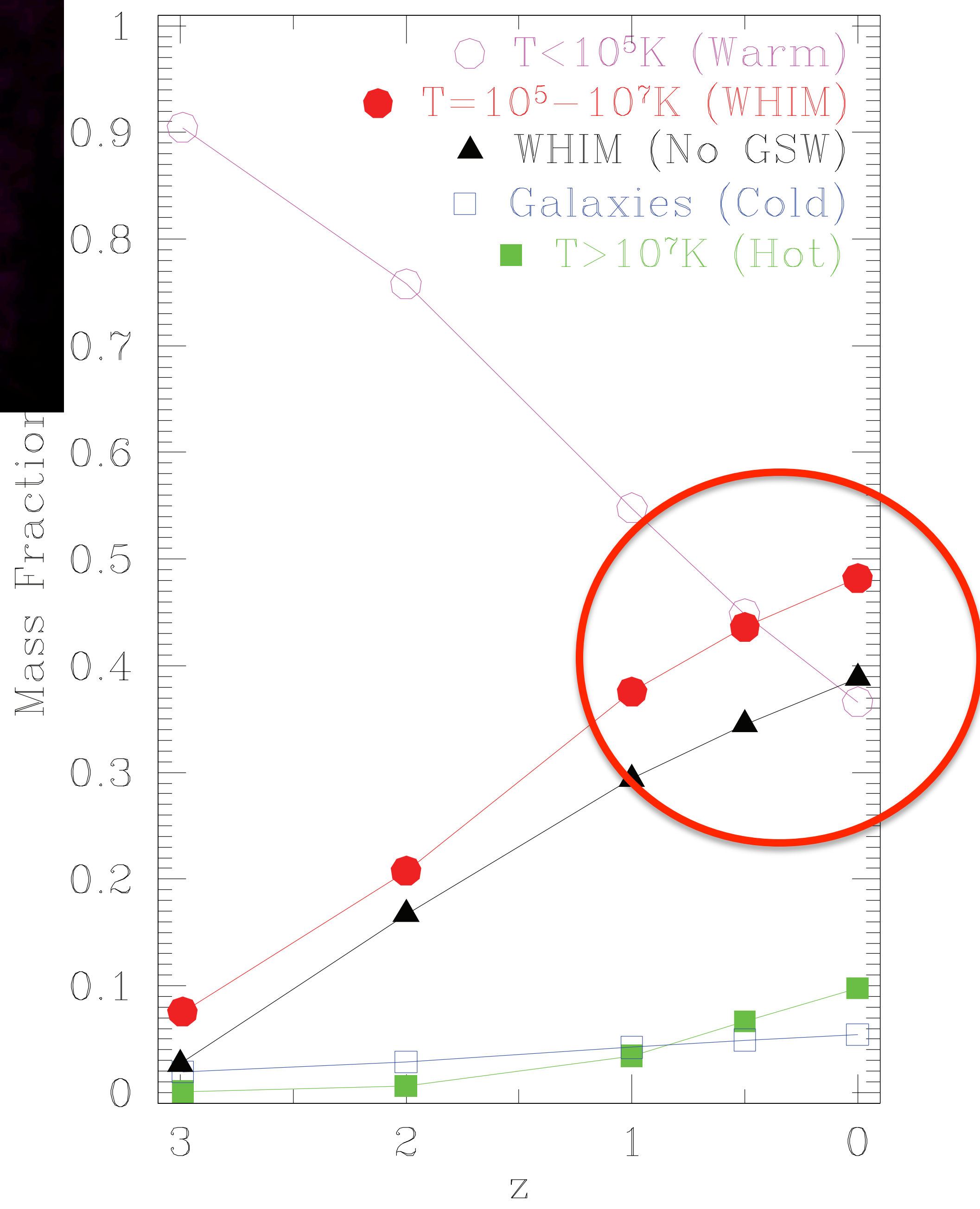
Detection of the Missing Baryons through thermal and kinetic Sunyaev-Zeldovich effect

Yin-Zhe Ma (马寅哲)
University of KwaZulu-Natal, Durban, South Africa
NAOC—UKZN Computational Astrophysics Centre

Collaborators: D. Contreras, C. Hernandez-Monteagudo, G. Hinshaw, A. Hojjati, Y.-C. Li, K. Moodley, M. Remazeilles, D. Scott, H. Tanimura, L. Van Waerbeke, J. Zuntz, & Planck team



Cen and Ostriker 2006
Bregman 2007

X-ray: ~ n_e(r)^2

thermal Sunyaev-Zeldovich effect X Weak Lensing

and compare with halo model prediction and hydrodynamic simulation

YZM, L. Van Waerbeke et al., 2015, JCAP
A. Hojjati, I. McCarthy, J. Harnois-Deraps, YZM et al., 2015, JCAP

kinetic Sunyaev-Zeldovich effect X Peculiar velocity field

Planck intermediate results XXXVII, 2016, A&A
C.Hernandez-Monteagudo, YZM, F-S Kitaura, W.Wang et al., 2015, Phys. Rev. Lett.

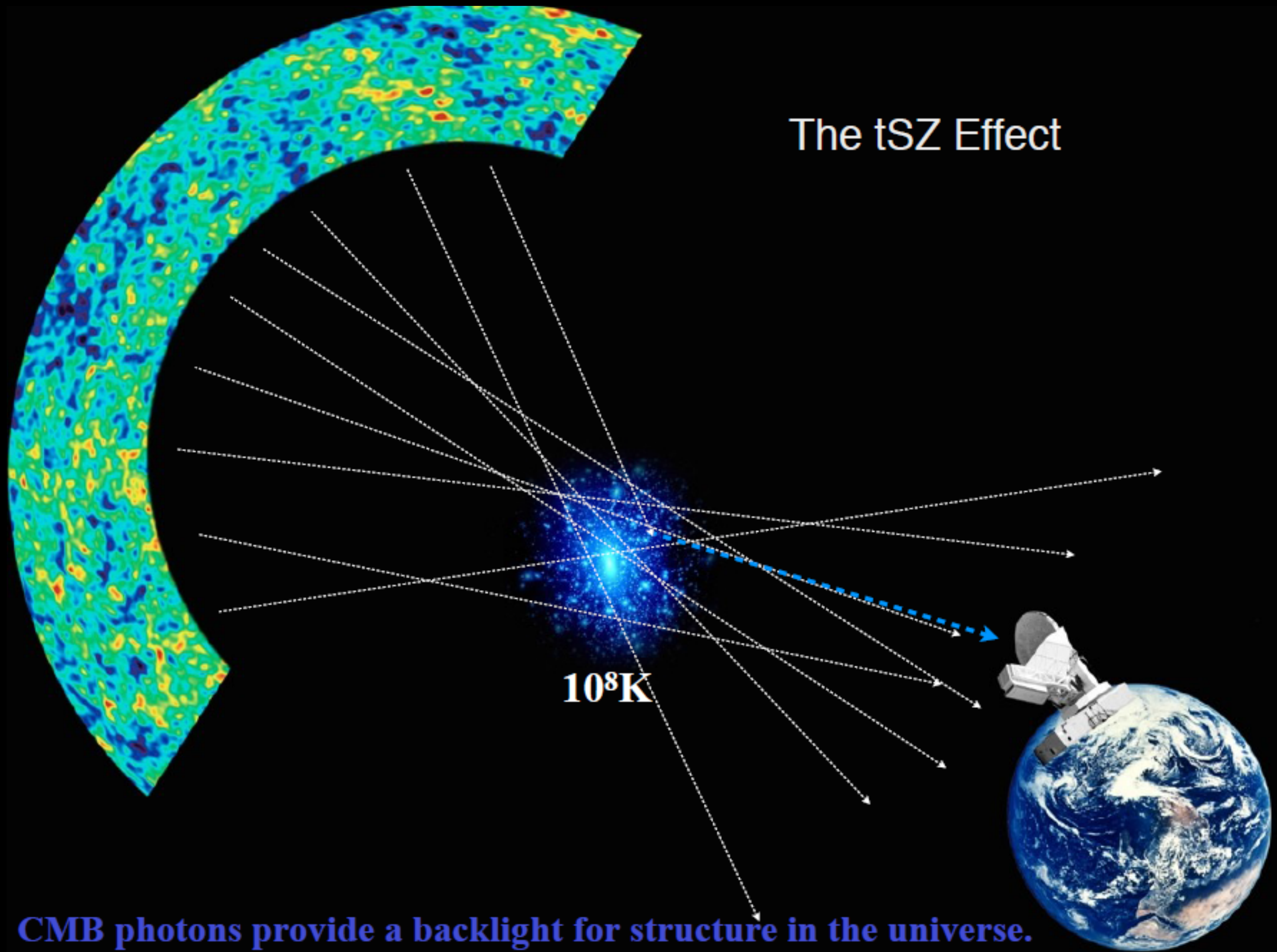
Dispersion measurement of kinetic Sunyaev-Zeldovich effect

