

THE COSMIC MICROWAVE BACKGROUND RADIATION AND ITS POLARIZATION

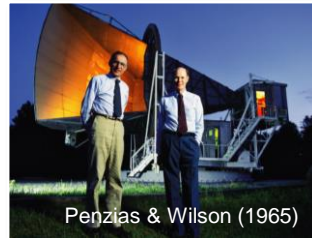
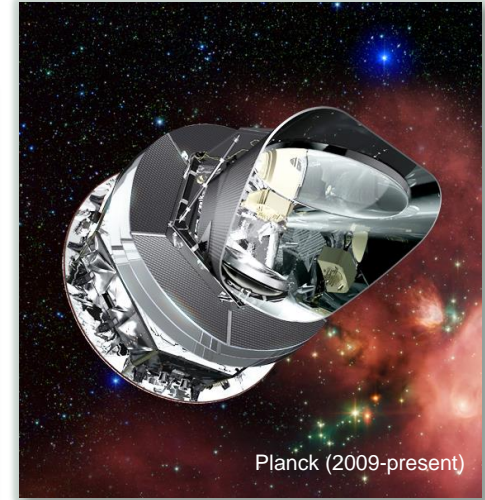
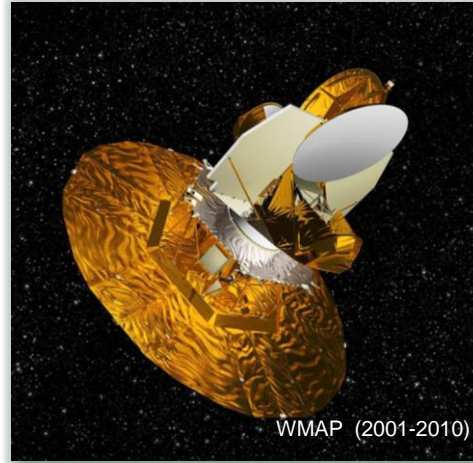
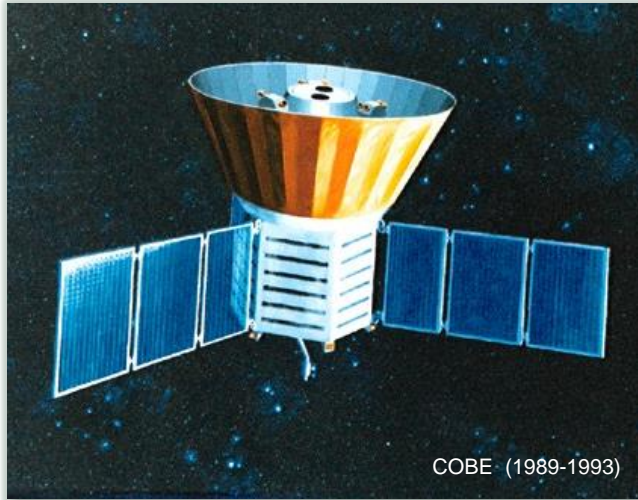
Inflation Probe Science Interest Group (IPSIG)

Jamie Bock for Edward J. Wollack, with input from Shaul Hanany

American Astronomical Society

January 8, 2018

CMB: Past and Present...



CMB Polarization Anisotropy

Inflation Paradigm:

