Measurement Goals & Science Requirements

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CMB-S4 / SO Workshop March 1, 2022

Charge

- Compare the use of SO and ASO with the CMB-S4 baseline to meet science requirements. (slide 14-17)
- Are the current estimates of using ASO to replace a CMB-S4 CHLAT/ LATR good enough or is more simulation/estimation needed to show scientific performance? (slide 18)
- Compare the map depth estimates from the two projects from their currently planned surveys. (slide 11)
- Also provide a simplified analysis based on comparing estimates of target sensitivities for single detectors in each band for the SO LATR versus the CMB-S4 LATR (slide 13), combined with adjustments for survey sizes and durations.
- Are the scan strategies for the two projects (for LATs in Chile) aligned, regarding cadences for time domain targets? (slide 8)
- Describe the benefits to CMB-S4, and particularly to the time domain community, for continued operation of SO between the start of SO operations and the start of CMB-S4 operations, if the ASO MSRI-2 proposal is not funded. (slide 18)

CMB-S4 Science Goals

Science Goals and associated Science Requirements are designed to enable the full range of CMB-S4 Science

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.

CMB-S4 Science Requirements

Science Requirement 1.0: CMB-S4 shall test models of inflation by putting an upper limit on r of $r \leq 0.001$ at 95% confidence if $r = 0$, or by measuring r at a 5σ level if $r > 0.003$.

Science Requirement 2.0: CMB-S4 shall determine $N_{\rm eff}$ with an uncertainty ≤ 0.06 at the 95% confidence level. ⟸ **Chile LAT**

Science Requirement 3.1: CMB-S4 shall detect at $\geq 5\sigma$ all galaxy clusters at $z \geq 1.5$ with an integrated Compton $Y_{\rm SZ,500} \geq 2.4 \times 10^{-5}\,\rm arcmin^2$ over at least 50% of the sky. ⟸ **Chile LAT**

Science Requirement 3.2: CMB-S4 shall detect at $\geq 5\sigma$ all galaxy clusters at $z \geq 1.5$ with an integrated Compton $Y_{\rm SZ,500} \geq 1.2 \times 10^{-5}\,\rm arcmin^2$ over at least 3% of the sky.

Science Requirement 4.1: CMB-S4 shall detect GRB afterglows brighter than 30 mJy at 93 and 145 GHz over at least 50% of the sky and enable followup by issuing timely alerts to the community. ⟸ **Chile LAT**

Science Requirement 4.2: CMB-S4 shall detect GRB afterglows brighter than 9 mJy at 93 and 145 GHz over at least 3% of the sky and enable followup by issuing timely alerts to the community.

CMB-S4 Chile LAT Measurement requirements
Reqts 2.0, 3.1, & 4.1

Measurement Requirement 2.0: CMB-S4 shall measure Stokes I, Q, and U over 60% of the sky at frequencies of 25, 40, 90, 150, 230, and 280 GHz, with angular resolutions of 7.4, 5.1, 2.2, 1.4, 1.0, and 0.9 arcminutes, respectively, with I-map noise levels $\leq$ 21.8, 12.4, 2.0, 2.0, 6.9 , and 16.7 μK-arcmin, respectively, and Q/U-map noise levels of $\leq$ 30.8, 17.6, 2.9, 2.8, 9.8, and 23.6 μK-arcmin, respectively. Maximum noise levels as a function of multipole are given in Figure 17.

Measurement Requirement 3.1: CMB-S4 shall measure I over 60% of the sky at frequencies of 25, 40, 90, 150, 230, and 280 GHz, with angular resolutions of 7.4, 5.1, 2.2, 1.4, 1.0, and 0.9 arcminutes, respectively, with I-map noise levels $\leq$ 21.8, 12.4, 2.0, 2.0, 6.9 , and 16.7 μK-arcmin, respectively. Maximum noise levels as a function of multipole are given in Figure 17.

