Why is the B-mode Polarization measurement so important for Cosmology? -BICEP2 as an example-

Ade et al. 112, PRL 241101

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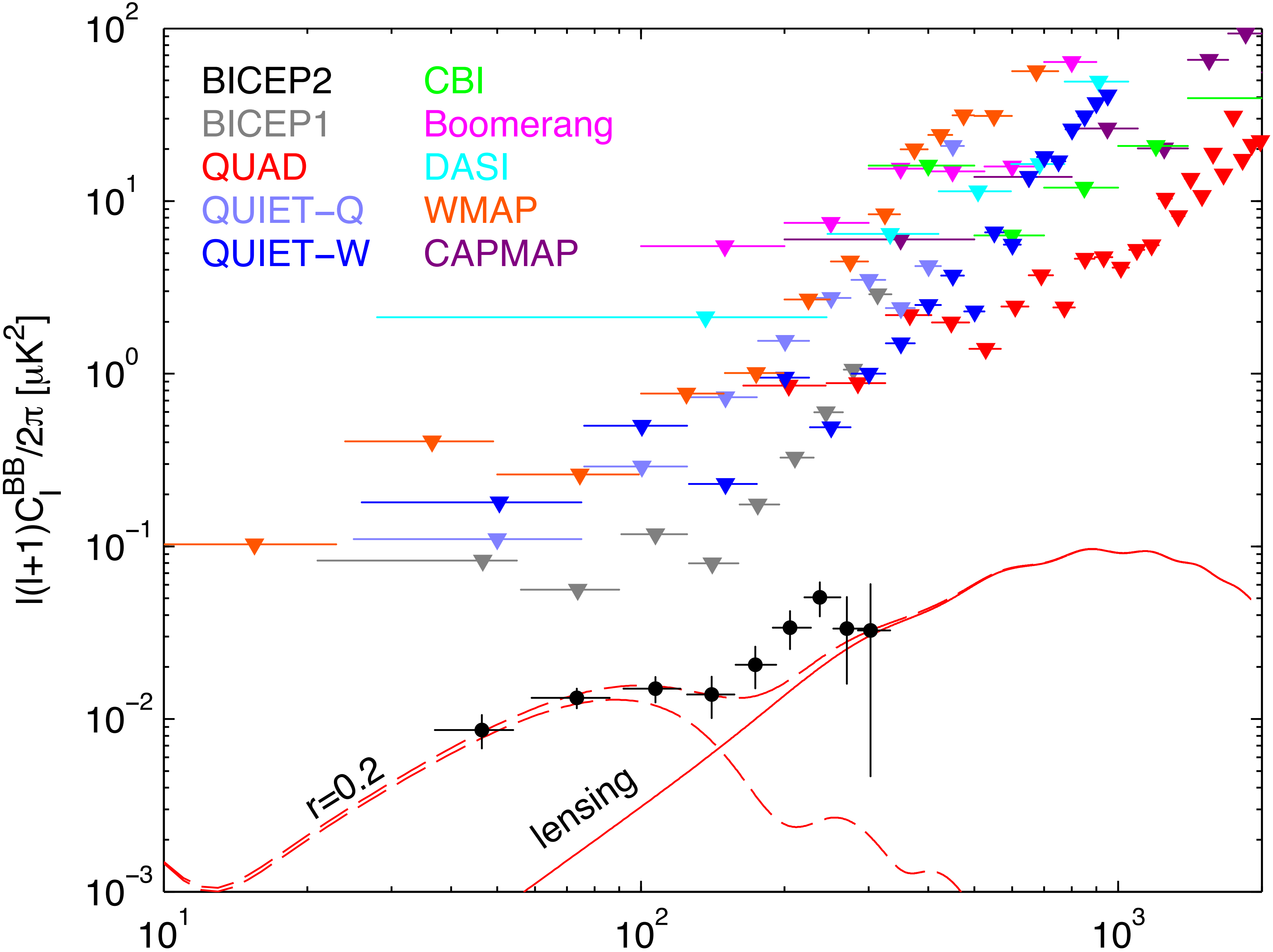


ariXiv:1403.3985

Why is the BICEP2 result so important for Cosmology?

- B-mode polarization can be evidence of tensor perturbations (Gravitational Wave).

Indirect Detection of Gravitational Wave on very large wave lengths

- If one can find the consistency relation between tensor and scalar perturbations, the existence of inflation can be proved!

Indirect Proof of Inflation

Why is the BICEP2 result so important for Cosmology?

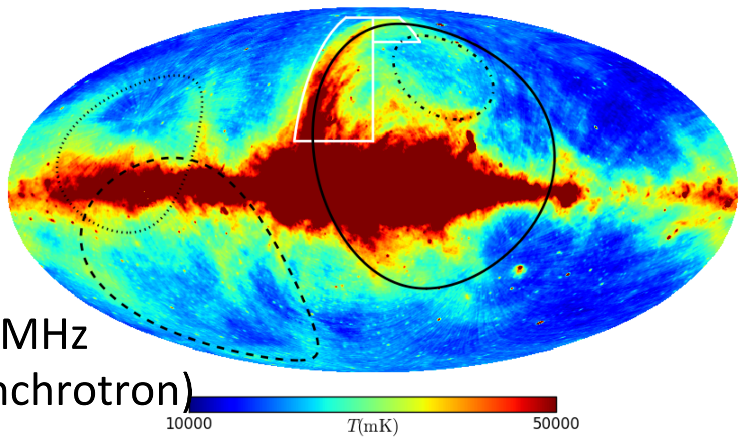
- In ADS, the Number of papers with the word "BICEP2" in the abstract are 336 by Sep 23.
- Number of Citations of the BICEP2 B-mode detection paper is 668 by Sep 23.

Questions have to answer are

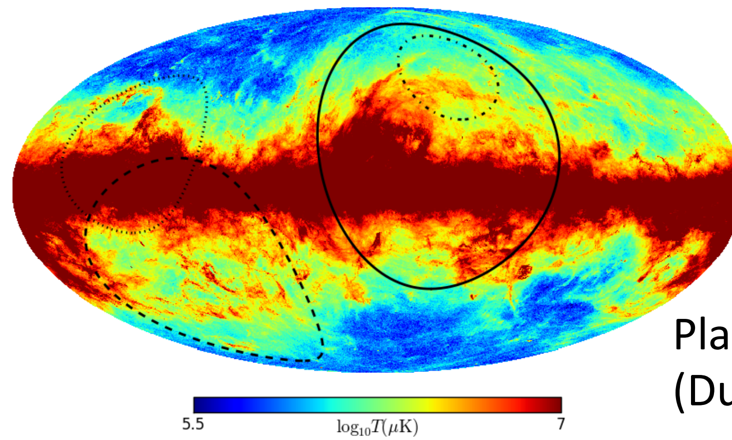
1) Are BICEP2 signals really primordial?
   – Foreground?
2) Does B-mode really mean gravitational wave?
   – Vector mode?
3) Are BICEP2 tensor perturbations consistent with PLANCK temperature anisotropies?
   – Running spectrum index?
4) What do we learn about inflation?
   – Large field inflation?

Q1) Are BICEP2 signals really primordial?

- You may have convinced… but
- Galactic Loop? Liu, Mertsch, Sarkar, arXiv:1404.1899

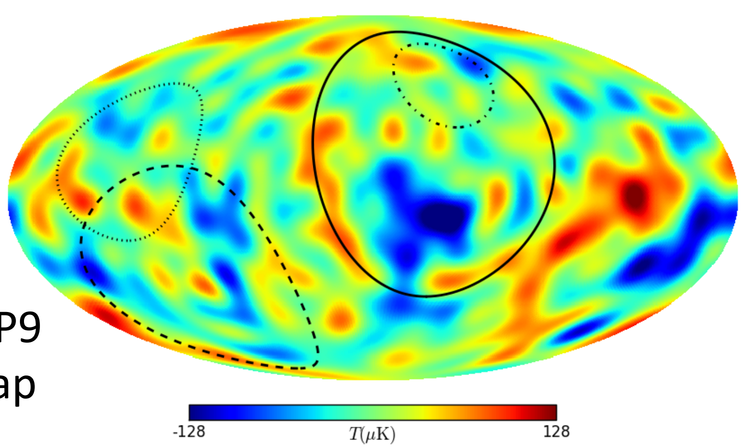


408MHz
(Synchrotron)

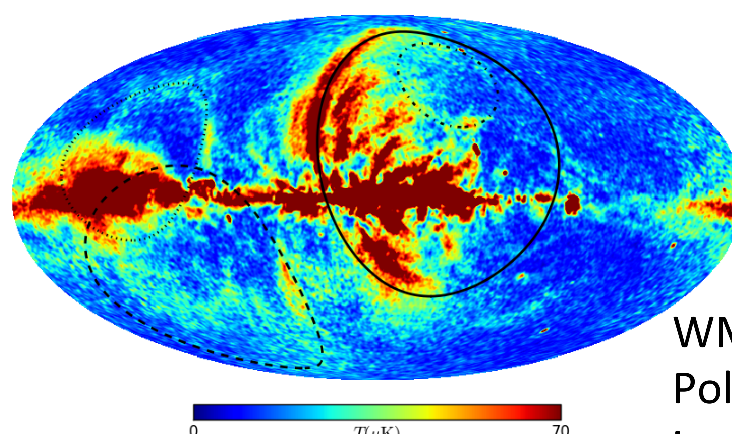


Evidence of Magnetized dust?

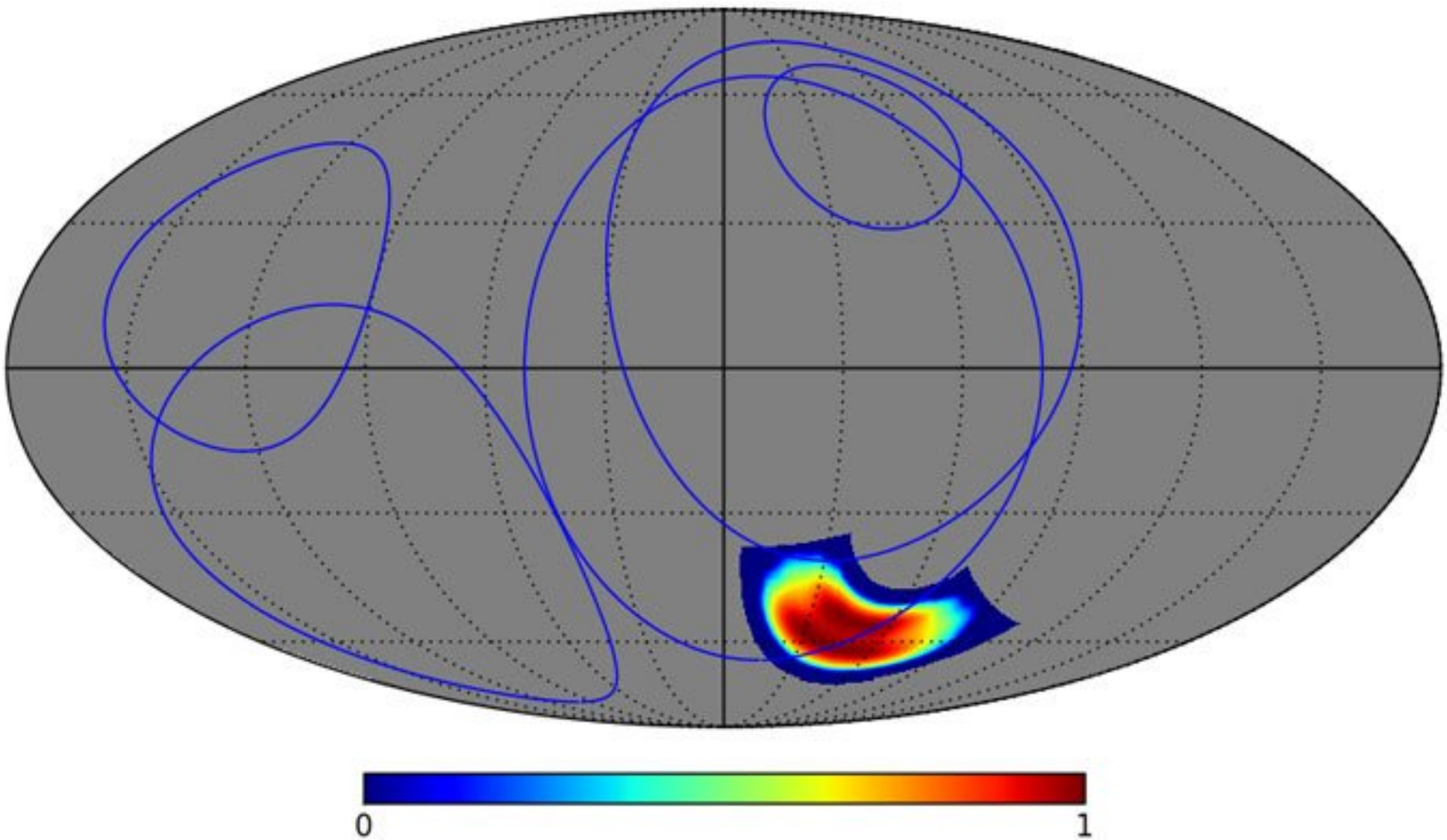
Planck 857GHz
(Dust)



WMAP9
ILC map



WMAP9 K-band
Polarized
intensity map


0
1

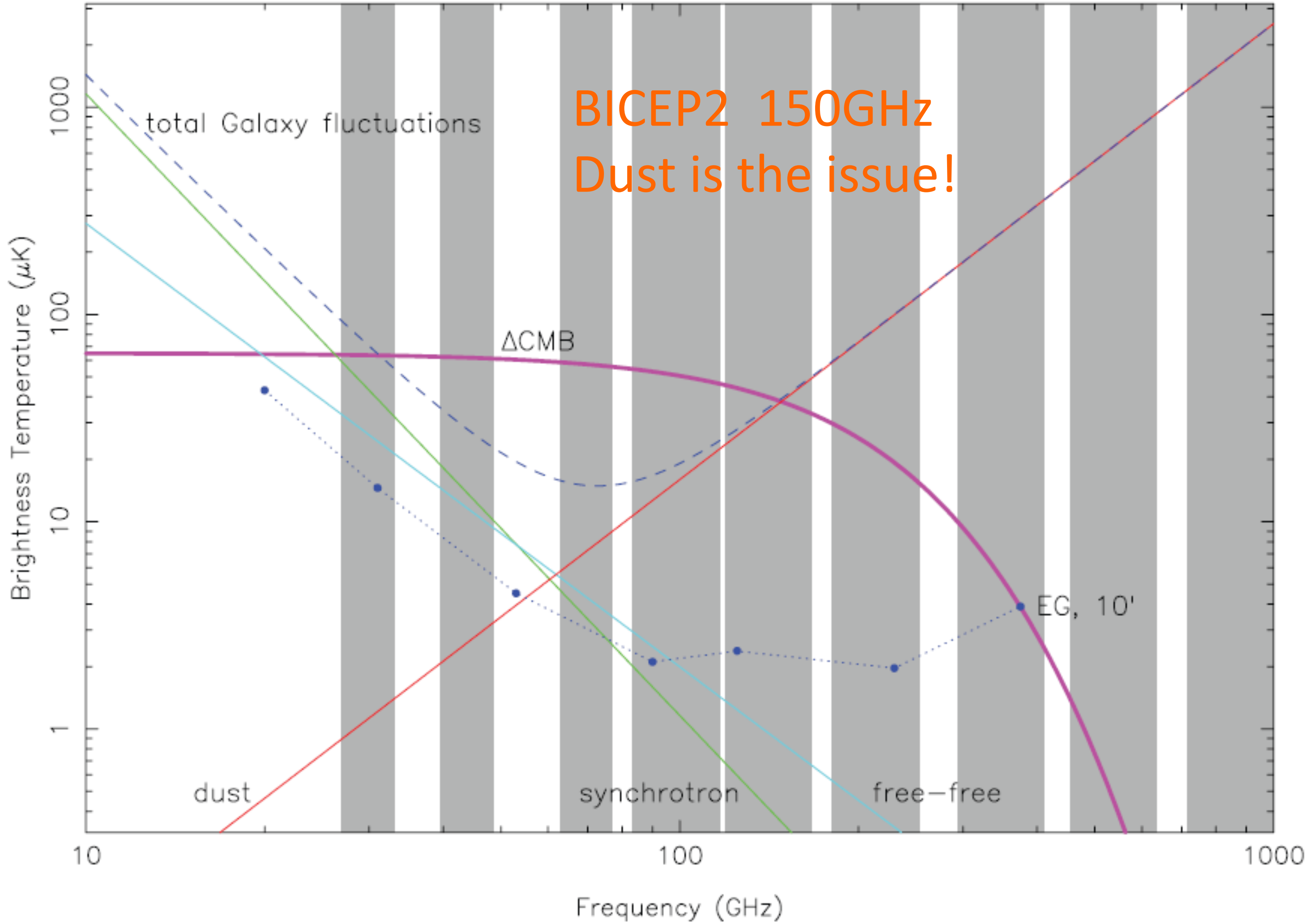


FIG 1.3.— Spectrum of the CMB, and the frequency coverage of the *Planck* channels. Also indicated are the spectra of other sources of fluctuations in the microwave sky. Dust, synchrotron, and free-free temperature fluctuation (i.e., unpolarized) levels correspond to the *WMAP* Kp2 levels (85% of the sky; Bennett et al. 2003). The CMB and Galactic fluctuation levels depend on angular scale, and are shown for $\sim 1°$. On small angular scales, extragalactic

Q1) Are BICEP2 signals really primordial?

Modification of the abstract: the last sentence

- Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.

- Accounting for the contribution of foreground, dust will shift this value downward by an amount which will be better constrained with upcoming data sets.

Q1) Are BICEP2 signals really primordial?

- Dust is the issue
  - PLANCK has the best dust polarization sky data
  - But the data was not available
  - In BICEP2 paper, a Data driven dust model is constructed from “publically available Planck data products”. What are these products?

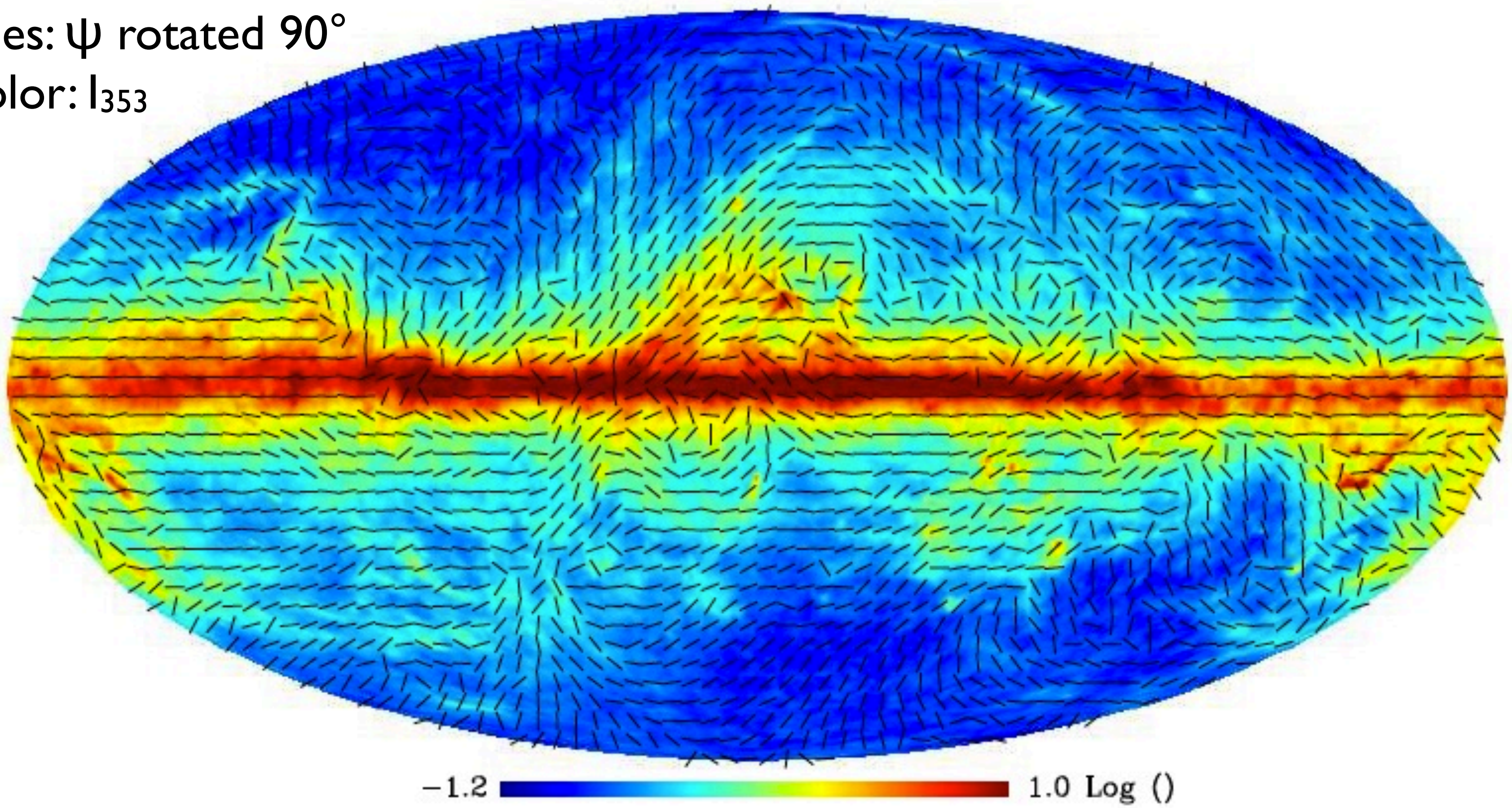
Reconstruct from someone’s slides for a meeting!

