CLASS
Collaborators

NASA GSFC
- D. Chuss
- K. Denis
- A. Kogut
- N. Miller
- H. Moseley
- K. Rostem
- E. Wollack

UBC
- M. Amiri
- M. Halpern
- G. Hinshaw

Northwestern
- G. Novak

JHU
- A. Ali
- J. Appel
- C. Bennett (PI)
- J. Eimer
- T. Essinger-Hileman
- D. Gothe
- K. Harrington
- C. Huang
- J. Karakla
- D. Larson
- T. Marriage
- D. Watts
- Z. Xu

NIST
- H-M. Cho
- K. Irwin
- G. Hilton
- C. Reintsema

CfA-SAO
- L. Zeng

PUC de Chile
- R. Dünner

Columbia
- D. Araujo
- G. Jones
- M. Limon
- A. Miller
CLASS targets CMB B-modes at large angles.

1) **Recombination bump** packs a lot of signal.

2) **Avoids lensing B-modes.**

Also E-mode **Reionization** Constraints

---

(20 uK-arcmin over 50% of total sky)
CLASS targets CMB **B-modes** at **large angles**.

Katayama & Komatsu 2012

**significant S/N in first 10 ell**

\[ \ell(\ell+1)C^{BB}_\ell/2\pi \] [\(\mu K^2\)]

**Fractional Error, \(\sigma_\ell/r_{input}\)**

- \(r=0.001, \text{ with lensing}\)
- \(r=0.001, \text{ w/o lensing}\)
- \(r=0.01, \text{ with lensing}\)
- \(r=0.01, \text{ w/o lensing}\)

\(20 \text{ arcmin over } 50\% \text{ of total sky}\)
CLASS targets CMB B-modes at large angles.

A unique range of angular scales! (in a field largely targeting the recombination peak) CLASS is the leader in this regime.

Katayama & Komatsu 2012

significant S/N in first 10 ell
CLASS is an array of 4 telescopes operating at three frequencies that straddle the foreground minimum.

Additional foreground constraints from PIPER (200 GHz, 270 GHz) and Planck (217, 353 GHz)

<table>
<thead>
<tr>
<th>CLASS Survey Design Parameters</th>
<th>Frequency</th>
<th>Detectors</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 GHz</td>
<td>72</td>
<td>1.5°</td>
<td></td>
</tr>
<tr>
<td>90 GHz</td>
<td>1200</td>
<td>40’</td>
<td></td>
</tr>
<tr>
<td>150 GHz</td>
<td>120</td>
<td>24’</td>
<td></td>
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</tbody>
</table>
To detect **large-angle modes**, **CLASS** needs a **wide survey**.

The Atacama is the best site for large sky coverage.

Site in Atacama Desert is not far from the equator: **most of sky** is surveyed at zenith angle 45 deg.
To detect **large-angle modes**, CLASS needs a **wide survey**.

**CLASS Survey Boundary**

**Galactic Mask**

**65% of the Extragalactic Sky**

**Extragalactic Survey Region in Black**

Site in Atacama Desert is not far from the equator: **most of sky** is surveyed at zenith angle 45 deg.
To detect **large-angle modes**, **CLASS** needs a **wide survey**.

Multiple observing angles through **sky** and **deck rotation**

Site in Atacama Desert is not far from the equator: **most of sky** is surveyed at zenith angle 45 deg.
The CLASS Way

1. Systematics control with front end modulation.

2. Sensitivity with high efficiency optics and TES bolometers cooled to 150 mK.

3. Galactic foreground cleaning with multifrequency telescope array.
The CLASS Way

Continuous Operation with 50 μW at 100 mK

1. Systematics control with front end modulation.

2. Sensitivity with high efficiency optics and TES bolometers cooled to 150 mK.


One of the four CLASS receivers (PT+DR Cooler) undergoing tilt test.

Wednesday, September 25, 13
The CLASS Way

1. Systematics control with front end modulation.

2. Sensitivity with high efficiency optics and TES bolometers cooled to 150 mK.

3. Galactic foreground cleaning with multifrequency telescope array.

40 GHz Focal Plane Assembly.
The CLASS Way #1: Systematics control with front end modulation
CLASS uses **modulation** to measure **large scales**.

A Variable-Delay Polarization Modulator (VPM) is the front-end optical element.

Modulates signal at $\sim 5$ Hz to separate signal from the I-to-Q leakage of atmosphere and other instrument-related drift.

$-dP/dI \\ Q : 1st harmonic \\ V: 2nd harmonic$
CLASS uses **modulation** to measure large scales.

A Variable-Delay Polarization Modulator (VPM) is the front-end optical element.

Modulates signal at **5-10 Hz** to separate signal from the (unpolarized) atmosphere and other instrument-related drift.

