CMB-S4 Study to Support the Alternative Analysis and Selection

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on behalf of the AoA Study group

Outline

- What is the Analysis of Alternatives Study?
- Overview of the AoA Study and the work remaining
- Non-*r* forecasts for the alternatives
- Foreground models
- *r*-forecasts method, initial results, and next steps
    - Deaggregation of factors leading to achieved performance
    - Delensing validation
    - Map validation of Fisher-based r-forecasts
- Discussion

Reminder about the Analysis of Alternatives (AoA)

A DOE requirement for CD-1 is a reviewed AoA document for which the alternatives to be analyzed are agreed to in advance with the DOE. It covers the science reach, construction and lifecycle costs, schedule, and risks (both science and technical). See DOE G 413.3-22 AoA guide.

This talk is focused on a document that covers the scientific reach of the alternatives that will inform the DOE AoA document. It is entitled the ***"CMB-S4 Study to Support the Alternative Analysis and Selection."*** We refer to it as the ***AoA Study***.

We will also need the AoA Study for justification of our alternative to NSF at CDR, and will likely get new additional CDR guidelines beforehand.

This means we should complete the AoA Study in June, or earlier.

Reminder of the 2022 Analysis of Alternatives Exercise

As you know, in Feb 2022 DOE and NSF requested that the CMB-S4 Project perform an analysis of alternatives (AoA) to assess options for configuration of the project that place reduced demands on infrastructure and logistics at the South Pole compared to those required by the design at that time and that can achieve all of the science goals.

Following an initial set of studies, three alternatives were selected for detailed analysis.

Alternative	South Pole Scope	Chile (Atacama) Scope
Alternative 1: SATs & LAT at South Pole	3 Small-Aperture Telescopes 1 Large-Aperture Telescope	2 Large-Aperture Telescopes
Alternative 2: Only SATs at South Pole	4 Small-Aperture Telescopes	3 to 5 Large-Aperture Telescopes
Alternative 3: Nothing at South Pole	None	≥9 Small-Aperture Telescopes ≥3 Large-Aperture Telescopes

Reminder of the 2022 Analysis of Alternatives Exercise

A great deal of the Project's and Collaboration's effort in 2022 was devoted to working on the AoA.

A tremendous amount of work was done by many of you (thank you!) and documented on confluence. It was a huge effort.

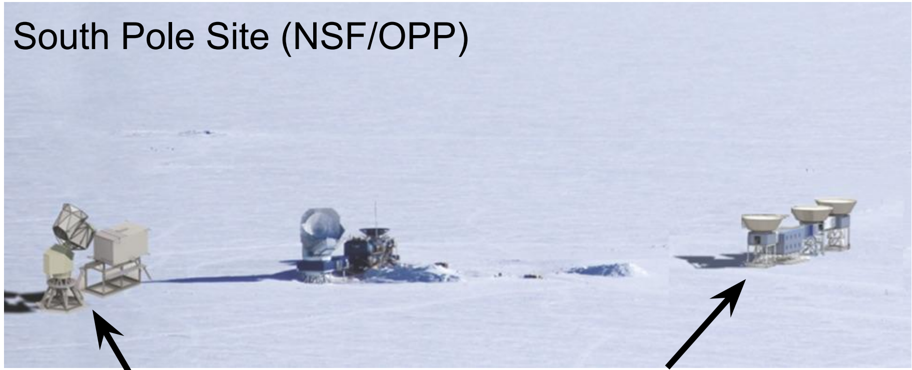
The process and results were vetted by the Collaboration on Oct 12 & 14, reviewed by an external panel of experts on Nov 4-5, and presented to the agencies on Dec 7, 2022.

The process resulted in the new conceptual design for CMB-S4.

