Cosmology and Cluster Astrophysics with Weak Gravitational Lensing and the Sunyaev-Zel'dovich Effect

第31回理論懇シンポジウム

2018/12/20 京都大学基礎物理学研究所

大里 健

東京大学物理学専攻

Based on

KO, Flender, Nagai, Shirasaki, and Yoshida; MNRAS, 475, 532 (2018)

KO, Miyatake, Nagai, Shirasaki, Yoshida, and HSC WL WG; *in prep.*

Cosmology and Cluster Astrophysics with Weak Gravitational Lensing and the Sunyaev-Zel'dovich Effect

第31回理論懇シンポジウム

2018/12/20 京都大学基礎物理学研究所

大里 健

東京大学物理学専攻

Based on

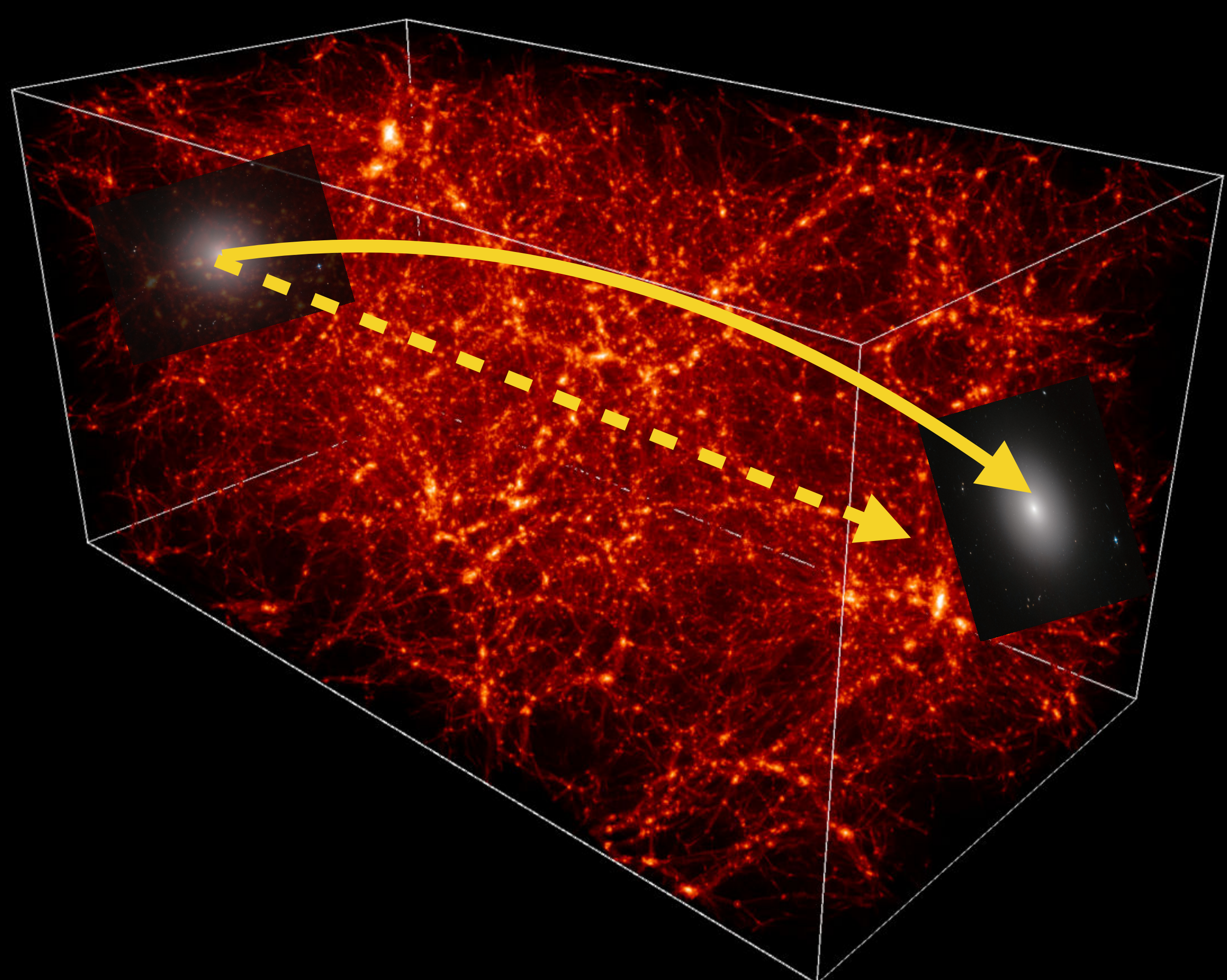
KO, Flender, Nagai, Shirasaki, and Yoshida; MNRAS, 475, 532 (2018)

KO, Miyatake, Nagai, Shirasaki, Yoshida, and HSC WL WG; *in prep.*

Weak Gravitational Lensing

The ***large-scale structures*** induce weak gravitational lensing effect.
We can probe into the matter distribution in an **unbiased** way.

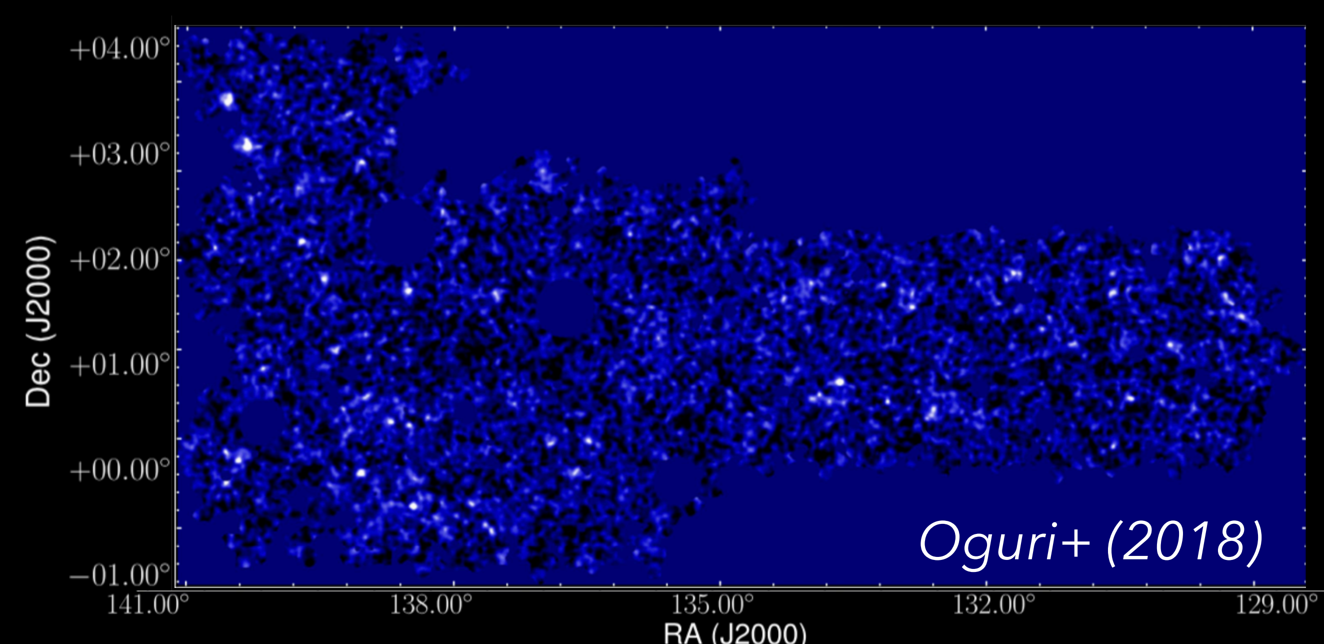
The images of galaxies are distorted due to the foreground gravitational field, and the distortion can be detected by statistically analyzing many images.



Convergence field:

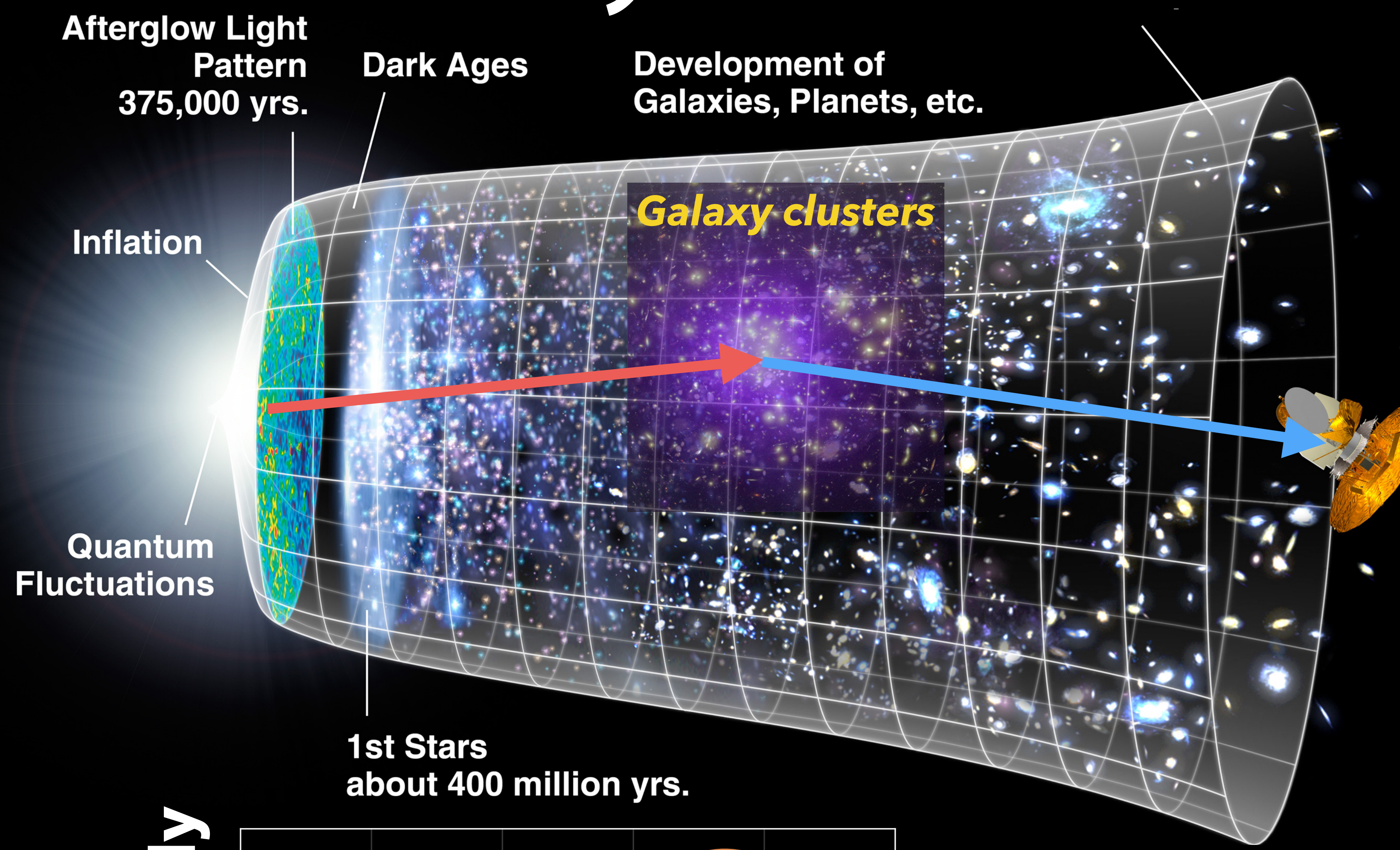
$$\kappa(\theta) = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \Omega_\mathrm{m} \times \int d\chi\, f(\chi_s, \chi)\delta(D_A(\chi)\theta, \chi)$$

