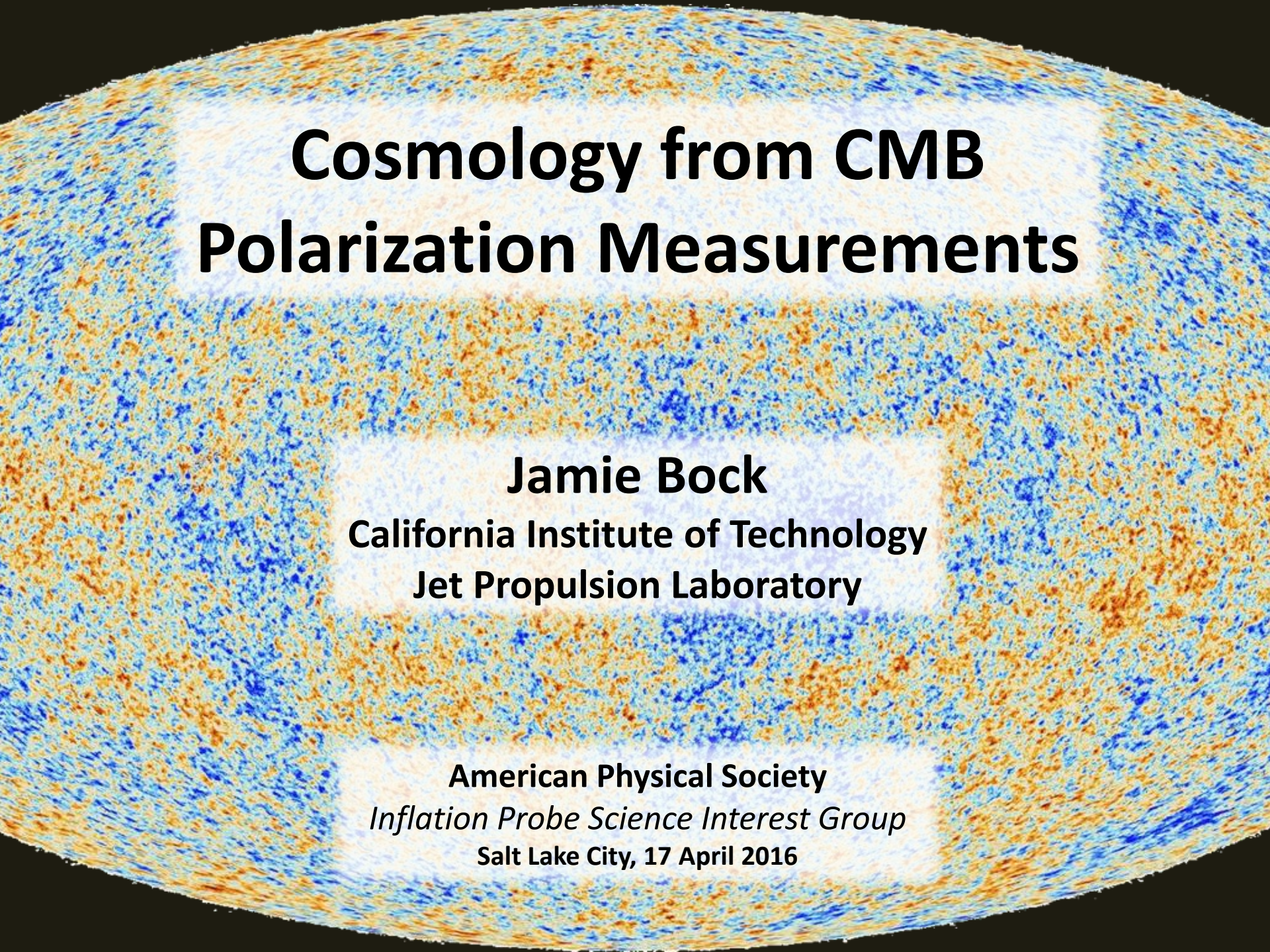
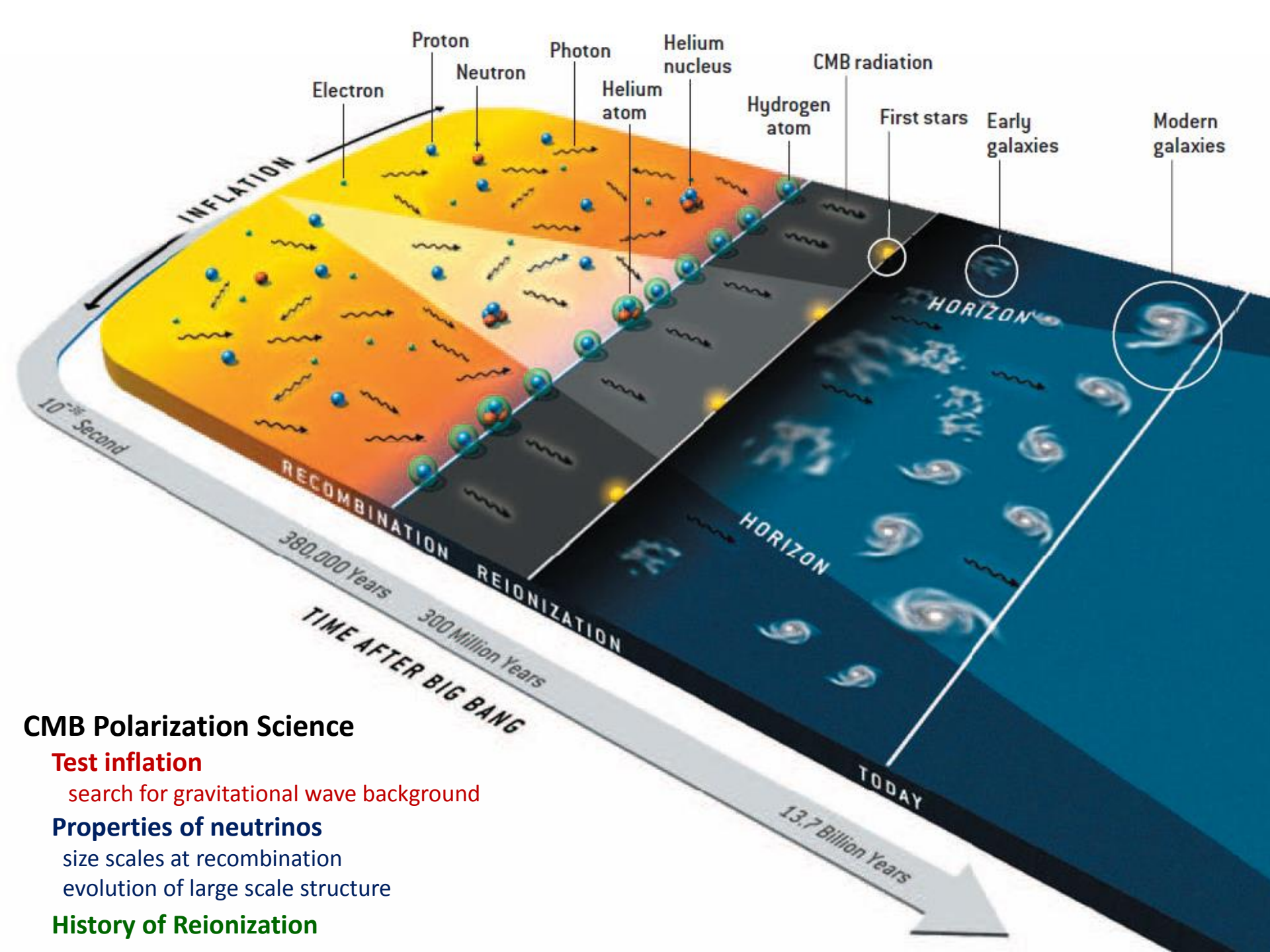


Cosmology from CMB Polarization Measurements

Jamie Bock
California Institute of Technology
Jet Propulsion Laboratory

American Physical Society
Inflation Probe Science Interest Group
Salt Lake City, 17 April 2016



CMB Polarization Science

Test inflation

search for gravitational wave background

Properties of neutrinos

size scales at recombination

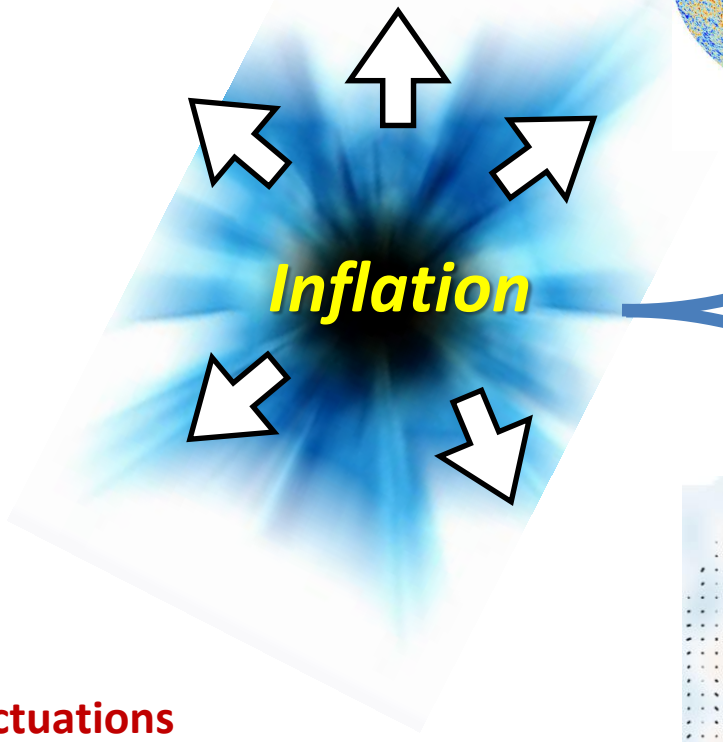
evolution of large scale structure

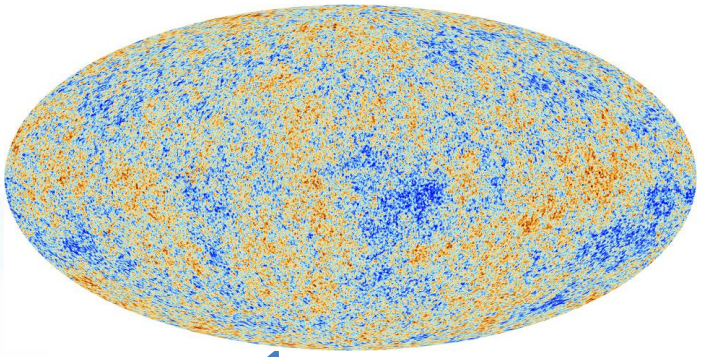
History of Reionization

How Can We Test Inflation?

- **Inflationary gravitational waves:** CMB "B-mode" polarization
- **Spectral index of fluctuations:** CMB and large-scale structure
- **Non-Gaussianity:** Large-scale structure (galaxies, HI)

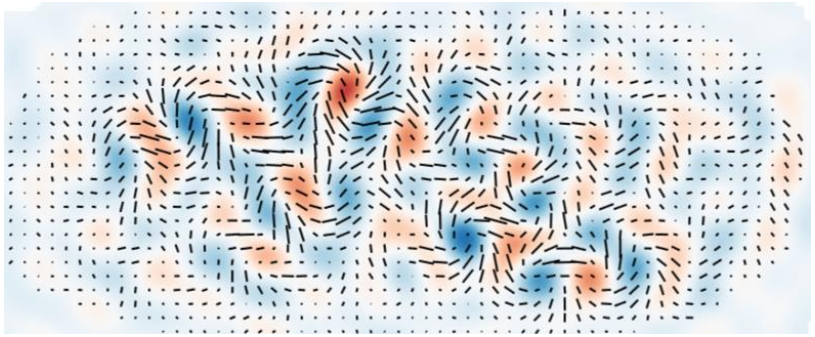
Sub-atomic vacuum fluctuations of "inflaton"





