CMB and Inflation

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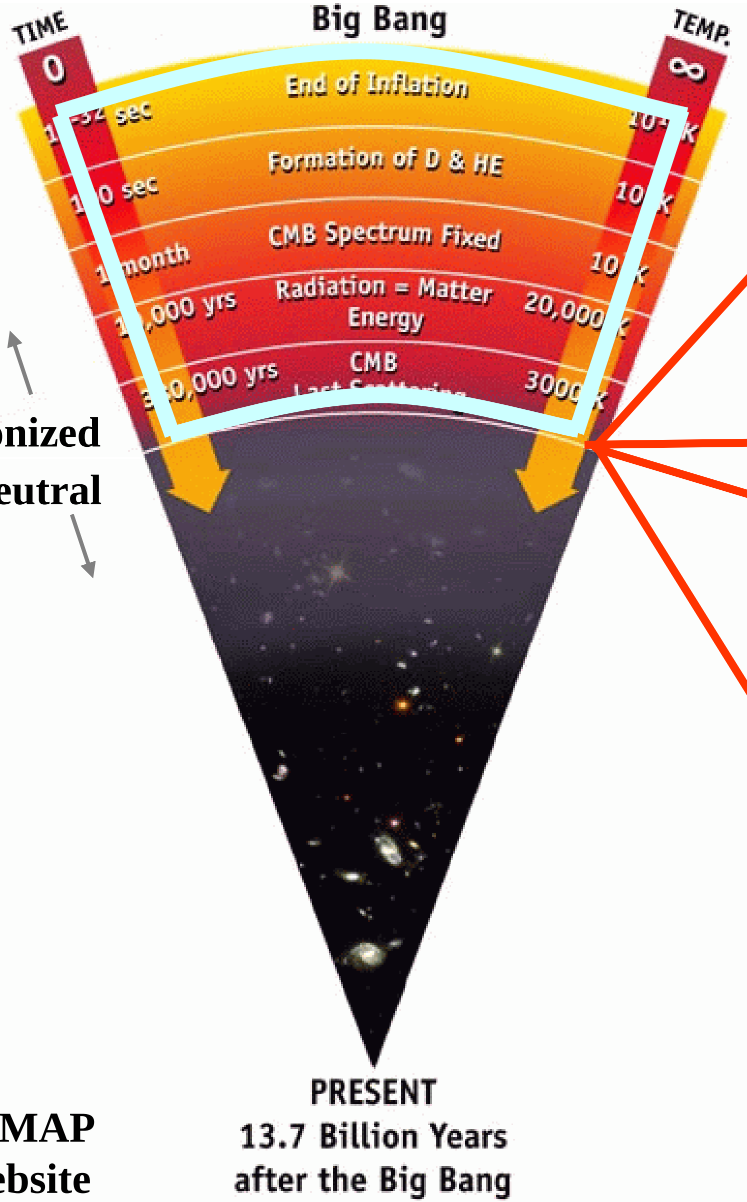
Inflation observables

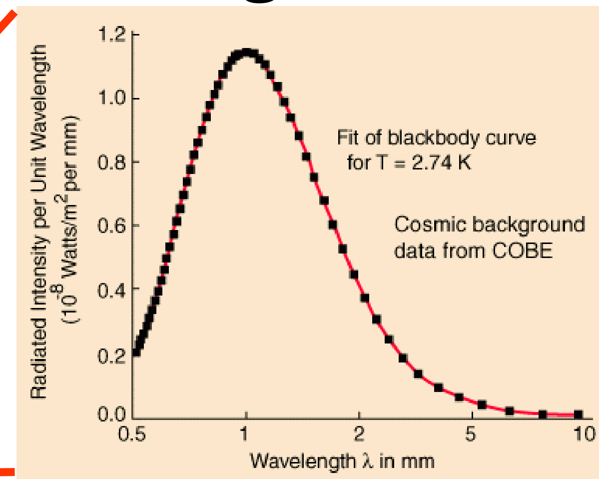
- Flatness, with refined precision
- Super-horizon uniformity/perturbations
- Sharp acoustic oscillations
- Properties of initial perturbations
  - Adiabaticity
  - Scale-invariance
  - Gaussianity
- Polarization in the CMB
  - E-mode polarization, TE correlation
  - *B-mode polarization (future test)*

The Best Tool:
Cosmic Microwave Background

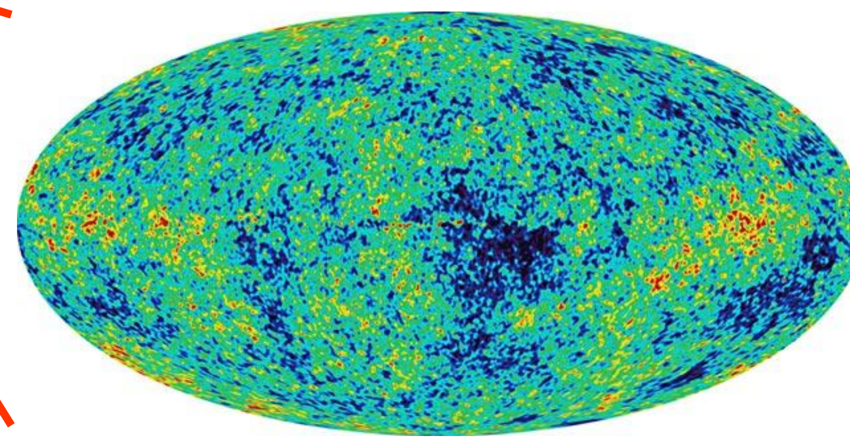


ionized

neutral



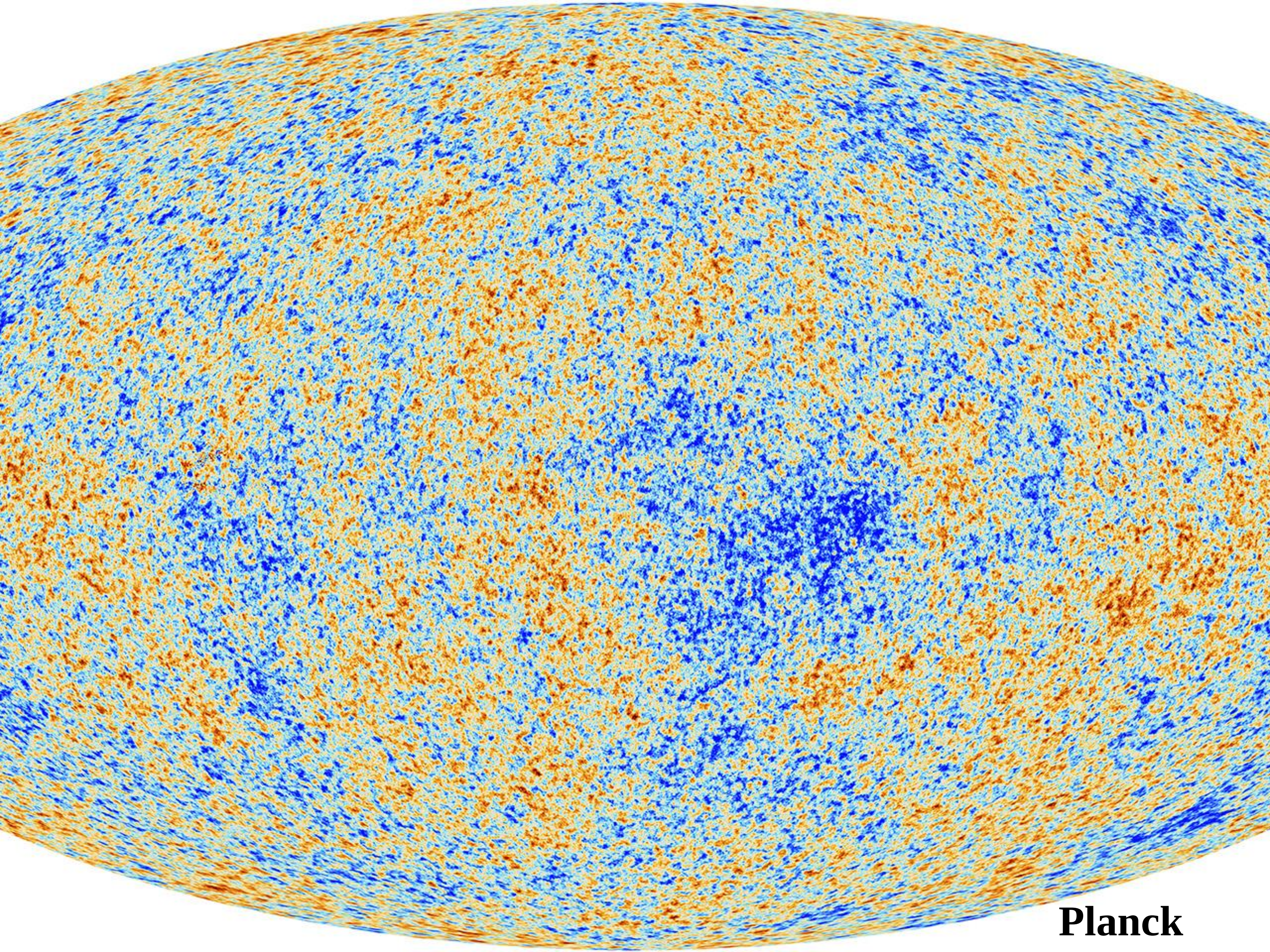
1. blackbody emission law



2. angular anisotropy → power spectrum

3. And, it is polarized! (Rees, 1968)

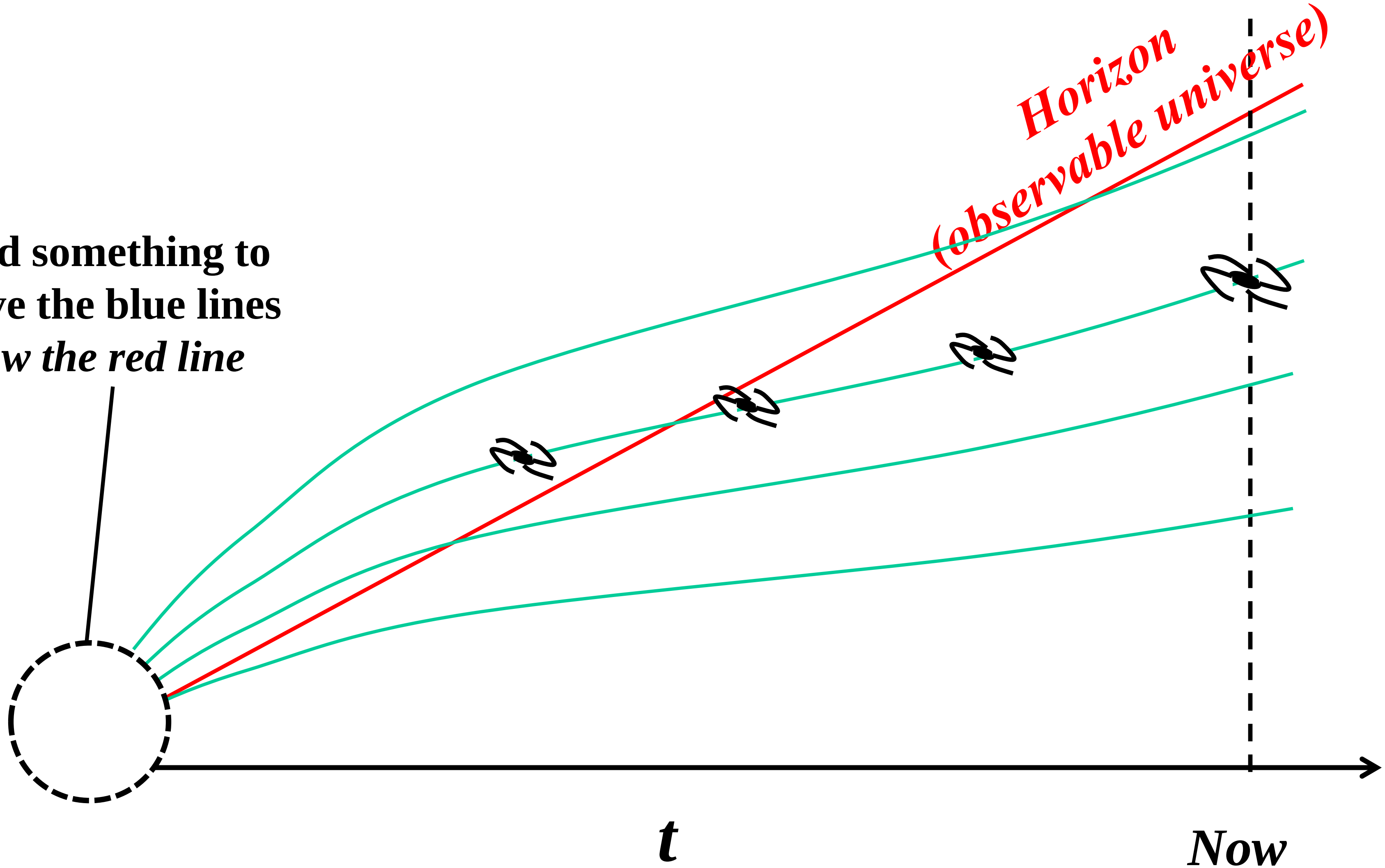
WMAP website



Planck

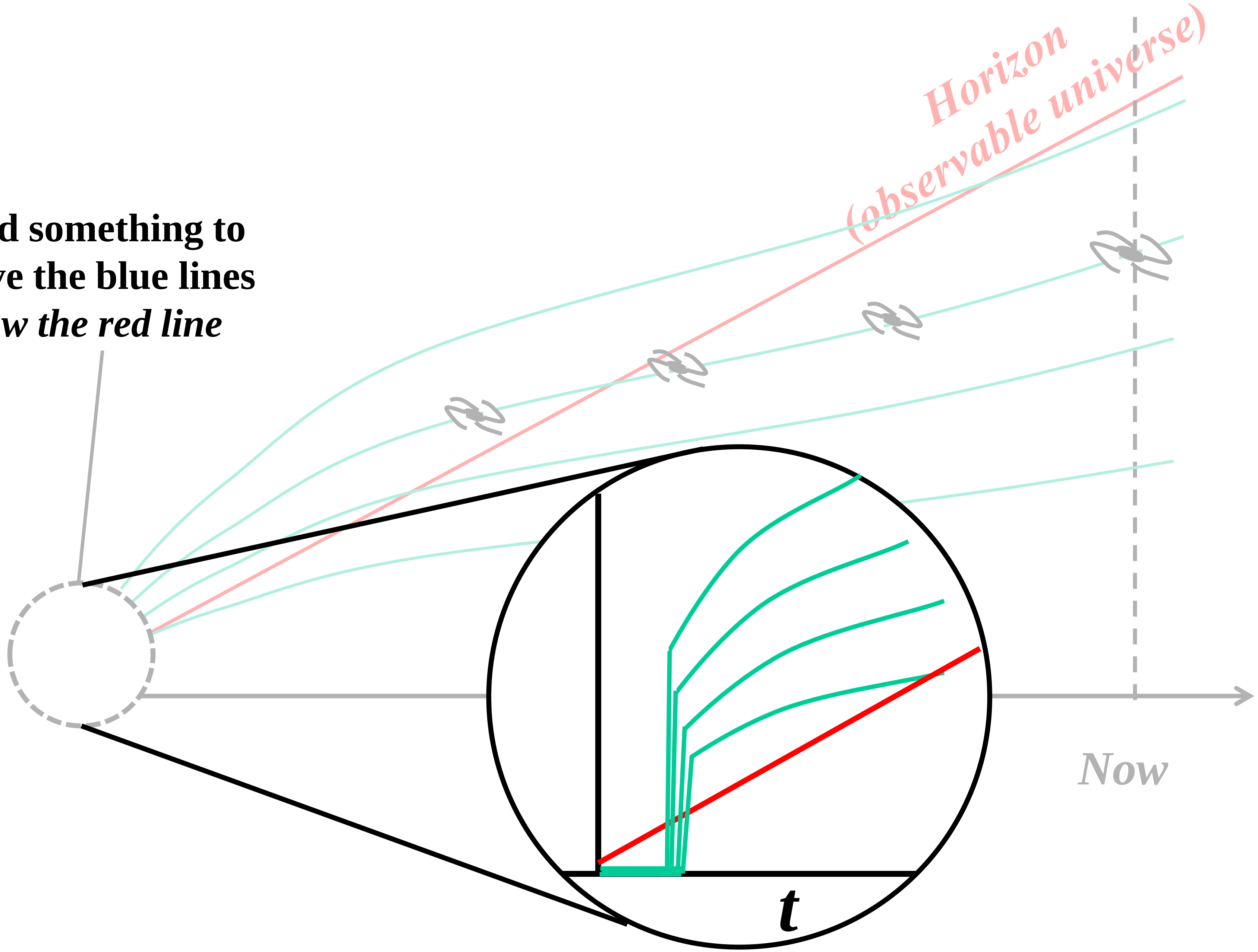
Inflation

Need something to
move the blue lines
below the red line



Inflation

Need something to move the blue lines *below the red line*



Peculiarities about the early universe

- Horizon problem [✓]
- Flatness problem; old and new

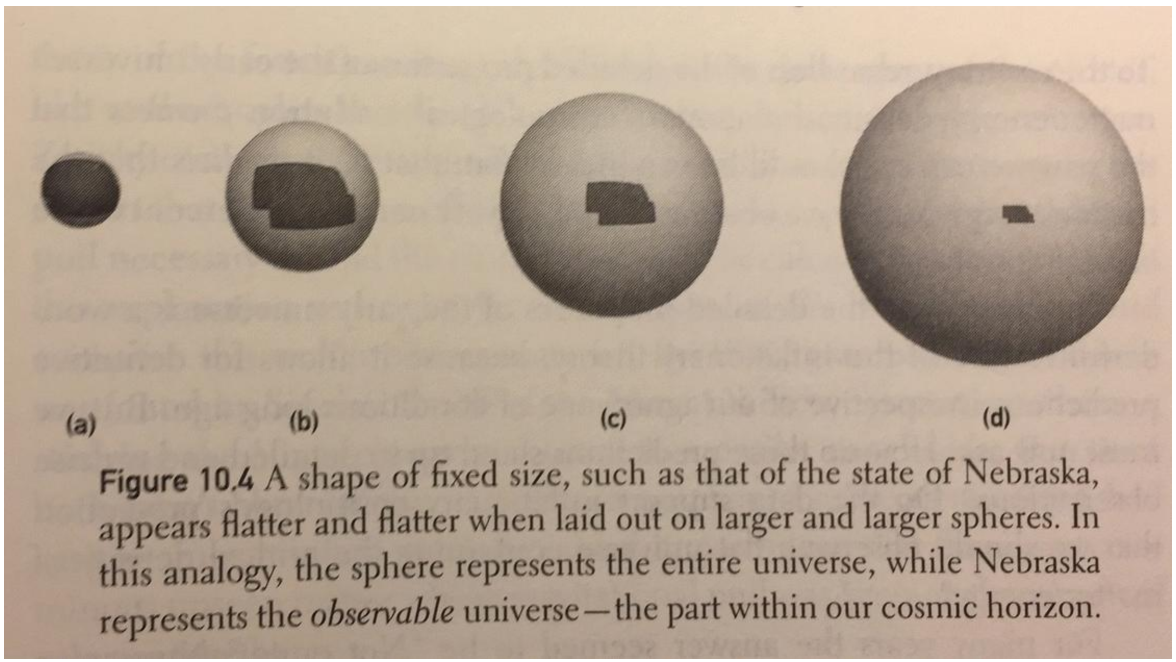


Figure 10.4 A shape of fixed size, such as that of the state of Nebraska, appears flatter and flatter when laid out on larger and larger spheres. In this analogy, the sphere represents the entire universe, while Nebraska represents the *observable* universe—the part within our cosmic horizon.

B. Greene

Peculiarities about the early universe

- Horizon problem [✓]
- Flatness problem; old and new [✓]

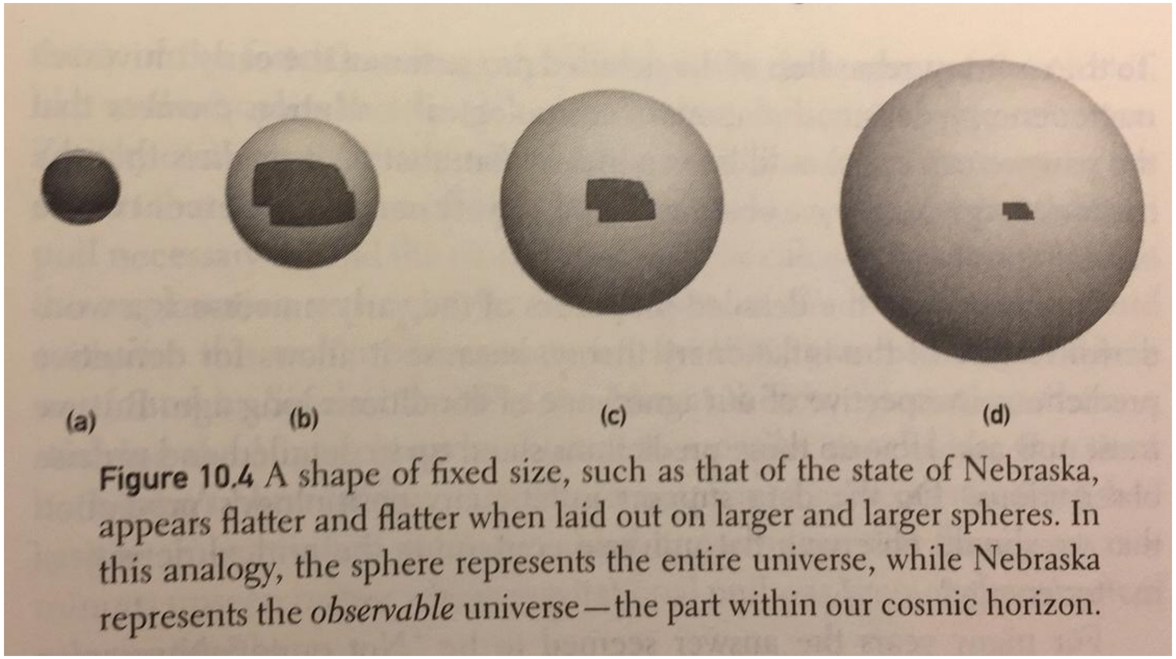


Figure 10.4 A shape of fixed size, such as that of the state of Nebraska, appears flatter and flatter when laid out on larger and larger spheres. In this analogy, the sphere represents the entire universe, while Nebraska represents the *observable* universe—the part within our cosmic horizon.

B. Greene

Inflation

- Solved the horizon and flatness problems
- How is it achieved ? Exponential expansion.

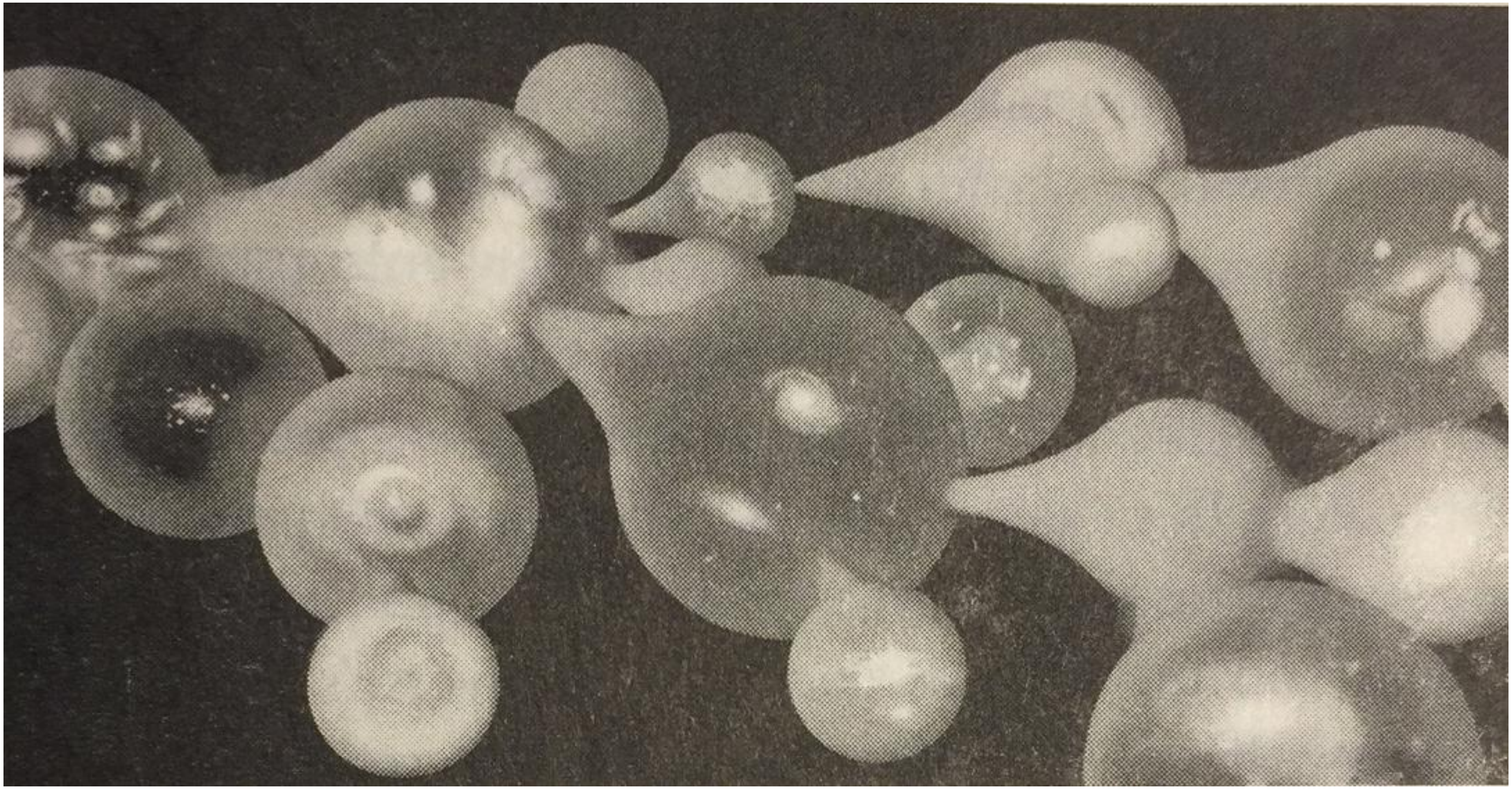
$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \qquad \longleftrightarrow \qquad \nabla^2 \Phi = 4\pi G \rho$$

$$T_{\mu\nu} = \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} g_{\mu\nu} \partial^\sigma \varphi \partial_\sigma \varphi - g_{\mu\nu} V(\varphi)$$

$$H^2 = \frac{8\pi G}{3} V(\varphi)$$

Slow roll, ~ const. Hubble
~ exponential expansion (inflation)

Big Bang or Inflation ? Who cares ?
(Aren't they similar enough ?)



(and what about all these debates on its naturalness?) arXiv:1511.05143

Generation of perturbations

- Assuming an inflationary 'background', *linearize the Einstein equation*

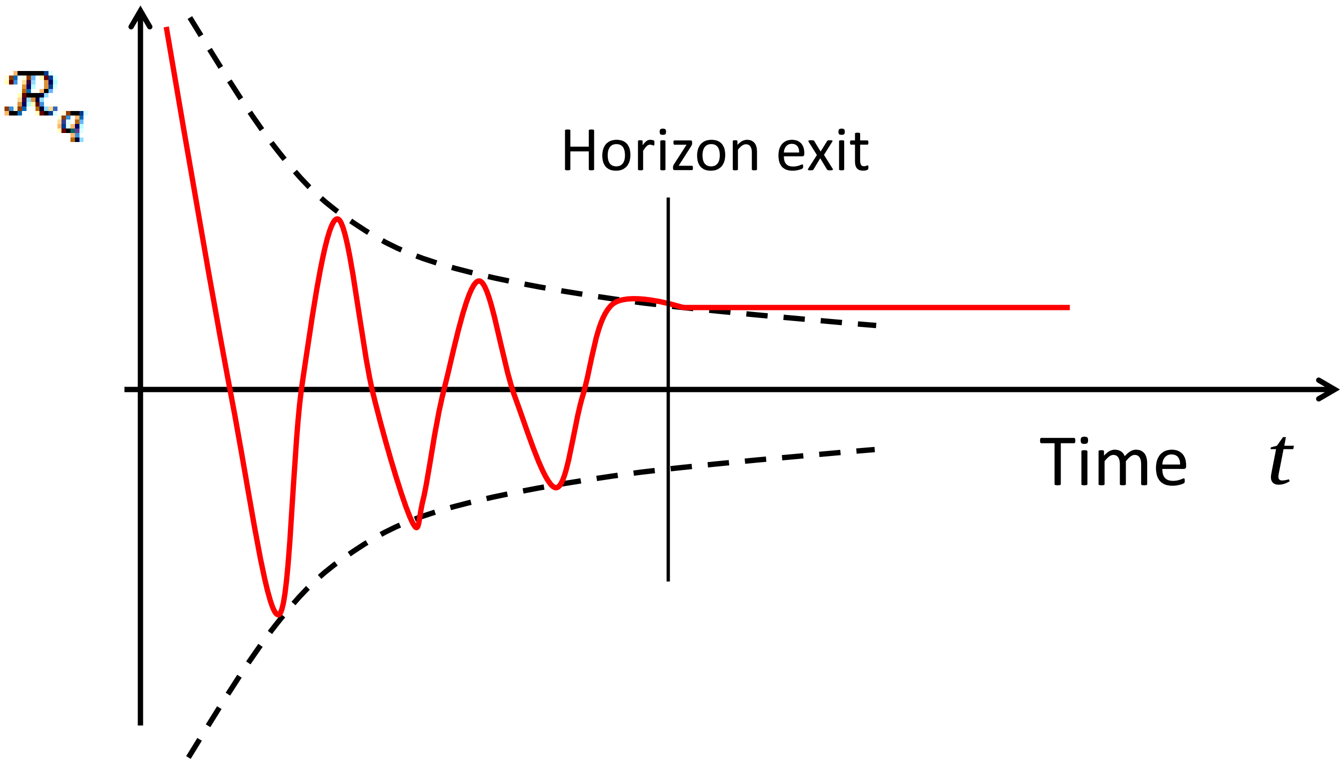
$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \longrightarrow \delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

- Once linearized, each comoving Fourier component is independent
- 3 types of wave-like perturbations, scalars, ~~vectors,~~ and tensors (density, ~~vorticity~~, gravitational waves)
- The Fourier component $\mathcal{R}_q$ that describes the amplitude of the *scalar* perturbations satisfies a linear differential eq.

$$\frac{d^2\mathcal{R}_q}{d\tau^2} + \frac{2}{z}\frac{dz}{d\tau}\frac{d\mathcal{R}_q}{d\tau} + q^2\mathcal{R}_q = 0 \qquad z \equiv \frac{a\dot{\varphi}}{H}$$

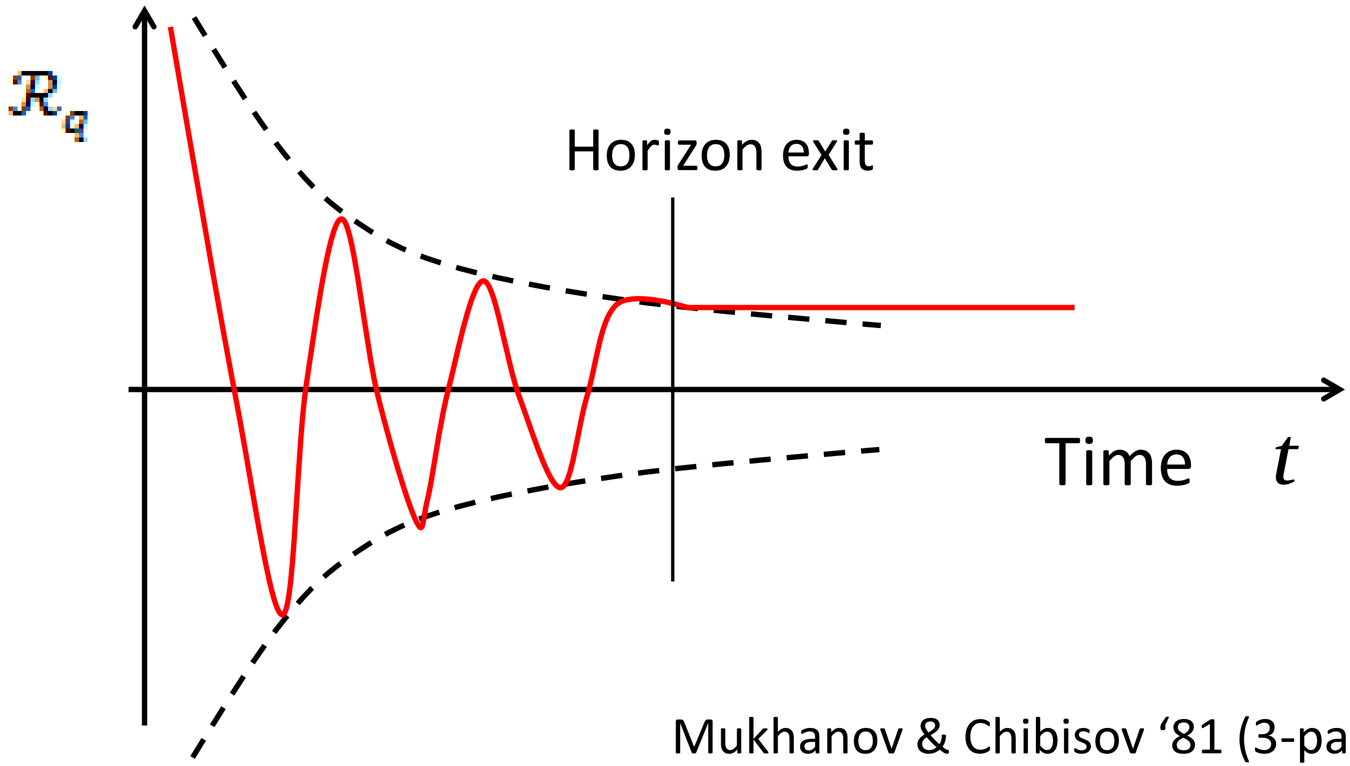
- q : comoving wavenumber, τ is the conformal time

Generation of perturbations



- What fixes the amplitude of *linear* solution ??