lensing kernel **density**

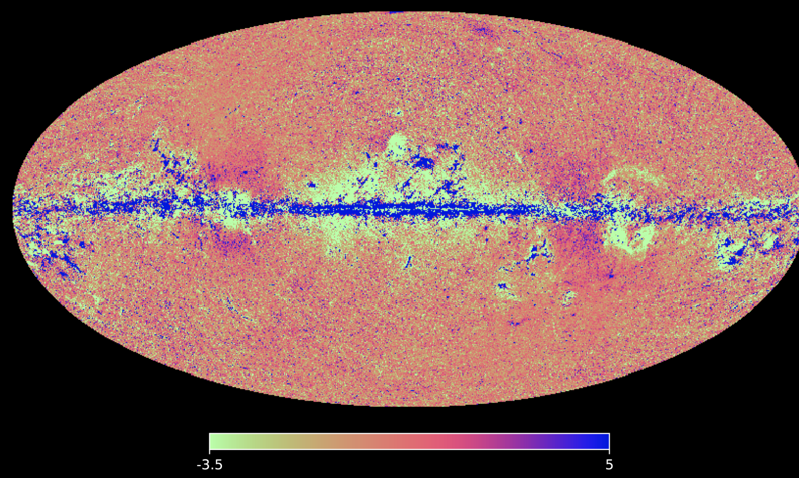


2D mass map from HSC

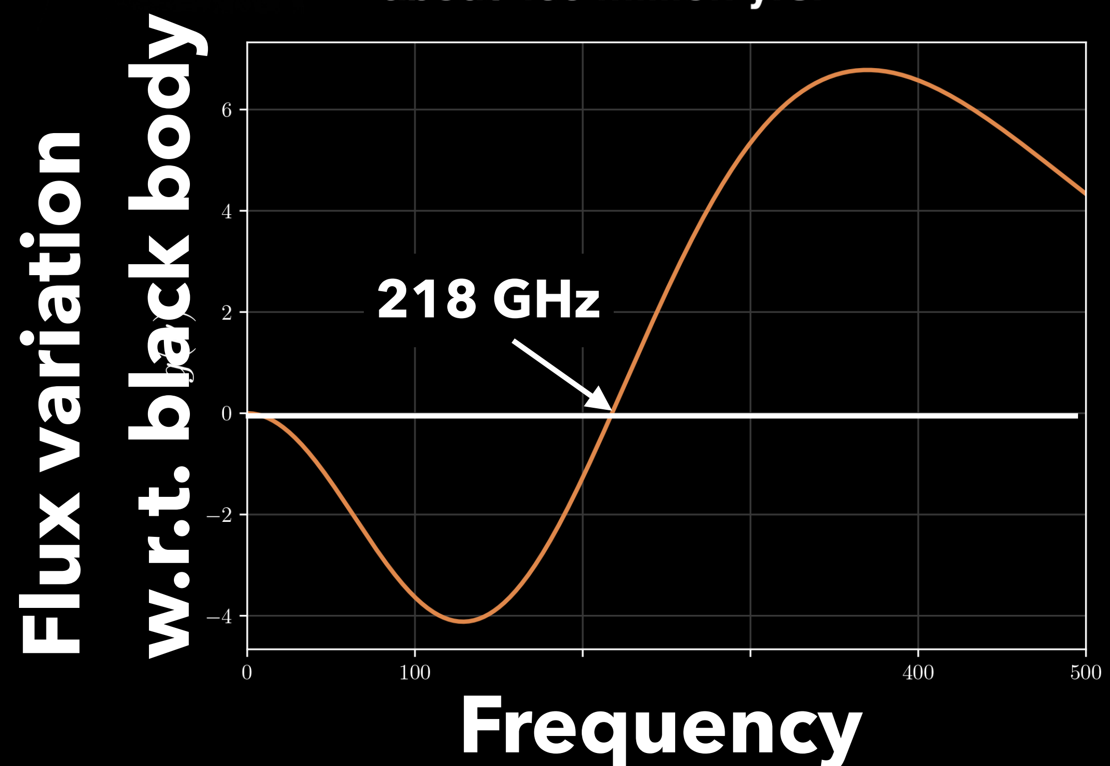
The Sunyaev-Zel'dovich Effect



all-sky Compton-y map by Planck



Planck col. (2016)



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

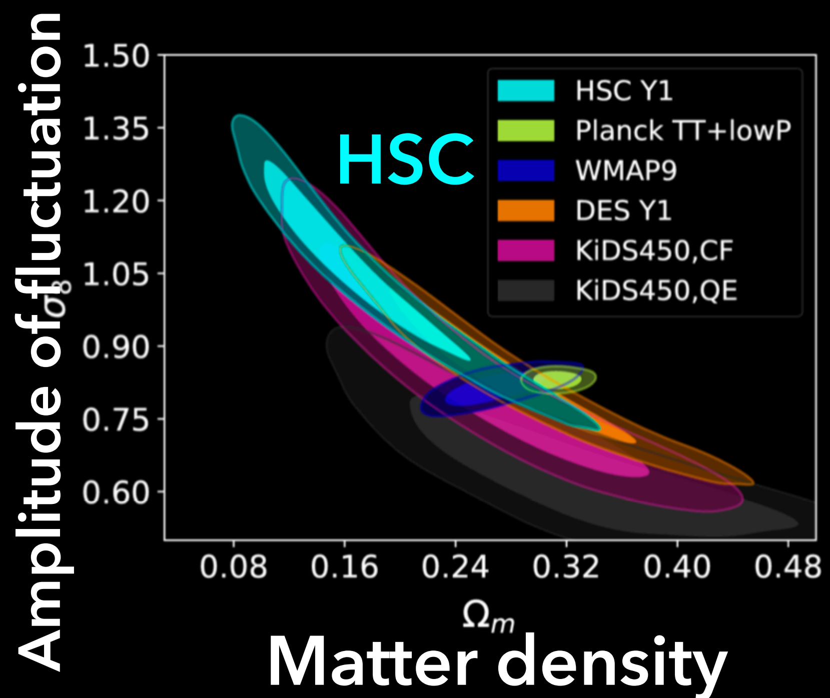
Compton-y $$y = \frac{\sigma_{\mathrm{T}} k_{\mathrm{B}}}{m_e c^2}\int P_e\, dl$$

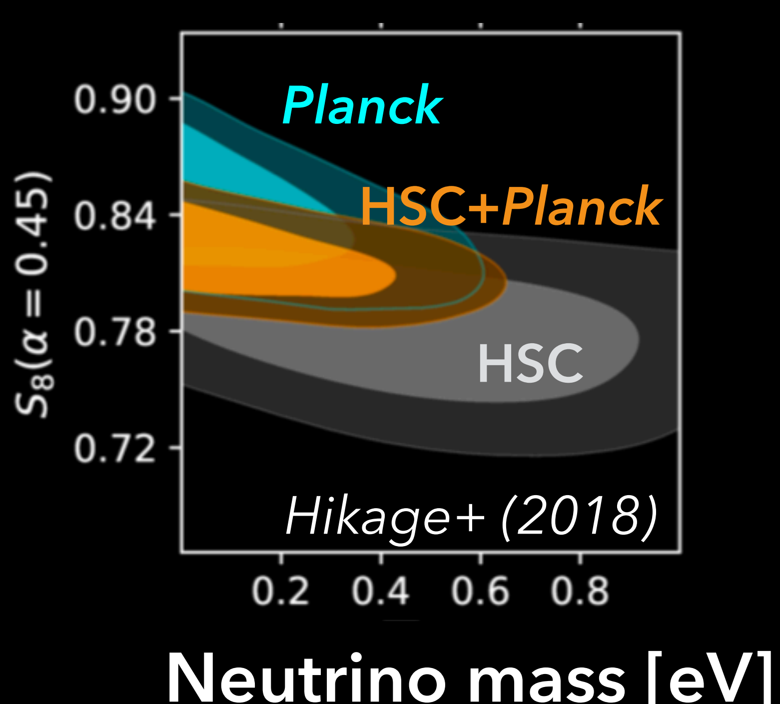
Sunyaev and Zel'dovich (1972, 1980)

Cosmology with WL and tSZ

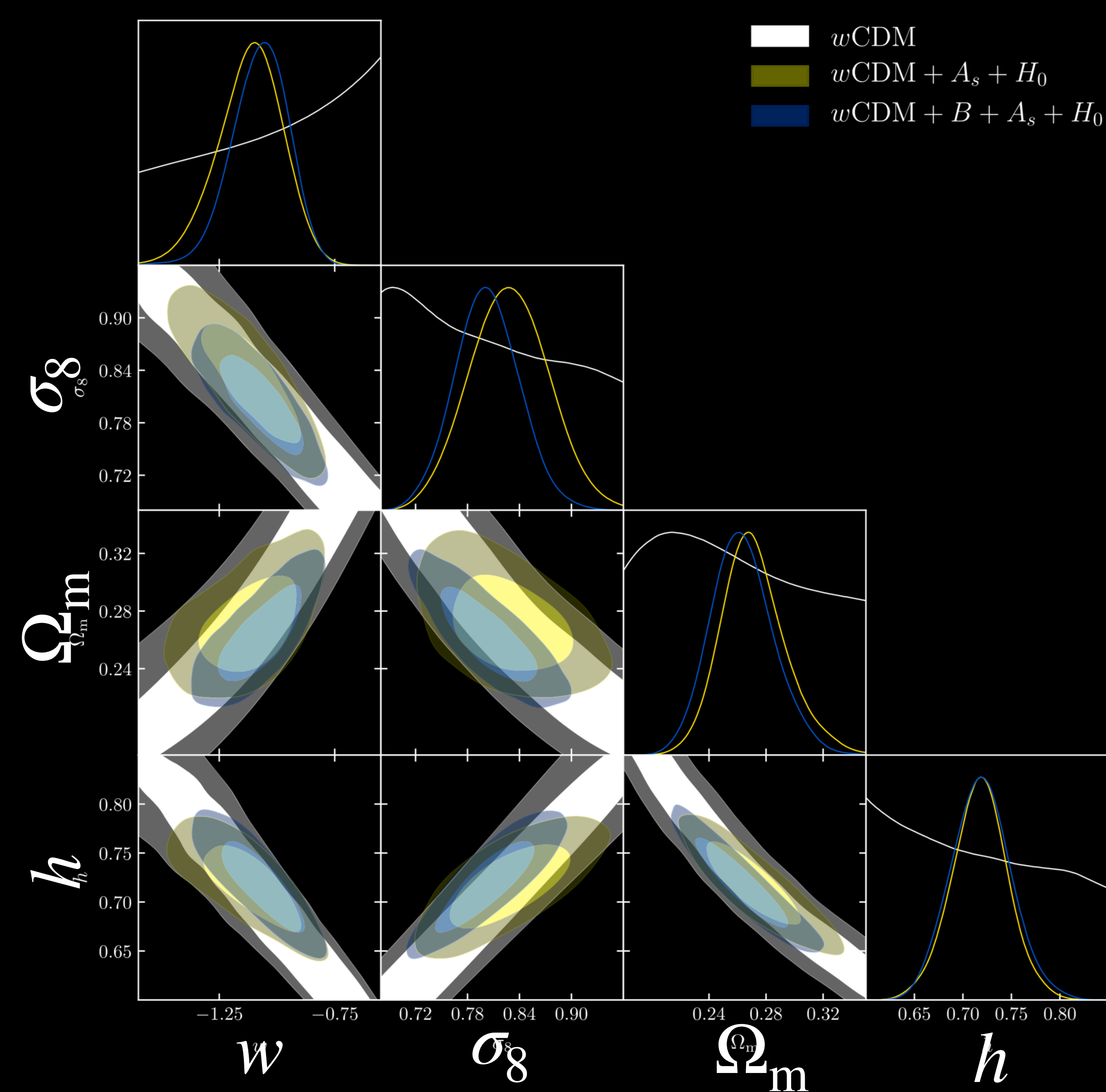
We can place stringent constraints on ***cosmological parameters*** with auto-power spectra of convergence (WL) and Compton-*y* (tSZ).