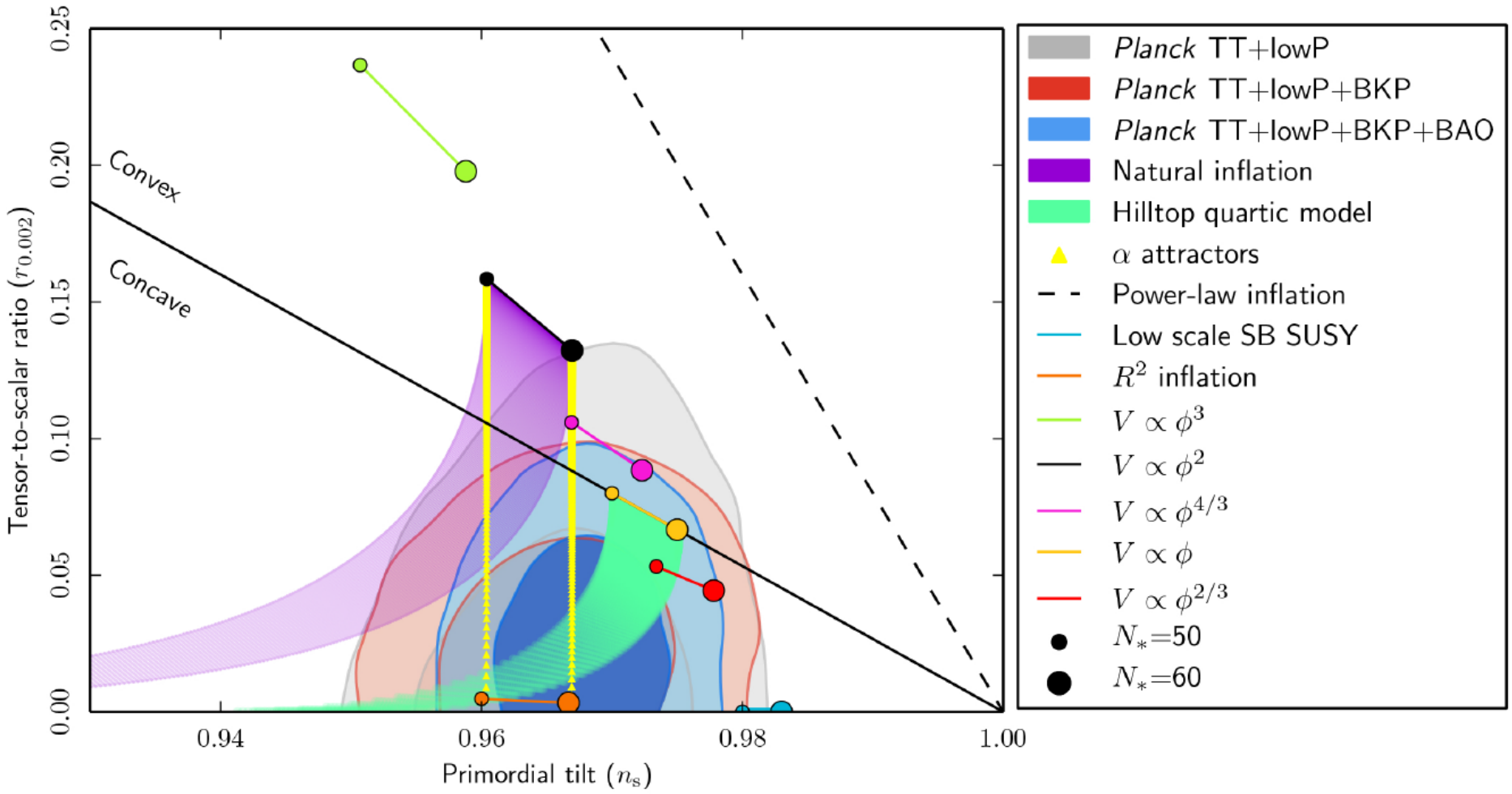
Density perturbations studied by Planck, WMAP, SPT, etc.

Gravitational waves?
→ telltale polarization pattern



Sub-atomic vacuum fluctuations of *graviton* (quanta of gravity)

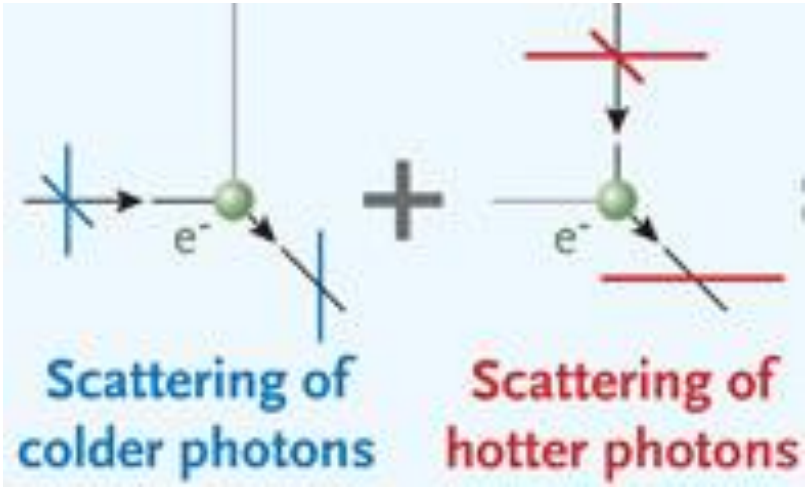
Testing Models of Inflation

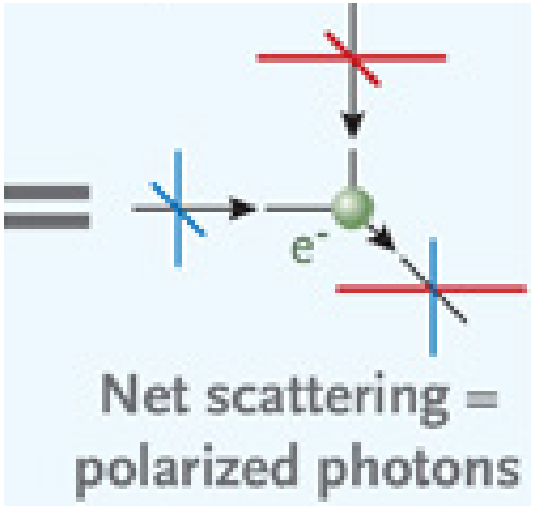


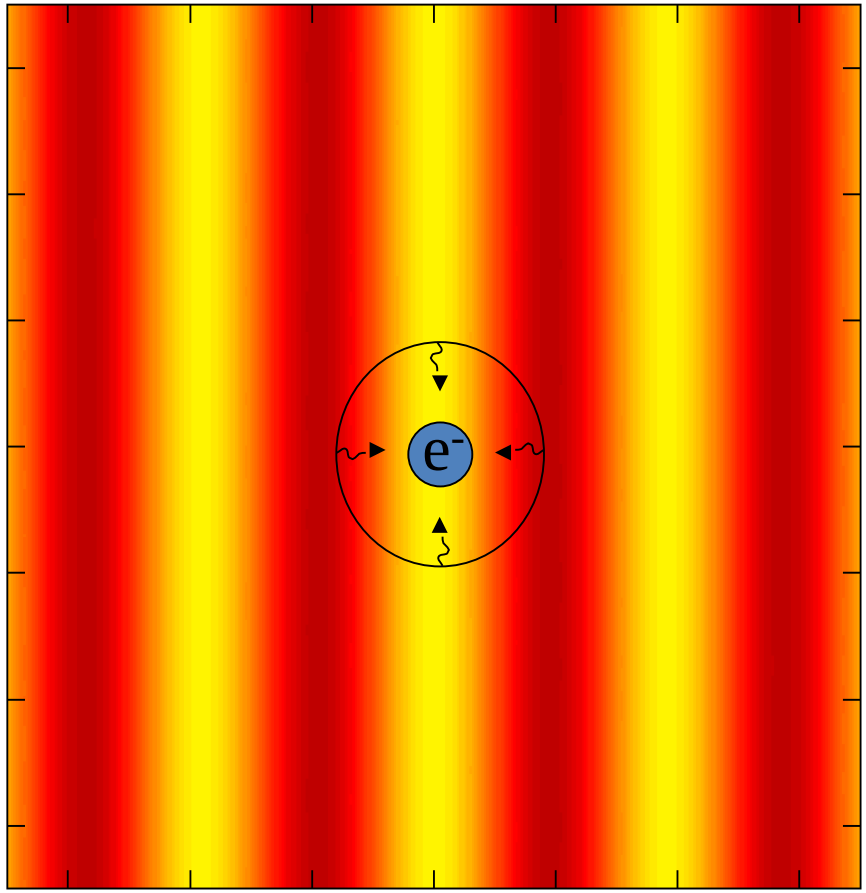
Slow-roll inflation models predict a relation between tensor-to-scalar ratio (r) and the tilt of the primordial power spectrum (1-n_s)

