Cosmological constraints from the Planck cluster catalogue with new multi-wavelength mass calibration

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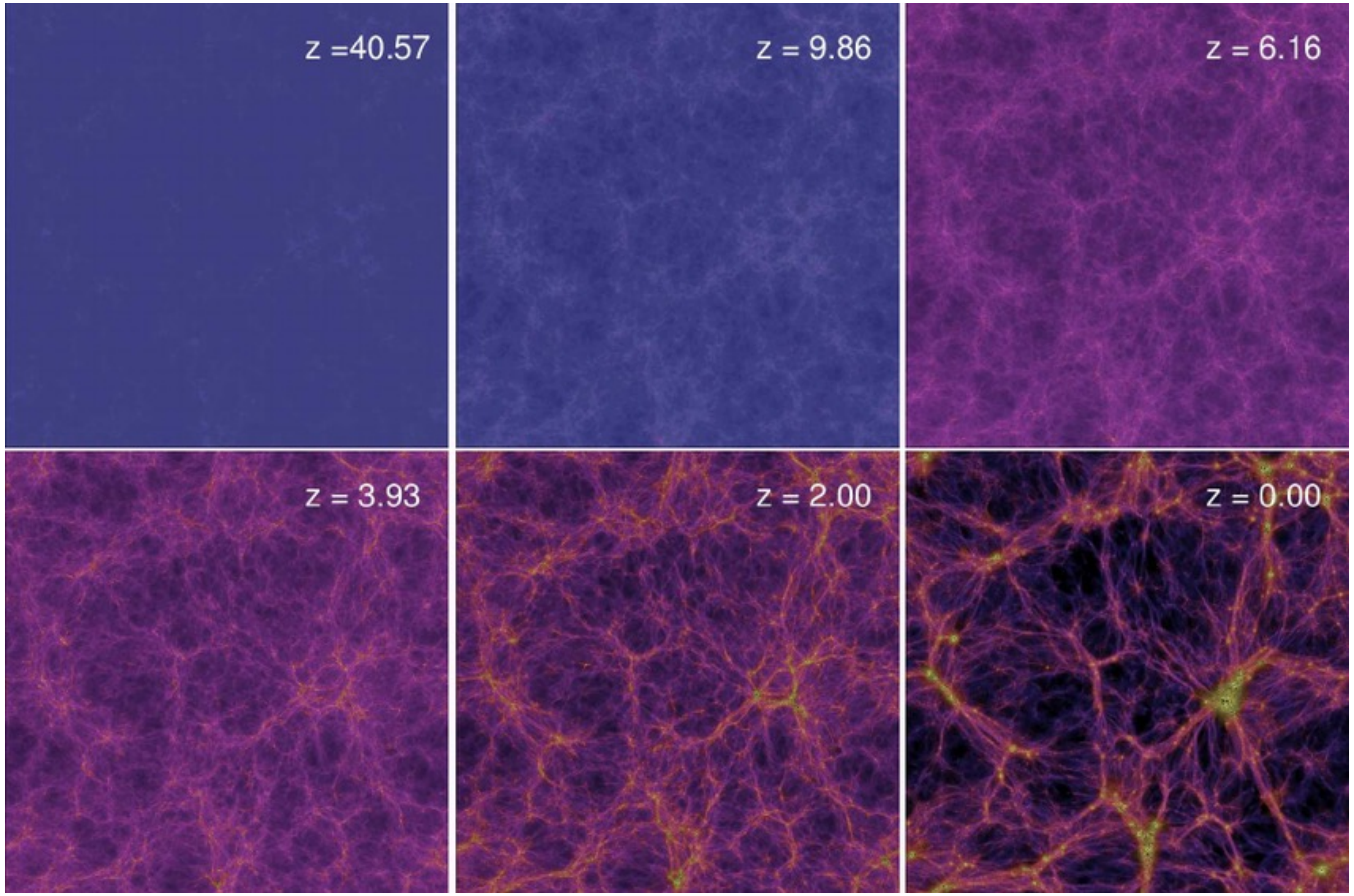
arXiv:2402.04006

Formation of galaxy clusters

Gravitational collapse & expansion of Universe:
Formation of a cosmic web, with extreme overdensities at the nodes, **galaxy clusters**



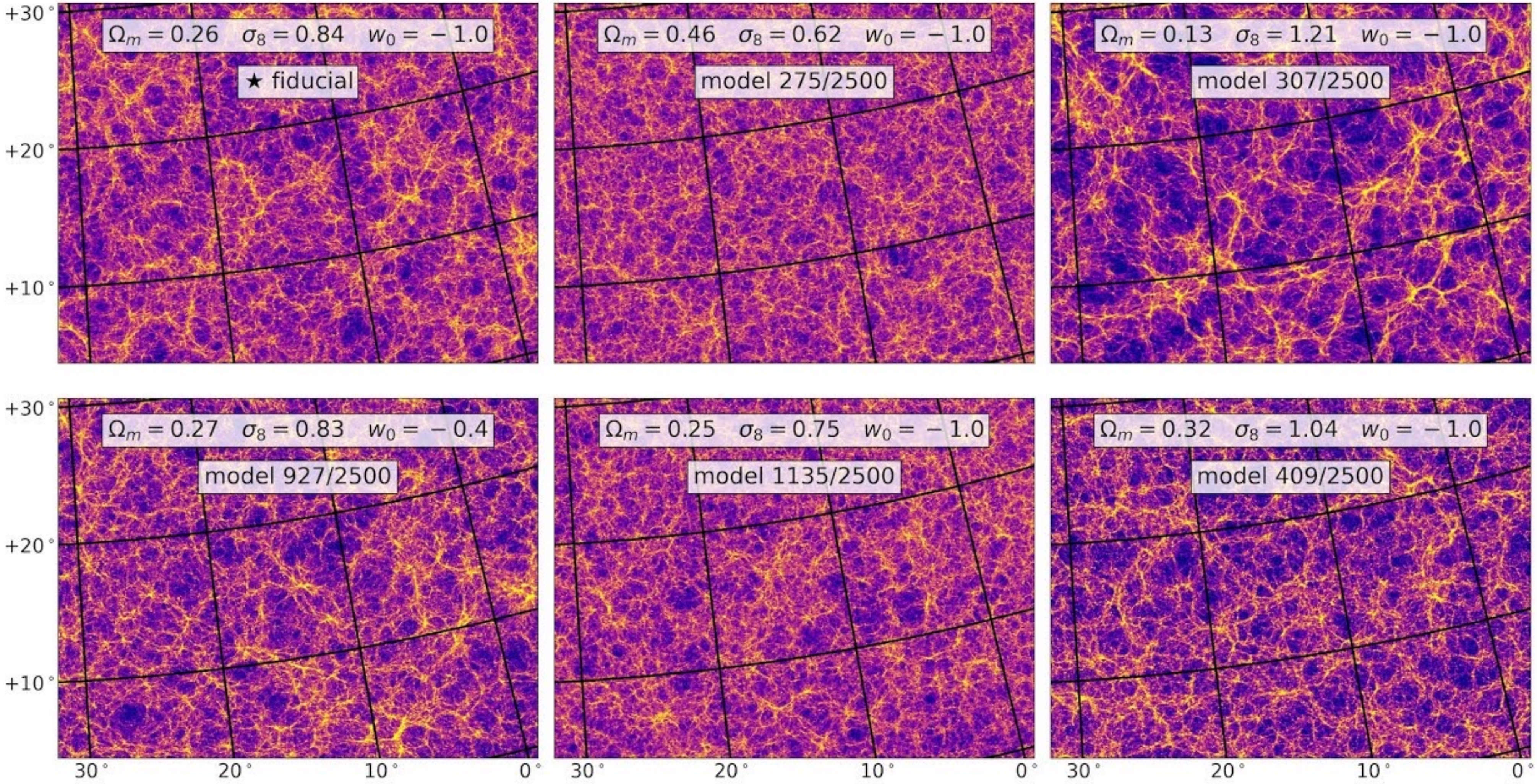
Zhao et al. 2012

« Typical » galaxy cluster:
1 Mpc, $5.10^{14} M_{\odot}$

80% dark matter
16% hot gas (>1 keV)
4% stars

Galaxy clusters & cosmology

How can galaxy clusters be used as a cosmological probe ?



