The “missing baryons” in the cosmic web: what it is? where it is? how much?

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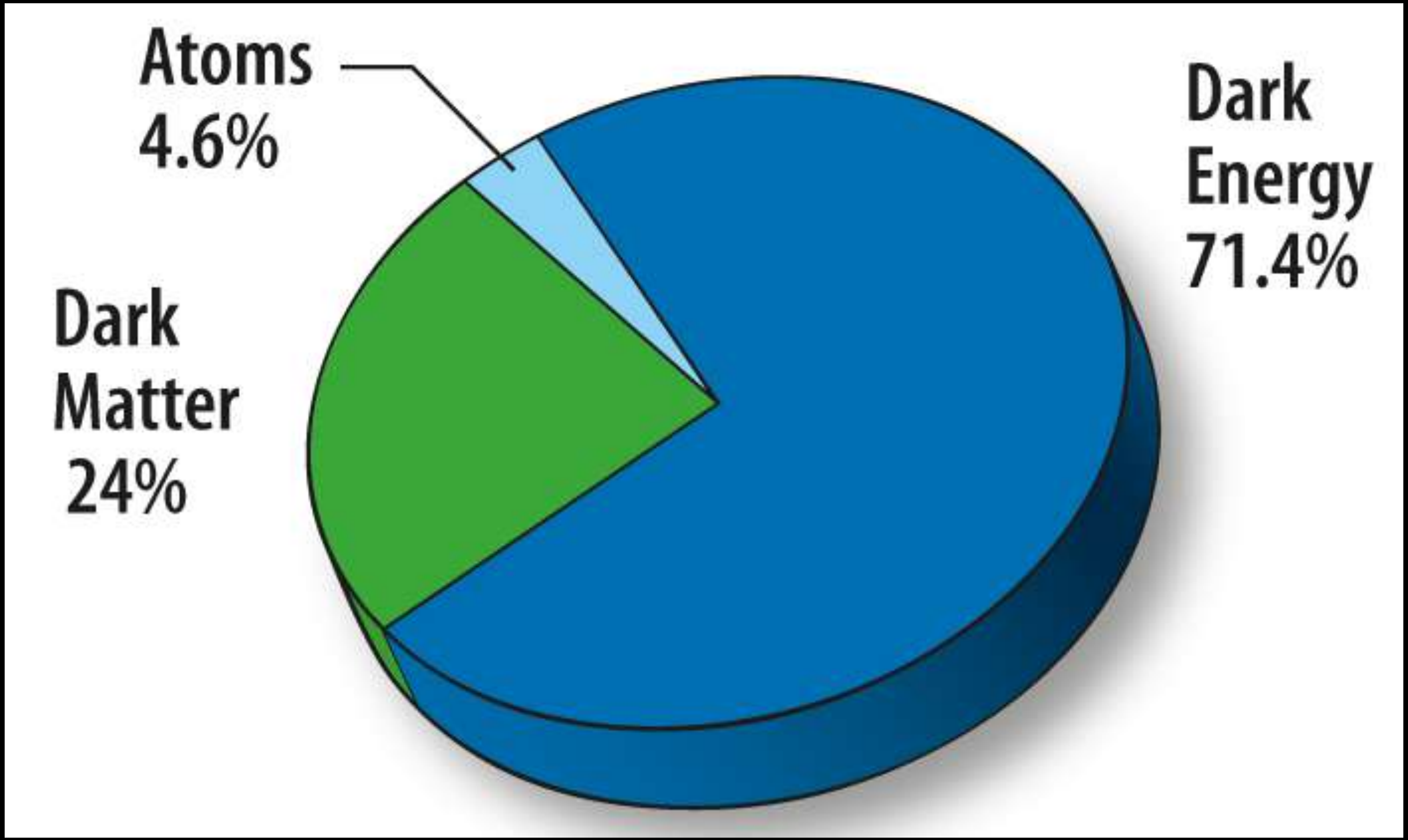
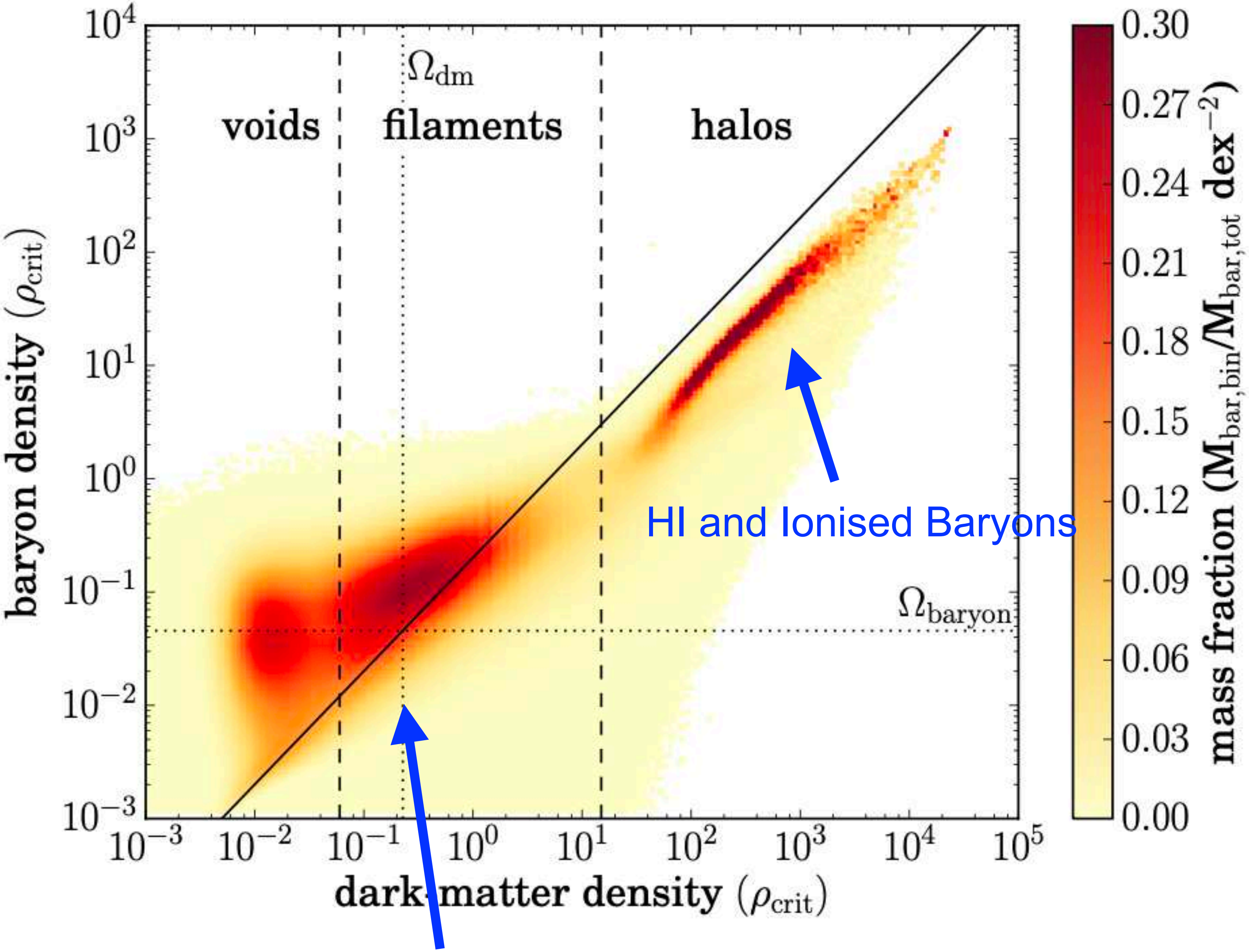


