CMB-S4 Performance-Based Constraints on Primordial Gravitational Waves

On behalf of the CMB-S4 Collaboration

Rencontres de Moriond 2018
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Harvard University
Stage 4 CMB experiment: CMB-S4

- A next generation ground-based program to pursue inflation, neutrino properties, dark radiation, dark energy and new discoveries.

- Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2) to cross critical science thresholds.

- O(500,000) detectors spanning 20-270 GHz using multiple telescopes and sites to map most of the sky, as well as deep targeted fields.

- Broad participation of the CMB community, including the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array, Simons Obs & SPT), National Labs and the High Energy Physics community. International partnerships expected and desired.

Recommended by P5 & NRC Antarctic reports from John Carlstrom
Continued Series of community workshops to advance CMB-S4

U. Minnesota, Jan 16, 2015

LBNL, Berkeley, Mar 7-9, 2016

U. Michigan, Sep 21-22, 2015

U. Chicago, Sep 19-20, 2016

SLAC, Feb 27-28, 2017

ANL, Mar 5-7, 2018

Harvard, Aug 24-25, 2017
<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity ($\mu K^2$)</th>
<th>$\sigma(r)$</th>
<th>$\sigma(N_{\text{eff}})$</th>
<th>$\sigma(\Sigma m_\nu)$</th>
<th>Dark Energy F.O.M</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000</td>
<td>$\gtrsim 10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15 eV</td>
<td>~180</td>
</tr>
<tr>
<td>2016</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06 eV</td>
<td>~300-600</td>
</tr>
<tr>
<td>2017</td>
<td>Stage 4</td>
<td>CMB-S4</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015 eV</td>
<td>1250</td>
</tr>
</tbody>
</table>

Stage 2
- 1000 detectors
- \( \geq 10^{-5} \)
- \( \sigma(r) = 0.035 \)

Stage 3
- 10,000 detectors
- \( 10^{-6} \)
- \( \sigma(r) = 0.006 \)

Stage 4
- CMB-S4
- \( \sim 500,000 \) detectors
- \( 10^{-8} \)
- \( \sigma(r) = 0.0005 \)

2015
- Sensitivity: \( \mu K^2 \)
- \( \sigma(N_{\text{eff}}) = 0.14 \)
- \( \sigma(\Sigma m_\nu) = 0.15\text{eV} \)
- Dark Energy F.O.M. \( \sim 180 \)

2016
- Sensitivity: \( \mu K^2 \)
- \( \sigma(N_{\text{eff}}) = 0.06 \)
- \( \sigma(\Sigma m_\nu) = 0.06\text{eV} \)
- Dark Energy F.O.M. \( \sim 300-600 \)

2017
- Sensitivity: \( \mu K^2 \)
- \( \sigma(N_{\text{eff}}) = 0.027 \)
- \( \sigma(\Sigma m_\nu) = 0.015\text{eV} \)
- Dark Energy F.O.M. \( 1250 \)

CMB-S4 Science Book [arXiv:1610.02743]
CMB-S4 Survey Baseline

Nine frequency bands: \{20, 30, 40, 85, 95, 145, 155, 215, 270\} GHz

At the South Pole and in Chile

Heterogeneous survey with (~500k detectors \times 4\ yrs = ~2M\ detector-yrs):
  • 1/2\ effort\ on\ 3\%\ of\ the\ sky\ for\ primordial\ B-modes
    • degree-scales\ with\ small-aperture\ (~0.5\ m)\ telescopes
    • arcminute-scales\ (to\ remove\ lensing\ B-modes)\ with\ large-aperture\ (~6m)\ telescopes
  • 1/2\ effort\ on\ 40\%\ of\ the\ sky\ for\ CMB-lensing,\ Neutrino\ Science,\ Dark\ Energy,\ etc.
    • large-aperture\ (>6m)\ telescopes

Small\ aperture\ (big\ beam)\ CMB\ telescopes

High\ resolution\ CMB\ experiments
Achieved Performance from S3 datasets

Scalable Instrument Specification & Sky model

Semi-analytic Forecasting Framework

Optimized Forecasting for \( r \)

