Additional Questions for Astro2020 CMB-S4 Evaluation
dated February 19, 2020

Responses provided by CMB-S4 on March 3, 2020

CMB-S4 Technical Risk Related Questions:

1) Please describe the technology maturation required and overall risk to the project for scaling up production of state-of-the-art detector technology to achieve the required production quantities and rate to achieve the project’s schedule. How will yield levels be improved and consistency across multiple production facilities be ensured from current lower than desired detector yields and hand selection of the devices?

The CMB-S4 TES detector technology is highly mature. TES detectors with similar designs and requirements as CMB-S4 have been deployed across many Stage 2 (~1,000 detectors) and Stage 3 (~10,000 detectors) CMB experiments, including: ABS, ACTpol, AdvACT, BICEP2, BICEP3, CLASS, KECK, Polarbear, SPIDER, SPTpol, and SPT-3G. Additionally, these detectors have also been made at several of the fabrication sites being considered for CMB-S4, including: ANL, GSFC, JPL, NIST, and UC-Berkeley. Our costing and production model assumes that for every batch of six candidate wafers, four will be qualified for science operations.

Detectors are on the critical path for the CMB-S4 project and scaling up detector production to deliver the total quantities required is a fully recognized challenge. Ensuring sufficient fabrication throughput with consistent yields is key to reducing schedule and cost risk.

The CMB-S4 fabrication plan has three or more fabrication sites to provide the required production capacity while also mitigating some risk. Each site will have quality control testing incorporated into the production of the wafers. All completed candidate wafers will be tested in fully-integrated modules (including both optical coupling and readout) at dedicated test facilities to characterize their performance. The CMB-S4 cost and schedule conservatively assumes the yield of science grade wafers to be 66%, consistent with the yield achieved by recent Stage 3 projects. Improvements to this yield are likely, but are not required to achieve CMB-S4 goals.

The main challenge with scaling up detector production will be sustaining the required fabrication and testing throughput at a larger scale and a longer period compared to previous efforts. The CMB-S4 fabrication plan mitigates this risk by interleaving dedicated quality control tests over the course of fabricating each batch of six candidate wafers. For every wafer batch in the CMB-S4 schedule, we include fabrication and testing of dedicated quality control wafers (19 for every six candidate science wafers). These quality control wafers include tracking film properties (e.g., deposition/etch rates, stress) along with dedicated cryogenic test structures (e.g. microstrip test structures and TES test structures). The quality control tests will be performed at every fabrication site and the data will be archived as part of an electronic traveler system that is open to the entire multisite fabrication program. The data will be reviewed and used to improve yield and efficiency across all sites.
Equally challenging to scaling up detector production is the required testing of the integrated detector modules. The CMB-S4 schedule includes a full complement of dark and optical tests on every wafer that exits the fabrication line. These tests are planned to be carried out by a suite of identical dedicated cryogenic testbeds at two testing sites (currently planned as four dark cryogenic testbeds and four optical cryogenic testbeds, each equipped to handle six integrated detector modules per cooldown). There will be standard test wafers periodically run in these testbeds to ensure testing consistency from one testbed to another and over time. This extensive testing program will ensure consistency over the duration of the project and across multiple detector fabrication and testing sites.

The CMB-S4 detector fabrication and testing plan outlined above has been developed through a number of internal studies as well as reviews by external experts. Starting in early 2019 the CMB-S4 Integrated Project Office (IPO) established a Detectors and Readout Fabrication Task Force to evaluate fabrication capacity in the U.S. The Task Force validated the assumed yield through a Request for Information (RFI) issued to a large number of fabrication facilities with relevant capabilities and experience. The information provided in response to the RFI provided production rates and yields across multiple fabrication sites. These rates and yields are consistent with the assumptions used in the CMB-S4 project planning. The Task Force also found that at least three fabrication sites should be pursued to mitigate risk. The IPO followed-up this Task Force finding by conducting a detector fabrication readiness review by independent experts of plans for scaling up detector fabrication capacity and evaluating the production readiness of the three DOE laboratories (ANL, LBNL/SeeQC, and SLAC). This external fabrication readiness review found the three DOE laboratories would be sufficient for meeting the CMB-S4 requirements. In early 2020 the IPO formed the CMB-S4 Detector Fabrication Group (CDFG), a technical group collaborating on delivery of the CMB-S4 detectors. The CDFG is engaging detector fabrication experts from the DOE labs and additional CMB detector fabrication facilities outside the DOE lab system, including the National Institute of Standards and Technology (NIST) and the Jet Propulsion Laboratory (JPL). CMB-S4 is assembling an external advisory committee to provide ongoing technical recommendations as the detector fabrication plan is implemented.

