CMB-S4 Clusters

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for CMB-S4 Clusters (and Sources) analysis working group(s)

CMB-S4 Spring Collaboration Meeting
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CMB-S4

Thermal Sunyaev-Zeldovich (SZ) effect

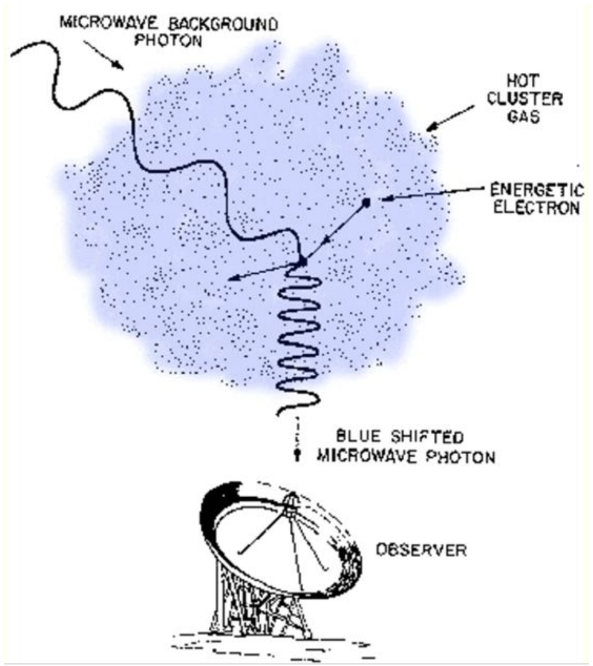
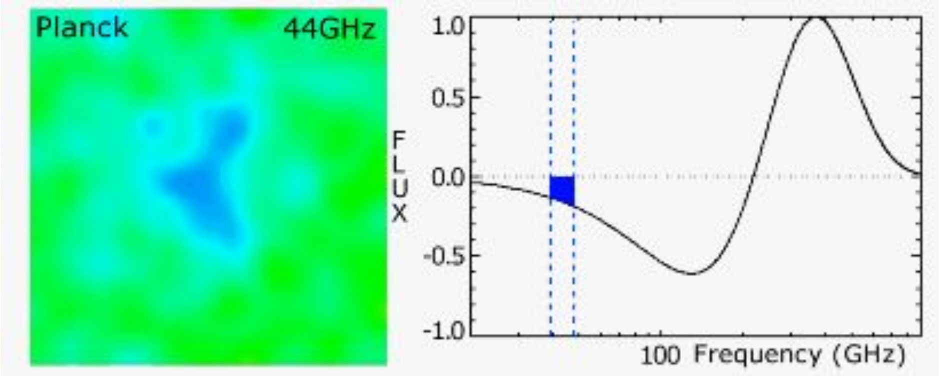


Image: L. Van Speybroeck

- Galaxy clusters contain hot gas (free electrons).
- CMB photons, that pass through clusters of galaxies, are inverse Compton scattered by free electrons in the intracluster medium (ICM).
- Used for blind detections of clusters in CMB surveys.
- ***Surface brightness of the SZ effect is redshift independent and hence allows us detect distant clusters.***
- Cluster abundance as a fn(M,z) is also an excellent probe of structure formation ***with parameter degeneracies that are different compared to the primary CMB***.



Frequency dependence of thermal SZ (Image: ESA)

CMB-S4 cluster forecasts

- **CMB-S4 cluster SZ surveys:**
  - 6-metre telescopes → 1.4 arcmin beam at 145 GHz.
  - CMB-S4 Wide: Chilean survey: f_{sky} = 67%.
  - CMB-S4 Ultra-deep: South Pole survey: f_{sky} = 3%.
    - 6m Crossed-Dragone design **`V3R025`**.
    - Also have estimates for 5m TMA.
- **Forecasting inputs:**
  - **Bands:** 27, 39, 93, 145, 225 and 278 GHz
  - **Noise and Beams:** PBDR values.
  - **Footprint:** fsky = 0.67 using a minimum observing elevation=40 degrees.
    - Split into **clean (fsky = 0.5)** and **dirty (fsky = 0.17)** regions.
  - **Extragalactic foregrounds:** Radio, CIB, tSZ and kSZ power spectra from SPT measurements.
  - **Galactic foregrounds:** Dust and Synchrotron power spectra obtained from pySM3 simulations.
  - **Cluster signal:** Generalised NFW (Navarro Frenk and White) with Planck Y-M relation.

Frequency (GHz)	27	39	93	145	225	278
θ_{FWHM} (arcmin)	7.4	5.1	2.2	1.4	1.0	0.9
Δ_T (μK-arcmin)	21.34	11.67	1.89	2.09	6.9	16.88
ℓ^T_{knee}	415	391	1932	3917	6740	6792
α_T	3.5	3.5	3.5	3.5	3.5	3.5
Δ_P (μK-arcmin)	30.23	16.53	2.68	2.96	9.78	23.93
ℓ^P_{knee}	700	700	700	700	700	700
α_P	1.4	1.4	1.4	1.4	1.4	1.4

