CMB-Bharat

Exploring Cosmic History and Origin

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- Jasjeet Bagla (IISER Mohali)
- Zeeshan Ahmed (SLAC, Stanford)
- Mayuri Rao (UC Berkeley & RRI)
- Tirthankar Roy Chowdhury (NCRA)
- Ranajoy Banerjee (U Olso)
- Aditya Rotti (U Manchester)

Rishi Khatri

TIFR

On behalf of CMB-Bharat

(An Indian Cosmology consortium)

Next CMB space mission: Why ?

- **CMB measurements have been transformational for Cosmology**

- Planck mission (ESA) extracted ≈100% of CMB temperature information
  But only a small fraction (10%) of the rich **CMB polarisation information**

Scientific promise:

•**ULTRA- HIGH: Reveal first clear signature of quantum gravity and ultra-HEP in the very early universe**

(GW of Quantum Origin. Note, LIGO detected 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**

CMB space mission proposals

	Spectral distortions (Absolute Calibration)		B-modes
Low resolution	PRISTINE (ESA)		LITEBIRD (JAXA)
		PIXIE (NASA)	
	ECHO (ISRO)?		
High resolution			CORE (ESA) PICO (NASA) ECHO (ISRO)
		PRISM (ESA)	

Indian response: Context

- **Context:** European CMB proposal CORE (Cosmic Origins Explorer)
  Did not pass the initial programmatic screening by ESA in Jan 2017.
  High science rating (APPEC, CNES prospective) & support from member states, **but cost did not fit within an M-class envelope**.
  Suggested to seek international partners

- **First discussions** of Indian participation June 2017, mentioned at ISRO-Astrosat panel discussion in Sep 2017. Meeting of CORE proposal PI & co-PI with SSPO, ISRO in Oct 2017 to explore joint collaboration prospects .

- **Meeting at ISRO-HQ on Jan 8-9, 2018** to demonstrate an Indian community capable of taking on the science.
  - Possibility of launching ISRO-ESA joint study
  - **CMB-Bharat:** Cross-institutional Indian cosmology consortium

  Set up formally on Jan 9th at ISRO HQ meet ~ 90 members from ~15 institutions/laboratories & growing
- **Suggested to respond to AO as next step**

- **Proposal by CMB-Bharat consortium to ISRO on Apr 16, 2018.**
- **Presentation to evaluation committee Jun 6, 2018**
- **Shortlisted for presentation to ADCOSS Dec 29, 2018**

Balanced Impact-Returns profile

Science

Path-breaking

High value

Legacy

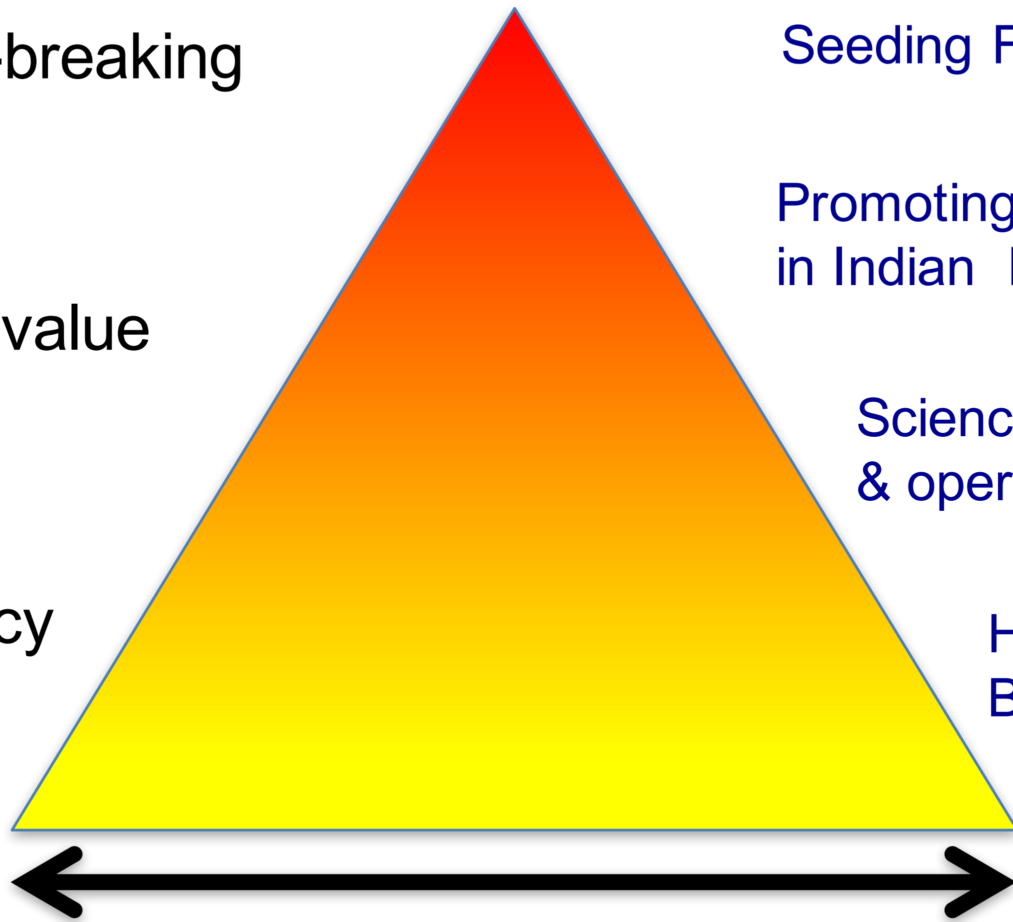
Technology

Seeding Frontier programs

Promoting nascent technology in Indian Labs & Industry

Science mission planning & operation at L2

HPC, IT and Big-data



breadth

Discovery Space for the next CMB mission

Discovery

Primordial B-modes
(Gravitons)

