Galaxy clusters in mm wavelengths

Cosmological analysis and future prospects

Laura Salvati

Outline

Galaxy clusters as a cosmological probe

- Observations in mm wavelengths
  - New analysis of Planck clusters
    - Impact of Mass calibration
  - First combined analysis of Planck and SPT clusters

in collaboration with M. Douspis and N. Aghanim

A&A 614, A13 (2018)
A&A 626, A27 (2019)

in collaboration with A. Saro and SPT

arXiv:2112.03606 [astro-ph.CO]

See posters from: Iñigo Zubeldia, Boris Bolliet, Marian Douspis

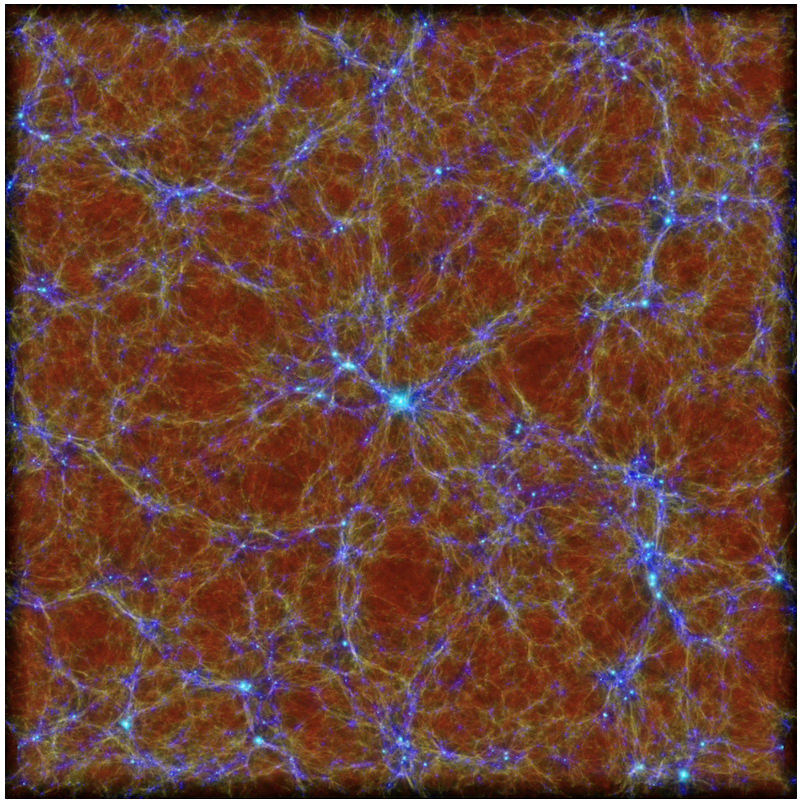
Galaxy Clusters

Credit: E. Siegel

- Largest gravitationally bound structures in the Universe
- Peaks in the cosmic web
- Multi-component systems:
  - Observables at different wavelengths

<u>Dependence on cosmological parameters:</u> $\sigma_8, \;\Omega_m$

$$\sigma^2 = \frac{1}{2\pi^2}\int \mathrm{d}k\, k^2 P(k,z)\,|W(kR)|^2$$



Credit: Hirschmann et al. 2014

Cluster cosmology

Cluster cosmology: *mass* and *redshift* of clusters

Scaling Relations: Mass calibration

Astrophysics
Survey observable - cluster mass

Multi-wavelengths analysis:
Unique way to calibrate cluster mass

Clusters observed in mm wavelengths:
thermal Sunyaev-Zeldovich (tSZ) effect

- Self-similarity: gravity is the only acting force
- Spherical symmetry
- Hydrostatic equilibrium

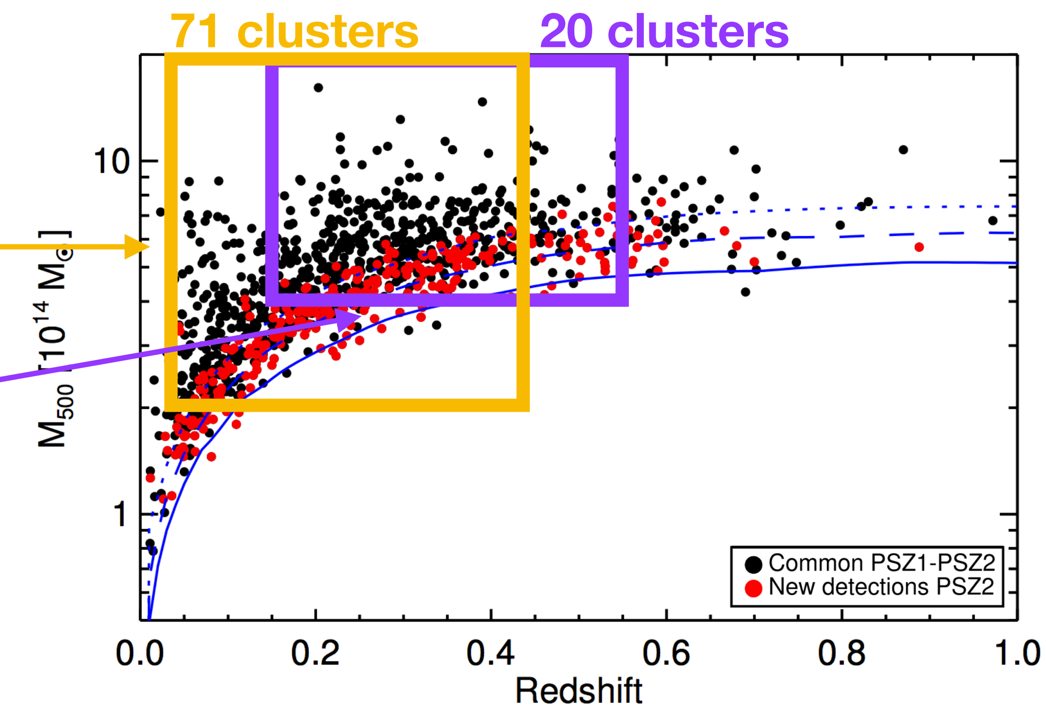
$$Y_{\rm SZ} D_A^2 \propto M_{\rm tot}^{5/3} E(z)^{2/3}$$

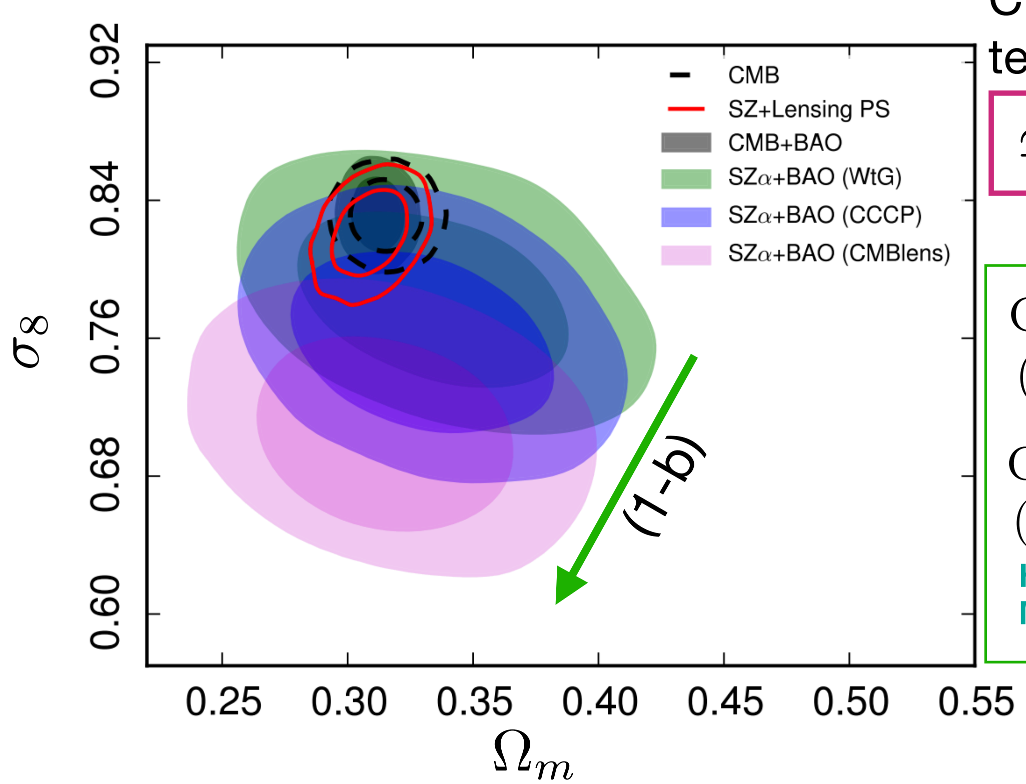
tSZ clusters: Planck

$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_* \left[\frac{h}{0.7}\right]^{-2+\alpha} \left[\frac{(1-b)\,M_{500}}{6\cdot 10^{14} M_\odot}\right]^{\alpha}$$

- $\alpha,\ Y_*$ → from X-ray observations
- $\beta = 2/3$ → from self-similarity
- $(1-b)$ → from WL mass evaluations

$$(1-b) = \frac{M_{\rm SZ}}{M_{500}} \sim 0.8$$





CMB - Galaxy Clusters tension:

$\simeq 2.4\,\sigma$ on σ_8

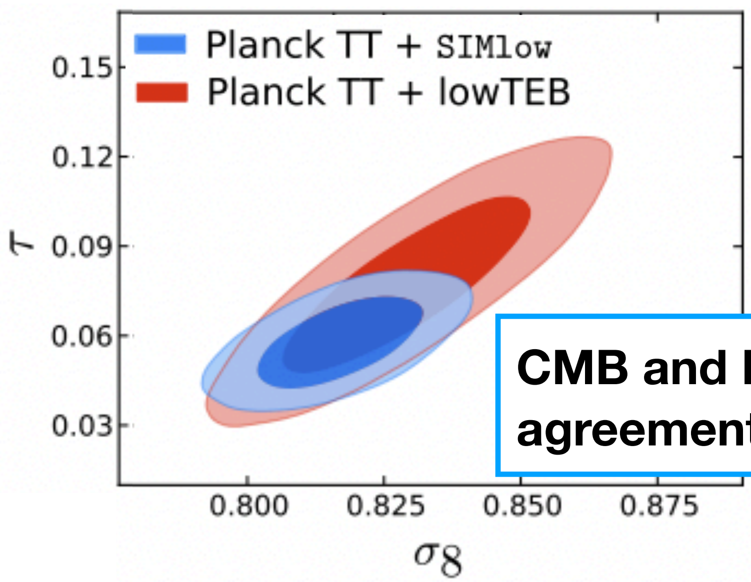
CMB + $\mathrm{NC}^{\rm tSZ}$:
$(1-b) = 0.58 \pm 0.04$

CCCP:
$(1-b) = 0.780 \pm 0.092$

Hoekstra et al., MNRAS 449 (2015) no.1, 685

- **Tight correlation between cosmological and scaling relation parameters**
- **Mass calibration: largest source of uncertainty in current cluster cosmology**

Planck Collaboration, A&A 596, A107 (2016)



