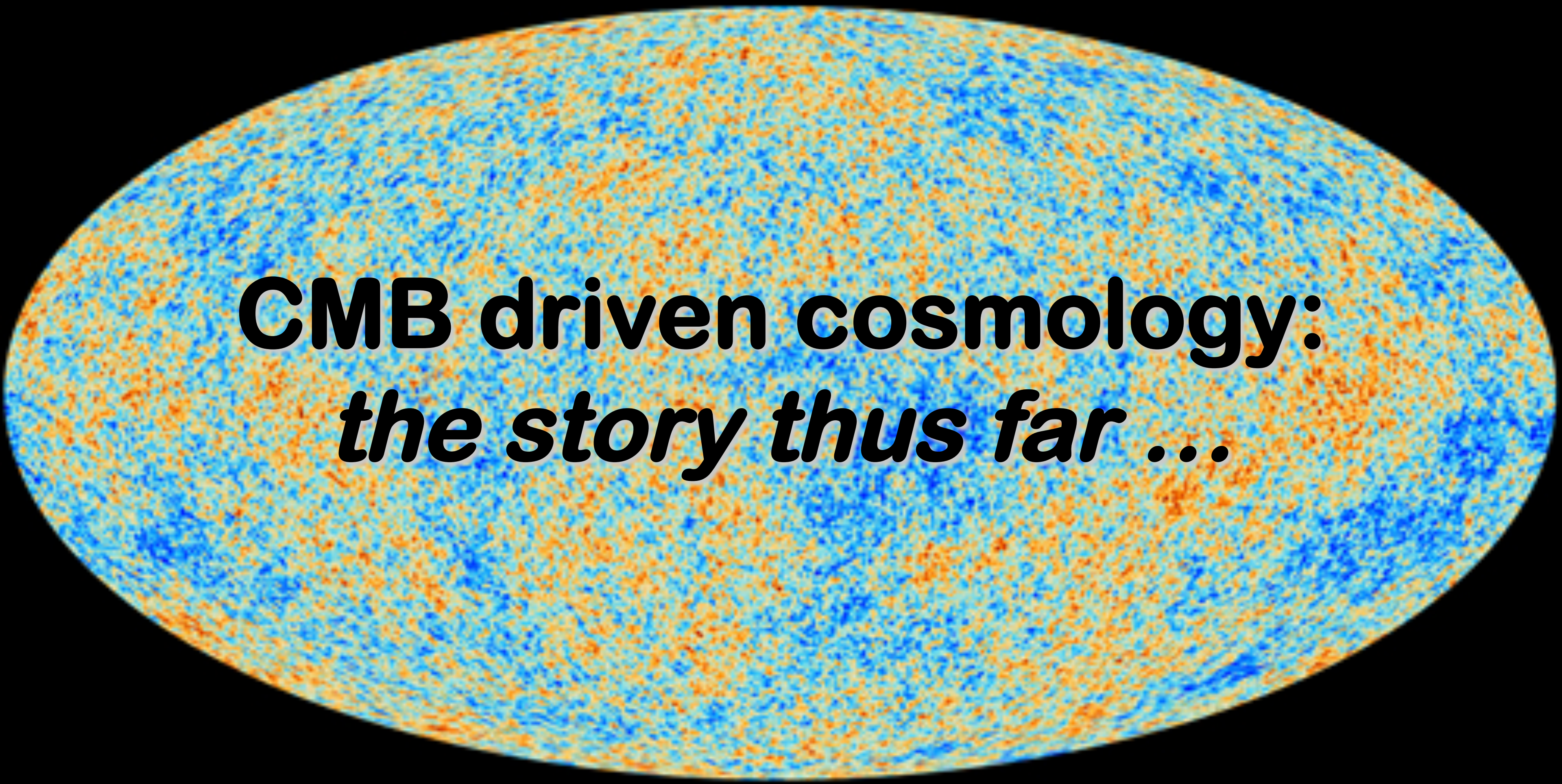


CMB driven cosmology: *the story thus far …*

Tarun Souradeep

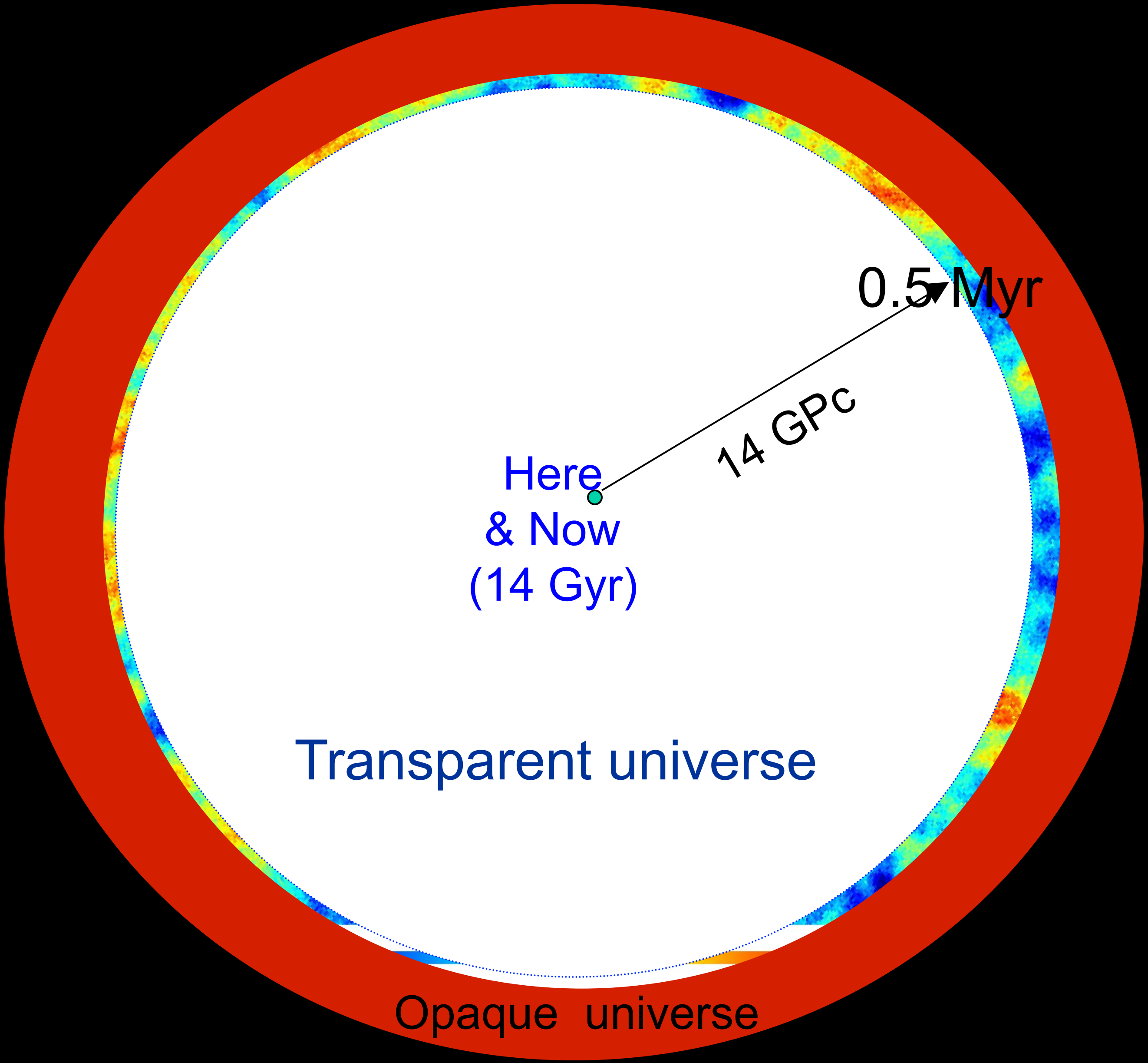
I.U.C.A.A.

ICTS Cosmology day

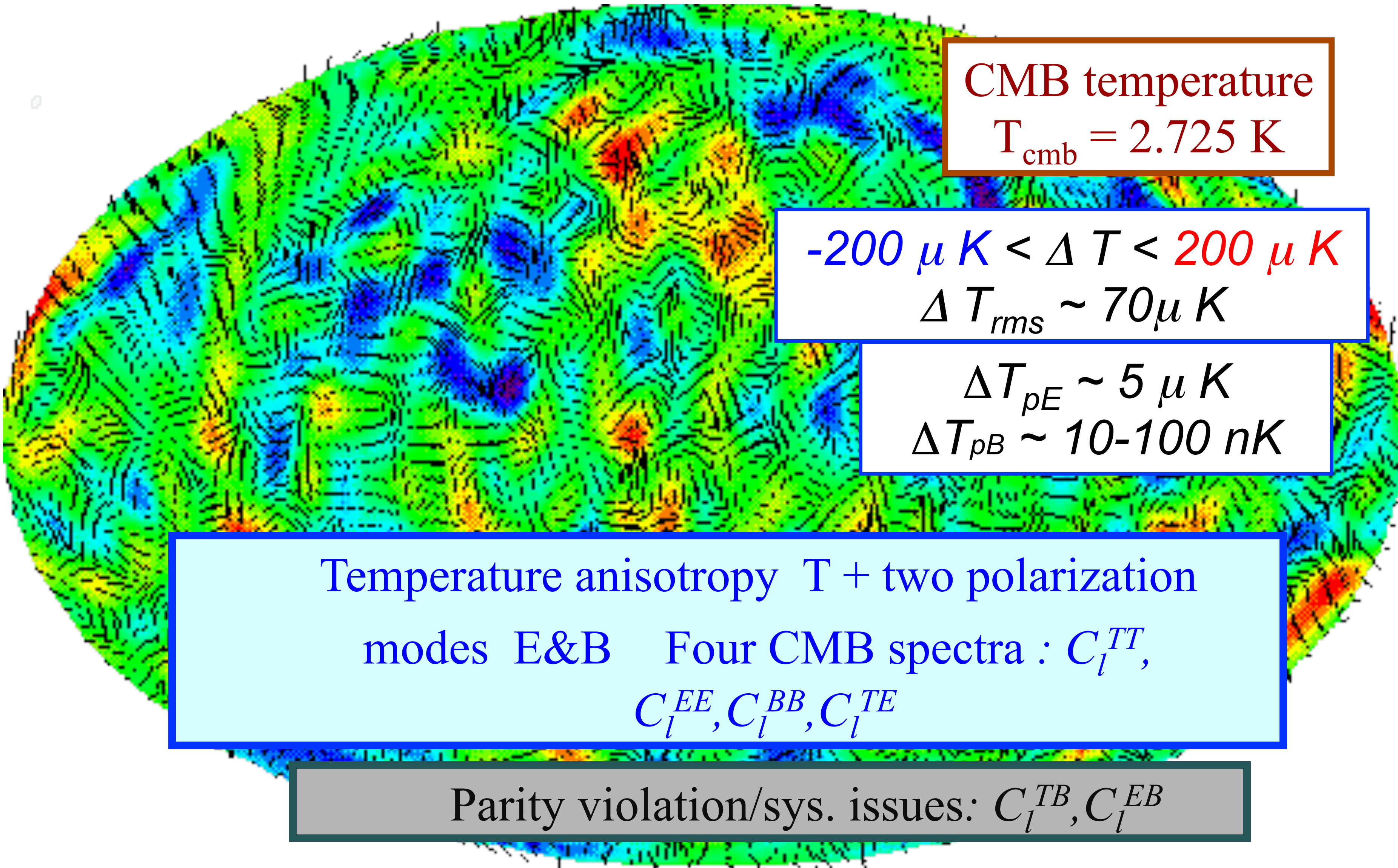
(April 8, 2014)

(Thanks to Sanjit Mitra's IUCAA talk)

Cosmic "Super–IMAX" theater



CMB Anisotropy & Polarization



CMB temperature
$T_{cmb} = 2.725$ K

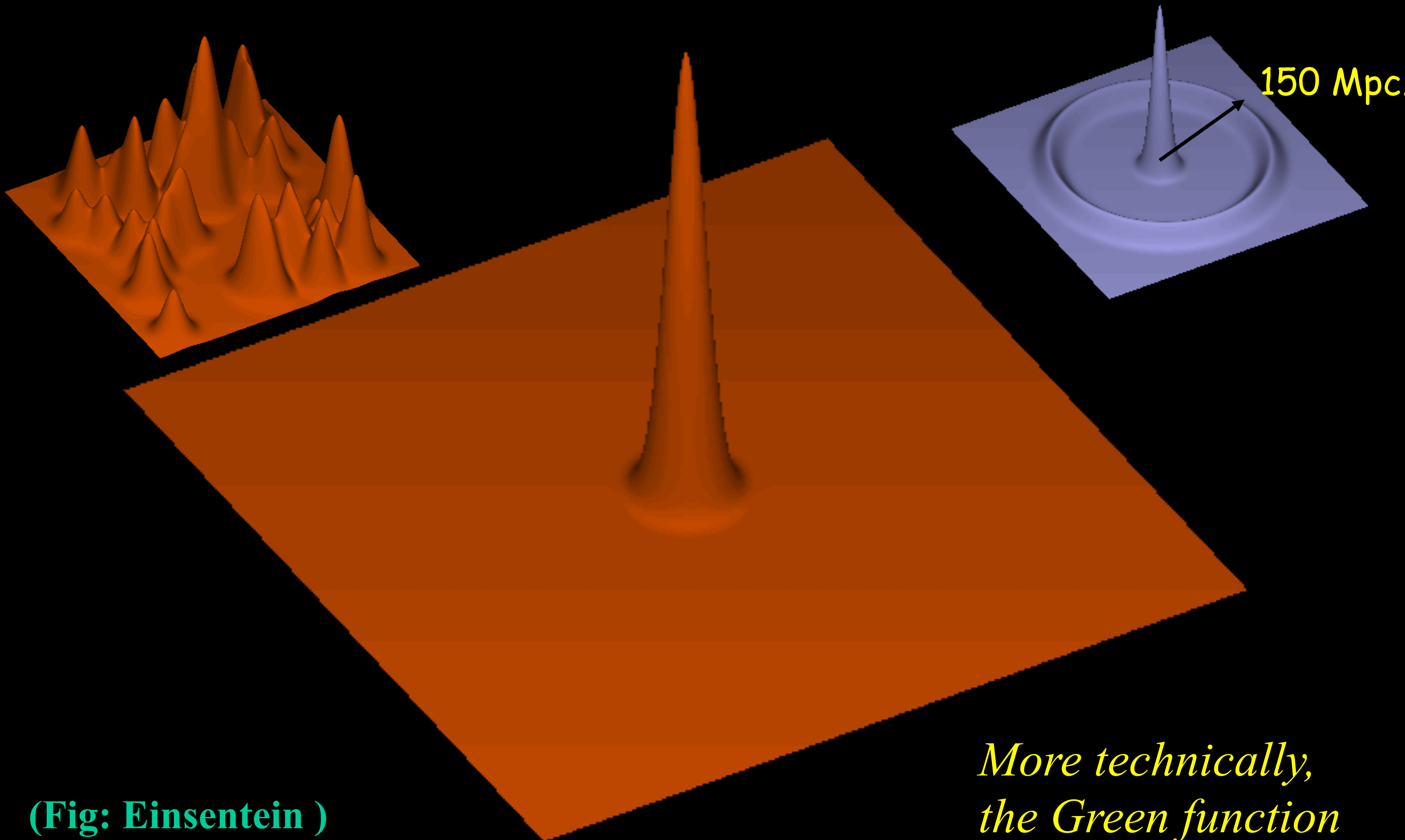
$-200\ \mu K < \Delta T < 200\ \mu K$
$\Delta T_{rms} \sim 70 \mu K$

$\Delta T_{pE} \sim 5\ \mu K$
$\Delta T_{pB} \sim 10\text{-}100$ nK

Temperature anisotropy T + two polarization modes E&B Four CMB spectra : C_l^{TT}, $C_l^{EE}, C_l^{BB}, C_l^{TE}$

Parity violation/sys. issues: C_l^{TB}, C_l^{EB}

Ping the 'Cosmic drum'

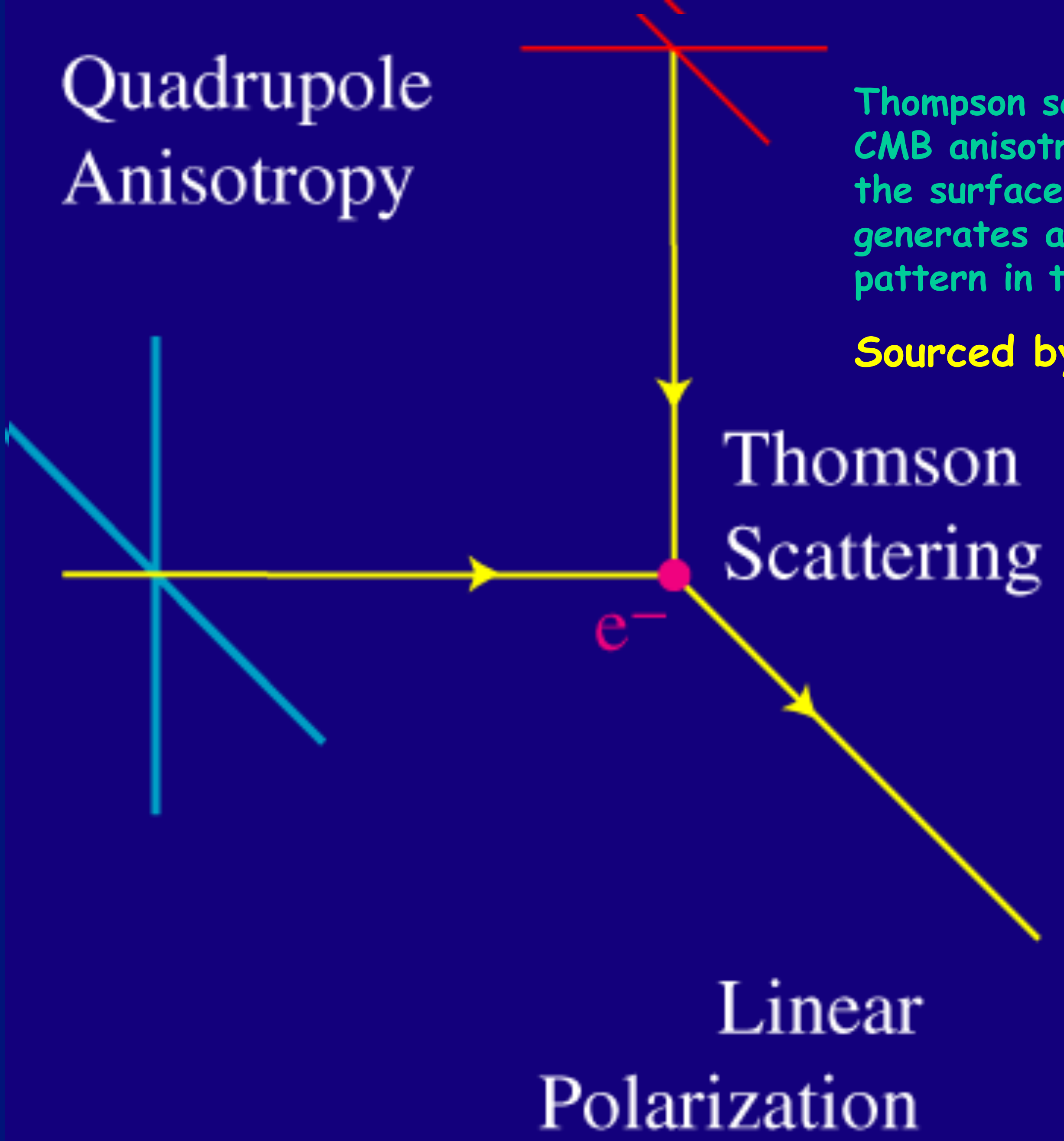


(Fig: Einsentein)

More technically,
the Green function

Thompson scattering of the CMB anisotropy quadrupole at the surface of last scattering generates a linear polarization pattern in the CMB.

