Title: Overview

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Abstract:

B-modes!

Kendrick Smith
Perimeter, April 2014

BICEP2 has detected B-modes!

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(*) loopholes: foregrounds, systematics

Inflation is the correct model of the early universe!

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Inflation is the correct model of the early universe! (*)

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Inflation takes place at energy scale 10^{-2} M_{Pl}; field excursions are of order M_{pl}

Let's bask in how amazing this is

If we ignore the loopholes:

- Inflation, a theory originally proposed with almost no observational clues, is testable and confirmed!
- We can observe physics at energies near the Planck scale!
- We have observed a quantum gravitational effect! (in semiclassical regime)

Standard cosmological model

Pre-BICEP2, six parameters were needed to fit a wide variety of observations:

$\{\Omega_b, \Omega_c, H_0\}$	Flat **Λ**CDM expansion history
$\{\Delta_\zeta, n_s\}$	Gaussian scalar adiabatic power-law initial conditions: $(k^3/2\pi^2)P_\zeta(k) = \Delta_\zeta^2(k/k_0)^{n_s-1}$
τ	Optical depth to recombination (nuisance parameter)

Philosophy: "parameterize all surprises and shrink error bars"

No evidence for: isocurvature modes, primordial non-Gaussianity, spatial curvature, deviation from **Λ**CDM, extra neutrino species, non-power law initial conditions, etc…

Standard cosmological model

17 March 2014: BICEP2 announces detection of primordial tensor modes!

Seventh parameter needed: tensor-to-scalar ratio r

$$(k^3/2\pi^2)P_\zeta(k) = \Delta_\zeta^2(k/k_0)^{n_s-1}$$

$$(k^3/2\pi^2)P_T(k) = r\Delta_\zeta^2(k/k_0)^{n_t}$$

Initial conditions are given by metric (in appropriate gauge)

$$ds^2 = -dt^2 + a(t)^2 e^{2\zeta(x)}(\delta_{ij} + h_{ij}(x))$$

Gaussian scalar field with power spectrum P_ζ

Gaussian traceless symmetric tensor with power spectrum P_T

Slow-roll single-field inflation

Scalar field ϕ slowly rolling down nearly flat potential V(ϕ)

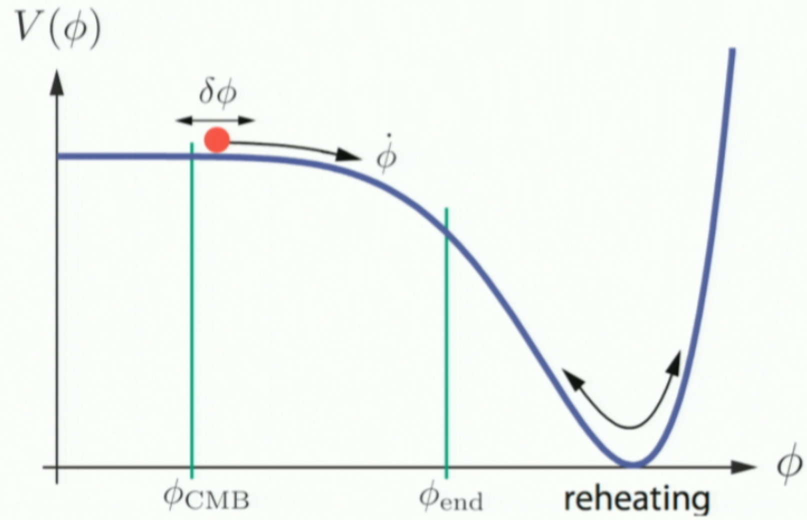
$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2}(\partial\phi)^2 - V(\phi) \right)$$

Flatness condition:

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

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

are $\ll 1$.



Slow-roll single-field inflation

As inflation progresses, the ϕ and g_{ij} fields are quantum mechanically excited and are Gaussian fields at the end of inflation. The observables $\{\Delta_\zeta, n_s, r\}$ are related to $V(\phi)$ by:

$$\Delta_\zeta^2 = \frac{1}{8\pi^2\epsilon}\frac{H^2}{M_{\rm Pl}^2} \qquad n_s - 1 = -6\epsilon + 2\eta \qquad r = 16\epsilon$$

Post-BICEP2, everything is pinned down!

$$\Delta_\zeta^2 = 2.2 \times 10^{-9} \qquad n_s = 0.96 \qquad r = 0.2$$

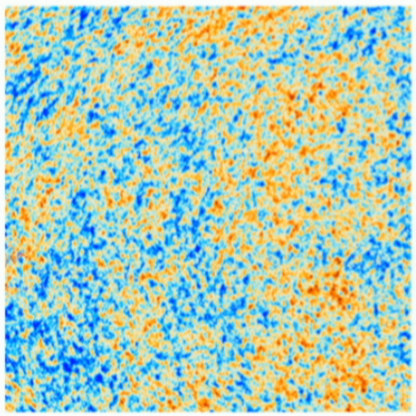
$\Rightarrow$ Energy scale of inflation $V^{1/4} = 0.0090\, M_{\rm Pl} = 2.2 \times 10^{16}$ GeV

First two derivatives $\dfrac{V'}{V} = 0.6\, M_{\rm Pl}^{-1}$, $\dfrac{V''}{V} = 0.017\, M_{\rm Pl}^{-2}$

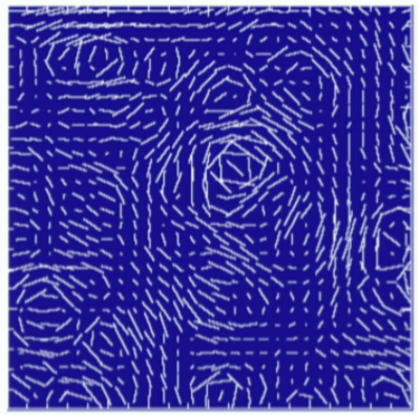
Field excursion per e-folding $\dfrac{d\phi}{d\log a} = 0.06\, M_{\rm Pl}$

