Have primordial gravitational waves been detected?

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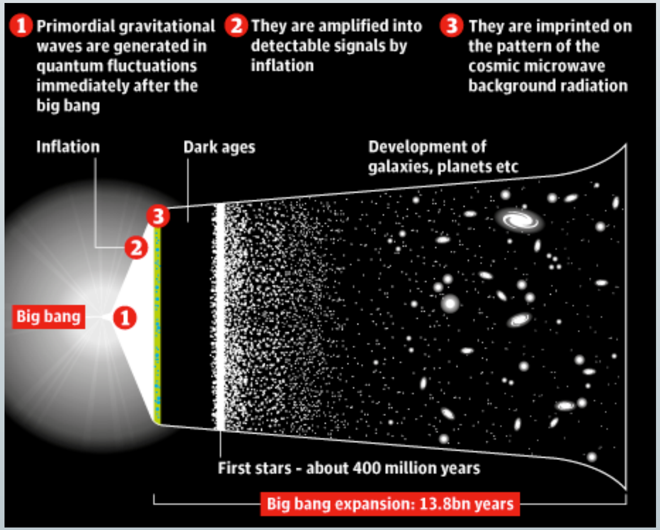
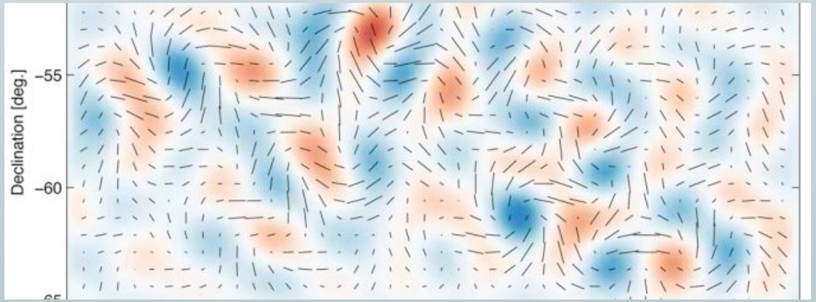
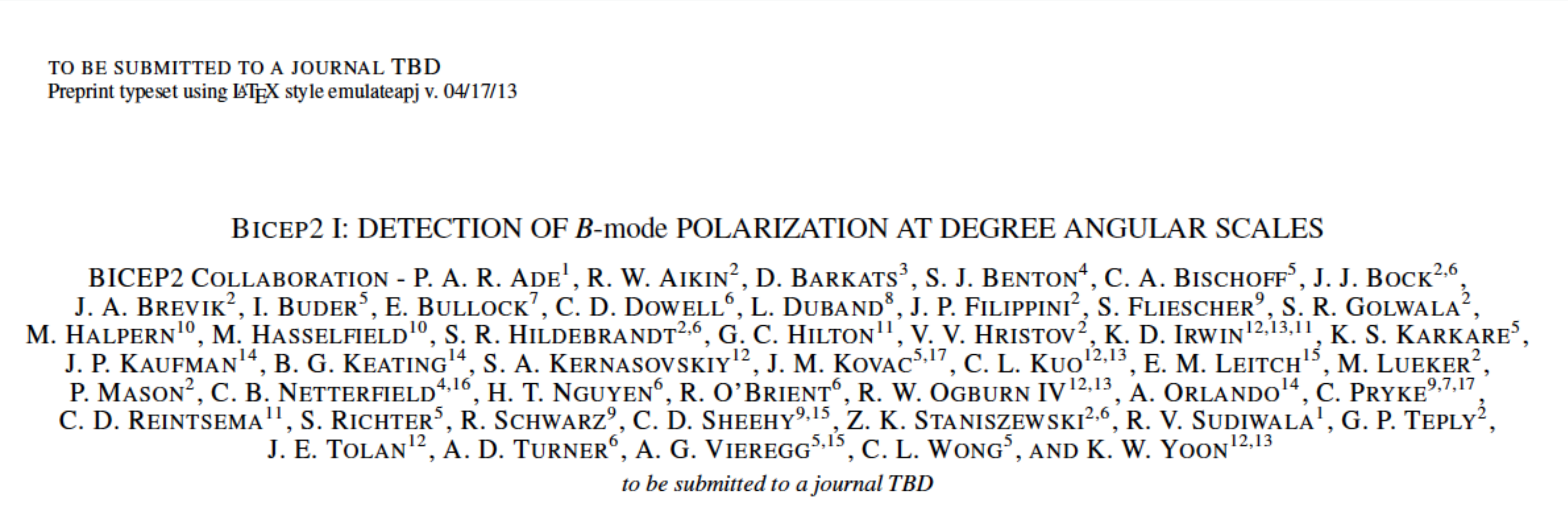
“a major discovery ...”

17 March 2014 press conference at Harvard-Smithsonian CfA: A team of US scientists detected signs of gravitational waves using the Bicep2 telescope at the South Pole. Primordial gravitational wave discovery heralds a ’new era' in physics. “Gravitational waves could help unite general relativity and quantum mechanics ...”. The detection also provides the first direct evidence for the *inflation* paradigm, according to which a fraction of a second after the Big Bang, the universe was driven to expand hugely.





arXiv:1403.3985



TO BE SUBMITTED TO A JOURNAL TBD
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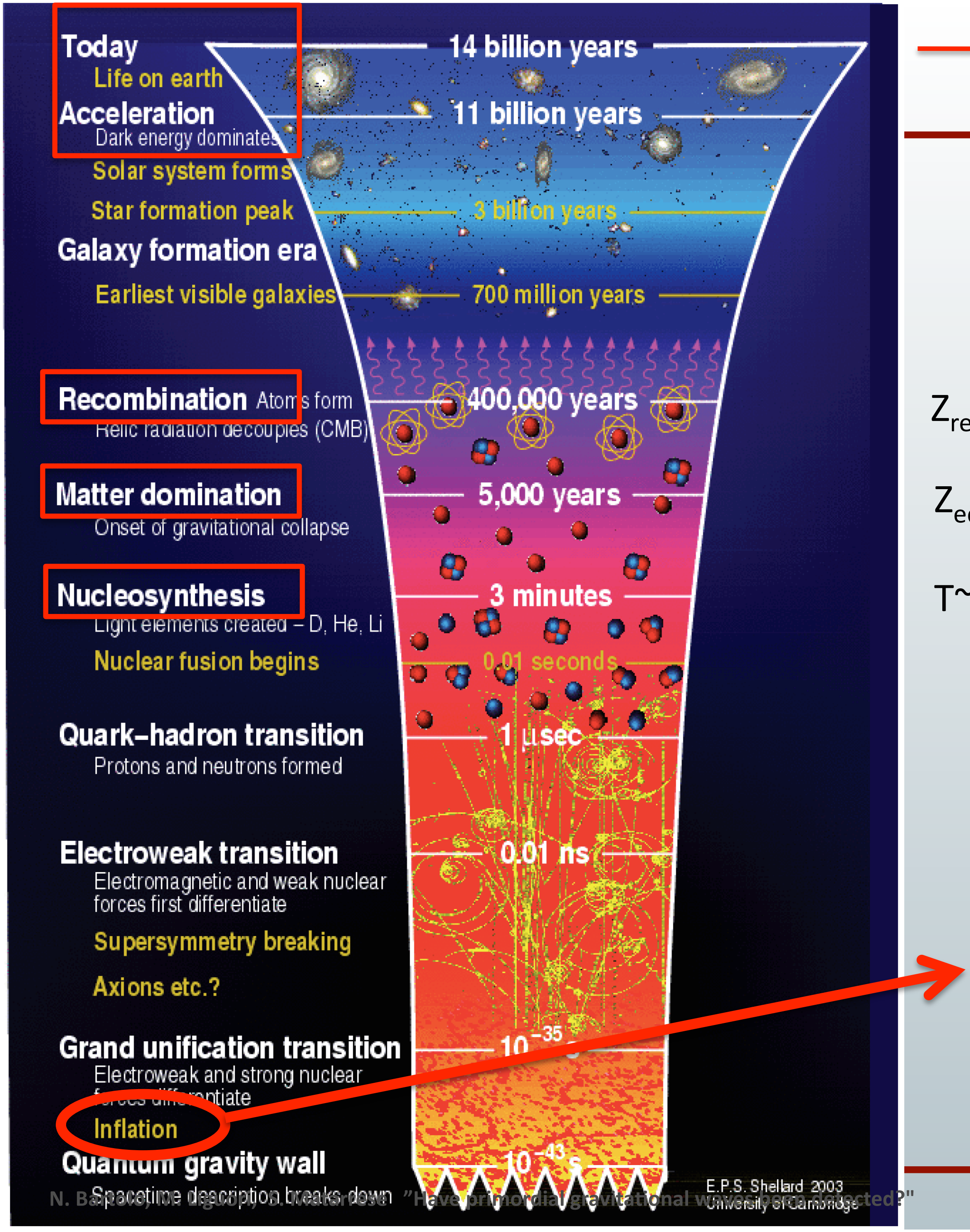
BICEP2 I: DETECTION OF *B*-mode POLARIZATION AT DEGREE ANGULAR SCALES

BICEP2 COLLABORATION - P. A. R. ADE[1], R. W. AIKIN[2], D. BARKATS[3], S. J. BENTON[4], C. A. BISCHOFF[5], J. J. BOCK[2,6], J. A. BREVIK[2], I. BUDER[5], E. BULLOCK[7], C. D. DOWELL[6], L. DUBAND[8], J. P. FILIPPINI[2], S. FLIESCHER[9], S. R. GOLWALA[2], M. HALPERN[10], M. HASSELFIELD[10], S. R. HILDEBRANDT[2,6], G. C. HILTON[11], V. V. HRISTOV[2], K. D. IRWIN[12,13,11], K. S. KARKARE[5], J. P. KAUFMAN[14], B. G. KEATING[14], S. A. KERNASOVSKIY[12], J. M. KOVAC[5,17], C. L. KUO[12,13], E. M. LEITCH[15], M. LUEKER[2], P. MASON[2], C. B. NETTERFIELD[4,16], H. T. NGUYEN[6], R. O'BRIENT[6], R. W. OGBURN IV[12,13], A. ORLANDO[14], C. PRYKE[9,7,17], C. D. REINTSEMA[11], S. RICHTER[5], R. SCHWARZ[9], C. D. SHEEHY[9,15], Z. K. STANISZEWSKI[2,6], R. V. SUDIWALA[1], G. P. TEPLY[2], J. E. TOLAN[12], A. D. TURNER[6], A. G. VIEREGG[5,15], C. L. WONG[5], AND K. W. YOON[12,13]

to be submitted to a journal TBD



We are here

Z_{rec}~1100

Z_{eq}~3500

T~1 MeV

We seek information about very early times and very high energies E~10^{16} GeV

... and we got it!

Inflation in the early Universe

- Inflation is an epoch of accelerated expansion in the early Universe (~ 10^{-34} s after the “Big Bang”) which allows to solve two inconsistencies of the standard Big Bang model (horizon: why is the Universe so homogeneous and isotropic on average + flatness: why is the Universe spatial curvature so small even ~ 14 billion years after the Big Bang?).

- Inflation (Brout et al. 1978; Starobinski 1980; Kazanas 1980; Sato 1981; Guth 1981; Linde 1982, Albrecht & Steinhardt 1982; etc. ...) is based upon the idea that the vacuum energy of a scalar quantum field, dubbed the “inflaton”, dominates over other forms of energy, hence giving rise to a quasi-exponential (de Sitter) expansion, with scale-factor

$$\mathbf{a(t) \approx \exp(Ht)}$$

The rise and fall … of the comoving Hubble horizon

(late-time dark energy dominance neglected for simplicity)

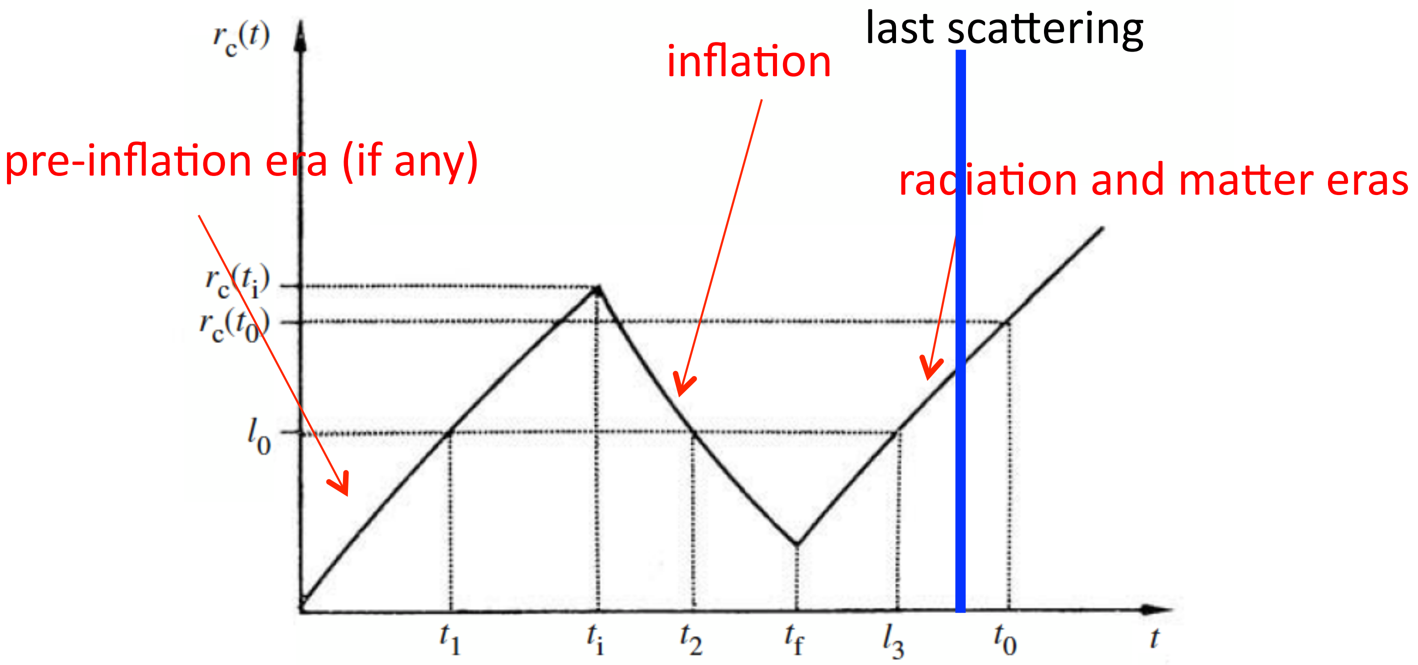


Figure 7.4 Evolution of the comoving cosmological horizon $r_c(t)$ in a universe characterised by a phase with an accelerated expansion (inflation) from t_i to t_f. The scale l_0 enters the horizon at t_1, leaves at t_2 and re-enters at t_3. In a model without inflation the horizon scale would never decrease so scales entering at t_0 could never have been in causal contact before. The horizon problem is resolved if $r_c(t_0) \leqslant r_c(t_i)$.

credits: Coles & Lucchin 2002

Inflation predictions

- Quantum vacuum oscillations of the inflaton (or other scalar fields, such as the "curvaton") give rise to classical fluctuations in the energy density, which provide the seeds for Cosmic Microwave Background (CMB) radiation temperature anisotropies and polarization, as well as for the formation of Large Scale Structures (LSS) in the present Universe.