Planck intermediate results LIII, A&A in press, arXiv: 1707.00132

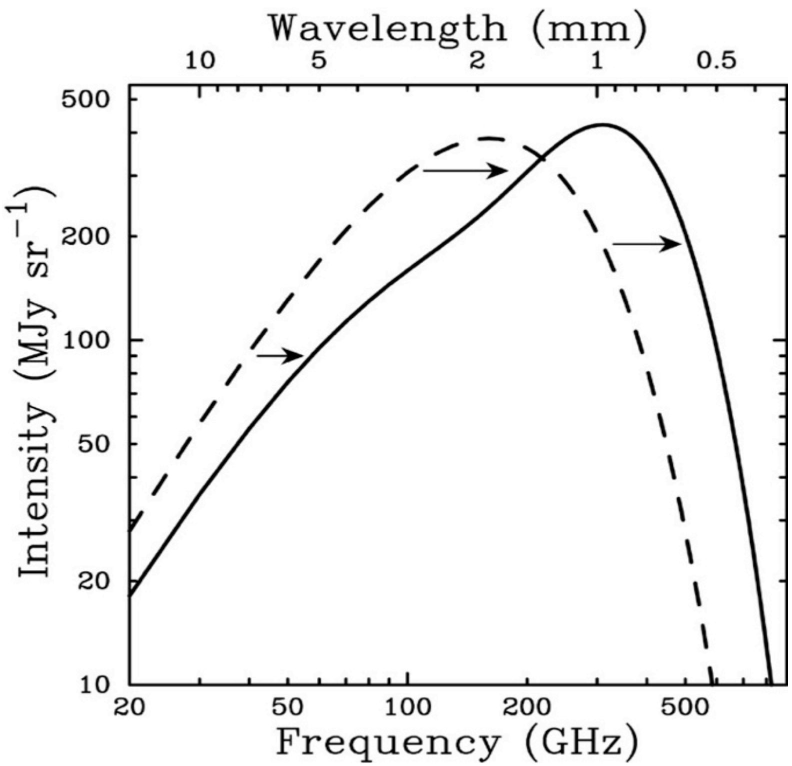
Stacking of LRG pairs to search for filament

--- see Hideki Tanimura's talk

The thermal Sunyaev-Zeldovich effect



Thermal Sunyaev-Zeldovich effect (tSZ):



$$\frac{\Delta T}{T} = \left[\eta \frac{e^{\eta}+1}{e^{\eta}-1} - 4\right] y \equiv g_{\nu} y$$

$$g_{\nu} \equiv (\eta(e^{\eta}+1)/(e^{\eta}-1))-4$$

$$\eta = \frac{h\nu}{k_B T_{\mathrm{CMB}}} = \frac{h\nu_0}{k_B T_0} = 1.76\left(\frac{\nu_0}{100\mathrm{GHz}}\right)$$

$$y = \frac{k_B \sigma_T}{m_e c^2} \int_0^l T_e(l) n_e(l)\, \mathrm{d}l$$

SZ map from linear combination of Planck frequency bands:
ν_i = 100, 143, 217, 353 GHz.

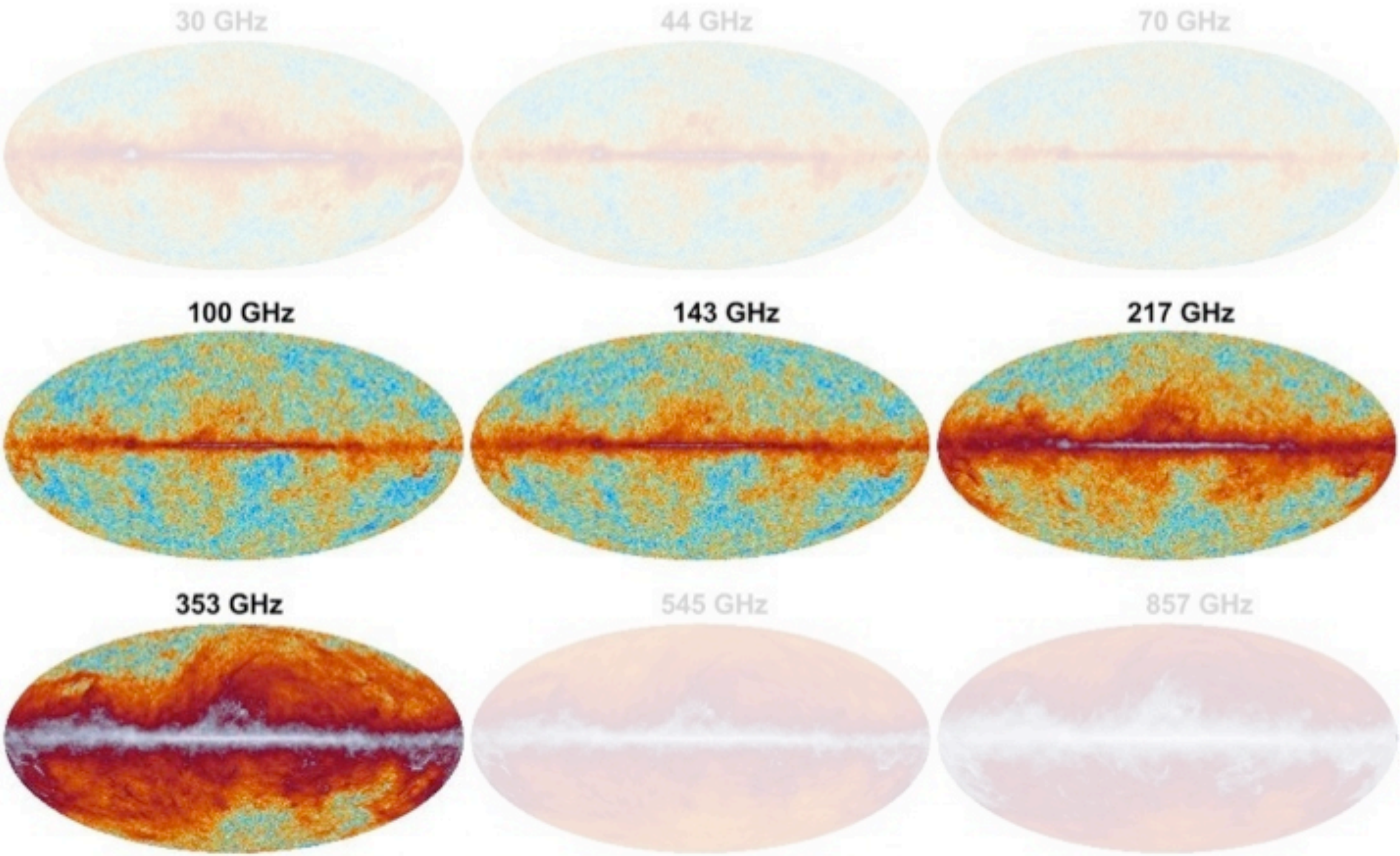
$$T_{SZ}/T_0 \equiv y\, S_{SZ}(\nu_i) = \sum b_i\, T(\nu_i)$$

1. $\sum b_i\, S_{SZ}(\nu_i) = 1$ $\qquad S_{SZ}(x) = x \coth(x/2) - 4 \quad (x = h\nu/kT)$