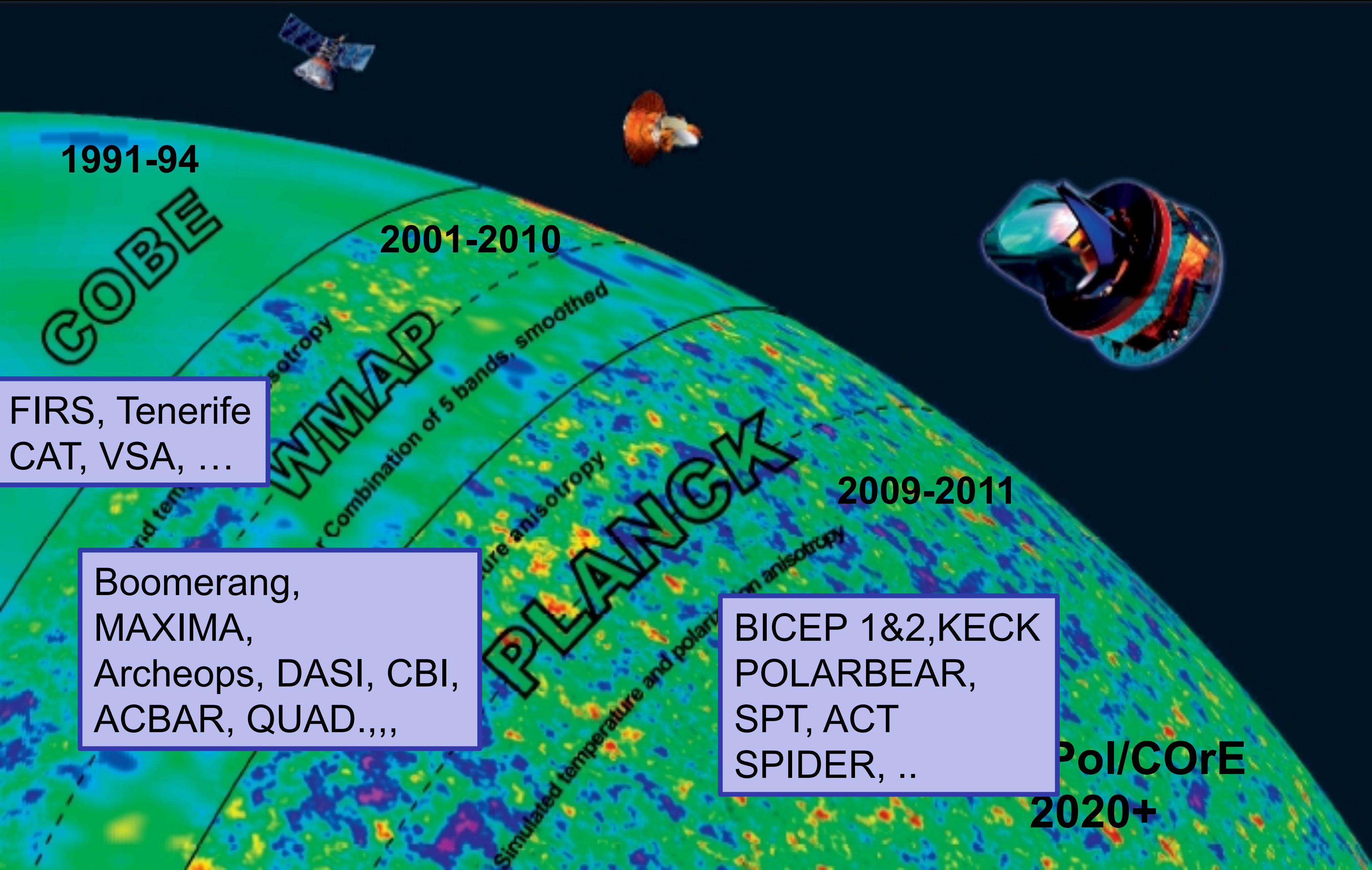
Sourced by electron velocity



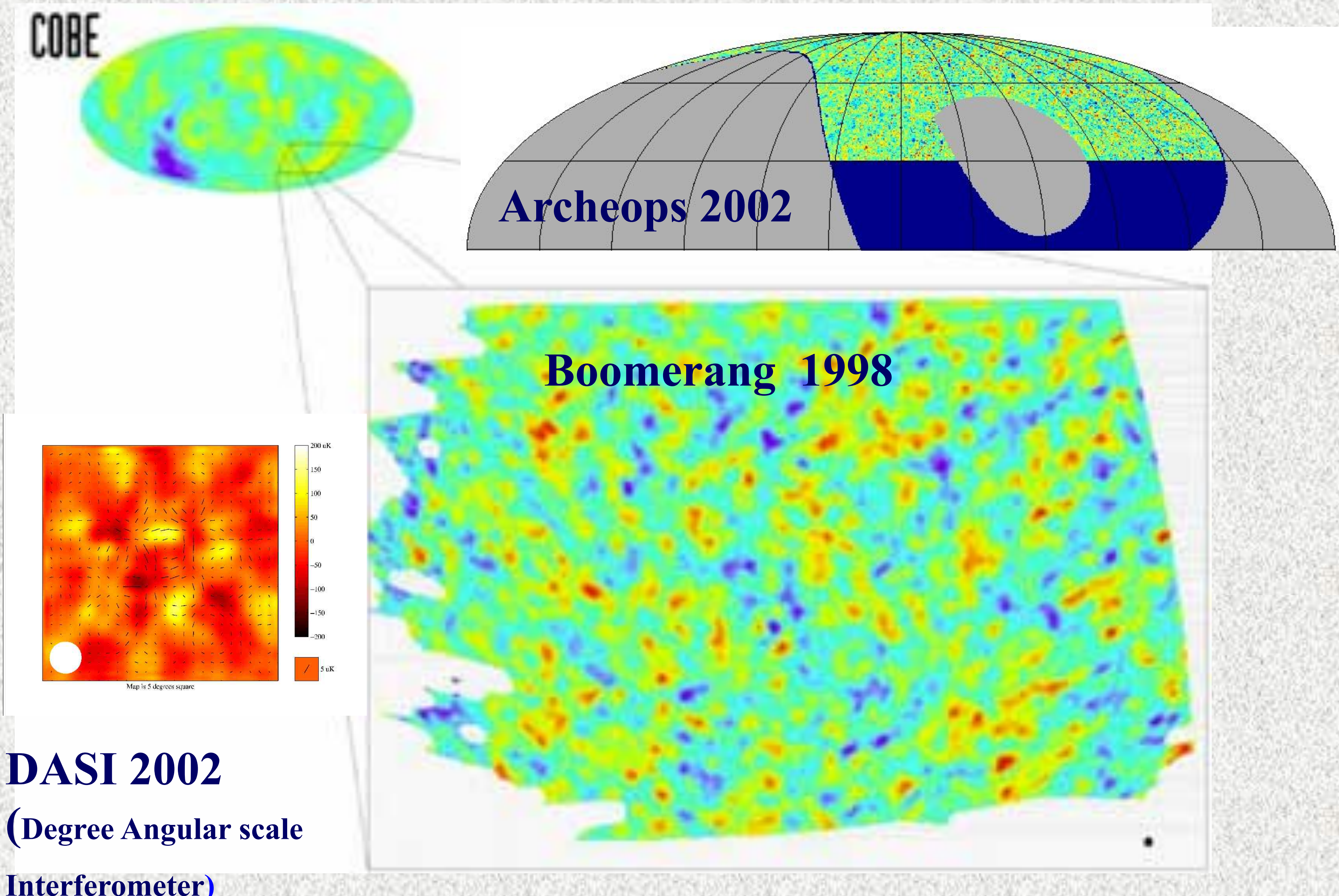
(Fig: Hu & White , 97)

CMB anisotropy measurements

1st, 2nd and into the 3rd decade



COBE, Post-COBE Ground & Balloon Experiments



Pre-Planck Angular power spectrum

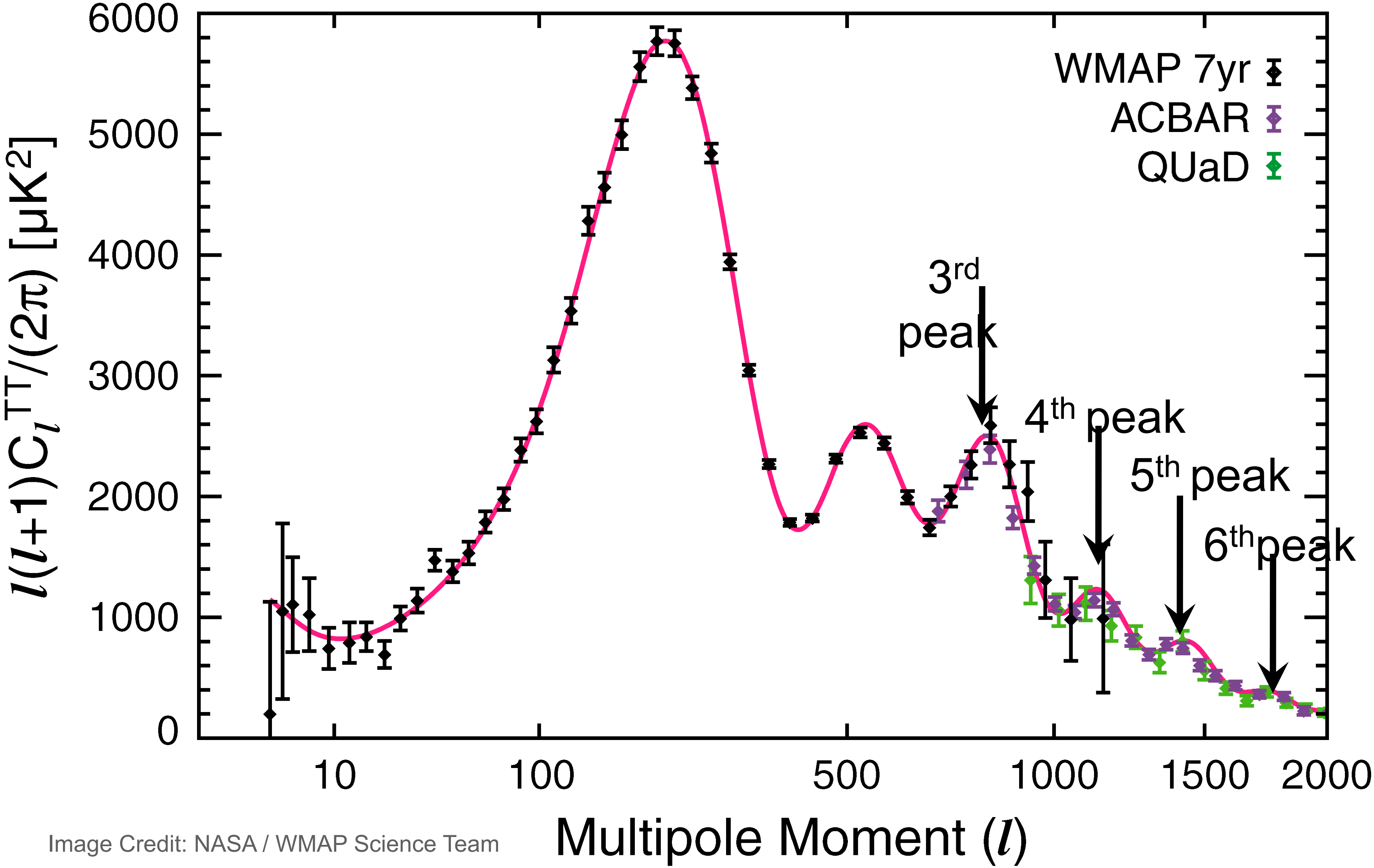
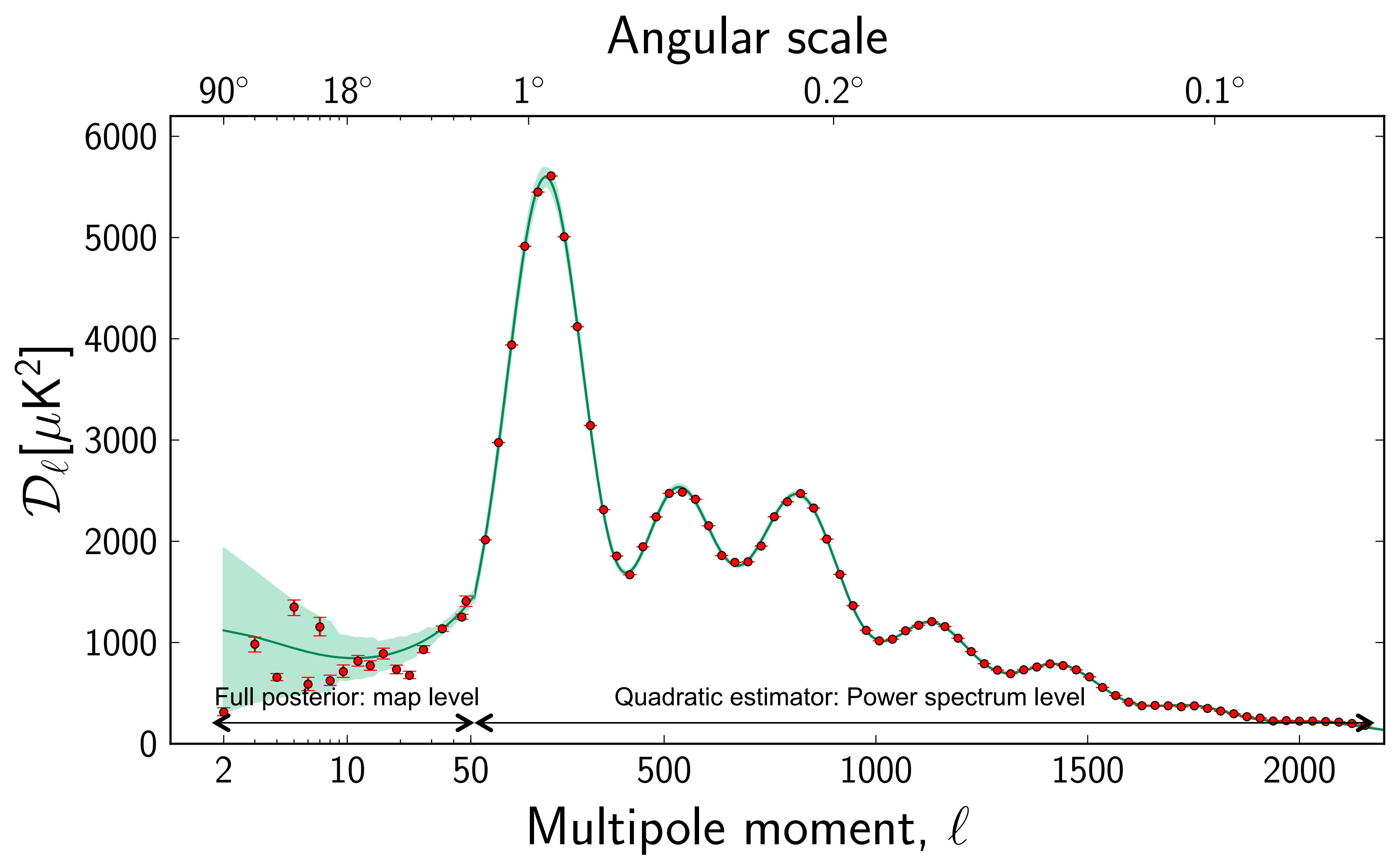


