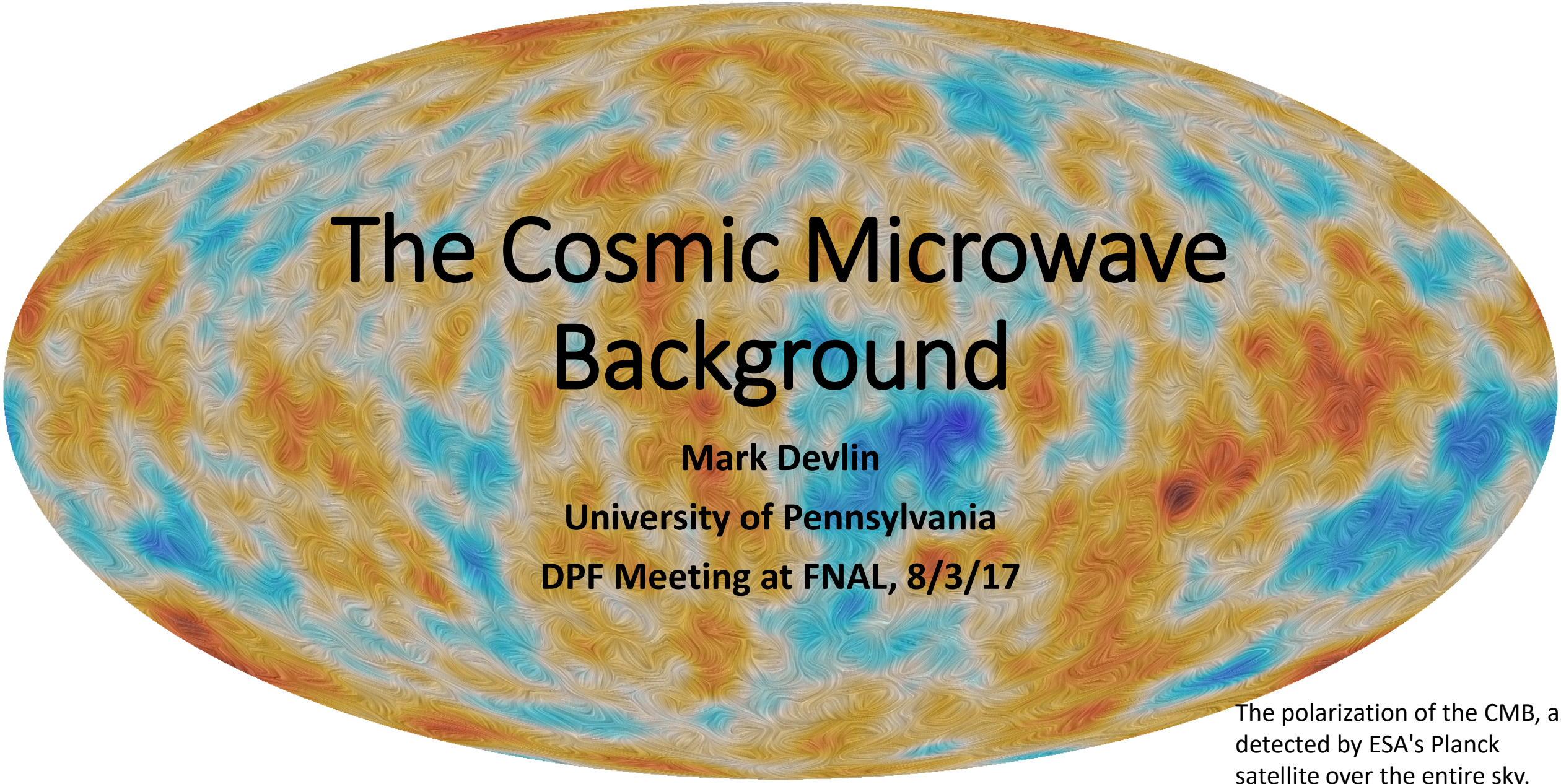


The Cosmic Microwave Background

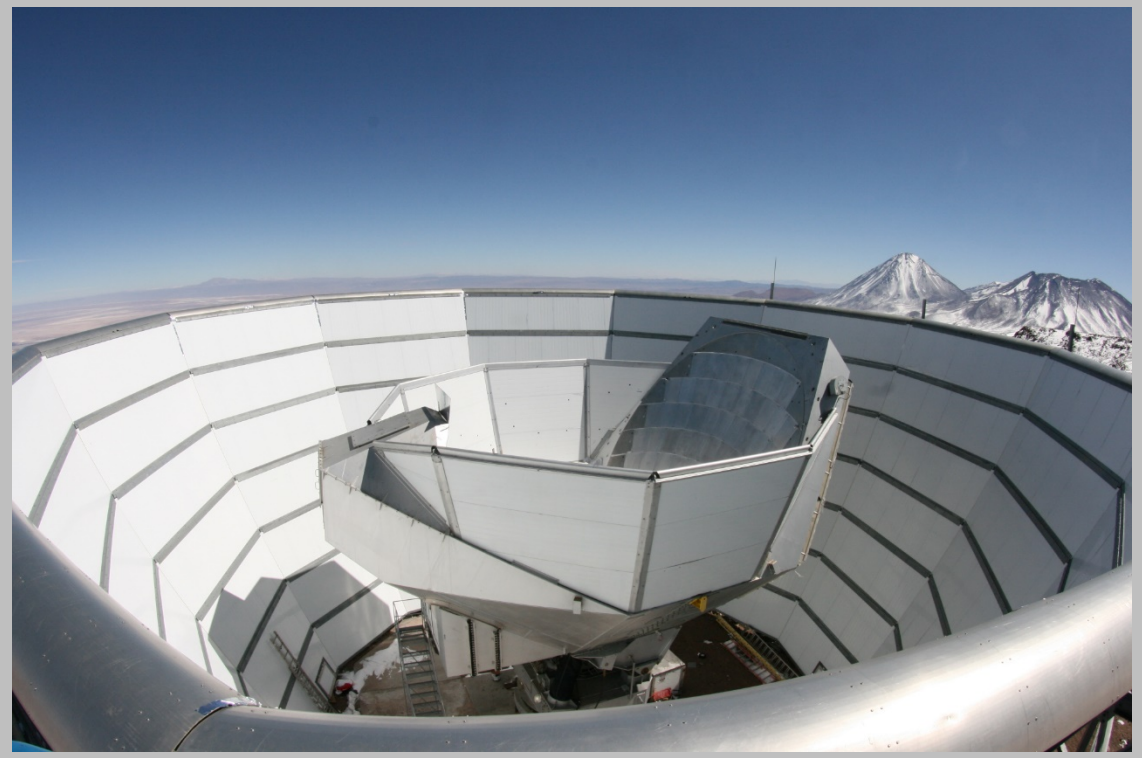
Mark Devlin

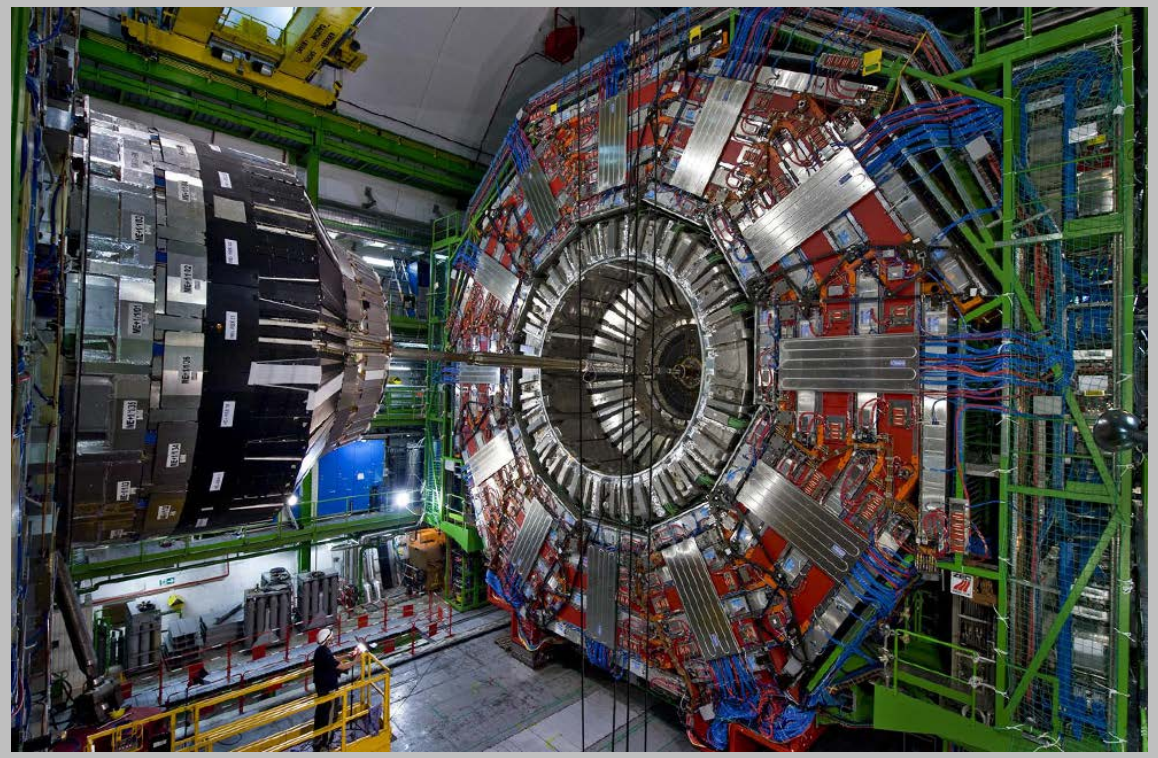
University of Pennsylvania

DPF Meeting at FNAL, 8/3/17

The polarization of the CMB, as detected by ESA's Planck satellite over the entire sky.

How Can a Simple Telescope Tell Us So Much About Fundamental Physics?





(Maximilien Brice; Michael Hoch; Joseph Gobin, © CERN)

CMB Telescopes:

Energy Scales Probed: $>10^{13}$ GeV

Integration Time: 13+ billion years

~100's scientists

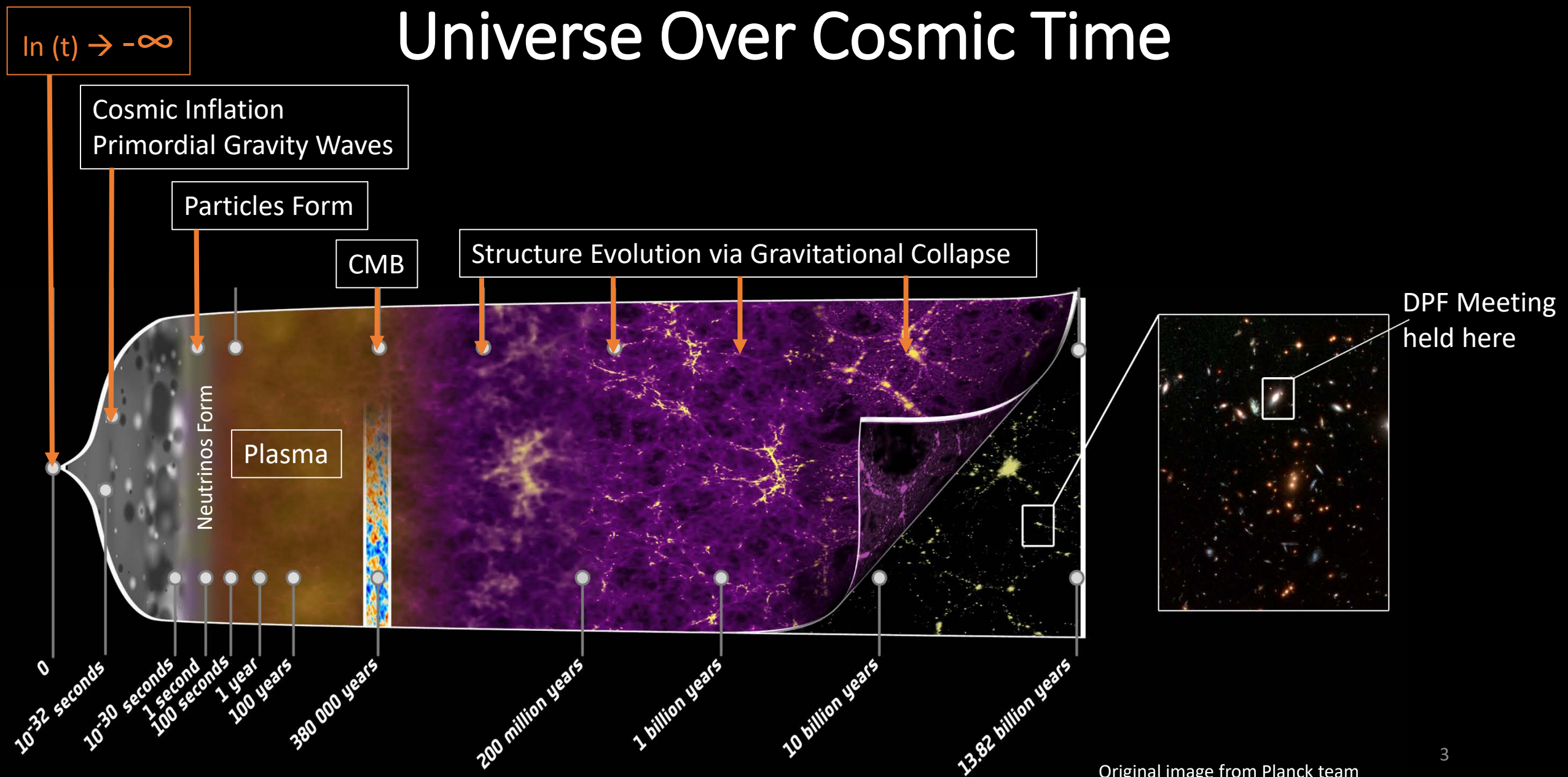
LHC:

