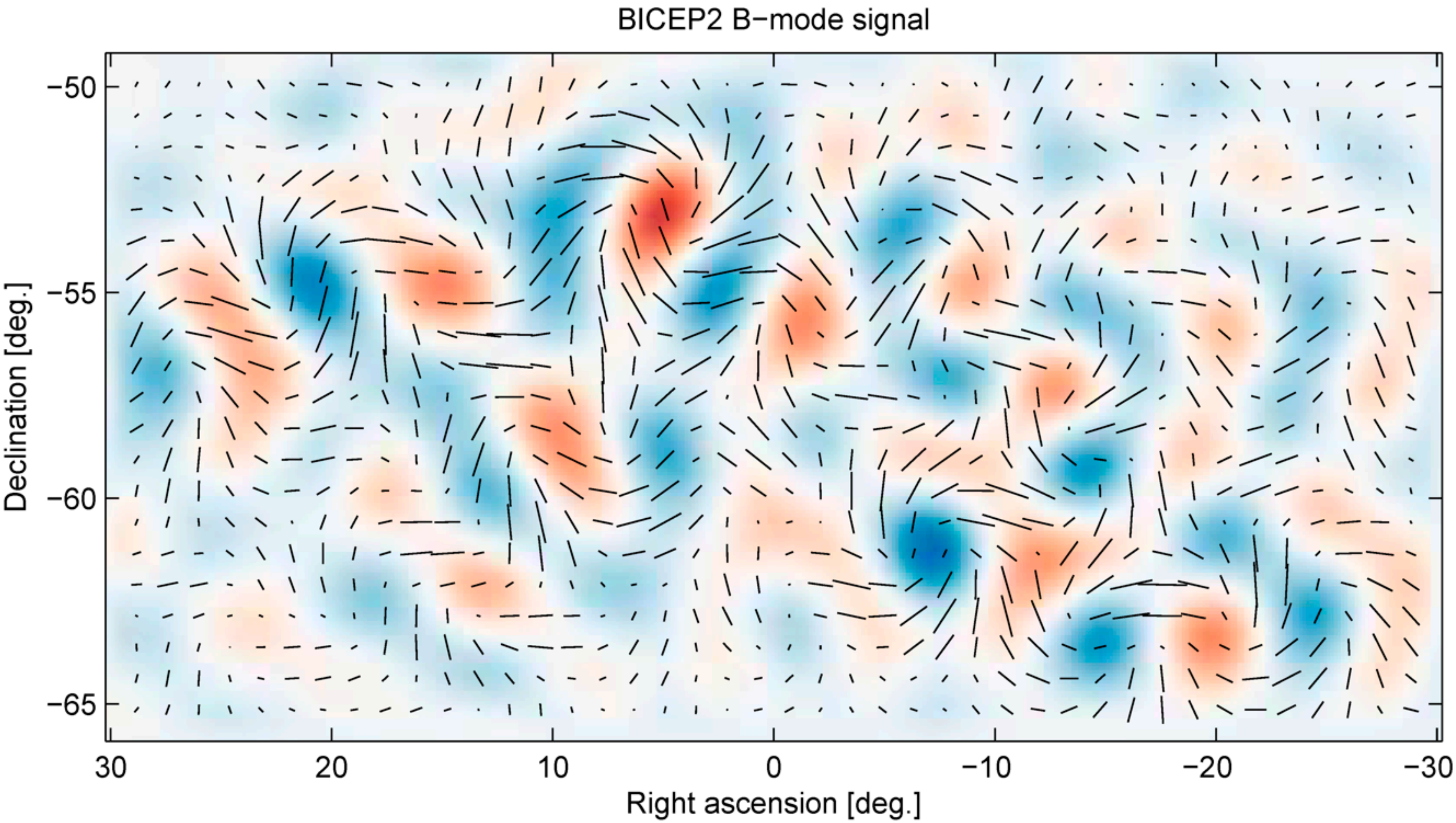
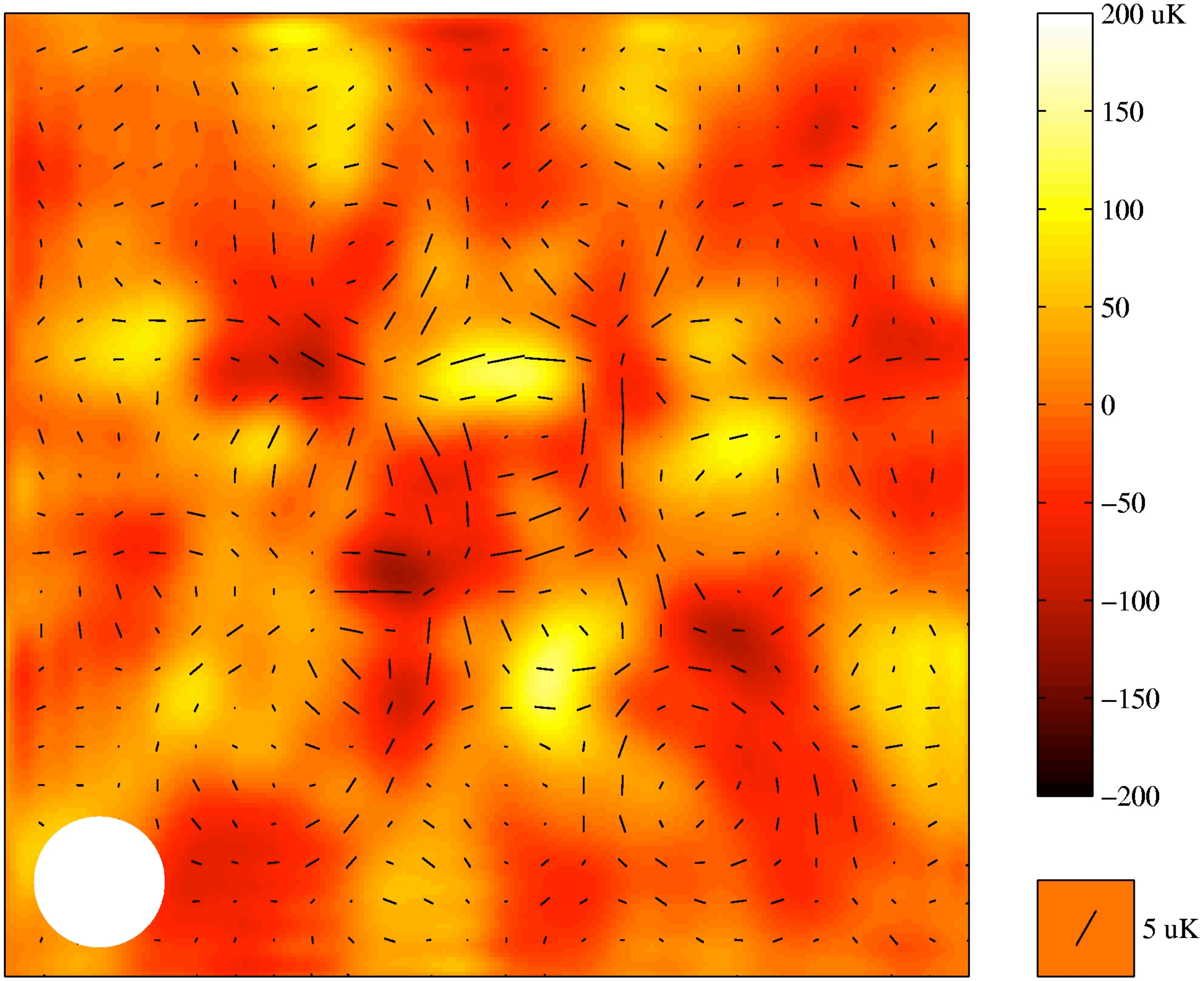
Implications of the BICEP results



