Cosmological constraints from the Planck cluster catalogue with DES weak-lensing mass calibration

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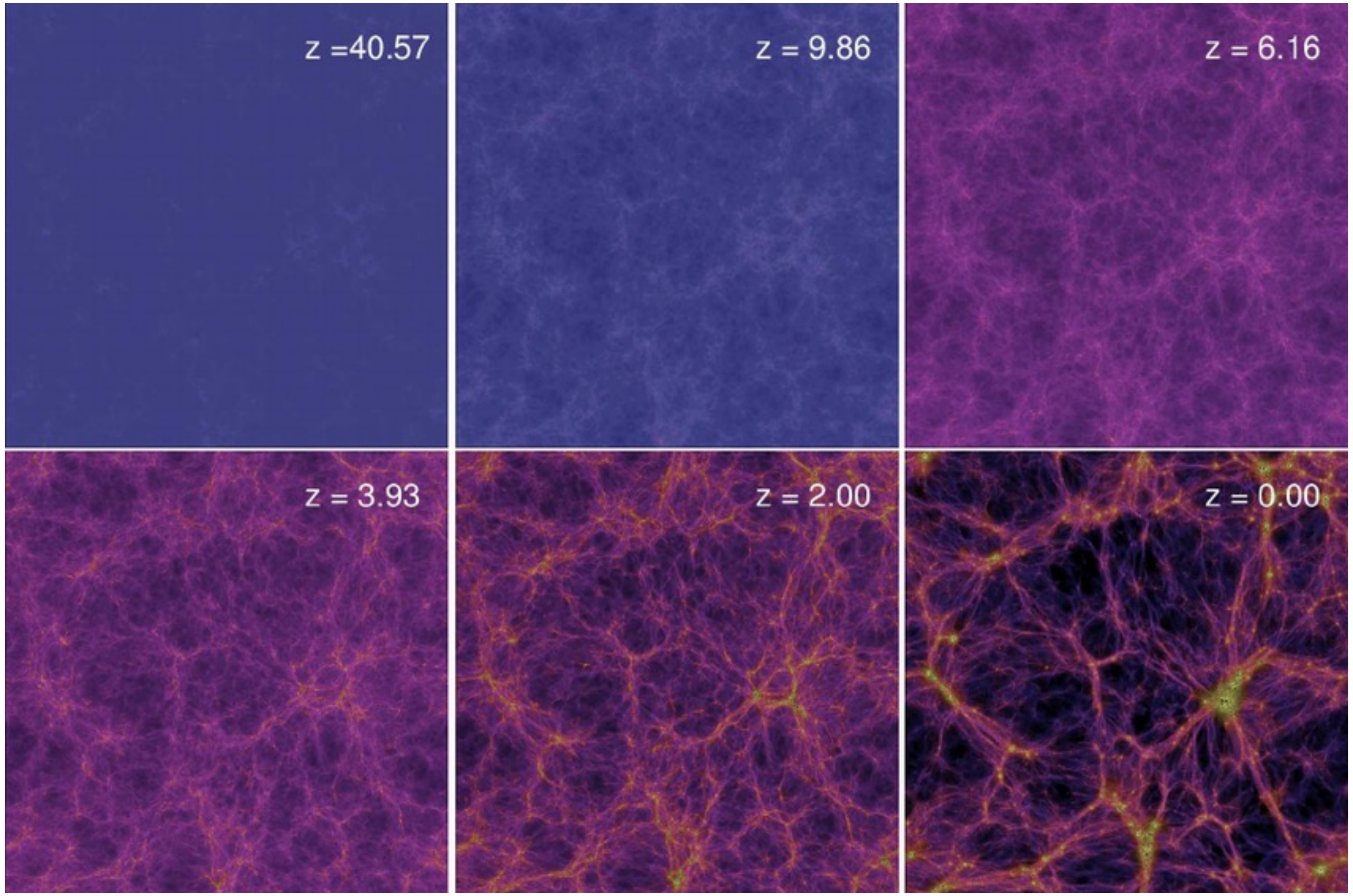
Formation of galaxy clusters

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

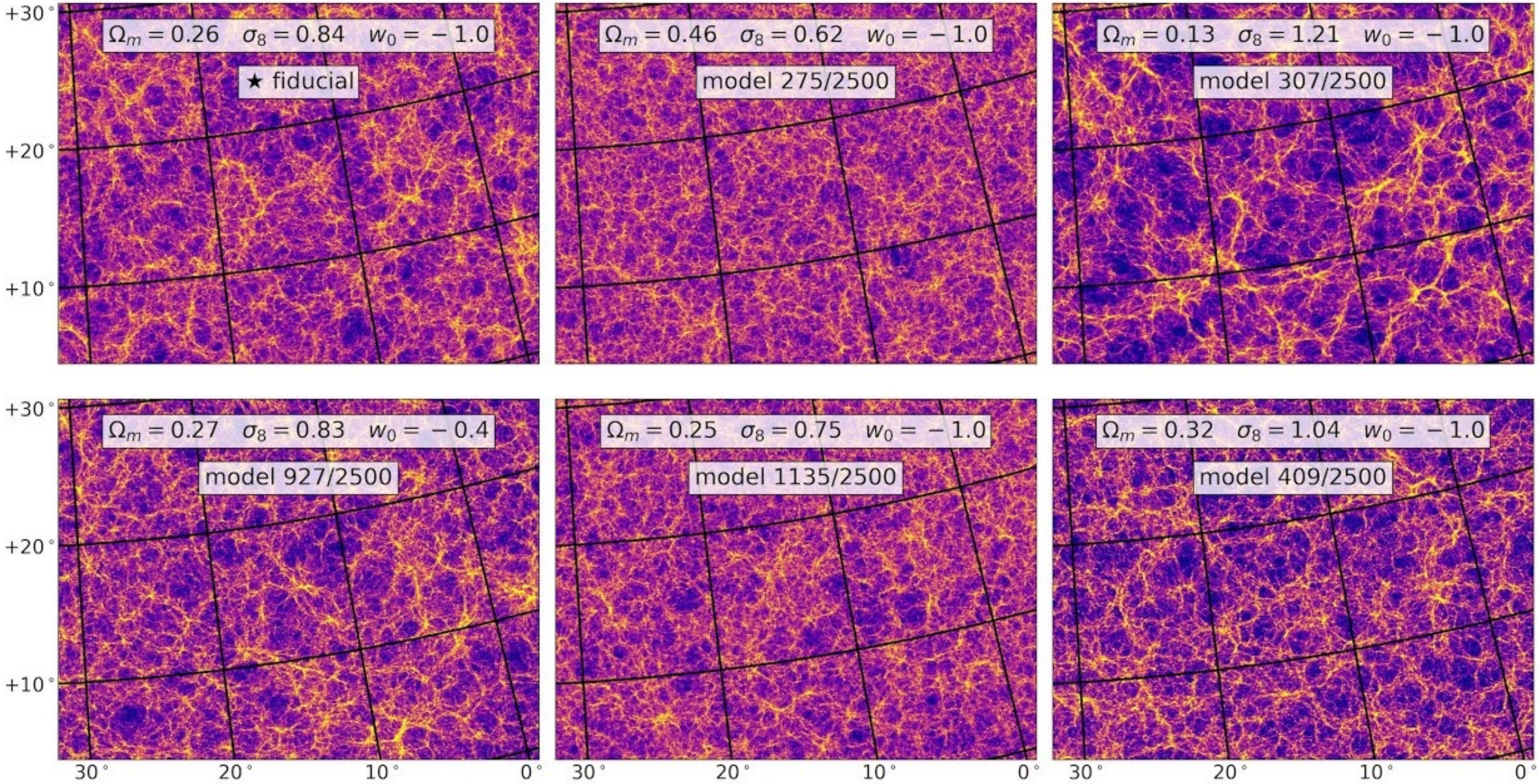


Zhao et al. 2012

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

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

How can galaxy clusters be used as a cosmological probe ?



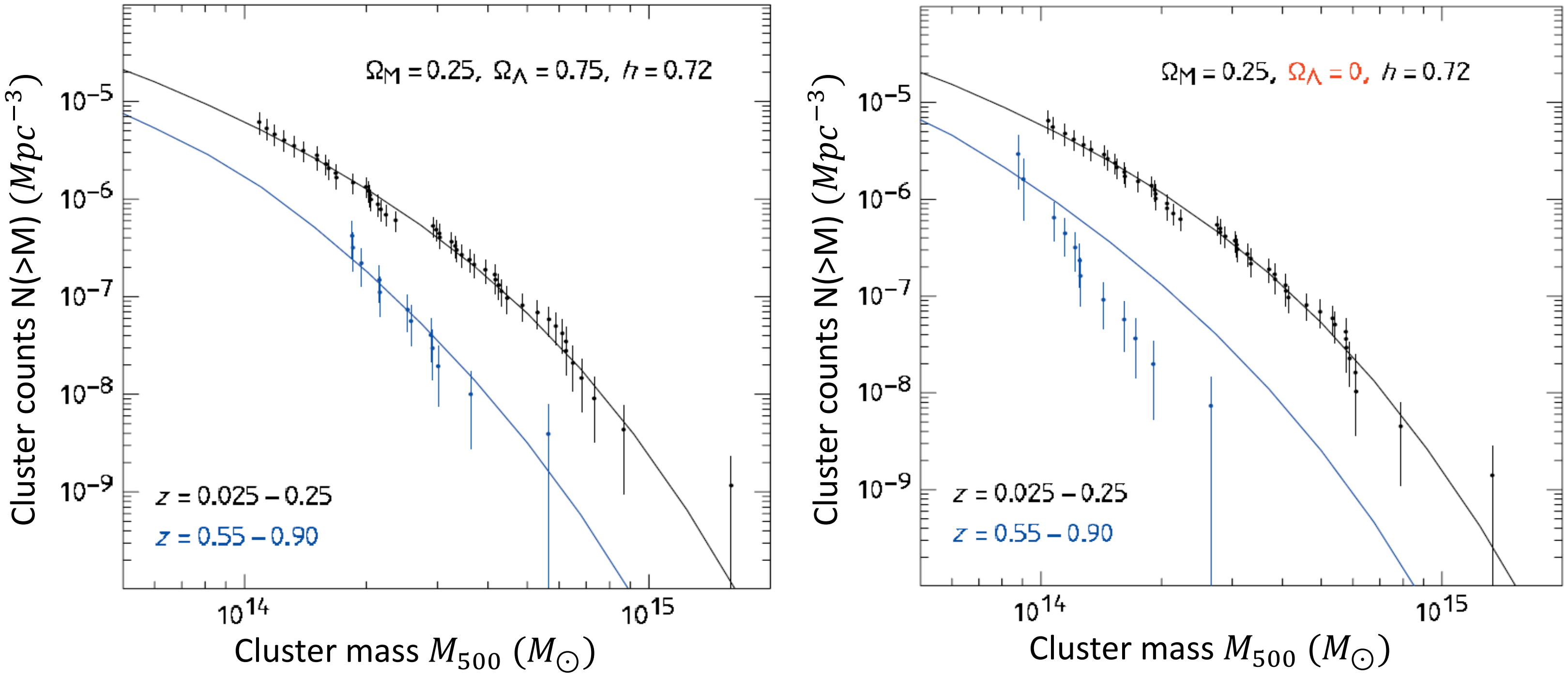
cosmogrid.ai

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

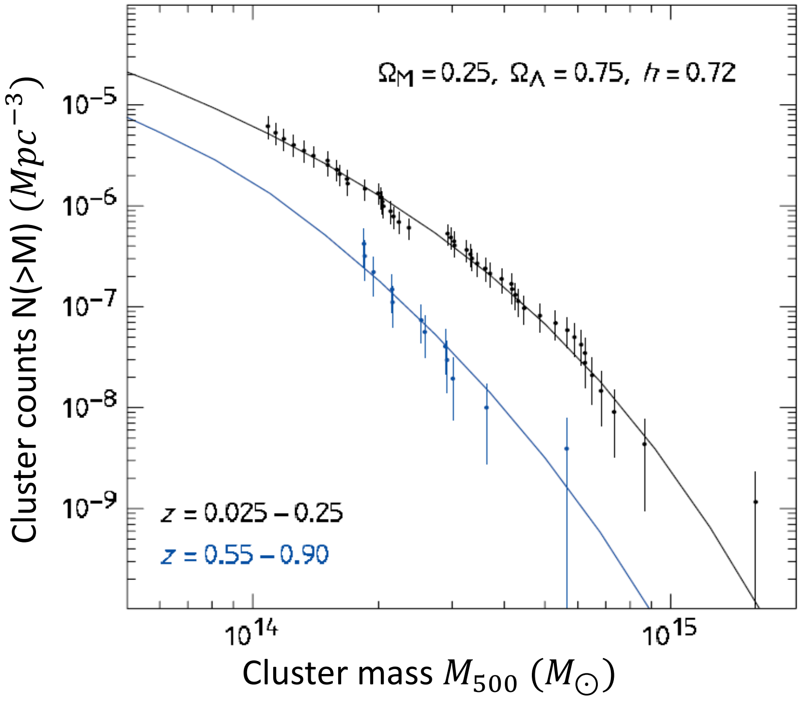
3 ingredients in a cluster analysis:

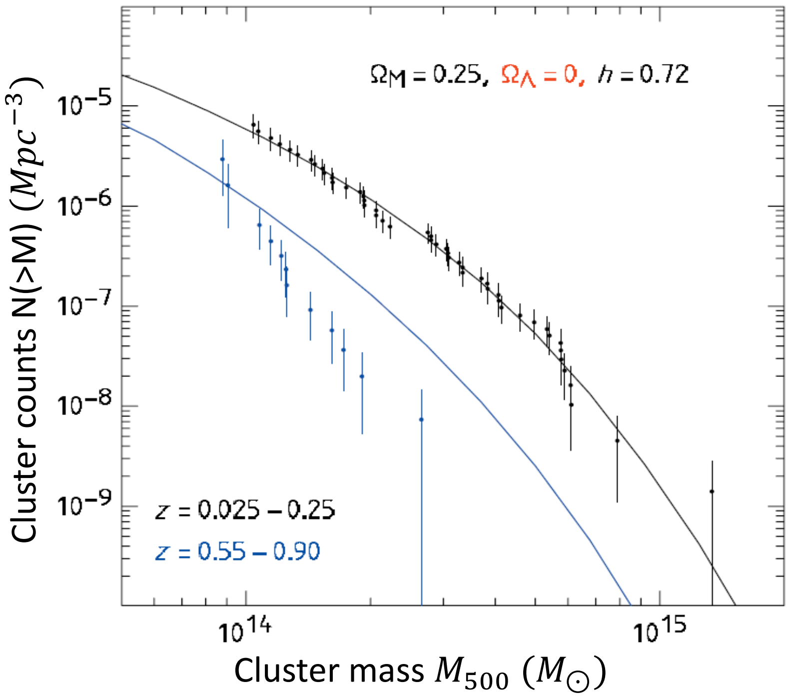
- Systematically detected sample (with known selection function)
- Link between halo mass and observables
- Cosmology-dependent mass function

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

3 ingredients in a cluster analysis:

Systematically detected sample (with known selection function)

Link between halo mass and observables

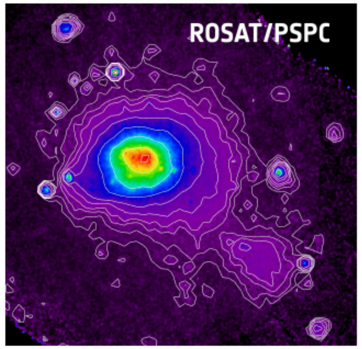
Cosmology-dependent mass function

Observing galaxy clusters

How can we observe them ?

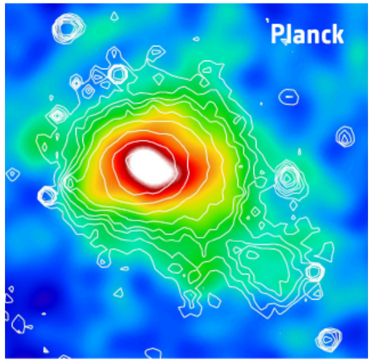
Different wavelengths probe different properties of clusters

Combining all wavelengths allows for more precise characterisation of cluster properties



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

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



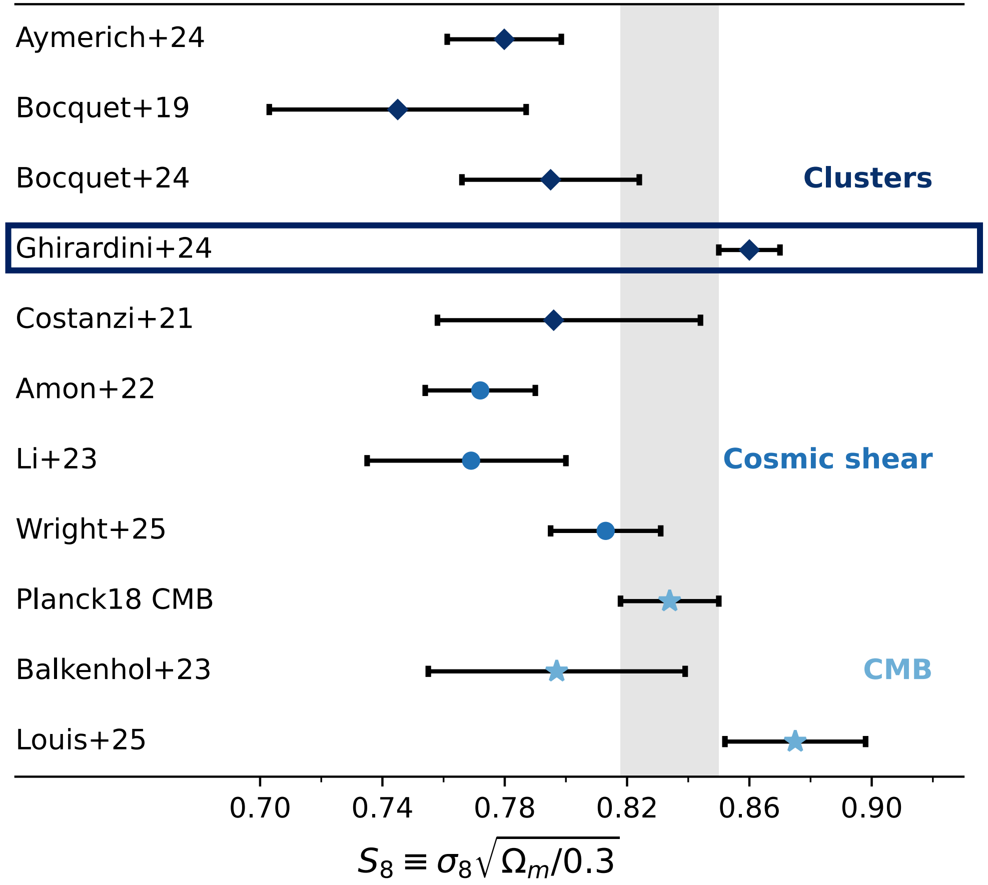
mm-wavelength:
Thermal Sunyaev-Zeldovich effect
(inverse Compton scattering)
Sensitive to **gas pressure**

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

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

Motivation for investigation

eRASS1 results are in tension with other late-time probes



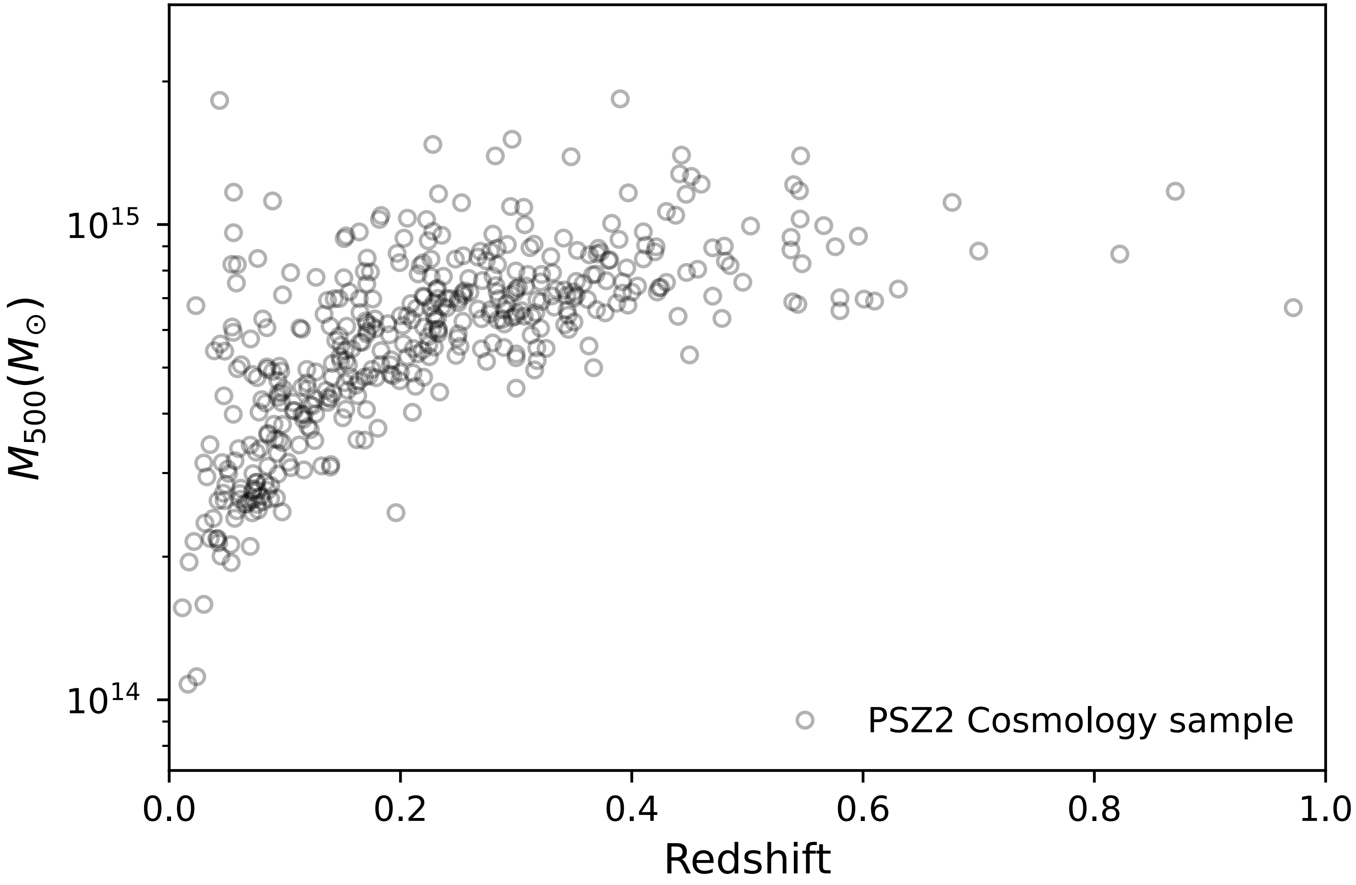
Preference for **higher S_8 values**

Different catalogue, selection function and mass calibration sample
Where does the tension come from?

Is the Planck catalogue relevant in the Stage IV era?

