The Cosmic Microwave Background:
The Path to a Stage 4 CMB Experiment

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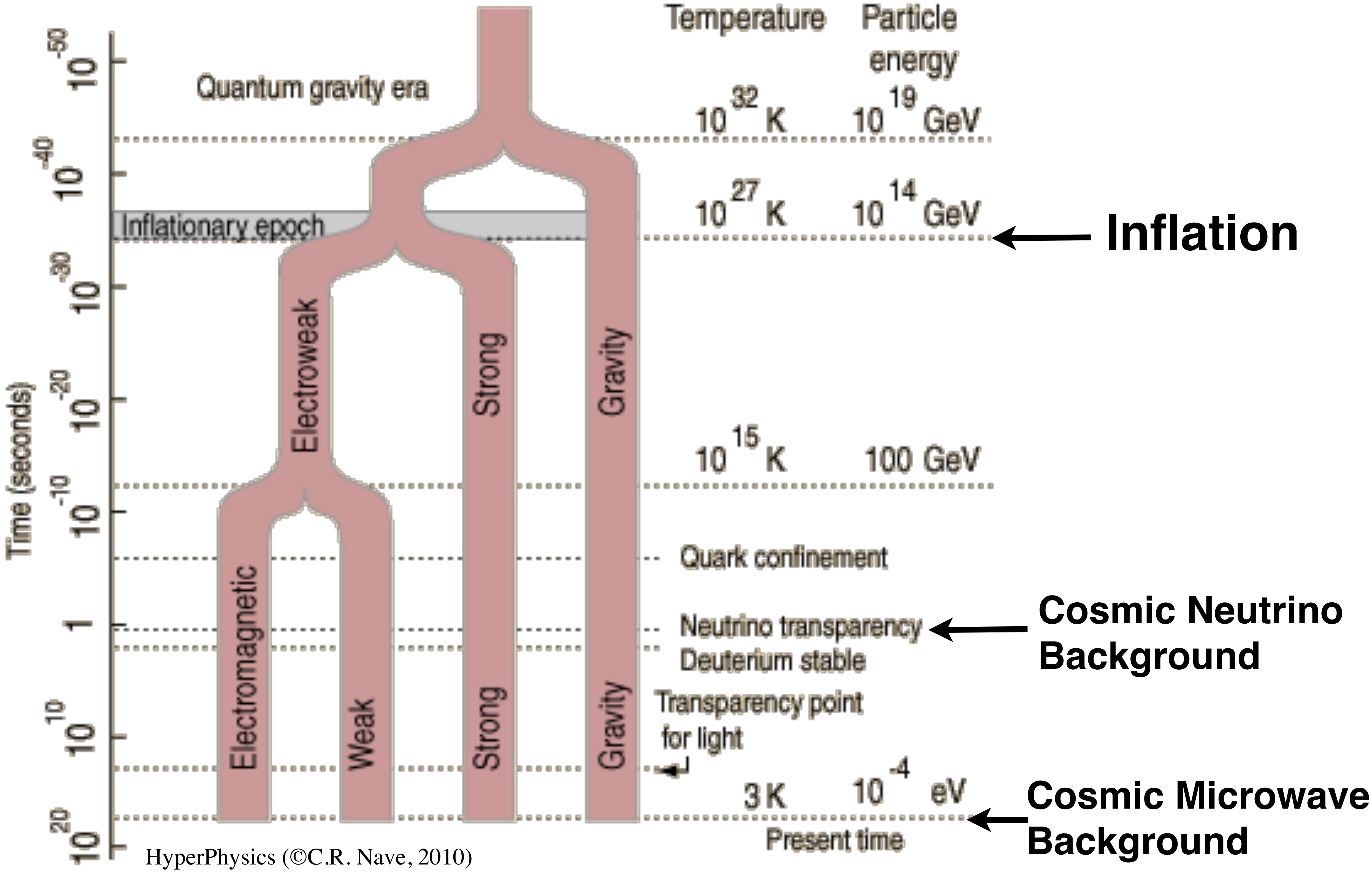
12-June-2014

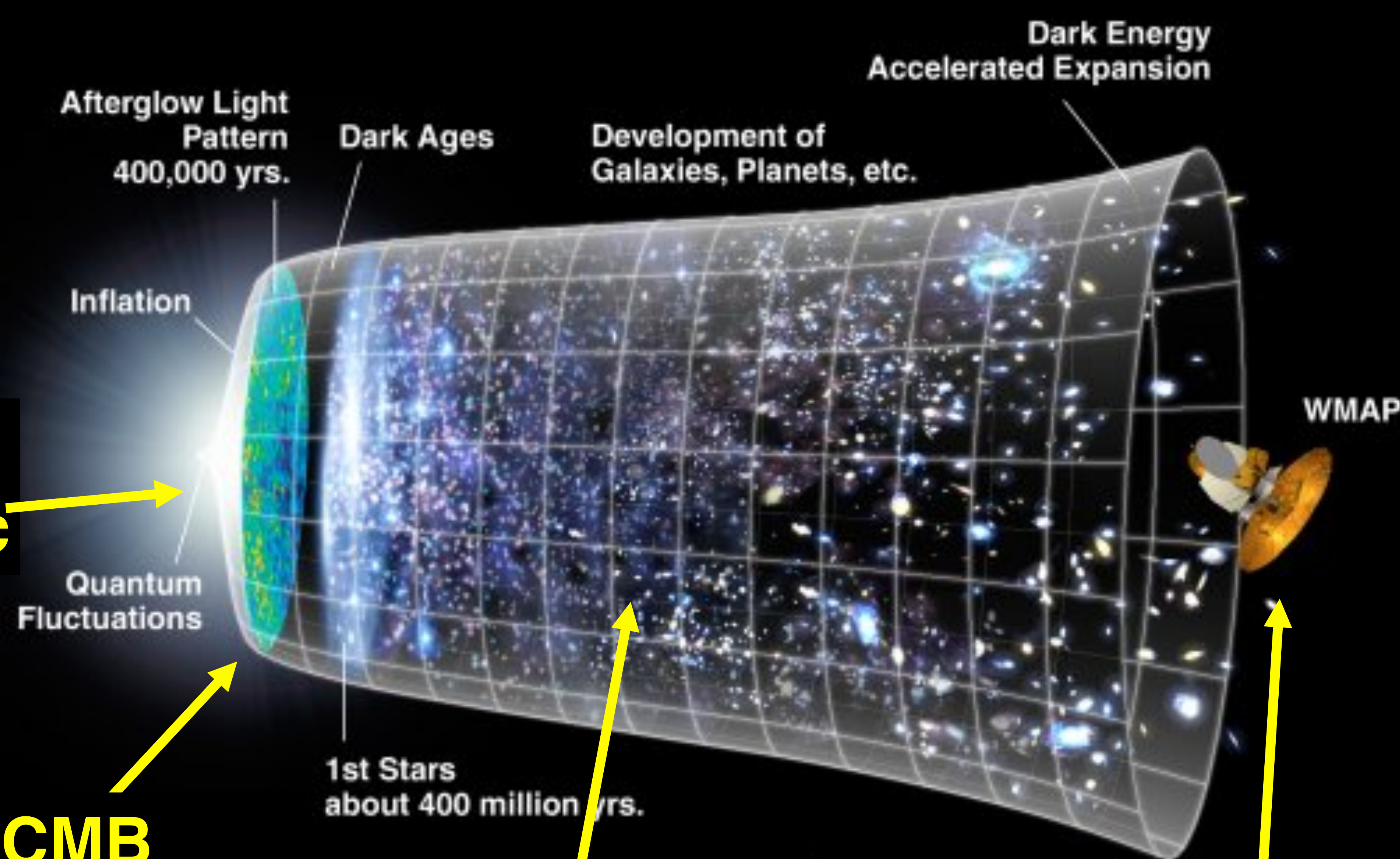
The Early Universe as a High-Energy Physics Lab



HyperPhysics (©C.R. Nave, 2010)

The Standard Cosmological Model

(time since Big Bang)



Inflation
10^{-34} sec

The CMB
400,000 years

First clusters of galaxies
~4 billion years

Today
14 billion years

graphic from NASA/WMAP

Three Tests of Fundamental Physics

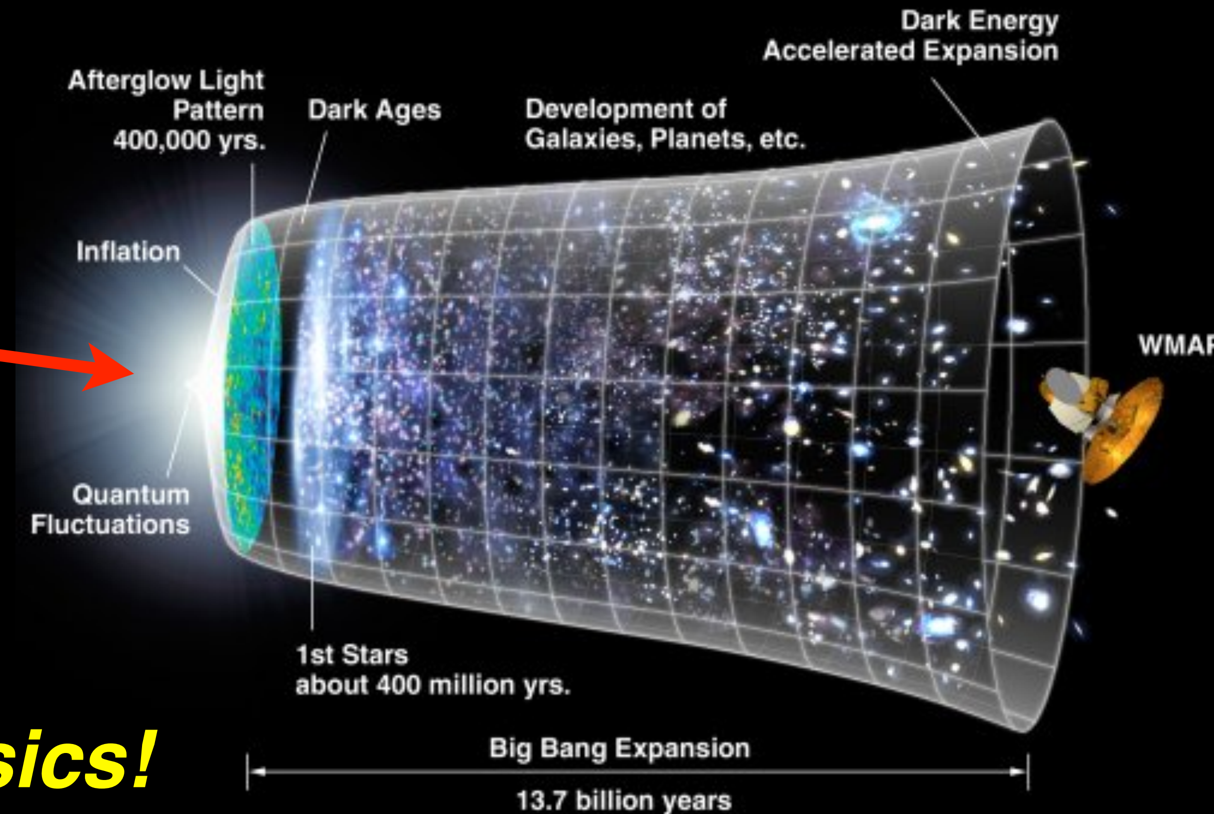
1) Inflation

Universe expands by $>e^{60}$ solving smoothness problem, flatness and more..

Did inflation happen?

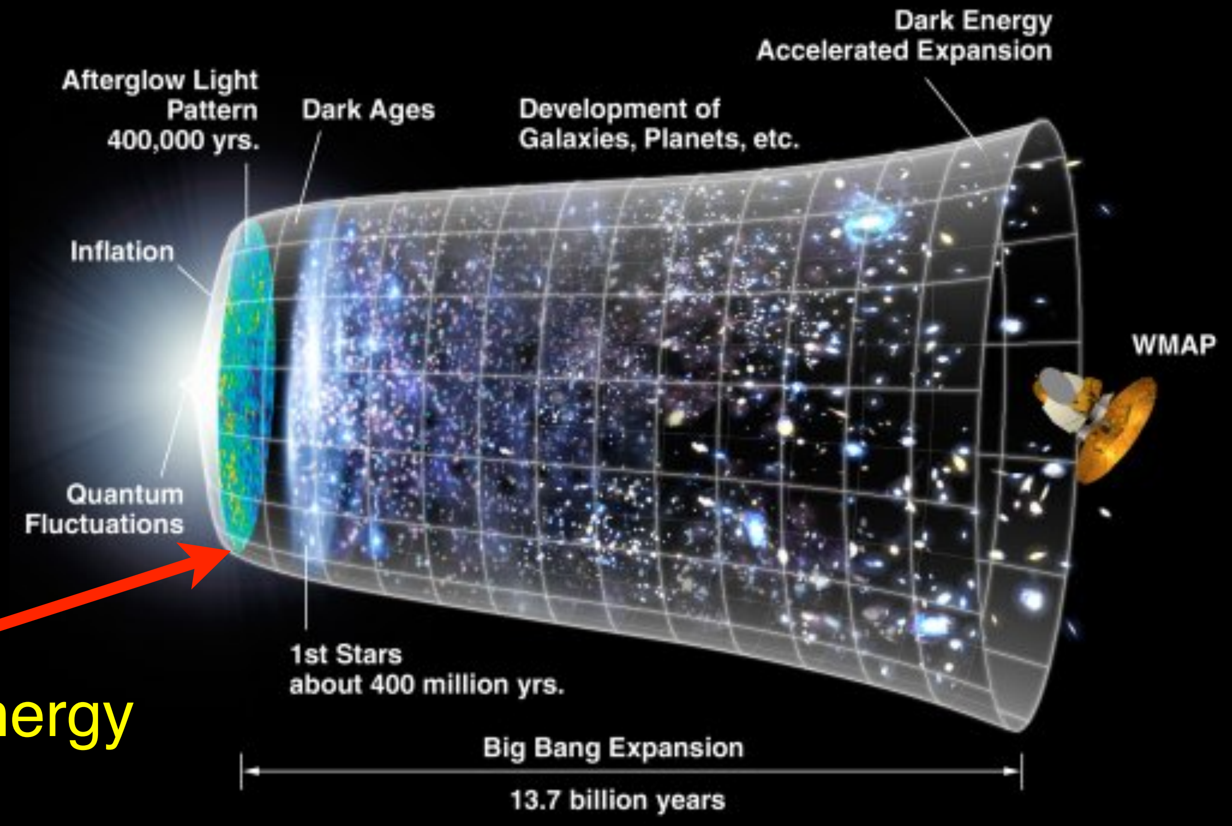
What physics drove inflation?