Precision measurement
(of things already discovered)

Lensing B-modes
Spectral Distortions
E-modes

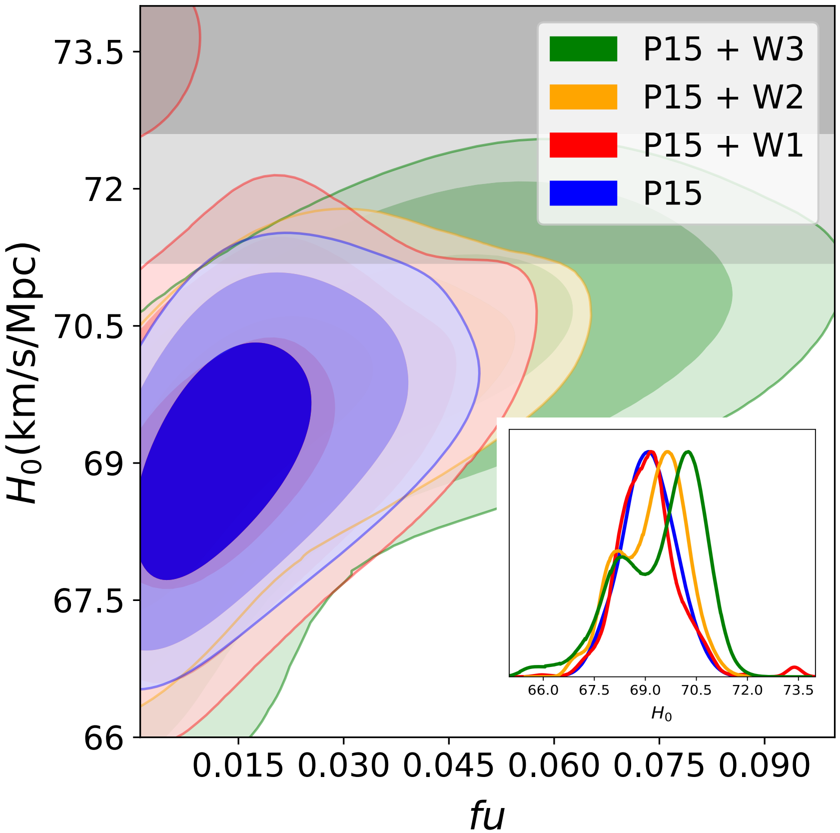
Discovery

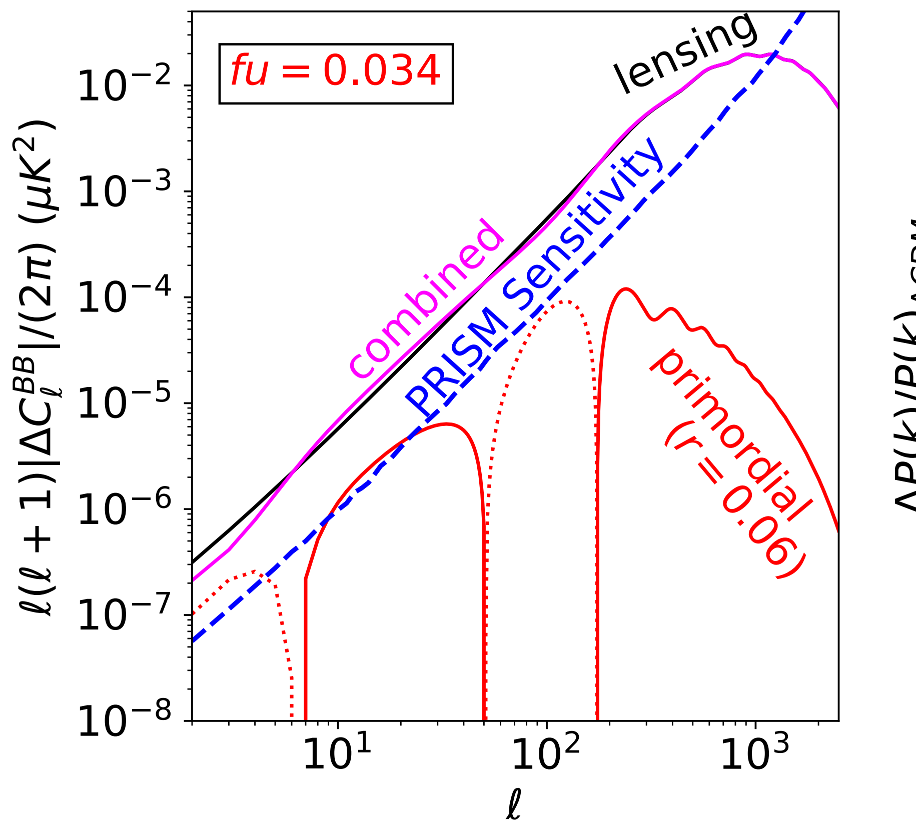
17 e-folds of inflation, Nature of Dark Sector,
Primodial Black Holes, Topological Defects,
New interactions, particles