HSC cosmic shear analysis





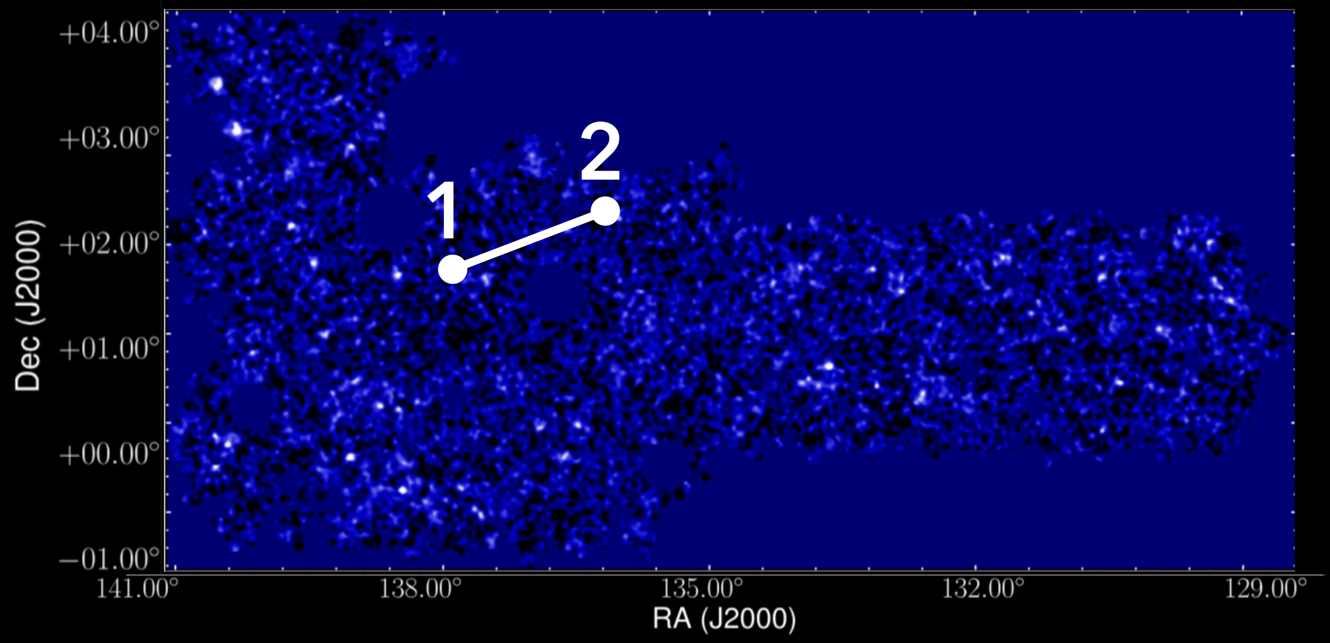
tSZ auto-power spectrum analysis



Bolliet+ (2018)