CMB and NCtSZ: agreement at $1.5\,\sigma$ on σ_8

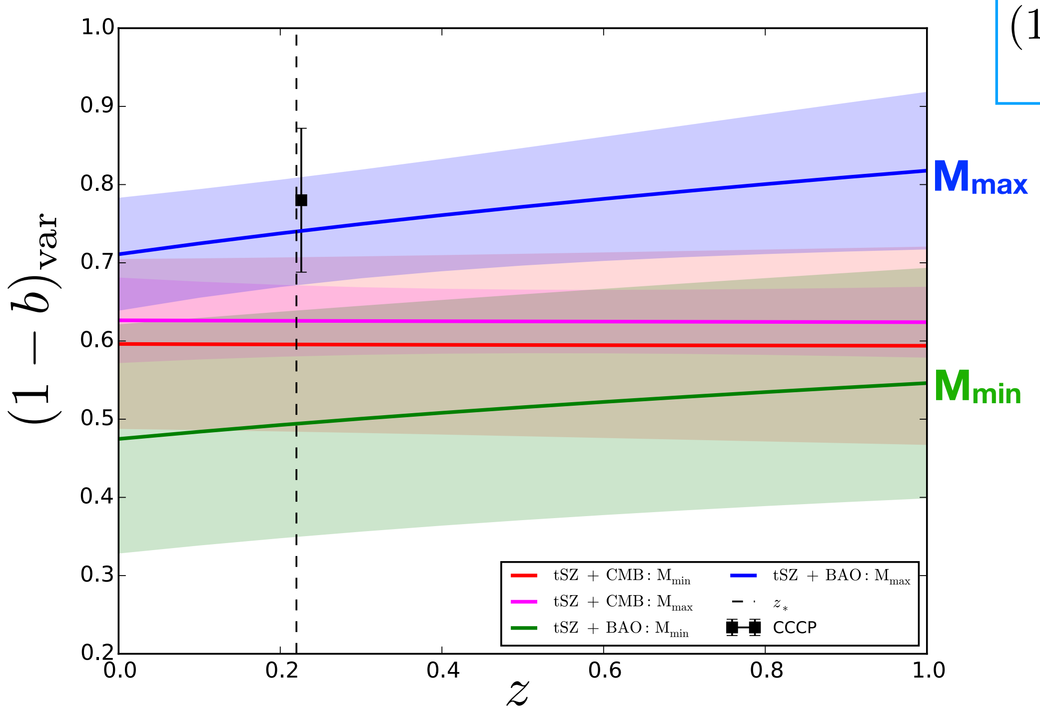
CMB + NCtSZ

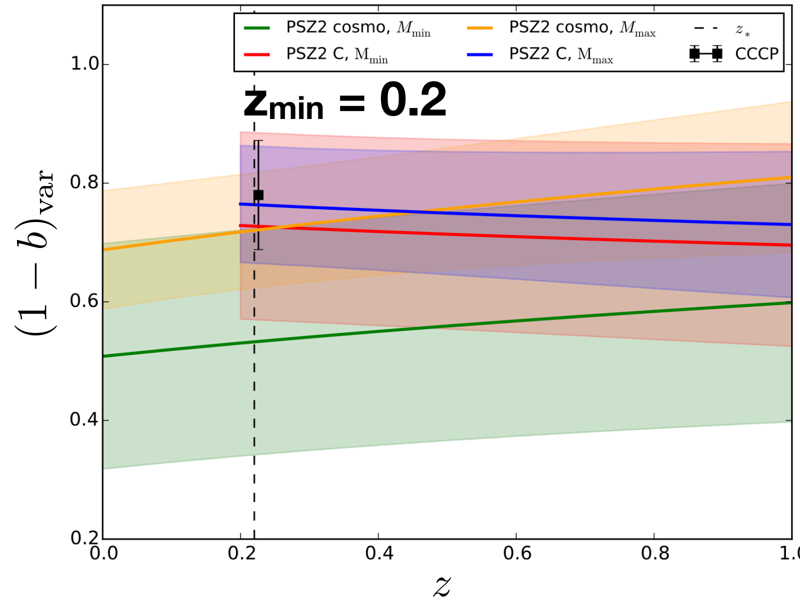
$(1-b) = 0.58 \pm 0.04$	P15
$(1-b) = 0.65 \pm 0.04$	LCDM
$(1-b) = 0.67 \pm 0.04$	Neutrinos
$(1-b) = 0.63 \pm 0.04$	DE
$(1-b) = 0.62 \pm 0.03$	P18

Salvati et al., A&A 614, A13 (2018)

Salvati et al., A&A 626, A27 (2019)

$$(1-b)_{\rm var} = (1-\mathcal{B}) \cdot \left(\frac{M}{M_*}\right)^{\alpha_b} \cdot \left(\frac{1+z}{1+z_*}\right)^{\beta_b}$$





(1-b) increasing with redshift

Selection effects:
results change for different cluster samples

Planck+SPT

Mass calibration might be affected by selection choices
- Multi-wavelengths observations for the full cluster sample
- Independent constraints on mass calibration parameters

Combine Planck and SPT cluster catalogs

Planck

Planck 2015. A&A 594, A24 (2016)
Planck 2015. A&A 594, A27 (2016)

- Survey characteristics:
  - 65% of the sky (~26815 deg2)
  - Frequencies: 100, 143, 217, 353, 545, and 857 GHz (HFI instrument)
  - Resolution: [5’,10’]
- Cosmological Catalog
  - 439 clusters
  - z = [0,1]
- Cluster extraction: Matched Multi-filters approach
  - Arnaud profile
- EXTERNAL Mass calibration
  - X-ray and WL observations

SPT-SZ

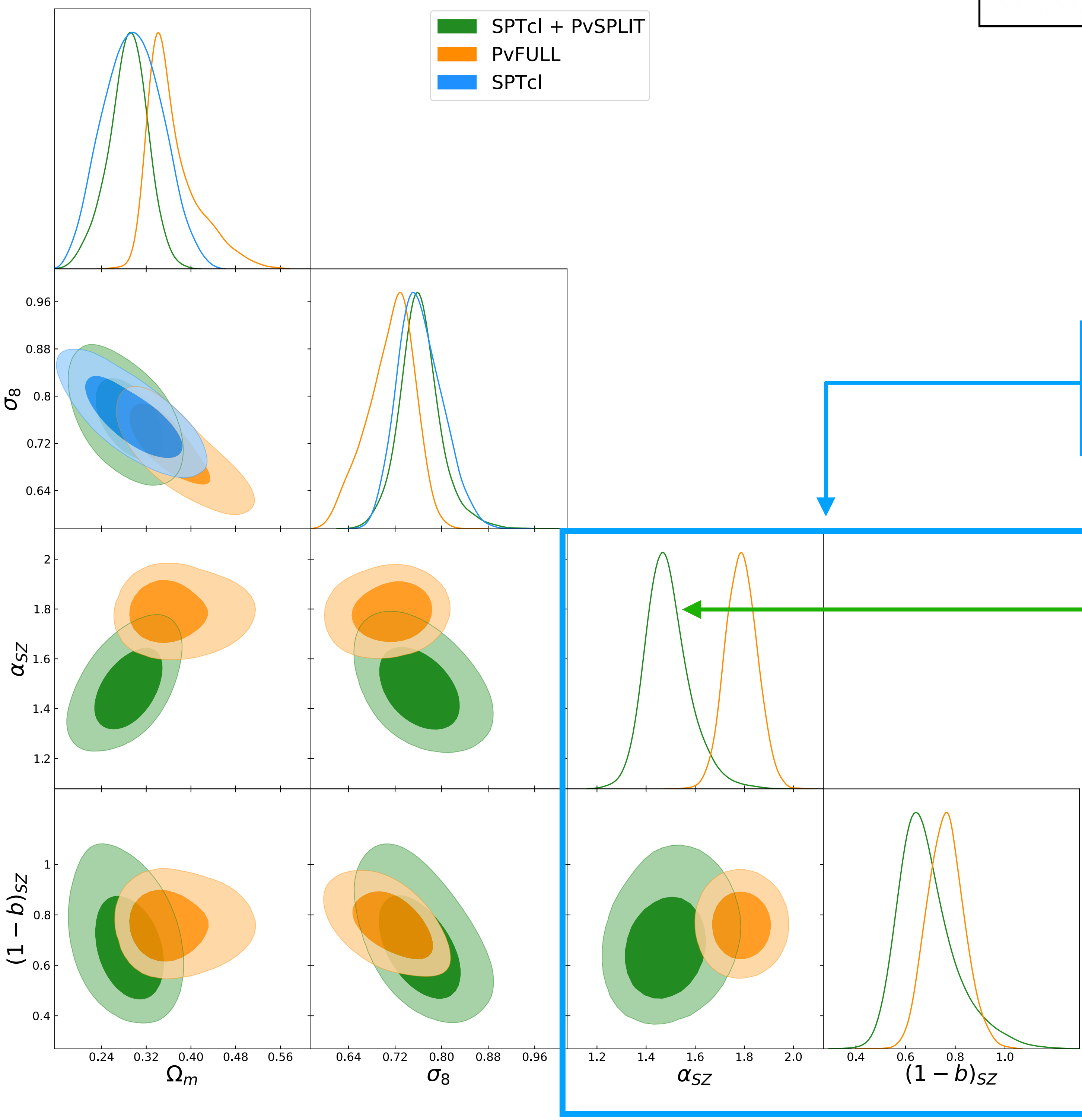
SPT. Bleem at al., APJ Suppl. 216 (2015) no.2, 27
SPT. Bocquet et al., APJ 878 (2019) no.1, 55

- Survey characteristics:
  - 2500 deg2 area
  - Frequencies: 95, 150 GHz
  - Resolution: ~ 1’
- Cosmological catalog
  - 365 clusters
  - z = [0.25,1.7]
- Cluster extraction: Matched Multi-filters approach
  - Beta profile
- INTERNAL Mass calibration
  - X-ray and WL observations
  - empirical, multi-observable approach

Planck+SPT

$$E^{-\beta_{\rm SZ}}(z)\left[\frac{D_A^2(z)\bar{Y}_{500}}{10^{-4}{\rm Mpc}^2}\right] = Y_{*,{\rm SZ}}\left[\frac{h}{0.7}\right]^{-2+\alpha_{\rm SZ}}\left[\frac{(1-b)_{\rm SZ}M_{500}}{6\times10^{14}M_\odot}\right]^{\alpha_{\rm SZ}}$$

Paramater	$\nu\Lambda$CDM		
	SPTcl + PvSPLIT	PvFULL	SPTcl
Ω_m	$0.29^{+0.04}_{-0.03}$	$0.37^{+0.02}_{-0.06}$	0.30 ± 0.03
σ_8	$0.76^{+0.03}_{-0.04}$	$0.71^{+0.05}_{-0.03}$	$0.76^{+0.03}_{-0.04}$
$\alpha_{\rm SZ}$	$1.49^{+0.07}_{-0.10}$	1.79 ± 0.06	–
$(1-b)_{\rm SZ}$	$0.69^{+0.07}_{-0.14}$	$0.76^{+0.07}_{-0.08}$	–



