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

Rencontres du Vietnam: Cosmology
(July10-July15, 2017)

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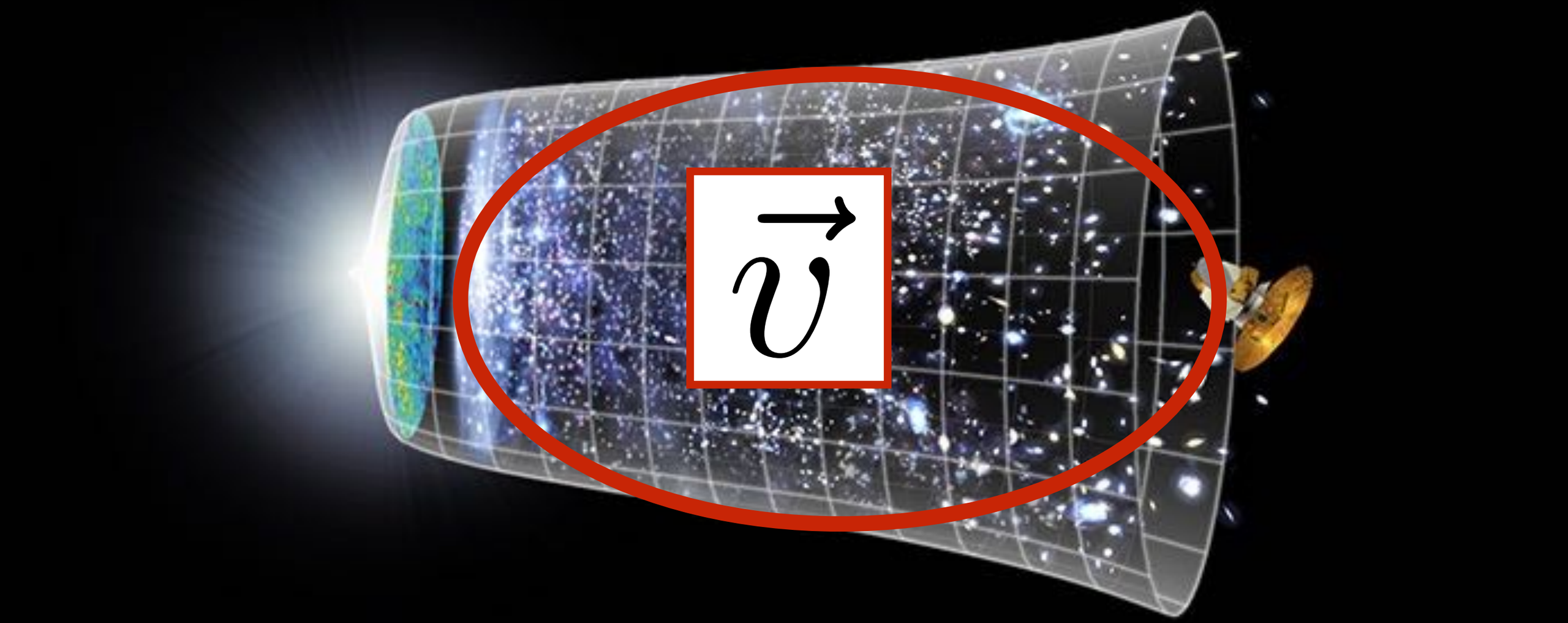
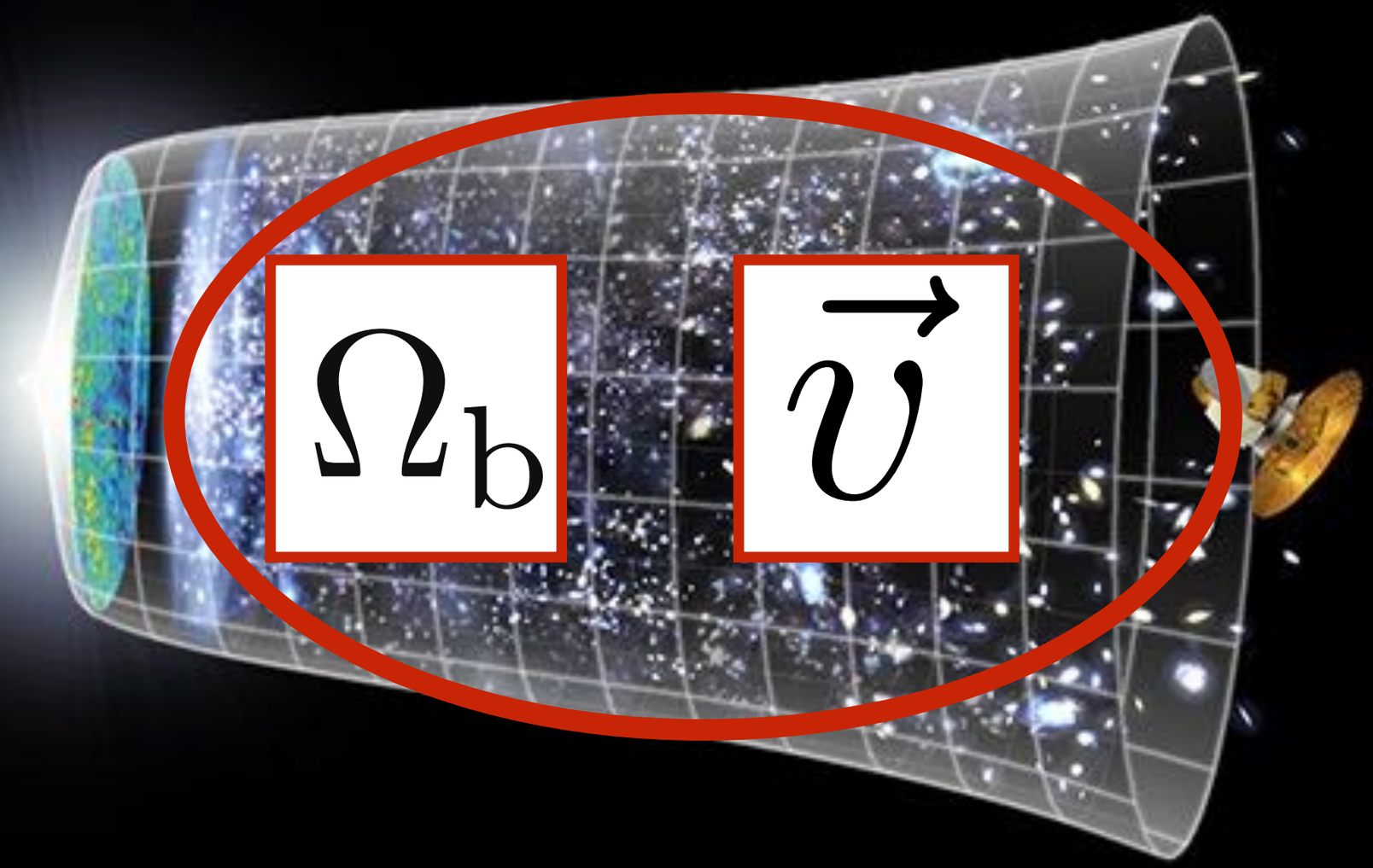
Galaxy Redshift Surveys



Time-dependence of peculiar velocities

➡ Testing modified gravity

Motivation of Kinematic SZ



(1) **Peculiar velocities** (Cosmology)
(2) **Baryons** (Astrophysics)

NASA/WMAP Science Team

Contents

- Review of the Kinematic SZ effect
- Previous works

- A new estimator in Fouier-space
- Theoretical modeling
- Measurements(BOSS x Planck)

- Forecast for future surveys

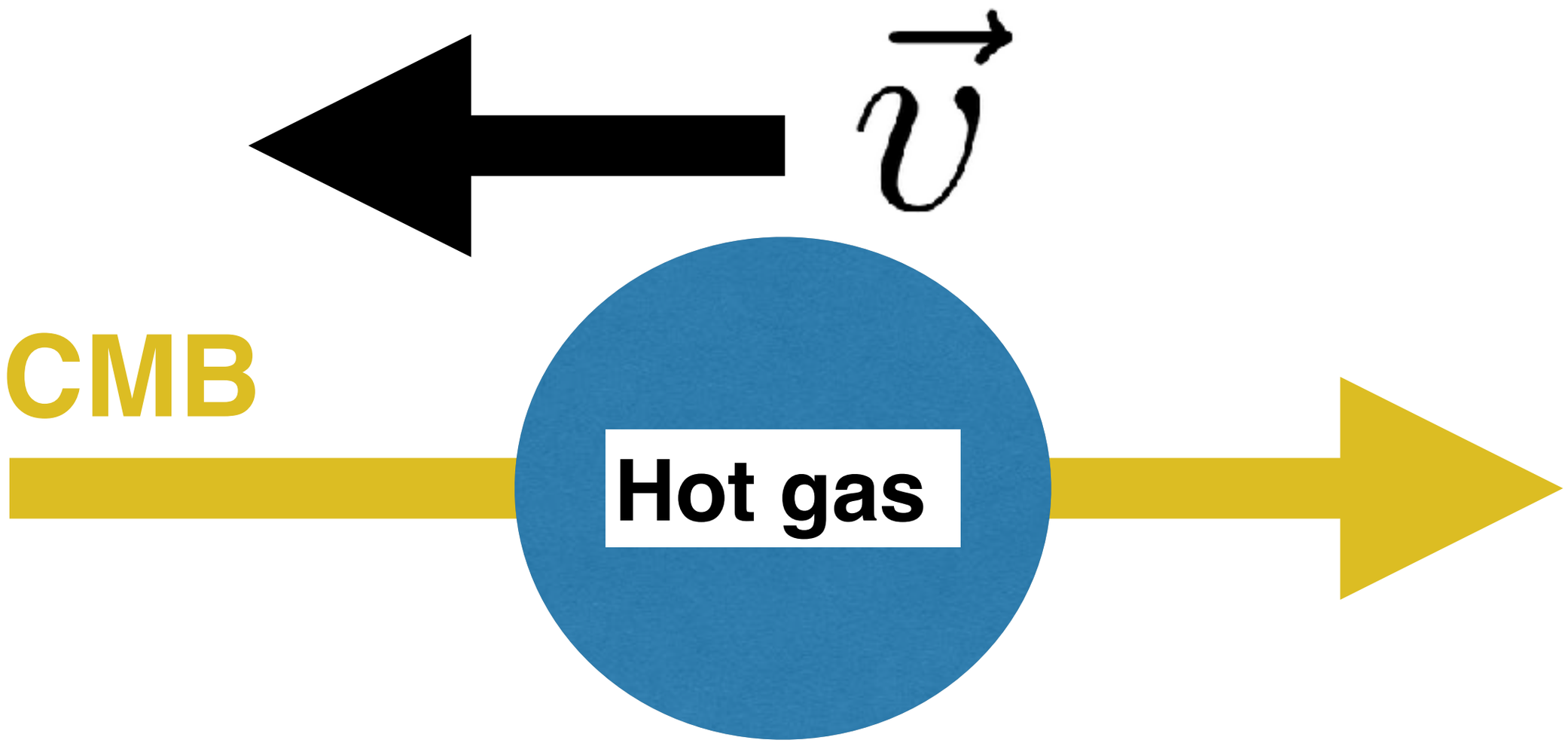
Sunyaev-Zel'dovich(SZ) Effect

- Inverse Compton Scattering of CMB photons with free, high-energy electrons in a gas cloud.
- Thermal and kinematic components.

Thermal SZ Effect

– Caused by hot thermal distribution of free electrons
– Dependent of gas temperature
– Cause a small distortion in the CMB blackbody spectrum.

Kinematic SZ Effect



— Sourced by free electron peculiar velocities along the line-of-sight.

Characteristic features of Kinematic SZ

$$\frac{\delta T_{\rm kSZ}(\hat{n})}{T_{\rm CMB}} = -\tau \frac{\vec{v}\cdot\hat{n}}{c}$$

$$\tau = \sigma_{\rm T} \int dl n_{\rm c}$$

— insensitive to halo mass (Astrophysics)

TSZ ~ M^(5/3), KSZ ~ M

$\sim 10^{14} M_\odot$	$\sim 10^{13} M_\odot$	$\sim 10^{12} M_\odot$
X-ray tSZ kSZ	kSZ	kSZ

Characteristic features of Kinematic SZ

$$\frac{\delta T_{\rm kSZ}(\hat{n})}{T_{\rm CMB}} = -\tau \frac{\vec{v}\cdot\hat{n}}{c}$$

$$\tau = \sigma_{\rm T} \int dl n_{\rm c}$$

— **Proportional to the peculiar velocity**

baryons trace dark matter (Cosmology)