B field direction at 353 GHz, 1° resolution

$\psi = 0.5 \times \mathrm{tg}^{-1}(U, Q)$,

lines: ψ rotated 90°

color: I_{353}



Field direction consistent with B in MW plane

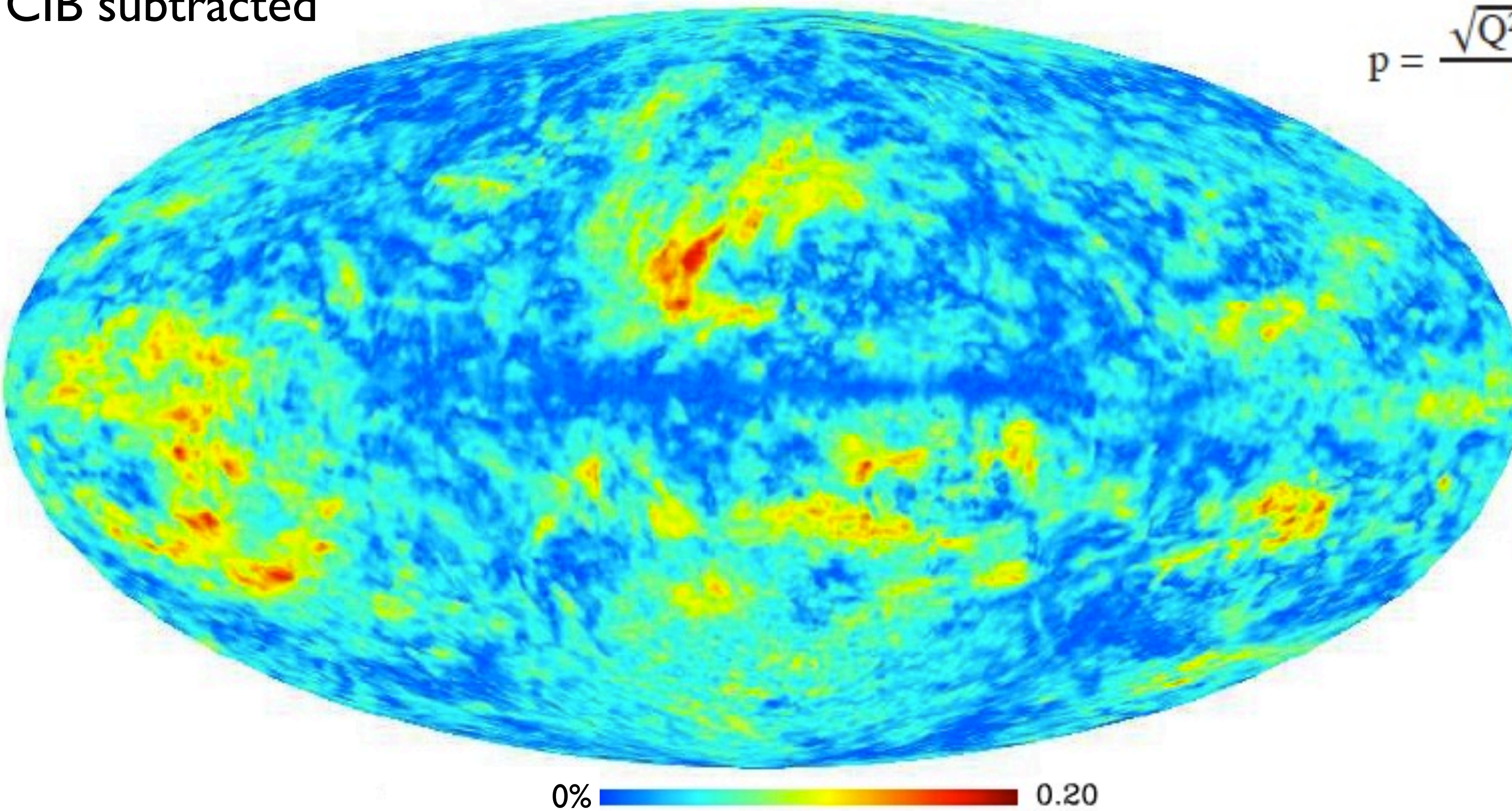
Field homogeneous over large regions with strong p (e.g. Fan)

Bernard J.Ph., ESLAB 2013

Apparent polarization fraction (p) at 353 GHz, 1° resolution

Not CIB subtracted

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$



- p ranges from 0 to ~20%
- Low p values in inner MW plane. Consistent with unpolarized CIB
- Large p values in outer plane and intermediate latitudes

Bernard J.Ph., ESLAB 2013

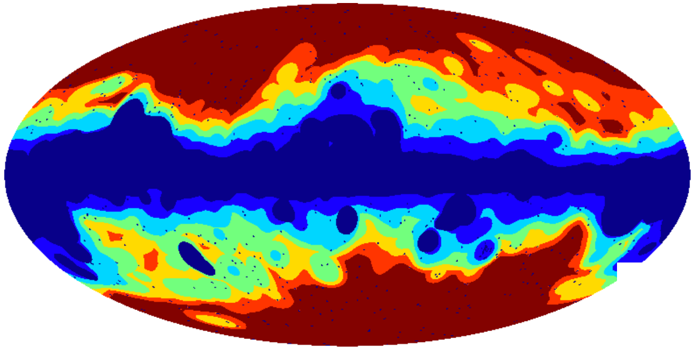
Q1) Are BICEP2 signals really primordial?

- Dust: Flauger, Colin, Spergel JCAP 08, 39 (2014) arXiv: 1405.7351
  - Reanalyze the Bicep2 results and show that the data are consistent with a cosmology with r = 0.2 and negligible foregrounds, but also with a cosmology with r = 0 and a significant dust polarization signal.
  - Using 4 models of polarization: (1) data-driven models based on Planck 353 GHz intensity, (2) the same set of pre-Planck models used by the Bicep2 team but taking into account the higher polarization fractions observed in the CMB- and CIB-corrected map, (3) a measurement of neutral hydrogen gas column density combined with an extrapolation of a relation between HI column density and dust polarization derived by Planck, (4) a dust polarization map based on digitized Planck data

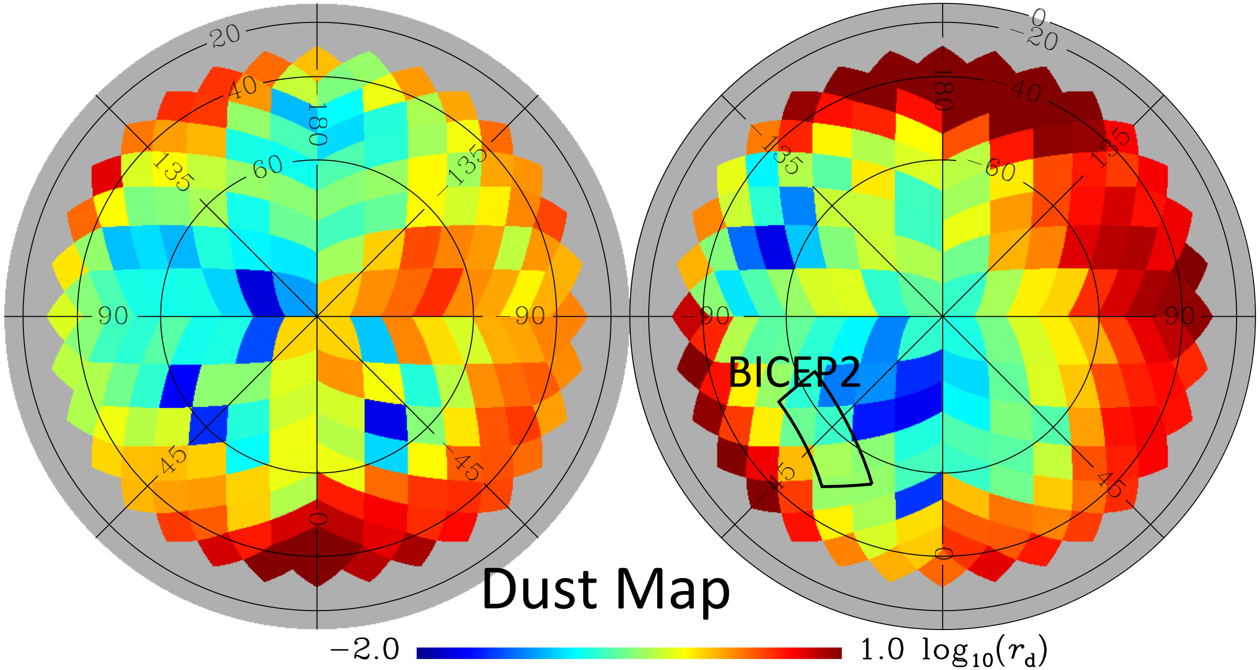
Planck Dust Map of this region was missing

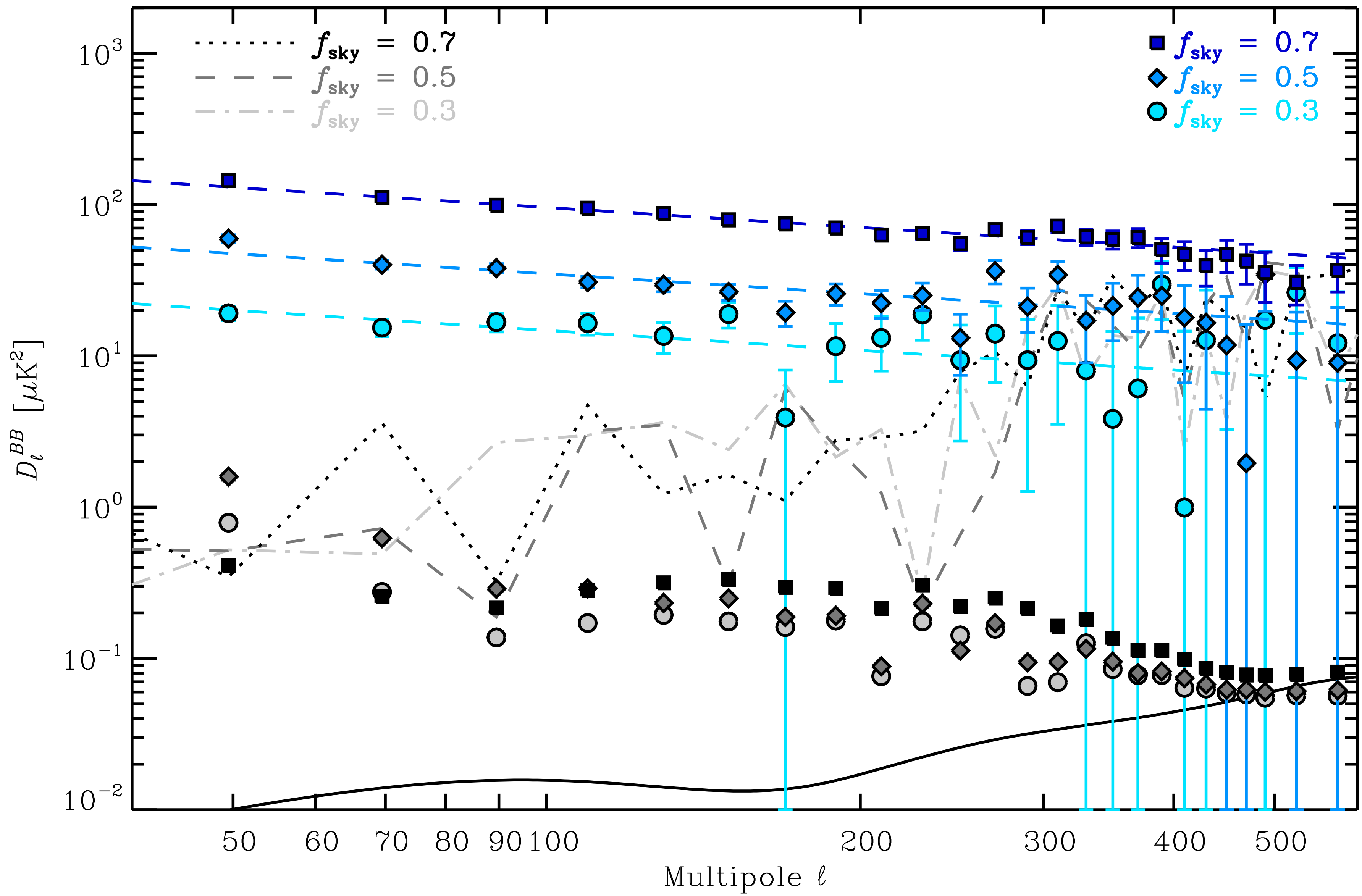
Q1) Are BICEP2 signals really primordial?

- Planck Dust Map Paper: arXiv:1409.5738

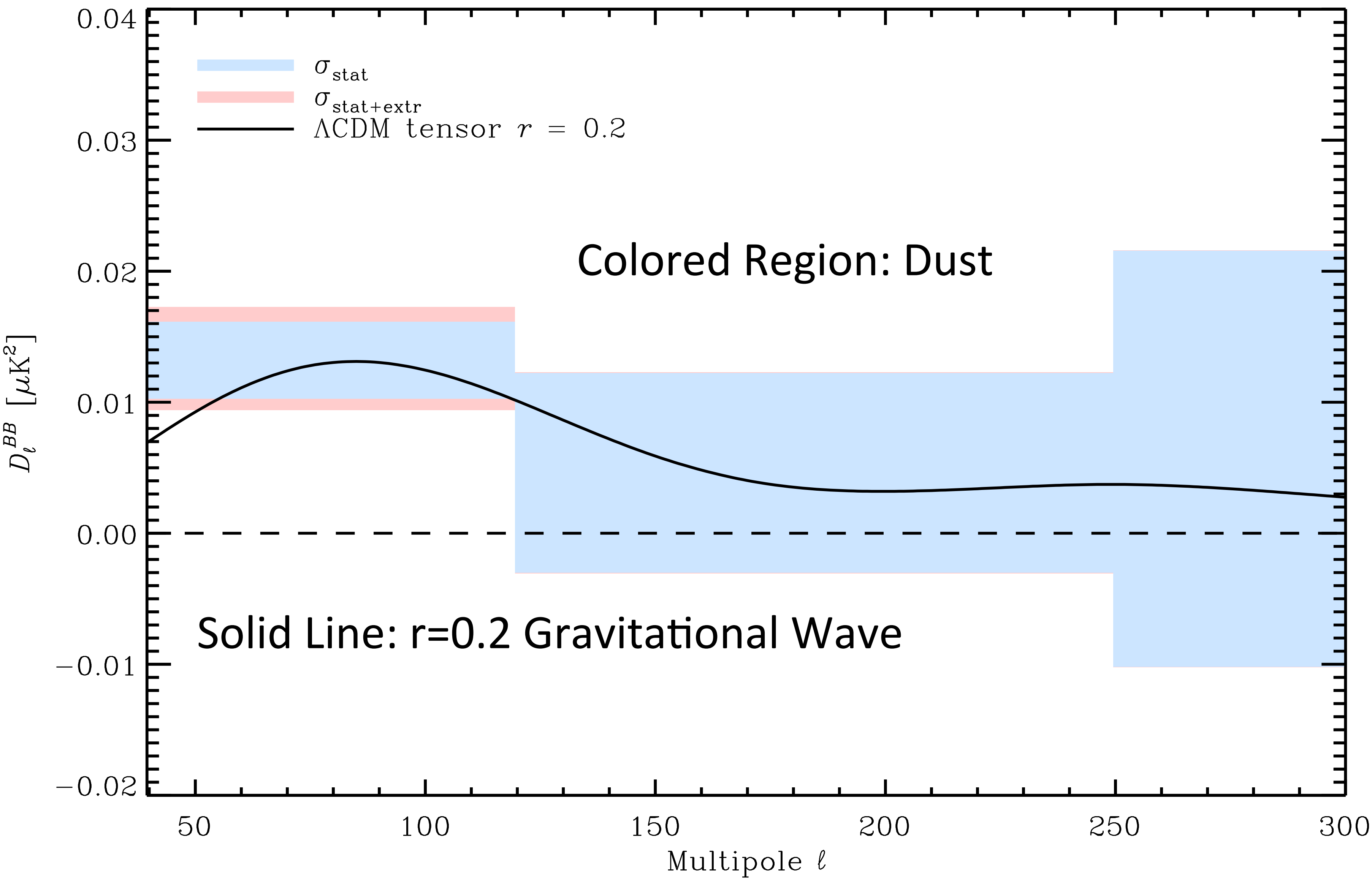


Selected regions: fsky=0.3~0.8





B model spectrum from Dust @ 353 GHz



Extrapolation of Planck 353 GHz spectrum to 150 GHz spectrum

Planck Dust Map Paper: Bicep2 region

Over the multipole range $40 < \ell < 120$, the *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ power spectrum extrapolated to 150 GHz yields a value $1.32\times10^{-2}\,\mu\mathrm{K}^2_{\mathrm{CMB}}$, with statistical error $\pm0.29\times10^{-2}\,\mu\mathrm{K}^2_{\mathrm{CMB}}$ and a further uncertainty $(+0.28, -0.24)\times10^{-2}\,\mu\mathrm{K}^2_{\mathrm{CMB}}$ from the extrapolation. This value is comparable in magnitude to the BICEP2 measurements at these multipoles that correspond to the recombination bump.

- Frequency dependence is consistent with Dust
- Joint analysis between BICEP2 and Planck is needed: On Going!
- Some regions are factor 2 better than BICEP2 region

Q2) Does B-mode really mean gravitational wave?

- Two independent parity modes
  - E mode: Parity even / Divergence
  - B mode: Parity odd / Curl (Rotation)
- E-mode is generated by density fluctuations (scalar perturbations).
- B-mode is generated by vector or tensor perturbations on large scales.
- E-mode can be converted into B-mode via gravitational lensing on intermediate scales

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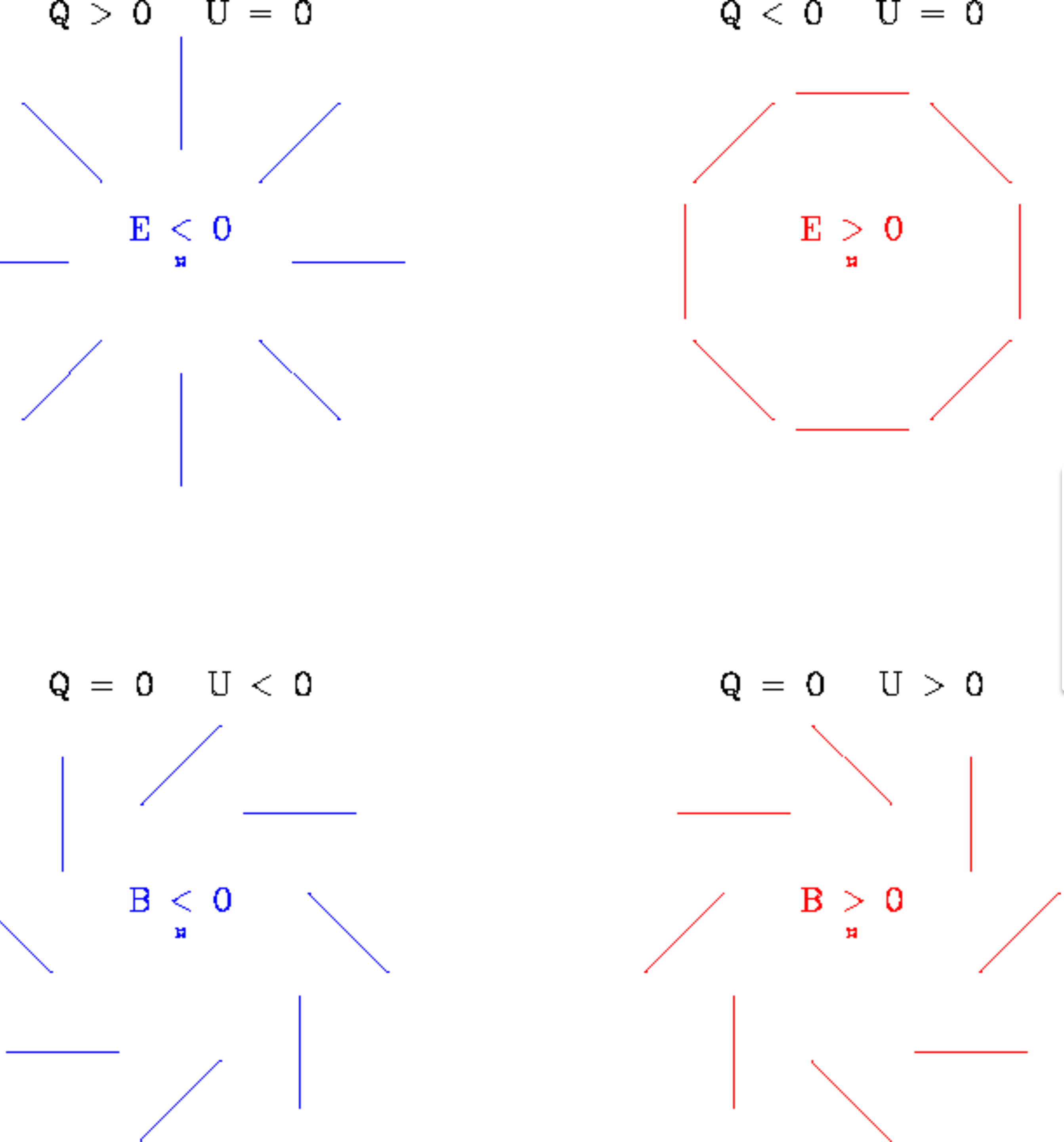


E-mode

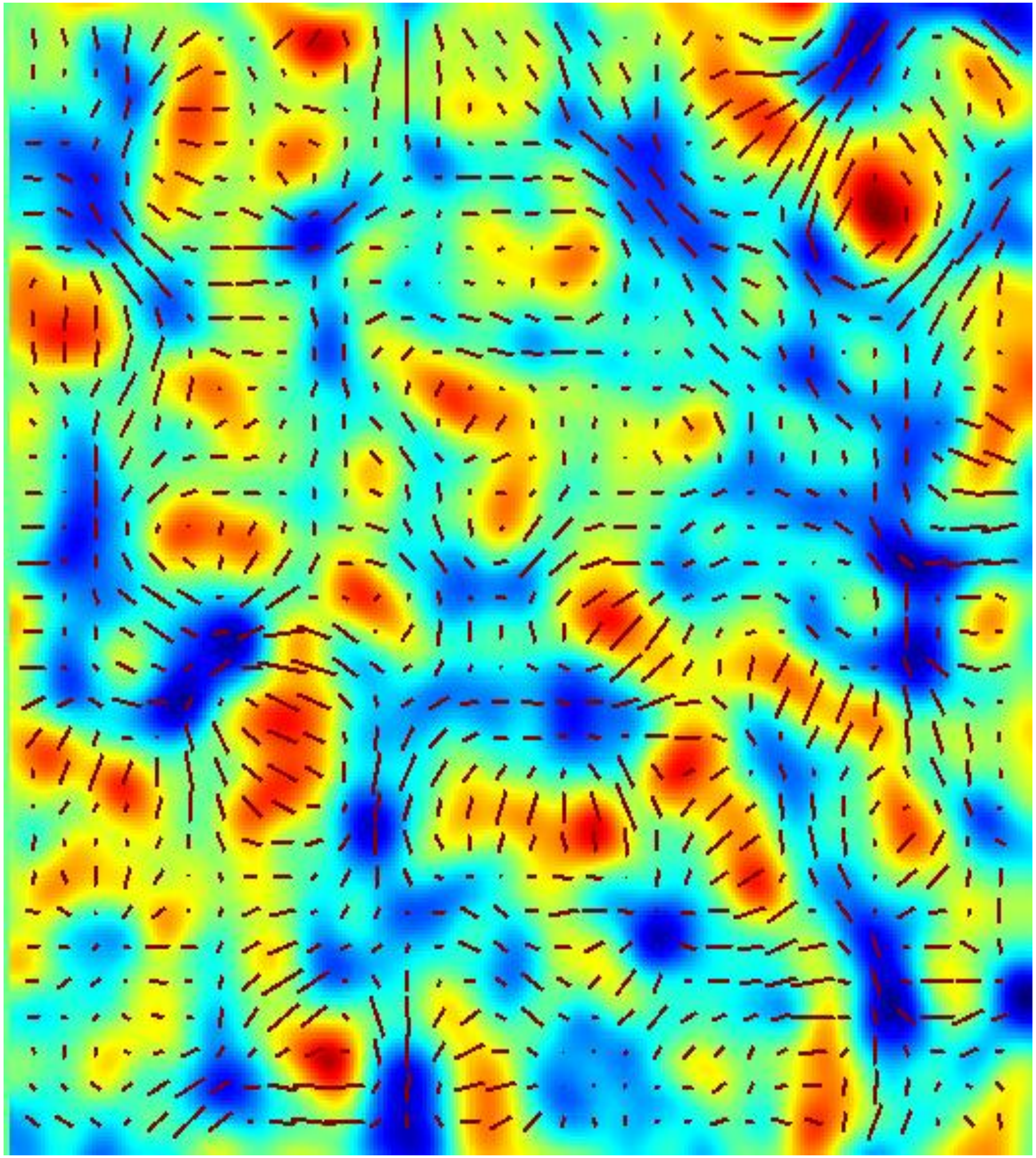
Divergence

2 independent parity modes

B-mode

Curl/Rotation

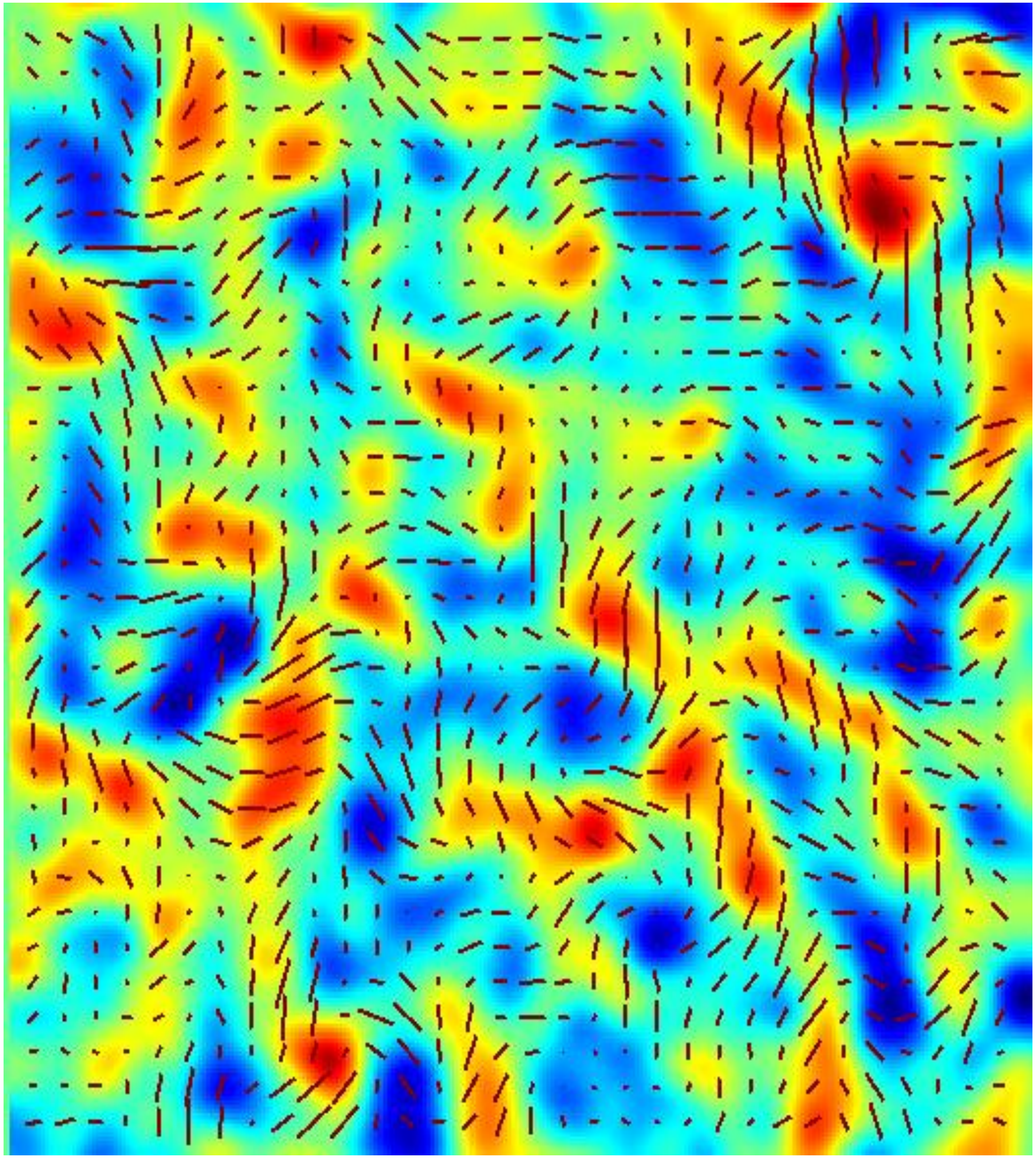
Seljak



E-mode

Seljak

Scalar Perturbations only produce E-mode



B-mode

Tensor perturbations produce both E- and B- modes

Q2) Does B-mode really mean gravitational wave?