Energy Scales Probed: 10^{4} GeV

Integration Time: 25 ns -> several years

1000's of scientists

Cosmology is the Study of the Evolution of the Universe Over Cosmic Time

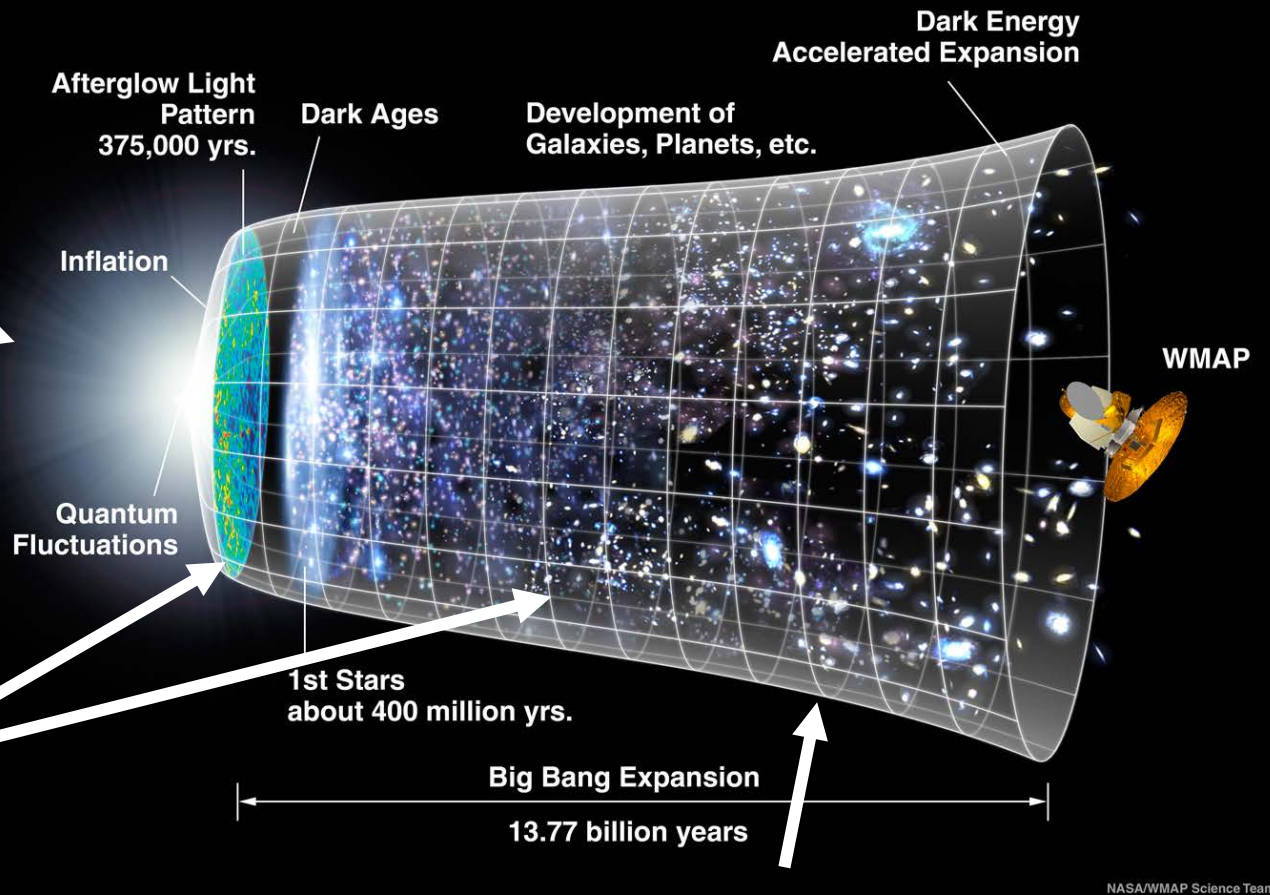


Original image from Planck team

The Cosmic Microwave Background is a Probe of Fundamental Physics

Inflation

- Spectral Index of fluctuations, n_s
- Gravity waves – quantized gravity!



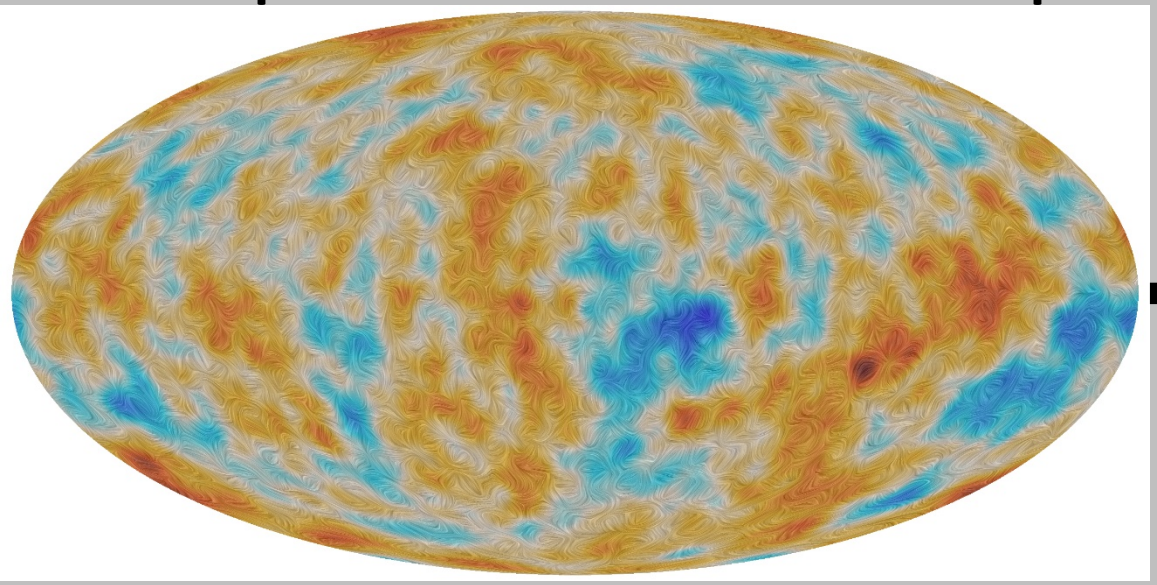
Neutrinos and Light Relics

- Number of Relativistic Species (N_{eff} or "dark radiation")
- Sum of the neutrino mass (Σm_ν)

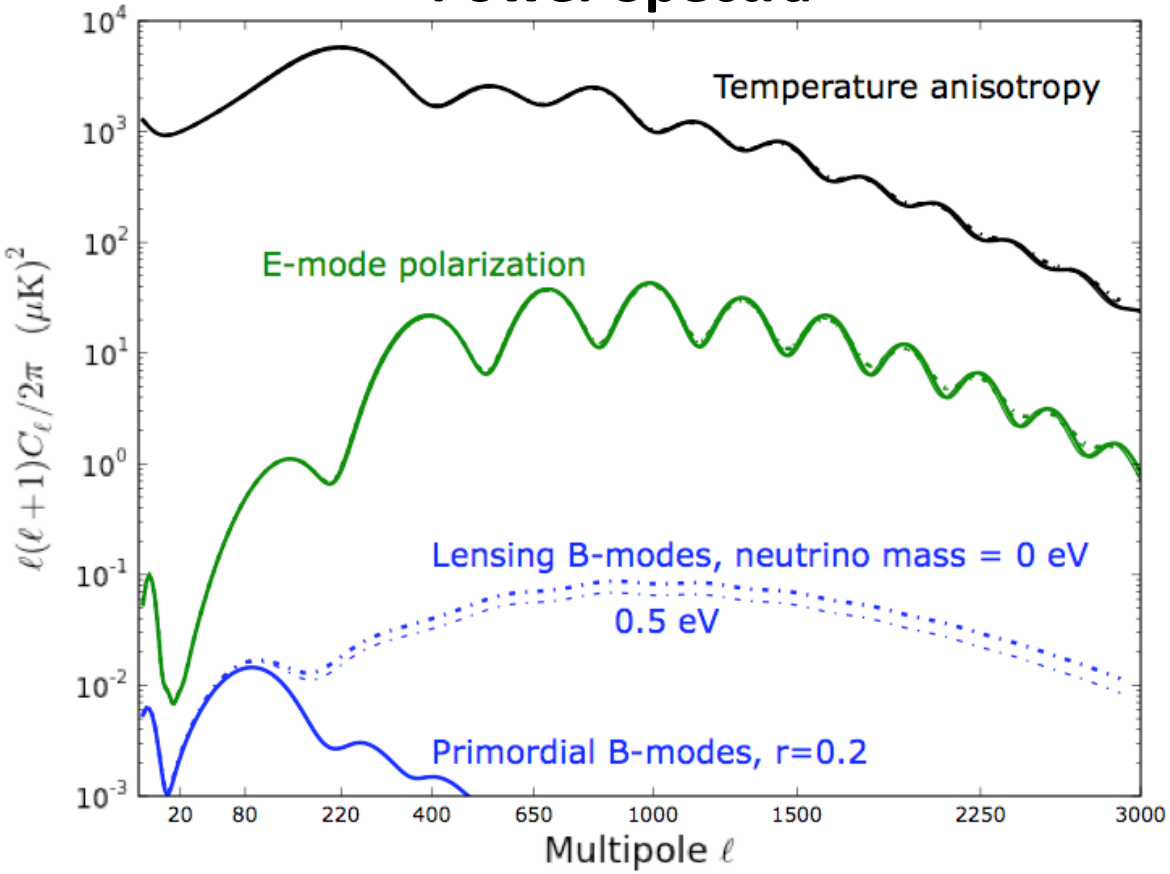
Dark Energy

- Evolution of structure (Galaxy Clusters)
- CMB Lensing

Temperature and Polarization Maps



Power Spectra



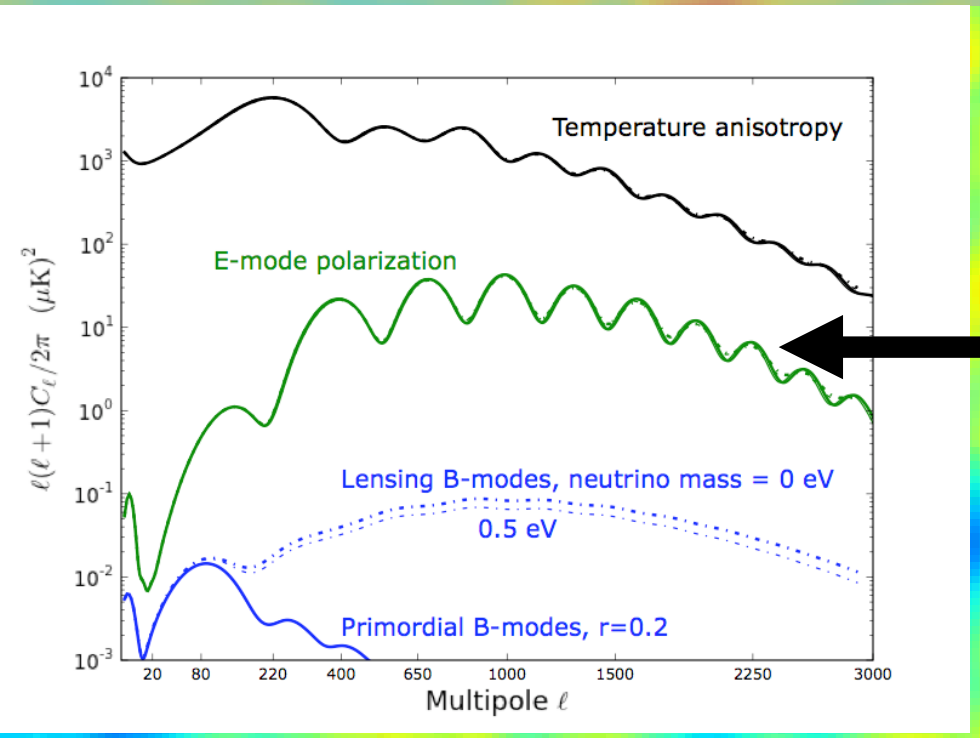
Cosmological Parameters

$\Omega_b h^2$ - Baryon Density
$\Omega_c h^2$ - Cold Dark Matter Density
Θ - Angular scale of horizon at decoupling
τ - Optical Depth to Reionization
n_s - Spectral Index of Primordial Adiabatic Fluctuations
A_s - Amplitude of perturbations
r - Tensor to scalar ratio

Derived Parameters

Ω_Λ - Dark Energy Density
Ω_m - Matter Density
σ_8 - Amplitude of the Matter Power Spectrum
Σm_ν - Sum of the masses of neutrinos
N_{eff} - Number of neutrino species
Energy scale of inflation….

How Does the CMB Get Polarized, and What Can We Learn From It?