Image Credit: NASA / WMAP Science Team

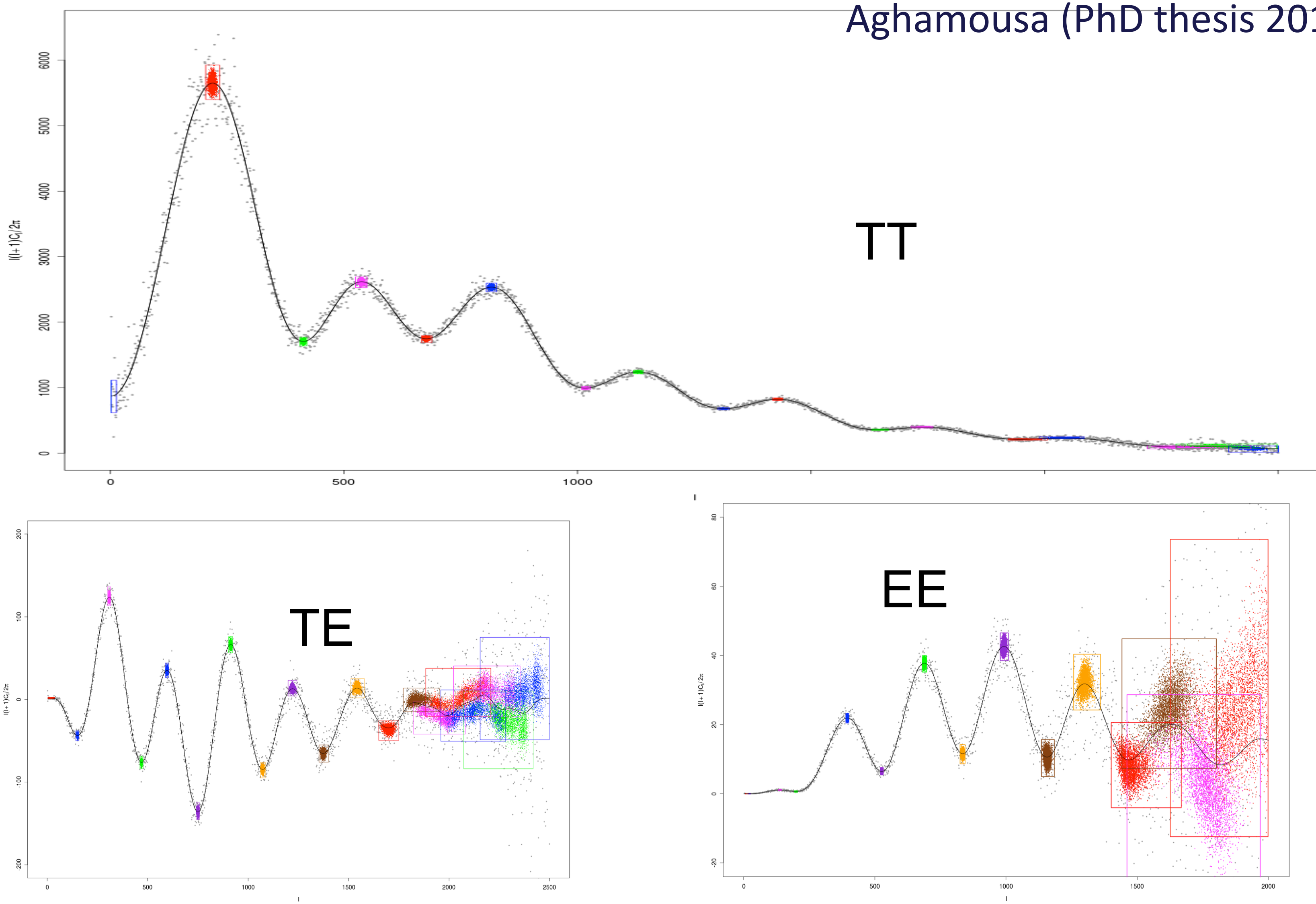
Planck Angular power spectrum



Planck: Non-Parametric Peak Location forecast

(Amir Aghamousa, Mihir Arjunwadkar , TS *Phys Rev D. 2014*)

Aghamousa (PhD thesis 2013)



Cosmological Parameters

6-Parameter ΛCDM

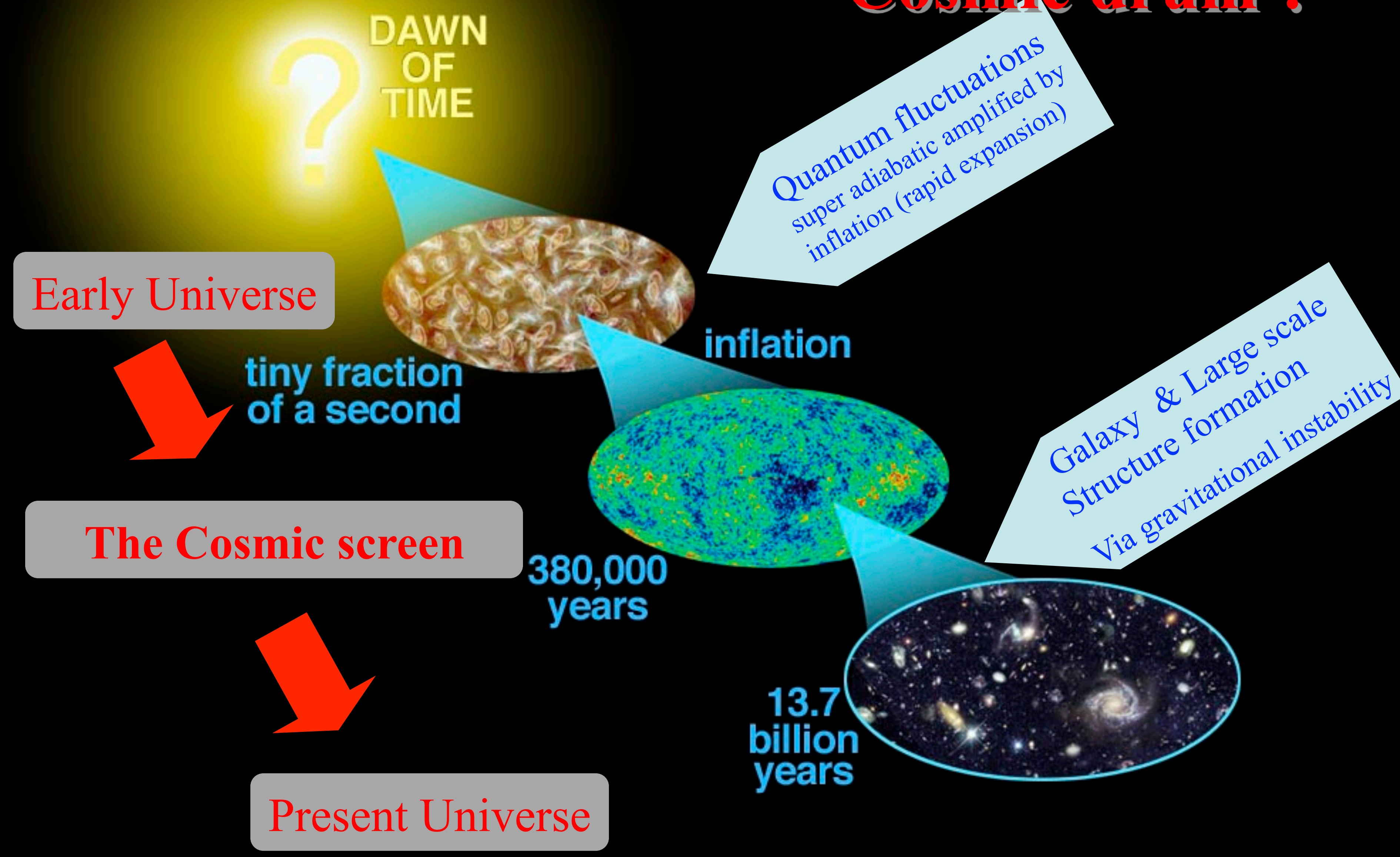
Parameter	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limit	*WMAP*-7+SPT (S12) Best fit	*WMAP*-7+SPT (S12) 68% limits
$100\Omega_b h^2$	2.207	2.207 ± 0.027	2.223	2.229 ± 0.037
$\Omega_c h^2$	0.1203	0.1198 ± 0.0026	0.1097	0.1093 ± 0.0040
$10^9 A_s$	2.211	2.198 ± 0.056	2.143	2.142 ± 0.061
n_s	0.958	0.959 ± 0.007	0.963	0.962 ± 0.010
τ	0.093	0.091 ± 0.014	0.083	0.083 ± 0.014
$100\theta_*$	1.0415	1.0415 ± 0.0006	1.0425	1.0429 ± 0.0010
Ω_Λ	0.683	0.685 ± 0.017	0.747	0.750 ± 0.020
H_0	67.2	67.3 ± 1.2	72.3	72.5 ± 1.9

Simple... yet, an exotic universe

FRW Universe + Gravitational Structure formation tells us :

- 95% of the energy of the universe is in some exotic form
- Dark Matter: we cannot see it directly, only via gravitational clustering effect.
- Dark Energy: smooth form of energy which does NOT cluster under gravity.
- Some new Ultra-high energy (possibly, fundamental) physics for generating primordial perturbations.

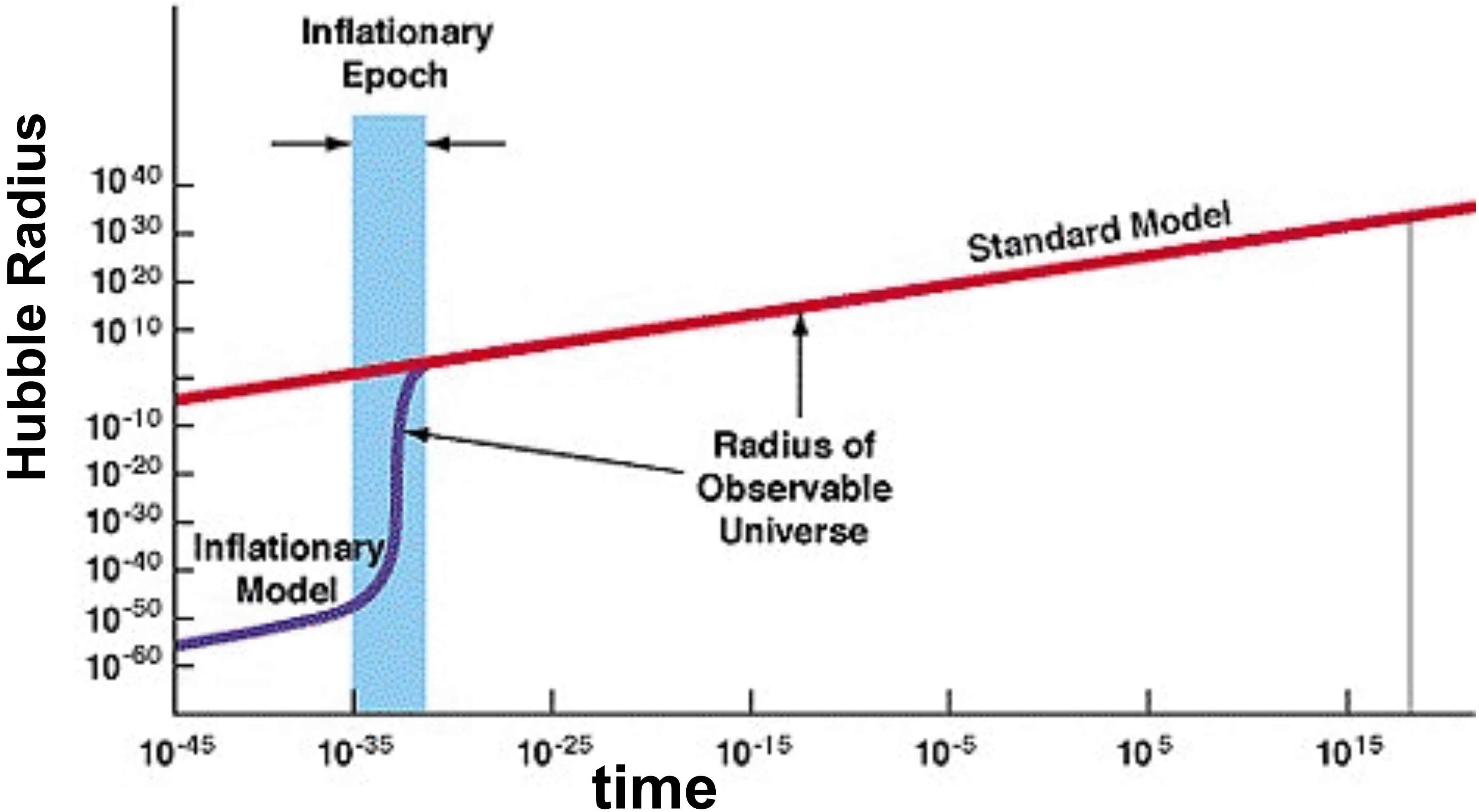
Who pinged the Cosmic drum ?



