Exploring the very early universe with CMB observations

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the KIAA/DoA Colloquium @ Peking U

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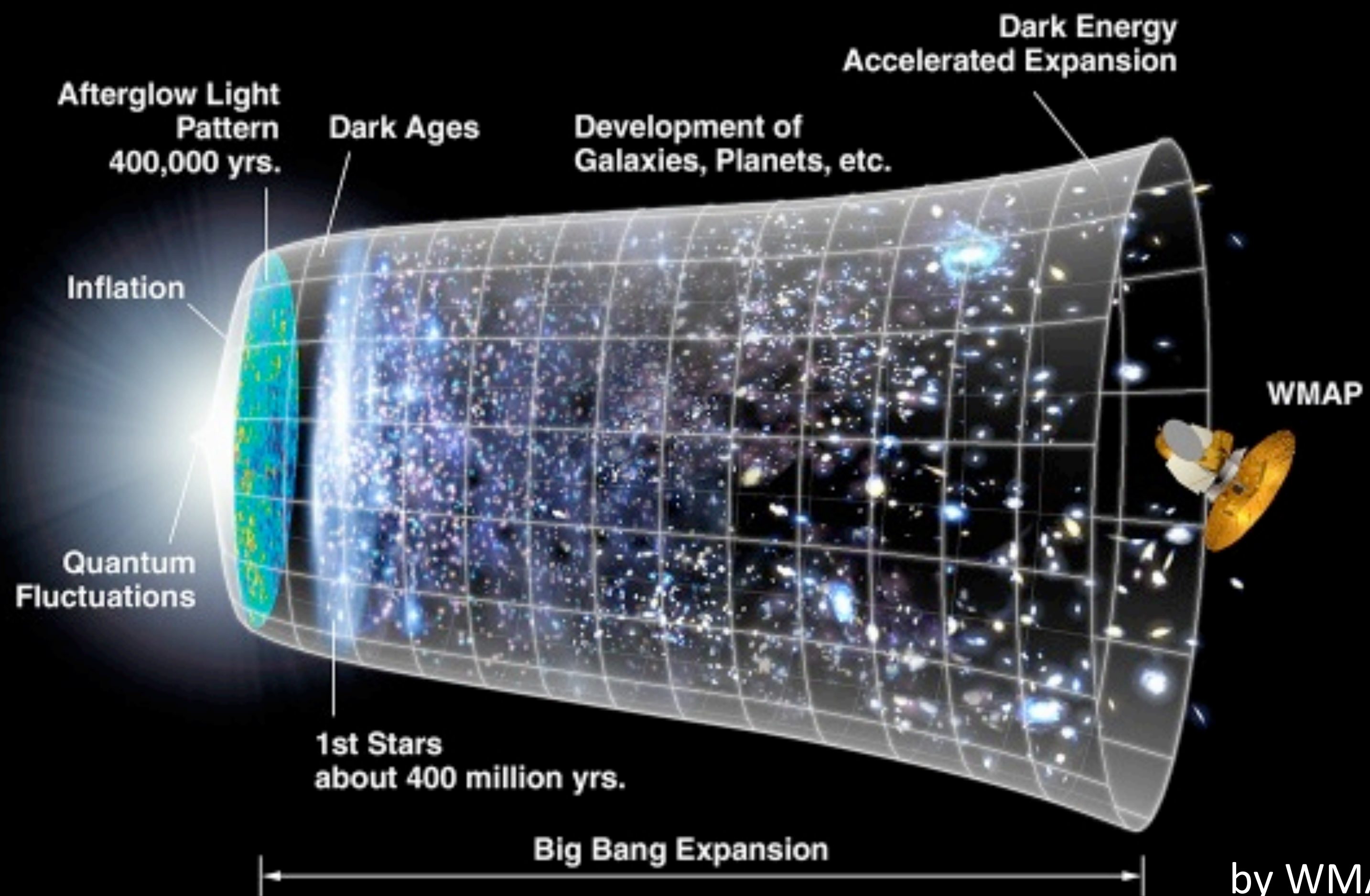
中国科学技术大学天文学系

Department of Astronomy, University of Science and Technology of China

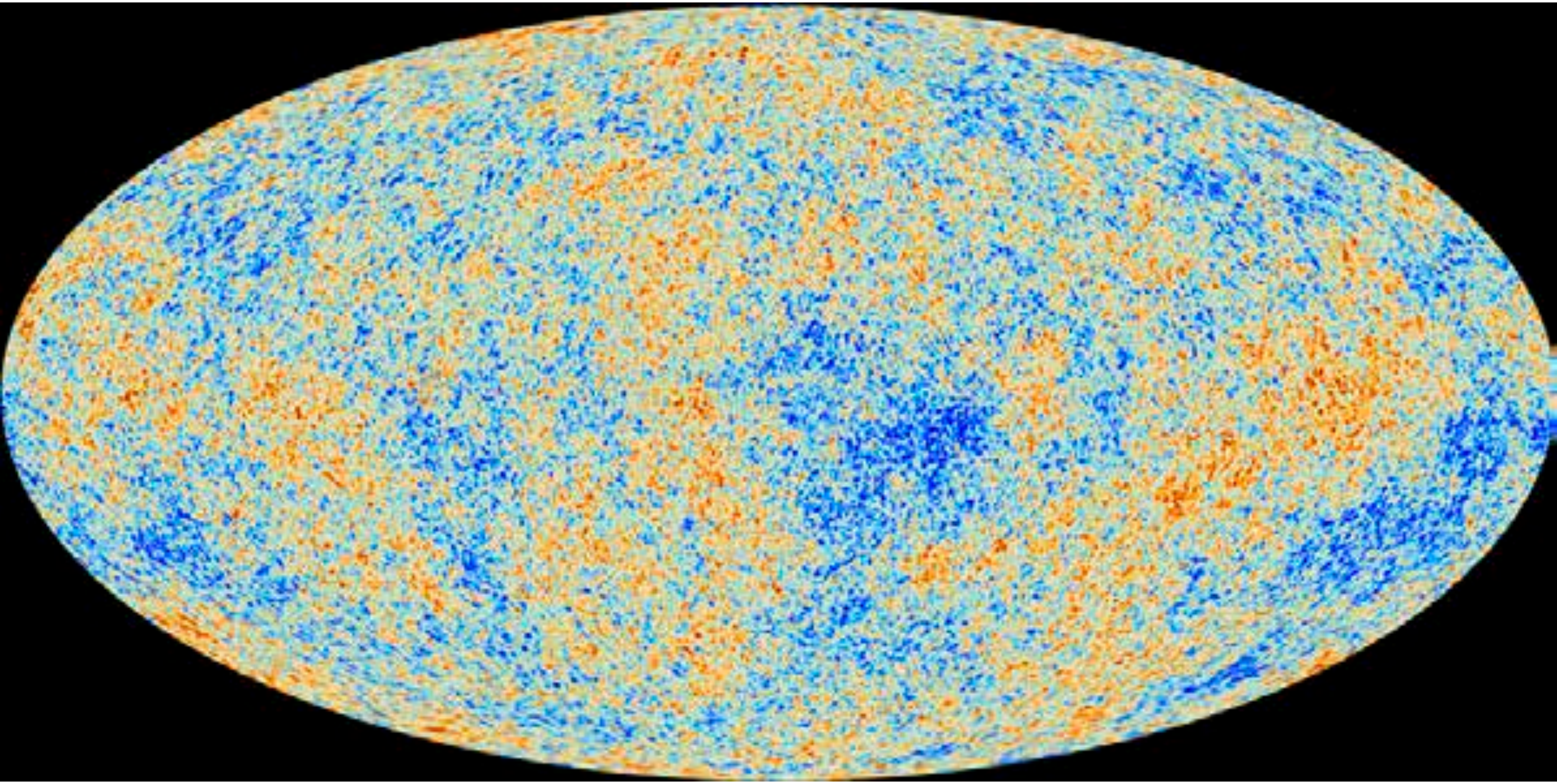
Standard Model: Inflation & hot Big Bang



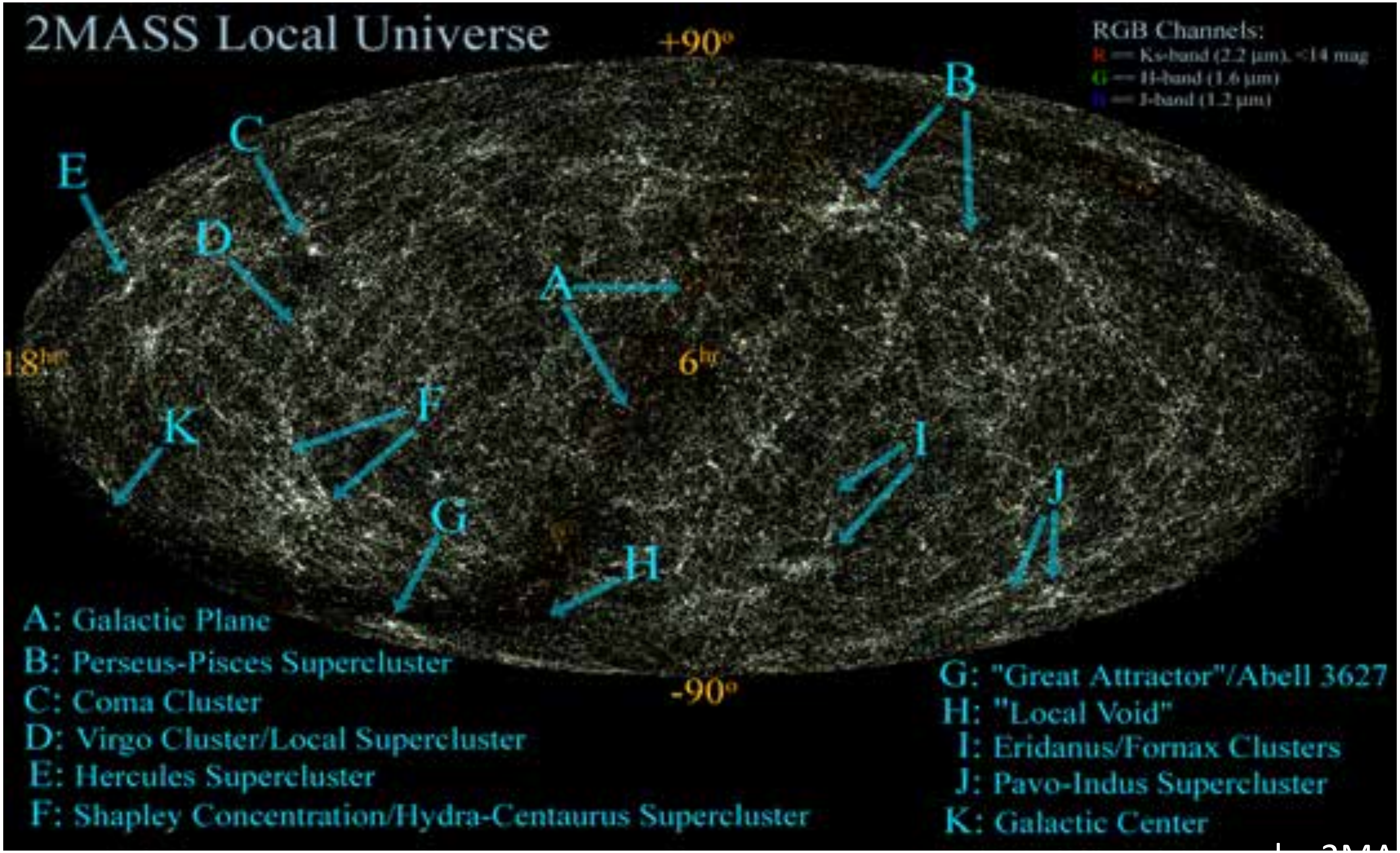
by WMAP/NASA

13.8 billion years

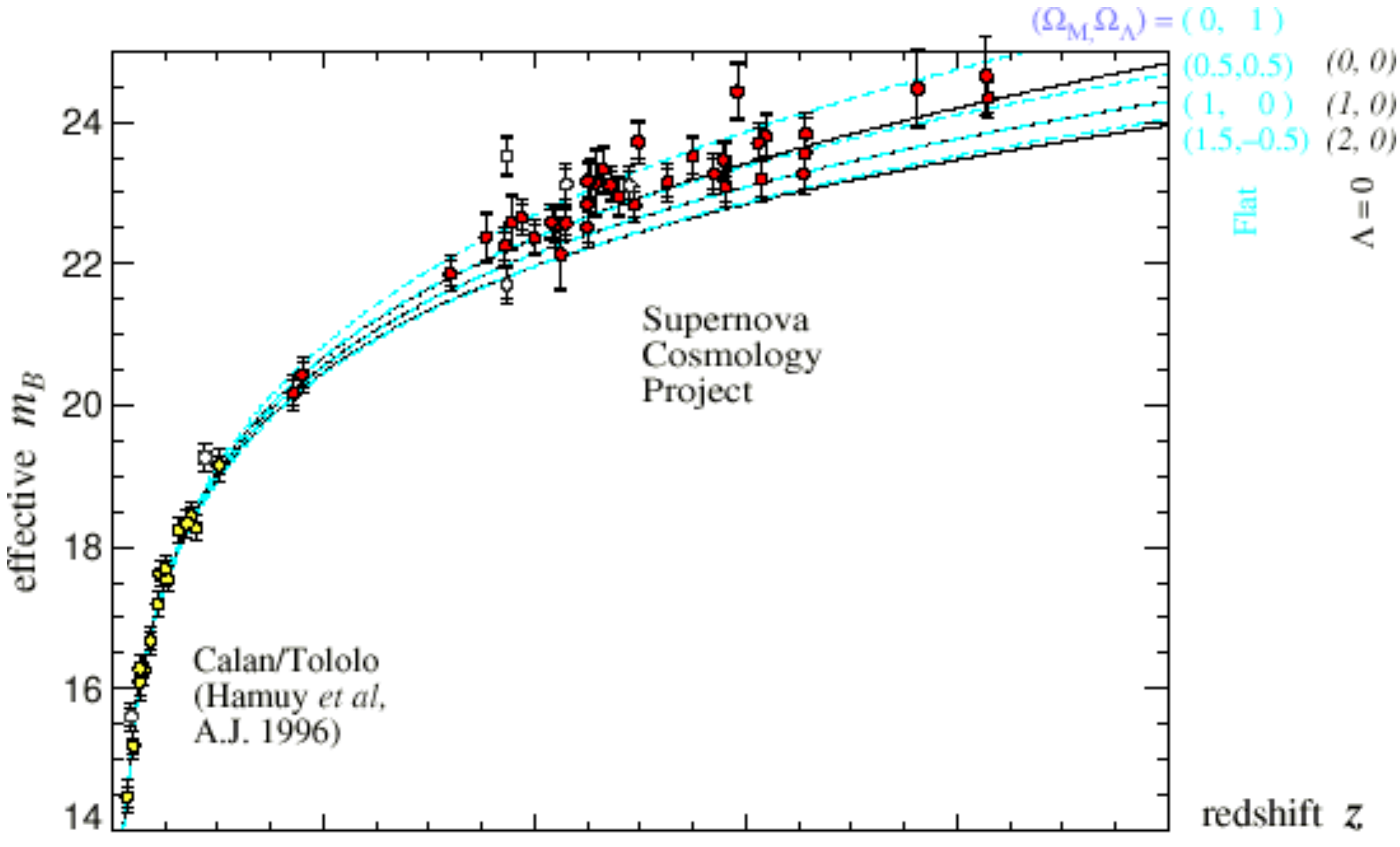
Cosmic Microwave Background (CMB) Anisotropies



