Tensions in the LCDM paradigm

Constraints on cosmological parameters from galaxy clusters:

tSZ cluster counts and power spectrum combined with CMB

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IAS Orsay

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ByoPiC

Introduction

Galaxy Clusters

↓

Largest structures gravitationally bound in the Universe

↓

Strong dependence on cosmological parameters

Ω_m, σ_8

Measurements of tSZ effect from Planck Satellite

tSZ Number counts + tSZ Power spectrum

Constraints on:

- standard LCDM scenario
- mass of neutrinos
- DE equation of state

Theoretical assumptions:

- discuss the effect on cosmological parameters
- new parametrisation

Model

tSZ Number counts

$$n_i = \int_{z_i}^{z_{i+1}} dz \int d\Omega \, \frac{dV_c}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM_{500} \, \hat{\chi}(z, M_{500}; l, b) \frac{dN(M_{500}, z)}{dM_{500}}$$

tSZ Power Spectrum

$$C_\ell^{\rm tSZ} = C_\ell^{\rm 1halo} + C_\ell^{\rm 2halo}$$

$$C_\ell^{\rm 1halo} = \int_0^{z_{\max}} dz \frac{dV_c}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \frac{dN(M_{500}, z)}{dM_{500}} |\tilde{y}_\ell(M_{500}, z)|^2 \cdot \exp\left(\frac{1}{2}\sigma^2_{\ln Y^*}\right)$$

$$C_\ell^{\rm 2halo} = \int_0^{z_{\max}} dz \frac{dV_c}{dz d\Omega} \left[\int_{M_{\min}}^{M_{\max}} dM \frac{dN(M_{500}, z)}{dM_{500}} \tilde{y}_\ell(M_{500}, z) \, B(M_{500}, z)\right]^2 P(k, z)$$

$$T_{\ell\ell'} \simeq \int_0^{z_{\max}} dz \frac{dV_c}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \left[\frac{dN(M_{500}, z)}{dM_{500}} |\tilde{y}_\ell(M_{500}, z)|^2 |\tilde{y}_{\ell'}(M_{500}, z)|^2\right]$$

Selection function

Planck 2015 results. XXVII. A&A 594 (2016) A27

Mass function

$$\frac{dN(M_{500}, z)}{dM_{500}} = f(\sigma) \frac{\rho_m(z=0)}{M_{500}} \frac{d\ln\sigma^{-1}}{dM_{500}}$$

$$f(\sigma) = A \left[1 + \left(\frac{\sigma}{b}\right)^{-a}\right] \exp\left(-\frac{c}{\sigma^2}\right)$$

Tinker et al., Astrophys. J. 688 (2008) 709

Scaling Relations

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

$$\theta_{500} = \theta_* \left[\frac{h}{0.7}\right]^{-2/3} \left[\frac{(1-b) \, M_{500}}{3 \cdot 10^{14} \, M_\odot}\right]^{1/3} E^{-2/3}(z) \left[\frac{D_A(z)}{500 \, \mathrm{Mpc}}\right]^{-1}$$

Planck 2015 results. XXIV. A&A 594 (2016) A24

$$(1-b) = \frac{M_{\rm est}}{M_{\rm true}}$$

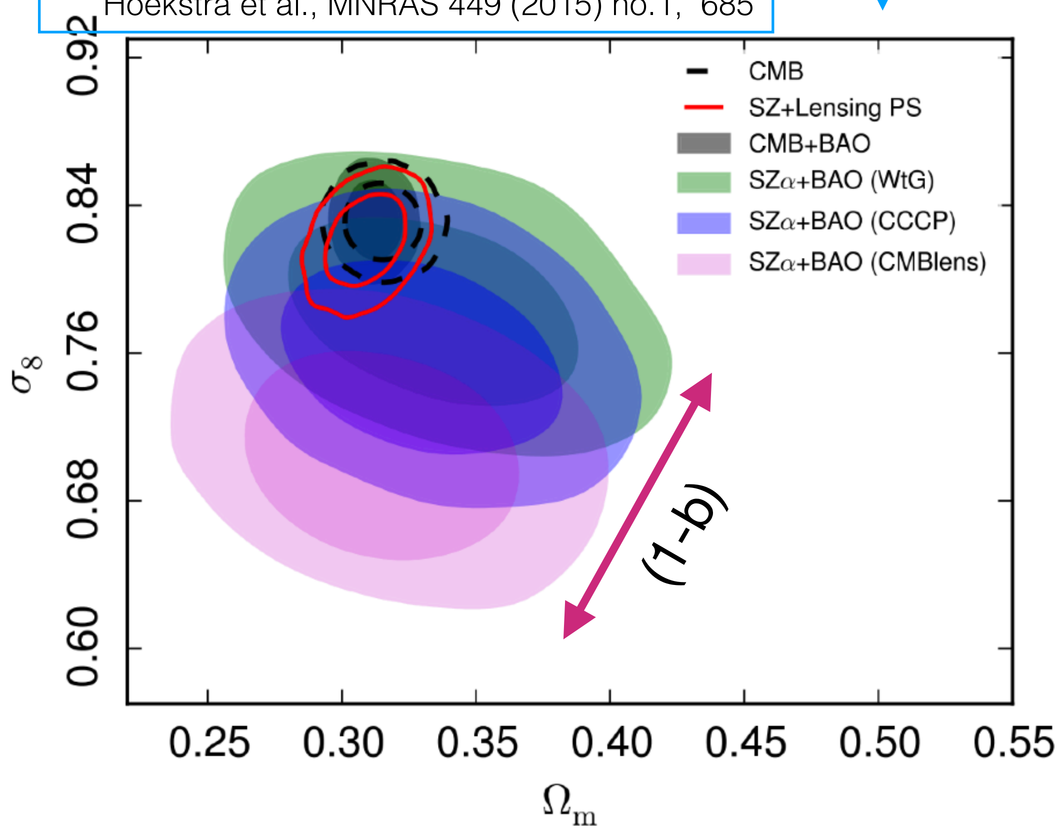
Assumptions of the model

- Mass function
- Scaling relations
  - Mass bias
- Selection function

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

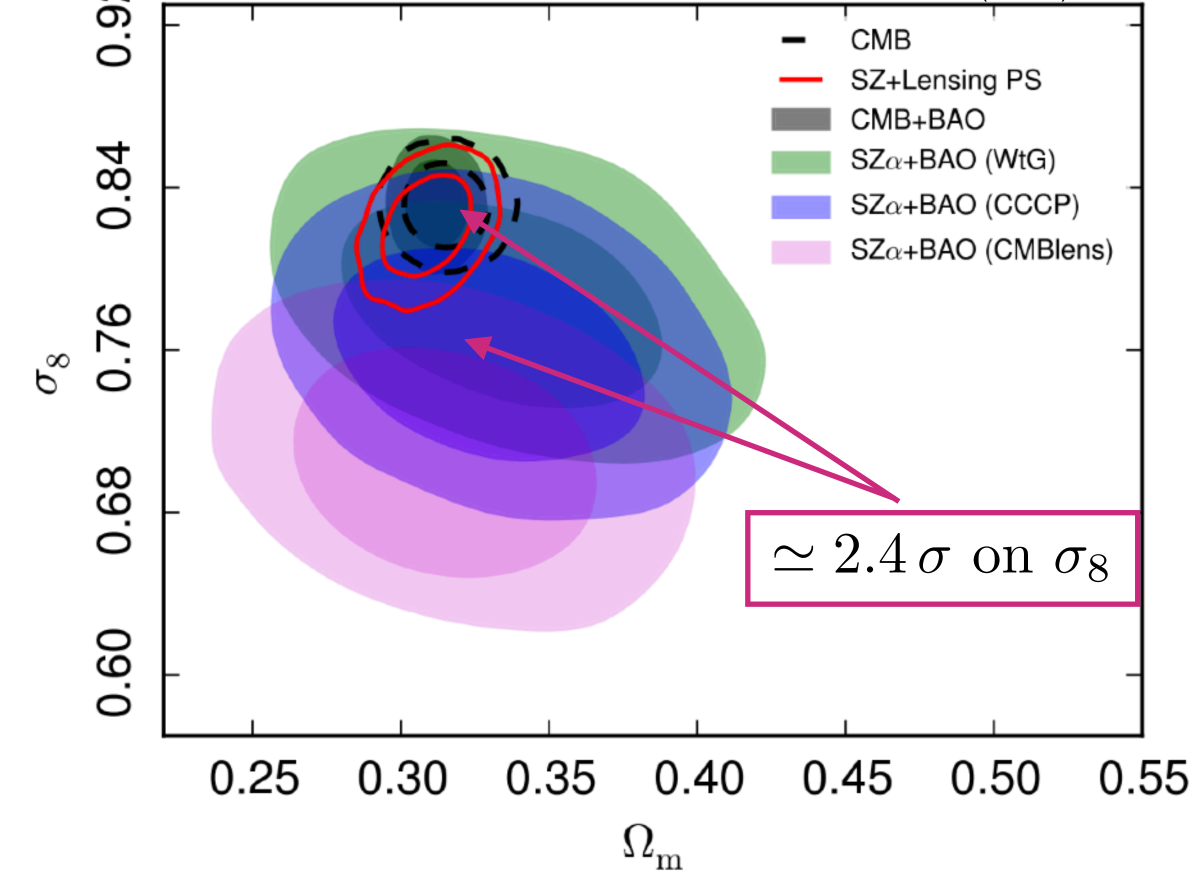
$\mathrm{CCCP}: (1-b) = 0.780 \pm 0.092$

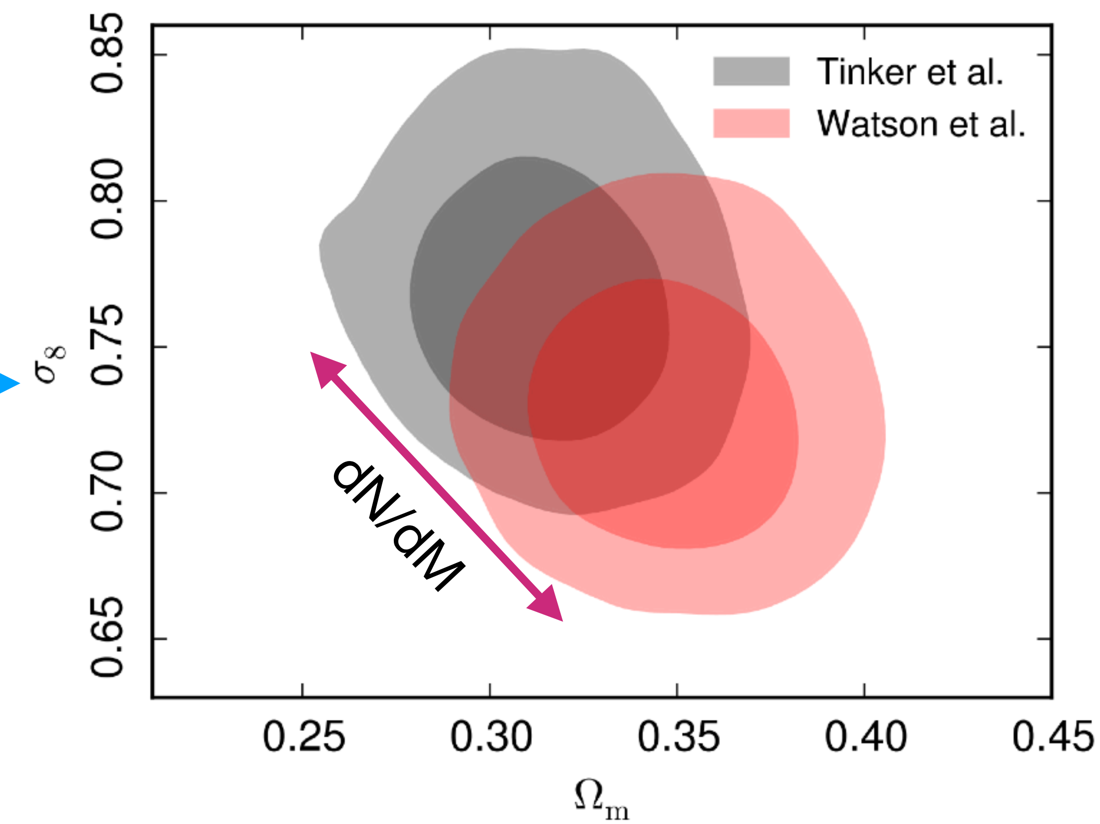
Hoekstra et al., MNRAS 449 (2015) no.1, 685