-*Unique probe of ~10^{16} GeV physics!*



graphic from NASA/WMAP

Three Tests of Fundamental Physics



2) “Dark” Radiation

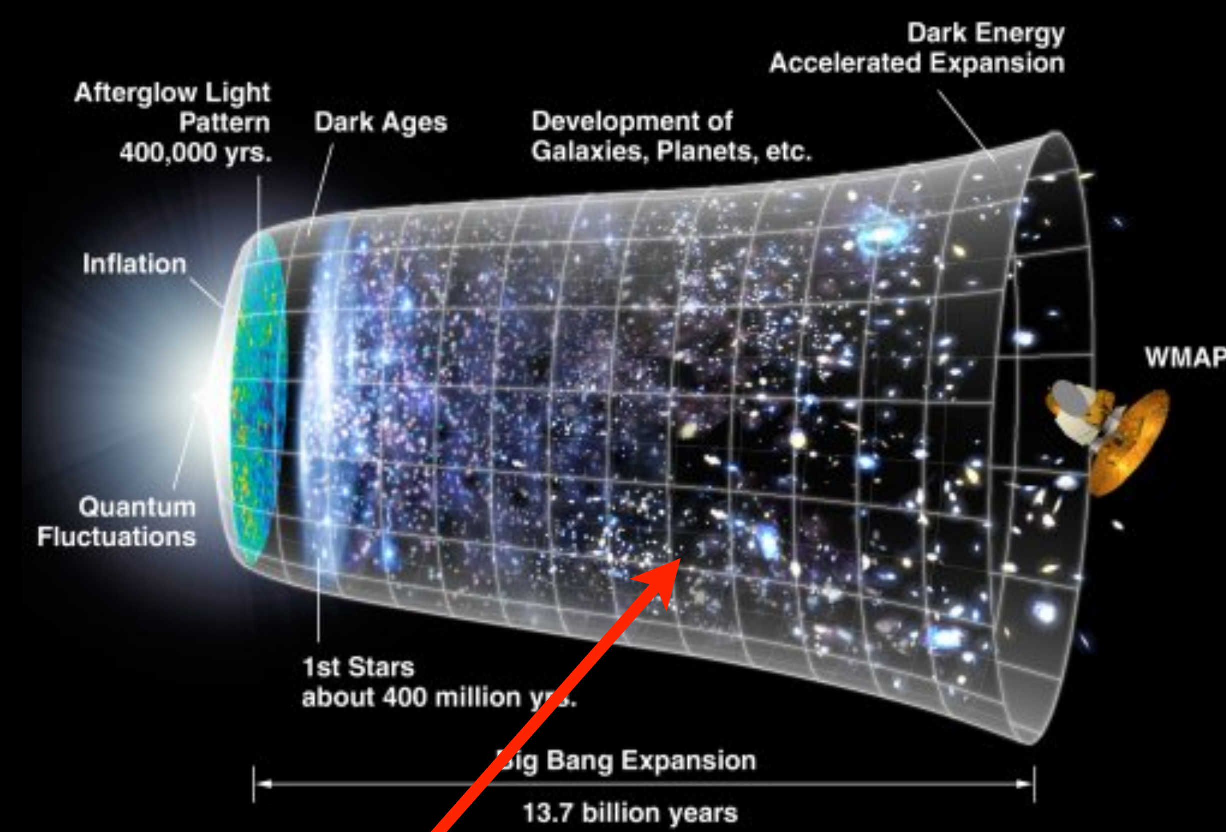
Precise measurement of the relativistic energy density of the Universe

Is it just neutrinos?

Is there any “Dark” Radiation, from unknown relativistic particles (e.g., sterile neutrinos)

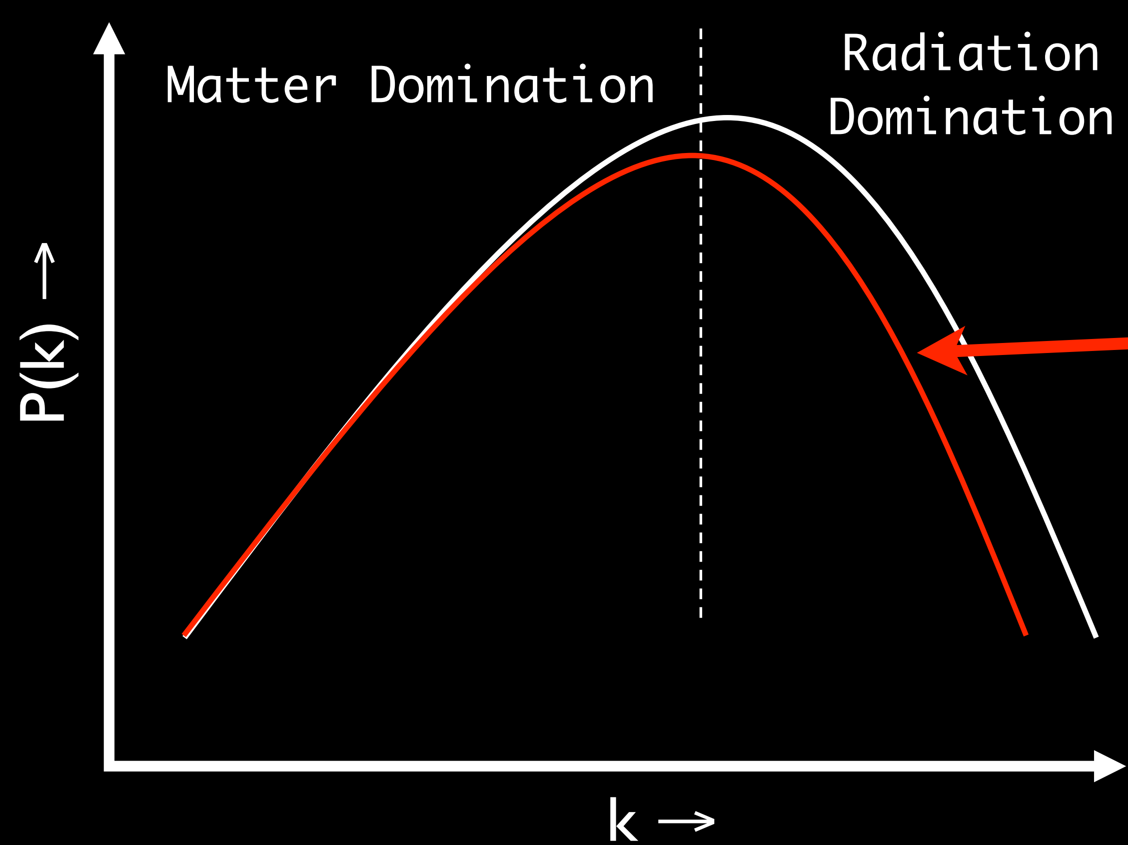
graphic from NASA/WMAP

Three Tests of Fundamental Physics



3) Neutrino Mass

Cosmologically detect the sum of the neutrino masses.



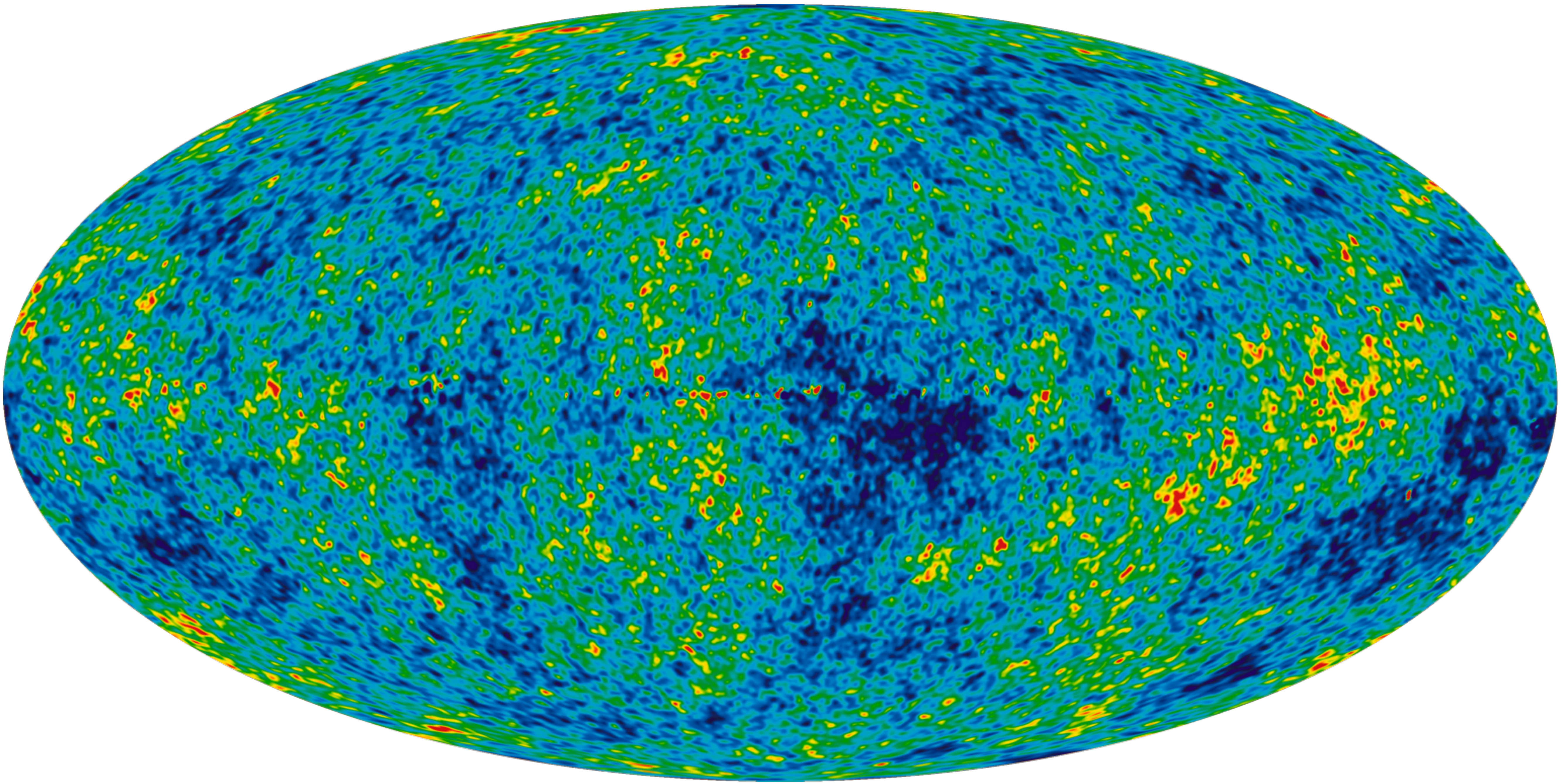
$\Sigma m_\nu > 0$

Sum of the neutrino masses impacts growth of large scale structure, i.e., the matter power spectrum

graphic from NASA/WMAP

2001-2010: WMAP

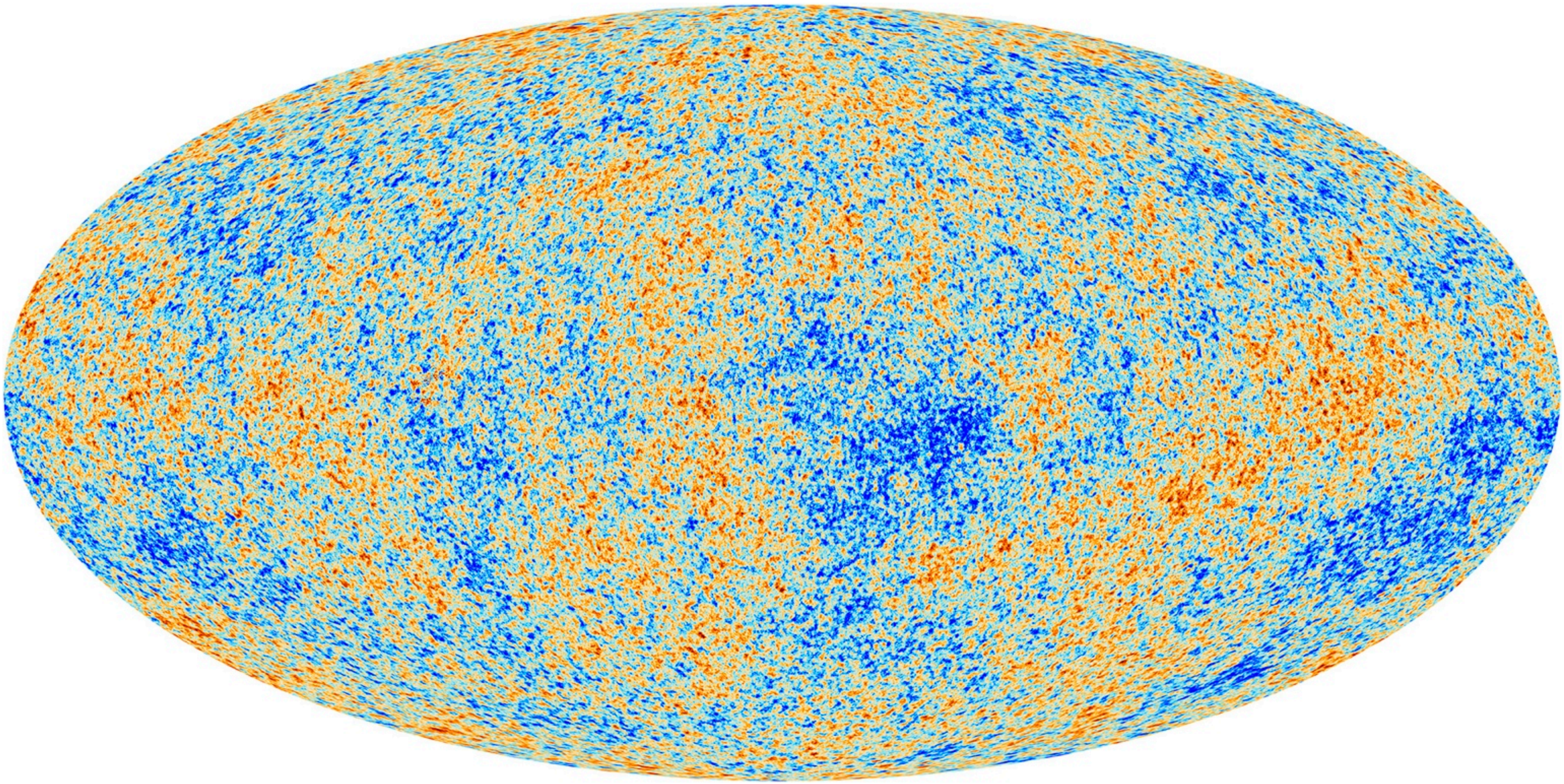
30μK RMS fluctuations on 3 K background



Credit: NASA (WMAP)