- All the matter and radiation which we see today must have been generated after inflation (during "reheating"), since all previous forms of matter and radiation have been tremendously diluted by the accelerated expansion ("Cosmic no-hair conjecture").

Gravity-wave background from inflation

- As originally noticed by Starobinski (1979) an early period of quasi-de Sitter evolution leaves its imprint in terms of a low-amplitude *stochastic background of gravitational waves* (see also Grishchuck 1975, Rubakov et al. 1982, Fabbri & Pollock 1982, Abbott & Wise 1984) which originated from quantum vacuum fluctuations of (linearized) spin-2 gravitational perturbations ("gravitons"), left the horizon during inflation (hence remaining frozen and unobservable) and rentered the horizon recently, hence becoming potentially observable as classical tensor perturbations of space-time.

- The detection of these primordial gravitational waves represents the "smoking gun" proof of the validity of the inflationary theory, otherwise very hard to "falsify"; other crucial specific imprints being: the existence of perturbations with a super-horizon seed (***detected!***), specific non-Gaussian signatures of primordial perturbations (***strongly constrained by Planck, which strongly supports the simplest inflation models***).

Inflation and the Inflaton

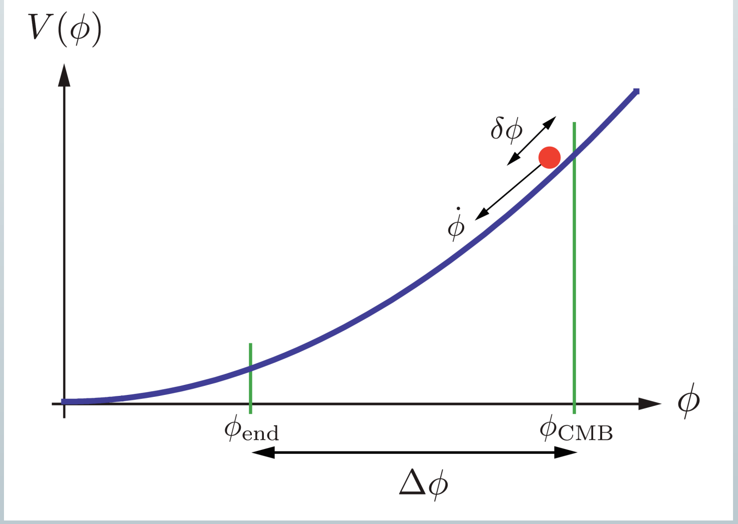
$$\mathcal{L}_\phi[\phi, g_{\mu\nu}] = \frac{1}{2} g^{\mu\nu} \phi_{,\mu} \phi_{,\nu} - V(\phi)$$

Standard kinetic term

Inflaton potential: describes the self-interactions of the inflaton field and its interactions with the rest of the world

Think the inflaton mean field as a particle moving under a force induced by the potential V

Ex: $V(\phi) = \frac{m^2}{2}\phi^2$



Slow-roll Inflation

$$\begin{cases} H^2 \simeq \dfrac{8\pi G}{3} V(\phi) \\[2ex] \dot{\phi} \simeq -\dfrac{V_{,\phi}}{3H} \end{cases} \longrightarrow$$

$$V(\phi) \gg \frac{1}{2}\dot{\phi}^2 \Rightarrow \frac{(V_{,\phi})^2}{V} \ll H^2$$

AND

$$\ddot{\phi} << 3H\dot{\phi} \Rightarrow V_{,\phi\phi} \ll H^2$$

So the slow-roll conditions, as expected, means that the inflaton potential is very flat

It is then customary to parametrize inflationary models (i.e. the form of the inflaton potential) in a sort of model-independent way by introducing the slow-roll parameters

$$\epsilon = -\frac{\dot{H}}{H^2} = 4\pi G \frac{\dot{\phi}^2}{H^2} \simeq \frac{1}{16\pi G}\left(\frac{V_{,\phi}}{V}\right)^2 \ll 1$$: the Hubble rate change slowly

$$\eta = \frac{1}{3}\frac{V_{,\phi\phi}}{H^2} = \frac{1}{8\pi G}\left(\frac{V_{,\phi\phi}}{V}\right) \ll 1$$: attractor solution

Primordial gravitational waves

GWs are tensor perturbations of the metric. Restricting ourselves to a flat FRW background (and disregarding scalar and vector modes)

$$\mathbf{ds^2=a^2(\tau)[-\,d\tau^2 + (\delta_{ij} + h_{ij}(\underline{x},\tau))\, dx^i\, dx^j]}$$

where h_{ij} are tensor modes which have the following properties

$h_{ij} = h_{ji}$ (symmetric)

$h^i_{\ i} = 0$ (traceless)

$h^i_{\ j|i}= 0$ (transverse)

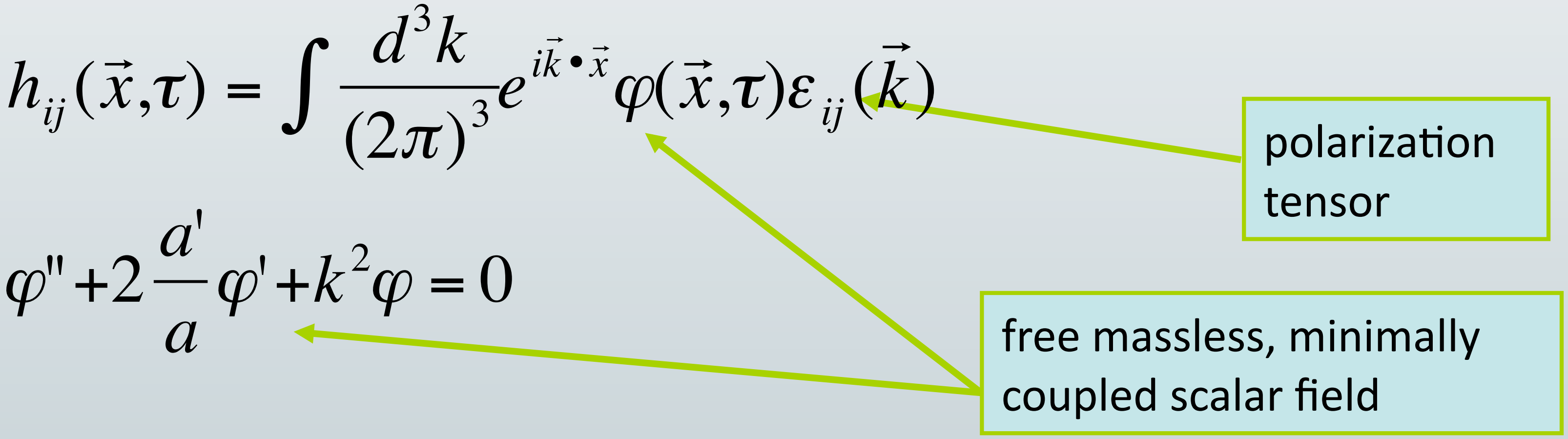
and satisfy the equation of motion

$$h''_{ij} + 2\frac{a'}{a}h'_{ij} - \nabla^2 h_{ij} = 0$$

$' = d/d\tau$

Primordial gravitational waves

GWs have only (9→6-1-3=) 2 independent degrees of freedom, corresponding to the 2 polarization states of the graviton



$$h_{ij}(\vec{x},\tau) = \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\bullet\vec{x}} \varphi(\vec{x},\tau)\varepsilon_{ij}(\vec{k})$$

$$\varphi'' + 2\frac{a'}{a}\varphi' + k^2\varphi = 0$$

polarization tensor

free massless, minimally coupled scalar field

behaviour:

k « aH (outside the horizon) **φ ≈ const + decaying mode**

k » aH (inside the horizon**)** **φ ≈ $e^{\pm ik\tau}$/a** gravitational wave; it freely streams, experiencing redshift and dilution, like a free photon)

Slow-roll parameters and observables

$$\epsilon = \frac{M_{\rm P}^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta = M_{\rm P}^2\left(\frac{V''}{V}\right)$$

$$\xi^2 = M_P^2 V' V''' / V^2$$

$$M_{\rm P} \equiv (8\pi G_{\rm N})^{-1/2}$$

scalar (comoving curvature) perturbation power-spectrum

$$\mathscr{P}_{\mathscr{R}}(k) = \frac{1}{2M_{\rm P}^2\epsilon}\left(\frac{H_*}{2\pi}\right)^2\left(\frac{k}{aH_*}\right)^{n_{\mathscr{R}}-1}$$

scalar spectral index

$$n_R - 1 = -6\varepsilon + 2\eta$$

"running"

$$dn_R / d\ln k = -2\xi + 16\varepsilon\eta - 24\varepsilon^2$$

tensor (gravity-wave) perturbation power-spectrum

$$\mathscr{P}_T(k) = \frac{k^3}{2\pi^2}\langle h_{ij}^* h^{ij}\rangle = \frac{8}{M_{\rm P}^2}\left(\frac{H_*}{2\pi}\right)^2\left(\frac{k}{aH_*}\right)^{n_T}$$

tensor-to-scalar ratio

$$r = \frac{\mathscr{P}_T}{\mathscr{P}_{\mathscr{R}}} = 16\epsilon$$

tensor spectral index

$$n_T = -2\epsilon$$

Observational predictions of inflation

- **Primordial density (scalar) perturbations**

$$\mathcal{P}_\zeta(k) = \underline{\frac{16}{9}\frac{V^2}{M_{\rm Pl}^4\dot{\phi}^2}}\left(\frac{k}{k_0}\right)^{n-1}$$

amplitude

spectral index: (or ``tilt'') $n-1 = 2\eta - 6\epsilon$

$$\epsilon = \frac{M_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \ll 1;\ \eta = \frac{M_{\rm Pl}^2}{8\pi}\left(\frac{V''}{V}\right) \ll 1$$

- **Primordial (tensor) gravitational waves**

$$\mathcal{P}_{\rm T}(k) = \frac{128}{3}\frac{V}{M_{\rm Pl}^4}\left(\frac{k}{k_0}\right)^{n_{\rm T}}$$

Tensor spectral index: $n_{\rm T} = -2\epsilon$

- **Tensor-to-scalar perturbation ratio**

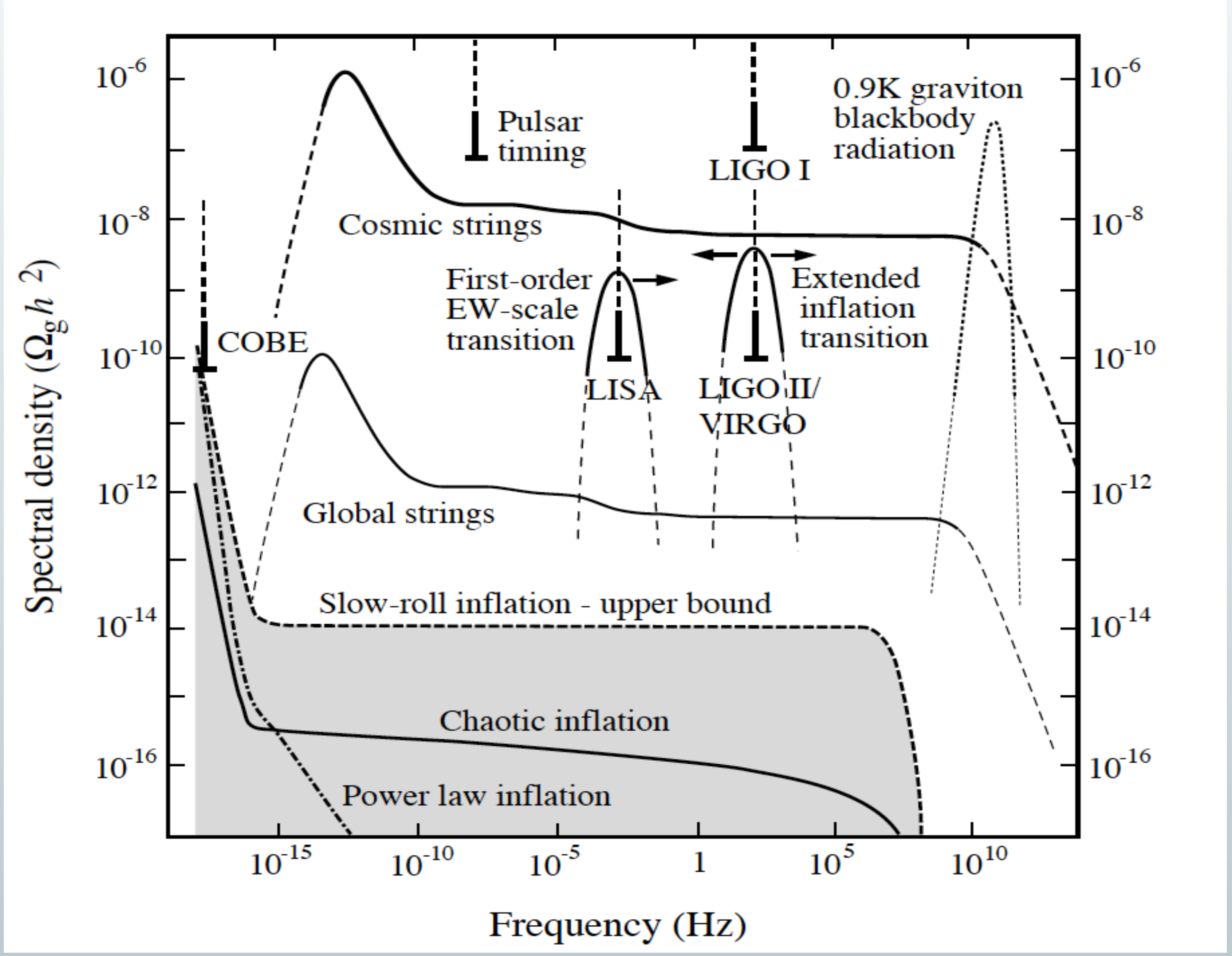
$$r = \frac{\mathcal{P}_{\rm T}}{\mathcal{P}_\zeta} = 16\epsilon$$

