21 May 2014
Lunch seminar @YITP

Primordial gravitational waves detected ?

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Contents

Searching for primordial gravitational waves from cosmic microwave background polarizations

- Gravitational-wave background (GWB)
- Cosmic microwave background polarizations
- BICEP2 results: detection or systematics ?

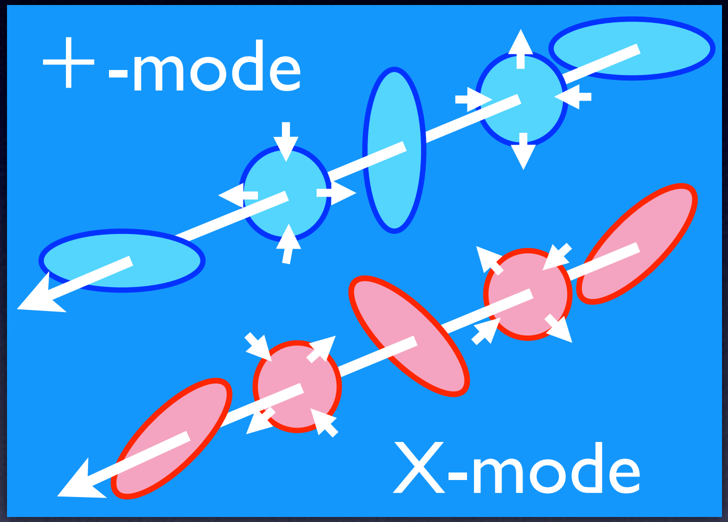
Ref. BICEP2 collaboration, arXiv:1403.3985

- 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 <u>cosmological</u> origin (early universe)

Inflation

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

✓Amplitude of GWB tells us the energy scale of inflation

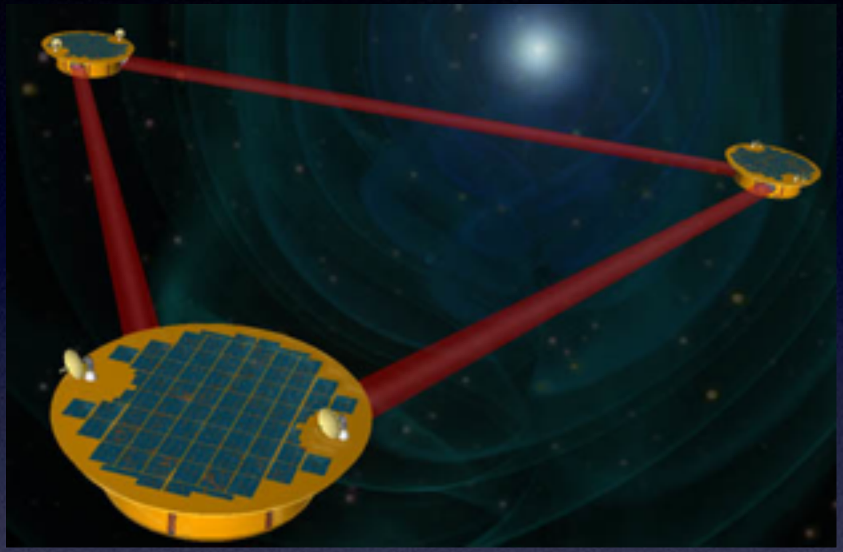
Detection of this GWB gives a strong evidence of inflation, and it greatly improves our view of the early universe

Searching for inflationary GWB

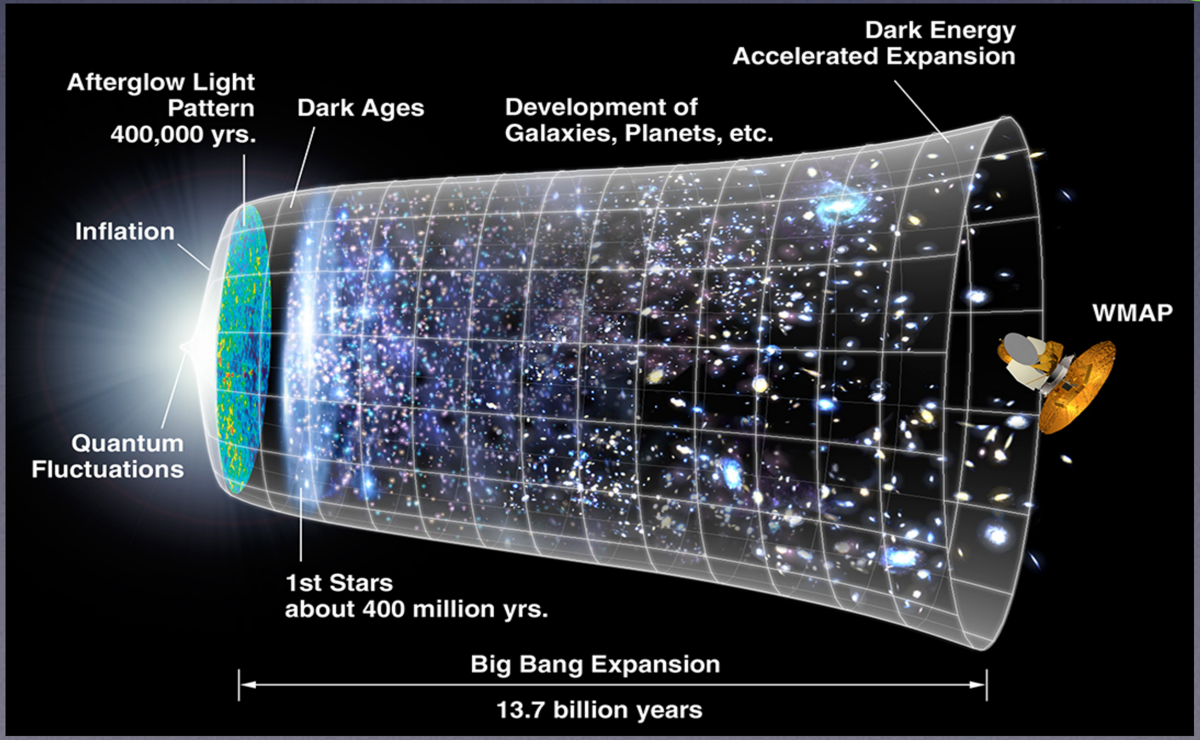
- Direct detection by space laser interferometer at f~0.1Hz

DECIGO — DECI-herz Interferometer Gravitational-wave Observatory

BBO (Big-Bang Observer)



