Have we found all missing baryons in the Universe?

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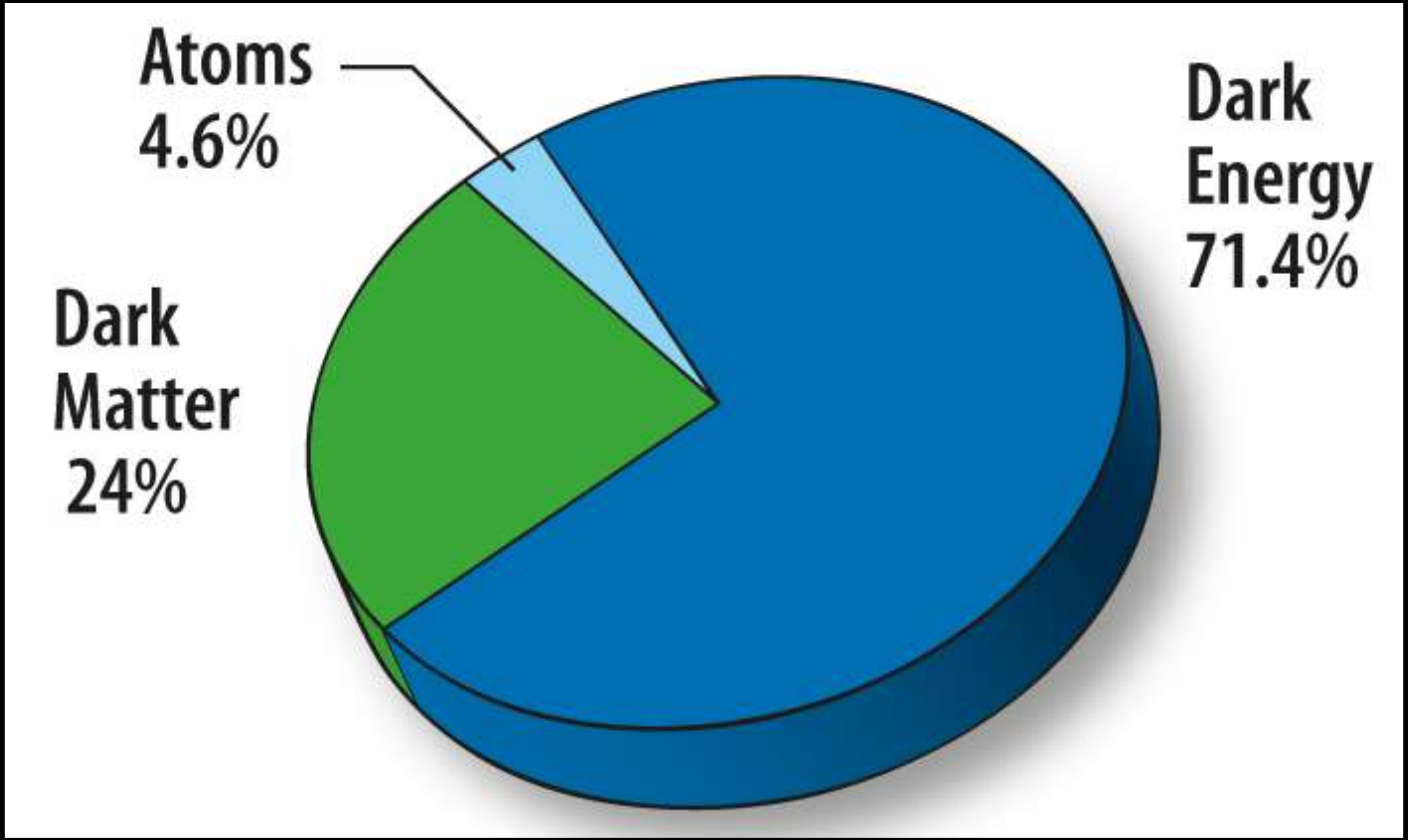
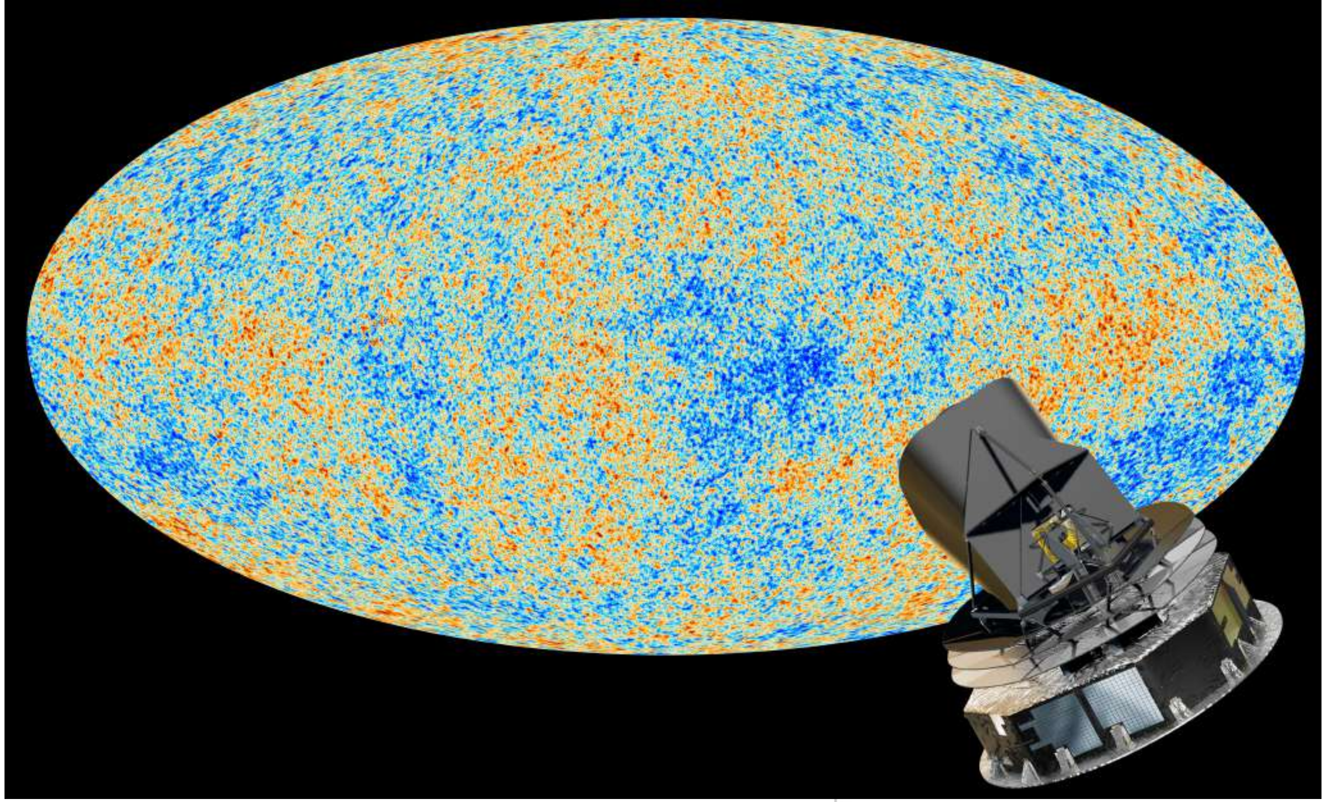
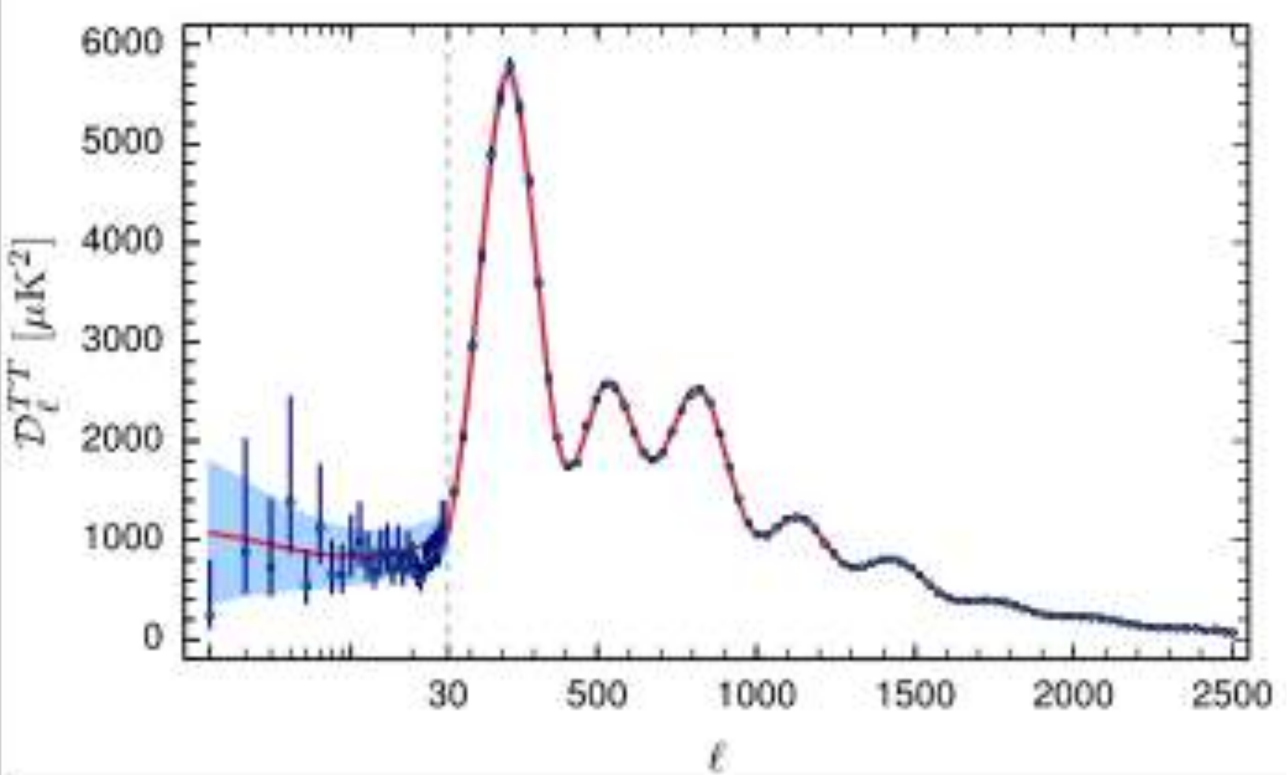


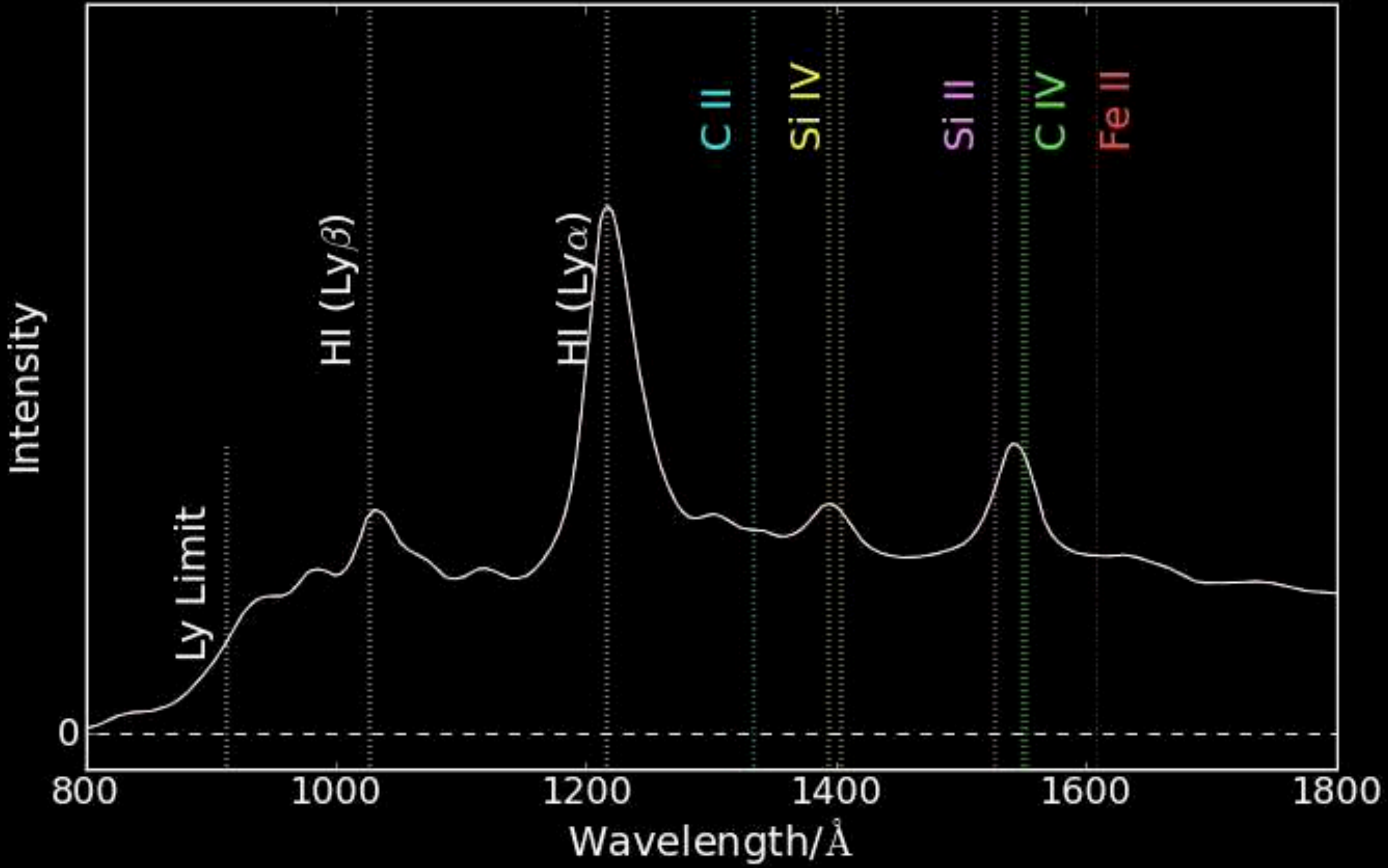
Collaborators: R. Battye, D. Contreras, C. Dickinson, C. Hernandez-Monteagudo, G. Hinshaw, A. Hojjati, Y.-C. Li, I. McCarthy, K. Moodley, M. Remazeilles, D. Scott, L. Staveley-Smith, H. Tanimura, D. Tramonte, L. Van Waerbeke, J. Zuntz, & Planck team & MeerKAT team