2013: Planck

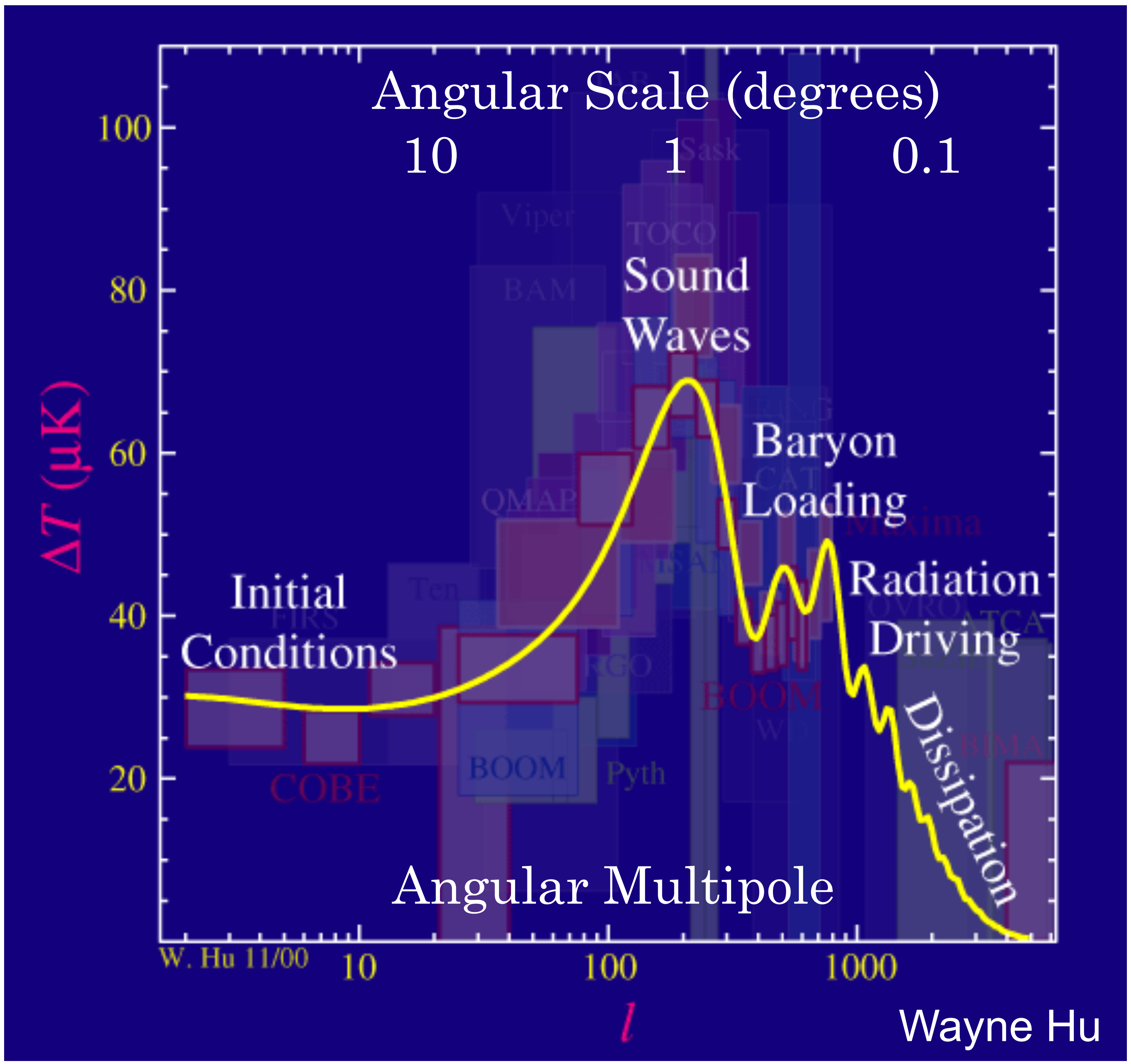
30μK RMS fluctuations on 3 K background

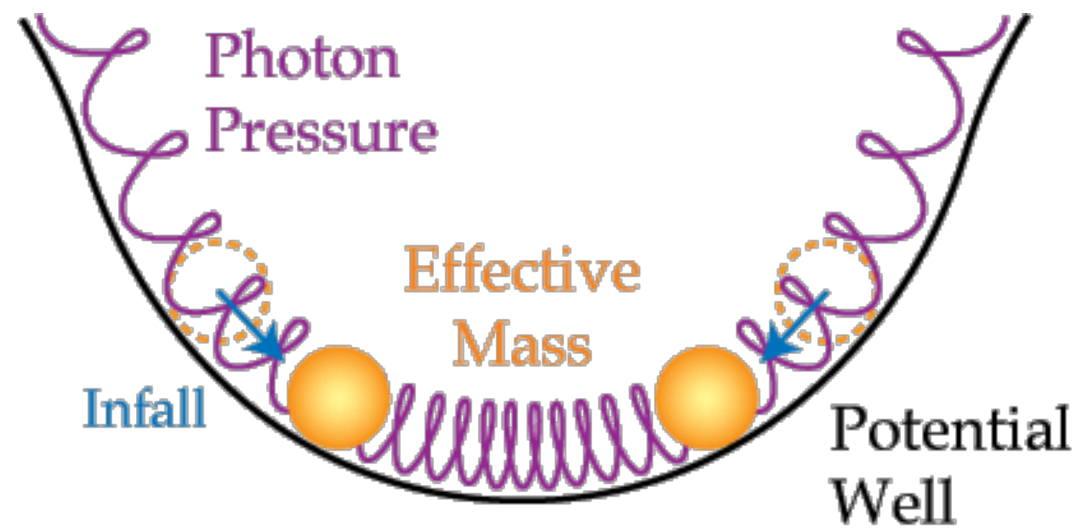


Credit: ESA (Planck)

The CMB Power Spectrum

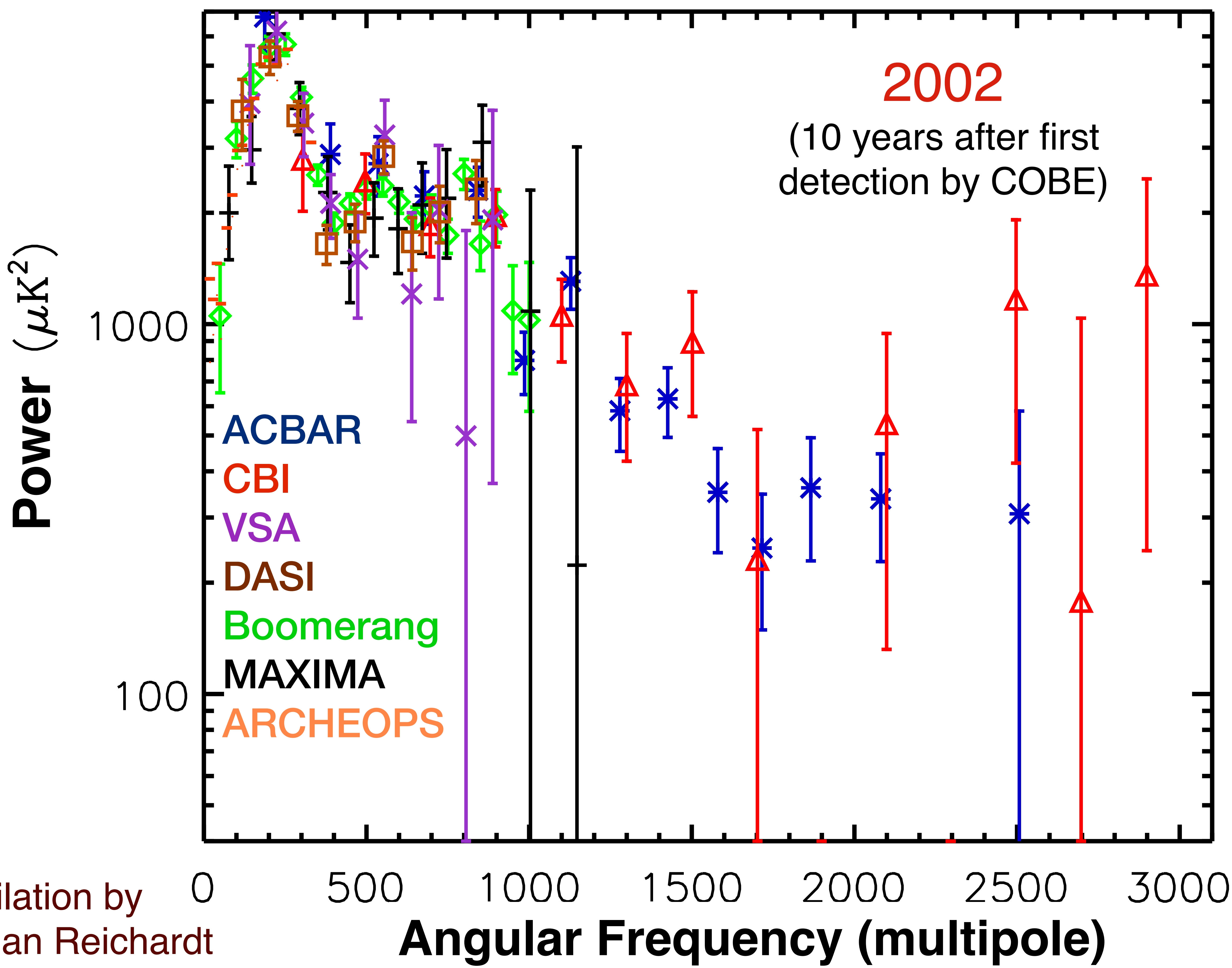
Encoded within the primordial CMB power spectrum is information regarding the Universe's **initial conditions**, its **geometry** (flat vs curved), and its **content** (baryons, dark matter)





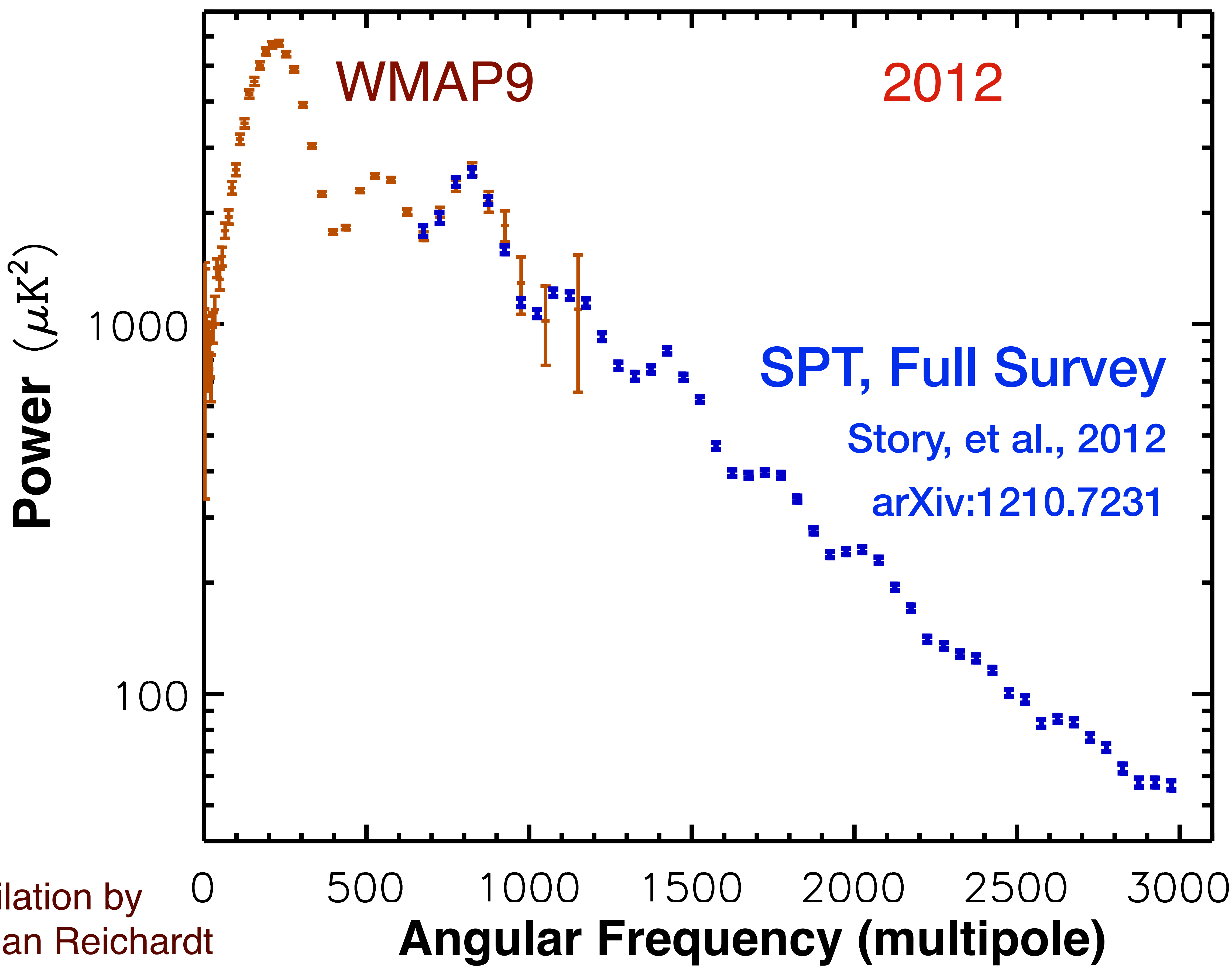
Peaks in power spectrum generated by acoustic oscillations in ~3000 K plasma