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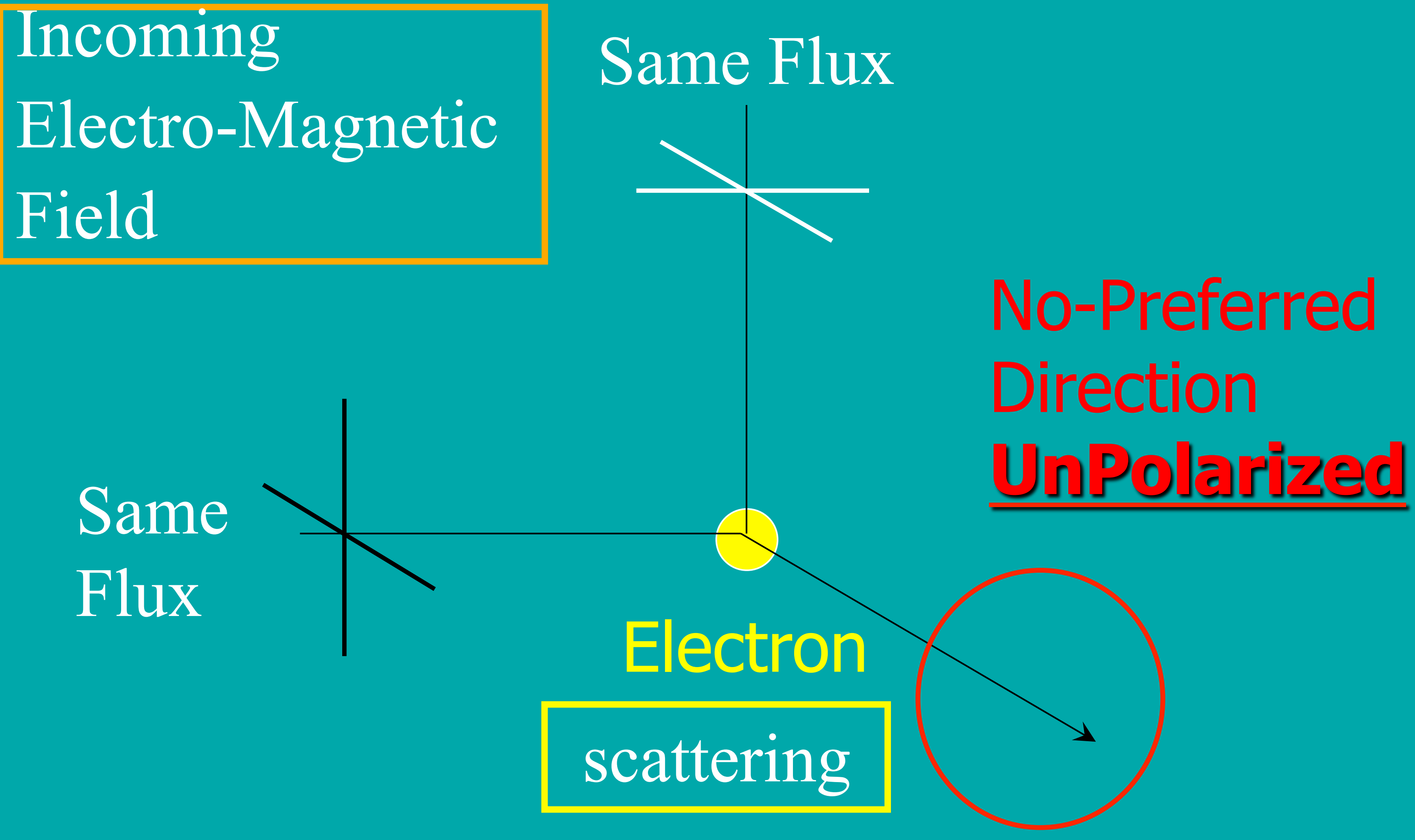
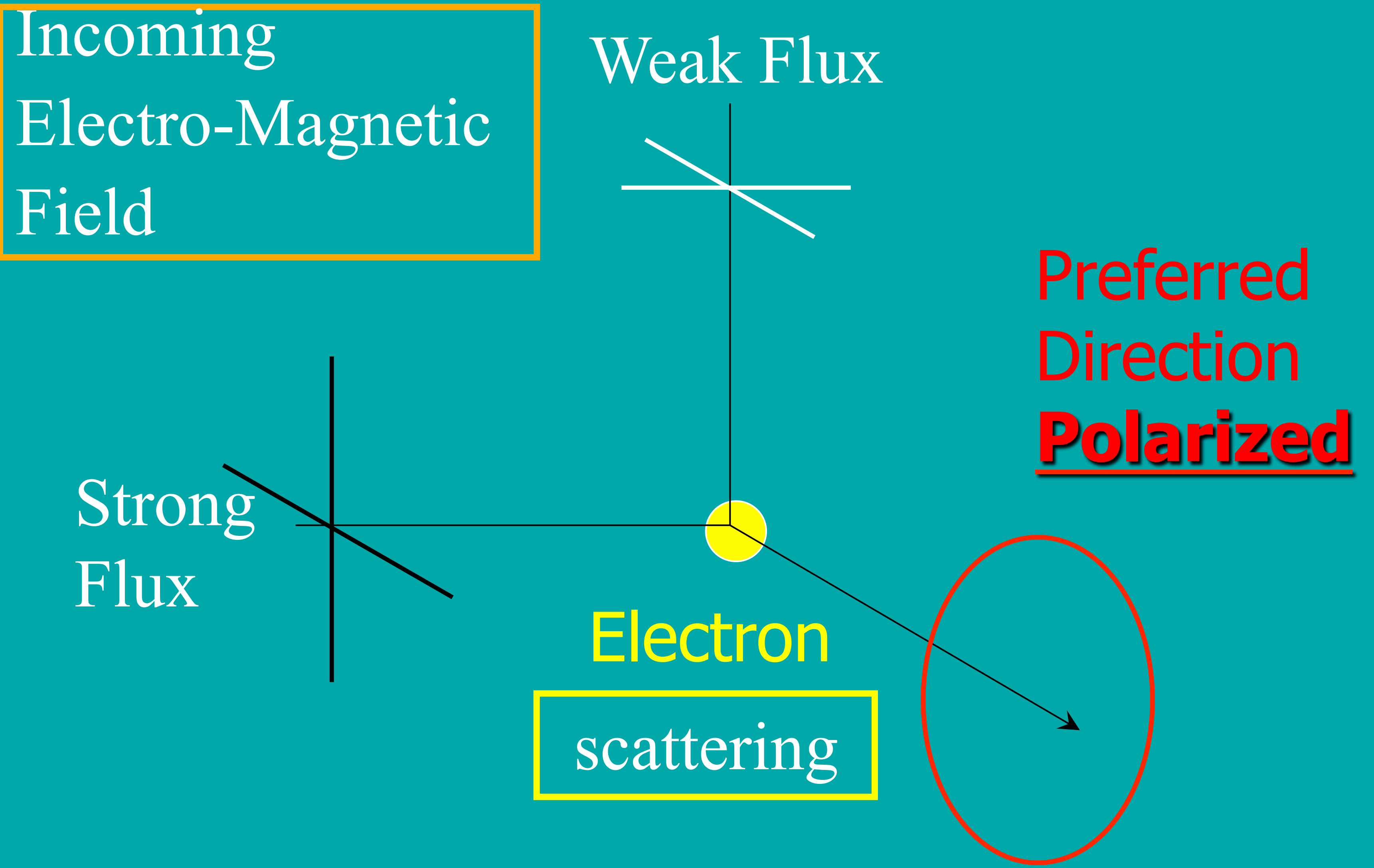
Polarization

- Bottom line is
  - Polarization can be generated through scattering of photons
  - Quadrupole anisotropy of photon distribution is needed



Homogeneously Distributed Photons



Photon Distributions with the Quadrupole Pattern

Scalar and Tensor Modes

- Perturbations of FRW-metric

$$ds^2 = -(1+2A)dt^2 - 2aB_i dt dx^i + a^2(\delta_{ij} + 2H_L\delta_{ij} + 2H_{Tij})dx^i dx^j$$

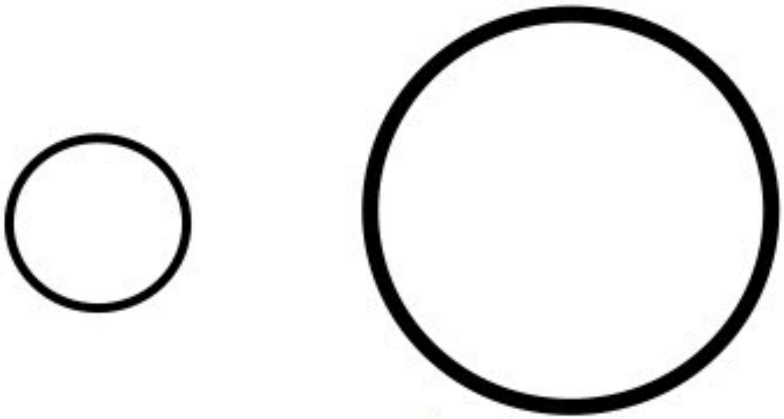
- Perturbations can be decomposed:

Scalar $$ds^2 = -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^2$$

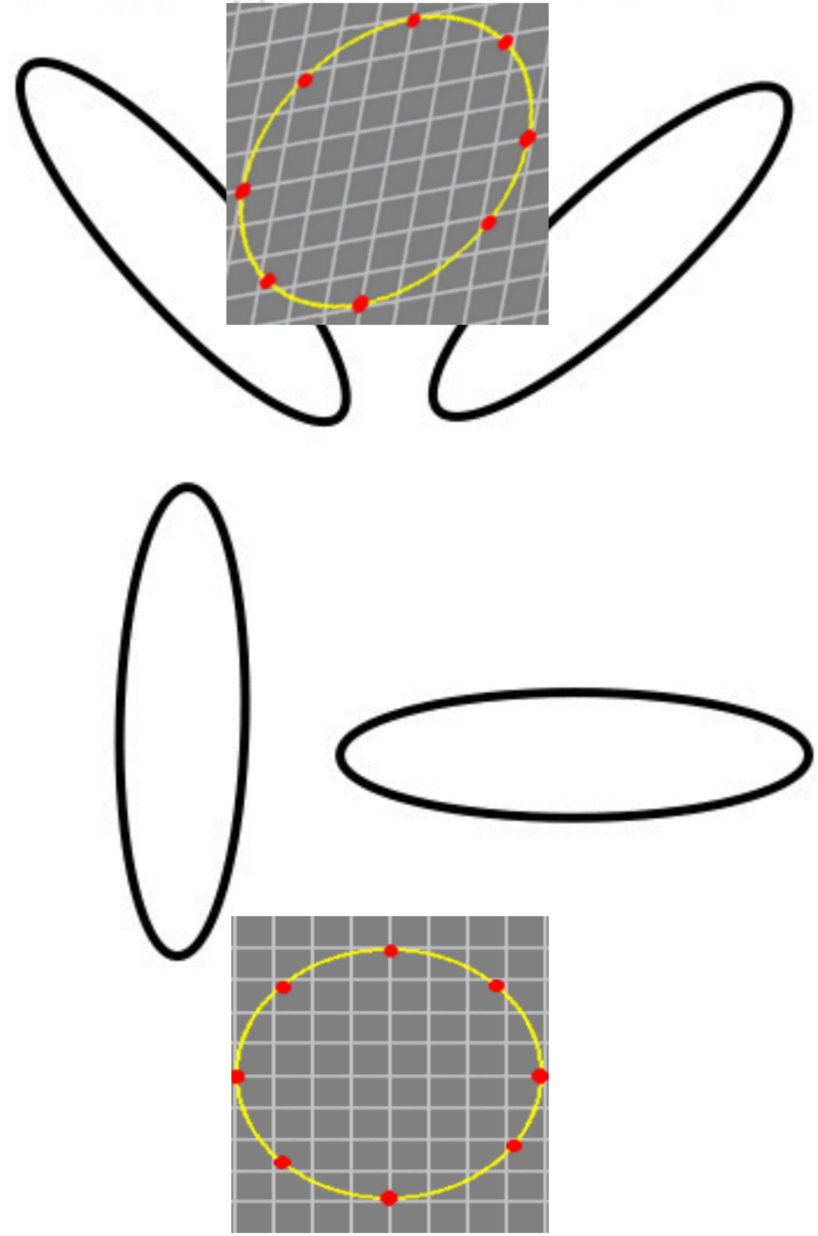
Vector $$ds^2 = -dt^2 + av_i dt dx^i + a^2(\delta_{ij} + c_{i,j} + c_{j,i})dx^i dx^j$$

