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

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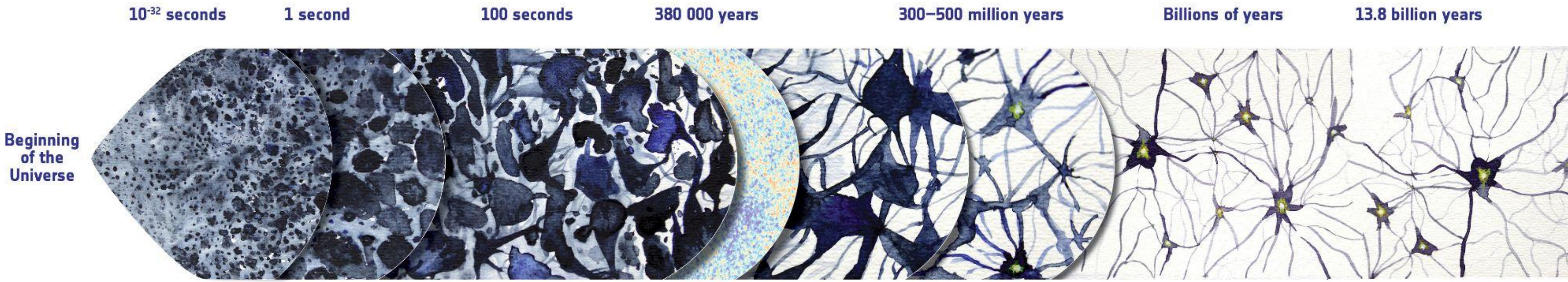
OUTLINE

- INTRODUCTION : Galaxy clusters and their gas mass fraction
- The hydrostatic mass bias in a cosmological study
- Sample dependence of the results
- CONCLUSION

Galaxy clusters and their gas mass fraction

- Galaxy clusters : most massive gravitationally bound structures of the universe
- Result of the hierarchical growth of structures
- Nodes of the cosmic web

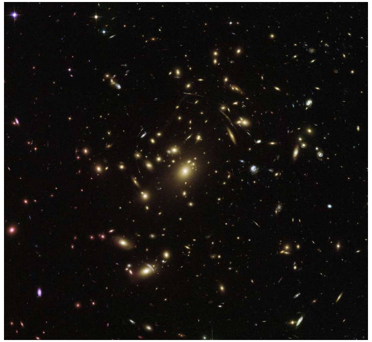


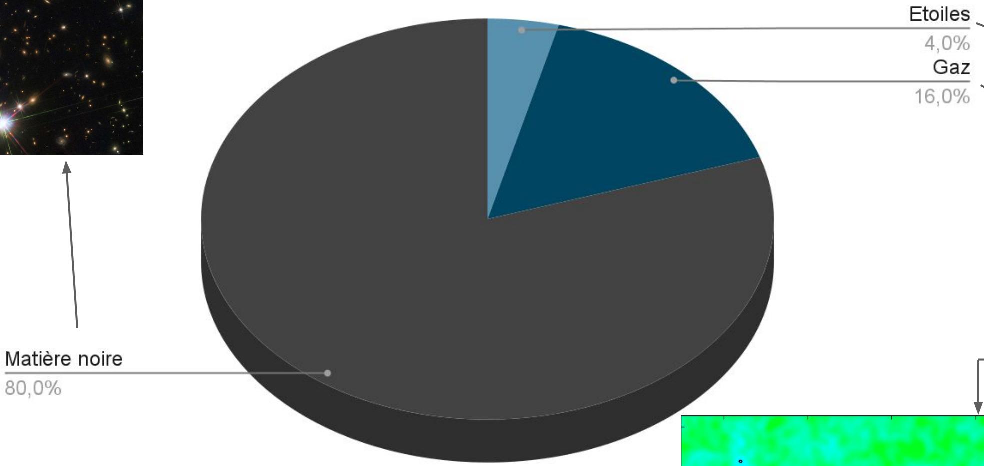
PSZ1G311.65-18-.48
Credits : ESA, NASA, HST, Rivera-Thorsen et al.

Gravitational lensing

Abell 2357
Crédits: ESA, HST, NASA

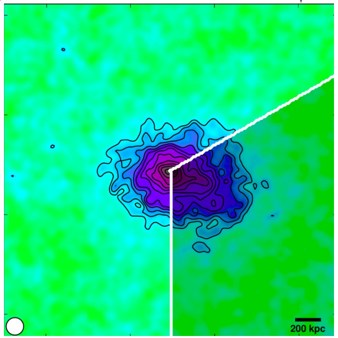
Optical



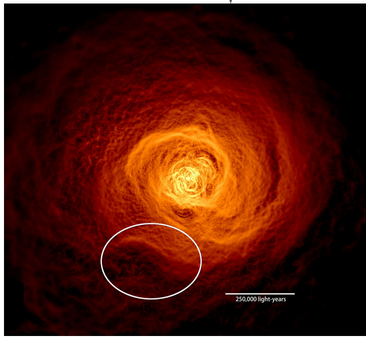


SZ Effect

X-rays



PSZ2 G144.83+25.11
Credit : NIKA2, Ruppin et al. 2017



Perseus cluster
Credit : Chandra, Walker et al.

Galaxy clusters and their gas mass fraction

ByoPiC

Galaxy clusters can be used to constrain cosmological parameters.

- Number counts, clustering, sparsity etc…
- One can also use $f_{gas} = \frac{M_{gas}}{M_{tot}}$

$$f_{gas} \propto \frac{\Omega_b}{\Omega_m}$$

M_{gas}: Measured using the gas density profile *inside a certain radius*

M_{tot}: Measured using the gas density and temperature profiles, *assuming hydrostatic equilibrium (HE)*

Galaxy clusters and their gas mass fraction

Assuming HE introduces a bias in the total mass measurement : the *hydrostatic mass bias*.