- **Consistency relation** (valid for *all* single field models of slow-roll inflation):

$$r = -8n_T$$

The search for primordial GW

Note: this is an “historical” plot, used for illustration purposes

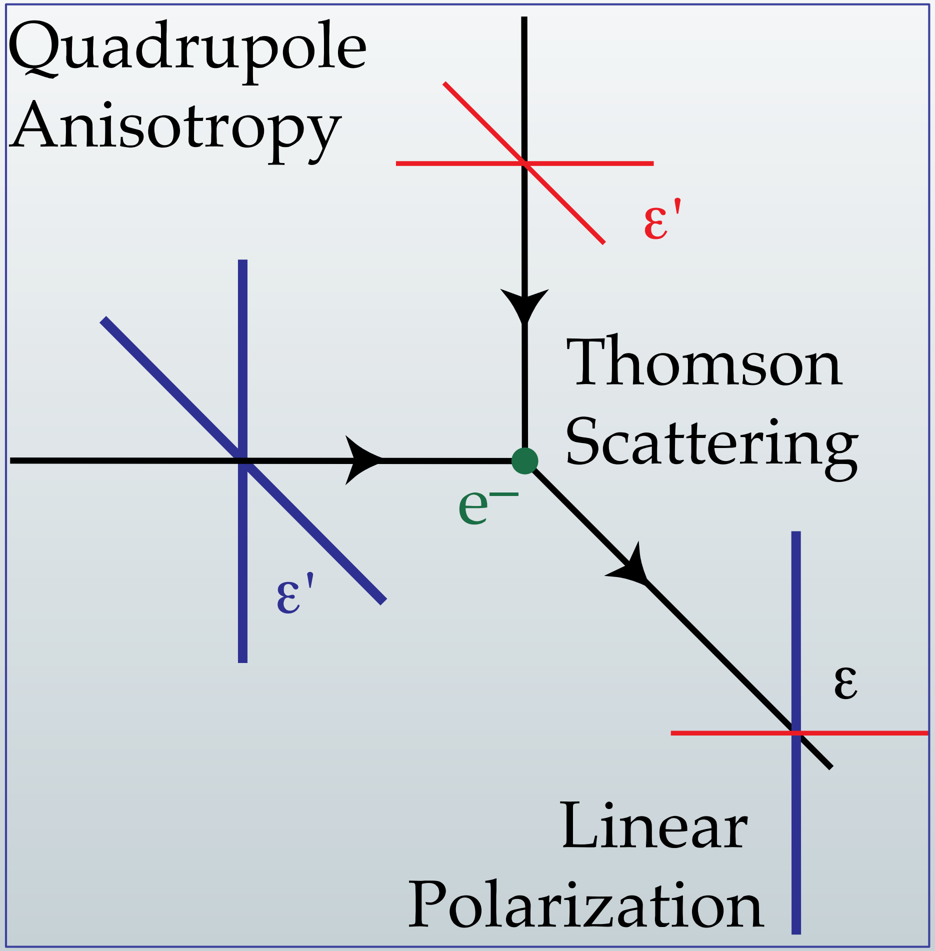


Battye & Shellard 1996

Search for primordial GW

- The primordial GW amplitude is maximal at horizon reentering → search for primordial GW background effects on CMB temperature anisotropy and polarization
- CMB temperature anisotropy mixes up scalar and tensor modes (hence indirect upper bound by e.g. *Planck*)
- Tensor modes (and vector modes too, if present) induce a specific polarization type ("B-mode") which can't be induced by scalar perturbations (which produce the "E-mode" only)
- However, a cosmological foreground B-mode is non-linearly induced by the conversion of E-modes into B-modes owing to gravitational lensing from LSS (***recently detected by SPT and POLARBEAR!***) → GWs detectable only if their amplitude is above a certain level ...

CMB polarization



$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} \left| \hat{\varepsilon}' \cdot \hat{\varepsilon} \right|$$

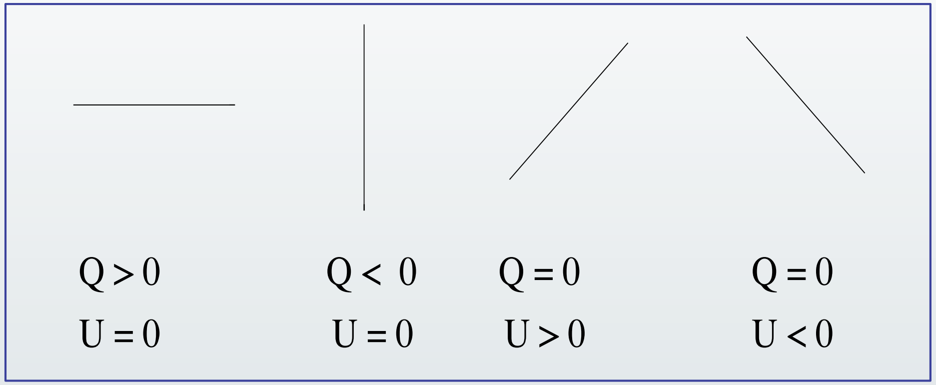
- Thomson scattering generates linear polarized radiation if the intensity of the incident radiation present a quadrupole moment

- An incident quadrupole can arise from

  1. Anisotropies in the density of photons surrounding the electron (scalar perturbations)
  2. **A quadrupolar stretching of space due to a passing gravitational wave**

Assume we observed polarization in the CMB. Can we tell whether the source is a scalar or a tensor?

Stokes Q, U parameters

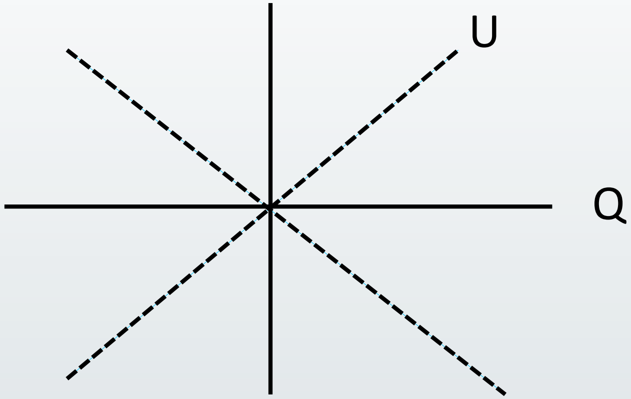


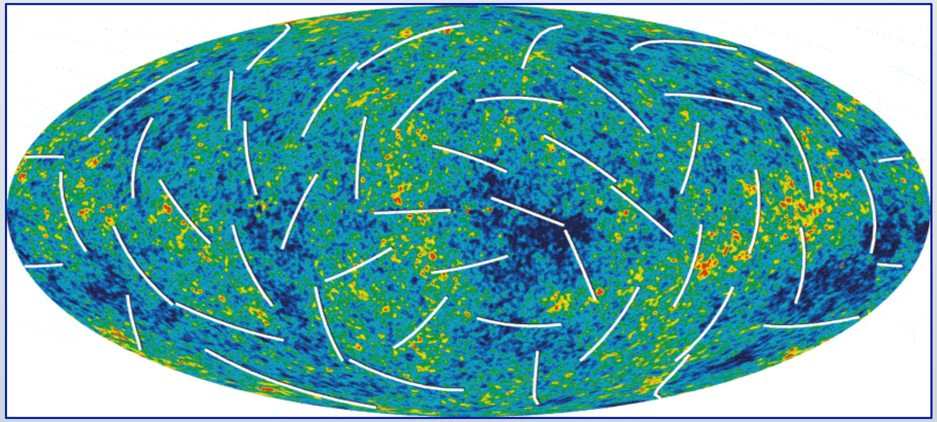
$Q > 0$, $U = 0$

$Q < 0$, $U = 0$

$Q = 0$, $U > 0$

$Q = 0$, $U < 0$





You can think of describing polarization using a “headless vector” P with:

$$|P| = \sqrt{Q^2 + U^2} \longrightarrow \text{Intensity}$$

$$\alpha = \frac{1}{2}\arctan\frac{U}{Q} \longrightarrow \text{Orientation with respect to x-axis}$$

E, B polarization modes

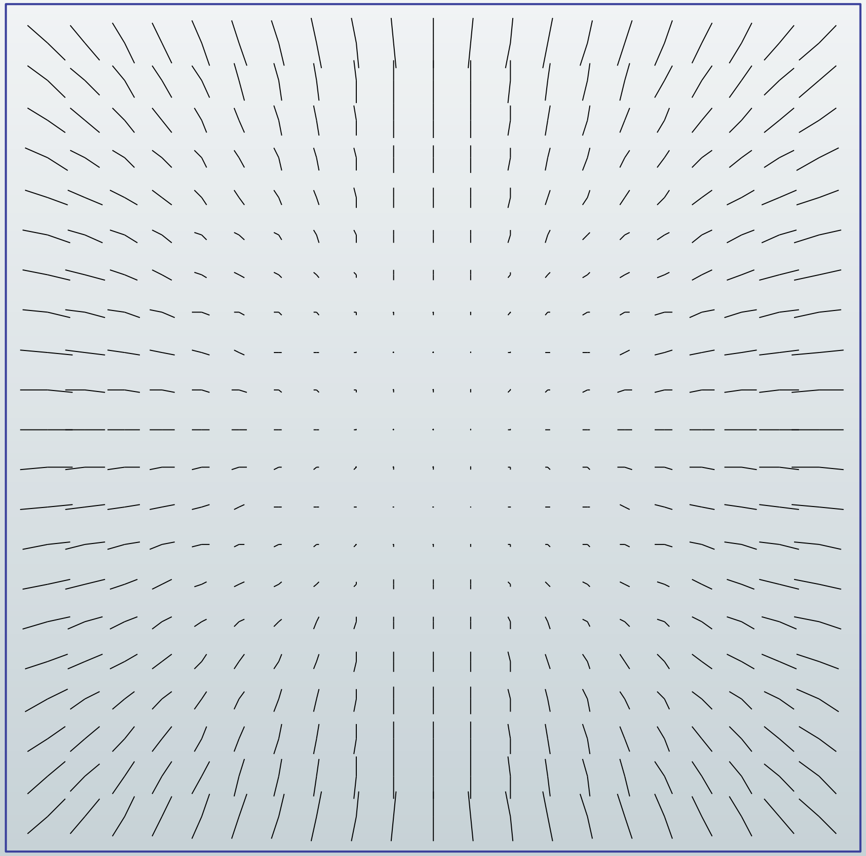
- A vector can always be decomposed into a curl-free (electric) and a divergenceless (magnetic) component.

$$\vec{v} = \vec{\nabla}\phi + \vec{\nabla} \times \vec{A}$$

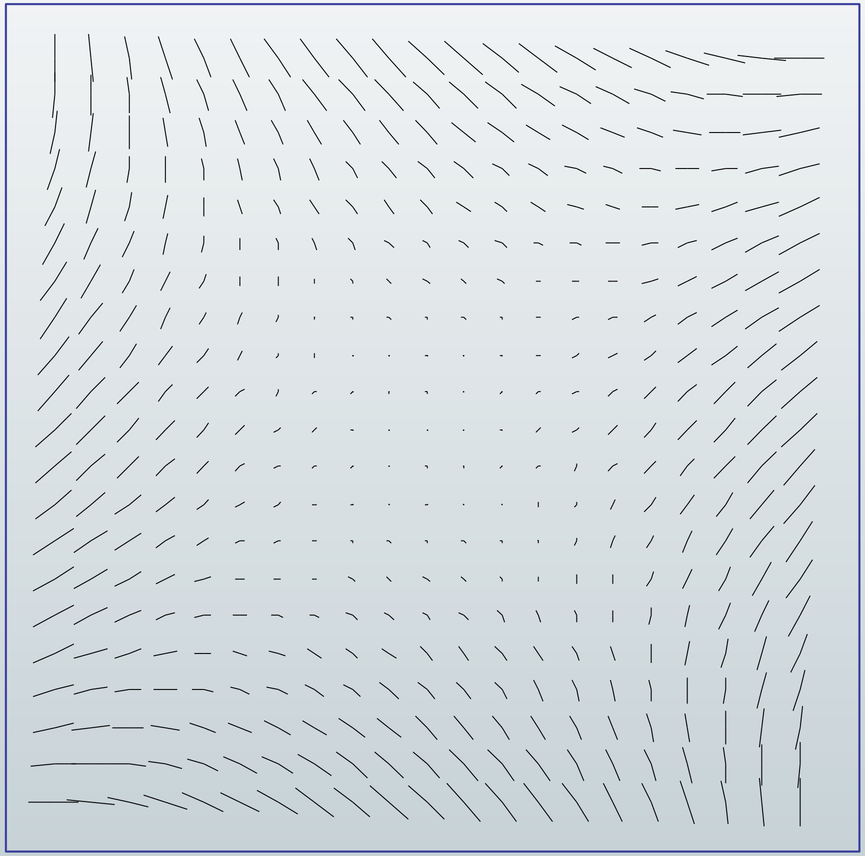
- P=(Q,U) does not transform as vector but as a trace-free symmetric 2x2 tensor. A decomposition similar to the vector case still exists but it involves *second* (covariant) derivatives of two scalar fields called the E and B mode, in analogy with the vector case

