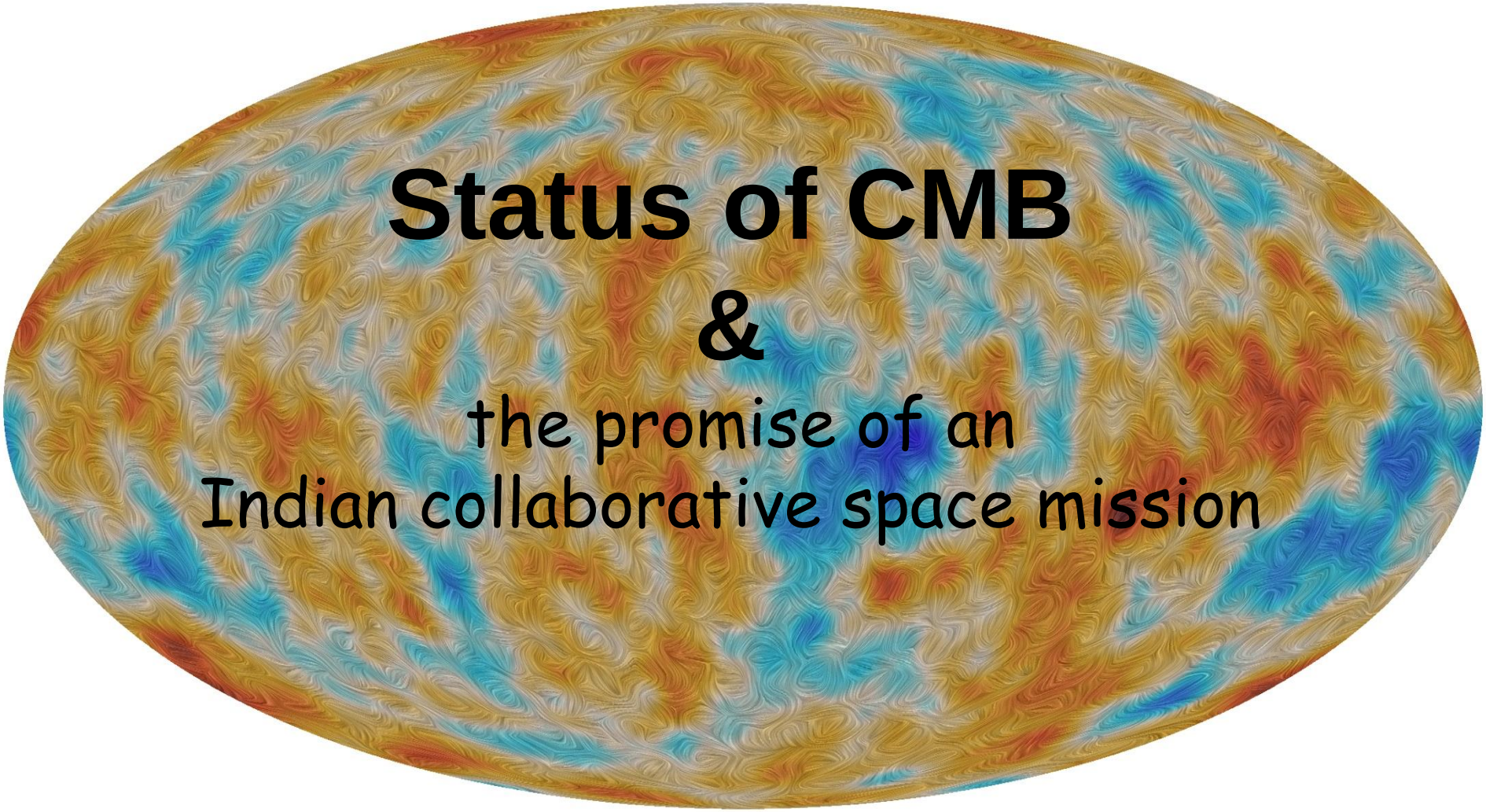


Status of CMB
&
the promise of an Indian collaborative space mission

Astro-Particle Physics meet

CGPA-IFTHEP@ IISER Pune

Feb. 25, 2018

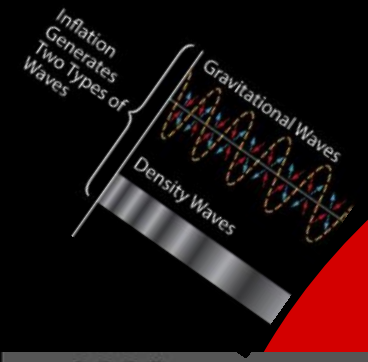
Tarun Souradeep

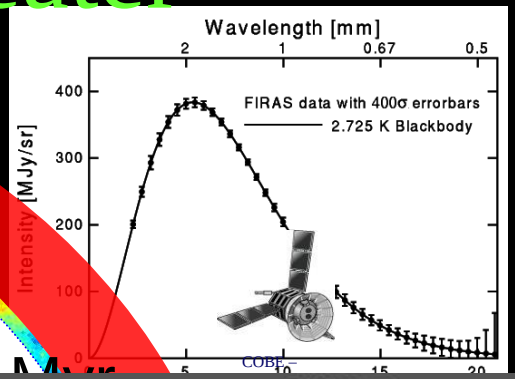
IUCAA, Pune

On behalf of *CMB-Bharat*

(Indian CMB consortium)

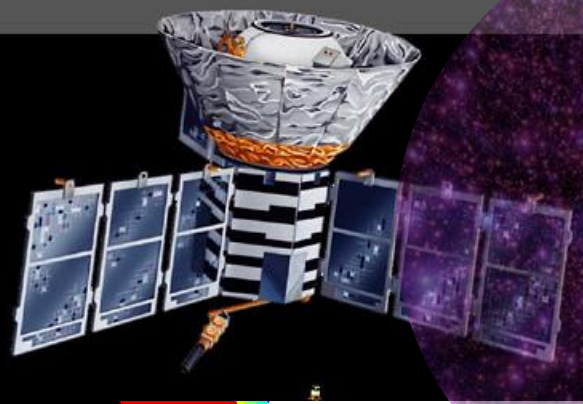
Cosmic “Super–IMAX” theater

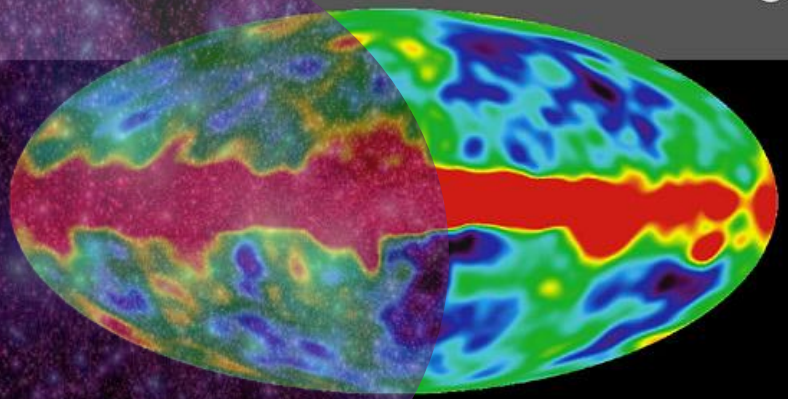




1992

COBE

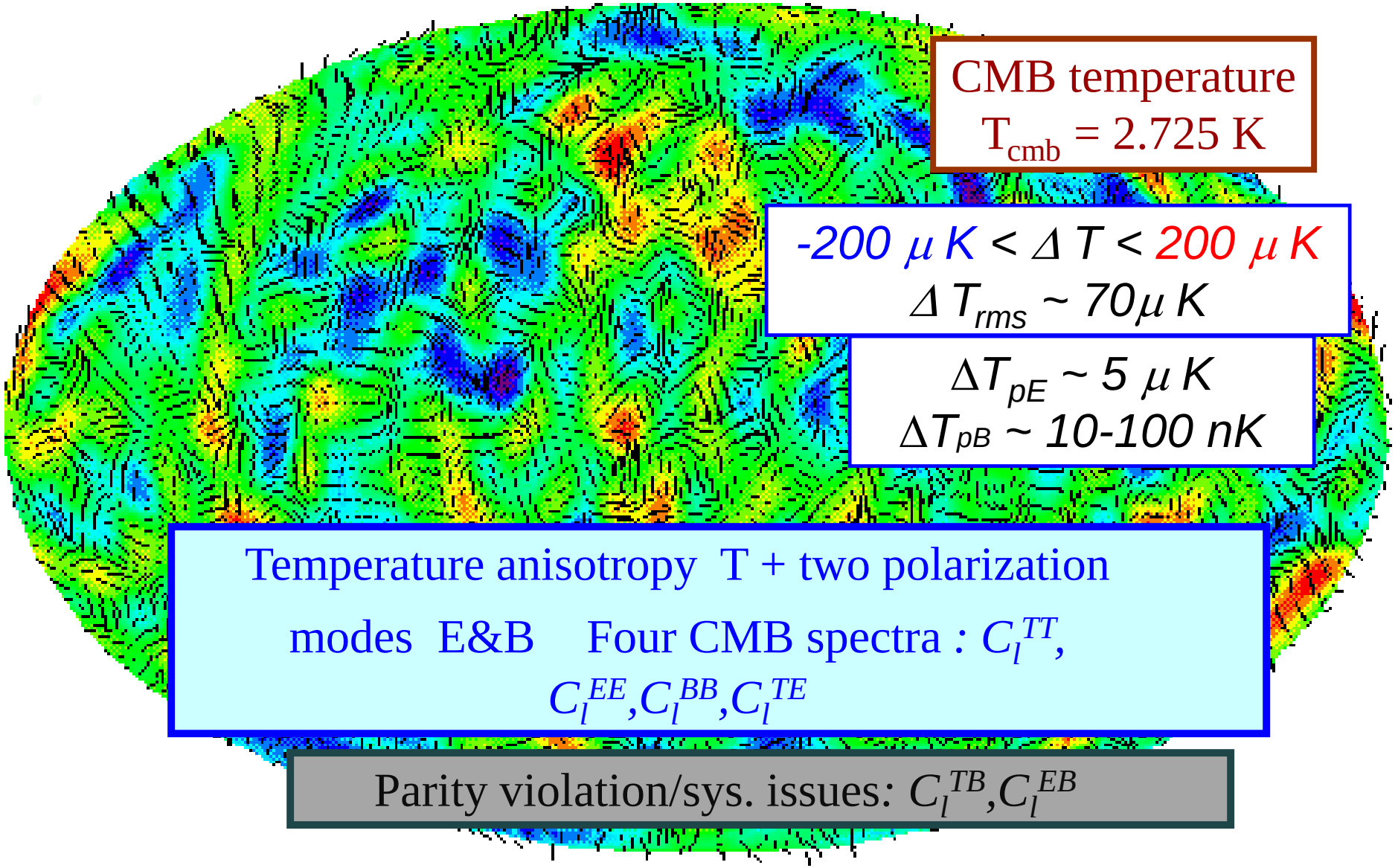




Transparent universe

Opaque universe

CMB Anisotropy & Polarization



CMB temperature
$T_{cmb} = 2.725$ K

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

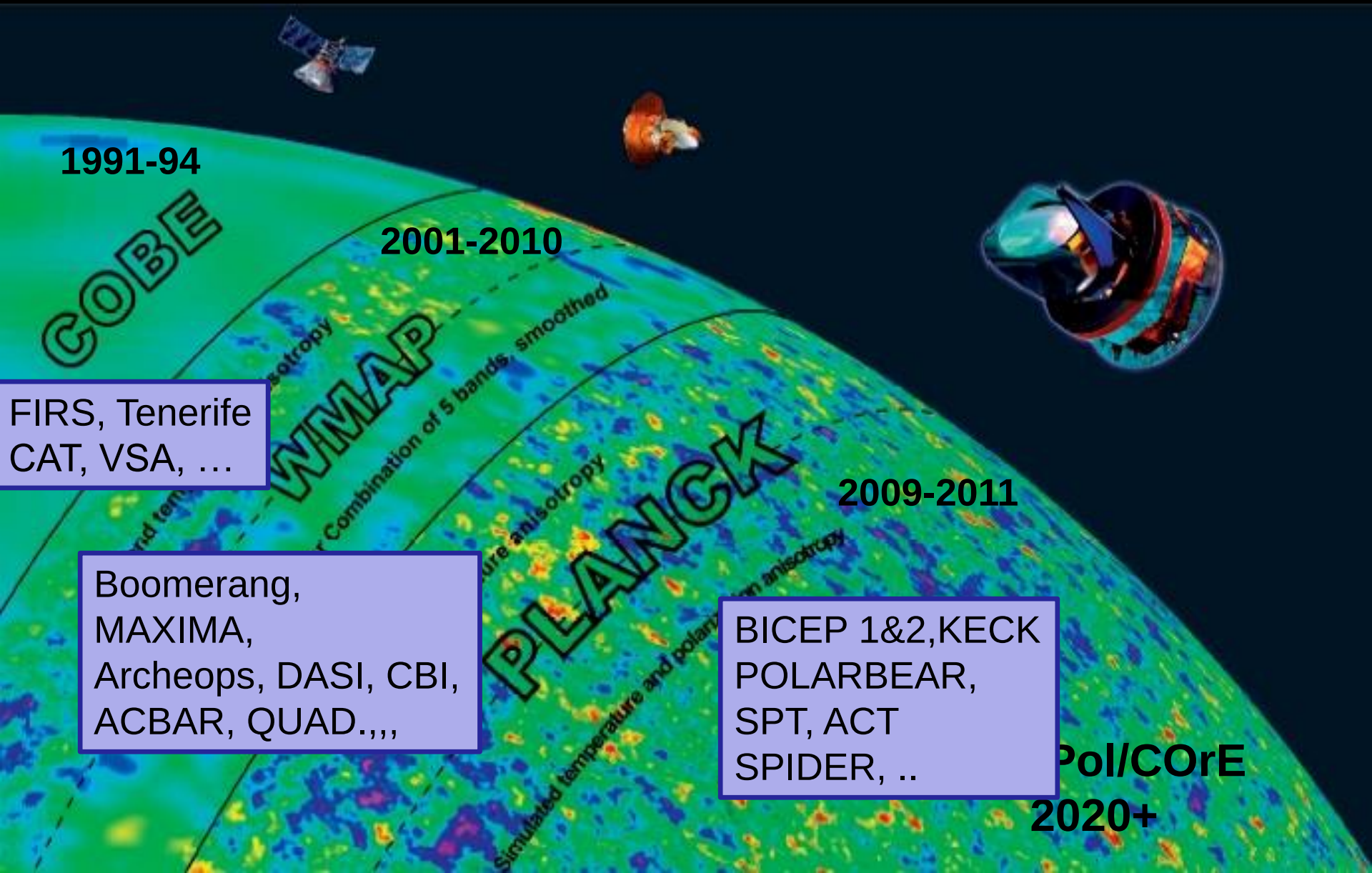
$\Delta T_{pE} \sim 5\ \mu K$
$\Delta T_{pB} \sim 10\text{-}100$ nK

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}

CMB anisotropy measurements

1st, 2nd and into the 3rd decade



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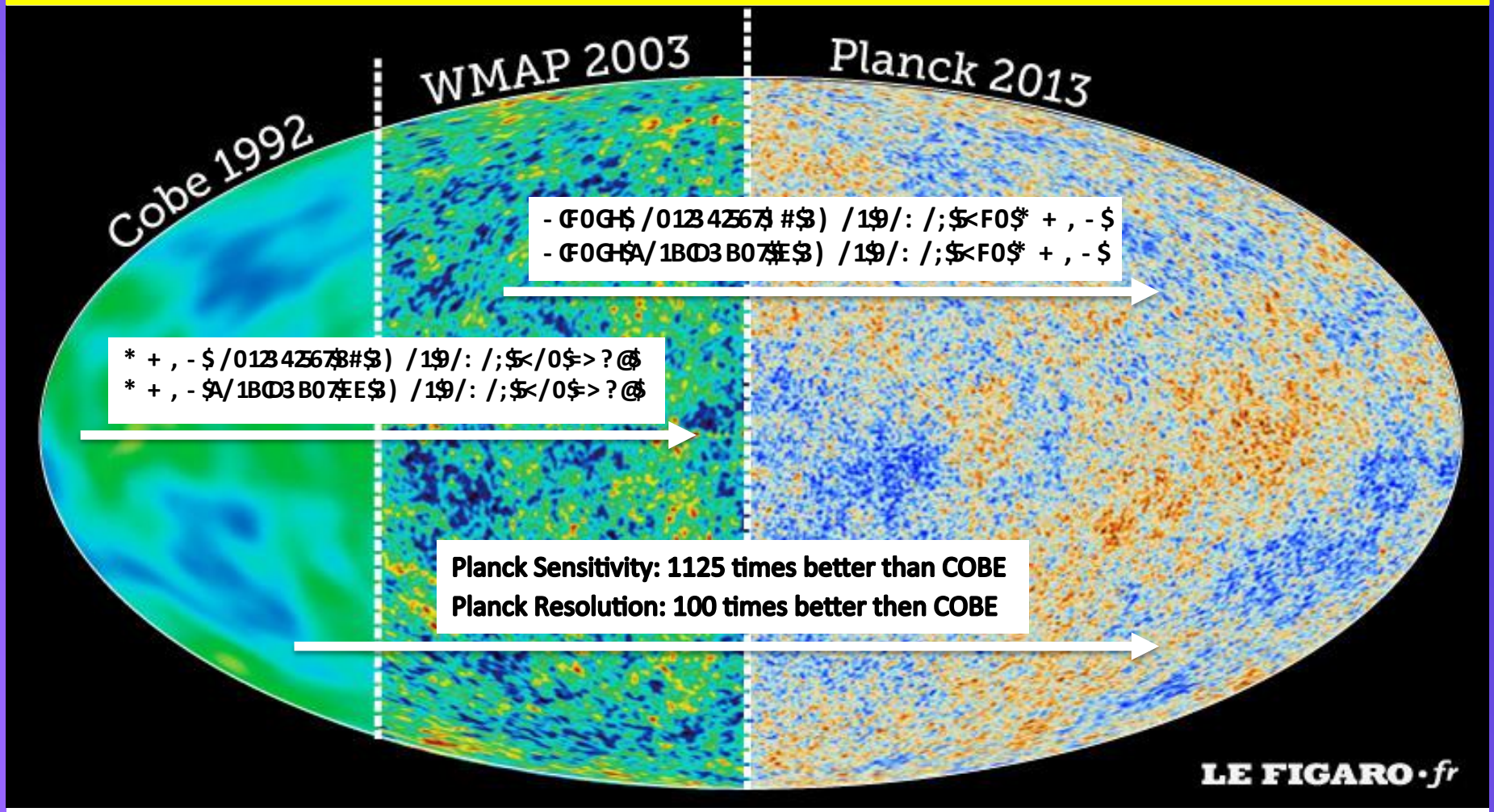

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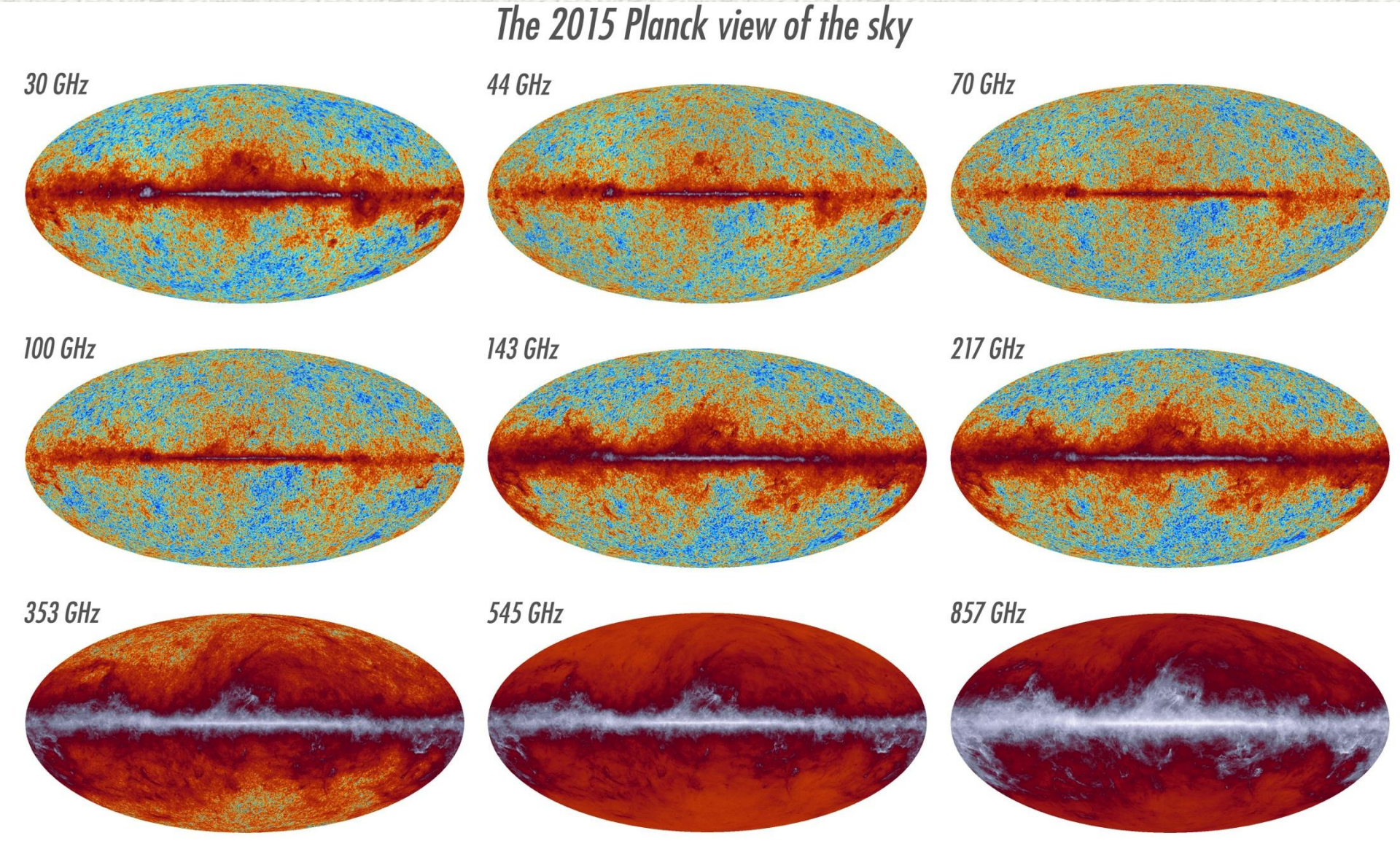
Courtesy: Soumen Basak

