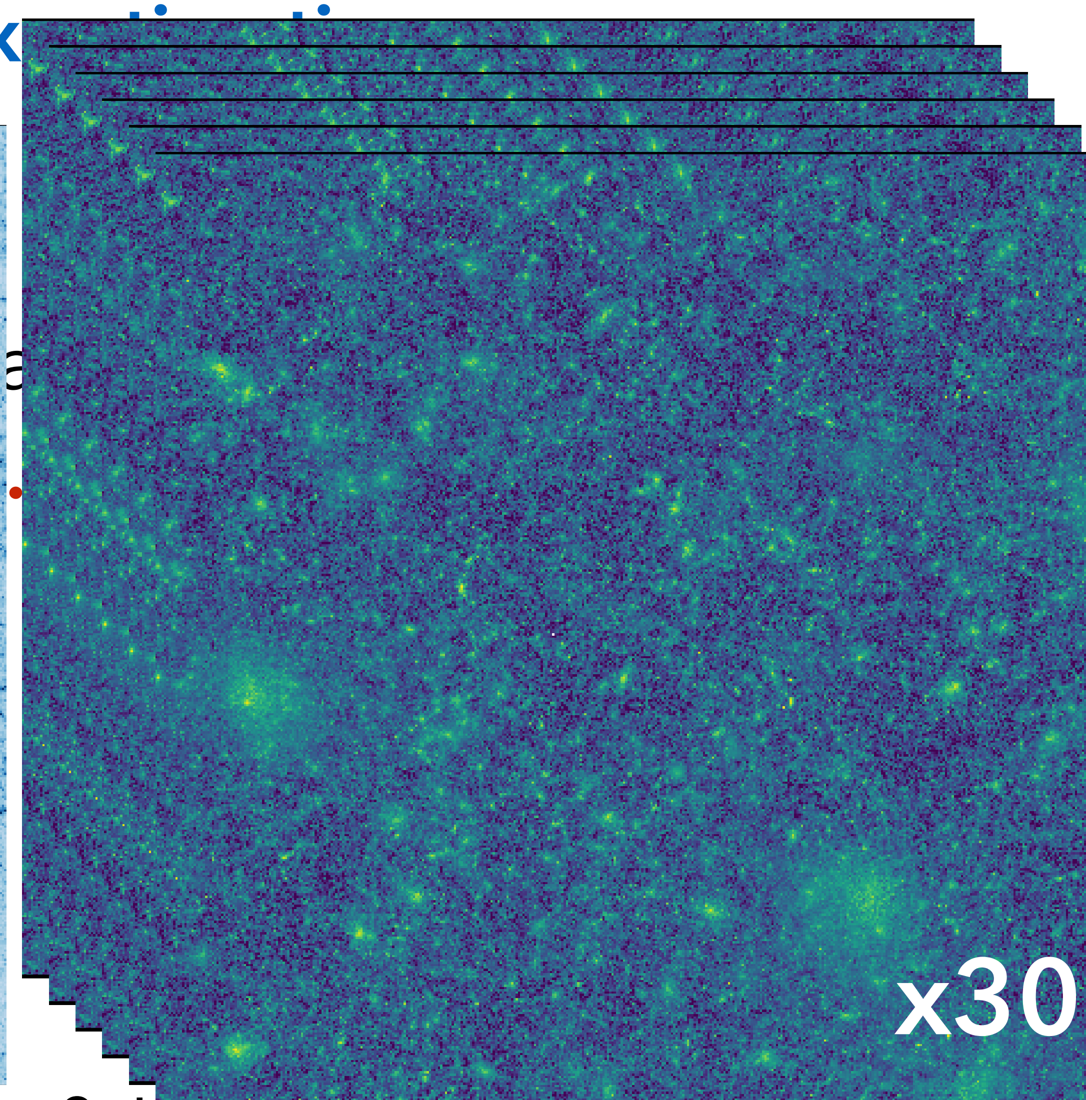
Covariance Estimation

✦Let u ... trix





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Box

of

Cosm

• Mock

WL: Multiple plane method (White & Hu, 2000)

tSZ: First, we find halos with Rockstar (Behroozi+, 2013).