Optimized Detector Allocation

Baseline Survey Definition

DC map synthesis standardized, version-numbered, data challenge map sets

Additional Complexity more realistic foregrounds, systematics

Cost Model cost scaling of instrument specification

Validated Baseline Instrument and Survey Definition

DC parameter recovery
- sensitivity
- biases
- derivatives w.r.t. survey design

Independent Analysis Methods

Forecasting Loop
Achieved Performance from S3 datasets

Forecasting Loop

Semi-analytic Forecasting Framework

Optimized Forecasting for $r$

Cost Model
cost scaling of
instrument specification

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Independent Analysis Methods
Achieved Performance from S3 datasets

Forecasting Loop

- We use full BICEP/Keck noise spectra based on achieved performance over multiple years at 95, 150, 220 GHz
- These include real world inefficiencies such as:
  - imperfect detector yield
  - non-uniform detector performance
  - read-out noise
  - observing inefficiency
  - atmospheric effects
  - time stream filtering losses
  - beam smoothing
  - non-uniform sky coverage, etc.

- We use full BICEP/Keck simulations of signal $\times$ signal, noise $\times$ noise, and signal $\times$ noise to construct a covariance matrix based on achieved performance, which can scale to any noise level and general theory model.
Forecasting Loop

- Start with a particular sky model
  - For the first iteration pick the maximum-likelihood model from the most recent BICEP/Keck analysis
- And nominal instrument specifications [determined by the band-definition group (see here)]:
  - frequencies,
  - bandwidths,
  - beams,
  - detector sensitivities (NET’s)

- Rescale the achieved performance BK noise spectra using the square of the ratio of NET’s between the S4 band and closest BK band, and their respective beams, to obtain the performance-based per detector S4 noise performance.
The multicomponent model parameters are:

1. $r$ — tensor-to-scalar ratio
2. $A_L$ — lensing amplitude
3. $A_d$ — dust amplitude, in $\mu K_{CMB}^2$, at 353 GHz and $\ell = 80$.
4. $\beta_{dust}$ — dust spectral index
5. $T_{dust}$ — dust greybody temperature
6. $\alpha_{dust}$ — dust spatial spectral index
7. $R_{dust}$ — dust frequency decorrelation
8. EE / BB ratio for dust
9. $A_s$ — sync amplitude, in $\mu K_{CMB}^2$, at 23 GHz and $\ell = 80$.
10. $\beta_{sync}$ — sync spectral index
11. $\alpha_{sync}$ — sync spatial spectral index
12. $R_{sync}$ — sync frequency decorrelation
13. EE / BB ratio for synchrotron
14. $\epsilon$ — synchrotron–dust spatial correlation
Achieved Performance from S3 datasets

Forecasting Loop

Scalable Instrument Specification & Sky model

Semi-analytic Forecasting Framework

Multicomponent Theory Model Code

BPCM Rescaling Code

• Obtain model expectation values \( \mu(\theta) \) and expectation value derivatives with respect to the theory parameters \( \theta \).

\[
F_{ij} = \frac{\partial \mu}{\partial \theta_i} \Sigma^{-1} \frac{\partial \mu}{\partial \theta_j} + \frac{1}{2} Tr(\Sigma^{-1} \frac{\partial \Sigma}{\partial \theta_i} \Sigma^{-1} \frac{\partial \Sigma}{\partial \theta_i})
\]

Fisher Forecasting Code

Parameter Constraints

• Use the obtained noise spectra and input model to rescale the full covariance matrix \( \Sigma \) to the appropriate noise level and theory model.

Optimized Forecasting for \( r \)

DC parameter refinement
• sensitivity
• bias
• derivatives

Validated Baseline Instrument and Survey Definition

Cost Model cost scaling of instrument specification
• Use the forecasting tool to optimize the allocation of detector effort across frequencies:
  - for various sky fractions,
  - with degree-scale component separation
  - and arcminute-scale delensing
• Determine baseline "checkpoints" in survey definition space.