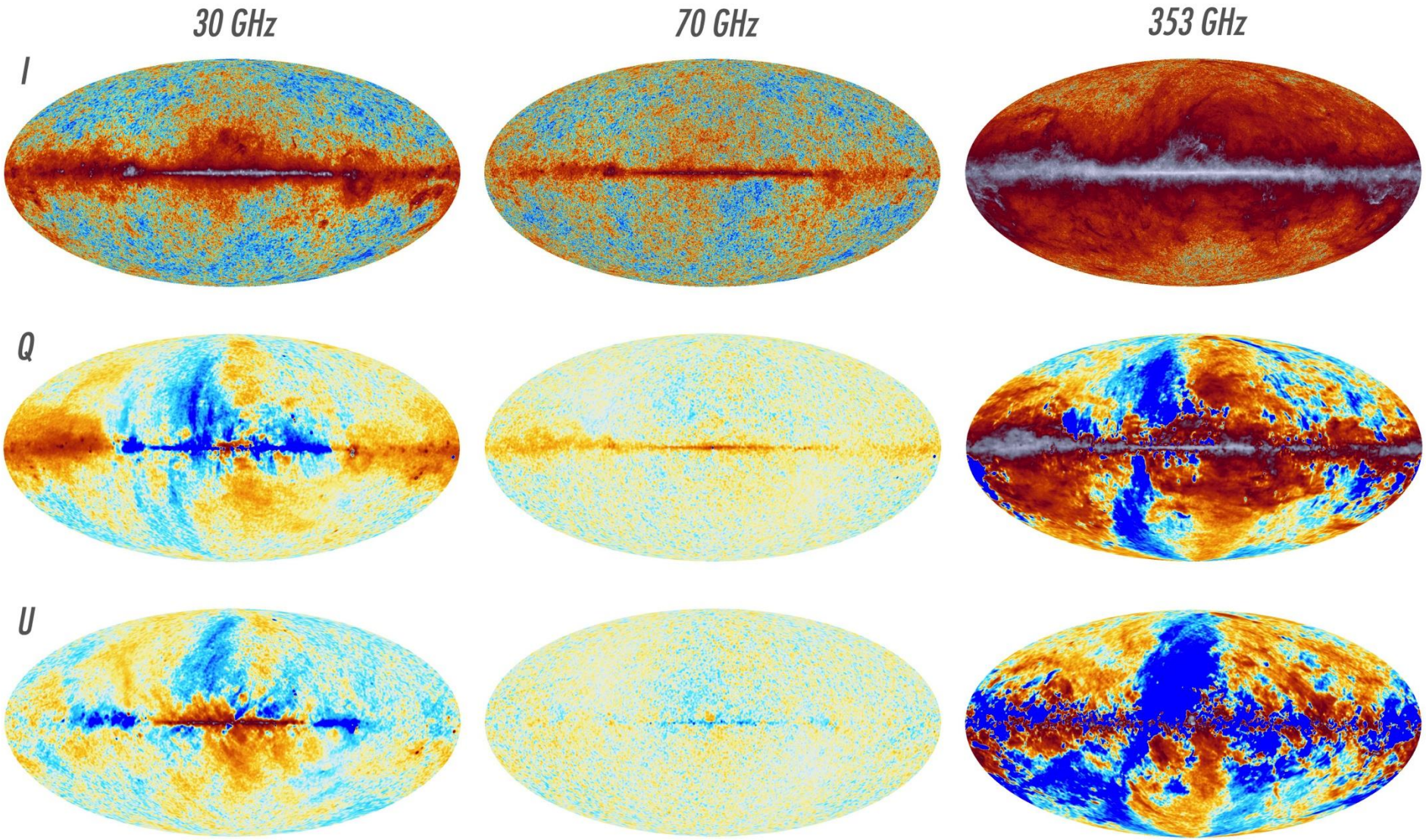
CMB Temperature at Planck Frequencies

Credit: ESA, HFI & LFI consortia

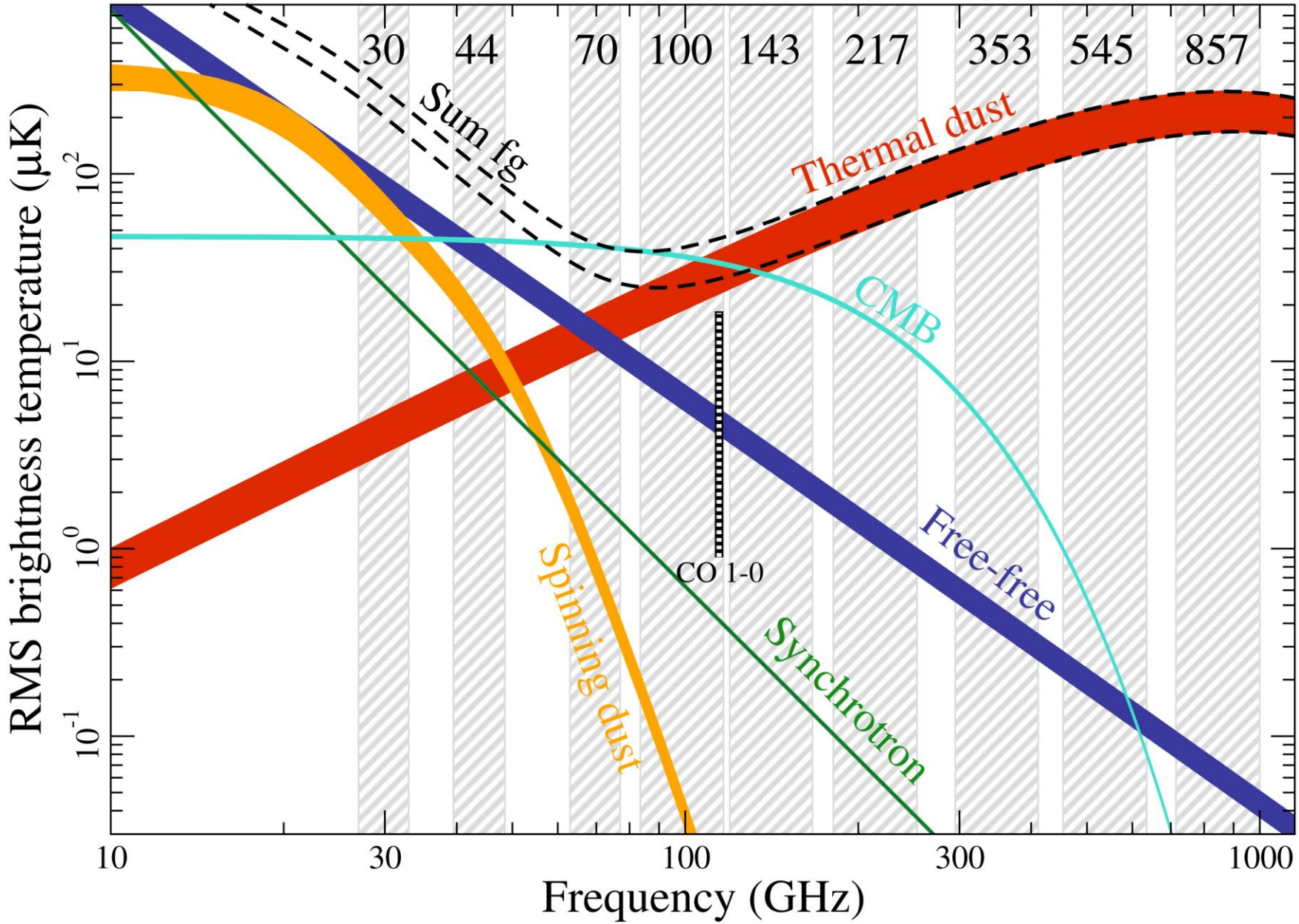


CMB Polarization at Planck Frequencies

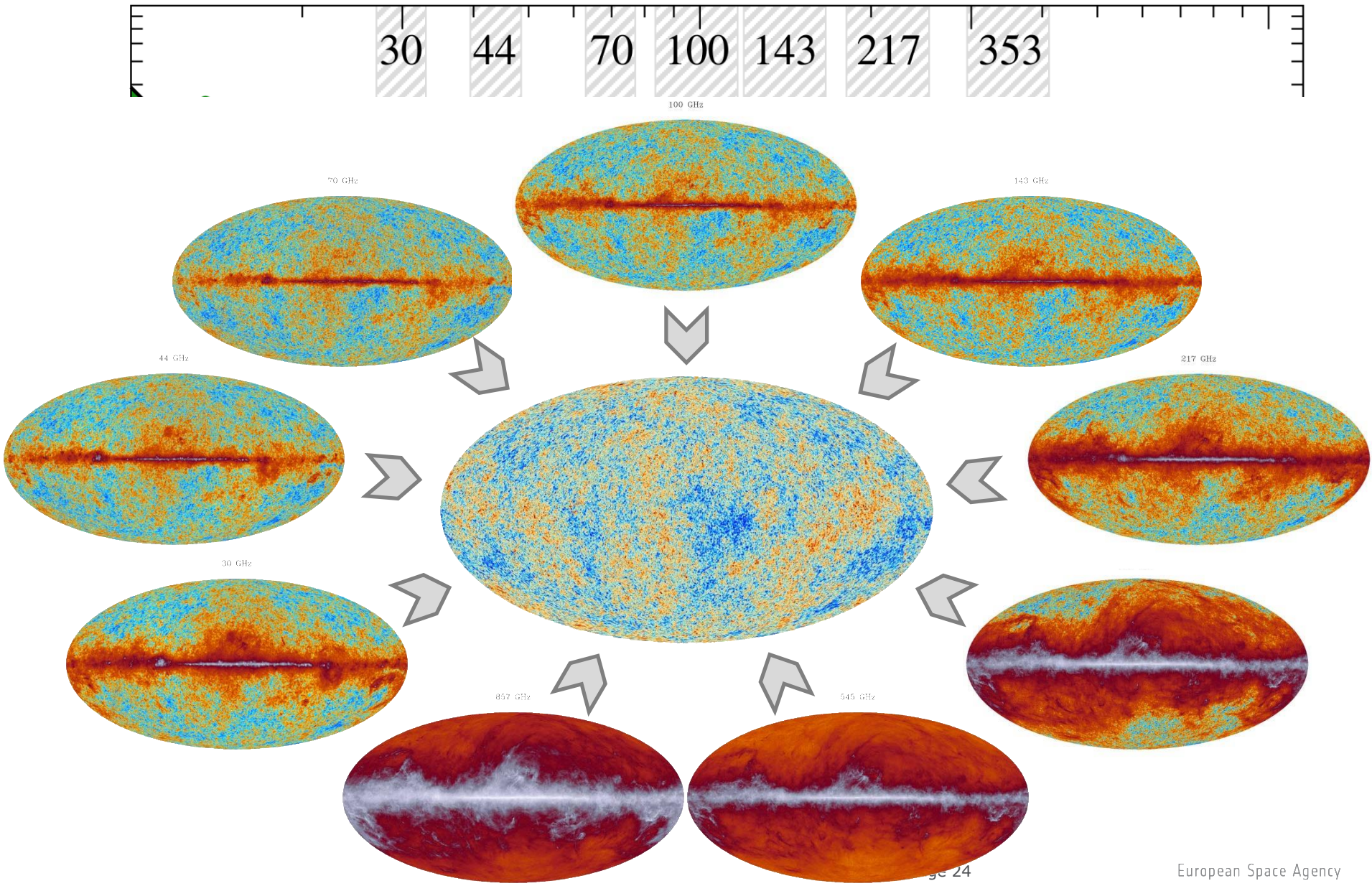
Credit: ESA, HFI & LFI consortia



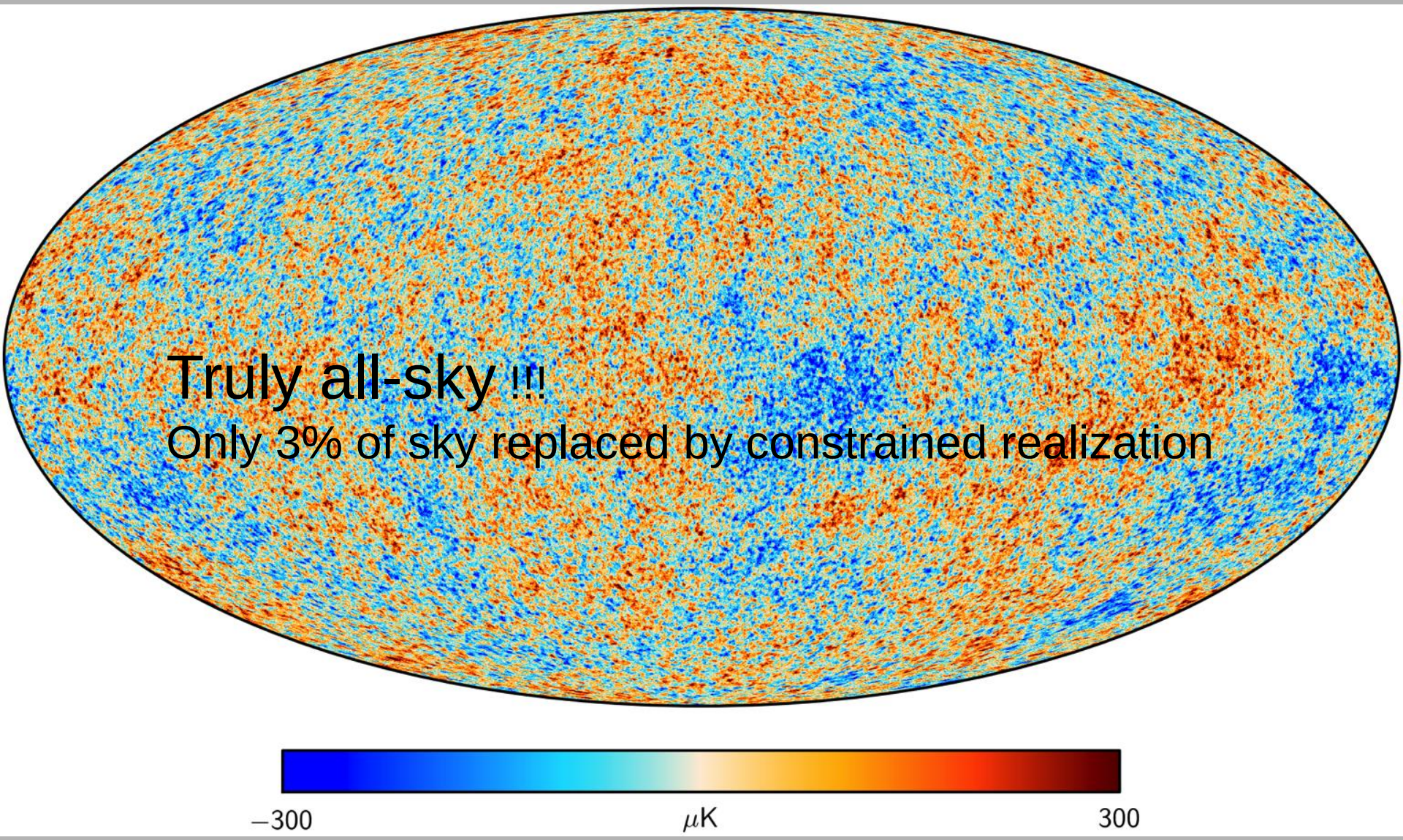
Foreground for CMB anisotropy



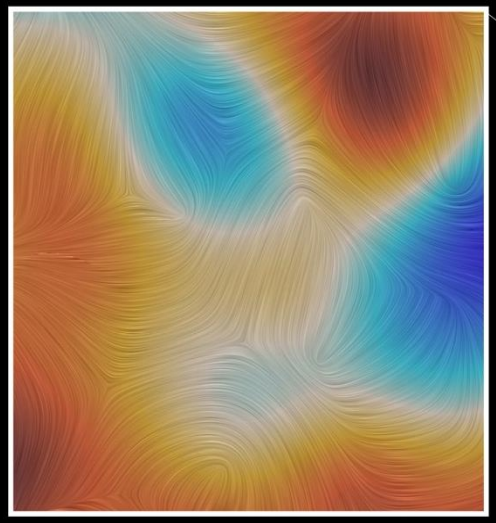
Foreground for CMB Polarization



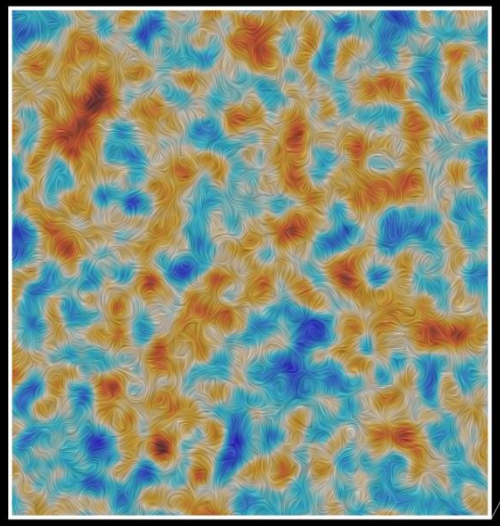
Planck CMB sky map



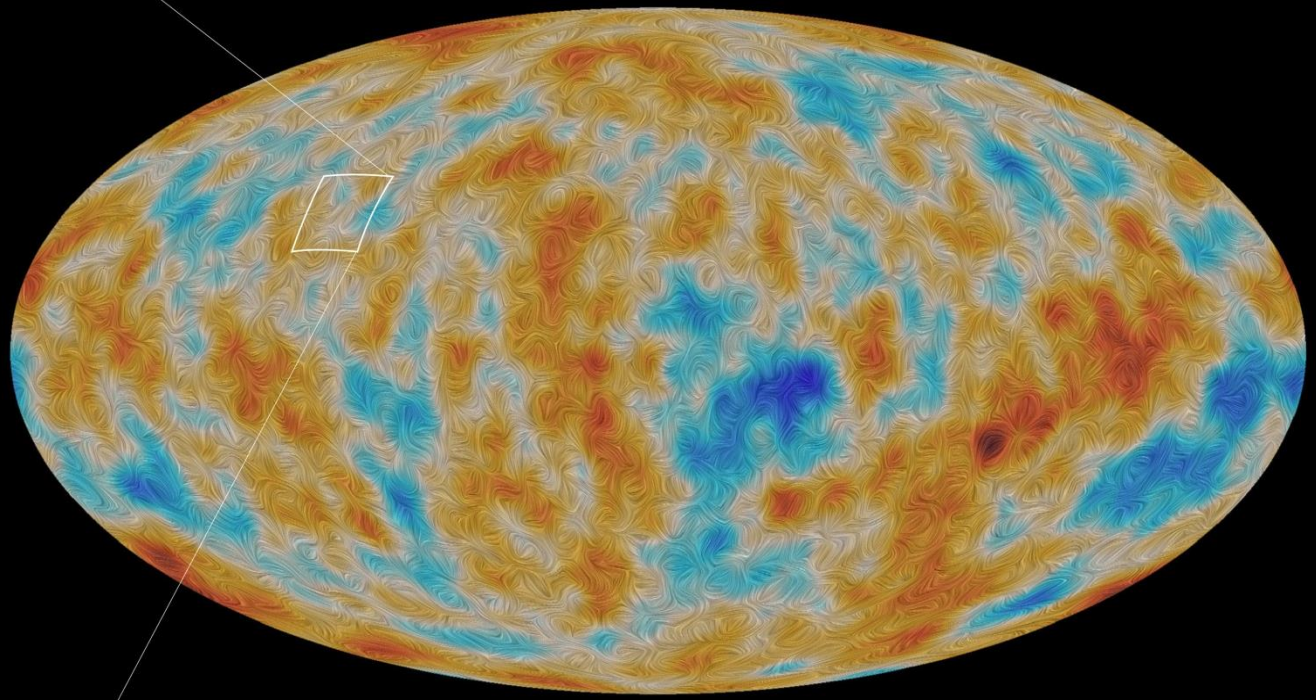
→ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 5 degrees

