中国科学技术大学
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Primordial Cosmology:

Primordial Gravitational Waves & CMB Physics II

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From PGWs to the CMB

CMB Blackbody background

- CMB is a (nearly) perfect blackbody characterized by a phase space distribution function

$$f = \frac{1}{e^{E/T} - 1}$$

where the temperature $T(x, \hat{n}, t)$ is observed at our position x=0 and time t_0 to be nearly isotropic with a mean temperature of 2.725K

- Our observable is the temperature anisotropy

$$\Theta(\hat{\mathbf{n}}) \equiv \frac{T(0, \hat{\mathbf{n}}, t_0) - \bar{T}}{\bar{T}}$$

- Given that physical processes essentially put a band limit on this function it is useful to decompose it into a complete set of harmonic coefficients

PGWs induce temperature fluctuations & polarization in CMB

- The polarization is induced by Thomson scattering of this anisotropic radiation field. To account for the polarization, we must follow the time evolution of four distribution functions:

$$f_s(\boldsymbol{x}, \boldsymbol{q}; \eta)$$

q is photon momentum; s=(I,Q,U,V) are four Stokes parameters

- At unperturbed background:

$$\bar{f}_I(\boldsymbol{q}, \boldsymbol{x}; \eta) = \left[e^{h\nu/k_B T(\eta)} - 1\right]^{-1} \qquad \bar{f}_Q = \bar{f}_U = \bar{f}_V = 0$$

- Then we introduce the perturbations

$$\Delta_s e^{i\boldsymbol{k}\cdot\boldsymbol{x}} = 4\delta f_s / (\partial \bar{f} / \partial \ln T)$$

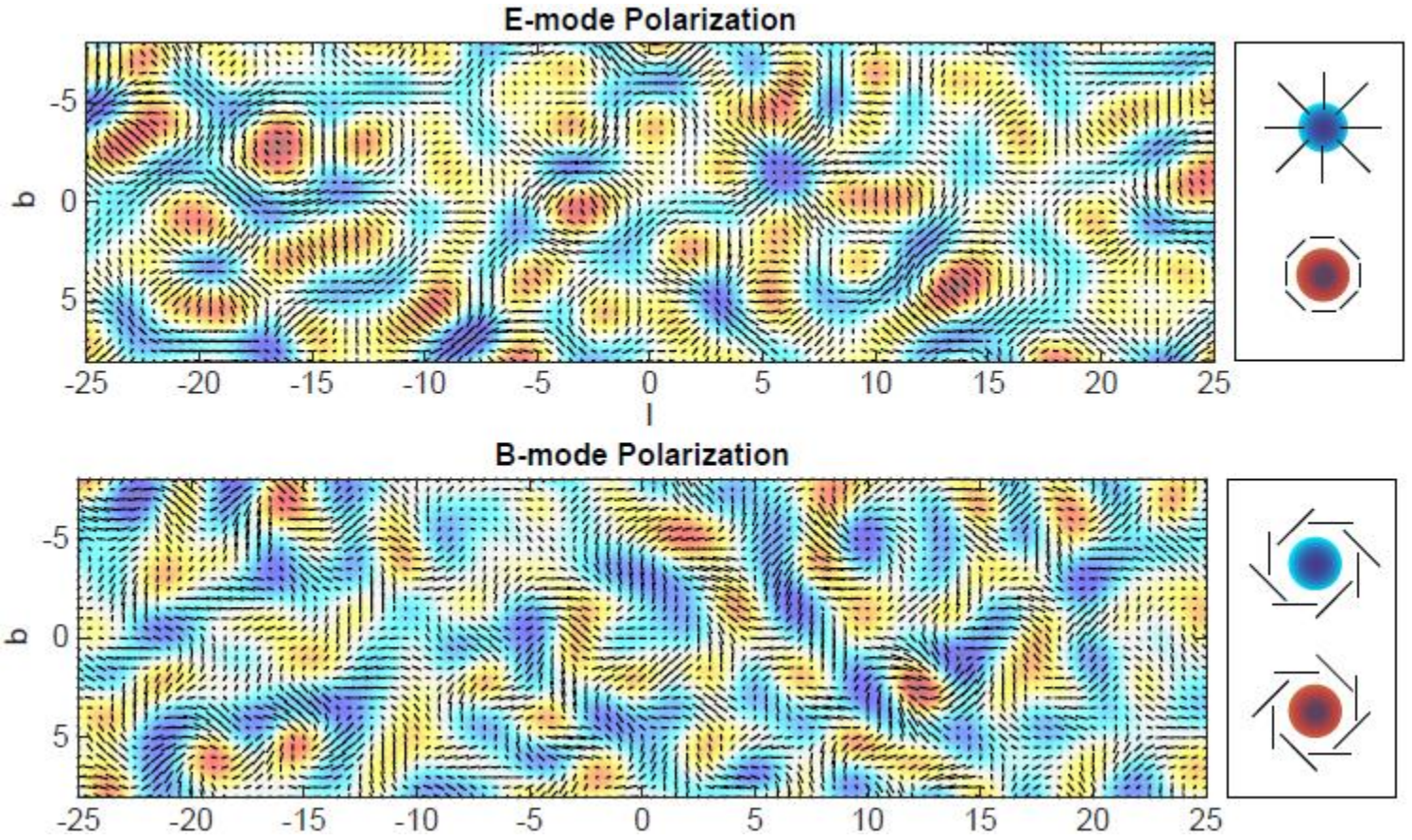
$$\Delta_I = \tilde{\Delta}_I (1-\mu)^2 \cos 2\phi, \qquad \Delta_Q = \tilde{\Delta}_Q (1+\mu)^2 \cos 2\phi, \qquad \Delta_U = \tilde{\Delta}_U 2\mu \sin 2\phi,$$

which are variables as functions only of μ and time.

