Optimizing the observing bandwidths for the CLASS HF detectors

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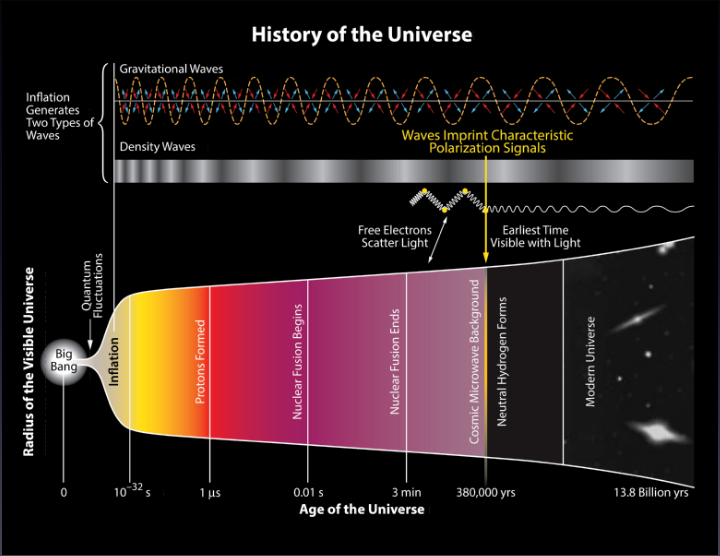
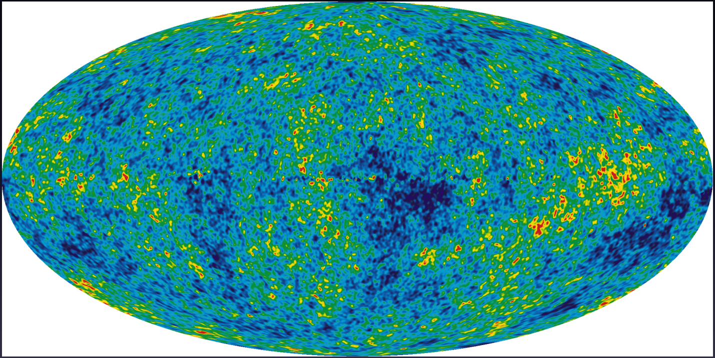
Events in the Early Universe



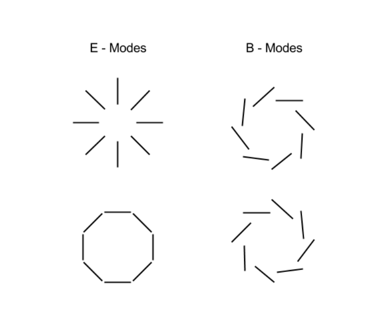
Imprints of Inflation on the Cosmic Microwave Background



- Small fluctuations in the early moments of the universe become anisotropies in temperature of the CMB, 2.7260 ± 0.0013 K

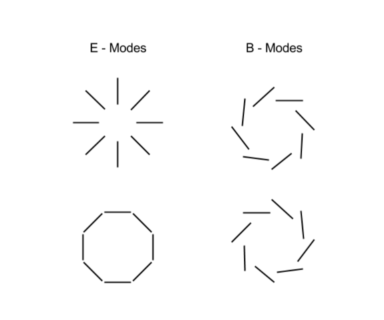
Imprints of Inflation on the Cosmic Microwave Background

- Process of inflation yields large gravitational waves



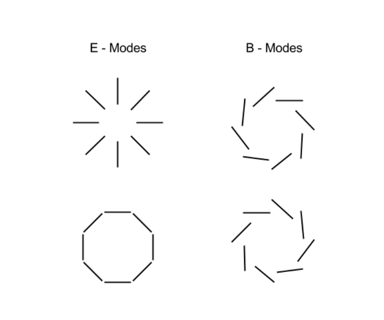
Imprints of Inflation on the Cosmic Microwave Background

- Process of inflation yields large gravitational waves
- GW's uniquely cause B-mode polarization