The Conclusion of the 2022 AoA

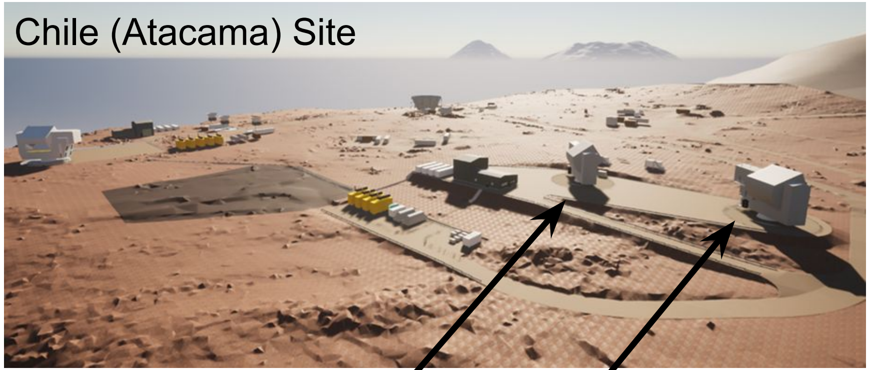
Alternative 1 was determined to be the best configuration because:

- The South Pole offers the best conditions for the ultra-deep survey focused on inflation science.
- The combination of small- and large-aperture telescopes observing the same patch of the sky provides unique checks on systematic errors.
- The Atacama site in Chile provides excellent conditions for the deep, wide-field survey with 2 large-aperture telescopes that addresses N_{eff} and many other science goals.



One Large Aperture (5 m) Telescope

3 Small Aperture Telescopes (9 0.56-m aperture optics tubes)



Two Large Aperture (6 m) Telescopes

So are we done with the AoA?

No, unfortunately.

We still need to write the DOE required AoA document and the supporting science study, i.e., the AoA Study.

In addition, we also need to add **Alternative 0, “status quo”** which is to do nothing new. We interpret this as continued operation of the South Pole Observatory and the upcoming Simons Observatory.

While a lot of the AoA Study effort has been completed over the last year and most of it is written up, there is still important work yet to be addressed.

Status the AoA Study

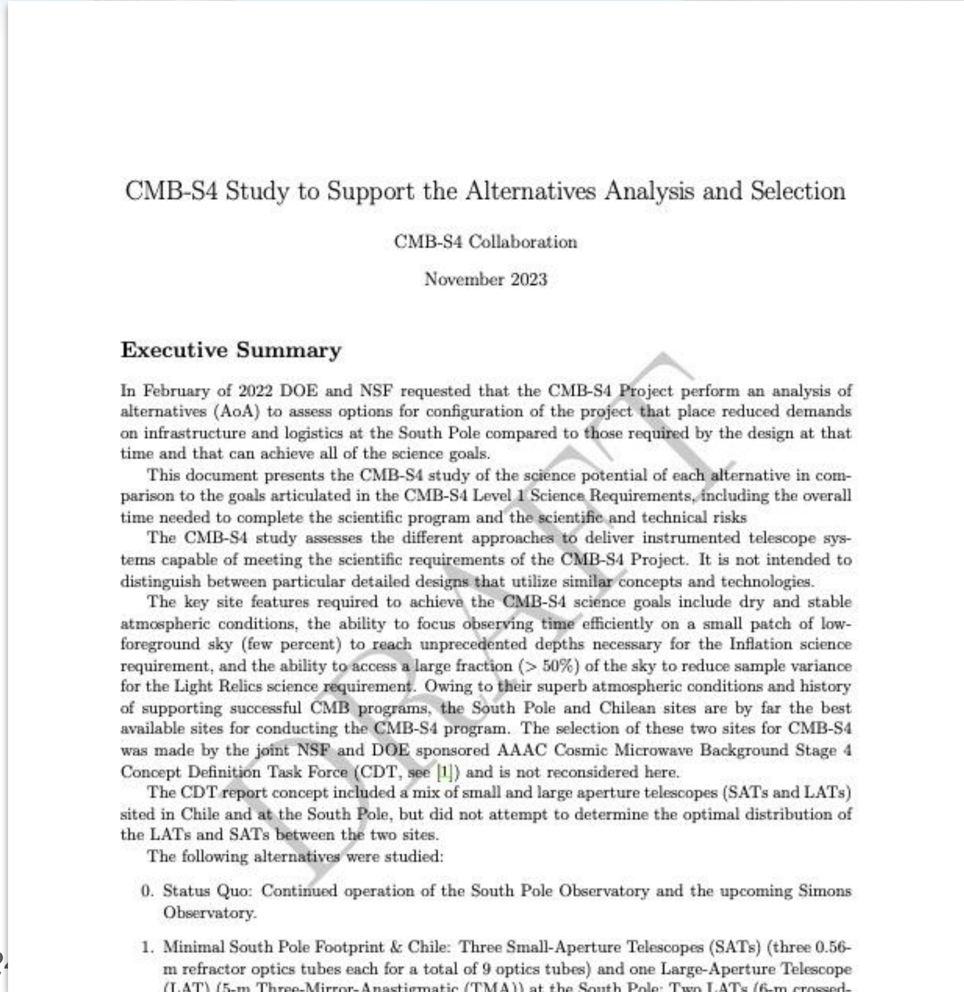
Builds on 2022 AoA effort which was reviewed and presented to NSF/DOE

