Cosmology with galaxy clusters

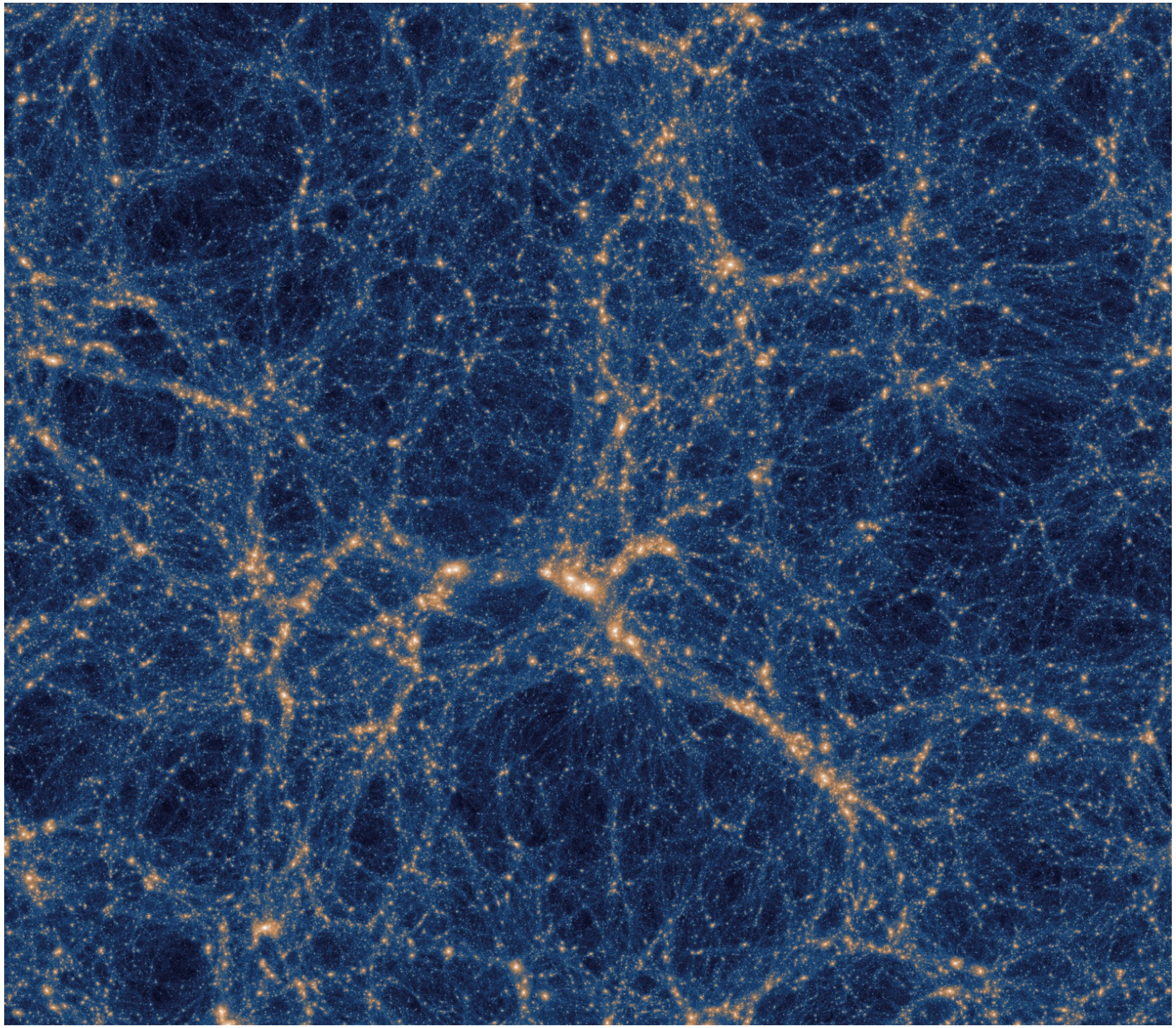
Jean-Baptiste Melin (CEA Paris-Saclay)

Astroparticle Symposium 2022, 9 November

Content

- Galaxy clusters as cosmological probes
- Current constraints and major uncertainties
- Multi-experiment analyses / Multiwavelength analyses
- Future cluster surveys

Clusters of galaxies & cosmology



TNG simulations

300 Mpc

A galaxy cluster ID card

- **Galaxies**
  - 10-1000 per cluster
  - **$M_{gal} \sim 0.02\ M_{cluster}$**
- **Gas**
  - Hydrogen, helium
  - $T_{gas} \sim 10^{7\text{-}8}$ K, 1-10 keV
  - **$M_{gas} \sim 0.1\ M_{cluster}$**
- **Dark matter**
  - $R_{cluster} \sim 1$ Mpc
  - **$M_{cluster} \sim 10^{14} – 10^{15}\ M_{\odot}$**

http://chandra.harvard.edu/photo/2008/a1689/

Abell 1689

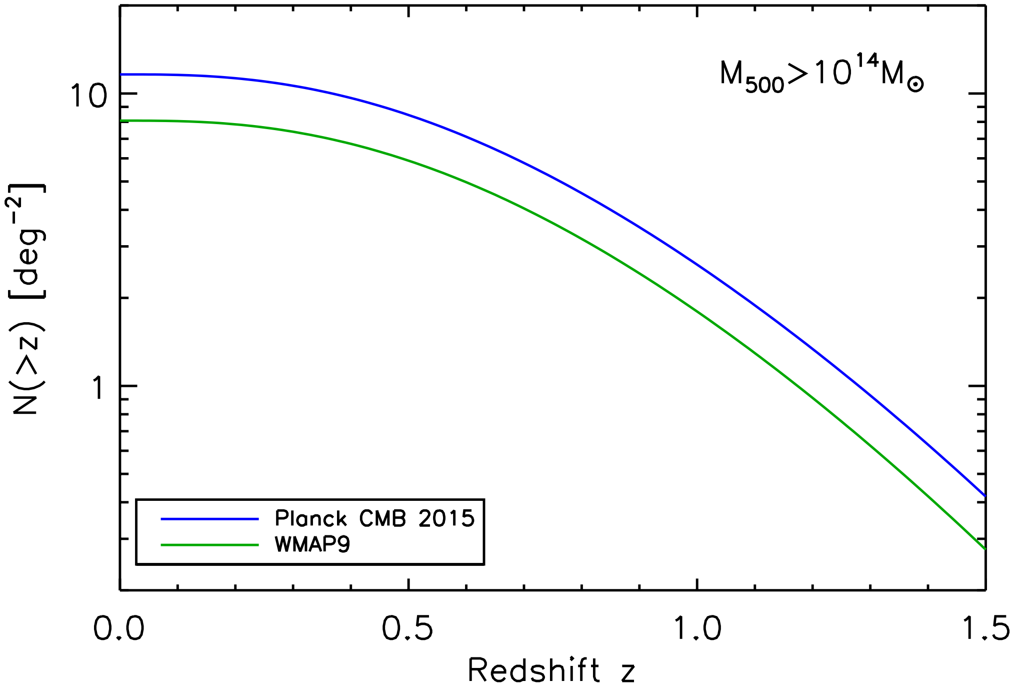
Clusters are highly non linear structures but

A galaxy cluster ID card

- **Galaxies** → optical
  - 10-1000 per cluster
  - **M_{gal} ~ 0.02 $M_{cluster}$**
- **Gas** → X-ray & millimetre (SZ)
  - Hydrogen, helium
  - T_{gas} ~ $10^{7\text{-}8}$ K, 1-10 keV
  - **M_{gas} ~ 0.1 $M_{cluster}$**
- **Dark matter** → lensing
  - $R_{cluster}$ ~ 1 Mpc
  - **$M_{cluster}$ ~ 10^{14} – 10^{15} $M_{\odot}$**

Clusters are highly non linear structures but
- they can be detected and characterized at many wavelengths

Cluster counts and cosmology



e.g. Press&Schechter 1974
Tinker et al. 2008
Despali et al. 2016

Cluster abundance and evolution are very sensitive to cosmological parameters

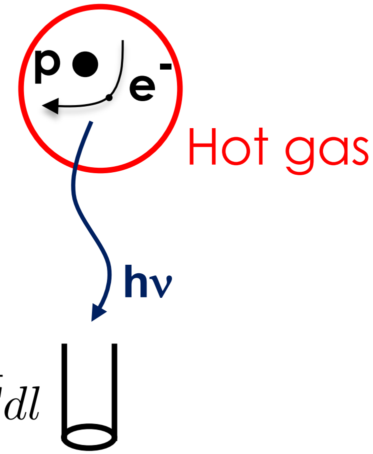
$$\sigma_8 \quad \Omega_m \quad \sum m_\nu$$

→ independent from primary CMB, BAO, SNIa

Clusters are highly non linear structures but
- they can be detected and characterized at many wavelengths
- cluster distribution can be predicted for a given set of cosmological parameters.

Detecting the intra cluster gas

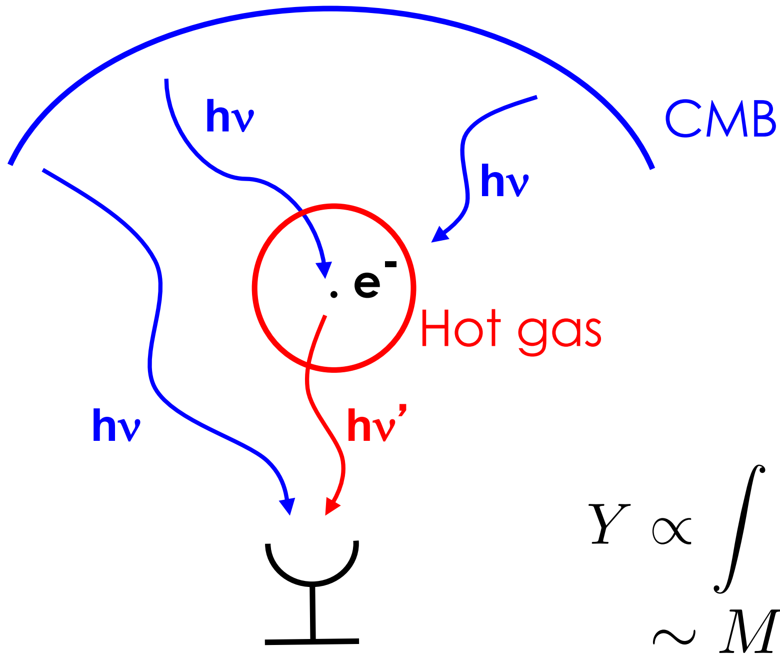
X-ray
Bremsstrahlung



$$S_X \propto \frac{1}{(1+z)^4} \int n_e^2 \sqrt{T} dl$$

ROSAT, eROSITA

Millimetre wavelengths
Sunyaev-Zeldovich (SZ) effect



$$Y \propto \int P_e dl d\Omega$$
$$\sim M_g T$$

Planck, SPT, ACT

Clusters and cosmology

Since the beginning of cosmology, galaxy clusters played an important role in shaping and strengthening the model (ΛCDM)

- **Mass-to-light ratio** e.g. Carlberg et al. 1996
- **Baryon fraction** e.g. White et al. 1993
- **Correlation function** Croft et al. 1997, Hong et al. 2012, …
- **Cluster profiles** See talks by T. Richardson and P.-S. Corasaniti
- **Power spectrum** e.g. Planck Coll 2015 XXII, …
- **Cluster counts** ←

The master equation for cluster counts

Observation ⟷ **Theory**

$$\frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}\mathcal{O}_{\rm obs}} = \int \mathrm{d}M \int \mathrm{d}\mathcal{O}_{\rm true}\, P[\mathcal{O}_{\rm obs}|\mathcal{O}_{\rm true}]\, P[\mathcal{O}_{\rm true}|z, M, \Theta]\, \frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}M}(\Theta)$$

Mass

Cosmological parameters

Redshift

Observable

"Observable" could be
Y (SZ), λ (optical), CR (X-ray)