HOT

COLD

Thomson Scattering

COLD

e^-

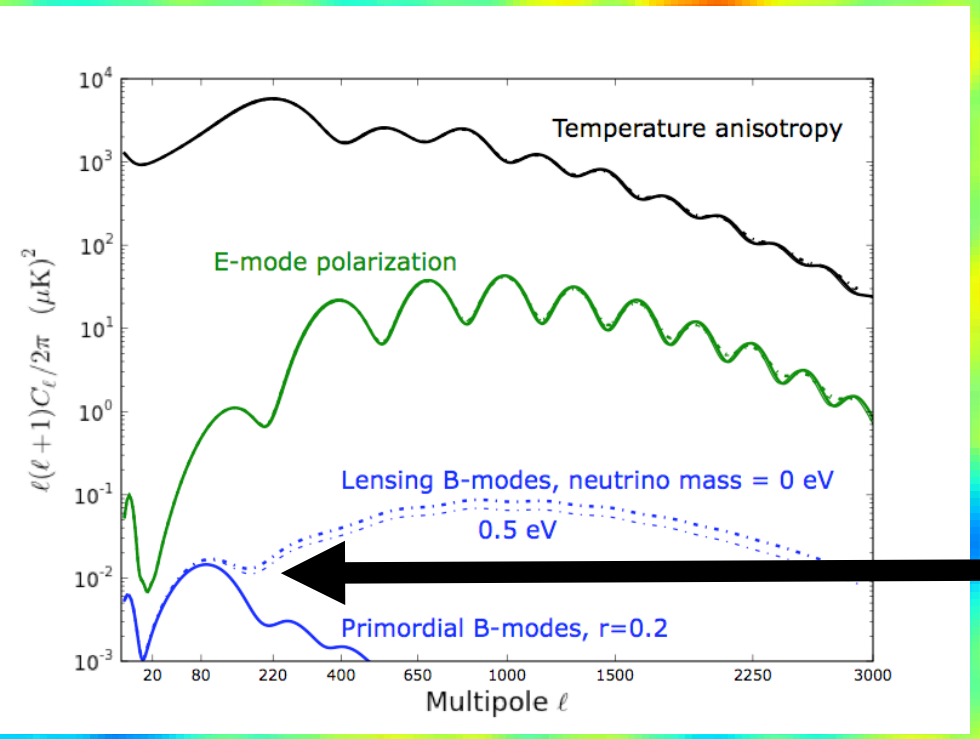
Linear Polarization

HOT

Adapted from Hu and White

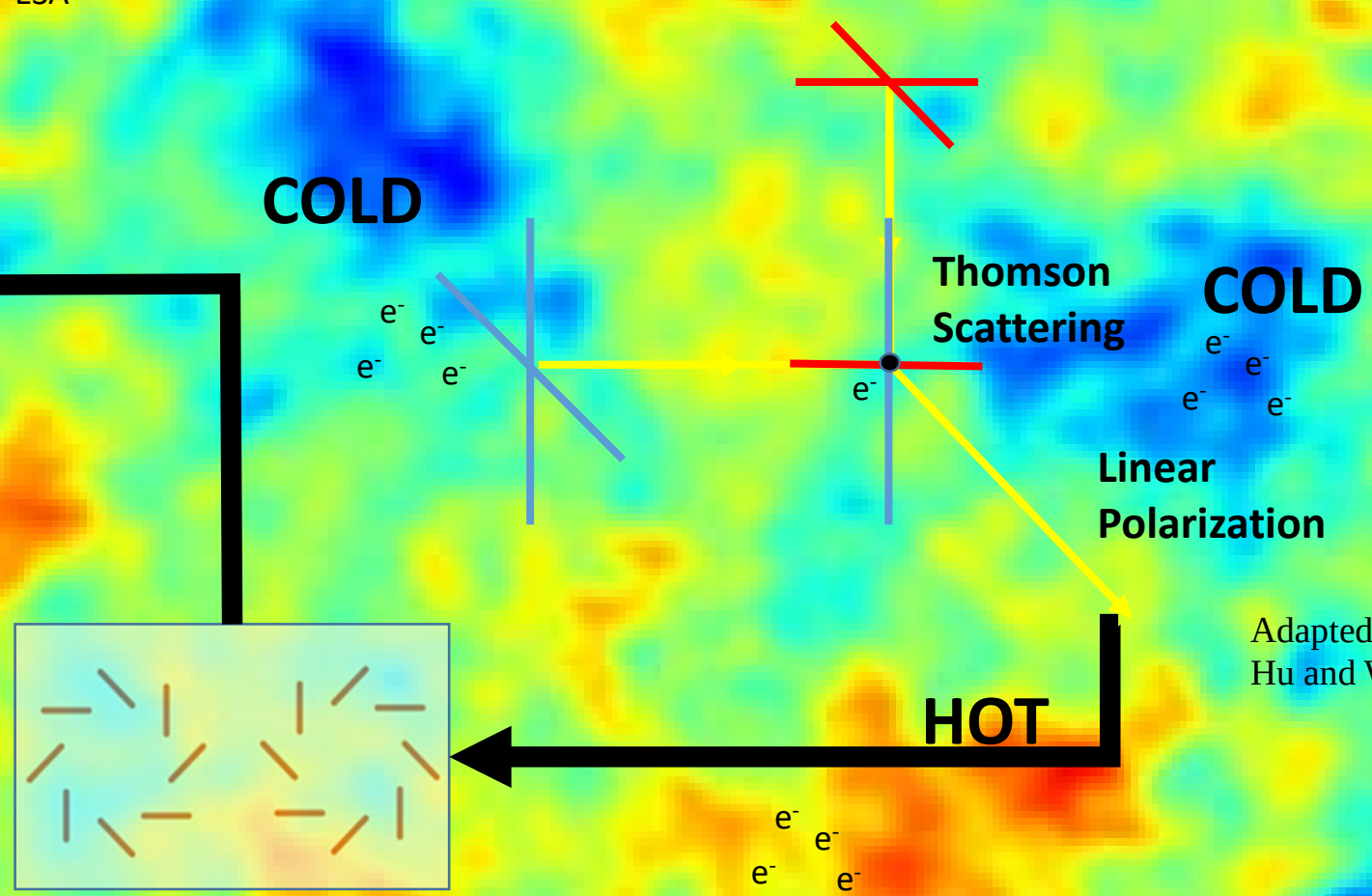
E modes: The **pattern** does not change when observed in a mirror -> No change under a parity transformation.

Gravitational Waves and B-Mode Polarization



ESA

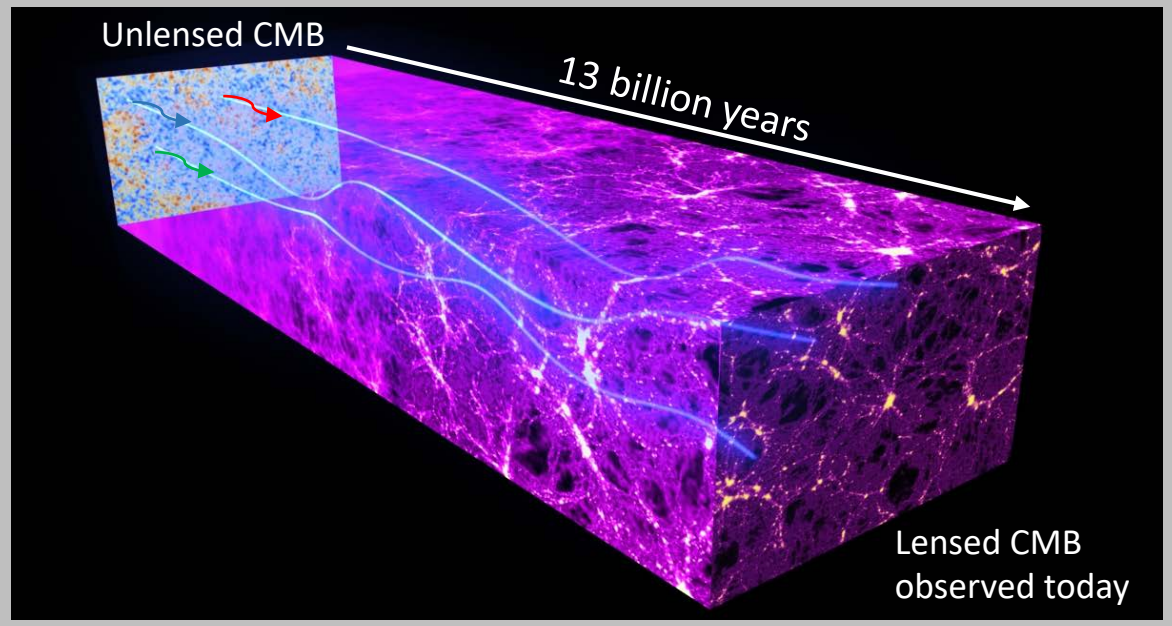
Gravitational waves induce a "velocity" in the electrons. This results in a quadrupole signal.

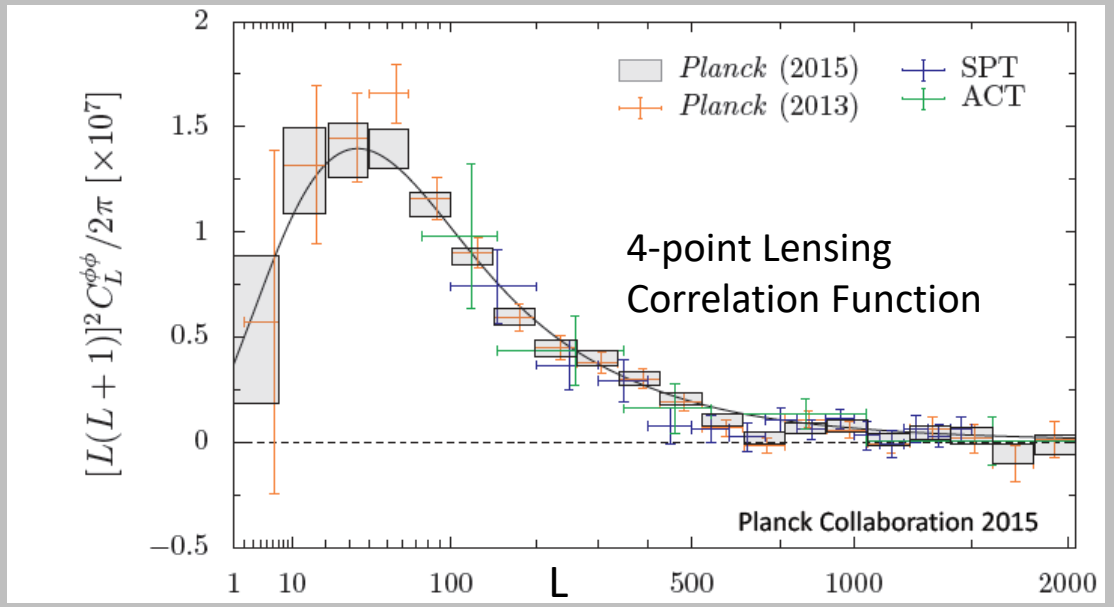


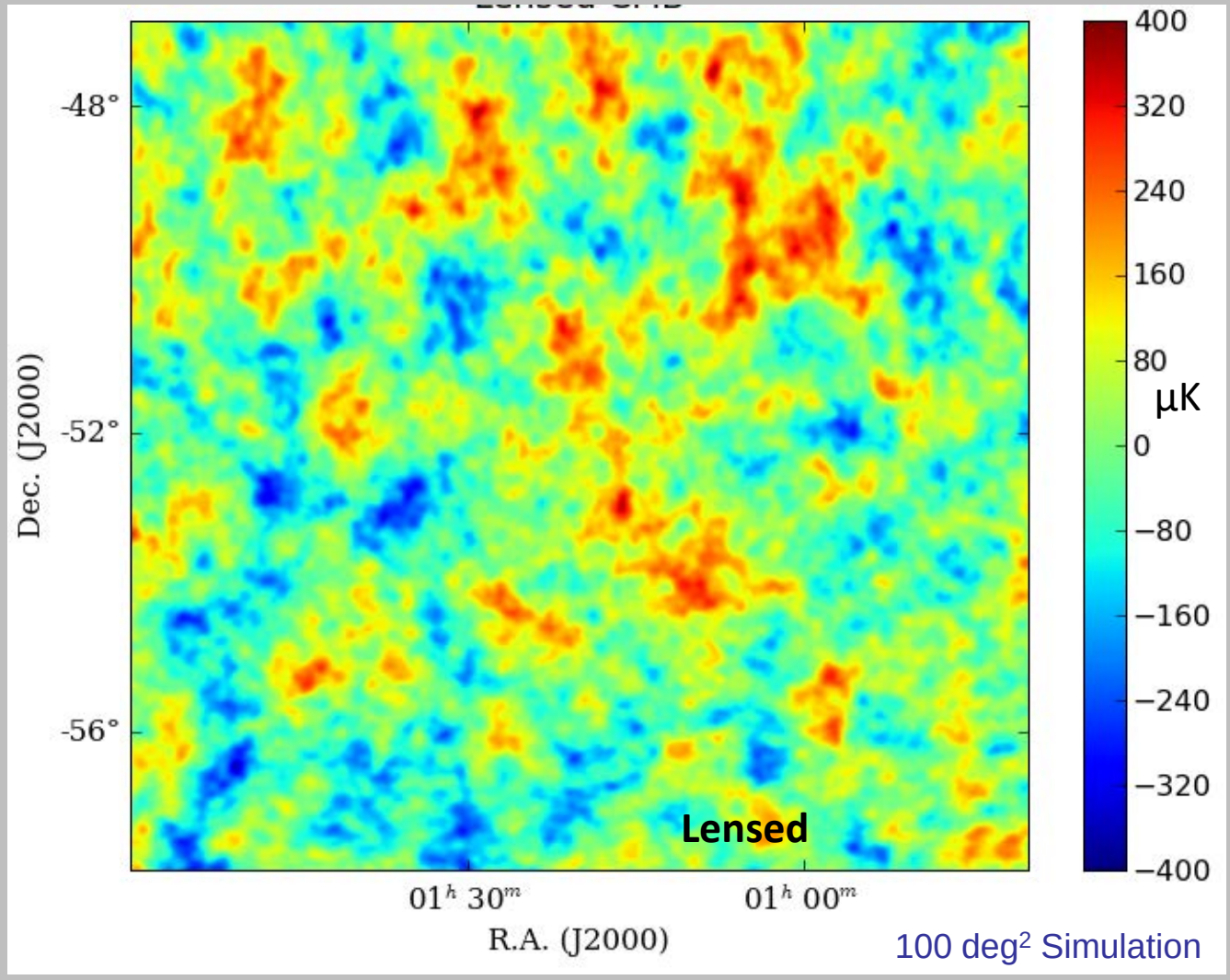
Adapted from Hu and White

B modes: The pattern changes when observed in a mirror -> it **does** change under a parity transformation. E-modes are also created.