Auto 2pt Correlations

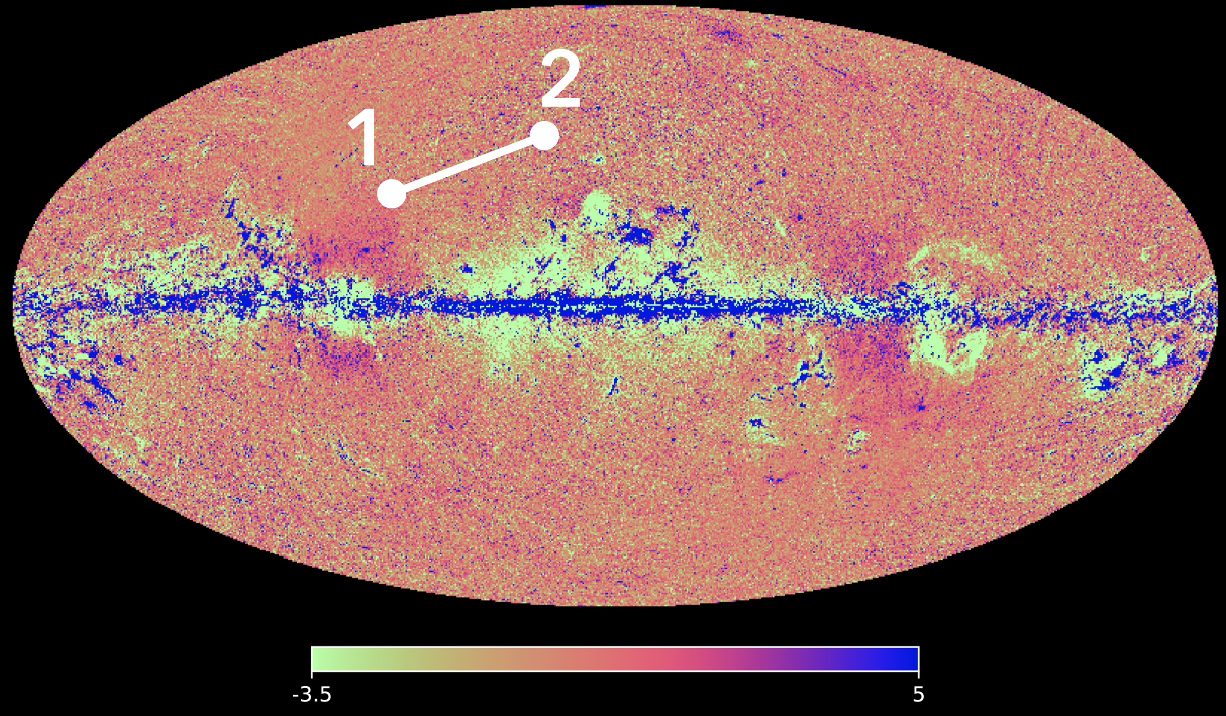
WL



Power spectrum / 2pt correlation

Cosmology

tSZ

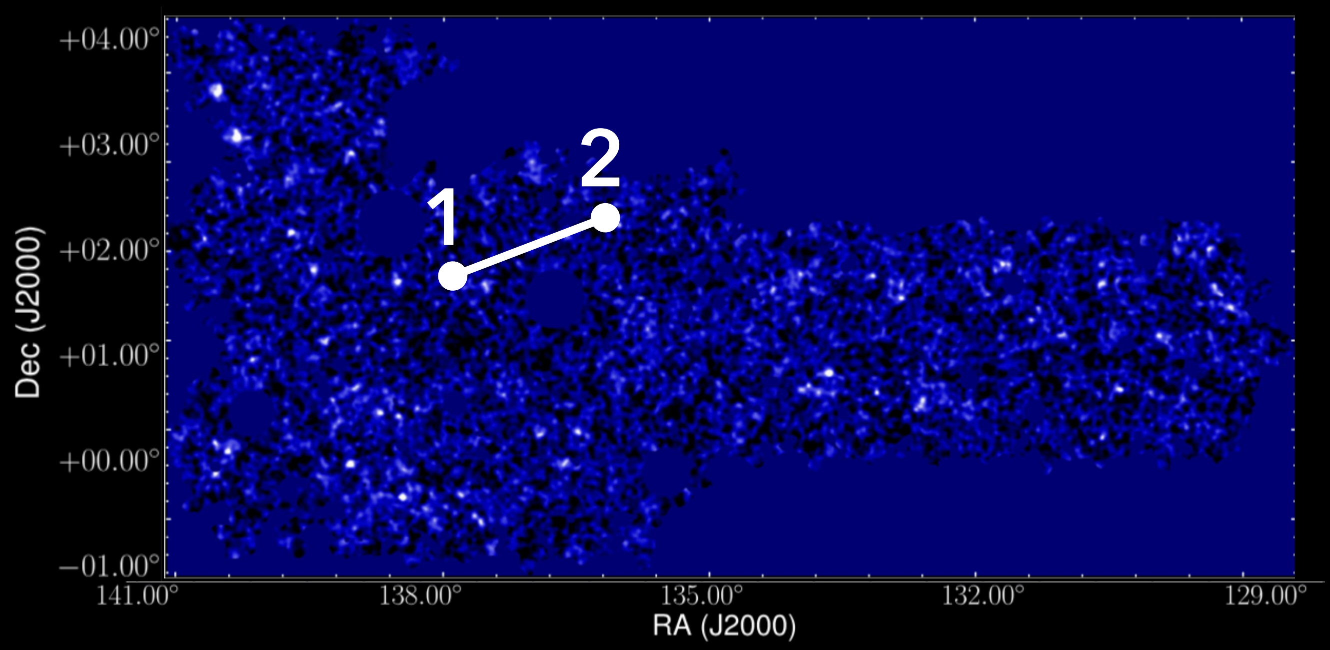


Cosmology

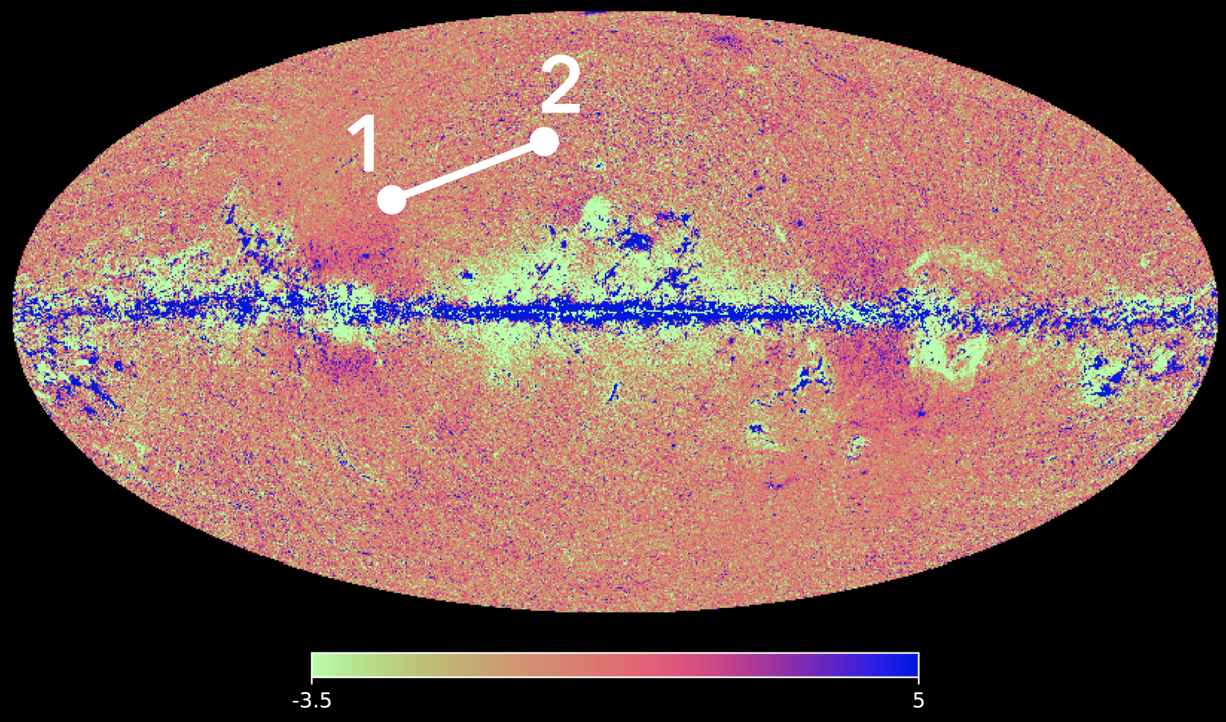
Power spectrum / 2pt correlation

Auto 2pt Correlations

WL



tSZ



Power spectrum / 2pt correlation

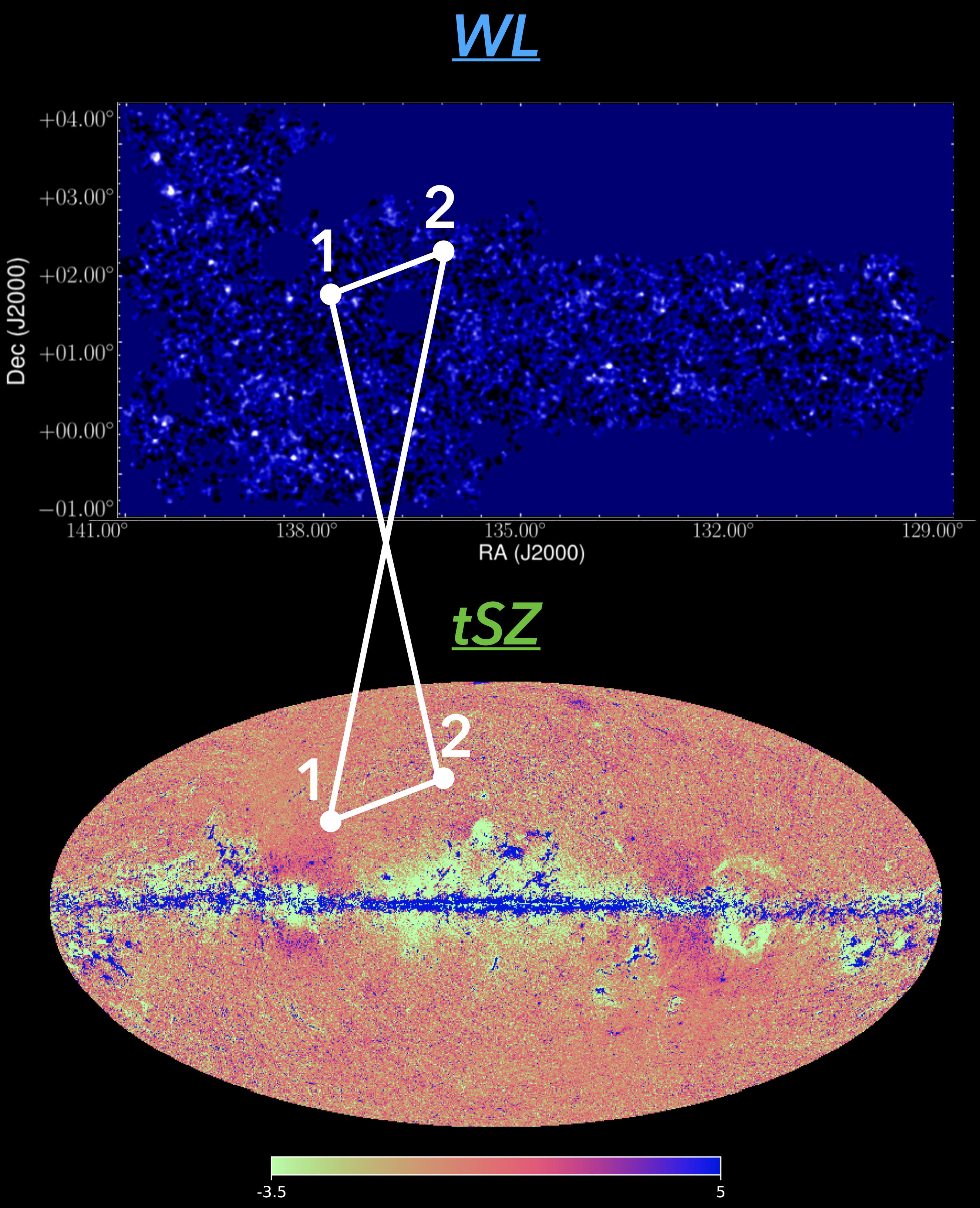
Cosmology

Joint Analysis?

Cosmology

Power spectrum / 2pt correlation

Cross 2pt Correlations



Cross-correlations!

Why Cross-Correlation?

- A naive advantage over auto-correlation is addition of independent information useful for breaking parameter degeneracy.

Why Cross-Correlation?

- A naive advantage over auto-correlation is addition of independent information useful for breaking parameter degeneracy.

✦Especially in the case of cross-correlation between ***high S/N*** and *low S/N* observables, the cross-correlation becomes more powerful!

X = **WL**, galaxies, CMB temp. Y = **tSZ,** CMB pol., GW source

$$\frac{(S/N)^2_{\rm XY}}{(S/N)^2_{\rm YY}} \gg 1$$

Cross-correlation outperforms auto-correlation!

Why Cross-Correlation?

- A naive advantage over auto-correlation is addition of independent information useful for breaking parameter degeneracy.

✦Especially in the case of cross-correlation between ***high S/N*** and *low S/N* observables, the cross-correlation becomes more powerful!

X = **WL**, galaxies, CMB temp. Y = **tSZ,** CMB pol., GW source

$$\frac{(S/N)^2_{\mathrm{XY}}}{(S/N)^2_{\mathrm{YY}}} \gg 1$$

Cross-correlation outperforms auto-correlation!

If the observable Y contains unique information (e.g., cluster astrophysics), cross-correlation should be the first way to go!

Why Cross-Correlation?

- A naive advantage over auto-correlation is addition of independent information useful for breaking parameter degeneracy.

✦Especially in the case of cross-correlation between ***high S/N*** and *low S/N* observables, the cross-correlation becomes

<u>Contents of this talk</u>

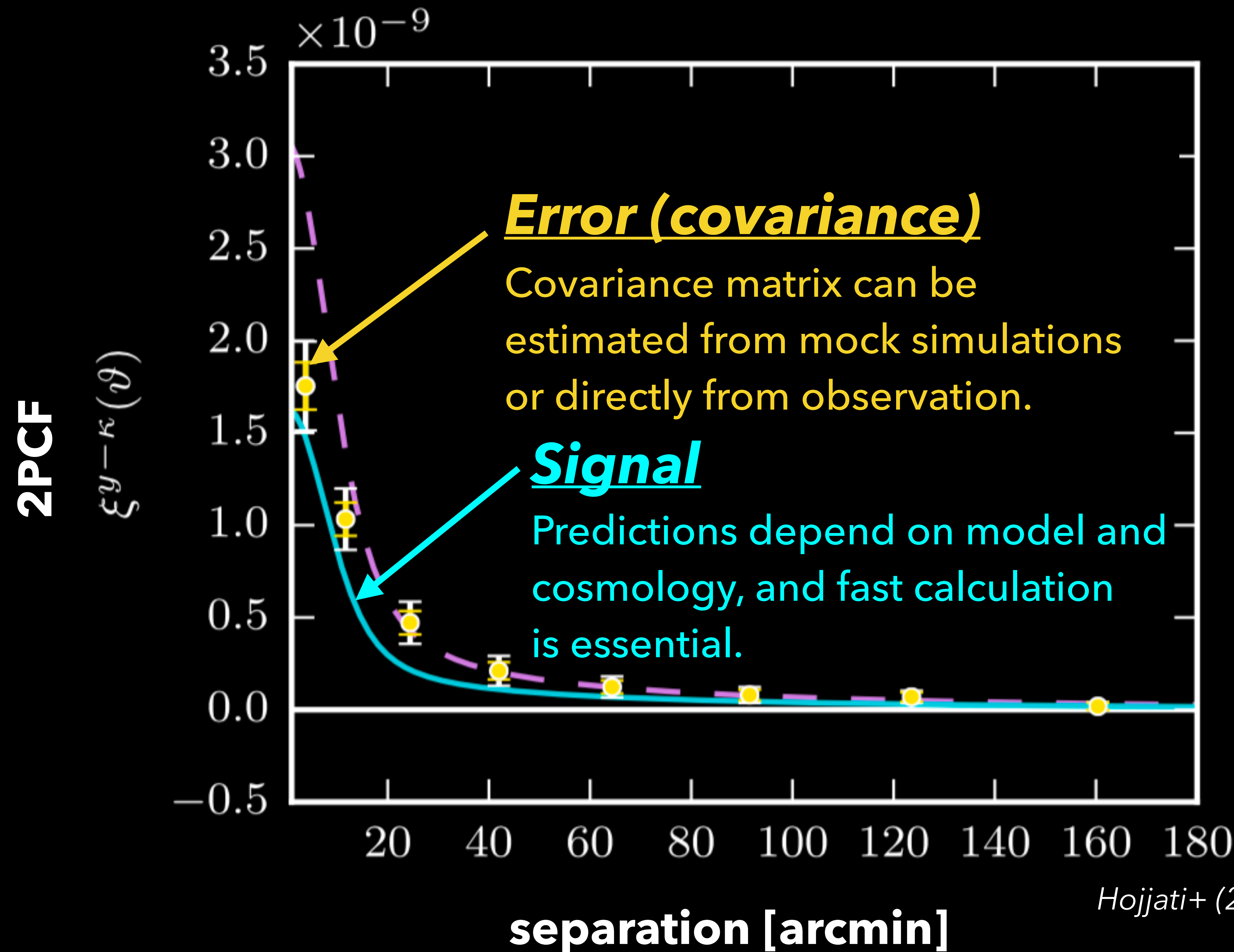
Part I: Cosmological analysis of the measurement of tSZ-WL cross-correlations with RCSLenS and *Planck*

Part II: Measurements of the tSZ-WL cross-correlations with HSC and *Planck*

If the observable Y contains unique information (e.g., cluster astrophysics), cross-correlation should be the first way to go!

Strategy

✦Example: RCSLenS x *Planck* measurement of WL-tSZ cross-correlations.



Hojjati+ (2017)

Analytical Prediction of Signal

Theoretical prediction of cross spectra is based on ***halo model***.
All matter and gas is associated with halos.