Cluster samples

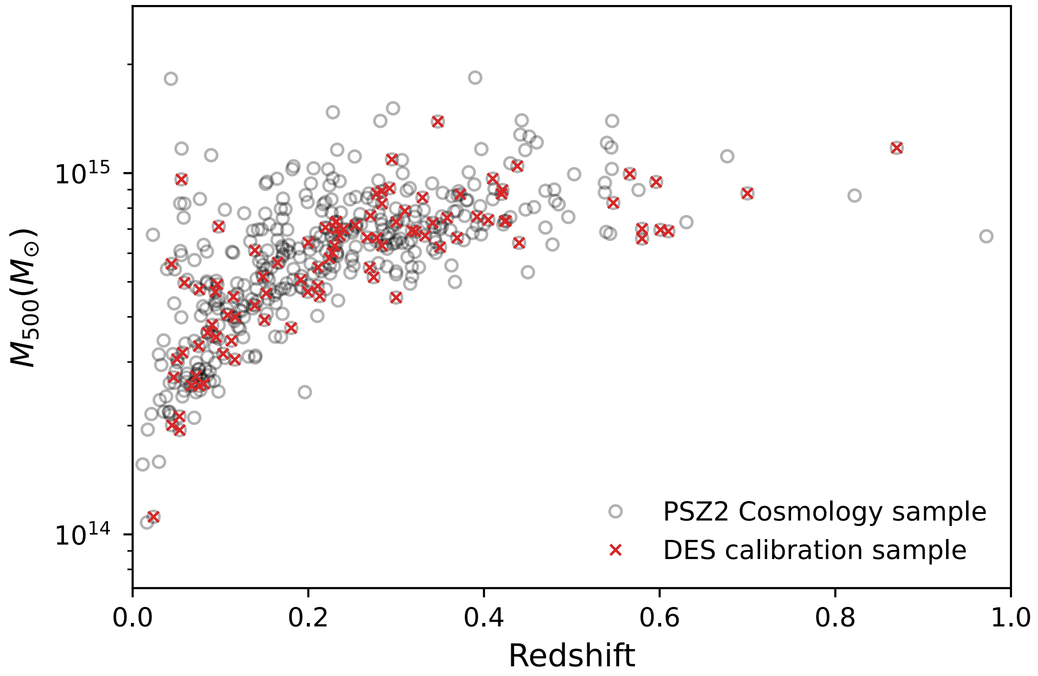
A multi-wavelength dataset



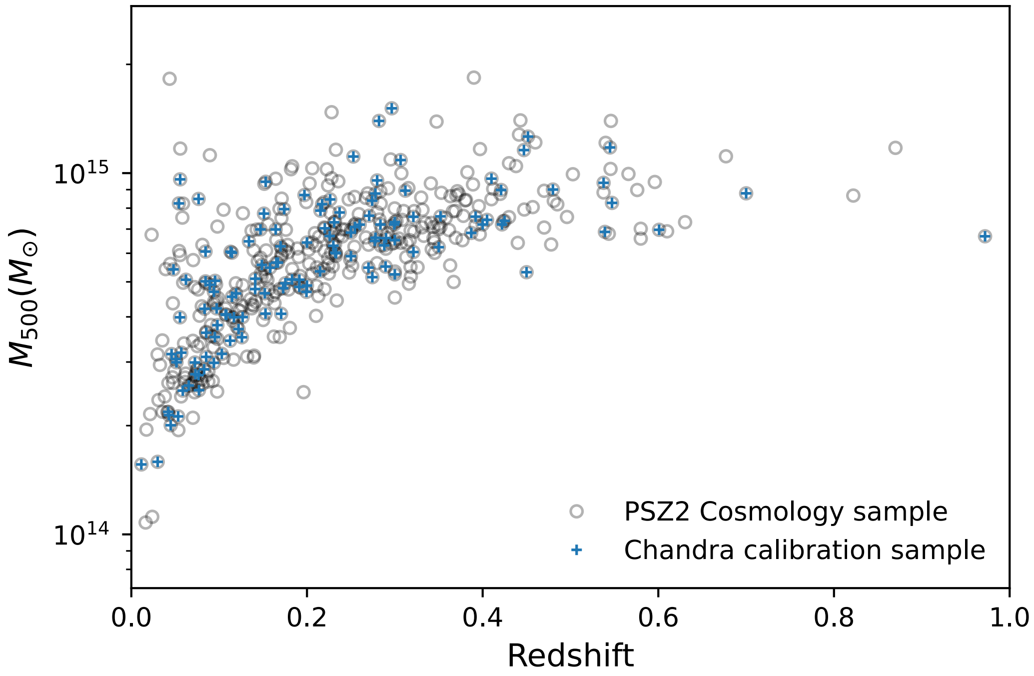
439 SZ-detected clusters in the cosmological sample

Cluster samples

A multi-wavelength dataset



93 clusters within DES footprint

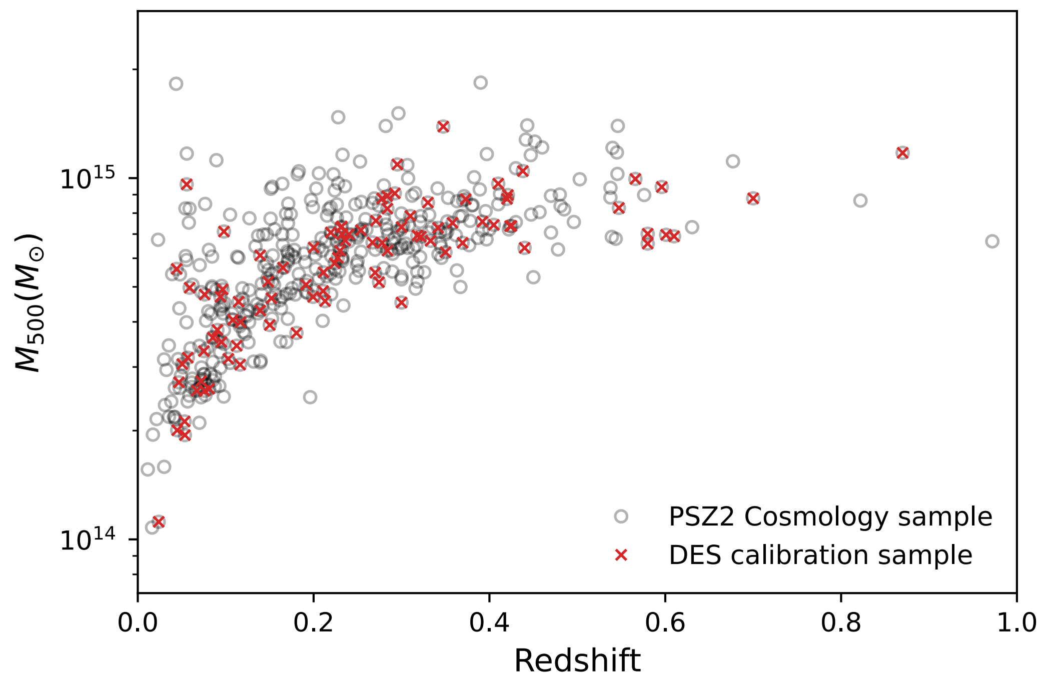


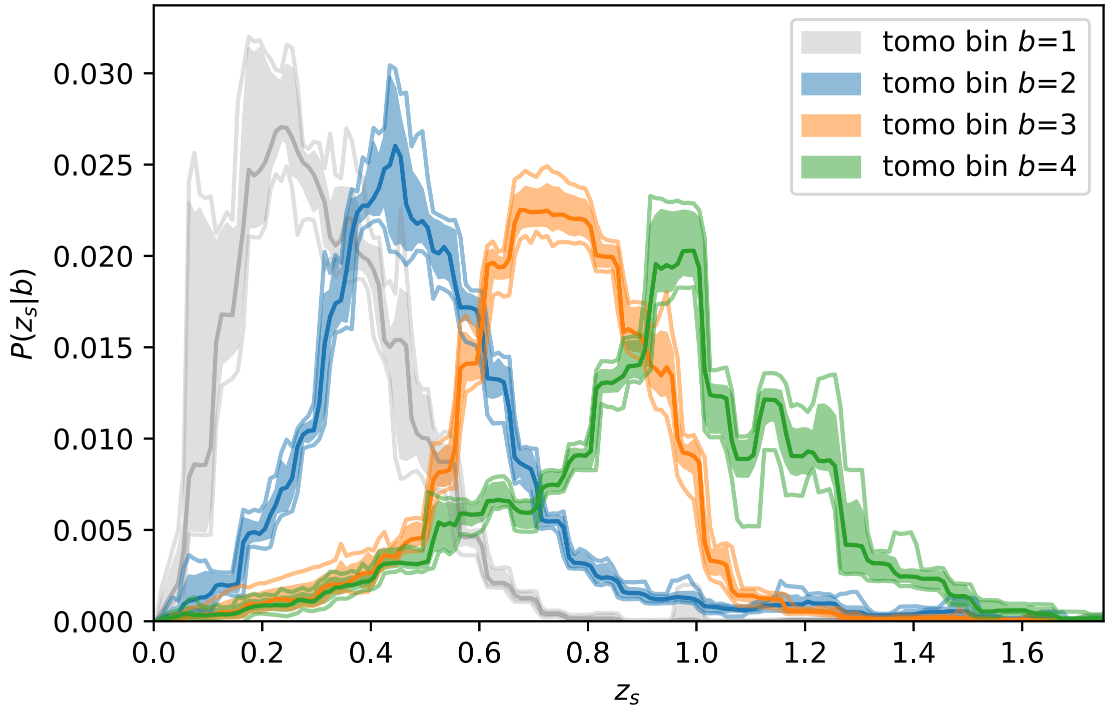
146 clusters observed with Chandra X-ray telescope
Re-observation of highest SNR Planck detections

29 clusters in common

Planck cluster catalogue

DES calibration sample



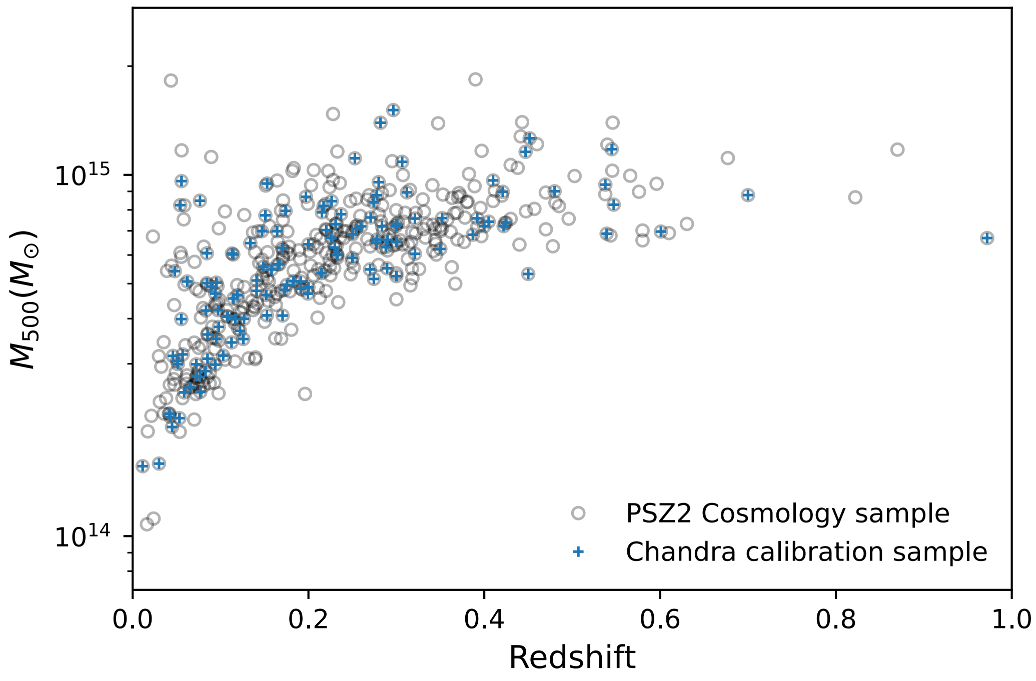


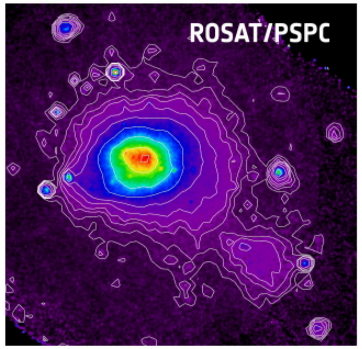
Relatively low redshifts, enough background sources for all clusters

