CMB Polarization Measurements

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• Three major research challenges in astrophysics and cosmology research could lead to discoveries with potentially momentous implications for particle physics:
  – The direct detection of dark matter in terrestrial laboratories, the results of which could then be combined with measurements of candidate dark matter particles produced in accelerators.
  – *The precision measurement of the cosmic microwave background (CMB) polarization, which would probe the physics during the inflation that appears to have occurred within a tiny fraction of a second following the big bang.*
  – The measurement of key properties of dark energy.
Cosmic Microwave Background

Figure from WMAP; Bennett et al. 2003
CMB has been very effective at constraining cosmological parameters especially when combined with other data sets.

Figures from Allen et al. 2008
Temperature Spectrum has been measured with very high precision

Reichardt et al. 2007
(Kuo – SLAC/KIPAC)

...hints of lensing of the CMB by intervening matter are beginning to be seen
Constraining power of the CMB comes from…

New physics here can affect the CMB. For instance could inflation generate primordial gravitational waves?

Well-understood linear processes

Vanilla universe:
• Scale invariant spectrum \((n = 1)\) of density fluctuations with a gaussian distribution
The constraining power of the CMB comes from...

- Straight-forward physics $\Rightarrow$ accurate theoretical predictions with cosmological/physical quantities as the free parameters
- Measurements are the key
- Precision measurements $\Rightarrow$ “precision cosmology”

Table from Spergel et al. 2007

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Lambda$CDM + Tensor</th>
<th>$\Lambda$CDM + Running + Tensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.0233 $\pm$ 0.0010</td>
<td>0.0219 $\pm$ 0.0012</td>
</tr>
<tr>
<td>$\Omega_m h^2$</td>
<td>0.1195$^{+0.0094}_{-0.0093}$</td>
<td>0.128 $\pm$ 0.011</td>
</tr>
<tr>
<td>$h$</td>
<td>0.787 $\pm$ 0.052</td>
<td>0.731 $\pm$ 0.055</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.984$^{+0.029}_{-0.028}$</td>
<td>1.16 $\pm$ 0.10</td>
</tr>
<tr>
<td>$d n_s/d \ln k$</td>
<td>Set to 0</td>
<td>$-0.085 \pm 0.043$</td>
</tr>
<tr>
<td>$r$</td>
<td>$&lt;0.65$ (95% CL)</td>
<td>$&lt;1.1$ (95% CL)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.090 $\pm$ 0.031</td>
<td>0.108$^{+0.034}_{-0.033}$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.702 $\pm$ 0.062</td>
<td>0.712 $\pm$ 0.056</td>
</tr>
</tbody>
</table>

Figure from WMAP; Bennett et al. 2003.
One particular class of inflationary models

Figure from Kallosh, Stanford Institute for Theoretical Physics

\[ V = \frac{\lambda}{4}(\phi^2 - \nu^2)^2 \]

Ratio of primordial gravitational waves to density fluctuations
The constraining power of the CMB comes from...

- Straight-forward physics ⇒ accurate theoretical predictions with cosmological quantities as the free parameters
- Measurements are the key
- Precision measurements ⇒ “precision cosmology”

Table from Spergel et al. 2007

Figure from WMAP; Bennett et al. 2003,
CMB polarization anisotropies

• Only quadrupoles at the surface of last scattering generate a polarization pattern

• Quadrupoles generated by:
  - Velocity gradients in the photon-baryon fluid - SCALAR MODES
  - Gravitational redshifts associated with gravitational waves - TENSOR MODES

All pictures by Wayne Hu
E and B modes

- These modes retain their character on rotation of the local coordinate system.
- E-modes are invariant under a parity change, B modes are not.
- Scalar modes (density fluctuations) cannot generate B-modes.
- Tensor modes (gravitational waves) generate a mixture of E and B modes.
The Science

*Hu, Hedman, Zaldarriga, 2002*

![Graph showing temperature spectrum and various modes from primordial gravitational waves.](image)