Note: Measurement Reqt 2.0 driven by N_{eff} includes Reqt 3.1 driven by Clusters

CMB-S4 Chile LAT Measurement requirements
Reqts 2.0, 3.1, & 4.1

Measurement Requirement 4.1: During normal operations, CMB-S4 shall measure I, Q, and U at 90 and 150 GHz, over $\geq 25\%$ of the sky daily, with angular resolution $\leq$ 3.0 arcminutes and noise level $\leq 10\,\mathrm{mJy/day}$. At least 90% of the time, the same $\geq 25\%$ of the sky shall be observed for ≥ 5 consecutive days.

Notes:

- Measurement Reqt 4.1 driven by GRB, written to be achievable when accounting for Sun and Moon avoidance and other observational practicalities.
- Needs to be revisited to include false detection rate on daily cadence

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CMB-S4 Chile LAT Measurement requirements
Reqts 2.0, 3.1

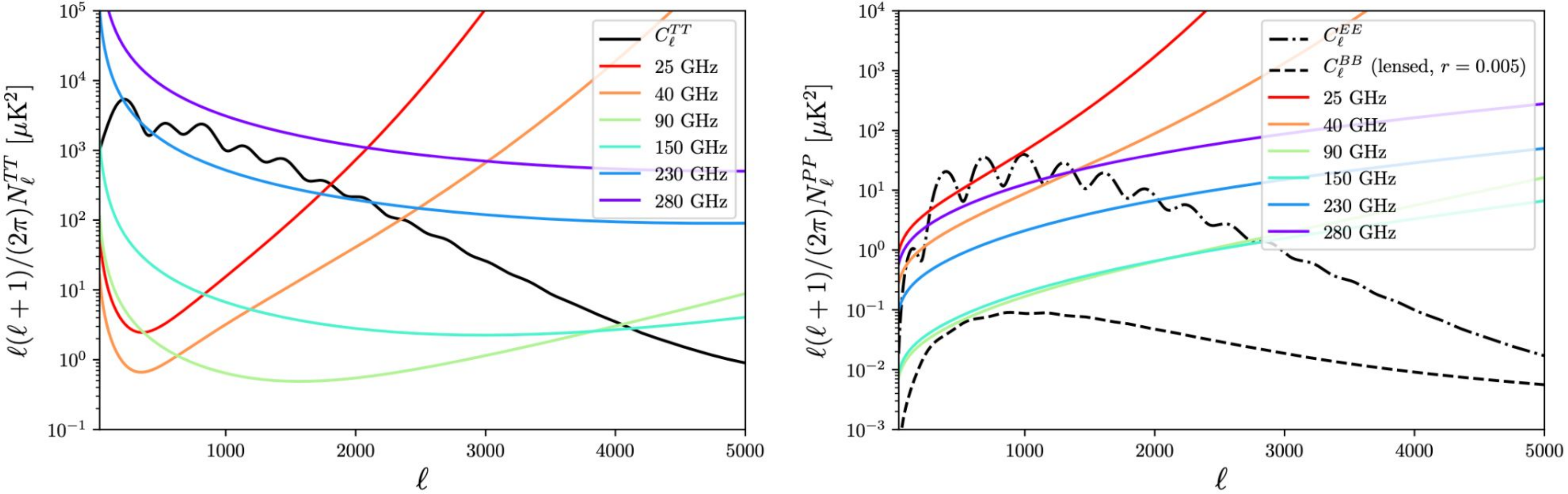

Figure 17: Required noise as a function of multipole for each frequency in intensity (left) and polarization (right) for the high-resolution, wide and deep survey of 60% of the sky.

For reference: These correspond to the PLR per wafer white-noise sensitivities [62.2, 33.4, 13.5, 14.8, 31.0, 75.7 uk-rt(s) in each of these bands] and other reasonable assumptions, e.g., observing efficiencies, 1/ell knee, etc.