Tensor $$ds^2 = -dt^2 + a^2(\delta_{ij} + h_{ij})dx^i dx^j$$

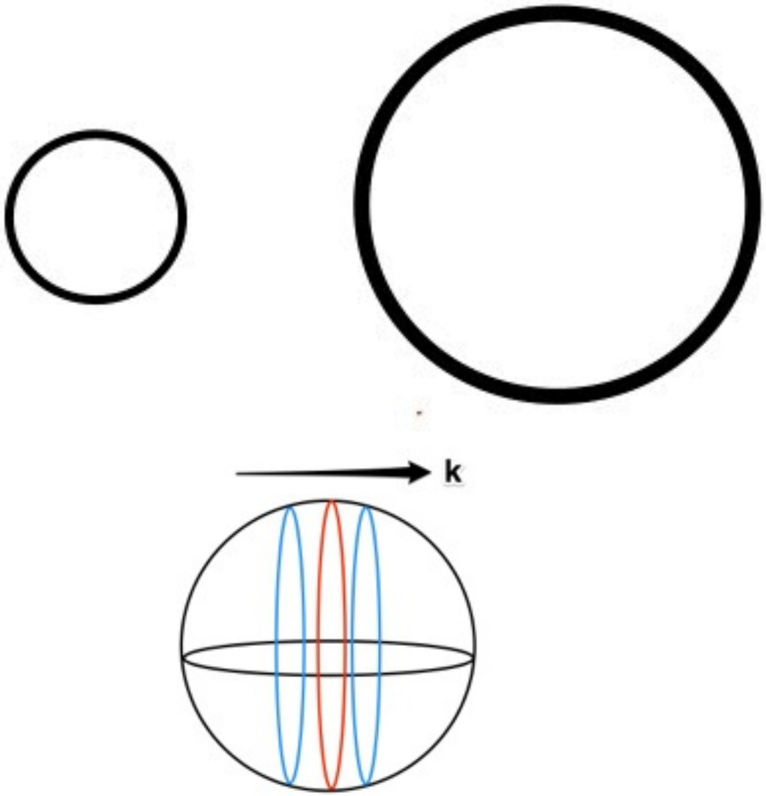
Scalar perturbations



Tensor perturbations

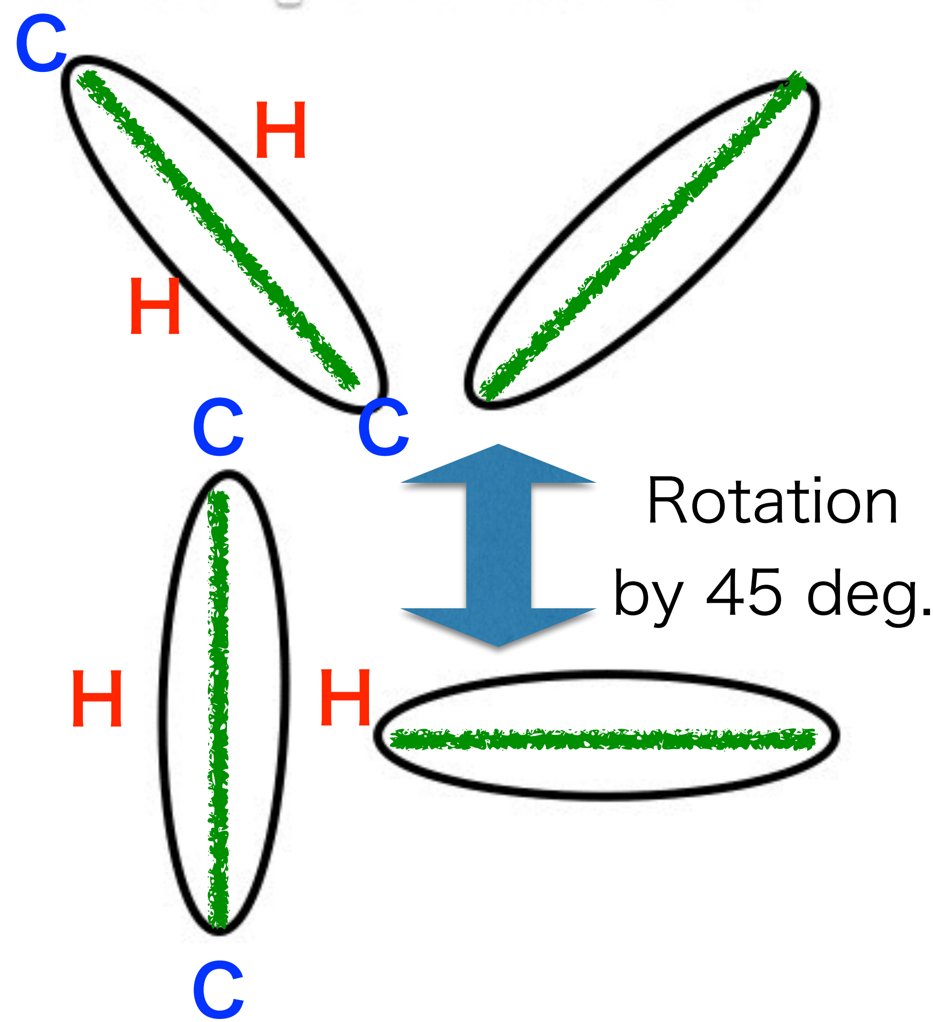


Scalar perturbations



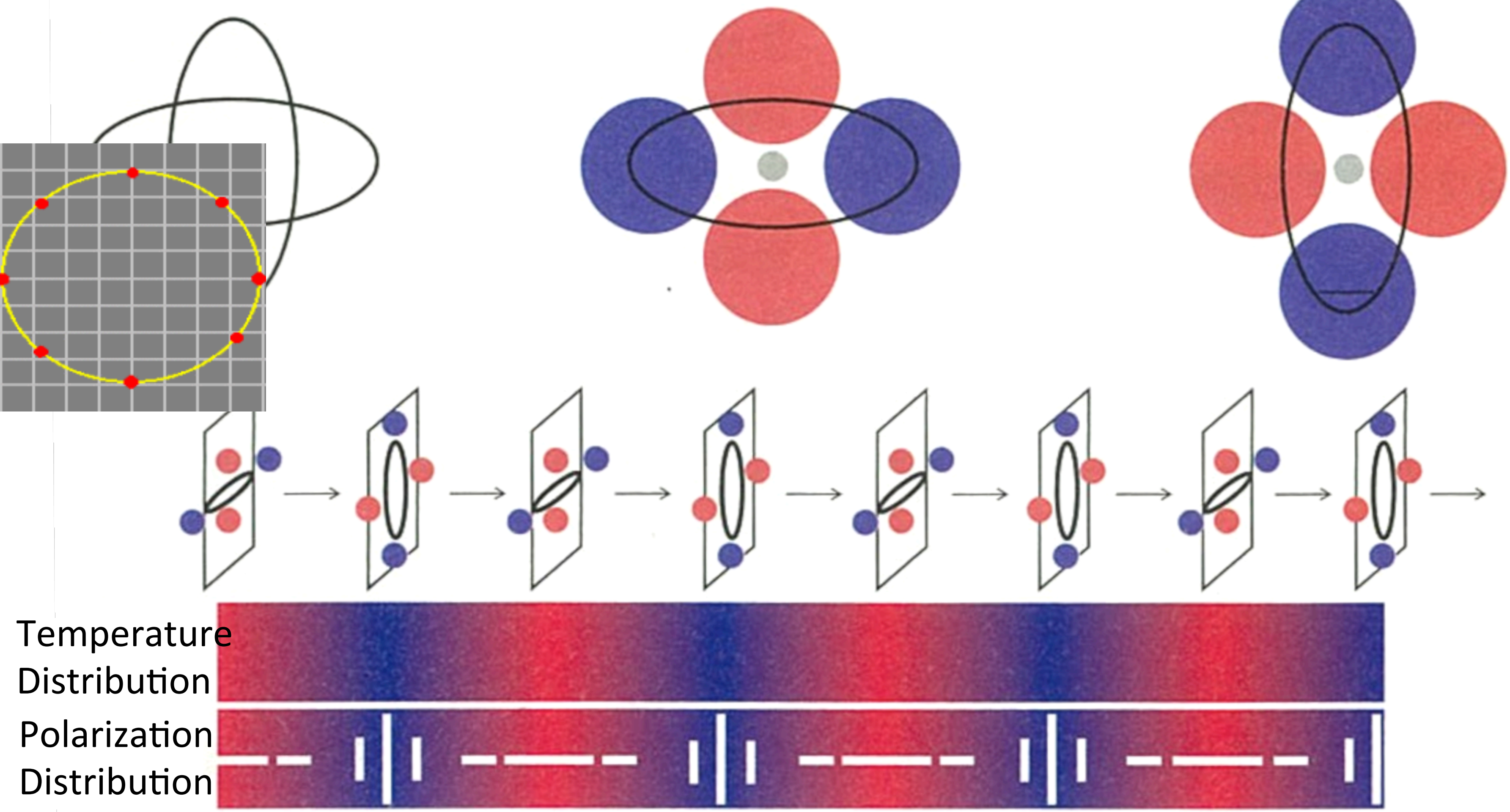
E-mode ONLY

Tensor perturbations

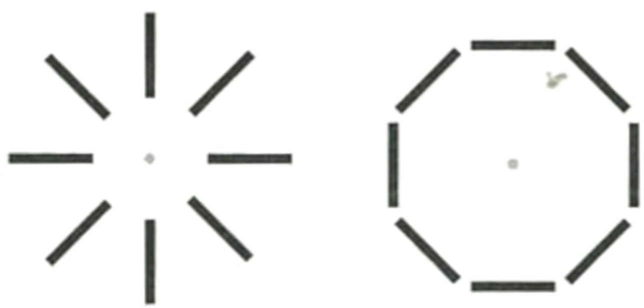


BOTH E-mode
and B-mode

Gravitational Wave can generate both E and B modes



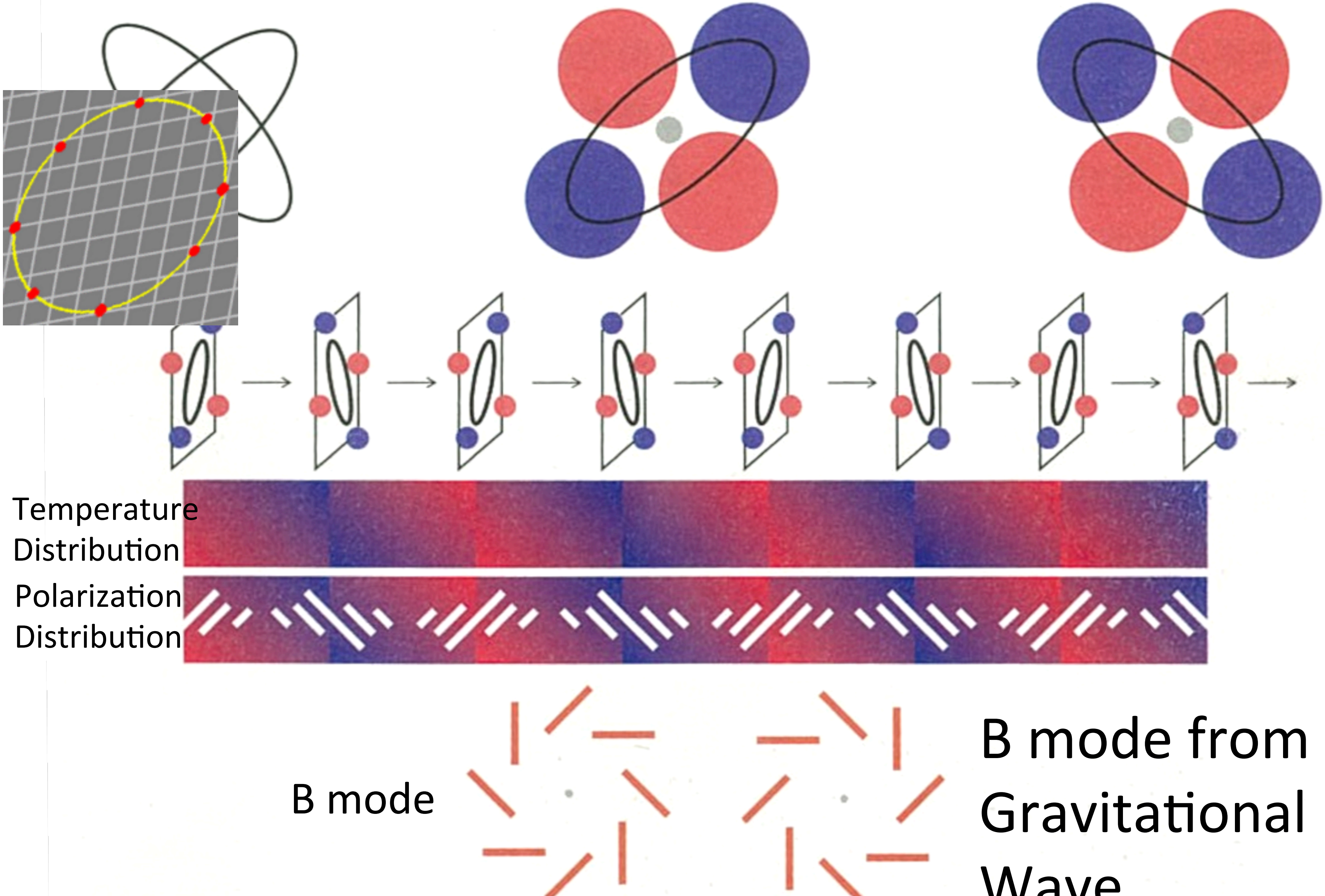
E mode



E mode from Gravitational Wave

E. Komatsu

Gravitational Wave can generate both E and B modes



E. Komatsu

Vector Mode

- The Vector mode generates mostly B-mode polarization
- However, the vector mode perturbations from the early universe are decaying modes and damped away at the epoch of recombination
- Possibility: Generate vector modes afterwards, such as Cosmic Strings, Topological Defects and modified gravity theory …

Q2) Does B-mode really mean gravitational wave?

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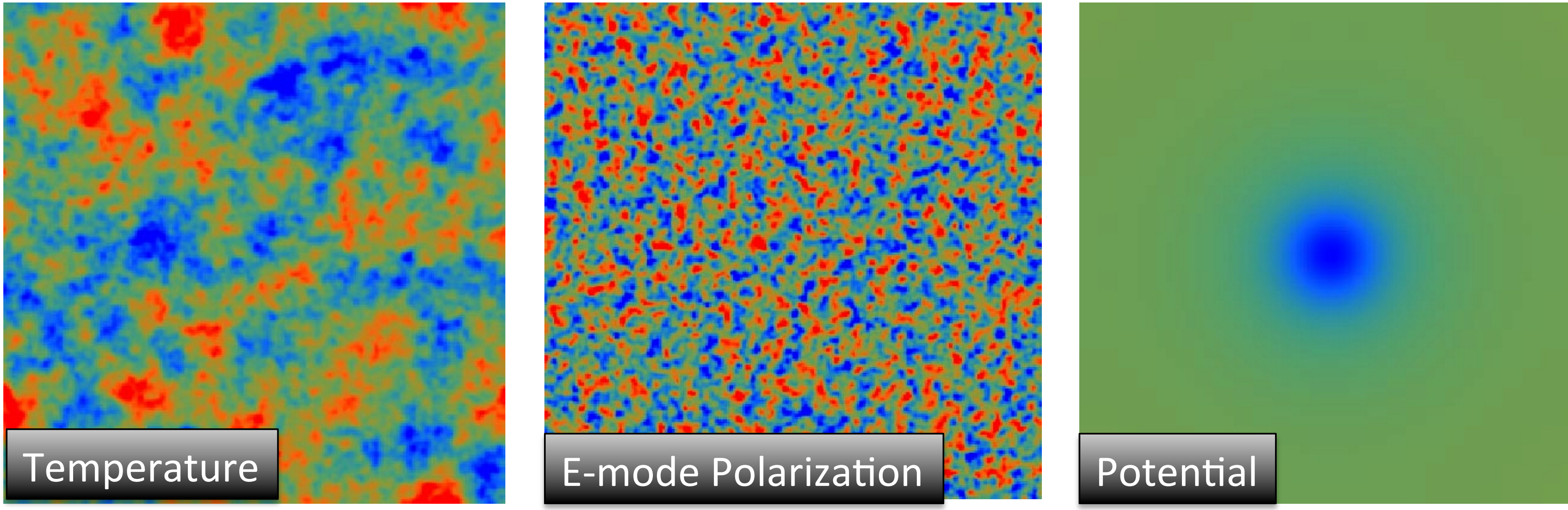
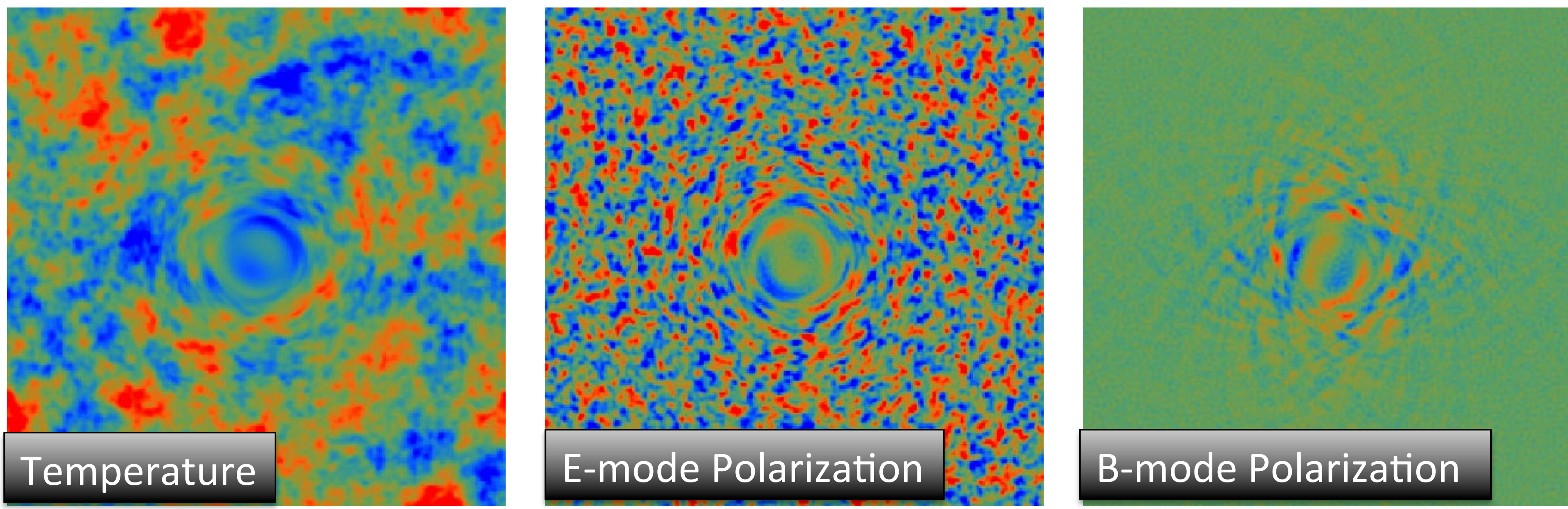
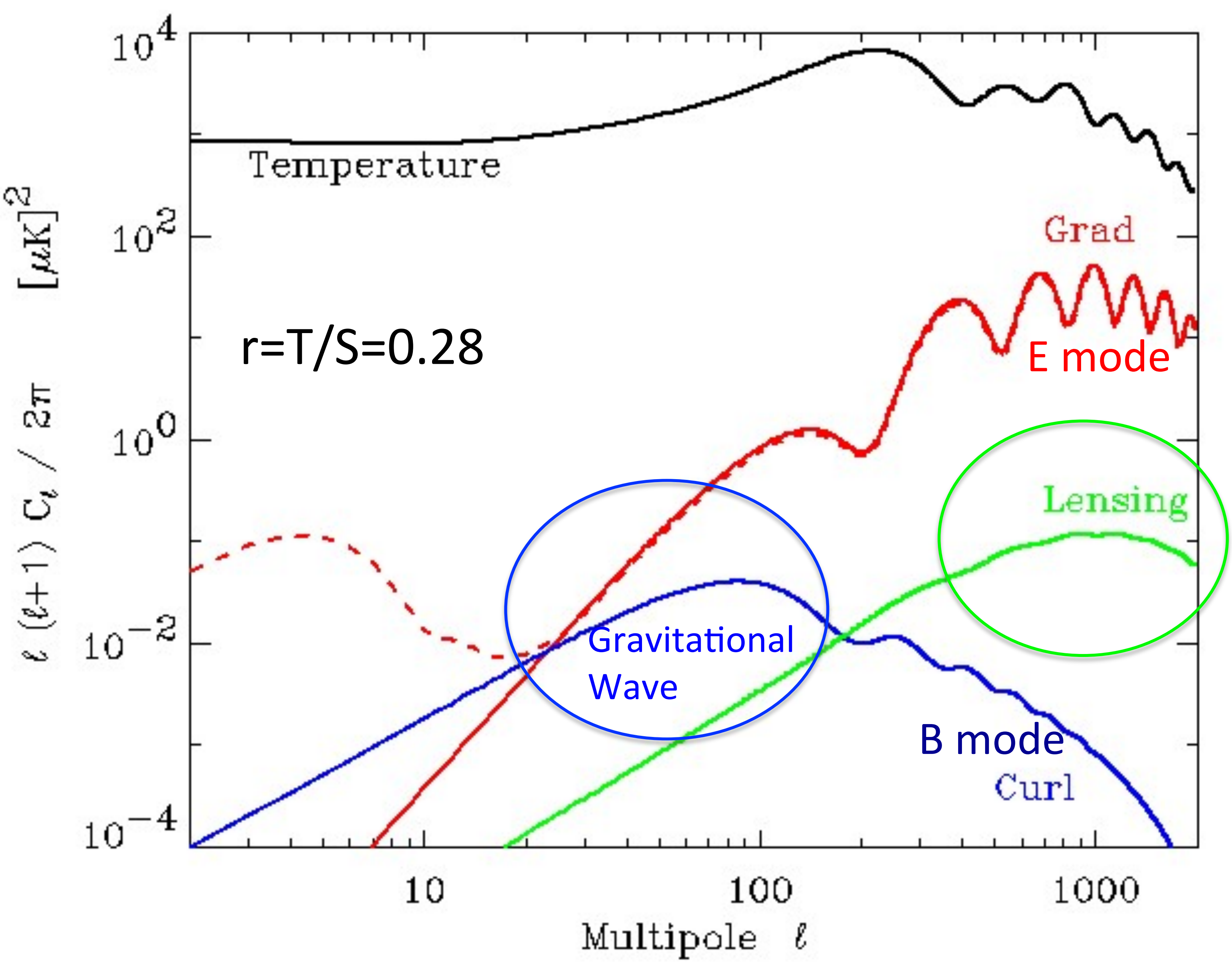
Unlensed Warping of the polarization field generates B-modes from E-modes



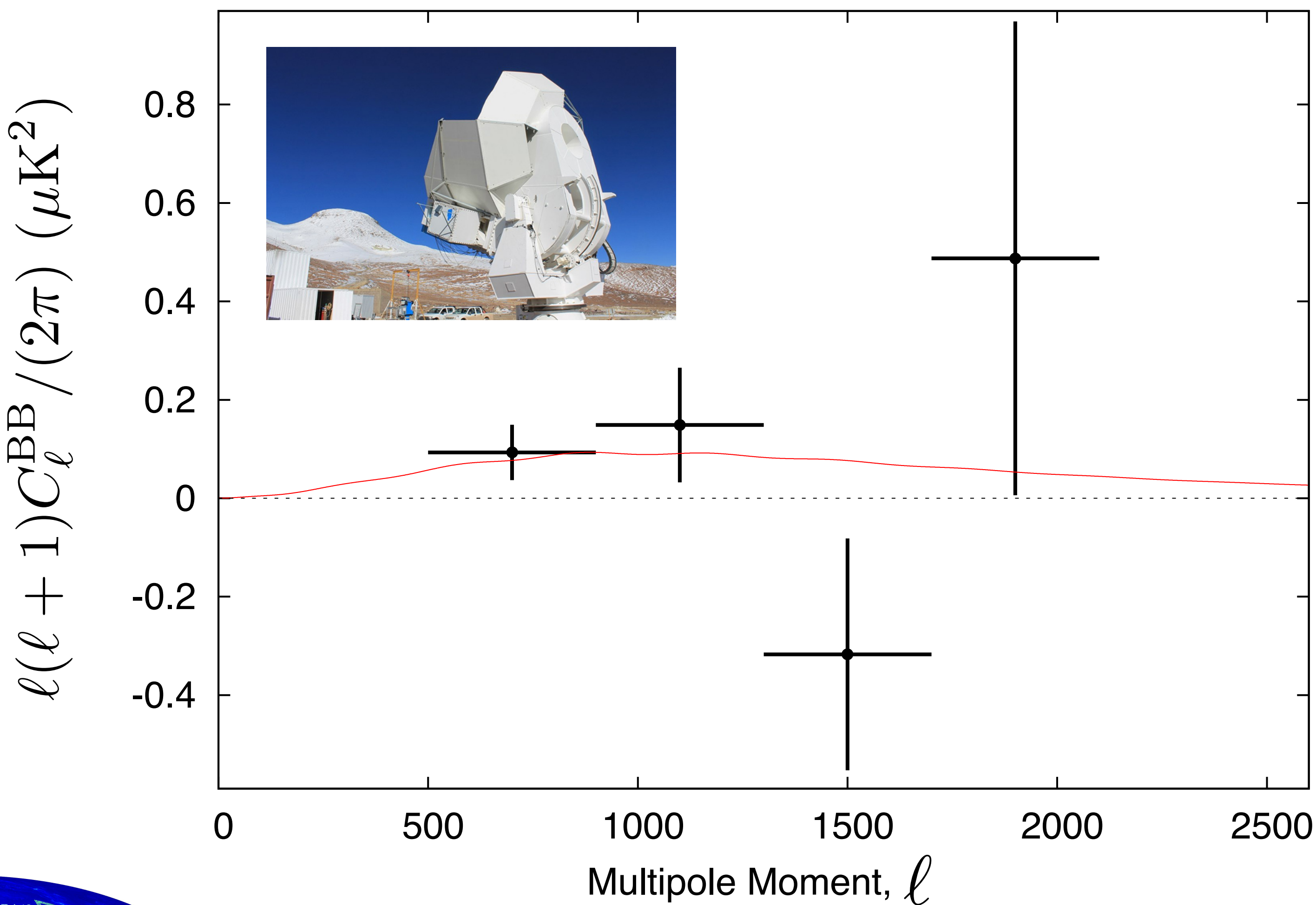
lensed Hu and Okamoto 2002

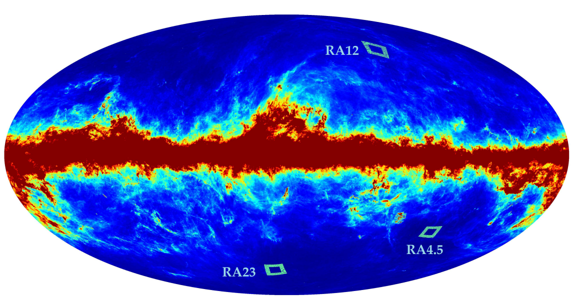




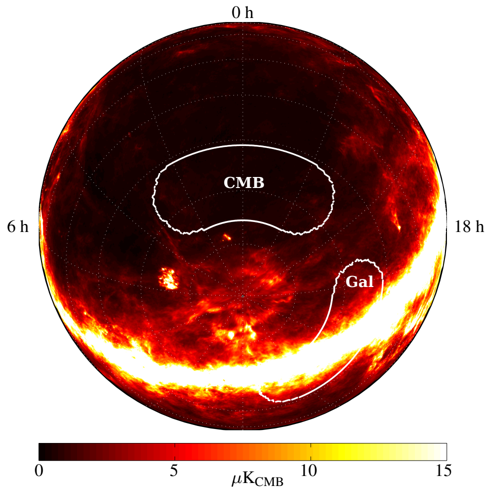
http://bicep.caltech.edu/public/

Detection of B-mode from lensing by POLARBEAR   ariXiv:1403.2369



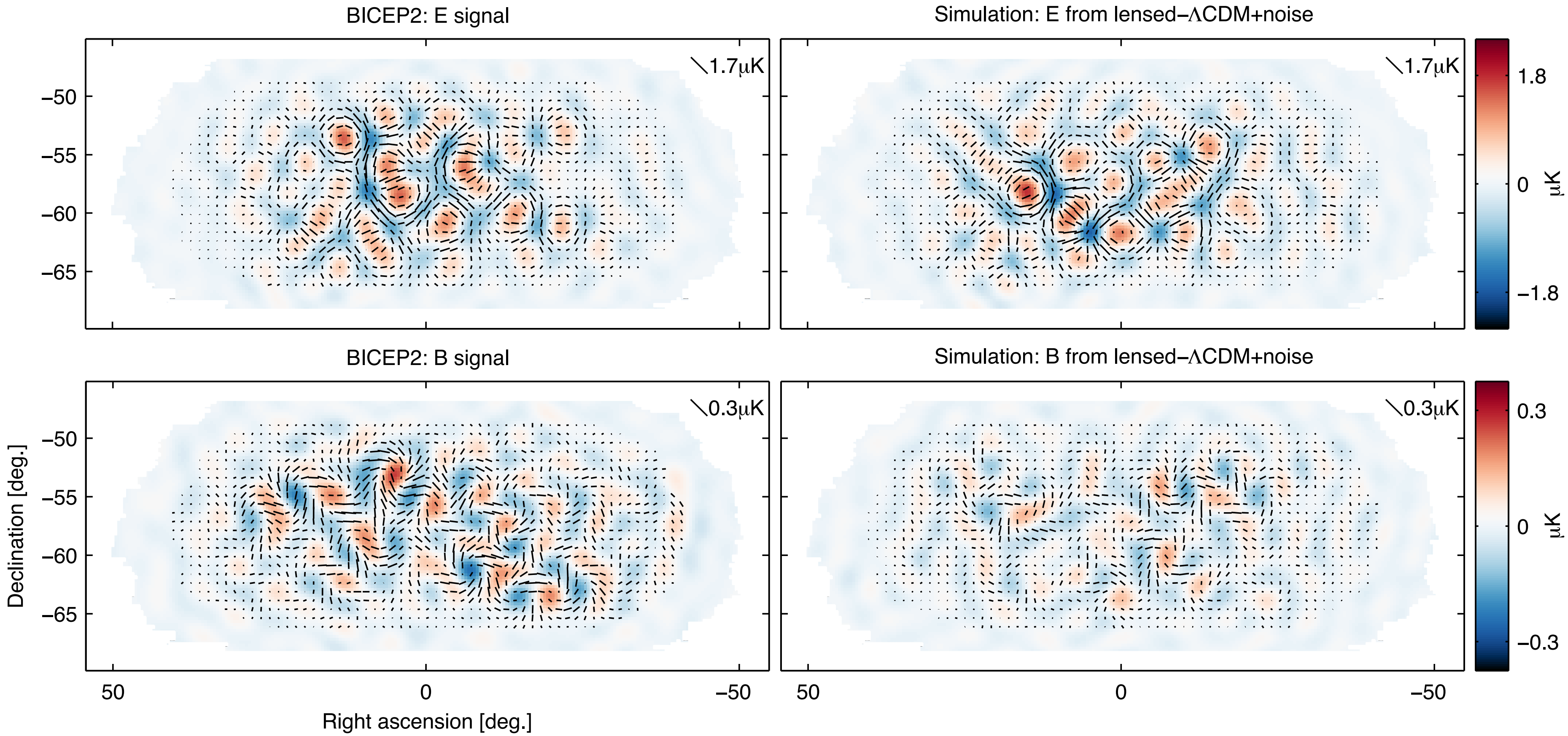


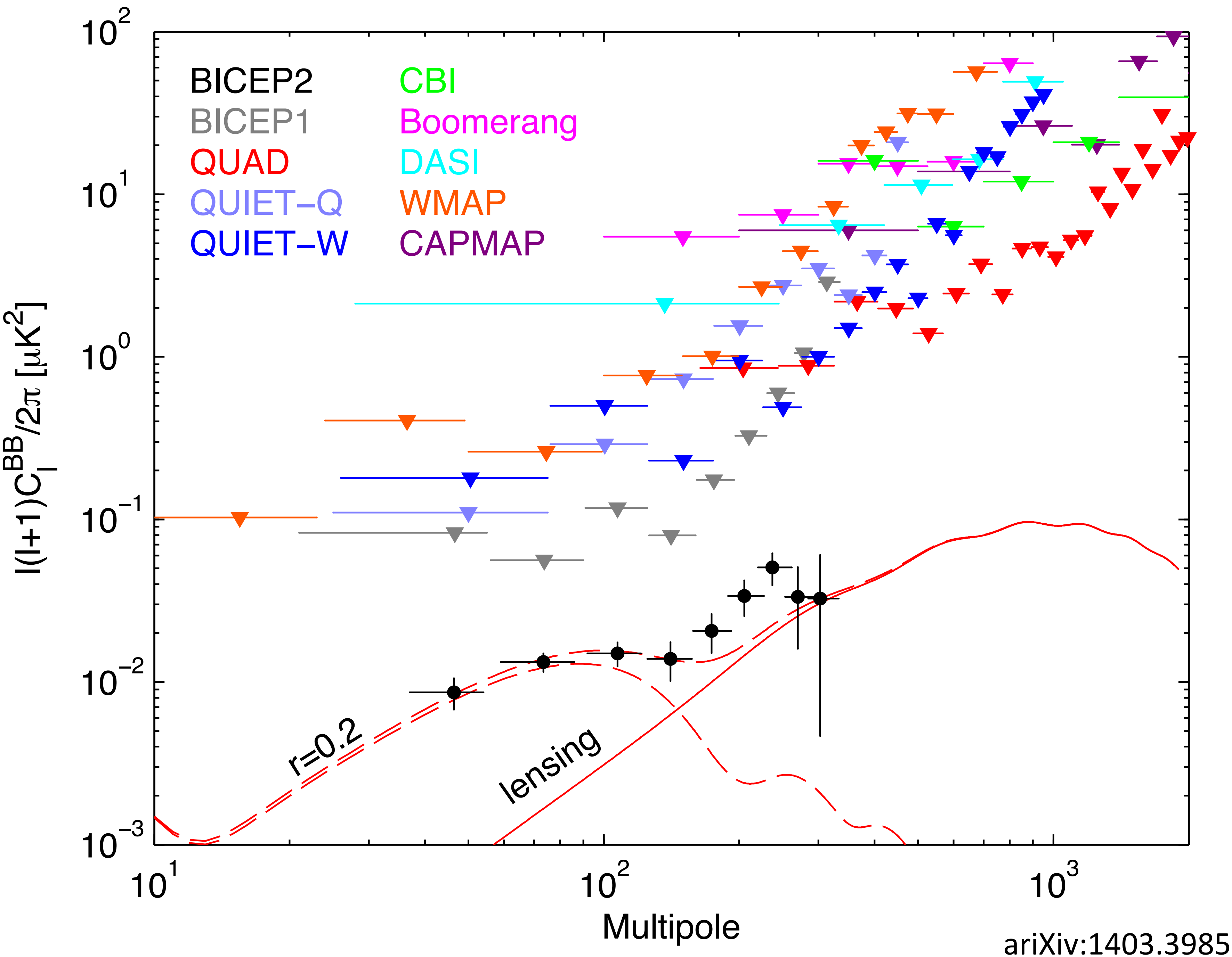
Small patches. Reject no-lensing at 97.5%.