Primordial CMB Polarization

Sourced by Thomson Scattering

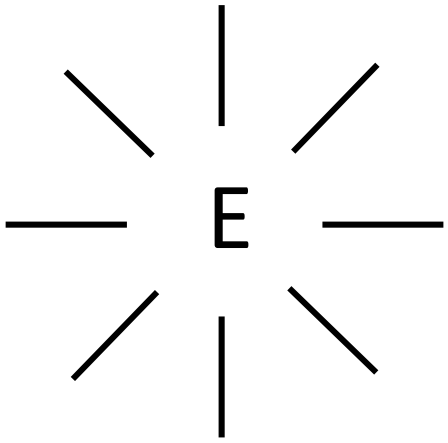


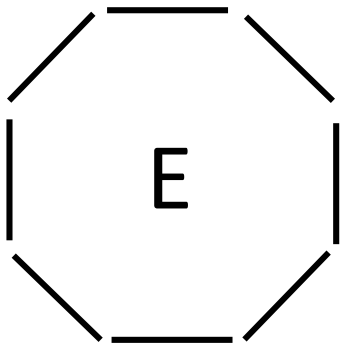


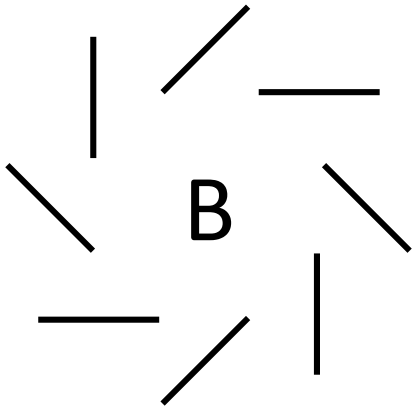


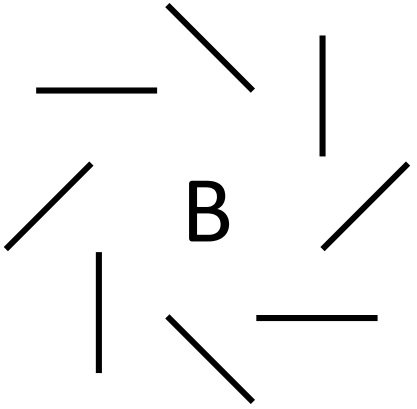
An electron at last scattering

The Signature of Gravitational Waves



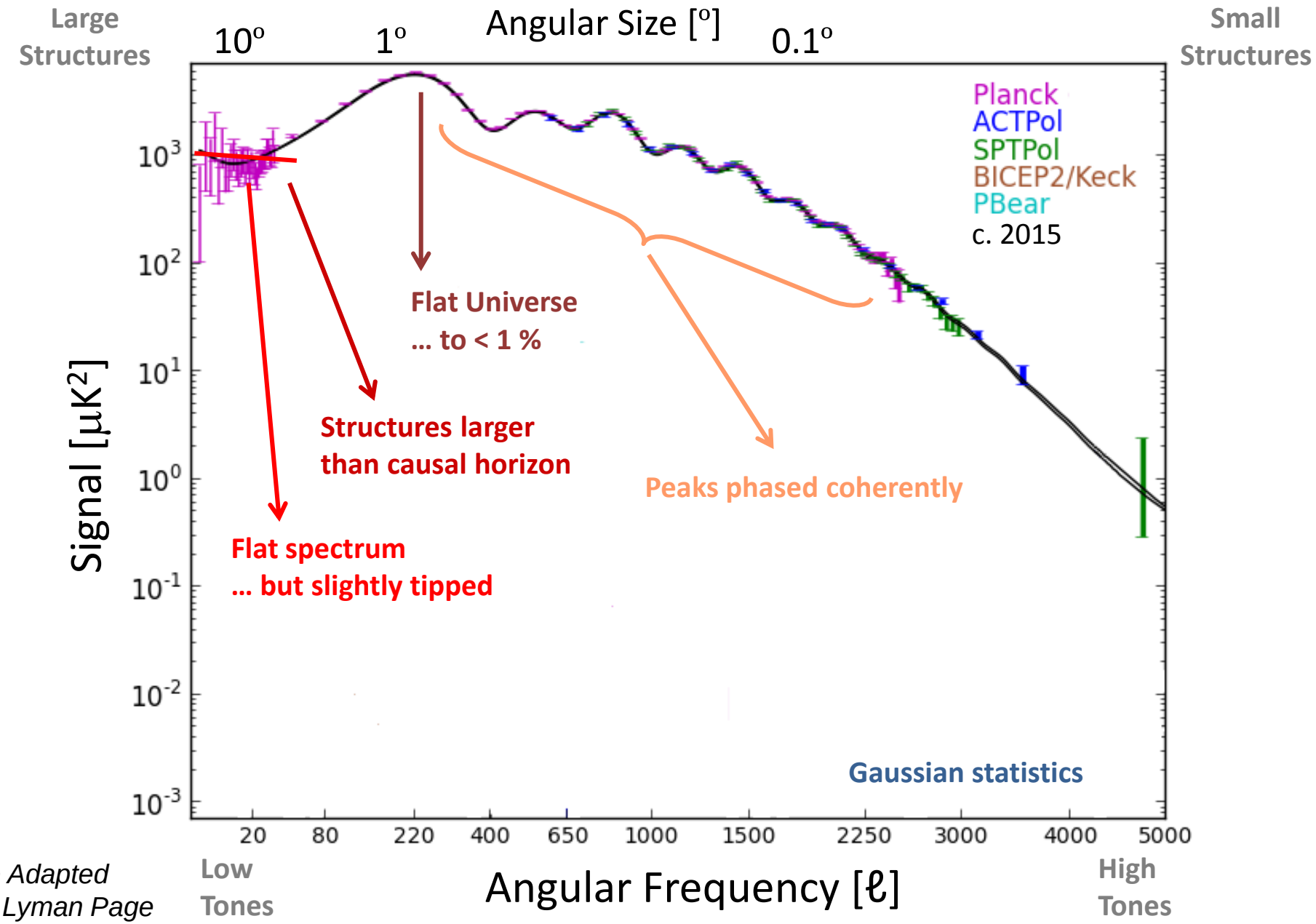






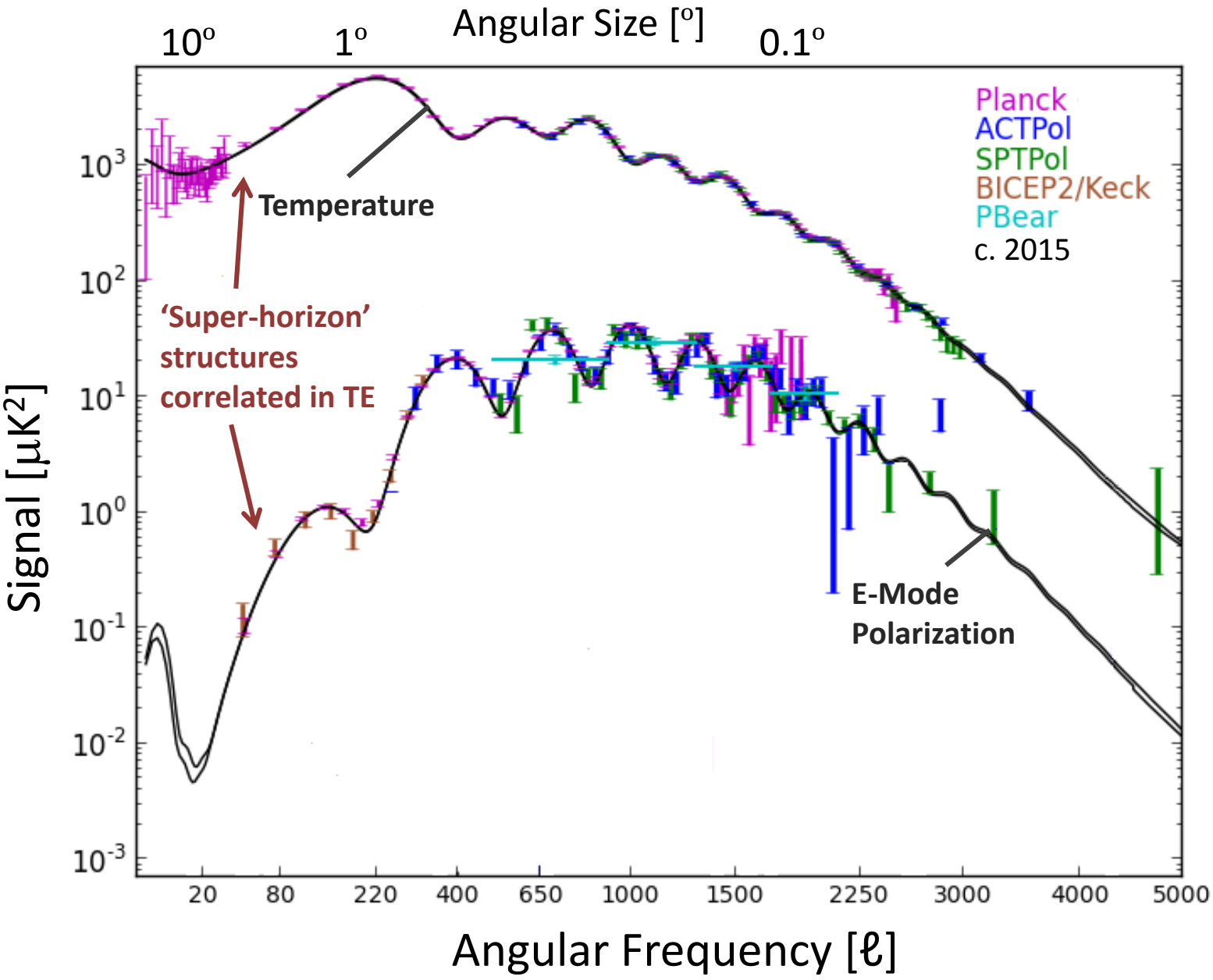
Density fluctuations *cannot* make B-mode patterns

CMB Power Spectra

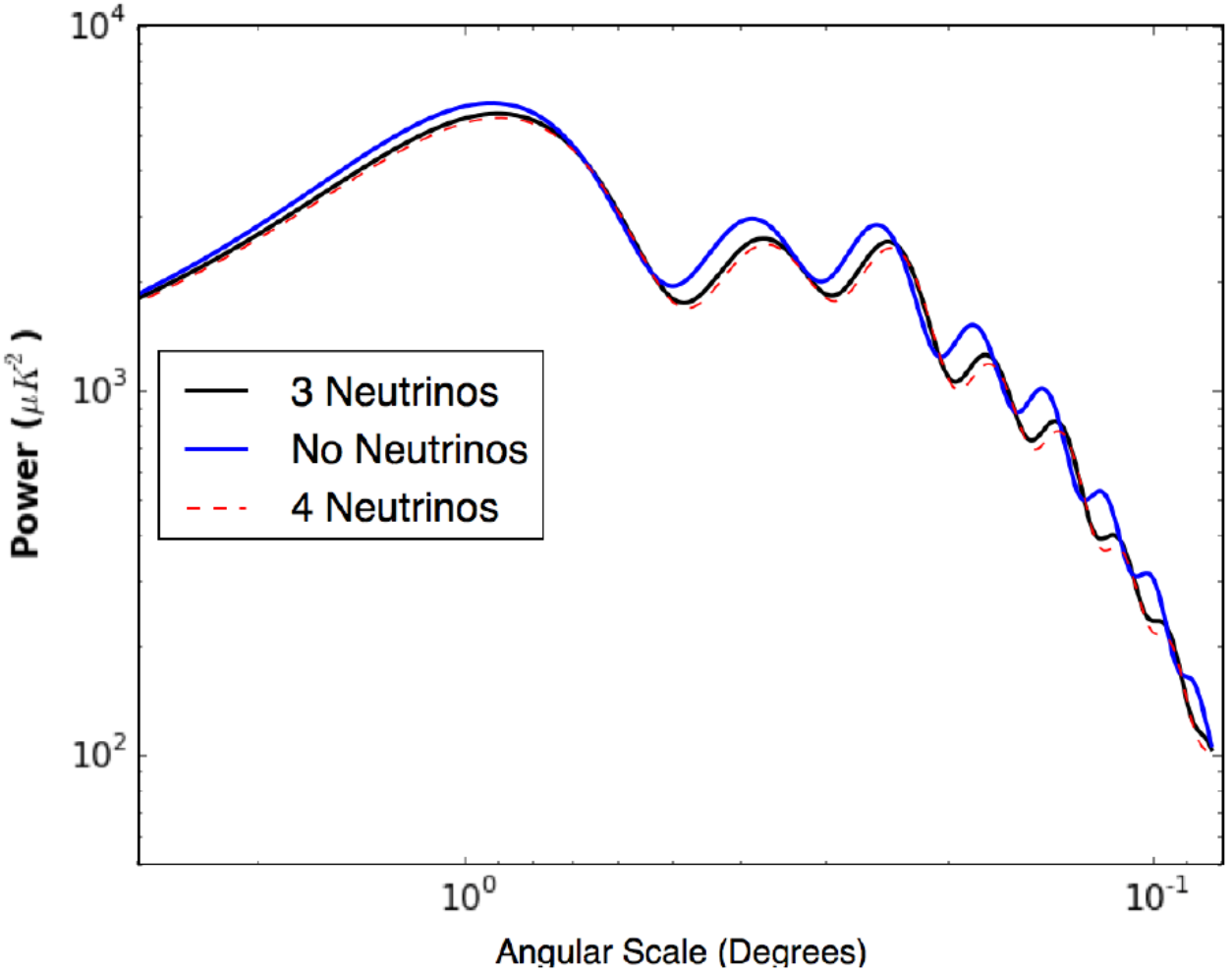


Slide Adapted from Lyman Page

CMB Power Spectra



Test of Light Particles



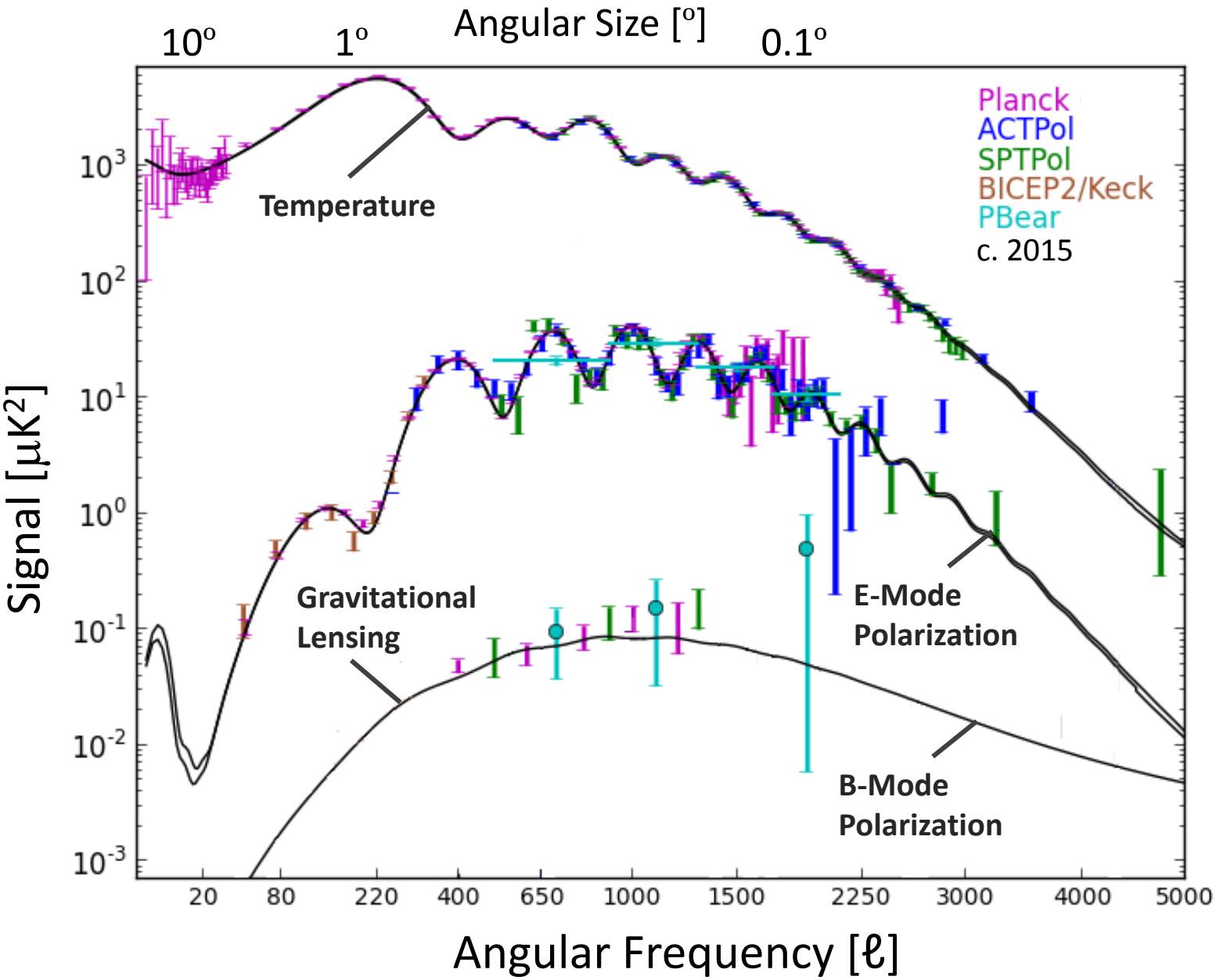
Two speeds: sound speed in the plasma and diffusion speed of photons

N_{eff} = 3.046 (neutrinos only) Currently N_{eff} = 3.04 ± 0.33 Planck+ext 2015

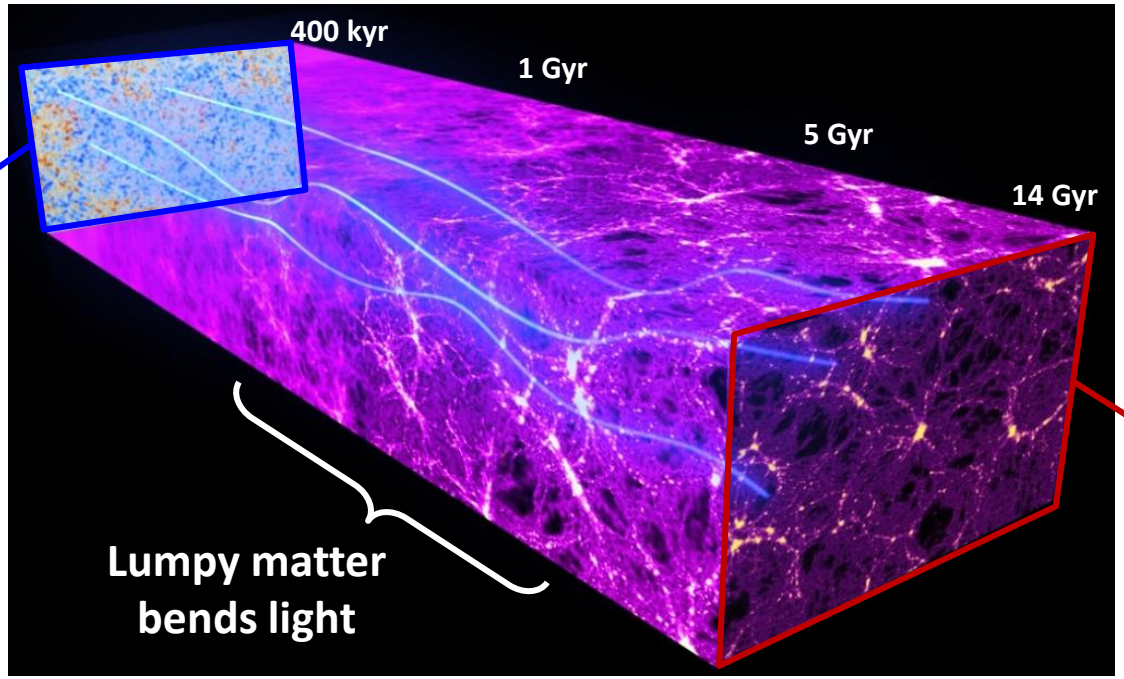
More information available in the E-mode power spectrum: sharper peaks