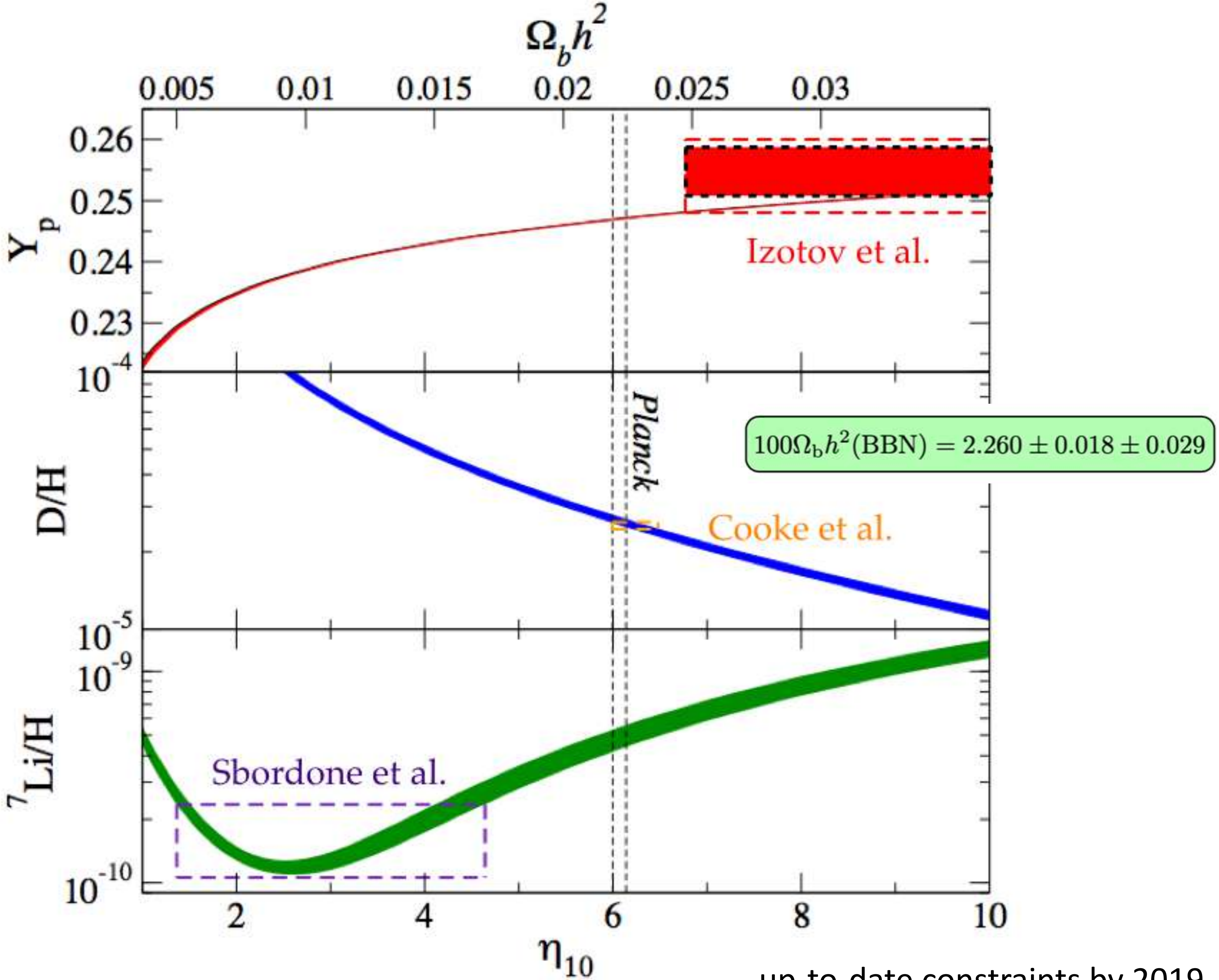


$$\boxed{100\Omega_{\rm b}h^2(\mathrm{CMB}) = 2.226 \pm 0.023}$$

Planck collaboration 2018 (including **YZM**)



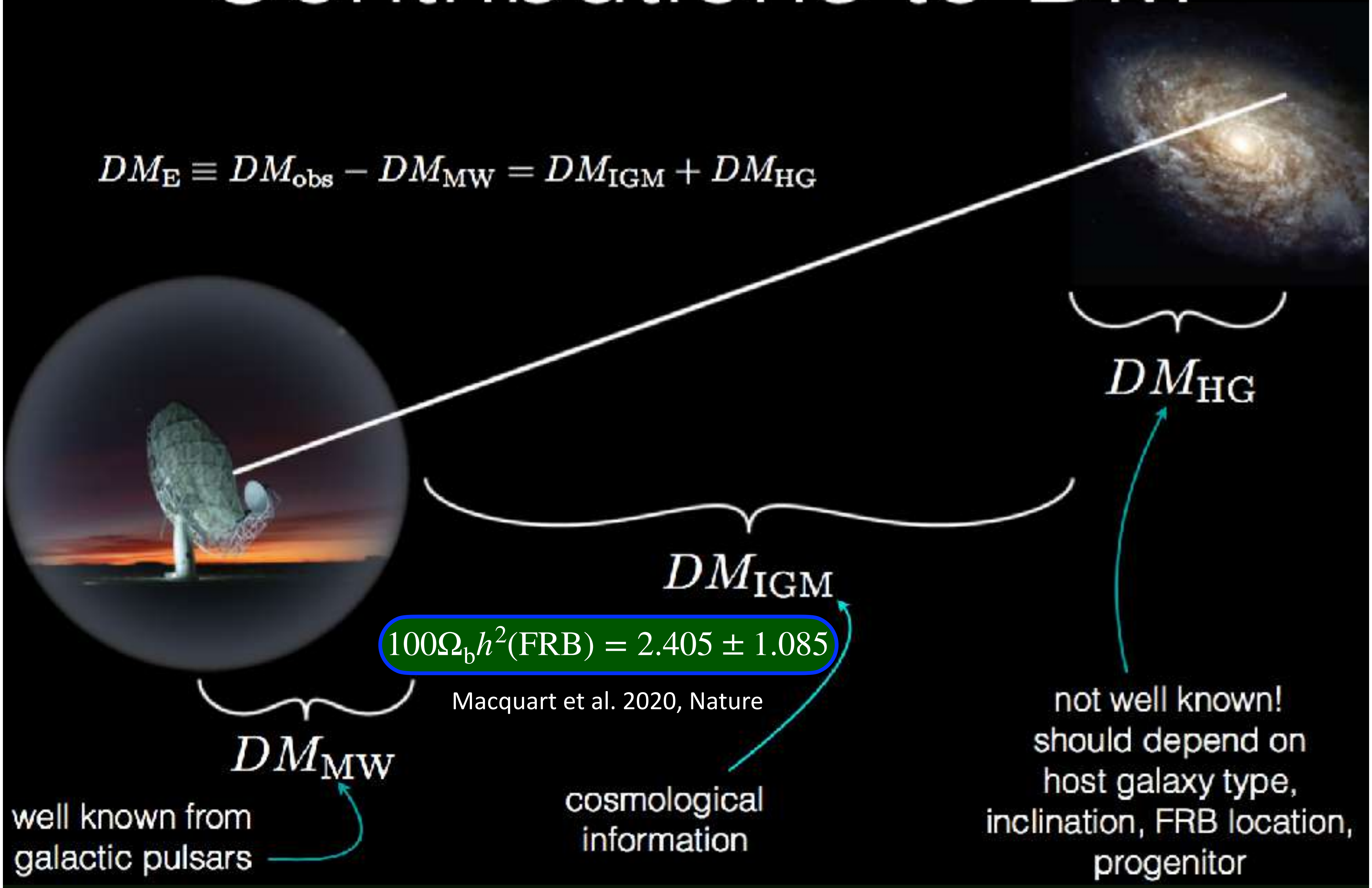
Intensity
0
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II
800
1000
1200
1400
1600
1800
Wavelength/Å



$100\Omega_b h^2(\text{BBN}) = 2.260 \pm 0.018 \pm 0.029$

up-to-date constraints by 2019

Contributions to DM



$$DM_{\mathrm{E}} \equiv DM_{\mathrm{obs}} - DM_{\mathrm{MW}} = DM_{\mathrm{IGM}} + DM_{\mathrm{HG}}$$

DM_{HG}

DM_{IGM}

DM_{MW}

$$\boxed{100\Omega_{\mathrm{b}}h^2(\mathrm{FRB}) = 2.405 \pm 1.085}$$

Macquart et al. 2020, Nature

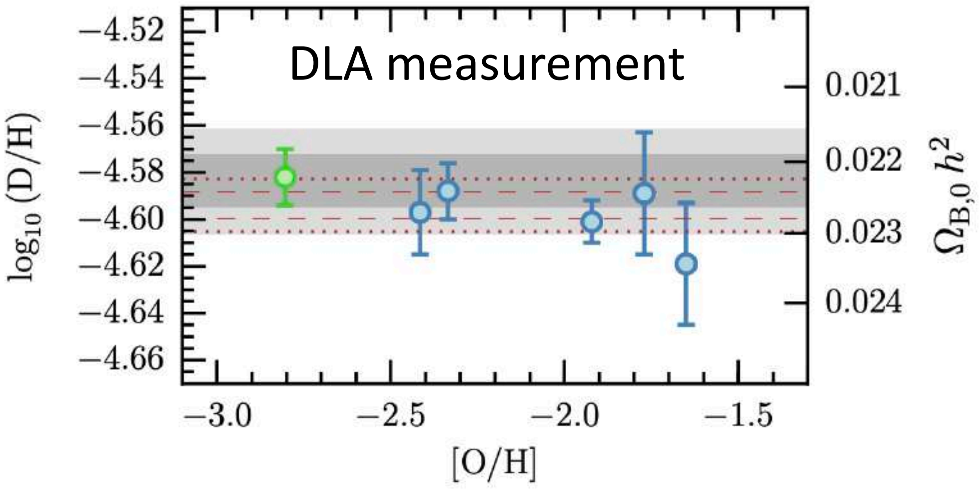
well known from
galactic pulsars

cosmological
information

not well known!
should depend on
host galaxy type,
inclination, FRB location,
progenitor

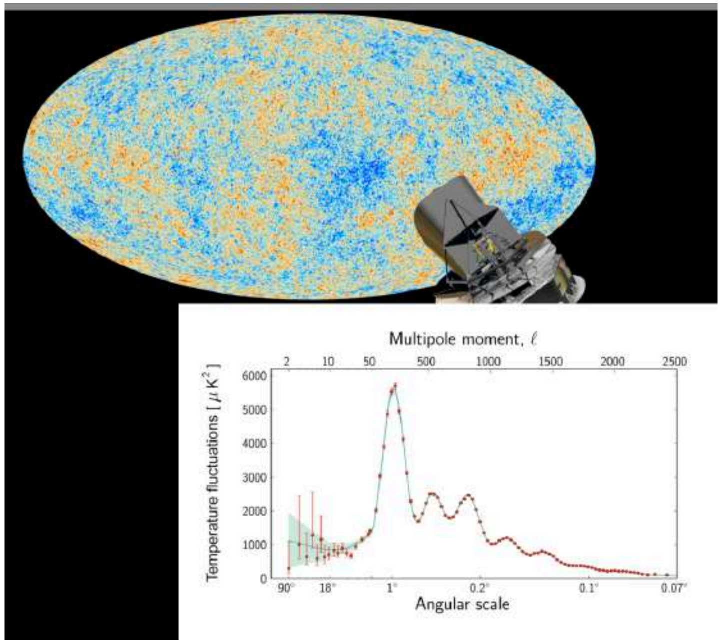
$$100\Omega_b h^2(\mathrm{BBN}) = 2.260 \pm 0.018 \pm 0.029$$