Currently using constant focal plane area

Cost Model
cost scaling of instrument specification

Optimized Forecasting for \( r \)

Optimized Detector Allocation

Baseline Survey Definition

DC map synthesis
standardized, version-numbered, data challenge map sets

Additional Complexity
more realistic foregrounds, systematics

Independent Analysis Methods

Semi-analytic Forecasting Framework

Scalable Instrument

Achieved Performance
from S3 datasets

Validated Baseline Instrument and Survey Definition
CMB-S4 Science Book Optimization, assuming $r = 0$ and $f_{\text{sky}} = 3\%$.

![Graph showing the optimization of CMB-S4 Science Book with various parameters and total detection years (150 equiv).](image)
Baseline Checkpoint
pre-Concept Definition Team (CDT) Report to DOE

<table>
<thead>
<tr>
<th>$\nu$, GHz</th>
<th>$f_{\text{sky}} = 0.03$</th>
<th>Analytic Fitting parameters (BB)</th>
<th>Analytic Fitting parameters (EE)</th>
<th>Analytic Fitting parameters (TT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$#, , \text{det-yr}$</td>
<td>FWHM, $\mu K\cdot$arcmin</td>
<td>$\sigma_{\text{map}}$, $\mu K\cdot$arcmin</td>
</tr>
<tr>
<td>20</td>
<td>30,000</td>
<td>533</td>
<td>76.6</td>
<td>14.69</td>
</tr>
<tr>
<td>30</td>
<td>22,500</td>
<td>900</td>
<td>76.6</td>
<td>9.36</td>
</tr>
<tr>
<td>40</td>
<td>22,500</td>
<td>1,600</td>
<td>57.5</td>
<td>8.88</td>
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<tr>
<td>85</td>
<td>182,500</td>
<td>58,600</td>
<td>27.0</td>
<td>1.77</td>
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<tr>
<td>95</td>
<td>182,500</td>
<td>73,200</td>
<td>24.2</td>
<td>1.40</td>
</tr>
<tr>
<td>145</td>
<td>67,500</td>
<td>63,075</td>
<td>15.9</td>
<td>2.19</td>
</tr>
<tr>
<td>155</td>
<td>67,500</td>
<td>72,075</td>
<td>14.8</td>
<td>2.19</td>
</tr>
<tr>
<td>220</td>
<td>57,500</td>
<td>118,130</td>
<td>10.7</td>
<td>5.61</td>
</tr>
<tr>
<td>270</td>
<td>57,500</td>
<td>186,300</td>
<td>8.5</td>
<td>7.65</td>
</tr>
<tr>
<td>Total Degree Scale Effort</td>
<td>690,000</td>
<td>574,420</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Arcmin Scale Effort</td>
<td>310,000</td>
<td>289,680</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Effort</td>
<td>1,000,000</td>
<td>864,100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Full write-up of the procedure on the CMB-S4 Wiki ([link](#))
Forecasting Loop

- **Achieved Performance** from S3 datasets
- **Scalable Instrument Specification & Sky model**
- **Semi-analytic Forecasting Framework**
- **Optimized Forecasting for \( r \)**
- **Optimized Detector Allocation**
- **Baseline Survey Definition**
- **DC map synthesis** standardized, version-numbered, data challenge map sets
- **Additional Complexity** more realistic foregrounds, systematics
- **Validated Baseline Instrument and Survey Definition**
- **DC parameter recovery**
  - sensitivity
  - biases
  - derivatives w.r.t. survey design
- **Independent Analysis Methods**
- **Cost Model** cost scaling of instrument specification
Forecasting Loop

- Inject forecasting complexity: sky model / systematic effects / unmodeled residuals
  - Analyses of real experiments are used to validate the form, parameterization and likely amplitude of systematics
The baseline checkpoints and additional complexities are used as basis for standardized Data Challenges, which consist of:

- noise maps corresponding to the level of noise suggested by the forecast
- signal maps corresponding to 7 different sky models

0. Simple Gaussian realizations of synchrotron and dust
1. The PySM4 model a1d1f1s1 (Thorne et al. 2016)
2. The PySM model a2d4f1s3, w/AME, sync. curvature, and 2-temp dust (Thorne et al. 2016)
3. The PySM model a2d7f1s3, dust grain model of Hensley (2015)
4. HI column density maps as tracers of the dust intensity structures as Ghosh et al. (2017)
5. Dust decorrelation of Planck Collaboration (2017), where R(217×353) = 0.85
So far we have had two independent analyses:
- A map-based ILC cleaning method
- A parametric multi-component spectral method