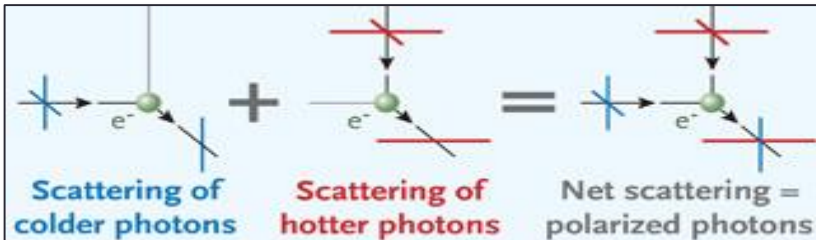
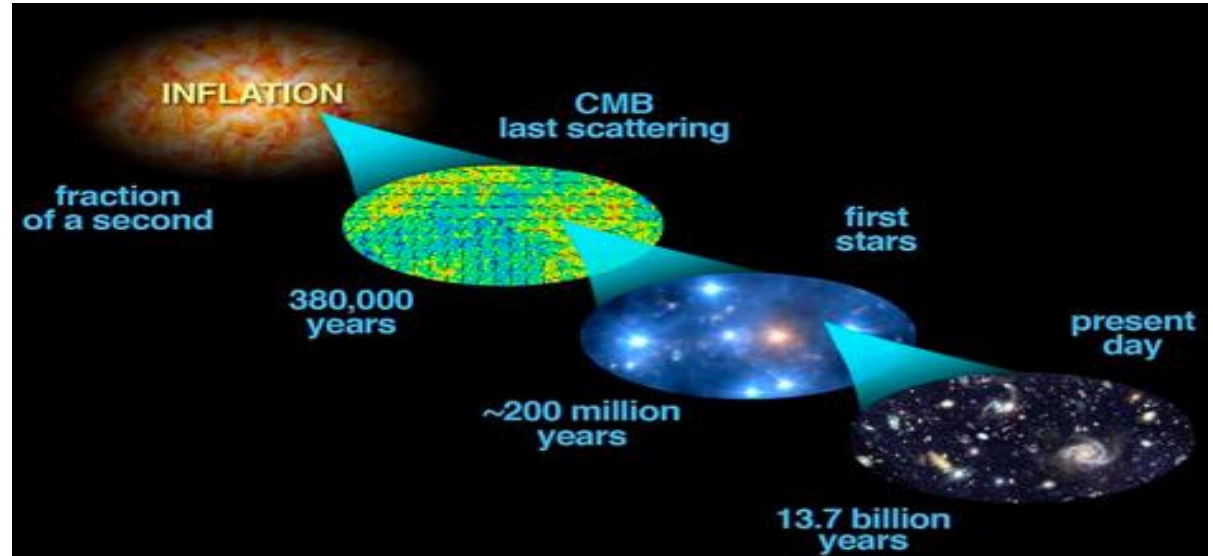
Quantum fluctuations in the metric and inflaton expand to astronomical scales.

Scalar perturbations

create density perturbations.

Tensor perturbations

create gravity waves that propagate from early to late times.

