The Einstein Inflation Probe:  
Experimental Probe of Inflationary Cosmology (EPIC) Study

Jamie Bock  
Jet Propulsion Laboratory / Caltech

The EPIC Consortium:

<table>
<thead>
<tr>
<th>Charles Beichman</th>
<th>Robert Caldwell</th>
<th>John Carlstrom</th>
<th>Sarah Church</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asantha Cooray</td>
<td>Peter Day</td>
<td>Scott Dodelson</td>
<td>Darren Dowell</td>
</tr>
<tr>
<td>Mark Dragovan</td>
<td>Todd Gaier</td>
<td>Ken Ganga</td>
<td>Walter Gear</td>
</tr>
<tr>
<td>Jason Glenn</td>
<td>Alexey Goldin</td>
<td>Krzysztof Gorski</td>
<td>Shaul Hanany</td>
</tr>
<tr>
<td>Carl Heiles</td>
<td>Eric Hivon</td>
<td>William Holzapfel</td>
<td>Kent Irwin</td>
</tr>
<tr>
<td>Jeff Jewell</td>
<td>Marc Kamionkowski</td>
<td>Manoj Kaplinghat</td>
<td>Brian Keating</td>
</tr>
<tr>
<td>Lloyd Knox</td>
<td>Andrew Lange</td>
<td>Charles Lawrence</td>
<td>Rick LeDuc</td>
</tr>
<tr>
<td>Adrian Lee</td>
<td>Erik Leitch</td>
<td>Steven Levin</td>
<td>Hien Nguyen</td>
</tr>
<tr>
<td>Gary Parks</td>
<td>Tim Pearson</td>
<td>Jeffrey Peterson</td>
<td>Clem Pryke</td>
</tr>
<tr>
<td>Jean-Loup Puget</td>
<td>Anthony Readhead</td>
<td>Paul Richards</td>
<td>Ron Ross</td>
</tr>
<tr>
<td>Mike Seiffert</td>
<td>Helmuth Spieler</td>
<td>Thomas Spiiker</td>
<td>Martin White</td>
</tr>
<tr>
<td>Jonas Zmuidzinas</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cosmic Microwave Background Polarization

Scalars = Polarization from physics at decoupling
Cosmic Shear = Gravitational lensing of CMB by matter
IGB = Signal from Inflationary Gravity-wave Background

EPIC = Experimental Probe of Inflationary Cosmology
Parameters for a Future Space Mission

**Science Goals:**
- Definitively search for IGB signal
- Use lensing signal to measure $P(k)$
- Map scalar signal to cosmic variance

**Instrument Parameters**
- All-sky coverage: optimal for GW search
- Complete frequency coverage
- Control systematic errors
- Sensitivity: $\sim 1 \mu K\sqrt{s}$, 30x better than Planck
- Angular resolution: $\sim 5'$ to clean lensing

Asantha Cooray, UCI
A Wealth of Cosmology in Polarization

Reionization from Low-l Polarization

CMB Cosmic Shear Measures P(k)
- neutrino mass
- dark energy w
- n & n'
- precision tests of BBN

Extract All Cosmology from Scalar-Pol
Sunyaev-Zel'Dovich Effect & Polarization
Non-Gaussianity, Galactic B-Fields, …

New Cosmological Tools: Lensing and SZ-pol

Llyod Knox,
Manoj Kaplinghat, UCD
Advances in Focal Plane Technology

Semi-Conducting Bolometers
- Realize fundamental noise properties
- Engineering limits to large arrays
- Even so, \( \text{NET} \approx 3 \mu K/\sqrt{s} \) is achievable

Superconducting Arrays
- TES bolos achieve needed performance
- Multiplexed readouts exist
- Need to develop coupling for mm-waves

![Planck PSB](image1)
![Planck 143 GHz bolometer](image2)
![SHARCII](image3)
![SPIRE](image4)

![Nb Leads](image5)
![Absorber](image6)

\[ \text{NEP} = 1.8e-17 \text{ W/}\sqrt{\text{Hz}} \text{ at } 300 \text{ mK} \]
\[ \tau = 400 \mu s \]

![Graph](image7)
Systematic Error Control with CMB Imager

WMAP 94 GHz

(WMAP + BOOM) / 2

WMAP
- Satellite
- All-sky coverage
- 1st-year release
- 1.65 mK √s per feed
- HEMTs

BOOM 150 GHz

(WMAP - BOOM) / 2

BOOM (1998)
- Balloon
- ~3 % of sky
- 10-day flight
- 190 uK √s per feed
- Bolometers

- WMAP filtered to match BOOM ~10º high-pass filter
- Both maps smoothed to 1º resolution
BOOMERANG / WMAP: Excellent Agreement

The Punchline

WMAP
- full-sky
- highly accurate calibration
  → smaller errors at low $l$

BOOM
- higher sensitivity
- higher resolution
  → smaller errors at high $l$

Important Details

- Identical binning
- Sample variance included
- BOOM scaled by 0.95
  (-0.5 sigma_cal)
- BOOM excludes beam errors

Also see astro-ph 0308355:
Excellent agreement between MAXIMA and WMAP
**BOOM 2003: 140 GHz Temperature (Sum) Map**

*Very familiar structures in ΔT map…*

- ~raw map made almost immediately after flight
- data from a single feed and detector pair
- no deglitching or gain correction
- note E-W filtering along scan direction
BOOM 2003: 140 GHz Polarization (Difference) Map

Observation Parameters

- Galactic Plane
- Shallow Region: ~2% of sky
- Deep Region: 100 square degrees @ ~2uK/pixel!