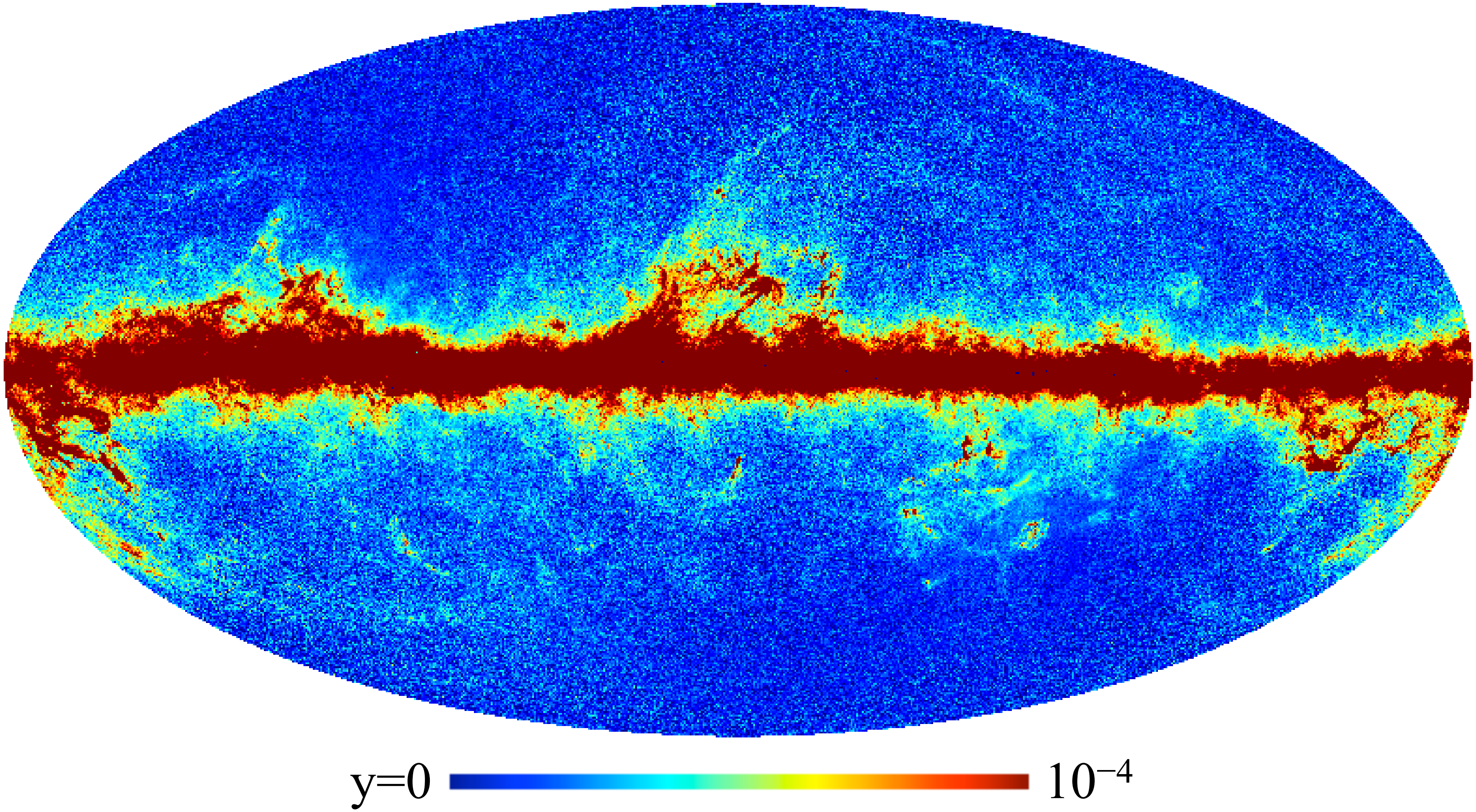
2. $\sum b_i\, S_{CMB}(\nu_i) = 0$ $\qquad S_{CMB}(x) = 1$

3. $\sum b_i\, S_{''dust''}(\nu_i) = 0$ $\qquad S_{''dust''}(\nu_i) = \nu^\beta\, g(x)$