E and B modes from PGWs

- Note that the polarization is spin-2 field:

$$\begin{pmatrix} Q & U \\ U & -Q \end{pmatrix} \Rightarrow \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$



E and B modes from PGWs

- PGWs of k wave-number can induce the polarization tensor:

$$\mathcal{P}^{ab}_{k,+}(\theta,\phi) = \frac{T_0}{4\sqrt{2}}\sum_\ell (2\ell+1) P_\ell(\cos\theta)\tilde{\Delta}_{Q\ell} \begin{pmatrix} (1+\cos^2\theta)\cos 2\phi & 2\cot\theta\sin 2\phi \\ 2\cot\theta\sin 2\phi & -(1+\cos^2\theta)\csc^2\theta\cos 2\phi \end{pmatrix}$$

- It yields the E & B coefficients:

$$a^{\mathrm{E}\,k,+}_{\ell m} = \frac{\sqrt{\pi(2\ell+1)}}{4(\delta_{m,2}+\delta_{m,-2})^{-1}}\left[\frac{(\ell+2)(\ell+1)\tilde{\Delta}_{Q,\ell-2}}{(2\ell-1)(2\ell+1)} + \frac{6\ell(\ell+1)\tilde{\Delta}_{Q\ell}}{(2\ell+3)(2\ell-1)} + \frac{\ell(\ell-1)\tilde{\Delta}_{Q,\ell+2}}{(2\ell+3)(2\ell+1)}\right]$$

$$a^{\mathrm{B}\,k,+}_{\ell m} = \frac{-i}{2\sqrt{2}}\sqrt{\frac{2\pi}{(2\ell+1)}}(\delta_{m,2}-\delta_{m,-2})\left[(\ell+2)\tilde{\Delta}_{Q,\ell-1} + (\ell-1)\tilde{\Delta}_{Q,\ell+1}\right]$$

- The angular power of B mode for fixing k takes:

$$C^{\mathrm{BB},\,k,+}_\ell = \frac{1}{2l+1}\sum_m |a^B_{\ell m}|^2 = \frac{\pi}{2}\left[\frac{\ell+2}{2\ell+1}\tilde{\Delta}_{Q,\ell-1} + \frac{\ell-1}{2\ell+1}\tilde{\Delta}_{Q,\ell+1}\right]^2$$

- Integrating out k, one gets the BB angular power spectrum

$$C^{\mathrm{BB}}_\ell = \frac{1}{2\pi}\int k^2\,dk\left[\frac{\ell+2}{2\ell+1}\tilde{\Delta}_{Q,\ell-1}(k) + \frac{\ell-1}{2\ell+1}\tilde{\Delta}_{Q,\ell-1}(k)\right]^2$$

E and B modes from PGWs

- Comments:
  - Similar process applies for C_l^{EE}
  - The E-B cross correlation vanishes for the standard model
  - Taking the same analysis, it is easy to see that scalar perturbation only produces T and E, simply due to the fact that density perturbations do not produce a curl at linear level
  - But, B modes may still arise from density perturbations at nonlinear order
  - Question: How large are these foreground contaminations?

Lensing induced B modes

- The most relevant nonlinear effect is weak gravitational lensing induced by (scalar type) density perturbations between us and the CMB surface of last scatter.

astro-ph/9803150

- The Stokes parameters displace along a given direction:

$$\begin{pmatrix} T \\ Q \\ U \end{pmatrix}_{\rm obs.}(\theta) = \begin{pmatrix} T \\ Q \\ U \end{pmatrix}_{\rm ls}(\theta+\delta\theta) \simeq \begin{pmatrix} T \\ Q \\ U \end{pmatrix}_{\rm ls}(\theta) + \delta\theta\cdot\nabla \begin{pmatrix} T \\ Q \\ U \end{pmatrix}_{\rm ls}(\theta)$$

where $\delta\theta = \nabla\Phi$ is the lensing deflection along gravitational potential.

- If no PGWs, there is only E mode at LSS with:

$$\tilde{Q}(\ell) = 2\tilde{E}(\ell)\cos 2\varphi_\ell \qquad U(\ell) = -2E(\ell)\sin 2\varphi_\ell$$

Lensing induced B modes

- Gravitational deflection leads to

$$B(\ell) = \frac{1}{2}[\sin 2\varphi_\ell\, \delta Q(\ell) - \cos 2\varphi_\ell\, \delta U(\ell)] = \int \frac{d^2 l_1}{(2\pi)^2}[\ell_1 \cdot (\ell - \ell_1)] E(\ell_1) \Phi(\ell - \ell_1) \sin 2\varphi_{\ell_1}$$

- The angular power spectrum of lensing B modes takes

$$C_\ell^{\rm BB} = \int \frac{d^2 l_1}{(2\pi)^2}[\ell_1 \cdot (\ell - \ell_1)]^2 \sin^2 2\varphi_{\ell_1} C^{\Phi\Phi}_{|\ell - \ell_1|} C^{\rm EE}_{\ell_1}$$

- It was detected by SPT in 2013.