Hubble Tension and Lensing B-modes

$$\cos(\,kr_s + \phi_\nu(k)) \Rightarrow \ell_{peak} \approx \frac{D_A(m\pi - \phi_\nu)}{r_s}$$

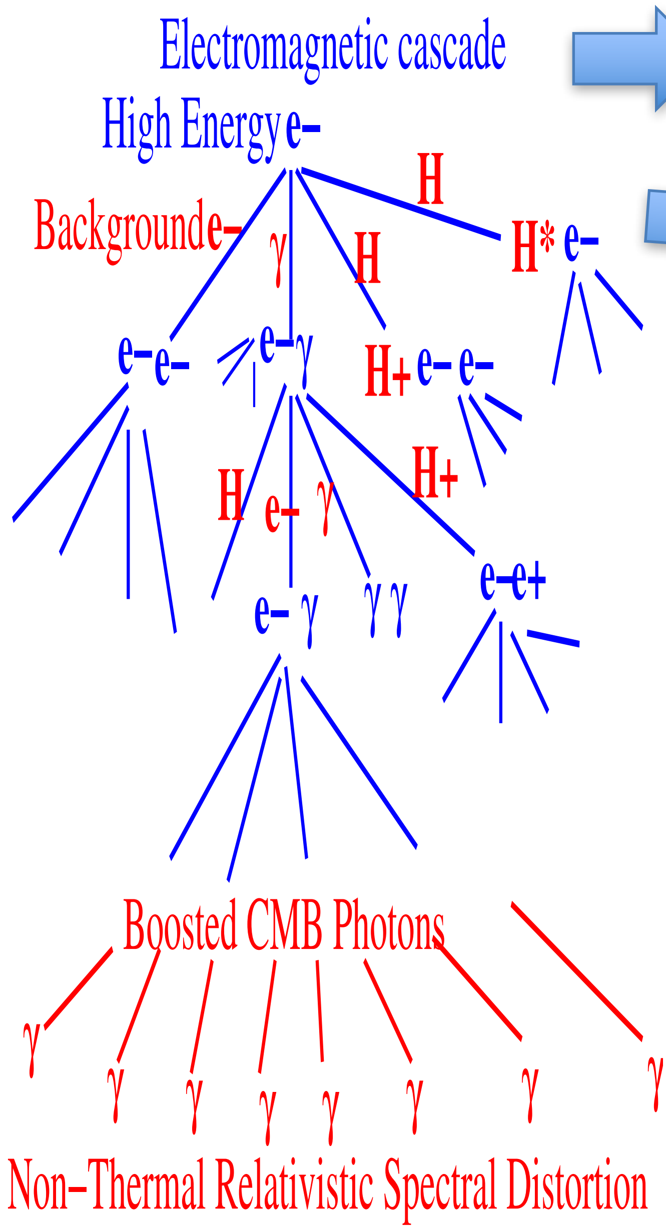
Stopping neutrinos from free streaming shifts acoustic peaks