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

$$C_\ell^{y\kappa(1\mathrm{h})} = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} y_\ell(M,z) \kappa_\ell(M,z)$$

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

$$\times \int dM_1 dM_2 \frac{dn}{dM_1} b(M_1,z) y_\ell(M_1,z) \frac{dn}{dM_2} b(M_2,z) \kappa_\ell(M_2,z)$$

Correlation function can be obtained via Hankel transform.

$$\xi^{y\kappa}(\theta) = \int \frac{\ell d\ell}{2\pi} C_\ell^{y\kappa} J_0(\ell\theta)$$

Analytical Prediction of Signal

Theoretical prediction of cross spectra is based on ***halo model***.
All matter and gas is associated with halos.

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

well calibrated with *N*-body simulations

$$C_\ell^{y\kappa(1\mathrm{h})} = \int dz \frac{d^2V}{dzd\Omega} \int dM \frac{dn}{dM} y_\ell(M,z)\kappa_\ell(M,z)$$

$$C_\ell^{y\kappa(2\mathrm{h})} = \int dz \frac{d^2V}{dzd\Omega} P_\mathrm{m}(k=\ell/D_A, z)$$

$$\times \int dM_1 dM_2 \frac{dn}{dM_1} b(M_1,z) y_\ell(M_1,z) \frac{dn}{dM_2} b(M_2,z)\kappa_\ell(M_2,z)$$

Correlation function can be obtained via Hankel transform.

$$\xi^{y\kappa}(\theta) = \int \frac{\ell d\ell}{2\pi} C_\ell^{y\kappa} J_0(\ell\theta)$$

Analytical Prediction of Signal

Theoretical prediction of cross spectra is based on ***halo model***.
All matter and gas is associated with halos.

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

well calibrated with *N*-body simulations

Convergence Projection of NFW profile

$$C_\ell^{y\kappa(1\mathrm{h})} = \int dz \frac{d^2V}{dzd\Omega} \int dM \frac{dn}{dM} y_\ell(M,z)\kappa_\ell(M,z)$$

$$C_\ell^{y\kappa(2\mathrm{h})} = \int dz \frac{d^2V}{dzd\Omega} P_\mathrm{m}(k=\ell/D_A, z)$$

$$\times \int dM_1 dM_2 \frac{dn}{dM_1} b(M_1,z) y_\ell(M_1,z) \frac{dn}{dM_2} b(M_2,z)\kappa_\ell(M_2,z)$$

Correlation function can be obtained via Hankel transform.

$$\xi^{y\kappa}(\theta) = \int \frac{\ell d\ell}{2\pi} C_\ell^{y\kappa} J_0(\ell\theta)$$

Analytical Prediction of Signal

Theoretical prediction of cross spectra is based on ***halo model***.
All matter and gas is associated with halos.

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

well calibrated with *N*-body simulations

$$C_\ell^{y\kappa(1\mathrm{h})} = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} y_\ell(M,z) \kappa_\ell(M,z)$$

Convergence
Projection of NFW profile

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

$$\times \int dM_1 dM_2 \frac{dn}{dM_1} b(M_1,z) y_\ell(M_1,z) \frac{dn}{dM_2} b(M_2,z) \kappa_\ell(M_2,z)$$

Compton-y
Projection of *pressure profile*

Correlation function can be obtained via Hankel transform.

$$\xi^{y\kappa}(\theta) = \int \frac{\ell d\ell}{2\pi} C_\ell^{y\kappa} J_0(\ell\theta)$$

Analytical Prediction of Signal

Theoretical prediction of cross spectra is based on ***halo model***.
All matter and gas is associated with halos.

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

well calibrated with *N*-body simulations

$$C_\ell^{y\kappa(1\mathrm{h})} = \int dz \, \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} y_\ell(M, z) \kappa_\ell(M, z)$$

Convergence
Projection of NFW profile

$$C_\ell^{y\kappa(2\mathrm{h})} = \int dz \, \frac{d^2V}{dz d\Omega} P_\mathrm{m}(k = \ell / D_\mathrm{A}, z)$$

$$\times \int dM \cdots dn \cdots dn \cdots b(M_2, z) \kappa_\ell(M_2, z)$$

Compton-y
Projection of *pressure profile*

Analytical modeling of pressure profile is critical!

Correlation function can be obtained via Hankel transform.

$$\xi^{y\kappa}(\theta) = \int \frac{\ell d\ell}{2\pi} C_\ell^{y\kappa} J_0(\ell \theta)$$

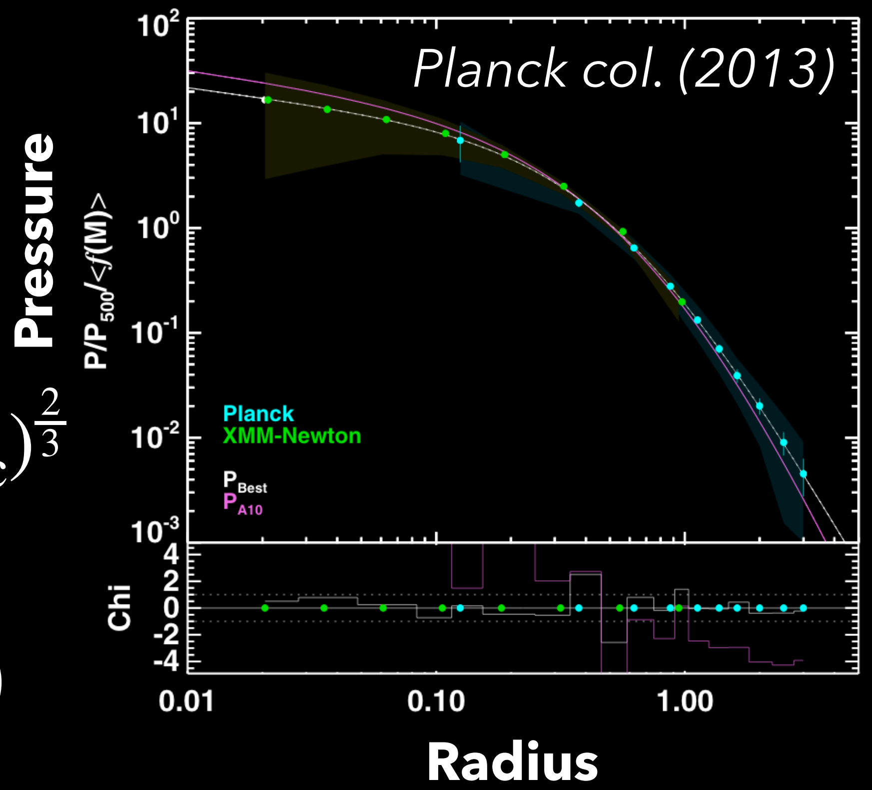
Models of ICM Profiles

Earlier works include Kaiser (1986); Makino+ (1998); Suto+ (1998); Komatsu & Seljak (2001, 2002); Ostriker+ (2005); Bode+ (2009)

Generalized NFW (GNFW) profile

Parametrized in the similar way to NFW profile.
Parameters are fitted against X-ray or SZ observations.

$$P_e(r) = \frac{P_0}{x^\gamma(1+x^\alpha)^{(\beta-\gamma)/\alpha}} \qquad x = r/R_{500c},\ P_0 \propto (M_{500c})^{\frac{2}{3}}$$



Analytical model (Shaw+, 2010; Flender+, 2016)

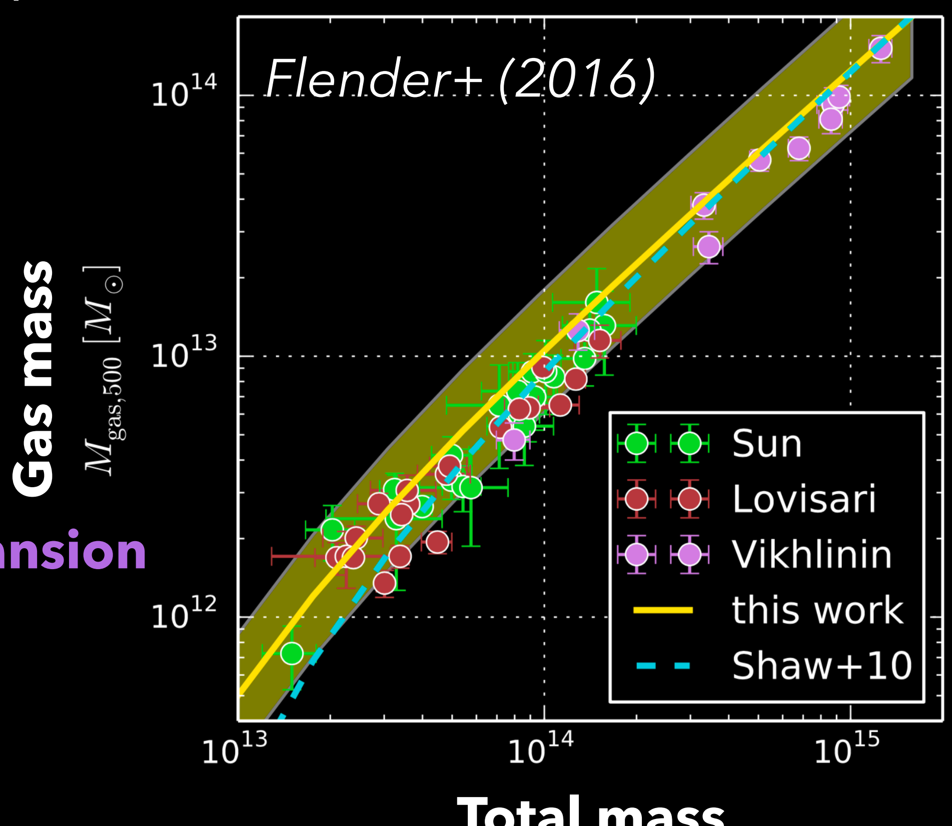
The gas density/pressure profiles are determined from fluid equations. Feedback processes are incorporated by introducing free parameters.

$$\frac{dP_{tot}}{dr} = -\rho_g(r)\frac{d\Phi(r)}{dr},\ P_{tot} \propto \rho_g^{1.2}$$

To determine the normalization,

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

Dynamical friction SNe/AGN feedback Work by expansion



Non-thermal Pressure

NOTE: From X-ray and SZ, only **thermal pressure** component can be observed, but simulations suggest that turbulent motion can also balance the self-gravity of galaxy clusters.
This another source of pressure is called as ***non-thermal pressure***.

Non-thermal Pressure

NOTE: From X-ray and SZ, only **thermal pressure** component can be observed, but simulations suggest that turbulent motion can also balance the self-gravity of galaxy clusters.
This another source of pressure is called as ***non-thermal pressure***.

BUT it is hard to measure the non-thermal pressure since it requires high-res. spectroscopy.
We incorporate this effect in a phenomenological manner.

Hydrostatic bias

for GNFW profile

$$\frac{M_{\rm HSE}}{M_{\rm true}} = 1 - b$$

Studies on mass calibration with WL suggest b ~ 0.1–0.4.