Brookhaven National Laboratory
April 2014

The Anisotropies are polarized

DASI

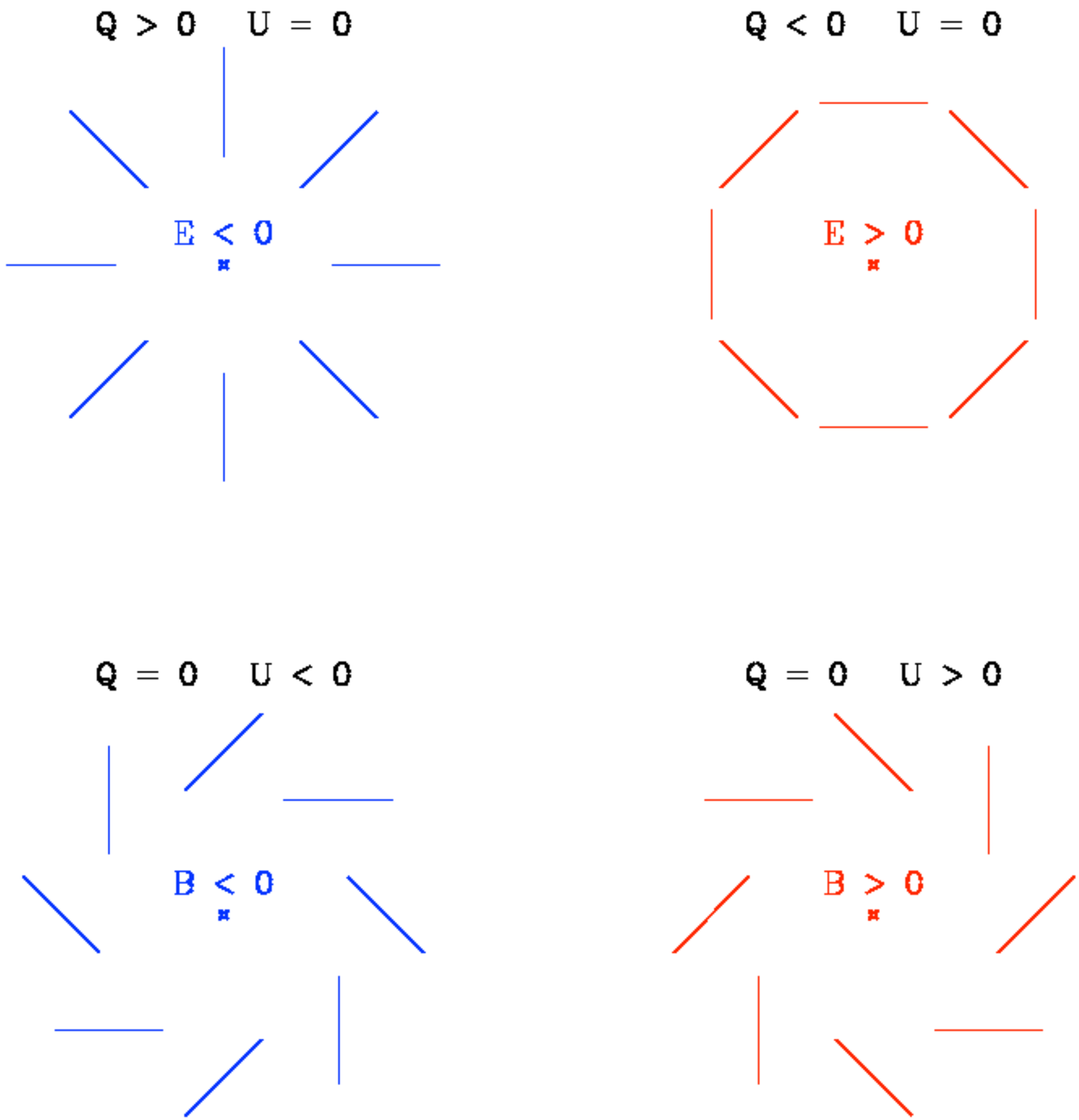


Map is 5 degrees square

Kovac et al.
astro-ph/0209478

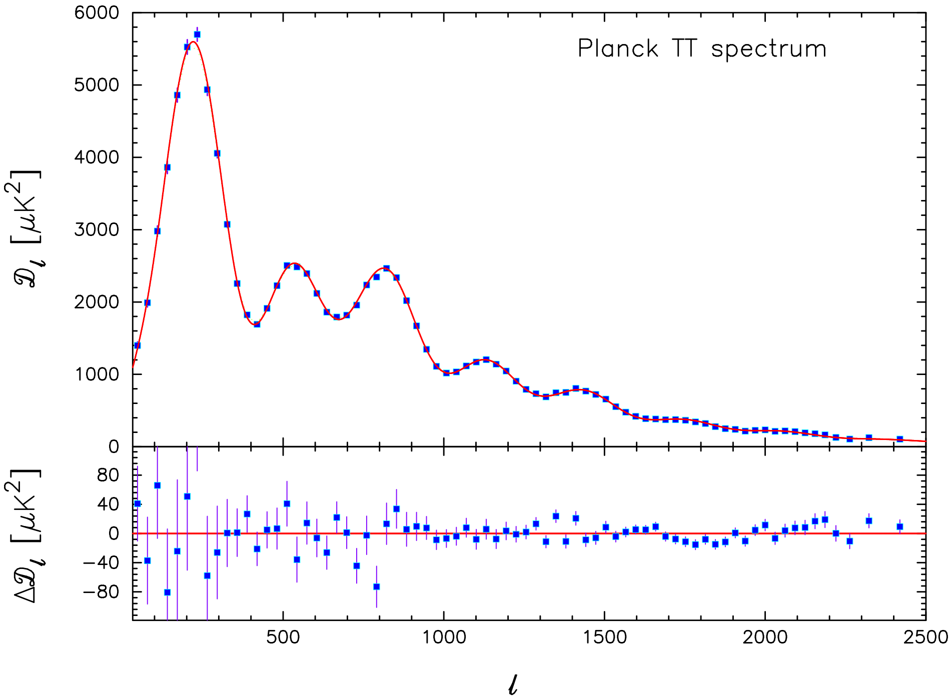
Density pert.
&
Gravity Waves

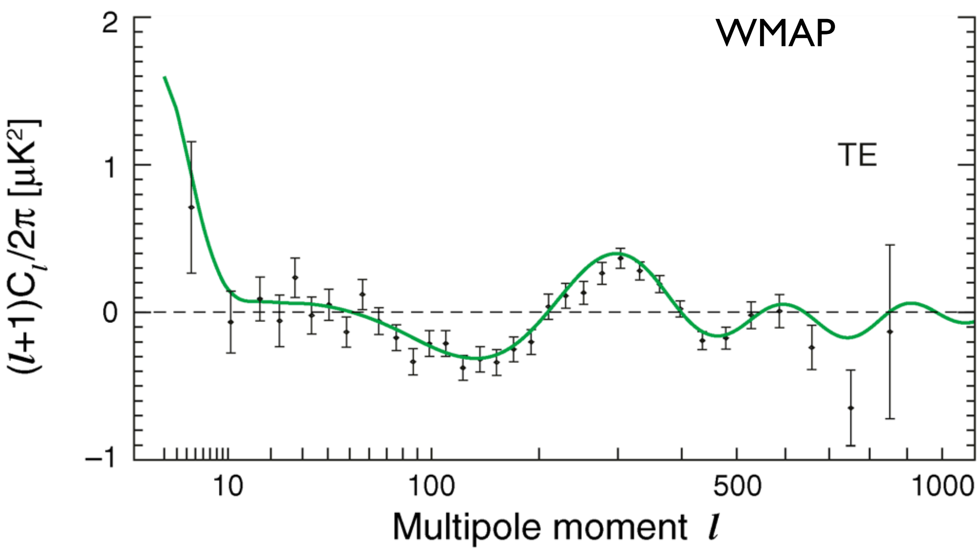
Gravity
Waves

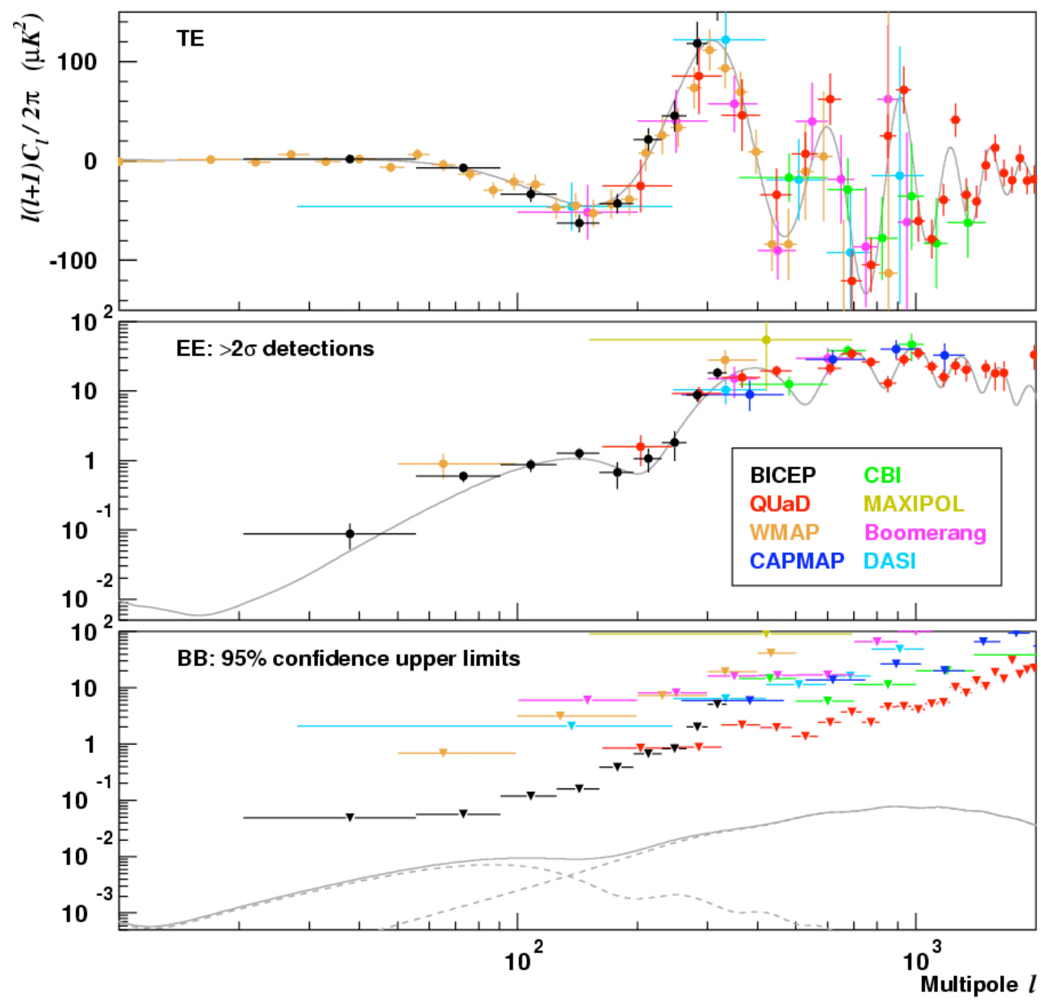


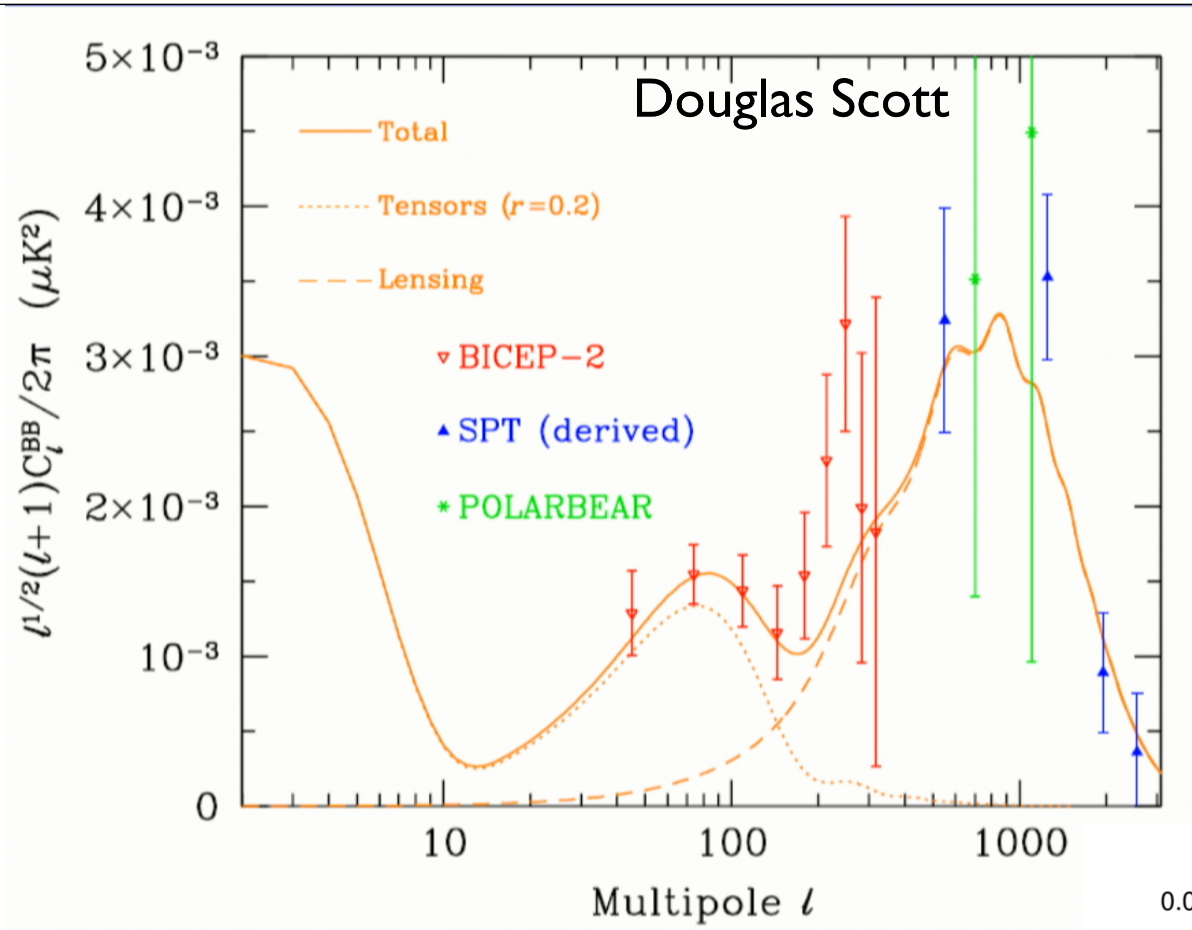
State of the art prior to BICEP2

$$T \sim 10 \text{ to } 70\ \mu K$$