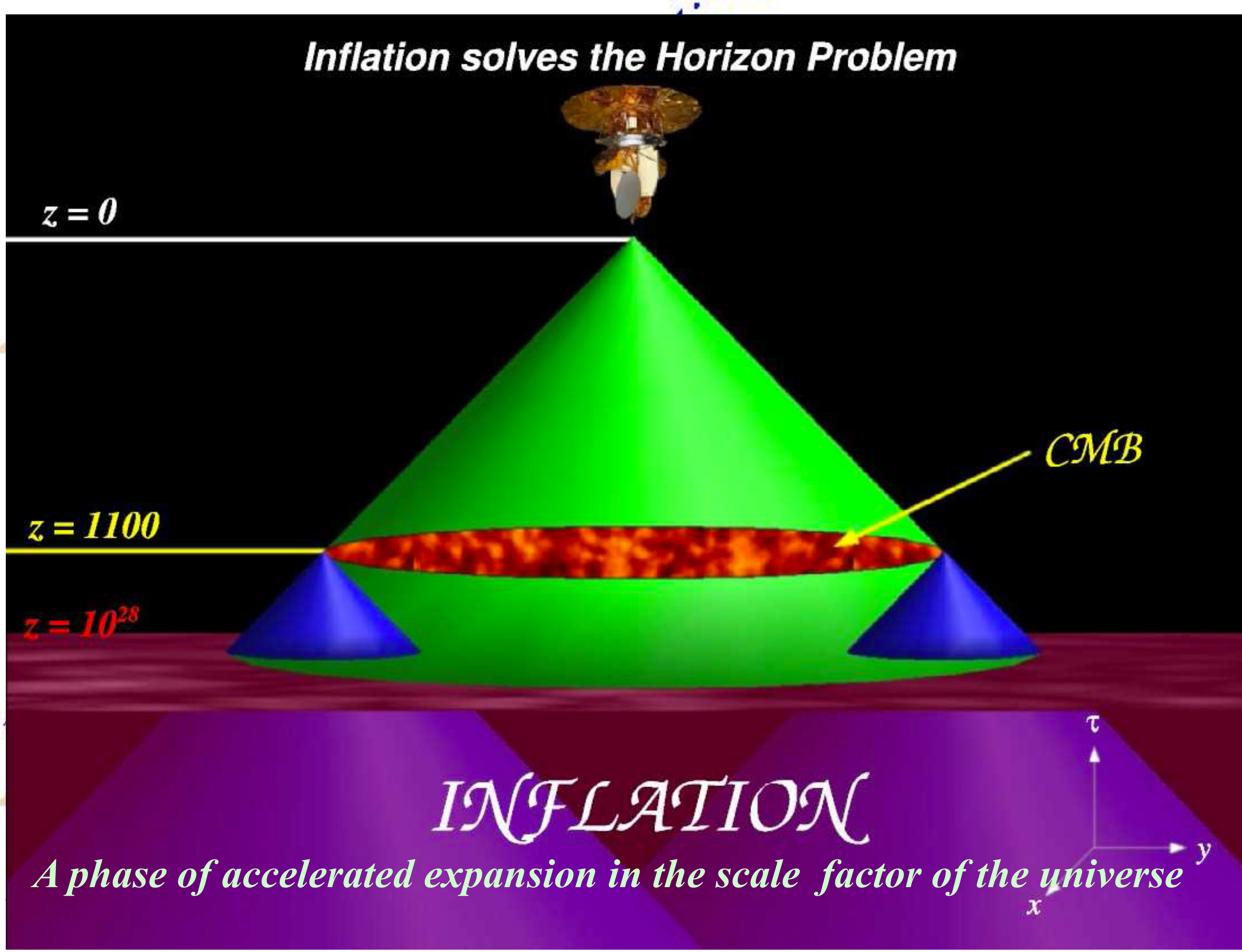
Inflation

a paradigm in search of a model

A phase of rapid expansion in the scale factor of the universe



Inflation: *a paradigm in search of a model*



Generic Inflation model

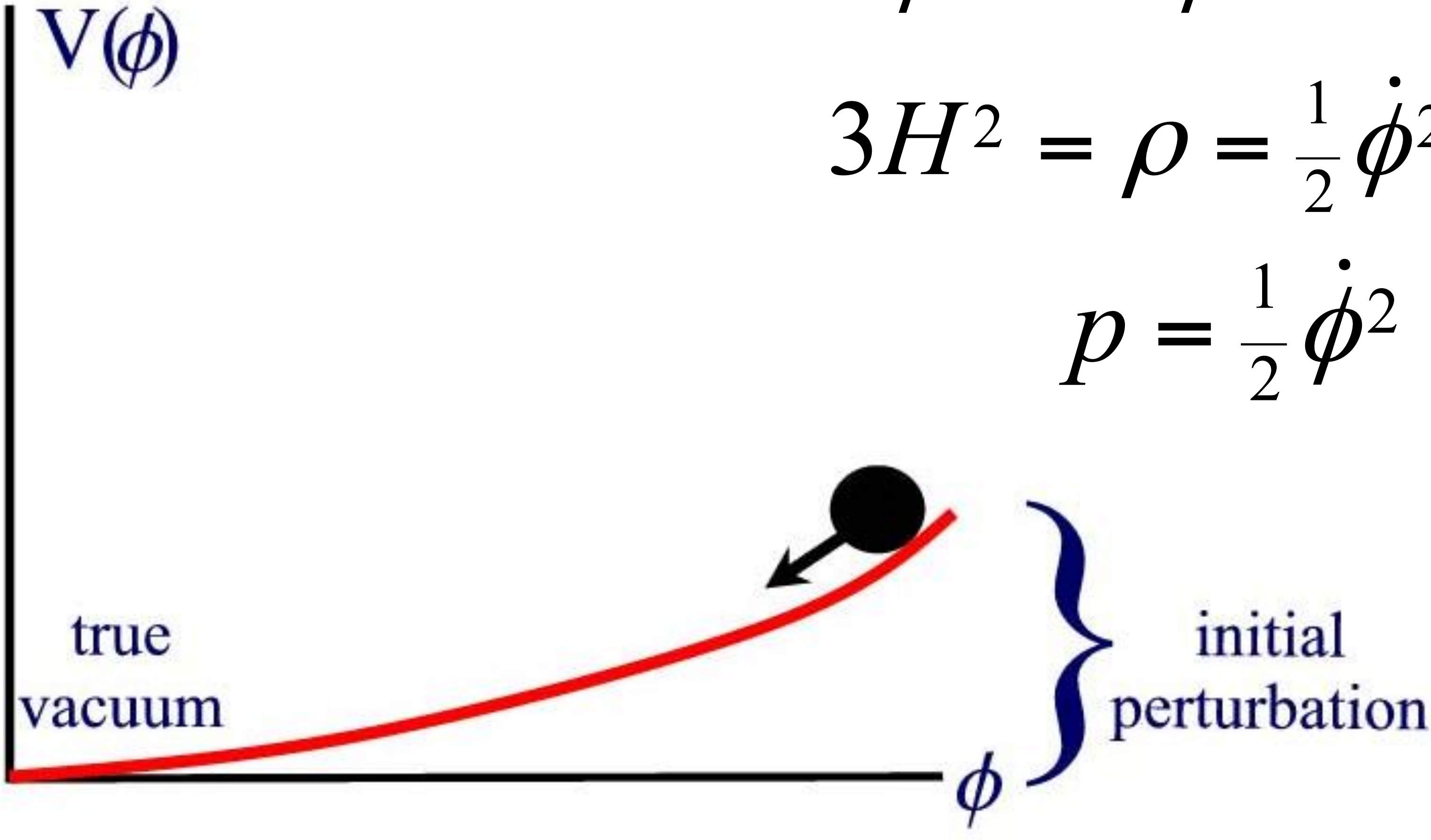
A scalar field displaced from the minima of its potential

Linde's chaotic inflation

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

$$3H^2 = \rho = \frac{1}{2}\dot{\phi}^2 + V$$

$$p = \frac{1}{2}\dot{\phi}^2 - V$$



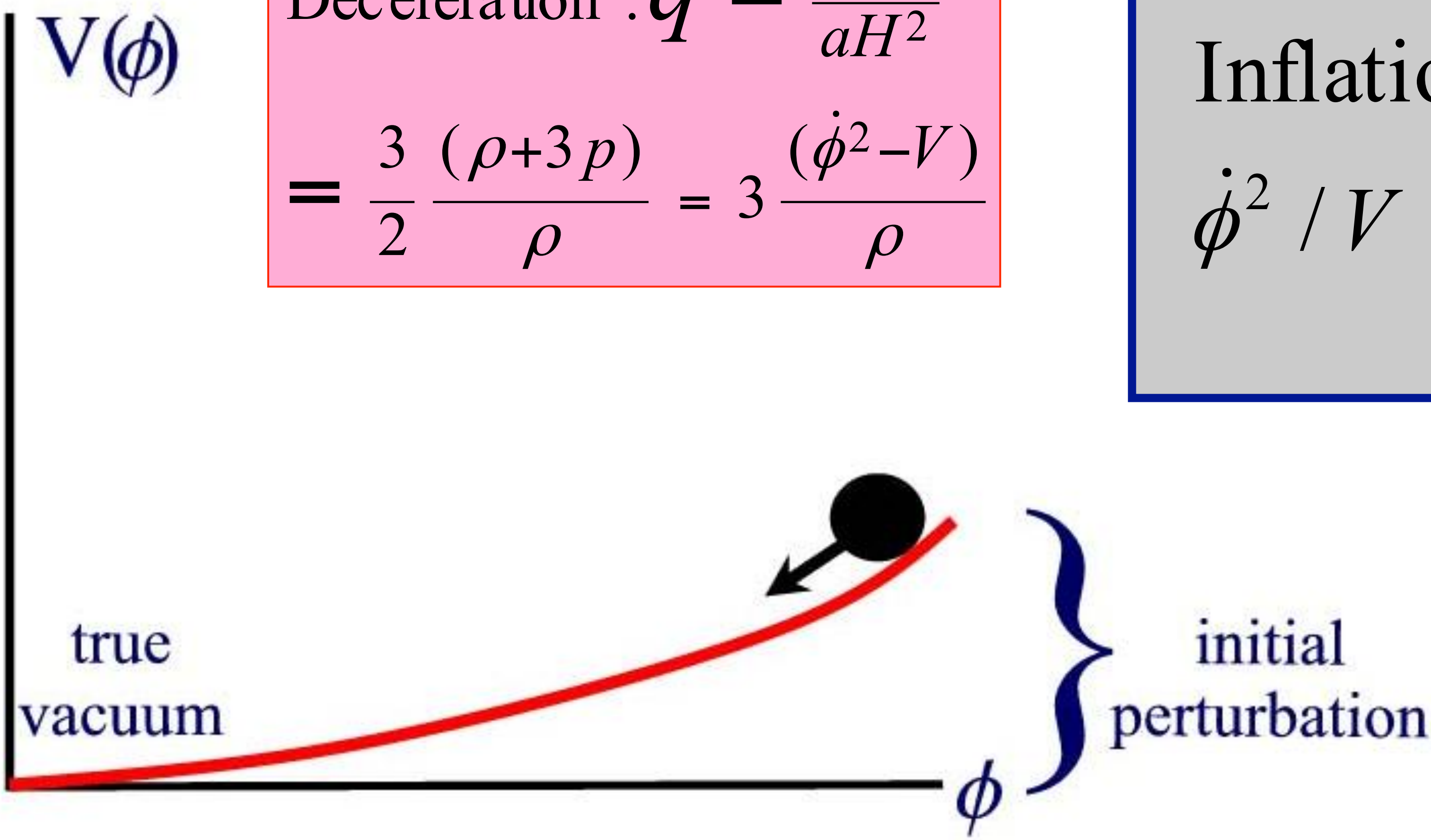
Generic Inflation model

A scalar field displaced from the minima of its potential

$$\text{Deceleration}: q = \frac{-\ddot{a}}{aH^2} = \frac{3}{2}\frac{(\rho+3p)}{\rho} = 3\frac{(\dot{\phi}^2 - V)}{\rho}$$

Inflation

$$\dot{\phi}^2 / V < 1$$

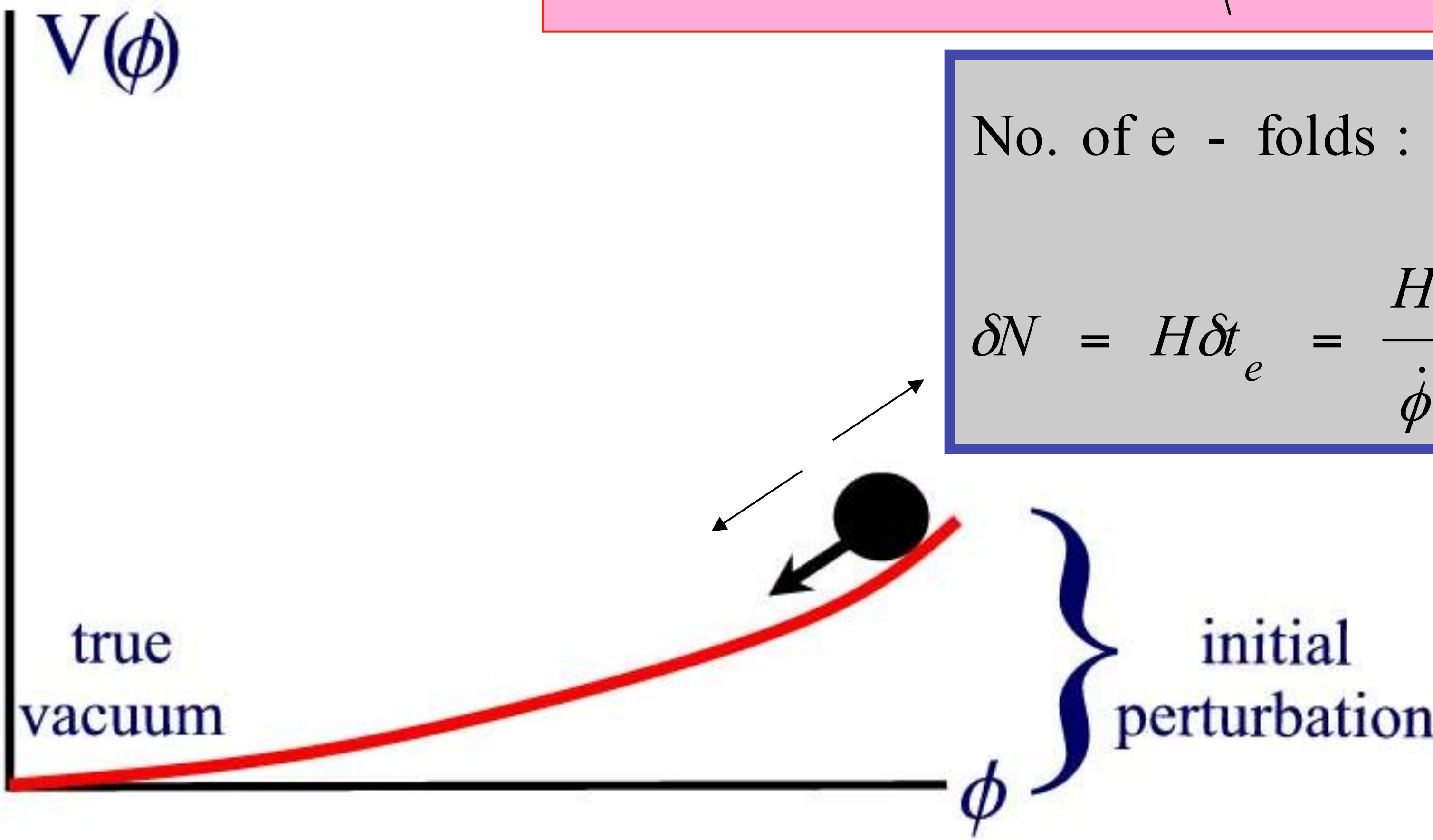


Generation of fluctuations

"DeSitter" q. fluc.: $\delta\phi \equiv \left\langle (\delta\phi)^2 \right\rangle^{\frac{1}{2}} \approx H$

No. of e - folds : $N = \int H\,dt$

$$\delta N = H\delta t_e = \frac{H}{\dot{\phi}}\delta\phi$$



Adiabatic scalar perturbations

- **The inhomogeneous scale factor on which the space creation rate is constant is a measure of adiabatic scalar perturbations**

$$\delta N(x, t_{rh}) \equiv \delta(\ln a)\,|_{H_{rh}}$$

$$= \frac{H}{\dot{\phi}}\ \delta\phi$$

- **It is equivalent to the Gauge invariant Bardeen potential on super-Hubble radius scales**

$$\text{Bardeen potential}: \ \zeta \cong \delta(\ln a)\,|_{H_{rh}}, \quad k << aH$$

$$\zeta = \left.\frac{\delta\rho}{(\rho + p)}\right|_{k=aH} \Rightarrow \left.\frac{\delta\rho}{\rho}\right|_{reenter} >> \left.\frac{\delta\rho}{\rho}\right|_{exit}$$

Early Universe in CMB

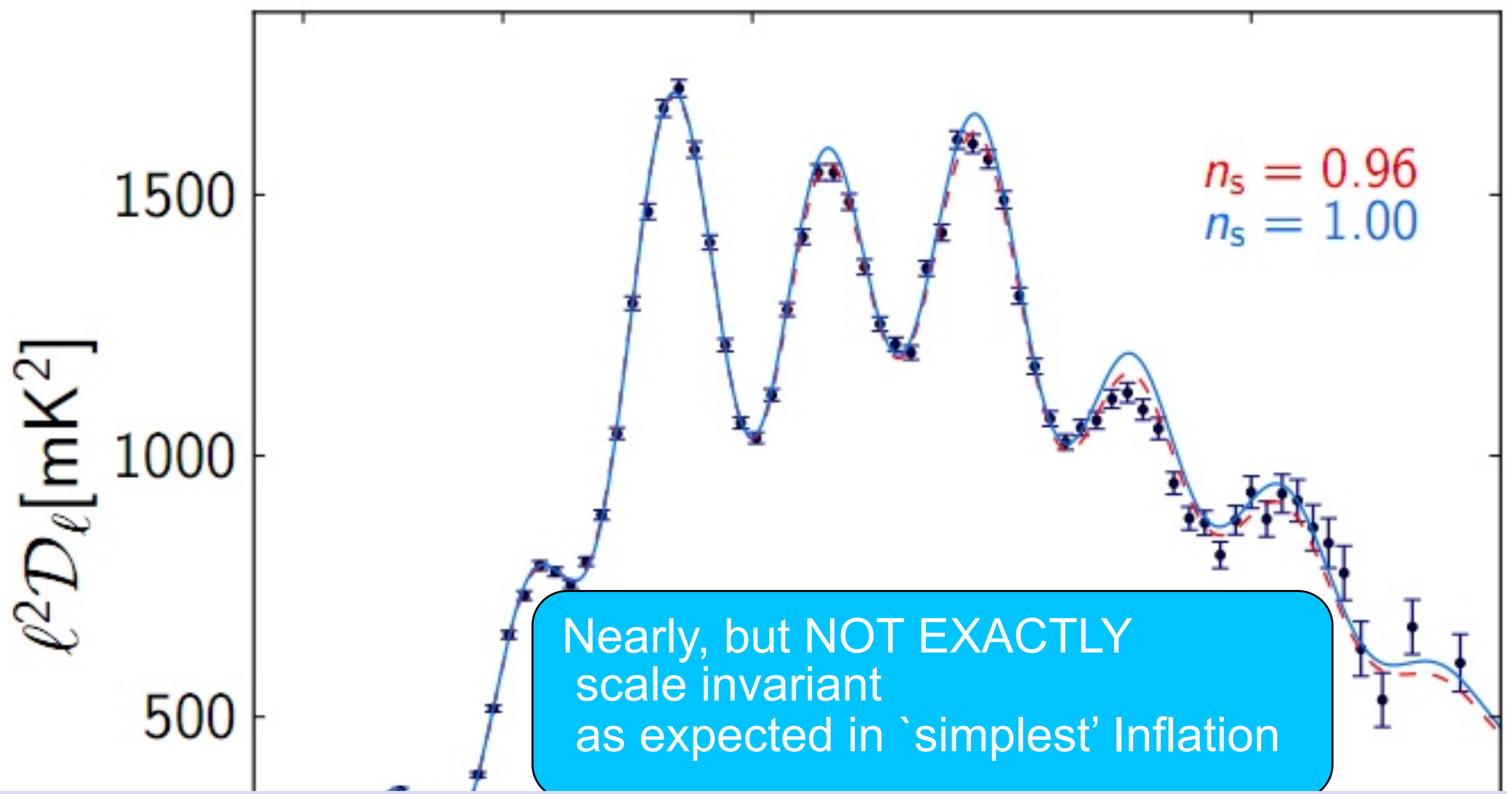
The Background universe

- Homogeneous & isotropic space: ***Cosmological principle*** ?
- Flat (Euclidean) Geometry

The nature of initial/primordial perturbations

- **Power spectrum :** ***'Nearly' Scale invariant /scale free form***
- **Spin characteristics: (*Scalar) Density perturbations***
- **Type of scalar perturbation: *Adiabatic -- no entropy fluctuations***
- **Underlying statistics: *Gaussian***