It is the “write up” of that work which will support the required AoA document, which will be reviewed along with the AoA Study.

A draft AoA Study was reviewed at the November 2023 Directors Review

It includes feedback and anticipates additional requests from NSF/DOE

It is on the CMB-S4 Github repository and accessible via Overleaf.



CMB-S4 Study to Support the Alternatives Analysis and Selection

CMB-S4 Collaboration

November 2023

Executive Summary

In February of 2022 DOE and NSF requested that the CMB-S4 Project perform an analysis of alternatives (AoA) to assess options for configuration of the project that place reduced demands on infrastructure and logistics at the South Pole compared to those required by the design at that time and that can achieve all of the science goals.

This document presents the CMB-S4 study of the science potential of each alternative in comparison to the goals articulated in the CMB-S4 Level 1 Science Requirements, including the overall time needed to complete the scientific program and the scientific and technical risks

The CMB-S4 study assesses the different approaches to deliver instrumented telescope systems capable of meeting the scientific requirements of the CMB-S4 Project. It is not intended to distinguish between particular detailed designs that utilize similar concepts and technologies.

The key site features required to achieve the CMB-S4 science goals include dry and stable atmospheric conditions, the ability to focus observing time efficiently on a small patch of low-foreground sky (few percent) to reach unprecedented depths necessary for the Inflation science requirement, and the ability to access a large fraction (> 50%) of the sky to reduce sample variance for the Light Relics science requirement. Owing to their superb atmospheric conditions and history of supporting successful CMB programs, the South Pole and Chilean sites are by far the best available sites for conducting the CMB-S4 program. The selection of these two sites for CMB-S4 was made by the joint NSF and DOE sponsored AAAC Cosmic Microwave Background Stage 4 Concept Definition Task Force (CDT, see [1]) and is not reconsidered here.

The CDT report concept included a mix of small and large aperture telescopes (SATs and LATs) sited in Chile and at the South Pole, but did not attempt to determine the optimal distribution of the LATs and SATs between the two sites.

The following alternatives were studied:

0. Status Quo: Continued operation of the South Pole Observatory and the upcoming Simons Observatory.

1. Minimal South Pole Footprint & Chile: Three Small-Aperture Telescopes (SATs) (three 0.56-m refractor optics tubes each for a total of 9 optics tubes) and one Large-Aperture Telescope (LAT) (5-m Three-Mirror-Anastigmatic (TMA)) at the South Pole; Two LATs (6-m crossed-