Medezinski+ (2018); Miyatake, …, KO, … (2018)

Non-thermal pressure profile

for analytic profile

$$\frac{P_{\rm nth}}{P_{\rm tot}}(r) = \alpha(1+z)^{\beta}\left(\frac{r}{R_{500c}}\right)^{1.8}$$

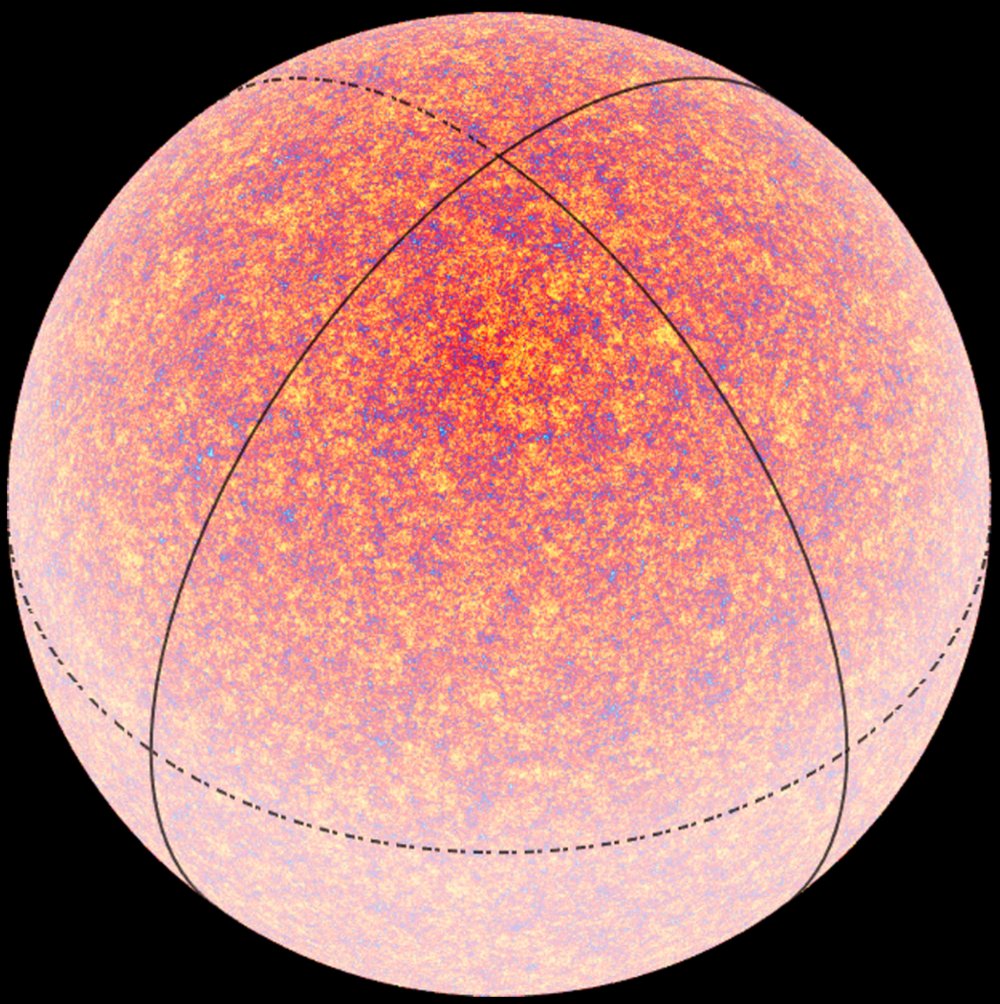
Based on hydro. simulations.

Lau+ (2009); Nelson+ (2014)

All-Sky Mock Simulations

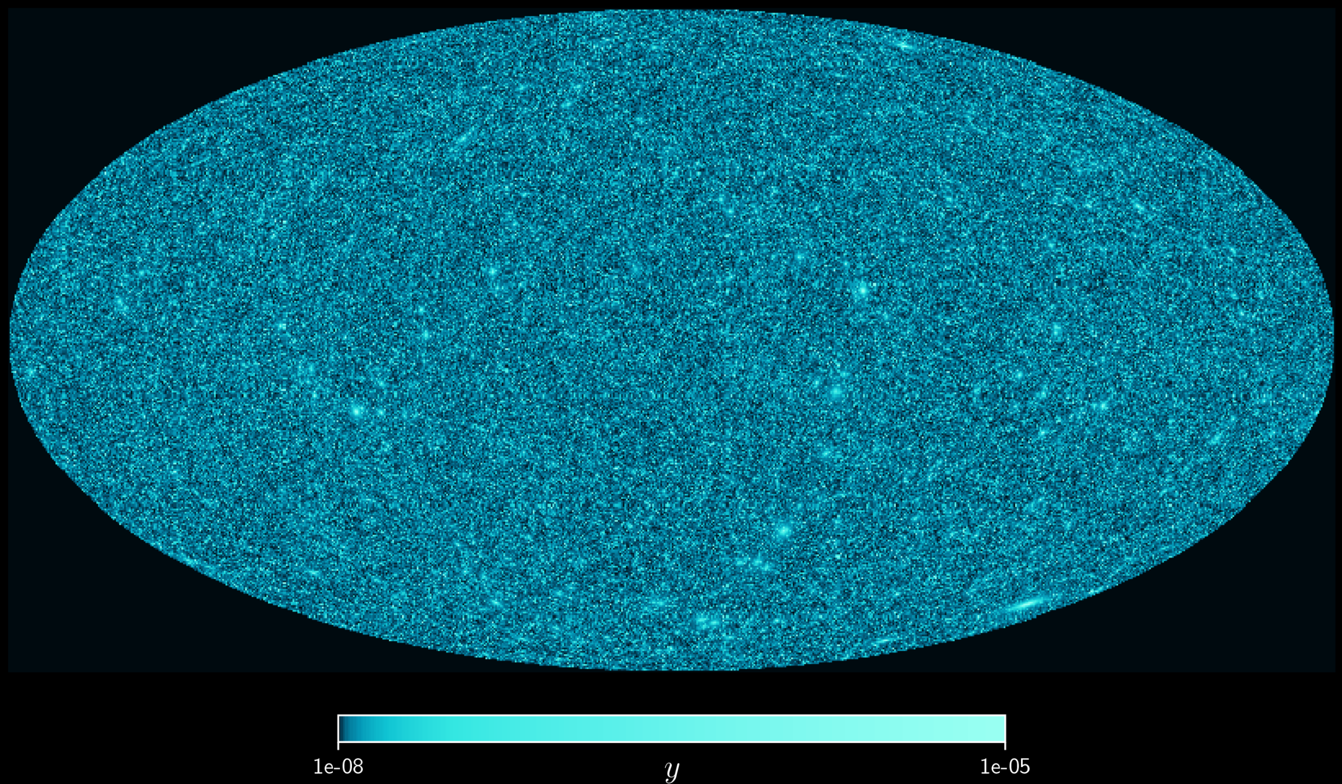
- For more reliable estimation of covariance, we make advantage of ***all-sky N-body simulations***. We can incorporate various effects, e.g., survey geometry, noise, and beam convolution.

All-sky convergence map



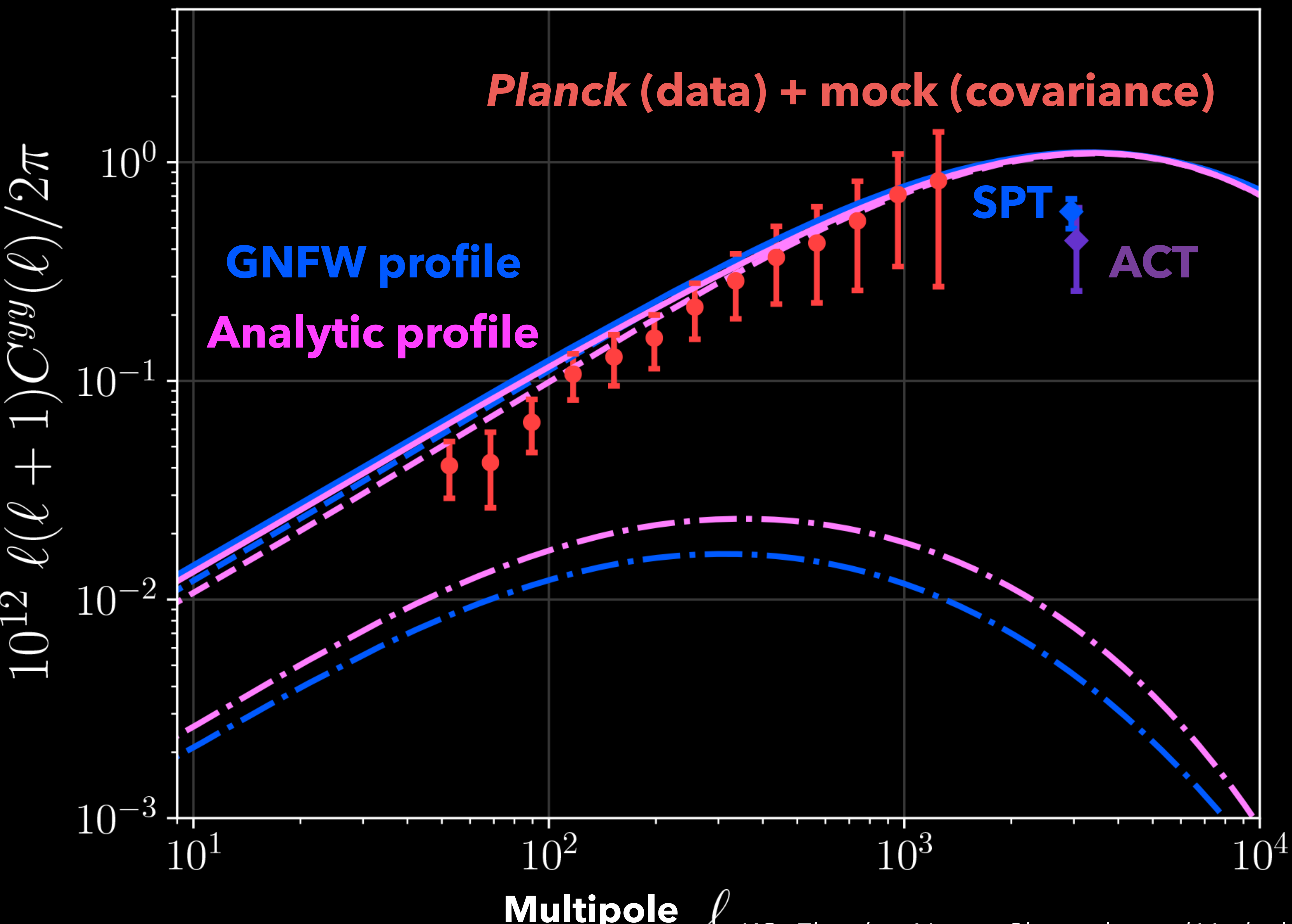
Shirasaki+ (2015); Takahashi,…,KO,… (2017)