1307.5830

Foreground contributions to B modes

- Galactic foregrounds:
  - Synchrotron: Galactic synchrotron emission is dominant at frequencies below 100 GHz, and both WMAP and Planck have observed its polarization signature at frequencies from 30 to 90 GHz;
  - Dust: Above 100 GHz, thermal emission from asymmetric dust in the interstellar medium, which align themselves with the Galactic magnetic field, induces a strong polarization signal;
  - …
- One must use techniques of de-lensing and non-Gaussian diagnosis to eliminate foreground contaminations to extract signals of PGWs.

So far where we are …

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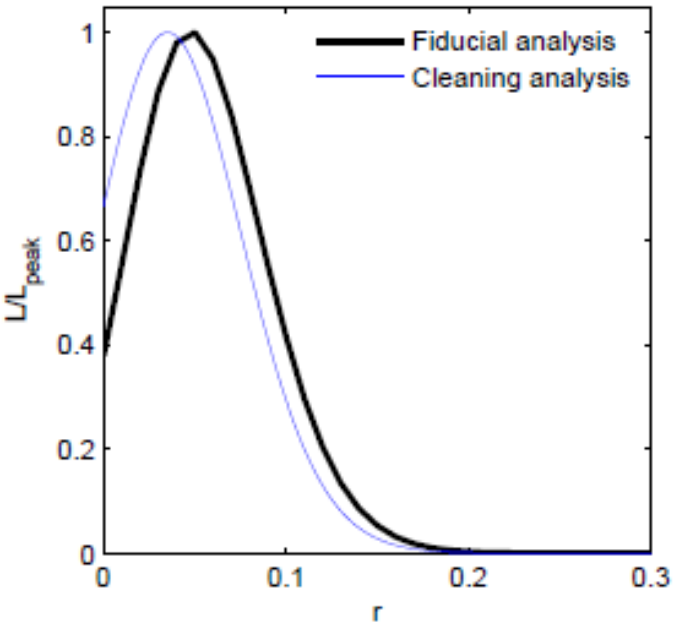
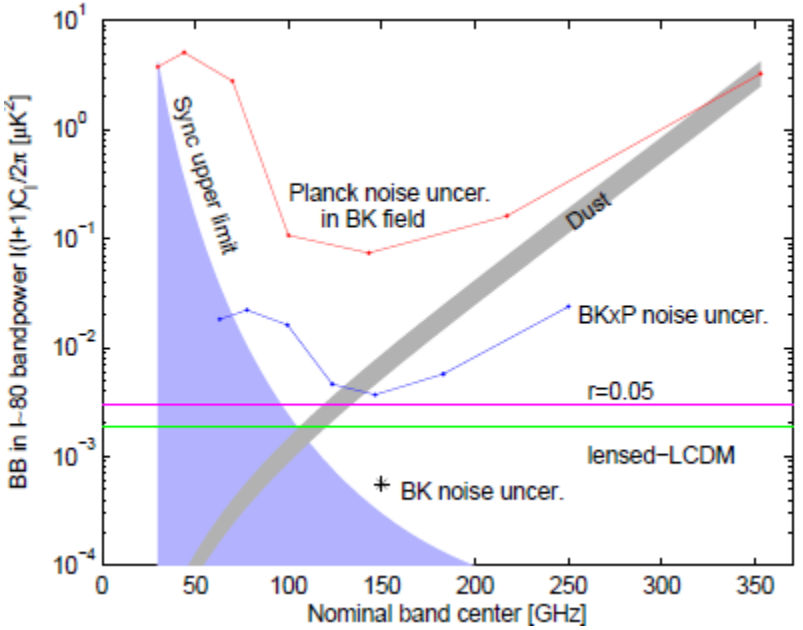




- No signal of PGWs: $r < 0.07$ at 2σ under a joint analysis of data from BICEP/Keck Array & Planck 2015.

A good but not perfect lesson from BICEP2

BICEP instrument at the South Pole

BICEP2 gives:

$$r \equiv \frac{P_T}{P_S} = 0.20^{+0.07}_{-0.05} \quad (68\% \ \ \text{C.L.})$$

Note: dust foreground contamination was not considered!

Planck13 yields:

$$\ln(10^{10} A_s) = 3.089^{+0.024}_{-0.027}$$
$$n_s = 0.9603 \pm 0.0073 \quad (68\% \ \ \text{C.L.})$$
$$r < 0.11 \ (95\% \ \text{C.L.})$$

There exists a severe tension between BICEP2 and Planck !