- The usefulness of the E-B decomposition of CMB polarization will be clear shortly. as an anticipation: **scalar (Density) perturbations can generate only an E-mode, while tensor (GW) perturbations source both E and B modes.**

E vs. B-mode polarization patterns



Pure E pattern



Pure B pattern

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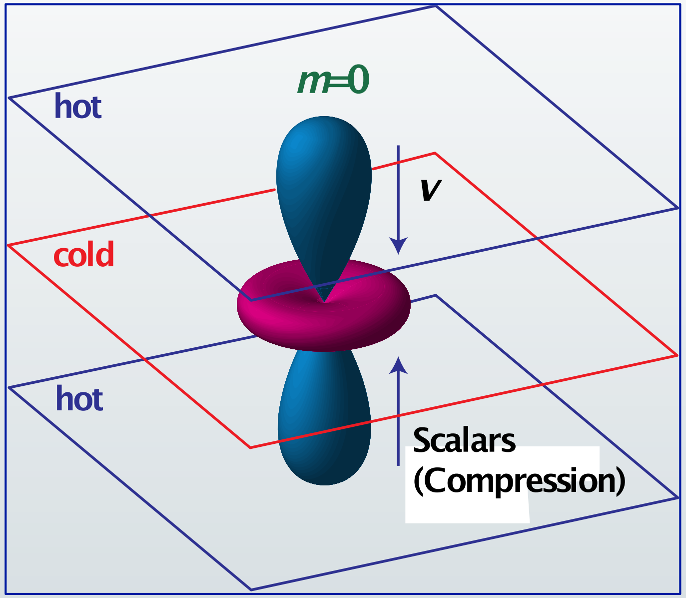
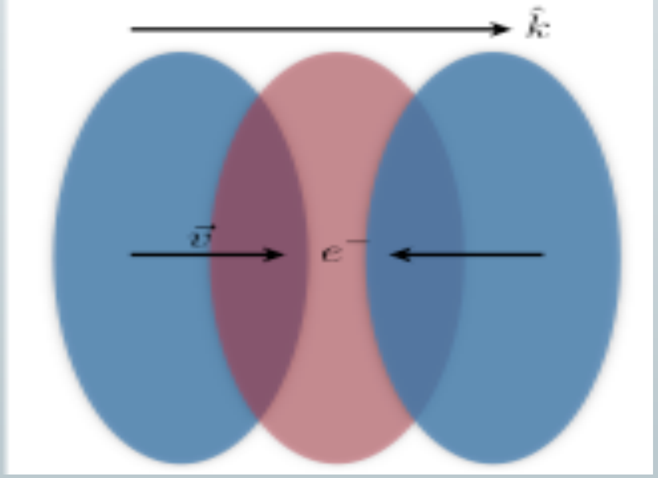
CMB polarization from scalar perturbations



Hu and White 1997

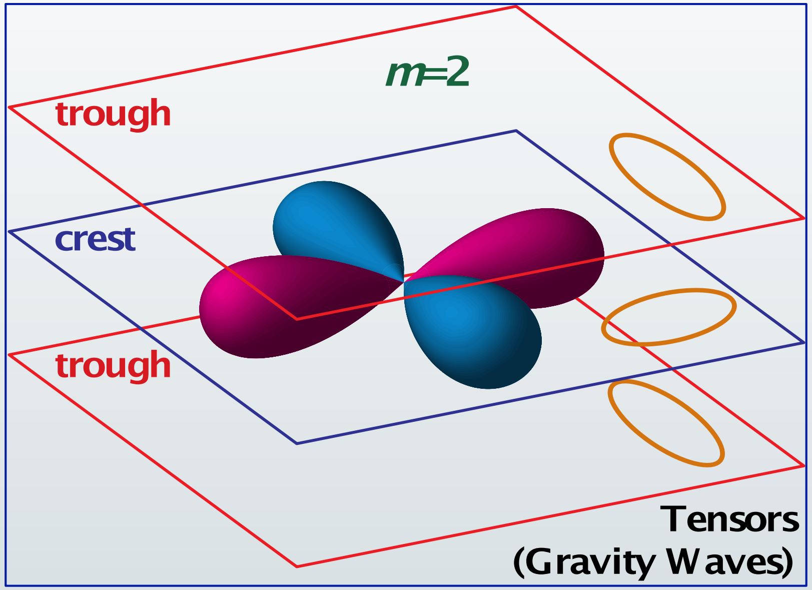
- Consider a plane wave density perturbation
- Before recombination, photons flow from underdense (CMB hot spots) to overdense (CMB cold spots) regions
- An electron sitting in the middle of e.g. an overdense region sees a larger incident radiation intensity in the direction of the flow, and lower intensity from the plane orthogonal to the flow



A net vertical polarization is generated for the photon scattered out of the screen. Rotating k in the plane of the screen does not change the polarization state

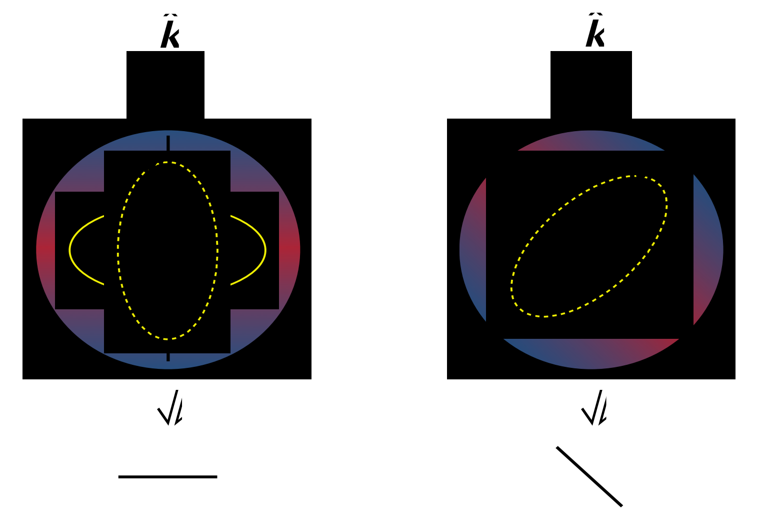
$\vec{v} \,||\, \vec{k} \Rightarrow$ **curl-free polarization (pure E-mode)**

CMB polarization from tensor perturbations



Hu and White 1997

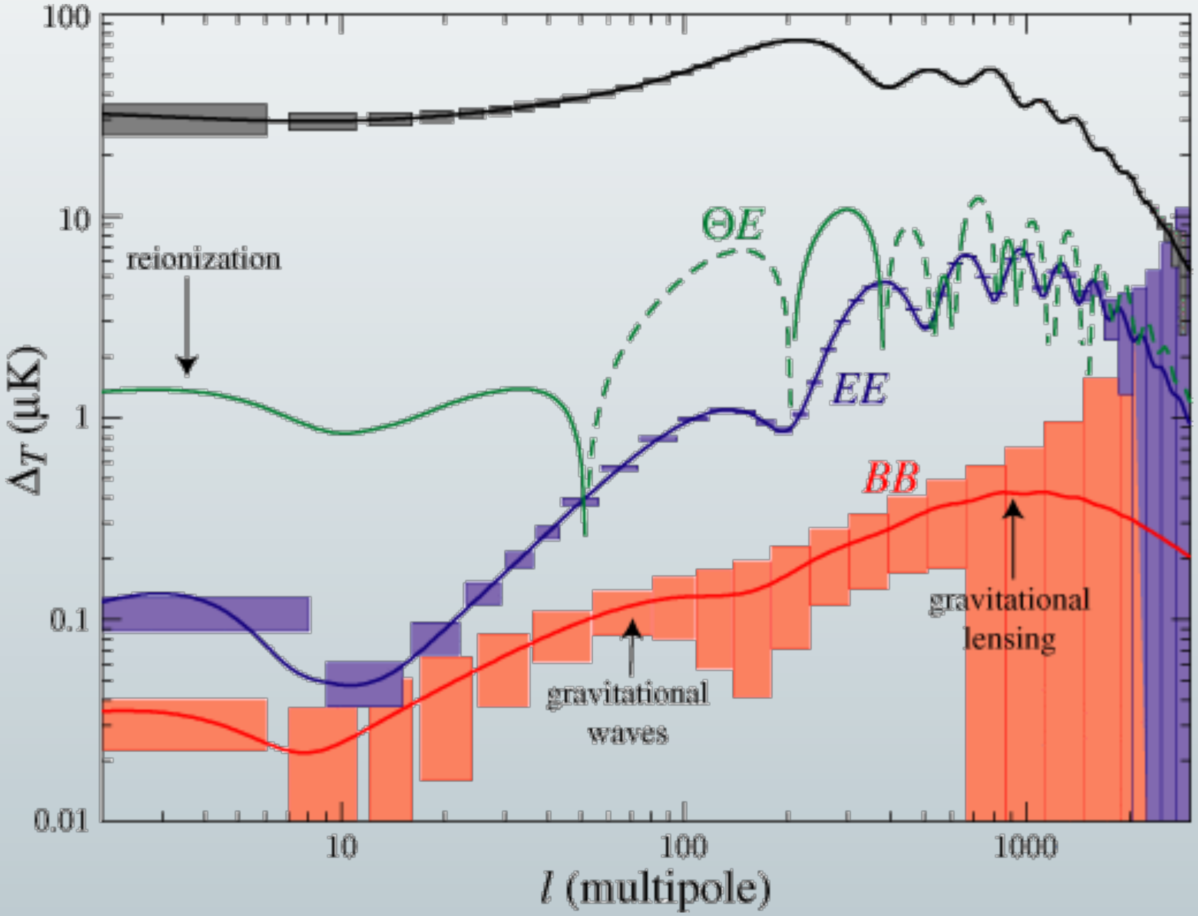
- GW stretch a circular ring of test particles into an ellipse like in figure
- The lobes are no longer aligned with the velocity flows
- That allows to generate a curl polarization pattern.
- **GW generate both E and B modes!**



Rotation about the direction of GW propagation also rotates the polarization direction, contrary to the scalar case

Power spectra

T, E, B are Gaussian scalar fields on the sphere. They are entirely defined by their **angular power spectrum**.



ℓ defines the wave angular frequency, corresponding to an angular scale $\vartheta \sim \frac{\pi}{\ell}$

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BICEP2: the instrument

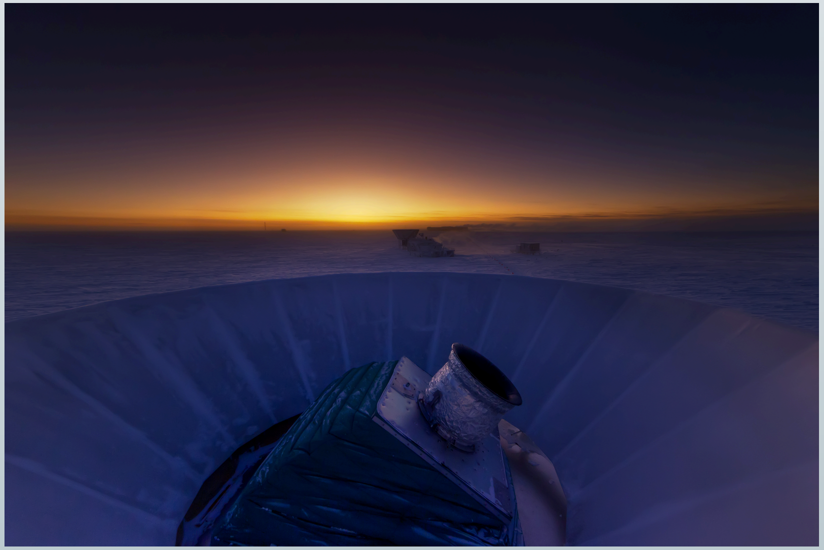
- BICEP2 is the second in a series of experiments at the South Pole (BICEP1, BICEP2, Keck Array, BICEP3), aimed at mapping a small region of the sky with high-sensitivity bolometers, in search for CMB polarization B-modes.

- It features 512 Transition-Edge-Sensor (TES) polarization-sensitive antenna-coupled bolometers, in the focal plane of a 26 cm diameter refractor. The telescope optics are cooled at 4K, while the focal plane is cooled at 250 mK.

