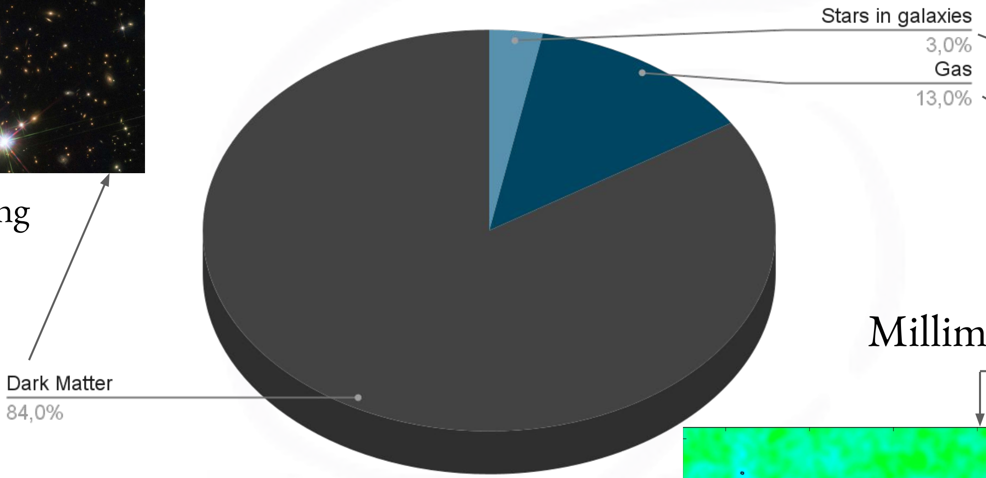
Constraining the mass and redshift evolution of the hydrostatic mass bias using the gas mass fraction in galaxy clusters

Raphaël Wicker (IAS)

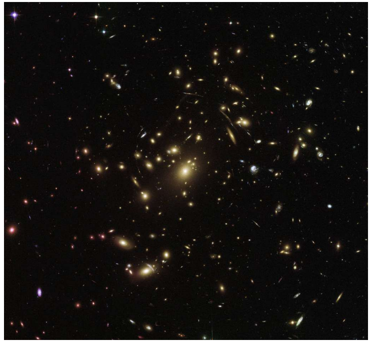
Marian Douspis, Laura Salvati, Nabila Aghanim

PSZ1G311.65-18-.48
Credits : ESA, NASA, HST,
Rivera-Thorsen et al.

Gravitational lensing
(Weak and strong)



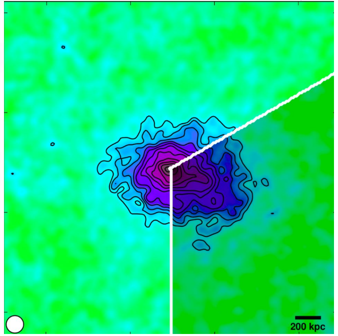
Abell 2357
Crédits: ESA, HST,
NASA



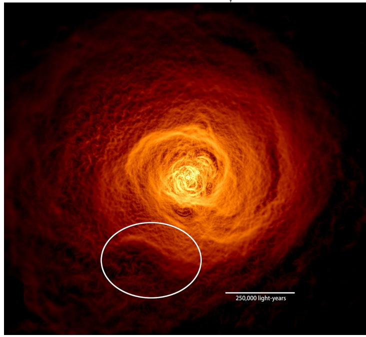
Optical

Millimeter (SZ Effect)

X-rays



PSZ2 G144.83+25.11
NIKA2, Ruppin et al.
A&A 597, A110 (2017)



Perseus cluster
Chandra, Walker et al.,
2017MNRAS.468.2506W

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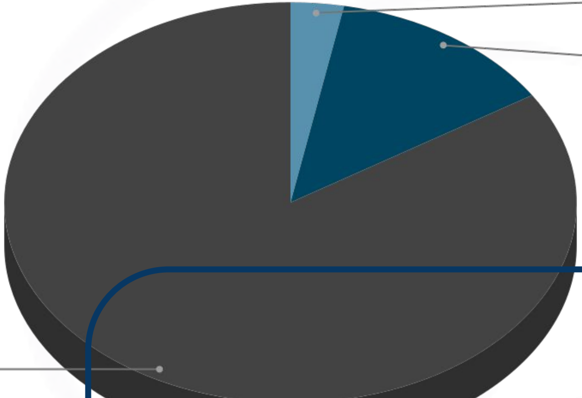

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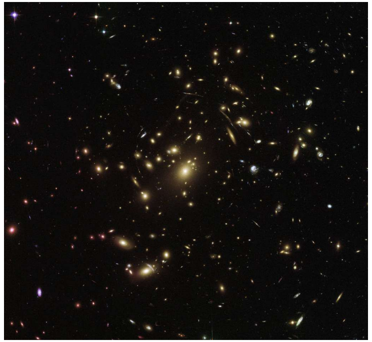

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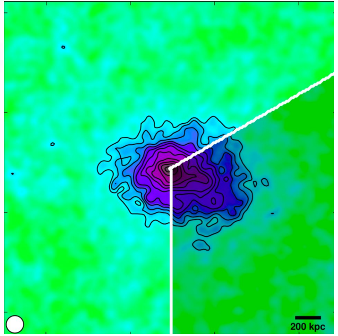

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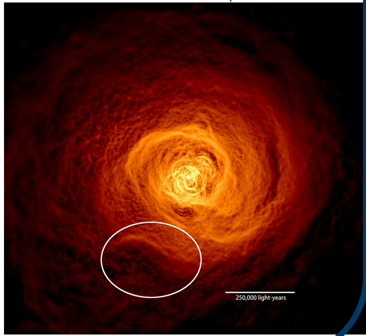

Perseus cluster
Chandra, Walker et
al. 2017

THE GAS MASS FRACTION AS A PROBE FOR THE HYDROSTATIC MASS BIAS

Galaxy clusters can be used to constrain cosmological parameters.

- Number counts, clustering, sparsity etc…
- One can also use $f_{gas} \propto \dfrac{\Omega_b}{\Omega_m}$

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \longrightarrow$$

From X-ray/SZ measurements, assuming modelling hypothesis:

- Sphericity
- Self-similarity
- *Hydrostatic equilibrium*

↓

"Hydrostatic mass bias" $B = M_{HE}/M_{tot}$

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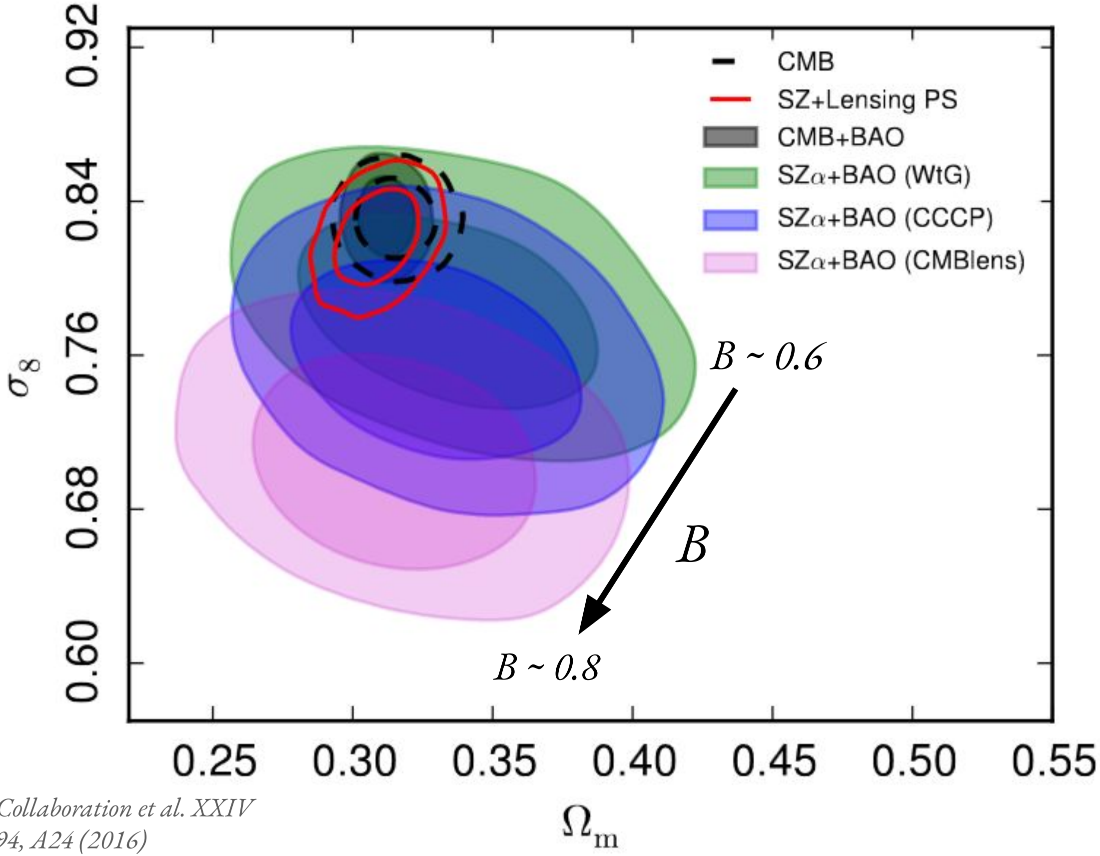
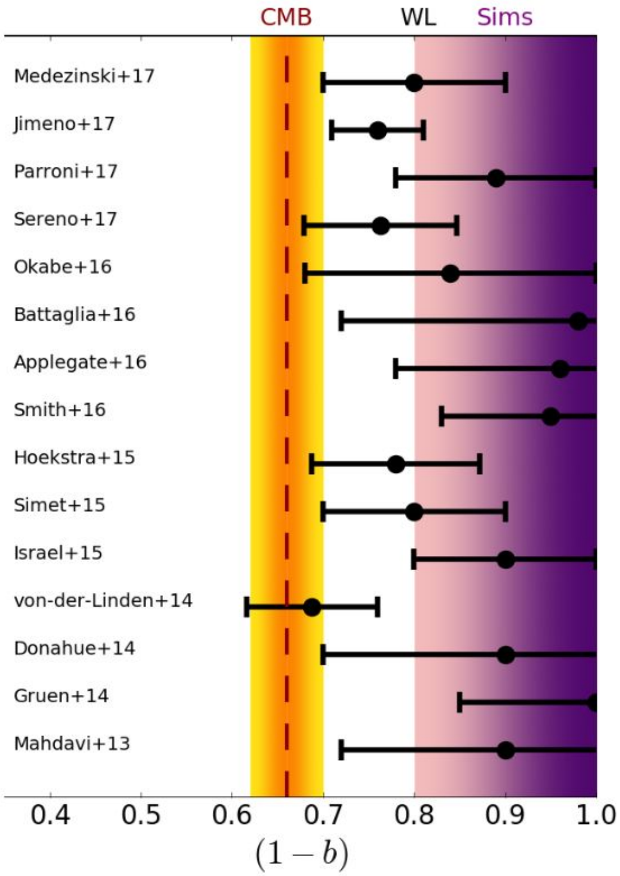


Planck Collaboration et al. XXIV
A&A 594, A24 (2016)



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

THE GAS MASS FRACTION AS A PROBE FOR THE HYDROSTATIC MASS BIAS

- *Purpose :* study the hydrostatic mass bias using cluster gas mass fraction data
- *In particular :* look for an evolution of B with M and z

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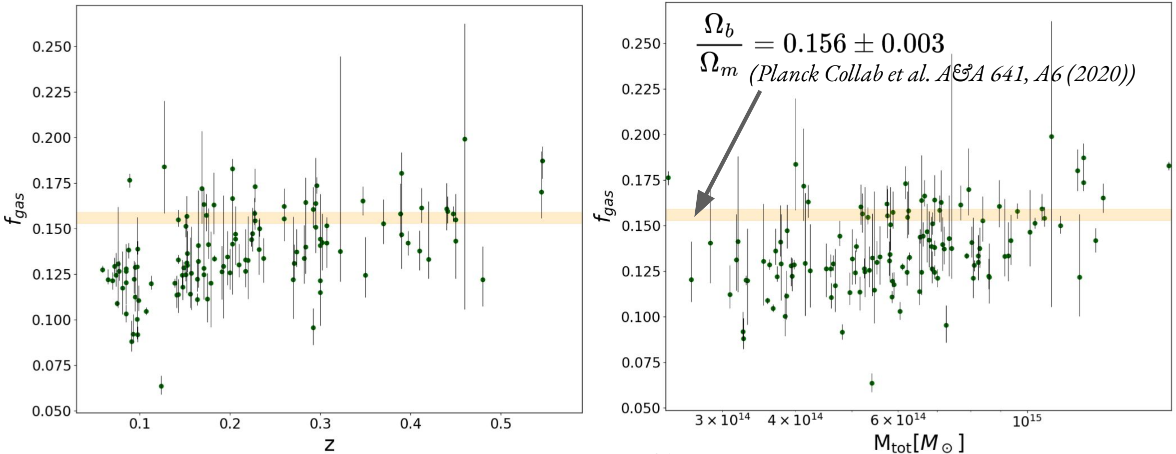

$$\frac{\Omega_b}{\Omega_m} = 0.156 \pm 0.003$$

(Planck Collab et al. A&A 641, A6 (2020))

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

The sample of gas fractions is publicly available

120 clusters from the *Planck-ESZ sample*. Observed by *XMM-Newton*, data taken at R_{500}, with z $\in$[0.059; 0.546], and $M_{500} \in$ [2.22; 17.5] $\times 10^{14} M_\odot$. (Masses from *Lovisari et al 2020 ApJ 892 102)*

THE GAS MASS FRACTION AS A PROBE FOR THE HYDROSTATIC MASS BIAS

We model the observed gas fraction as follows :

$$M_{mes} = B \times M_{true}$$

$$\Rightarrow f_{gas} = \frac{M_{gas}}{M_{mes}} = \frac{M_{gas}}{B \times M_{true}}$$

Allen et al. 2008MNRAS.383..879A

$$f_{gas,Th}(M,z) = \underbrace{K}_{\text{Instrumental effects}} \underbrace{\frac{\Upsilon(M,z)}{B(M,z)}}_{\text{Baryonic effects}} \underbrace{A(z)\left(\frac{\Omega_b}{\Omega_m}\right)\left(\frac{D_A^{ref}(z)}{D_A(z)}\right)^{3/2}}_{\text{Cosmology}} \underbrace{- f_*}_{\text{Stellar content}}$$

THE GAS MASS FRACTION AS A PROBE FOR THE HYDROSTATIC MASS BIAS

Redshift dependence

Mass dependence

$$B(M,\, z) \;=\; \boxed{B_0}\left(\frac{M}{\langle M\rangle}\right)^{\boxed{\alpha}}\left(\frac{1+z}{\langle 1+z\rangle}\right)^{\boxed{\beta}}$$

Amplitude

=> 3 free parameters to describe the bias

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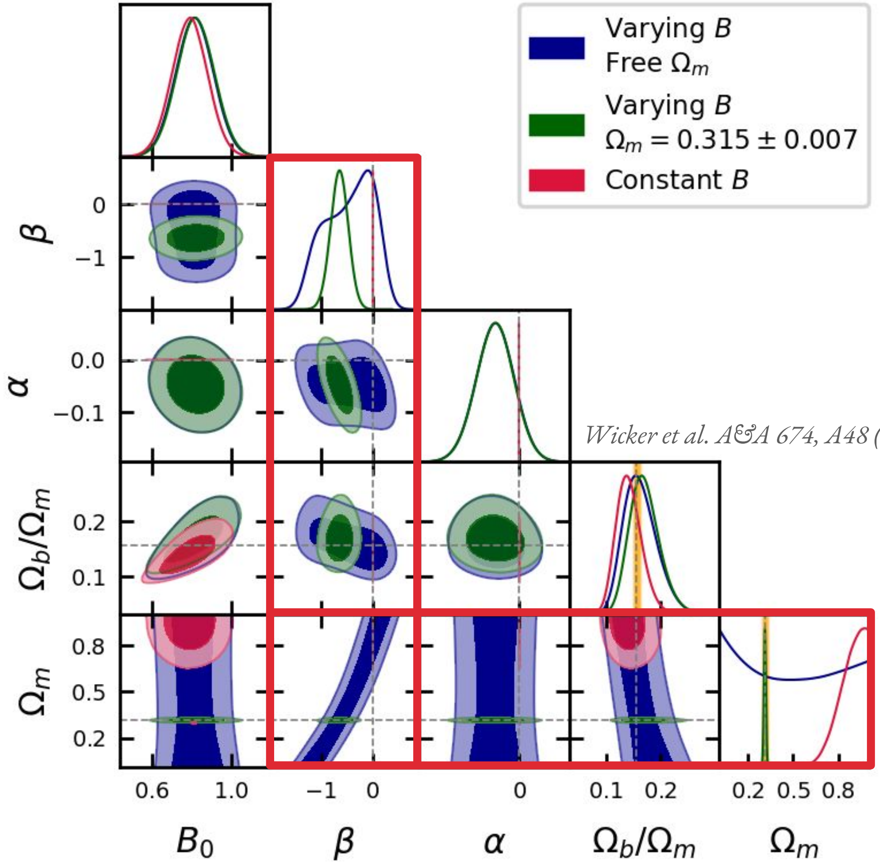
=> 3 free parameters to describe the bias

We check how assuming a *constant* or *varying* bias impacts our cosmological constraints from gas fraction.

