Outline

1. Inflation and its generic predictions (brief reminder)
2. Inflation vs. Planck data
3. Polarisation of the Cosmic Microwave Background
4. BICEP2
5. Theoretical implications of BICEP2's results
Inflation
Planck's CMB temperature map

Where do the anisotropies come from?
Inflation

Potential energy domination ("slow-roll" inflation)
- Attractor solution
- Scale factor grows exponentially with time
- Hubble parameter close to constant
- Space is flattened

Reheating
- Potential energy is converted to standard model particles
The origin of the primordial perturbations: inflation

Quantum fluctuations of $\phi$ are stretched beyond the horizon and freeze in
Perturbations of the metric

- In General Relativity, need to take into account perturbations of the whole metric, not just the inflaton field
- Decompose metric perturbations into scalar, vector and tensor perturbations
- Inflation generates scalar (curvature) and tensor perturbations (gravitational waves), but no vector perturbations
- Properties of the perturbations depend on the inflaton potential
Inflationary perturbations

Scalar (curvature) perturbations

\[ P_\mathcal{R}(k) \propto \frac{V}{\epsilon} \bigg|_{k=aH} \approx A_s \left( \frac{k}{k_*} \right)^{n_s-1+...} \]

\[ \epsilon \propto \left( \frac{V'}{V} \right)^2 \]

Tensor perturbations (gravitational waves)

\[ P_t(k) \propto V \bigg|_{k=aH} \approx A_t \left( \frac{k}{k_*} \right)^{n_t+...} \]

Tensor-to-Scalar ratio

\[ r \equiv \left. \frac{P_t}{P_\mathcal{R}} \right|_{k=0.002 \text{ Mpc}^{-1}} \]
Inflationary perturbations

Scalar (curvature) perturbations

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Also, generically:

- no significant non-trivial higher-order correlations (non-Gaussianities)
- if single field: adiabatic perturbations (i.e., no isocurvature modes)
Predictions of the simplest models

- **single-field canonical slow-roll inflation**
  - Adiabatic initial conditions
  - Nearly Gaussian initial fluctuations \( f_{NL} < 1 \)
  - Almost (but not exactly) scale-invariant curvature perturbations
  - Background of gravitational waves (tensor perturbations)
  - Spatial flatness \( \Omega_K \sim 10^{-5} \)
Probing the predictions of inflation

CMB temperature power spectrum (+ E-polarisation, large scale structure, ...)

Adiabatic initial conditions

Nearly Gaussian initial fluctuations \( f_{\text{NL}} < 1 \)

Spatial flatness \( \Omega_K \sim 10^{-5} \)

Almost (but not exactly) scale-invariant curvature perturbations

CMB bispectrum

Background of gravitational waves (tensor perturbations)

CMB B-polarisation power spectrum
Inflation vs. Planck
Spatial curvature constraints

Planck + WP

Planck + WP + BAO

No evidence for non-zero spatial curvature

[Planck 2013]
Constraints on scalar power spectrum

- Scale dependence clearly required
- No hints for anything more complicated than power-law

Power-law scalar spectrum fits Planck data very well

[Planck 2013]
Adiabaticity: constraints on isocurvature perturbations

Isocurvature fraction at ...

Types of isocurvature

Large scales

Intermediate scales

Small scales

Planck data are perfectly compatible with adiabatic initial conditions

[Planck 2013]
Non-Gaussianity: CMB angular bispectrum

[Planck 2013]
Non-Gaussianity

\[
\langle \Phi(\vec{k}_1) \Phi(\vec{k}_2) \Phi(\vec{k}_3) \rangle = (2\pi)^3 \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) f_{NL} F(k_1, k_2, k_3)
\]

Three-point correlation enforces triangular configurations Bispectrum

Three limiting cases

<table>
<thead>
<tr>
<th></th>
<th>Local</th>
<th>Equilateral</th>
<th>Orthogonal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_{NL})</td>
<td>2.7 ± 5.8</td>
<td>-42 ± 75</td>
<td>-25 ± 39</td>
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</tbody>
</table>

No evidence for non-Gaussianity

[Planck 2013]
Status of inflation last month

single-field canonical slow-roll inflation

Adiabatic initial conditions

Nearly Gaussian initial fluctuations

Almost (but not exactly) scale-invariant curvature perturbations

Background of gravitational waves (tensor perturbations)

Spatial flatness

\( \Omega_K \sim 10^{-5} \)

\( f_{\text{NL}} < 1 \)
Inflation model constraints (pre BICEP2)
Polarisation of the CMB
CMB polarisation

- The CMB is weakly linearly polarised:

[WMAP 2006]
E- and B-modes

Polarisation pattern can be described in terms of

- Stokes parameters Q and U (easier to measure)
- Parity-even, curl-free E-mode and parity-odd, grad-free B-mode (easier to handle theoretically)

E-mode

B-mode

taken from [Hu 2001]
Why is the CMB polarised?

- Thomson scattering results in linear polarisation
  (which is cancelled unless there is a quadrupole anisotropy)

taken from [Hu 2001]
Why is the CMB polarised?