③ observational errors + selection function

Instrument

② scaling relation

Cluster physics

① mass function

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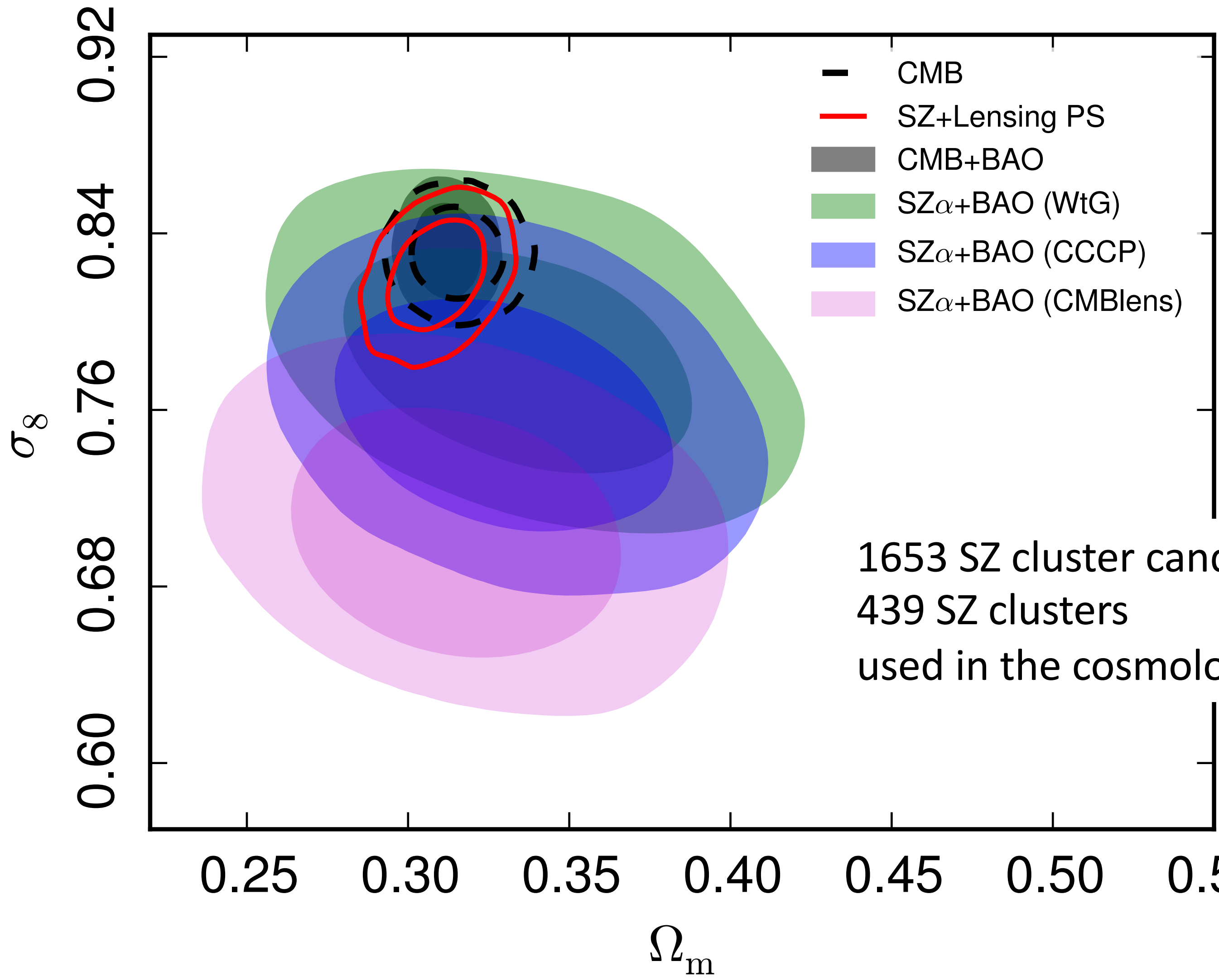
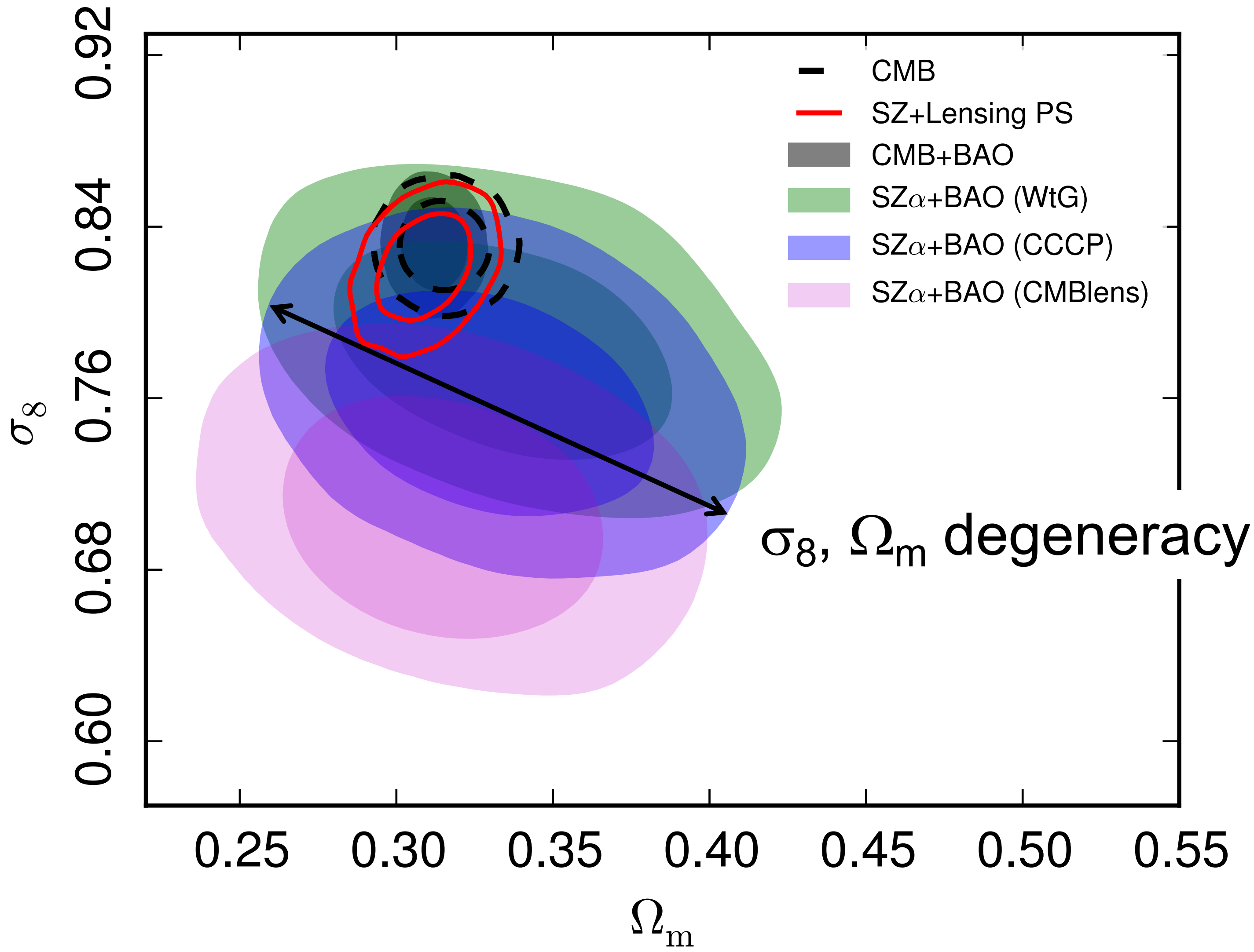
Planck cluster cosmology (2015)



1653 SZ cluster candidates
439 SZ clusters
used in the cosmological analysis

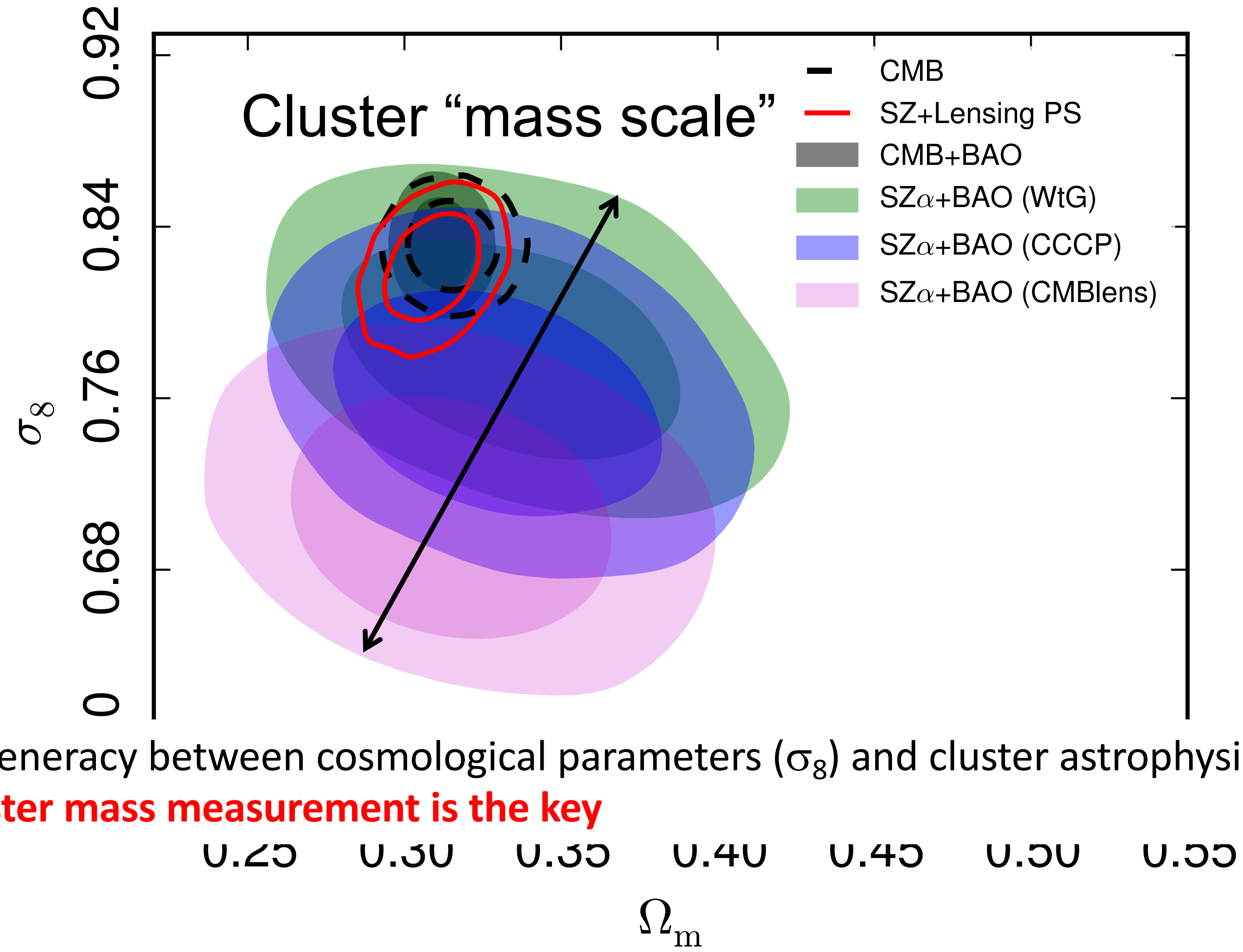
Planck Results XXIV 2015

Planck cluster cosmology (2015)



Planck Results XXIV 2015

Planck cluster cosmology (2015)

