Design Challenges for Future CMB Experiments

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Precision Cosmology

\[ \Lambda CDM \]

6 adjustable parameters

“Standard Model” for cosmology

Successfully explains many disparate measurements

Lensing

CMB

Galaxy Surveys
Another Successful Model

Aesthetics and Observation
Astonishingly successful
Modestly complicated

14 adjustable parameters
(eventually 28)
Testing Inflation with CMB Polarization

Inflating Space-Time ...

Creates Gravitational-Wave Background ...

B-Mode Polarization: “Smoking Gun” Signature of Inflation

Which Sources CMB Polarization

E Modes
Even Parity

B Modes
Odd Parity
A Theorist's View of Instrumentation
B-modes in a Nutshell

Requirements for Detection
- Photon-Limited Sensitivity
- Accurate Foreground Subtraction
- Immunity to Instrumental Effects
Challenge #1: Sensitivity

Small Signal

CMB intensity $\sim 4 \times 10^{-18} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$

$\sim 2.725 \text{ K}$

B-modes ($r=0.001$) $\sim 4 \times 10^{-27} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$

$\sim 3 \text{ nK}$

Need to measure difference between two orthogonal polarization states to part-per-billion accuracy

Photon Noise

$\Delta T \sim 25 \mu \text{K} \sqrt{\text{s}}$ for single-mode bolometer with 30% bandwidth

Reaching few nK requires $\sim 10^8 \text{ s}$ integration or $10^8$ bolometers (per beam spot on the sky)

Solution: Collect LOTS of photons!
Challenge #2: Foregrounds

Separate CMB from foreground emission using difference in frequency spectra and spatial distribution.

Foregrounds Brighter Than Primordial Signal – Everywhere!
A Rogue's Gallery of Foregrounds

**Definitely Polarized**
- Synchrotron
- Thermal dust
- Radio sources
- CMB lensing

**Probably not (very) polarized**
- Free-free emission
- Anomalous microwave emission
- Galactic lines (CO, C+, ...)
- Cosmic infrared background

*Sorting it out to part-per-thousand accuracy or better requires frequency, spatial, and astrophysical information*
A Cautionary Tale

What can happen when your model is simple, but the Universe is not ...

Phenomenological dust model $I(\nu) = \epsilon \nu^\beta B_\nu(T)$

How many components to fit?

Test:

- Generate simulated sky using broad distribution of dust temperatures
- Fit simulated sky using only two temperatures
A Cautionary Tale

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Phenomenological dust model

\[ I(\nu) = \epsilon \nu^\beta B_\nu(T) \]

How many components to fit?

- Generate simulated sky using broad distribution of dust temperatures
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Results: CMB biased at \( r \sim 10^{-3} \)

While fitting combined emission to 30 parts per million precision
The Problem With Parametric Models

Solution:

*Don't try to think more about the same data,*

*Think about getting more data!*

Measure frequencies above 1 THz or CMB sensitivity $10^{-6}$ per channel

*With seven free parameters, you can fit a charging rhino.*
Systematic Errors:
What You Don't Know Can Hurt You

Can we really control systematics at the nK level?
Challenge #3: Systematic Errors

How Do You Measure Signals at Parts-Per-Billion Level?

Everything in the Universe is hotter than a few nK!
- Stray light
- Instrumental emission
- Differential calibration

Solution: Modulate polarized signal
Challenge #3: Systematic Errors

The Joy of Nulling

Stray Light Error Signal:

\[
\text{Error Signal} = \frac{\text{Emission from Instrument} - \text{Missing emission from sky} - T_{\text{Sky}}}{T_{\text{Inst}} - T_{\text{Sky}}}
\]

Maintain instrument close to 2.7K CMB temperature
The Problem with Ground-Based Cosmology
Balloons Help, But Not Enough
In Space, You Can Let It All Hang Out ...