Only selection is position in the sky, representative sub-sample

Computing hydrostatic masses

X-ray calibration data





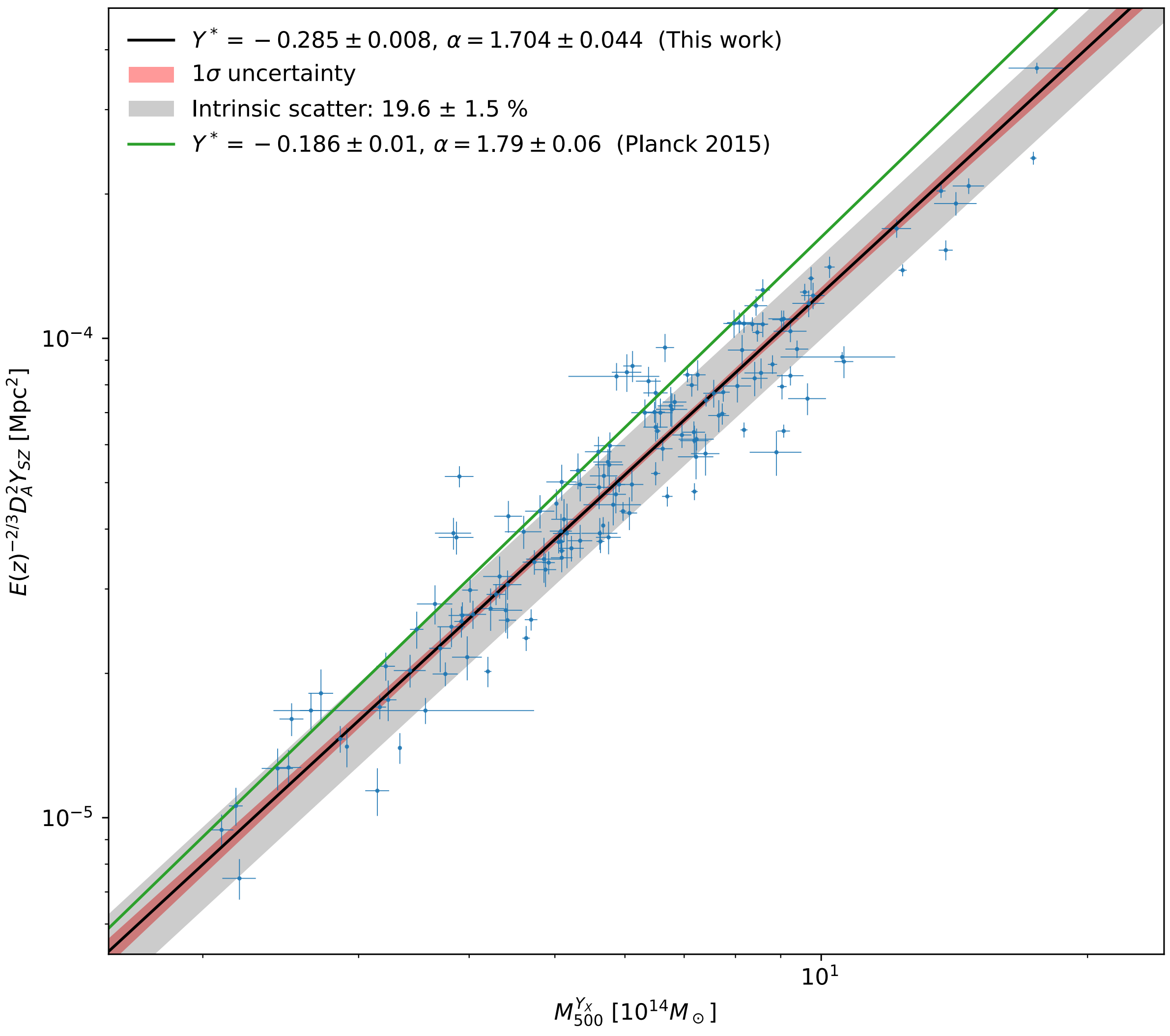
X-ray emission:
Sensitive to **gas density squared**
Can also do **spectroscopy** to
estimate **gas temperature**

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

X-ray observation can yield mass estimates under hydrostatic equilibrium assumption
(assuming that the gravitational potential compensates for the gas pressure)

Computing hydrostatic masses

Calibrating the Ysz to hydro mass 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

$$E^{-2/3}(z)\frac{D_A^2\,Y_{SZ}}{Y_{piv}} = 10^{-0.29\pm0.01}\left(\frac{M_H}{M_{piv}}\right)^{1.70\pm0.1}$$

Scatter: 21%

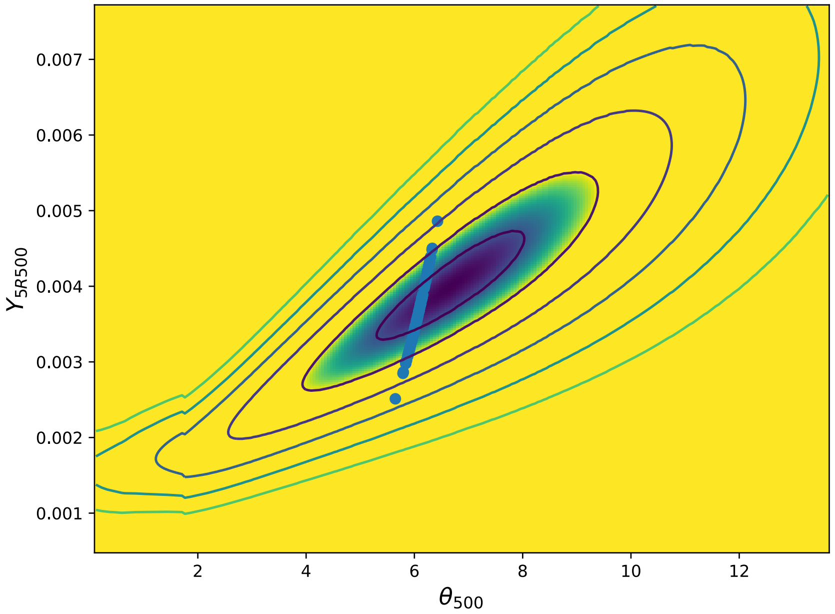
Robust to fitting method (emcee, LinMix, BCES)

Computing hydrostatic masses

Apply the Ysz to hydro mass relation to the full cosmological sample

Combine Ysz to hydro mass relation: $$E^{-2/3}(z)\frac{D_A^2\, Y_{\rm SZ}}{Y_{\rm piv}} = 10^{-0.29\pm0.01}\left(\frac{M_{\rm H}}{M_{\rm piv}}\right)^{1.70\pm0.1}$$

with the geometrical mass-size relation: $$\theta_{500} = \theta_*\left[\frac{h}{0.7}\right]^{-2/3}\left[\frac{M_{500}}{3.10^{14}M_\odot}\right]^{1/3} E^{-2/3}(z)\left[\frac{D_A(z)}{500\,{\rm Mpc}}\right]^{-1}$$



Run MCMC exploration of the Y_{500}- θ_{500} space to compute hydrostatic mass estimates

Weak lensing likelihood

Hydrostatic masses are biased, need to correct them with WL data

Tangential shear profile

Hydro mass from Ysz + Xray scaling relation

$$\mathcal{L}^i = P(\hat{g}_{\rm t}^i | M_{\rm H}^i, z^i) = \frac{P(\hat{g}_{\rm t}^i, M_{\rm H}^i | z^i)}{P(M_{\rm H}^i | z^i)}$$

Assuming scatter-less mass bias, i.e. $P(M_{\rm H}^i | M, z^i) = \delta(M_{\rm H}^i - (1-b)M)$

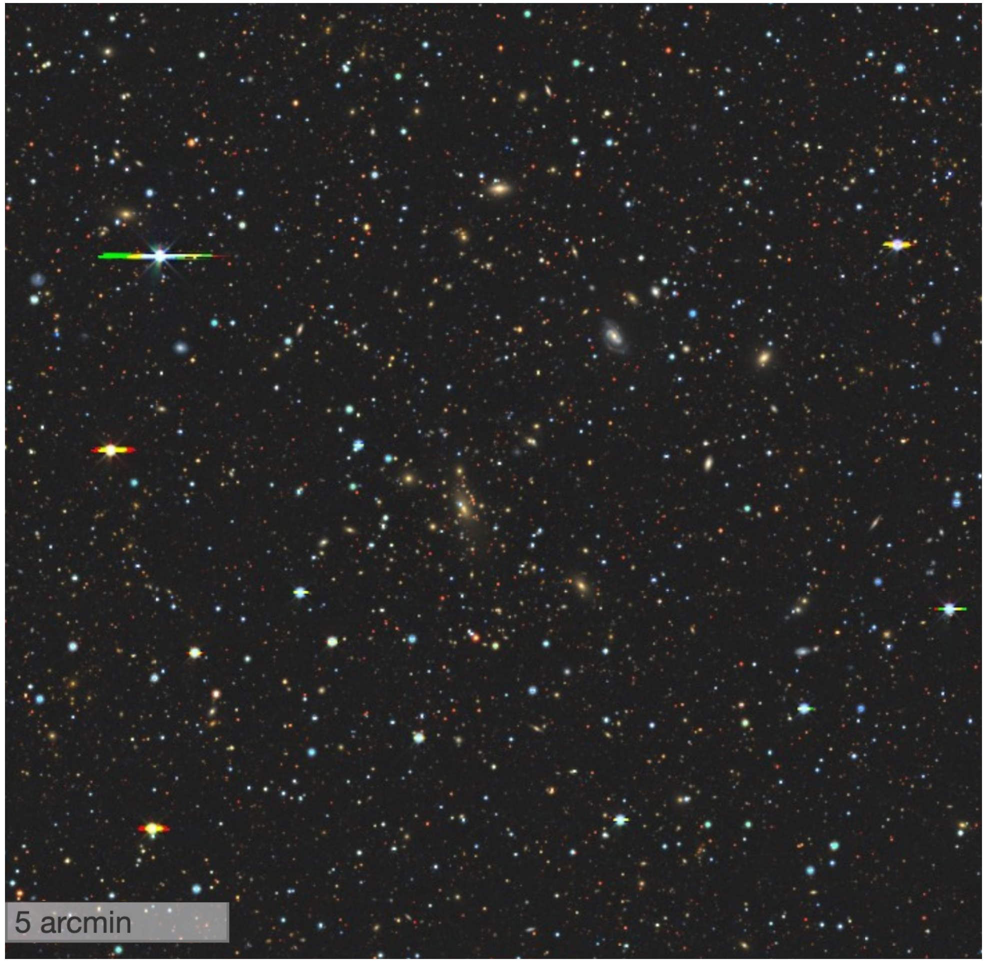
The likelihood can be written as:

$$\mathcal{L}^i = \int {\rm d}M_{\rm WL} P(\hat{g}_{\rm t}^i | M_{\rm WL}, z^i) P(M_{\rm WL} | M = \frac{M_{\rm H}^i}{1-b}, z^i)$$

Centering problem

Planck's limitation

Space telescope observing in mm-wavelength: large PSF (7 arcmin)