CMB Lensing Probes Structure Evolution Over Cosmic Time





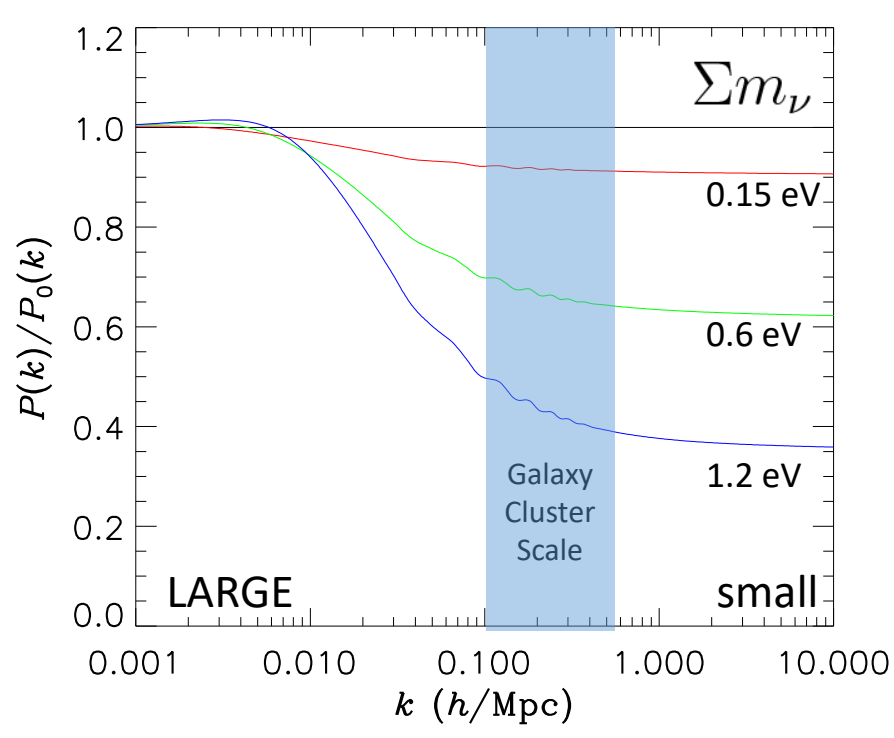


AAS, Jan 7 2010

- **CMB photons are deflected an average of 50 times.**
- **Lens redshift in the 2-3 range (10 – 11 billion years ago)**
- **The net deflection is 2-3 arcminutes.**
- **Induces correlations on scales of 2-3 degrees.**

Massive Free-streaming Neutrinos Suppress Structure Formation

Matter Power Spectrum Divided by ΛCDM Matter Power Spectrum

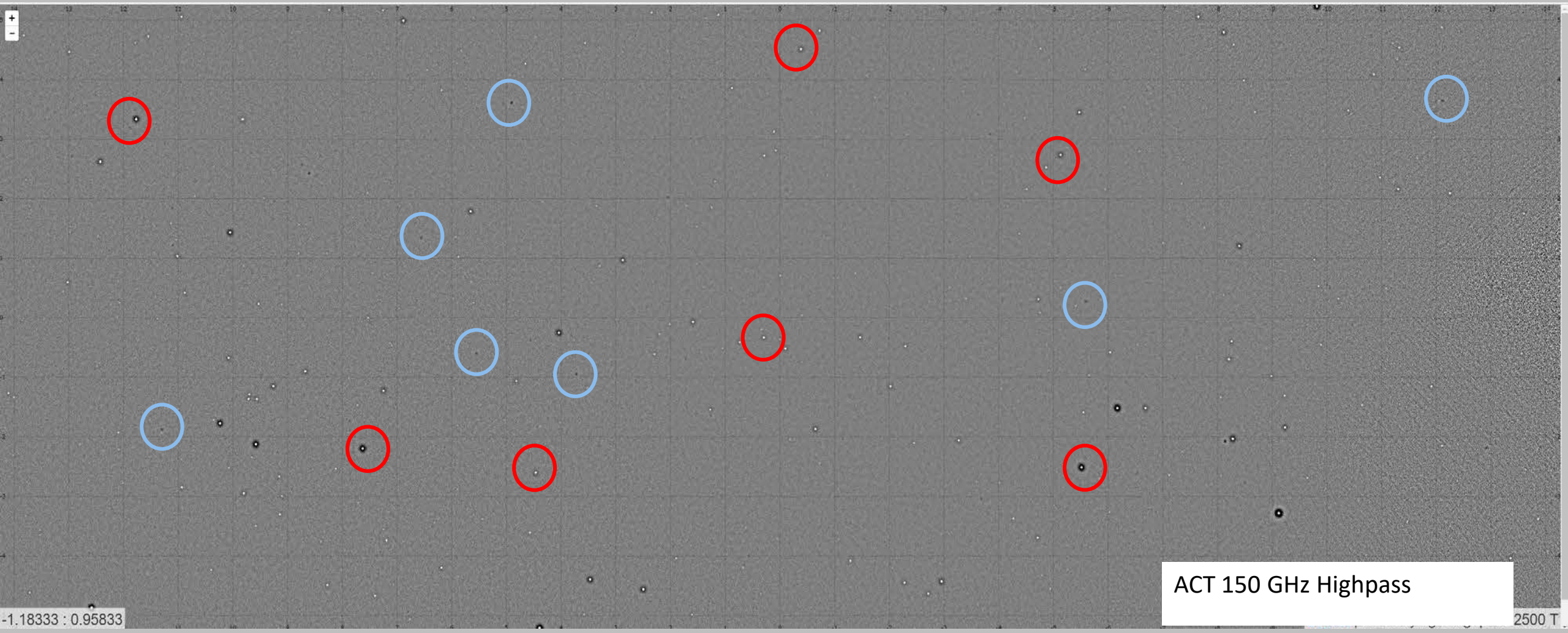


Adapted from Hannestad review, 2010

Francisco Villaescusa-Navarro

Combined with baryon acoustic oscillation (BAO) these measurements can place limits on Σm_ν (~0.06 eV) and N_{eff}

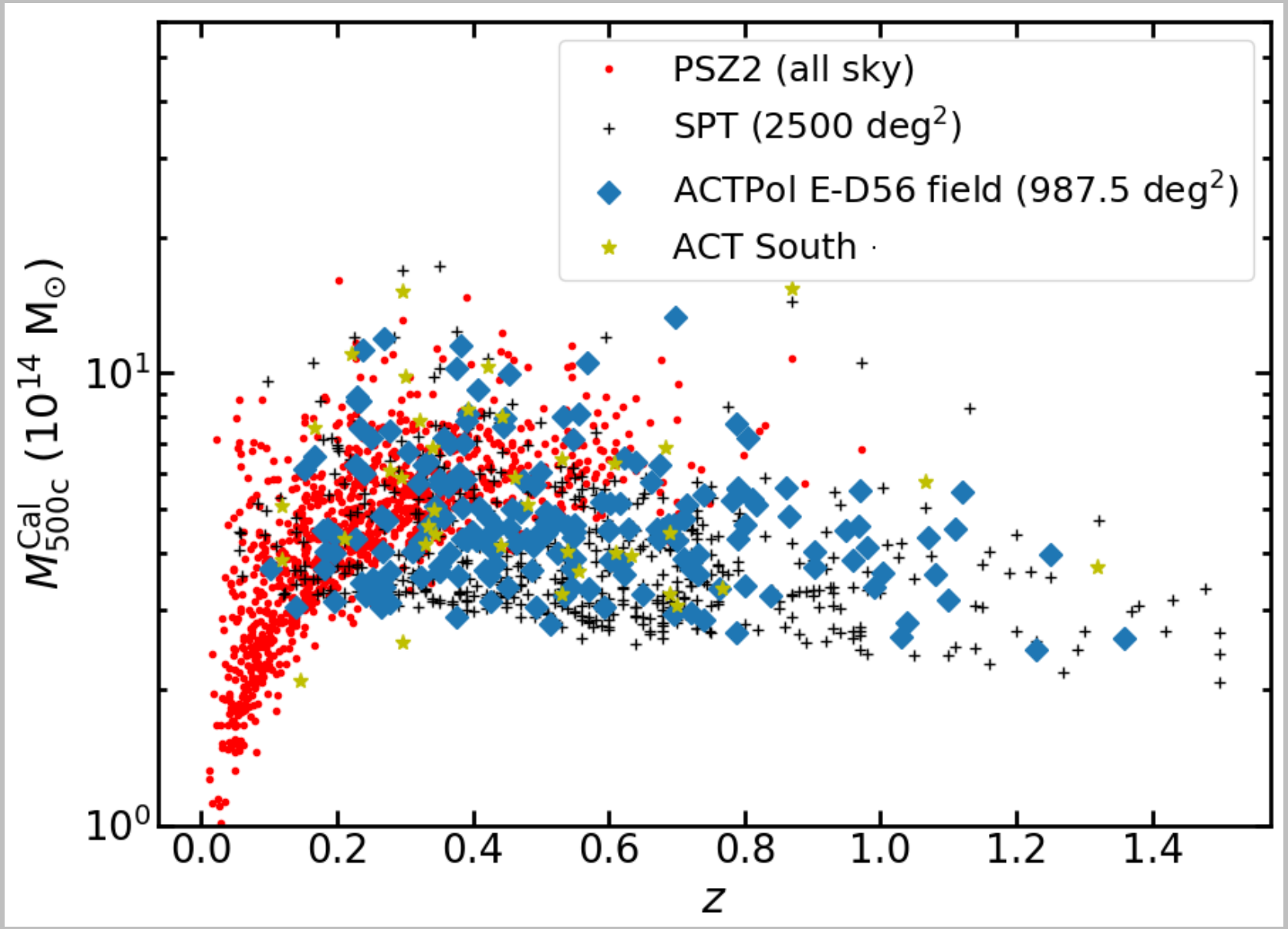
ACT MAPS (and similar from SPT)