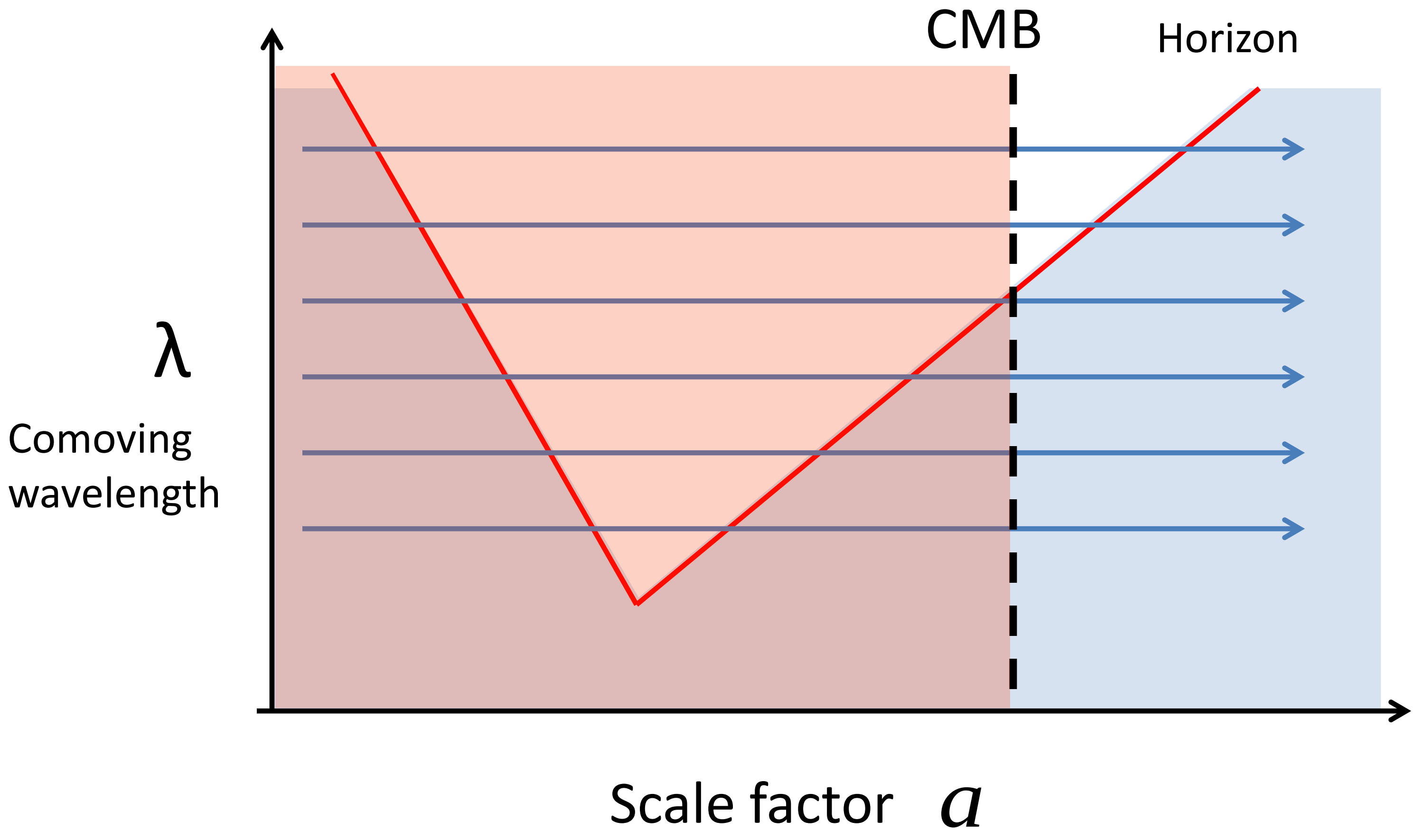
Generation of perturbations



Mukhanov & Chibisov ‘81 (3-page paper)
Guth& Pi; Hawking; ‘82; Bardeen et al., ‘83

- *Quantum fluctuations* in the vacuum state of the inflaton field fixes the r.m.s. of $\mathcal{R}_q$

Inflation



The Evidence for Inflation II.

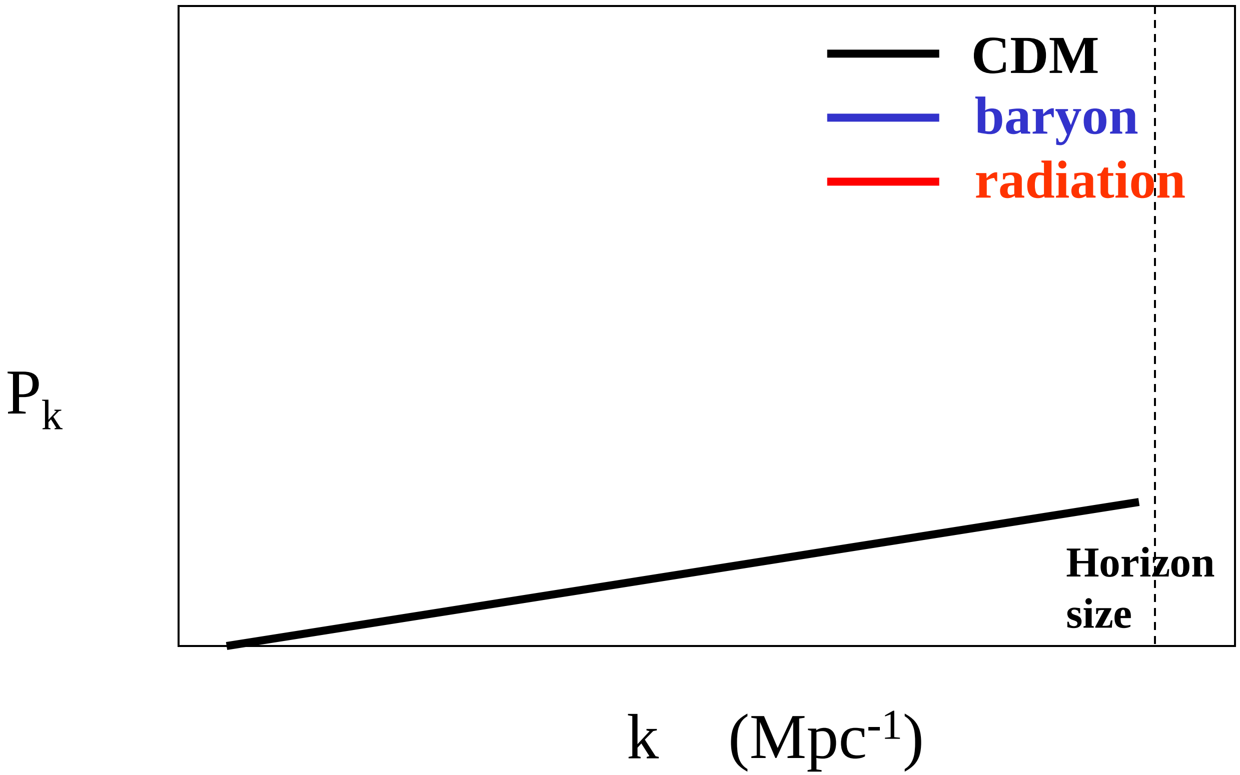
Acoustic Oscillations

(non-relativistic)

Table 1.1: Growth of Linear Perturbations

Padmanabhan

Epoch	δ_R (radiation)	δ_{CDM} (dark matter)	δ_B (baryonic)
$t < t_{enter} < t_{eq}$	$\propto a^2$	$\propto a^2$	$\propto a^2$
$t_{enter} < t < t_{eq}$	oscillates	$\propto \log a$	oscillates
$t_{eq} < t < t_{dec}$	oscillates	$\propto a$	oscillates
$t_{dec} < t$	oscillates	$\propto a$	$\propto a$



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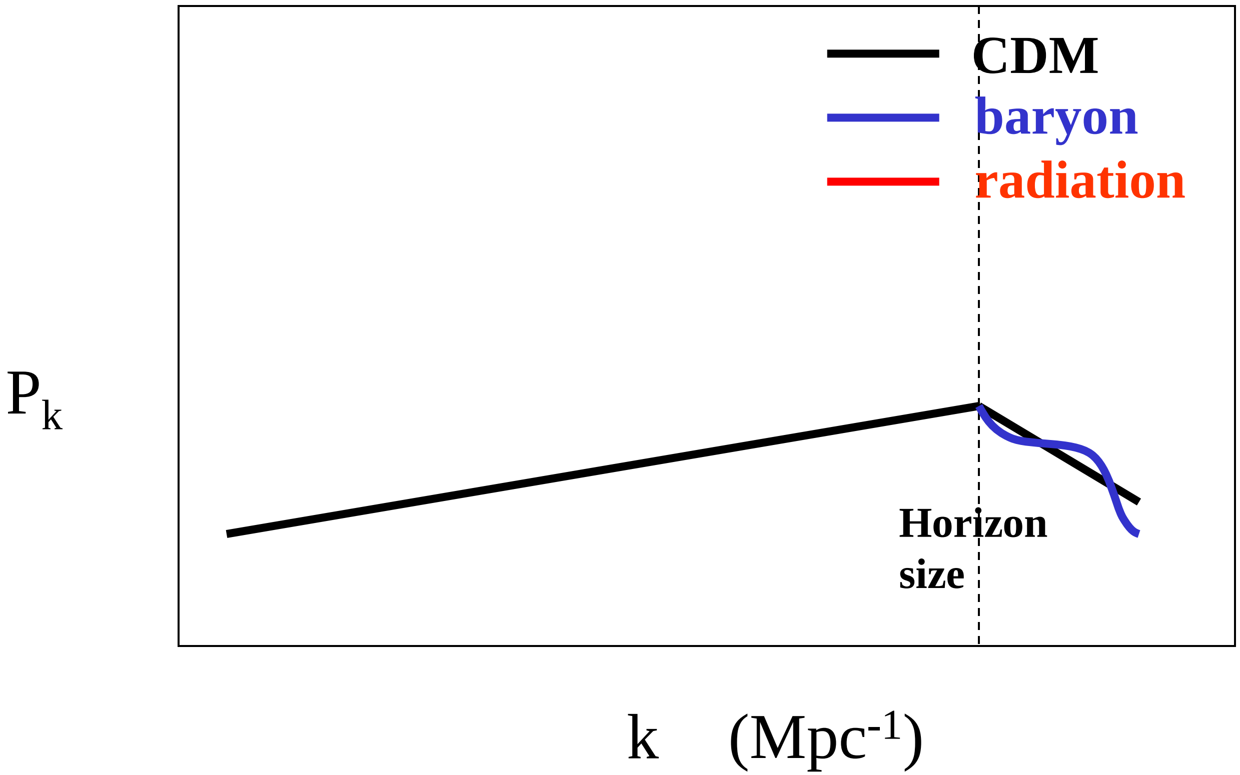

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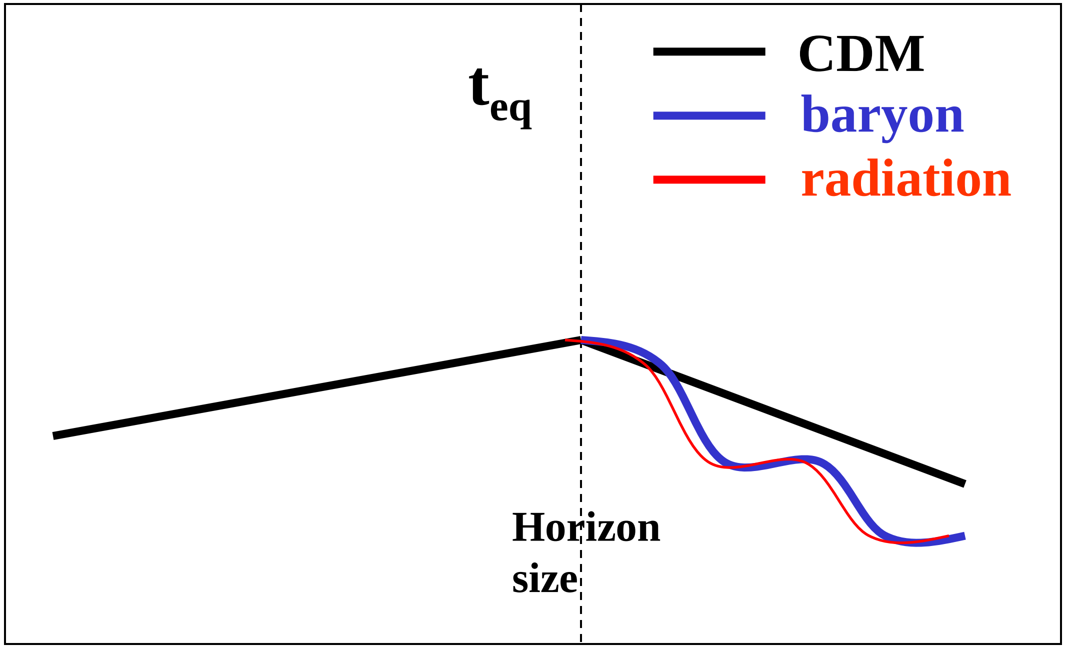
P_k



k (Mpc^{-1})

(non-relativistic)

Padmanabhan

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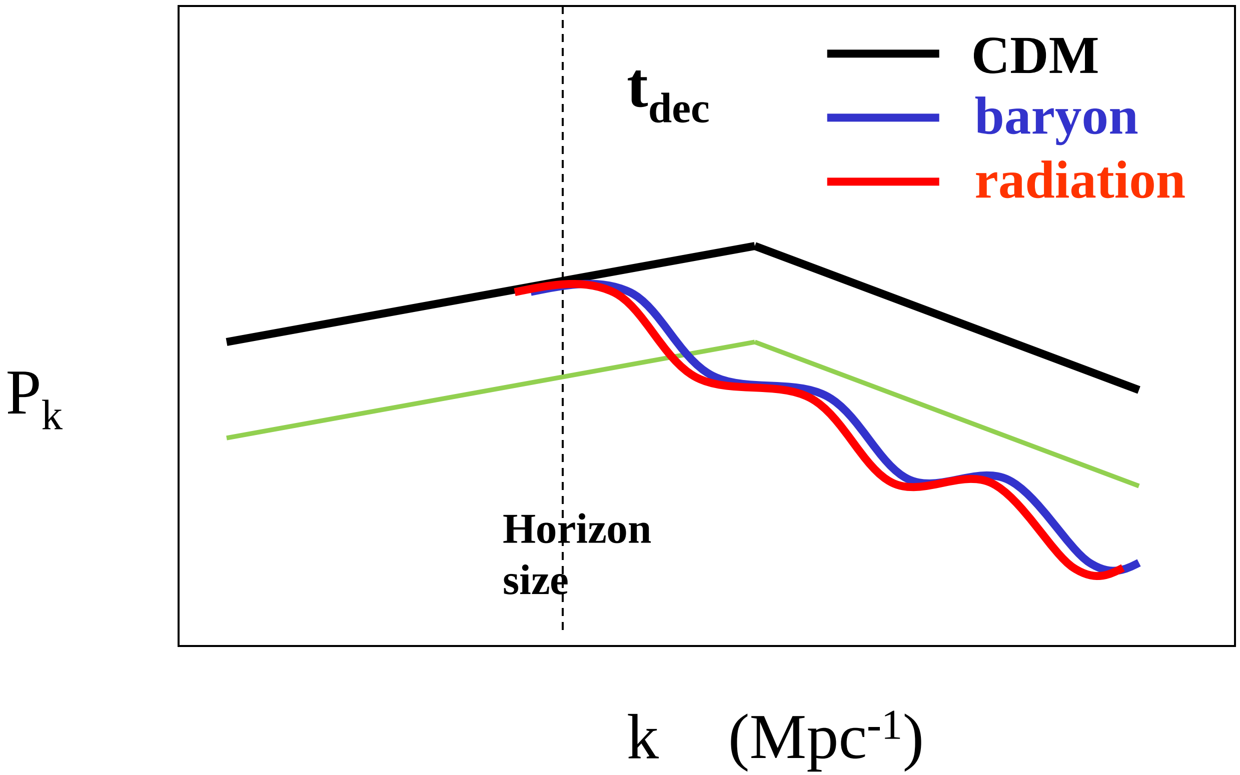

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Padmanabhan

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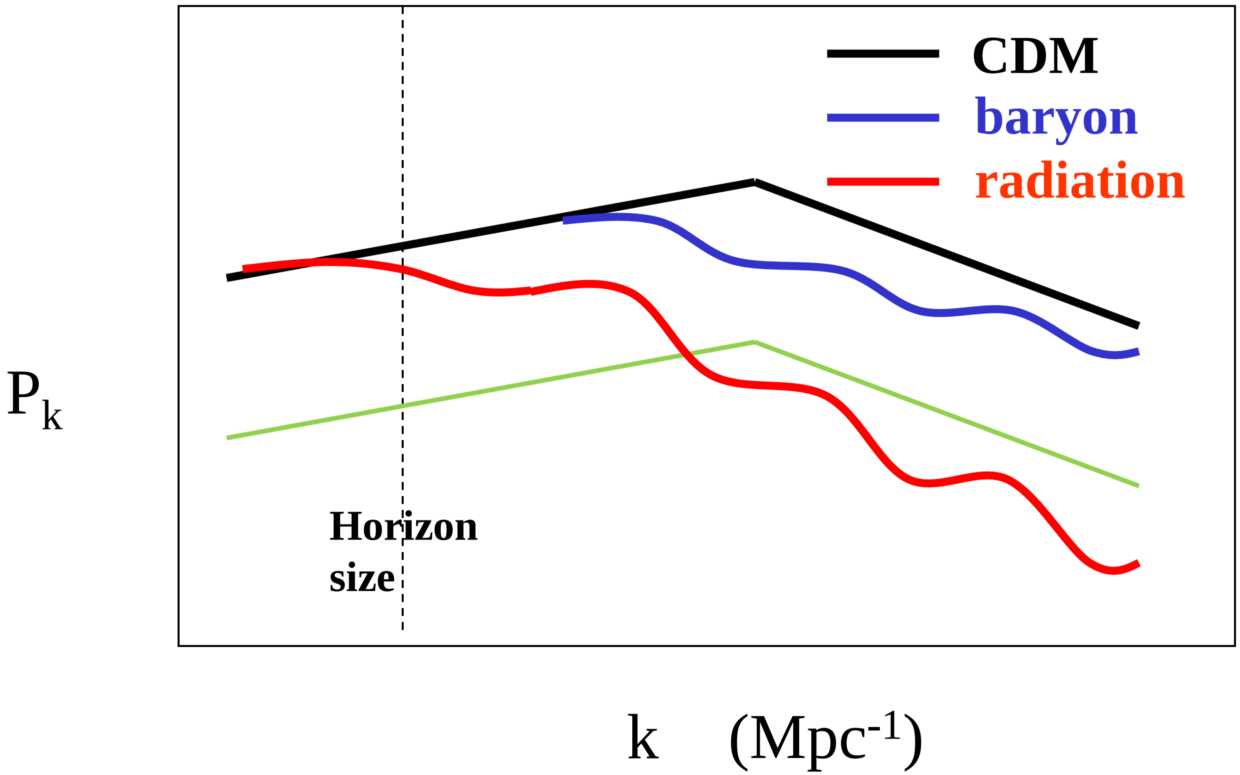
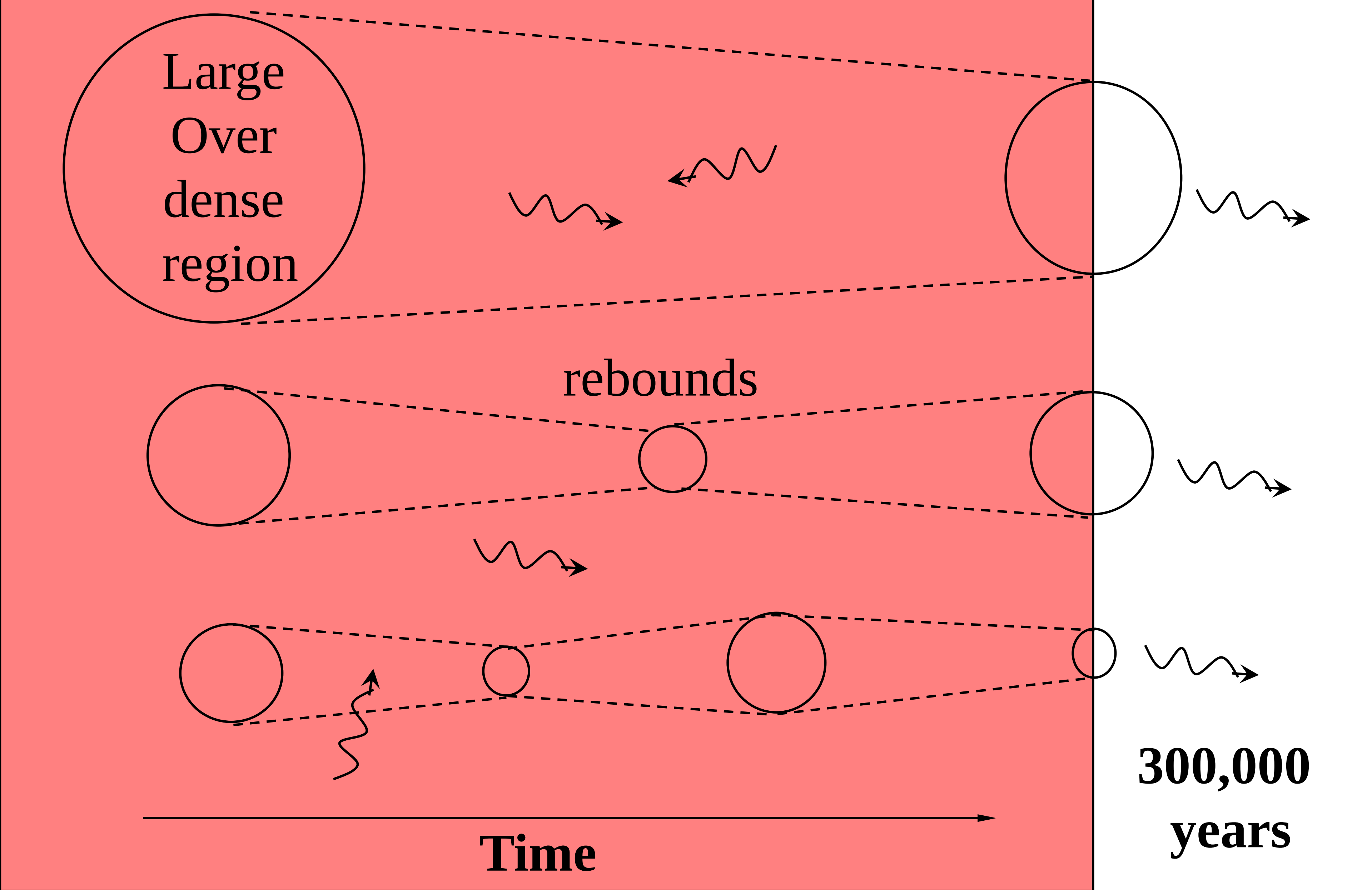
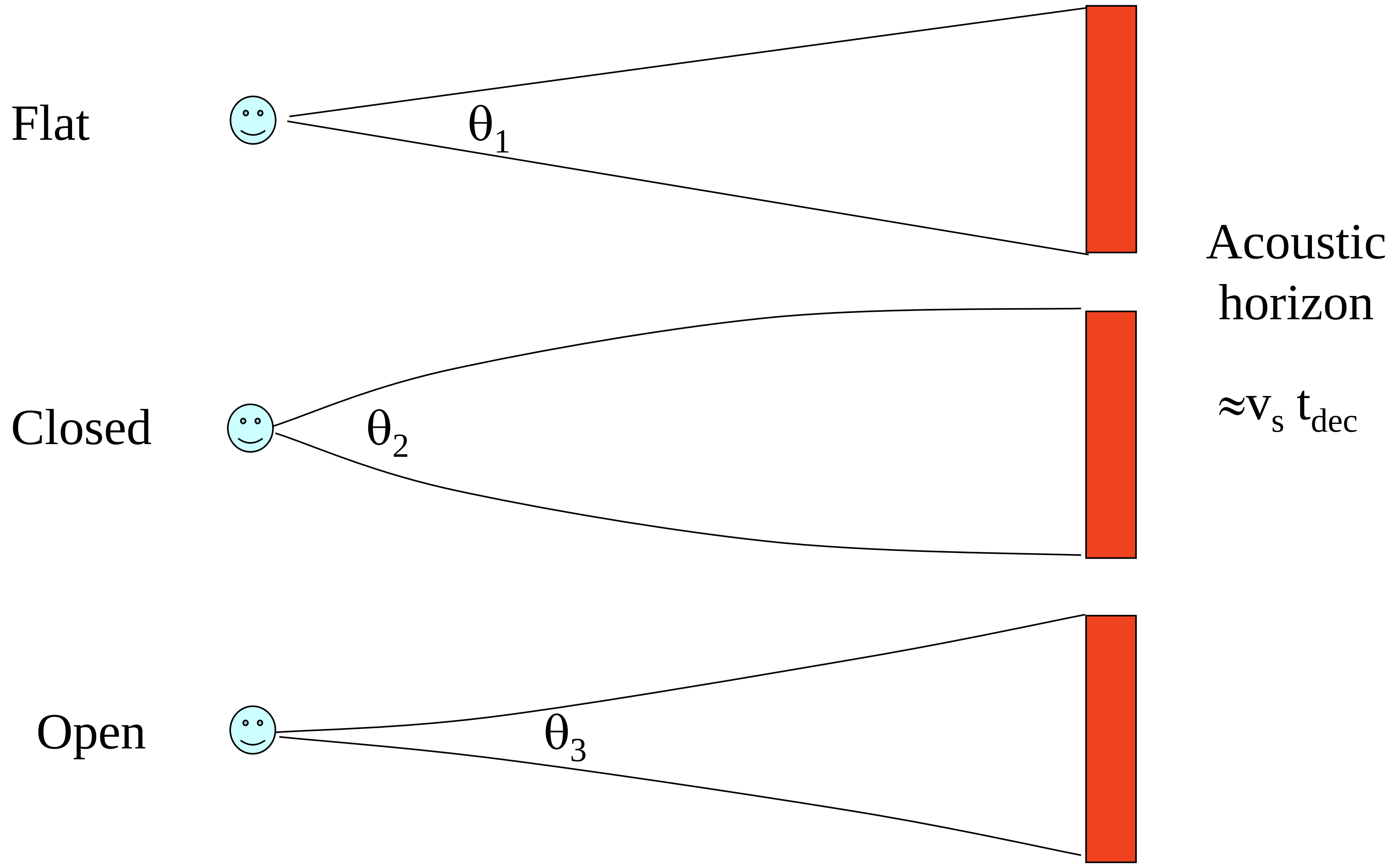


Gravitationally driven oscillations of plasma produce harmonic series of peaks in power



Measuring curvature of the universe with the CMB...



Structure on an angular scale of 1° (*l*=200) expected for a flat universe...

