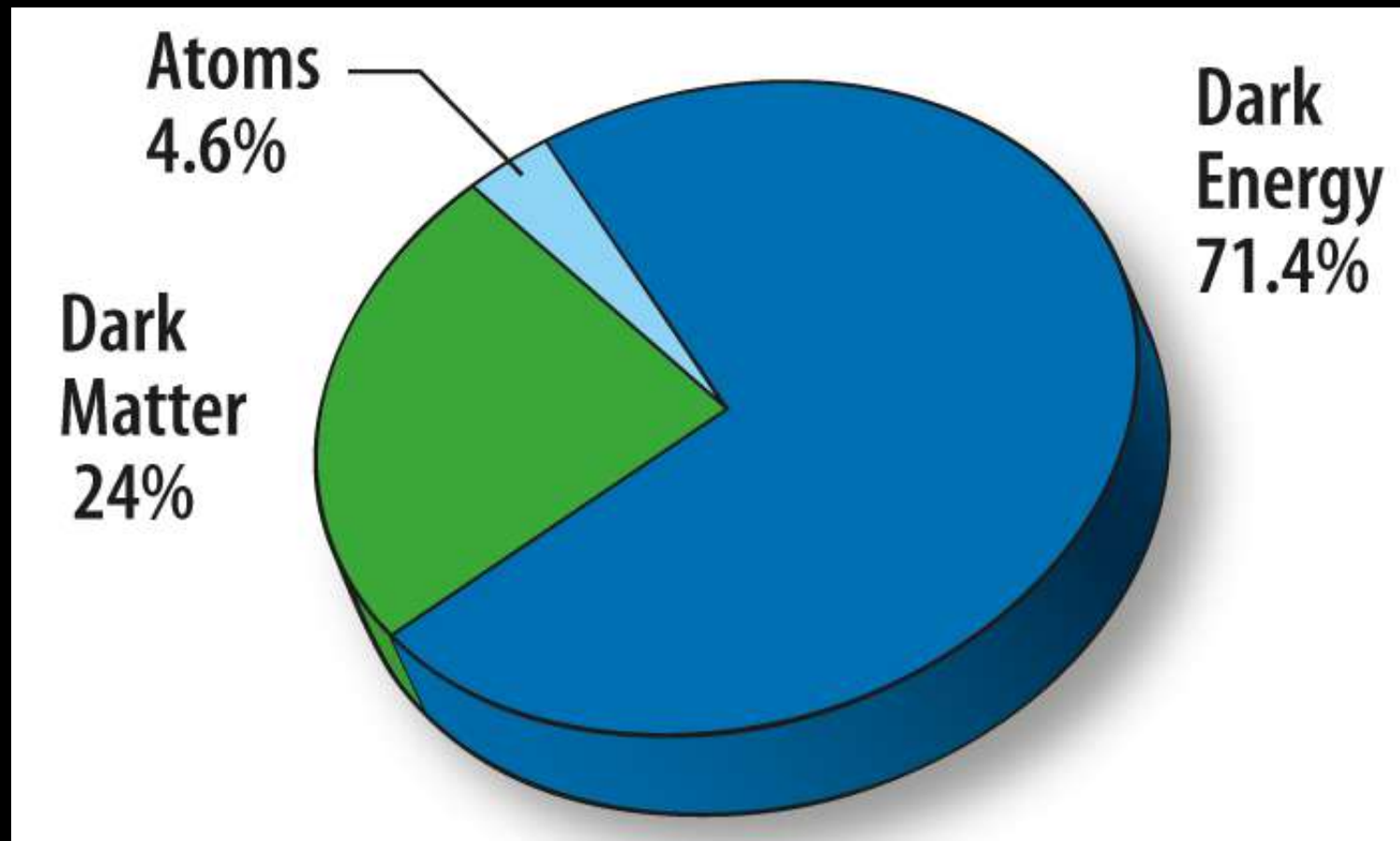


# The “missing baryons” in the cosmic web: what it is? where it is? how much?

**Yin-Zhe Ma**

Professor, Head of Astrophysics Division  
Department of Physics, Stellenbosch University