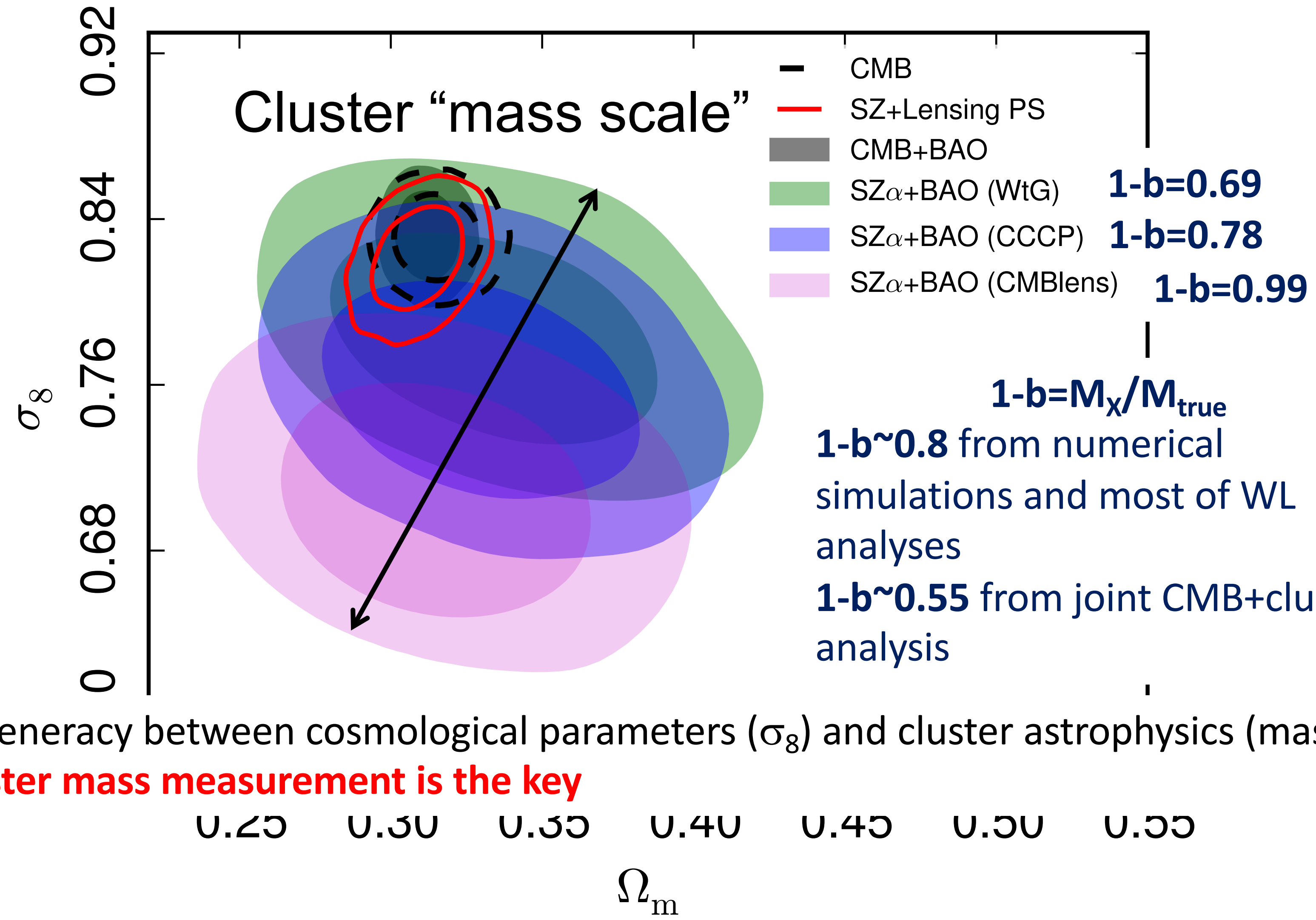


Degeneracy between cosmological parameters (σ_8) and cluster astrophysics (mass)

Cluster mass measurement is the key

Planck Results XXIV 2015

Planck cluster cosmology (2015)



$1\text{-}b = M_X/M_{true}$

1-b~0.8 from numerical simulations and most of WL analyses

1-b~0.55 from joint CMB+cluster analysis

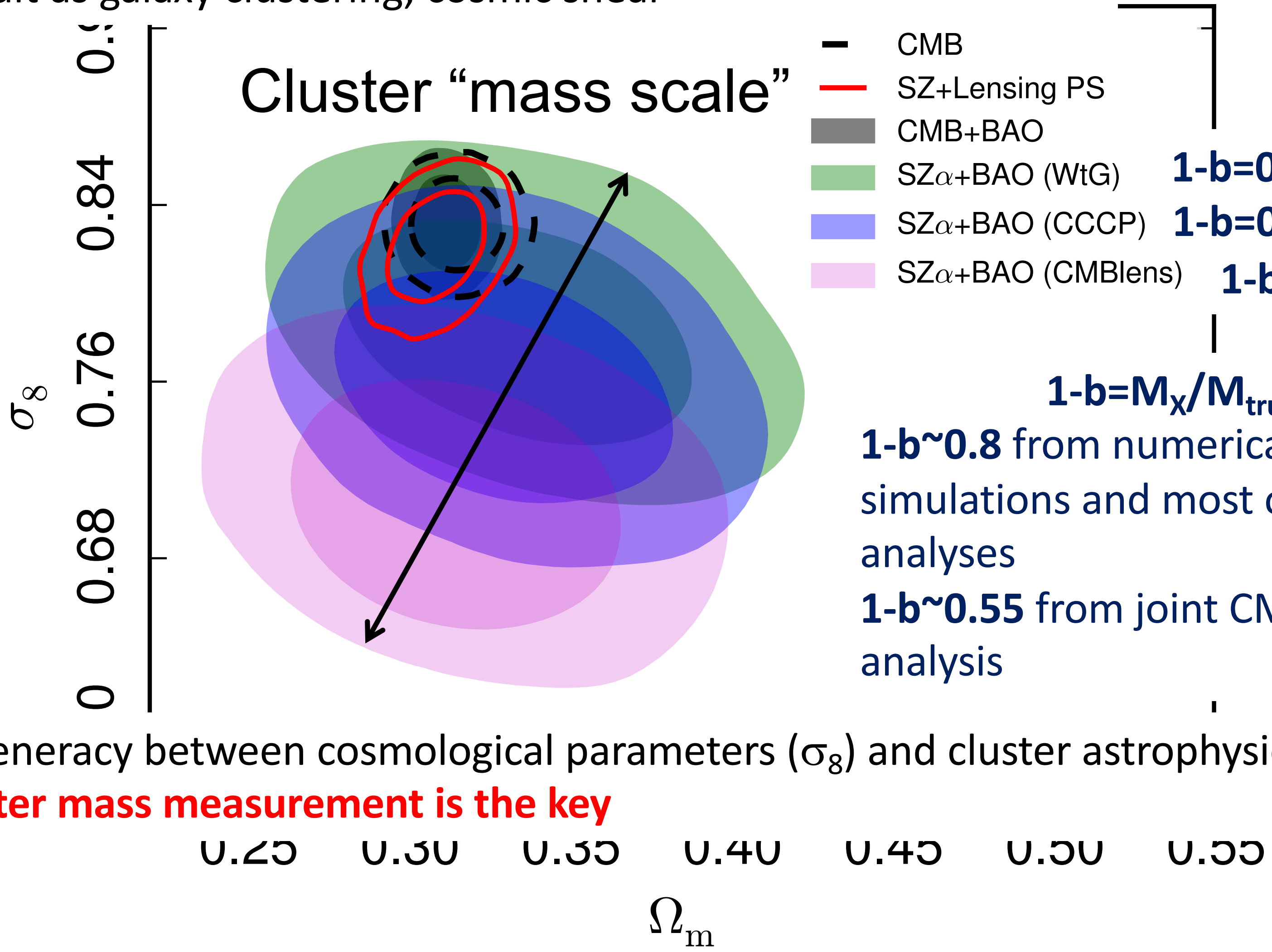
Degeneracy between cosmological parameters (σ_8) and cluster astrophysics (mass)

Cluster mass measurement is the key

Planck Results XXIV 2015

Planck cluster cosmology (2015)

σ_8 from clusters lower than σ_8 from primary CMB
→Same result as galaxy clustering, cosmic shear



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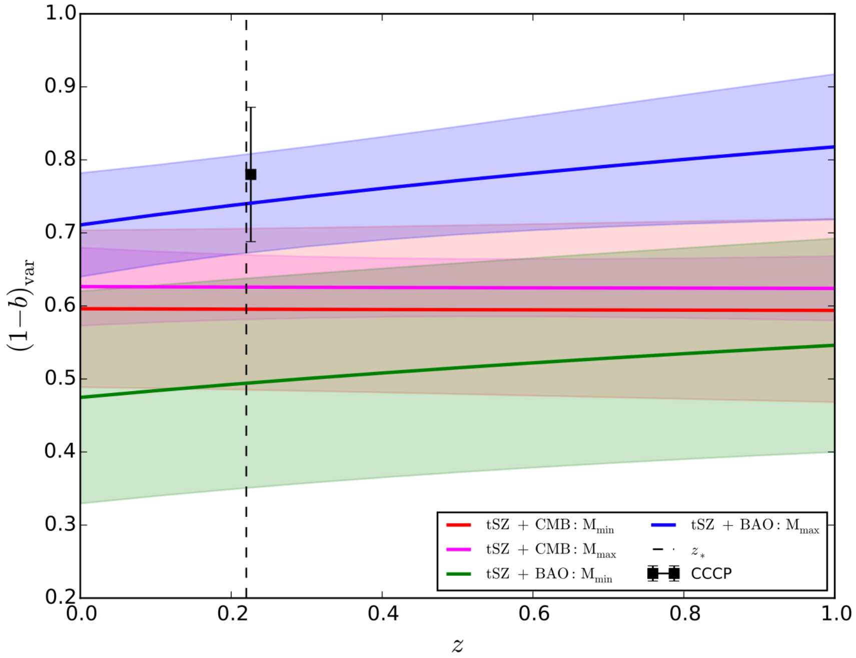
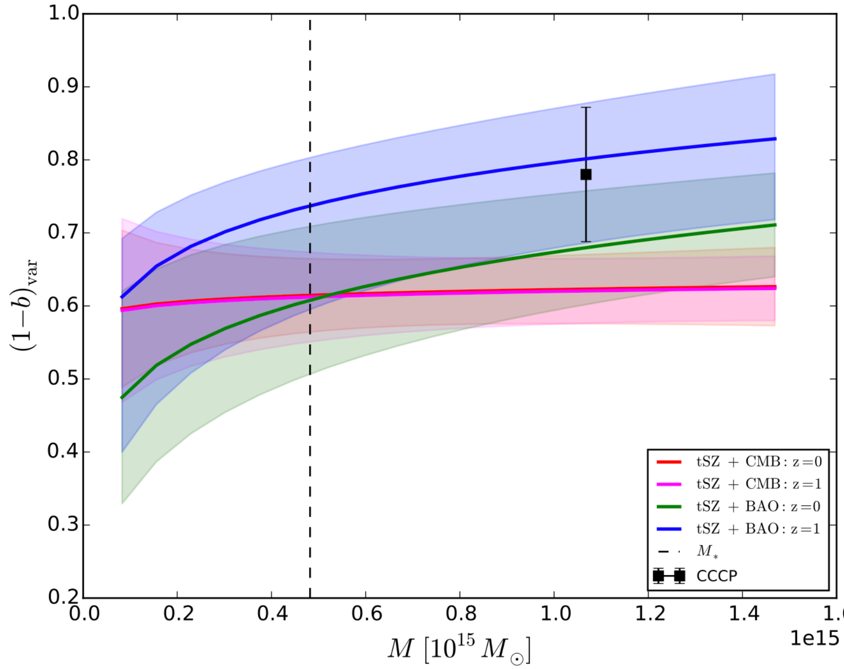
Planck Results XXIV 2015

Planck cluster cosmology – scaling laws ?