Causal seeds versus acausal seeds

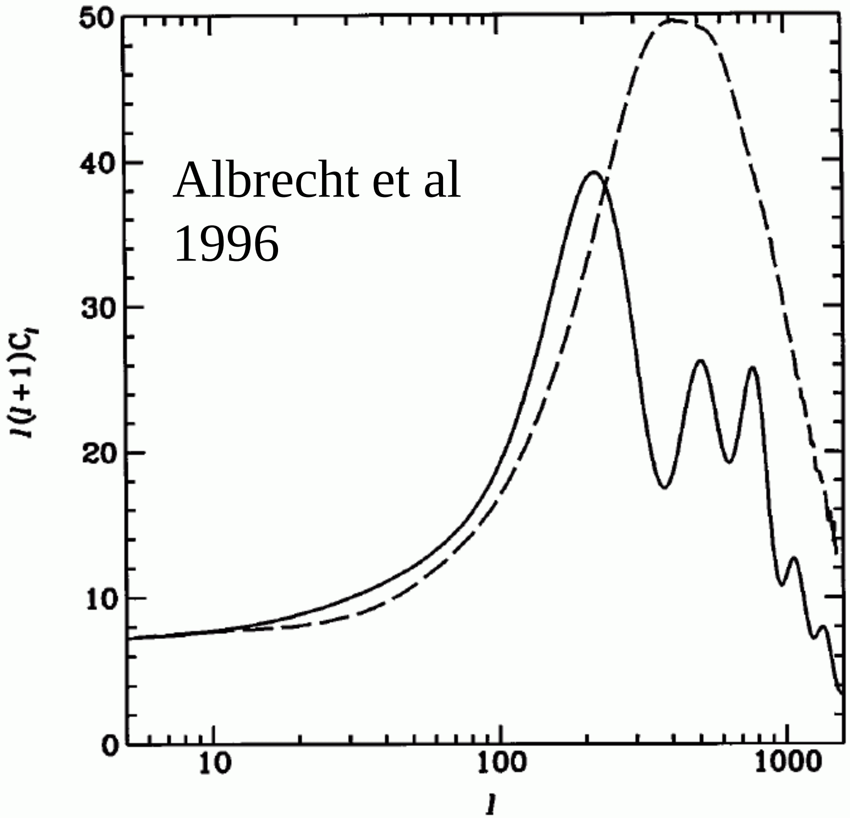


FIG. 4. Angular power spectrum of temperature fluctuations generated by cosmic strings (dashed) and arising from a typical model of scale invariant primordial fluctuations (solid) in arbitrary units. The all-sky temperature maps are decomposed

- Acausal perturbations are sometimes known as coherent perturbations
- Although, this does not mean there is any spatial phase relation between different Fourier modes
- Incoherently generated perturbations, such as those by defects (strings etc.) cause a single broad peak in the CMB power spectrum

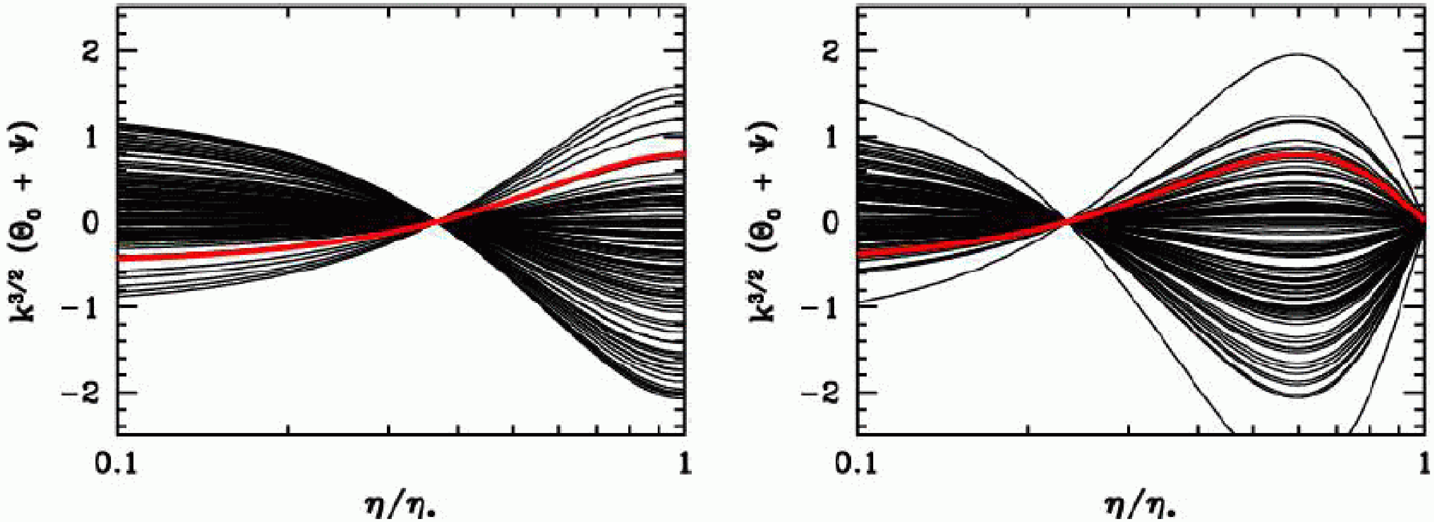


FIGURE 4. The evolution of an infinite number of modes all with the same wavelength. Left panel shows the wavelength corresponding to the first peak, right to the first trough. Although the amplitudes of all these different modes differ from one another, since they start with the same phase, the ones on the left all reach maximum amplitude at recombination; the ones on the right all go to zero at recombination.

Dodelson 2003

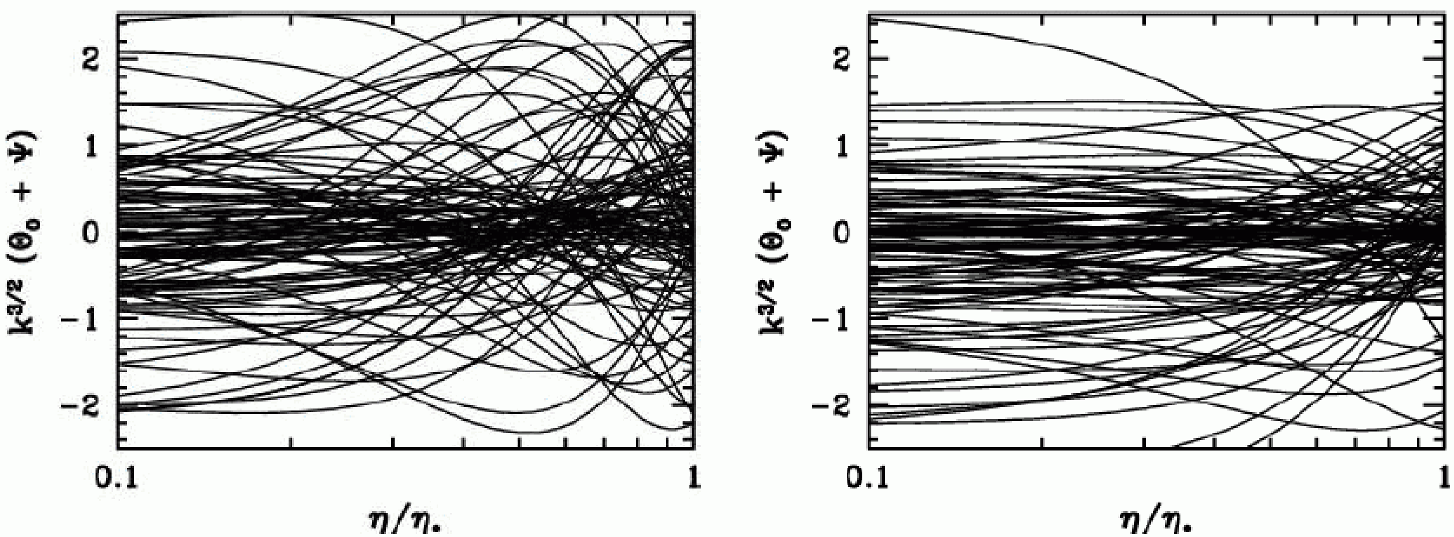
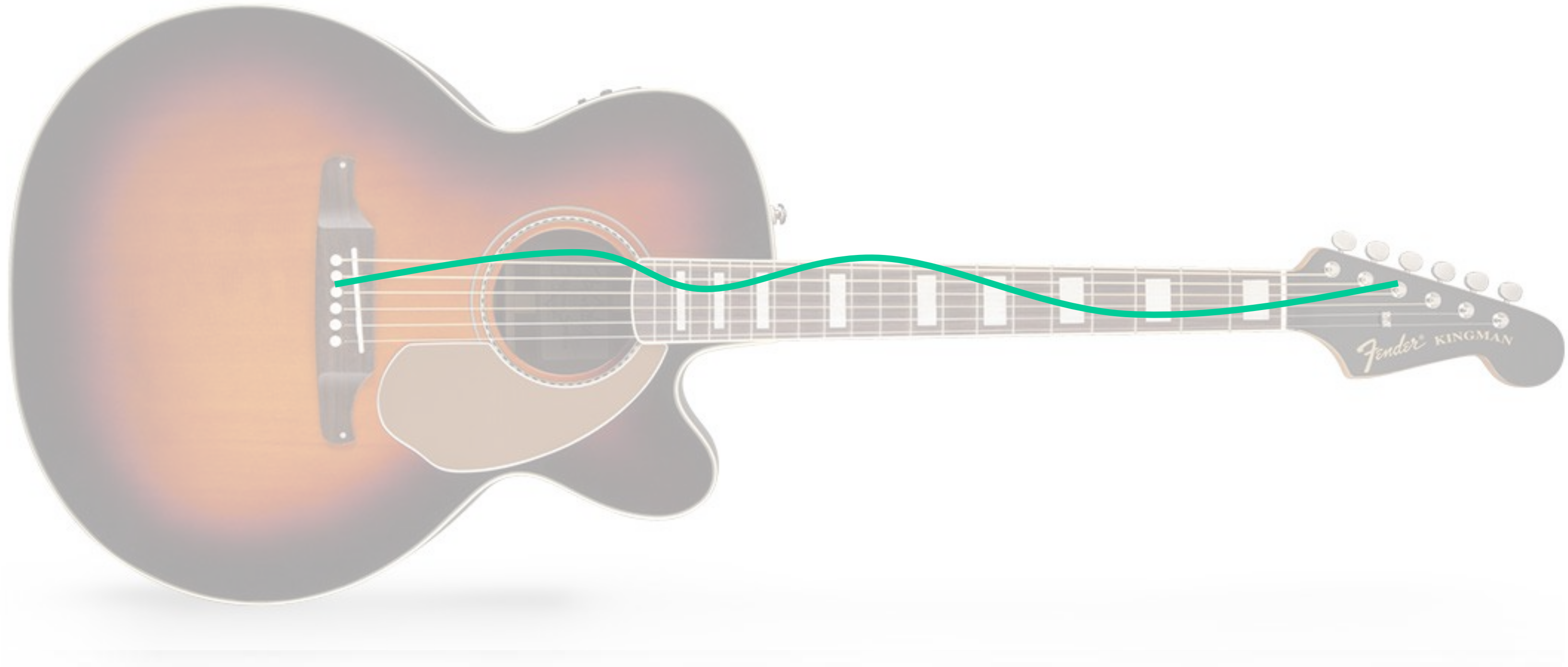


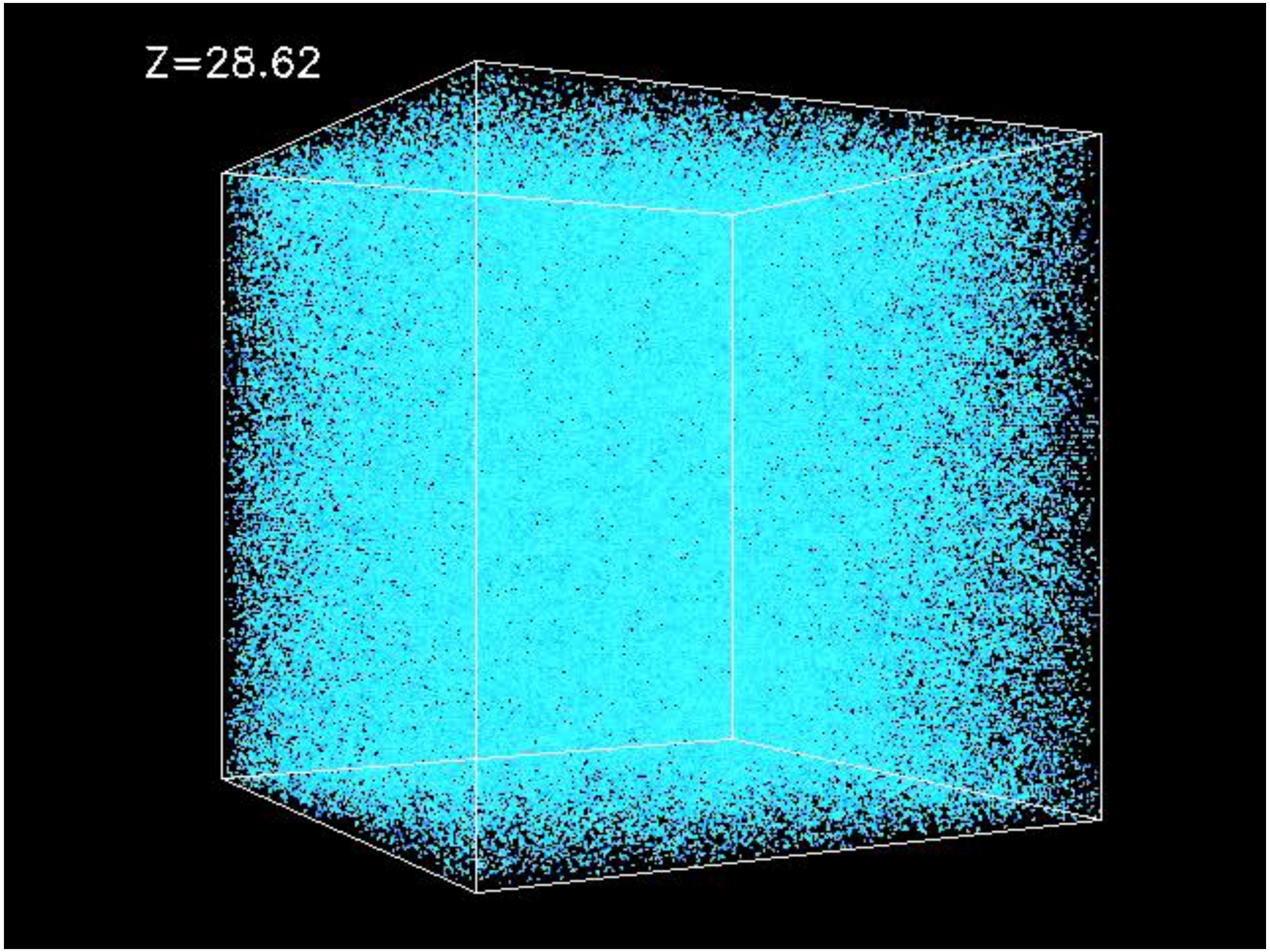
FIGURE 5. Modes corresponding to the same two wavelengths (*First Peak* and *First Trough*) as in Fig. 4, but this time with initial phases scrambled. The anisotropies at the angular scales corresponding to these wavelengths would have identical rms's if the phases were random.



An analogy : at *t*=0, force the string to be like a certain way, and let go.

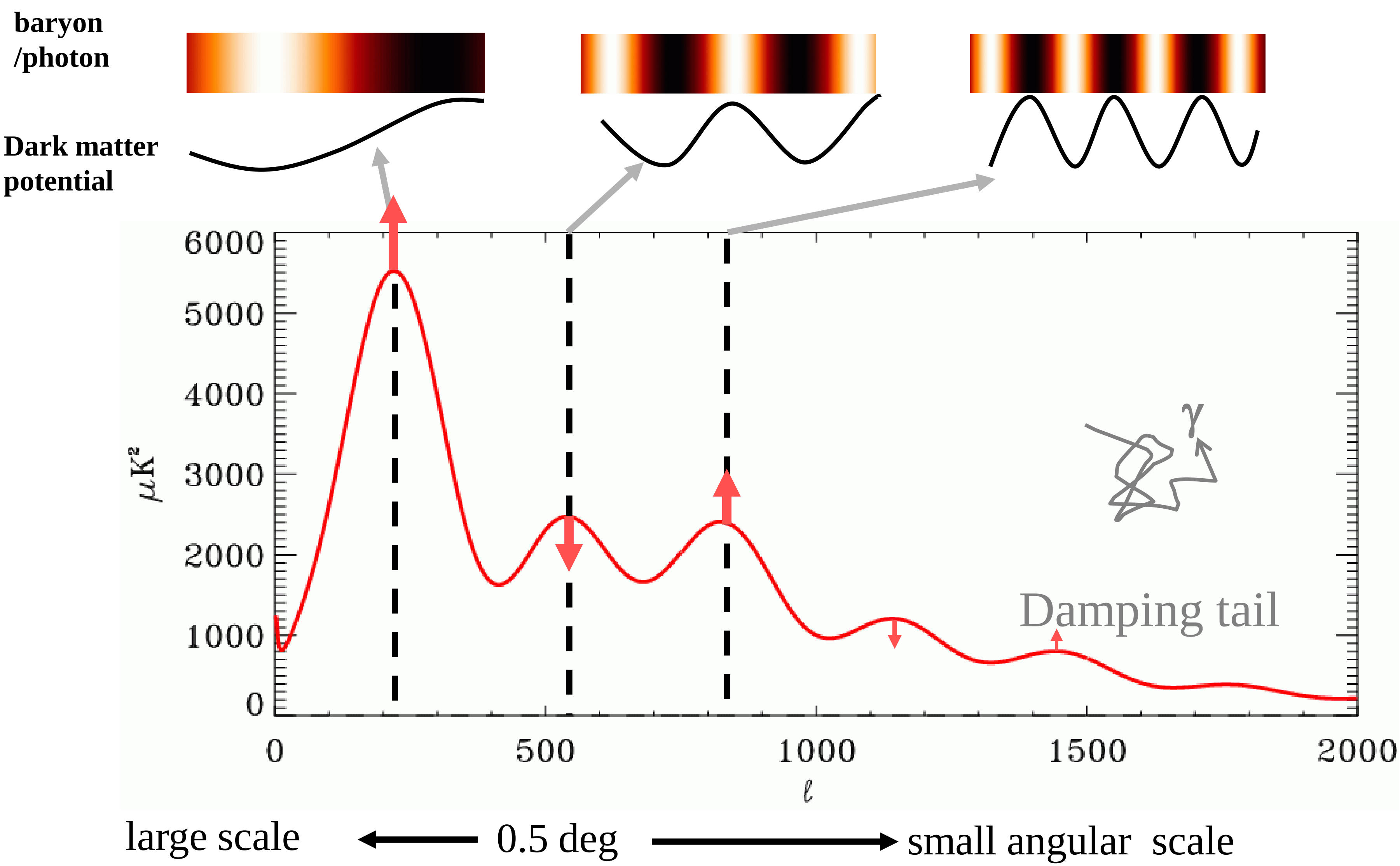
This is *not* the only way that the string can vibrate. Imagine you could pluck it once in a while to add more vibration modes incoherently.

But that coherence is what's been observed in the fluctuations in the CMB.



Another place that manifests this “synchronicity”:

CMB power spectrum



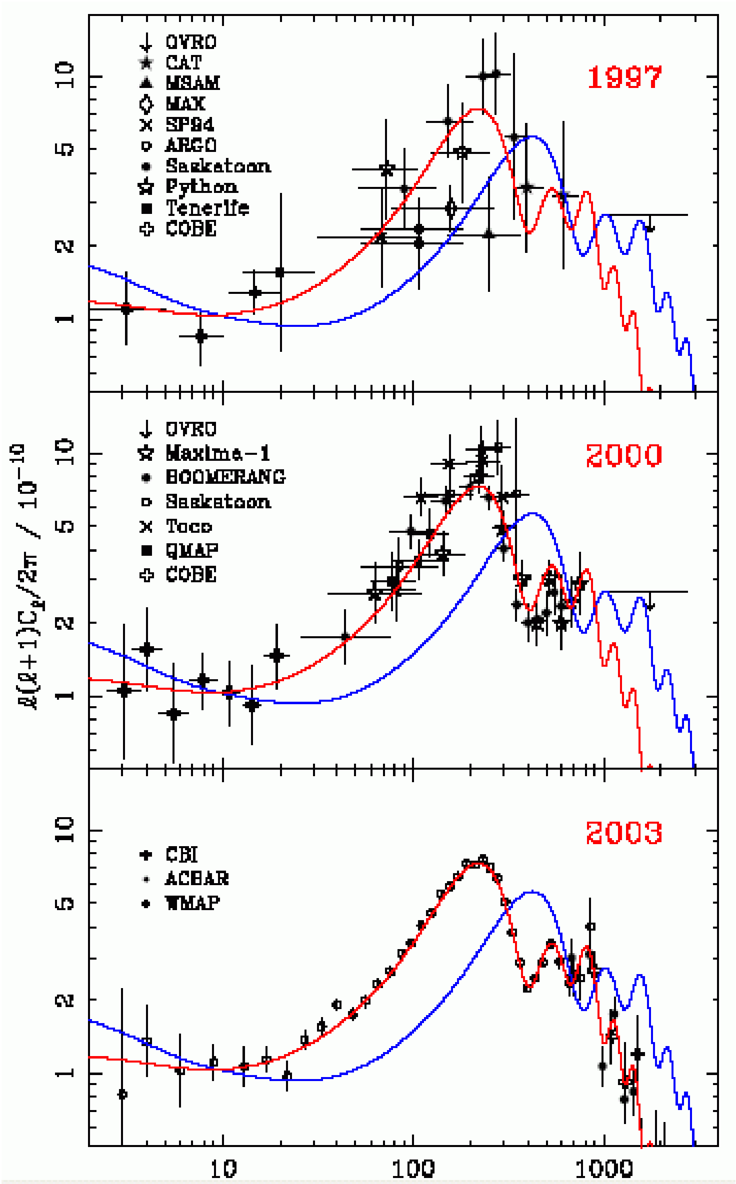
* Acoustic peaks (Sakharov) – compression/rarefaction of plasma in dark matter potential well

* Not are the acoustic peaks observed – they are in perfect agreement with BBNS !

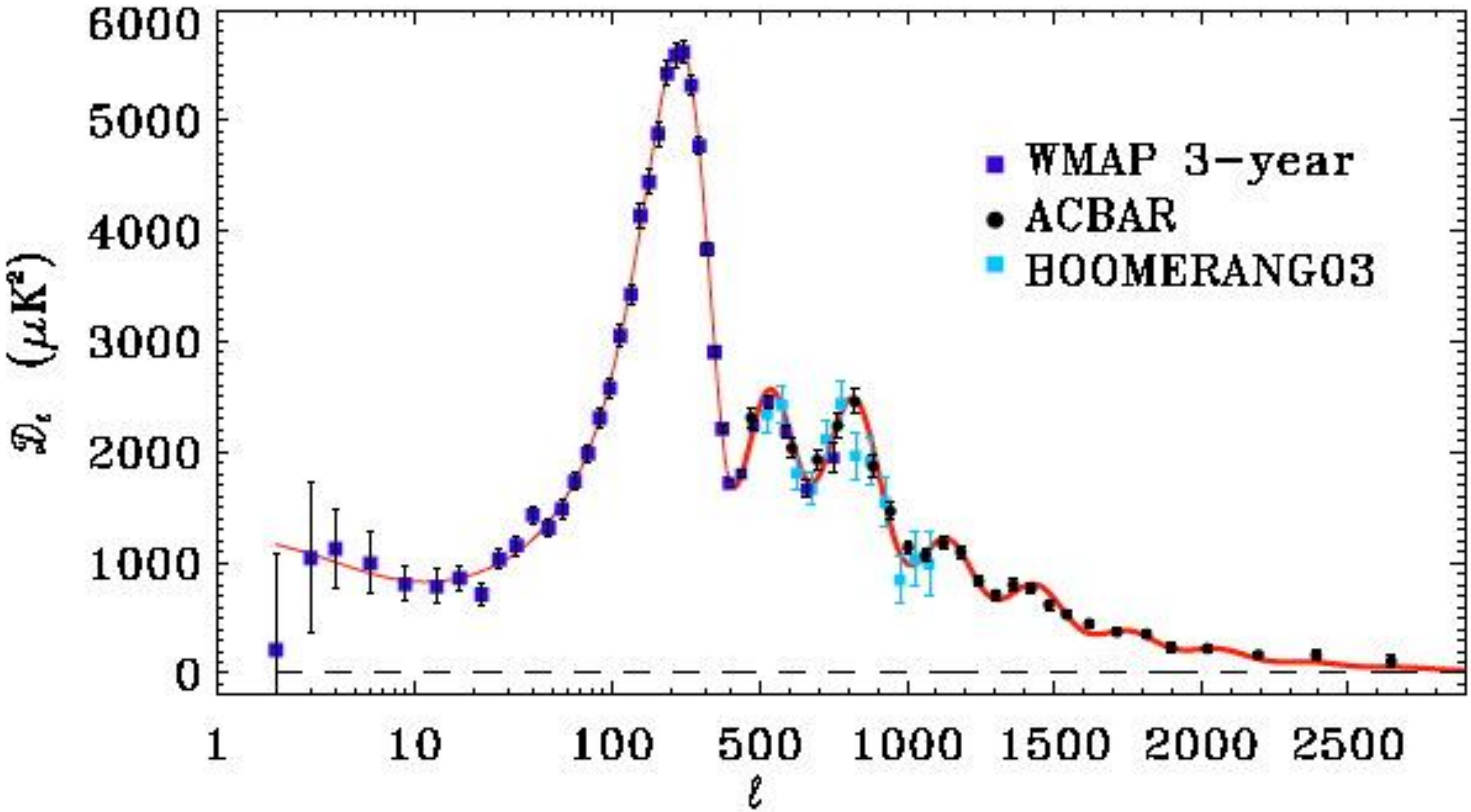
Boomerang, Maxima, DASI

The race to the peak..
1996-2001

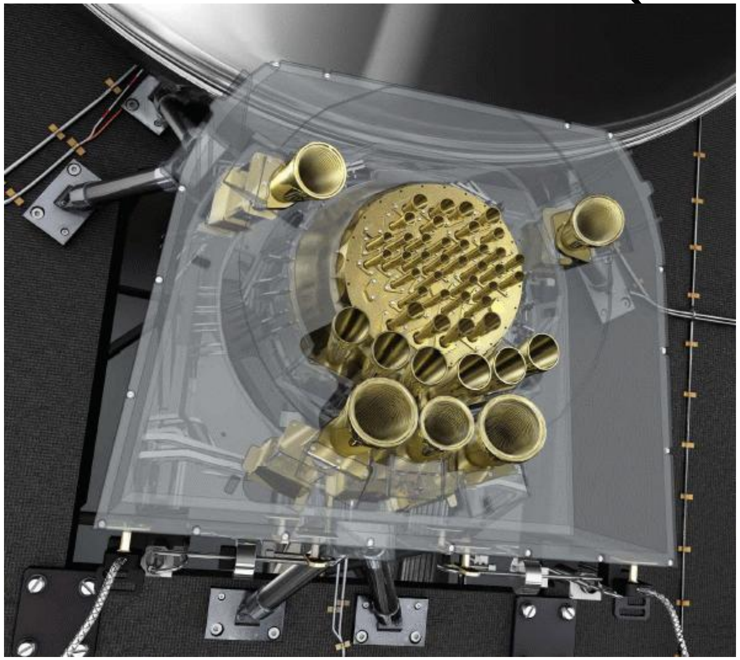
Progress in CMB experiments in the past 15 years

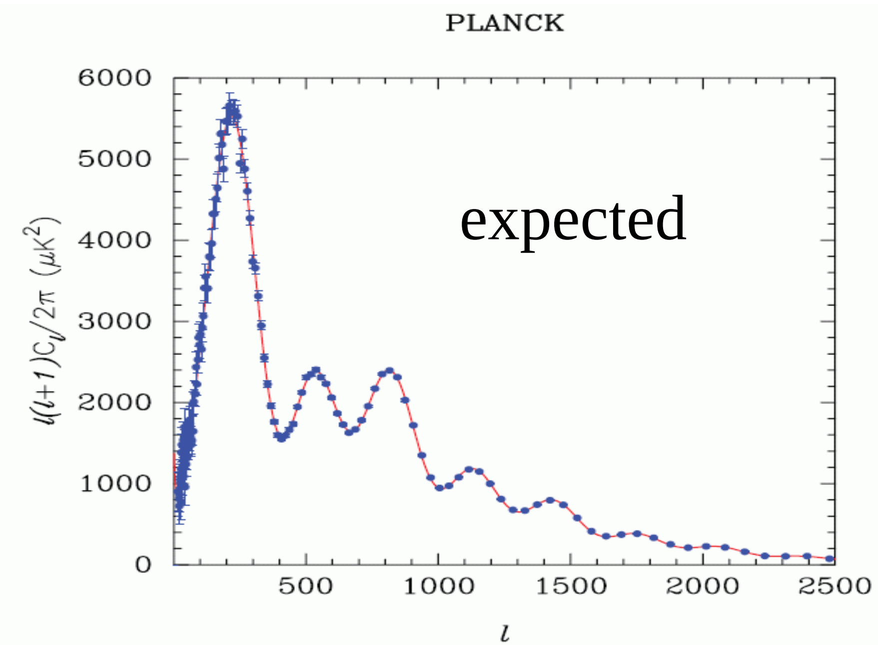


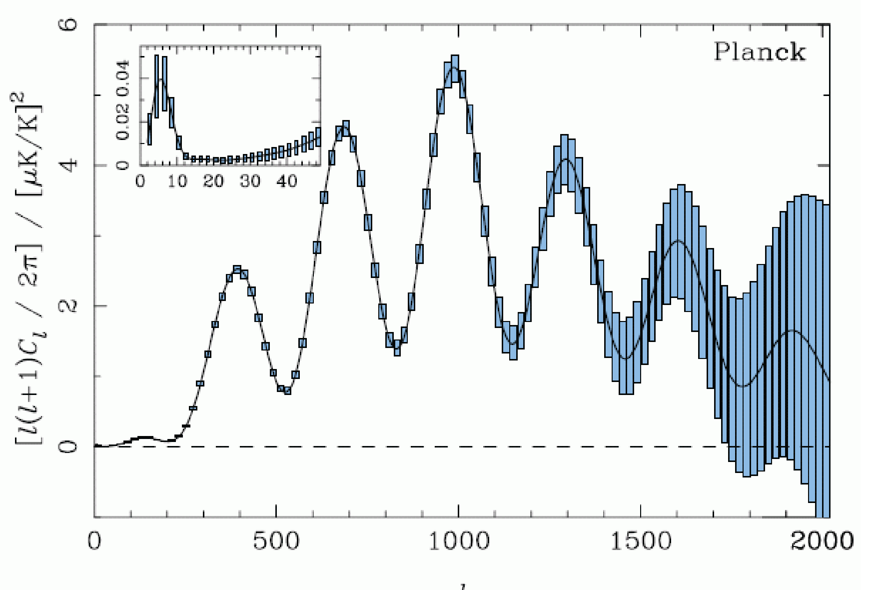
CMB temperature power spectrum circ. 2008