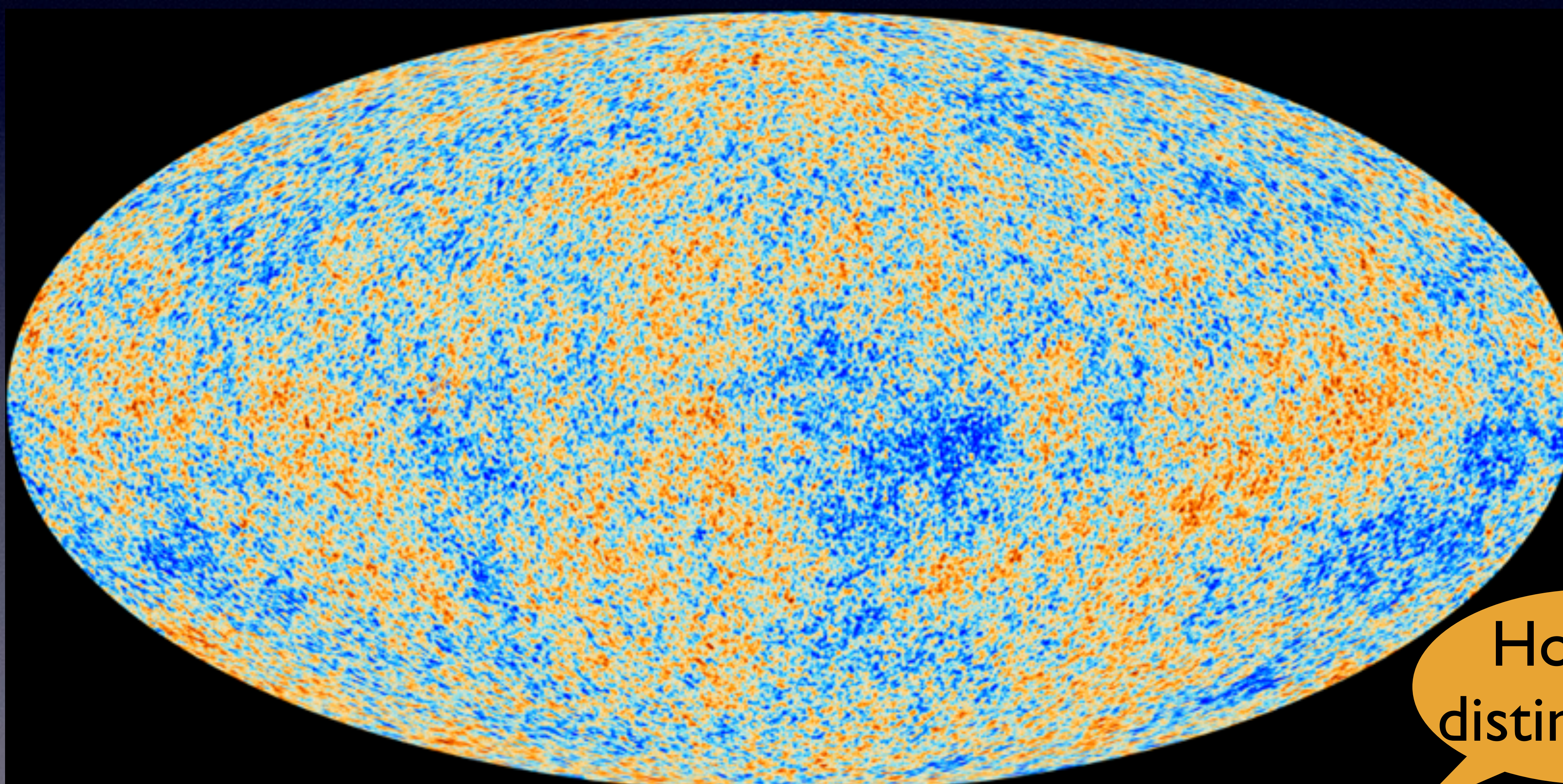
- Indirect detection from cosmic microwave background (CMB) experiments



Cosmic microwave background (CMB)

Black body radiation at $T=2.7K$

with tiny anisotropies of ΔT~10^(-5)



How to distinguish ?

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

CMB polarizations

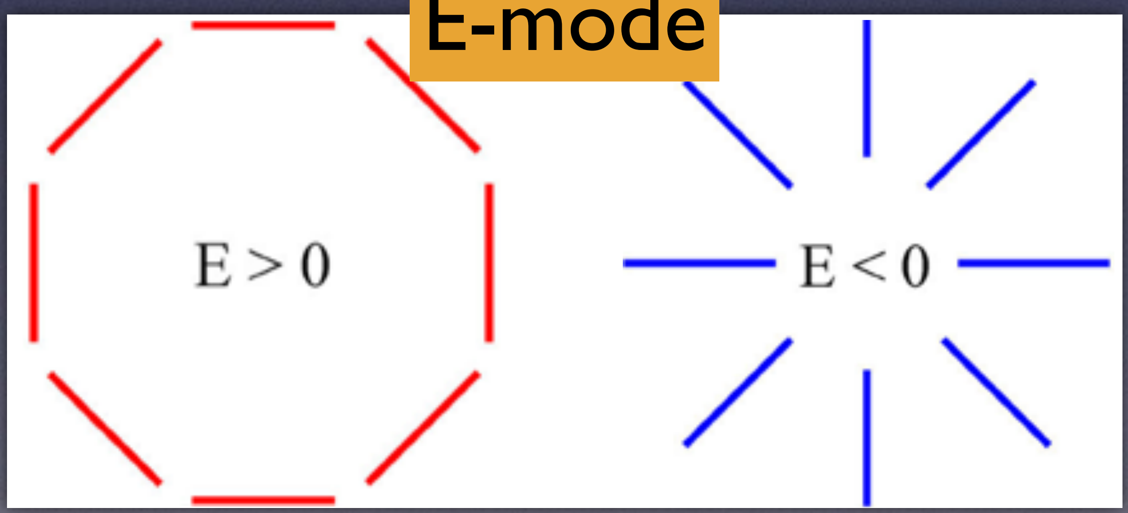
A clever way to distinguish between scalar & tensor fluctuations

CMB is (very) weakly polarized via the Thomson scattering with primeval electrons in inhomogeneous media

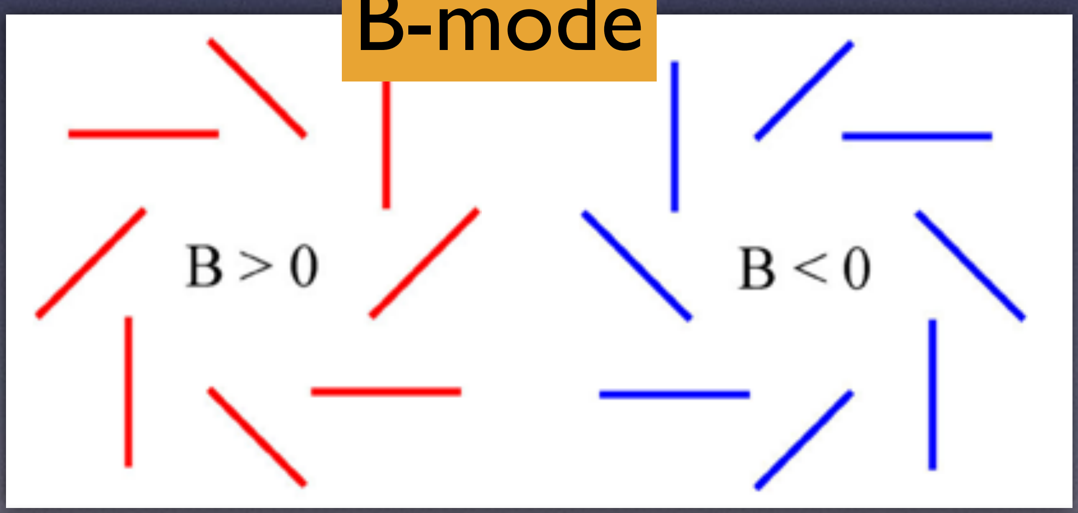
(scalar or tensor fluc.)