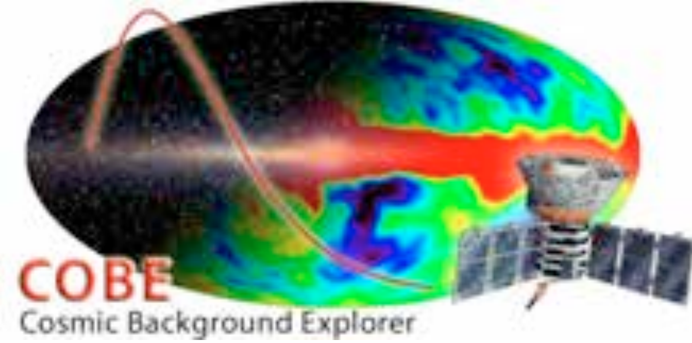
Large Scale Structure (LSS) Survey



Hubble Diagram from Supernova



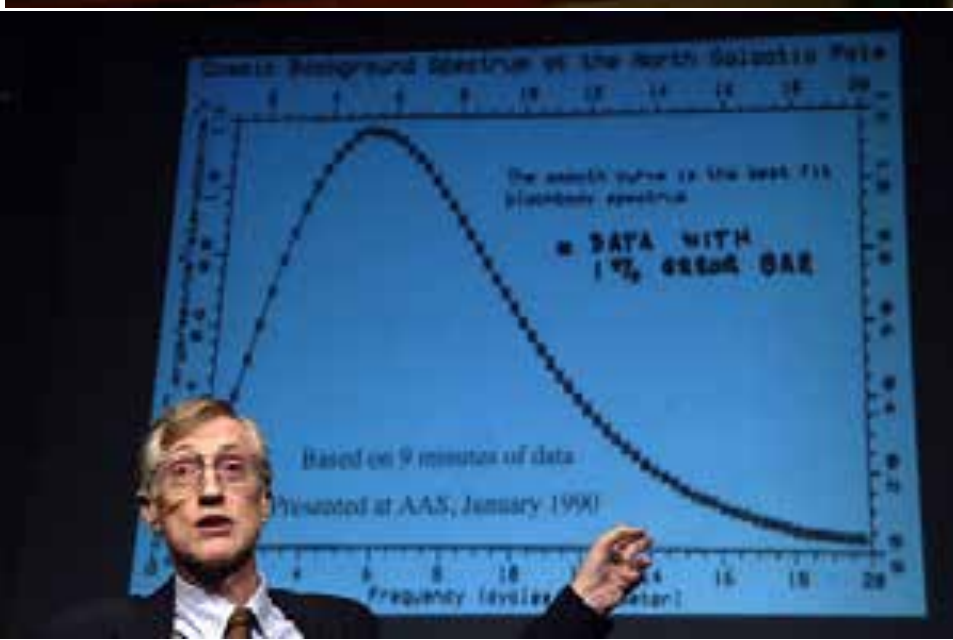
The Nobel Prize in Physics 2006

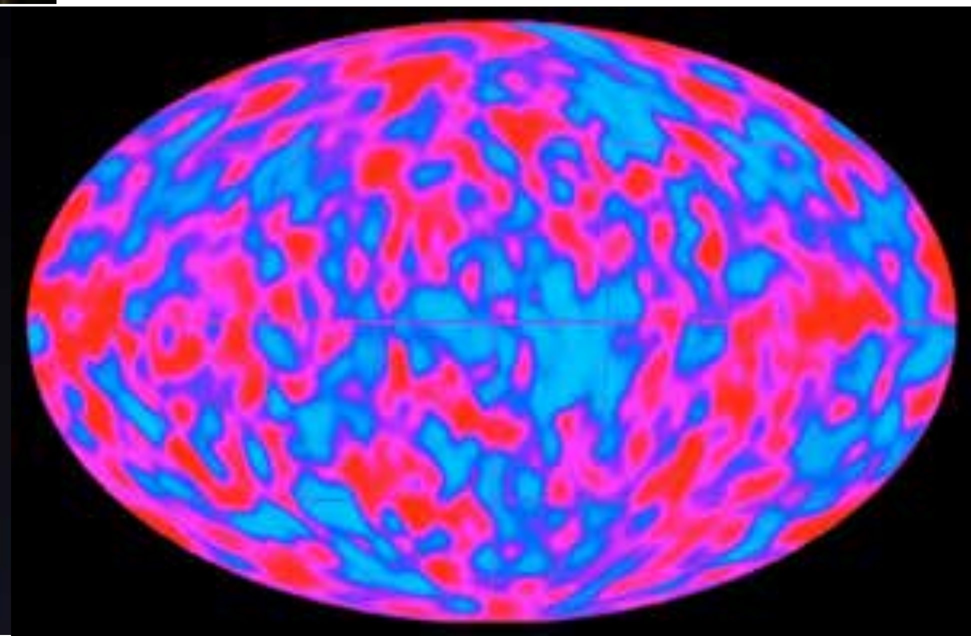


John C. Mather

George F. Smoot

"for their discovery of the ***blackbody form*** and ***anisotropy*** of the cosmic microwave background radiation"

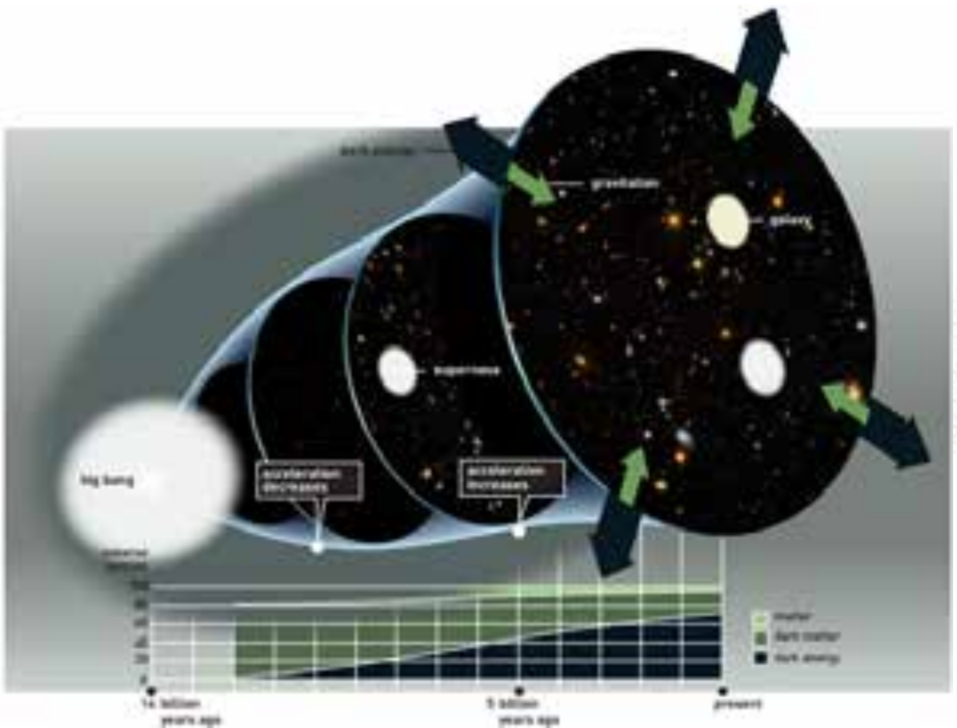


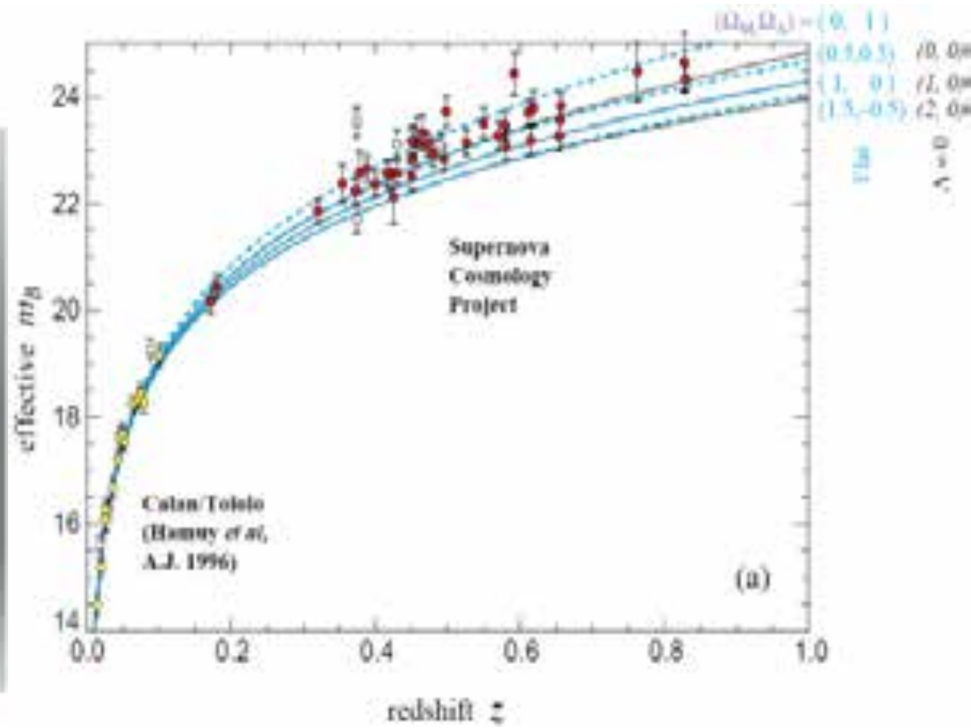


The Nobel Prize in Physics 2011

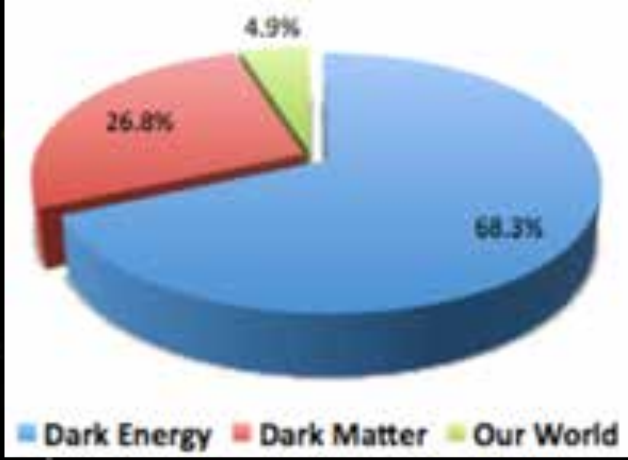
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

"for their discovery of the ***accelerating expansion*** of the Universe through observations of distant supernovae"





Observational Facts:

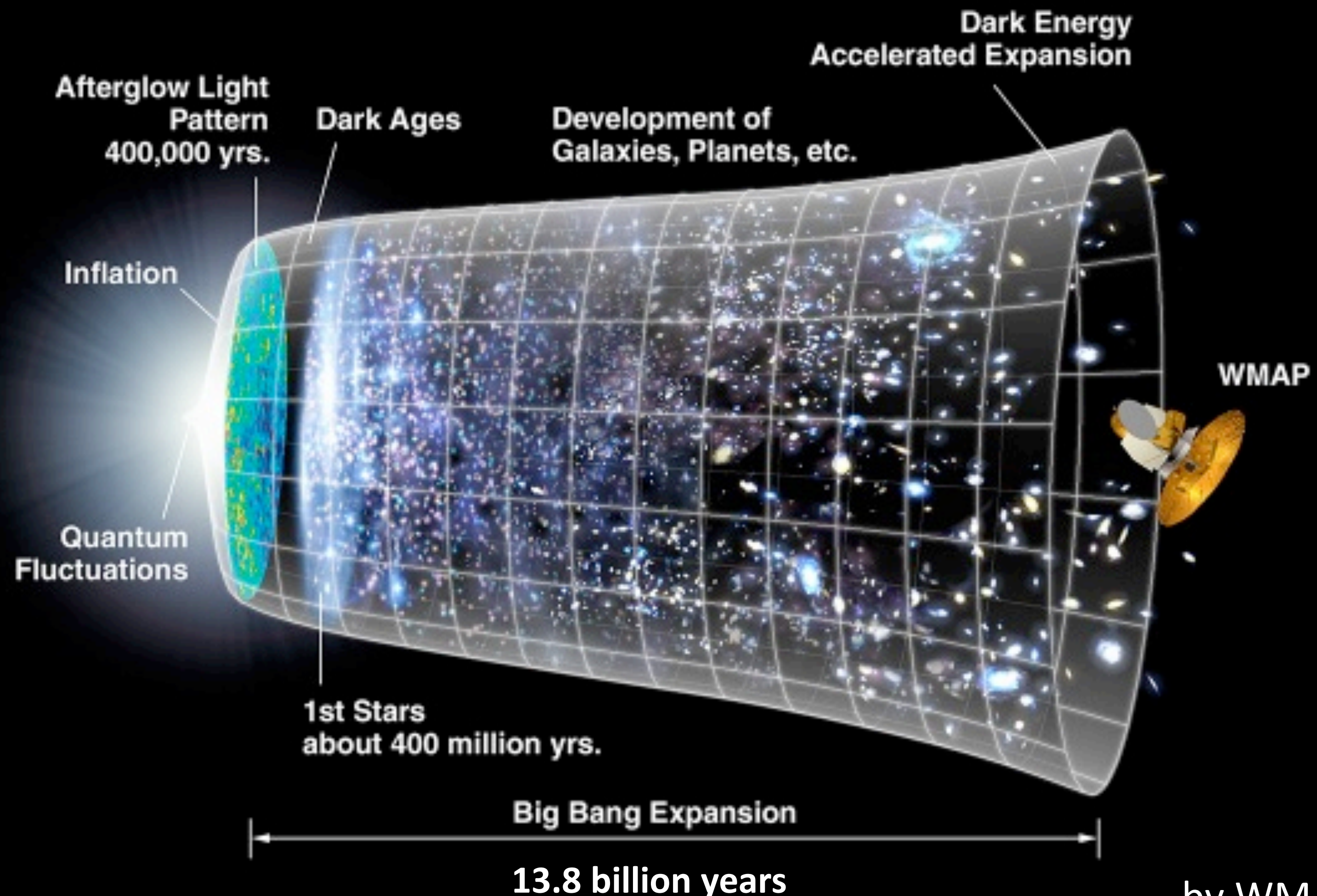


- Our universe has a thermal expanding history with 13.8 billion years

- The background looks the same at anywhere on sufficiently large scales

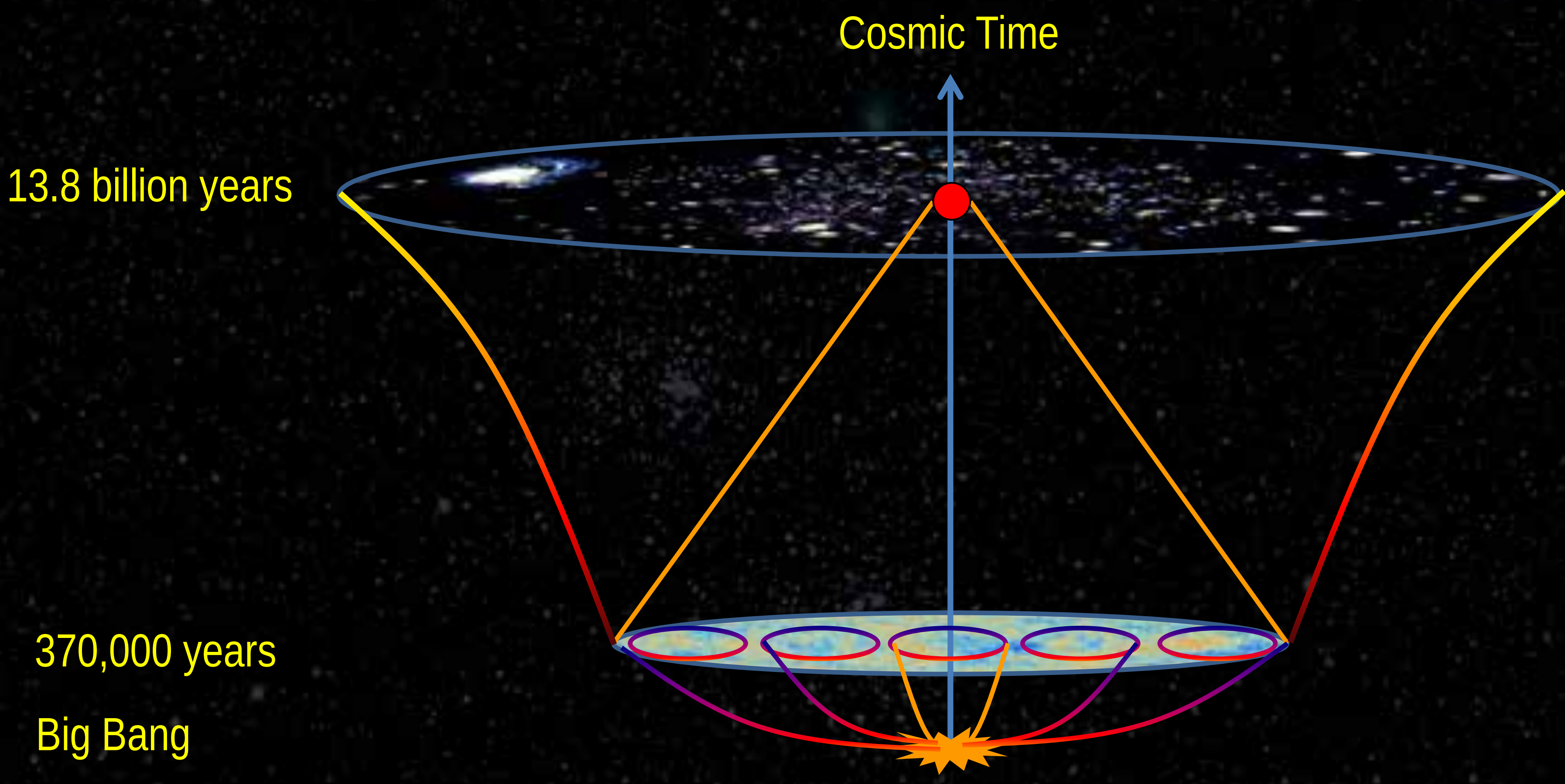
- Galaxies and clusters are basic blocks to form the LSS

Inflationary Cosmology (Guth, Starobinsky, Sato, Fang, 1980s)