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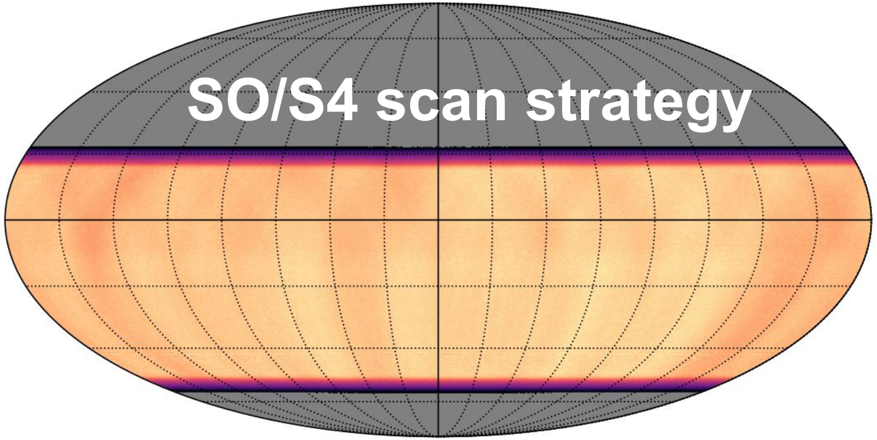
CMB-S4 CHLAT & SO Survey

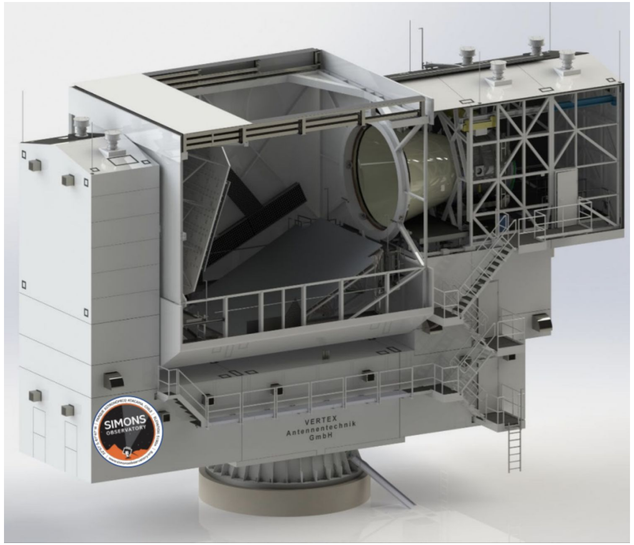
- Nominal SO / CMB-S4 scan strategy from Reijo
  - Elevation 40º
  - Varying scan speed
  - Sun avoidance
  - Meets sky area and cadence requirements
- SO scan strategy
  - This strategy was developed after SO's initial planning
  - AWGs already forecasting with this strategy
  - The gears are in motion to formally adopt this strategy soon



The SO strategy meets the uniformity and cadence requirements of CMB-S4

CMB-S4 CHLAT & SO design

They are same; see LAT talk for caveats (co-rotator, receiver deployment, etc)



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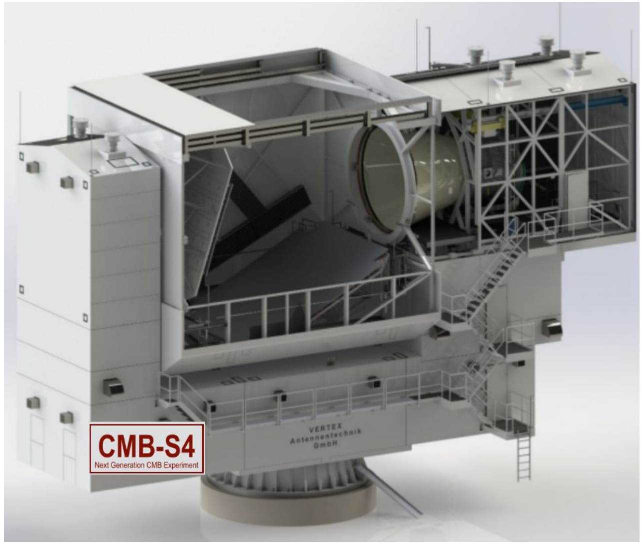
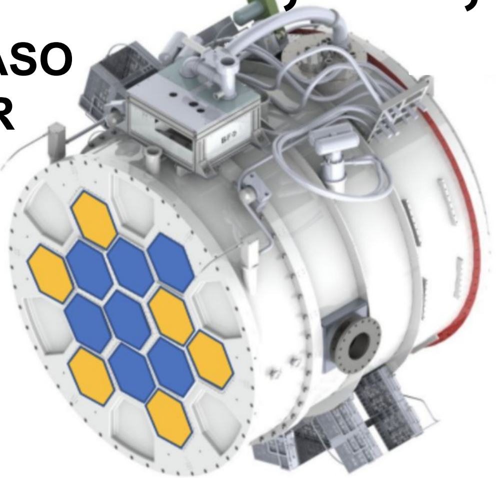
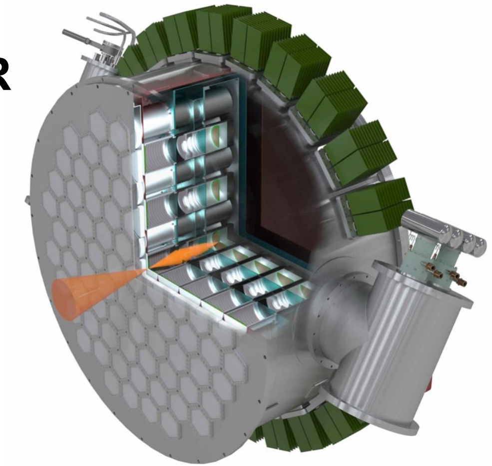