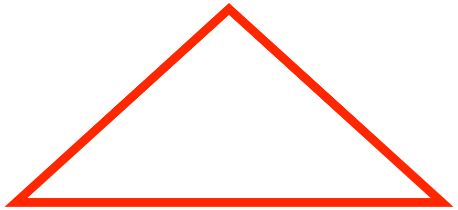
Cooke+ 2016



$$100\Omega_b h^2(\mathrm{CMB}) = 2.226 \pm 0.023$$

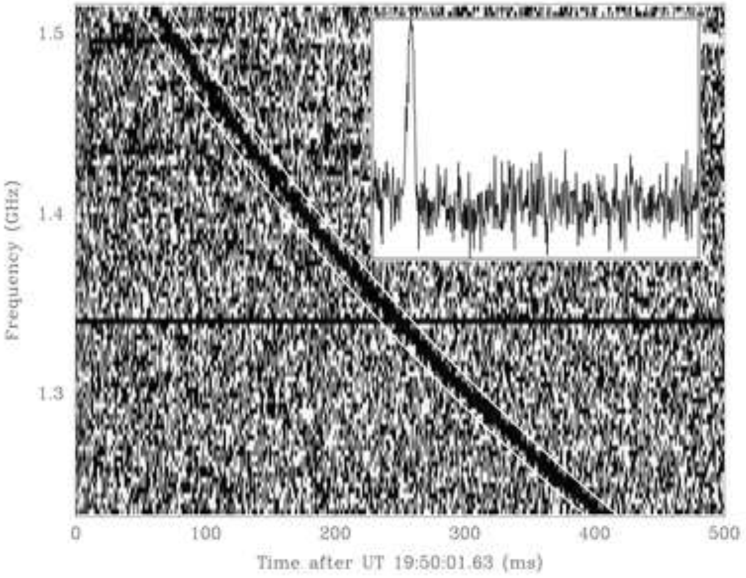
Planck collaboration 2018 (including **YZM**)





$$100\Omega_b h^2(\mathrm{FRB}) = 2.405 \pm 1.085$$

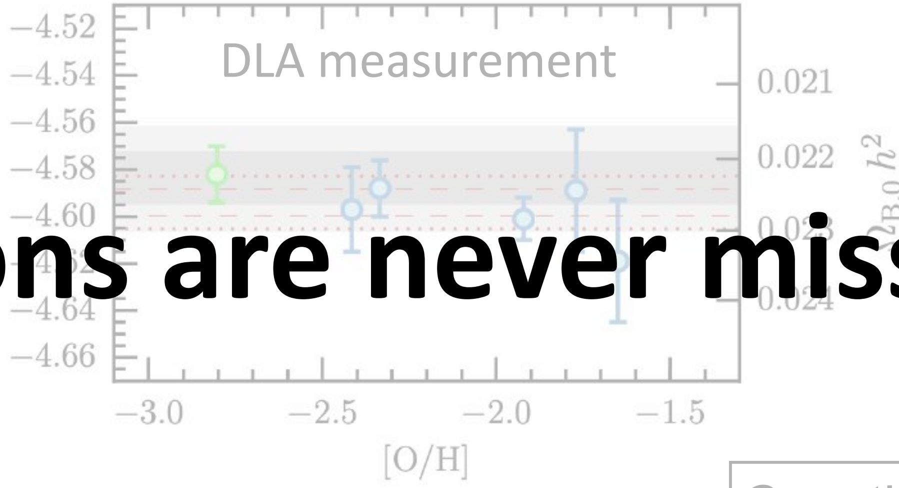
Macquart et al. 2020, Nature



Model parameter

$100\Omega_b h^2(\mathrm{BBN}) = 2.260 \pm 0.018 \pm 0.029$

Cooke+ 2016



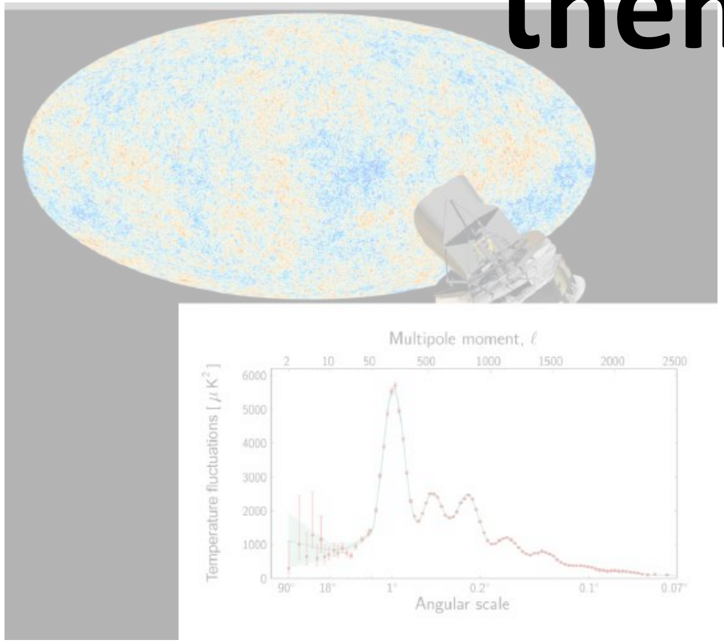
Baryons are never missing!

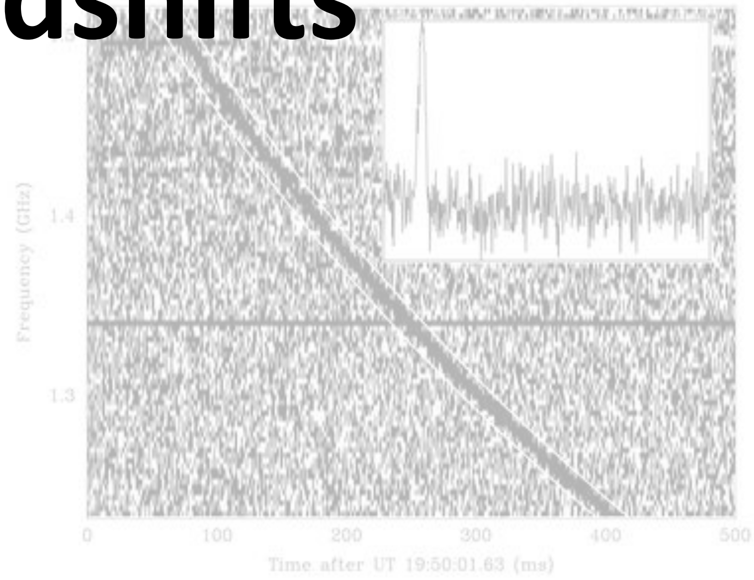
Counting from dispersion

We just haven’t counted enough of them at low redshifts

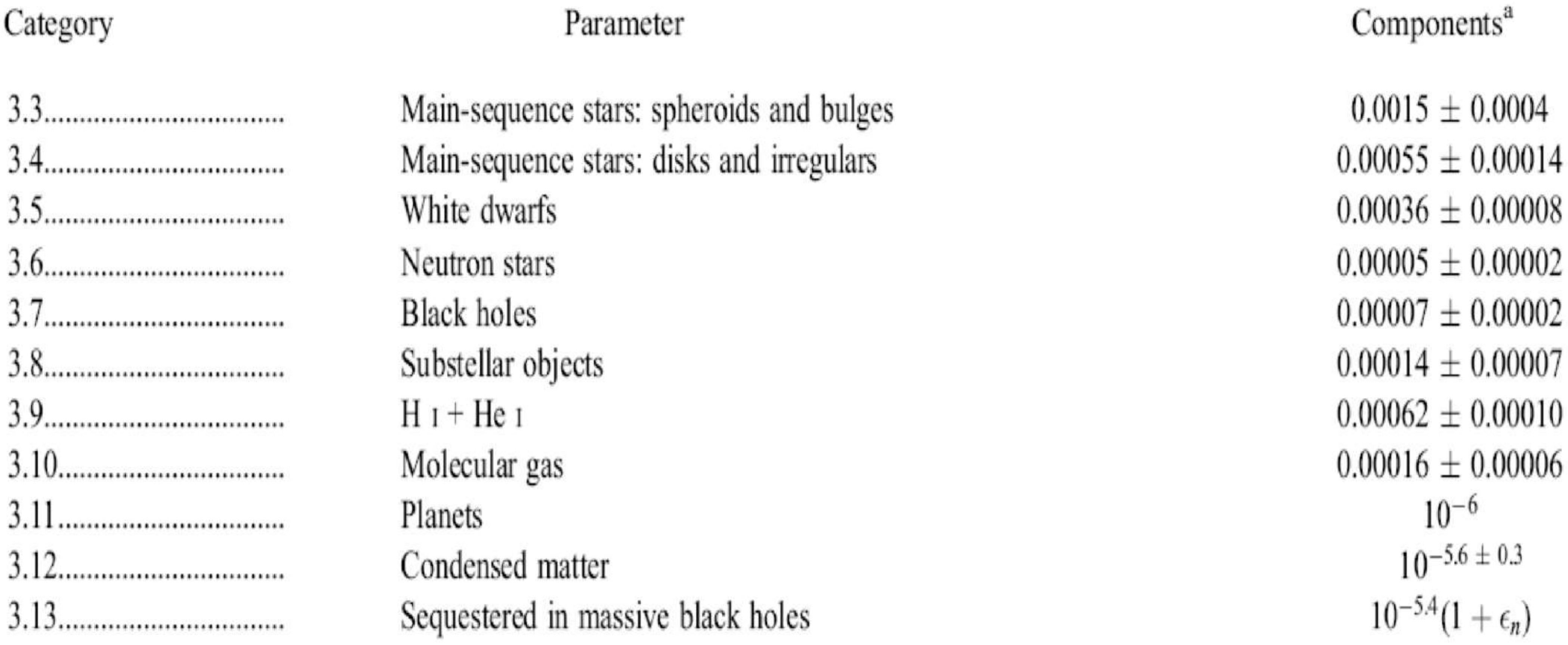
Planck collaboration 2018 (including YZM)

Macquart et al. 2020, Nature





Cosmic baryon inventory:



Category	Parameter	Components[a]
3.3	Main-sequence stars: spheroids and bulges	0.0015 ± 0.0004
3.4	Main-sequence stars: disks and irregulars	0.00055 ± 0.00014
3.5	White dwarfs	0.00036 ± 0.00008
3.6	Neutron stars	0.00005 ± 0.00002
3.7	Black holes	0.00007 ± 0.00002
3.8	Substellar objects	0.00014 ± 0.00007
3.9	H I + He I	0.00062 ± 0.00010
3.10	Molecular gas	0.00016 ± 0.00006
3.11	Planets	10^{-6}
3.12	Condensed matter	$10^{-5.6 \pm 0.3}$
3.13	Sequestered in massive black holes	$10^{-5.4}(1 + \epsilon_n)$