Spatial patterns of polarizations are decomposed into:

E-mode



B-mode



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

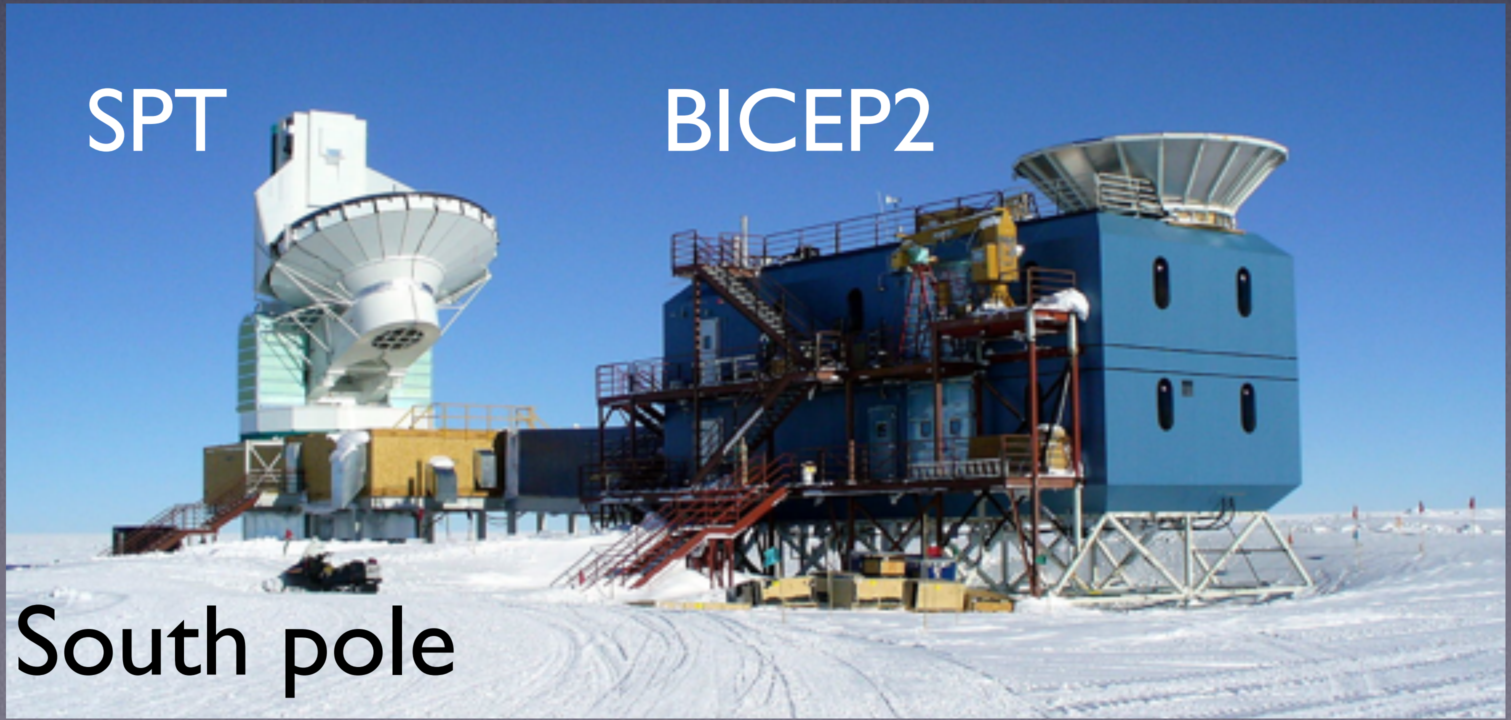
Harvard, Stanford, Caltech, JPL,…

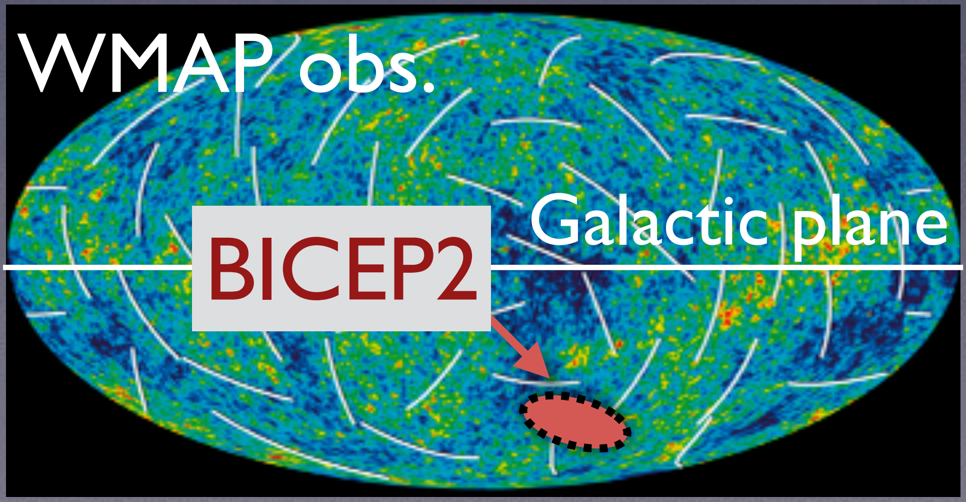
(Background Imaging of Cosmic Extragalactic Polarization)

