Quest for Cosmic Origin

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Proposal lead,
CMB-Bharat proposal

IISER PUNE

CMB BHĀRAT: AN INDIAN COSMOLOGY CONSORTIUM

Department Colloquium

IIT Madras

Sept. 18, 2019

The Cosmic stage

The Realm of Cosmology

Basic unit: Galaxy

Size : 10-100 kilo parsec (kpc.)

Mass : 100 billion Stars

Measure distances in

light travel time

1 pc. (parsec) = 200,000 AU

= 3.26 light yr.

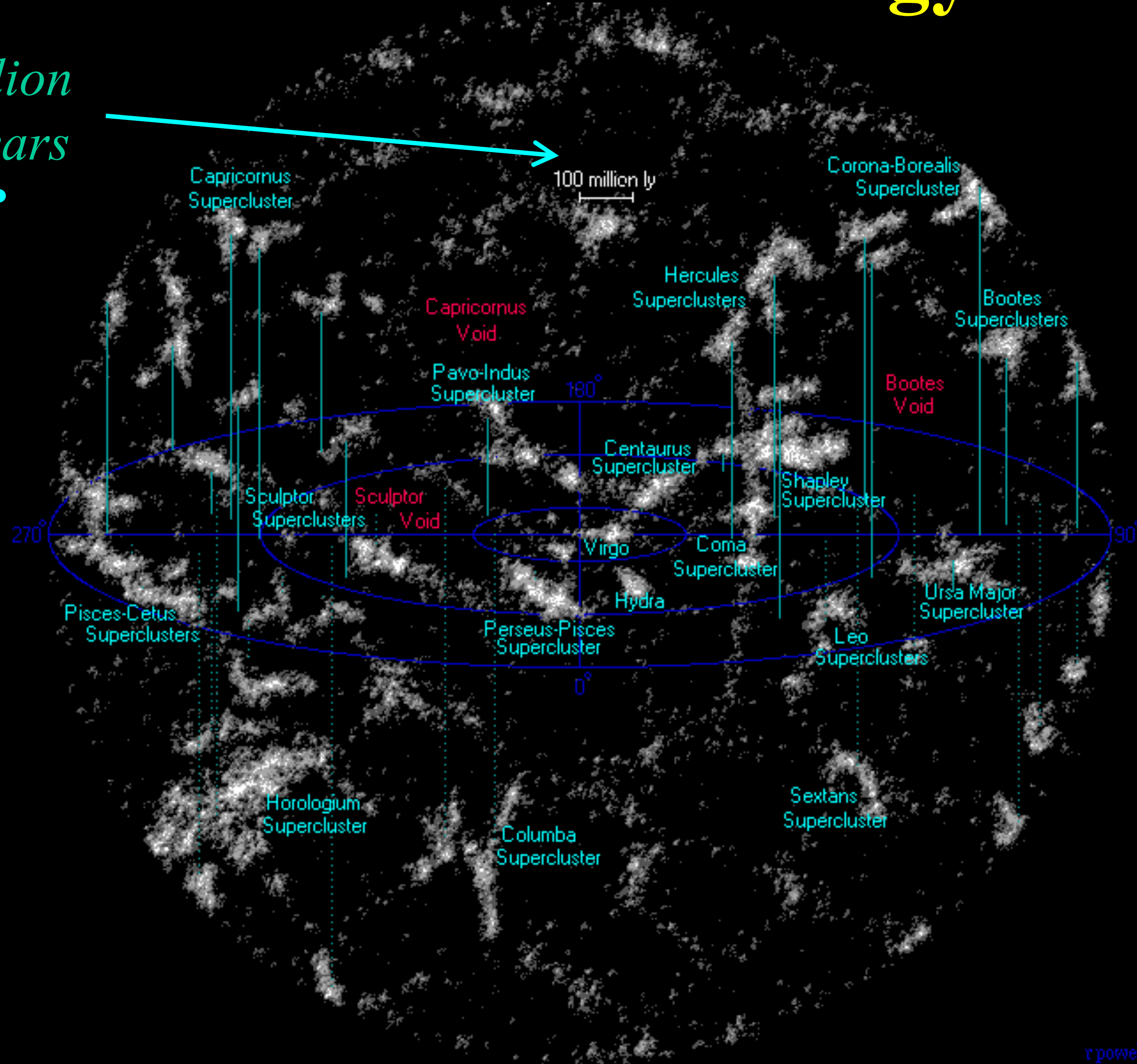
Measure Mass in Solar mass

$$\boxed{= 2 \times 10^{30}\,Kg.}$$

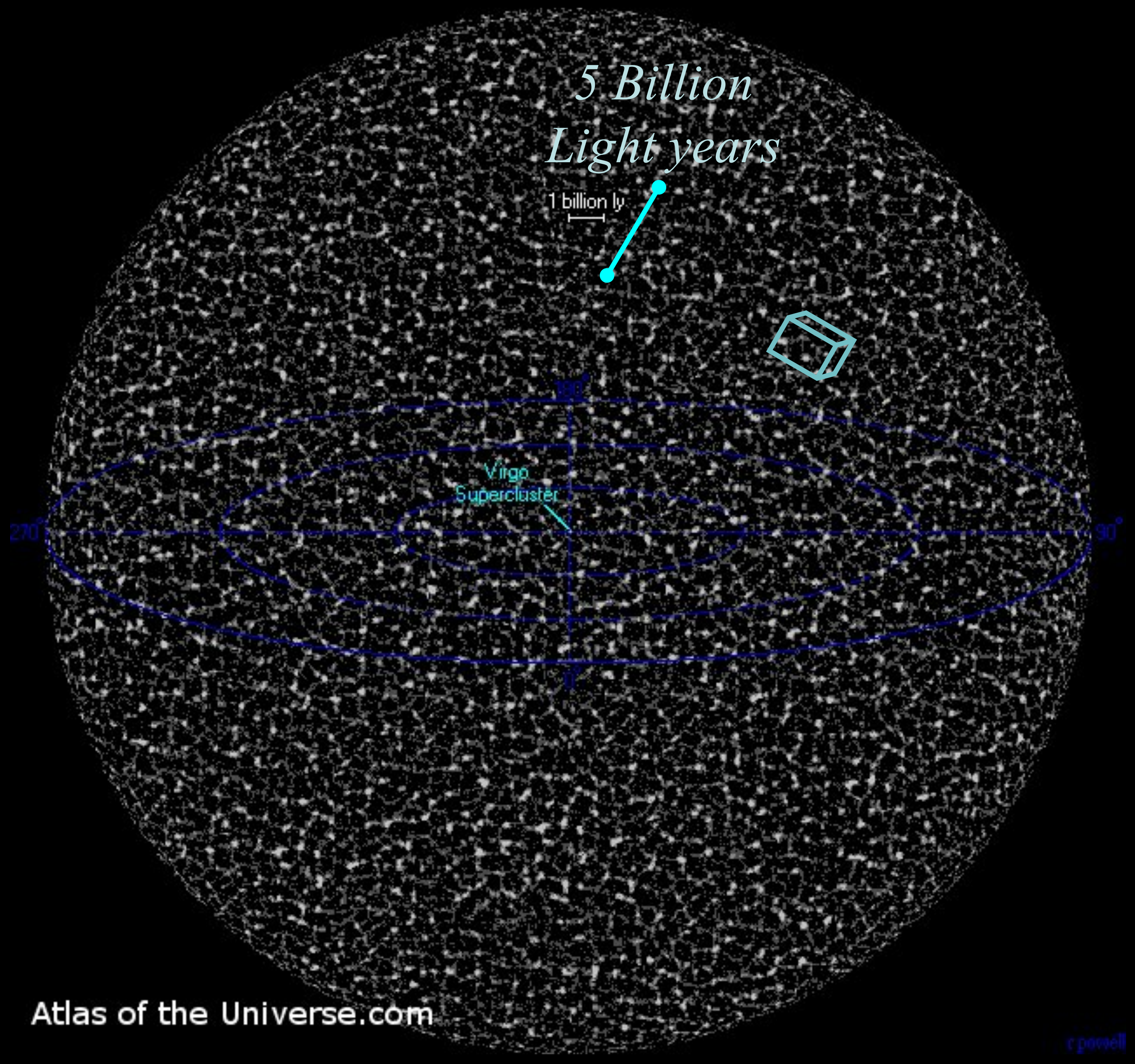
Andromeda Galaxy

The Realm of Cosmology

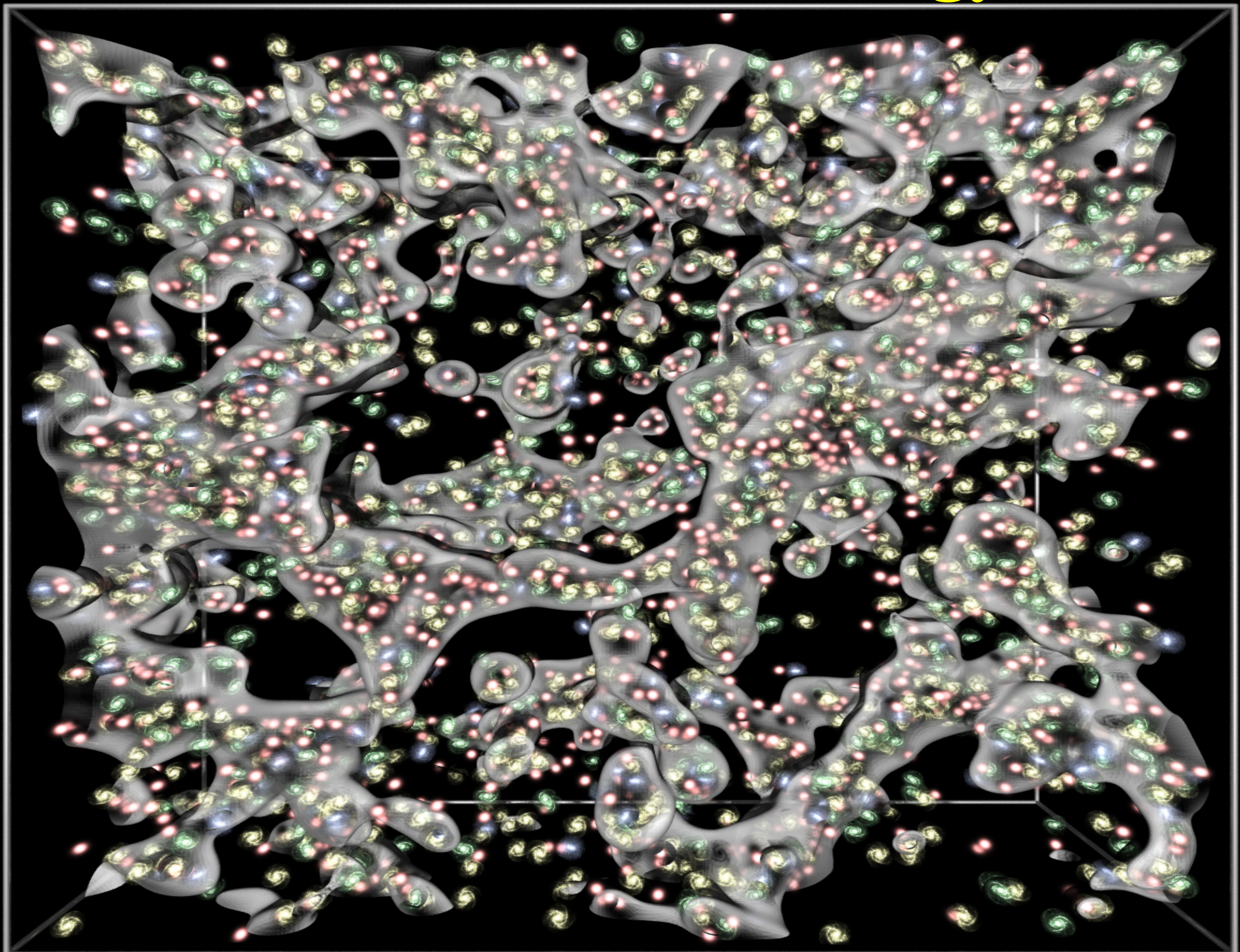
100 million Light years



The Realm of Cosmology



The Realm of Cosmology



How can we even hope to comprehend this immensely large & complex Universe !?!

Look for an appropriate simple model

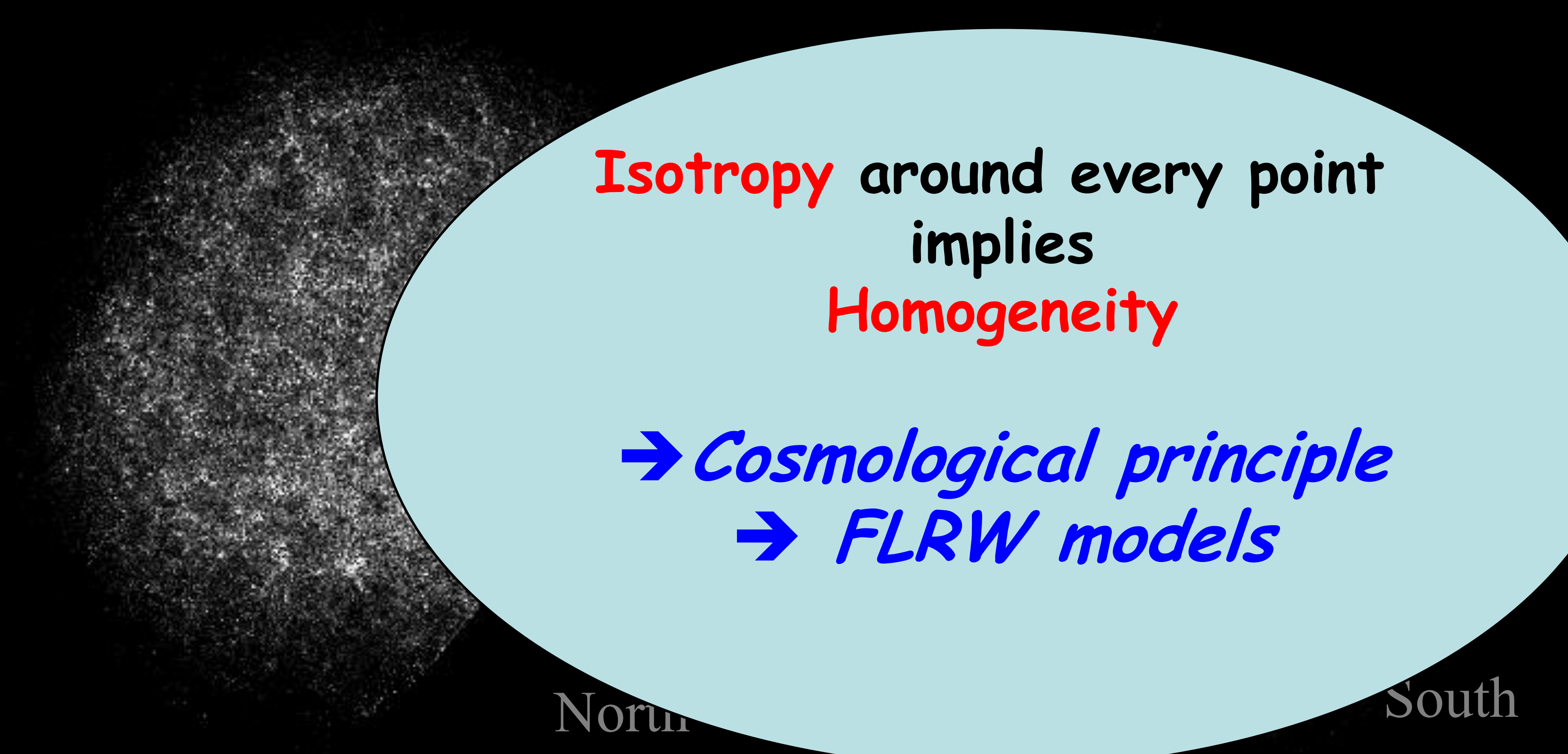
The Isotropic Universe

Distribution of galaxies on the sky is broadly isotropic

Isotropy around every point implies Homogeneity

➔ ***Cosmological principle***

➔ ***FLRW models***



Lick Observatory survey

The Expanding Universe

Einstein's *General relativity* applied to
an uniform distribution of matter
on cosmic scales
leads to a smooth

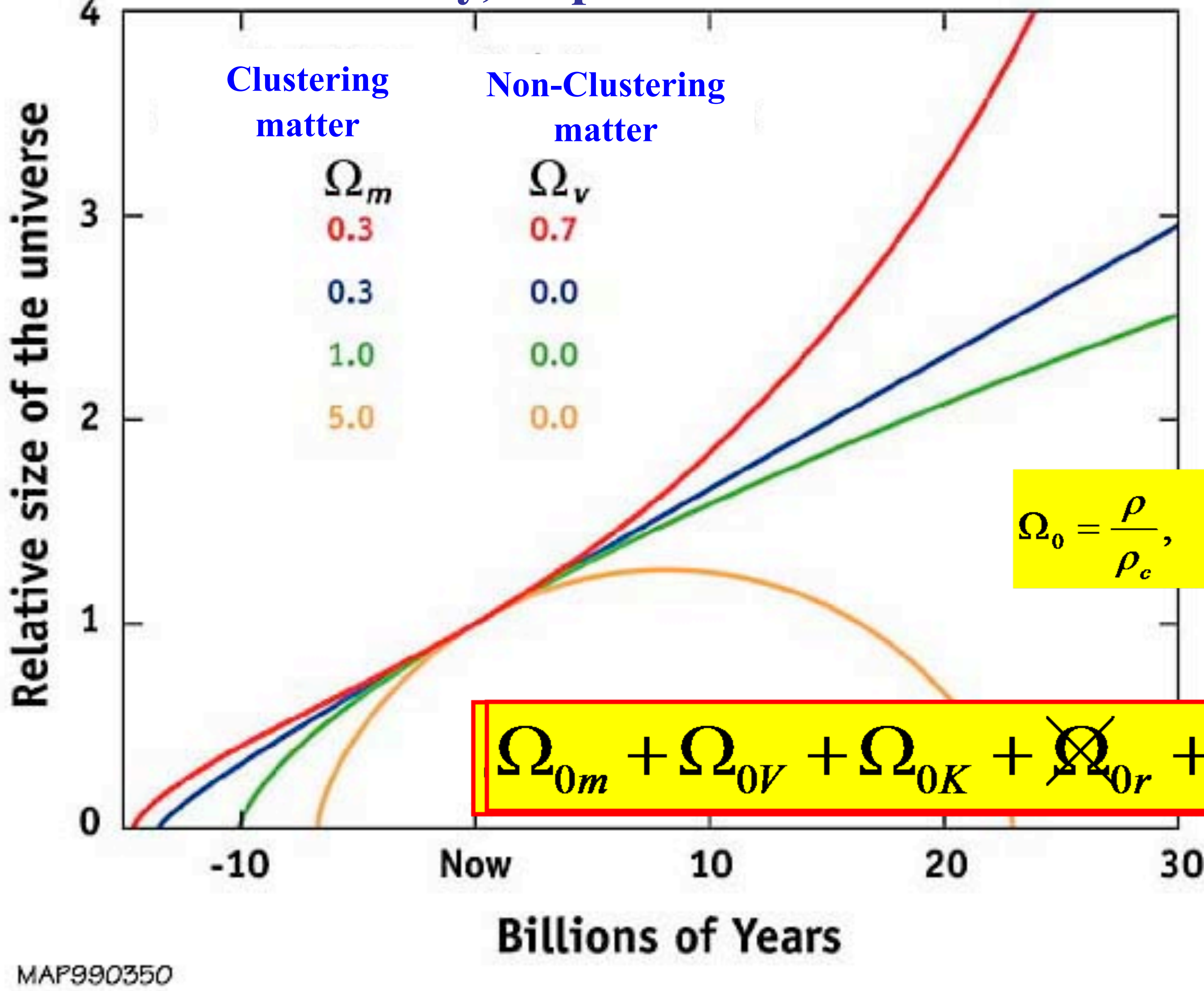
Present Expansion rate: $H_0 = 71 \quad km/s/Mpc.$

$$\Rightarrow \text{Critical density, } \rho_c = \frac{3H_0^2}{8\pi G} = 10^{-29}\,\text{gm/cm}^3$$