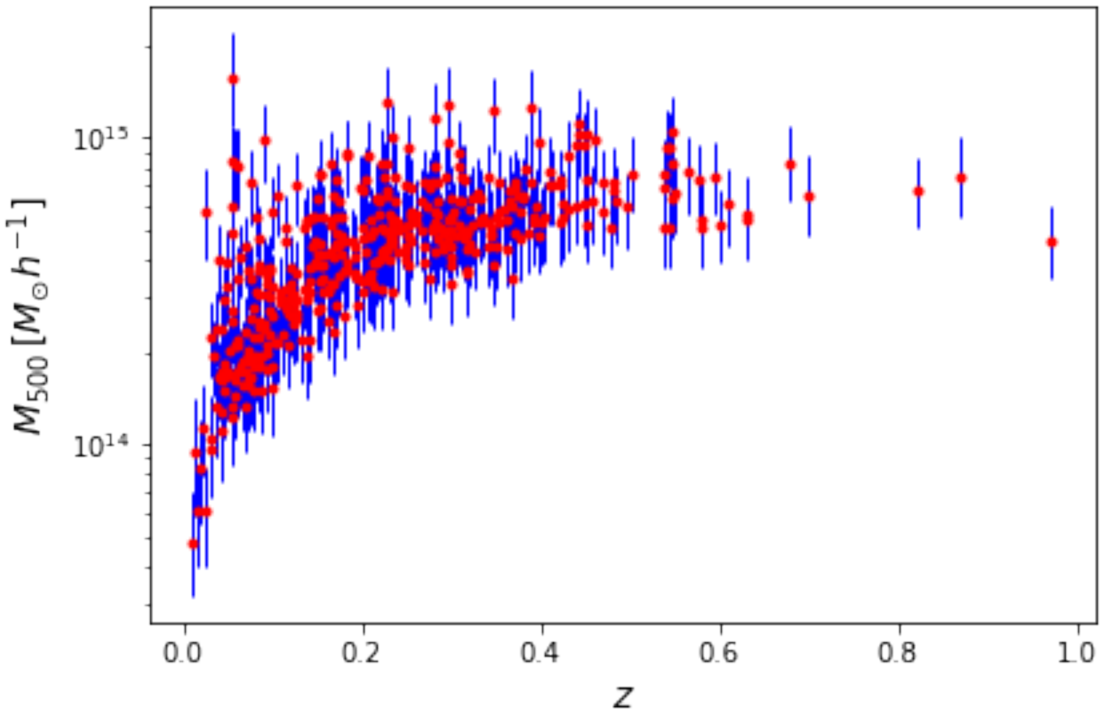
$\sim 4\sigma$ lower than self-similar value: lower value of Ω_m

- tilt in the HMF (accounting for less objects at lowM)
- accomodate for this tilt (balancing highM - lowM)

Salvati, Saro + SPT collab.
arXiv:2112.03606 [astro-ph.CO]

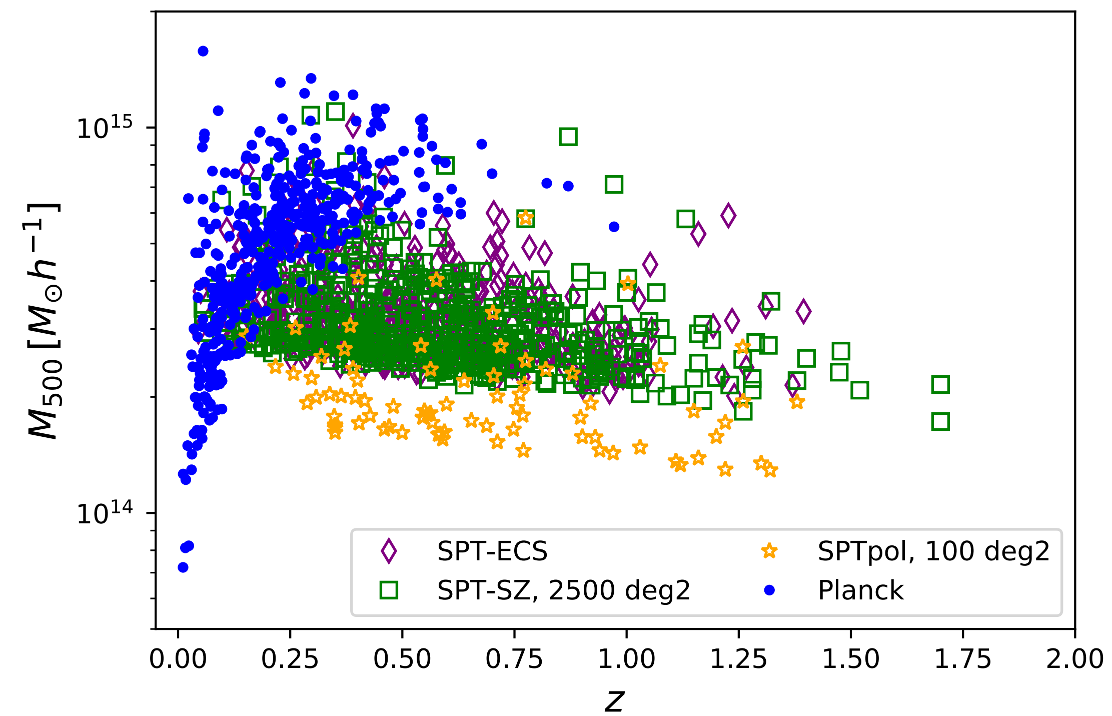
Released Catalogs

https://pole.uchicago.edu/public/data/sptplanck_cluster/



Cluster masses M_{500}

- marginalising over cosmological and scaling relation parameters



Cluster masses M_{500}

- fixed values of cosmological and scaling relation parameters

Planck+SPT

Mass bias

$$(1-b)_M = \frac{M_{\rm SZ}}{M_{500}}$$

$$(1-b)_M = \mathrm{Amp} \cdot \left(\frac{M_{500}}{M_*}\right)^{\gamma_M} \cdot \left(\frac{1+z}{1+z_*}\right)^{\gamma_z} \cdot \left(\frac{\sigma_f(\theta)}{\bar{\sigma_f}(\theta)}\right)^{\gamma_n}$$

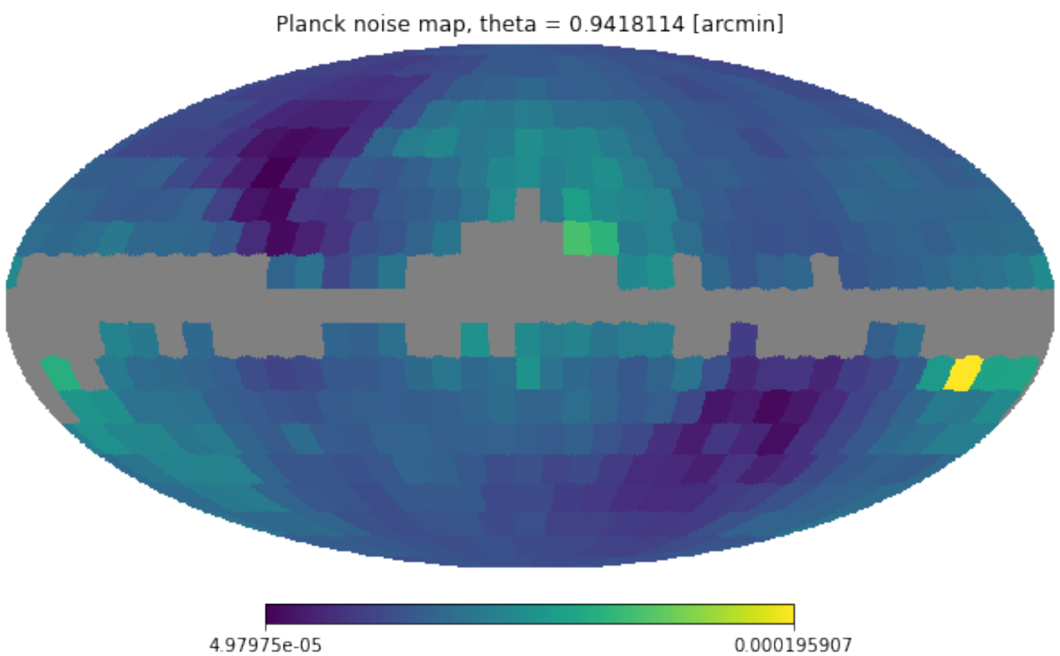
	bias(M,z)	bias(noise)	bias(M,z,noise)
Amp	$0.69^{+0.05}_{-0.10}$	$0.60^{+0.06}_{-0.14}$	$0.69^{+0.04}_{-0.09}$
γ_M	$-0.40^{+0.04}_{-0.06}$	-	$-0.41^{+0.04}_{-0.06}$
γ_z	0.74 ± 0.13	-	0.81 ± 0.13
γ_n	-	$-0.37^{+0.14}_{-0.12}$	$0.05^{+0.06}_{-0.08}$

Increasing trend for high-z and low-M

Increasing trend for high-z and low-M

Mass estimation in patches with higher noise are more biased (possibly due to a loss in tSZ signal)

Systematic related to cluster detection



Conclusions and future prospectives

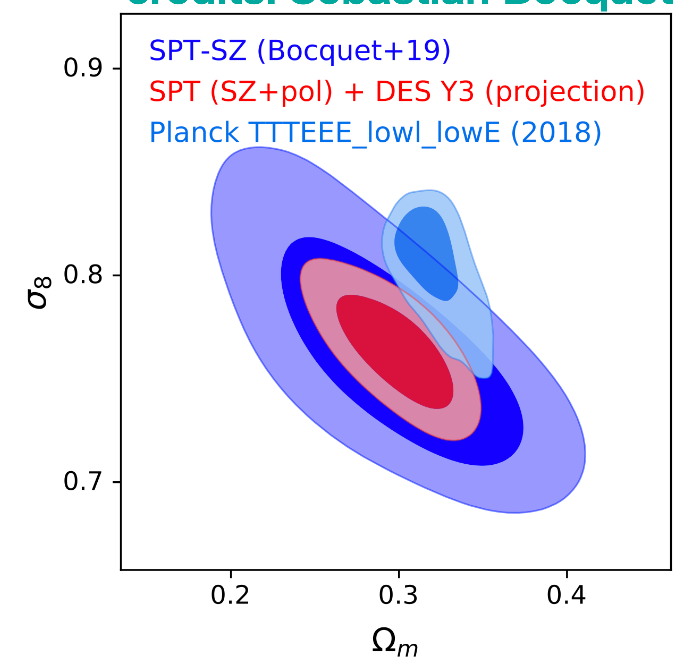
See talk from Federica Guidi for SPT-3G results

Combine tSZ cluster catalogs
- Independent mass calibration

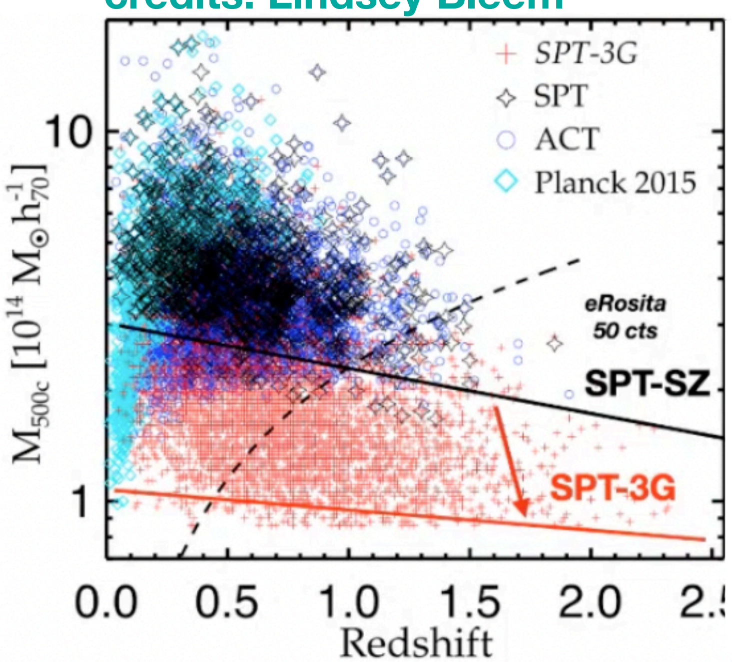
Next steps
- Build a consistent Planck-SPT likelihood
- Exploiting internal calibration