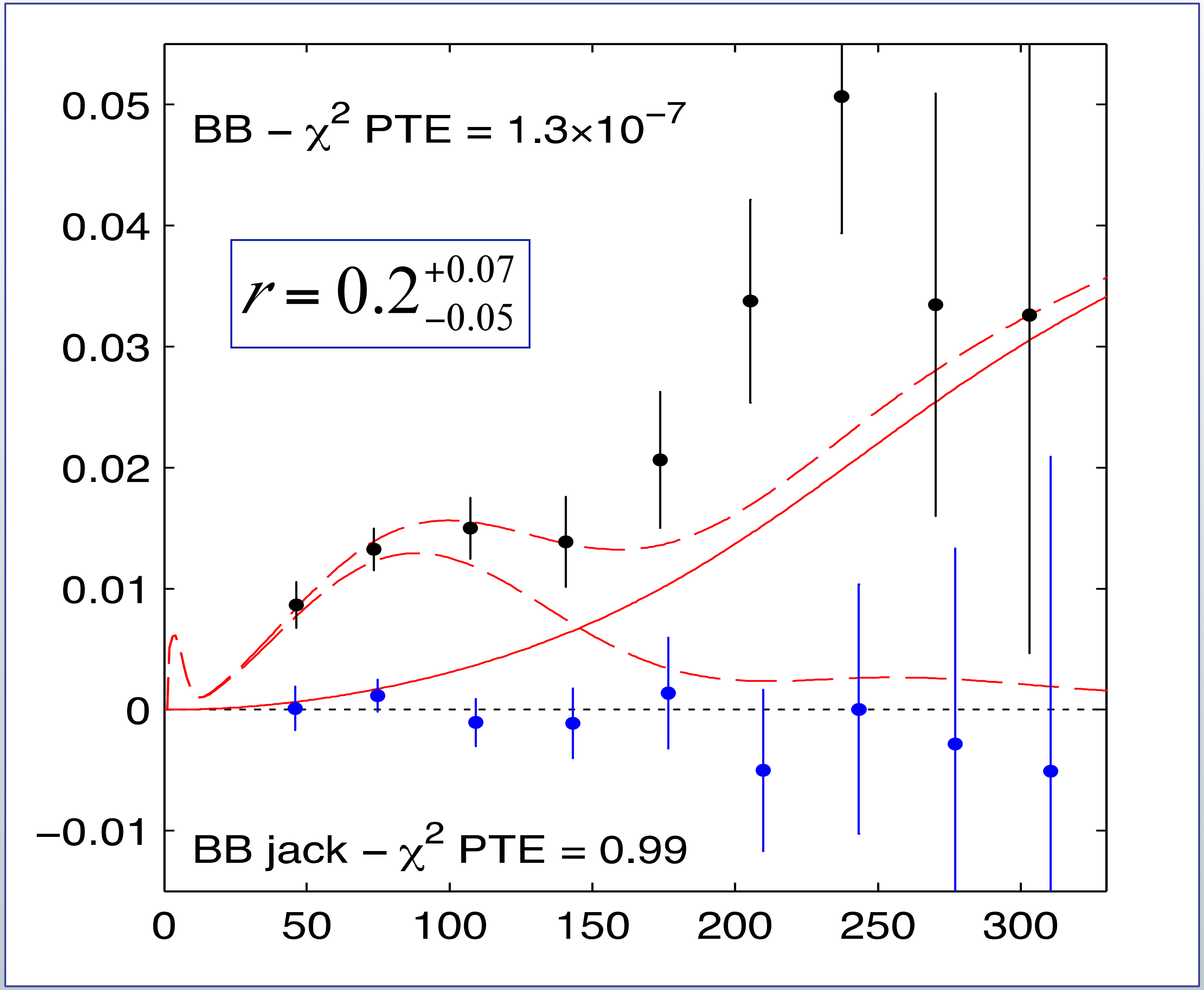
- All receivers observe at 150 Ghz (maximum CMB emission, small integrated foreground and atmospheric emission).

- The targeted region for observations was a $\sim$800 degree^2 patch of the sky at high galactic latitudes (chosen for its very low contamination from galactic dust emission)

- 17000 scansets of data were accumulated in a 3 years observational campaign (2010-2012)

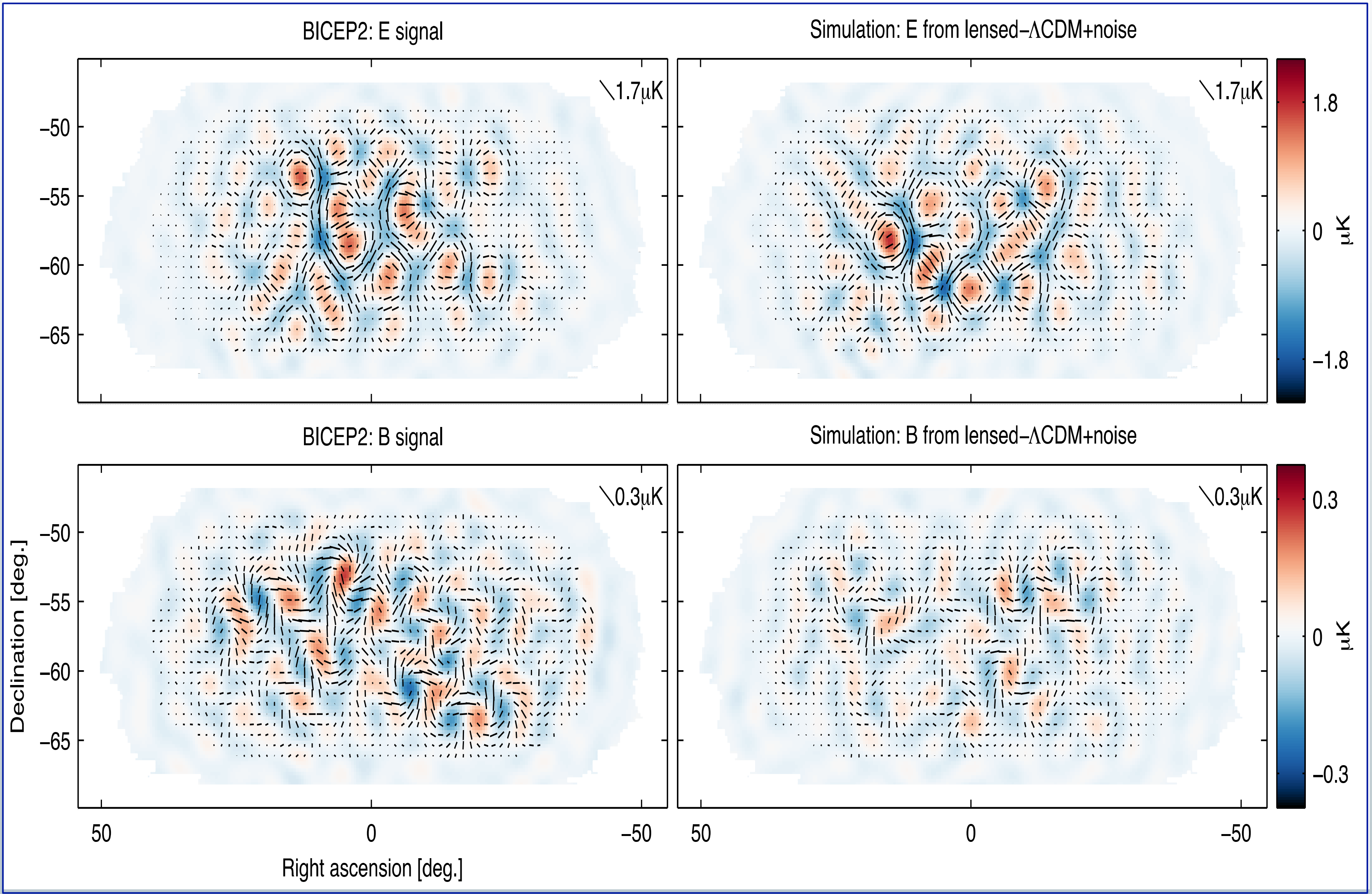


BICEP2 results: BB power spectrum



r=0 excluded at the 5.9 σ level

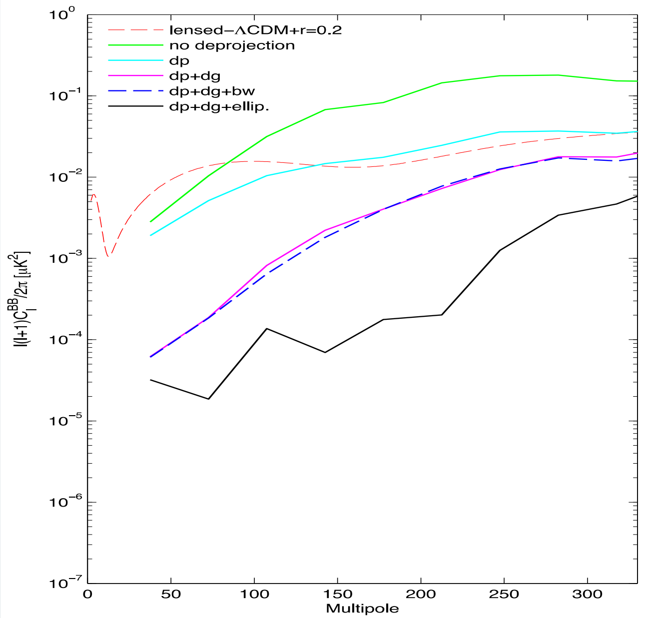
E and B maps

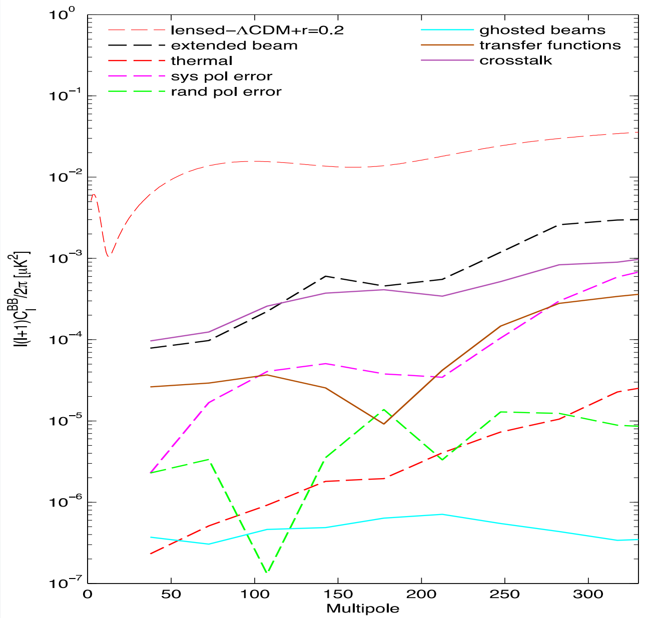

BICEP2: E signal
Simulation: E from lensed–ΛCDM+noise
BICEP2: B signal
Simulation: B from lensed–ΛCDM+noise
1.7μK
1.7μK
0.3μK
0.3μK
1.8
0
−1.8
0.3
0
−0.3
μK
μK
−50
−55
−60
−65
Declination [deg.]
50
0
−50
Right ascension [deg.]

Systematic uncertainties

Many potential sources of sytematics can cause leakage of temperature into polarization: differential pointing, diff. beam ellipticity and width, detector transfer function mismactch, detector cross-talk etc

1. The level of systematic contamination was strongly reduced by building and deprojecting templates of the spurious polarization (using *Planck* 143 Ghz T data) from various effect
2. The amplitude of known residual systematics has been assessed through simulations
3. Potential unknown systematic effects have been addressed through internal consistency tests (jackknife)

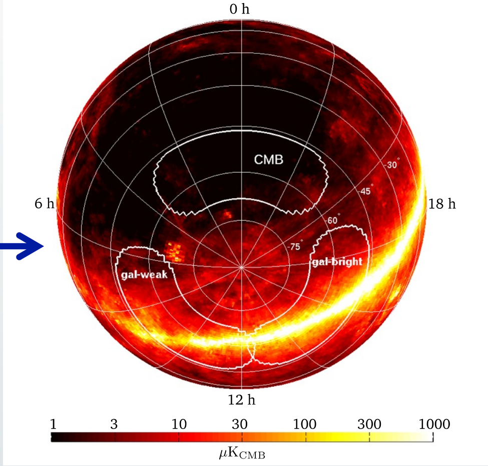


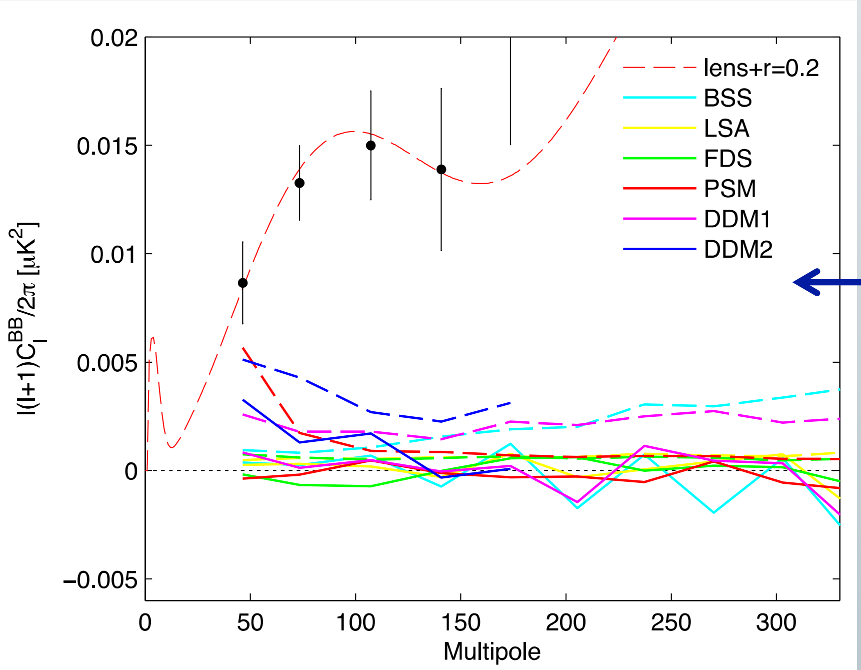


Results seem robust to residual systematic contamination

Foregrounds

- Synchrotron and dust emission from the galaxy contaminates B-mode measurements. External templates are necessary to separate foregrounds in a single frequency analysis like this one
- The observed region of the sky was selected to minimize foreground emission (especially dust)
- Synchrotron contamination is very low at these frequencies, as also verified by scaling WMAP polarized synchrotron template to 150 Ghz