CMB-S4 cluster forecasts

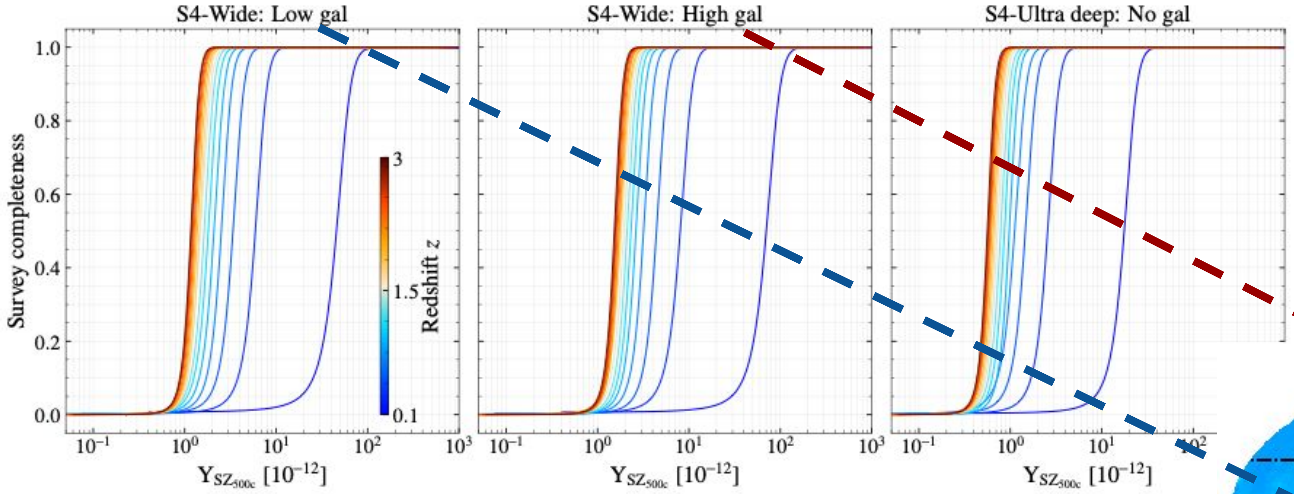
- **CMB-S4 cluster SZ surveys:**
  - 6-metre telescopes → 1.4 arcmin beam at 145 GHz.
  - CMB-S4 Wide: Chilean survey: fsky = 67%.
  - CMB-S4 Ultra-deep: South Pole survey: fsky = 3%.

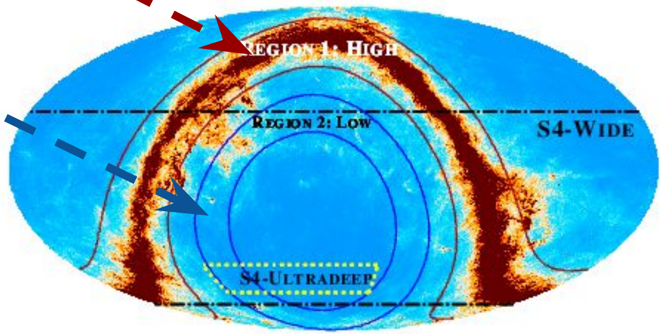
- **Signal-to-noise threshold:** 5σ.

- **Observable:**

CMB-S4 shall detect (at 5σ) all galaxy clusters with an integrated Compton $Y_{SZ} \geq XX$ at z ≥ 1.5 over the large area survey footprint (f_{sky} = 67%). Furthermore, it shall detect (at 5 sigma) all galaxy clusters with an integrated Compton $Y_{SZ} \geq YY$ at z ≥ 1.5 over the de-lensing survey footprint (f_{sky} = 3%).

CMB-S4 cluster survey completeness



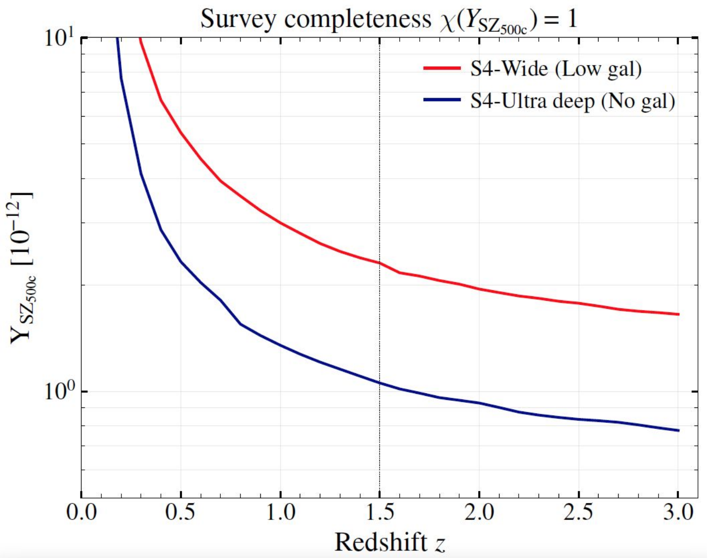


$$\int_{q\sigma_{Y_{SZ}}}^{\infty} dY_{SZ}\, P(Y_{SZ} \,|\, Y_{SZ}^{\text{true}}) = 0.5 \left(1 + \text{erf}\left[\frac{Y_{SZ}^{\text{true}} - q\sigma_{Y_{SZ}}}{\sqrt{2}\sigma_{Y_{SZ}}}\right]\right)$$

CMB-S4 PBDR (in prep.)