$$E \sim 1 \text{ to } 5\ \mu K$$

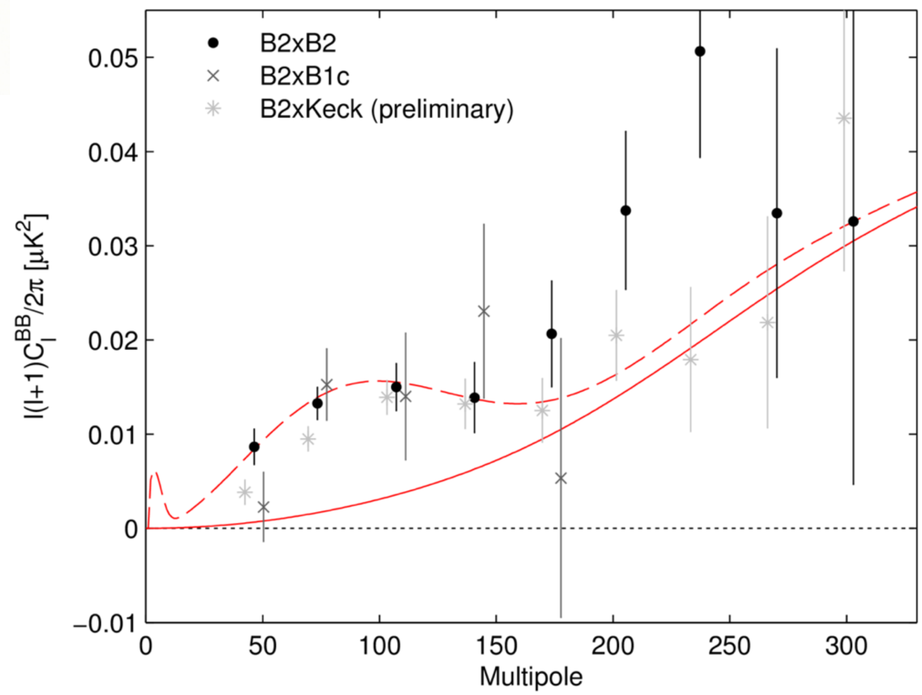








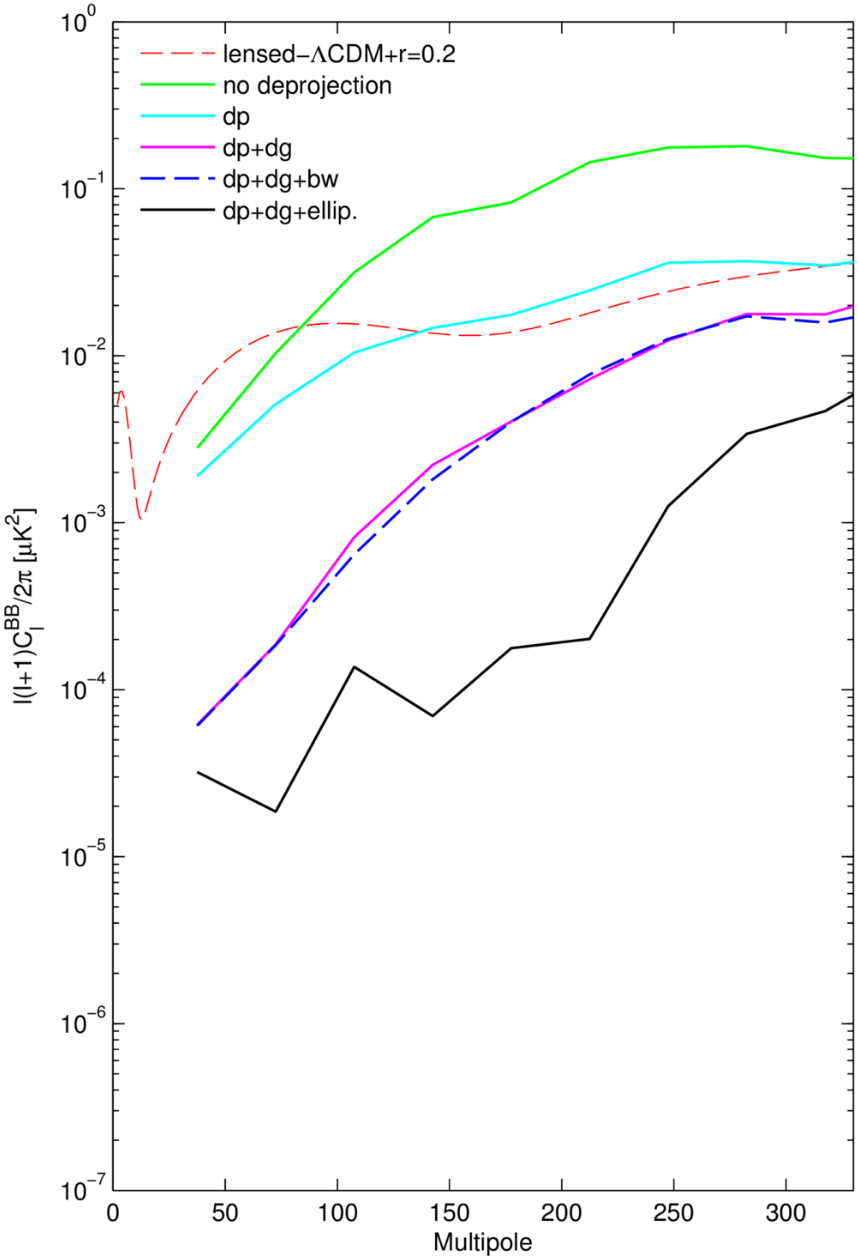
Douglas Scott
Total
Tensors (r=0.2)
Lensing
BICEP-2
SPT (derived)
POLARBEAR
$\ell^{1/2}(\ell+1)C_\ell^{BB}/2\pi$ (μK^2)
Multipole ℓ

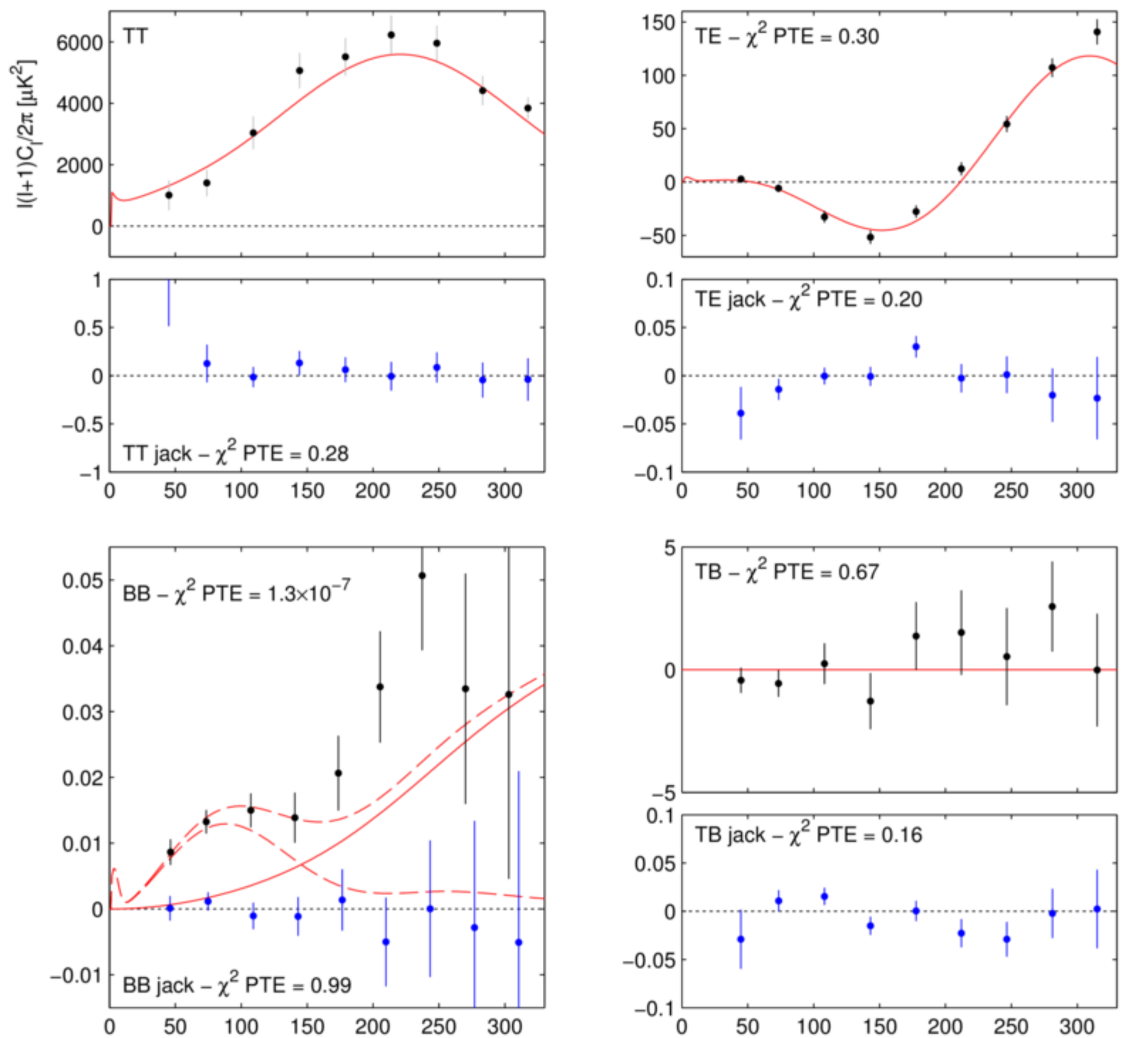


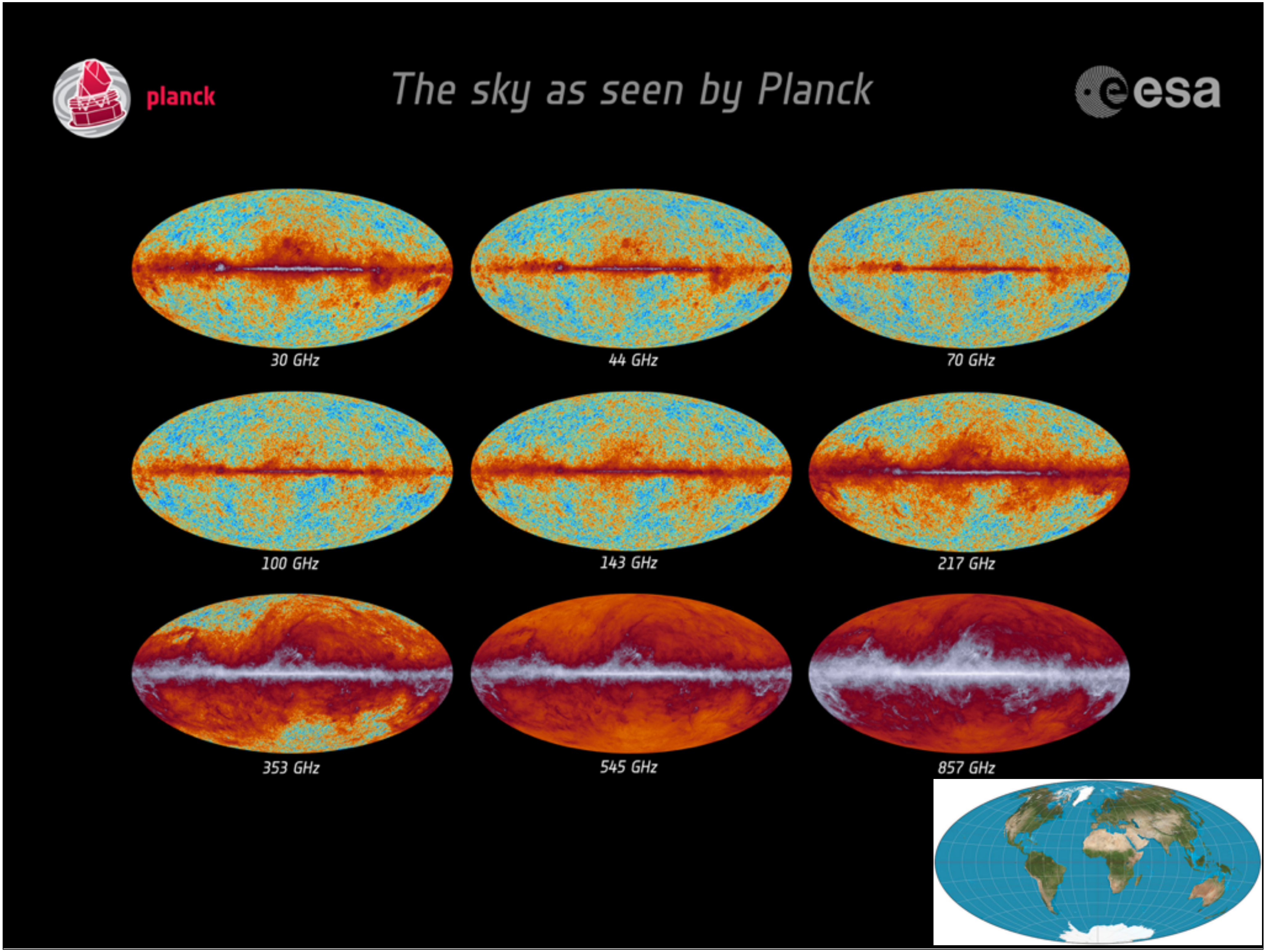
B2xB2
B2xB1c
B2xKeck (preliminary)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole

Potential worries

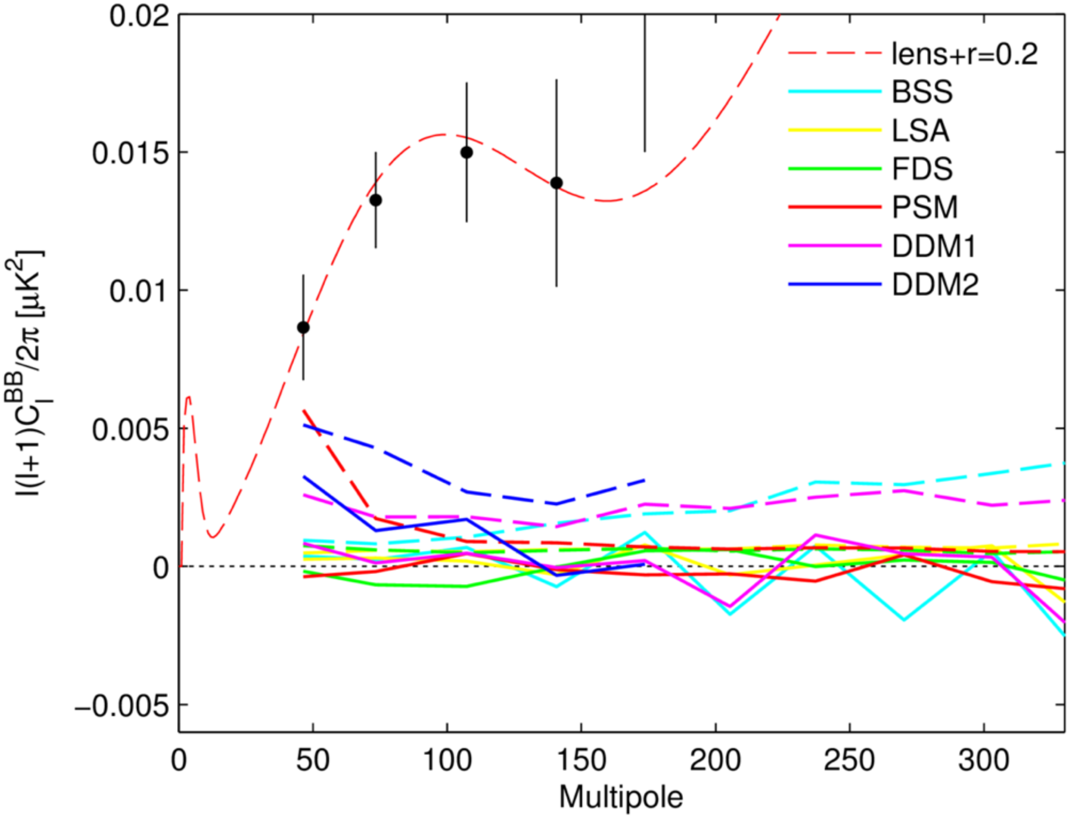
Systematic effects

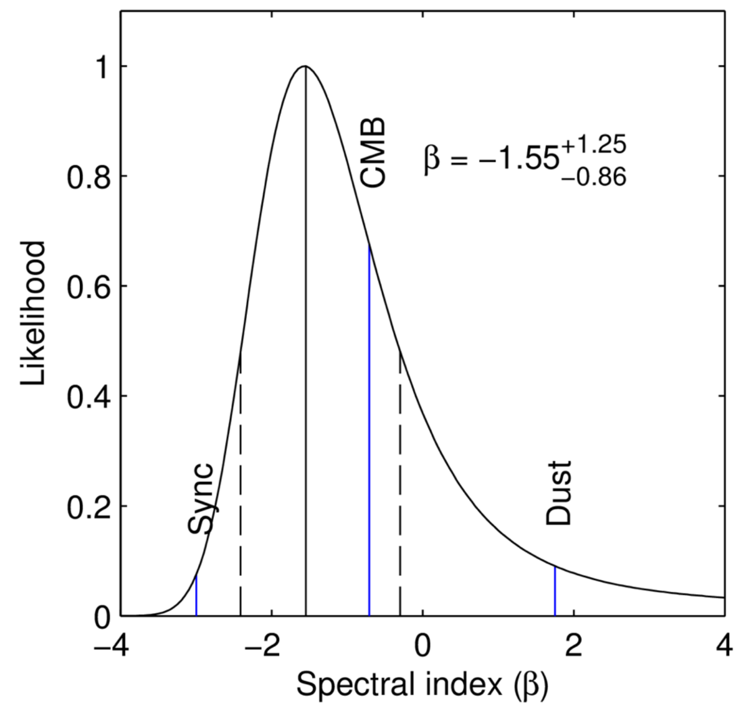


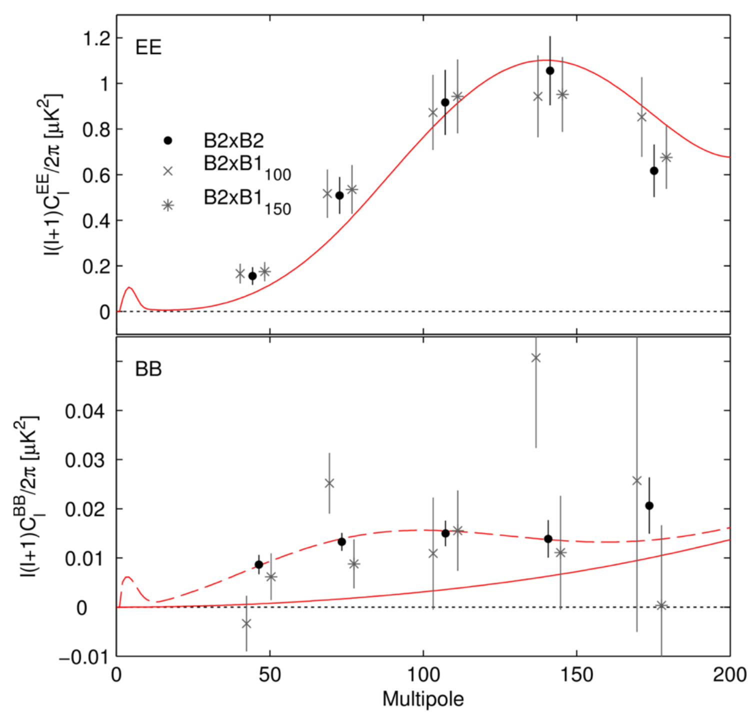


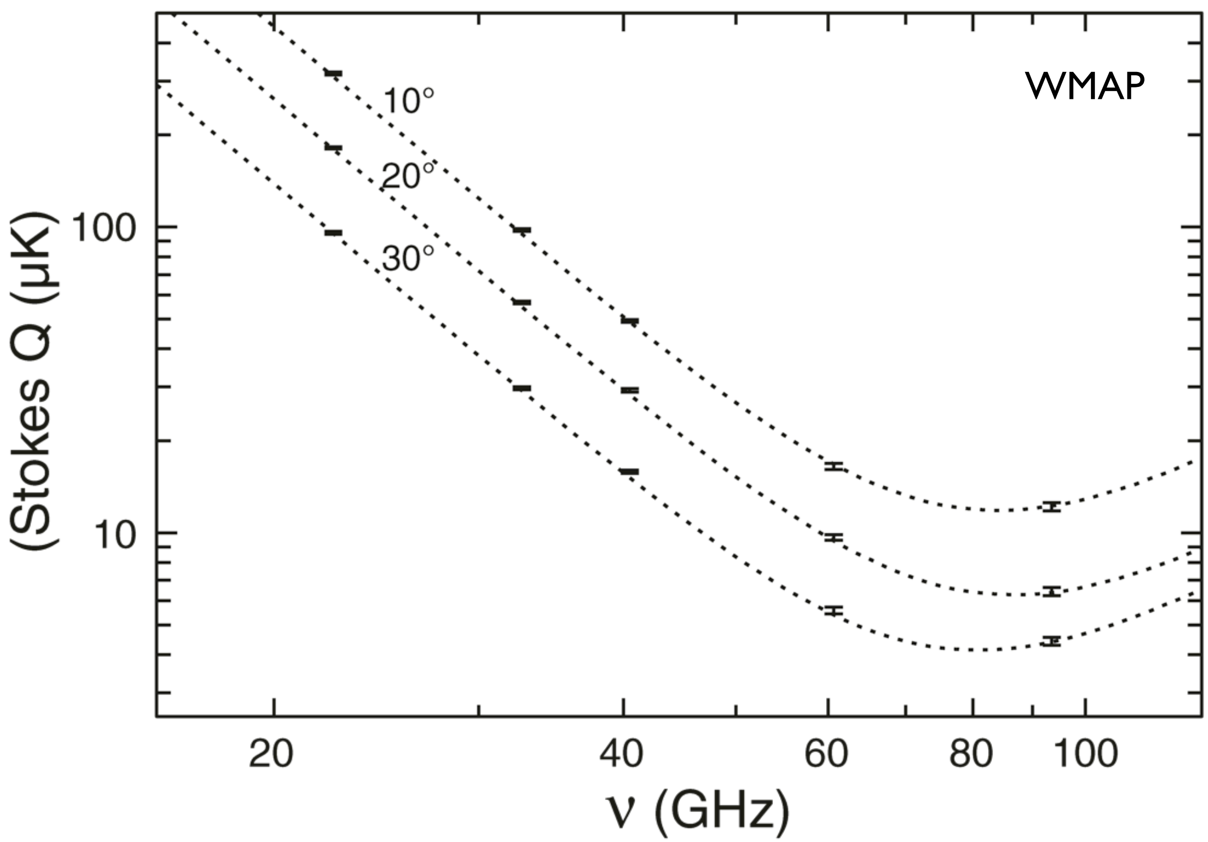

planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

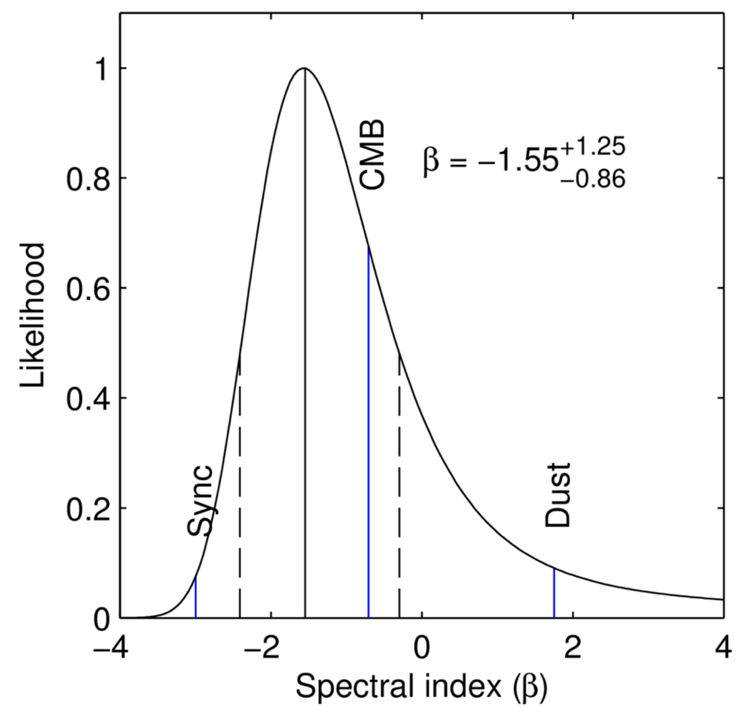
Foregrounds








WMAP
10°
20°
30°
(Stokes Q (μK)
100
10
20
40
60
80
100
ν (GHz)


$\beta = -1.55^{+1.25}_{-0.86}$
CMB
Sync
Dust
Likelihood
Spectral index (β)
0
0.2
0.4
0.6
0.8
1
−4
−2
0
2
4

Consistency with previous results

“The tension”

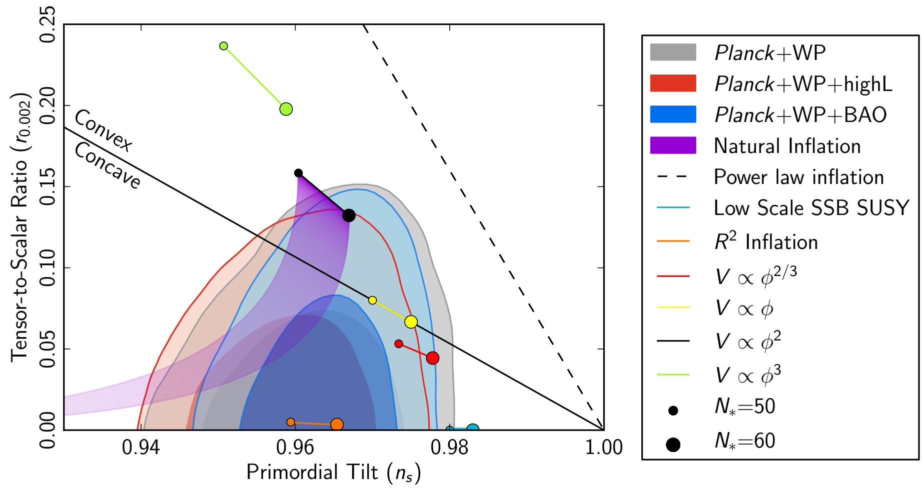


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

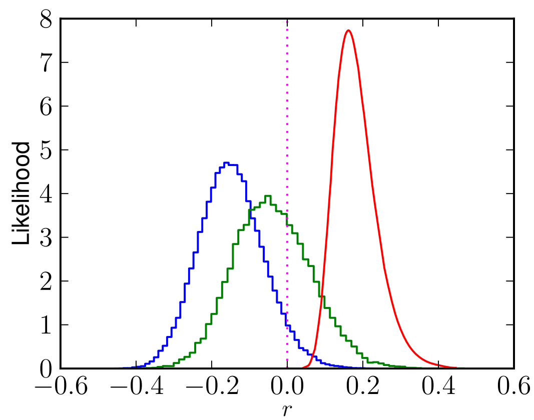


FIG. 2: 1D probability distribution functions for the tensor-to-scalar ratio r using Planck+WP data (blue/left), WMAP+SPT+BAO+H_0 data (green/middle), and BICEP2 data (red/right). We use the CosmoMC [5] code with the six cosmological parameters $\{\Omega_b h^2, \Omega_m h^2, \Omega_\Lambda, A_\zeta, \tau, n_s\}$ marginalized. As discussed in the text, we allow r to be negative in order to parameterize a possible power deficit on large angular scales.

