CMB S4

Report on the Chile Configuration

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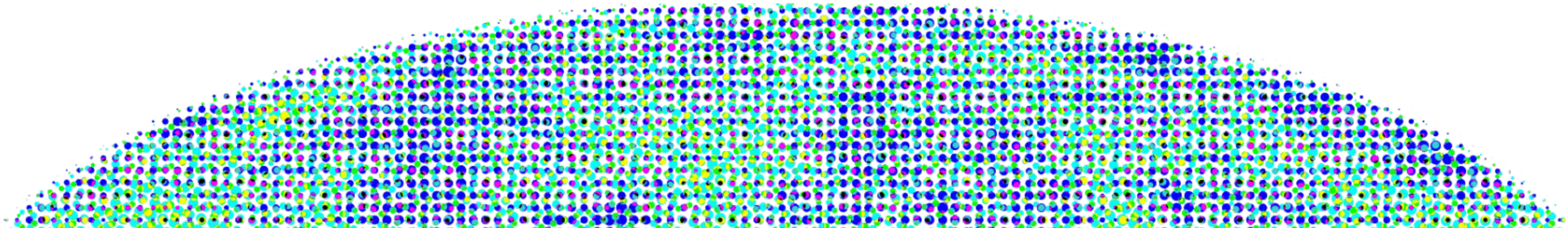


Overview of Chile Optimization Work, Goals, & Status

- The goal is to develop an all-Chile configuration that is able to address all of the CMB-S4 science goals, and is optimized to meet the inflation science goal of $r \leq 0.001$ at 95% CL for $r = 0$ ($\sigma(r) \leq 5 \times 10^{-4}$) within a reasonable survey duration ($\lesssim$ 10 years), with an acceptable level of scientific risk.
- Met weekly at 11:00 am PT Wednesdays, open to everyone in CMB-S4. Thanks to all that have participated. In addition, sub-groups also met weekly or biweekly.
- We have completed the draft report and can specify a configuration that meets our goals.
  - **r-forecasts for 7, 10 and 20-year duration** of 2 different map-based analyses agree well
  - Associated **opportunities, uncertainties, and risks** have been identified
  - A parametric cost estimate was developed, based on work done for the 2023 Director's Review
- Note that the configuration is **not the project plan**. It is exercise to show "**what it would take**"
- The draft report is posted for Collaboration review.

Overview of Optimized Chile-Only Configuration

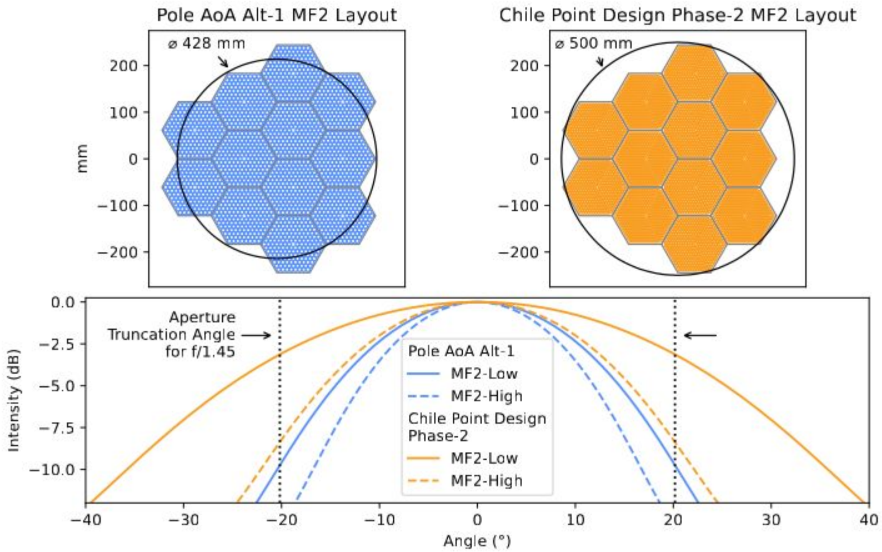
- **27 SATs with 56 cm aperture**, deployed in units of 3 in a common cryostat and common mount, with a design based on that for the previous SP configuration, adapted to the conditions in Chile.
  - Rotating half-wave-plate (HWP) polarization modulators
  - Higher-density focal planes, following the SO approach
  - Six frequency bands from 25 GHz to 280 GHz; MF bands (90 and 150 GHz) are un-split
- **Three 6-m LATs** with Crossed-Dragone Optics, essentially identical to the ones proposed for the previous 2-site configuration and very similar to the SO LAT now being commissioned and to the CCAT-prime LAT.
  - Seven frequency bands ranging from 20 GHz to 280 GHz
  - All LATs are of the same design with the same receiver
- **Sited at Cerro Toco** within the Parque Astronómico Atacama at an altitude of 5,200 m, which is currently the site of CLASS and SO, and was recently also the site for the ACT and the Simons Array.