Planck **collaboration 2014 XX, arXiv: 1303.5080**
Alonso, Louis, Bull et al. 2016, arXiv: 1604.01382

CMB-S4 cluster survey completeness



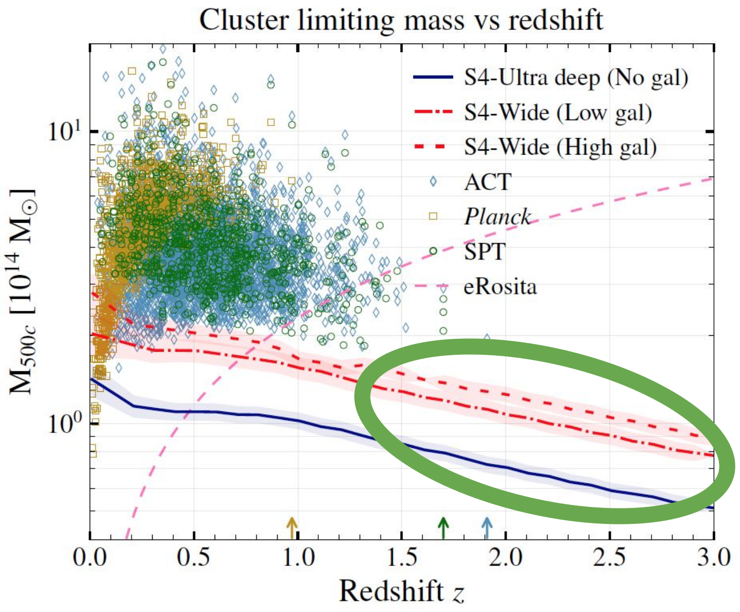
CMB-S4 PBDR (in prep.)

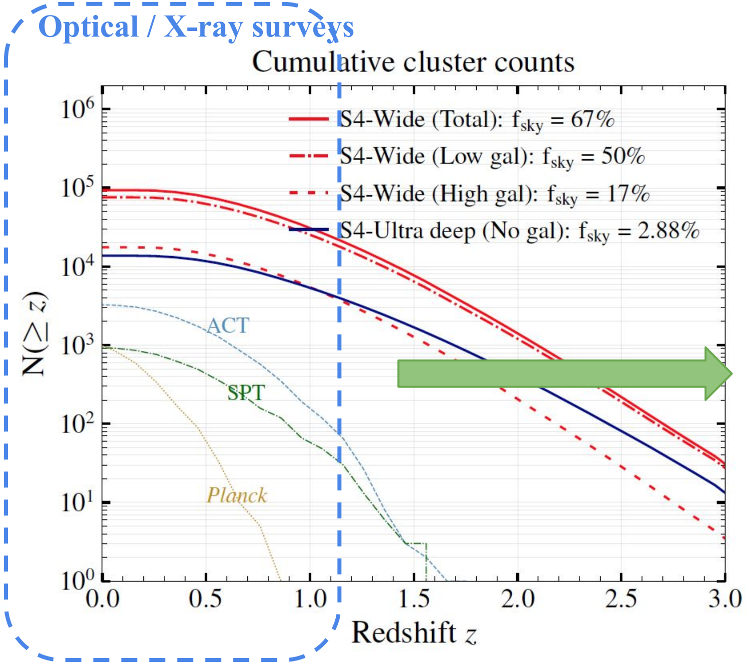
Science requirement:

CMB-S4 shall detect (at 5σ) all galaxy clusters with an integrated Compton ***$Y_{SZ} \geq 2 \times 10^{-12}$ sr or 2.4 $\times 10^{-5}$ arcmin^2 at $z \geq 1.5$ over the large area survey footprint (f_{sky} = ~~65%~~ 50%)****. Furthermore, it shall detect (at 5σ) all galaxy clusters with an integrated Compton* ***$Y_{SZ} \geq 10^{-12}$ sr or 1.2 $\times 10^{-5}$ arcmin^2 at $z \geq 1.5$ over the de-lensing survey footprint (f_{sky} = 3%)****.*

CMB-S4 cluster sensitivity / counts

- **S4-Wide:** Contains clusters from low (f_{sky} = 0.5) + high (f_{sky} = 0.15) Galactic emission regions. Removing high Galactic emission region reduces ~20% objects.
- **High-z (z>=2) clusters:** S4-Wide → ~1000 clusters; S4-Ultra deep → ~350 clusters.
- ***Wee understood selection function even at high redshifts.***





CMB-S4 PBDR (in prep.)

CMB-S4 Cluster Science

PBDR Chapter 1 - Science Goals to Science Requirements

Goal 1: Test models of inflation by measuring or putting upper limits on r, the ratio of tensor fluctuations to scalar fluctuations.