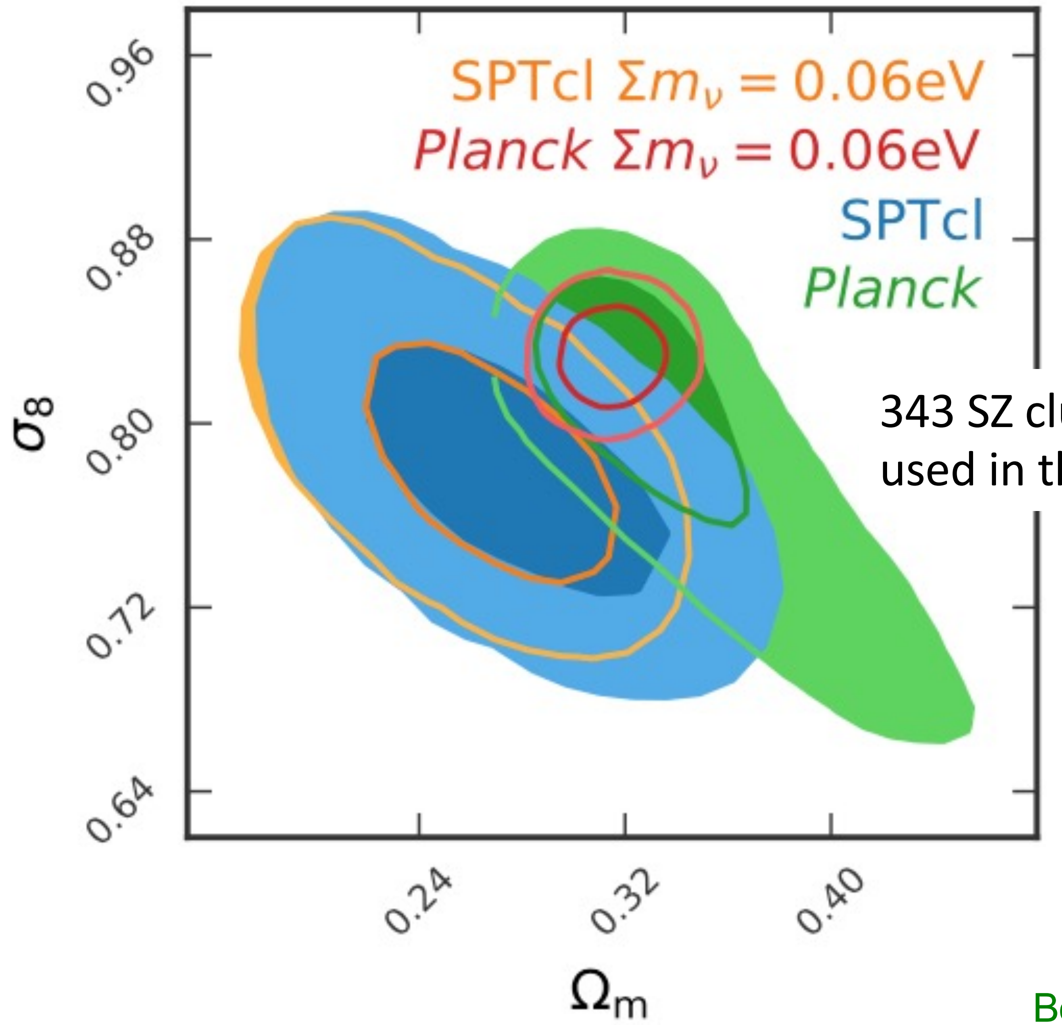




Salvati et al. 2019 studied mass and redshift evolution of the cluster mass scale 1-b using cluster counts+power spectrum

Some hints of redshift dependence of 1-b but depends on the considered subsample
➞Not sufficient to explain the discrepancy on σ_8 between clusters and primary CMB

South Pole Telescope cosmology (2019)

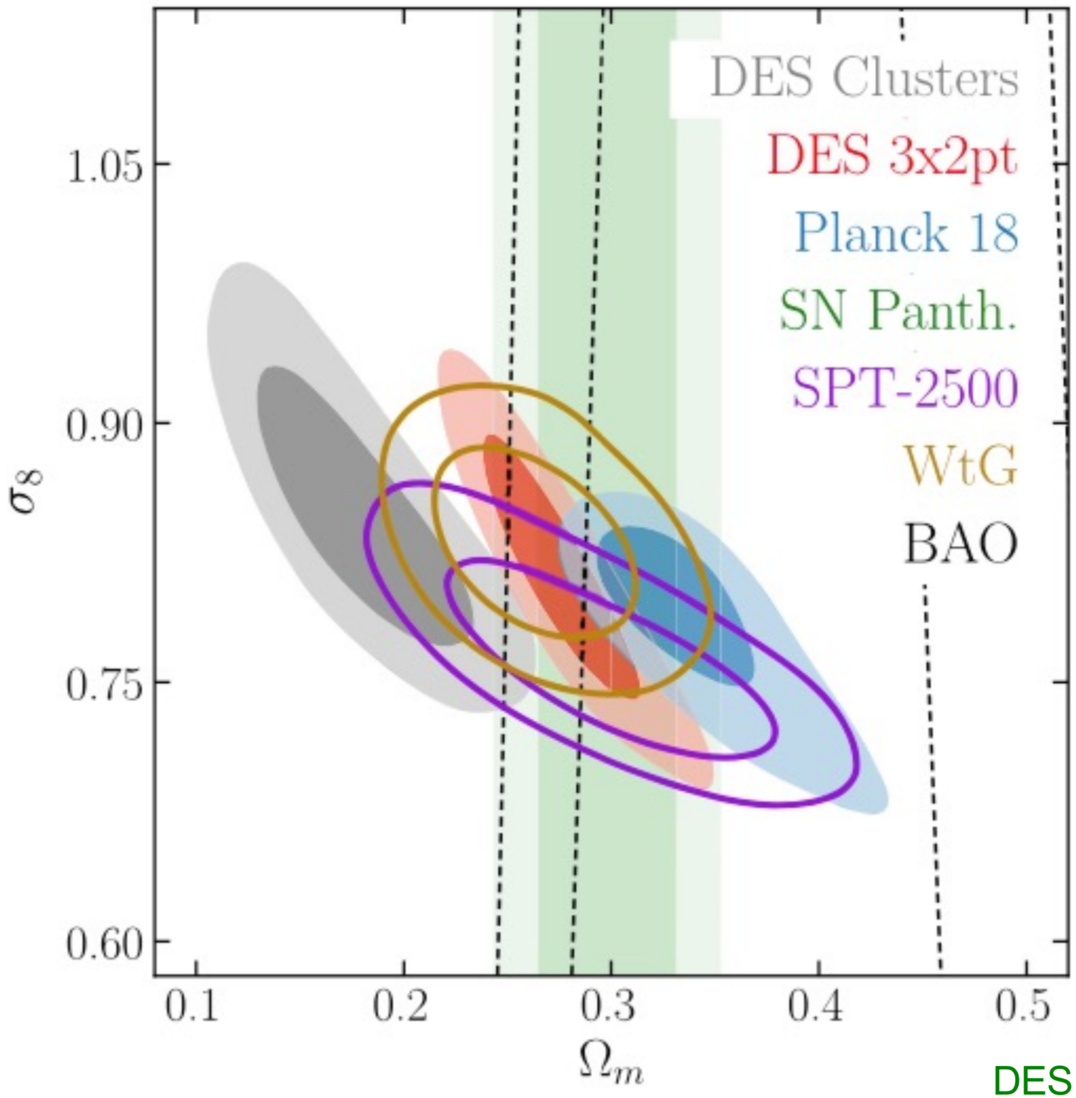


343 SZ clusters
used in the cosmological analysis

Bocquet et al. 2019

See talk by S. Bocquet

Dark Energy Survey cosmology

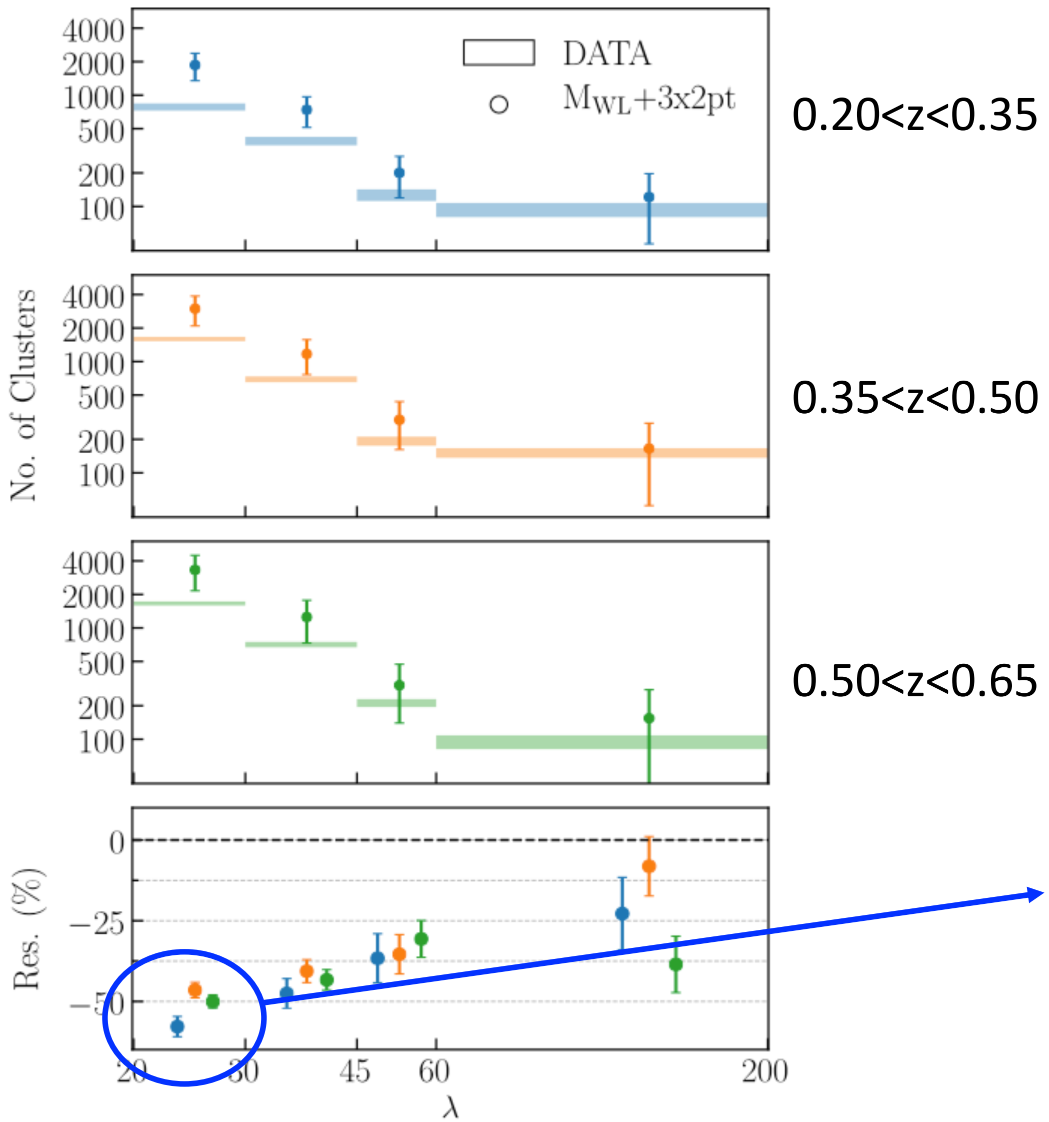


6,504 optical clusters
(**lower mass**)