CMB fields

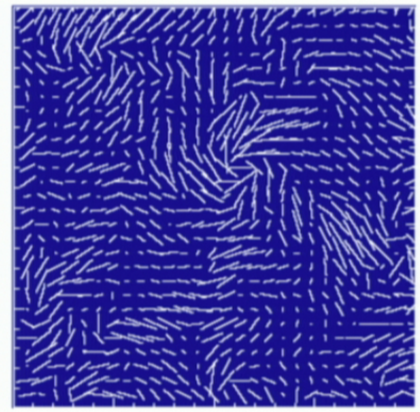
Temperature



E-mode linear polarization



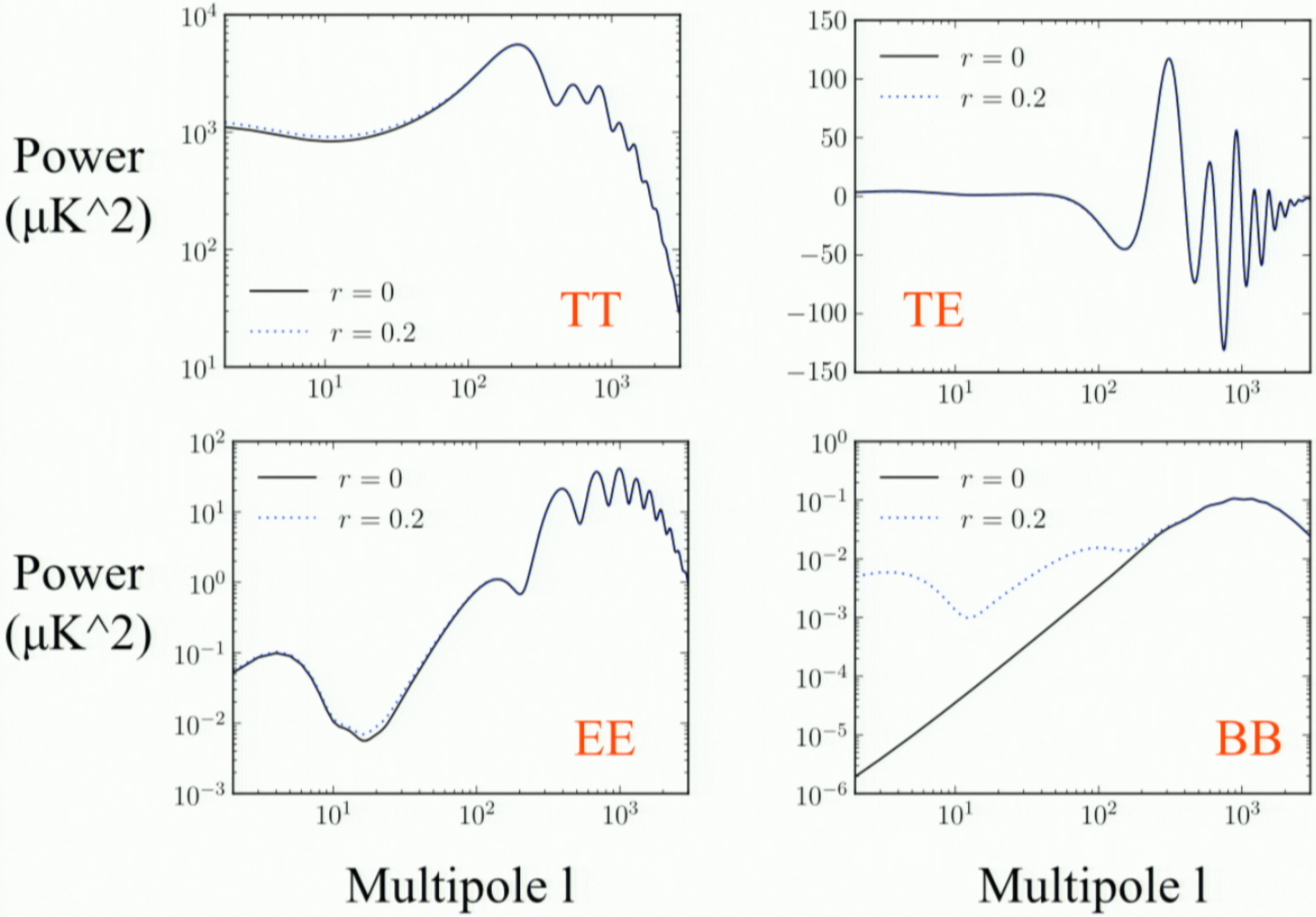
B-mode linear polarization



E/B decomposition of linear polarization (traceless symmetric tensor) is similar to gradient/curl decomposition of vector field

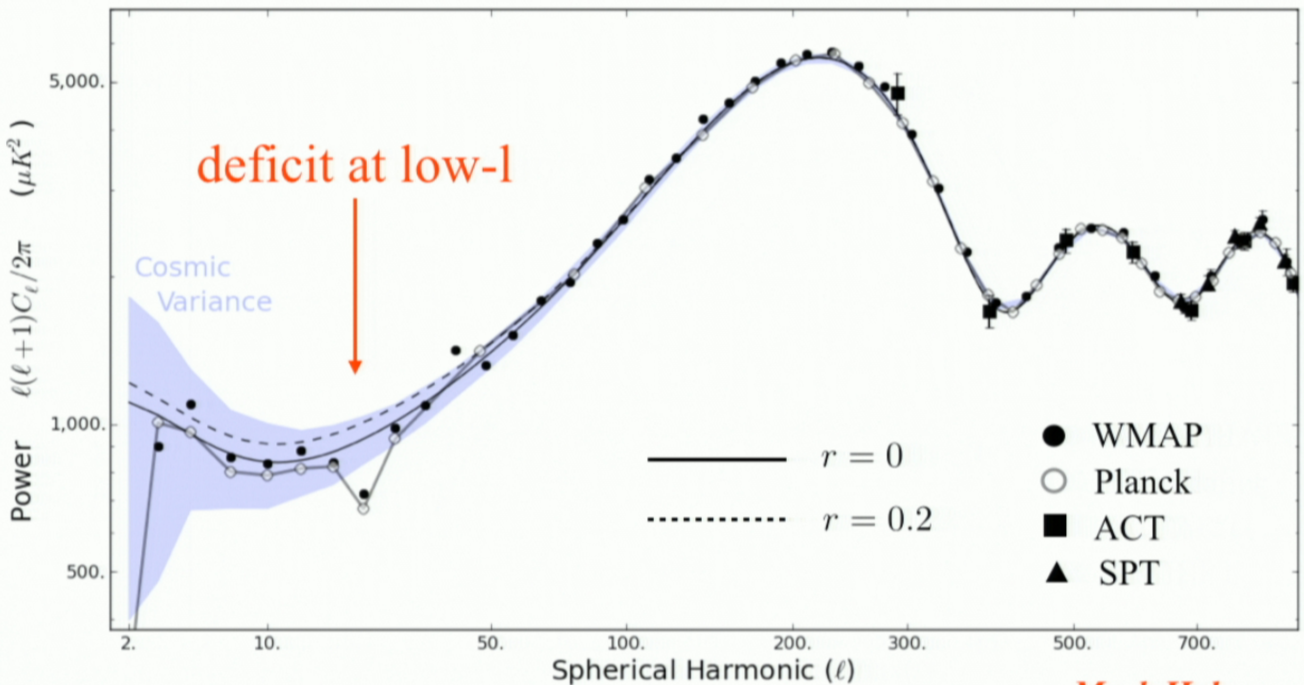
Theorem: (scalar perturbations) + (linear perturbation theory)
$\Rightarrow$ (no B-modes are generated)

CMB power spectra



Pre-BICEP2 measurements

TT power spectrum:

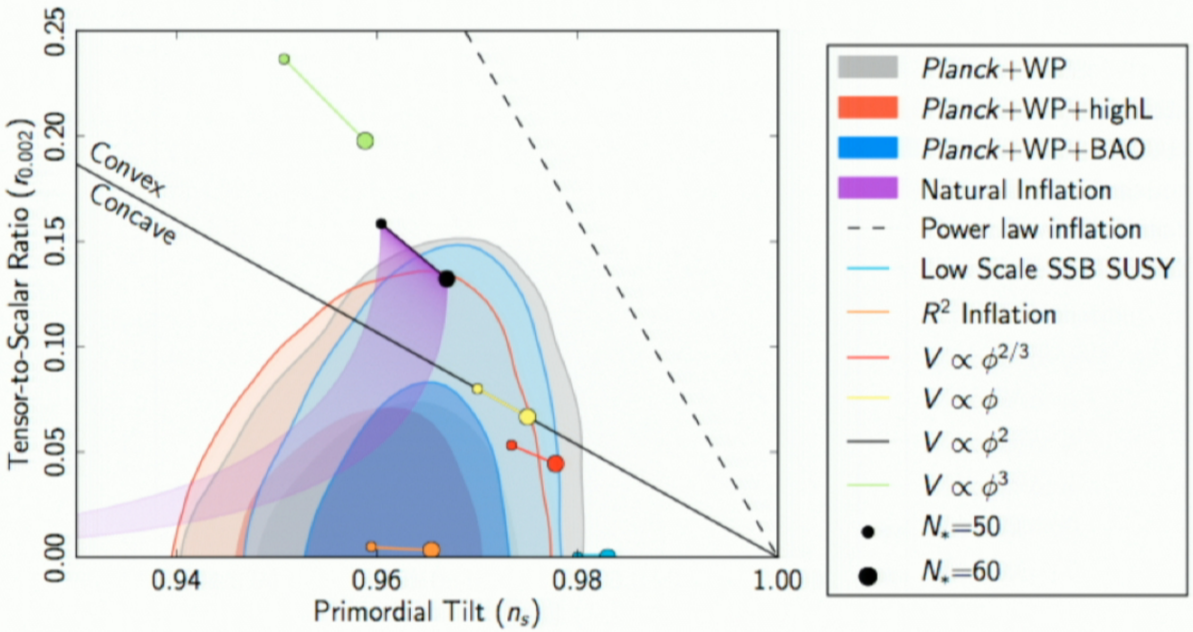


Mark Halpern

TE and EE are not yet very informative, but coming soon (Planck)