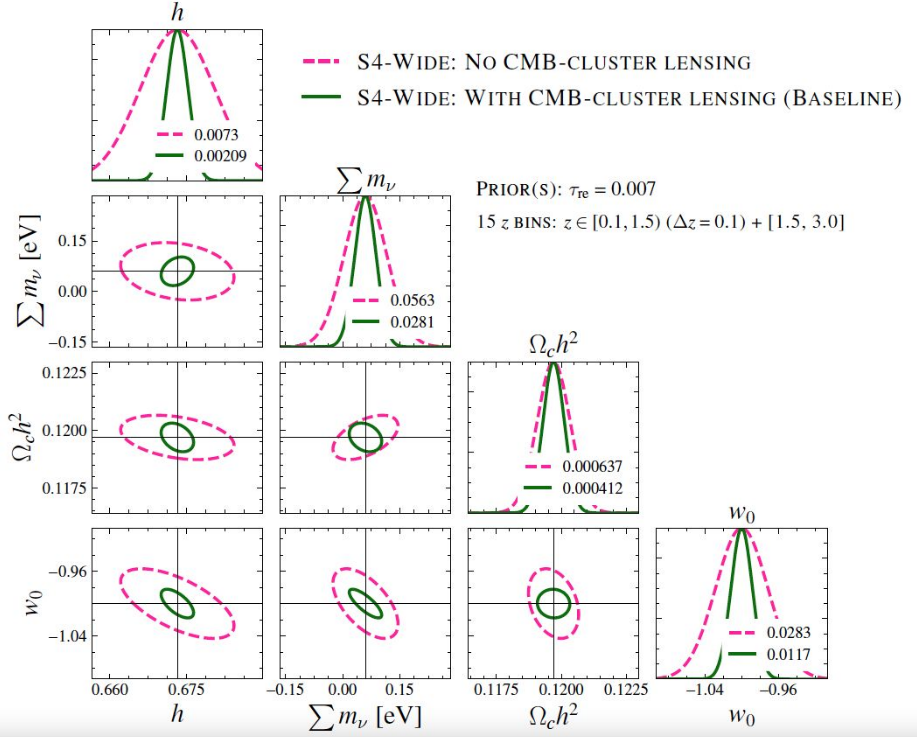
Goal 2: Determine the role of light relic particles in fundamental physics, and in the structure and evolution of the Universe.

Goal 3: Measure the emergence of galaxy clusters as we know them today. Quantify the formation and evolution of the clusters and the intracluster medium during the crucial early period of galaxy formation.

Goal 4: Explore the millimeter-wave transient sky. Measure the rate of mm-transients for the first time. Use the rate of mm-wave GRBs to constrain GRB mechanisms. Provide mm-wave variability and polarization measurements for stars and active galactic nuclei.

Cosmological constraints

CMB-S4 Wide: CMB (TT/EE/TE) with Cluster counts using CMB-cluster lensing mass calibration.

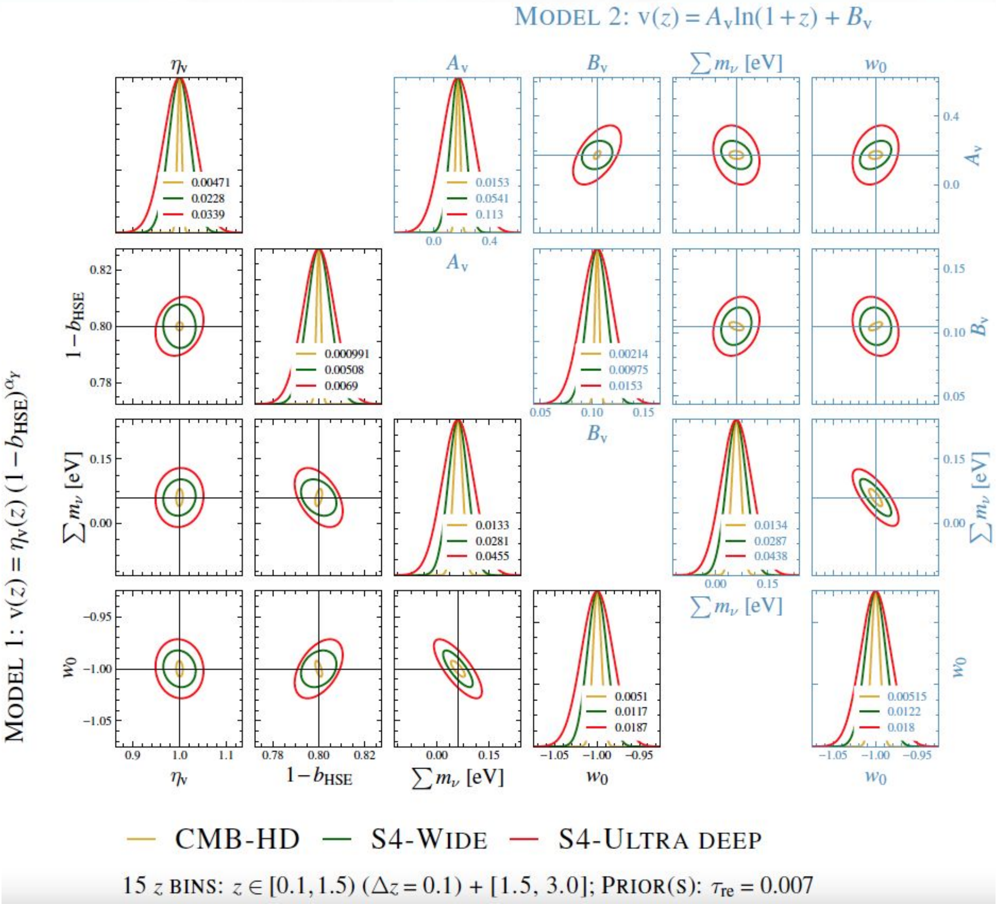


Including information from galaxy weak lensing will further strengthen the constraints and also offer an important systematic check.