DES collaboration 2020

See talk by M. Costanzi

Dark Energy Survey cosmology



0.20<z<0.35

0.35<z<0.50

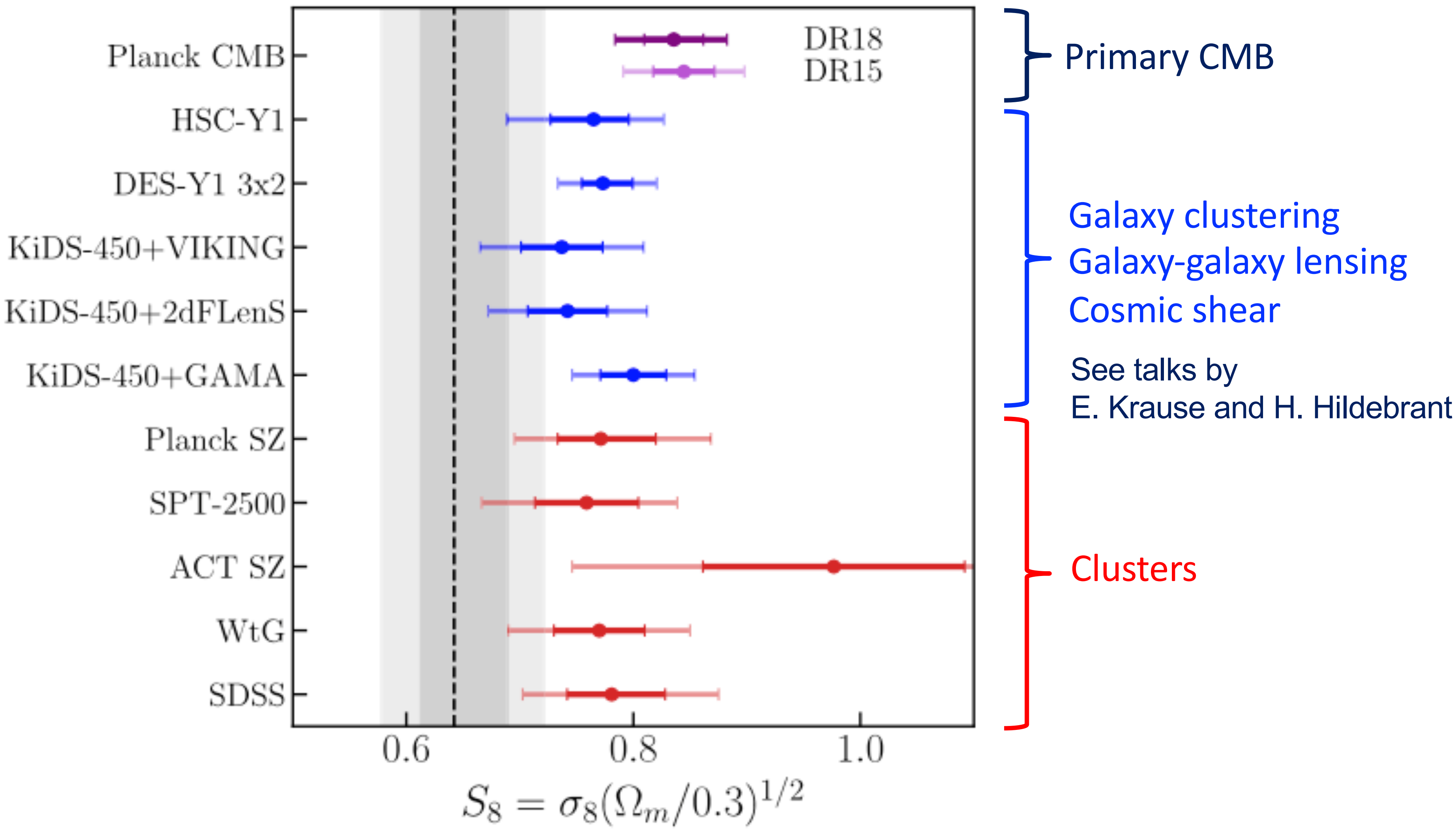
0.50<z<0.65

Problem with weak lensing mass measurement in the lowest richness bins

DES collaboration 2020

See talk by M. Costanzi

Where do we stand?



DES collaboration 2020

See talk by M. Costanzi

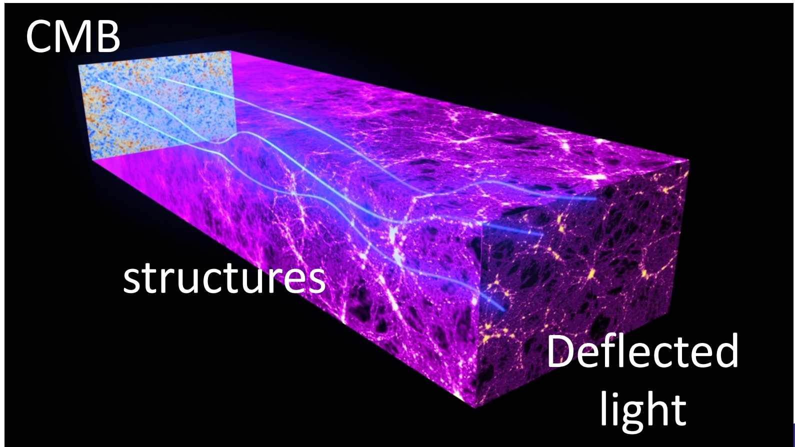
Major uncertainties

CLUSTER
MASS SCALE

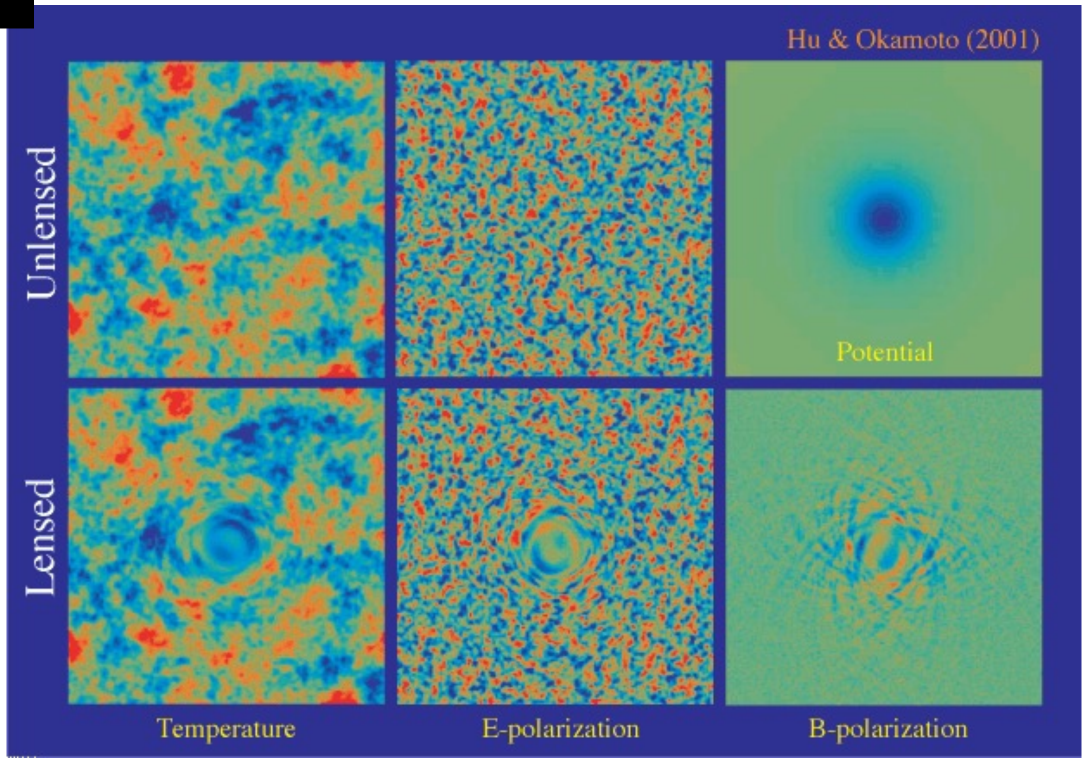
Weal lensing (optical)
and/or
CMB lensing (millimetre wavelength)