RSD + kSZ

Characteristic features of Kinematic SZ

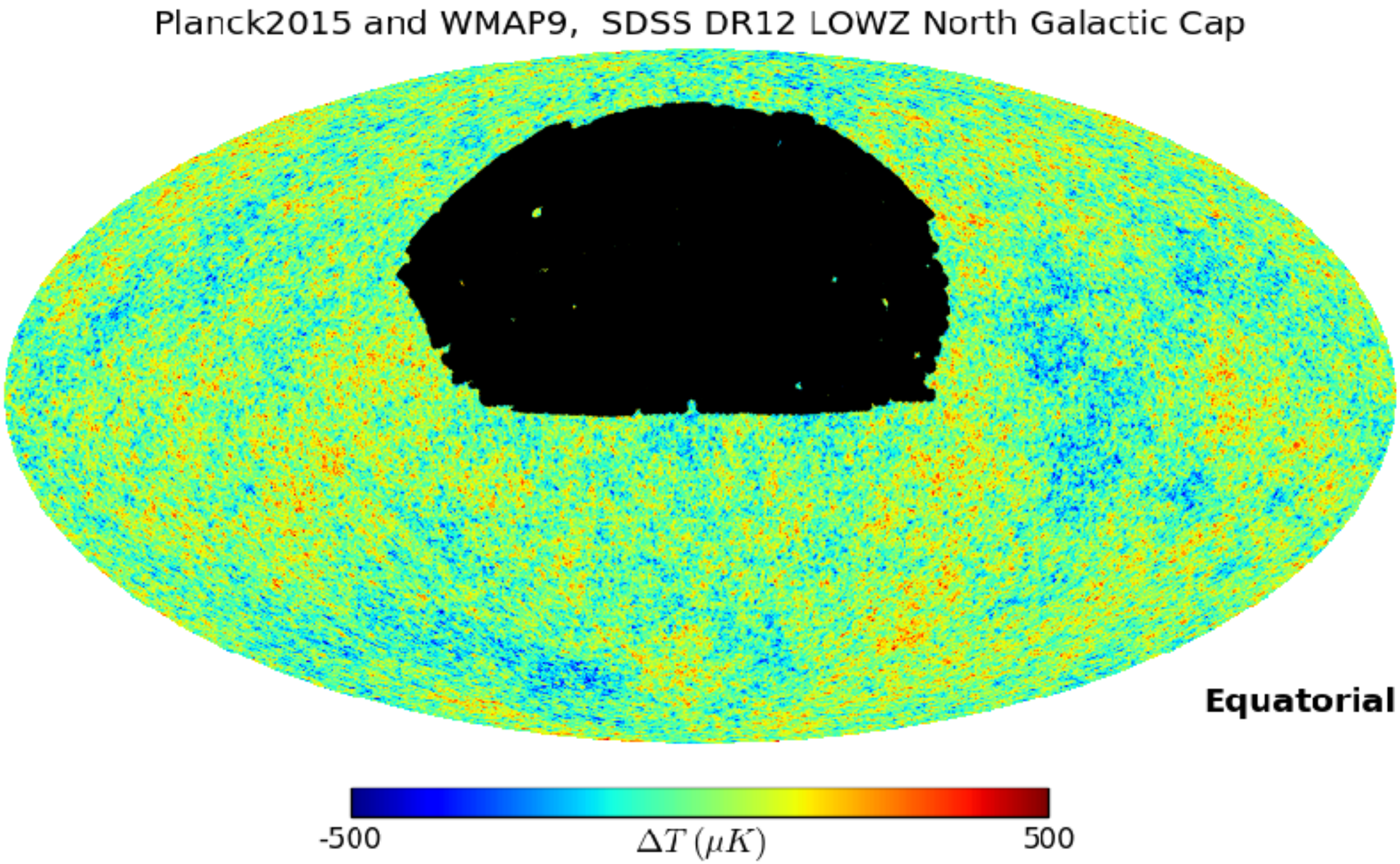
$$\frac{\delta T_{\rm kSZ}(\hat{n})}{T_{\rm CMB}} = -\tau \frac{\vec{v}\cdot\hat{n}}{c}$$

$$\tau = \sigma_{\rm T} \int dl n_{\rm c}$$

Typical S/N ~ 0.01 at each object

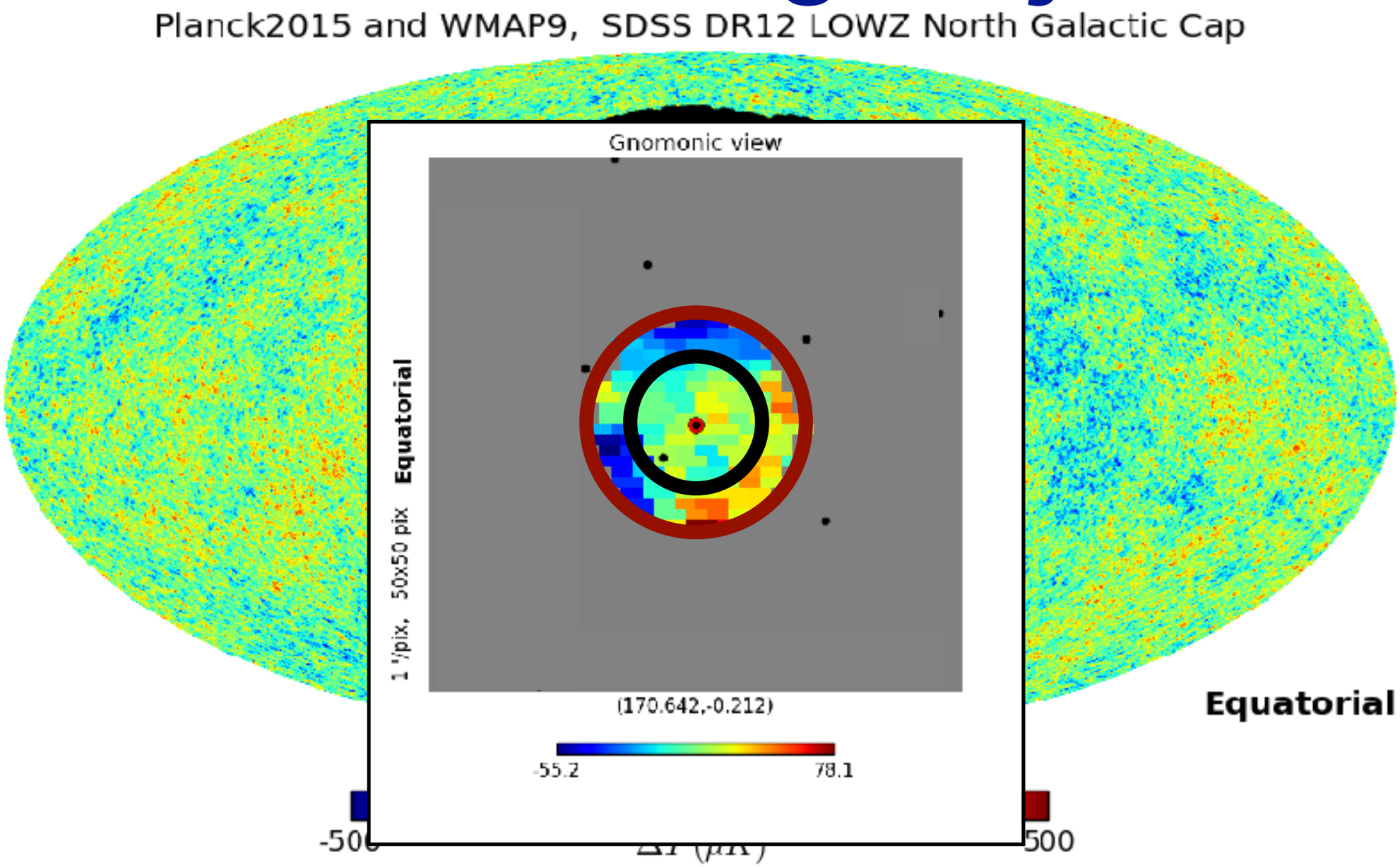
kSZ ~ 1.0 uK and CMB ~ 100 uK

How do we measure the kSZ signal?



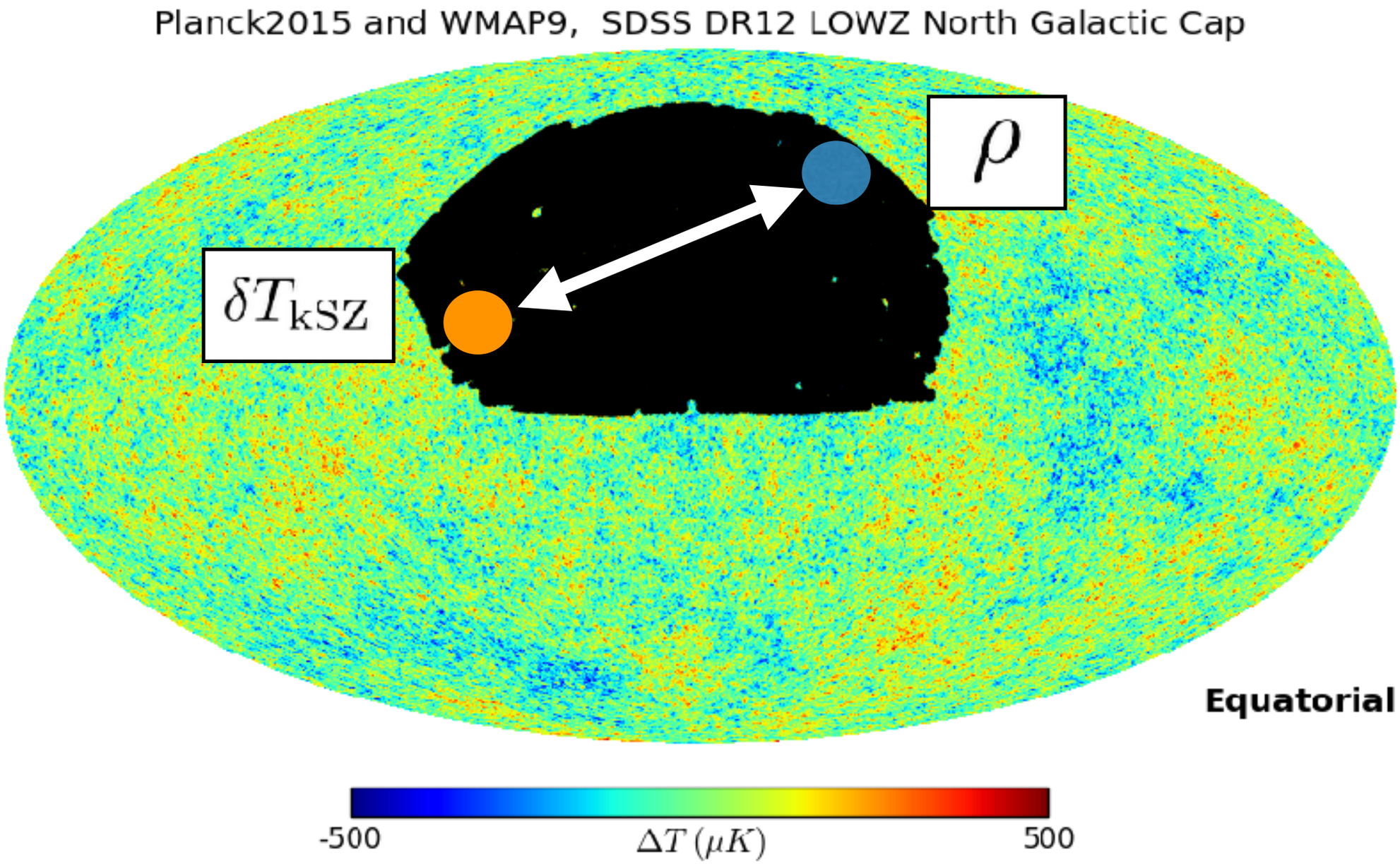
CMB x LSS

Filtered CMB temperature at each galaxy

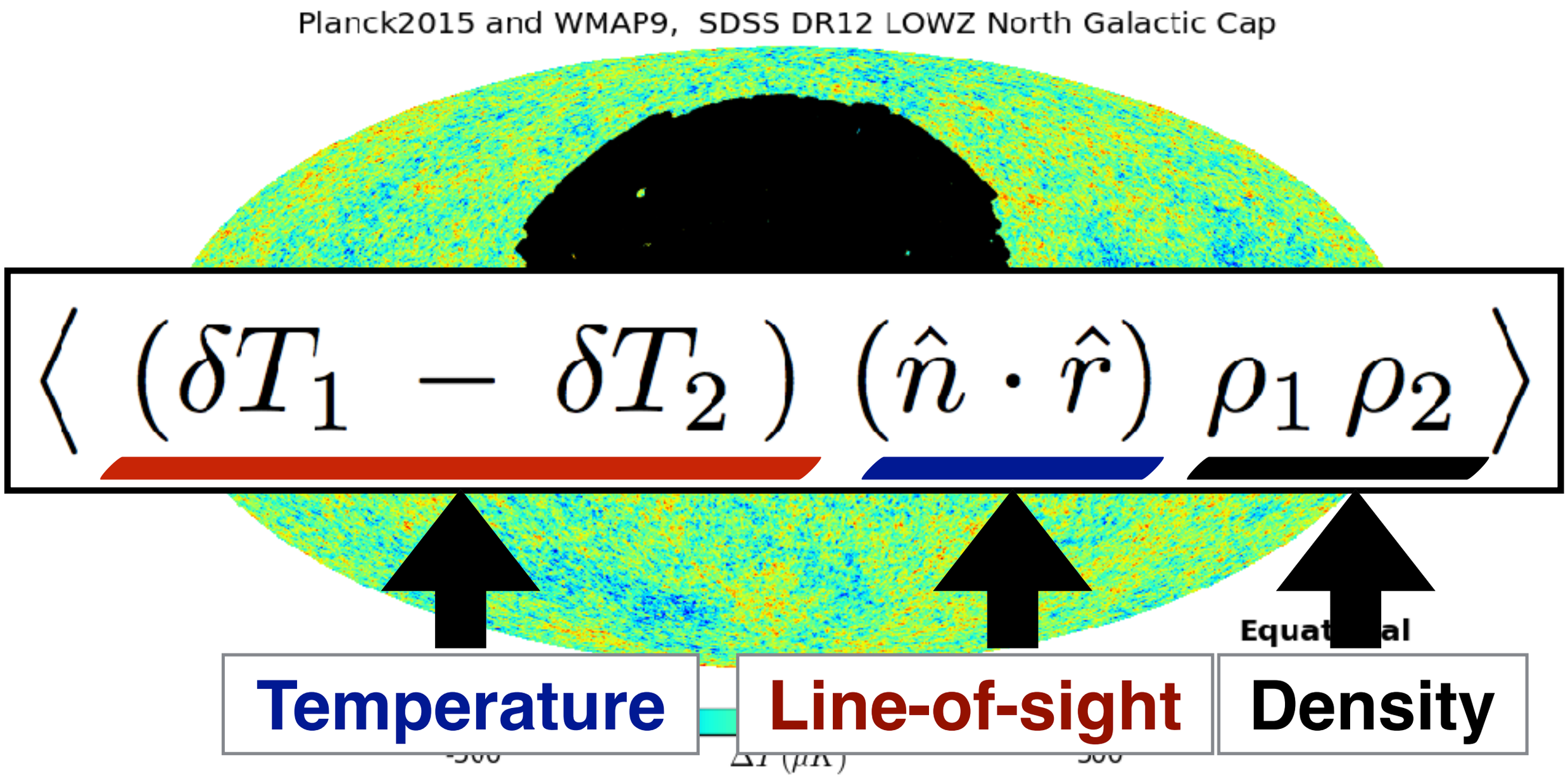


Compensated top-hat filter
(Aperture photometry filter)