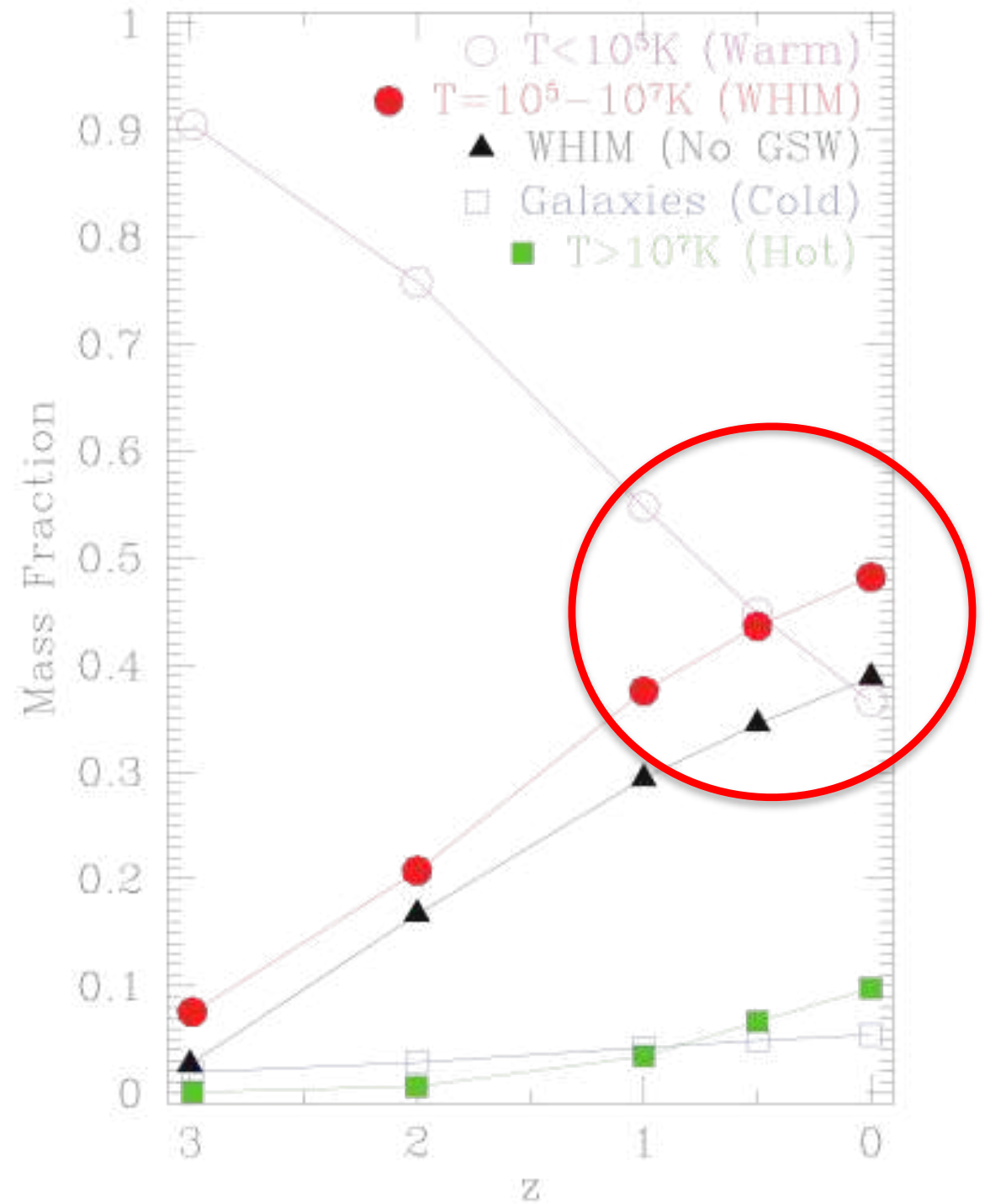


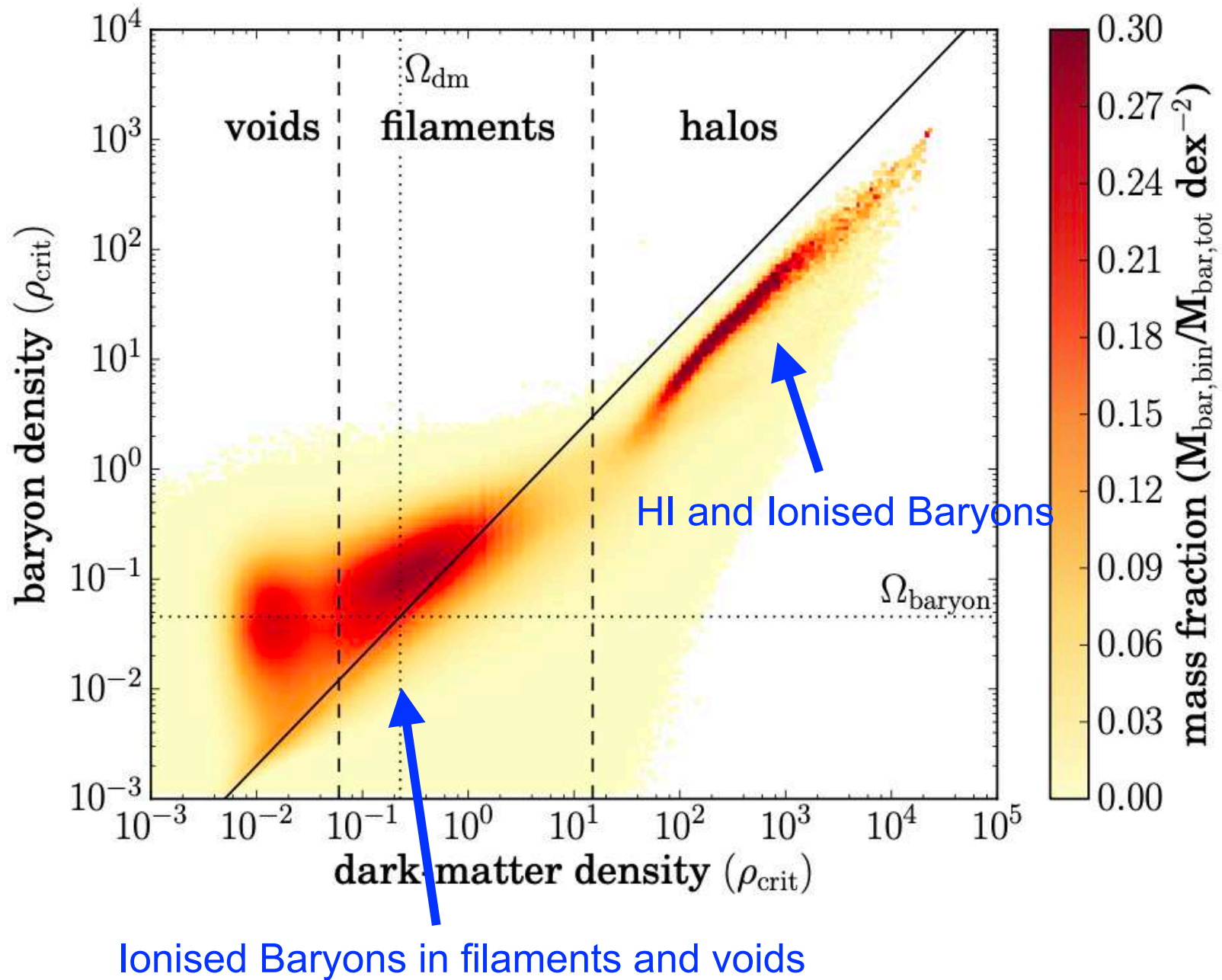
Collaborators: R. Battye, D. Contreras, C. Dickinson, C. Hernandez-Monteagudo, G. Hinshaw, A. Hojjati, Y.-C. Li, I. McCarthy, K. Moodley, M. Remazeilles, D. Scott, L. Staveley-Smith, H. Tanimura, D. Tramonte, L. Van Waerbeke, J. Zuntz, & Planck team & MeerKAT team