See Madhavacheril, Battaglia & Miyatake 2017, arXiv: 1708.07502.

Look into arXiv:2107.10250 for more details.
Also see Louis & Alonso 2017, arXiv: 1609.03997; Madhavacheril, Battaglia & Miyatake 2017, arXiv: 1708.07502.

Constraining astrophysics and cosmology with clusters



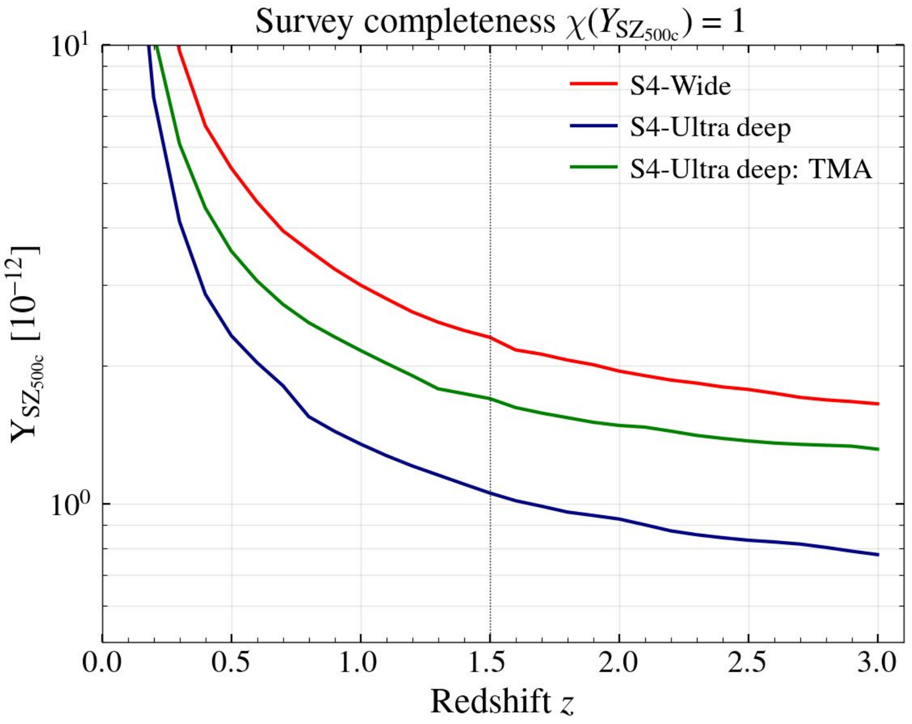
- **Virialisation model 1:**
  - $v(z) = \eta_v(z)\ (1 - b_{HSE})^{\alpha}$
  - 2-4 per cent on cluster virialisation parameter.
  - Sub-percent constraint on (constant) HSE bias.
- **Virialisation model 2:**
  - $v(z) = A_v \ln(1 + z) + B_v$
  - <5 per cent on B_v and ~30 per cent on redshift evolution A_v.
- Swapping cluster virialisation model 1 to model 2 does not affect cosmological constraints significantly.

Look into arXiv:2107.10250 for more details.

Analysis alternatives

Cluster forecasts: SPLAT design alternative - CD vs TMA

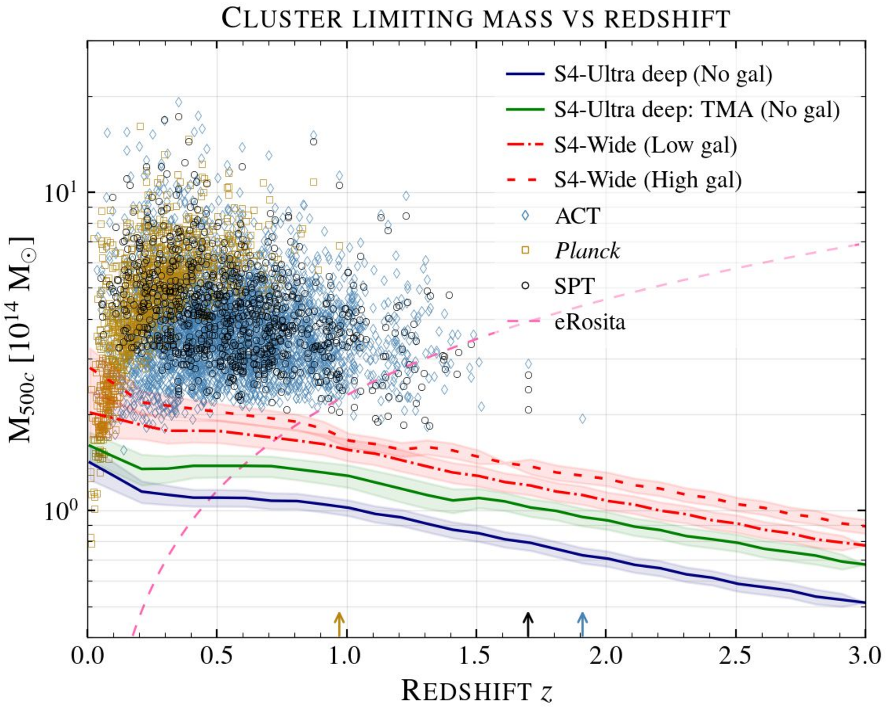
6m Crossed-Dragone (CD) design has 20 per cent better beam than the 5m Three-mirror anastigmat (TMA) design and this beam degradation affects cluster sensitivity.