Planck Full-Sky Maps – 4 Frequencies

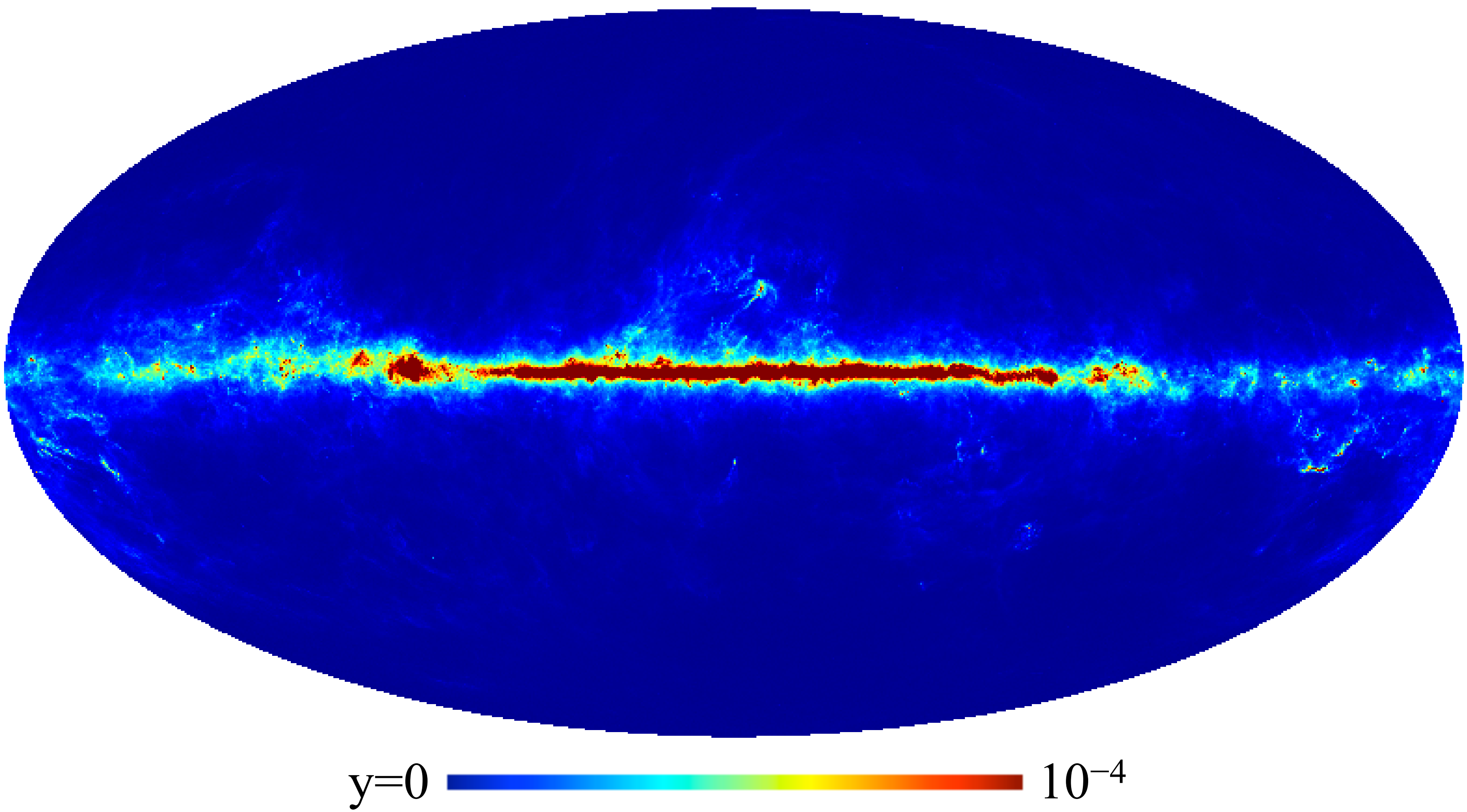


Planck SZ y map, version E



Reject $\beta_{dust} = 2.0$, $r_{2.0}(100\ \mathrm{GHz}) = 0$

Planck SZ no-y map, version E

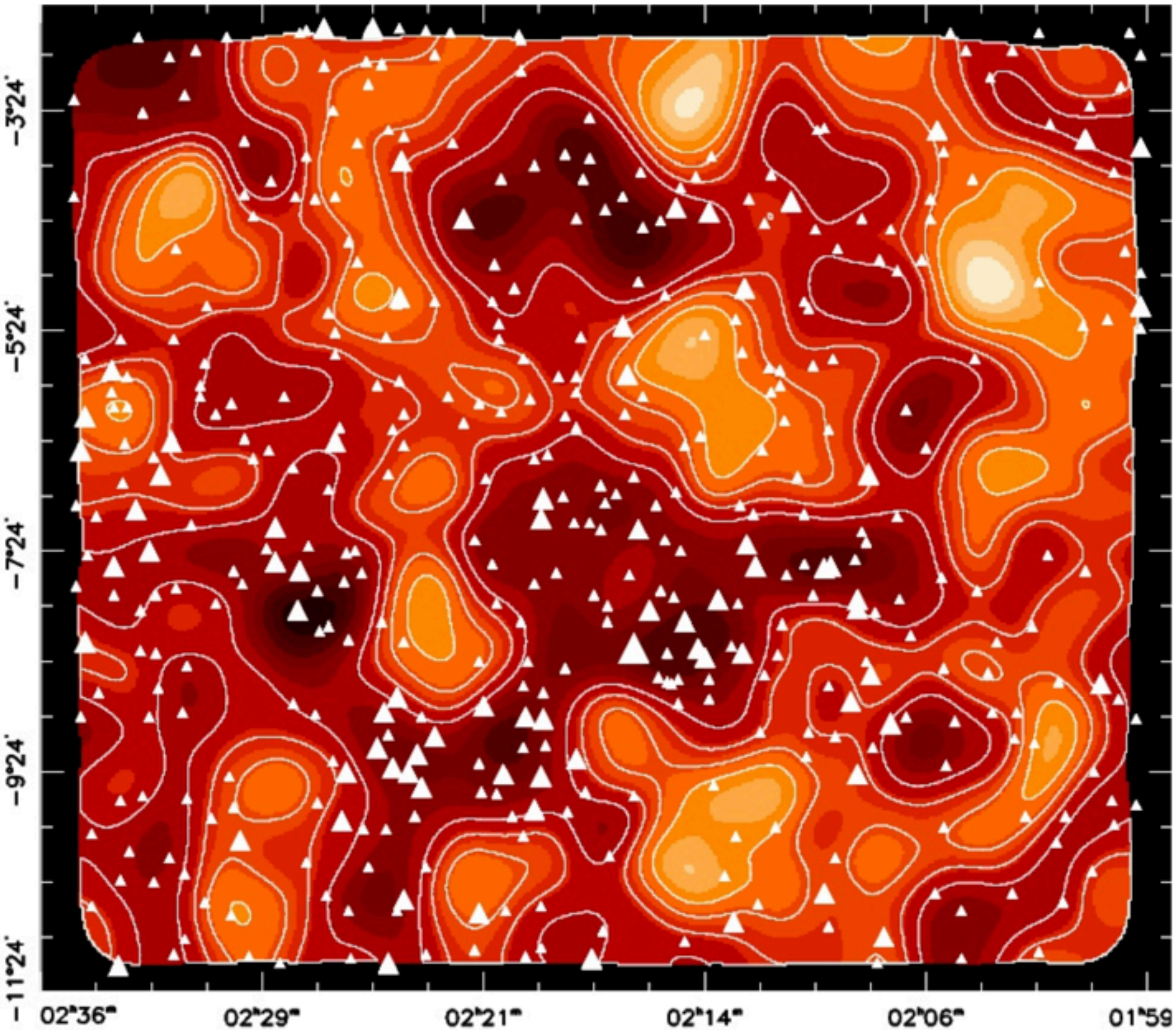


Reject $S_{SZ}(\nu)$, retain $\beta_{dust} = 1.8$

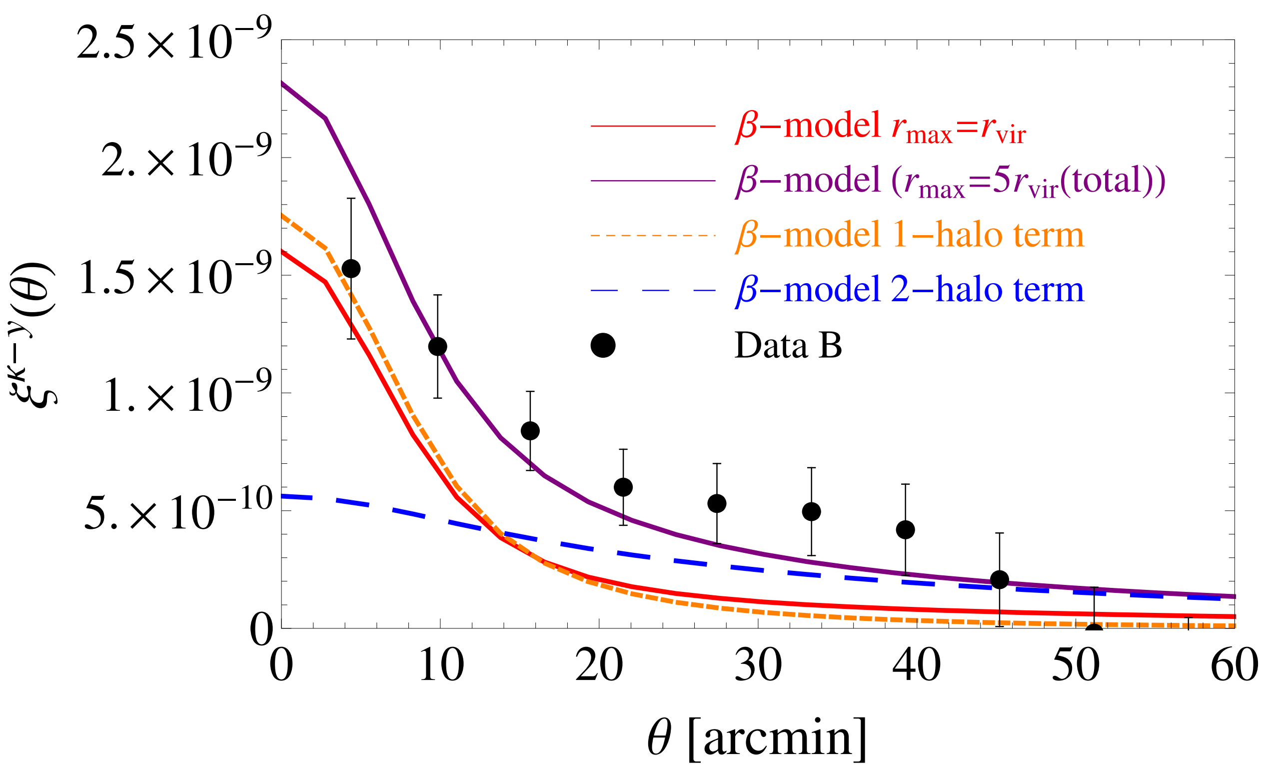
CFHT mass map:

154 deg^2 in 4 patches

Van Waerbeke et al., 2014, MNRAS



Halo model:



Ma et al. fits a halo model to the observed correlation function. A β model fits well, but in this context the data requires a 2-halo term to fit the large angular scale separation.

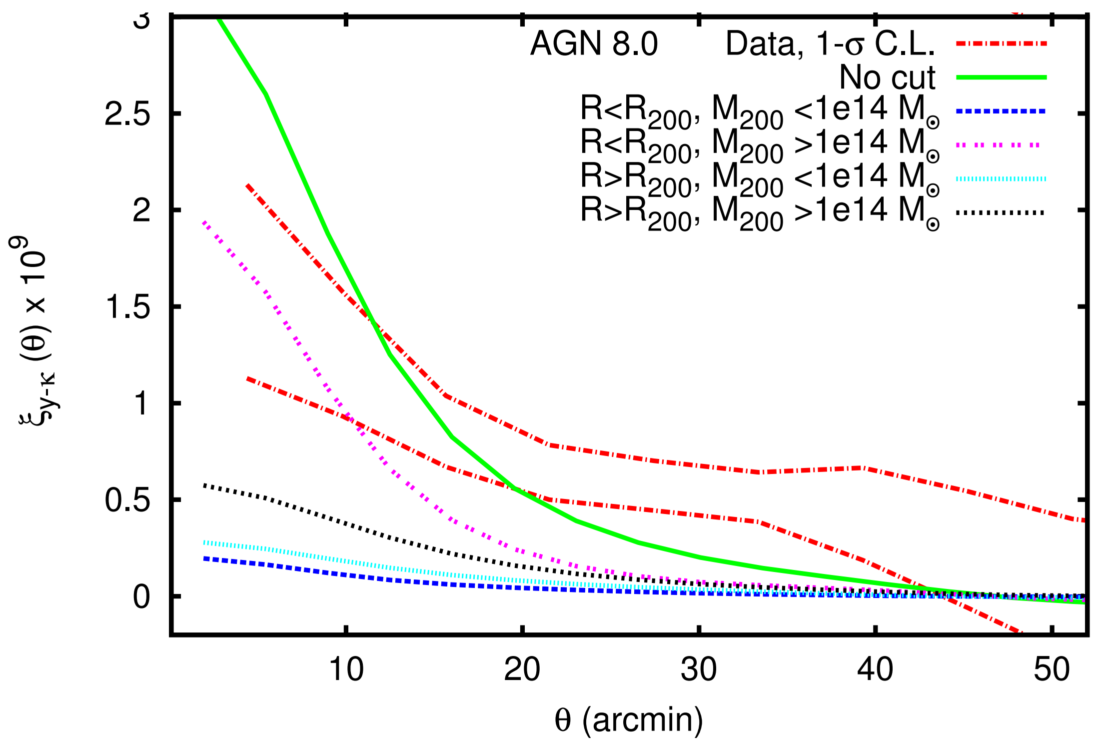
YZM, L. Van Waerbeke, G. Hinshaw, A. Hojatti, D. Scott, 2015 JCAP, arXiv: 1404.4808

	$10^{12}\,\mathrm{M}_\odot$–$10^{14}\,\mathrm{M}_\odot$	$10^{14}\,\mathrm{M}_\odot$–$10^{16}\,\mathrm{M}_\odot$
$(0.01$–$1)\,r_{\mathrm{vir}}$	26%	28%
$(1$–$100)\,r_{\mathrm{vir}}$	14%	32%

By applying the virial theorem with z = 0.37, for the mass range 10^12—10^16 M_sun, we get T_e = 10^5—10^8 K.

