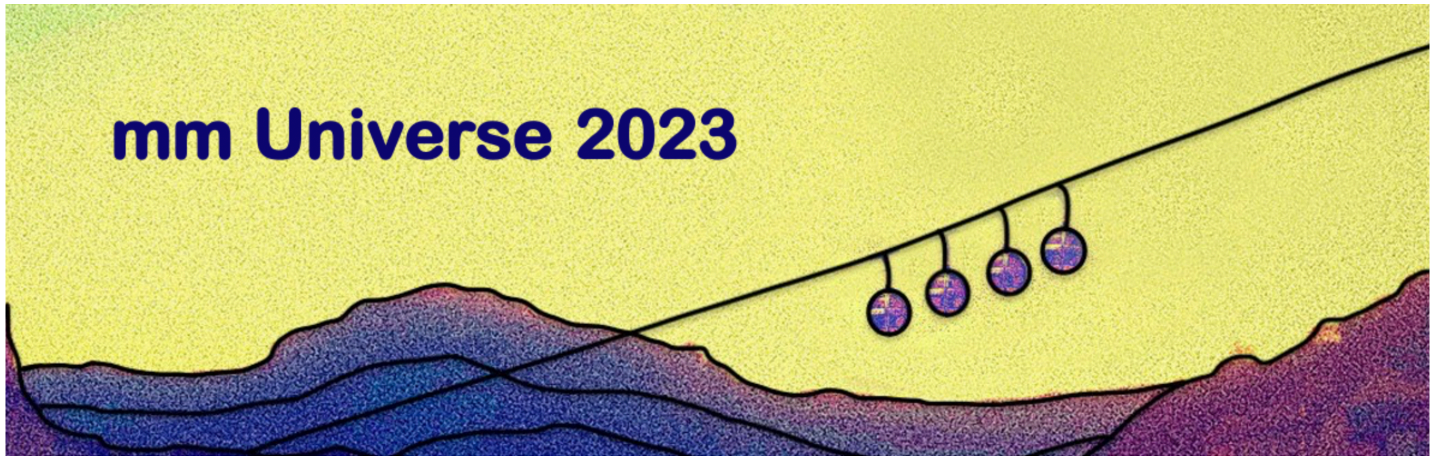


Planck and SPT cluster catalogs

A combined analysis

Laura Salvati

IAS Orsay
Osservatorio Astronomico di Trieste – INAF Istituto Nazionale di Astrofisica
cnrs
ClustersXCosmo
erc European Research Council

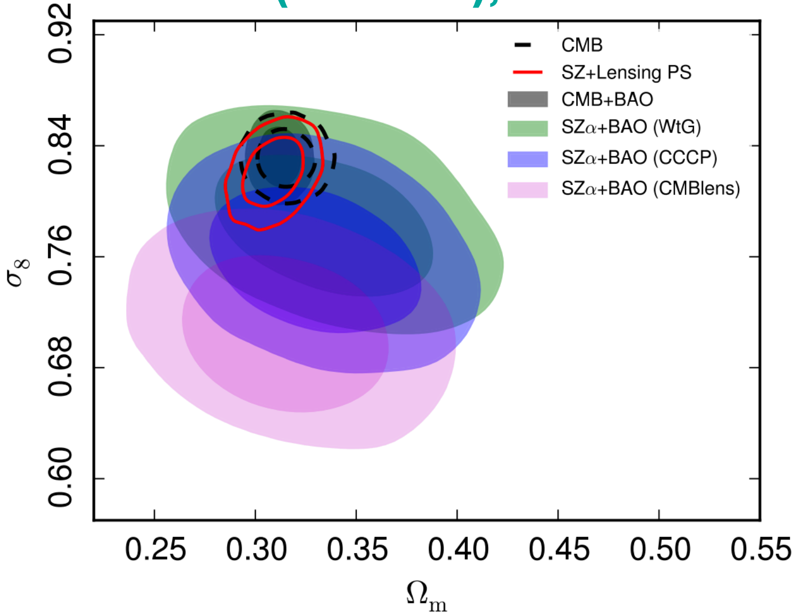
Outline

Cluster Cosmology

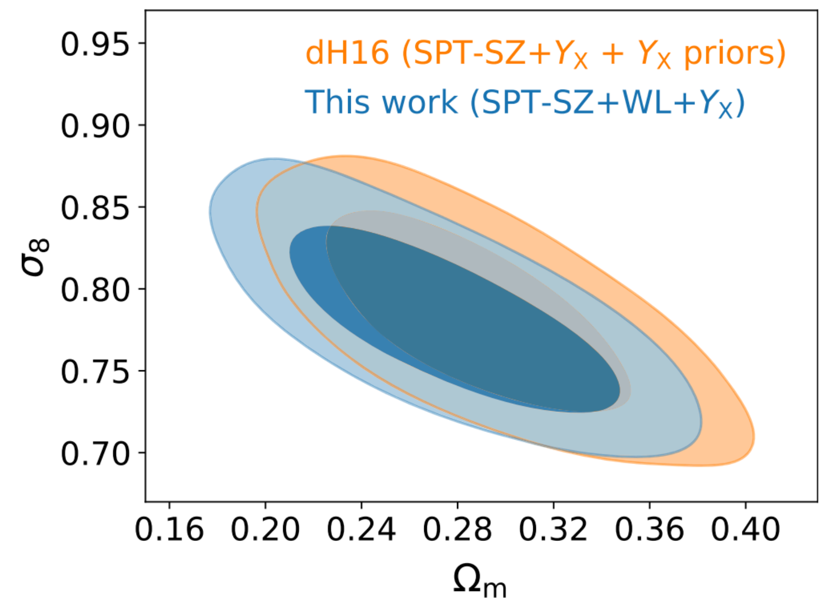
- Impact of cluster mass calibration
- Combine cluster catalogs:
  - Planck and SPT
    - Step I: independent calibration of Planck scaling relations

Cluster Cosmology

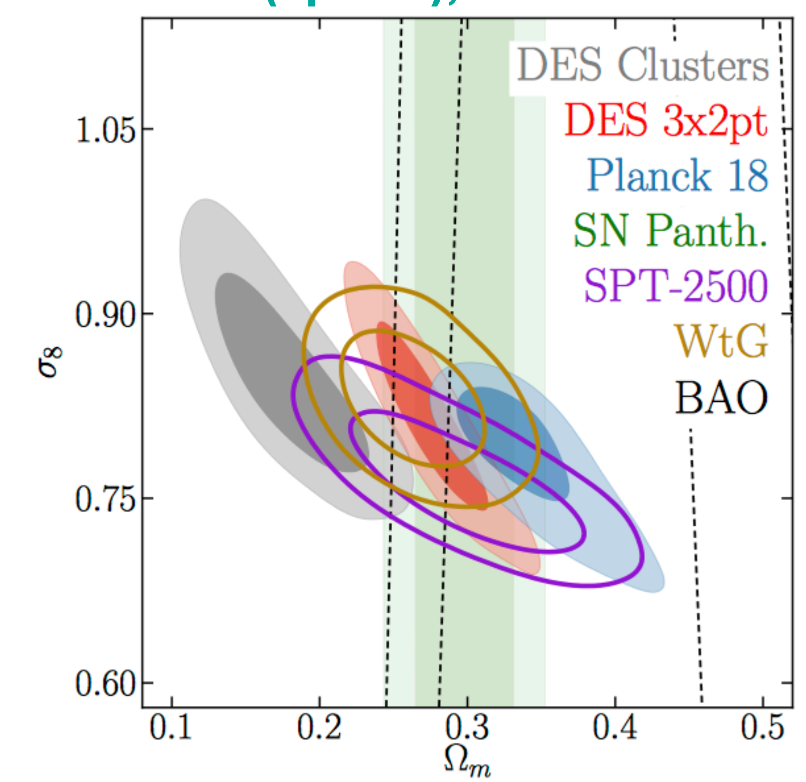
Planck (tSZ-mm), Ade et al. 2016



SPT (tSZ-mm), Bocquet et al. 2019

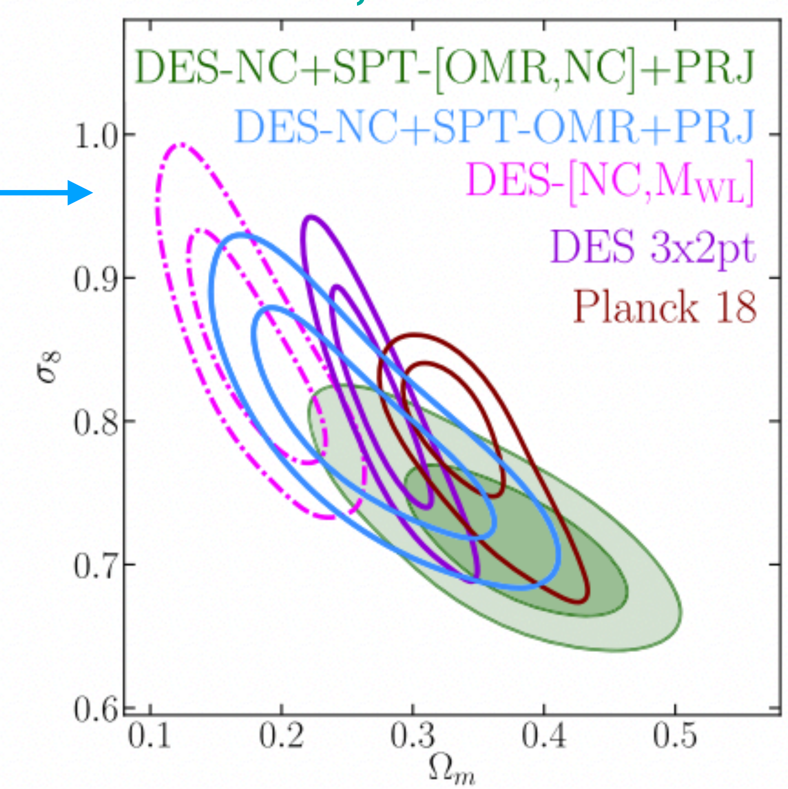


DES (optical), Abbott et al. 2020

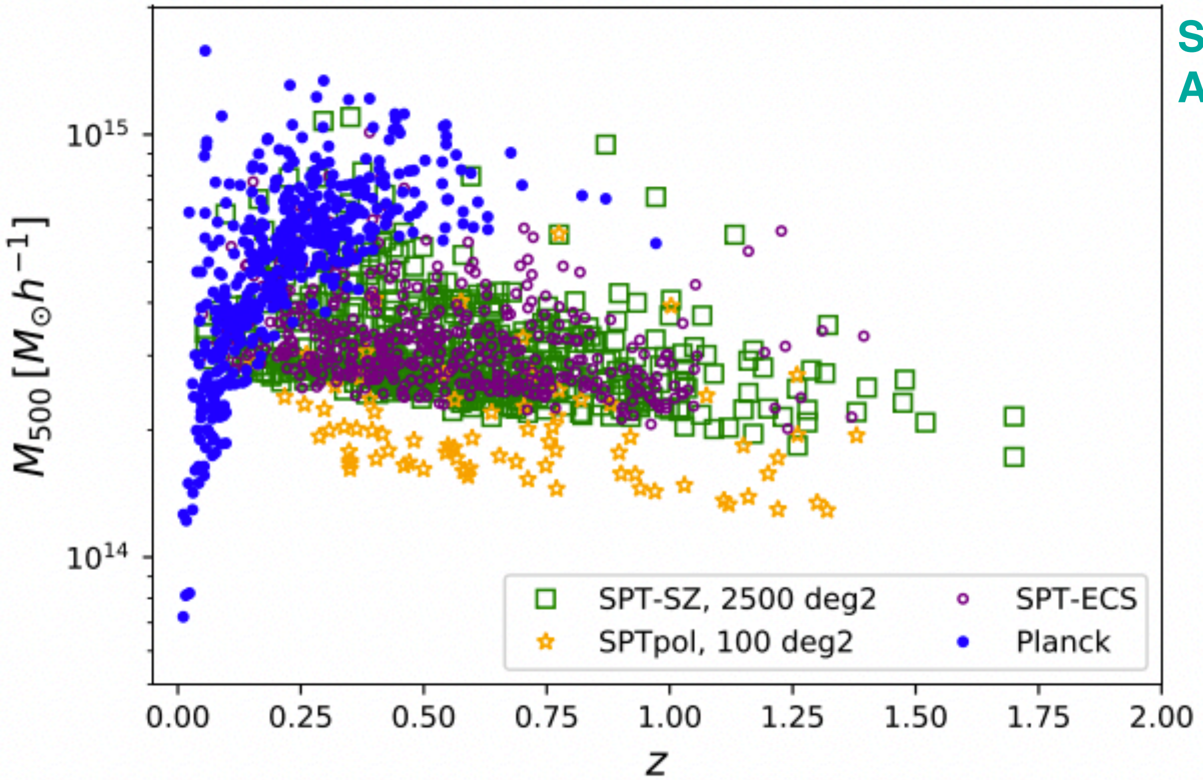


See talks of
Lindsey Bleem and Sebastian Bocquet

SPT+DES, Costanzi et al. 2021



Planck + SPT



Salvati et al., ApJ 934, no.2, 129 (2022)