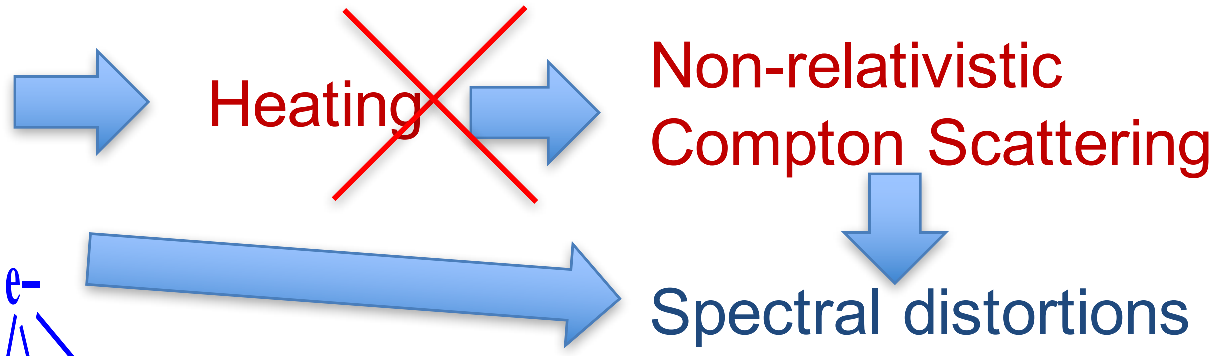


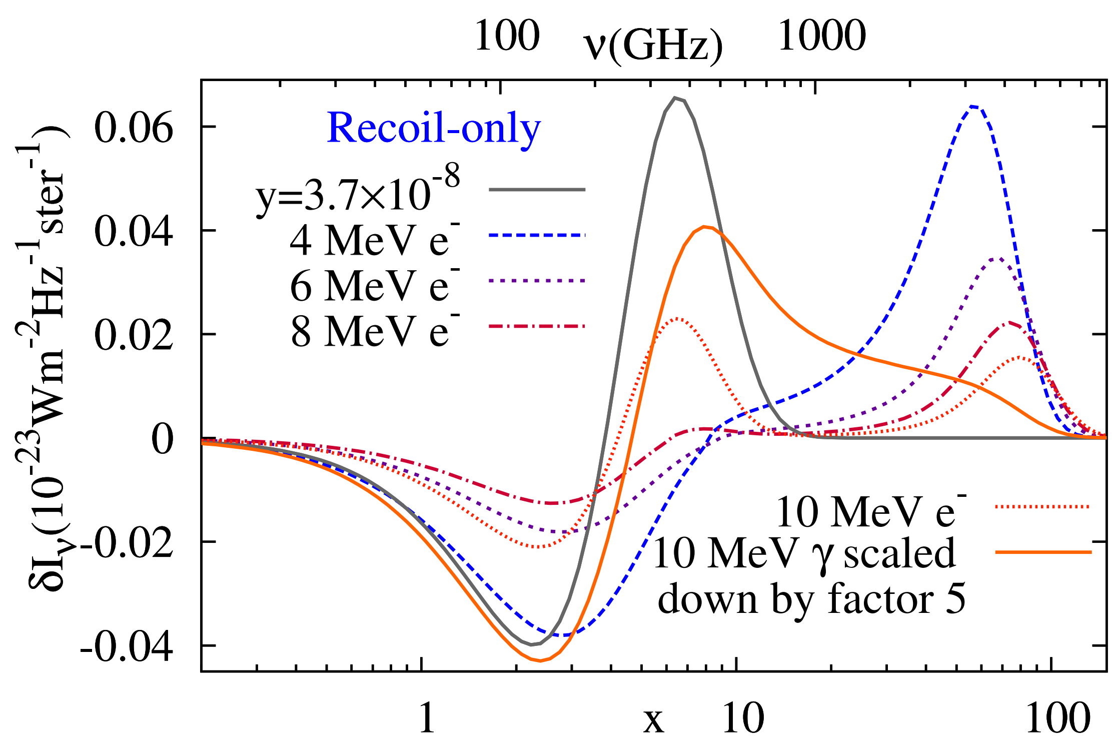


Ghosh, Khatri & Roy 2019

Rich information in CMB spectral distortions







Acharya & Khatri 2019

CMB-Bharat

- ***A "near-ultimate" CMB polarisation survey***
  (2μK.arcmin sensitivity, ~20 bands in 60-900 GHz)

\+ possibly

- ***spectral capability--On-board absolute BB calibrator, Spectrometer***
- ***Observatory mode (2 years) after survey (4 years)***

. New Science	• Primordial gravitational waves • Dark matter distribution • Neutrino mass, hierarchy and species • Reionization history • Cosmic thermal history
i. Extension/ Improvisation to the previous findings	• Highly precise standard model parameters • Dark matter annihilation • Galaxy clusters • Nature of dark energy • Cosmic anomalies
ii. Supplementary / complementary science	• Cosmic Infrared Background • Magnetic field and dust in the Milky Way • Magnetic dipolar emission

~ Quantum gravitation

Tighest limits

17 e-folds of inflation

HUGE DISCOVERY SPACE

CMB-Bharat

- ***A "near-ultimate" CMB polarisation survey***
  (2μK.arcmin sensitivity, ~20 bands in 60-900 GHz)

•Proposal explicitly envisages International collab.
•Projected full costing of mission with launch

CMB-Bharat mission design and technical specification builds upon several mature designs proposed elsewhere (in particular, CORE and PiXiE)