Small-Aperture Telescopes: design changes for this study

SAT design choices must maximize sensitivity while limiting systematics risks, to achieve final uncertainties < 10nK on degree scales from a challenging terrestrial environment

For Chile Point Design, changes have aimed to minimize number of SAT tubes needed to meet *r* goals in Chile:

1. **Increase horn density**
2. **Increase field of view**
3. Use of Chile site with changes to atm / terrain
4. Continuously rotating HWP
5. Changes to shielding geometry
6. Use of full (non-split) MF bands



- More aggressive aperture illumination at LF and MF bring increased power truncation (~4x) and increased detector counts per tube (~3x)
- 30° → 35° increased FOV now encircles all feedhorns

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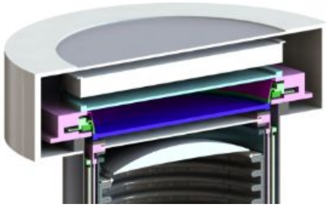
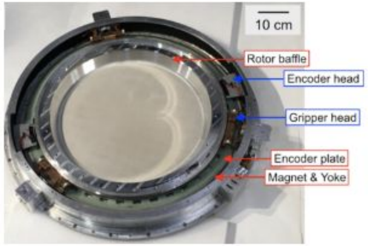


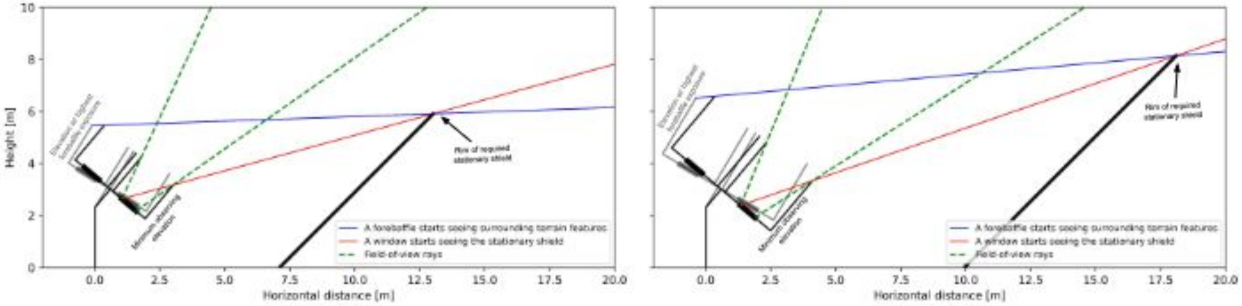


Half-Wave Plate (HWP) at 50K mitigates increased atm fluctuations in Chile.

Based on SO design, requires increase in size (50→65cm).

SO experience will inform systematics tradeoffs.

Forebaffle and groundshield geometry adapted for $30^0 \rightarrow 35^0$ FOV and $2^0 \rightarrow 5^0$ horizon, by increasing tube spacing 28%.
Cerro Toco horizon is <5^0 except toward NE



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Use of non-split bands reduces number of frequencies available for foreground separation and cross-checks, but increases avg. per-tube MF mapping speed by 25-31%

Dichroic Detector Type	LF		MF		HF	
Nominal Frequency [GHz]	25	40	90	150	230	280
Band Center (on-wafer filters) [GHz]	24.75	36.5	91.5	148.5	227.0	285.5
Fractional bandwidth	0.263	0.466	0.317	0.276	0.256	0.207
Detector NET_{CMB} $\mu K\sqrt{s}$	214	148	221	287	720	1817
NET Correlation Factor	1.06	1.04	1.03	1.03	1.01	1.00
Number of pixels per wafer	37		430		467	
Number of detectors per wafer	74	74	860	860	934	934
Number of wafers in one SAT	12					
Number of detectors in one SAT	888	888	10320	10320	11208	11208
Number of SAT optics tubes	3		18		6	
Aperture diameter	560 mm					
FOV (diameter)	34.9°					
f/#	1.45					
Half-Wave Plate	Yes					
Beam FWHM (arcminutes)	79.2	56.6	21.4	14.0	9.4	7.8
Edge Taper [dB]	-3.32	-7.36	-3.15	-7.99	-9.90	-13.80
Fractional spillover	0.482	0.227	0.477	0.148	0.06	0.02

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Observations from Simons Observatory will quantify and hopefully retire the science risks in this point design. This will facilitate further optimization of the tradeoffs between sensitivity and mitigation of systematic effects. Comparative validation of systematics control and achieved sensitivity under these design choices will be made possible with full-season, deep B-mode survey maps and power spectra, which identify what fraction of data pass consistency tests to the level of instrumental noise, using sensitive internal null tests or in comparisons with existing deep Stage-3 surveys. Data from Simons Observatory and BICEP/Keck will both be valuable in this process. Risks and opportunities are further discussed in Section 5.

