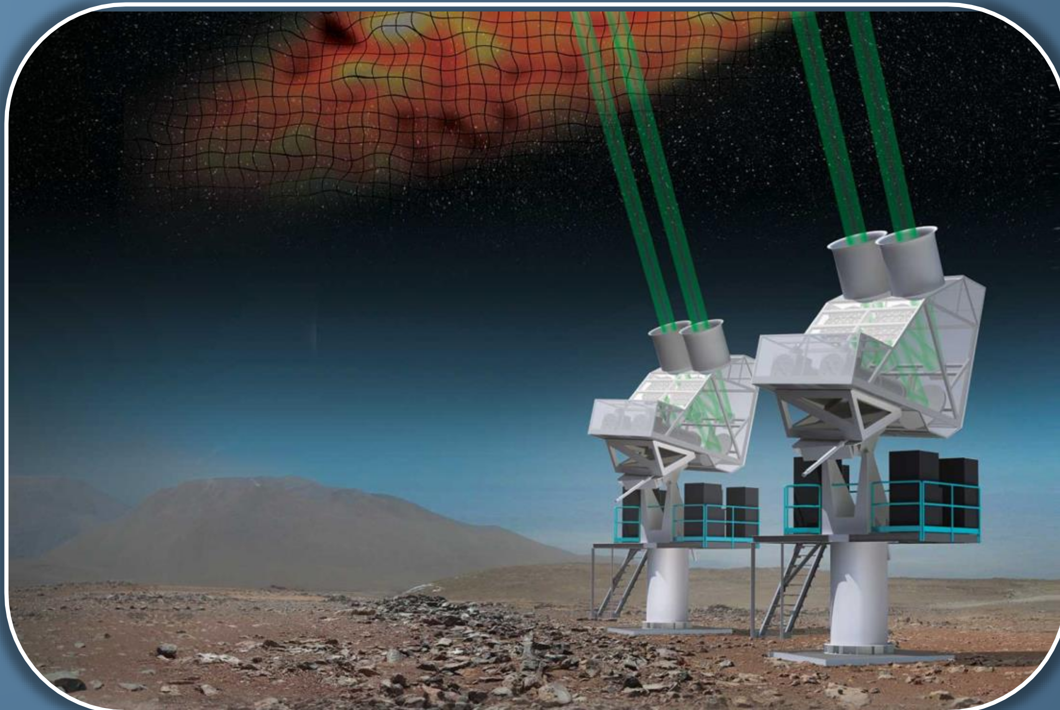
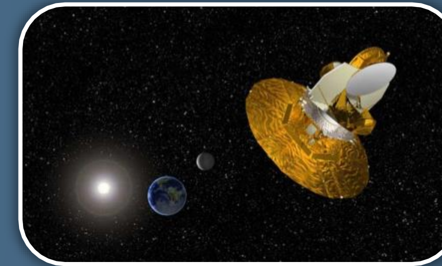
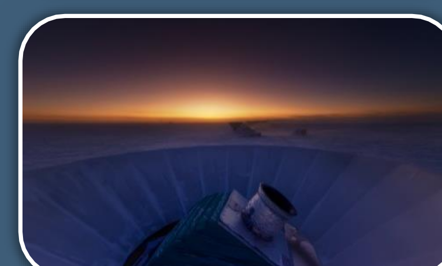






Dominik Gothe

Johns Hopkins University

Prepared for USC Colloquium

September 18th 2014

Measuring Inflation

The CLASSy way!

The Cosmology Large Angular Scale Surveyor (CLASS)

JOHNS HOPKINS UNIVERSITY

NIST

NASA

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

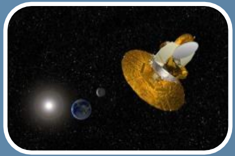
UBC

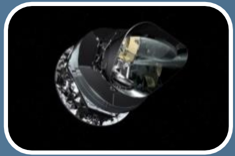
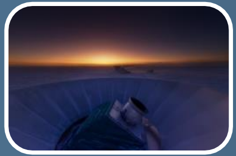
NORTHWESTERN UNIVERSITY 1851

COLUMBIA UNIVERSITY

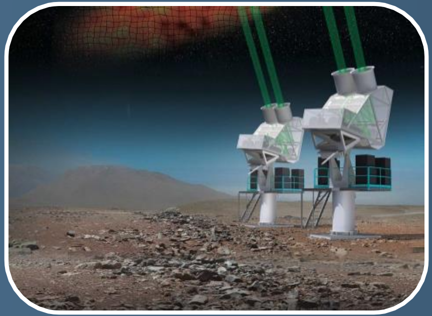
NSF

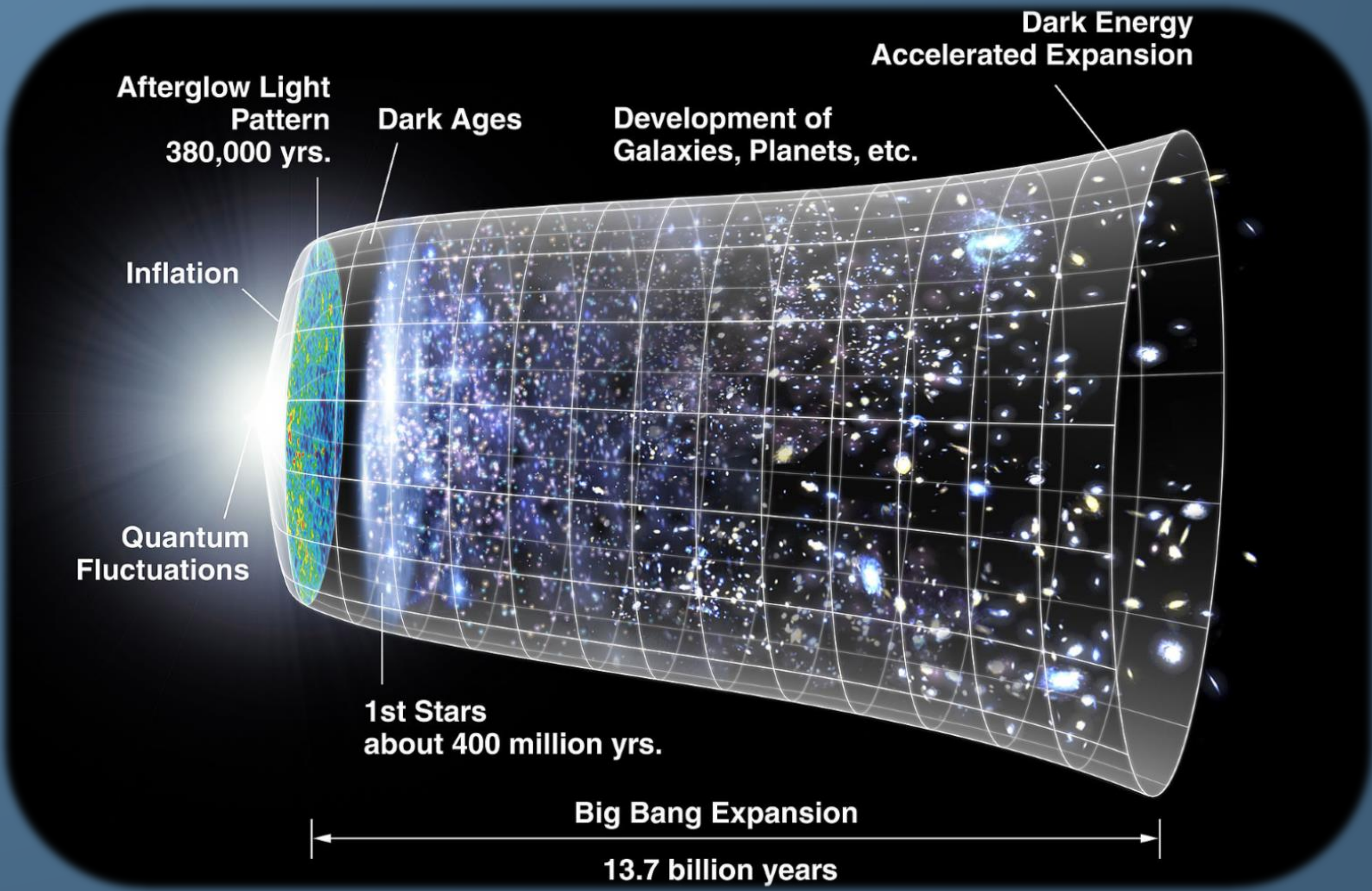
CONICYT
COMISIÓN NACIONAL DE INVESTIGACIÓN CIENTÍFICA Y TECNOLÓGICA

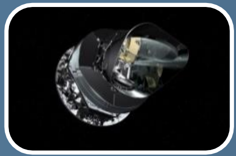
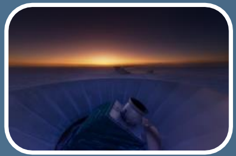
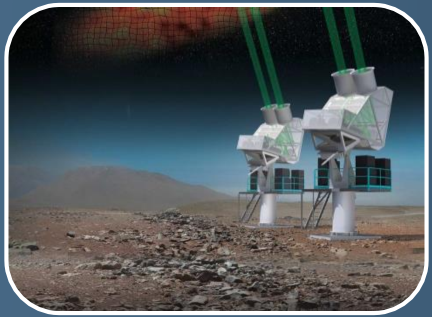


The Big Picture

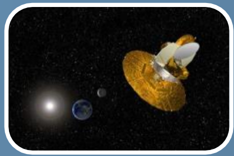


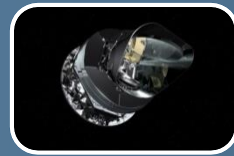
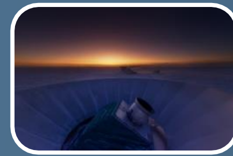
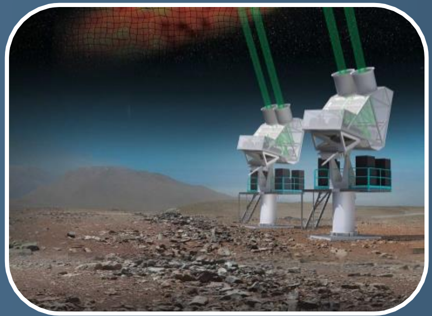


Wait! What am I doing here?

- What do we know about the Cosmic Microwave Background so far?
  - What are the unexplained phenomena?
- What is the tensor-to-scalar ratio?
  - Why do we care?
- How do we test Inflation?
  - WMAP, ACT, SPT, PLANCK, and BICEP
  - The CLASS approach
- What is unique about CLASS?
  - The Variable delay Polarization Modulator
  - The super-conducting Transition Edge Sensors