Fig.: Ned Wright

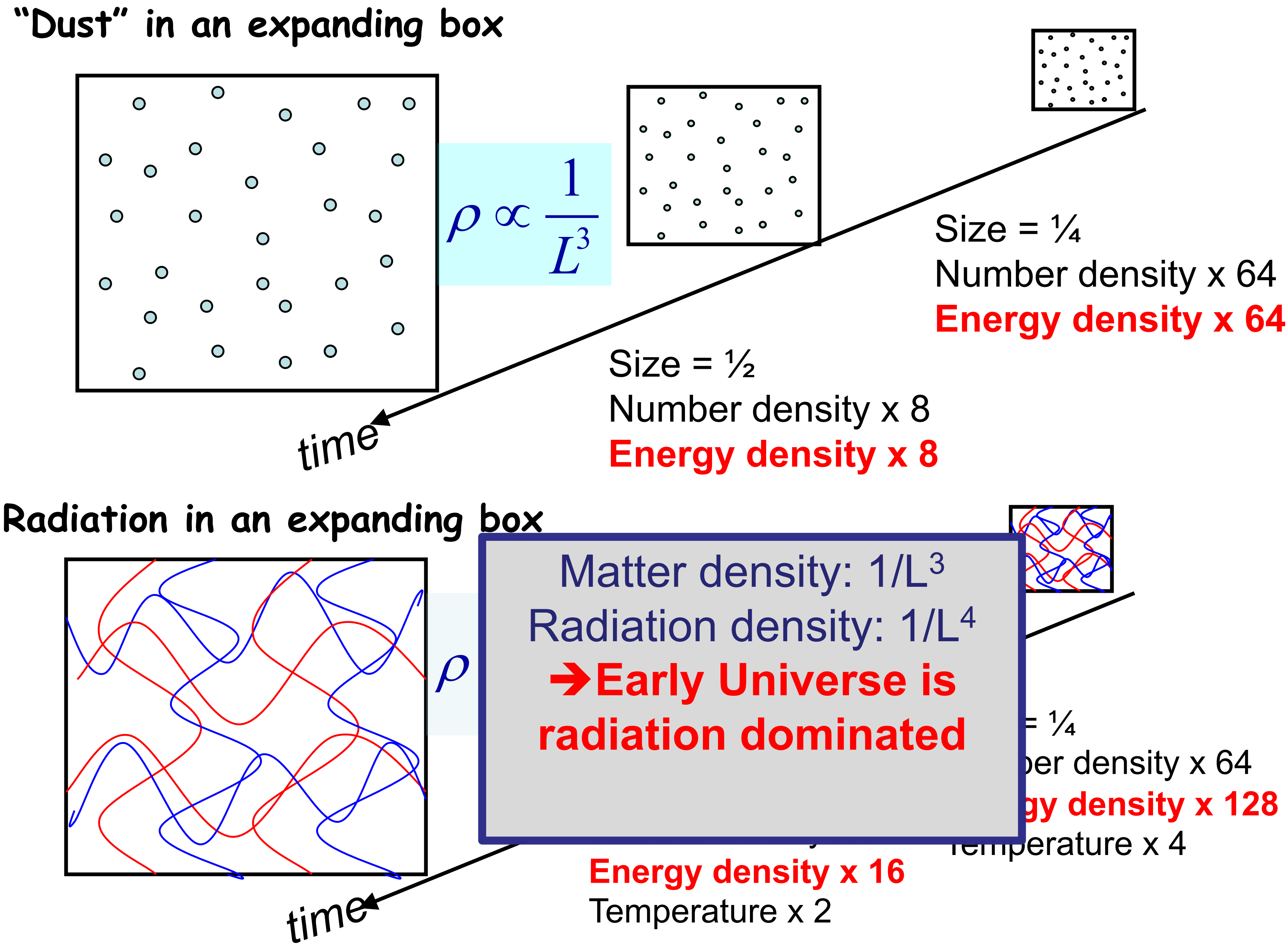
`Standard' cosmological model

Geometry, Expansion & Matter



$$\Omega_0 = \frac{\rho}{\rho_c}, \qquad \rho_c = \frac{3H^2}{8\pi G}$$

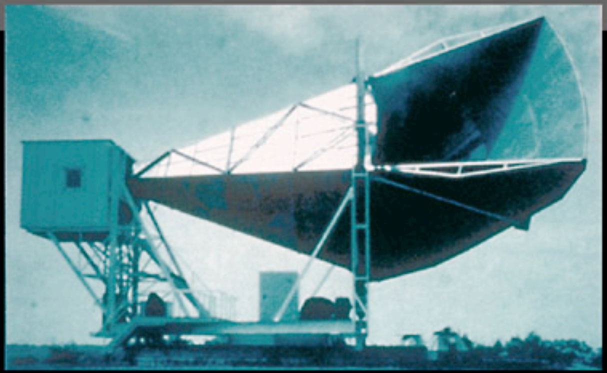
$$\boxed{\Omega_{0m} + \Omega_{0V} + \Omega_{0K} + \cancel{\Omega_{0r}} + \ldots = 1}$$

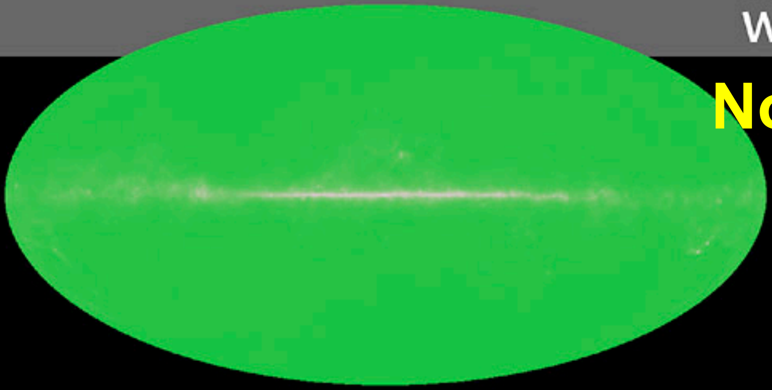


"Dust" in an expanding box
$\rho \propto \frac{1}{L^3}$
time
Size = ½
Number density x 8
Energy density x 8
Size = ¼
Number density x 64
Energy density x 64
Radiation in an expanding box
ρ
time
Energy density x 16
Temperature x 2
Matter density: $1/L^3$
Radiation density: $1/L^4$
➔Early Universe is radiation dominated

Where is all the Cosmic radiation ?

Cosmic Microwave Background





Nobel prize
1978

Serendipitous discovery of the **dominant** radiation content of the universe as an extremely **isotropic**, **Black-body** bath at temperature T_0=2.725 (+/-0.002)K .

“Clinching support for Hot Big Bang model”

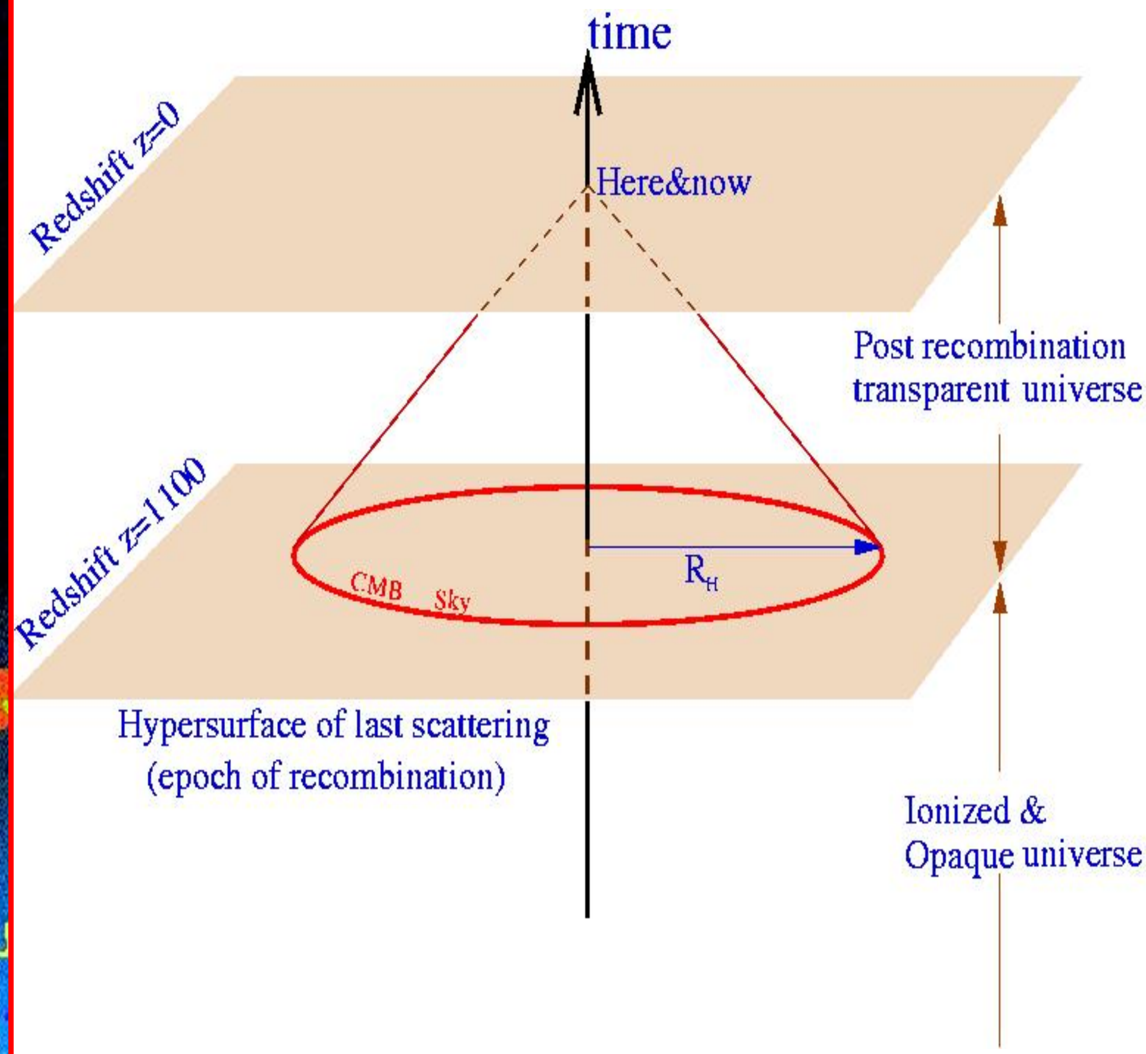
Cosmic Microwave Background

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

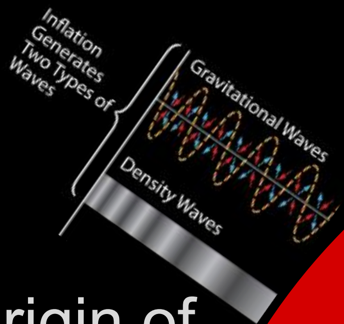
Post-recombination :Freely propagating through (weakly perturbed) homogeneous & isotropic cosmos.

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

(text background: W. Hu)

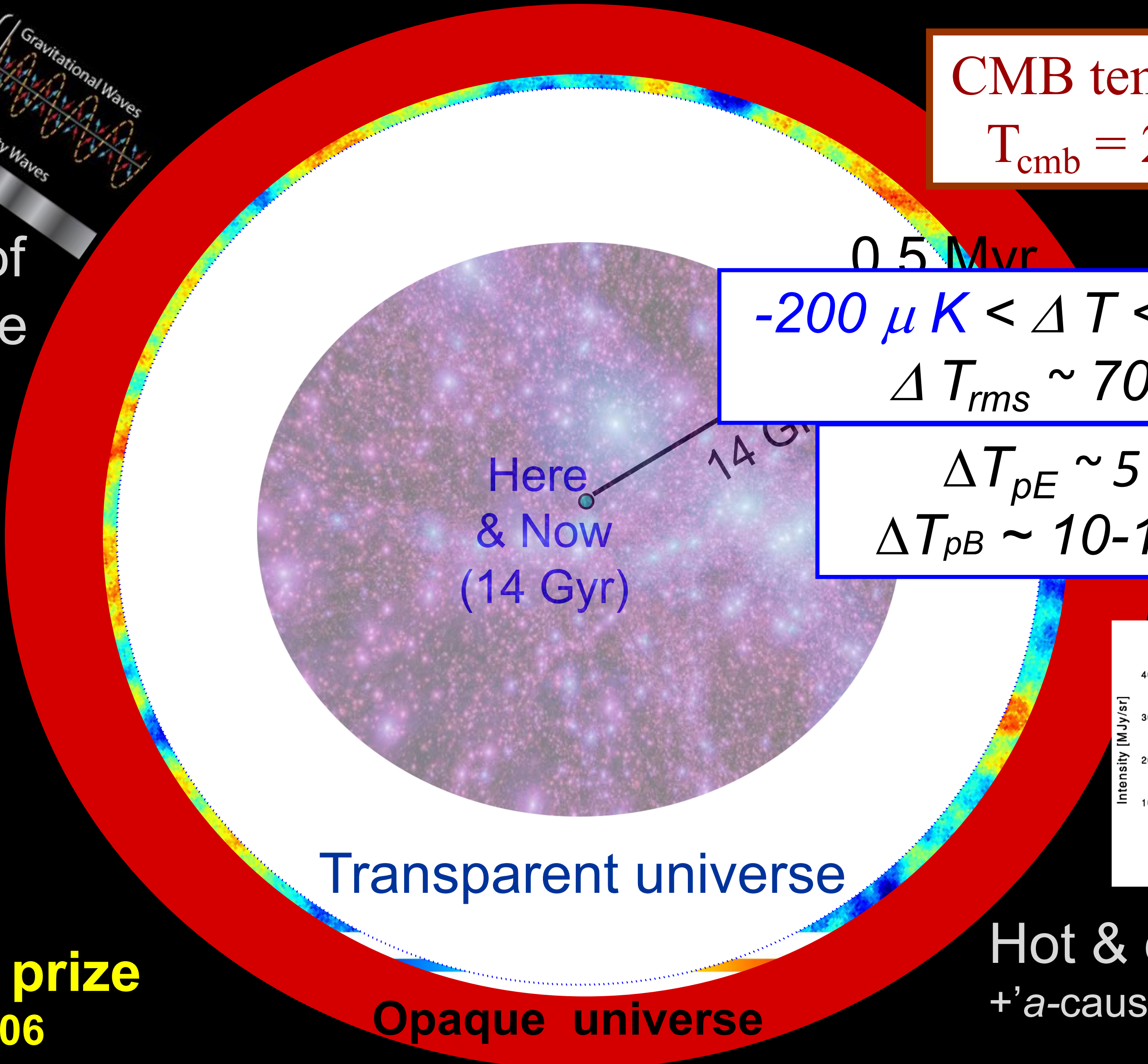


Cosmic "Super–IMAX" theater



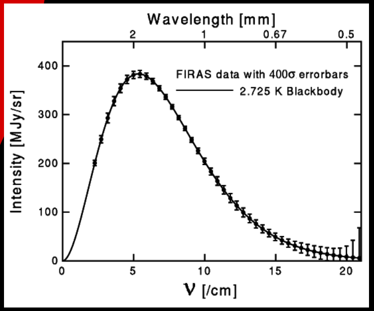
origin of structure

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

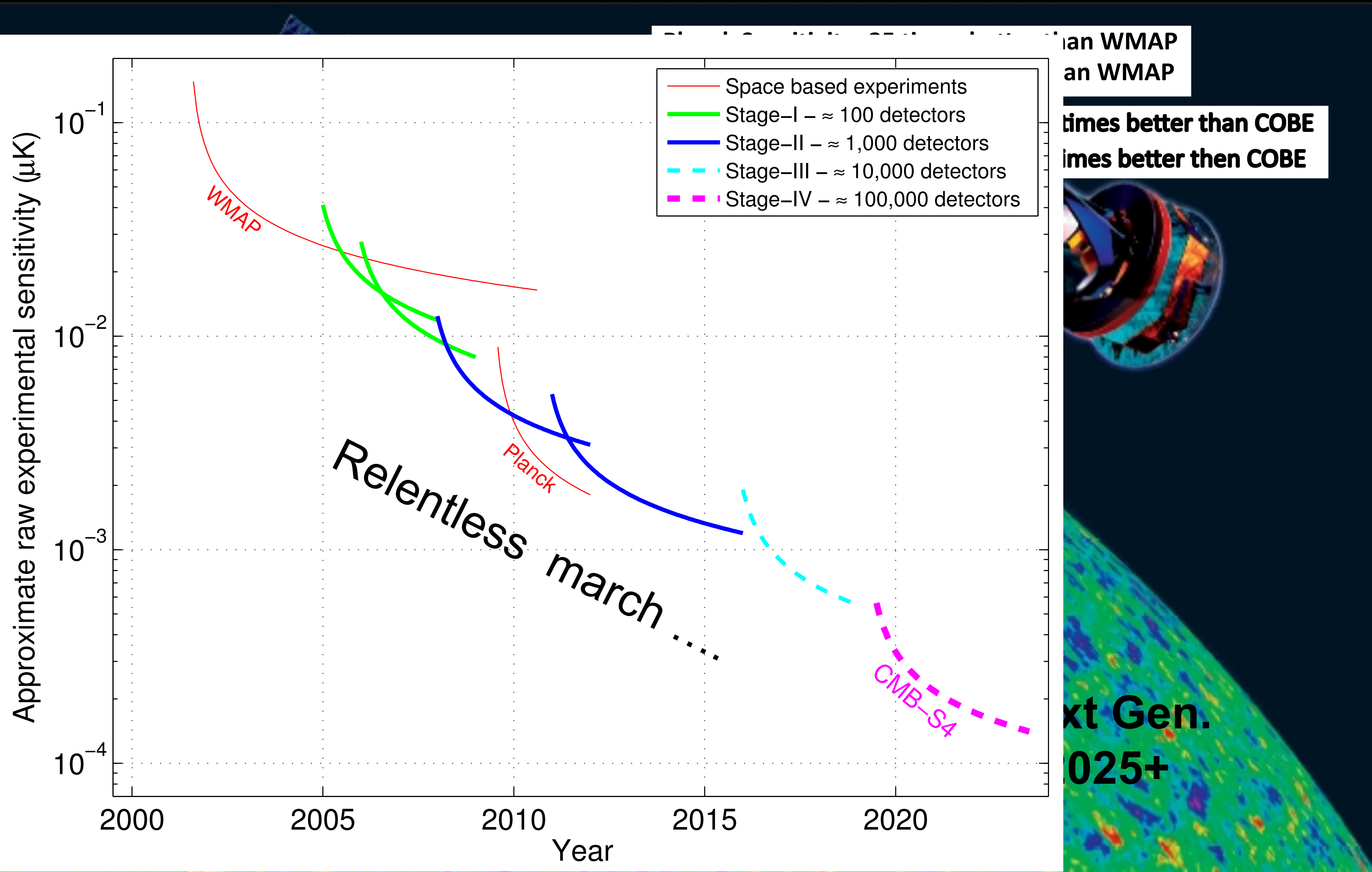


Hot & dense origin
+'*a*-causal' correlations

Nobel prize
2006

CMB measurements

1st, 2nd and the 3rd decade



CMB measurements

1st, 2nd and the 3rd decade

STANDARD MODEL OF COSMOLOGY (~few% level)