CMB-S4, SO, & ASO LATRs

SO/ASO LATR



S4 LATR



- **SO LATR**
  - 7 of 13 optics tube cryostat filled (blue)
    - Each tube contains 3 detector wafers, at f# 2.06
  - 21 wafers total
    - LF = 3 wafers, MF = 12 wafer, UHF = 6 wafers
  - Wafer Count Ratio to CMB-S4: 3/8, 12/54, 6/23 (note S4 'HF' = SO 'UHF')
- **ASO LATR**
  - Same as SO, with all 13 optics tubes filled
  - 39 wafers total
    - LF = 3 wafers, MF = 24, UHF = 12
  - Wafer Count Ratio to CMB-S4: 3/8, 24/54, 12/23
- **S4 LATR**
  - 85 single wafer optic tube cryostat, at f# 1.9
  - 85 wafers total
    - LF = 8, MF = 54, HF = 23 wafers

SO & ASO Survey

- Managing both SO and ASO projects to achieve “goal” performance. See next slide for status of testing
- The noise levels here are for f_sky = 0.40, and should be multiplied by 1.2 for comparison to the f_sky = 0.60 S4 survey.
- To achieve the CMB-S4 survey reqt depths ASO integration time or detector count would need to be increased by a factor of
  LF: 4.6,3.7; MF: 4.4,5.2, UHF: 2.5,2.5

SO

Frequency (GHz)	FWHM (arcmin)	Baseline (μK-arcmin)	Goal (μK-arcmin)	Frequency Bands	Detector Number	Optics Tubes
27	7.4	71	52	LF	222	1
39	5.1	36	27		222	
93	2.2	8.0	5.8	MF	10,320	4
145	1.4	10	6.3		10,320	
225	1.0	22	15	UHF	5,160	2
280	0.9	54	37		5,160	

ASO

Frequency (GHz)	FWHM (arcmin)	Baseline (μK-arcmin)	Goal (μK-arcmin)	Frequency Bands	Detector Number	Optics Tubes
27	7.4	58	39	LF	222	1
39	5.1	30	20		222	
93	2.2	5.25	3.5	MF	20,640	8
145	1.4	5.7	3.8		20,640	
225	1.0	14	9	UHF	10,320	4
280	0.9	33	22		10.320	

Table goal values should be multiplied by 1.2x to account for f_sky=0.60 in comparisons with the CMB-S4 map depth requirements.