Use of non-split bands reduces number of frequencies available for foreground separation and cross-checks, but increases avg. per-tube MF mapping speed by 25-31%

Large Aperture Telescopes Baseline

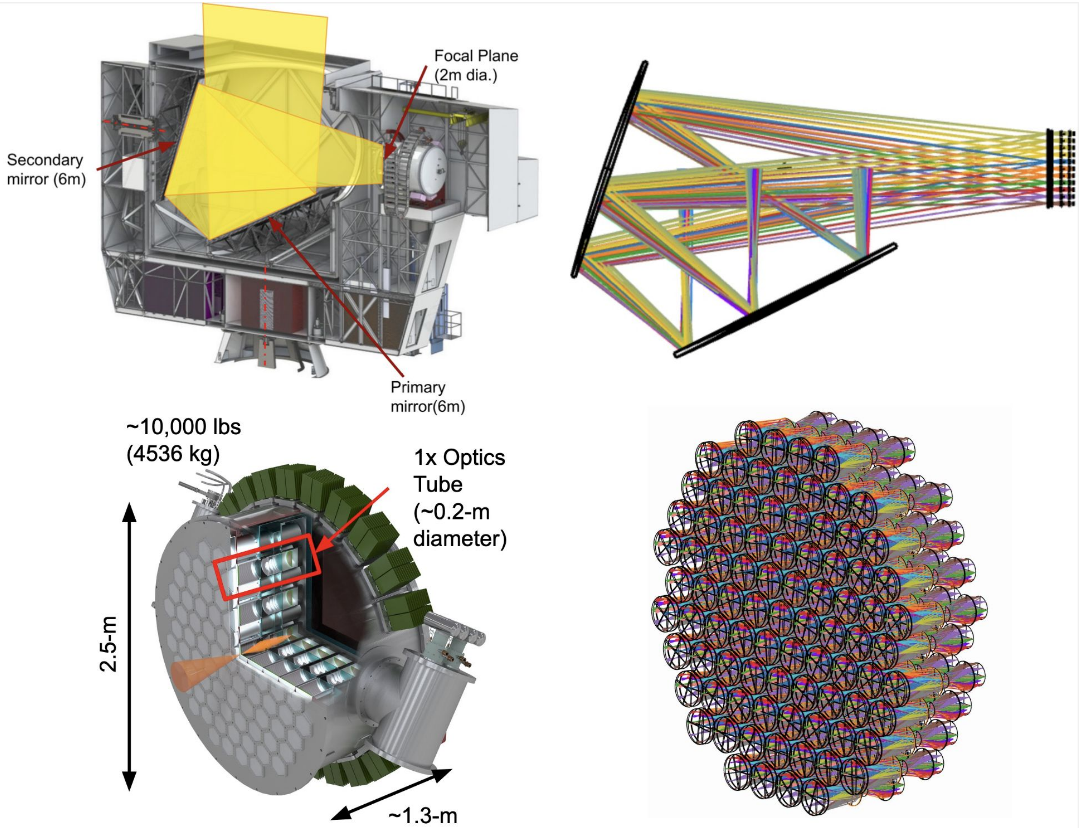
3 CD LATs is the new baseline

Rationale:

- Operational simplicity - flexibility between deep and wide surveys
- Higher angular resolution needed for wide-field science

TMAs still under consideration for de-lensing

- Monolithic mirrors lead to lower sidelobes and ground pick-up
  - Could be incorporated into CD
- Taking advantage of low-ell systematics control is harder given Chilean atmosphere



Large Aperture Telescopes Considerations

- LATR design is nearly unchanged
  - ULF band now integrated into CD

- No polarization modulators in baseline design
  - CHWPs pose significant operational complexity and risk
  - ~30% mapping speed penalty

- SO LAT recently achieved first light, and experience is highly relevant to CMB-S4

Dichroic Detector Type	**ULF**	**LF**		**MF**		**HF**	
Nom. Frequency [GHz]	20	25	40	90	150	230	280
Band Center [GHz]	20.0	24.75	36.5	91.5	148.5	227.0	285.5
Fractional bandwidth	0.250	0.263	0.466	0.317	0.276	0.256	0.207
Detector NET_{CMB} $\mu K\sqrt{s}$	413	391	239	300	329	723	1774
NET Correlation Factor	1.28	1.30	1.14	1.18	1.01	1.02	1.01
Pixels per wafer	27	48		430		467	
Detectors per wafer	54	96	96	860	860	934	934
Wafers per LAT	4	8		54		19	
Detectors per LAT	216	768	768	46440	46440	17746	17746
Primary diameter	6 m						
Field of View	7.8°						
Beam size (FWHM [′])	9.6	7.8	5.3	2.1	1.3	0.95	0.83

Detectors, Readout, Modules, and DAQ/Controls

- **Very limited changes to designs and production plans for detector wafers, readout elements and detector modules**
  - SAT individual detector parameters re-optimized for Chilean sky conditions as needed
  - Higher-density SAT LF and SAT MF pixel spacing for more aggressive illumination
  - Larger quantities of readout components per SAT LF and MF detector modules
  - No changes to DRM for LAT