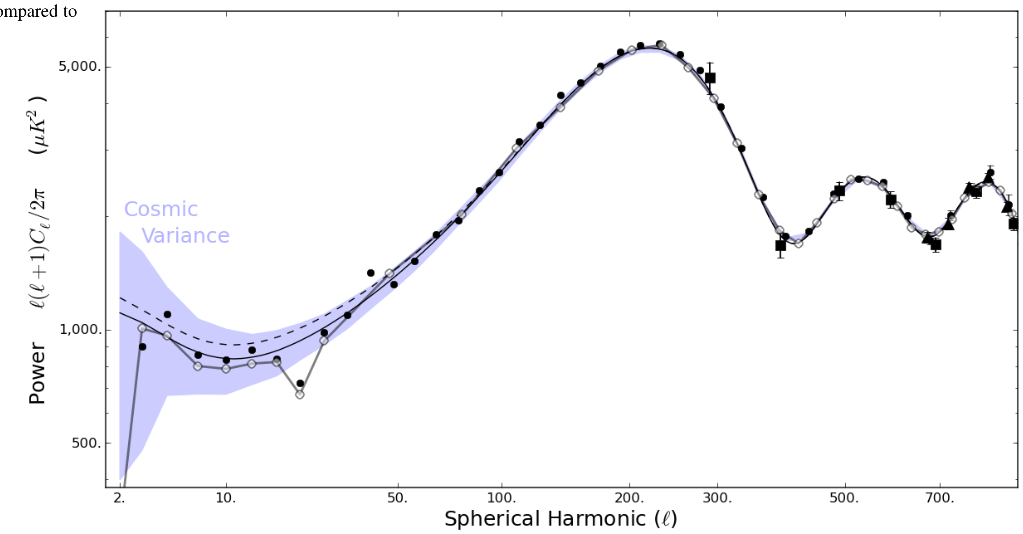
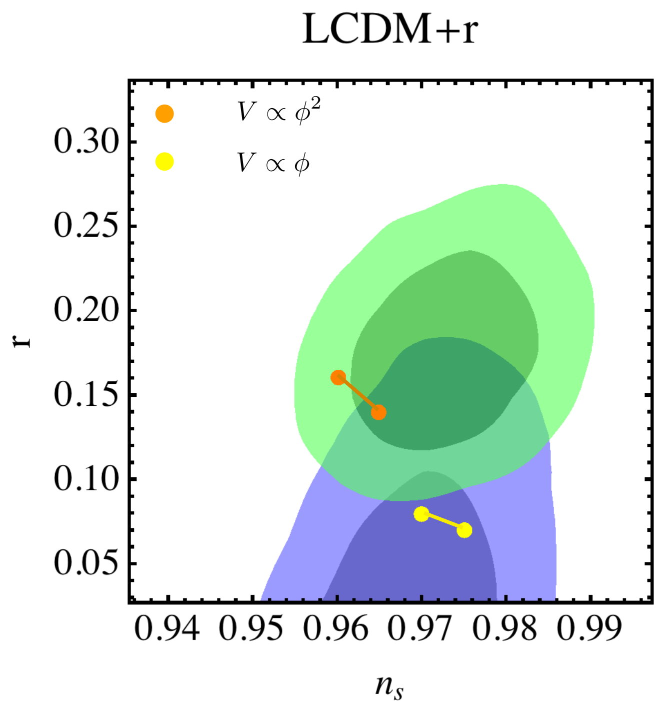


FIG. 1: Current measurements of the CMB temperature power spectrum, from Planck (open circles), WMAP (closed circles), ACT (squares) and SPT (triangles). Error bars include noise variance only; the shaded region represents cosmic variance. There is a small deficit of power on large angular scales relative to an $r = 0$ model (solid curve) which becomes more statistically significant if $r = 0.2$ as BICEP2 suggests (dashed curve).

"The tension"



(Spectra, covariance matrix from Spergel, Flauger, Hlozek 2013)

Planck numbers may move around.

BiCEP numbers do not correct for foregrounds

$$r \sim 0.2 \to 0.16$$

Premature discussion

- Running (unacceptably large, "rules out slow-roll inflation")
- A brake in the spectrum (Evidence for Bubble-nucleation event)
- Additional relativistic species (does not really look like the signal)

Are the B modes primordial? Defects

Lizarraga et al 1403.4924

$$\Delta\theta \approx 2^o$$

Moss & Pogosian1403.6105

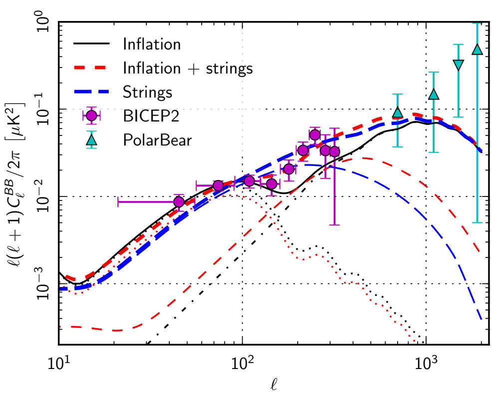


FIG. 1. The thick blue long dashed line is the best fit lensing+strings model (r=0), with the thin blue long dashed line showing the corresponding string contribution alone. The thick red short dash is the best fit lensing+strings+inflation model (r=0.15), with the corresponding string contribution plotted as a thin red short dashed line. The lensing contribution is shown separately with a thin black dot-dashed line. The BICEP2 best fit inflationary model (r=0.2) contribution is shown with a thin black dotted line, and the solid thin black line is the sum of r=0.2 and lensing contributions. The circles show the band powers measured by BICEP2 and the triangles are the POLARBEAR data (the third band is negative with its absolute value plotted as an inverted triangle).

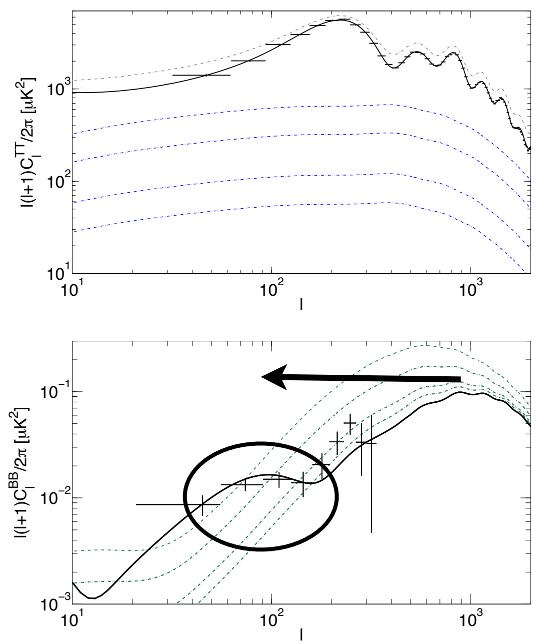


FIG. 3: Temperature (upper panel) and B-mode polarization (lower panel) power spectra compared to the *Planck* temperature and the BICEP2 B-mode polarization data. The black curve in the upper panel is the best-fit ΛCDM model and the blue dashed lines show the contribution from strings for f_{10} = 0.3, 0.15, 0.06, and 0.03. The green-dotted curves in the lower panel show the combined contribution from strings and the lensing of the scalar perturbations, for the same values of f_{10} as in the upper panel. The lowest dotted curve, for f_{10} = 0.03, shows roughly the maximal allowed contribution from strings to the temperature power spectrum, given the *Planck* data. The highest dotted curve, f_{10} = 0.3, matches the BICEP2 B-mode polarization at ℓ = 80. The grey dashed line is the sum of the f_{10} = 0.3 string prediction with the *Planck* best-fit ΛCDM model.

Location of peak constrained by Causality.

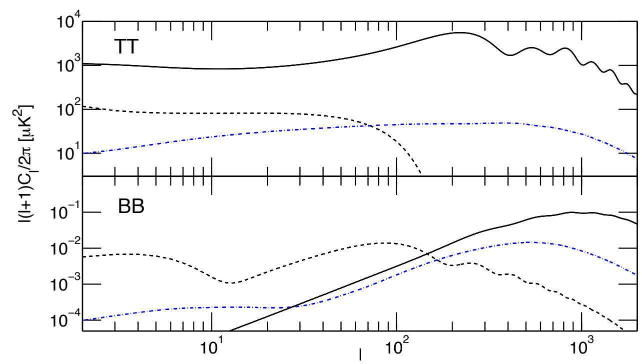
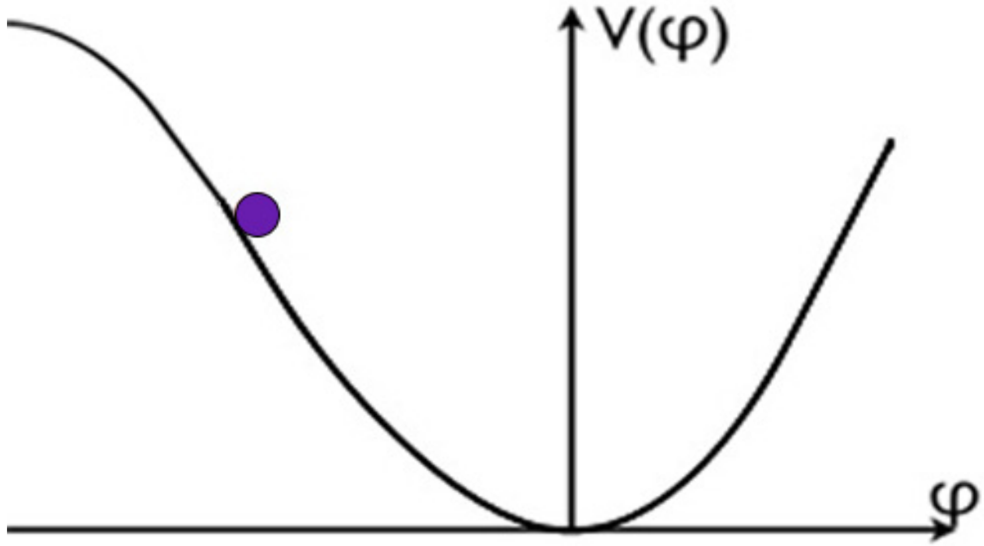


FIG. 1: The CMB temperature and polarization power spectra contributions from inflationary scalar modes (black solid), inflationary tensor modes (black dashed), and cosmic strings (blue dot-dashed) [16]. The inflationary tensors have r = 0.2 while the string contribution has f_{10} = 0.03.

$$C_{Bl} \;=\; 2\pi \int_0^\pi \theta d\theta \, \{[C_Q(\theta) + C_U(\theta)]\; J_0(l\theta) - [C_Q(\theta) - C_U(\theta)]\; J_4(l\theta)\}$$

Back to the 80's



$$M_{pl} \sim 10^{18} \text{ GeV}$$
$$V^{1/4} \sim 10^{16} \text{ GeV}$$
$$H \sim 10^{14} \text{ GeV}$$
$$m \sim 10^{13} \text{ GeV}$$
$$\Delta\phi \sim 15 \; M_{pl}$$

$$\mathcal{L}(\phi) = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2$$

- Flat Universe
- Primordial Fluctuations
- Almost scale invariant with red tilt (ns-1 = - 4/N)
- No fluctuations in the composition
- Very small departures from Gaussianity, unobservable now
- Large tensor modes

UV sensitivity

$$\frac{\Delta\phi}{M_{\rm pl}} \approx \frac{1}{\sqrt{8}} \int_0^N \mathrm{d}N\,\sqrt{r}$$

$$\boxed{\frac{\Delta\phi}{M_{\rm pl}} = \mathcal{O}(1) \times \left(\frac{r}{0.01}\right)^{1/2}}$$

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

Shift symmetry forbids these terms $\quad \phi \to \phi + const.$

Symmetry needs to be respected by quantum gravity
For a while there were no example in ST so it was conjectured that you could not get gravity waves.
Now there is a counter example: axion monodromy

Other sources of GW during inflation

Senatore, Silverstein and MZ, Mirbabayi

$$\dot{\phi}^2 >> H^4$$

Perhaps you can tap to this source of energy and create some GW.

Be careful: You also create scalars

$$r = 16\epsilon \to 16\epsilon\alpha \sim 16\epsilon^2$$

BICEP level so large that it is difficult to hide the scalars. They must be the ones we observe $\to \epsilon \sim 0.1$

Need to worry about Gaussianity

This kind of scenario can barely be made to work.

Effective theory of inflation:

Chung, Creminelli, Fitzpatrick, Kaplan & Senatore. 0709.0293

Use the measured time in the clock as the time coordinate.
The clock disappears from the action, everything is in the metric.
Can still make time dependent transformations of the spatial coordinates but time has been fixed. Terms must respect the residual symmetry.

$$S_{\text{E.H. + S.F.}} = \int d^4x \, \sqrt{-g} \Big[\frac{1}{2} M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2 (3H^2 + \dot{H}) + \\ + \frac{1}{2!} M_2(t)^4 (g^{00}+1)^2 + \frac{1}{3!} M_3(t)^4 (g^{00}+1)^3 + \\ - \frac{\bar{M}_1(t)^3}{2} (g^{00}+1) \delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2} \delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2} \delta K^\mu{}_\nu \delta K^\nu{}_\mu + ... \Big]$$

$\delta K_{\mu\nu}$ the variation of the extrinsic curvature of constant time surfaces

Has one more derivative.
Expansion in fluctuations and in derivatives. Coefficients in the first line are such that the action starts quadratic.

