Probing the Epoch of Inflation by
Deep Small-sky CMB Polarization Observations

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Cosmic Microwave Background (CMB) Radiation

- relic radiation from very young universe (379,000 yrs old)
- polarized
- described by 3 Stokes parameters: $T$ (Temperature) $Q, U$ (Polarization)
- very close to uniform in all directions
- small anisotropies contain a lot of cosmological information
Cosmic Microwave Background Radiation

power spectra of fluctuations in temperature (T) map and polarization (Q, U) maps

\[ C^{TT}_l, C^{TE}_l, C^{EE}_l, C^{BB}_l \]

E-mode, B-mode
B-modes: probing energy scale of inflation

✧ (cosmic) B-mode **only** produced by gravity waves (on large scales), a necessary by-product of inflation.

\[ V^{1/4} \sim 10^{16} \text{GeV} \left( \frac{r}{0.01} \right)^{1/4} \]

amplitude of B-modes

inflationary potential

detection of large B-modes ( \( r \sim 0.01 \) or larger)

\[ \downarrow \]

inflation happened at large energy scales (GUT scales?)
as predicted by standard inflation scenarios
strong confirmation of these theories
B-modes Experiments

BICEP, QUIET, EBEX, KECK, ABS, Planck, Spider, ...

Spider
balloon-borne experiment to measure the polarization of CMB

LDB flight (20-40 days),
December 2011 (Antarctica)
GOAL:
what is the optimum sky coverage for measuring $r$?
CMB Analysis Pipeline

- Foregrounds subtraction
- Power spectra estimation
- Model testing
- Parameters: $(\tau, r, \ldots)$
- Amplitude of gravity waves
Sources of “noise”

- instrument noise
- cosmic variance: we only have one CMB sky.
- galactic foregrounds

- E/B mixing?
  Part of E-mode polarization looks like B-mode. A geometrical effect due to observing finite sky patches and absent in ideal full sky experiments.
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Avoid E/B mixing?
CMB Analysis Pipeline

parameters
$(\tau, r, ...)$

foregrounds subtraction

model testing

power spectra estimation
CMB Analysis Pipeline

Map-based likelihood estimator
Map-based maximum likelihood estimator

likelihood\quad \mathcal{L}_\Delta(\alpha) \equiv P(\Delta|\alpha) = \frac{1}{(2\pi)^{N/2}|C|^{1/2}} e^{-\frac{1}{2}\Delta^T C^{-1} \Delta}

here: \quad \Delta = s + n

map\quad \Delta = s + n

covariance matrix\quad C = \langle \Delta \Delta^\dagger \rangle

\quad = C_T + C_N

\quad = \langle ss^\dagger \rangle + \langle nn^\dagger \rangle

\quad \text{instrument noise} \quad + \quad \text{uncertainty in foregrounds subtraction}

Naturally and optimally deals with the E/B mixing problem and does the best theoretically possible job.
Goal

Optimizing sky coverage for measuring $r$

Simulations/Results

1- Observe a portion of the sky with *Spider* (beam, instrument sensitivity, ...). How well is the input model recovered?

2- Challenges:
   - the signal we are after is very weak.
   - dealing with huge matrices.
CMB sky simulated with $r=0.12$

as predicted by $V \propto m^2 \phi^2$

How well can we measure $r$ for different sky cuts? (with the same observation time)
CMB sky simulated with $r \sim 0$.
What is upper bound on $r$ for different sky cuts?
optical depth to reionization

\[ r \] tells only about the amplitude.

\[ \tau \] tells us about the shape of the tensor perturbation.

consistency line (slow-roll inflation)

tilt parameter
Summary

In experiments with small sky coverage, E/B mixing introduces non-negligible errors in measuring the gravity wave amplitude. To avoid these errors, $r$ can be measured directly using a map-based likelihood analysis on a feasible time-scale thanks to large parallel computations.

This method naturally and optimally deals with E/B mixing. Recovery of $r$ to better than $\pm 0.02$ seems feasible (with foregrounds ignored.)
Cosmic Microwave Background Radiation

power spectra of fluctuations in temperature (T) and polarization (Q, U)

\[ \delta T(\hat{n}) = \sum_{lm} a_{lm}^T Y_{lm} \]

\[ Q + iU(\hat{n}) = \sum_{lm} 2a_{lm} Y_{lm} \]

\[ Q - iU(\hat{n}) = \sum_{lm} -2a_{lm} Y_{lm} \]

\[ a_{lm}^E = -\left(\frac{2a_{lm} + -2a_{lm}}{2}\right) \]

\[ a_{lm}^B = i\left(\frac{2a_{lm} - -2a_{lm}}{2}\right) \]
Planck + Spider

\[ \rightarrow \text{small sky Spider} + (\text{full sky}) \text{ Planck} \]