Multi-experiment /
Multiwavelength analyses

Cosmic Microwave Background halo lensing



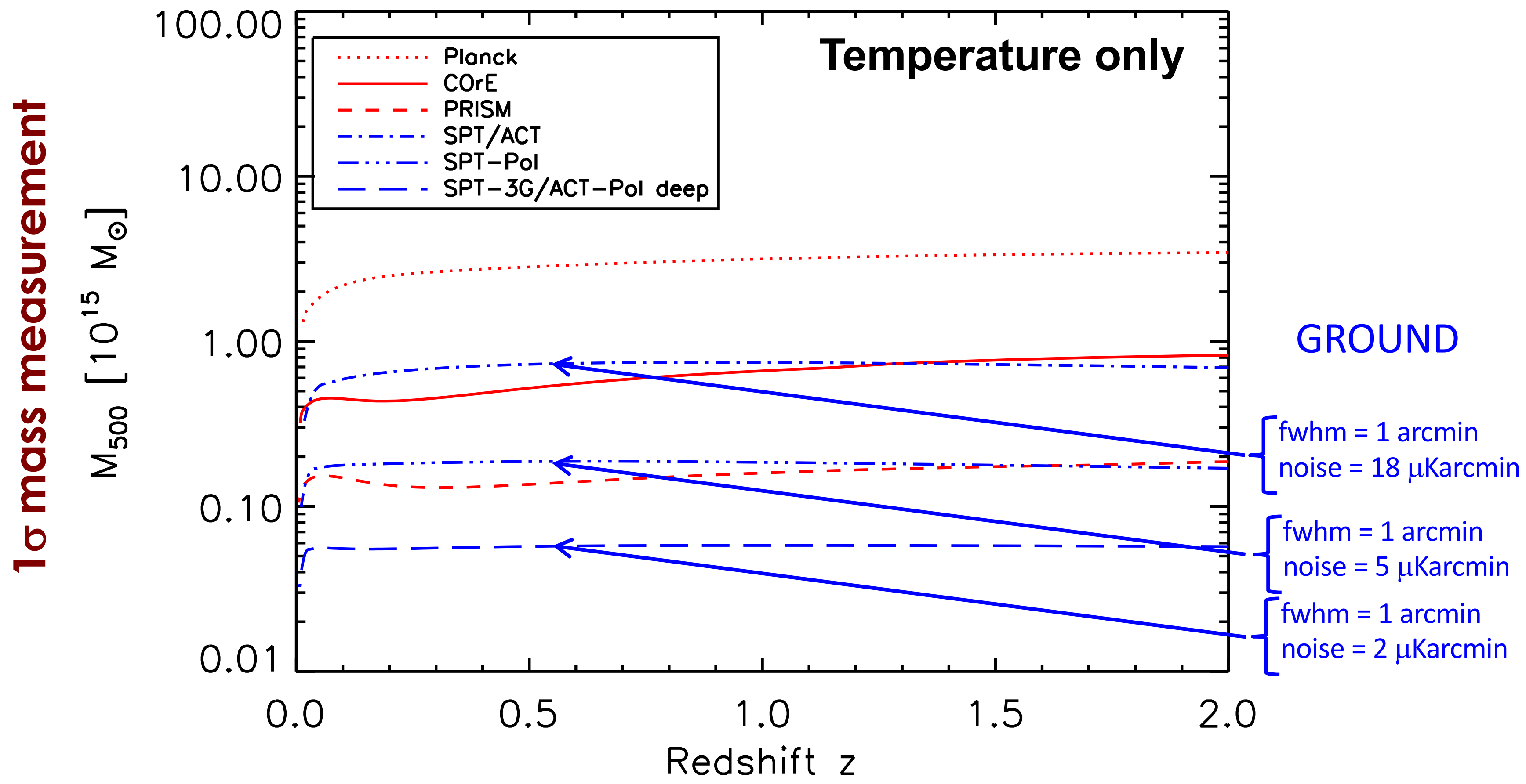
Credit: ESA



Hu & Okamoto 2001

Cluster CMB lensing

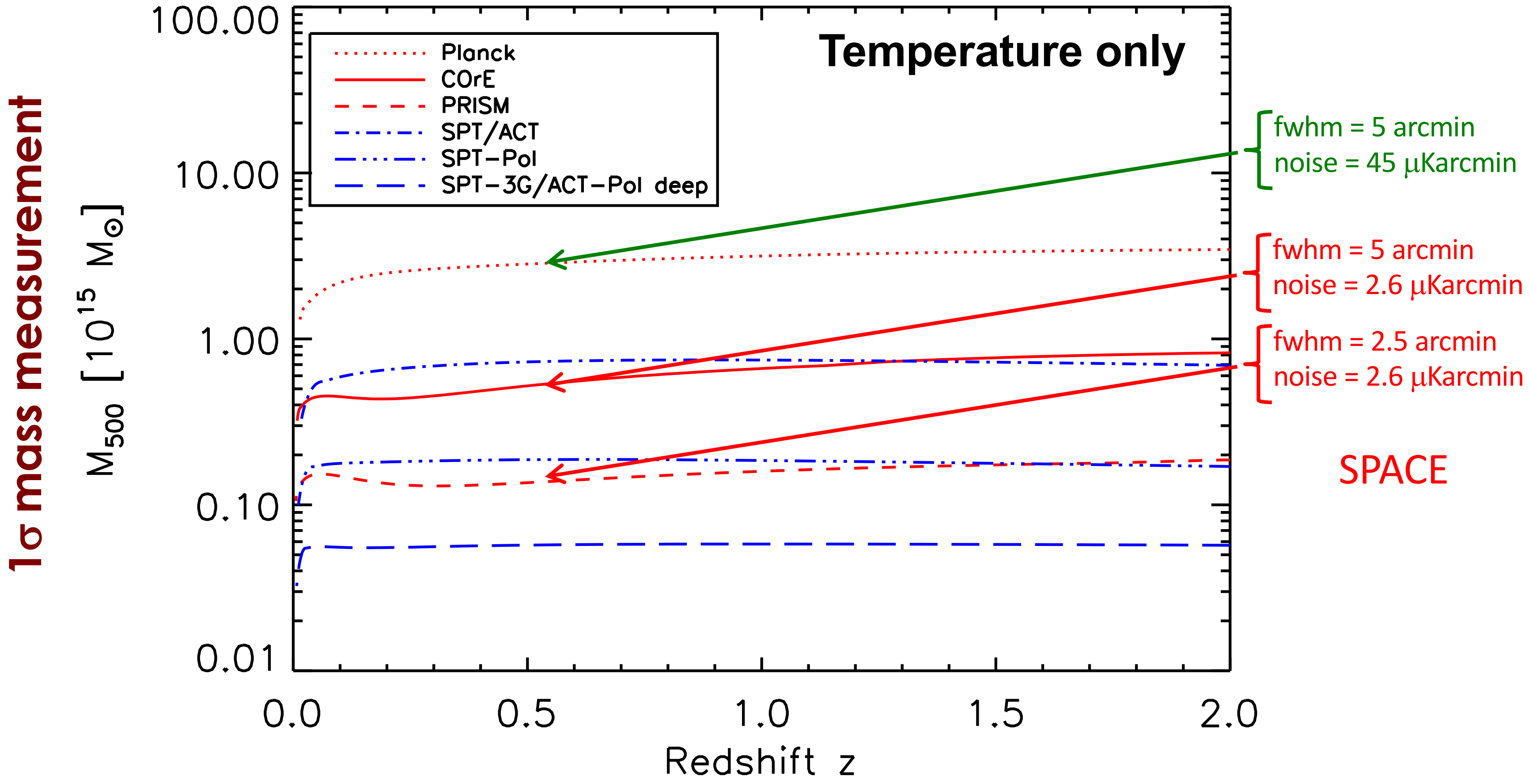
Melin & Bartlett 2015



does not take into account ability to eliminate contaminating signals

Cluster CMB lensing

Melin & Bartlett 2015



does not take into account ability to eliminate contaminating signals

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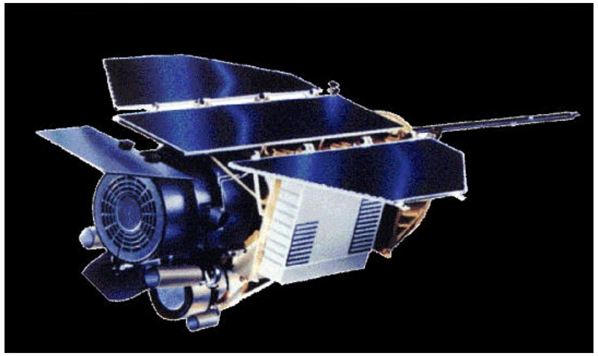
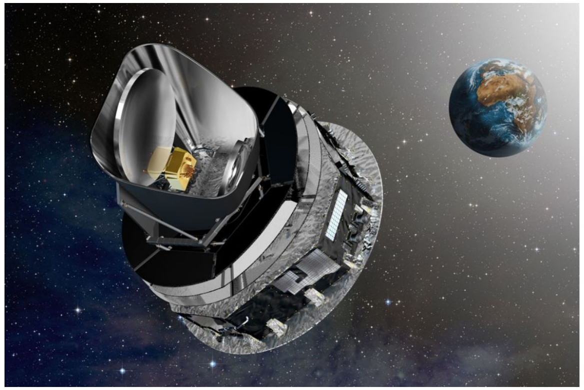
Motivations – data public!

- **ROSAT(RASS)** data public (since 2000) – all-sky 42,000 deg^2
- **Planck** data public (since 2013) – all-sky 42,000 deg^2
- Ground based **SPT** data – 2,500 deg^2 *Chown et al. 2018*
  ACT data – 18,000 deg^2 *Naess et al. 2020*


ROSAT satellite


Planck satellite


South Pole Telescope (SPT)


Atacama Cosmology Telescope (ACT)

Motivations – combination!

- **Comparing** the datasets allows better understanding of the characteristics/systematics of the experiments and cluster physics
- **Combining** the datasets allows the detection of fainter clusters

- First catalogue ROSAT+Planck *(Tarrío et al. 2019)*
- First combination ACT+Planck by *Aghanim et al. 2019*
- First catalogue SPT+Planck *(Melin et al. 2021)*

SPT-SZ and **Planck** datasets

Combination!

PSZSPT

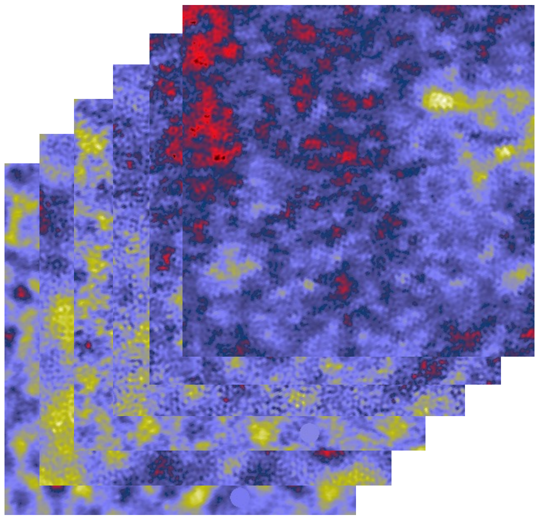
Melin J.-B., Bartlett J. G., Tarrío P., Pratt G. W., 2021, A&A, 627, A106

SPT-SZ and Planck complementarity

	SPT	Planck
Spatial resolution	+ (fwhm=1.75arcmin)	− (fwhm>5arcmin)
Instrumental noise	+ (20μKarcmin@150GHz)	− (33μKarcmin@143GHz)
Filter transfer function	− (scales smaller 1/2deg)	+ (all scales)
Frequency range	− (95-220GHz)	+ (100-857GHz)

The thermal SZ Matched Multi-Filter (MMF)