The Phase I and Phase II reports of the Detectors and Readout Fabrication Task Force, and the report of DOE Detection Fabrication Review held in August 2019 are available to the committee upon request.

2) RFI-1 page 15, Section 1.3.1 Sensitivity to Technical Requirements states: “Failure to meet our instantaneous sensitivity requirement - whether through detector yield or performance, or through reduced observing efficiency - can be compensated for by simply extending the observation.” RFI-1 page 20, Section 7: In response to “What are the three greatest risks to cost, schedule, and performance?” there is no mention of any risk related to schedule as a result of failure to meet the instantaneous sensitivity requirement. Additionally, based on the RFI-1 page 46 question 4 response, the observation efficiency is 25-40% which is already low due to calibration and maintenance.
a. What is the risk to the program of not being able to meet instantaneous sensitivity requirements in terms of likelihood and consequence, including schedule and budget risk? What is the justification for the risk rating?

b. What are the operational impacts and costs for extending observations, if needed due to low detector yield, performance shortfalls, or reduced observing efficiencies? Will any changes to the current scope or plan be required in the event that extended observations will be required? Will any modifications to the observatory hardware or software be required as well?

RFI-1 Page 20, Section 7 refers solely to Large Aperture Telescope (LAT) risks. Risks leading to failure to meet the instantaneous detector sensitivity requirement are covered in RFI-1 Page 26, Section 6. Highlights of the overall risk registry are also provided in DSR Table 6.6. The efficiency factors assumed for detector yield (80%), calibration and maintenance (75%), and disruption by weather and solar/lunar-avoidance (40%) imply a total efficiency of 25%. This is very conservative compared to experience in the laboratory and field to date and provides us with significant margin.

a. The risk to the program of not being able to meet our instantaneous sensitivity requirements was initially assessed as critical, based on our evaluations of its probability (high), cost (> $3M), schedule impact (> 6 months), and performance impact (high) if unmitigated. Our mitigation strategy has reduced this risk to moderate. As noted in our response to Q1, these mitigations include: deploying multiple detector fabrication lines to avoid any single-point failures, prioritizing the demonstration of sustained yield early in the fabrication process, identifying the fabrication of science-grade wafers as a long-lead item to commence at CD-3a, and including 6 months of schedule float on the critical path. We have also adopted conservative yields and observing efficiencies based on those historically achieved by individual university groups. Given the maturity of the technologies now, and the addition of project-scale management and systems engineering and the full capacities and capabilities of the DOE laboratories, we expect to exceed these conservative yields, which then provide additional margin.

b. Note again that we have made conservative assumptions for each of the factors going into our overall assumed efficiency, and in practice we expect these to give us significant margin. However, should we fail to meet our instantaneous sensitivity goal despite all of the above, our backstop is that we can extend the observation duration to compensate. Almost all of our science goals require specific numbers of integrated detector-years. Any reduction in the detector yield or observing efficiency can therefore be compensated for by a corresponding increase in the observation duration to conserve the product Yield x Efficiency x Duration - for example, a 20% reduction in yield or observing efficiency would require a 25% increase in observing time. While this implies a cost and schedule risk in operations duration, it would not require any change of project scope, plan, observatory hardware or software.
3) On Page 137 of the CMB-S4 Science Case, Reference Design, and Project Plan (SCRDP), it is stated that, for the 150-mm SQUID multiplexer wafer a production rate of 10 science grade wafers/year/FTE may be assumed. The paragraph also says that each successful 150-mm wafer will provide 4096 channels of TDM readout. This means the production rate is 4096 x 10 channels per year/FTE. At this rate it will take 10 years to produce wafers for 500,000 channels unless more than 10 science grade wafers are produced per year. Please clarify.