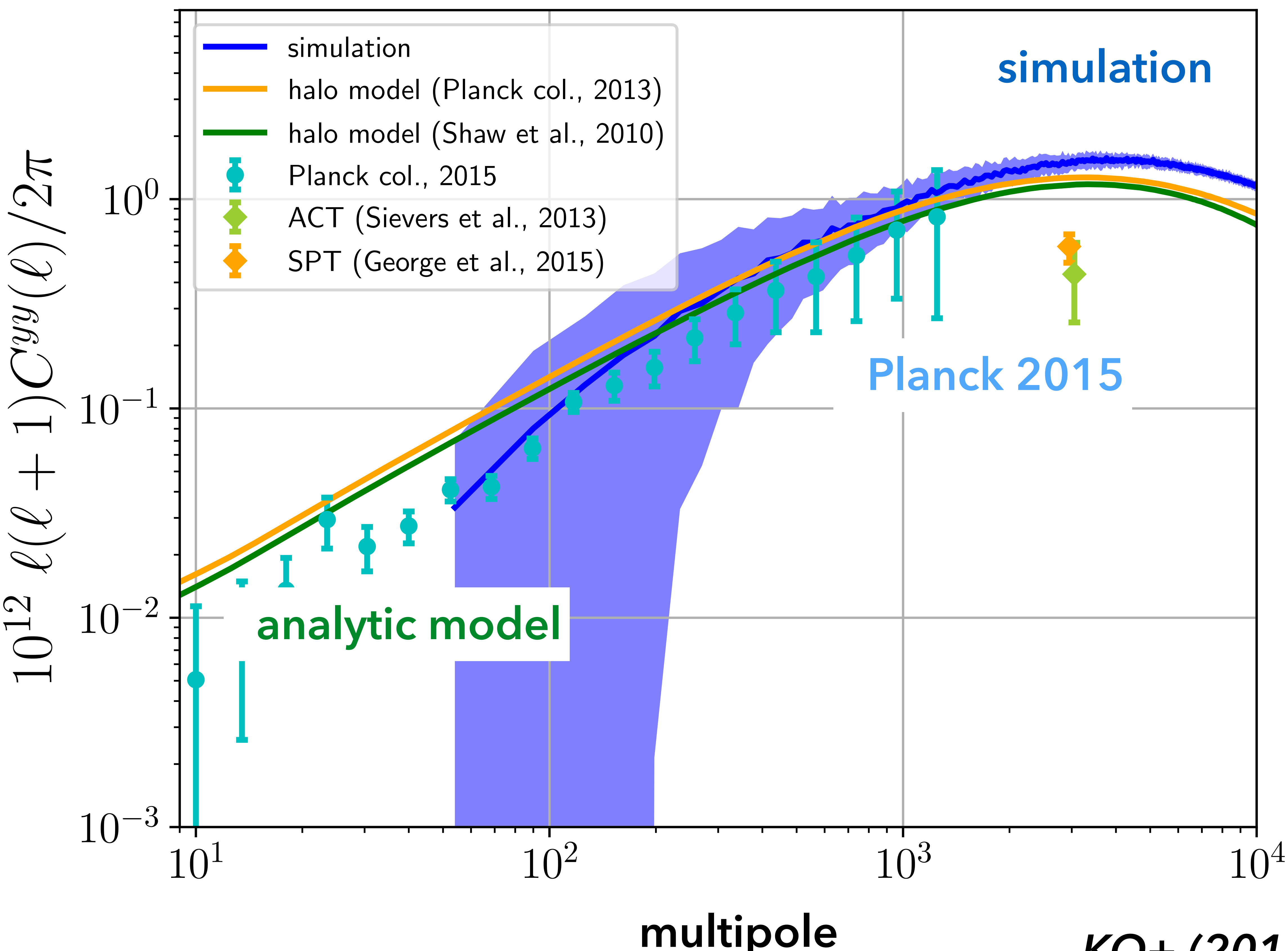
For each halo, we solve the analytic model, and assign

the covariance matrix

thermal pressure to the member particles.