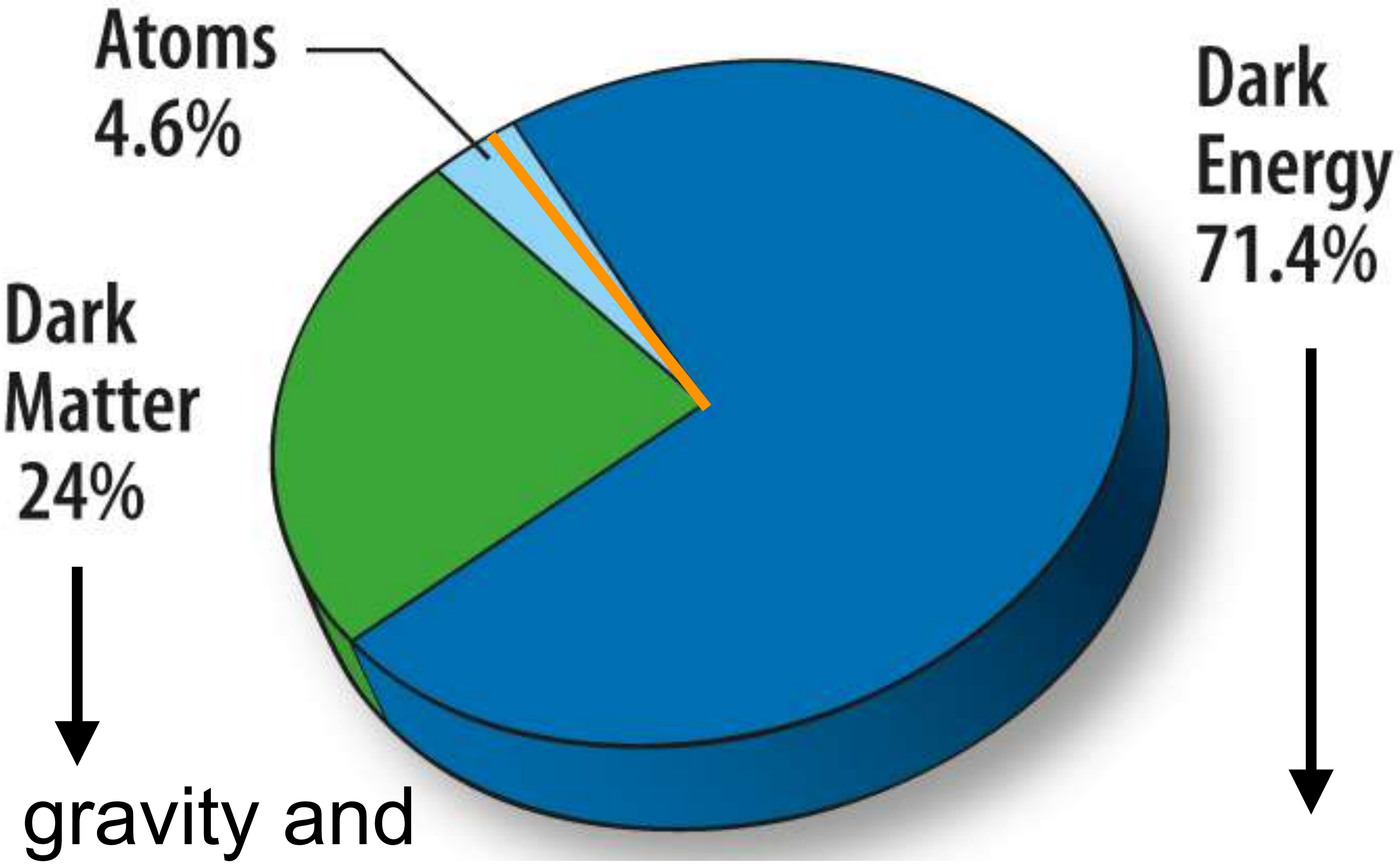
3.3+…+3.13: $\Omega_{b,g} = 0.0035$ =8% total baryon density

90% of baryons are in either intergalactic or intracluster medium

Fukugita, & Peebles 2004

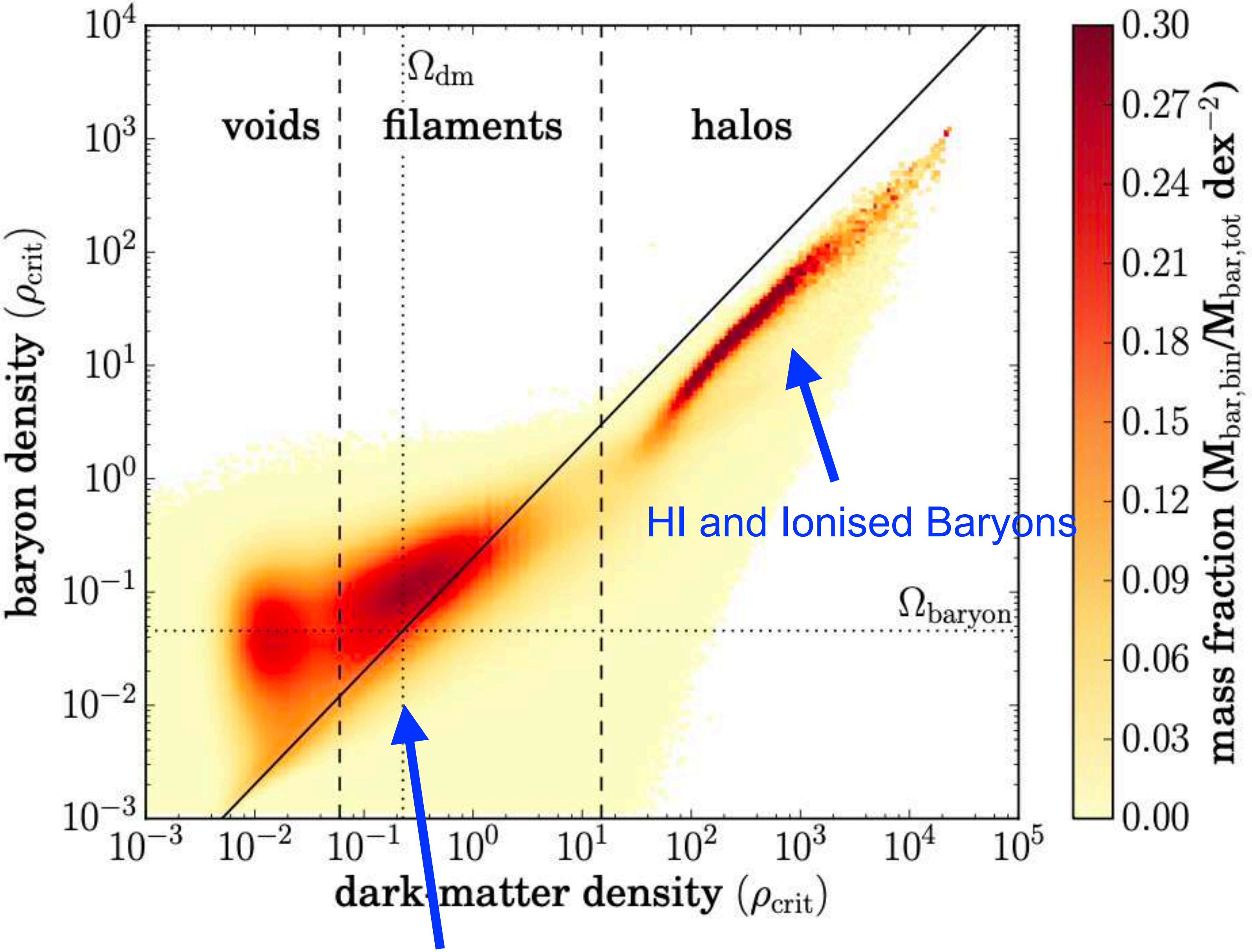
90% of atoms we know
its nature, but NOT locations

10% of the atoms we know its
nature and location



Only gravity and
nothing else

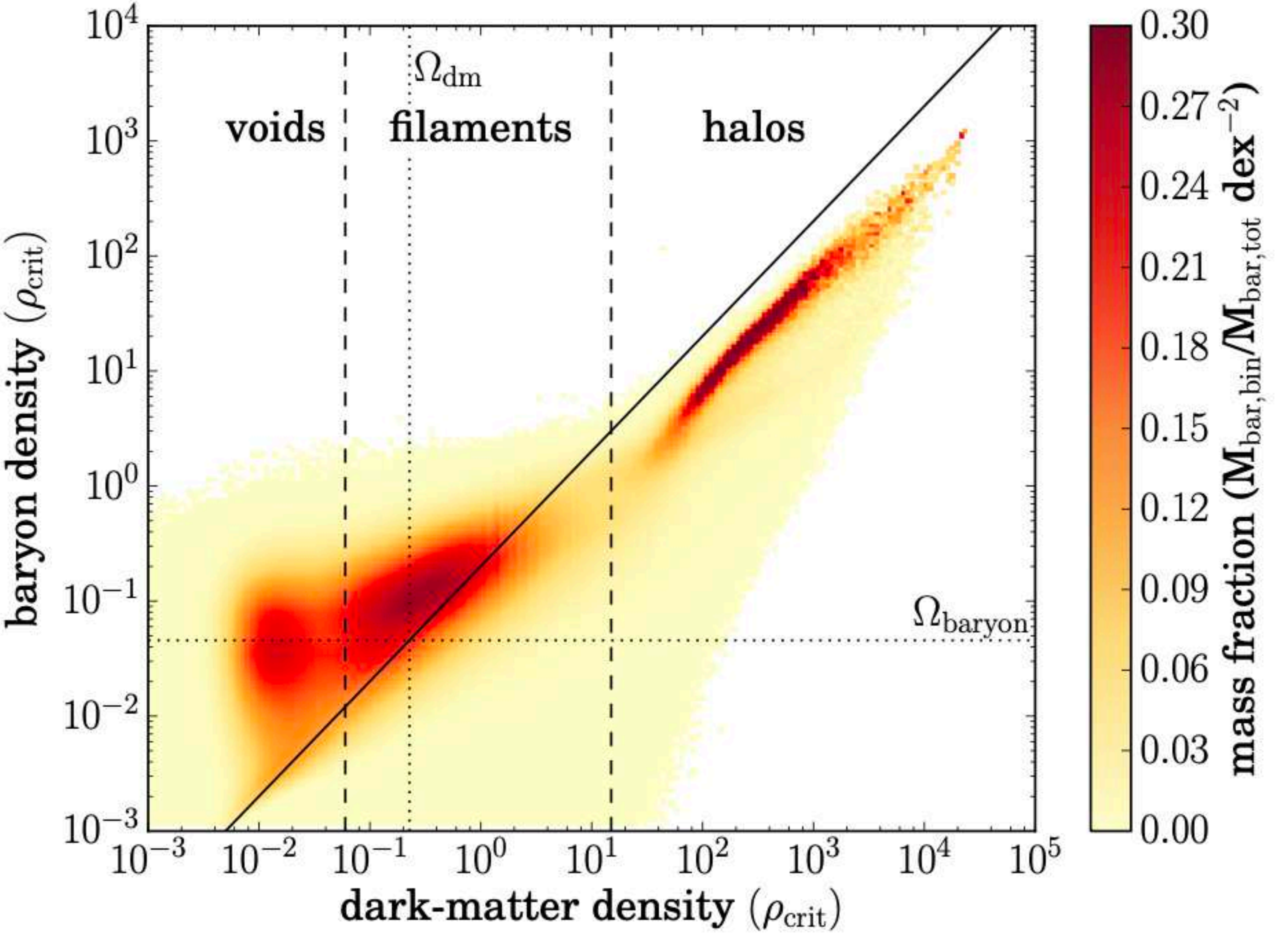
Nature not known



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*

Thermal SZ maps X Galaxy clusters

*D. Tramonte, **YZM**, et al., 2023, ApJS, 265, 55, arXiv: 2302.06266*

21-cm Intensity Mapping X (central) Galaxies

*D. Tramonte, **YZM**, 2020, MNRAS, 498, 591605935*
S. Cunnington et al. 2022, MNRAS, 518, 6262-6272

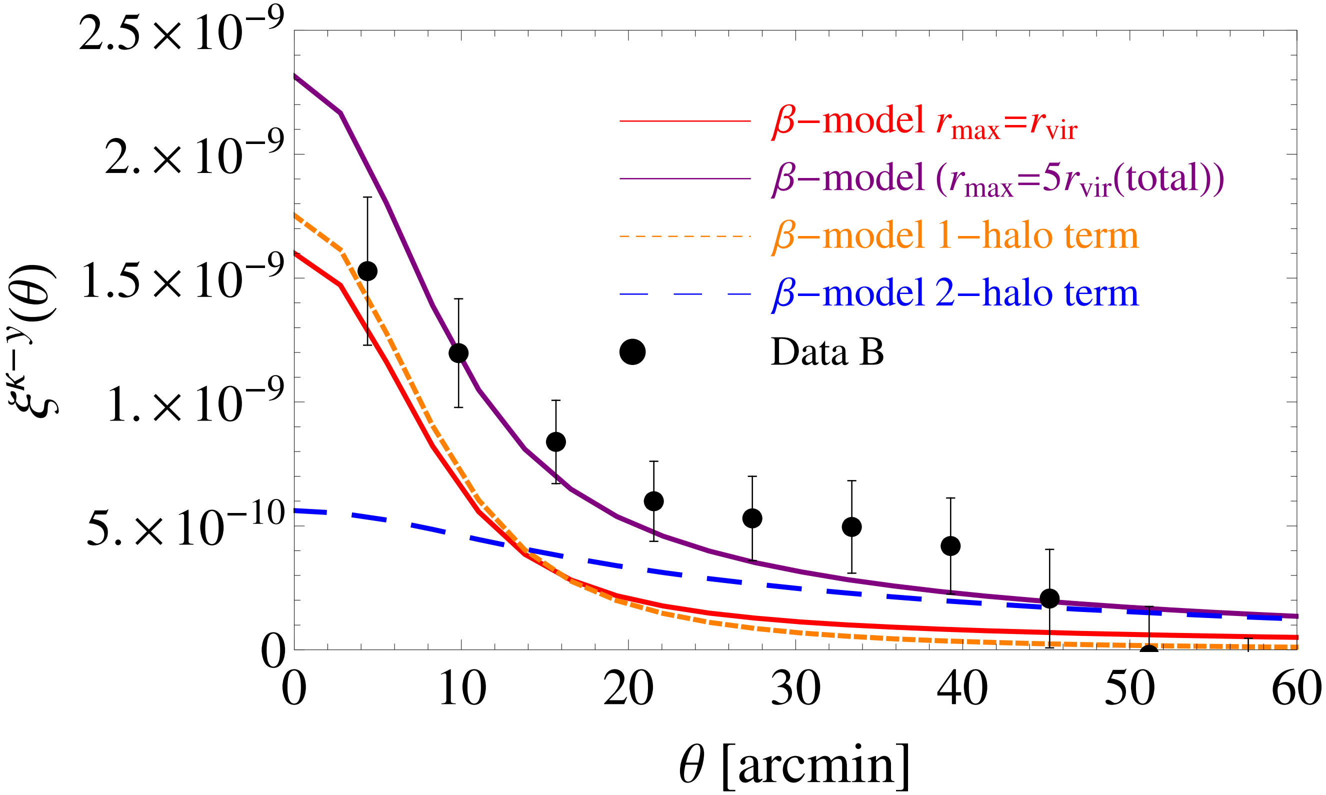
Thermal SZ maps X Luminous red galaxies

*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*

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*

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

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 Galaxy clusters

*D. Tramonte, **YZM**, et al., 2023, ApJS, 265, 55, arXiv: 2302.06266*

Universal Pressure Profile

$$\mathbb{P}(x) \equiv \frac{P_{\mathrm{e}}(r)}{P_{500}}$$
$$= \frac{P_0}{(c_{500}x)^{\gamma}[1+(c_{500}x)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