Planck

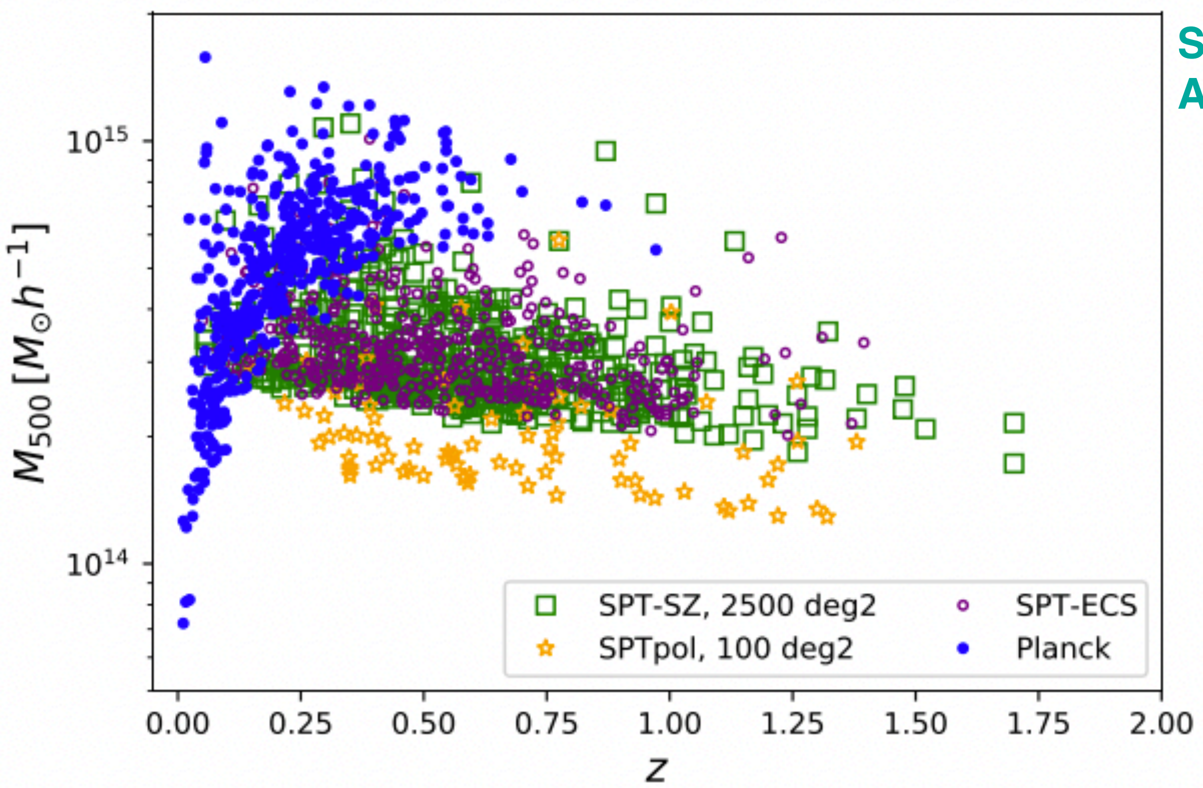
Planck 2015. A&A 594, A24 (2016)
Planck 2015. A&A 594, A27 (2016)

- 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



Salvati et al.,
ApJ 934, no.2, 129 (2022)

Paper I. Combining Planck and SPT Cluster Catalogs:
Cosmological Analysis and Impact on the Planck Scaling Relation Calibration

- First combined cosmological analysis of Planck and SPT-SZ cluster catalogs
- Independent calibration of Planck scaling relations, exploiting cosmological constraining power of SPT-SZ sample

Mass calibration

Cluster number counts:

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

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

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

Planck Scaling Relations

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

$\alpha,\ Y_*$ → from X-ray observations

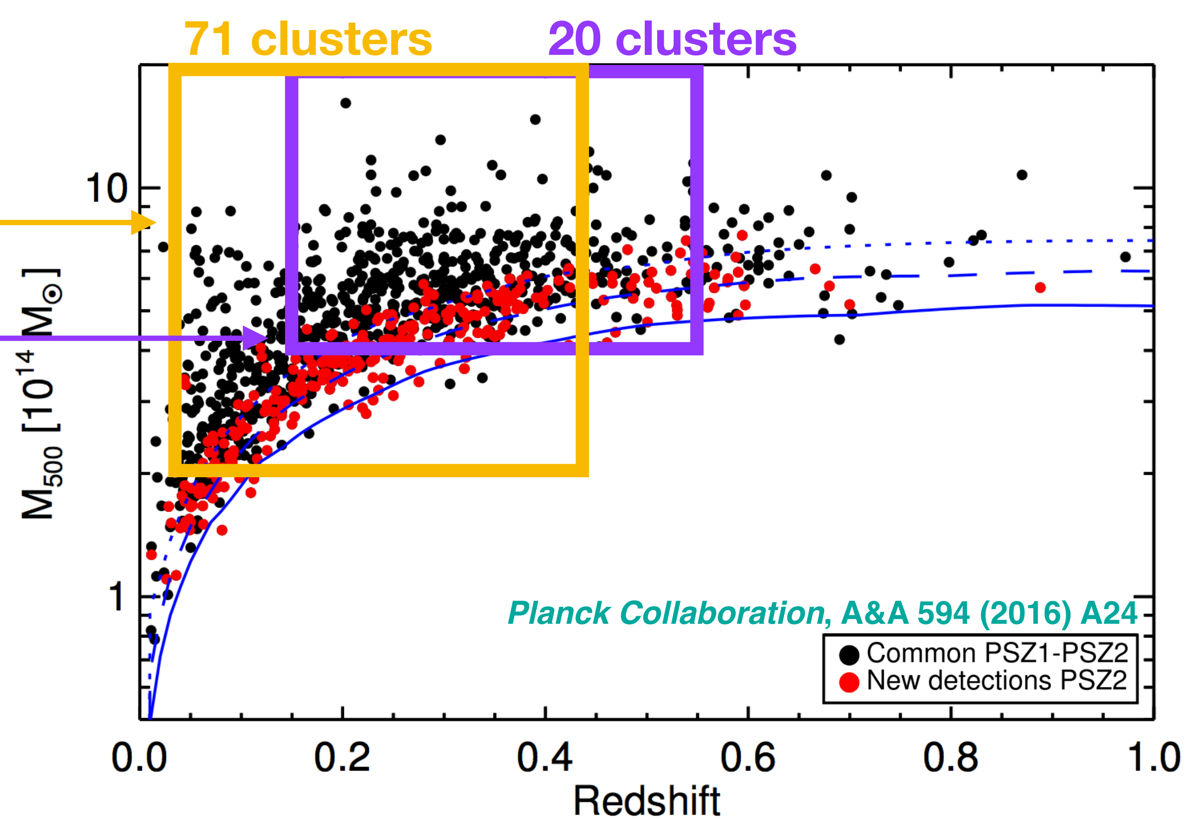
$(1-b)$ → from WL mass evaluations

$\beta = 2/3$ → from self-similarity

Planck Collaboration, A&A 594 (2016) A24

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

Planck cosmological cluster sample: 439 clusters



tSZ clusters: Planck

Mass calibration

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- Hydrostatic equilibrium

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$\alpha,\ Y_*$ → from X-ray observations

$(1-b)$ → from WL mass evaluations

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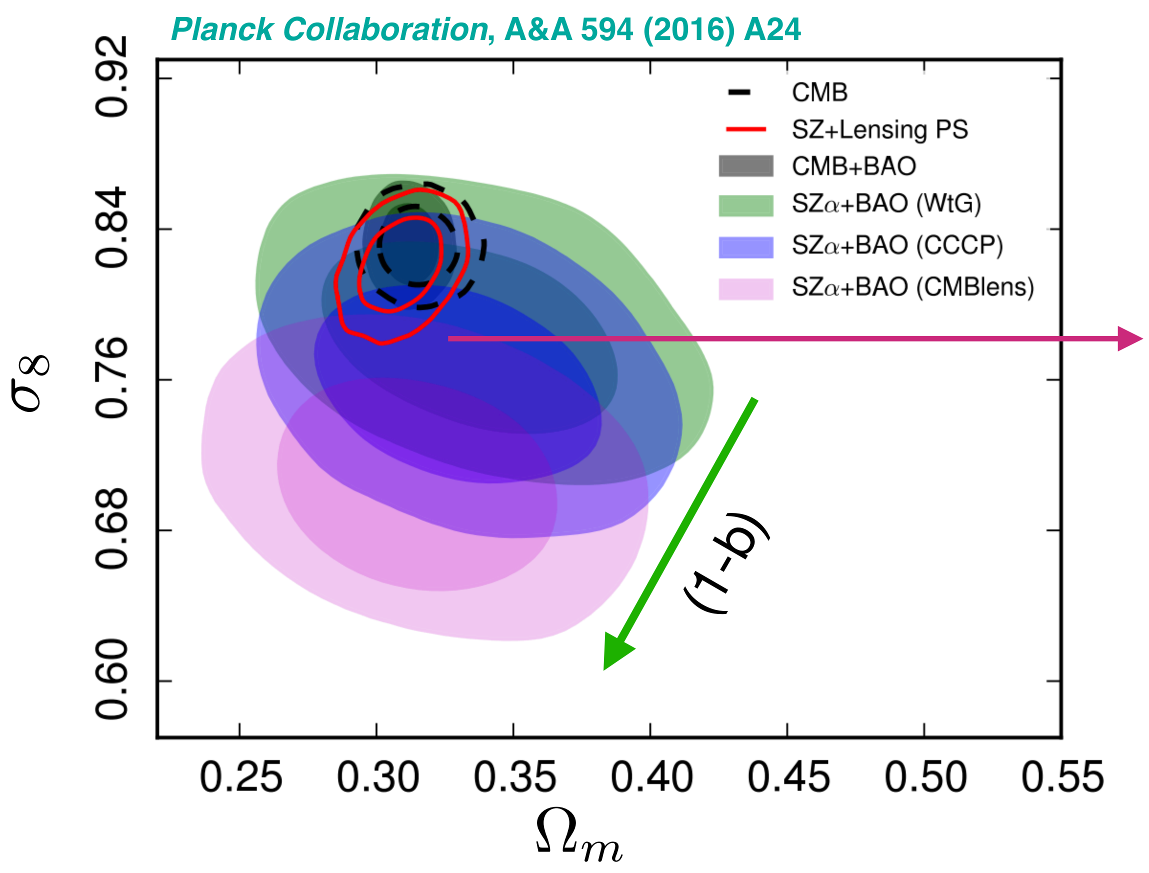
Planck Collaboration, A&A 594 (2016) A24

New scaling relation calibration
Gaspard Aymerich

Cosmology and mass calibration



tension between CMB primary anisotropies and Galaxy Clusters: $\simeq 2.4\,\sigma$ on σ_8

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

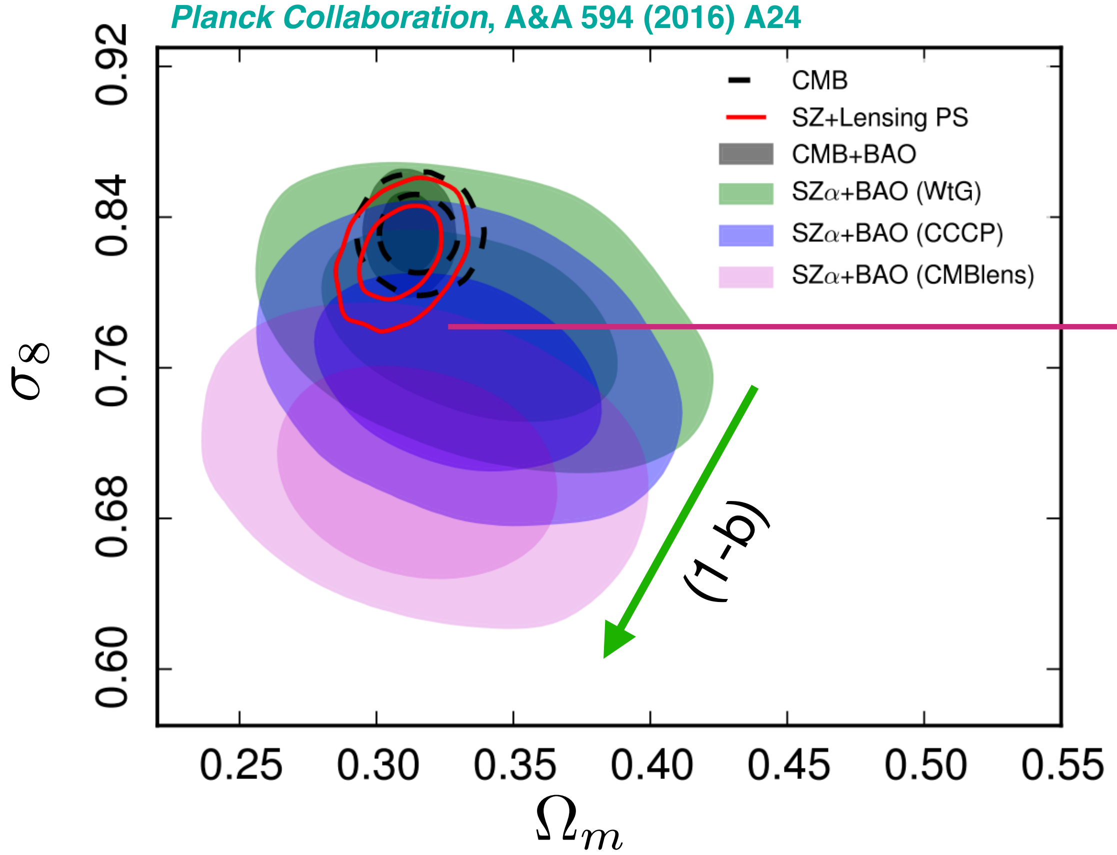
$$\mathrm{CMB + NC^{tSZ}}: (1-b) = 0.58 \pm 0.04$$