CMB-S4’s SQUID multiplexer fabrication plan uses eight (8) fabrication technicians in pairs to achieve production of 80 science-grade wafers per year (10 wafers/year/FTE x 8 FTE). The full complement of science-grade SQUID multiplexers will be completed in one and a half (1.5) years. Our plan assumes two separate SQUID microfabrication facilities with independent fabrication toolsets to hedge against schedule risk from unexpected equipment downtime. One of the possible facilities (NIST) already has the complete toolset in place, has nearly 20 years of fabrication experience with SQUID multiplexers, and has a significant fraction of the necessary personnel already in place. Candidates for the second facility include SLAC, MIT Lincoln Lab, and a few commercial superconducting fabrication foundries.

4) Manufacturing of High-Density Feed-Horn Array (CMBS-4 SCRDP page 133): There is an estimate given that a CMB-S4 like 90/150-GHz feedhorn array with 507 feedhorns would take 20 hours to machine. CMB-S4 needs approximately 100,000 feeds for the LATs. Please describe the production and tooling concept to produce the required number of feed arrays, including the effect of tool wear and how often re-tooling will be required to meet the desired performance?

The tooling consists of a profiled roughing drill and finishing reamer. These can be ordered commercially for <$100 per set of drill and reamer, and their price is included in the cost per array in the CMB-S4 budget. For each batch of arrays, a new drill/reamer set is used. At the beginning of each batch, a cross sectional profile is measured with laser metrology to verify that the profile matches the designed profile and to tune the drill depth. Between each array a witness sample consisting of a single cross-sectioned horn is produced that can be tested with laser metrology to check for tool wear. We note that not every cross section needs to be tested if the last cross-section in a batch shows no tool wear. Production on Simons Observatory (SO) showed slight signs of tool wear after machining 10 arrays with 432 horns each, so we currently limit the batch size to 5 arrays. The full measured machining time required on the SO arrays is 7 hours per array (432 horns each), and 5 arrays can be machined in a week using a single CNC machine. This can be parallelized across many machine shops.

5) It is noted in CMBS-4 SCRDP page 134 that the alignment of Feed-horn array with the detector array is a challenging task and differential thermal contraction can cause greater misalignment and add additional stress to the array. To reduce the risk, the team is planning to test arrays with only 30 feedhorns. Please discuss how testing
Simons Observatory is fabricating more than thirty full aluminum feedhorn arrays with 432 horns each, which will demonstrate this technology (as opposed to feedhorn arrays with 30 horns). The differential thermal contraction of aluminum 6061 is well known and uniform across the feedhorn arrays. A pin at the array center fixes the relative position of the horn and array and a slot near the edge constrains the rotation while accommodating the CTE differences while cooling. The CTE correction need only be accurate to 5% to meet the CMB-S4 requirements. This system has heritage to the BLAST-TNG experiment which used a related design comprised of aluminum feed arrays interfaced with 100 mm diameter silicon detector wafers at higher frequencies (1.25 THz) with a tighter alignment tolerance (16 microns). Their testing did not reveal any evidence of misalignments. The main effect of a potential misalignment is a decrease in co-polar coupling, so the optical tests of efficiency across the array will provide confirmation of the alignment.

CMB-S4 Facilities Related Questions:

6) Please verify functional area square footage (SF) and provide overall SF for each building/facility. (RFI-1 page 33,36-42, Tables 8 & 9)

Background – Only main functional net areas provided. Primary functional areas are listed however references are made to existing facilities for MAPO/DSL with no additional information provided for those facilities; Likewise, reference is made to Simons Observatory but lacks specificity. Assume restrooms, break areas, support mech & elect other areas are required and will be derived and accounted. This will add to overall SF, cost.

The new “Support Laboratory” building (Table 9) at the South Pole will be similar to the existing Dark Sector Laboratory (DSL) currently used by the SPT and BICEP experiments. The two-story DSL has exterior dimensions of 28 ft x 63 ft (providing roughly 1680 sqft interior per floor), and approximately 1450 sqft of functional space per floor, after subtracting the area needed for electrical or utility space. For restrooms, barrel equipped bathroom areas are provided as outhouses during the summer, and indoors in the winter (serving a much smaller population). Fresh water is delivered by container from the main station supply.