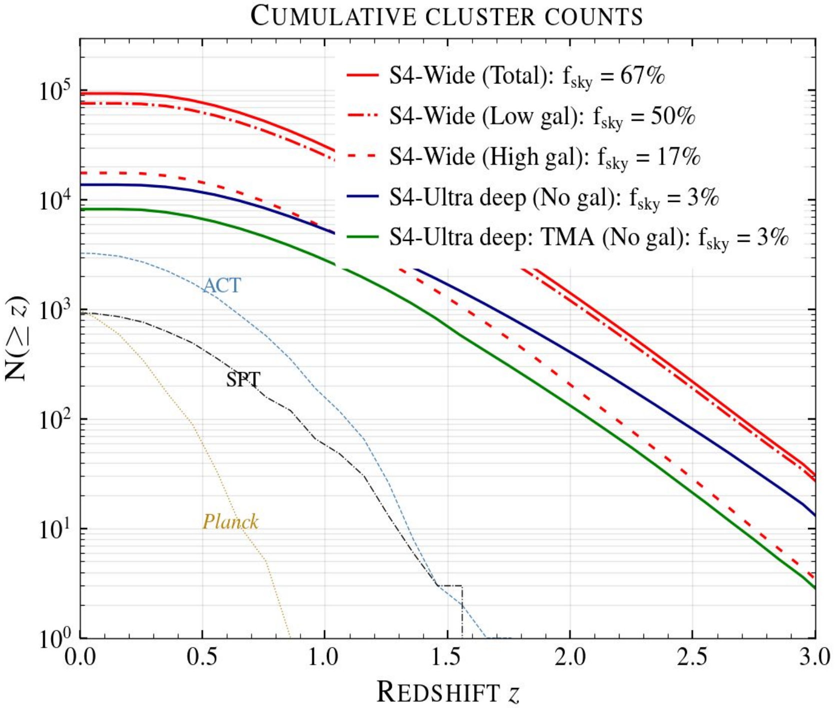


CMB-S4 PBDR (in prep.)

Cluster forecasts: SPLAT design alternative - CD vs TMA

With TMA's 20 per cent larger beam compared to the current CD design, we will miss roughly* x2.5 *clusters at z>=1.5 and* x3 *at z>=2.





CMB-S4 PBDR (in prep.)

Cluster forecasts: SPLAT design alternative - CD vs TMA

With TMA's 20 per cent larger beam compared to the current CD design, we will miss roughly x2.5 clusters at z>=1.5 and x3 at z>=2.

South Pole-only option:

- We did not consider this for clusters.
- Mapping f_{sky}~25 per cent with the same map depth as the S4-Ultra deep (f_{sky} = 3 per cent) will help us detect a lot of low mass clusters.
- However, that option is not viable for N_{eff} science (see maps2cell talk by Francis-Yan Racine).

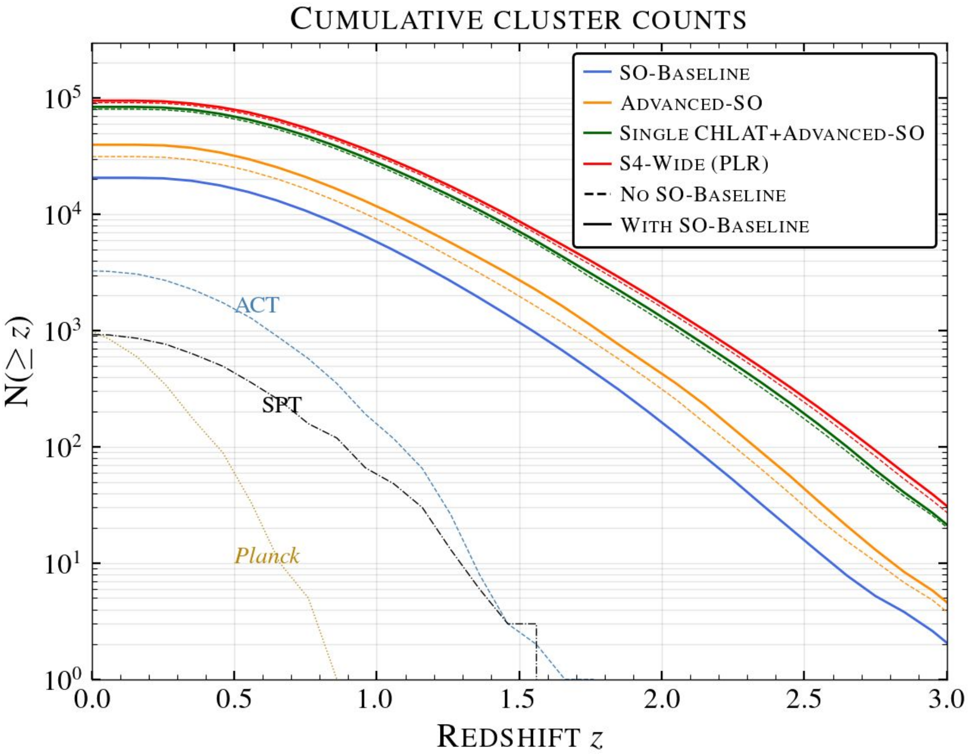
CMB-S4 PBDR (in prep.)