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

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**

Cosmology and mass calibration



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

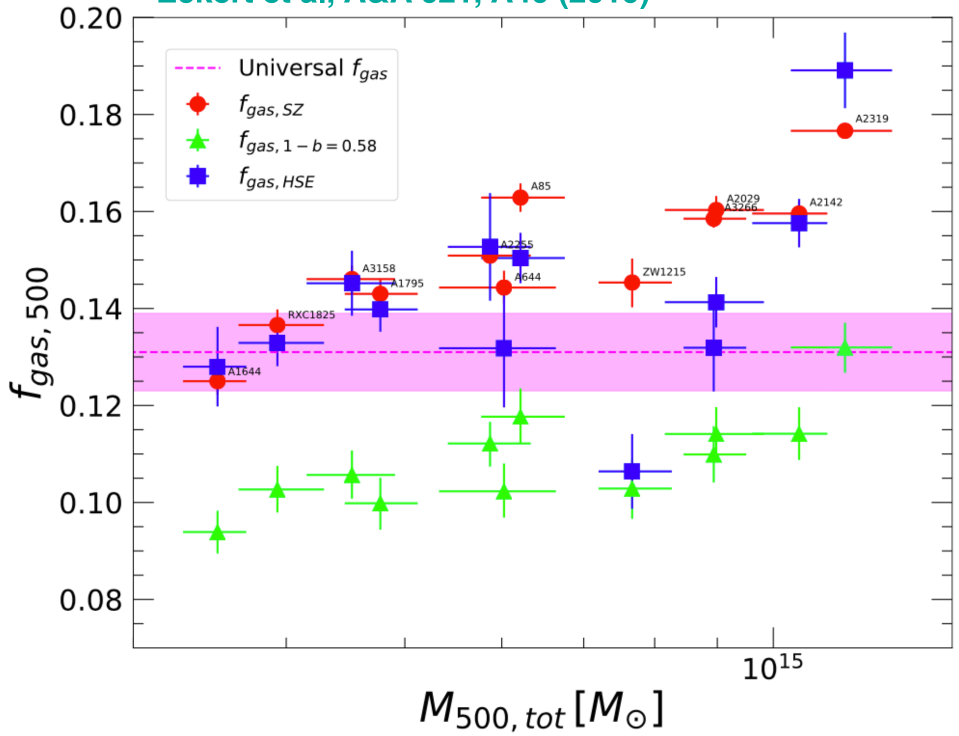
Characterisation of the mass bias
Théo Lebeau

Mass bias

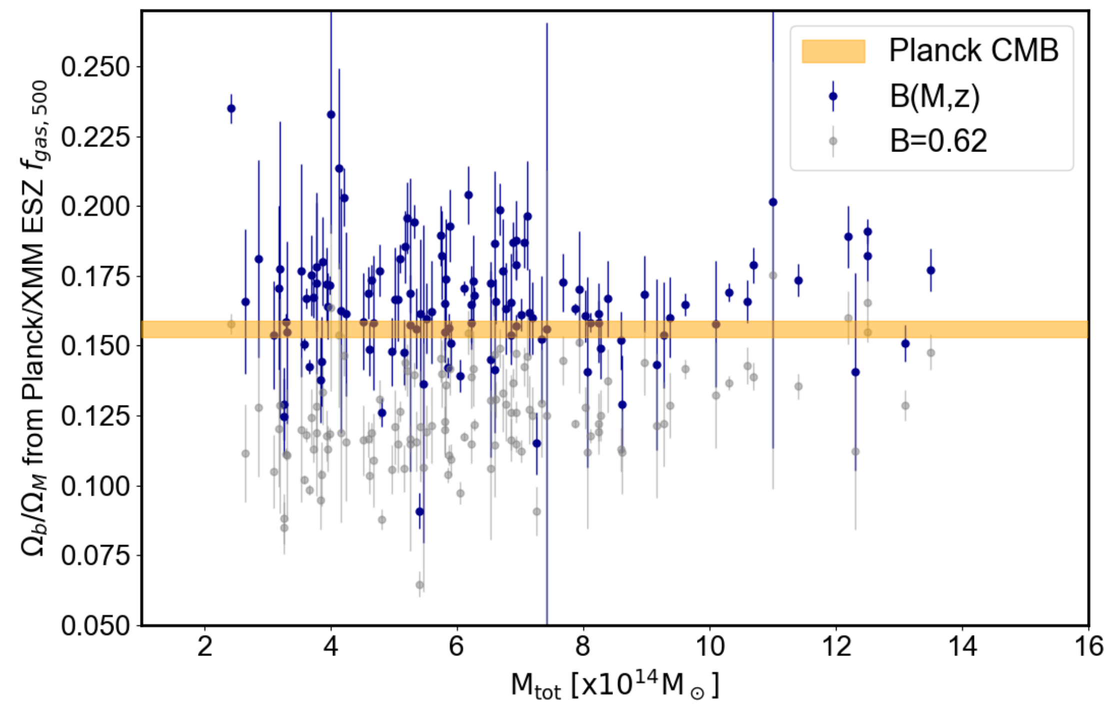
$(1-b) \simeq 0.6$ too low!

Gas fraction

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



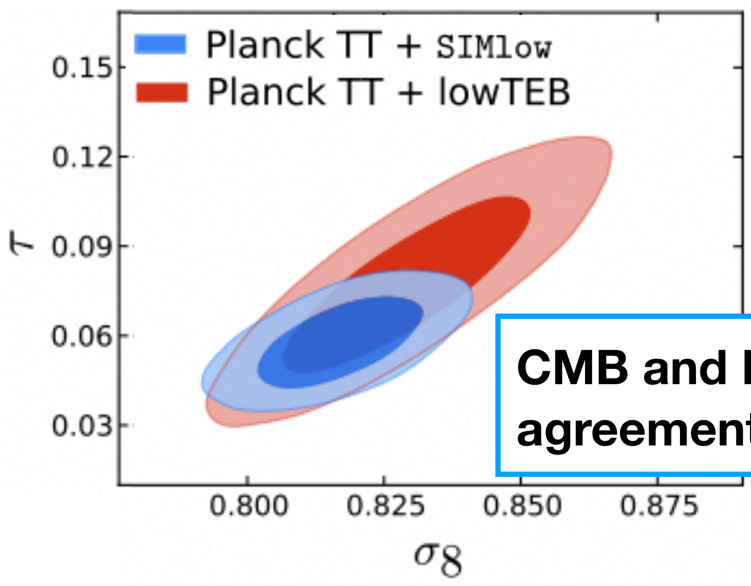
Wicker et al., A&A 674 (2023), A48



Gas fraction and mass bias
Raphael Wicker

Tension or mass calibration

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



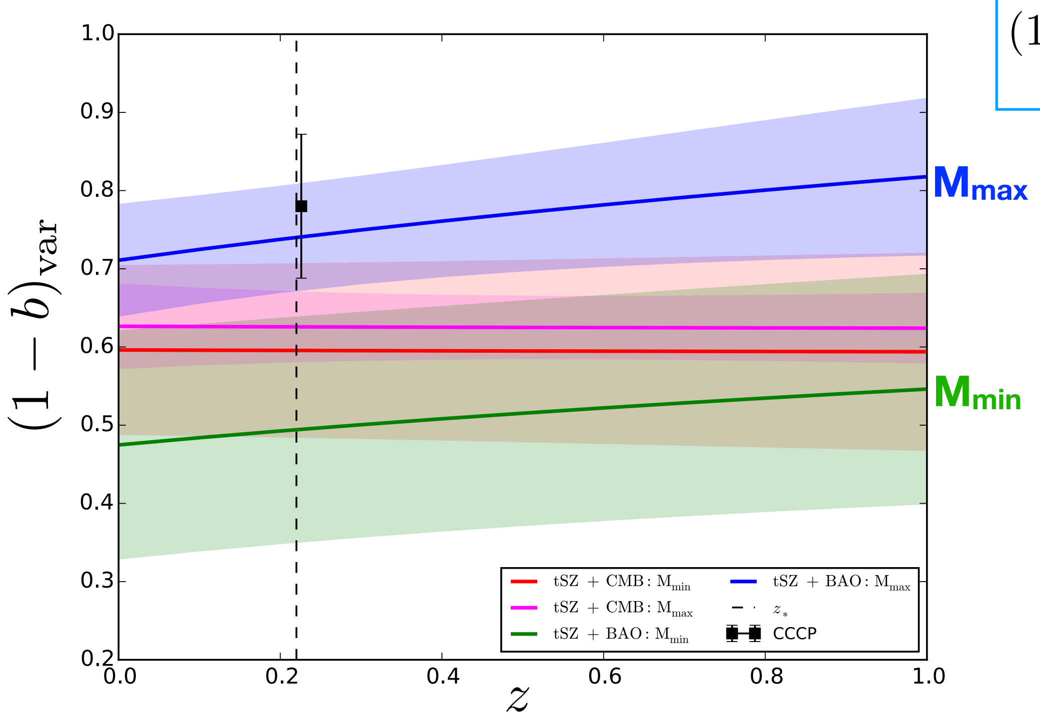
CMB and NCtSZ: agreement at $1.5\,\sigma$ on σ_8

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

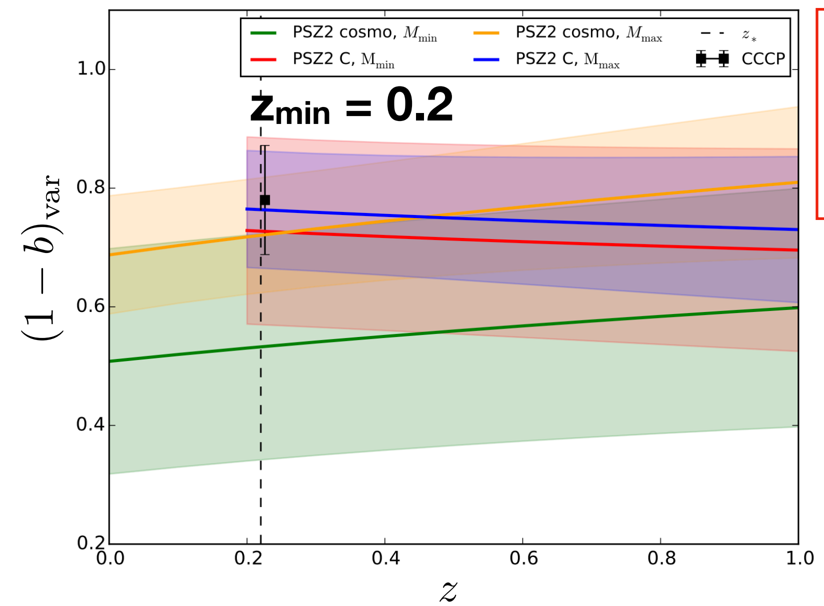
Salvati et al., A&A 614, A13 (2018)