+ Establishing Fundamental Tenets

(WMAP, Planck : > 30K citation each → High scientific impact)

Background universe:

•Paradigm of Hot & Dense early Universe: *Absence of spectral distortions in CMB (COBE-FIRAS 1994), Cosmic thermal history*

•Isotropy of the Universe: *Statistical isotropy of CMB fluctuations*

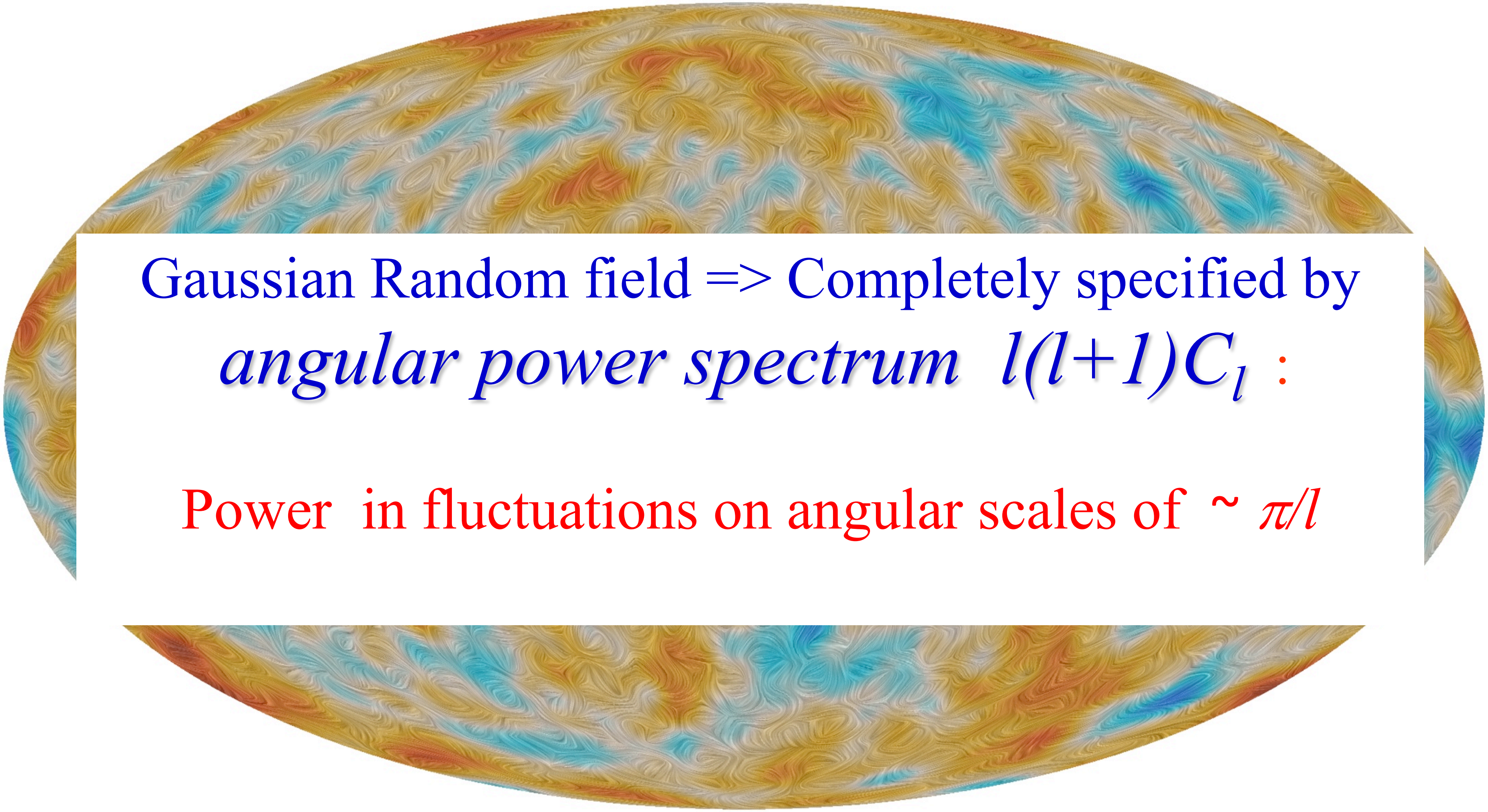
Perturbed universe:

•Paradigm of CMB fluctuations: *Acoustic phenomena in the pre-recombination Plasma universe established thru CMB Polarization*

•Paradigm of Structure formation: *Gravitational instability with adiabatic initial conditions established with Weak lensing of CMB, Baryon Acoustic Oscillations & CMB polarization*

•Paradigm of Initial conditions: *Indicative of simple Inflationary early Universe-- 'a-causal' scale of perturbations adiabatic initial conditions*

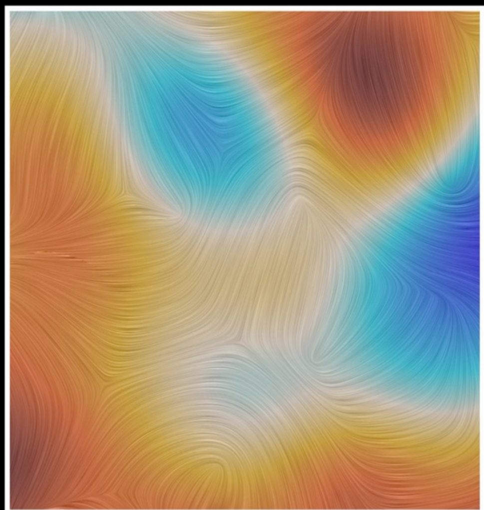
Planck sky maps



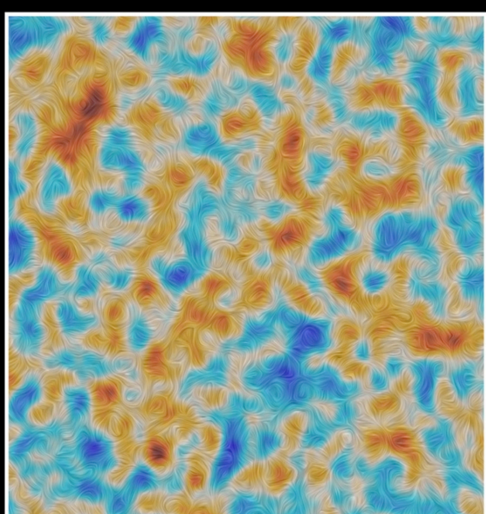
Gaussian Random field => Completely specified by *angular power spectrum* $l(l+1)C_l$:

Power in fluctuations on angular scales of $\sim \pi/l$

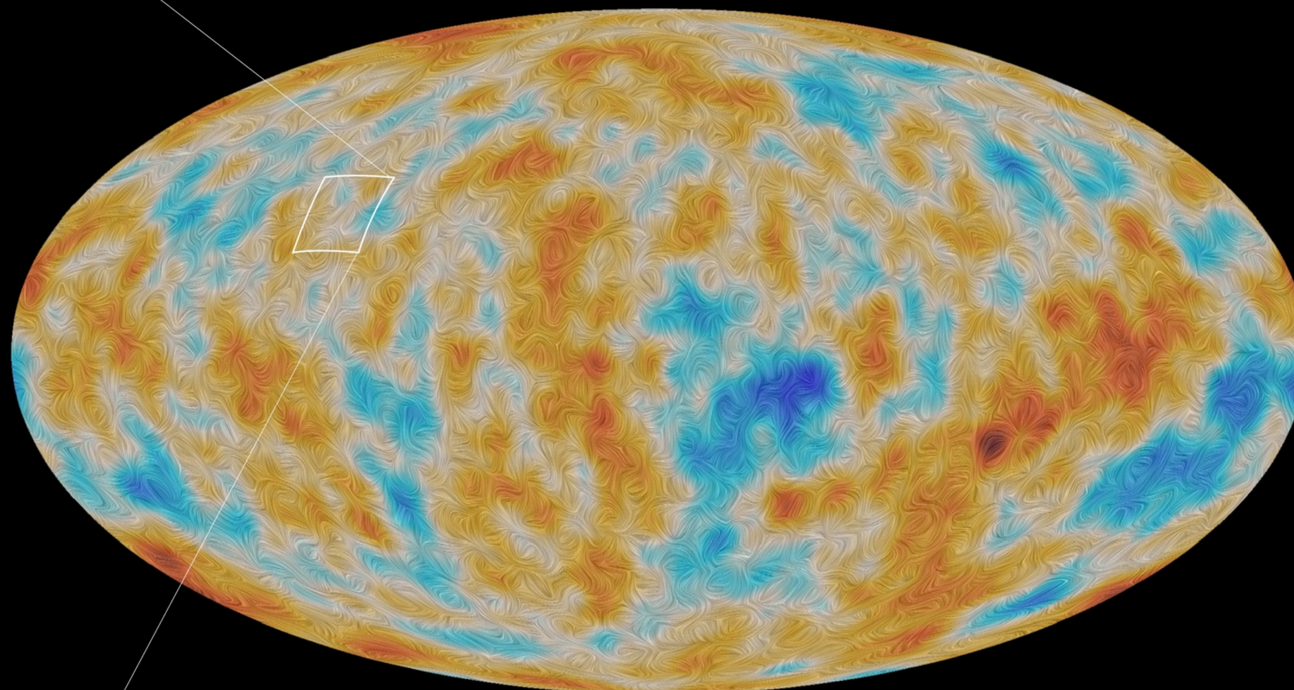
→ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 5 degrees



Filtered at 20 arcminutes



Full sky map
Filtered at 5 degrees

Planck Angular power spectrum

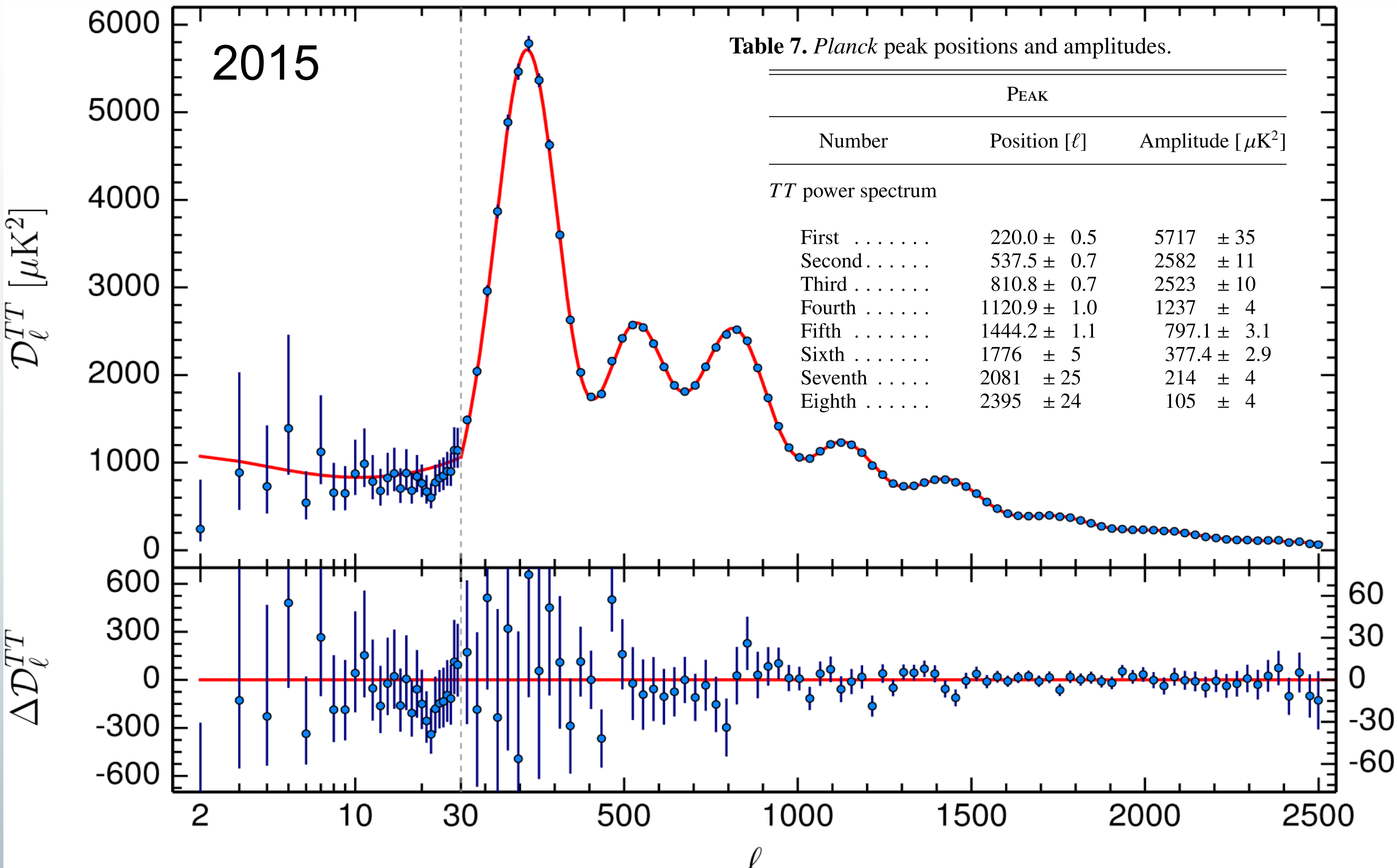
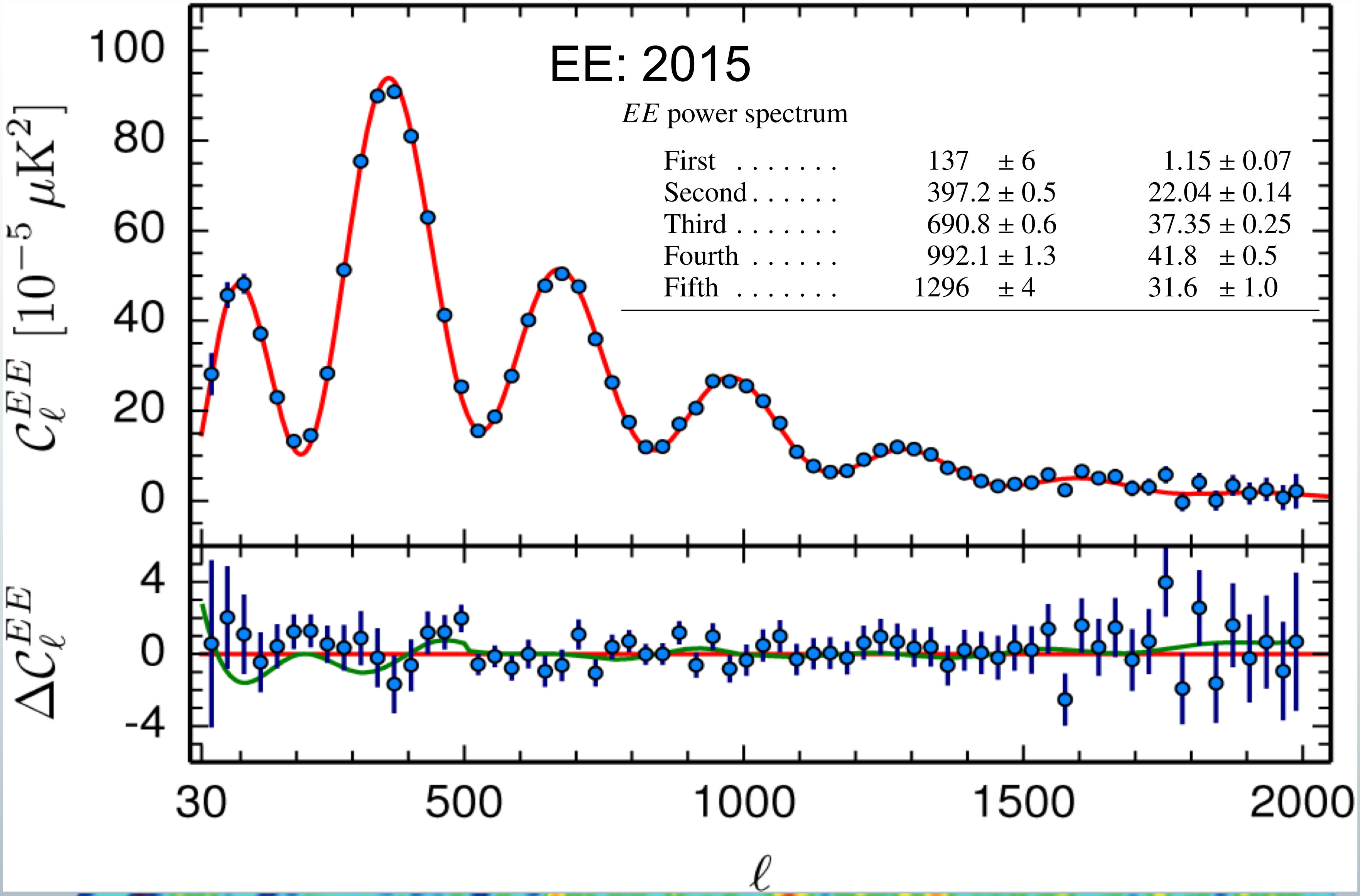
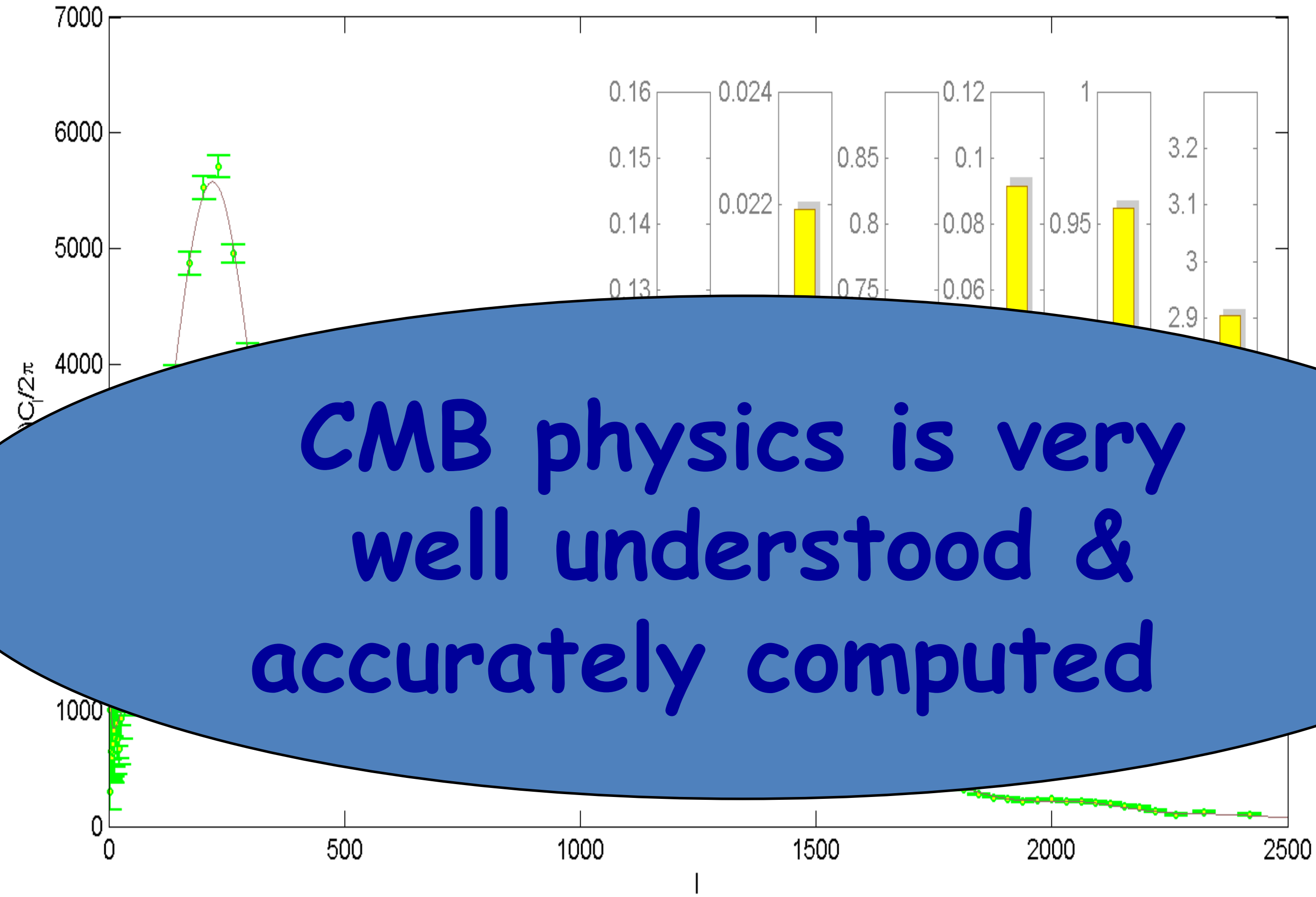


