#### In pursuit of elusive Cosmic Gravitational waves in the cosmic microwave background

Silver Jubilee Colloquium Chennai Mathematical Institute

> Chennai March 3, 2015

Tarun Souradeep I.U.C.A.A., Pune

#### The Gravitational Wave Spectrum



http://science.gsfc.nasa.gov/

#### **Cosmic Microwave Background**

#### Pristine relic of a hot, dense & smooth early universe -Hot Big Bang model

Post-recombination :Freely propagating through (weakly perturbed) homogeneous & isotropic cosmos.

Pre-recombination : Tightly coupled to, and in thermal equilibrium with, ionized matter

(text background: W. Hu)



#### Cosmic "Super-IMAX" theater



#### **History of the Universe**



#### Ping the 'Cosmic drum'

(Fig: Einsentein)

More technically, the Green function

150 Mpc.

#### **Dissected CMB Angular power spectrum**

•Low multipole : Sachs-Wolfe plateau • Moderate multipole : Acoustic "Doppler" peaks • High multipole : Damping tail



#### **CMB** space missions



#### Planck CMB sky map

#### Truly all-sky !!! Only 3% of sky replaced by constrained realization



#### **Foreground for CMB anisotropy**





**Tarun Souradeep** 





#### 6-Parameter $\Lambda CDM$

	Planck	Planck (CMB+lensing)		Planck+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits	
$\Omega_{\rm b} h^2$	0.022242	$0.02217 \pm 0.00033$	0.022161	$0.02214 \pm 0.00024$	
$\Omega_{ m c}h^2$				$0.1187 \pm 0.0017$	
100 <i>θ</i> <sub>МС</sub>				0.00056	
<sup>7</sup> 'Stand	lard' (	cosmologia	cal mo	del:	
Flat ACDM with nearly					
Power Law (PL) primordial power spectrum					
- Power I	AW (PL)	primoralal pov	ver sdeci	rum 🦰	
Power I	-aw (PL)	primoraiai pov	ver speci	rum	

Tarun Souradeep

## **Non Parametric inference**

**Cosmological parameter estimation is carried out WITHIN FRW model framework + other priors** 

# What can we say just from data !?!

#### Planck: Non-Parametric Peak harmonicity



#### **Planck : Non-Parametric Acoustic scale**

(Aghamousa, Shafieloo, Arjunwadkar, TS, JCAP 2015)





Towards 'Observing' the Early Universe

## **Inflation:** *a paradigm in search of a model*



## **Generic Inflation model**

A scalar field displaced from the minima of its potential



## **Generation of fluctuations**



## **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 perturbation

- Type of scalar perturbation: Adiabatic no entropy fluctuations
- Underlying statistics: Gaussian



## **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

# Cosmic GW background From Inflation

Each polarization of Graviton behaves like a Massless, Minimally coupled scalar field (akin to fluctuations of inflaton)

➔ Generation of scalar perturbations is accompanied by generation of Inflationary GW

Ratio of GW/Density perturbation: r ~ Energy scale of inflation



#### **Direct Detection of Gravitational Waves**

[Note: Indirect detection of GW emission from binary Pulsar systems confirmed : Hulse & Taylor –awarded Nobel prize 1993]



#### **Cosmic GW detector**



#### **History of the Universe**





#### → PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 5 degrees





Full sky map Filtered at 5 degrees

Filtered at 20 arcminutes









#### **Planck CMB Polarization spectra**





**Tarun Souradeep** 



#### 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 Polarization Maps**



BICEP2: arXiv:1403.3985

#### **Main Results claimed**

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



BICEP2: arXiv:1403.3985



# Any concerns !!!?!!!

- Essentially based on single frequency measurements !!!!
- Is the 'cleanest' patch clean enough in \*polarized\* foregrounds?

#### **Foreground for CMB Polarization**





#### **Planck Polarised dust emission**





## **PIP-XXX** :Planck intermediate results (1409.5738.v2)

Dust temp  $T_d$ =19.6 K , Graybody index prior,  $\beta_d$ =-1.59+-0.11





## **BICEP/KECK+Planck**



#### **Main Result**



## Planck 2015 + BKP prior on r

#### Planck 2015 results. XIII. Cosmological parameters

- $r_{0.002} < 0.10$ , *Planck* TT+lowP,
- $r_{0.002} < 0.11$ , *Planck* TT+lowP+lensing+ext,
- $r_{0.002} < 0.08$ , *Planck* TT+lowP+BKP,
- $r_{0.002} < 0.09$ , *Planck* TT+lowP+lensing+ext+BKP.



## Planck 2015 + BKP prior on r



# Finally, still an upper limit on r

... and the search goes on for the elusive GW from inflation

# CORE + Cosmic ORigins Explorer

ESA cosmic vision proposal (2020-25) Core proposal doc.



#### **Other Results**

- Dust power amplitude  $A_d = 3.6 \text{ muK}^2$
- fixed spatial scaling  $l^{-0.42}$
- fixed dust temp  $T_d$ =19.6 K , graybody index prior,  $\beta_d$ =-1.59+-0.11 [Consistent with PIP-XXX]



#### The Current Landscape



Spectral Energy Density



• Cosmic Gravity wave background from inflation

 $\log_{10}(f/3)$  (Hz.)



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



# • SGWB : SGWB end to set the set of $SGWB = \frac{1}{\rho_{crit}} \frac{d\rho_{GW}(f)}{d \ln f}$

- Critical (charactersitic)  $\rho_{\rm crit} = \frac{3 c^2 H_0^2}{8 \pi G}$ density for universe:

$$\Omega_{\rm GW} = \int_{-\infty}^{\infty} \Omega_{\rm GW}(f) \, \mathrm{d} \ln f$$

$$- \text{ total SGWB energy density:}$$

$$\Omega_{GW}(k) = \frac{4\pi}{3} \left(\frac{c}{H_0}\right)^2 k^3 P_T(k) [k\mathcal{T}']^2$$