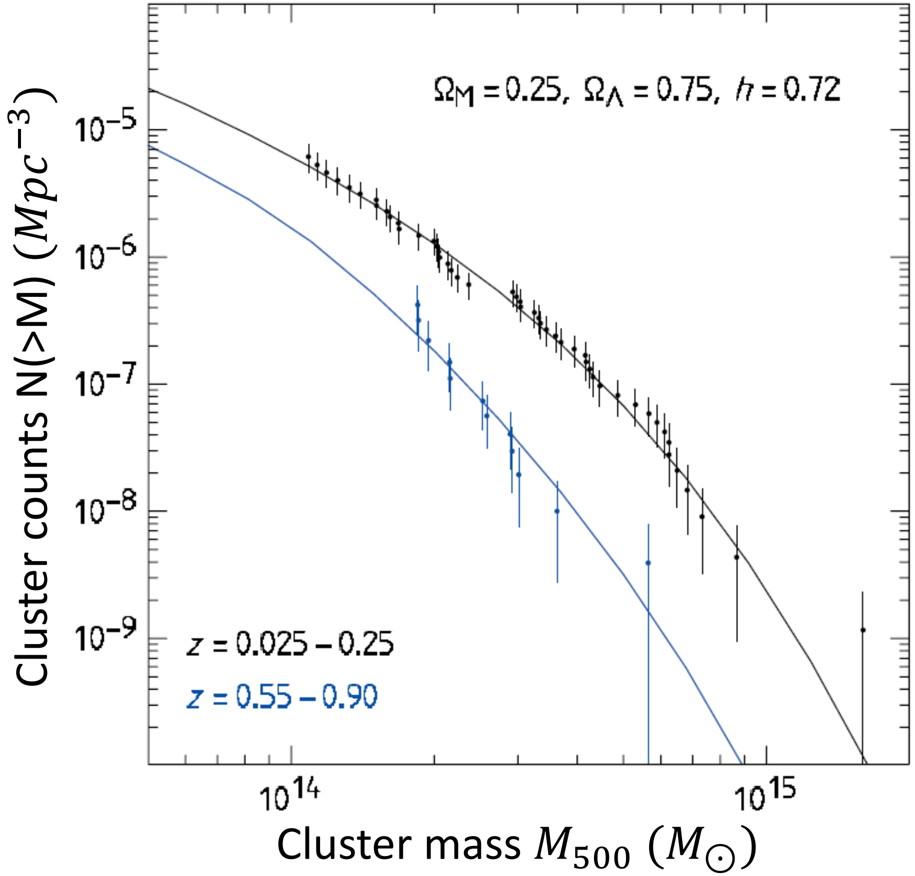
cosmogrid.ai

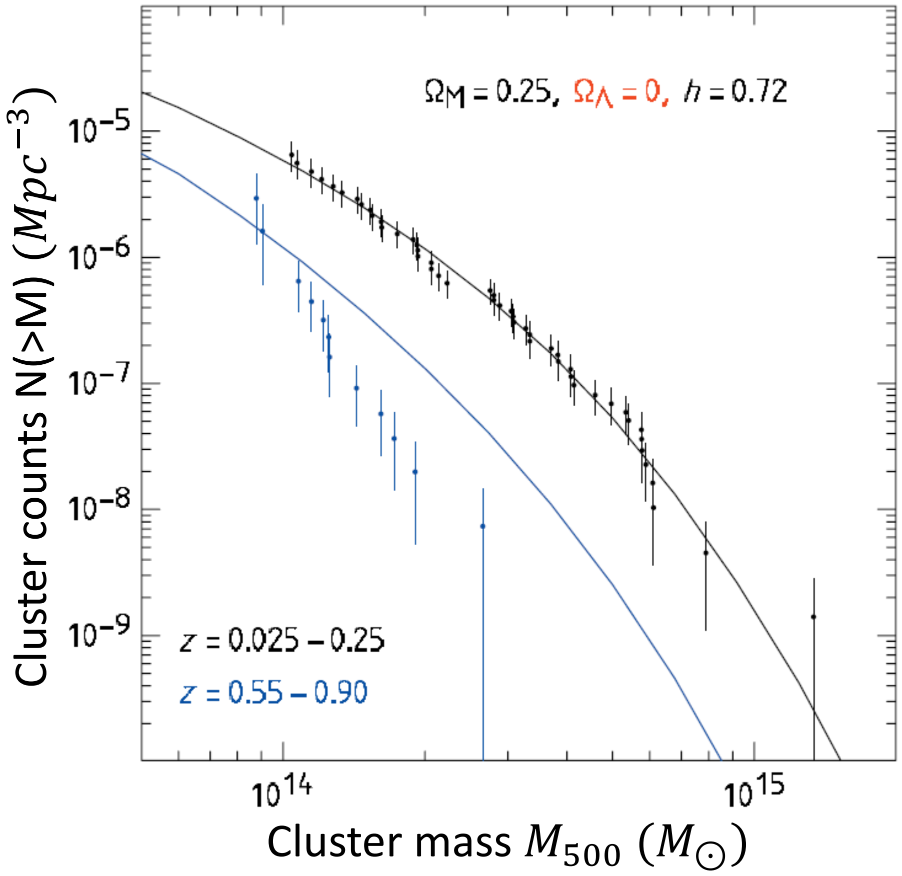
The formation of structures depends on the underlying cosmological model,
leading to **different populations of galaxy clusters**

Galaxy clusters & cosmology

How can galaxy clusters be used as a cosmological probe ?

Mass function: theoretical **prediction of cluster abundance** as function of **mass and redshift**



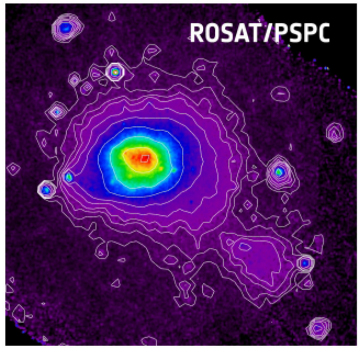


Vikhlinin et al. 2009

How can we observe them ?

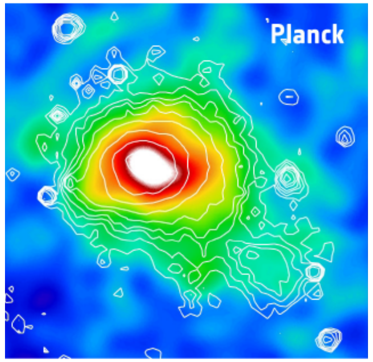
Different wavelengths probe different properties of clusters

Combining all wavelengths allow for more precise characterisation of cluster properties



X-ray emission:
Bremmstrahlung
Sensitive to **gas density squared**
High resolution

$$E_X \propto \int_V n_e^2 \Lambda(T) dV$$



mm-wavelength:
Thermal Sunyaev-Zeldovich effect
(inverse Compton scattering)
Sensitive to **gas pressure**

$$F_\nu \propto \int_\Omega (P = n_e T) d\Omega$$

Optical/near IR wavelength:
Stars (small part of total mass)
Gravitational lensing
(total mass, limited precision)

Combining X-ray and SZ

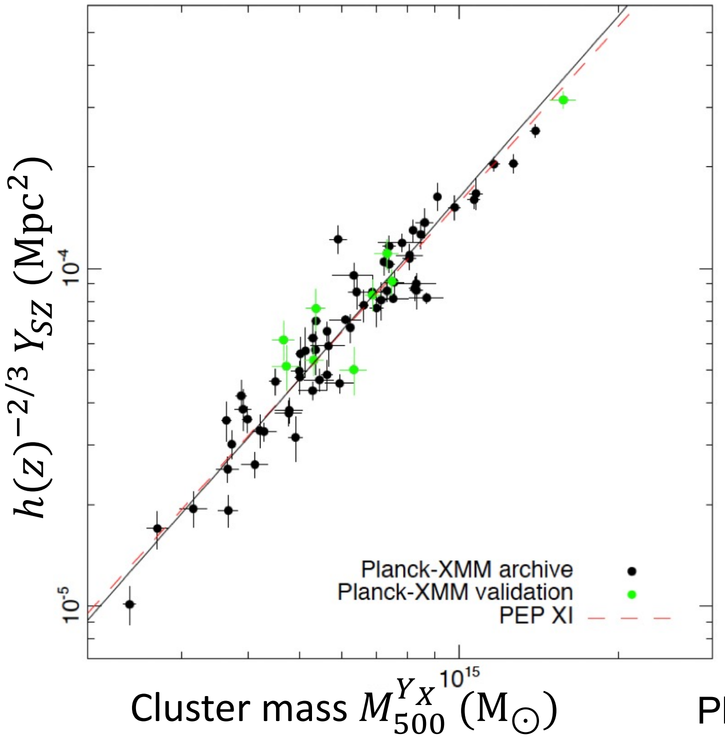
Improving on Planck 2015: a better calibration sample

Planck data provides full sky SZ-survey: great opportunity for cosmological analysis