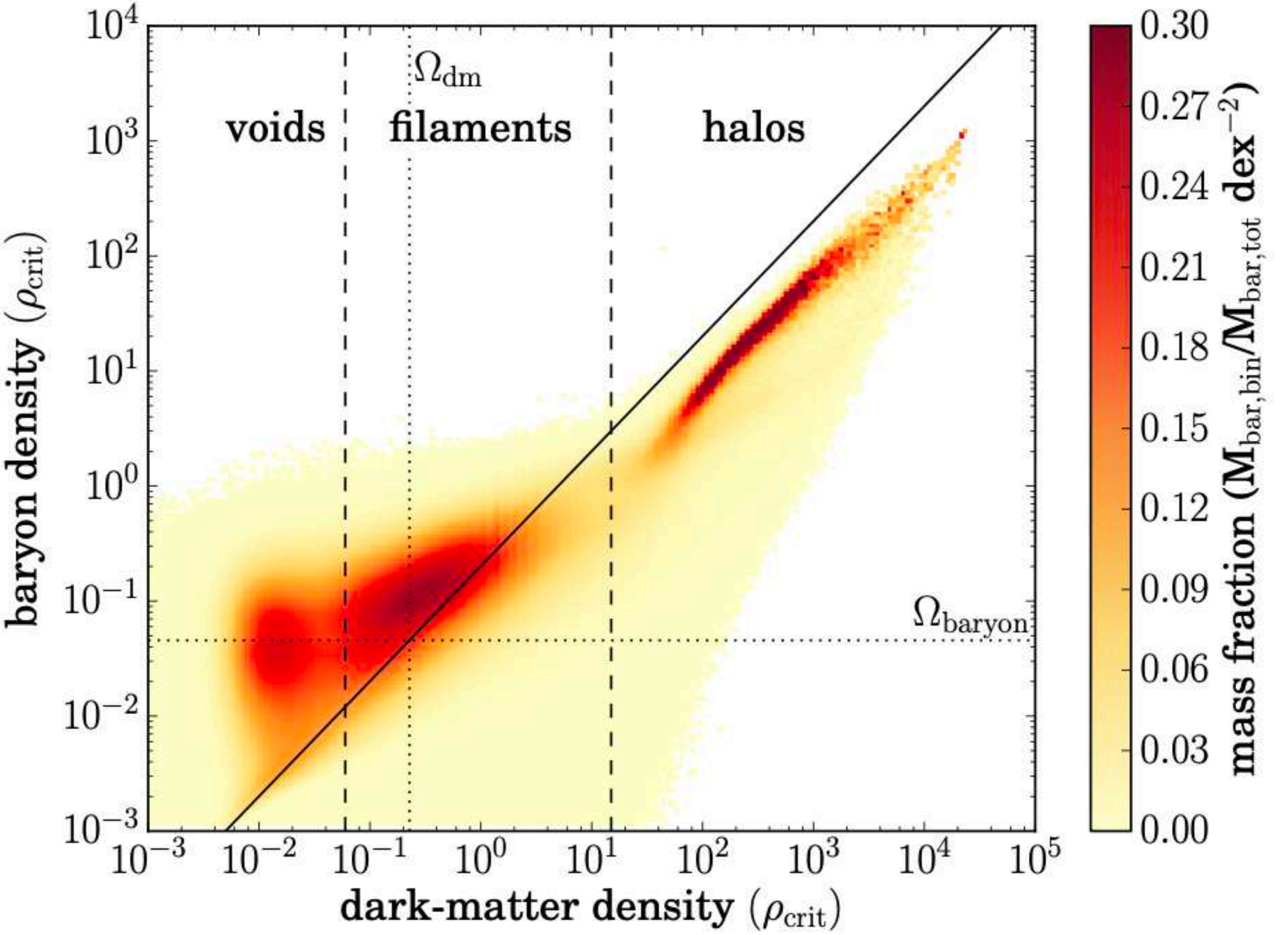
Collaborators: R. Battye, D. Contreras, C. Dickinson, C. Hernandez-Monteagudo, G. Hinshaw, A. Hojjati, Y.-C. Li, I. McCarthy, K. Moodley, M. Remazeilles, D. Scott, L. Staveley-Smith, H. Tanimura, D. Tramonte, L. Van Waerbeke, J. Zuntz, & Planck team & MeerKAT team



HI and Ionised Baryons

Ionised Baryons in filaments and voids

M. Haider et al. 2016, MNRAS



Baryons in voids + Baryons in Filaments + Baryons in halos + HI in cluster =? 100%

thermal Sunyaev-Zeldovich effect X Weak Lensing

YZM*, L. Van Waerbeke et al., 2015, JCAP, 09, 046*
A. Hojjati, I. McCarthy, J. Harnois-Deraps, ***YZM*** *et al., 2015, JCAP, 10, 047*
A. Hojjati, …. , ***YZM****,… 2017, JCAP, 471, 1565*
A. Ibitoye, W. Dai, ***YZM****, et al., 2023, ApJS in press, arXiv: 2310.18478*