- SPT-SZ + SPTpol + DES-Y3 coming up!
- Future: SPT-3G cluster analysis

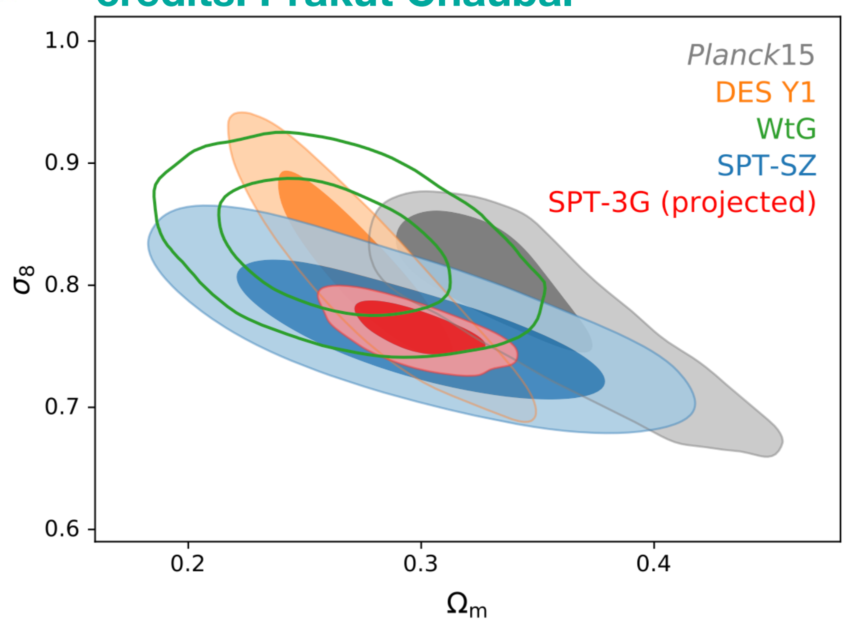
credits: Sebastian Bocquet



credits: Lindsey Bleem



credits: Prakut Chaubal



Expected Number of S/N $\geqslant$ 5 Clusters from SZ Surveys

Experiment	Total Clusters: Total	Total Clusters: $z \geqslant 1.5$	Total Clusters: $z \geqslant 2$	z^{med}	M_{500c}^{med} [10^{14} $M_\odot$]
SPT-SZ	410	7	...	0.6	3.6
SPTpol	600	24	3	0.7	2.5
SPT-3G	6935	477	80	0.7	1.3

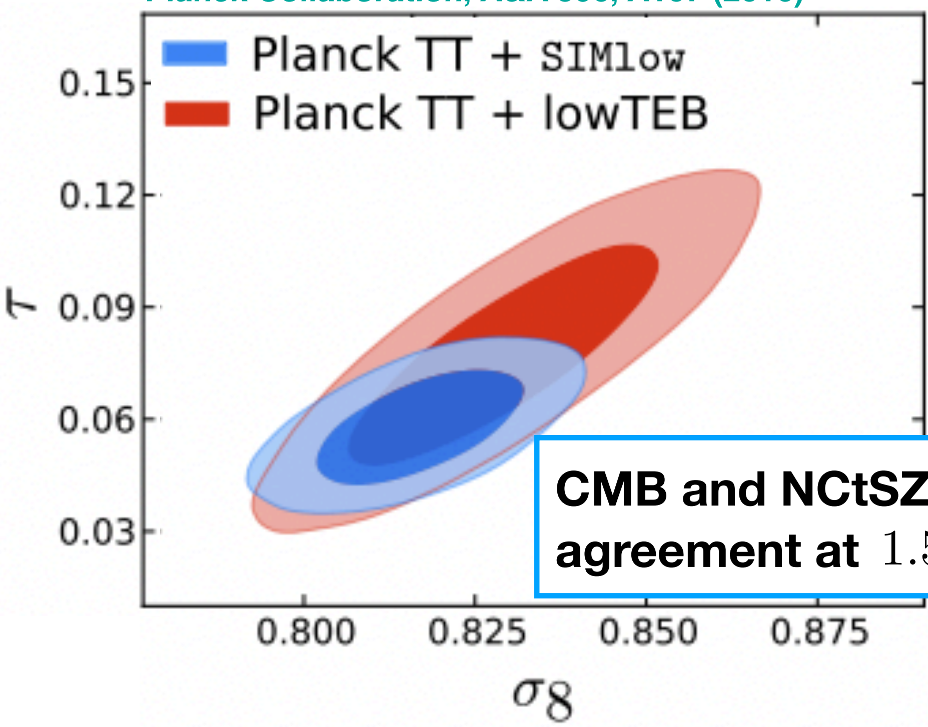
S. Raghunathan, 2022 ApJ 928 16

Back up

Tension or Mass calibration?

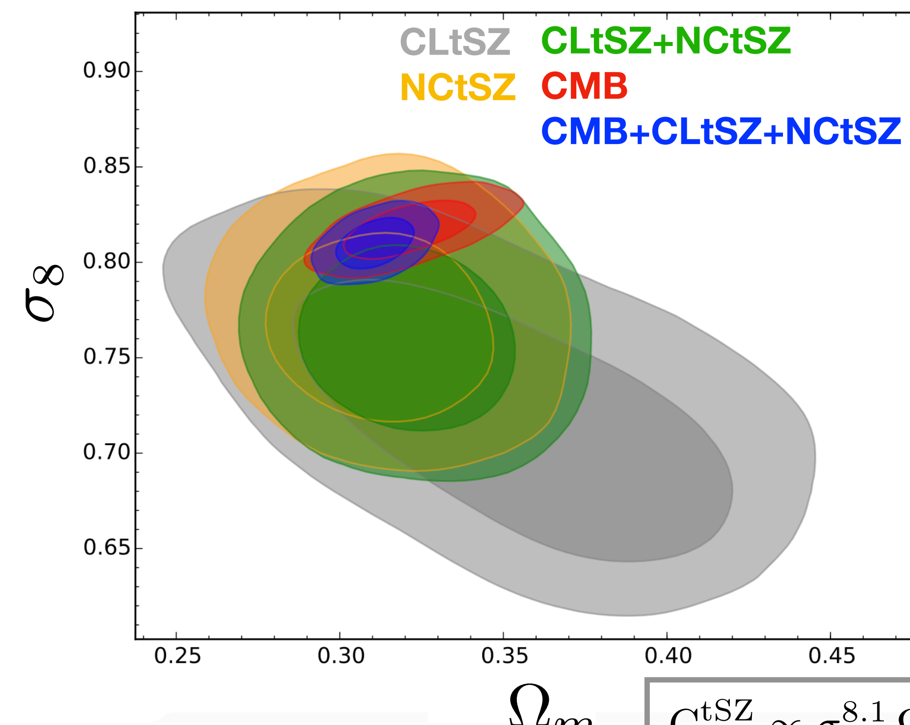
Salvati+
A&A 614 (2018) A13

Planck Collaboration, A&A 596, A107 (2016)



CMB and NCtSZ: agreement at $1.5\,\sigma$ on σ_8

LCDM



$$C_\ell^{\rm tSZ} \propto \sigma_8^{8.1}\,\Omega_m^{3.2}\,(1-b)^{3.2}$$

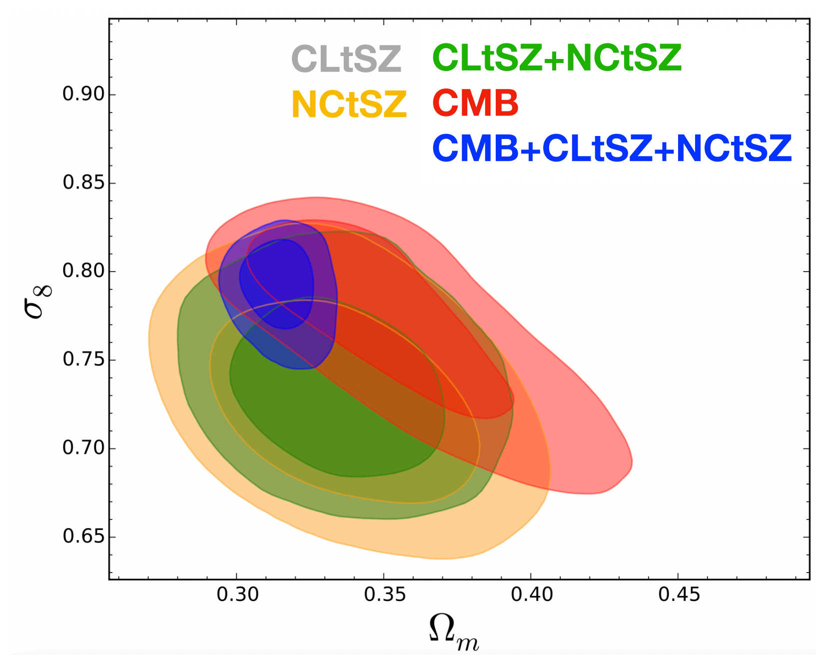
$$NC^{\rm tSZ} \propto \sigma_8^{9}\,\Omega_m^{3}\,(1-b)^{3.6}$$

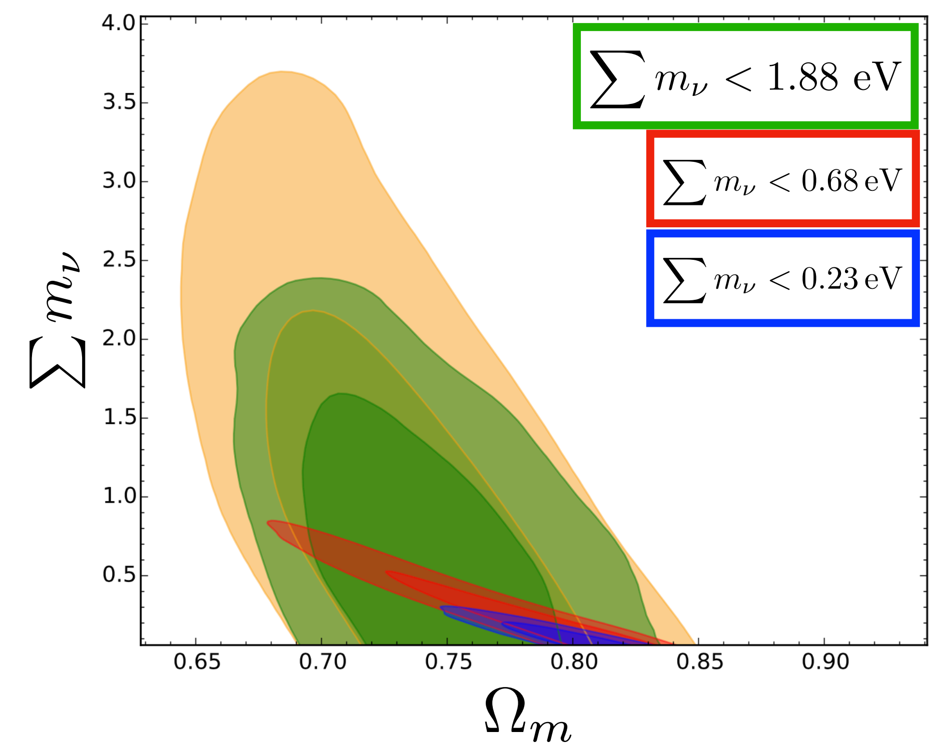
Still discrepancy on (1-b).
Mass bias: strong source of systematics

CMB + NCtSZ

$(1-b) = 0.58 \pm 0.04$	P15
$(1-b) = 0.65 \pm 0.04$	LCDM
$(1-b) = 0.67 \pm 0.04$	Neutrinos
$(1-b) = 0.63 \pm 0.04$	DE
$(1-b) = 0.62 \pm 0.03$	P18

