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

2017/11/14, IESC, Cargèse
XIII$_{th}$ School of Cosmology "The CMB from A to Z"

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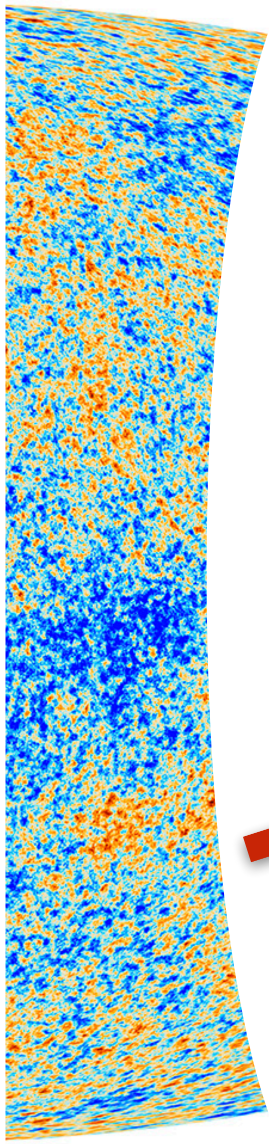
Based on ArXiv:1706.08972

Contents

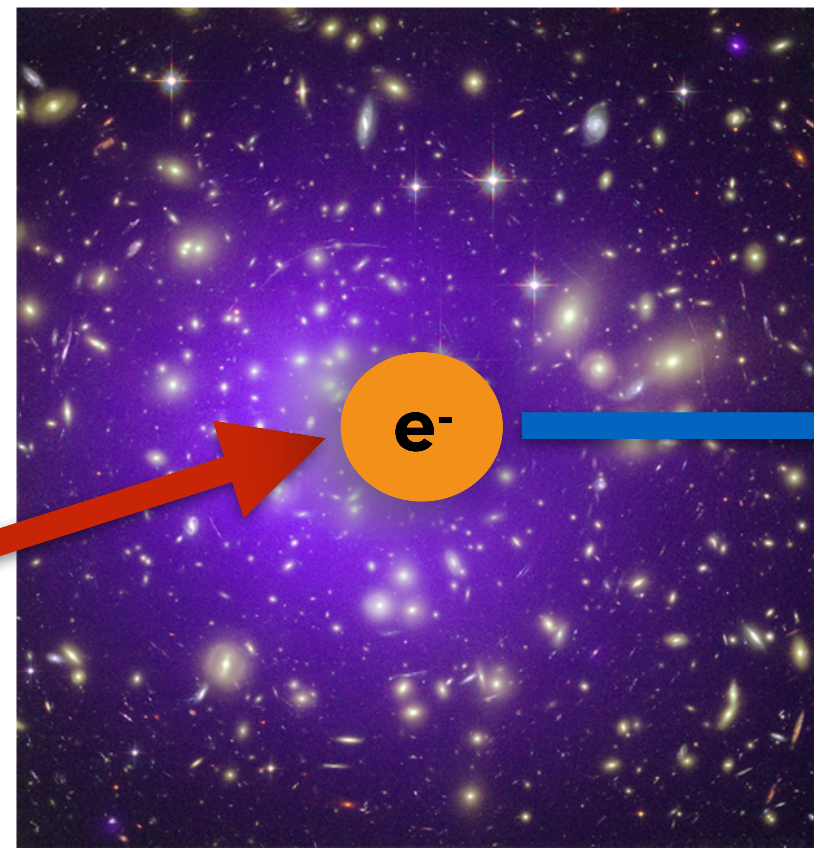
Thermal Sunyaev-Zel'dovich Effect

CMB | **Hot gas (galaxy cluster)** | **Observer**

z ~ 1300 | **z ~ 3 - 0** | **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

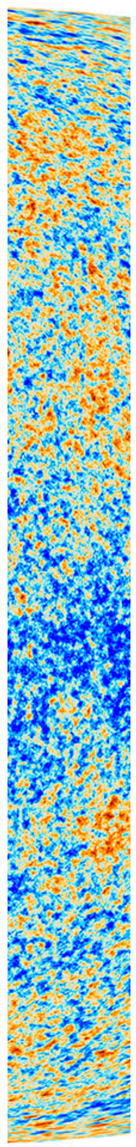
$$y = \frac{\sigma_T k_B}{m_e c^2}\int n_e T_e dl$$

Sunyaev and Zel'dovich (1972, 1980)

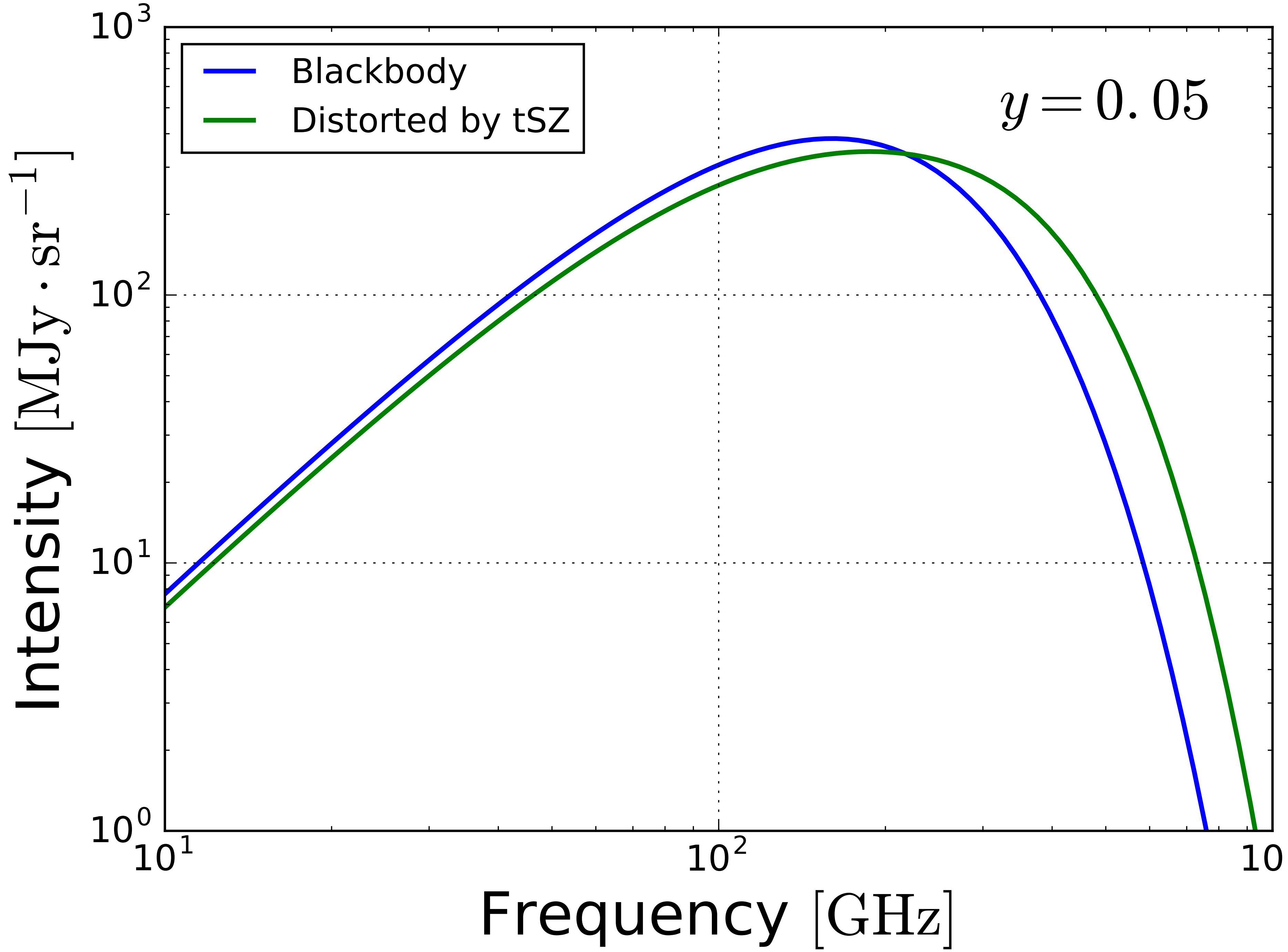
Thermal Sunyaev-Zel'dovich Effect

CMB

z ~ 1



✦ **Distorted spectrum by tSZ**



Observer

z = 0

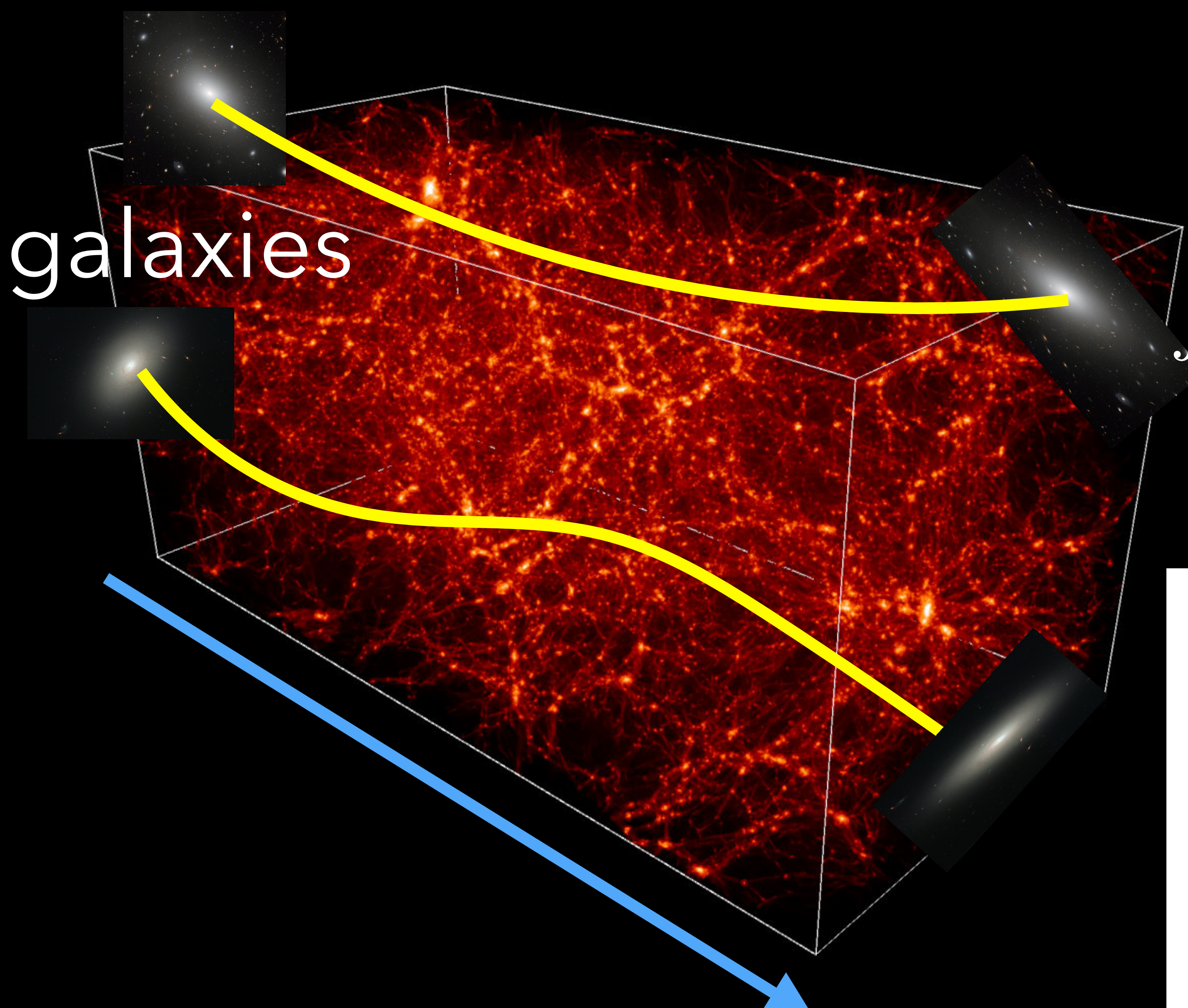
$$x = \frac{h\nu}{kT}$$

Sunyaev and Zel'dovich (1972, 1980)