This Lagrangian is both general and unique. It describes 3 degrees of freedom.

$$S_{\text{E.H. + S.F.}} = \int d^4x \, \sqrt{-g} \Big[\frac{1}{2} M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2 (3H^2 + \dot{H}) +$$
$$+ \frac{1}{2!} M_2(t)^4 (g^{00}+1)^2 + \frac{1}{3!} M_3(t)^4 (g^{00}+1)^3 +$$
$$- \frac{\bar{M}_1(t)^3}{2} (g^{00}+1) \delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2} \delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2} \delta K^\mu{}_\nu \delta K^\nu{}_\mu + \ldots \Big]$$

This Lagrangian is not quadratic, there are interactions.

There is a minimum level of interactions coming from the terms that are fixed by the cosmic history. This level is small but not minuscule.

Only get scale invariant fluctuations from the clock around an inflationary background.

$$
\begin{aligned}
S_{\mathrm{E.H.\,+\,S.F.}} = \int d^4x\,\sqrt{-g}\Big[&\frac{1}{2}M_{\mathrm{Pl}}^2 R + M_{\mathrm{Pl}}^2 \dot{H} g^{00} - M_{\mathrm{Pl}}^2(3H^2+\dot{H}) + \\
&\xcancel{+\frac{1}{2!}M_2(t)^4(g^{00}+1)^2 + \frac{1}{3!}M_3(t)^4(g^{00}+1)^3 +} \\
&\xcancel{-\frac{\bar{M}_1(t)^3}{2}(g^{00}+1)\delta K^{\mu}{}_{\mu} - \frac{\bar{M}_2(t)^2}{2}\delta K^{\mu}{}_{\mu}{}^2 - \frac{\bar{M}_3(t)^2}{2}\delta K^{\mu}{}_{\nu}\delta K^{\nu}{}_{\mu} + \ldots}\Big]
\end{aligned}
$$

$$
S_\pi = \int d^4x\sqrt{-g}M_{pl}^2|\dot{H}|(\dot{\pi}^2 - \frac{(\partial_i\pi)^2}{a^2})
$$

Energy Scales

Energy

M_{pl}

$V^{1/4}$

Λ_b

H

$m \sim \sqrt{\eta} H$

$$\Lambda_b^4 = 2M_{pl}^2 |\dot{H}|$$

$$\zeta \sim \frac{H^2}{\Lambda_b^2}$$

$$h \sim \frac{H}{M_{pl}}$$

Could there be more interesting dynamics ?

Lowering the braking scale

$$\zeta \sim \frac{H^2}{\Lambda_b^2} \qquad \Lambda_b^4 = 2M_{pl}^2|\dot{H}|$$

Models with small speed of sound, large dissipation, etc.

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2}M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2(3H^2 + \dot{H}) + \right.$$
$$+ \frac{1}{2!}M_2(t)^4(g^{00}+1)^2 + \frac{1}{3!}M_3(t)^4(g^{00}+1)^3 +$$
$$\left. - \frac{\bar{M}_1(t)^3}{2}(g^{00}+1)\delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2}\delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2}\delta K^\mu{}_\nu \delta K^\nu{}_\mu + \ldots \right]$$

Change the dispersion relation of the fluctuations

$$S = \int d^4x \sqrt{-g} \left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2 \frac{(\partial_i \pi)^2}{a^2}\right) + (M_{\rm Pl}^2 \dot{H})\frac{1-c_s^2}{c_s^2}\left(\frac{\dot{\pi}(\partial_i\pi)^2}{a^2} + \frac{A}{c_s^2}\dot{\pi}^3\right) + \cdots \right]$$

Energy Scales

Energy

M_{pl}

Λ_b

Λ_*

H

$$\Lambda_b^4 = 2M_{pl}^2|\dot{H}|c_s \to \dot{\phi}^2 \qquad \langle\zeta^2\rangle = \frac{1}{2}(\frac{H}{\Lambda_b})^4$$

$$\Lambda_*^4 = 2M_{pl}^2|\dot{H}|\frac{c_s^5}{(1-c_s^2)} \qquad \frac{\mathcal{L}_3}{\mathcal{L}_2}|_{\omega=\Lambda_*} \sim 1$$

$$\frac{\langle\zeta^3\rangle}{\langle\zeta^2\rangle^{3/2}} \sim \frac{\mathcal{L}_3}{\mathcal{L}_2}|_{\omega=H} \qquad \frac{\langle\zeta^3\rangle}{\langle\zeta^2\rangle^{3/2}} \sim f_{NL} \times \zeta \sim (\frac{H}{\Lambda_*})^2$$

Enhanced scalar fluctuations

Speed of sound

$r = 16\epsilon c_s$

$n_s - 1 \subset 6\epsilon$

BICEP $\longrightarrow$ $c_s \sim 1$

(non-G Planck) $c_s > 0.02$ $\longrightarrow$ $\epsilon \sim 1$

non-G no longer useful to constrain cs

Energy Scales

Energy

$$\Lambda_b^4 = 2M_{pl}^2|\dot{H}|$$

M_{pl}

$V^{1/4}$

Λ_b

H

$m \sim \sqrt{\eta}H$ Additional light states

Could there be more interesting dynamics ?
Could the fluctuations we see not be those of the clock?

Other Light fields

- Local type non-Gaussianities
- wide range of behavior in the squeezed limit.
- Different shapes than those that can be produced by single field
- 4-pt functions with large signal to noise

EFT of multifield inflation 1009.2093

Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4\ ,\ \dot\sigma^2(\partial_i\sigma)^2\ ,(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma^p(\partial_i\partial_j\sigma)^{(4-p)}$		X	Ad., Iso.	Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$^\dagger_s$, non-Ab.$^\dagger_s$.	X
$\sigma^2\dot\sigma^2\ ,\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$^\star_s$.	X
$\dot\sigma^3\ ,\ \dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2\ ,\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2\ ,\ \sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$.	X

Table 1: Signatures in Multi-field Inflation. In the first column we give the operator generating the non-Gaussian signal: operators quartic in the σ's lead to a four-point function, operators cubic in the σ's lead to a three-point function. In the second and third columns we explain with which dispersion relation the signal can be generated. In the third we explain if the signal can appear in the Adiabatic (Ad.) or the Isocurvature (Iso.) fluctuations. In the fourth we state the potential origin of the signal. Here Ab. stands for Abelian; non-Ab. stands for non-Abelian, S stands for supersymmetry, and R stands for generated by non-linearities at reheating. The subscript $_s$ indicates that the term is generated by soft-breaking terms. The symbol † represents that such a signal can be generated in the case the soft symmetry breaking term is such that it forbids some of the lowest dimensional terms. The symbol * represents the fact that the signal is in general subleading, but still possibly detectable. In the last column we explicitly mention if the induced signal has a non-vanishing squeezed limit and is therefore detectable also in clustering statistics of collapsed objects.

Signatures of SUSY from the Early Universe1109.0292

Table 1: *Non-Gaussianity in Quasi-Single Field Inflation.*

Interaction	$f_{\rm NL}^{(1)}$	$f_{\rm NL}^{(2)}$	**Large NG**	**S.L.**	**SUSY**	**Natural**
$\mathcal{L}_{1a} = m_a^3(\partial_\mu\pi)^2\sigma$	$\left(\frac{\rho}{H}\right)^2$	$\alpha\,\frac{\rho}{H}$		✓	✓	
$\mathcal{L}_{1b} = m_b^3(\dot\pi)^2\sigma$	$\left(\frac{\rho}{H}\right)^2$	$\alpha\,\frac{\rho}{H}$		✓	✓	
$\mathcal{L}_2 = \hat m^2(\partial_\mu\pi)^2\dot\sigma$	$\frac{\rho}{H}\,\alpha$	α^2				
$\mathcal{L}_3 = \tilde m^2\dot\pi\sigma^2$	$\left(\frac{\rho}{H}\right)^2\left(\frac{\tilde m}{H}\right)^2$	$\alpha^2\left(\frac{\tilde m}{H}\right)^2$		✓		
$\mathcal{L}_{4a} = \bar m_a\partial_\mu\pi\partial^\mu\sigma\sigma$	$\left(\frac{\rho}{H}\right)^2\frac{\bar m_a}{H}$	$\alpha^2\,\frac{\bar m_a}{H}$		✓	✓	
$\mathcal{L}_{4b} = \bar m_b\dot\pi\dot\sigma\sigma$	$\left(\frac{\rho}{H}\right)^2\frac{\bar m_b}{H}$	$\alpha^2\,\frac{\bar m_b}{H}$		✓		
$\mathcal{L}_{5a} = \lambda_a\dot\pi(\partial_\mu\sigma)^2$	$\left(\frac{\rho}{H}\right)^2\lambda_a$	$\alpha^2\,\lambda_a$				
$\mathcal{L}_{5b} = \lambda_b\partial_\mu\pi\partial^\mu\sigma\dot\sigma$	$\left(\frac{\rho}{H}\right)^2\lambda_b$	$\alpha^2\,\lambda_b$				
$\mathcal{L}_{5c} = \lambda_c\dot\pi\dot\sigma^2$	$\left(\frac{\rho}{H}\right)^2\lambda_c$	$\alpha^2\,\lambda_c$				
$\mathcal{L}_6 = \mu\sigma^3$	$\left(\frac{\rho}{H}\right)^3\frac{\mu}{H}\,\Delta_\zeta^{-1}$	$\alpha^3\,\frac{\mu}{H}\,\Delta_\zeta^{-1}$	✓	✓	✓	✓
$\mathcal{L}_7 = \lambda\dot\sigma\sigma^2$	$\left(\frac{\rho}{H}\right)^3\lambda\,\Delta_\zeta^{-1}$	$\alpha^3\,\lambda\,\Delta_\zeta^{-1}$	✓	✓		(?)
$\mathcal{L}_{8a} = \Lambda_1^{-1}(\partial_\mu\sigma)^2\sigma$	$\left(\frac{\rho}{H}\right)^3\frac{H}{\Lambda_1}\,\Delta_\zeta^{-1}$	$\alpha^3\,\frac{H}{\Lambda_1}\,\Delta_\zeta^{-1}$	✓	✓	✓	✓
$\mathcal{L}_{8b} = \Lambda_2^{-1}\dot\sigma^2\sigma$	$\left(\frac{\rho}{H}\right)^3\frac{H}{\Lambda_2}\,\Delta_\zeta^{-1}$	$\alpha^3\,\frac{H}{\Lambda_2}\,\Delta_\zeta^{-1}$	✓	✓		(?)
$\mathcal{L}_{9a} = \Lambda_3^{-2}\dot\sigma(\partial_\mu\sigma)^2$	$\left(\frac{\rho}{H}\right)^3\left(\frac{H}{\Lambda_3}\right)^2\Delta_\zeta^{-1}$	$\alpha^3\left(\frac{H}{\Lambda_3}\right)^2\Delta_\zeta^{-1}$	✓			✓
$\mathcal{L}_{9b} = \Lambda_4^{-2}\dot\sigma^3$	$\left(\frac{\rho}{H}\right)^3\left(\frac{H}{\Lambda_4}\right)^2\Delta_\zeta^{-1}$	$\alpha^3\left(\frac{H}{\Lambda_4}\right)^2\Delta_\zeta^{-1}$	✓			✓

Were fluctuations converted into curvature fluctuations at the beginning/during the hot big bang?

$$ds^2 = -N^2 + a^2(t)e^{2\zeta(x,t)}(dx^i + N^i dt)(dx^j + N^j dt)$$

$$\zeta \ll 10^{-5} \to \zeta \sim 10^{-5}$$

$$H^2 = \frac{\rho}{M_{pl}^2}$$

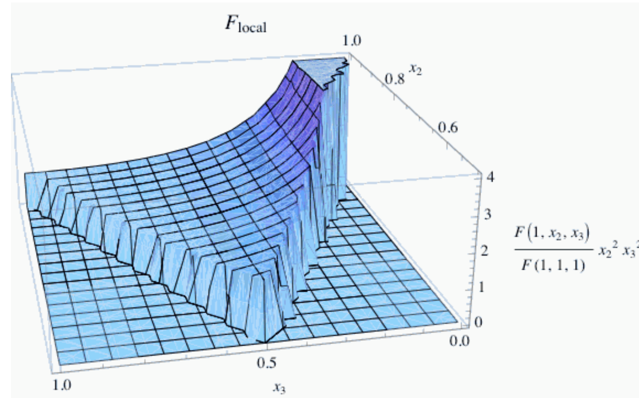
$$\zeta \leftrightarrow \delta \log a$$

$$\dot{H} = -\frac{3}{2}\frac{\rho + p}{M_{pl}^2}$$

Did super-horizon modes ever produce locally observable differences that modulate the equation of state?