tSZ Number counts

Planck Collaboration, A&A 594 (2016) A24

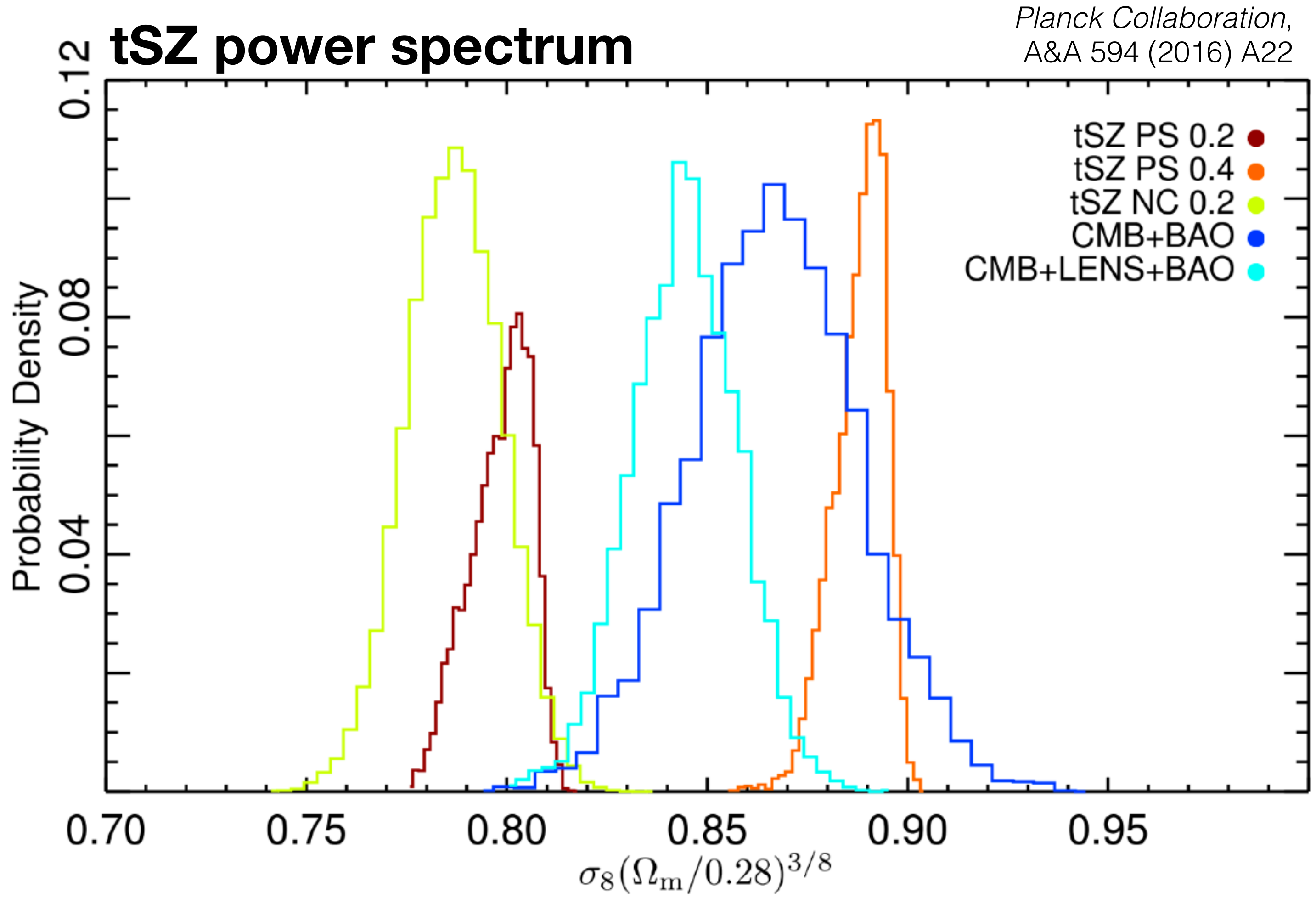




Model

Assumptions of the model

- Mass function
- Scaling relations
  - Mass bias
- Selection function



(1-b)

Dataset - Methods

tSZ Number counts
Planck Collaboration, A&A 594 (2016) A24

- PSZ2 cosmological sample
- 438 clusters (MMF3), $z = [0, 1]$

tSZ Power spectrum
Planck Collaboration, A&A 594 (2016) A22

- $z = [0, 3]$
- $M_{500} = [10^{13} M_\odot, 5 \cdot 10^{15} M_\odot]$
- $\ell = 10 - 1000$, 50% of sky
- SPT data: $\ell = 3000$
  George, E. M. et al. 2015, Astrophys. J., 799, 177

Sampling at the same time on **COSMOLOGICAL parameters** AND on **SCALING RELATIONS parameters**

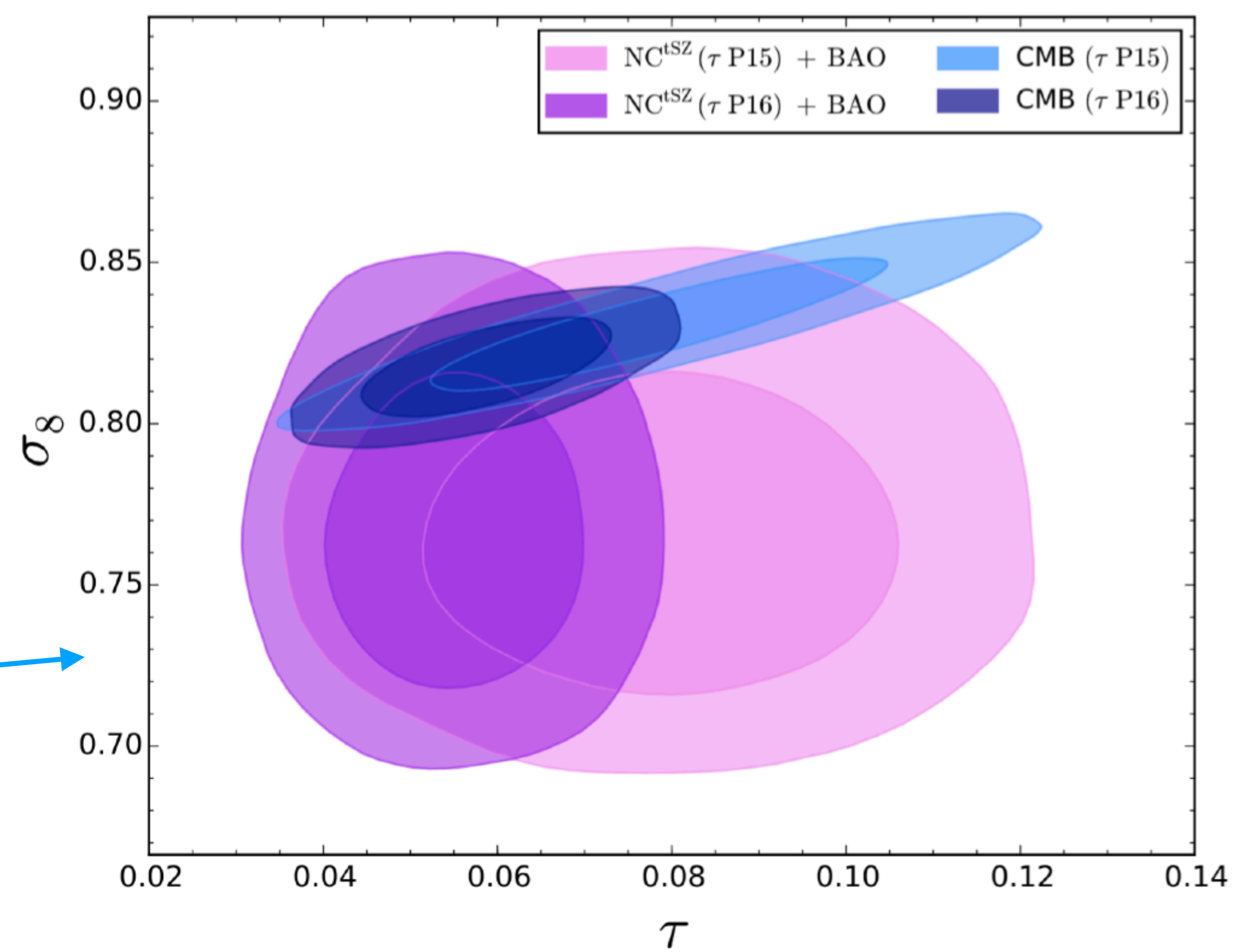
<u>Baseline</u>

- Tinker mass function
- cccp prior on mass bias

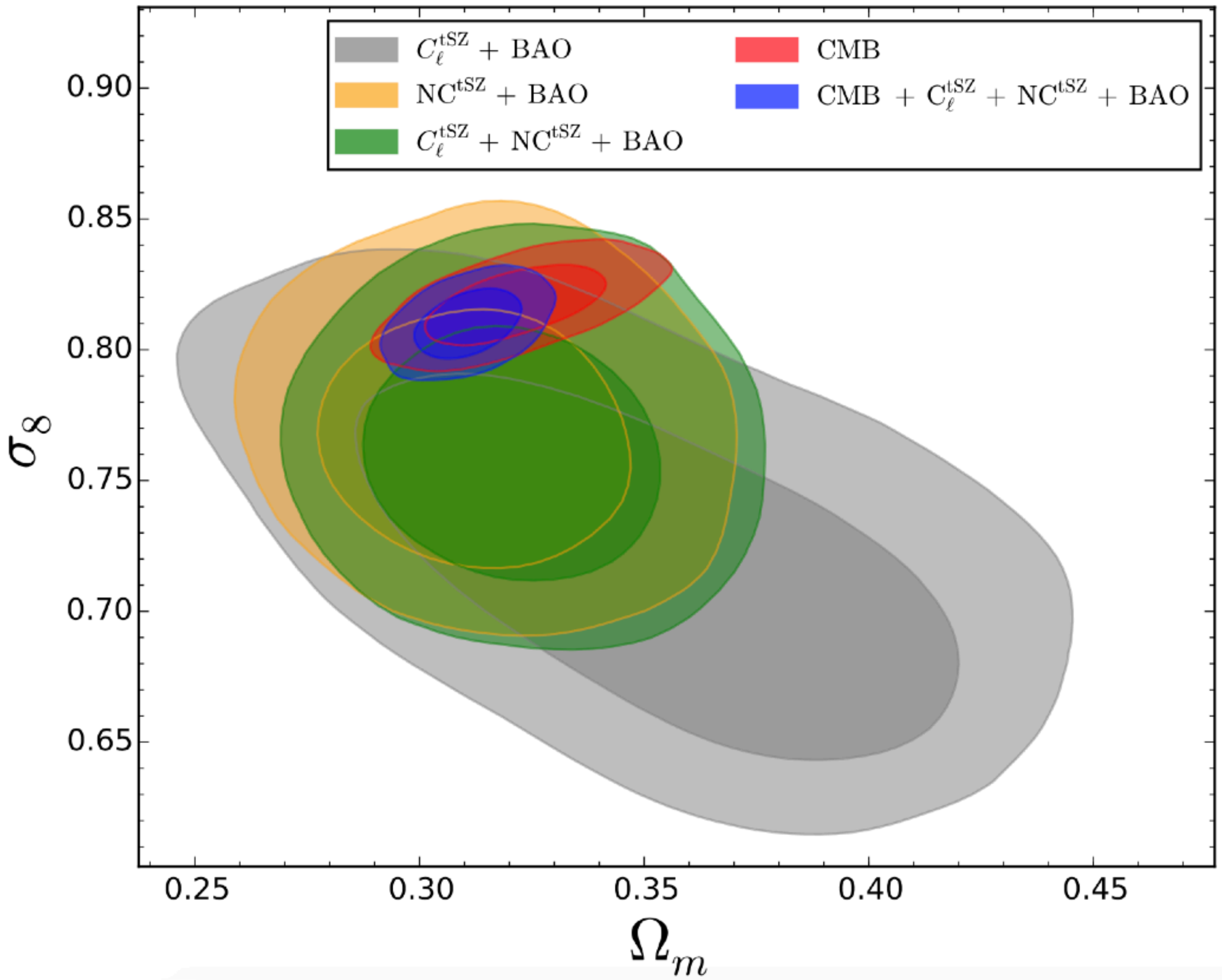
$$(1 - b) = 0.780 \pm 0.092$$

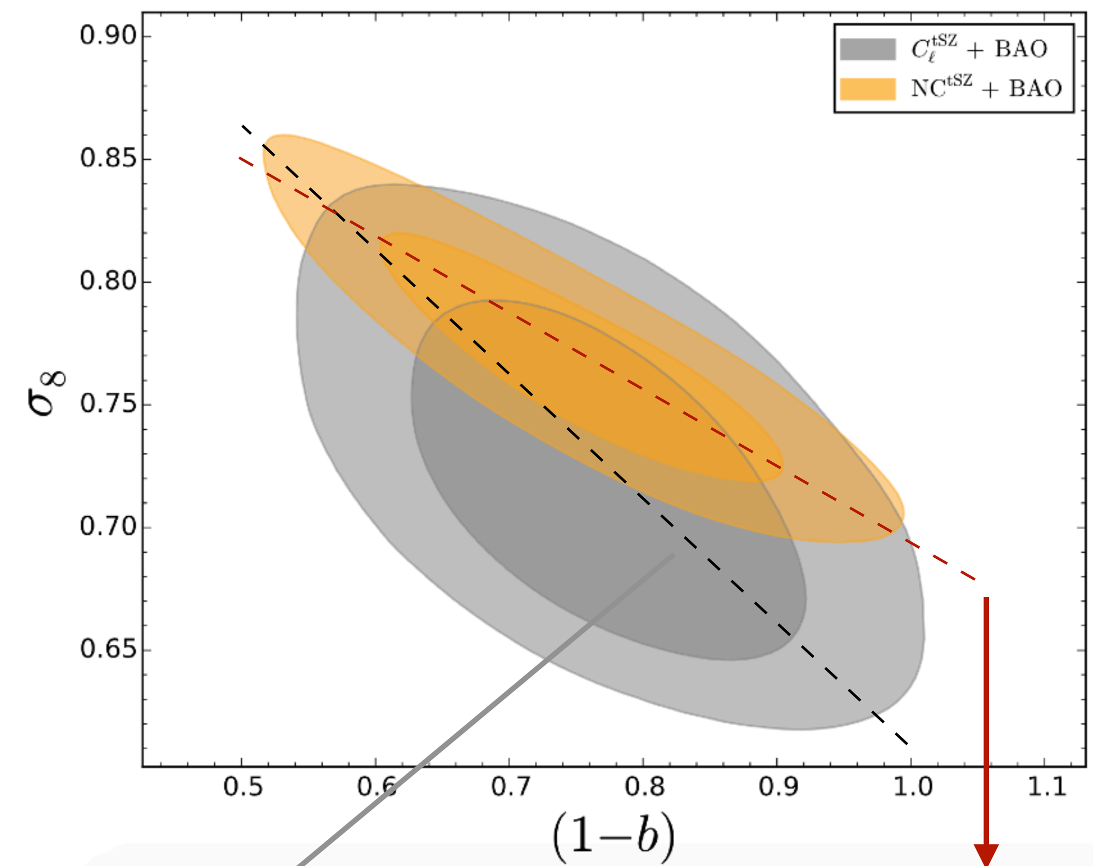
Hoekstra et al., MNRAS 449 (2015) no.1, 685