YZM, L. Van Waerbeke, G. Hinshaw, A. Hojatti, D. Scott, J. Zuntz, 2015 JCAP

Simulation vs data



	Simulation		Halo model
Bin	Signal	Baryon	Signal
Low mass, inner radii	7%	6%	26%
Low mass, outer radii	12%	24%	14%
High mass, inner radii	56%	4%	28%
High mass, outer radii	25%	7%	32%

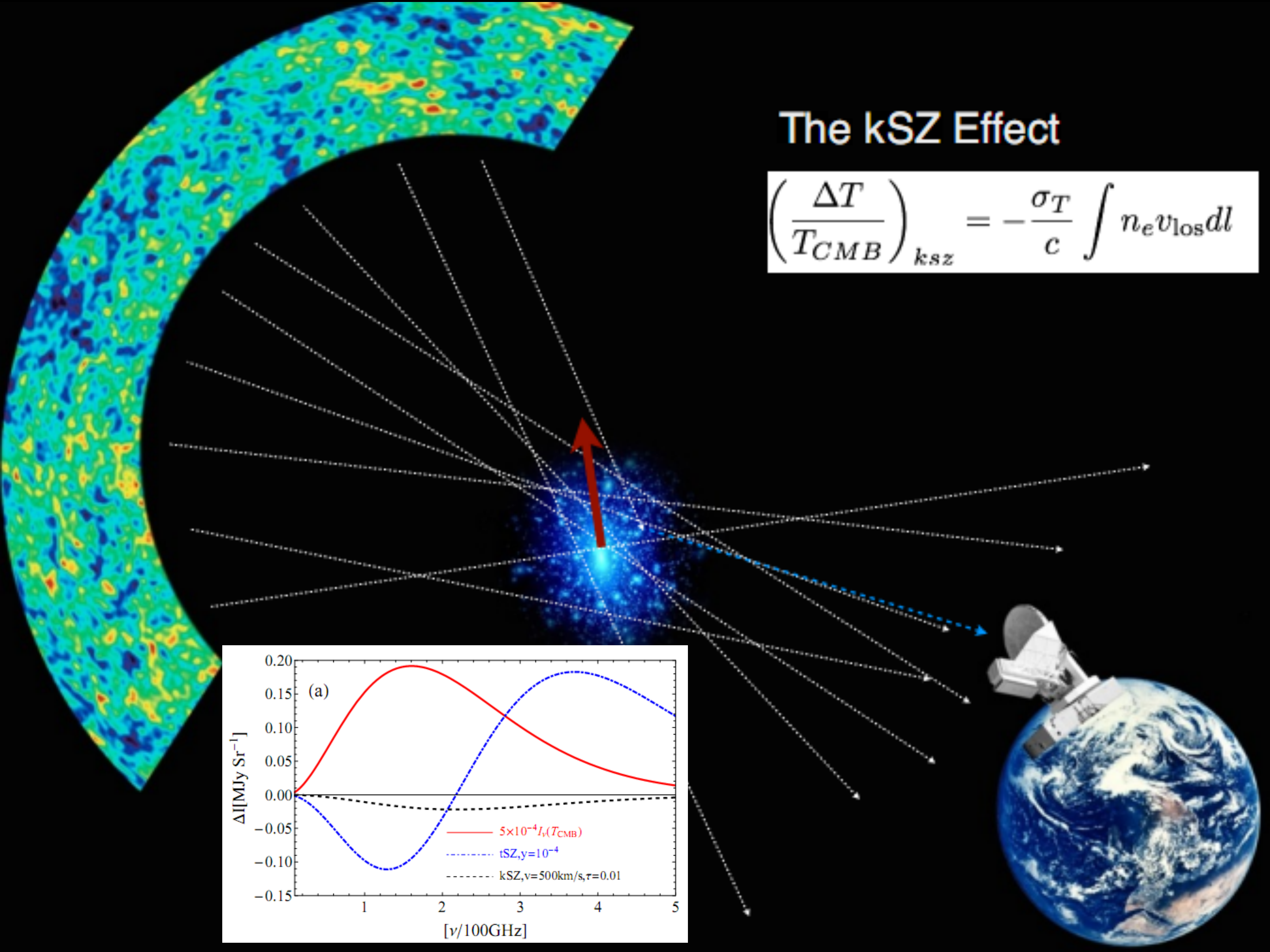
Kinetic SZ studies

Method	Reference	kSZ data	Tracer type	Tracer data	Significance
Pairwise temperature difference	Hand et al. (2012)[a]	ACT	Galaxies (spec-z)	BOSS III/DR9	$2.9\,\sigma$
	Planck Collaboration Int. XXXVII (2016)	*Planck*	Galaxies (spec-z)	SDSS/DR7	1.8–$2.5\,\sigma$
	Hernández-Monteagudo et al. (2015)	*WMAP*	Galaxies (spec-z)	SDSS/DR7	$3.3\,\sigma$
	Soergel et al. (2016)	SPT	Clusters (photo-z)	1-yr DES	$4.2\,\sigma$
	De Bernardis et al. (2017)	ACT	Galaxies (spec-z)	BOSS/DR11	3.6–$4.1\,\sigma$
	Sugiyama et al. (2017)[b]	*Planck*	Galaxies (spec-z)	BOSS/DR12	$2.45\,\sigma$
	Li et al. (2018)[b]	*Planck*	Galaxies (spec-z)	BOSS/DR12	$1.65\,\sigma$
kSZ $\times\, v_{\mathrm{pec}}$	Planck Collaboration Int. XXXVII (2016)[c]	*Planck*	Galaxy velocities	SDSS/DR7	3.0–$3.7\,\sigma$
	Schaan et al. (2016)[c]	ACT	Galaxy velocities	BOSS/DR10	$2.9\,\sigma$, $3.3\,\sigma$
kSZ^2 $\times$ projected density field	Hill et al. (2016), Ferraro et al. (2016)[d]	*Planck*, *WMAP*	Projected overdensities	WISE catalogue	3.8–$4.5\,\sigma$
kSZ dispersion	This work	*Planck*	Clusters	MCXC	$2.8\,\sigma$

Planck intermediate results XXXVII, 2016, A&A
C.Hernandez-Monteagudo, YZM, F-S Kitaura, W.Wang et al., 2015, Phys. Rev. Lett.

The kSZ Effect

$$\left(\frac{\Delta T}{T_{CMB}}\right)_{ksz} = -\frac{\sigma_T}{c}\int n_e v_{\mathrm{los}} dl$$



SZ map from linear combination of Planck frequency bands:
ν_i = 100, 143, 217, 353 GHz.