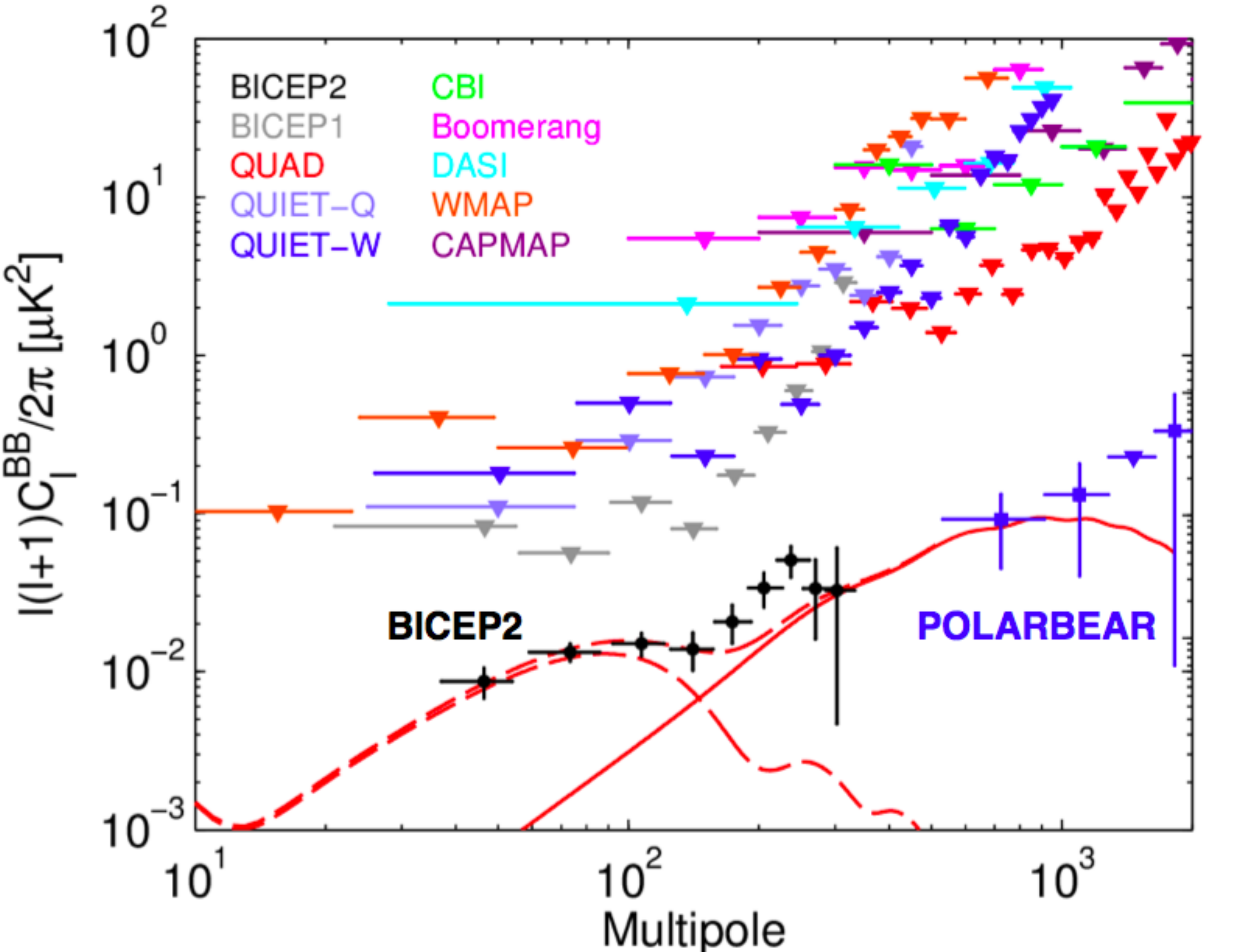
BICEP2

ariXiv:1403.3985





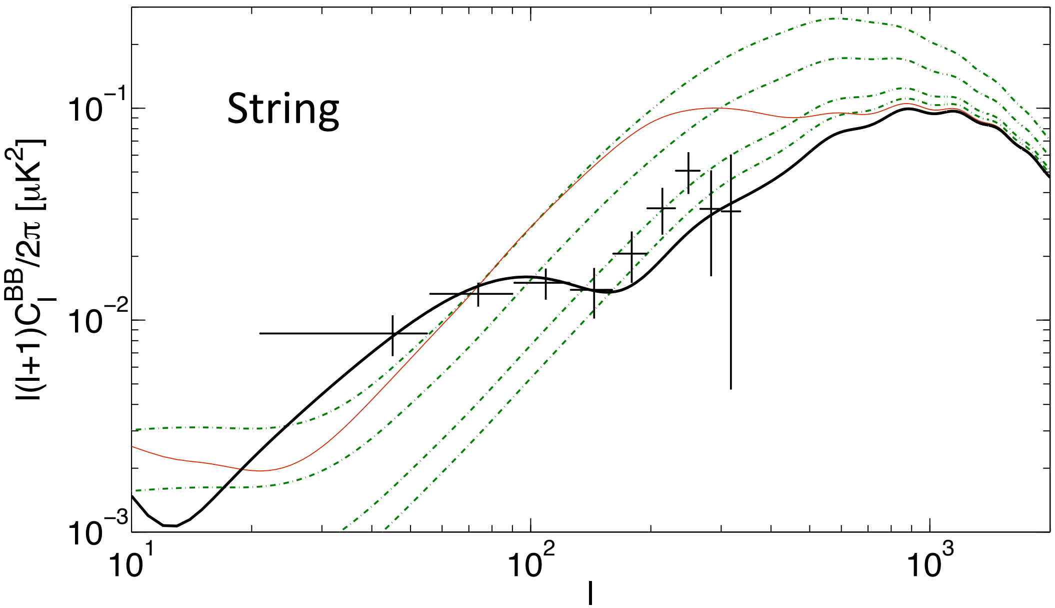
BICEP2
BICEP1
QUAD
QUIET−Q
QUIET−W
CBI
Boomerang
DASI
WMAP
CAPMAP
r=0.2
lensing
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{1}
10^{2}
10^{3}
Multipole
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
ariXiv:1403.3985

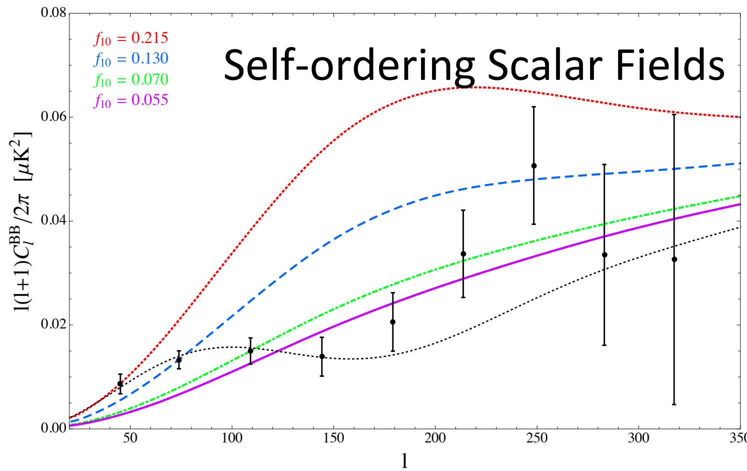


BICEP2
BICEP1
QUAD
QUIET-Q
QUIET-W
CBI
Boomerang
DASI
WMAP
CAPMAP
BICEP2
POLARBEAR
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
Multipole
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{1}
10^{2}
10^{3}

Can BICEP2 results be explained by a Vector mode?

- Vector generates B-mode, but it seems to be difficult: the slope of the spectrum is wrong
  - Cosmic String: Lizarraga et al., arXiv:1403.492
  - self-ordering scalar fields: Durrer et al. arXiv:1404.3855



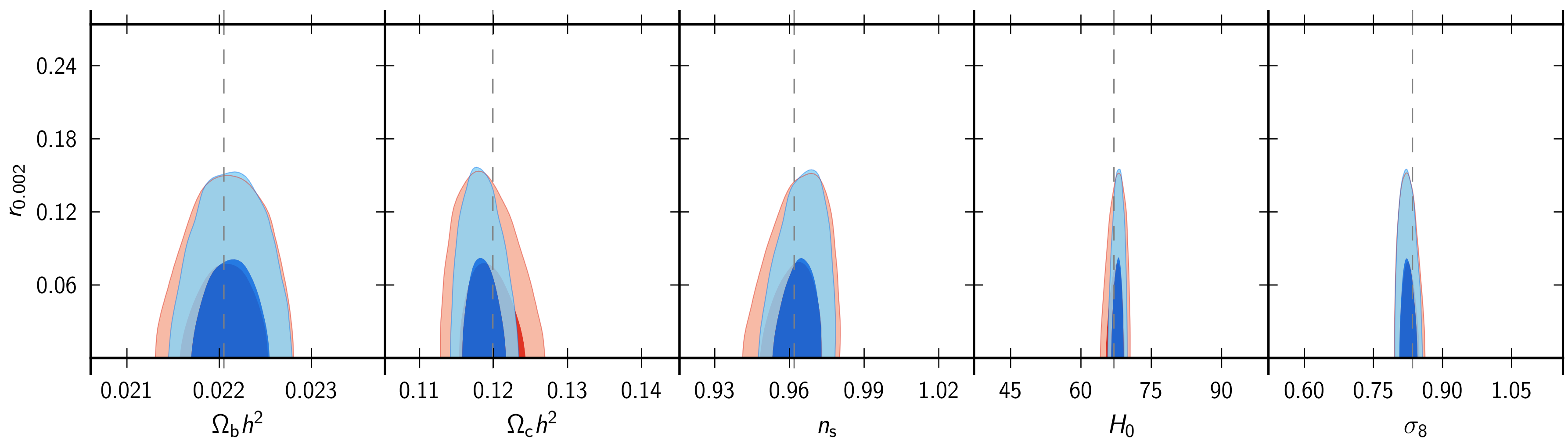


Q3) Are BICEP2 tensor modes consistent with PLANCK temperature anisotropies?

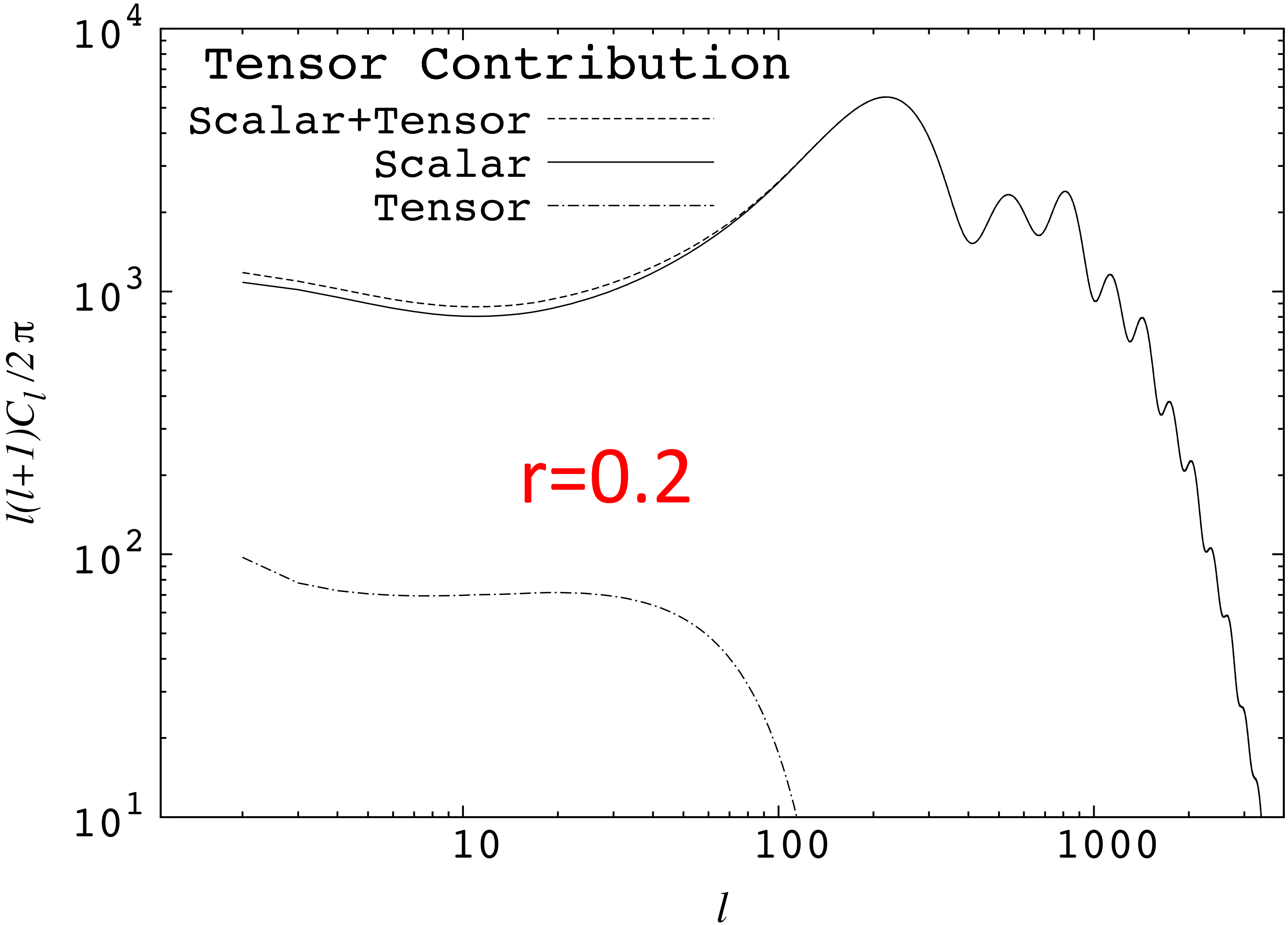
- PLANCK sets a constraint on tensor perturbations from the temperature spectrum (TT)

Additional Contribution on TT spectrum from Tensor!

$$r_{0.002} < 0.11 \quad (95\%; \text{no running}),$$
$$r_{0.002} < 0.26 \quad (95\%; \text{including running})$$



ariXiv:1303.5076



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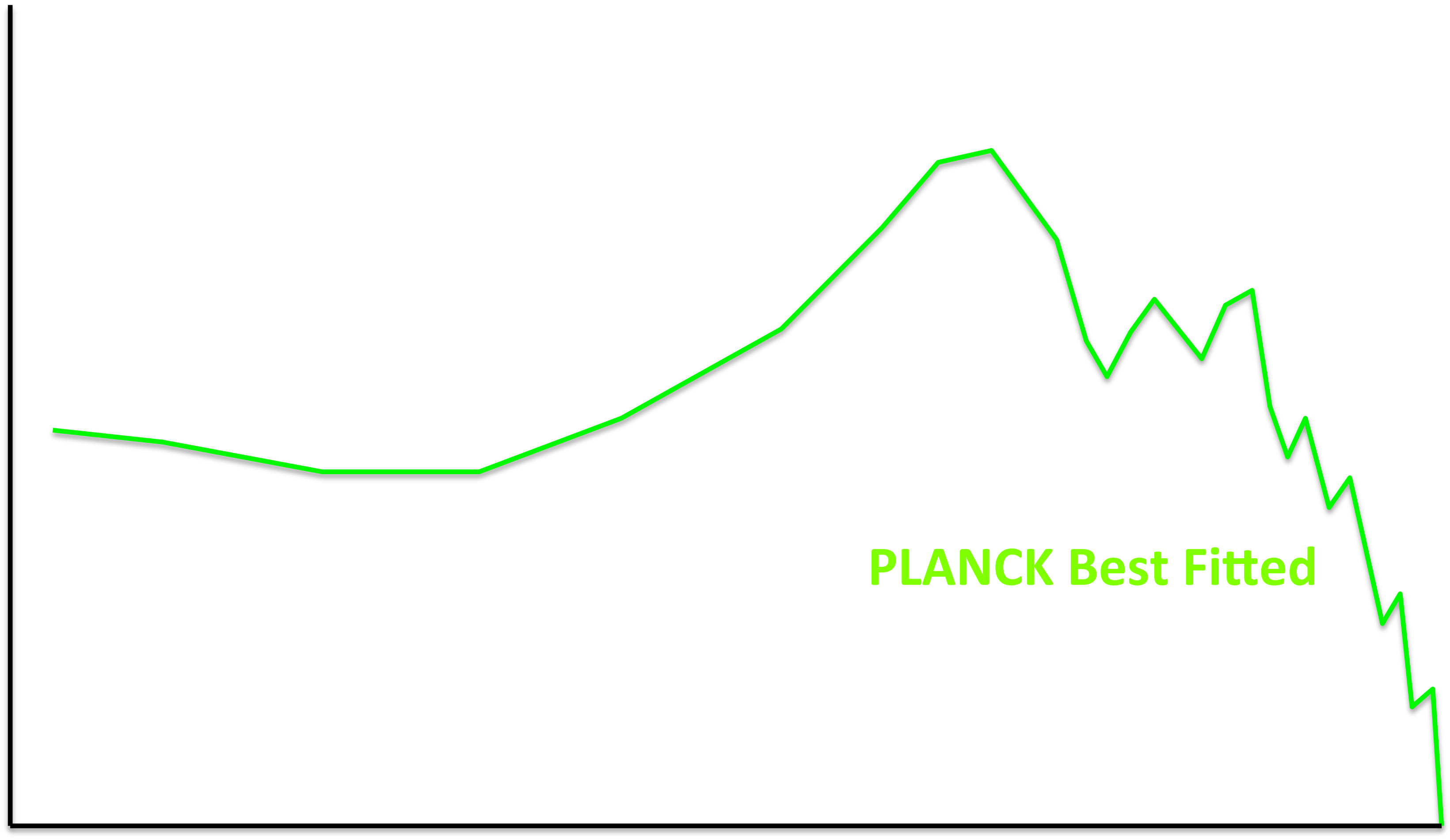
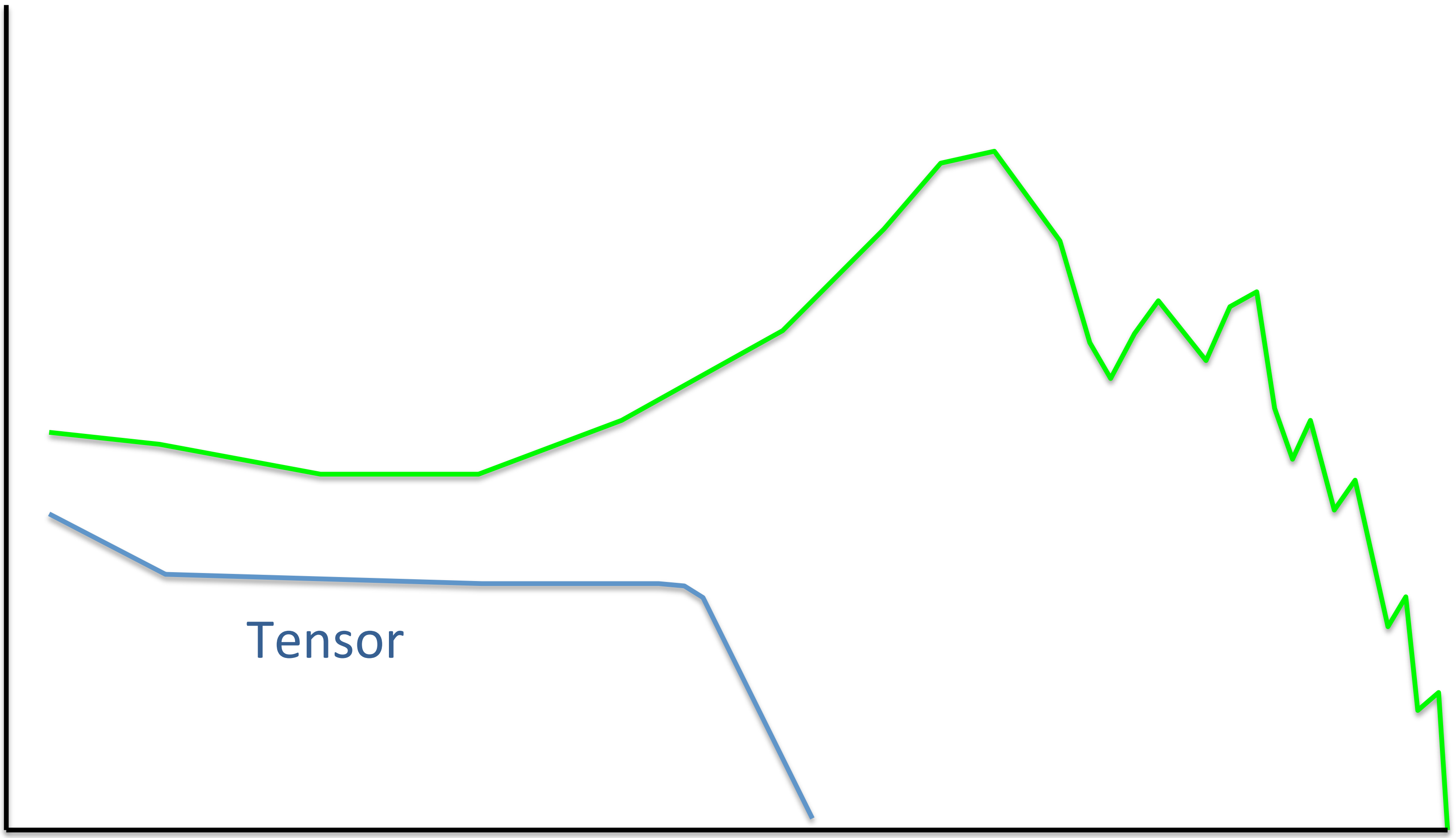
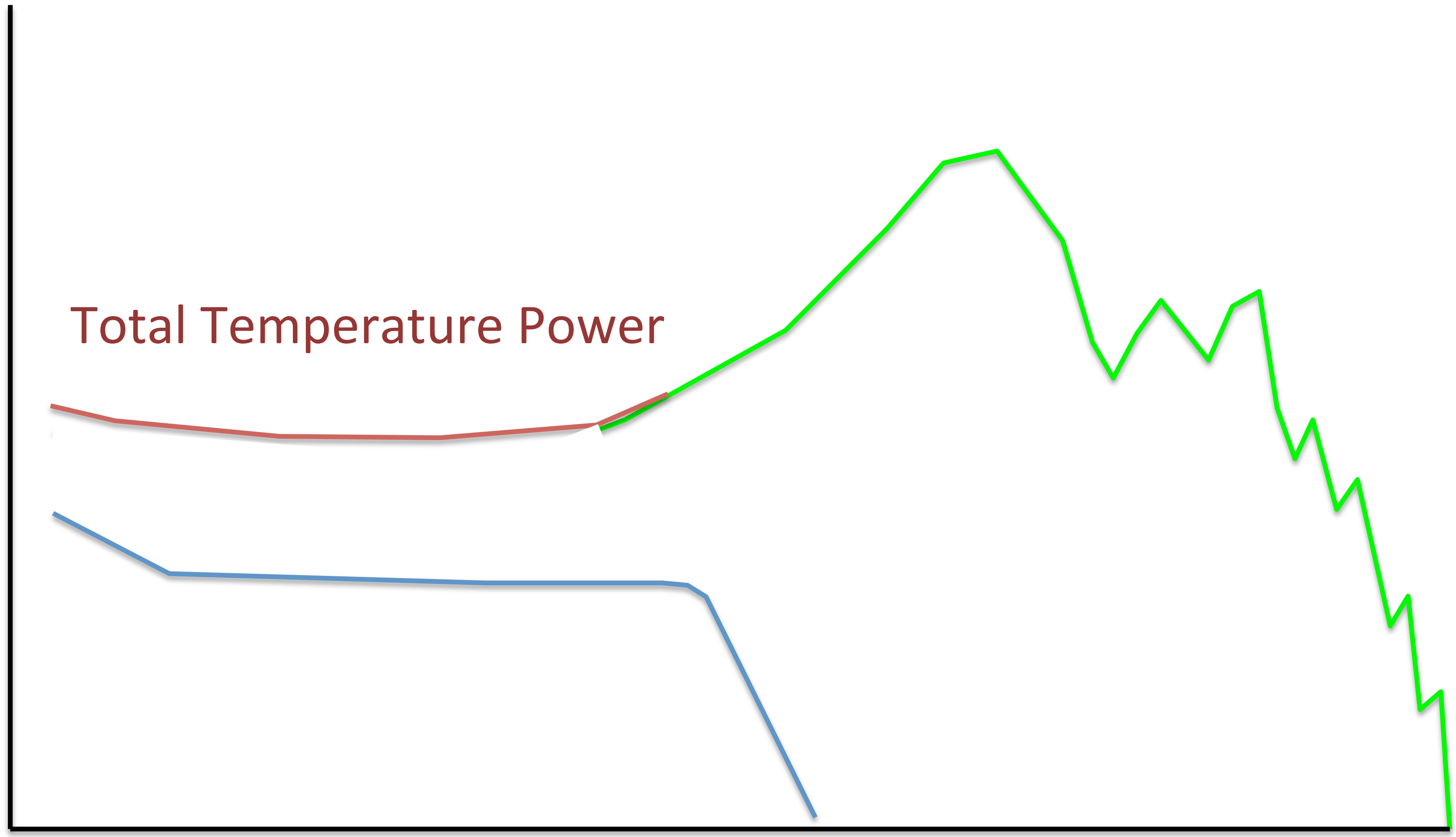
Tension between BICEP2 and PLANCK
or
Running Spectrum Index