Cross-correlating between galaxy and CMB



Pairwise kSZ signal



Pairwise kSZ signal

$$\boxed{\left\langle \; (\delta T_1 \; - \; \delta T_2 \,) \; \underline{(\hat{n} \cdot \hat{r})} \; \rho_1 \, \rho_2 \; \right\rangle}$$

$$\mu = \hat{n} \cdot \hat{r}$$

$$\int_{-1}^{1} d\mu \, \underline{\mu} \, f(\mu) =$$

Non-zero **for kSZ** $\boxed{\propto \; \mu}$

Zero **for the other components (CMB, detector noise, tSZ, etc.)**

Theoretical expression of Pairwise kSZ signal

Astrophysics **Cosmology**

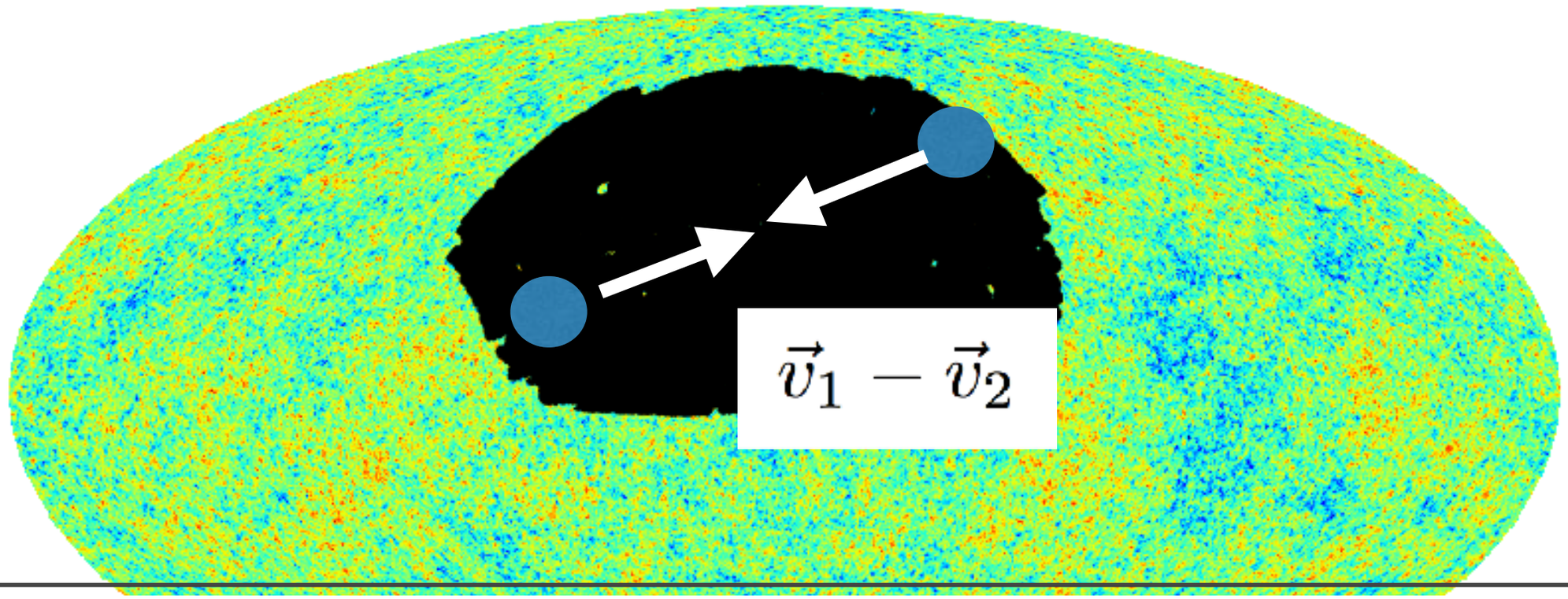
$$\left(\frac{T_{\rm CMB}\,\tau(\theta)}{c}\right)\left\langle\ (\hat{n}\cdot\vec{v}_1-\hat{n}\cdot\vec{v}_2)\ (\hat{n}\cdot\hat{r})\ \rho_1\,\rho_2\ \right\rangle$$

Filtered optical depth

Pairwise velocity

Cross-correlating between galaxy and CMB

Planck2015 and WMAP9, SDSS DR12 LOWZ North Galactic Cap

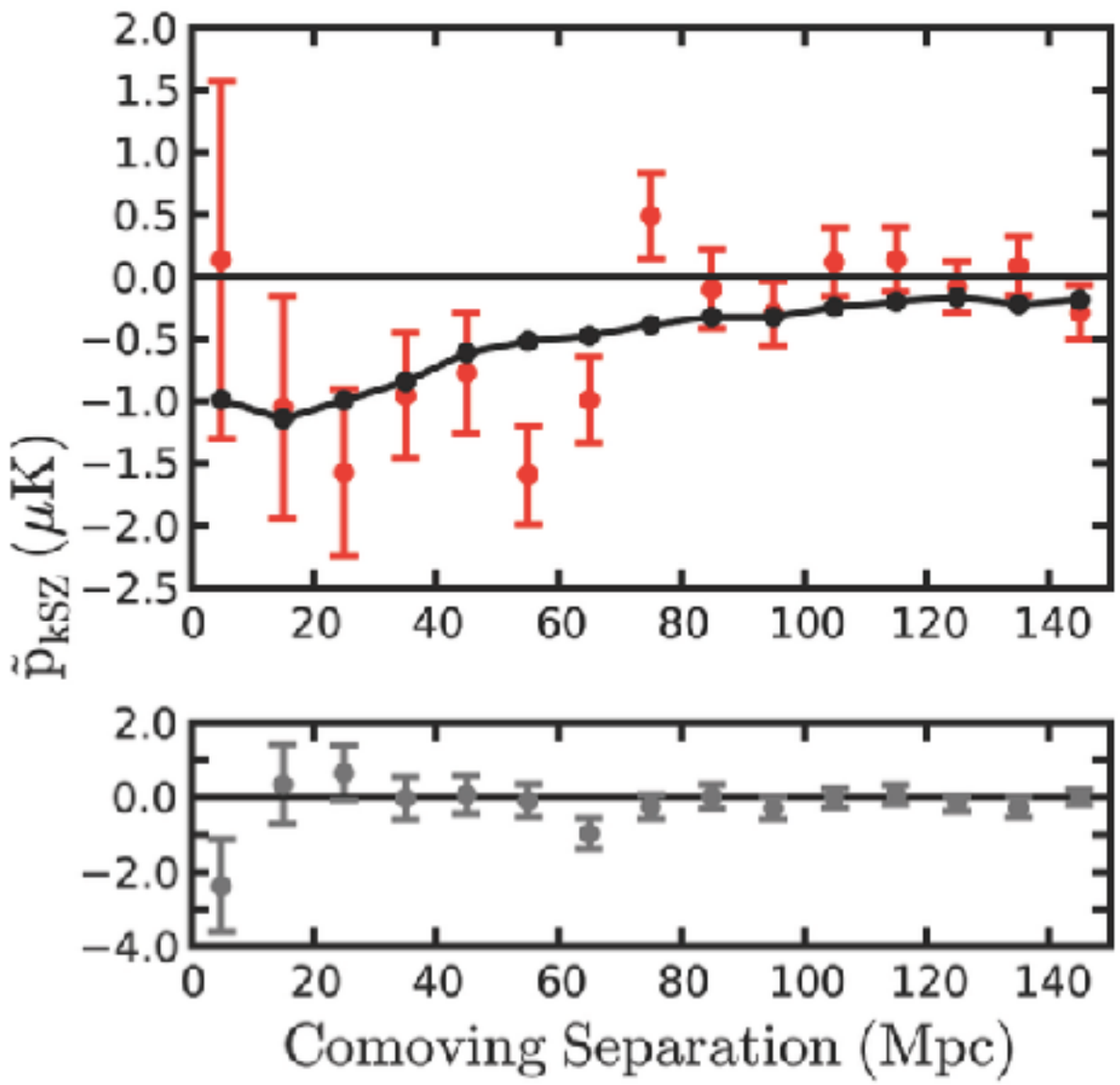


$$\left(\frac{T_{\rm CMB}\,\tau(\theta)}{c}\right)\left\langle\ (\hat{n}\cdot\vec{v}_1 - \hat{n}\cdot\vec{v}_2)\ (\hat{n}\cdot\hat{r})\ \rho_1\,\rho_2\ \right\rangle$$

Filtered optical depth

Pairwise velocity

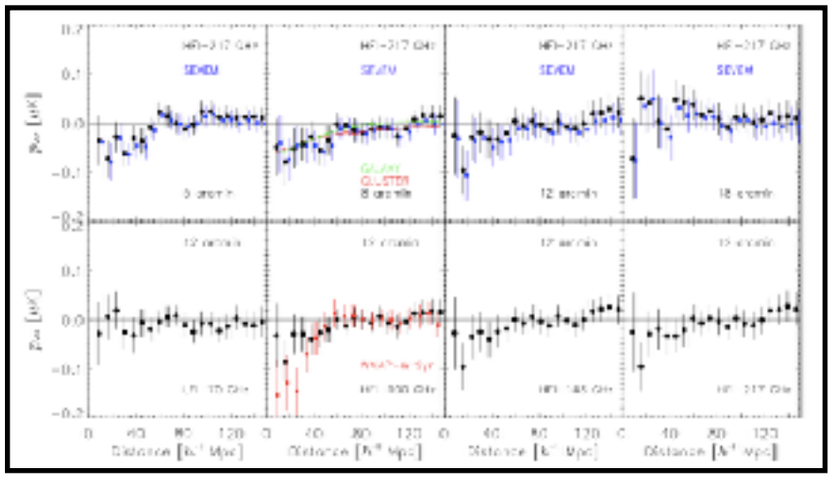
First measurement



- Hand et al. (2012)
- After four decades since the kSZ effect was first proposed in 1970.
- ACT x CMASS