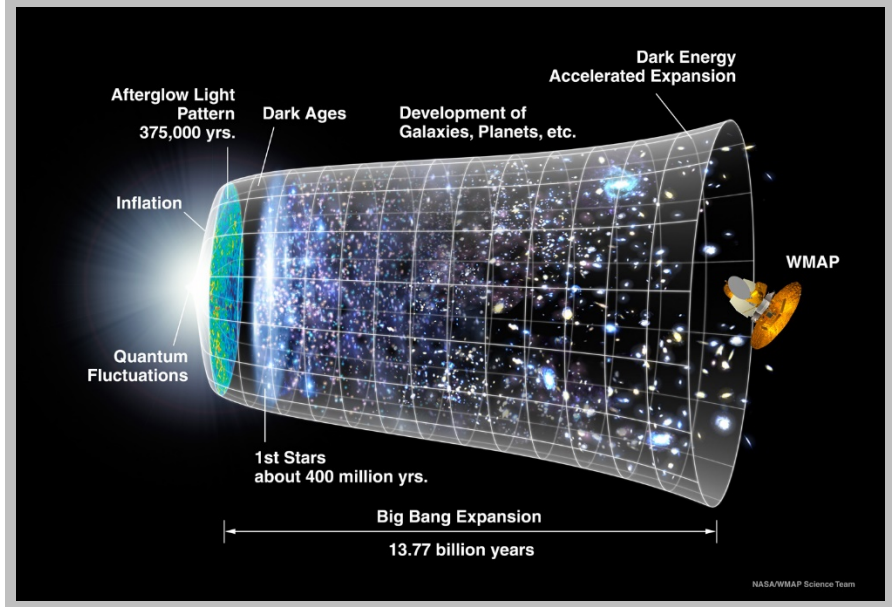


Galaxy Clusters

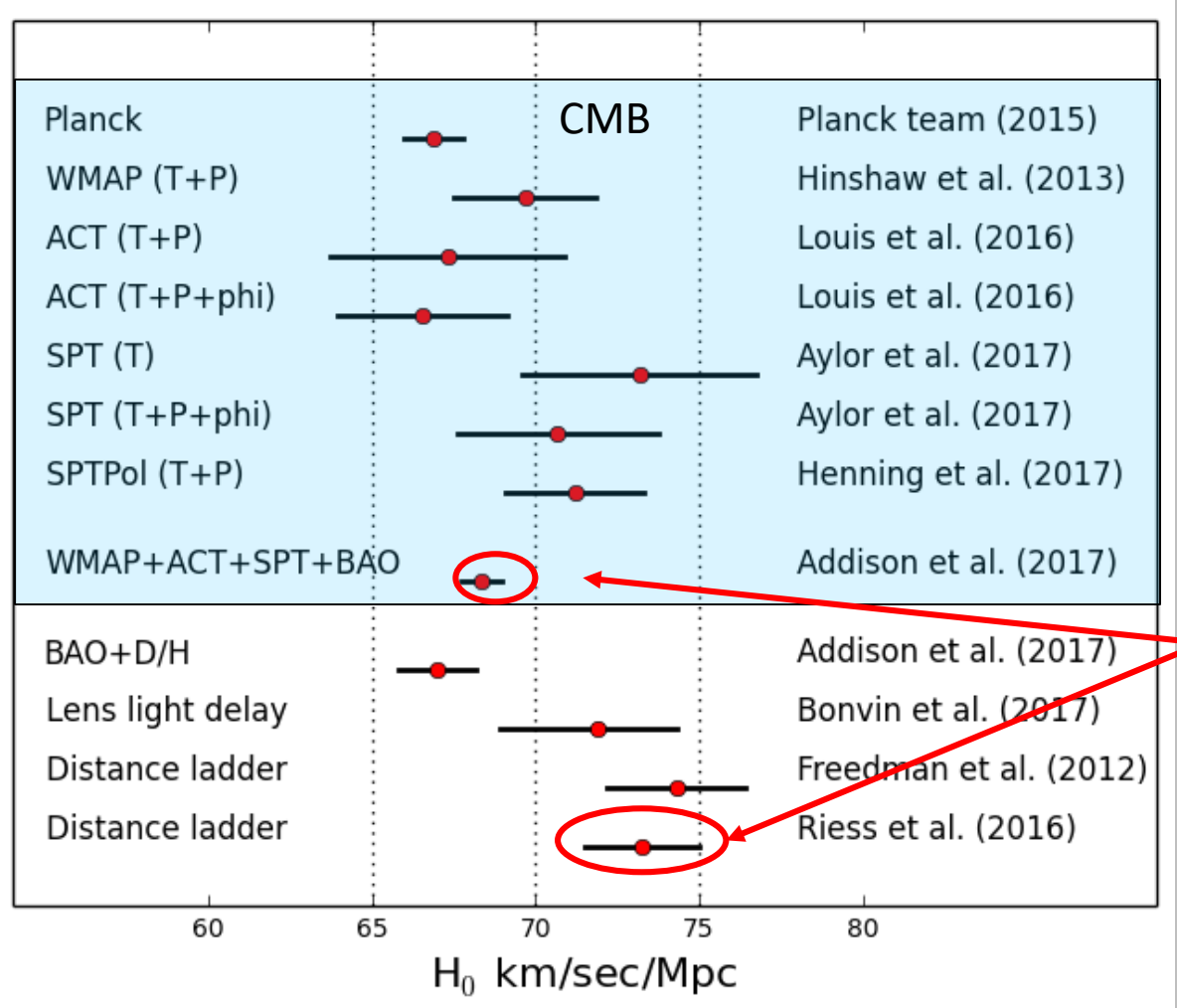
Dusty Star-forming Galaxies

Cluster Mass vs. Redshift Provides a Test of Cosmology





Up-to-date comparison of H_0

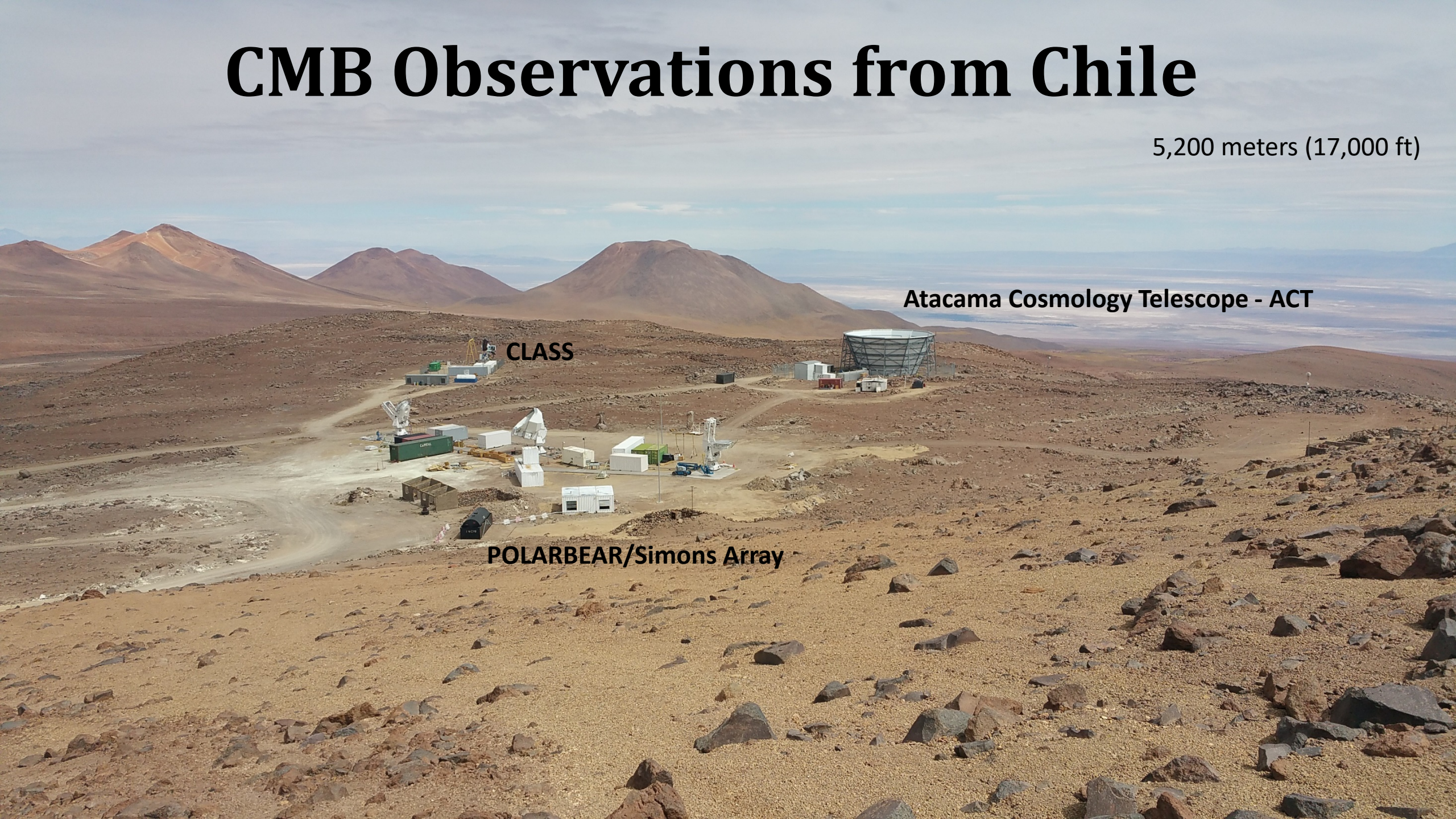


The Hubble constant determined from the CMB differs from that determined by the "distance ladder" which is based on Cepheids + SN.

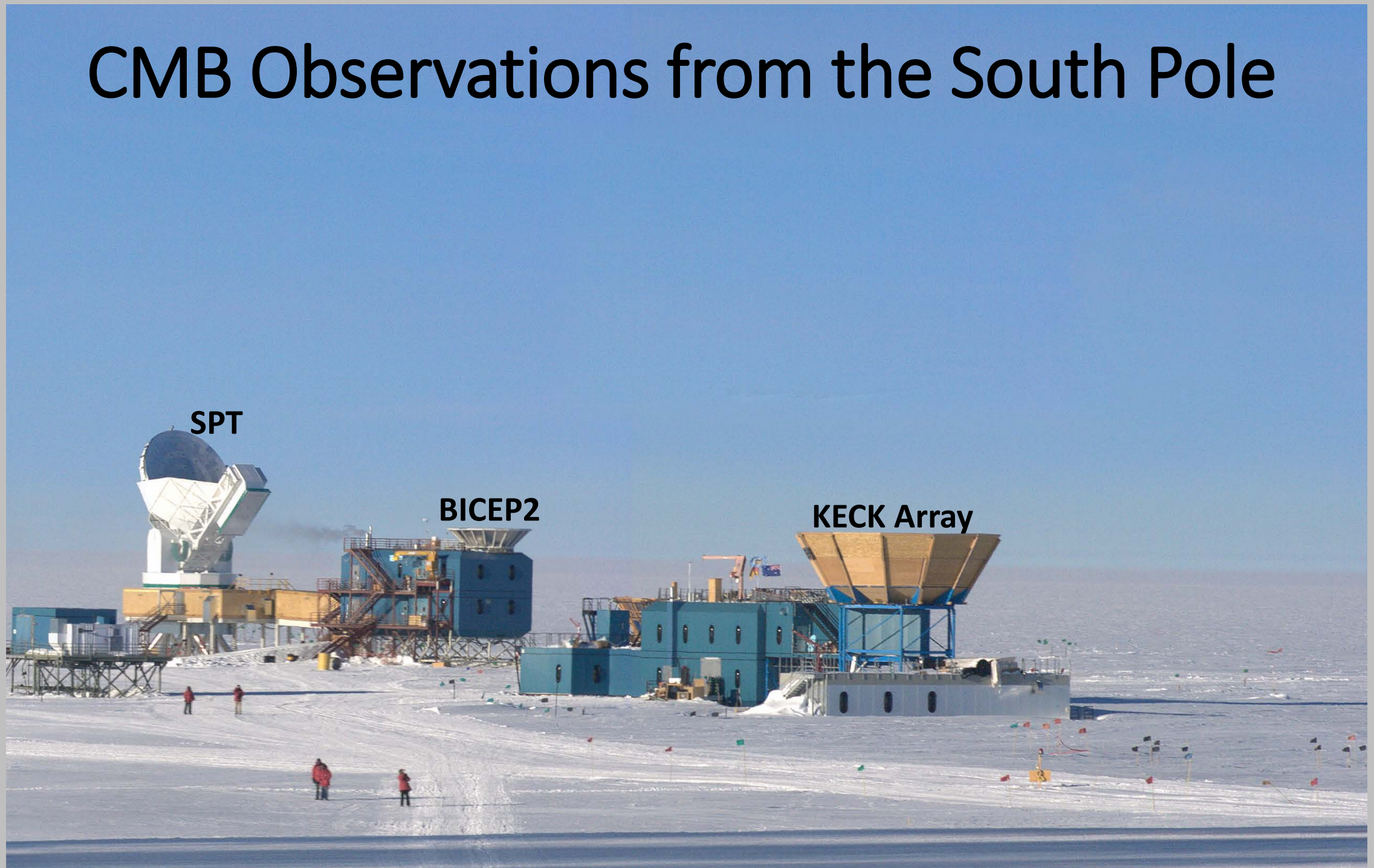
The tension is ~3 sigma.

This tension can be resolved with continued observations of the CMB.