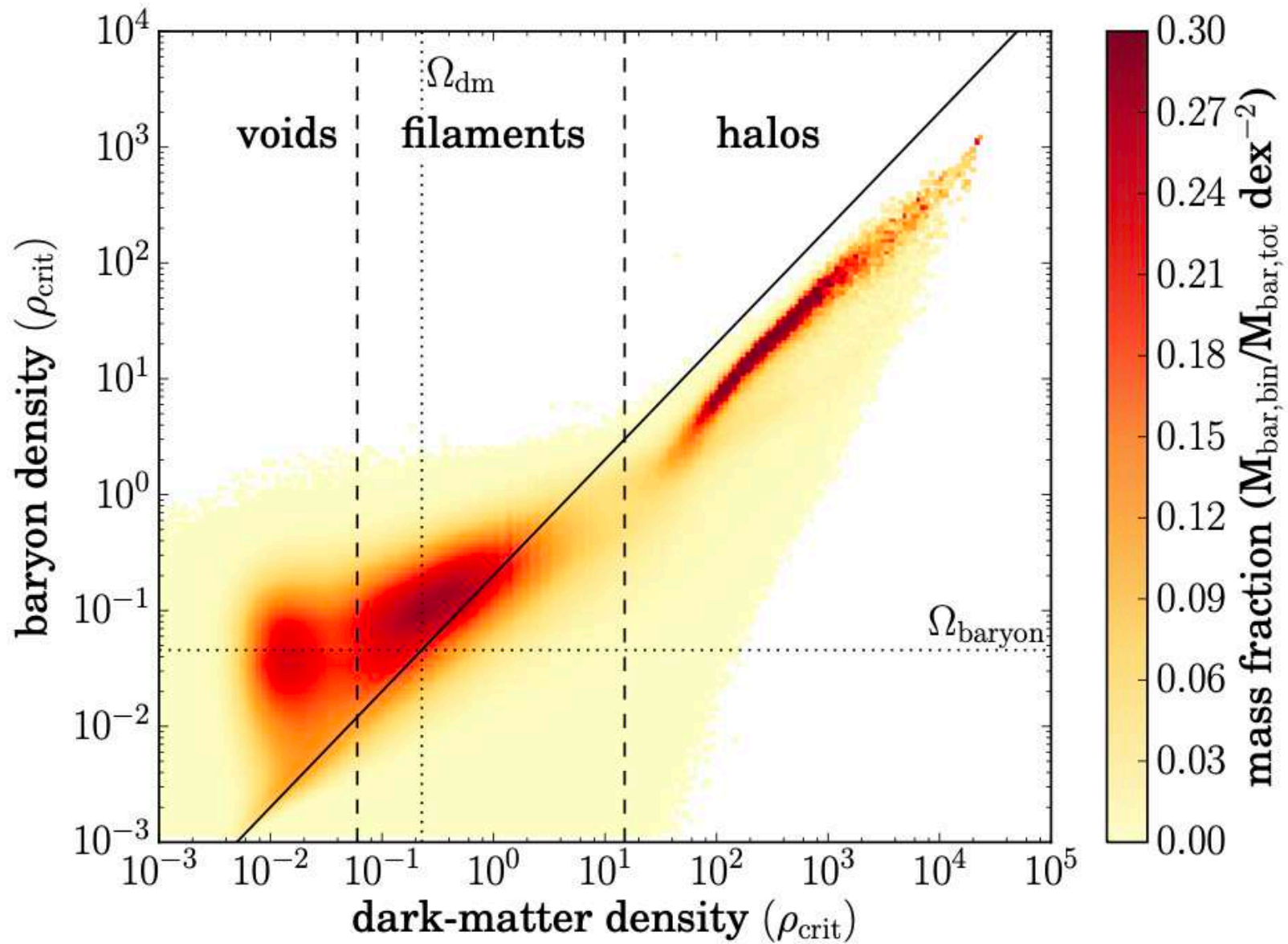


Cen and Ostriker 2006

X-ray:  $\sim n_e^2(r)$







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*

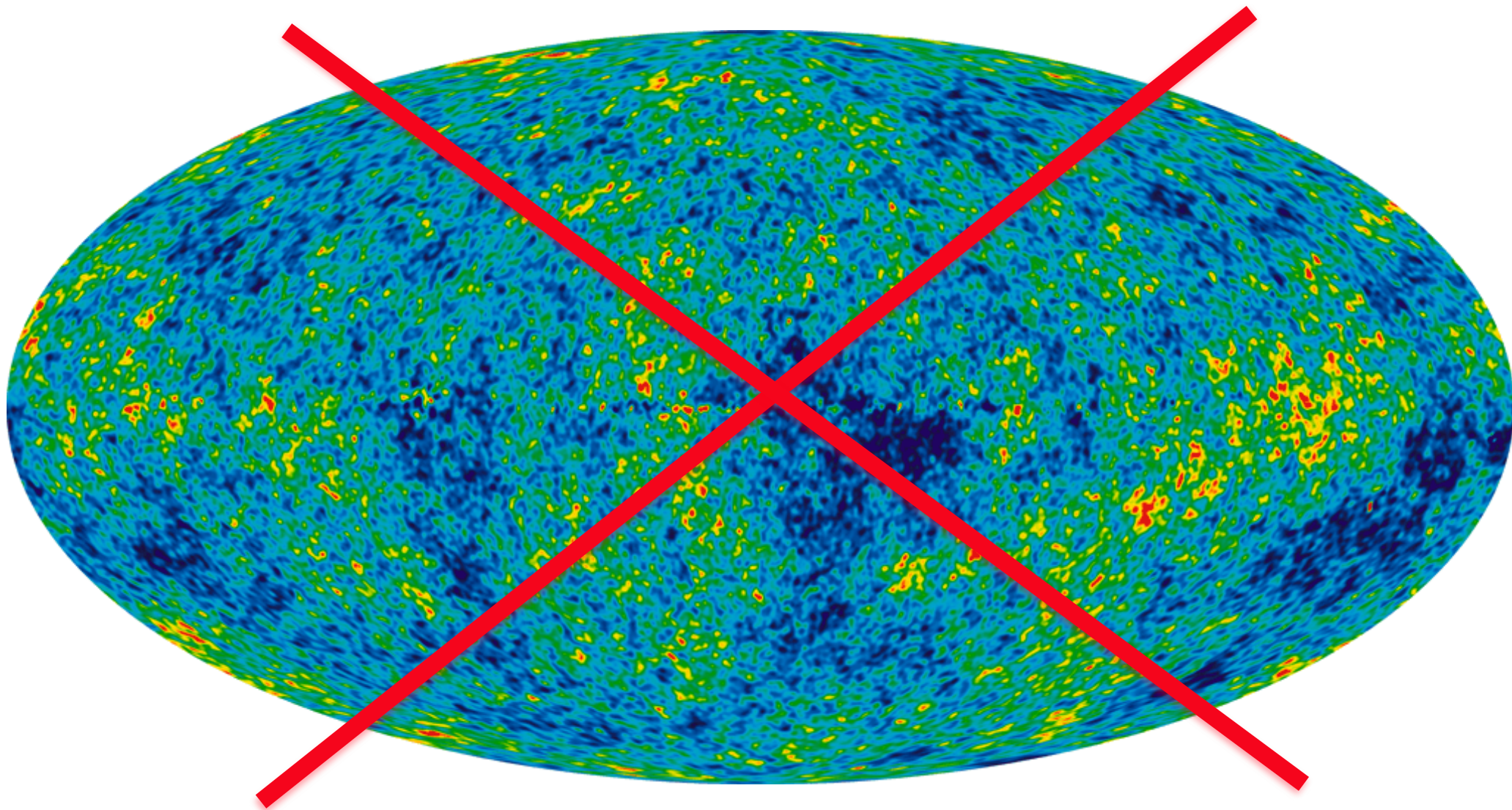
Thermal SZ maps

X

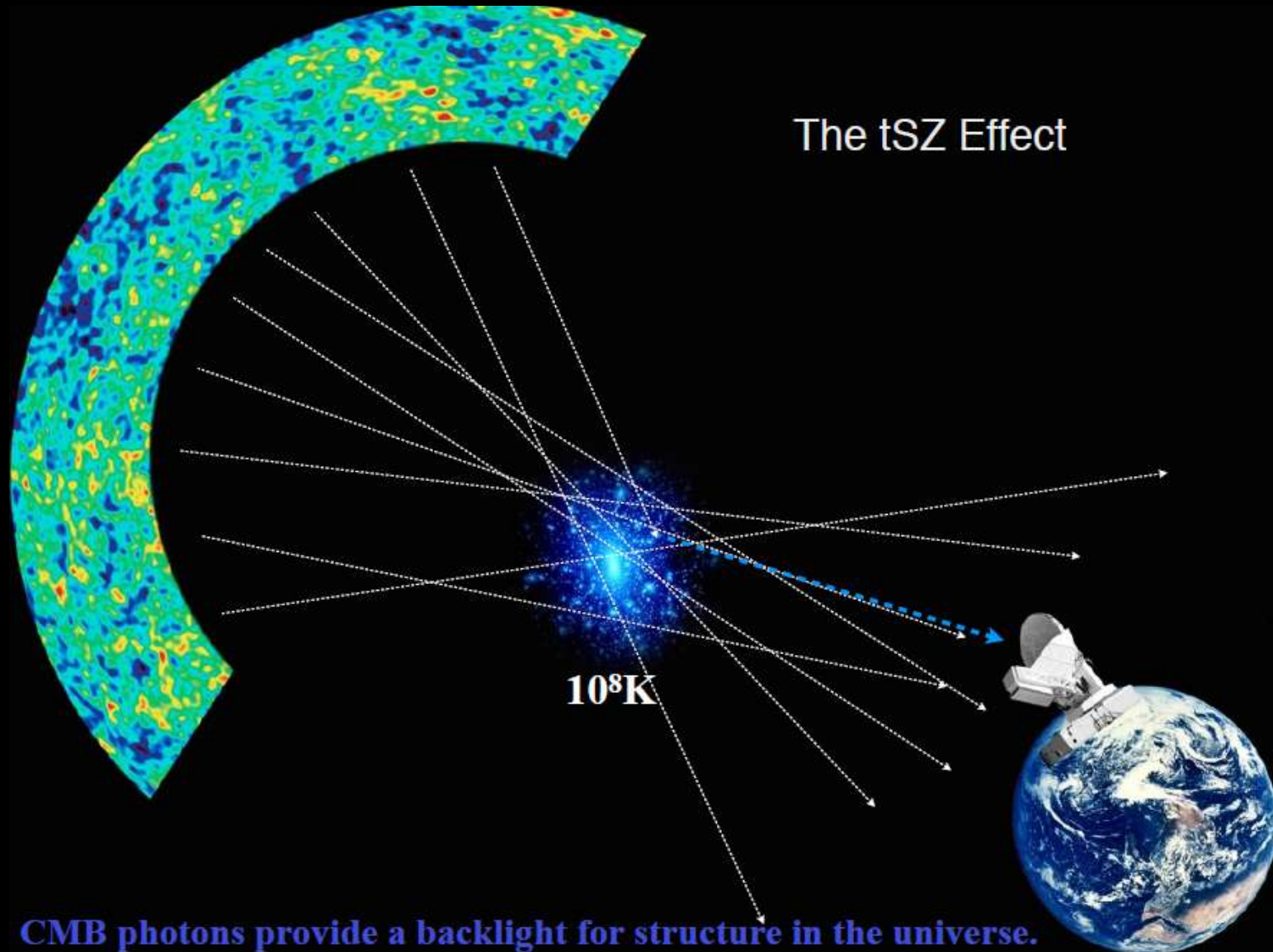
Cosmic Voids

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

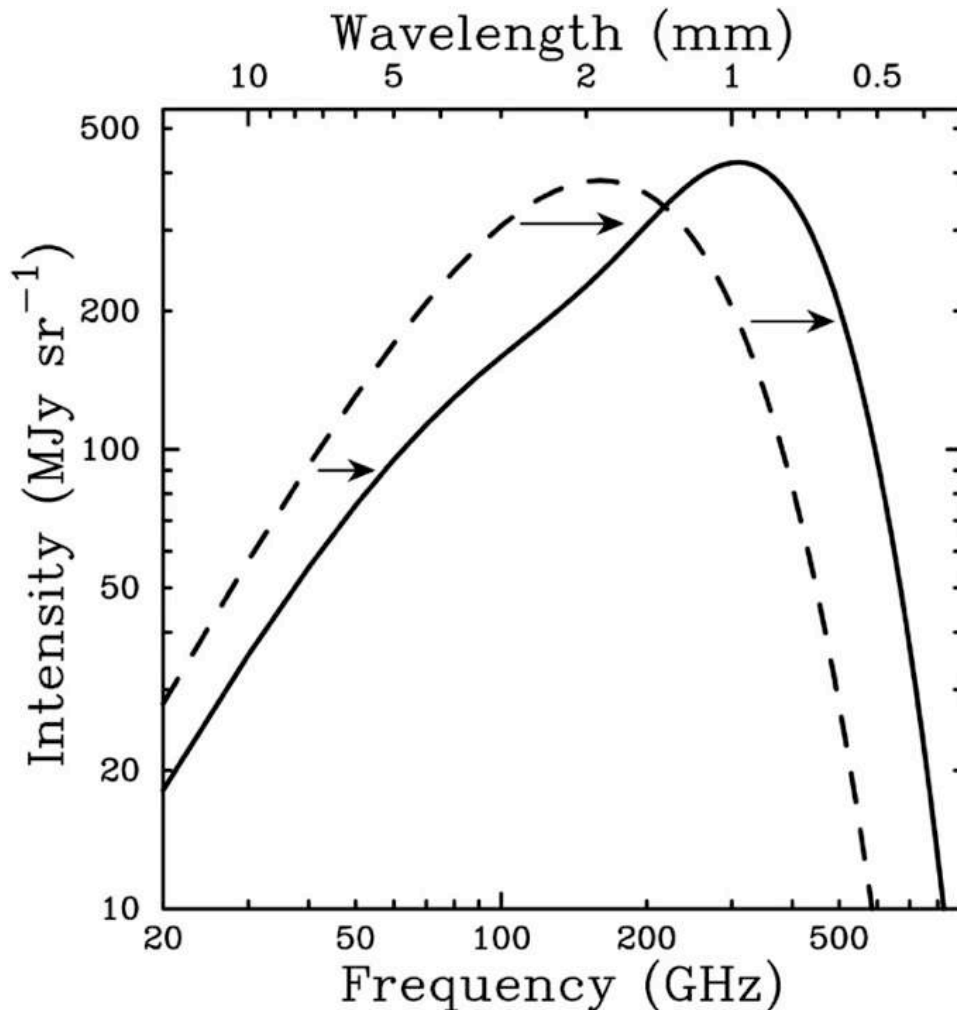




# The thermal Sunyaev-Zeldovich effect



Thermal Sunyaev-Zeldovich effect (tSZ):