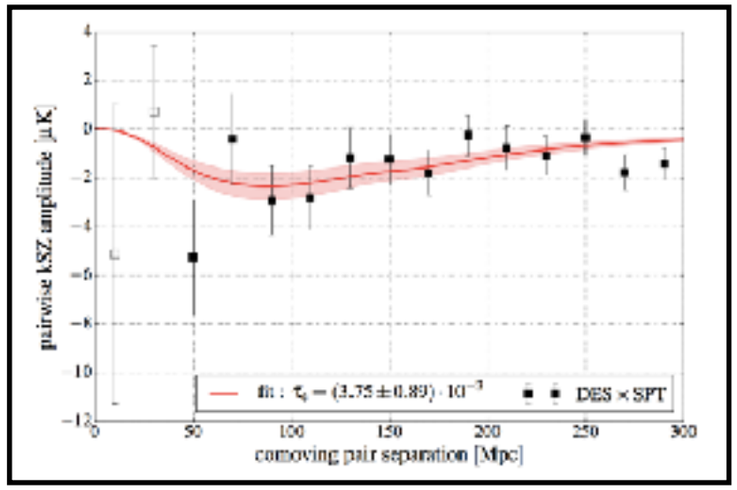
KSZ measurements

Planck collaboration (2016)
Planck x SDSS DR7



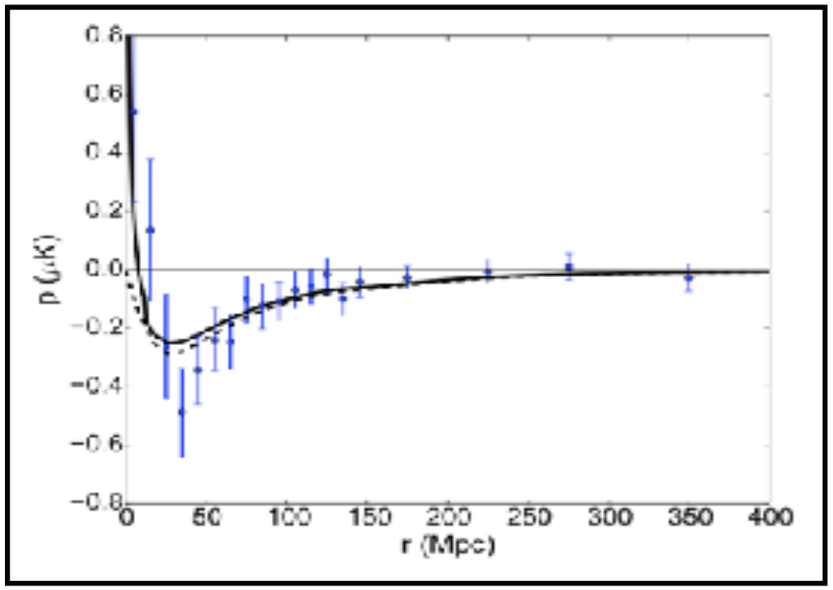
S/N
~ 2.3

Soergel et al. (2016)
SPT x DES



S/N
~ 4.2

De Bernardis et al. (2016)
ACT x BOSS

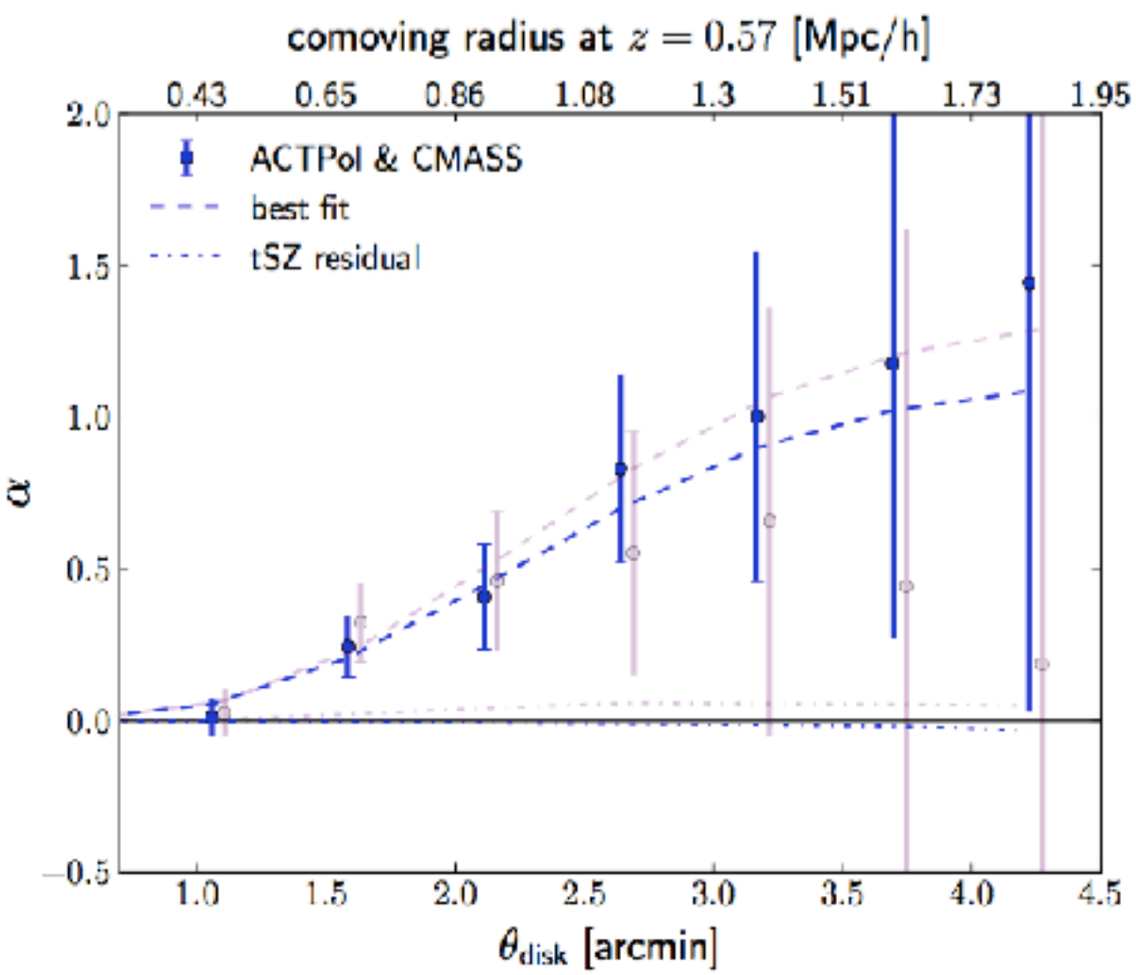


S/N
~ 4.1

- **Pairwise kSZ estimator**
- **Within 2 years**

Other kSZ Measurements: stacking analysis

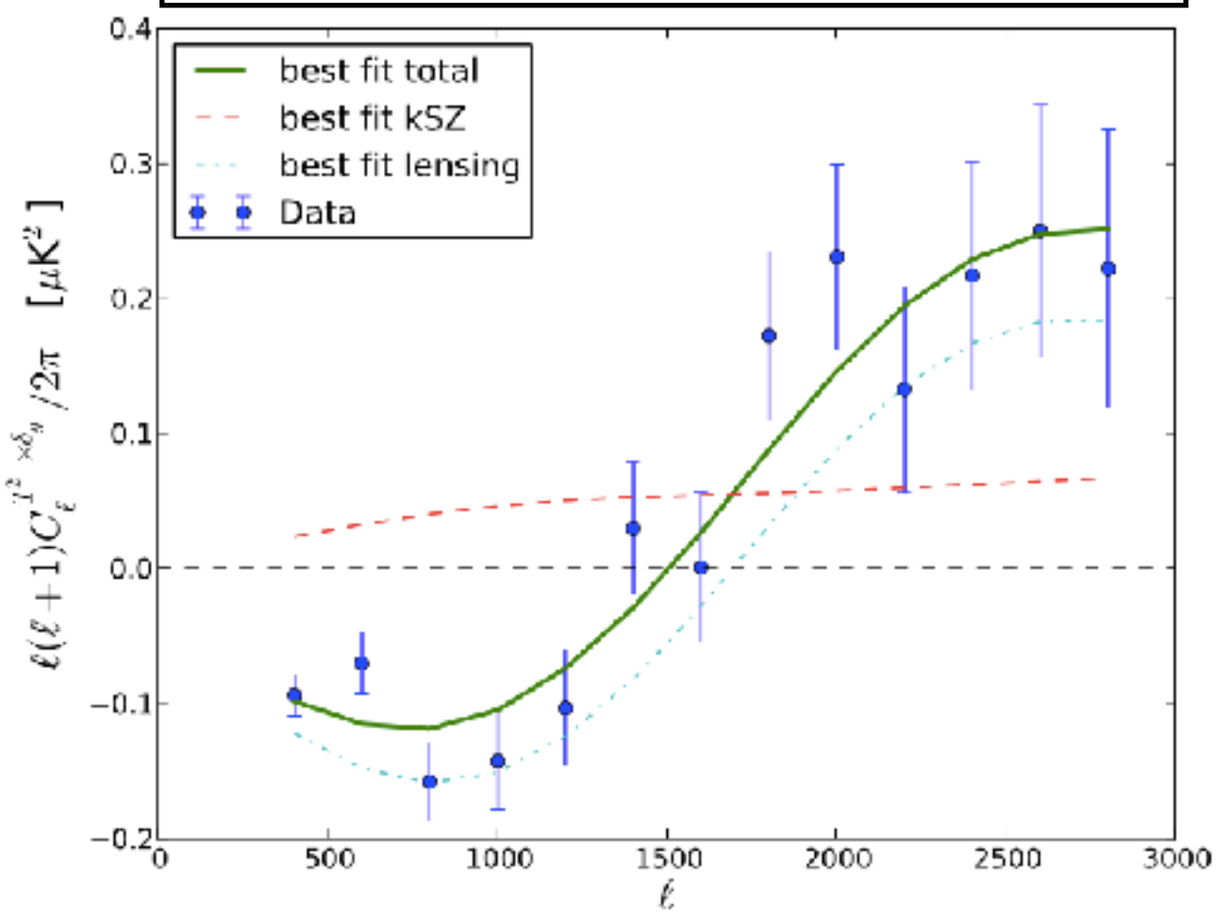
$$\sum_i \frac{(\delta T_i/T_{\rm CMB} + \alpha\, \tau_i v_{{\rm rec},i}/c)^2}{\sigma_i^2}$$



- Schaan et al. (2016)
- ACT x CMASS
- Stacking analysis
- Velocity reconstruction
- S/N ~ 2.9 and 3.3

Other kSZ Measurements (2D): kSZ2 x density

$$\langle \Theta_f^2(\boldsymbol{\ell})\delta_g(\boldsymbol{\ell}')\rangle = (2\pi)^2\delta_D(\boldsymbol{\ell}+\boldsymbol{\ell}')\; C_\ell^{\mathrm{kSZ}^2\times\delta_g}$$



- Hill et al. (2016)
- Ferraro et al. (2016)
- Planck x WISE
- kSZ^2 x density
- Lensing effects are dominant.

- S/N ~ **3.8-4.5**

This work

—We started this work a few years ago.
—There was only Hand et al. 2012 when we started.

Our goal is:

1) To propose a new estimator
2) To construct a model for the estimator
3) To measure the kSZ signal by ourselves
4) To motivate the kSZ business

What do we measure？

Pairwise kSZ power spectrum

$$P_{\rm kSZ}(k) \propto \underbrace{\int d^3x_1 \int d^3x_2\, e^{-i\vec{k}\cdot(\vec{x}_1-\vec{x}_2)}}_{\text{Fourier transform}}\ \underbrace{\mathcal{L}_{\ell=\rm odd}\left(\hat{n}\cdot\hat{k}\right)}_{\text{Odd pole}}\ \underbrace{\left[\delta T(\vec{x}_1)\,\delta n(\vec{x}_2) - \delta n(\vec{x}_1)\delta T(\vec{x}_2)\right]}_{\text{Pairwise kSZ signal}}$$

Fourier-space quantities are:

1) Easy to predict **(Theory provides power spectrum.)**

2) Easy to analyze **(Covariance is nearly diagonal.)**

3) Fast to measure **(FFT can be used.)**

Pairwise velocity

Pairwise velocity

$$v_{\rm pair}(r) = -\frac{\int_0^r r'^2 dr' \frac{\partial}{\partial t}\xi(r')}{r^2(1+\xi(r))}$$

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

Shown by Peebles 1976, 1980

Pairwise velocity is related to the two-point correlation function of density fluctuations.

Pairwise velocity

Pairwise velocity

$$v_{\rm pair}(r) = -\frac{\int_0^r r'^2 dr' \frac{\partial}{\partial t}\xi(r')}{r^2(1+\xi(r))}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

Continuity equation

Can we use this formula?

Assumptions:

1)Continuity equation

2)Isotropic velocity

3)Isotropic clustering

Pairwise velocity

Pairwise velocity

$$v_{\rm pair}(r) = -\frac{\int_0^r r'^2 dr' \frac{\partial}{\partial t}\xi(r')}{r^2(1+\xi(r))}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

Continuity equation

Can we use this formula?

Assumptions:

1)Continuity equation

2)Isotropic velocity

3)Isotropic clustering

1) Non-conservation of # of particles.

2) LOS velocity

3) Anisotropic clustering due to RSDs

Generalization of the Peebles relation

$$\hat{\xi}(r) = \frac{V}{N_{\rm p}^2} \sum_{i,j} \underline{[\hat{n}\cdot\vec{v}_i - \hat{n}\cdot\vec{v}_j]}\, \delta_{\rm D}\left(\vec{r} - (\vec{x}_i - \vec{x}_j) - \underline{\left(\frac{\hat{n}\cdot\vec{v}_i}{aH} - \frac{\hat{n}\cdot\vec{v}_j}{aH}\right)\hat{n}}\right)$$

RSD

Fourier transformation

$$\hat{P}(k) = \frac{V}{N_{\rm p}^2} \sum_{i,j} \underline{[\hat{n}\cdot\vec{v}_i - \hat{n}\cdot\vec{v}_j]}\, e^{-i\vec{k}\cdot(\vec{x}_i - \vec{x}_j) - \underline{i\vec{k}\cdot\left(\frac{\hat{n}\cdot\vec{v}_i}{aH} - \frac{\hat{n}\cdot\vec{v}_j}{aH}\right)\hat{n}}}$$

RSD

Generalization of the Peebles relation

$$\hat{P}(k) = \frac{V}{N_{\rm p}^2} \sum_{i,j} \underline{[\hat{n}\cdot\vec{v}_i - \hat{n}\cdot\vec{v}_j]}\, e^{-i\vec{k}\cdot(\vec{x}_i-\vec{x}_j)-i\vec{k}\cdot\left(\frac{\hat{n}\cdot\vec{v}_i}{aH}-\frac{\hat{n}\cdot\vec{v}_j}{aH}\right)\hat{n}}$$

RSD

$$P_{\rm pv} = \partial_v P_{\rm galaxy}$$

Pairwise velocity

Pairwise velocity power spectrum

$$P_{\rm pair}(\vec{k}) = \left(i \frac{aH}{\vec{k}\cdot\hat{n}} \right) \frac{\partial}{\partial\gamma} P_{\rm s}(\vec{k};\gamma\vec{v}) \Big|_{\gamma=1}$$

Density power spectrum with RSD

$$P_{\rm s}(\vec{k}) = \left\langle \frac{V}{N^2} \sum_{i,j} e^{-i\vec{k}\cdot(\vec{s}_i - \vec{s}_j)} \right\rangle$$

1) **Non-conservation of # of particles**
2) **LOS velocity**
3) **Anisotropic Clustering**

Let's Practice!

Linear theory:

$$P_{\rm pair}(\vec{k}) = \left(i\frac{aHf}{\vec{k}\cdot\hat{n}}\right)\frac{\partial}{\partial f}\left(b+f\mu^2\right)^2 D^2 P_{\rm lin}(k)$$

Kaiser factor

Growth rate

Let's Practice!

Linear theory:

$$P_{\rm pair}(\vec{k}) = \left(i\frac{aHf}{\vec{k}\cdot\hat{n}}\right)\frac{\partial}{\partial f}\left(b+f\mu^2\right)^2 D^2 P_{\rm lin}(k)$$

Kaiser factor

Growth rate

$$= 2iaHf\mu\left(b+f\mu^2\right)D^2\frac{P_{\rm lin}(k)}{k}$$

Imaginary

Kaiser factor

Pairwise Velocity!!

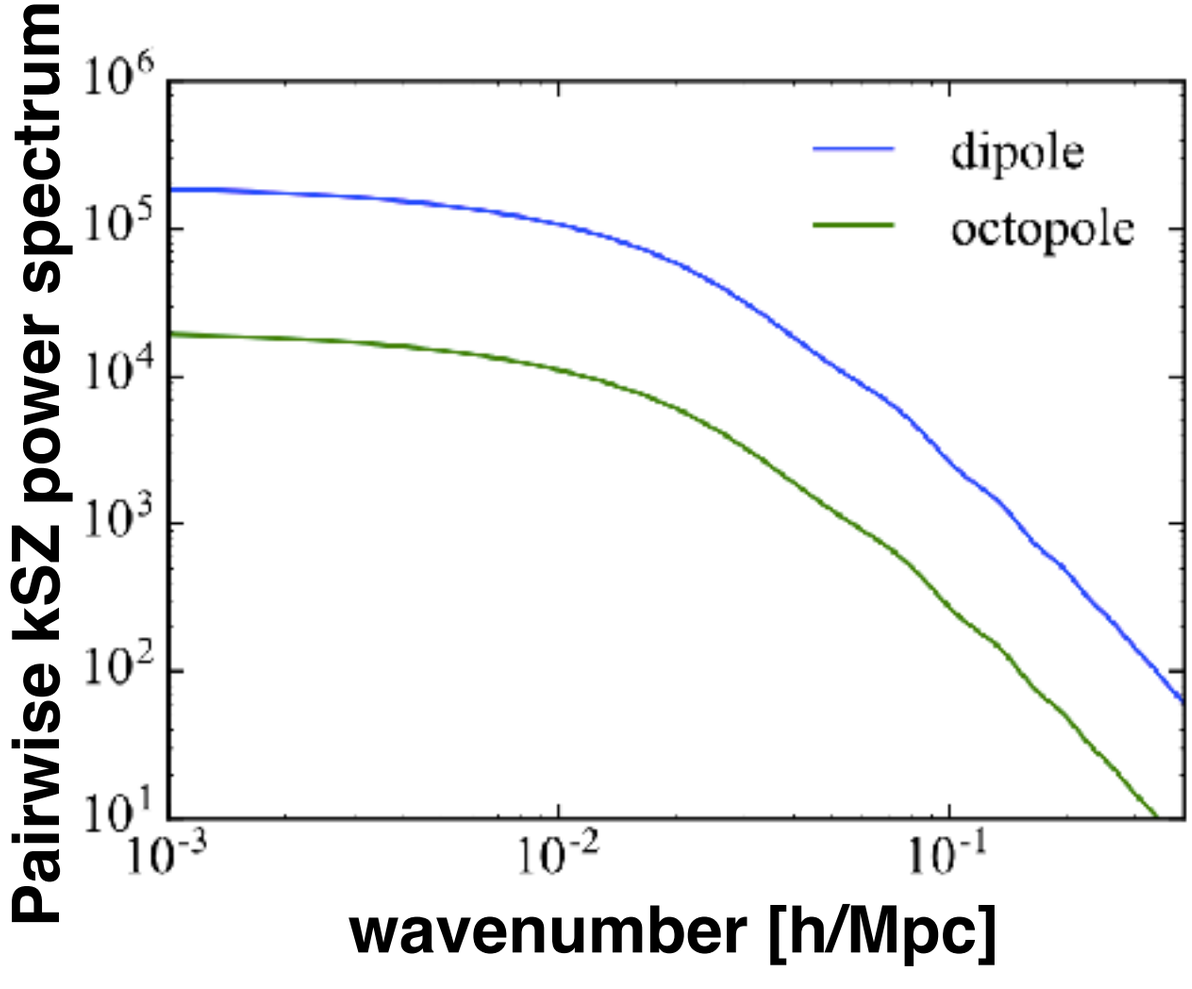
Pairwise kSZ power spectrum

Pairwise kSZ dipole:

$$P_{\mathrm{kSZ},\ell=1}(k) = 2i\frac{T_0 H_0}{c}(a\tau E)\left[(f\sigma_8)(b\sigma_8) + \frac{3}{5}(f\sigma_8)^2\right]\frac{P_{\mathrm{lin}}(k)}{k}$$