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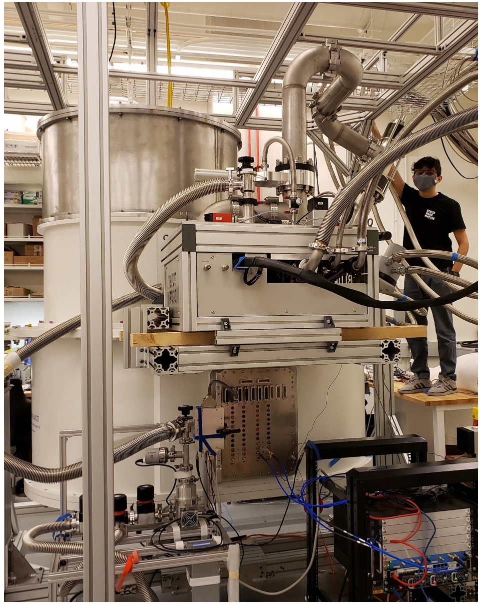
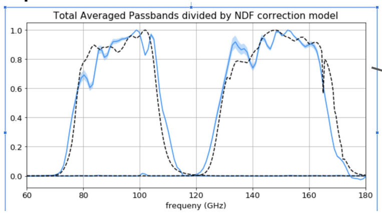
Optics Tube: Integrated Performance

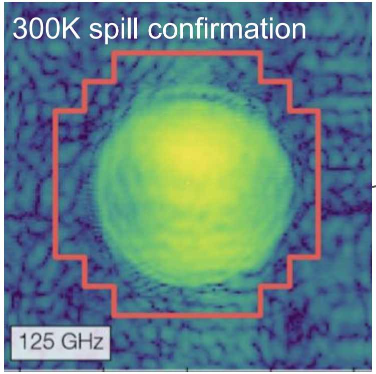
SO is deep into the testing and verification phase with LAT MF verification nearly complete