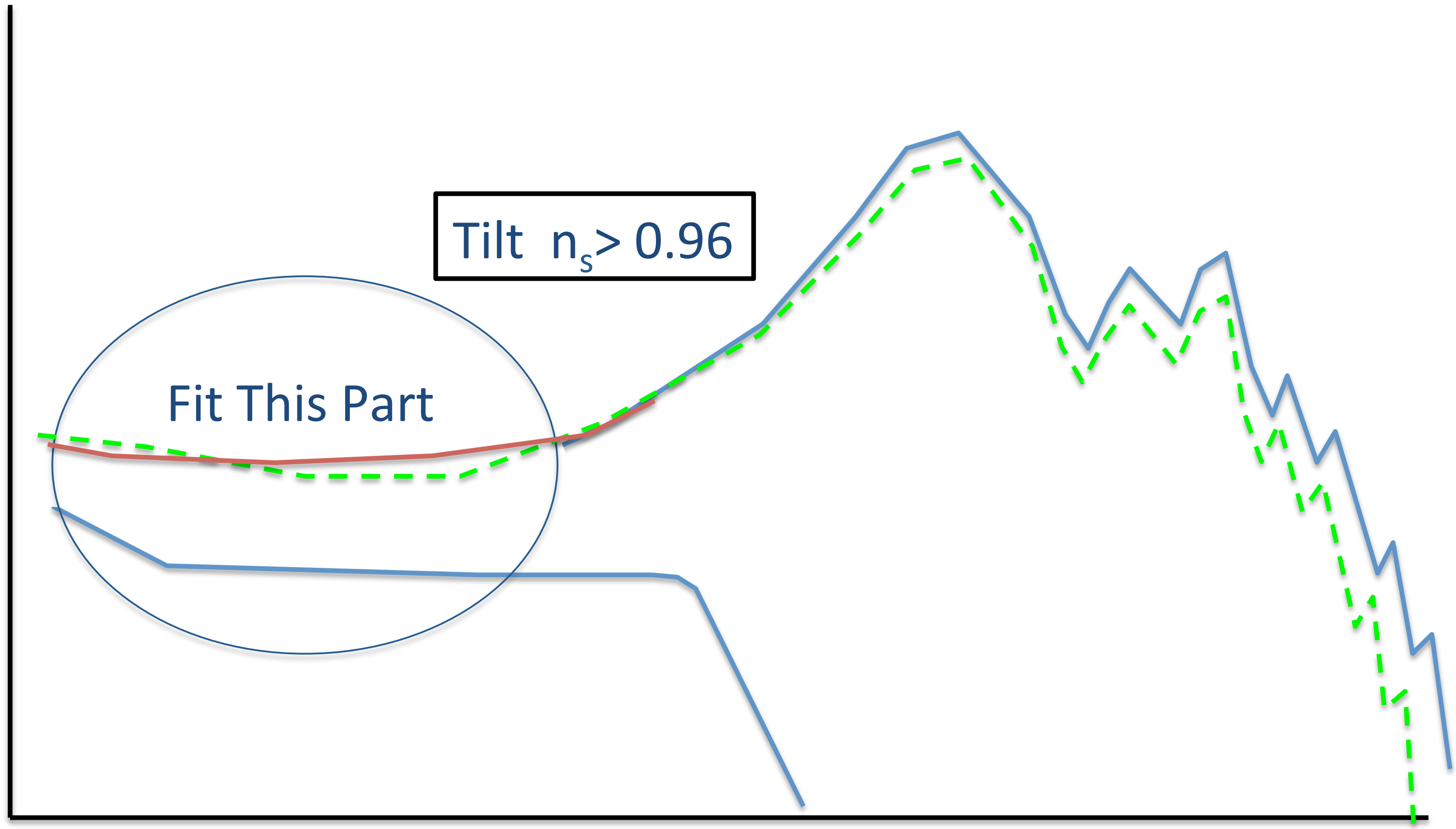
Why Running?

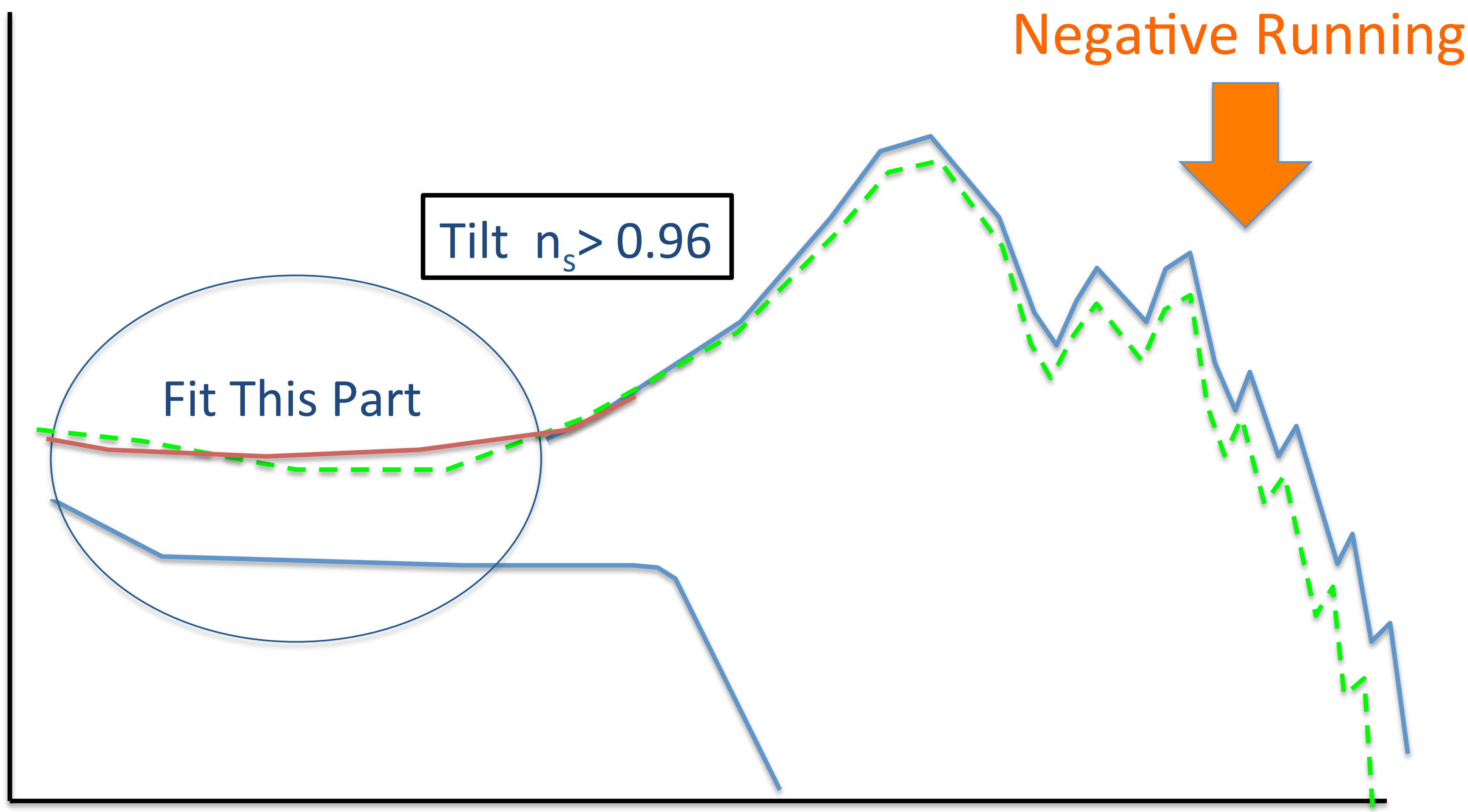
- to reduce the Scalar power on large scales (small l's), a bit of tilted (blue) spectrum is needed
- to match with CMB on smaller scales, negative running is needed.

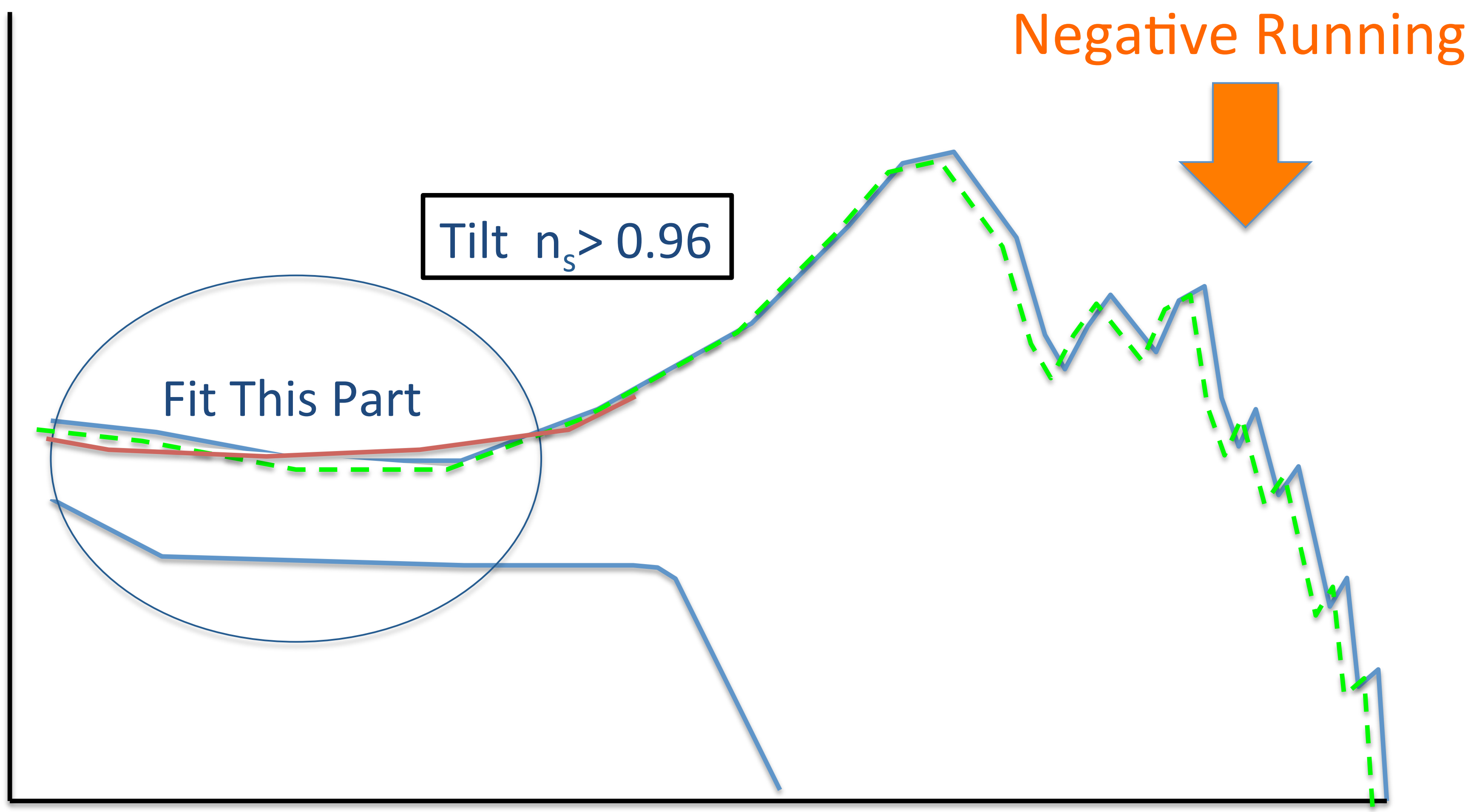

PLANCK Best Fitted


Tensor


Total Temperature Power


Tilt $n_s > 0.96$
Fit This Part

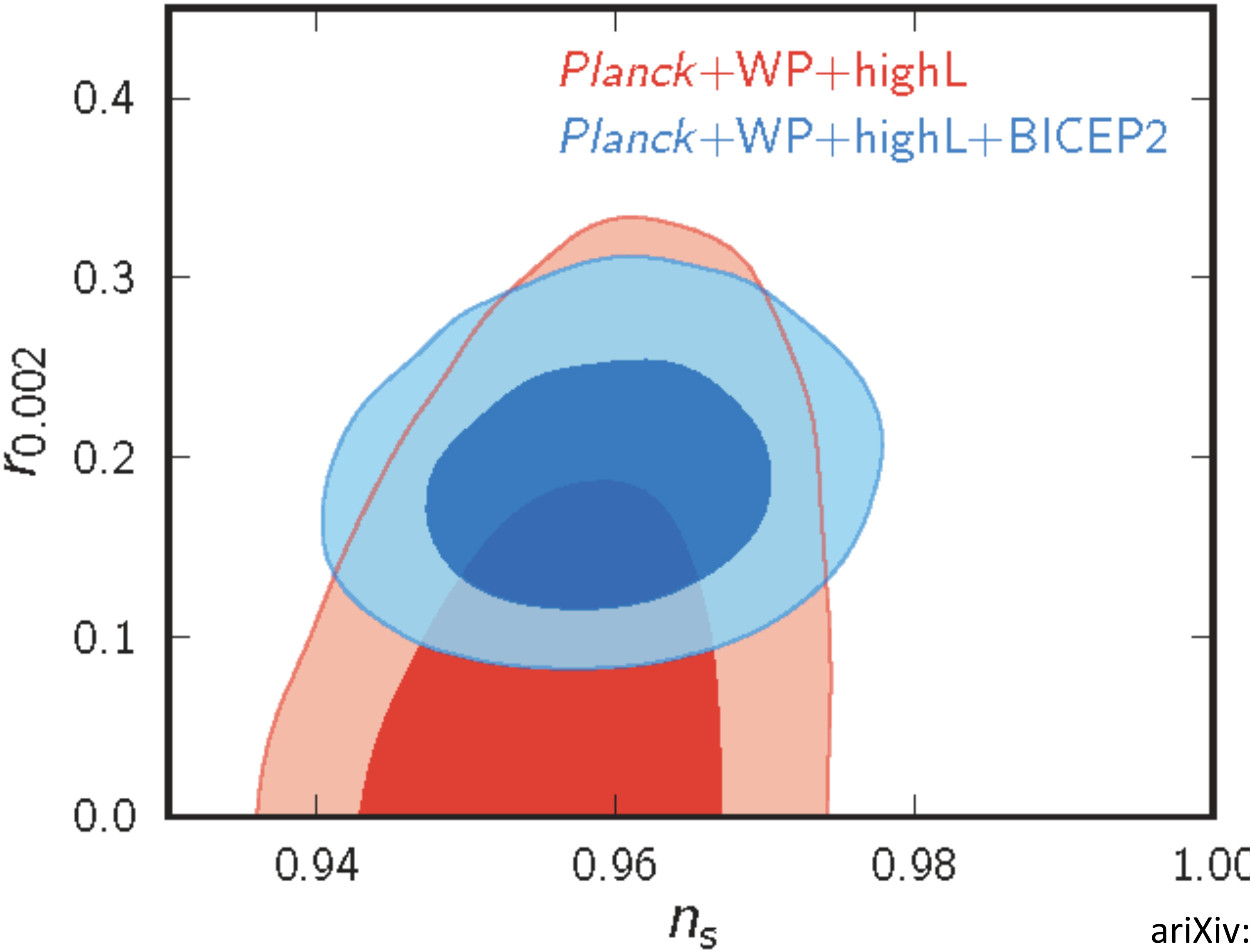

Negative Running
Tilt $n_s > 0.96$
Fit This Part



Negative Running
Tilt $n_s > 0.96$
Fit This Part

With running, no tension!

Best fit: $\alpha = dn_s/d\log k = -0.028$

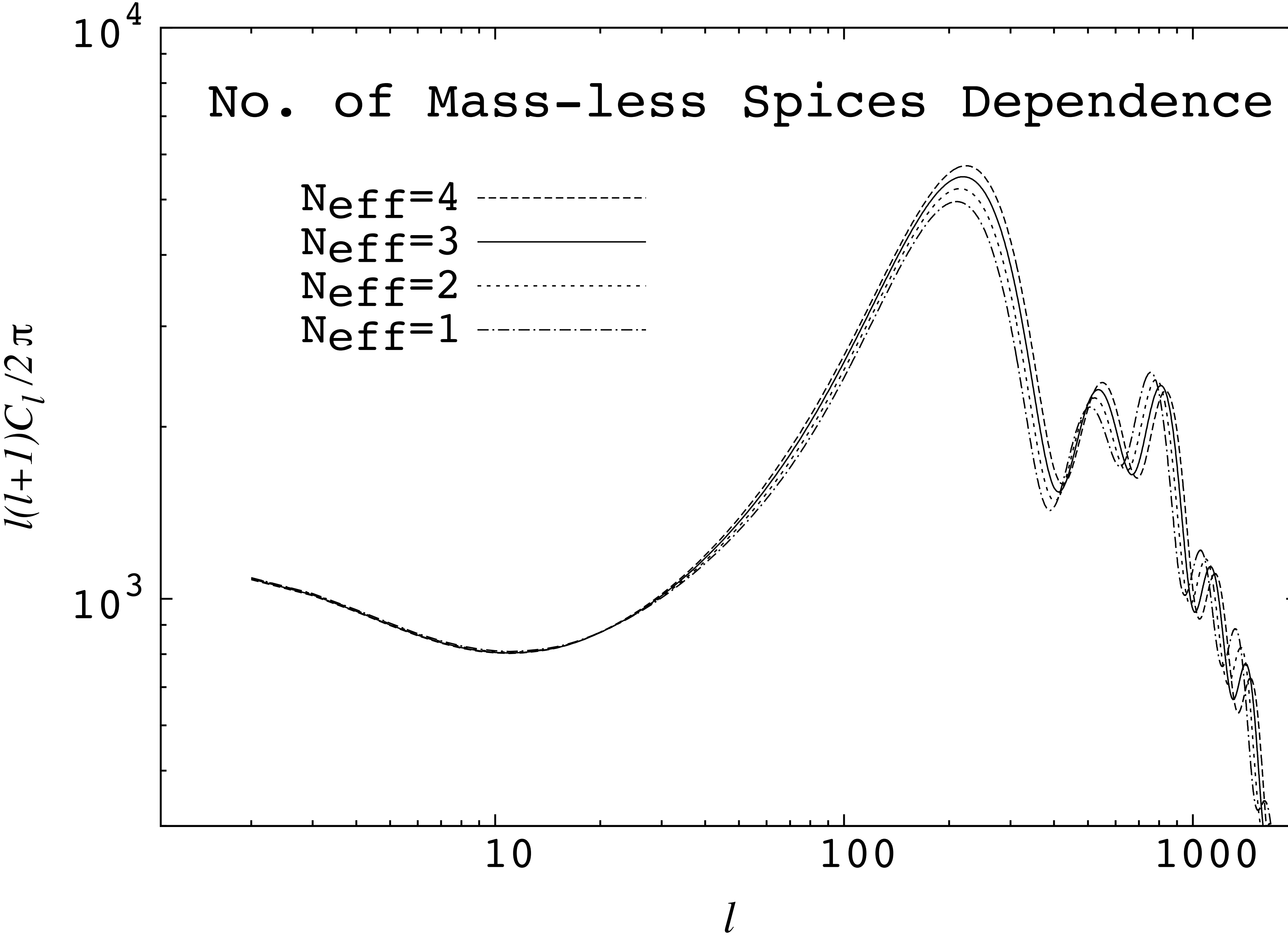


ariXiv:1403.3985

Tension between BICEP2 and PLANCK
or
Running Spectrum Index

Alternatives

- to reduce the Scalar power on large scales (small l's), a bit of tilted (blue) spectrum is needed
- to match with CMB on smaller scales,
  - ✓ [Negative running]
  - ✓ Increase effective number of massless spices
  - ✓ Increase tensor spectral index n_t to 0.9 (Smith et al. arXiv;1404.0373)
  - ✓ Increase optical depth (but E-mode polarization…)