- $\tau = 0.055 \pm 0.009$
  Planck Collaboration, A&A 596 (2016) A107



LCDM Results





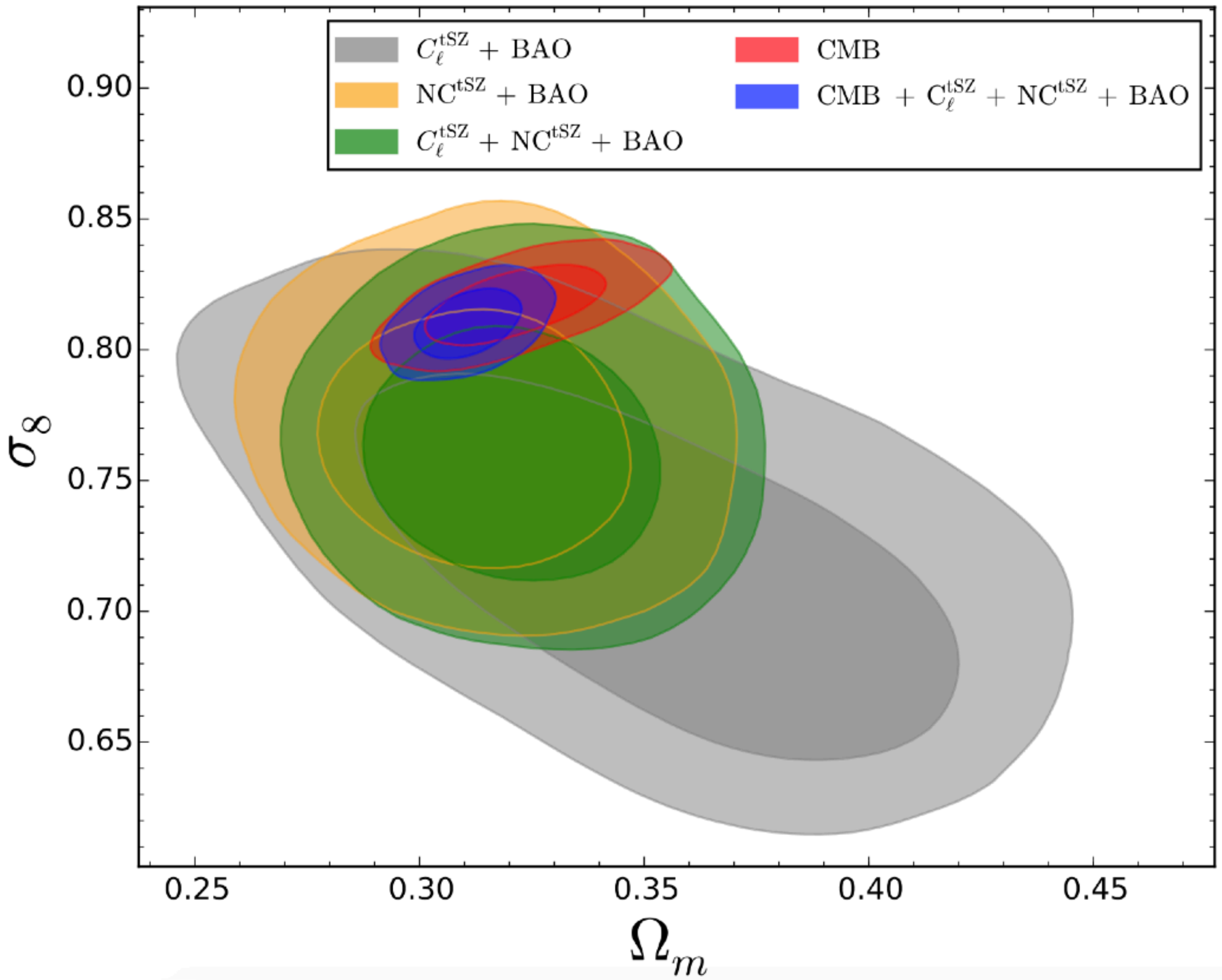
$$NC^{tSZ} \propto \sigma_8^9\, \Omega_m^3\, (1-b)^{3.6}$$

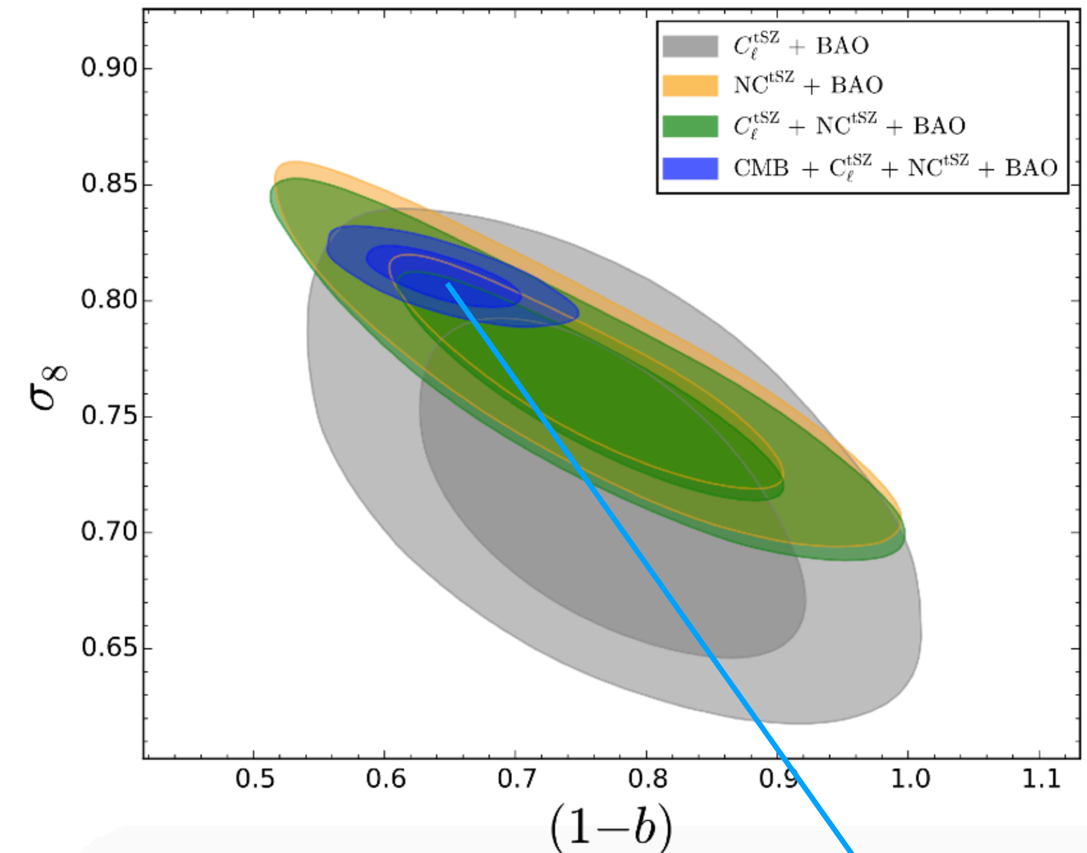
$$C_\ell^{tSZ} \propto \sigma_8^{8.1}\, \Omega_m^{3.2}\, (1-b)^{3.2}$$

$\simeq 1.5\,\sigma$ discrepancy (NC + BAO vs CMB)

Cosmological parameters	CL + BAO	NC + BAO	CL + NC + BAO	CMB	CMB + CL + NC + BAO
Ω_m	$0.352^{+0.047}_{-0.038}$	$0.314^{+0.020}_{-0.024}$	$0.322^{+0.020}_{-0.022}$	$0.321^{+0.012}_{-0.014}$	0.311 ± 0.007
σ_8	$0.721^{+0.039}_{-0.053}$	$0.768^{+0.028}_{-0.035}$	$0.762^{+0.027}_{-0.034}$	0.817 ± 0.010	0.810 ± 0.008

$\simeq 1.8\,\sigma$ discrepancy (CL + NC + BAO vs CMB)





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

$\simeq 1.5\,\sigma$ discrepancy

Cosmological parameters	CL + BAO	NC + BAO	CL + NC + BAO	CMB	CMB + CL + NC + BAO
$\Omega_{\rm m}$	$0.352^{+0.047}_{-0.038}$	$0.314^{+0.020}_{-0.024}$	$0.322^{+0.020}_{-0.022}$	$0.321^{+0.012}_{-0.014}$	0.311 ± 0.007
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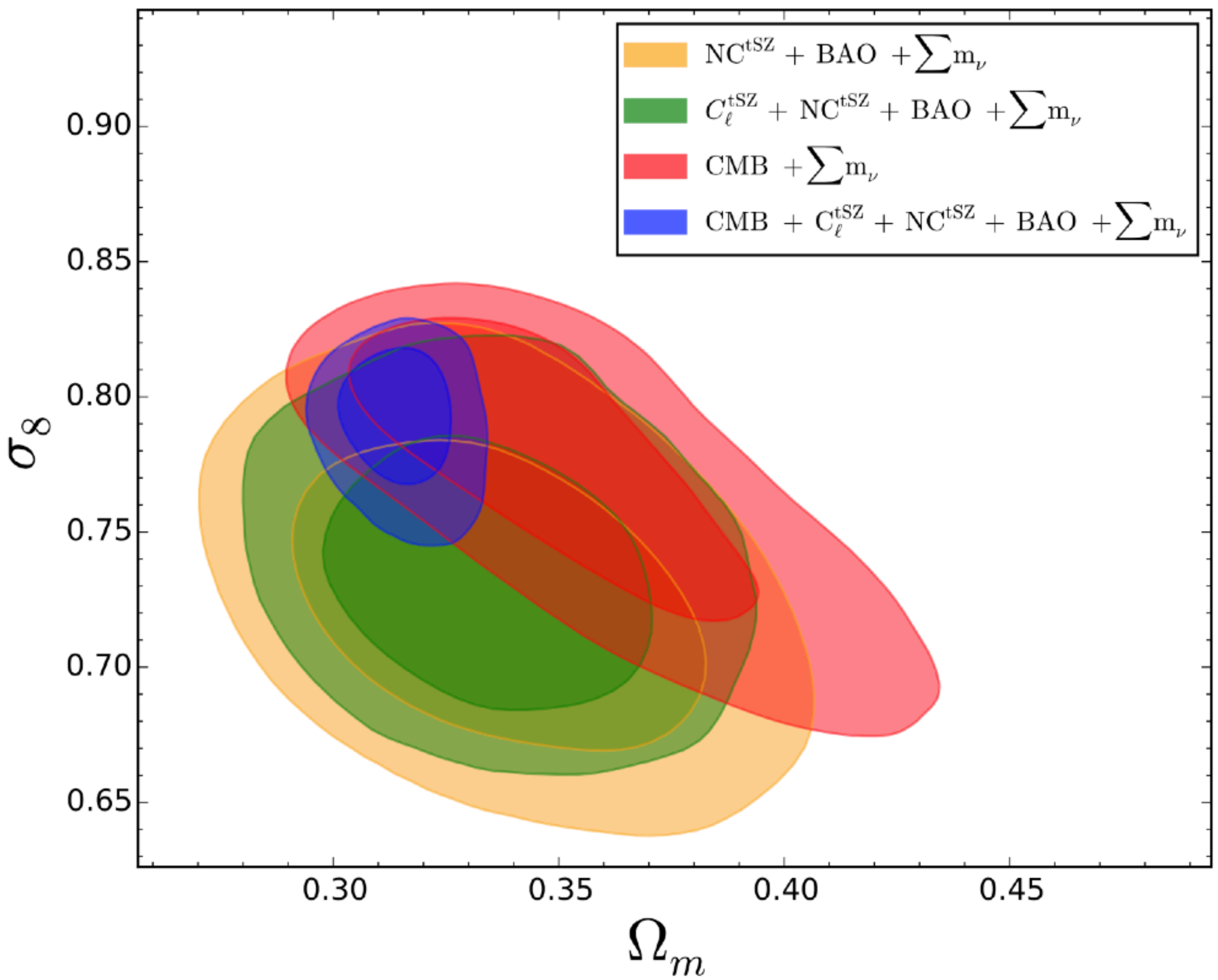
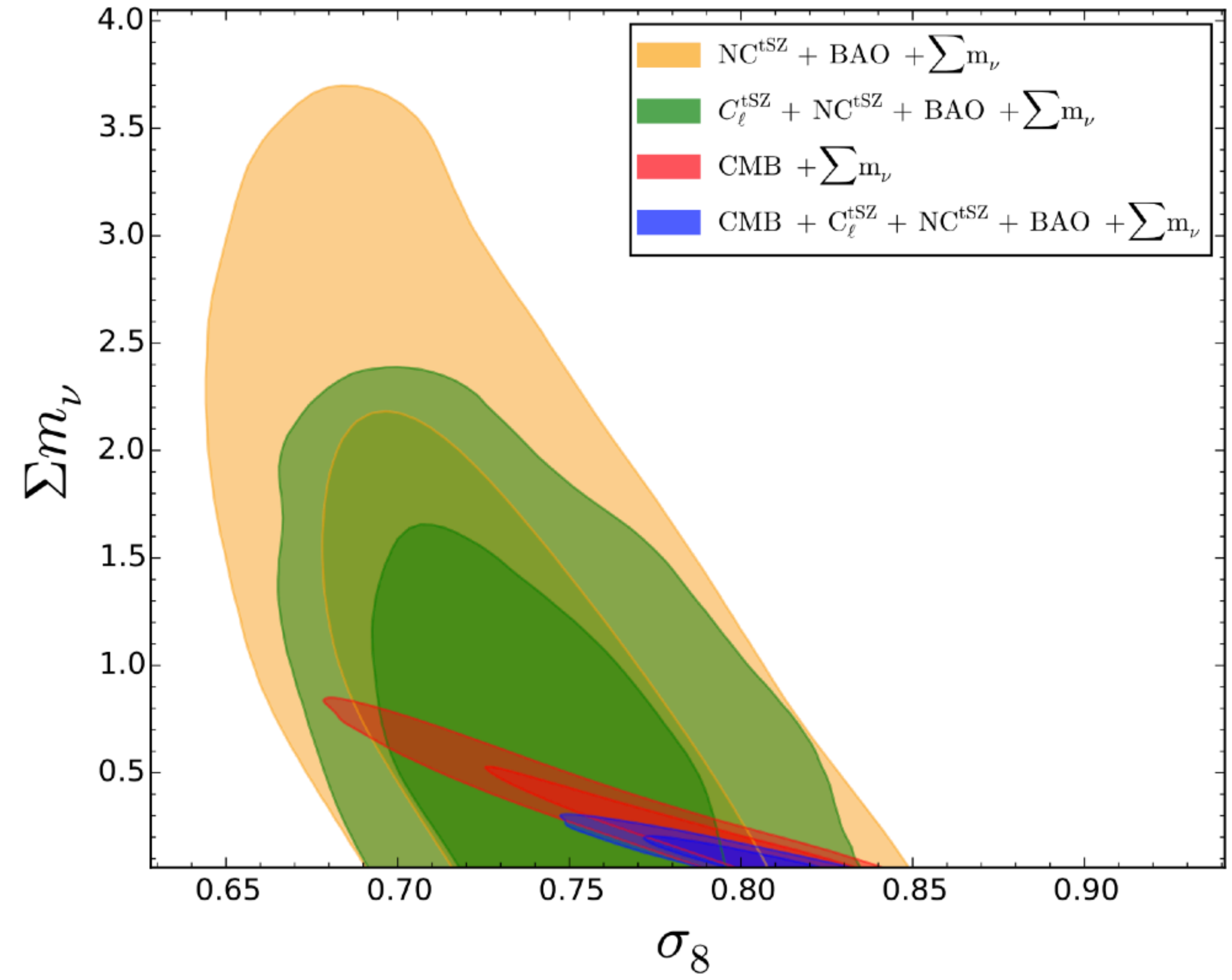
$\simeq 1.8\,\sigma$ discrepancy