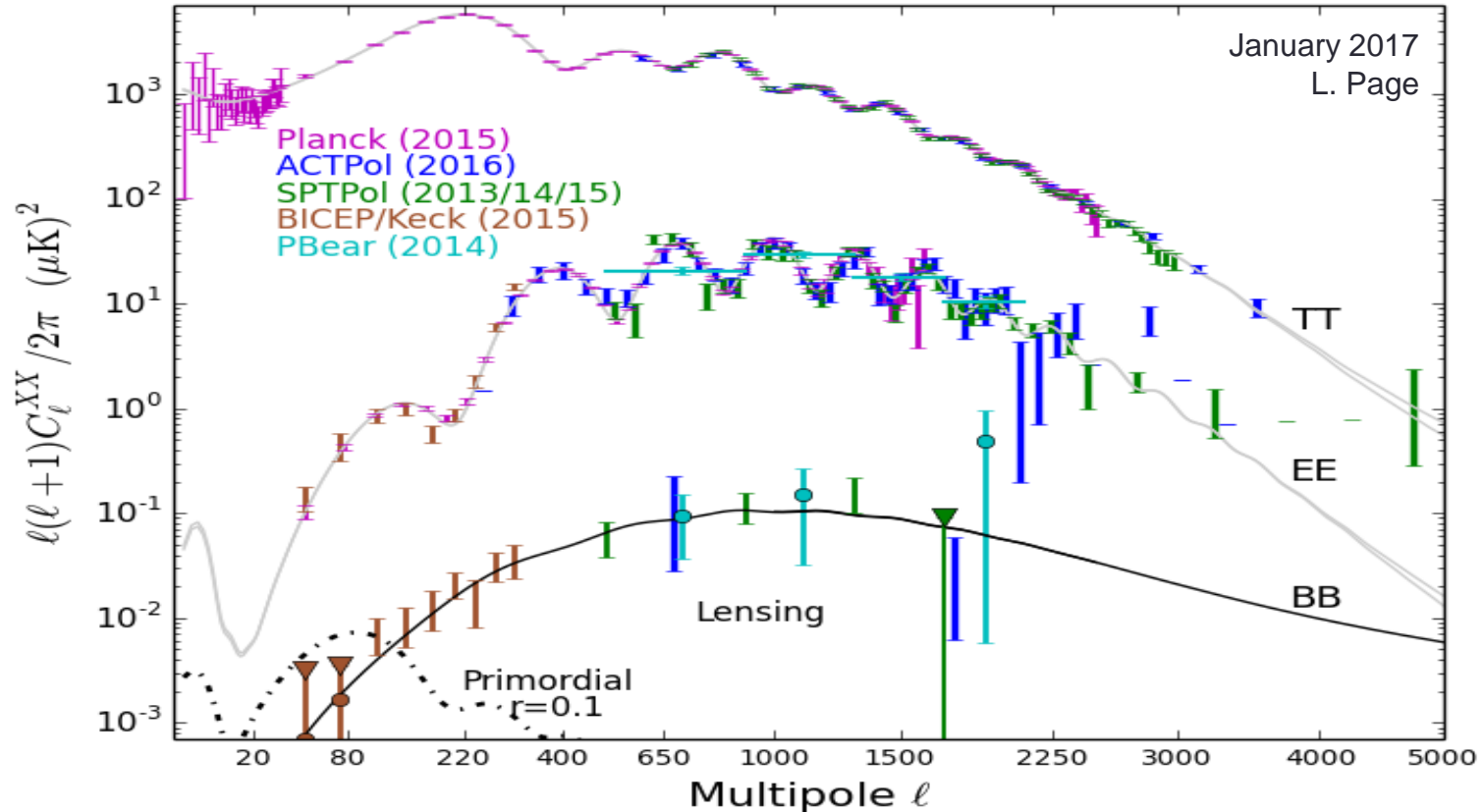


Comic Microwave Background:

Thomson scattering → CMB Polarization

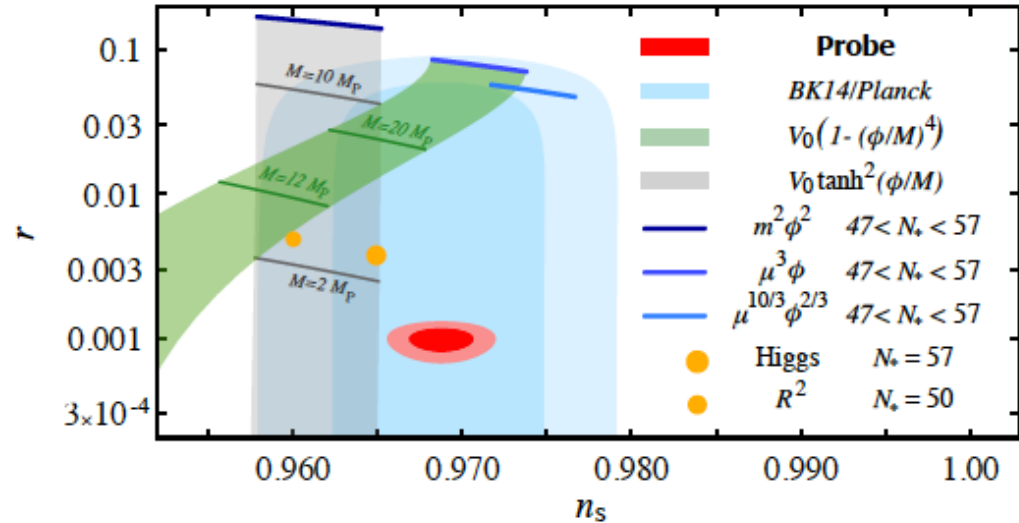
- Density perturbations (scalar) – *E mode only*
- Gravity waves (tensor) – *E and B modes*

CMB Temperature and Polarization Data



How Did The Universe Begin?