Implications on inflation models from string cosmology

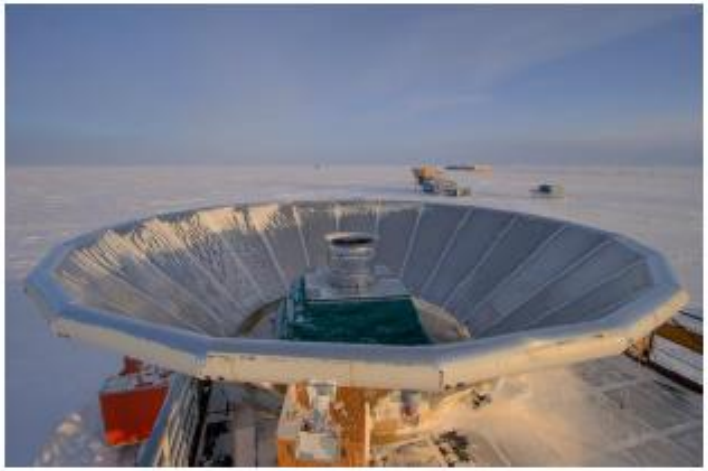
Burgess, Cicoli, Quevedo, 1306.3512

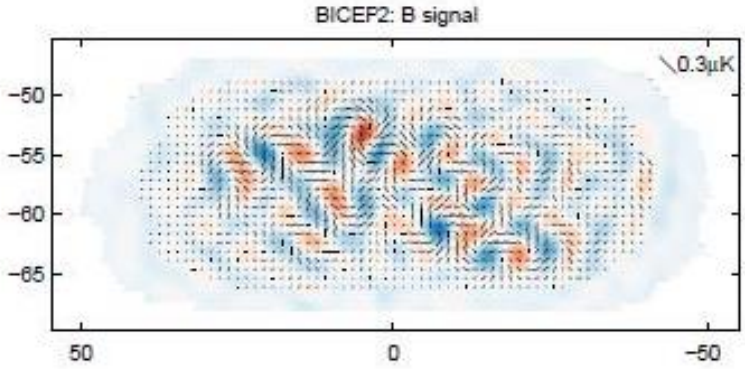
String Scenario	n_s	r
$D3/\overline{D3}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$
Inflection Point Inflation	$0.92 \leq n_s \leq 0.93$	$r \leq 10^{-6}$
DBI Inflation	$0.93 \leq n_s \leq 0.93$	$r \leq 10^{-7}$
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$
D3/D7 Inflation	$0.95 \leq n_s \leq 0.97$	$10^{-12} \leq r \leq 10^{-5}$
Racetrack Inflation	$0.95 \leq n_s \leq 0.96$	$r \leq 10^{-8}$
N-flation	$0.93 \leq n_s \leq 0.95$	$r \leq 10^{-3}$
Axion Monodromy	$0.97 \leq n_s \leq 0.98$	$0.04 \leq r \leq 0.07$
Kahler Moduli Inflation	$0.96 \leq n_s \leq 0.967$	$r \leq 10^{-10}$
Fibre Inflation	$0.965 \leq n_s \leq 0.97$	$0.0057 \leq r \leq 0.007$
Poly-instanton Inflation	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$

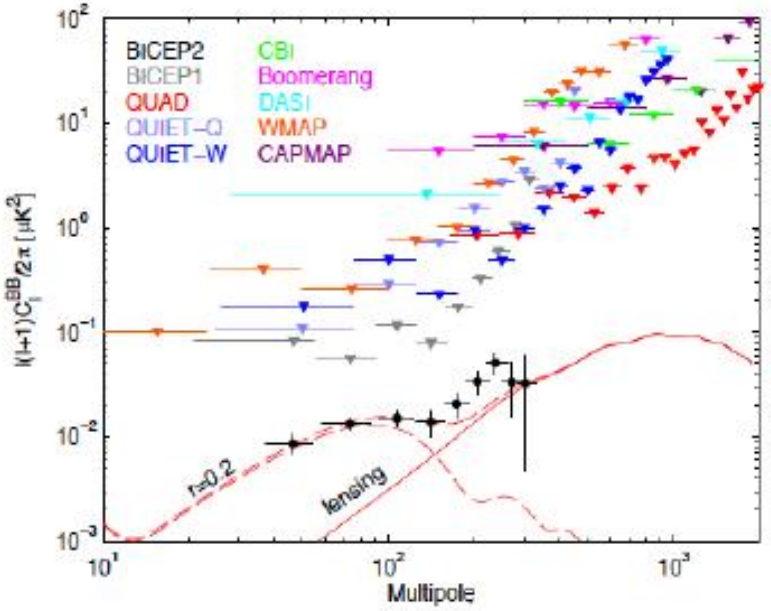
Table 1. Predictions for the cosmological observables n_s and r for different string inflationary models.

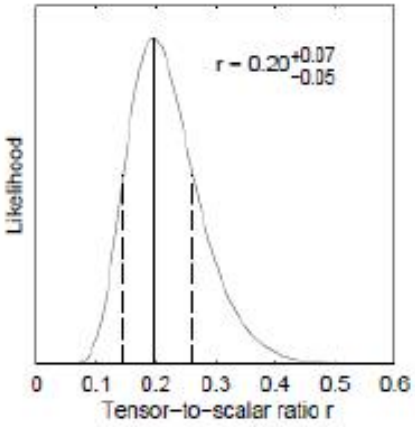
If BICEP2 were correct, all above models would have been ruled out!