PI's of CORE and PiXIE are listed as international POC in the Proposal

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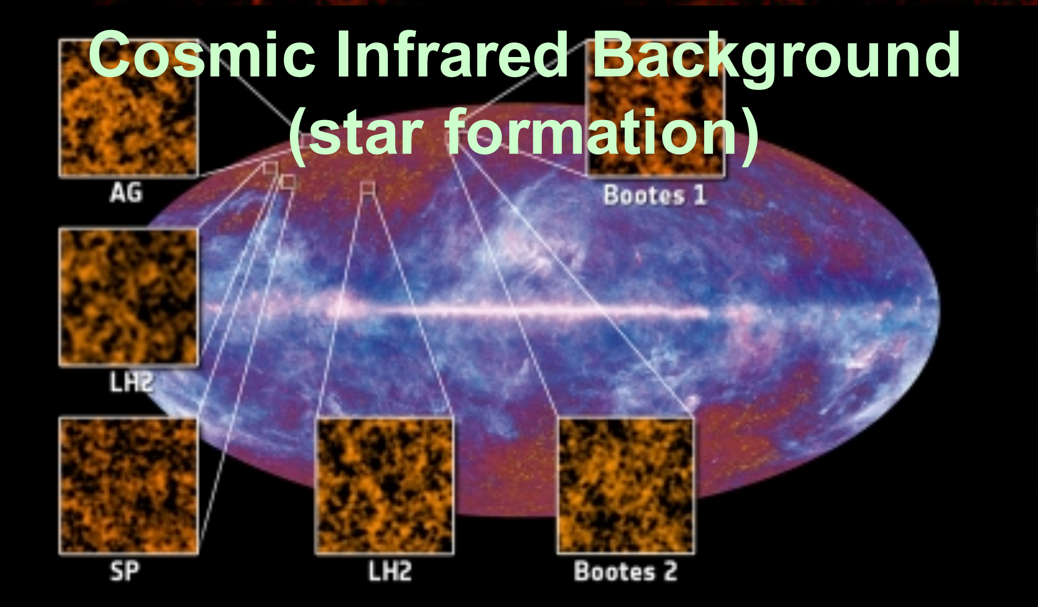
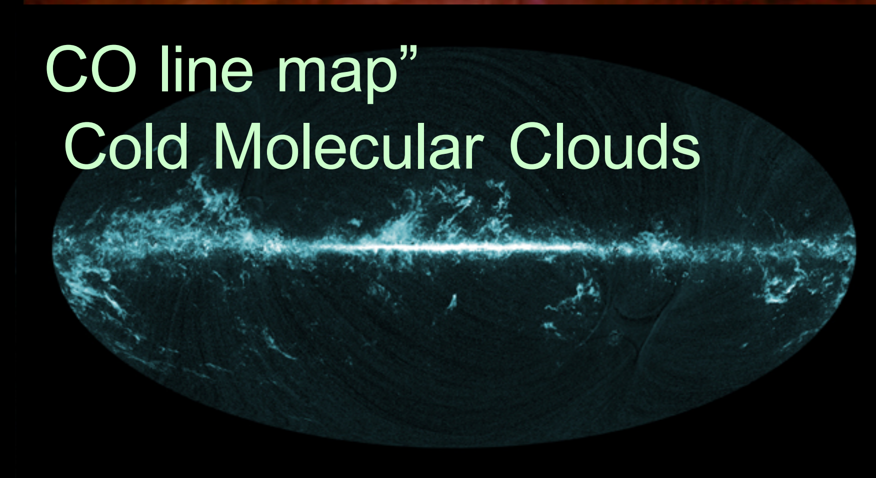
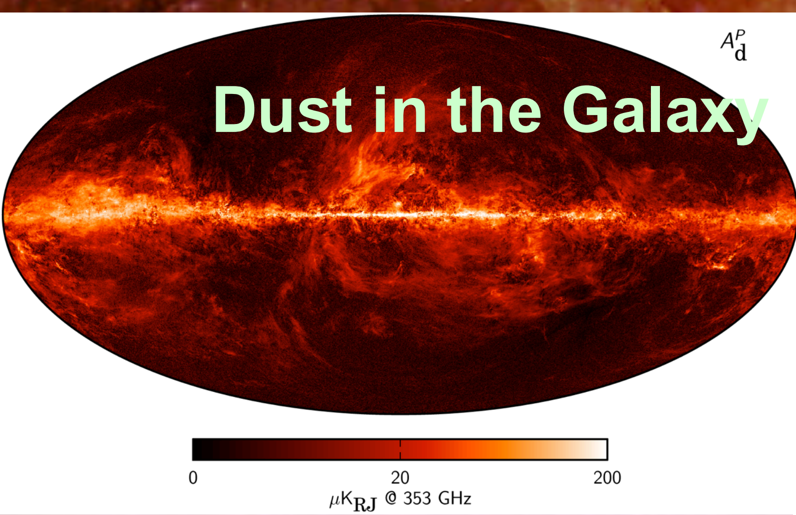
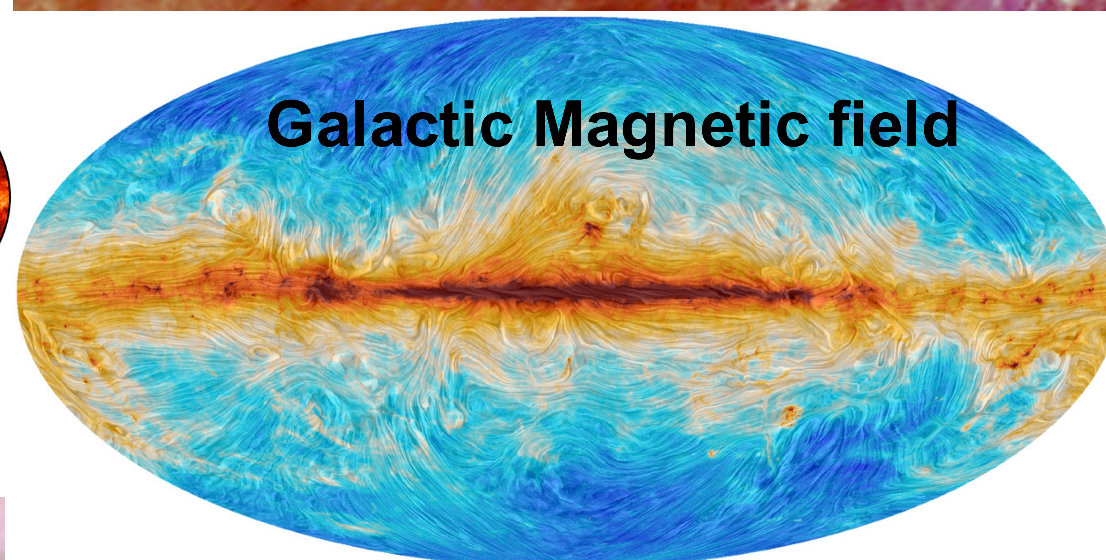
i. E... the ...	
ii. Supplementary / complementary science	• Cosmic Infrared Background • Magnetic field and dust in the Milky Way • Magnetic dipolar emission