Evolution of CMB Power Spectrum Measurements



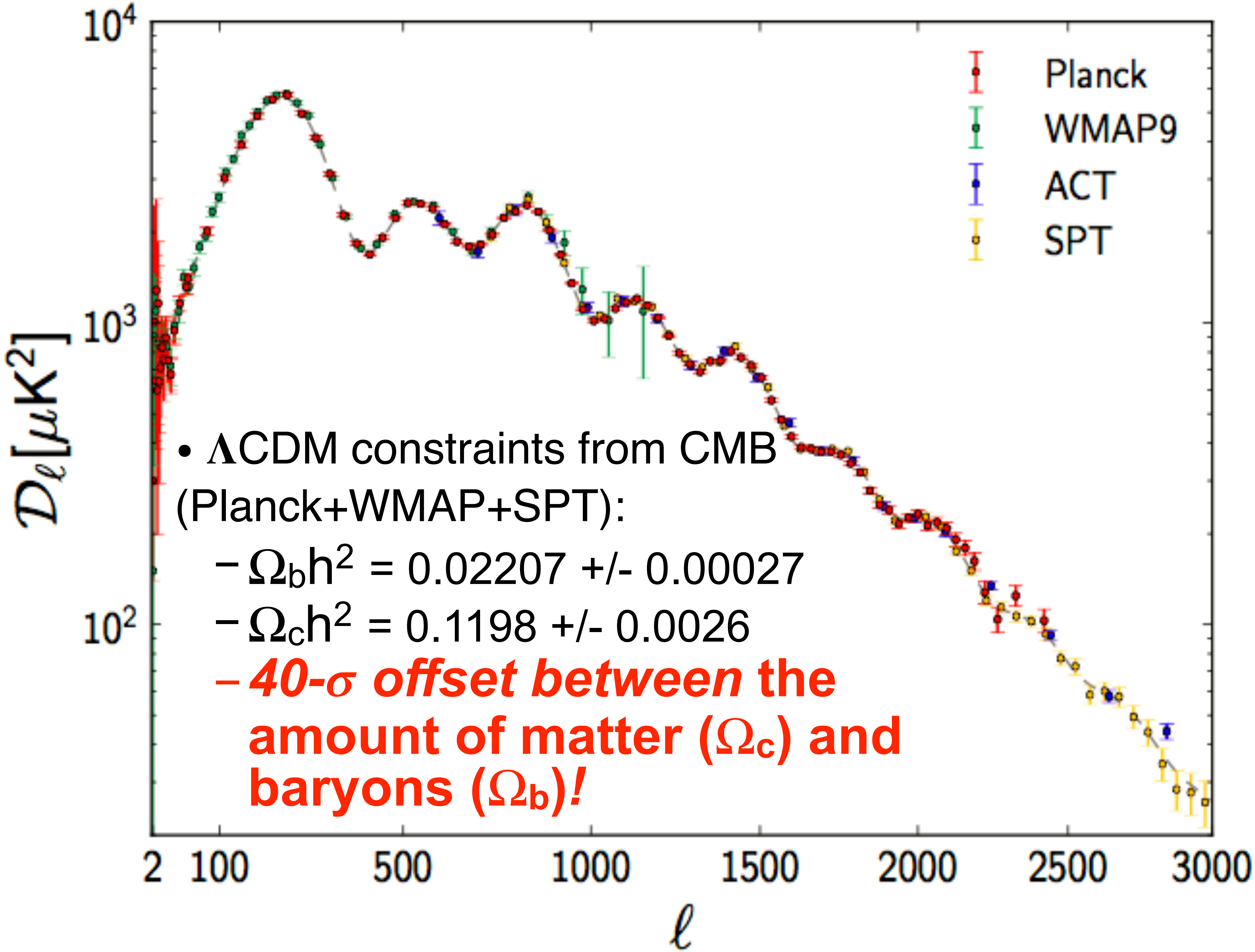
Compilation by Christian Reichardt

Evolution of CMB Power Spectrum Measurements



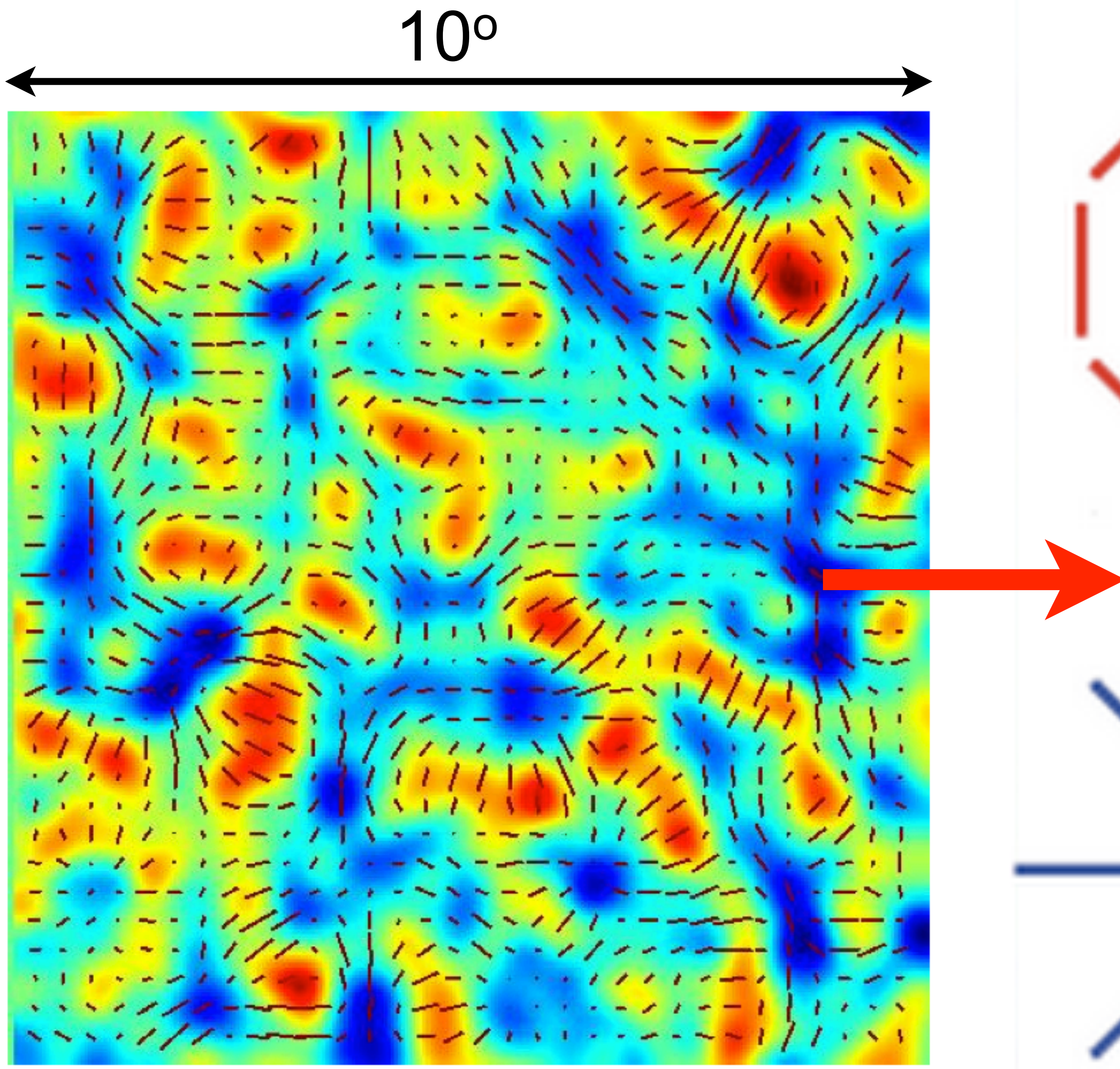
Compilation by
Christian Reichardt

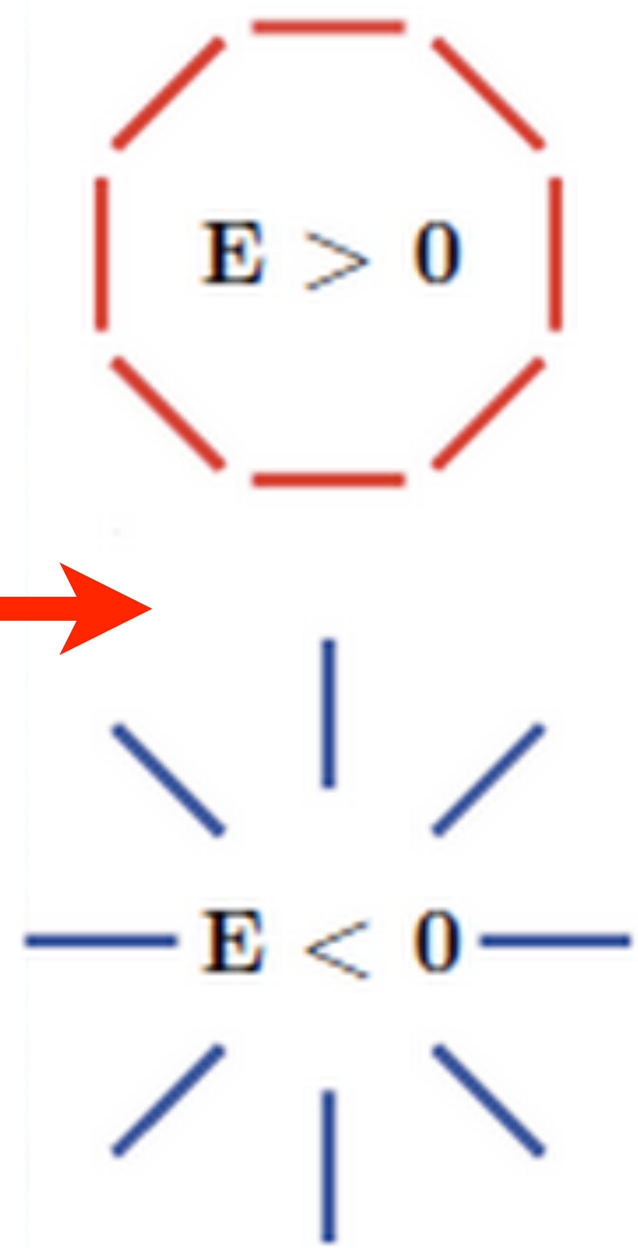
Today: Outstanding agreement between CMB power spectrum measurements



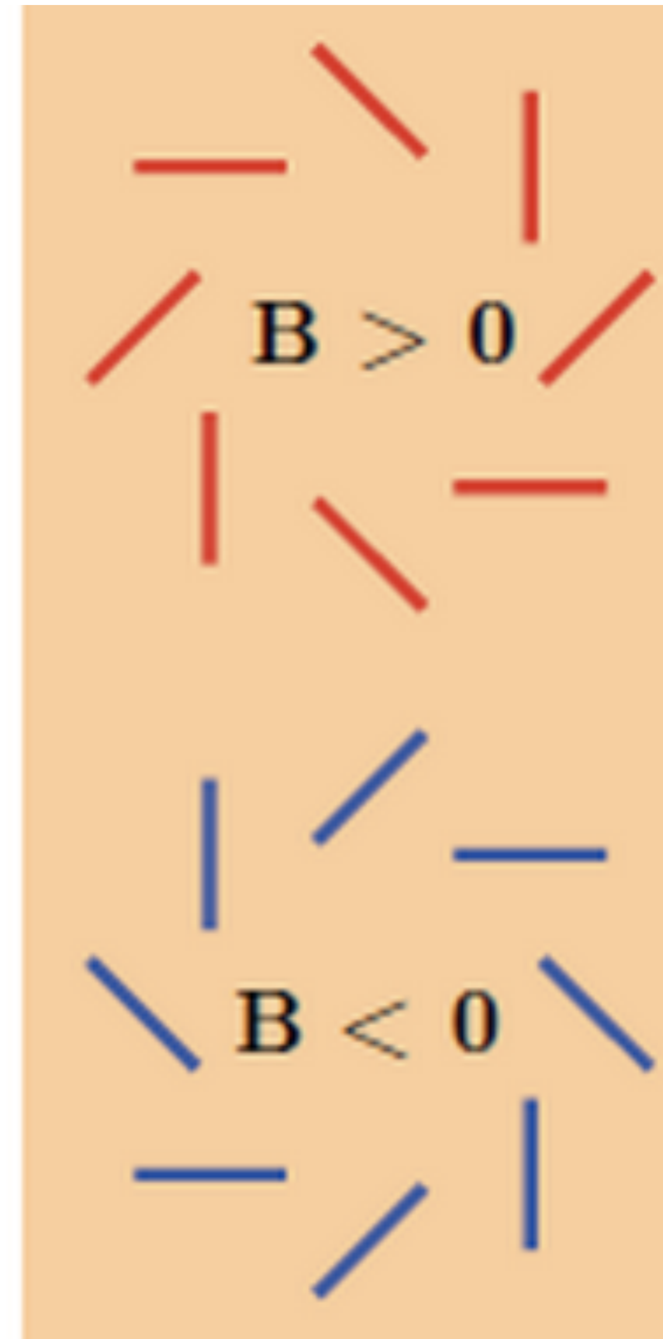
- ΛCDM constraints from CMB (Planck+WMAP+SPT):
  - $\Omega_b h^2$ = 0.02207 +/- 0.00027
  - $\Omega_c h^2$ = 0.1198 +/- 0.0026
  - ***40-σ offset between*** **the amount of matter (Ω_c) and baryons (Ω_b)*!***