Weak Lensing: Cosmic Shear

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

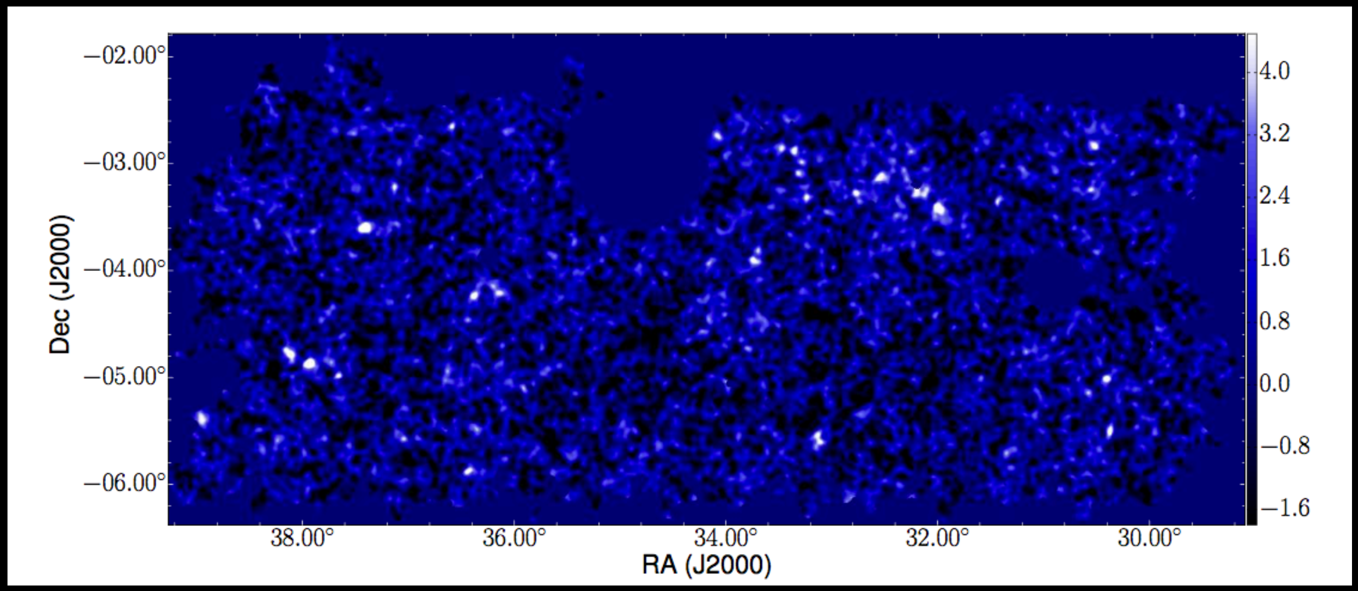
unbiased tracer of dark matter.



convergence

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

position kernel **density**

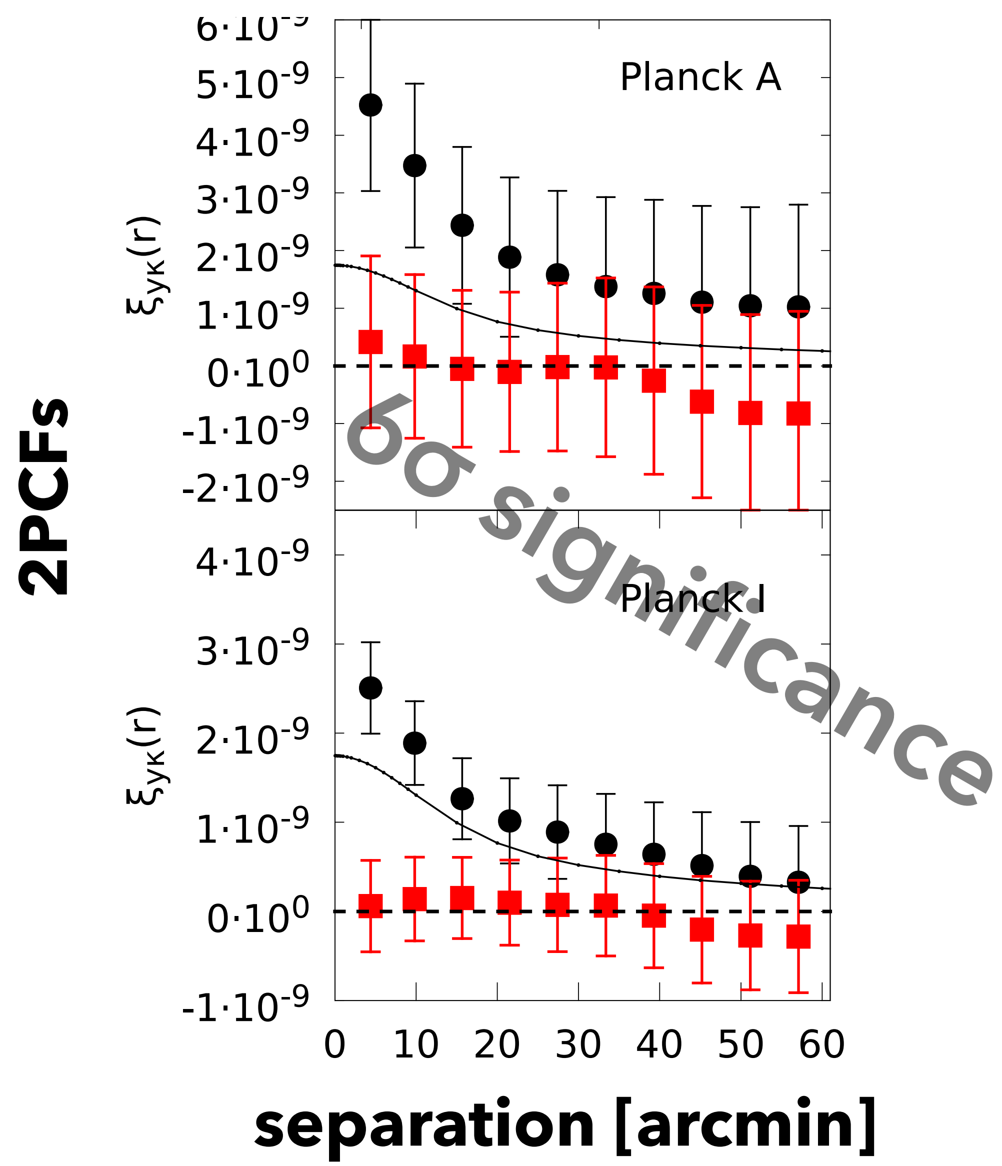


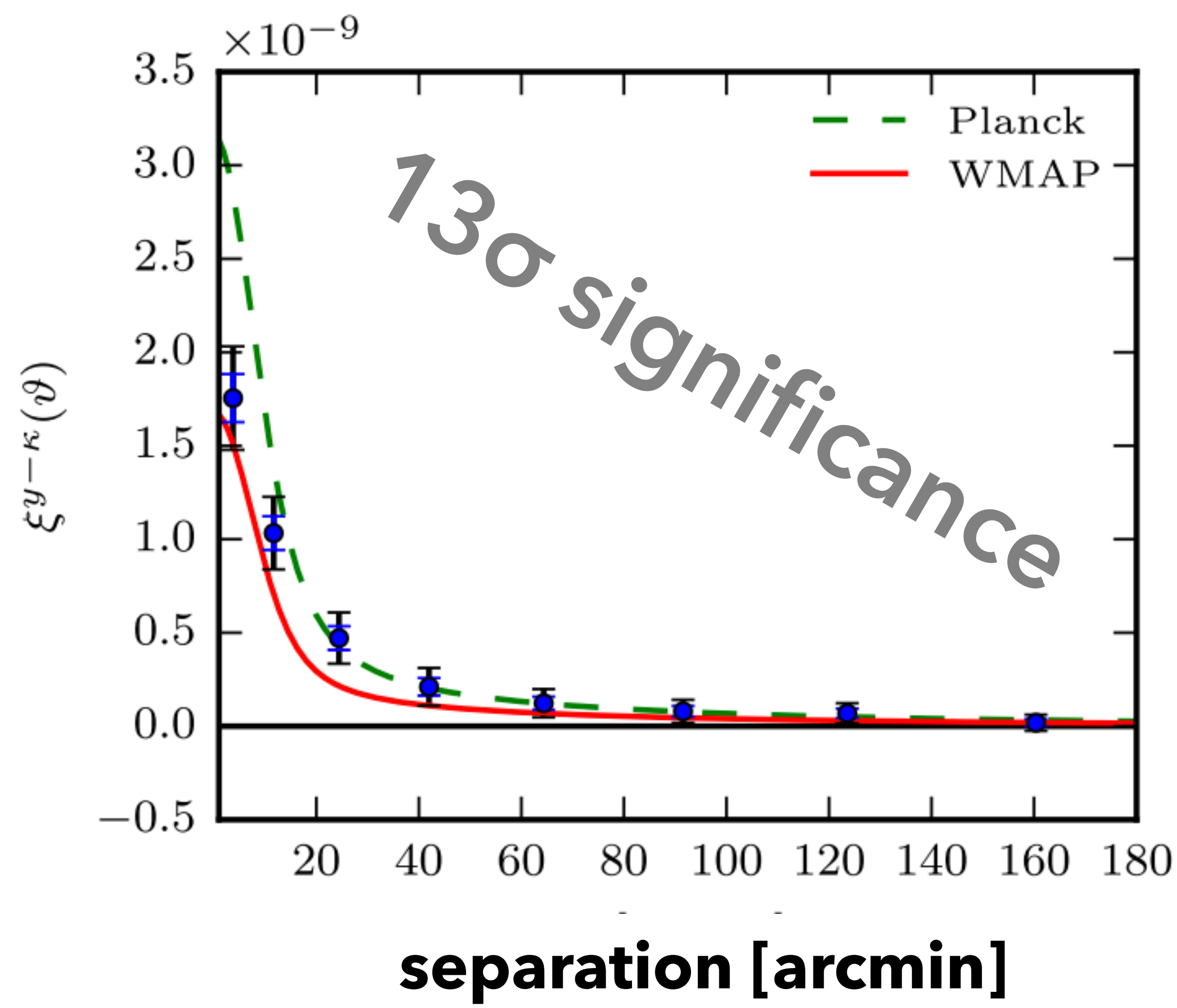
Convergence map from HSC (Oguri+, 2017)

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)





Contents

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. Measurements: HSC x Planck

5. 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.