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

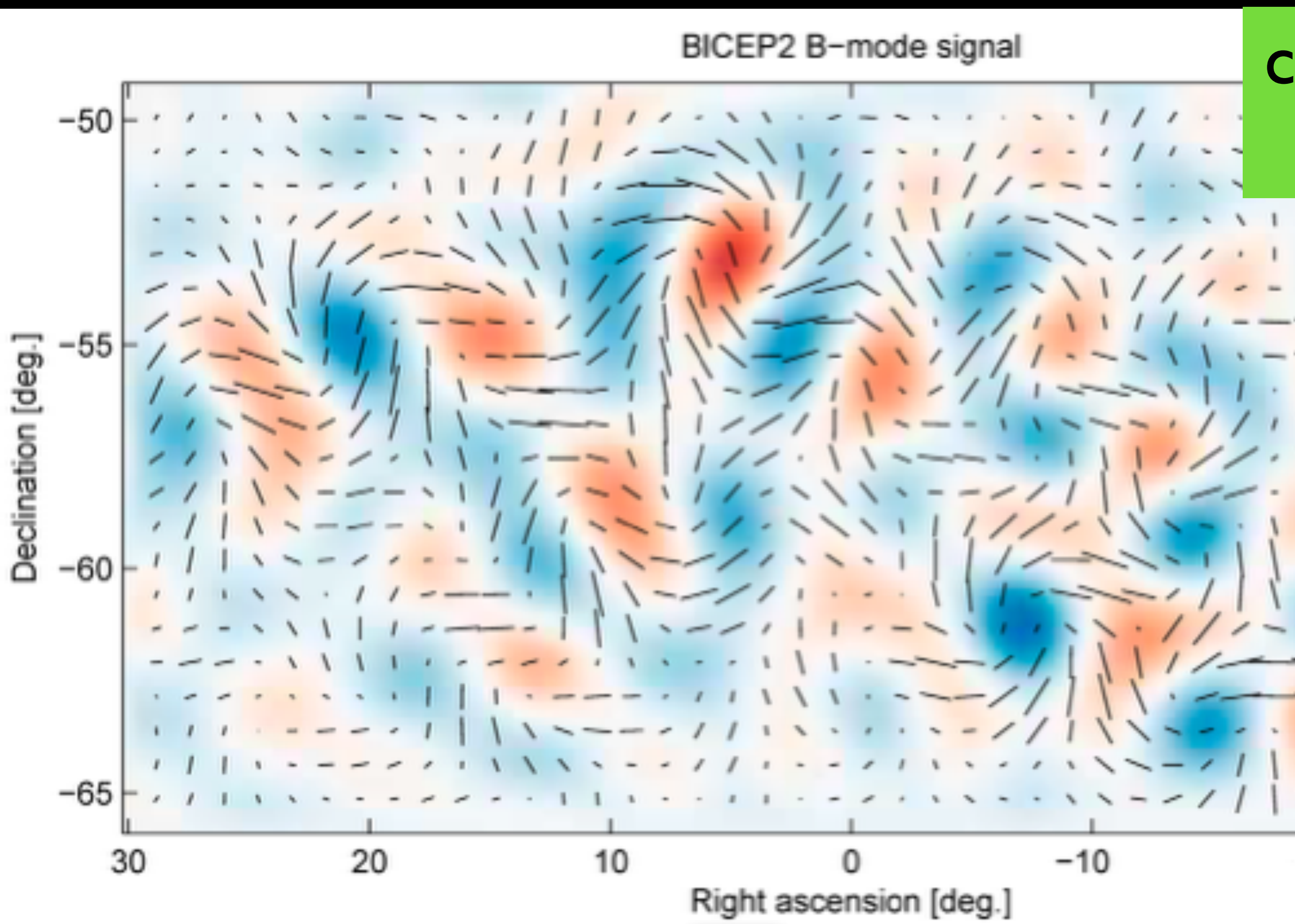
- Observe a small patch of the sky (380 deg^2) over 3 yrs

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





Detection of B-mode signal !



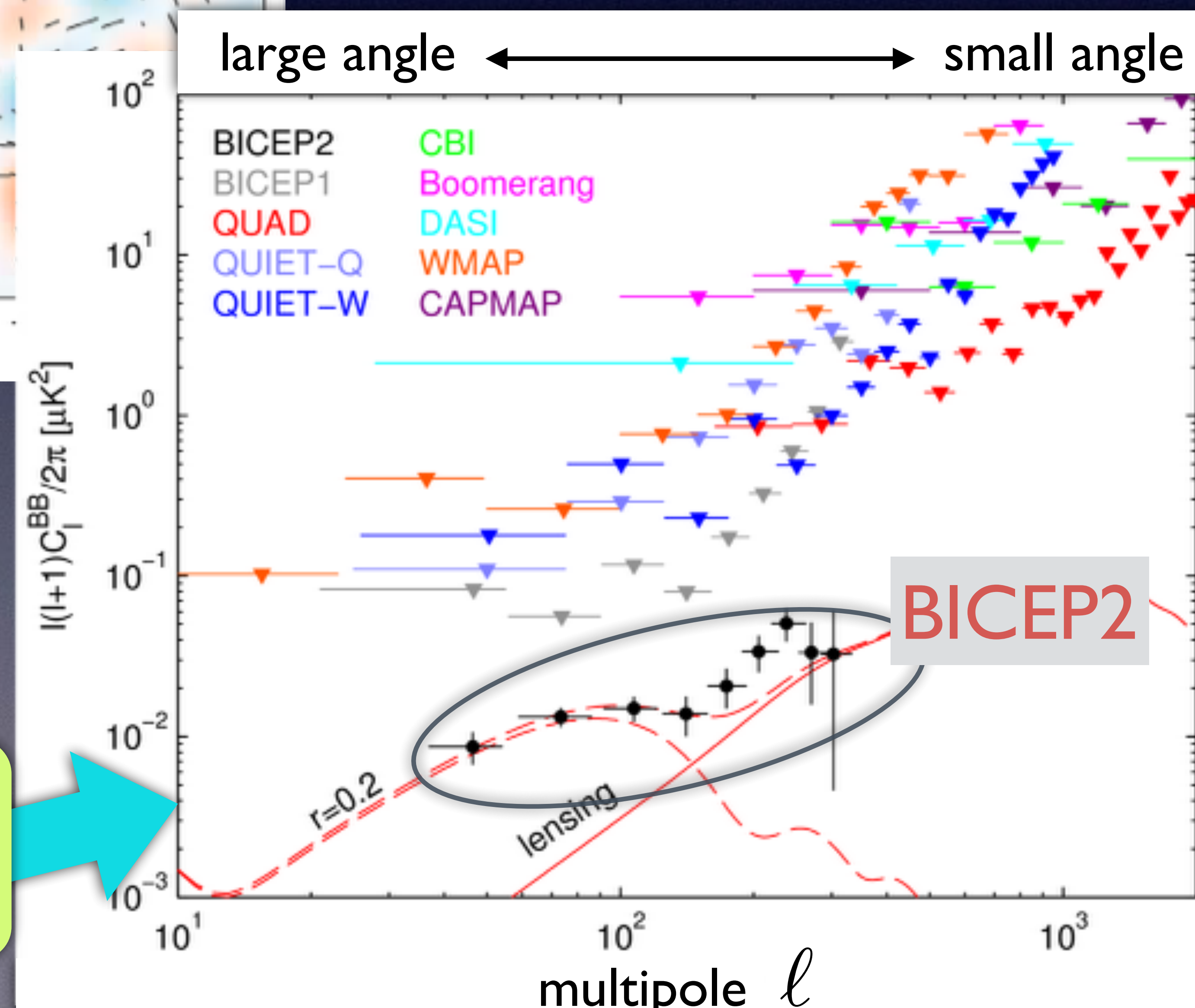
color scale 0.3 μK

Harmonic expansion

$$B(\hat{\boldsymbol{\theta}}) = \sum_{\ell,m} a_{\ell m}^{\mathrm{B}} Y_{\ell m}(\hat{\boldsymbol{\theta}})$$