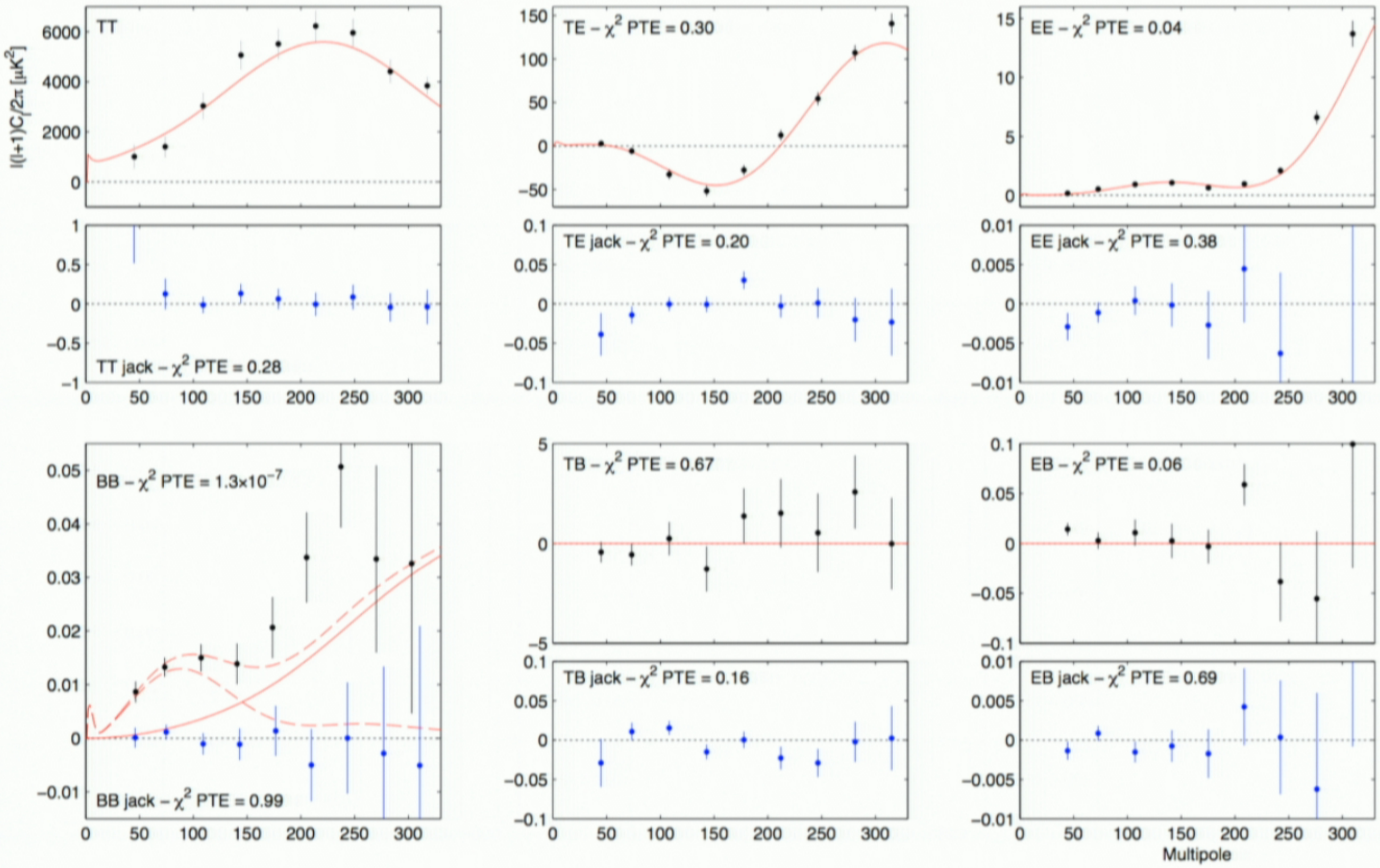
Pre-BICEP2 measurements

Observed temperature power spectrum is low, even relative to r=0
This gives a strong upper limit: r < 0.11 (95% CL, Planck+WP)



Planck collaboration

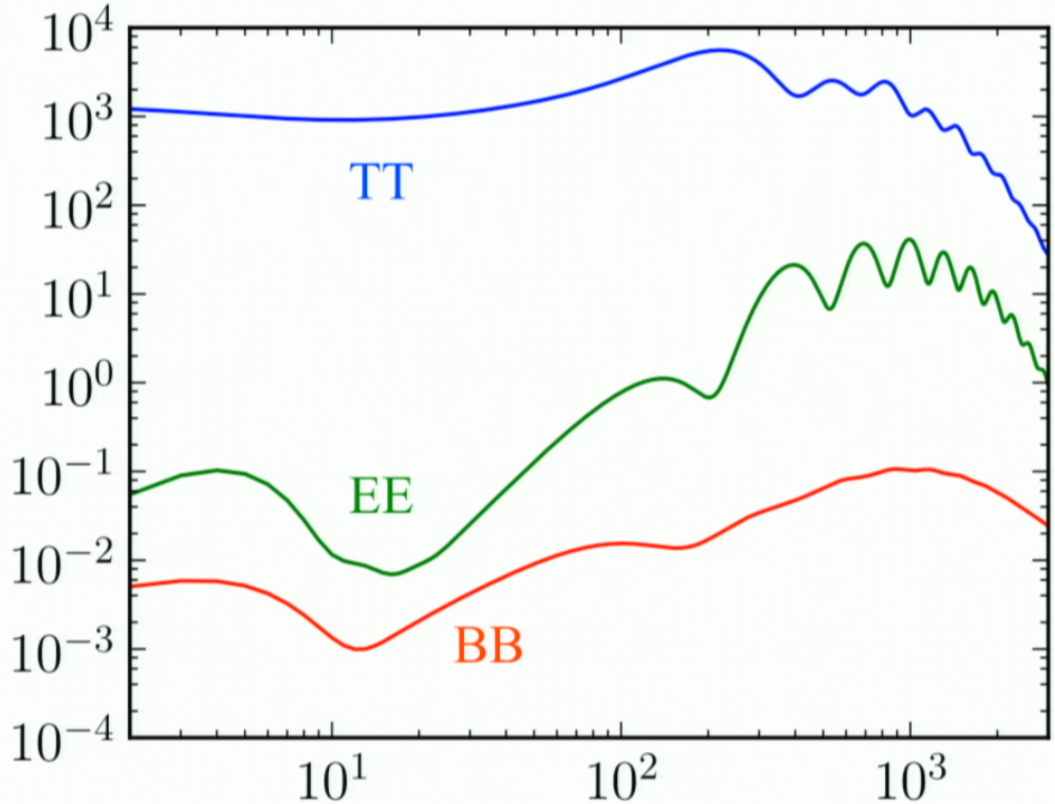
BICEP2 measurement



BICEP2 collaboration

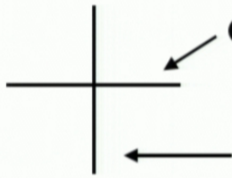
Systematics

Instrumental effects can convert the (much larger) temperature or E-mode anisotropy into B-modes



Systematics

Cartoon polarization sensitive bolometer:



one wire measures $\langle E_x^2 \rangle$

one wire measures $\langle E_y^2 \rangle$

Signals are subtracted to get linear polarization

$$Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle$$

If the two signals don't

have the correct relative calibration ("differential gain")
have the same beam pattern on the sky ("differential beam")
point to the same place on the sky ("differential pointing")

then temperature will "leak" into the polarization measurement Q

Systematics

Characterizing and projecting out systematics is the hardest, most time-consuming part of an analysis like BICEP2.