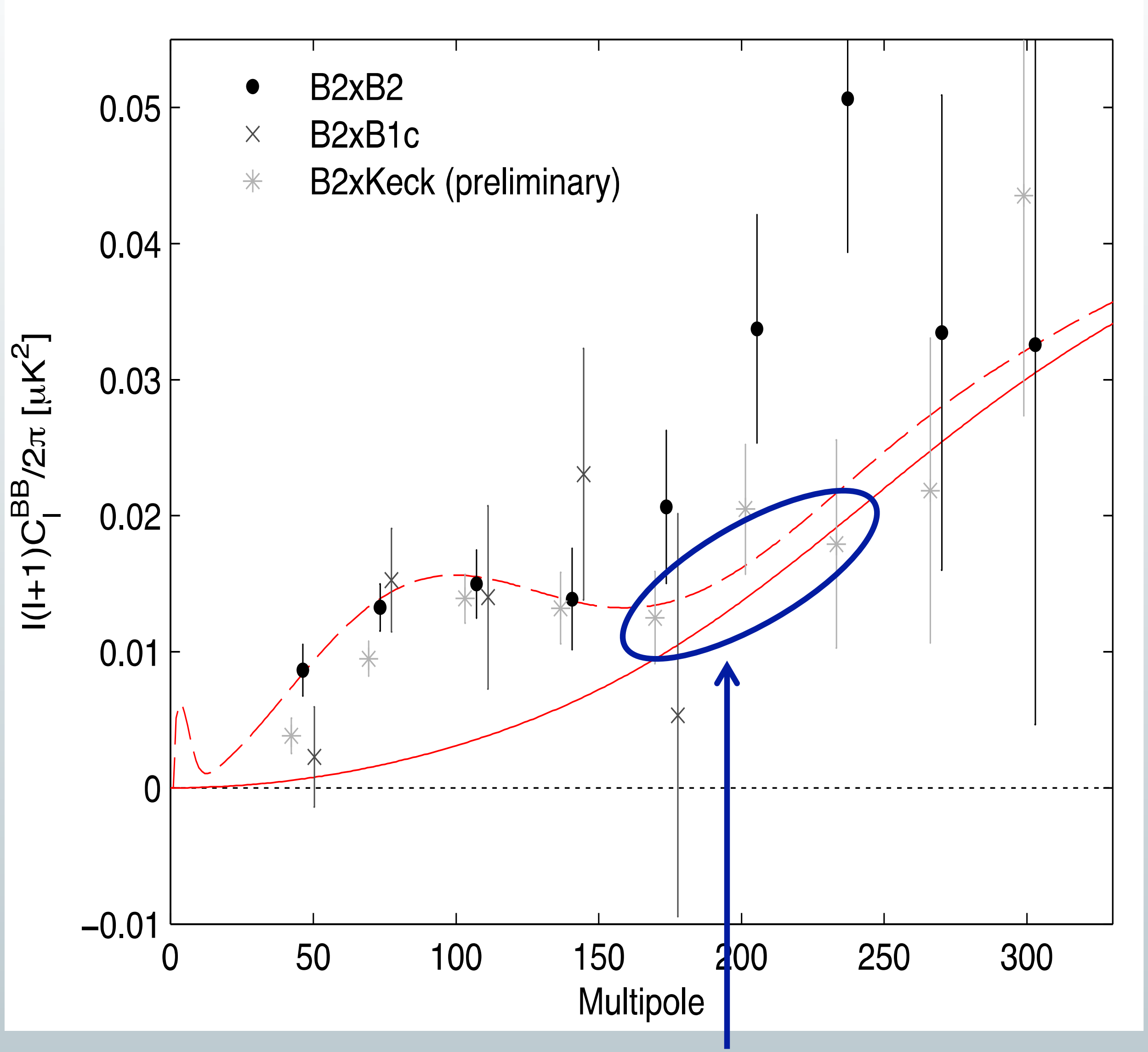




- B-mode dust polarized template unavailable (expected by *Planck*)
- Several dust emission models were fitted to and cross-correlated with the data, showing very low contamination
- Foreground subtraction using the DDM2 model (353 Ghz *Planck*-based) yields

$$\boxed{r = 0.16^{+0.06}_{-0.05}}$$

Bicep2 x Keck



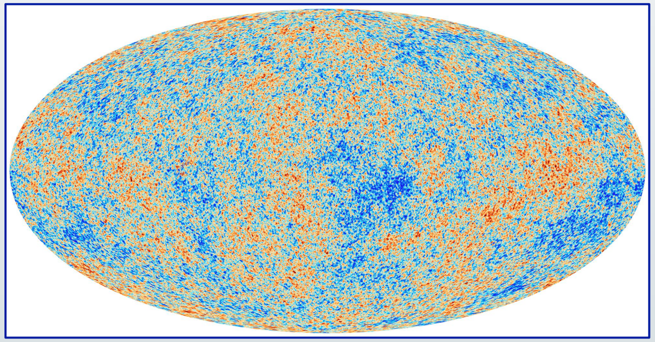
No more outliers!

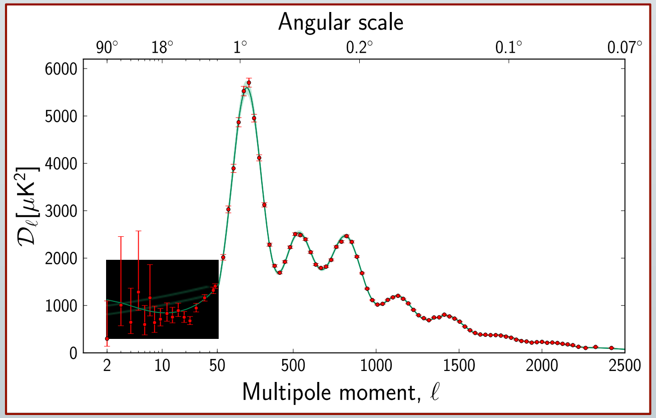
Comparison with *Planck*

Tensor perturbations provide a contribution to the TT power spectrum. *Planck* could use this to set a constraint on r (in good agreement, and improving on previous WMAP constraint).

$r = 0.2^{+0.07}_{-0.05}$ BICEP2 (BB)

$r < 0.11 \ (95\% \ c.l.)$ *Planck* (TT)





- There is some tension between the two measurements. It can be alleviated allowing a running of the scalar spectral index. However the required level of running is not easy to realize in an inflationary context.

- Note however that dust subraction already brings r from BICEP2 down to r=0.16. The preliminary plot from Keck array also shows that high-l outliers disappear. That might bring r down further

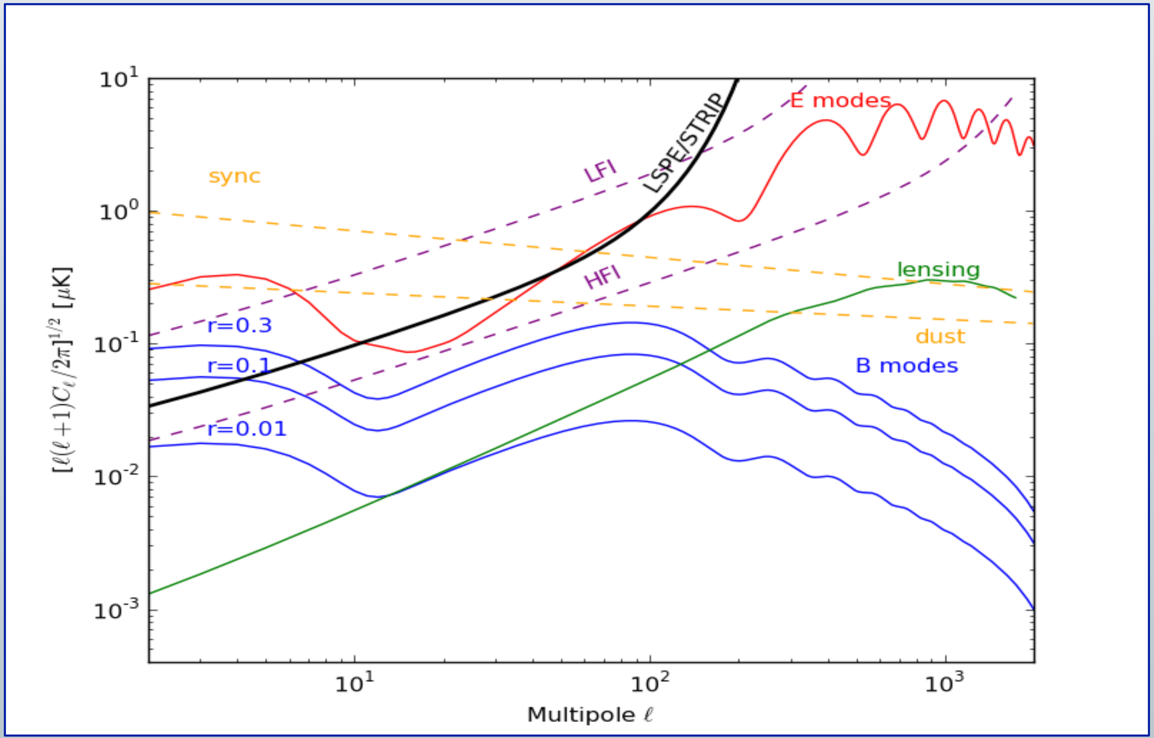
Future prospects

- **The primordial B-mode detection by BICEP2 looks robust**

- Additional and more accurate measurements from the ground will come from Keck array and BICEP3. Preliminary Keck analysis in BICEP2 paper looks good.

- Planck can play a crucial role in confirming the discovery:

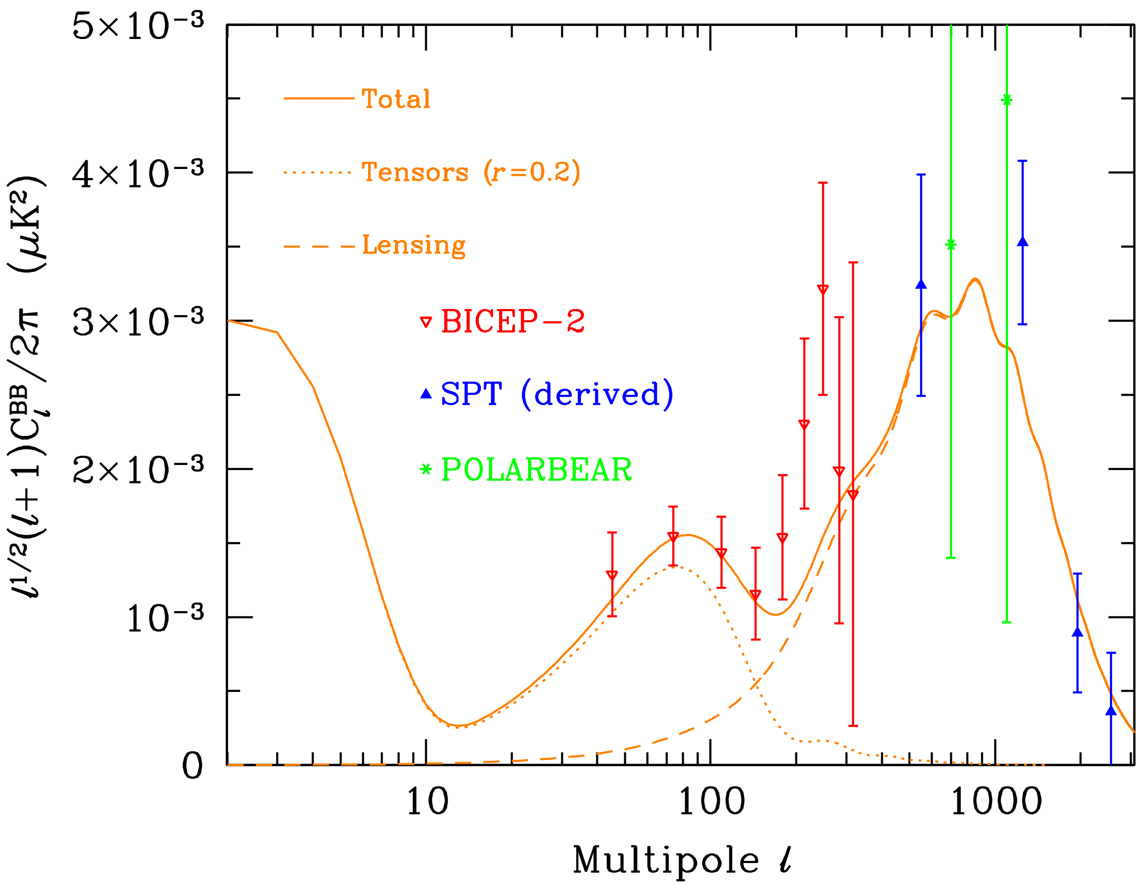
  1. *Full sky* measurements => low-l reionization BB spectrum bump is accessible
  2. *Multi-frequency* measurements. Accurate characterization of B-mode dust emission



- **Caveat: foregrounds are now a much more complicated issue:** Fortunately the detected B-mode signal is large. Previous forecasts and shows that *Planck* can detect r > 0.05, with foregrounds being a less limiting factor at r > 0.1 . But several assumptions were made there…

Early days still, but the results seem robust, the prospects exciting, and the consequences of this result for Cosmology and Fundamental Physics are **huge**