LATR-tester

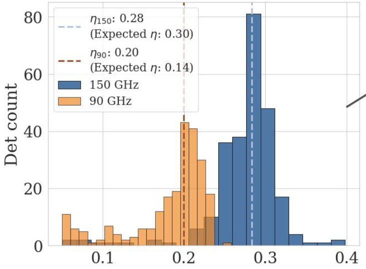


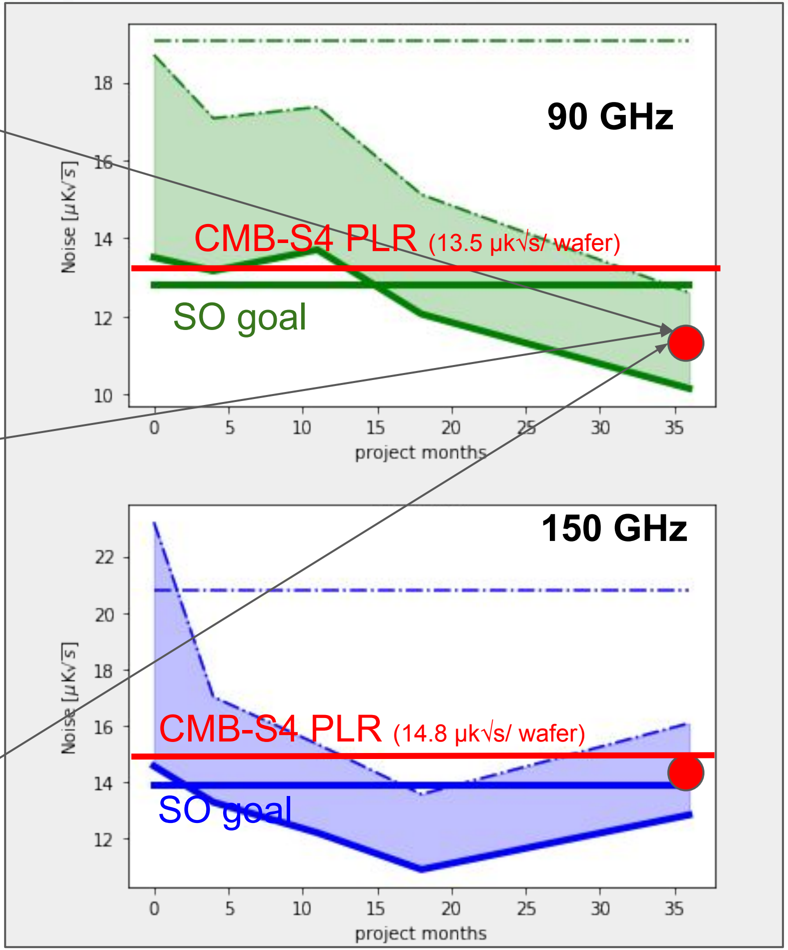
pass-band confirmation





optical efficiency confirmation





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CMB-S4

Comparison CMB-S4 / SO / ASO sensitivity

- Model presented here is based on common assumptions for SO / S4
  - Assumptions of common components are identical
  - differences in per wafer mapping speed almost entirely derived from the estimated difference in f# for S4
  - Difference in system mapping speed come down to the number of wafers (2.25x more in MF) and f/# (1.1x average in MF)
  - These ratios can be used to compare forecasts

This is the detector sensitivity comparison

Flat band model, nominal optics tubes with assumptions made equal where possible.							
		LF_1	**LF_2**	**MF_1**	**MF_2**	**HF_1**	**HF_2**
S4	P_optical (pW)	0.23	1.21	1.37	4.16	11.54	16.09
(One LAT)	NET_wafer (uKrtsec)	39.07	26.10	11.01	10.85	24.01	61.02
	Number of wafers	8	8	54	54	23	23
	NET_total (uKrtsec)	13.81	9.23	1.50	1.48	5.01	12.72
ASO	P_optical (pW)	0.18	0.94	1.04	3.28	9.97	14.95
	NET_wafer (uKrtsec)	42.17	28.75	11.78	11.17	24.61	59.82
	Number of wafers	3	3	24	24	12	12
	NET_total (uKrtsec)	24.35	16.60	2.40	2.28	7.10	17.27
	S4/ASO 1-wafer mapping speed ratio	**1.16**	**1.21**	**1.15**	**1.06**	**1.05**	**0.96**
(One LAT)	**S4/ASO total mapping speed ratio**	**3.11**	**3.24**	**2.58**	**2.38**	**2.01**	**1.84**