Useful benchmark: jackknifes (null tests).

Divide data into uncorrelated subsets

Make maps m_1, m_2

Compute power spectrum of null map (m_1-m_2)

Test for consistency with noise

Systematics

TABLE 1
JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.020	0.005	0.045	0.352
BB	0.452	0.095	0.261	0.045
EB	0.307	0.633	0.201	0.266
Scan Dir jackknife				
EE	0.704	0.678	0.910	0.965
BB	0.497	0.658	0.915	0.487
EB	0.879	0.864	0.643	0.829
Temporal Split jackknife				
EE	0.462	0.352	0.905	0.955
BB	0.844	0.990	0.457	0.482
EB	0.402	0.648	0.769	0.533
Tile jackknife				
EE	0.010	0.035	0.000	0.010
BB	0.568	0.668	0.472	0.221
EB	0.121	0.442	0.965	0.804
Azimuth jackknife				
EE	0.668	0.447	0.111	0.332
BB	0.608	0.809	0.693	0.894
EB	0.588	0.543	0.693	0.603
Mux Col jackknife				
EE	0.779	0.623	0.206	0.206
BB	0.492	0.854	0.261	0.156
EB	0.965	0.945	0.774	0.628

… (9 more)

BICEP2 collaboration

Foregrounds

The most important "foreground" (i.e. astrophysical) sources of emission at CMB frequencies are

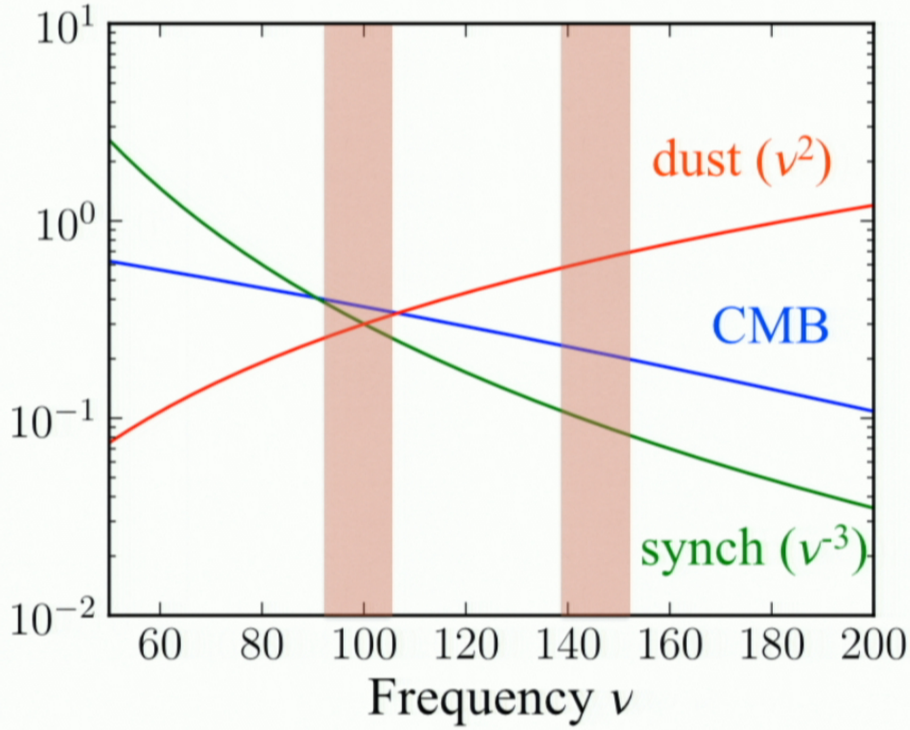
Synchrotron radiation from high-energy electrons accelerating in the magnetic field of our galaxy (polarized perpendicular to magnetic field)

Thermal dust emission, weakly polarized perpendicular to B due to tendency for shortest axis of dust grains to line up with magnetic field

BICEP2 observes in a small (~1%) patch of sky chosen to minimize these foregrounds

Foregrounds

Foregrounds/CMB can be separated by making observations at multiple frequencies



BICEP1
100+150 GHz

BICEP2
150 GHz only

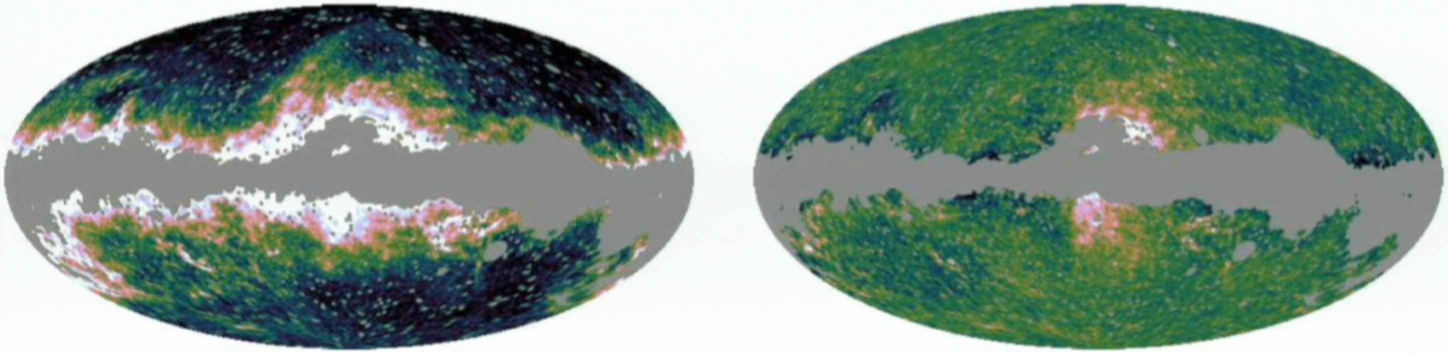
WMAP
23-94 GHz

Planck
30-353 GHz
(polarization)

Synchrotron foreground

Unpolarized synchrotron very well mapped and characterized

Spectrum is "harder" near the galactic center ("microwave haze") and can be fit by a two-component model with $\nu^{-3.1}$ and $\nu^{-2.5}$ components



Planck collaboration

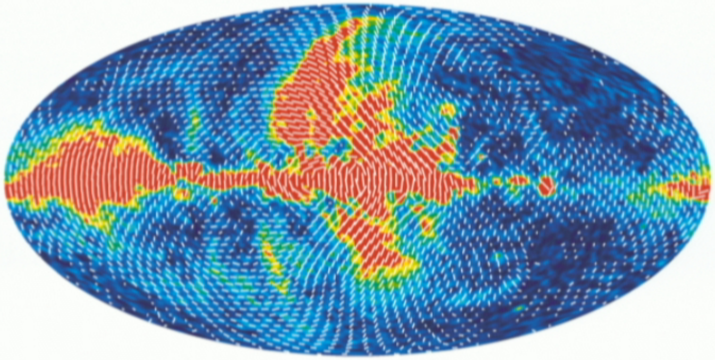
Synchrotron foreground

Best polarized synchrotron measurements come from WMAP 23 GHz channel

Polarization fraction $(Q^2+U^2)^{1/2}/T$ varies between 0.05-0.3 (larger away from galactic plane)

No evidence for "hard" component in polarization

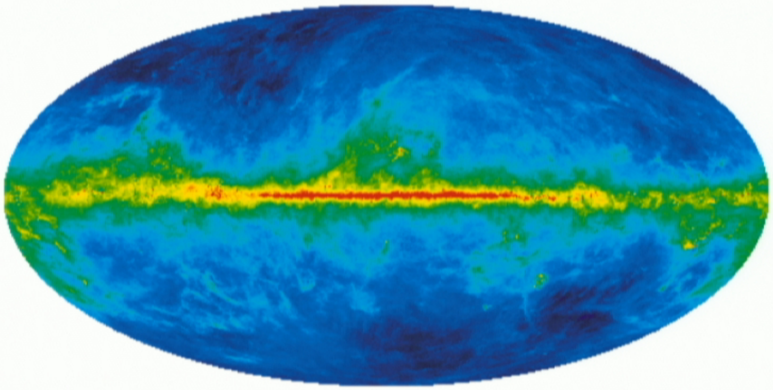
"Templates" for polarized synchrotron are available in the BICEP2 patch (although S/N isn't much higher than BICEP2!)