Spectral index of perturbations

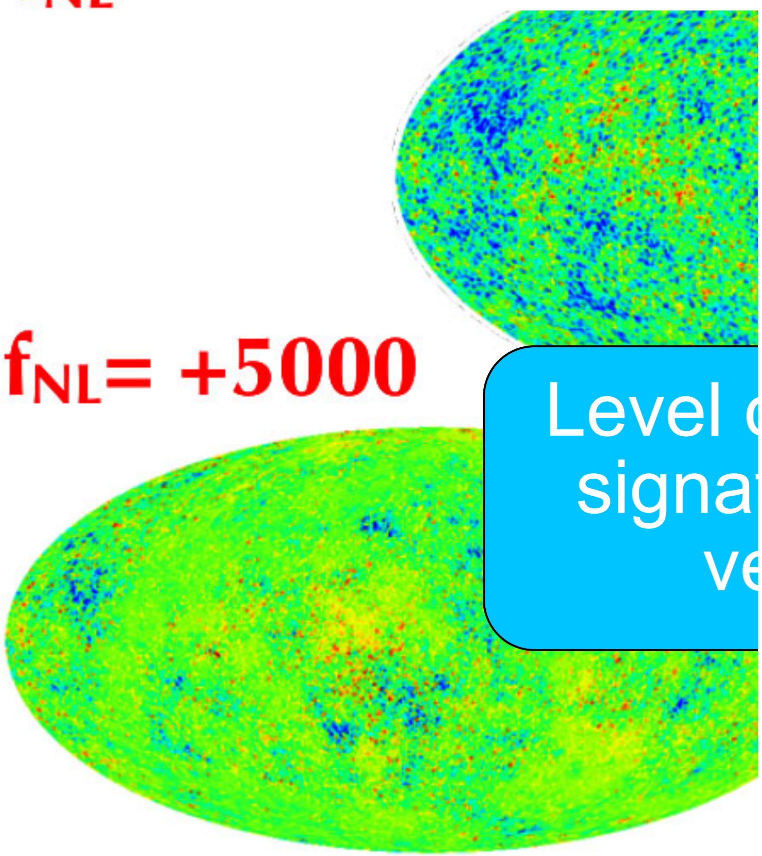


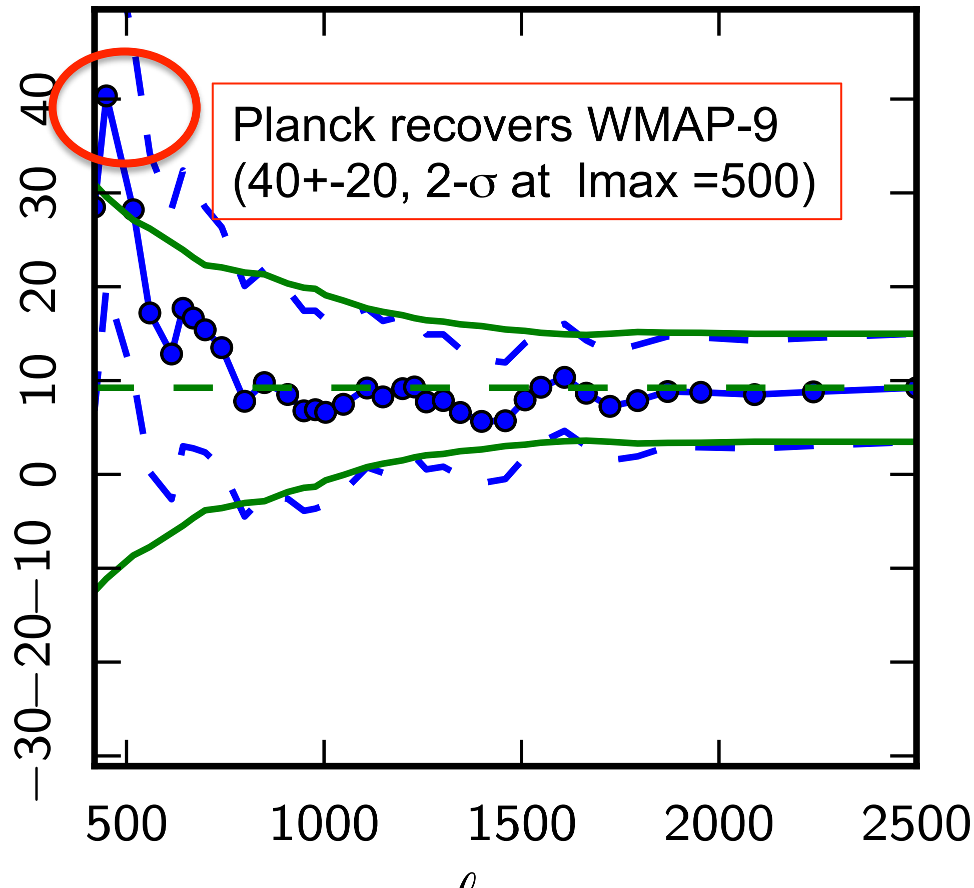
Nearly, but NOT EXACTLY
scale invariant
as expected in `simplest' Inflation

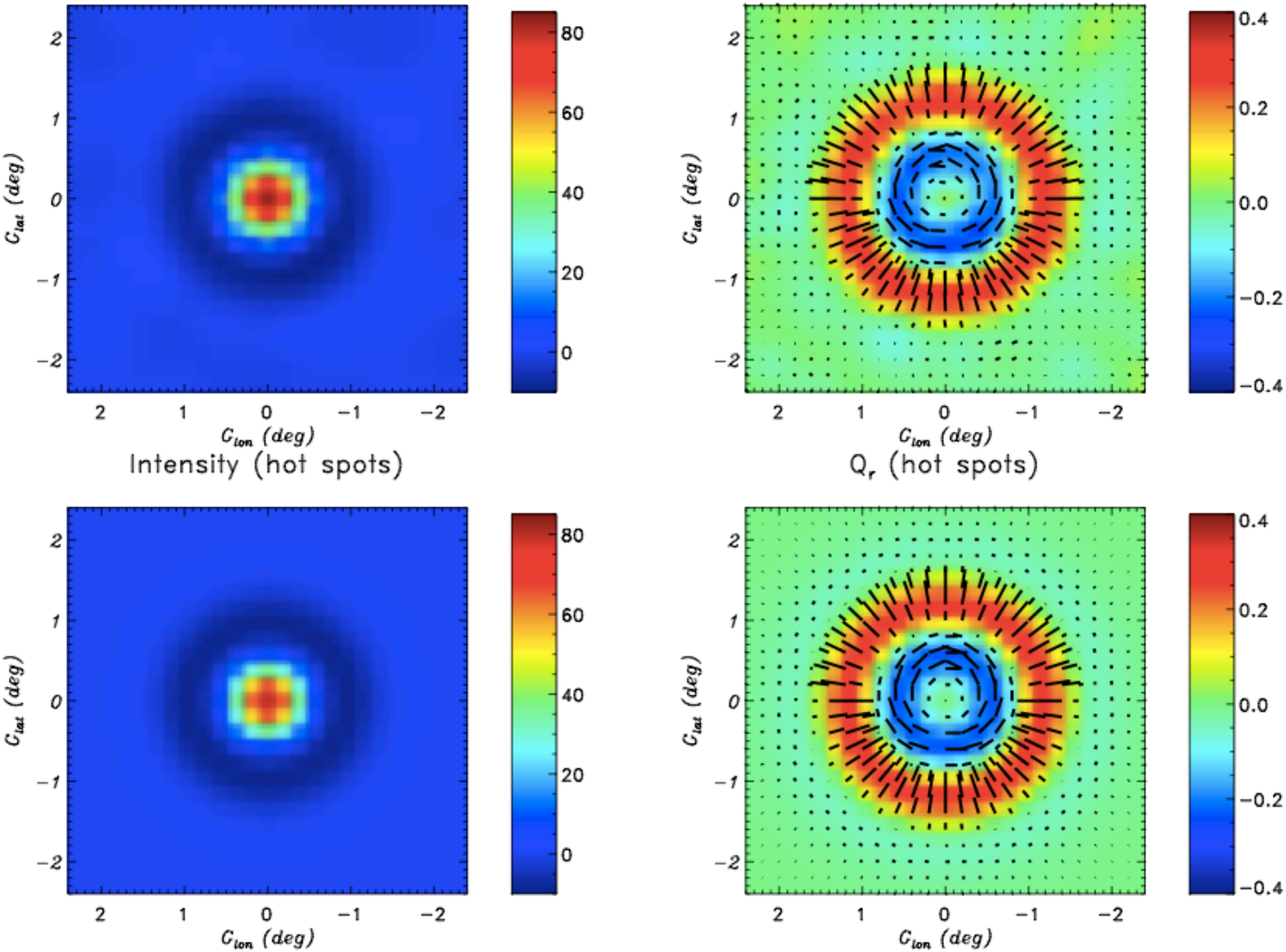
Planck Collaboration: Constraints on inflation

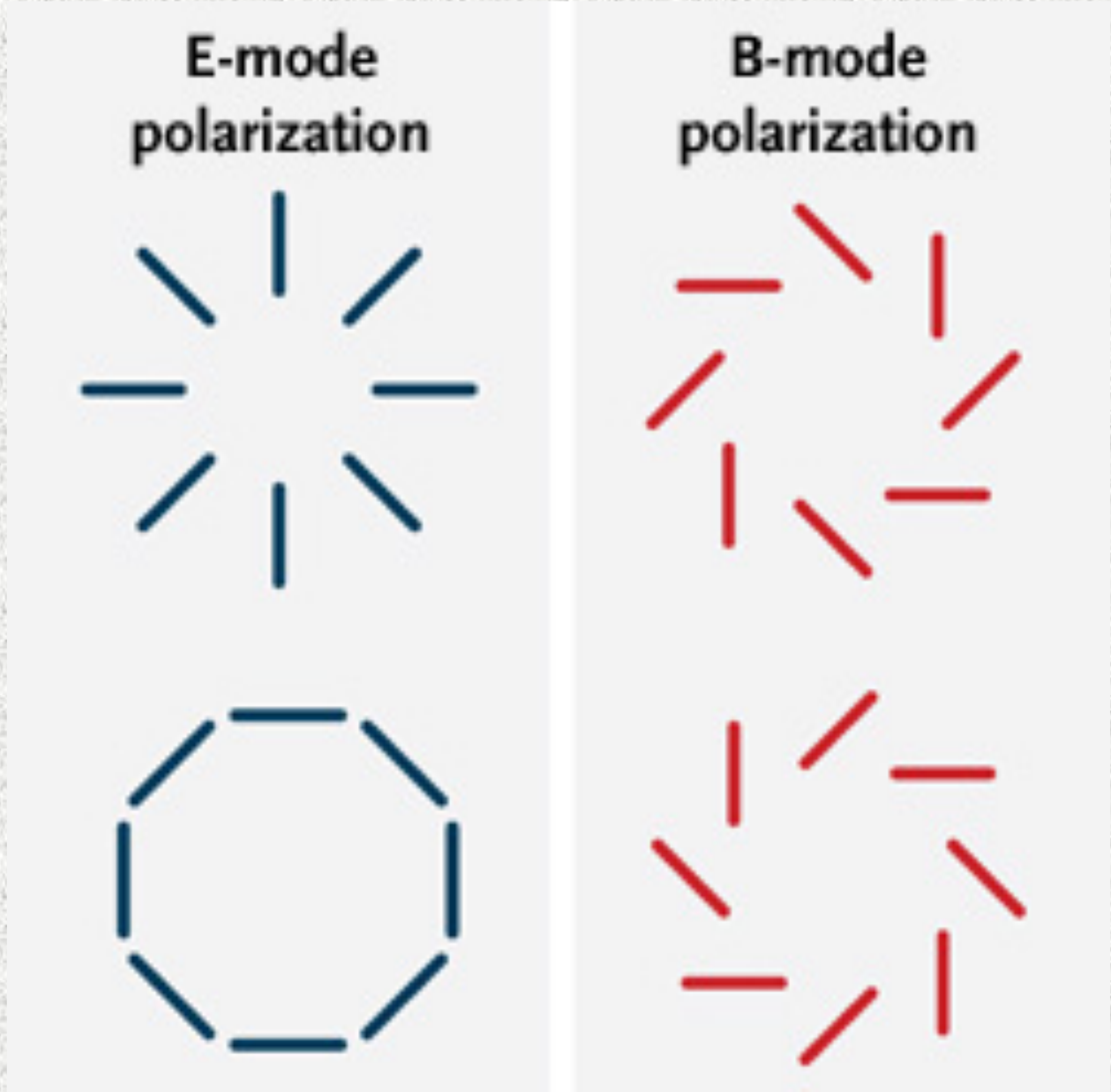
Model	Parameter	*Planck*+WP	*Planck*+WP+lensing	*Planck* + WP+high-ℓ	*Planck*+WP+BAO
ΛCDM + tensor	n_s	0.9624 ± 0.0075	0.9653 ± 0.0069	0.9600 ± 0.0071	$0.9643 + 0.0059$
	$r_{0.002}$	< 0.12	< 0.13	< 0.11	< 0.12
	$-2\Delta \ln \mathcal{L}_{max}$	0	0	0	-0.31

	Independent KSW	ISW-lensing subtracted KSW
SMICA		
Local	9.8 ± 5.8	**2.7 ± 5.8**
Equilateral	−37 ± 75	**−42 ± 75**
Orthogonal	−46 ± 39	**−25 ± 39**

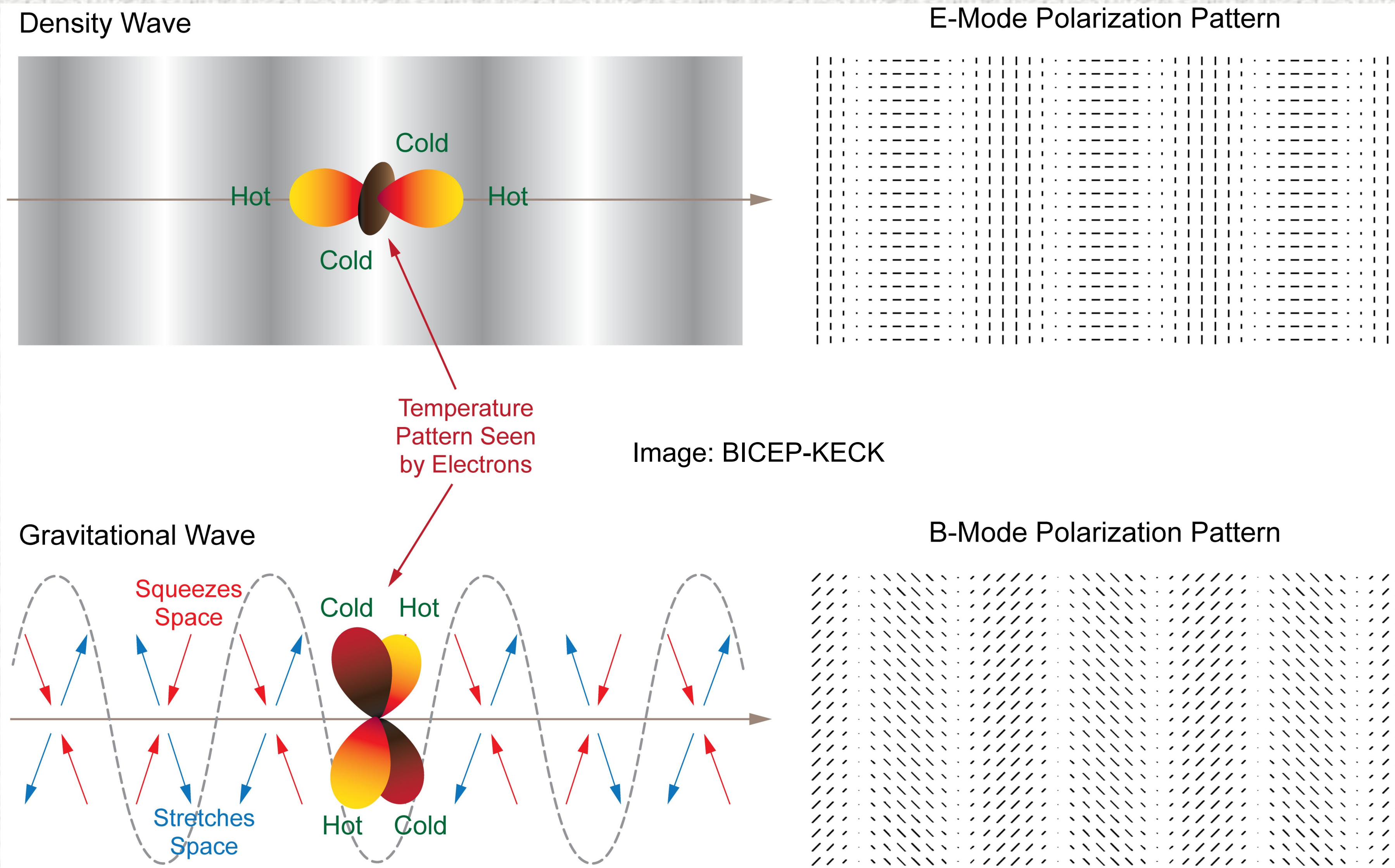





Intensity (hot spots)
Q_r (hot spots)
C_lat (deg)
C_lon (deg)
2
1
0
−1
−2
80
60
40
20
0
0.4
0.2
0.0
−0.2
−0.4