Optical depth

Kaiser factor



- Kaiser effect increases the amplitude by ~ 20%.
- Octopole is 10 times smaller than dipole.
- See also Okumura et al. 2014

Data

1) CMB data:

Planck (FWHM ~ 5 arcmin)

2) Galaxy data: BOSS LOWZ

— z = 0.3

— M~10^13 Msun

— Apparent size = ~ 6 arcmin

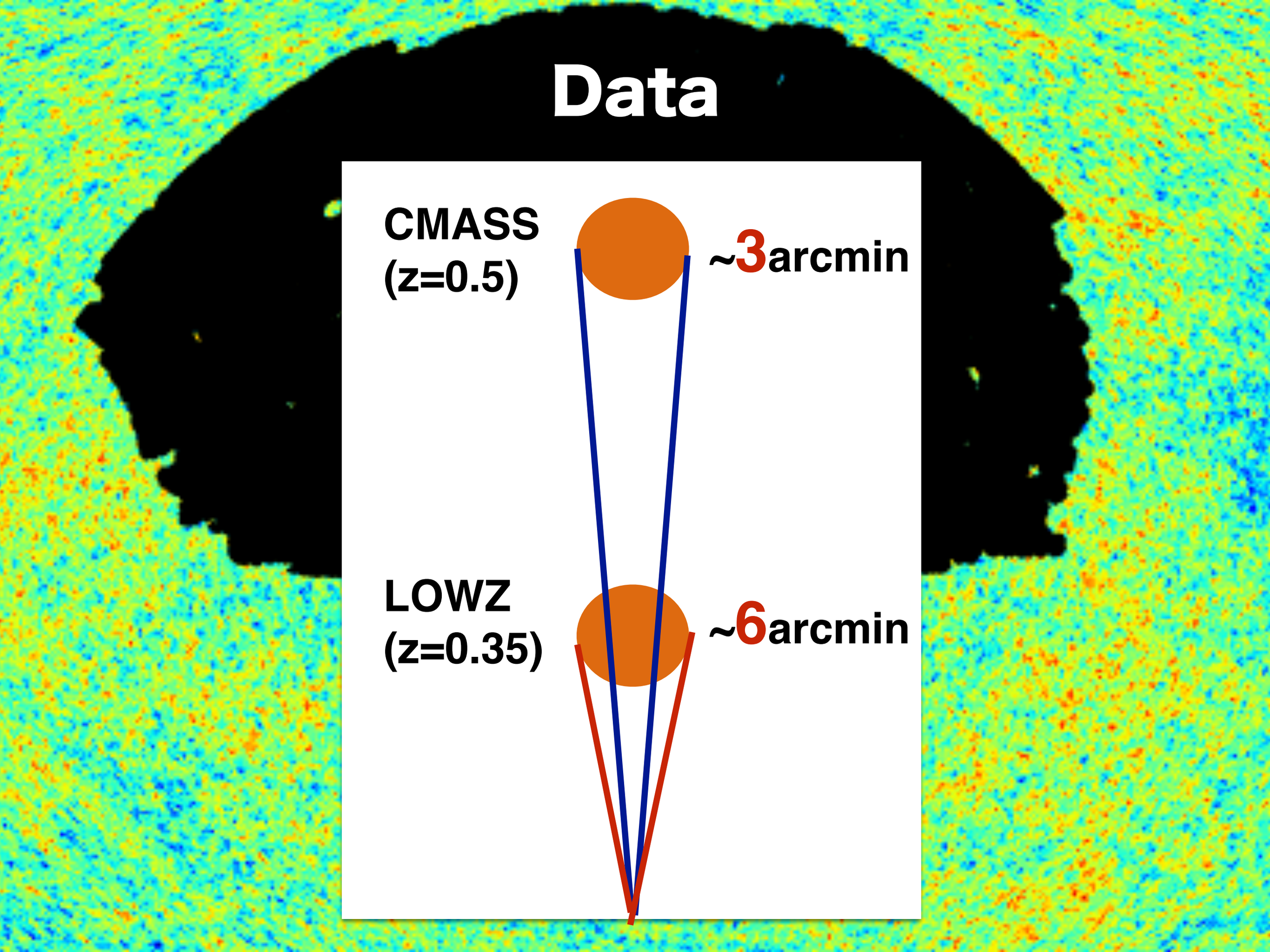
Galaxy data: BOSS CMASS

— z = 0.5

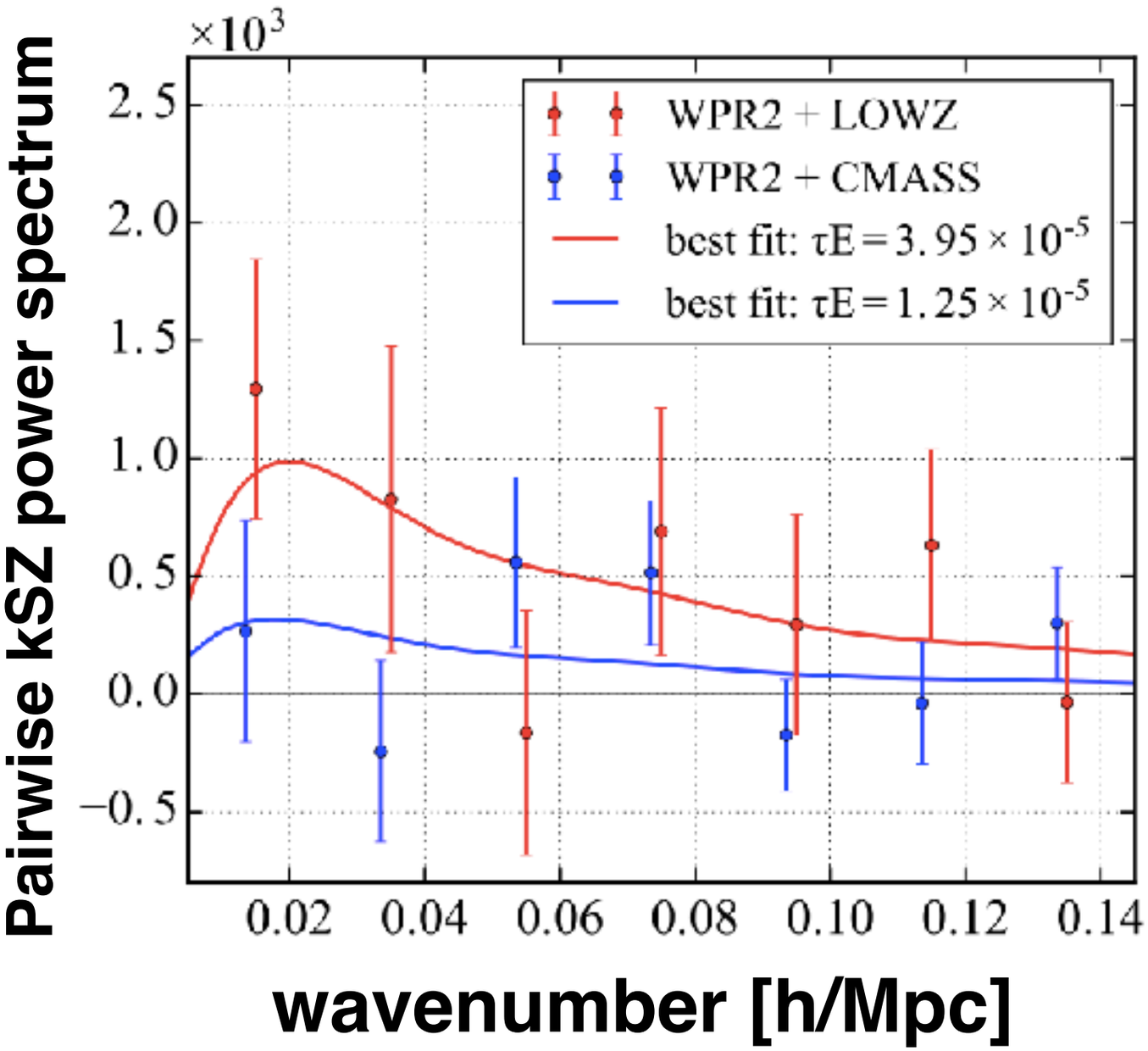
— M~10^13 Msun

—Apparent size = ~ 3 arcmin

Data



Measurements: Pairwise kSZ power spectrum



- **LOWZ**: S/N ~ **2.5**
- **CMASS**: S/N ~ **1.1**

Optical depth

Astrophysics **Cosmology**

$$\left(\frac{T_{\rm CMB}\,\tau(\theta)}{c}\right) \left\langle\ (\hat{n}\cdot\vec{v}_1 - \hat{n}\cdot\vec{v}_2)\ (\hat{n}\cdot\hat{r})\ \rho_1\,\rho_2\ \right\rangle$$

Filtered optical depth

Pairwise velocity

Optical depth

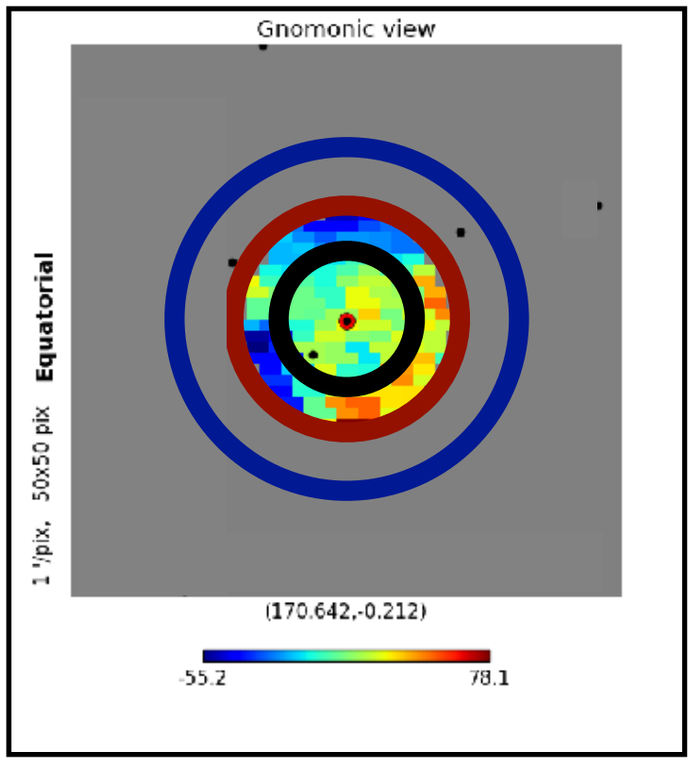
Astrophysics **Cosmology**

$$\left(\frac{T_{\rm CMB}\,\tau(\theta)}{c}\right) \left\langle (\hat{n}\cdot\vec{v}_1 - \hat{n}\cdot\vec{v}_2)\ (\hat{n}\cdot\hat{r})\ \rho_1\,\rho_2 \right\rangle$$

Filtered optical depth

Pairwise velocity

Repeating the pairwise kSZ power analysis for various aperture radii.