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

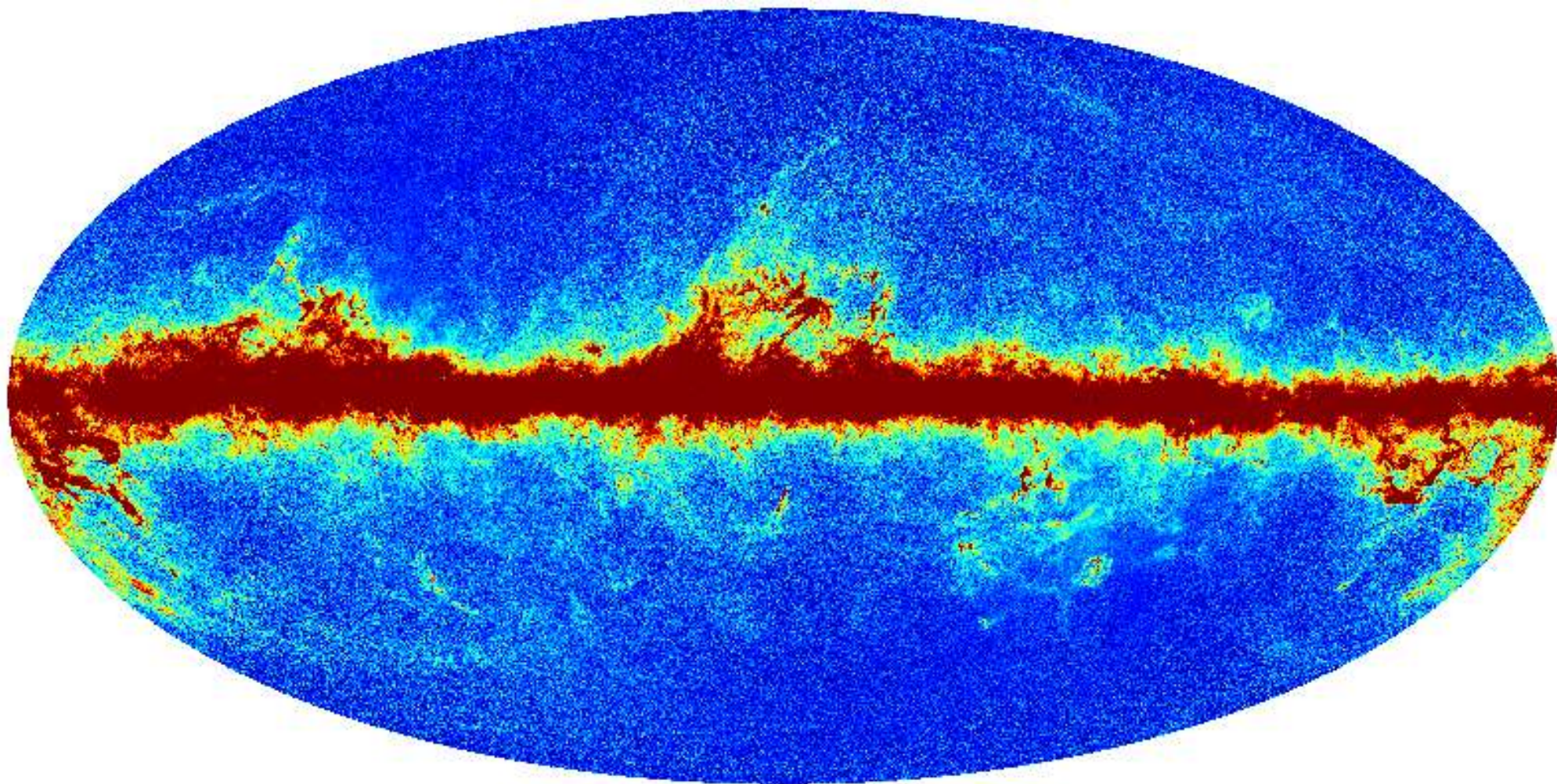
$$g_\nu \equiv (\eta(e^\eta + 1)/(e^\eta - 1)) - 4$$

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

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



# Planck SZ y map, version E



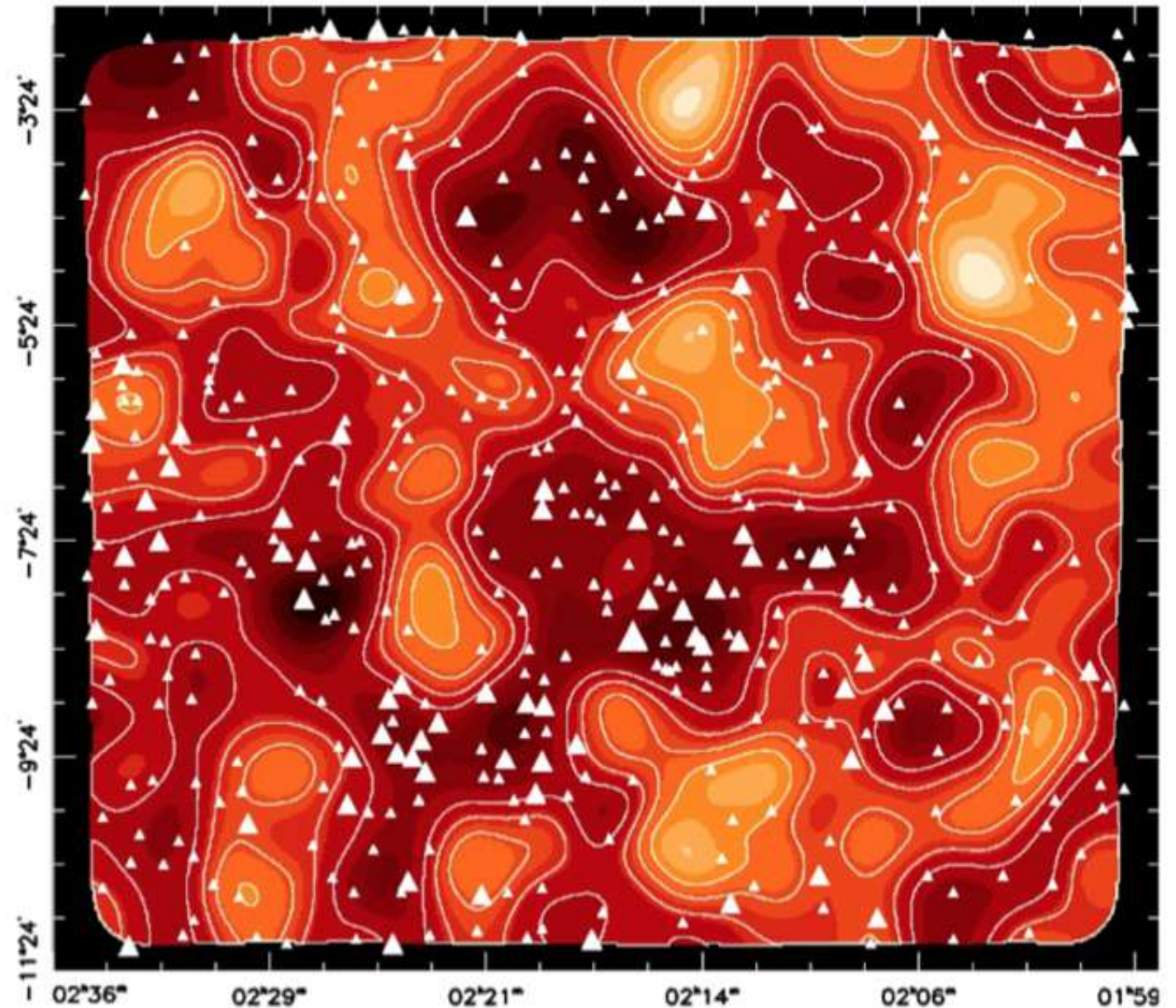
$y=0$    $10^{-4}$

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



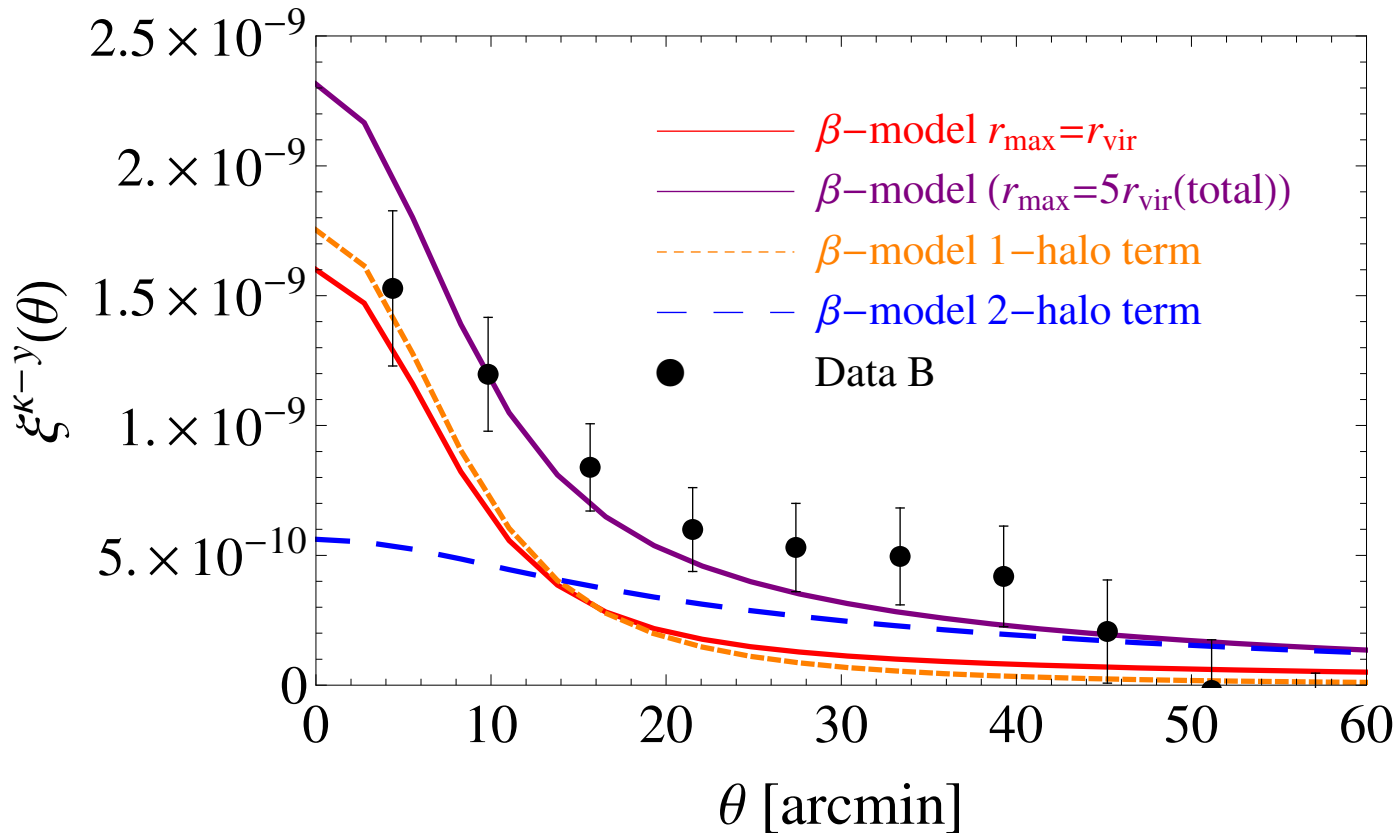
# CFHT mass map:

154 deg<sup>2</sup> in 4 patches



*Van Waerbeke et al.,  
2014, MNRAS*

# Halo model:



Ma et al. fits a halo model to the observed correlation function. A  $\beta$  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*

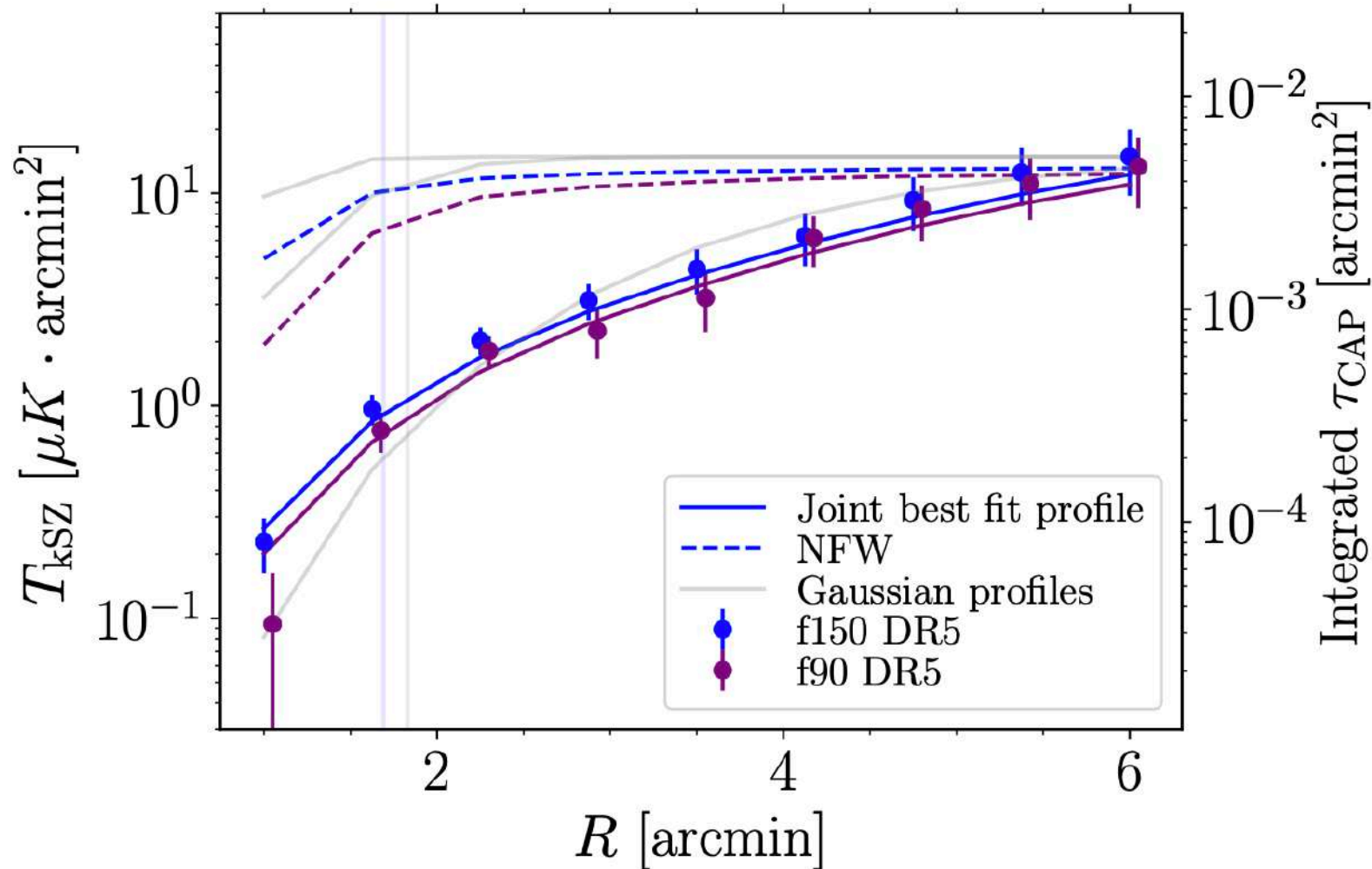
# CMASS kSZ profile

Comoving radius [Mpc/h] at  $z=0.55$

0.83

1.67

2.5



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



	$10^{12} M_{\odot} - 10^{14} M_{\odot}$	$10^{14} M_{\odot} - 10^{16} M_{\odot}$
$(0.01-1) r_{\text{vir}}$	26%	28%
$(1-100) r_{\text{vir}}$	14%	32%