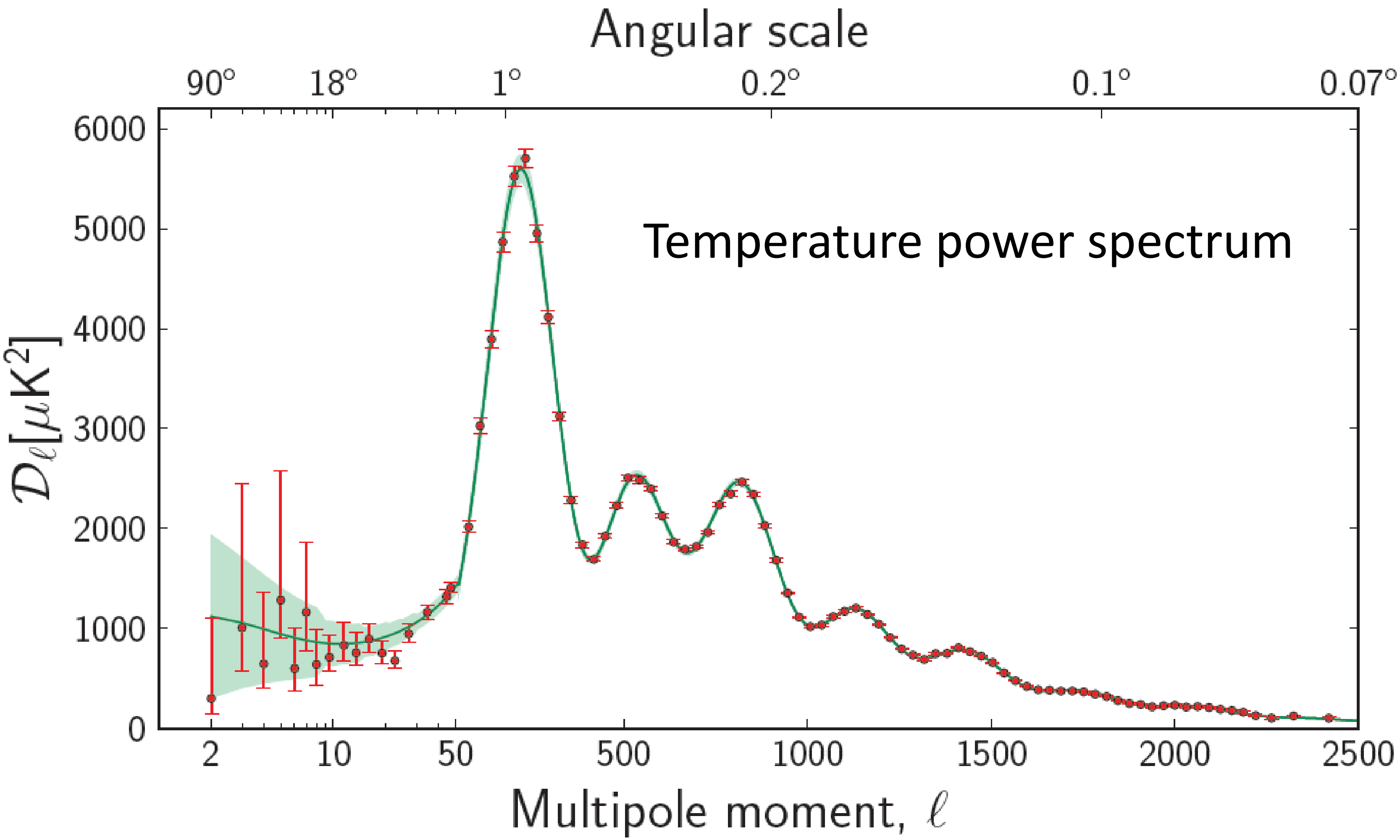
Planck (launched in May 2009)







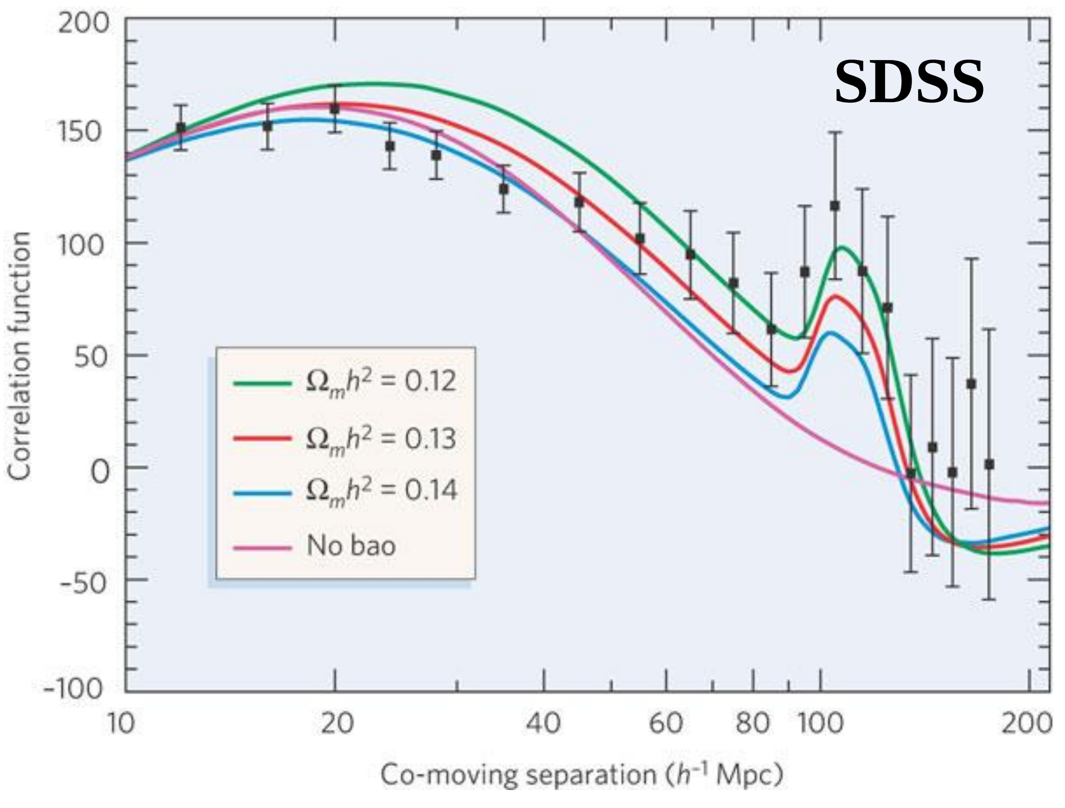
Imprints of perturbations on the CMB



Planck, 2013

Baryon acoustic oscillation (BAO)

- Observed in the galaxy distributions, which reflects dark matter distributions
- The oscillating baryon density perturbations create a reaction on the dark matter



Fourier Transform of power spectrum

The Evidence for Inflation III.

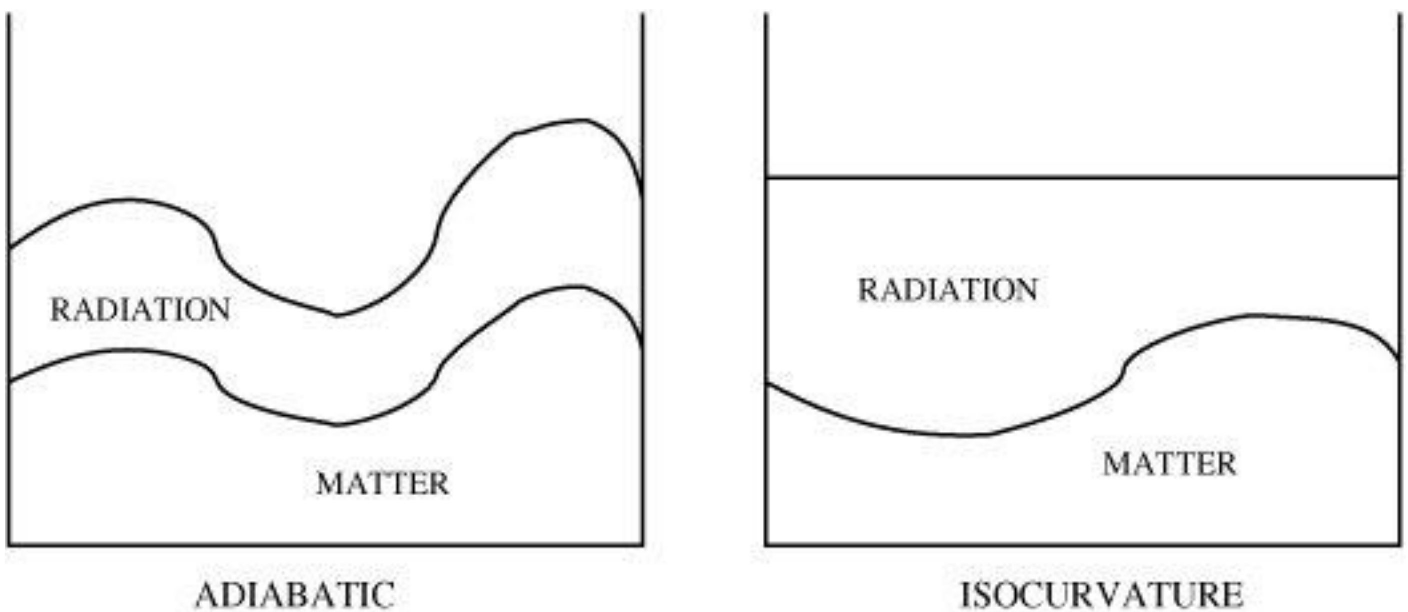
- Properties of Initial Perturbations
  - Adiabatic perturbations
  - (near) Scale Invariance
  - Gaussianity

A good entry level introduction:

W. Kinney
TASI Lectures on Inflation
arXiv:0902.1529

What is adiabaticity ?

- The universe has more than one components
- There are different types of perturbations
- Adiabatic, or “honest to God” perturbation means different components are perturbed in the same way
- Isocurvature perturbations have no fluctuation in total energy density → no curvature variations, no initial gravitational pull



Why does Inflation predict adiabaticity?

- During Inflation, the universe has a single component, the inflationary scalar field.
- There is only one way to perturb this energy field – this perturbation has to be a curvature perturbation because energy → curvature
- The energy/density perturbations later decay adiabatically into different particles → all species have the same perturbed spatial distribution
- More complicated inflation models, e.g., those involving more than one field, do predict deviation from adiabaticity.

  » However, see S. Weinberg, astro-ph/0405397

What is the evidence for adiabaticity?

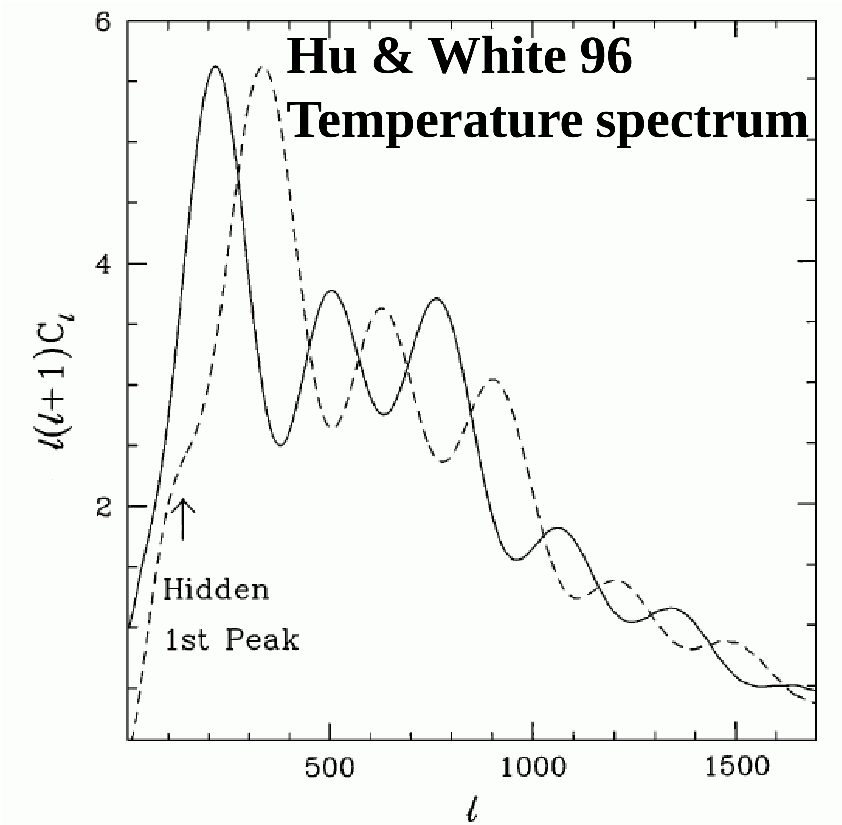
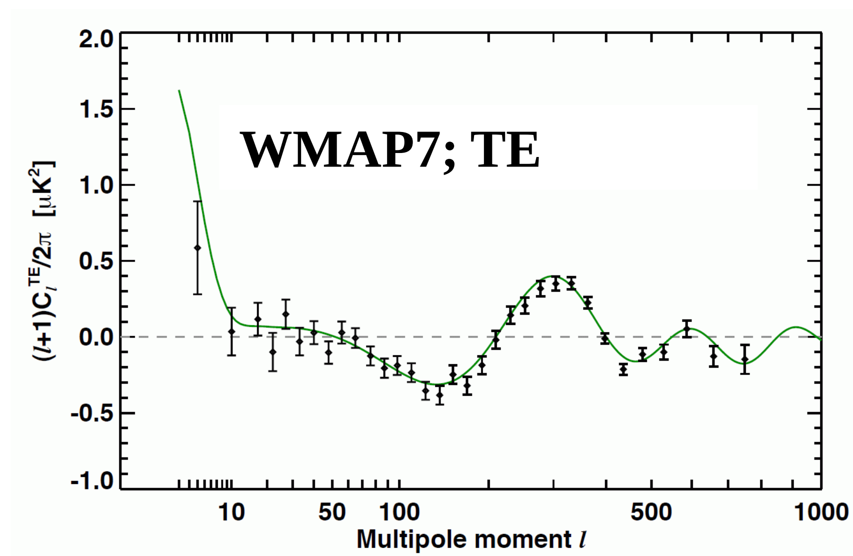
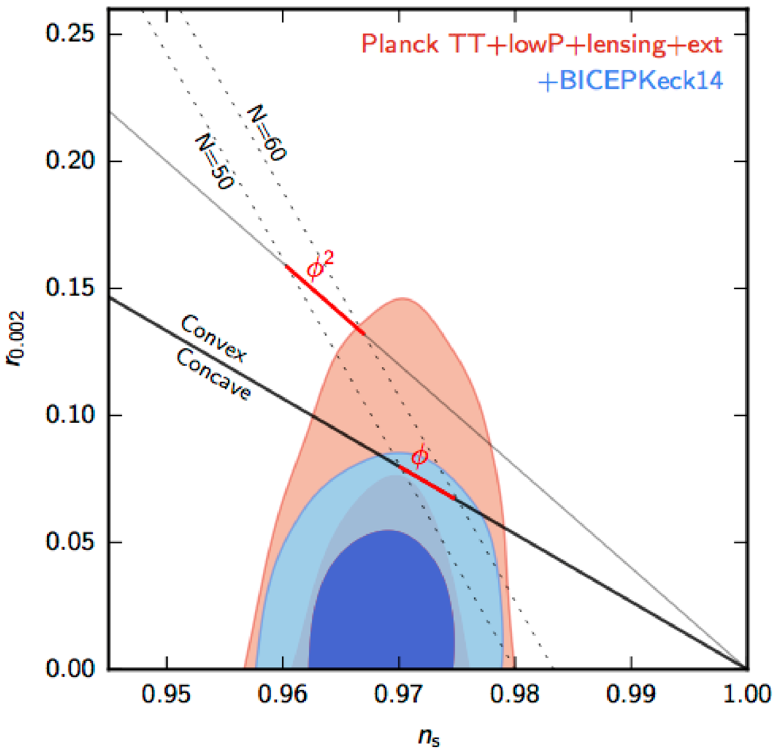


Figure 4 The angular power spectrum for an inflationary model with primordial adiabatic perturbations and for another with primordial isocurvature perturbations. *Solid line*, cold dark matter and inflation; *dashed line*, axion isocurvature. (From Reference 186.)

- Isocurvature perturbations have no initial gravitational pull, therefore it is out of phase with the predictions of adiabaticity
- Not just the location of the first peak, the relative locations of the peaks
- It is even clearer in polarization



Inflation and (near) Scale-Invariance



- Slow roll inflation predicts a nearly scale invariant initial spectrum
- This is related to the nearly exponential growth during slow-roll inflation
- As the inflaton potential decays slowly, the spectrum deviates slightly from scale invariance, in the red direction

Inflation and Gaussianity

- Definition of Gaussianity
  - The parameter follows a Gaussian PDF
  - In Fourier space, each Fourier mode is independent
- Inflation:
  - Quantum fluctuations in $\phi \rightarrow$ Potential/curvature perturbations $\rightarrow$ anisotropy in the CMB
- Inflation generates Gaussian initial perturbations
  - Related to the ground state wave function (commutation relation)
- For slow-roll inflation, which is a linear process, each Fourier mode evolves independently (sees the same potential V)

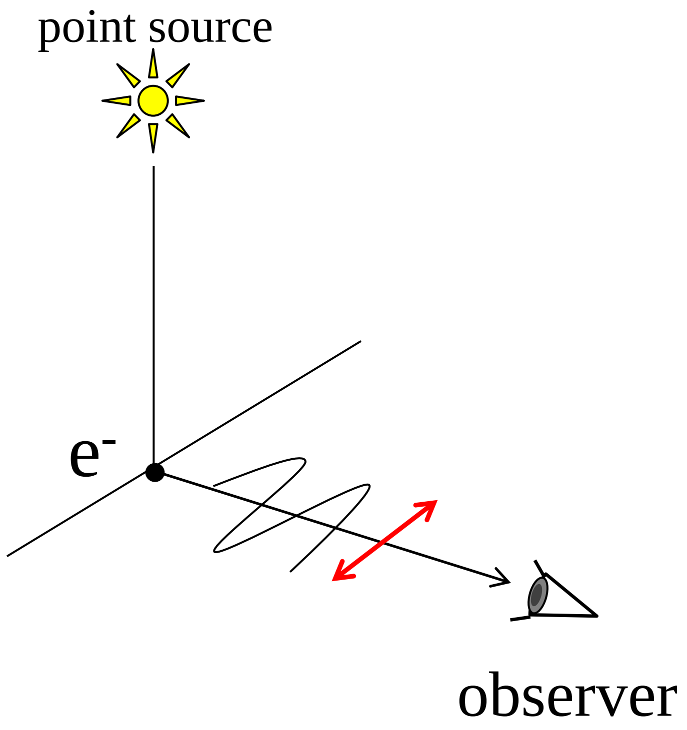
Gaussianity Observables

- So far, CMB is found to be extremely Gaussian
- Non-Gaussianity, modeled by f_{NL} through $\Phi = \Phi_G + f_{NL} \Phi_G^2$
- From WMAP 7-year data, $-10 < f_{NL} < 74$
- Planck: $f_{NL} = 0.8 \pm 5$
- For simple single field inflation, $f_{NL} \sim 1 - n_s \sim r$ (<0.07)
- Future LSS survey will probe f_{NL} down to ~1
- Gaussianity means two point functions are sufficient
- Non-Gaussianity requires 3-point functions (or higher) to describe : shape matters; very rich phenomenology (different types of f_{NL})

Possible future evidence for Inflation

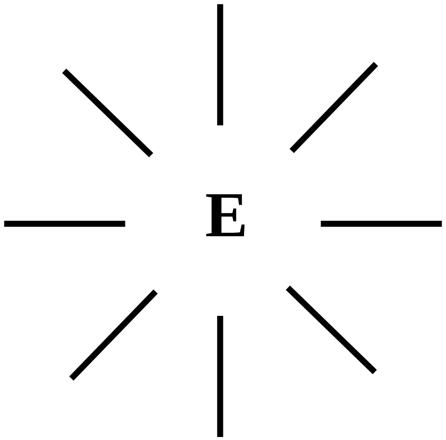
B-mode polarization

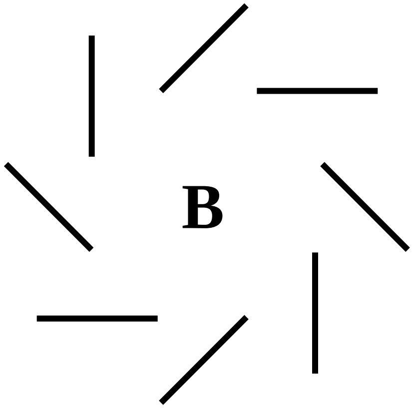
CMB is polarized. Why?



- Induced by radiation anisotropy through Thomson scattering
- To be exact, quadrapole radiation field
- *Generated only at the ionized/neutral interface (completely ionized: no anisotropy; completely neutral: no electrons to scatter)*

E-mode and B-mode





- Polarization fields can be linearly decomposed to E and B mode
- Linear, scalar perturbation cannot generate B-mode polarizations

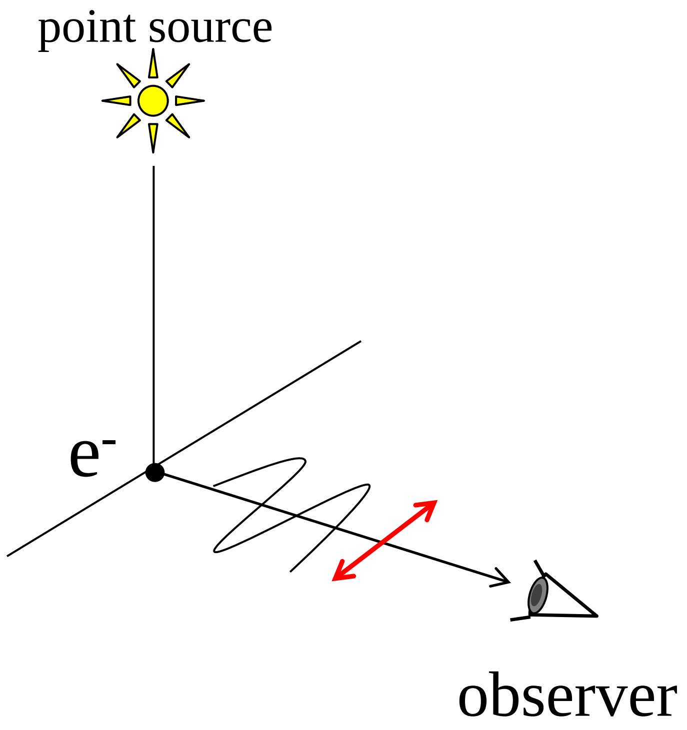
(Seljak & Zaldarriaga; Kamionkowski et al, 1997)

- Creation of E-mode:

adiabatic perturbations → peculiar velocity → local quadrapole → polarization

- E-mode is out of phase with temperature perturbations

B-mode is forbidden *for density perturbations*



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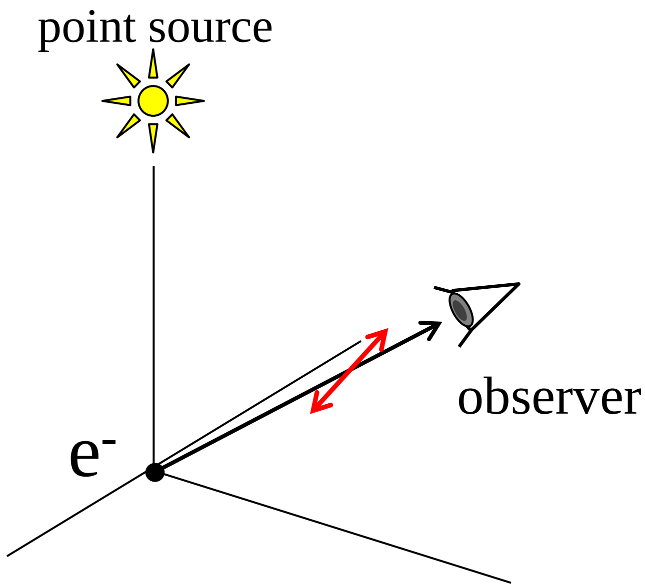
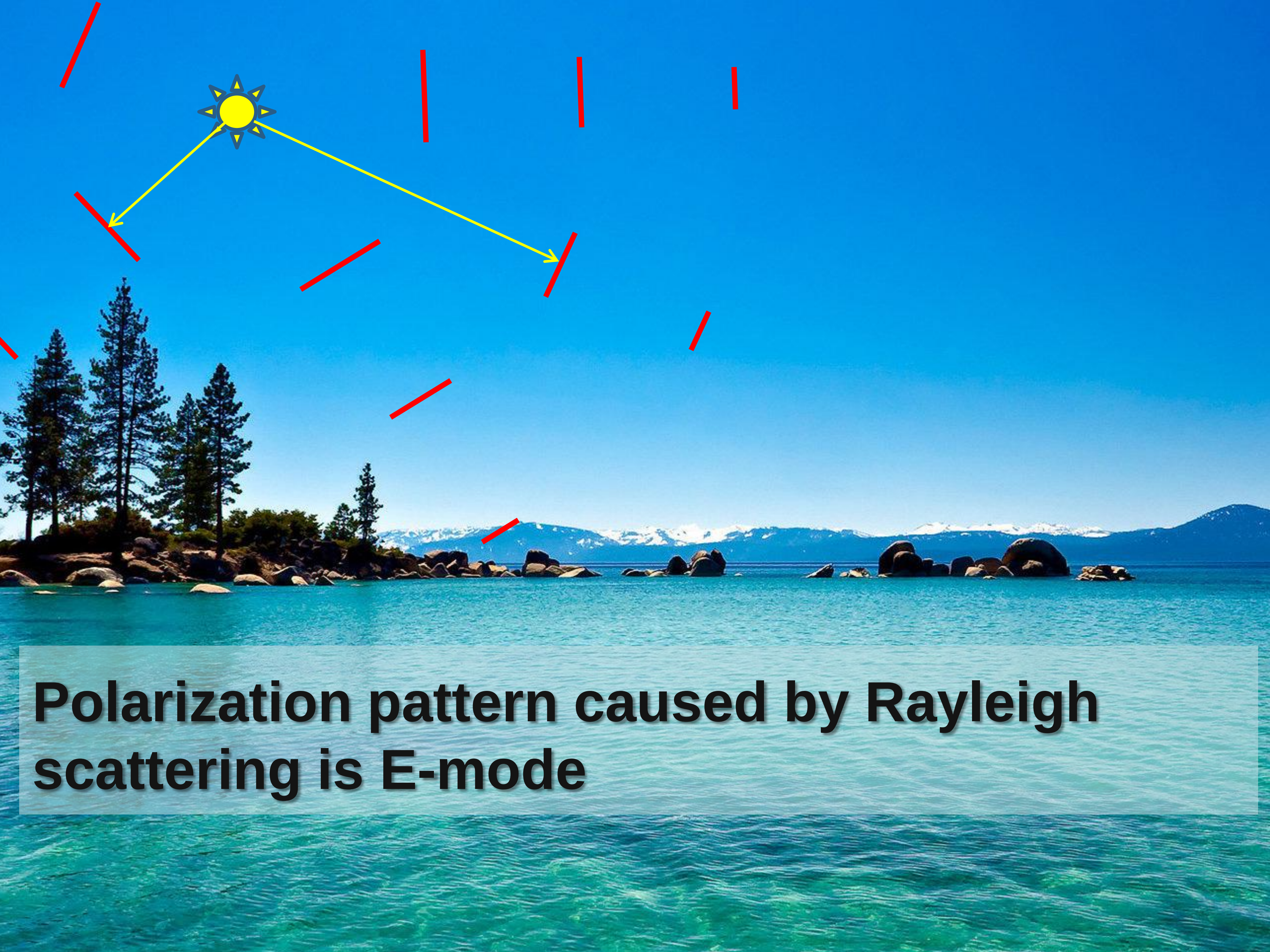
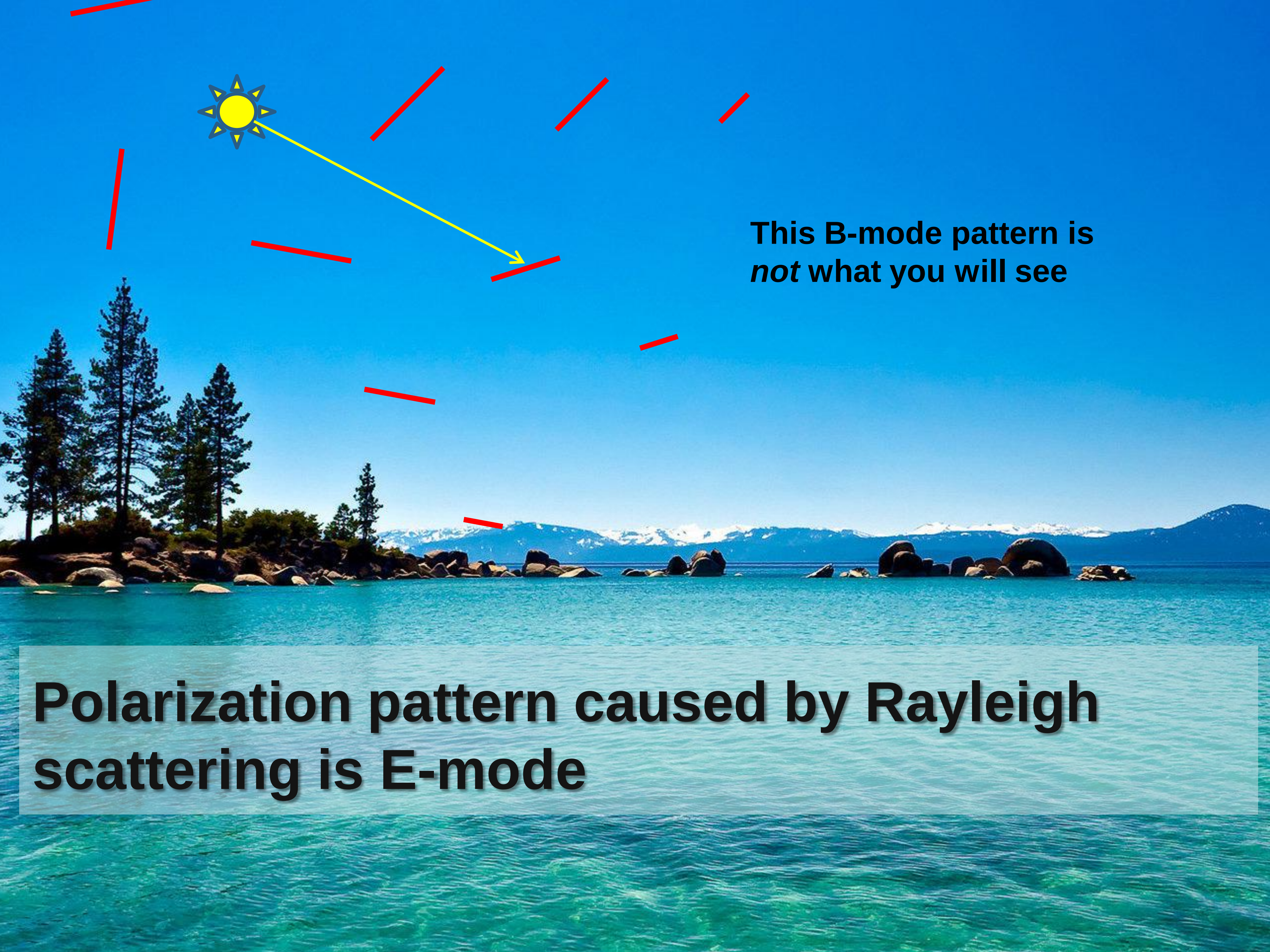
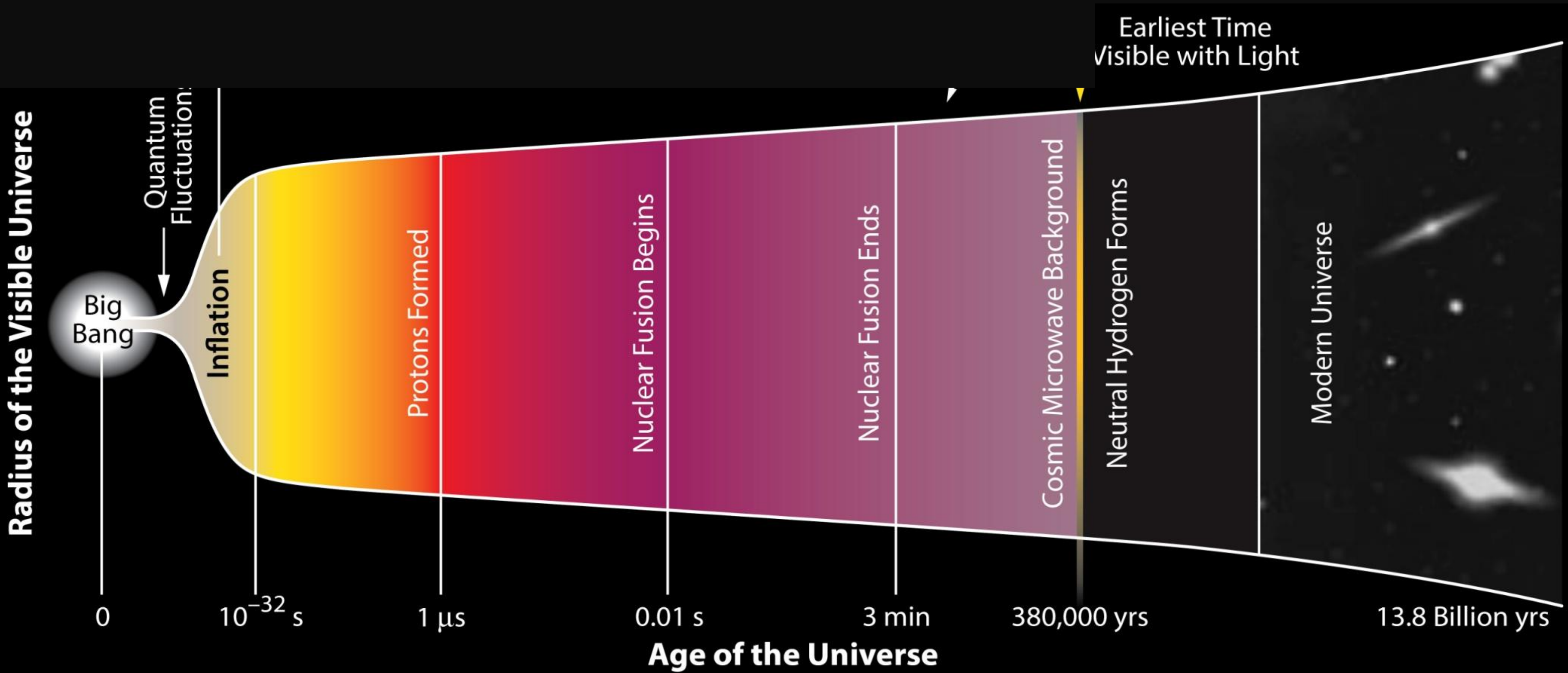