The Next Frontier for the CMB:
CMB Polarization



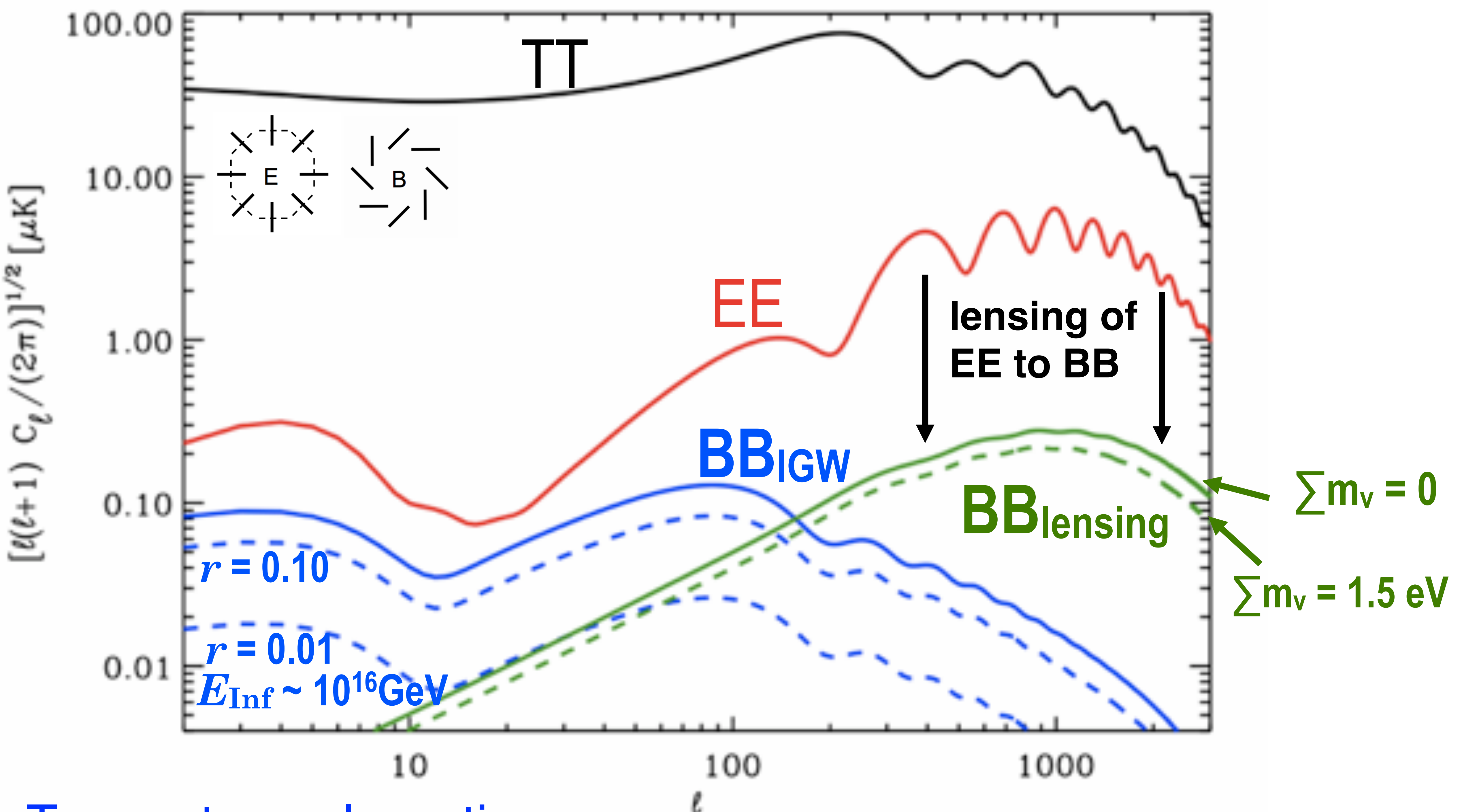


E-modes:
Even Parity



B-modes:
Odd Parity

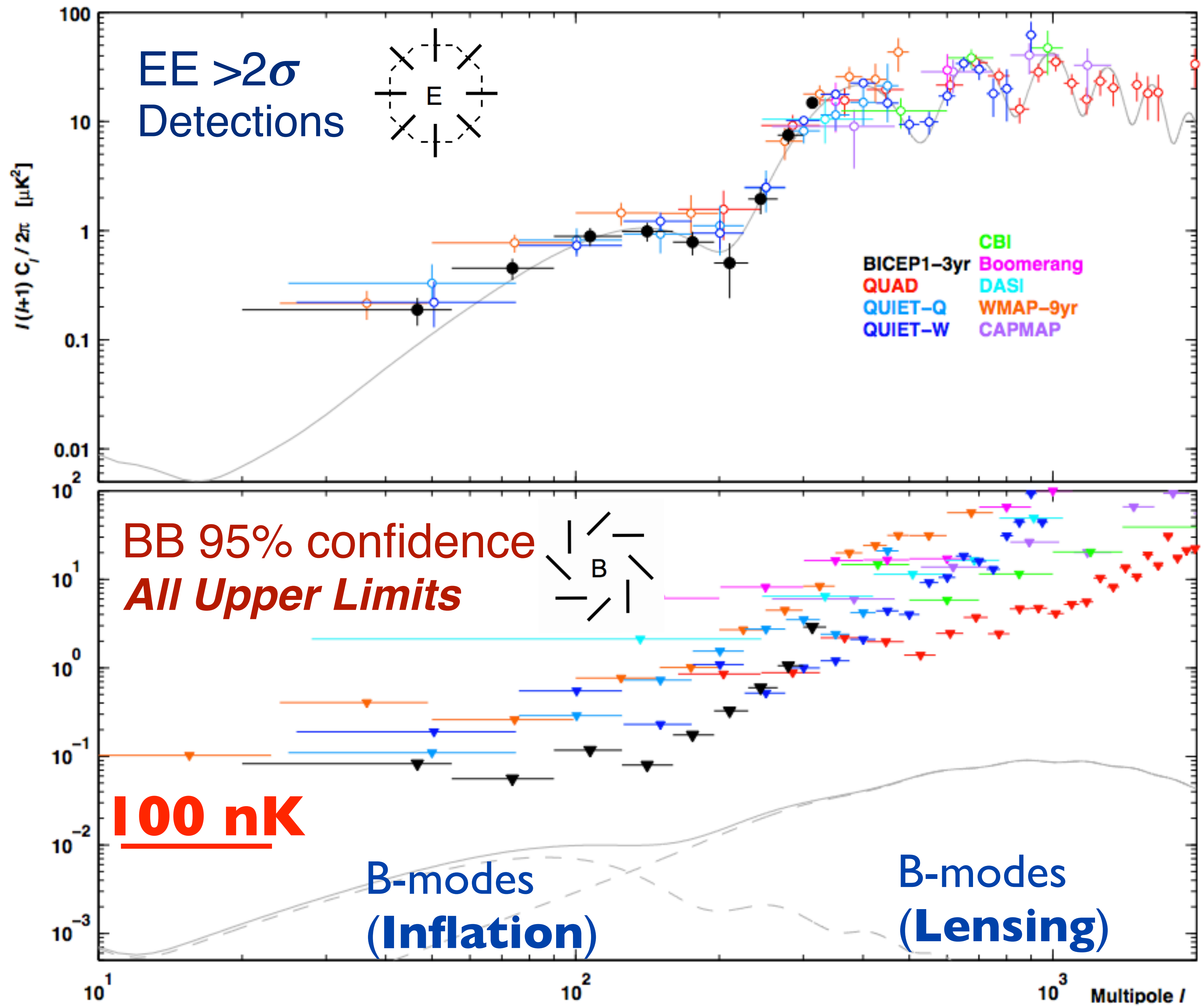
CMB Polarization contains information on Inflation and Neutrinos



r == Tensor-to-scalar ratio

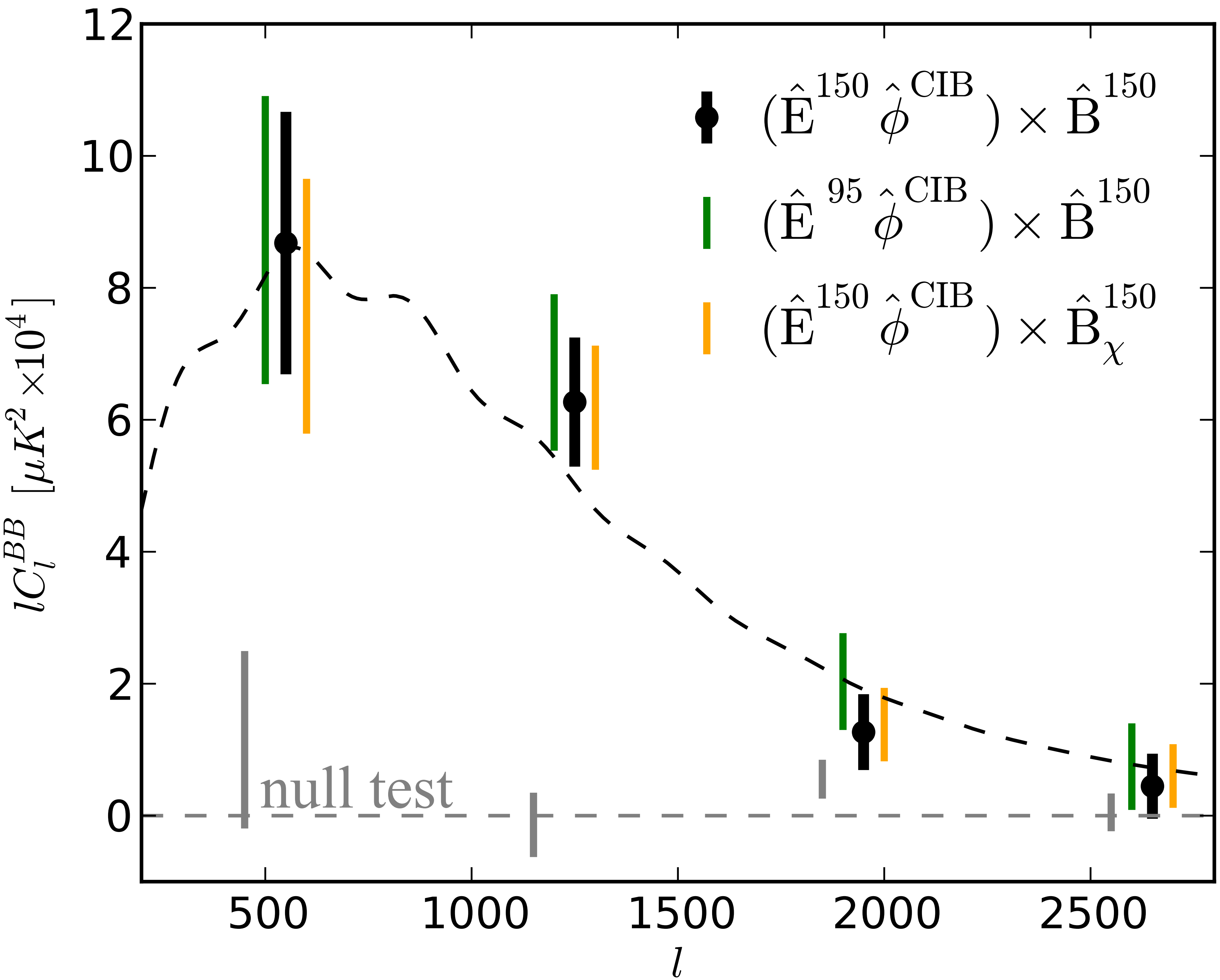
$E_{\rm Inf}$ == Energy scale of Inflation