Future projections for a 2020s Stage-4 CMB survey: $\Delta N_{eff} \sim 0.02$

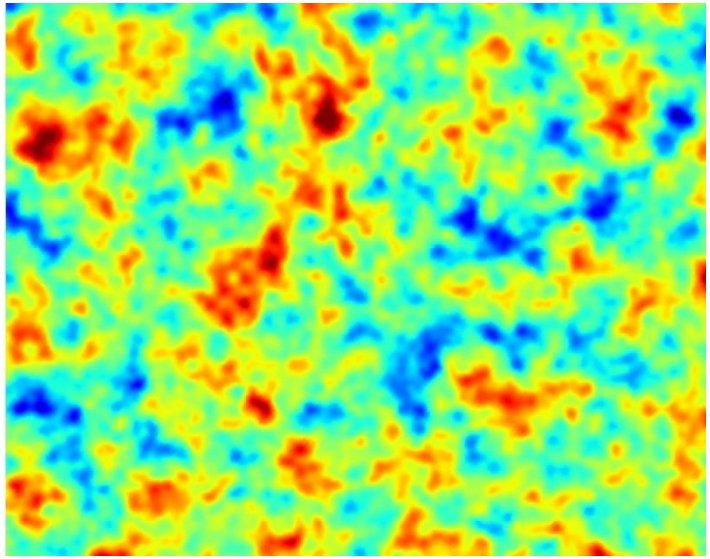
CMB Power Spectra



Gravitational Lensing of the CMB

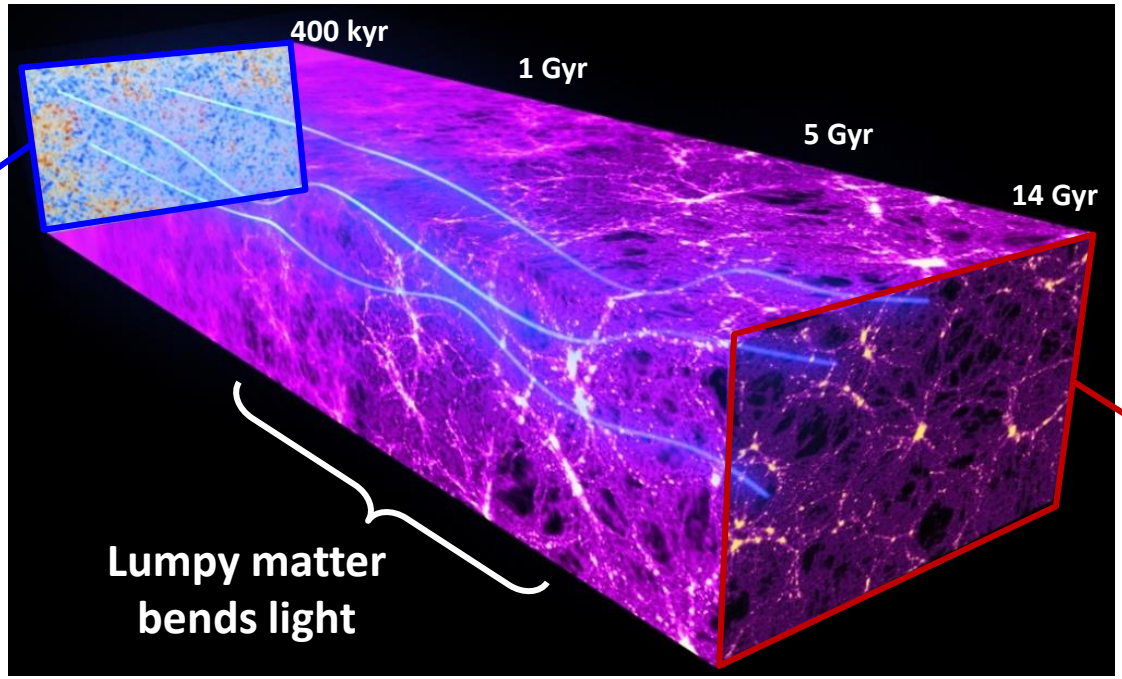


CMB without lensing

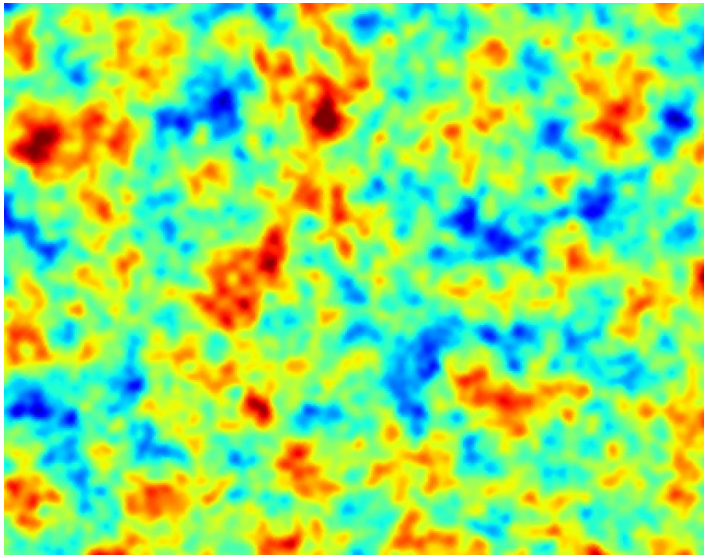


Observed CMB: slightly deflected by gravitational lensing

Gravitational Lensing of the CMB

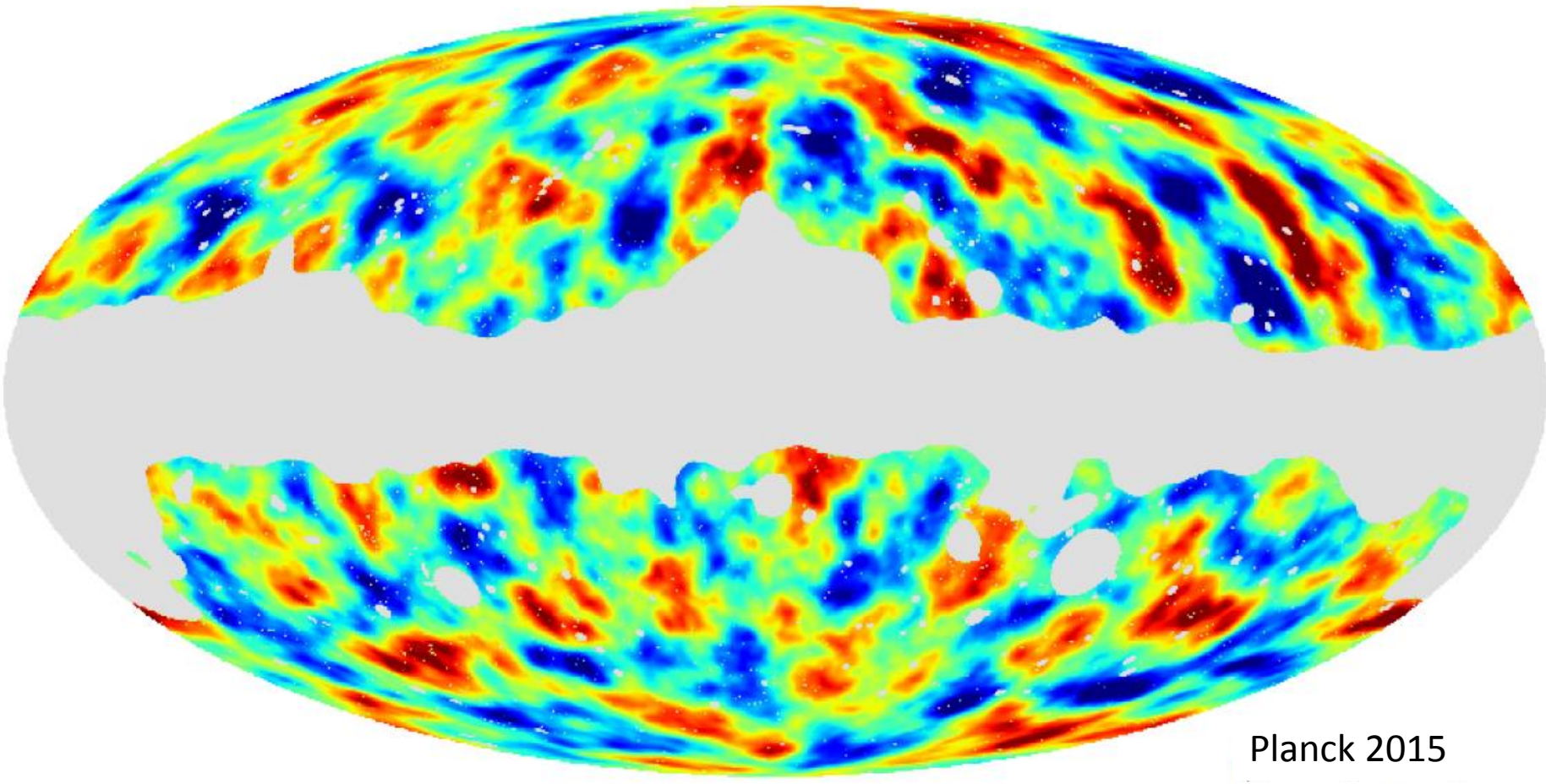


CMB with lensing



Observed CMB: slightly deflected by gravitational lensing

CMB Lensing Traces Large-Scale Structure

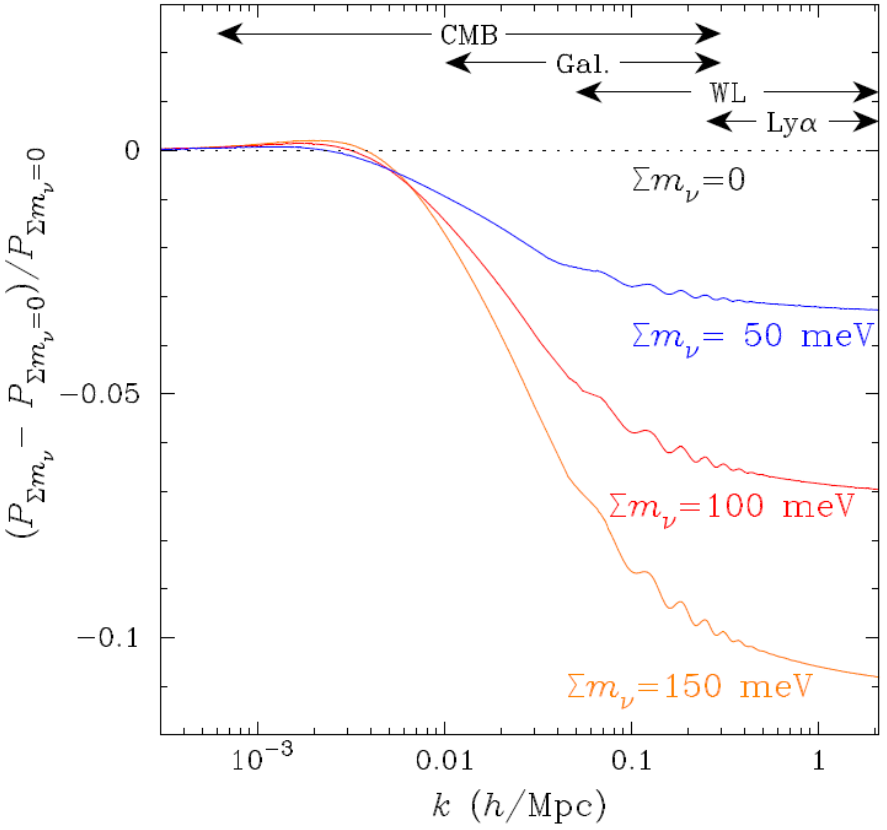


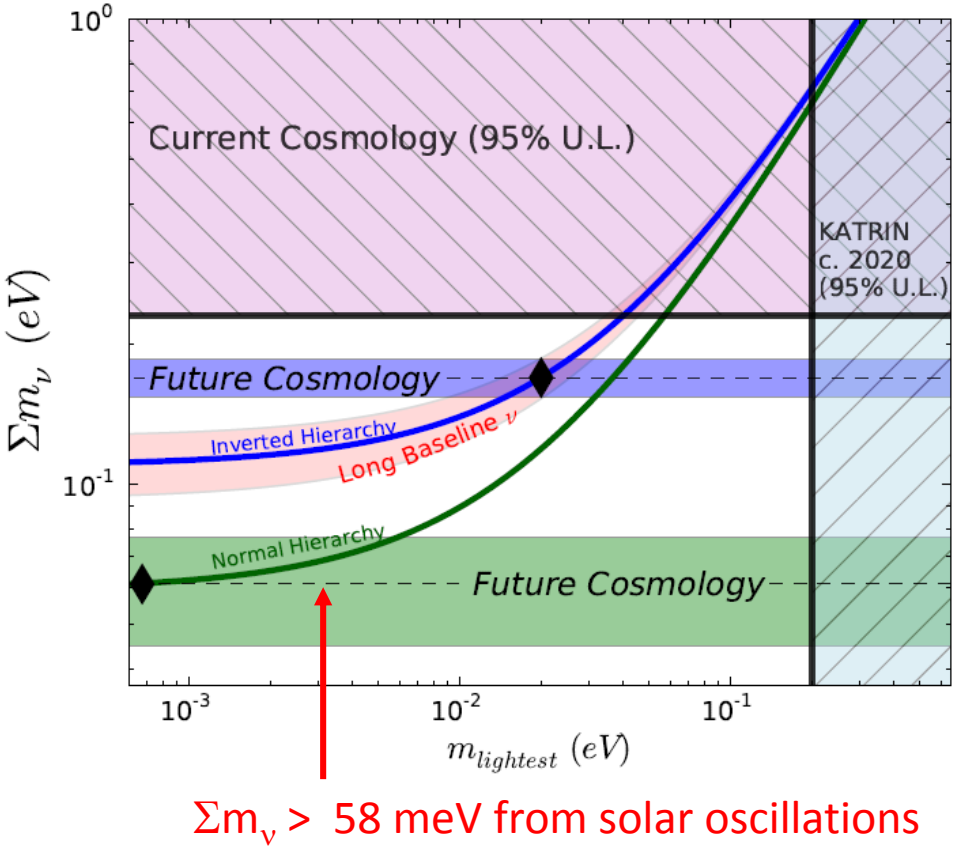
- Lensing derived from the gradient of the CMB temperature (and E-mode polarization)

$$T^{lensed}(\vec{\theta}) = T^{unl}(\vec{\theta} + \vec{\nabla}\phi) \simeq T^{unl}(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla} T^{unl}(\vec{\theta}) + \ldots$$

- However TT and EE have cosmological noise: best information will come from BB!