Cosmic Microwave Background

- In 1964 Arno Penzias and Robert Wilson discovered the CMB.
- They measured an excess temperature of 3.5 ± 1 K at 4.08 GHz.
- How can the isotropy of the CMB be explained?
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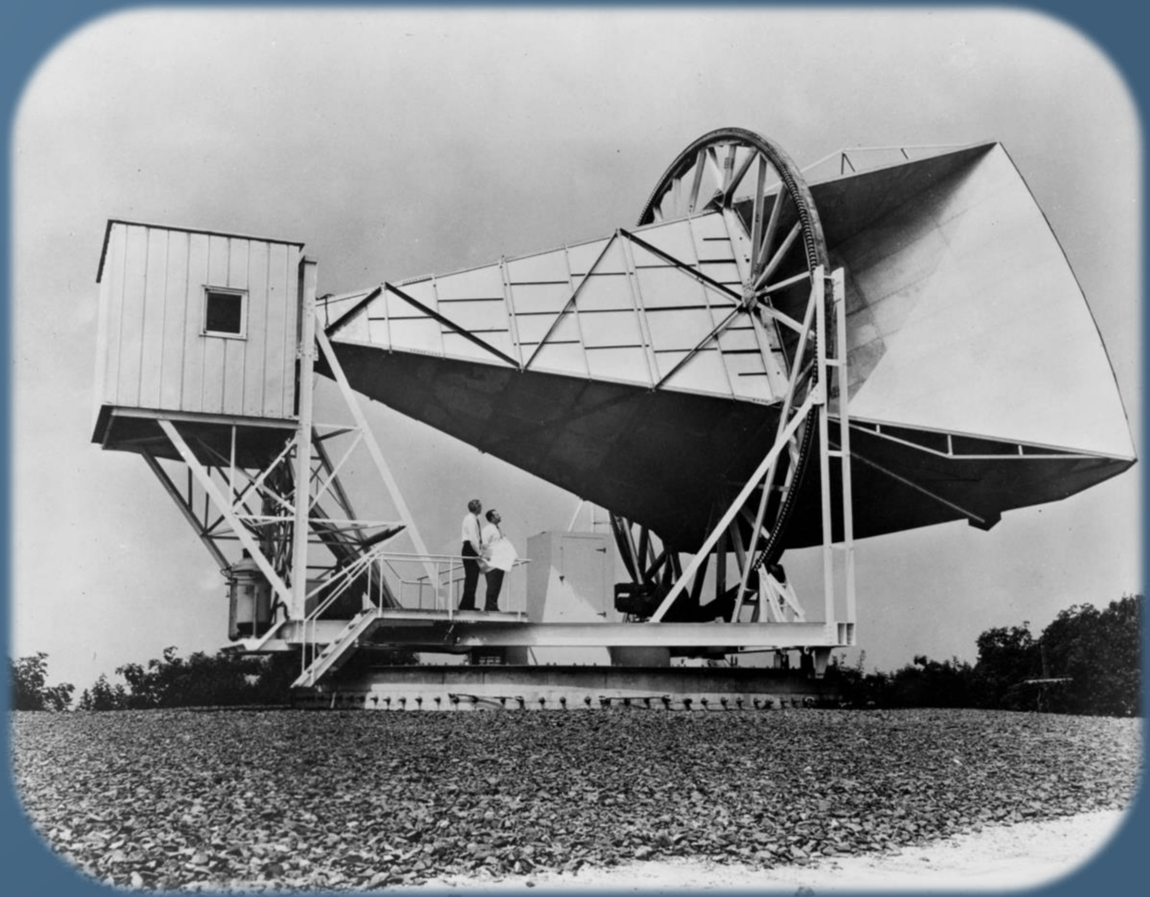
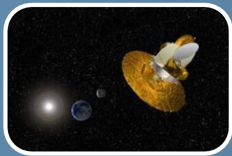
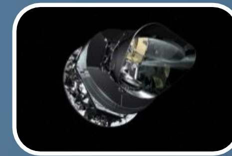
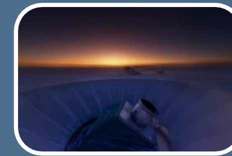
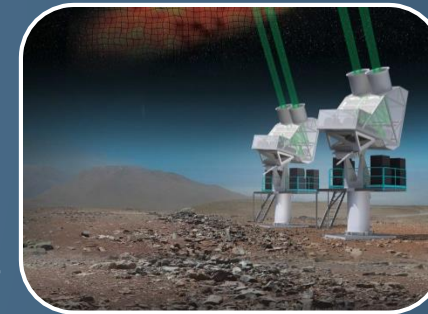
- 2.7 K with 18.4 μK (rms)





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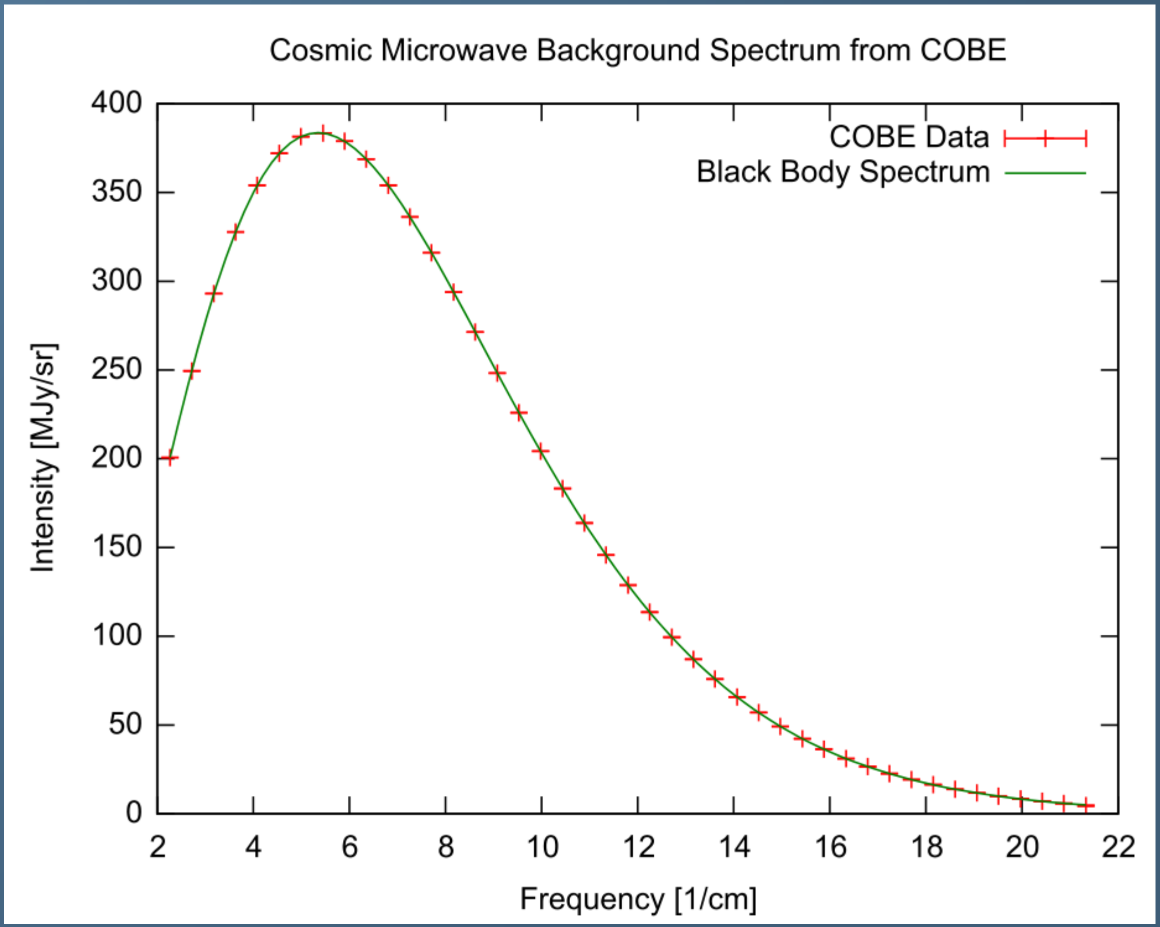
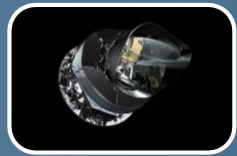
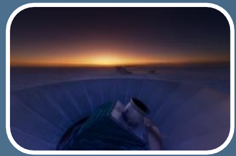
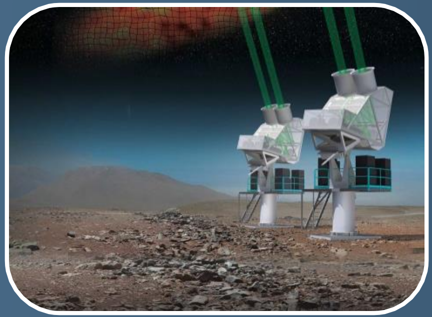


Cosmic Microwave Background



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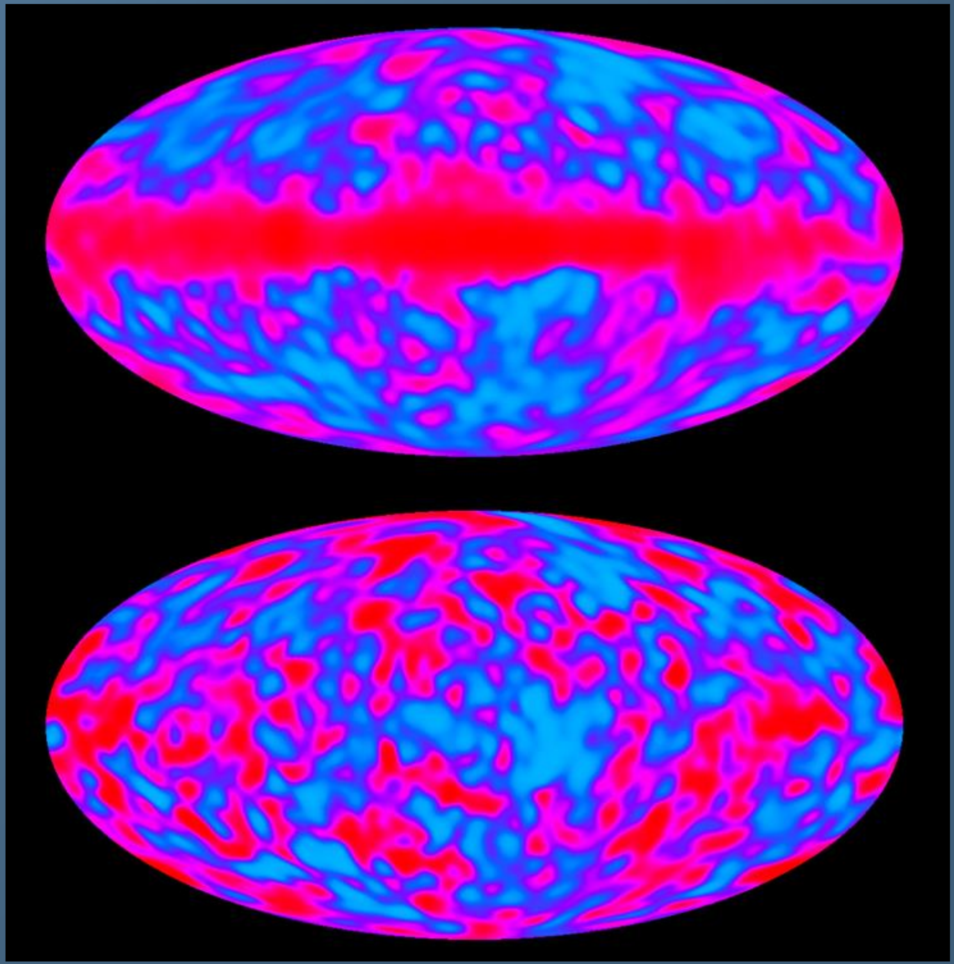
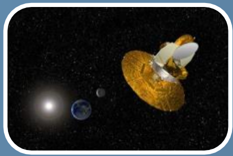
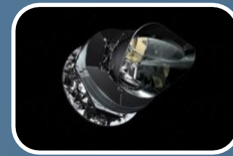
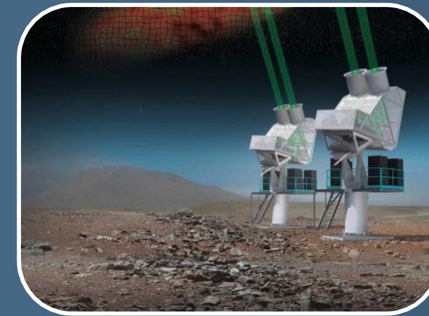