For the South Pole high bay building (Table 9): the number listed is the intended total square footage of the structure, with only a small fraction (<15%) of this area needed for utility space. Both the “Support Laboratory” and high bay facility are included in the CMB-S4 project budget.

The “Office” (Table 8) in Chile is intended to be a space for break areas. There will be other modified shipping containers used to house utilities and provide storage. The ones for utilities
are called out as interface containers. Storage containers were not called out specifically in the RFI but are included. For a restroom, the plan is to have an incinerating toilet in a modified shipping container. No other facilities are assumed.

7) **Please verify minimum wind load for the Cerro Toro site and confirm whether the discrepancy in wind load provided is intentional. (RFI-1 page 36)**

**Background – Code requirements, specifically wind loading, are inconsistent for buildings (page 36) and antennas (page 37) for Cerro Toro site.**

We confirm the discrepancy in wind specifications used. The LAT survival is specified requiring consideration of a longer time period over which it is considered likely that the wind will not exceed that value.

8) **Please provide minimum wind load criteria required for the South Pole Site. (RFI-1, page 37)**

**Background – Verify wind load requirements for the South Pole site that the antennas and buildings need to meet. Text states only that there is less risk than at Chilean site.**

The minimum wind load criteria for our structures at the South Pole is 35 meters/sec for survival. The highest recorded wind-speed at the South Pole is 26 meters/sec.

9) **Verify SF areas for the functions listed in Table 8, as the SF/person seems to fall below typical space planning best practices. (RFI-1 Tables 8, 9, pgs. 36-42)**

**Background – Overall, area SF seem tight relative to number of staff and functions relative to best practices; please verify requirements for each site.**

The occupancy numbers in Table 8 need clarification/correction. We consider the combined square footage of the High Bay Lab and Office/Control building in Chile to be acceptable for 20 persons total to be working on-site during deployment activities. The office/control room is designed to comfortably accommodate 8 people at desks during more routine site activity.

Note that we interpreted Table 9 to include only new facilities at the South Pole. We will also have space available in existing facilities at the South Pole available for our use. As is the case with our current experiments there, we expect to have available ~600 sq. ft. in the South Pole Station’s B2 Science Area (for software and analysis related tasks). The MAPO building currently houses the Keck Array and the Dark Sector machine shop. We expect to continue to use the machine shop. We also expect that the space currently used by BICEP3 (in DSL) and the Keck Array (in MAPO) will be available for CMB-S4’s use, though that is not required in our current baseline. The highbay is listed as having a maximum occupancy of 20, but we would
not expect that to be the typical occupancy; operations at South Pole run in three shifts during construction when staffing levels are high.

10) Please clarify what infrastructure is existing versus required as new, particularly in regard to electrical/power requirements

Background – Power requirements; not clear whether sites will be providing or whether new infrastructure is required to be built to support loads/requirements (seems to imply that power loads are within existing site capability for Cerro Toro, but not clear.)

Chile - The cost of the power infrastructure required to meet the CMB-S4 requirements in Chile is included in the CMB-S4 project cost. Other electrical/power/data infrastructure, except the high-bandwidth connection from Chile to North America which will be installed by 2022, is included in the CMB-S4 project budget. The power generation facilities currently in Chile are not capable of supporting the S4 load. Table 8 is confusing in this regard, because it says the size of the new facility is unknown. This is because of uncertainty in whether the project will construct the facility or AUI will construct outside of project funding in coordination with AAP. The CMB-S4 project budget includes a $10M investment in a hybrid photovoltaic/battery/diesel power plant.

South Pole - Any upgrade to or expansion of the power generation facilities at the South Pole are not included in project cost, as those are considered station facilities. This assumption is consistent with all previous experience for experiments at South Pole including the South Pole Telescope, BICEP/KECK, IceCube, etc. Other electrical/power/data infrastructure, except the high-bandwidth link from South Pole to North America, which is maintained by NSF-OPP, is included in the CMB-S4 project budget.