Tests of Neutrino Mass





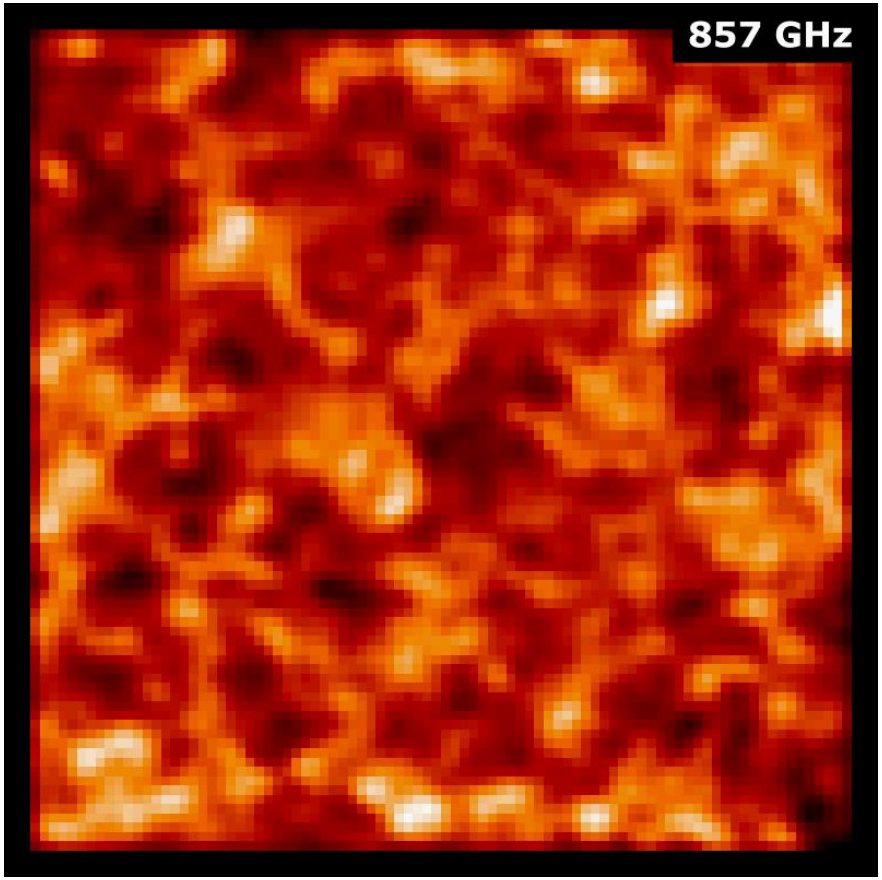
$\Sigma m_\nu >$ 58 meV from solar oscillations

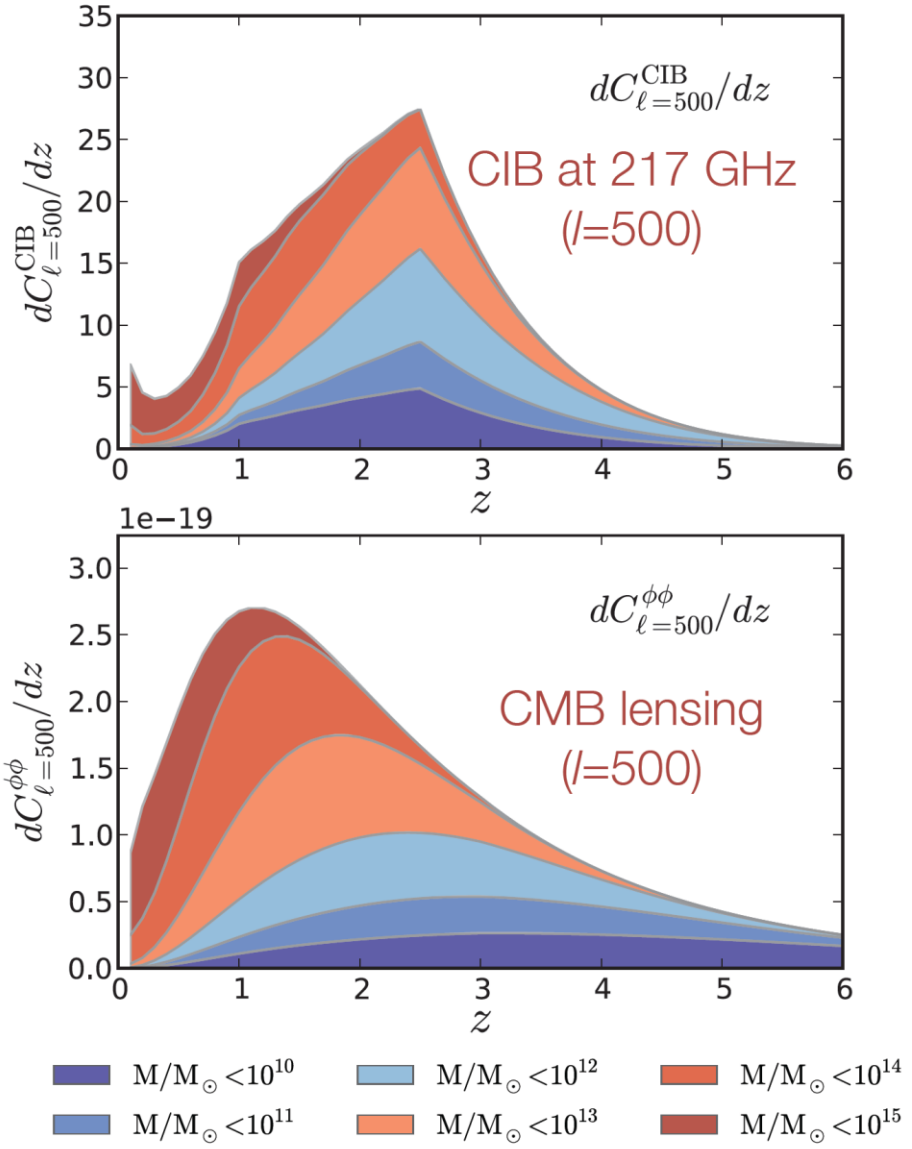
Relativistic neutrinos prevent small structures from clustering

Transition from relativistic to non-relativistic happens at late times, depends on m_ν

Future CMB and LSS measurements will go from today's $\Sigma m_\nu < 230$ meV to $\Delta\Sigma m_\nu \sim 15$ meV

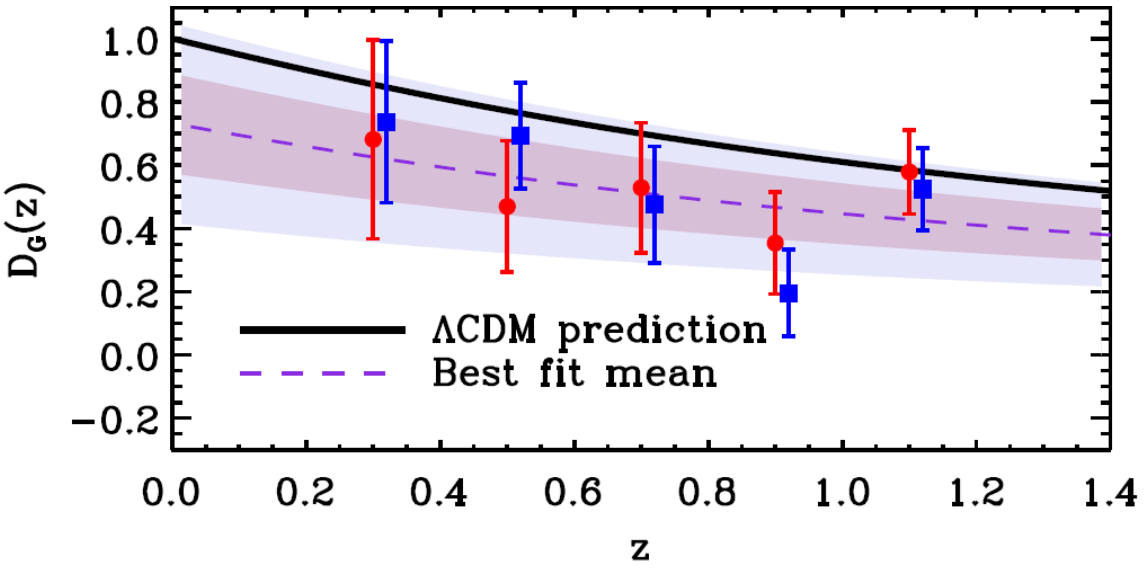
CMB Lensing Traces Far-Infrared Galaxies