Cluster forecasts: CMB-S4 + Advanced SO

- The other analysis alternative is to ***replace one of the CMB-S4 Chilean LAT by the Advanced Simons Observatory (ASO) LAT.***
- In the following slides we will compare cumulative cluster counts at the end of observation period from the following configurations:
    - **SO-Baseline (4 years of observation).**
    - **Advanced SO (5 years of observation).**
    - **CMB-S4 Single CHLAT + Advanced SO (+ SO-Baseline).**
    - **Nominal CMB-S4 PBDR or PLR configuration (2 CMB-S4 CHLATs).**
- **Note:**
    - *The SO noise levels are not exactly the same as in SO overview paper but a scaled version to include differences in sensitivities.*
    - *SO forecasts assume the same sky fraction as CMB-S4 (f_{sky} = 0.67).*

Cluster forecasts: CMB-S4 + Advanced SO

- ***Roughly 30 (22) per cent lower clusters at z>=2 (z>=1.5) when one S4 CHLAT is replaced by ASO LAT.***
- ***Excluding SO-baseline reduces the number counts by 5 - 8 per cent.***



CMB-S4 PBDR (in prep.)

CMB-S4

Summary

- Given the number of detectors, the configuration we have currently for CMB-S4 CHLATs is close to the nominal for cluster survey (and also for N_{eff}).
- **Science Requirement:**
  - S4-Wide: $Y_{SZ} \geq 2.4 \times 10^{-5}$ arcmin^2 and S4-Ultra deep: $Y_{SZ} \geq 1.2 \times 10^{-5}$ arcmin^2.
- **Counts:**
  - S4-Wide - Total: 75k and z >= 2: 1000 clusters.
  - S4-Ultra deep - Total: 13k and z>=2: 300 clusters.
- **Parameter constraints:** CMB (TT/EE/TE) + cluster counts with CMB-lensing mass calibration.
  - $\sigma(w_{DE}) \sim 1$ per cent and 2.5-3σ detection of sum of neutrino masses.
  - $\sigma(\mathrm{bias}_{HSE}) < 1$ per cent.
- **Design alternatives:**
  - **6m CD vs 5m TMA SPLAT:** Degrades counts by x2.5 at z>=1.5 and x3 at z>=2.
  - **Combining CMB-S4 with ASO:** >20 per cent lower clusters at z>=1.5.

References: CMB-S4 PBDR; arXiv: 2112.07656; arXiv: 2112.07656;
Madhavacheril, Battaglia & Miyatake 2017, arXiv: 1708.07502; Louis & Alonso 2017, arXiv: 1609.03997.

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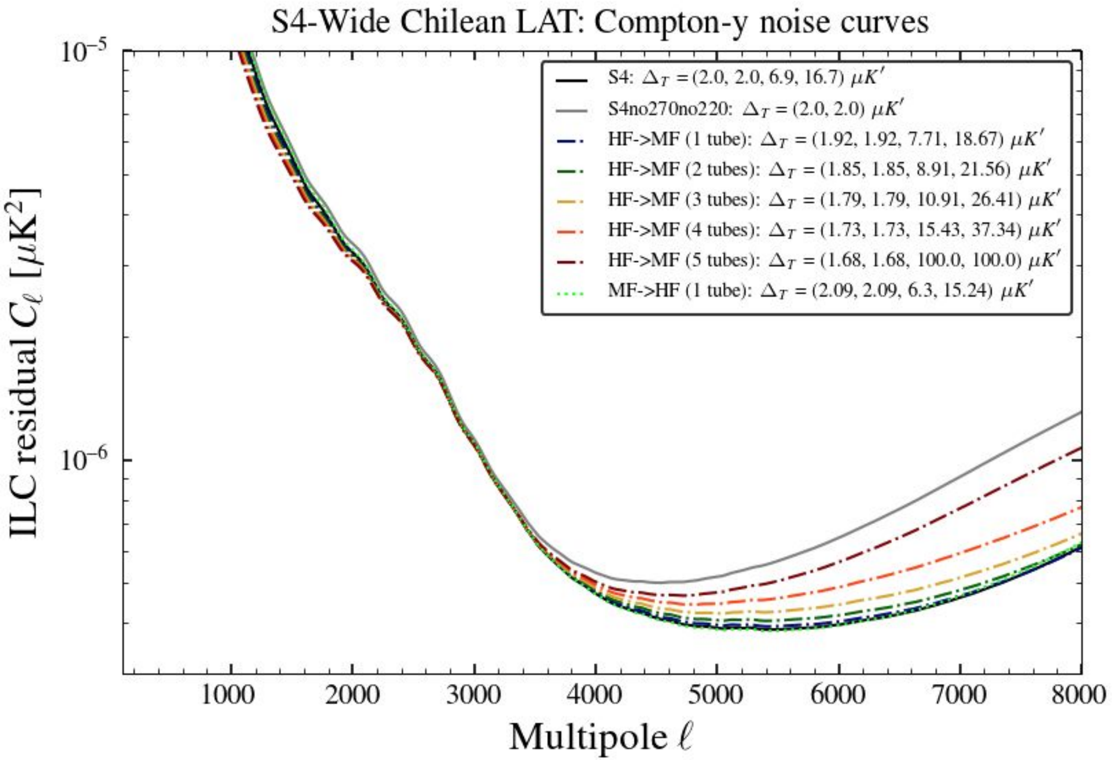
Backup slides