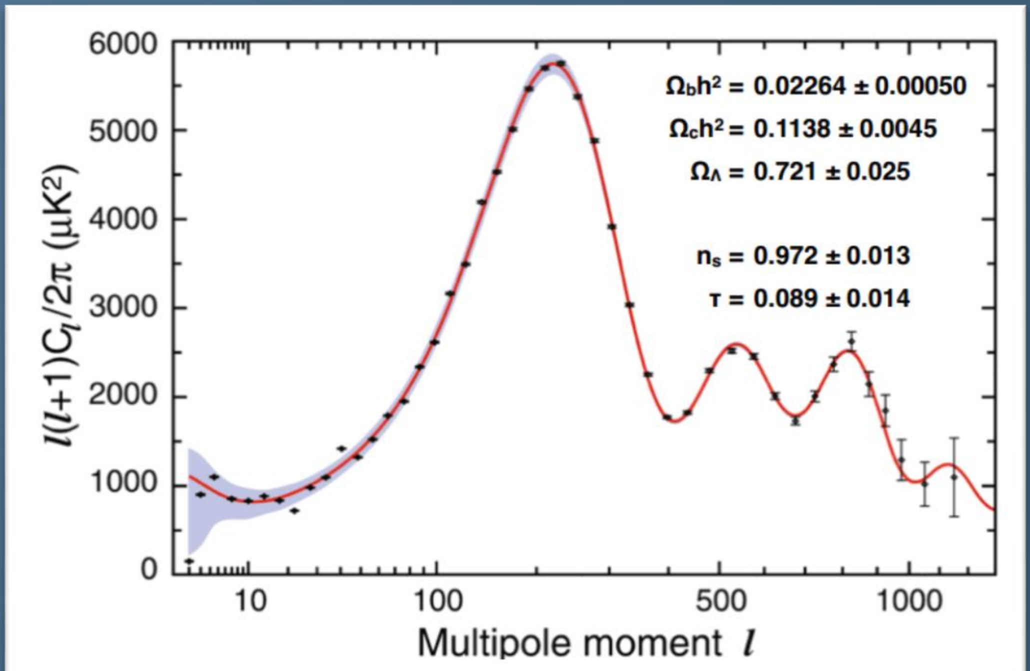




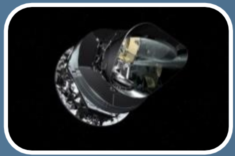
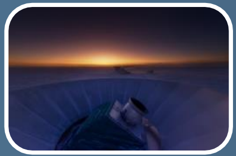
Unexplained Discoveries

- The homogeneity was not predicted and is not explained by the Big Bang theory.
- Taking a prior on H_o WMAP is able constrain Ω_o to be one within 1%.
- Together they form the two problems of the Big Bang theory.
  - *The Horizon Problem*
  - *The Flatness Problem*

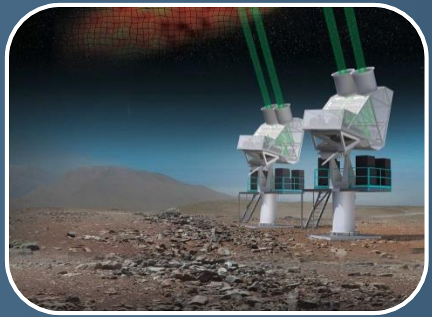


WMAP's measurement of the CMB power spectrum constrained several parameters of the ΛCDM with exquisite precision.

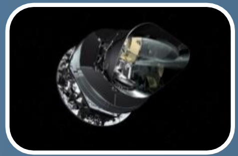
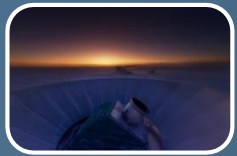
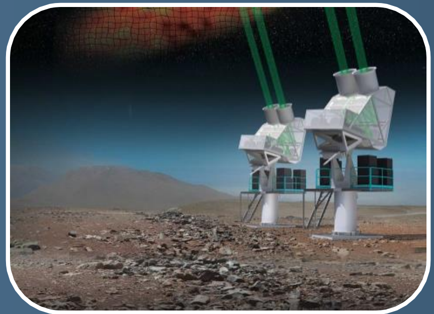


Inflationary Modification

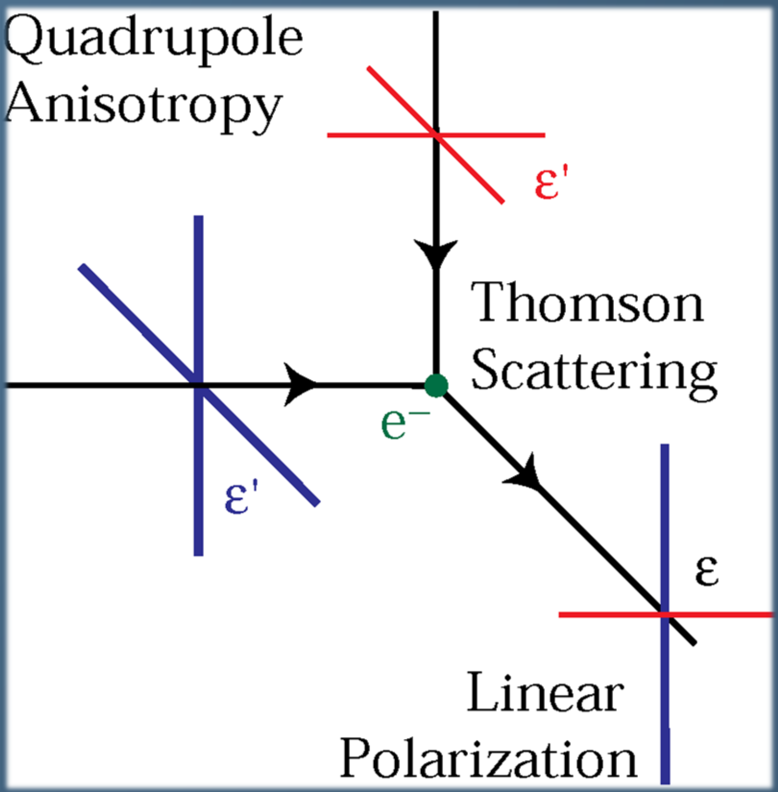


- Accelerated expansion of space very early in the universe.
  - Accelerated expansion of roughly 60 e-folding is necessary to flatten space to what we observe today.
  - While not in causal contact today, patches of the sky used to be in causal contact.
- The primordial seeds can be explained as quantum fluctuations of a scalar inflation field.
- Different inflationary theories predict different features of the Cosmic Microwave Background anisotropies.
  - Theorized inflation models are thus testable with highly sensitive surveys of the CMB across a wide range of angular scales.
- The predicted impacts on the CMB anisotropy are on the order of $10^{-9}\,K$. Requiring highly sensitive detection schemes.

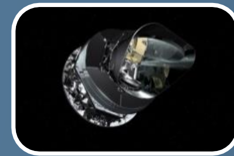


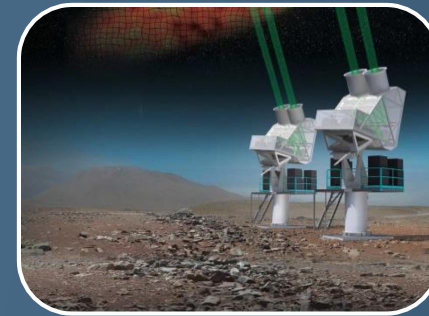
What Polarization?

- Thomson Scattering of a plane wave results in linearly polarized light.
- If incoming radiation were isotropic the resulting emission would be polarized.
- Anisotropies in temperature produced polarized light.
- Polarization pattern of the CMB reduce to understanding the quadrupolar temperature fluctuations at last scattering.





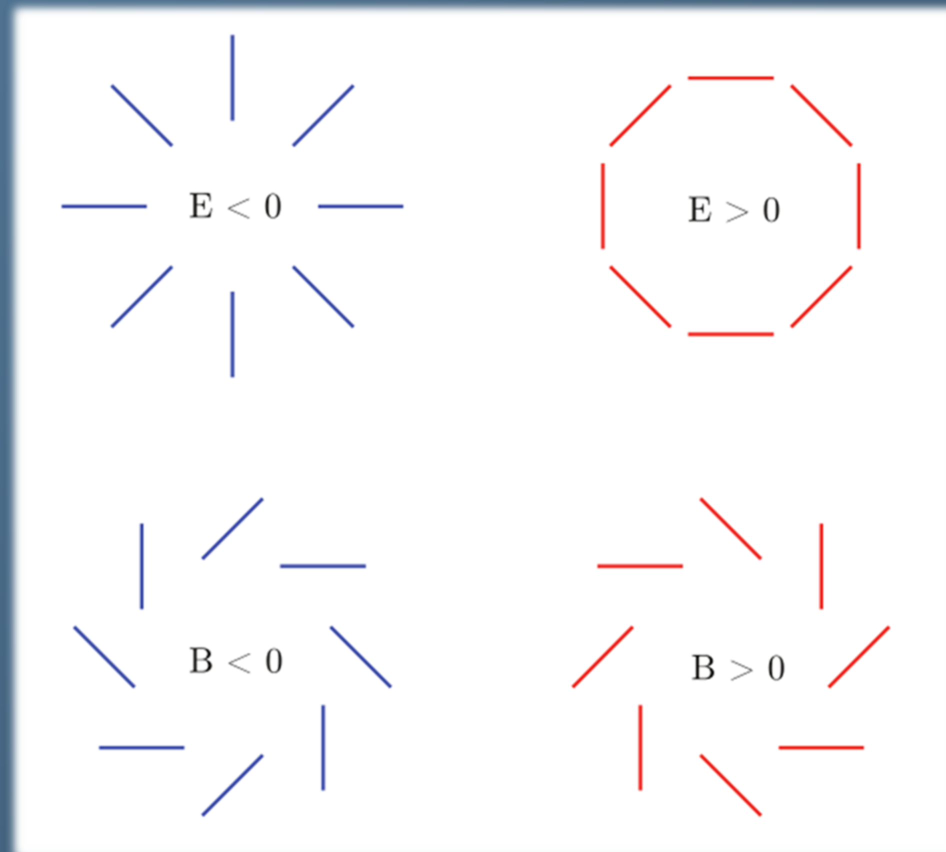





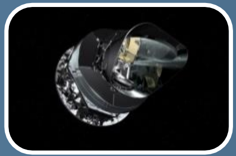
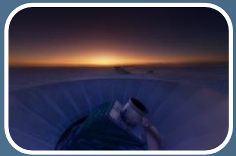
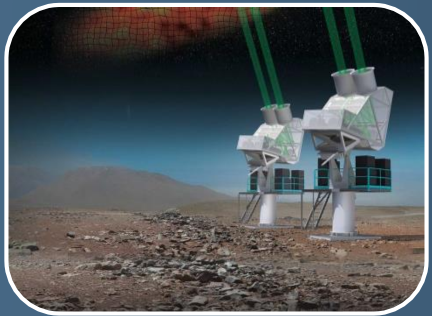
E and B Modes

- The polarization field can be decomposed into two orthogonal modes: E and B.
- Scalar perturbations create only E-modes.
- Tensor perturbations create both E-modes and B-modes.

- *Observation of B-modes is an observation of gravitational waves.*

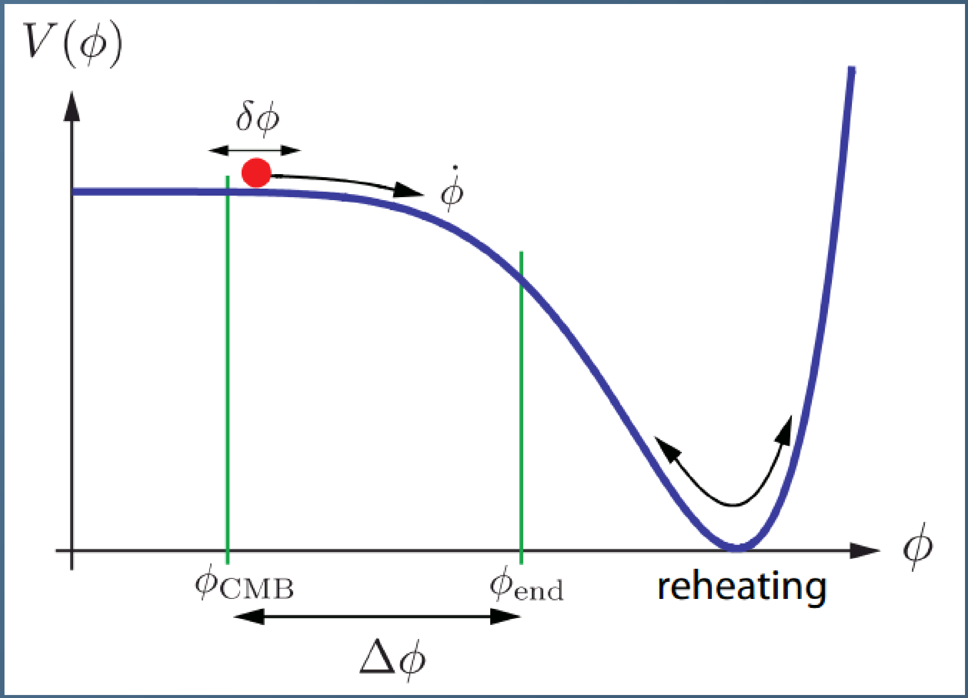




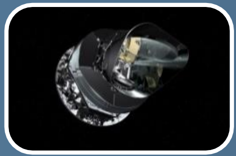
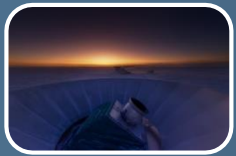





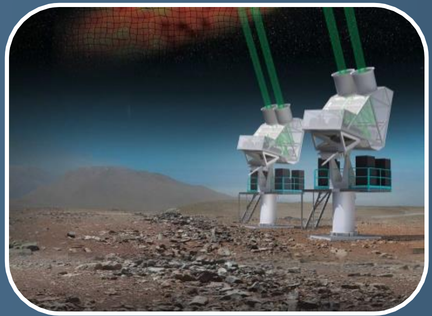
Inflationary Predictions

- Inflation predicts a flat and homogeneous space.
- Consequently it predicts an isotropic CMB.
- Inflation explains primordial seeds as the consequence of quantum fluctuations in the inflation field.
- Inflation predicts gravitational waves, which would be detectable as polarized patterns in the CMB anisotropies.
- So we measure B-modes.