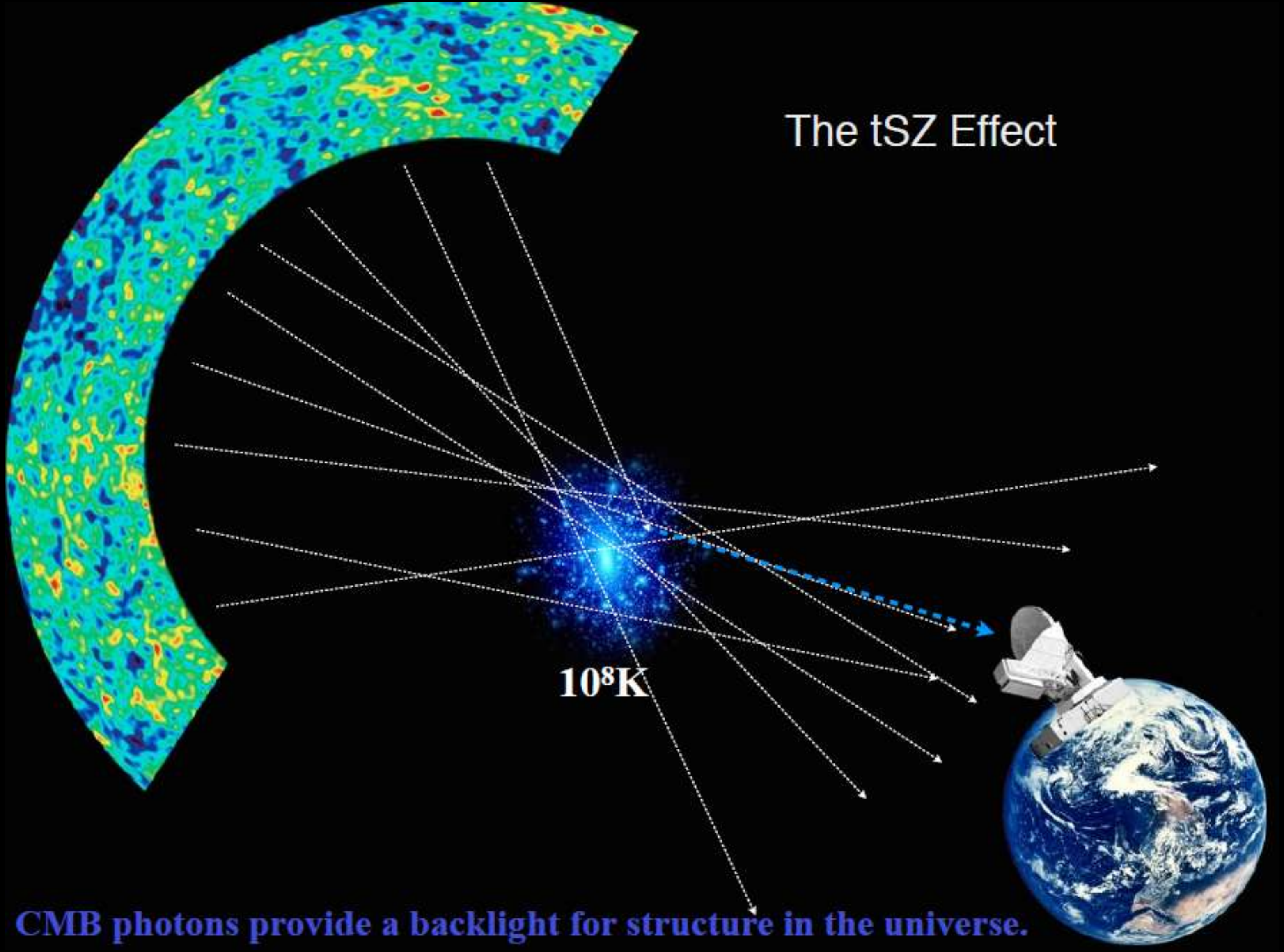
Thermal SZ maps X Luminous red galaxies

H Tanimura, …, ***YZM****,… et al. 2018, MNRAS, 483, 223*

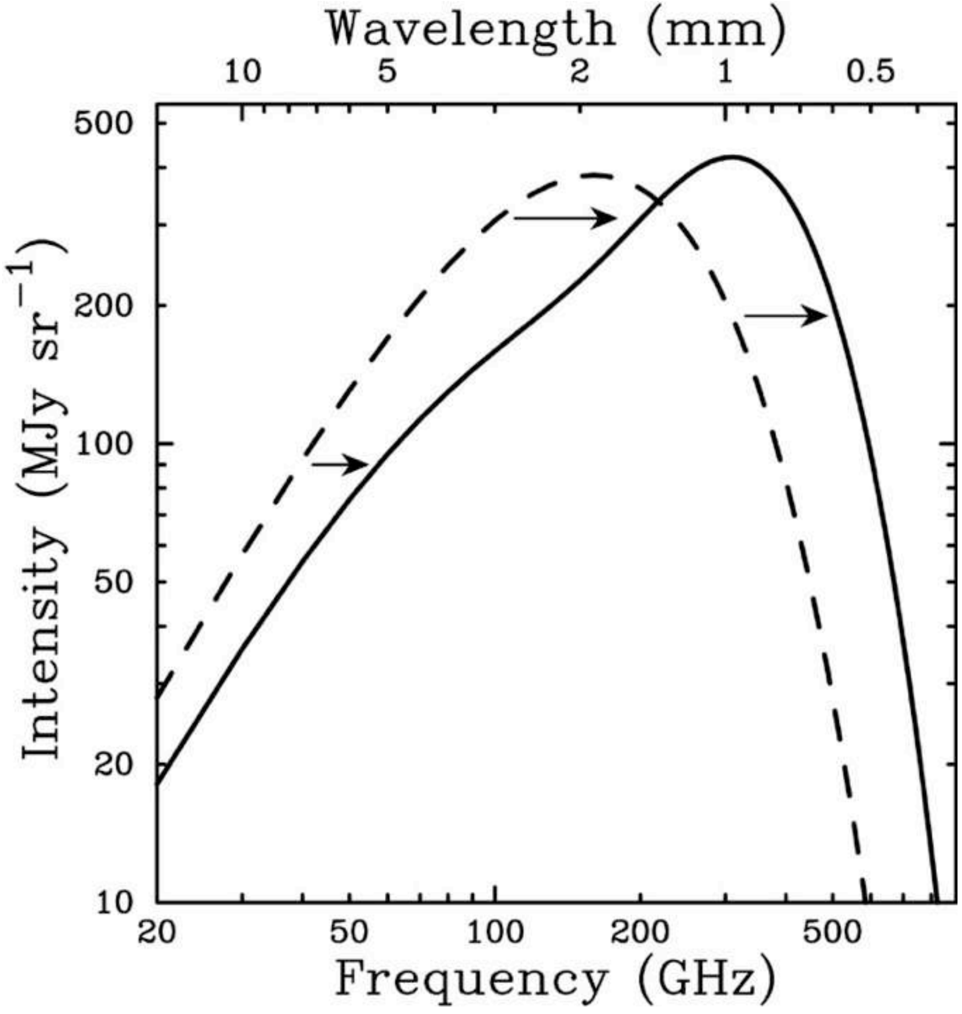
Thermal SZ maps X Cosmic Voids

G. Li, ***YZM,*** *D. Tramonte, G. Li et al. 2024, MNRAS, arXiv: 2311.00826*

The thermal Sunyaev-Zeldovich effect



Thermal Sunyaev-Zeldovich effect (tSZ):



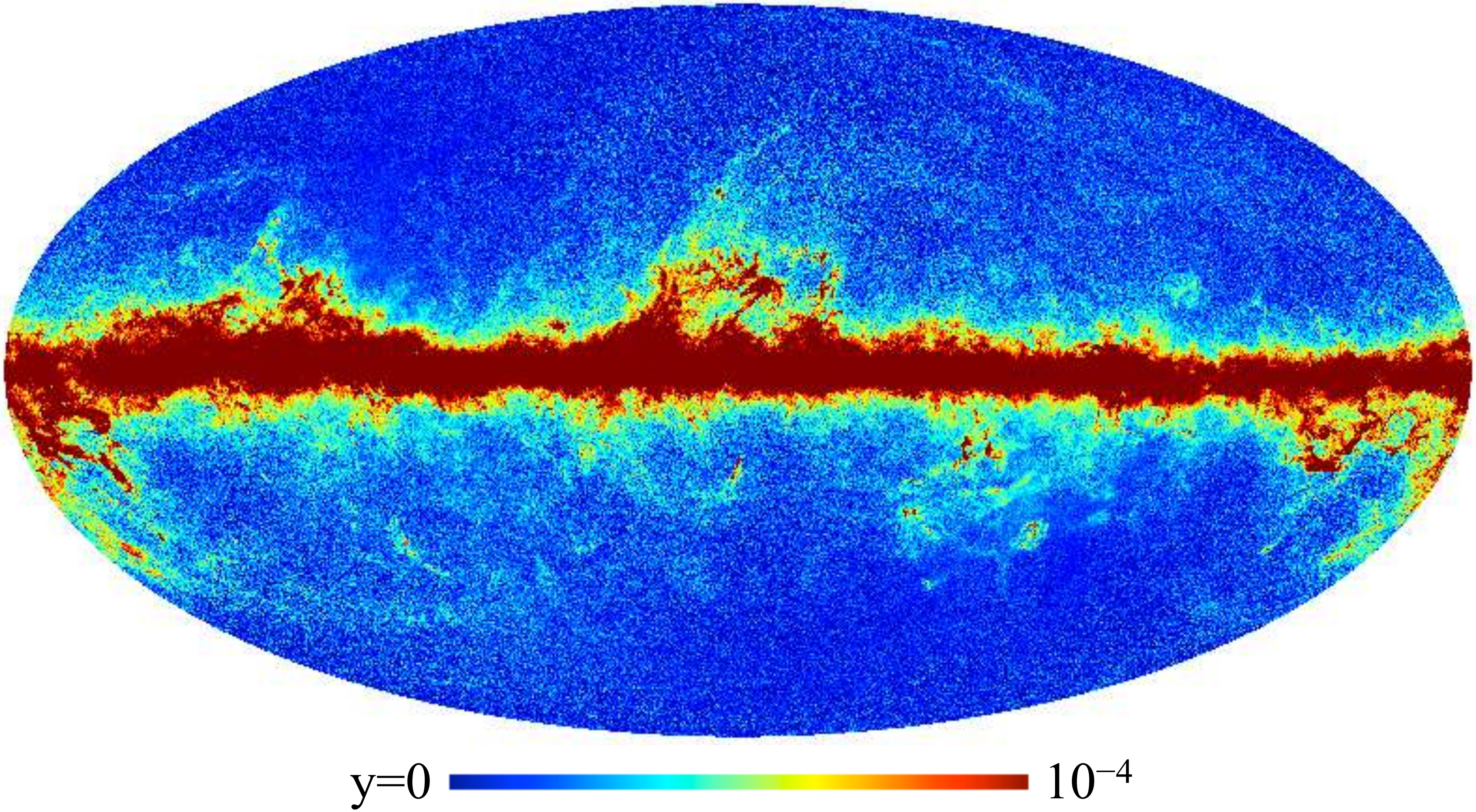
$$\frac{\Delta T}{T} = \left[\eta\frac{e^{\eta}+1}{e^{\eta}-1}-4\right] y \equiv g_{\nu} y$$