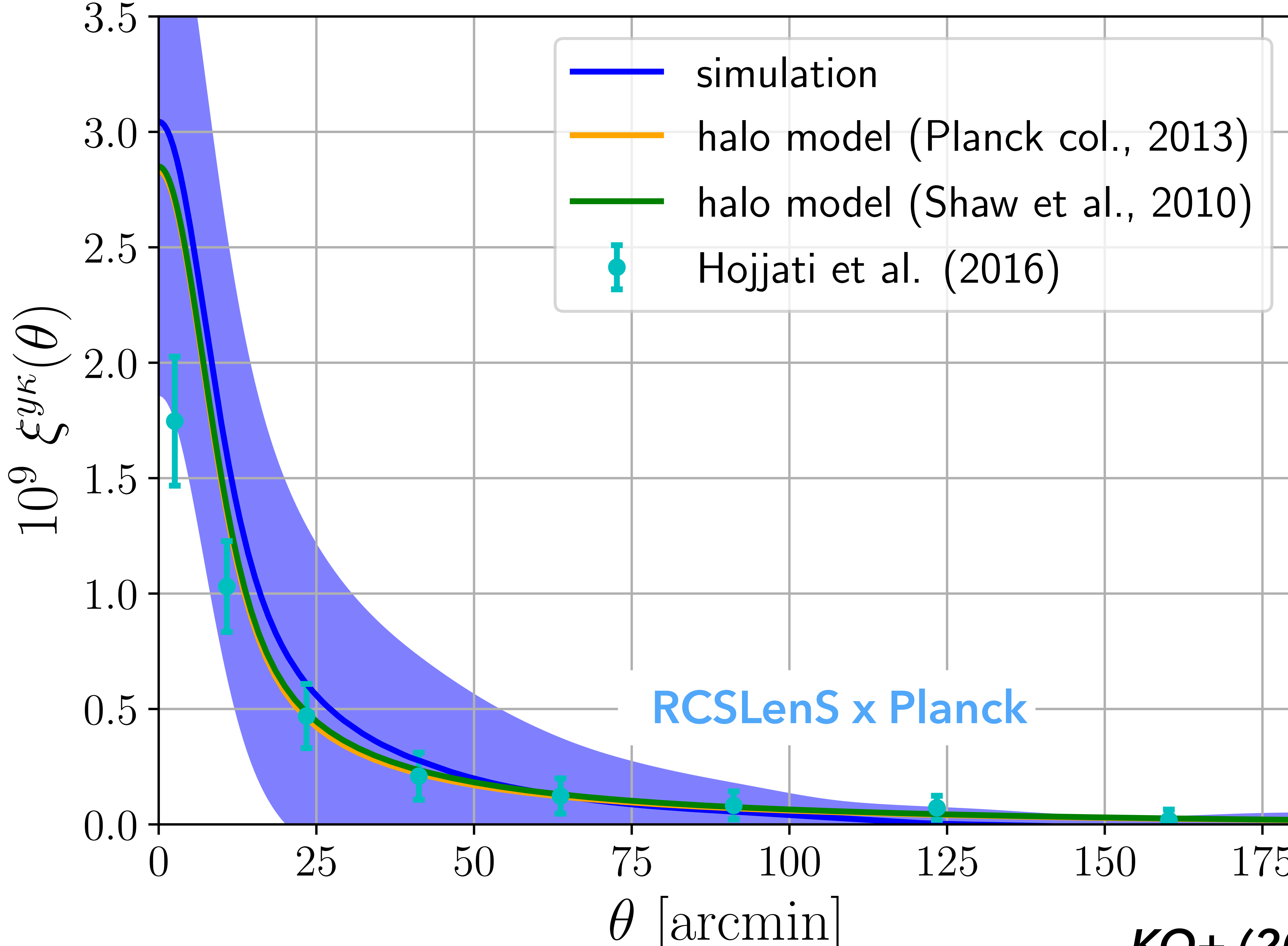
Contents

Compton-y Spectra



KO+ (2017)

Cross-Correlation Function



KO+ (2017)