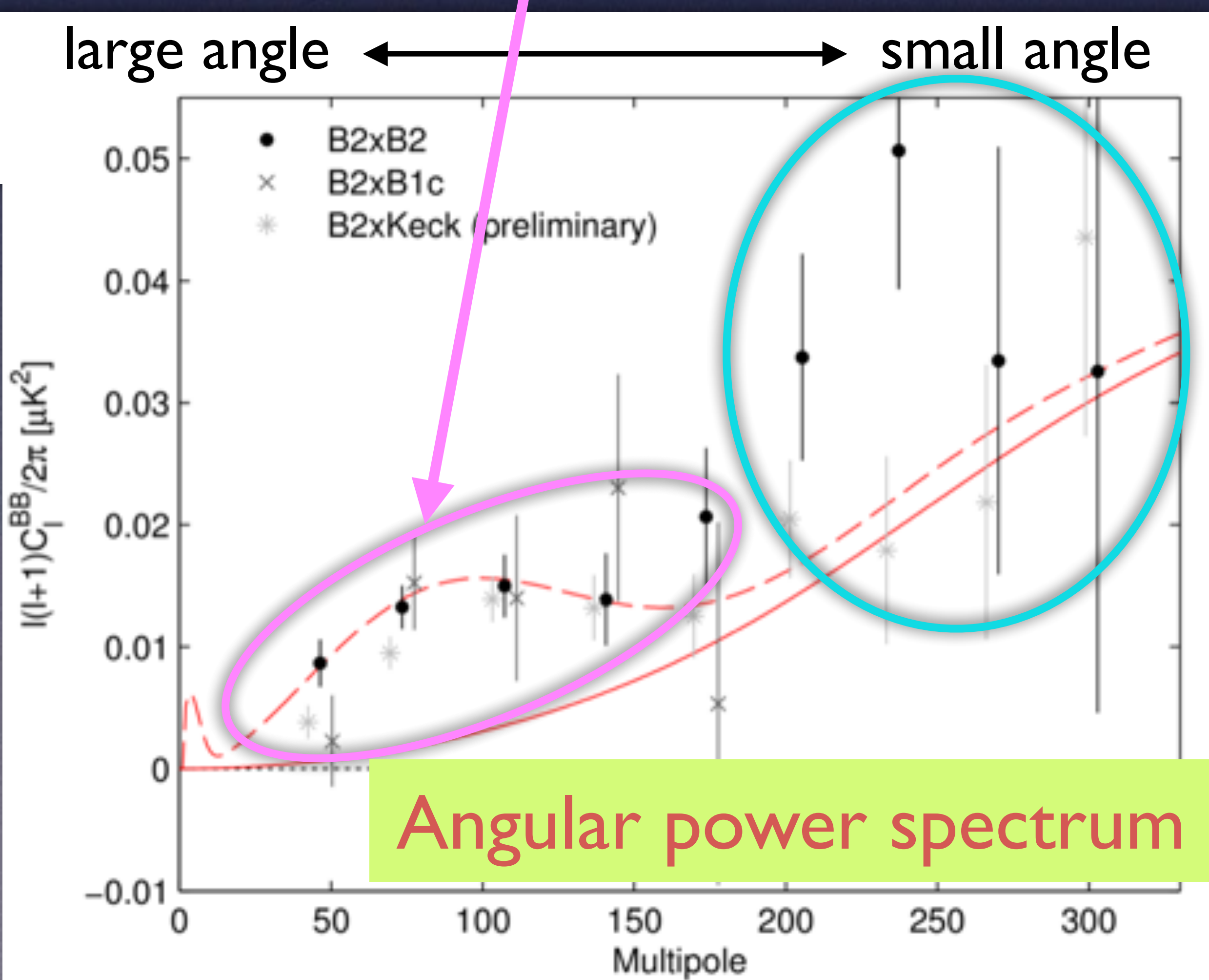
Angular power spectrum

$$C_\ell^{\mathrm{BB}} = \frac{1}{2\ell+1}\sum_m |a_{\ell m}^{\mathrm{B}}|^2$$



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 !!



Angular power spectrum

Tensor-to-scalar ratio of fluc. amplitude: **r ~0.2**

- favor large-field inflation at GUT scale
- but in tension with Planck result (temperature data)

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citation # 327 !!! (as of 21 May)

Title: BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales

Authors: BICEP2 Collaboration; Ade, P. A. R; Aikin, R. W.; Barkats, D.; Benton, S. J.; Bischoff, C. A.; Bock, J
Duband, L.; Filippini, J. P.; Fliescher, S.; Golwala, S. R.; Halpern, M.; Hasselfield, M.; Hildebrandt, S.
Kaufman, J. P.; Keating, B. G.; Kernasovskiy, S. A.; Kovac, J. M.; Kuo, C. L.; Leitch, E. M.; Lueker, M
Ogburn, R. W., IV; Orlando, A.; Pryke, C.; Reintsema, C. D.; Richter, S.; Schwarz, R.; Sheehy, C. D.;
Tolan, J. E.; Turner, A. D.; Vieregg, A. G.; Wong, C. L.; Yoon, K. W.

Publication: eprint arXiv:1403.3985

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Origin: ARXIV

Keywords: Astrophysics - Cosmology and Extragalactic Astrophysics, General Relativity and Quantum Cosmolog
Physics - Theory