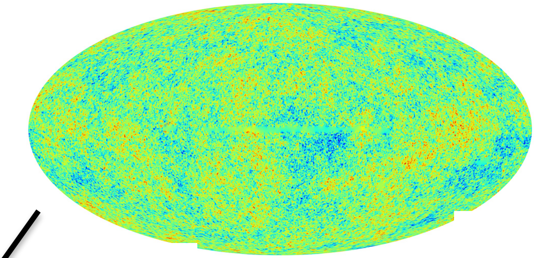
$$T_{SZ}/T_0 \equiv y\, S_{SZ}(\nu_i) = \sum b_i\, T(\nu_i)$$

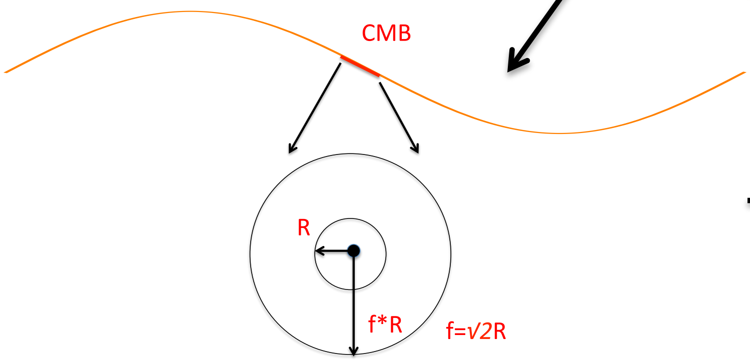
1. $\sum b_i\, S_{SZ}(\nu_i) = 1$ → 0 ! $\quad S_{SZ}(x) = x \coth(x/2) - 4 \quad (x = h\nu/kT)$

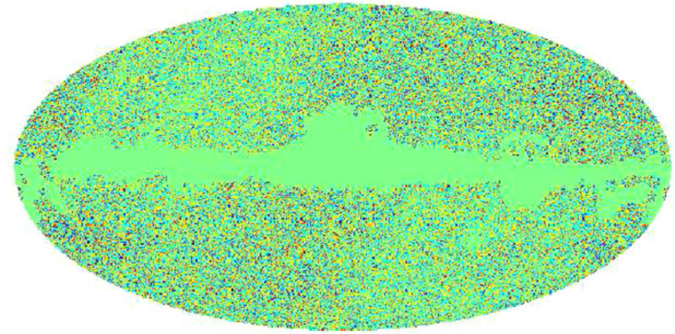
2. $\sum b_i\, S_{CMB}(\nu_i) = 0$ → 1 ! $\quad S_{CMB}(x) = 1$

3. $\sum b_i\, S_{\text{"dust"}}(\nu_i) = 0 \quad S_{\text{"dust"}}(\nu_i) = \nu^\beta\, g(x)$