Constraints on Non-thermal Pressure

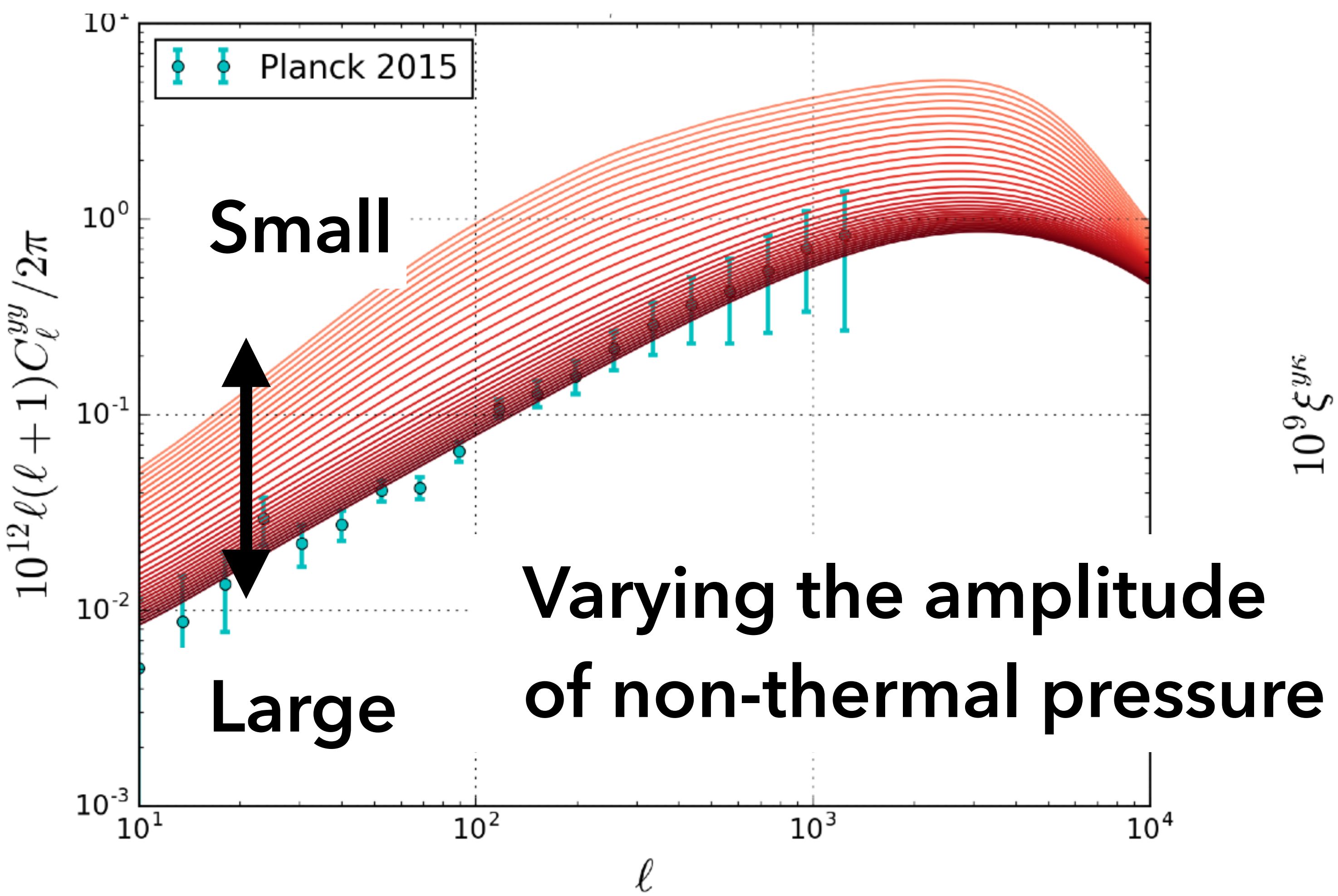
- **Non-thermal pressure**

  Non-thermal contribution is hard to measure by conventional X-ray observations of clusters.