Planck maps



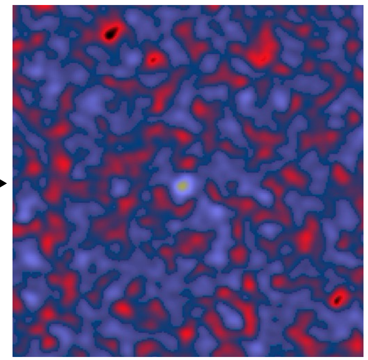
MMF

assumes

- SZ frequency spectrum
- cluster profile

Herranz et al. 2002
Melin, Bartlett, Delabrouille 2006

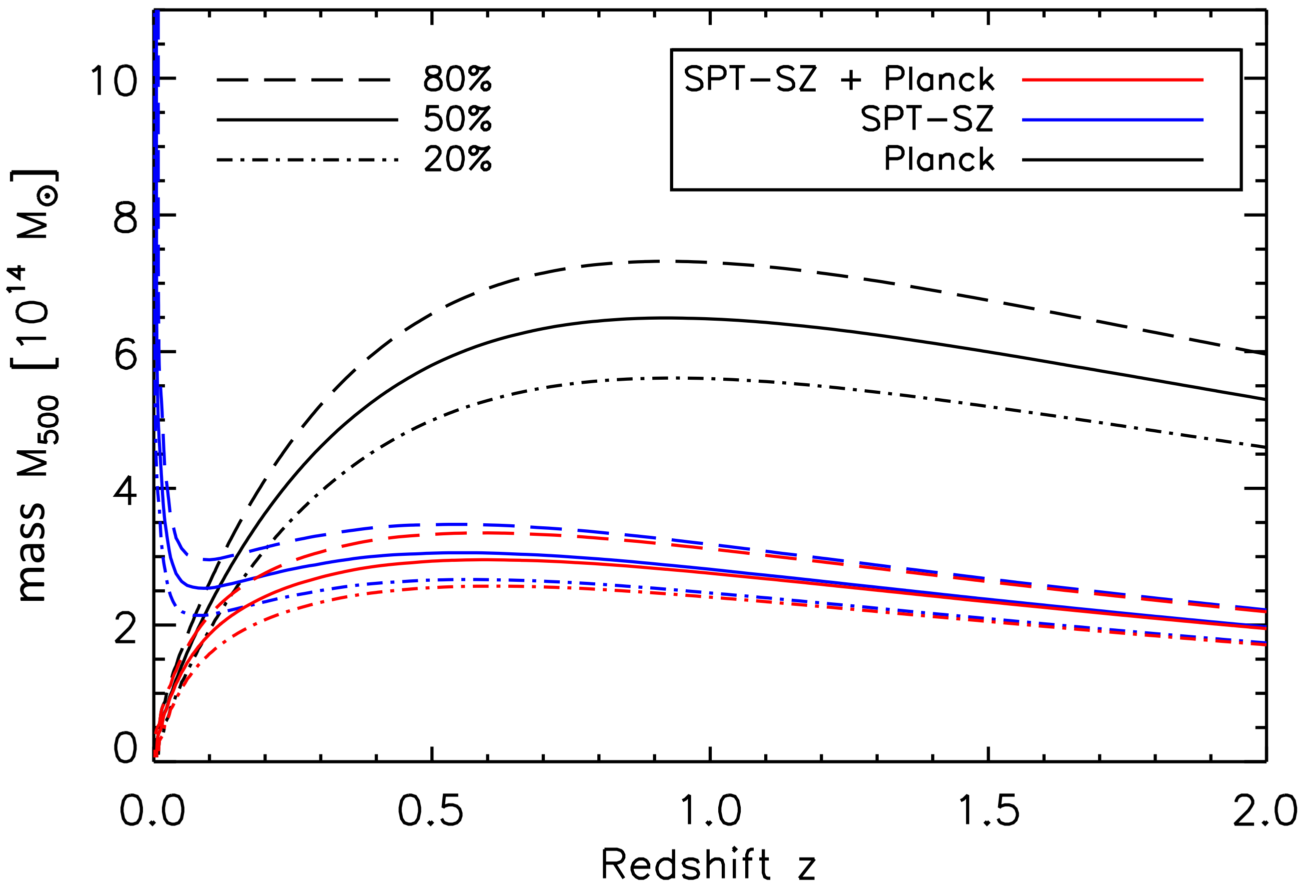
Filtered map



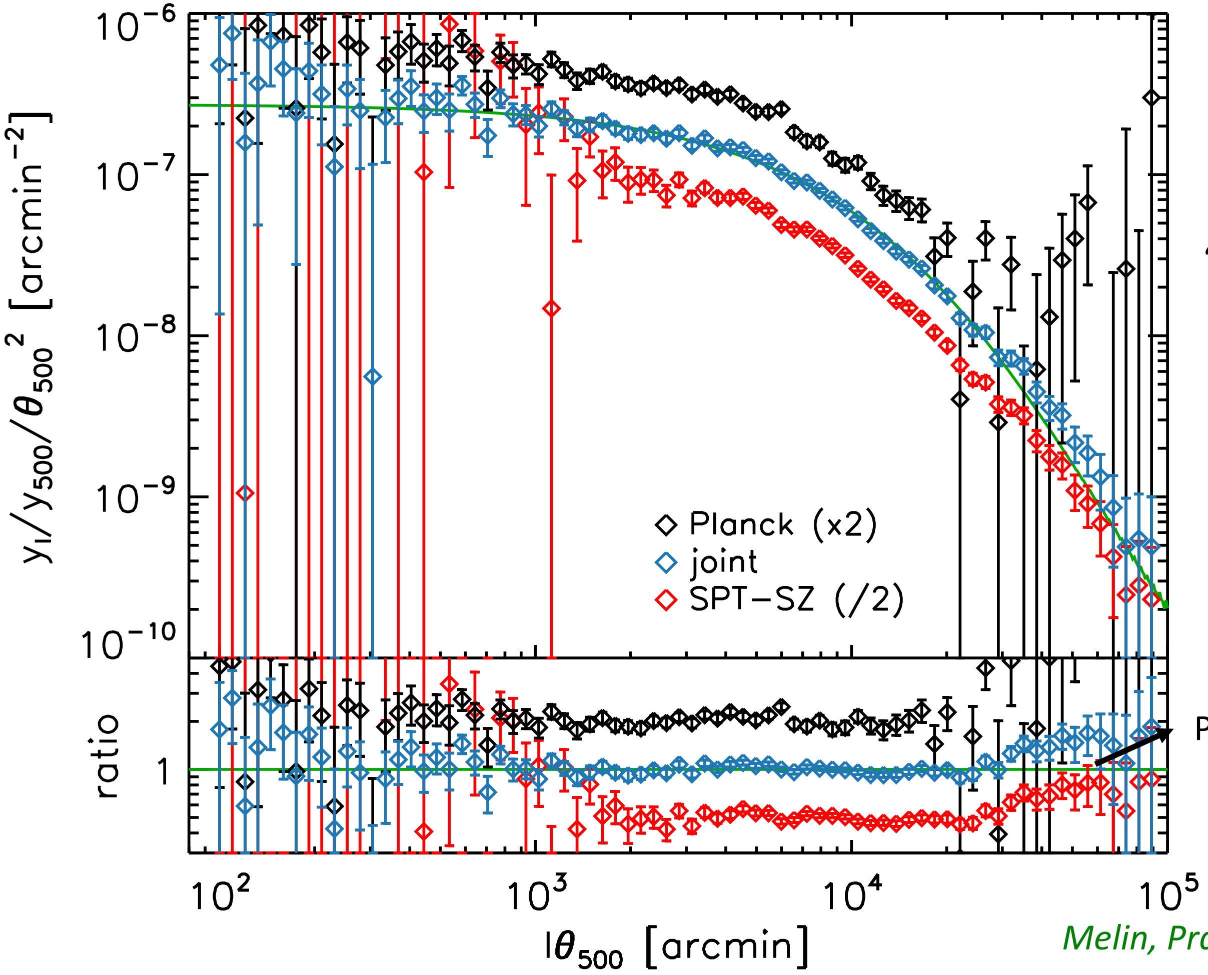
Planck MMF3

✧ Linear estimator
✧ Minimizes the variance of the noise
✧ Unbiased

Joint SPT+Planck blind SZ catalogue



SPT-SZ and Planck profiles

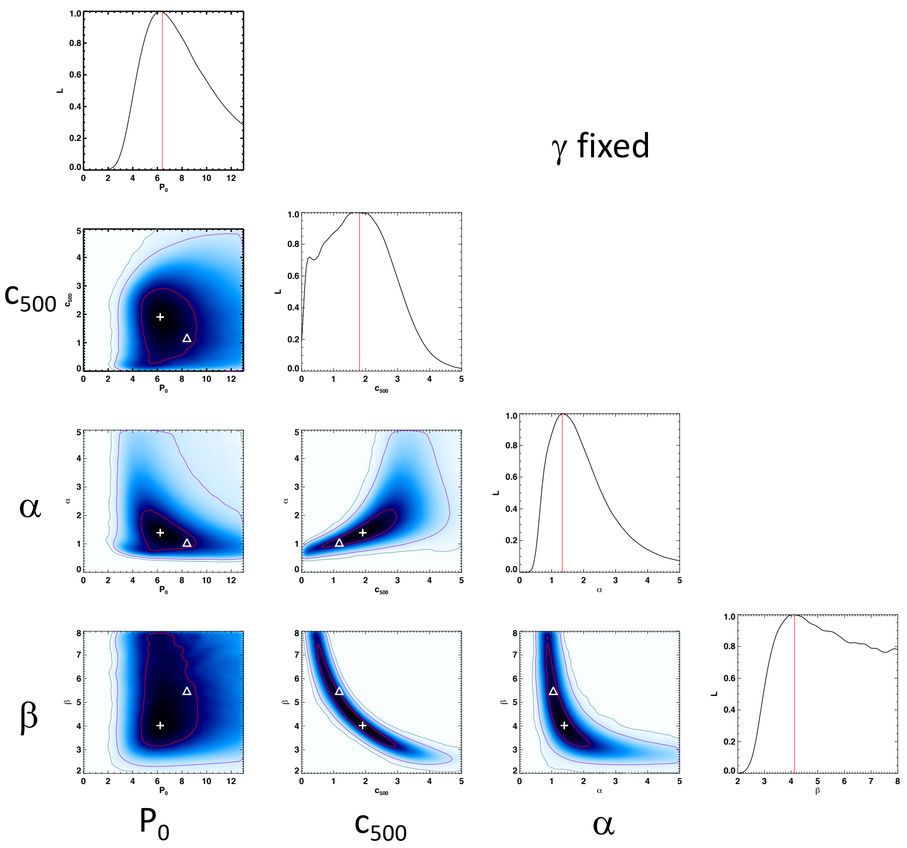


461 SPT-SZ clusters

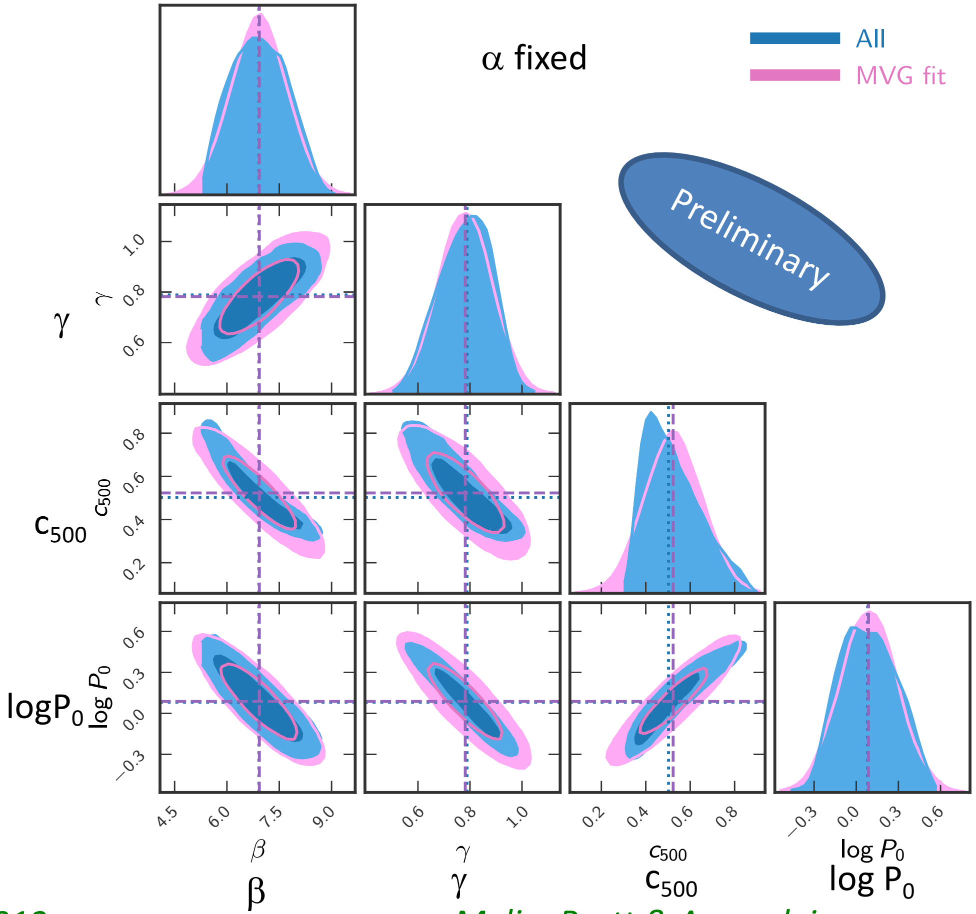
Planck Pressure Profile (PIPV)

Melin, Pratt & Arnaud, in prep.

Best fit



Planck Intermediate Results V, 2012



Melin, Pratt & Arnaud, in prep.

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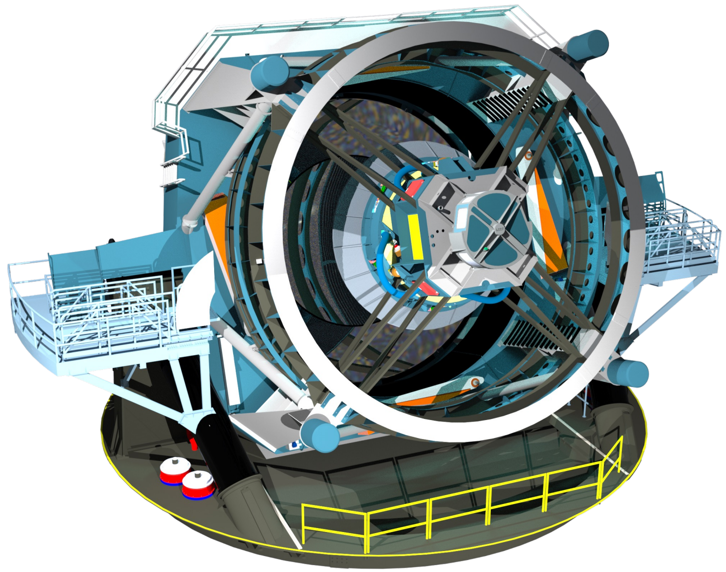
Euclid & Rubin Observatory