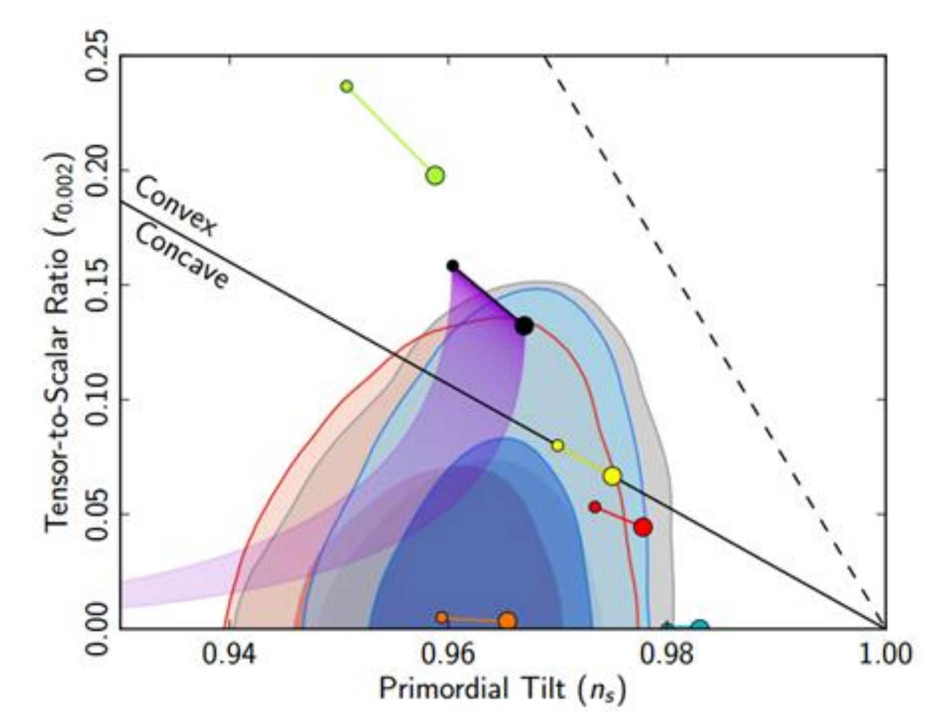
A typical example of scalar inflation field corresponding to slow-roll single field inflation.

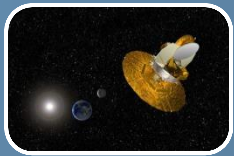


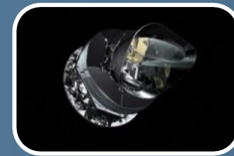
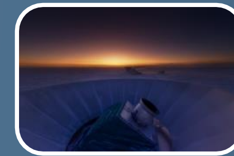
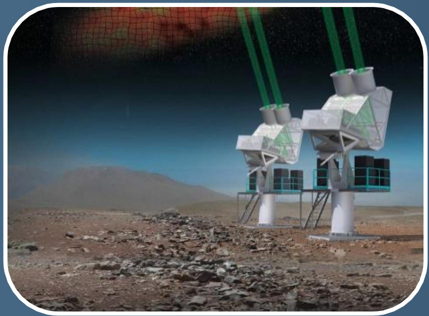
Testing Inflation via **r**

- Scalar properties of the CMB power-spectrum are measured exquisitely by PLANCK.
- Measurements of the Tensor-to-Scalar ratio (r) would provide empirical data to restrict the vast landscape of theoretical models.
- Measurements of r require experiments that have an ultra-high sensitivity to B-modes on the largest scales.

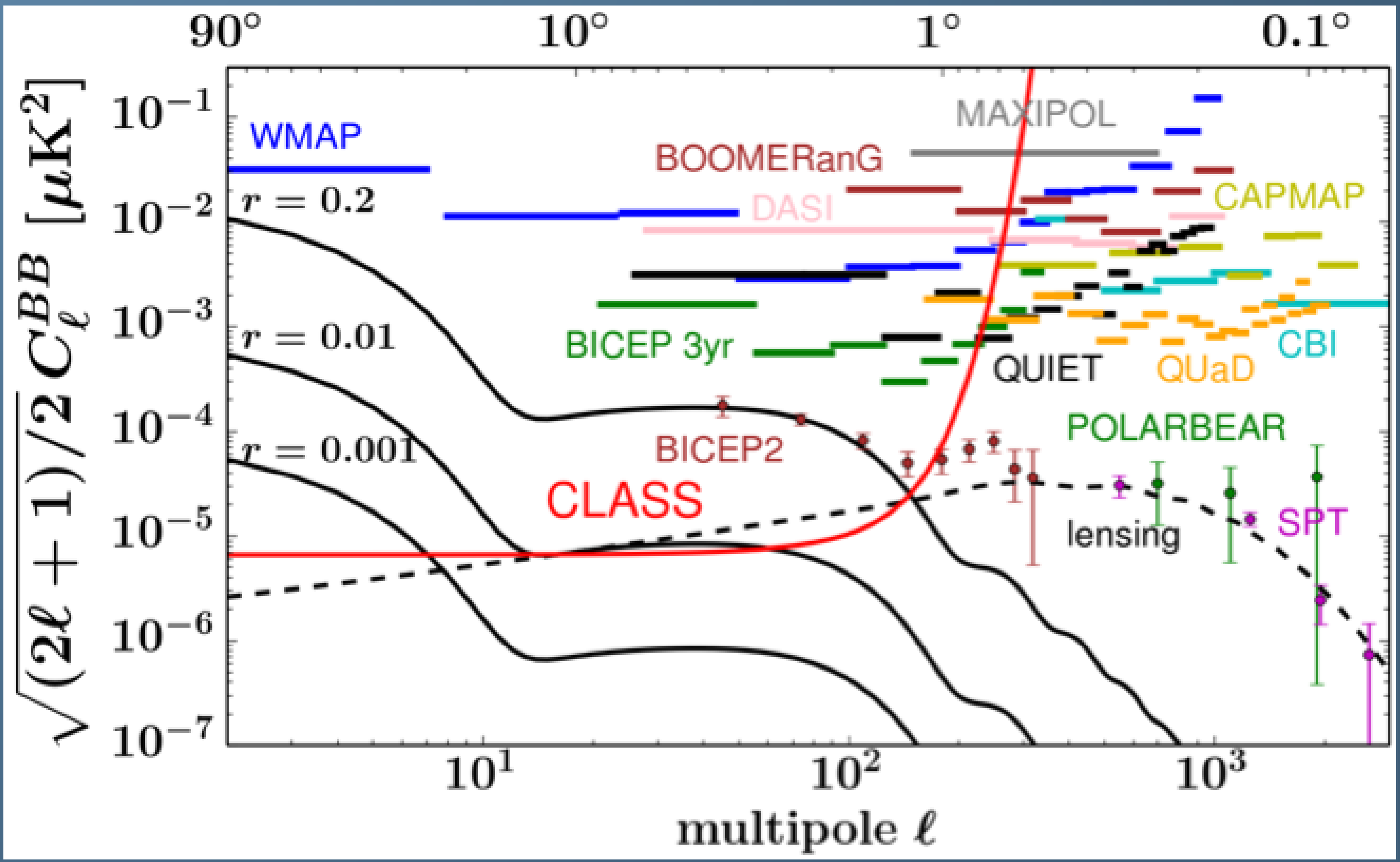


Various theories can be described to be unlikely when considering the probability space formed by the Tensor-to-Scalar ratio and the Primordial Tilt.

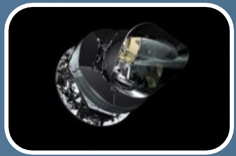
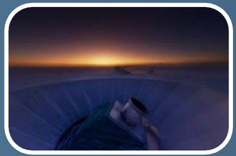
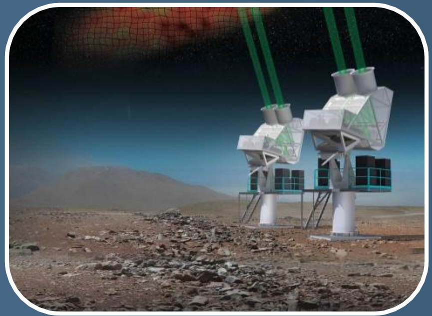


The feature-full spectrum

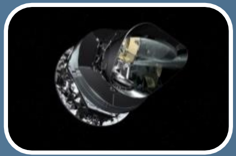


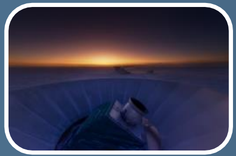


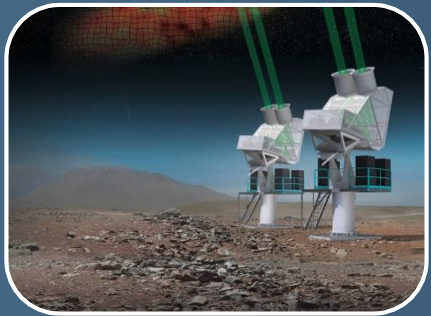





Review: What is needed?

- Full B-Mode spectra with multiple peaks
  - Reionization and Recombination
- Multi-Frequency data to assess foregrounds
- Independent instrument design
  - Independent survey design
  - Independent data analysis
  - Independent team
  - Independent but complementary
- Large sky coverage to better assess isotropy
- CLASS will compliment the surveys of WMAP, ACT, SPT, PLANCK, BICEP, and many others.