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

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

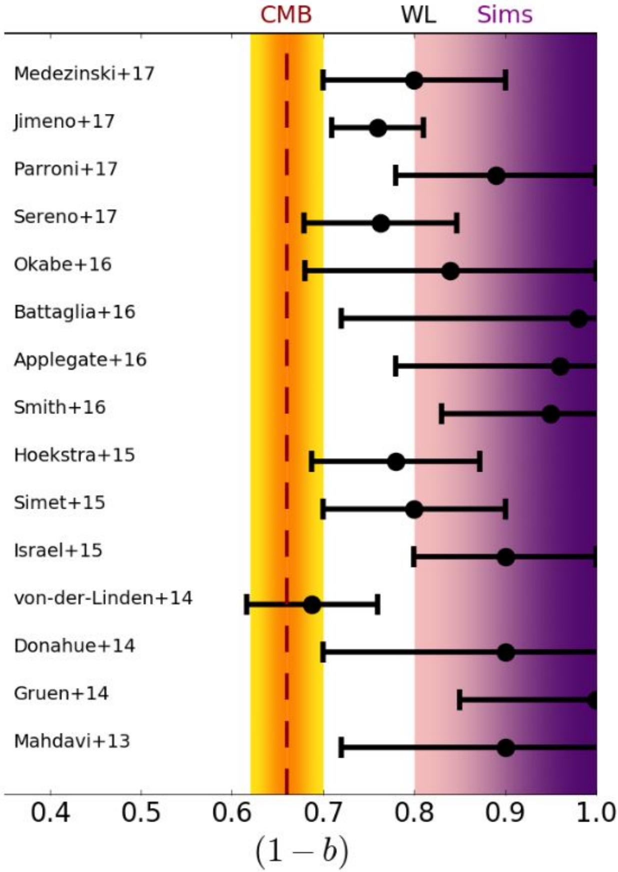
The hydrostatic mass bias in a cosmological study

Problem : the value of this parameter is still openly debated.

- Required by CMB: $B \sim 0.6 - 0.65$
- Observed and simulated:

$B \sim 0.8 - 0.85$

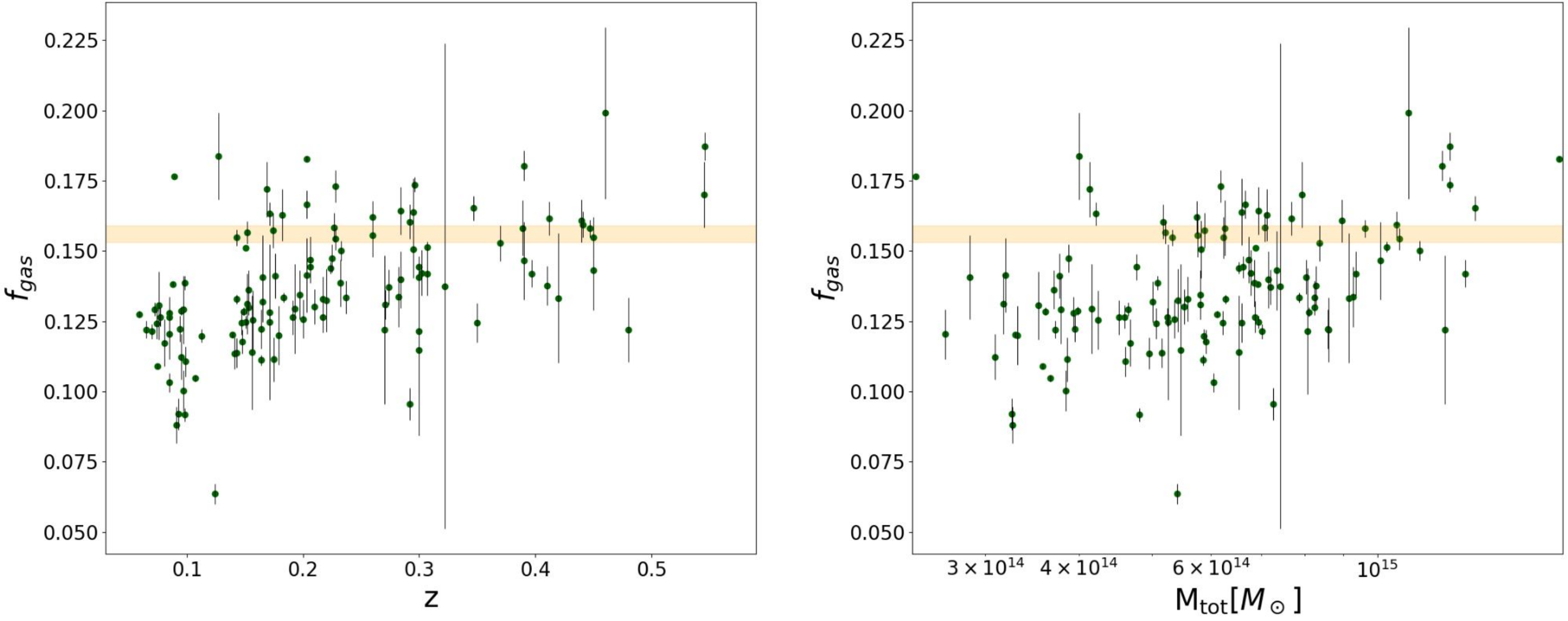
Yet, this bias impacts the cosmological constraints obtained from clusters.



Salvati et al. 2018

The hydrostatic mass bias in a cosmological study

Using a sample of 120 cluster gas mass fraction at R_{500}, we measure the bias and test its possible evolution with cluster mass and redshift



Wicker et al. 2022

arXiv:2204.12823

The hydrostatic mass bias in a cosmological study

$$f_{gas,Th}(M,z) = K \frac{\Upsilon(M,z)}{B(M,z)} A(z) \left(\frac{\Omega_b}{\Omega_m}\right) \left(\frac{D_A^{ref}(z)}{D_A(z)}\right)^{3/2} - f_*$$

Instrumental effects

Baryonic effects

Cosmology

Stellar content

Allen et al. 2008

BYOPIC

We test the effect of assuming a varying/constant bias on the subsequent cosmological constraints derived from our gas fraction data.