Robust signature: Local non-Gaussianty

Modulate the equation of state:



$$p(\rho) = \bar{p}(\rho) + \delta p(\sigma)$$

The conversion into curvature perturbations happens outside the horizon. Gradients are negligible and thus it leads to local type of non-Gaussianity.

$$\zeta(x) = f(\sigma(x)) = \epsilon(\sigma + \alpha\sigma^2 + \cdots) \qquad f_{NL}^{local} \sim \frac{1}{\epsilon}$$

There are many contributions to the non-linearities. Friedman equation, relation between field and the change in the equation of state, etc.

Only part of the pressure is modulated. Mechanism need not be perfectly efficient.

Examples, translation between decay rate and expansion or fractional contribution to the energy density by the curvaton.

$$r_{\rm D} = [3\rho_{\rm curvaton}/(3\rho_{\rm curvaton} + 4\rho_{\rm radiation})]_{\rm D}$$

$$r_{\rm D} \geq 0.15 \qquad 95\%\ \text{CL}\,.$$

$$\zeta(x) = \frac{1}{6}\frac{\delta\Gamma}{\Gamma}$$

Enhanced scalar fluctuations

Second field (curvaton/variable reheating)

$$r = 16\epsilon q$$

$$q = \frac{P_\zeta^\phi}{P_\zeta^\phi + P_\zeta^\sigma}$$

BICEP $\longrightarrow$ $q \sim 1$

One can only accommodate a subdominant component.

$$n_s - 1 \subset 2\epsilon$$

$$\frac{\langle\zeta^3\rangle}{\langle\zeta^2\rangle^{3/2}} = NG^\zeta = NG^\sigma(1-q)^{3/2}$$

$$\approx NG^\sigma(\frac{P_\zeta^\sigma}{P_\zeta^\phi})^{3/2}$$

Energy Scales

Energy

M_{pl}

$V^{1/4}$

Λ_b

H

$m \sim \sqrt{\eta} H$

$$\Lambda_b^4 = 2M_{pl}^2 |\dot{H}|$$

Additional states that mix with the clock

Could there be more interesting dynamics ?

The EFT view

$$S = \int d^4x \, \sqrt{-g} \quad \Big[\quad \frac{1}{2} M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H} g^{00} - M_{\rm Pl}^2 (3H^2 + \dot{H}) + \\ + \frac{1}{2!} M_2(t)^4 (g^{00}+1)^2 + \frac{1}{3!} M_3(t)^4 (g^{00}+1)^3 + \\ - \frac{\bar{M}_1(t)^3}{2} (g^{00}+1) \delta K^\mu{}_\mu - \frac{\bar{M}_2(t)^2}{2} \delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2} \delta K^\mu{}_\nu \delta K^\nu{}_\mu + \ldots \Big]$$

$$g^{00} \quad \to \quad -1 - 2\dot{\pi} - \dot{\pi}^2 + \frac{1}{a^2} (\partial_i \pi)^2$$

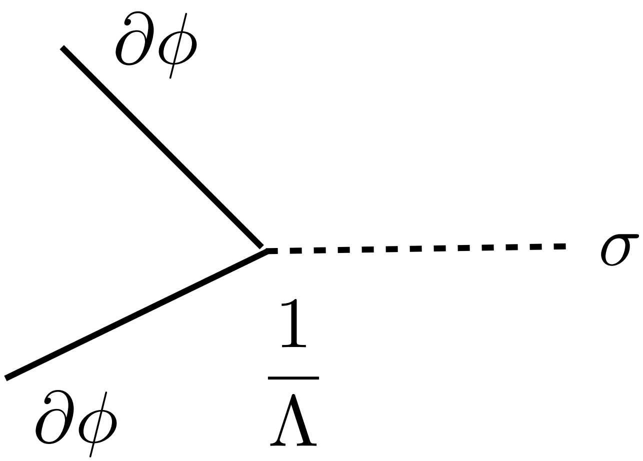
$$S_\pi = \int d^4x \sqrt{-g} \left[-M_{\rm Pl}^2 \dot{H} \left(\dot{\pi}^2 - \frac{(\partial_i \pi)^2}{a^2} \right) + 2M_2^4 \left(\dot{\pi}^2 + \dot{\pi}^3 - \dot{\pi} \frac{(\partial_i \pi)^2}{a^2} \right) - \frac{4}{3} M_3^4 \dot{\pi}^3 + \ldots \right]$$

c_s^2

$f_{\rm NL} \sim \dfrac{1}{c_s^2}$

QSF dynamics with large non-G (Xingang Chen)

$$\mathcal{L}_\sigma = -\tfrac{1}{2}[\partial_\mu\sigma\partial^\mu\sigma + m^2\sigma^2] - \mu\sigma^3 + \frac{\sigma}{\Lambda}[\partial_\mu\phi\partial^\mu\phi - \langle\dot{\phi}\rangle^2]$$



Mixing

$$\frac{\dot{\phi}}{\Lambda H}$$

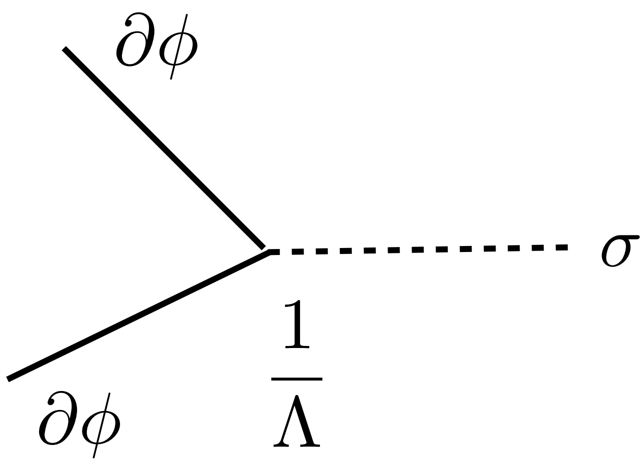
$$\left(\frac{\dot{\phi}}{\Lambda H}\right) \sim \epsilon^{1/2}\left(\frac{M_{pl}}{\Lambda}\right)$$

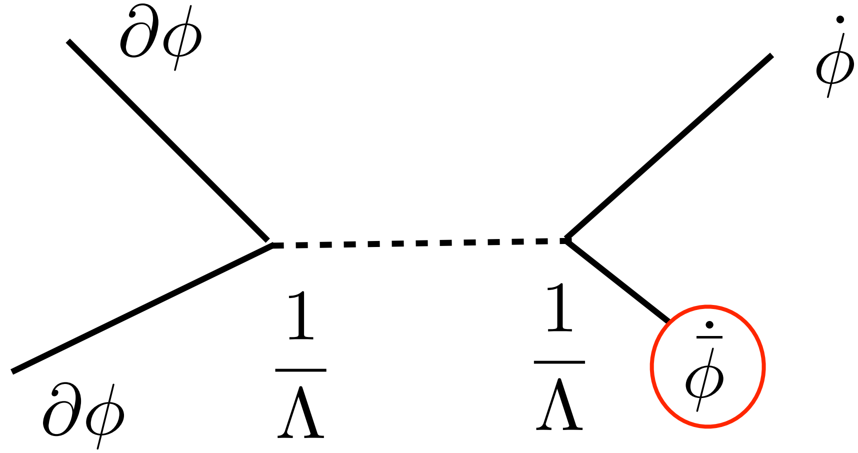
Testing Split Supersymmetry with Inflation

Nathaniel Craig♠ and Daniel Green♦,♣

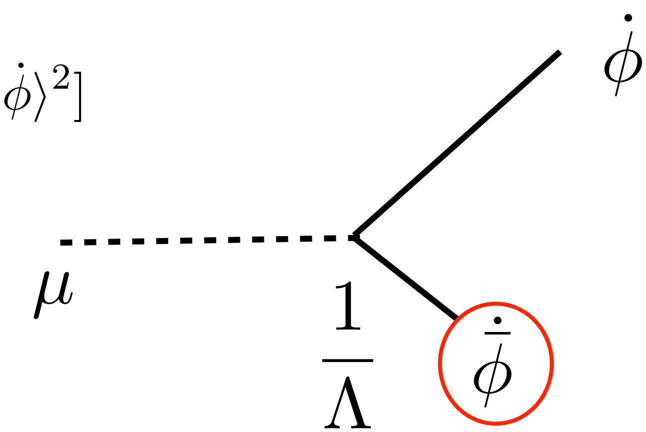
Planck-Suppressed Operators

Valentin Assassi,★ Daniel Baumann,★ Daniel Green,♦,♣ and Liam McAllister♠





$$\mathcal{L}_\sigma = -\frac{1}{2}[\partial_\mu\sigma\partial^\mu\sigma + m^2\sigma^2] - \mu\sigma^3 + \frac{\sigma}{\Lambda}[\partial_\mu\phi\partial^\mu\phi - \langle\dot{\phi}\rangle^2]$$



$$\frac{f_{\rm NL}^{\rm equil.}}{75} \sim 12\,\frac{\mu}{H}\left(\frac{r}{0.2}\right)^{1/2}\left(\frac{M_{\rm pl}}{\Lambda}\right)^3$$

$$f_{\rm NL}^{\rm equil.} \;=\; -42 \pm 75 \;\;(\text{at}\;\; 1\sigma)$$

Current constraint from Planck

Testing Split Supersymmetry with Inflation

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Energy Scales

Energy

M_{pl} $\qquad \Lambda_b^4 = 2M_{pl}^2|\dot{H}|$

$V^{1/4}$

Λ_b

H

$m \sim \sqrt{\eta}H$

- Only weak breaking of dS symmetry
- We are looking at vacuum fluctuations of the clock
- Interesting signatures could remain if there are light states.

The future?

Deviation from the line

$$(n_s - 1) + \frac{r}{4} + \frac{11}{24}(n_s - 1)^2 = 0$$

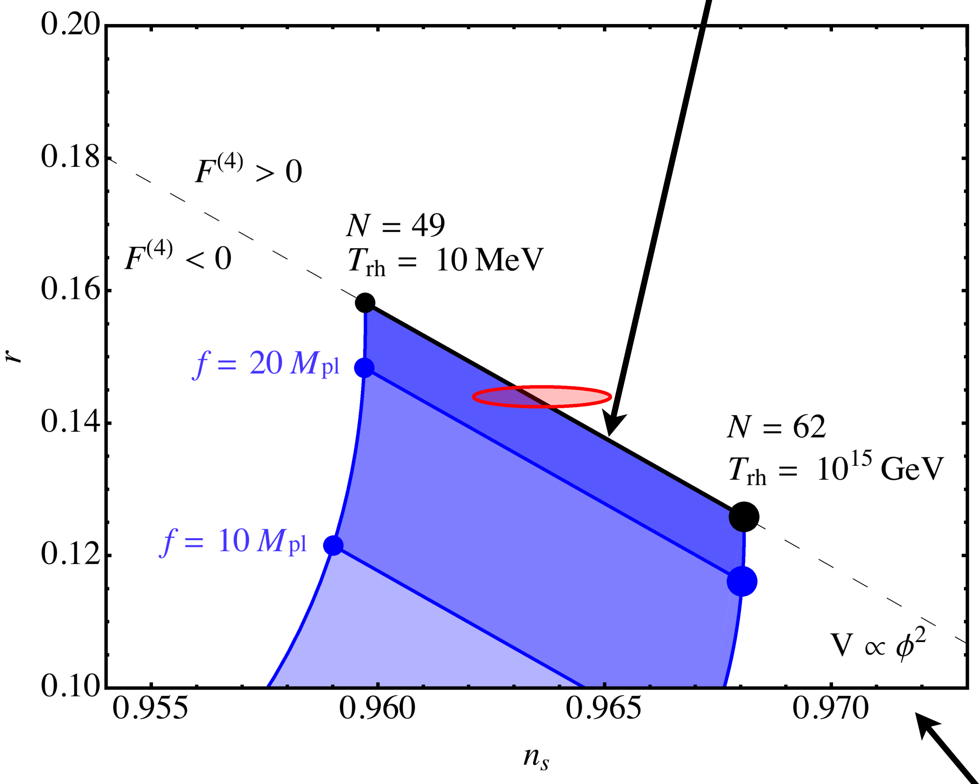


FIG. 1: *Future constraints on f assuming a simple cosine potential. The dashed curve corresponds to Eq. (1) and the black segment covers the interval of reheating temperatures $T_{\rm rh} \in [10\ \text{MeV}, 10^{15}\ \text{GeV}]$. A wider range of N is allowed if one considers non-standard cosmological evolutions after inflation. Red 1σ contour corresponds to a futuristic measurement with $\sigma_{n_s-1} = \sigma_r = 10^{-3}$, compatible with a quadratic potential.*

- Crucial to measure ns better
- Error in N around 0.4
- Constraints on small departures:

$$V(\phi) = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right) \rightarrow f > 30 M_{pl}$$

$$(\partial\phi)^4/\Lambda^4 \rightarrow \Lambda \gtrsim 2\cdot 10^{16}\ \text{GeV}$$

$$c_s^2 - 1 = 16\frac{\dot{H} M_{\rm pl}^2}{\Lambda^4}$$

- Running for consistency

$V \propto \phi$

Lives outside the plot !