Results

arXiv: 1708.00697
A&A, in press



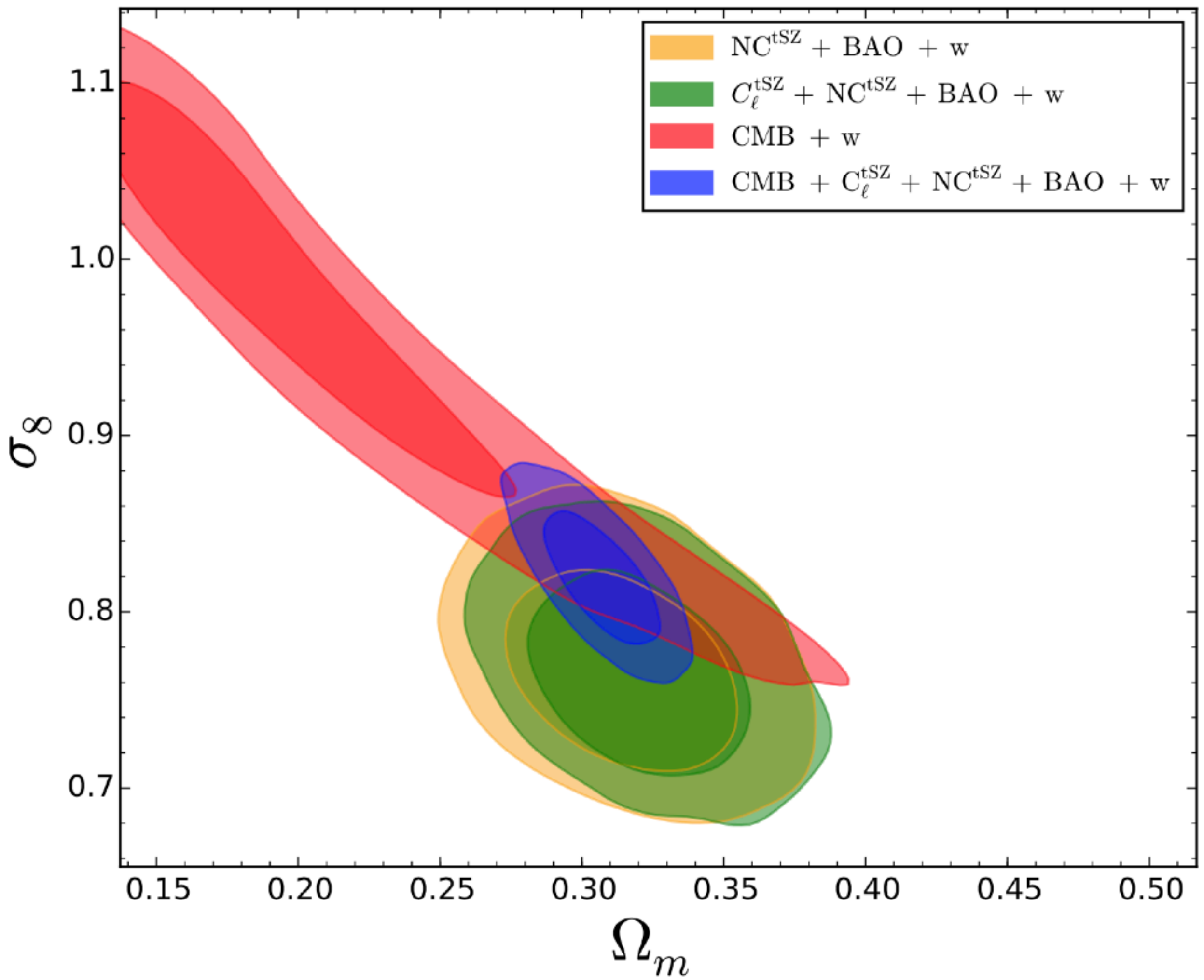


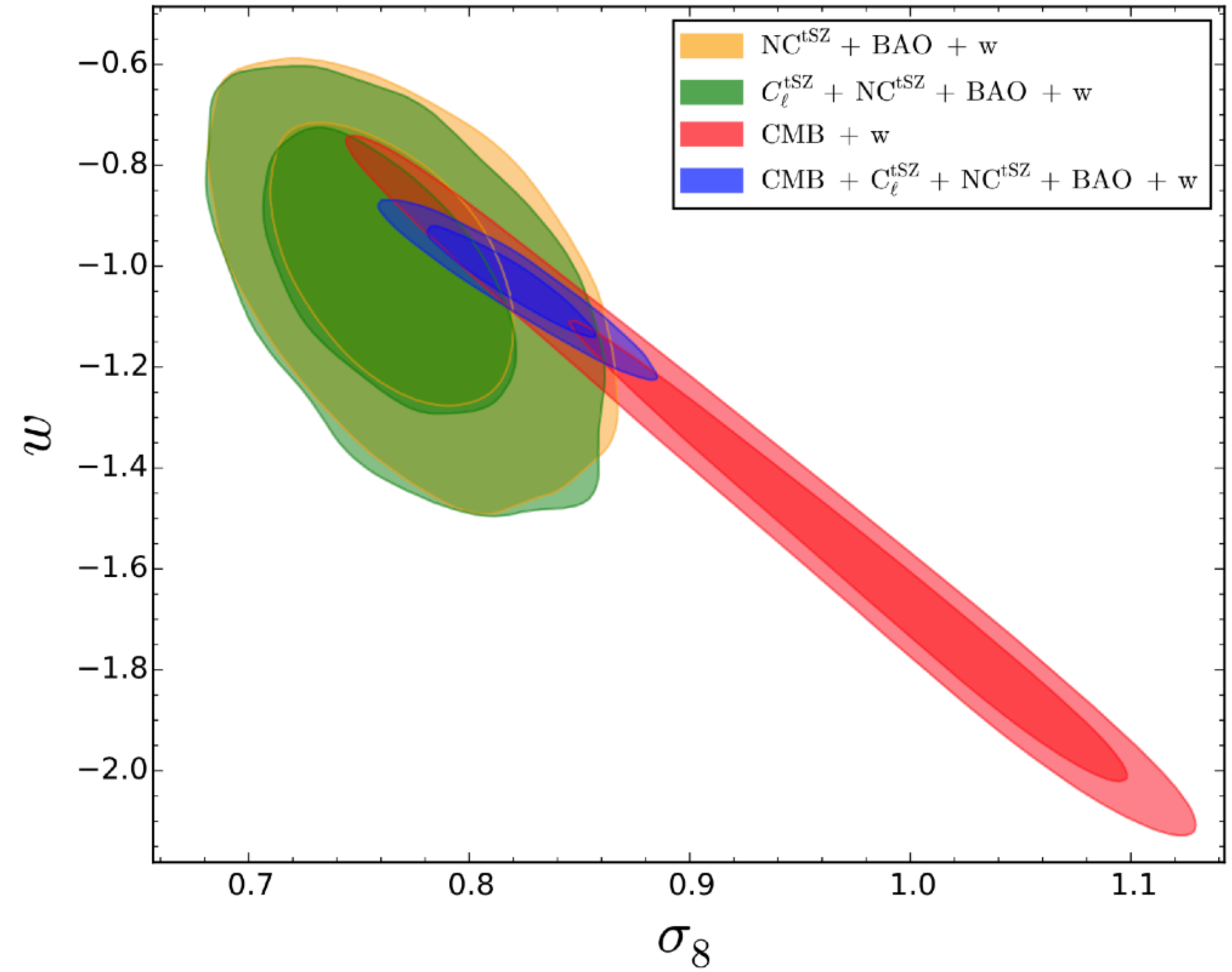
Cosmological parameters	NC + BAO	CL + NC + BAO	CMB	CMB + CL + NC + BAO
Ω_m	$0.337^{+0.027}_{-0.031}$	$0.335^{+0.023}_{-0.024}$	$0.353^{+0.020}_{-0.037}$	0.315 ± 0.008
σ_8	$0.728^{+0.032}_{-0.038}$	$0.737^{+0.028}_{-0.037}$	$0.772^{+0.049}_{-0.024}$	$0.792^{+0.020}_{-0.013}$
$\sum m_\nu$	$< 2.84\,\mathrm{eV}$	$< 1.88\,\mathrm{eV}$	$< 0.68\,\mathrm{eV}$	$< 0.23\,\mathrm{eV}$

$(1-b) = 0.67 \pm 0.04$

Results

arXiv: 1708.00697
A&A, in press





Cosmological parameters	NC + BAO	CL + NC + BAO	CMB	CMB + CL + NC + BAO
Ω_m	$0.315^{+0.025}_{-0.028}$	$0.321^{+0.024}_{-0.027}$	$0.209^{+0.023}_{-0.071}$	0.306 ± 0.013
σ_8	$0.769^{+0.032}_{-0.041}$	$0.766^{+0.031}_{-0.042}$	$0.969^{+0.109}_{-0.057}$	$0.820^{+0.023}_{-0.027}$
w	$-1.01^{+0.20}_{-0.17}$	$-1.04^{+0.20}_{-0.17}$	$-1.56^{+0.21}_{-0.40}$	$-1.03^{+0.08}_{-0.06}$