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

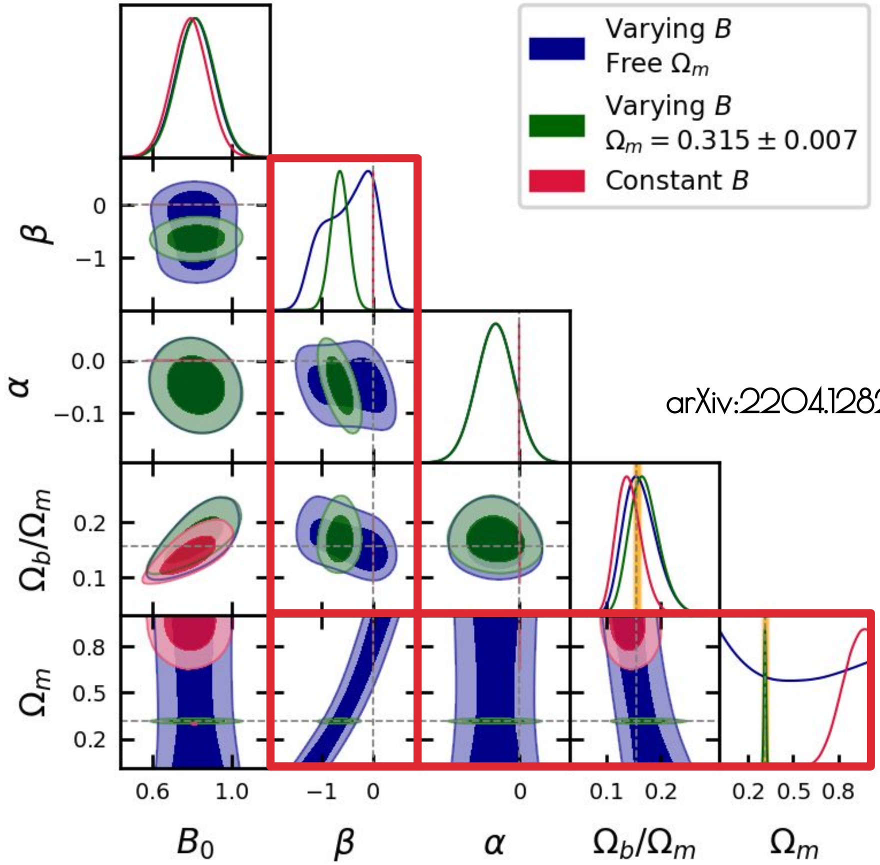
Amplitude (B_0)

Mass dependence (α)

Redshift dependence (β)

=> 3 free parameters to describe the bias

The hydrostatic mass bias in a cosmological study



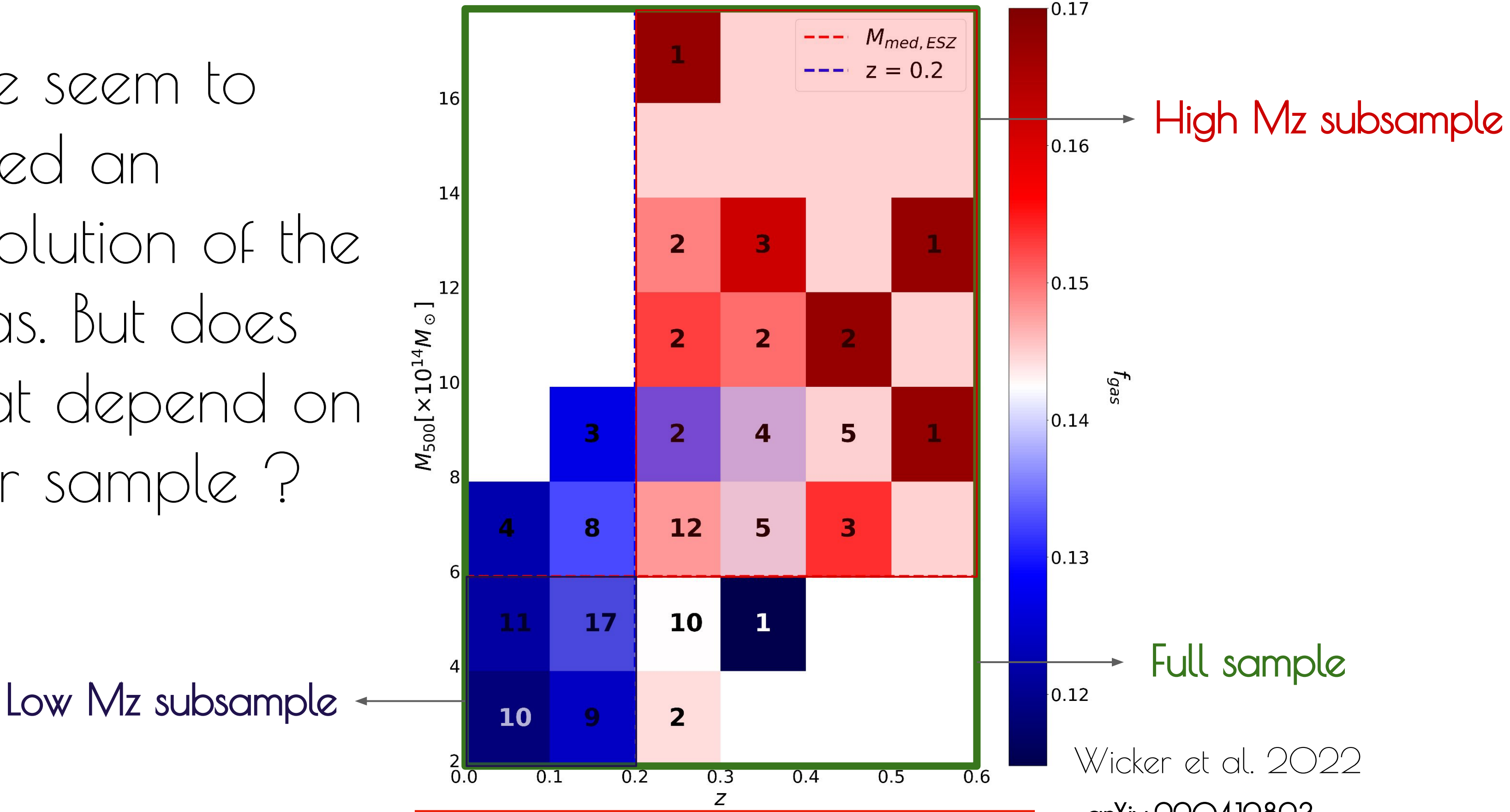
Wicker et al. 2022

arXiv:2204.12823

- Degeneracy between β and Ω_m : higher, closer to 0 β calls for higher Ω_m
- Assuming a constant bias $(\alpha = \beta = 0)$ leads to aberrant values of $\Omega_m > 0.860$
- When assuming a standard *Planck* cosmology, $\beta = -0.64 \pm 0.17$ is incompatible with 0
- α is compatible with 0, B_0 with ~ 0.8