Which we use to analyze the DC maps and obtain parameter biases, parameter constraints, and parameter changes w.r.t. the survey design.
**Sky Model Complexities**

<table>
<thead>
<tr>
<th>$r$ value</th>
<th>Sky model</th>
<th>$\sigma(r) \times 10^4$</th>
<th>$r$ bias $\times 10^4$</th>
<th>ILC</th>
<th>$\sigma(r) \times 10^4$</th>
<th>$r$ bias $\times 10^4$</th>
<th>Parametric</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>5.7</td>
<td>0.0</td>
<td>6.7</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7.0</td>
<td>0.3</td>
<td>7.8</td>
<td>5.8</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.7</td>
<td>0.8</td>
<td>7.1</td>
<td>3.1</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.6</td>
<td>0.8</td>
<td>8.1</td>
<td>1.8</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7.5</td>
<td>5.0</td>
<td>9.3</td>
<td>-3.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5$^a$</td>
<td>16</td>
<td>18</td>
<td>14</td>
<td>-2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>5.8</td>
<td>-1.1</td>
<td>7.3</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.003</td>
<td>0</td>
<td>7.2</td>
<td>-4.0</td>
<td>10</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>9.1</td>
<td>0.0</td>
<td>9.0</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9.6</td>
<td>-1.9</td>
<td>9.4</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7.2</td>
<td>-0.3</td>
<td>10</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10</td>
<td>5.8</td>
<td>11</td>
<td>-1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5$^a$</td>
<td>20</td>
<td>20</td>
<td>15</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8.3</td>
<td>-1.1</td>
<td>9.9</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ An extreme decorrelation model—see § A.1.2. The parametric analysis includes a decorrelation parameter. No attempt is made in the ILC analysis to model decorrelation.
## Systematics / Unmodeled Residual Complexities

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Uncorrected</th>
<th>Corrected</th>
<th>ILC</th>
<th>Parametric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A [%]  B [%]</td>
<td>A [%]  B [%]</td>
<td>$\sigma(r) \times 10^4$  $r$ bias $\times 10^4$</td>
<td>$\sigma(r) \times 10^4$  $r$ bias $\times 10^4$</td>
</tr>
<tr>
<td>None</td>
<td>0  0</td>
<td>0  0</td>
<td>5.3  0.0</td>
<td>7.2  0.0</td>
</tr>
<tr>
<td>Uncorrelated white</td>
<td>3.3  0</td>
<td>0  0</td>
<td>6.0  0.84</td>
<td>8.0  0.63</td>
</tr>
<tr>
<td>Uncorrelated $1/\ell$</td>
<td>0  6.8</td>
<td>0  0</td>
<td>5.0  0.99</td>
<td>7.0  0.85</td>
</tr>
<tr>
<td>Correlated white</td>
<td>0  0</td>
<td>5.8  0</td>
<td>6.3  1.2</td>
<td>7.3  1.41</td>
</tr>
<tr>
<td>Correlated $1/\ell$</td>
<td>0  0</td>
<td>0  10.5</td>
<td>5.2  1.0</td>
<td>6.7  0.97</td>
</tr>
<tr>
<td>Uncorrelated white + $1/\ell$</td>
<td>1.6  3.5</td>
<td>0  0</td>
<td>5.6  0.89</td>
<td>7.5  0.76</td>
</tr>
<tr>
<td>Correlated white + $1/\ell$</td>
<td>0  0</td>
<td>2.9  5.3</td>
<td>5.5  0.98</td>
<td>6.9  1.04</td>
</tr>
<tr>
<td>Both, white + $1/\ell$</td>
<td>0.8  1.7</td>
<td>1.5  2.6</td>
<td>5.6  1.1</td>
<td>7.9  0.98</td>
</tr>
</tbody>
</table>
Forecasting Loop