Table 7. *Planck* peak positions and amplitudes.

Number	Position [ℓ]	Amplitude [μK^2]
TT power spectrum		
First	220.0 ± 0.5	5717 ± 35
Second	537.5 ± 0.7	2582 ± 11
Third	810.8 ± 0.7	2523 ± 10
Fourth	1120.9 ± 1.0	1237 ± 4
Fifth	1444.2 ± 1.1	797.1 ± 3.1
Sixth	1776 ± 5	377.4 ± 2.9
Seventh	2081 ± 25	214 ± 4
Eighth	2395 ± 24	105 ± 4

Planck CMB Polarization spectra



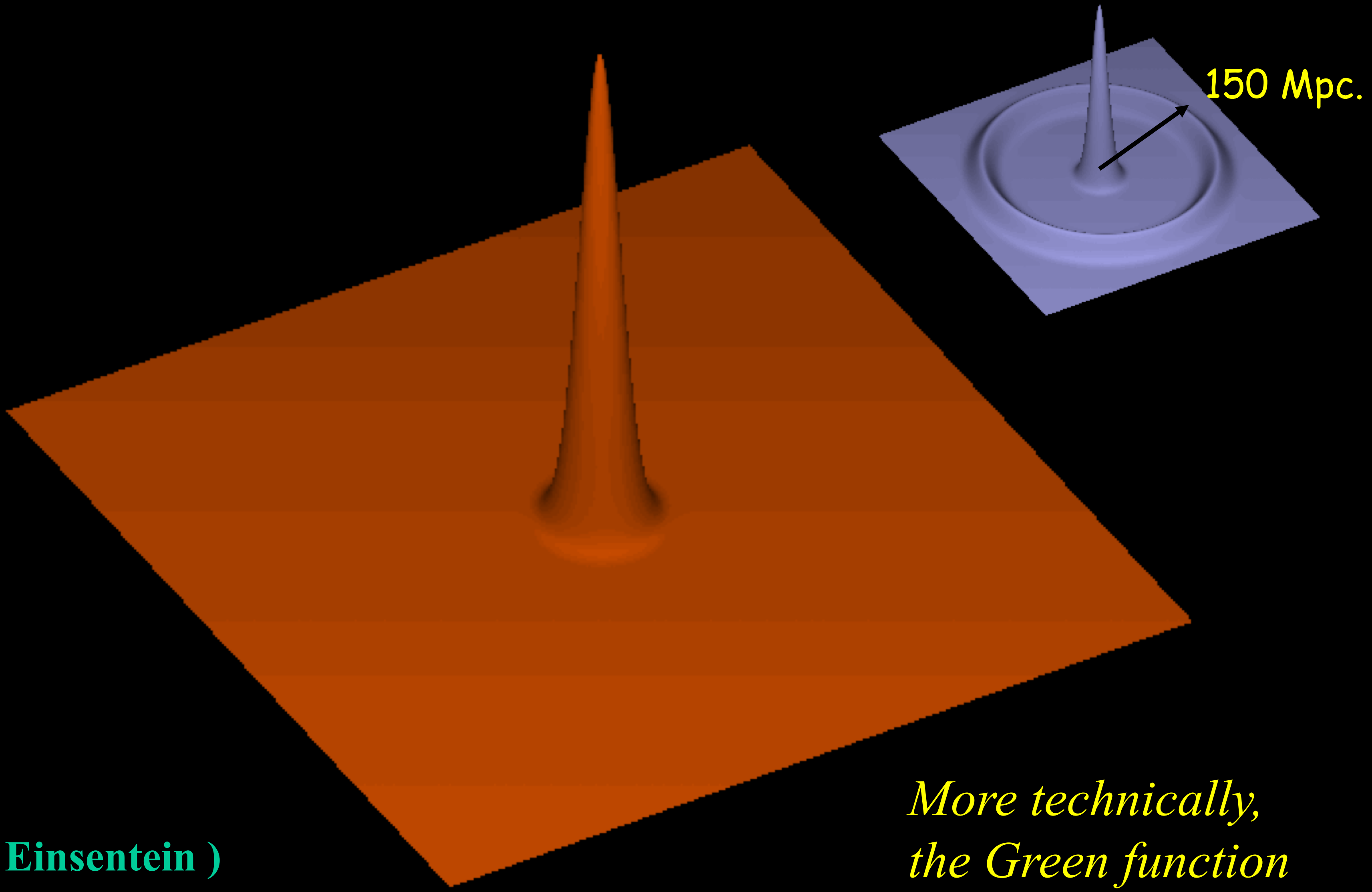


CMB physics is very well understood & accurately computed

CMB@IUCAA: CMBAns Boltzmann code by Santanu Das

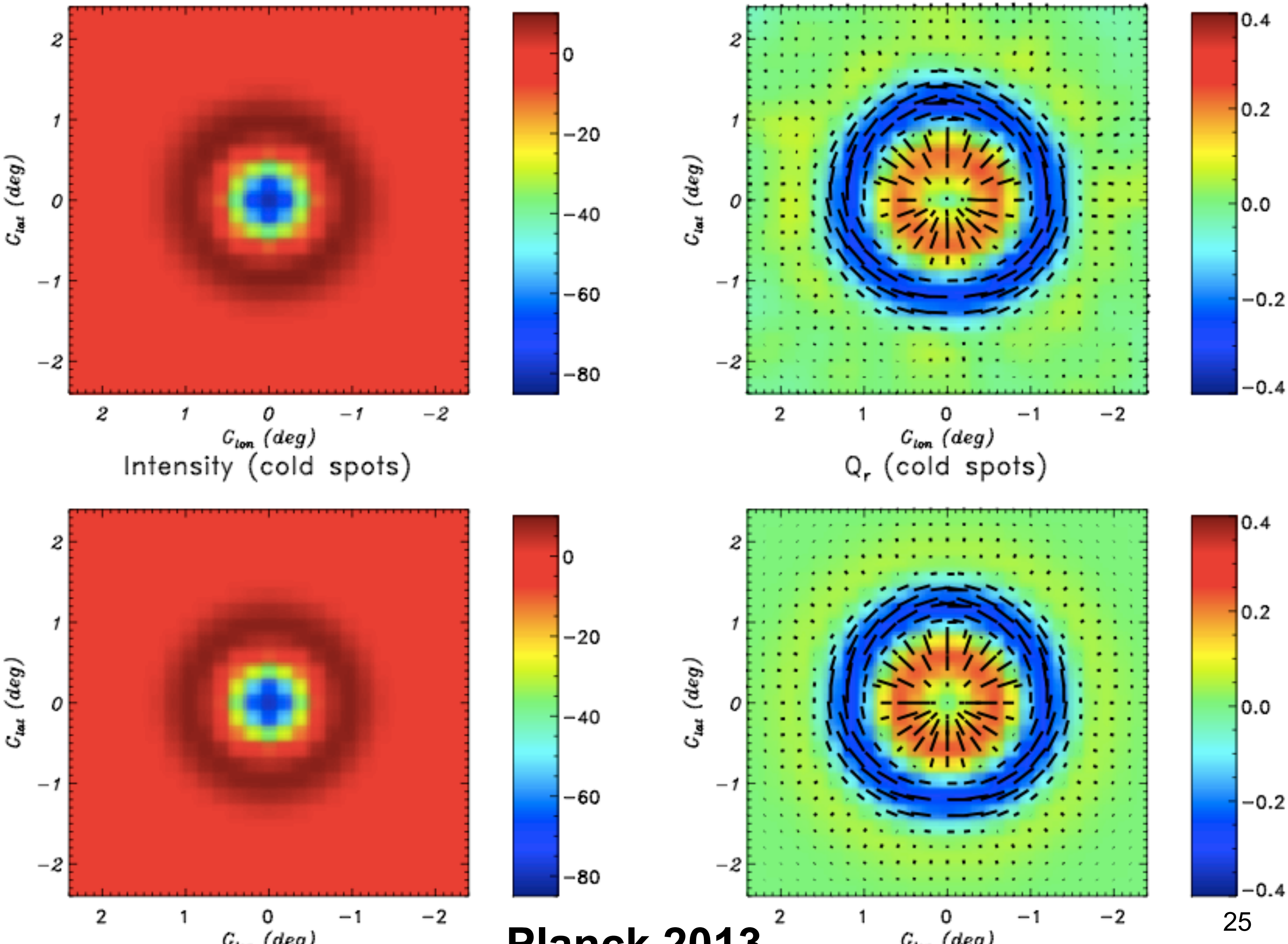
Music of the Cosmic Drum

Ping the 'Cosmic drum'



More technically,
the Green function

(Fig: Einsentein)