- **Data acquisition and observatory control are fundamentally unchanged**
- A couple of things are easier:
  - Ample bandwidth off-site enables remote monitoring and remote real-time control
  - Transient alerts do not need to be integrated with the S.P. network, so are more straightforward, with fewer interfaces
- The **main additional scope for Chile-only is control and monitoring of SAT cryogenic half wave plates**, which should benefit from SO experience

Data Management

The proposed all-Chile configuration significantly increases the Chile data volume, zeros the South Pole data volume, and slightly increases the overall data volume. As a result it:

- Increases the Chile site steady-state and catch-up bandwidth requirements, while staying well within the capacity available to us.
- Increases the Chile site 1-month archival storage requirement, but removes the need for the much larger 45-month archival storage at the South Pole.
- Increases the US daily compute cycle requirements but removes the need for any on-site compute cycles.
- Reduces the peak memory requirements (currently set by the longest LAT observation).

(see Table 3.4 for details).

The relocation of the SATs to Chile, and the changes in their design (including more aggressive optics and the addition of HWPs), modifies the way existing systematic effects will manifest themselves and adds new ones, requiring additional work in instrument modeling, simulation, and mitigation. The Simons Observatory experience will be very informative here.

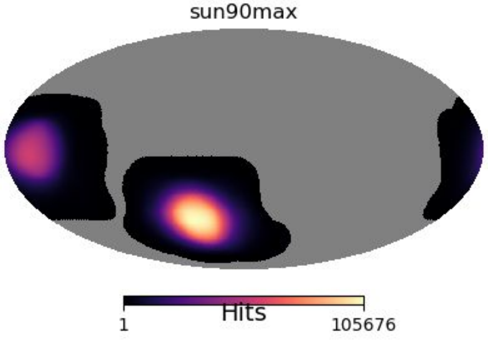
Data Management

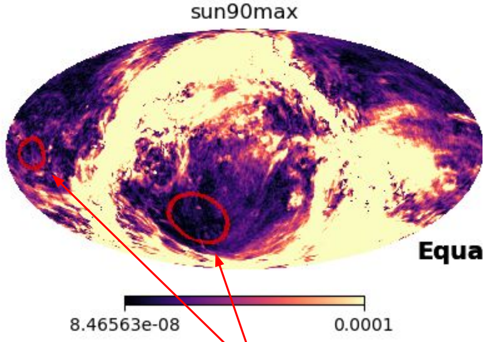
Table 3.4: Comparison of the computational requirements for Chile/South Pole and All-Chile configurations

	Chile/South Pole Configuration			All-Chile Configuration	
Computational Resource	Chile 2 LAT	Pole 1 LAT 3 SAT	US	Chile 3 LAT 9 SAT	US
Steady-State Bandwidth (Gbps)	0.9	-	-	1.5	-
Catch-Up Bandwidth (Gbps)	4.5	0.5	-	7.4	-
Spinning Storage (PB)	-	0.1	43.3	-	41.7
Archival Storage (PB)	0.3	5.9	61.0	0.5	61.0
Daily Computation: Cycles/Day	-	4.2e15	7.0e15	-	1.2e16
Daily Computation: Peak Memory (GB)	-	310.4	147.8	-	147.8
Annual Computation: Cycles/Year	-	-	2.5e22	-	2.5e22
Annual Computation: Peak Memory (GB)	-	-	310.4	-	147.8

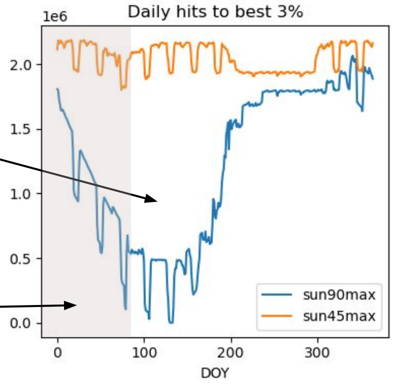
Survey Design - SATs

- Completely reworked survey design since Analysis of Alternatives (AoA)
- Dropped two of the three secondary fields
- “Max” SAT strategy improves the deep field survey weight by more than 20%
  - Observes patch even when only the focalplane edge can see the target
- SAT observing schedules now comply with a 90° Solar avoidance radius
  - Severely limits field availability in February-May
  - 35% loss of survey weight in April-December compared to 45° avoidance used in AoA