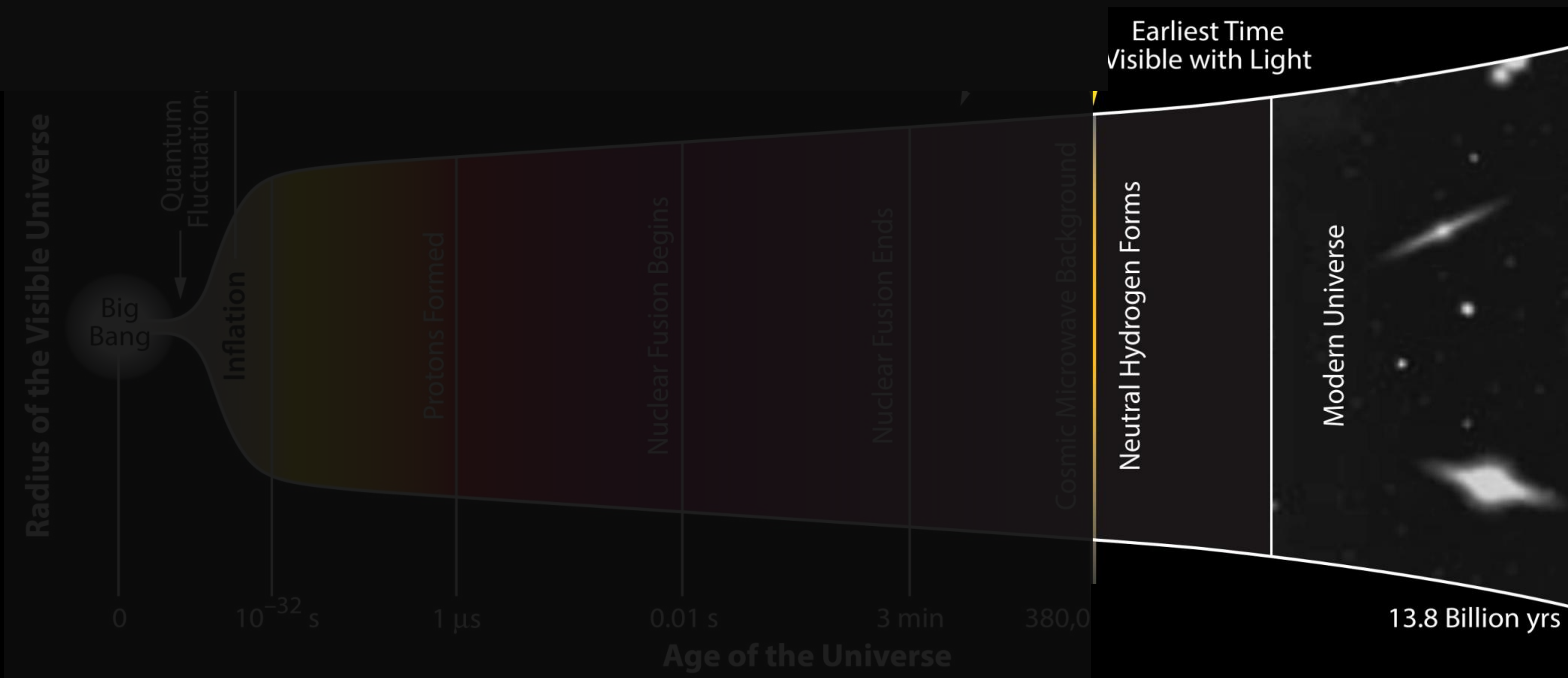

Polarization pattern caused by Rayleigh scattering is E-mode


This B-mode pattern is
not what you will see
Polarization pattern caused by Rayleigh scattering is E-mode

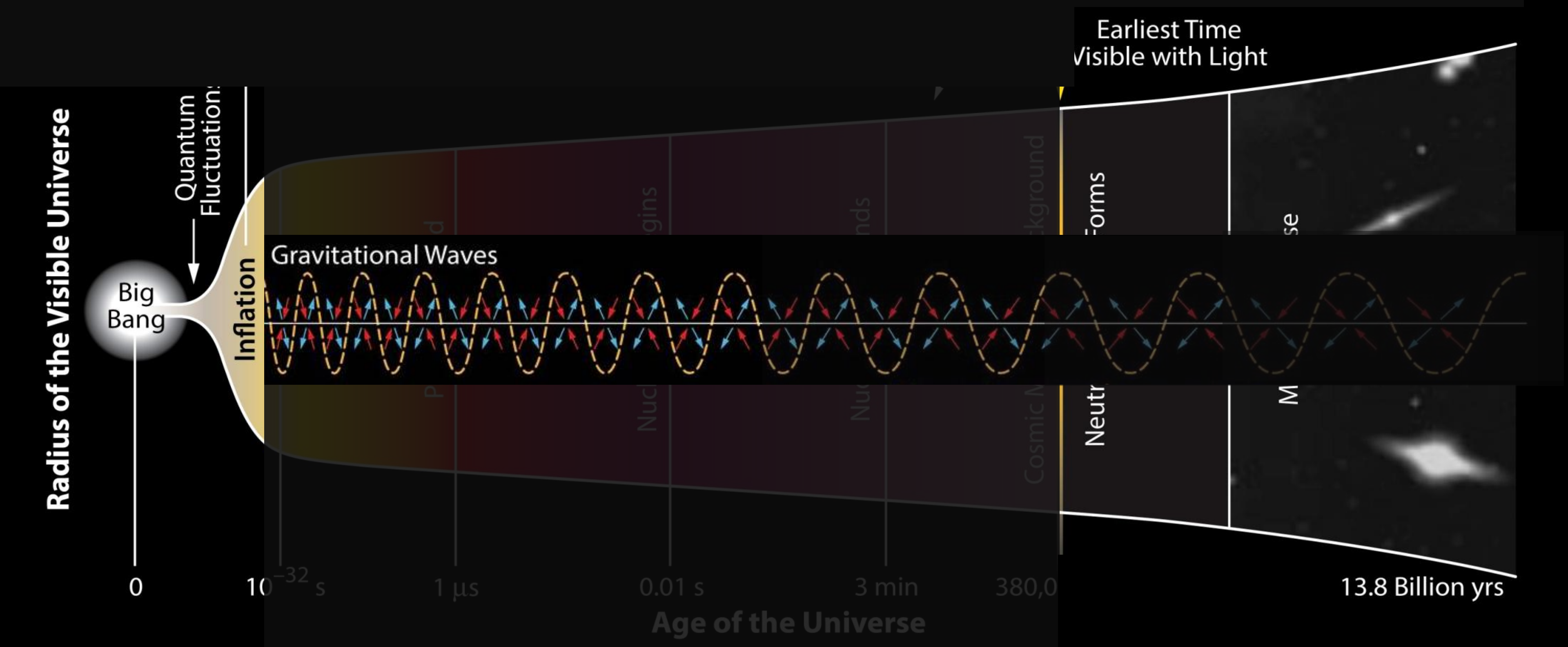
Gravitational waves & CMB



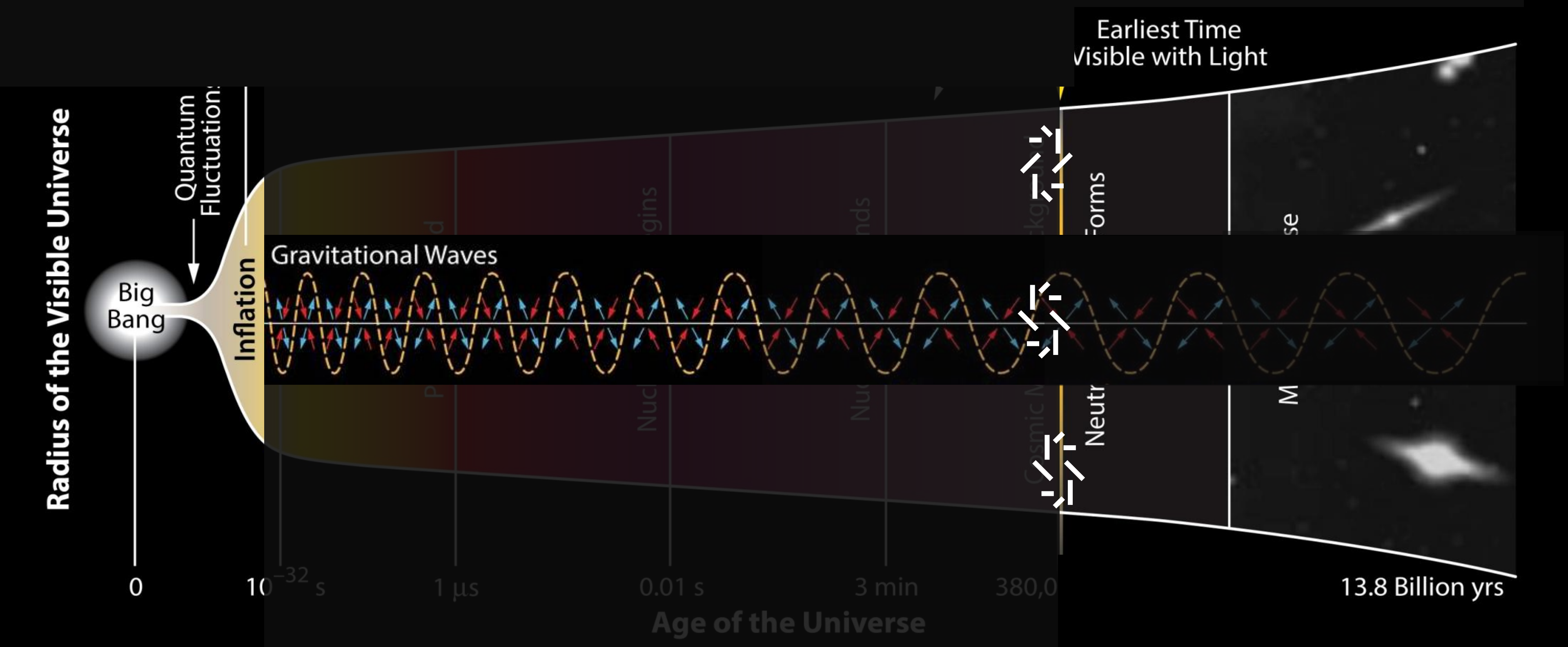
Gravitational waves & CMB



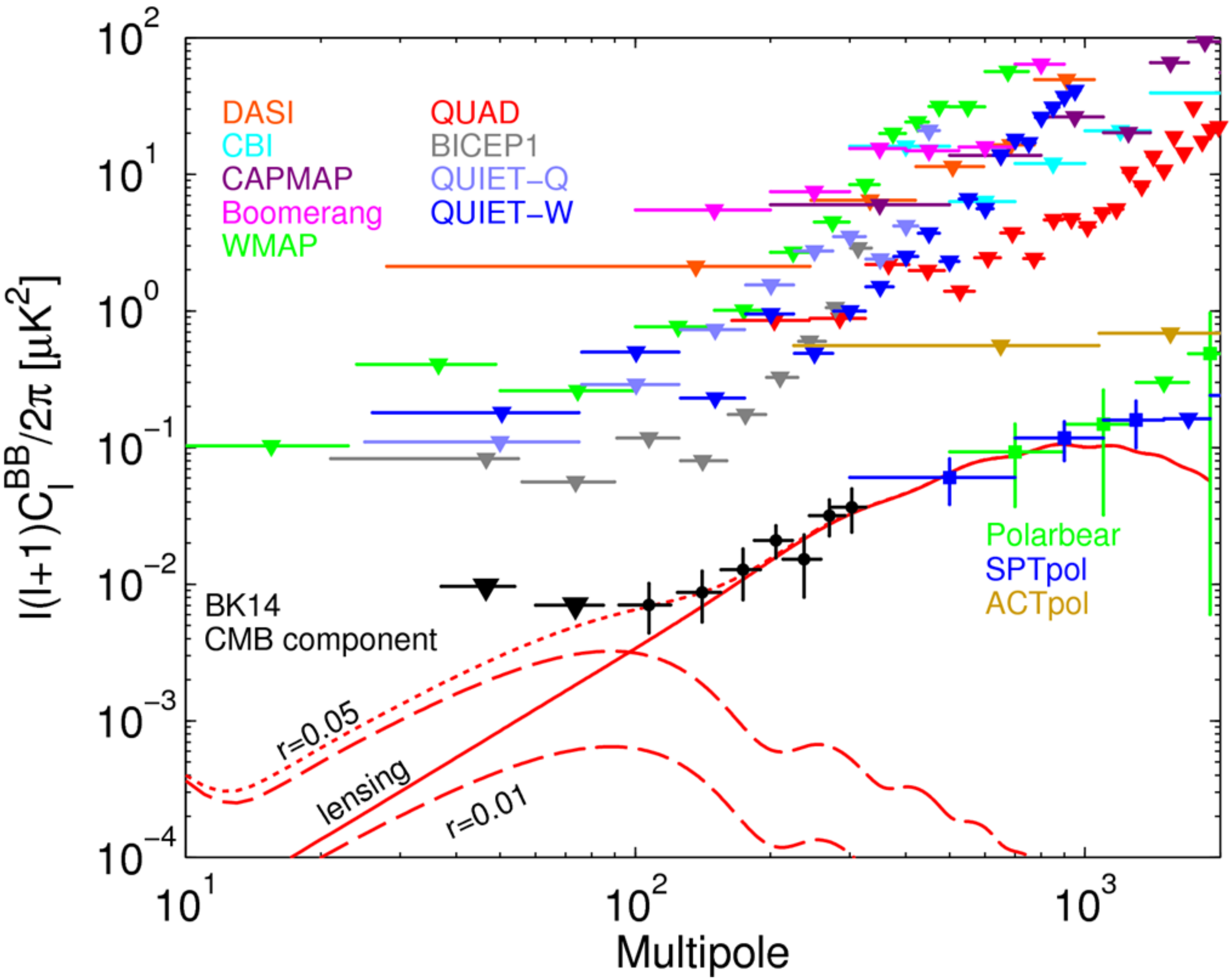
Gravitational waves & CMB



Gravitational waves & CMB

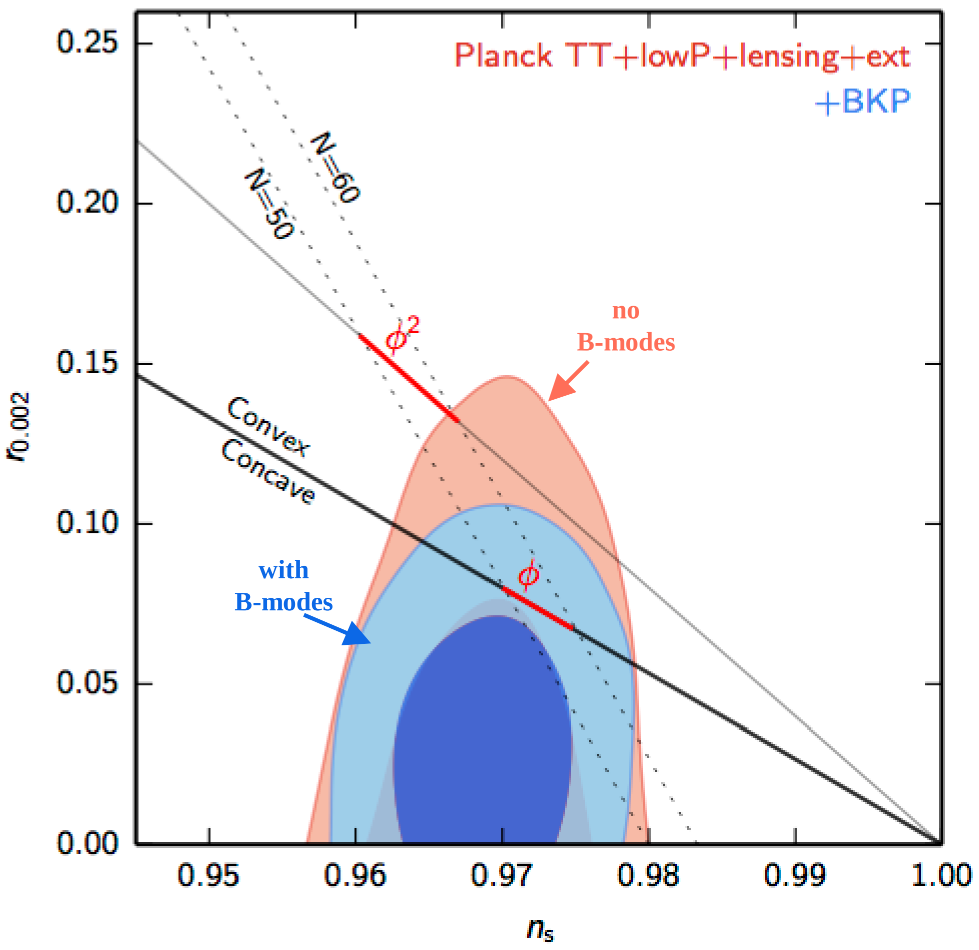


B-mode measurements now



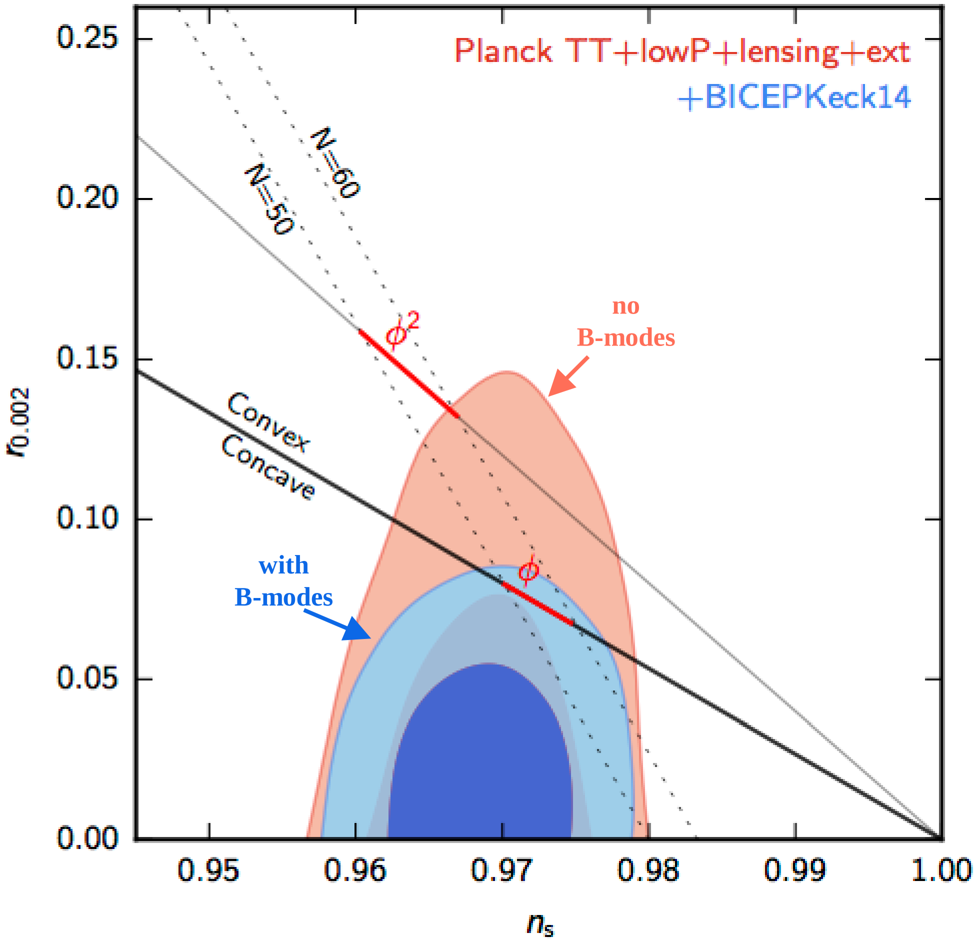
150<*l*<350 dominated by lensing – it has the right ampltude anyway..

Adding in temperature



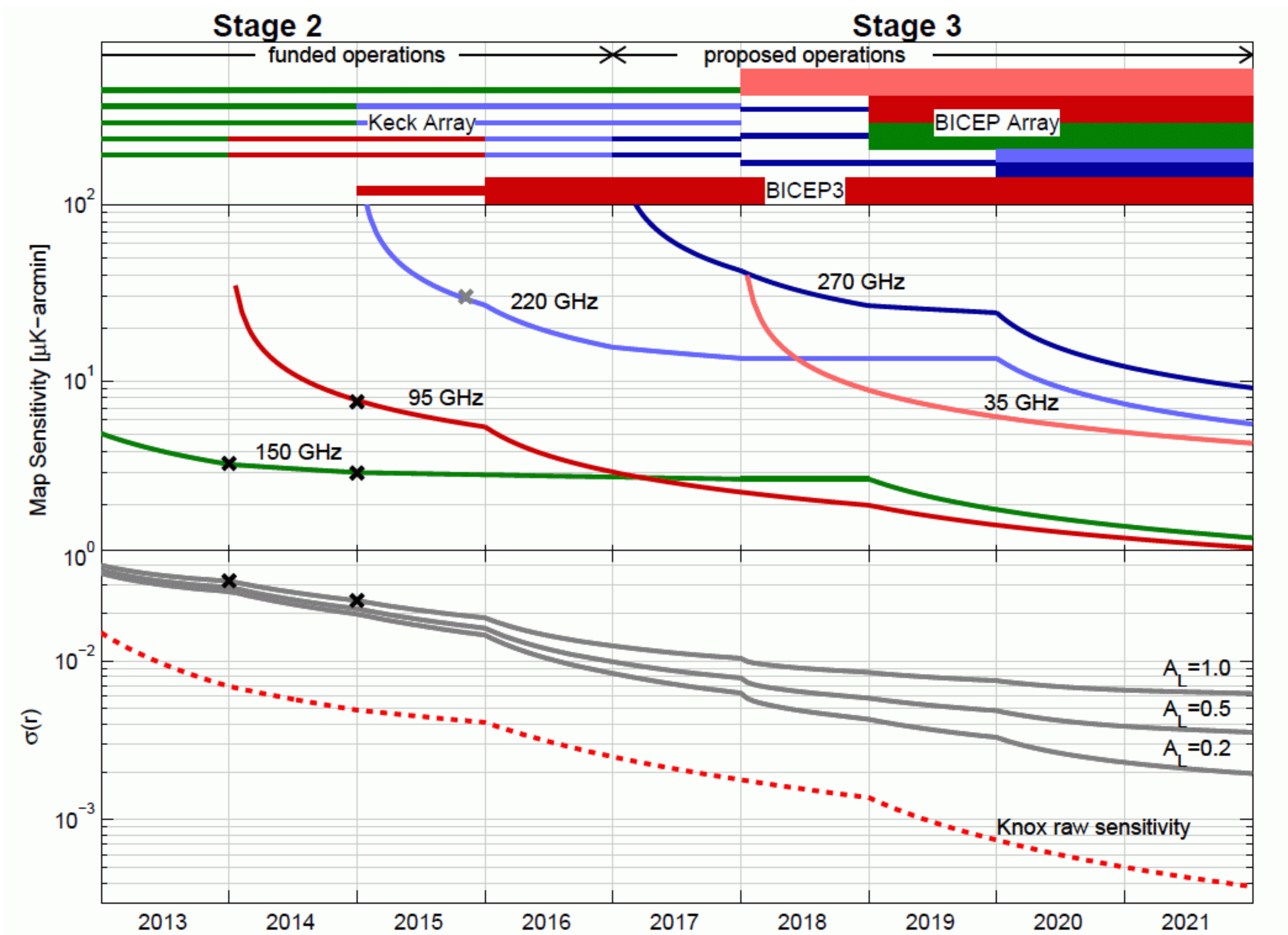
r < 0.09

Adding in temperature



$r_{.05} < 0.07$

(best ever)



Constraints from n_s:

ϕ^2 Inflation:

best-fit r	3σ bound
0.13	0.057

Monodromy ϕ:

best-fit r	3σ bound
0.087	0.038

Monodromy $\phi^{2/3}$:

best-fit r	3σ bound
0.065	0.028

R^2 Inflation:

best-fit r	3σ bound
0.003	6×10^{-4}

Natural Inflation:

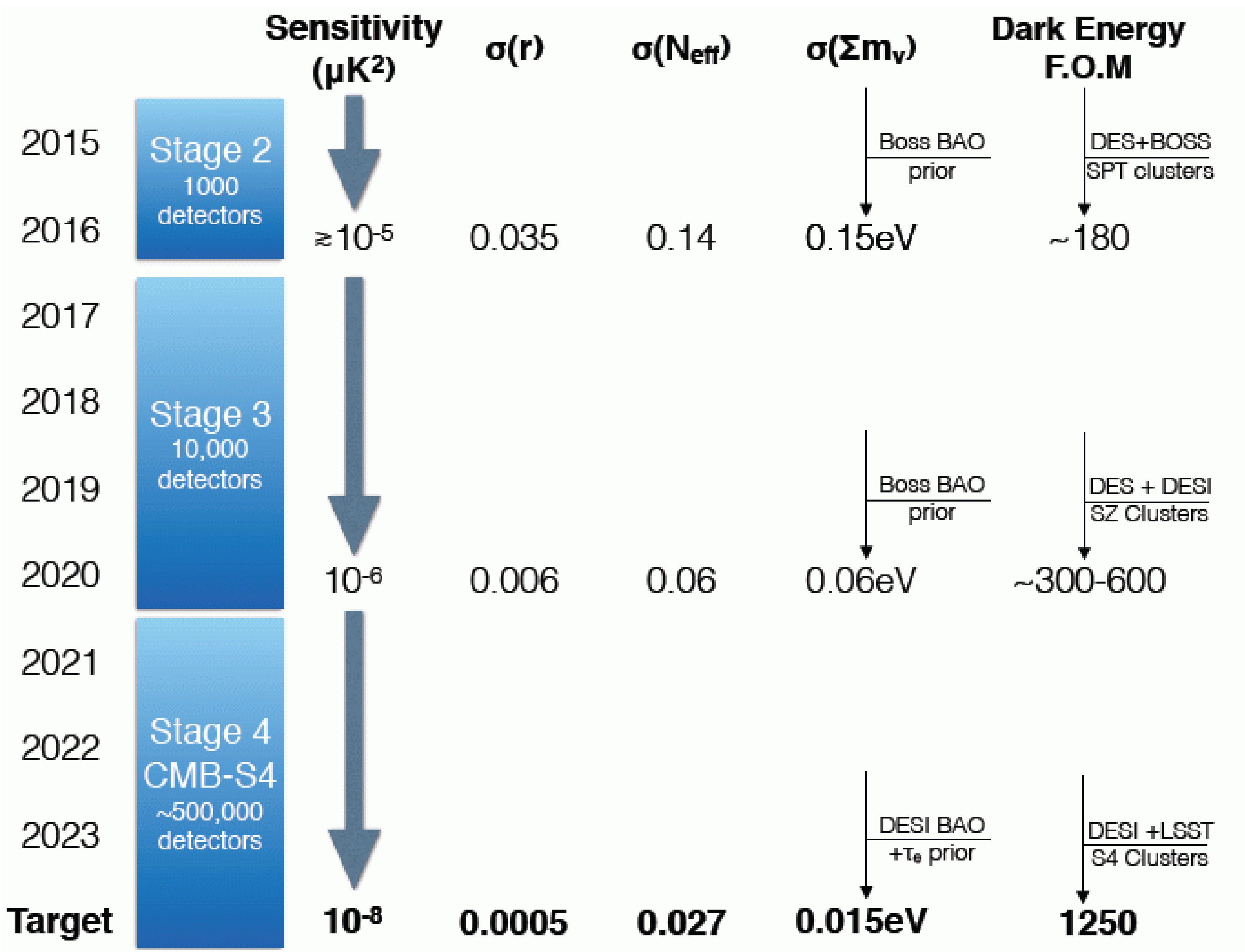
3σ bound
0.04

Higgs-like Potential:

3σ bound
0.03

BICEP program on its way to σ(*r*)=0.004 (before S4 starts)