Sample dependence of the results

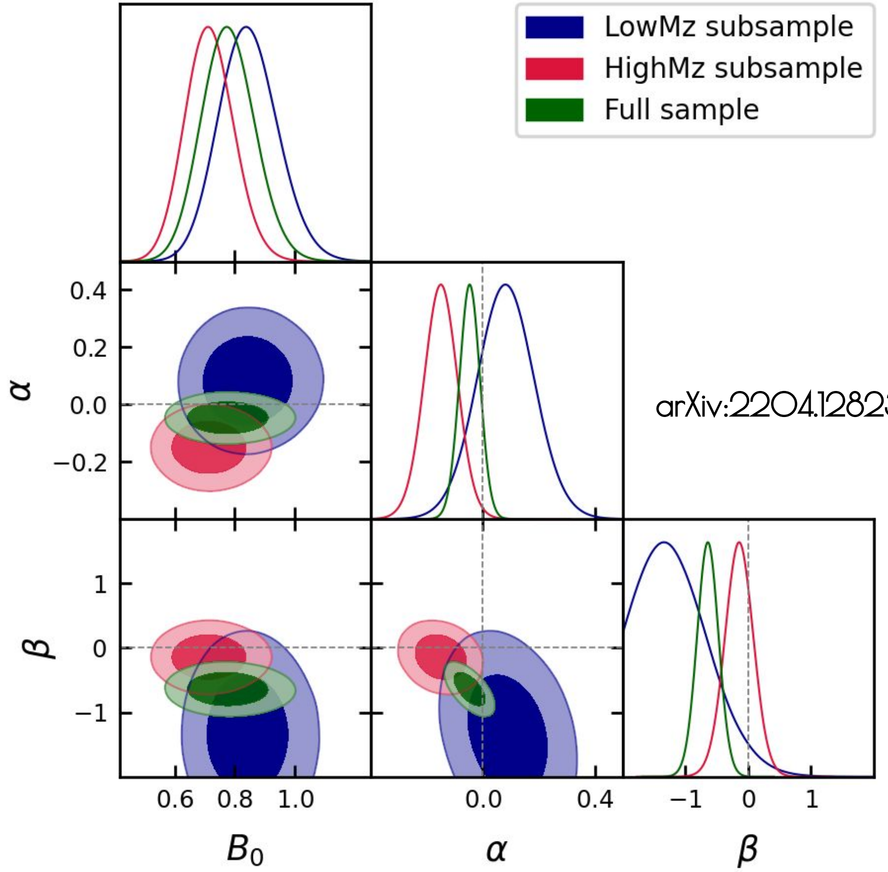
We seem to need an evolution of the bias. But does that depend on our sample ?