• Thomson scattering results in linear polarisation (which is cancelled unless there is a quadrupole anisotropy)

Polarisation signal survives:
• from last scattering surface
• from reionisation

→ expect contributions on the largest scales (reionisation) and intermediate to small ($\ell > 100$) scales (last scattering)

Also: gravitational lensing can generate B-mode from initial E-mode polarisation
Polarisation spectra

Reionisation bump

[WMAP 2006]
CMB signals from primordial perturbations

B-polarisation is the ideal probe of tensor perturbations
BICEP2
BICEP2 is a microwave telescope at the south pole, and measured the CMB at a frequency of 150 GHz.
BICEP2: survey area

[BICEP2 2014]
BICEP2: polarisation maps

**Fig. 3.** *Left:* BICEP2 apodized $E$-mode and $B$-mode maps filtered to $50 < \ell < 120$. *Right:* The equivalent maps for the first of the lensed-$\Lambda$CDM+noise simulations. The color scale displays the $E$-mode scalar and $B$-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess $B$-mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at $\ell \approx 70$). (Also note that the $E$-mode and $B$-mode maps use different color/length scales.)

[BICEP2 2014]
FIG. 2.— BICEP2 power spectrum results for signal (black points) and temporal-split jackknife (blue points). The red curves show the lensed-$\Lambda$CDM theory expectations — in the case of $BB$ an $r = 0.2$ spectrum is also shown. The error bars are the standard deviations of the lensed-$\Lambda$CDM+noise simulations. The probability to exceed (PTE) the observed value of a simple $\chi^2$ statistic is given (as evaluated against the simulations). Note the very different y-axis scales for the jackknife spectra (other than $BB$). See the text for additional discussion of the $BB$ spectrum.
BB angular power spectrum measured by BICEP2

Consistent with expected lensing from E-polarisation
BB angular power spectrum measured by BICEP2

Excess signal
Due to tensor modes (?!)

[BICEP2 2014]
Is the signal real?

Experimental systematics?
- Pointing error
- Beam uncertainty

Passed consistency checks:
- jackknife tests
- no EB- and TB-signal

→ very unlikely to account for excess signal
Is the signal of cosmological origin?

Astrophysical foregrounds
- Polarised point sources
- Synchrotron emission
- Polarised dust emission
Is the signal of cosmological origin?

Astrophysical foregrounds

- Polarised point sources
- Synchrotron emission
- Polarised dust emission

→ likely some contribution to signal, not very likely to account for all of it

Ideally:
Want multi-frequency information
Is the signal of cosmological origin?

Adding BICEP1 data to determine frequency-dependence of the signal

→ signal consistent with CMB expectation

Foreground removal will greatly benefit from Planck polarised dust maps

Fig. 8.— The constraint on the spectral index of the $BB$ signal based on joint consideration of the BICEP2 auto, BICEP1$_{100}$ auto, and BICEP2 × BICEP1$_{100}$ cross spectra. The curve shows the marginalized likelihood as a function of assumed spectral index. The vertical solid and dashed lines indicate the maximum likelihood and the $\pm 1\sigma$ interval. The blue vertical lines indicate the equivalent spectral indices under these conventions for the CMB, synchrotron, and dust. The observed signal is consistent with a CMB spectrum, while synchrotron and dust are both disfavored by $\gtrsim 2\sigma$. 
Is the signal really from inflationary tensor modes?

Alternative mechanisms:

- Topological defects
  → too much small scale power
  [Lizarraga et al. 2014]

- Primordial magnetic fields
  → possible, but simplest models predict too much NG
  [Bonvin et al. 2014]

→ inflation remains most likely origin
Implications of BICEP2

DISCLAIMER:
In the following, I will assume this signal is real and that it is caused by primordial tensor perturbations from inflation.
Implications of BICEP2 results

Energy scale of inflation:

\[ V_{\text{inf}}^{1/4} \approx 2.2 \cdot 10^{16} \left( \frac{r}{0.2} \right)^{1/4} \text{ GeV} \]

(This could in principle have been as low as O(10) MeV, we are incredibly lucky!)
Implications of BICEP2 results

• Lyth bound:
  For inflation to last sufficiently long, \( \phi \) has to take on super-Planckian values

\[
\Delta \phi \gtrsim m_{\text{Pl}} (r/0.01)^{1/2}
\]

[Lyth 1997]

• In effective field theory, Planck-mass suppressed higher order operators would mess up things...

  \( \rightarrow \) Challenge for inflation model-builders
Inflation model constraints (post BICEP2)

BICEP2 constraint on tensor-to-scalar ratio

Graph showing the relationship between primordial tilt ($n_s$) and tensor-to-scalar ratio ($r_{0.002}$) with various inflation models and constraints indicated on the graph.
Tension with temperature data?

Even in $\Lambda$CDM with $r=0$, there is a lack of power at the largest scales. Adding a tensor contribution would exacerbate the problem.

Possible solutions:

- Suppress primordial scalar power at large scales
- Suppress late integrated Sachs-Wolfe effect (DE)
- Anticorrelated isocurvature perturbations
- Anticorrelated tensor perturbations
- Extra radiation (e.g., $\Delta N_{\text{eff}} \approx 1$ sterile neutrinos)

[Contaldi, Peloso, Sorbo 2014]

[Zhang et al., Dvorkin et al. 2014]
Conclusions

- Predictions of simplest inflationary models pass all challenges thrown at them by Planck data
- BICEP2 measurement of the CMB's BB angular power spectrum (if confirmed) probably most spectacular result in cosmology in last 15 years
  - Can be interpreted as gravitational wave signal from inflation
  - Energy scale of inflation ~ GUT scale
  - Inflation was large-field
  - Quite possibly signs of further new physics
- These measurements do not prove inflation happened, but certainly make it look even more attractive than before!