- Detection of **inflationary B-mode polarization** would be the first observation of quantum gravity
- Would point to likely inflation potentials and motivate connection between large field inflation and string theory
- Upper limit will exclude classes of potentials as the driving force of inflation



Vigorous Technology Development

Large-format, multi-frequency background-limited polarized detector arrays

- Superconducting bolometer arrays with SQUID readout
- Current state of the art is several thousand detectors
- Resonator-based detectors promise higher muxing factors
- Synergies with superconducting far-IR and X-ray detectors

Strong synergy with experiments

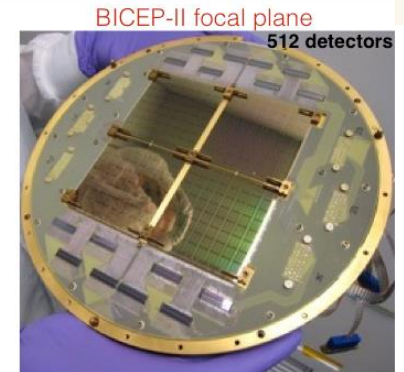
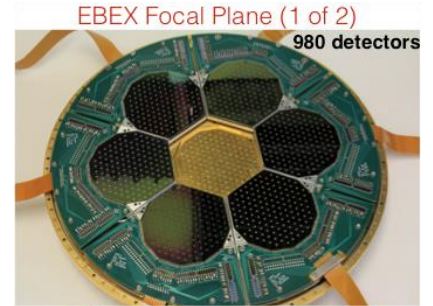
- Ground-based: ABS, ACTPol, BICEP2/BICEP3/Keck, POLARBEAR, SPTPol
- Balloon-borne: EBEX, SPIDER

Projects in Launch/Deployment Phase

- CLASS (ground, low ell)
- PIPER (balloon, low ell)

Funded extensions to ~20,000 detectors

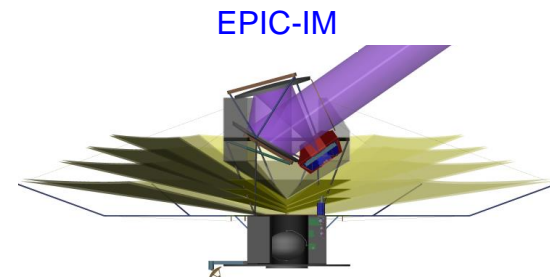
- Advanced ACTPol, BICEP Array, Simons Array, SPT3G



Inflation Probe Mission Landscape

NASA

- Probe-Scale Mission Study: ~ \$400M - \$1000M
 - Proposal accepted and study under way
 - Part of NASA preparations for 2020 Decadal Panel
 - Single proposal representing entire CMB community
 - *Science: Inflation/Quantum Gravity, Particle Physics, Dark matter, Dark energy, Galactic Astrophysics*
- PIXIE - submitted as 2016 MIDEX mission -- declined
 - Low Resolution (~1.6 deg@150GHz), LEO, FTS
 - *Science: Inflation, Spectral Distortions, Galactic*



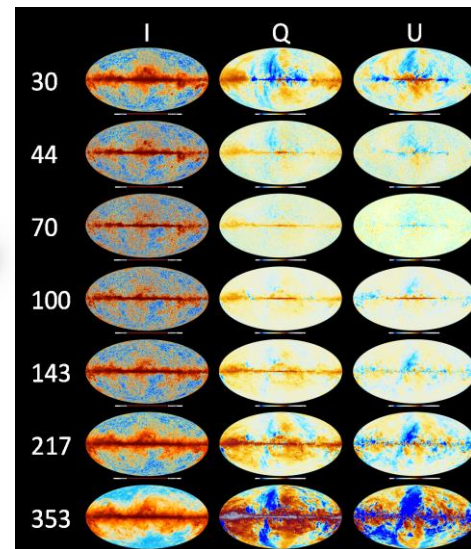
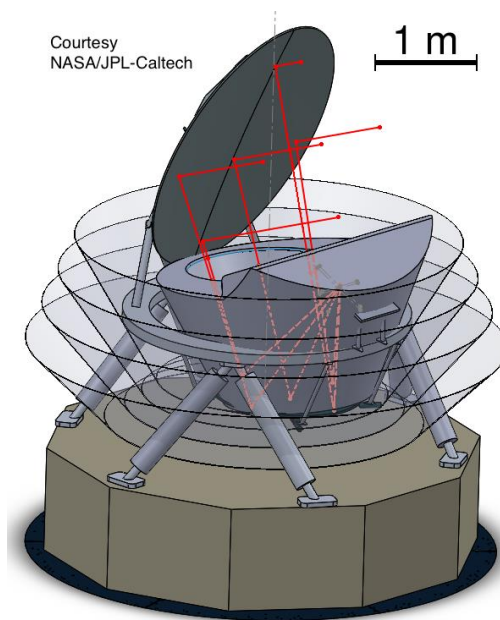
ESA M5, CORe+