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

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

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

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

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

well calibrated by N-body sim.

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).
Free parameters are calibrated by gas density and gas fraction of X-ray clusters.

✦**Non-thermal pressure**

Turbulent motion also can support the self-gravity of the halo.
This effect is parametrized as,

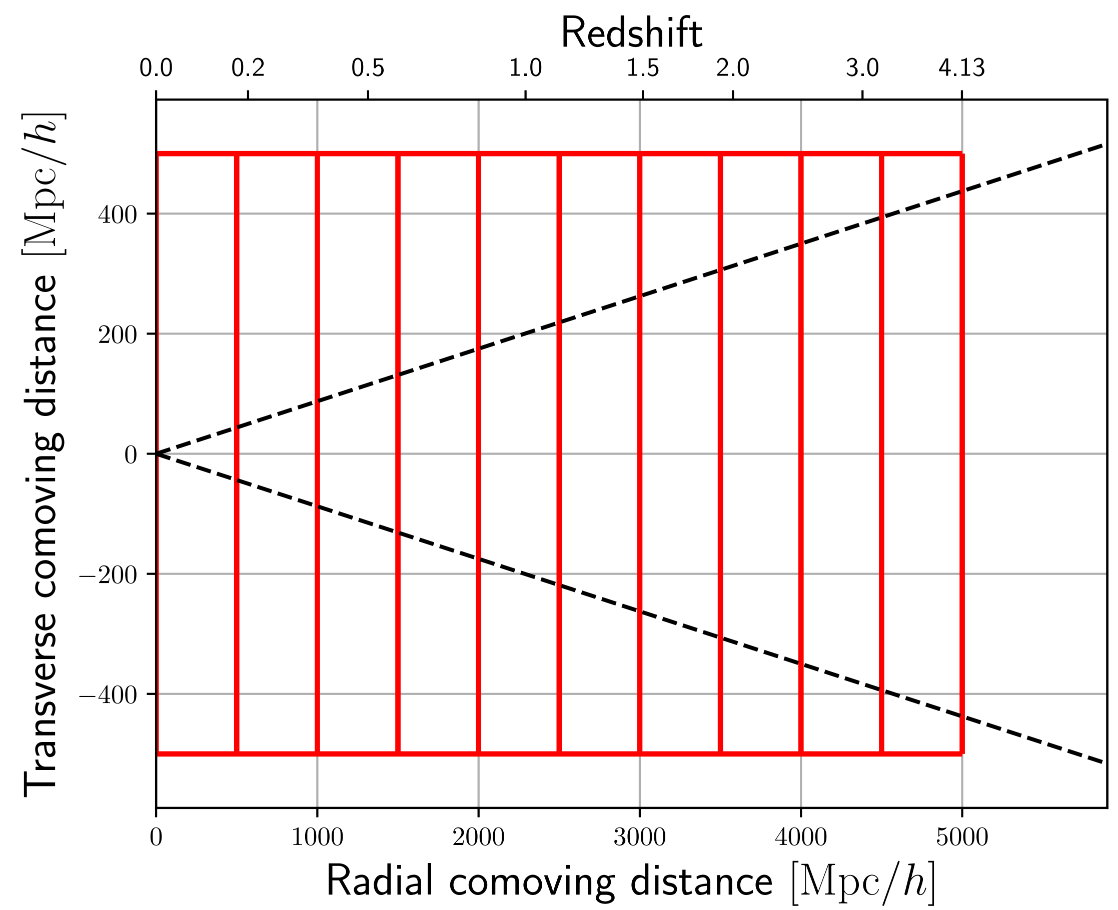
$$\frac{P_{\rm nth}}{P_{\rm tot}}(r) = \alpha(1+z)^{\beta}\left(\frac{r}{R_{500}}\right)^{0.8}$$

Free parameter constrained with measurements.

Covariance Estimation

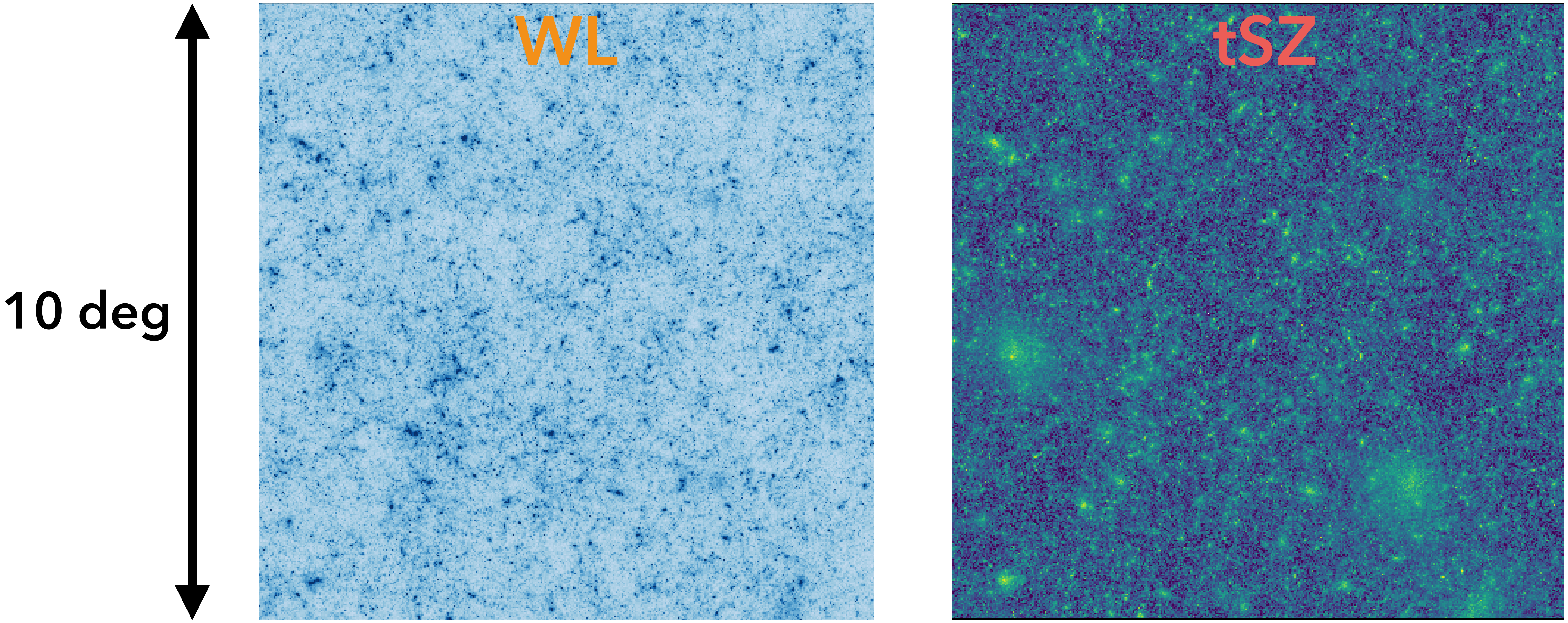
✦**Let us move on covariance matrix estimation.**

- **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.

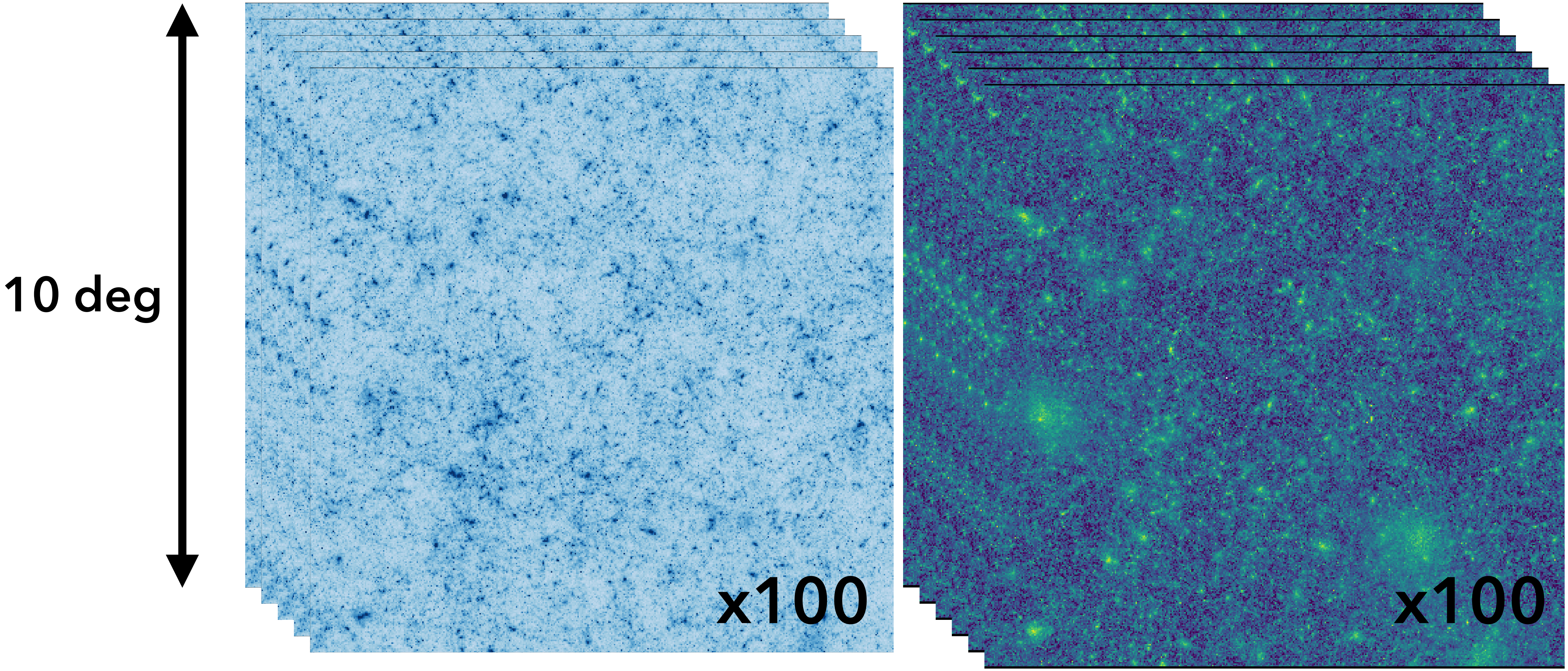


- **Mock observations**
  WL: Multiple plane method (White & Hu, 2000)
  tSZ: First, we find halos with Rockstar (Behroozi+, 2013).
  For each halo, we solve the analytic model, and assign thermal pressure to the member particles.