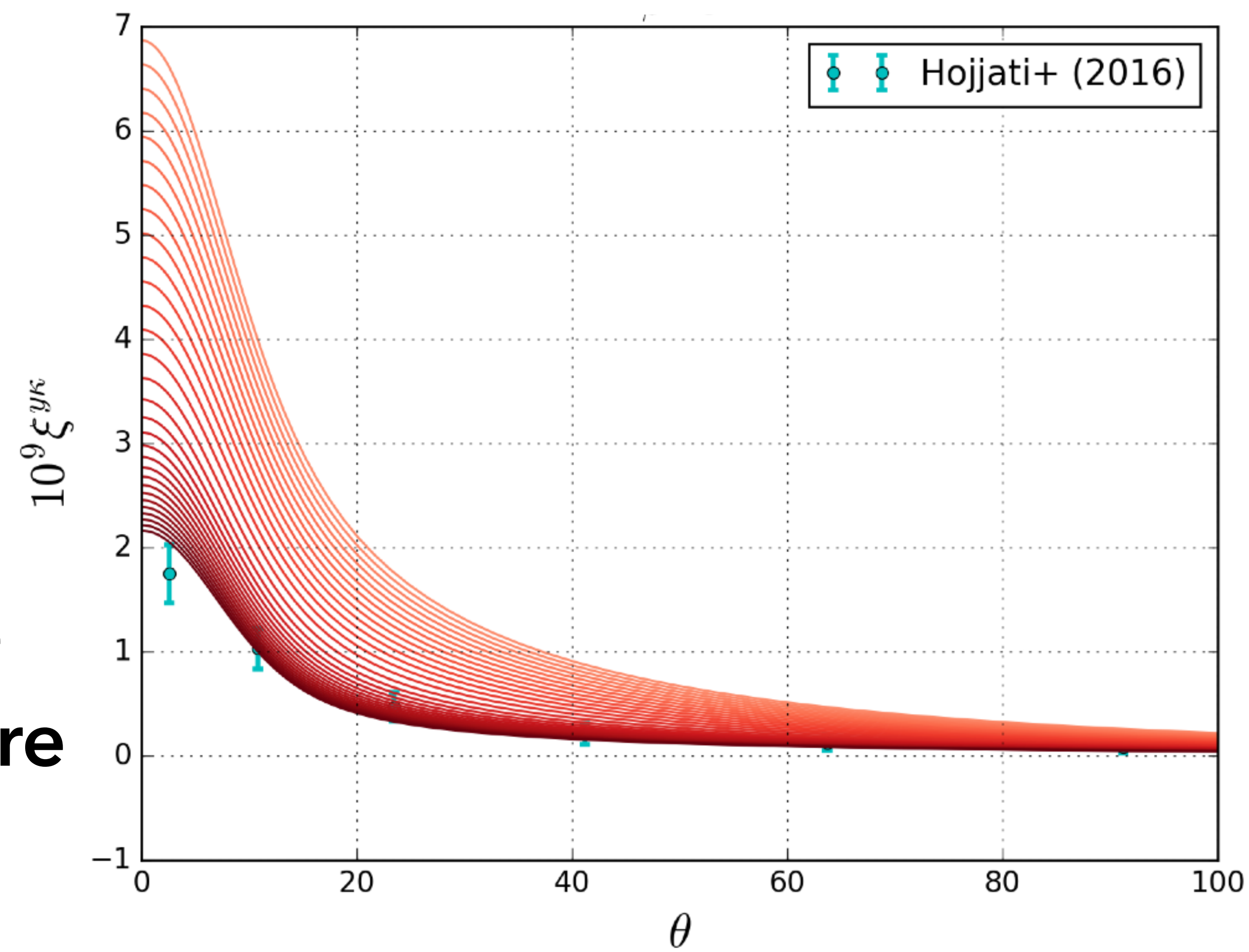
  However, the power spectrum and the cross-correlation are sensitive to it and can be used to estimate its contribution.

  Note: Non-thermal pressure and σ_8 are strongly degenerate.