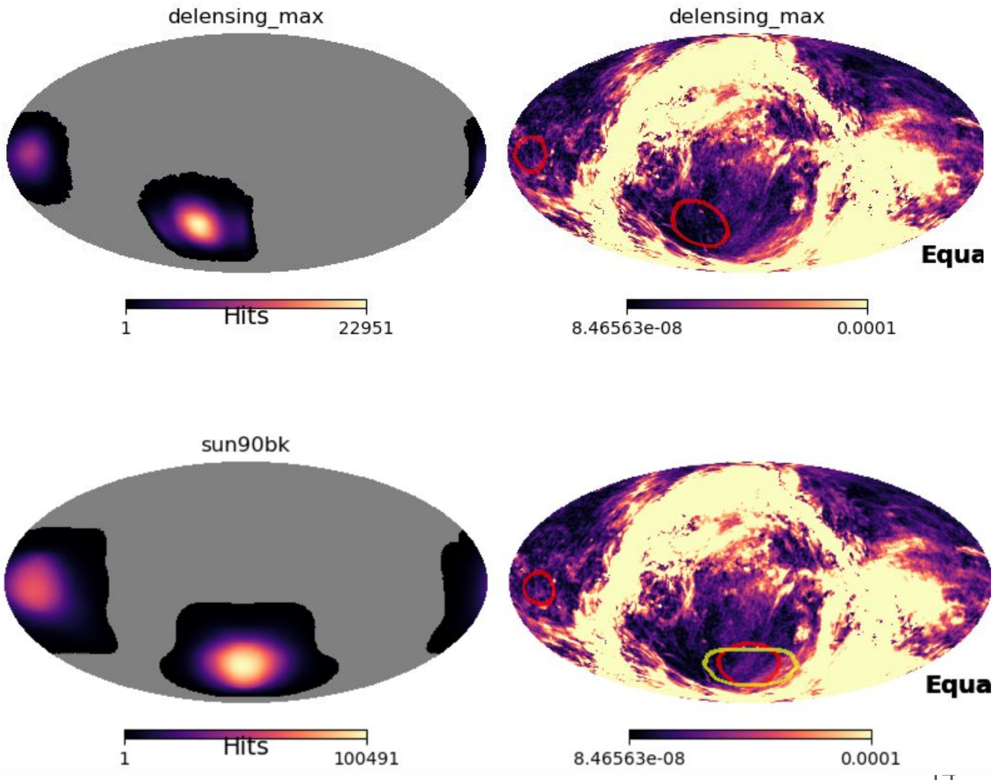
Deepest 3% of the survey. Background is polarized dust.



Typically inclement weather but potential for some observations

Survey Design - LATs

- Wide survey is the same as that assumed in the AoA
- Overlapping weighted tile approach to LAT delensing allows for much more faithful emulation of the SAT depth
  - Priority of each tile depends on square of SAT relative hit maps
- These new strategies can support targeting the BICEP/Keck patch with no loss of observing efficiency



Survey Design - Observation Efficiency Changes

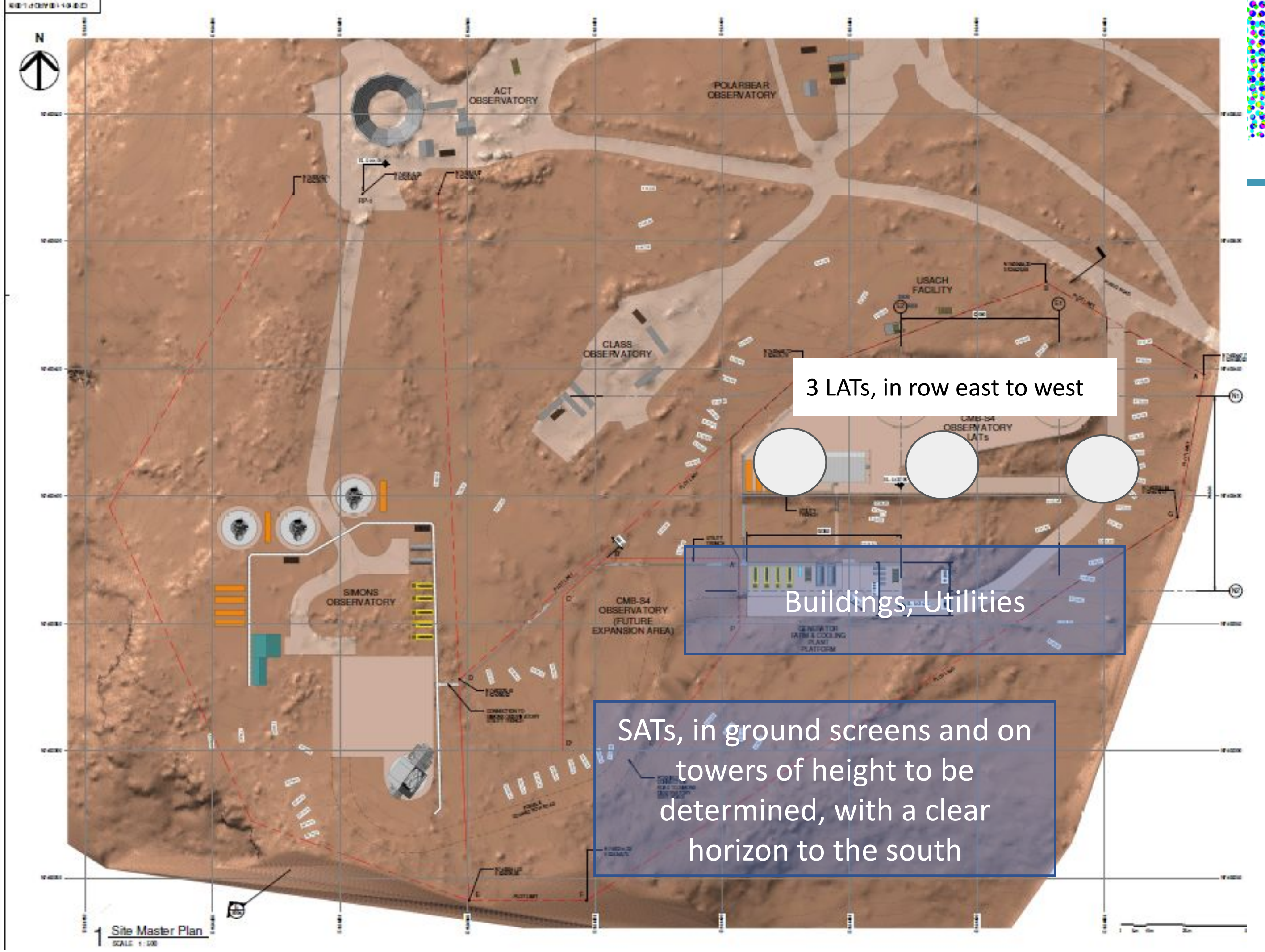
- Assume 19 days of observing time outside the nominal season (5% increase in season time)
    - Median number of days with precipitable water vapor (PWV) < 3 mm for more than 2 hours, < 0.2 mm change in PWV) based on APEX data
- Assume that the 10% of time lost to extended weather outages is recovered
    - Due to poor power infrastructure (mitigated by solar power + snowplow)
- Field availability and turnaround efficiencies have changed with modified scan strategies
- ⅓ more data cut during daytime observations for LATs based on new ACT data