Long integration
Access to all electromagnetic frequencies
Stable thermal environment
No atmospheric noise / turbulence
No far-field reflections from surroundings
The Big Split

**Single-Moded Optics**

Sky

Optics

Focal Plane

**Multi-Moded Optics**

Sky

Optics

FTS Phase Shift

Aperture

Concentrator

Detector

Diffraction Limit: $\Delta \Omega = \lambda^2$

Single mode on each of 10,000 detectors

Conserve etendu: $N_{\text{mode}} = \Delta \Omega / \lambda^2$

10,000 modes on each single detector

*Trade angular resolution for frequency coverage*
Adventures in Fourier Space

Fringe Pattern vs Frequency Spectrum

All the power hits the detector all the time

\[ S_\nu = \sum_{k=0}^{N_s-1} S_i \exp\left(\frac{2\pi i \nu k}{N_s}\right) \]

\[ S_i = \int S_\nu \exp\left(\frac{2\pi i z_i}{c}\right) d\nu \]

Fit sampled fringe pattern to Fourier series \( \cos(k*x) \)
\[ a_0 + a_1 \cos(x) + a_2 \cos(2x) + a_3 \cos(3x) + \ldots + a_N \cos(Nx) \]
Adventures in Fourier Space

Channel Selection

Get $N$ samples of fringe pattern as phase delay goes from $-L$ to $+L$

Maximum phase delay sets channel width (hence lowest frequency)

$$\Delta \nu = \frac{c}{L}$$

Number of samples $N$ sets highest frequency

$$\nu_i = \Delta \nu, 2\Delta \nu, 3\Delta \nu, \ldots, \frac{N}{2} \Delta \nu$$

Sample more often $\rightarrow$ Get more (higher frequency) channels
Increase mirror throw $\rightarrow$ Decrease channel width (go to lower frequencies)
Trades: Angular Resolution

Photometer: Diffraction-limited resolution
\[ A\Omega = \lambda^2 \]
Can reach arc-min resolution at 150 GHz

Spectrometer: Fixed resolution
\[ A\Omega = \text{Constant} \]
30 arc-min resolution at all freqs

Advantage: Photometer
Trades: Sensitivity

**Photon Noise**

\[ \text{NEP}^2 = \int h\nu P(\nu) d\nu \]

Proportional to $\sqrt{\text{Power}}$ at detector

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**Advantage:** Photometer
Trades: Spectral channels

Photometer: One channel per detector

Spectrometer: Many channels per detector

Advantage: Spectrometer
Trades: Channel Shape

FTS channel shape set by apodization
Trade resolution vs channel-to-channel correlations
Weighted sampling → Nearest-neighbors
Force CO lines to center of Nth channels
Band shape is fixed *a priori* by math!

Photometer passbands set by filters
Complicated shape
Hard to control at few-percent level

**Advantage: Spectrometer**
What should we expect from a future CMB space mission?
The Past as Prologue

*Dedicated CMB space missions have been indispensable for precision cosmology*

COBE 1989—1993 (NASA)
- Confirm blackbody spectrum
- Discovery of primordial density perturbations

WMAP 2001—2010 (NASA)
- Temperature power spectrum
- Superhorizon modes
- First look at polarization

Planck 2009—2013 (ESA)
- Temperature power spectrum
- Polarization power spectrum
- Lensing power spectrum
Swing and a Miss ...

*Recent attempts for CMB space mission not so successful*

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Meanwhile, steady progress from ground & balloon instruments

- BICEP2, Keck, Polarbear, CLASS, ACT, SPT, Simons Array, ...
- EBEX, SPIDER, PIPER
- Take advantage of "small ball" incremental approach
- CMB-S4 as final ground-based measurements?

What is the ultimate limit within fixed atmospheric windows?
Ultimate CMB Mission

Space probably is the final frontier for CMB missions
  • Unique access across entire electromagnetic band
  • Long integrations in ultra-stable observing environment
  • Freedom to point/rotate/scan to minimize systematics

Continued interest from funding agencies
  • JAXA: LiteBIRD Phase A study
  • NASA: PICO concept study

Future: Multi-agency "ultimate mission"?
The Past and Future of Cosmology

"Big Picture" of cosmology
- Consistent theory fits many observations
- Flat universe dominated by dark matter and dark energy
- Stars, planets, chili dogs, etc are only 4% of the total

ΩCDM model has 6 free parameters
- Not so different from Ptolemy’s 28
- Unknown stuff dominates the universe
- Will our picture last 1500 years?

Exciting new tests for fundamental physics
- Quantum gravity and inflation
- Particle physics "Theory of Everything"

Technology now allows next big test: Stay Tuned!