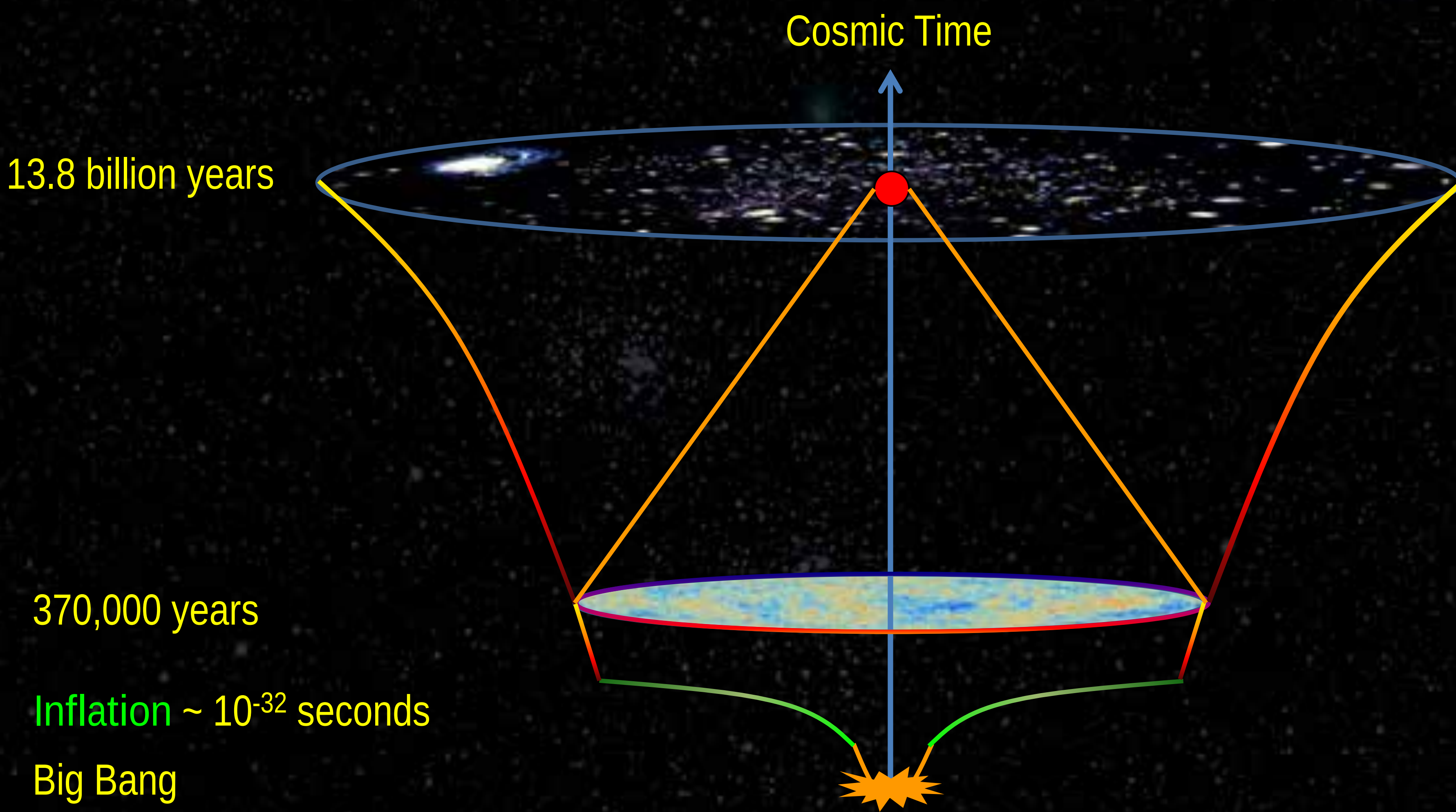


by WMAP/NASA

Solution to Horizon Problem



Solution to Horizon Problem



The Physics of Inflation

- A period of accelerated expansion in the very early universe
- That requires a matter field with negative pressure
- This can be realized by a scalar field ϕ slowly rolling down along a very flat potential
- ϕ field quantum fluctuations lead to scale invariant primordial power spectrum and explain CMB and LSS

Successes of Inflationary Cosmology

- Horizon problem
- Flatness problem
- Unwanted relics problem
- LSS Formation
  (Chibisov & Mukhanov, 1981)

Inflation's challenges

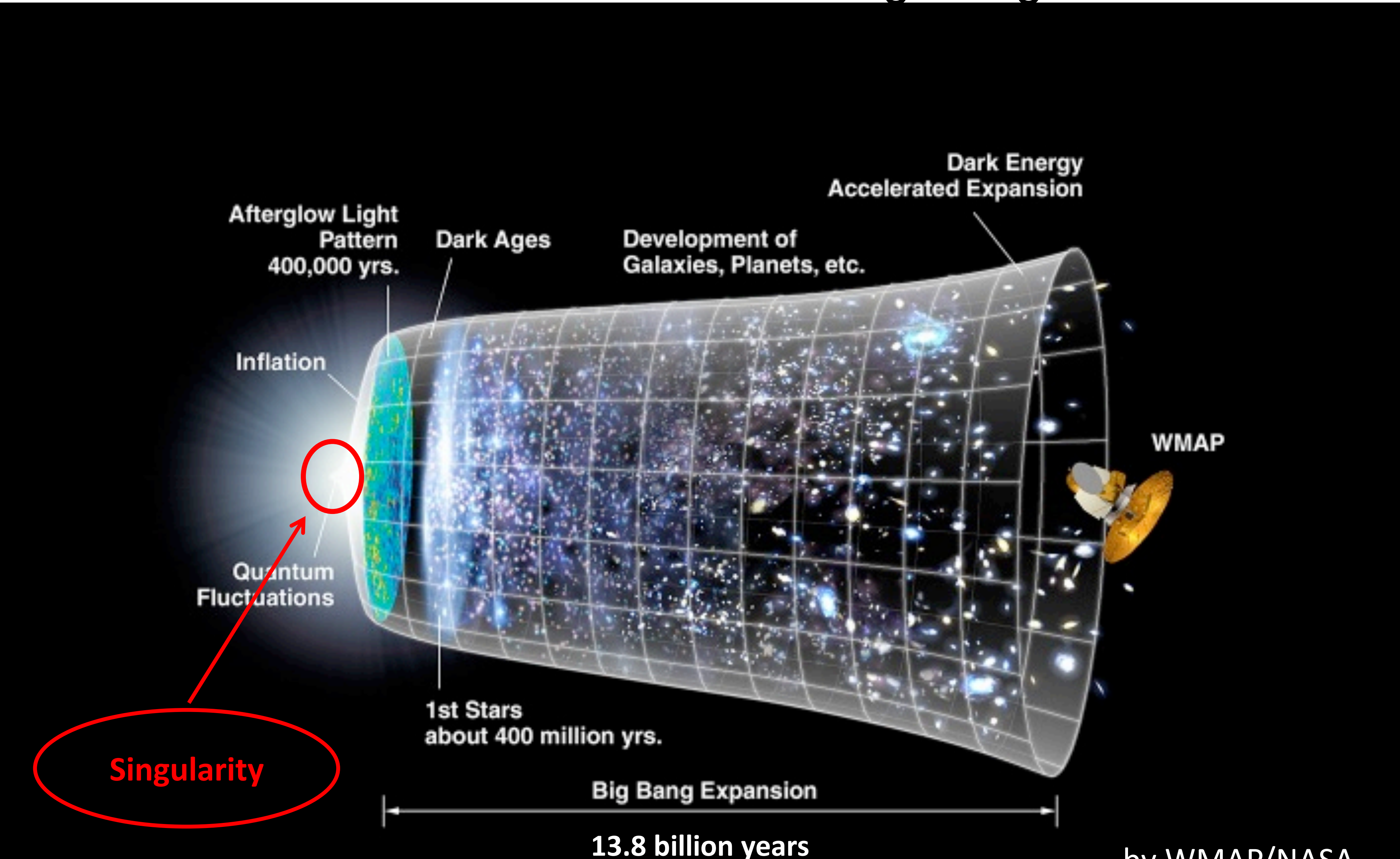
- Trans-Planckian Problem
  (Martin & Brandenberger, 2000)

- Microscopic origin of the scalar field driving inflation

- Big Bang Singularity

→ A competitive paradigm:
Bounce Cosmology

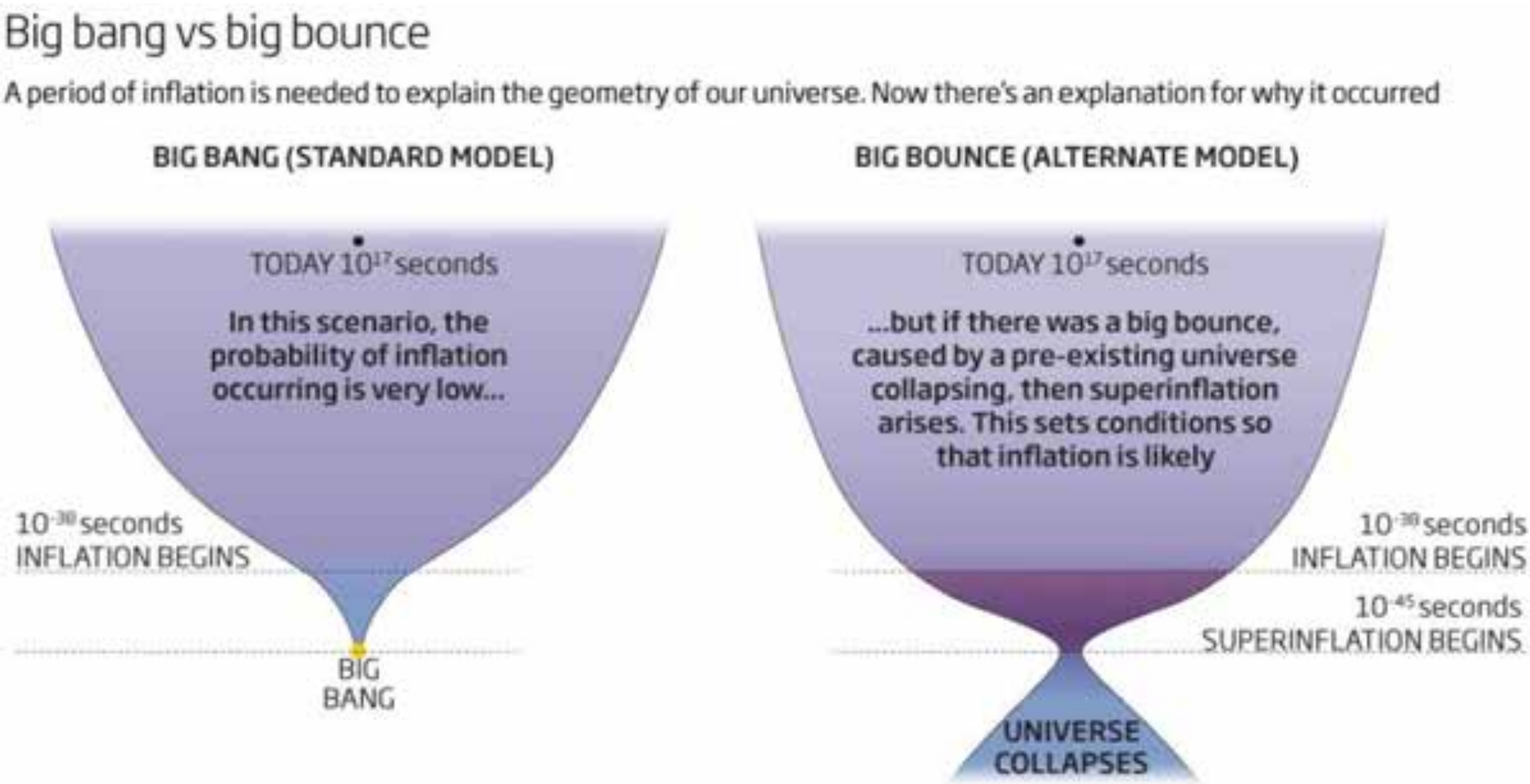
Standard Model: Inflation & hot Big Bang



by WMAP/NASA

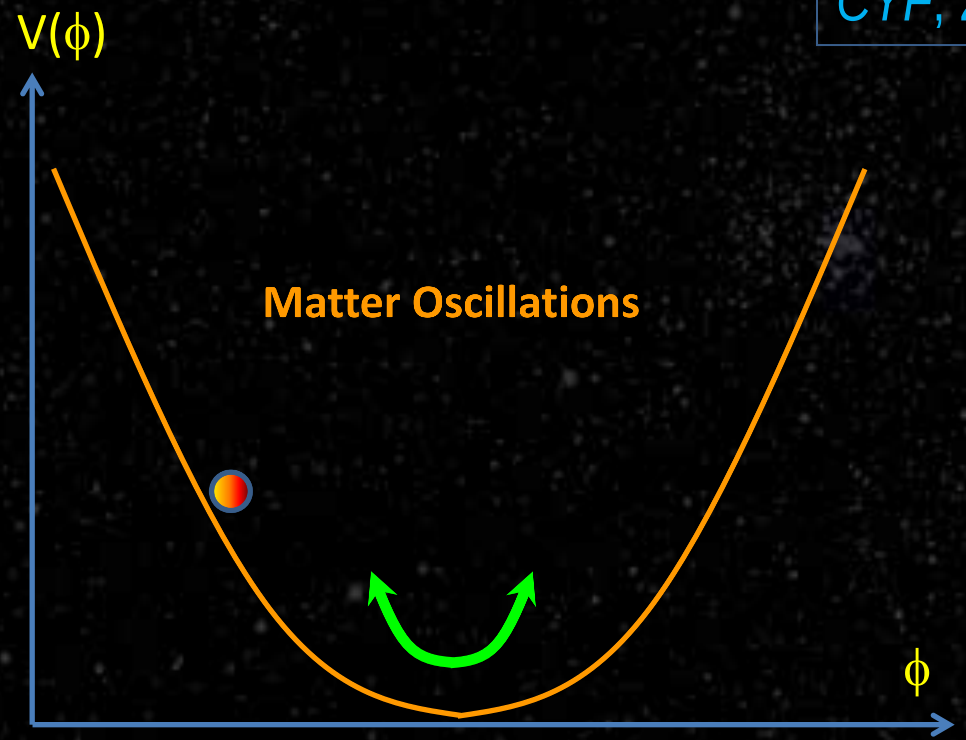
Bounce Cosmology

- **Connecting fundamental theories with observations**



Effective Field theory of Bounce Cosmology

CYF, Qiu, Brandenberger & Zhang, 2008
CYF, Easson & Brandenberger, 2012
CYF, 2015