Covariance Estimation



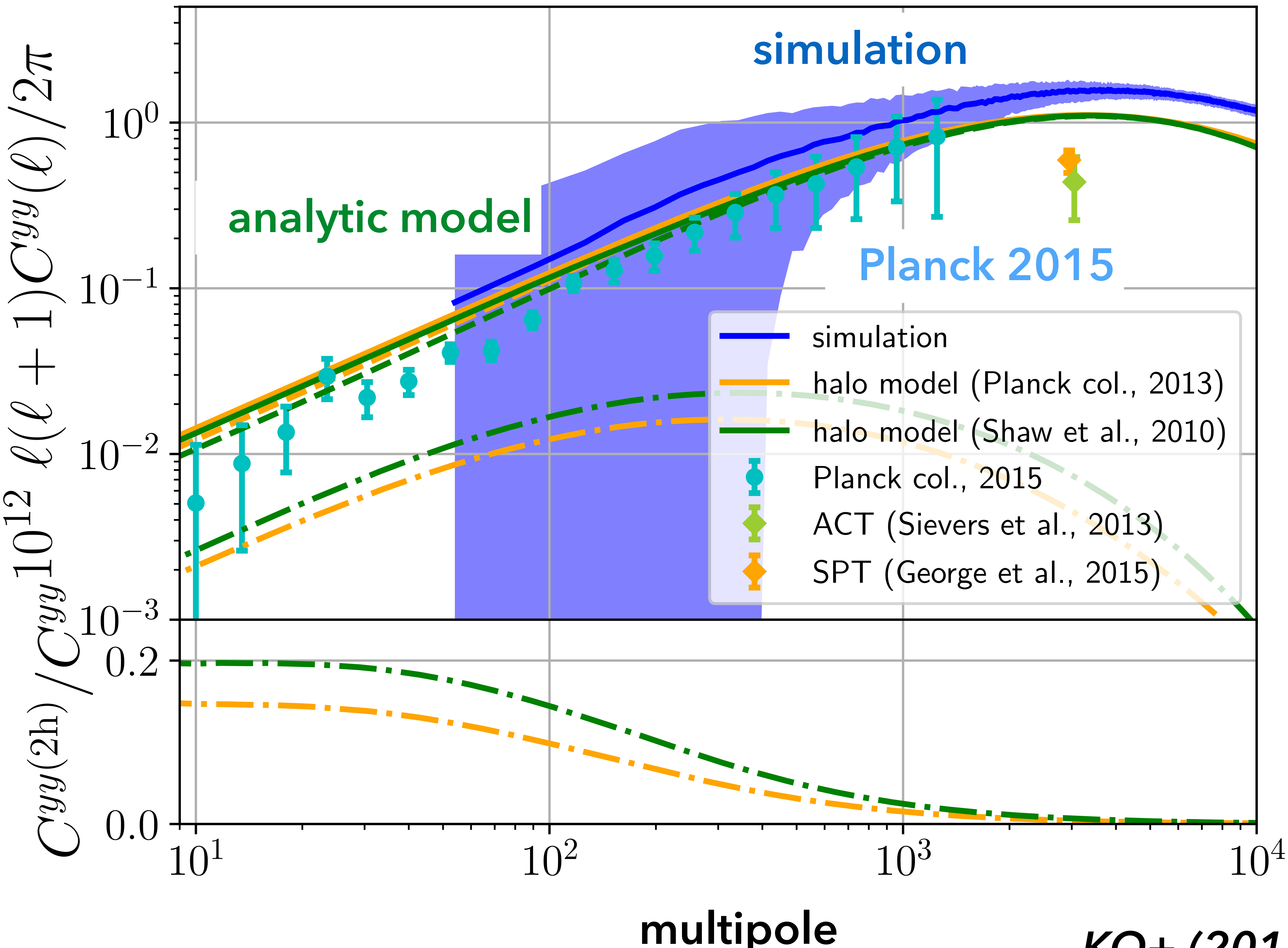
Covariance Estimation



The variance of maps corresponds to
the covariance matrix.

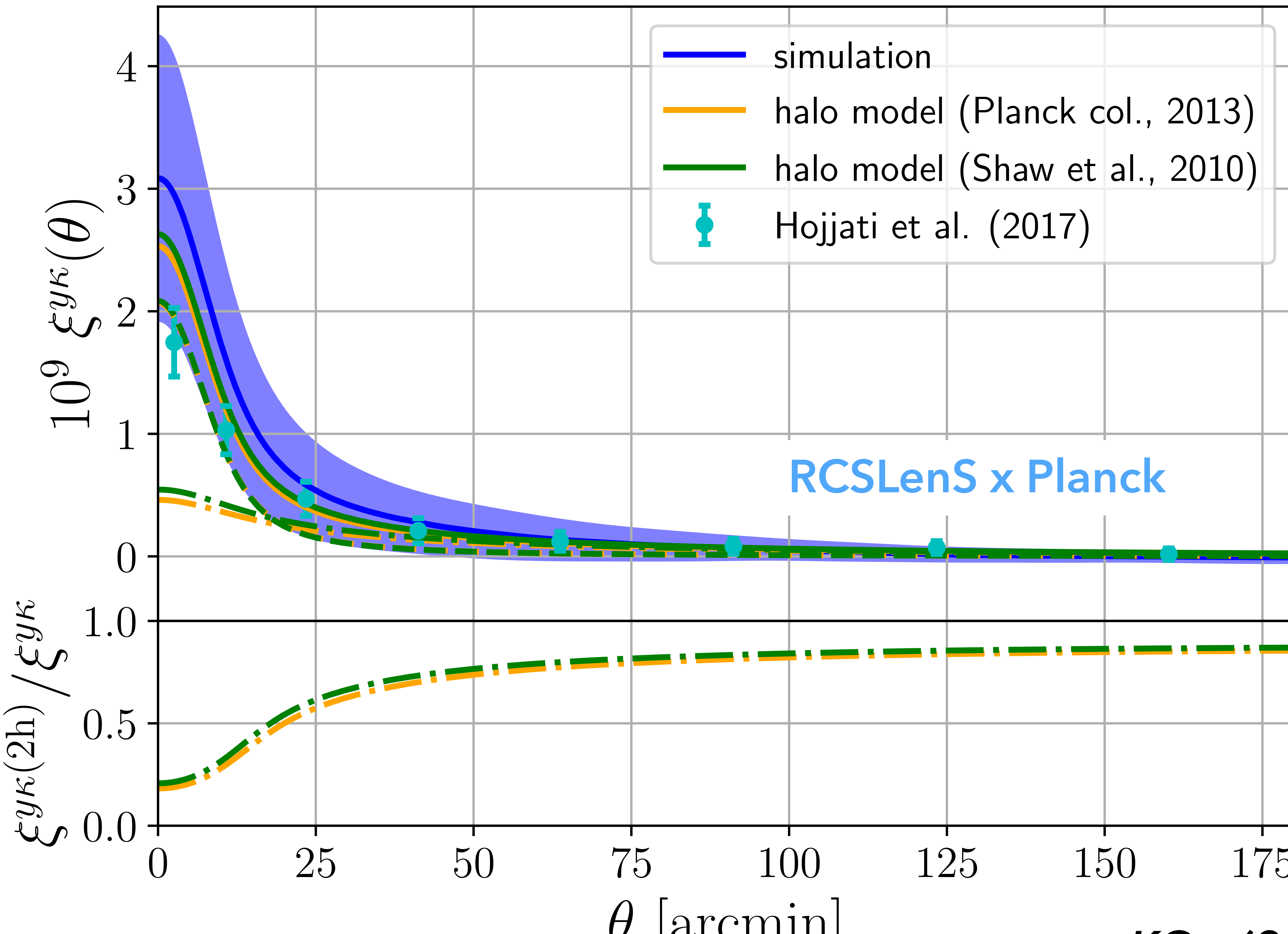
Contents

Compton-y Spectra



KO+ (2017)

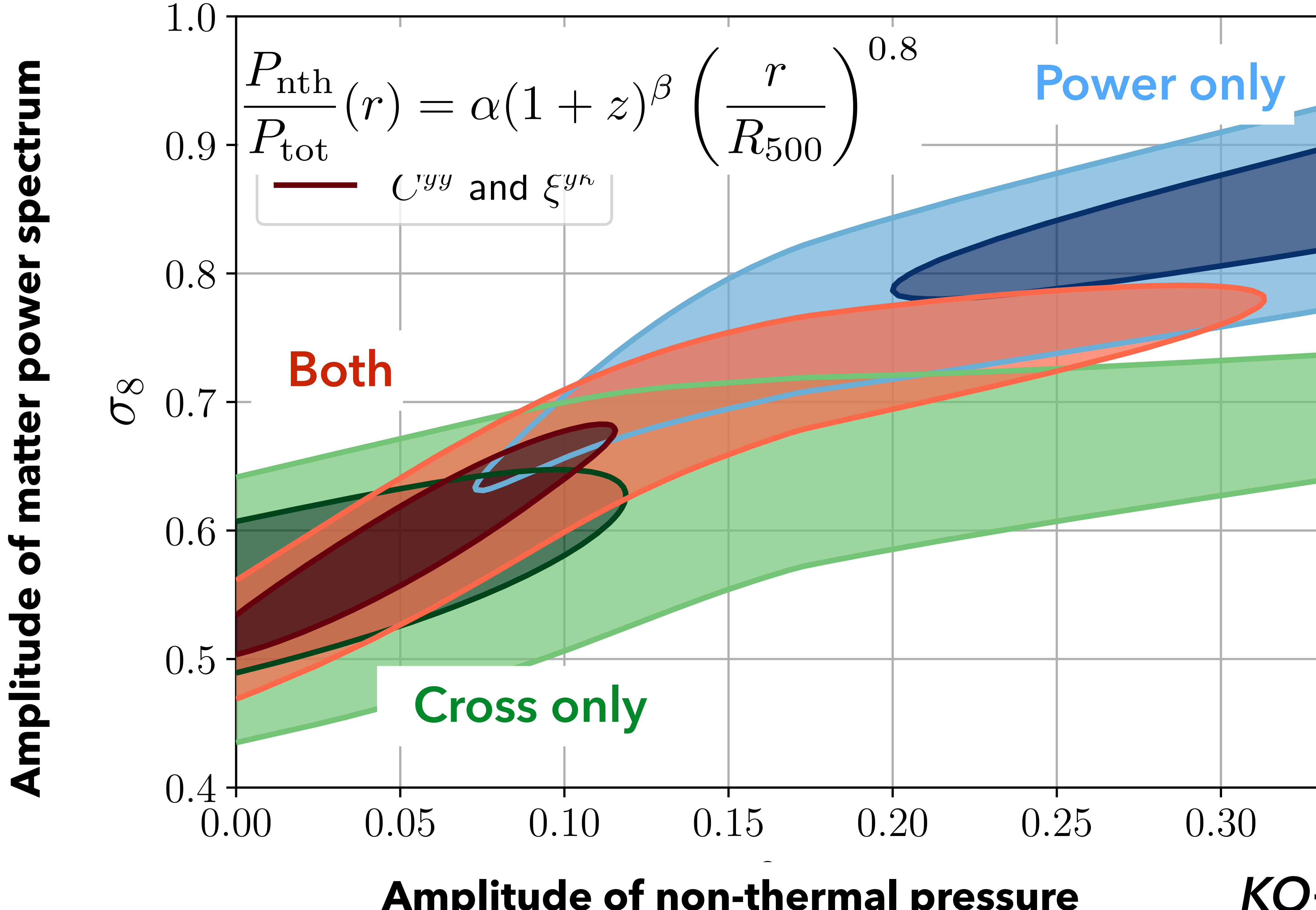
Cross-Correlation Function



KO+ (2017)