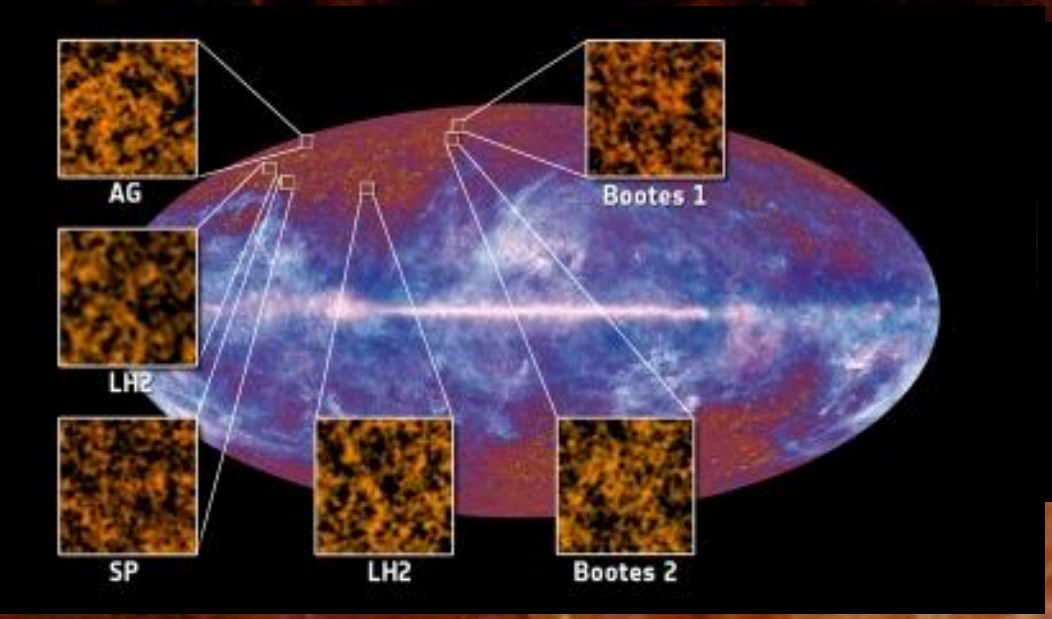


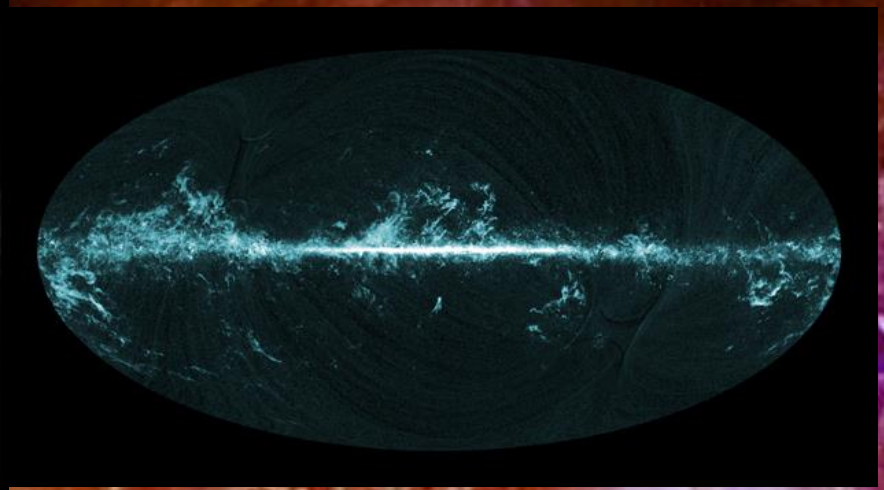
Filtered at 20 arcminutes

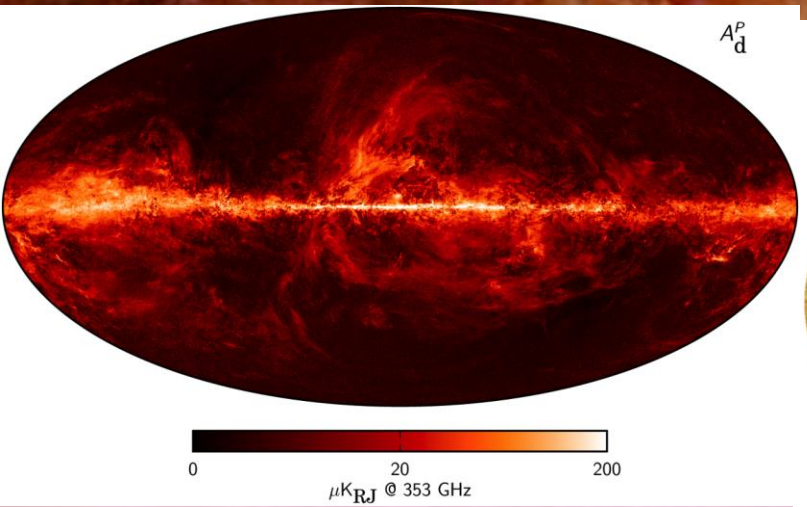


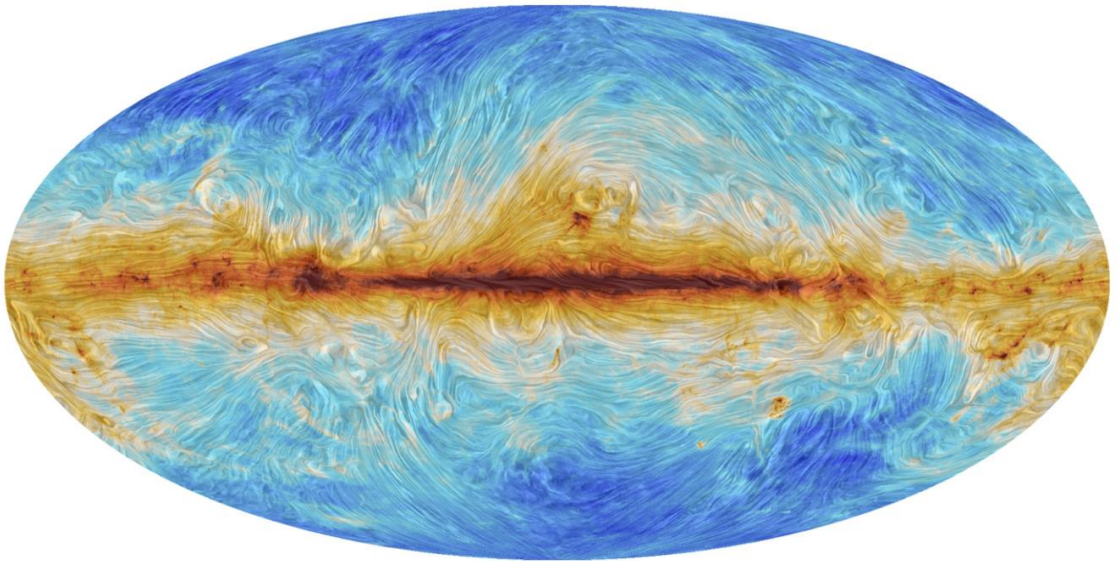
Full sky map
Filtered at 5 degrees

CMB Foregrounds : Rich A&A science



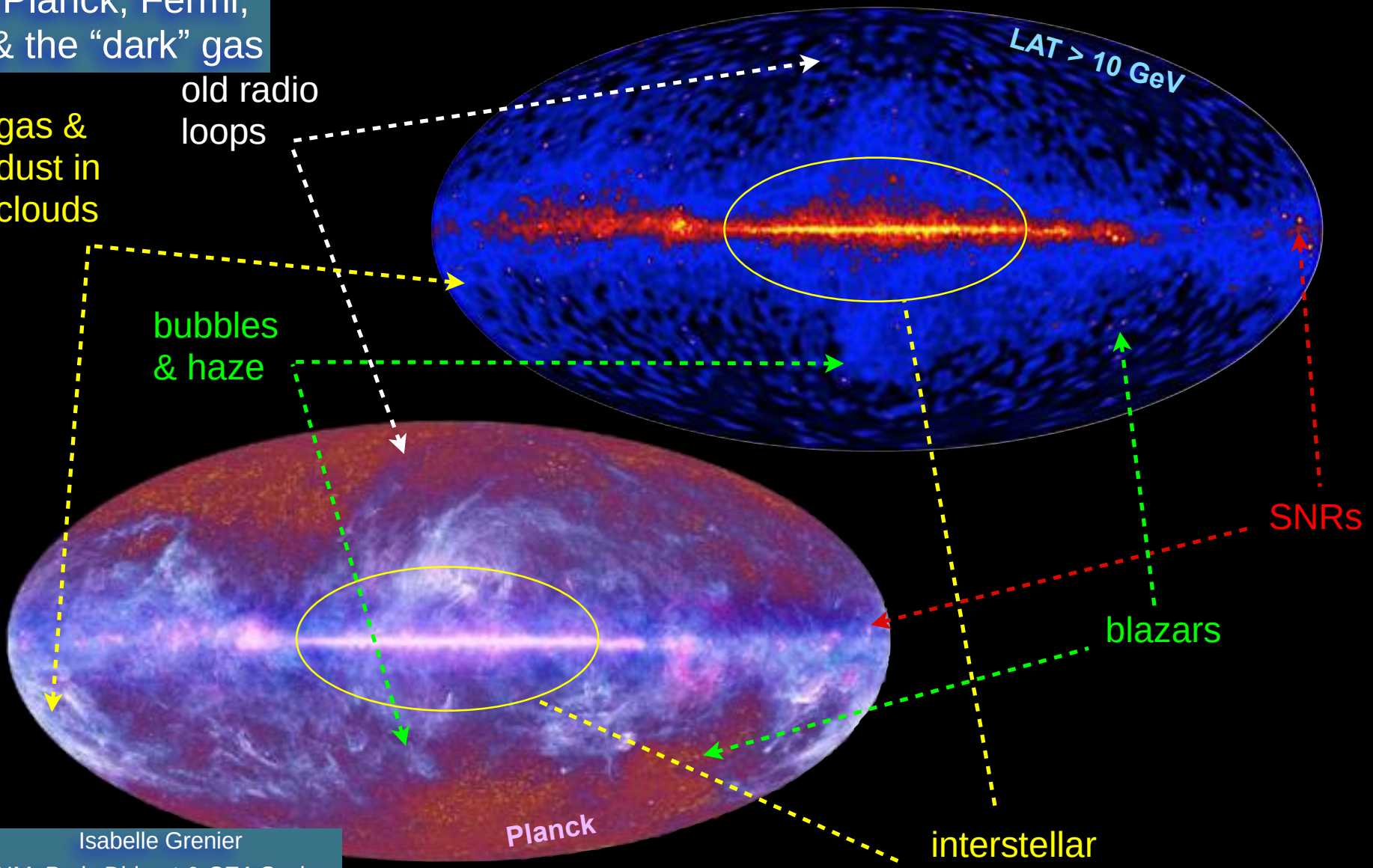






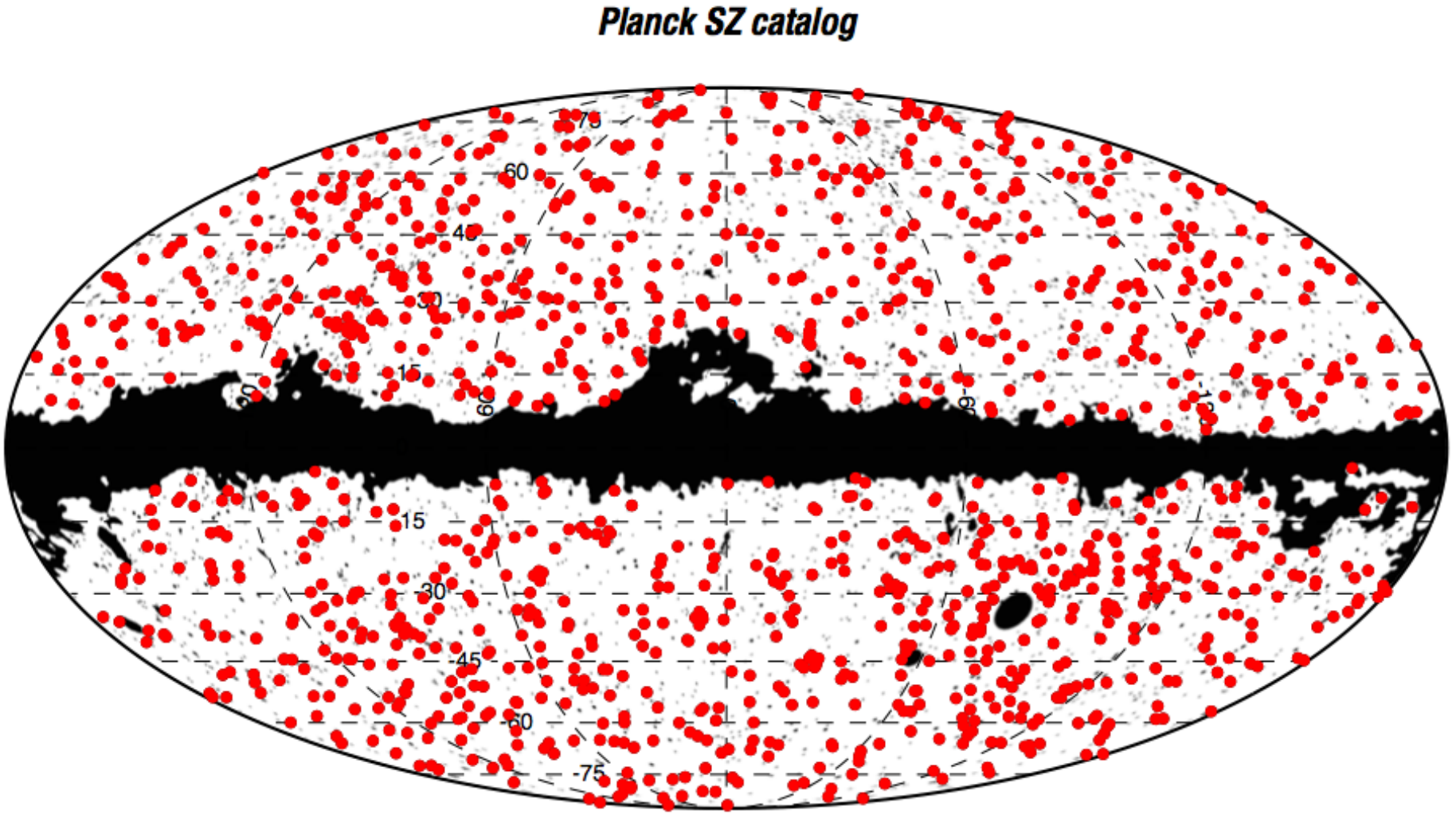
Fermi Planck multiple synergies

Planck, Fermi, & the "dark" gas

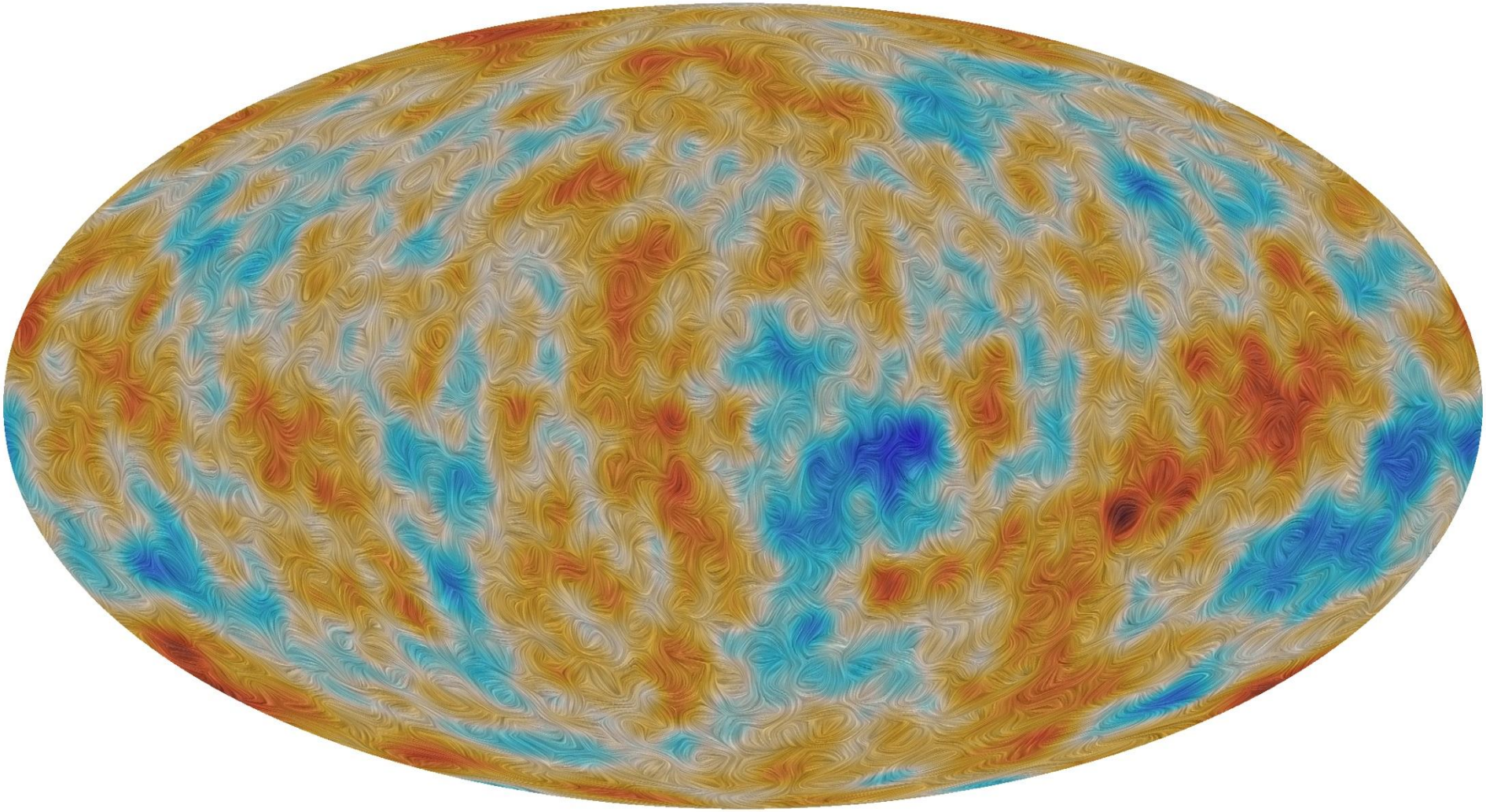


Isabelle Grenier
AIM, Paris Diderot & CEA Saclay
on behalf of both collaborations

SZ clusters from Planck

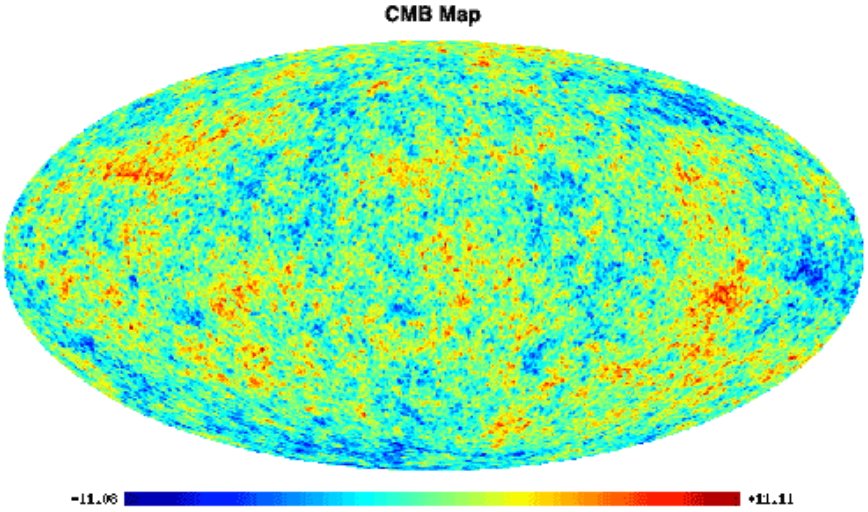


Planck sky maps



Statistics of CMB

CMB Anisotropy Sky map => Spherical Harmonic decomposition



$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

$$\left\langle a_{lm}\, a^{*}_{l'm'} \right\rangle = C_l\, \delta_{ll'} \delta_{mm'}$$

Gaussian Random field => Completely specified by

angular power spectrum $D_l = l(l+1)C_l$:

D_l : Power in fluctuations on angular scales of ~ π/l radians

Planck Angular power spectrum

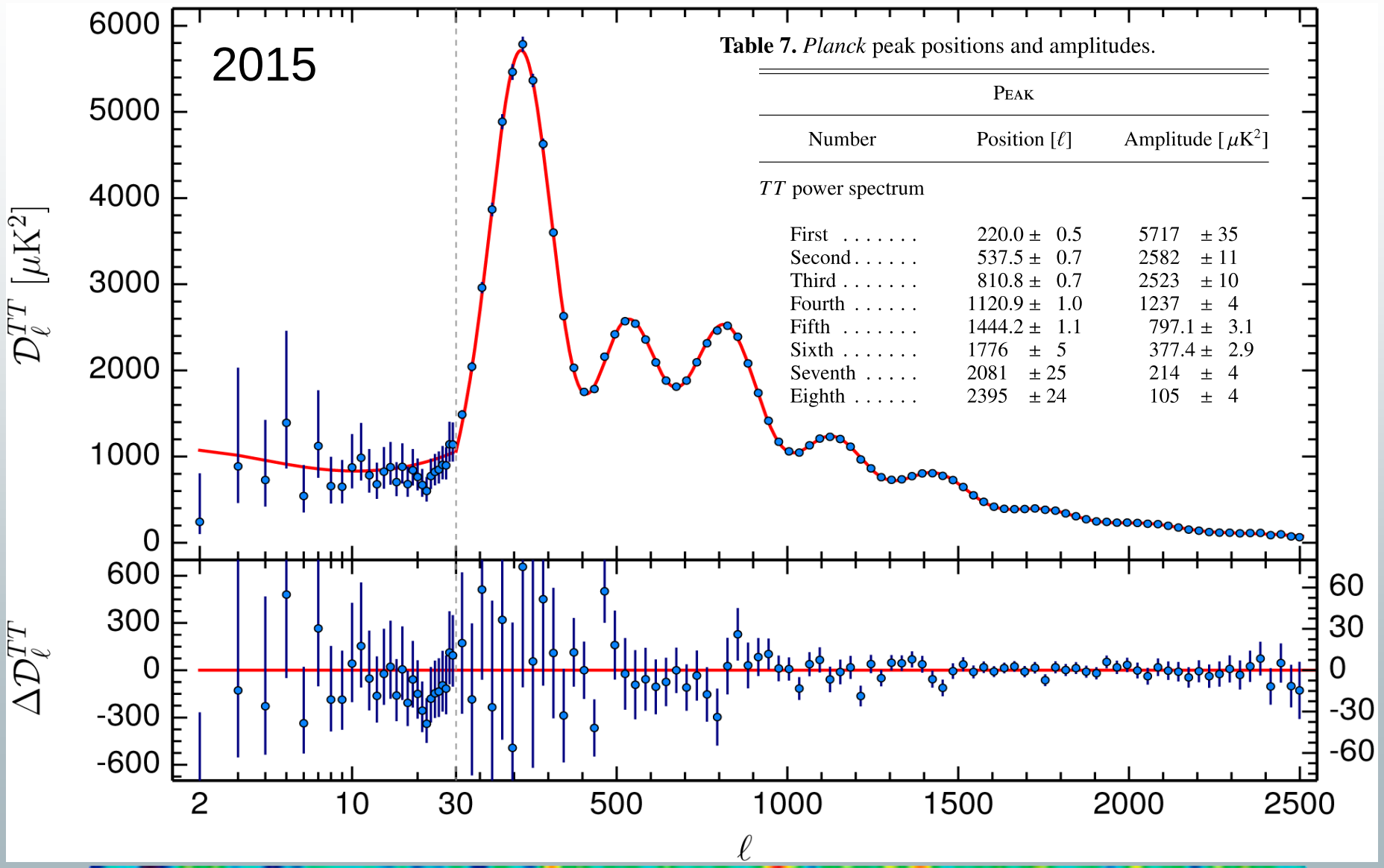
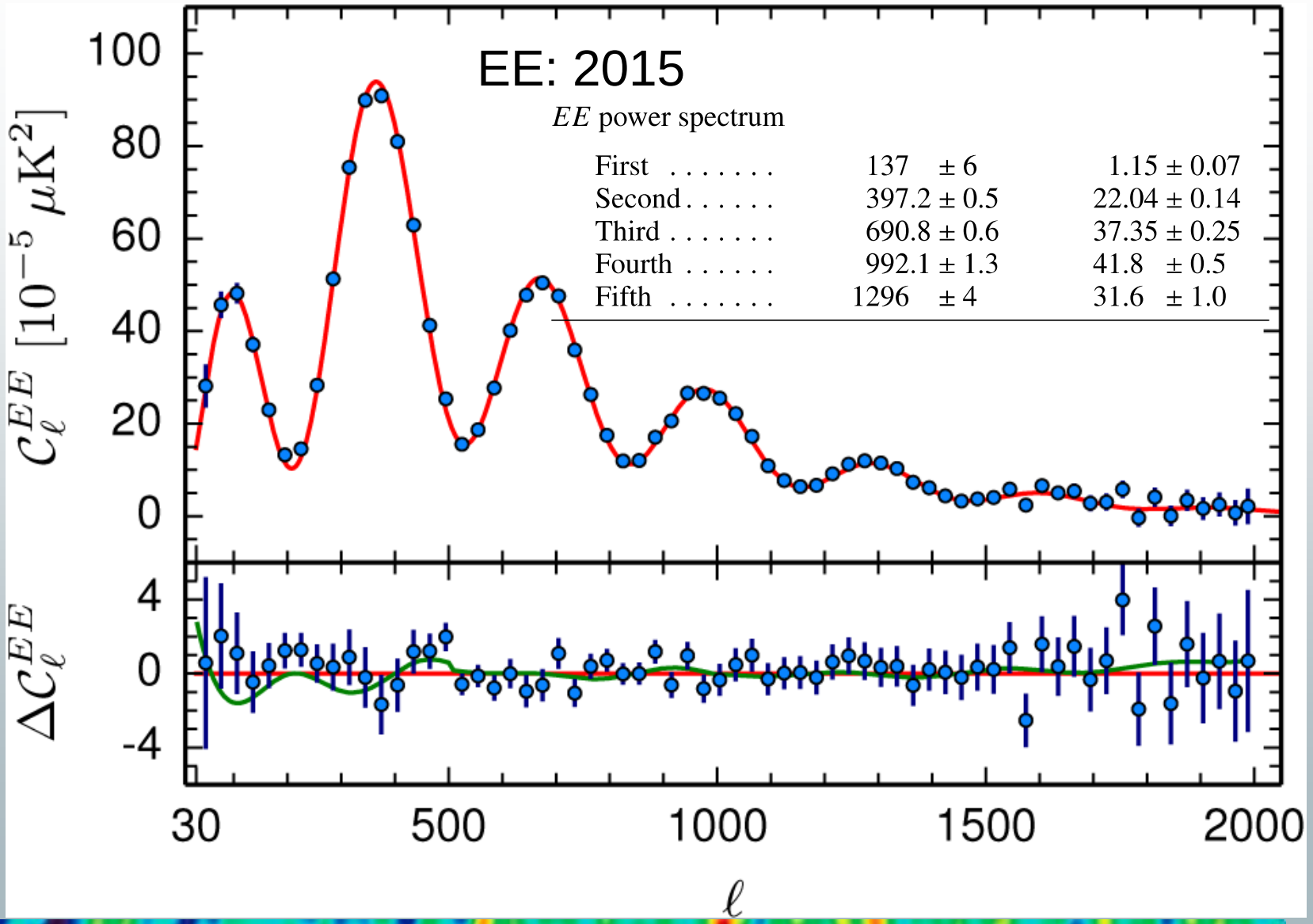


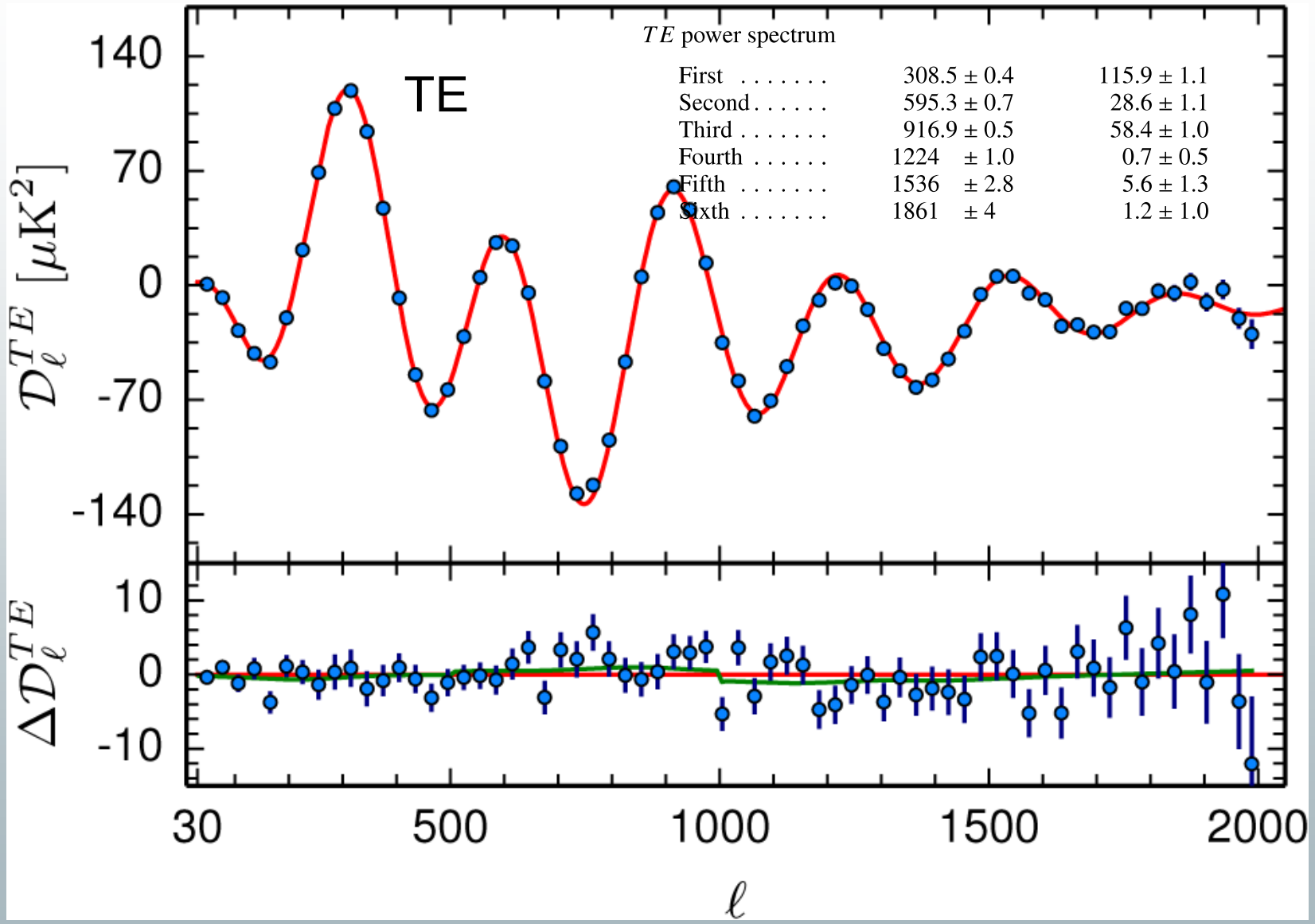
Table 7. *Planck* peak positions and amplitudes.

	Peak	
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

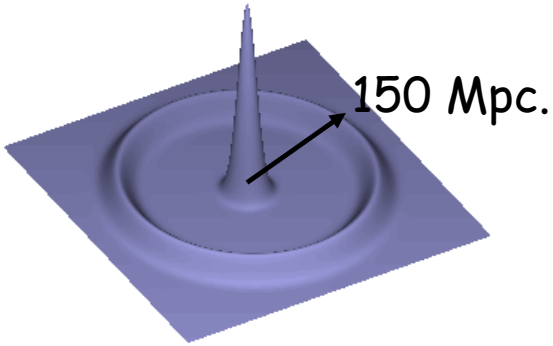
Planck CMB Polarization spectra

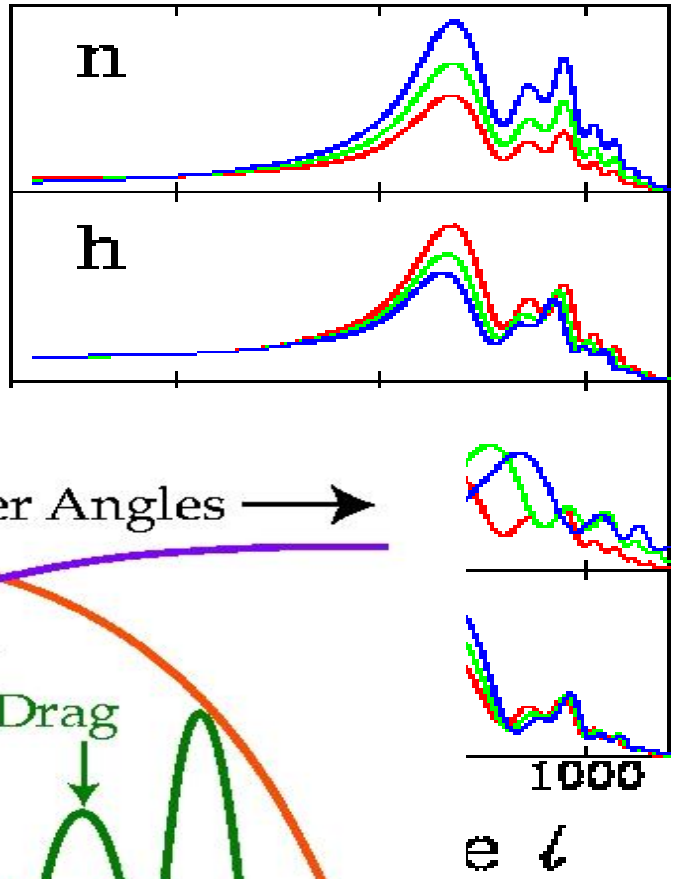


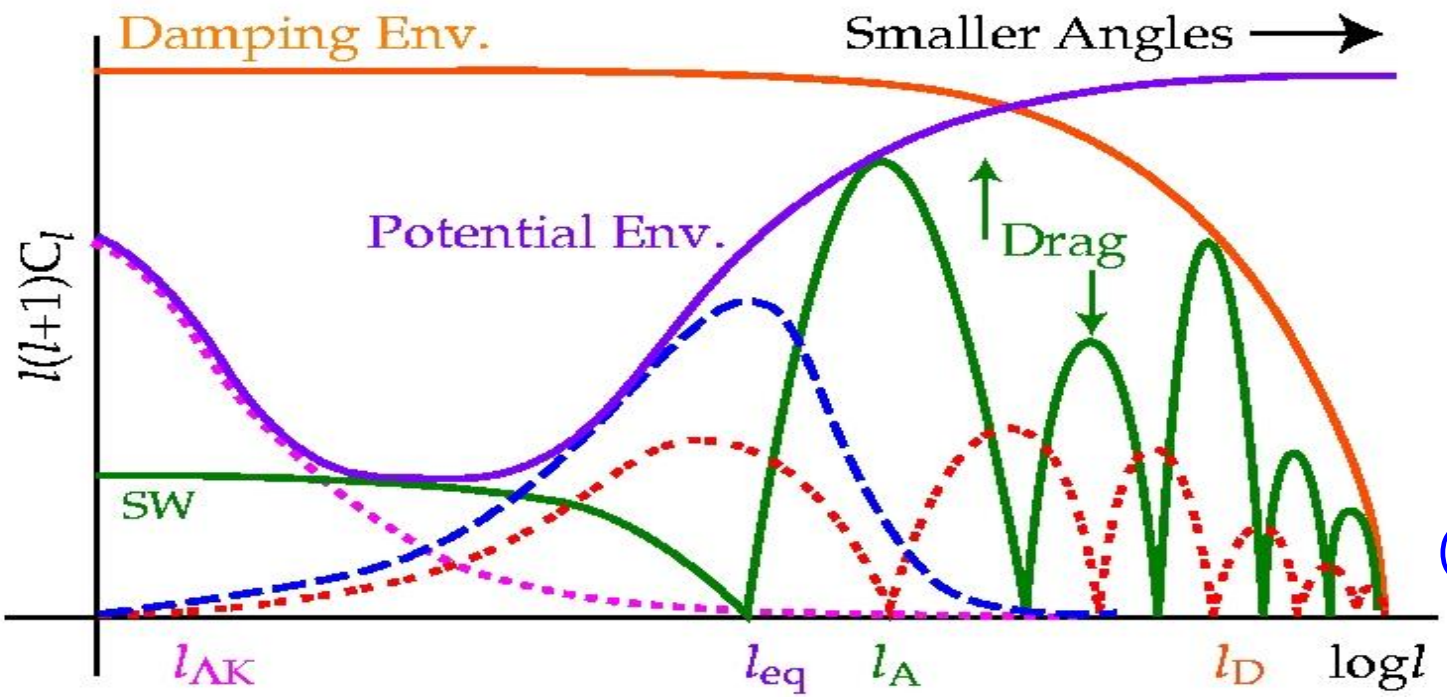
Planck CMB Polarization spectra



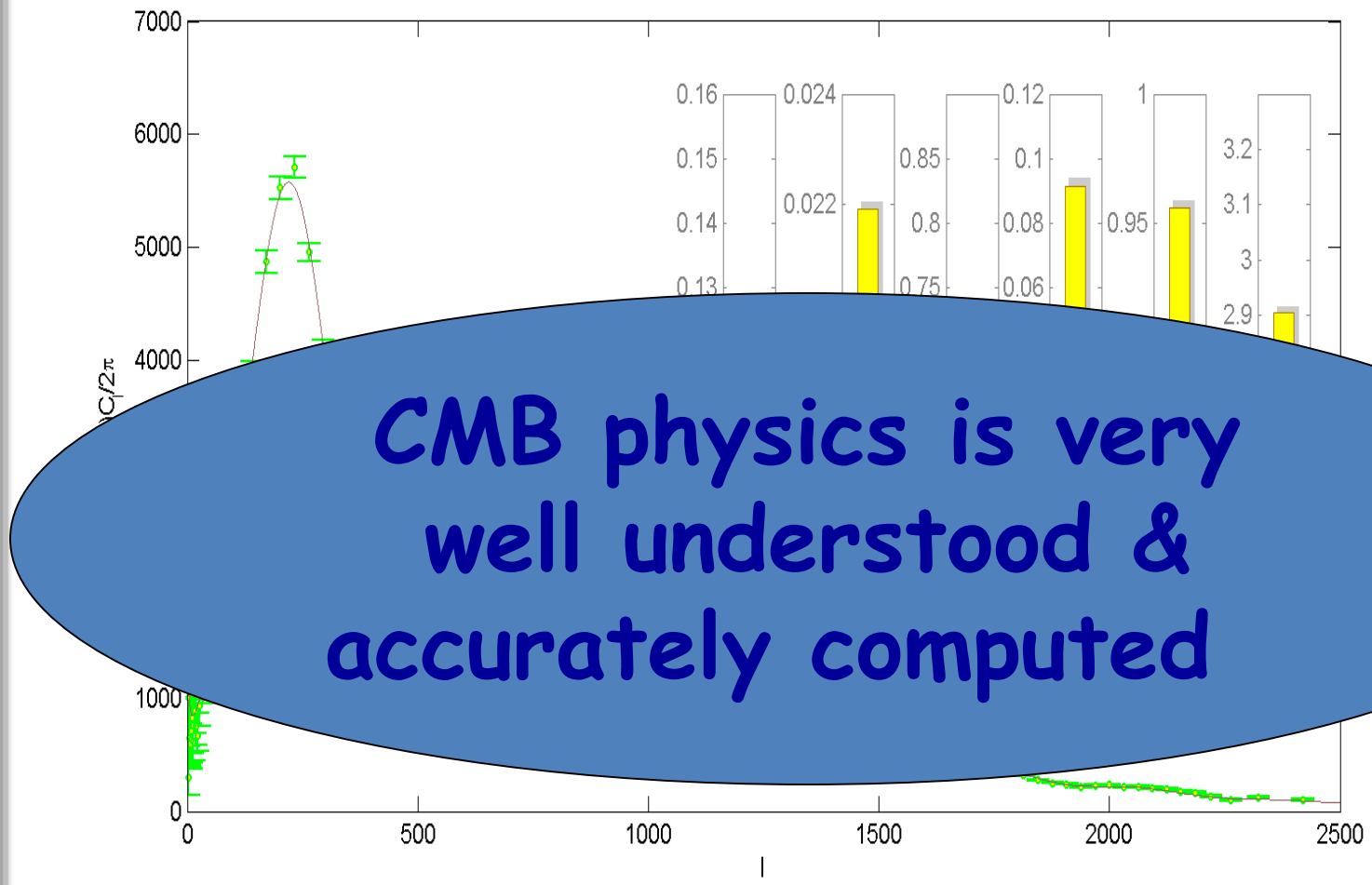
Acoustic physics
CMB Angular power spectrum







(fig credit: W. Hu)