THE GAS MASS FRACTION AS A PROBE FOR THE HYDROSTATIC MASS BIAS



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

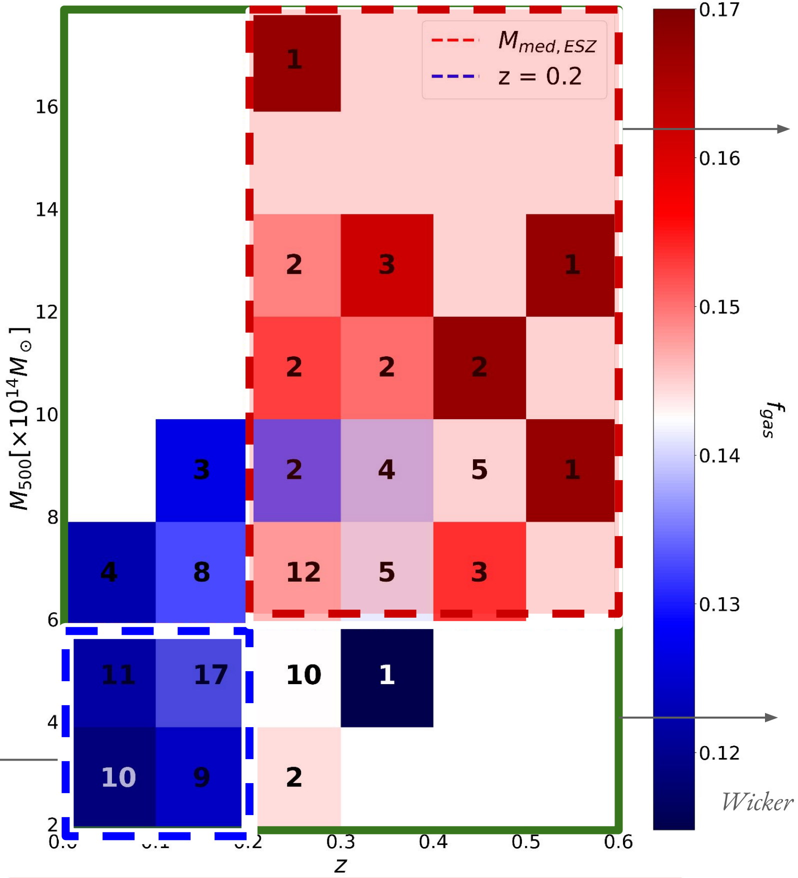
- β and Ω_m are *degenerate*
- Assuming a constant bias leads to $\Omega_m > 0.860$
- Assuming a *Planck Collab. et al. (2020)* cosmology:
- $\beta = -0.64 \pm 0.17$ (in tension with 0)
- $\alpha = -0.057 \pm 0.038$ (compatible with 0)
- $B_0 = 0.828 \pm 0.039$ (compatible with 0.8)

The gas mass fraction as a probe for the hydrostatic mass bias

We seem to need an evolution of the bias. But does that depend on our sample ?

Studies of tSZ counts show a sample dependence

(see e.g. *Salvati et al. A&A 626, A27 (2019), Laura Salvati's talk*)



High Mz subsample

Full sample

Low Mz subsample

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

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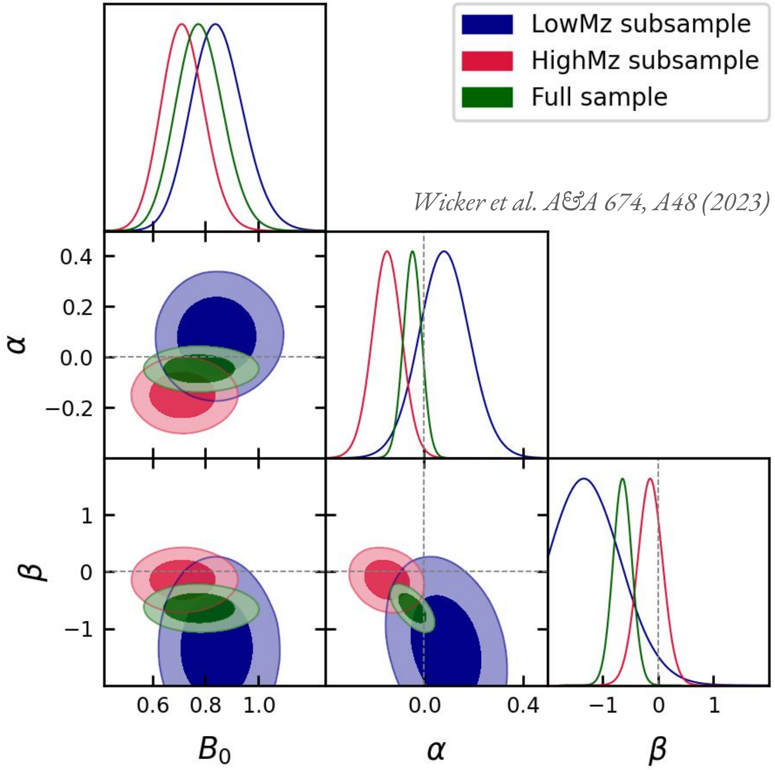

Wicker et al. A&A 674, A48 (2023)

- All samples favor an amplitude $B_0 \sim 0.8$
- ***Low Mz***: favors a strong redshift evolution, but compatible with no mass evolution
- ***High Mz***: compatible with no redshift evolution, but favors a mass evolution
- ***Full sample***: Strongly favors a redshift evolution, compatible with no mass evolution

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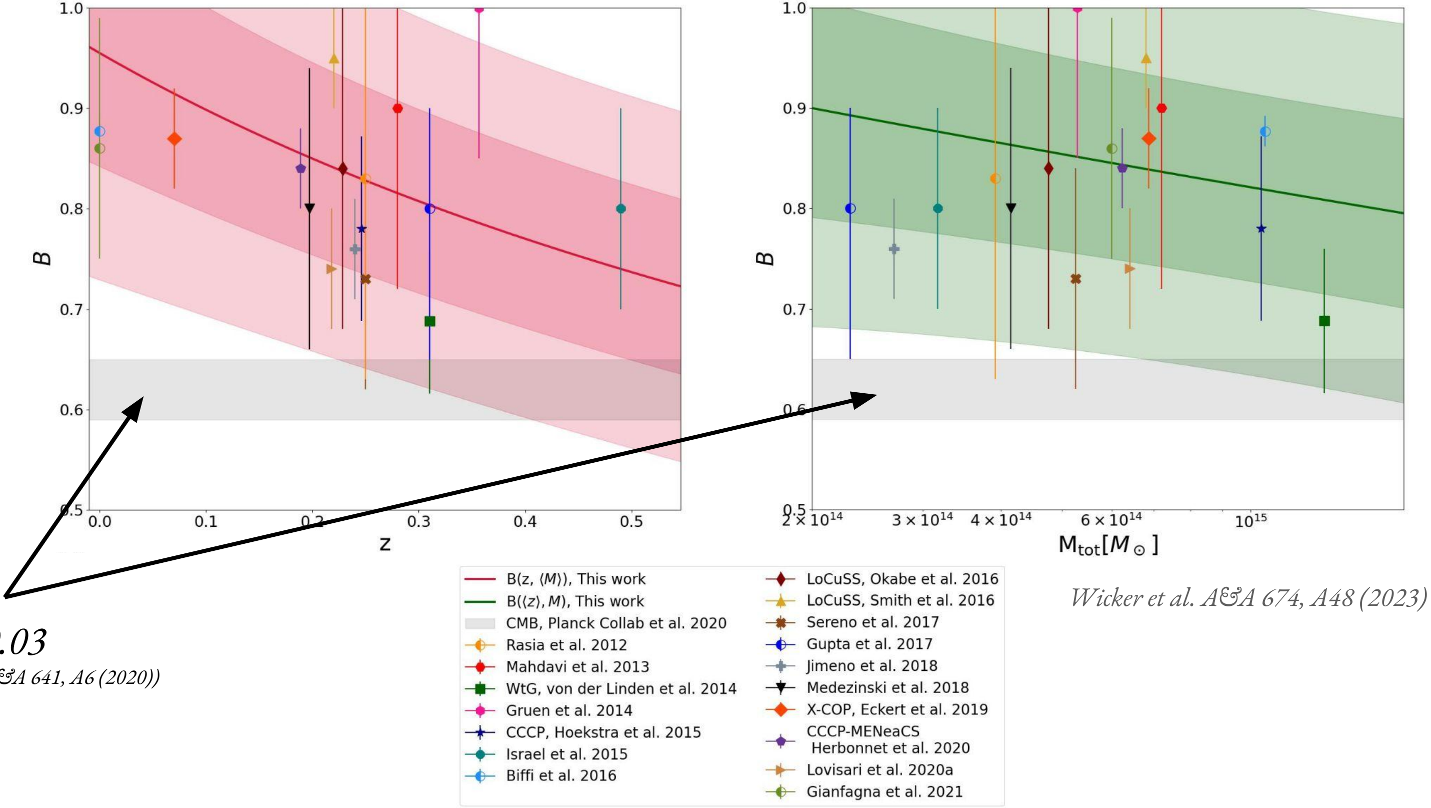