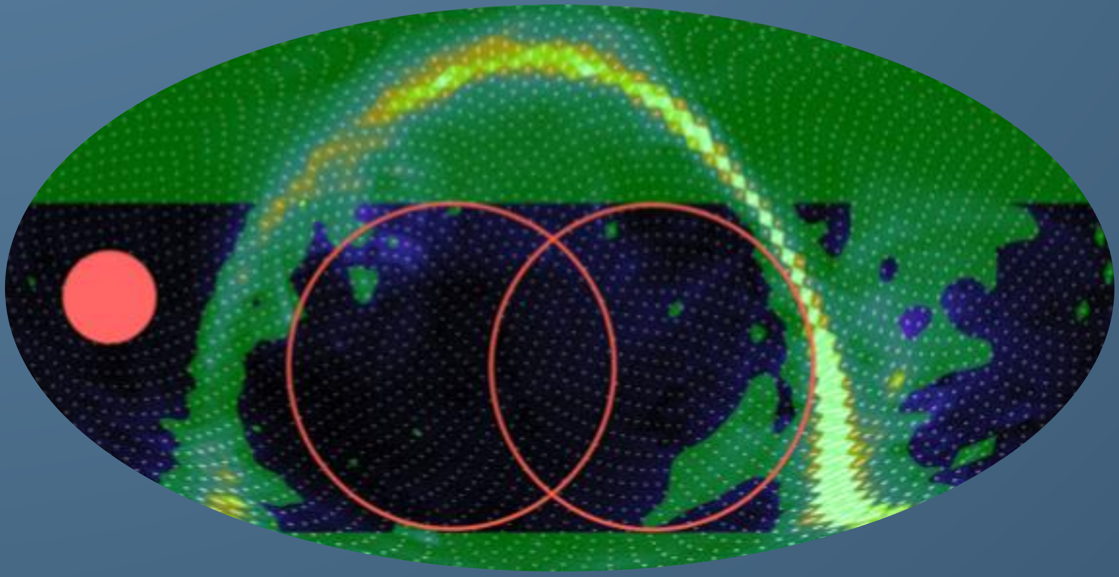


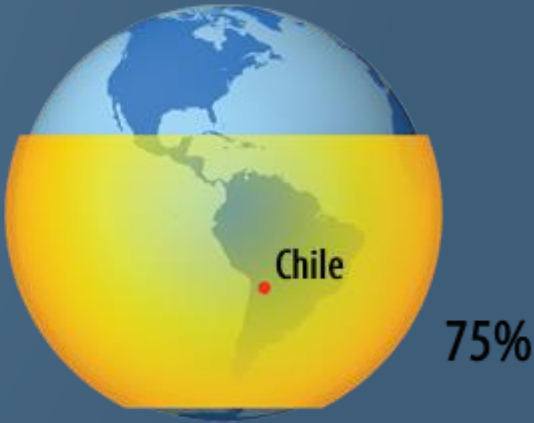




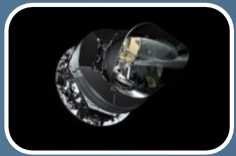
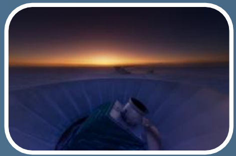
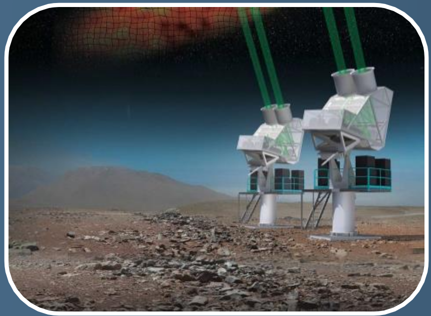
Designing for low l sensitivity!

- 360° constant-elevation azimuth scans at $1°/sec$
- Boresight angle changed daily in 15° increments
- Covers full survey area every day, with different instrument-to-sky angle, allowing important checks on systematics.

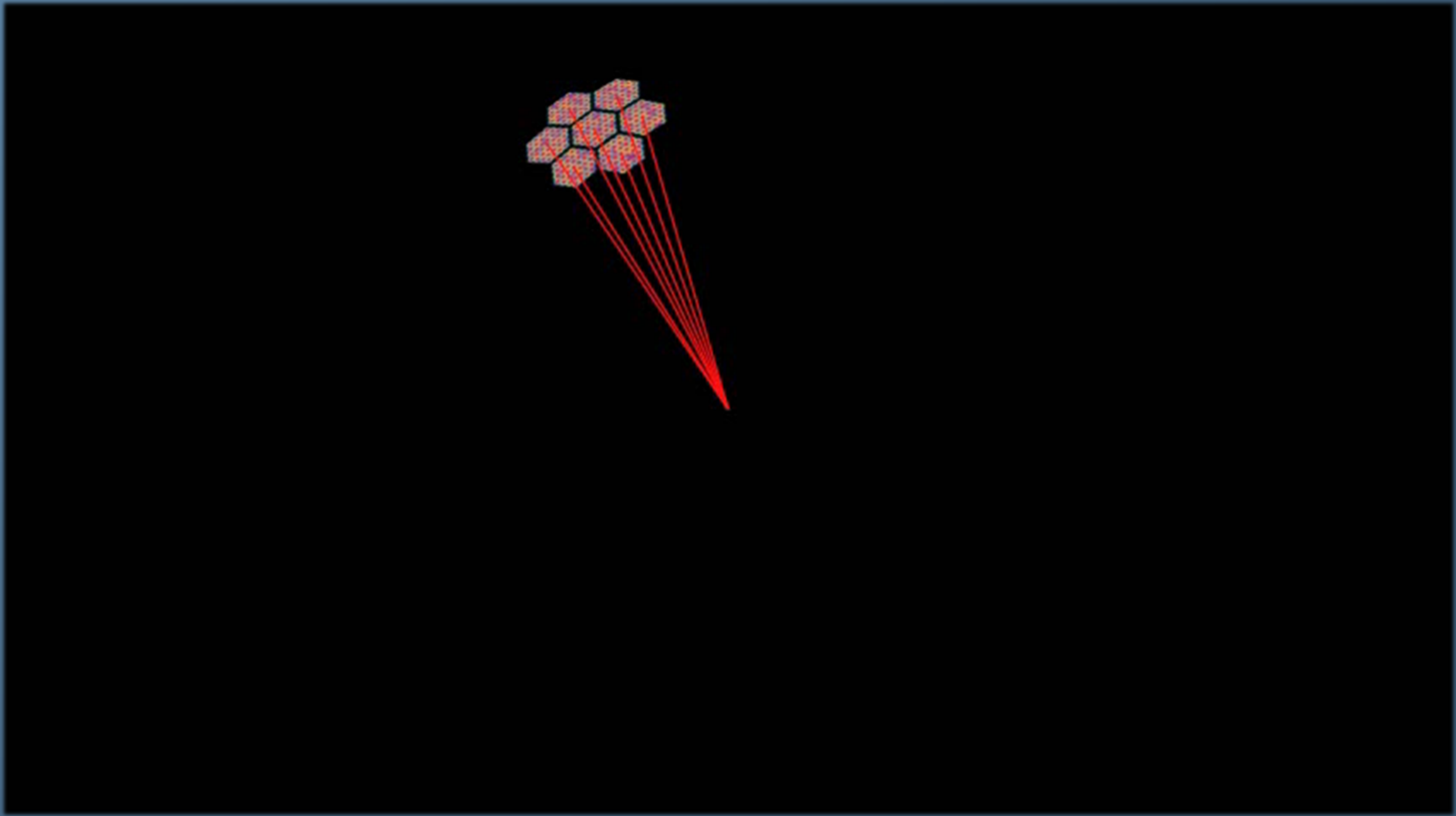


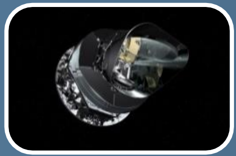


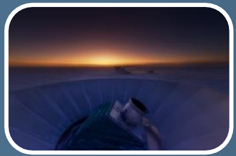


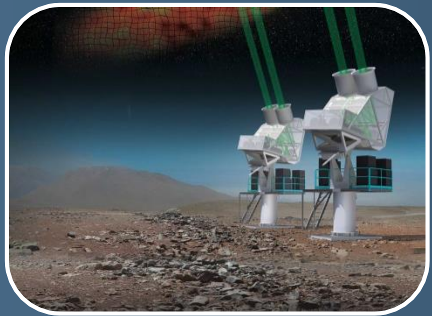





CLASS Scan Strategy



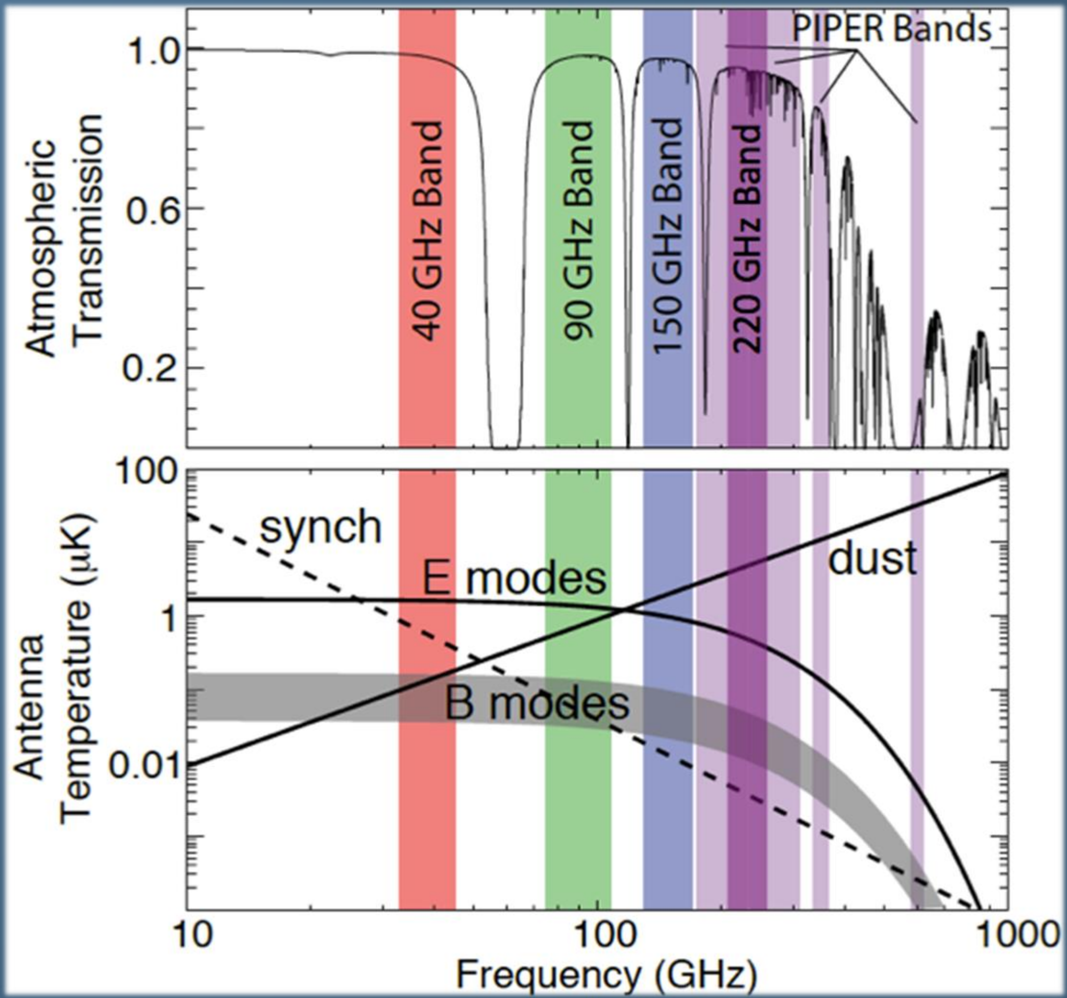




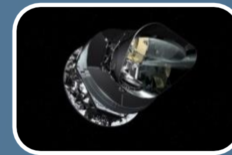
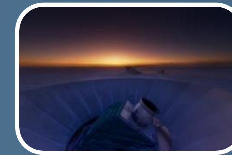
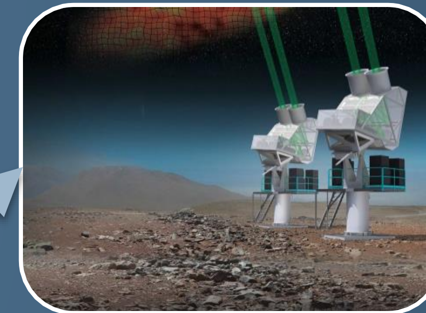