Planck 2013

CMB Angular power spectrum

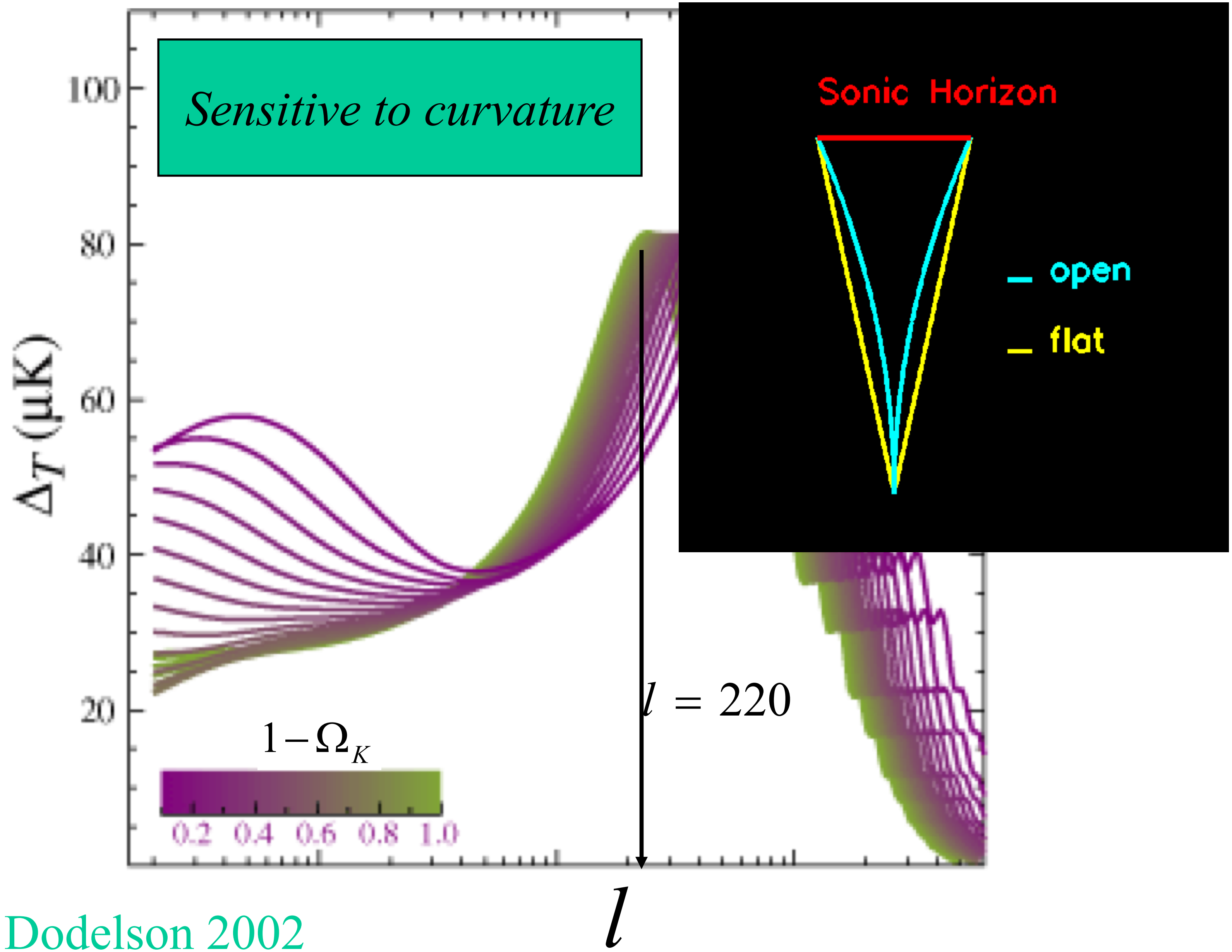


Fig:Hu & Dodelson 2002

CMB Angular power spectrum

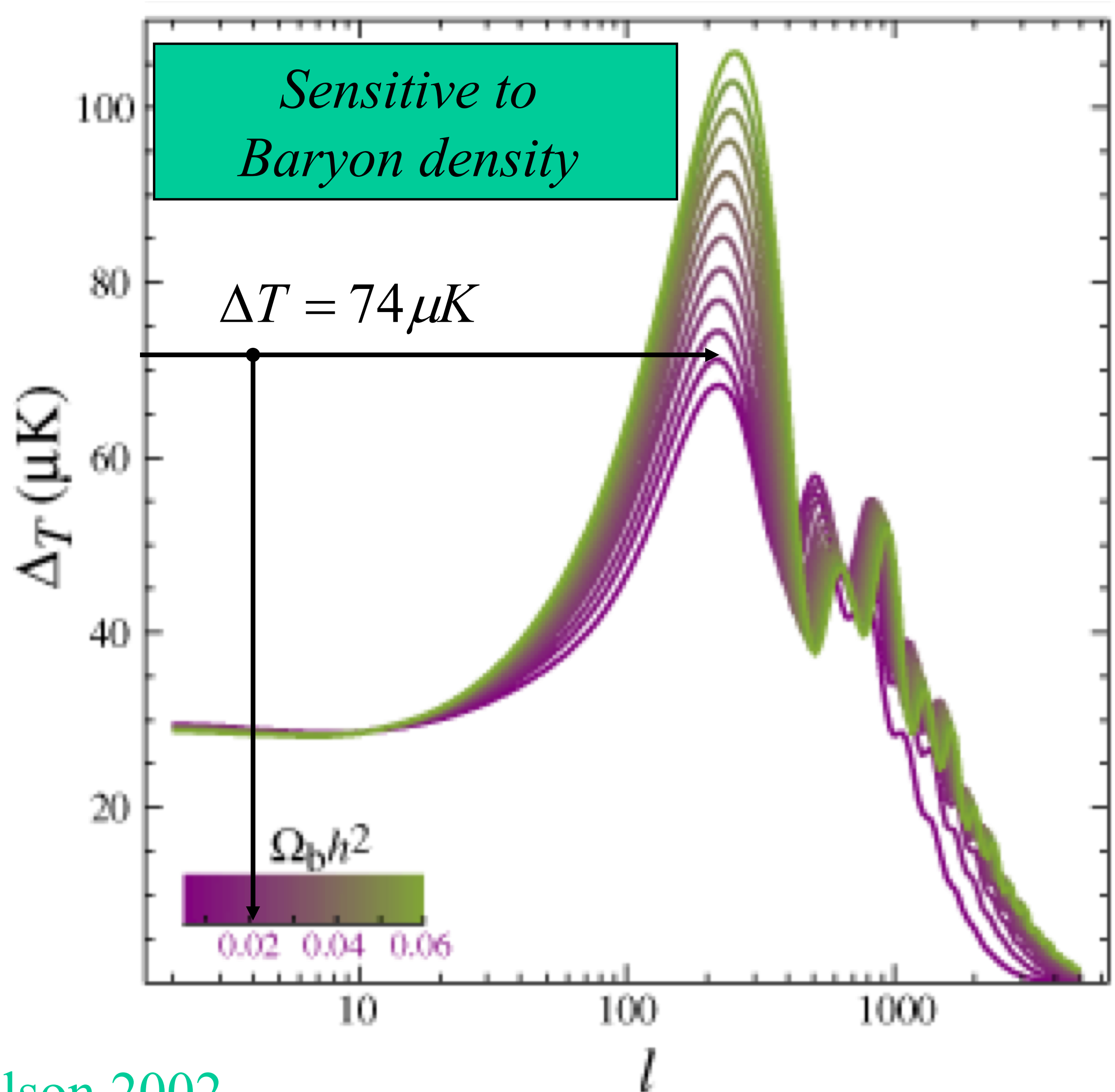
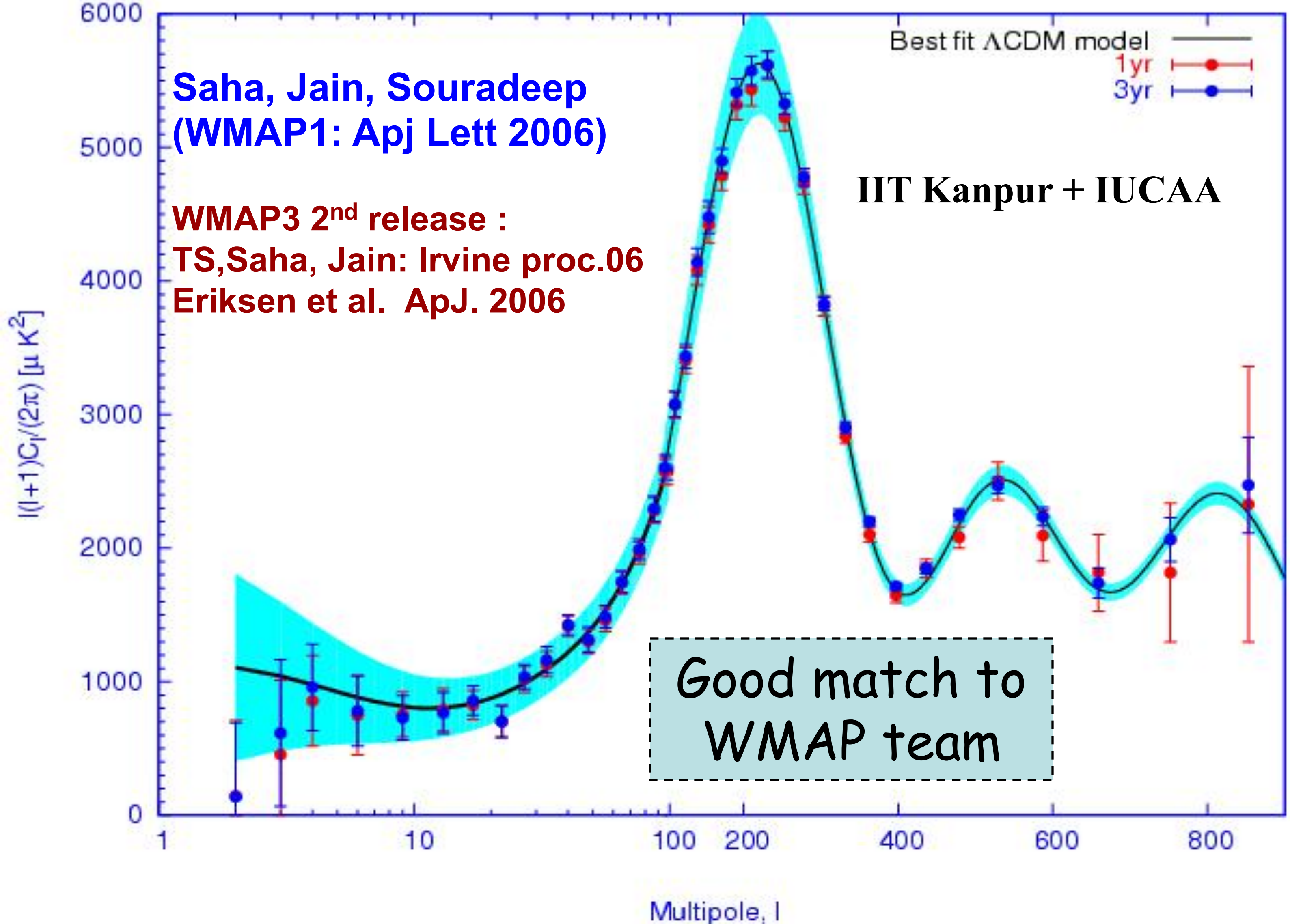


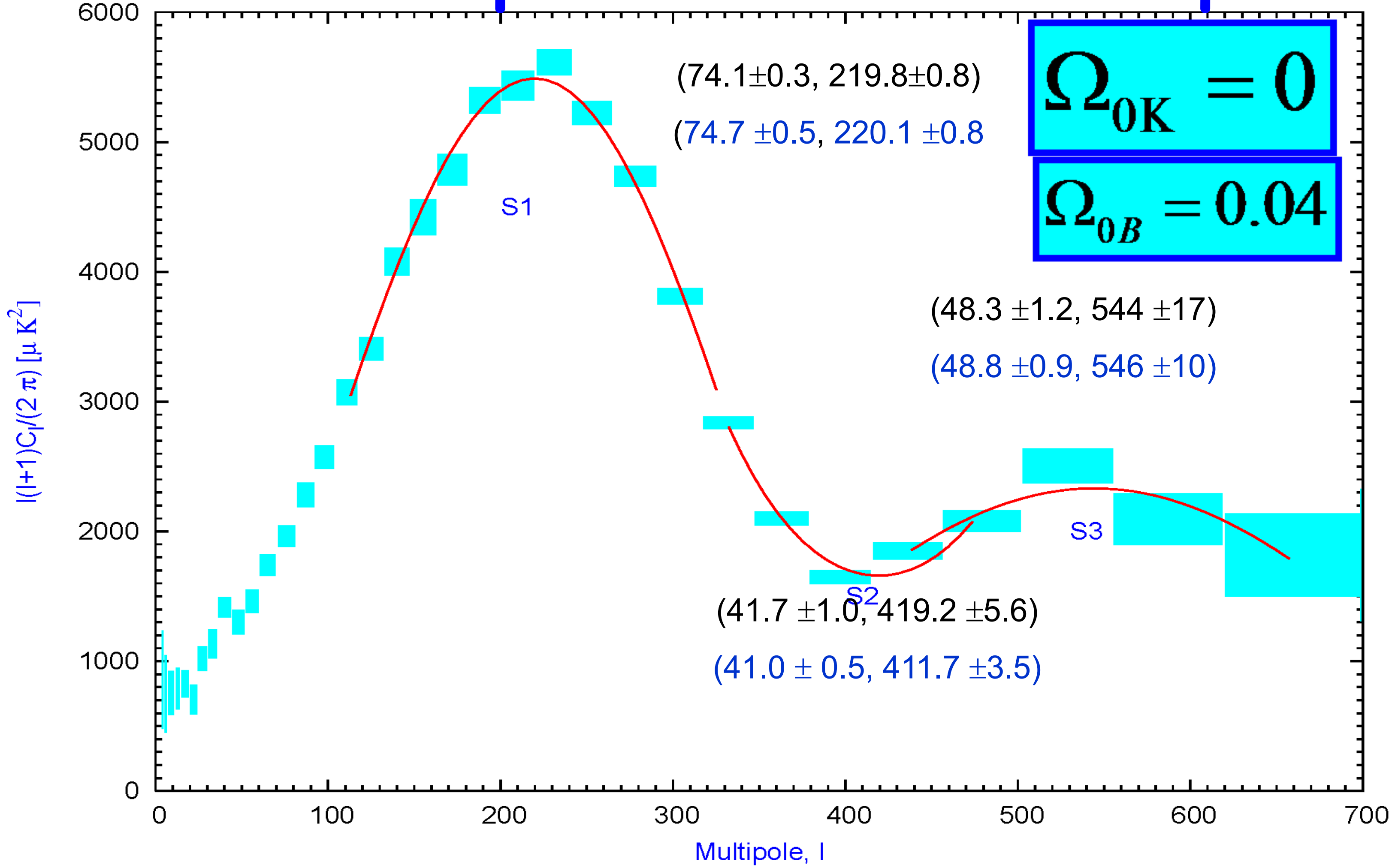
Fig:Hu & Dodelson 2002

WMAP: Angular power spectrum

Independent, **self contained** analysis of WMAP multi-frequency maps



Characteristic size & amplitude of hot/cold spots in the CMB map



(Saha, Jain, Souradeep Apj Lett 2006)

Cosmological Parameters

6-Parameter ΛCDM

Parameter	*Planck* TT+lowP+lensing	
$\Omega_b h^2$	0.02226 ± 0.00023	1%
$\Omega_c h^2$	0.1186 ± 0.0020	1.7%
$100\theta_{MC}$	1.04103 ± 0.00046	0.04%
τ		
r_{drag} . . .		
k_{eq}	0.01027 ± 0.00014	1.4%

'Standard' cosmological model:

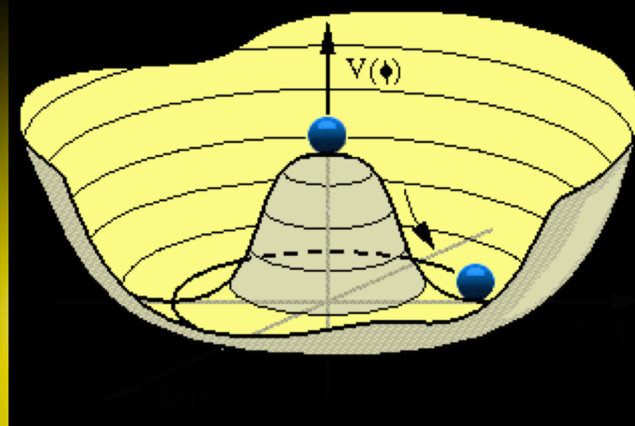
Flat, ΛCDM with nearly

Power Law (PL) primordial power spectrum

Simple… yet, an exotic universe

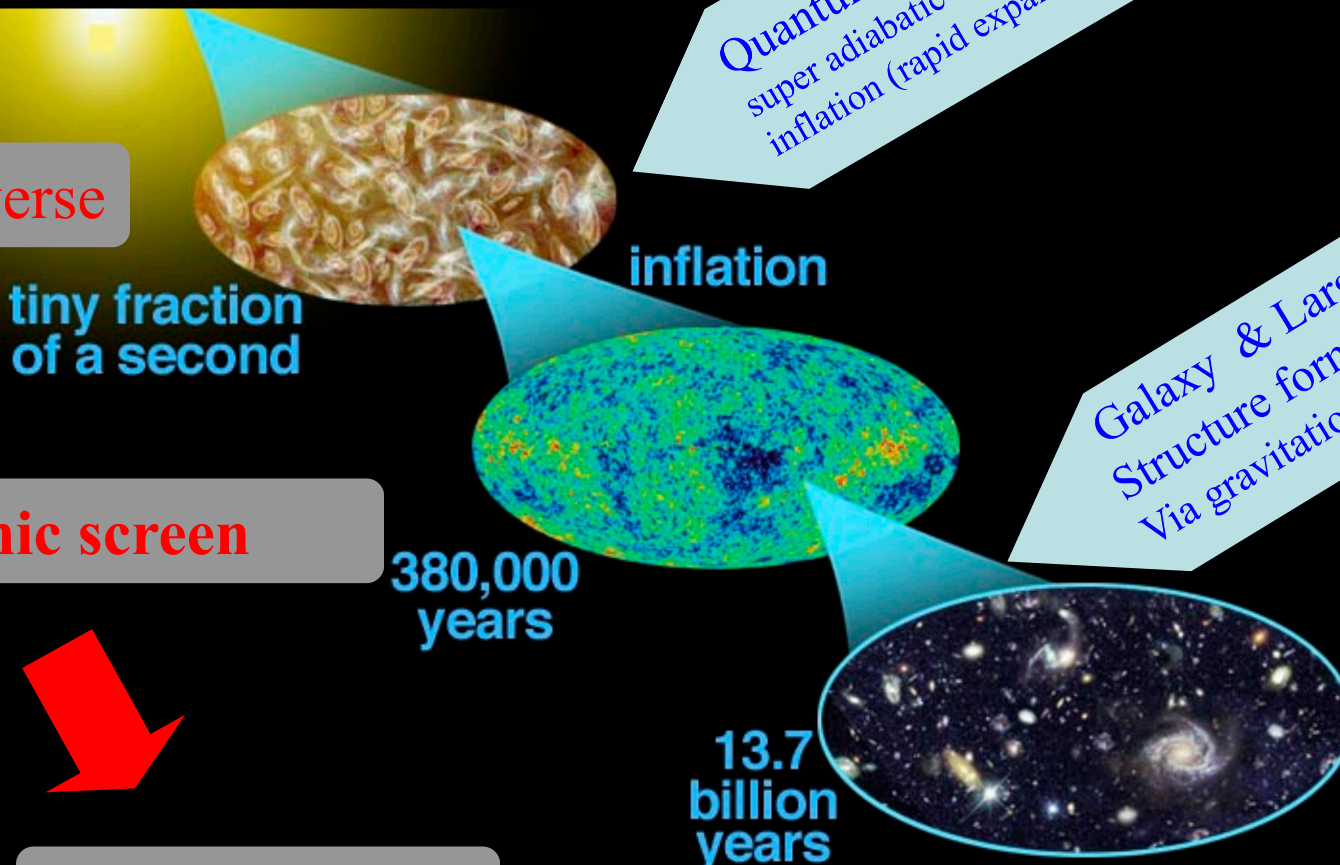
- 95% of the energy of the universe is in some exotic form
- Dark Matter: we cannot see it directly, only via its gravitational affect.
- Dark Energy: smooth form of energy which acts repulsively under gravity.
- Some new Ultra-high energy (possibly, fundamental) physics for generating primordial perturbations.

Who pinged the Cosmic drum ?



Quantum fluctuations
super adiabatic amplified by
inflation (rapid expansion)

Early Universe



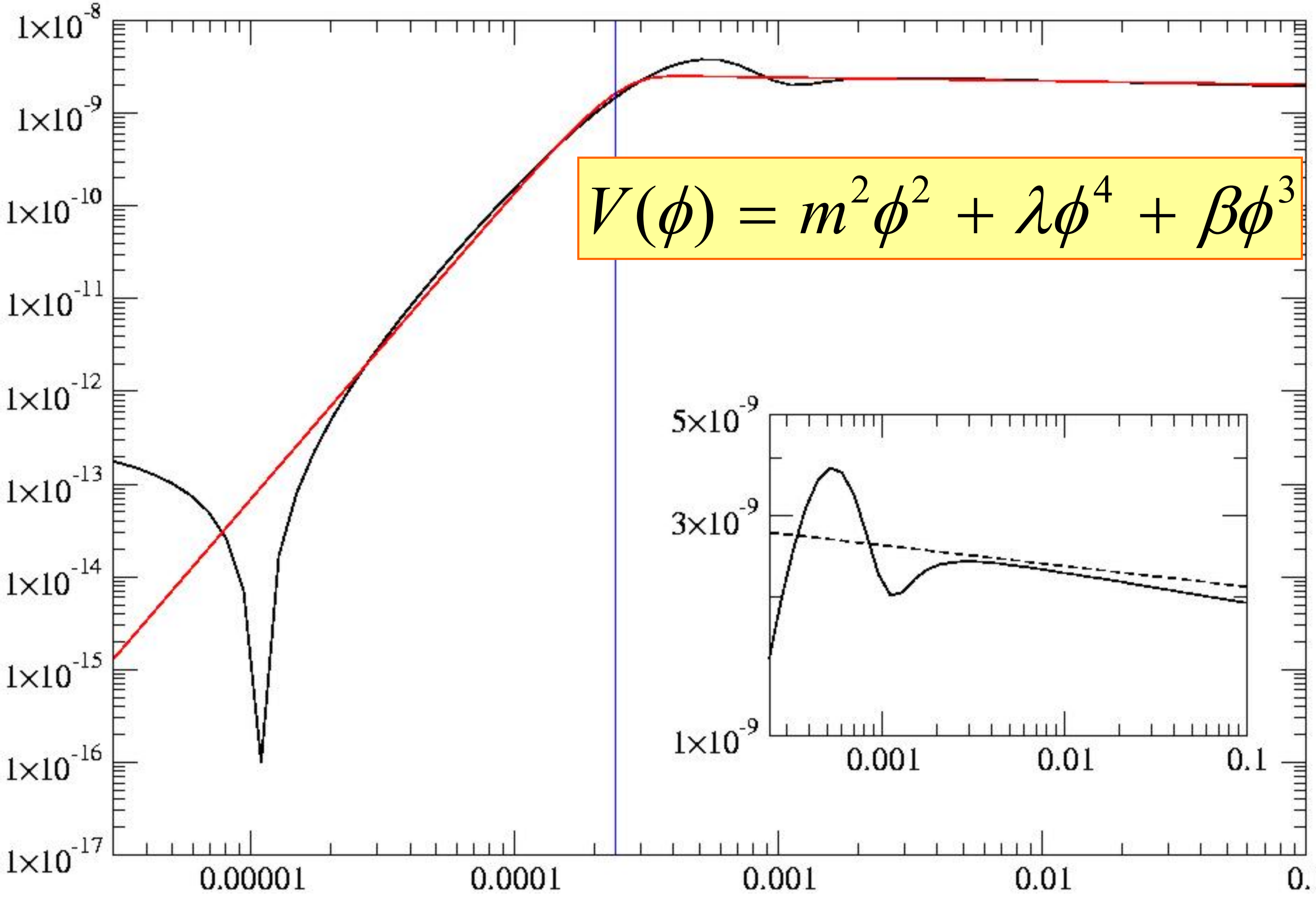
Galaxy & Large scale
Structure formation
Via gravitational instability

The Cosmic screen

Present Universe

Punctuated inflation

(R. Jain, Chingangbam, Gong, Sriramkumar, TS: JCAP 2009)