BICEP2 claimed the detection of primordial GWs for the first time, but…

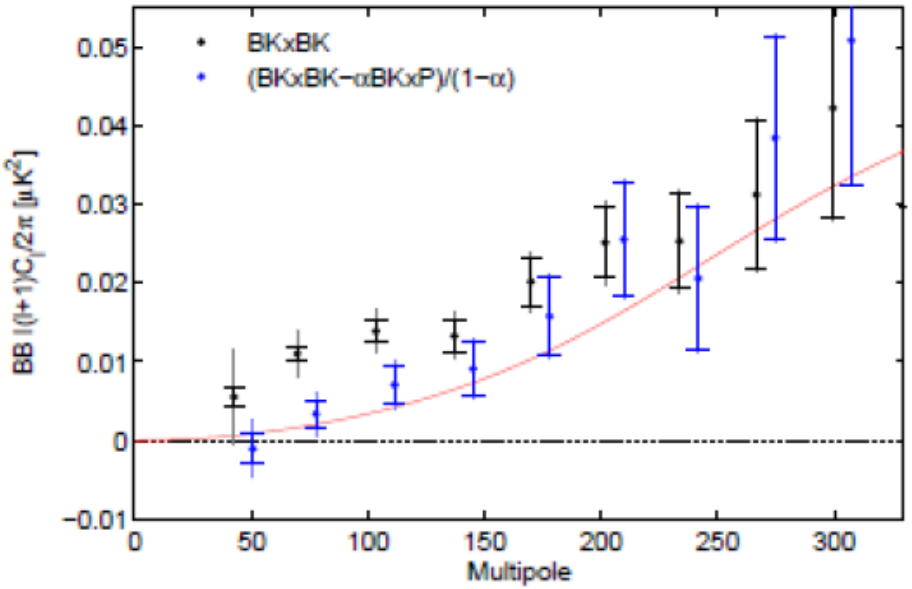








BICEP2 signals are very likely from the foreground dust contamination

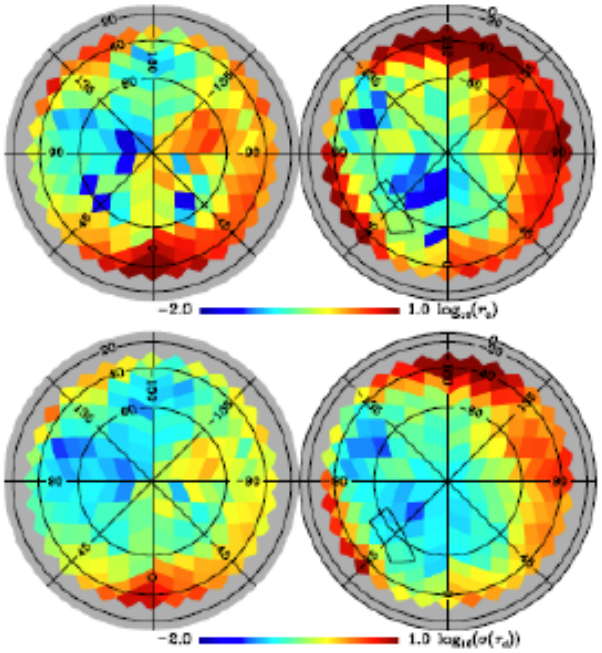


No winner yet! Who first hit to 21 points?

Searching for primordial GWs becomes important in the community.

Polarization foreground from galaxy

full sky coveraged is required !

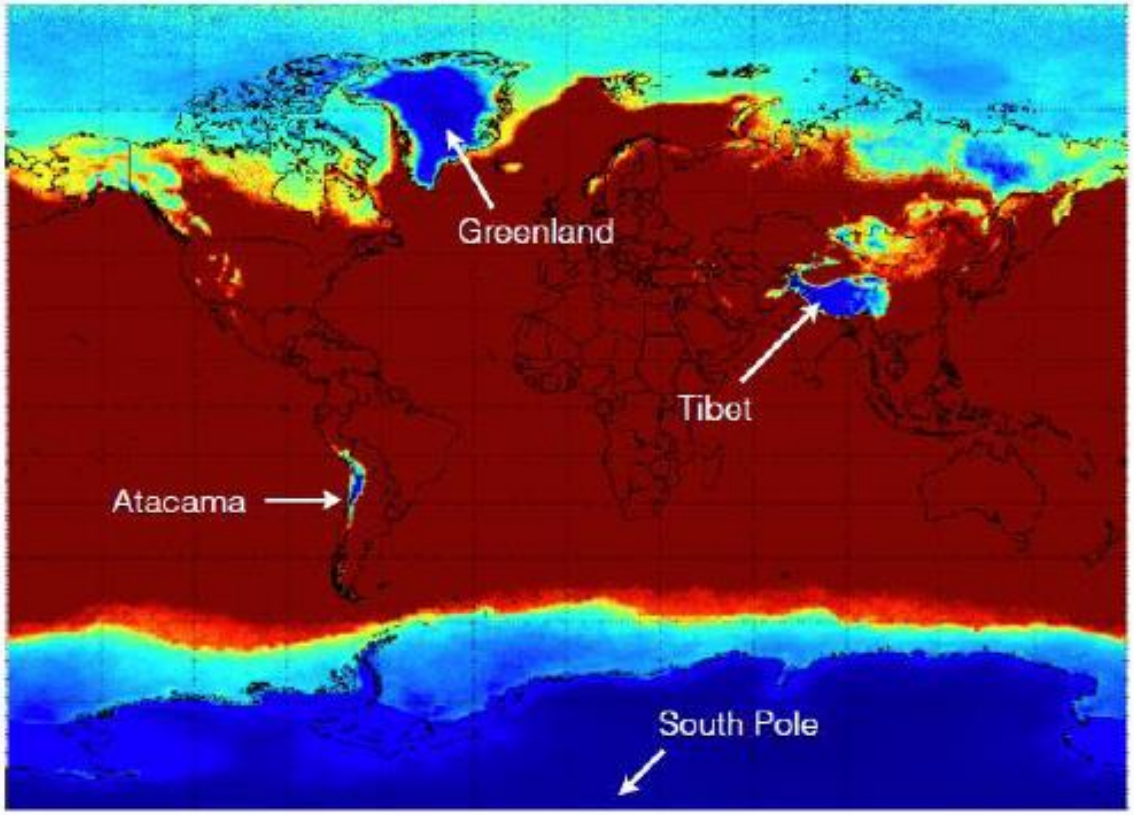


north hemisphere south hemisphere

- Planck can provide us the full sky coverage, but the S/N is very limited;
- After Planck, there is so far no further space-based projects;
- The ground-based CMB polarization projects will be the key developments in the next decade.