PSZ2 G000.40-41.86
z=0.165

Centering problem

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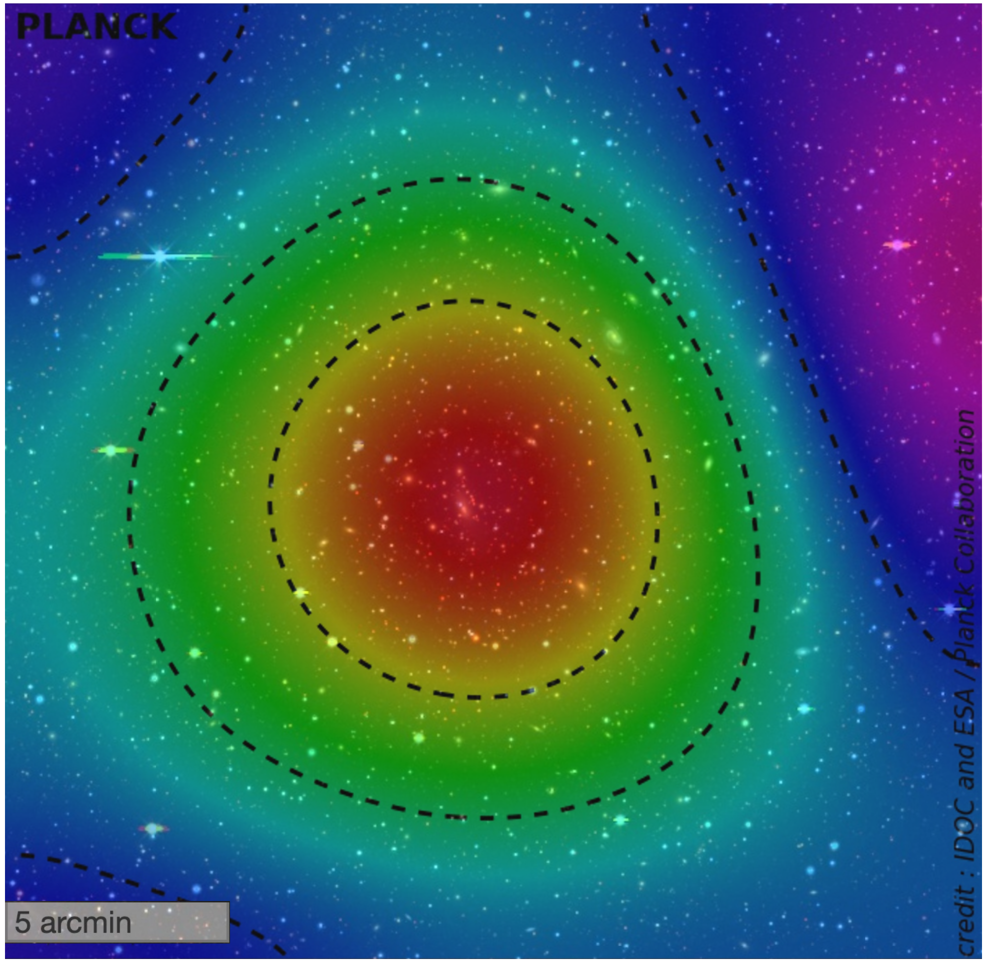
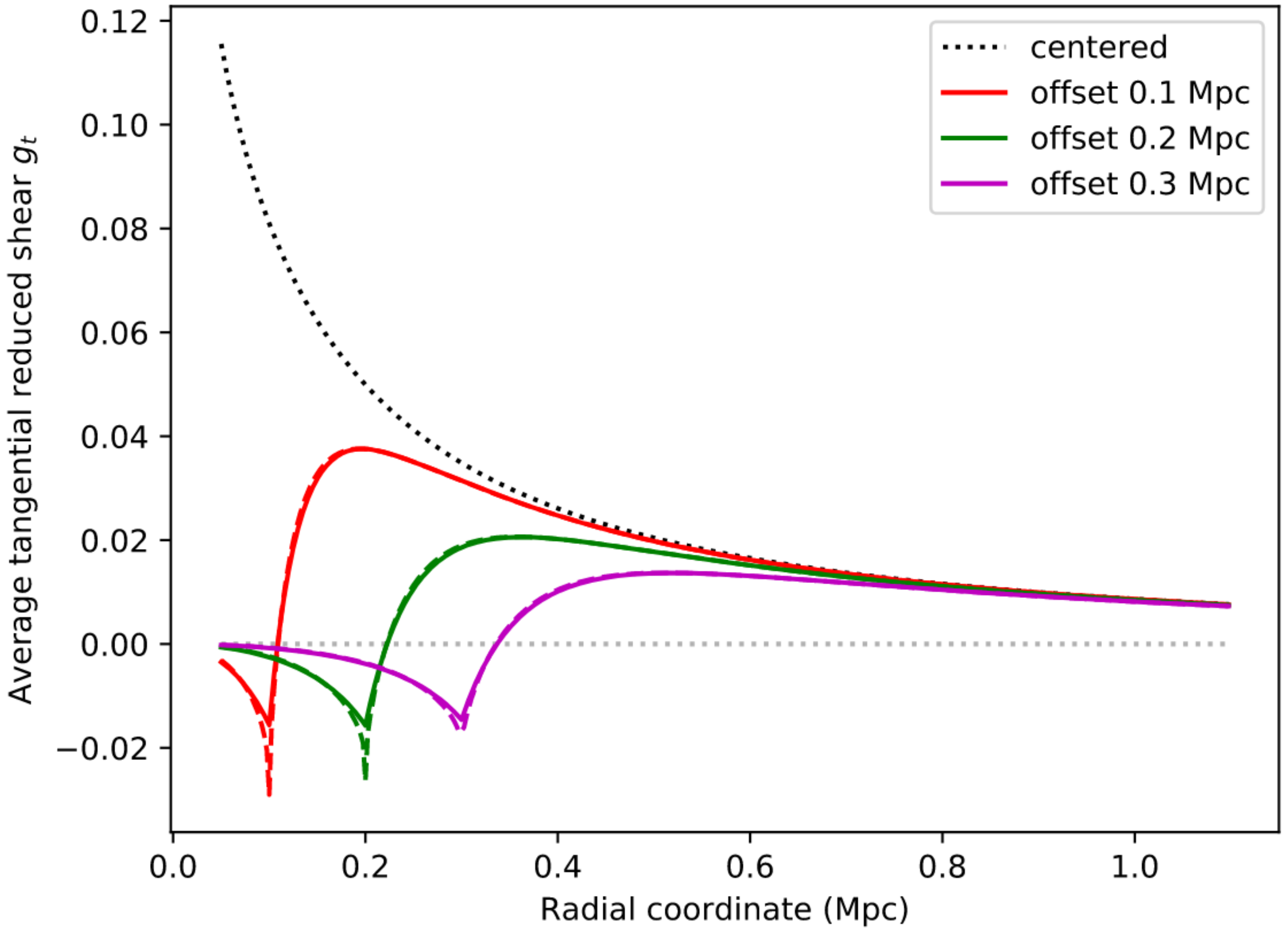


PSZ2 G000.40-41.86
z=0.165

Expected miscentering: SNR/PSF ~ 1 arcmin

Centering problem

A center is needed to derive shear profiles



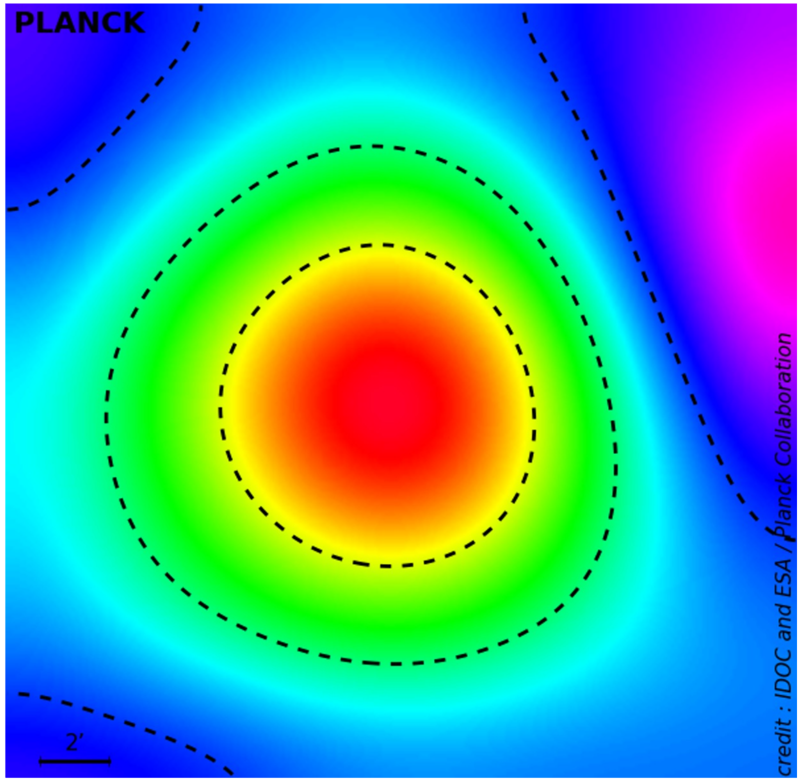
~ 1 arcmin at z=0.1
~ 1 arcmin at z=0.2
~ 1 arcmin at z=0.35

Sommer et al. 24

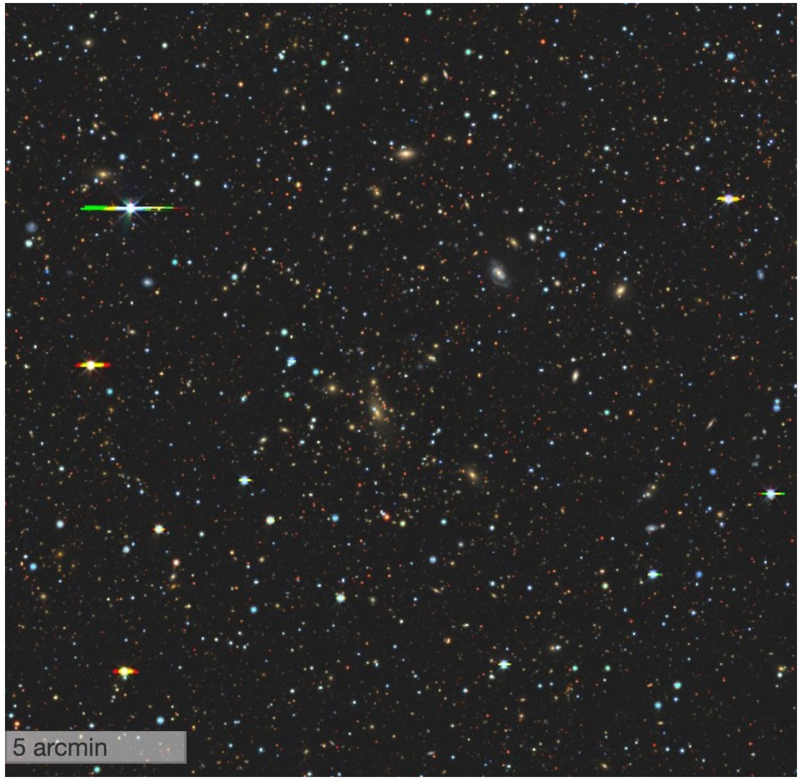
Miscentering has an effect on the shear profile at 2-3 times the offset