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



$$T_e = 10^5 - 10^7 \text{ K}$$

**Thermal SZ maps**

**X**

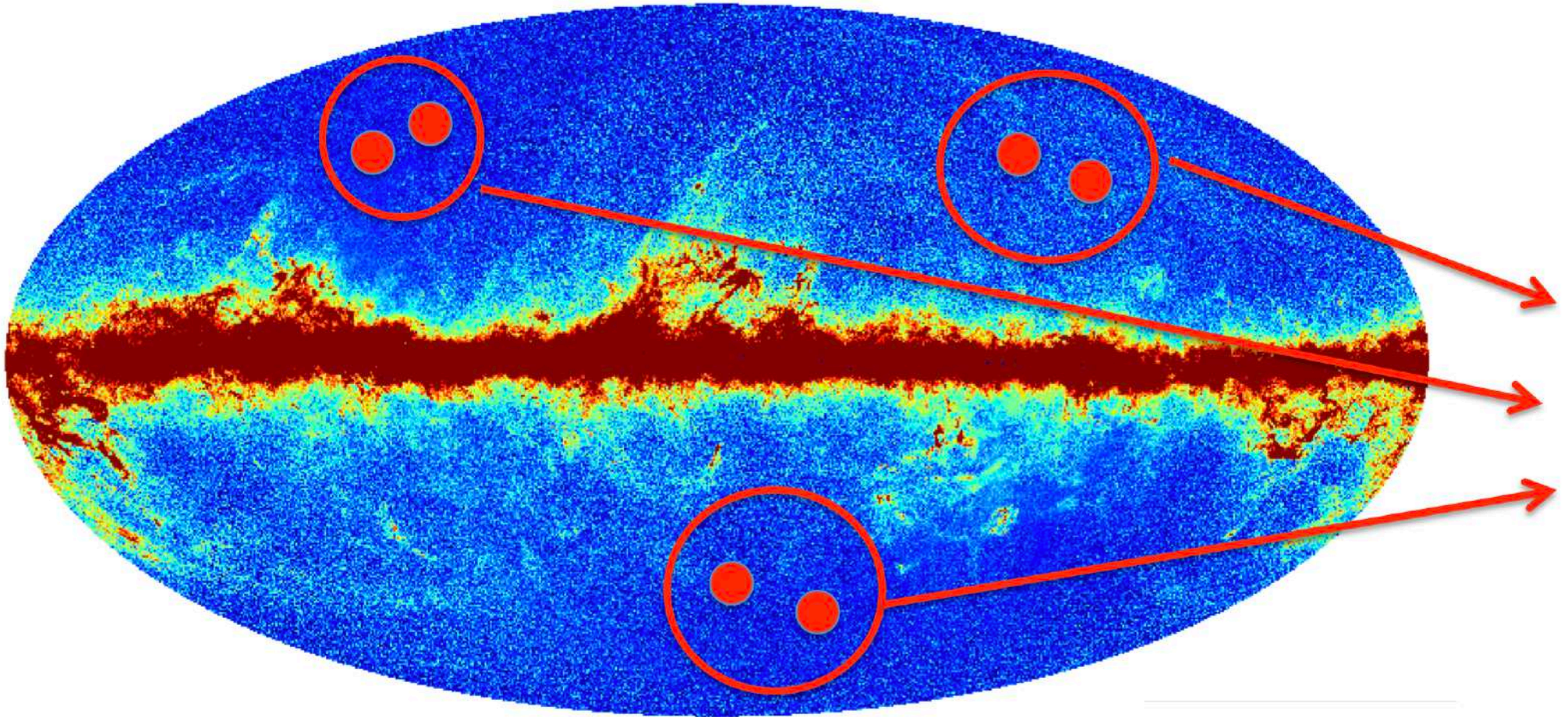
**Luminous red galaxies**

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

# Selecting LRG/SDSS pairs:

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

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

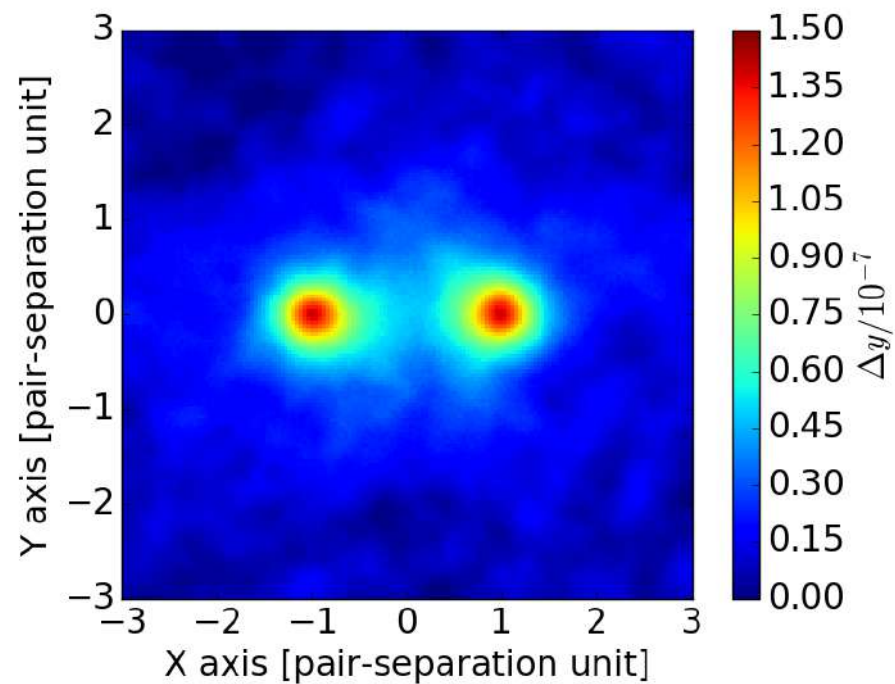


Squeeze

Stretch

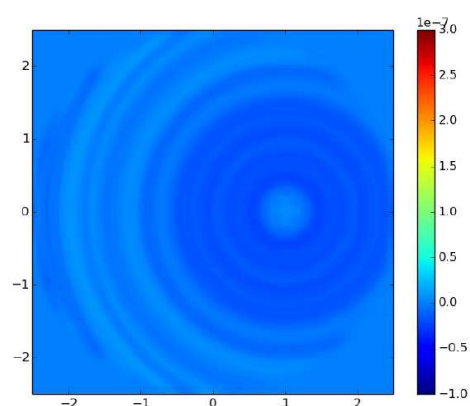
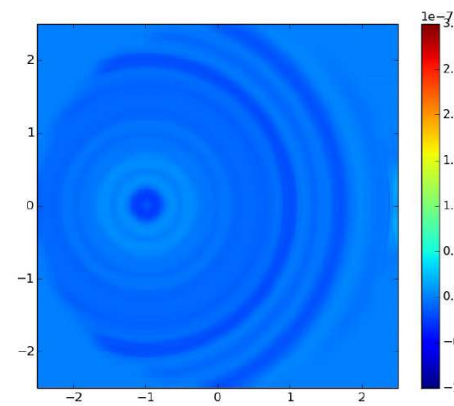
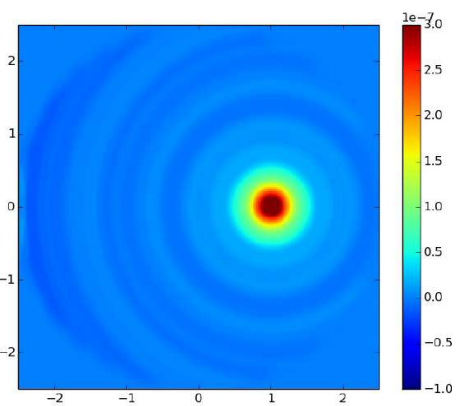
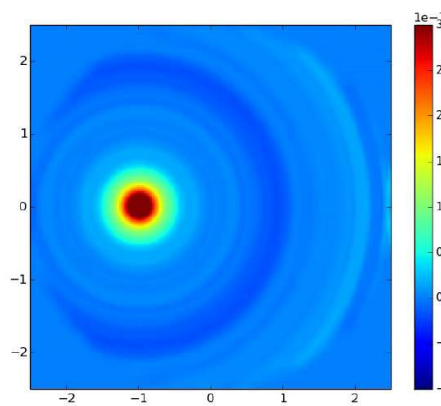
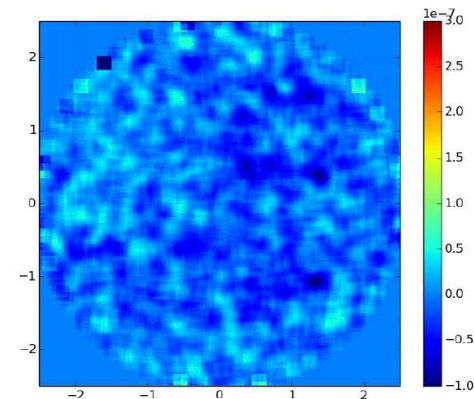
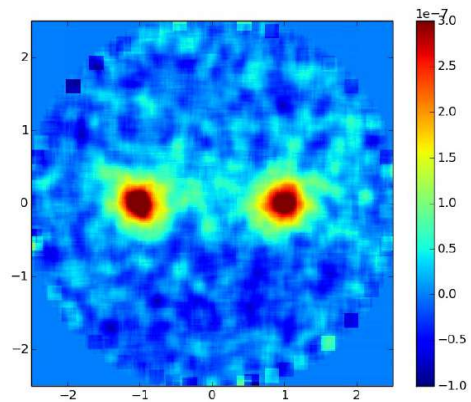
Uniform the sizes

stack

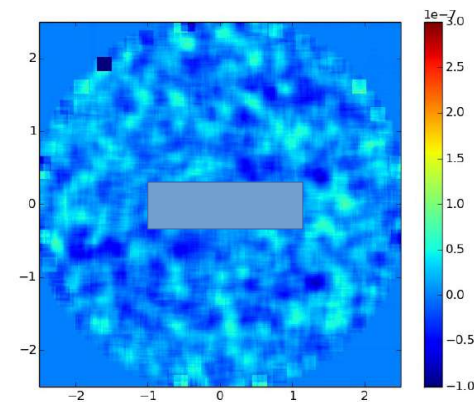
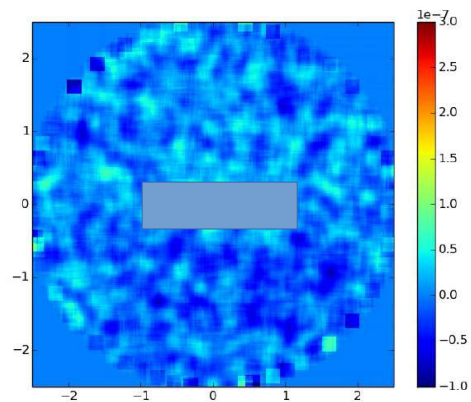