WMAP collaboration

Dust foreground

Unpolarized dust modeling is extremely important in many branches of astronomy and it has been modeled to death! Full-sky maps are available as a function of frequency



Polarized dust emission is harder. From WMAP (94 GHz), the polarization fraction is "a few percent", but WMAP is nowhere near sensitive enough to provide templates in the BICEP2 patch…

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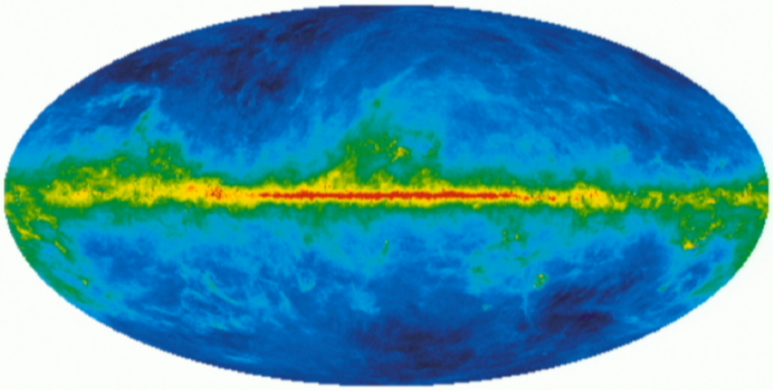

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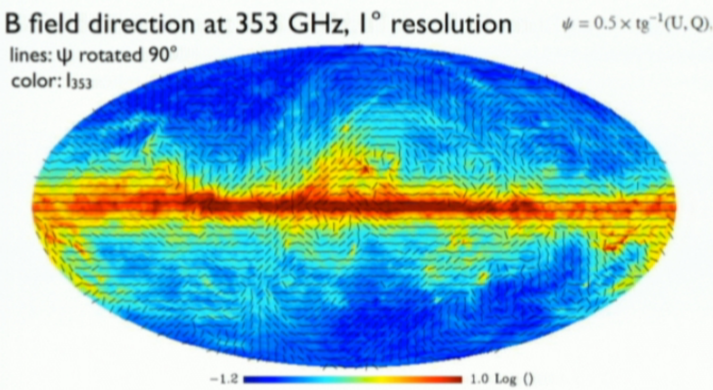
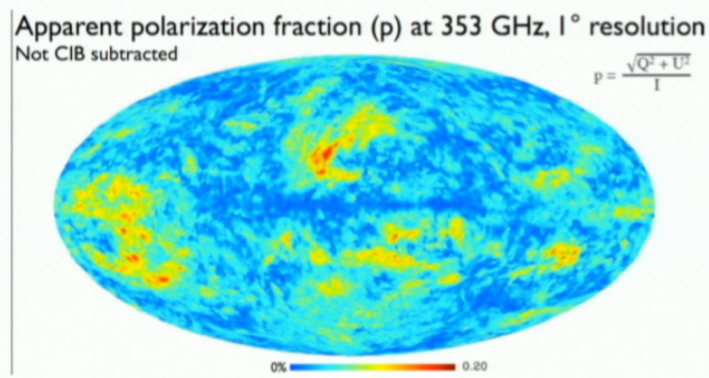
Dust foreground

Templates will become available soon when Planck makes 353 GHz polarization maps public. In the meantime, one can…

Combine *unpolarized* dust templates with a model of the Galactic magnetic field (to guess polarization fraction and direction)

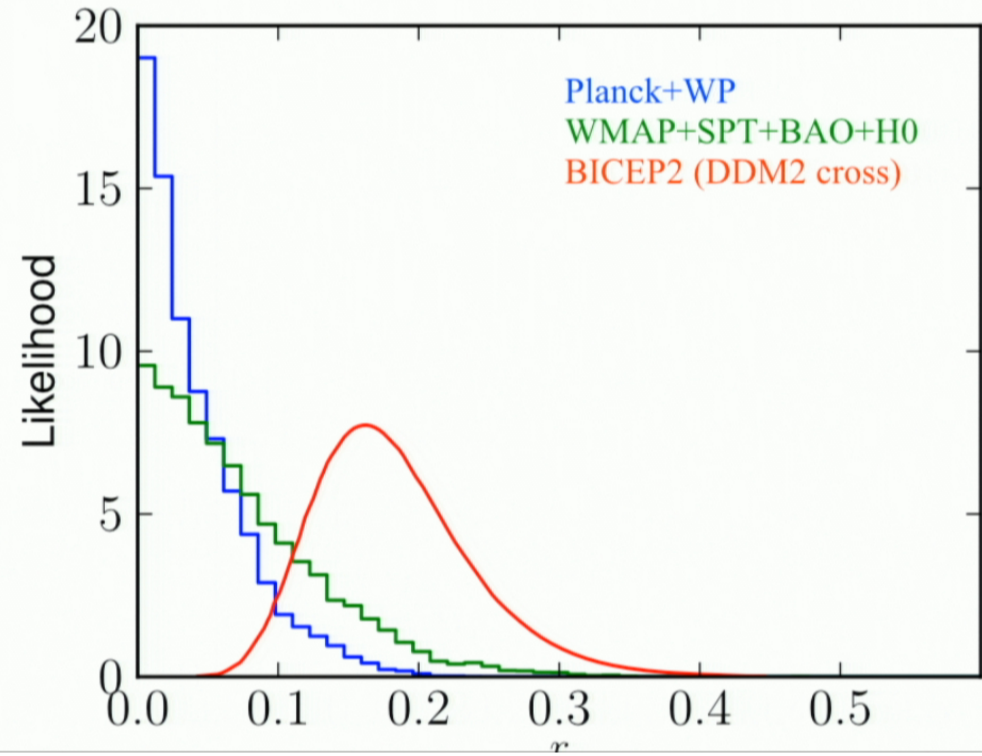
Or use these images from a Planck talk online! (ESLAB 2013)