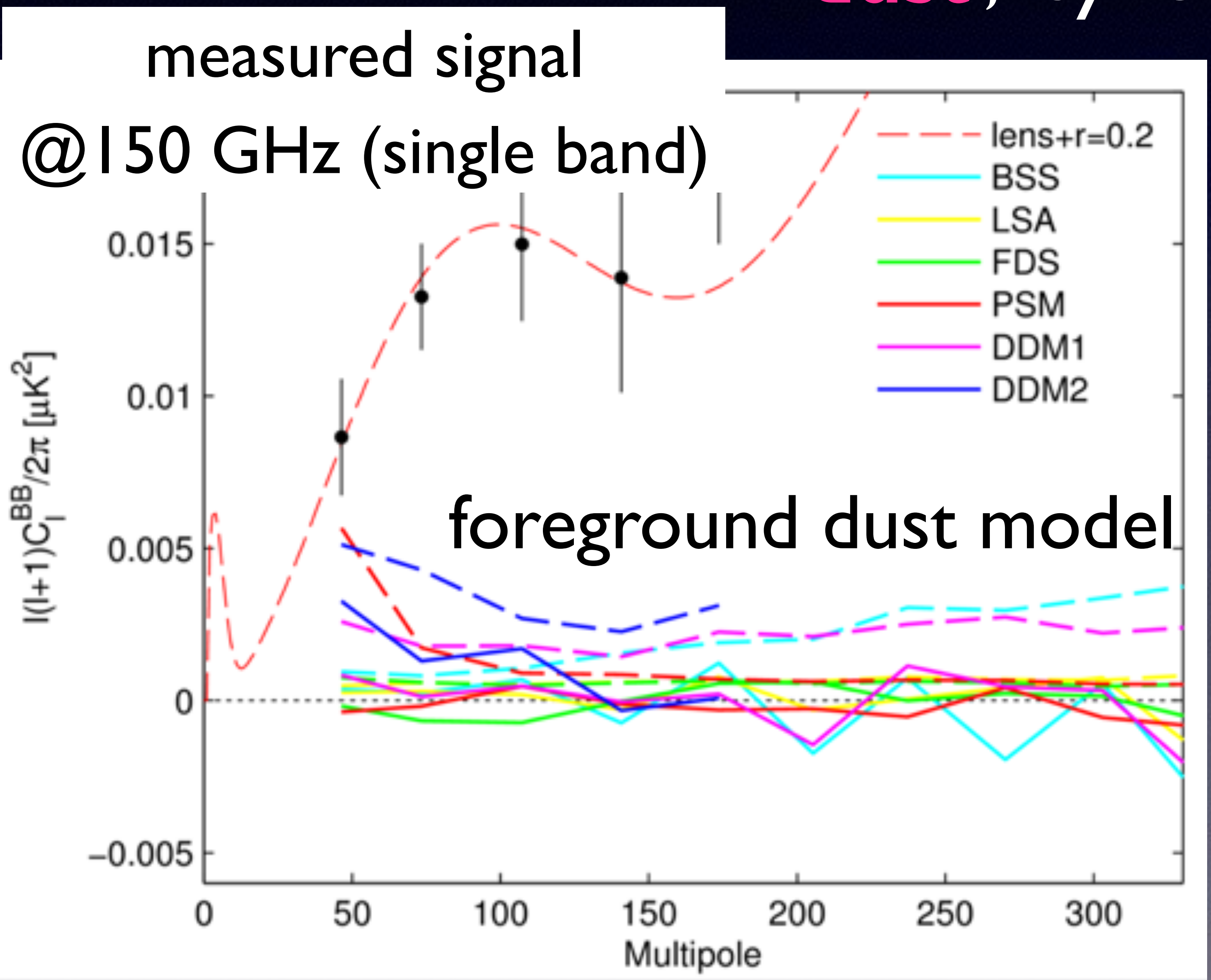
Comment: 19 pages, 14 figures

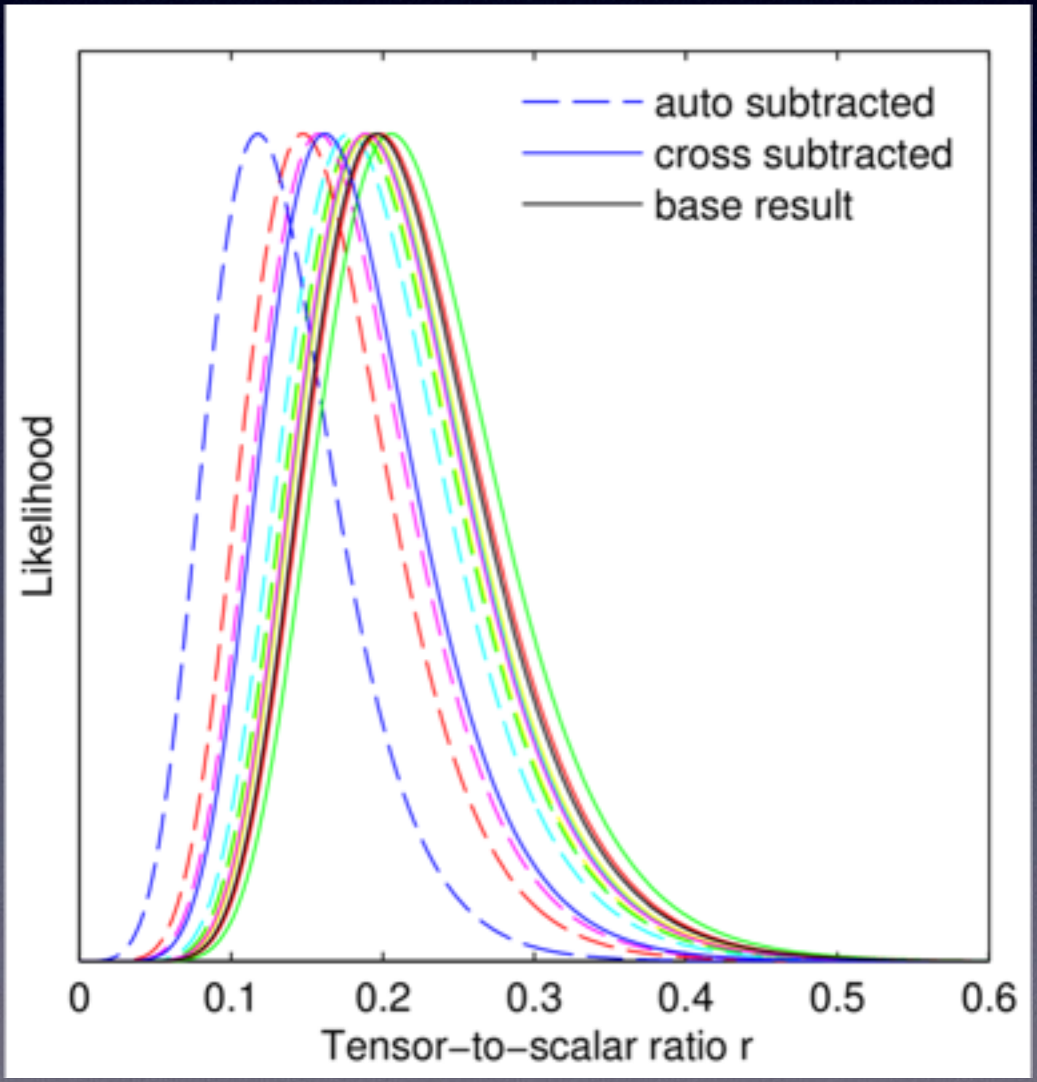
Bibliographic Code: 2014arXiv1403.3985B

Curse of single-band obs.