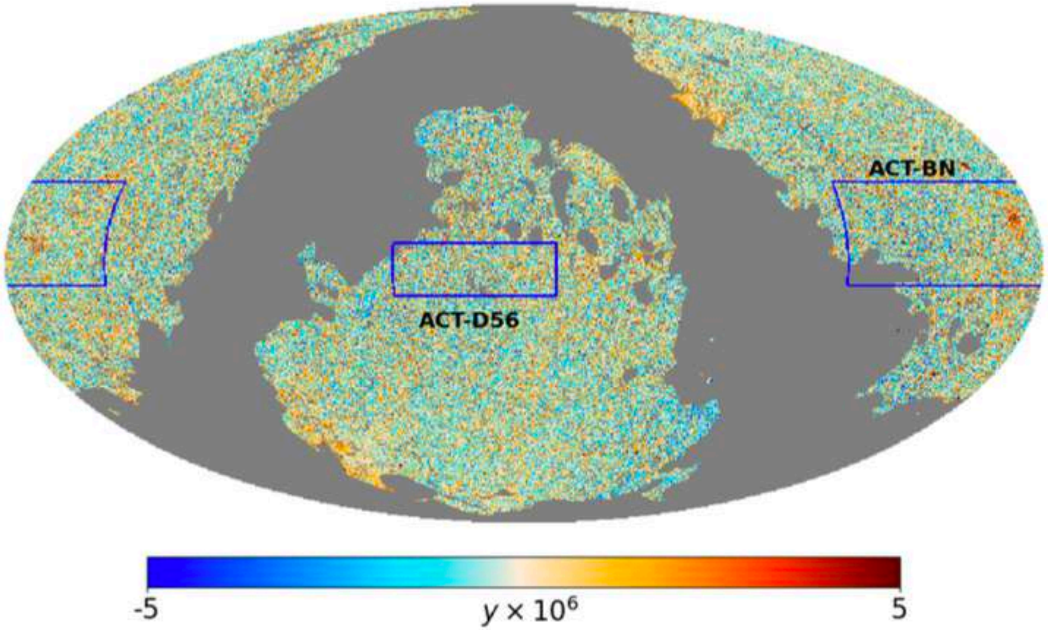
$x \equiv r/R_{500}$

Nagai et al. (2007)
Arnaud er al. (2010)
Planck collaboration (2013)

Tested for 62 nearby (z<0.1)massive clusters

Our motivation:

1. To include a larger range of samples in mass and redshifts to test Universal Pressure Profile
2. To include recent ACT DR4 Compton-y map to allow better resolution measurement
3. To test the off-centering problem

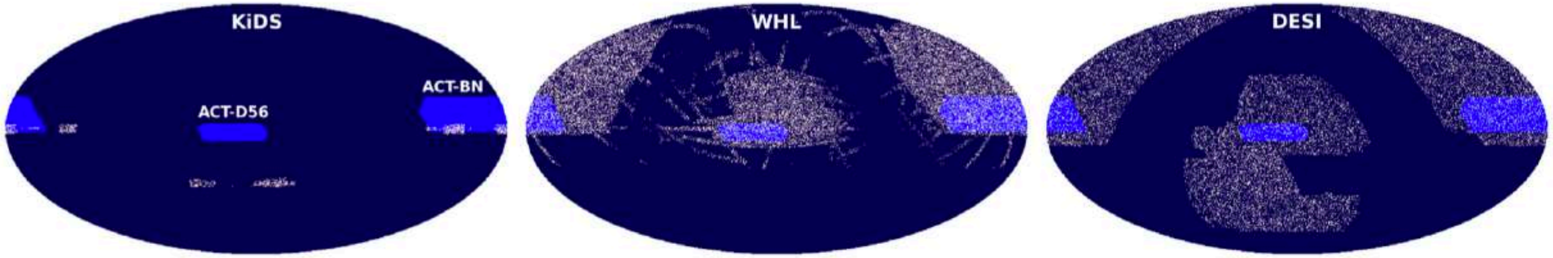


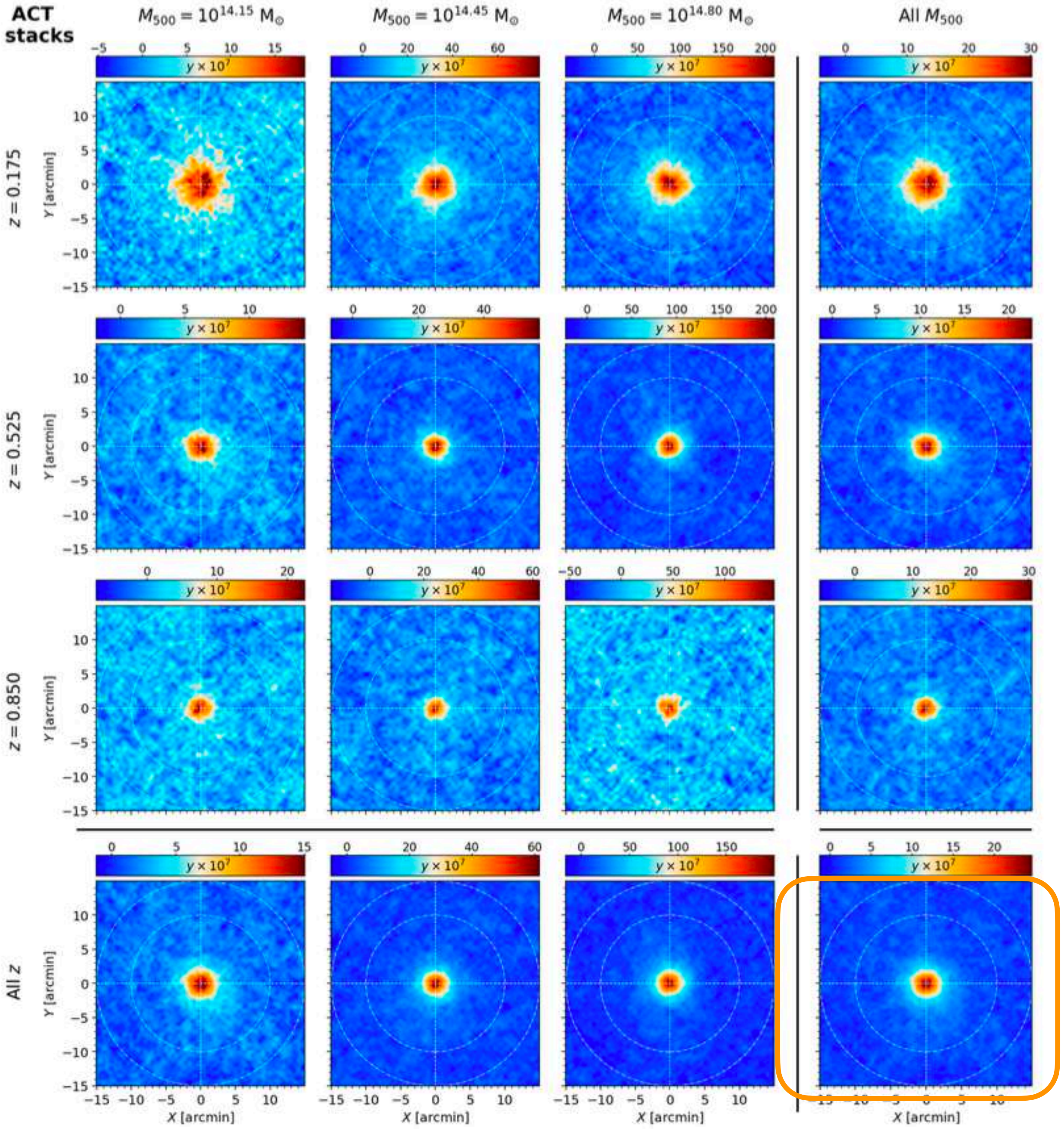
$[10^{14},10^{15.1}]\mathrm{M}_\odot$

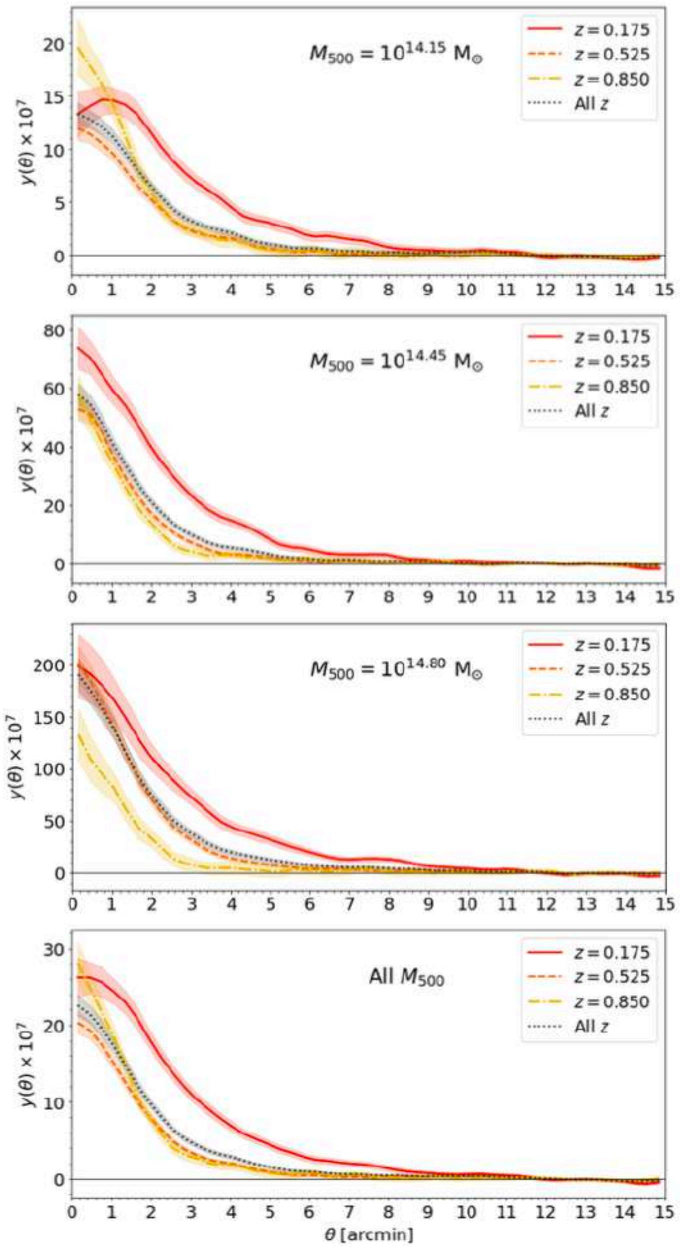
23820 samples for $z = [0.02,0.97]$

$\Uparrow$

806 + 11893 + 11121




ACT stacks
$M_{500} = 10^{14.15}$ M$_\odot$
$M_{500} = 10^{14.45}$ M$_\odot$
$M_{500} = 10^{14.80}$ M$_\odot$
All M_{500}
$z = 0.175$
$z = 0.525$
$z = 0.850$
All z
$y \times 10^7$
Y [arcmin]
X [arcmin]