Varying total neutrino mass

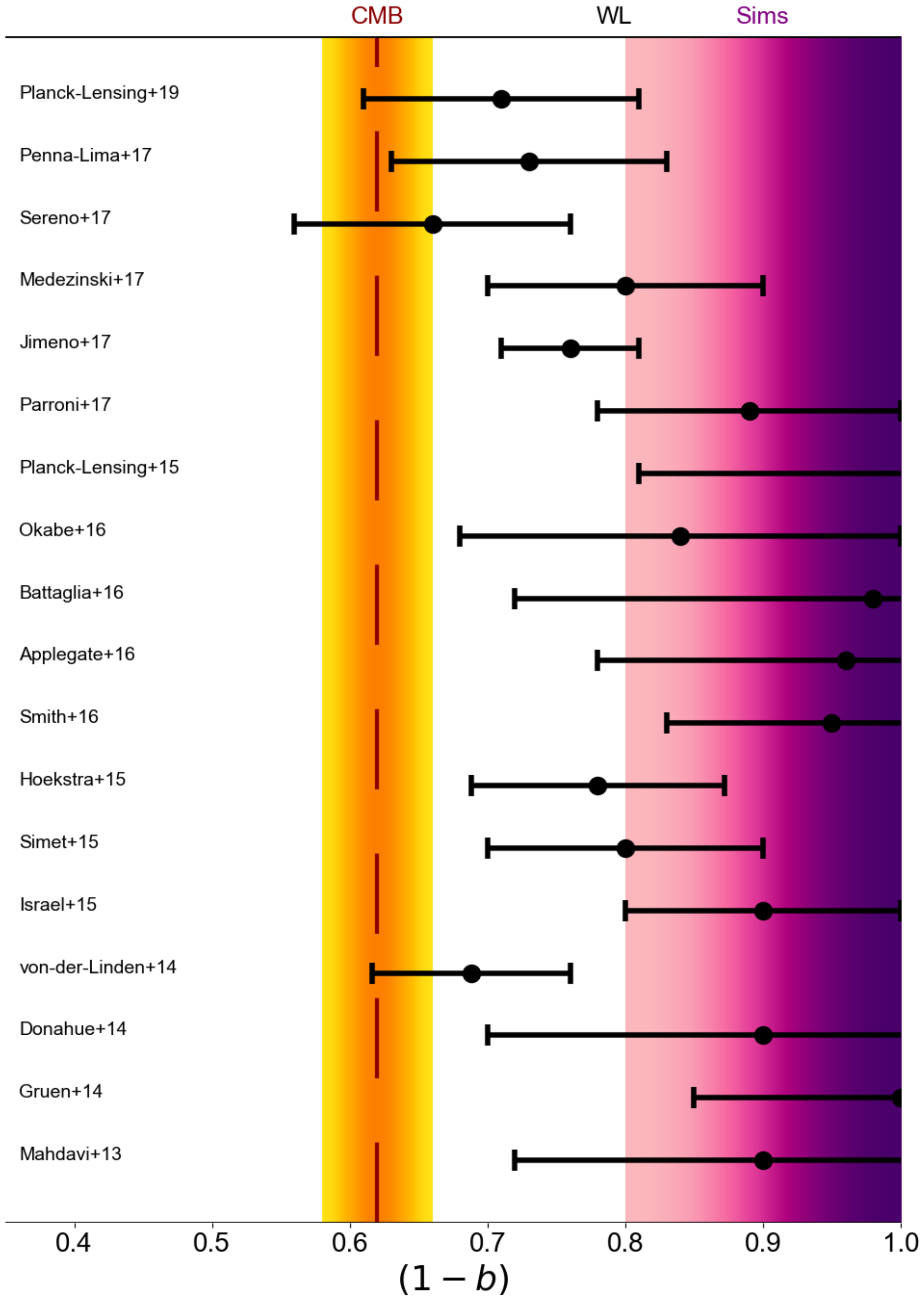




Mass bias

$(1-b) \simeq 0.6$ too low!

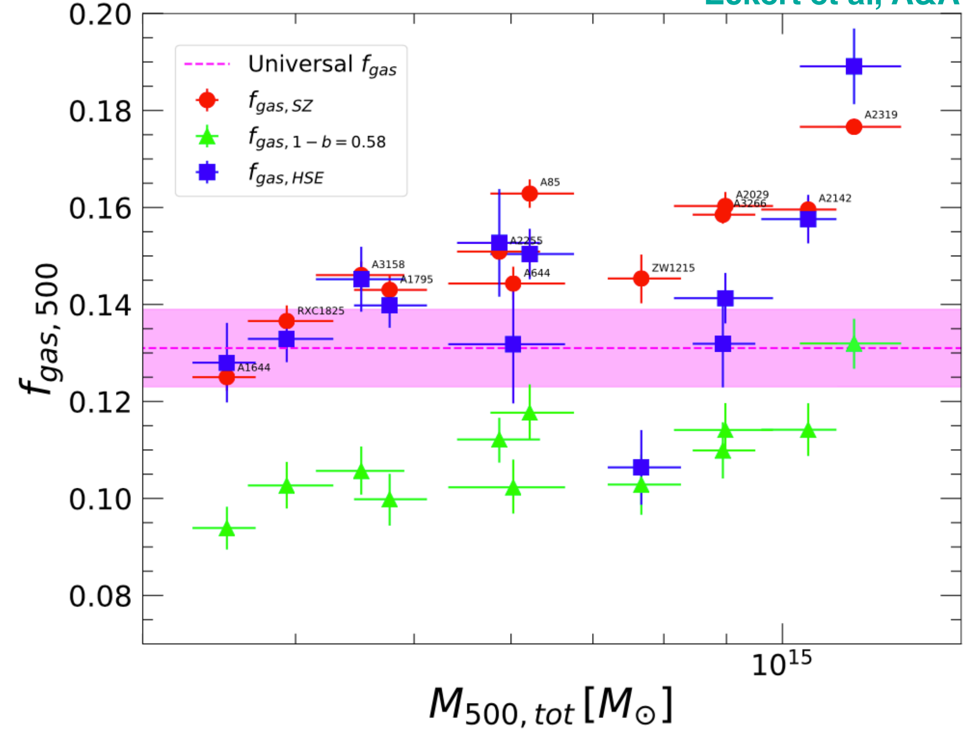
Salvati et al, A&A 614 (2018) A13

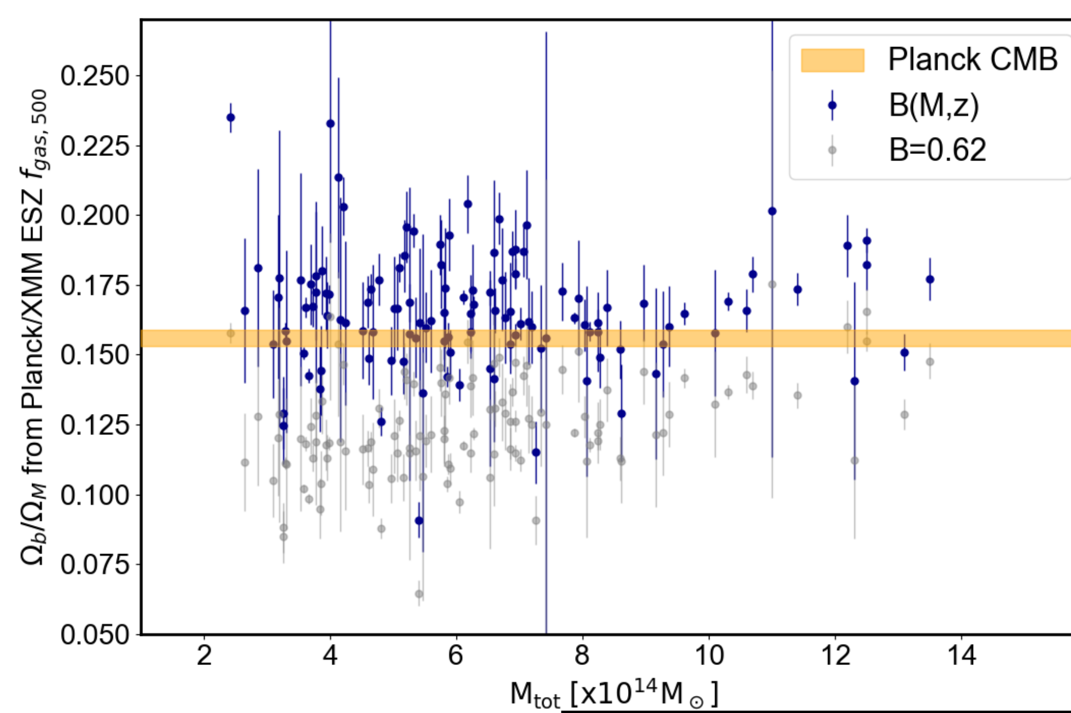


see also results in
Gianfagna et al, MNRAS 502 (2021) no.4, 5115-5133

Mass bias and Gas fraction

Eckert et al, A&A 621, A40 (2019)





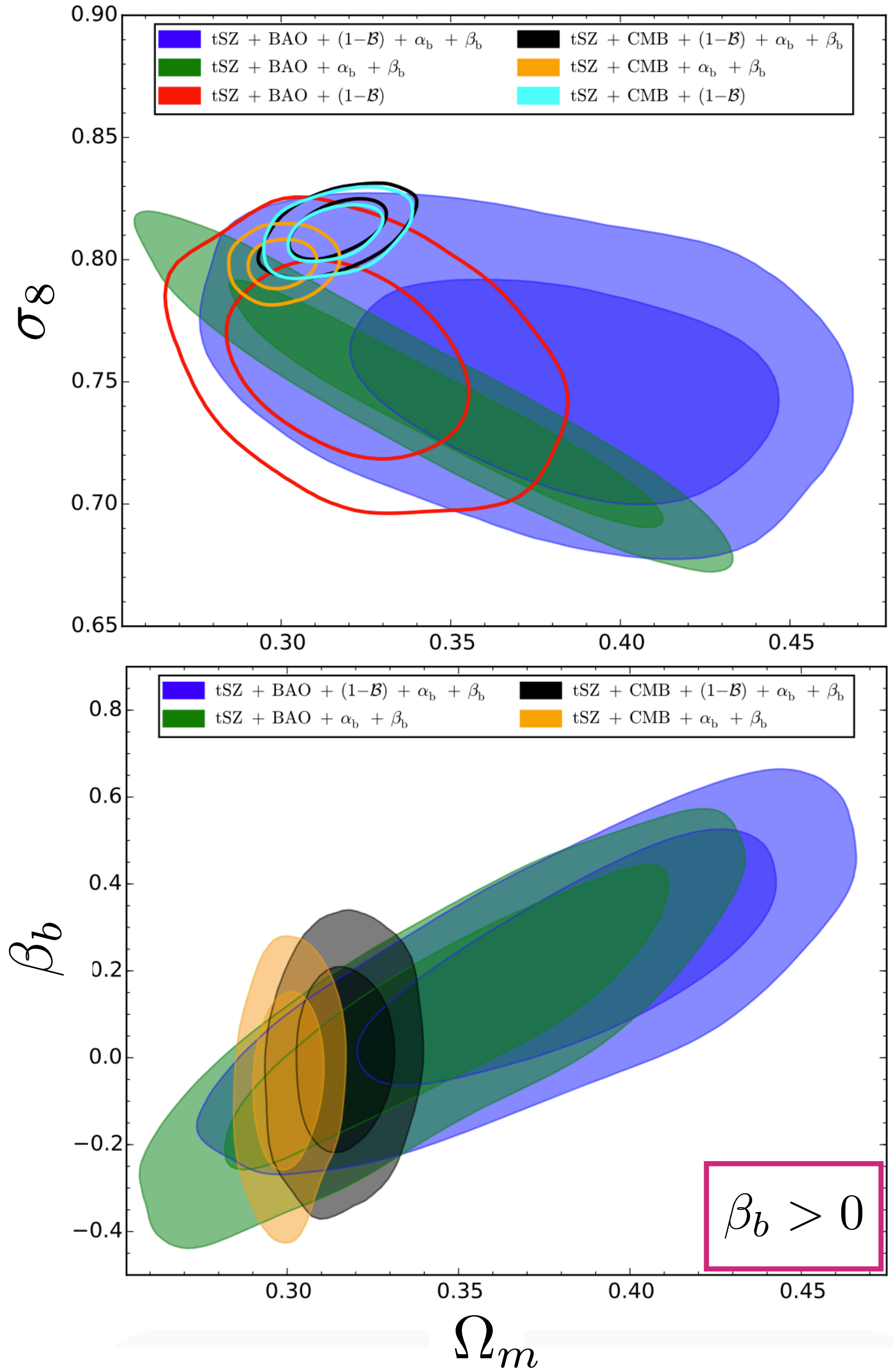
Wicker et al., arXiv:2204.12823 [astro-ph.CO]