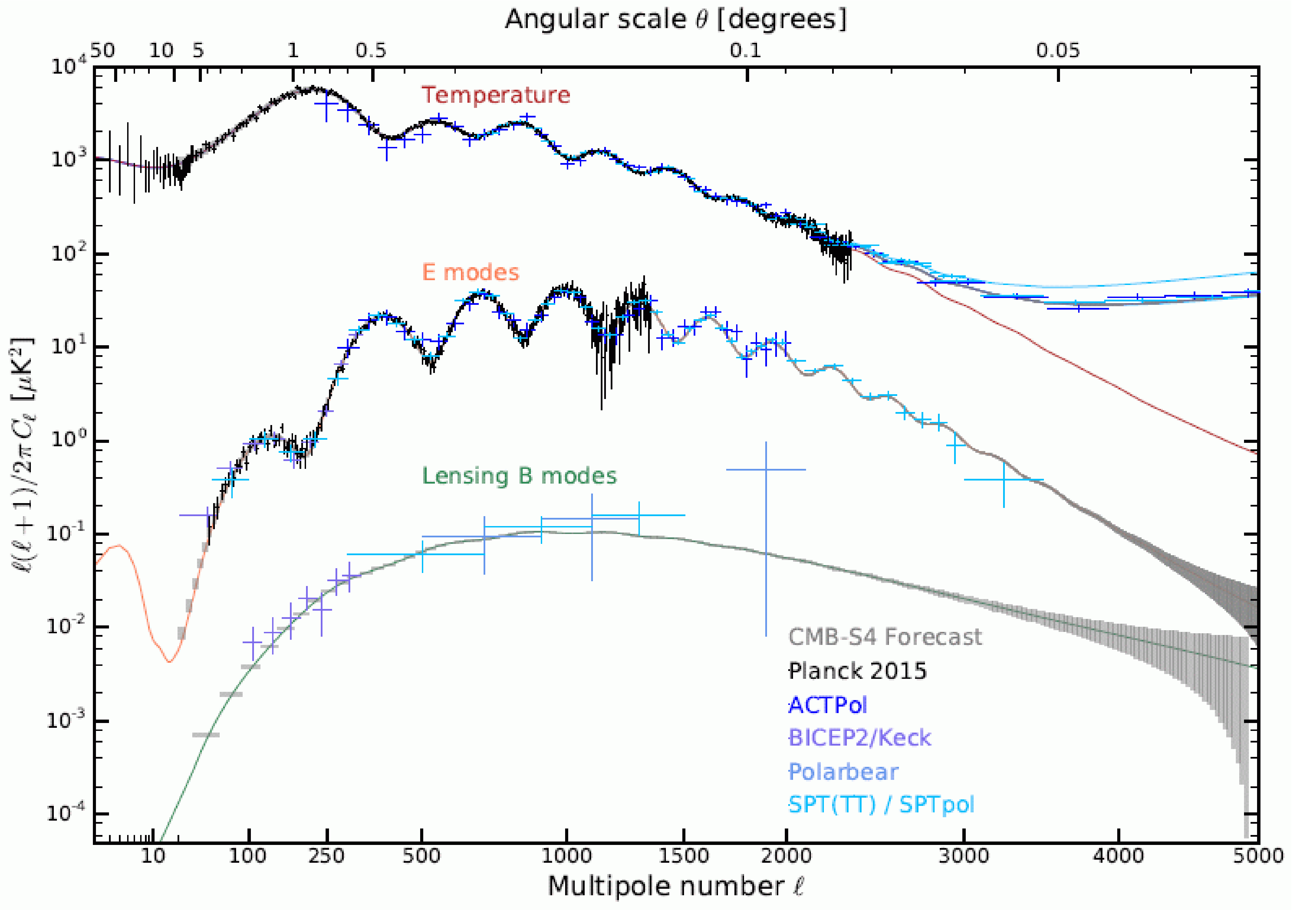
When


Sensitivity (μK^2)
$\sigma(r)$
$\sigma(N_{eff})$
$\sigma(\Sigma m_\nu)$
Dark Energy F.O.M
2015
2016
Stage 2
1000 detectors
Boss BAO prior
DES+BOSS SPT clusters
$\gtrsim 10^{-5}$
0.035
0.14
0.15eV
~180
2017
2018
2019
2020
Stage 3
10,000 detectors
Boss BAO prior
DES + DESI SZ Clusters
10^{-6}
0.006
0.06
0.06eV
~300-600
2021
2022
2023
Stage 4
CMB-S4
~500,000 detectors
DESI BAO $+\tau_e$ prior
DESI +LSST S4 Clusters
Target
10^{-8}
0.0005
0.027
0.015eV
1250

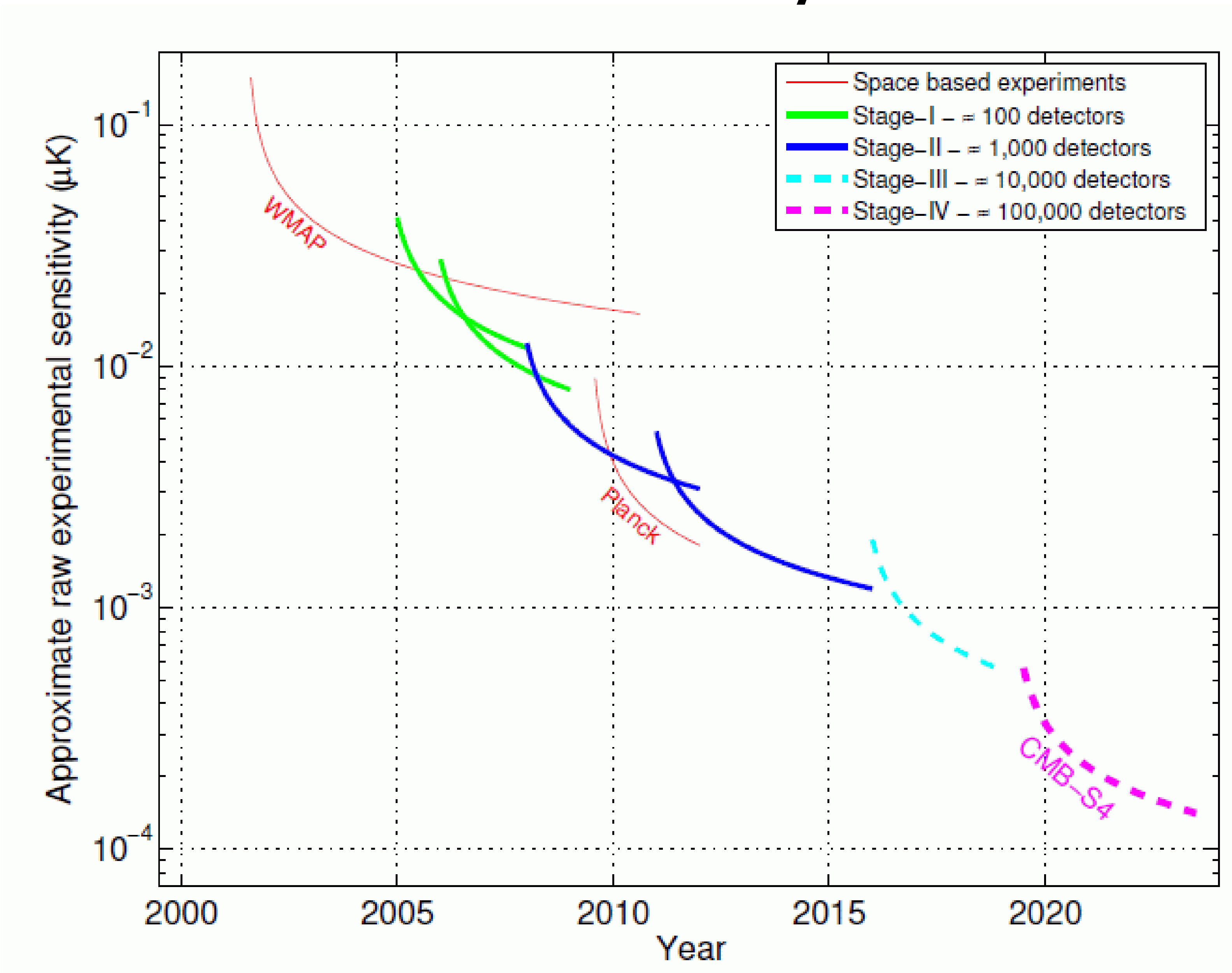
Challenges

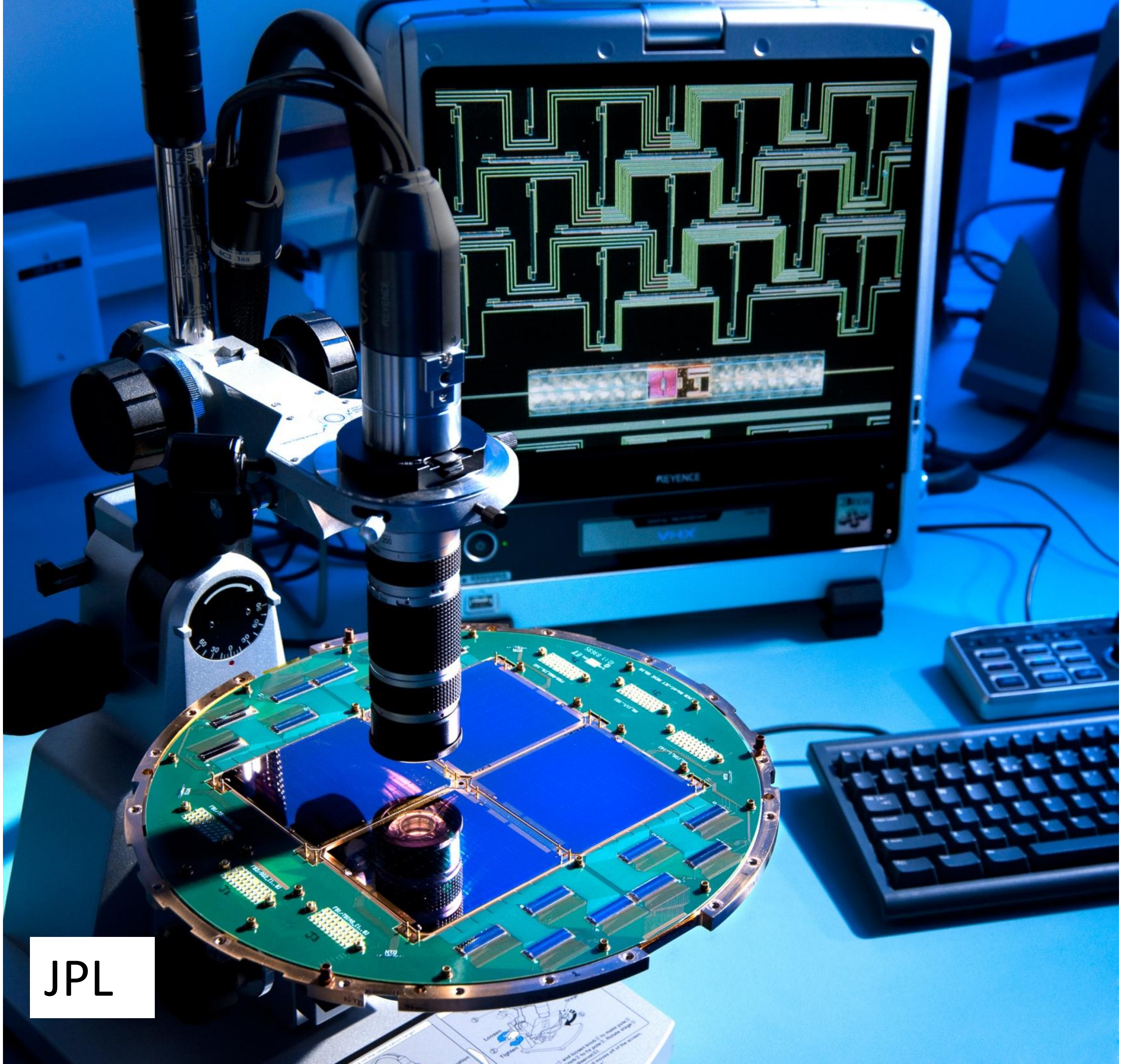
- Observing from a ~~good~~ great site
- Achieving required sensitivity
- Removal of Foregrounds
- Control of Systematics

Temperature & E-modes leak into B-modes



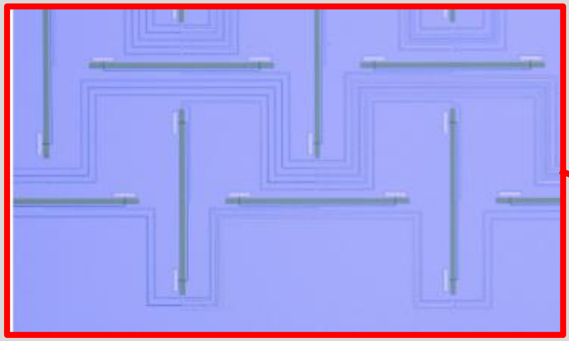
Sensitivity




KEYENCE
JPL

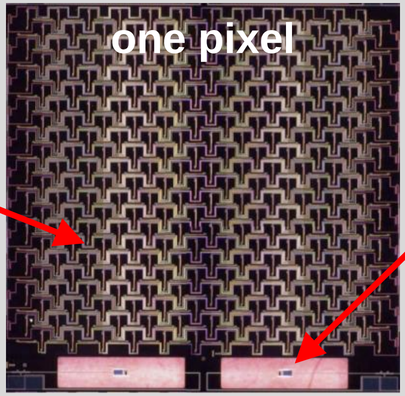
Transition-edge sensor bolometers

Planar antenna array



- Orthogonal slot sub-antennas
- Difference measures scalar Q or U Stokes parameter
- Sum measures intensity

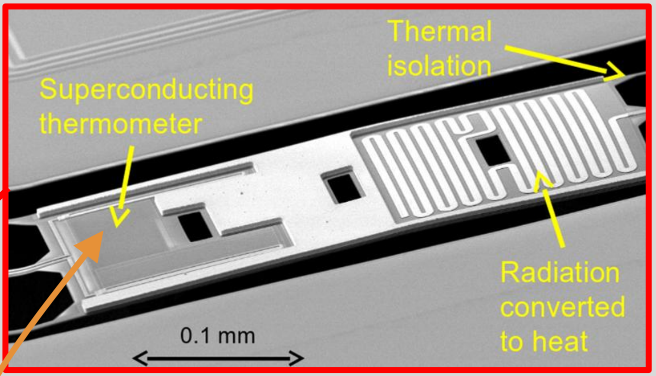
Lithographic → scalable!



8 mm

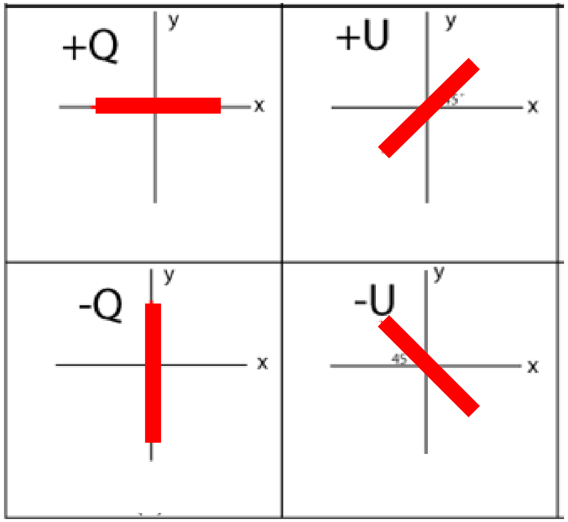
fab at Caltech/JPL

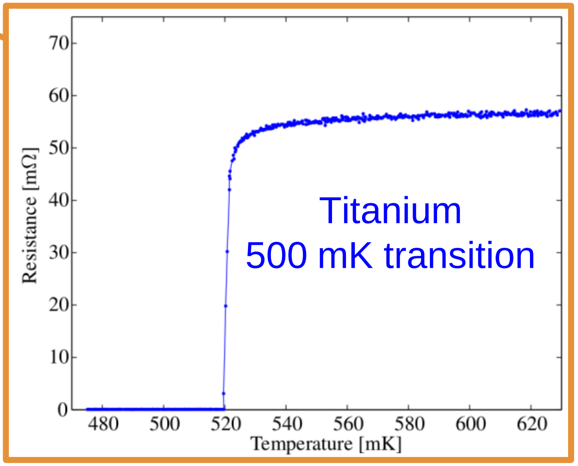
TES on bolometer island



- Absorbs power from one polarization
- Bolometer temperature T(P,G)
- 250 mK bath (focal plane)

- Natural Stokes polarization parametrization
- Rotate pixel to measure both Q and U

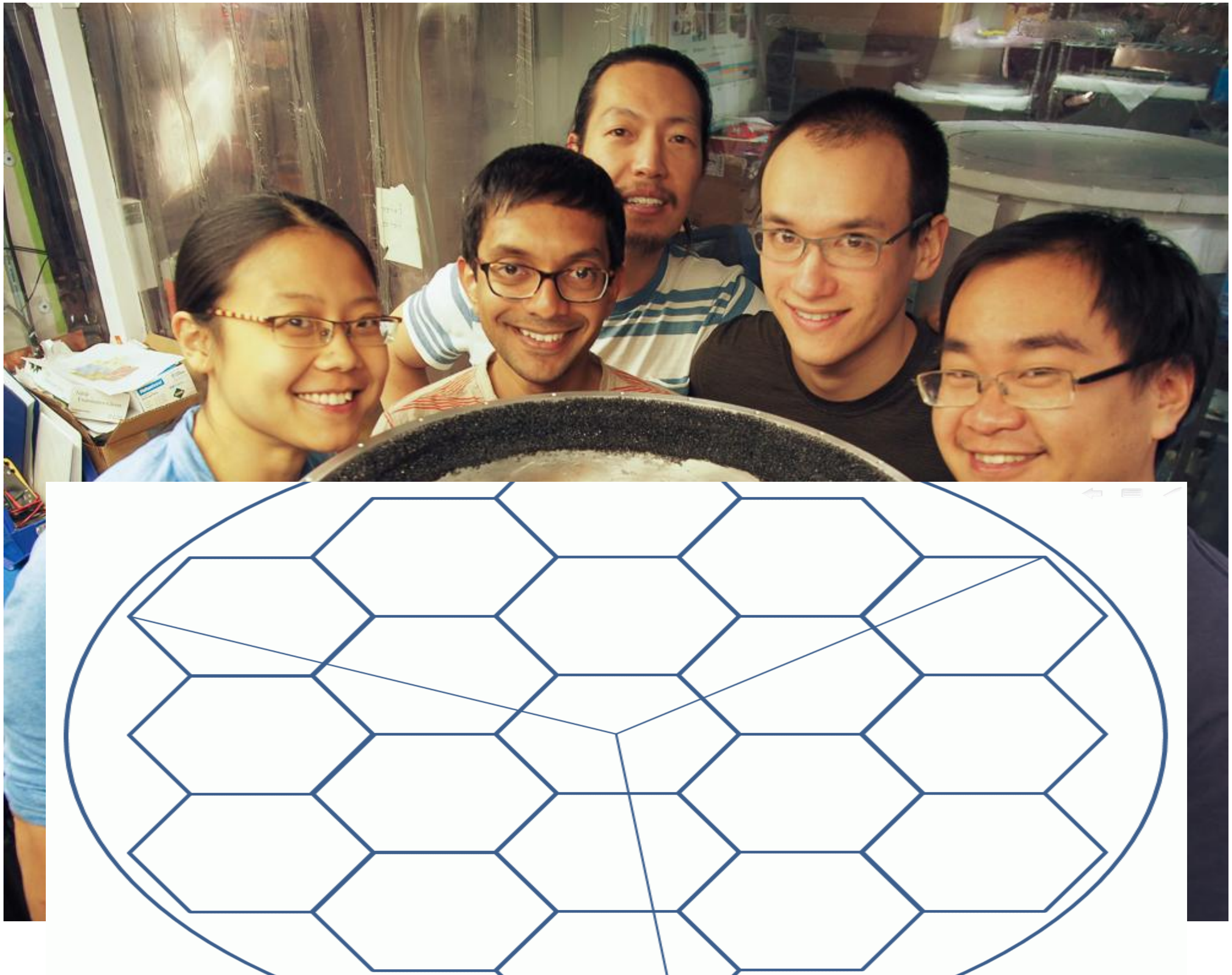




- TES transition has sharp R(T)

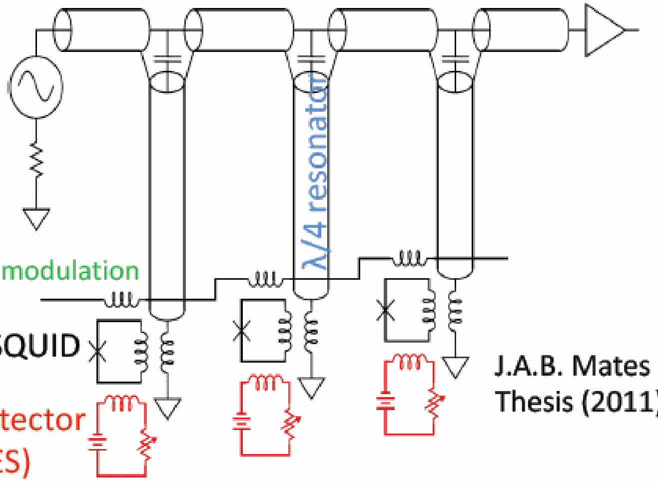
Dec. 2015

Dec. 2015

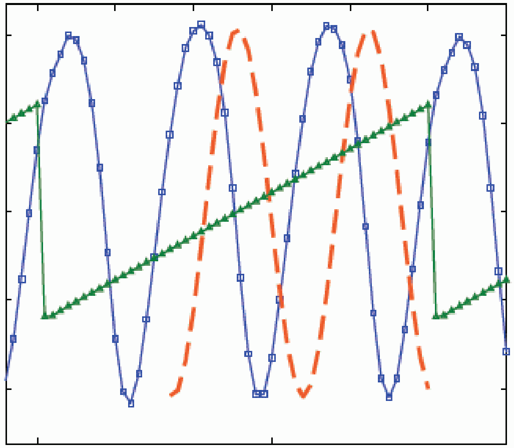


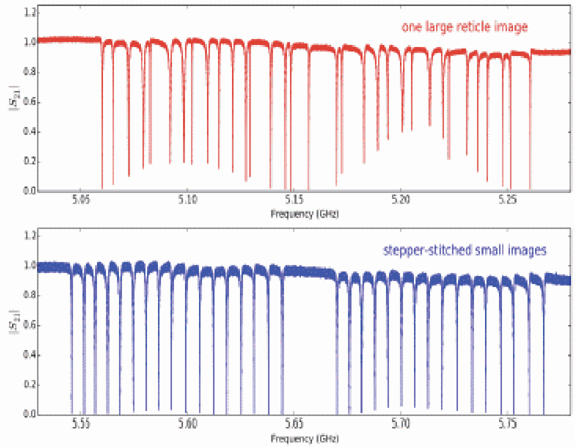
from ~2,500 to 40,000 sensors (each one tile ~ entire BICEP3)

Microwave SQUID readout

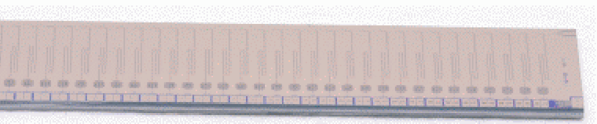


J.A.B. Mates Thesis (2011)

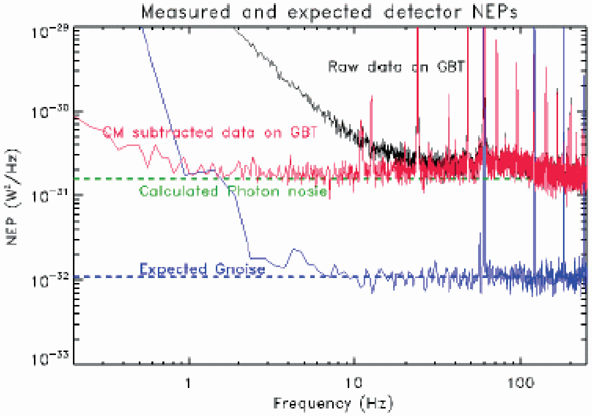




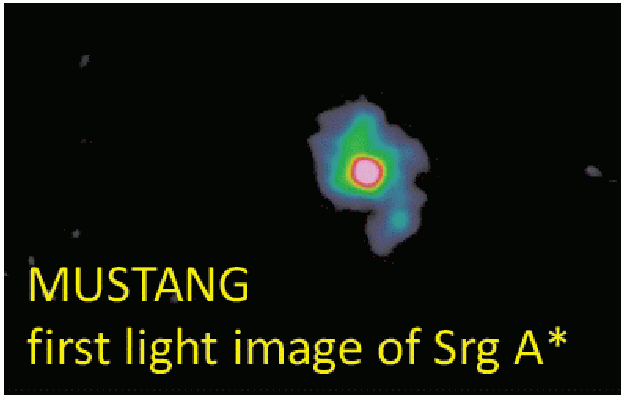
33-channel uMUX



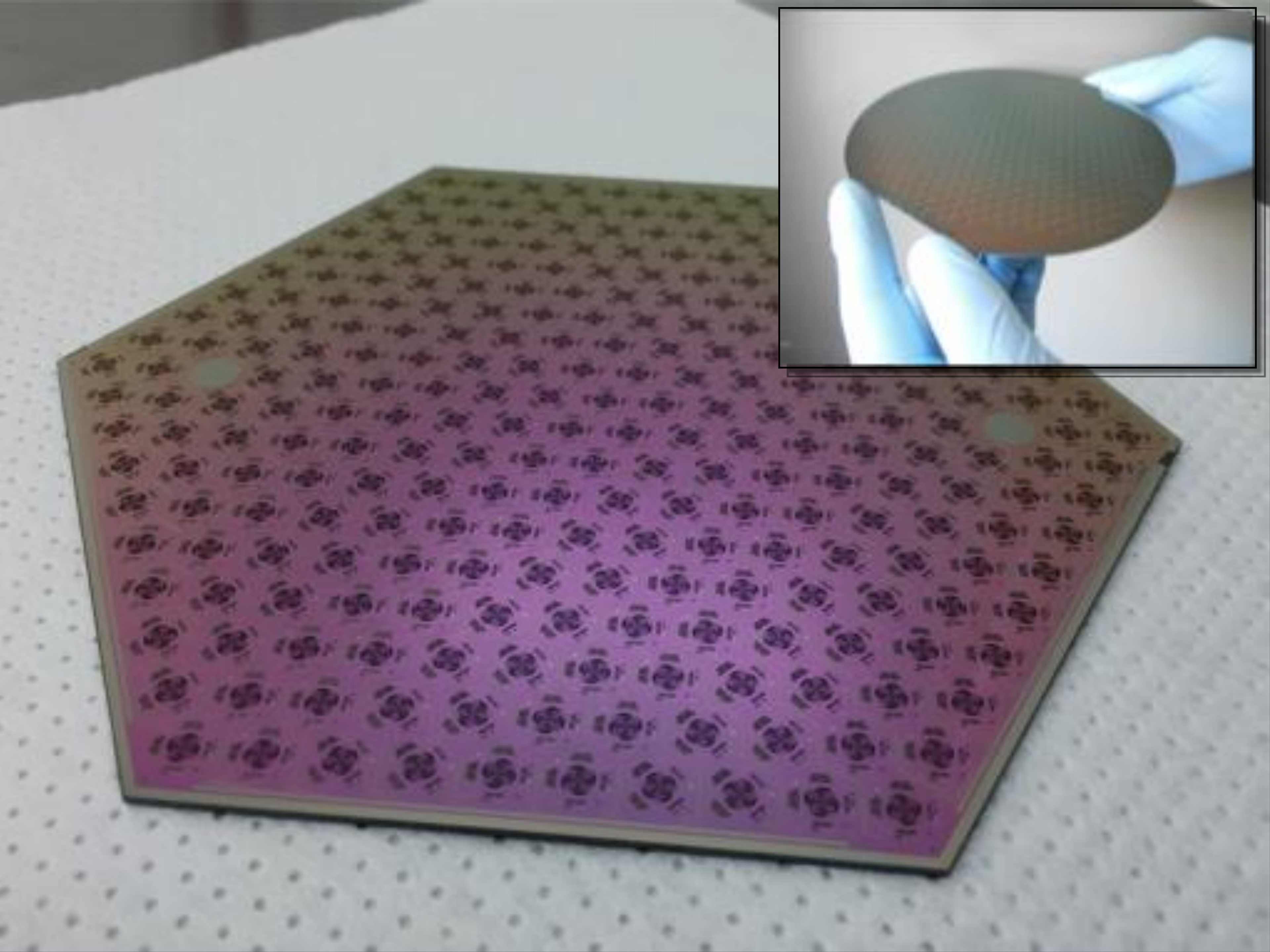
20mm x 4 mm



Stanchfield et al Proc of SPIE (2016)

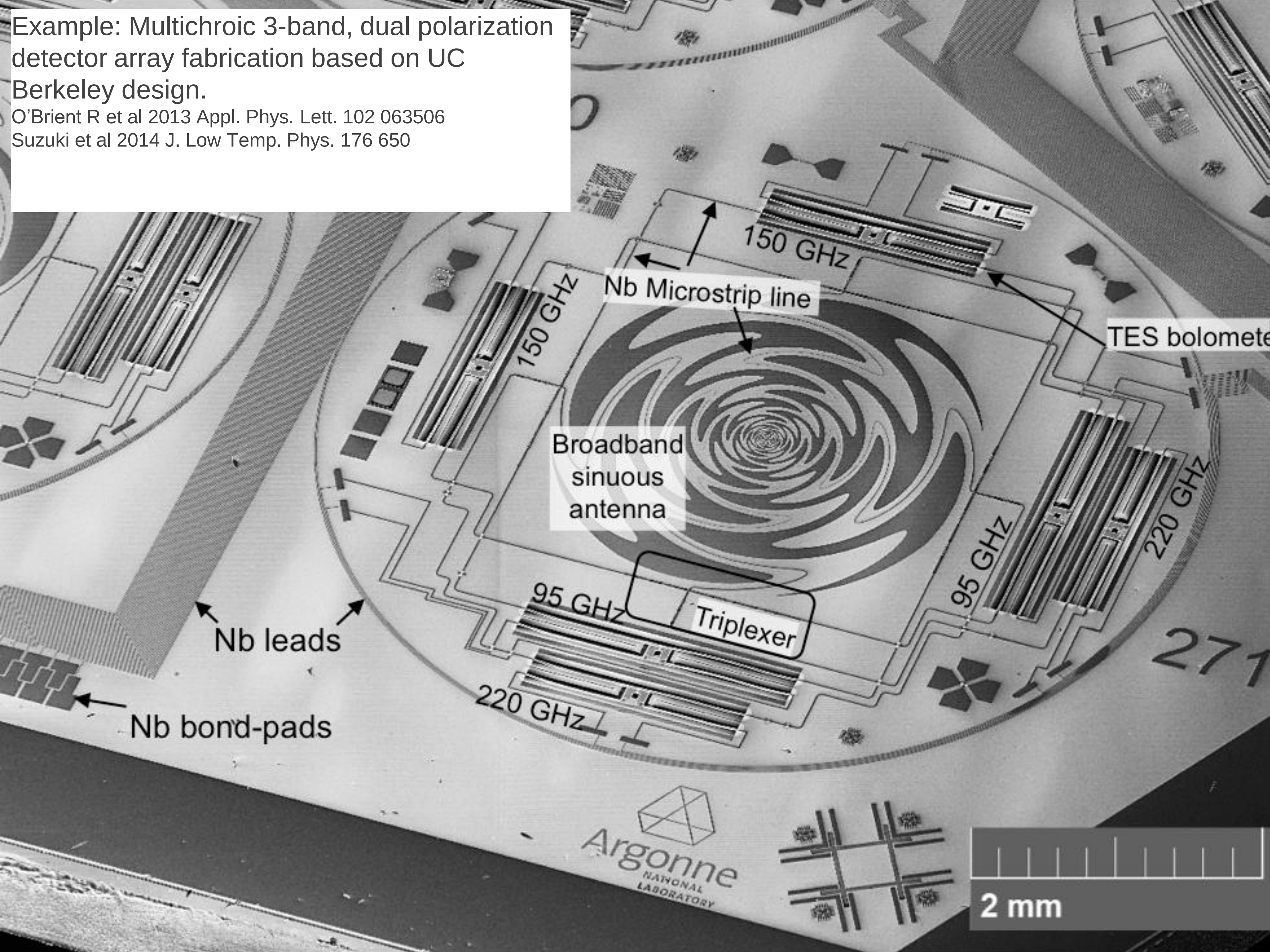


Slide from NIST

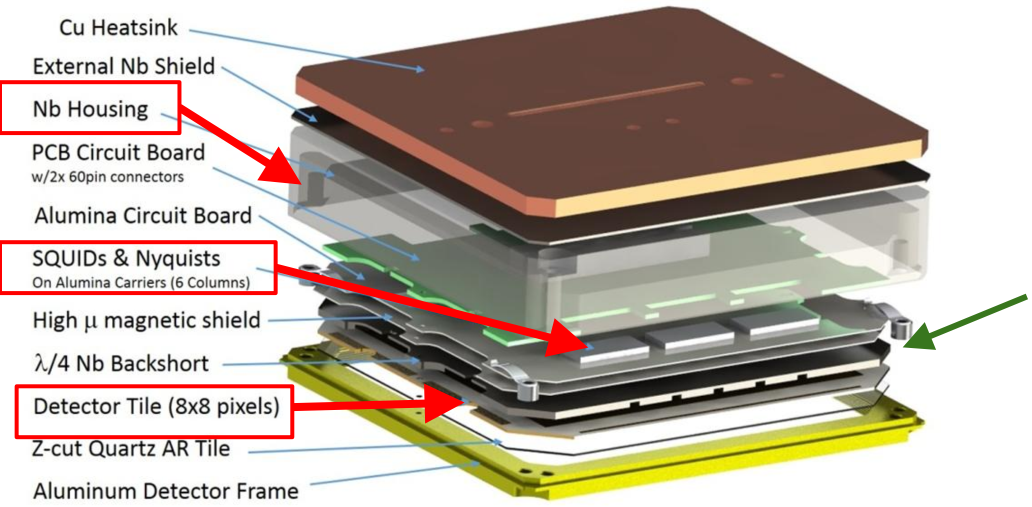


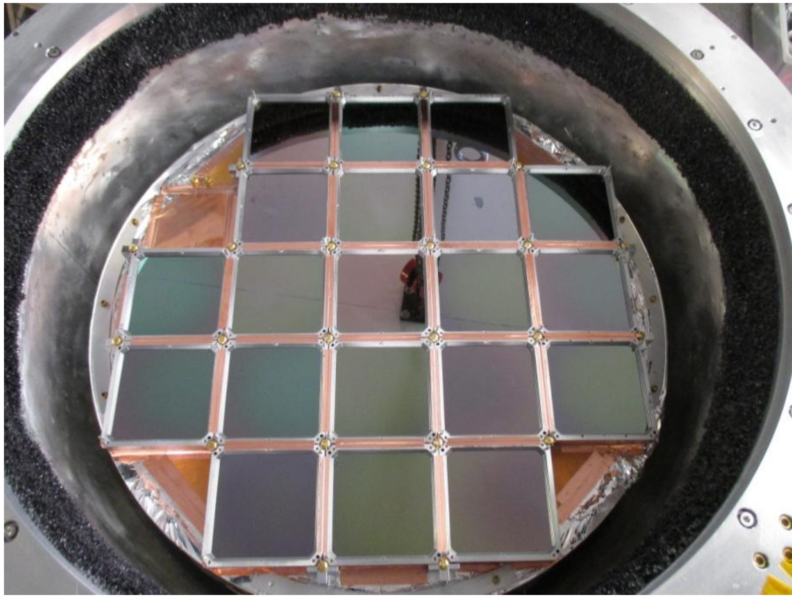
Example: Multichroic 3-band, dual polarization detector array fabrication based on UC Berkeley design.