All-sky Compton-*y* map



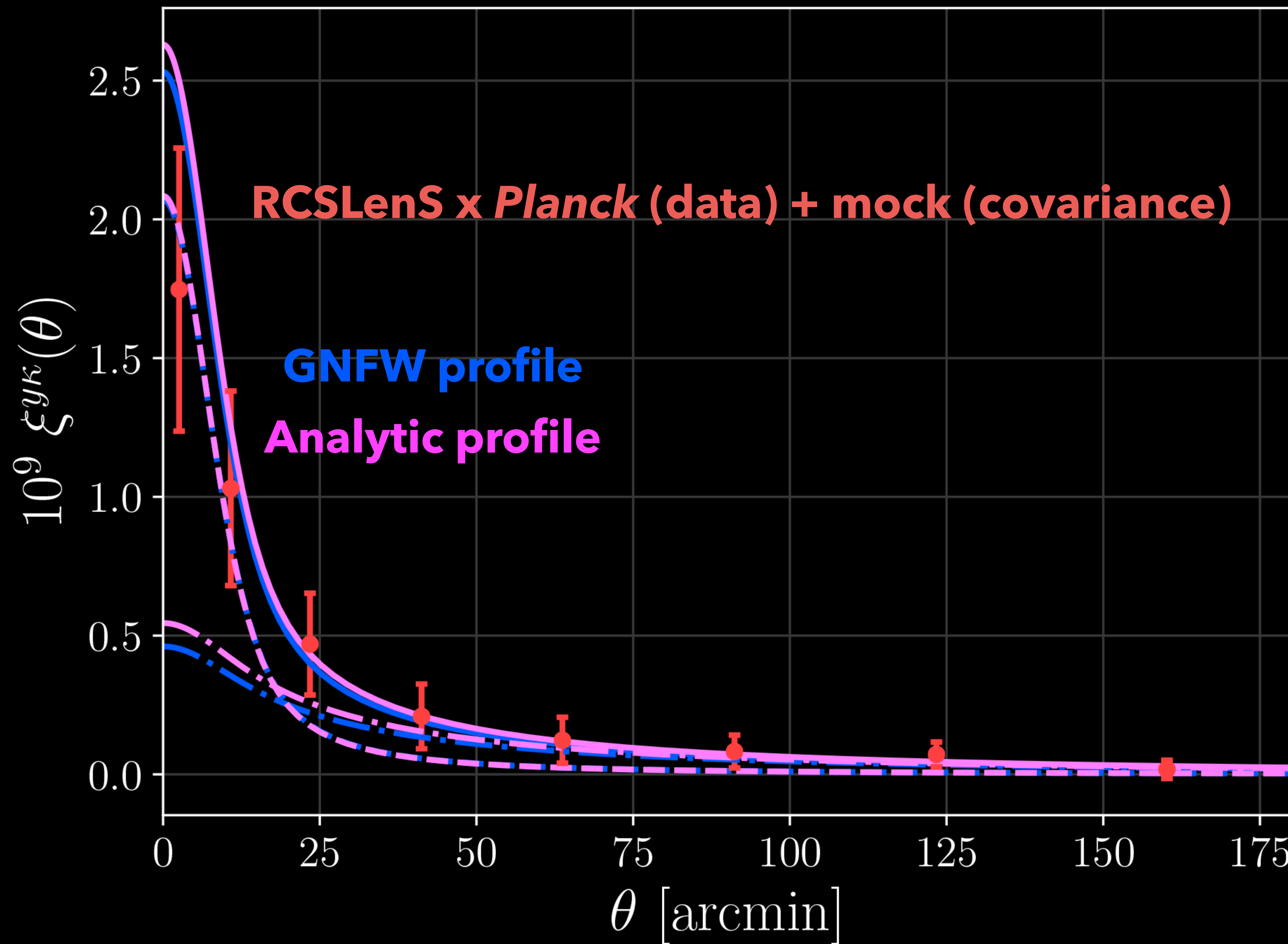
KO+ (in prep.)

Compton-y Auto-Spectra



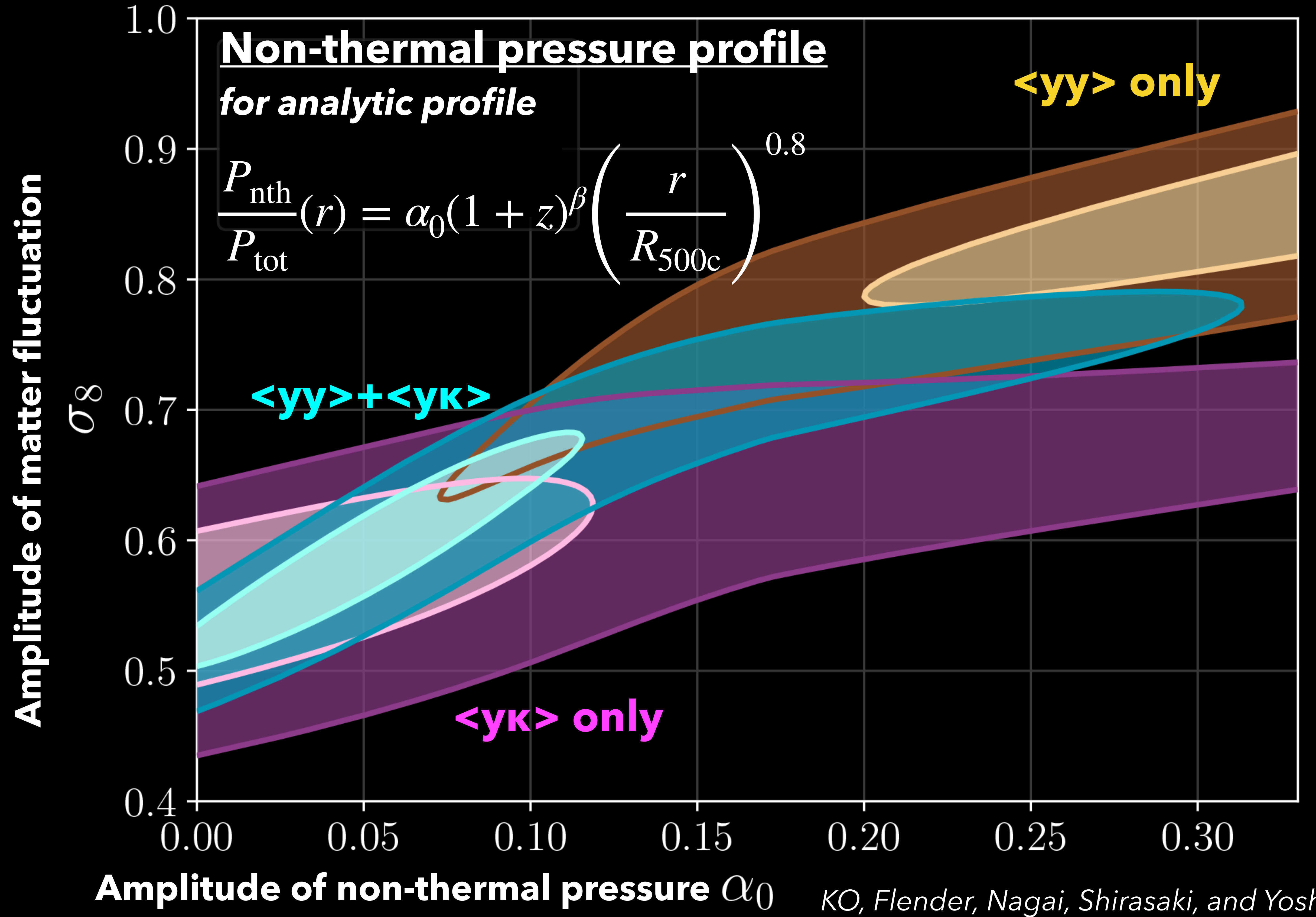
KO, Flender, Nagai, Shirasaki, and Yoshida (2018)

Cross-Correlation Functions



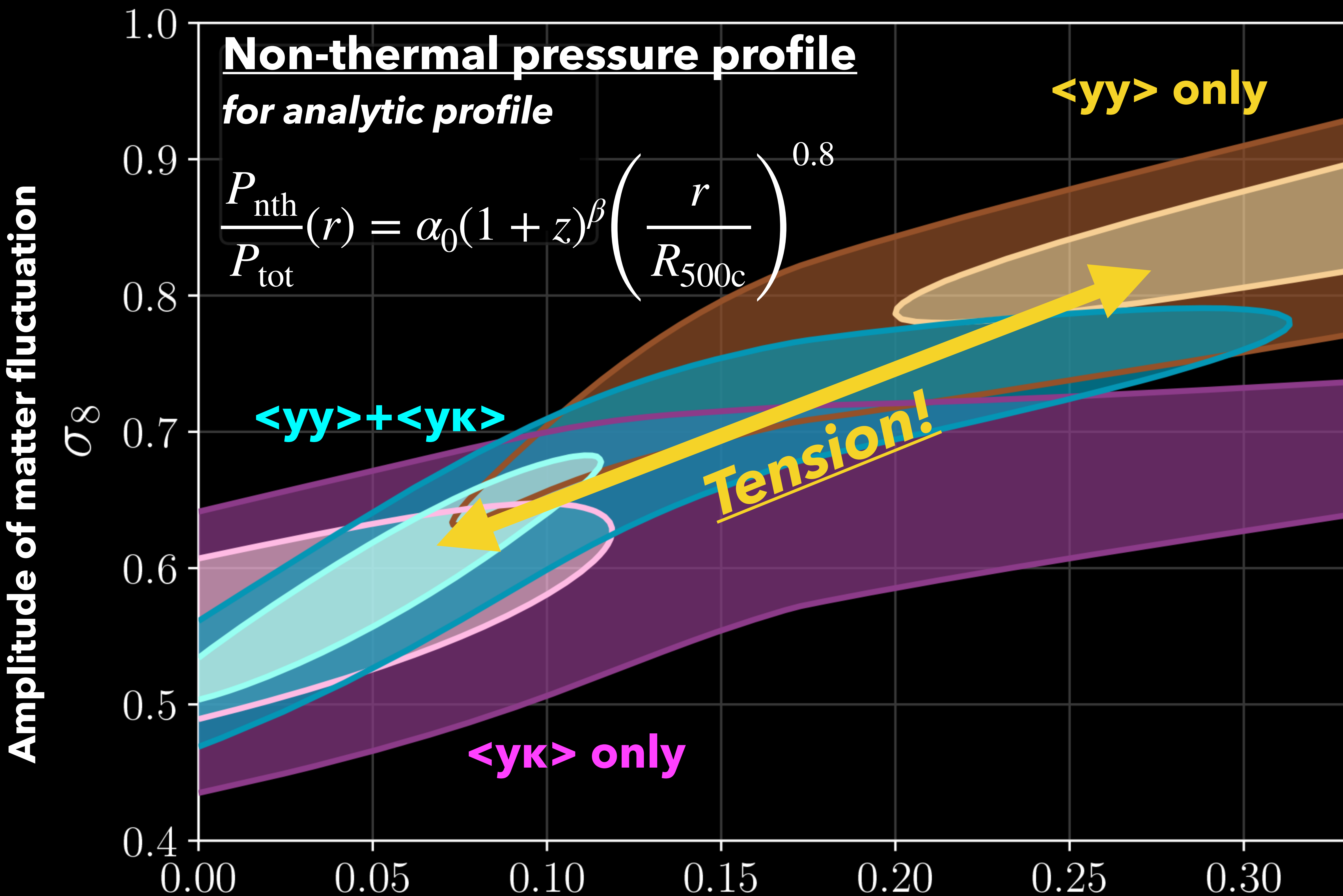
KO, Flender, Nagai, Shirasaki, and Yoshida (2018)