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

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

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

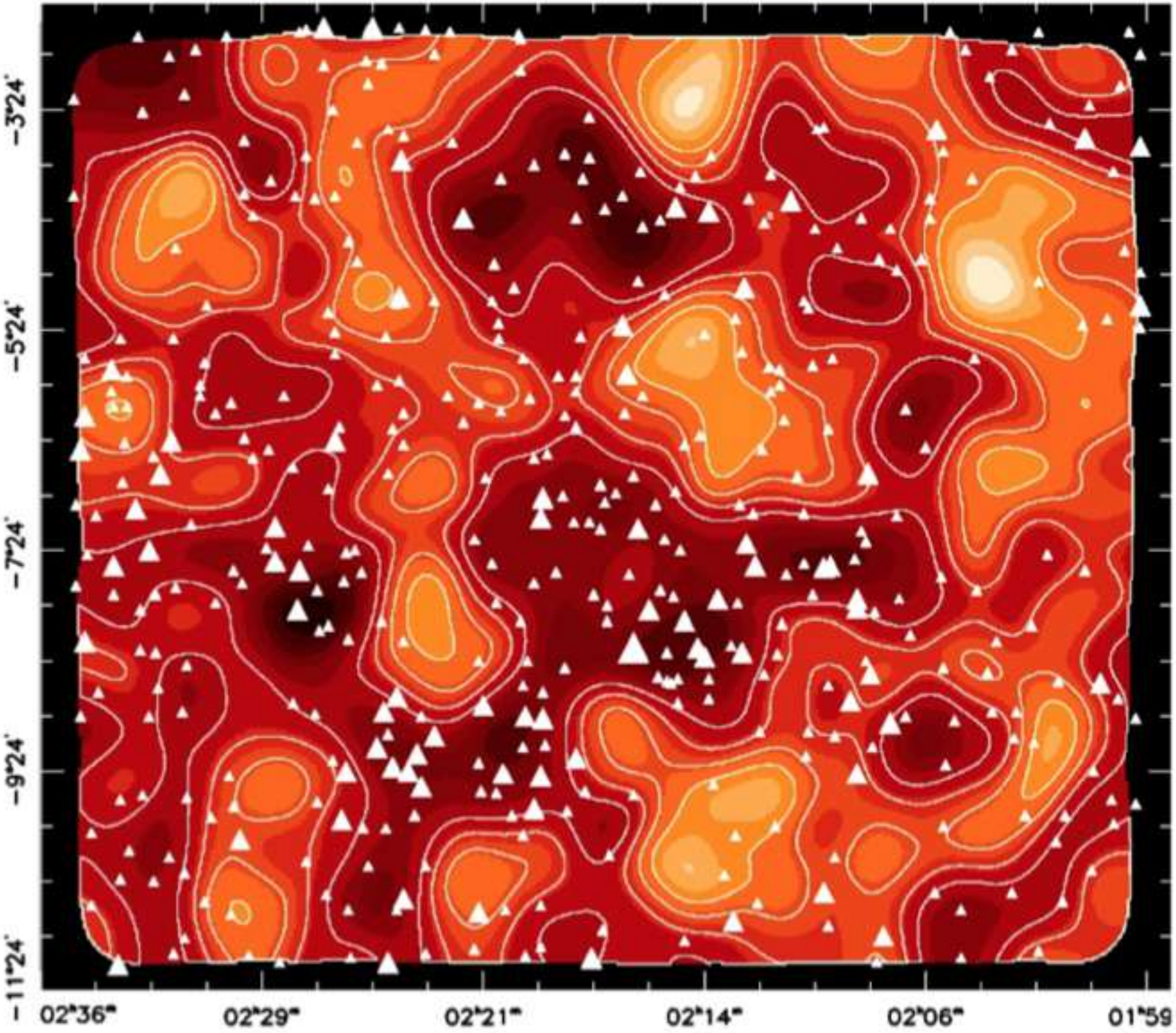
Planck SZ y map, version E



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

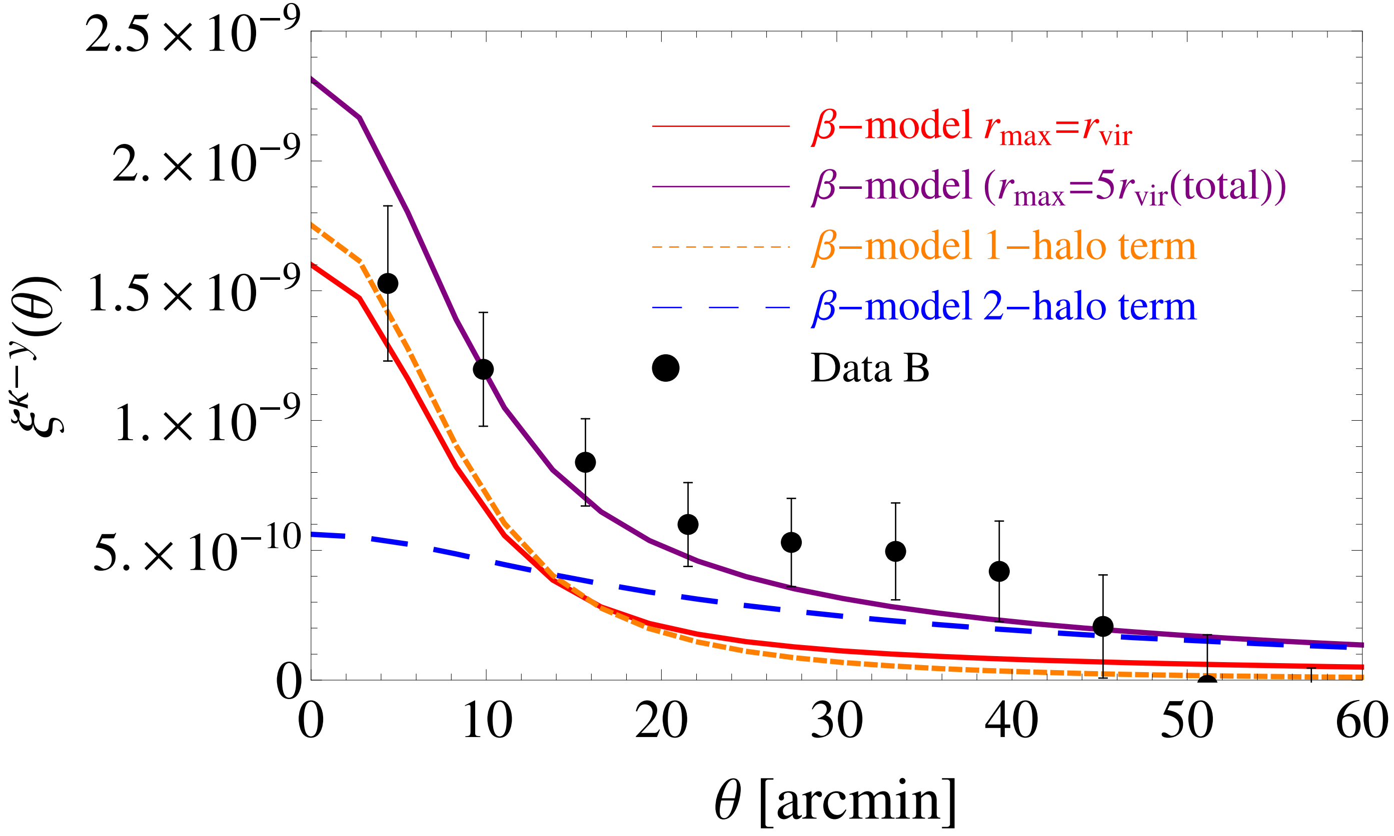
CFHT mass map:

154 deg^2 in 4 patches



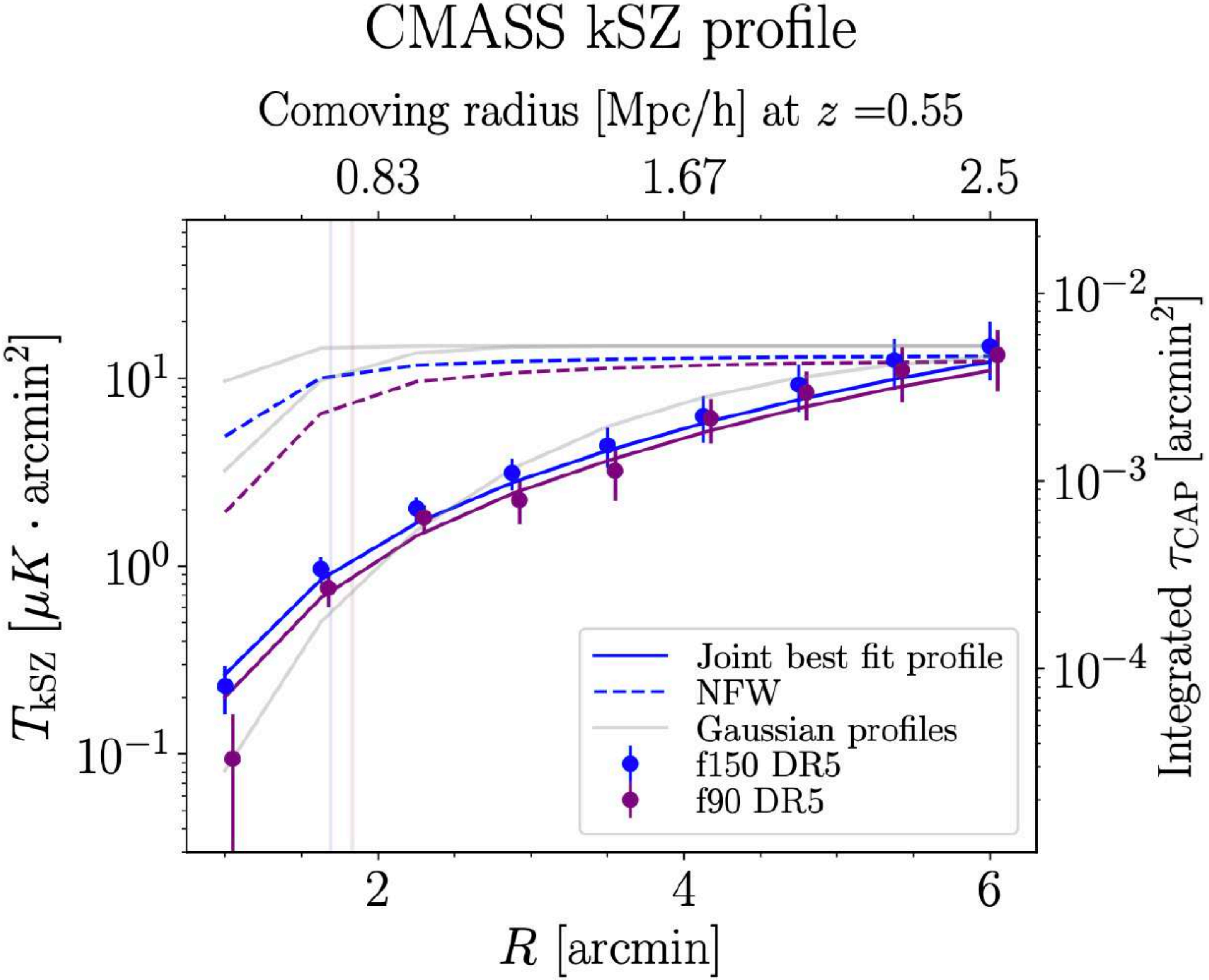
Van Waerbeke et al., 2014, MNRAS

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 et al., 2015, JCAP, 09, 046*
A. Hojjati, I. McCarthy, J. Harnois-Deraps, ***YZM*** *et al., 2015, JCAP, 10, 047*



Atacama Cosmology Telescope 2020 results:
Schaan et al., 2021; Amodeo et al. 2021

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

Virial theorem with $z = 0.37,\, M = 10^{12} - 10^{16}\mathrm{M}_\odot$

↓

$$T_\mathrm{e} = 10^5 - 10^7\,\mathrm{K}$$

YZM, *L. Van Waerbeke et al., 2015, JCAP, 09, 046*

A. Hojjati, I. McCarthy, J. Harnois-Deraps, ***YZM*** *et al., 2015, JCAP, 10, 047*

Thermal SZ maps X Luminous red galaxies

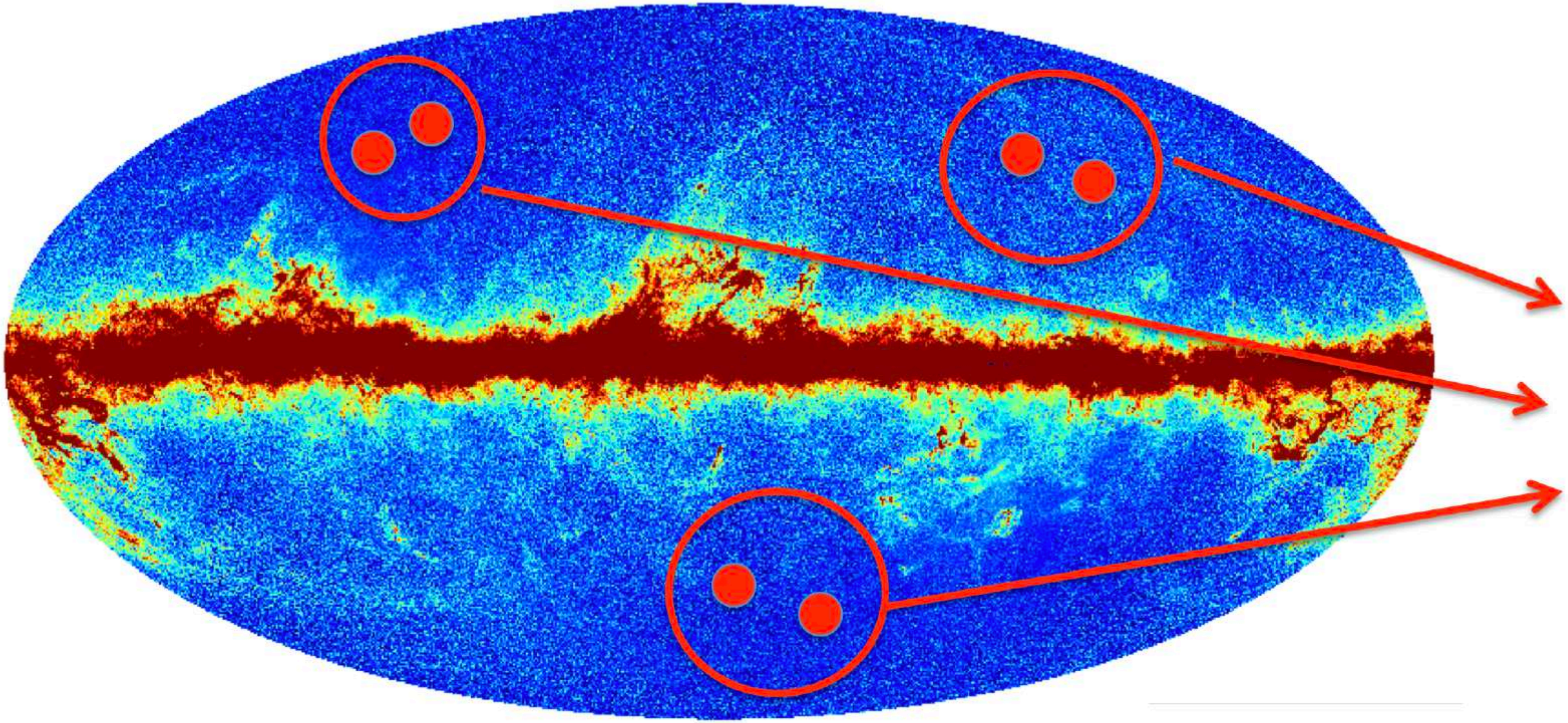
*H Tanimura, …, **YZM**,… et al. 2018, MNRAS, 483, 223*