Bicep 2 vs. other observations



Observational predictions

- **Primordial density (scalar) perturbations**

$$\mathcal{P}_\zeta(k) = \underline{\frac{16}{9}\frac{V^2}{M_{\rm Pl}^4\dot{\phi}^2}}\left(\frac{k}{k_0}\right)^{\boxed{n-1}}$$

amplitude

spectral index: $n - 1 = 2\eta - 6\epsilon$
(or ``tilt'')

$$\epsilon = \frac{M_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \ll 1; \ \eta = \frac{M_{\rm Pl}^2}{8\pi}\left(\frac{V''}{V}\right) \ll 1$$

- **Primordial (tensor) gravitational waves**

$$\mathcal{P}_{\rm T}(k) = \frac{128}{3}\frac{V}{M_{\rm Pl}^4}\left(\frac{k}{k_0}\right)^{n_{\rm T}}$$

Tensor spectral index: $n_{\rm T} = -2\epsilon$

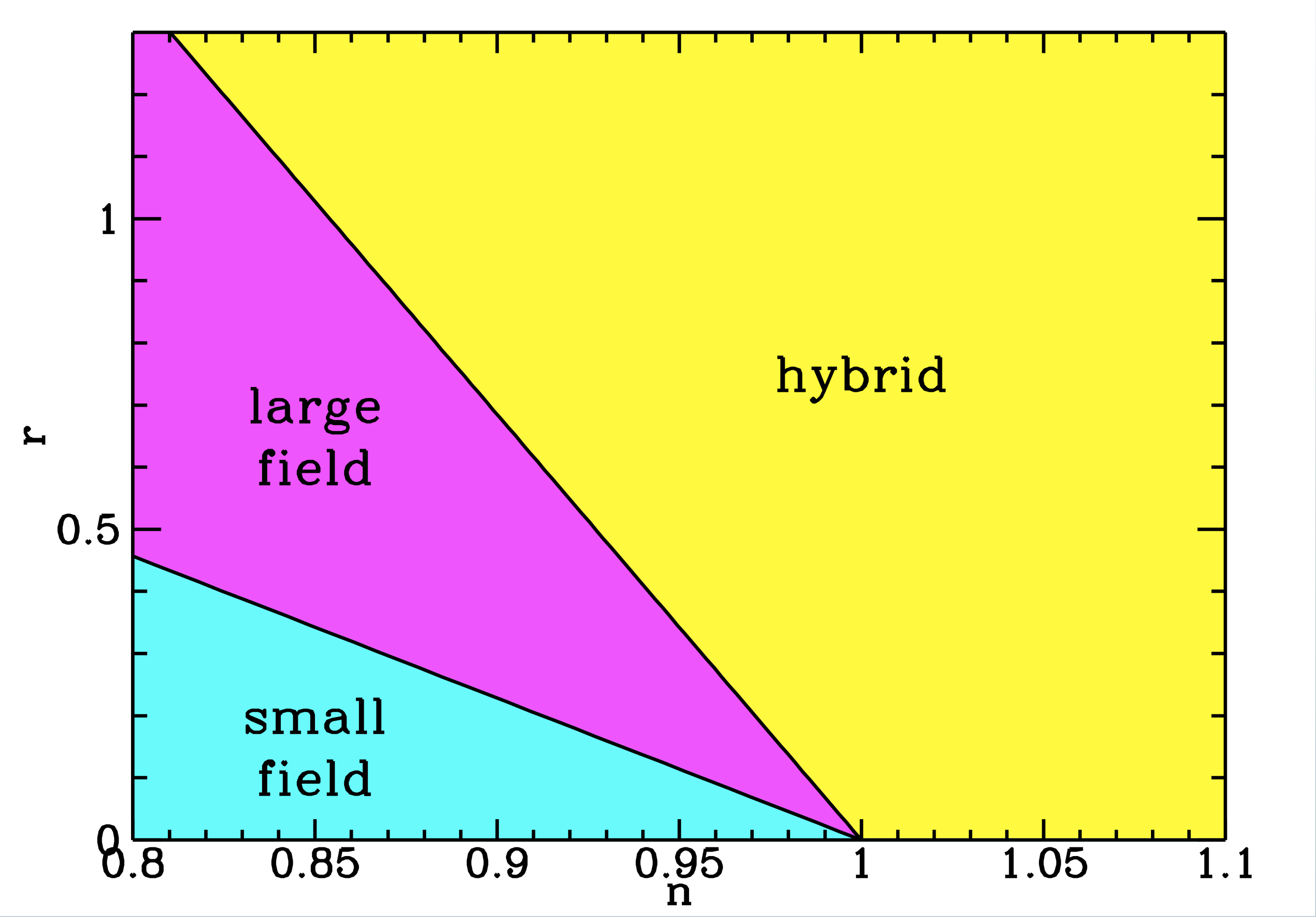
- **Tensor-to-scalar perturbation ratio**

$$r = \frac{\mathcal{P}_{\rm T}}{\mathcal{P}_\zeta} = 16\epsilon$$

- **Consistency relation** (valid for *all* single field models of slow-roll inflation):

$$r = -8n_T$$

Classifying inflationary models



See,e.g., Kinney et al.
astro-ph/0007375

Two simple but very important examples

``Large field'' models

$$V(\phi) \propto \phi^{\alpha}$$

typical of ``caothic inflation scenario''
(Linde `83)

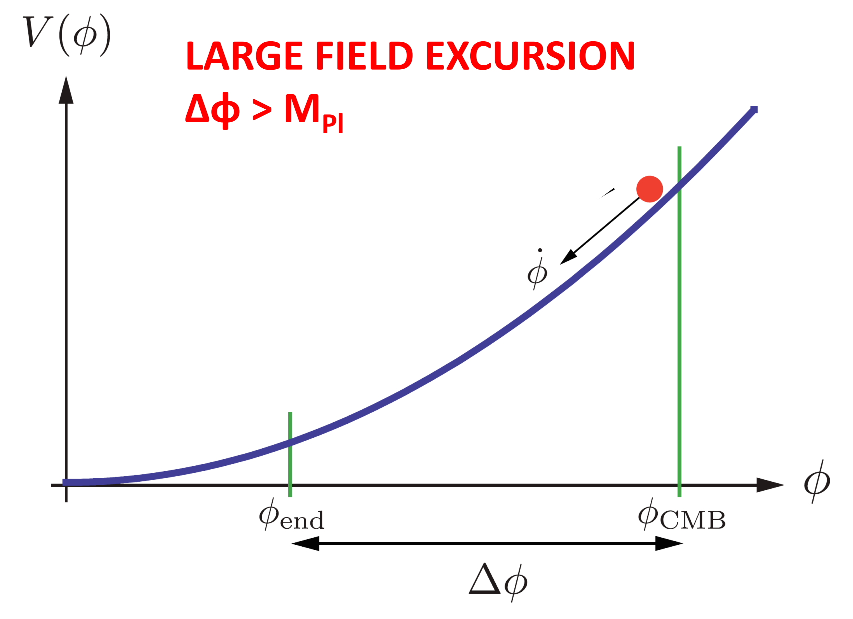
$$V(\phi) \propto \exp[\phi/\mu]$$

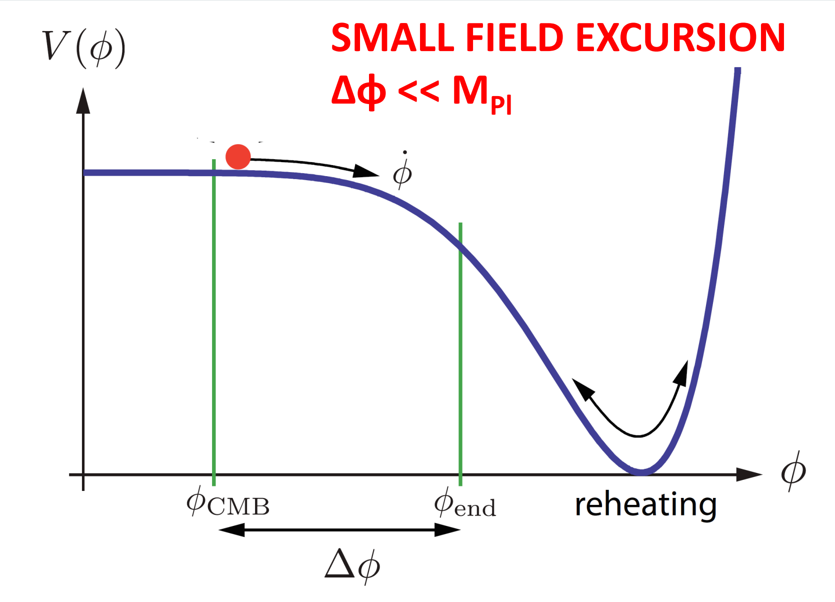
``power law inflation'' (Lucchin, Matarrese'85)

``Small field'' models

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{\mu}\right)^{p}\right] \qquad \phi < \mu < M_{\rm Pl}$$

from spontaneous symmetry breaking or Goldstone, axion models (Linde; Albrecht, Steinhardt `82; Freese et al '90)





Inflaton dynamics and the level of gravity waves

"Large field" models can produce a high level of gravity waves (r>0.01)

"Small field" models produce a low level of gravity waves (r<0.01)

$$\boxed{\frac{\Delta\phi}{m_{\rm Pl}} \simeq \left(\frac{N}{30}\right) \times \left(\frac{r}{0.01}\right)^{1/2}}$$

30 ≤ N ≤ 60.

So the bigger the field excursion during inflation the bigger the amplitude of gravity waves

Planck constraints on inflation

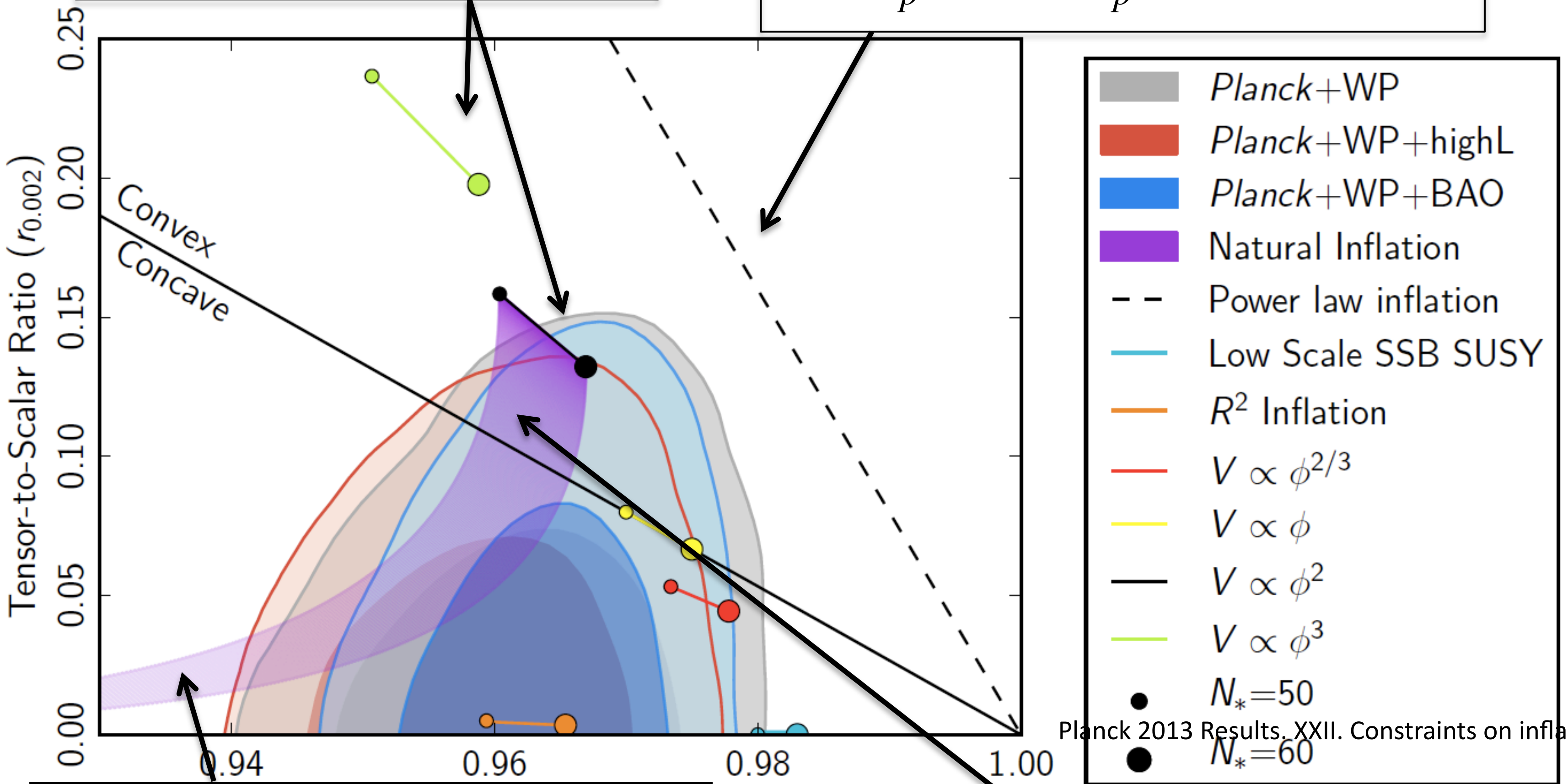
Large field models $V(\phi) \propto \phi^{\alpha}$

$$r = \frac{4\alpha}{N} \qquad 1 - n = \frac{\alpha + 2}{2N}$$

Exponential models

$$V(\phi) \propto \exp[-\sqrt{2/p}\ \phi / M_{Pl}] \rightarrow a(t) \propto t^{p}$$