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



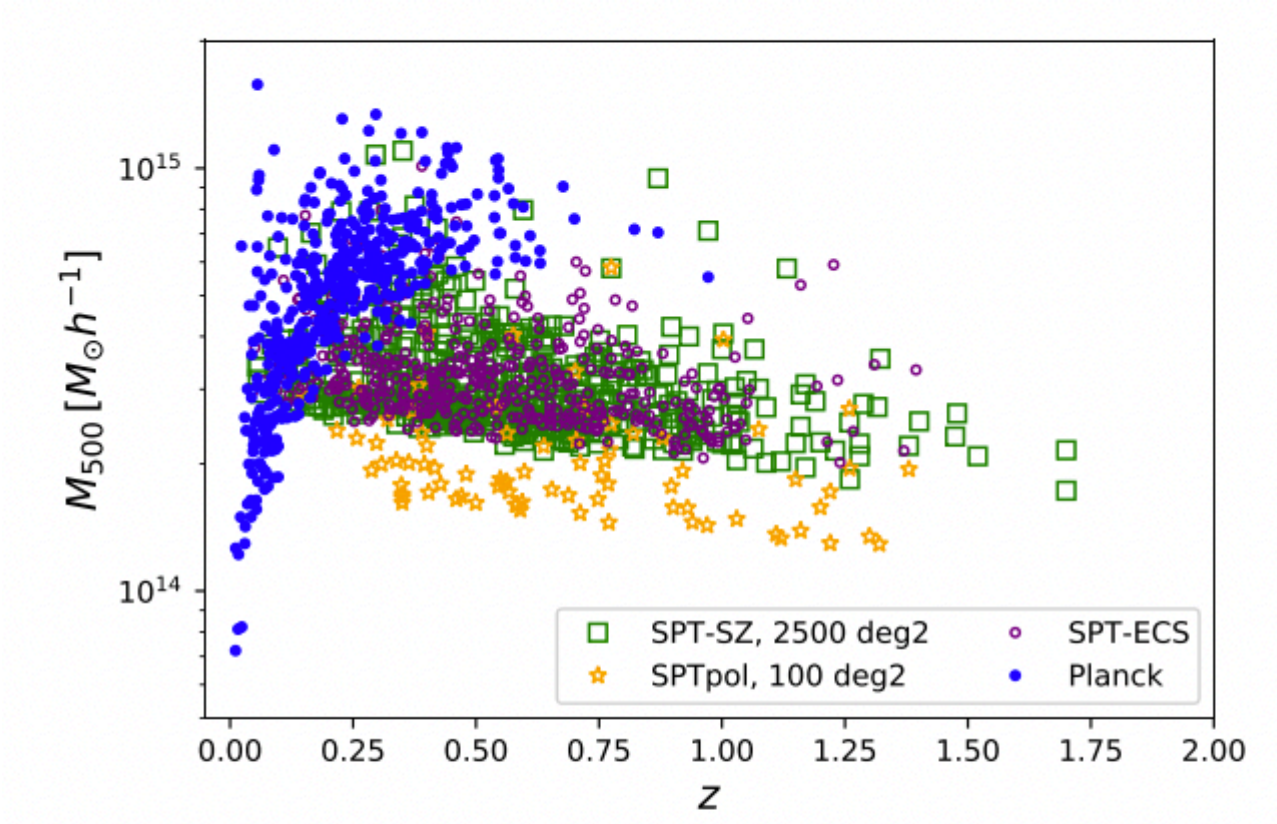
(1-b) increasing with redshift

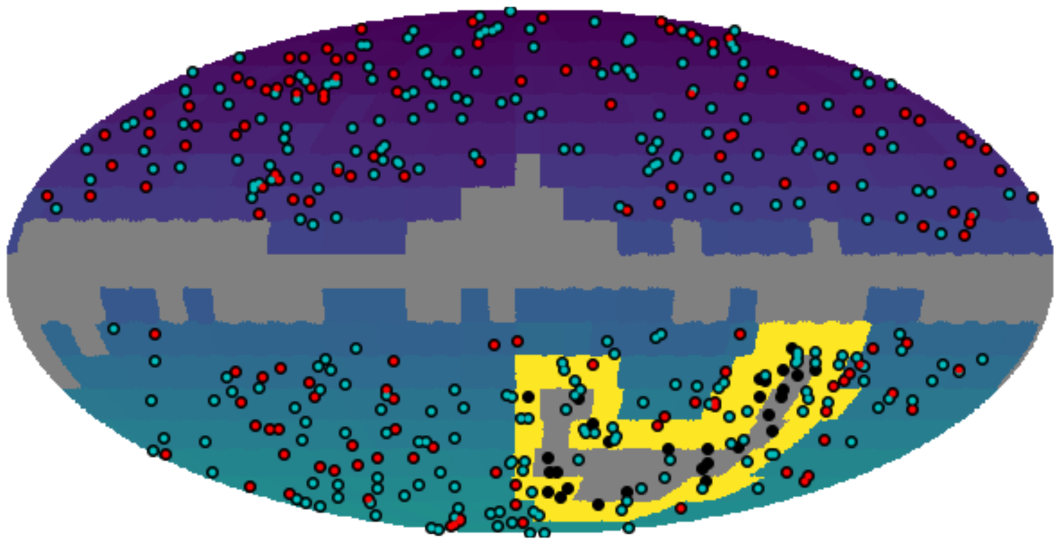
$$(1-b)_{\rm var} = (1-\mathcal{B}) \cdot \left(\frac{M}{M_*}\right)^{\alpha_b} \cdot \left(\frac{1+z}{1+z_*}\right)^{\beta_b}$$



Selection effects:
results change for different cluster samples

Planck + SPT





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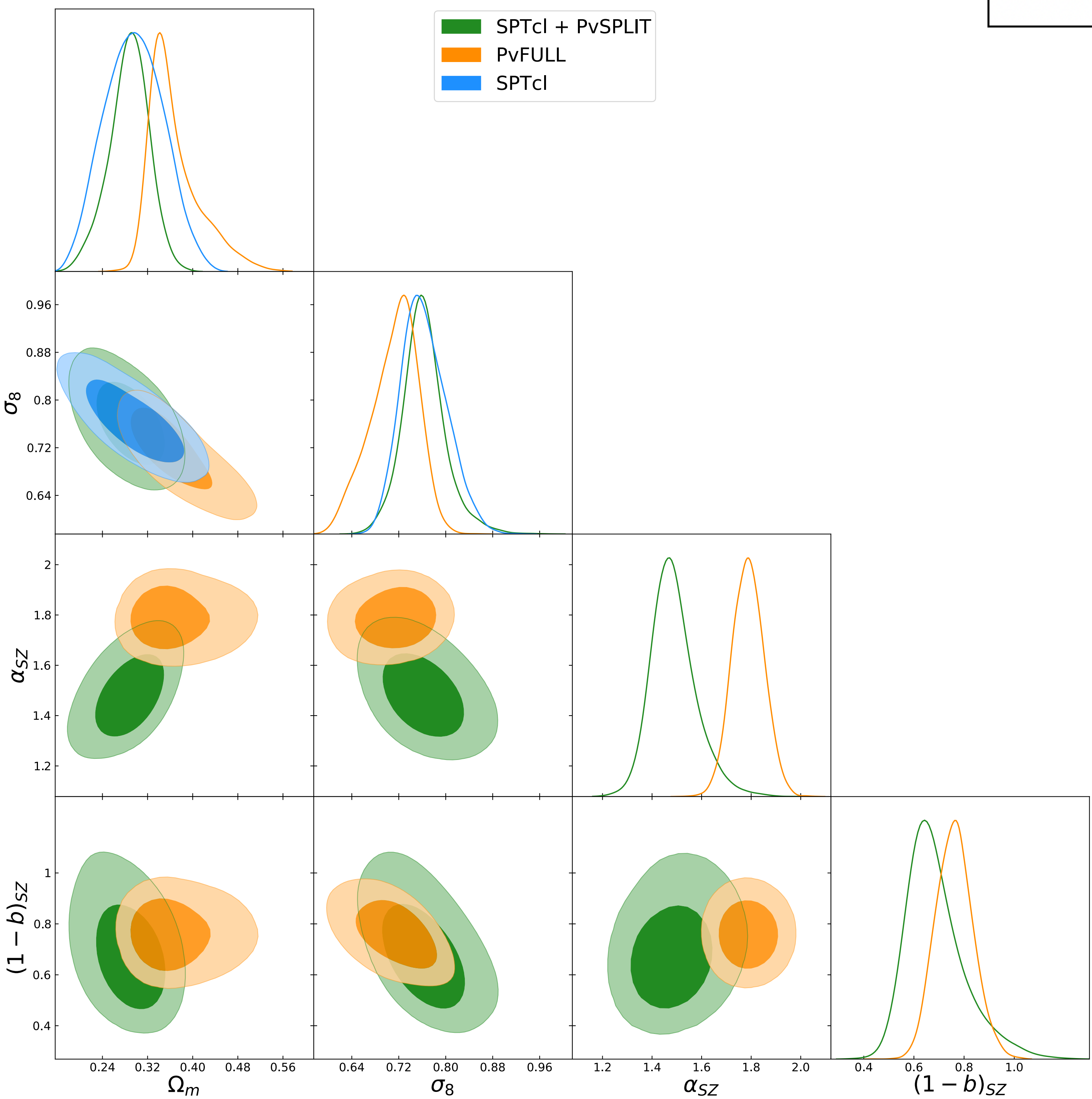

$\nu\Lambda$CDM			
	SPTcl + PvSPLIT	PvFULL	SPTcl
Ω_m	$0.29^{+0.04}_{-0.03}$	$0.37^{+0.02}_{-0.06}$	0.30 ± 0.03
σ_8	$0.76^{+0.03}_{-0.04}$	$0.71^{+0.05}_{-0.03}$	$0.76^{+0.03}_{-0.04}$
α_{SZ}	$1.49^{+0.07}_{-0.10}$	1.79 ± 0.06	–
$(1-b)_{SZ}$	$0.69^{+0.07}_{-0.14}$	$0.76^{+0.07}_{-0.08}$	–

Parameter	Value
$\log Y_{*,SZ}$	-0.19 ± 0.02
α_{SZ}	1.79 ± 0.08
β_{SZ}	0.66
$\sigma^a_{\ln Y_{SZ}}$	0.173 ± 0.023
$(1-b)_{SZ}$	0.780 ± 0.092