Centering problem

3 center definitions



SZ



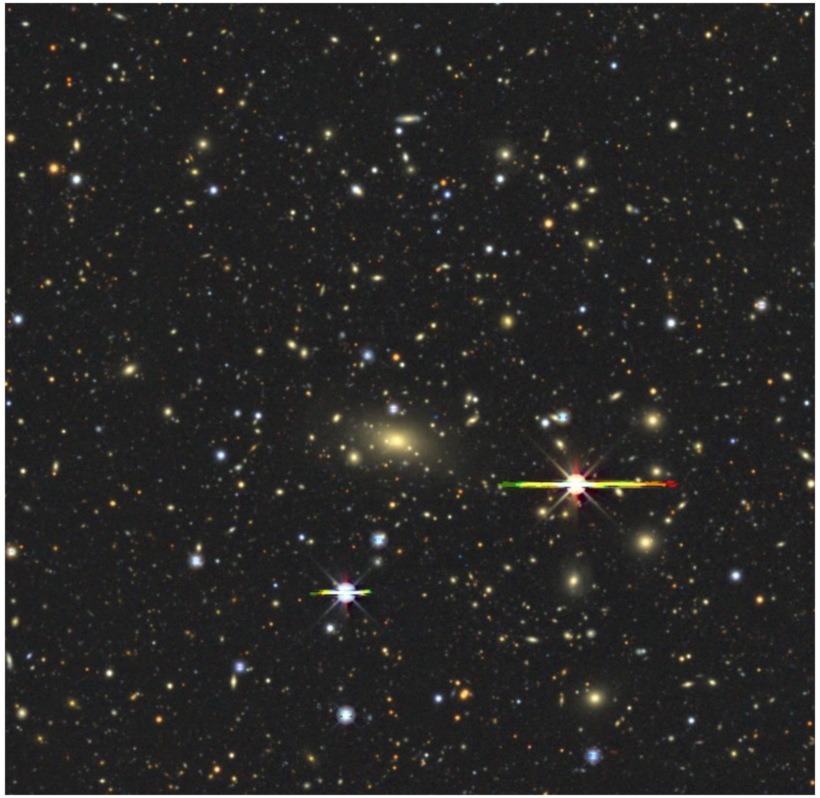
Optical

Automatic detection with MCMF algorithm

Handpicking BCG

Centering problem

Optical centers are challenging



Very clear BCG

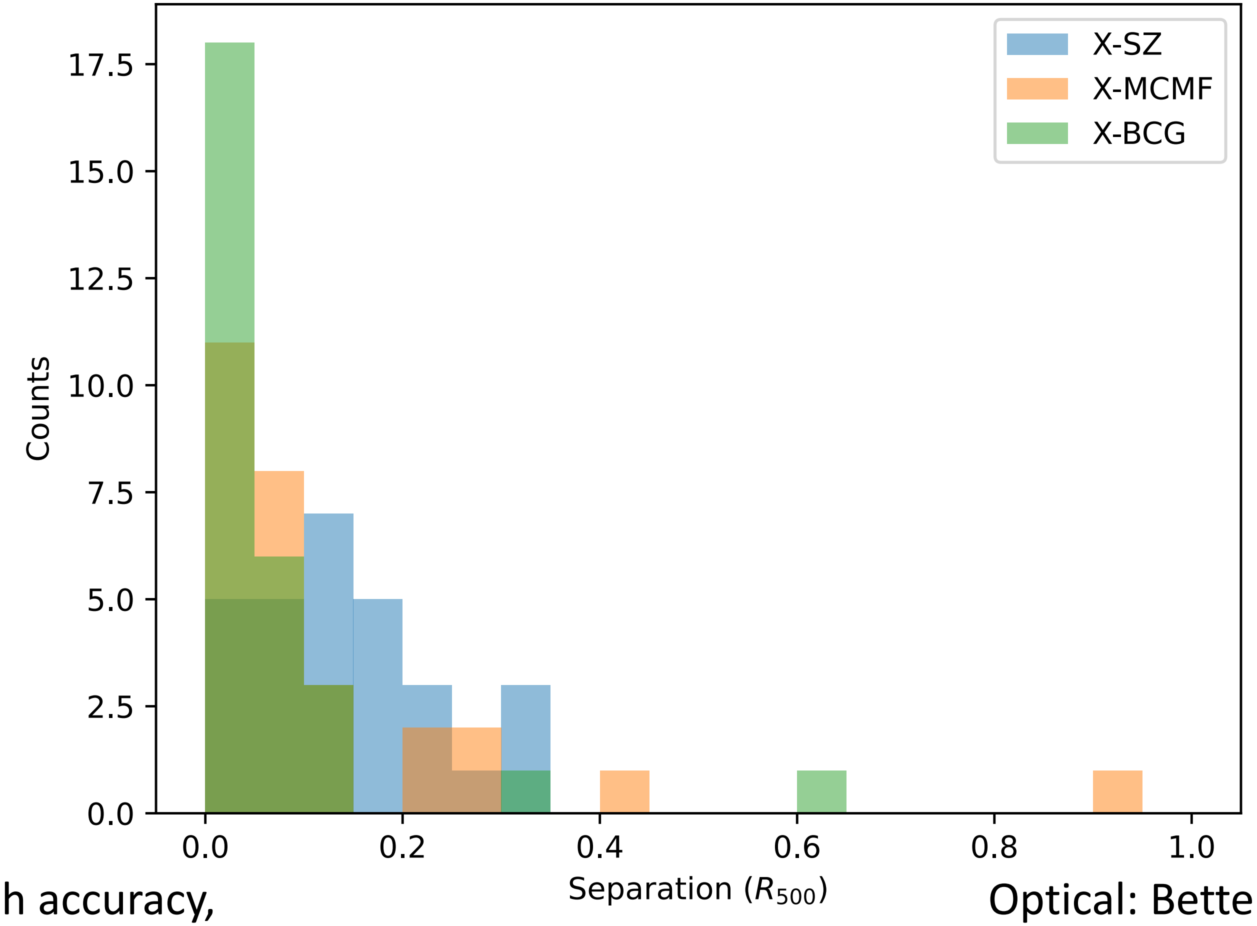
Complex system, no clear optical center

Optical detection, especially automated with MCMF, is very complex
SZ signal gives a very wide prior, leading to potentially very large errors

Centering problem

3 center definitions

Comparison with precise X-ray centers for cluster subset



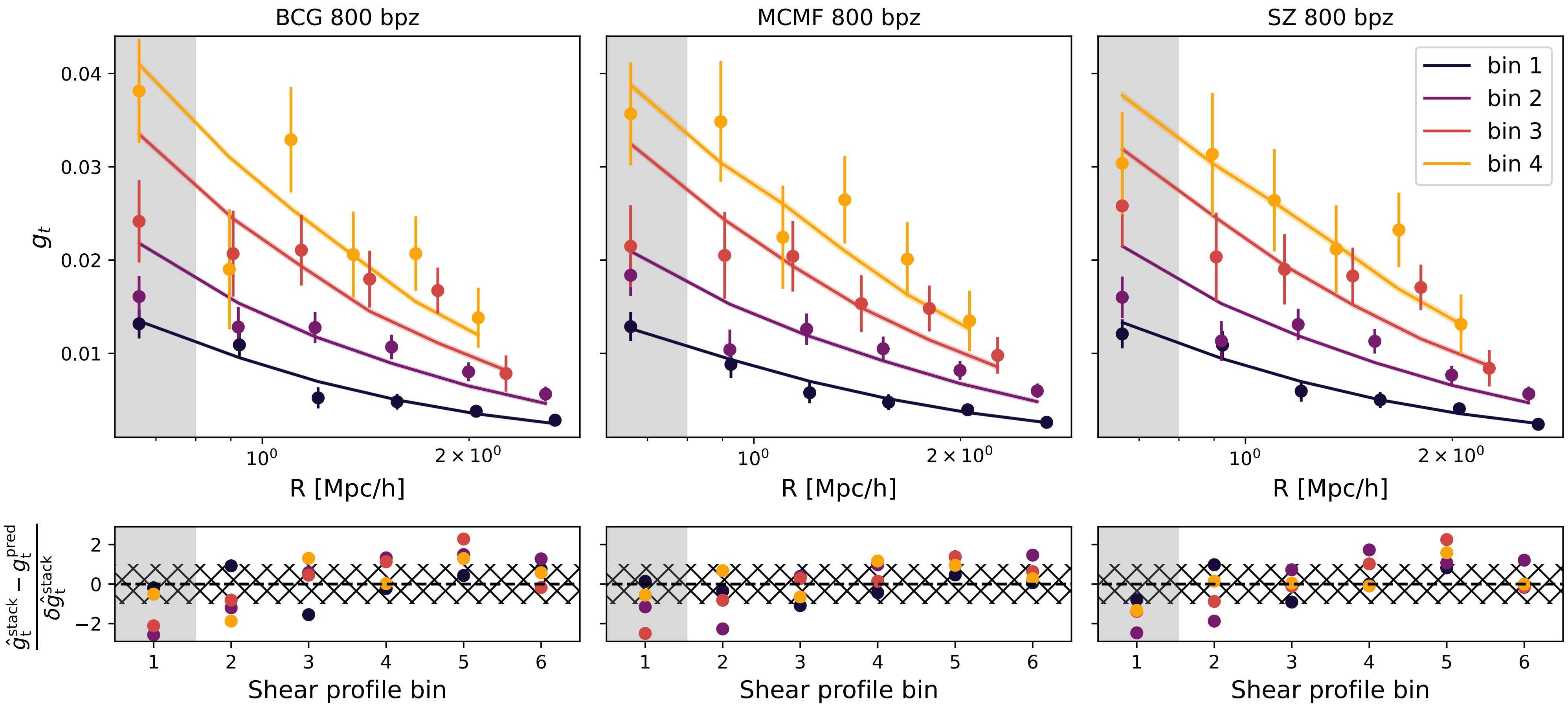
SZ: High accuracy, low precision

Optical: Better precision but extreme outliers (especially MCMF)

Fit centering distribution

Centering problem

Extraction of shear profiles for all centers



Include miscentering effect in theoretical shear profile
To limit the effect we exclude the inner bin of the profiles from the baseline analysis

$$\mathcal{L}^i = \int \mathrm{d}M_{\mathrm{WL}} \boxed{P(\hat{g}_{\mathrm{t}}^i | M_{\mathrm{WL}}, z^i)} P(M_{\mathrm{WL}} | M = \frac{M_{\mathrm{H}}^i}{1-b}, z^i)$$

Cosmological constraints

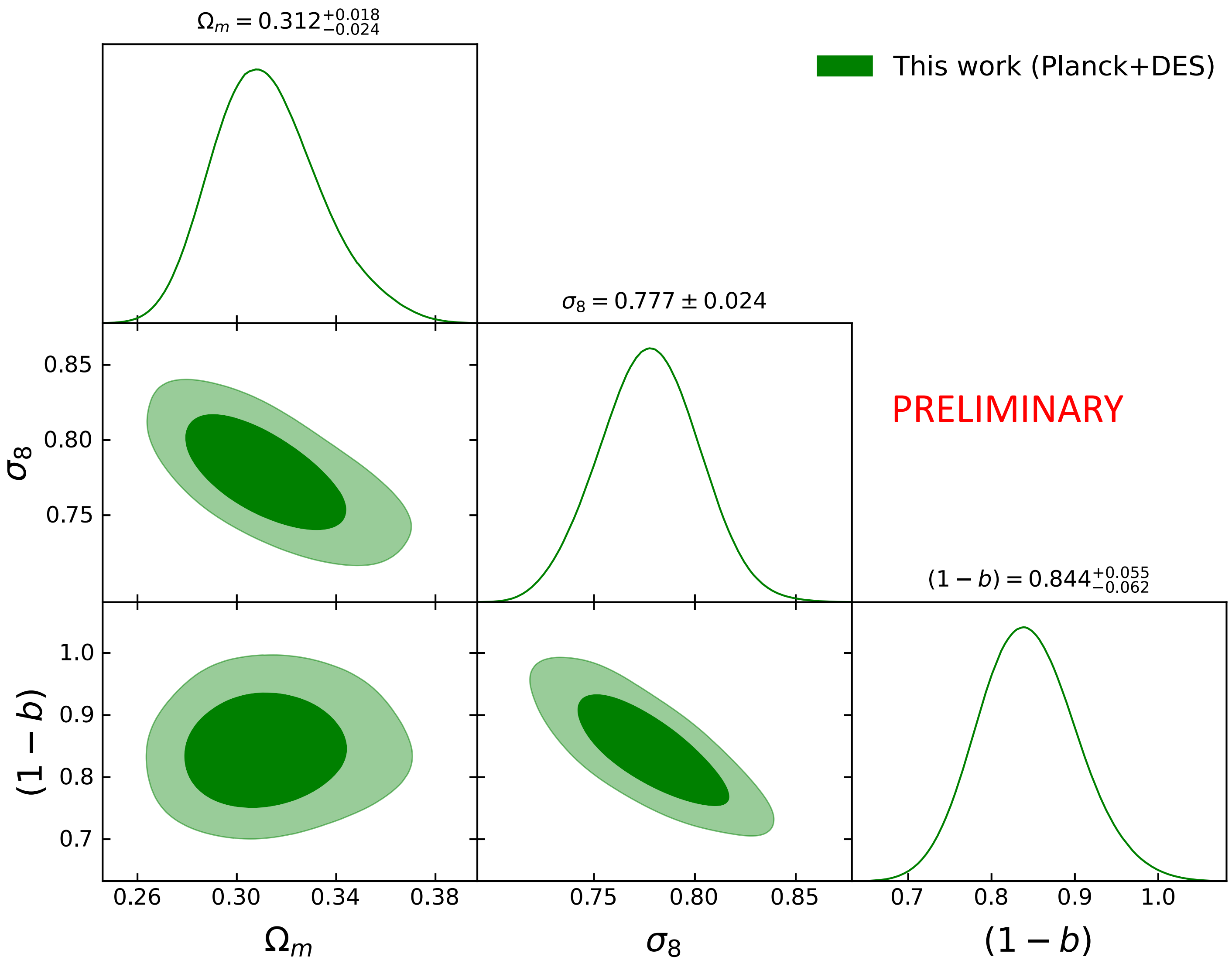
Center definition	Source z measurement	Innermost bin	Bias evolution
BCG	BPZ	800 kpc/h	$(1-b)$
MCMF	DNF	500 kpc/h	$(1-b)\left(\frac{M}{M_{piv}}\right)^{\alpha}$
SZ			$(1-b)\left(\frac{1+z}{1+z_{piv}}\right)^{\beta}$
			$(1-b)\left(\frac{M}{M_{piv}}\right)^{\alpha}\left(\frac{1+z}{1+z_{piv}}\right)^{\beta}$