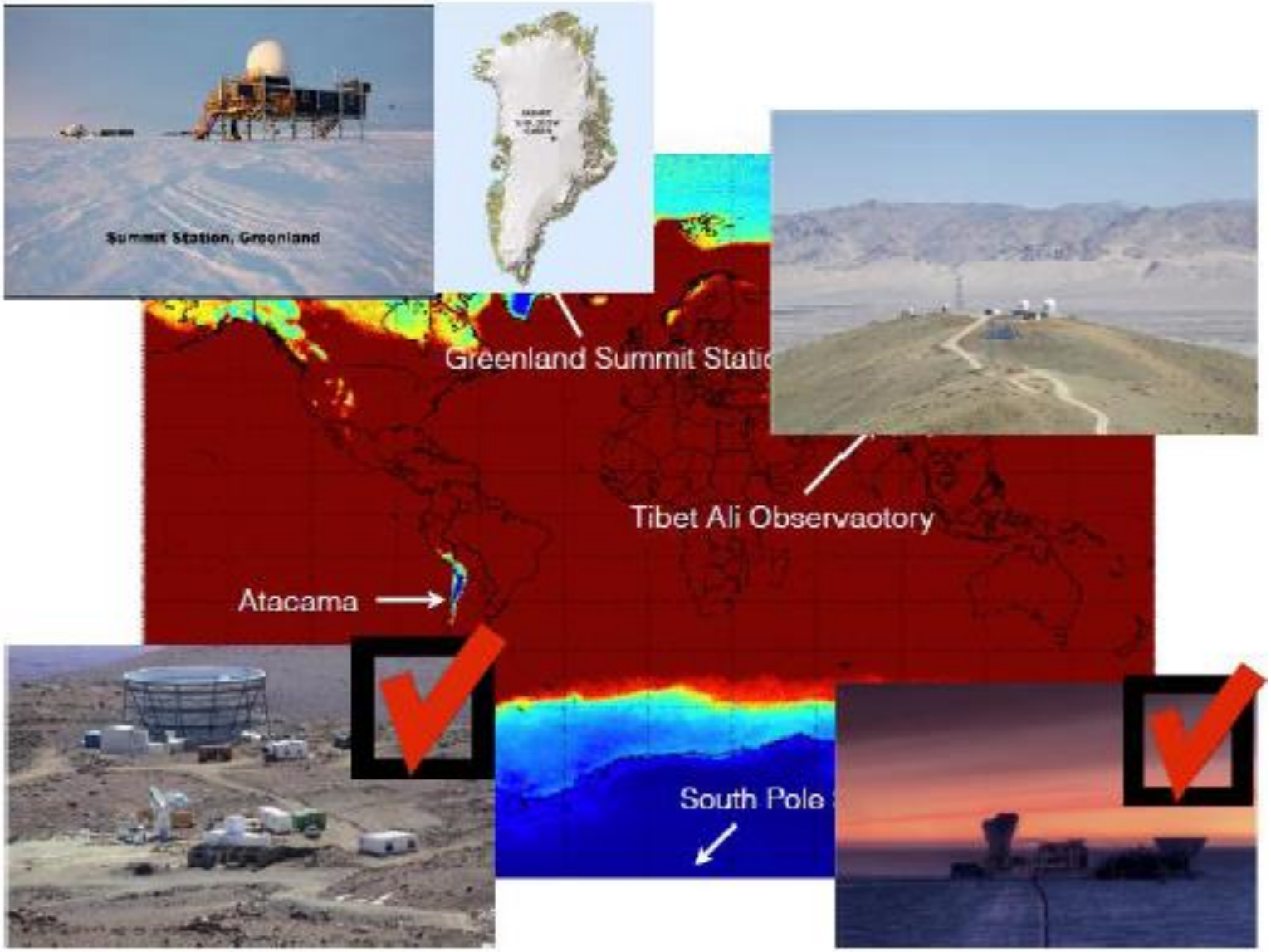
A full sky coverage is needed!

How many places suitable for CMB?



- Blue areas indicate high atmospheric transmission rate, which are suitable for CMB observations!
- Four best places on Earth: Greenland, Tibet, Atacama desert, Antarctica