CMB physics is very well understood & accurately computed

CMB@IUCAA: CMBAns Boltzmann code by Santanu Das

Multi-D Joint Posterior distribution

$P(\text{parameters} \mid C_\ell)$

Baryons: $\Omega_b h^2$

Cold Dark Matter: $\Omega_m h^2$

Hubble constant : H_0

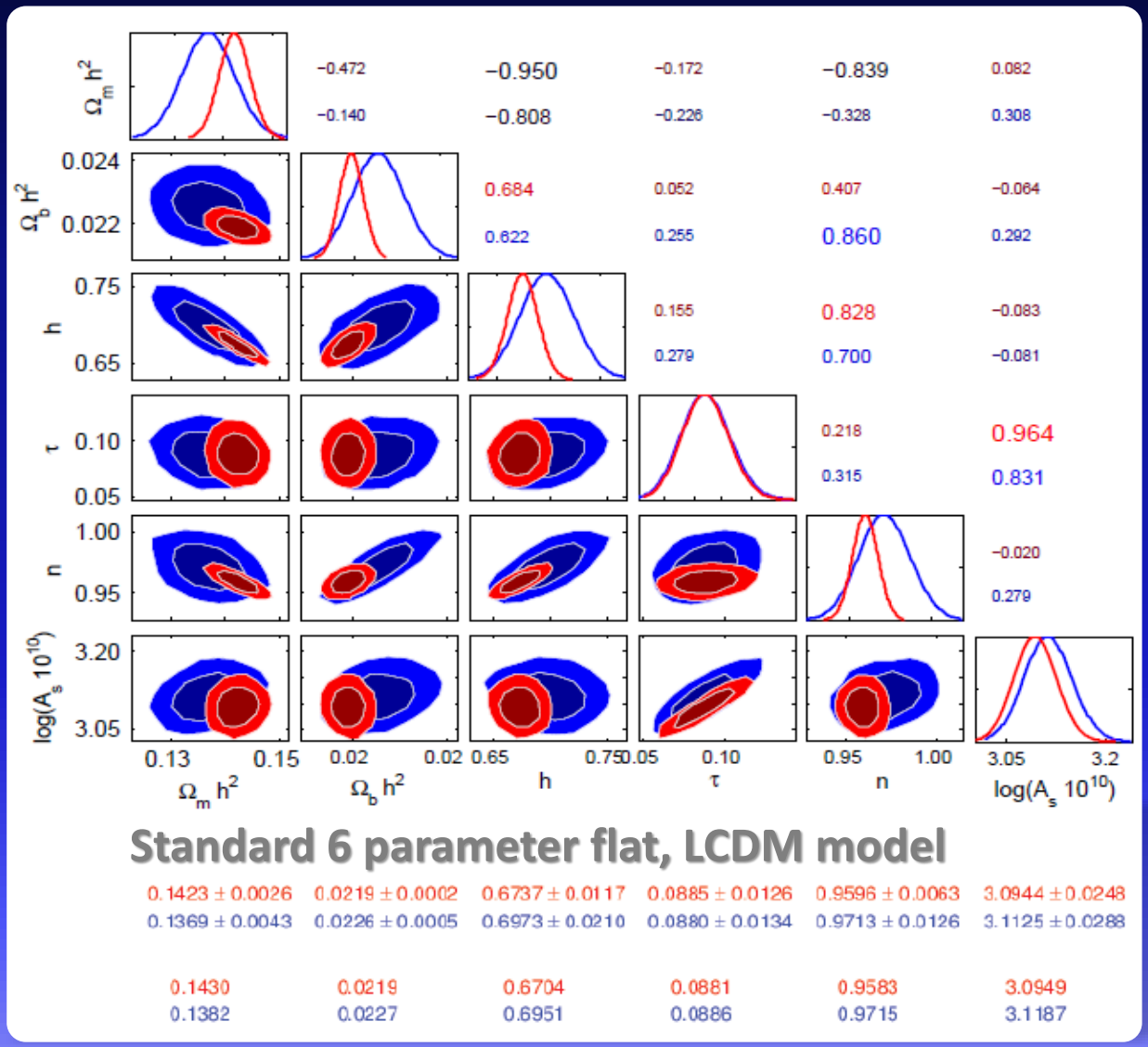
Reionization Depth : τ

Primordial fluctuations –

Spectral index: n_s

Amplitude: A_s

(S Das & TS : JCAP 2014)



Cosmological Parameters

6-Parameter ΛCDM

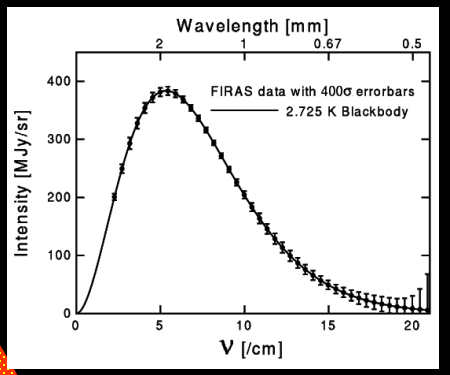
Parameter	*Planck* TT+lowP+lensing	
$\Omega_b h^2$	0.02226 ± 0.00023	1%
$\Omega_c h^2$	0.1186 ± 0.0020	1.7%
$100\theta_{MC}$	1.04103 ± 0.00046	0.04%
τ		
r_{drag} . . .		
k_{eq}	0.01027 ± 0.00014	1.4%

'Standard' cosmological model:
Flat, ΛCDM with nearly
Power Law (PL) primordial power spectrum

Paradigm of Hot & Dense early Universe

i.e., 'Big Bang' model

Cosmic "Super-IMAX" theater



0.5 Mega-years

43 Billion Light-years

Here & Now

(14 Giga-year

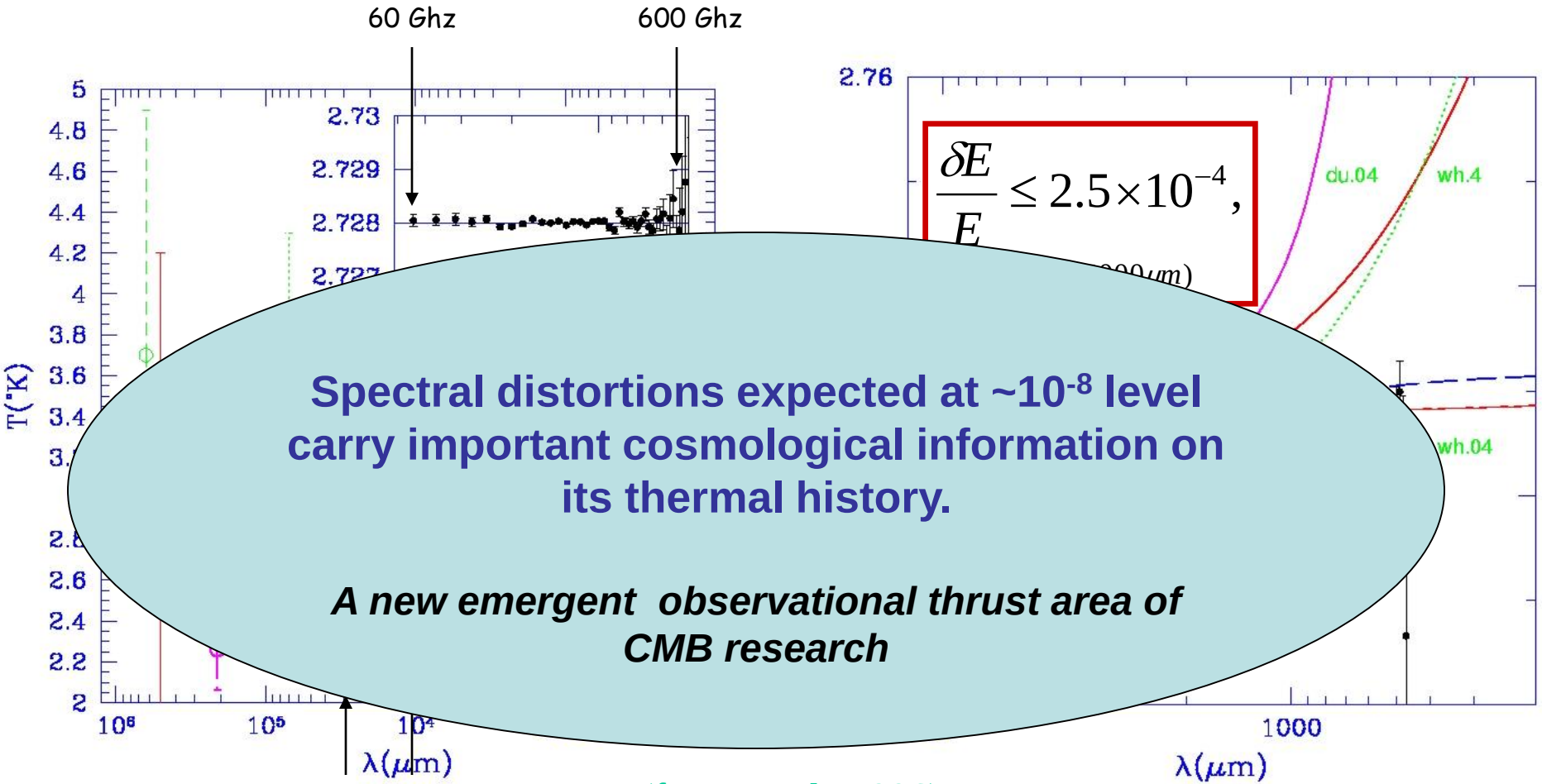
Tra

Opaque

Universe must have been at least (10^7x) hotter & 10^{21} x denser in its past

Cosmic Microwave Background

COBE-FIRAS results strongly constrain any Energy input into the CMB in the not-so-early universe ($z<10^5$)

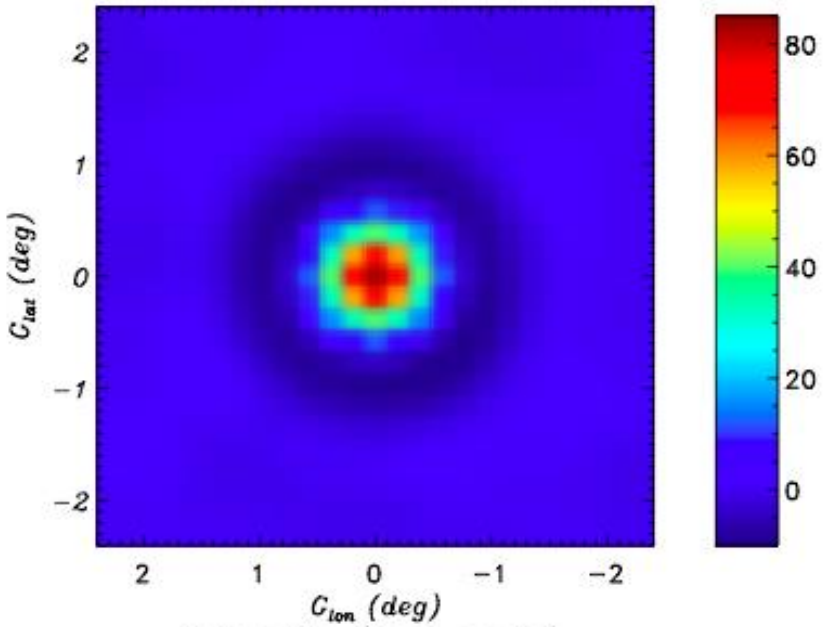


Spectral distortions expected at ~10^{-8} level carry important cosmological information on its thermal history.

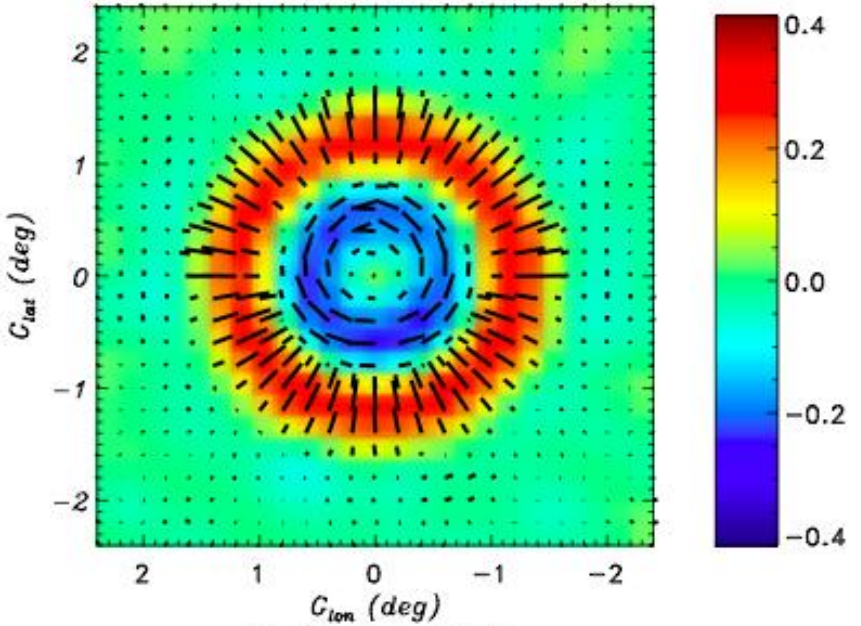
A new emergent observational thrust area of CMB research

(figs: Bond, 1996)

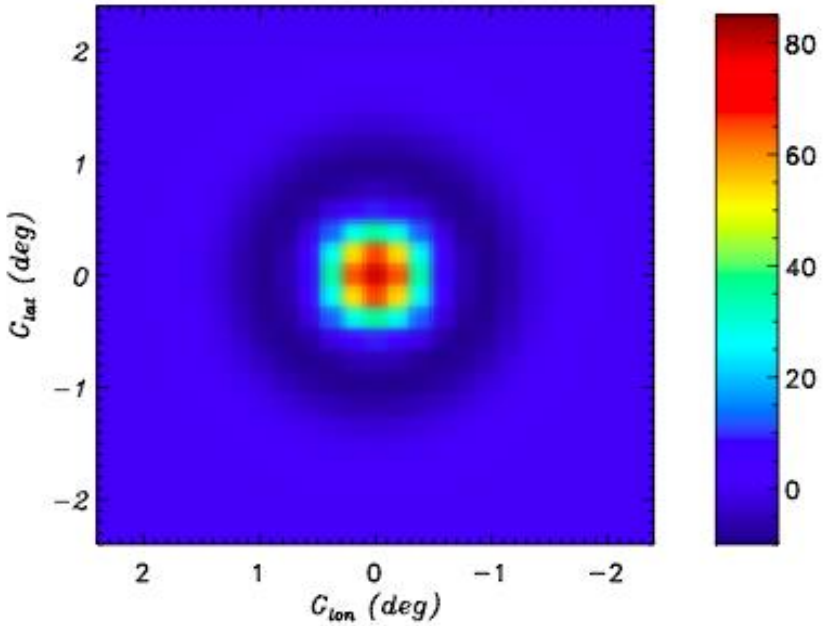
Paradigm of CMB flucs: Acoustic phenomena pre-recombination Plasma universe

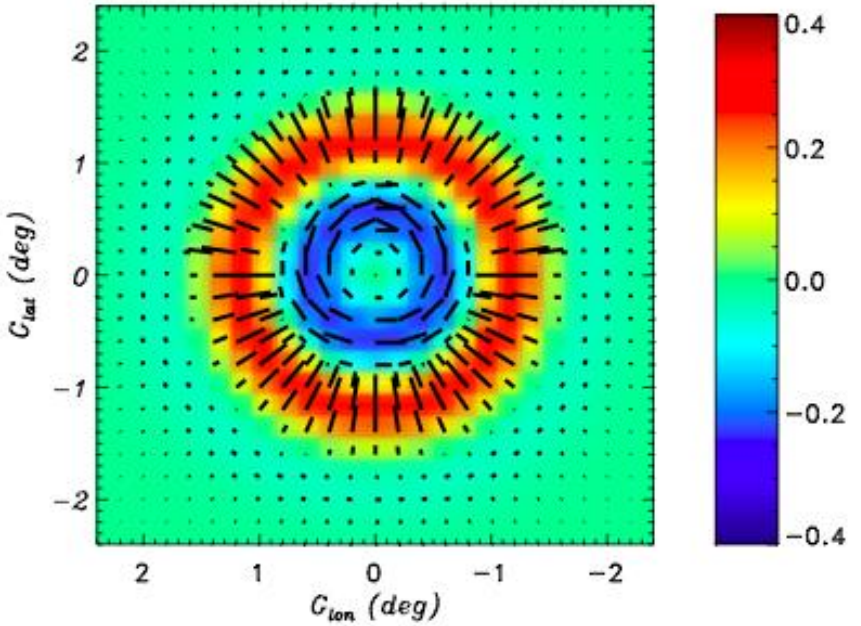


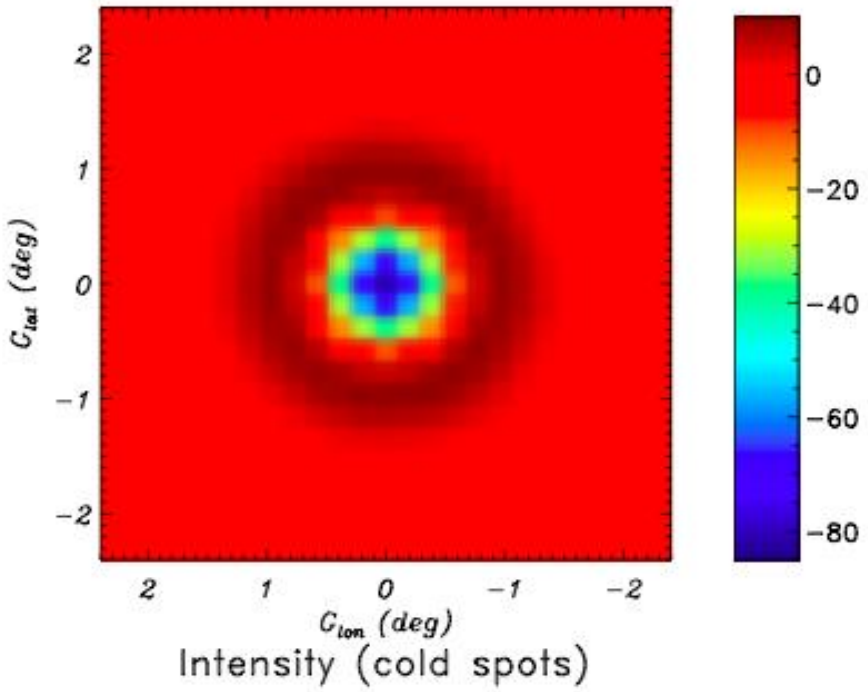
Intensity (hot spots)



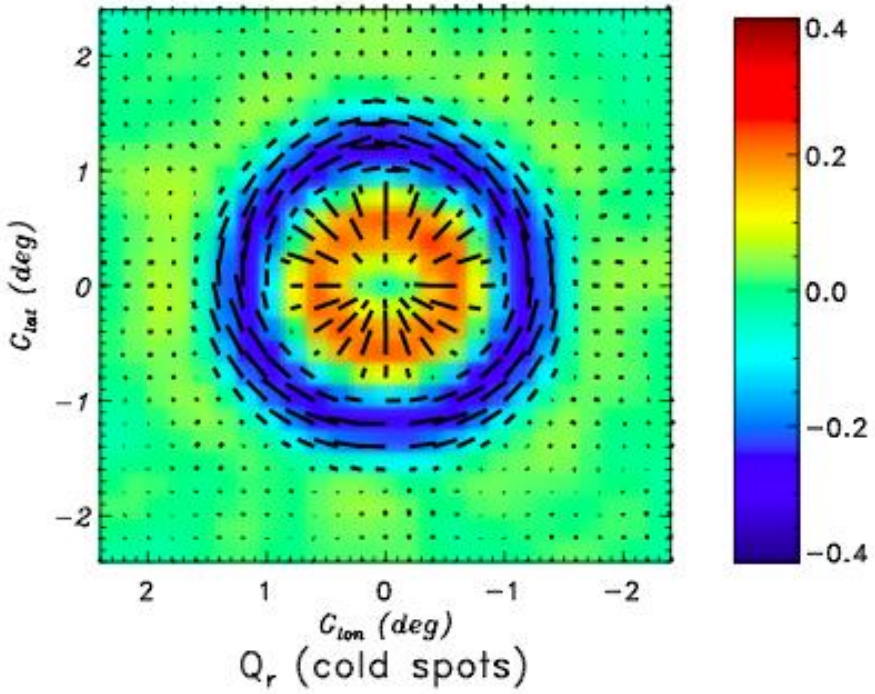
Q_r (hot spots)



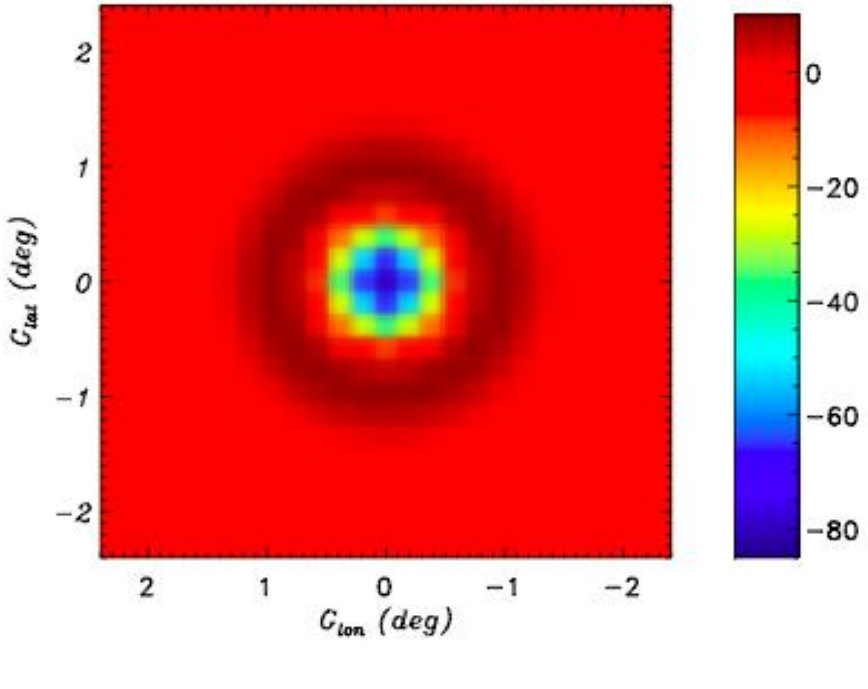


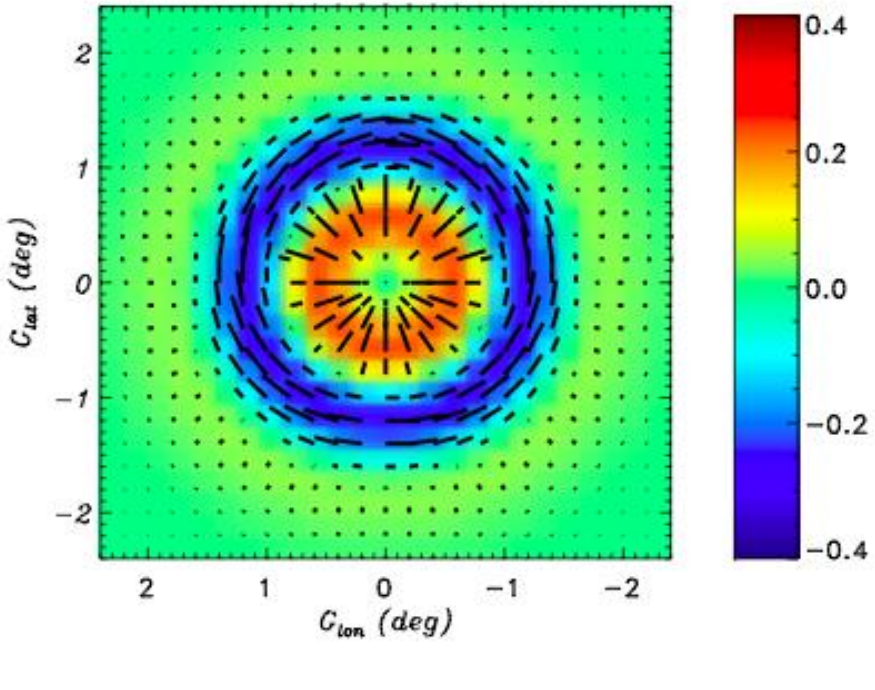


Intensity (cold spots)



Q_r (cold spots)



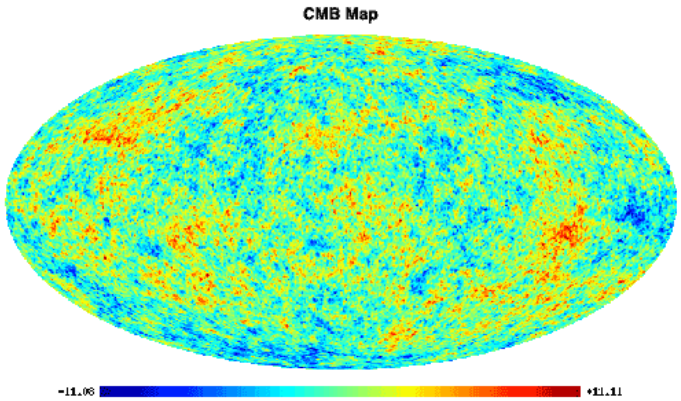


Paradigm of Structure formation?