Wicker et al. 2022

arXiv:2204.12823

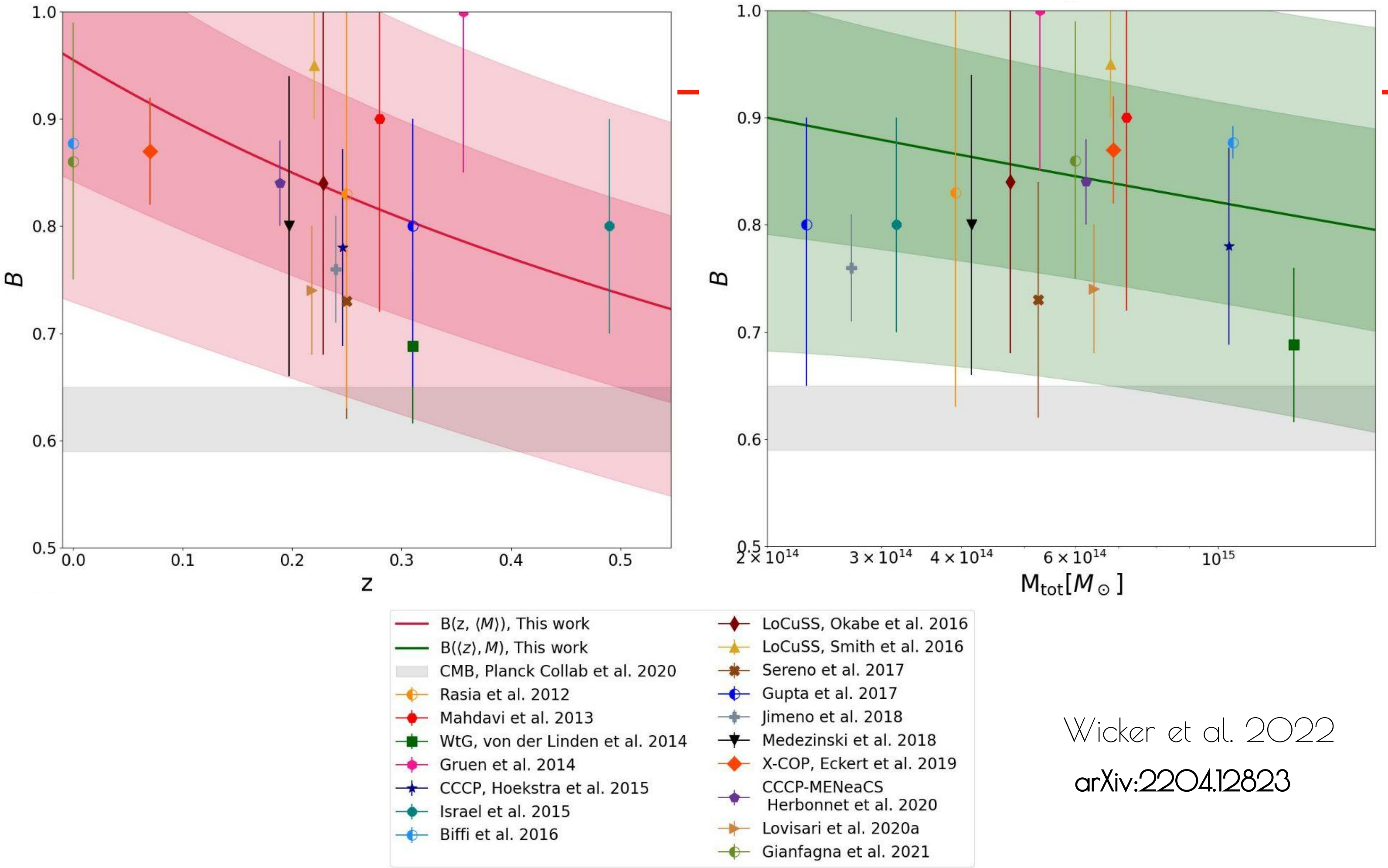
Sample dependence of the results



Wicker et al. 2022

arXiv:2204.12823

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



Wicker et al. 2022

arXiv:2204.12823

Conclusion

- An evolution of the bias seems to be necessary to properly constrain cosmological parameters
- We observe a strong dependence of our results to the considered sample
- We however are compatible with B ~ 0.8, in agreement with a collection of other measurements

Thank you !

Galaxy clusters and their gas mass fraction

- Gas mass : obtained using the density profile of the gas in the cluster

$$M_{gas}(< r) = \int_0^r 4\pi r'^2 \rho_{gas}(r')dr'$$

- Total mass :

can be obtained from HE equation :

$$M_{tot}(< r) = -\frac{r k_B T(r)}{G \mu m_p}\left(\frac{d\ln \rho(r)}{d\ln r} + \frac{d\ln T(r)}{d\ln r}\right)$$

or from observable-to-mass scaling relations

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

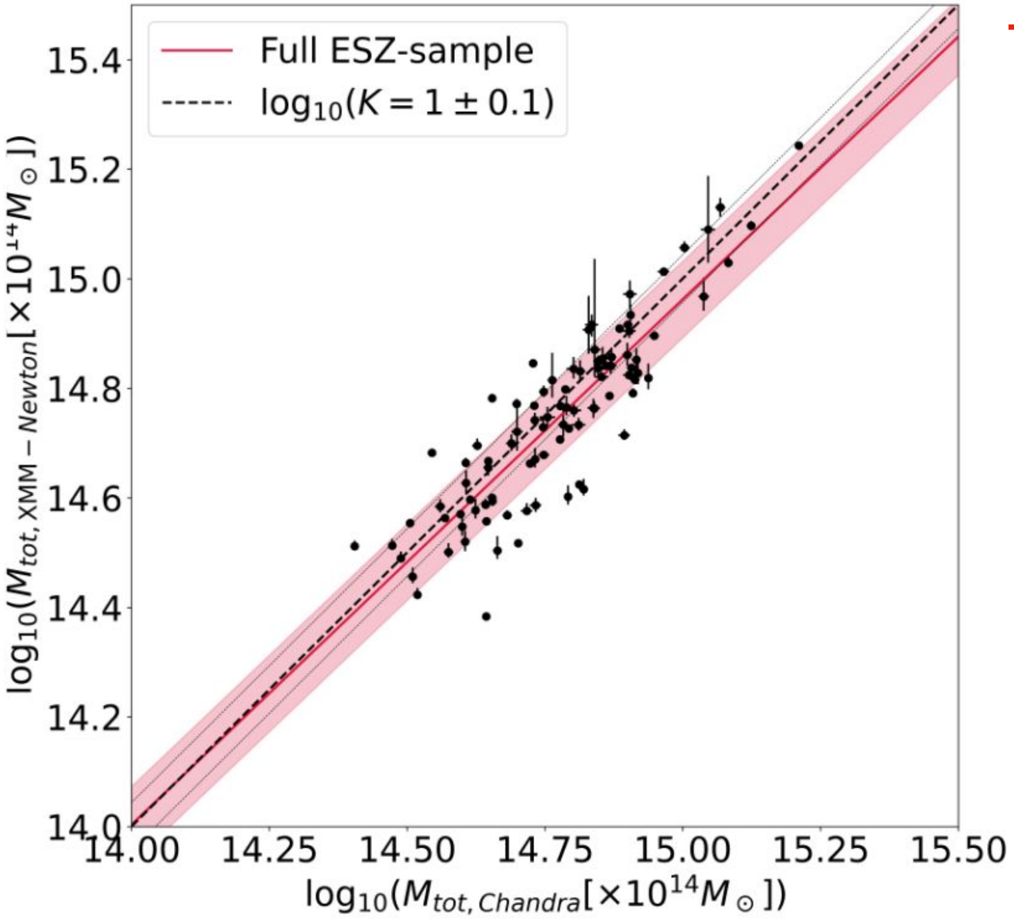
$$A(z) = \left(\frac{\theta_{500}^{ref}}{\theta_{500}} \right)^{\eta} \simeq \left(\frac{H(z)D_A(z)}{[H(z)D_A(z)]^{ref}} \right)^{\eta}$$