DRAFT

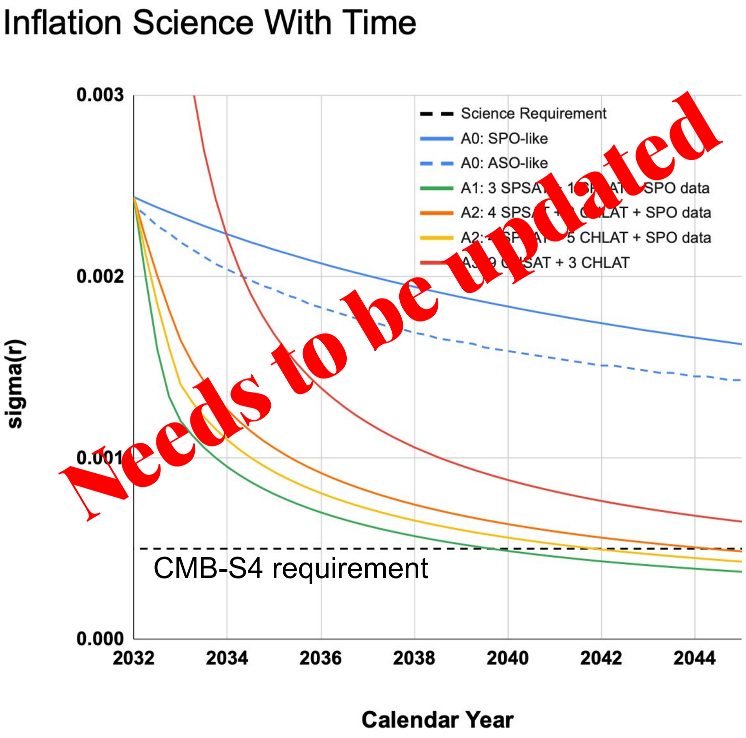
Contents

What's left to do for the AoA Study?

- The **non-*r*** AoA analyses are essentially done.
- The AoA Study currently provides a solid ***comparative analysis*** of the *r* forecasts of the various alternatives, which are based on scaling from achieved performance from the South Pole, which are in turn 'transferred' to Chile.
- We have considered three foreground models of varying complexity for the forecasts; for the final AoA Study results, we should probably assume only one benchmark model for comparison.
- We should probably report the results of only one benchmark forecasting methodology if we understand why it works best. We would like to show map-based validation of the Fisher-based forecasts.

What's left to do for the AoA Study?

- Based on feedback and anticipated requests from NSF for CDR, we need to provide simple comparative plots of σ(r) v time for the alternatives.
- To aid in comparing our results with those for other experiments, we need to provide the breakdown of the major factors that lead from idealized *r* forecasts to those using achieved performance.



Reminder of our Science Requirements

SR 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 $r > 0.003$. **[$\sigma(r) \leq 5 \times 10^{-4}$]**

SR 2.0: CMB-S4 shall determine N_{eff} with an uncertainty ≤ 0.06 at the 95% confidence level.

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

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

SR 4.1: CMB-S4 shall detect GRB afterglows brighter than 30 mJy at 90 and 150 GHz over at least 50% of the sky and enable followup by issuing timely alerts to the community.

SR 4.2: CMB-S4 shall detect GRB afterglows brighter than 9 mJy at 90 and 150 GHz over at least 3% of the sky and enable followup by issuing timely alerts to the community.

General Considerations for Non-r Science

Alt 0: Status Quo: Higher noise levels - would require ~35 years of observing with advanced SO.

Alt 1. 3 SATs and 1 LAT at South Pole & 2 LATs in Chile: Preliminary Baseline Design - constructed to meet Science Requirements

Alt 2. Only SATs at the South Pole and increased LATs in Chile: Wide survey unchanged compared to Alternative 1, Delensing survey wider ($f_{sky}\uparrow$) and shallower ($N_{ell}\uparrow$) with smaller beam ($\theta_b\downarrow$)

Alt 3. All Telescopes in Chile: Very similar to Alternative 2 for non-r science, since SATs do not contribute to other Science Requirements

AoA Study Results for Non-r Science

Science Case	Requirement	Alt 1	Alt 2a	Alt 2b	Alt 3
Light Relics	MR 2.0	✓	✓	✓	✓
	SR 2.0	✓	✓	✓	✓
Clusters	MR 3.1	✓	✓	✓	✓
	SR 3.1	✓	✓	✓	✓
	MR 3.2	✓	✗	✓	✗
	SR 3.2	✓	✓†	✓	✗‡
Transients	MR 4.1	✓	✓	✓	✓
	SR 4.1	✓	✓	✓	✓
	MR 4.2	✓	✓	✓	✓
	SR 4.2	✓	✓	✓	✓

Light Relics: Benefits from wider sky coverage at fixed effort

Clusters: Benefits from smaller beam, negatively impacted by higher noise

Transients: Benefits from smaller beam, negatively impacted by higher noise

†: Despite failing Measurement Requirement 3.2 due to the higher noise in the delensing patch, the smaller beam of Alternative 2 compared to Alternative 1 allows Science Requirement 3.2 to still be met in this case.