Optical Depth

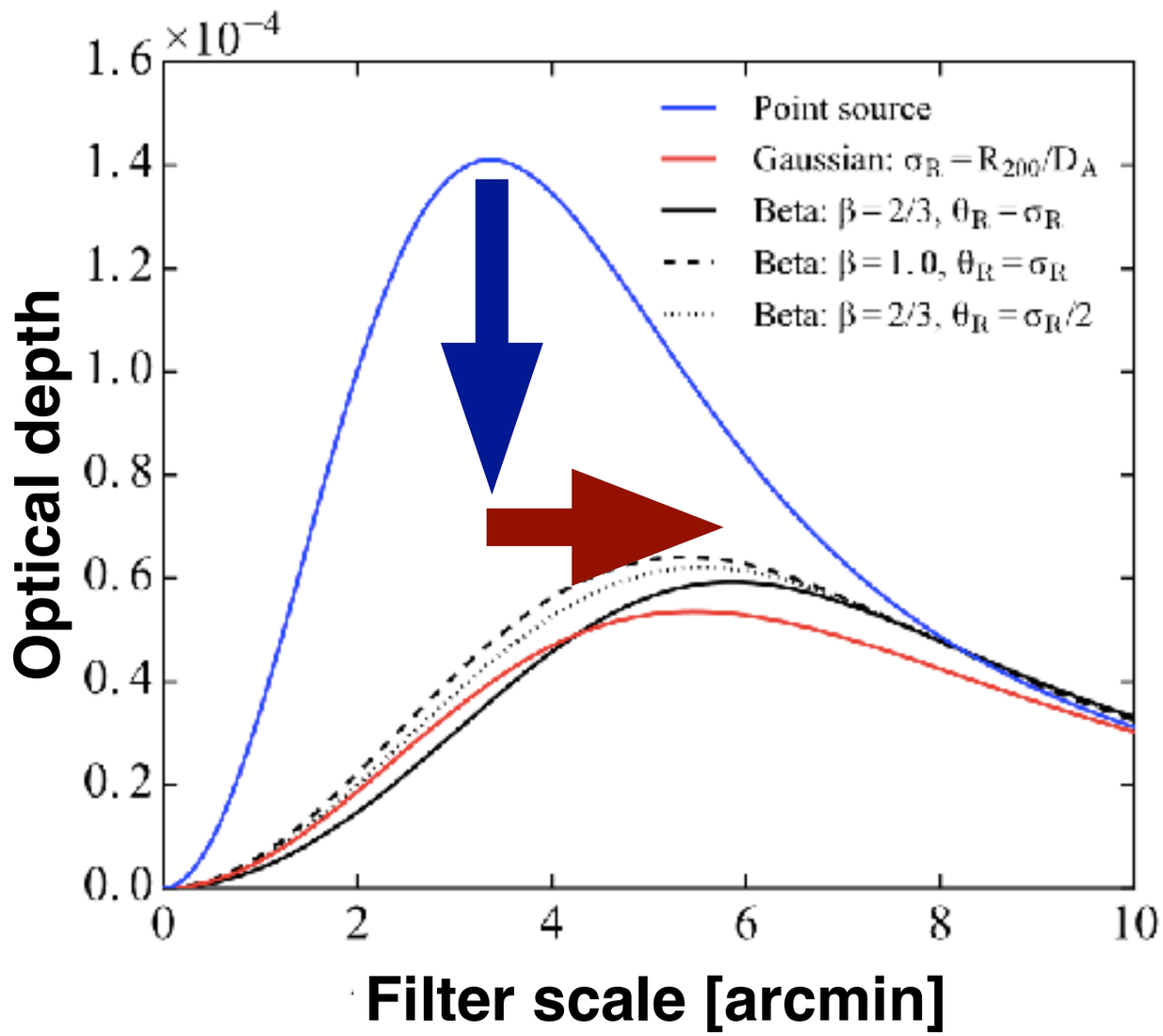
$$\tau = \frac{\sigma_{\rm T} f_{\rm gas} M}{\mu_{\rm e} m_{\rm p} D_{\rm A}^2(z_{\rm eff})} \int \frac{d^2\ell}{(2\pi)^2} U(\ell\theta_{\rm c}) N(\ell) e^{-\sigma_{\rm B}^2 \ell^2/2}$$

Amplitude

AP filter

Beam

Gas profile

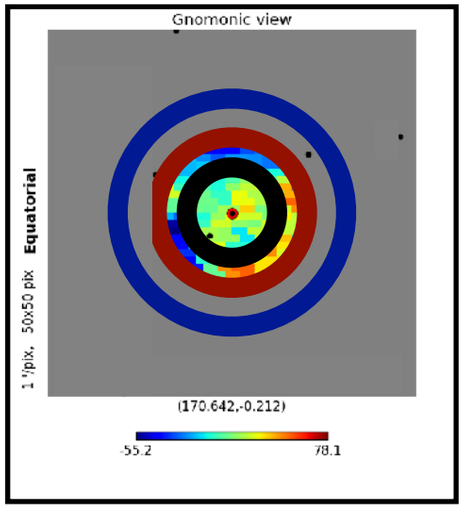


— Assumed gas profiles:
  - Point source
  - Gaussian profile
  - beta-profile

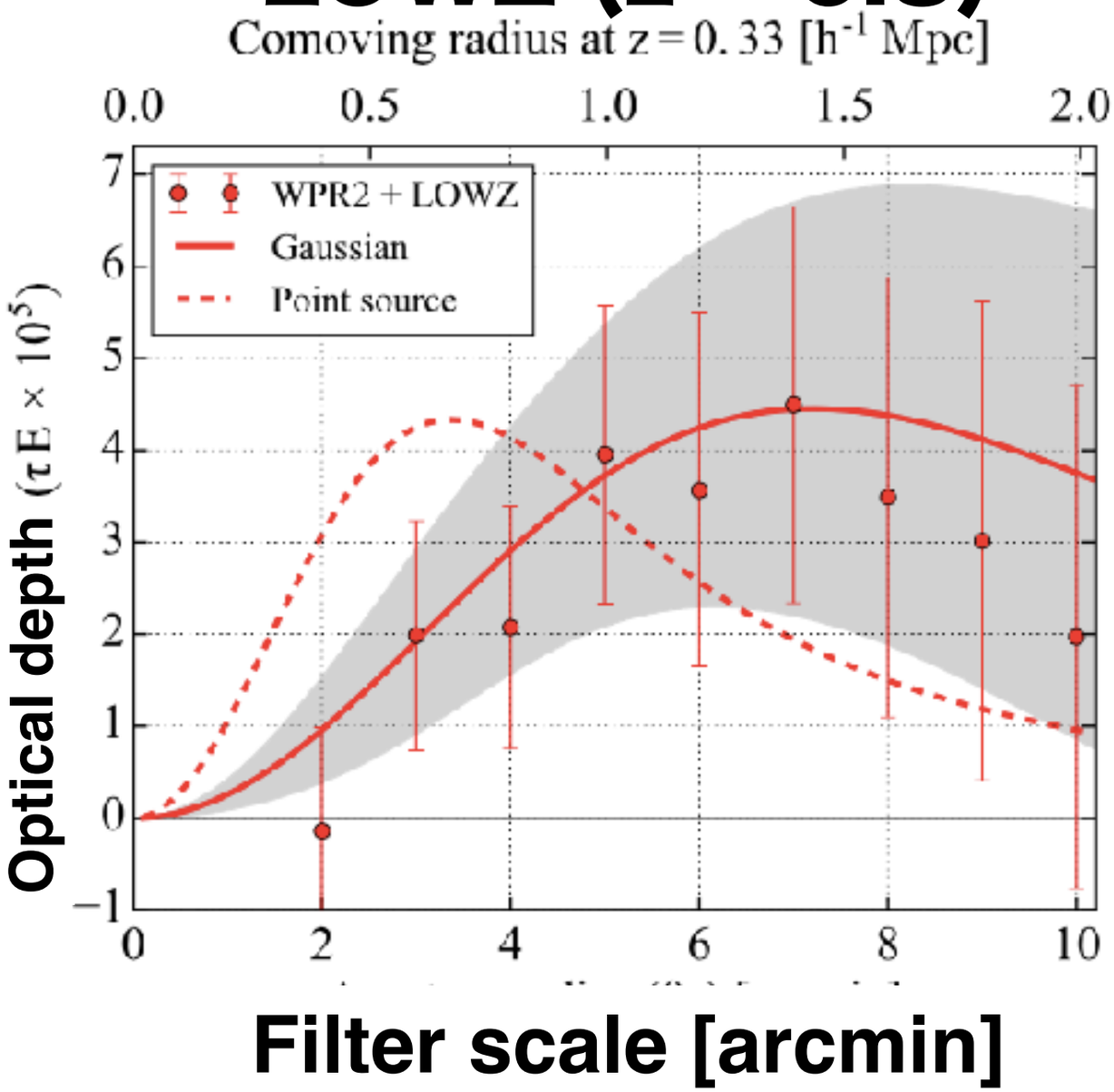
— Suppression of the amplitude

— Shift of the peak position outward

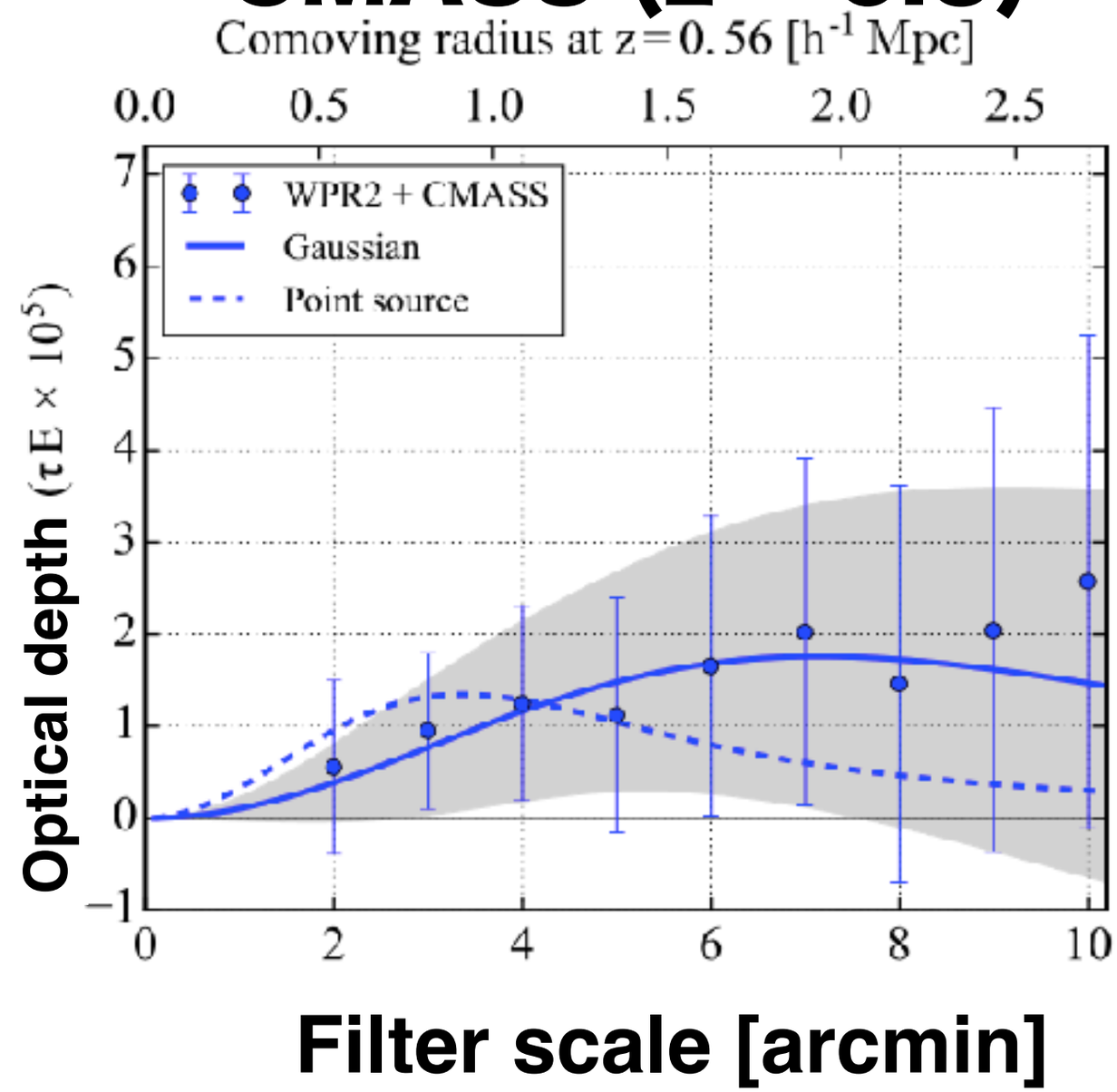
Measurement: Optical Depth



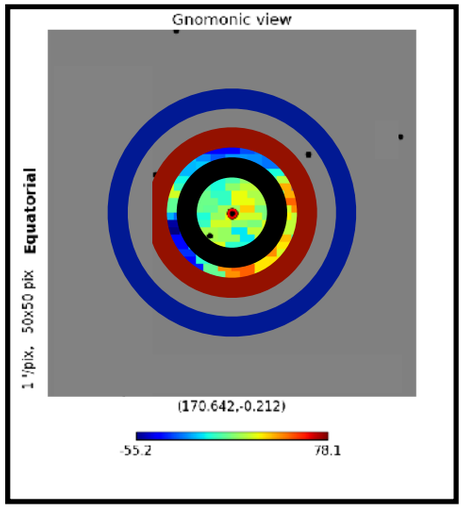
LOWZ (z = 0.3)



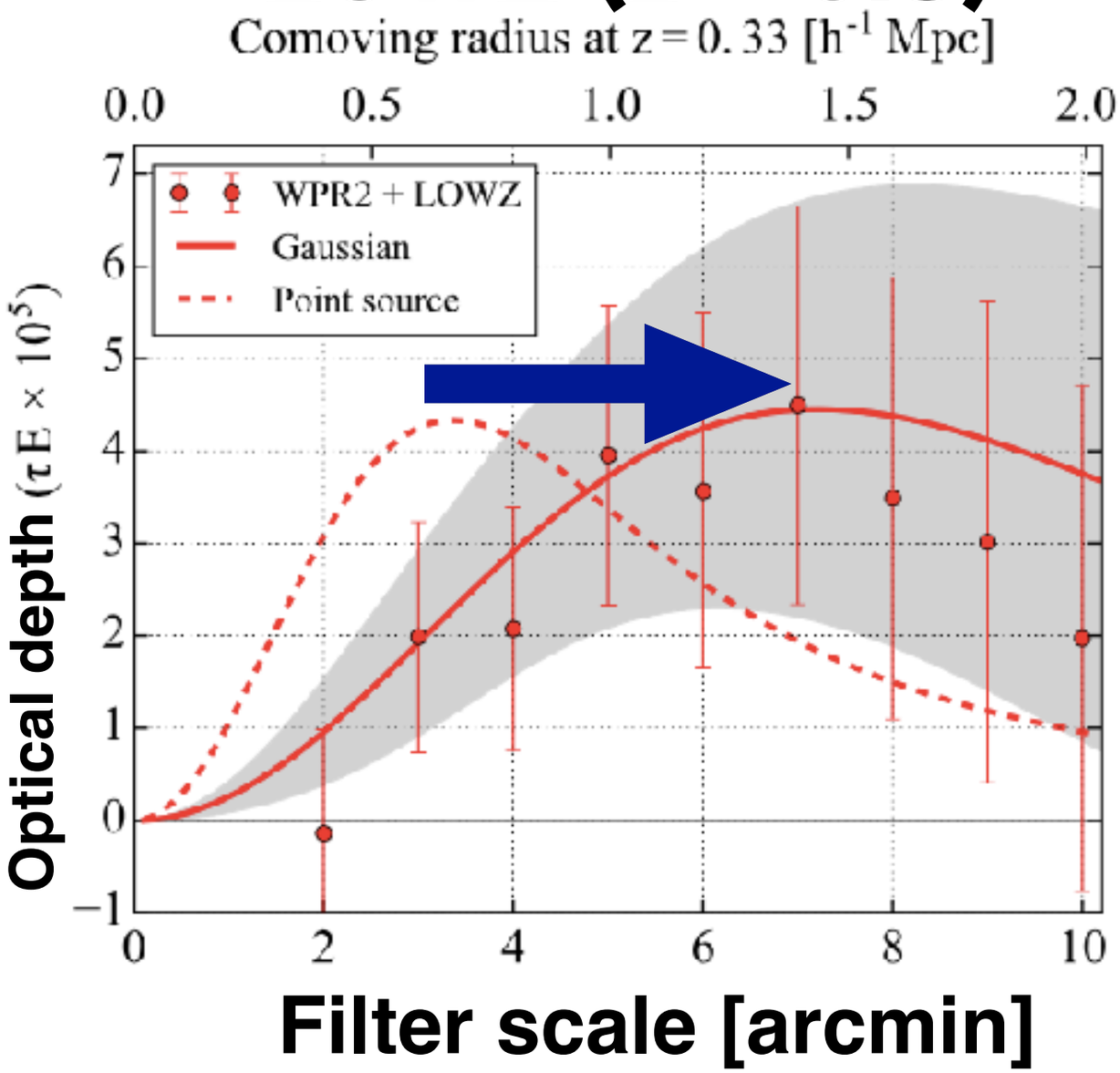
CMASS (z = 0.5)