Chile Site

- The Cerro Toco Site can be expanded to support the Chile-only configuration of CMB-S4.
  - It provides facilities for instrument integration and test, power generation and distribution, data communication and management, cooling systems, and personnel support.
  - It is scalable, should the details of the system configuration change.
  - It supports remote science operations at all time, and immediate transfer of data to centers around the world.
  - It is designed to remain fully operational even if access is prevented by weather for up to 14 days, while the access plan also supports vehicles that can access the site after significant snowfall.
- The bureaucratic conditions to operate in Chile are not affected by the change to the Chile-only configuration
  - This includes staffing, importation requirements and the special legal status as an international organization in Chile.

Cerro Toco Site Baseline Layout

- The site is capable of supporting all SATs and LATs
- The Chile-only layout has all 3 LATs in a row from east to west with spacing set by horizon requirements as in previous baseline.
- The SATs are at the southern end of the infrastructure, with a clear view south to the primary observing patch



Science Reach

High-level science goals that drive the design and against which the design of CMB-S4 is evaluated.

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. Use the rate of mm-wave GRBs to constrain GRB mechanisms. Provide mm-wave variability and polarization measurements for stars and active galactic nuclei.

The ability to achieve goals 2, 3 and 4 is largely unaffected by the reconfiguration to Chile

=> The main focus is to demonstrate that Goal 1, "Test models of inflation" can be met.