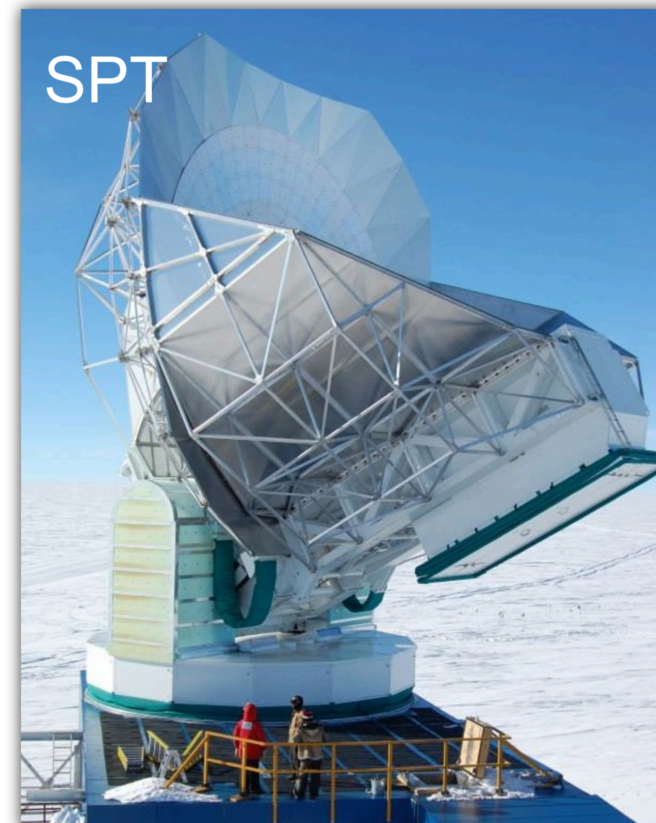
mid-2013: CMB Polarization Measurements

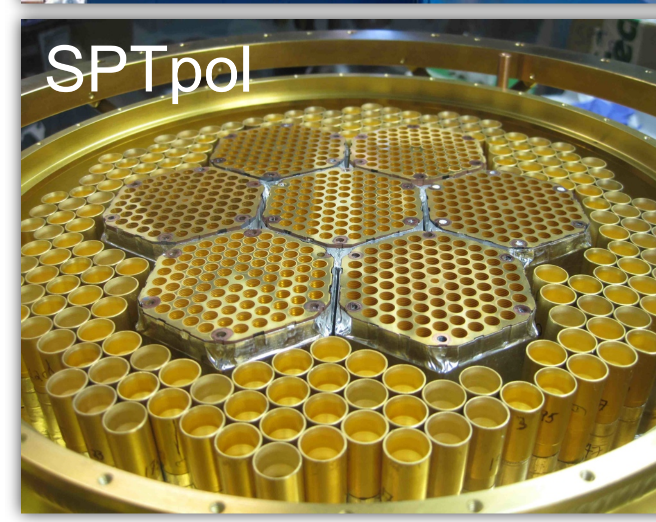


BICEP (Barkats et al. 2013, arxiv:1310.1422)

July 2013: SPTpol Detection of Lensing B-modes

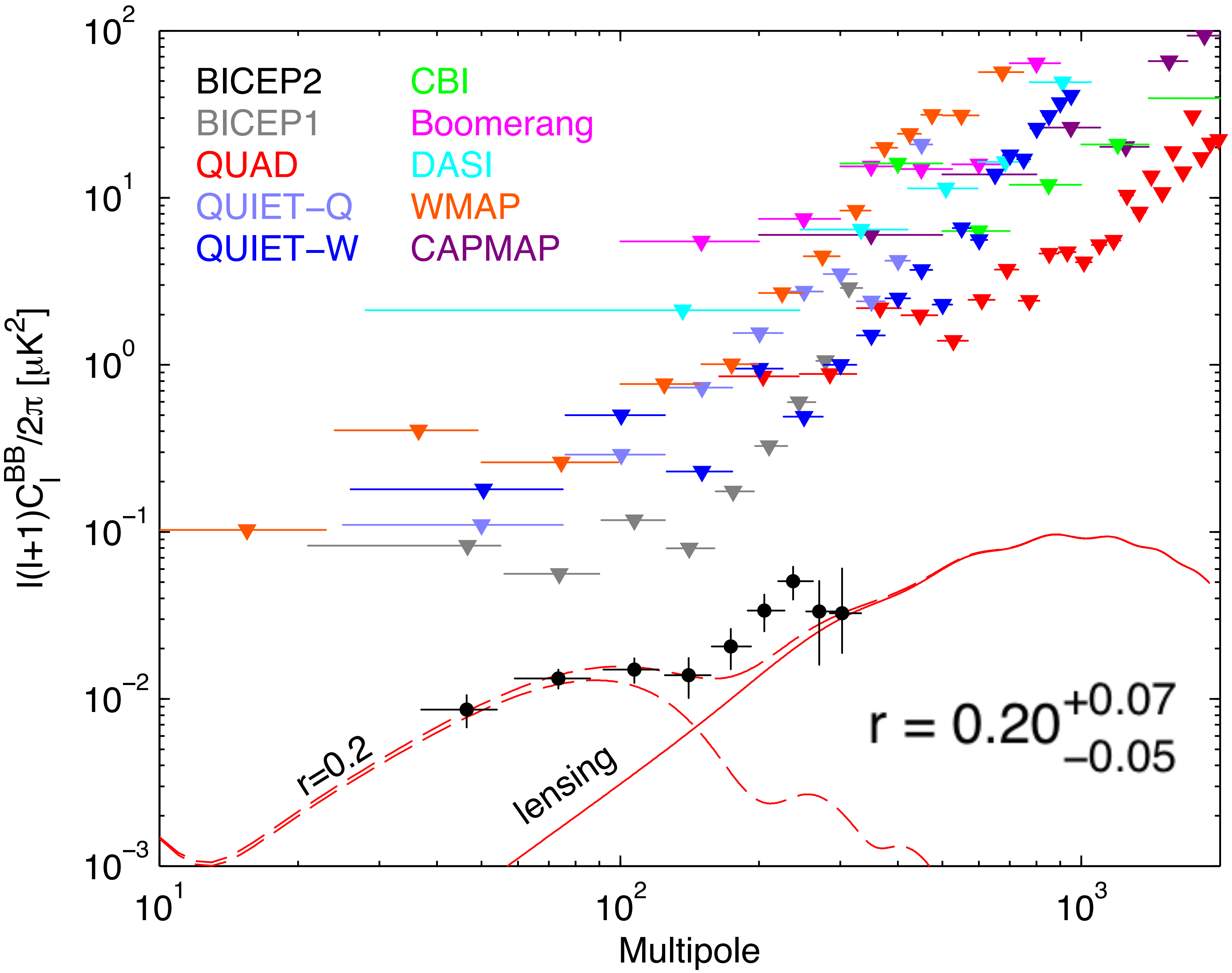


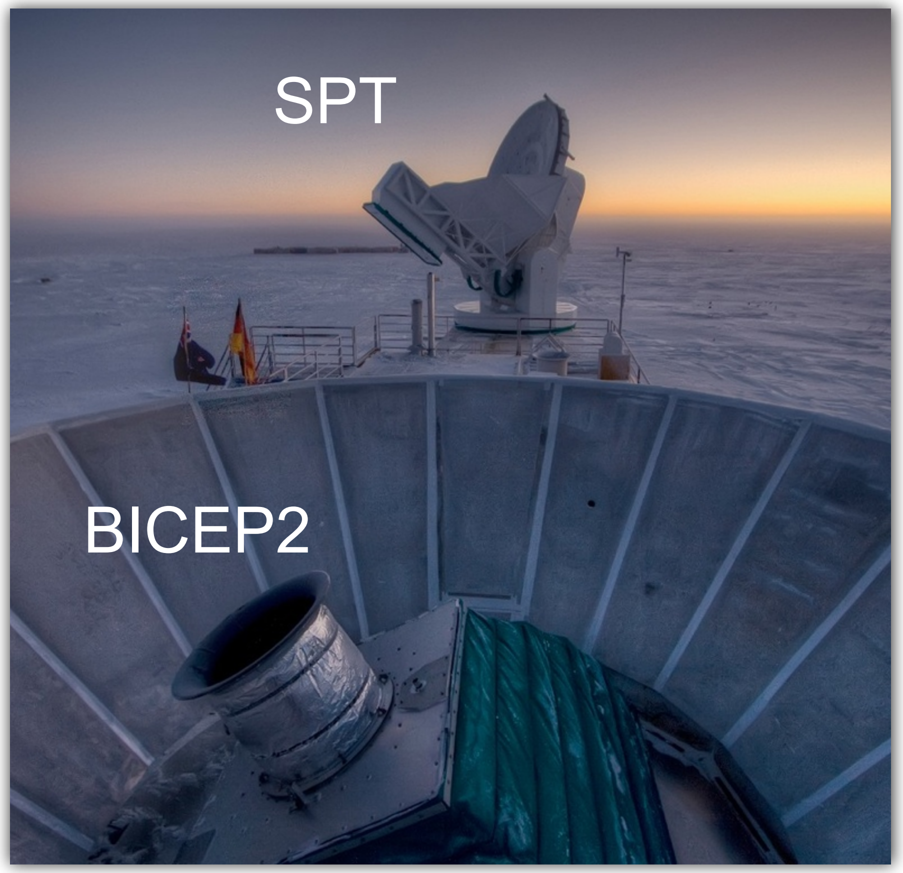


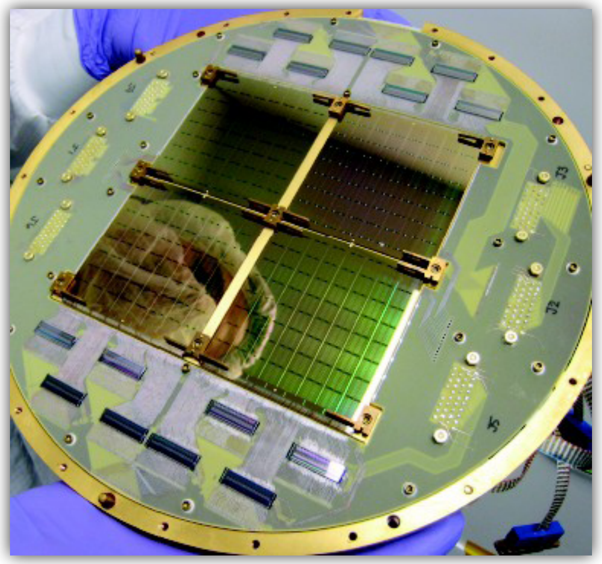


SPTpol: Hanson et al, Phys.Rev.Lett.111:141301,2013 (arXiv:1307.5830)
Also recently detected by Polarbear arXiv:1312.6645, 1312.6646, 1403.2369

March 2014: BICEP2 Detection of B-modes!





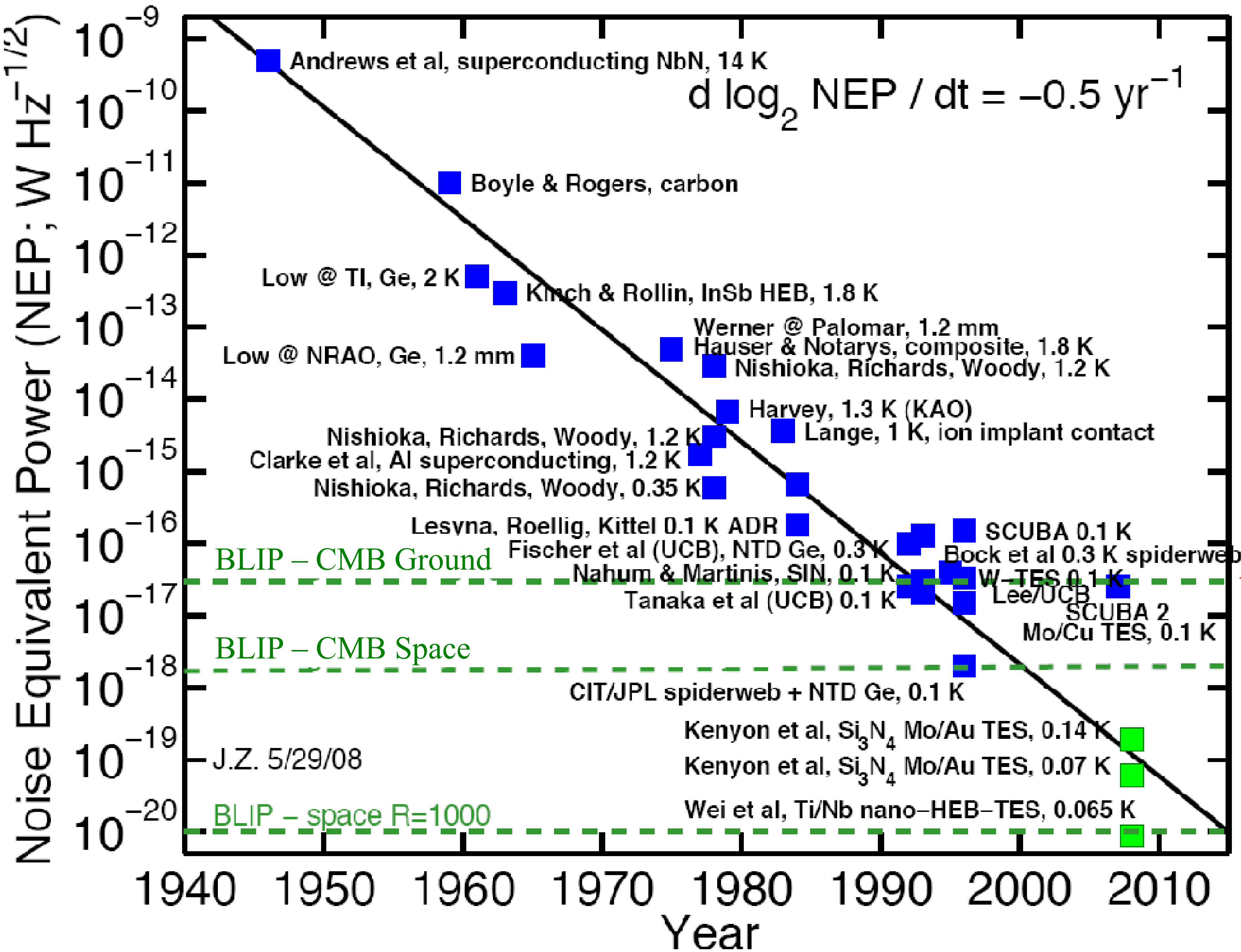


BICEP2: 512 detectors
150 GHz made by JPL

BICEP2 Collaboration (arXiv:1403.3985, arXiv:1403.4302)

Evolution of Detector Sensitivity

CMB science has been driven by advances in detector technology;
detector speed has ~doubled every year for 50 years!