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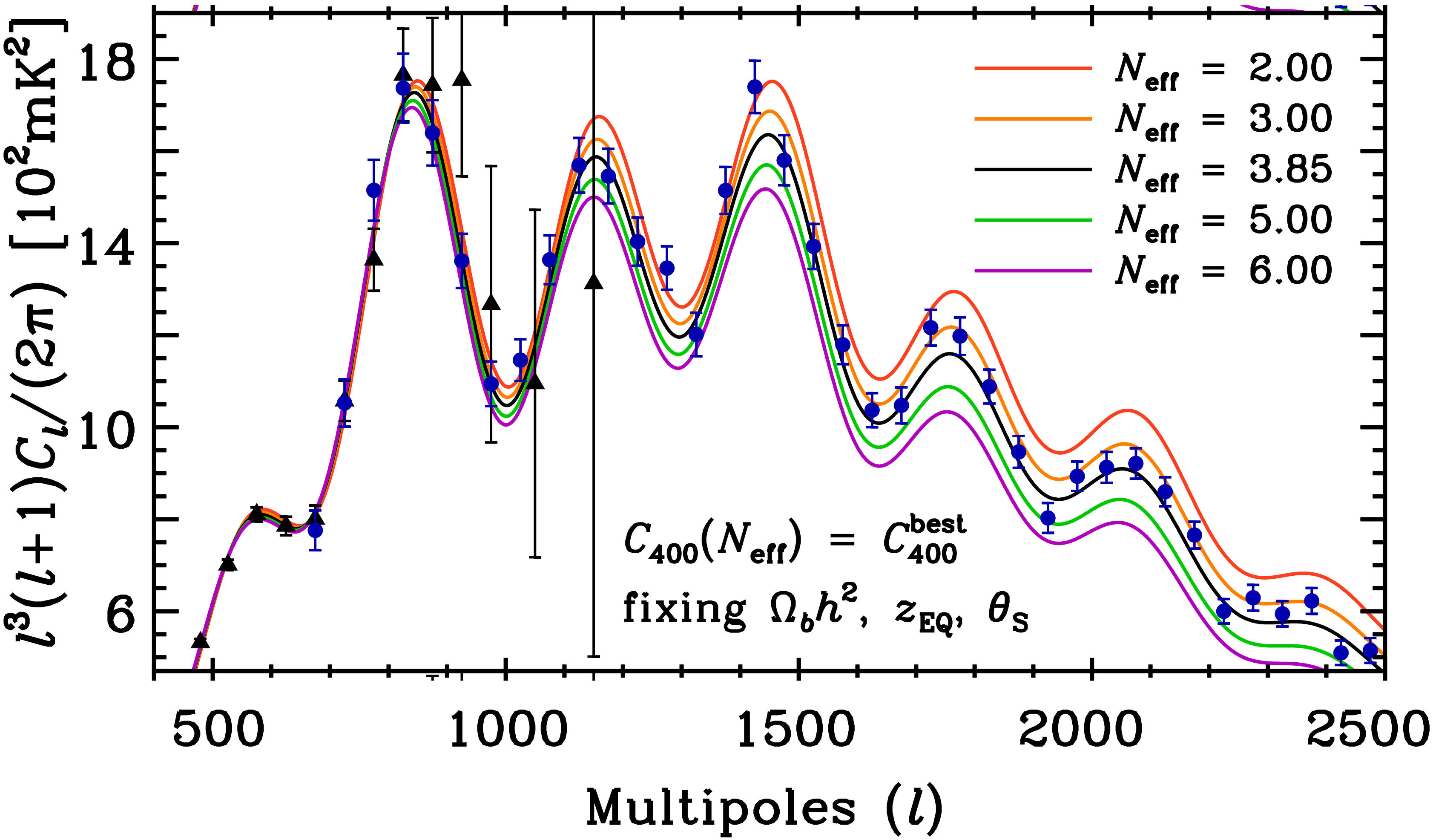
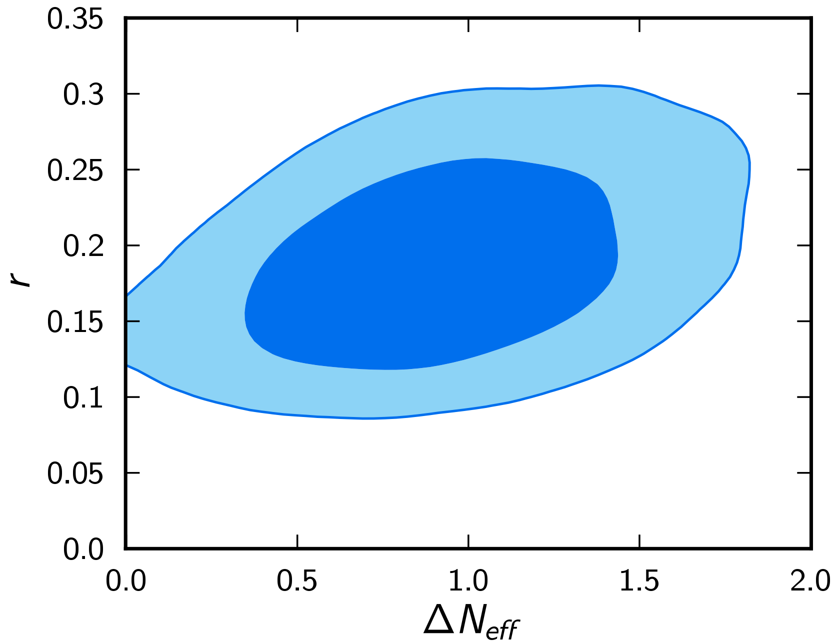
Zhen Hou,[1] Ryan Keisler,[2] Lloyd Knox,[1] Marius Millea,[1] and Christian Reichardt[3]
PHYSICAL REVIEW D **87,** 083008 (2013)



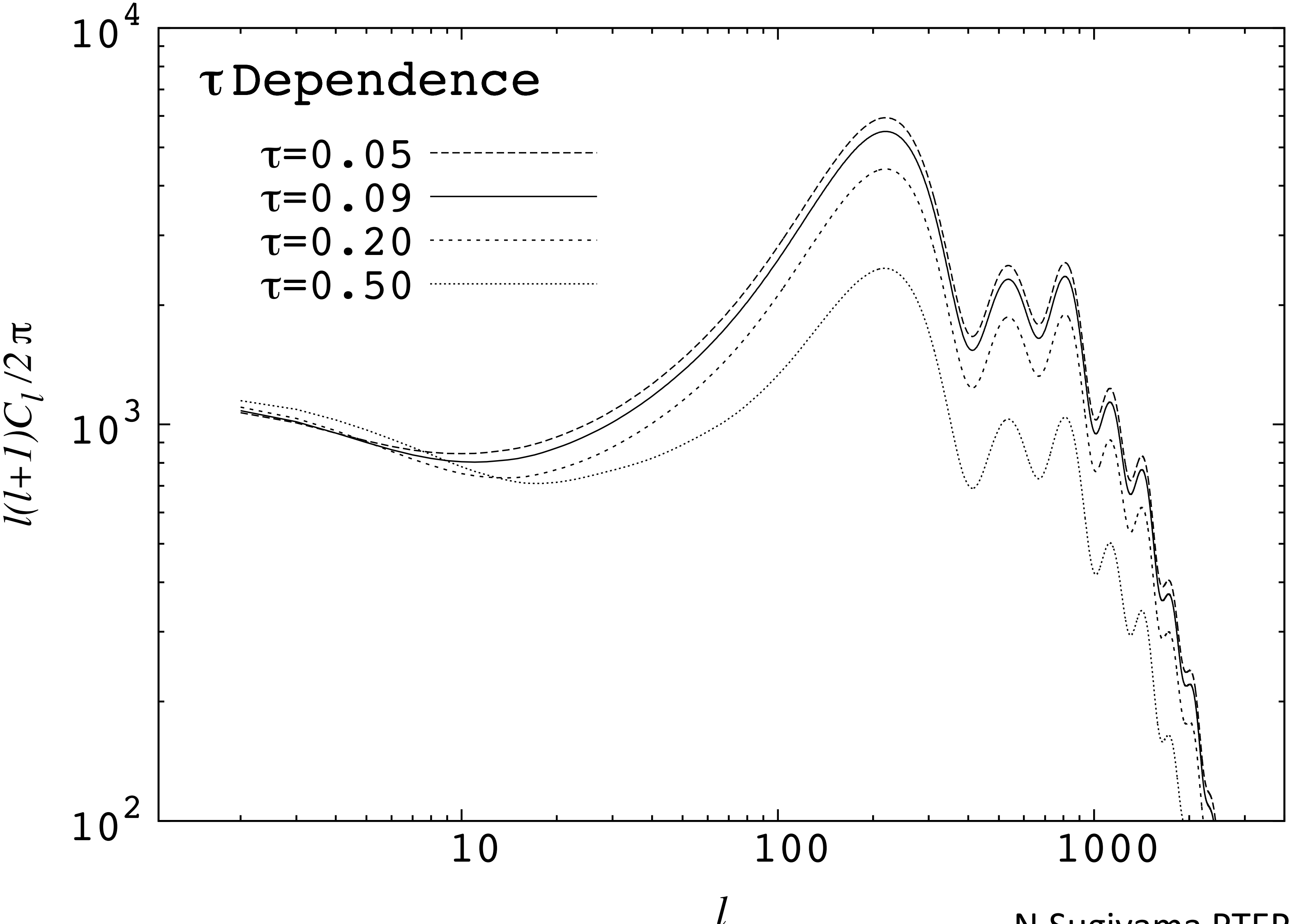
Fixed Baryon density, Sound Horizon Scale and Redshift of matter-radiation equality

Dvorkin, Wyman, Rudd , Hu   ariXiv:1403.8049



Planck, WMAP9 polarization, SPT/ACT and BICEP2 suggest Neff ~ 4

Optical Depth can also explain this tension



N.Sugiyama PTEP 2014

If BICEP2 B-mode polarization is primordial

Inflation is the most plausible explanation!

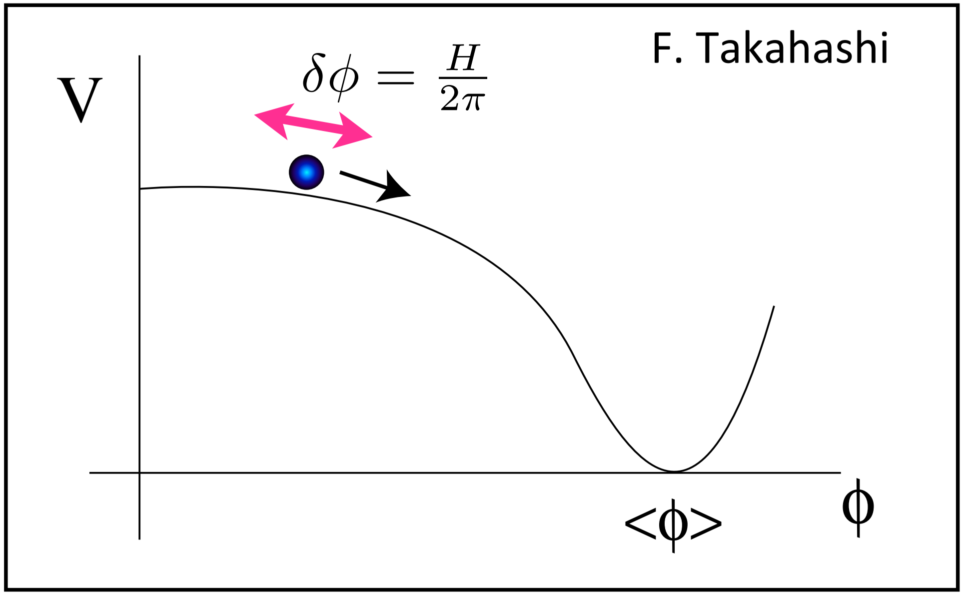
Simplest Inflation, i.e., single scalar field, can work

Q4) What do we learn about inflation?

- Energy Scale of inflaton potential suggests the Grand Unified Theory (GUT) Scale
- Evidence of Large Field Inflation
- Consistency Relation?

Inflation

- Exponential expansion to solve horizon and flatness problems.
- Slow Roll of a scalar field (Inflaton) causes inflation
- Quantum Fluctuations of inflaton $\delta\phi$ generate density fluctuations (seeds of structure)

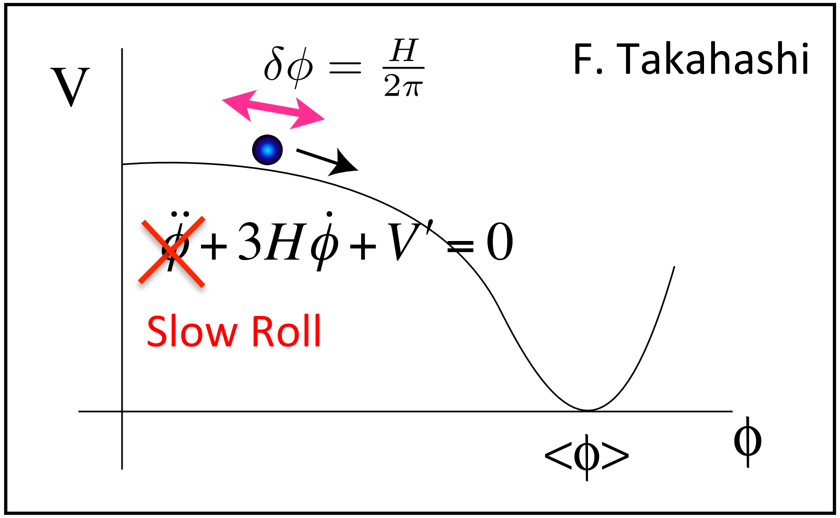


Scalar mode

$$ds^2 = -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^2$$

- Fluctuations are induced by time shift due to inflaton's quantum fluctuations

$$\Psi \sim \left.\frac{\delta\rho}{\rho}\right|_{HC} \sim H\delta t \sim H\frac{\delta\phi}{\dot{\phi}} \sim \frac{H^2}{\dot{\phi}} \sim \left|\frac{V^{3/2}}{V' M_{PL}^3}\right|$$



$$\delta\phi = \frac{H}{2\pi}$$

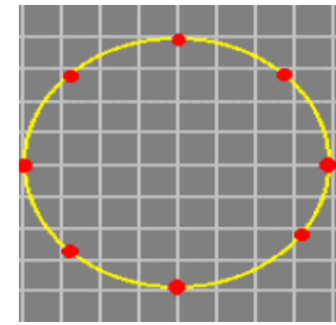
$$H^2 = V / 3M_{PL}^2$$ Friedmann Eq.

$$\dot{\phi} \approx V' / 3H = V' M_{PL} / V^{1/2} 3^{1/2}$$

Slow Roll Condition

Tensor Mode

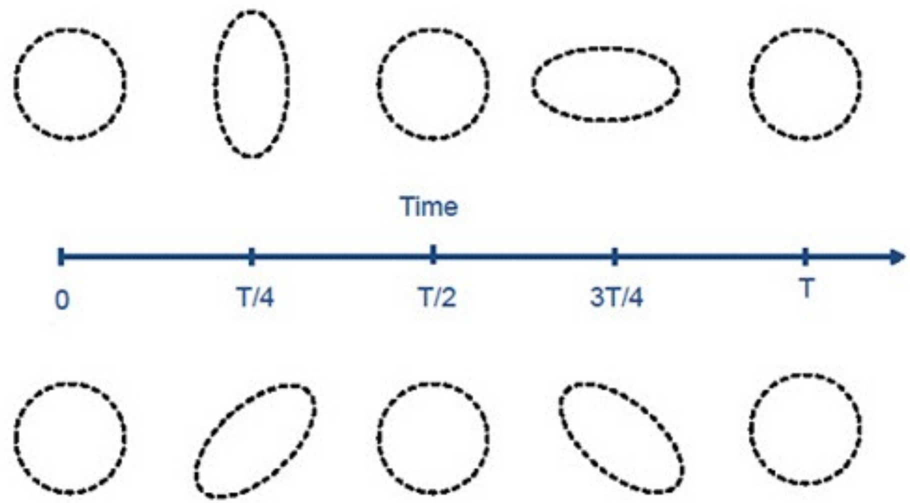
$$ds^2 = -dt^2 + a^2(\delta_{ij} + h_{ij})dx^{ij}$$



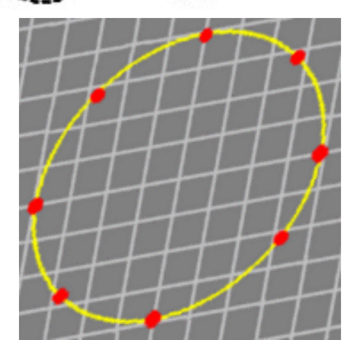
- Fluctuations of graviton!

$$h_{ij} = \frac{\delta\phi}{M_P} \sim \frac{H}{M_P} \sim \left| \frac{V^{1/2}}{M_P^2} \right|$$

h_+



h_x



Observation and Theory

- Initial Scalar mode

$$P_S(k) = A_S(k/k_0)^{n_s - 1}$$

- Initial Tensor mode

$$P_T(k) = A_T(k/k_0)^{n_T}$$

<u>Observables</u>

$$A_S, n_S, A_T, n_T$$

or

$$A_S, n_S, r \equiv A_T / A_S, n_T$$

<u>Observables & Potential *V*</u>

$$A_S = V^3 / 2\sqrt{3} V'^2$$

$$n_S = 1 + 2V''/V - 3(V'/V)^2$$

$$r = 8(V'/V)^2$$

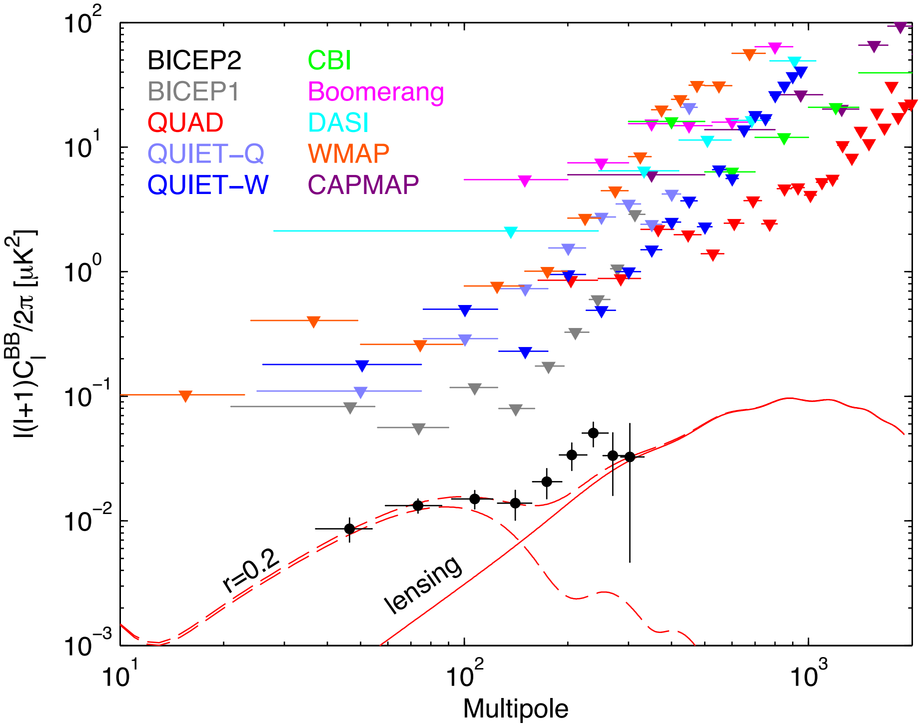
$$n_T = -(V'/V)^2$$

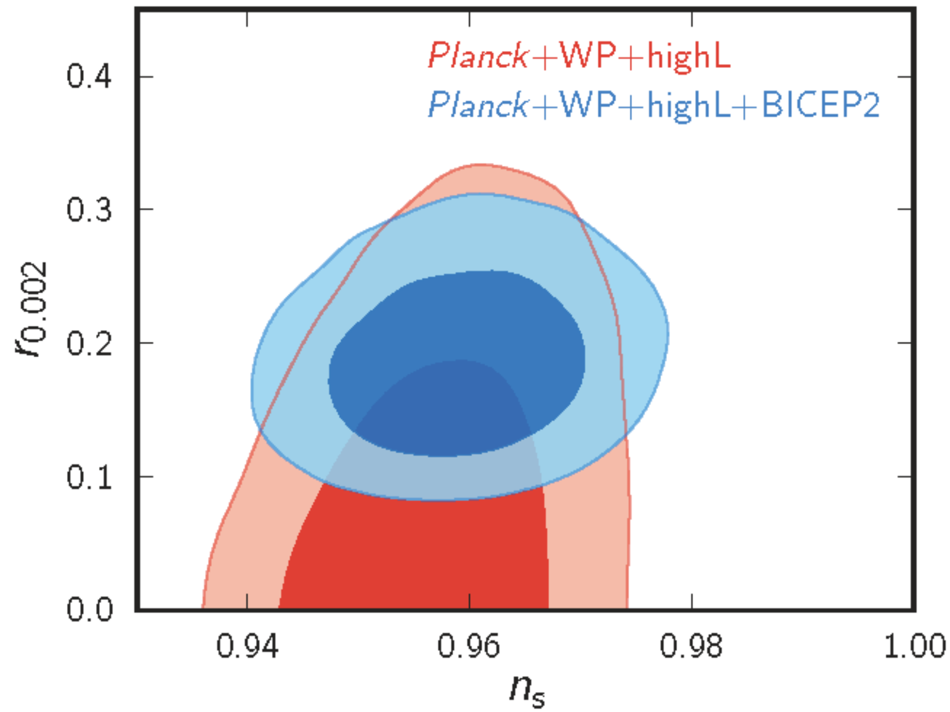
Here take $M_{PL} = 1$

4 Observables and
3 parameters *V*, *V'*, *V''*

One Consistency Relation e.g.,
n_T=-r/8

BICEP2 Observation





$$r = 0.20^{+0.07}_{-0.05}$$

ariXiv:1403.3985

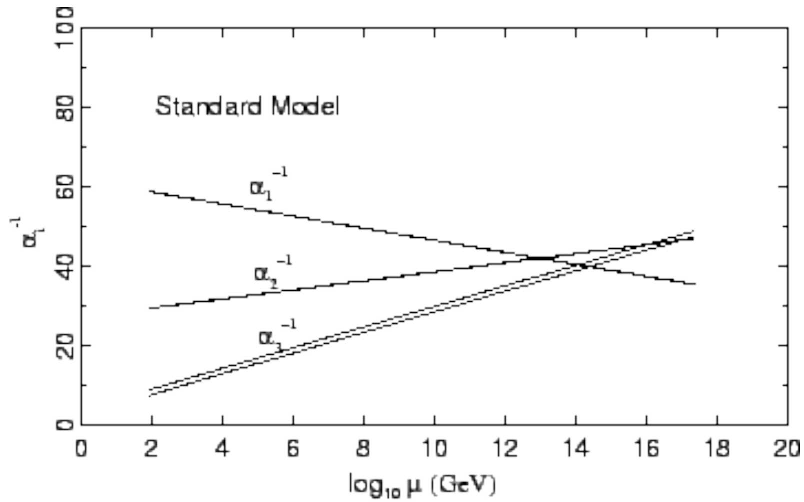
Impact on Inflation

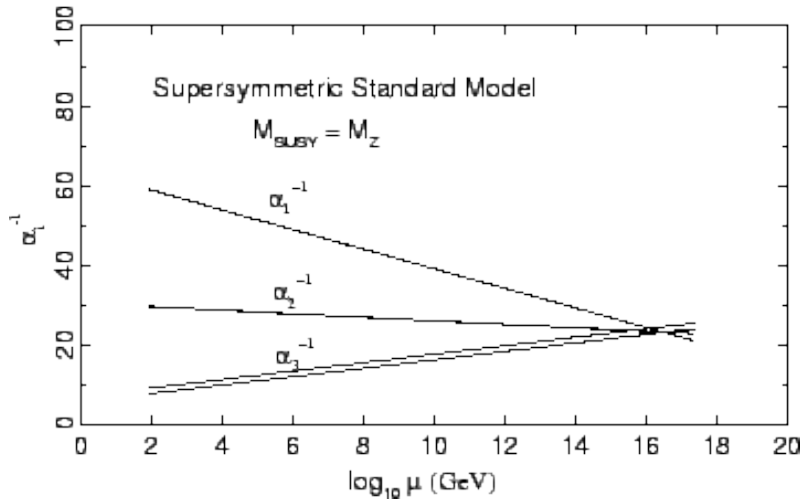
- Knowing A_T, n_T, r, one can determine all V, V', V''

$$V \approx (2.2\times 10^{16}\,\mathrm{GeV})^4 \left(\frac{r}{0.20}\right)$$

$$H \approx 1.1\times 10^{14}\,\mathrm{GeV} \left(\frac{r}{0.20}\right)^{1/2}$$

Unification Scale!?