Power spectrum of Compton-y

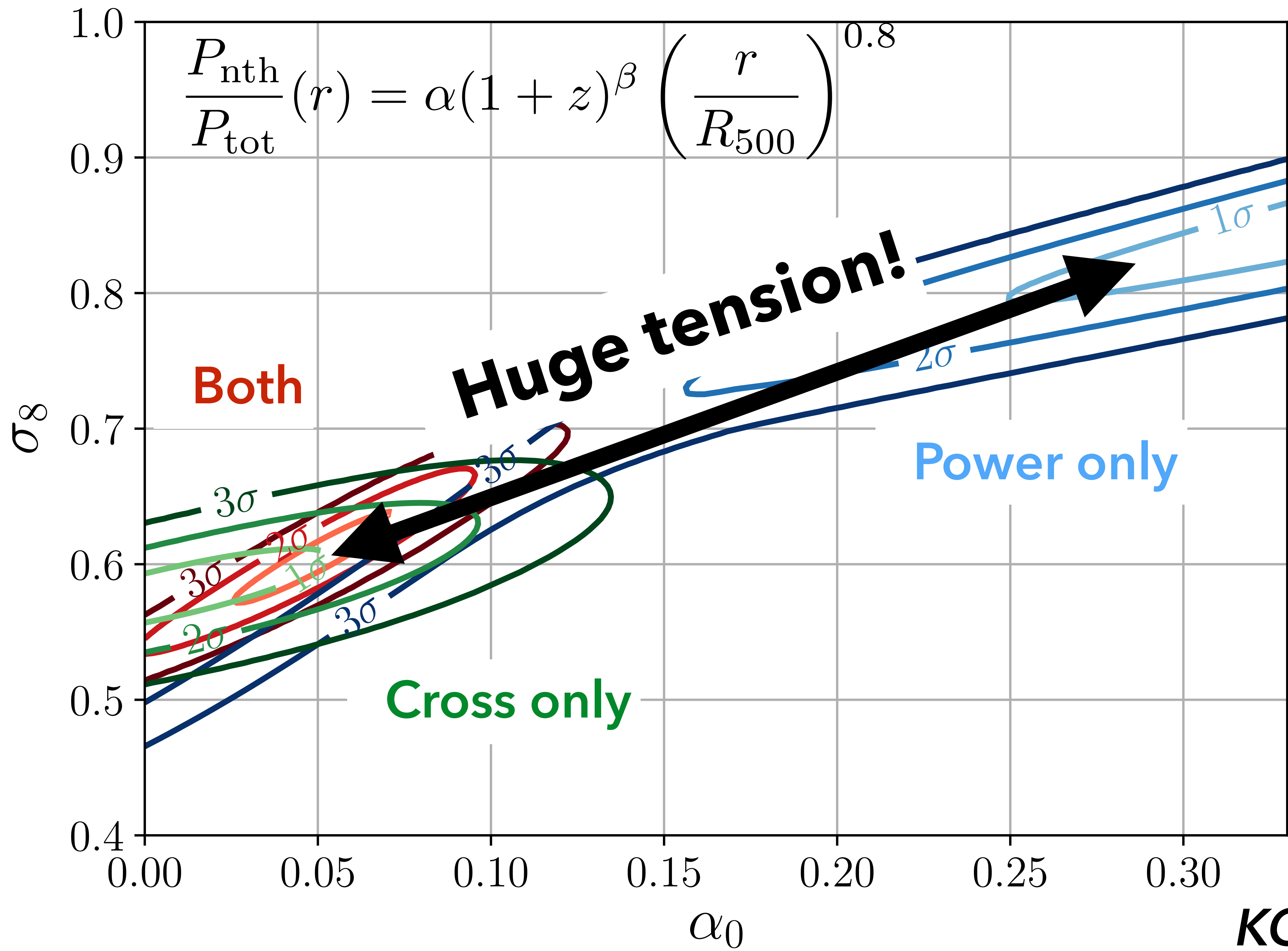


Cross-correlation function



Constraints from Cross-Correlation

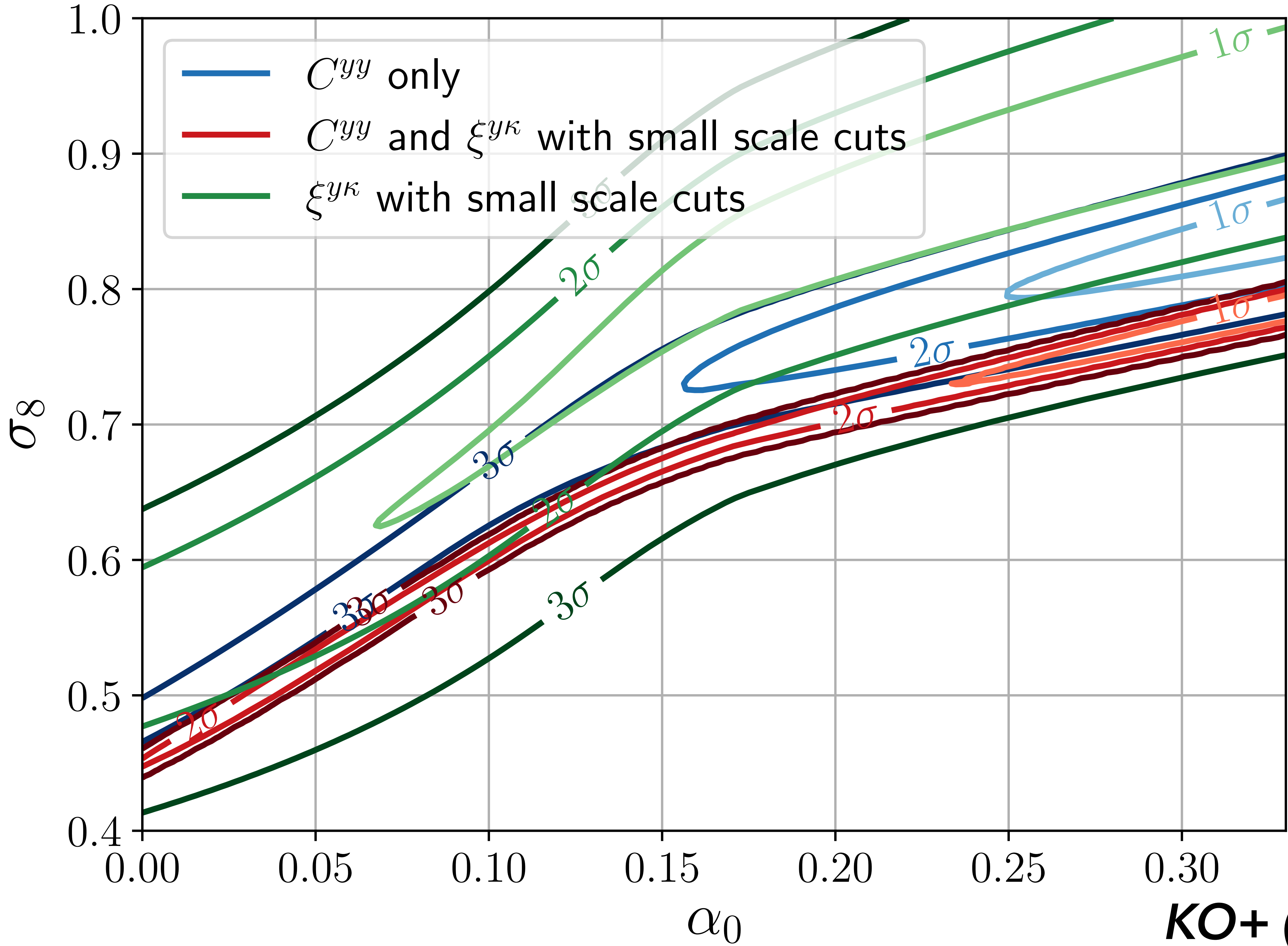
- **We can constrain the amplitude of non-thermal pressure and σ_8 with power spectrum and cross-correlation.**