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

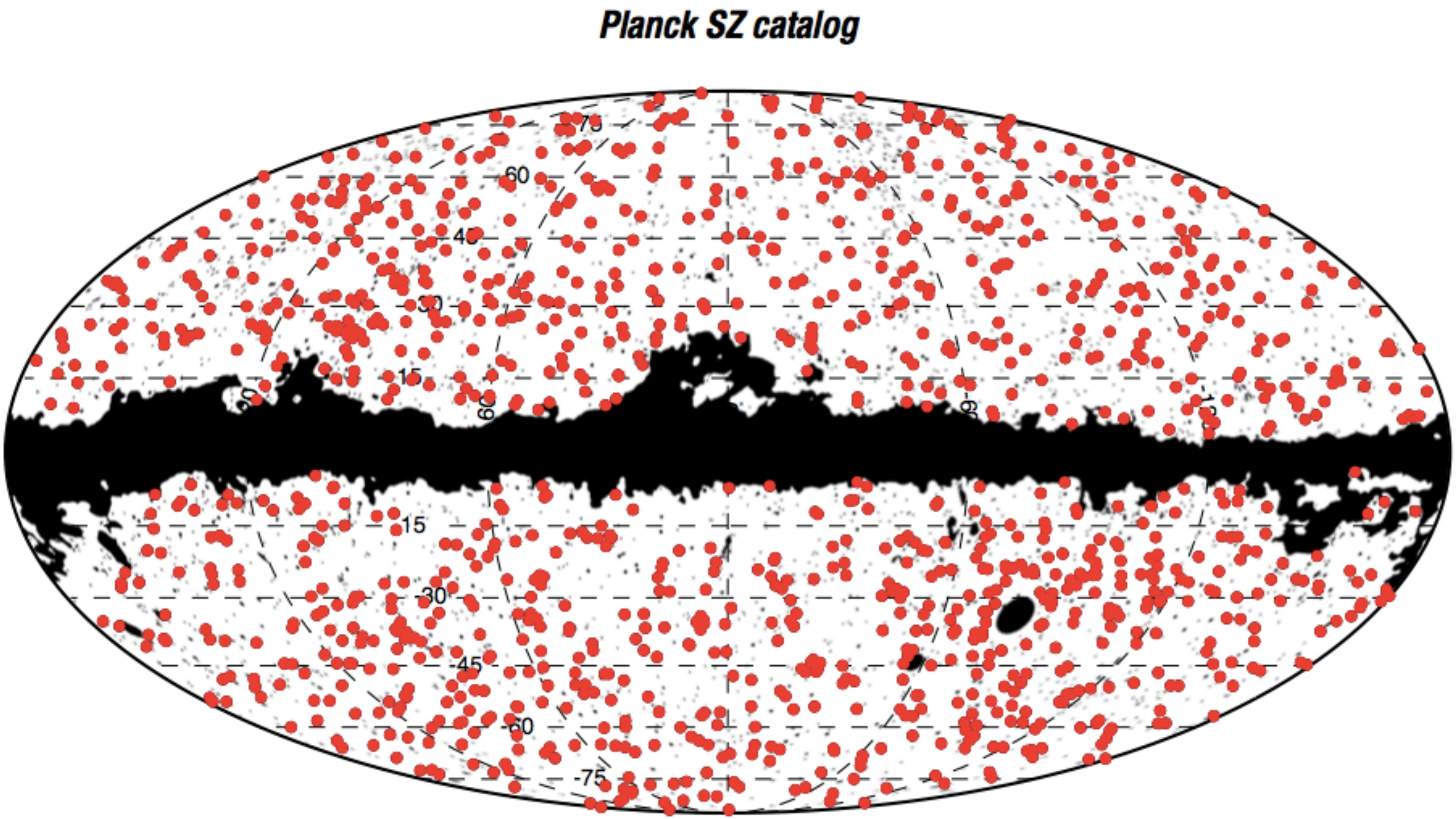






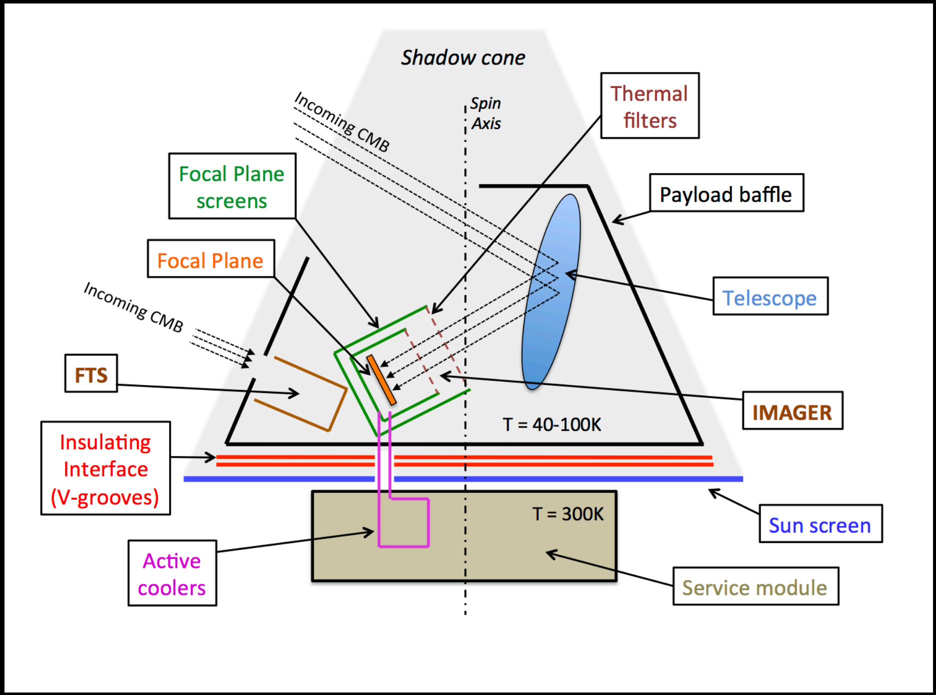


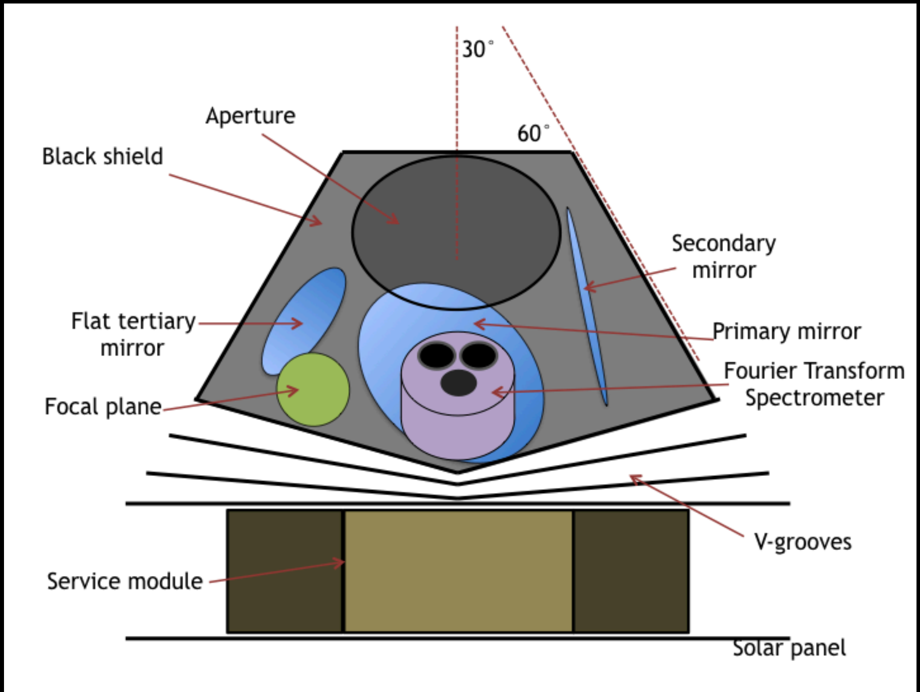
SZ clusters from Planck



50,000 clusters of mass above $10^{14} M_{sol}$ up to a redshift z~2.5

CMB-Bharat Payload schematic



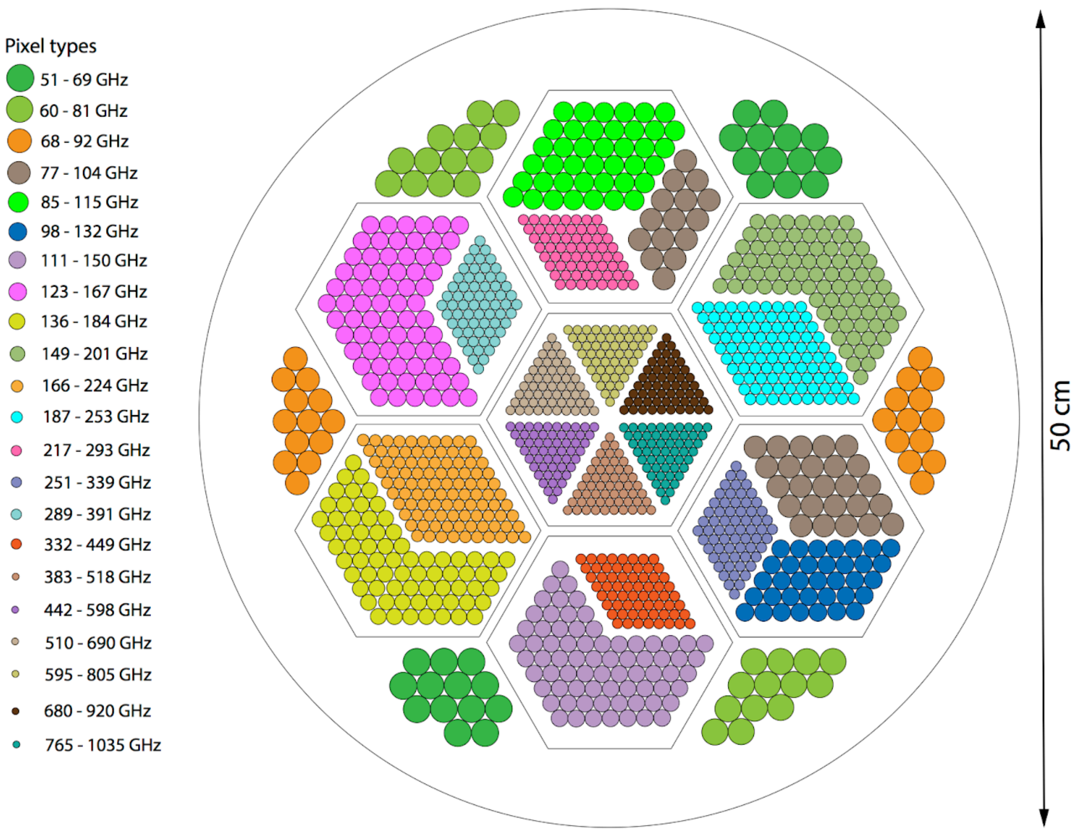


A multifaceted frontier science and astronomy mission

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

Focal plane-1A

FREQ. (GHz)	BEAM. (arc-min)	N_{DET}.	ΔT μK_{CMB}	ΔP μK_{CMB}
60	14.3	48	7.5	10.6