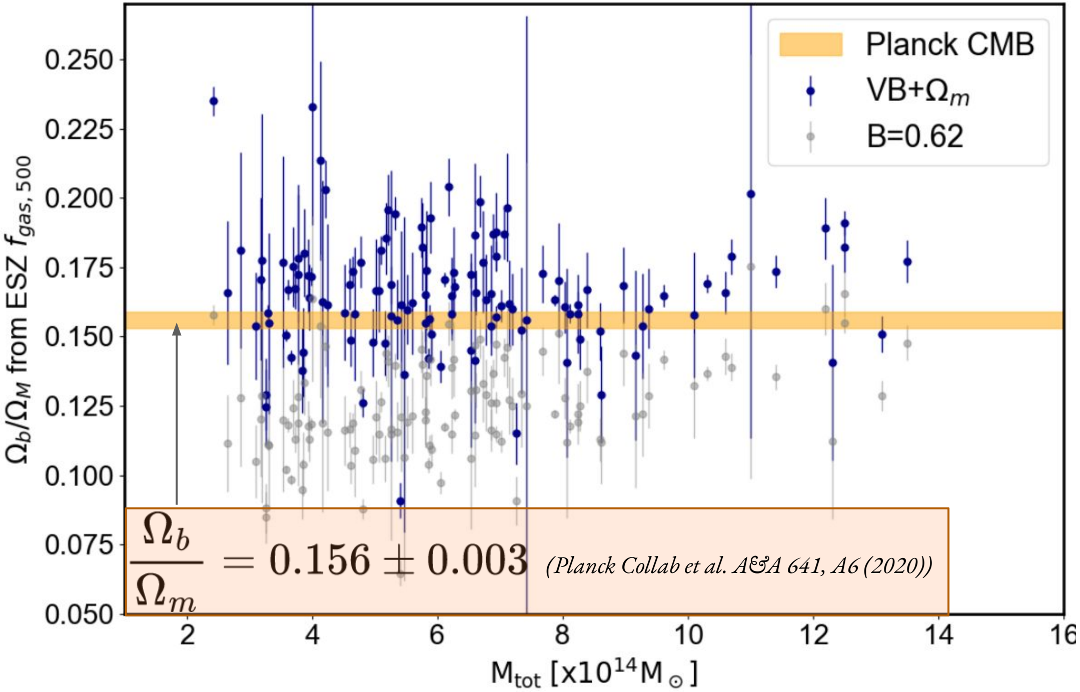
Wicker et al. A&A 674, A48 (2023)

$B = 0.62 \pm 0.03$

(Planck Collab. et al. A&A 641, A6 (2020))

THE GAS MASS FRACTION AS A PROBE FOR THE HYDROSTATIC MASS BIAS

If we assume *B=0.62* from Planck Collab. et al (2020), we then obtain $\Omega_b/\Omega_m = 0.108 \pm 0.018$ *in tension with* Planck *measurements.*



$$\frac{\Omega_b}{\Omega_m} = 0.156 \pm 0.003$$ *(Planck Collab et al. A&A 641, A6 (2020))*

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

COMBINING THE GAS FRACTION WITH NUMBER COUNTS

- *Cluster gas fraction*
  - Puts constraints on B (provided the cosmology is known)
  - Limited cosmological sensitivity
- *Cluster counts :*
  - Strong sensitivity to cosmology
  - Major dependence on the prior on B

=> Could we combine these probes and benefit from both strengths ?

PRELIMINARY WORK !

COMBINING THE GAS FRACTION WITH NUMBER COUNTS

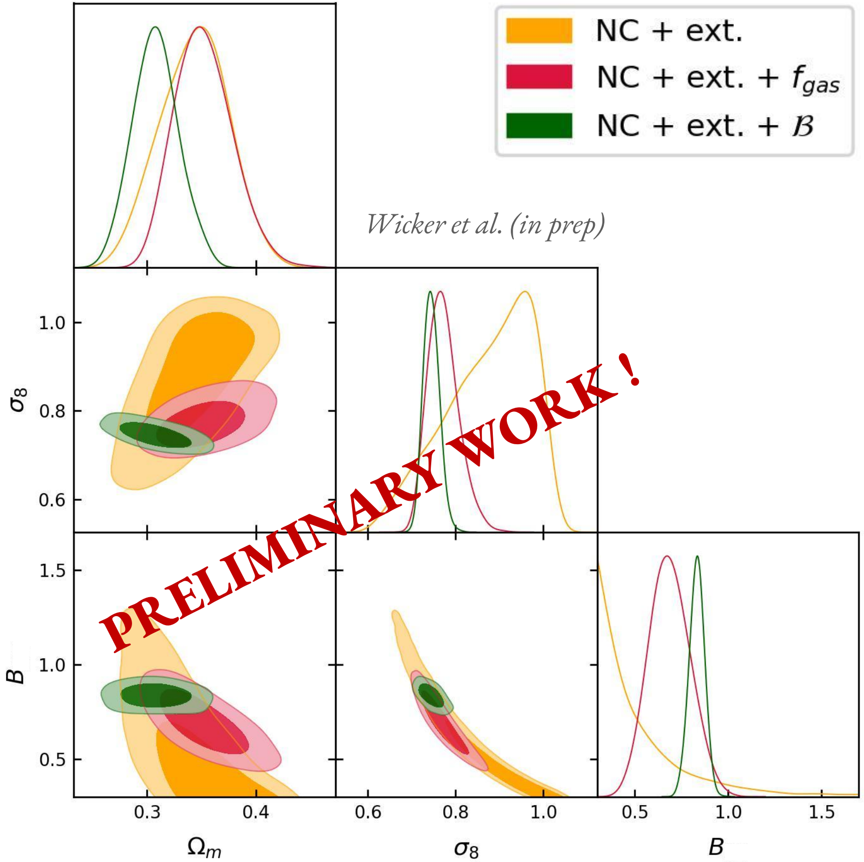
- *Gas fractions :* *Planck*-ESZ sample
- *tSZ cluster counts :* PSZ2Cosmo sample

(Planck Collab. et al. 2016 XXVII)

Baseline : NC + (BAO + n_s + $\Omega_b h^2$)

Two different tests :

- Test baseline + prior on B *(Herbonnet et al. 2020)*
- Test baseline + f_{gas}



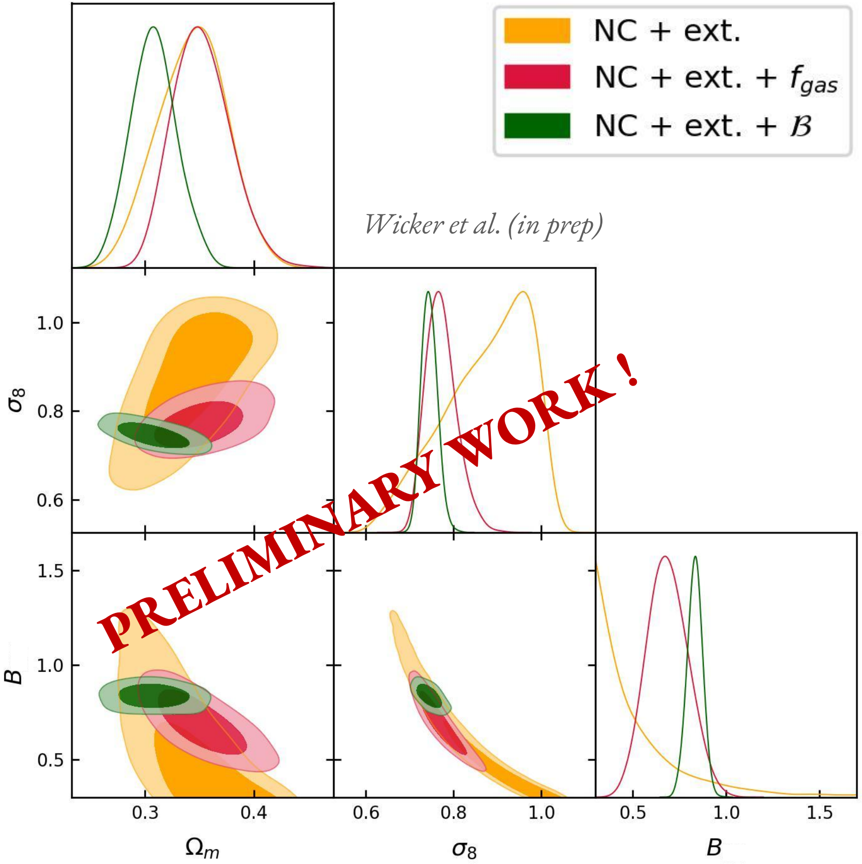
Wicker et al. (in prep)