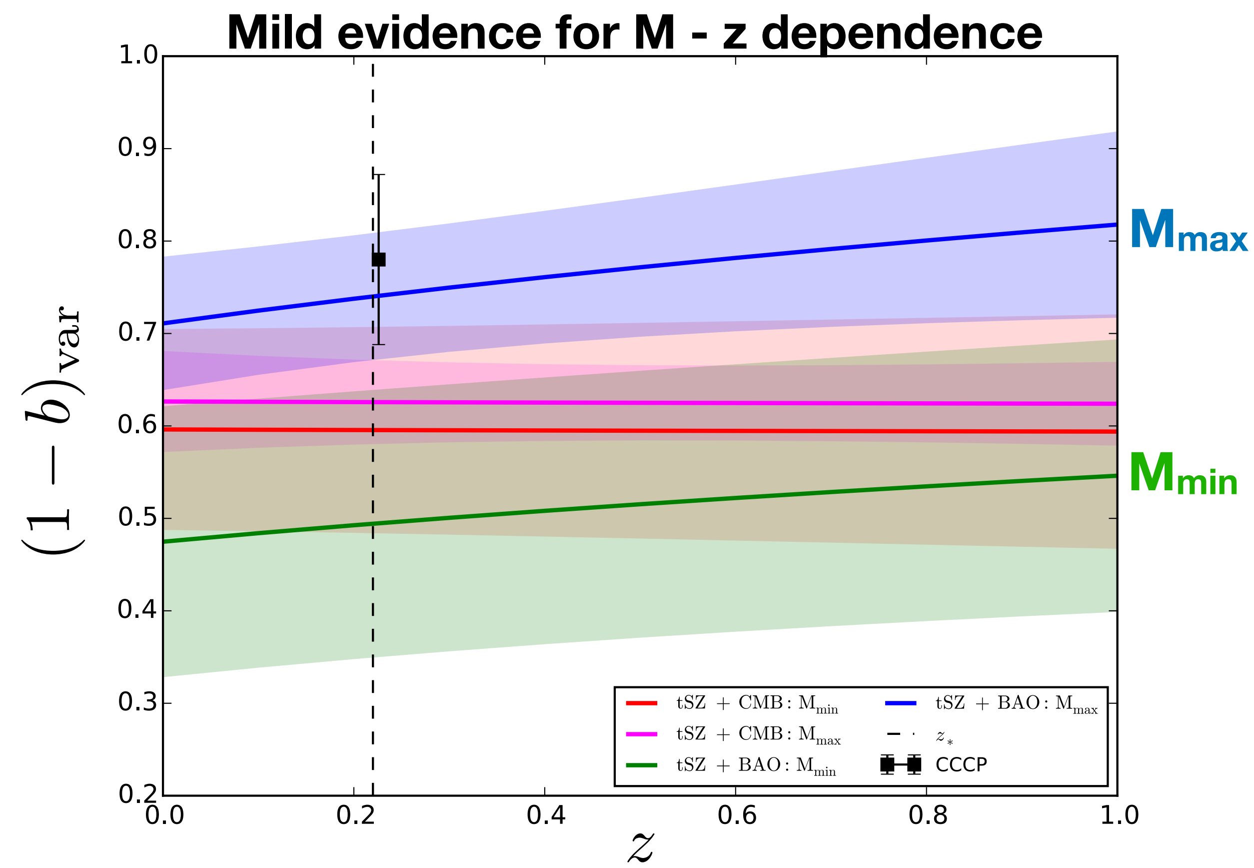
Mass bias: M-z evolution

Salvati+
A&A 626, A27 (2019)

Mass-redshift Parametrisation

$$(1-b)_{\rm var} = (1-\mathcal{B}) \cdot \left(\frac{M}{M_*}\right)^{\alpha_b} \cdot \left(\frac{1+z}{1+z_*}\right)^{\beta_b}$$





(1-b) increasing with redshift

Need fo further understanding!

Laura Salvati

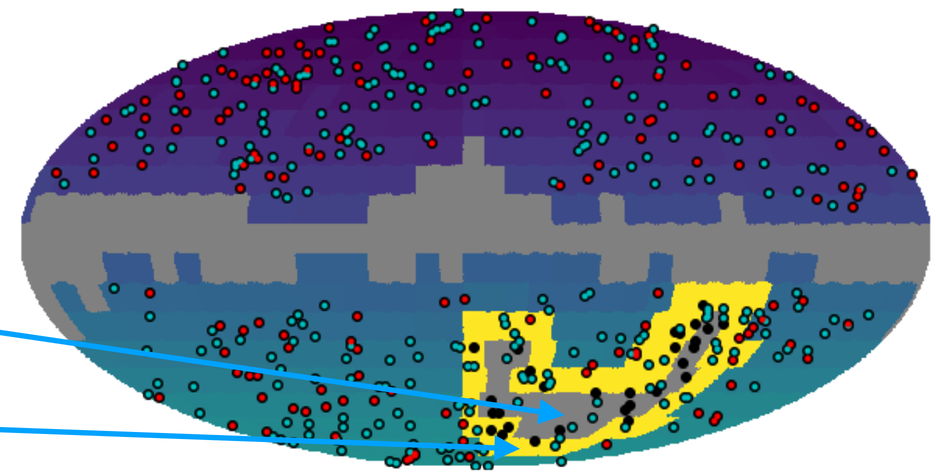
Analysis

Salvati, Saro + SPT collab.
arXiv:2112.03606 [astro-ph.CO]

Combine Planck and SPT-SZ cluster likelihood

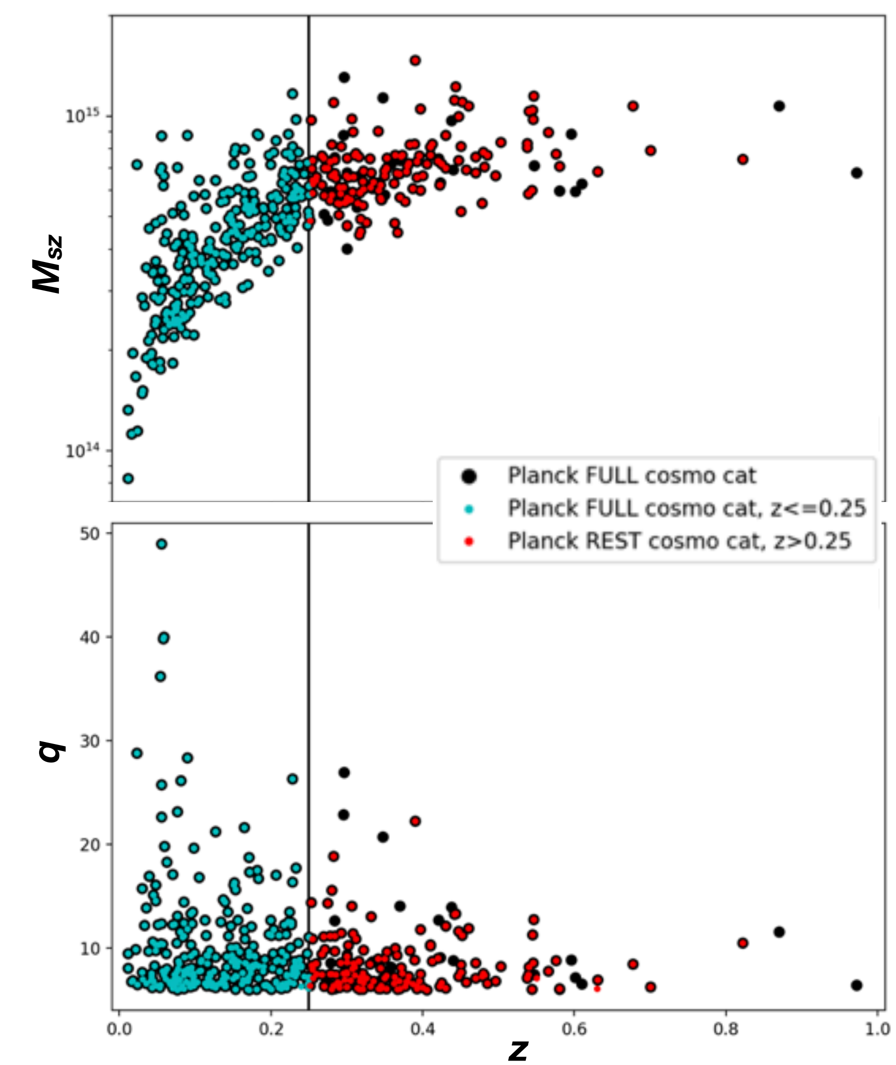
<u>Pre-processing of Planck map</u>

- Starting from original Planck sky
- 417 patches, after applying galactic mask
- Removing 16 sky patches completely overlapping with SPT sky
- Reducing sky fraction of 35 patches partly overlapping with SPT sky



<u>Pre-processing of Planck cluster catalog</u>

- Removing 27 Planck clusters overlapping with SPT catalog + 2 clusters in removed patches