Early Universe in CMB

The Background universe

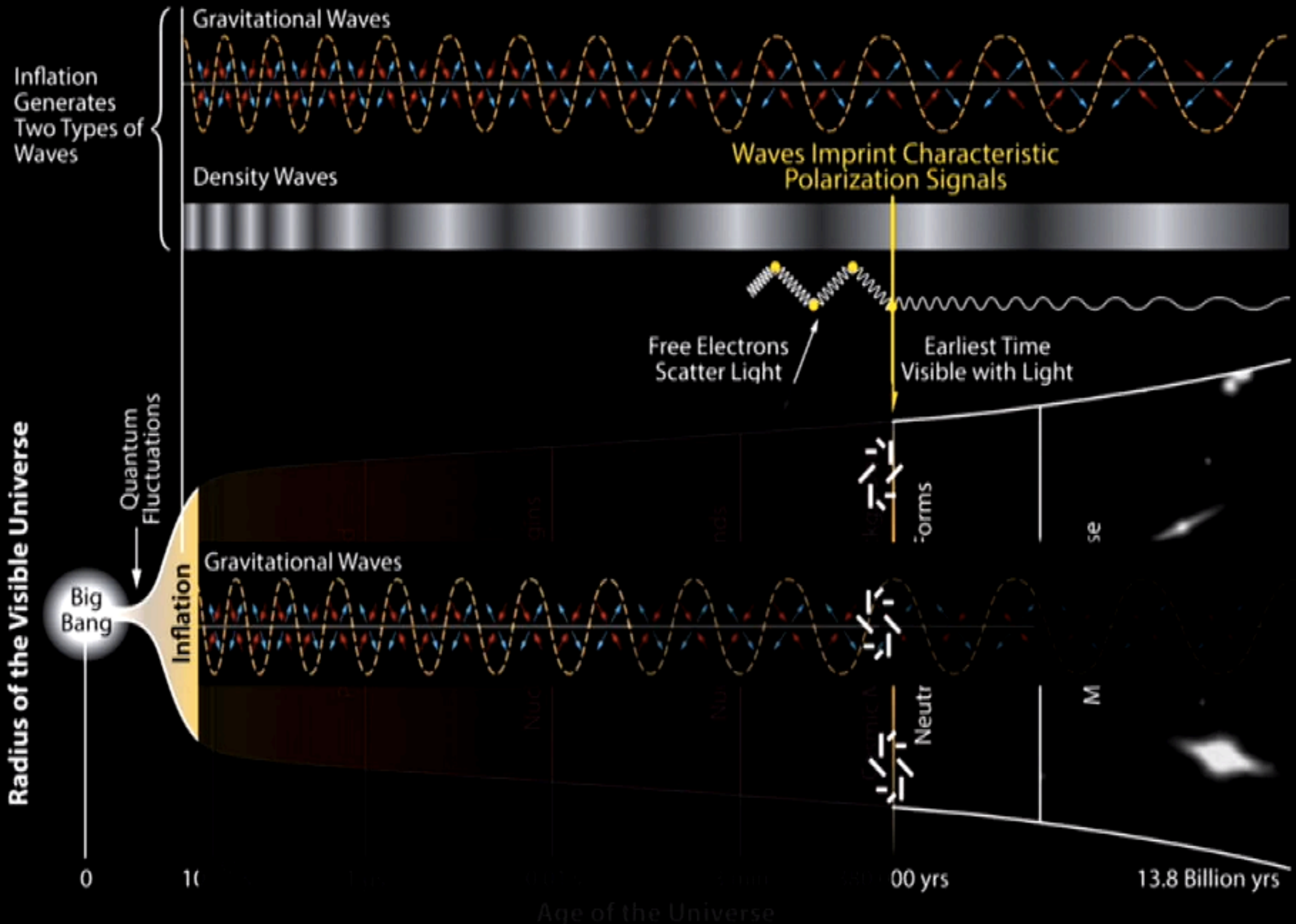
- Homogeneous & isotropic space: ***Cosmological principle***
- Flat (Euclidean) Geometry

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***

History of the Universe



Cosmic GW background From Inflation

Each polarization of Graviton behaves like a
Massless Mi ... lar field
(a

To/Must-Do for cosmology !!!!

a ... GW

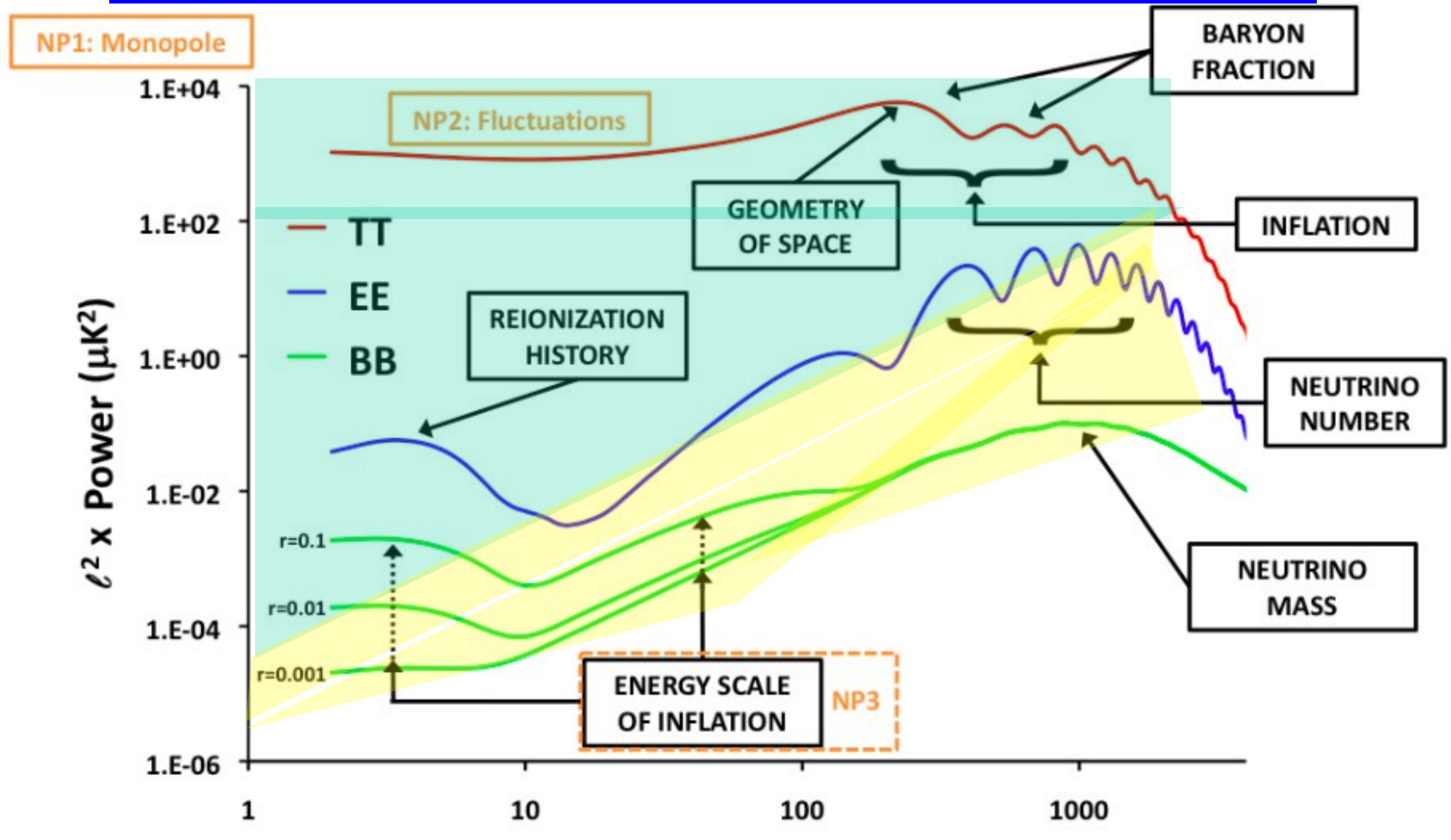
Ratio of GW/Density perturbation:
r ~ Energy scale of inflation

Currently, r < 0.07

Cosmic Information in CMB

Temperature anisotropy T + two polarization modes E&B

Four CMB spectra : $C_l^{TT}, C_l^{EE}, C_l^{BB}, C_l^{TE}$



CMB-Bhārat: a new Indian quest

भारत

CMB BHĀRAT: AN INDIAN COSMOLOGY CONSORTIUM

Proposal to ISRO: Exploring Cosmic History & Origin (ECHO)

A multifaceted frontier science and astronomy mission

- map sky temperature, linear polarization (~60-1000 GHz),
- Multi-frequency (20+) → Spectral science
- unprecedented sensitivity, accuracy and angular resolution.

Quest for Primordial Gravitational waves

- ***A "near-ultimate" CMB polarisation survey***
  (2μK.arcmin sensitivity, 22 bands in 60-900 GHz)
- ***CMB Spectral capability*** *(x 100 COBE-FIRAS)*

Scientific promise:

•ULTRA- HIGH: Reveal signature of quantum gravity and ultra-HEP in the very early universe Nobel category

GW of Quantum Origin *(LIGO detection: classical GW)*

•HIGH Goals: Neutrino physics: number of species, total mass and hierarchy; Map all dark matter and most baryons in the observable universe

•Legacy : Improve probe of cosmological model by a factor of > 10 million; Rich Galactic and extra Galactic Astrophysics datasets

•Unexpected Discovery space: Unique probe of 'entire'($z<2\ x10^6$) thermal history of the universe

Balanced Impact-Returns profile

Science

Path-breaking

High value

Legacy

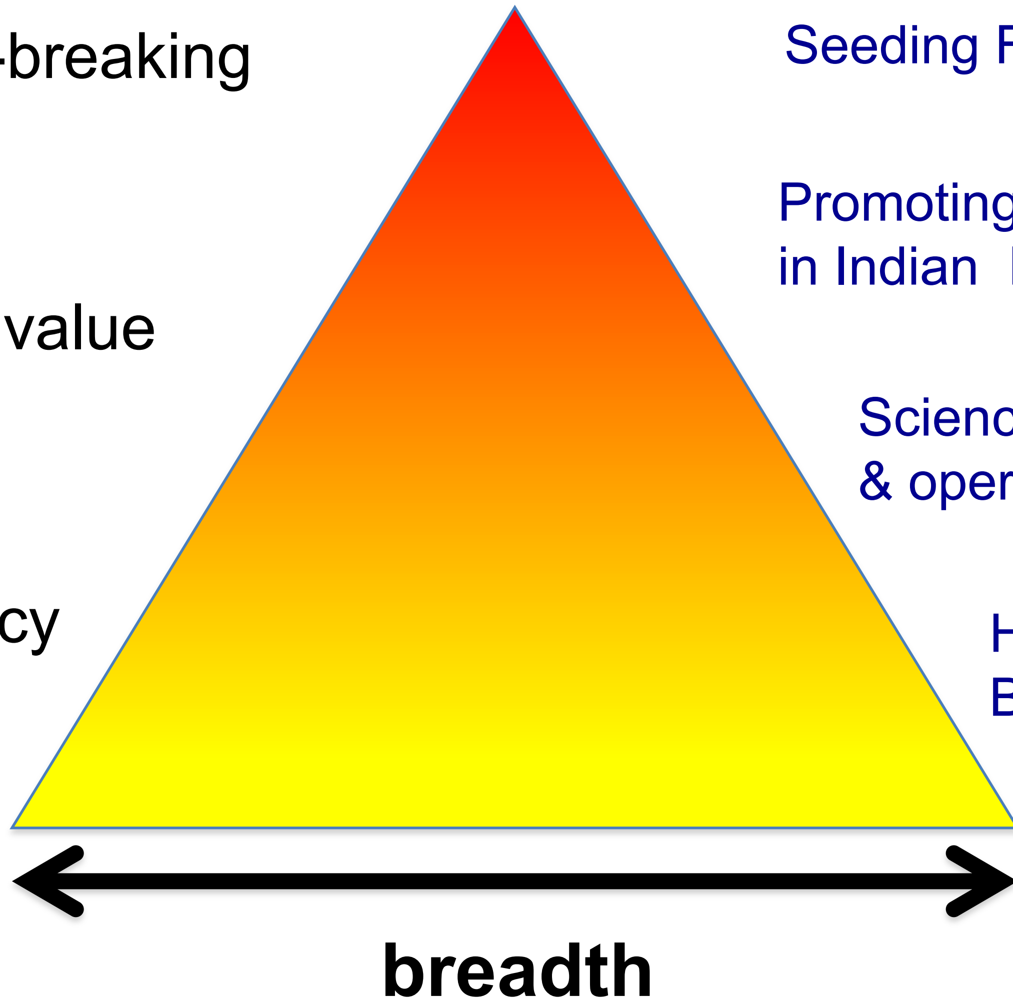
Technology

Seeding Frontier programs

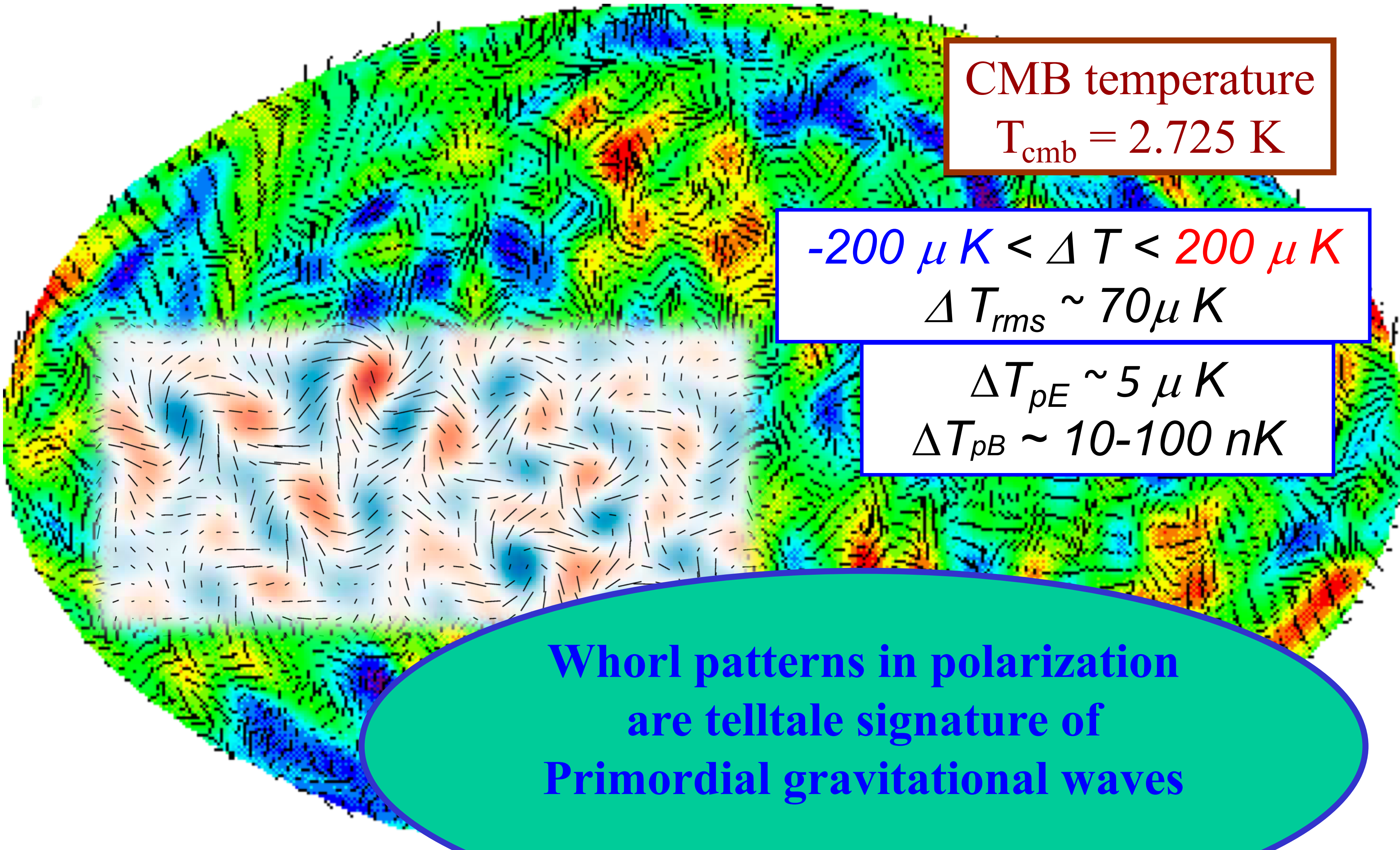
Promoting nascent technology in Indian Labs & Industry