Planck/BICEP2 tension

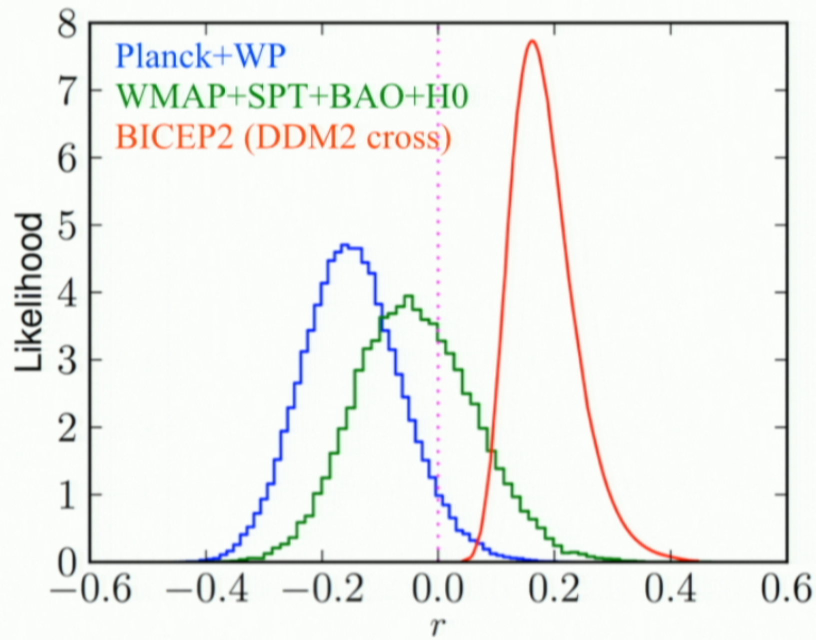
Comparison of r likelihoods suggests Planck/BICEP2 tension is a few percent unlikely (precise value depends on foreground model)



Planck/BICEP2 tension

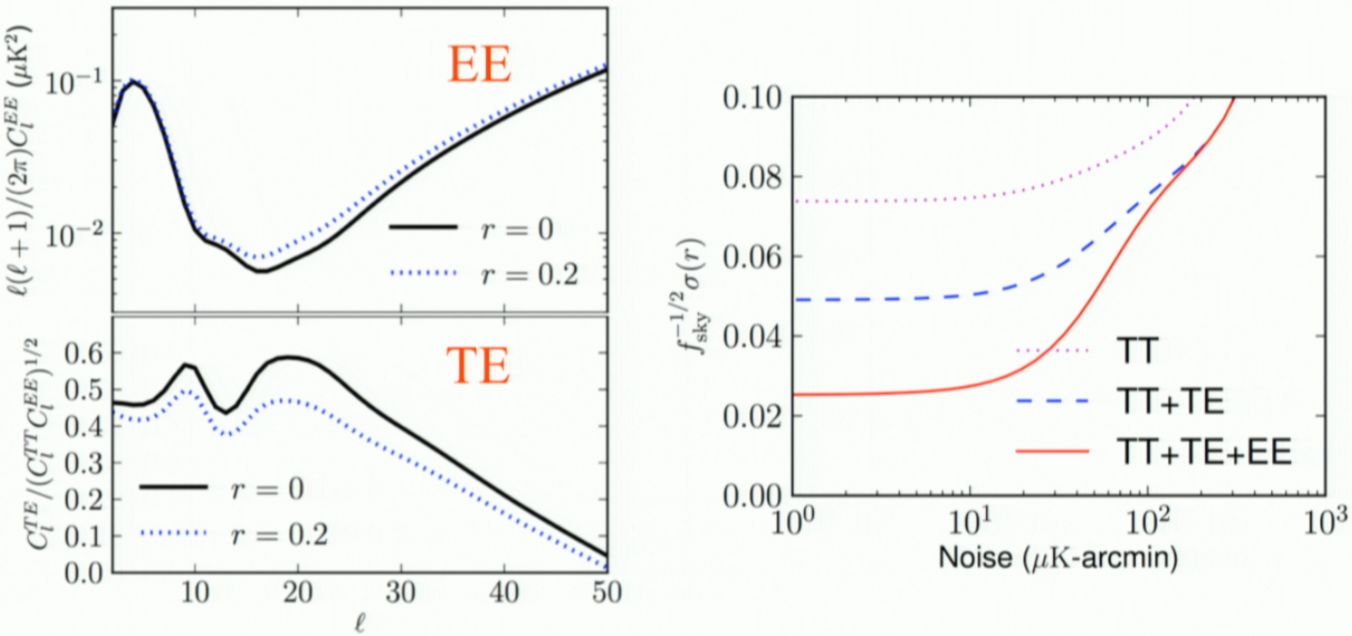
If r likelihoods are continued to negative r, Planck likelihood peaks negative at 1.6σ, and tension is around 0.1%.

Negative r does not make sense physically but is a way of parameterizing TT power deficit without making *a posteriori* choice of l-weighting



Planck/BICEP2 tension

E-mode measurements will tell us soon whether tension is cosmological or a statistical fluke



In the meantime, it's interesting to enumerate possible cosmological explanations. The result of a "brute force" search follows…

Planck/BICEP2 tension

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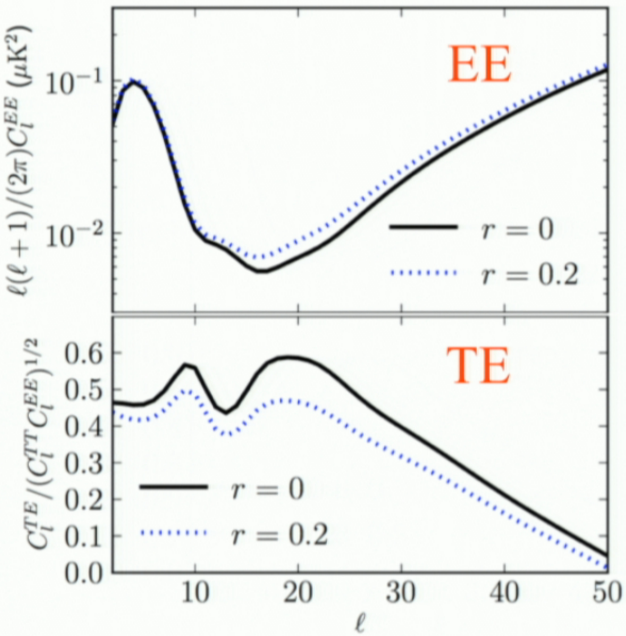
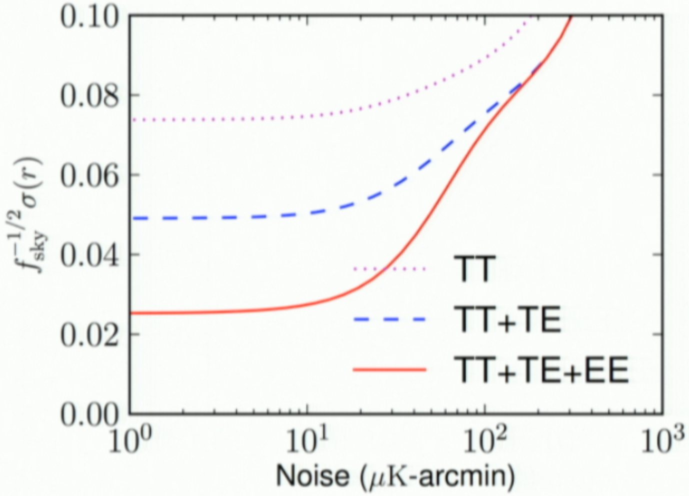




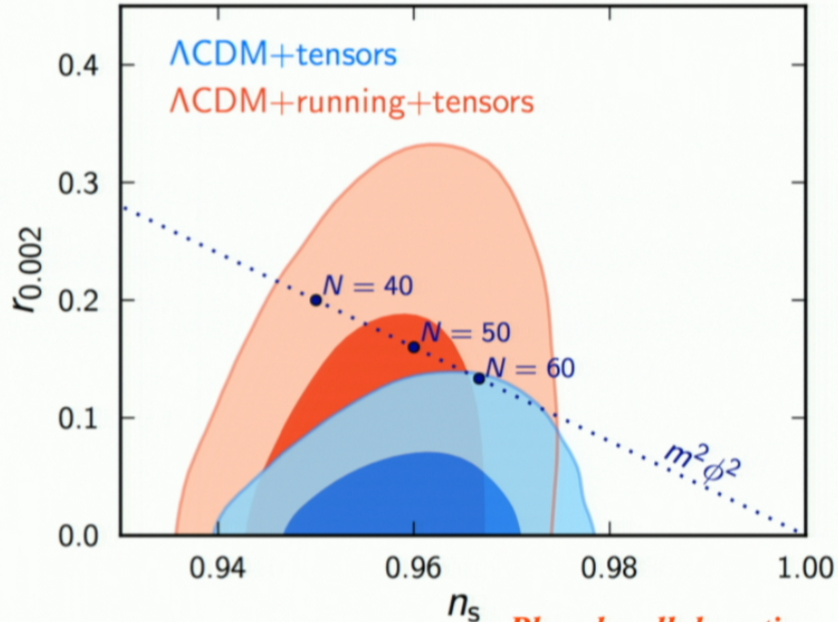
In the meantime, it's interesting to enumerate possible cosmological explanations. The result of a "brute force" search follows…

"Running" scalar power spectrum?