Constraints from Cross-Correlation

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



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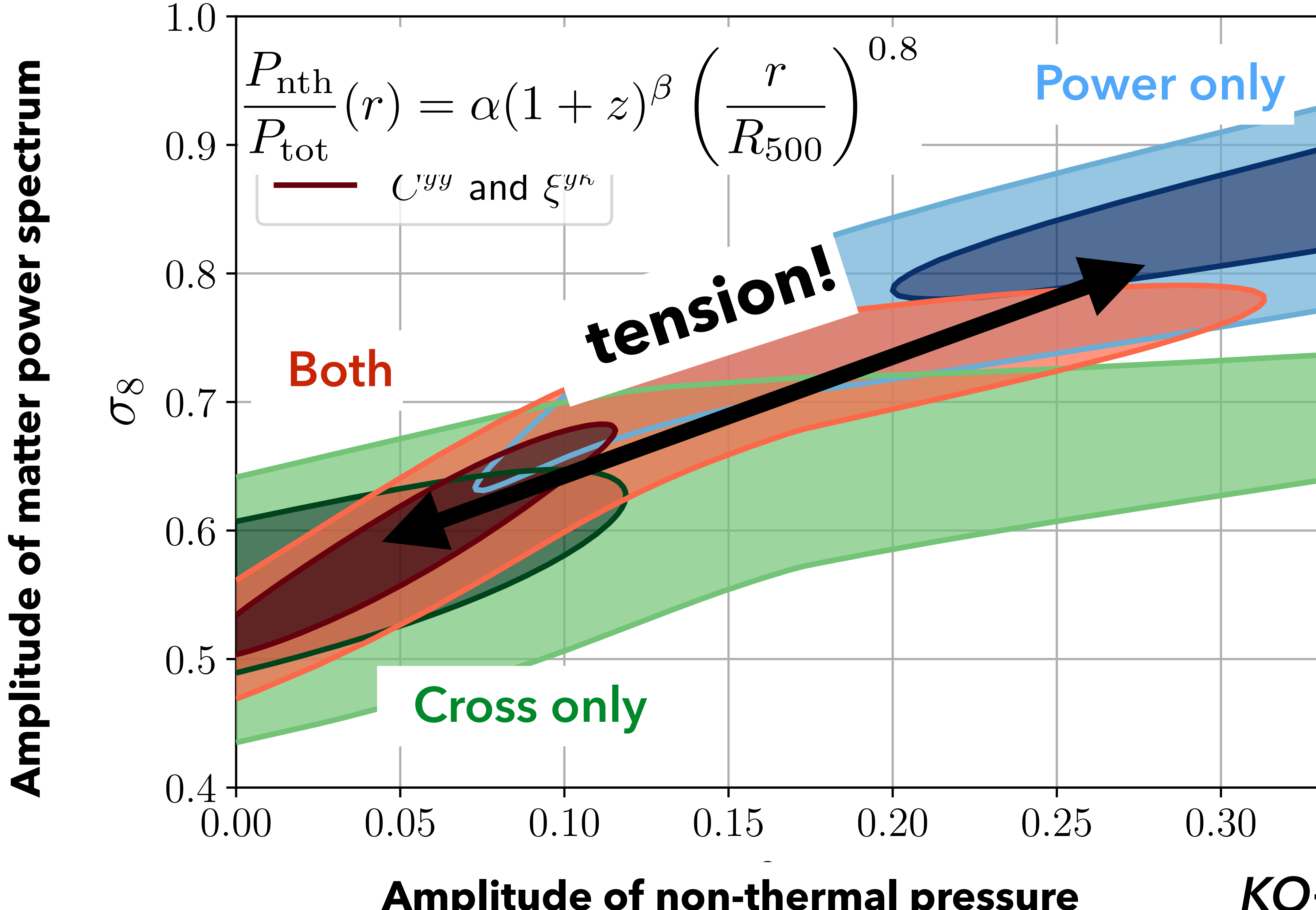
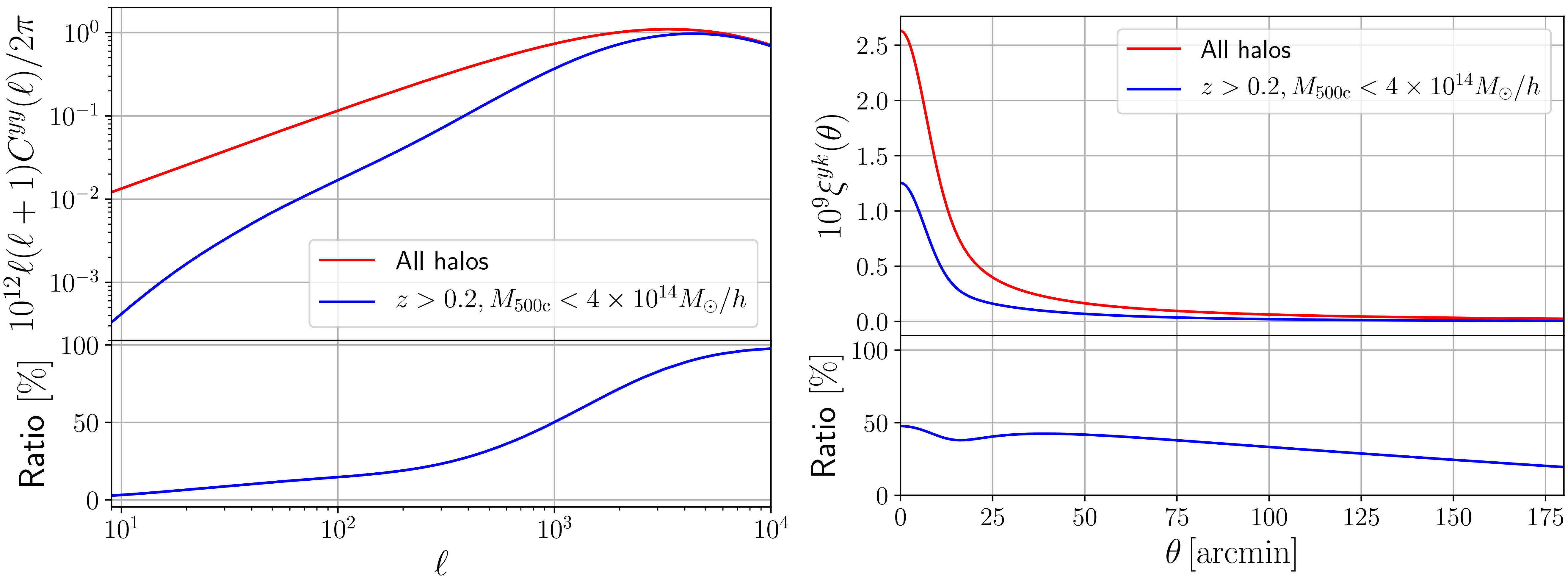


KO+ (2017)

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)**



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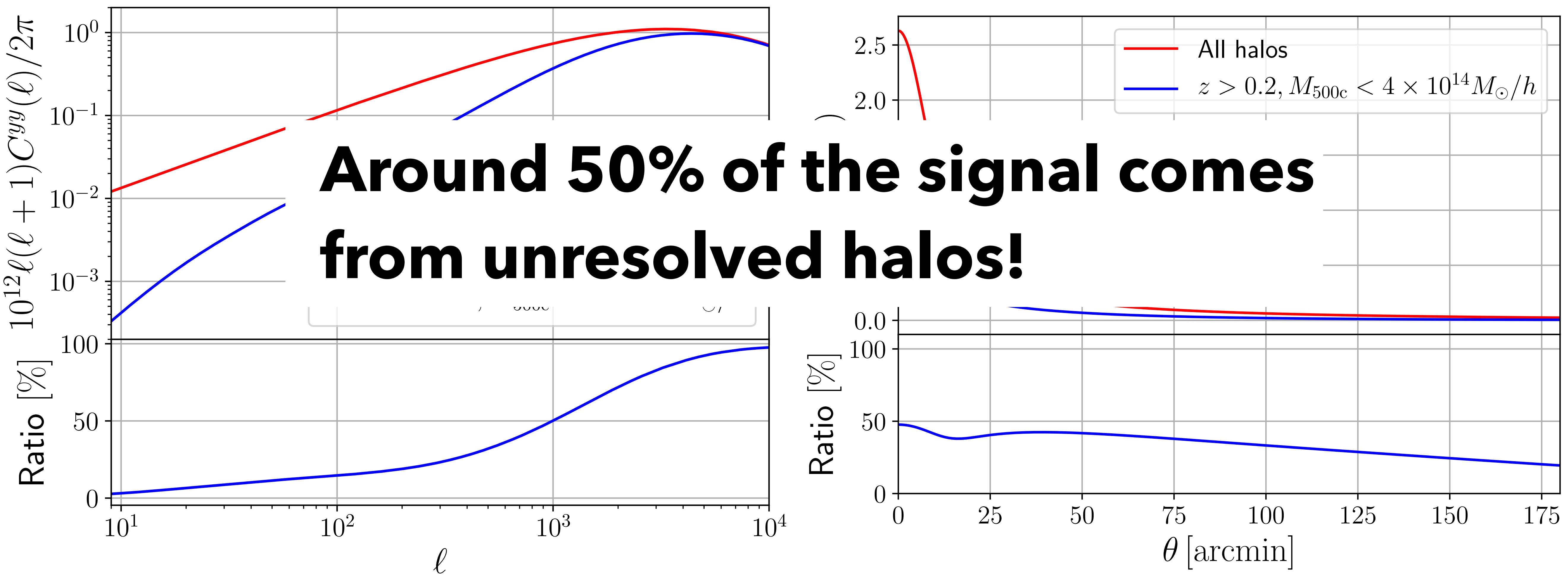
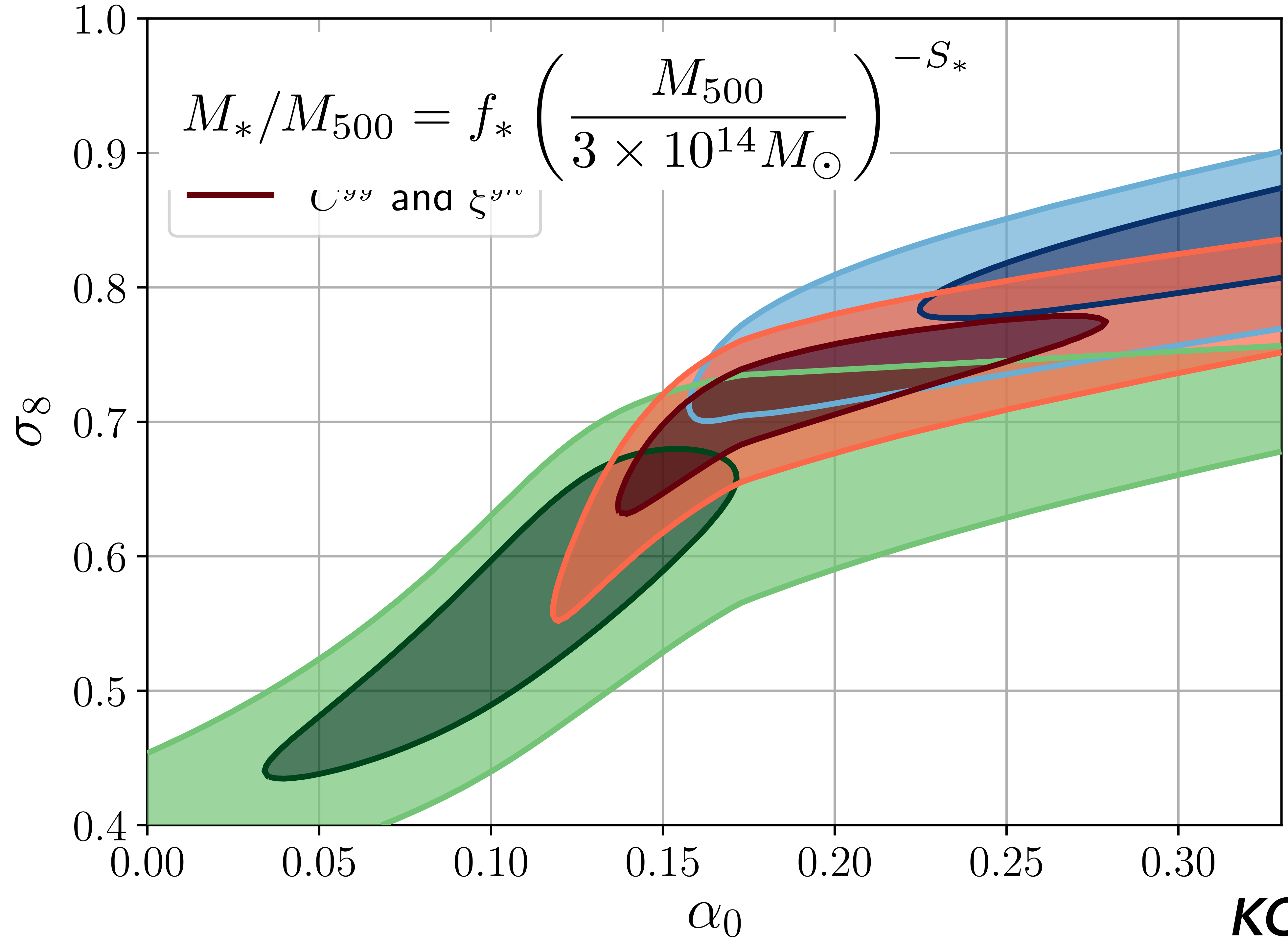