Effective Field theory of Bounce Cosmology

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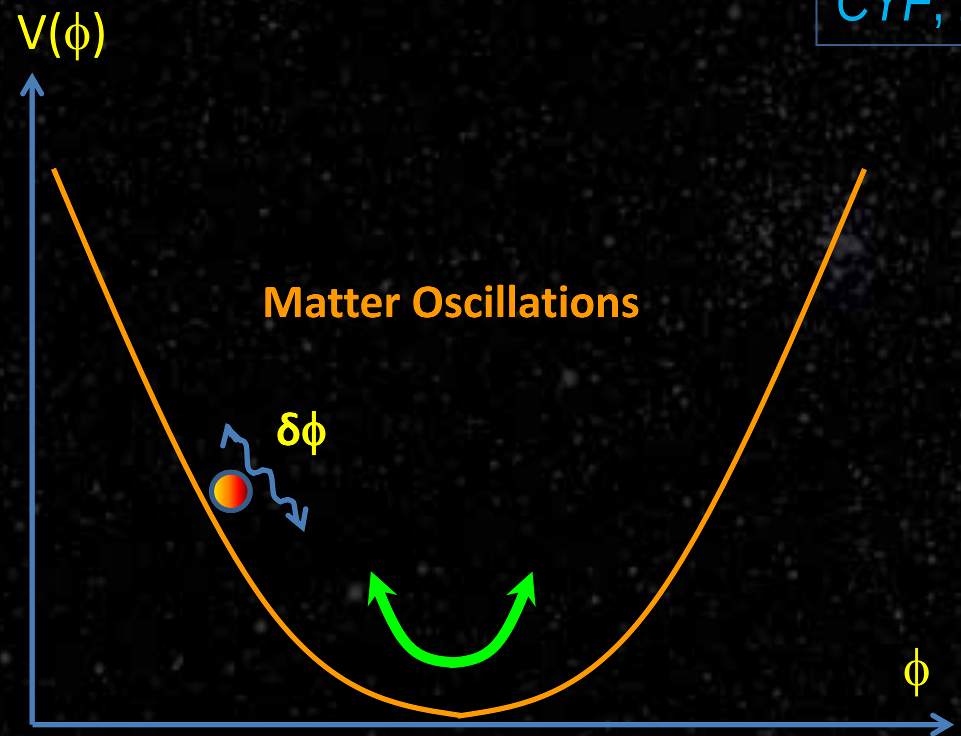
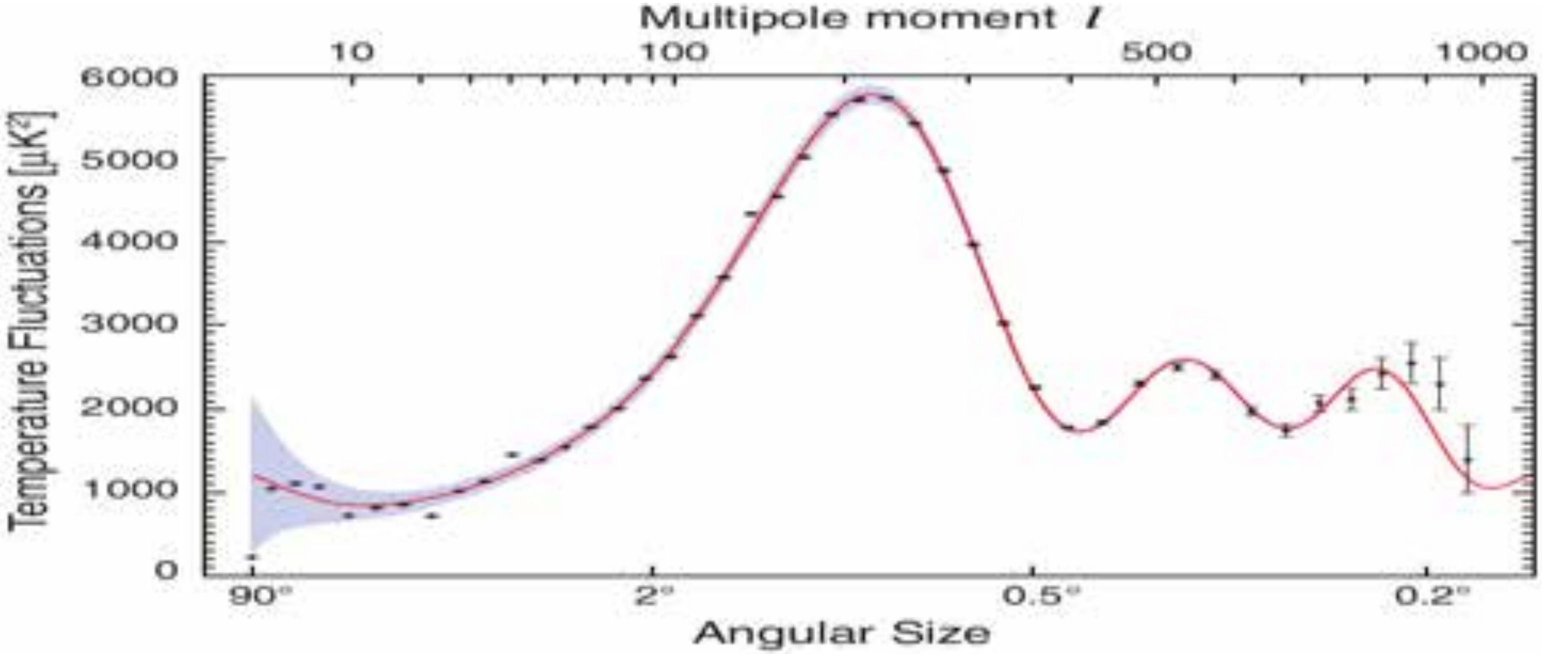
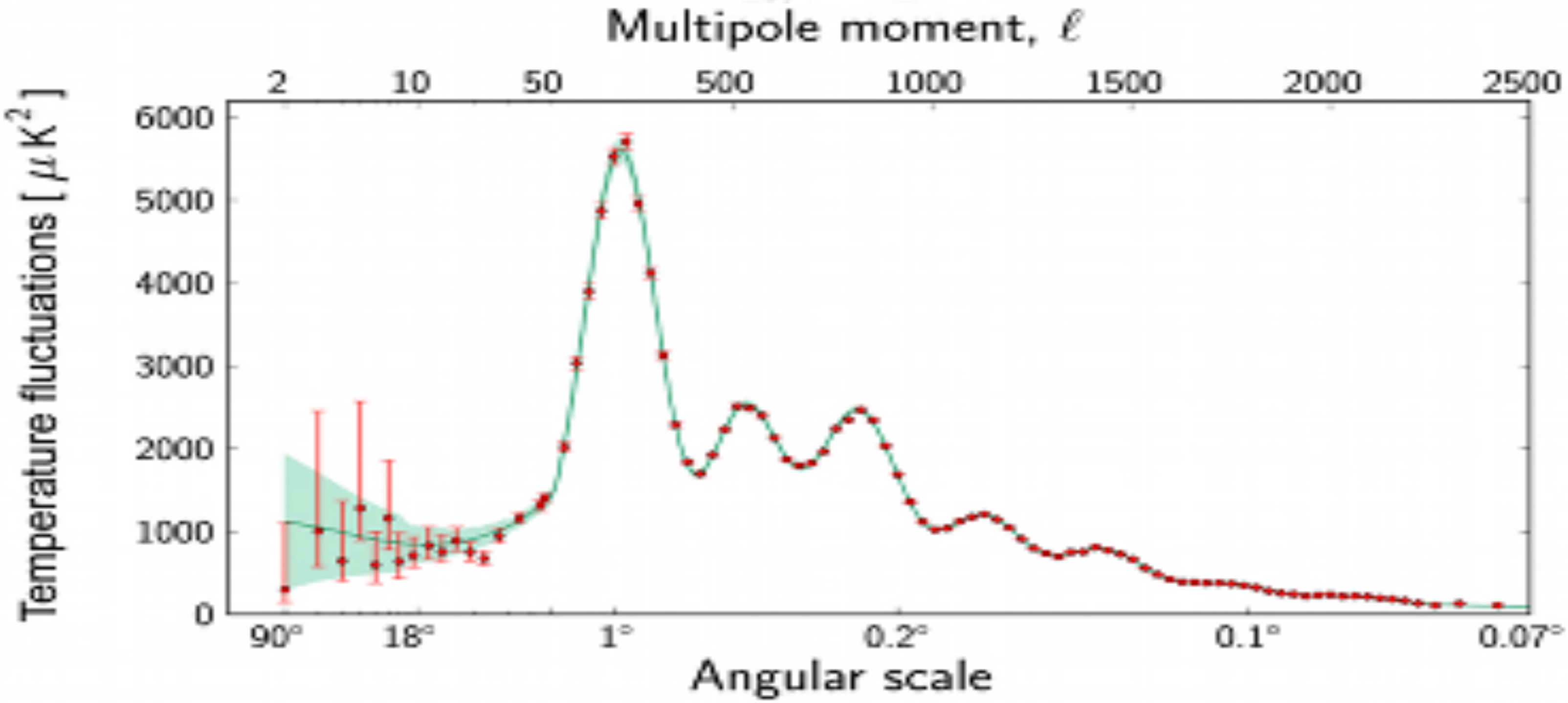


- A period of **matter field contraction** before the bounce
- A bounce can be triggered by quantum effects
- **Scale-invariant power spectrum**

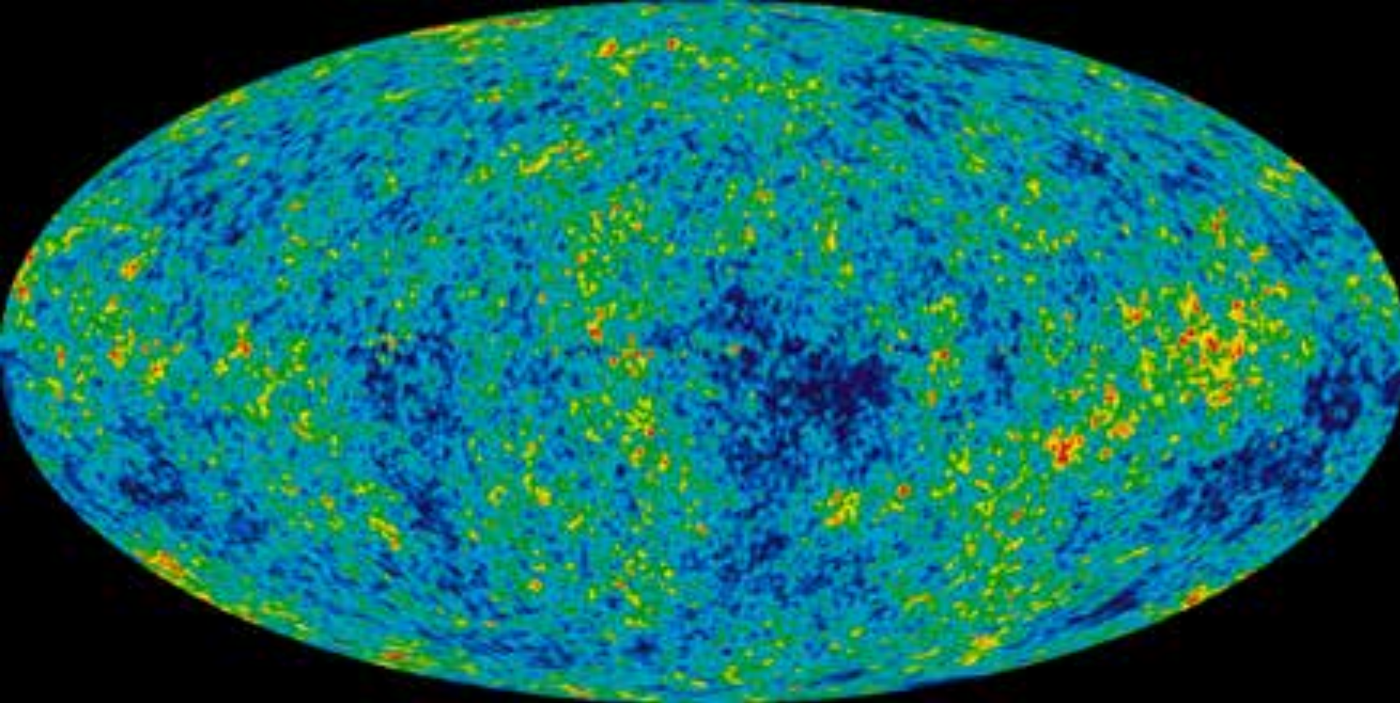
$$\delta\phi|_{\mathrm{Contraction}} \rightarrow \zeta|_{\mathrm{Contraction}} \rightarrow \frac{\delta\rho}{\rho}|_{\mathrm{Post-Bounce}} \rightarrow \frac{\delta T}{T}|_{\mathrm{CMB}}$$



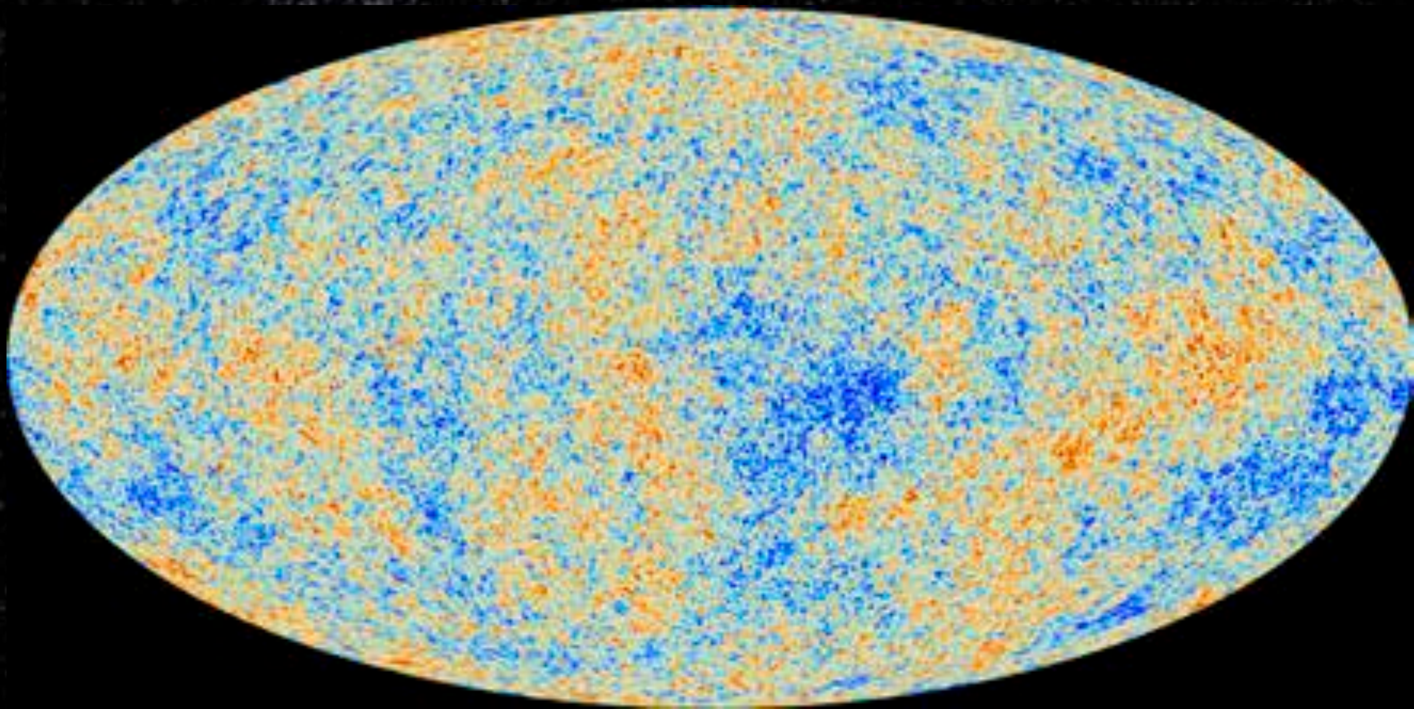
Multipole moment l
10
100
500
1000
6000
5000
4000
3000
2000
1000
0
Temperature Fluctuations [μK²]
90°
2°
0.5°
0.2°
Angular Size



Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
6000
5000
4000
3000
2000
1000
0
Temperature fluctuations [μK²]
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale



WMAP/NASA



Planck/ESA

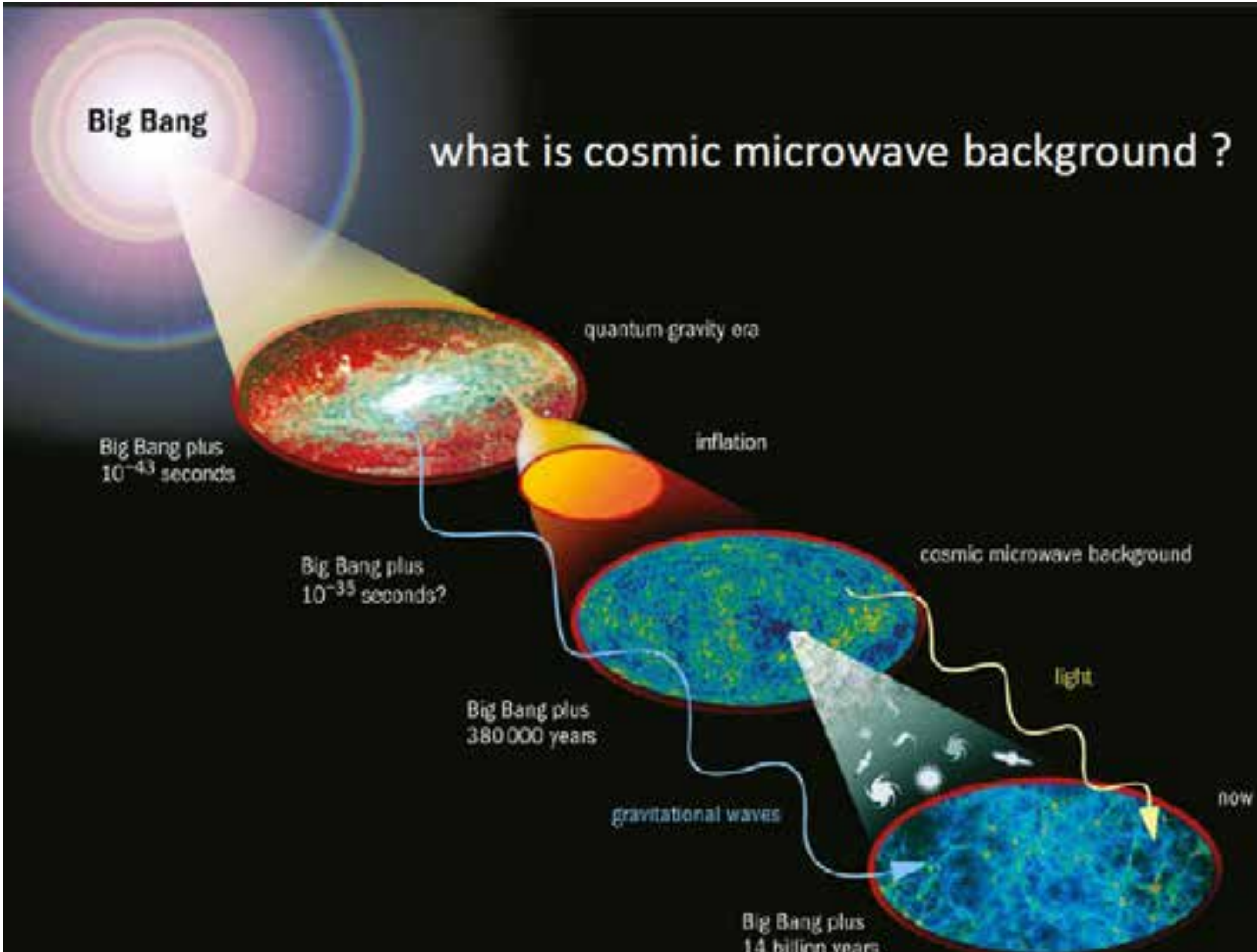
The Physics of Bounce

- No initial singularity

- An alternative to inflation in explaining the CMB & LSS

- Applied to examine fundamental particle theories

- Inflation or Bounce? This is a question about how to probe the origin of our Universe?