- Backbone of `precision' cosmology

Gravitational Instability

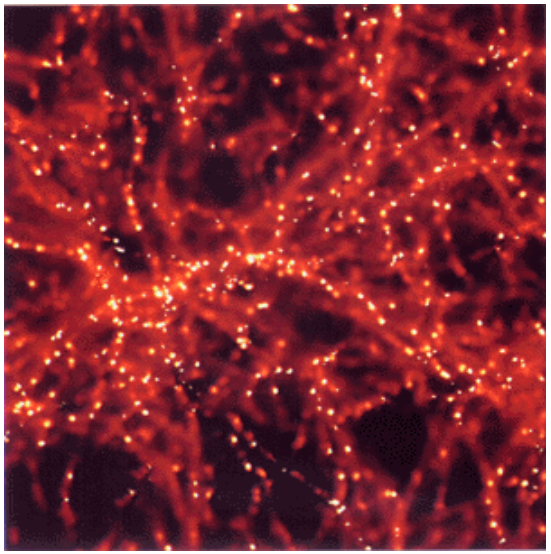
Mildly Perturbed universe at z=1100



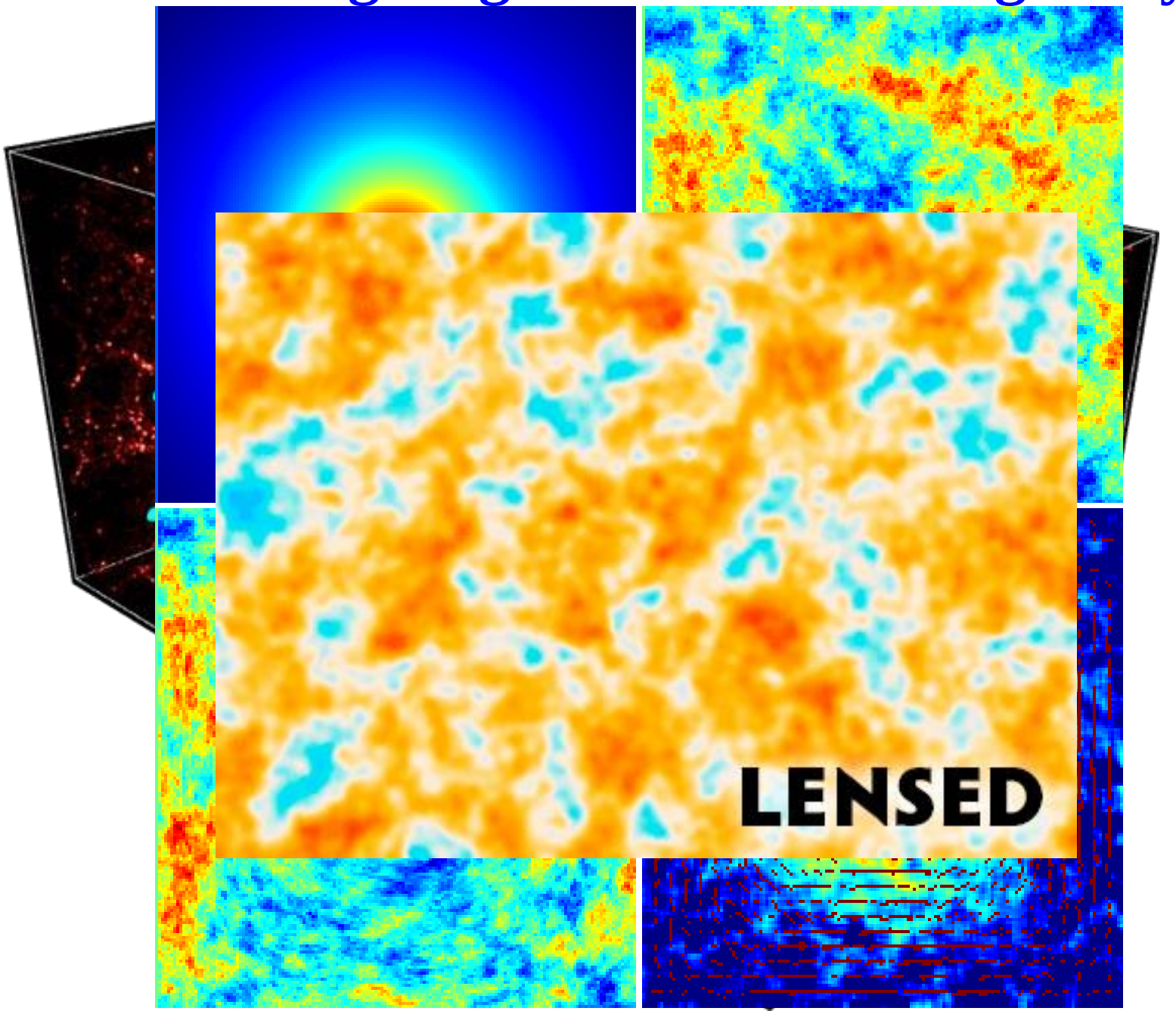
Cosmic matter content

Ω_{tot}
Ω_b
Ω_{DM}
Ω_Λ
H_0

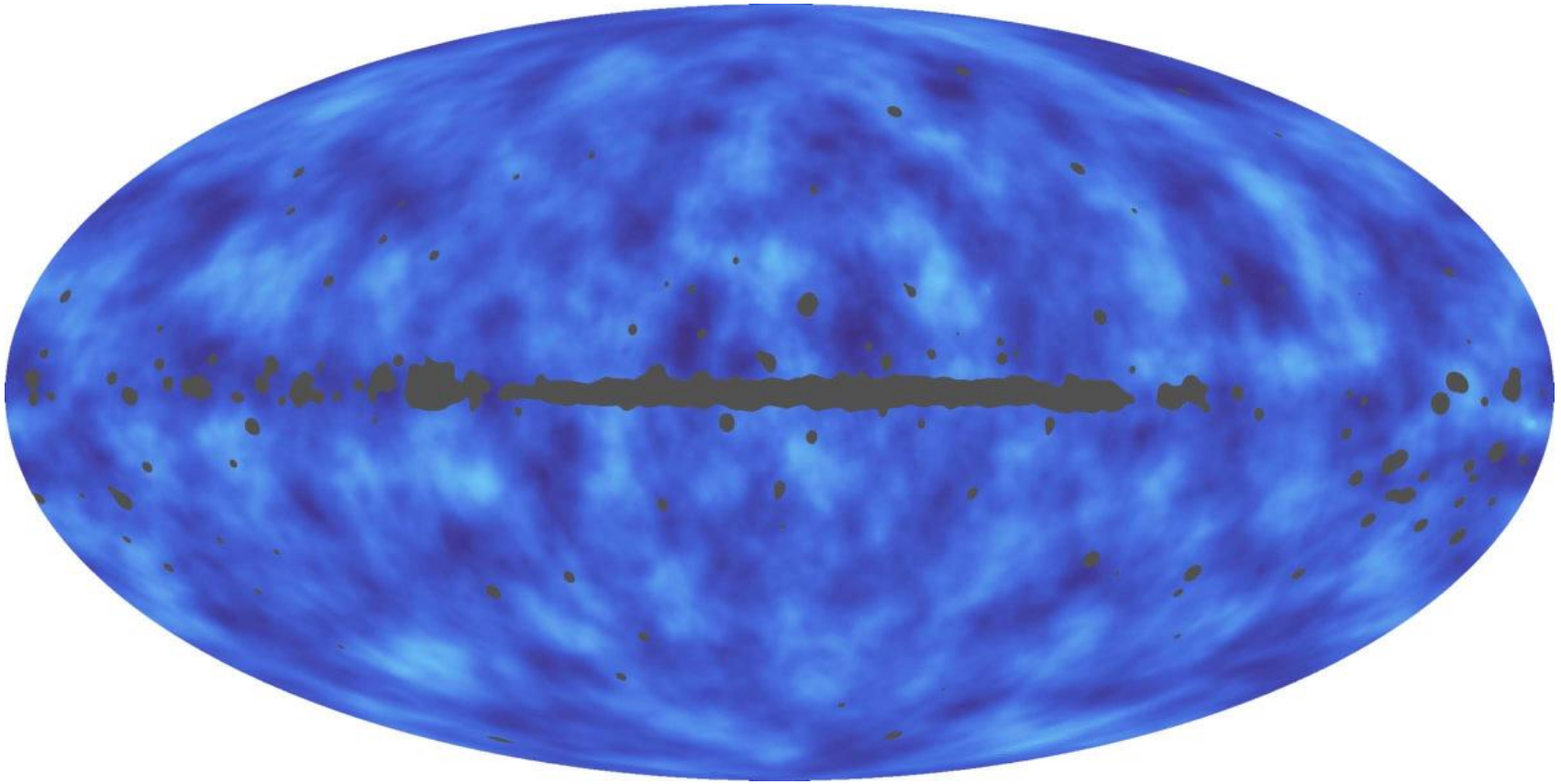
Present universe at z=0



Weak lensing: Light deflects due to gravity



Projected Lensing potential from Planck



01 2)#(&%, θ)

- r #* 748)5?#)01 2)k#+/)L %?' 95)
  $?7(, %,)&9".7$#)H"%?5(#&&)

  $$\Delta T(\hat{n}) \leftarrow \Delta T\left(\hat{n} + \vec{d}(\hat{n})\right)$$

)

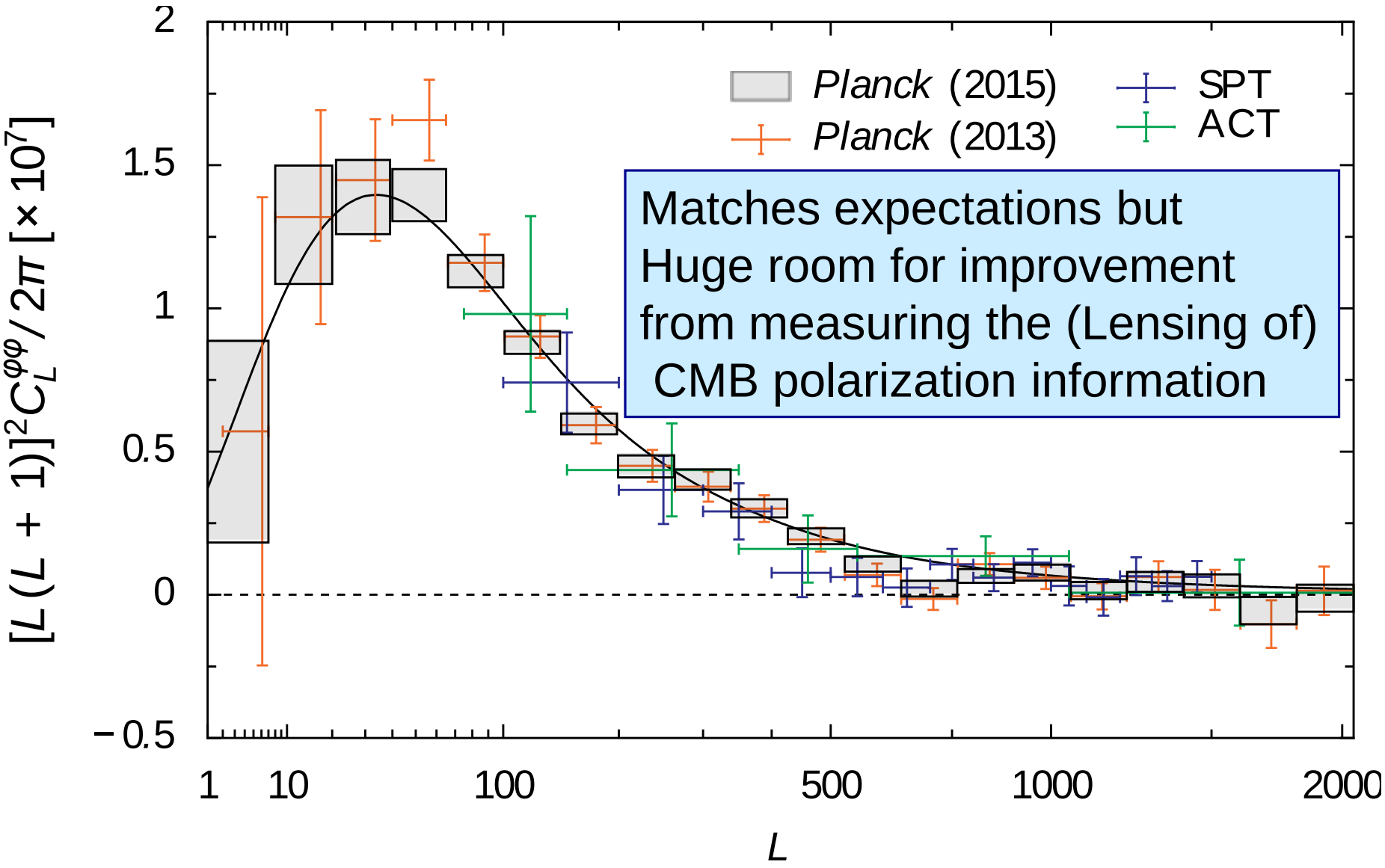
$$\vec{d}(\hat{n}) = \vec{\nabla}\Phi(\hat{n}) \quad \text{K\#(\&\%,)4' 5\#(I 7+)}$$

)

)))))>- 4%$7+)r 1 :)A7+9#)' .)/ θ)s)Q`])7"$* %))

Planck is the first experiment to provide a full-sky reconstruction of the projected mass, along every line of sight back to the surface of last scattering.)F;%247! #&! "&! #N! $!

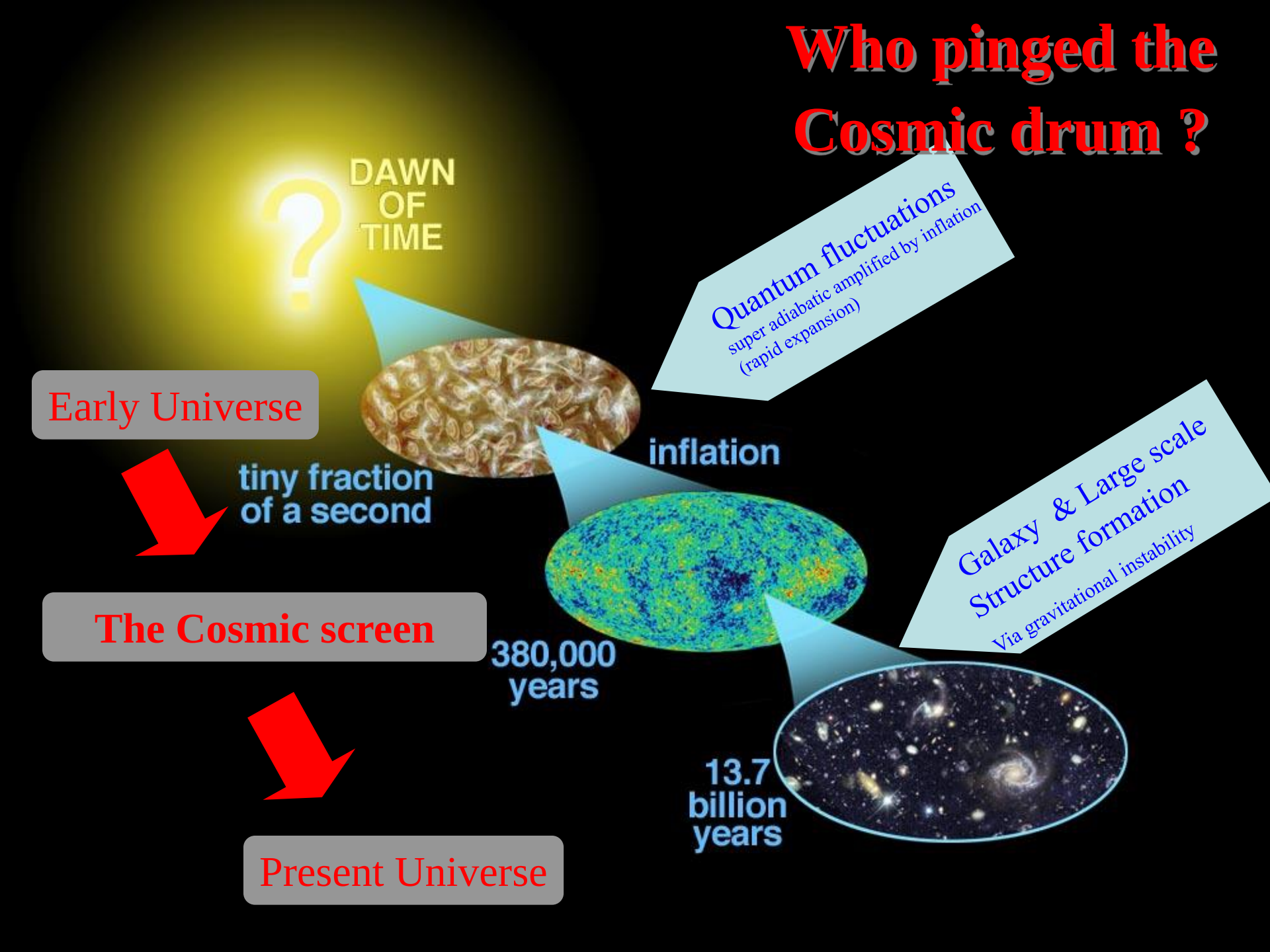
Projected Lensing power spectrum



Paradigm of Inflation in the Early Universe ?

- necessary to seed structure

Who pinged the Cosmic drum ?