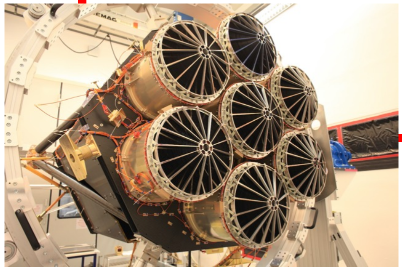
Euclid



Rubin Observatory

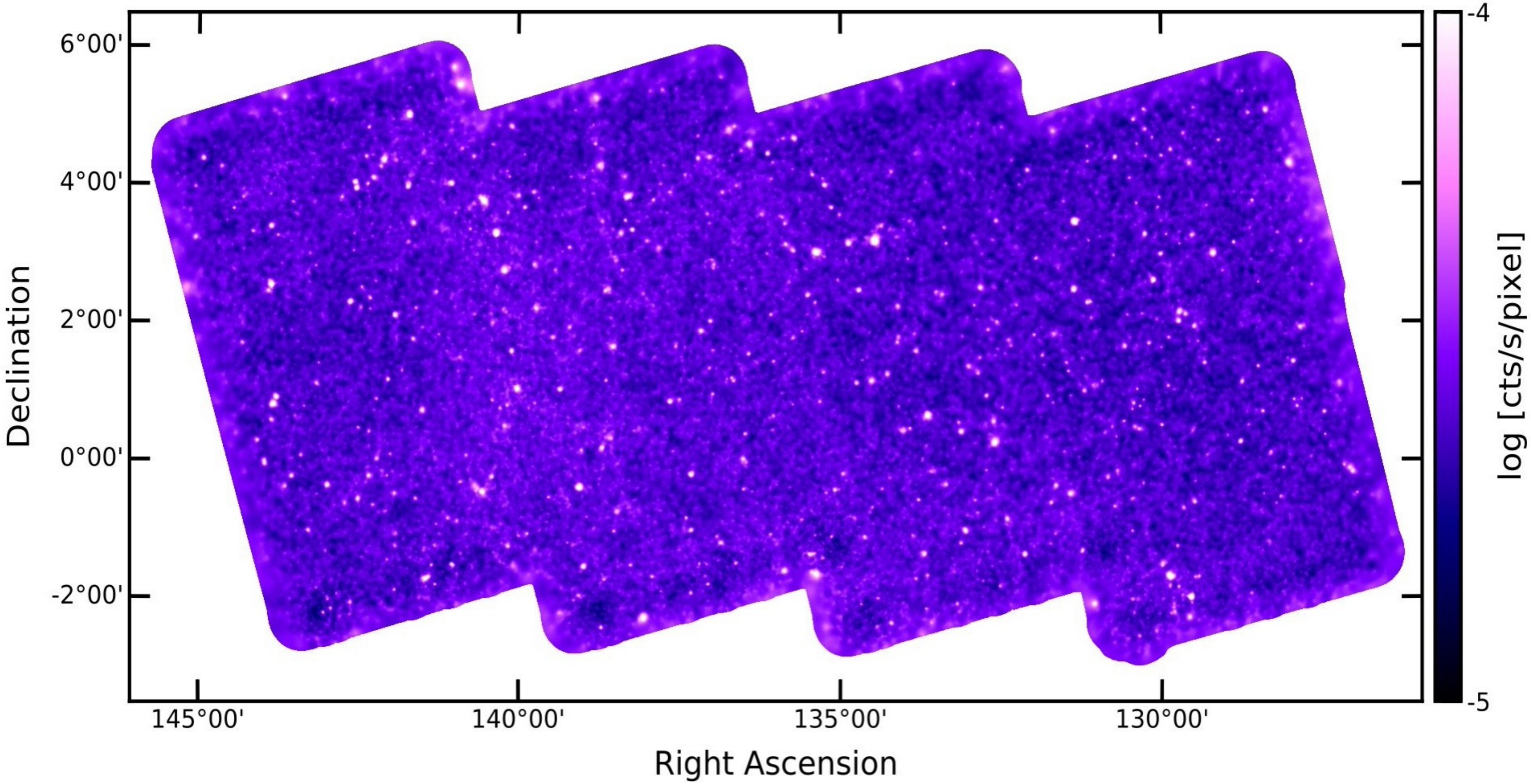
- Large cluster catalogues (between 50,000 to 100,000 clusters)
- Direct mass measurement with weak lensing

(1% error on the cluster mass scale)



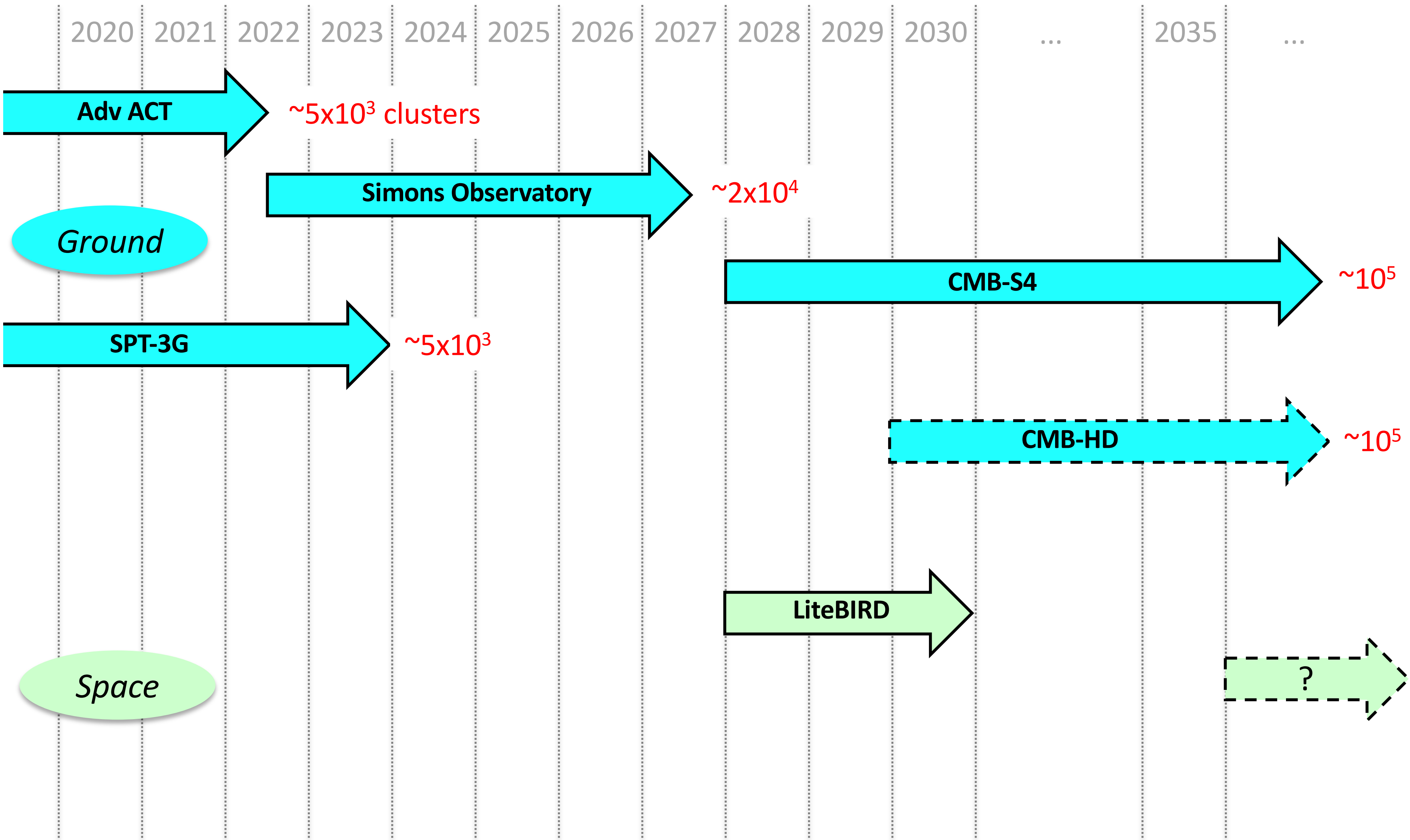
eROSITA

Liu et al. 2021

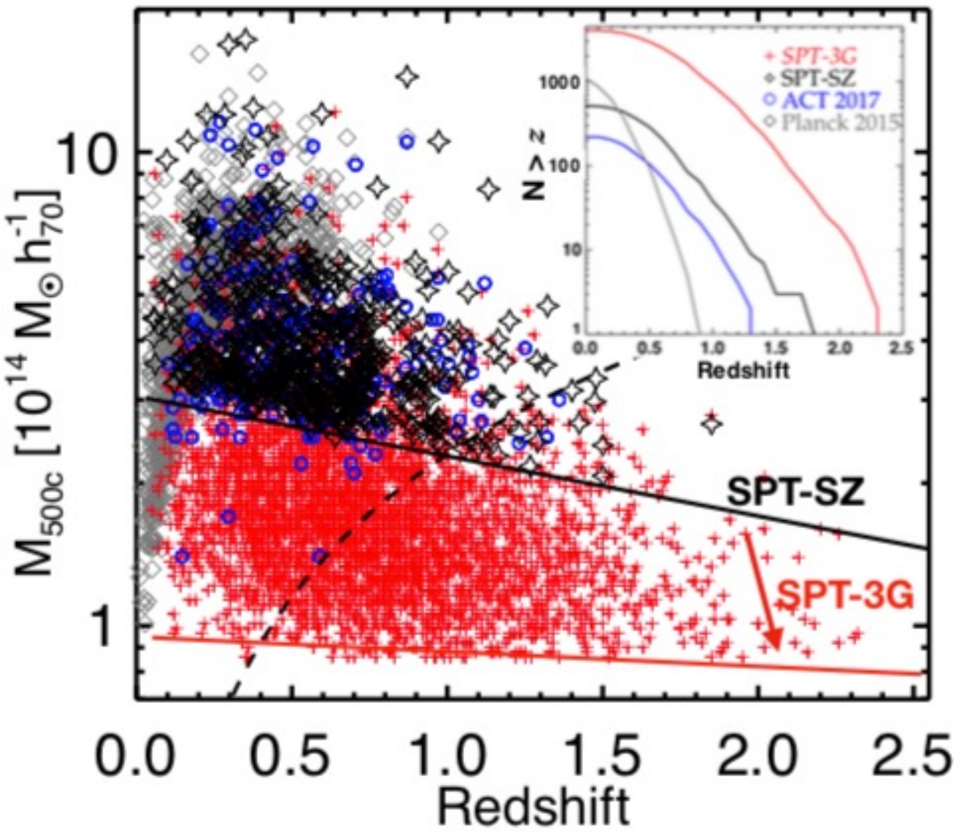


Russian-German instrument **successfully launched** in 2019
X-ray All-sky survey
Large cluster catalogue (~100 000 clusters expected)

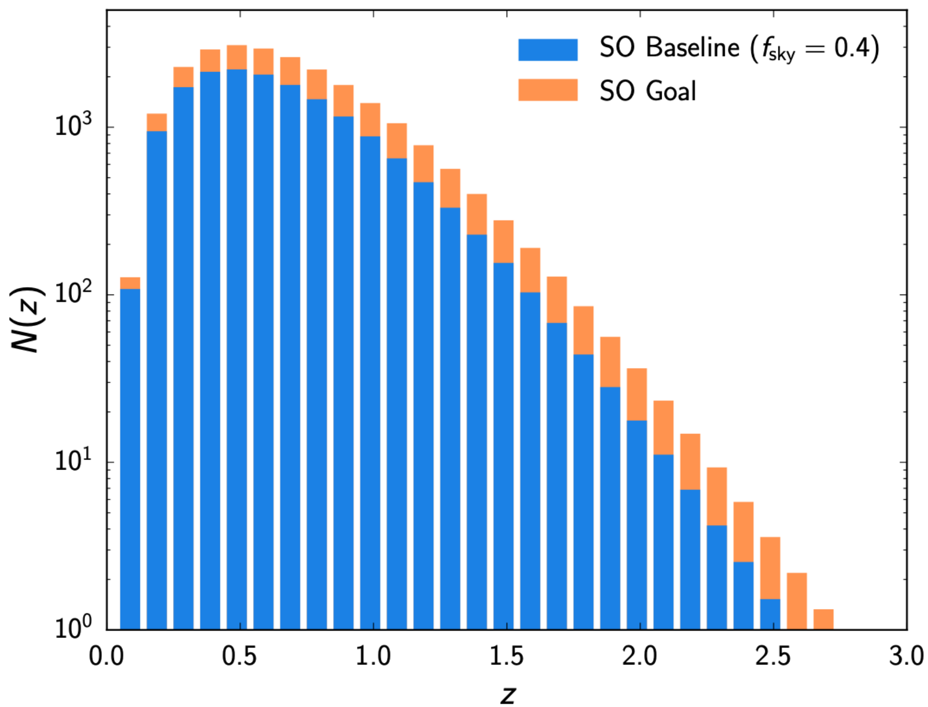
Current and future SZ surveys



Future SZ cluster catalogues



Benson @ Sesto2019



Simons Observatory:
science goals and forecasts 2019

- ~1000 clusters at z>1 with **SPT-3G**
- many thousands at z>1 with **SO**
- hundreds of clusters at z>2 with **CMB-S4**

In the coming years, SZ surveys will:
- detect the first clusters
- increase redshift leverage (important for cosmology !)

Conclusions

- Clusters have an **important role** to play **in the measurement of σ_8** (primary CMB vs. optical 3x2pts vs. clusters)
- Cluster constraints still **limited by our knowledge on the cluster mass scale** (~10%).
- Joint analyses of SZ data : proof of concept that **ground based and space based experiments can be analysed jointly** (SPT+Planck, ACT+Planck).
- **Inhomogeneous datasets can also be analysed jointly** (ROSAT+Planck).
- Future: on-going and planned experiments (optical, SZ, X-ray) will **increase the number of detected clusters by a factor 10 to 100**. Mass will be determined to percent accuracy via weak lensing and CMB lensing.
- These experiments will provide a **multiwavelength view,** which is crucial to improve our knowledge on cluster physics and deal with systematics