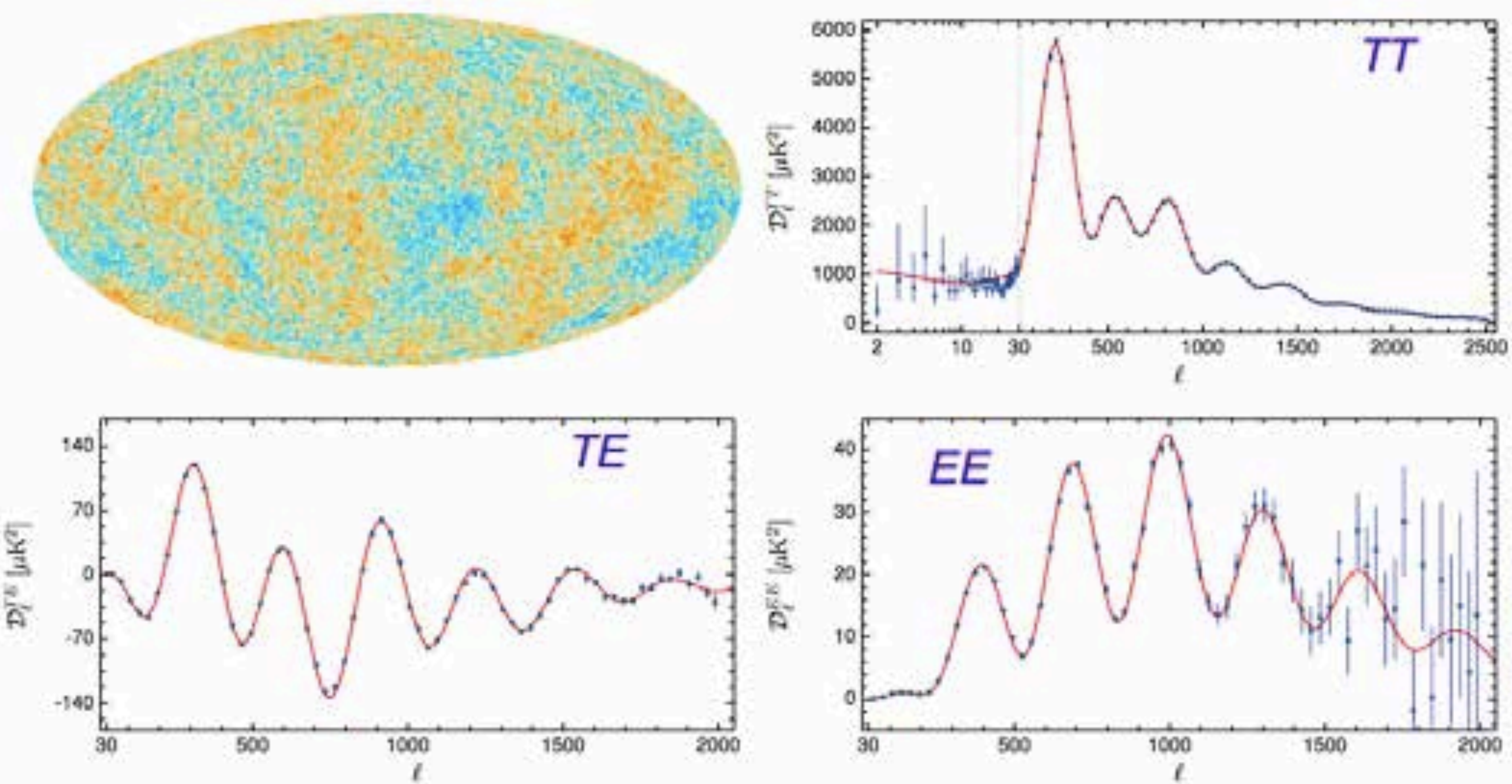


Big Bang
what is cosmic microwave background ?
quantum gravity era
Big Bang plus
10^{-43} seconds
inflation
Big Bang plus
10^{-35} seconds?
cosmic microwave background
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years

CMB is super important to the study of cosmology

A **novel** lesson from Planck

CMB maps from Planck 2015



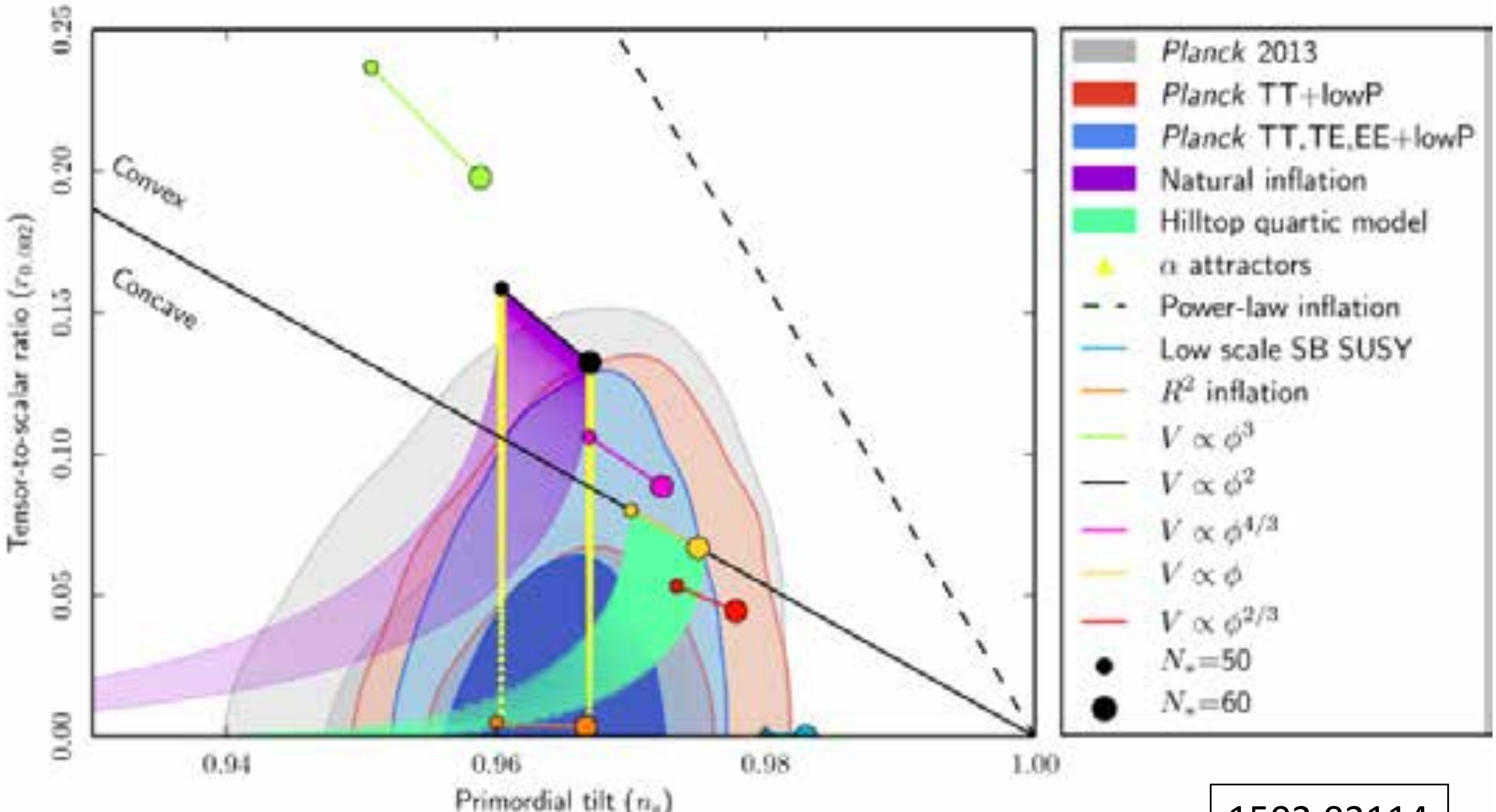
1502.01589

Concordance model: inflationary LCDM

$$\{H_0, \Omega_b, \Omega_c, A_s, n_s, \tau\}$$

- 7 peaks in 2013, 19 peaks in 2015;
- LCDM is perfect in explaining three CMB maps from l =30 until l=2000;
- A nearly scale-invariant, adiabatic, Gaussian power spectrum of primordial fluctuations as predicted by inflation seems highly consistent with data.

Concordance model: inflationary LCDM



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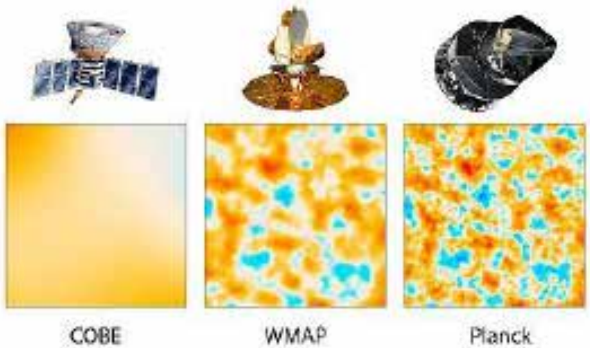
Planck 2015 data severely constrains the parameter space of inflationary cosmology.

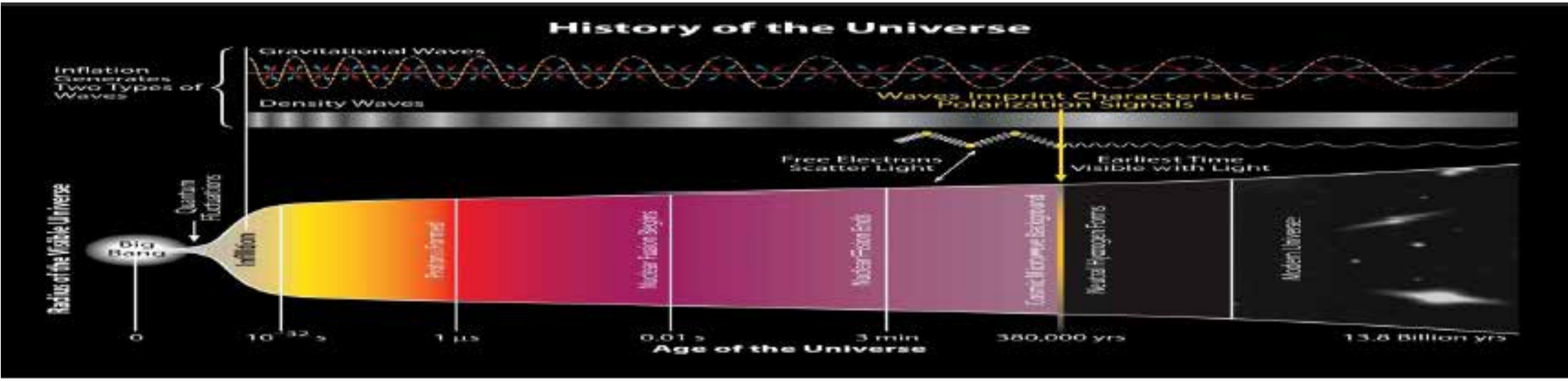
CMB leads to the precision cosmology

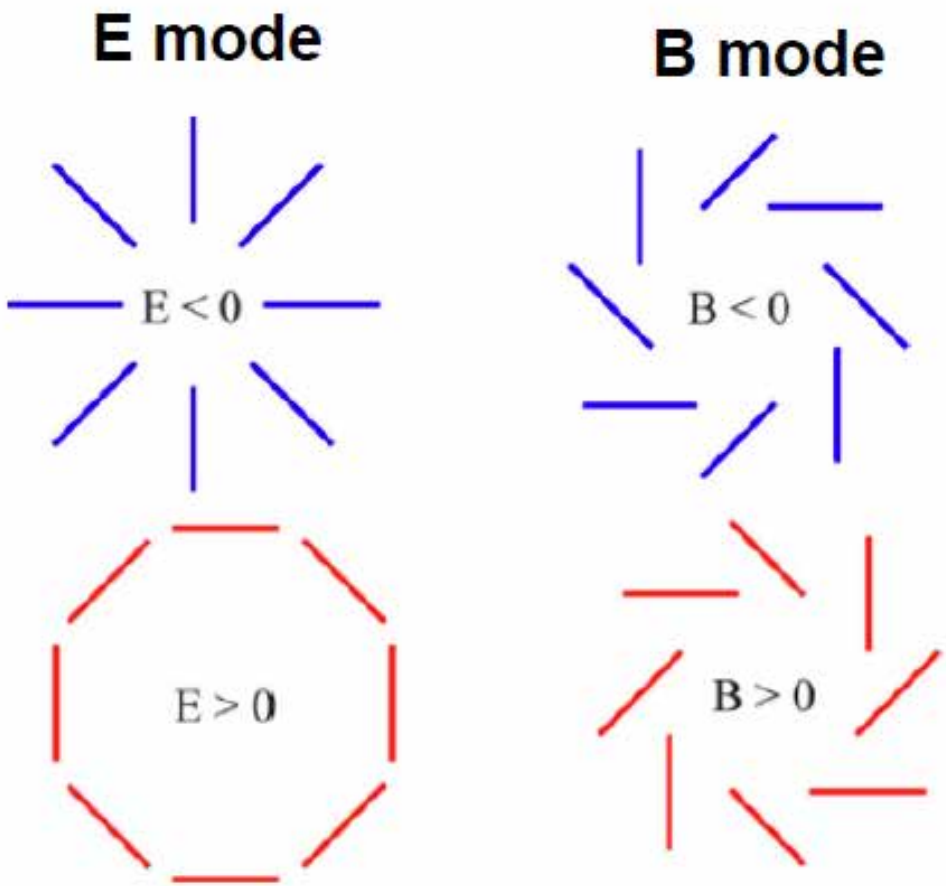


- 1998, cosmic acceleration: top ten breakthrough of 《science》
- 2003, CMB Involved in top ten breakthrough
- 1978 and 2006, Nobel prize
- 2011, cosmic acceleration win Nobel
- 2010 and 2012, WMAP win Shao's prize and Gruber prize

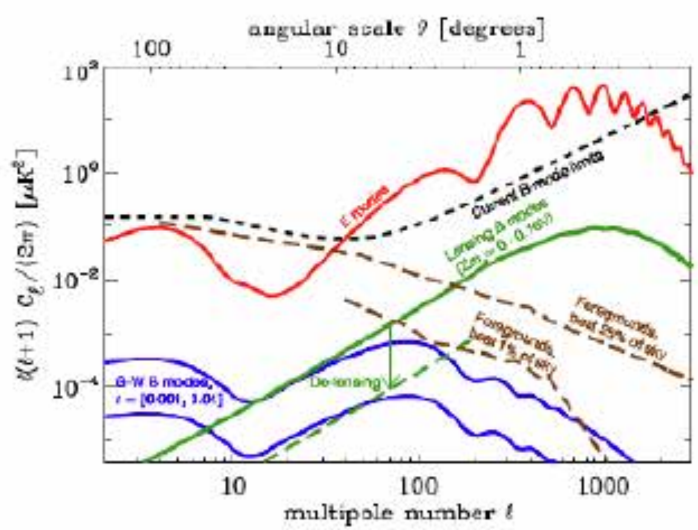
SPT BICEP/ keck Array   ACT

CMB polarization is significant in next generation measurements



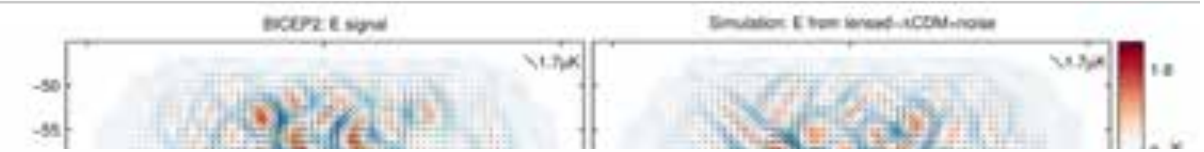


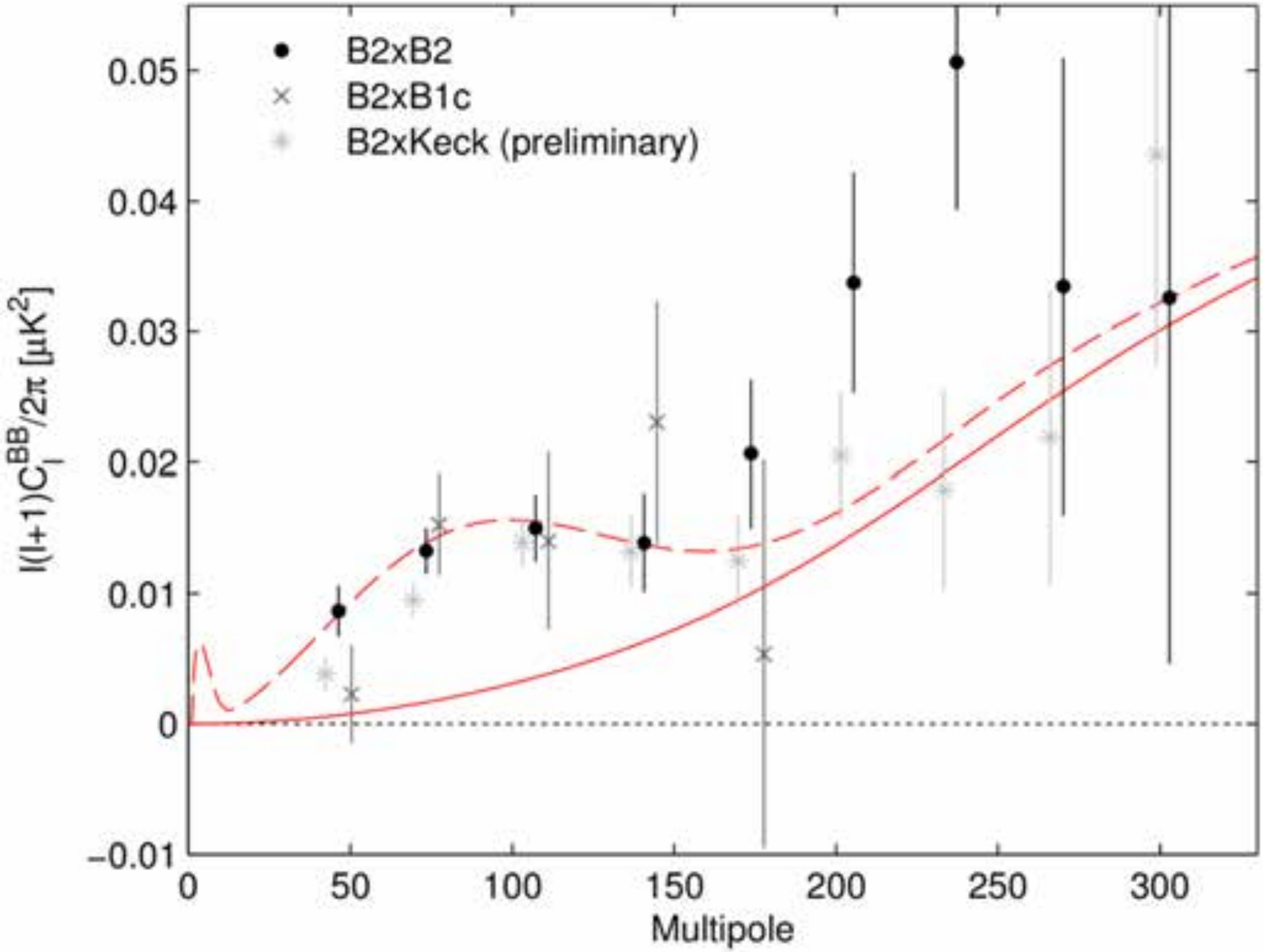
B mode survey can discriminate early universe models, namely, inflation; as well as testing the fundamental symmetries, such as CPT.