Simultaneous sampling of the number count and mass calibration likelihoods

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

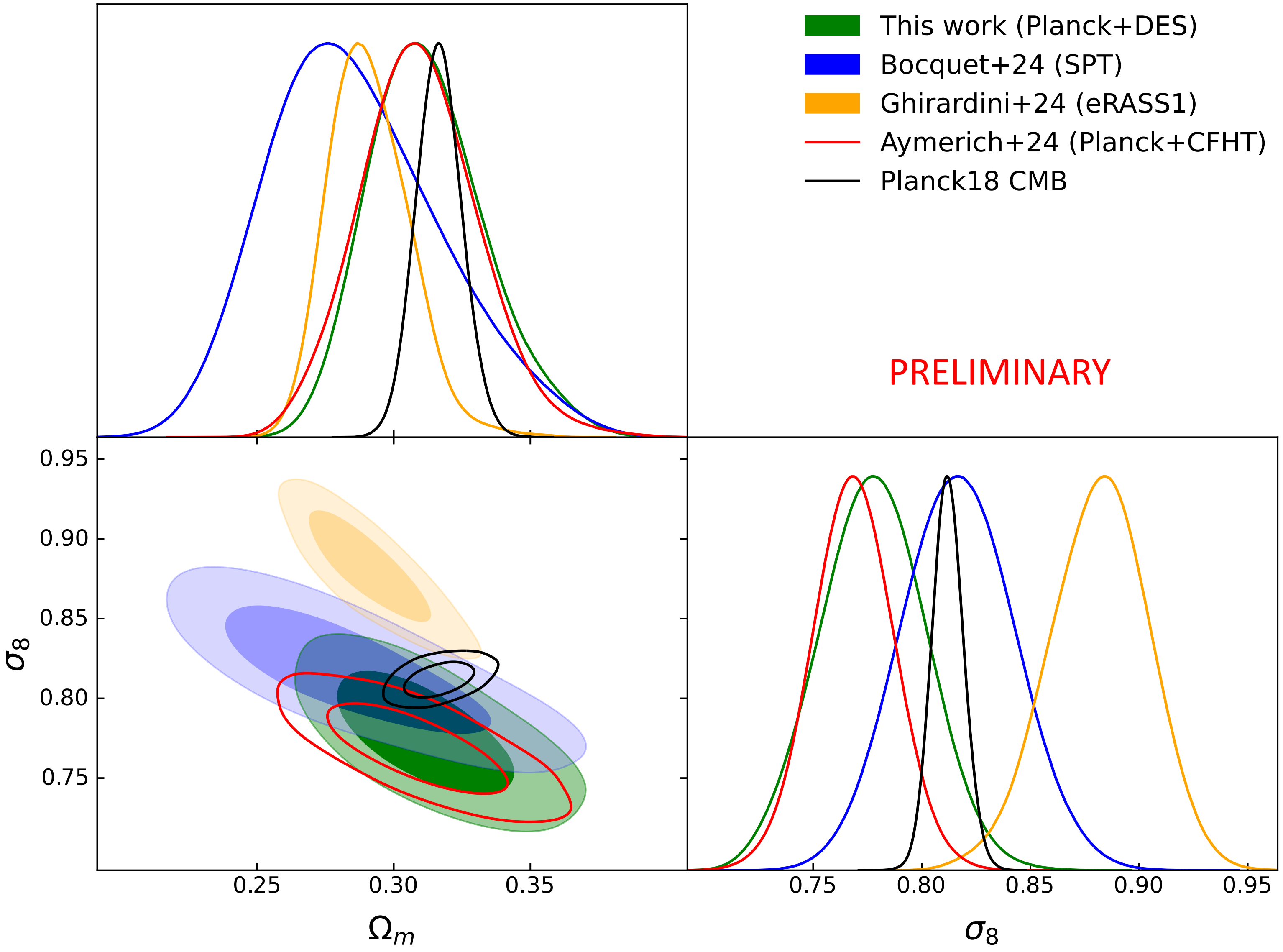
$$\mathcal{L}^i = \int \mathrm{d}M_{\mathrm{WL}} P(\hat{g}_{\mathrm{t}}^i|M_{\mathrm{WL}}, z^i) P(M_{\mathrm{WL}}|M = \frac{M_{\mathrm{H}}^i}{1-b}, z^i)$$

Cosmological constraints



Our results are in reasonable agreement with SPT and Planck, and in 2.9σ tension with eRASS1 results

Cosmological constraints



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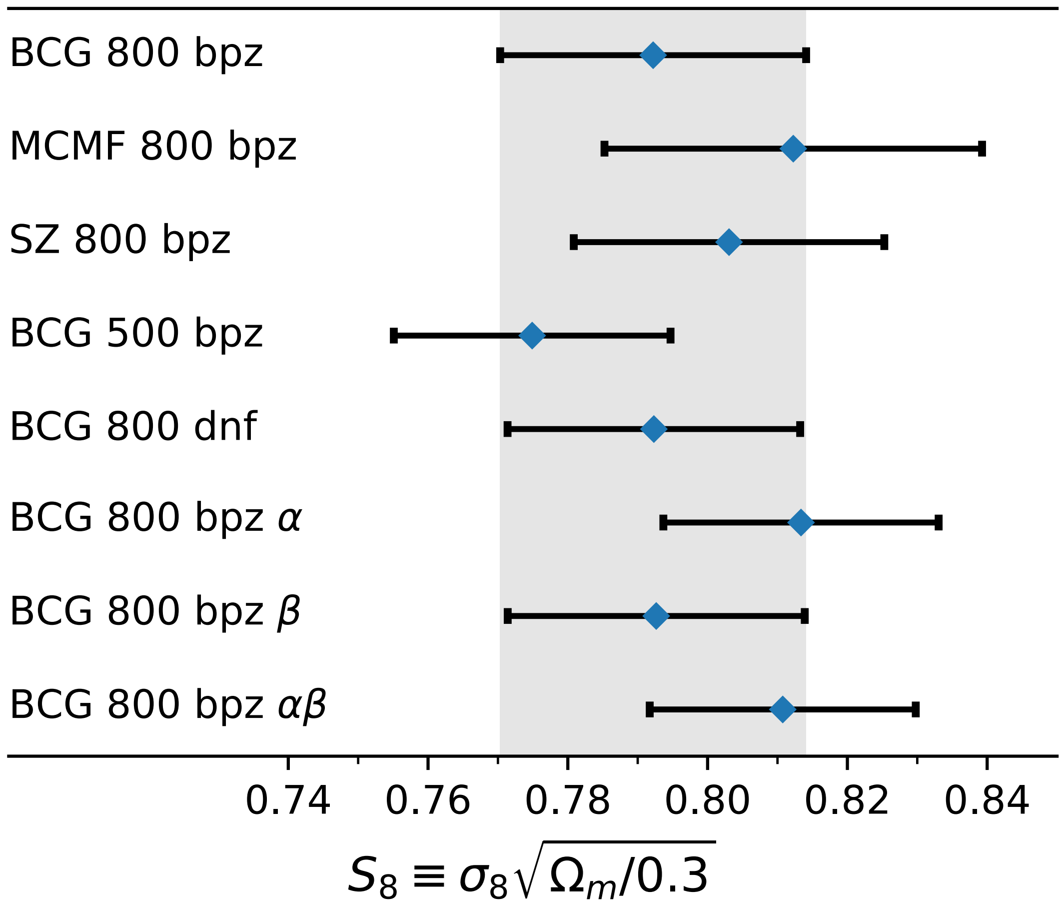
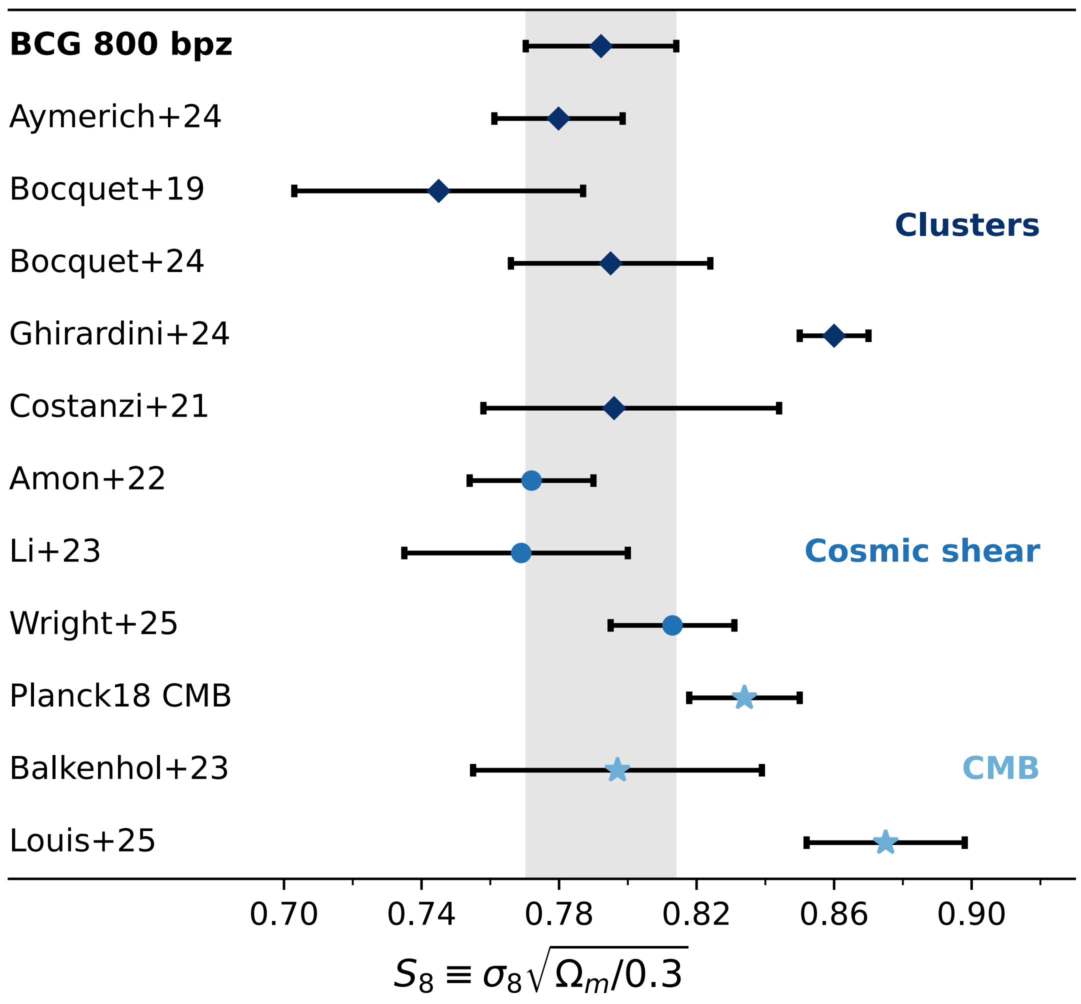
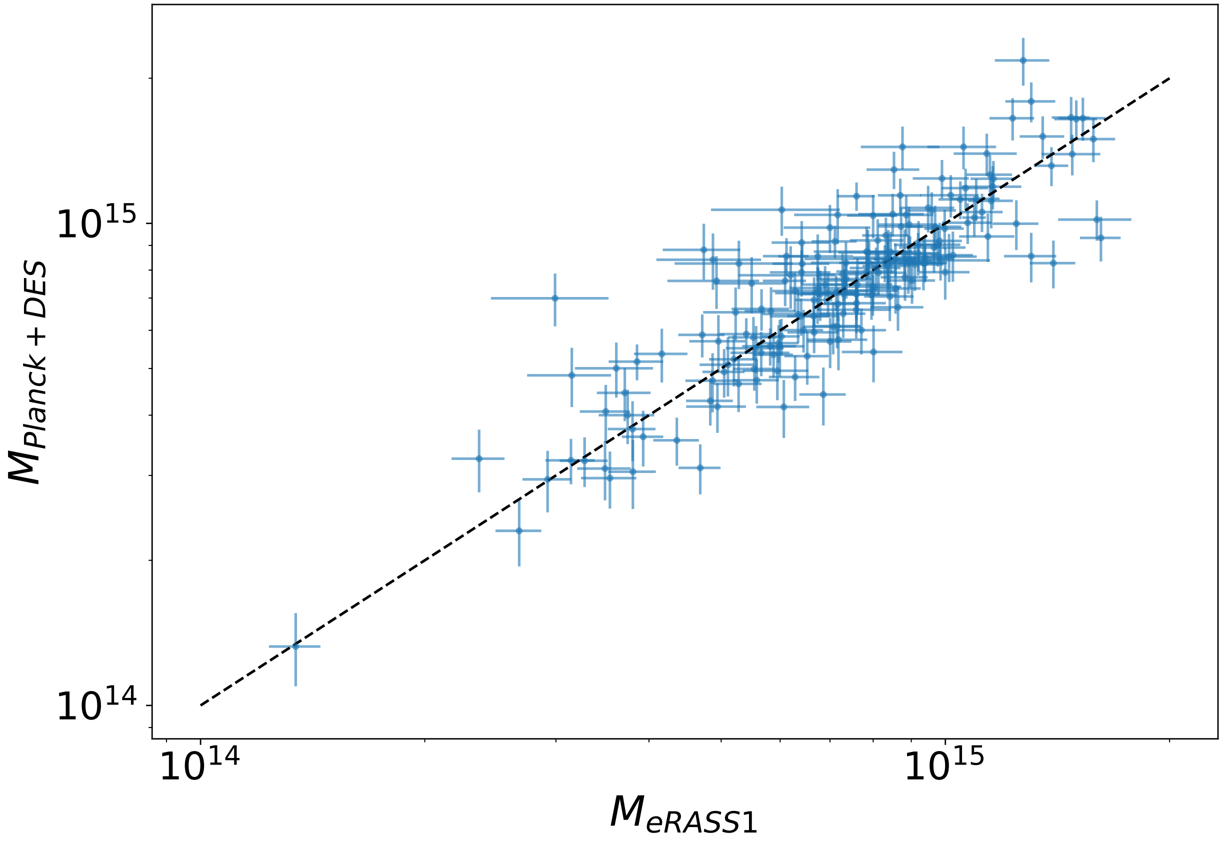