Summary

We may have entered a complete new era with a new fossil from the early Universe to measure.

The models from the 80s have stood the test of time remarkably well.

Direct test

Baumann & MZ 0901.0958

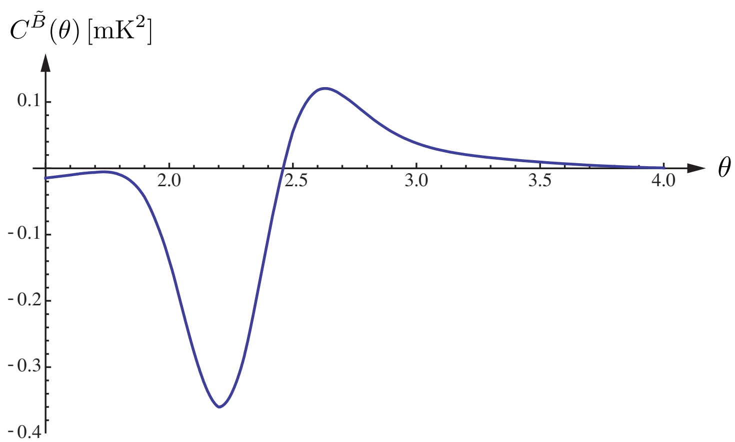
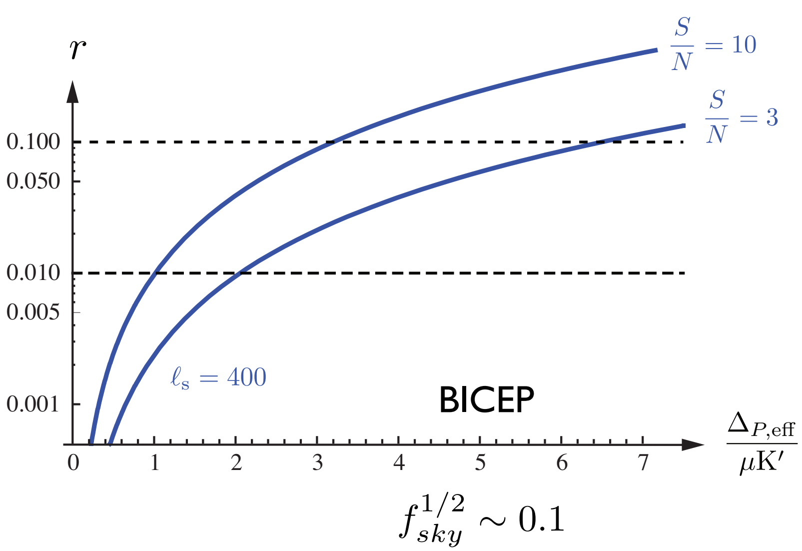


Figure 3: $C^{\tilde{B}}(\theta) = \langle \tilde{B}\tilde{B} \rangle(\theta)$: real space correlation function on superhorizon scales. $C^{\tilde{B}}(\theta \gtrsim 2^\circ) \neq 0$ is a unique signature of inflationary tensor modes.



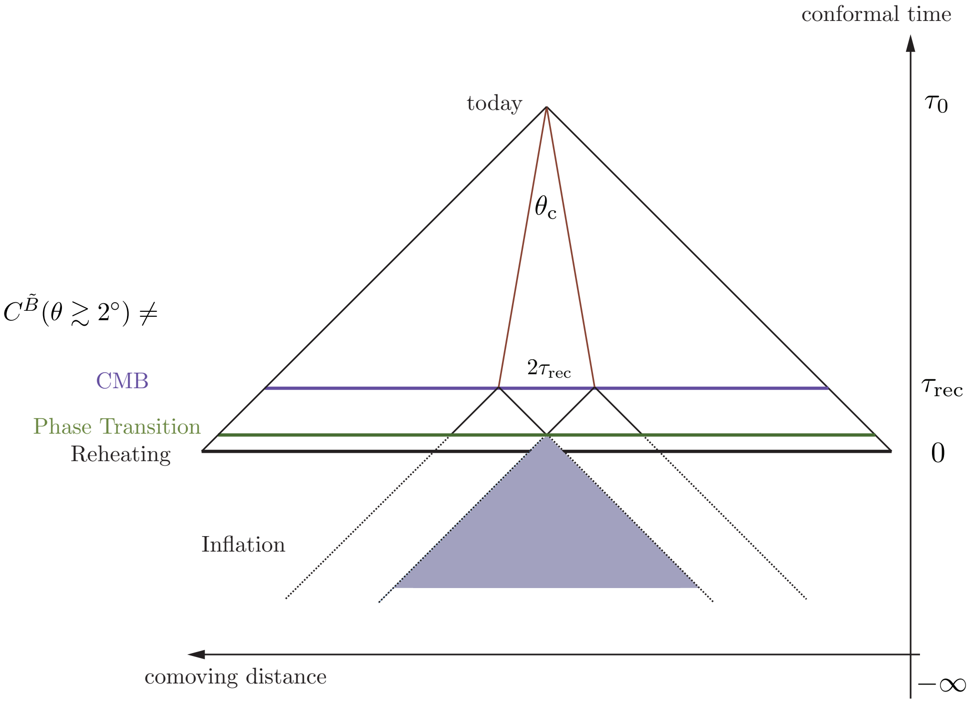


Figure 1: Causal structure of the universe. Correlations between any local variables at any two spacetime points vanish if their backward light cones fail to intersect on the spacelike hypersurface Σ corresponding to the phase transition at $\tau = \tau_{\mathrm{pt}}$ [14]. On the surface of last-scattering at τ_{rec} this corresponds to angular separations $\theta > \theta_c \approx 2^\circ$. Longer range correlations are established during inflation at negative values of conformal time, $\tau < 0$.

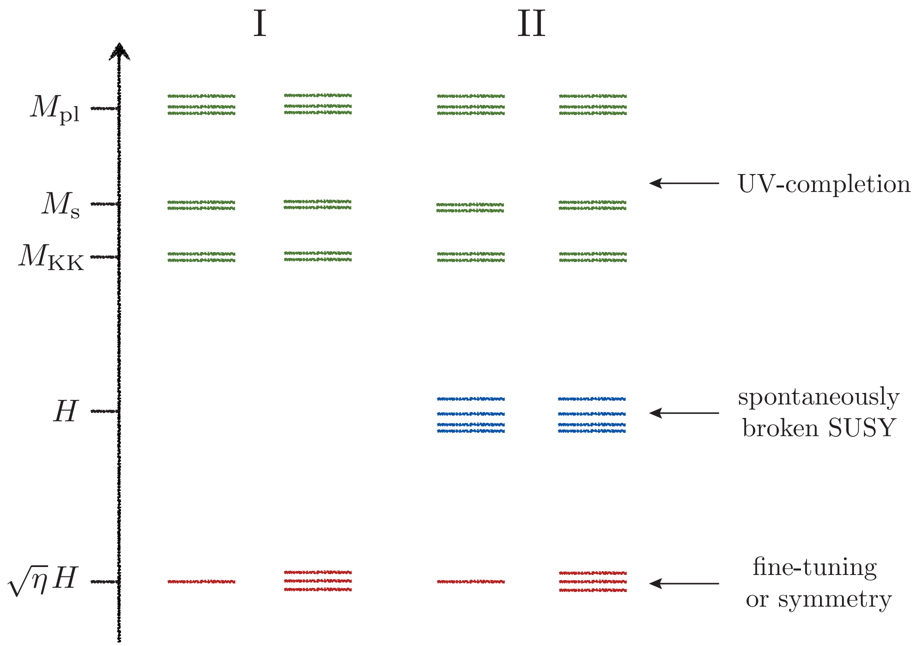


Fig. 4.1. Mass spectra of inflationary models. Phenomenological models of inflation frequently assume a large hierarchy between one or more light inflaton fields and the extra states of the UV completion (I). On the other hand, concrete examples of inflation in string theory often contain fields with masses of order the Hubble scale (II) arising from the spontaneous breaking of supersymmetry. Robust symmetries, or fine-tuning, are required to explain the presence of scalars with masses $m \sim \sqrt{\eta}\,H$.

1404.2601 Baumann & McAllister

What to conclude

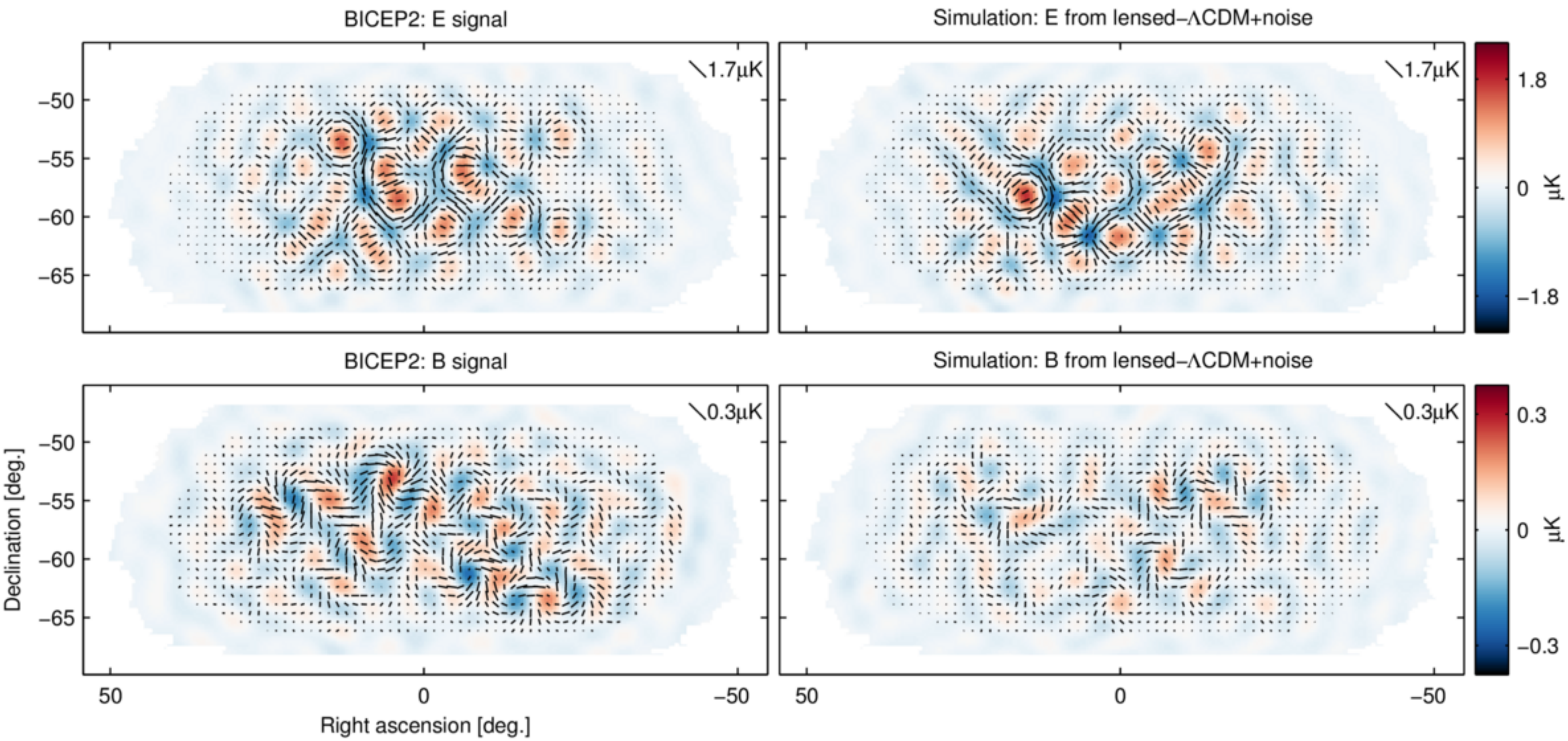
"Probably" fluctuations were not converted into curvature at the beginning of the HBB but the window is not completely closed. How do we close it?

This is particularly interesting because only inflationary backgrounds gives us scale invariant curvature perturbations. One can tune the two point function to be scale invariant around other backgrounds but interactions (higher order moments) are not scale invariant. In inflation, time translational is the origin of scale invariance and thus it is a very robust outcome, irrespective of the details of how the perturbations are generated or interact.

To get scale invariant perturbations around other backgrounds people have to invoke a second field that converts later.

Furthermore building a theory for some of the anomalies requires a second field so not seeing local non-G provides an interesting constrain.

We are led to think about the adiabatic fluctuations during inflation.


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