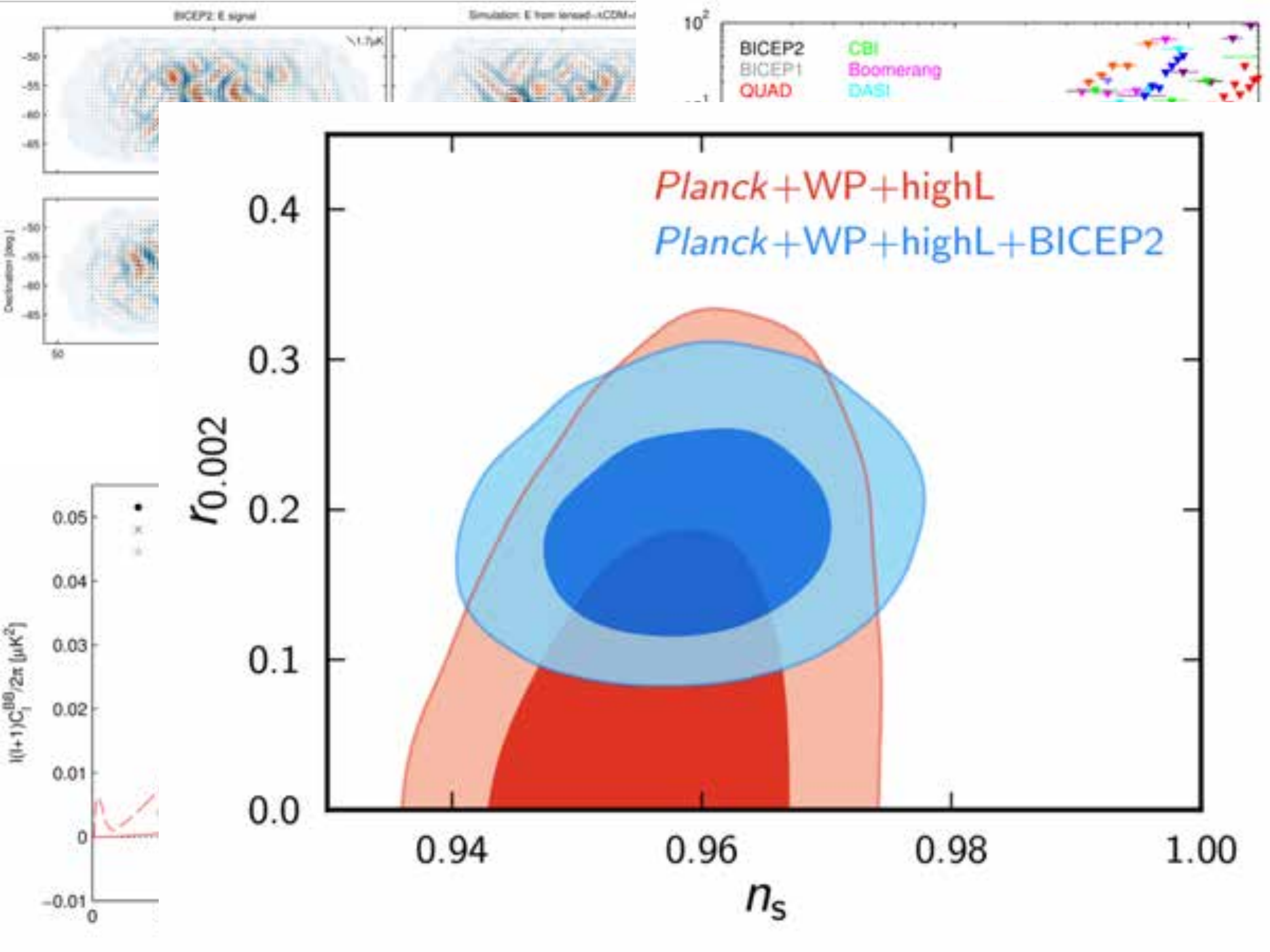
A good but not perfect lesson from BICEP2

BICEP instrument at the South Pole





B2xB2
B2xB1c
B2xKeck (preliminary)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300



BICEP2: E signal
Simulation: E from lensed-ΛCDM
BICEP2
BICEP1
QUAD
CBI
Boomerang
DASI
Planck+WP+highL
Planck+WP+highL+BICEP2
$r_{0.002}$
n_s
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
$l(l+1)C_l^{BB}/2\pi$ [μK^2]

BICEP2 gives:

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

Note: dust foreground contamination was not considered!

Planck13 yields:

$$\ln(10^{10} A_s) = 3.089^{+0.024}_{-0.027}$$

$$n_s = 0.9603 \pm 0.0073 \quad (68\% \quad \text{C.L.})$$

$$r < 0.11 \ (95\% \ \text{C.L.})$$

There exists a severe tension between BICEP2 and Planck !

Implications on inflation models from string cosmology

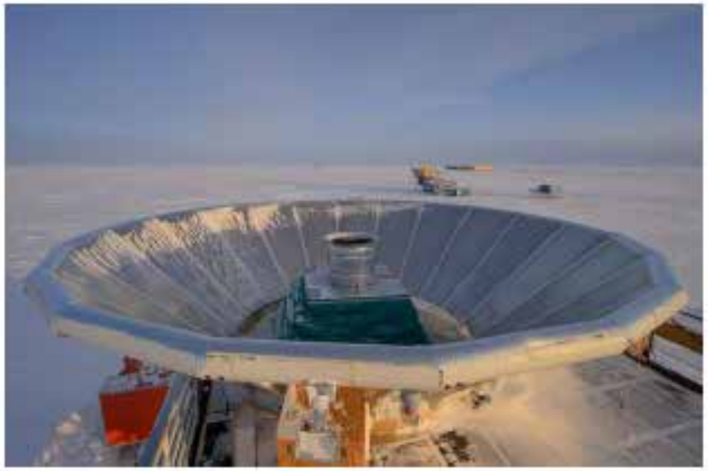
Burgess, Cicoli, Quevedo, 1306.3512

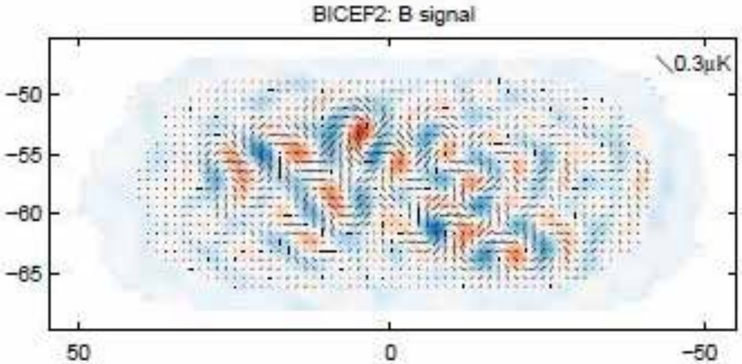
String Scenario	n_s	r
$D3/\overline{D3}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$
Inflection Point Inflation	$0.92 \leq n_s \leq 0.93$	$r \leq 10^{-6}$
DBI Inflation	$0.93 \leq n_s \leq 0.93$	$r \leq 10^{-7}$
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$
D3/D7 Inflation	$0.95 \leq n_s \leq 0.97$	$10^{-12} \leq r \leq 10^{-5}$
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	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$

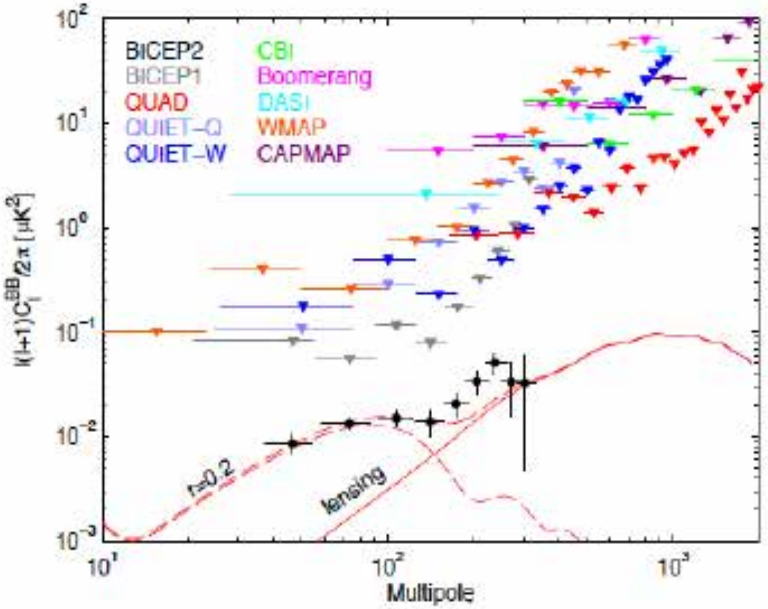
Table 1. Predictions for the cosmological observables n_s and r for different string inflationary models.

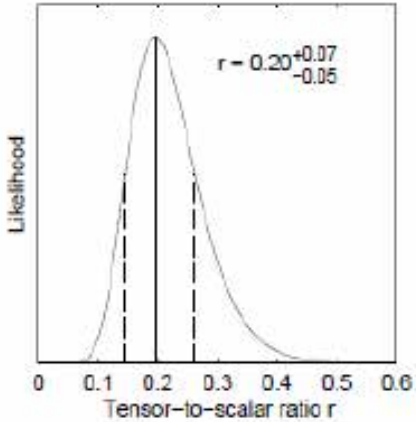
If BICEP2 were correct, all above models would have been ruled out!

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

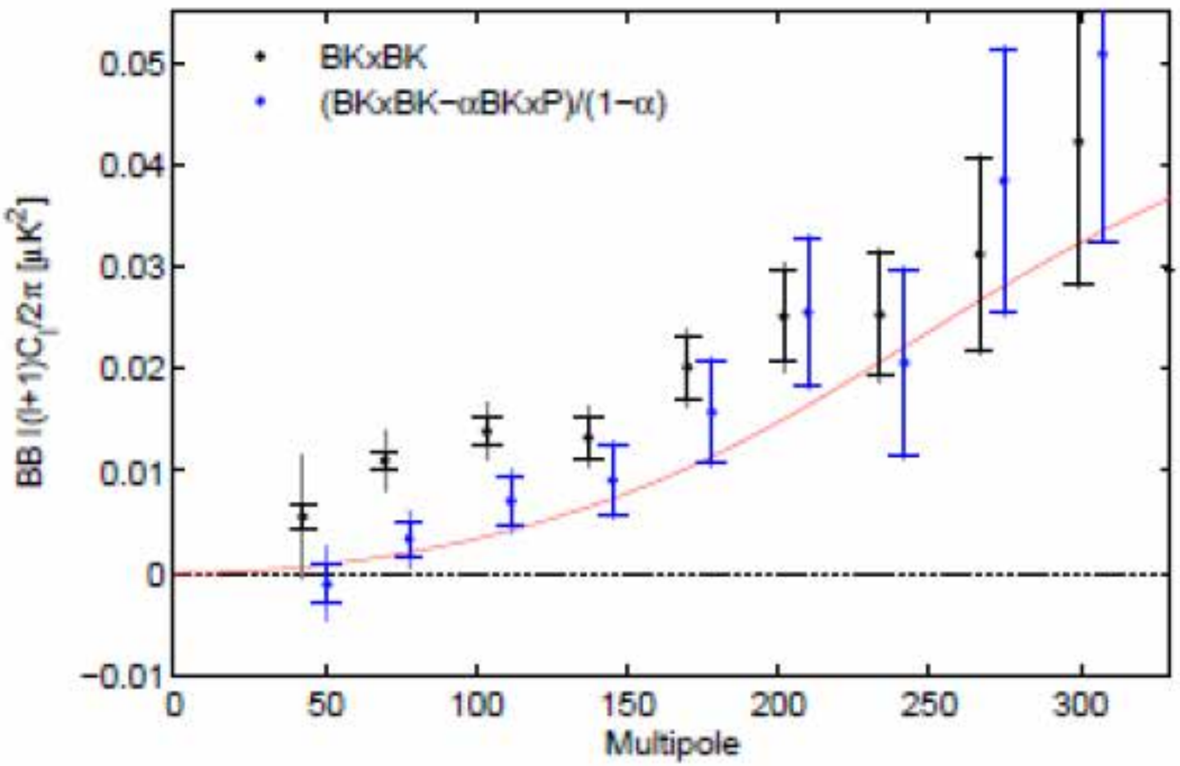








BICEP2 signals are very likely from the foreground dust contamination



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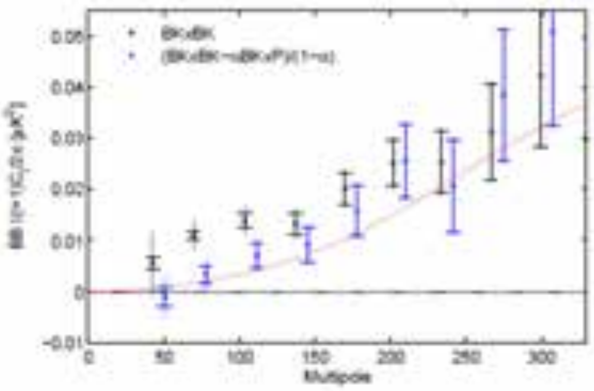
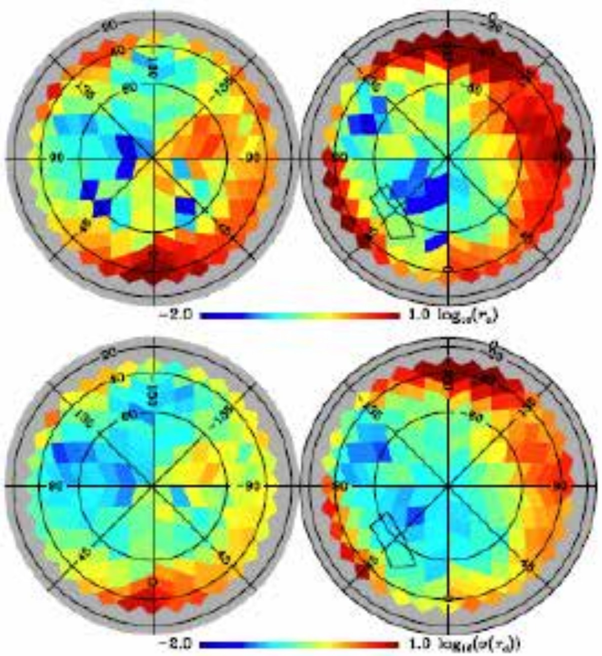


No winner yet! Who first hit to 21 points?

Searching for primordial GWs becomes important in the community.

Polarization foreground from galaxy

full sky coveraged is required !