Around 50% of the signal comes from unresolved halos!

KO+ (2017)

Possible Solution of Tension

- **Let us consider an extreme case of enhanced star formation for group size halos by changing S_* to 0.7 from 0.12.**
  That corresponds to severe depletion of hot gas for such halos.



KO+ (2017)

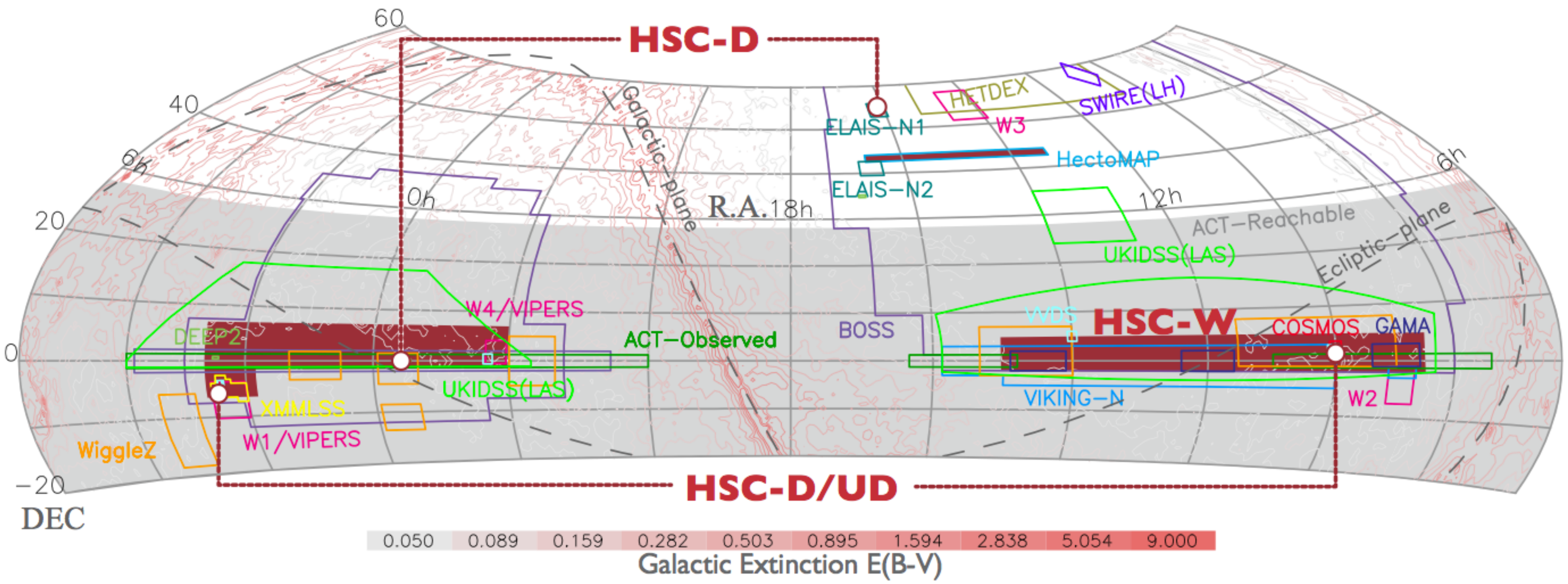
Contents

Hyper Suprime-Cam Subaru Strategic Survey in a Nutshell

We are carrying out a three-layered, multi-band (*grizy* plus 4 narrow-band filters) imaging survey with the Hyper Suprime-Cam (HSC) on the 8.2m Subaru Telescope. Details of the instrument can be found on the instrument page, but in brief, the camera has 104 science CCDs covering a 1.5 degree diameter field of view with a 0.168 arcsec pixel scale. The delivered image quality is excellent across the field of view; the median seeing in the i-band is about 0.6 arcsec.

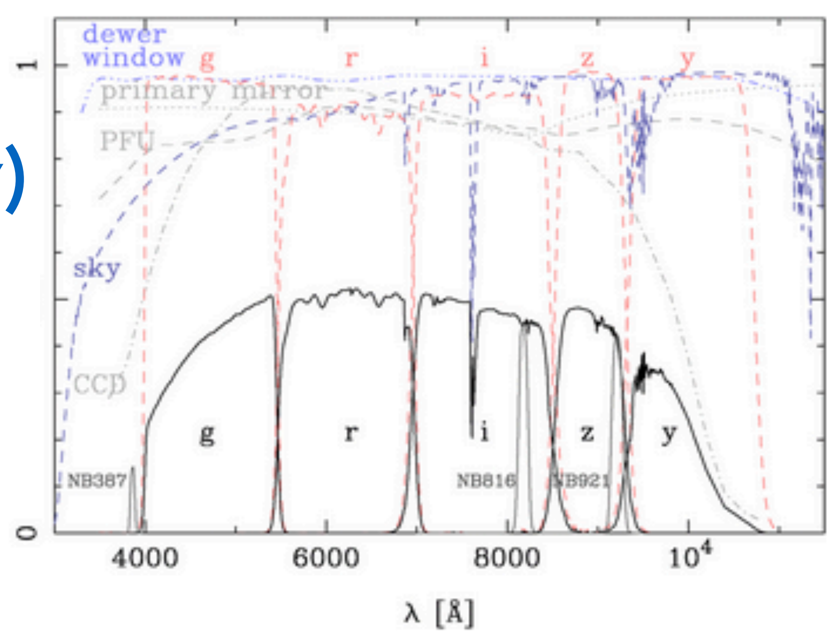
By combining data from the three layers (Wide: 1400 deg^2, r~26; Deep: 27 deg^2, r~27; Ultradeep: 3.5 deg^2,r~28), we will address some of the most pressing problems in modern cosmology and astrophysics with a particular focus on grantational weak lensing, galaxy evolution, supernovae, and galactic structure. The survey is uniquely designed to enable various science cases, with particular attention to controlling systematic errors. The survey is awarded 300 nights over 5-6 years and it started in March 2014. For more details, refer to the proposal here.

