Space/Ground Complementarity

Al Kogut
NASA Goddard Space Flight Center
B-modes in a Nutshell

Requirements for Detection

- Sub-Percent Foreground Subtraction
- Large AND small angular scales
- Immunity to Instrumental Effects
Those Annoying Foregrounds

*Into The Swamp ..*
Foregrounds: Size Matters!

Want Similar Angular Resolution Across Broad Frequency Range
But ...Angular Resolution $\theta \sim \lambda / D$

5' at 300 GHz: 80 cm primary

5' at 10 GHz: 24m primary

Cost to L2 deep-space orbit is about $250,000 / kg
Mapping low frequencies requires a ground-based observatory
Foregrounds: Visibility Matters!

The problem with ground-based cosmology ...

The graph shows the atmospheric transmission as a function of frequency. The red curve represents the Cosmic Microwave Background (CMB), and the blue curve represents dust emission. The y-axis represents atmospheric transmission, ranging from 0.0 to 1.0, and the x-axis represents frequency in GHz, ranging from 0 to 1000.
Foregrounds: Visibility Matters!

Atmosphere is opaque at frequencies above 300 GHz. Mapping high frequencies requires a space observatory.
Do we need data above 300 GHz?

*It depends on how well you want to do...*

Dust properties vary across the sky

\[
\tilde{T}_d
\]

Planck temperature variation \(\sigma_T = 1.9\) K

\[
\beta_d
\]

Planck spectral index variation \(\sigma_\beta = 0.05\)

Assume similar variation along line of sight

Fit dust using standard modified blackbody over frequency range [30, 250 GHz]

\[
\text{Angular Scale (Deg)}
\]

\[
\begin{align*}
\text{Power} (\ell(\ell+1)/(2\pi) C^{BB}_\ell (\mu K^2) \\
\text{Multipole } \ell
\end{align*}
\]

- \(r = 0.01\)
- \(r = 0.001\)
- \(r = 0.0001\)
- CMB Bias \(\sigma_\eta = 0.05\)
- \(\sigma_T = 2\) K
Foreground Complementarity

Graph showing the relationship between frequency (GHz) and multipole $\ell$ for different foreground contributions. The graph illustrates the regions of space and ground contributions, with a peak at foreground minimum and a lensing effect indicated.

- **Space**: Represented by a larger area.
- **Ground (Foregrounds)**: Shown in a smaller, distinct region.
- **Ground (CMB)**: Located within the ground contribution area.
- **B-Mode**: Indicated by a curve on the right side.
- **Synchrotron**: Illustrated by a blue curve on the right side.
- **Dust**: Shown by a green curve on the right side.
- **Recombination Peak at Foreground Minimum**: Marked by an orange star within the ground contribution area.

The graph also includes a line labeled $r=0.01$, indicating a specific threshold or parameter.
Those Difficult Angular Scales

How Big Is Big Enough?
Lensing vs Primordial B-Modes

Why large angular scales are important

![Graph showing power spectrum for different angular resolutions and bump features.](image-url)
Lensing vs Primordial B-Modes

Why large angular scales are important

![Graph showing power spectrum](image)
Lensing vs Primordial B-Modes

Why large angular scales are important

![Graph showing the power spectrum of lensing and primordial B-modes](image)
Reionization and Large Angular Scales

Guaranteed science for high-energy physics
Reionization and Neutrino Mass

Last Unknown Parameter for Standard Model of Particle Physics

Neutrino mass affects growth of structure
Larger mass → Faster expansion → Less growth

Lensing determines structure in nearby universe
CMB density perturbations set initial structure

up to a correction for reionization optical depth

Measure E-modes on large angular scales:
Cosmic-variance-limited measurement of
reionization optical depth

Need a space mission!

LiteBIRD, PIXIE, PICO, ...
Controlling Systematic Error

Would you rather tame a lion ... ... Or a kitten?

<table>
<thead>
<tr>
<th>Potential Problem</th>
<th>Ground</th>
<th>Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Turbulence</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Far Sidelobe Pickup</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Changing Thermal Environment</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Radio-Frequency Interference</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>That Darned Gravity</td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>

Angular Scales > 30 deg requires a space mission
Space/Ground Complementarity

Things that space missions do very well
Measurements across entire electromagnetic spectrum
  Foregrounds outside atmospheric windows
  Ancillary science
Exceptionally stable observing environment
  Measure largest angular scales
  Calibration stability
Minimal constraints on pointing / roll
  Systematic error control

Things that ground-based missions do very well
Large physical size for collecting optics
  Small angular scales
  Low-frequency foregrounds
Multiple instruments / facilities
  Deep integrations
  Cross-check vs technologies, observing modes
Incremental upgrades to instruments / facilities
  Cutting-edge technologies & development
  Robust reaction
A Mix of Methods

Don't assume a single mission must do it all

**Table: Requirements for Detection**

<table>
<thead>
<tr>
<th>Goal</th>
<th>Requirement</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detect reionization bump</td>
<td>Access large angular scales</td>
<td>Space</td>
</tr>
<tr>
<td>Detect recombination bump</td>
<td>0.5 to 1 deg resolution over ~20 deg patch</td>
<td>Space</td>
</tr>
<tr>
<td>Remove lensing</td>
<td>Arcmin resolution over relevant patch of sky</td>
<td>Space</td>
</tr>
<tr>
<td>Clean dust foreground</td>
<td>ν &gt; 300 GHz</td>
<td>Space</td>
</tr>
<tr>
<td>Clean synchrotron foreground</td>
<td>ν &lt; 30 GHz</td>
<td>Ground</td>
</tr>
</tbody>
</table>
The Past as Prologue

*Long track record of space/ground complementarity*

Space missions have been indispensable for precision cosmology

Ground-based measurements have been indispensable pathfinders
Do we need data above 300 GHz?

*Simple models OK for now, but we want to do 50x better*

Dust far-IR emission depends on...
- Local radiation field
- Dust chemical composition
- Dust physical composition
- Elapsed time since UV absorption

All of which vary everywhere!

There are a lot of possible models

Distinguish them at THz frequencies inaccessible to ground!
Reionization and Large Angular Scales

Neutrino mass: Last unknown parameter for Standard Model

![Graph showing E-Mode and B-Mode Reionization with optical depth and neutrino mass axes.](image)