Scalar "running" α_s parameterizes subleading deviation from scale invariance:

$$\log P_\zeta(k) = \log P_\zeta(k_0) + (n_s - 4)\left(\log \frac{k}{k_0}\right) + \frac{1}{2}\alpha_s \left(\log \frac{k}{k_0}\right)^2$$

As pointed out by BICEP2, Planck allows r as large as 0.2 if running is allowed to be large:



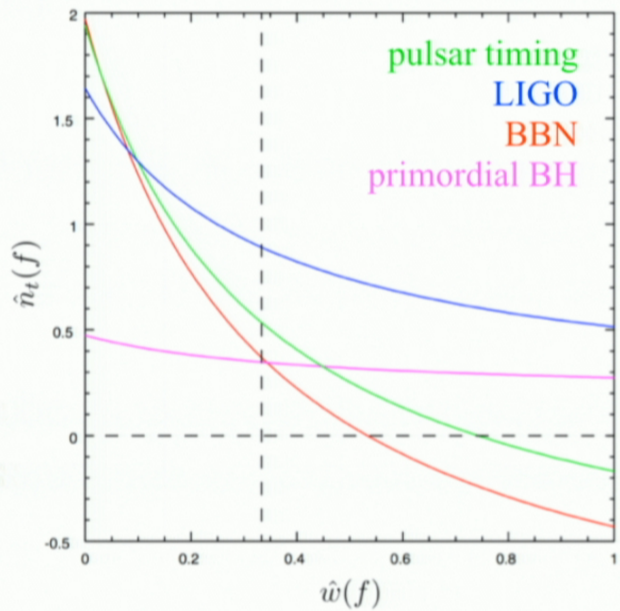
Planck collaboration

“Running” scalar power spectrum?

- Planck+BICEP2: best-fit $\alpha_s = -0.028$, nonzero at 3σ
- Larger than slow-roll prediction by factor ~100, but can be accommodated if one is willing to tune at the ~1% level
- Associated bispectrum signal is too small to be detected
- Running this large would have implications for futuristic direct gravity wave experiments (forecast in a few slides…)

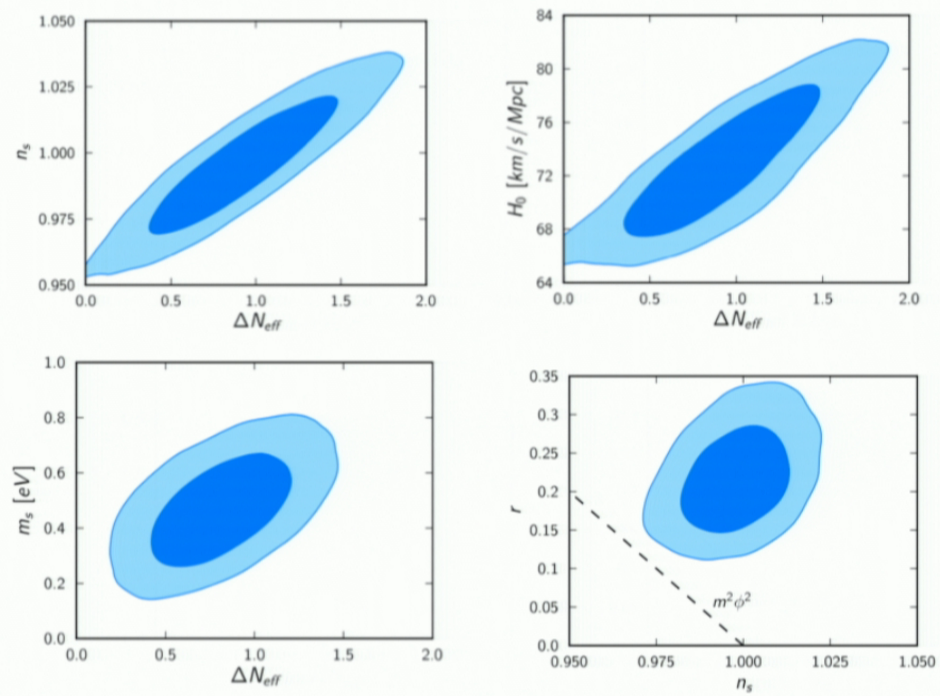
"Tilted" tensor spectrum?

- Since Planck/BICEP2 r-measurements are on slightly different scales (l=35 vs l=60), tension would be resolved by a tensor power spectrum $P_T(k)$ which is very non scale invariant
- Quantitatively, fitting Planck+BICEP2 to $k^3 P_T(k) \propto k^{n_T}$ gives $0.42 < n_t < 1.27$ (95% CL)
- In strange model-building territory since $n_t < 0$ and $\mathcal{O}(10^{-2})$ in single-field slow-roll!
- BBN / black hole constraints can be evaded if mean over many efoldings satisfies $\langle n_t \rangle \lesssim 0.4$



Sterile neutrinos?

Dvorkin, Wyman, Rudd, Hu (Monday): a sterile neutrino with mass m_s=0.5 eV reconciles both Planck/BICEP2 and Planck/H_0, but pushes n_s to 1 and disfavors ϕ^2 inflation:



What's next?

Near future: Race to confirm the B-mode bump!

Many imminent B-mode experiments (Planck, SPTpol, ACTpol, ABS, EBEX, Polar, Polarbear, SPIDER, CLASS) designed with $r=10^{-2}$ in mind, overkill for $r=0.2$!

E-mode polarization measurements should also resolve or sharpen the Planck/BICEP2 discrepancy

What's next?

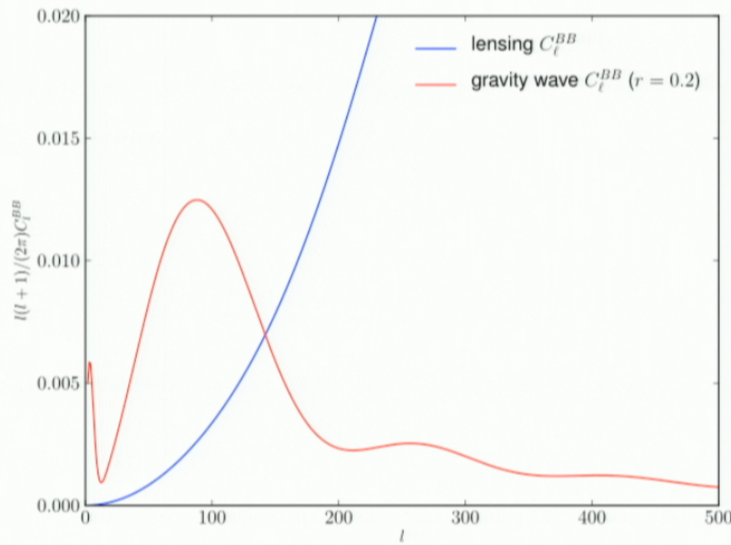
Longer term: if r=0.2, we can think about characterizing scale dependence of the *tensor* power spectrum