- Submitted in 10/2016; Response expected in Spring 2017; Launch = 2028
- E550M ESA + E50-100M Members = E600-650M
- Medium resolution (5.5 arcmin @150 GHz), L2
- Intense European interest for US contribution; Strong community backing
- *Science: Inflation, Lensing/Clusters, Neutrinos, Galactic*



Inflation Probe Mission Study (Shaul Hanany PI)

- Polarimetric survey of the entire sky
 - Emphases on **large angular scales**, and
 - **Comprehensive foreground removal**
- 21 bands (25% bandwidth) between 20 GHz (15 mm) and 800 GHz (0.375 mm)
- 1.4 m aperture telescope
- Diffraction limited resolution: 38' to 1'
- 12,400 transition edge sensor bolometers + multiplexed readouts
- 4 year survey from L2
- 70 times the sensitivity of Planck



Slide courtesy S. Hanany

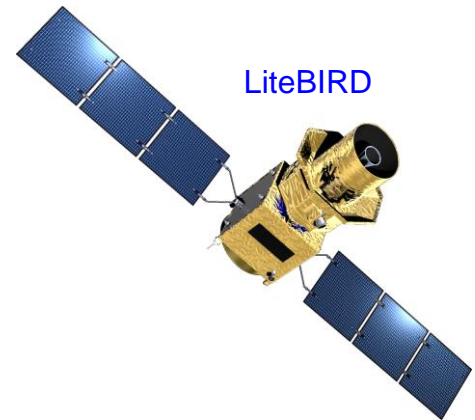
Inflation Probe Mission Landscape

JAXA, LiteBIRD

- Low Angular Resolution
- Includes US contribution (Focal Plane); 2014 SMEX Mission of Opportunity Proposal (declined)
- Phase A studies funded in Japan (conclusion in 2017, SRR early 2018) and in the US (concluded in summer 2016)
- Launch (if approved): 2025+
- **Science: *Inflation, Galactic***

ESA/JAXA Collaboration

Discussions ongoing between ESA/JAXA and science teams regarding possible collaboration as part of M5: Main discussion point is targeted angular resolution



CMB Community Meetings and Inputs

- NASA Probe-Scale Mission Study proposal accepted and effort under way:
 - ...see AAS Session 121.01: “The Probe of Inflation and Cosmic Origins” by *Shaul Hanany*...
- Workshop: “CMB Foregrounds”, sponsored by NASA’s CMB Probe Mission Study; University of California, San Diego Nov. 29 – Dec. 1, 2017.
- Workshop: “B-Modes from Space”, primary concentration on LiteBIRD mission; University of California – Berkeley, December 4-6, 2017.
- CMB-S4 Concept Definition Team presented its final report to NSF-NASA-DOE Astronomy and Astrophysics Advisory Committee (AAAC) on October 23, 2017.
- Workshop Series – “Cosmology with CMB-S4”:
 - SLAC-2017; Stanford, February 27-28, 2017
 - Harvard-2017; Harvard, August 24-25, 2017
 - ANL-2018; Argonne, March 5-8, 2018 → *save the date!*

BACKUP

CMB Status: Temperature & Polarization

- Temperature power spectra characterized over ~ four decades by a variety of experiments
- Space has been critical for comprehensive measurements, especially on large angular scales
- Temperature and E-mode spectra underpin Inflationary Λ CDM
- Detections of *B*-mode gravitational lensing: opens up the field of all-sky lensing measurements for the 2020s
- No detections of inflationary polarization yet