- **Achieved Performance from S3 datasets**
- **Cost Model** cost scaling of instrument specification
- **Scalable Instrument Specification & Sky model**
- **Semi-analytic Forecasting Framework**
- **Optimized Forecasting for \( r \)**
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  - sensitivity
  - biases
  - derivatives w.r.t. survey design
- **Validated Baseline Instrument and Survey Definition**
- **Independent Analysis Methods**

**Cost Model** cost scaling of instrument specification
• Offer a baseline CMB-S4 configuration that achieves the desired science goals

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>85</th>
<th>95</th>
<th>145</th>
<th>155</th>
<th>220</th>
<th>270</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$.............</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$14 \times 0.5$-m cameras</td>
<td>260</td>
<td>470</td>
<td>17k</td>
<td>21k</td>
<td>18k</td>
<td>21k</td>
<td>34k</td>
<td>54k</td>
<td>168k</td>
<td></td>
</tr>
<tr>
<td># detectors</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular resolution [FWHM]</td>
<td>77'</td>
<td>58'</td>
<td>27'</td>
<td>24'</td>
<td>16'</td>
<td>15'</td>
<td>11'</td>
<td>8.5'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1 \times 6$-m telescope</td>
<td>130</td>
<td>250</td>
<td>500</td>
<td>25k</td>
<td>25k</td>
<td>...</td>
<td>8.7k</td>
<td>8.7k</td>
<td>68k</td>
<td></td>
</tr>
<tr>
<td># detectors</td>
<td>11'</td>
<td>7.0</td>
<td>5.2</td>
<td>2'2</td>
<td>1.4</td>
<td>...</td>
<td>1.0</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular resolution [FWHM]</td>
<td>130</td>
<td>250</td>
<td>500</td>
<td>25k</td>
<td>25k</td>
<td>...</td>
<td>8.7k</td>
<td>8.7k</td>
<td>68k</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$r$ value</th>
<th>Duration</th>
<th>Sky model</th>
<th>$\sigma(r) \times 10^4$</th>
<th>$r$ bias $\times 10^4$</th>
<th>95% CL</th>
<th>UL</th>
<th>Detection Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0..........</td>
<td>4 years</td>
<td>6</td>
<td>4.7</td>
<td>0.5</td>
<td>1.0 $\times 10^{-3}$</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>0.003</td>
<td>4 years</td>
<td>6</td>
<td>6.9</td>
<td>-1.2</td>
<td>...</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

CDT Report, Appendix A
Conclusions

➢ We use on-sky current achieved performances from various CMB experiments to make robust forecasts for future CMB-polarization endeavors.

➢ We developed a closed-loop framework that has been used and validated in the context of optimizing various survey configurations, including the current CMB-S4 baseline.

➢ The paper containing all the details of this framework is in progress.

➢ However, we have an open group, with most of the work presented in detail in many public Logbook write-ups: https://cmb-s4.org/CMB-S4workshops/index.php/Simulation_and_Forecasting_Logbook

➢ There will be a CMB-S4 Science Book v2.0, likely in 2018.

➢ CMB-S4 brings us to $\sigma(r)<0.0005$ allowing us to significantly narrow down the space of possible inflationary models and do exciting new science!
Back-up
Achieved Performance from S3 datasets

Sky model

Likelihood Framework

Multicomponent Theory Model Code

- Obtain model expectation values $\mu(\theta)$ given the theory parameters $\theta$.

BPCM Rescaling Code

- Use the obtained noise spectra and input model to form the full covariance matrix $\Sigma$ for the appropriate theory model.

Real Bandpowers

Likelihood Evaluation Code

Parameter Constraints
Comparing Fisher vs real BKP constraints
Comparing Fisher vs real BK14 constraints
Forecasted CMB-S4 r-ns constraints, assuming $r = 0$ (top panel) and $r = 0.01$ (bottom panel).

- In the absence of a detection, CMB-S4 would rule out or disfavour all models that naturally explain the observed value of the scalar spectral index (in the sense that $n_s(N)-1 \sim 1/N$) and in which the characteristic scale in field space exceeds the Planck scale.

- A detection of primordial B modes with CMB-S4 would provide evidence that the theory of quantum gravity must accommodate a Planckian field range for the inflaton.

CMB-S4 Science Book arXiv:1610.02743