$$(k^3/2\pi^2)P_T(k) = r\Delta_\zeta^2(k/k_0)^{n_t}$$

Cosmic variance limit for B-modes: $\sigma(n_t) \approx 0.03$

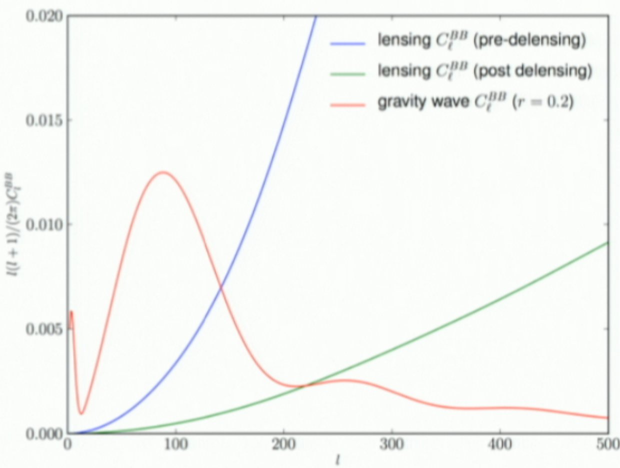
Can compare to "single field consistency relation"
$n_t = -r/8 \approx 0.0225$

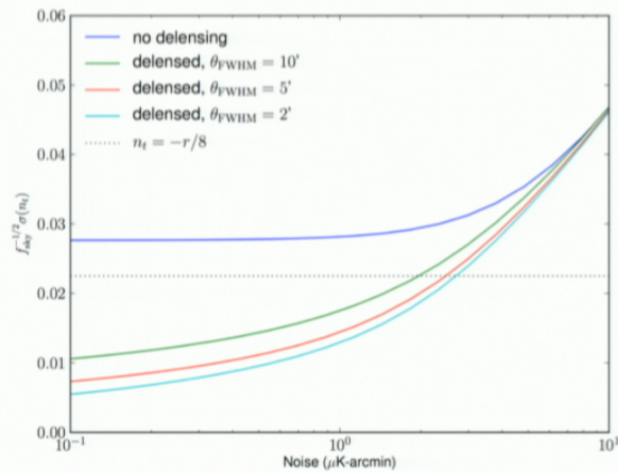
[in single-field slow roll, $r = 16\varepsilon$ and $n_t = -2\varepsilon$]



What's next?

"Delensing": a class of statistical algorithms which can separate the lensing B-modes (which are non-Gaussian) and tensor B-modes (Gaussian), lowering the effective lensing background



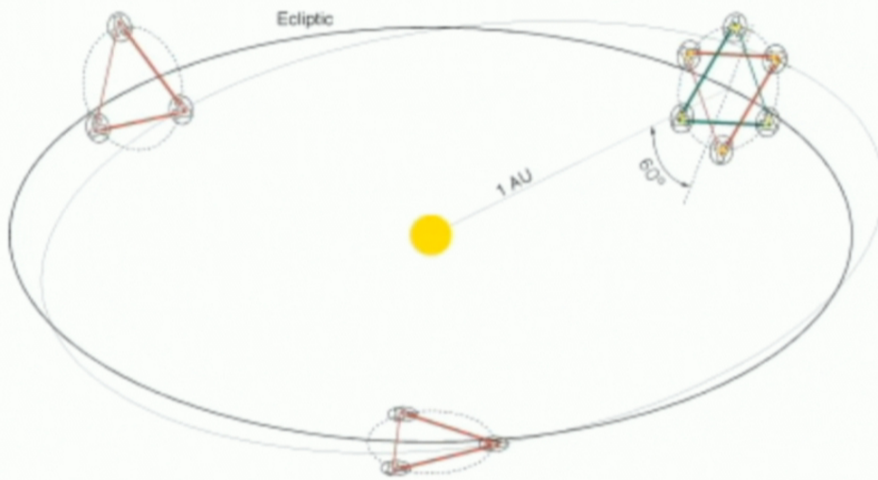


Very futuristic, but the CMB may be able to distinguish the consistency relation (n_T=-r/8) and scale invariance (n_T=0) at a few sigma

What's next?

BBO: proposed experiment to measure primordial gravity waves on solar system scales ($k_{BBO}/k_{CMB} \sim 10^{17} \sim e^{39}$!)

Essentially measures one number $\Omega_{gw}(k_{BBO})$ which complements CMB observables { Δ_ζ, n_s, r, n_t }. For a "typical" slow-roll potential (e.g. $m^2\phi^2/2$), detection is 30σ!

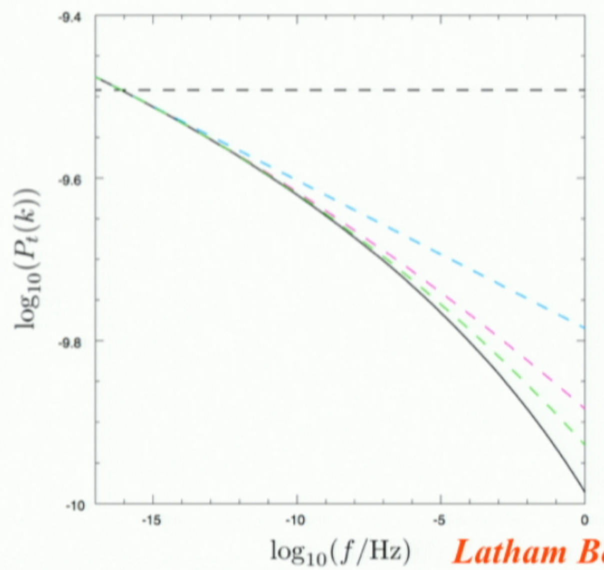


What's next?

Given a slow-roll potential (e.g. $V(\phi) = m^2\phi^2/2$), can integrate equations of motion to compute $P_T(k_{BBO})$.

Power-law spectrum $P_T(k) \propto k^n$ is not a good approximation over 39 e-foldings. Get a decent approximation by expanding log $P_T(k)$ in powers of $\log(k/k_0)$ and keeping 3 terms:

$$\begin{aligned}\log P_T(k) = \log P_T(k_{\rm CMB}) \\ +(n_t - 3)\left(\log\frac{k}{k_0}\right) \\ +\frac{1}{2}\alpha_t\left(\log\frac{k}{k_0}\right)^2 \\ +\frac{1}{6}\beta_t\left(\log\frac{k}{k_0}\right)^3\end{aligned}$$



Latham Boyle

What's next?

Generalization of single-field consistency relation: coefficient of each term can be computed in terms of r, n_s, and running α_s

$$n_t = -r/8$$

$$\alpha_t = \frac{r}{8}\left(n_s - 1 + \frac{r}{8}\right)$$

$$\beta_t = \frac{r}{8}\left(\alpha_s + (n_s - 1)^2 - \frac{3r}{8}(n_s - 1) + \frac{r^2}{32}\right)$$

relating $\Omega_{gw}(k_{BBO})$ to CMB observables

What's next?

BBO in action:

Consider a scenario where future measurements of ns, r are consistent with $m^2\phi^2$, so we believe this to be the correct model. Then we get a sharp prediction for $\Omega_{gw}(k_{BBO})$ which can be measured to ~3%, thus testing the $m^2\phi^2$ form over 39 e-foldings!

Consider a scenario where the Planck/BICEP2 tension holds up and we are left wondering whether running is the explanation. Then BBO can measure α_s to 10^{-3}!

Suppose we fit r, n_s, α_s from the CMB and want to test the single-field consistency relation. BBO can do this at ~20σ!

Conclusions

It's a new world! (*)

(*) probably