O'Brient R et al 2013 Appl. Phys. Lett. 102 063506
Suzuki et al 2014 J. Low Temp. Phys. 176 650

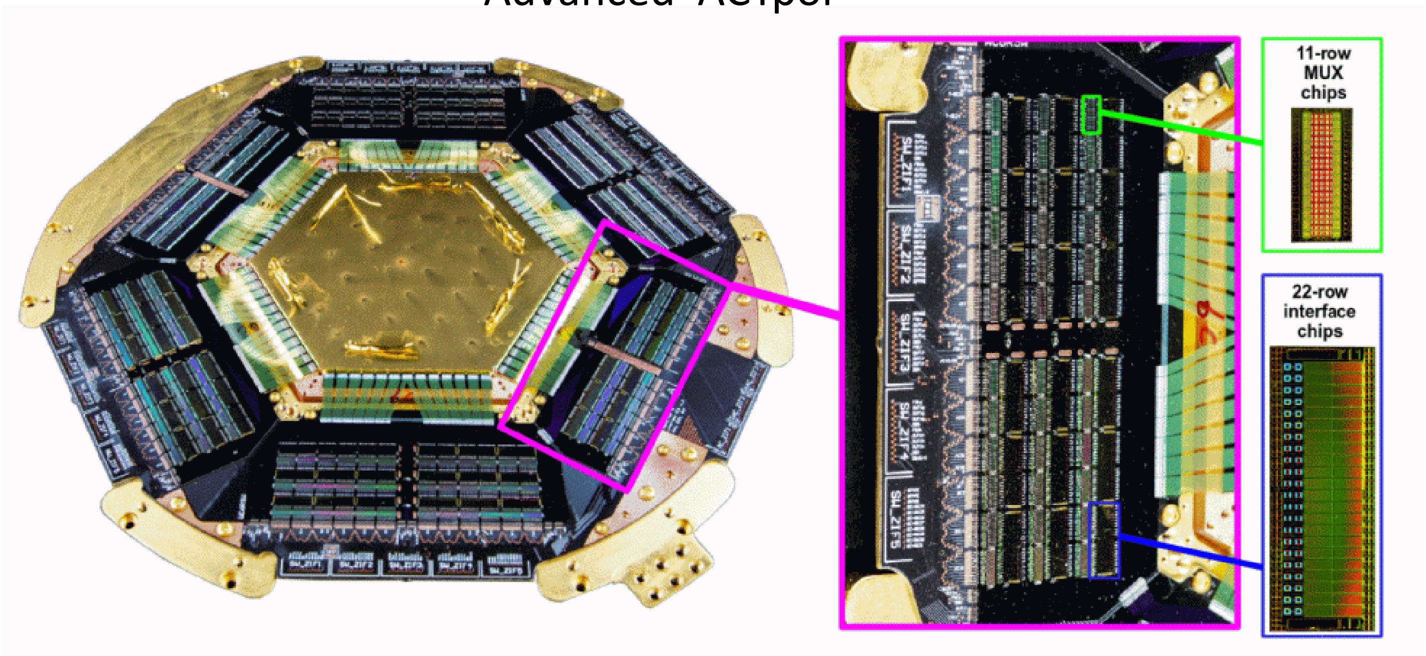


BICEP3 modules





Advanced ACTpol

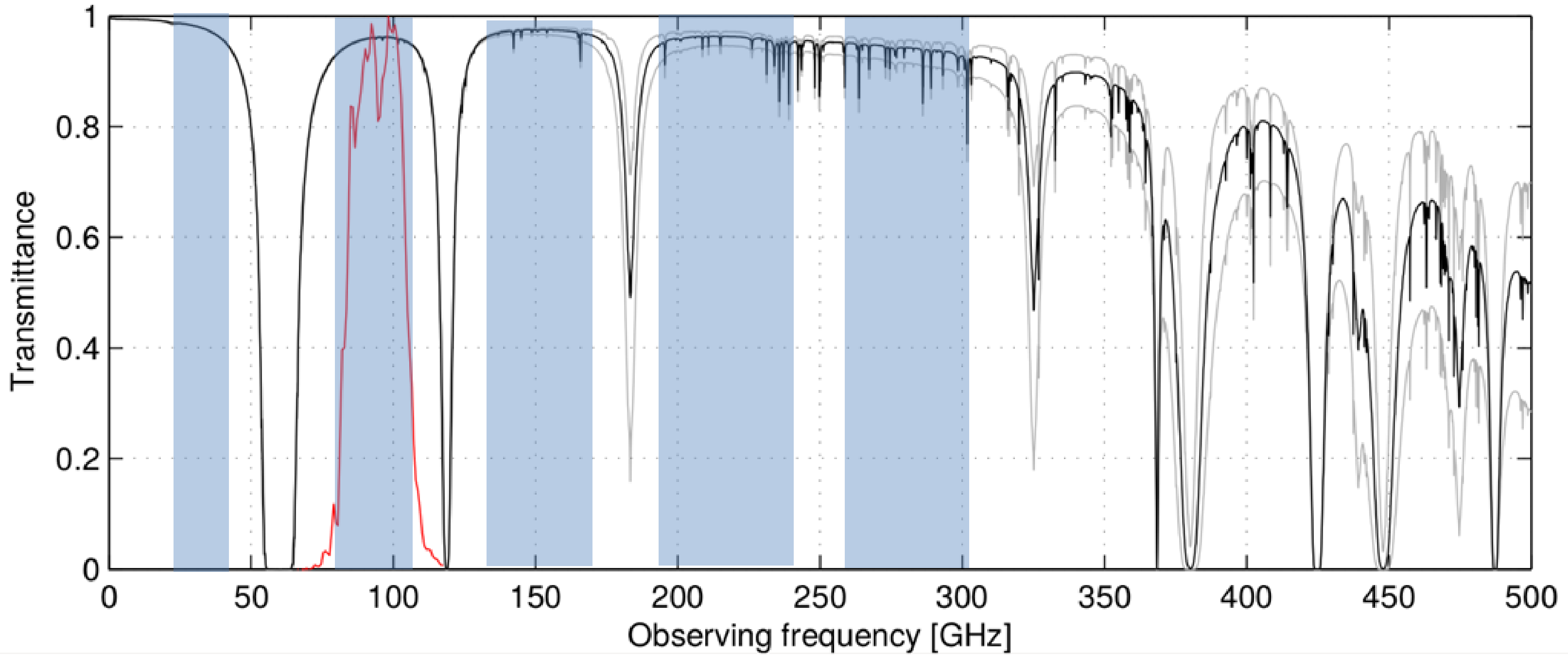


Hunting for primordial *B*-modes from the South Pole

- Ground-based telescopes at the South Pole
  - Good atmospheric conditions for microwave frequencies (dry!)
  - Continuously observe small sky patch to detect faint primordial *B*-mode
  - Focused on the 2 deg anisotropy peak of the primordial *B*-mode pattern
    - only needed small aperture telescopes! Until now.. Lensing is becoming a factor

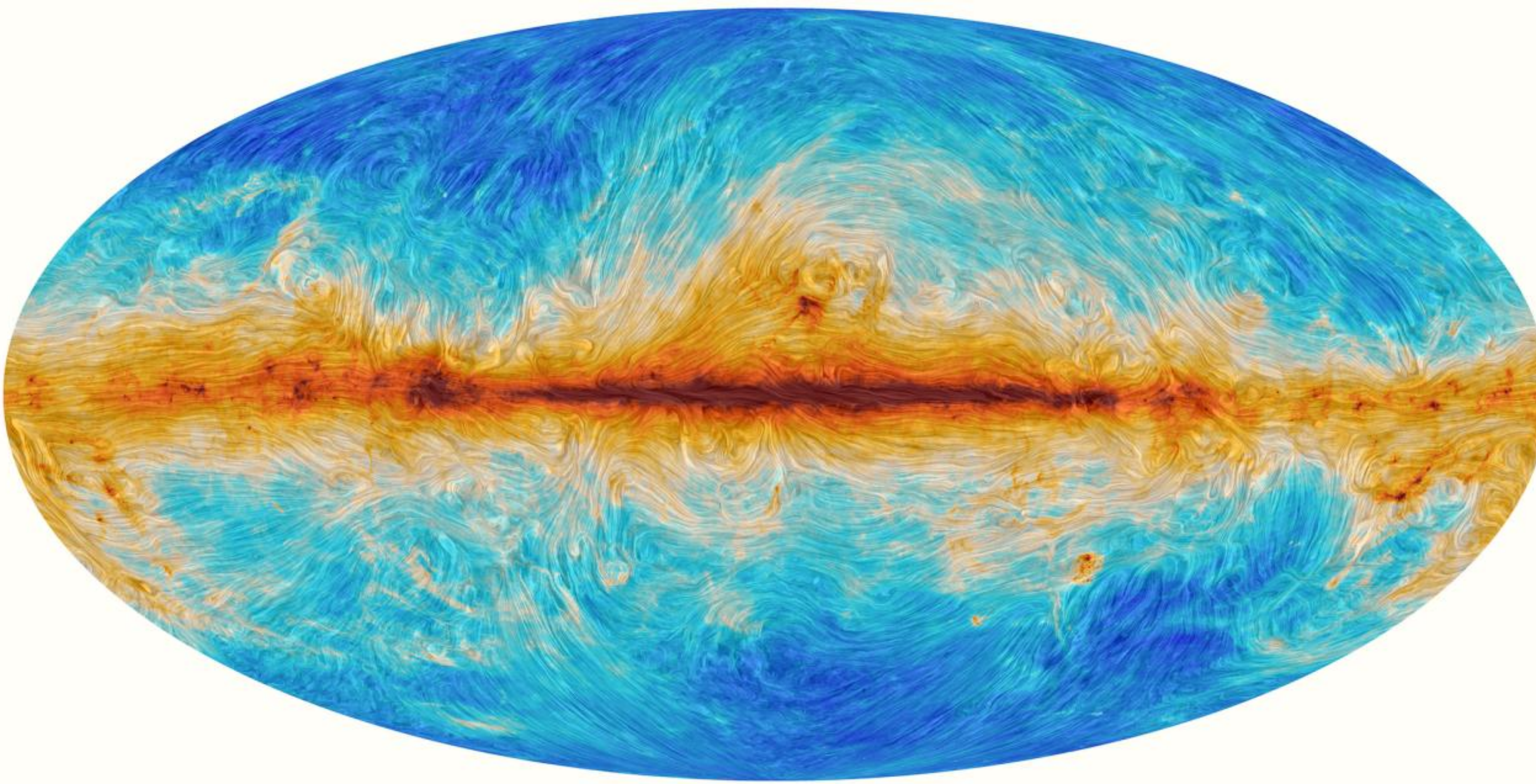
Why go to the South Pole or High Plateaus?

- Good microwave transmittance!
  - A cold desert: lowest precipitable water vapor
- Ground based program can observe in 30-300 GHz window



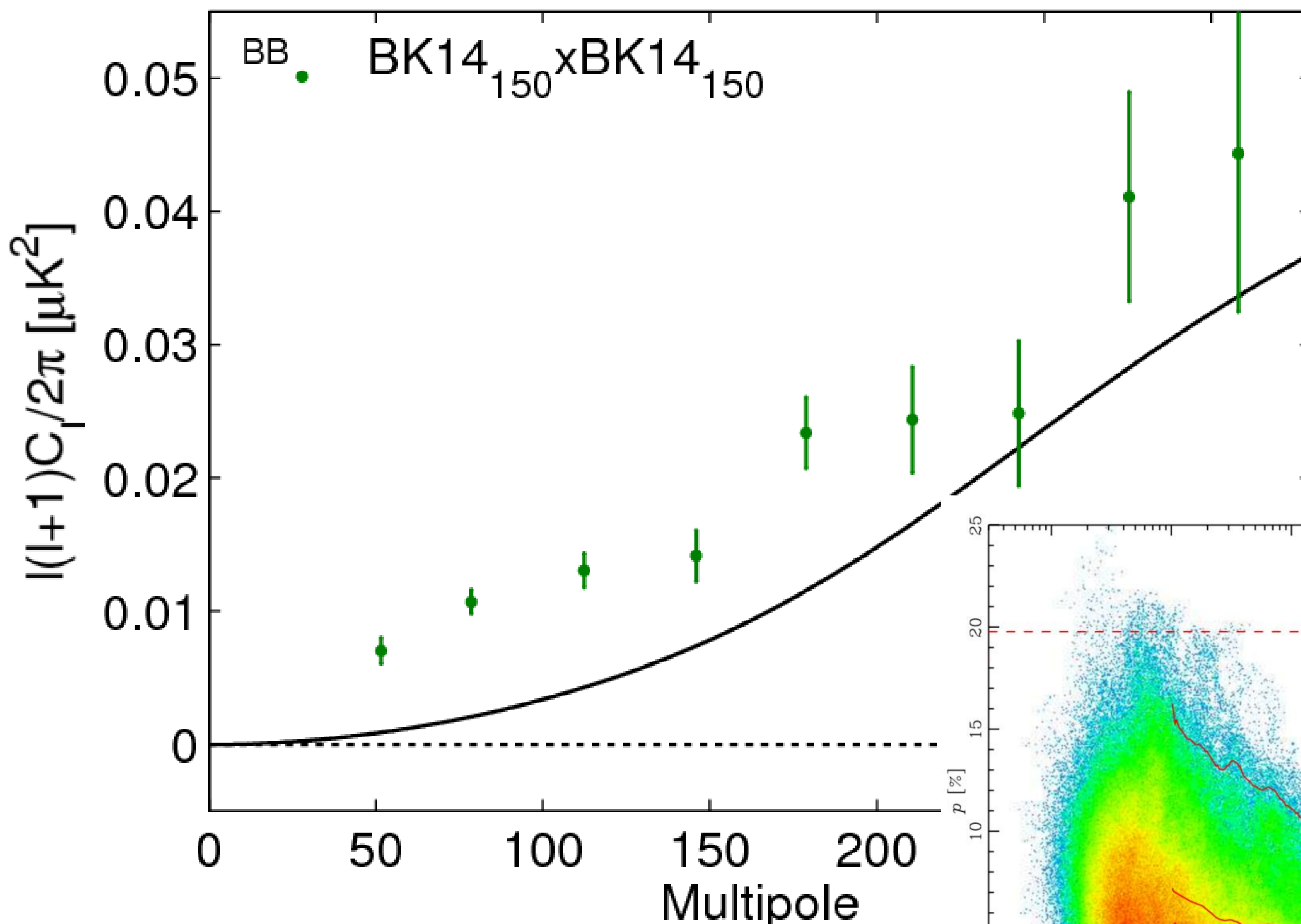
- NOAA weather balloon data for 2010-12 winters at 57 deg obs elevation

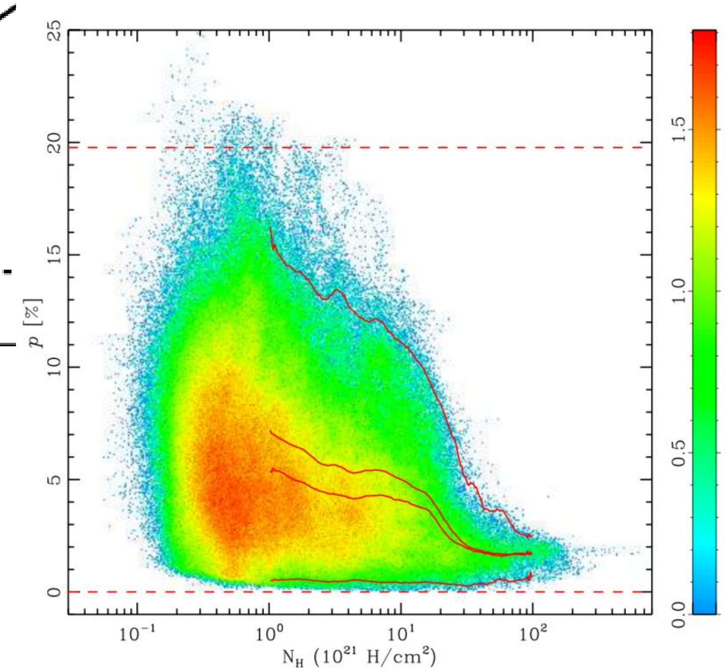
Foregrounds



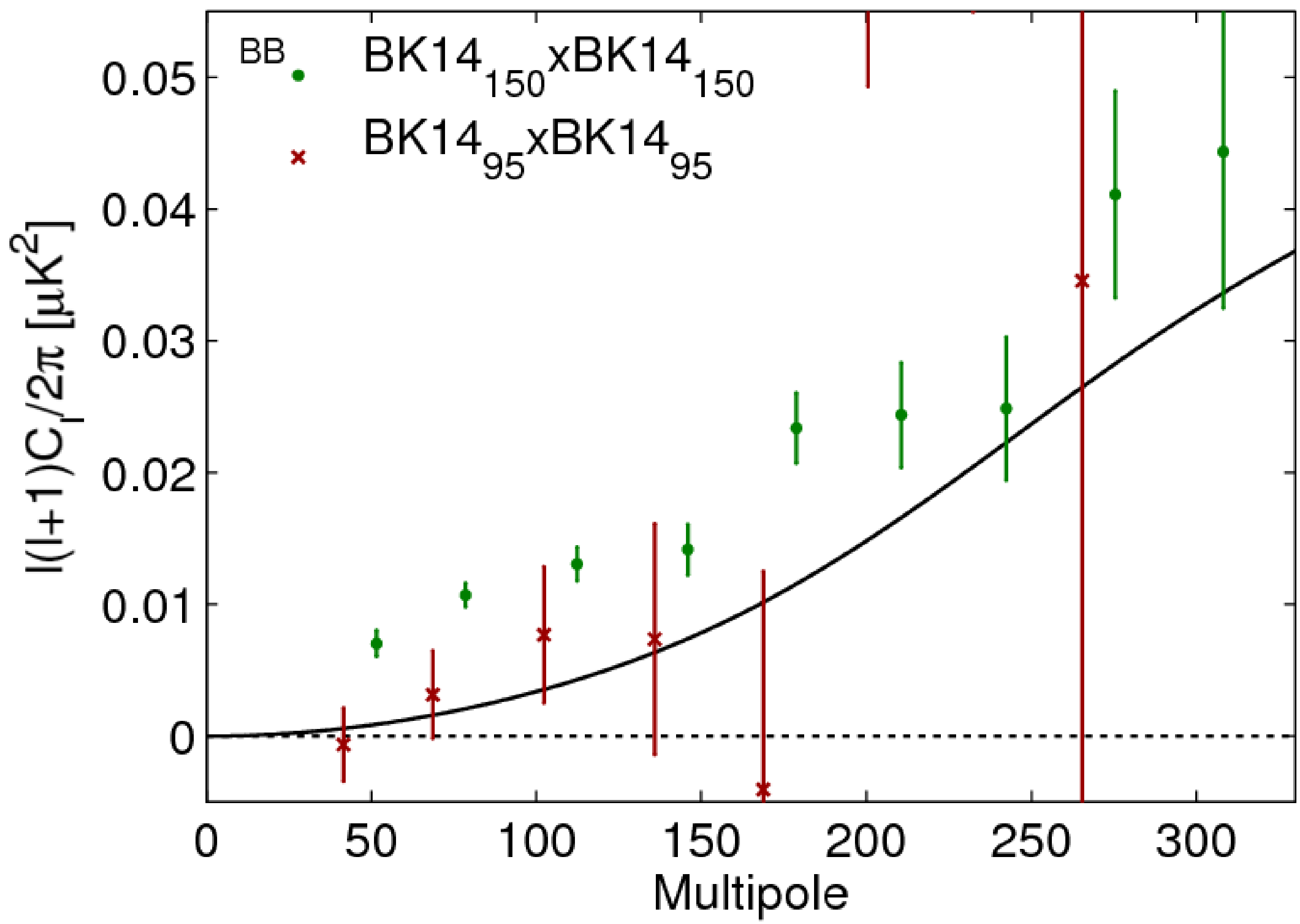
Galactic magnetic field and polarized mm emission seen by Planck

BICEP2 + Keck BB auto and cross-spectra

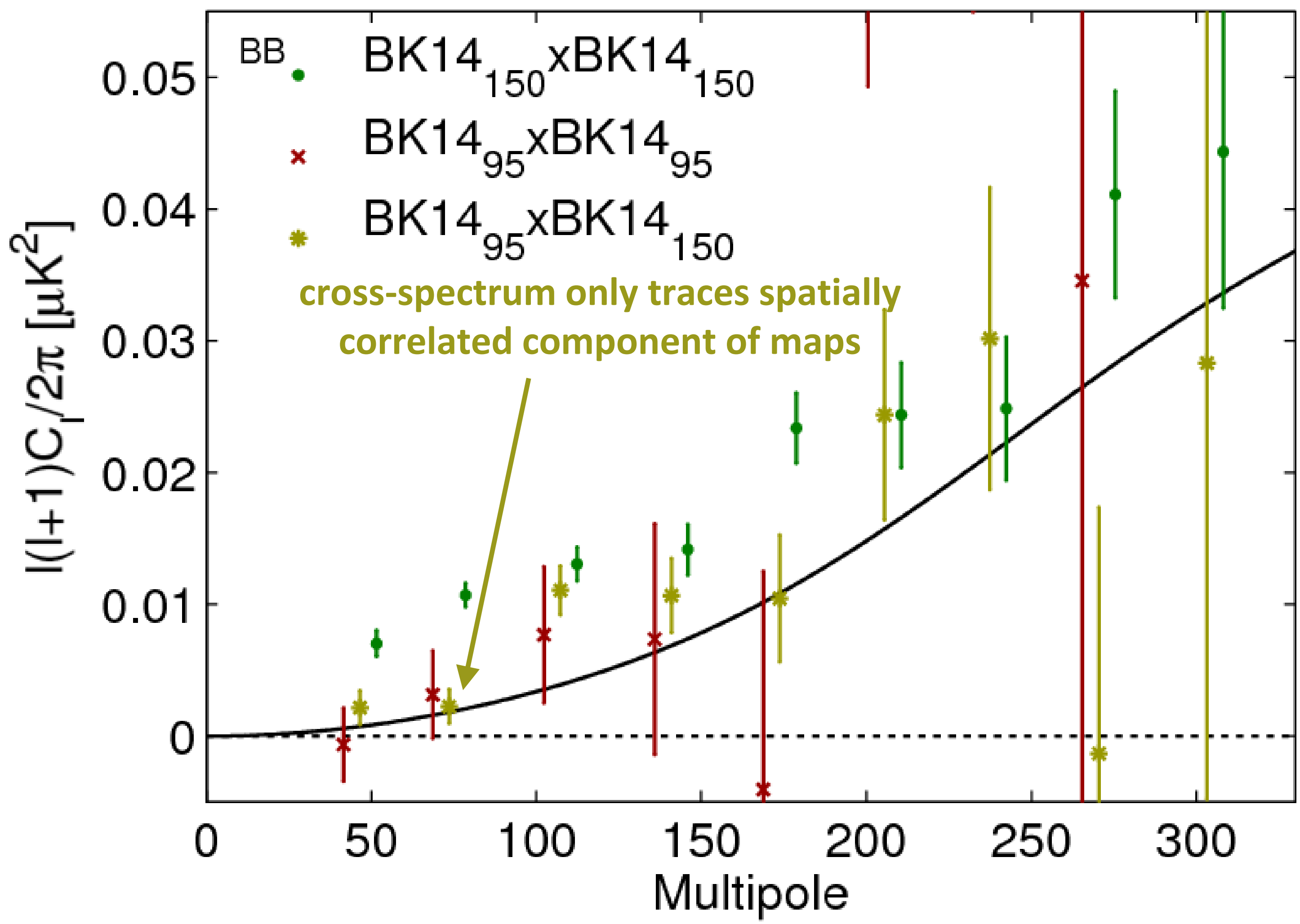




BICEP2 + Keck BB auto and cross-spectra

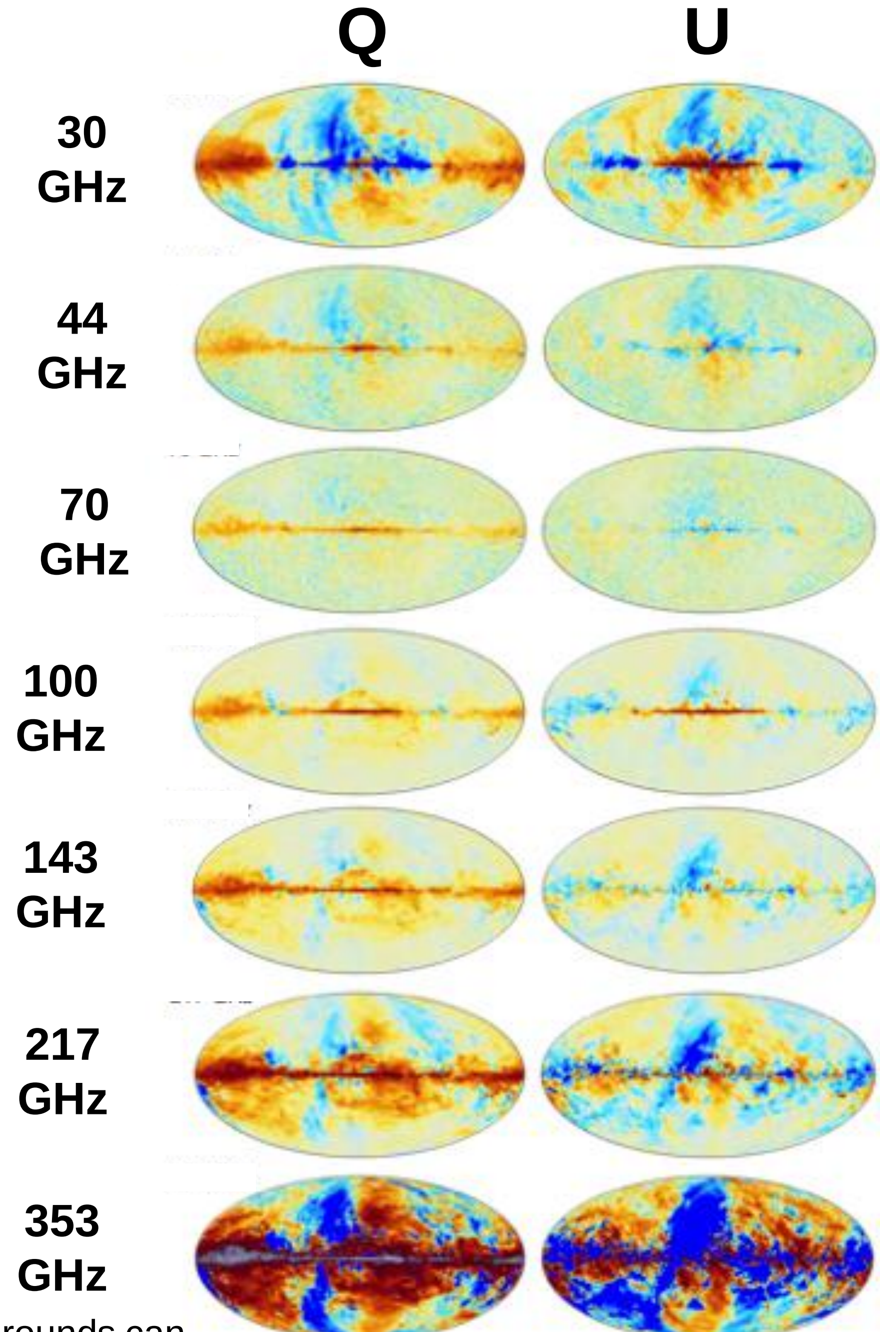


BICEP2 + Keck BB auto and cross-spectra



Polarized galactic
synchrotron
dominates
at low frequencies

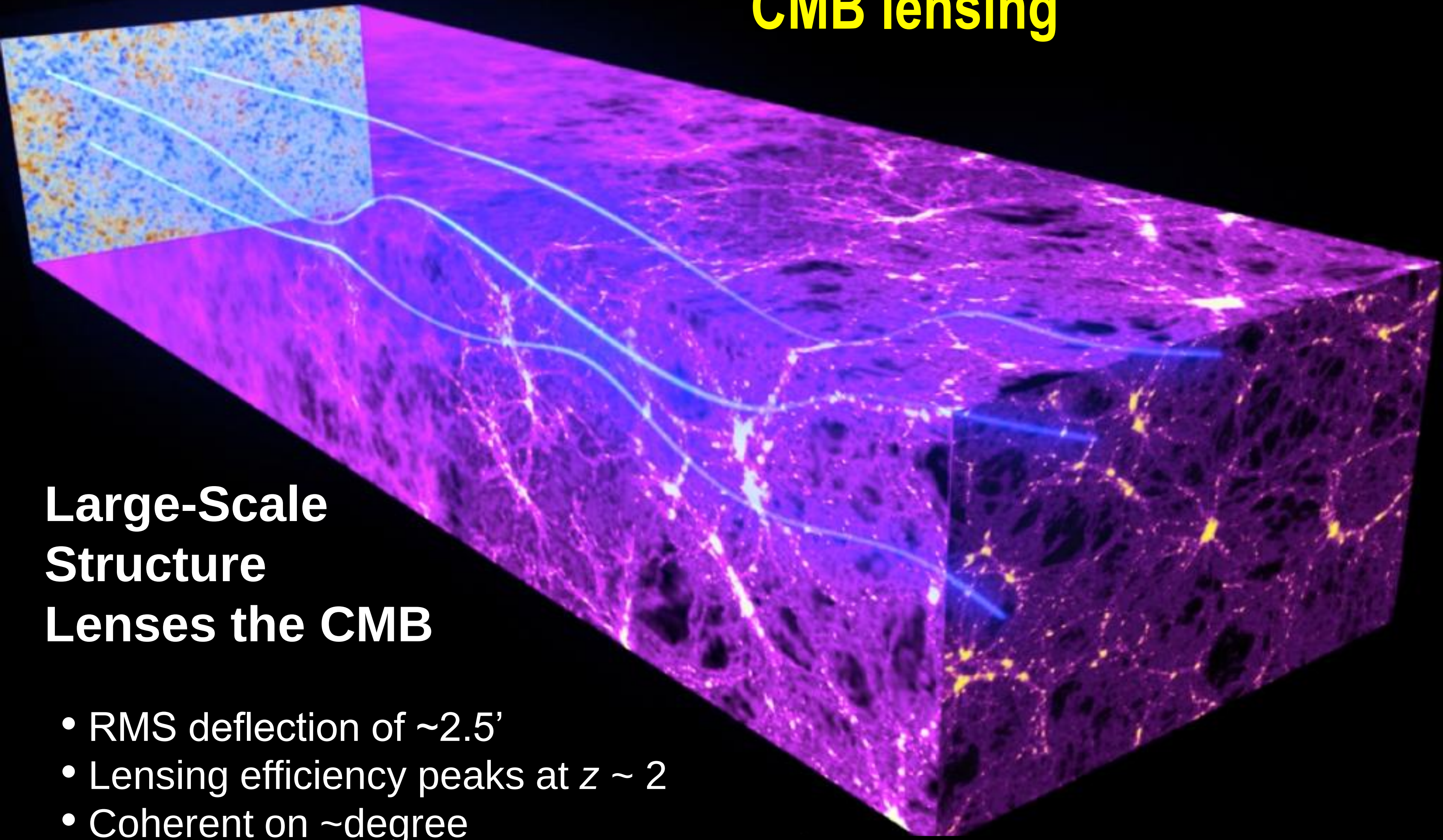
Planck provides polarized maps at 7 frequencies