$$r = \frac{16}{p} \qquad 1 - n = \frac{2}{p}$$



Planck 2013 Results. XXII. Constraints on inflation

Small field models $V(\phi) \propto 1 - (\phi/\mu)^p, p \geq 3$

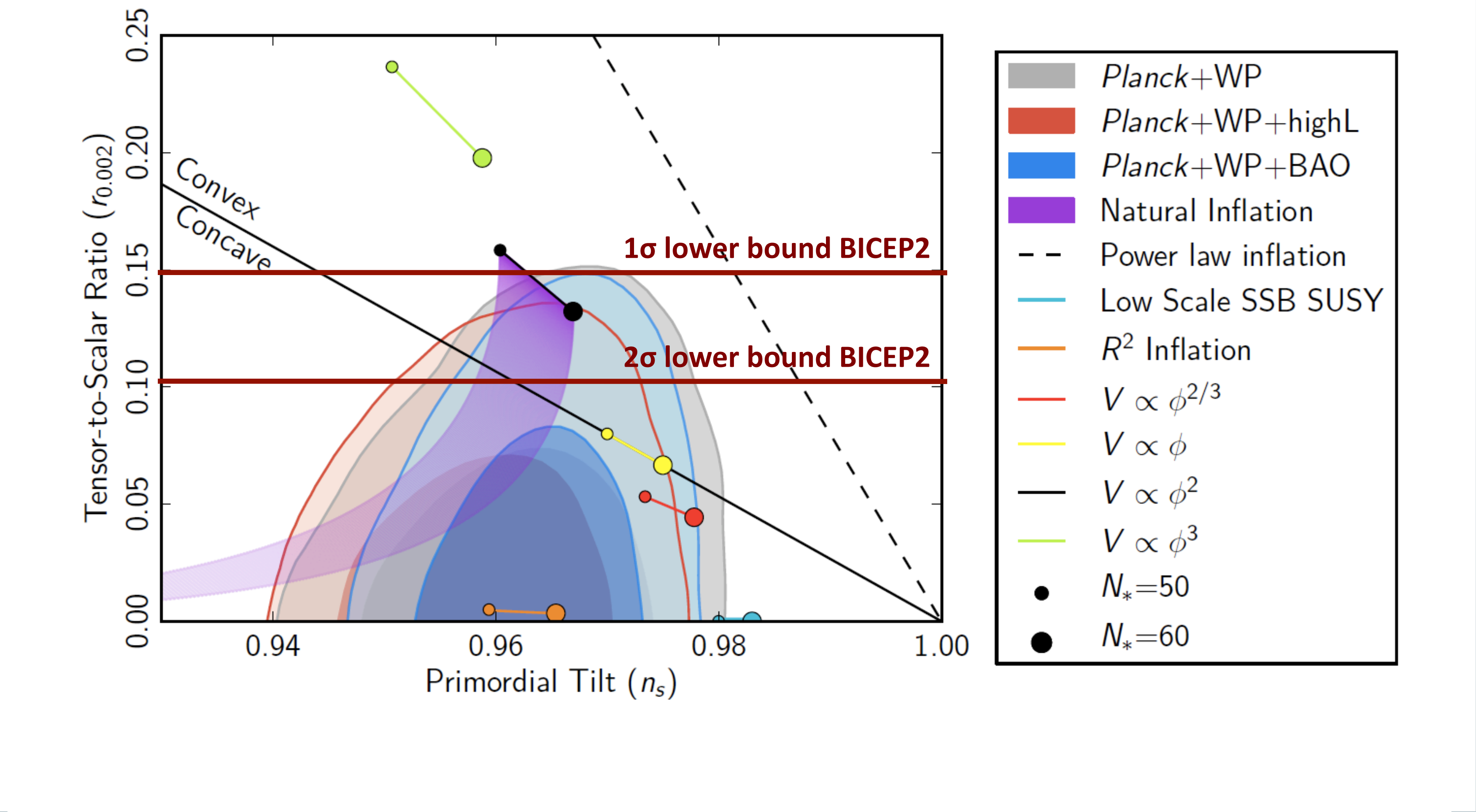
$$r \sim 0 \quad 1 - n = \frac{2}{N}\frac{(p-1)}{(p-2)}$$

for example p = 3 out of 95% *CL*

Natural inflation $V(\phi) \propto 1 + \cos(\phi / f)$

consistent for $f \geq 5 M_{Pl}$

After BICEP2..................



Consequences for high energy physics

- Inflation is probing the GUT scale!
  Tremendously high-energy scales never achievable in laboratories

$$V^{1/4} = 1.94 \times 10^{16} \left(\frac{r}{0.12}\right)^{1/4} \mathrm{GeV}$$

- Inflation is providing a clear evidence of physics beyond the Standard Model of particle physics

- Who is the inflaton??
  Now this question is becoming more and more pressing
  (most probably it is not the Higgs field).

Consequences for inflationary models

BICEP2 *strongly* reduces the number of inflationary models that agree with data

- ✓ **Low-energy scale inflation models are strongly RULED OUT**
- ✓ Higgs-inflation (Bezrukov & Shaponiskov 2008) tries to identify the Higgs of the SM with the inflaton (needs non-minimal coupling with gravity)

  Prediction: $r \approx 0.0034$: **RULED OUT**

- ✓ R^2 inflation (Starobinsky '80):

  Prediction: $r \approx 0.0034$: **RULED OUT**

- ✓ ... and many more!

Consequences for inflationary models

- ***A simple quadratic potential*** $V(\phi) = \frac{m^2}{2}\phi^2$ ***(Linde '82) perfectly sits within 1σ-regions.***

- ``Natural'' inflation (Freese et al. 90):
  flat potential arises naturally as result of a shift symmetry

$$V(\phi) = V_0 \left[1 - \cos\left(\frac{\phi}{\mu}\right)\right]$$

consistent with the data.

Sensitivity of Inflation to fundamental physics?

An example.
The question is:
is the excursion of the field $\Delta\varphi > M_{PL}$ a problem for inflation models?

No. Rather, it is an opportunity to probe high-energy physics and the physics behind inflation.

Sensitivity of Inflation to fundamental physics?

✧ Case A: no shift symmetry; just $\phi \rightarrow -\phi$

Cutoff $\Lambda \sim M_{Pl}$

$$\mathcal{L}_{\rm eff}(\phi) = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}\lambda\phi^4 - \sum_{p=1}^{\infty}\left[\lambda_p\phi^4 + \nu_p(\partial\phi)^2\right]\left(\frac{g\,\phi}{\Lambda}\right)^{2p} + \dots$$

the general expectations is λ_p and ν_p~1, and the inflaton potential can get important correction for inflaton field excursion ~M_{Pl} → need ***$\Delta\phi << M_{Pl}$: small field models of inflation***

✧ Case B: approximate shift symmetry $\phi \rightarrow \phi + \text{const}$

Flatness of the inflaton potential is guaranteed because the ***symmetry of the UV theory*** forbids coefficients λ_p and ν_p~1.

Example: $V(\phi)=\mu^{4-p}\,\phi^p$,
with $\mu << M_{Pl}$ from scalar power spectrum

Such Lagrangians support large field models of inflation ($\Delta\phi >> M_{Pl}$)

Interpreting the energy scale ...

- “The inflationary energy density ($\rho^{1/4} = 1.5 \times 10^{16}$ GeV) is the same as the GUT scale M_G . That ust be a coincidence, though, because M_G represebts the vev of tge GUT Higgs fields and not teh height of their potential. The height of their potential will be some coupling constant $\lambda << 1$ times M_G^4. The energy scale of GUT inflation models which generate the inflationary energy density from the GUT Higgs fields, is therefore too low to generate the observed r.”

D. Lyth, 28/04/2014

The future: a new era of gravity-wave based cosmology!

- Measure the tensor spectral index

$$\mathcal{P}_{\rm T}(k) = \frac{128}{3}\frac{V}{M_{\rm Pl}^4}\left(\frac{k}{k_0}\right)^{n_{\rm T}}$$

Tensor spectral index: $n_{\rm T} = -2\epsilon$

- Test the consistency relation (``the holy grail of inflation''):

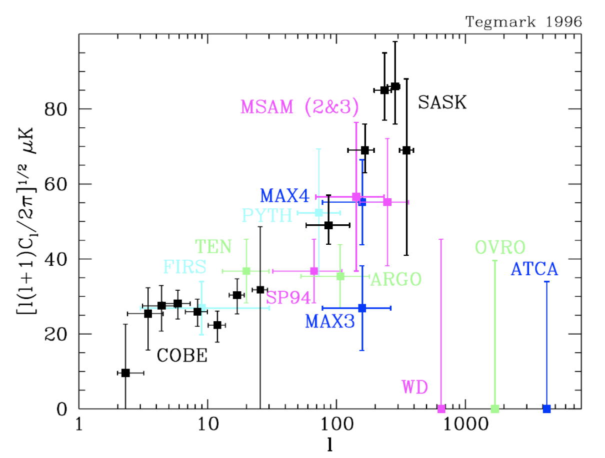
$$r = -8n_T$$

- Try to measure higher-order correlators of the tensor perturbations, like the 3-point function of tensors <hhh> → graviton interactions

- Try to constrain deviation from GR at very high-energies.

The future: a new era of gravity-wave based cosmology!

Temperature CMB anisotropies: from the early 90s till the present



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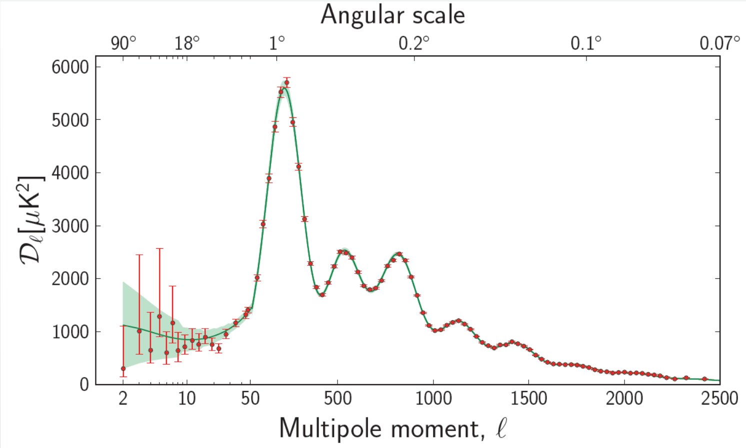
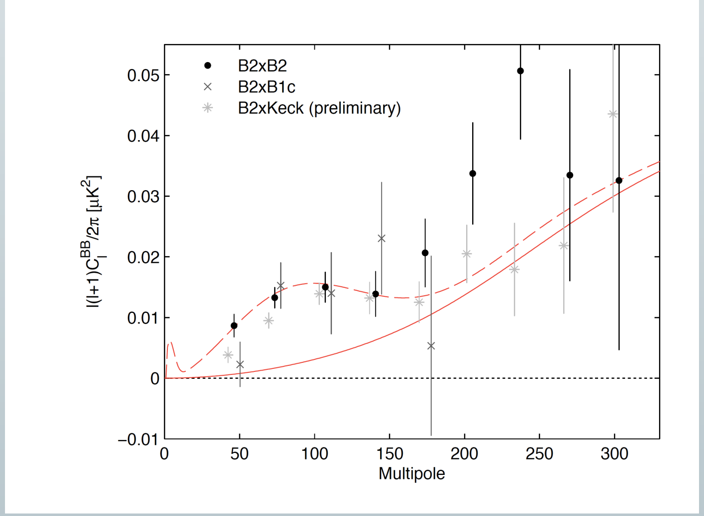


CMB B-mode polarization



→

?

``The long search for tensor B-modes is apparently over and a new era of B-mode cosmology has begun''

Conclusions

- The Bicep 2 detection of CMB polarization B-modes, sourced by a primordial background of gravitational waves produced quantum-mechanically during inflation, opens up a new window into the physics of the very early Universe and very high energies (GUT scale) and provides the “smoking gun” proof of the validity of the inflationary theory.

- The discovery calls for confirmation by independent observations, such as *Planck* CMB polarization data analysis can soon provide.

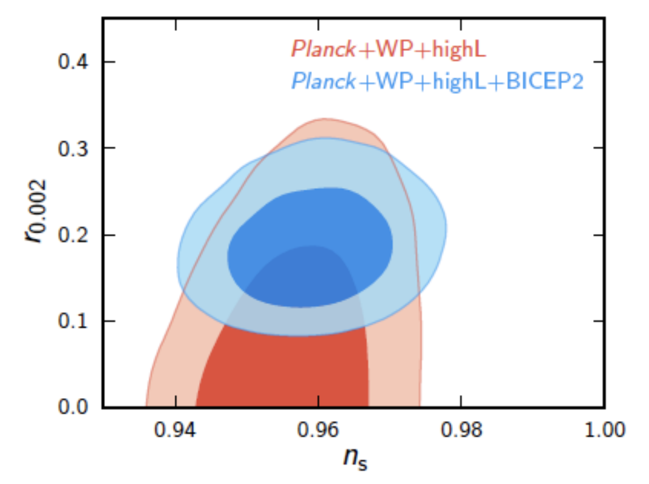
- If confirmed it will open up a new era for gravitational-wave astronomy.

Is there a tension between *Planck* and Bicep2?

Suppose the tension is real. Various ways to reconcile the two limits.

The idea is very simple: suppress the scalar (density) perturbations of 10% to allow 10% more of gravity waves on the largest angular.

- A negative *running of the spectral index*



$$\frac{dn_s}{d\ln k} \sim -2\%$$

BUT THIS WOULD RULE OUT ALL THE SIMPLEST MODELS OF INFLATION
(they typically predict a running O(10^{-3})).

- A negative cross-correlation of tensors and scalars (allowed in anisotropic models of inflation), e.g. *Contaldi et al. arXiV:1403.4596*

- A (step) feature in the inflaton potential, e.g. Miranda et al. *arXiV:1403.5231*