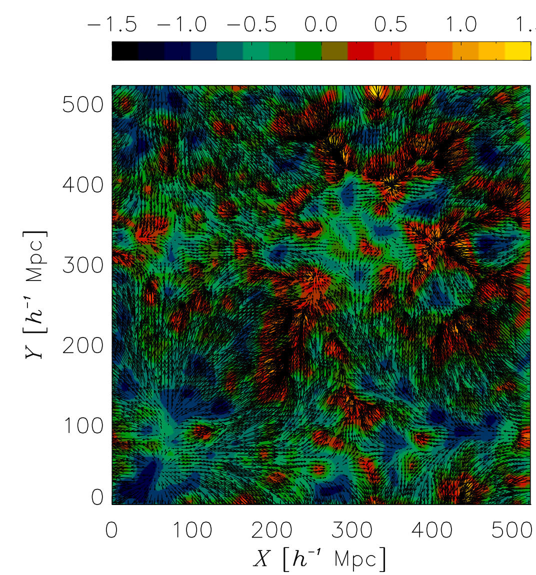
Planck SMICA, SEVEM, NILC maps





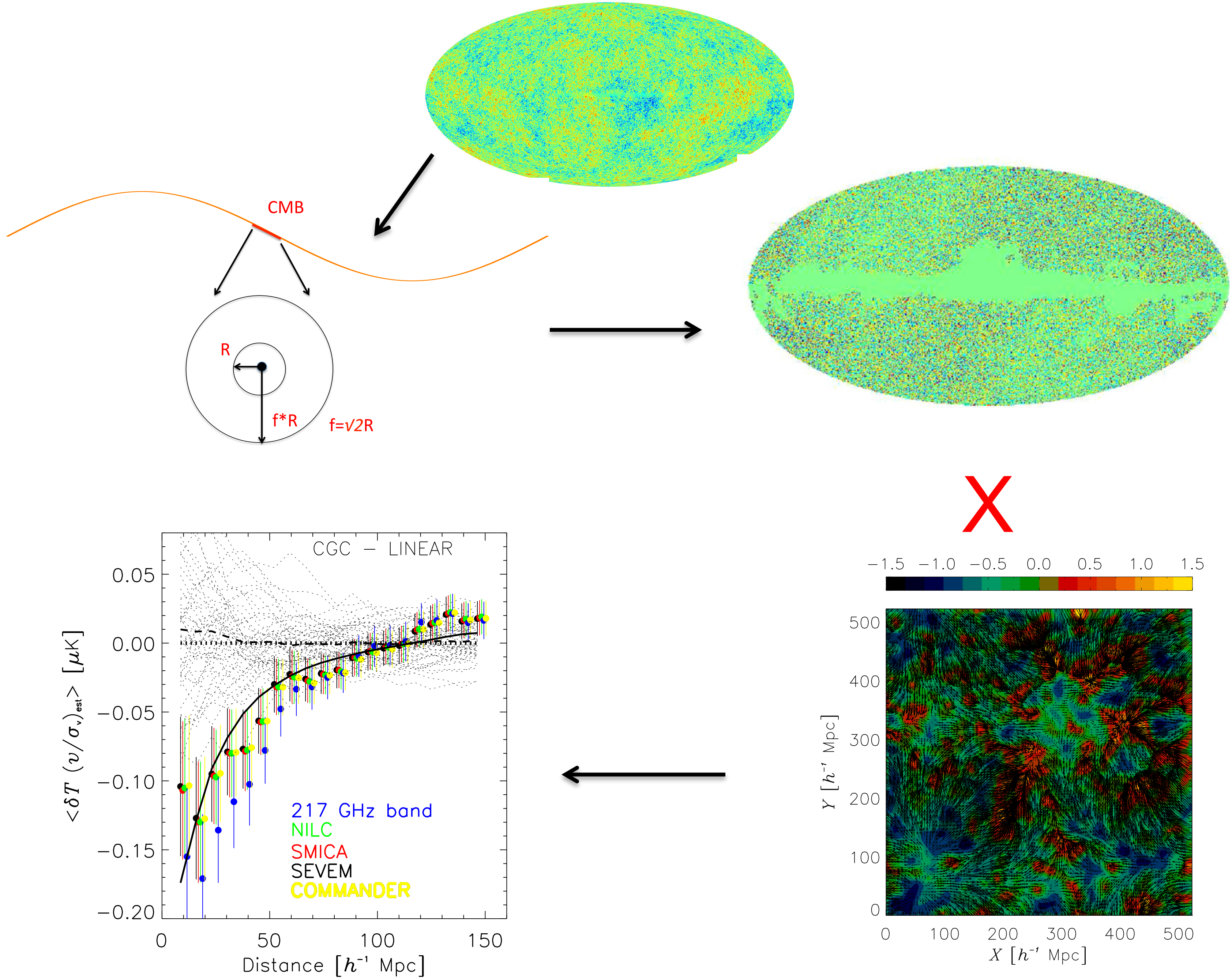


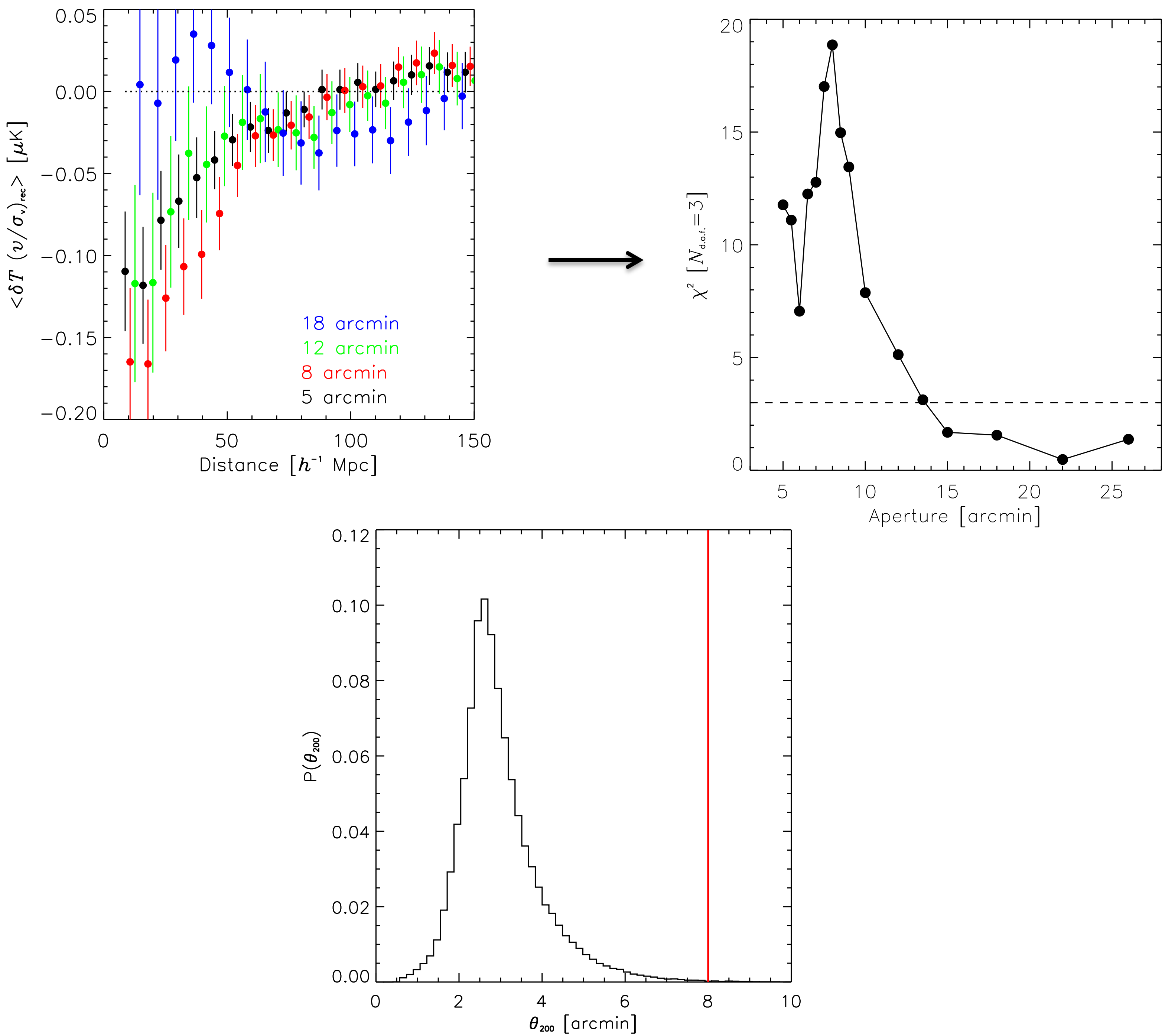
X



$$w^{T,v}(r) = \langle \delta T_i v^{\rm rec}_{\rm los}(\boldsymbol{x}_j) \rangle_{i,j}(r)$$

Planck SMICA, SEVEM, NILC maps





0.05
0.00
−0.05
−0.10
−0.15
−0.20
0
50
100
150
<δT (v/σ_v)_rec> [μK]
Distance [h^-1 Mpc]
18 arcmin
12 arcmin
8 arcmin
5 arcmin
20
15
10
5
0
5
10
15
20
25
χ² [N_d.o.f.=3]
Aperture [arcmin]
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
P(θ_200)
θ_200 [arcmin]

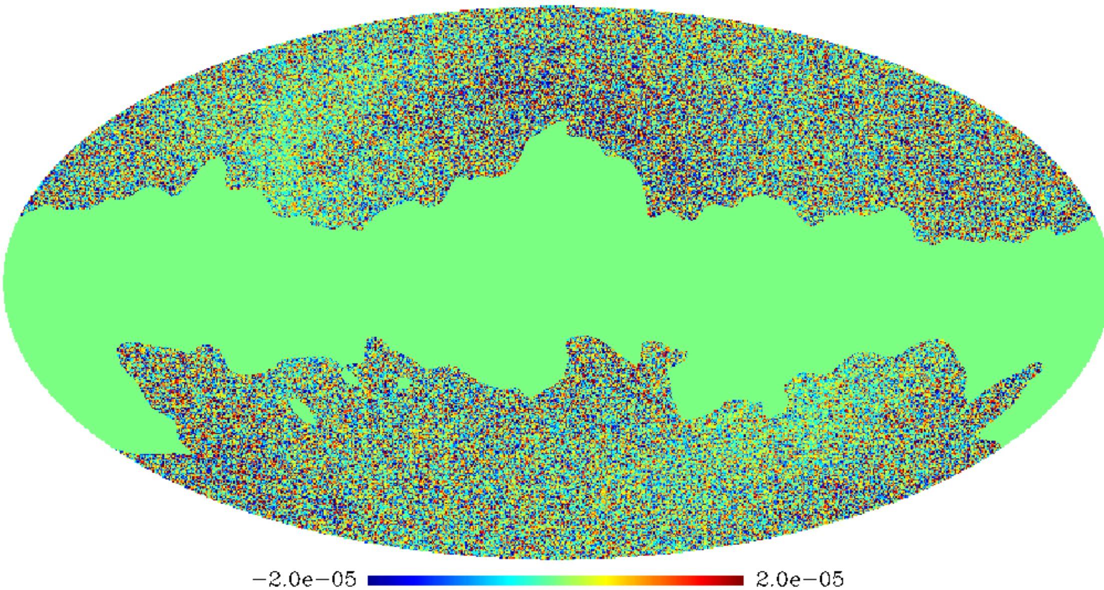
Dispersion measurement of kSZ

Method	Reference	kSZ data	Tracer type	Tracer data	Significance
Pairwise temperature difference	Hand et al. (2012)[a]	ACT	Galaxies (spec-z)	BOSS III/DR9	$2.9\,\sigma$
	Planck Collaboration Int. XXXVII (2016)	*Planck*	Galaxies (spec-z)	SDSS/DR7	$1.8–2.5\,\sigma$
	Hernández-Monteagudo et al. (2015)	*WMAP*	Galaxies (spec-z)	SDSS/DR7	$3.3\,\sigma$
	Soergel et al. (2016)	SPT	Clusters (photo-z)	1-yr DES	$4.2\,\sigma$
	De Bernardis et al. (2017)	ACT	Galaxies (spec-z)	BOSS/DR11	$3.6–4.1\,\sigma$
	Sugiyama et al. (2017)[b]	*Planck*	Galaxies (spec-z)	BOSS/DR12	$2.45\,\sigma$
	Li et al. (2018)[b]	*Planck*	Galaxies (spec-z)	BOSS/DR12	$1.65\,\sigma$
kSZ $\times\, v_{\rm pec}$	Planck Collaboration Int. XXXVII (2016)[c]	*Planck*	Galaxy velocities	SDSS/DR7	$3.0–3.7\,\sigma$
	Schaan et al. (2016)[c]	ACT	Galaxy velocities	BOSS/DR10	$2.9\,\sigma$, $3.3\,\sigma$
kSZ^2 $\times$ projected density field	Hill et al. (2016), Ferraro et al. (2016)[d]	*Planck*, *WMAP*	Projected overdensities	WISE catalogue	$3.8–4.5\,\sigma$
kSZ dispersion	This work	*Planck*	Clusters	MCXC	$2.8\,\sigma$

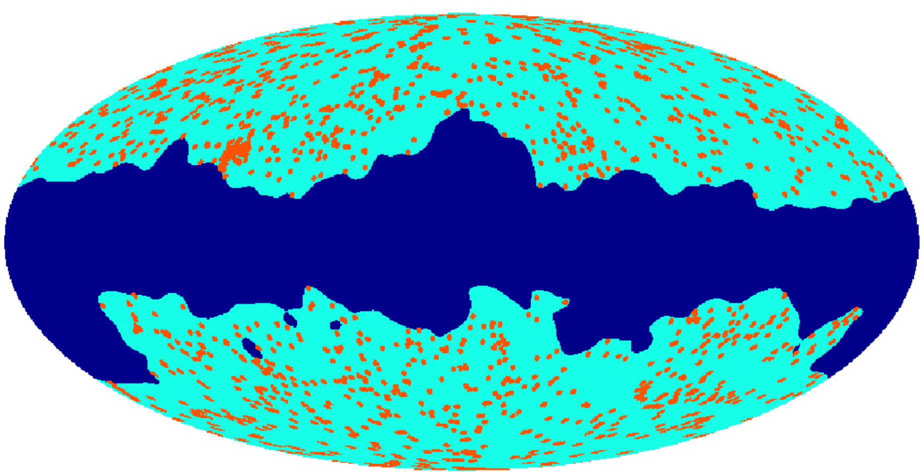
Planck intermediate results LIII, A&A in press, arXiv: 1707.00132