$(1-b) = 0.63 \pm 0.04$

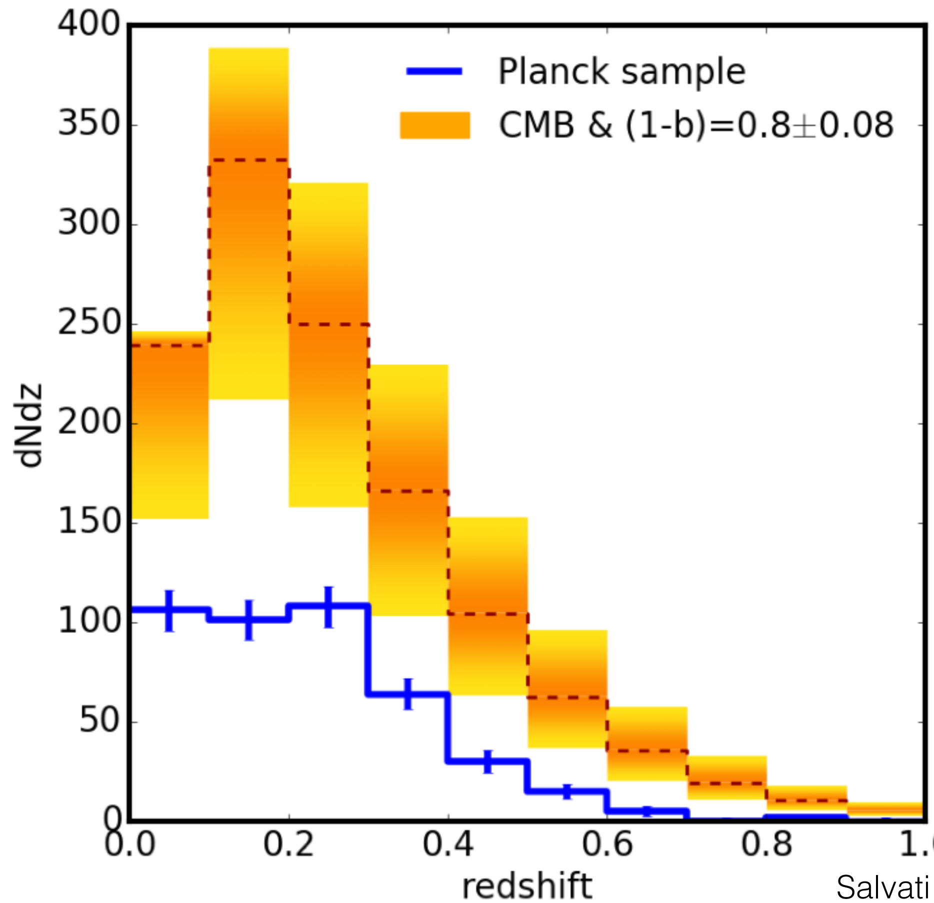
Discussion

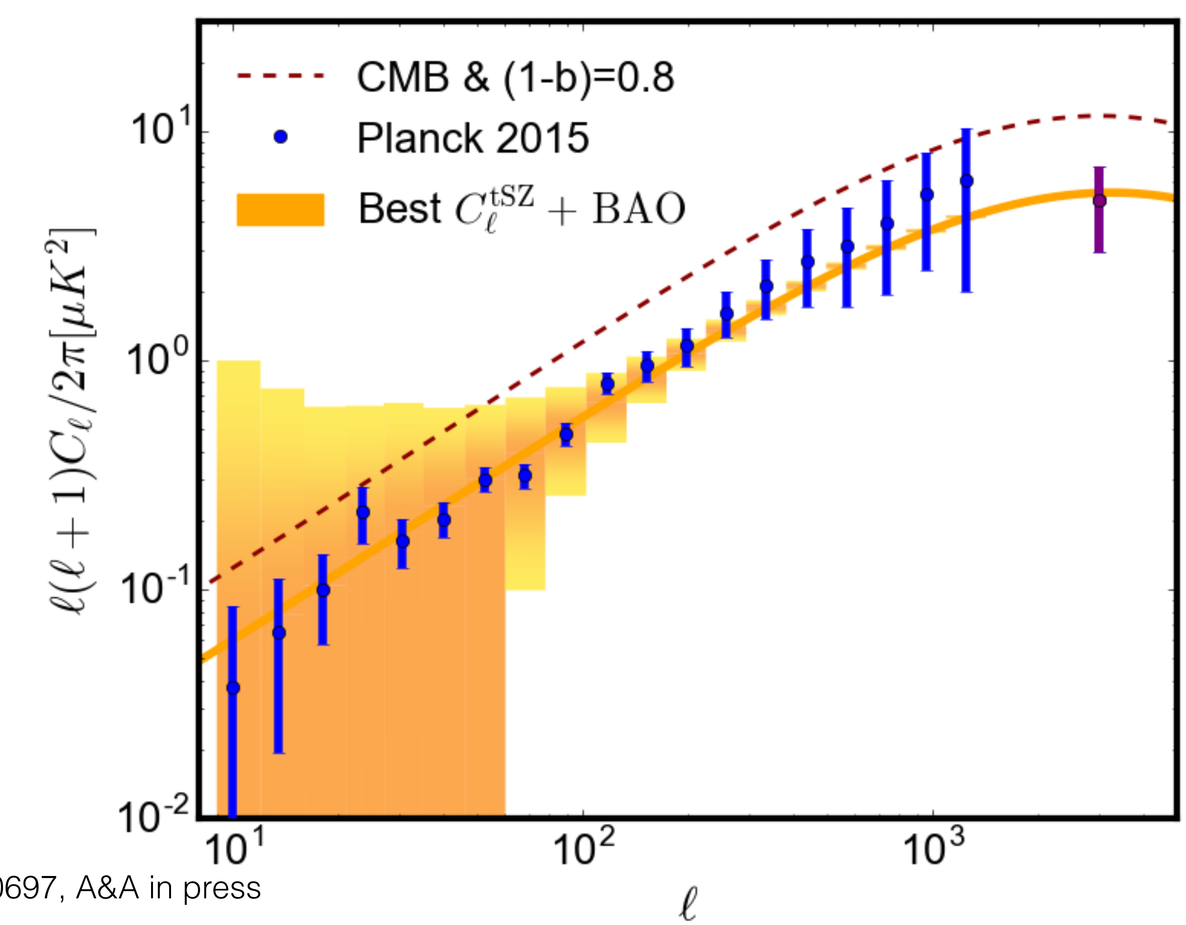
<u>Constraints on cosmological parameters from tSZ observations</u>

tSZ Number counts
+
tSZ power spectrum

⇒

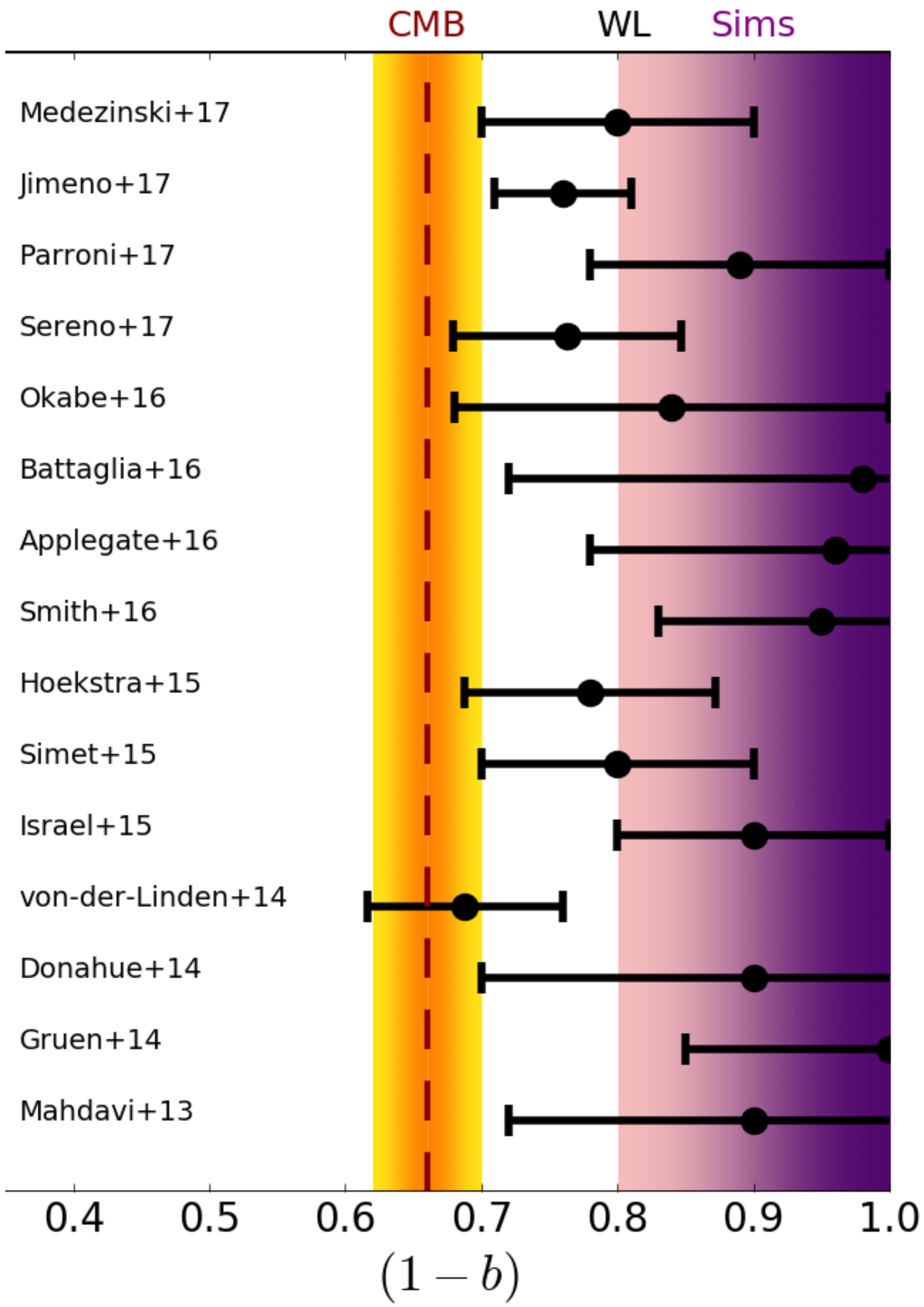
- improvement in constraining power
- able in constraining extensions to LCDM
- reduced discrepancy wrt CMB primary anisotropie





Salvati et al, arXiv: 1708.00697, A&A in press

Mass bias



Salvati et al, arXiv: 1708.00697, A&A in press

mass-bias varying wrt MASS and REDSHIFT

A.

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

$M_* = 6 \cdot 10^{14} M_\odot$ → consistent with scaling relations

$z_* = 0.22$ → median value of the P15 catalog

B.

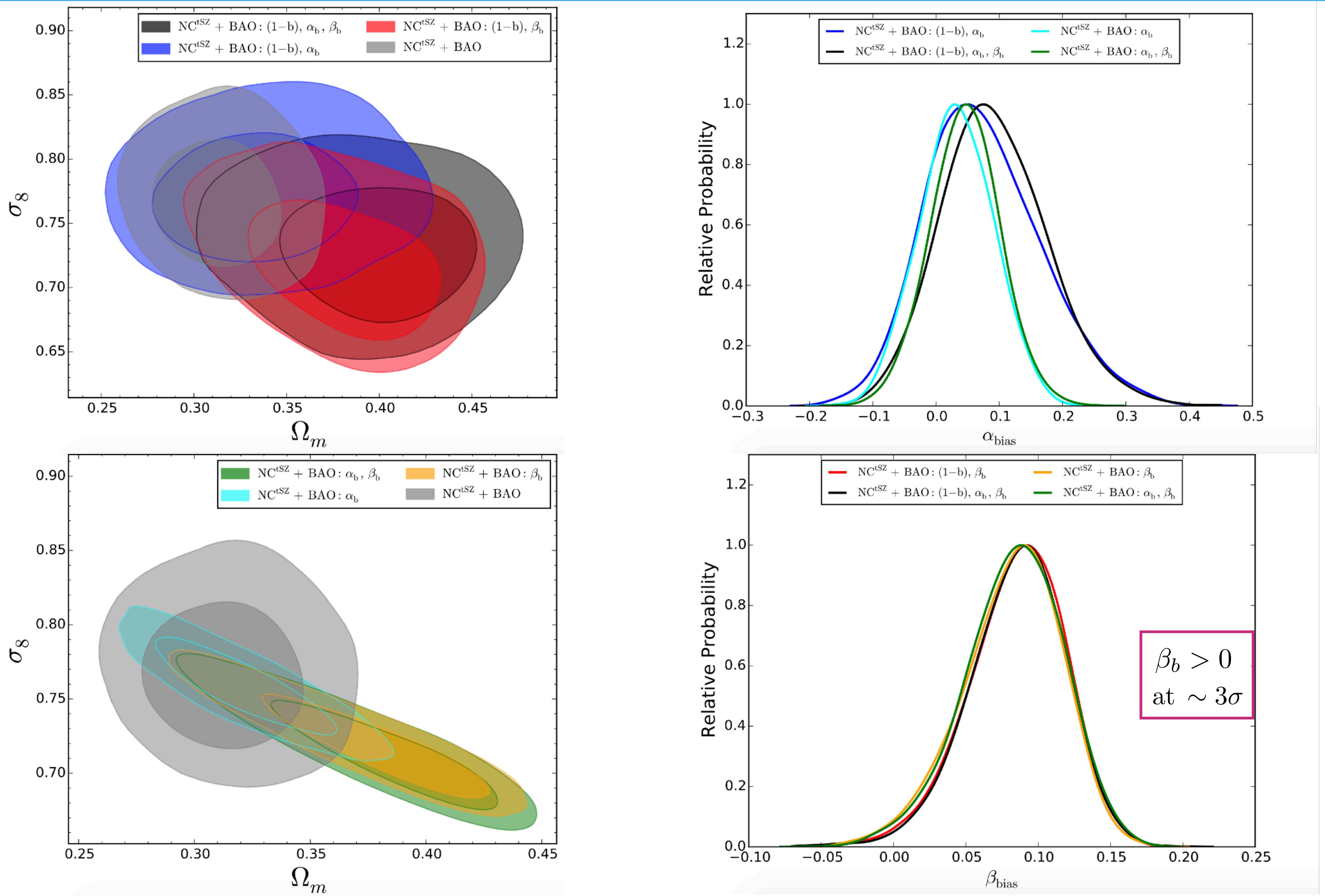
Bins in redshift, with different bias values