Removing Foregrounds

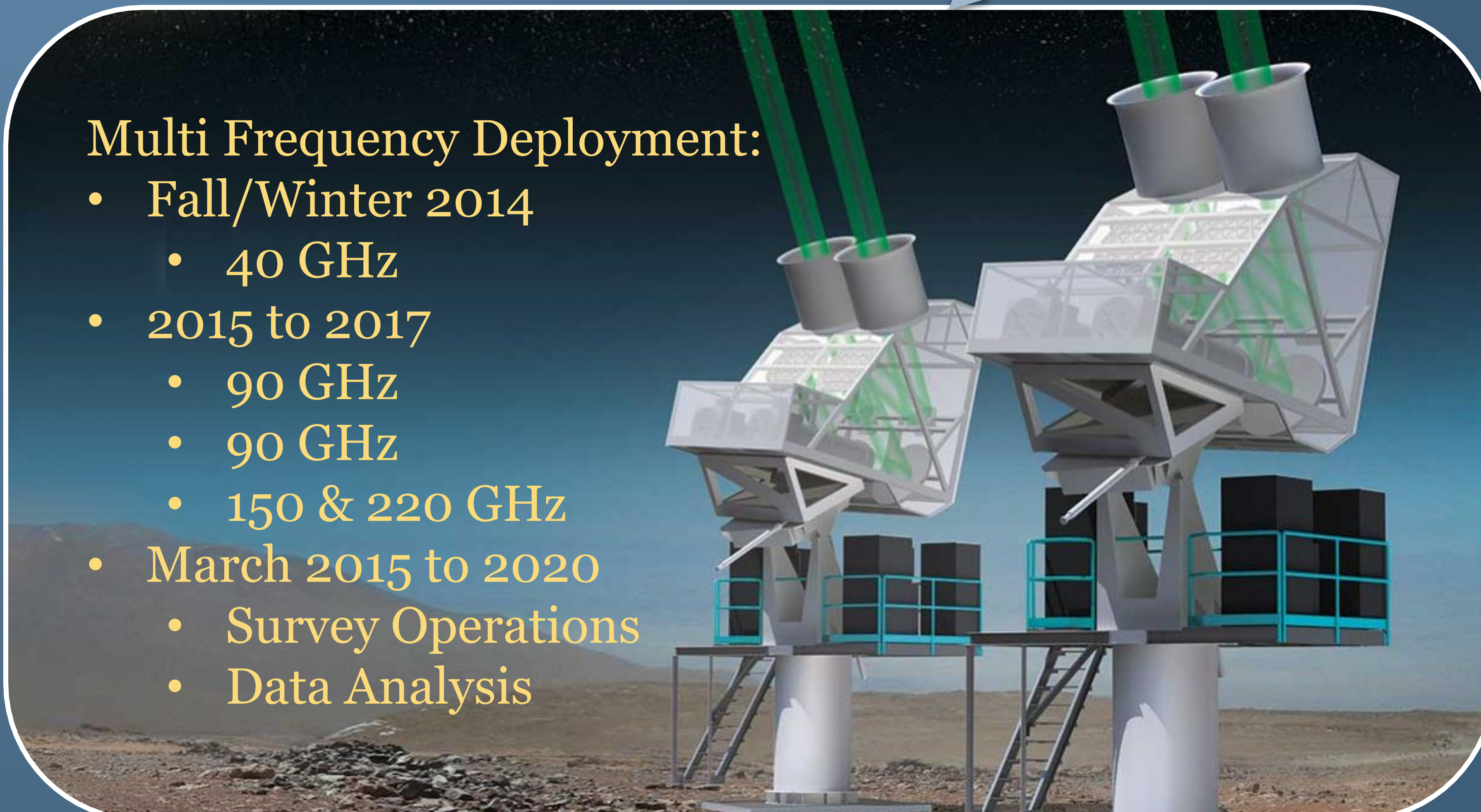
- A multi-frequency experiment allows us to break the degeneracy between synchrotron and dust foregrounds with primordial signals.
- Three primary frequencies straddle the foreground minimum.
- PIPER Provides additional foreground constrains from 200 GHz and 270 GHz.





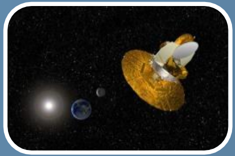
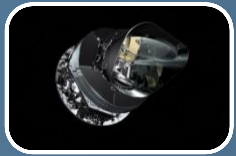
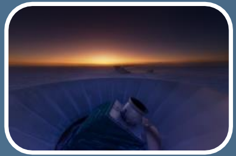





The CLASSy approach!

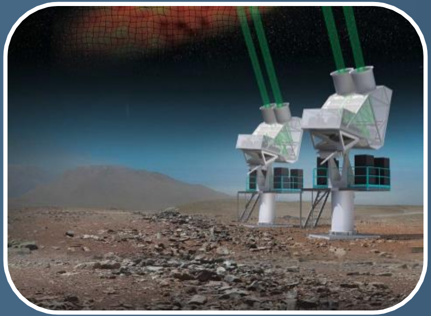


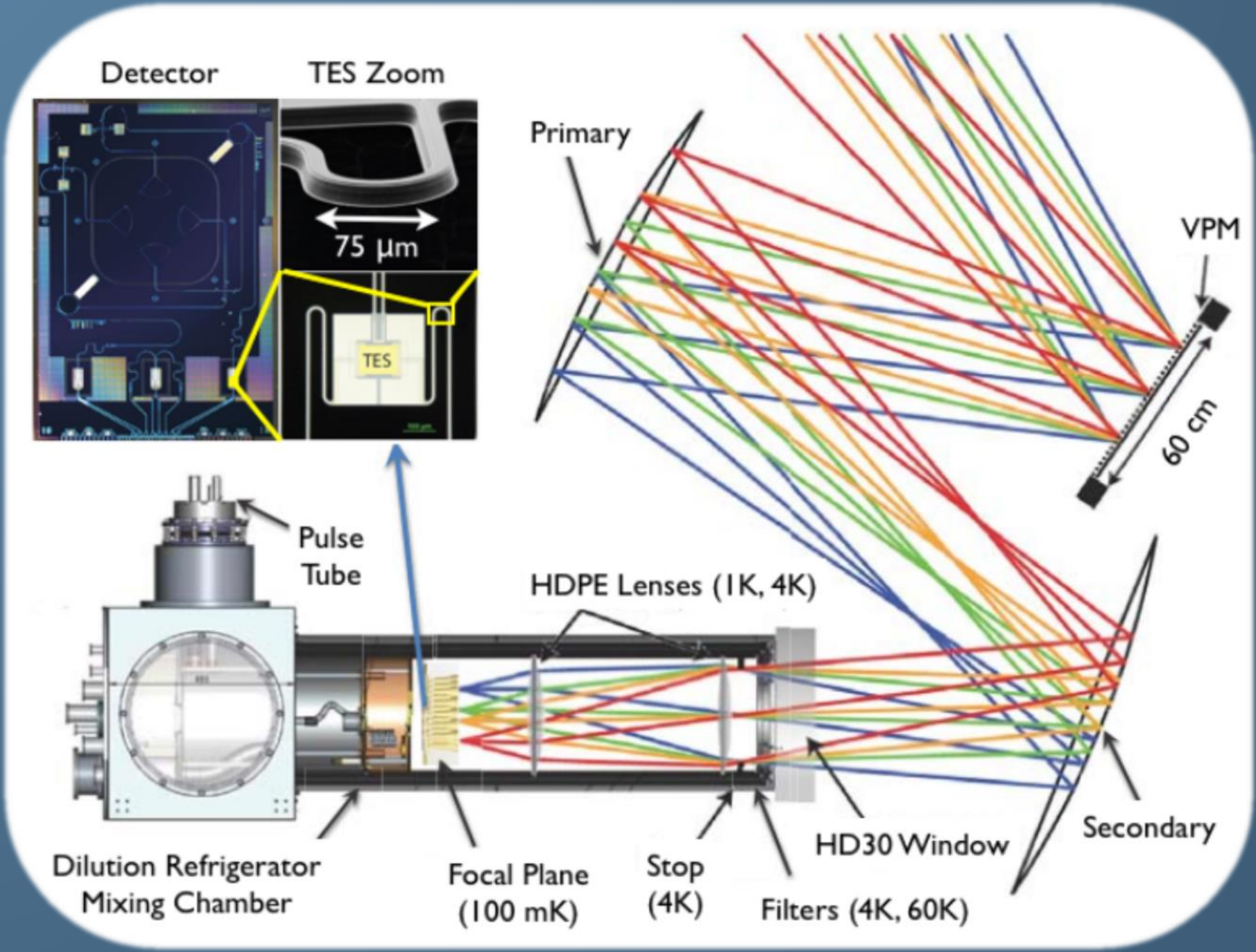
Multi Frequency Deployment:

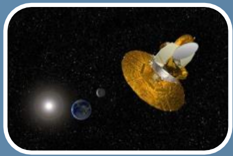
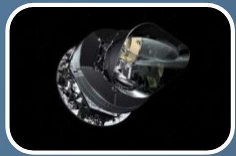
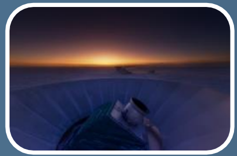
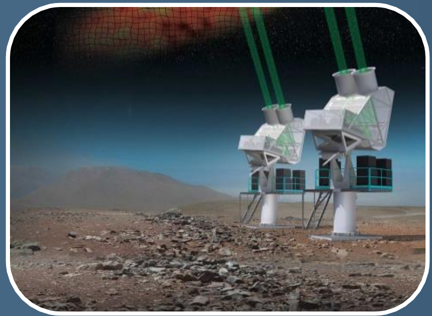
- Fall/Winter 2014
  - 40 GHz
- 2015 to 2017
  - 90 GHz
  - 90 GHz
  - 150 & 220 GHz
- March 2015 to 2020
  - Survey Operations
  - Data Analysis



Instrument Design!