Parameter	Value
$\log Y_{*,SZ}$	-0.19 ± 0.02
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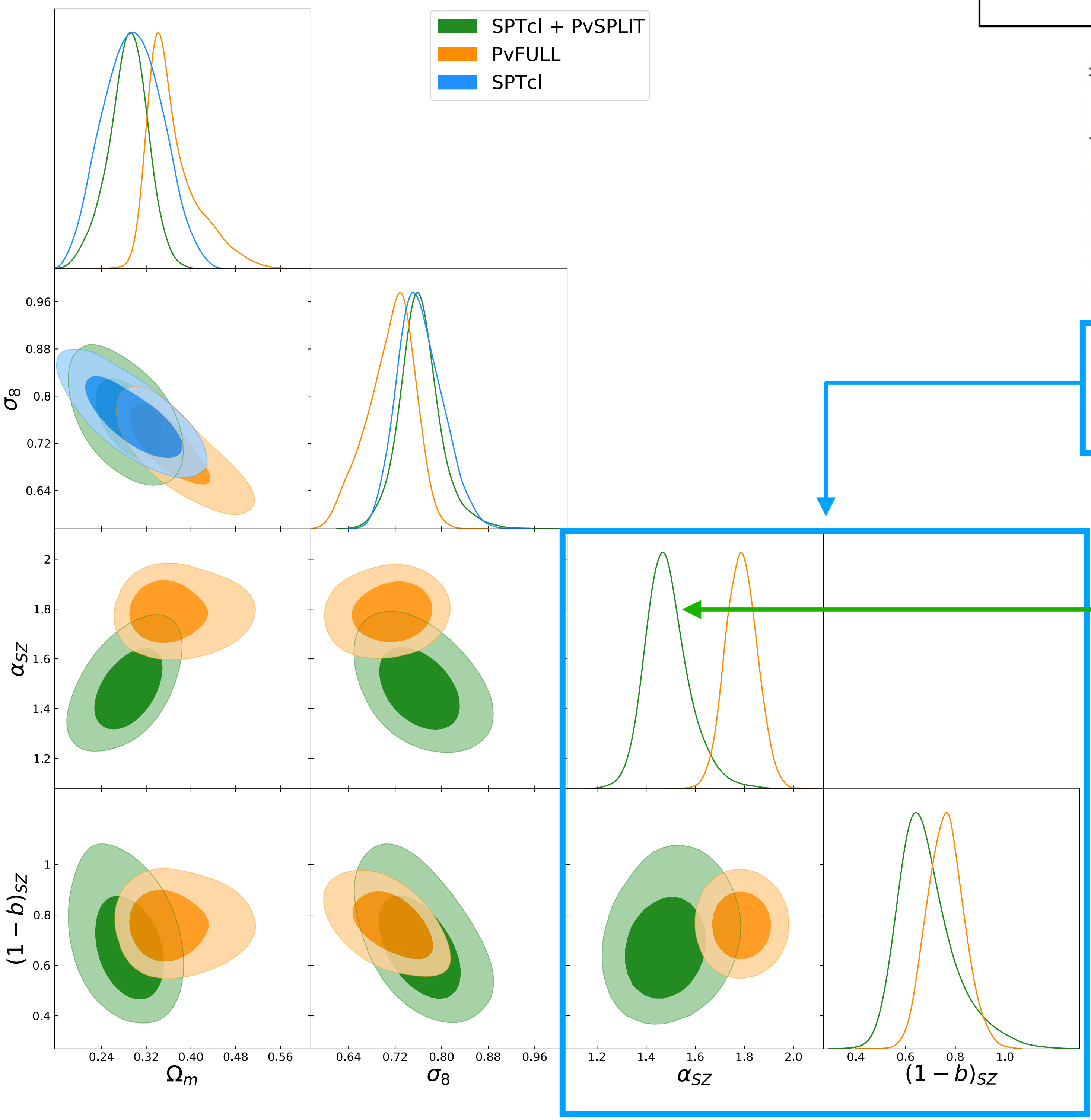
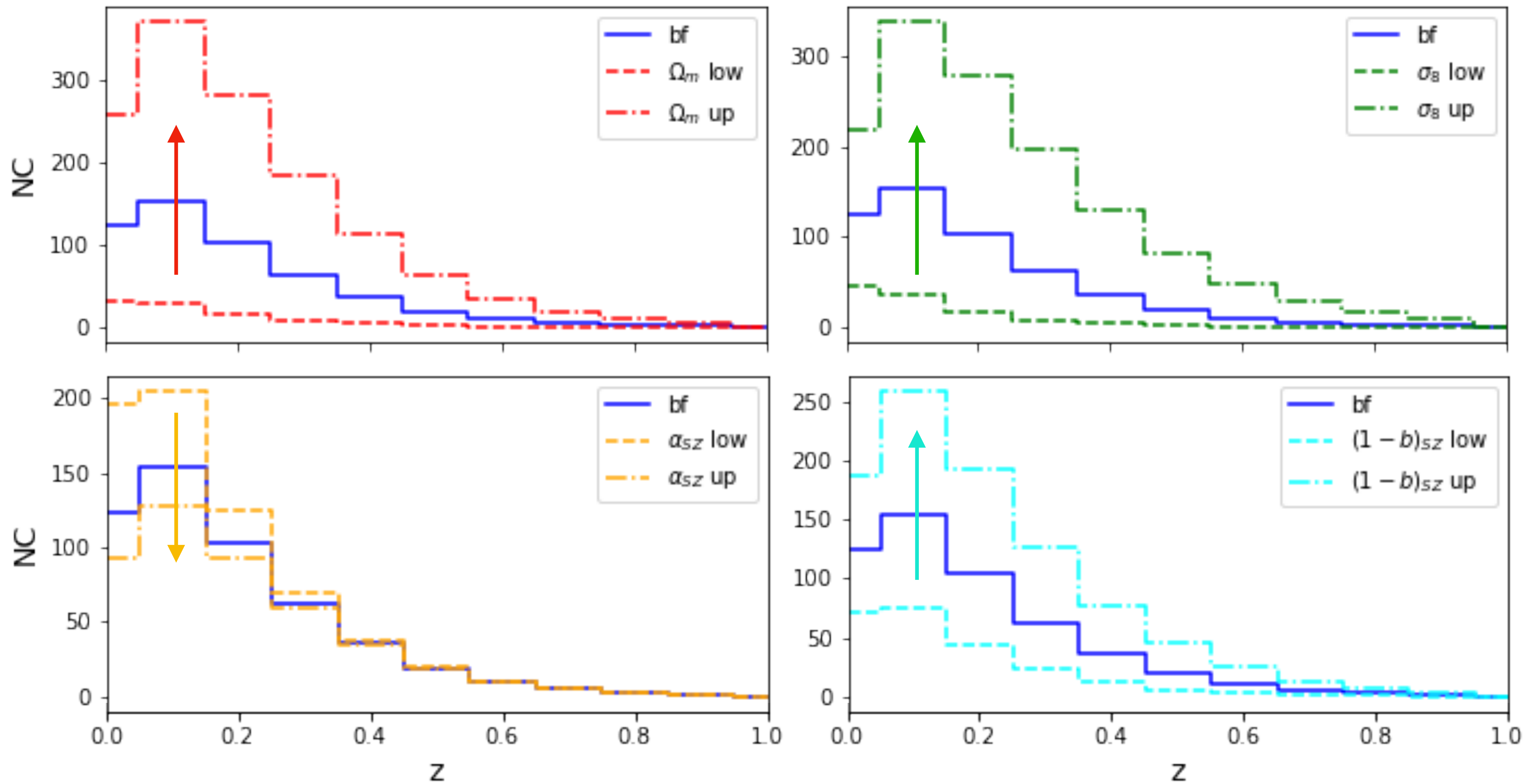


lower value of Ω_m

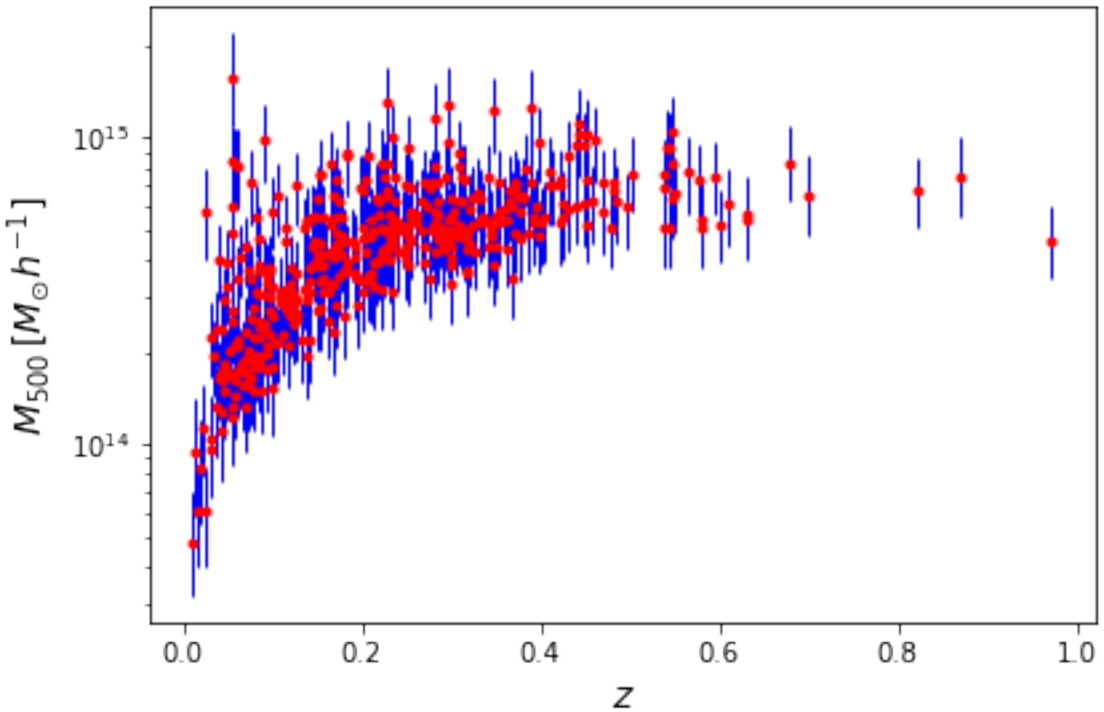
- tilt in the HMF (accounting for less objects at lowM)
- accomodate for this tilt (balancing highM - lowM)

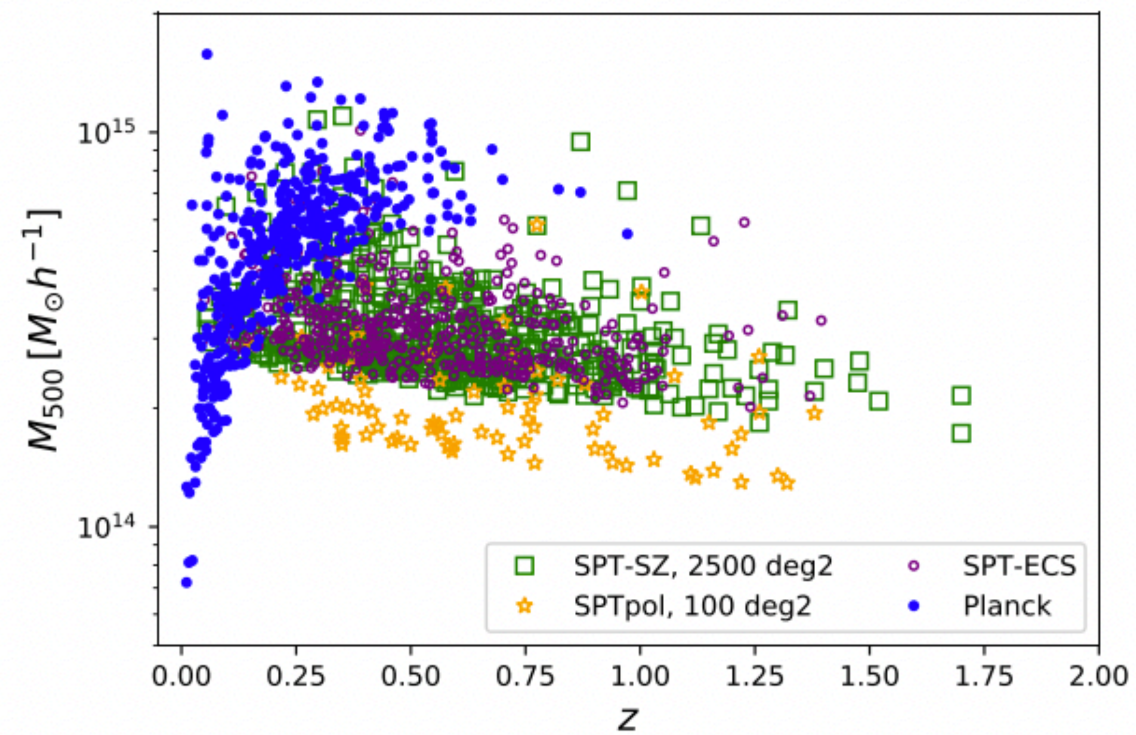
Cosmology and mass calibration



Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)

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

Mass bias

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)

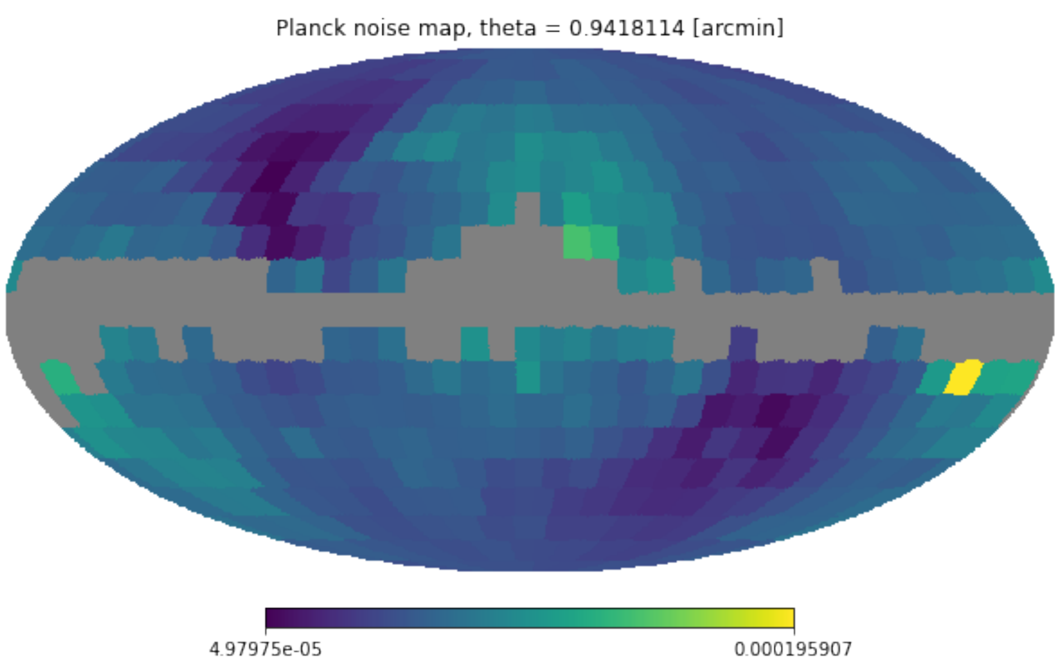
$$(1-b)_M = \frac{M_{\rm SZ}}{M_{500}}$$

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

	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 (bias(M,z))

Increasing trend for high-z and low-M (bias(M,z,noise))



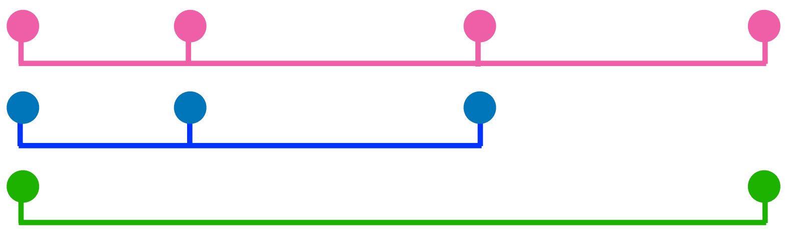
Mass estimation in patches with higher noise are more biased (possibly due to a loss in tSZ signal)

Systematic related to cluster detection

Mass bias

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

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



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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)

Increasing trend for high-z and low-M

Systematic related to cluster detection

Characterisation of the selection function
Stefano Gallo

Conclusions

Cluster cosmology in the high-precision and accuracy domain

- Mass calibration: open issue in current cluster cosmology
    - Use of external calibrations: necessary starting point
    - Need for improvement
        - Larger samples for the calibration
        - Combination with other observations
- Need to improve our understanding of cluster physics before talking about tensions!