Science Reach: Methodology

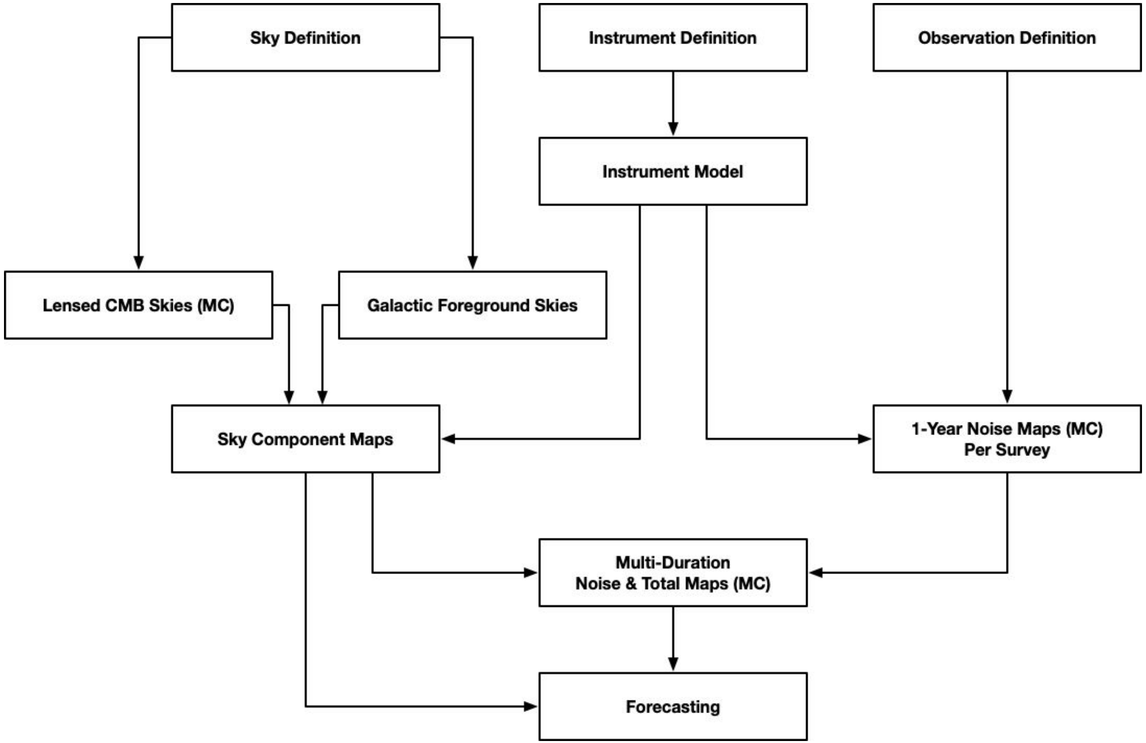
1. Develop a model of each of the telescopes at each of their observing frequencies
    - SAT models for full and split MF bands have been generated
    - Models with 3, 4 or 5 LATs are generated.
2. Develop a model of the survey strategies these telescopes will perform
    - 14 LAT-years are reserved for the wide-area survey, the rest are devoted to delensing.
3. Generate the per-survey, per-frequency, noise maps corresponding to performing the surveys with the telescopes.
    - SAT models use either *ab initio* noise estimates or noise scaled from BK. Difference in survey weight (or mapping speed) between two noise forecasts depends on frequency band and ranges from 1.2x at 270 GHz to 2.9x at 150 GHz.
4. Choose a fiducial cosmology and generate a Monte Carlo set of realizations of the CMB sky corresponding to this cosmology
    - ΛCDM cosmology with $r = 0$ is chosen

Science Reach: Methodology

6. Choose a suitable Galactic foreground model
    - PanEx “medium complexity” model is used (PySM: d10, s5, f1, a1, co3).
7. Convolve the CMB and Galactic foreground skies with the beam and bandpass for each frequency on each telescope
8. Combine the noise and sky signals to produce a set of maps corresponding to performing the experiment as configured
    - 100 simulations are generated for each configuration and each of 7, 10 and 20 years observing duration
    - Simulations do not include instrumental systematics of any kind
9. Analyze these maps to determine the r-constraint that they support
    - A lensing template is generated using an iterative delensing pipeline.
    - r estimates are then generated by two independent pipelines

Science Reach: Simulation Workflow

- Chile Coordination Group provides instrument & observation definitions
- PanEx Galactic Science Group provides sky models
- Many thanks to Colin Bischoff, Julian Carron, Reijo Keskitalo, Clem Pryke, Sara Simon & Andrea Zonca for repeatedly refining and executing this workflow.



Science Reach: Forecasting Methodologies

- xCl pipeline (Bischoff): Based on component separation / delensing pipeline used by BICEP/Keck
  - SAT frequency maps and lensing template are reduced to the full set of auto and cross spectra (using NaMaster pure-B estimator)
  - Search for the parametric model that maximizes the likelihood for the spectra from each realization. One cosmological parameter, r, and nine foreground parameters, including decorrelation parameters for dust and synchrotron.
  - Results show small bias on r (1-2e-4) for field 1 but large bias (~2e-3) for field 2, indicating that the foreground model is not a good description in that field. Exploration of more flexible / robust parametric foreground models is needed.
- ILC pipeline (Ghosh): Harmonic-space Internal Linear Combination of delensed SAT maps
  - ILC map minimizes combination of noise and foreground residuals while preserving CMB signal.
  - Results show larger bias on r (7-8e-4) for field 1. Still need to explore options for marginalizing over bias from foreground residuals.

Science Reach: r-forecasts

Table 4.1: Inflation r-forecasts for 10 years of science operations with 27 SATs and 3 LATs

SAT bands	Noise model	r_{bias} $\times 10^{-4}$	$\sigma(r)$ $\times 10^{-4}$
full MF bands	*ab initio*	1 – 8	4.0 – 4.8
full MF bands	BK-scaling	2 – 9	5.3 – 5.6
split MF bands	*ab initio*	2 – 8	4.7 – 5.7
split MF bands	BK-scaling	3 – 9	5.8 – 6.4

σ(r) goal is achieved with this configuration

The range of values in each case spans the results from two independent map-based forecasting methods.

Opportunities, Uncertainties, and Risks

- **Opportunities:** potential ways that the sensitivity and efficiency of CMB-S4 could be improved that may reduce the required observing time or number of telescopes
- **Uncertainties:** factors that could yield either better or worse performance
- **Risks:** factors that could result in poorer performance, e.g. by lowering the survey weight per year or increasing systematic errors.

Many of the SAT and LAT risks will be addressed with upcoming Simons Observatory measurements.