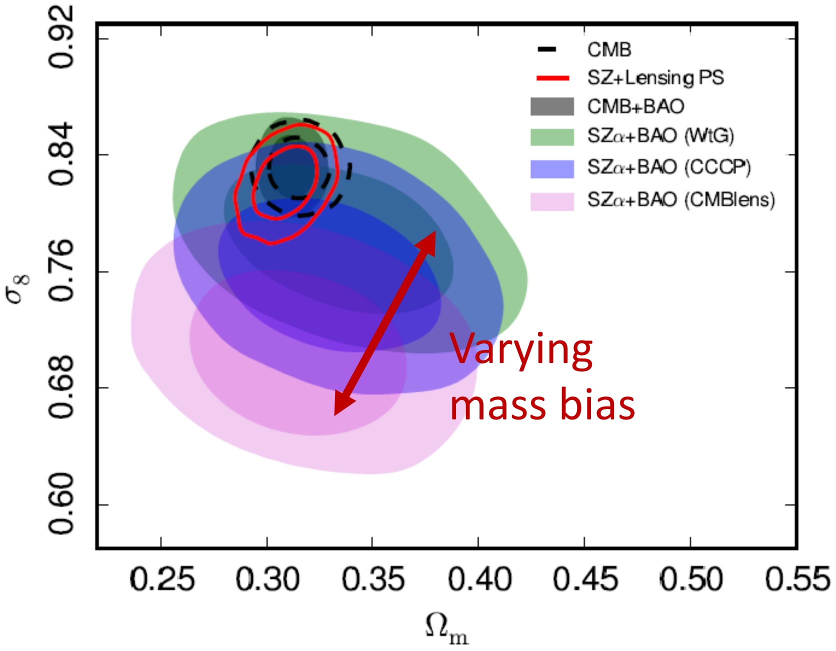
Cluster mass can't be directly inferred from SZ signal

Arnaud et al. 2010 relates X-ray signal from XMM-Newton to mass under hydrostatic equilibrium assumption

Y500-M500 is calibrated on a common XMM/SZ set of 71 clusters: $E^{-2/3}(z)\left[\frac{D_A^2\, Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = 10^{-0.19\pm0.02}\left(\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right)^{1.79\pm0.08}$



Planck 2013



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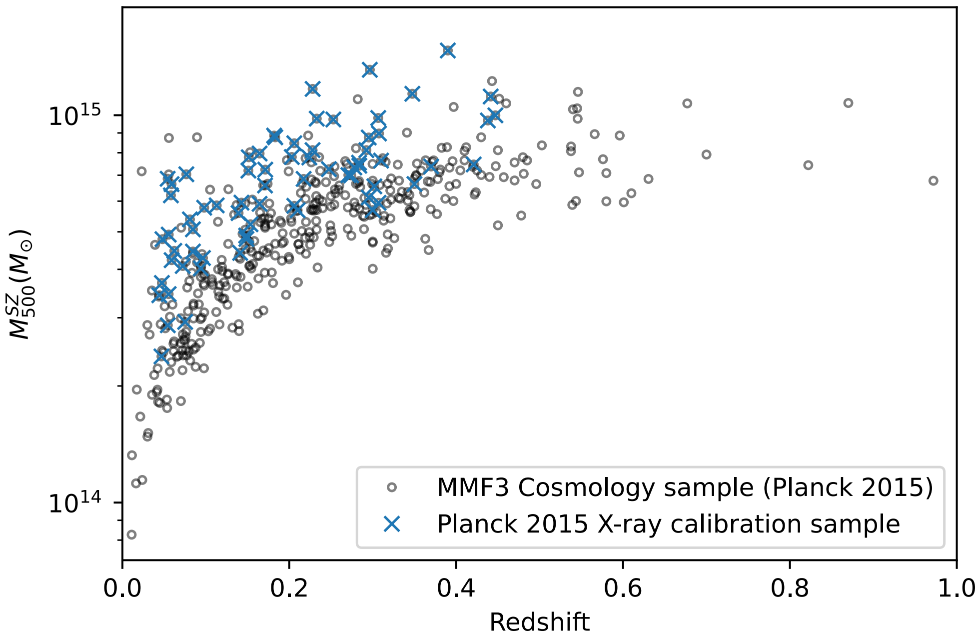

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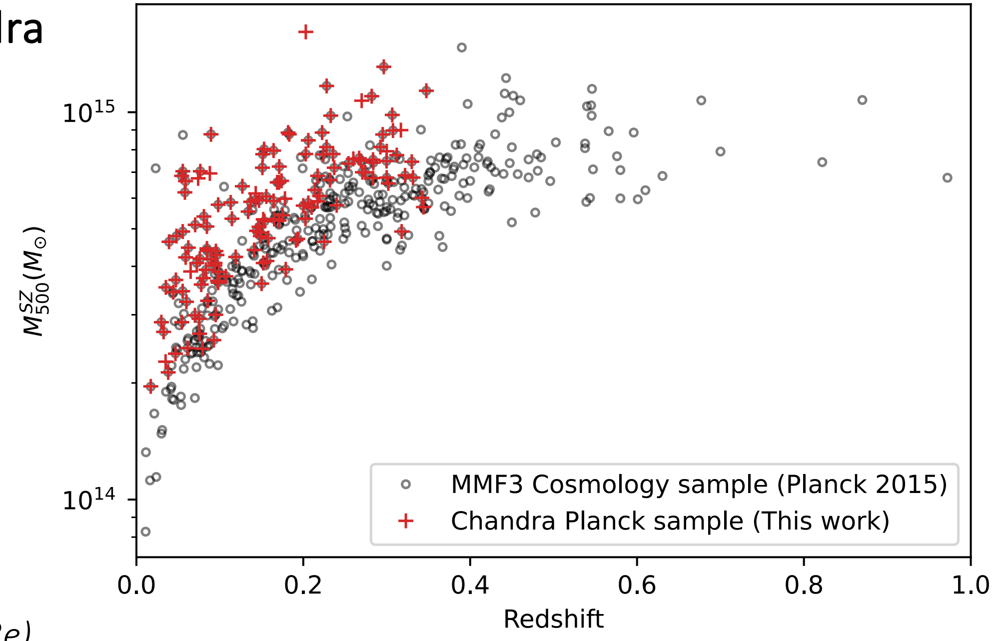
Full re-observation of Planck ESZ sample (with z<0.35) by Chandra

SZ-selected sample
More clusters (146 vs 71)
Better low-mass leverage
Similar high-mass leverage
Better low-redshift leverage
Slightly worse high-redshift leverage



Work done by CfA team (Santos et al. 2021, https://doi.org/10.3847/1538-4357/abf73e)

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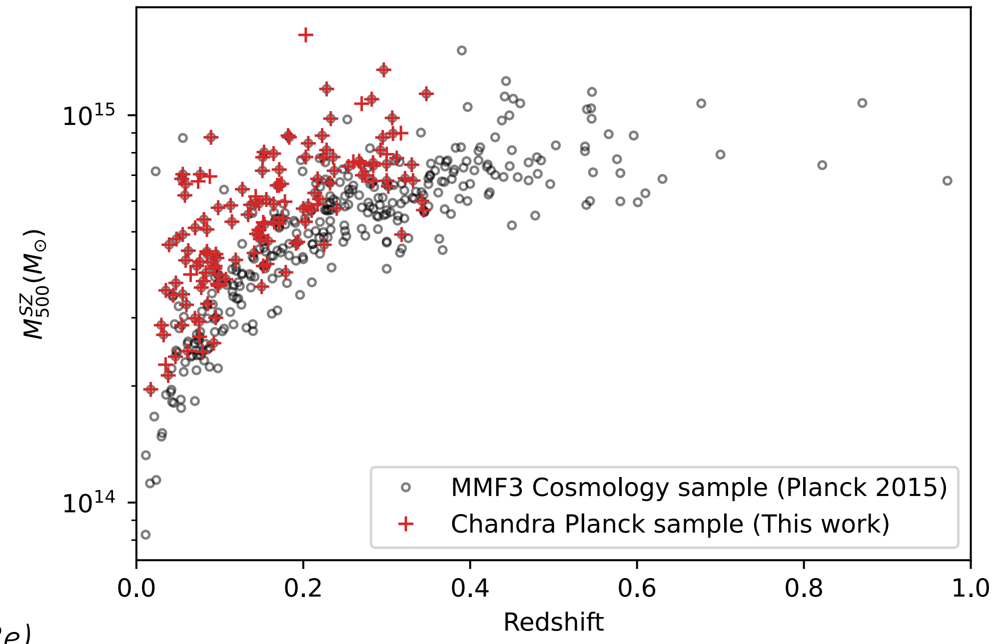
146 clusters from Planck ESZ sample were observed by Chandra