CMB-S4 Compton-y noise curves



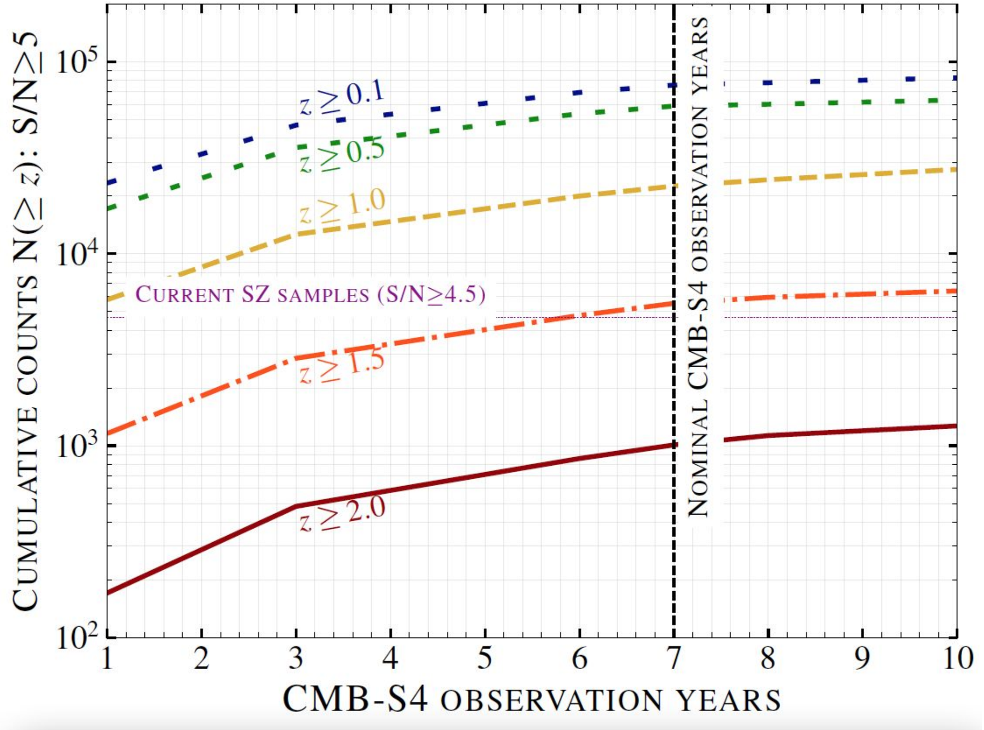
Lensing mass estimates to enable parameters constraints

CMB lensing mass calibration: **Average mass of the sample**

Survey	f_{sky}	Cluster counts		Median mass M500c [10^{14} Msol]		Lensing mass error M500c [10^{14} Msol]	
		Total	z>=2	Total	z>=2	Total	z>=2
S4-Wide	0.5	75701	992	1.6	0.8	0.02	0.31
S4-Ultra deep	0.03	13699	341	1.0	0.6	0.05	0.55

- Foregrounds (tSZ/kSZ) in temperature-based lensing reconstruction are not an issue because we have multiple fancy estimators now.
- S4-Ultra deep lensing is dominated by polarisation.
- ***Combing T and P, we can measure the average mass of z≥2 clusters at 18-20 per cent level with S4-Wide or S4-Ultra deep.***

CMB-S4 cluster forecasts: Expected counts



Look into arXiv:2107.10250 for more details.

Virialisation mechanism of distant clusters (Remove(?))

What about the virialisation process of high-z clusters?

- **Observations:** Only one cluster at z~2. Mantz et al. 2014, 2018 (arXiv: 1401.2087, 1703.08221) find the properties of this cluster to be consistent with low-z clusters.
- CMB-S4 will make a giant leap in the field of cluster science.

$$Y_{SZ_{500c}} = \mathrm{v}(z)\ Y_*\ \left[\frac{h}{0.7}\right]^{-2+\alpha} \left[\frac{M_{500c}}{M_*}\right]^{\alpha} \left[\frac{D_A(z)}{100\mathrm{Mpc}}\right]^{-2} E^{2/3}(z)$$

Planck Y_{SZ}- M scaling relation with a constant HSE bias.

Model 1: $\mathrm{v}(z) = \eta_{\mathrm{v}}(z)\ (1 - b_{\mathrm{HSE}})^{\alpha}$

Simple linear scaling.

Model 2: $\mathrm{v}(z) = A_{\mathrm{v}}\ln(1+z) + B_{\mathrm{v}}$

Analytic model tested using simulations.