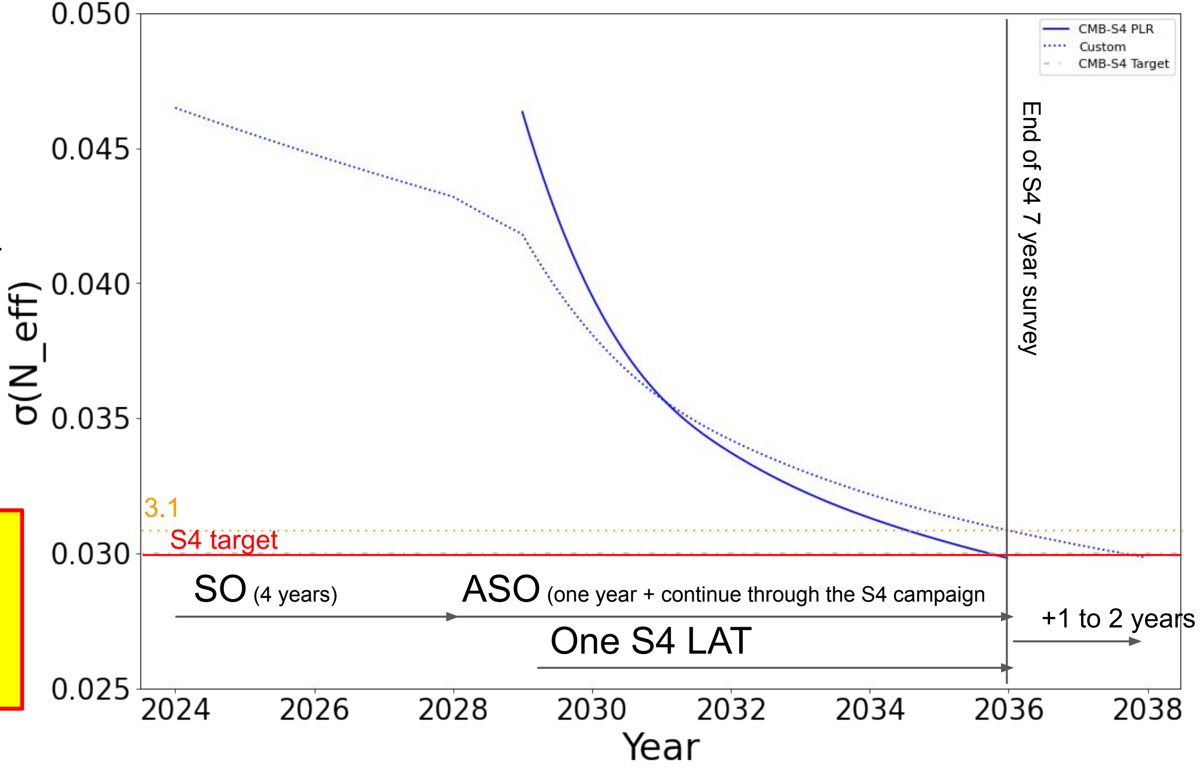
Back of the Envelope comparison

- Based on the sensitivity analysis on the last slide, the MF sensitivity of ASO is roughly equivalent to 0.4 CMB-S4 LATs (SO is 0.2)
- The **CMB-S4 survey is 14 CMB-S4 LAT years (14 S4Ly)**
- Consider an alternative survey using SO and ASO
  - SO operates from 2024 to 2028, 4 years
    - 4*0.2 = 0.8 S4Ly
  - ASO operates in 2028 (one year)
    - 0.4 S4Ly
  - One CMB-S4 LAT and ASO operate from 2029 to 2036 (7 years)
    - 7*1.4 = 9.8 S4Ly
    - The instantaneous sensitivity is reduced by a factor of 1.2 compared to S4
- The total **survey weight of this alternative configuration is 11 S4Ly**
  - 3 additional S4Ly would be needed to equal the CMB-S4 survey (14 S4Ly total)
    - This could be achieved by extending S4 operations 2.15 additional years, which is costly
    - Running SO alone would require 7.5 years to make up this deficit
    - The f# difference makes only a small change to this picture

N_{eff} forecast with SO, ASO, and one S4 LAT

- Toy forecast made with [this](#) tool
- Gives a snapshot of the situation
  - Confirms the need for ~2 additional years to achieve the S4 survey requirements.
  - This alternative configuration misses the N_eff targets, but potentially by a small amount.

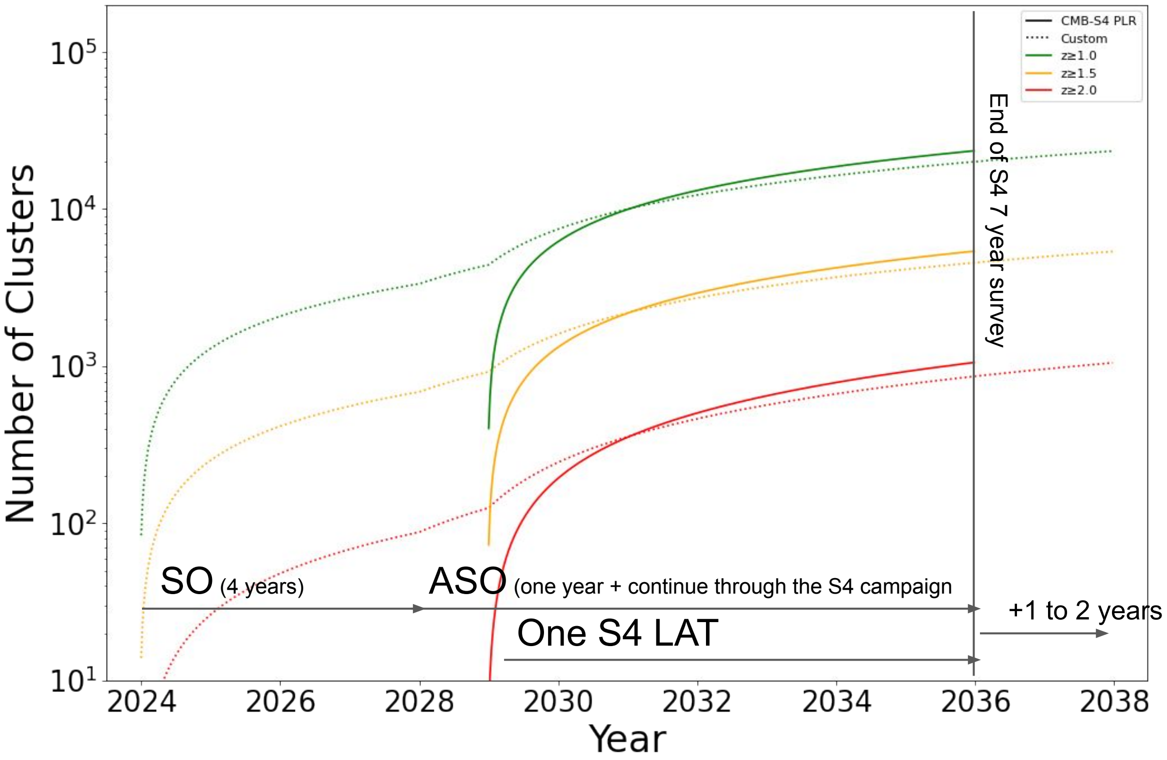
More work is needed to quantify the performance of this alternative configuration