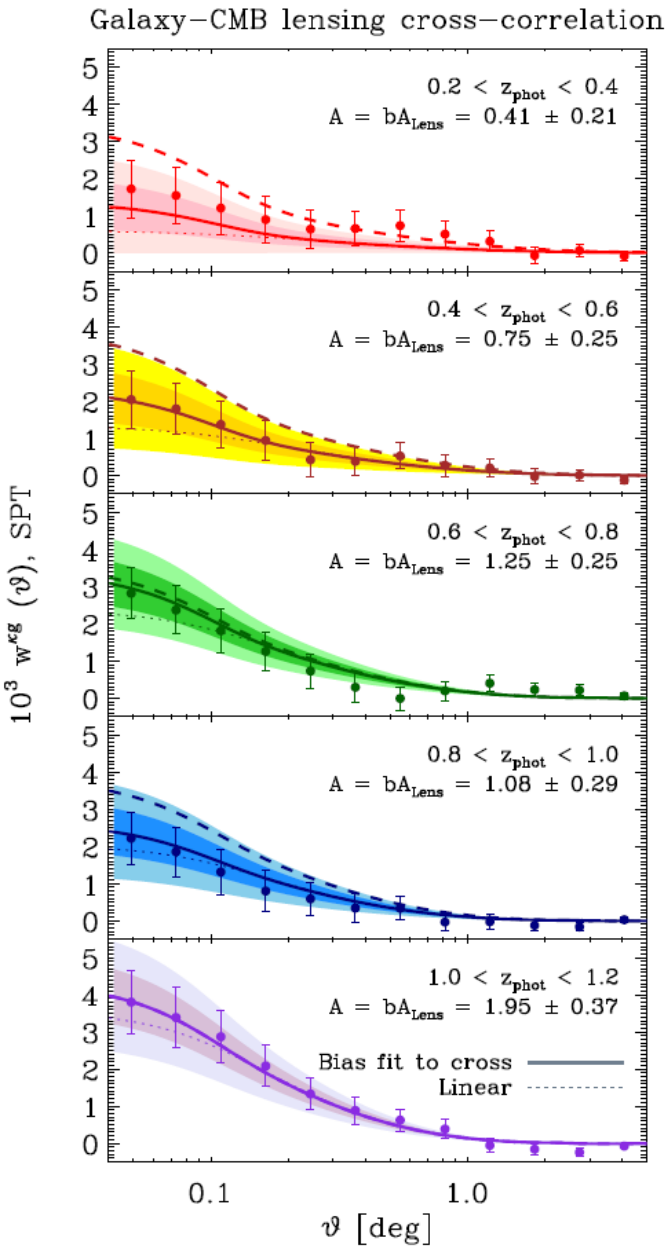




Galaxy-CMB Test of Gravity

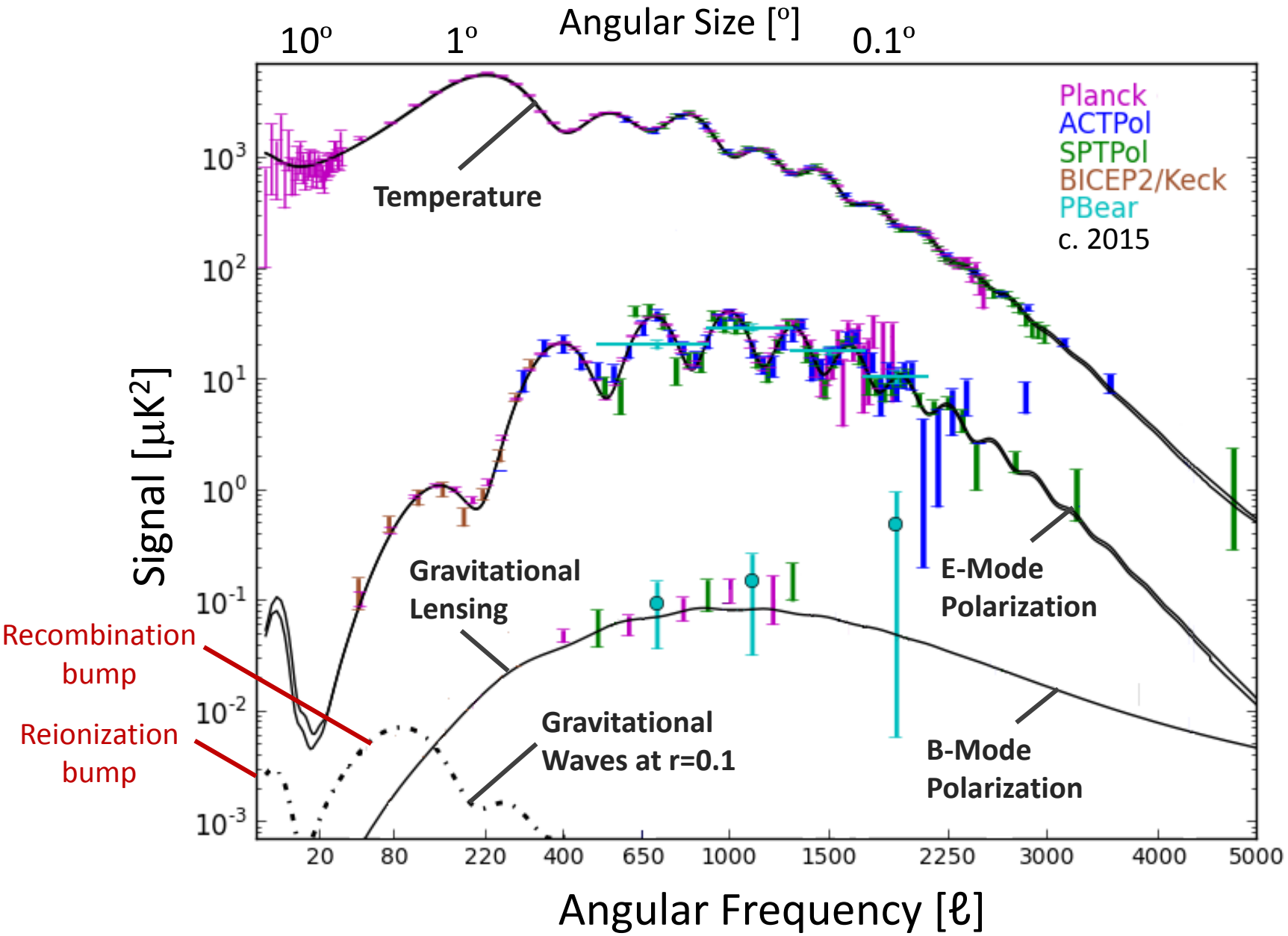
Use CMB x galaxies and galaxies x galaxies to derive the growth of structure $D_G(z)$



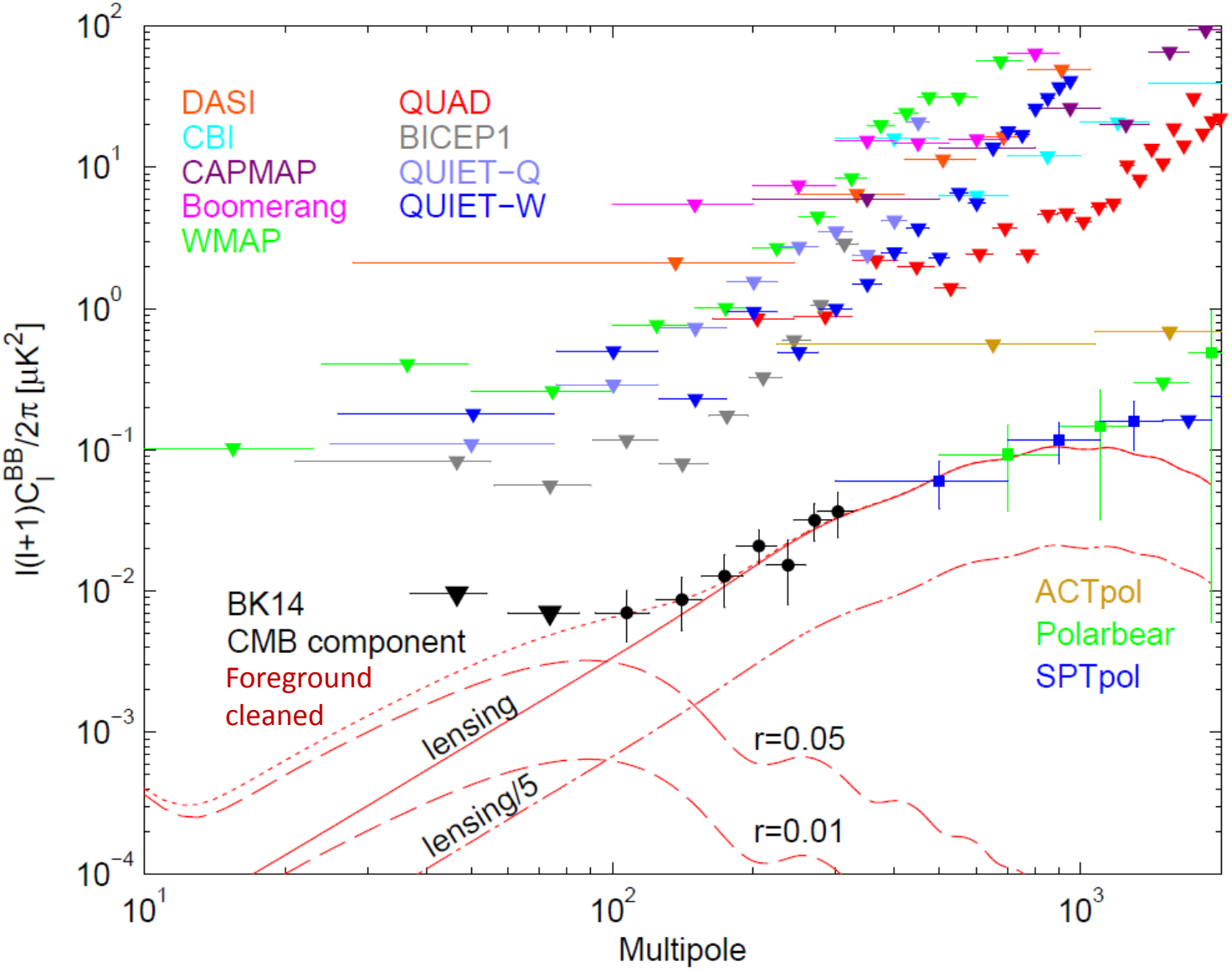


Giannantonio et al 2015

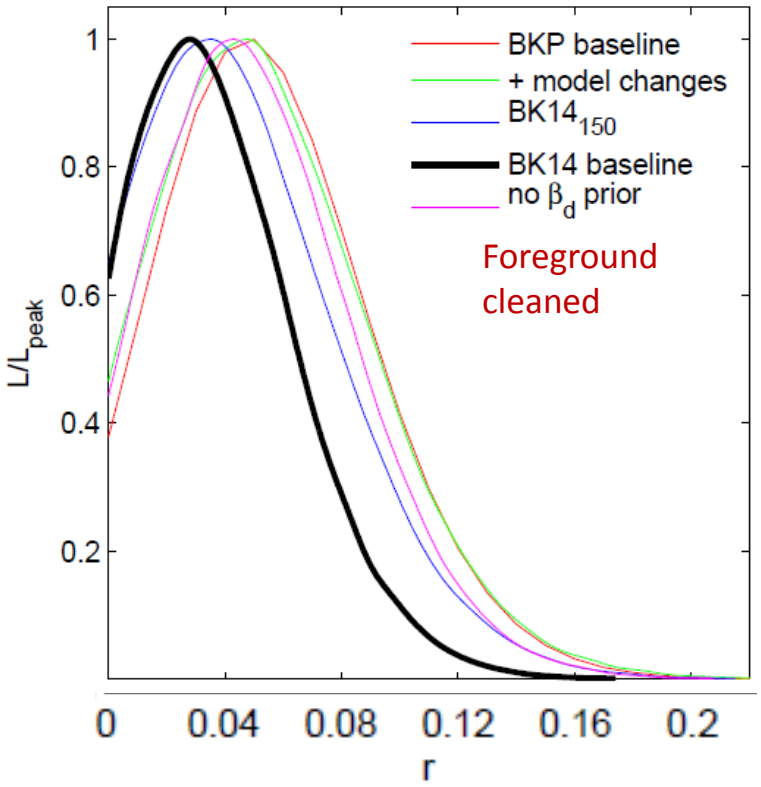
CMB Power Spectra



Current State of B-Mode Polarization Data



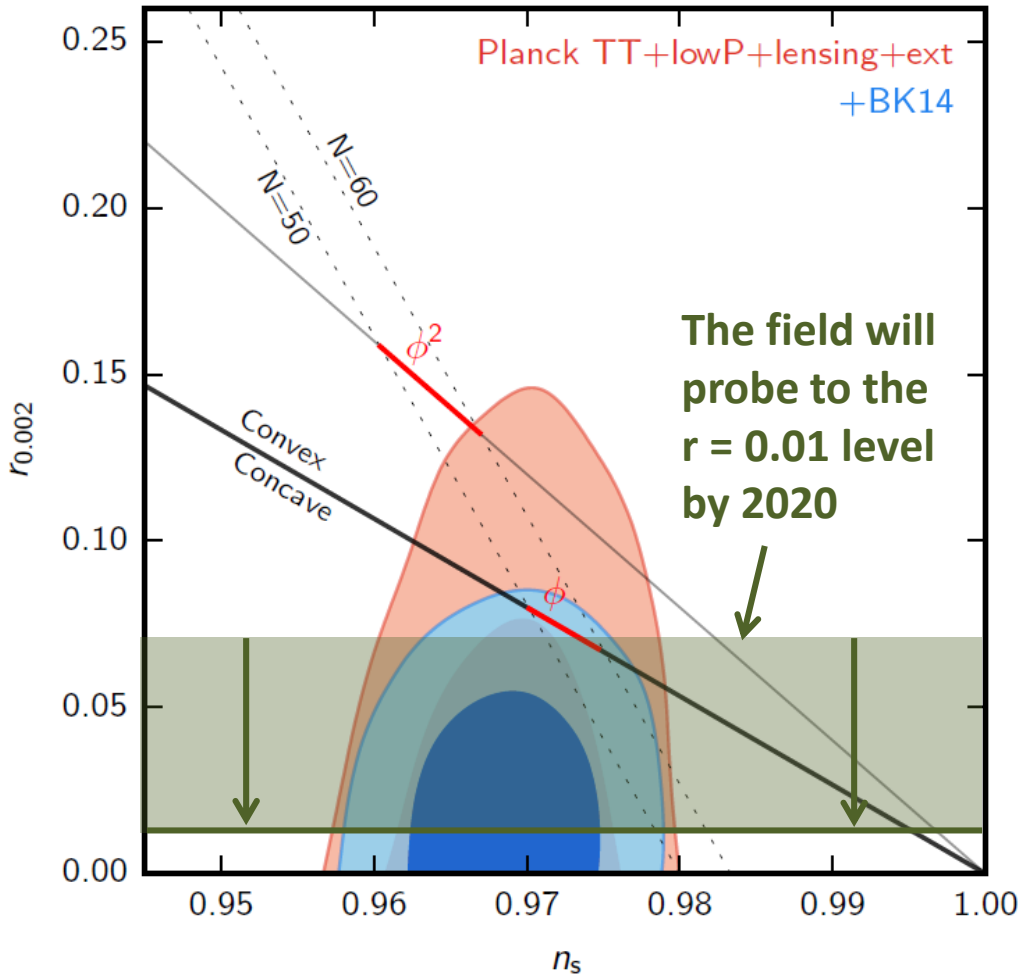
Implications for Inflation



$r = 0.028^{+0.026}_{-0.025}$

$r < 0.09$ (95 % CF)

Polarization data have overtaken CMB temperature info!