Early Universe in CMB

The Background universe

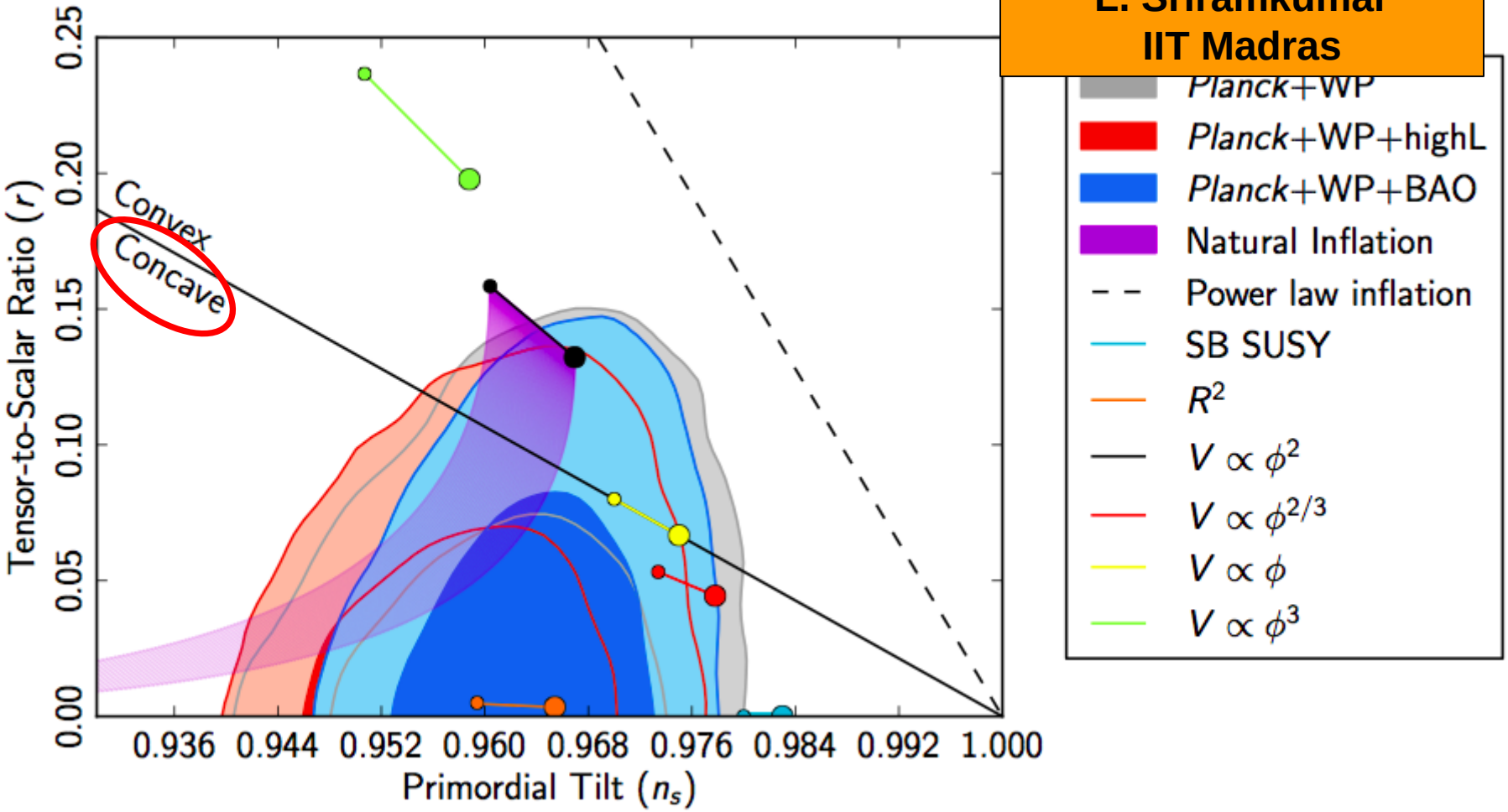
- Homogeneous & isotropic space: ***Cosmological principle***
- Flat (Euclidean) Geometry

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***

Status of Inflationary models

Talk by
L. Sriramkumar
IIT Madras



	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**

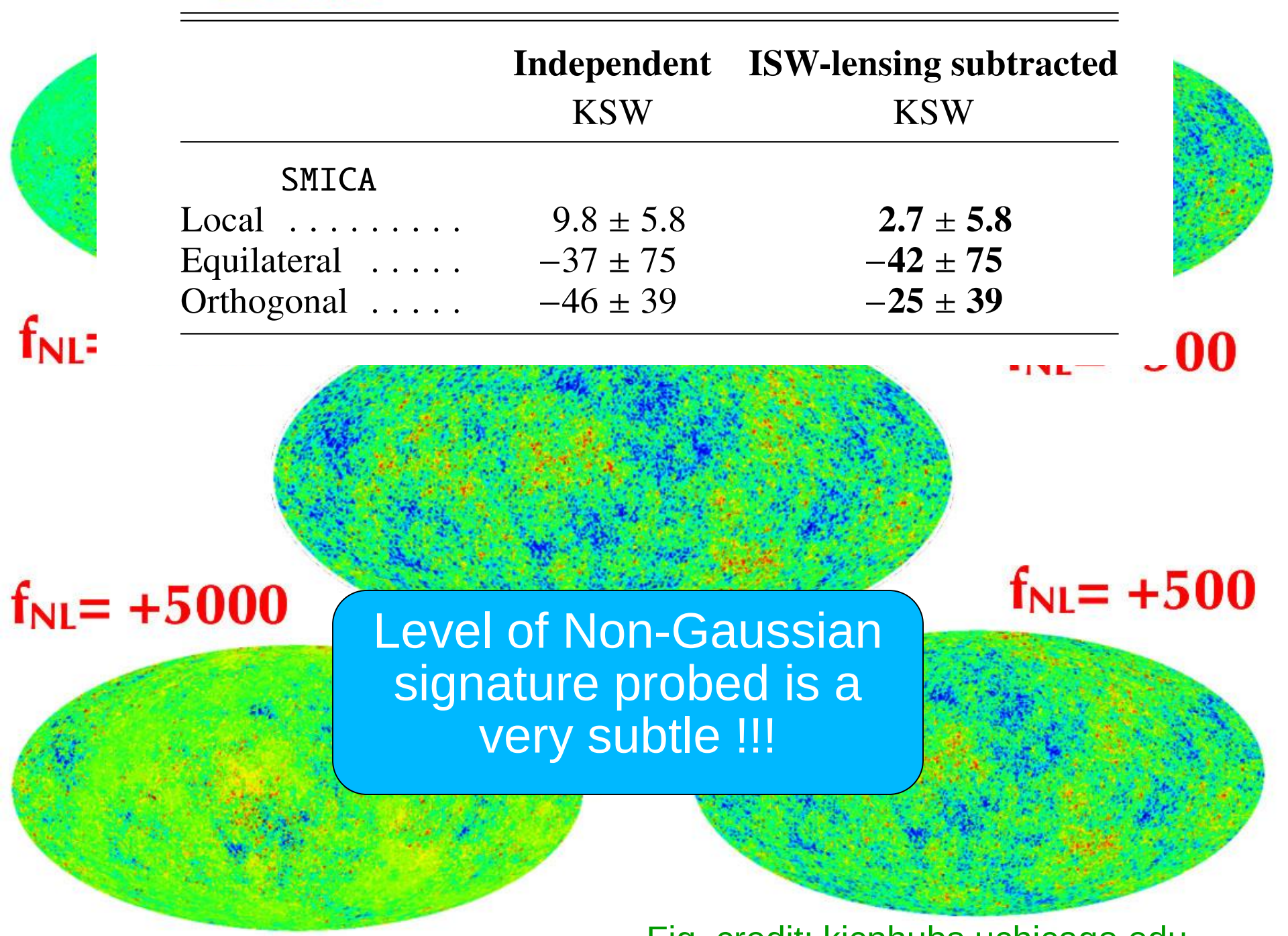


Fig. credit: kicphubs.uchicago.edu

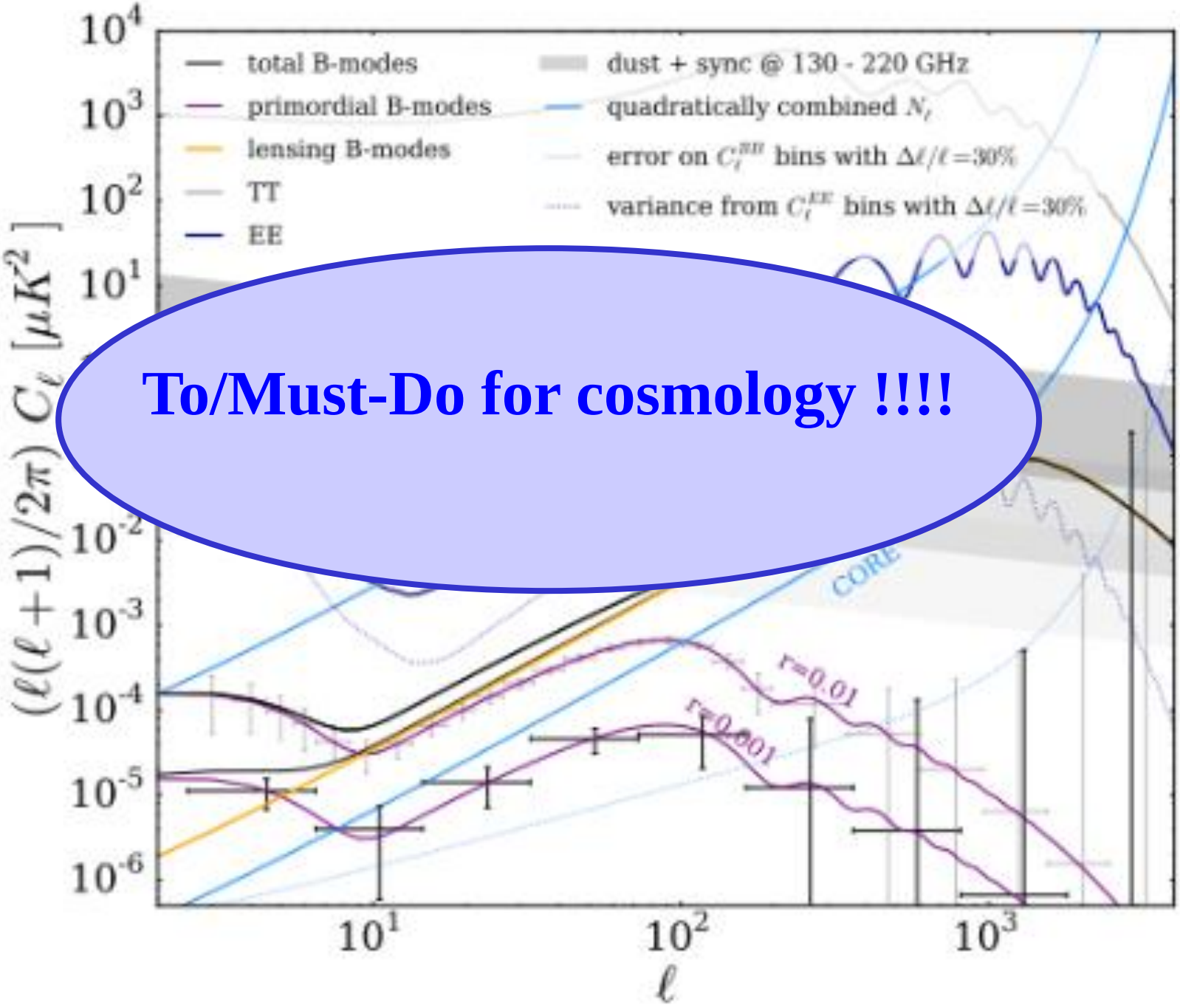
Early Universe in CMB

The Background universe

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

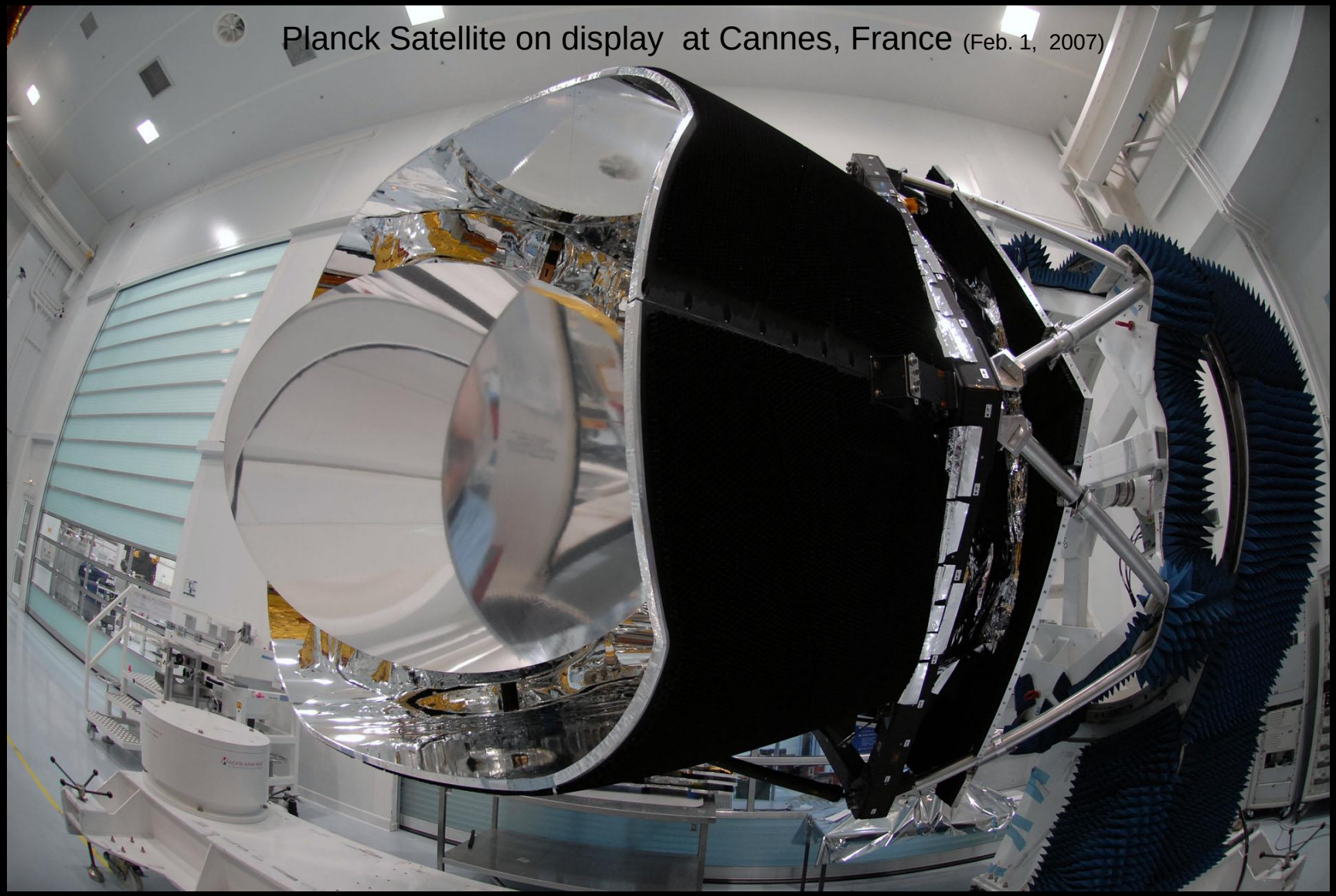
The nature of initial/primordial perturbations

- **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***


total B-modes
primordial B-modes
lensing B-modes
TT
EE
dust + sync @ 130 - 220 GHz
quadratically combined N_ℓ
error on C_ℓ^{BB} bins with $\Delta\ell/\ell=30\%$
variance from C_ℓ^{EE} bins with $\Delta\ell/\ell=30\%$
$(\ell(\ell+1)/2\pi)\ C_\ell\ [\mu K^2]$
ℓ
CORE
r=0.01
r=0.001
To/Must-Do for cosmology !!!!

Planck Surveyor Satellite

European Space Agency: Launched May 14, 2009 HFI completed Jan 2012



Planck Satellite on display at Cannes, France (Feb. 1, 2007)

4th Generation Mission Proposals/ Concepts

ESA

- COrE -> 2010
- PRISM -> 2013

  Comprehensive large scale mission
- COrE+ -> 2015
- CORE -> 2017

NASA

- EPIC/CMBpol -> 2009
- PIXIE -> 2017

  Spectroscopic study over several decades of frequency
- CMB Probe/PICO -> 2020

JAXA

- LiteBIRD -> 2008

  Has not yet been selected. Currently undergoing a Phase A study

Next CMB space mission: Why ?

- **Cosmic Microwave Background (CMB) measurements have been transformational for Cosmology**

- Planck mission (ESA) extracted ≈100% of CMB temperature information (> 1000 × information compared to COBE 1994, > 10 × WMAP)

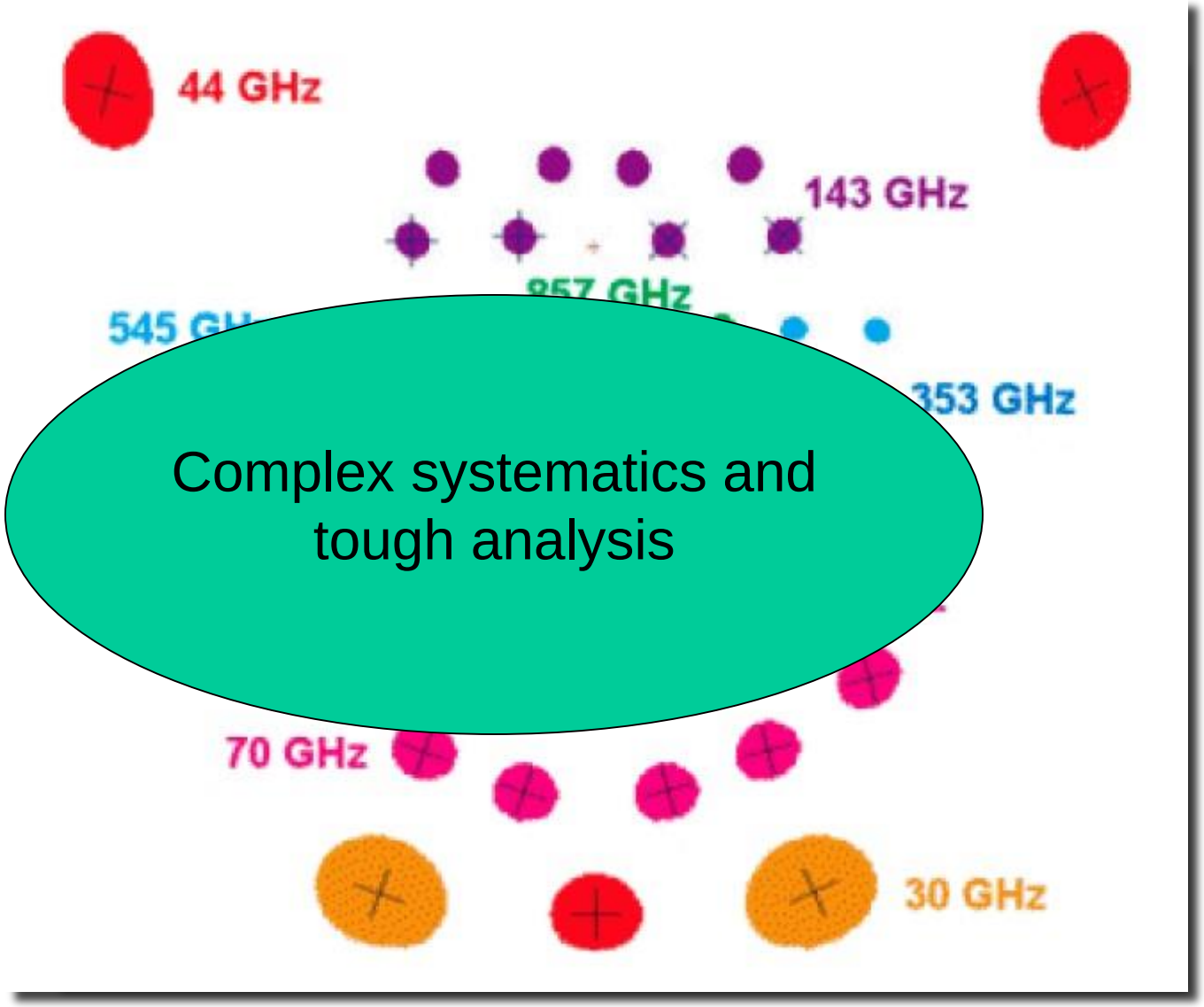
  But extracted only a small fraction (10%) of the rich **CMB polarisation information available** (and much less for specific measures)

  And, no significant addition on CMB spectral information since COBE

Scientific promise

- **Reveal signature of quantum gravity and ultra-HEP in the very early universe**
- **Improve probe of cosmological model by a factor of > 10 million**
- **Map all dark matter and most baryons in the observable universe**
- **Unique probe of the 'entire' thermal history of the universe**