Channels at 140, 240, 340 GHz
BICEP: A 1\textsuperscript{st} Generation B-Mode Polarimeter

**Refracting Optics**
- Large $A\Omega$
- Low resolution (0.7°)
- Low polarization
- Cold pupil stop
- Telecentric FP

**Focal Plane**
- Dual analyzers

**Five Levels of Differencing**
- Difference two detectors
- Rotate polarization with FM at 10 Hz
- Rotate instrument at 1 RPM continuously
- Scan/drift beams on the sky
- Calibrate instrument with beam-filling source

Systematics, Systematics, Systematics.
Current and future focal planes

<table>
<thead>
<tr>
<th>Freq</th>
<th>Future</th>
<th>Planck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NET (calc)</td>
<td># feeds for 1 uK√s</td>
</tr>
<tr>
<td>30</td>
<td>38</td>
<td>1500</td>
</tr>
<tr>
<td>45</td>
<td>42</td>
<td>1750</td>
</tr>
<tr>
<td>70</td>
<td>25</td>
<td>750</td>
</tr>
<tr>
<td>100</td>
<td>25</td>
<td>750</td>
</tr>
<tr>
<td>150</td>
<td>25</td>
<td>750</td>
</tr>
<tr>
<td>220</td>
<td>38</td>
<td>1500</td>
</tr>
<tr>
<td>350</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HEMTs  \( T_A = 3h\nu/k \)  \( \Delta\nu/\nu = 30\% \)
Bolometers  \( \eta_{opt} = 50\% \)  \( \Delta\nu/\nu = 30\% \)
Q&U / feed  \( Q_{\max}/Q_0 = 5 \)
& telescope with  \( T = 60\, K, \varepsilon = 1\% \)
How to Build a Bigger Focal Plane?

- Corrugated feeds
- 4K filters & lenses
- Thermal gap
- 250mK filt & lenes
- Vespel legs

Get rid of discrete feeds and filters!
Directed Beams for mm-wave Polarimetry

Background-limited filled array vs. $2f_{\lambda}$ feedhorn array:

- ~3x better mapping speed
- 16 times more detectors
- Simpler operating modes
- Requires straylight control

Millimeter-wave case:

- Sky is 2.7 K
- Need extreme control of beams even in a 2 K environment
- Sub-K re-imaging optics? Or
- Directed beams

See Griffin, Bock & Gear
Applied Optics 2002
Astro-ph 0205264
Antenna Coupled Bolometer Arrays

**Planar Antennas**

- 25% BW filter
- Planar antenna
- Dual-polarization pixel
- TES bolometer

**Lens Coupled**

- Dual-slot antenna
- RF filters
- Dual-polarization pixel
- Lens array demo

**Advantages:**

- Polarization sensitivity, beam collimation
- Small active volumes
- High optical efficiency demonstrated
- Extendable to low frequencies
- On array filters, modulators possible
SQUID Multiplexing

**Time Domain**

Full-wafer SQUID multiplexer: 1,280 channels

**Frequency Domain**

Demonstrated 8:1 mux chip

Adrian Lee
UC Berkeley+LBNL
Kinetic Inductance Detectors

- Bandgap detector (unlike bolometer)
- Elegantly multiplexed readout uses room-temperature GHz electronics!

---

MMIC-Amplifier Based Polarimeter

- Simultaneous Q/U polarimeter
- 20 K operation
- Electronic polarization modulation
- Scalable to large arrays
- Room-temperature readout

---

90 GHz Correlation Radiometer IC

Peter Day, Rick LeDuc / JPL
Jonas Zmuidzinas / Caltech

Todd Gaier & Mike Seiffert / JPL
Polarization Modulators

Why use a modulator?
+ Stabilizes instrument sensitivity
+ Provides uniform Q/U sampling

Rotating Waveplate
+/- Modulates entire focal plane
- Multi-plates to get 1 octave BW

Superconducting Microstrip Modulator
+ Eliminates BW problem
+ Q, U & I per pixel
- Modulates upstream optical polarization
- Complicates focal plane

Faraday Modulation in Waveguide
+ All Solid State
- One per feed
- Current design gives 30 % BW

Faraday Modulator
Brian Keating / UCSD

Superconducting Bearing
Shaul Hanany / UMinn

Microstrip Modulator
Alexey Goldin / JPL
The Not-So Distant Future

We’re soon to learn a great deal more about:

- Scalar and lensing signals
- Foregrounds
- Methodology
- Technology
Conclusions

“EPIC” (-JPL) concept study based on imager approach
Demonstrated approach, rapidly improving technology
Planck PSBs are near background limited
NET ≈ 3 μK√s achievable scaling existing technologies
Higher sensitivity requires polarimeter focal planes

Key outstanding questions
Angular resolution, optics, systematics, foregrounds, cost…

Need space for definitive B-mode polarization survey
Optimal survey requires whole sky
Frequency coverage for foregrounds