We will also learn much more about foregrounds in the deep field region from BK, SPT, CLASS, SPIDER and SO.

Opportunities and Risks

Opportunities:

- Include Northern field data (so far not included because of high foregrounds, high bias, low weight)
- Potential further optimization of survey strategies
- Relocating the deep survey (to SPO region) improves survey efficiency in the main observing season by virtue solar avoidance
- Re-optimization of SAT frequency band distribution may improve foreground separation
- Alternate site for SATs at the Honar Summit - slightly higher altitude, simpler horizon
- Analysis algorithm development (eg AI/ML, or just better)
- SAT sensitivity improvements, e.g, from lower loss window, HWP, etc

and

- Partner with:
  - SO and SPO to reduce hardware scope and shorten schedule timeline
  - LiteBIRD to improve foreground modeling/removal

Opportunities and Risks

Uncertainties:

- Receiver sensitivity models have a variety of uncertain inputs, e.g., material properties that could be better constrained.
- Foreground model uncertainties - foregrounds may be of lower or higher complexity than the "medium complexity" model we've adopted.

Opportunities and Risks

Risks

- SAT and LAT noise models - *Ab initio* may be too optimistic *(esp given CMB history)*
- HWP for 56 cm aperture (vs. SO's 42cm) required for modeled throughput but not yet proven.
- SAT solar avoidance - 90° avoidance may be insufficient; have assumed daytime observing is okay
- LAT solar avoidance - 30° avoidance may be insufficient
- SAT survey design - possible efficiency loss to mitigate ground pickup (eg az-locked scans)
- Weather and Atmospheric conditions may limit observing efficiency more than modeled
- SAT design evolution (eg aggressive focal planes, HWPs) may induce/increase systematics
- Split MF SAT bands may be needed to control foregrounds

Mitigation strategies for most of these are likely to require more observing time or more hardware.
We hope that SO will help us better understand some of these in the coming years.

Construction Project Cost and Schedule

- Developed a parametric cost model, based on the updated Chile Only P6 resource-loaded schedule, assuming CD-1/CDR by the end of FY2026.
- Identified each activity and cost in the P6 schedule as:
  - Fixed Cost (does not vary with quantities of telescopes)
  - Per-SAT cost
  - Per-LAT cost
- Calculated "marching army" costs to capture cost differences due different project durations
- Applied 40% cost contingency
- Calculated project cost for combinations of # SATs and # LATs

Cost of Stand-alone configuration (27 SATs and 3 LATs)	
Subsystem	Cost including contingency ($M)
WBS 1.01 Project Office	$156
WBS 1.03 Detectors	$135
WBS 1.04 Readout	$172
WBS 1.05 Module Assembly & Test	$73
WBS 1.06 Large Aperture Telescopes	$152
WBS 1.07 Small Aperture Telescopes	$187
WBS 1.08 DAQ / Controls	$26
WBS 1.09 Data Management	$71
WBS 1.10 Site Infrastructure / I&C	$172
Total project cost, including contingency	$1,144
Project completion year	2036

An example of a reduced-scope option, with 15 SATs and 2 LATs, yields total cost including contingency of $861M, with a completion year of 2034.

Operations and Divestment Costs

- The operations model for CMB-S4 consists of observations conducted using multiple telescopes and receivers operated in the Chilean altiplano near Cerro Chajnantor.
- CMB-S4 Operations team and scientists working at laboratories and universities, will coordinate the observations, monitor the data, design and implement the data pipeline, and carry out science analyses.
- Nearly all observations will be automated, so no local operators are needed during routine observations.
- Decommissioning and divestment of the CMB-S4 facilities in Chile is governed by agreements with the Republic of Chile and the Parque Astronómico Atacama (PAA) and generally require returning the land to its pre-construction state.

Calendar Year	2036		
Costs are in $M	TOTAL	NSF	DOE
Director's Office	$10.74	$5.14	$5.60
Data Production / Data Management	$14.97	$7.49	$7.49
Science Analysis / System Performance	$10.74	$5.37	$5.37
Education & Public Outreach	$1.97	$1.74	$0.23
Common Support Materials	$1.39	$0.70	$0.70
Common Support Operations - Travel	$2.53	$1.38	$1.16
Subtotal Common Operations	$42.35	$21.81	$20.53
Observatory Operations Chile	$9.68	$4.84	$4.84
Chile Materials	$9.34	$4.67	$4.67
Chile Operations - Travel	$2.53	$1.38	$1.16
Subtotal Chile Operations	$21.55	$10.89	$10.67
Annual Operations Cost ($M)	$63.90	$32.70	$31.20
10 Year Lifetime Operations Cost ($M)	$732.53	$374.87	$357.66
Divestment Cost ($M)	$9.7		

Stand-alone configuration (27 SAT receivers & 3 LATs)

A reduced-scope option with 15 SATs & 2 LATs would yield a total Operations cost of $723M over 10 years.

Questions / Discussion