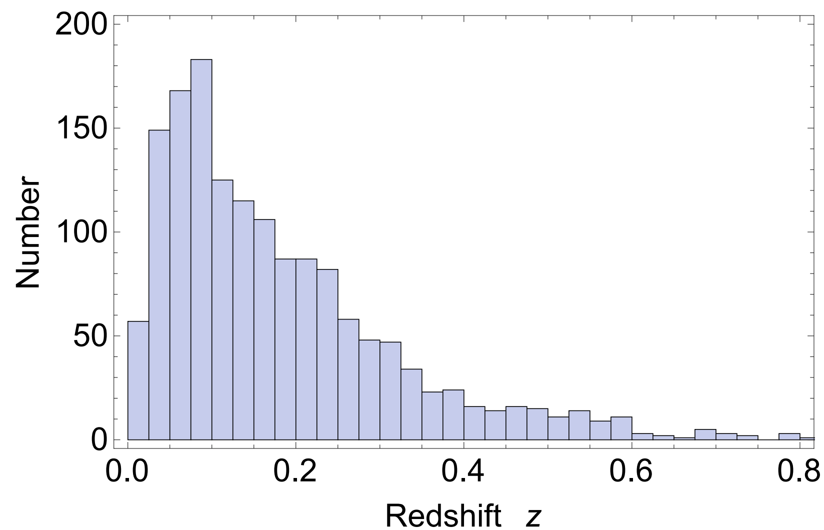
Global filter:

$$W_\ell = \frac{B_\ell}{B_\ell^2 C_\ell^{\rm CMB} + N_\ell} = \frac{B_\ell}{C_\ell^{\rm noise}}$$

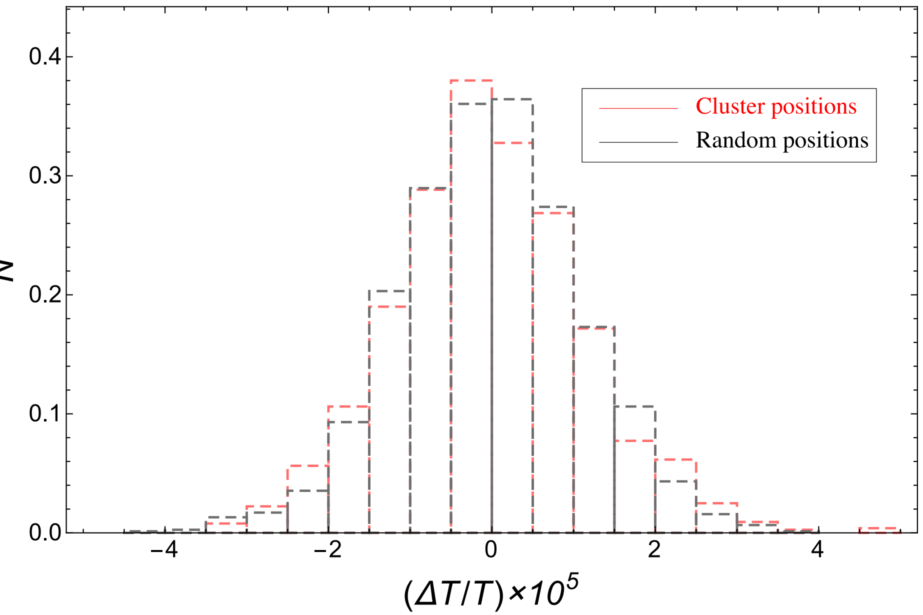


1526 MCXC clusters
outside Galactic mask



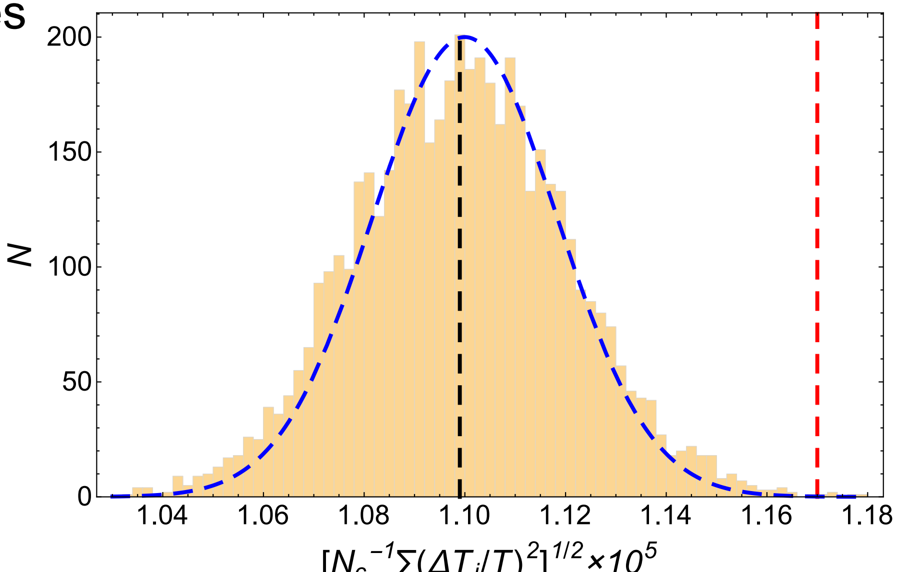


	True positions	Random positions
Mean	−0.015	−0.021
Variance	1.38	1.23
Skewness	0.37	0.09
Kurtosis	4.44	3.29



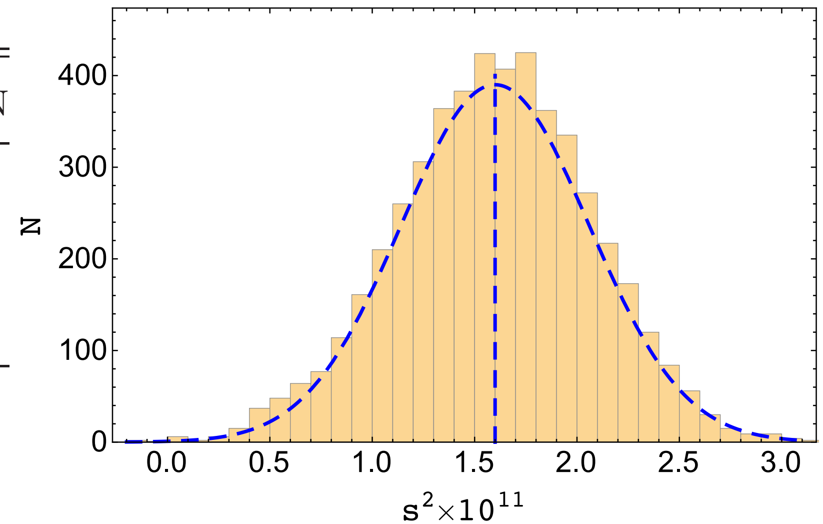
Then we choose 5000 random catalogues

Map	$\sigma_{\rm MCXC}\times 10^5$	$\sigma_{\rm ran}\times 10^5$	$\sigma(\sigma_{\rm ran})\times 10^5$
2D-ILC	1.17	1.10	0.022
SMICA	1.11	0.97	0.019
NILC	1.09	0.97	0.019
SEVEM	1.12	1.00	0.020
Commander	1.09	1.03	0.020



$$\widehat{s^2} = \frac{1}{N_\mathrm{c}} \sum_i \delta_i^2 - \frac{1}{N_\mathrm{c}} \sum_i \hat{n}_i^2$$

Map	$E[s^2] \times 10^{11}$	$\left(V[s^2]\right)^{1/2} \times 10^{11}$	S/N
2D-ILC	1.64	0.48	3.4
SMICA	3.53	0.37	9.4
NILC	2.75	0.38	7.3
SEVEM	3.19	0.40	8.1
Commander	1.47	0.42	3.5



$P(s_\mathrm{w}^2 < 0)$ = 0.07%

Corrected for lensing contribution:

$$\left(\hat{s^2}\right) = (1.35 \pm 0.48) \times 10^{-11}$$

$2.8\,\sigma$

↓

$$\langle v^2 \rangle = (123\,000 \pm 71\,000)\,(\,\mathrm{km\,s^{-1}})^2$$

Statistical homogeneity on 600 Mpc scale

Conclusion:

- We probe gas by cross-correlating the Sunyaev-Zeldovich map from Planck with CFHTLens lensing mass maps and SDSS LRG pair catalogue to probe gas distributions that are difficult to trace.
- Significant correlation is seen with lensing mass. Data is reasonably well fit by a halo model, but requires gas out to 5 × virial radius. By the virial theorem, the temperature of this gas exactly corresponds to the 10^5—10^7K, i.e. warm-hot intergalactic medium. This is consistent with the finding from numerical simulation.
- We use the aperture photometry filter to the kSZ map, and find the maximum correlation between kSZ-velocity field is at theta=8 arcmin, corresponding to gas outside virial radius.
- We also show the detection of the temperature dispersion effect of kSZ at 2.8 sigma C.L, which opens a new way of analyzing the gaseous distribution of galaxy clusters through higher order statistics.
- These studies will potentially provide better measurement on the intergalactic baryon component.