HSC-SSP will cover 1400 deg^2 over 300 nights



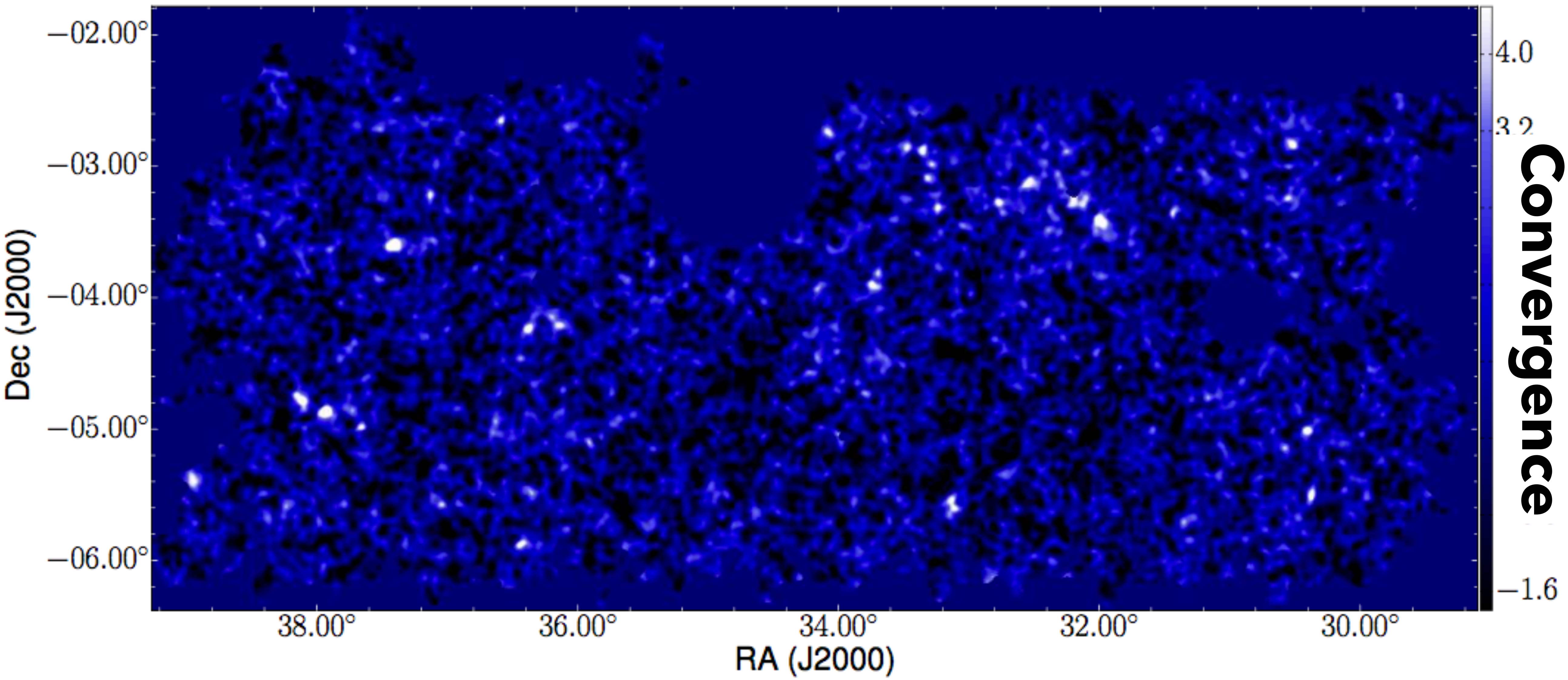
Filters and Depths

multi-band imaging (*grizy*) survey down to r~28 mag



HSC Weak Lensing

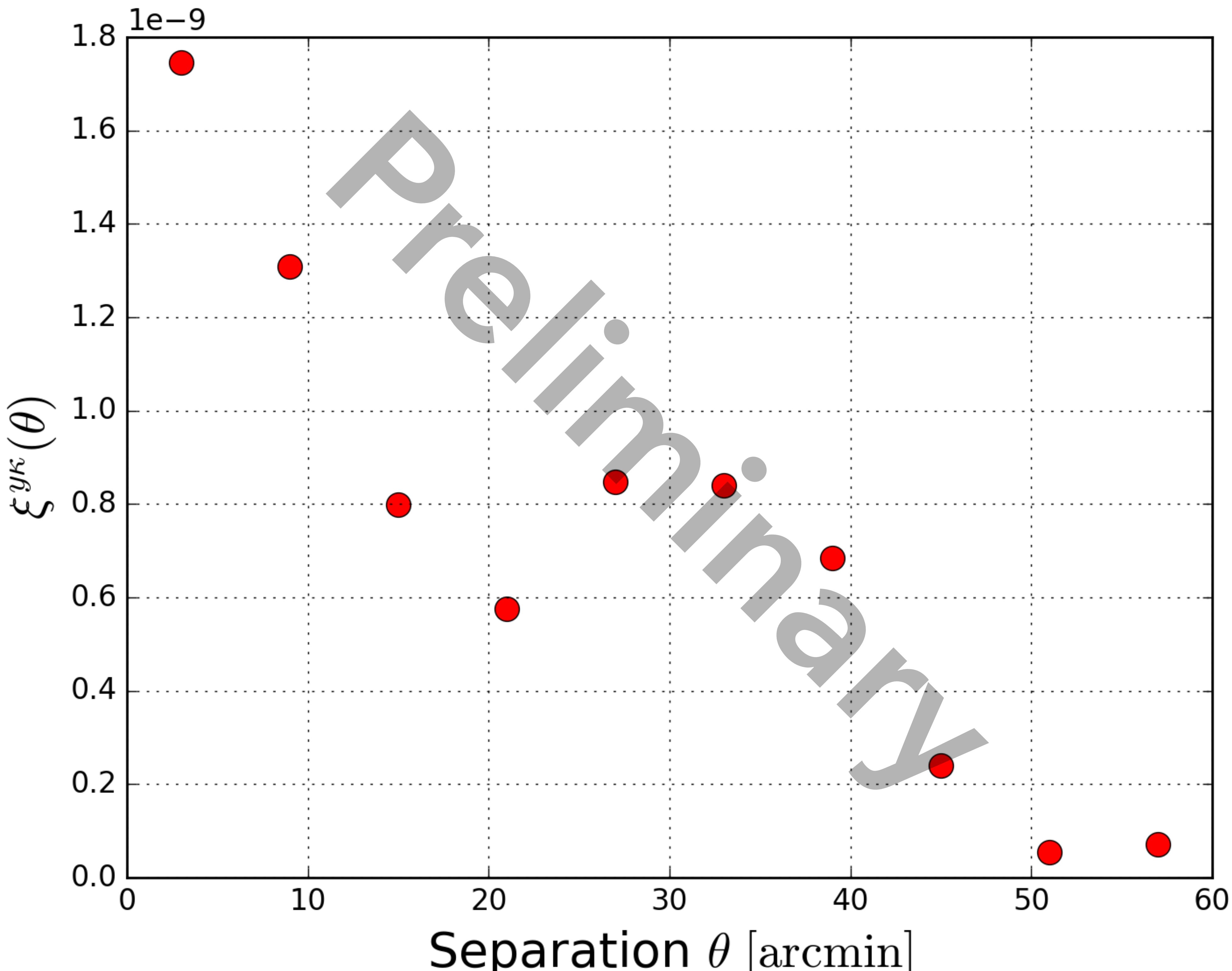
Weak lensing measurements have already done!



Oguri+ (2017)

Convergence and Compton-y maps

✦**Non-zero amplitude has already been detected!**



KO+ (in prep.)

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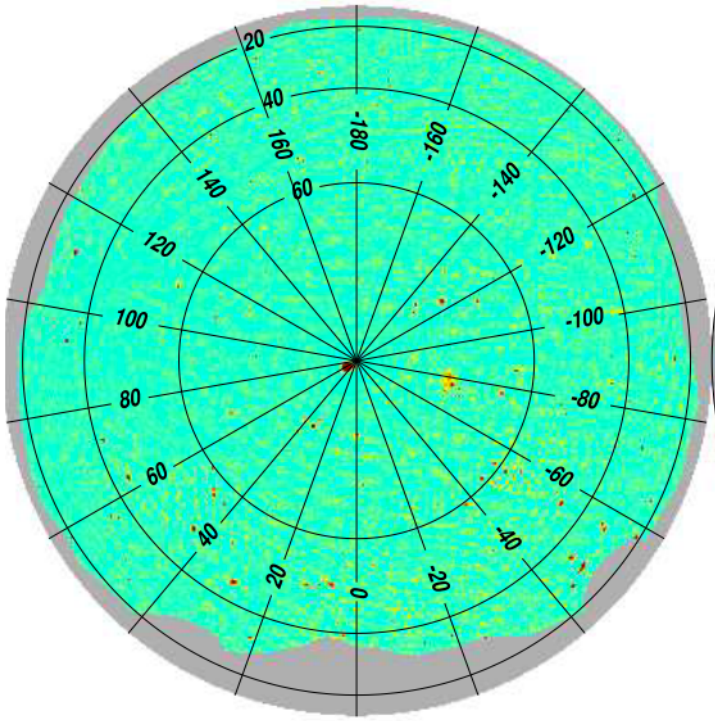
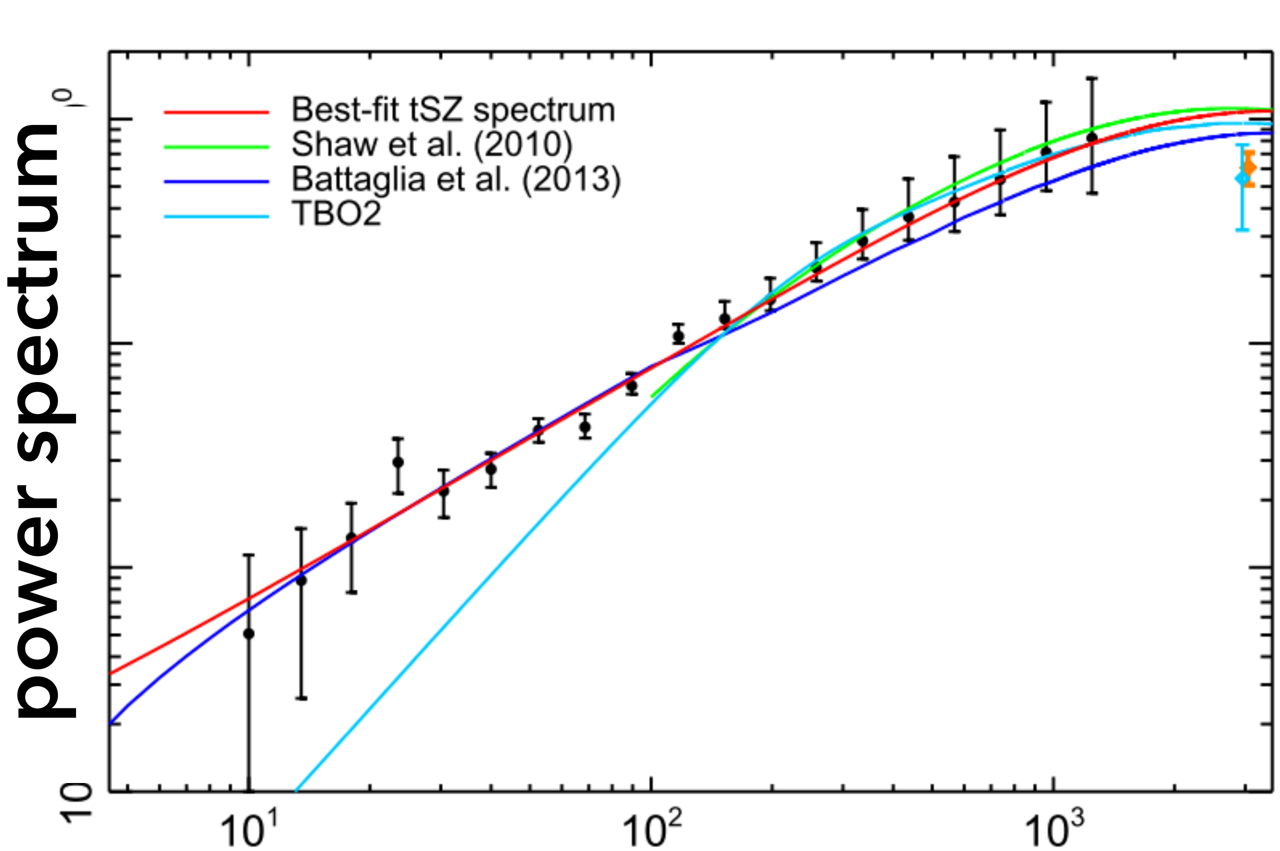
Summary

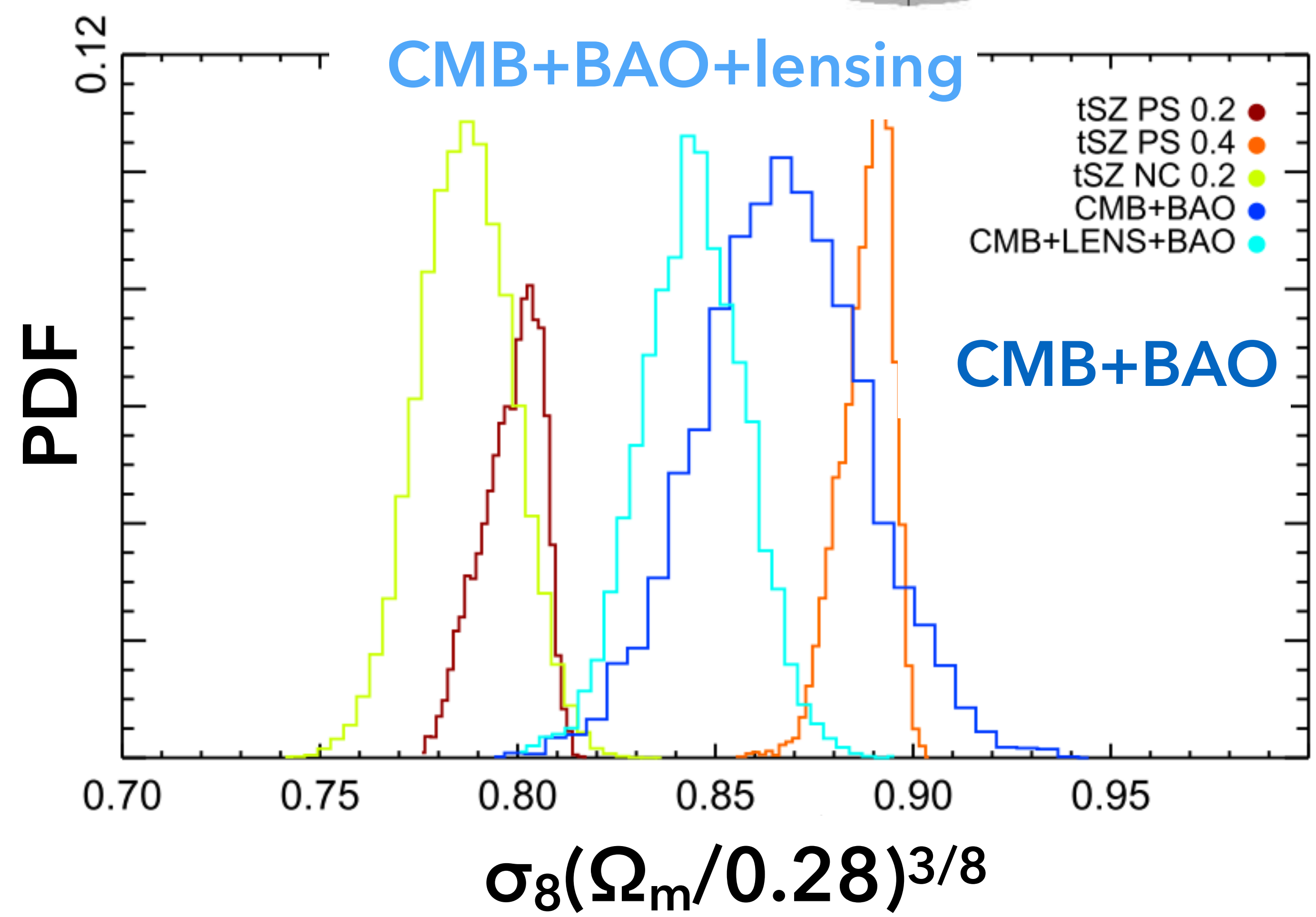
- Weak lensing and thermal Sunyaev-Zel'dovich effect are promising probes into the large-scale structure.
- Theoretical modeling and simulations can be used to estimate the signal and covariance matrix.
- The cross-correlation of them can provide us with additional information of cosmology and cluster astrophysics.
- We are currently working on the measurement of the cross-correlation with HSC and Planck data.