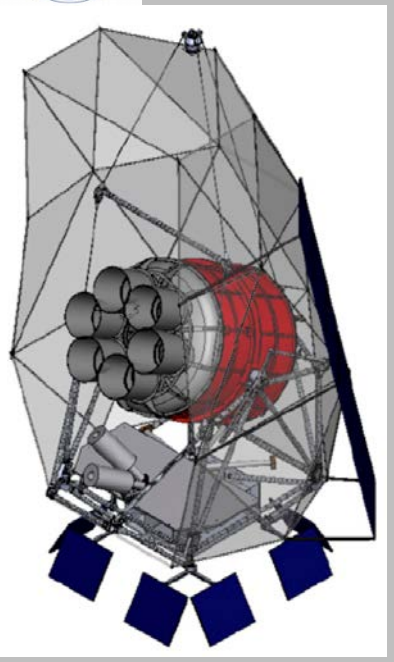
CMB Observations from Chile



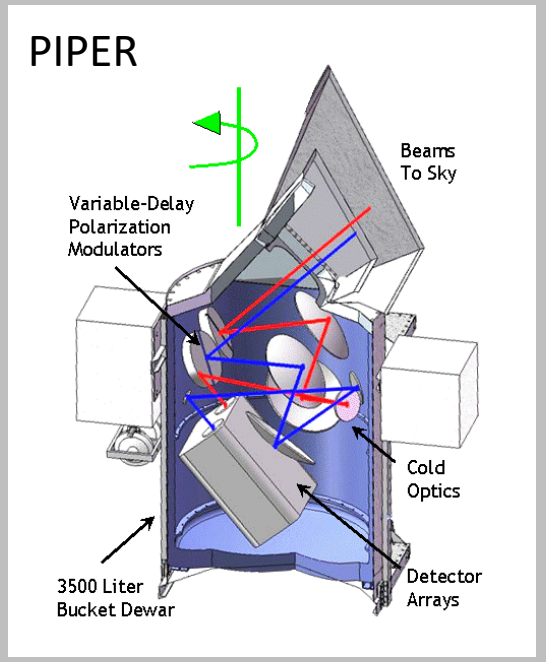
CMB Observations from the South Pole

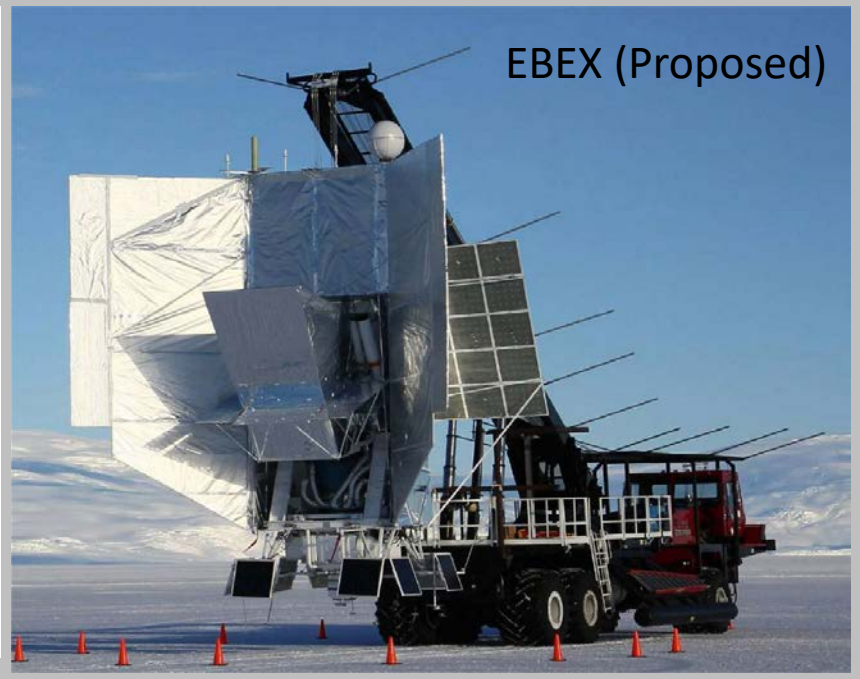


Sub-Orbital and Satellite CMB Observations

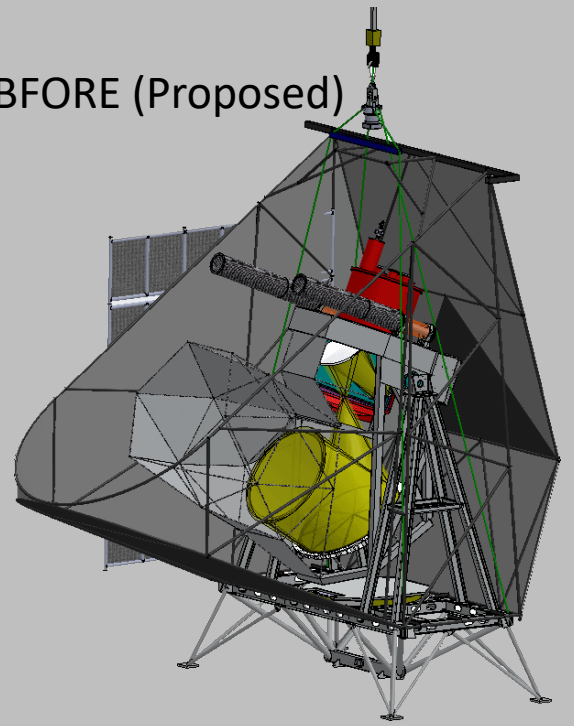


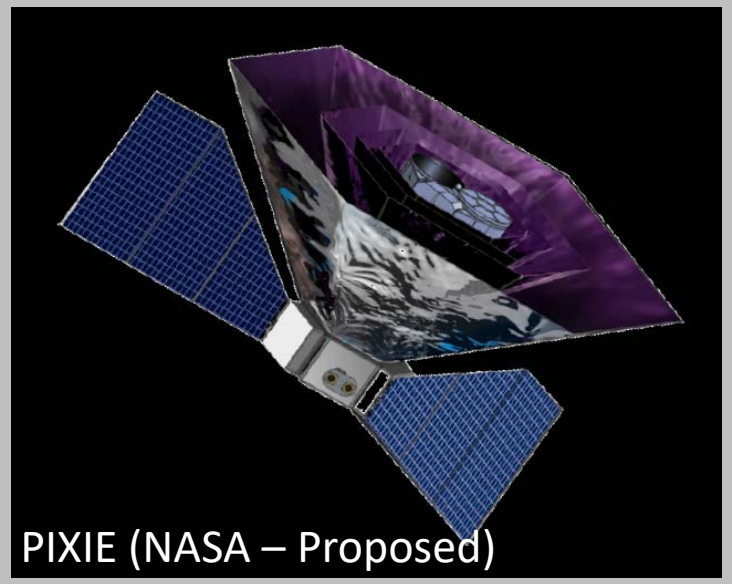
PIPER



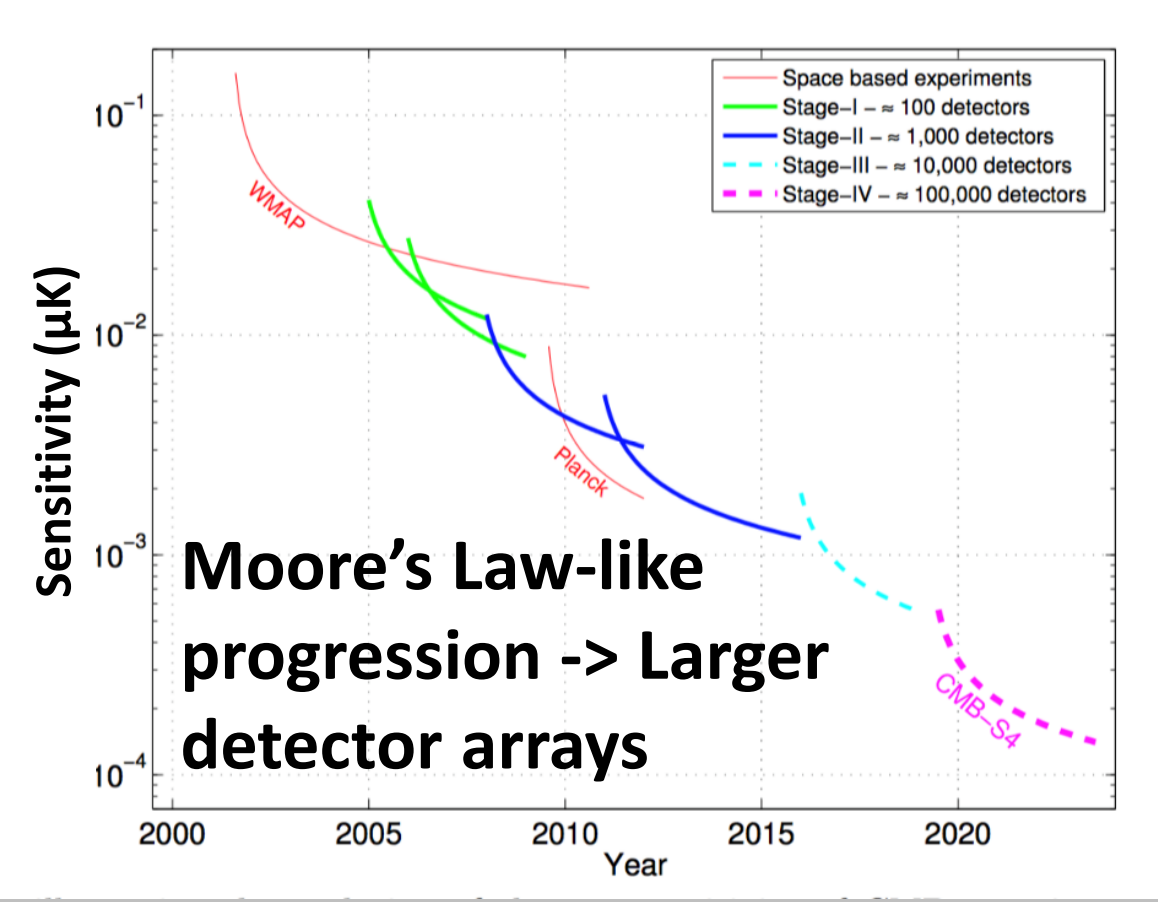


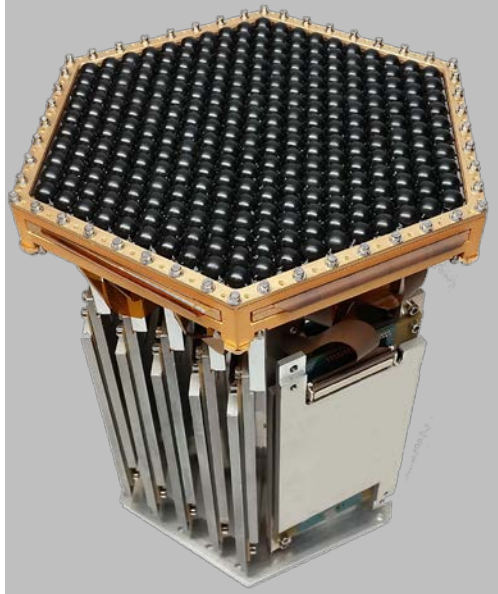
BFORE (Proposed)

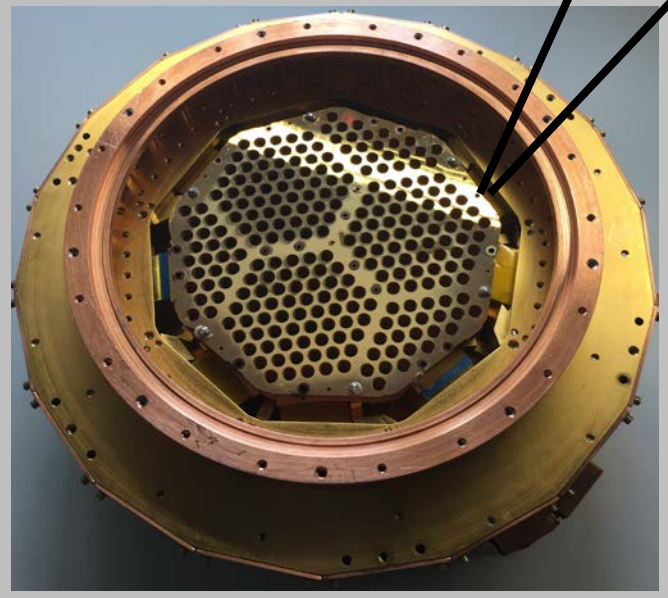




Challenges: It's All About the Detectors!







Arrays of 100's to 1000's of detectors are the state-of-the-art.

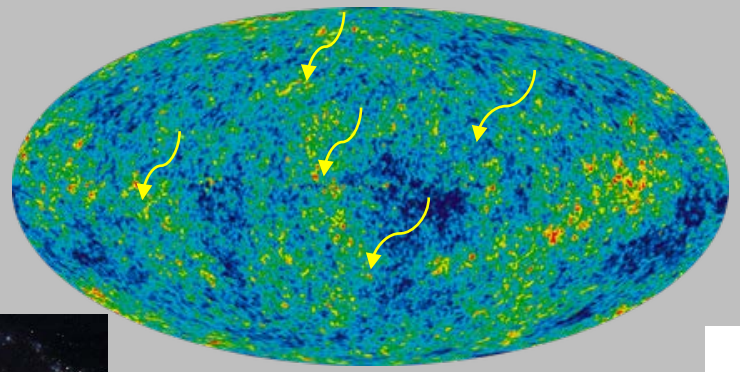
Current Experiments: ~20,000 Detectors.

CMB S4: ~500,000+ detectors

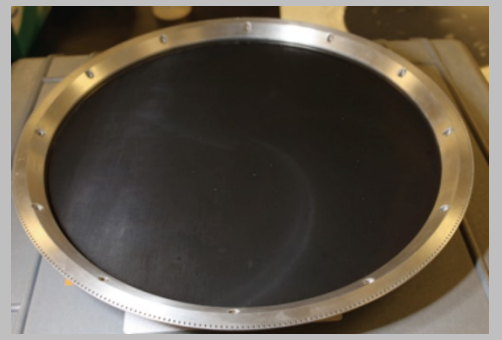
- **Typical sensitivity ~10^{-17} W-√s.**
- **Operate at 100 mK!**
- **The sensitivity is LIMITED by the photon noise.**

Challenges: Systematics and Foregrounds

- **Primary Temperature Anisotropy - ~120 μK RMS**
- **Primordial B-Mode - 30-90 nK RMS**
- **Systematics and Foreground emission can easily dominate the B-Mode signal.**

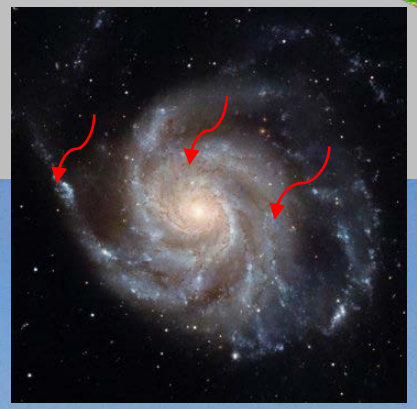


Meet the Challenge!



Rotating Half Wave Plates to modulate the polarization signal.

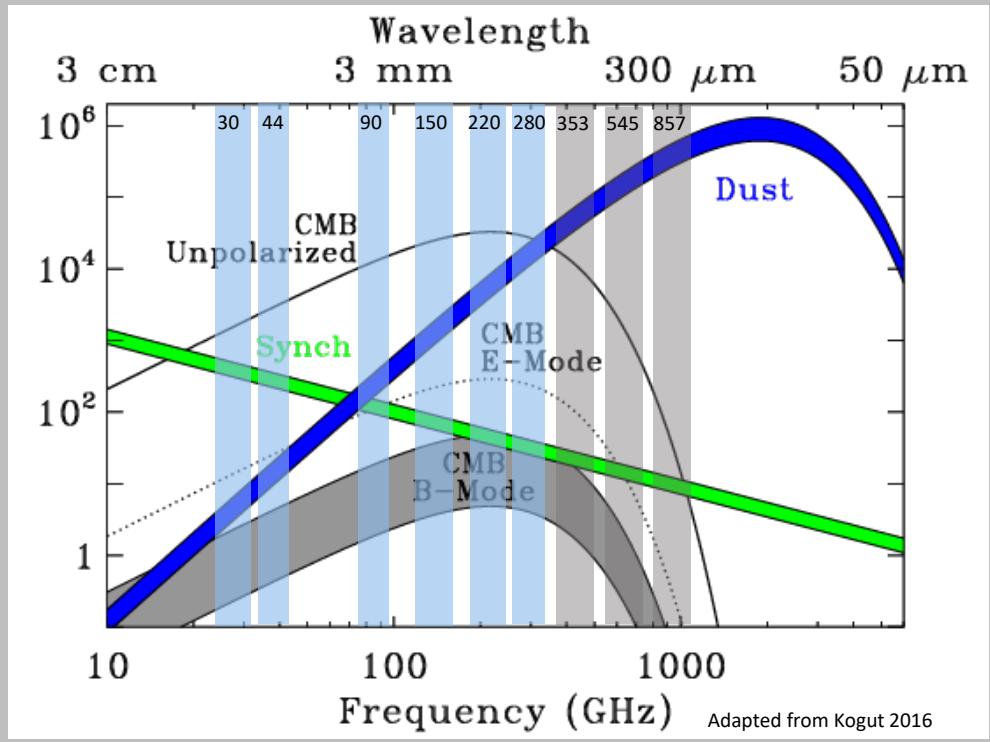
Galactic Dust



Ground and Sky Pickup!