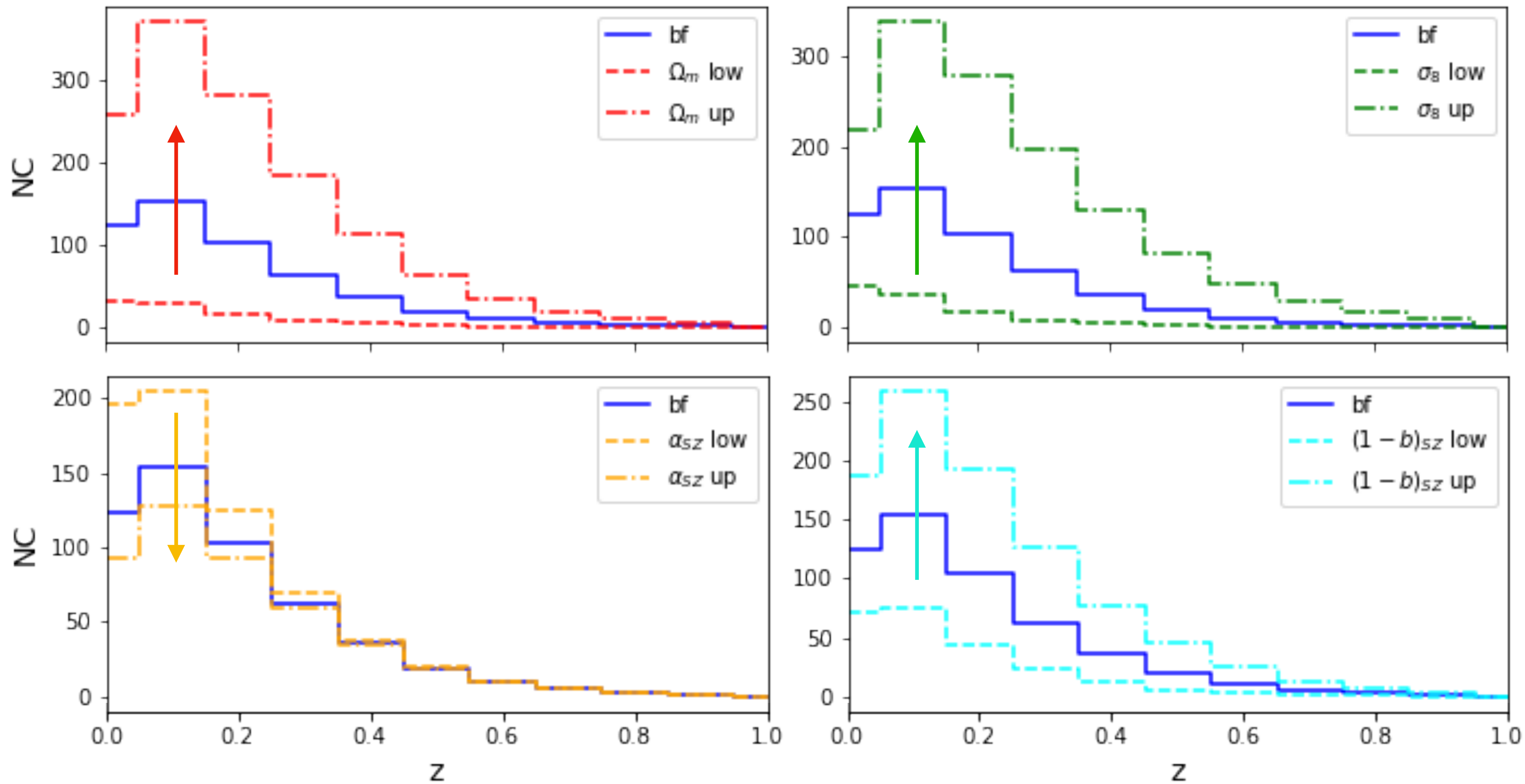


<u>Planck vSPLIT cluster counts likelihood</u>

- z <= 0.25
  - 271 clusters, 417 patches
- z > 0.25
  - 139 clusters, 401 patches

$$\ln \mathscr{L}_{\rm TOT} = \ln \mathscr{L}_{\rm SPT} + \ln \mathscr{L}_{\rm P1} + \ln \mathscr{L}_{\rm P2}$$

Cosmology and Mass Calibration



Planck vs SPT

Different approach for Scaling Relation calibration

Planck: "external"

Planck 2015. A&A 594, A24 (2016)

$$E^{-\beta}(z)\left[\frac{D_{\mathrm{A}}^2(z)\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right]^{\alpha}$$

$$\bar{\theta}_{500} = \theta_*\left[\frac{h}{0.7}\right]^{-2/3}\left[\frac{(1-b)\,M_{500}}{3\times10^{14}\,M_\odot}\right]^{1/3} E^{-2/3}(z)\left[\frac{D_{\mathrm{A}}(z)}{500\,\mathrm{Mpc}}\right]^{-1}$$

$\alpha,\ Y_*$ — From X-ray observations: Subsamples of 20 and 71 clusters

$\frac{M_{SZ}}{M_{500}} = (1-b)$ — From Weak Lensing measurements: 20 X-ray selected massive clusters

β — From the assumption of self-similarity

SPT: "internal"

SPT. Bocquet et al., APJ 878 (2019) no.1, 55

$$\langle \ln\zeta\rangle = \ln A_{\mathrm{SZ}} + B_{\mathrm{SZ}}\ln\left(\frac{M_{500c}\,h_{70}}{4.3\times10^{14}M_\odot}\right) + C_{\mathrm{SZ}}\ln\left(\frac{E(z)}{E(0.6)}\right)$$

$$\ln\left(\frac{M_{500c}\,h_{70}}{8.37\times10^{13}M_\odot}\right) = \ln A_{Y_{\mathrm{X}}} + B_{Y_{\mathrm{X}}}\langle\ln Y_{\mathrm{X}}\rangle + B_{Y_{\mathrm{X}}}\ln\left(\frac{h_{70}^{5/2}}{3\times10^{14}M_\odot\mathrm{keV}}\right) + C_{Y_{\mathrm{X}}}\ln E(z)$$

$$\langle\ln M_{\mathrm{WL}}\rangle = \ln b_{\mathrm{WL}} + \ln M_{500c}.$$

Weak Lensing measurements of 32 clusters

X-ray measurements of 89 clusters

Planck vs SPT

Different approach for Scaling Relation calibration

Planck: "external"

Planck 2015. A&A 594, A24 (2016)

$$\ln \mathscr{L}_p = \sum_{i,j}^{N_z N_q} \left[N_{ij} \ln \bar{N}_{ij} - \bar{N}_{ij} - \ln (N_{ij}!) \right]$$

$$\bar{N}_{ij} = \frac{dN}{dz dq}(z_i, q_j) \Delta z \Delta q$$

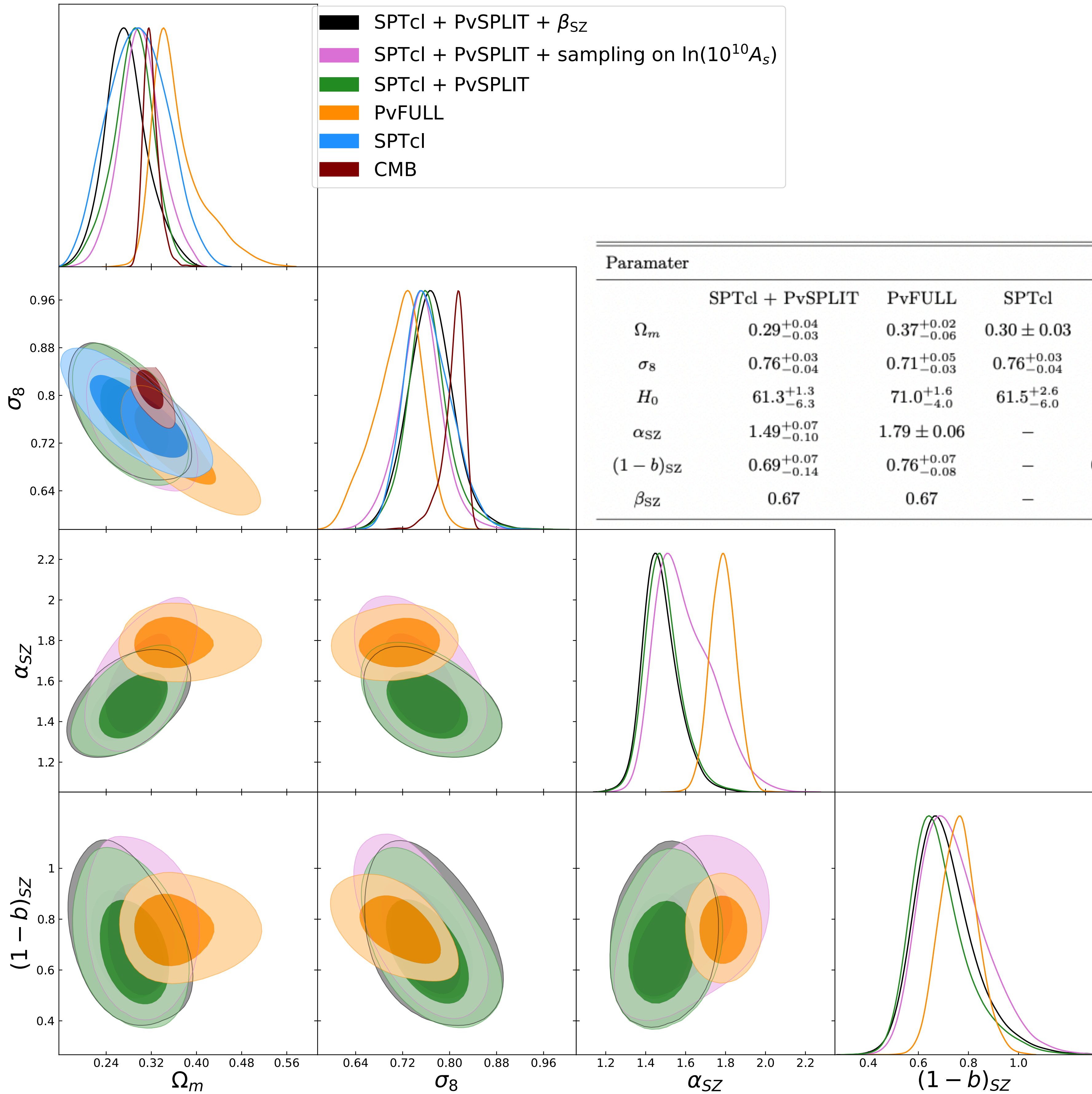
SPT: "internal"

SPT. Bocquet et al., APJ 878 (2019) no.1, 55

$$\ln \mathscr{L}_s = \sum_i \ln \frac{dN(\xi, z|\mathbf{p})}{d\xi dz}\Big|_{\xi_i, z_i} - \int_{z_{\rm cut}}^{\infty} dz \int_{\xi_{\rm cut}}^{\infty} d\xi \frac{dN(\xi, z|\mathbf{p})}{d\xi dz} + \sum_j \ln P(Y_X, g_t|\xi_j, z_j, \mathbf{p})|_{Y_{X_j}, g_{t_j}}$$