Combining cluster catalogs: unique way to

- Get different/independent informations on cluster physics
- Test our modelling on large (M,z) range
- Provide a coherent description of latest evolution of the Universe

→ Planck + SPT full combination
→ Amazing results!!!

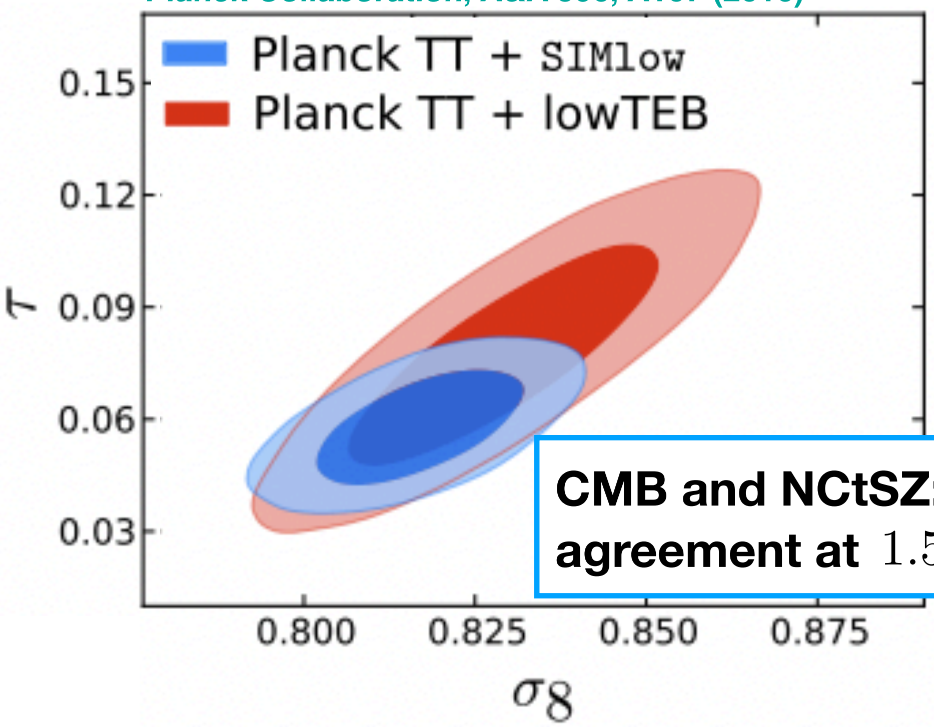
19

Backup

Tension or Mass calibration?