Estimation of foreground systematics is very very crucial !!

dust, synchrotron radiation of our Galaxy





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

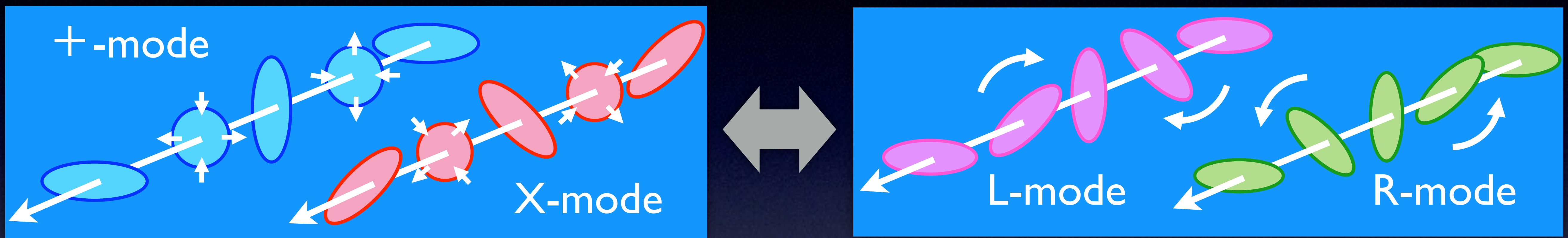
✓spectral feature ✓tensorial nature

✓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,

Chern-Simons term coupled with scalar field

$$S_{\rm int} \supseteq \int d^4x\sqrt{-g}\, f(\phi)\, \frac{1}{2}\epsilon^{\alpha\beta\gamma\delta} R_{\alpha\beta\rho\sigma}\, R_{\gamma\delta}{}^{\rho\sigma}$$

$\longrightarrow$ Circularly polarized GWB

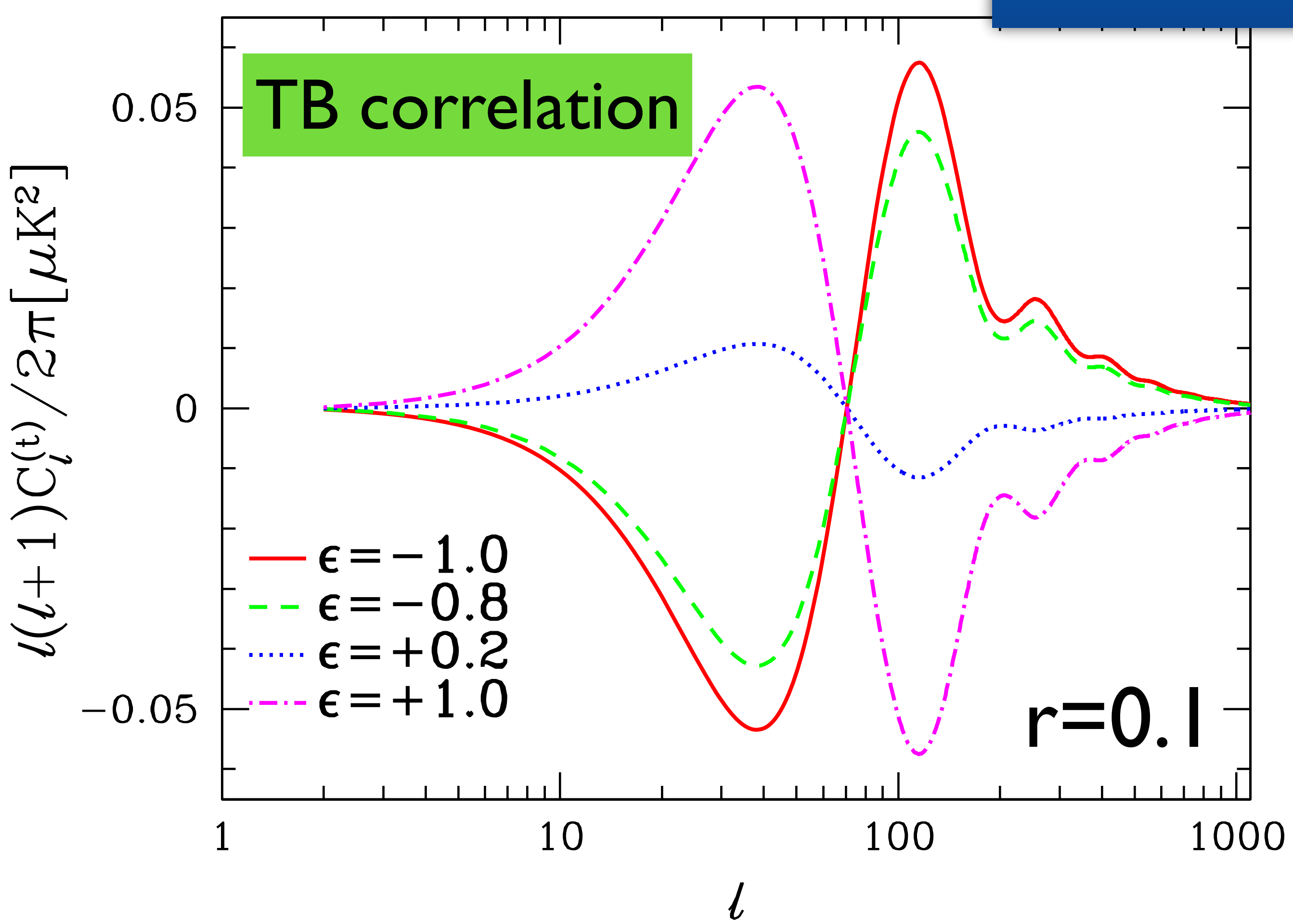
How well we can characterize and measure polarized GWB ?