E-mode polarization
B-mode polarization

Generation of E & B modes



Scalar & Tensor perturbations

$$u_k \equiv a\delta\phi_k, \qquad v_k \equiv a h_k$$

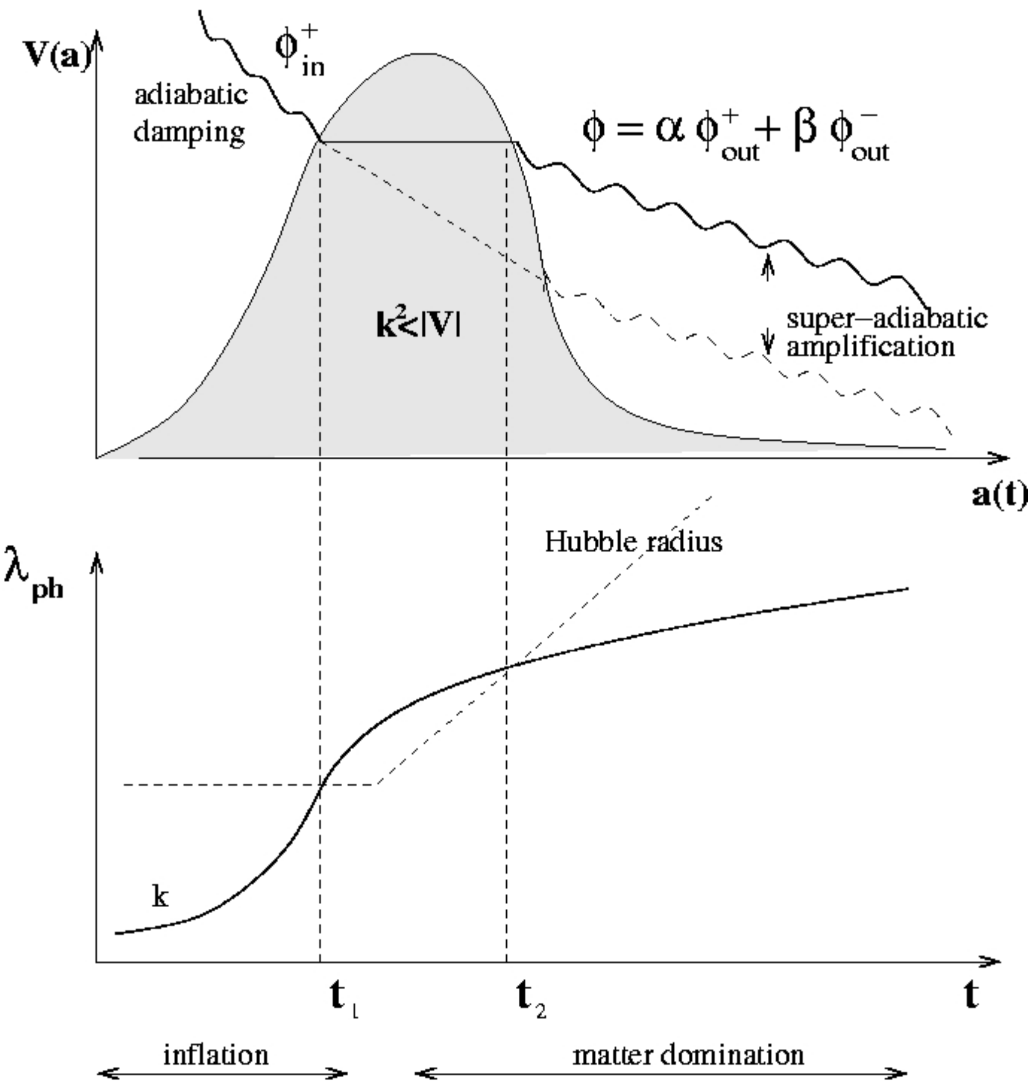
$$u_k'' + \left[k^2 - V_S(\eta)\right] u_k = 0$$

$$v_k'' + \left[k^2 - V_T(\eta)\right] v_k = 0$$

$$V_S = \frac{a''}{a} - \frac{m_{eff}^2}{H^2}, \quad V_T = \frac{a''}{a}$$

$$\frac{m_{eff}^2}{H^2} = (\varepsilon + \delta)(\delta + 3) + \frac{\dot{\varepsilon} - \dot{\delta}}{H}$$

$$\approx \frac{4\pi}{m_P^2} \frac{d^2 \ln H}{d\phi^2}$$



(Fig:Souradeep, Thesis 1995)

Early Universe in CMB

The Background universe

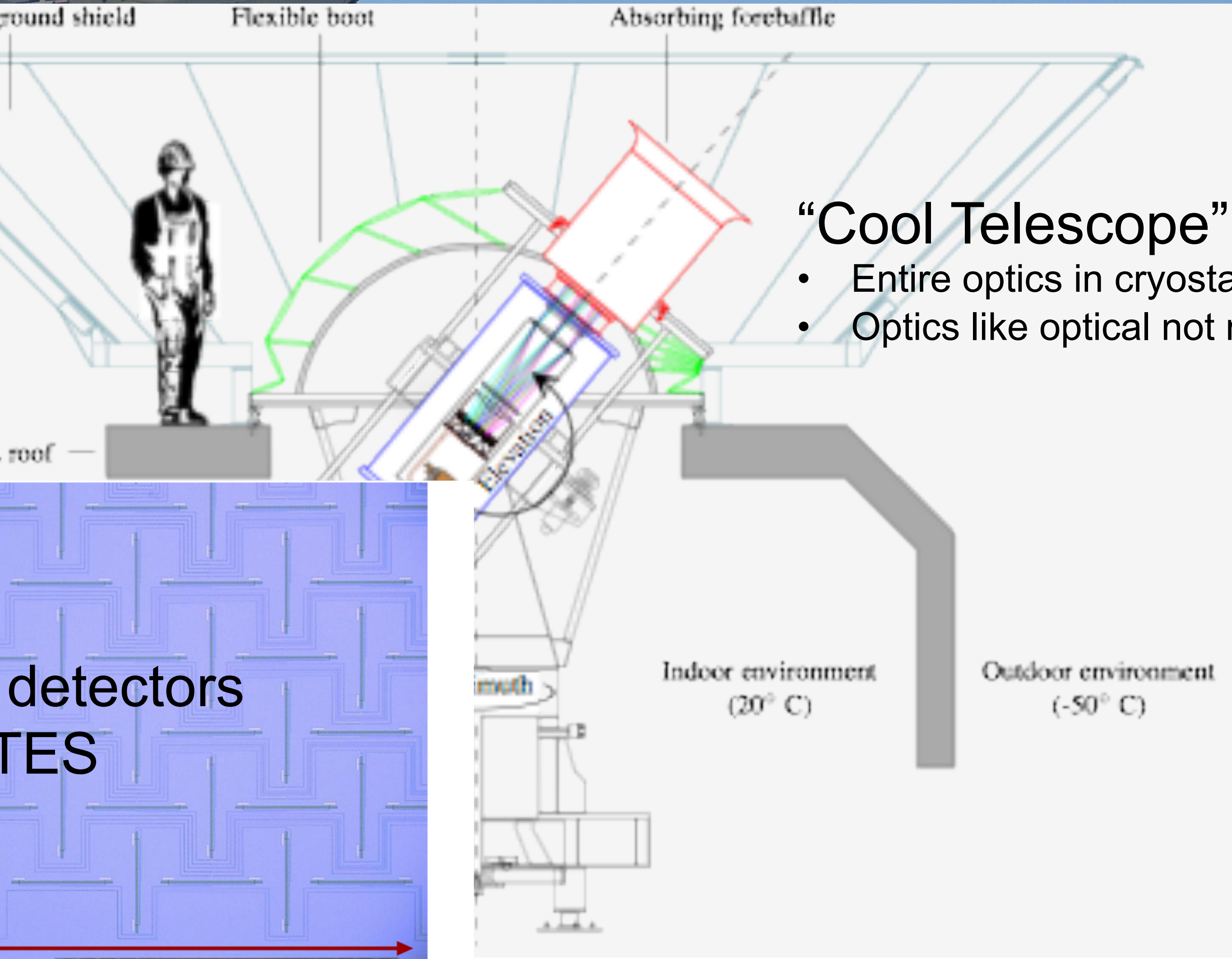
- Homogeneous & isotropic space: *Cosmological principle*
- Flat (Euclidean) Geometry

The nature of initial/primordial perturbations

- **Power spectrum :** *'Nearly' Scale invariant /scale free form*
- **Spin characteristics:** (*Scalar) Density perturbations*

  … cosmic (Tensor) Gravity waves !?!
- **Type of scalar perturbation:** *Adiabatic – no entropy fluctuations*
- **Underlying statistics:** *Gaussian*

BICEP2



"Cool Telescope"

- Entire optics in cryostat
- Optics like optical not radio

New tech detectors

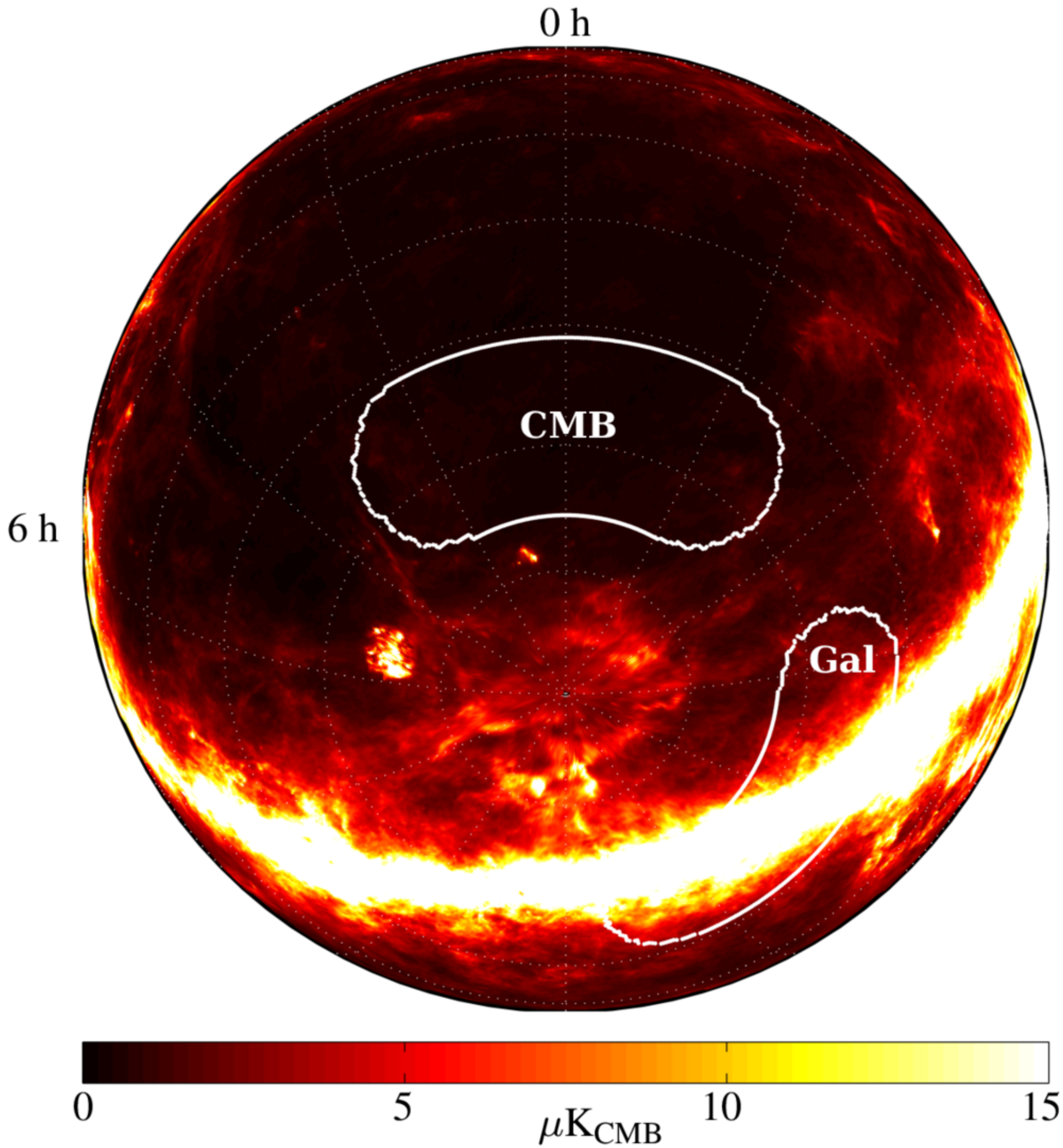
512x512 TES

0.3 $nKs^{0.5}$

Location: South Pole

- **“An excellent site for millimeter-wave observation from the ground (DASI, BICEP1, QUAD & SPT)**
  - Dry: exceptionally low precipitable water vapour, reducing atmospheric noise due to the absorption & emission of water at ~150GHz observing band.
  - Calm : very stable weather, especially during the dark winter months,
  - Finally, the Amundsen-Scott South Pole Station has hosted scientific research continuously since 1958. The station offers well-developed facilities with year-round staff and an established transportation infrastructure.”

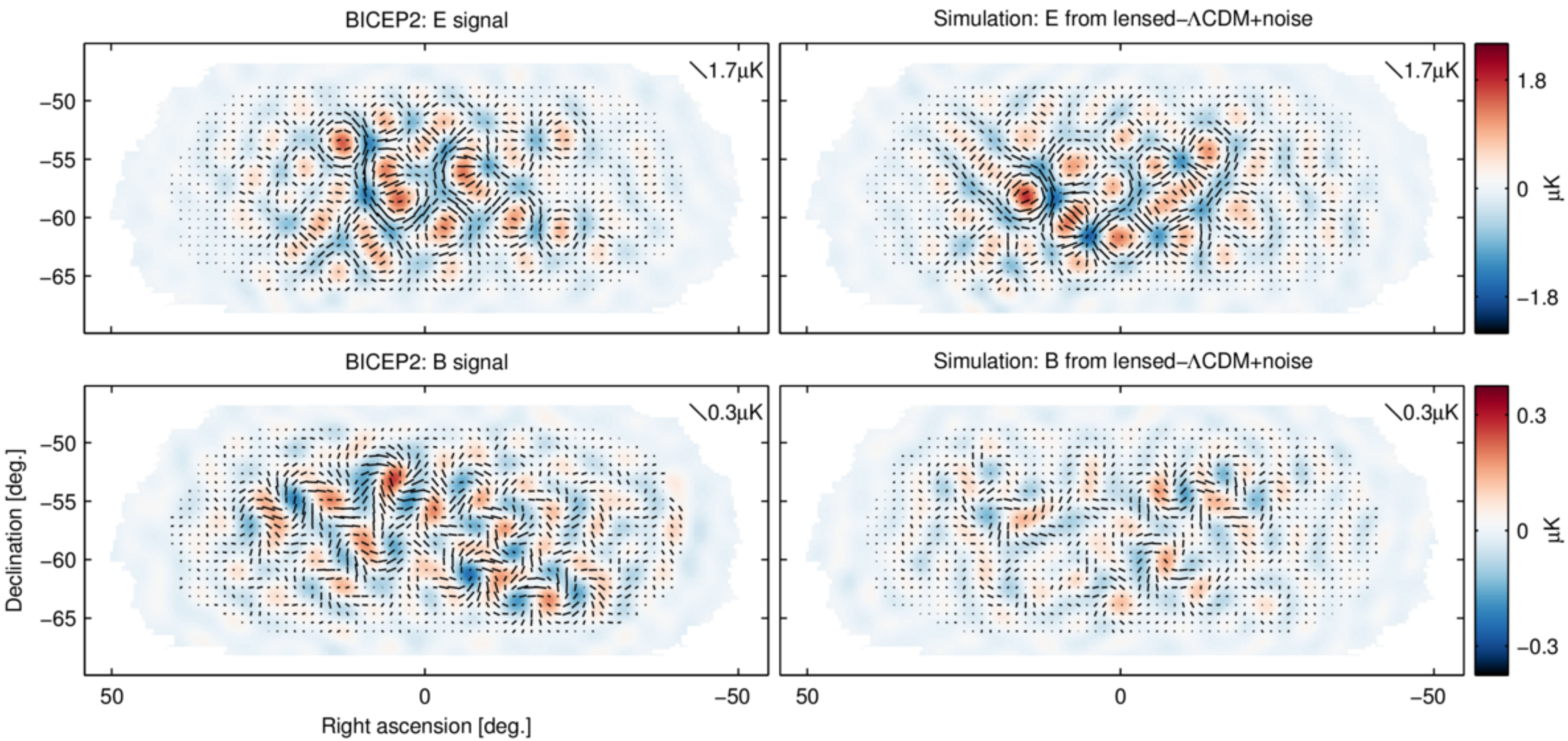
BICEP philosophy: Deep observations in 'cleanest' patch