COMBINING THE GAS FRACTION WITH NUMBER COUNTS

- *fgas* is less constraining than a prior on *B*
- However breaks the degeneracy between *B* and σ_8 .

Strong caveats :

- Non negligible impact of the priors
- Shallower M, z range of the f_{gas} sample
- Correlations between probes



Wicker et al. (in prep)

PRELIMINARY WORK !

CONCLUSION

- Gas fraction of clusters : good probe for the study of the hydrostatic mass bias, and its *evolution with mass and redshift*
- The evolution of B is *degenerate with cosmological parameters*
- A *low bias* (favoured by CMB+tSZ counts) is *not compatible with gas fraction data* and other direct measurements

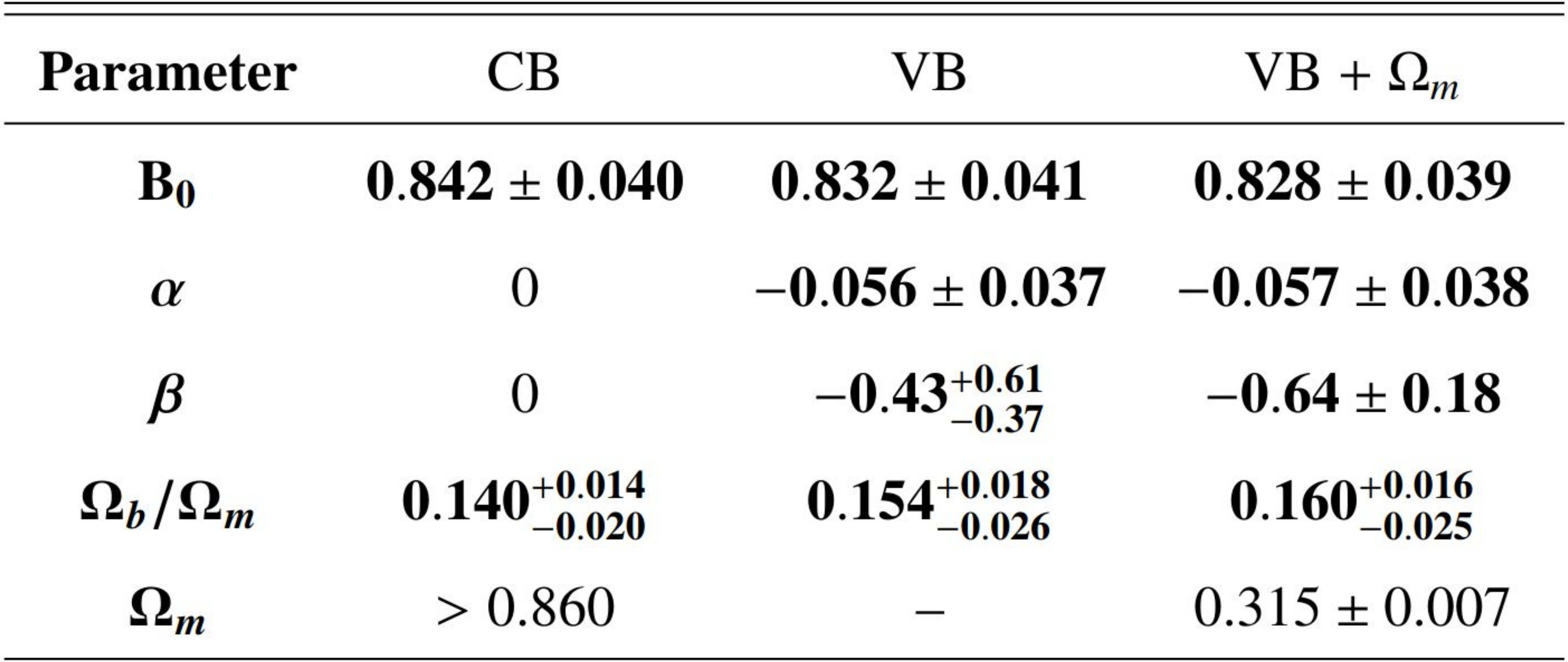
- The trends of B are *highly sample-dependent*
- Combining number counts and gas fraction : *cosmological constraints from counts without using a prior on B* **(PRELIMINARY !)**

THANK YOU !

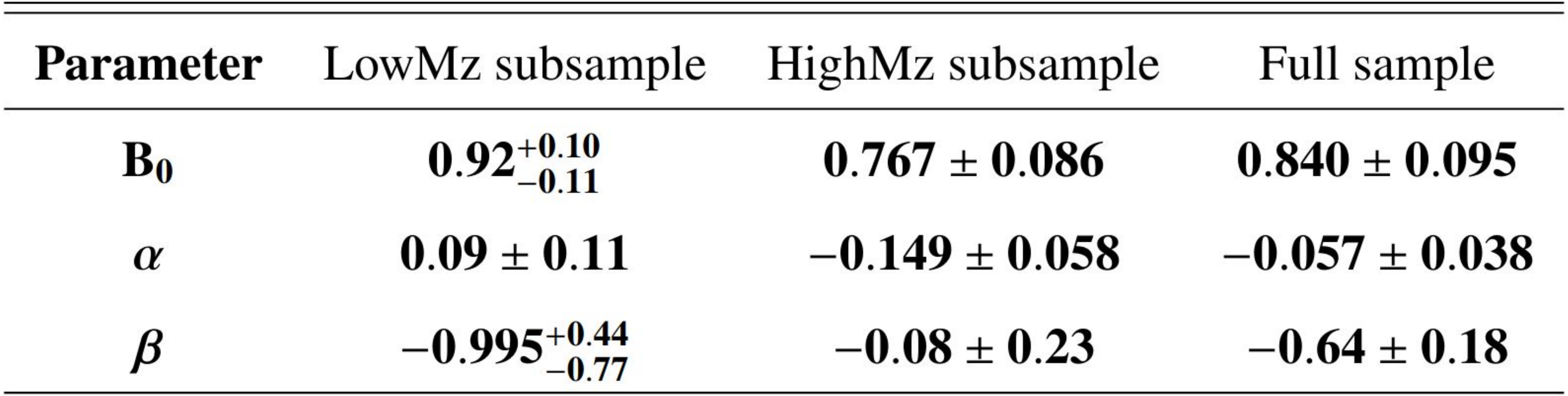
	Bias evolution study	**Sample dependence of the results**	**Reference**
Parameter	Prior	Prior	
B_0	–	$\mathcal{U}(0.3, 1.7)$	–
$B(z_{CCCP}, M_{CCCP})$	$\boldsymbol{\mathcal{N}(0.84, 0.04)}$	–	1
f_*	$\mathcal{N}(0.015, 0.005)$	$\mathcal{N}(0.015, 0.005)$	2
Υ_0	$\boldsymbol{\mathcal{N}(0.85, 0.03)}$	$\boldsymbol{\mathcal{N}(0.85, 0.03)}$	3
K	$\mathcal{N}(1, 0.1)$	$\mathcal{N}(1, 0.1)$	4
σ_f	$\mathcal{U}(0, 1)$	$\mathcal{U}(0, 1)$	–
h	$\mathcal{N}(0.674, 0.005)$	$\mathcal{N}(0.674, 0.005)$	5
Ω_b/Ω_m	$\mathcal{U}(0.05, 0.3)$	$\mathcal{N}(0.156, 0.003)$	5
Ω_m	$\mathcal{U}(0.01, 1)$ **(CB, VB)** or $\mathcal{N}(0.315, 0.007)$ **(VB +** $\boldsymbol{\Omega_m}$**)**	$\mathcal{N}(0.315, 0.007)$	5
α	Fixed at 0 **(CB)** or $\mathcal{U}(-2, 2)$ **(VB, VB +** $\boldsymbol{\Omega_m}$**)**	$\mathcal{U}(-2, 2)$	–
β	Fixed at 0 **(CB)** or $\mathcal{U}(-2, 2)$ **(VB, VB +** $\boldsymbol{\Omega_m}$**)**	$\mathcal{U}(-2, 2)$	–