$z < 0.2$ → $(1-b)_1$

$0.2 \leq z < 0.55$ → $(1-b)_2$

$0.55 < z$ → $(1-b)_3$

PRELIMINARY Mass bias: A Number Counts

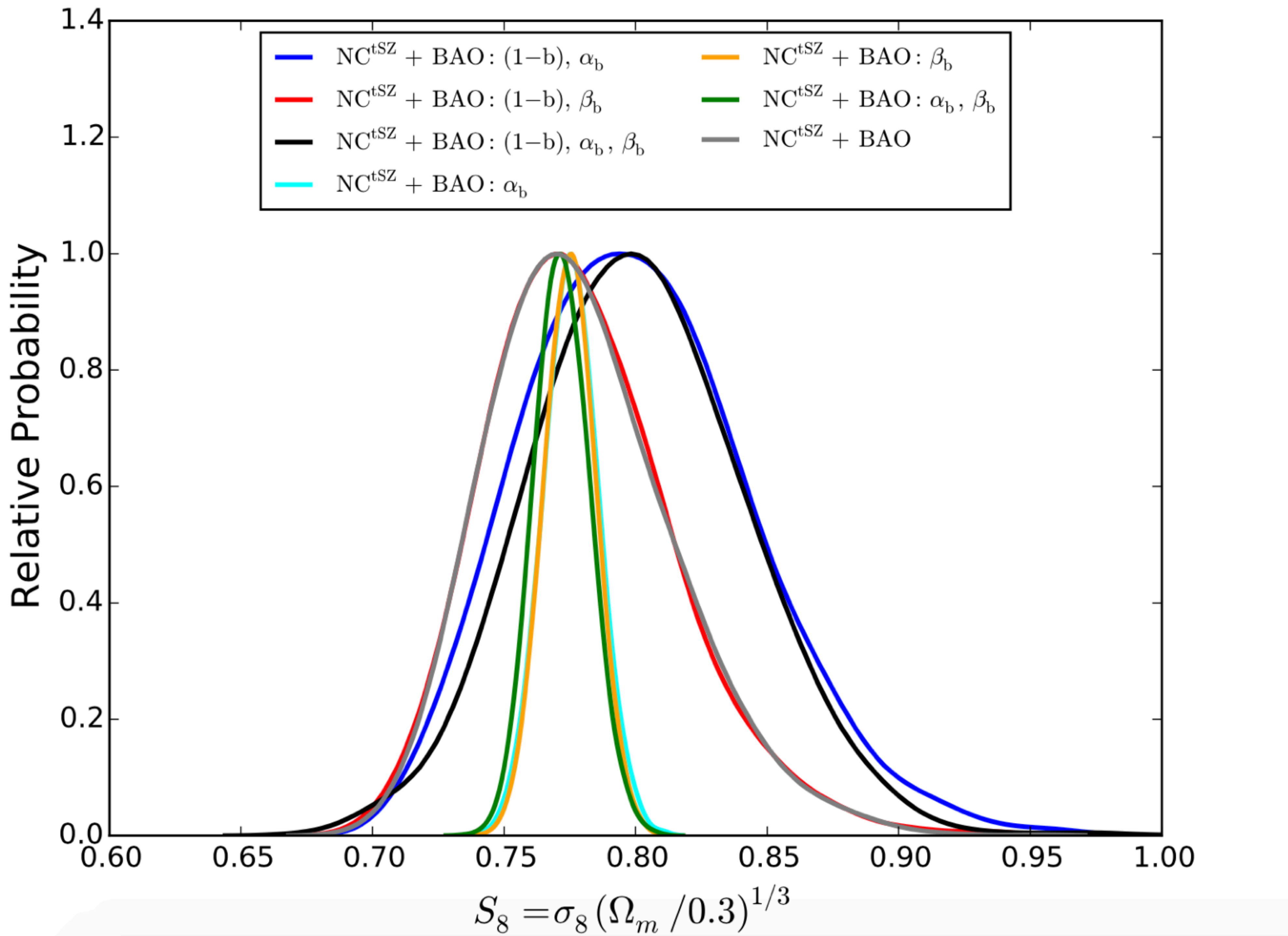


PRELIMINARY

Mass bias: A Number Counts

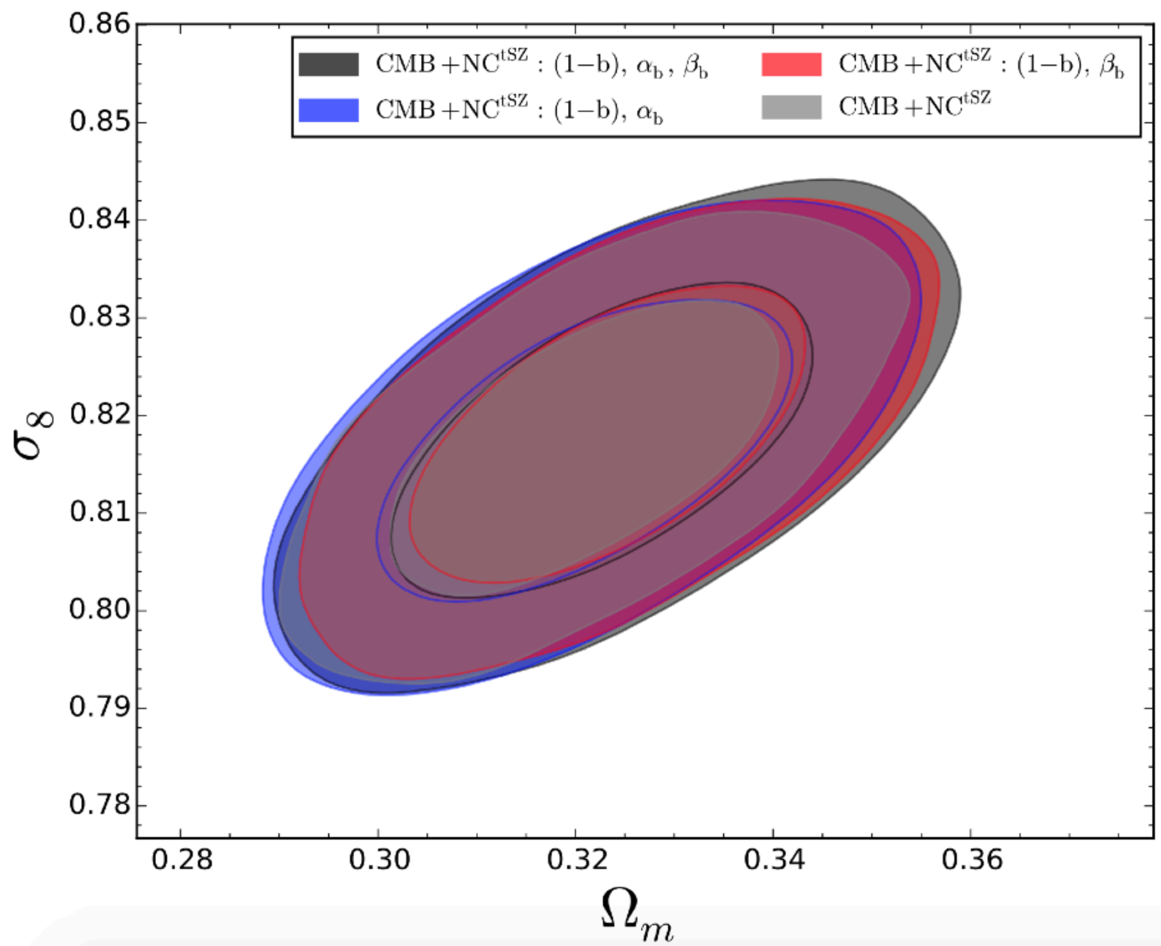
Datasets	Ω_m	σ_8	$S_8 = \sigma_8(\Omega_m/0.3)^{1/3}$	$(1-b)$	α_b	β_b	χ^2
NC+BAO	$0.314^{+0.020}_{-0.024}$	$0.768^{+0.028}_{-0.035}$	$0.780^{+0.028}_{-0.042}$	0.752 ± 0.093	0	0	142
NC+BAO+(1-b)+a	$0.336^{+0.031}_{-0.038}$	$0.773^{+0.027}_{-0.035}$	$0.801^{+0.038}_{-0.050}$	0.68 ± 0.12	$0.076^{+0.078}_{-0.104}$	0	142
NC+BAO+(1-b)+b	$0.381^{+0.037}_{-0.030}$	$0.721^{+0.029}_{-0.040}$	$0.780^{+0.029}_{-0.041}$	0.748 ± 0.091	0	$0.085^{+0.037}_{-0.028}$	138
NC+BAO+(1-b)+a+b	$0.396^{+0.040}_{-0.027}$	$0.731^{+0.030}_{-0.036}$	$0.801^{+0.039}_{-0.044}$	$0.67^{+0.11}_{-0.12}$	$0.092^{+0.077}_{-0.091}$	$0.085^{+0.036}_{-0.029}$	136
NC+BAO+a	$0.322^{+0.022}_{-0.027}$	0.758 ± 0.020	0.775 ± 0.010	0.75	0.032 ± 0.059	0	142
NC+BAO+b	$0.375^{+0.040}_{-0.025}$	$0.721^{+0.017}_{-0.027}$	0.775 ± 0.010	0.75	0	$0.082^{+0.039}_{-0.029}$	138
NC+BAO+a+b	$0.380^{+0.040}_{-0.022}$	$0.718^{+0.017}_{-0.028}$	0.772 ± 0.010	0.75	$0.087^{+0.079}_{-0.095}$	$0.086^{+0.036}_{-0.031}$	137

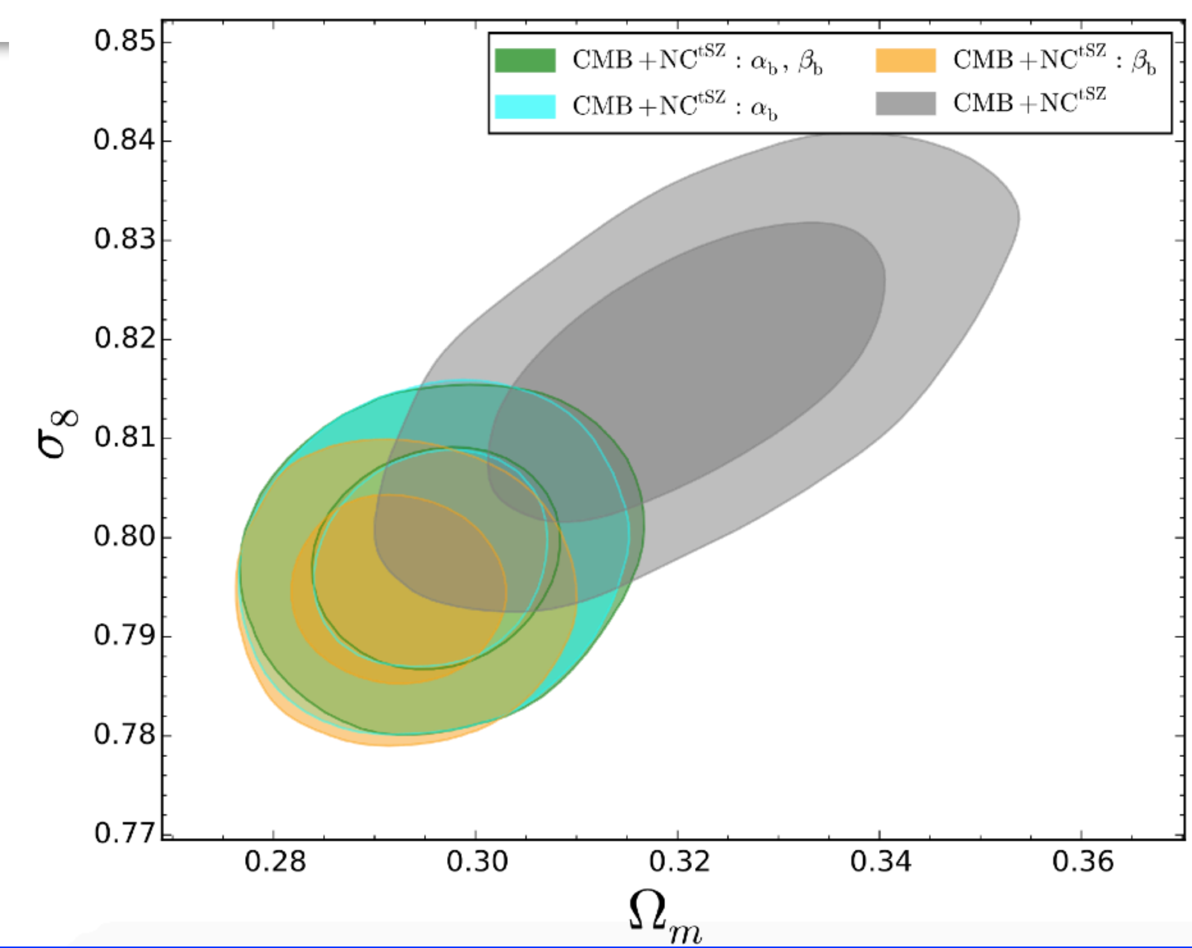
Mass bias: A Number Counts



Mass bias: A CMB + Number Counts

Datasets	Ω_m	σ_8	$S_8 = \sigma_8(\Omega_m/0.3)^{1/3}$	$(1-b)$	α_b	β_b	χ^2	
CMB+NC	0.321 ± 0.012	0.817 ± 0.009	0.836 ± 0.018	0.616 ± 0.066	0	0	923	
CMB+NC+(1-b)+a	$0.321^{+0.012}_{-0.014}$	0.816 ± 0.009	0.835 ± 0.018	0.598 ± 0.055	$0.012^{+0.060}_{-0.071}$	0	925	
CMB+NC+(1-b)+b	0.324 ± 0.013	0.818 ± 0.010	0.839 ± 0.018	$0.587^{+0.042}_{-0.051}$	0	0.023 ± 0.026	923	
CMB+NC+(1-b)+a+b	$0.323^{+0.013}_{-0.014}$	0.818 ± 0.010	0.838 ± 0.019	0.593 ± 0.055	$0.007^{+0.066}_{-0.080}$	$0.023^{+0.030}_{-0.027}$	924	
CMB+NC+a	0.296 ± 0.007	0.798 ± 0.007	0.794 ± 0.010	0.75	$-0.064^{+0.049}_{-0.059}$	0	932	✗
CMB+NC+b	0.292 ± 0.007	0.795 ± 0.006	0.788 ± 0.008	0.75	0	-0.004 ± 0.024	934	✗
CMB+NC+a+b	0.296 ± 0.007	0.798 ± 0.007	0.795 ± 0.010	0.75	$-0.078^{+0.056}_{-0.067}$	$0.012^{+0.029}_{-0.025}$	932	✗