‡: Alternative 3 fails both Measurement Requirement 3.2 and Science Requirement 3.2 due to the higher noise in the delensing survey; in this case the integrated Compton $Y_{\mathrm{SZ}_{500c}}$ will be slightly larger than that of Science Requirement 3.2, though the wider sky coverage implies that a greater number of clusters will be detected.

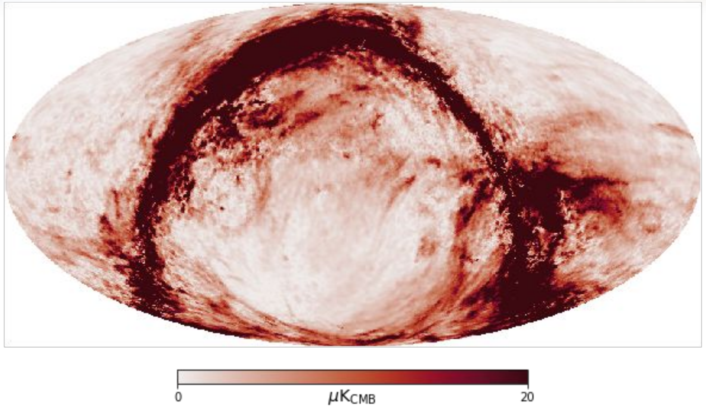
Table 16: Summary of the performance of the Alternatives with regard to the Measurement Requirements and Science Requirements for the science cases other than primordial gravitational waves.

Foreground models

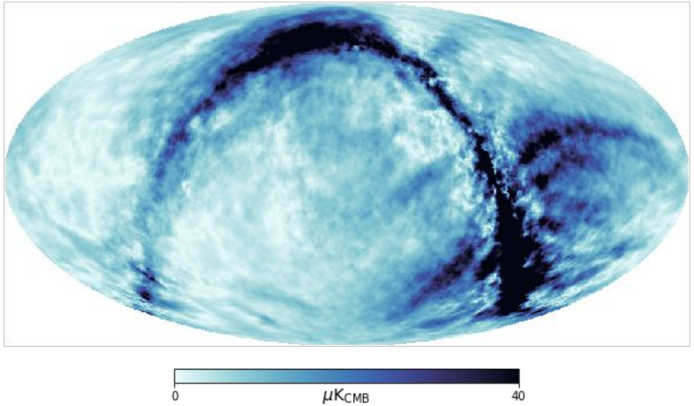
- New suite of PySM models developed by PanEx Group
  - Improved emission templates based on latest component separation analyses
  - Small-scale fluctuations in amplitudes as well as spectral parameters
  - “Layer model” (MKD) with line-of-sight frequency decorrelation (2018 MNRAS, 476, 1310)
- Three sky models, all consistent with current data:
  - **Best Estimate:** Parameter maps based on component separation with extrapolation to small scales in both amplitudes and spectral parameters
  - **Low Complexity:** Small-scale fluctuations in amplitudes only, no decorrelation
  - **High Complexity:** Near maximum-allowed decorrelation for dust emission, line-of-sight dust SED variations, AME polarization, synchrotron curvature

Available on Github: https://github.com/galsci/pysm

353 GHz P



30 GHz P



Foreground models

Updates since December 2022 Meeting

- Finalized implementation of small scale emission, making the transition from data-driven large scales to synthetic small scales more smooth (transition point less evident in power spectra)
- Models distributed as a stable PySM release (v3.4.0)
- ApJ paper describing models in late draft stage