Analyse the data and calibrate a new scaling relation
Constrain cosmological parameters



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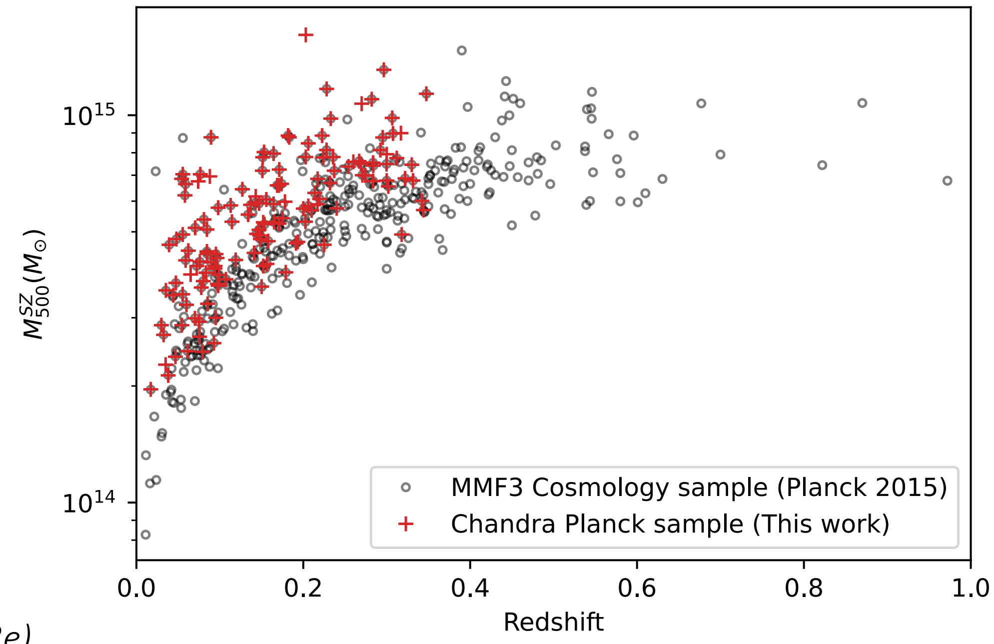
Analysis of the raw data up to X-ray derived masses done by collaborators at CfA



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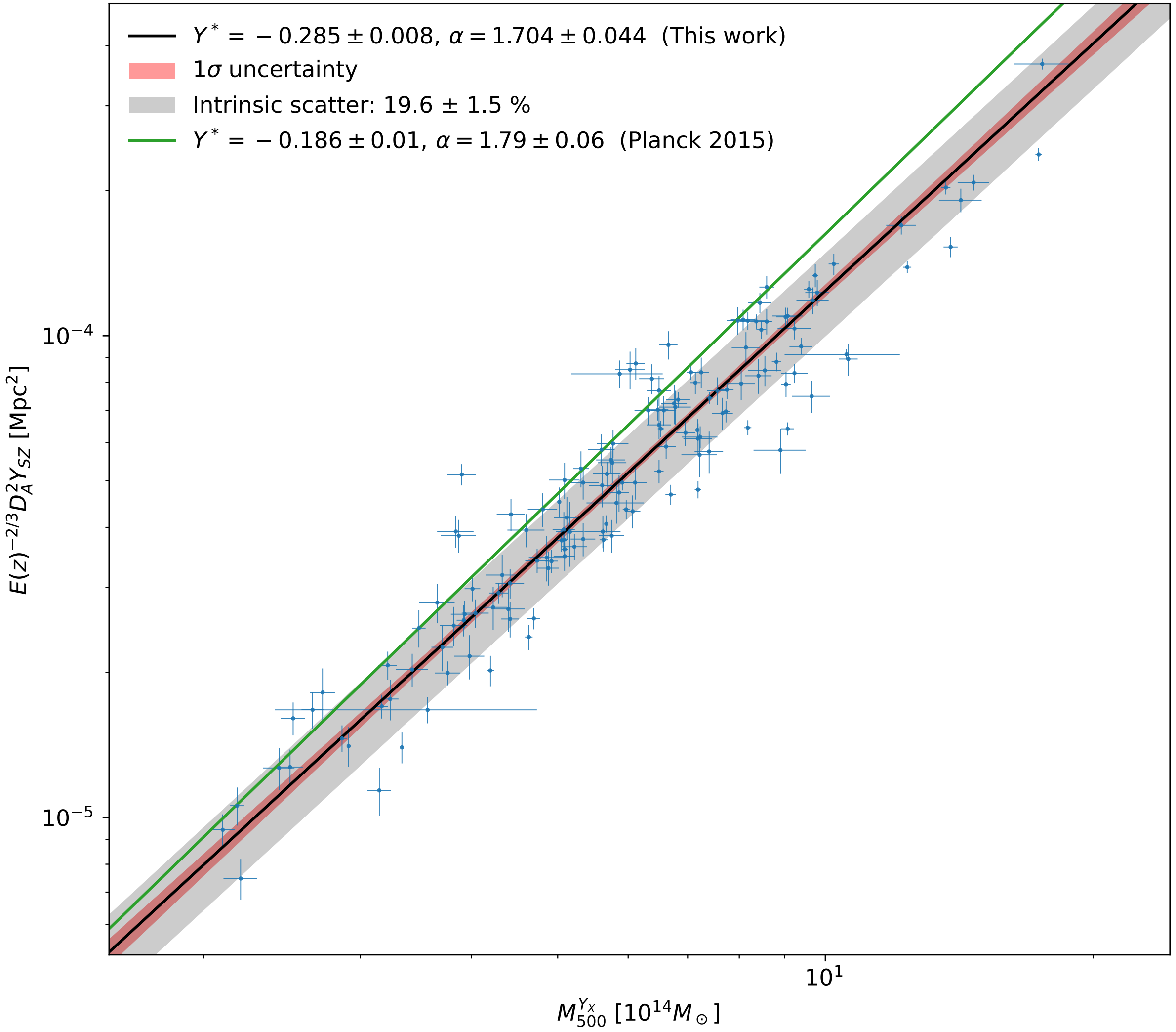
Obtaining masses

Calibrating the Ysz-M relation



Run **MMF algorithm with X-ray positions and apertures**
Obtain Ysz with uncertainties

Correct for Malmquist bias:
Divide each individual Ysz by mean bias at that value

After **adding statistical uncertainty and scatter from X-ray scaling relation**:

$$E^{-2/3}(z)\frac{D_A^2\, Y_{500}}{10^{-4}\mathrm{Mpc}^2} = 10^{-0.29\pm0.01}\left(\frac{(1-b)M_{500}}{6\cdot10^{14}M_\odot}\right)^{1.70\pm0.1}$$

Scatter: 21%

Robust to fitting method (emcee, LinMix, BCES)

Obtaining masses

Comparison with Planck 2015 results

Chandra scaling relation:

$$E^{-2/3}(z)\frac{D_A^2\,Y_{500}}{10^{-4}\mathrm{Mpc}^2} = \underline{10^{-0.29\pm0.01}}\left(\frac{(1-b)M_{500}}{6\cdot10^{14}M_\odot}\right)^{\underline{1.70\pm0.1}}$$

Scatter: 21%

Planck collab. 2015 Cosmology from SZ number counts scaling relation :

$$E^{-2/3}(z)\left[\frac{D_\mathrm{A}^2\,Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = \underline{10^{-0.19\pm0.02}}\left(\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right)^{\underline{1.79\pm0.08}}$$

Scatter: 18%

The new scaling relation has:

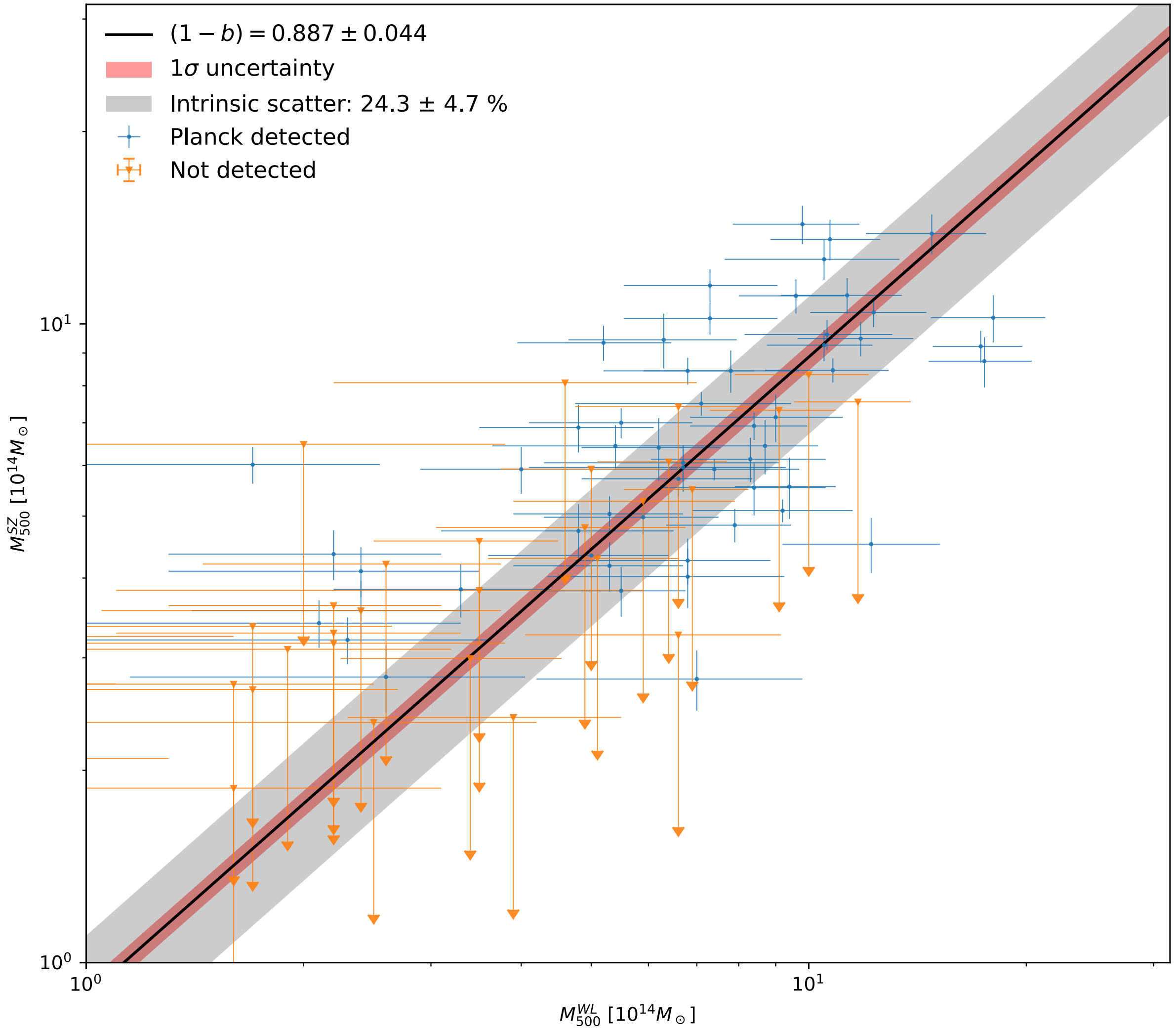
Lower normalization: Chandra and XMM temperature calibration don't match, Chandra measures hotter and thus heavier cluster. The **difference is coherent with predictions from Schellenberger et al. 2015** (20% difference)

Shallower slope: The new scaling relation is closer to self-similar (slope of 5/3)

Comparable uncertainties: Lower uncertainties on Y_{SZ}-M_{Y_X} (larger sample) but higher uncertainties on Y_X-M_{Y_X} compensates the difference

Obtaining masses

Calibrating the hydrostatic mass bias



X-Ray masses are obtained under the assumption of hydrostatic equilibrium (i.e. thermal pressure perfectly balancing gravity)

Non thermal pressure support and deviations from equilibrium lead to **under-estimation of the true mass**

Effect accounted for by a **multiplicative factor, calibrated with weak lensing mass estimates**

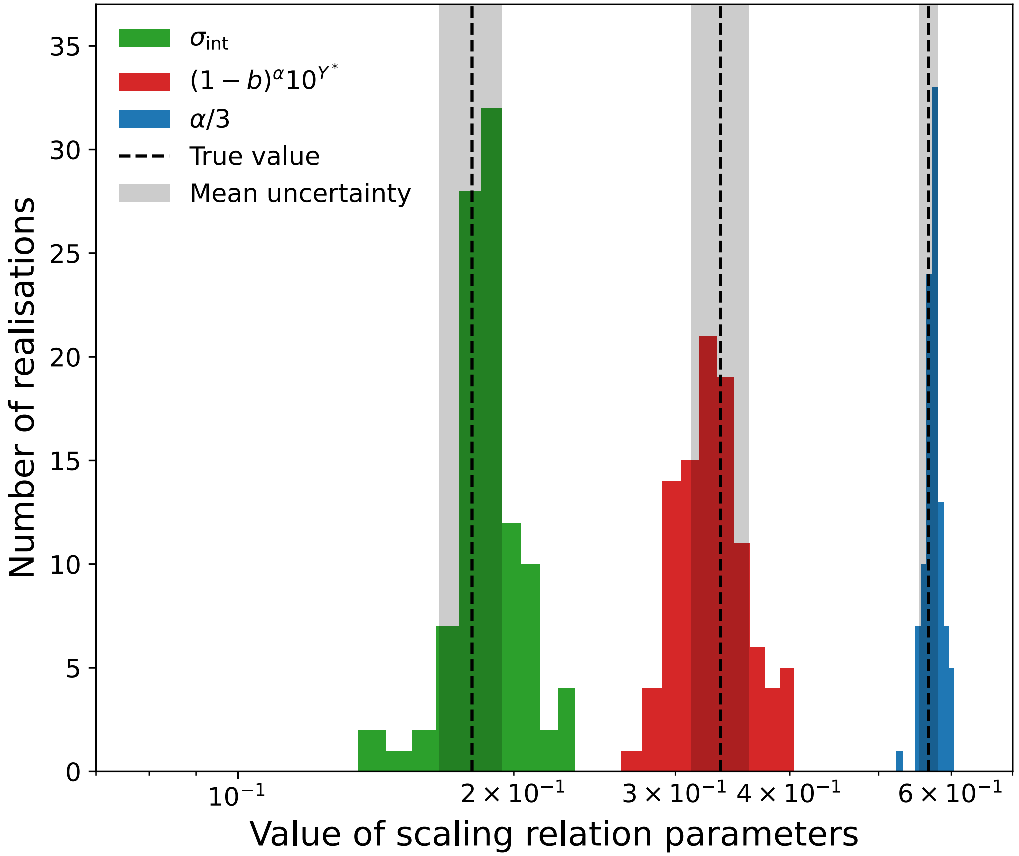
$$E^{-2/3}(z)\frac{D_A^2 Y_{500}}{10^{-4}\mathrm{Mpc}^2} = 10^{-0.29\pm0.01}\left(\frac{\boxed{(1-b)}M_{500}}{6\cdot10^{14}M_\odot}\right)^{1.70\pm0.1}$$

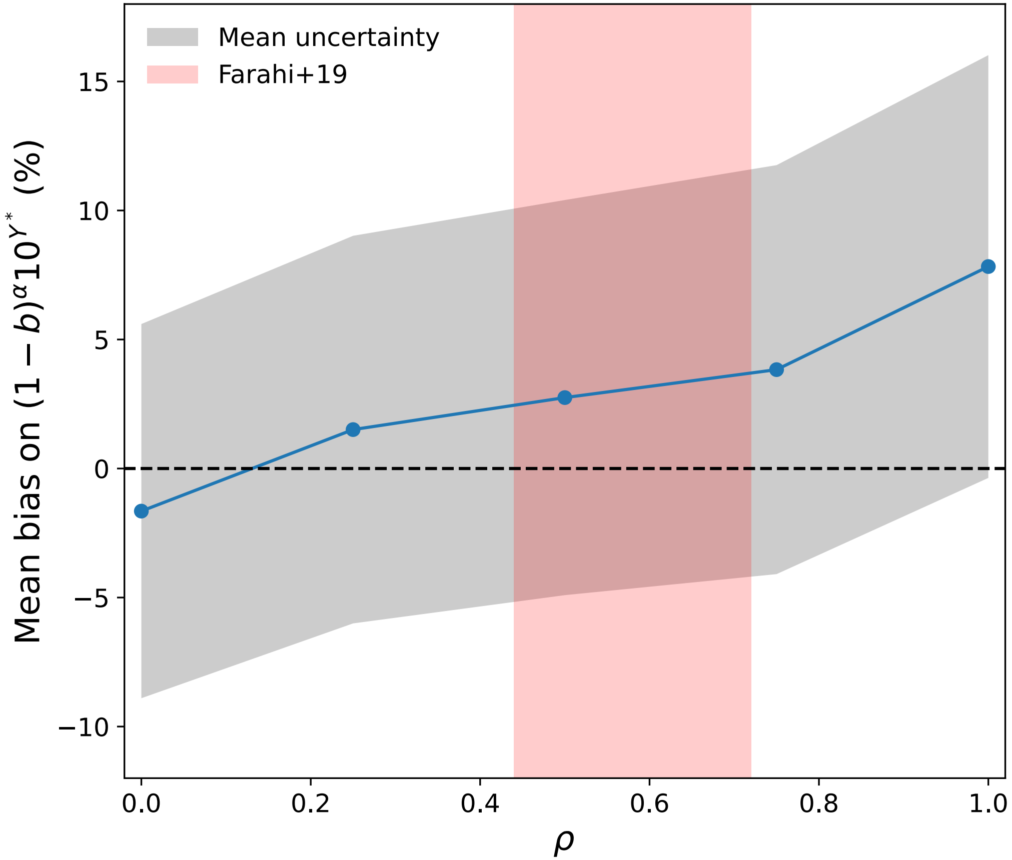
Use WL data from Herbonnet et al. 2020

Calibration sample	D+nD	D
Chandra	0.89 ± 0.04	0.91 ± 0.05
XMM-Newton	0.76 ± 0.04	0.78 ± 0.04
Herbonnet+20	X	0.81 ± 0.04
CCCP (P15)	X	0.78 ± 0.09