$M_{500} = 10^{14.15}$ M$_\odot$
$M_{500} = 10^{14.45}$ M$_\odot$
$M_{500} = 10^{14.80}$ M$_\odot$
All M_{500}
$z = 0.175$
$z = 0.525$
$z = 0.850$
All z
$y(\theta) \times 10^7$
θ [arcmin]

Models and Fitting results

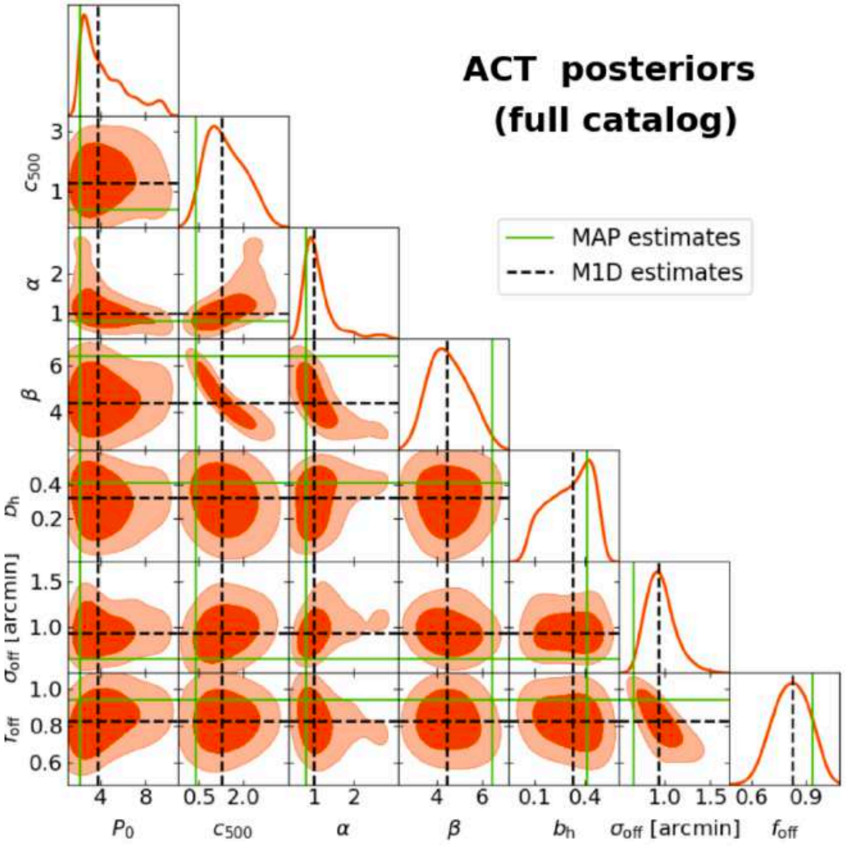
$$C_\ell = C_\ell^{1\mathrm{h}} + C_\ell^{2\mathrm{h}}$$

hydrostatic bias: $M_{500} \rightarrow (1 - b_\mathrm{h}) M_{500}$

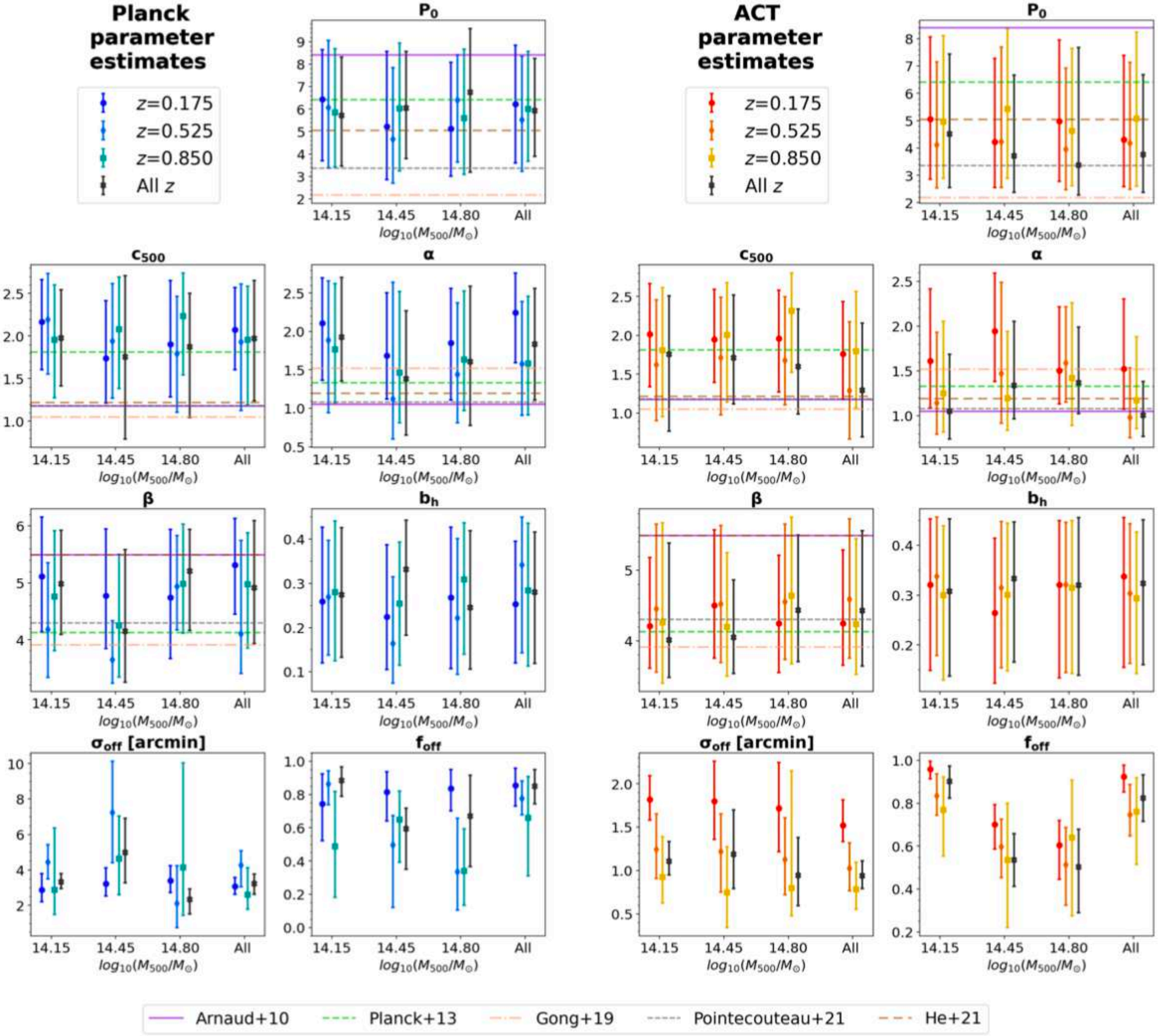
$$y_\mathrm{msc}(\theta) = f_\mathrm{off}\, \bar{y}_\mathrm{off}(\theta) + (1 - f_\mathrm{off})\, y(\theta).$$

ACT parameter estimates

Priors:		[2.0, 10.0]	[0.0, 3.0]	[0.0, 3.0]	[2.0, 6.5]	[0.1, 0.5]	[0.0, 3.0]	[0.0, 1.0]
z	$M_{500} [M_\odot]$	P_0	c_{500}	α	β	b_h	σ_off [arcmin]	f_off
0.175	$10^{14.15}$	$5.1^{+3.0}_{-2.2}$	$2.0^{+0.7}_{-0.7}$	$1.6^{+0.8}_{-0.5}$	$4.2^{+1.0}_{-0.6}$	$0.3^{+0.1}_{-0.2}$	$1.8^{+0.3}_{-0.2}$	$1.0^{+0.0}_{-0.0}$
0.175	$10^{14.45}$	$4.2^{+3.1}_{-1.7}$	$1.9^{+0.6}_{-0.6}$	$1.9^{+0.6}_{-0.6}$	$4.5^{+1.1}_{-0.8}$	$0.3^{+0.1}_{-0.1}$	$1.8^{+0.5}_{-0.4}$	$0.7^{+0.1}_{-0.1}$
0.175	$10^{14.80}$	$5.0^{+3.0}_{-2.2}$	$2.0^{+0.6}_{-0.7}$	$1.5^{+0.7}_{-0.4}$	$4.2^{+1.0}_{-0.7}$	$0.3^{+0.1}_{-0.2}$	$1.7^{+0.5}_{-0.5}$	$0.6^{+0.1}_{-0.2}$
0.175	All M_{500}	$4.3^{+3.1}_{-1.7}$	$1.8^{+0.7}_{-0.6}$	$1.5^{+0.8}_{-0.5}$	$4.2^{+1.0}_{-0.6}$	$0.3^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.2}$	$0.9^{+0.1}_{-0.1}$
0.525	$10^{14.15}$	$4.1^{+3.0}_{-1.6}$	$1.6^{+0.8}_{-0.7}$	$1.1^{+0.8}_{-0.4}$	$4.4^{+1.2}_{-0.9}$	$0.3^{+0.1}_{-0.2}$	$1.2^{+0.4}_{-0.3}$	$0.8^{+0.1}_{-0.1}$
0.525	$10^{14.45}$	$4.2^{+3.5}_{-1.7}$	$1.7^{+0.8}_{-0.7}$	$1.5^{+1.0}_{-0.6}$	$4.5^{+1.1}_{-0.8}$	$0.3^{+0.1}_{-0.2}$	$1.2^{+0.4}_{-0.5}$	$0.6^{+0.1}_{-0.1}$
0.525	$10^{14.80}$	$4.0^{+3.0}_{-1.5}$	$1.7^{+0.8}_{-0.6}$	$1.6^{+0.6}_{-0.4}$	$4.5^{+1.1}_{-0.8}$	$0.3^{+0.1}_{-0.2}$	$1.1^{+0.5}_{-0.4}$	$0.5^{+0.2}_{-0.2}$
0.525	All M_{500}	$4.2^{+3.0}_{-1.7}$	$1.3^{+0.9}_{-0.6}$	$1.0^{+0.6}_{-0.2}$	$4.6^{+1.1}_{-0.8}$	$0.3^{+0.1}_{-0.1}$	$1.0^{+0.3}_{-0.3}$	$0.7^{+0.1}_{-0.1}$
0.850	$10^{14.15}$	$5.0^{+3.1}_{-2.1}$	$1.8^{+0.8}_{-0.9}$	$1.3^{+0.8}_{-0.4}$	$4.3^{+1.4}_{-0.9}$	$0.3^{+0.1}_{-0.2}$	$0.9^{+0.5}_{-0.3}$	$0.8^{+0.2}_{-0.2}$
0.850	$10^{14.45}$	$5.4^{+2.9}_{-2.5}$	$2.0^{+0.7}_{-0.9}$	$1.2^{+0.7}_{-0.4}$	$4.2^{+1.0}_{-0.7}$	$0.3^{+0.1}_{-0.2}$	$0.7^{+0.5}_{-0.4}$	$0.5^{+0.3}_{-0.3}$
0.850	$10^{14.80}$	$4.6^{+3.0}_{-2.0}$	$2.3^{+0.5}_{-0.8}$	$1.4^{+0.8}_{-0.5}$	$4.6^{+1.1}_{-1.0}$	$0.3^{+0.1}_{-0.2}$	$0.8^{+1.4}_{-0.3}$	$0.6^{+0.3}_{-0.4}$
0.850	All M_{500}	$5.1^{+3.2}_{-2.5}$	$1.8^{+0.8}_{-0.7}$	$1.2^{+0.7}_{-0.3}$	$4.2^{+1.2}_{-0.7}$	$0.3^{+0.1}_{-0.2}$	$0.8^{+0.3}_{-0.2}$	$0.8^{+0.2}_{-0.2}$
All z	$10^{14.15}$	$4.5^{+2.9}_{-2.0}$	$1.8^{+0.8}_{-1.0}$	$1.1^{+0.6}_{-0.3}$	$4.0^{+1.4}_{-0.5}$	$0.3^{+0.1}_{-0.2}$	$1.1^{+0.2}_{-0.2}$	$0.9^{+0.1}_{-0.1}$
All z	$10^{14.45}$	$3.7^{+3.0}_{-1.3}$	$1.7^{+0.8}_{-0.6}$	$1.3^{+0.7}_{-0.4}$	$4.1^{+0.8}_{-0.5}$	$0.3^{+0.1}_{-0.2}$	$1.2^{+0.5}_{-0.4}$	$0.5^{+0.1}_{-0.1}$
All z	$10^{14.80}$	$3.4^{+4.3}_{-1.1}$	$1.6^{+0.7}_{-0.6}$	$1.4^{+0.6}_{-0.3}$	$4.4^{+1.1}_{-0.7}$	$0.3^{+0.1}_{-0.2}$	$0.9^{+0.4}_{-0.4}$	$0.5^{+0.2}_{-0.2}$
All z	All M_{500}	$3.8^{+2.9}_{-1.4}$	$1.3^{+0.9}_{-0.6}$	$1.0^{+0.4}_{-0.2}$	$4.4^{+1.1}_{-0.8}$	$0.3^{+0.1}_{-0.2}$	$0.9^{+0.2}_{-0.2}$	$0.8^{+0.1}_{-0.1}$