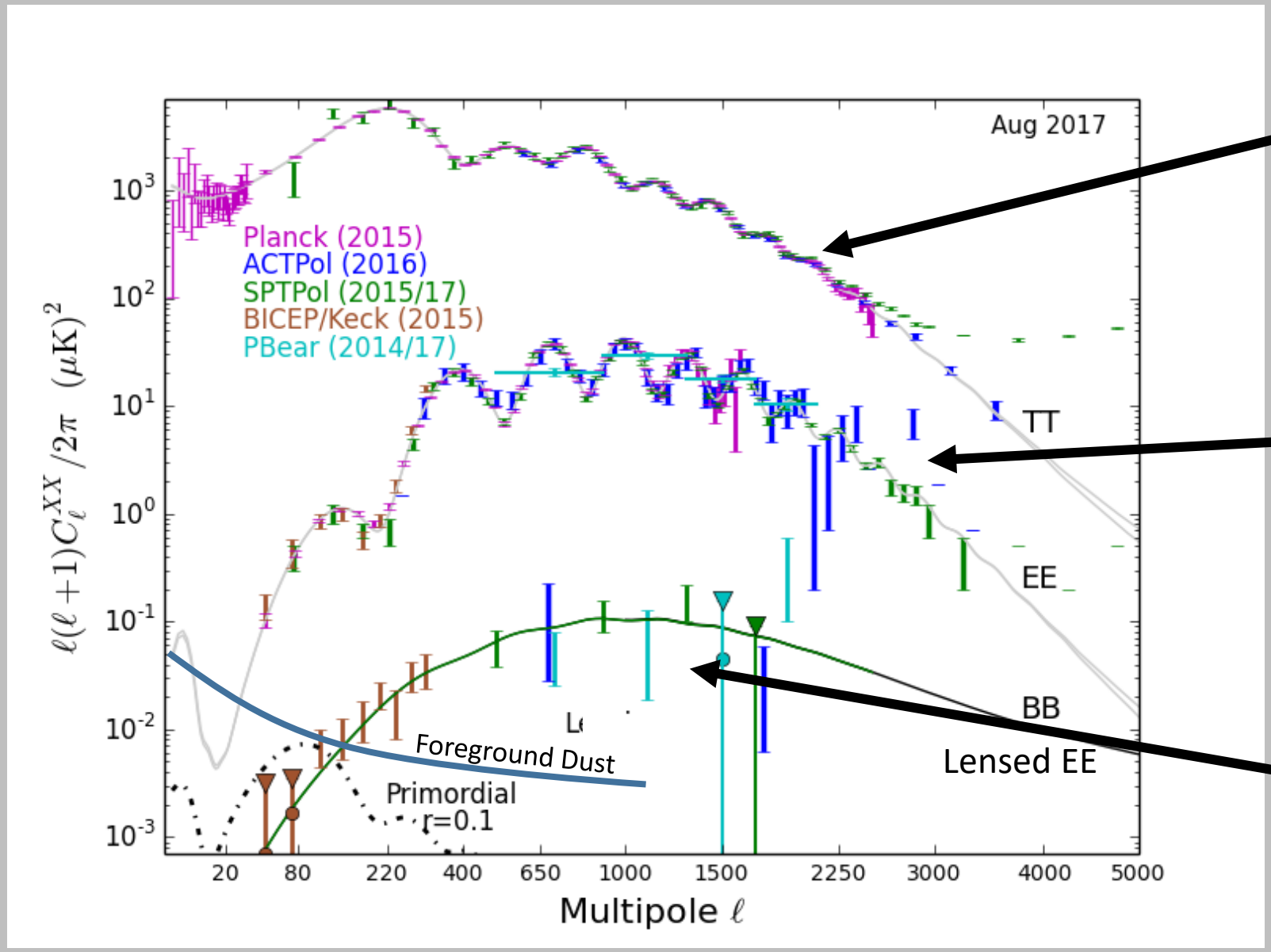
Careful optical design and baffling to minimize instrument and ground pickup.

Multiple Frequency Bands to Measure and Remove Foregrounds



Adapted from Kogut 2016

Current State of the Field



Nailed the Temperature Spectrum!

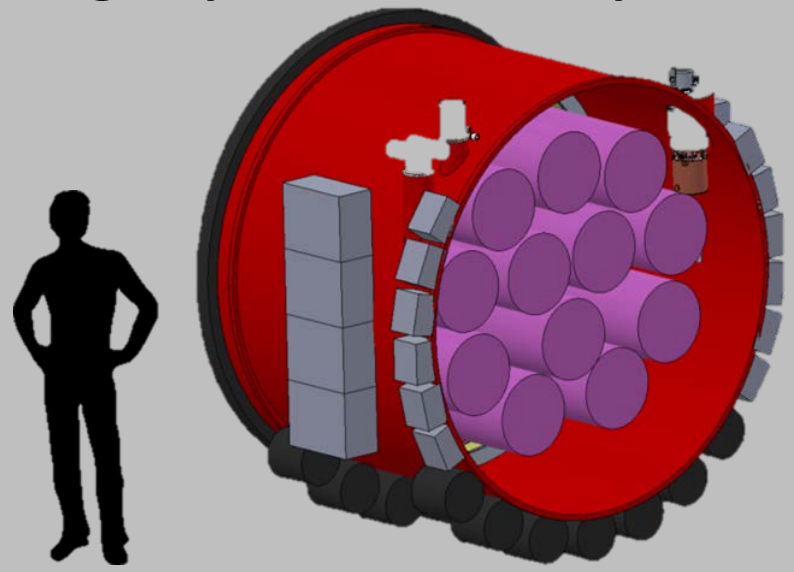
The E-mode Spectrum is predicted from Thomson Scattering. Distortions in this tell us about the evolution of structure.

The B-mode spectrum comes from Lensed E-modes (detected!) AND from Primordial Tensors (r<0.06).

Where do we go from here?

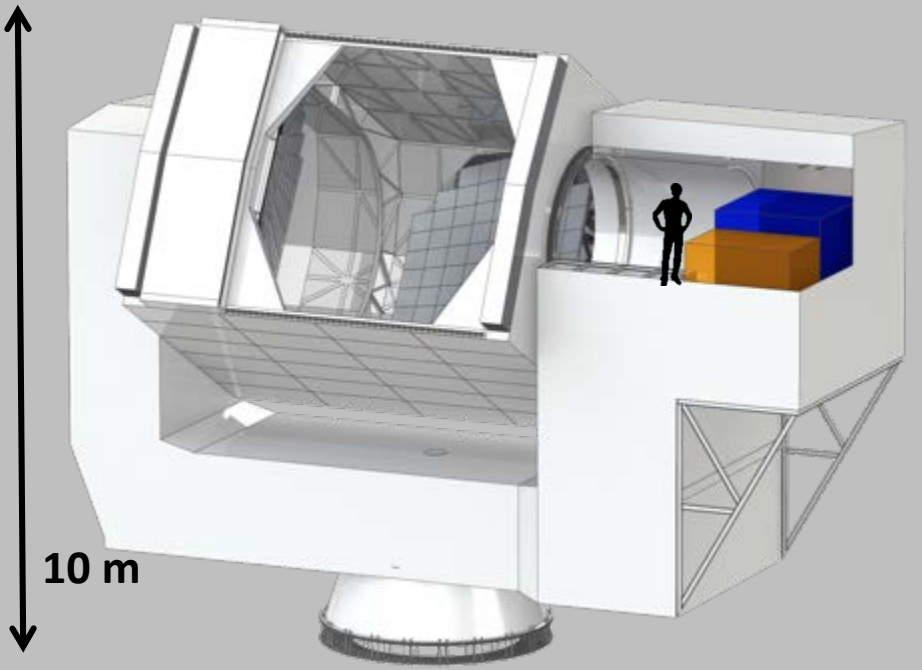
Simons Observatory

Large Aperture Telescope Camera



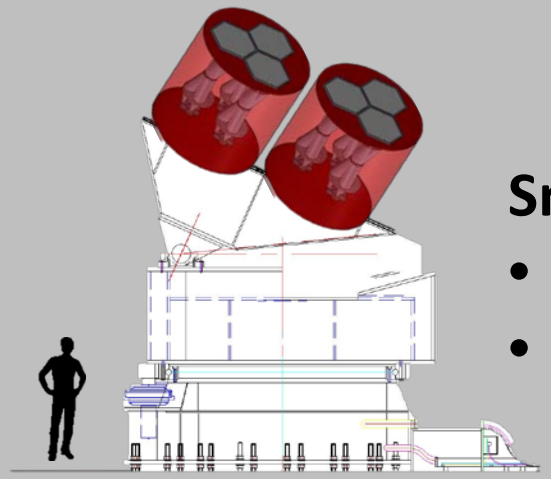
Up to 80,0000 Detectors

$40M grant from the Simons Foundation and the Heising-Simons Foundation.



6 meter diameter Cross-Dragone Telescope

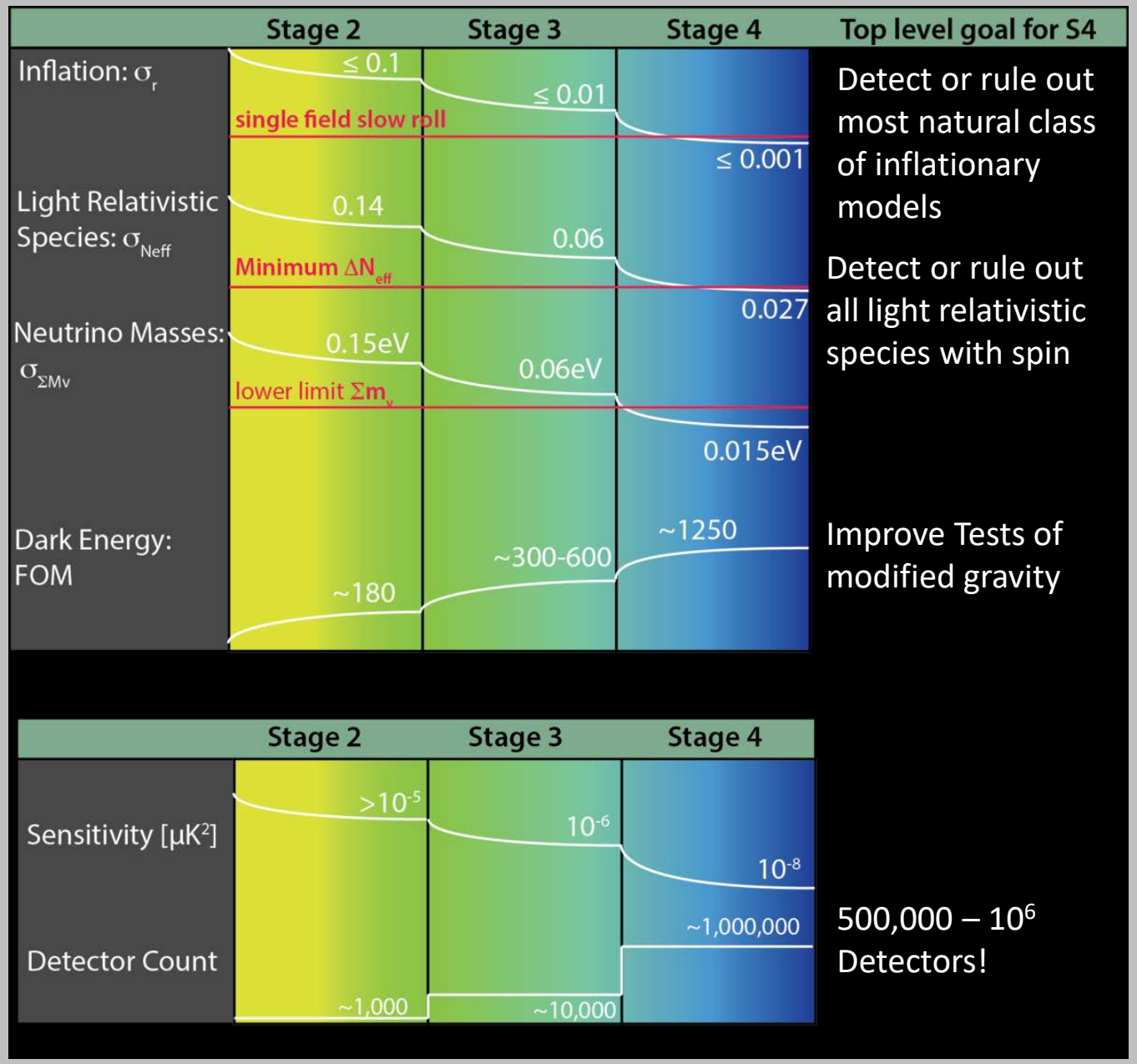
~1.7 arcminute resolution at 150 GHz



Small Aperture Cameras

- **30-50 cm apertures**
- **~ 1 degree resolution.**

Early 2021 Commissioning!



McMahon

CMB-S4

Next Generation CMB Experiment

A next generation ground-based program to pursue inflation, neutrino properties, dark radiation, dark energy and new discoveries.

Greater than tenfold increase in sensitivity of the combined Stage 3 experiments (>100x current Stage 2) to cross critical science thresholds.

Broad CMB community participation.

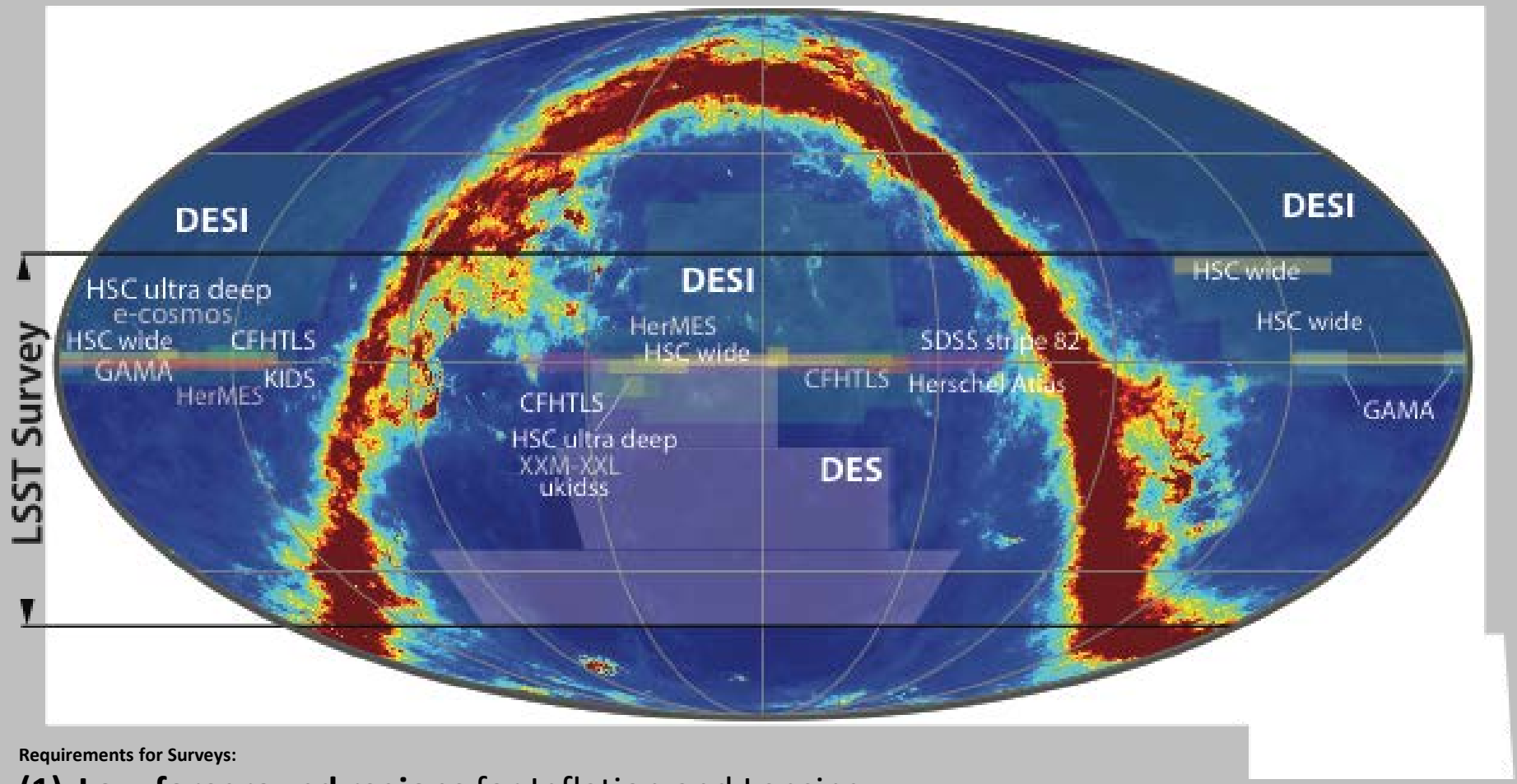
Check out the CMB-S4 Science Book or the CMB-S4 wiki: https://cmb-s4.org/ for many more + new details!