Ground-based CMB experiments



Full-sky coverage expects the CMB experiments in the north part of the earth

A future lesson from CMB experiments

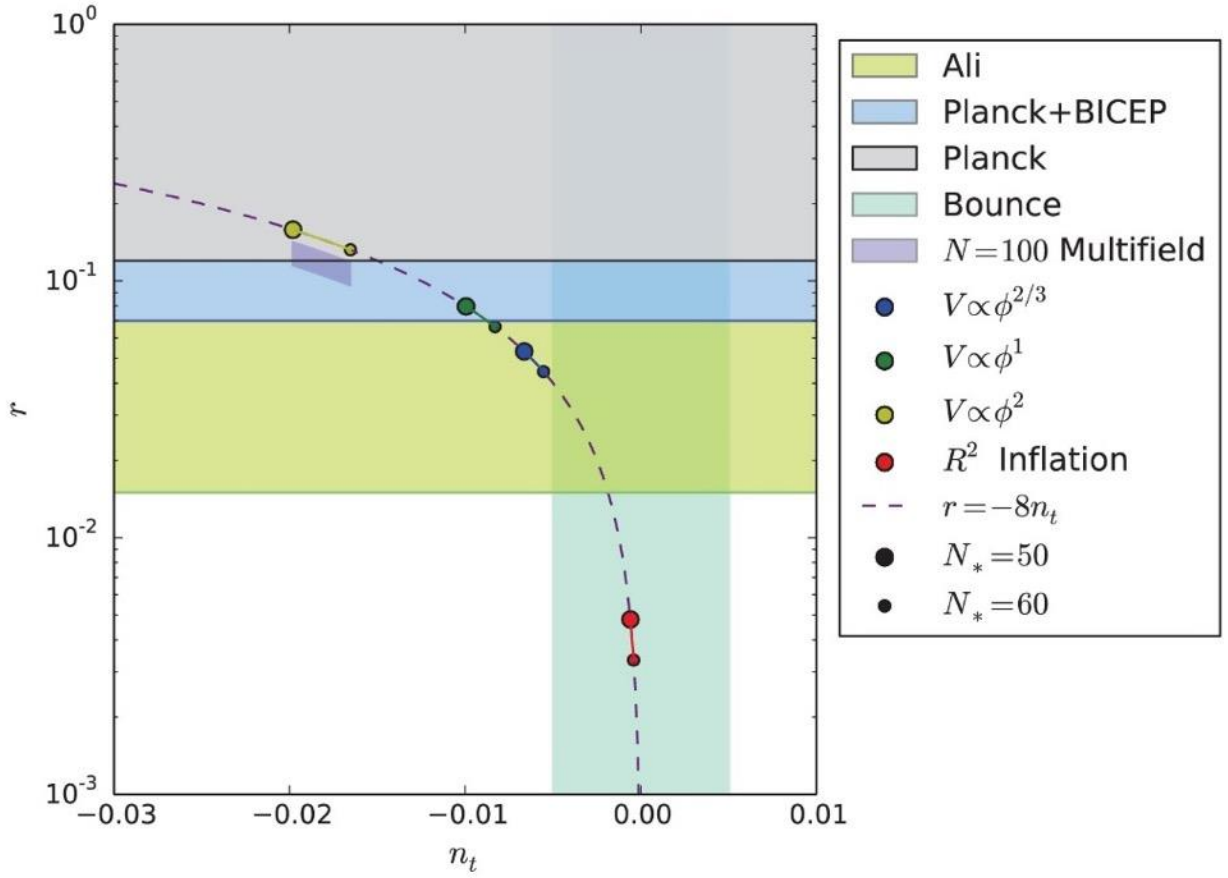
Overview: predictions of very early universe models

Models	Predictions			
Inflation	$r = 16\,\varepsilon$	$n_t = -2\,\varepsilon$	$\alpha_t < 0$	$f_{nl}=5(1-n_s)/12$
Bounce	$r \le O(1)$	$\lvert n_t \rvert < O(1)$	$\alpha_t > 0$	$f_{nl} \approx -5/2$
Ekpyrosis	$r \ll O(1)$	$n_t = 2$	$\alpha_t < 0$	$f_{nl} > 1$
String gas	$r \le O(1)$	$n_t \approx 1-n_s$	$\alpha_t > 0$	$f_{nl} \ll O(1)$

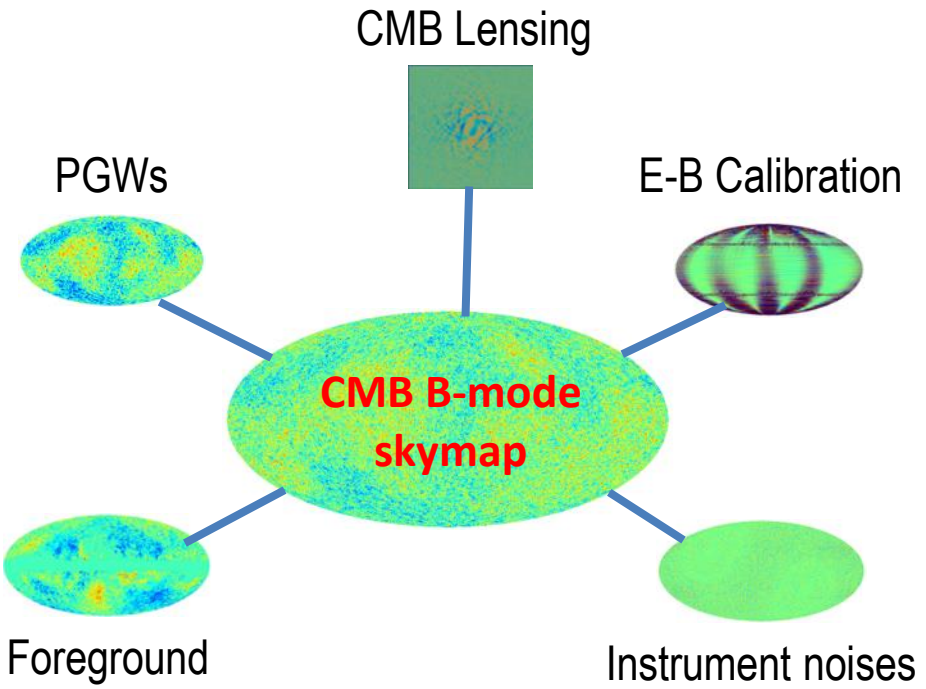
Constraining the very early universe models