With the same mass calibration, tension between Planck SZ and eRASS constraints remains
Difference most likely lies in the mass-observable modelling and/or sample purity

Comparing mass calibrations

Most Planck clusters are also in the eRASS1 catalogue, with masses derived from their cosmological pipeline that also relies on DES shear profiles for mass calibration



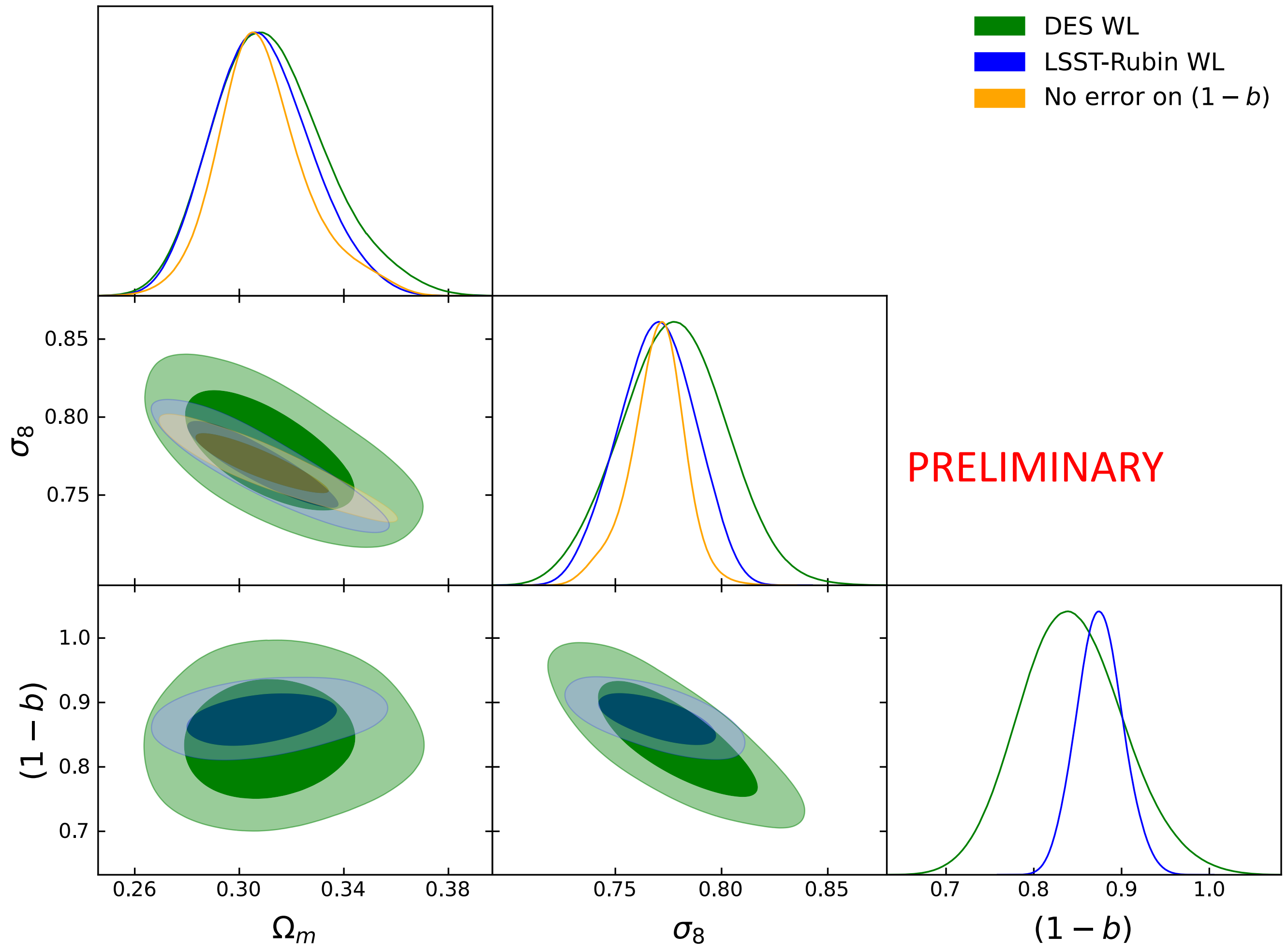
Comparing masses from eROSITA+DES and Planck+DES confirms that the mass calibration is consistent

Forecast constraints

Keeping everything else identical, we replace the lensing data with a mock Stage IV-like survey:

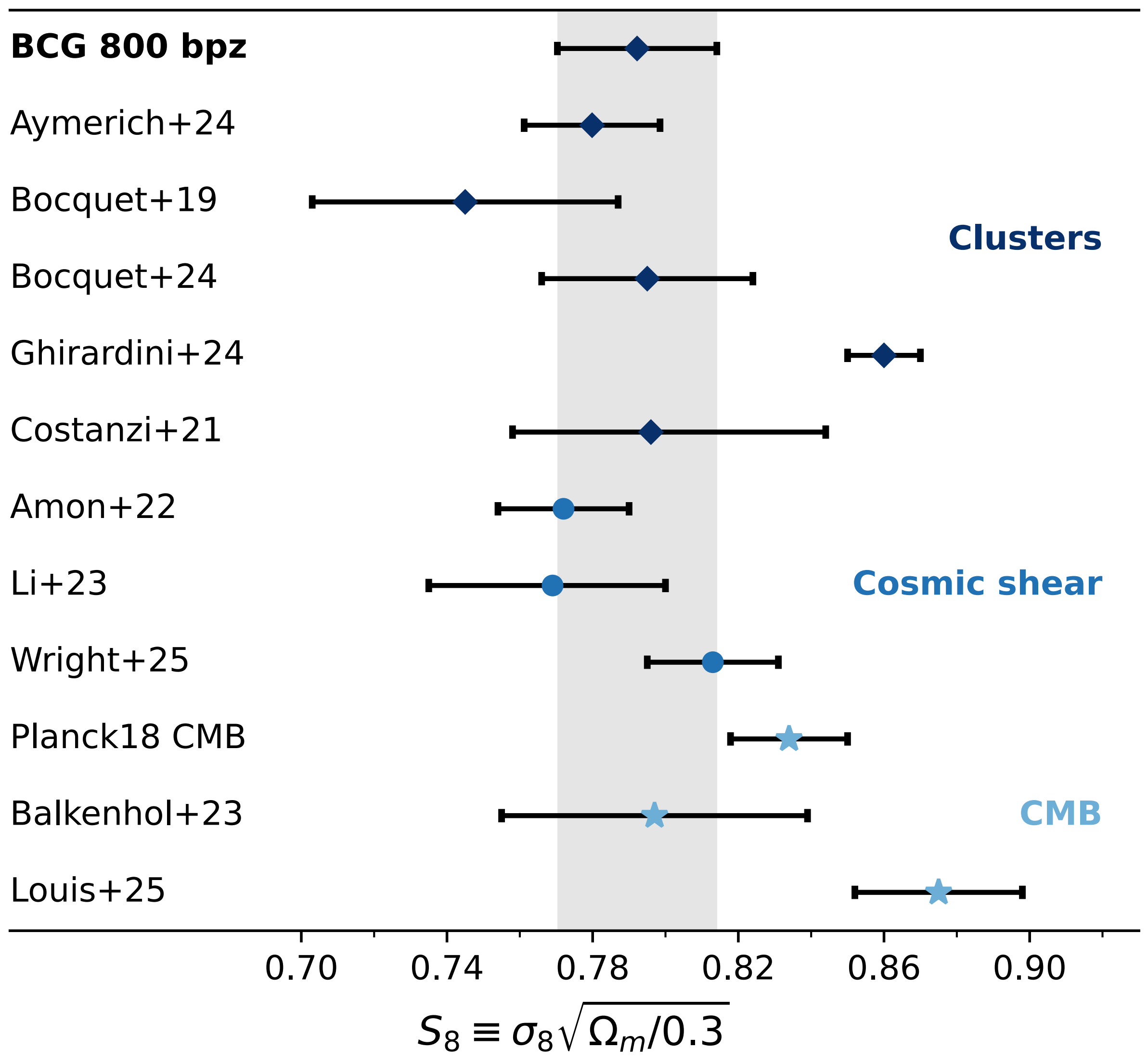
- Larger sky coverage (266 clusters in the calibration sample)
- LSST-like source density
- 1% error on the weak-lensing mass bias (**not hydro bias**)

We also study fixing the hydrostatic mass bias, to estimate the maximum statistical constraining power of the PSZ catalogue



Even if centering is an issue, Planck catalogue can still be relevant in the Stage IV lensing era

Take-home messages



- Centering issue of Planck **can be addressed**
- Constraining power can even be **relevant in Stage IV era**
- **Coherent constraints** with previous Planck and SPT results
- **Coherent mass calibration** with eRASS1
- **Final constraints in tension** with eRASS1 results
- Difference likely coming from the **sample and/or modelling**