400 sq. degs.
Centered at
Galactic:
316°,−59°
Celestial:
RA 0h, Dec. −57.5°

BICEP2: arXiv:1403.4302

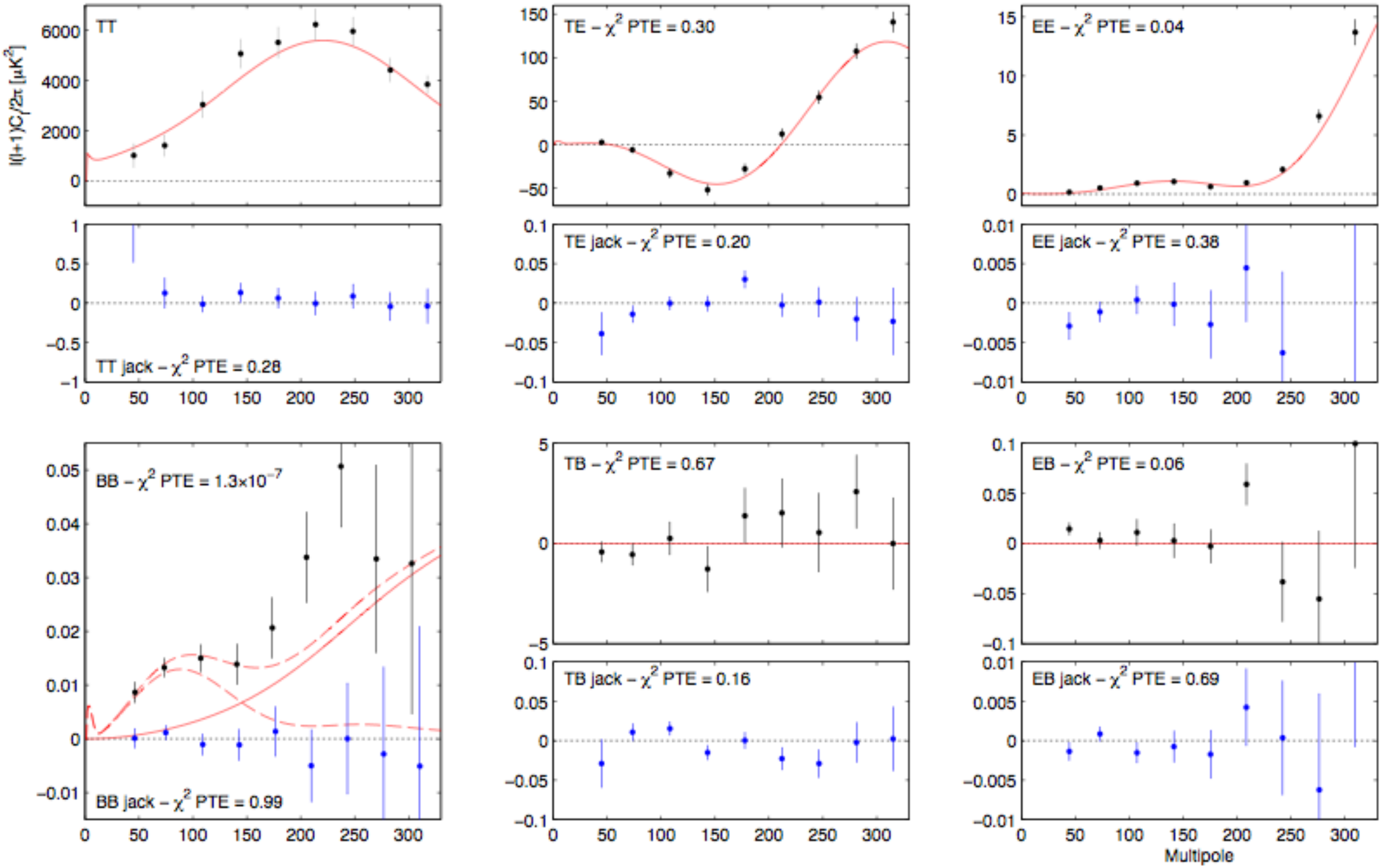
BICEP Polarization Maps



BICEP2: arXiv:1403.3985

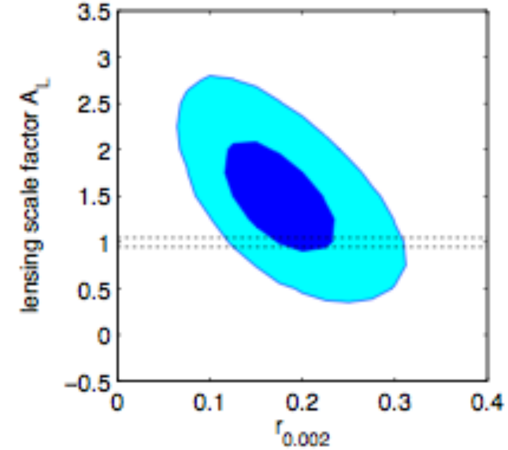
Power Spectra

BICEP2: arXiv:1403.3985

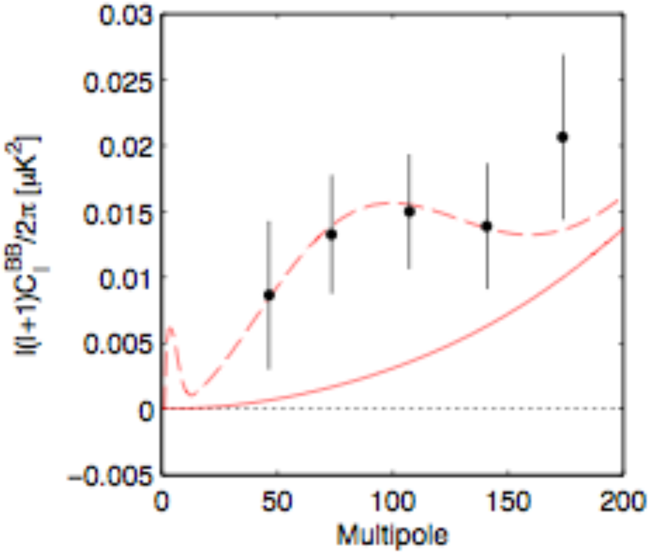


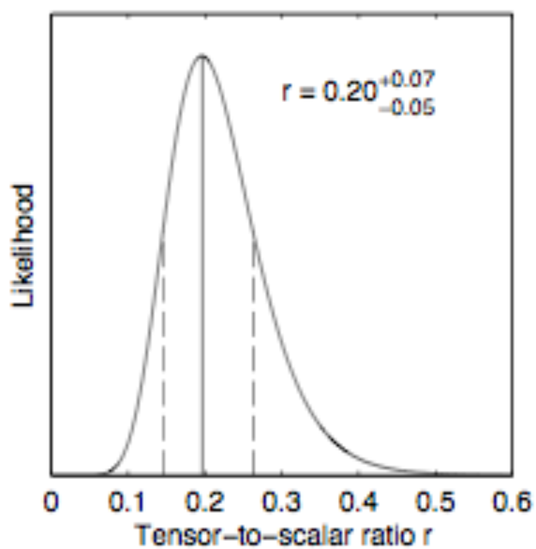
Main Results claimed

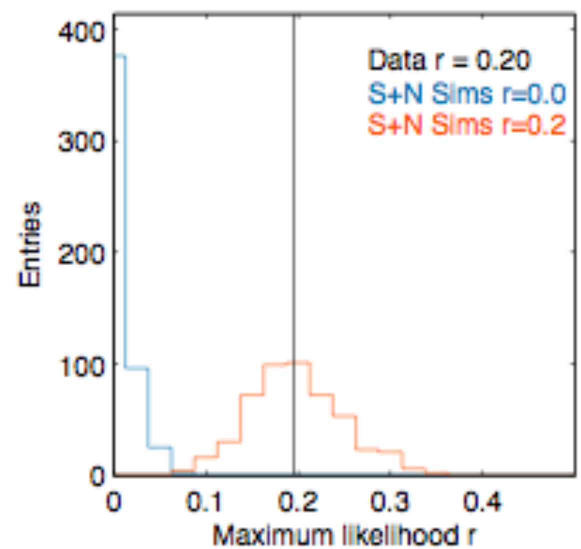
- r=0.2 (GW) detected at 5.2σ
- r=0.0 (no GW) ruled out at 7.0σ



BICEP2: arXiv:1403.3985







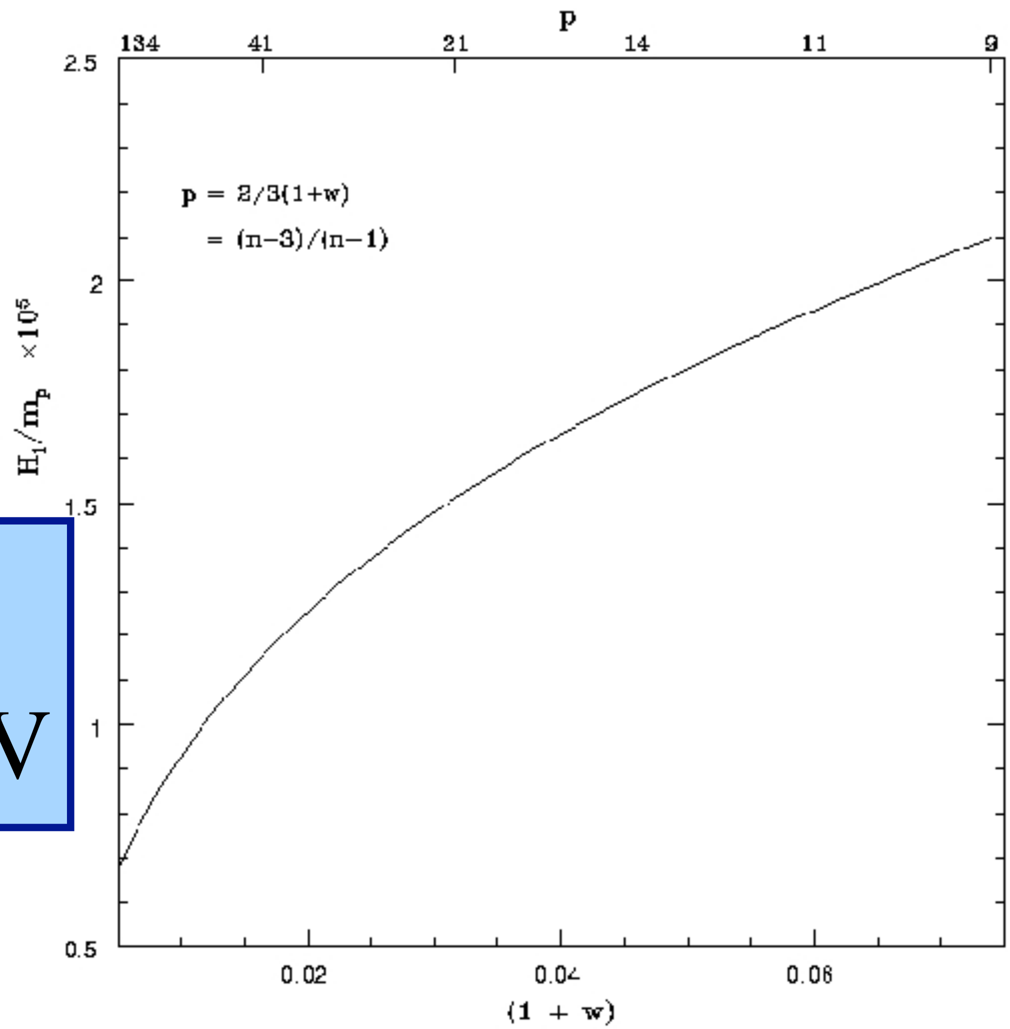
Early Universe from CMB

- **Energy scale and Model of inflation**

COBE-DMR normalized Hubble parameter during inflation

$$r = 0.2 \Rightarrow$$

$$H_{\text{inf}} = 2.10^{16}\ \text{GeV}$$



(Souradeep & Sahni, 1992, Souradeep, Ph.D.thesis, 1995)

Early Universe from CMB

- **Tensor to scalar ratio is crucial discriminant of EU scenarios**

Scalar --- Density perturbations

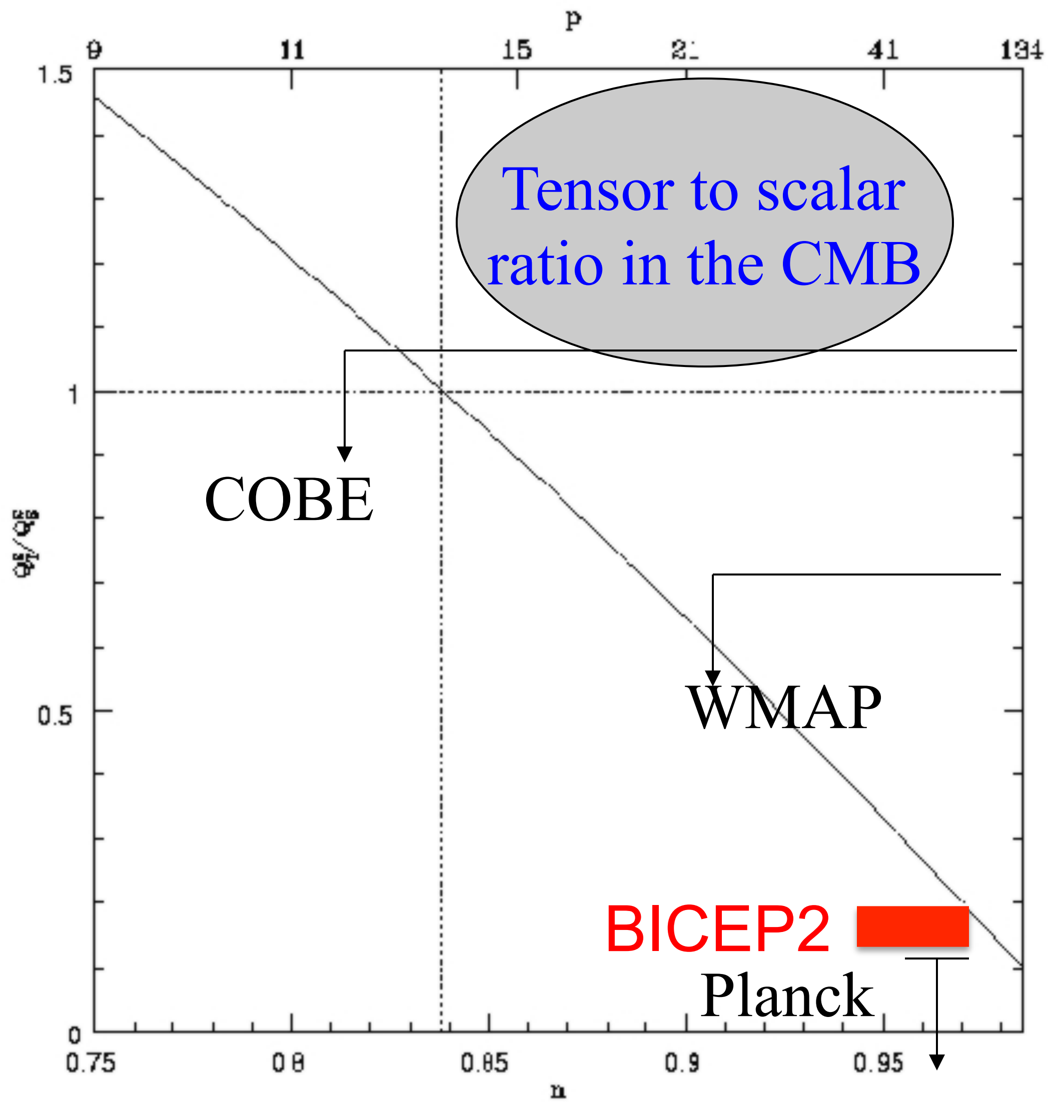
→ **Large scale structure in galaxy clustering**

Tensor --- Gravitational waves

→ **Relic stochastic GW background**

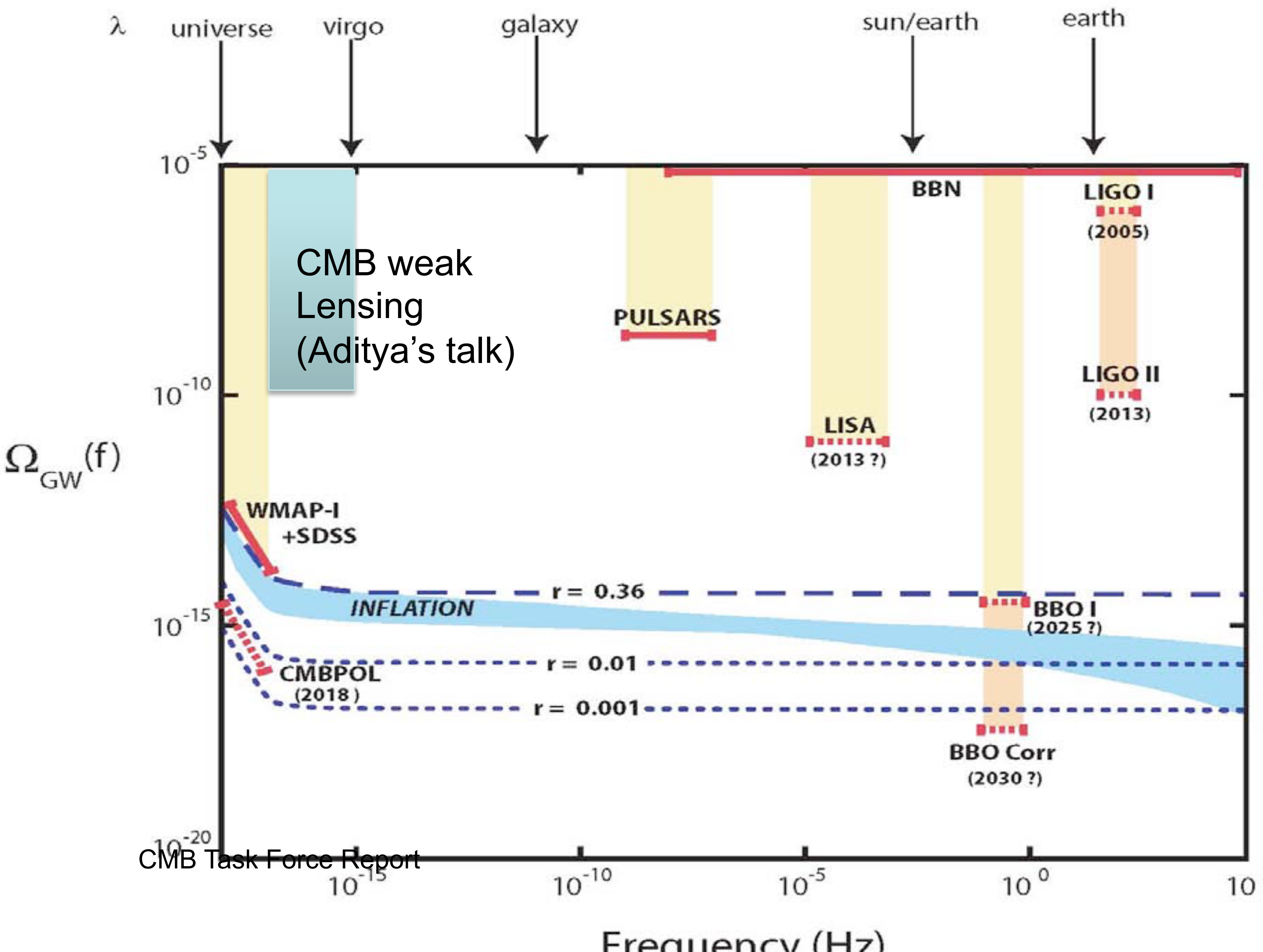
Vector --- rotational modes

→ **Perhaps unimportant, but primordial magnetic field**



(Souradeep & Sahni, 1992, Souradeep, Ph.D.thesis, 1995)

Same GW can be detected over 20-30 orders smaller scale !



