A Stage-IV CMB experiment, CMB-S4

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Goal: fully exploit CMB B-mode physics

- Explore the physics of inflation. $r = \text{gravitational wave / density wave}$

- Measure the Cosmic Neutrino Background. $N_{\text{eff}}$ and $\Sigma m_\nu$
Relevant numbers

• Lensing B-mode amplitude \( \sim 5 \mu\text{K-arcmin} \)

• High S/N measurement requires very deep maps with better than 3 arcmin resolution

• Sample variance

\[
\hat{C}_\ell = \langle |a_{lm}|^2 \rangle = \frac{1}{2\ell + 1} \sum_m |a_{lm}|^2 \\
\delta C_\ell \propto \frac{1}{\sqrt{(2\ell + 1)f_{\text{sky}}}}
\]

• Measure large areas of sky (10,000-20,000 sq deg)

• Instruments need lots of sensitivity!
Lots of detectors

\[
< n > = \frac{1}{e^{\frac{h\nu}{kT}} - 1}
\]

\[
< n^2 > = n(n + 1)
\]

- Sensitivity of individual detectors is now limited by shot noise of the photon flux
- Increasing sensitivity of an experiment requires increasing the number of detectors
Stages of CMB experiment

<table>
<thead>
<tr>
<th>Stage</th>
<th>Approximate raw experimental sensitivity (µK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>≈ 100 detectors</td>
</tr>
<tr>
<td>II</td>
<td>≈ 1,000 detectors</td>
</tr>
<tr>
<td>III</td>
<td>≈ 10,000 detectors</td>
</tr>
<tr>
<td>IV</td>
<td>≈ 100,000 detectors</td>
</tr>
</tbody>
</table>

- **Space based experiments**
- **WMAP**
- **Planck**
- **CMB-S4**
Stages of CMB experiment

You are here
Stages of CMB experiment

You are here

We see B-modes!
Specs

• Large angular coverage: degree angular scales for inflation, arcmin angular scales for lensing... minimum 3 arcmin resolution

• Large sky coverage: 20,000 sq deg \( (f_{\text{sky}} \sim 0.5) \)

• Lots of detectors: 500,000

• Broad frequency coverage for foreground removal: 40 - 240 GHz

• Target noise of 1 \( \mu \text{K}-\text{arcmin} \) over 50% of the sky starting 2020, observing for 5 years
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Primary technical development is one of scale
Core technology: TES bolometers

- Fabricated using thin film deposition and micromachining on Silicon wafer substrates: TES detectors are naturally manufactured as detector arrays

- Low impedance makes multiplexing feasible

- Strong history: Multiple detector architectures have been successfully deployed as Stage II experiments. Dominant technology for Stage II and upcoming Stage III projects

- At low frequencies (~40 GHz) MMIC or new superconducting amplifiers may also be used

Invented by HEP for Dark Matter detection
Technical Path for CMB-S4

• **Improved Production Reliability**: develop fabrication processes which control and stabilize material properties to achieve consistent high yield

• **Increased Production Volume and Throughput**: requires facilities with dedicated tooling and mass production throughput. Extensive QA testing program.

• **Multiplexed TES Readout**: modest improvements of existing successful multiplexer technologies. New microwave-based multiplexers may provide lower cost options with broader applicability

• **Large Cryogenic Optics**: large aperture, large optical bandwidth cryogenic optics. Incremental improvement over Stage-III

• **Computing**: data rate ~1 TB per day. ~10,000-times more observations per pixel compared to Planck
Evolution of CMB experiment

- HEP involvement in CMB has historically been small efforts focused on specific technical contributions (e.g.: multiplexing, detector fabrication and development, broadband antennas, MMICs)

- Moving from Stage-II to Stage-III and beyond, there is a consolidation of effort from multiple small experiments towards a few larger experiments

- There is increased involvement and impact from national lab resources
Science reach of CMB-S4

\[ \sigma(r) = 0.001; \text{ large field vs small field inflation?} \]
\[ \sigma(N_{\text{eff}}) = 0.02; \text{ CvB just SM neutrinos?} \]
\[ \sigma(\Sigma m_\nu) = 16 \text{ meV} \text{ (including DESI) mass hierarchy?} \]
Summary

• CMB-S4 will fully exploit B-mode measurement. Primary challenge is one of scale.

• TES Core technology. HEP invented technology. Major impact on Stage-II incl. first lensing B-mode detection. Focus on mass production for CMB-S4.

• Change from historical *Modus Operandi*... consolidation of effort. Increased contribution/leadership from national labs.

• Impact: $\sigma(r) = 0.001$; $\sigma(\text{Neff}) = 0.02$; $\sigma(\Sigma m_\nu) = 16$ meV

• CMB-S4 will continue US leadership in CMB science over the next 10 years.