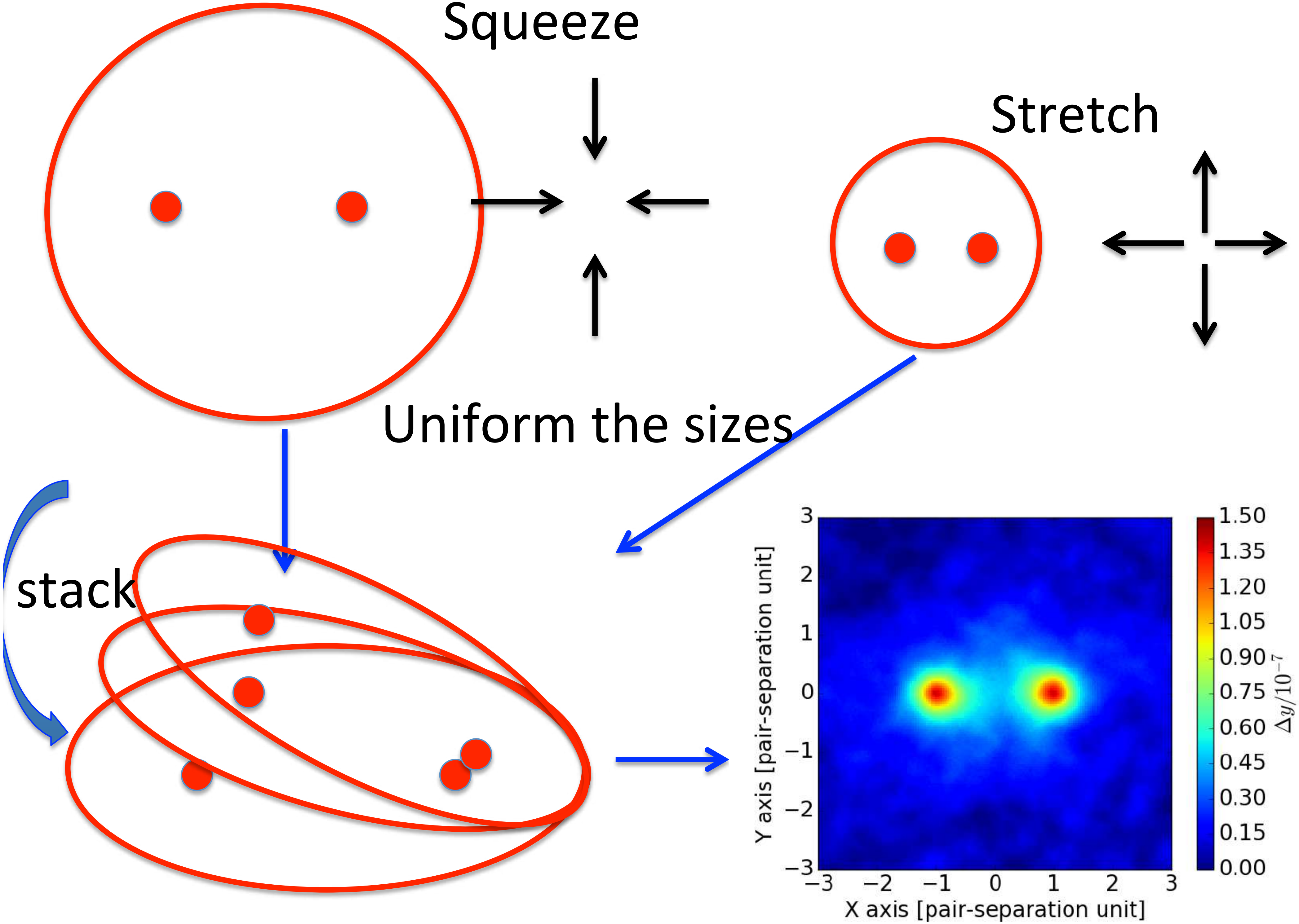
(see also) de Graff, Cai, Heymans, Peacock, 2019, A&A

Selecting LRG/SDSS pairs:

- $M_* > 10^{11.3}\,\mathrm{M}_\odot$
- $0.15 < z < 0.43$ (low-z catalogue)
- Tangential distance: $6 - 10\,h^{-1}\mathrm{Mpc}$
- Radial distance: $\pm 6\,h^{-1}\mathrm{Mpc}$