Ongoing Work for AoA

- Discrepancy between (noisy) Planck templates and BK constraints on dust BB in the BK patch: does adjusting the dust intensity in this patch affect AoA? Preliminary results suggest no, but a future goal is to incorporate information from partial sky datasets into PySM foreground models

r-forecasts method, initial results, and next steps

Forecasting $\sigma(r)$ is challenging, and comparison between the alternatives intersects with many of these challenges:

- **Foregrounds**: The alternatives have different sky coverage, so we need to understand how foreground complexity varies between the observing patches.
- **Delensing**: Each of the three alternatives has a different configuration of LAT(s) to achieve the necessary level of delensing.
- **Systematics**: Impact of instrumental systematics is hard to evaluate. BICEP has proven performance for a particular site and instrument design. Variations like HWP for SATs in Chile could help in some ways but hurt in others.

r-forecasts method, initial results, and next steps

To compare between alternatives, we tried to simulate the differences that we understand:

- Varying detector counts (SAT and LAT) across the alternatives
- Geometric sky coverage effects (deeper vs wider surveys)
- Variation in foreground amplitude *and complexity* over the sky -- partially understood by using a suite of data-driven foreground models
- Estimates for the difference in observing efficiency between sites due to length of observing season, differences in weather/PWV, sun/moon avoidance, etc.
- Effect of PWV variations and scan elevation on detector NET

Low-ell noise levels were normalized based on scaling from achieved performance, so effects that matter are ones that differ between alternatives.

We have not attempted to simulate differences in systematics.

r-forecasts method, initial results, and next steps

Forecasting yields estimated noise levels vs time for SATs and LATs.

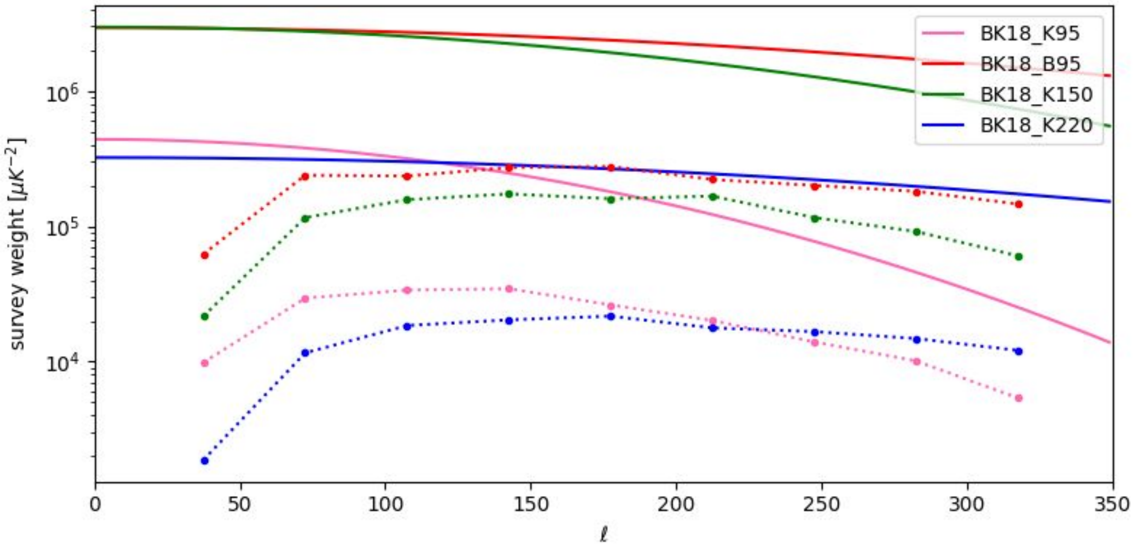
- LAT noise is used to estimate residual A_{lens} after delensing [Raphael]
- Two independent Fisher forecasts are used to estimate $\sigma(r)$ after component separation for three different foreground models (low, medium, high complexity)
    - Parametric likelihood analysis of auto/cross spectra (BICEP style analysis) [Colin]
    - Harmonic-space internal linear combination [Raphael]
- Both forecasts agree that alternative 1 reaches the science target fastest.
- We are working to understand disagreements between the two forecasts, especially the impact of varying foreground complexity.