Large Field Inflation!

- During Inflation, inflaton excursion should exceed the Planck Scale

N is e-folding: *N=Ht*

$$\Delta N = H\Delta t$$

$$r = 8\left(\frac{V'}{V}\right)^2$$

$$V' = 3H\dot{\phi}$$

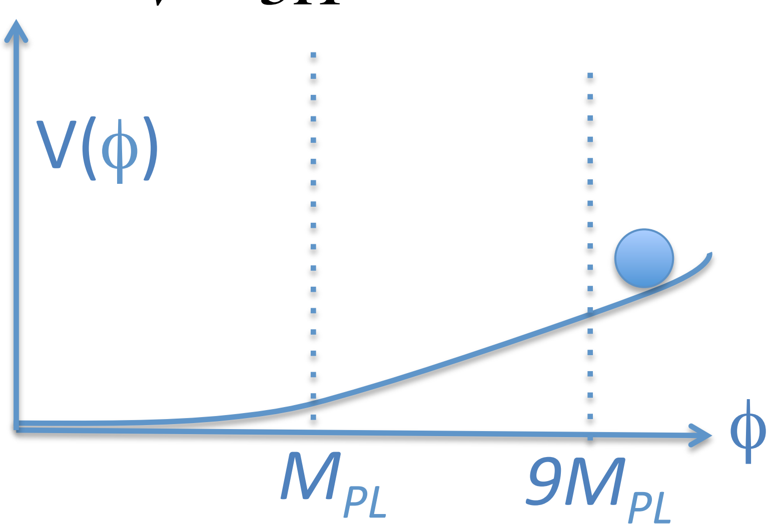
$$V = 3H^2$$

$$r = 8\left(\frac{\dot{\phi}}{H}\right)^2 = 8\left(\frac{\Delta\phi / \Delta N}{H}\frac{\Delta N}{\Delta t}\right)^2 = 8\left(\frac{\Delta\phi}{\Delta N}\right)^2$$

$\Delta N \gtrsim 55$ Horizon, Flatness Problems

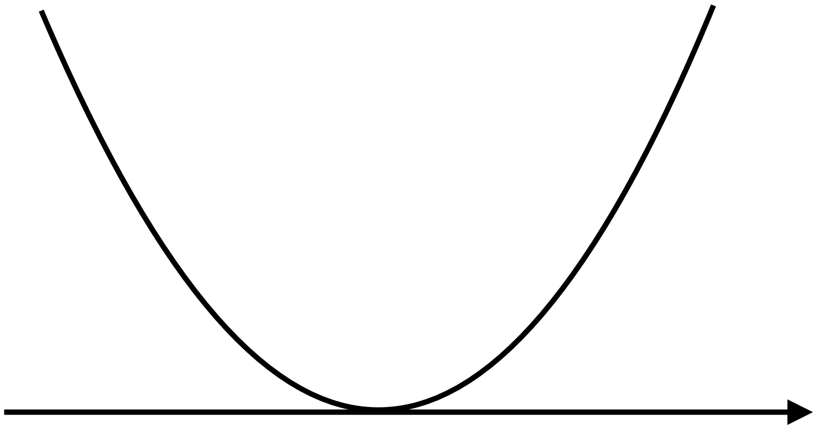
$$\Delta\phi \gtrsim 9M_{PL}\left(\frac{r}{0.2}\right)^{1/2}\left(\frac{\Delta N}{55}\right)$$

Lyth Bound (PRL 1997)



Some of Large Field Inflation Models

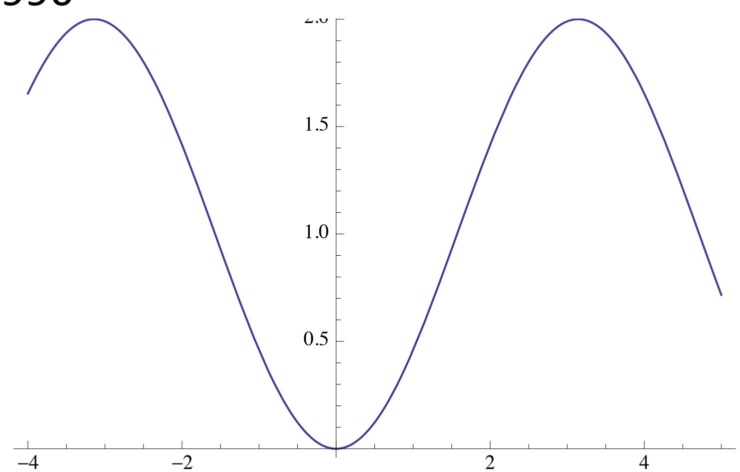
- Quadratic Chaotic Inflation Linde 1983



$$V = \frac{1}{2} m^2 \phi^2$$

$m \approx 2\times 10^{13}\,\mathrm{GeV}$ $\phi_{60} \sim 16 M_{PL}$

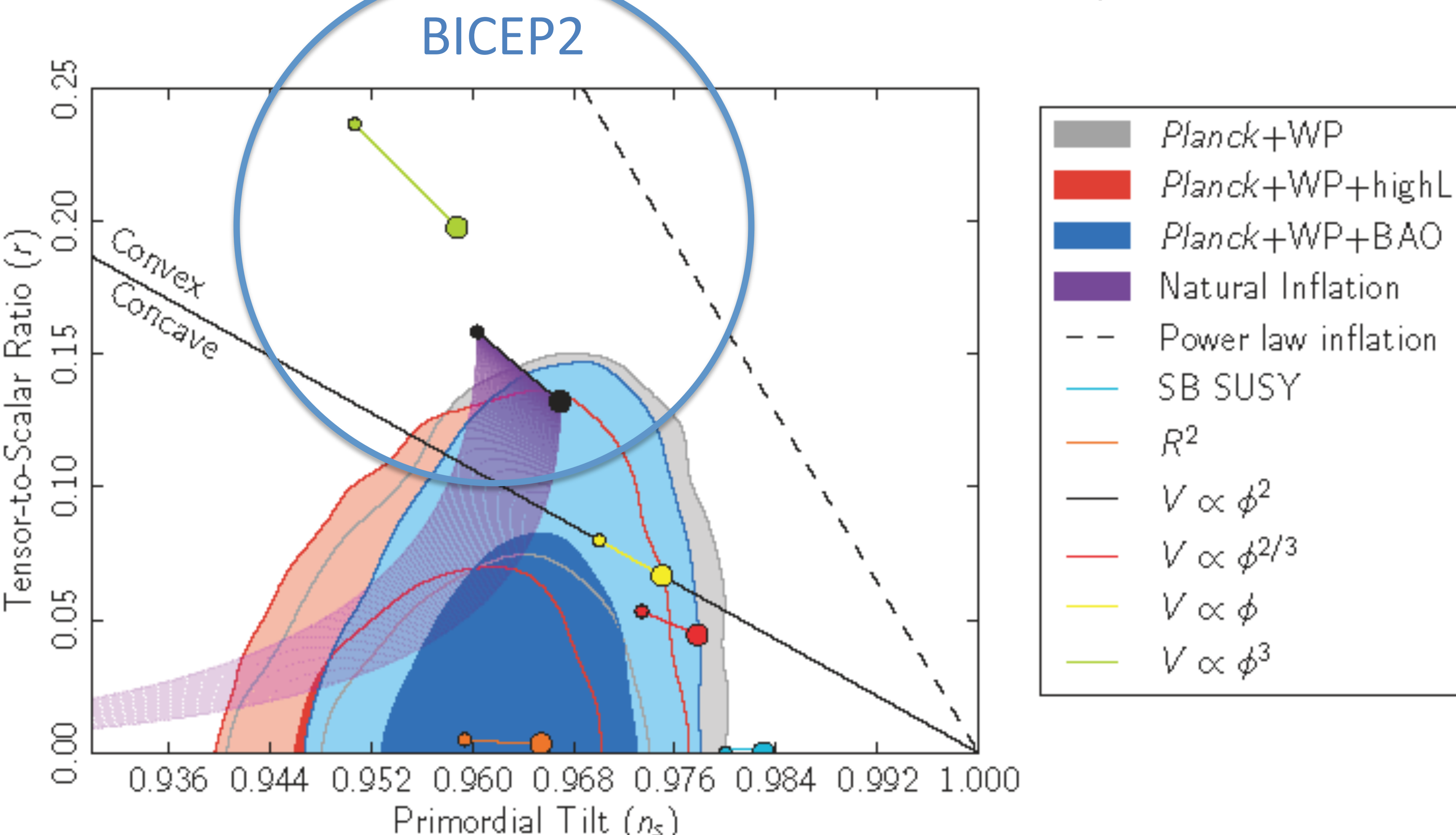
- Natural Inflation Freese et al. 1990



$$V = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$

$\Lambda \approx m_{GUT}$ $f \sim O(10) M_{PL}$

Predicted Values of n_s, r



Planck arXiv: 1303.5062,

Consistency Relation

- 4 Observables: n_S, A_s, r, n_T
- 3 Parameters: V,V',V''

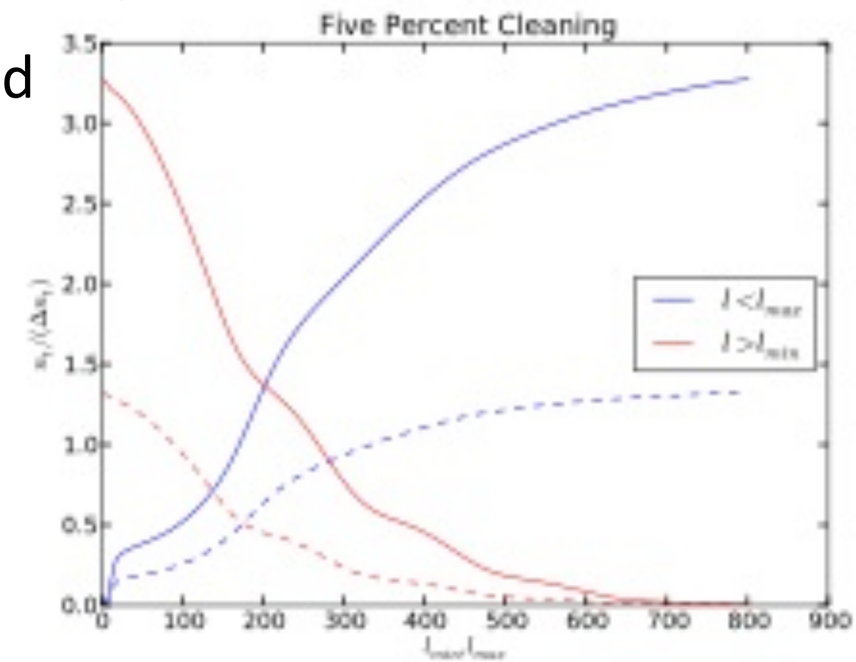
Consistency Relation
e.g., n_T=-r/8

Proof of Inflation

<u>How accurate can we determine n_T?</u>

✓ Fine angular resolution is needed
✓ Need to clean Lensing B-mode

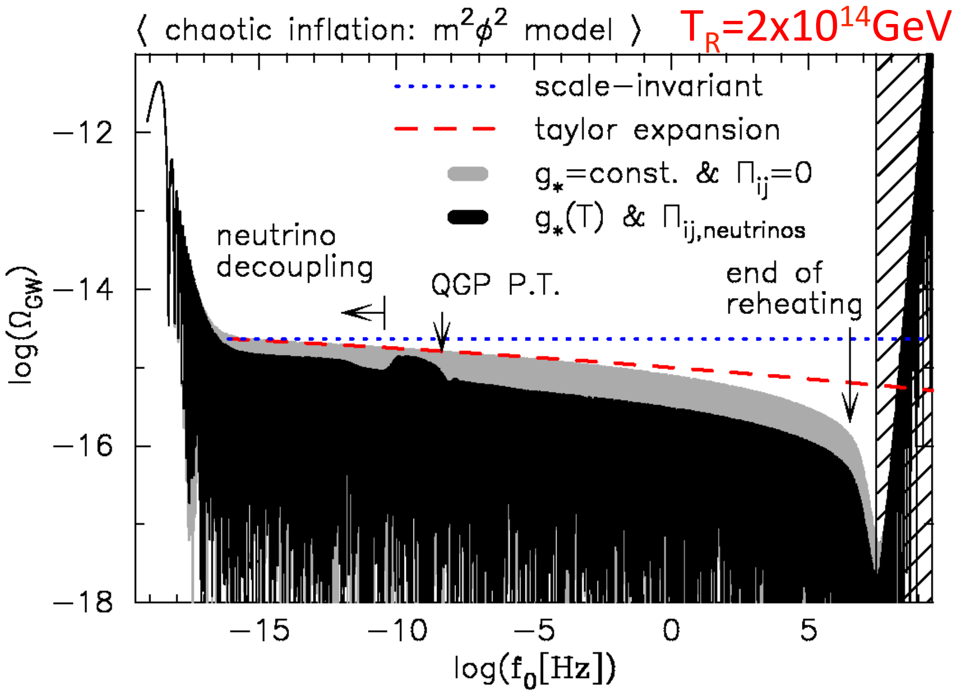
In the left panel, 95% of the lensing signal is removed.
If one can measure l up to 500, Signal to Noise Ratio can be as large as 3 for r=0.2, but 1.3 for r=0.1.



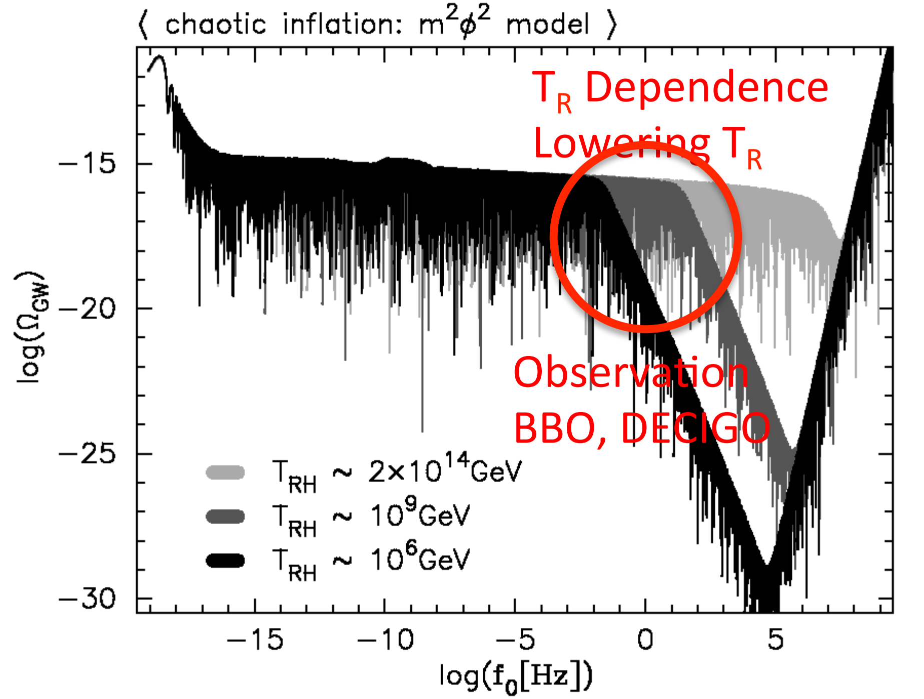
Dodelson arXive:1403.6310

Can we directly detect Gravitational Wave by Interferometer Experiment?

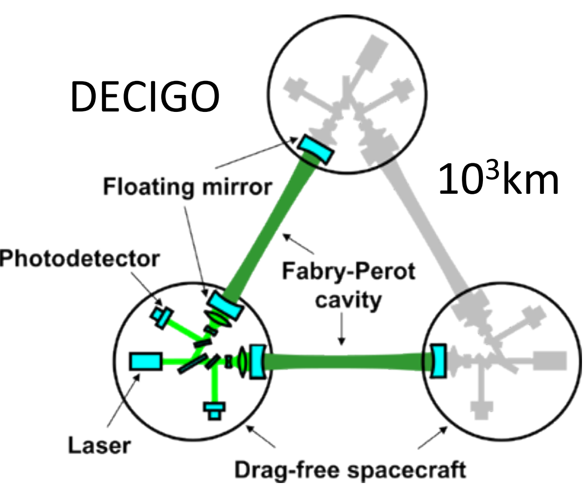
- Next (or Next Next) generation space interferometer is needed.
- It is possible to directly detect gravitational wave!
- One has a chance to measure the reheating temperature from the experiment

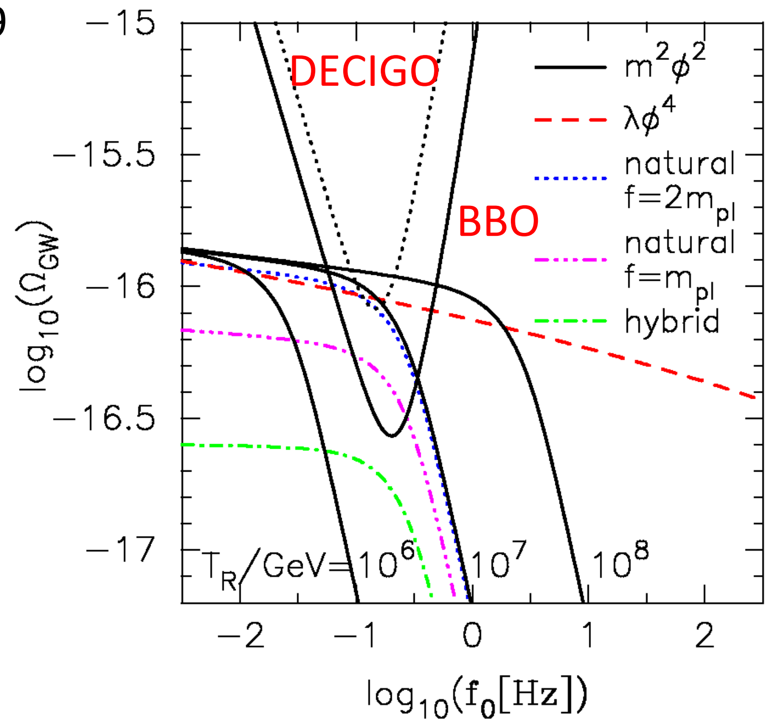


Kuroyanagi, Chiba, NS 2009



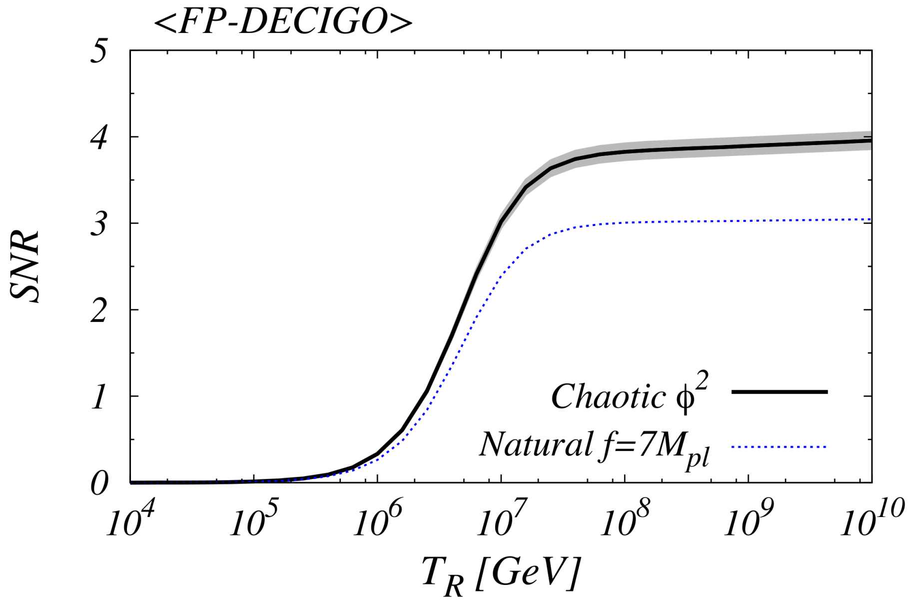
Kuroyanagi, Chiba, NS 2011

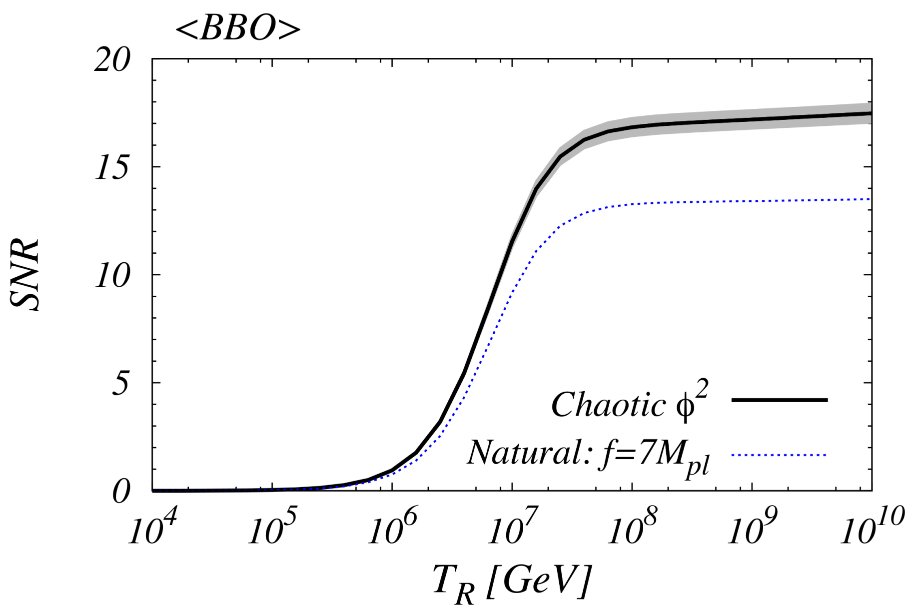




Kuroyanagi, Tsujikawa, Chiba, NS 2014

Forecast for Future GW experiment (10yr obs.)





Summary

- Dust (foreground) or Primordial is not yet clear
  - Wait Planck polarization paper, Nov. 2014
  - BICEP2 and Planck cross correlation
- If BICEP2 B-mode Polarization is not foreground origin, it means
  - Detection of Gravitational Wave (Tensor)
  - Measurement of Tensor-Scalar Ration *r*
- Implications on Cosmology are
  - Running Spectral Index or Neff~4 (Dark Radiation?)
  - GUT scale Inflation $V \sim 2 \times 10^{16}$GeV
  - Large Field Inflation $\phi > 9M_{PL}$
- Future
  - If r=0.2, the consistency relation can be checked by an all sky fine resolution experiment as a prove of Inflation
  - Direct measurement of gravitational wave by space interferometer is feasible.