$\Rightarrow N_{\mathrm{pair}} \simeq 260{,}000$





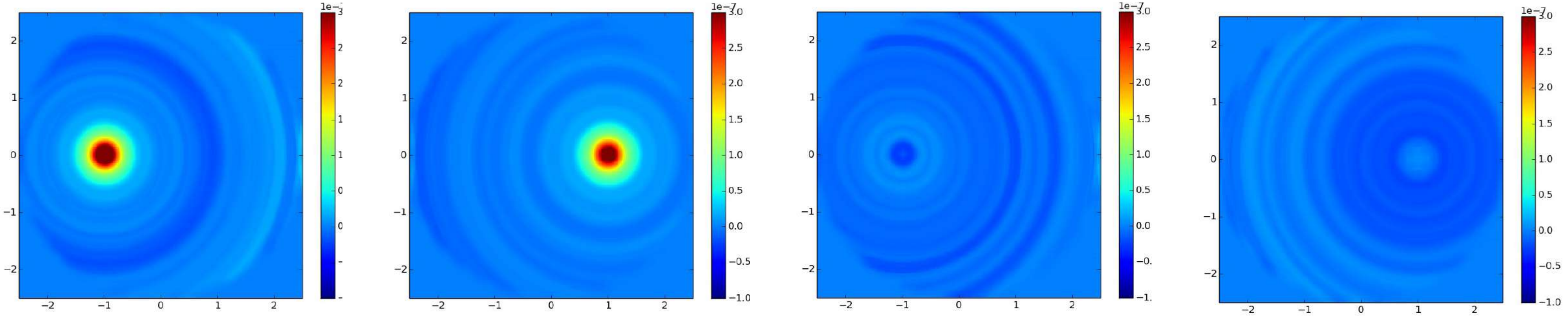
Squeeze

Stretch

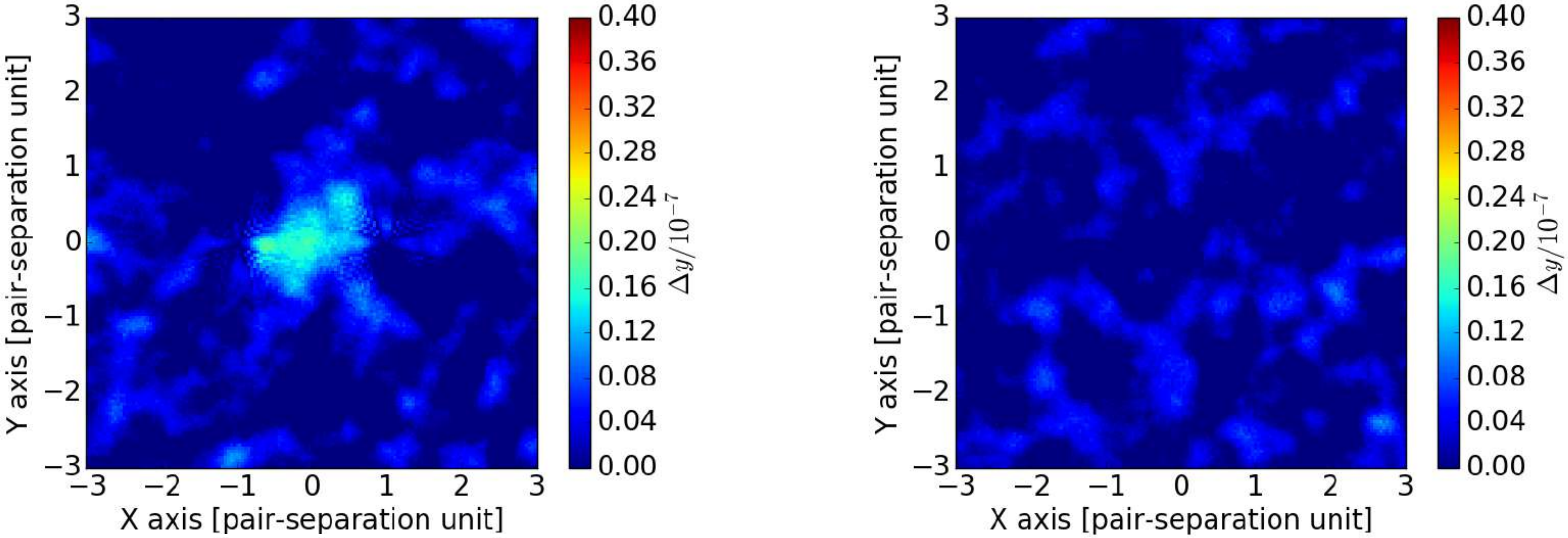
Uniform the sizes

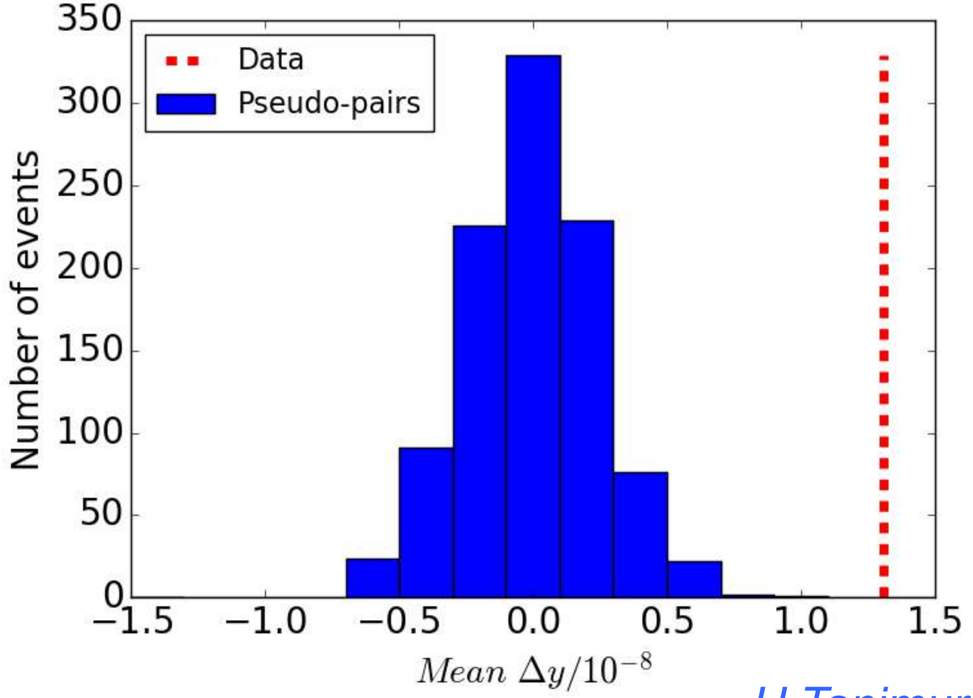
stack

Stacked



LRG SZ
Subtracted





$$\Delta y = (1.31 \pm 0.25) \times 10^{-8}$$

$$5.3\sigma$$

*H Tanimura, …, **YZM**,… et al. 2018, MNRAS, 483, 223*

$$y = \int n_{\rm e} \sigma_{\rm T} \frac{k_{\rm B} T_{\rm e}}{m_{\rm e} c^2} {\rm d}l$$

$$n_{\rm e} = \overline{n}_{\rm e,i}(1+\delta)$$

$$\overline{n}_{\rm e,i} = \frac{\chi \rho_{\rm b}(z)}{\mu_{\rm e} m_{\rm p}} \qquad \chi = \frac{1 - Y_{\rm p}(1 - N_{\rm H_e}/2)}{1 - Y_{\rm p}/2}$$

↓

$$\delta_c \left(\frac{T_{\rm e}}{10^7\ {\rm K}} \right) \left(\frac{r_c}{0.5 h^{-1}\ {\rm Mpc}} \right) = 2.7 \pm 0.5$$

*H Tanimura, …, **YZM**,… et al. 2018, MNRAS, 483, 223*

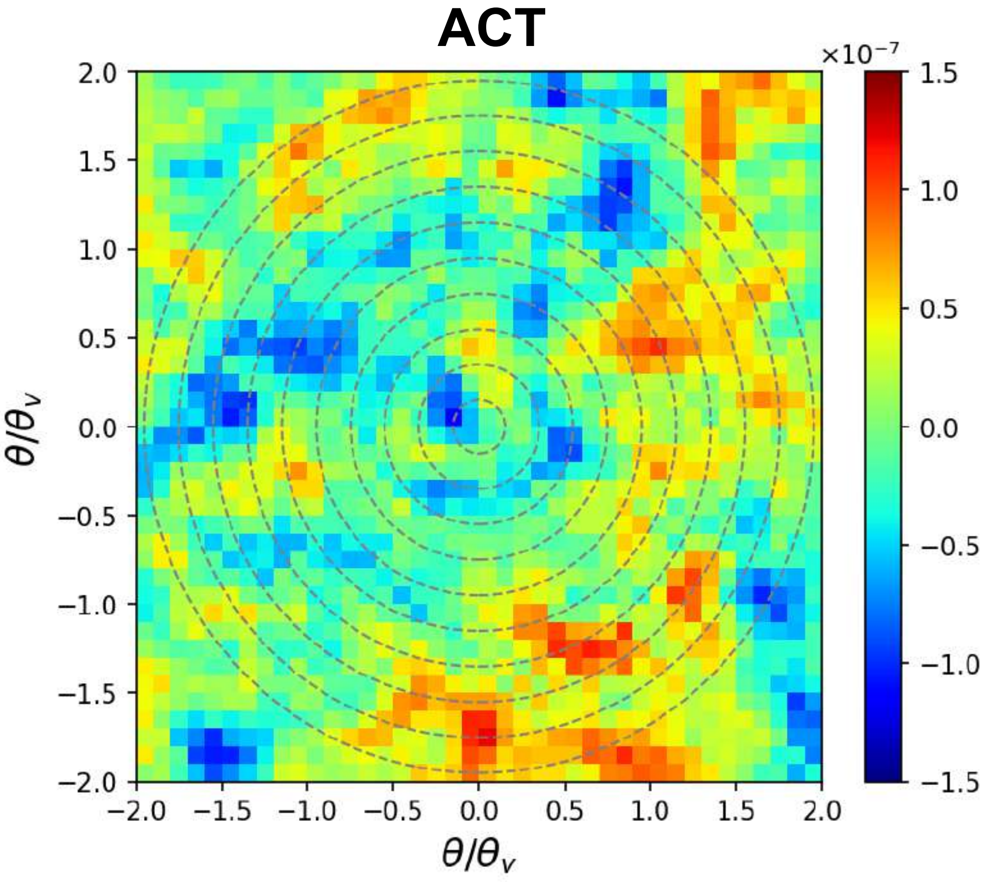
Cosmic voids stacking

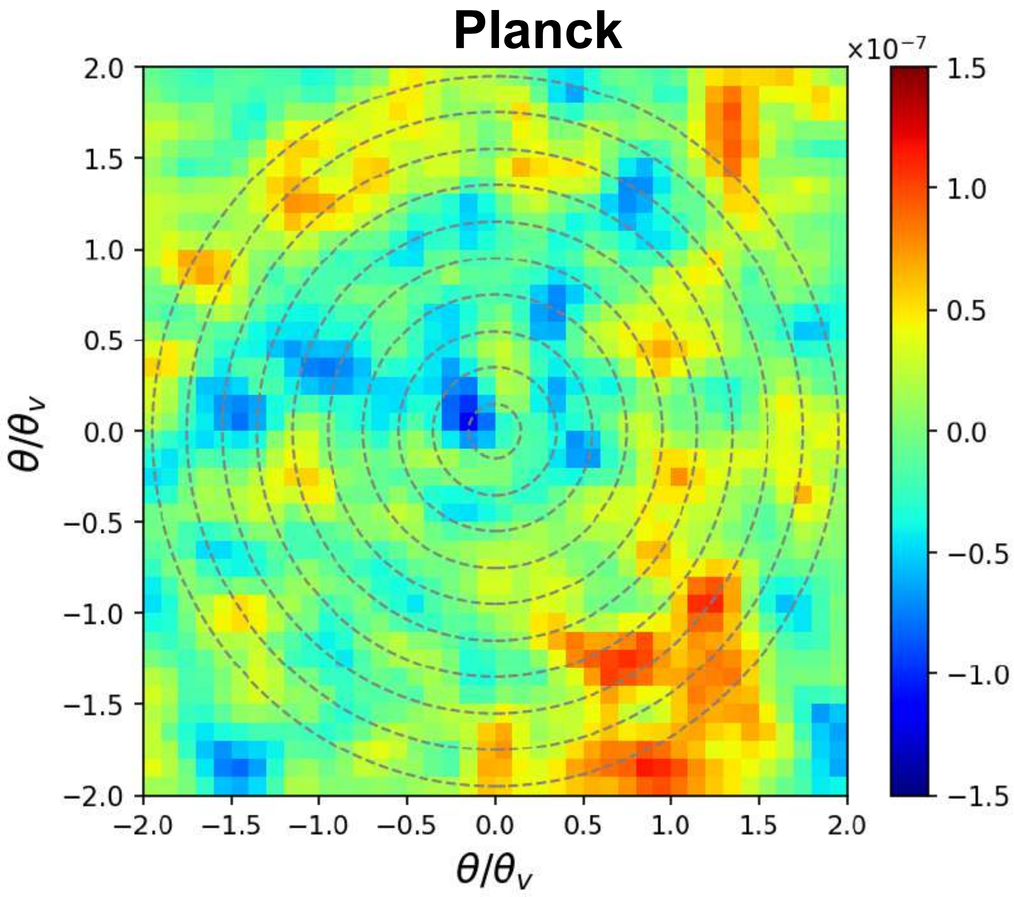
G. Li, **YZM,** D. Tramonte, G. Li et al. 2024, MNRAS, arXiv: 2311.00826

Voids: 97,090

Mean $z \simeq 0.32$ (BOSS DR12)