Calibration validation

Validation on mock cluster samples



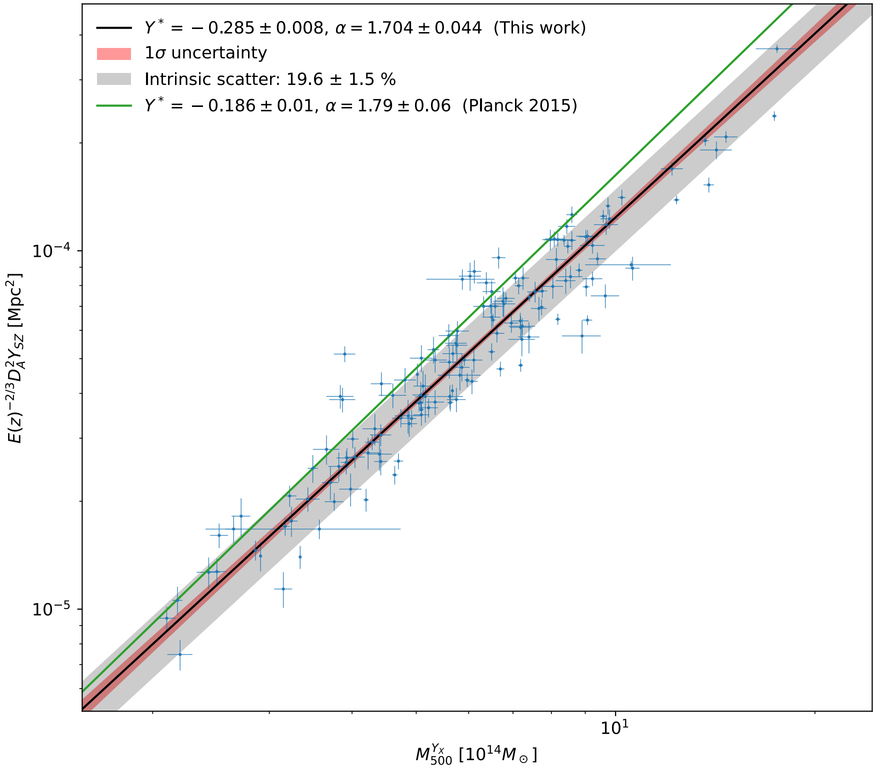


Scaling relation parameters are well recovered for mock samples

Calibration is robust to correlated scatter between X-ray and SZ observables

Constraining the cosmology

What are the effect of changing the scaling relation ?



Rest of the analysis is identical to Planck 2015 Cosmology with SZ number counts:

Use **cosmology cluster sample**, **two dimensional likelihood** (fit number counts as function of redshift and S/N), **additional priors from BBN and BAO** (only Ω_m and σ_8 are constrained by cluster number counts)

$$\frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}q} = \int \mathrm{d}\Omega_{\mathrm{mask}} \int \mathrm{d}M_{500} \, \frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}M_{500}\mathrm{d}\Omega} \, P[q|\bar{q}_{\mathrm{m}}(M_{500}, z, l, b)]$$ Fitted number counts

$$\frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}M_{500}\mathrm{d}\Omega} = \frac{\mathrm{d}N}{\mathrm{d}V\mathrm{d}M_{500}} \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega}$$ Theoretical mass function

$$\bar{q}_{\mathrm{m}} \equiv \underbrace{\bar{Y}_{500}(M_{500}, z)}_{\text{Scaling relation}} / \sigma_{\mathrm{f}}[\bar{\theta}_{500}(M_{500}, z), l, b]$$ Median S/N for given M and z

Constraining the cosmology

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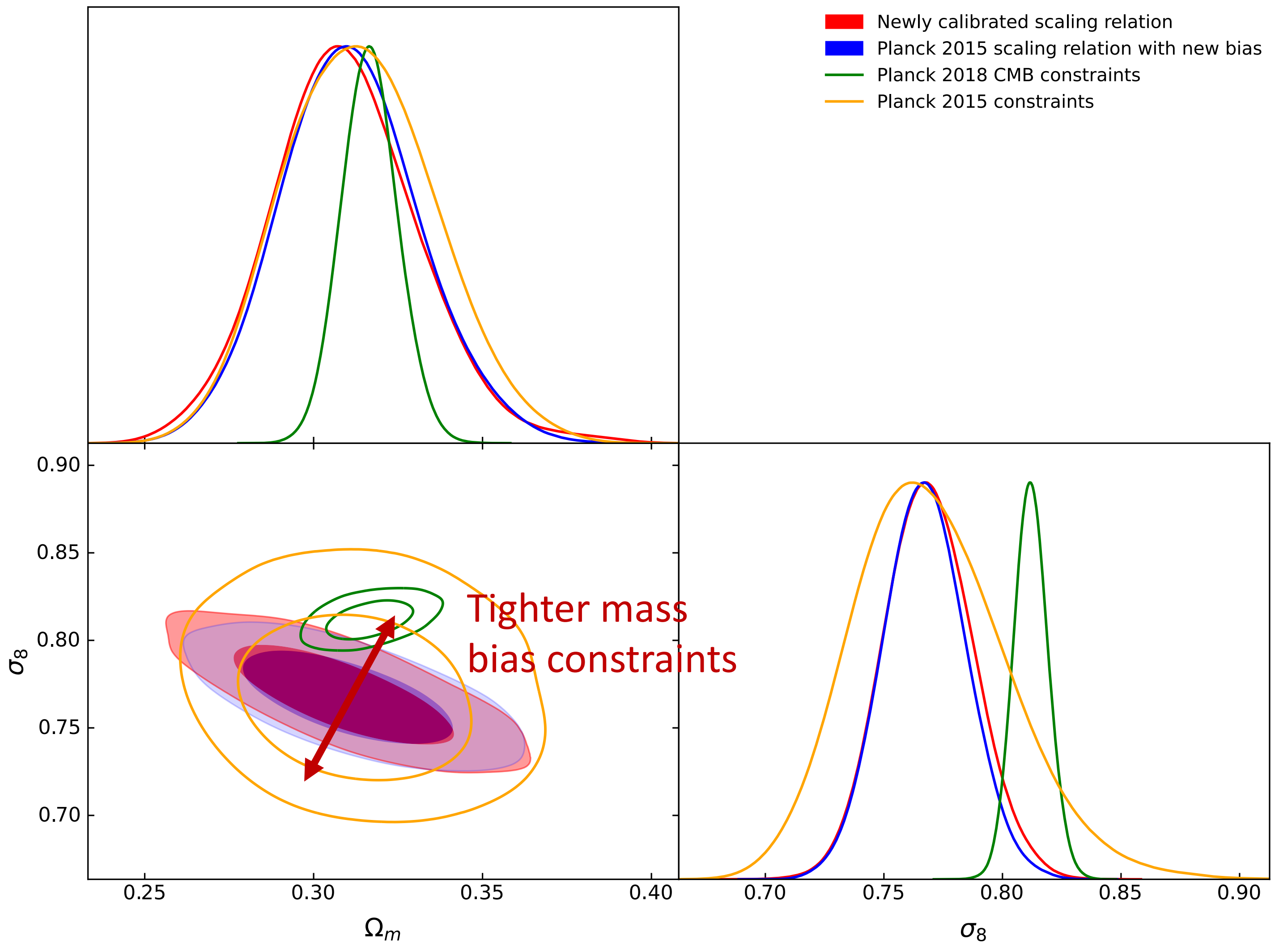


Cosmological constraints obtained:

X-ray sample	Ω_m	σ_8
Chandra	0.308 ± 0.022	0.764 ± 0.019
XMM-Newton	0.311 ± 0.020	0.755 ± 0.019

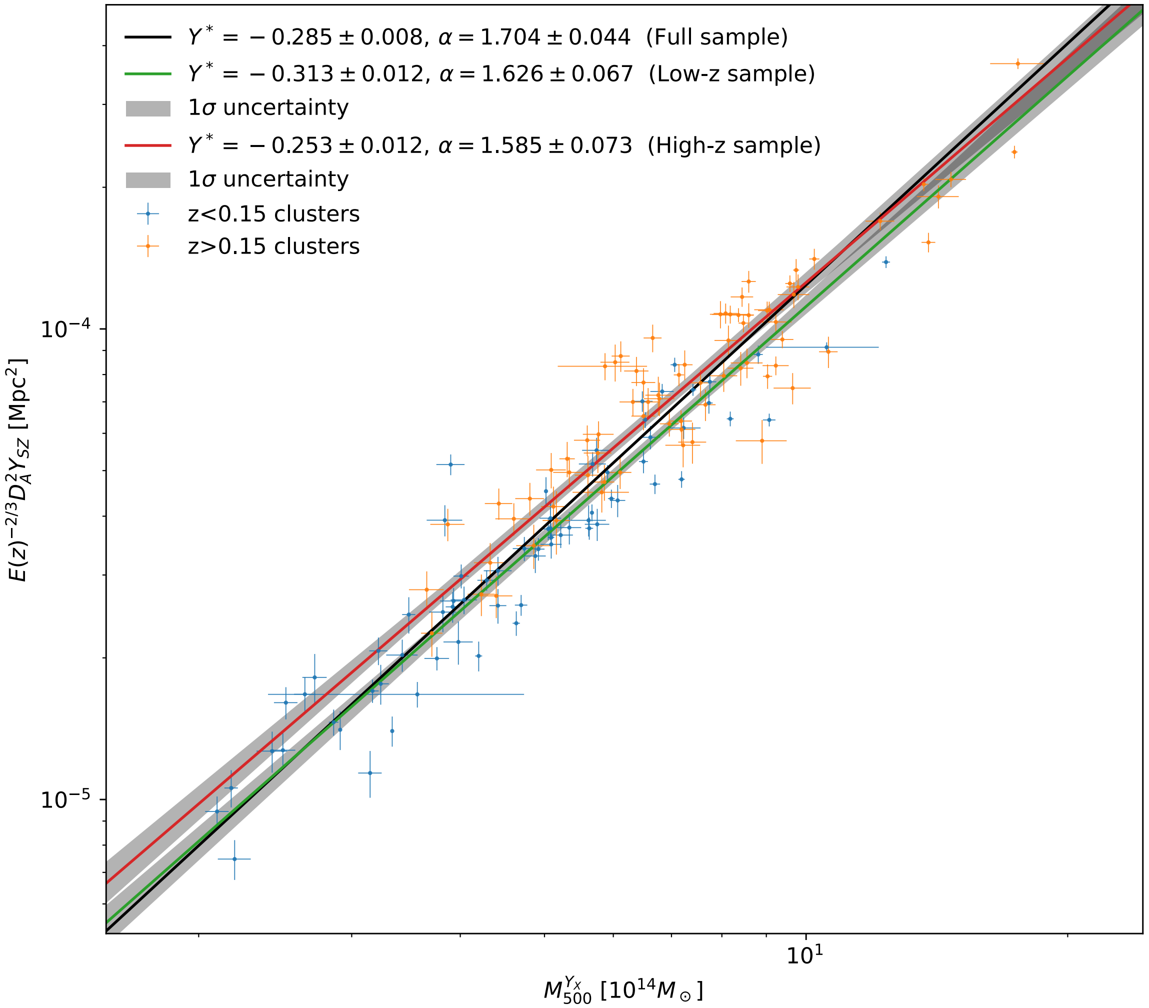
Even with **calibration problems** between the two telescopes, **the constraints are fully consistent**

Constraints are **centered on the same value and tighter than Planck 2015**, thus in **higher tension with the CMB**

Mass calibration, and **mass bias in particular is the most sensitive point of cluster cosmology**

Redshift dependence

Redshift dependence was fixed to self-similar value: can we constrain it from the data ?



Motivation for investigation:

Separating the calibration sample into **high-z and low-z subsamples yields different best fits**

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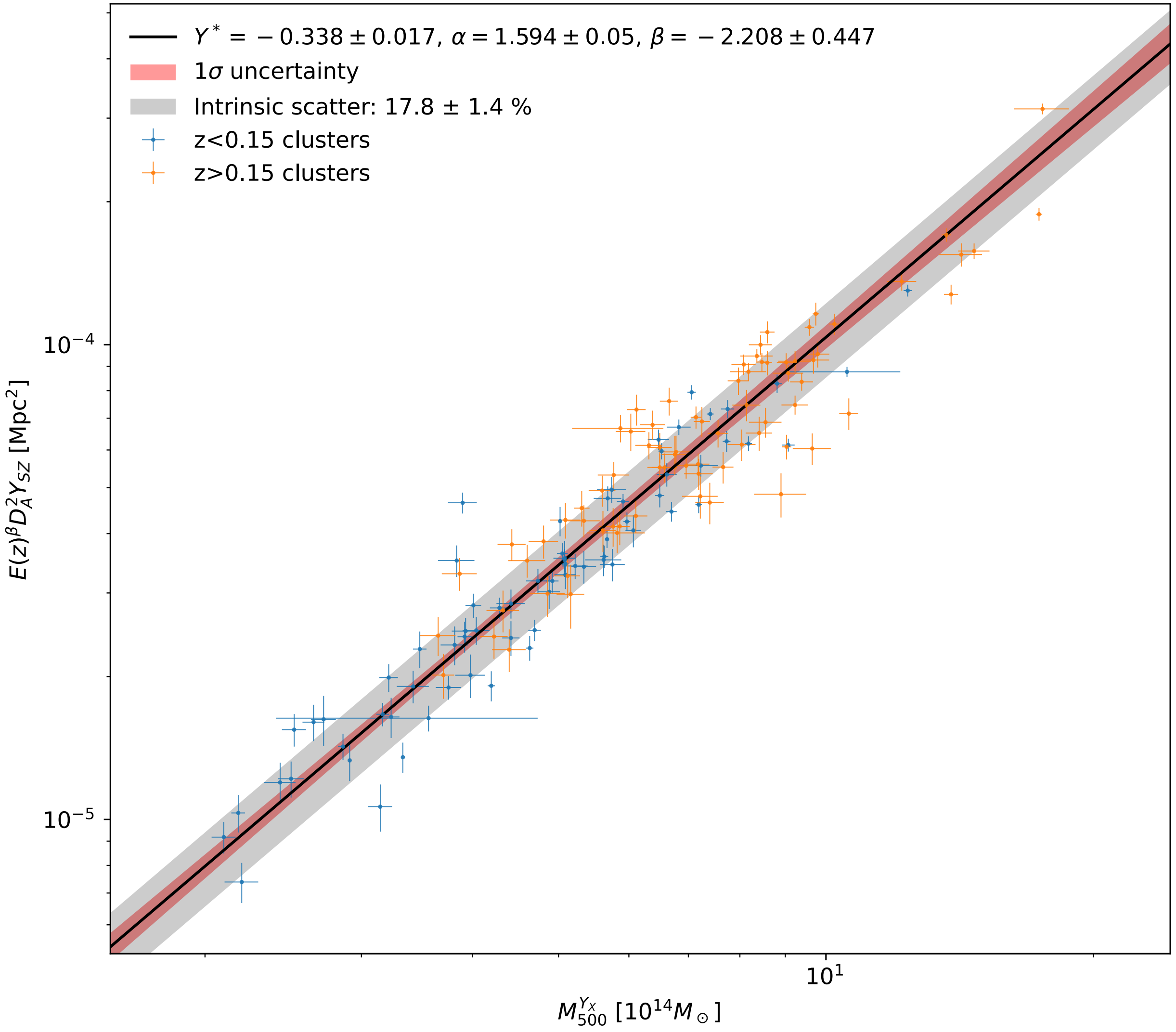

Modify likelihood to allow E(z) exponent to vary:

$$E^{\beta}(z) \frac{D_A^2 \, Y_{\rm SZ}}{Y_{\rm piv}} = 10^{Y^*} \left(\frac{M_{500}^{Y_{\rm X}}}{M_{\rm piv}} \right)^{\alpha}$$

Find a **strong preference (3-4 σ)for much higher redshift dependance**

This effect is **not sample-dependent and holds for XMM-Newton calibration sample**