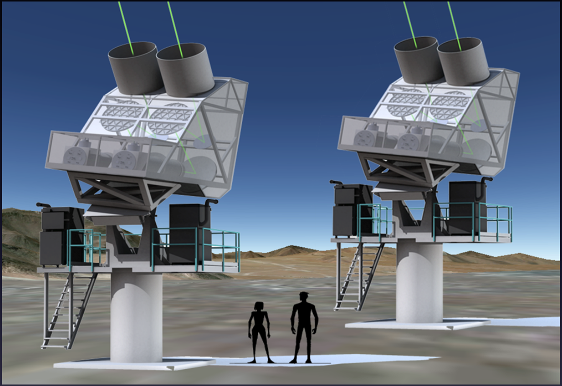


Imprints of Inflation on the Cosmic Microwave Background

- Process of inflation yields large gravitational waves
- GW's uniquely cause B-mode polarization
- Therefore, a B-mode signal in the CMB would be evidence for inflation



Detecting the CMB

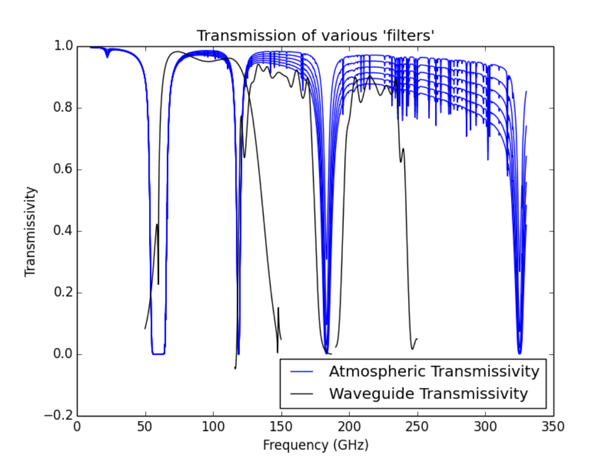


- The Cosmology Large Anuglar Scale Surveyor (CLASS) will use very sensitive, very cold bolometers at four different frequencies in order to detect the very low-frequency microwave photons from the CMB.

Avoiding Other Sources

- Optical filters, feed horns, waveguides and on-chip filters remove frequencies beyond the desired signal.
- Location in the Atacama desert will decrease microwave signal from the atmosphere
- The Variable Polarization Modulator distinguishes the polarization of the photons

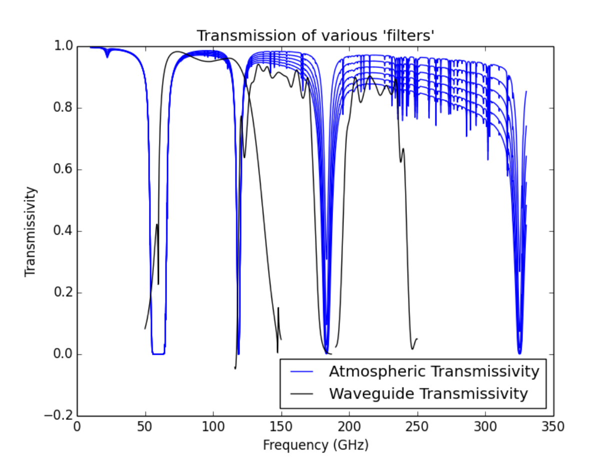
The Atmospheric Signal



Data from Refs. [1] and [2]

- The atmosphere behaves like a black body - absorbing and emitting - at about 270 K

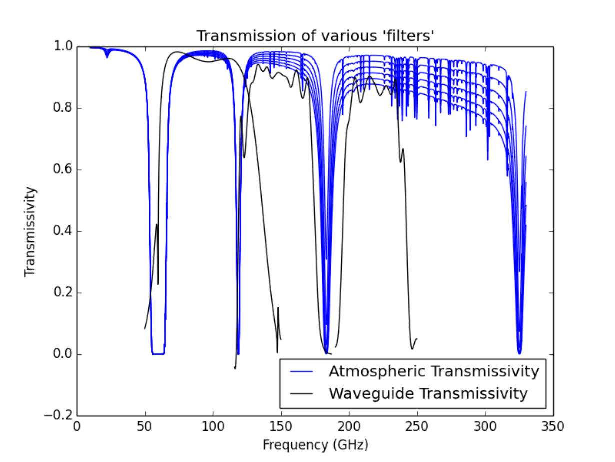
The Atmospheric Signal



Data from Refs. [1] and [2]

- It doesn't absorb and emit on all frequencies, but where it absorbs, it emits; where it doesn't absorb, it doesn't emit

The Atmospheric Signal



Data from Refs. [1] and [2]

- The waveguides only permit transmission of photons at certain wavelengths

Bandwidth Optimization Goals

To determine the optimal bandwidth for on-chip filter placement:

- Maximize power from the CMB
- Minimize noise from the signal
- Use a model based on variable atmospheric transmission

Mathematical Basis - Power

Planck's law (intensity per frequency)

$$B_\nu(T) = \frac{2h\nu^2}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1} \tag{1}$$

Power per frequency, Approximating $A\Omega = \lambda^2$ (Ref. [3])

$$p(\nu) = A\Omega B_\nu(T) = \alpha\epsilon f \frac{2h\nu}{e^{\frac{h\nu}{k_B T}} - 1} \tag{2}$$

Mathematical Basis - Noise

Variance per frequency

$$\sigma^2 = \langle n^2 \rangle - \langle n \rangle^2 \tag{3}$$

Derived for radio-frequency bolometers in Ref. [4]:

$$NEP^2 = \frac{4h^2\nu^2(\alpha\epsilon f)}{e^{\frac{h\nu}{k_B T}} - 1}\left(1 + \frac{\alpha\epsilon f}{e^{\frac{h\nu}{k_B T}} - 1}\right) \tag{4}$$

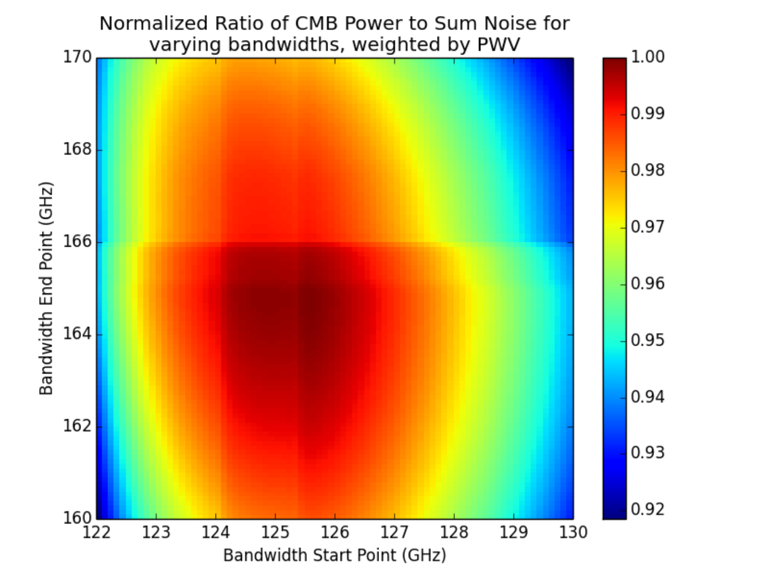
Weighting by PWV

Since the water in the atmosphere is variable and influences atmospheric transmissivity, I weighted the power and noise by the PWV on a Rayleigh distribution.

$$D = \frac{x}{\sigma^2} e^{\frac{-x^2}{2\sigma^2}} \tag{5}$$

Given the percent of time the Atacama is below a set of PWVs, I performed a χ^2 test to evaluate $\sigma = 1.056251$.

Optimization map



Results

The maxima represent the bandwidths with the highest CMB signal and the lowest noise and yield the following results.

Band	Recommended Band	Total Power	Total NEP
$90\,GHz$	$75.2\,to\,108.8\,GHz$	$4.9781\,pW$	$3.4497 \cdot 10^{-5}\,pW/\sqrt{Hz}$
$150\,GHz$	$125.5\,to\,164.7\,GHz$	$7.0871\,pW$	$5.0195 \cdot 10^{-5}\,pW/\sqrt{Hz}$
$220\,GHz$	$187.1\,to\,239.0\,GHz$	$13.6861\,pW$	$8.9116 \cdot 10^{-5}\,pW/\sqrt{Hz}$

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References

1. ALMA Collaboration, Atmosphere model based on Juan Pardo's ATM model for the altitude of the Atacama Desert, almascience.eso.org/about-alma/weather/atmosphere-model
2. K. U-Yen, High Frequency Structure Simulations for the CLASS waveguides.
3. J. Kraus, R. Marhefka, *Antennas* (McGraw-Hill, 2001) International Edition, Chap. 2.
4. J. Mather, "Bolometer noise: nonequelibrium theory," Appl. Opt. 21, 1125-1129 (1982).
5. W. Press, B. Flannery, W. Vetterling, S. Teukolsky, *Numerical Recipes in Pascal: The Art of Scientific Computing.* (Cambridge University Press, 1989). p. 122