References. (1) Herbonnet et al. (2020); (2)Eckert et al. (2019); (3)Planelles et al. (2013); (4)Allen et al. (2008); (5)Planck Collaboration et al. (2020).

$$A(z) = \left(\frac{\theta_{500}^{ref}}{\theta_{500}} \right)^{\eta} \simeq \left(\frac{H(z)D_A(z)}{[H(z)D_A(z)]^{ref}} \right)^{\eta}$$

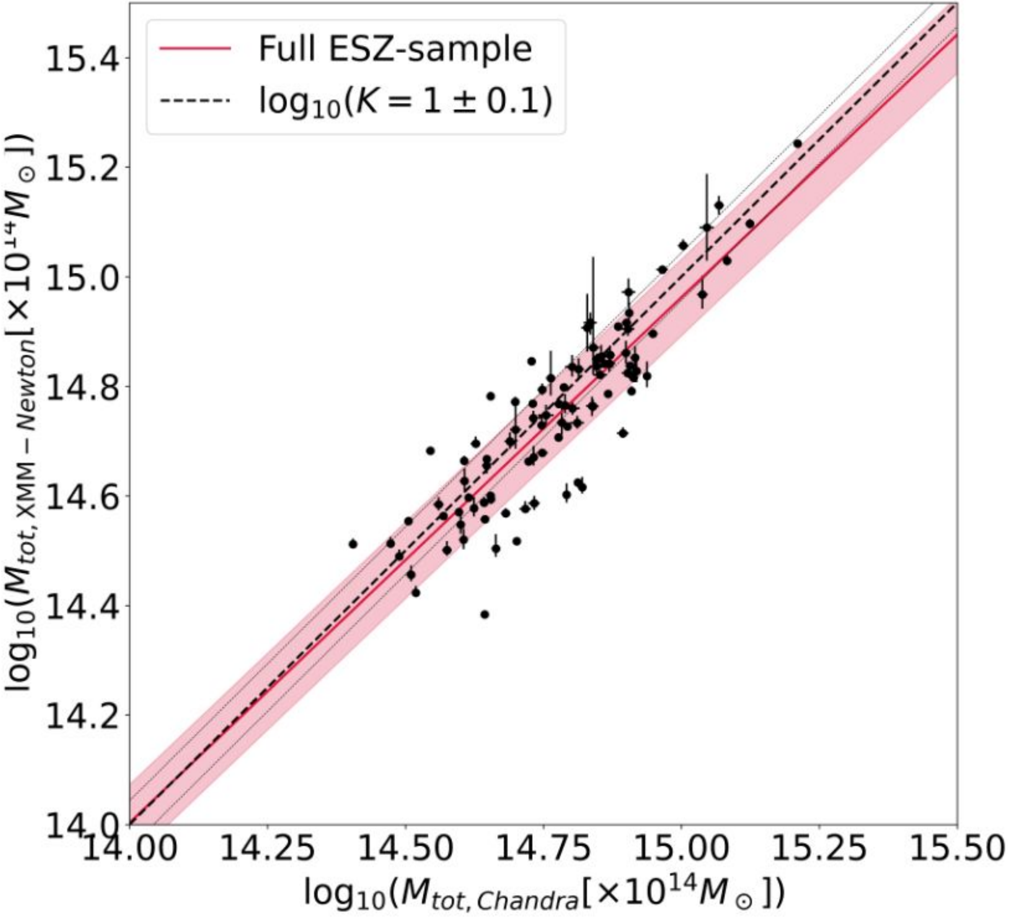


Parameter	CB	VB	VB + Ω_m
B_0	0.842 ± 0.040	0.832 ± 0.041	0.828 ± 0.039
α	0	-0.056 ± 0.037	-0.057 ± 0.038
β	0	$-0.43^{+0.61}_{-0.37}$	-0.64 ± 0.18
Ω_b/Ω_m	$0.140^{+0.014}_{-0.020}$	$0.154^{+0.018}_{-0.026}$	$0.160^{+0.016}_{-0.025}$
Ω_m	> 0.860	–	0.315 ± 0.007

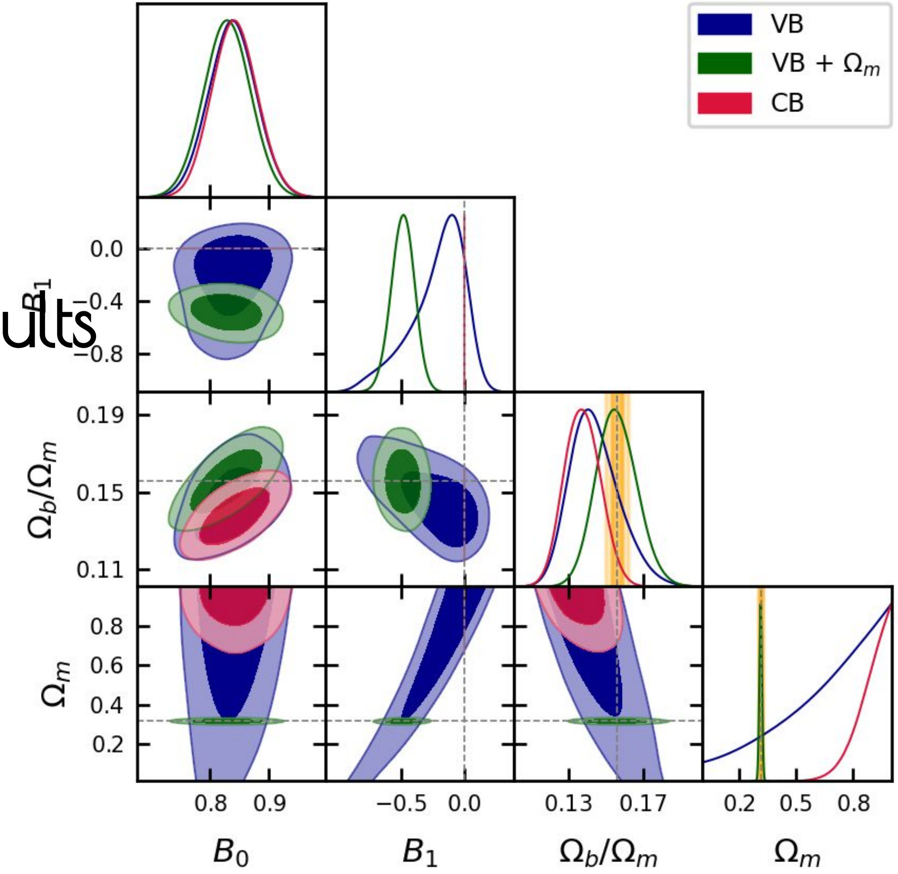


Parameter	LowMz subsample	HighMz subsample	Full sample
$\mathbf{B_0}$	$\mathbf{0.92^{+0.10}_{-0.11}}$	$\mathbf{0.767 \pm 0.086}$	$\mathbf{0.840 \pm 0.095}$
$\boldsymbol{\alpha}$	$\mathbf{0.09 \pm 0.11}$	$\mathbf{-0.149 \pm 0.058}$	$\mathbf{-0.057 \pm 0.038}$
$\boldsymbol{\beta}$	$\mathbf{-0.995^{+0.44}_{-0.77}}$	$\mathbf{-0.08 \pm 0.23}$	$\mathbf{-0.64 \pm 0.18}$

