Cosmology from the Stratosphere

measurements of primordial gravitational waves and gravitational lensing from near space

Nordita
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standing in for William Jones
Princeton University

on behalf of the SPIDER Collaboration
The Gold Standard
Terabytes of raw Planck data...

...compressed to a few 50MP images...
...reduced to about 10k coefficients (modes)...

...to which 6 parameters are fit...
But there are caveats...

- **Beyond LCDM — the early universe**
  - Pay no attention to the man behind the curtains
  - Mild indication of departure from LCDM
  - Inflation vs alternatives

- **Cosmological concordance**
  - The amplitude of linear fluctuations as measured at low redshift (with galaxy clusters and cosmic shear) appears significantly lower than that predicted by ΛCDM + CMB

- **Degeneracies with τ pose a limitation**
  - The optical depth of reionization is not well constrained, and degeneracies with cosmological parameters and neutrino mass are large

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**Future opportunities!**

- $\Omega b$
- $\Omega c$
- $\tau$
- $\Omega m$
- $H_0$

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**National Geographic**

Hildebrandt et al. (2016)

**SuperBIT**
The observational challenge

To clearly separate a primordial signal from more local sources we must

Constrain spectral energy distribution
The observational challenge

To clearly separate a primordial signal from more local sources we must

Constrain spectral energy distribution — Verify statistical isotropy

Commander dust intensity, 150 GHz
The observational challenge

To clearly separate a primordial signal from more local sources we must

Constrain spectral energy distribution — Verify statistical isotropy — Probe all angular scales

Lensing B-modes

Large scale polarization Reionization

Primordial gravitational waves

CLASS

LSPE

BICEP2 BICEP3

SPIDER

Keck Array

PIPER

SPIDER

AdvACT

SA
**Primary characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky coverage</td>
<td>About 10 %</td>
</tr>
<tr>
<td>Scan rate (az)</td>
<td>3.6 deg/s at peak</td>
</tr>
<tr>
<td>Polarization modulation</td>
<td>Stepped cryogenic HWP</td>
</tr>
<tr>
<td>Detector type</td>
<td>Antenna-coupled TES</td>
</tr>
<tr>
<td>Multipole range</td>
<td>$10 &lt; \ell &lt; 300$</td>
</tr>
<tr>
<td>Observation time</td>
<td>16 days at 36 km</td>
</tr>
<tr>
<td>Limits on $r^\dagger$</td>
<td>0.03</td>
</tr>
</tbody>
</table>

$^\dagger$ Assuming no foregrounds, at 99% confidence

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>95</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescopes</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Bandwidth [GHz]</td>
<td>22</td>
<td>36</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>30-45%</td>
<td>30-50%</td>
</tr>
<tr>
<td>Angular resolution $^*$ [arcmin]</td>
<td>41.1</td>
<td>28.2</td>
</tr>
<tr>
<td>Number of detectors $^\ddagger$</td>
<td>675</td>
<td>1188</td>
</tr>
<tr>
<td>Detector loading $^\ddagger$ [pW]</td>
<td>$\leq 0.25$</td>
<td>$\leq 0.35$</td>
</tr>
<tr>
<td>Instrument NET [μK·rts]</td>
<td>7.1</td>
<td>5.3</td>
</tr>
</tbody>
</table>

$^*$ FWHM. $^\ddagger$ Current channel cuts

$^\ddagger$ Including atmosphere, sleeve, window, and baffle
Long Duration Ballooning

- Circumpolar winds ~10 days/rev
- On average 20 day flights at 36 km

**Why Ballooning?**
- Space like loading (NET)
- Access to larger angular scales
- Wider frequency windows
- Preparation for SPB promised land

**Why Antarctica?**
- Continuous solar power
- Long flight times

**At what price?**
- Narrow launch windows
- Recovery difficulties
- Mass, power, and automation
Our trajectory
Feb 5, 2015 — data recovery

Fig. BAS
Nov 17, 2015 — payload recovery

Fig. Ed Young
Oct 13, 2016 — recycled aluminum
Observation regions

Fig. Sasha Rahlin
Polarization amplitude

- SPIDER scanned approximately 10% of the sky

Fig. Sasha Rahlin
SPIDER 150 GHz band: Temperature
Comparison to *Planck* HFI: Temperature

**Reobserved HFI 143-GHz**

Planck PR2 Maps, nominal Full Mission map
Stacking hot spots : SPIDER

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PRELIMINARY
PRELIMINARY

Fig. Sasha Rahlin
Stacking hot spots: Planck

Reobserved HFI 100 GHz All Stack

Reobserved HFI 143 GHz All Stack

Fig. Sasha Rahlin
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Figure removed from online version.
We detect polarized foregrounds
Recent limits on circular polarization

• Possible astrophysical V-pol production mechanisms:
  • Stellar remnant, galaxy cluster, and primordial magnetic fields, QED extensions, and so forth...

• Non-ideal half wave-plate partially transforms circular polarization to linear
  • Careful instrument characterization allows us to constrain circular polarization

• SPIDER improves limits by orders of magnitude

\[
\frac{k ((1)C_{\ell}^{
u}/(2\pi) [\mu K^2]
\]

\textbf{Nagy et al. (2017)}
\textit{arXiv:1704.00215}
SPIDER-2 development

- Receivers operating at 285 GHz are built and undergoing testing
- Project about 335 uKrts sensitivity per detector and 17 arcmin beam

(a) NIST OMTs and silicon platelete feedhorns

New cryostat built and leak tight!
SPB Ballooning

- Constant volume balloons
  - Stable altitude
- First science flight in 2016
- Potentially offers ~100 day flights
- Launch base in New-Zealand
- Intermediate latitudes
- Full diurnal cycles
- Payload mass ~1000 kg

First mid-latitude flight: March 2015, 33 days in air

Wanaka, New Zealand
44°42'S 169°09'E

Data from CSBF
SuperBIT Palestine 2016 Test Flight

- Deep, wide-field imager between 250-1000 nm
- Towards 0.5 meter class telescope flight on Super Pressure Balloon
  - Weak lensing mass calibrations for hundreds of clusters
  - Deep near-UV wide field imaging
  - Technical pathfinder for future 1.5 m class observatory
0.5 meter SuperBIT telescope:
Mapping speed \( \frac{1}{2} \times \) Hubble (5x less res)

1.5 meter (future) SuperBIT telescopes:
Mapping speed 40 x Hubble (2x less res)
SPIDER summary

• SPIDER is a completely autonomous payload
  • Electrical power, pointing control and reconstruction, redundant data systems (100 GB/day), cryogenic single-crystal sapphire polarization modulators
• Most sensitive microwave receiver to date
• Weighs a bit over 3.5 tons
  • Over 500 kg cooled to 4 K
  • About 30 kg cooled to 250 mK
• About 15 km of cryogenic wiring
• Hand-made with love (most of the time)
• Subsequent flight planned for 2018
Stay tuned!