Joint BICEP2/Keck Planck analysis: $r = 0.028 \pm 0.026$ and $r < 0.09$ at 95% CF

[BICEP2/Keck and Planck Collaborations, “Joint Analysis of BICEP2/Keck Array and Planck Data” PRL \(2015\) 114, 101301.](#)

[BICEP2/Keck Collaboration, “Improved Constraints on Cosmology and Foregrounds from BICEP2 and Keck Array Cosmic Microwave Background Data with Inclusion of 95 GHz Band” \(2016\) Phys. Rev. Lett. 116, 031302](#)

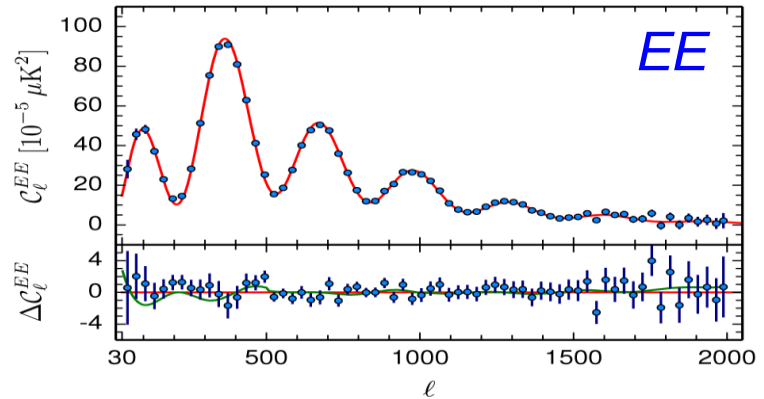
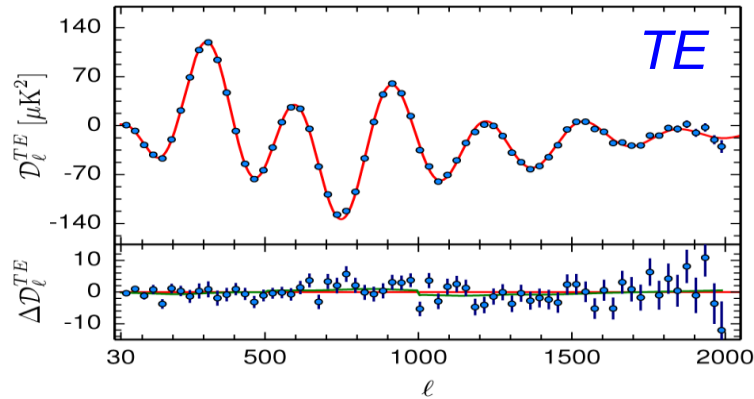
CMB Polarization Mission Planning

- NASA Inflation Probe to provide high-sensitivity measurements over entire sky enabling extraction of all cosmological information from CMB in polarization.
- B-mode polarization tests the physics behind the process of inflation plus tests of neutrino mass, mapping large-scale structure with gravitational lensing, and epoch of reionization science.
- Space provides access to the *largest spatial angular scales* and *entire spectral range* of interest – a combination of capabilities which far surpasses that achievable from other observational platforms.



CMB Status: Temperature & Polarization

- Planck – full sky maps with 4' resolution available...
- Rich cosmological and galactic data sets...
- Consistency within cosmological model...
- Consistency among numerous experiments...



Inflation Probe Science Interest Group:

- Goal: Develop a US community response which articulates a consensus for a Inflation Probe mission priorities. Inputs from all members of the community are welcomed.
- Inflation Probe SIG website and mailing list:
<http://pcos.gsfc.nasa.gov/sigs/ipsig.php>
<http://pcos.gsfc.nasa.gov/sags/ipsag/ipsag-maillist.php>
- Physics of the Cosmos Program Analysis Group (PhysPAG) Inflation Probe Science Interest Group (IPSIG) Community Representatives:
Amber Miller & Ed Wollack