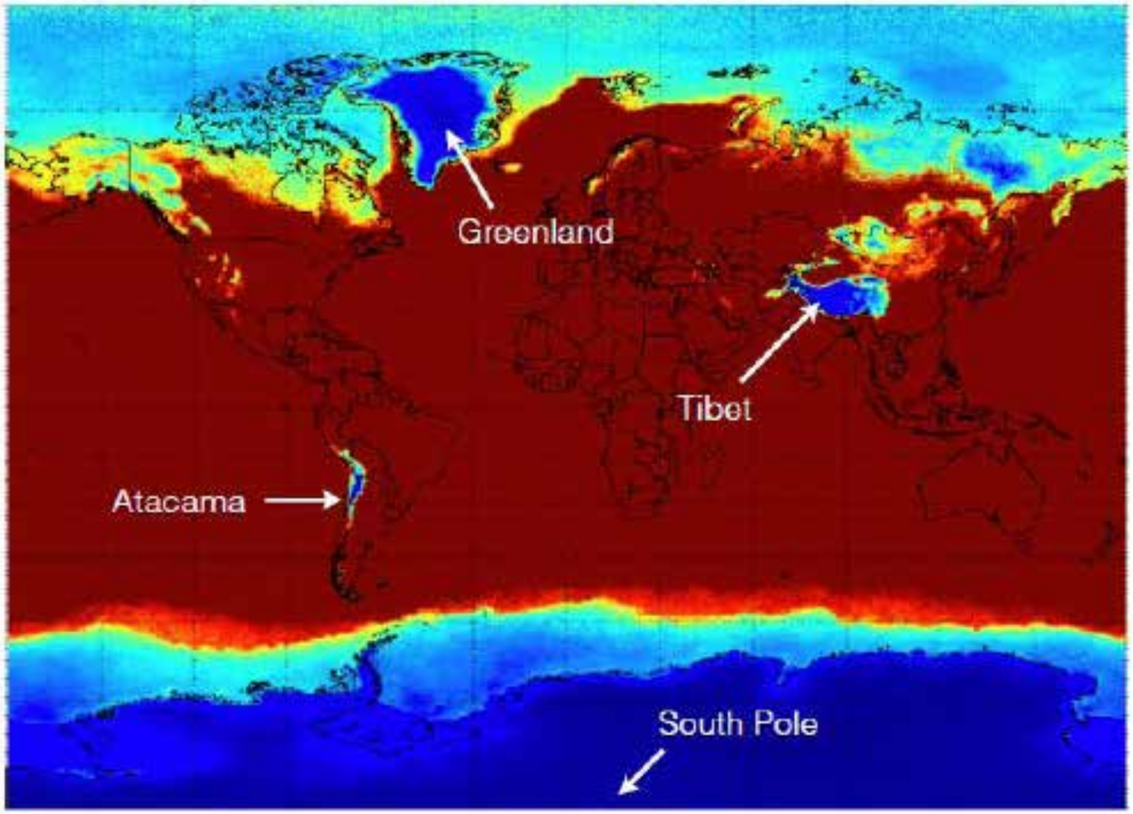


north hemisphere   south hemisphere

- 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.

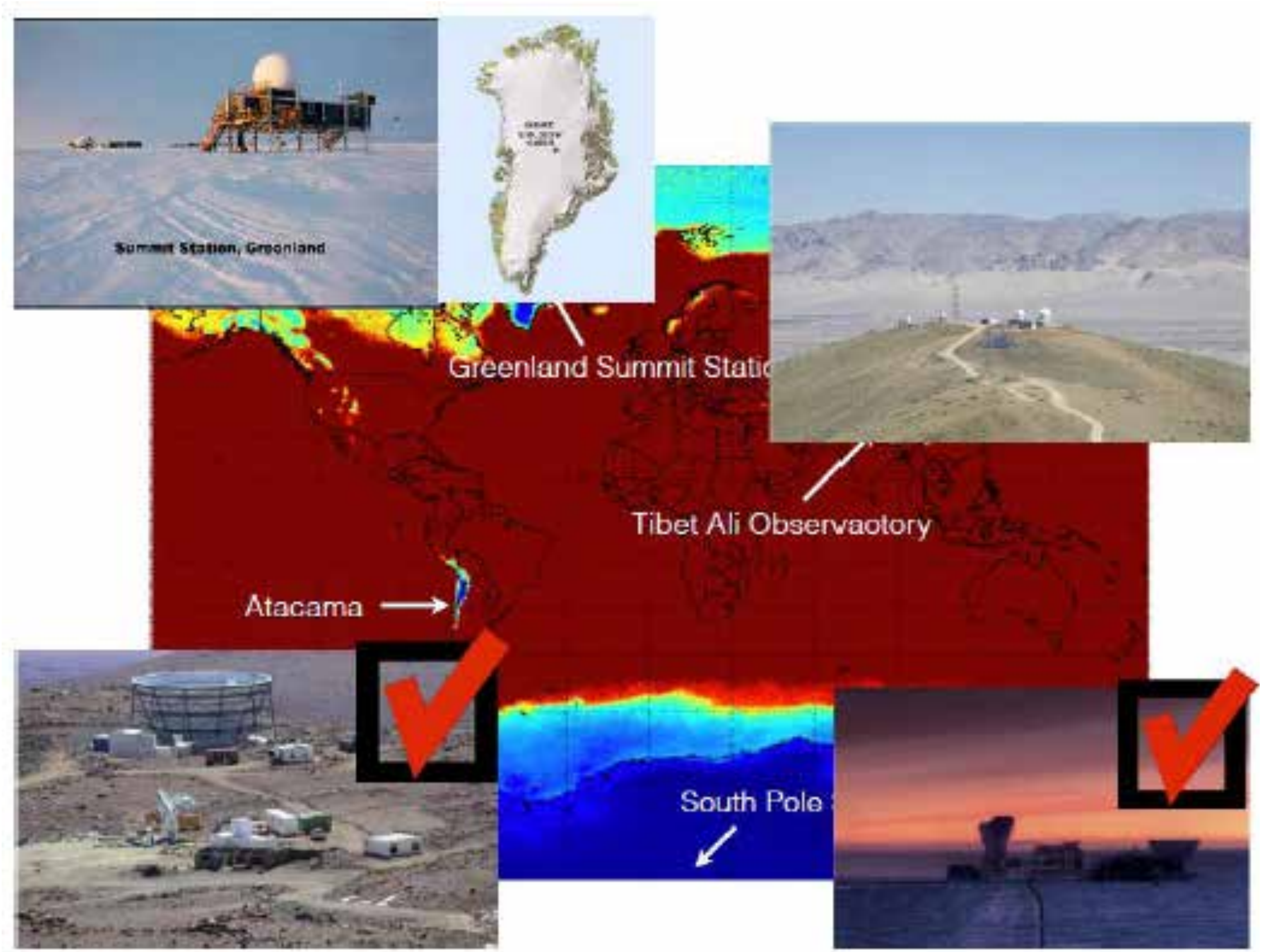
A full sky coverage is needed!

How many places suitable for CMB?

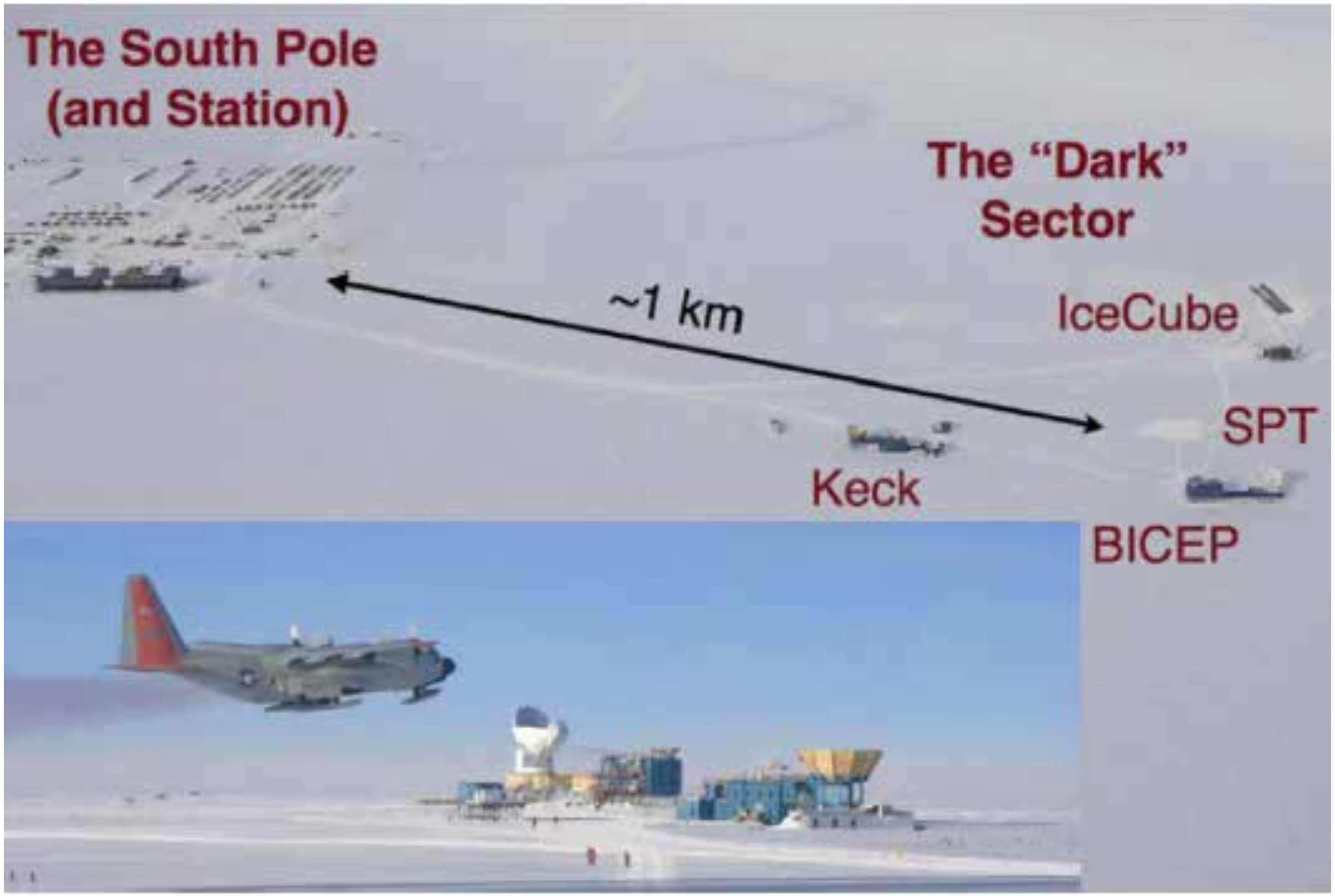


- Blue areas indicate high atmospheric transmission rate, which are suitable for CMB observations!
- Four best places on Earth: Greenland, Tibet, Atacama desert, Antarctica

Ground-based CMB experiments



CMB at South Pole



CMB at Atacama

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

Ali (Ngari) Vs Greenland

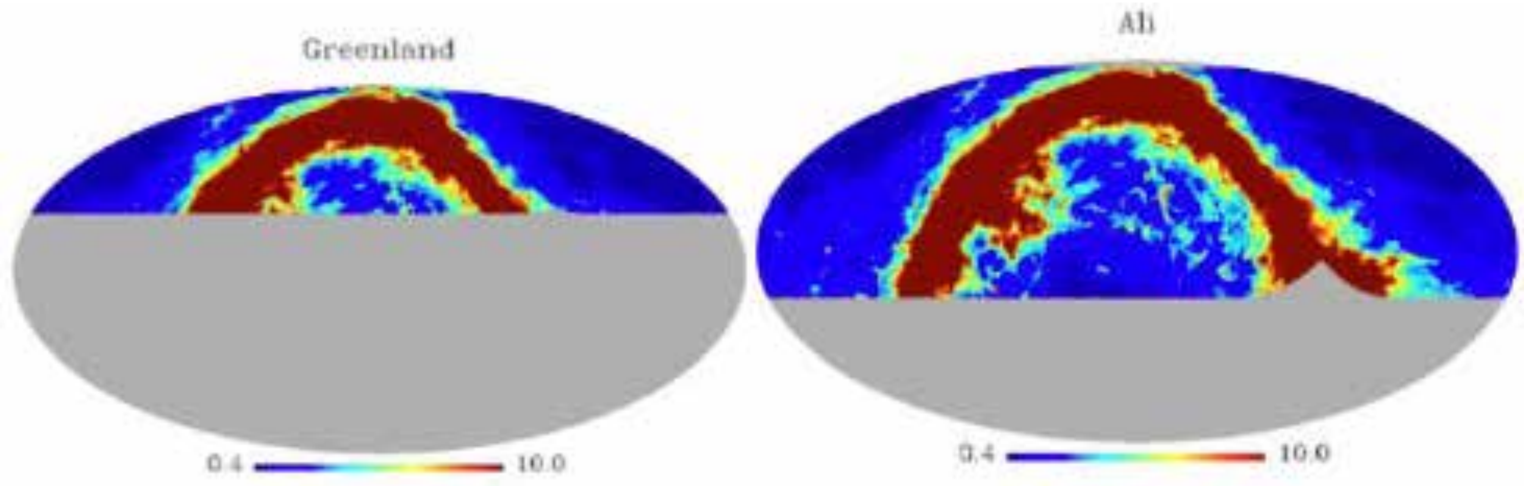
So far there is no CMB experiment in the north earth.

Facilities:

- Ali site has well established facilities including internet, electricity, public transportation, …
- Site at Greenland is now only supplied by the US army, …

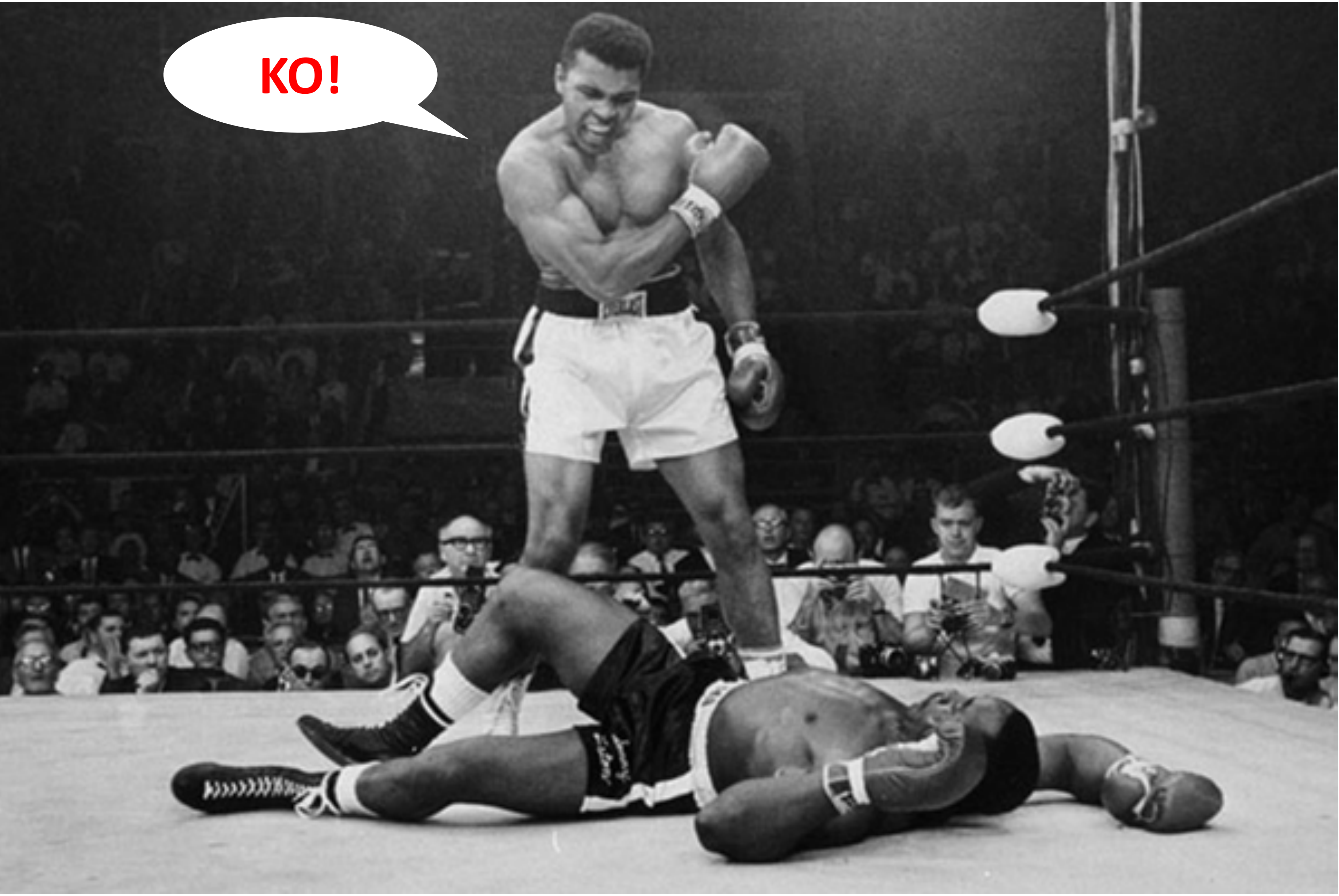
Ali (Ngari) Vs Greenland

The sky coverage of Ali is double of that of Greenland.



sky coverage: 30%

sky coverage: 65%


KO!

A future lesson from AliCPT

CMB observations of AliCPT @ Tibet

Scientific goals:

1, further depressing the parameter space of very early universe models through the CMB T- & E-mode;

2, attempting to detect primordial gravitational waves through the CMB B-mode;

3, falsifying very early universe models, so that shedding light on the exploration of fundamental physics.

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	$r \leq O(1)$	$\|n_t\|<O(1)$	$\alpha_t > 0$	$f_{nl} \approx -5/2$
Ekpyrosis	$r<<O(1)$	$n_t = 2$	$\alpha_t < 0$	$f_{nl} > 1$
String gas	$r \leq O(1)$	$n_t \approx 1-n_s$	$\alpha_t > 0$	$f_{nl} << O(1)$

Any bonus from AliCPT?