KO+ (2017)

Removing Small Scales Correlations

1. **Halo model assumption breaks down.**
2. **Incomplete separation from foreground contamination**

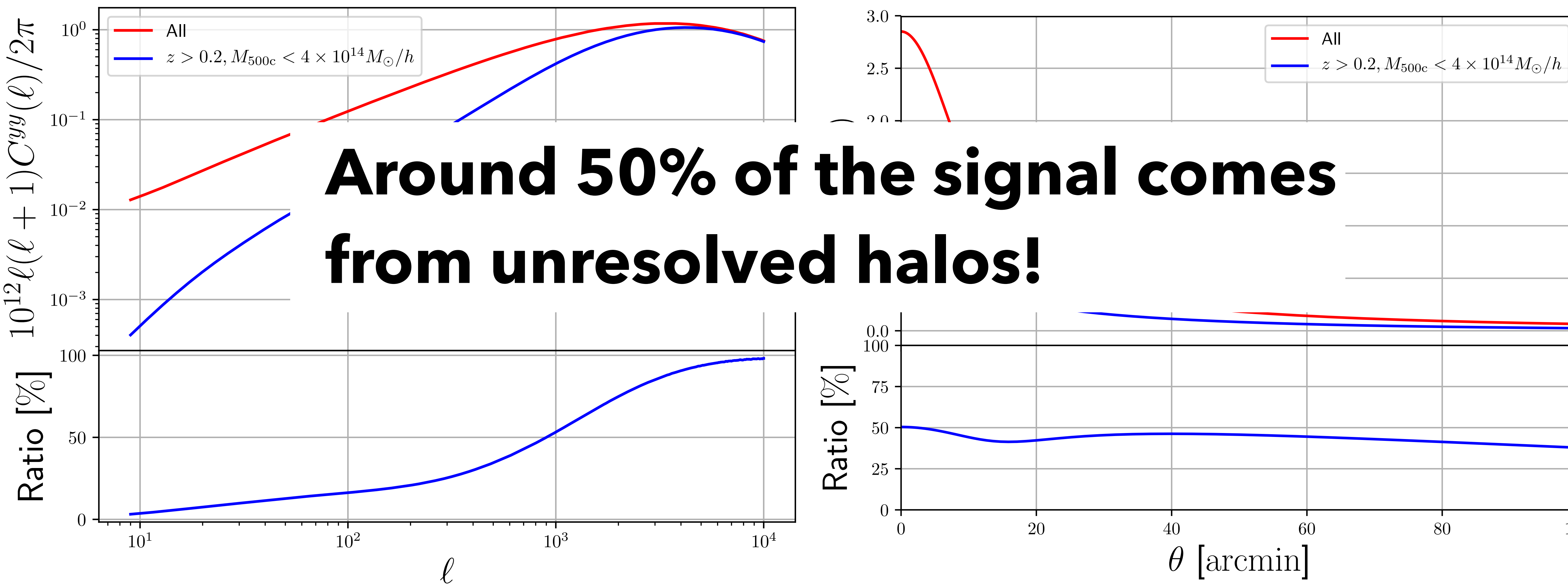


KO+ (2017)

Source of Tension

- The analytic model is calibrated with **galaxy clusters** and **low-z galaxy groups**. However, **high-z groups** contribute to a substantial fraction of signal. At this range, analytic model inevitably contains uncertainty.