Impact on Cluster Science Goal

Forecast made with this tool

Projection is consistent with the CMB-S4 goal to detect z > 2 clusters, but with ~10% fewer after 7 years



Impact for transients

- Transient detection flux threshold, compared to CMB-S4
  (based on instantaneous sensitivity scaling as square root of mapping speed)
  - SO: 3.3x and 3.1 higher flux threshold at 90 and 150 GHz
  - ASO: 2.3x and 2.2x higher flux threshold
  - ASO + one CMB-S4 LAT: 1.2x higher flux threshold

- SO / ASO forecasts:
  - “we estimate a daily 1 sigma rms sensitivity of 10 mJy for SO nominal. ~7 mJy for ASO” – Susan Clark

- CMB-S4 forecasts:
  - PBDR Appendix A1: “daily cadence and depth of 4.3 mJy/day (90 GHz) and 4.5 mJy/day (150 GHz)”
    (Combining these two bands and scaling with the flux ratio factors above is consistent with SC’s SO/ASO estimate)

- Comparison to CMB-S4 science requirement
  - Science Reqt 4.1: “Detect all GRB afterglows brighter than 30 mJy at 93 and 145 GHz over 50% of the sky” leads to >6 sigma detection threshold to ensure less than one false detection per map per day
  - CMB-S4 achieves 7.0 and 6.6 sigma at 93 and 145 GHz, respectively.
  - ASO + 1 S4 LAT achieves and 5.8 and 5.6 sigma, which leads to a higher false detection rate or a somewhat higher flux threshold.

Summary

- CMB-S4 CHLAT and the SO LAT are essentially interchangeable
- CMB-S4 and SO scan strategies are compatible
- A CMB-S4 LATR is roughly
    - a factor of 4 to 5x faster in MF and HF bands and 3x in LF than SO nominal LAT/LATR
    - a factor of 2 to 2.5x faster in MF and HF bands and 3x in LF bands than ASO LAT/LATR
- Further detailed science projections are needed, but it appears that
    - CMB-S4 transient science goals are almost met by a CMB-S4 CHLAT/LATR and a SO-LAT/LATR, may require a 10% higher daily detection flux threshold.
    - The CMB-S4 N_{eff} and Cluster science goals are not met by a CMB-S4 CHLAT/LATR and SO-LAT/LATR including 4 years of data from SO nominal, 8 years of SO LAT/LAT
- To replace a CMB-S4 LAT/LATR with an ASO LAT/LATR requires either
    - the CMB-S4 science goals need to be relaxed, or
    - additional observing time is needed
- The *benefits to CMB-S4, and particularly to the time domain community, for continued operation of SO between the start of SO operations and the start of CMB-S4 operations, if the ASO MSRI-2 proposal is not funded*, are reducing risk, DM implementation, insights to transient phenomenology (also by SPT), and contemporaneous observations with LSST (also by SPT).