Science mission planning & operation at L2

HPC, IT and Big-data



CMB Anisotropy & Polarization



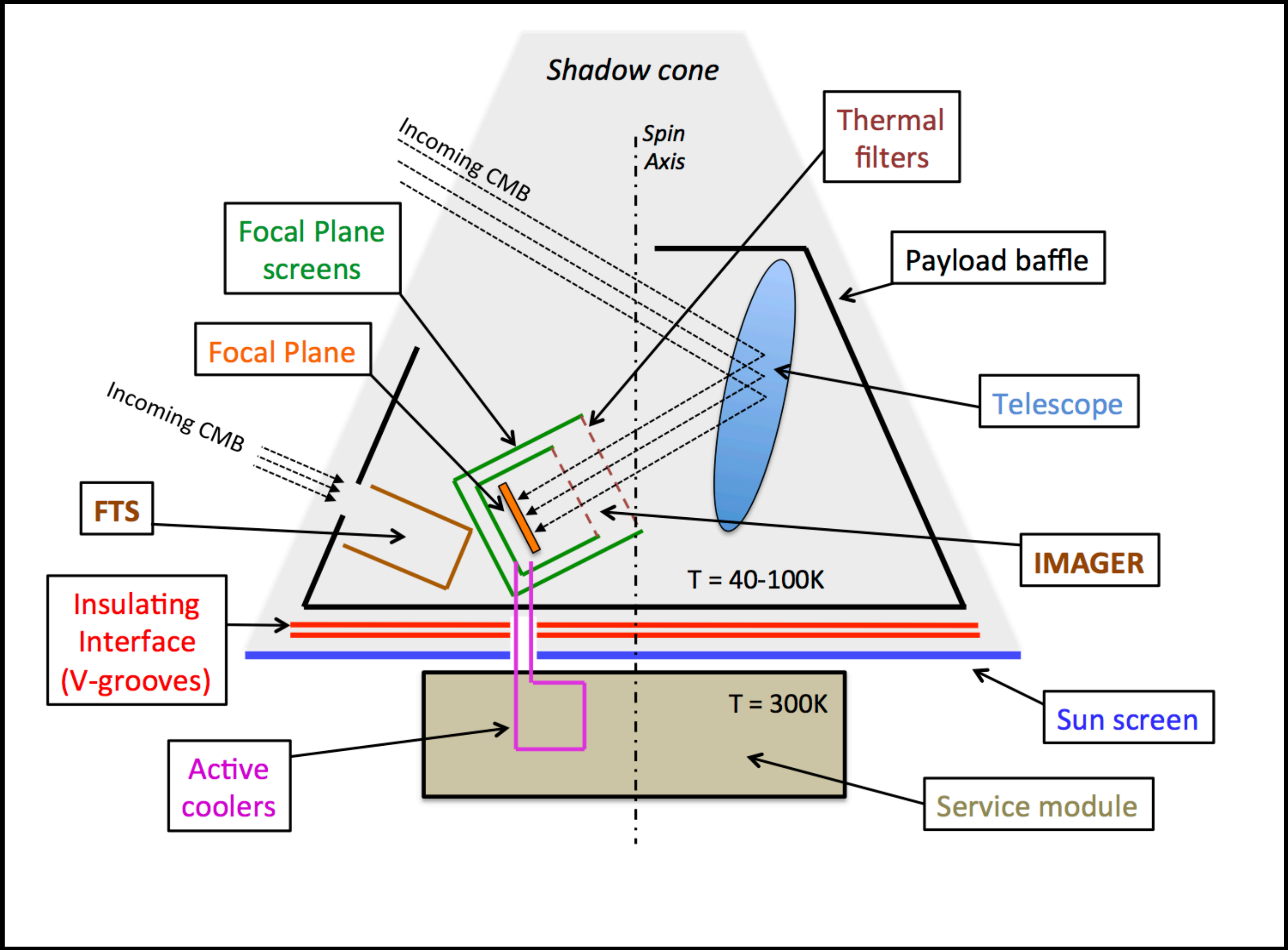
CMB temperature
$T_{cmb} = 2.725$ K

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

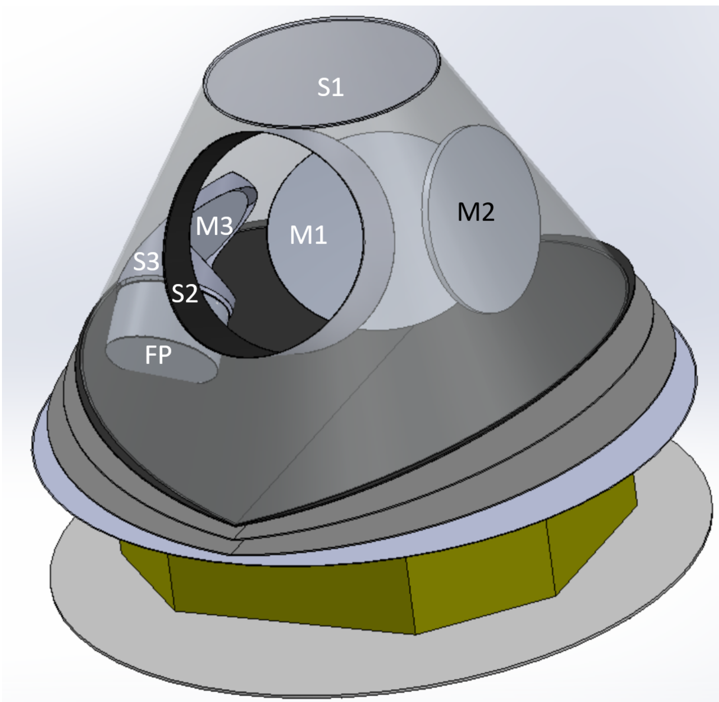
$\Delta T_{pE} \sim 5\ \mu K$
$\Delta T_{pB} \sim 10\text{-}100$ nK

Whorl patterns in polarization are telltale signature of Primordial gravitational waves

CMB-Bhārat Payload schematic



CMB-Bharat S/c Specs.



≈ 4.0 m

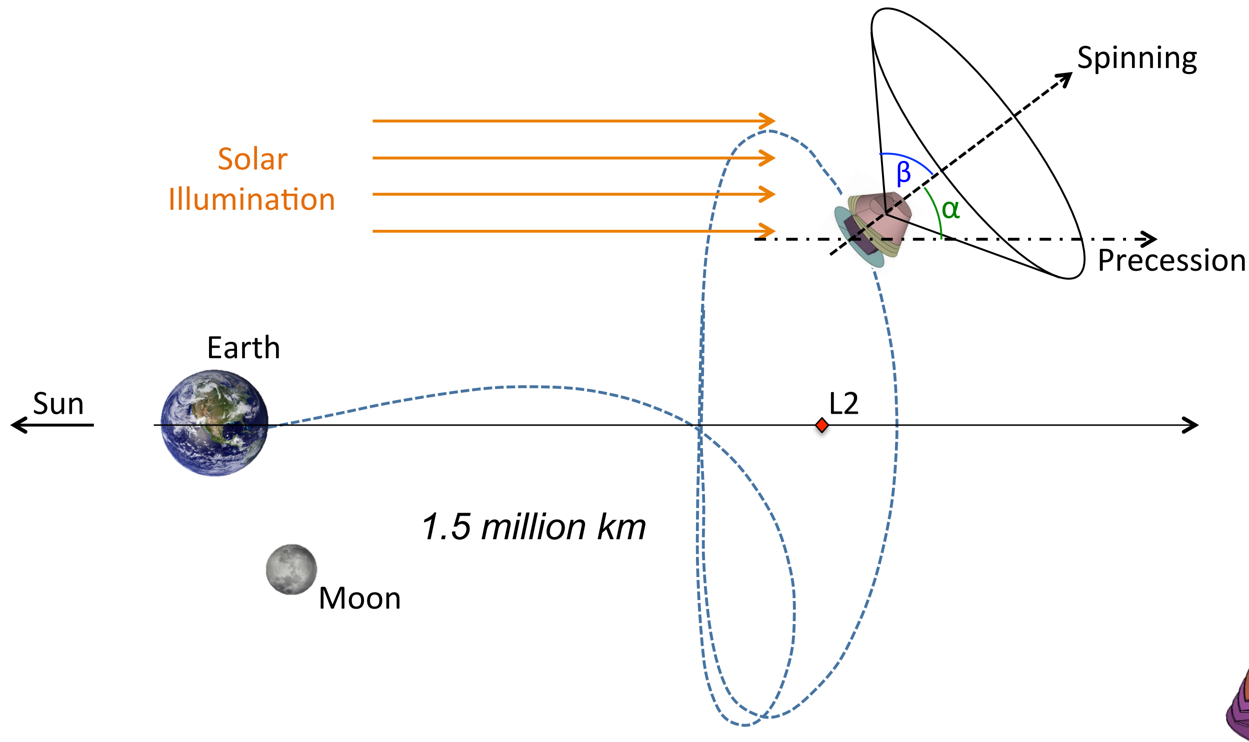
≈ 4.4 m

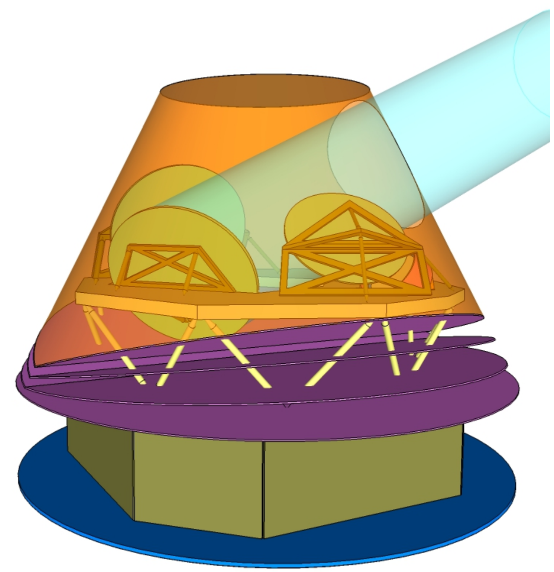
- Total wet mass ≈ 2.0 tons
- Diameter ≈ 4.4 meter
- Height ≈ 4.0 meter
- Power ≈ 2 KW

Adjustments are possible.

Max. Launch capacity: Well suited for a GSLV Mk-III launch towards a Sun-Earth L2 orbit

CMB-Bharat: Orbit and scanning

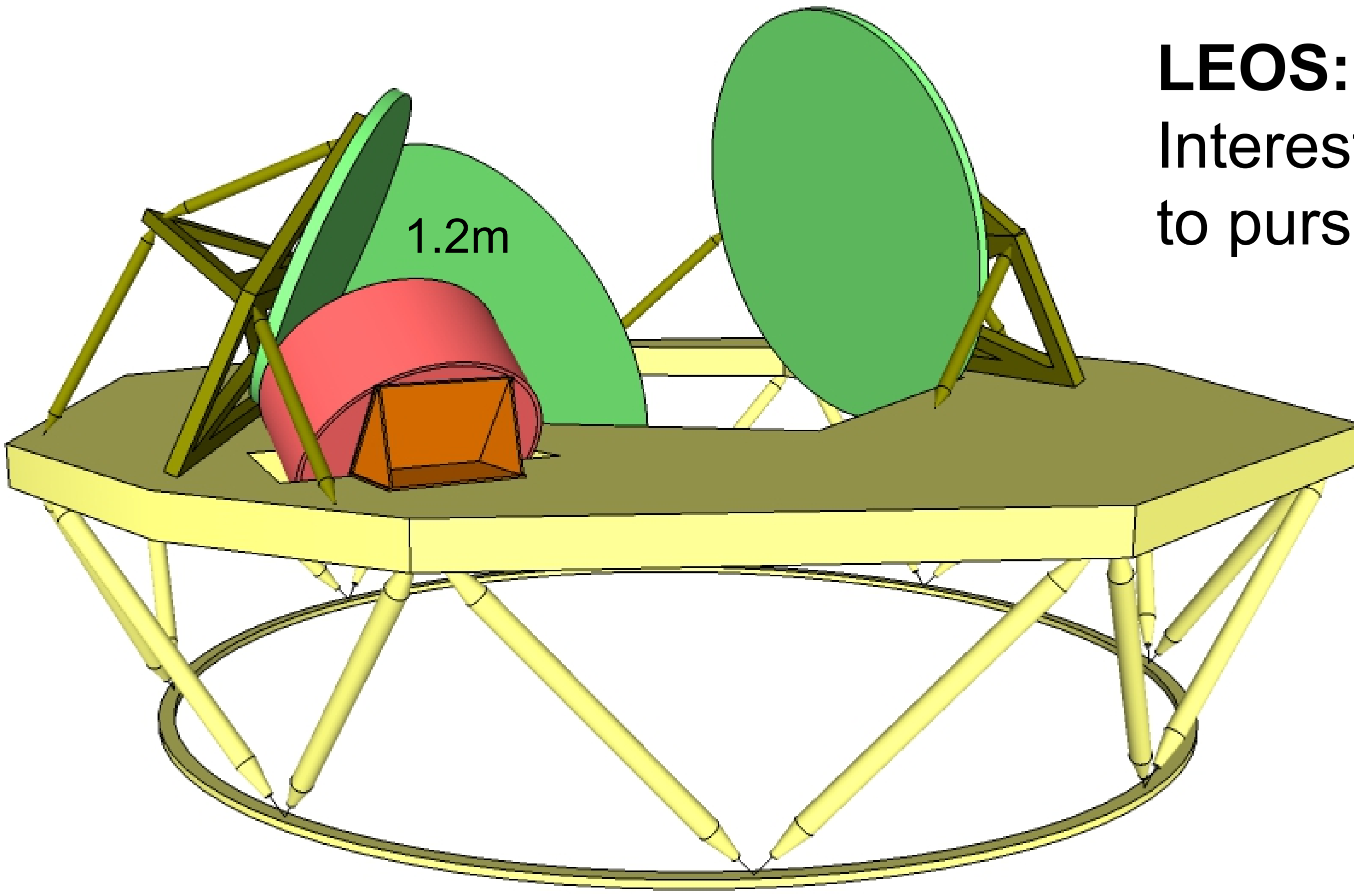




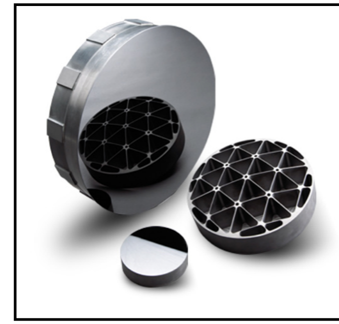
Challenges :

- orbitography
- pointing accuracy ≈ 10'
- pointing reconstruction ≈ 10"
- Data flow : ≈ 1 to 8 Mb/s (100 Gb/day)

SiC Telescope optics

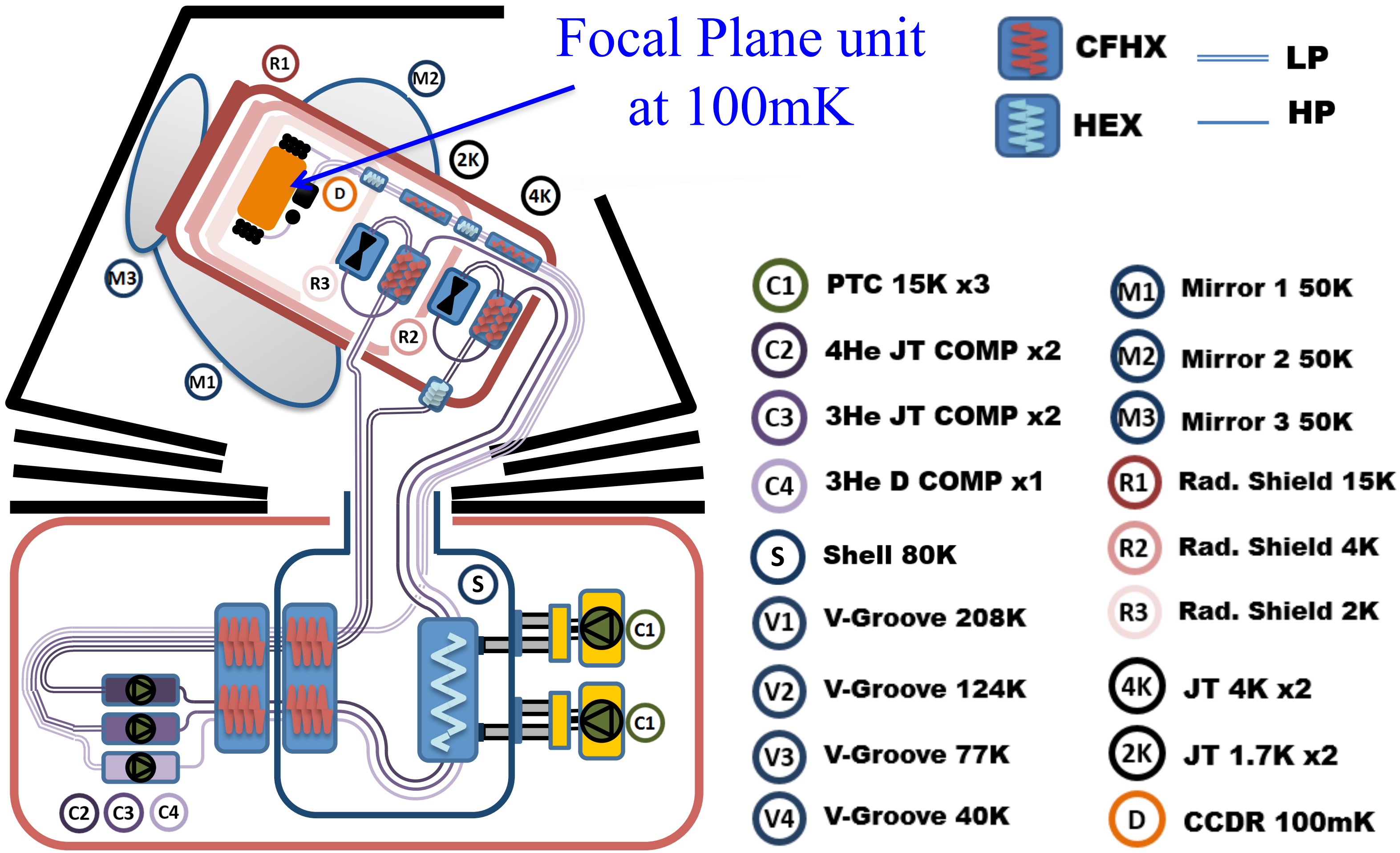


LEOS:
Interest & expertise to pursue with TDP



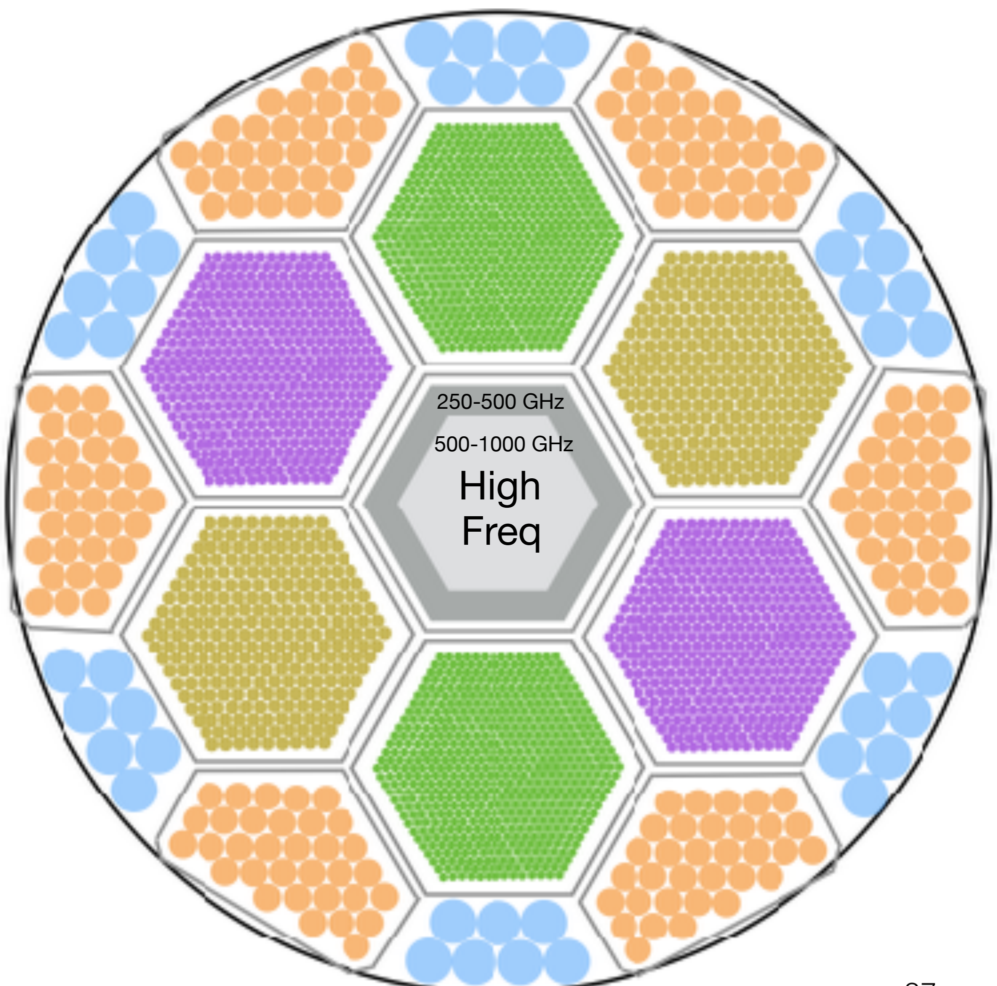
The telescope is made of silicon carbide, a technology that has been space proven with the *Herschel*