Photon ("shot") noise limit from ground-based observations with 0.3 Kelvin detectors

NEP ~
50×10^{-18} W Hz$^{-1/2}$

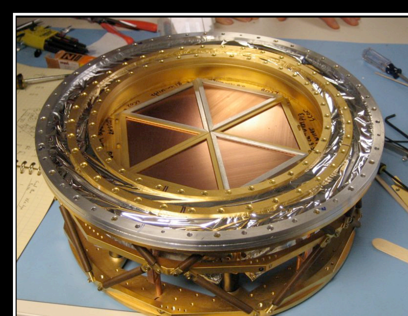
Plot from J. Zmuidzinas

The South Pole Telescope (SPT)

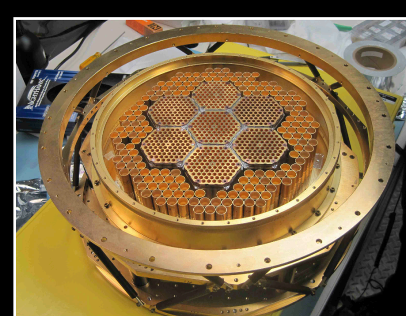
10-meter sub-mm quality wavelength telescope

100, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

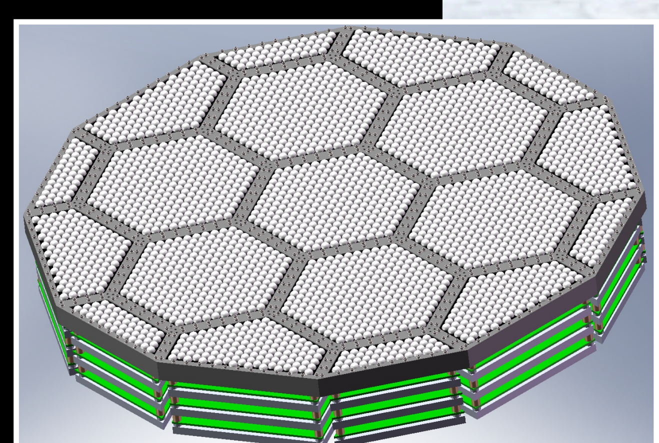
2007: SPT-SZ
960 detectors
100,150,220 GHz

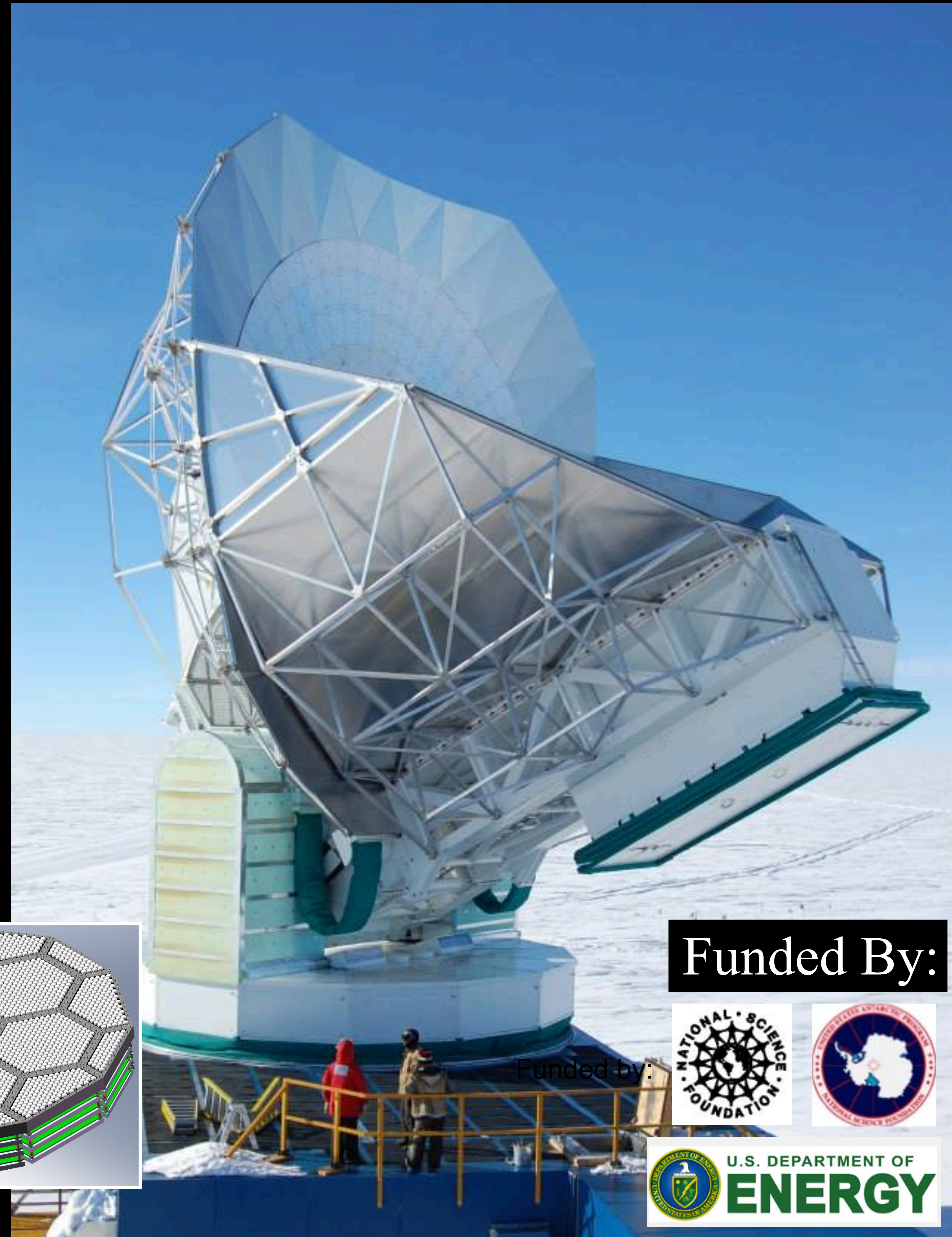


2012: SPTpol
1600 detectors
100,150 GHz
+Polarization



2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization



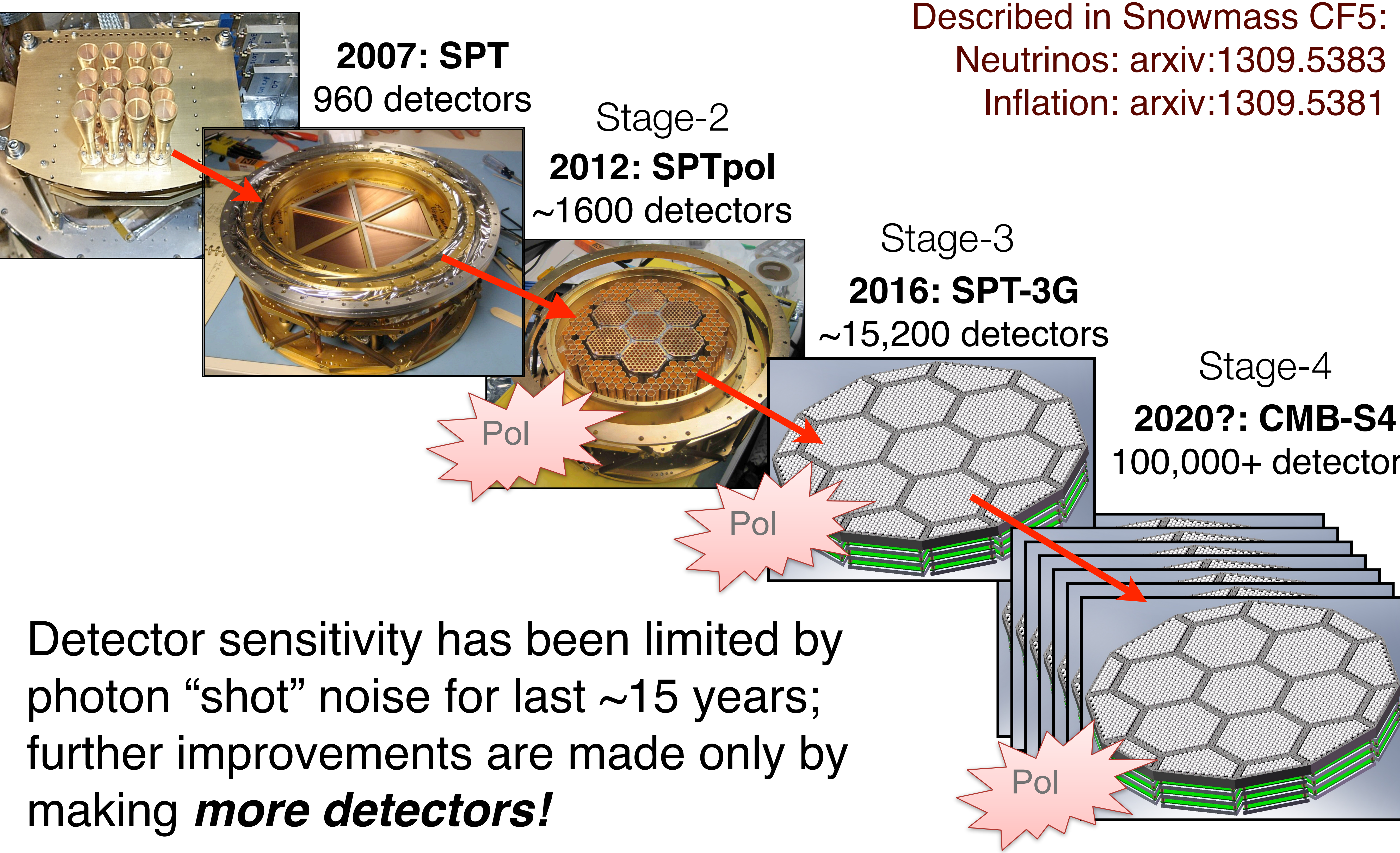


Funded By:

U.S. DEPARTMENT OF ENERGY

Evolution of CMB Focal Planes

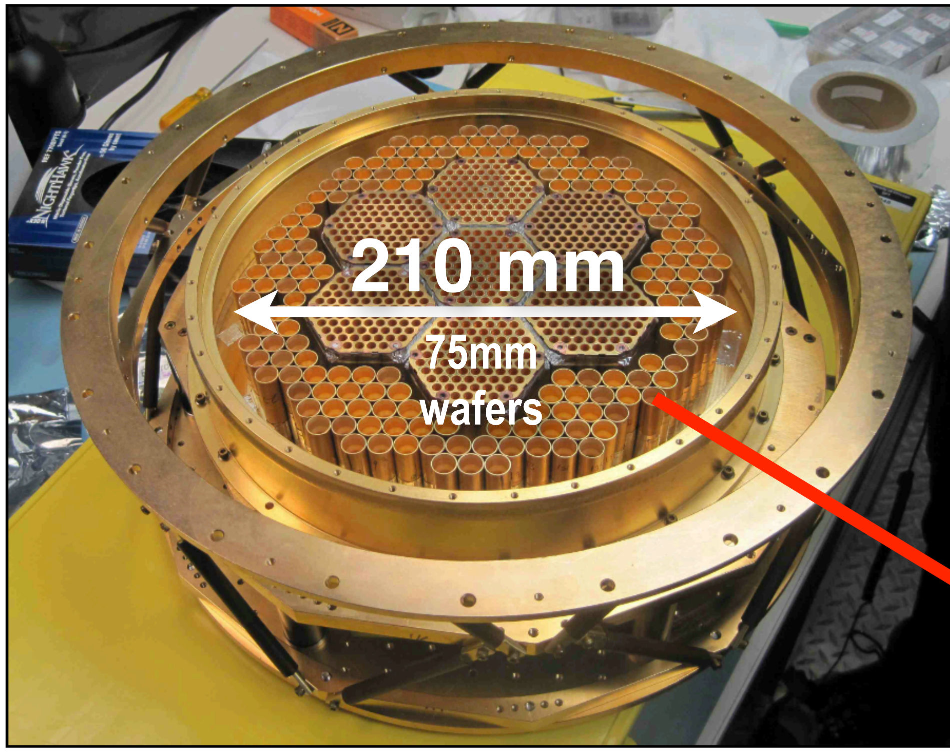
CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381



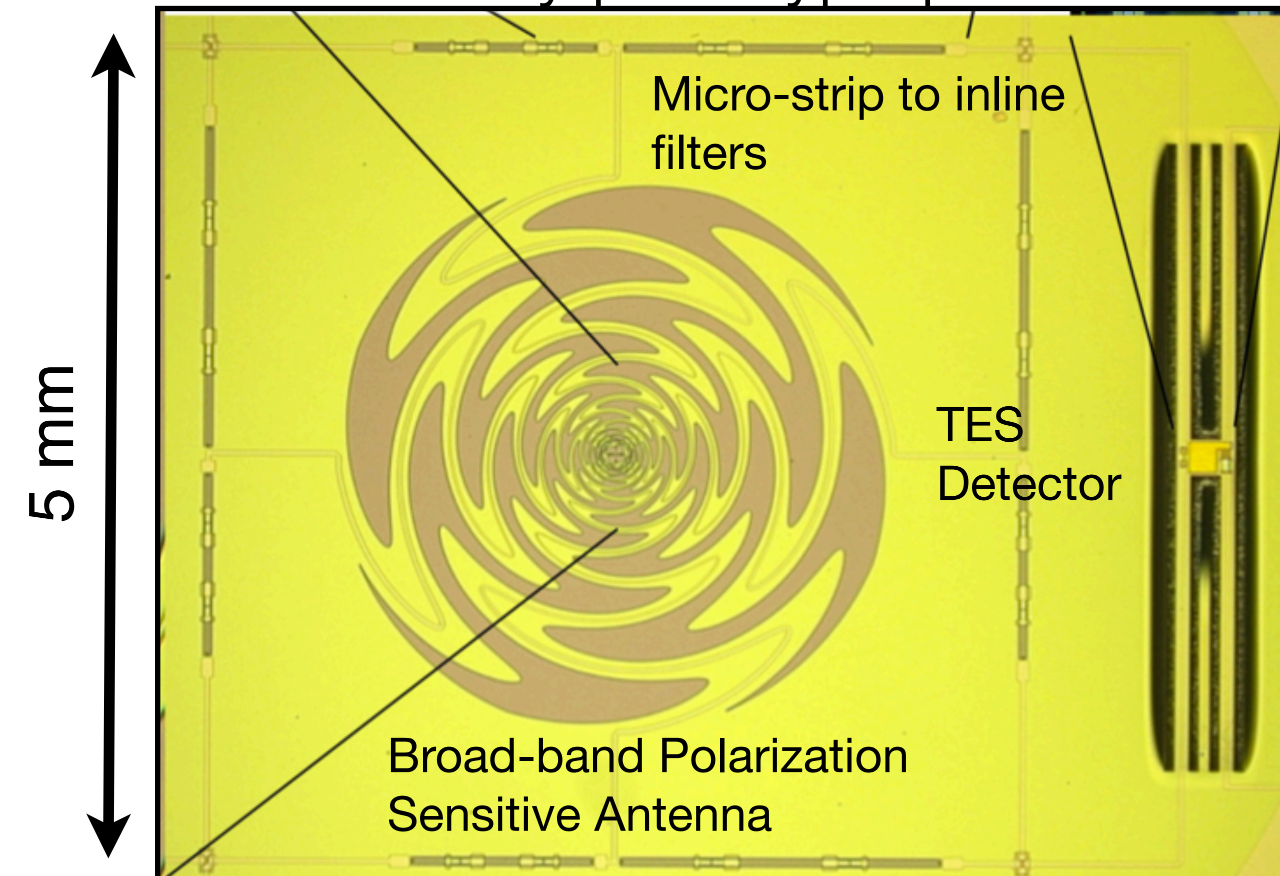
Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making ***more detectors!***