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.

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

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

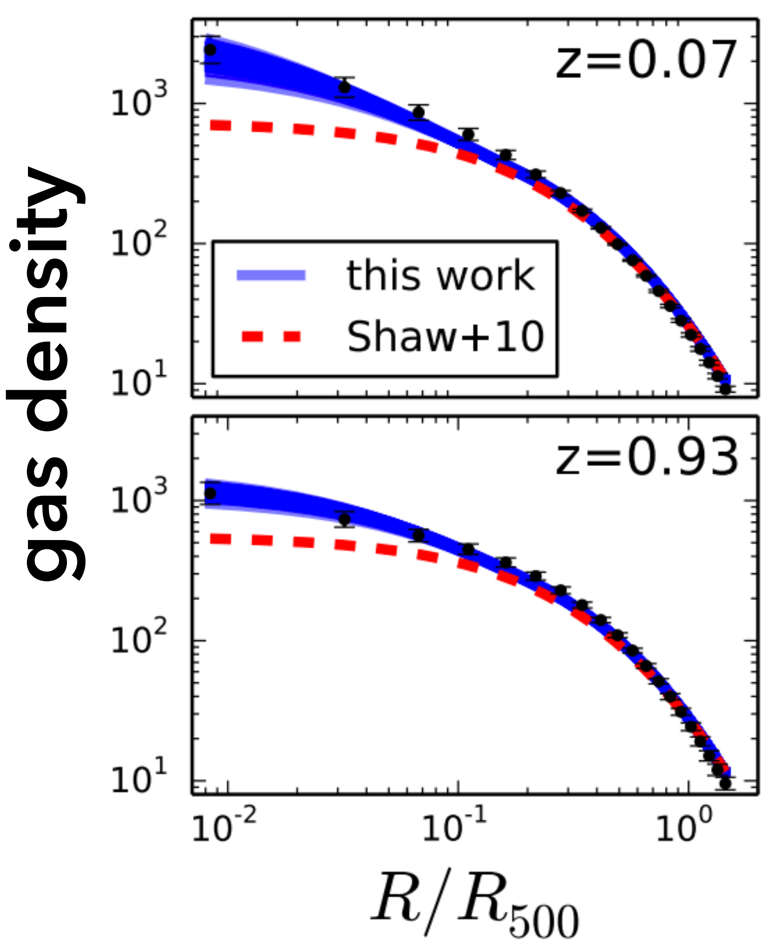
✦Non-thermal pressure

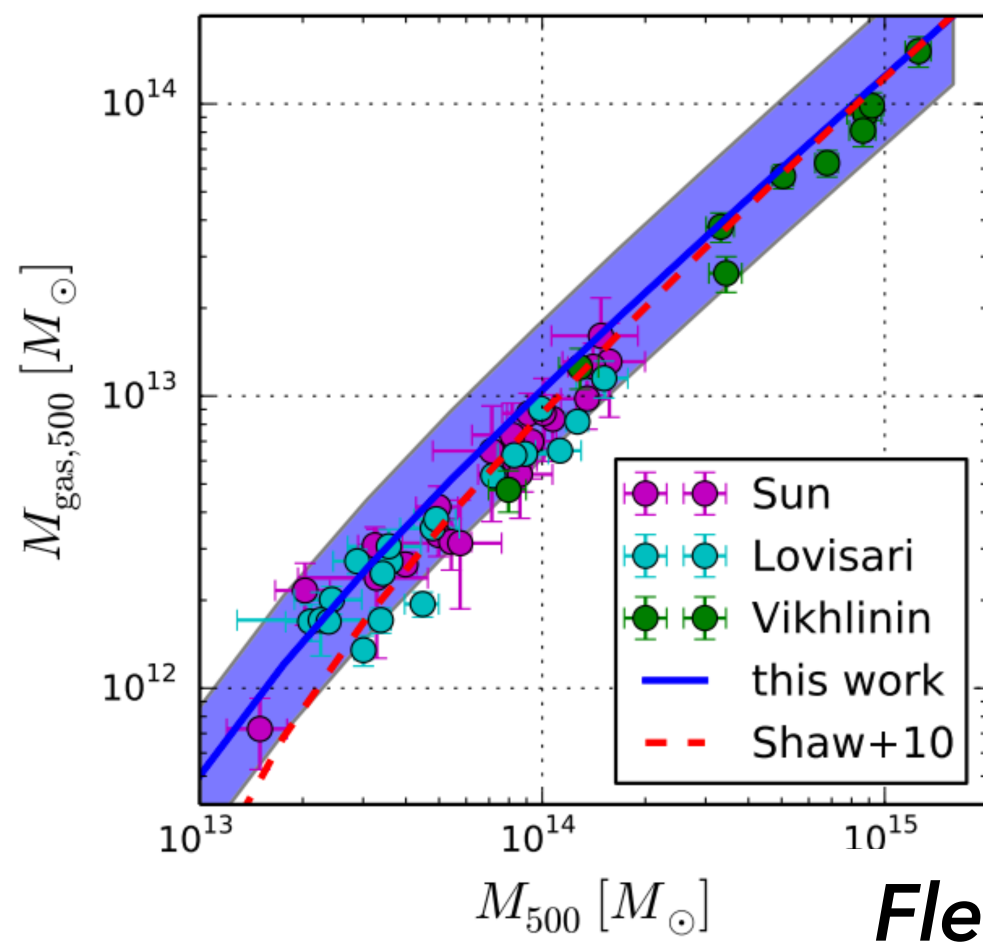
Turbulent motion also can support the self-gravity of the halo.
This effect is parametrized as,

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

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)

Constraints on Non-thermal Pressure

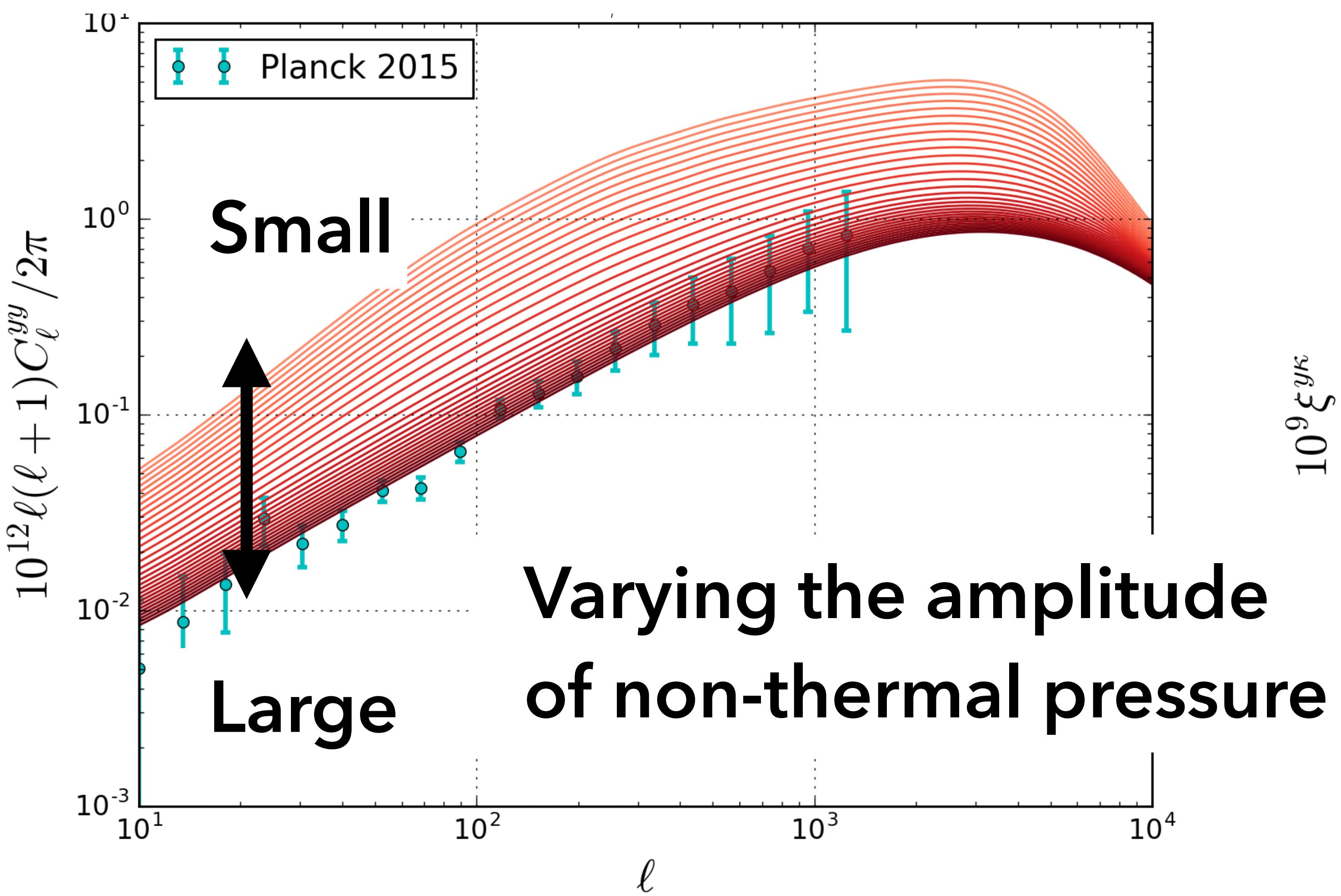
- **Non-thermal pressure**

  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