Cryogenic Cooling chain



Schematic of a possible CMB Imager

- Tiled 150 mm wafers on a 50 cm diameter telecentric focal plane
- Estimates for number of pixels per wafer based on scaling of numbers from demonstrated ground based Advanced ACT dichroic (two color) feed-horn coupled detector arrays
- Proper utilization of focal plane real estate requires careful optimization involving trade-offs between various parameters (this schematic is a rough estimate)



	2:1 Frequency band (split into 2 bands)	**# of pixels**
HF	500-1000	~400*
HF	250-500	~400*
	125-250	**1204****
	80-160	**888****
	50-100	252
	25-50	198
	15-30	42

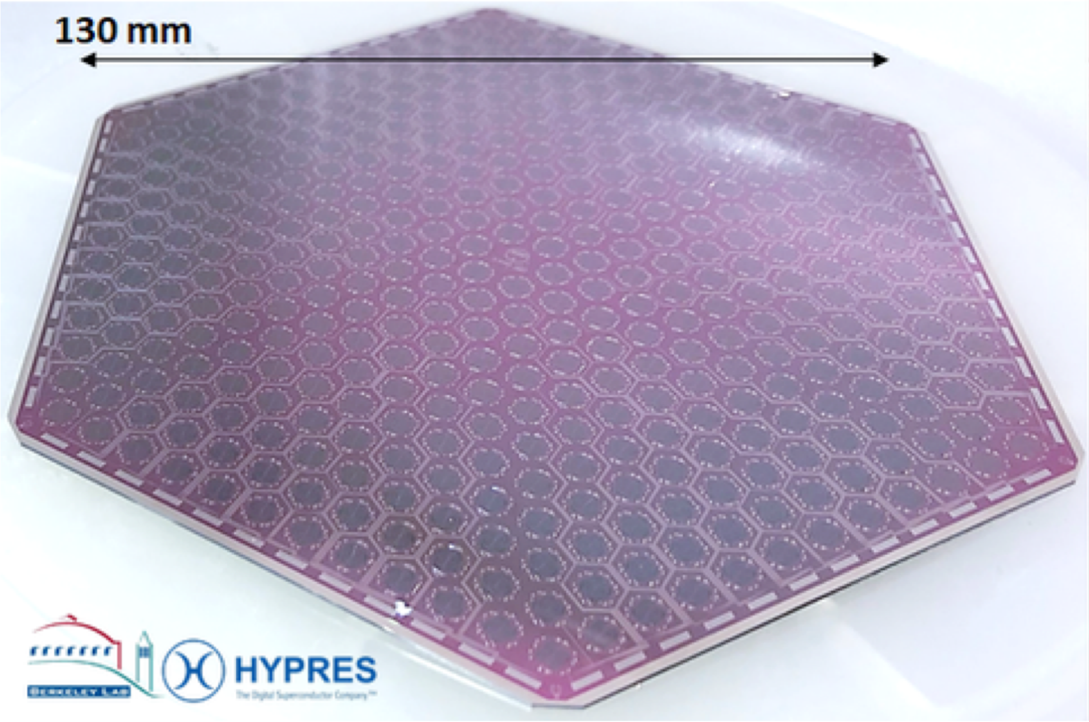
N_{pix_tot} ~3400

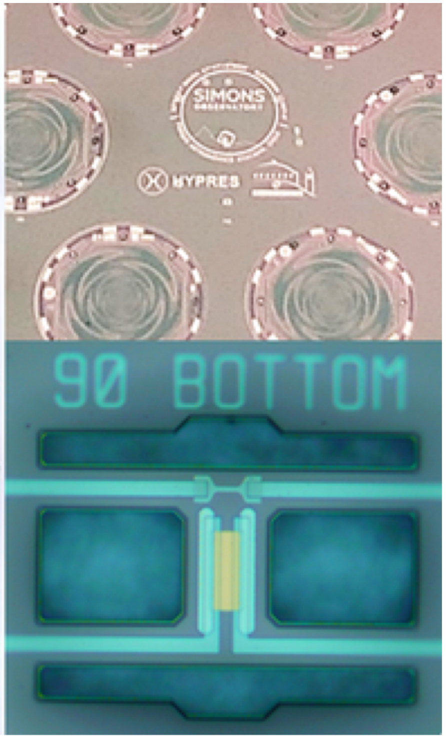
N_{det_tot} ~13600

(6800 per polarization)

- ***reading out these many TES detectors on a single 150 mm wafer will be challenging with existing technology, new technologies are an active area of research**
- **** greater than 60% of the detectors are in CMB bands**

TES: focal plane design





Ground based: Simons Observatory

Boundaries of measurements: Power

Astronomical: Solar 10^{26}watts

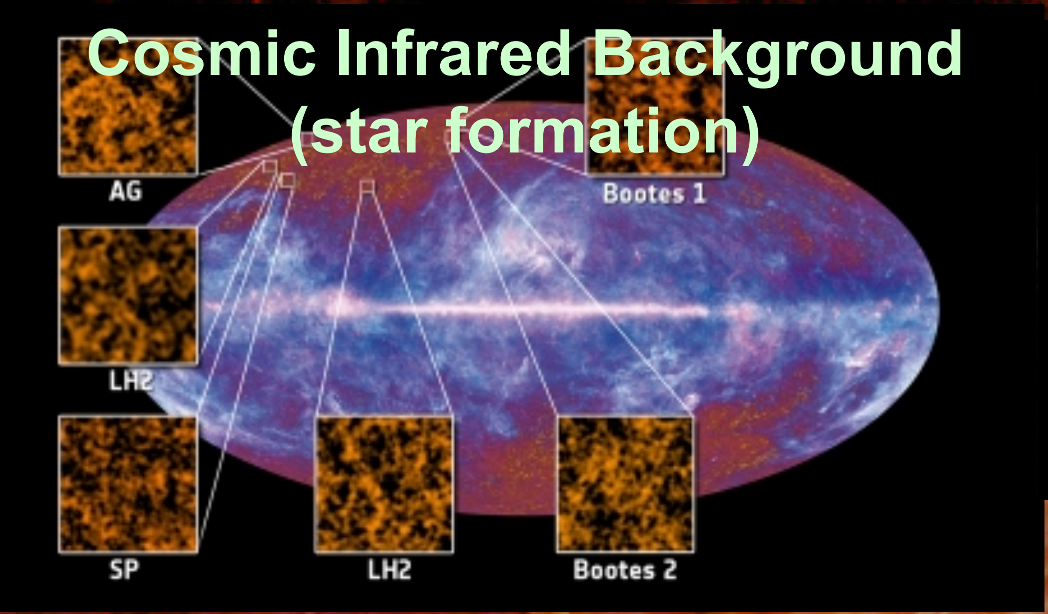
	1 000 000 000 000 000 000	10^{18}	18	Exa (E)
	1 000 000 000 000 000	10^{15}	15	Peta (P)
	1 000 000 000 000	10^{12}	12	Tera (T)
	1 000 000 000	10^{9}	9	Giga (G)
Daily experience	1 000 000	10^{6}	6	Mega (M)
	1 000	10^{3}	3	kilo (k)
	100	10^{2}	2	hecto (h)
	10	10^{1}	1	Deca (da)
	1 **watt**	10^{0}	0	
	0.1	10^{-1}	-1	deci (d)
	0.01	10^{-2}	-2	centi (c)
	0.001	10^{-3}	-3	milli (m)
	0.000 001	10^{-6}	-6	micro (μ)
FM reception →	0.000 000 001	10^{-9}	-9	nano (n)
Cell phone →	0.000 000 000 001	10^{-12}	-12	pico (p)
	0.000 000 000 000 001	10^{-15}	-15	femto (f)
!!?!!	0.000 000 000 000 000 001	10^{-18}	-18	atto (a)

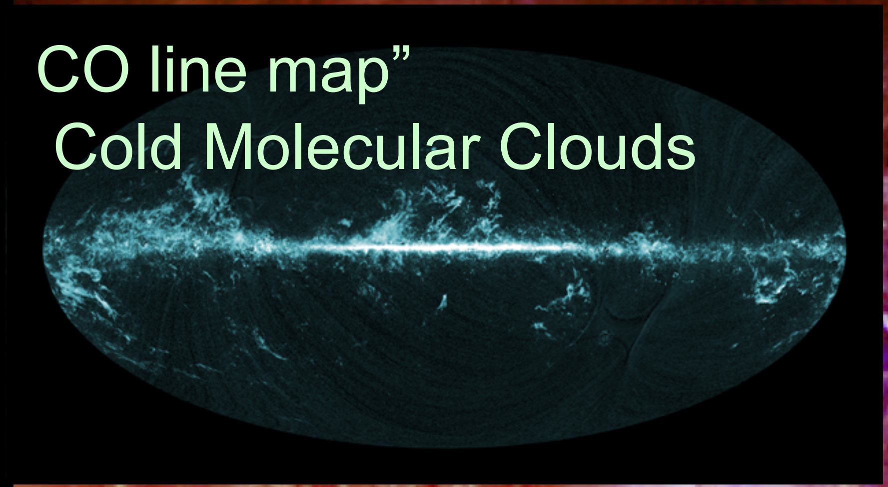
CMB-Bharat: multi-faceted science

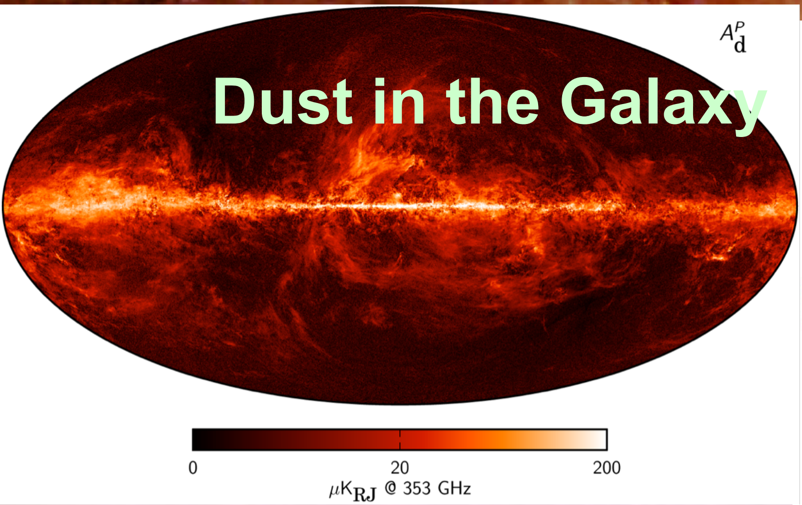
Indian Working groups

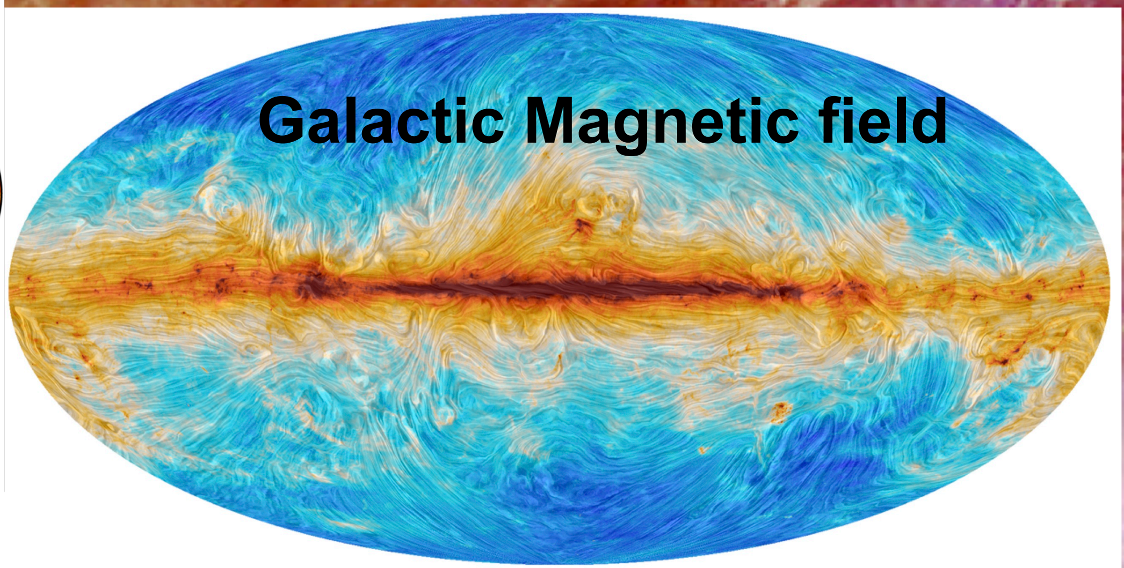
- ***Cosmological parameters:*** *Lead: Dhiraj Hazra (APC, Paris→ NISER?,…)*
- ***Weak Lensing:*** *Lead: Suvodip Mukherjee (CCA, NY)*
- ***Foregrounds and CIB:*** *Lead: Tuhin Ghosh (NISER)*
- ***Instrument science:*** *Lead: Zeeshan Ahmed (Stanford Univ)*
- ***Inflation:*** *Lead: L. Sriramkumar (IIT Madras)*
- **Statistics: Isotropy and Gaussianity:** Lead: Aditya Rotti (U Manchester)
- ***Spectral Distortions:*** *Lead: Rishi Khatri (TIFR)*
- ***Cluster Physics from CMB:*** *Lead: Subhabrata Majumdar (TIFR)*
- **End to end Modeling & Systematics:** Lead: Ranajoy Banerji (U. Oslo)
- ***Simulations and Data Pipelines:*** *Lead: Jasjeet Singh Bagla (IISER Mohali)*

CMB Foregrounds : Rich A&A science
(600-900GHz)

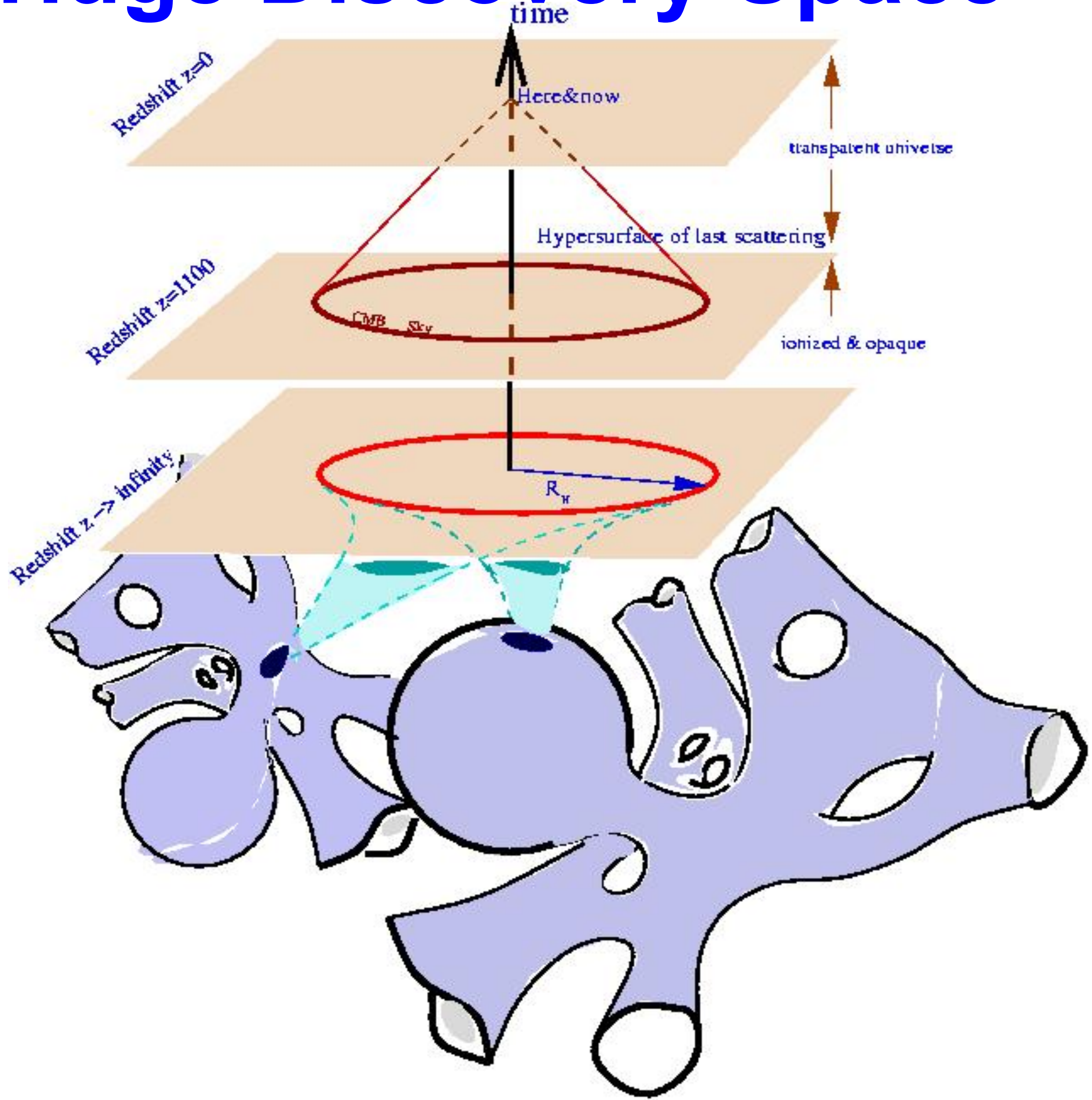








Huge Discovery Space



Planck launch 2009 **Next Generation CMB mission ?**

CMB-BHARAT mission presents an unique opportunity for India to take the lead on prized quests in fundamental science in a field that has proved to be a spectacular success, while simultaneously gaining valuable expertise in cutting-edge technology for space capability through global cooperation.

Thank you !!!