Q: there are too many models of the very early universe, namely,

- Inflationary models
- Nonsingular bounce models
- Models of emergent universe



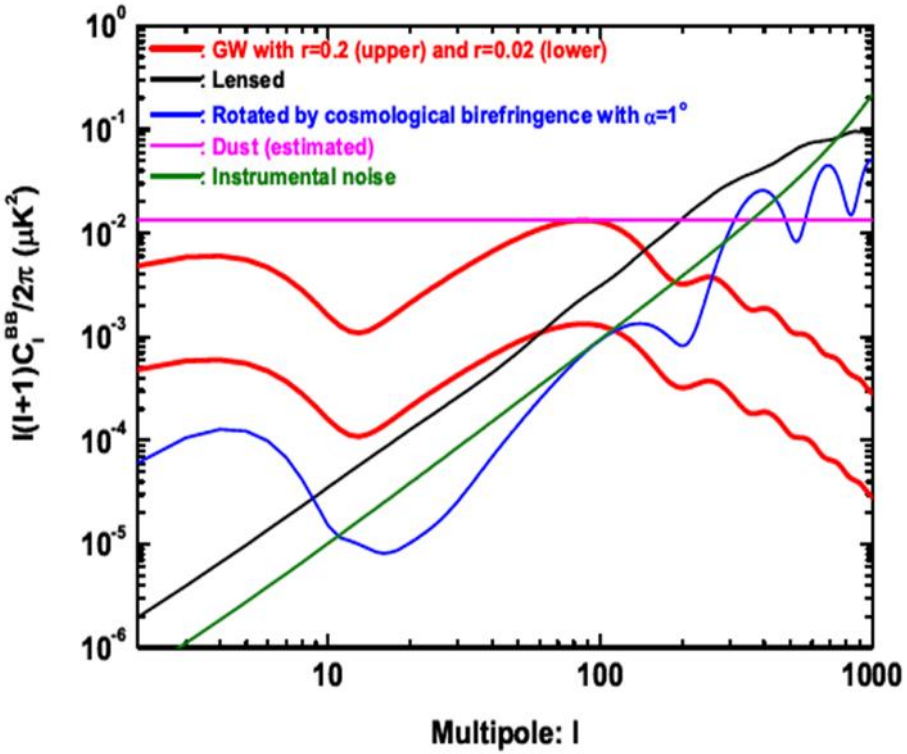
Statistics of all possible B-mode components



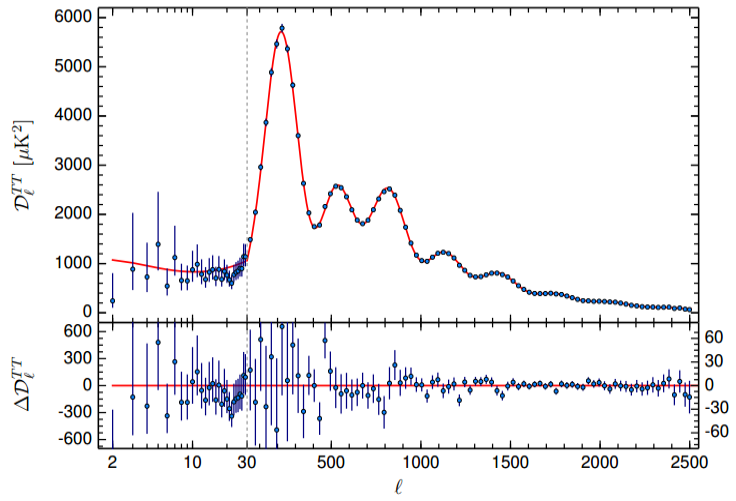
Q: How can we identify all the components that can give rise to CMB B-mode?

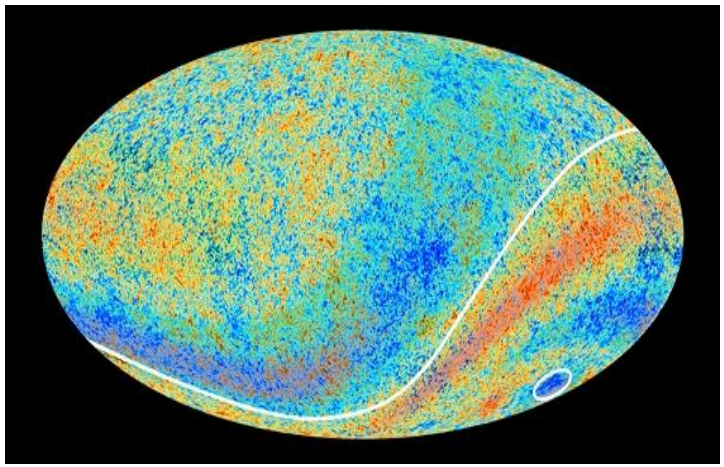
Plan：

Different components exhibit different statistical properties. These can be used to exact the signals from PGWs.



CMB large scale anomalies





- Large scale suppression
- Cold spot
- Hemispherical power asymmetry
- Power deficit near l=30

Q: primordial origin, or, observational contamination?

Plan:

✓ Combine together AliCPT in North sphere and BICEP, PolarBear in South sphere

✓ Build theoretical models to explain associated phenomena

Summary & Outlook

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Today

- The detection of CMB fluctuations can be regarded as the starting point for cosmology as a precision science
- The paradigm of early universe has been greatly developed
- The Big Bang has became the Standard Model in cosmology
- Inflationary cosmology obtained a large amount of initial achievements
- Bounce cosmology is ambitious on solving big bang singularity
- The GW Astronomy has initiated

In Near Future

- Very early universe is an alternative stage for exploring fundamental physics
- Multi-messenger provides a novel means of cosmological research
- It becomes possible to observationally probe accurate physics near the Big Bang: CMB B-modes
- China's Ali CMB project will be the first CMB experiment in the north earth

A new era has begun...

Thanks!