ACT posteriors (full catalog)



$$
\begin{aligned}
M_{\mathrm{gas}} &= (1-b_{\mathrm{h}})M_{\mathrm{halo}} \\
&\simeq (70\%)\,M_{\mathrm{halo}}
\end{aligned}
$$

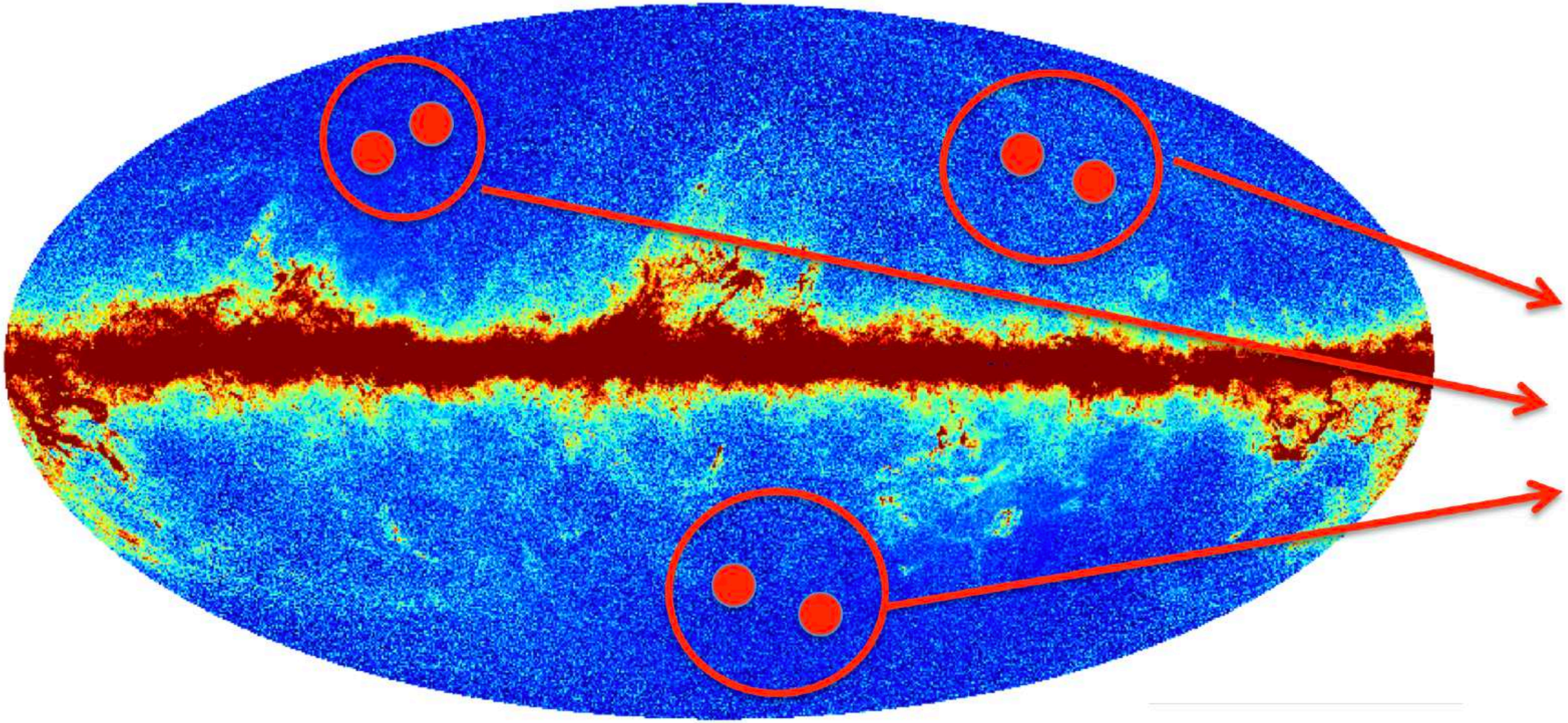
Thermal SZ maps X Luminous red galaxies

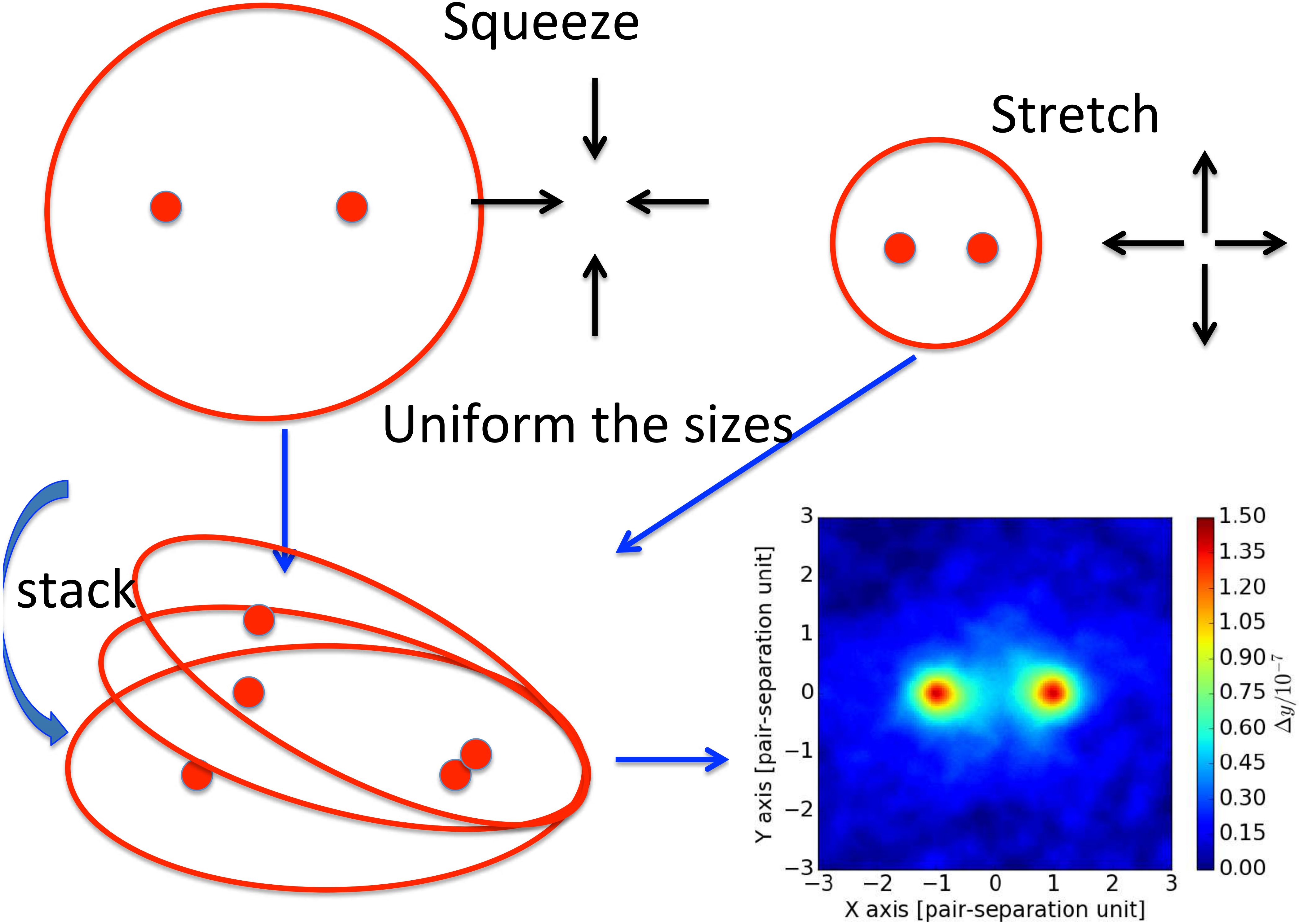
*H Tanimura, …, **YZM**,… et al. 2018, MNRAS, 483, 223*

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: $\pm 6\,h^{-1}\mathrm{Mpc}$