11) Clarify whether existing infrastructure will be supporting telescope or whether new infrastructure is required; if new is required, please clarify what items are required and provide sufficient data to quantify quantity/size. (RFI-1 page 39)

Background – Please clarify whether telescopes provided by existing infrastructure or will require new similar to what’s available. Text on page 39 is unclear in intent yet table indicates SF requirement. "Both the LAT and SAT telescopes will be supported by the same nearby laboratory building, which will be a hub for electrical, communication, and utility control."

All new telescopes at the South Pole will be supported by new infrastructure. Each new telescope will have its own new tower; the new “Support Laboratory” building listed in Table 9 (and called out as the “nearby laboratory building” on page 39) will support all the new telescopes. This support laboratory is sized based on our experience with the BICEP/Keck and SPT projects at the South Pole, which use the similarly-sized MAPO and Dark Sector Laboratory.
Note that in Tables 8 and 9 there are items listed that are for a single SAT telescope mount, each of which holds three optics tubes. In Table 8 these are the “SAT platform foundation” and the “SAT groundscreen area”. In Table 9 these are the “SAT platform foundation” and the “SAT control room”. The project will deploy 18 SAT optics tubes in a total of 6 SAT telescope mounts.

In Table 8, the item “LAT foundation” should also have had a “(2)” in the first column, indicating that two will be needed, one for each LAT.

12) Please clarify whether racks will be housed in the comm and control areas/functions. (RFI-1 table 8 & descriptions)

Background – Overall power is described, but not clear what the power supports.

The required computing and electrical racks will be housed in the office/control building. In contrast to the South Pole, these facilities will only store a small amount of data (weeks), and continuously transmit the data to North America through the high-bandwidth connection.

13) Please confirm that any modifications/upgrades to the South Pole power plant are not scoped as part of this project. (RFI-1 page 38)

Background – Statement in RFI indicates power plant might need modernization/upgrades and that NSF will coordinate/fund. However, it is not clear whether these costs will be levied against this CMB-S4 project.

Modifications or upgrades to the South Pole power plant are not part of the CMB-S4 project, rather they are the responsibility of the NSF Office of Polar Programs (OPP). The CMB-S4 Integrated Project Office will provide OPP with the information on our logistics and support requirements including power. OPP will then upgrade the power plant at the South Pole Station based on input from the CMB-S4 project and other stakeholders. The cost of these improvements to the South Pole Station infrastructure will be met by OPP as has been done in the past for utilities of common use.

14) Please clarify whether this lab is existing or a new facility that will support both LAT & SAT. (RFI-1 page 39)

Background – RFI States: Both the LAT and SAT telescopes will be supported by the same nearby laboratory building, which will be a hub for electrical, communication, and utility control.

This is a new facility, and is included in the CMB-S4 project budget.
15) Please clarify which functions are supported by new facility (facilities) vs. existing facilities. (RFI-1 page 42/Table 8)

All Facilities in Table 8 are new. There is no assumption of existing facilities in Chile except for the high-bandwidth connection to REUNA.

16) Please characterize/clarify infrastructure might be needed between facilities or whether using existing infrastructure.

In Chile, no existing trenches for power or communication, except the high-bandwidth connection from Cerro Toco to the outside world, will be used. All connection infrastructure would need to be new.

Similarly, at the South Pole all data and power connection infrastructure within the site would be new. We will use NSF-OPP’s existing high-bandwidth data connections to N. America.

17) Please characterize what is required for CMB-S4 specifically; include what is being provided by existing facilities/infrastructure and what is needs to be constructed as new as part of this program.

Background – Many references to other projects, experiments, telescopes but lacks information to understand scope and what’s specifically required. For example, there are references to “similar to Keck”, or similar to Simons Observatory but no explicit size or requirements described. As written, the RFI does not provide enough information to be able to size/scope and thereby adequately cost facilities & infrastructure.

All infrastructure listed in Tables 8 and 9 is new and none is considered existing, except for the high-bandwidth connections from Cerro Toco and South Pole to N. America. References to other projects’ infrastructure were solely to demonstrate heritage. We are not sure what additional parameters you are interested in; details not covered in the RFI should be in the DSR (Reference 6 in the RFI document) Sections 3 and 4, and we would be happy to provide any specific parameters of interest.