Constraints on Non-Thermal Pressure



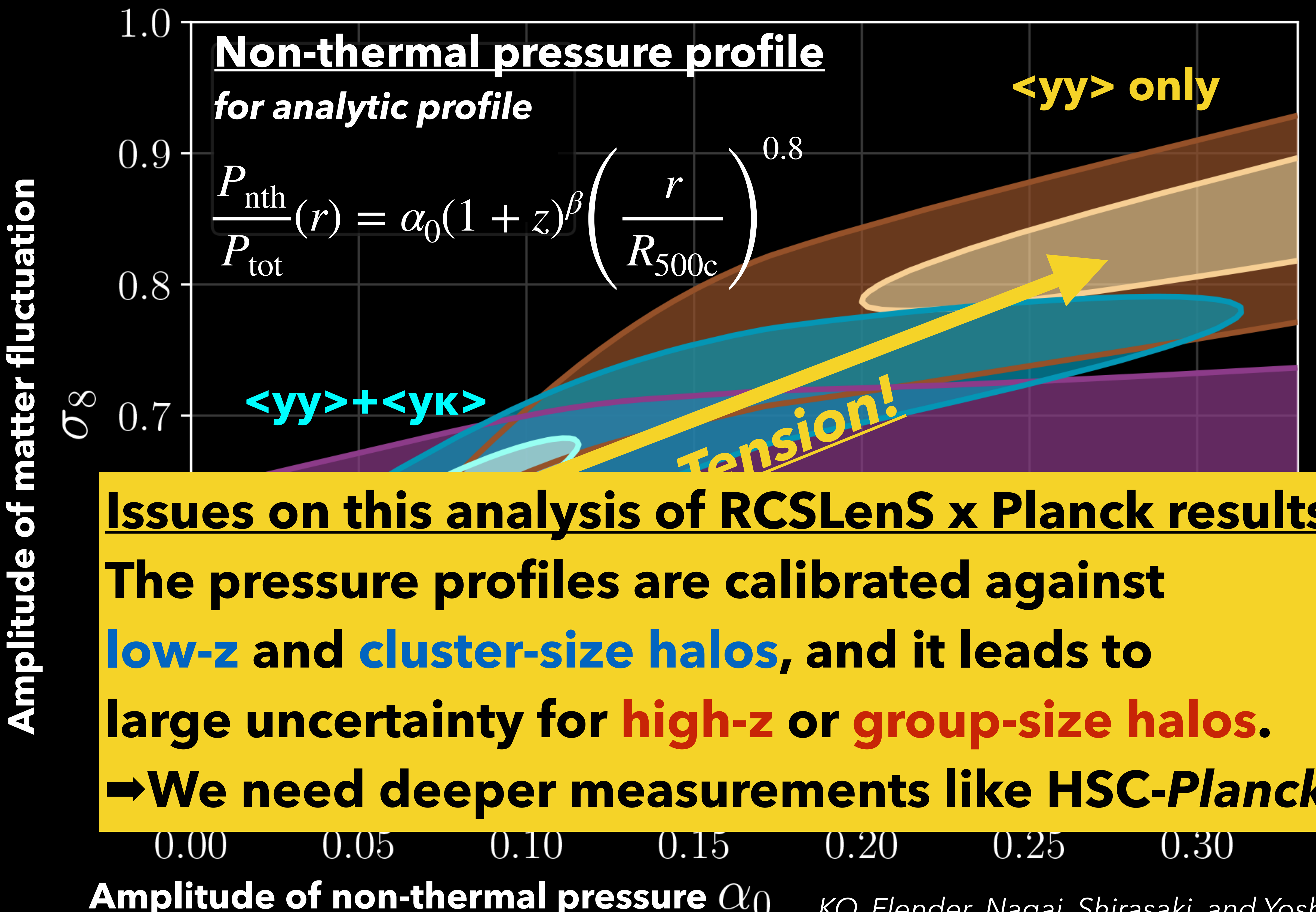
KO, Flender, Nagai, Shirasaki, and Yoshida (2018)

Constraints on Non-Thermal Pressure



KO, Flender, Nagai, Shirasaki, and Yoshida (2018)

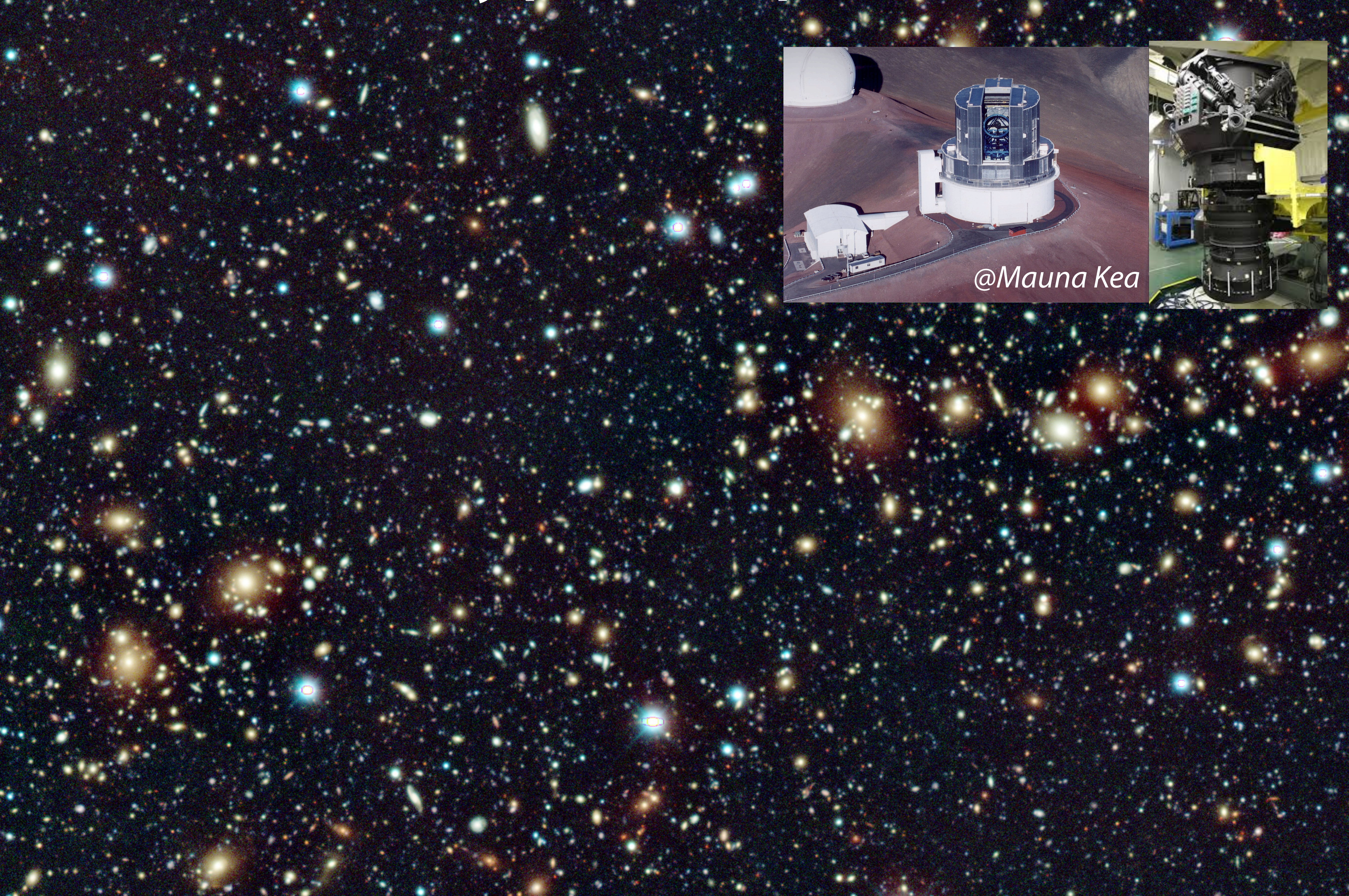
Constraints on Non-Thermal Pressure



Issues on this analysis of RCSLenS x Planck results:
The pressure profiles are calibrated against low-z and cluster-size halos, and it leads to large uncertainty for high-z or group-size halos.
➡We need deeper measurements like HSC-*Planck*!

KO, Flender, Nagai, Shirasaki, and Yoshida (2018)

Subaru Hyper Suprime-Cam



HSC-SSP WL Survey

✦**HSC S16A**

Wide and deep WL survey which covers 136.9 deg²
with mean *i*-band seeing ~ 0′′.58 and $n_{\rm eff} = 24.6\,{\rm arcmin}^{-2}$

c.f., for RCSLenS
$n_{\rm eff} = 5.8\,{\rm arcmin}^{-2}$

Convergence

KO, Miyatake, Nagai, Shirasaki, Yoshida+ (in prep.)

Measurements of Cross-Correlations

Null tests passed

6 HSC patches

Preliminary

GNFW

HSC x *Planck*

KO, Miyatake, Nagai, Shirasaki, Yoshida+ (in prep.)

Constraints on Cosmological Parameters

$\omega_{\rm b}$

In this analysis, GNFW profile is used.

With the prior from *Planck* CMB measurements, we can place tight constraints on cosmological parameters along with hydrostatic mass bias!

$\omega_{\rm c}$

$n_{\rm s}$

h

$A_{\rm s}$

b

Hydrostatic bias

for GNFW profile

$$\frac{M_{\rm HSE}}{M_{\rm true}} = 1 - b$$

KO, Miyatake, Nagai, Shirasaki, Yoshida+ (in prep.)

Constraints on Mass Bias

Fraction of mass supported by thermal pressure

CS82-ACT

No non-thermal pressure

HSC-*Planck*

LoCuSS

CCCP

CLASH

HSC-ACT

PSZ2LenS

WtG

Planck **tSZ auto-power spectrum**
(Bolliet+, 2018)

High non-thermal pressure

= Mass supported by thermal pressure

KO, Miyatake, Nagai, Shirasaki, Yoshida+ (in prep.)

Constraints on Mass Bias

Fraction of mass supported by thermal pressure

CS82-ACT

No non-thermal pressure

HSC-*Planck*

LoCuSS

CCCP

CLASH

HSC-ACT

PSZ2LenS

WtG

This work

***Planck* tSZ auto-power spectrum**
(Bolliet+, 2018)

High non-thermal pressure

= Mass supported by thermal pressure

KO, Miyatake, Nagai, Shirasaki, Yoshida+ (in prep.)

Constraints on Mass Bias

Fraction of mass supported by thermal pressure

CS82-ACT

No non-thermal pressure

HSC-*Planck*

LoCuSS

Our results show higher b than
WL mass calibration measurements,
and imply the possible redshift evolution of mass bias!

This work

Planck **tSZ auto-power spectrum**
(Bolliet+, 2018)

High non-thermal pressure

= Mass supported by thermal pressure

KO, Miyatake, Nagai, Shirasaki, Yoshida+ (in prep.)

Summary

- Weak lensing and the thermal Sunyaev-Zel'dovich effect are promising probes into the large-scale structure and thermodynamical properties of intra-cluster medium.

- Cross-correlation provides additional information with high S/N significance compared with auto-correlations.

- Halo model calculation and *N*-body simulations are used to predict the signal and estimate the covariance matrix. This study presents the first attempt to estimate covariance matrix from realistic mock simulations.

- **HSC is the unique WL survey which can probe into the large-scale structures and galaxy clusters at high redshifts, and the redshift evolution of them by tomography.**