SPTpol to SPT-3G

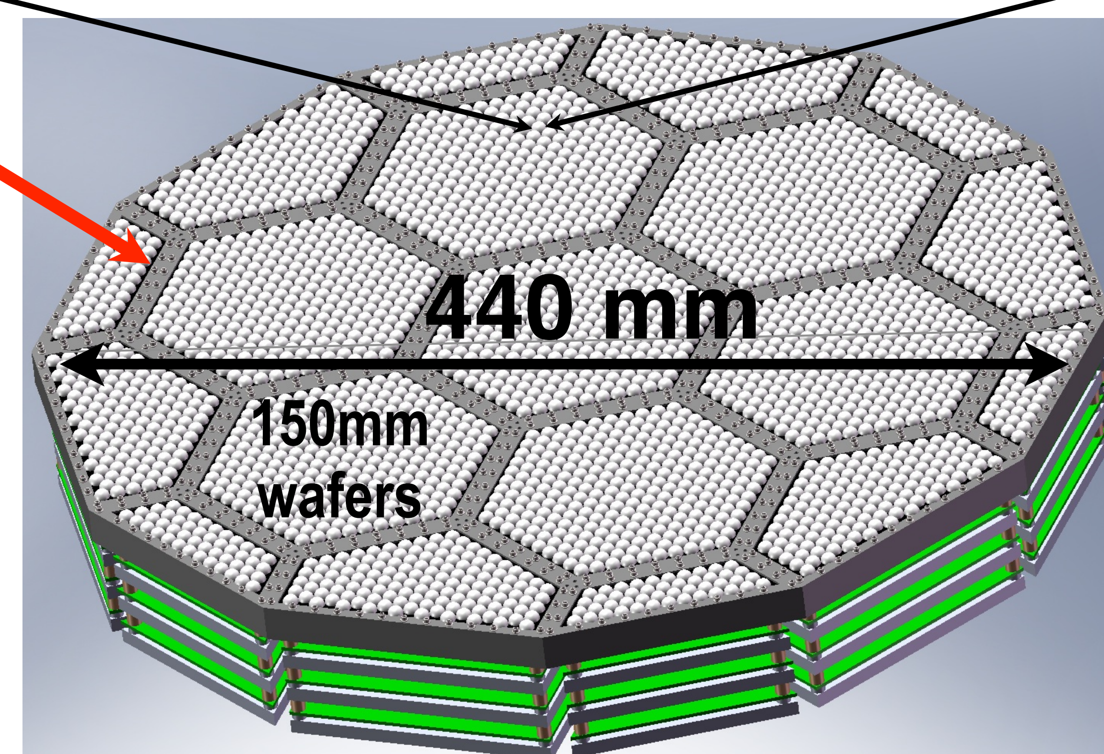
2012: SPTpol Stage II
1600 detectors (ANL/NIST)



UC Berkeley prototype pixel

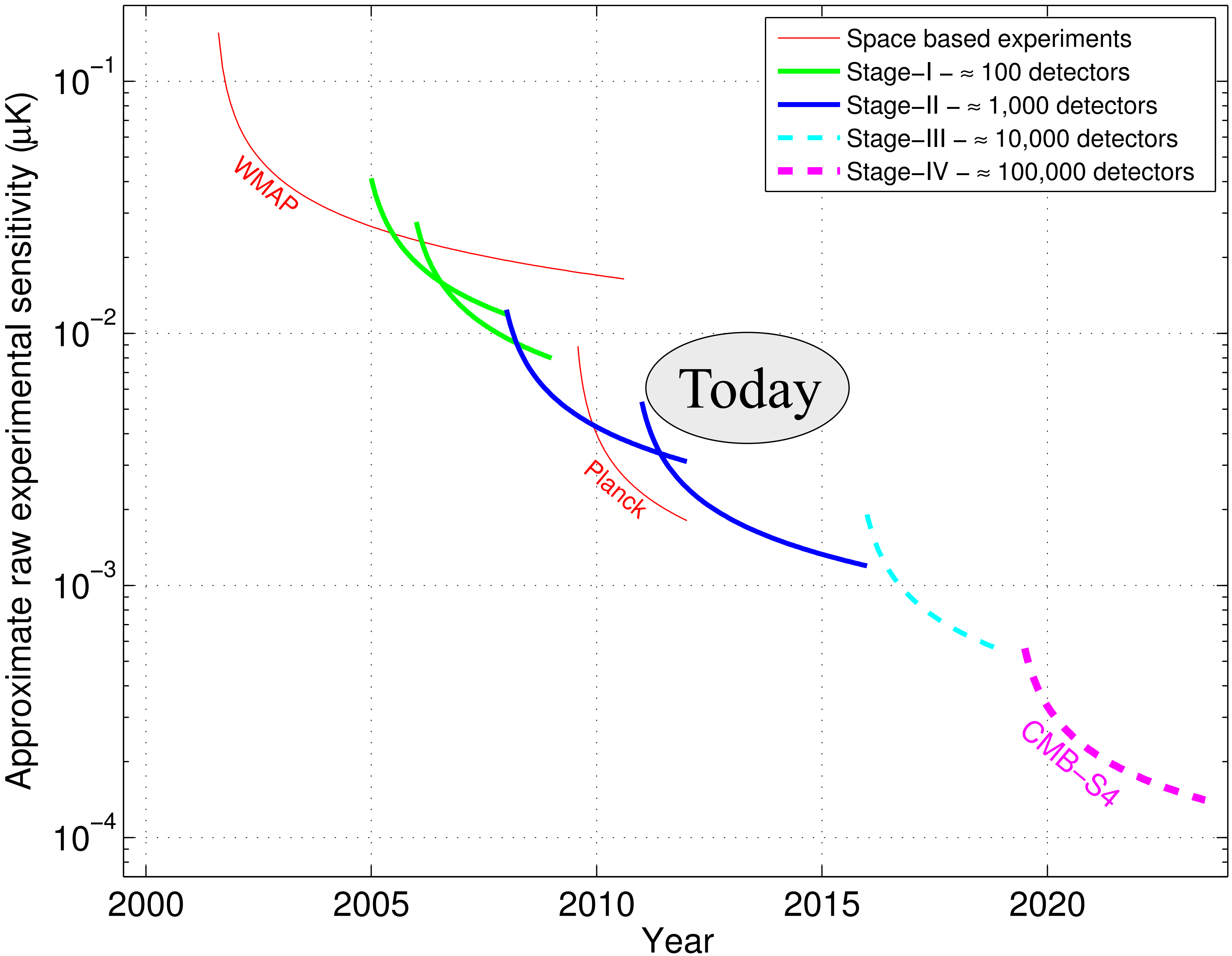


ANL, LBNL, SLAC, FNAL, Polarbear, and SPT teams working on Stage II to Stage III detector advance based on 3-band, dual polarization pixel.



2016: SPT-3G Stage III 4x larger area
15,234 detectors at 250mK

CMB Experimental Stages



Stage-IV CMB experiment = **CMB-S4**

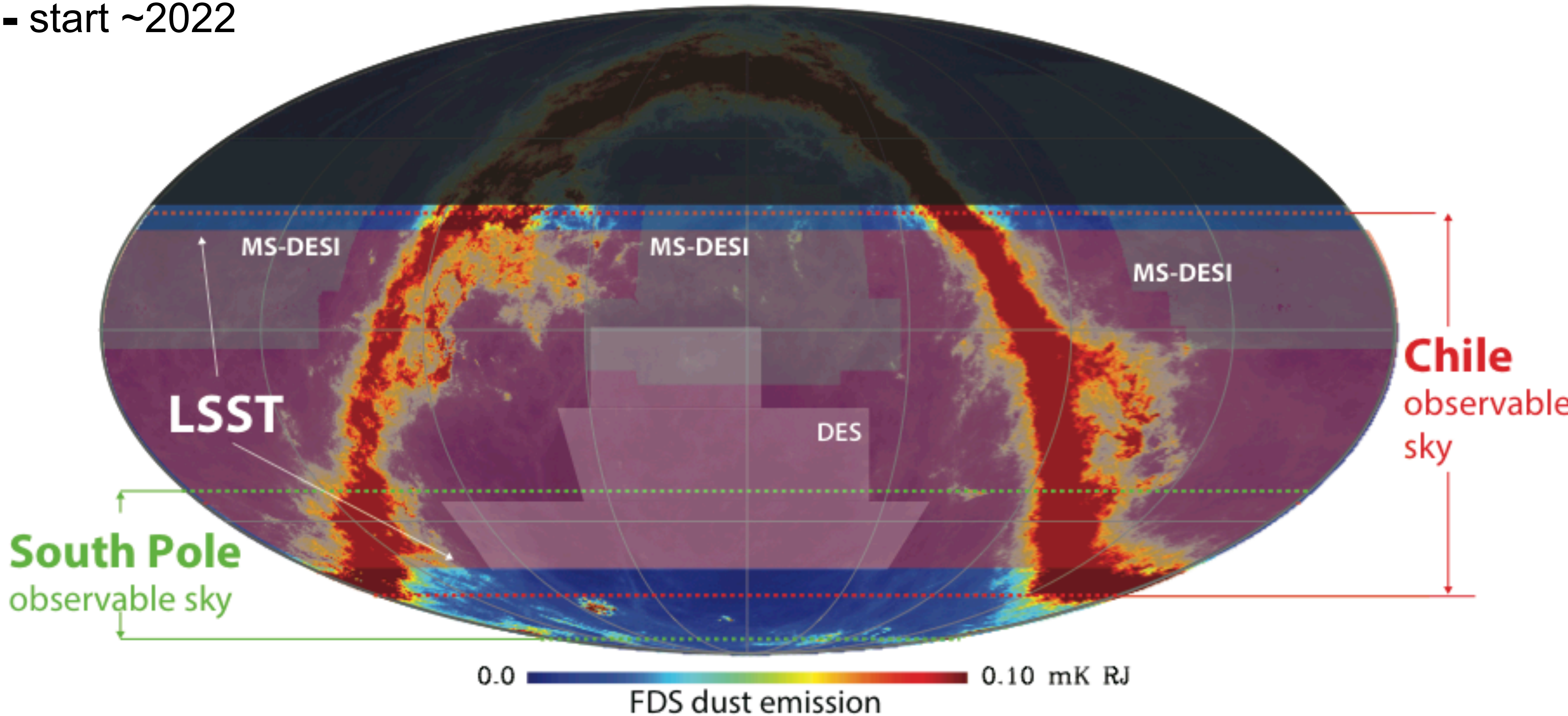
~200x faster than today's Stage 2 experiments

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB-S4: A CMB Stage 4 Experiment

footprint overlap with DES, LSST, DESI, etc.

- 200,000 - 500,000 detectors on multiple platforms
- span 40 - 240 GHz for foreground removal
- target noise of ~1 uK-arcmin depth over half the sky
- start ~2022



Primary technical challenge will be the scaling of the detector arrays

CMB-based Cosmological Constraints

	$\sigma(r)$	$\sigma(N_{\mathrm{eff}})$	$\sigma(\Sigma m_\nu)$ (meV)
Current CMB	**0.05**	**0.34**	**117**
Stage 2: SPTpol	0.03	0.12	96
Stage 3: SPT-3G	0.01	0.06	61*
Stage 4: CMB-S4	**0.001**	**0.02**	**16****

* Includes BOSS prior
** Includes DESI prior

The CMB-S4 sensitivity would achieve important benchmarks:

- $\sigma(r) \sim 0.001$; large vs small field inflation?
- $\sigma(N_{\mathrm{eff}}) \sim 0.02$; new physics in neutrino or dark sector?

deviations from standard model prediction of 3.046?

- $\sigma(\Sigma m_\nu) \sim 16$ meV ; cosmological detection of neutrino mass?

Snowmass: CF5 Neutrinos + Inflation Document
arxiv:1309.5383, 1309.5381

Summary and Big Questions

This science is just beginning!

- **2012**: First 5-σ detection of gravitational lensing of CMB
- **2013**: First 5-σ detection of "lensing" B-modes
- **2014**: First 5-σ detection of degree scale B-modes

The CMB is a unique cosmological probe which can study many fundamental questions:

Did the universe start with an epoch of inflation?

What is the energy scale of inflation?

Is there any "dark radiation"?

What is the sum of the neutrino masses?