Mean radius $13.6\,h^{-1}\mathrm{Mpc}$





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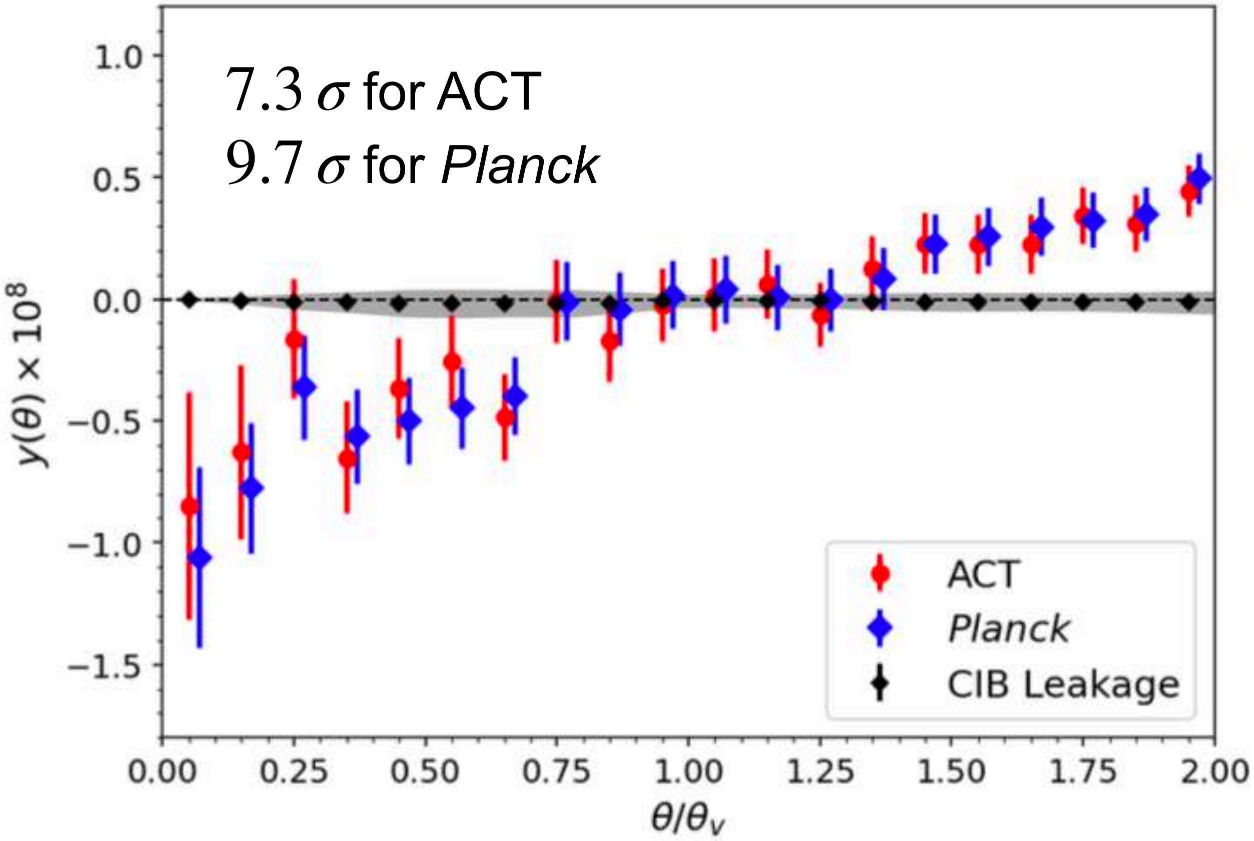


$7.3\,\sigma$ for ACT

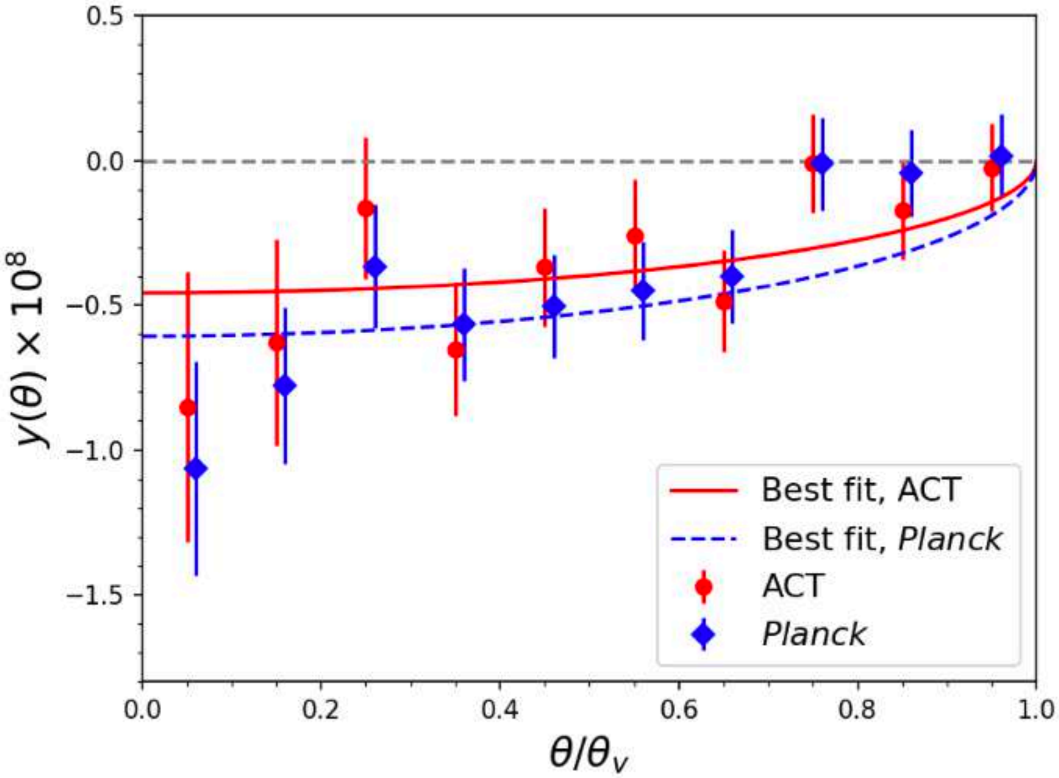
$9.7\,\sigma$ for *Planck*

Modelling:

$$n_\mathrm{e} = \bar{n}_\mathrm{e}(1 + \delta_\mathrm{v})$$

$$T_\mathrm{e} = \bar{T}_\mathrm{e}$$

$$\left(-\delta_{\rm v}\frac{T_{\rm e}}{10^5\,{\rm K}}\right) = \begin{cases} 6.5 \pm 2.3 & \text{ACT}, \\ 8.6 \pm 2.1 & \textit{Planck}, \end{cases}$$



$$\begin{aligned} \frac{n_{\rm e}^{\rm v}}{\bar{n}_{\rm e}} &= 1 + \delta_{\rm v} \\ &= 1 - \frac{(-\delta_{\rm v}(T_{\rm e}/10^5{\rm K}))}{(T_{\rm e}/10^5{\rm K})} \\ &\leqslant 1 - \frac{1}{10}\left(-\delta_{\rm v}\frac{T_{\rm e}}{10^5\,{\rm K}}\right) \\ &\leqslant \begin{cases} 0.73 & 95\%\ \text{C.L. for ACT}, \\ 0.49 & 95\%\ \text{C.L. for } \textit{Planck}, \end{cases} \end{aligned}$$

Summary

- Most of the baryons are diffuse and warm-hot IGM with $T = 10^4 - 10^7\,\mathrm{K}$.

SZ data	LSS tracers	Results
thermal SZ	weak lensing	Gas extends out to $5r_{\mathrm{vir}}$, with temperature for $M = 10^{12} - 10^{16}\mathrm{M}_\odot$ consistent with simulation
thermal SZ	Pairs of LRGs	Gas associated with filament is detected@5.3σ $y = (1.31 \pm 0.25) \times 10^{-8} \longrightarrow T_{\mathrm{filament}} \leqslant 10^7\,\mathrm{K}$
thermal SZ	SDSS Voids	The void significance is detected at 7.3σ and 9.7σ for ACT and Planck respectively, which leads to a joint constraint on void underdensity and the temperature of warm gas inside the voids.

- Our results suggest that missing baryon at low redshifts is *not* missing, but correlated with underlying LSS density field.
- By using multi-wavelength study, we are approaching the true examination of missing baryon problem