Stay Tuned!

CMB S4 Meeting at SLAC – February 2017

Comparison of CMB Sites

Foreground + optical survey coverage map



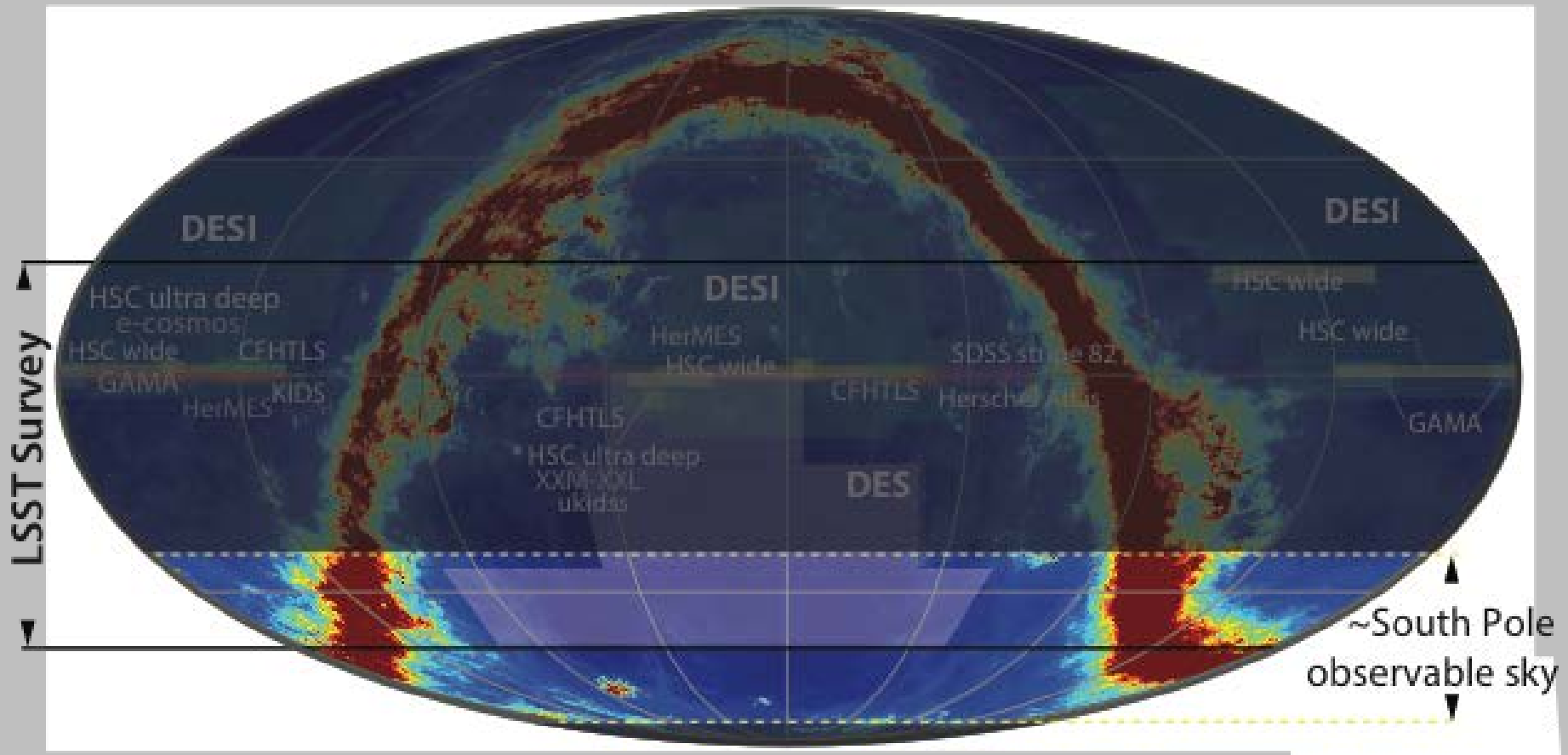
Requirements for Surveys:

(1) Low foreground regions for Inflation and Lensing

(2) Overlap with optical surveys to maximize impact of LSS measurements for neutrinos, dark energy, dark matter, and astrophysics.

Comparison of CMB Sites

Foreground + optical survey coverage map



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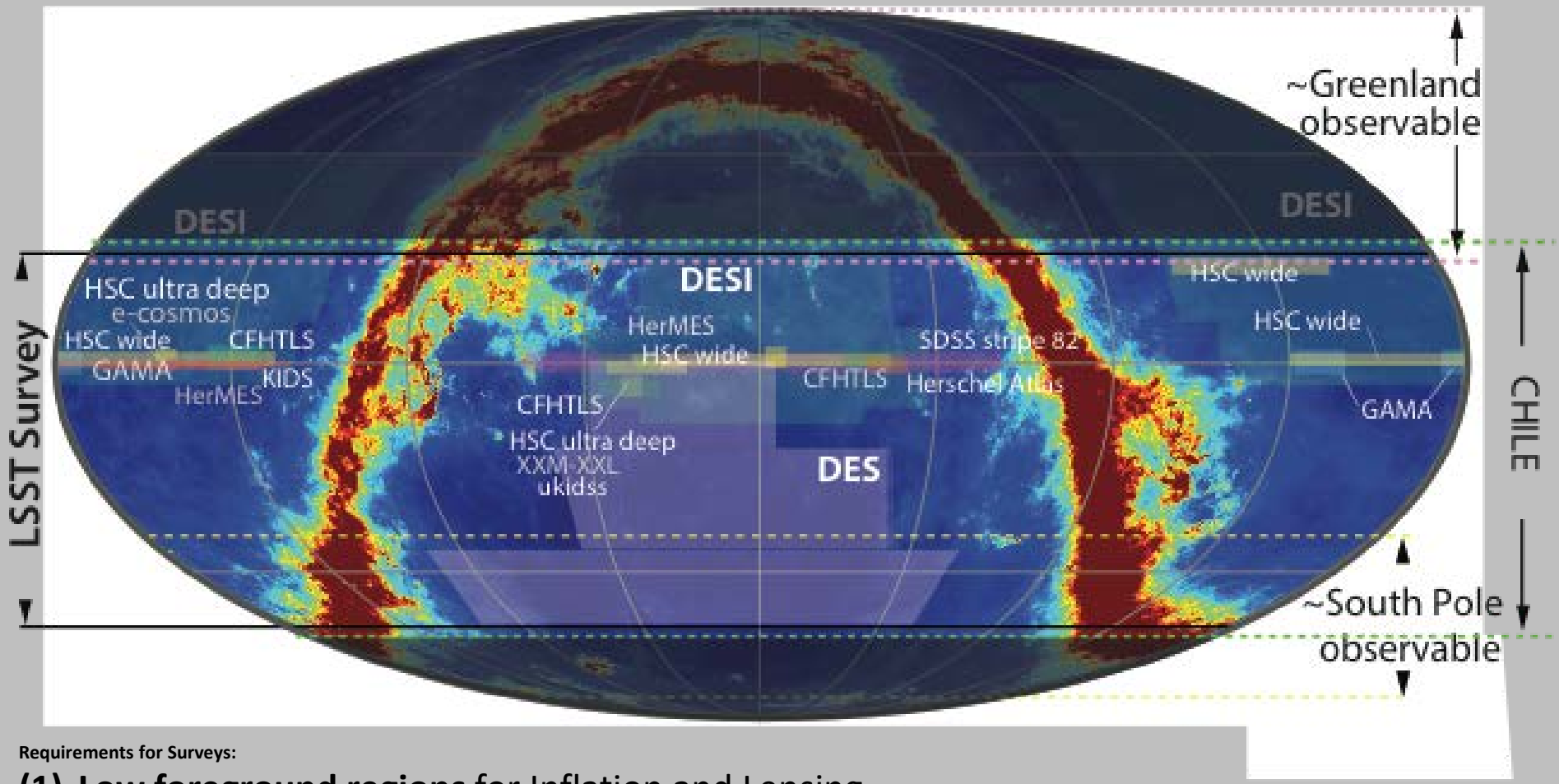

Requirements for Surveys:

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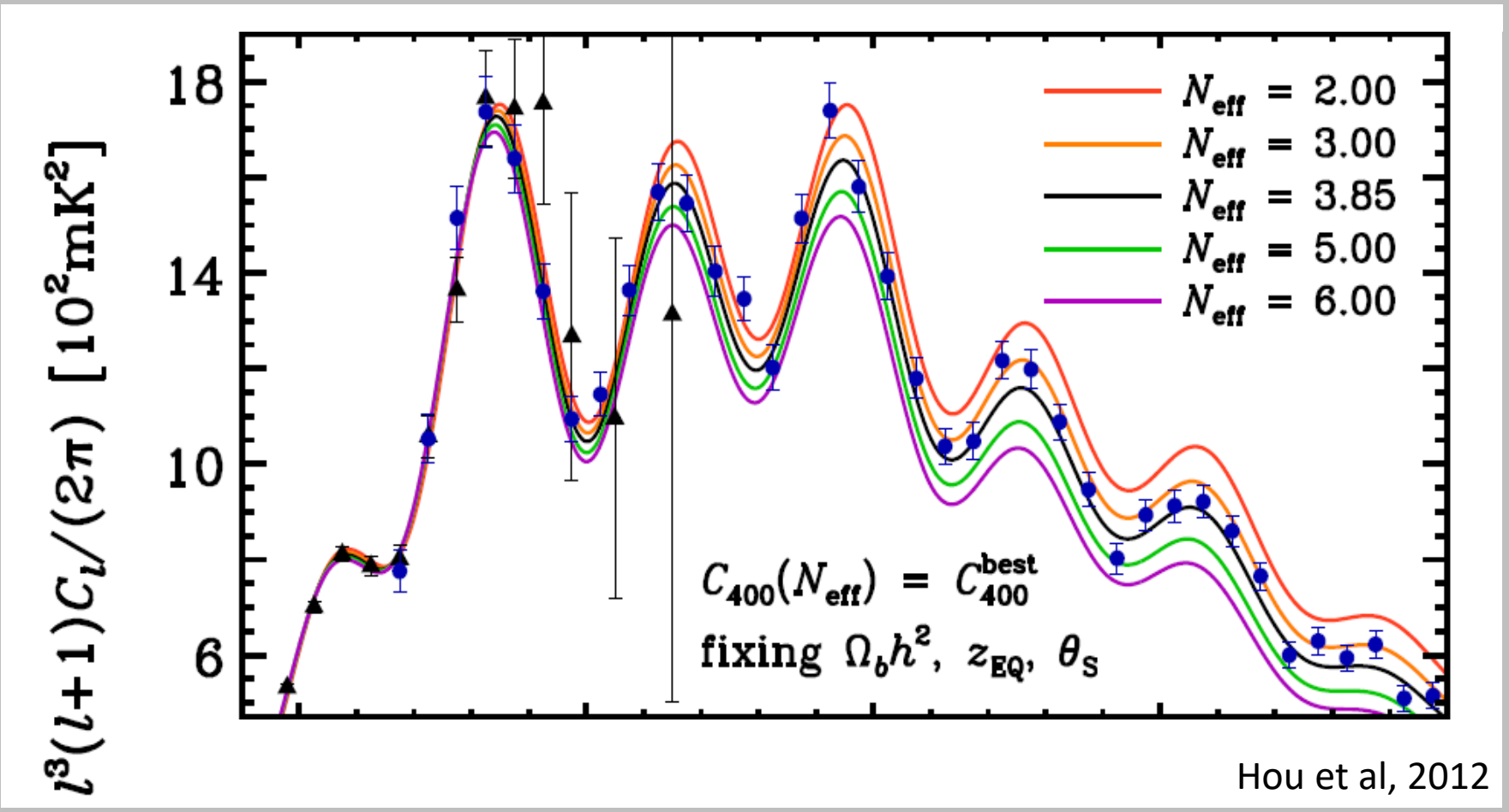
N_{eff} Probed With the Power Spectrum



Hou et al, 2012

N_{eff} affects the expansion rate during the radiation dominated era.

The sound horizon is shifted and the damping is increased.

More neutrinos → higher density → faster expansion