- **Contribution from high-z groups (z > 0.2 and $M_{500c} < 4 \times 10^{14}$ M_{sun}/h)**

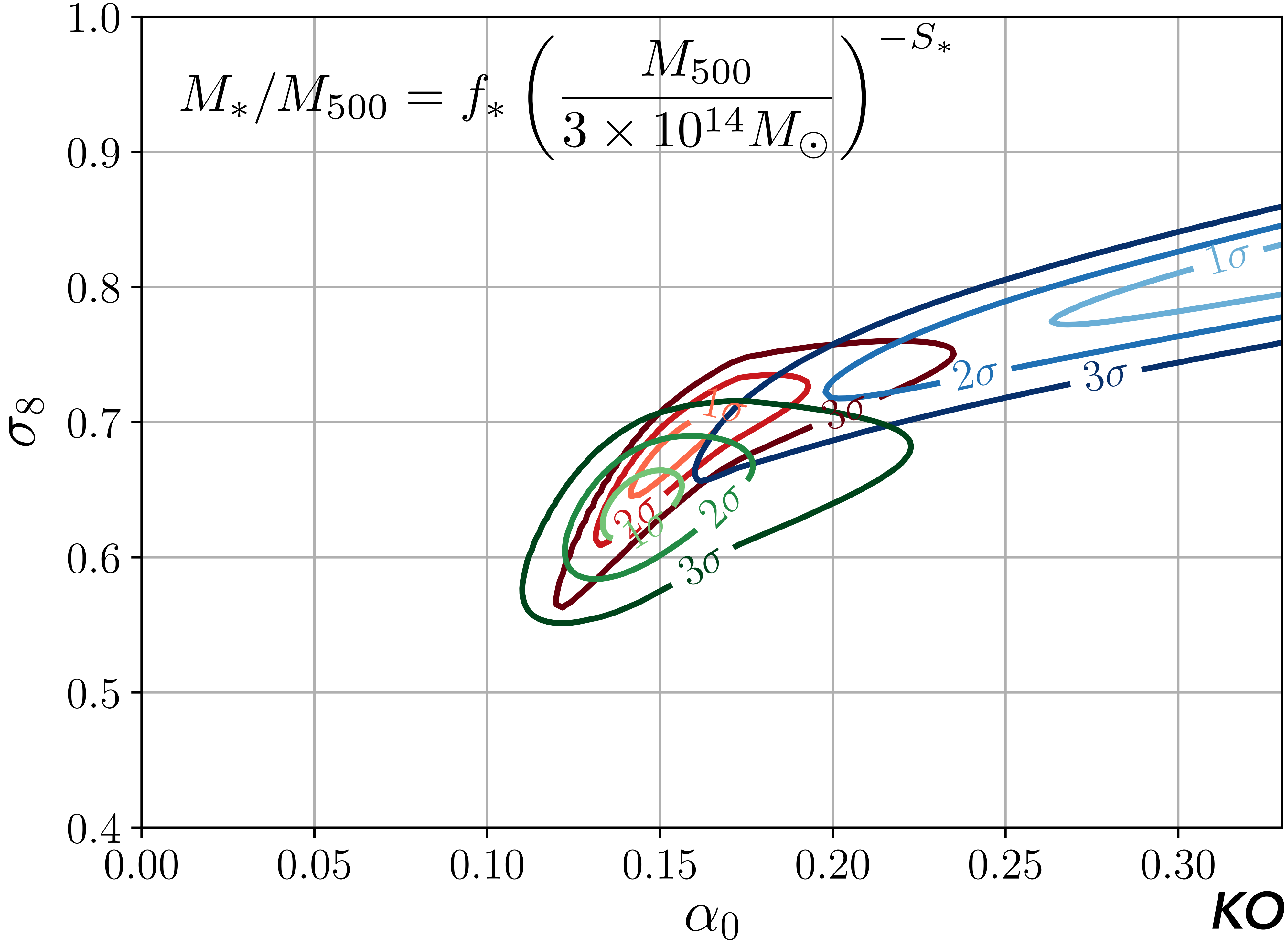


Around 50% of the signal comes from unresolved halos!

KO+ (2017)

Possible Solution of Tension

- **Let us consider an extreme case of enhanced star formation for group size halos.**
  That corresponds to severe depletion of hot gas for such halos.



KO+ (2017)

Contents

Summary

- Weak lensing and thermal Sunyaev-Zel'dovich effect are promising probes into the large-scale structure.

- Theoretical modeling and simulations can be used to estimate the signal and covariance matrix.

- The cross-correlation of them can provide us with additional information of cosmology and cluster astrophysics.

- We are currently working on the measurement of the cross-correlation with HSC and Planck data.