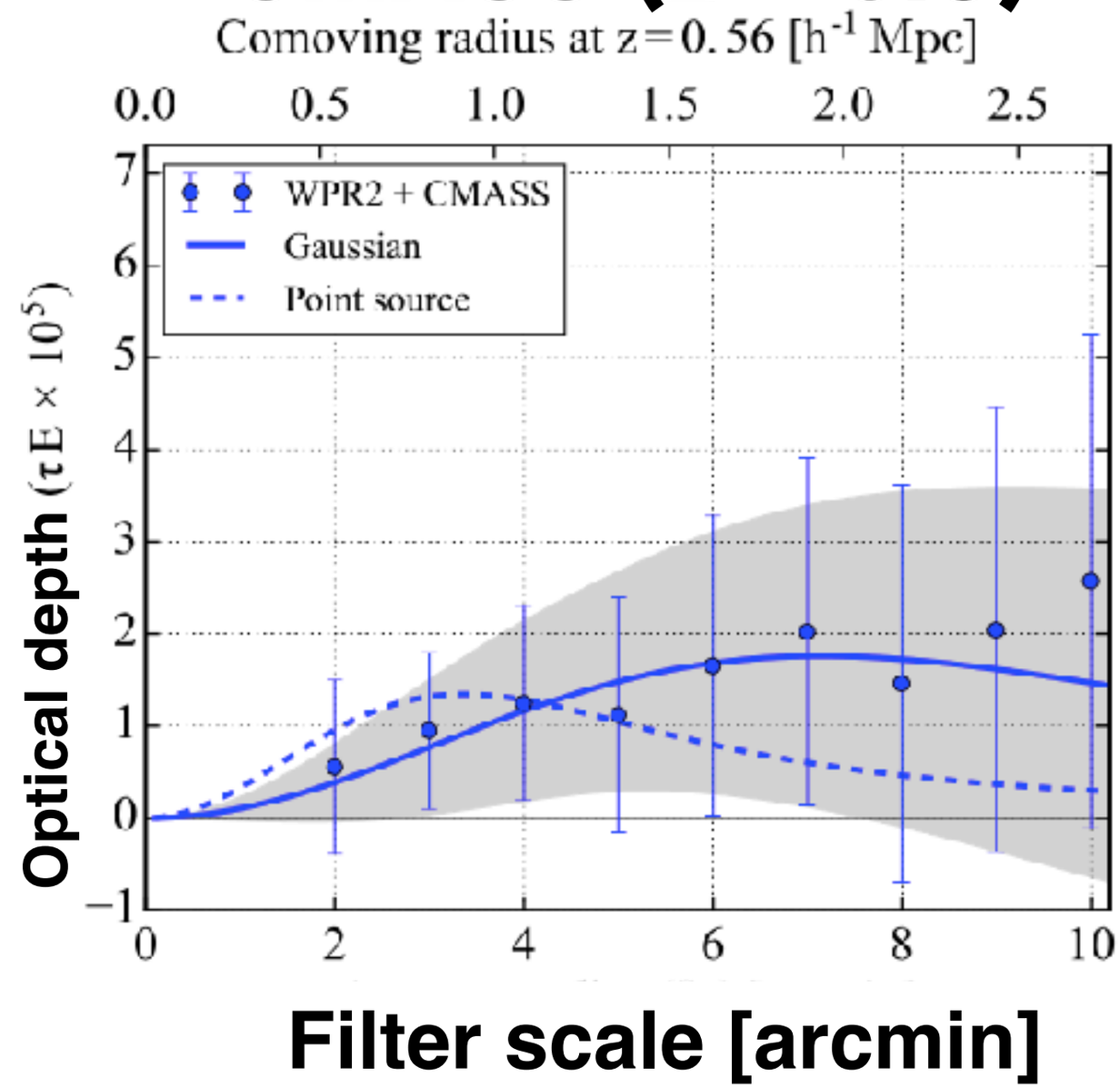
Measurement: Optical Depth



LOWZ (z = 0.3)

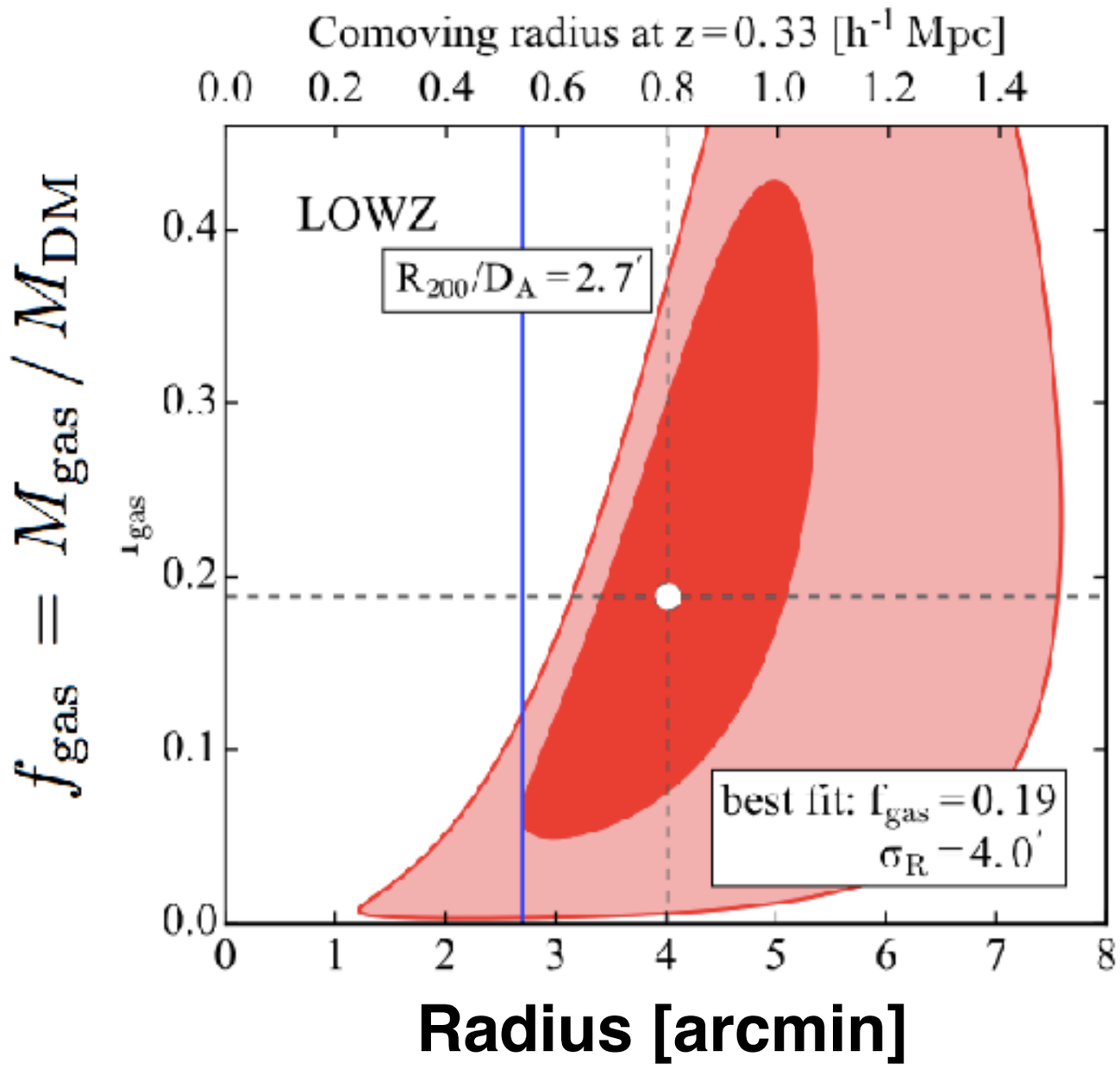


CMASS (z = 0.5)



Measurement: Optical Depth

$$\tau = \frac{\sigma_{\rm T} f_{\rm gas} M}{\mu_{\rm e} m_{\rm p} D_{\rm A}^2(z_{\rm eff})} \int \frac{d^2\ell}{(2\pi)^2} U(\ell\theta_{\rm c}) N(\ell) e^{-\sigma_{\rm B}^2 \ell^2/2}$$



Two parameters:

1) **gas fraction**
2) **Standard deviation of Gaussian profile**

The PS assumption is ruled out at 2.1 sigma level.

Future surveys

FWHM [arcmin]	noise [μK-arcmin]	galaxy	redshift	V [$(h^{-1}\,\mathrm{Gpc})^3$]	$\bar{n}_g$ [$(h^{-1}\,\mathrm{Mpc})^{-3}$]	b_g	M_{halo} [$h^{-1}\,M_\odot$]	S/N (FWHM = 1′, 1.5′, 2.0′, 3.0′)
CMB-S4 + BOSS								
1 − 3	2	LRG	0.3 ($0.15 < z < 0.43$)	2.0	3.0×10^{-4}	2.0	5.2×10^{13}	(13, 12, 12, 12)
1 − 3	2	LRG	0.5 ($0.43 < z < 0.70$)	4.0	3.0×10^{-4}	2.0	2.6×10^{13}	(46, 43, 39, 32)
CMB-S4 + DESI								
1 − 3	2	LRG	0.8 ($0.65 < z < 0.95$)	13.5	2.8×10^{-4}	2.5	5.0×10^{13}	(105, 98, 90, 75)
1 − 3	2	ELG	1.1 ($0.95 < z < 1.25$)	18.7	4.7×10^{-4}	1.4	4.0×10^{12}	(92, 69, 52, 28)
CMB-S4 + PFS								
1 − 3	2	ELG	0.9 ($0.6 < z < 1.2$)	2.3	4.9×10^{-4}	1.3	4.0×10^{12}	(34, 27, 21, 12)
1 − 3	2	ELG	1.5 ($1.2 < z < 2.0$)	4.9	4.7×10^{-4}	1.7	5.0×10^{12}	(54, 39, 30, 16)

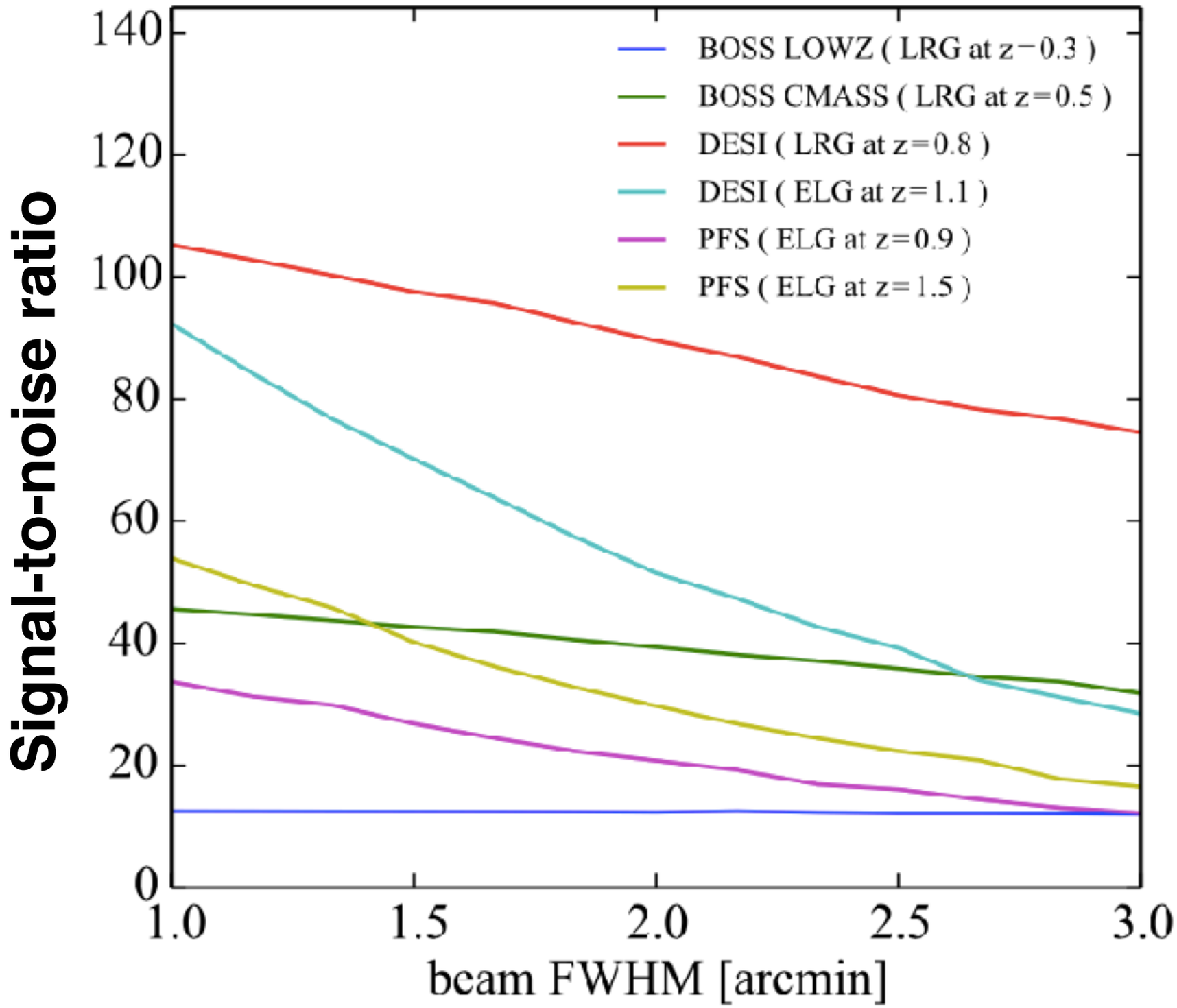
Surveys:

- **CMB-S4 (FWHM ~ 1 - 3 arcmin)**
- **BOSS**
- **DESI (Wide)**
- **PFS (Deep)**

Various mass (10^12 - 10^13 Msun)

Various redshift (z = 0.3 - 1.5)

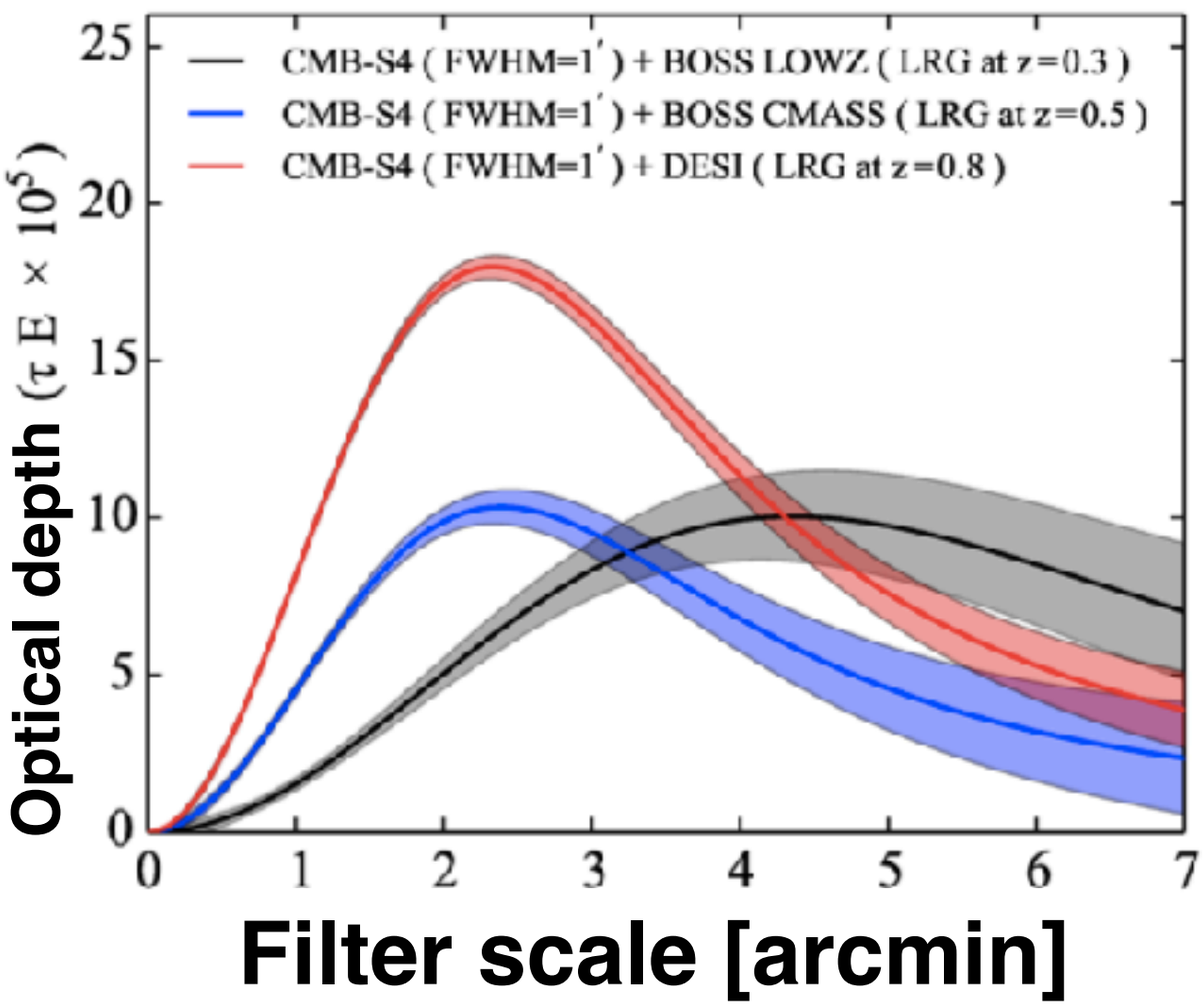
Future surveys



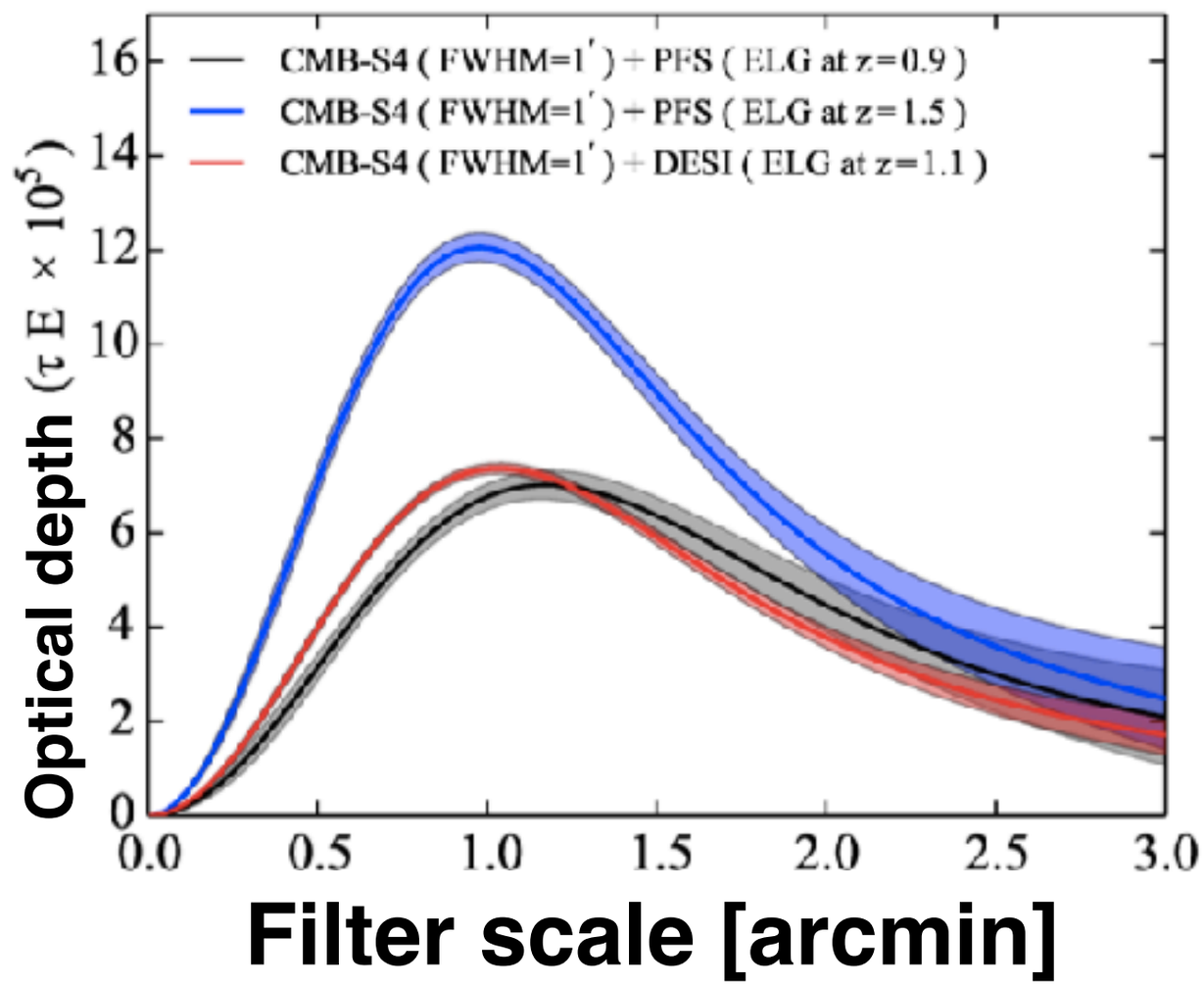
Resolution [arcmin]

Future surveys

LRGs
M ~ 10^13 Msun
z < 1.0



ELGs
M ~ 10^12 Msun
z > 1.0



Theoretical expression of Pairwise kSZ signal

Astrophysics **Cosmology**

$$\left(\frac{T_{\rm CMB}\,\tau(\theta)}{c}\right)\left\langle\ (\hat{n}\cdot\vec{v}_1-\hat{n}\cdot\vec{v}_2)\ (\hat{n}\cdot\hat{r})\ \rho_1\,\rho_2\ \right\rangle$$

Filtered optical depth

Pairwise velocity

$$\{\tau,\ D_{\rm A},\ H,\ f,\ b\}$$

Application to Cosmology

Galaxy clustering:

Power spectrum (Linear + Non-linear)

$$P_{\rm g} = P_0 + P_2 + P_4 + \cdots$$

$$\{D_{\rm A},\, H,\, f,\, b\}$$

kSZ:

Pairwise kSZ power (Linear + Non-linear)

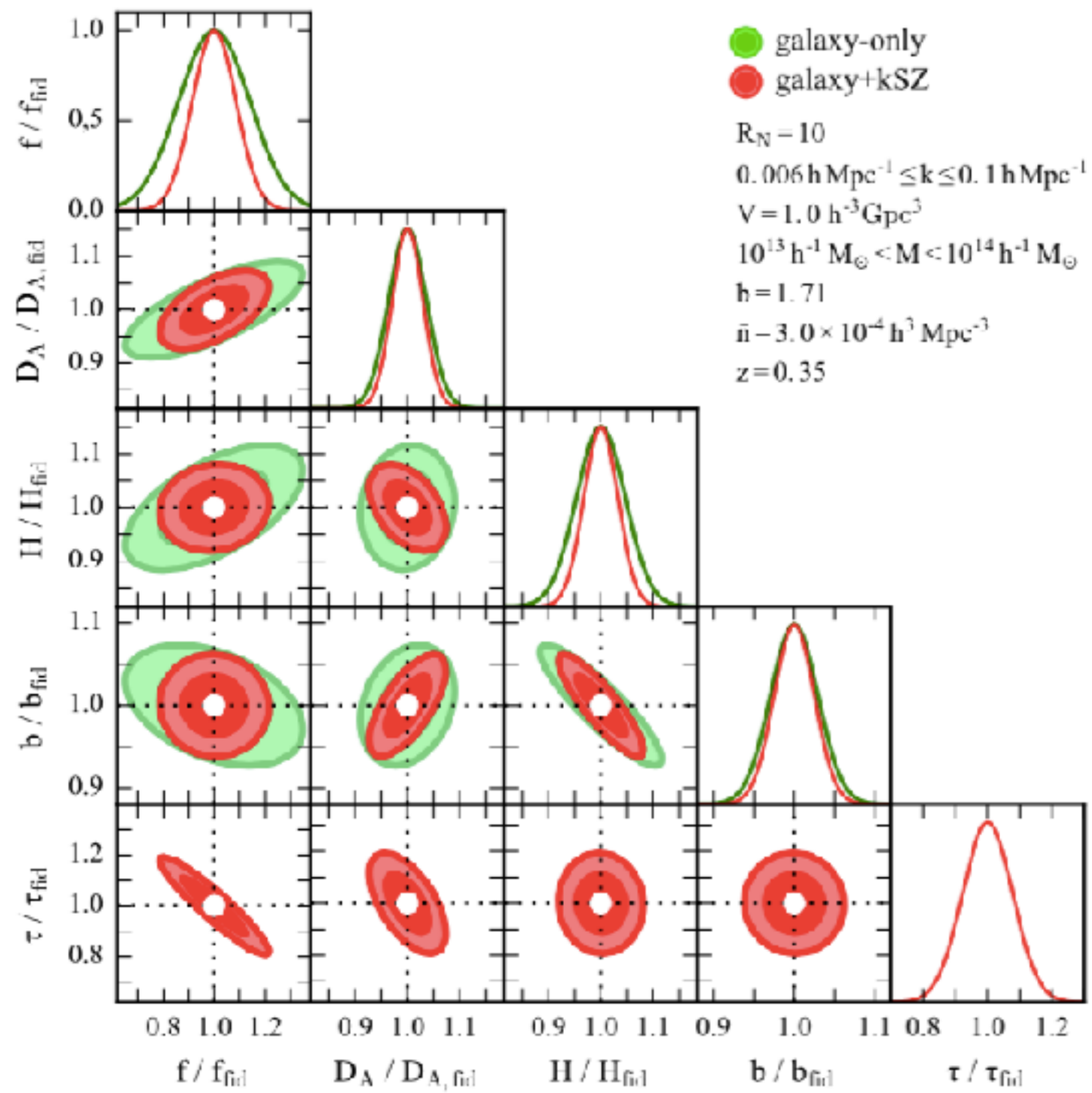
$$P_{\rm kSZ} = P_1 + P_3 + \cdots$$

$$\{\tau,\, D_{\rm A},\, H,\, f,\, b\}$$

Application to Cosmology

- **CMB-S4 (~ 3 arcmin)**
- **CMASS-like sample**
- **Green: galaxy-only**
- **Red: galaxy+kSZ**

Adding the kSZ reduces the errors of f and H by 30-50% compared to the galaxy-only analysis.



Summary

- Pairwise kSZ power spectrum
- Modeling
- Measurement of the pairwise kSZ power
- Measurement of the optical depth
- Forecast

NS, T.Okumura and D.N.Spergel
JCAP (2016) 07 001 [1509.08232]
JCAP (2017) 01 057 [1606.06367]
MNRAS (2017) submitted [1705.07449]