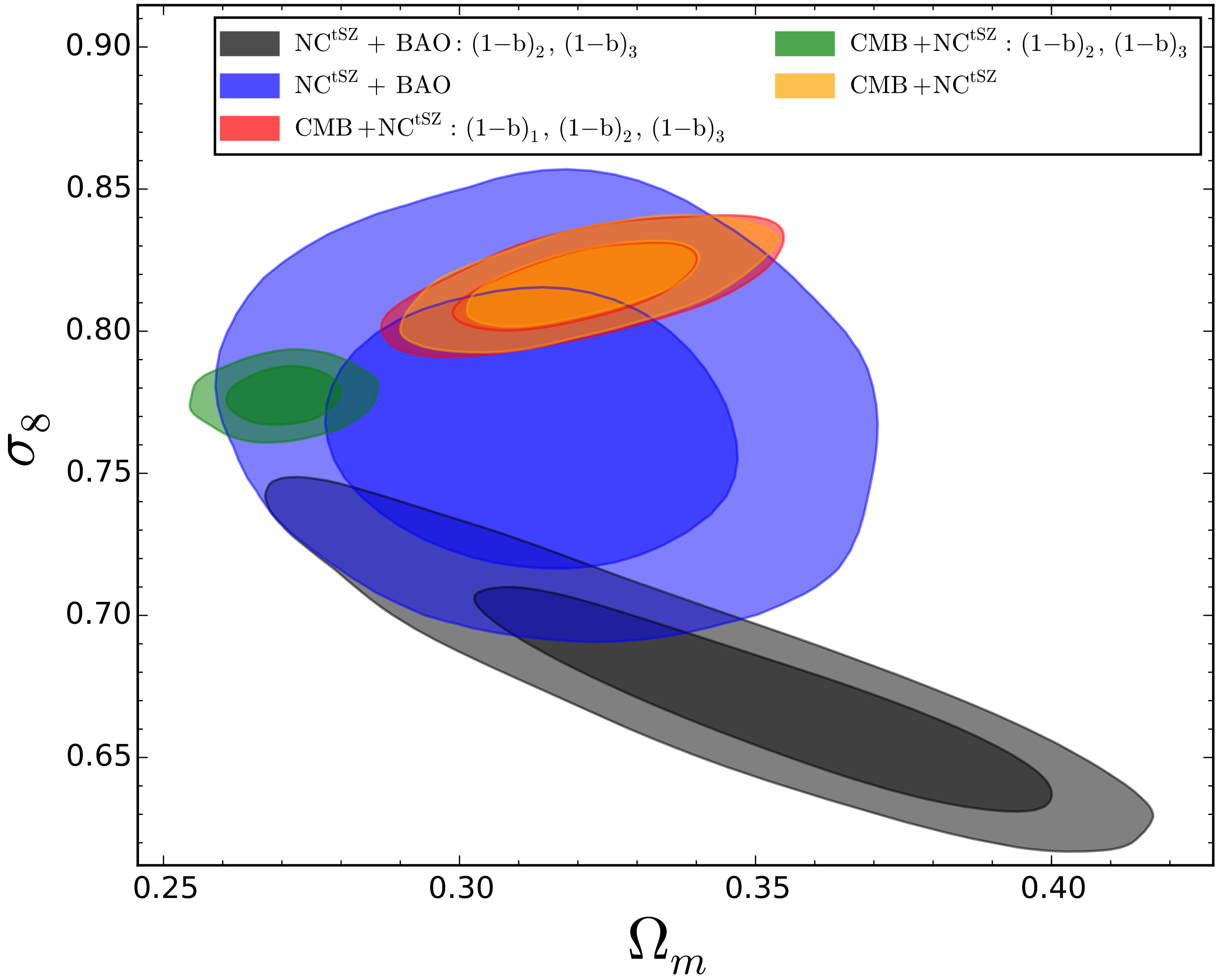


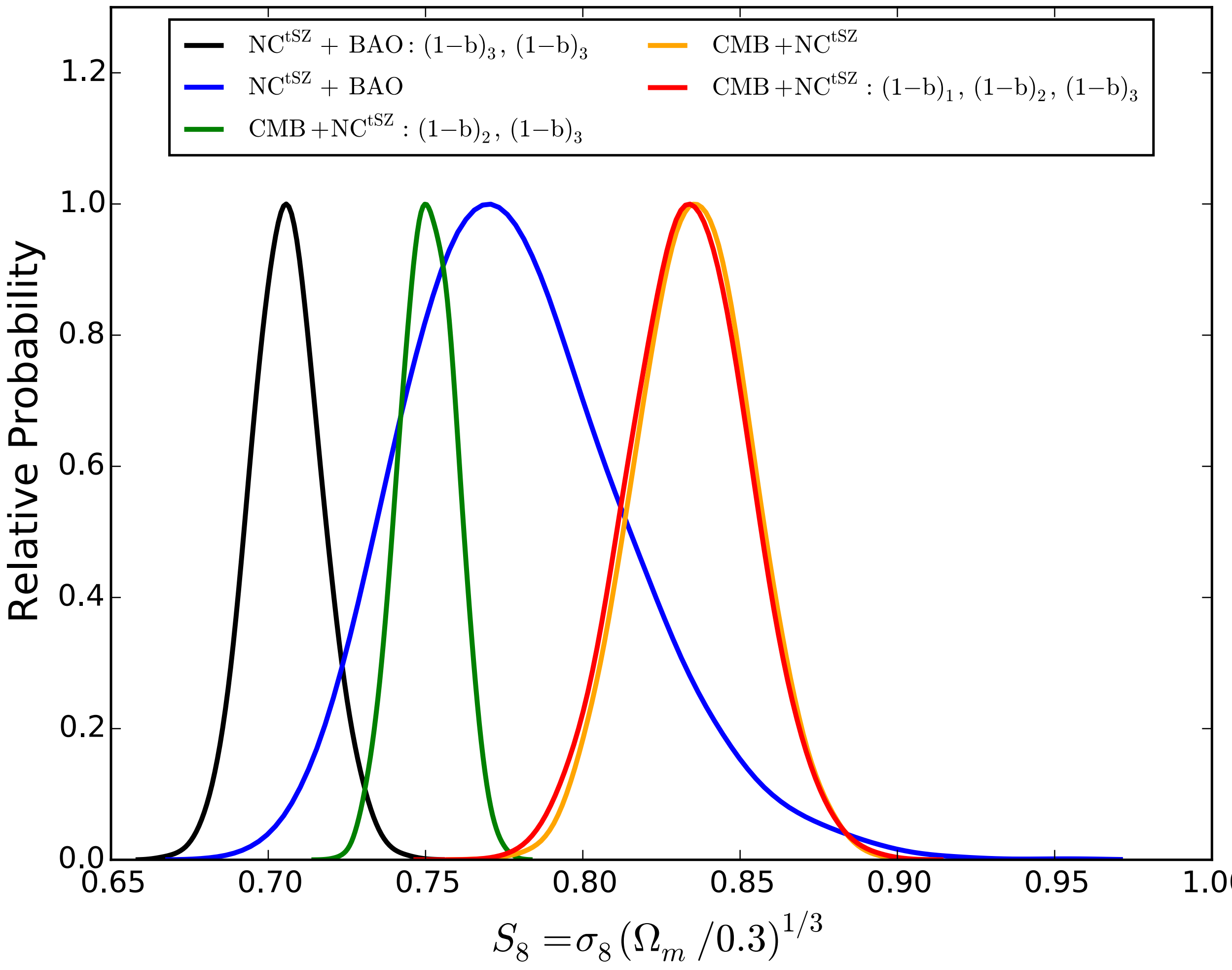


PRELIMINARY

Mass bias: B CMB and NC

Datasets	Ω_m	σ_8	$S_8 = \sigma_8(\Omega_m/0.3)^{1/3}$	$(1-b)_1$	$(1-b)_2$	$(1-b)_3$	χ^2
NC+BAO+(1-b)₂+(1-b)₃	$0.349^{+0.039}_{-0.025}$	$0.673^{+0.019}_{-0.031}$	0.706 ± 0.012	0.9	$1.081^{+0.056}_{-0.049}$	$0.983^{+0.091}_{-0.078}$	128
CMB+NC+(1-b)₂+(1-b)₃	0.270 ± 0.006	0.777 ± 0.006	0.751 ± 0.009	0.9	0.920 ± 0.034	0.766 ± 0.046	942
CMB+NC+(1-b)₁+(1-b)₂+(1-b)₃	0.320 ± 0.013	0.816 ± 0.010	0.833 ± 0.019	$0.565^{+0.047}_{-0.058}$	$0.638^{+0.048}_{-0.055}$	$0.545^{+0.047}_{-0.053}$	912





Conclusions

Varying mass bias wrt (M,z)

✦ Hint for redshift dependence → Need for further investigation

- when considering **Number Counts**

How to improve cosmological constraints from galaxy clusters

✦ better knowledge of cluster physics

- better description of the **mass bias**
- break degeneracy between **scaling relations** and **cosmological** parameters

✦ different modelling of **mass function**

e.g. Despali: free parametrisation of amplitude, shape

Despali et al, MNRAS 456 (2016) no.3, 2486

Back up

Scaling Relations

1. Baseline for mass - proxy relation

$Y_X - M_{500}^{\rm HE}$ from 20 local relaxed clusters
Arnaud et al., A&A 474 (2007) L37

HE mass: biased estimator of true mass

$$M_{500}^{\rm HE} = (1-b) M_{500}$$

- departure from HE equilibrium
- instrument calibration
- T inhomogeneities
- residual selection bias

mean value

$$E^{-2/3}\, Y_X = 10^{A \pm \sigma_A} \left[(1-b) M_{500}\right]^{\alpha \pm \sigma_\alpha}$$

from best-fit: mass proxy definition

$$E^{-2/3}(z)\, Y_X = 10^A \left[M_{500}^{Y_X}\right]^{\alpha}$$

$$M_{500}^{Y_X} = 10^{\pm \sigma_A/\alpha} \left[(1-b)\, M_{500}\right]^{1 \pm \sigma_\alpha/\alpha}$$

$Y_{500} - M_{500}$
independent of dynamical state

pass through Xray
- low-scatter mass proxy
- minimum HE bias

Scaling Relations

2. Relation $Y_{500} - M_{500}^{Y_X}$

from 71 Planck clusters with Xray follow-up from XMM-Newton

$$E^{-2/3}(z)\left[\frac{D_A^2\,Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = 10^{-0.19\pm0.01}\left[\frac{M_{500}^{Y_X}}{6\cdot10^{14}\,M_\odot}\right]^{1.79\pm0.06}$$

corrected for Malmquist bias

3. Combining everything

$$E^{-2/3}(z)\left[\frac{D_A^2\,Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = 10^{-0.19\pm0.02}\left[\frac{(1-b)\,M_{500}}{6\cdot10^{14}\,M_\odot}\right]^{1.79\pm0.08}$$

Mass bias

$$M_{500}^{\rm HE} = (1-b) M_{500}$$

$Y_{500} - M_{500}$

Comparison between observations and numerical simulations

Mass dependance: $b = b\left(M_{500}^{\rm true}\right)$

$$M_{500}^{\rm obs} = \left[1 - b\left(M_{500}^{\rm true}\right)\right] M_{500}^{\rm true}$$

$$R_{500}^{\rm obs} = \left[1 - b\left(M_{500}^{\rm true}\right)\right]^{1/3} R_{500}^{\rm true}$$