Polarized thermal emission
(~20K) from galactic **dust**
aligned in magnetic fields
dominates at high frequencies

Fortunately for the future .. Although modeling of foregrounds can be complicated, their frequency dependences are distinctly different

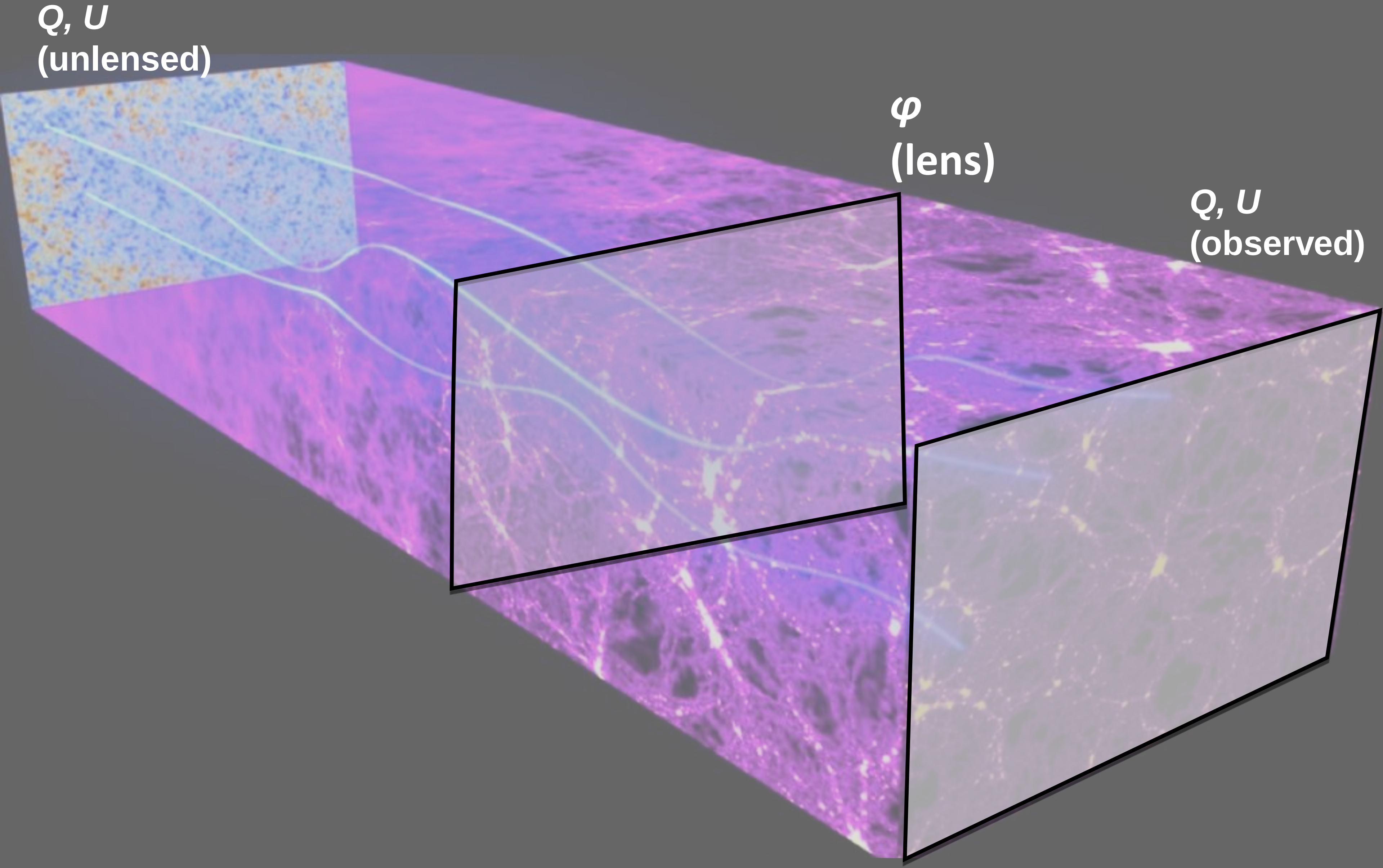
CMB lensing



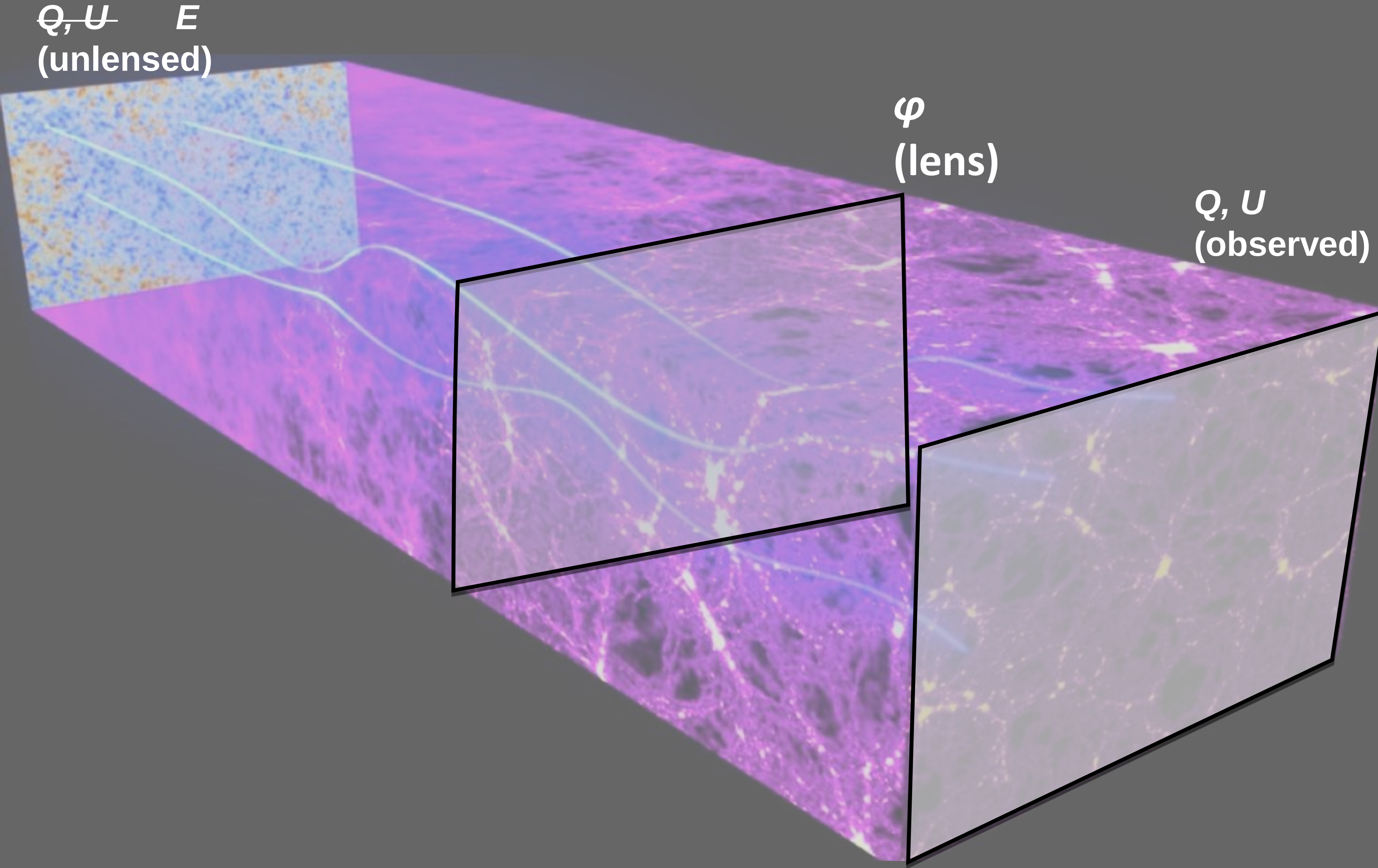
Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5’
- Lensing efficiency peaks at z ~ 2
- Coherent on ~degree (~300 Mpc) scales

graphic from ESA website



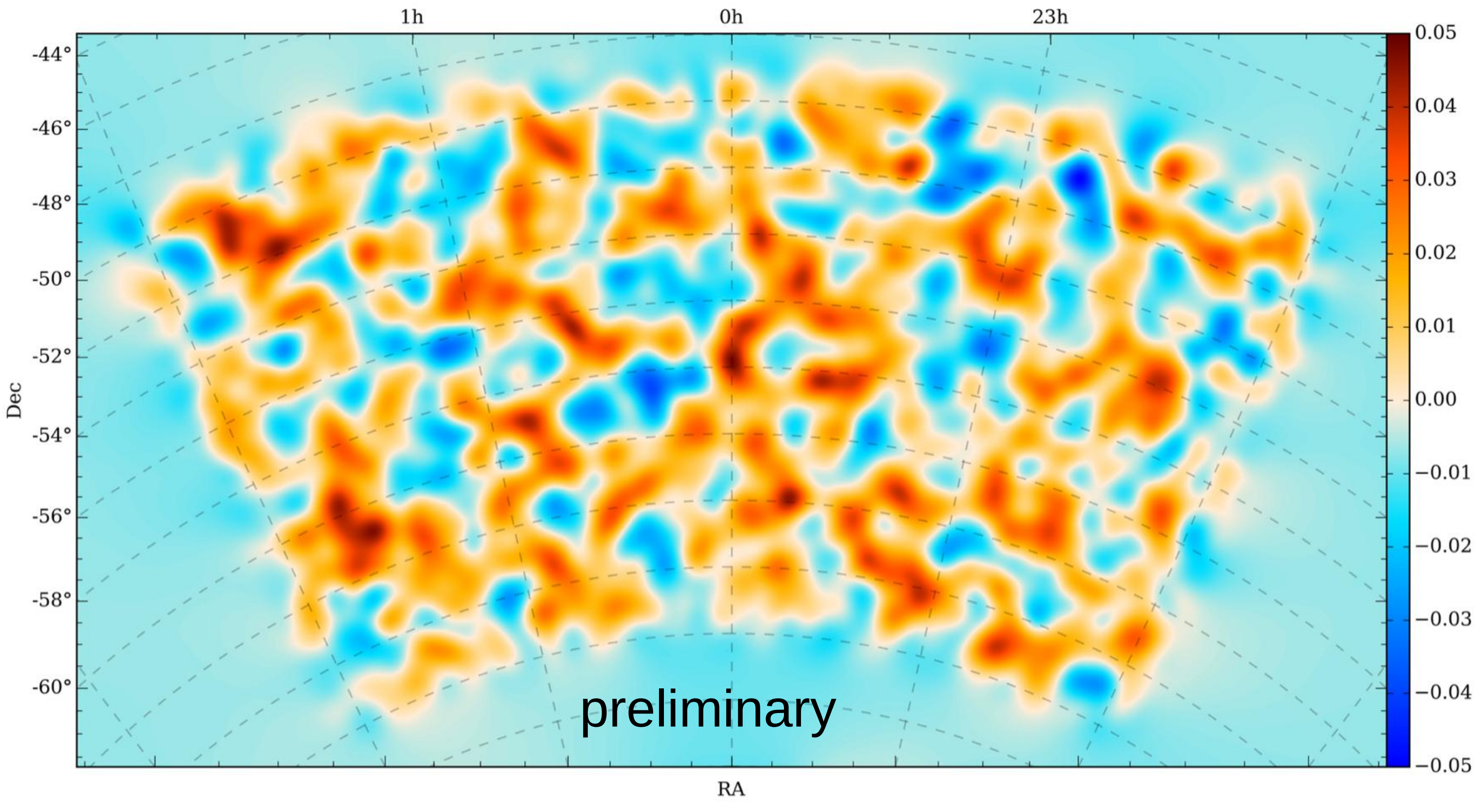
graphic from ESA website



graphic from ESA website

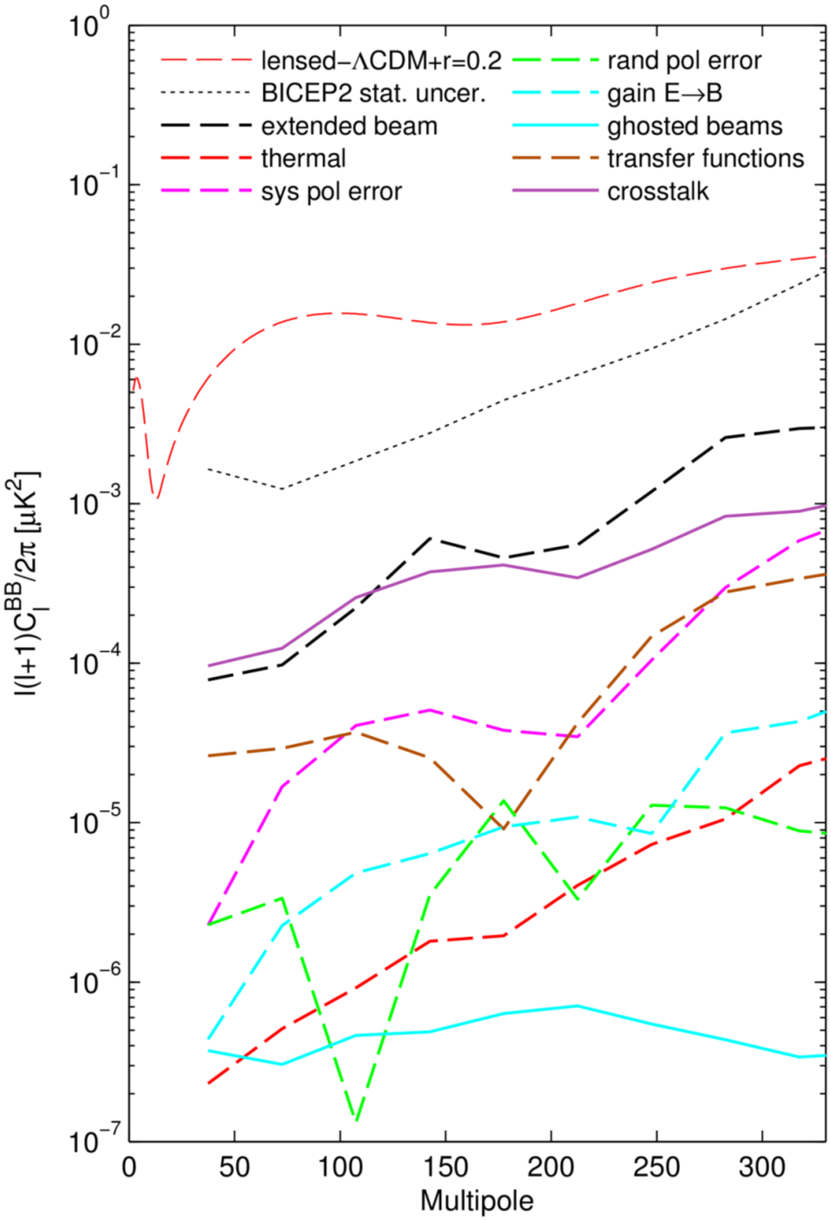
CMB lensing

SPTpol 500d lensing potential reconstruction of BICEP field, L < 250 imaged with s/n > 1.



CMB-S4 will measure modes with s/n > 1 to L ~ 1100 over most of the sky.

Systematics



BICEP2 systematics residuals

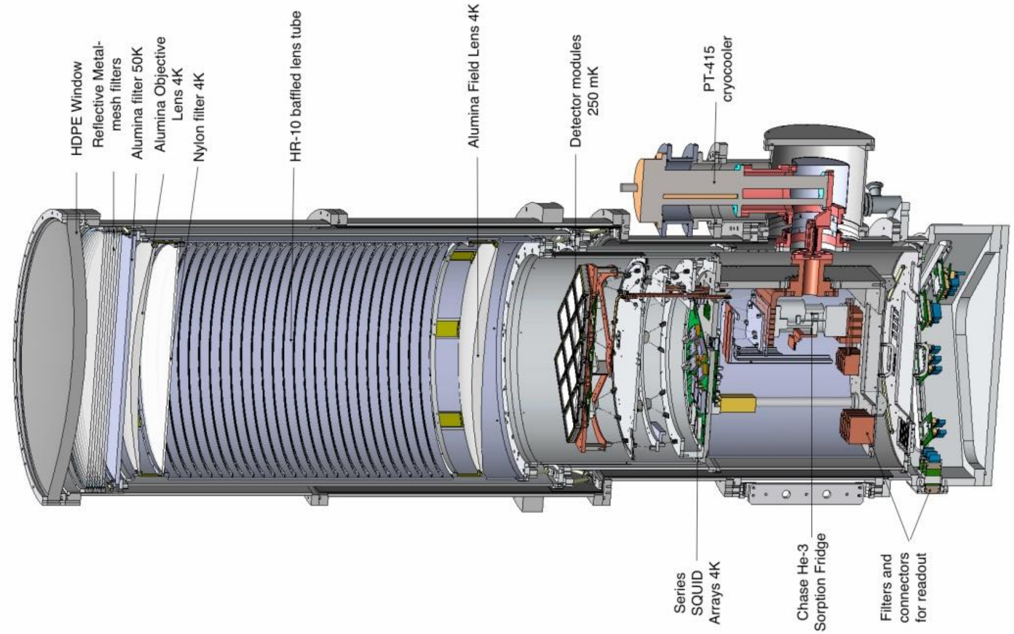
What does a modulator fix?

(mostly , $T \rightarrow P$ leakage)

	Continuously rotating HWP	Stepped HWP	No HWP
True $1/f$	yes	no	no
Main beam	yes	yes	deproj
Relative gain variations	yes	deproj	deproj
Bandpass mis.	yes	yes	*deproj*
Focal plane temp. (common mode)	yes	*deproj*	*deproj*
Focal plane temp. (spatial modes)	yes	no	no
Unpolarized atmosphere	yes	*gain corr.*	*gain corr.*
Polarized atmosphere	no	no	no
Implementation Complexity	high (optical and mechanical)	medium (optical)	low

Advantages of small aperture program

- Active boresight rotation of the entire instrument
- Co-moving forebaffle, improving sidelobe rejection
- Cold, on-axis, refracting optics, providing low and stable system offsets
- Full characterization pre-deployment with modest antenna range
- Reduced experiment cost, a sharp function of the size and weight of the instrument



These are now fully recognized in the CMB-S4 community

Signal is here

Not just the white noise level

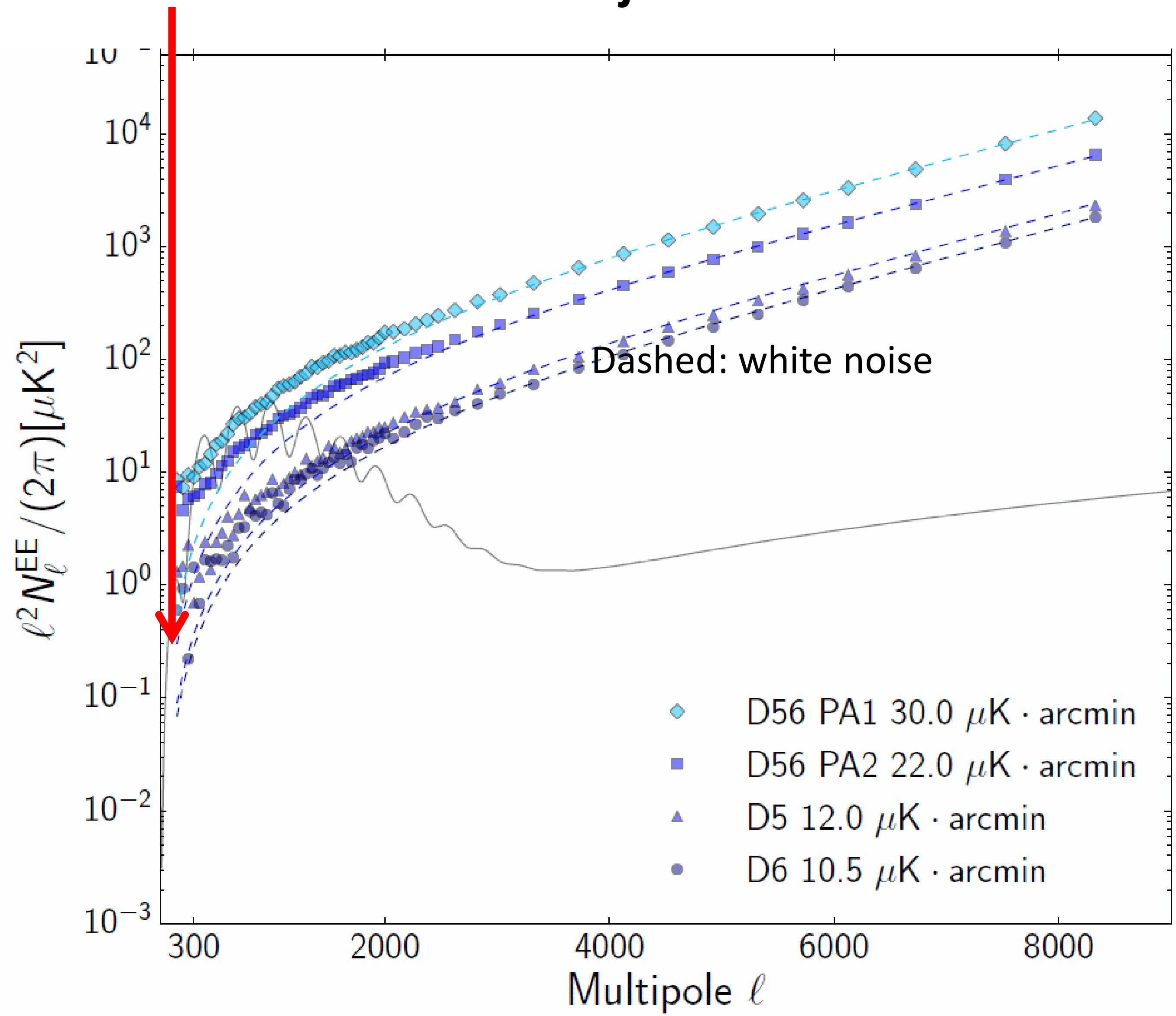


FIG. 8.— Noise levels in the ACTPol two-season maps, with ΛCDM theory spectra included for comparison. In temperature

Systematics, calibration errors, & mitigation

A lesson from Planck is that preflight requirements are often too tight ; knowledge requirements not enough (temporal responses, spectra, beams, ..). Eventually these parameters are obtained from the **data**:

- Information on far side-lobes from the Galaxy
- Main beams from planets
- Band centers & CO sensitivity from template fitting
- Time constants from planets & cosmic ray hits/modeling

If there is enough redundancy, unbiased measurements of the sky can still be made. If not, untrustworthy modes will be deprojected. We will comprehensively explore limitations of these mitigation techniques by searching for **degeneracy** in cosmological, foregrounds, and instrumental parameters in the data cube $TQU(\vec{r},\nu)$.

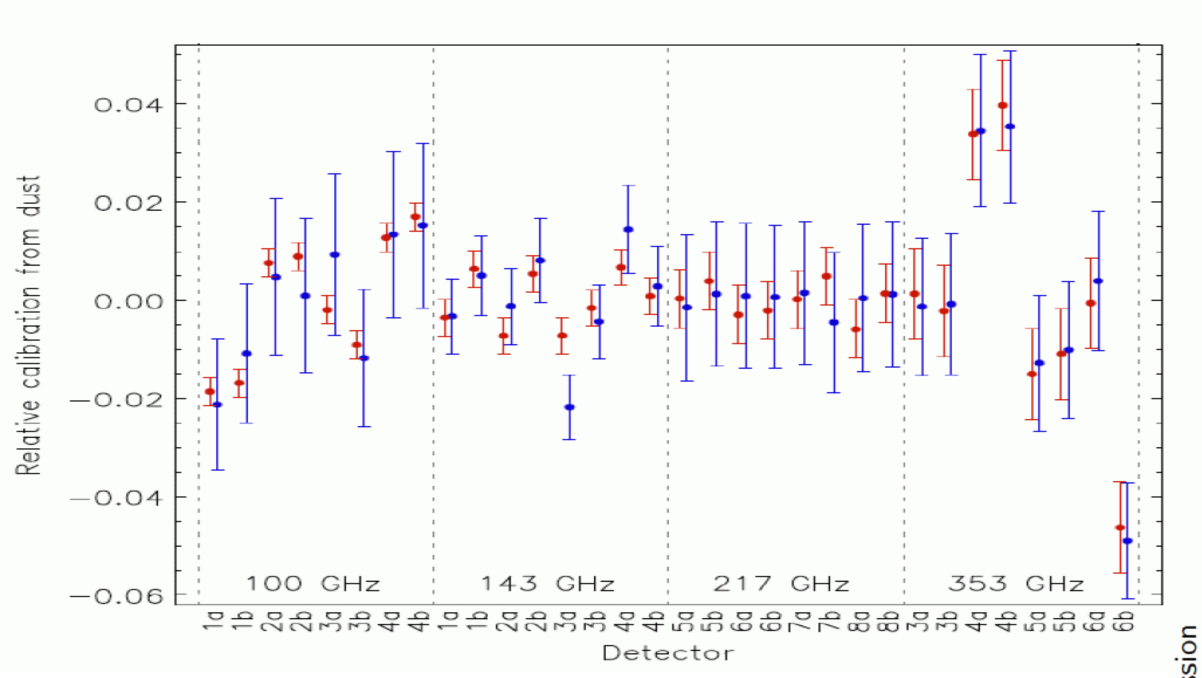
TABLE 3
DEPROJECTION TEMPLATES AND FIT COEFFICIENTS

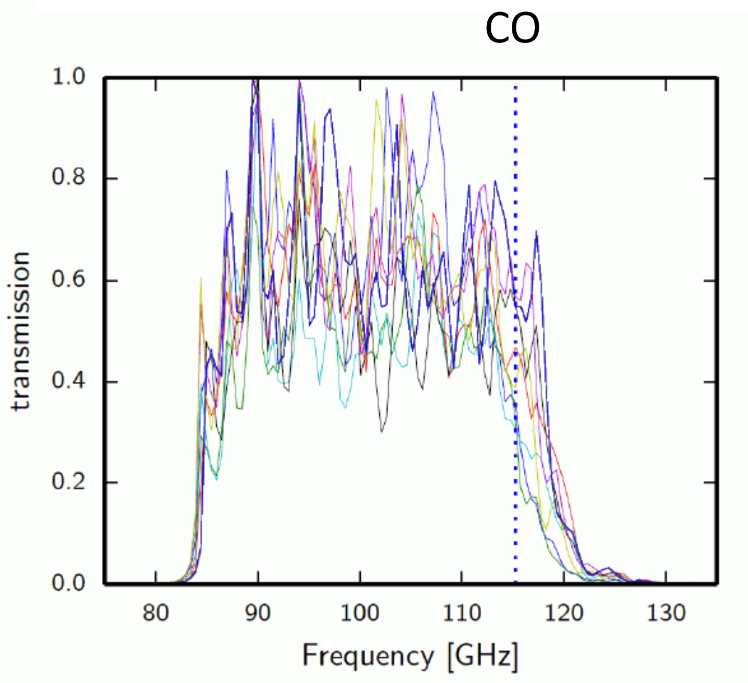
Differential Mode	Symbol	Definition	Fit Coefficient	Template
Gain	δg	$g_A - g_B$	δg	$\tilde{T}$
Pointing, x	δx	$x_A - x_B$	δx	$\nabla_x \tilde{T}$
Pointing, y	δy	$y_A - y_B$	δy	$\nabla_y \tilde{T}$
Beamwidth	$\delta\sigma$	$\sigma_A - \sigma_B$	$\sigma\delta\sigma$	$(\nabla_x^2 + \nabla_y^2)\tilde{T}$
Ellipticity, +	δp	$p_A - p_B$	$(\sigma^2/2)\delta p$	$(\nabla_x^2 - \nabla_y^2)\tilde{T}$
Ellipticity, ×	δc	$c_A - c_B$	$(\sigma^2/2)\delta c$	$2\nabla_x \nabla_y \tilde{T}$

BICEP/Keck instrument systematics, 2015

$\partial_\nu \tilde{T}$ deals with bandpass mismatches

Planck Example:





Blue: pre-flight
Red: component separation

When

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO +T_e prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**