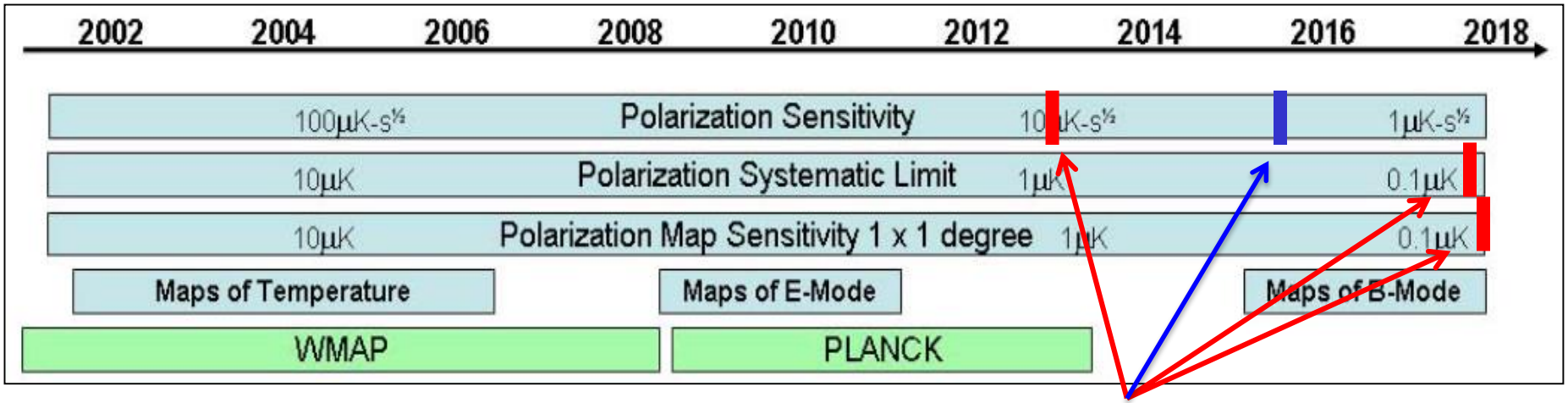


Combined with temperature: $r < 0.07$

Where We Are Today

Benchmarking Array Sensitivity and Systematics

Task Force for CMB Research Weiss Report: Projected Timeline from 2005



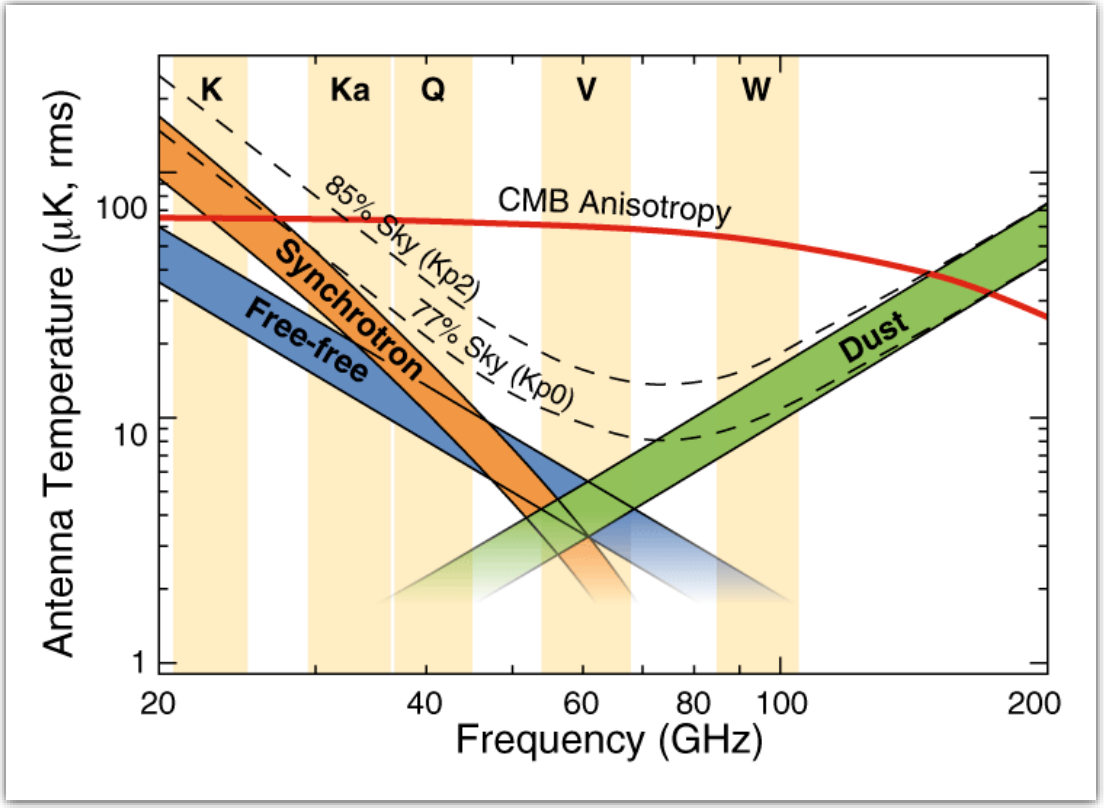
Where we are today in 2015 (Ground, Balloon)

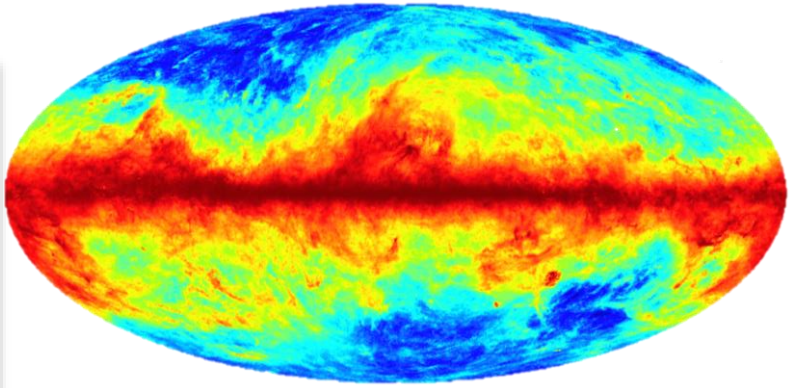
Polarization Sensitivity: 9.5 uK √s (ground; Keck Array arXiv 15002.00643)
~4 uK √s (balloon; SPIDER priv. comm.)

Polarization Systematics: < 2σ instrument sensitivity $2(\Delta D_\ell)^{1/2}$ ~ 60 nK at $\ell = 100$
(BICEP II/Keck arXiv 1510.09217)

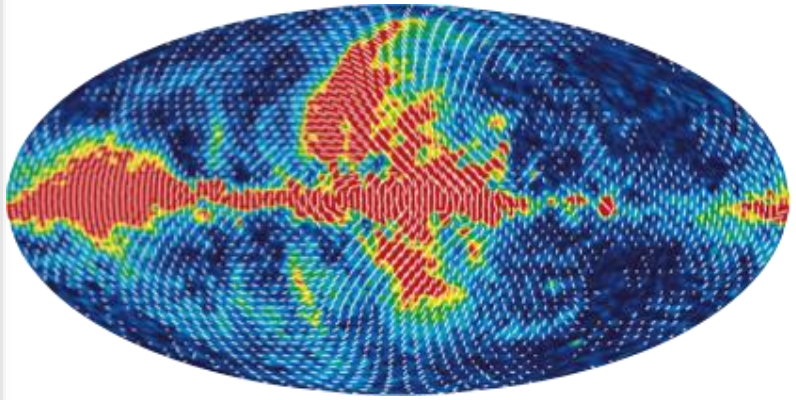
Polarization Map Sensitivity: 50 nK-deg in 395 sq. deg.
(BICEP II/Keck arXiv 1510.09217)

Foreground Challenges: the Galaxy





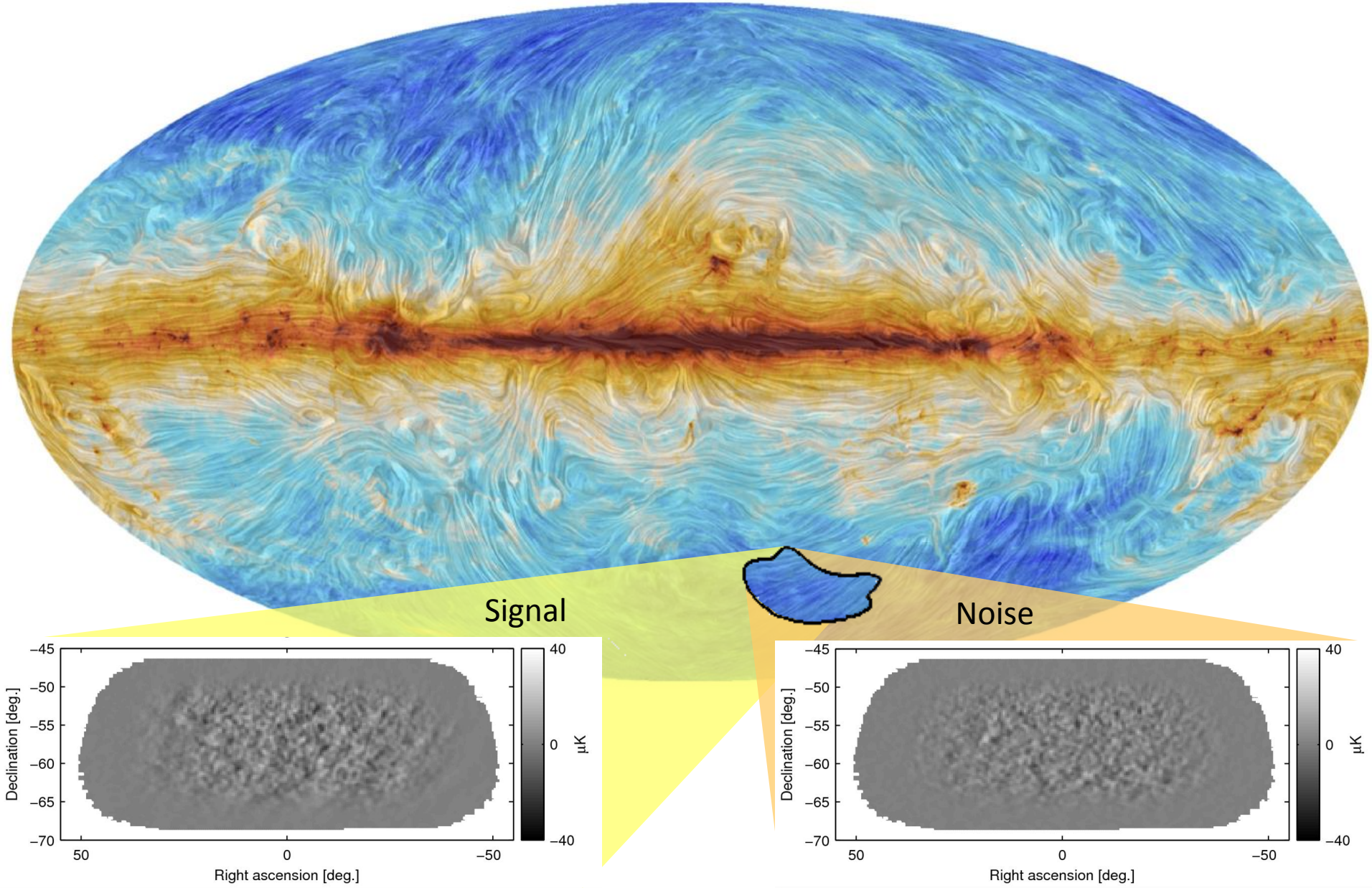
Model of Polarized Dust Emission



Map of Polarized Synchrotron Emission

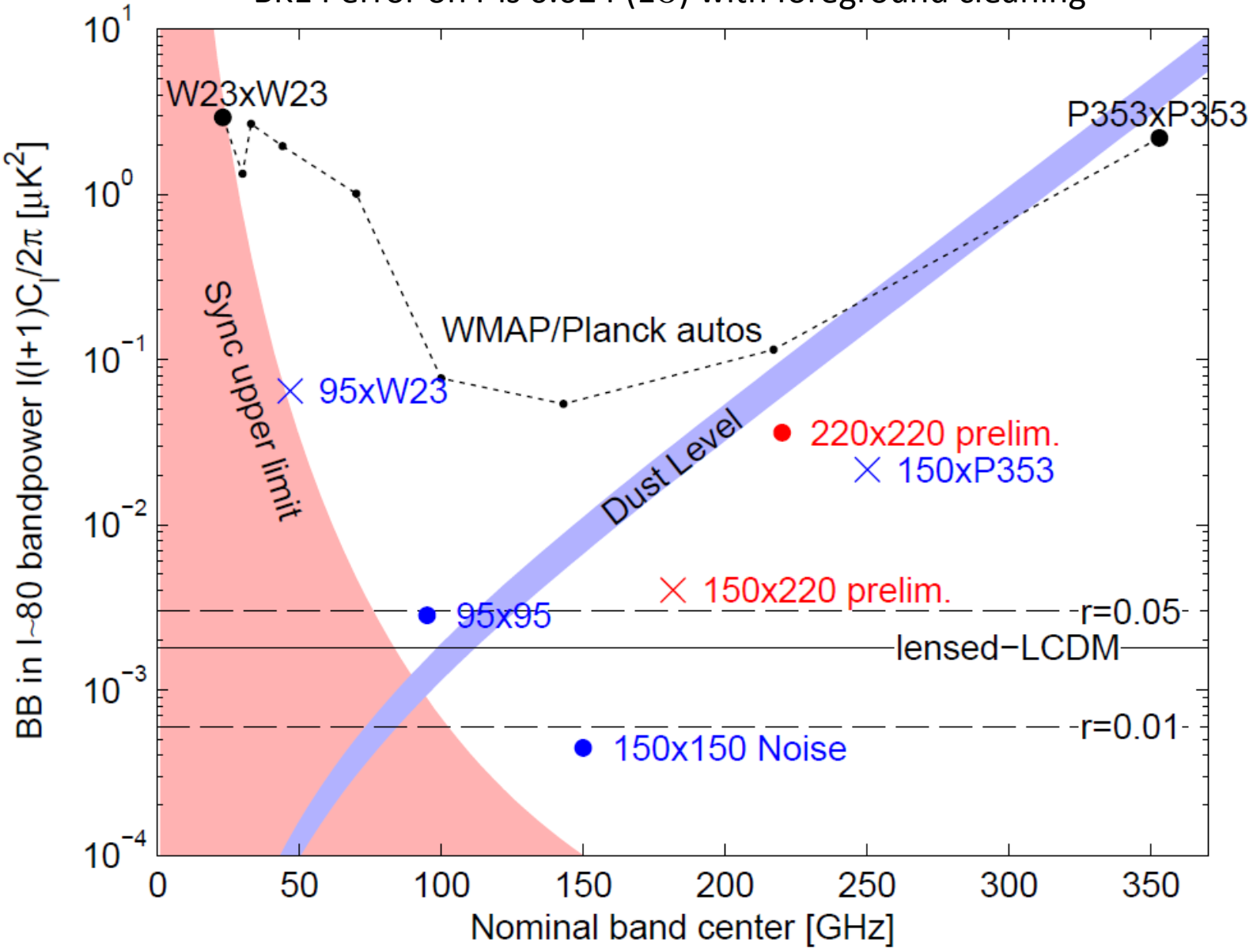
- **Synchrotron** Spiraling electrons Emission α (Frequency)$^{-3}$
- **Dust** Galactic dust grains Emission α (Frequency)$^{1.75}$