- **Temperature spectrum**
- **E-modes from density fluctuations**
  - Measure cosmological parameters
- **Gravitationally lensed E-modes**
  - (dark energy, massive neutrinos)
- **Reionization bump**
- **B modes from primordial gravitational waves**
  - Blue shading spans current limits and minimum detectable from CMB

Inflation???
QUaD experiment (KIPAC) first year power spectra

QUaD at the South Pole (Church PI)

Bolometers
100, 150 GHz
The Science

Hu, Hedman, Zaldarriga, 2002

Temperature spectrum

E-modes from density fluctuations

Gravitationally lensed E-modes (dark energy, massive neutrinos)

Reionization bump

B modes from primordial gravitational waves

Blue shading spans current limits and minimum detectable from CMB
The experimental landscape circa 2005 (NASA/NSF/DOE taskforce on CMB research)

CHIP, Polarbear, QUIET, SPUD, SPTPol
The goal

- Current experiments targeting $r \sim 0.1-0.2$
- Next generation targeting $r \sim 0.02$
- A space mission would target $r \sim 0.005$??

![Graph showing existing data, current experiments, and next generation in design phase.](image)
The Challenge

• Beyond $r \sim 0.1$ can only come from deploying very large numbers of detectors -- 1000’s rather than 100’s
  - Optimum experimental design not yet determined
  - Careful system engineering needed to minimize systematic effects that will otherwise dominate (signal < 1pt in $10^8$ of background)
  - Data sets will comprise tens of thousands of time streams compared to few tens for current expts.
  - Project size and analysis complexity will increase

• Requires a change in culture from small collaborations, few postdoc/grad students
  - Project management/data distribution issues

• Ideal for cross-agency collaboration (EPP2010, Quarks to Cosmos, joint DOE/NSF/NASA CMB taskforce)
Complementary approaches being pursued at SLAC/KIPAC for next generation experiments

• Large format radio interferometers based on coherent amplifier technology
  – Excellent control of systematics
• Large-format arrays of transition-edge sensor bolometric detectors
  – high instantaneous sensitivity
Activities that are matched to SLAC core capabilities

- **RF design**
  - Low-noise radio amplifier modules suitable for mass-reproduction.
  - On-chip antennas and filters for 30-300 GHz

- **Digital and Analog Electronics**
  - FPGAs or ASICs for large correlators – $10^7$ correlations
  - SQUID amplifier readout and multiplexing for SPUD TES detectors (Stanford/Berkeley/LBL)

- **Systems engineering and end-to-end characterization and calibration**

- **Project management (especially with view to ultimate space mission)**

- **Handling of very large data sets**

- **Analysis and signal processing methods to provide believable detection of very small signals in large backgrounds (1 pt in $10^8$)**
Radio Interferometers have played a key role in CMB polarization measurements. Need to move from 13 to ~1000 elements!

**Enabling technology:** miniaturized radio receivers 30-150 GHz

**DASI**
University of Chicago
First detection of CMB polarization

**CBI, Caltech**
Limits to isocurvature modes

**Cosmic Background Imager**
Enabling Technology: Antenna-coupled bolometers

Pictures from JPL microlab, but effort to duplicate at Stanford (Kuo)

Also LBL/Berkeley expertise
Projects with KIPAC Involvement

- Opportunities for major SLAC instrumental in addition to existing KIPAC and Stanford campus roles
- These will be large, multi-institutional, possibly international collaborations
- SLAC could play a leadership role in the technology and the science, enabling the culture change needed to effectively pursue this difficult science
Summary

• The CMB is still the best astrophysical probe of conditions in the very early universe
• Offers a means to probe physics beyond the standard model e.g. inflation
• SLAC capabilities are matched to requirements in
  - Technology development
  - Data handling and analysis
  - Project management
• Stanford is already a center for CMB research
• Potential to lead the next generation of experiments culminating in a space mission