Deaggregation of factors leading to achieved performance

- We have tried to understand, and incorporate into forecasts, factors that differ between the alternatives.
- There is still a need to better understand the differences in performance between *any* CMB-S4 configuration (like Alternative 1) and past/current experiments (BICEP/Keck) that are used for performance-based forecasting.
- We are currently working to deaggregate the factors that lead to achieved BB spectrum sensitivity.
  - Some factors, like detector yield and uniformity, are intended to be better for CMB-S4 than for past experiments.
  - We have little control over other factors, like weather cuts, so should assume that CMB-S4 will suffer similar impact as past experiments.
  - It is important that our model of observing efficiency is still grounded in achieved performance / can explain achieved BB spectrum error bars.

Deaggregation of factors leading to achieved performance

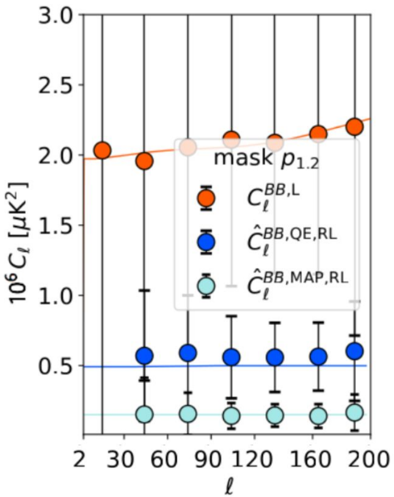
- Figure below shows the difference in survey weight between actual BK18 performance (dotted line with points) and hyper-idealized forecast (24/7 observations, detectors at design NET with perfect yield, etc).
- Figure illustrates that the combination of all factors adds up to factor of ~10 (more at low ell).
- Current ab initio sims contain observing efficiency factors derived from current experiments and have much smaller discrepancy with achieved performance.



Update on delensing for *r* forecasts

- Delensing validation: de-lensing is essential and reconstructions of lensing templates from the LAT maps and their validation (thanks to S. Belkner) is on-going
- This proceeds with software described in details in the recent CMB-S4 delensing paper: https://arxiv.org/abs/2310.06729
- The main limitations of this map-level delensing procedure is now that it must take foreground-cleaned maps as inputs, and its computational cost. Only a few cleaned LAT maps are available just now (where we reach A_L just below 0.06 for Alt 1), so that it is early for detailed quantitative comparisons.
- In previous iterations in the low-ellBB analysis working group the software has been shown to perform according to expectations, also in the presence of foregrounds and noise inhomogeneities.
- We expect this will be the case here as well, and there are no key points of concern at this point about de-lensing

From CMB-S4 delensing paper, Residual lensing BB spectrum results vs predictions for best templates in cyan



Map validation of Fisher-based r-forecasts

- Demonstrating the compatibility of forecasts with (semi-)realistic map-based simulations is required to strengthen the reliability of the conclusions of the AoA.
- In particular, forecasts predict errors, but not biases.
- Recent work on sky modeling recommends three foreground model options. Differences between those three models are representative of our lack of knowledge about the real-sky foreground emission.
- For two of these models (“medium” and “high” foreground complexity), map-based methods that were successful in previous work yield model-dependent, method-dependent biases that range from no detectable bias, to biases of up to r~0.002, which we do not fully understand yet.

Map validation of Fisher-based r-forecasts

- The origin of the biases, and ways to mitigate them, are being investigated. Several recent posts in the CMB-S4 logbook address various aspects of this issue.
- Ongoing work includes:
  - Identifying the origin of the biases and the reason for the difference with earlier results
  - Developing alternative foreground cleaning and mitigation tools, and testing their performance
  - Validation / Consolidation of the foreground models in patches of specific interest
- Significant progress has been made, but this has not fully converged yet.

Discussion

To help with the AoA Study:

- Please consider participating in the joint low-ell BB analysis working group and AoA Study group meetings held Mondays at 9:30am PT / 11:30 am CT / 12:30pm ET (see the CMB-S4 calendar)
- Read and comment on the AoA Study document