X-ray sample	*Chandra*	*XMM-Newton*
Y^*	-0.34 ± 0.02	-0.24 ± 0.03
α	1.59 ± 0.1	1.66 ± 0.1
β	-2.22 ± 0.45	-1.96 ± 0.47
$(1-b)$	0.84 ± 0.04	0.74 ± 0.04
scatter	20%	17%

Compatible with Andreon 2015 and Sereno&Ettori 2017

Including truly high-z clusters would allow for better understanding of this effect

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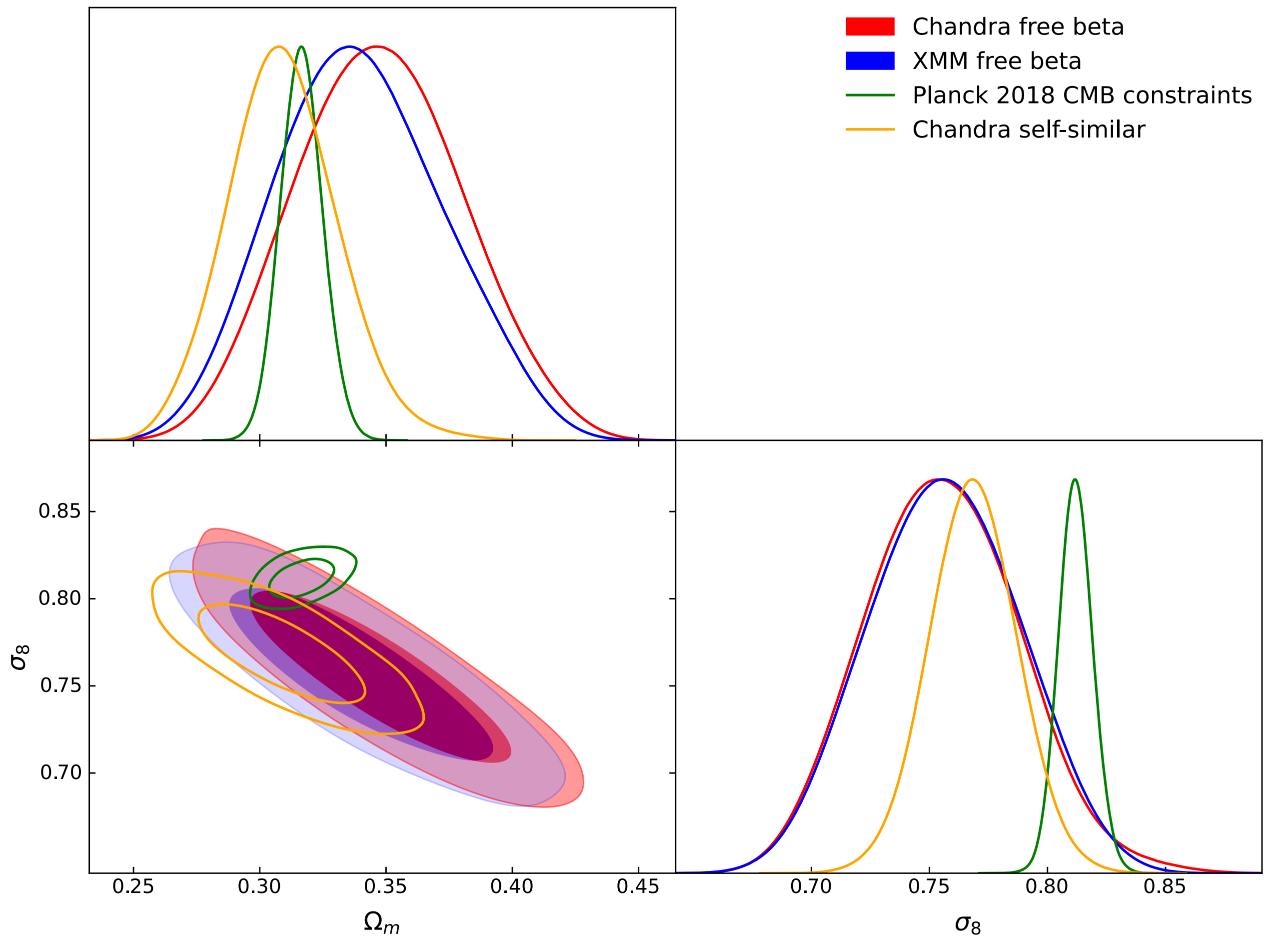
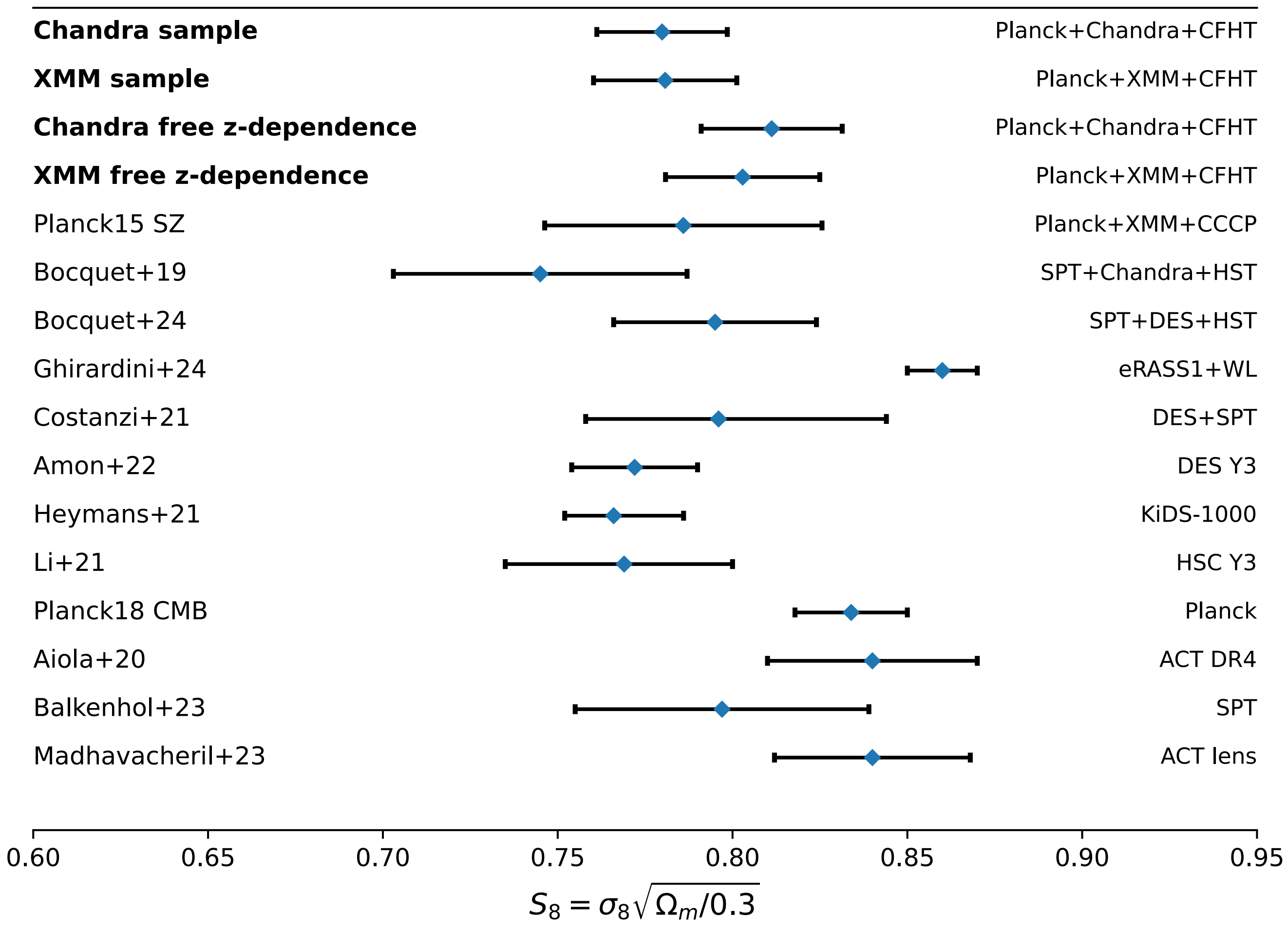


Loss of constraining power, but **preference for higher S_8 values**
Reduction of tension with the CMB constraints

Constraints in global context

Where do our results stand in the global picture ?



Preference for **lower S_8 values, like most late time probes**

Tension of 1-2 σ with the CMB, depending on z-evolution

Next project: **Planck catalogue with DES shear profiles** for mass calibration, to **understand difference with eRASS1 results**