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





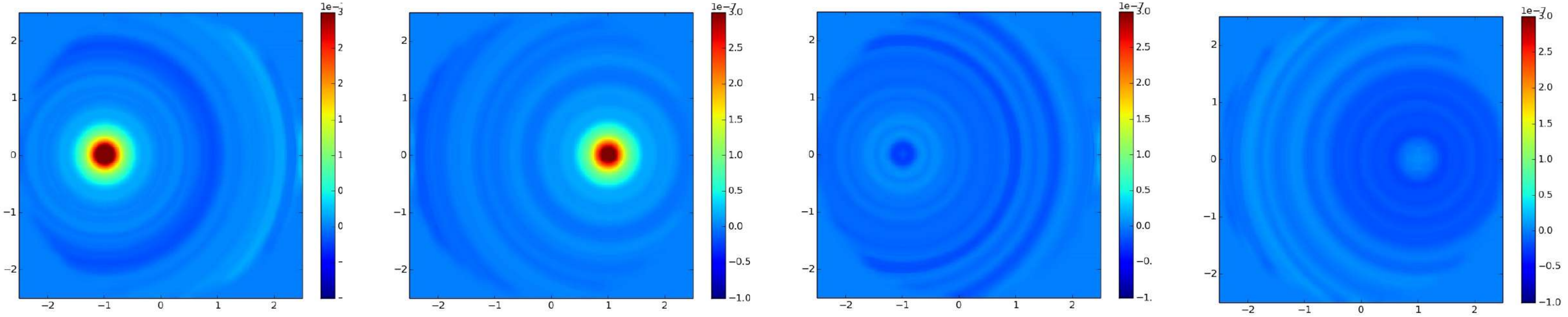
Squeeze

Stretch

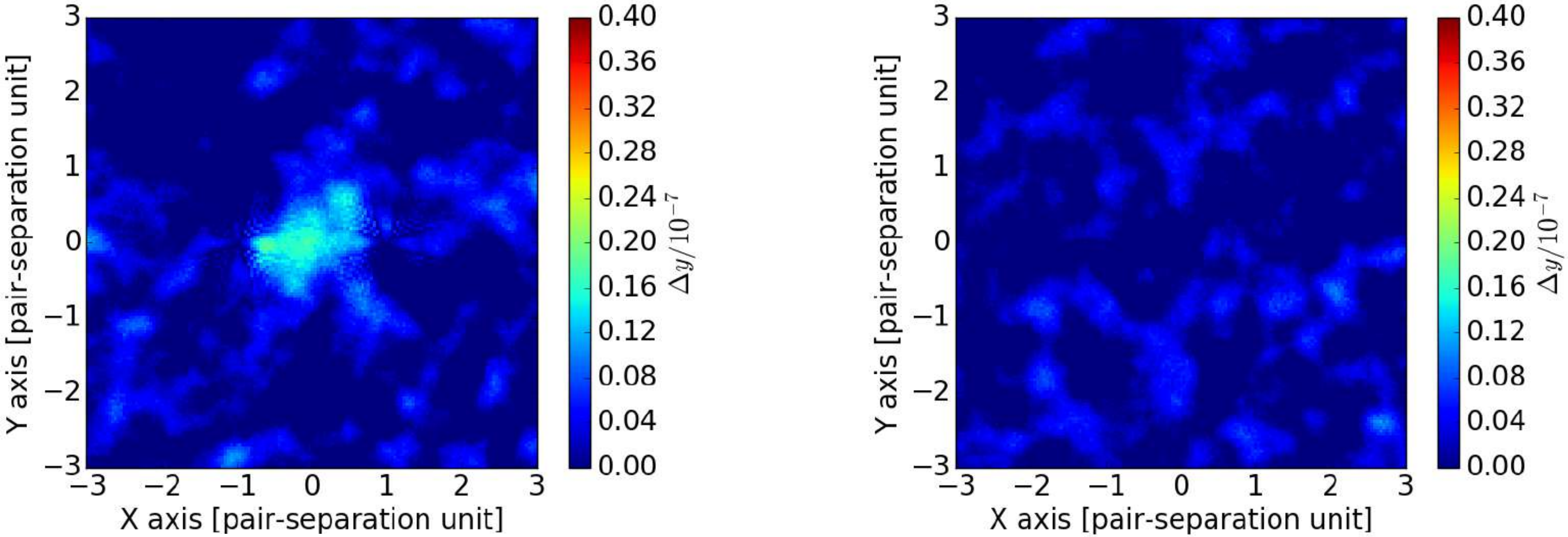
Uniform the sizes

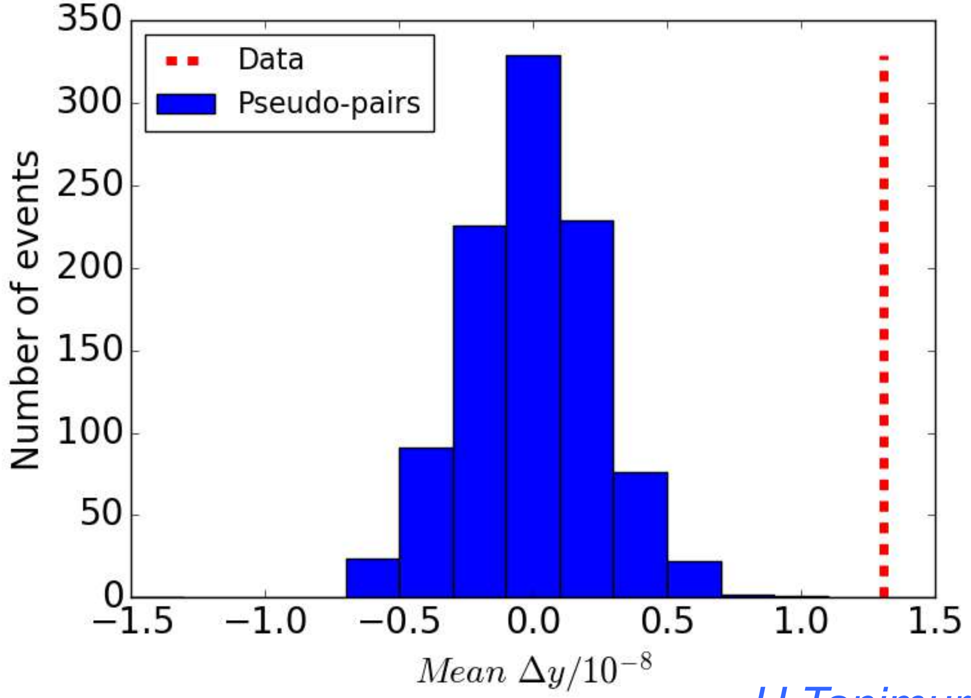
stack

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*

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

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

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

$$\Big\downarrow$$

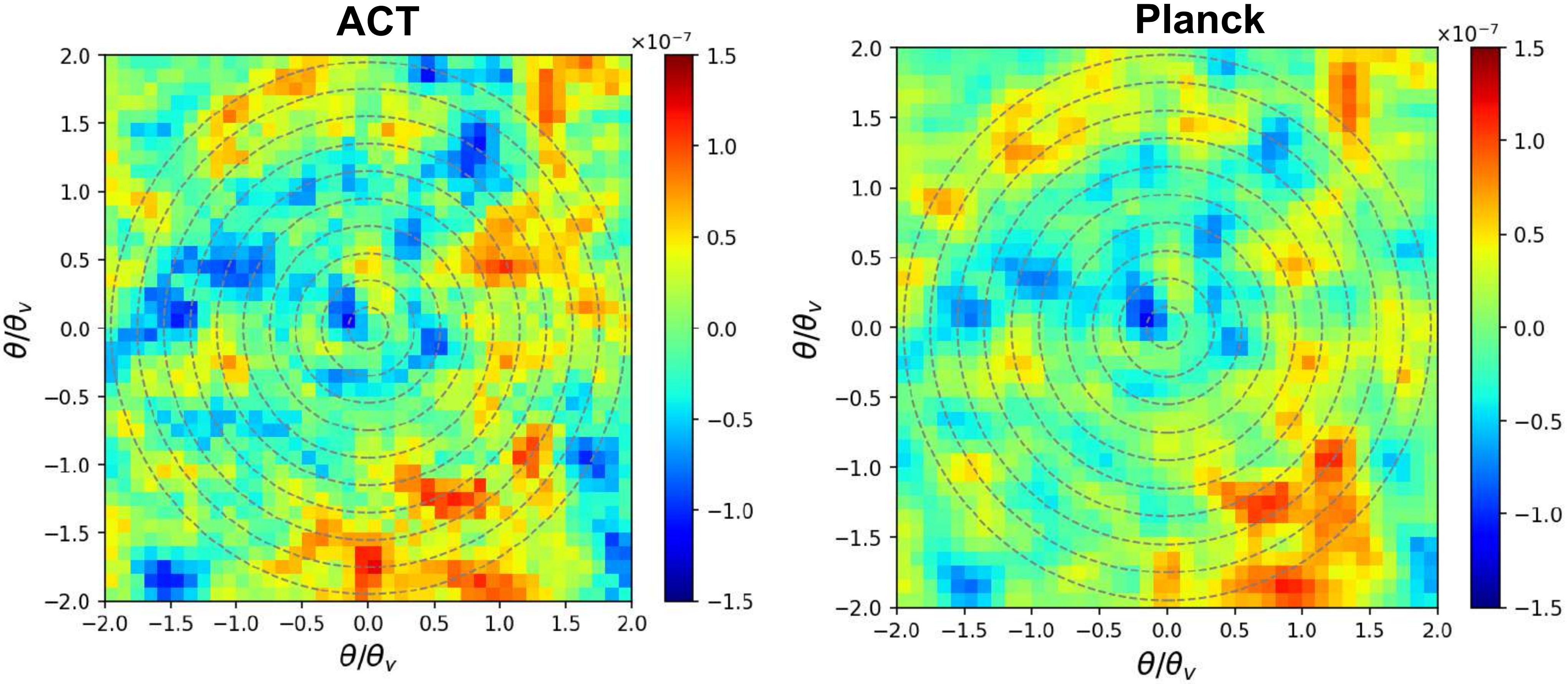
$$\delta_c \left(\frac{T_{\mathrm{e}}}{10^7\ \mathrm{K}} \right) \left(\frac{r_c}{0.5 h^{-1}\ \mathrm{Mpc}} \right) = 2.7 \pm 0.5$$

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

Cosmic voids stacking

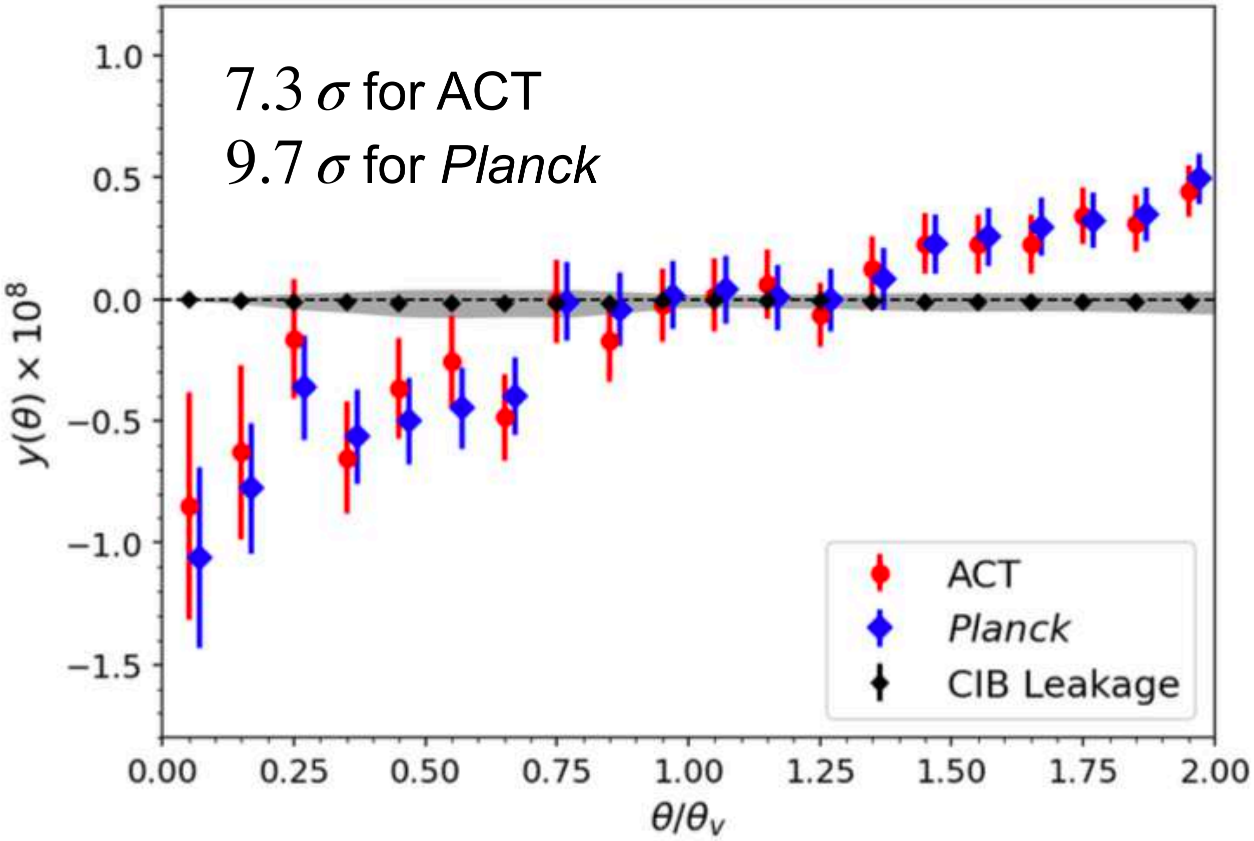
G. Li, **YZM,** D. Tramonte, G. Li et al. 2024, MNRAS, arXiv: 2311.00826

Voids: 97,090
Mean $z \simeq 0.32$ (BOSS DR12)
Mean radius $13.6\,h^{-1}\mathrm{Mpc}$



Cosmic voids stacking

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

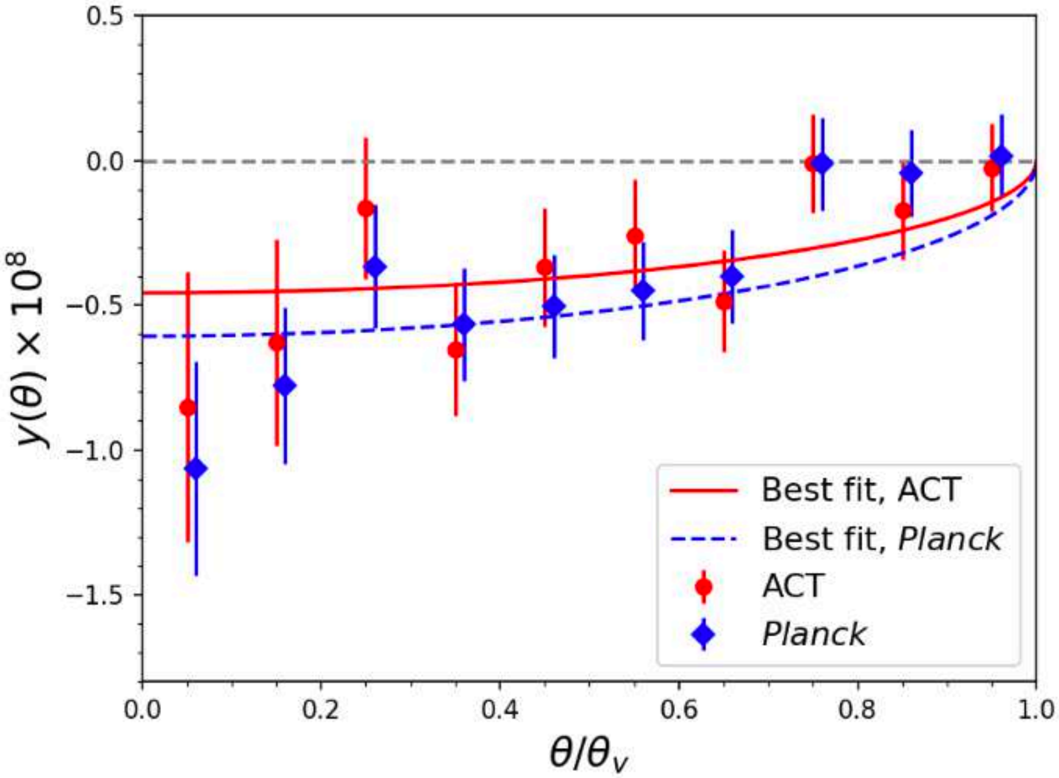


Modelling:

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

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

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



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

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	Clusters	Hydrodynamic bias is around 30%; UPP model fits halos in all masses and redshifts well
thermal SZ	Pairs of LRGs	Gas associated with filament is detected at 5.3σ $y = (1.31 \pm 0.25) \times 10^{-8} \longrightarrow T_{\mathrm{filament}} \leqslant 10^7\,\mathrm{K}$
thermal SZ	voids	The void significance is detected at 7.3σ and 9.7σ for ACT and Planck respectively, leading 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