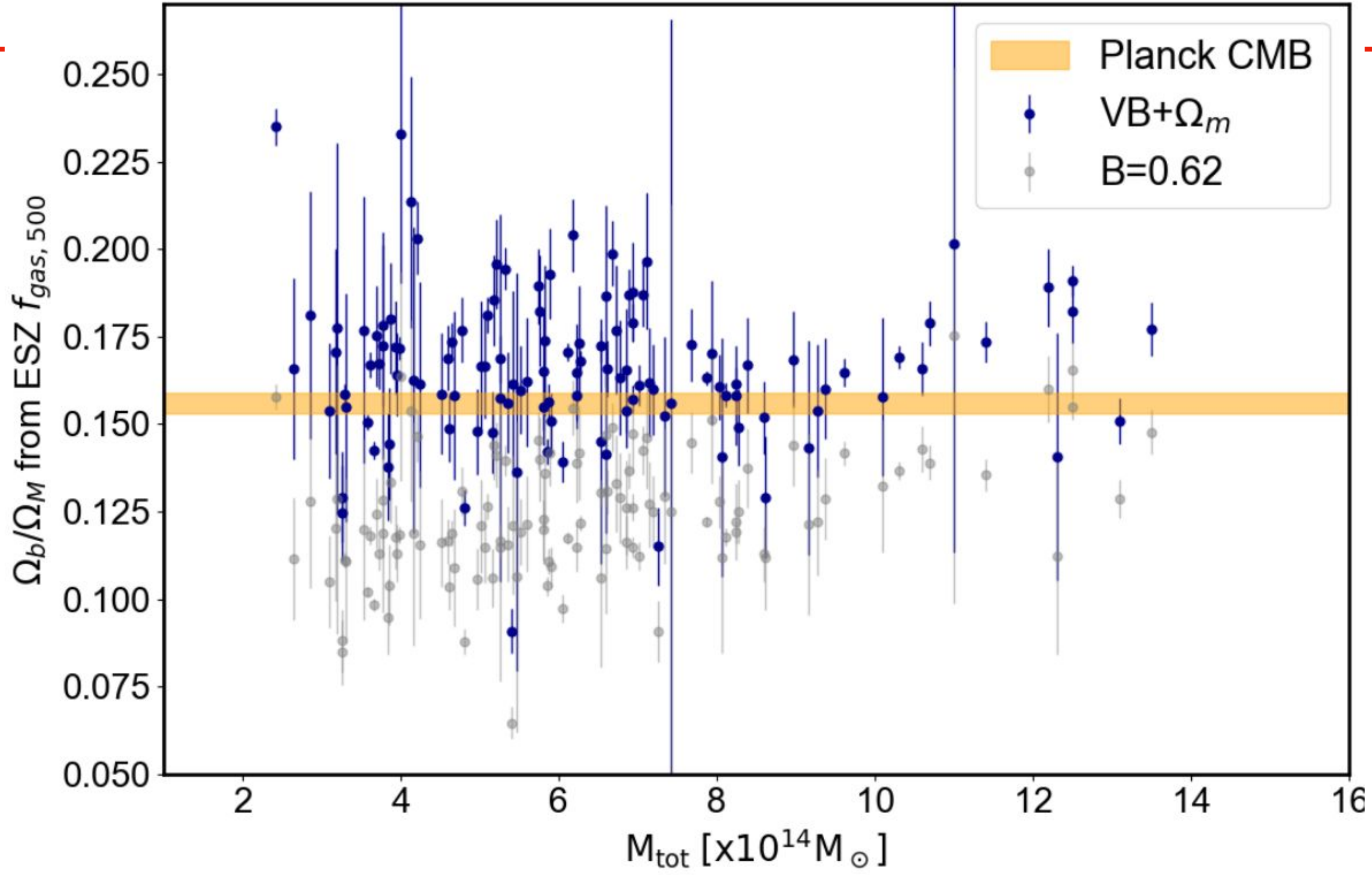
	Bias evolution study	Sample dependence of the results	Reference
Parameter	Prior	Prior	
B_0	–	$\mathcal{U}(0.3, 1.7)$	–
$B(z_{CCCP}, M_{CCCP})$	$\boldsymbol{\mathcal{N}(0.84, 0.04)}$	–	1
f_*	$\mathcal{N}(0.015, 0.005)$	$\mathcal{N}(0.015, 0.005)$	2
Υ_0	$\boldsymbol{\mathcal{N}(0.85, 0.03)}$	$\boldsymbol{\mathcal{N}(0.85, 0.03)}$	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 + Ω_m)**	$\mathcal{N}(0.315, 0.007)$	5
α	Fixed at 0 **(CB)** or $\mathcal{U}(-2, 2)$ **(VB, VB + Ω_m)**	$\mathcal{U}(-2, 2)$	–
β	Fixed at 0 **(CB)** or $\mathcal{U}(-2, 2)$ **(VB, VB + Ω_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).

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
$\mathbf{B_0}$	$\mathbf{0.92^{+0.10}_{-0.11}}$	$\mathbf{0.767 \pm 0.086}$	$\mathbf{0.840 \pm 0.095}$
α	$\mathbf{0.09 \pm 0.11}$	$\mathbf{-0.149 \pm 0.058}$	$\mathbf{-0.057 \pm 0.038}$
β	$\mathbf{-0.995^{+0.44}_{-0.77}}$	$\mathbf{-0.08 \pm 0.23}$	$\mathbf{-0.64 \pm 0.18}$


Full ESZ-sample
$\log_{10}(K = 1 \pm 0.1)$
15.4
15.2
15.0
14.8
14.6
14.4
14.2
14.0
$\log_{10}(M_{tot,\, XMM-Newton}[\times 10^{14} M_\odot])$
14.00
14.25
14.50
14.75
15.00
15.25
15.50
$\log_{10}(M_{tot,\, Chandra}[\times 10^{14} M_\odot])$



Planck CMB
VB+Ω_m
B=0.62
Ω_b/Ω_M from ESZ $f_{gas,500}$
0.250
0.225
0.200
0.175
0.150
0.125
0.100
0.075
0.050
2
4
6
8
10
12
14
16
M_{tot} [x$10^{14}M_\odot$]

Probing the redshift evolution of the mass bias

Instrumental effects

Cosmology

$$f_{gas}(z) = K \times \frac{\Upsilon(z)}{B(z)} \times A(z) \times \left(\frac{\Omega_b}{\Omega_m}\right) \times \left(\frac{D_A^{ref}(z)}{D_A(z)}\right)^{3/2}$$

PHYSICAL/BARYONIC EFFECTS

Allen et al. 2008

Probing the redshift evolution of the mass bias

- Hydrostatic equilibrium hypothesis biases the mass measurements :

$$M_{measured} = B(z) \times M_{true} \quad , B(z) = (1-b)(z)$$

- Hydrodynamical simulations based on Λ-CDM find no clear evolution of B with the redshift
- What we actually constrain is $\Upsilon(z)/B(z)$
- We assume a linear evolution of the bias:

$$B(z) = B_0 + B_1 \times (z - z_{pivot}), \text{ where } z_{pivot} = \langle z \rangle$$

- We chose Υ constant in z : Υ_0 (Planelles et al. 2013)
- See Bora et al. 2021 for investigation on the variation of Υ