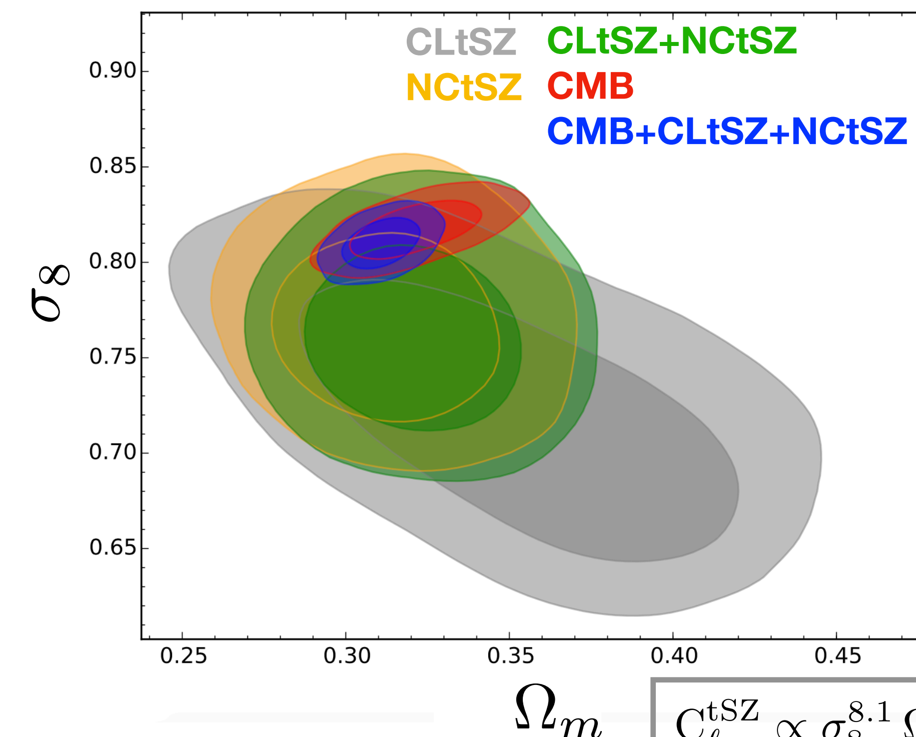
Salvati+
A&A 614 (2018) A13

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



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

LCDM



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

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

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

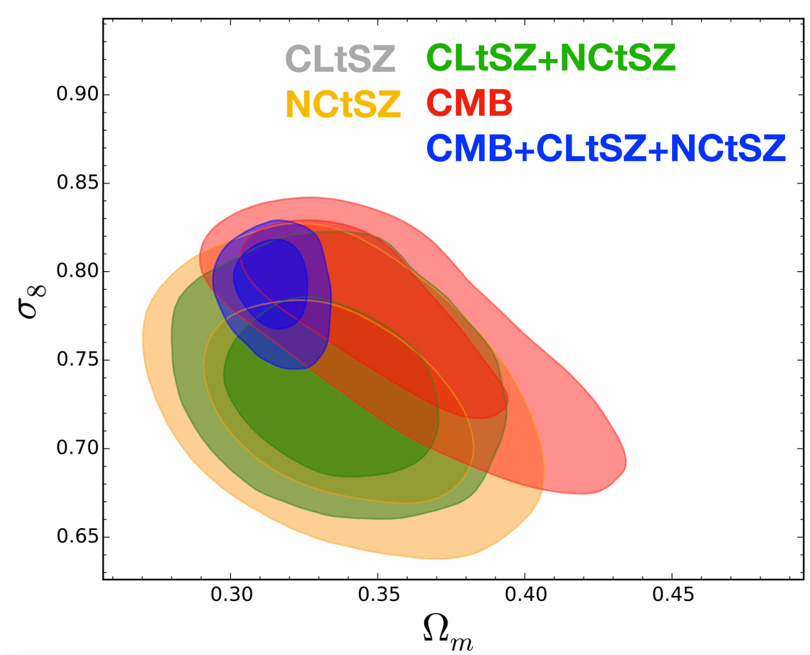
CMB + NCtSZ

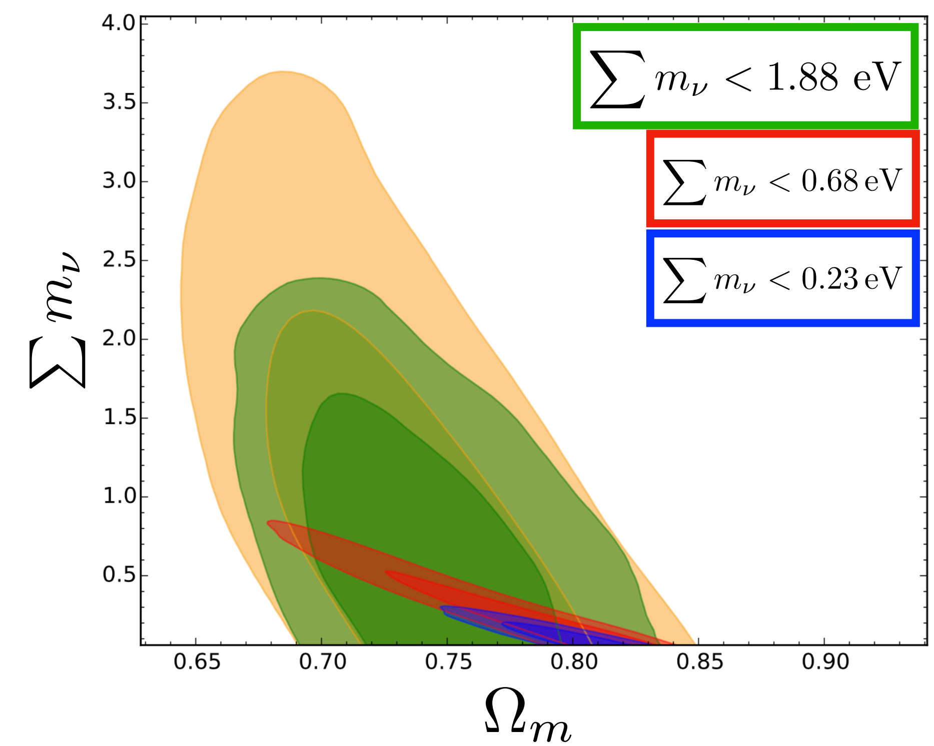
$(1-b) = 0.58 \pm 0.04$ P15

$(1-b) = 0.65 \pm 0.04$ 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



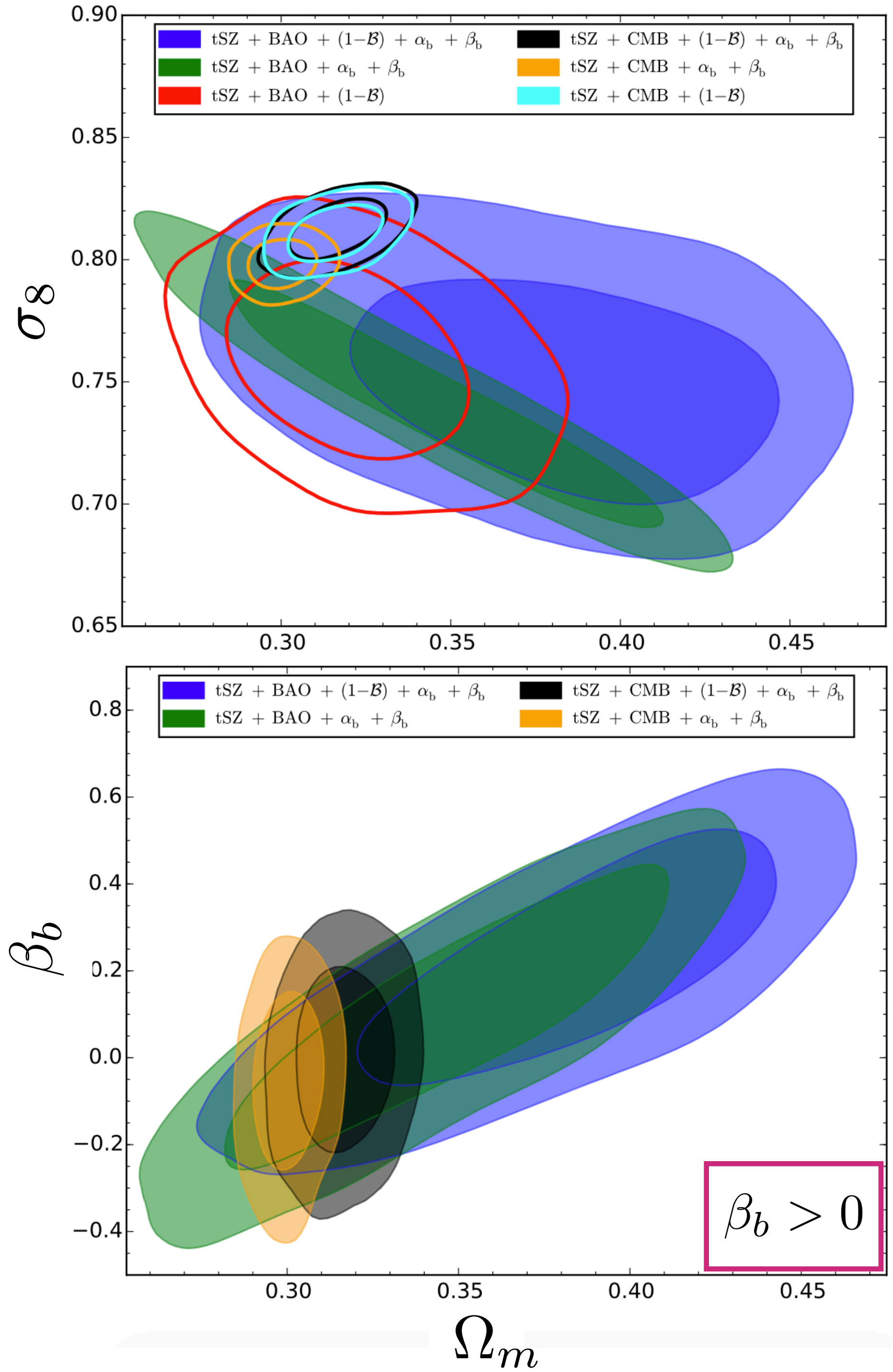


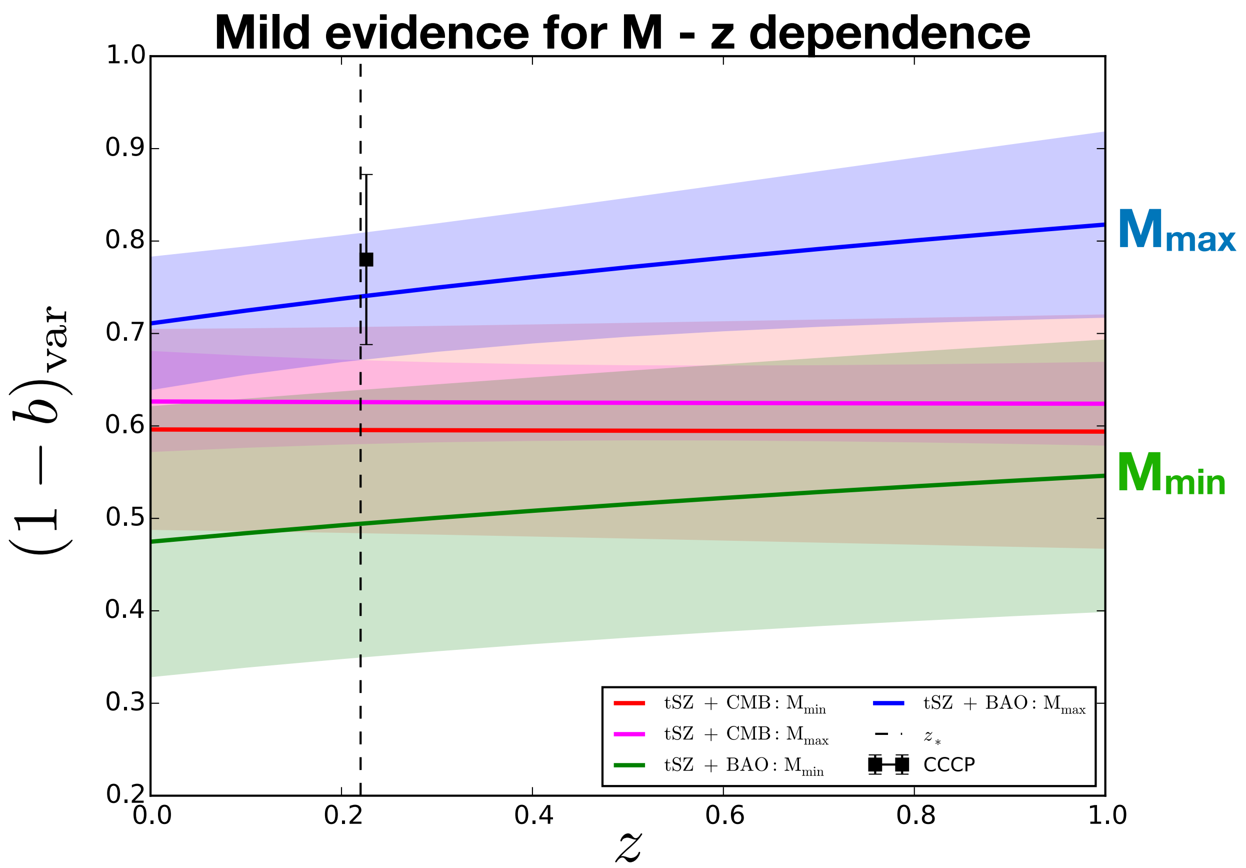
Mass bias: M-z evolution

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!

Planck vs SPT

Different approach for Scaling Relation calibration

Planck: "external"

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

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

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

$\alpha,\ Y_*$ — 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

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

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

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

- 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)

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

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

SPT: “internal”

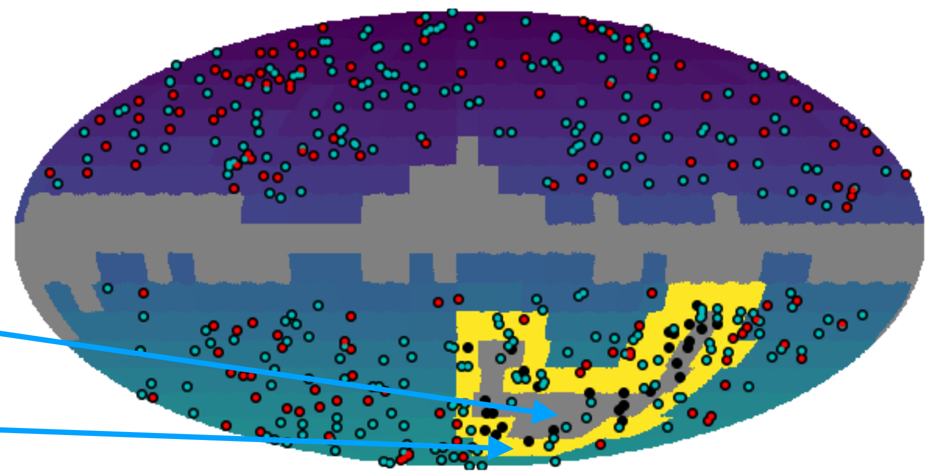
SPT. Bocquet et al., APJ 878 (2019) no.1, 55

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

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

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)

Combine Planck and SPT-SZ cluster likelihood



Pre-processing of Planck map

- 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

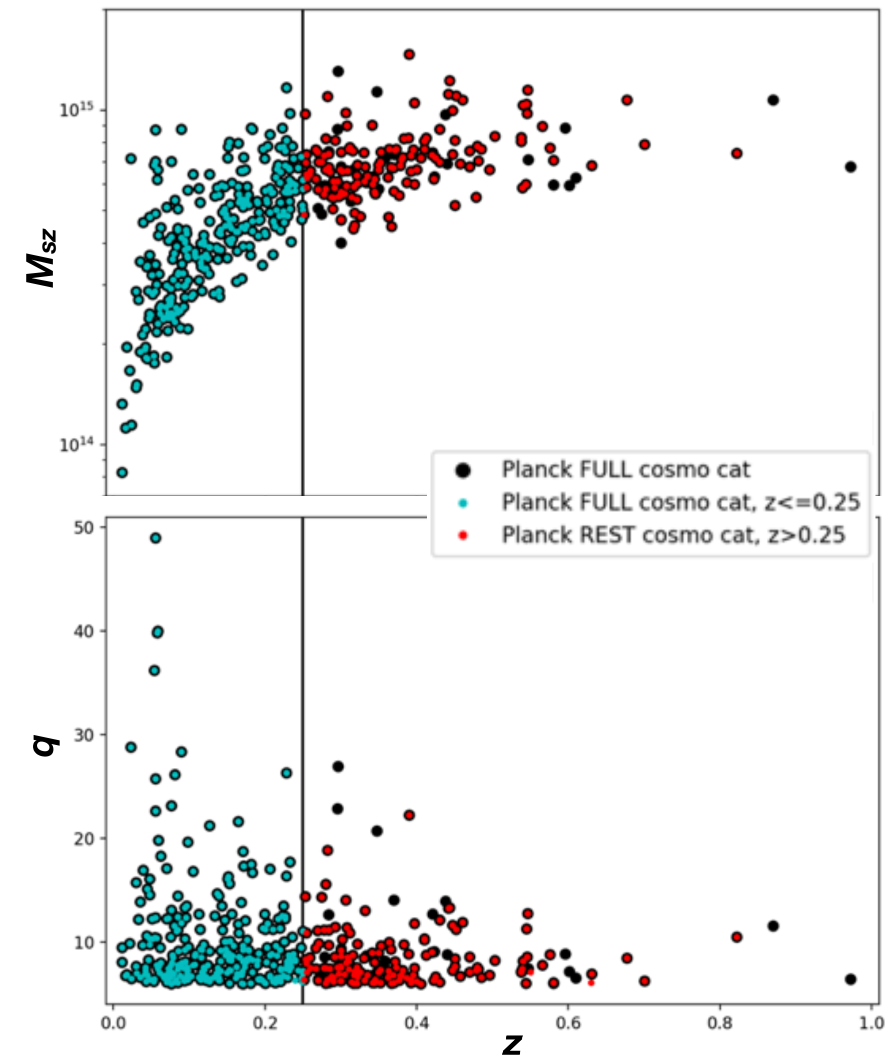
Pre-processing of Planck cluster catalog

