Primordial gravitational waves detected?

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  Ref. BICEP2 collaboration, arXiv:1403.3985

• Characterizing polarization state of GWB
  Ref. Saito, Ichiki, AT, JCAP 89, 043509 (’07)
Gravitational-wave backgrounds (GWB)

- Incoherent superposition of gravitational waves by diffuse or un-resolved many sources

- Astrophysical or cosmological origin (early universe)

✓ GWB can be quantum-mechanically generated together with density perturbation

✓ Amplitude of GWB tells us the energy scale of inflation

Detection of this GWB gives a strong evidence of inflation, and it greatly improves our view of the early universe
Searching for inflationary GWB

- Direct detection by space laser interferometer at $f \sim 0.1 \text{Hz}$
  - DECIGO
  - DECI-herz Interferometer
  - Gravitational-wave Observatory
  - BBO (Big-Bang Observer)

- Indirect detection from cosmic microwave background (CMB) experiments
Cosmic microwave background (CMB)

Black body radiation at $T=2.7K$

with tiny anisotropies of $\Delta T \approx 10^{-5}$

These anisotropies have been originated from primordial density (scalar) fluctuations & maybe from tensor fluctuation (GWB)
CMB polarizations

A clever way to distinguish between scalar & tensor fluctuations

CMB is (very) weakly polarized via the Thomson scattering with primeval electrons in inhomogeneous media (scalar or tensor fluc.)

Spatial patterns of polarizations are decomposed into:

- **E-mode**
  - $E > 0$
  - $E < 0$

- **B-mode**
  - $B > 0$
  - $B < 0$

B-mode can be created by tensor fluc., but not by scalar fluc.

non-zero B-mode signal is the smoking gun of inflationary GWB
BICEP 2

(Background Imaging of Cosmic Extragalactic Polarization)

• Ground-based CMB experiment with TES bolometer at f=150 GHz (λ=2mm)

• Observe a small patch of the sky (380 deg^2) over 3 yrs

---------- still sensitive to a large-angular signal of 1~5 deg (ell~40—200)
Detection of B-mode signal!

Harmonic expansion

\[ B(\hat{\theta}) = \sum_{\ell, m} a_{\ell m}^B Y_{\ell m}(\hat{\theta}) \]

Angular power spectrum

\[ C_{\ell}^{BB} = \frac{1}{2\ell + 1} \sum_{m} |a_{\ell m}^B|^2 \]
Interpreting BICEP2 result

- Small-angular (high-l) signal:
  gravitational lensing signals (SPT, POLARBEAR)

- Non-zero large-angular (low-l) signal:
  maybe cosmological

Detection of inflationary GWB!!

Tensor-to-scalar ratio of fluc. amplitude: \( r \sim 0.2 \)

- favor large-field inflation at GUT scale
- but in tension with Planck result (temperature data)
Title: BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales
Publication: eprint arXiv:1403.3985
Publication Date: 03/2014
Origin: ARXIV
Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics, General Relativity and Quantum Cosmology, Physics - Theory
Comment: 19 pages, 14 figures
Bibliographic Code: 2014arXiv1403.3985B
Curse of single-band obs.

Estimation of foreground systematics is very very crucial!! dust, synchrotron radiation of our Galaxy

measured signal @150 GHz (single band)

foreground dust model

Foreground systematics can be calibrated only by multi-freq. band experiment (like Planck)
What to do?

• Just wait for Planck polarization result (Nov. or Dec. 2014)

  Other ground-based experiments may also announce something

• In advance of detection, we may rethink about how well we can learn the early universe from CMB:

  Characterizing GWB

  ✓ spectral feature ✓ tensorial nature ✓ graviton mass ✓ polarization states

  implication to early-universe physics or test of general relativity
Polarization states of GWB

Gravitational wave has two distinct polarization modes:

In standard GR, unpolarized GWs are generated during inflation.

In the presence of parity violating interaction, however,

\[ S_{\text{int}} \geq \int d^4x \sqrt{-g} f(\phi) \frac{1}{2} \epsilon^{\alpha\beta\gamma\delta} R_{\alpha\beta\rho\sigma} R_{\gamma\delta}^\rho\sigma \]

Circularly polarized GWB

How well we can characterize and measure polarized GWB?
Parity-violation signature in CMB

Parity-violating GWB can induce *non-trivial* statistical correlation of CMB temperature (T) and polarizations (E-,B-modes)

Lue, Wang & Kamionkowski ’98, Saito, Ichiki & AT ’07

Figure 2. Dependence of circular polarization degree, \( \epsilon \), on the TB - (left) and EB-mode (right) power spectra for the fiducial model except for the reionization optical depth, \( \tau_{\text{ri}} = 0 \).

Figure 3. Dependence of the tensor-to-scalar ratio, \( r \), on the TB - (left) and EB-mode (right) power spectra for the fiducial model with \( \epsilon = -1 \). In these plots, the reionization optical depth is set to \( \tau_{\text{ri}} = 0 \), keeping the low-roll consistency relation \( n_T = -r/8 \).

4.2. Effects of secondary anisotropies

Let us move to the discussion on the effects of secondary anisotropies generated after the recombination epoch.

There are two possible sources to produce a large angular scale anisotropy: reionization and weak lensing. Among these, the weak lensing effect represents the gravitational deflection of a photon's propagation direction by the large-scale structure and it distorts the temperature and polarization maps of the CMB (see [41] for a review).

In particular, the effects from weak lensing are known as a big obstacle to detecting the gravitational waves from the BB-mode power spectrum, since weak lensing newly creates the B-mode polarization anisotropy from the scalar-type perturbations.
Constraining polarization state

Saito, Ichiki & AT (’07)

Vertical shaded-region

Expected 1-sigma error (68% CL) of polarization parameter $\varepsilon_{\text{obs}}$ for a fiducial value of $\varepsilon_{\text{true}}$ from CMB polarizations at $\ell < 100$

Circular polarization will be detected if

$$|\varepsilon_{\text{obs}}| \gtrsim 0.35 \left(\frac{r}{0.05}\right)^{-0.61}$$

from idealistic experiment (fundamental limit)
Summary

Searching for inflationary GWB is now in exciting time

• BICEP team has detected B-mode signal of CMB at large angular scales → inflationary GWB as smoking gun of inflation? however
• Interpretation of the detected B-mode signal is questionable due to foreground contamination

Just rethink about characterization prior to Planck data:

We may not only detect GWB but also measure its polarization (if we are very lucky to have a large tensor-to-scalar ratio r>0.1)

Polarization state of GWB can be also measured by laser interferometer:
Seto ('06, '07), Seto & AT ('07, '08)