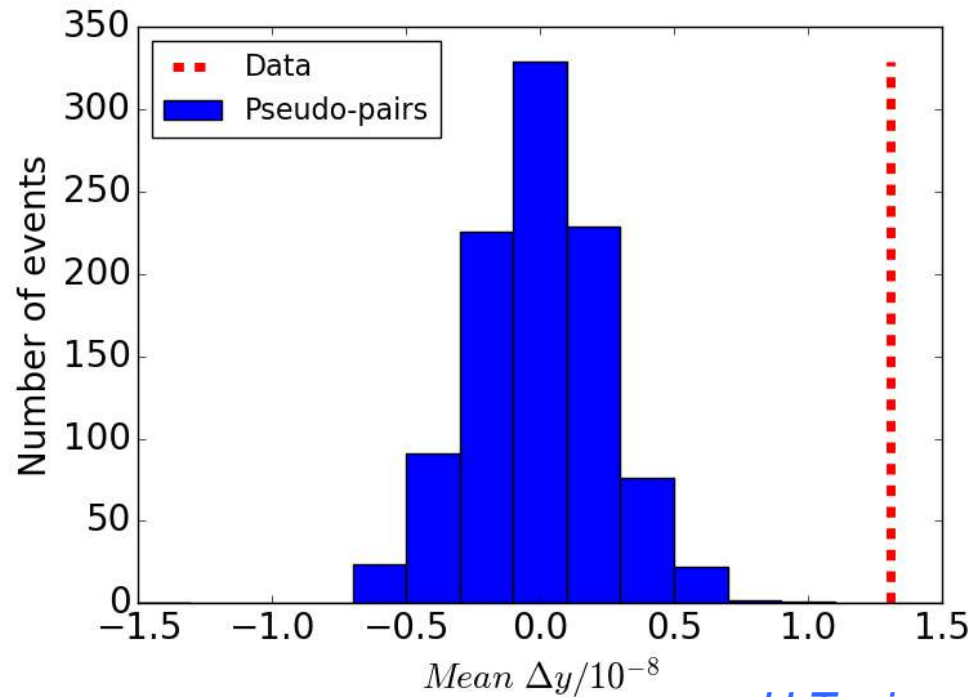
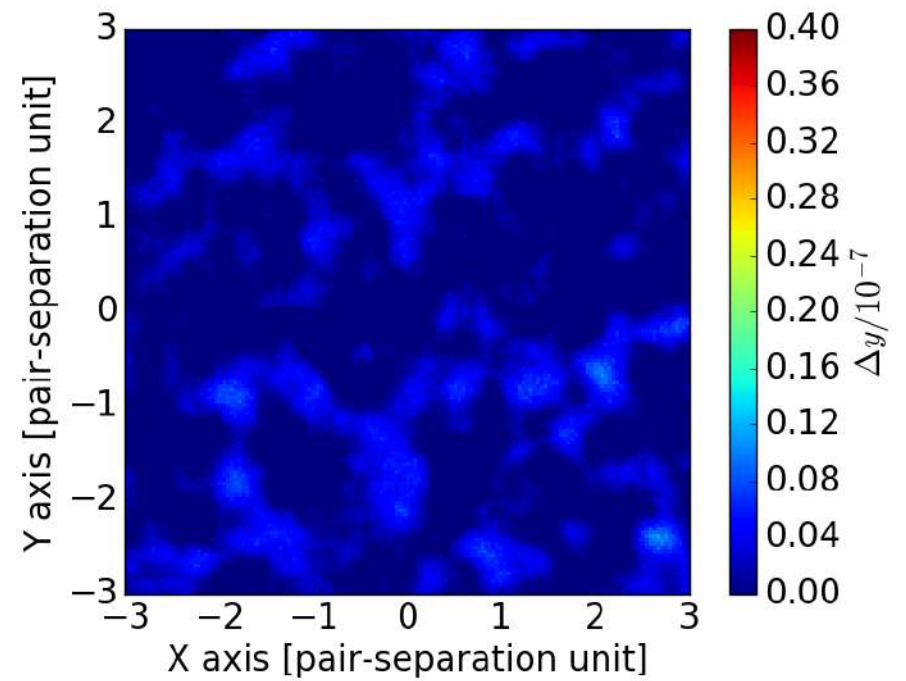
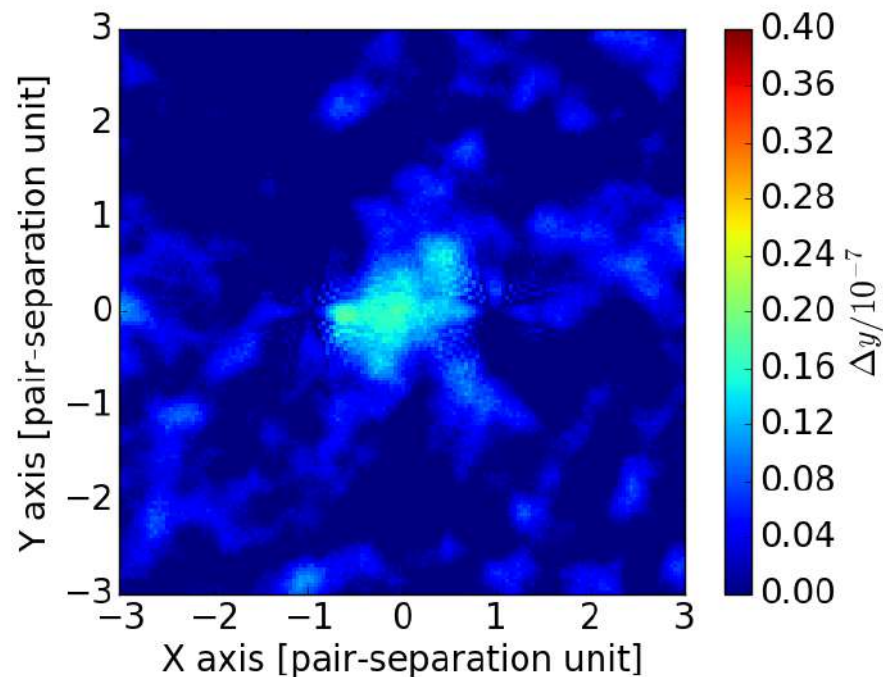


Stacked



LRG SZ  
Subtracted





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

$5.3\sigma$

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

$$n_e = \bar{n}_{e,i} (1 + \delta)$$

$$\bar{n}_{e,i} = \frac{\chi \rho_b(z)}{\mu_e m_p} \quad \chi = \frac{1 - Y_p(1 - N_{\text{He}}/2)}{1 - Y_p/2}$$



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

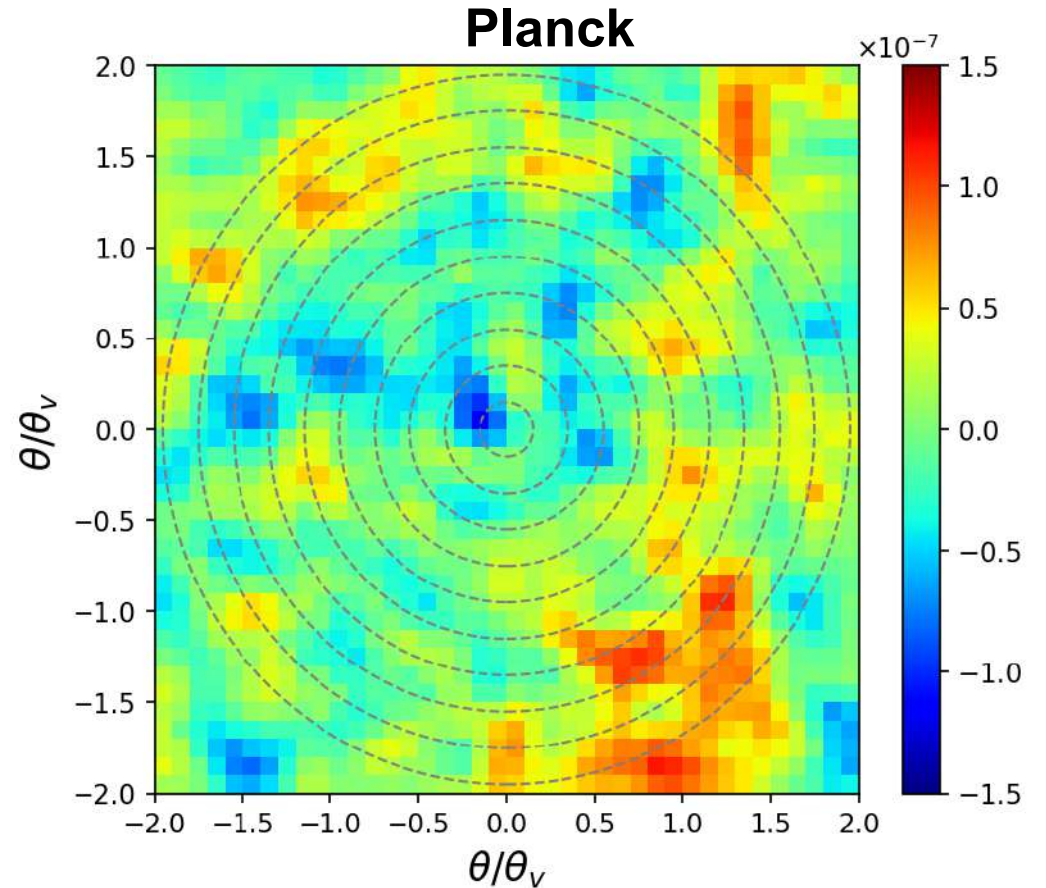
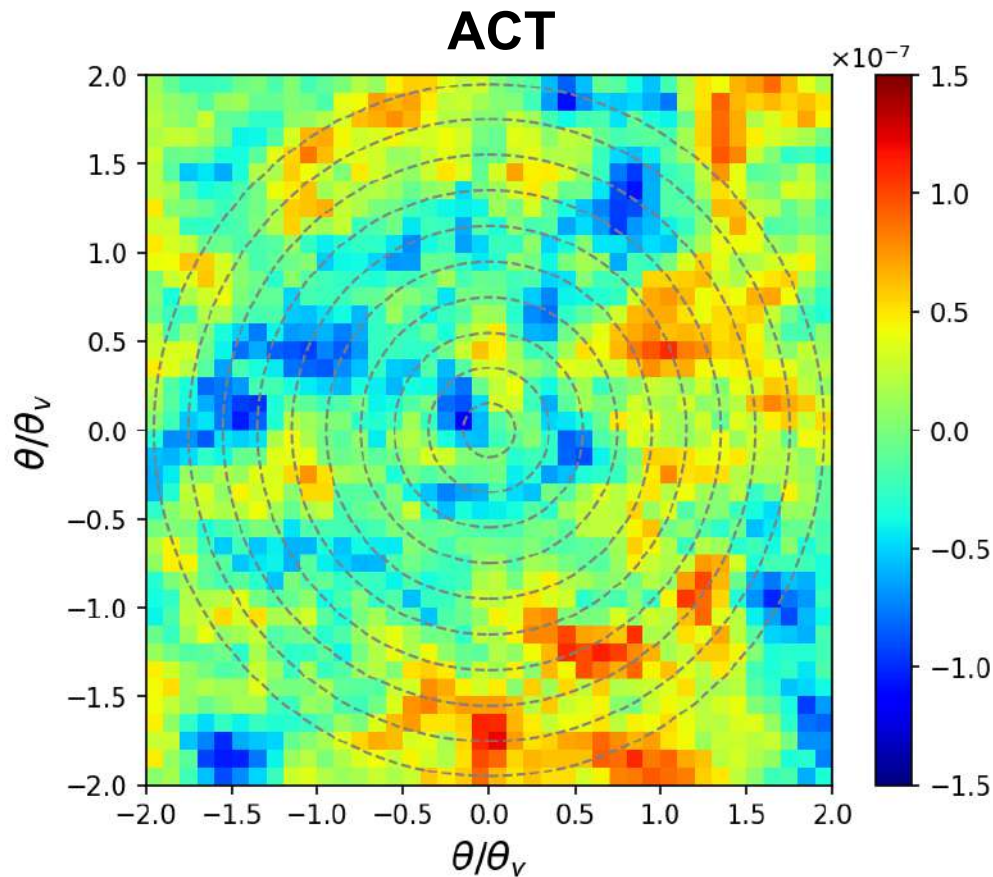
# Cosmic voids stacking