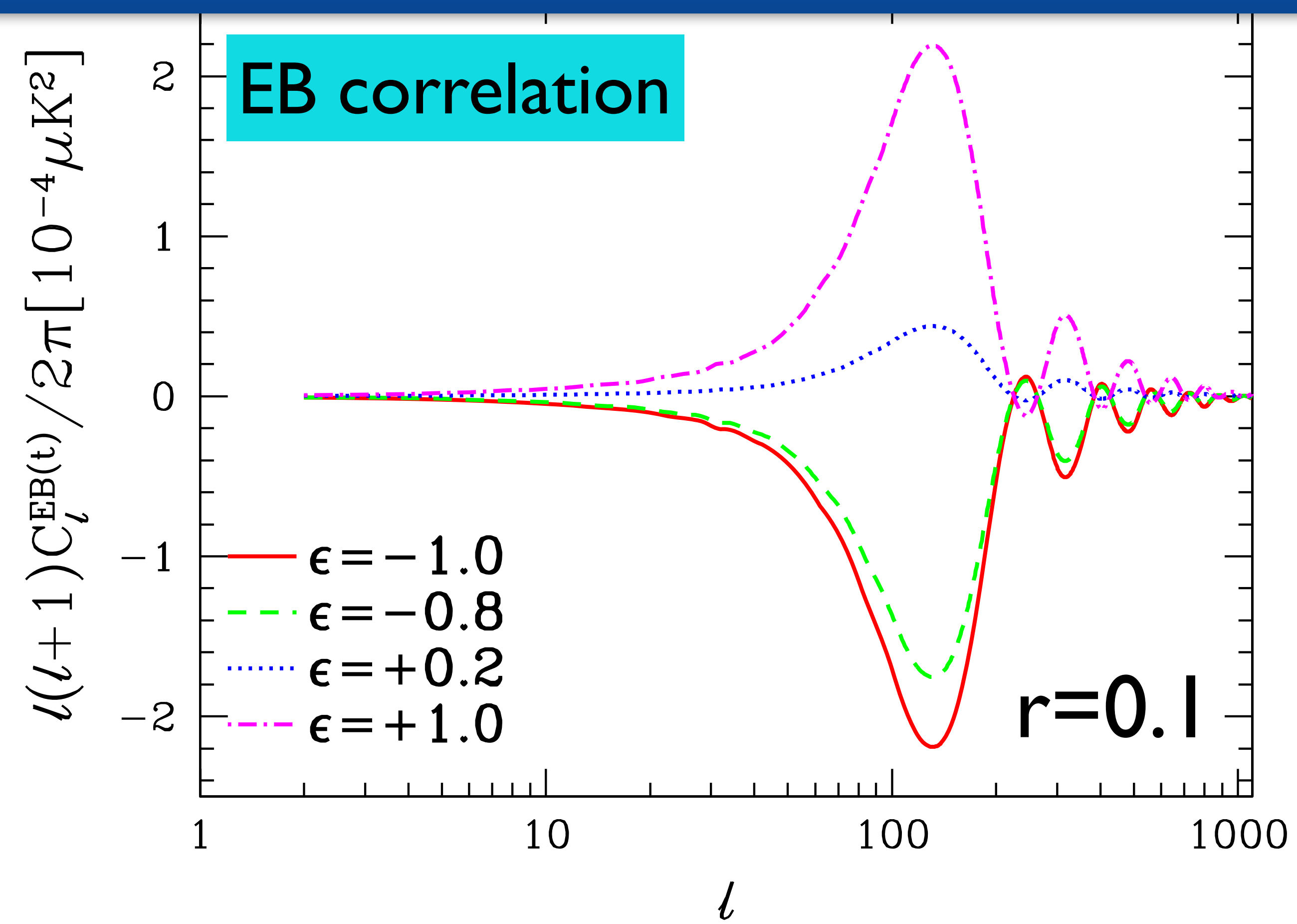
Parity-violation signature in CMB

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

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

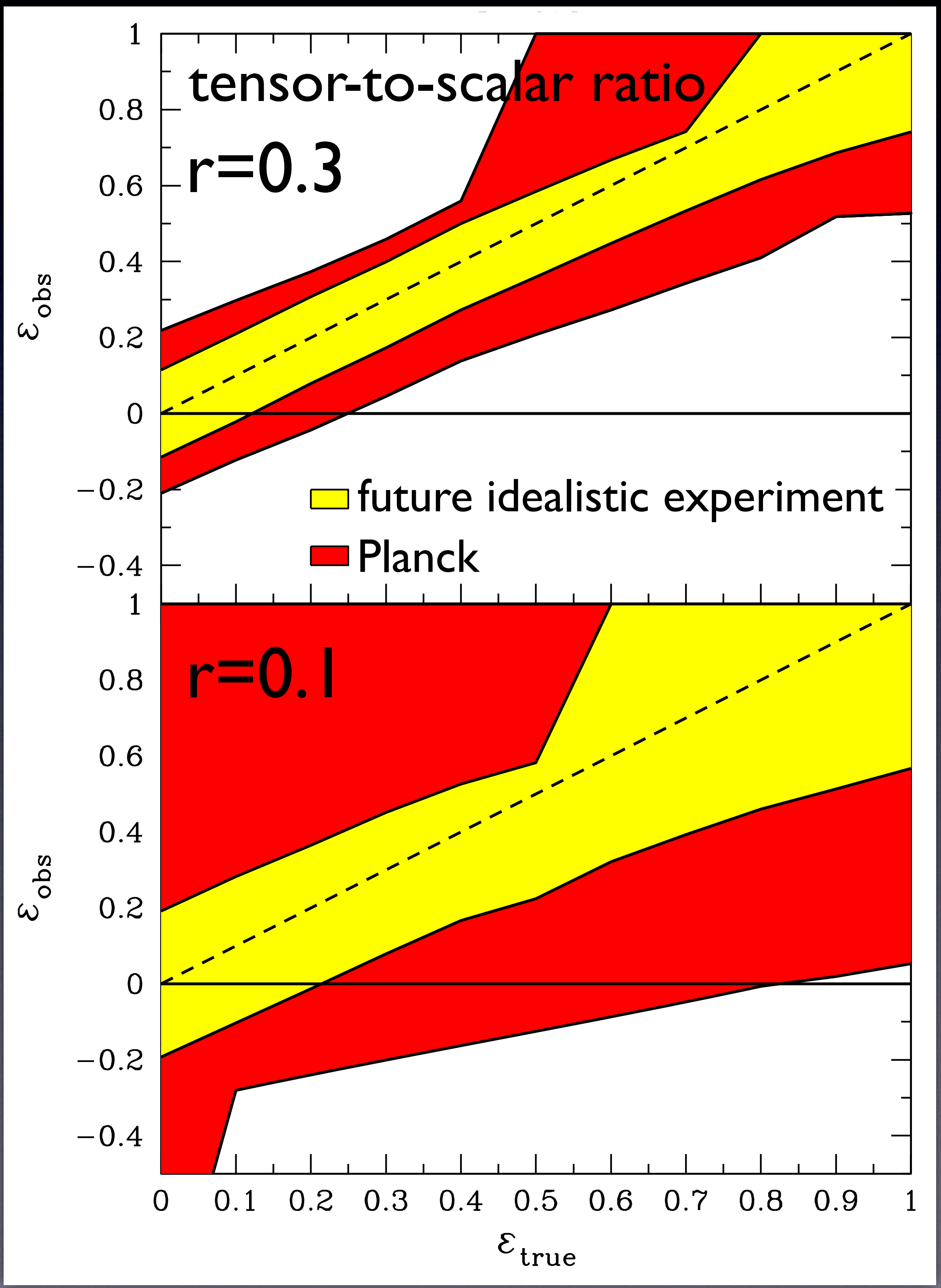
ε : polarization parameter $\begin{cases} +1 & \text{right-handed} \\ 0 & \text{un-polarized} \\ -1 & \text{left-handed} \end{cases}$





Constraining polarization state

Saito, Ichiki & AT ('07)



Vertical shaded-region

Expected 1-sigma error (68% CL) of polarization parameter $\varepsilon_{\rm obs}$ for a fiducial value of $\varepsilon_{\rm true}$

from CMB polarizations at ell<100

Circular polarization will be detected if

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

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)