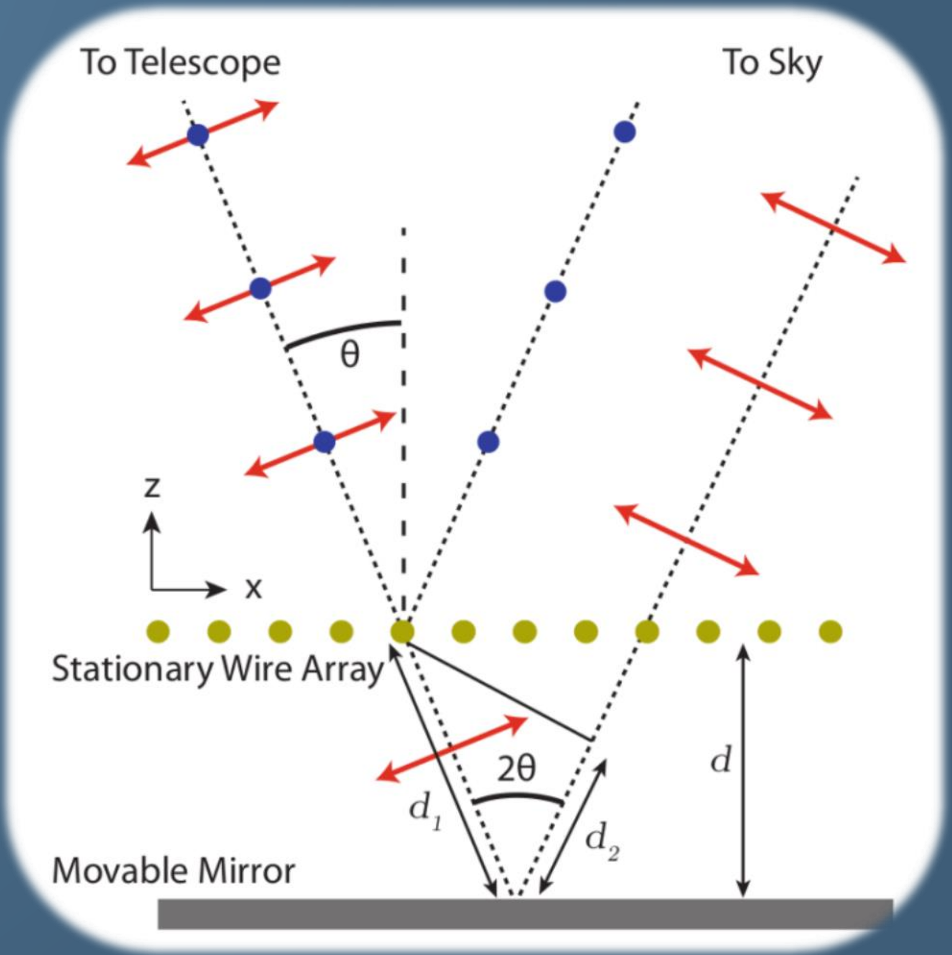




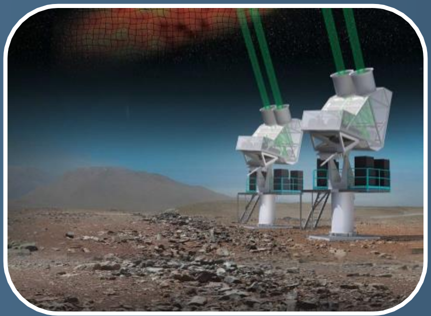
     

The VPM

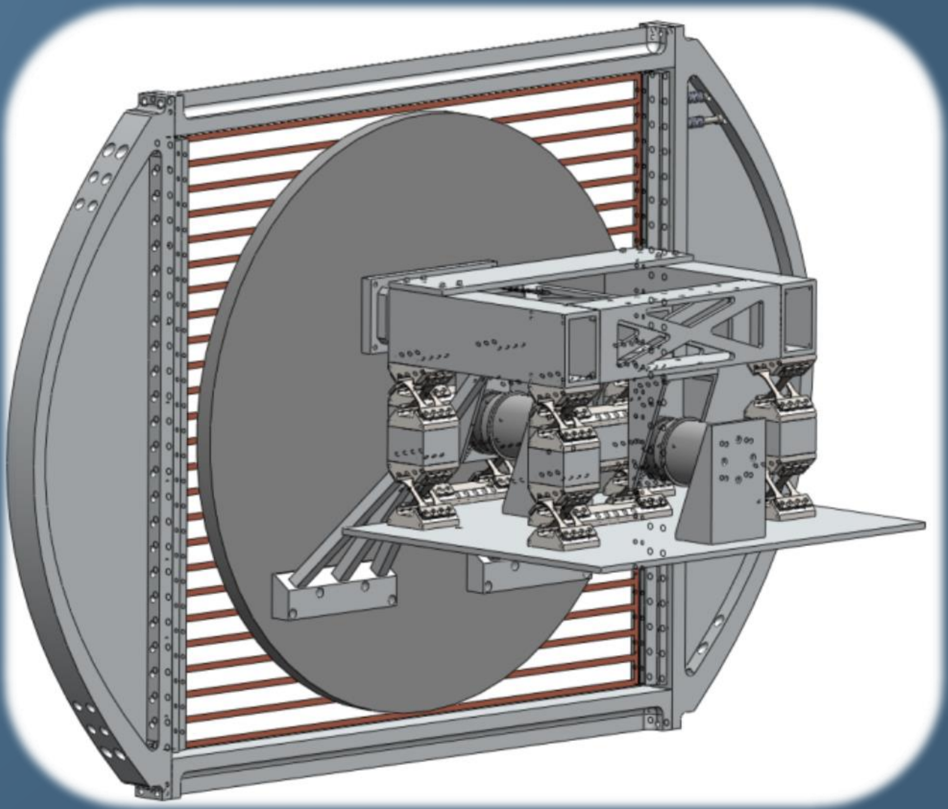
- The VPM is composed of a polarizing wire grid and a mirror.
- To combat $^1/_f$ noise we need a modulation technique similar to that of a lock-in amplifier.
- This modulation allows us to discard the non-modulated systematics.
- Our modulator is the first optical element.
- CLASS will be the first to measure circular polarization.



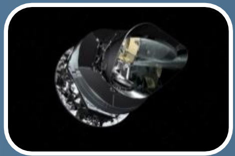
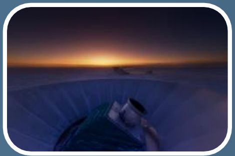
The VPM continued



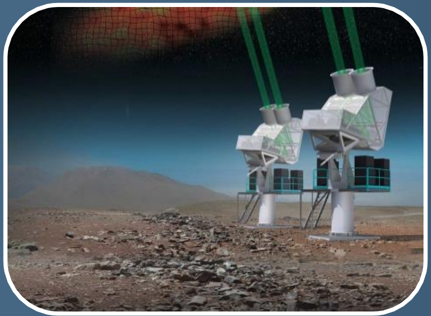
- Un-polarized light is unaffected by the VPM, not modulated.
- Parallel and Perpendicular polarizations are unaffected.
  - Q_{sky} is not modulated
- 45° Polarized light is mapped into circular polarization.
- Circular polarization is mapped into 45° polarization.
  - U_{sky} and V_{sky} is modulated
- A 45° degree boresight-rotation changes Q_{sky} and U_{sky}.

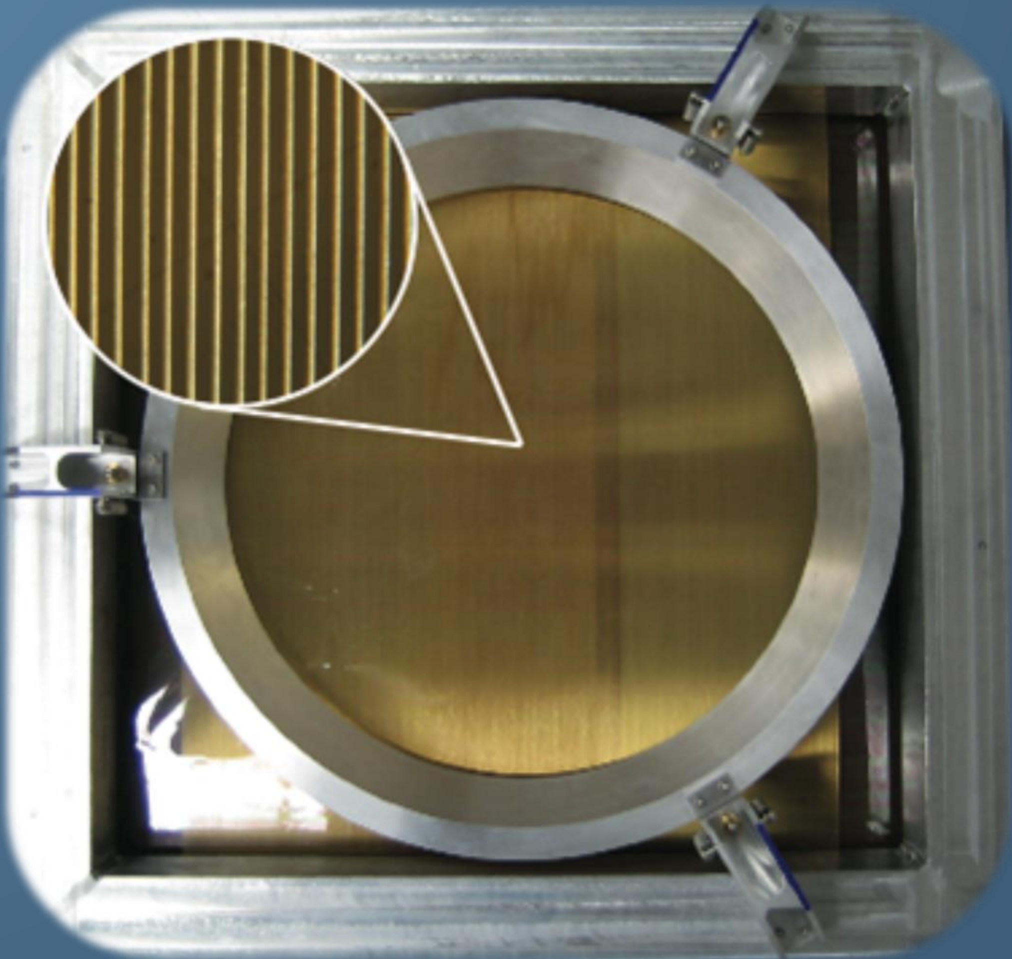


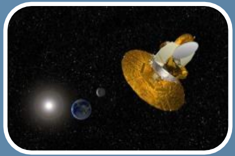


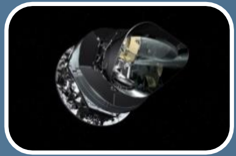
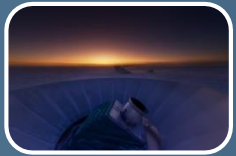




VPM Grid Prototype

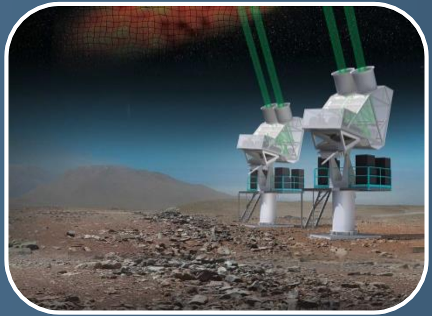




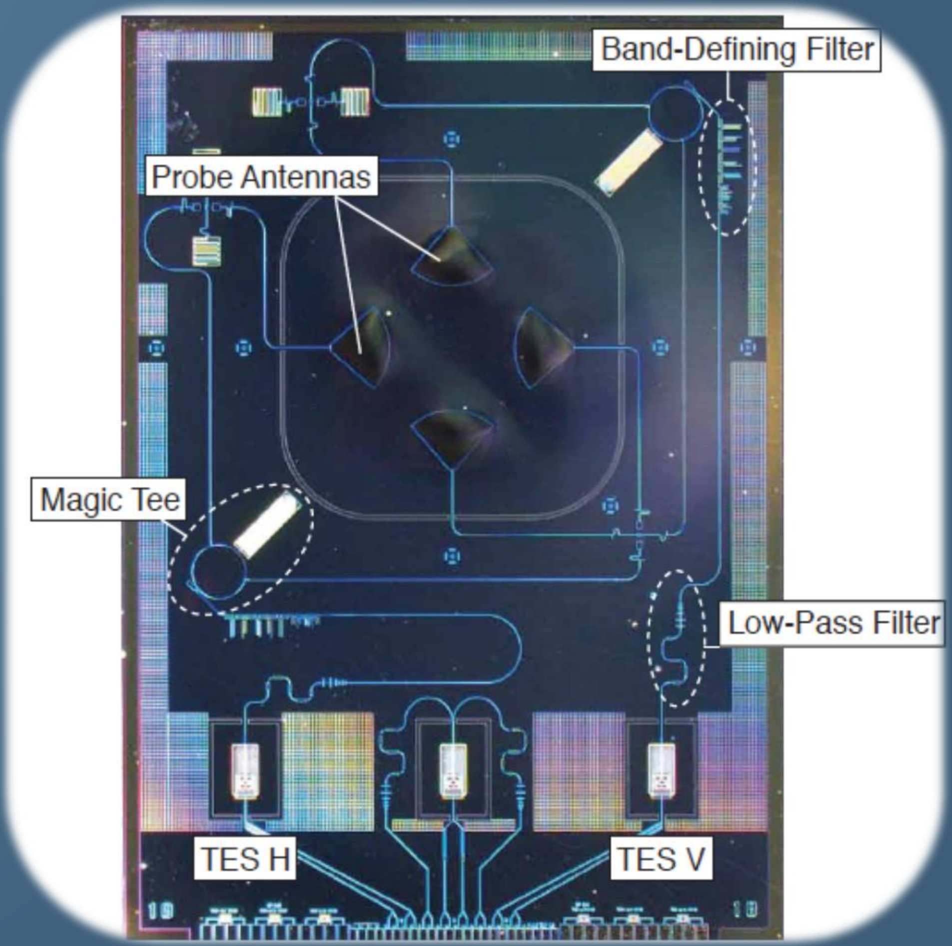


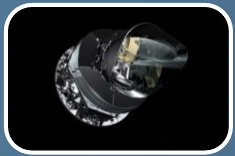
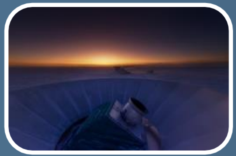
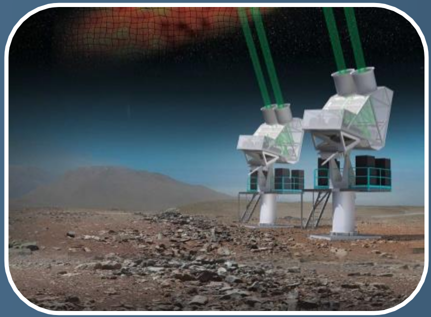
Transition Edge Sensors



- Molybdenum-Gold bolometers
  - Super conducting transition is tuned to ~150mK with the Gold bilayer.
- Background limited detectors.
- Increased sensitive requires increased number of detectors.
  - Distinct advantage over space borne missions.
  - Ground based missions can have a larger number of detectors.