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

Voids: 97,090

Mean  $z \simeq 0.32$  (BOSS DR12)

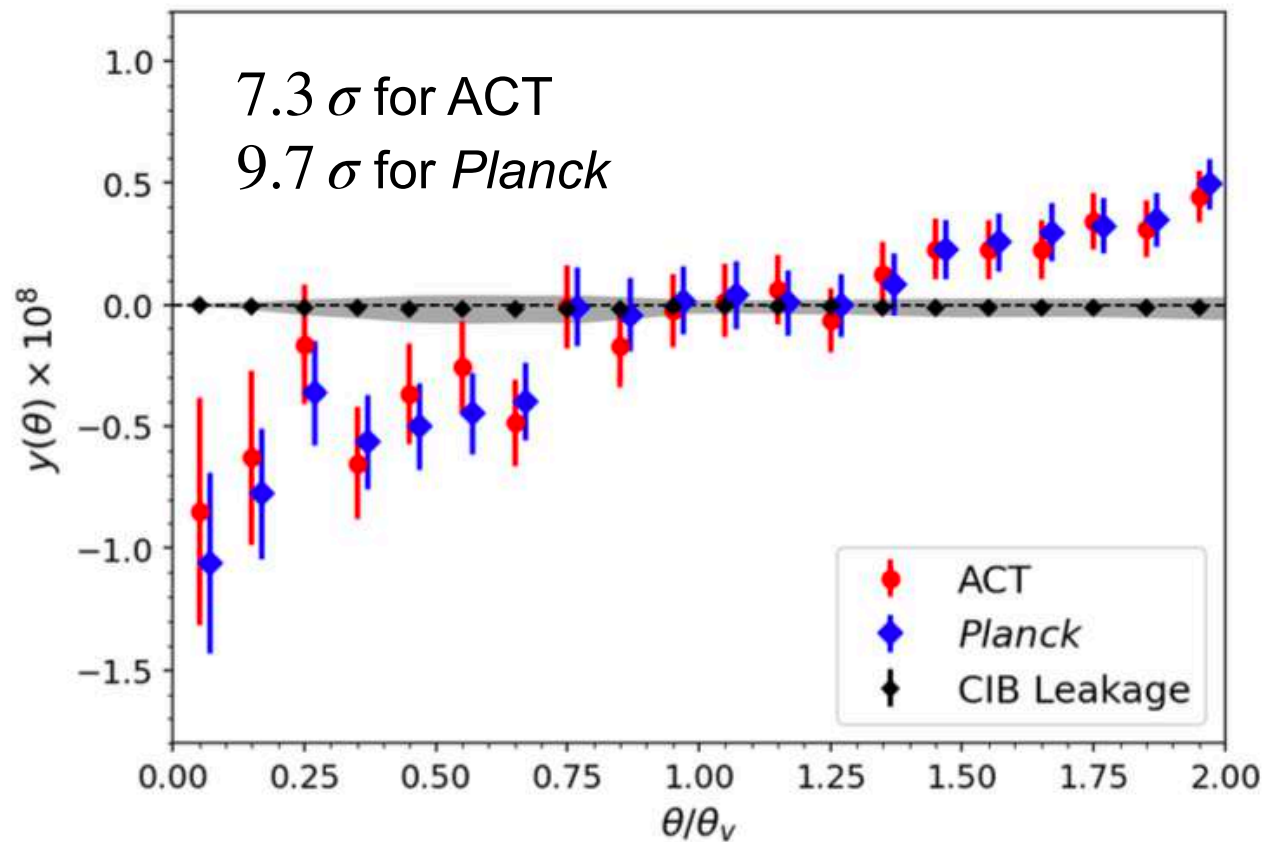
Mean radius  $13.6 h^{-1}\text{Mpc}$





# Cosmic voids stacking

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

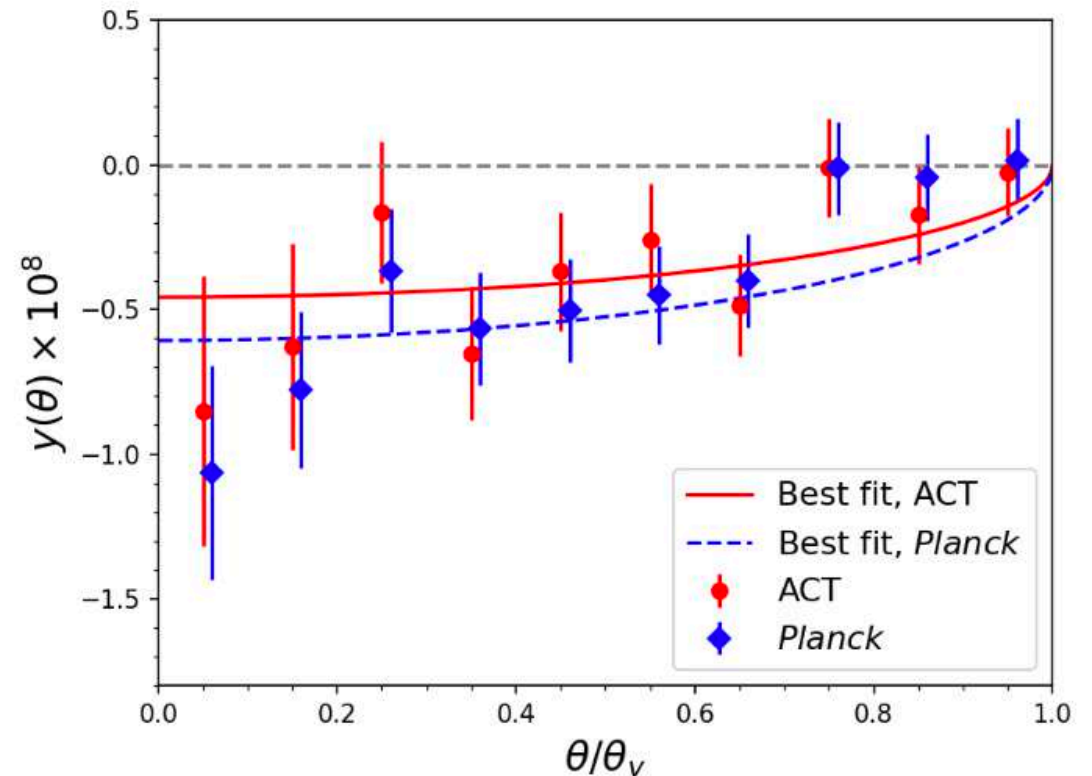


Modelling:

$$n_e = \bar{n}_e(1 + \delta_v)$$

$$T_e = \bar{T}_e$$

$$\left(-\delta_v \frac{T_e}{10^5 \text{ K}}\right) = \begin{cases} 6.5 \pm 2.3 & \text{ACT,} \\ 8.6 \pm 2.1 & \text{Planck,} \end{cases}$$



$$\begin{aligned} \frac{n_e^v}{\bar{n}_e} &= 1 + \delta_v \\ &= 1 - \frac{(-\delta_v(T_e/10^5 \text{ K}))}{(T_e/10^5 \text{ K})} \\ &\ll 1 - \frac{1}{10} \left(-\delta_v \frac{T_e}{10^5 \text{ K}}\right) \\ &\ll \begin{cases} 0.73 & 95\% \text{ C.L. for ACT,} \\ 0.49 & 95\% \text{ C.L. for } \textit{Planck}, \end{cases} \end{aligned}$$

# Summary

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

SZ data	LSS tracers	Results
thermal SZ	weak lensing	Gas extends out to $5r_{\text{vir}}$ , with temperature for $M = 10^{12} - 10^{16} M_{\odot}$ consistent with simulation
thermal SZ	Pairs of LRGs	Gas associated with filament is detected @ $5.3\sigma$ $y = (1.31 \pm 0.25) \times 10^{-8} \longrightarrow T_{\text{filament}} \leq 10^7$ K
thermal SZ	SDSS Voids	The void significance is detected at $7.3\sigma$ and $9.7\sigma$ 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