Probing the redshift evolution of the mass bias

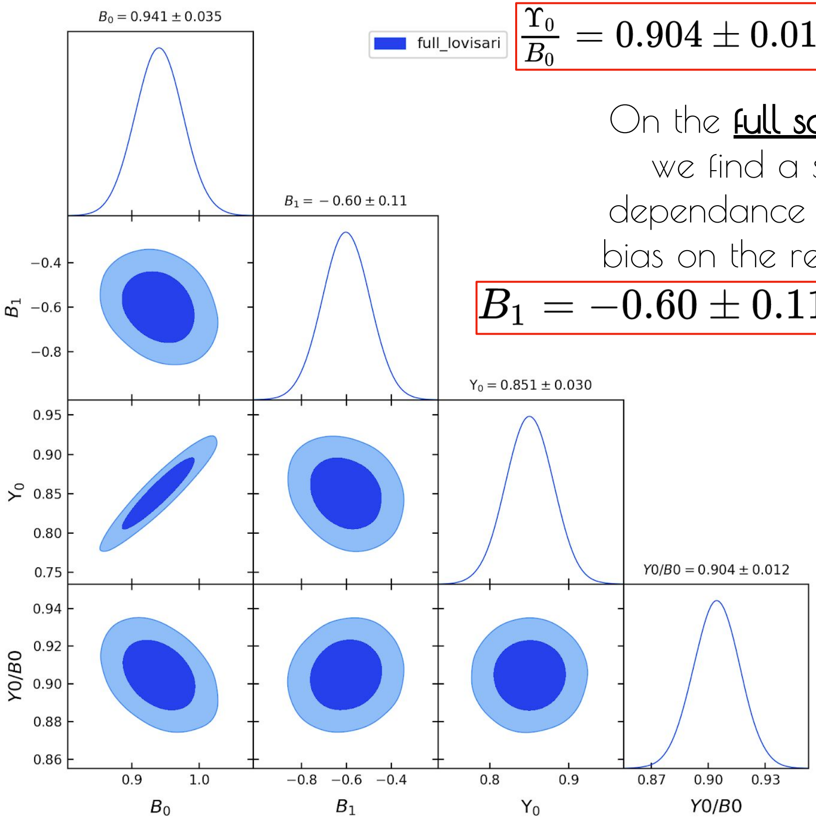
ByoPiC

To fit our data, we carry out a MCMC analysis.
Summary of the priors that have been used for this study :

$\mathbf{B_0}$	$\boldsymbol{U}$**(0.3, 1.7)**
$\mathbf{B_1}$	$\boldsymbol{U}$**(-1.5, 1.5)**
Υ_0	$\boldsymbol{N}$**(0.85, 0.03)** (Planelles et al. 2013)
σ_f (instrinsic scatter)	$\boldsymbol{U}$**(0, 1)**
Cosmological parameters	Planck Collaboration et al. 2018

$N(\mu, \sigma)$: normal prior of mean **μ** and of standard deviation **σ**
$U(l, u)$: uniform prior of lower bound l and upper bound u

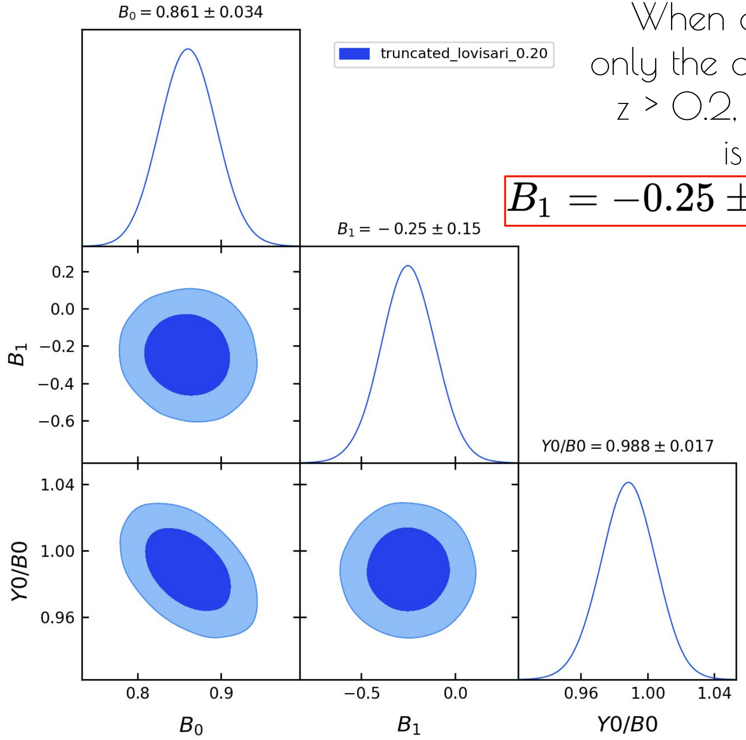
PROBING THE REDSHIFT EVOLUTION OF THE MASS BIAS



$$\frac{\Upsilon_0}{B_0} = 0.904 \pm 0.012(1\sigma)$$

On the <u>full sample</u>, we find a strong dependance of the bias on the redshift:

$$B_1 = -0.60 \pm 0.11(1\sigma)$$



$$\frac{\Upsilon_0}{B_0} = 0.988 \pm 0.017(1\sigma)$$

When considering only the clusters with z > 0.2, the tension is alleviated:

$$B_1 = -0.25 \pm 0.15(1\sigma)$$

Probing the redshift evolution of the mass bias

- $B_1 < 0$: higher bias with redshift
- In contradiction with hydrodynamical simulations
- In contradiction with the trends found in Salvati et al. 2019 from *Planck* tSZ number counts ***for low z clusters***
- In agreement with Salvati et al. 2019, ***for high z clusters***
- Consistent with the trends from CoMaLit (Sereno & Ettori 2017) and LoCuSS (Smith et al. 2016) from weak lensing to SZ/X mass ratios, ***on high z clusters***

The gas mass fraction as a cosmological probe

Instrumental effects

COSMOLOGY

$$f_{gas}(z) = K \times \frac{\Upsilon(z)}{B(z)} \times A(z) \times \left(\frac{\Omega_b}{\Omega_m}\right) \times \left(\frac{D_A^{ref}(z)}{D_A(z)}\right)^{3/2}$$