*Both the atmosphere and gain time streams have $1/f^2$ power spectra. The atmosphere has an amplitude of 0.05 K at 0.1 Hz and the gain fluctuation has an amplitude of 0.5% at 0.005 Hz.*
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**CMB Simulation**

**Recovery without Modulation and simple map-making**

**Atmosphere + Differential Gain**
**Preliminary Simulation Results**

EE theory, $r=0.01$

Effects Included:

* Atmosphere
* VPM temperature drift + differential emissivity
* Detector pair differential gain fluctuation
* VPM-Detector misalignment (0.5 deg)

10% BB systematic due to VPM-Detector misalignment likely further reduced by adjusting angle so $EB=0$

Miller et al. (in prep)
The CLASS Way #2: Sensitivity with high efficiency optics and tweaked-up detectors cooled to 150 mK
CLASS Detectors: Design

Horns and Planar OMT produce simple single-moded beams.

High-efficiency and design repeatability is achieved through use of monocrystalline silicon dielectric.

Intrinsic OMT design achieves broad 50% fractional bandwidth, which may be divided for multi-frequency operation.

On-chip transmission line filtering, shielding and niobium gap provide well defined bandpass and stringent blue leak control.

40 GHz Detector
Comparison of TES transition with and without Au stripes

TESs with tuned transitions and thermal conductances

Detectors coupled to thermal source show 90% efficiency and no out of band leakage.

CLASS Detectors: Excellent Design; Excellent Tests

Detectors coupled to thermal source show 90% efficiency and no out of band leakage.

Wollack et al. (in prep)
CLASS Detectors: Sensitivity
(or how to detect B-modes with fewer than 10,000 detectors)

Three Designs*

Phonons

NET = 270 μK-√s
150 GHz
modest efficiency
500 mK

Photons

200 μK-√s
150 GHz
high efficiency
150 mK

140 μK-√s
90 GHz
high efficiency
150 mK

*examples for argument; not exact; for instance need to add amplifier noise

Significant advances in SQUID amplifier noise over previous experiences.
CLASS Detectors: Sensitivity
(or how to detect B-modes with fewer than 10,000 detectors)

Three Designs*

Phonons

NET = 270 μK-√s

150 GHz
modest efficiency
500 mK

Bicep II has
nearly achieved
this

200 μK-√s

150 GHz
high efficiency
150 mK

Photons

140 μK-√s

90 GHz
high efficiency
150 mK

CLASS
goal

*examples for argument; not exact; for instance need to add amplifier noise

Significant advances in SQUID amplifier noise over previous experiences.
The CLASS Way #3: Galactic foreground cleaning with multi-frequency telescope array
Template-based Likelihood for \( r, s, \) and Foregrounds

(Efstathiou et al. 2009; Katayama & Komatsu 2011)

\[
\mathcal{L}(r, s, \alpha_i) \propto \exp \left[ -\frac{1}{2} x'(\alpha_i)^T C^{-1}(r, s, \alpha_i) x'(\alpha_i) \right] \sqrt{|C(r, s, \alpha_i)|},
\]

where

\[
x' = \frac{[Q, U](v) - \sum_i \alpha_i(v)[Q, U](v^\text{template})}{1 - \sum_i \alpha_i(v)}
\]

\[
C(r, s, \alpha_i) = r c^{\text{tensor}} + s c^{\text{scalar}} + \frac{N_1 + N_2}{(1 - \sum_i \alpha_i)^2},
\]

Full likelihood is computationally feasible because we are probing large angles=fewer data with larger signal per-\( a_{lm} \). Approach infeasible at smaller angles. Built-in handling of E-B mixing etc.
40 GHz

90 GHz

270 GHz (PIPER)

Galactic Coords

Template cleaned map
(Noise=11 μK-arcmin)

Residuals from CMB input map at 5nK level

15 μK-arcmin noise

Watts, Larson et al (in prep)
Exploring Constraints with Sky Cuts and Foregrounds

(Pixel-based likelihood as in Katayama & Komatsu 2011)

Note
Non-Gaussian likelihood using large angular scales can yield a detection with tail to high $r$.

Dashed lines = input values

$r_{\text{input}} = 0.02$

tensor-to-scalar ratio

Watts, Larson et al (in prep)

Preliminary!!! More work to be done.

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Exploring Constraints with Sky Cuts and Foregrounds

(Pixel-based likelihood as in Katayama & Komatsu 2011)

Analytic calculation (K&K ’11)

Note

Non-Gaussian likelihood using large angular scales can yield a detection with tail to high $r$.

tensor-to-scalar ratio Watts, Larson et al (in prep)

Preliminary!!! More work to be done.

Wednesday, September 25, 13
Outside View on $r$

(Upper limits)

- Temperature Data
- Polarization Data

Current experiment predictions

(trend ruled not just by shear sensitivity but systematics etc)

Mounts
Cryostats
Atacama Site Preparation

Optics
Focal Planes
VPMs

1.5 m