CMB Task Force Report

Planck Collab. View on CMB B-mode

- Planck measures polarisation and it is in our scientific objectives to detect or set limits on primordial B-modes in the CMB

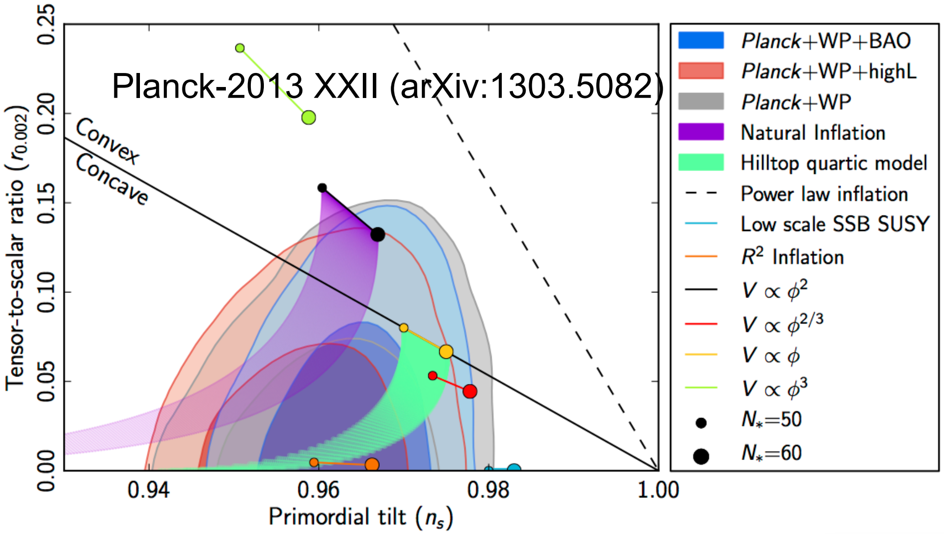
- Planck's sensitivity allows in principle to measure the tensor-to-scalar ratio at the high level of signal detected by BICEP2, though in practice this depends on controlling systematic effects and foregrounds

- We plan to release all our data, including polarisation maps,at the end of October 2014.

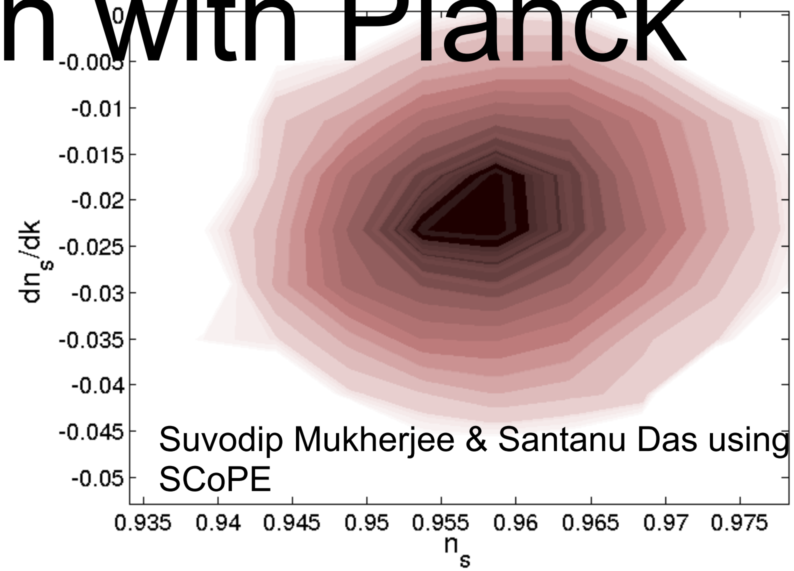
Any concerns !!!?!!!

- Essentially based on single frequency measurements !!!!
- Is it 'cleanest' patch in *polarized* foregrounds?

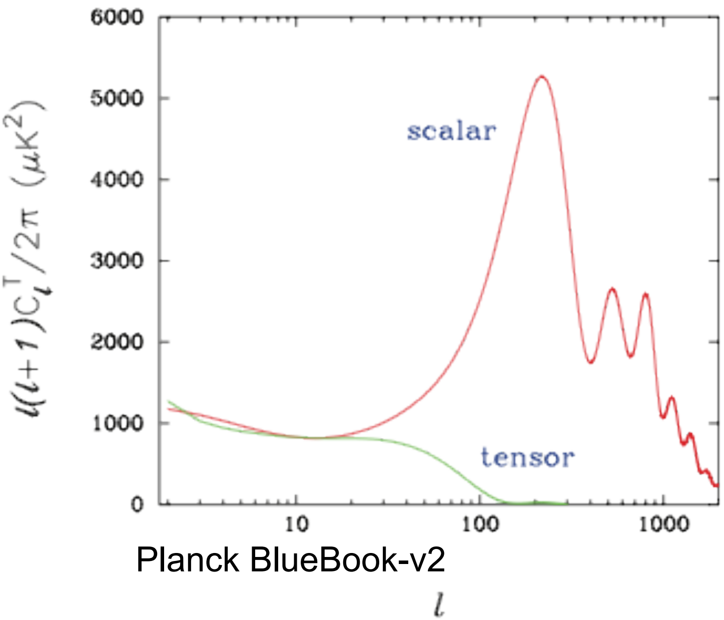
Concern: Tension with Planck



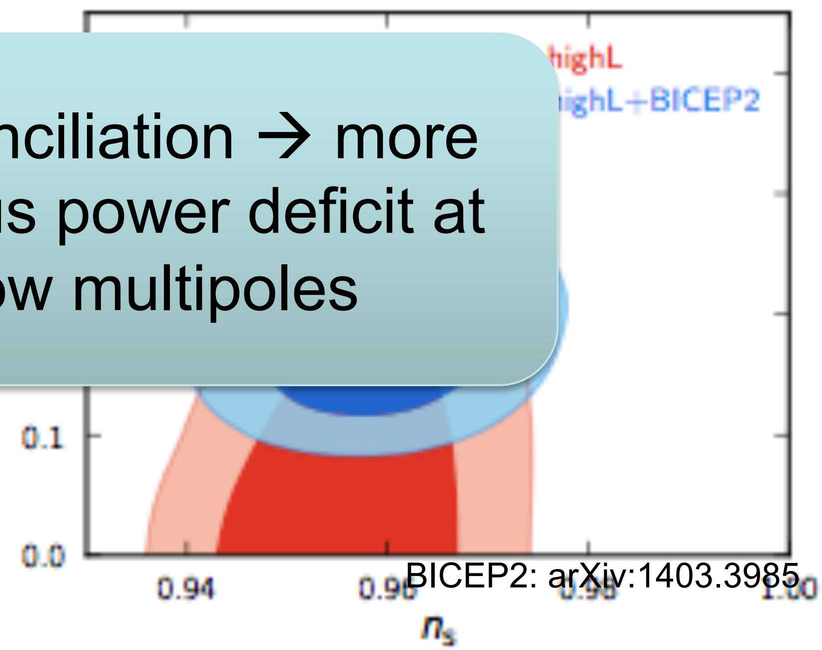
Planck-2013 XXII (arXiv:1303.5082)



Suvodip Mukherjee & Santanu Das using SCoPE



Planck BlueBook-v2

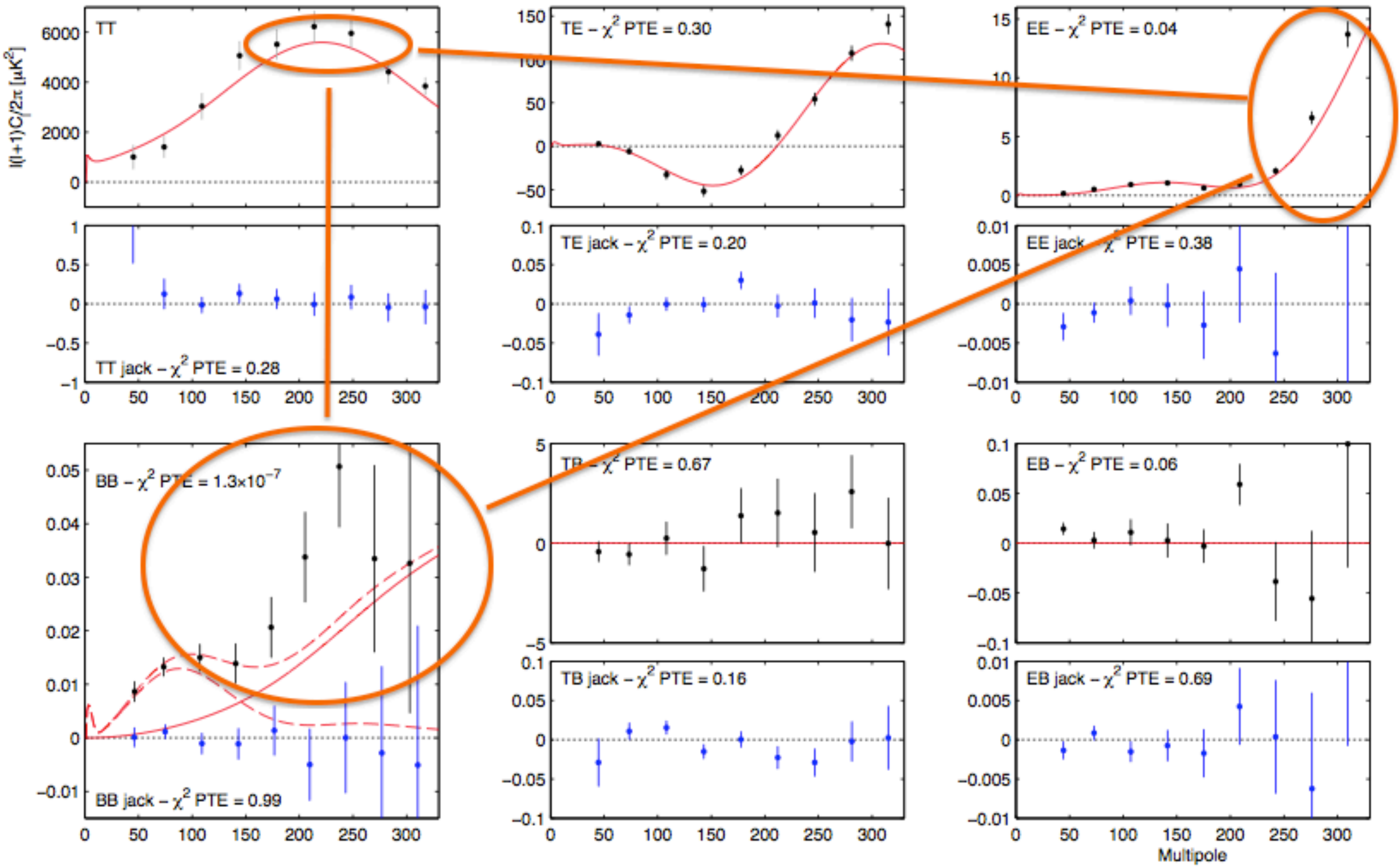


BICEP2: arXiv:1403.3985

Reconciliation → more serious power deficit at low multipoles

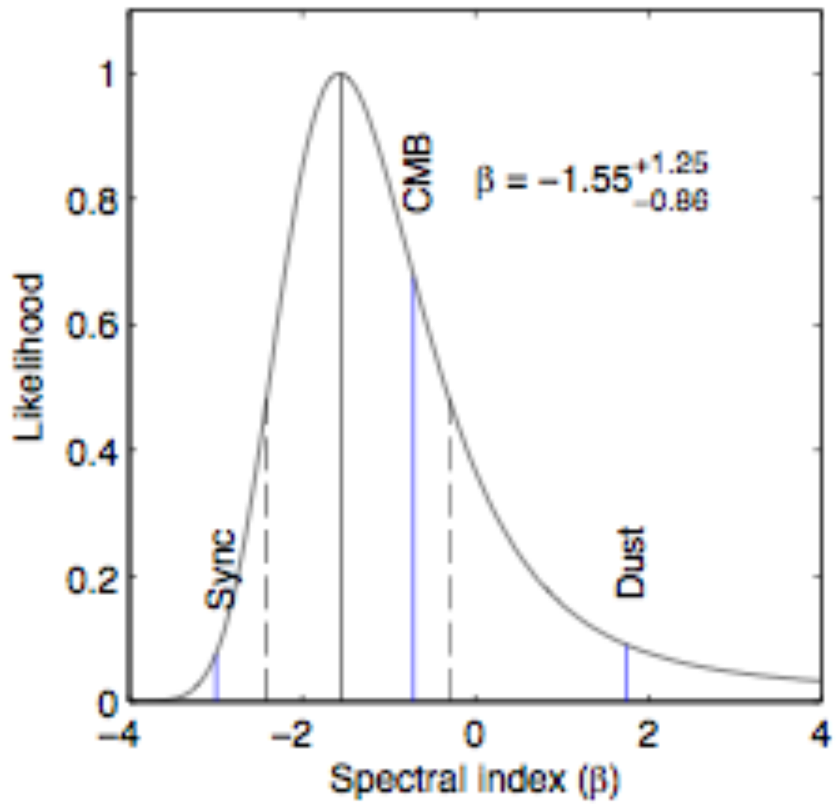
Concern

(Courtesy:Aditya)



Concern: foreground

- "detected signal is not foreground" ruled out at ~2σ?

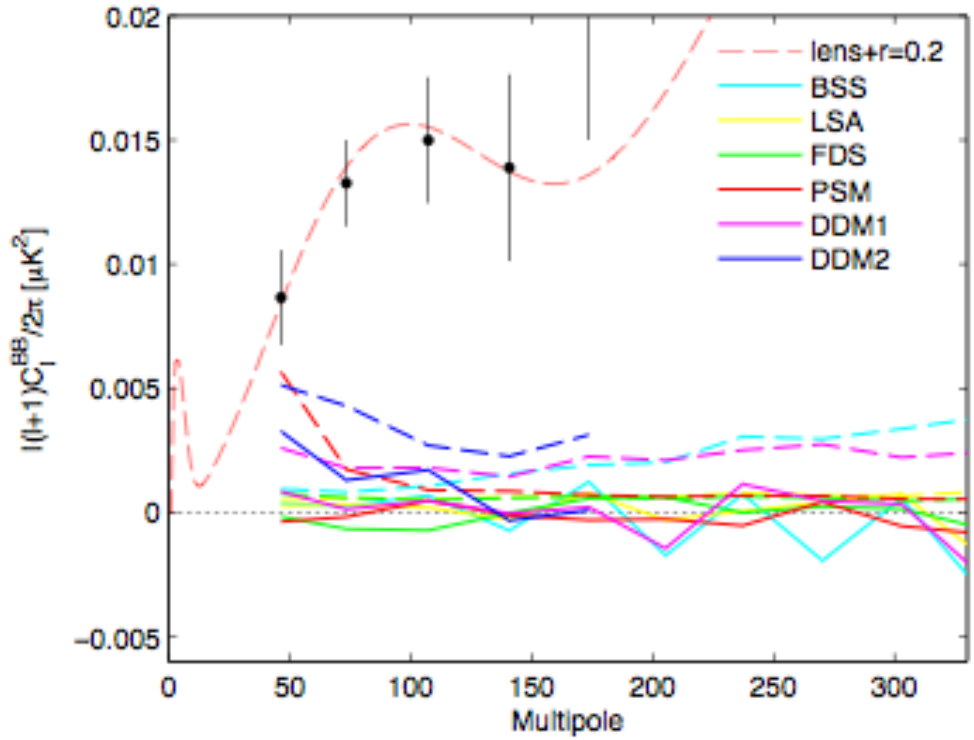


BICEP2: arXiv:1403.3985

"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 ±1σ 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 > ~2σ."

polarised dust

- “The main uncertainty in foreground modeling is currently the lack of a polarized dust map. (This will be alleviated soon by the next Planck data release.) In the meantime we have therefore investigated a number of existing models and have formulated two new ones.”



BICEP2: arXiv:1403.3985

CMB Foregrounds as observed by Planck

Slides Courtesy:

Tuhin Ghosh, IAS Orsay, France

Planck Collaboration

Recent review talk at Moriond meeting Apr. 2014

Summary

- Popular models of inflation predict primordial GWs

    Amplitude o

- GWs induces B-mode polarisation in CMB
- BICEP2 claimed a > 5σ detection of primordial B-modes,

  reinforcing the existence of **GW** and **Inflation**

➡potentially a major milestone in cosmology and High energy physics.

➡**but** we must wait for results from other frequency channels of Keck array and other detectors (**Planck**)

Thank You!