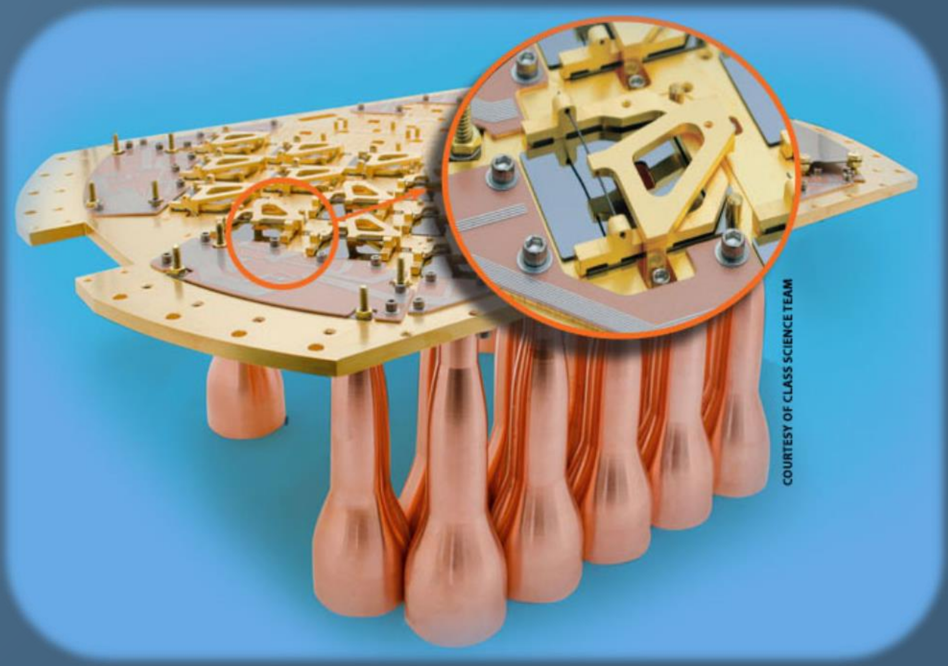




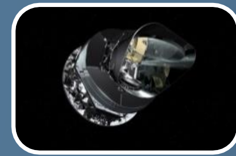
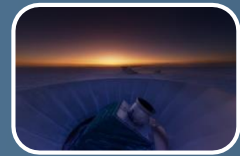
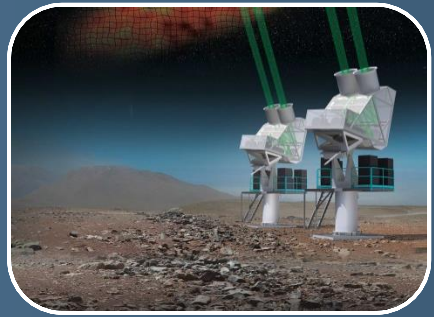





The Detectors

- Large number of detectors.
  - Q-band has 72 detectors
  - W-band has two times 518 detectors
  - The HF receiver has 2000 detectors each in the HF150 and HF220 bands.

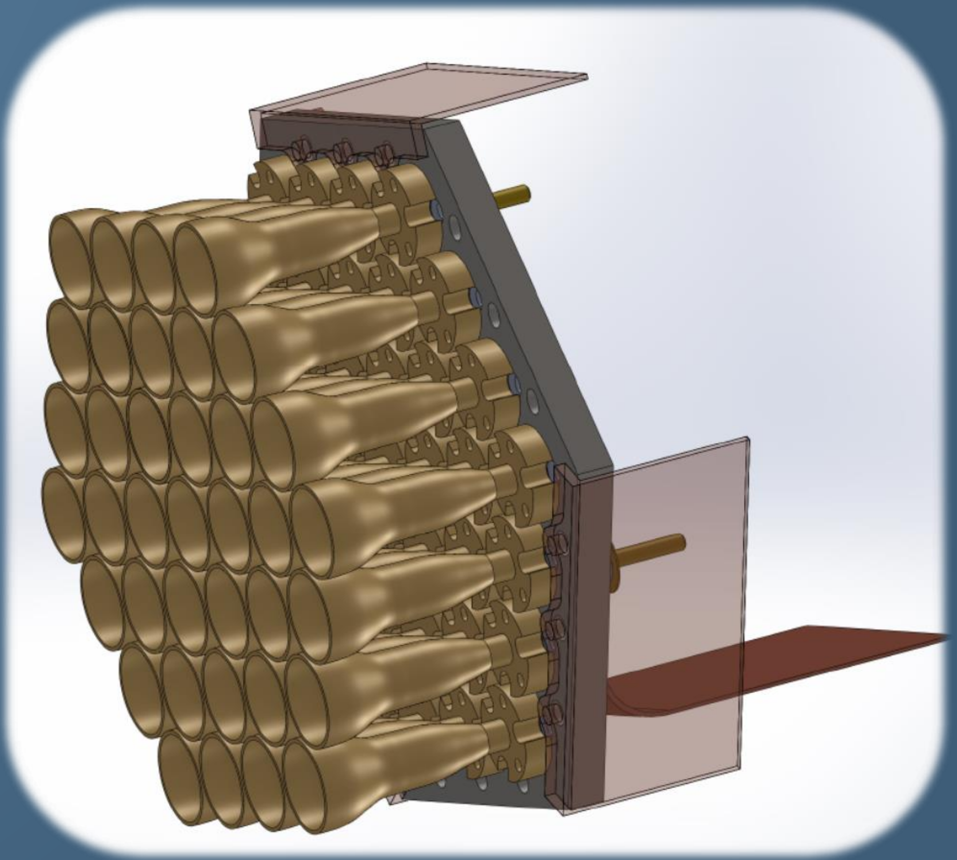


- 40ghz focal plane is being populated and tested as I speak.

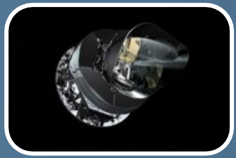
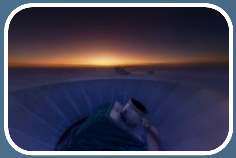
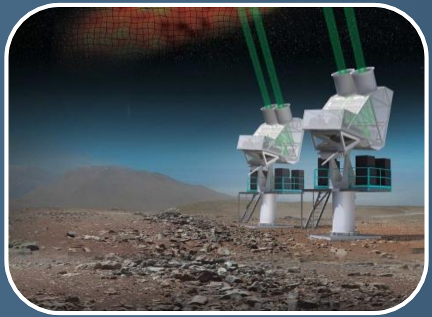
     

The Detectors

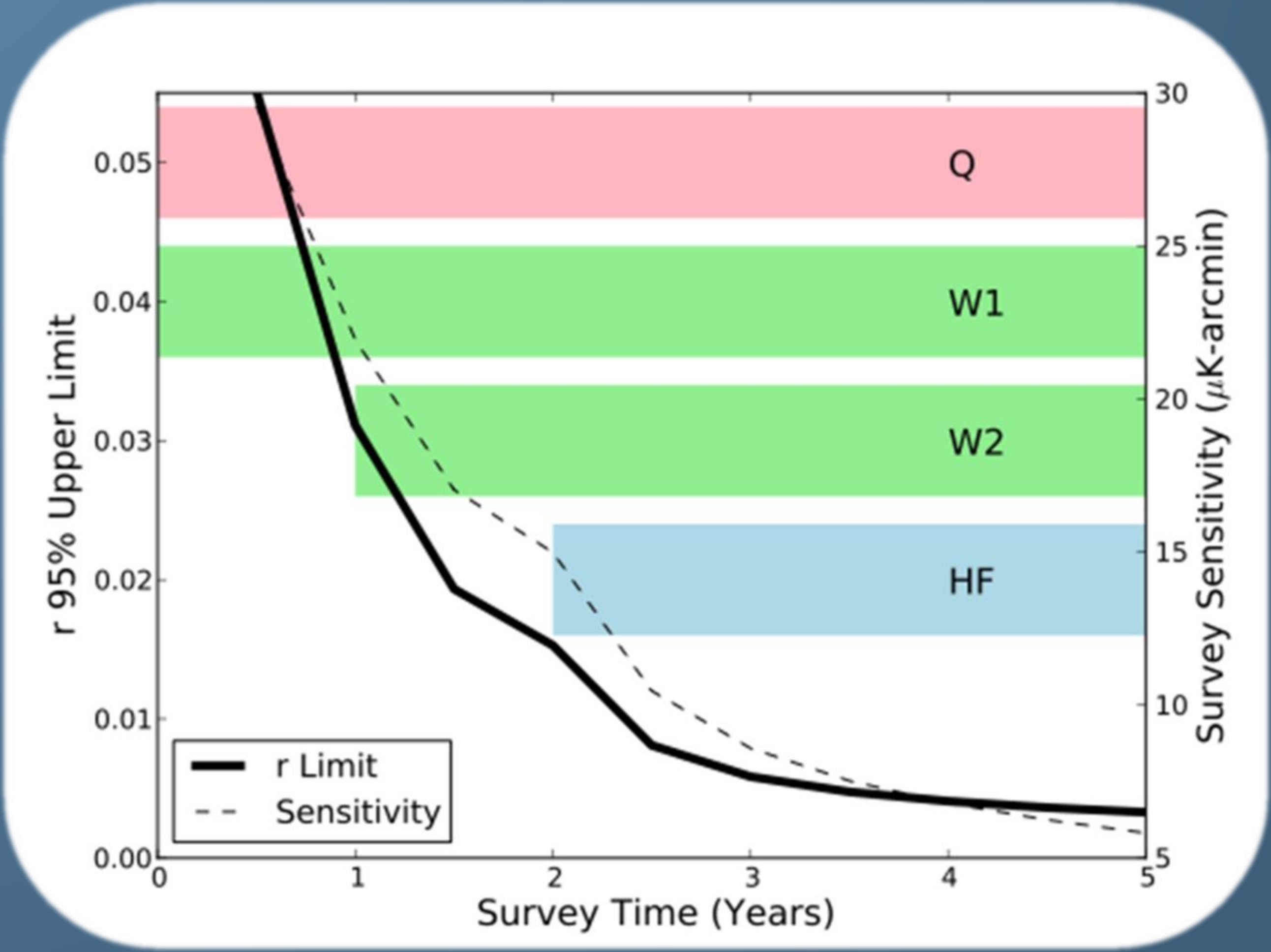
- Our custom feed-horns replace the standard corrugated configurations.
  - They are smooth-walled to allow for easier machining.
  - Additionally their cross-section is monotonically decreasing, allowing for plunge cutting.
  - This will become very important when we attempt to populated the HF receiver with four thousand detectors.

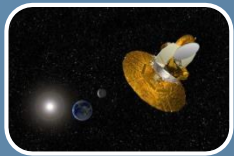


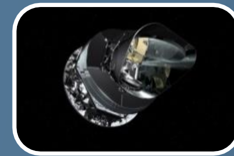


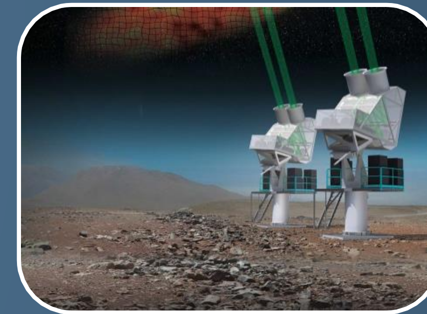





Survey Sensitivity







Conclusion

- CLASS will be able to measure and effectively remove polarization foregrounds, via our multi-frequency approach.
- Our key technologies, Variable delay Polarization Modulator and Transition Edge Sensors, afford us unprecedented sensitive to primordial signals.
- CLASS will make cosmic variance limited measurements of E-mode polarization for $l < 100$, making definitive measurements of the optical depth of reionizaiton (τ).
- By 2020 CLASS will be able to measure the tensor-to-scalar ratio at a level of $r = 0.01$.