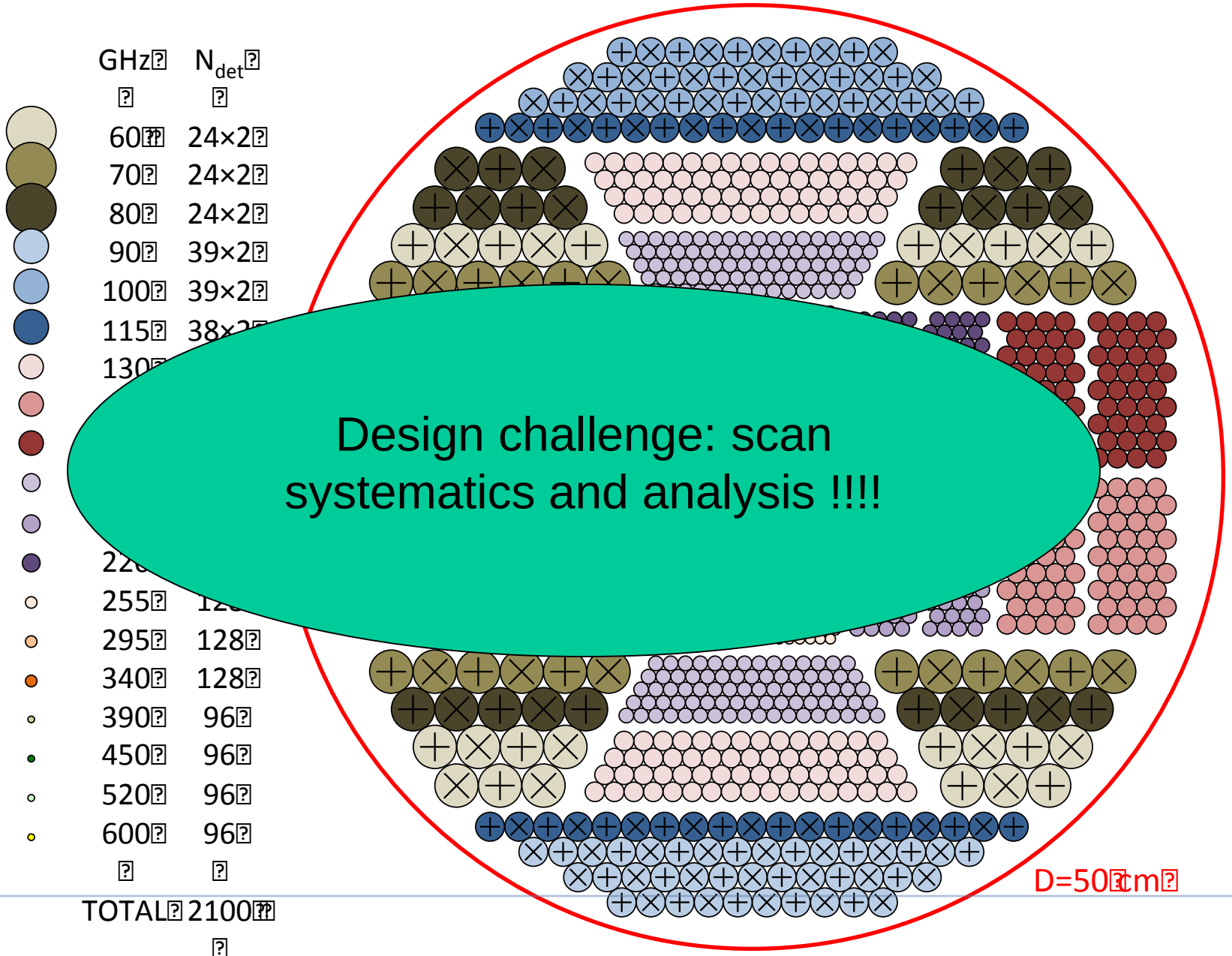
Planck Focal Plane



Complex systematics and tough analysis

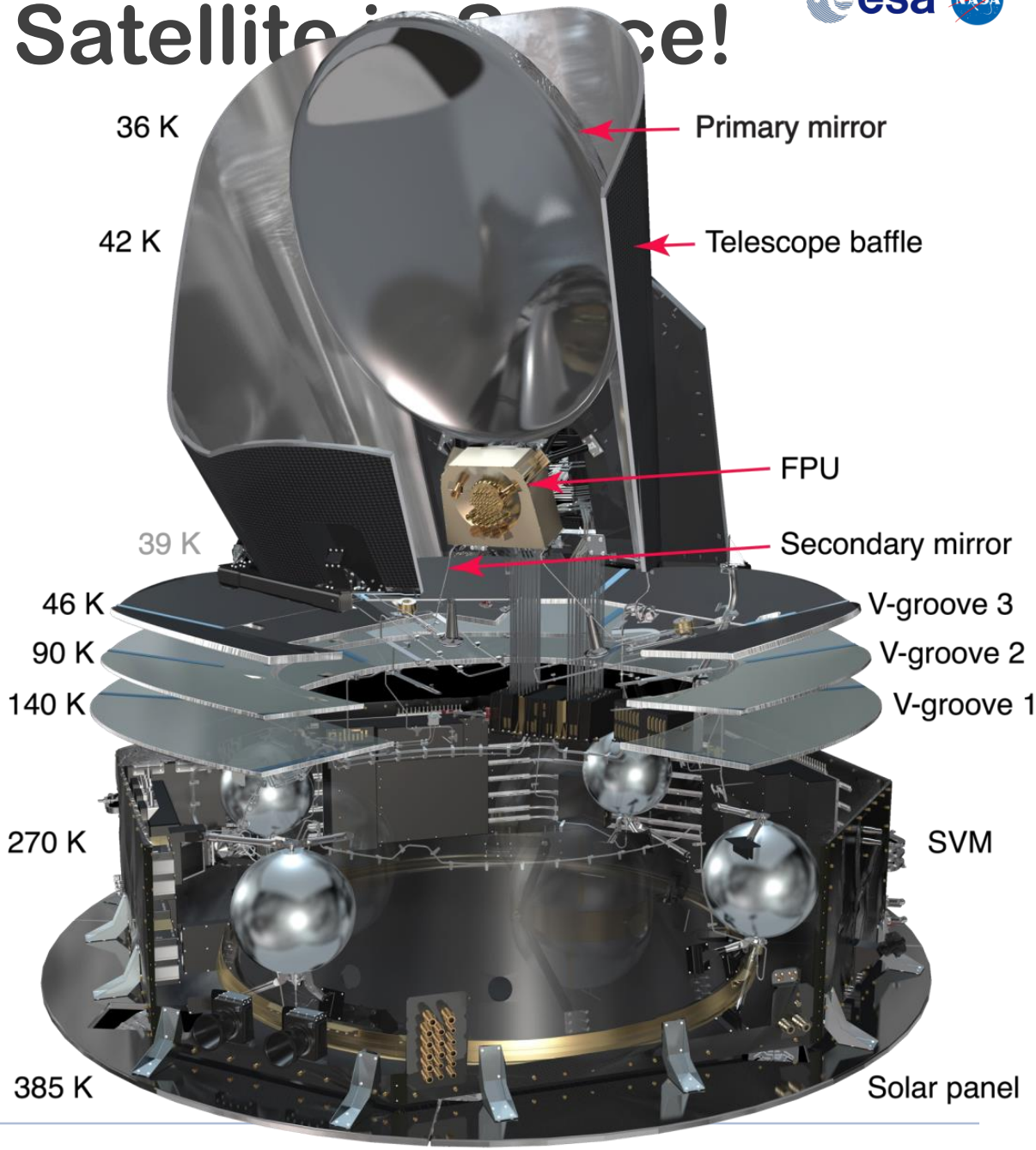
Credit: ESA, HFI & LFI consortia

CMB ‘next’ Focal Plane

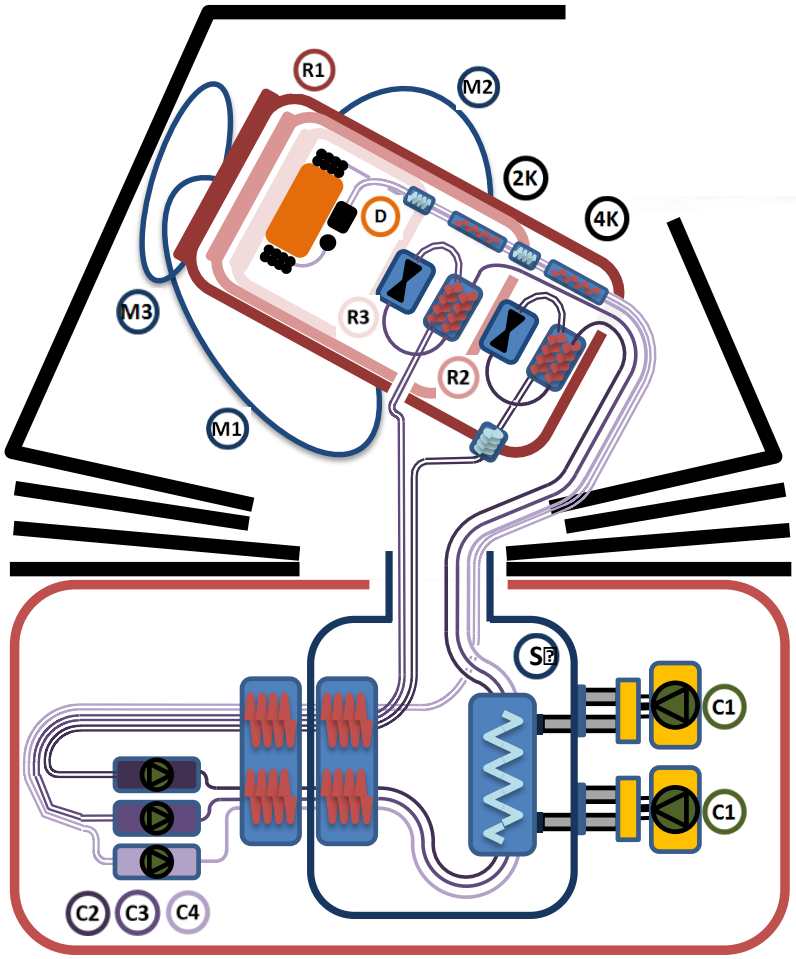


Coolest Satellite in Space!

- H_2 Sorption cooler
  - LFI FPU to < 20K
  - pre-cool lower stages
- ^{4}He J-T cooler
  - HFI FPU and LFI reference loads to < 5K
- Dilution cooler
  - HFI bolometers to 0.1K



Cryogenic Cooling chain

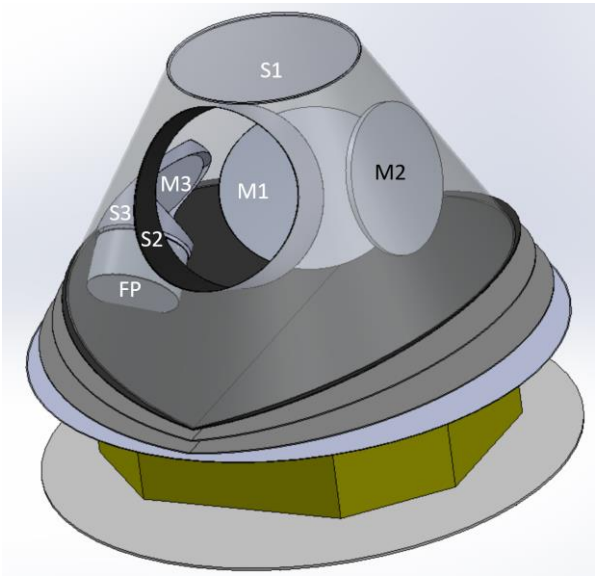


CFHX — LP

HEX — HP

C1	PTC 15K x3	M1	Mirror 1 50K
C2	4He JT COMP x2	M2	Mirror 2 50K
C3	3He JT COMP x2	M3	Mirror 3 50K
C4	3He D COMP x1	R1	Rad. Shield 15K
S	Shell 80K	R2	Rad. Shield 4K
V1	V-Groove 208K	R3	Rad. Shield 2K
V2	V-Groove 124K	4K	JT 4K x2
V3	V-Groove 77K	2K	JT 1.7K x2
V4	V-Groove 40K	D	CCDR 100mK

Strawman concept : CORE (ESA-M5)



≈ 4.0 m

≈ 4.4 m

CORE-M5 primary design driver: CMB polarisation

CORE-M5 Main characteristics:

-Total wet mass ≈ 2.0 tons

-Diameter ≈ 4.4 meter

-Height ≈ 4.0 meter

Adjustments are possible.

Designed for Ariane-6 but seems well suited for a GSLV Mk-III launcher towards a Sun-Earth L2 orbit

ISRO-ESA CMB mission Opportunity

- A next generation CMB mission is challenging, but doable
- Necessarily global cooperation: No single country/agency has all expertise, technology, resources, manpower to build it
- Post-Planck, European CMB community proposed the Cosmic Origins Explorer (CORE)
- **CORE designed to be a "near-ultimate" CMB polarisation mission** The proposed mission concept did not pass the initial technical and programmatic screening by ESA in January 2017.
- **The main issue is cost within an M-class envelope.**

ESA encouraged the CORE consortium to consider a joint proposal with a major international partner.

Indian contribution can be significant or even dominant with right partnerships and timely investments

Indian response

- A cross-institutional consortium of interested cosmologists *(**CMB-Bharat** set up formally on Jan 9th at ISRO HQ meet has ~ 50 members about 14 institutions/laboratories)*

- Meeting organized at ISRO-HQ on Jan 8-9, 2018 to demonstrate an Indian community capable of taking on the science.

- Meeting of ESA-CORE proposal PI & co-PI with Director, SSPO, ISRO in Oct 2018.

- ISRO announcement of opportunity (AO) for Astronomy missions & payloads with deadline Apr 16, 2018.
- Active working groups of CMB-Bharat now towards responding to AO

Scientific Objective

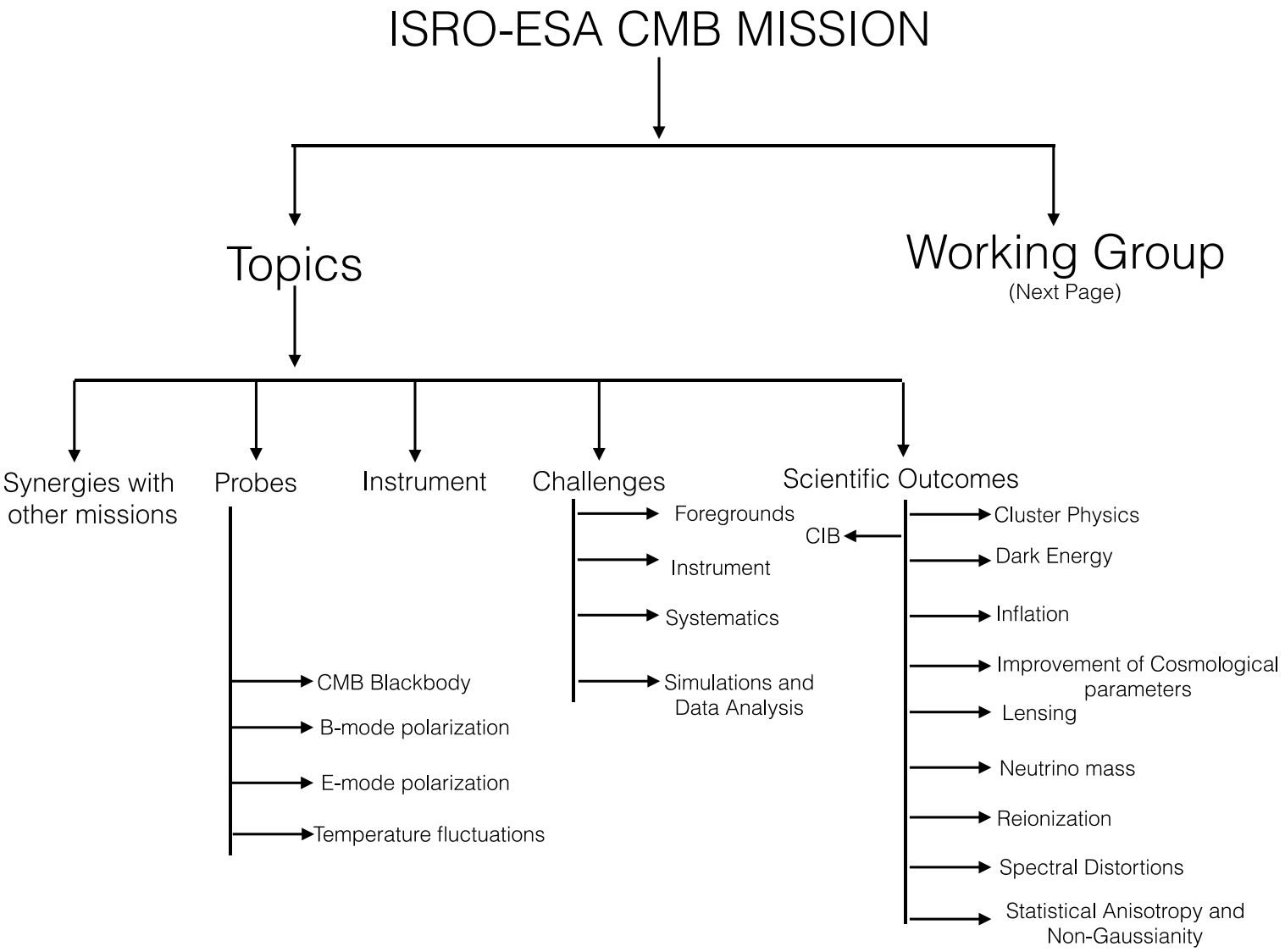
A "near-ultimate"
Cosmic Microwave Background polarisation survey

Options: * Enhanced spectral characterisation
**** Pointed observatory mode***

A "Capture-all" high value science and legacy CMB mission

- **Extract all cosmological information available in the CMB**
- **A unique window of opportunity: matched aspirations**
- **Balanced profile of S&T impact and returns**

The Scope & Challenge



Indian technical contribution

Capabilities achieved within India

- Service module
  - Design, fabrication, assembly, testing
- Launch to L2
- Tracking & control
- Orbit maintenance
- Science data downlink
- Data products and analysis
- Mission planning and operation

Indian technical contribution

Capabilities achieved with modest planned investments

- Telescope and Optics
  - Design, fabrication, assembly, testing
  - Reflectors, baffling
  - Reimaging optics, filters
- Science Payload
  - Design, assembly, testing

Indian technical contribution

Capabilities achieved with long-term planned investments

- Broadband photon-noise-limited sensors & readout for CMB frequency bands
- Cryogenic coolers at 100mK in space

Indian technical contribution

Benefits of making medium- and long-term strategic investments

- Build upon capabilities in ISRO, and enhance experimental physics efforts at academic institutions in India.
- Expand nanofabrication, MEMS and cryogenics capabilities as well as people trained to use and exploit these resources, which can have very wide applications in Indian science community.
- Quantum sensor technologies developed for CMB frequency bands can be extended to other bands in astronomy (X-ray, gamma ray), spectroscopy in various bands, particle physics applications and even to quantum computing.
- Developing Labs and Test Infrastructure will be useful in the long term for training young scientists and engineers.

CMB-Bharat Working groups

Cluster Physics from CMB:
Lead: Subhabrata Majumdar (TIFR)
Members: Suvodip Mukherjee, Dhiraj Hazra, K.P. Singh, Siddharth Savyasachi Malu, Abhirup Datta, Priyanka Singh

Foregrounds and CIB:
Lead: Tuhin Ghosh (NISER)
Members: Rajib Saha, Soumen Basak, Pavan K. Aluri, Moumita Aich, Ranajoy Banerji, Aditya Rotti, Abhirup Datta, Pravabati Chingangbam, Sandeep Rana (List Here)

Instrument science:
Lead: Zeeshan Ahmed (Stanford Univ)
Members: Aafaque R Khan, Rahul Datta, Mayuri S.Rao, Ritoban Thakur

Inflation:
Lead: L. Sriramkumar (IIT Madras)
Members: Dhiraj Hazra, Anshuman Maharana, Urjit Yajnik, Raghu Rangarajan, Supratik Pal, Anjan Ananda Sen, Subodh Patil, Rajeev Kumar Jain, Gaurav Goswami, V. Sreenath, Debika Chowdhury, Pravabati Chingangbam, Moumita Aich (List here)

CMB-Bharat Working groups

Cosmological parameters:

Lead: Dhiraj Hazra (APC, Paris → NISER?,…)

Members: Suvodip Mukherjee, Rajib Saha, Urjit Yajnik, Supratik Pal, Anjan Ananda Sen, Rajeev Kumar Jain, Ujjaini Alam, Barun Kumar Pal, Arindam Chatterjee, H K Jassal, Priyanka Singh

Lensing:

Lead: Suvodip Mukherjee (CCA, NY)

Members: Dhiraj Hazra, Anjan Ananda Sen, Supratik Pal, Aditya Rotti, Shabbir Shaikh, Rajorshi Sushovan Chandra, Barun Kumar Pal, Ashish Meena, Priyanka Singh

Simulations and Data Pipelines:

Lead: Jasjeet Singh Bagla (IISER Mohali)

Members: Soumen Basak, Tuhin Ghosh, Shamik Ghosh, Ranajoy Banerji, Rahul Kothari, Aditya Rotti, Abhirup Datta, Nishikanta Khandai

Spectral Distortions:

Lead: Rishi Khatri (TIFR)

Members: Suvodip Mukherjee, Anjan Ananda Sen, Aditya Rotti, Subodh Patil, Rajeev Kumar Jain, Biman Nath

CMB-Bharat Working groups

Statistics: Isotropy and Gaussianity:
Lead: Aditya Rotti (U Manchester)
Members: Suvodip Mukherjee, Dhiraj Hazra, Rajib Saha, Urjit Yajnik, Shamik Ghosh, Pavan K. Aluri, Subodh Patil, Rahul Kothari, Nidhi Pant, Shabbir Shaikh, Rajorshi Sushovan Chandra, Pravabati Chingangbam, Moumita Aich, Sandeep Rana

Systematics:
Lead: Ranajoy Banerji (U. Oslo)
Members: Abhirup Datta, (List Here)

Synergy with Astrophysics:
Dust in ICM/IGM, science at ~1.3 TeraHz
Members: K. P. Singh, Jasjeet Singh Bagla, Priyanka Singh

Synergy with ground experiments:
Lead: Mayuri Sathyanarayana Rao
Members: Abhirup Datta, Siddharth Malu

Most CMB space mission
Planck launch 2009

Indian mission
launch

?

Thank you !!!