Physical/baryonic effects

Allen et al. 2008

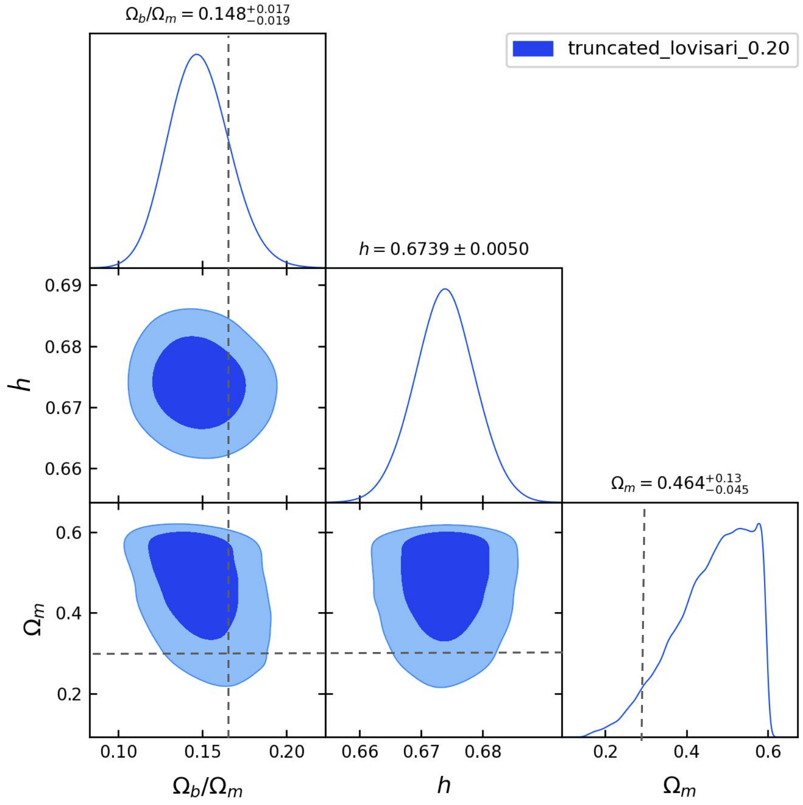
The gas mass fraction as as cosmological probe

ByoPiC

Summary of the priors that have been used at different steps of the study

	Full sample	z > 0.2
B_0	$\mathcal{N}(0.780, 0.092)$ (CCCP, Hoekstra et al. 2015)	$\mathcal{N}(0.780, 0.092)$ (CCCP, Hoekstra et al. 2015)
B_1	Fixed at 0, then $\mathcal{N}(-0.60, 0.11)$	Fixed at 0, then $\mathcal{N}(-0.25, 0.15)$
Ω_b/Ω_m	$\mathcal{U}(0.05, 0.3)$	$\mathcal{U}(0.05, 0.3)$
Ω_m	$\mathcal{N}(0.315, 0.007)$ (Planck Collab. et al. 2018) then $\mathcal{U}(0.01, 1.0)$	$\mathcal{N}(0.315, 0.007)$ (Planck Collab. et al. 2018) then $\mathcal{U}(0.01, 1.0)$
h	$\mathcal{N}(0.674, 0.005)$ (Planck Collab. et al. 2018)	$\mathcal{N}(0.674, 0.005)$ (Planck Collab. et al. 2018)

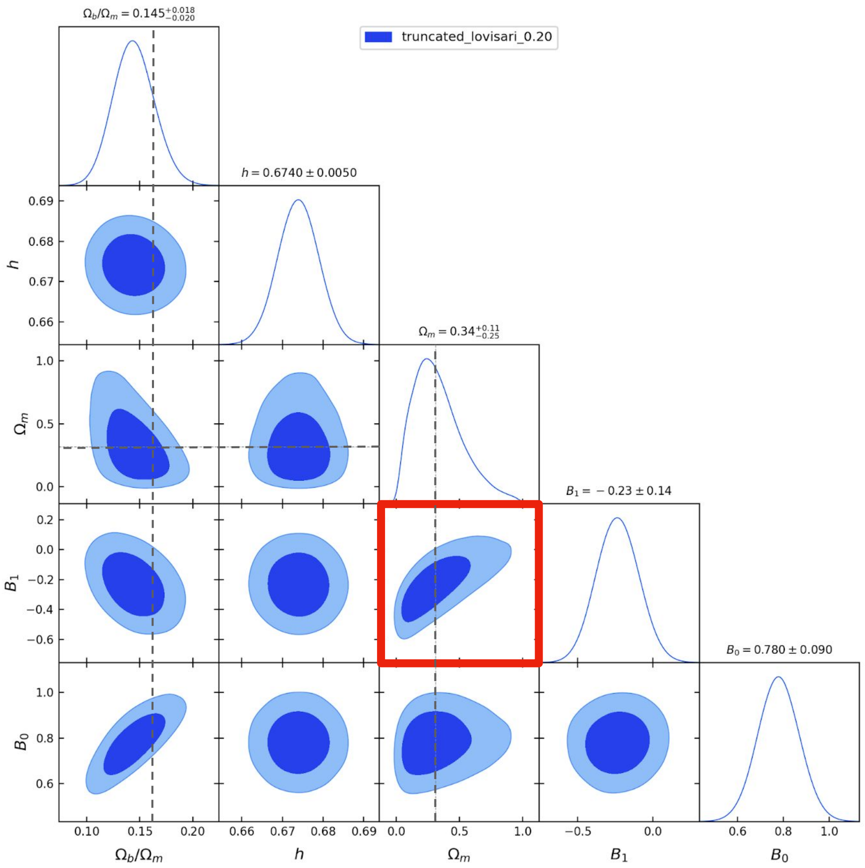
The gas mass fraction as as cosmological probe



Planck prior on h , Ω_m is free, $B_1 = 0$

If we consider no evolution of ***B(z)*** with z, the cosmological constraints are consistent with *Planck* for Ω_b/Ω_m , but are totally off for Ω_m

The gas mass fraction as a cosmological probe



This time we consider $B_1 = -0.25 \pm 0.15$

Ω_b/Ω_m is compatible with the *Planck* value, although slightly below.

Ω_m peaks below the *Planck* value, and has a strong degeneracy with B_1

CONCLUSION

- Results on the redshift evolution of the mass bias are strongly dependant on the sample.
- A mass dependence study will also be carried out using the same sample
- Need to be very careful about these effects when trying to use the gas mass fraction as a cosmological probe
- For investigations at R_{2500}, NIKA2 + X-ray data will be of great help