- To measure the spectral and running indices of primordial gravitational waves;

- To test CMB anomalies noticed by WMAP & Planck:
  - low ell suppression
  - CMB power asymmetry
  - l=20 power deficit
  - cold spot, …

- To improve the constraint of the nonlinearity parameter;

- To measure the E-mode in the north sky;

- …

AliCPT @ USTC

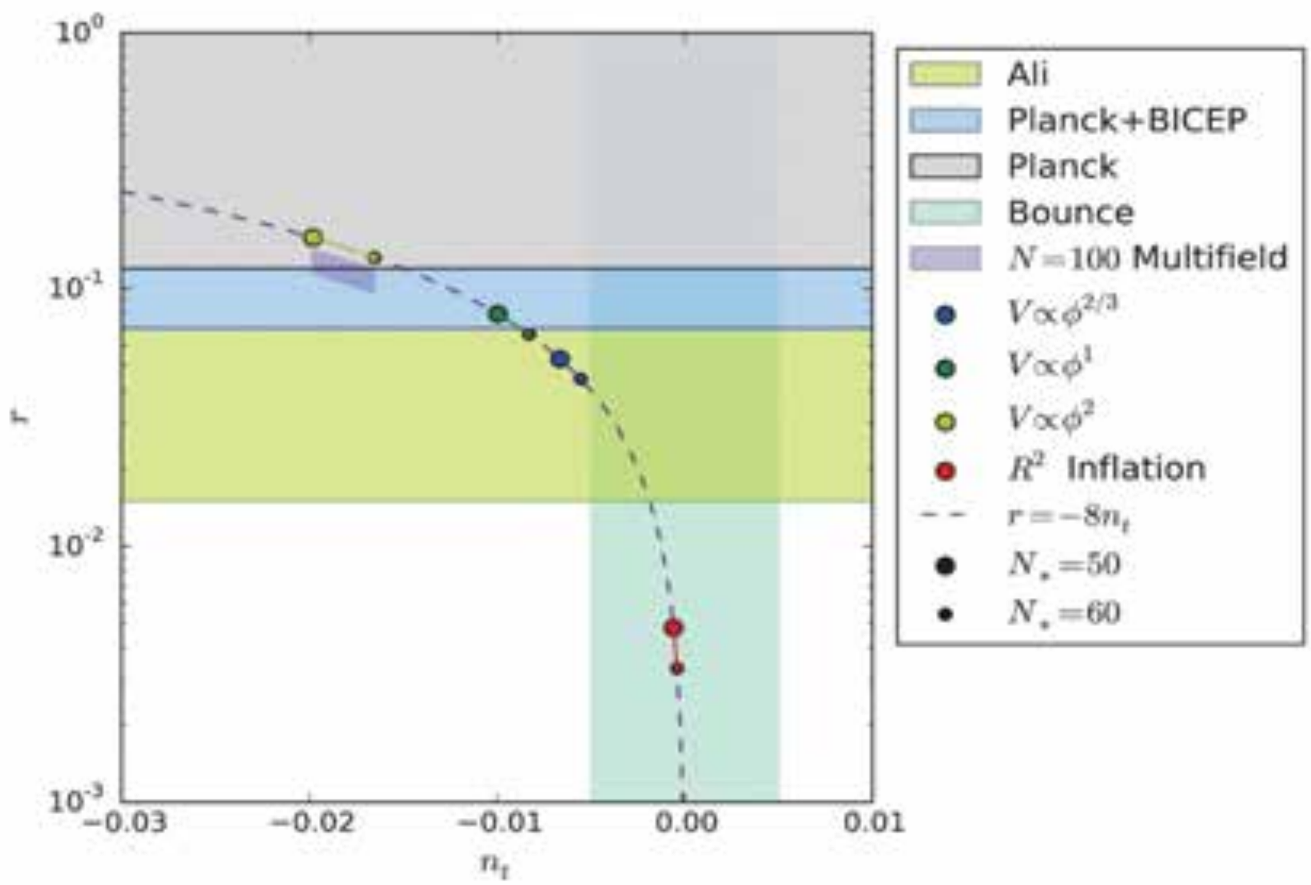
- Theoretical analyses of primordial gravitational waves
  - Constraining the very early universe models
  - Statistics of all possible B-mode components
  - CMB large scale anomalies

- CMB B mode testing CPT symmetry
  - Using CMB data to test CPT
  - De-rotation analysis of CMB polarizations

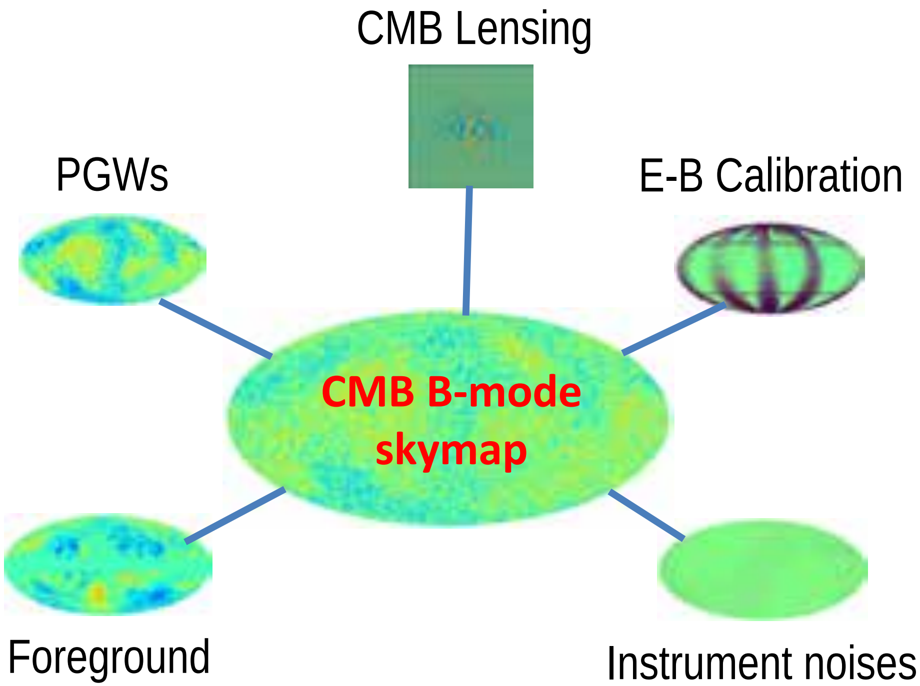
Constraining the very early universe models

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

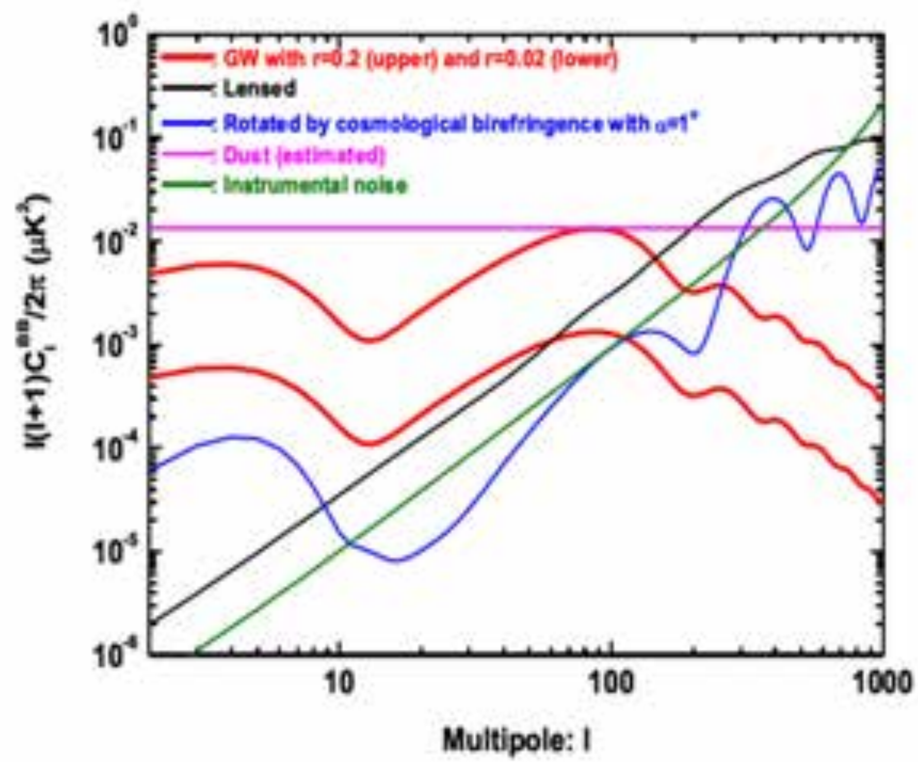
- Inflationary models
- Nonsingular bounce models
- Models of emergent universe



Statistics of all possible B-mode components



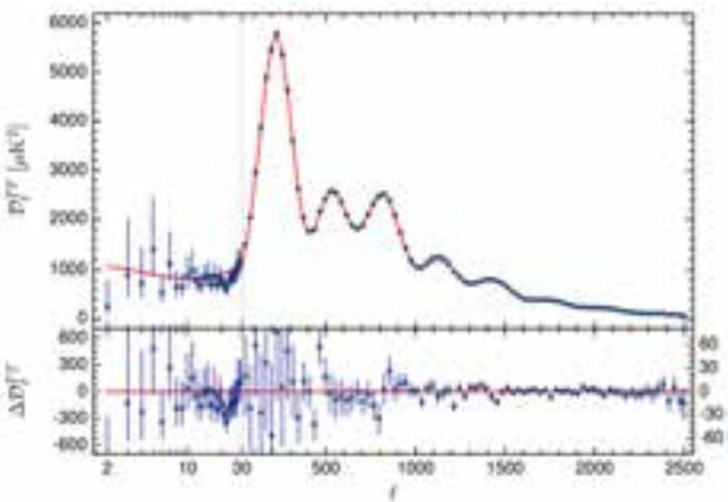
Q: How can we identify all the components that can give rise to CMB B-mode?



Plan:

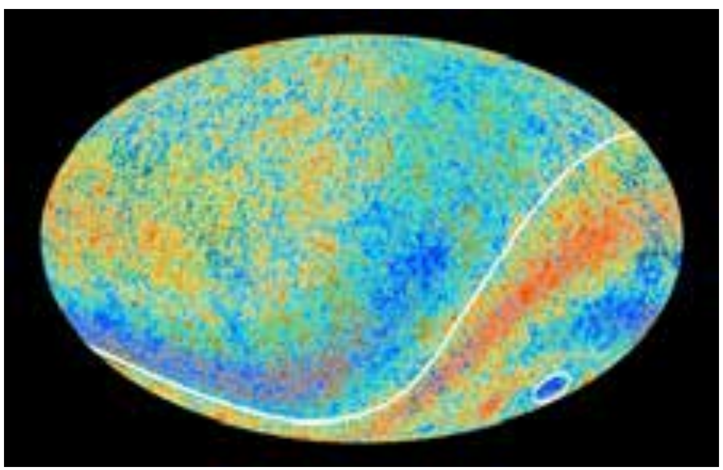
Different components exhibit different statistical properties. These can be used to exact the signals from PGWs.

CMB large scale anomalies



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

Q: primordial origin, or, observational contamination?



Plan:

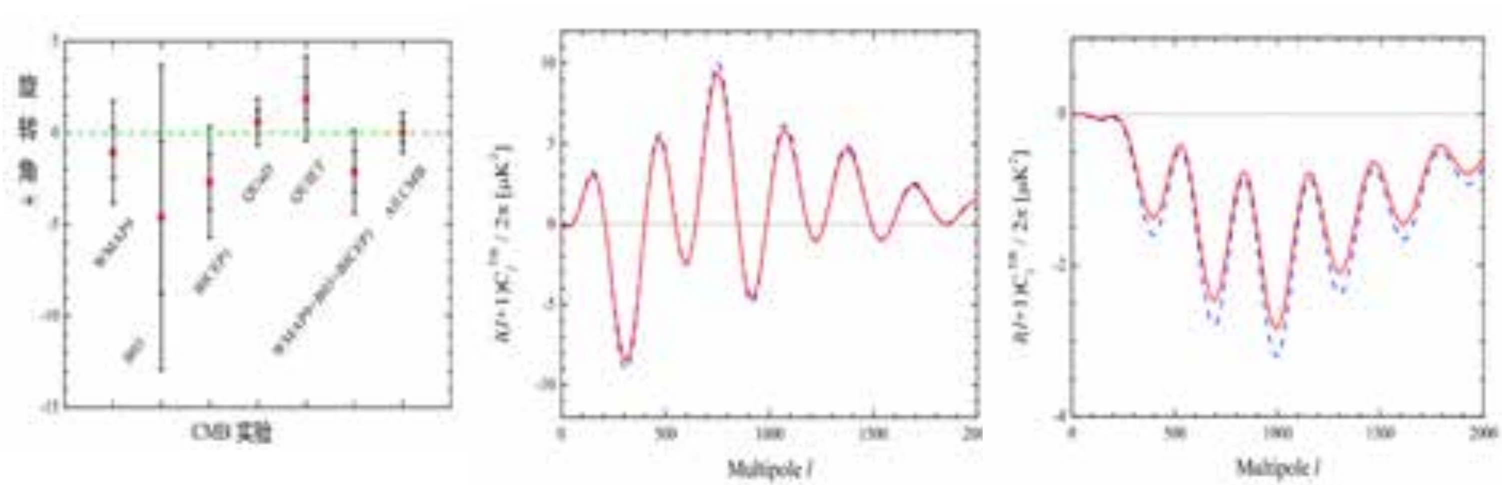
✓ Combine together AliCPT in North sphere and BICEP, PolarBear in South sphere

✓ Build theoretical models to explain associated phenomena

Using CMB data to test CPT

Q: Charge-Parity-Time reverse symmetry is viewed as the fundamental symmetry in particle physics. Is it true throughout the whole cosmological history? If not, how can we probe the associated violation?

➔Rotation between E and B modes of CMB



Plan:

- Develop the theory of CPT violation
- Mimic the observational signals in AliCPT
- Establish the effective field theory
- Parameterize the rotation angle using cosmological parameters

De-rotation analysis of CMB polarizations

CPT violation can lead to the rotation between E and B modes, and thus, this part of contribution to CMB B-mode can be categorized as foreground contamination.

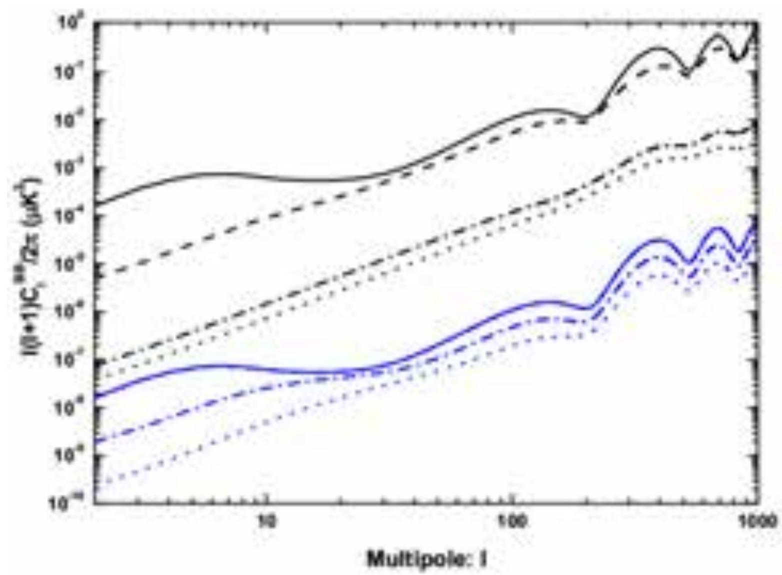
Q: How can we de-rotate the E and B modes that were induced by CPT violation?

Plan: In analogue with the CMB lensing technique, we can reconstruct the rotation angle by virtue of the data of T and E modes. Then, we can perform the de-rotation analysis with the AliCPT data in future.

$$\hat{B}_{\ell m} = \sum_{\ell_2 m_2} \sum_{\ell_3 m_3} f(\ell, m, \ell_2, m_2, \ell_3, m_3) \hat{\alpha}_{\ell_2 m_2} \hat{E}_{\ell_3 m_3}$$

↓

$$C_\ell^{BB}(\text{residual}) = \frac{1}{\pi} \sum_{\ell_2 \ell_3} (2\ell_2 + 1)(2\ell_3 + 1) C_{\ell_2}^{\alpha\alpha} C_{\ell_3}^{EE} (H_{\ell\ell_3}^{\ell_2})^2 (1 - \Theta_{\ell_2 \ell_3})$$



Summary & Outlook

Today

- The past decade has witnessed the era of precision cosmology
- The paradigm of very early universe has been greatly developed
- Big Bang cosmology has become the Standard Model
- Inflation obtained a large amount of initial achievements
- Bounce cosmology is ambitious on solving big bang singularity

In Near Future

- Very early universe opens a window to explore fundamental physics

- It becomes possible to observationally probe physics near the Big Bang: CMB experiments

- CMB experiments in the north earth is necessary

- China's Ali CMB project will be the first CMB experiment in the north earth

This is just the beginning …

Thanks!