Planck Noise on Polarized Dust Emission



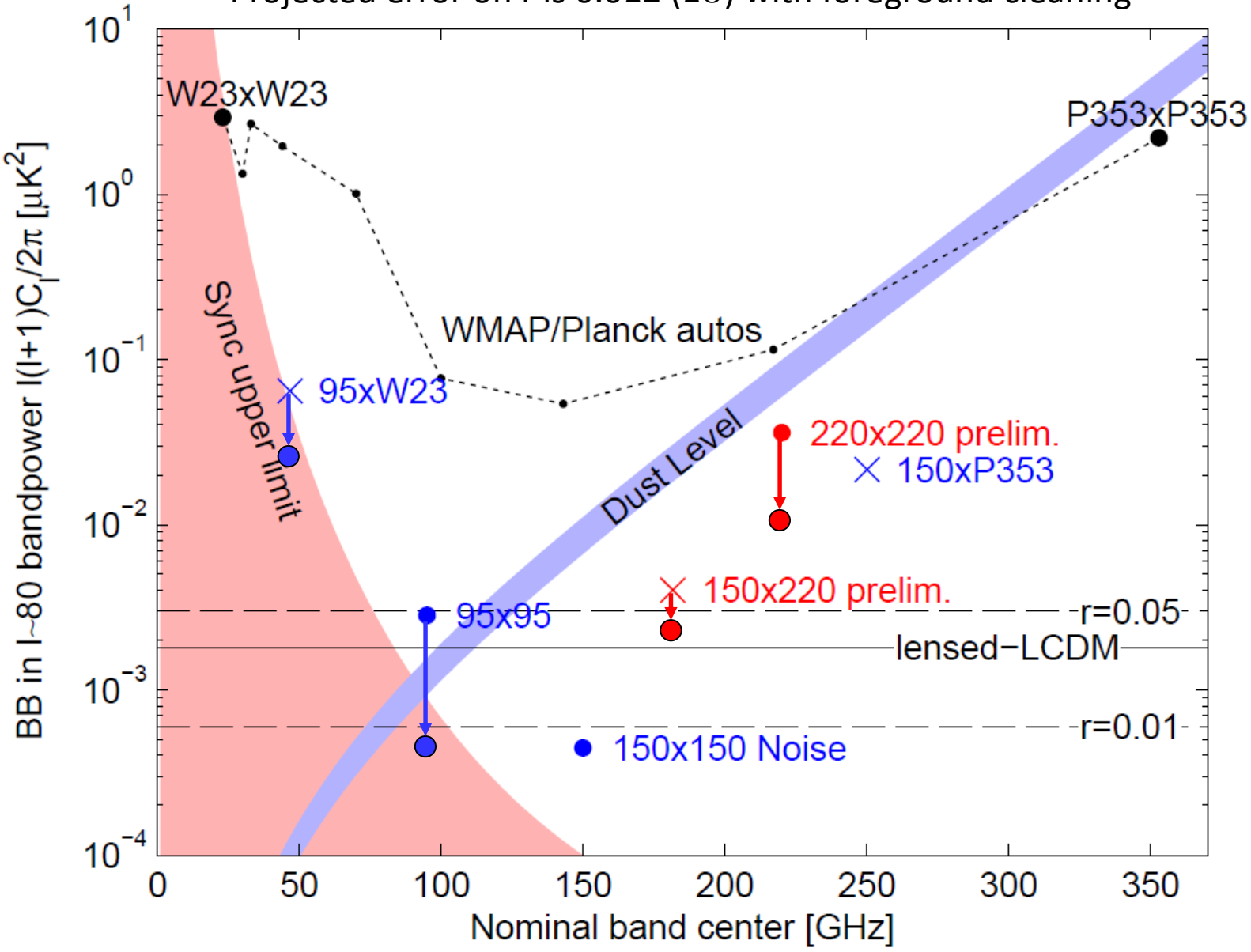
Why Multi-Frequency Data are Important

BK14 error on r is 0.024 (1σ) with foreground cleaning



Projections for BK2016

Projected error on r is 0.012 (1σ) with foreground cleaning



The Future of Polarization Measurements

Experiments 2016 – 2020

Measurements to r = 0.01 (3σ)

- Focused on recombination bump
- Deep foreground removal
- Partial lensing removal

Spaceborne Measurements

All-sky, all-frequency

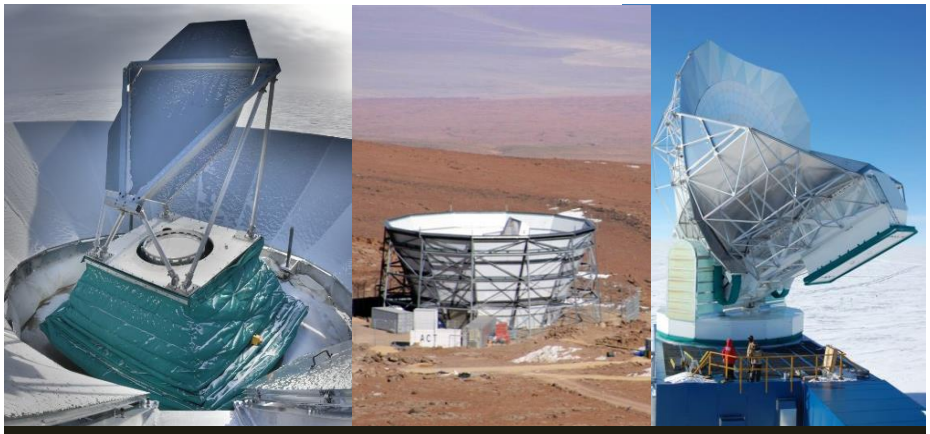
- Determine exact value of r
- Test statistical isotropy
- Measure full spatial spectrum

Ground-Based Measurements

Large Apertures

- Small regions to great depth
- Large-sky lensing
- Neutrino masses, N_{eff}

Space: Inflation Probe

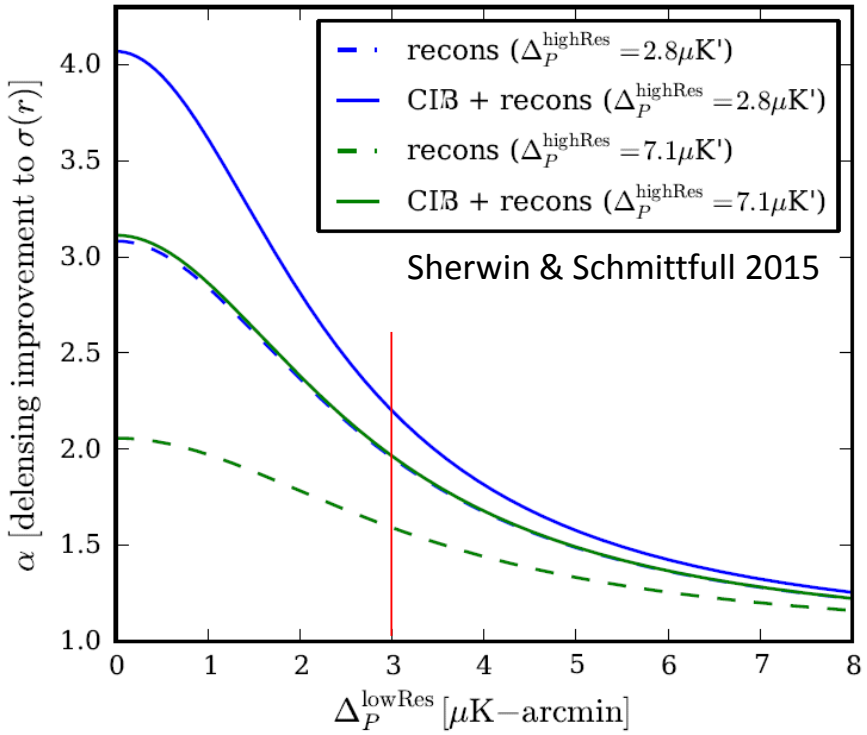


Ground: Stage-4 Program

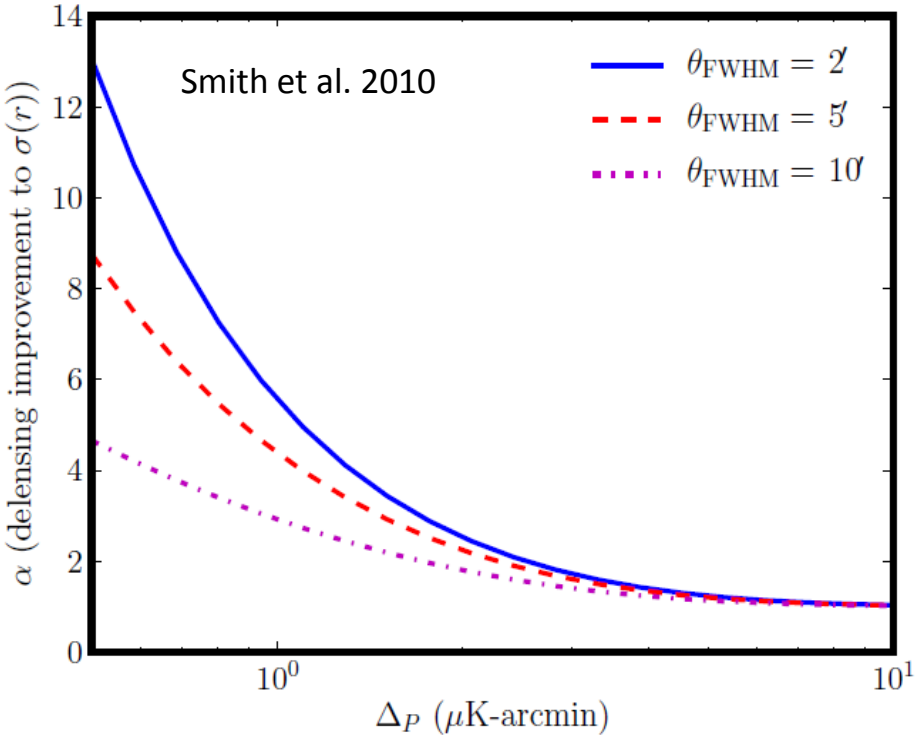
“Delensing” Gravitational B-Modes

Removing a Cosmological Foreground

Lensing from CMB + CIB



Lensing from CMB Only



Lensing B-modes from high-res polarization map

- Using CIB as a partial lensing tracer helps at low sensitivity (e.g. 7.1 uK-arcmin)
- Background E-modes from high-res map

In the future, lensing is best removed using CMB data only. Need high-sensitivity polarization measurements with several arcmin resolution

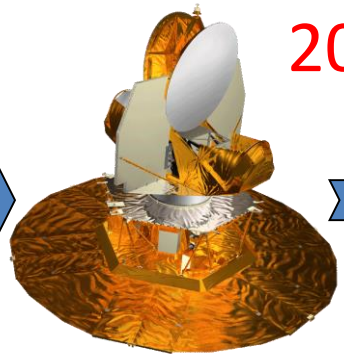
Synergistic Development for a Satellite Mission

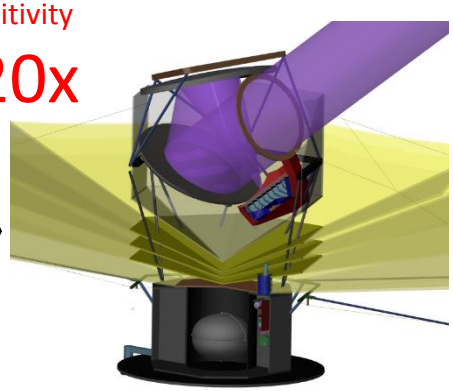
Satellite Mission

Sensitivity 60x

Sensitivity 20x

Sensitivity >20x





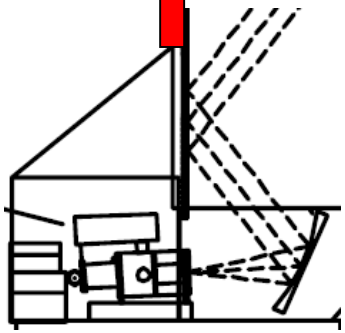
100 μK — 1 μK — 100 nK — few nK

Sub-Orbital Precursor

COBE 1989

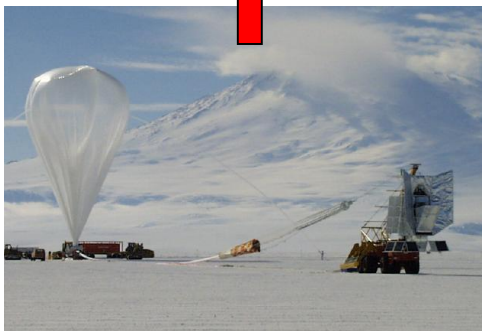
Woody-Richards

WMAP 2001



QMAP, SK, TOCO

Planck 2009



Archeops, Boomerang, Maxima

CMBPOL 2020s

BICEP/KECK, ACT, SPT, Simons Array, CLASS, EBEX, SPIDER…

Historical Interplay: Suborbital Experiments serve to

- Shape scientific objective of a space mission
- Train leaders of future orbital missions
- Develop experimental methodologies
- Develop technologies at systems level

Conclusions

Gravitational waves can tell us what powered inflation

- Inflation requires new physics at high energies
- Connects Einstein's gravity to quantum mechanics

Experiments will push to r = 0.01 in the next 5 years

- Experiments will measure foregrounds
- Delensing will go from theory to common practice

Polarization measurements will probe

- Number of light particle species
- Mass of neutrinos
- Structure of large-scale dark matter