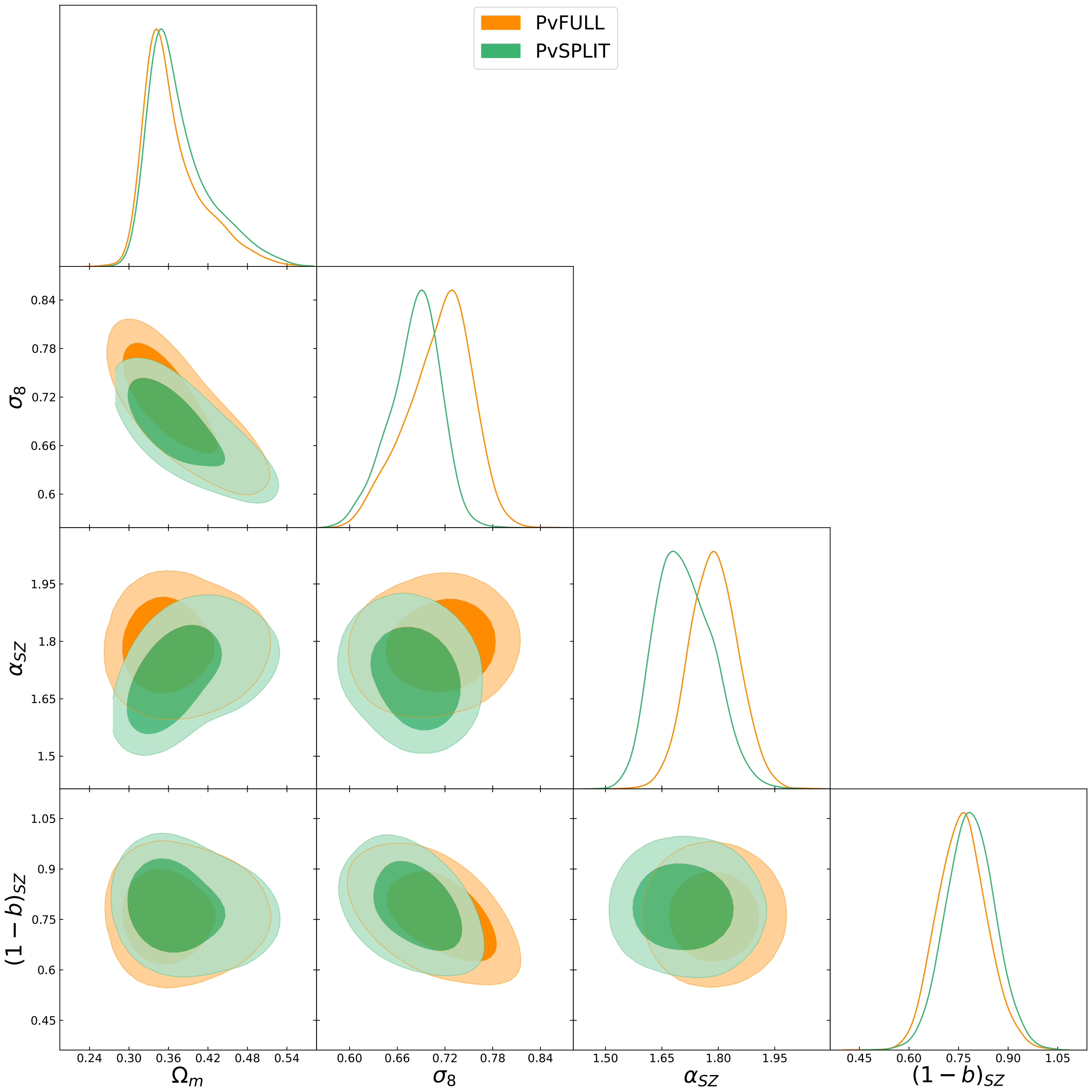
NC(z,obs) = **Mass Function** x **Scaling Relations** x **Selection Function**

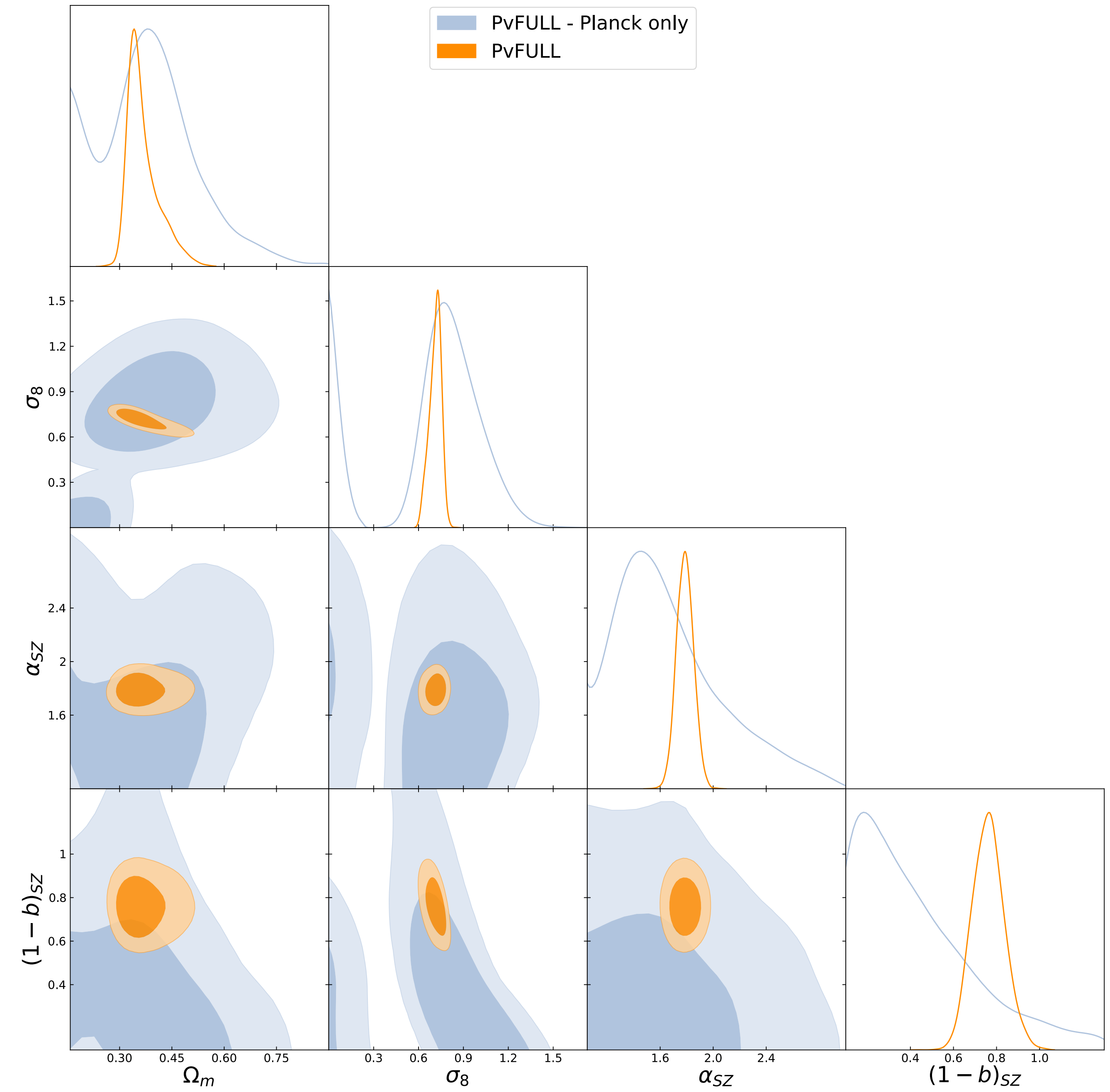
Cosmology and mass calibration



Paramater	$\nu\Lambda$CDM					
	SPTcl + PvSPLIT	PvFULL	SPTcl	PvSPLIT	SPTcl + PvSPLIT + $\ln A_s$	SPTcl + PvSPLIT + β_{SZ}
Ω_m	$0.29^{+0.04}_{-0.03}$	$0.37^{+0.02}_{-0.06}$	0.30 ± 0.03	$0.38^{+0.02}_{-0.06}$	$0.30^{+0.03}_{-0.04}$	$0.28^{+0.03}_{-0.04}$
σ_8	$0.76^{+0.03}_{-0.04}$	$0.71^{+0.05}_{-0.03}$	$0.76^{+0.03}_{-0.04}$	$0.68^{+0.04}_{-0.03}$	0.75 ± 0.03	0.77 ± 0.04
H_0	$61.3^{+1.3}_{-6.3}$	$71.0^{+1.6}_{-4.0}$	$61.5^{+2.6}_{-6.0}$	$71.2^{+1.7}_{-4.0}$	$69.4^{+5.9}_{-14.4}$	$61.8^{+1.3}_{-6.8}$
α_{SZ}	$1.49^{+0.07}_{-0.10}$	1.79 ± 0.06	–	$1.71^{+0.07}_{-0.09}$	$1.60^{+0.10}_{-0.18}$	$1.48^{+0.07}_{-0.10}$
$(1-b)_{SZ}$	$0.69^{+0.07}_{-0.14}$	$0.76^{+0.07}_{-0.08}$	–	0.79 ± 0.07	$0.74^{+0.09}_{-0.16}$	$0.71^{+0.08}_{-0.14}$
β_{SZ}	0.67	0.67	–	0.67	0.67	$0.57^{+0.20}_{-0.51}$

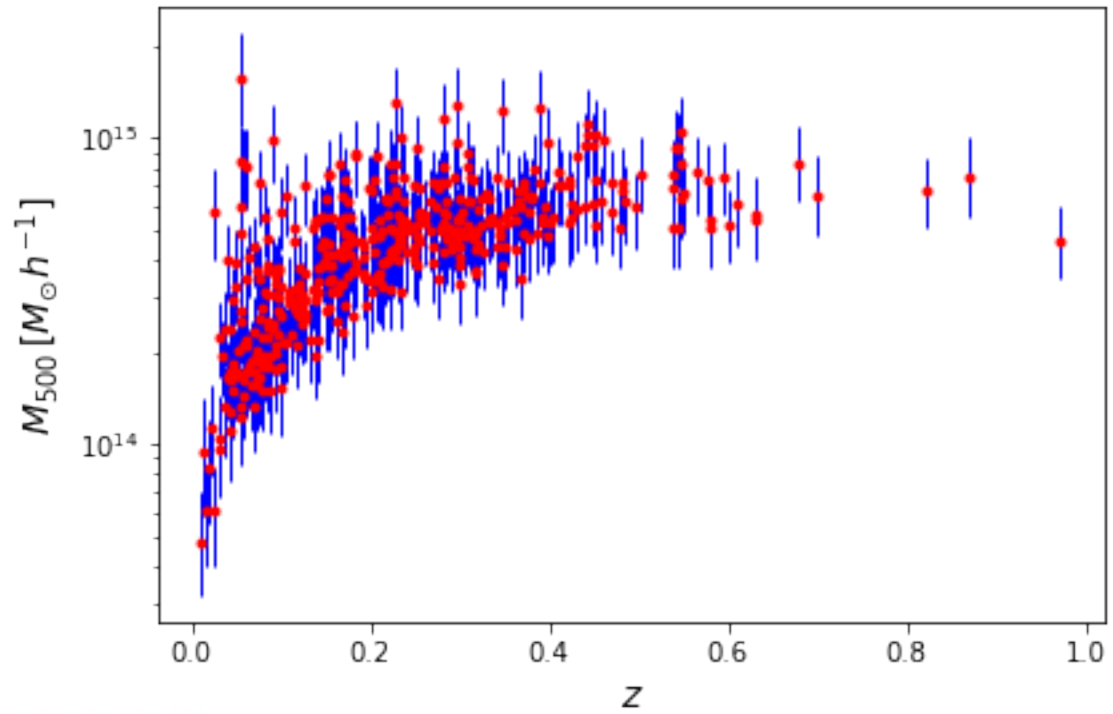
Cosmology and mass calibration





Mass evaluation

Through Monte-Carlo extraction



$$P(M_{500}|q) \propto P(q|M_{500}) \cdot P(M_{500})$$

$P(M_{500})$ → related to Mass Function

$P(q|M_{500})$ ↓

$$P[q|\bar{q}_m(M_{500}, z, l, b)] = \int d\ln q_m \frac{e^{-(q-q_m)^2/2}}{\sqrt{2\pi}} \frac{e^{-\ln^2(q_m/\bar{q}_m)/2\sigma^2_{\ln Y}}}{\sqrt{2\pi}\sigma_{\ln Y}}$$

link between theoretical signal-to-noise q_m to the observed one, assuming pure Gaussian noise

intrinsic scatter of the mass-observable relation

$$\bar{q}_m \equiv \frac{\bar{Y}_{500}}{\sigma_f(\bar{\theta}_{500}, l, b)}$$

$$E^{-\beta}(z)\left[\frac{D_A^2(z)\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right]^{\alpha}$$

$$\bar{\theta}_{500} = \theta_*\left[\frac{h}{0.7}\right]^{-2/3}\left[\frac{(1-b)\,M_{500}}{3\times10^{14}\,M_\odot}\right]^{1/3} E^{-2/3}(z)\left[\frac{D_A(z)}{500\,\mathrm{Mpc}}\right]^{-1},$$