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

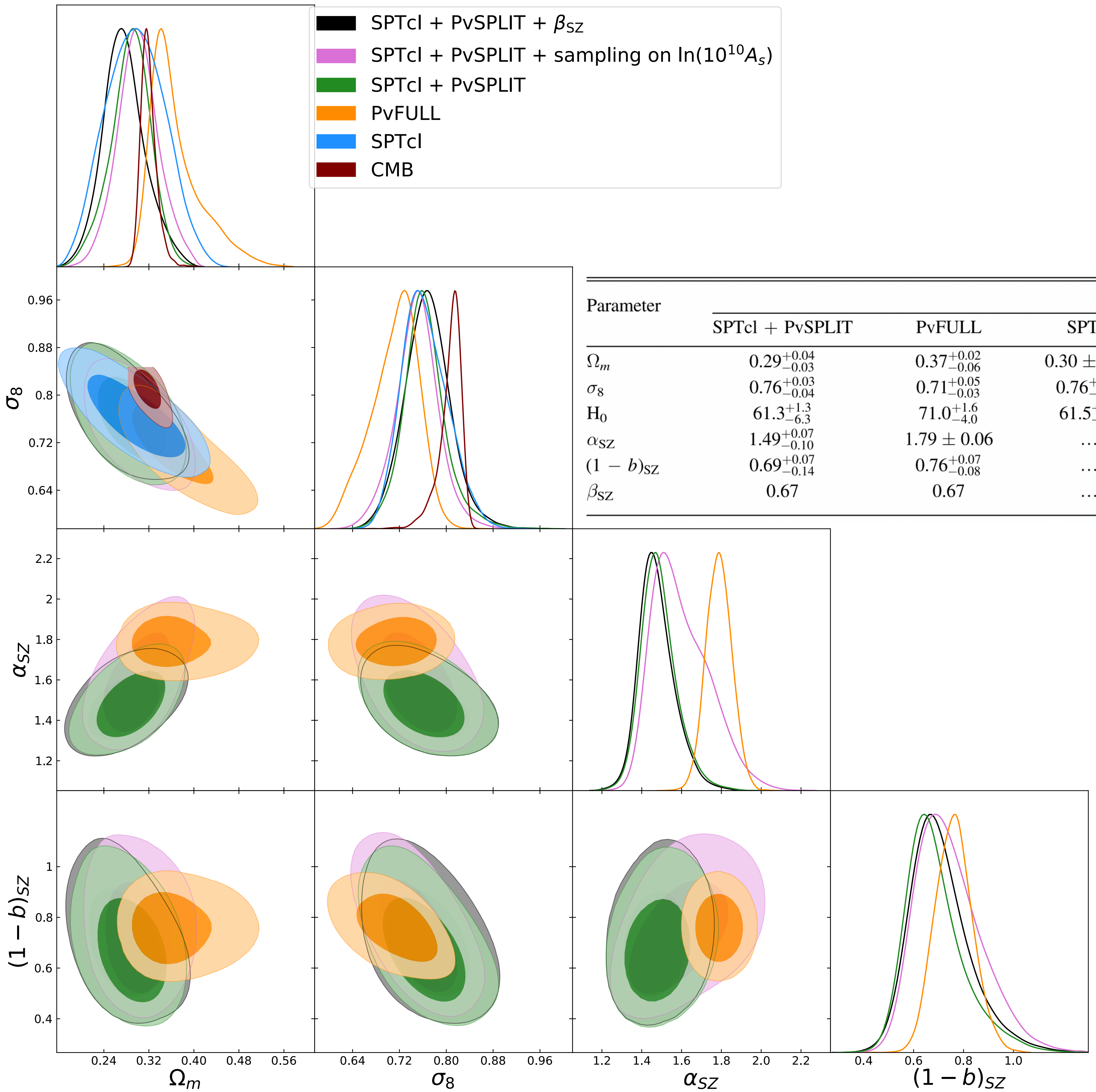
Planck vSPLIT cluster counts likelihood

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

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

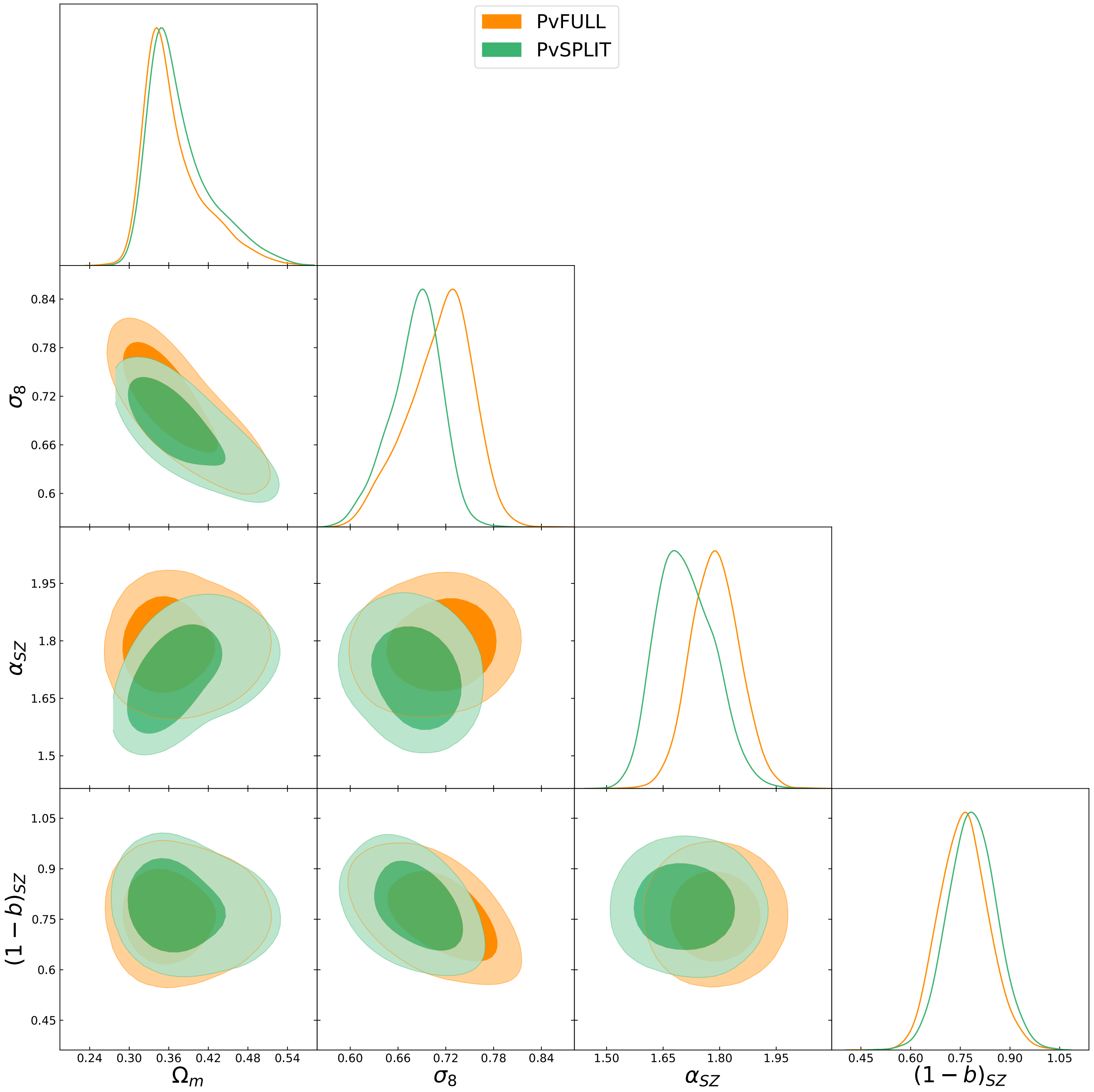


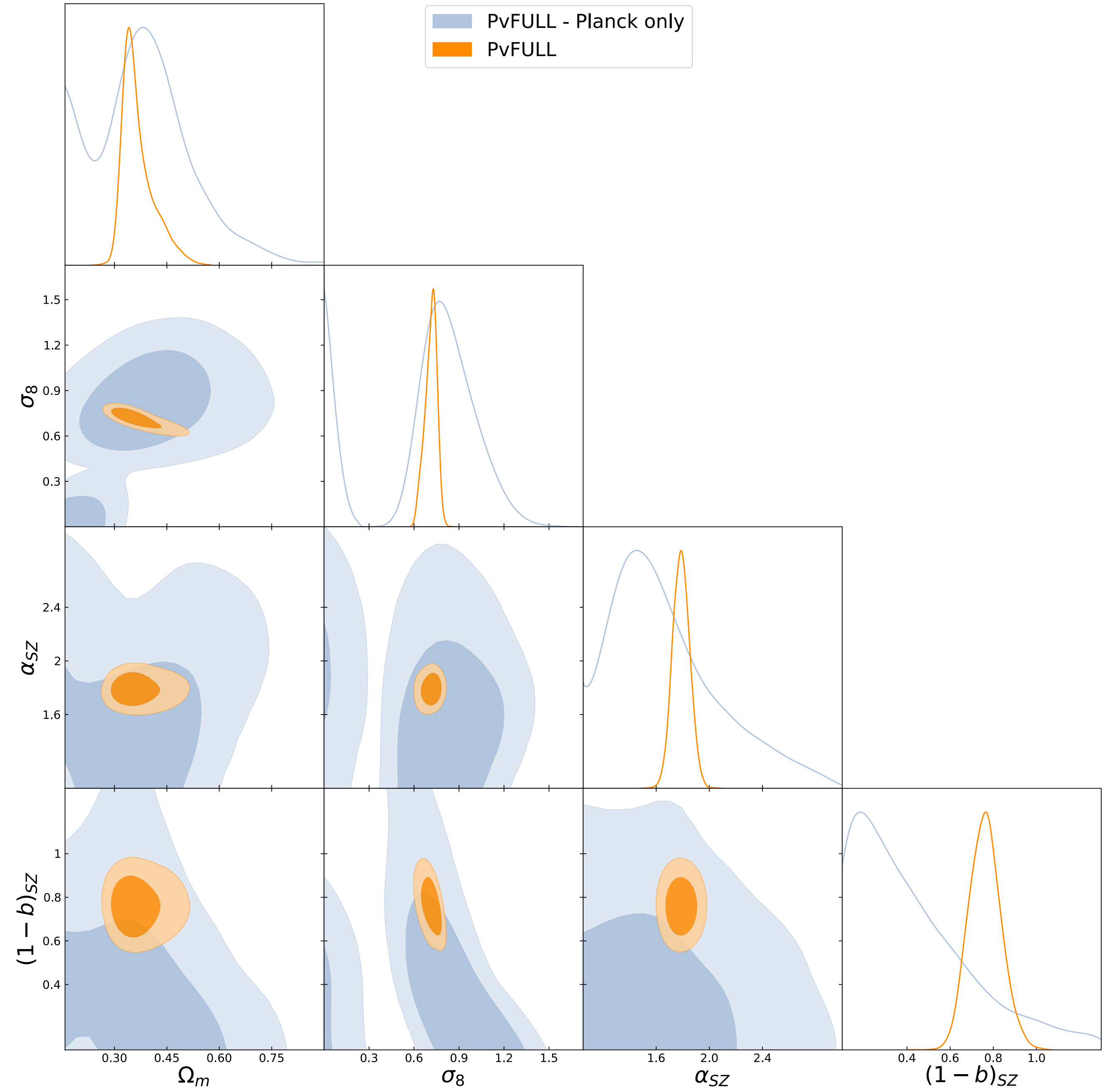
Cosmology and mass calibration



Parameter	$\nu\Lambda$ CDM					
	SPTcl + PvSPLIT	PvFULL	SPTcl	PvSPLIT	SPTcl + PvSPLIT + $\ln(10^{10}A_s)$	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	$0.57^{+0.20}_{-0.51}$

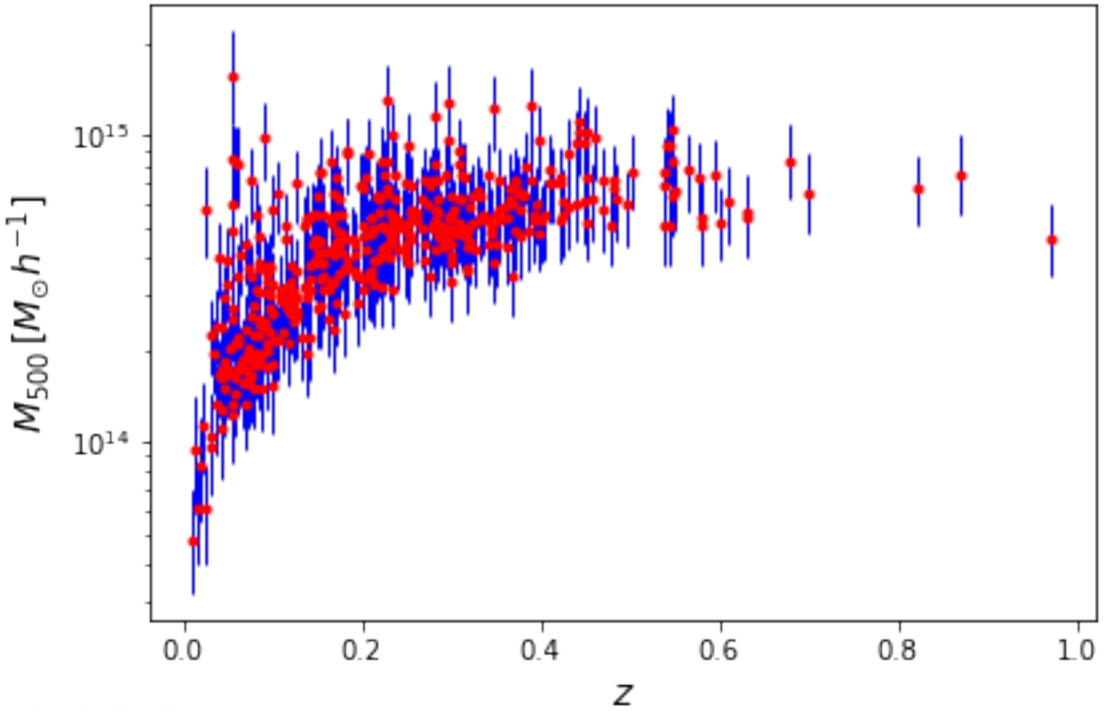
Cosmology and mass calibration





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

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

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

intrinsic scatter of the mass-observable relation

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

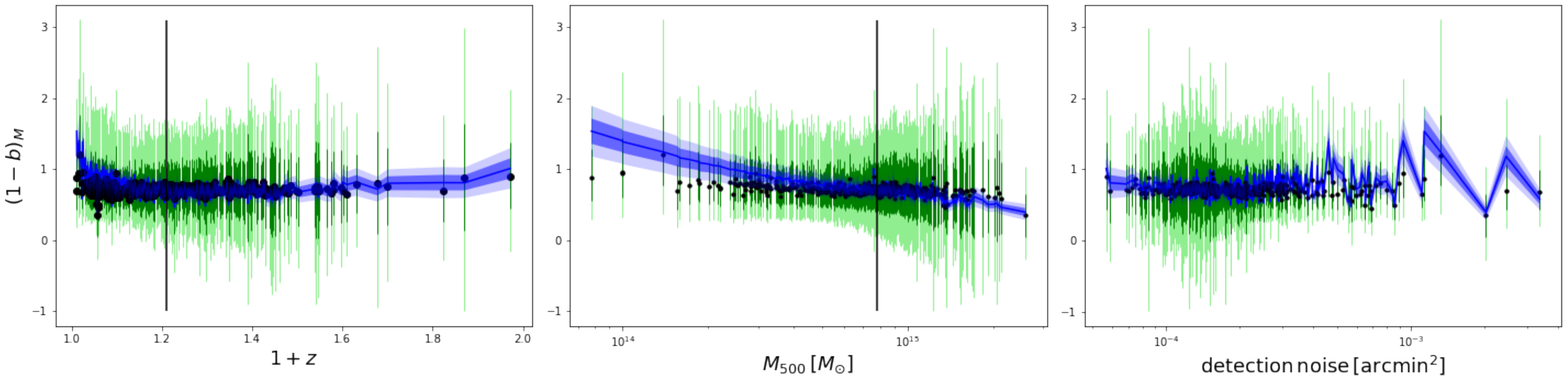
$$E^{-\beta}(z)\left[\frac{D_A^2(z)\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right]^{\alpha}$$

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

Mass bias

$$(1 - b)^{\mathrm{th}}_{M} = A_{\mathrm{bias}} \left(\frac{M_{500}}{M_*}\right)^{\gamma_M} \left(\frac{1 + z}{1 + z_*}\right)^{\gamma_z} \left(\frac{\sigma_{\mathrm{f}}(\theta_{500}, l, b)}{\sigma_{\mathrm{f},*}(\theta_{500})}\right)^{\gamma_n},$$

$$M^{\mathrm{th}}_{\mathrm{SZ}} = (1 - b)^{\mathrm{th}}_{M} \cdot M_{500},$$



Mass evaluation