Corresponding relations:

$$Y(< R_{500}^{\rm true}) = A_{\rm true}\left[M_{500}^{\rm true}\right]^{\beta}$$

$$Y(< R_{500}^{\rm obs}) = A_{\rm obs}\left[M_{500}^{\rm obs}\right]^{\alpha}$$

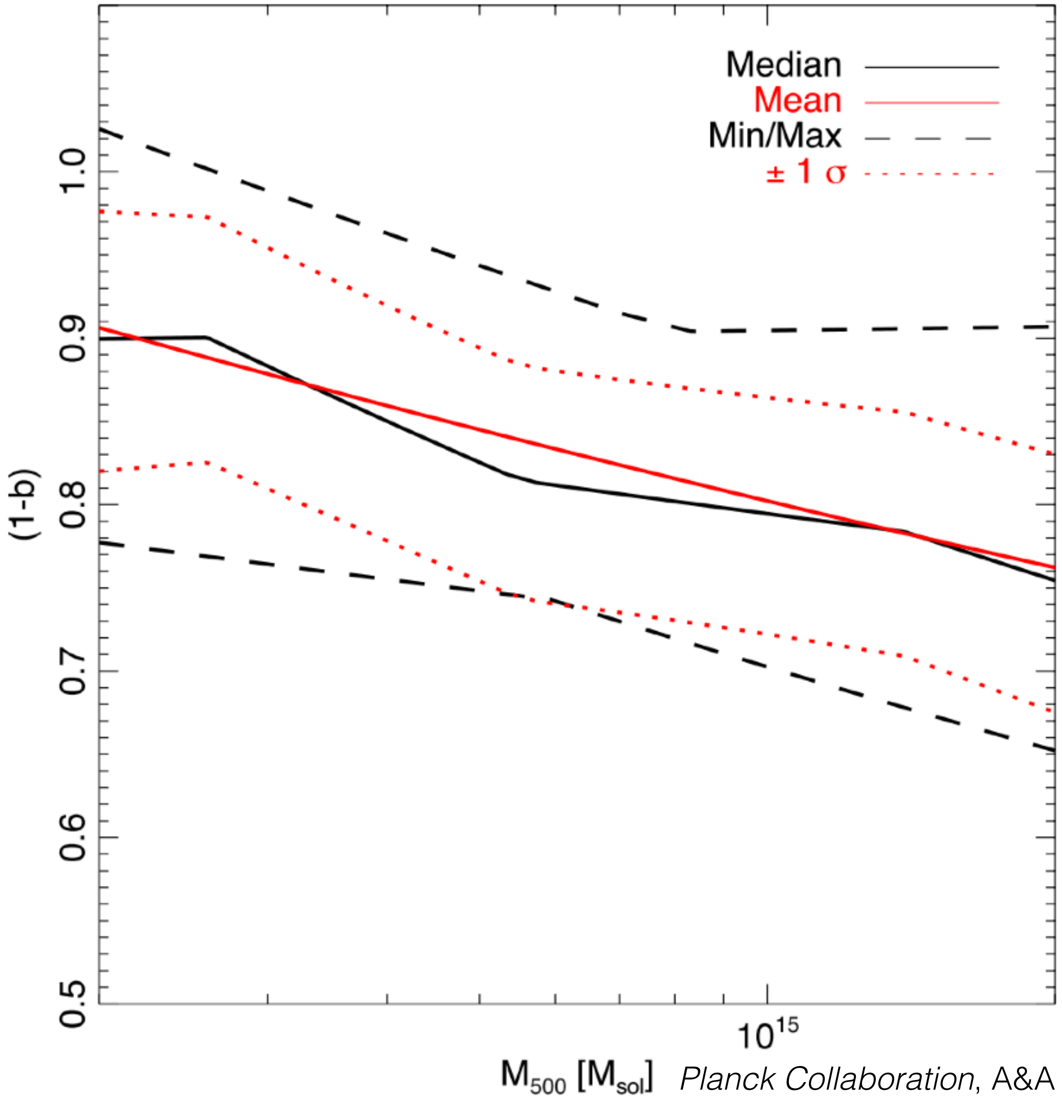
$$Y(< R_{500}^{\rm true}) / Y(< R_{500}^{\rm obs}) \propto (1-b)^{-1/4}$$

$$\left[1 - b\left(M_{500}^{\rm true}\right)\right] = \left[\frac{A_{\rm true}\left(M_{500}^{\rm true}\right)^{\beta}}{A_{\rm obs}\left(M_{500}^{\rm obs}\right)^{\alpha}}\right]^{-1/4+\alpha}$$

mass-dependent bias implies different slopes for observed and simulated relations

Mass bias

$$\left[1 - b\left(M_{500}^{\rm true}\right)\right] = \left[\frac{A_{\rm true}\left(M_{500}^{\rm true}\right)^{\beta}}{A_{\rm obs}\left(M_{500}^{\rm obs}\right)^{\alpha}}\right]^{-1/4+\alpha}$$



Planck Collaboration, A&A 571 (2014) A20

$$(1-b) = [0.7, 1.0]$$

$$(1-b)_{\rm mean} \simeq 0.8$$

Mass function

Tinker 2008

Tinker et al., Astrophys. J. 688 (2008) 709

$$f(\sigma) = A_1(z) \cdot \left[\left(\frac{\sigma(R,z)}{b(z)} \right)^{-a_2(z)} \right] \cdot \exp\left(-\frac{c}{\sigma^2(R,z)} \right)$$

$$\frac{dn}{dM} = -\frac{\rho_0}{M} \frac{d\sigma(R,z)}{dM} f(\sigma) \frac{h}{\sigma(R,z)}$$

$$A_1(z) = A_{1,0}(1+z)^{-0.14}$$
$$a_2(z) = a_{2,0}(1+z)^{-0.06}$$
$$b(z) = b_0(1+z)^{-\alpha}$$
$$c = c_0$$

Despali 2016

Despali et al, MNRAS 456 (2016) no.3, 2486

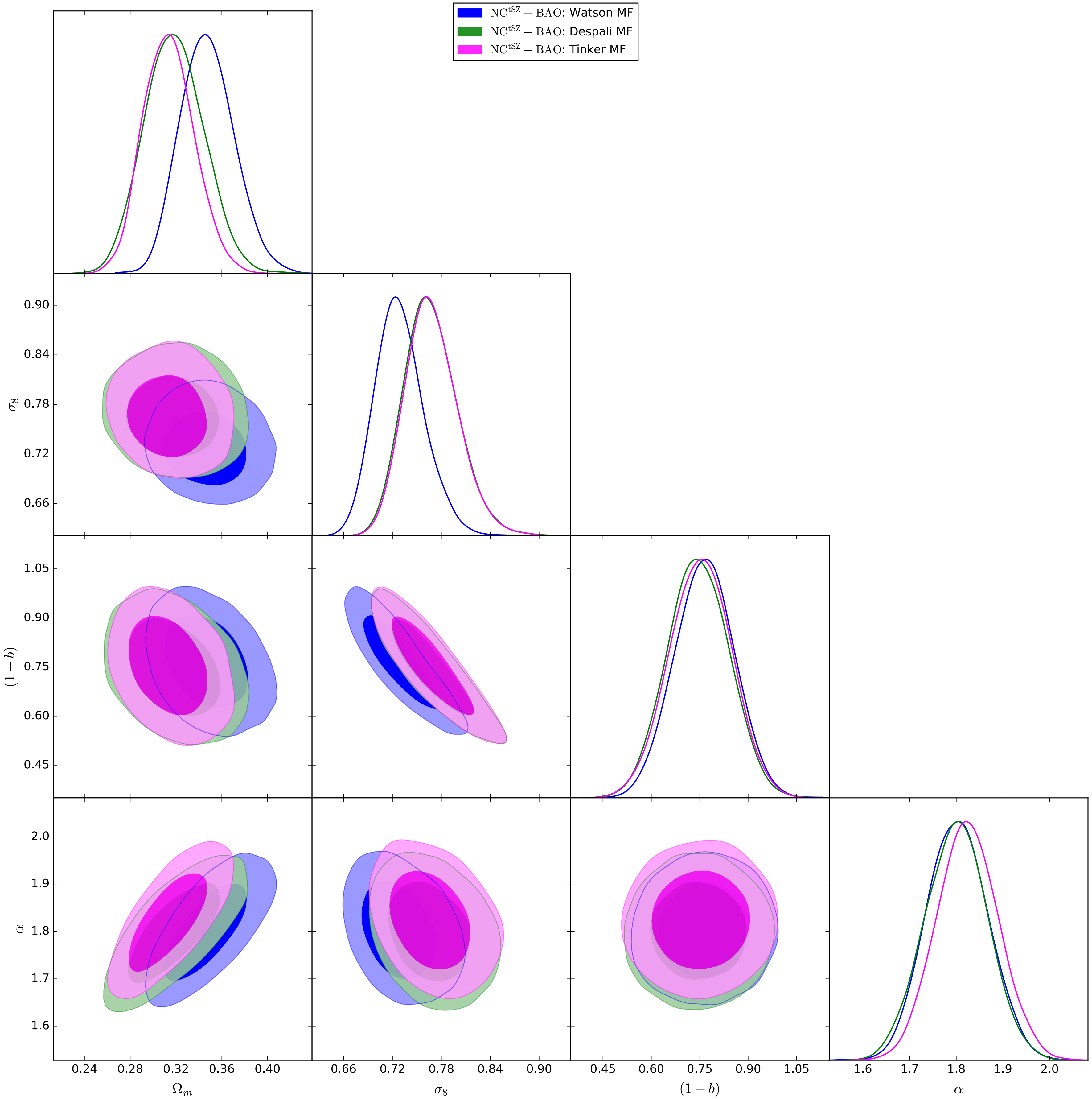
$$\nu f(\nu) = A \left[1 + (a\nu)^{-p} \right] \left(\frac{a\nu}{2\pi} \right)^{1/2} \exp\left(-\frac{a\nu}{2} \right)$$

$$\frac{dn}{dM} = -\frac{\rho_0}{M} \frac{2}{\sigma(R,z)} \nu f(\nu) \frac{d\sigma(R,z)}{dM} h$$

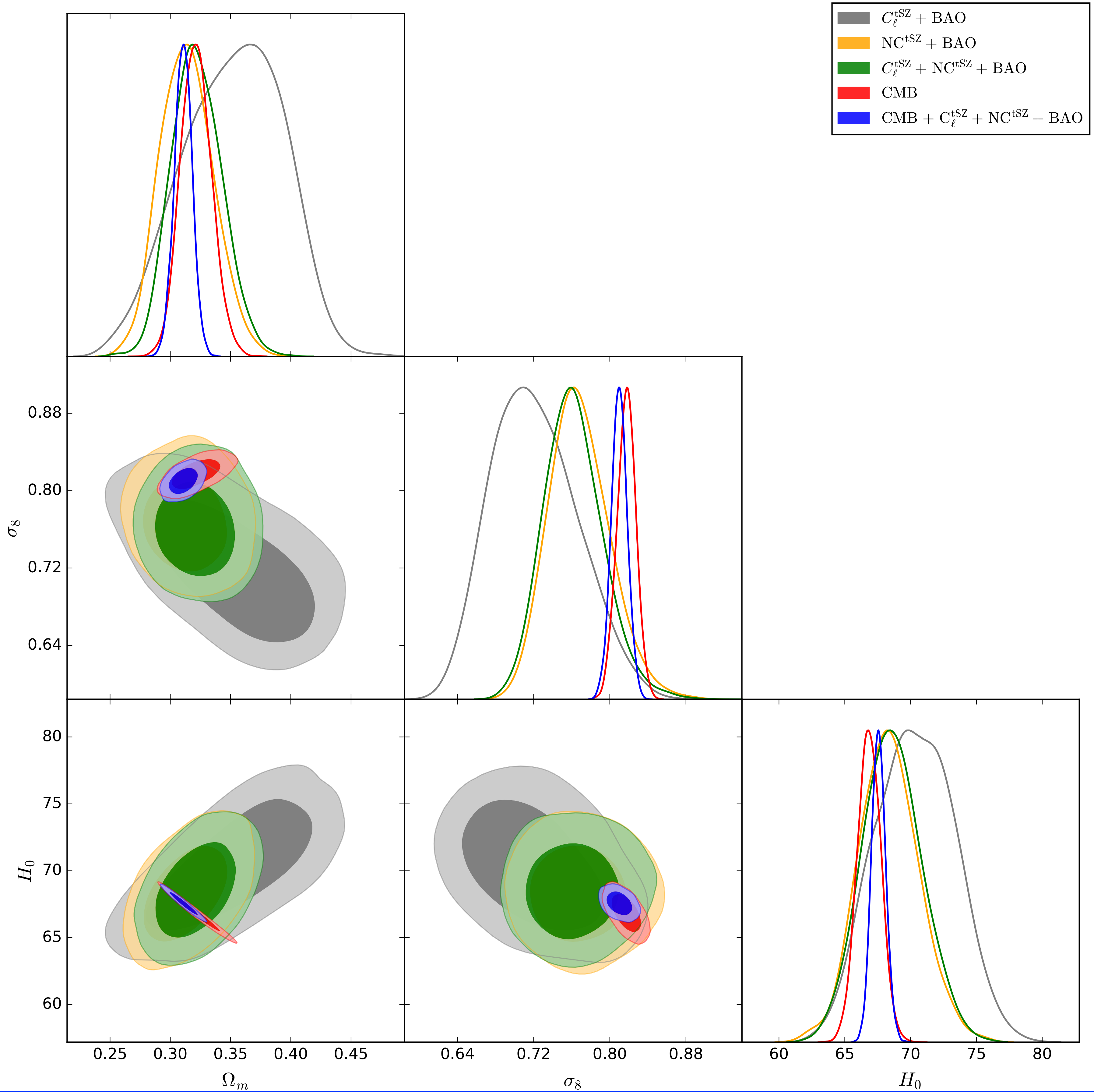
$$A = -0.1362\, x + 0.3292$$
$$a = 0.4332\, x^2 + 0.2263\, x + 0.7655$$
$$p = -0.1151\, x^2 + 0.2554\, x + 0.2488$$

$$x = \mathrm{Log}_{10}\left(\frac{500}{\Delta_{\mathrm{vir}}} \right)$$

Mass function



H_0



C_ℓ^{tSZ} + BAO
NC^{tSZ} + BAO
C_ℓ^{tSZ} + NC^{tSZ} + BAO
CMB
CMB + C_ℓ^{tSZ} + NC^{tSZ} + BAO
0.88
0.80
0.72
0.64
σ_8
80
75
70
65
60
H_0
0.25
0.30
0.35
0.40
0.45
Ω_m
0.64
0.72
0.80
0.88
σ_8
60
65
70
75
80
H_0

Datasets comparison