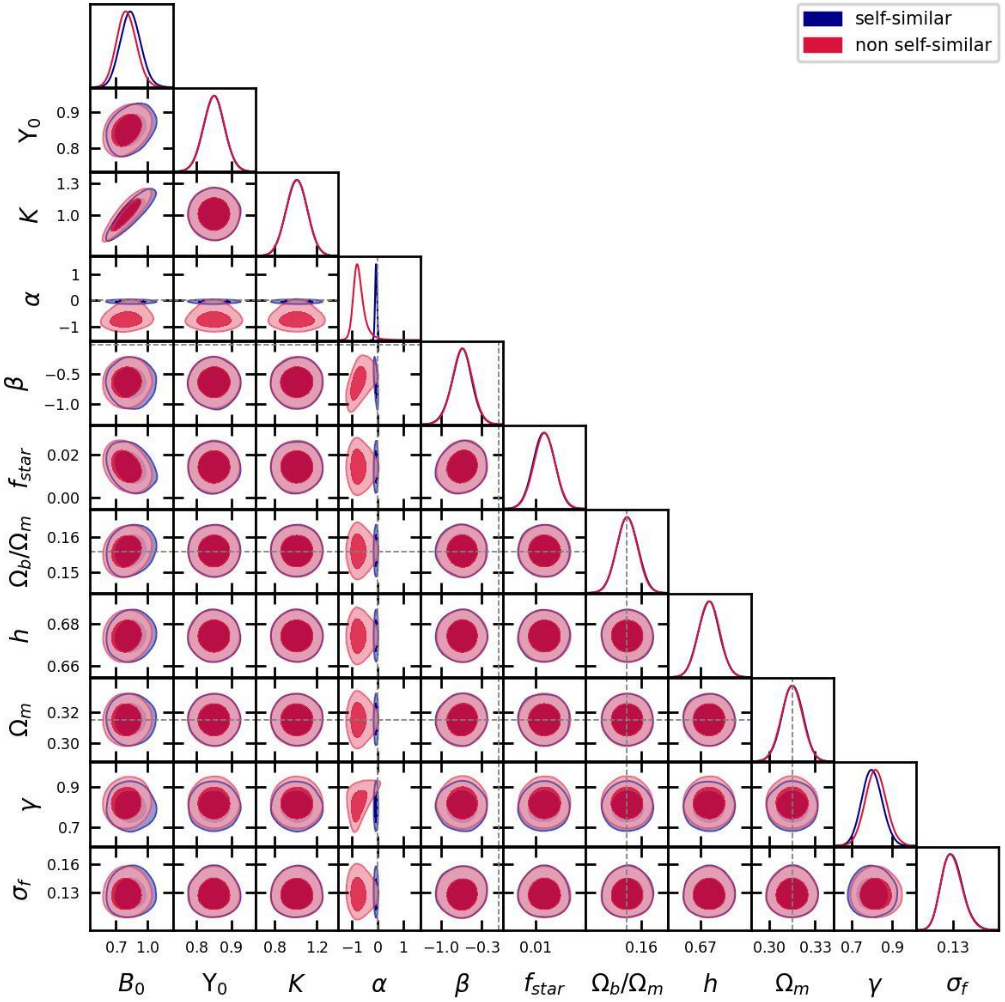
Calibration bias : M(XMM) vs M(Chandra)



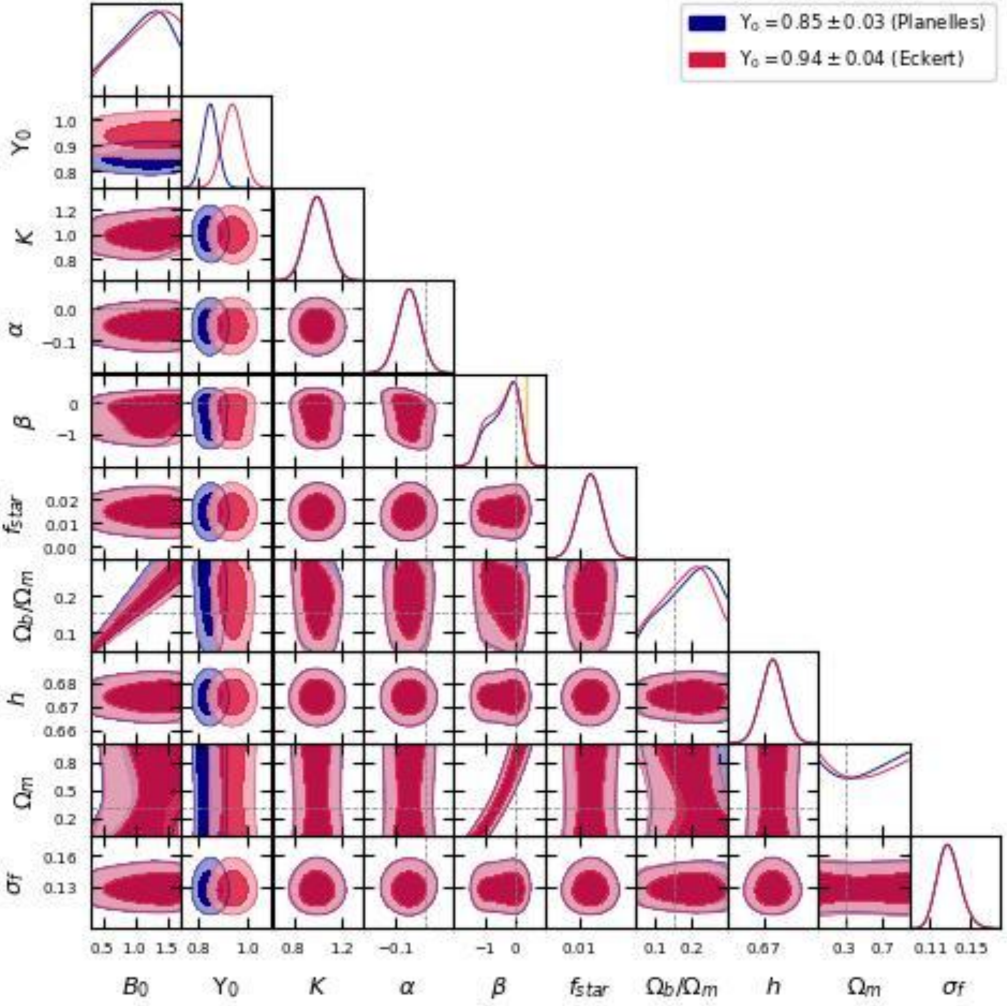
Dependence on parametrization : results assuming a linear dependence with M and z



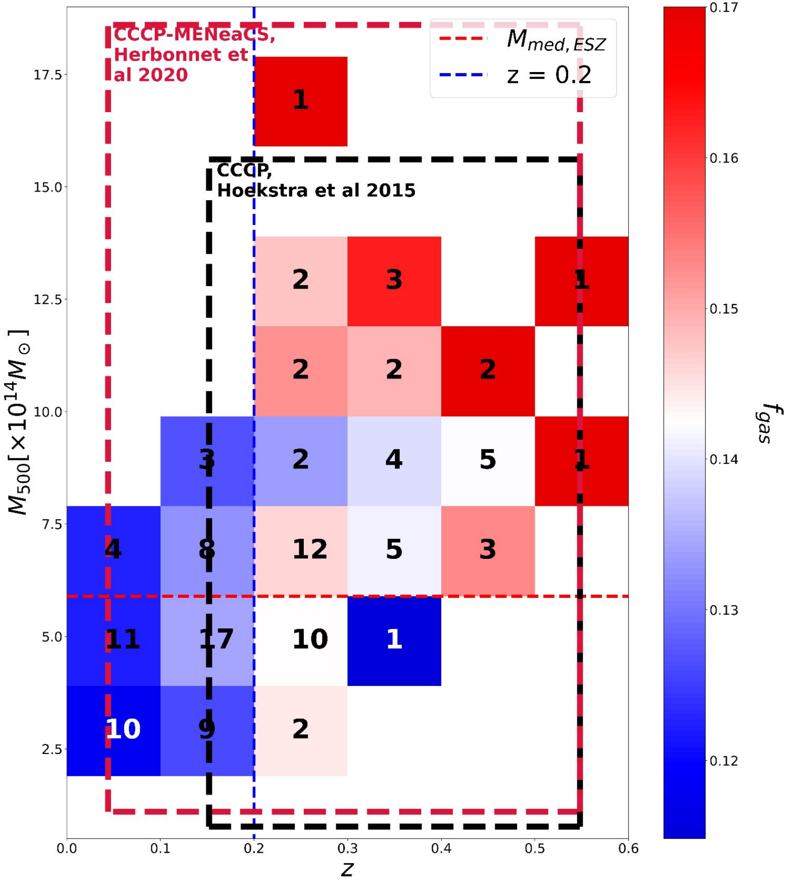
Taking into account (or not) deviations from self-similarity



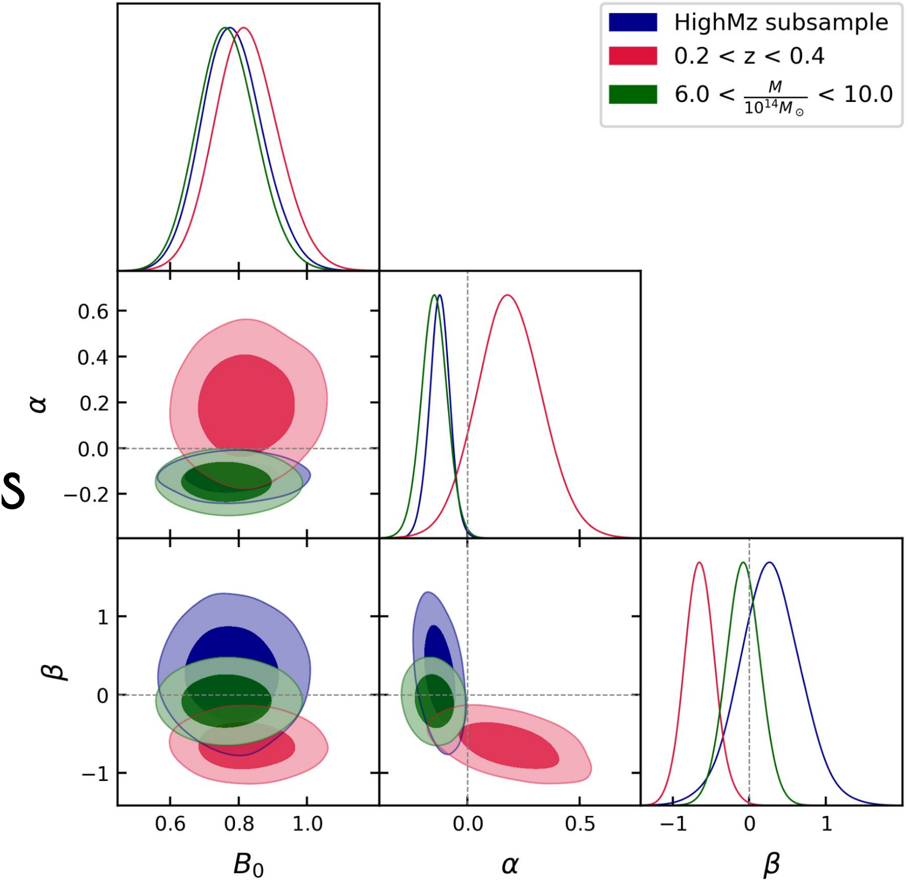
Role of the depletion factor

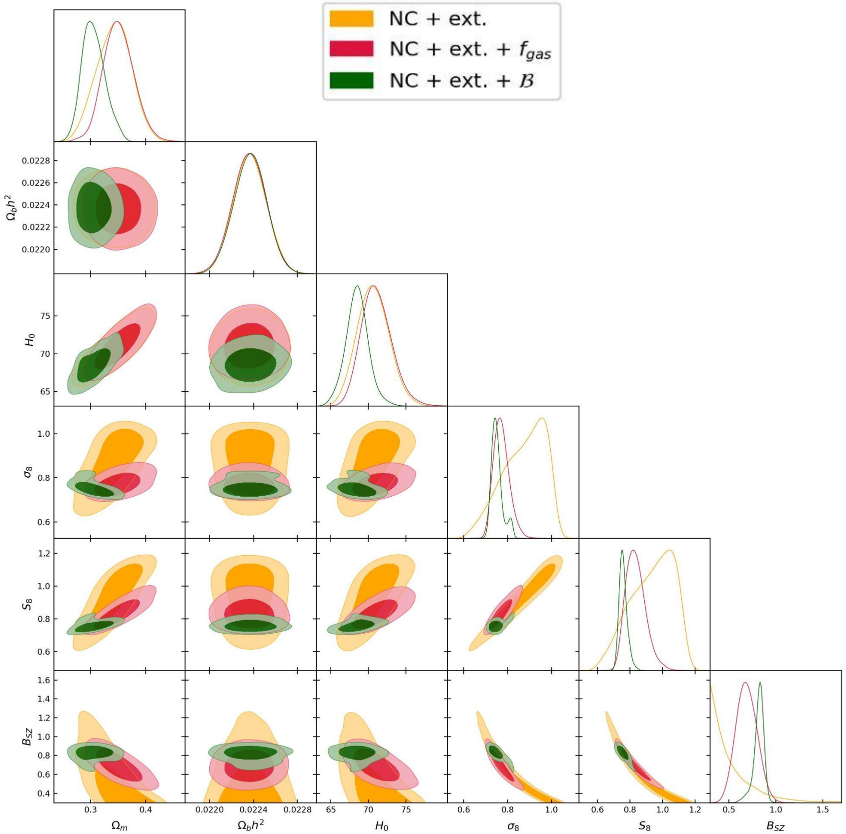


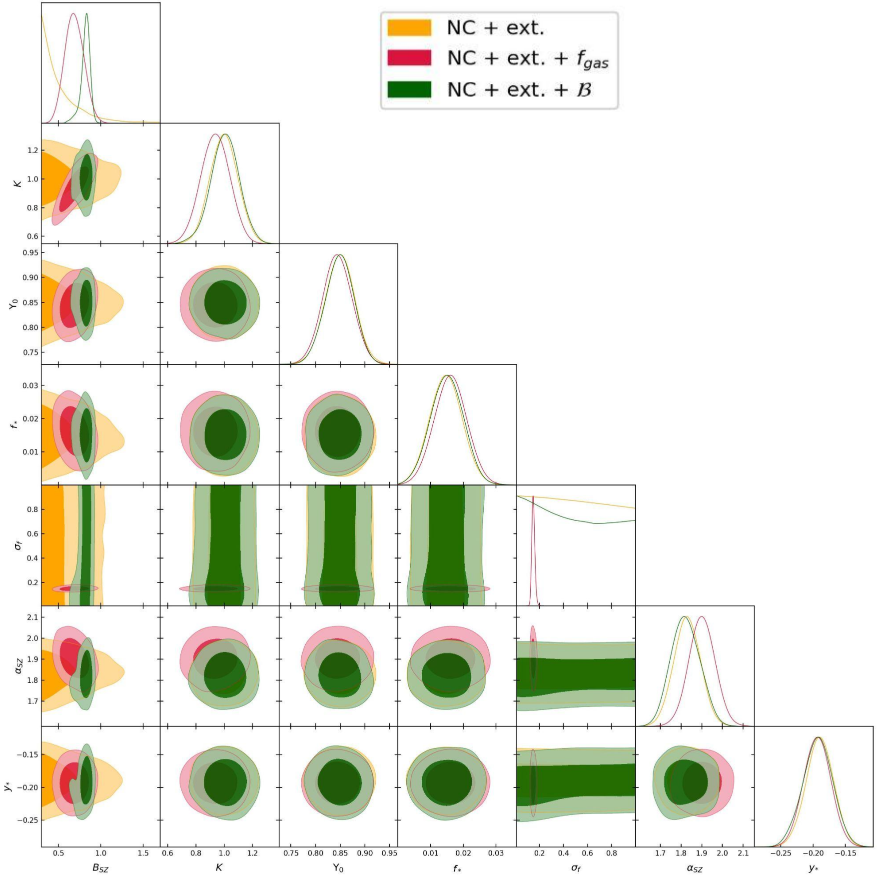
Validity of our prior on Btot(z, M)



Looking into a possible effect from a redshift dependence of the mass distribution




NC + ext.
NC + ext. + f_{gas}
NC + ext. + $\mathcal{B}$
Ω_m
$\Omega_b h^2$
H_0
σ_8
S_8
B_{SZ}
0.3
0.4
0.0220
0.0222
0.0224
0.0226
0.0228
65
70
75
0.6
0.8
1.0
1.2
1.4
1.6
0.5
1.5


NC + ext.
NC + ext. + f_{gas}
NC + ext. + $\mathcal{B}$
B_{SZ}
K
Y_0
f_*
σ_f
α_{SZ}
y_*
0.5
1.0
1.5
0.6
0.8
1.0
1.2
0.75
0.80
0.85
0.90
0.95
0.01
0.02
0.03
0.2
0.4
0.6
0.8
1.7
1.8
1.9
2.0
2.1
−0.25
−0.20
−0.15

THE GAS MASS FRACTION AS A PROBE FOR THE HYDROSTATIC MASS BIAS

Hydrostatic equilibrium assumption :

- *In simulations :*
  - Evidence for deviations (shocks, turbulence…)
  - Masses biased by ~15-20%
- *In observations :*
  - Tested with Weak Lensing
  - WL-to-HE mass ratio : ~15-20%

⇒ Introduction of the *hydrostatic mass bias* b.

Most of the time, we use $B = (1\text{-}b) = M_{HE}/M_{true} \sim 0.8$