70	12.31	48	7.1	10
80	10.82	48	6.8	9.6
90	9.66	78	5.1	7.3
100	8.73	78	5	7.1
115	7.65	76	5	7
130	6.81	124	3.9	5.5
145	6.15	144	3.6	5.1
160	5.61	144	3.7	5.2
175	5.16	160	3.6	5.1
195	4.67	192	3.5	4.9
220	4.18	192	3.8	5.4
255	3.65	128	5.6	7.9
295	3.19	128	7.4	10.5
340	2.79	128	11.1	15.7
390	2.45	96	22	31.1
450	2.12	96	45.8	64.8
520	1.84	96	116.4	164.6
600	1.59	96	357.8	506
700	1.36	96	1532	2166.6
800	1.18	96	6811.4	9632.8
900	1.05	96	31127.1	44020.3

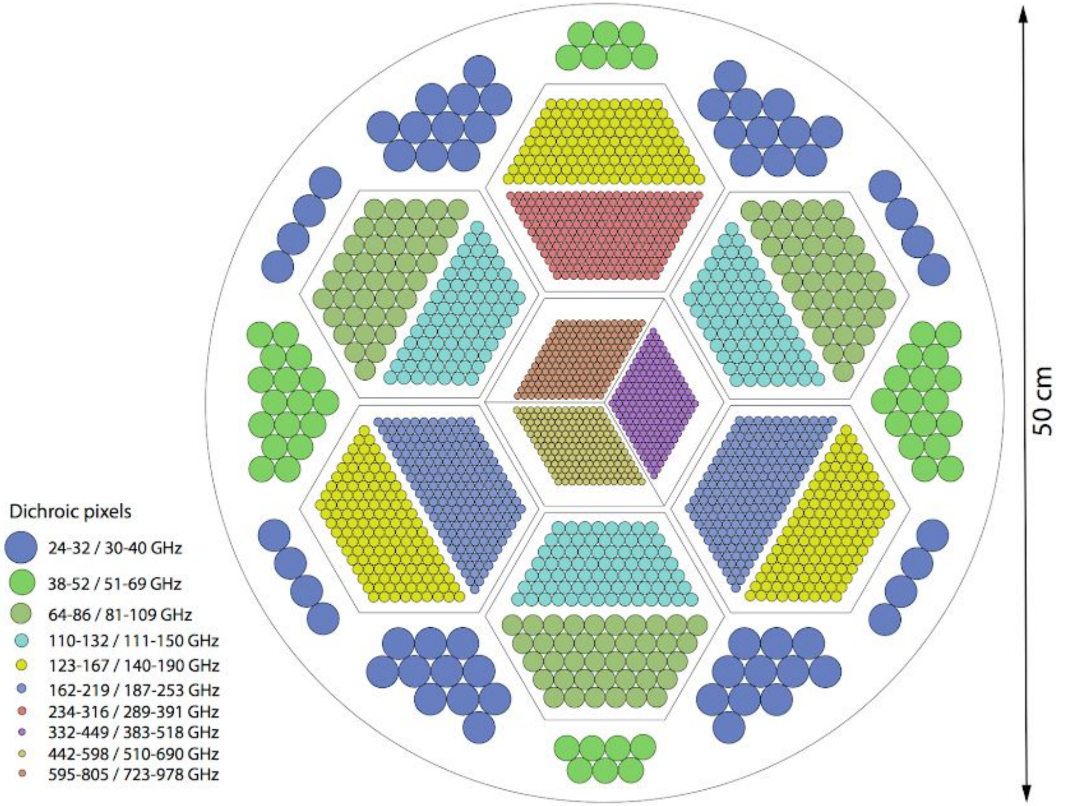


Extended CORE
700, 800, 900GHz

~2400 detectors
Sensitivity in CMB band: 2μK.arcmin

Focal plane-1B

ν_o GHz	Beam size arcmin (′)	N_{det}	ΔT $\mu K'_{CMB}$	ΔP $\mu K'_{CMB}$
28	39.9	120	11.7	16.5
35	31.9	120	9.4	13.3
45	24.8	96	8.4	11.9
65	17.1	96	6.3	8.9
75	14.9	240	3.6	5.1
95	11.7	240	3.2	4.6
115	9.72	462	2.2	3.1
130	8.59	462	2.2	3.1
145	7.70	810	1.7	2.4
165	6.77	810	1.7	2.5
190	5.88	752	2.0	2.8
220	5.08	752	2.3	3.3
275	4.06	444	4.5	6.3
340	3.28	444	8.1	11.4
390	2.86	338	15.6	21.9
450	2.48	338	30.7	43.4
520	2.14	338	72.2	102
600	1.86	338	204	288
700	1.59	338	794	1122
850	1.31	338	6752	9550



Ground expt inspired

Readout challenging

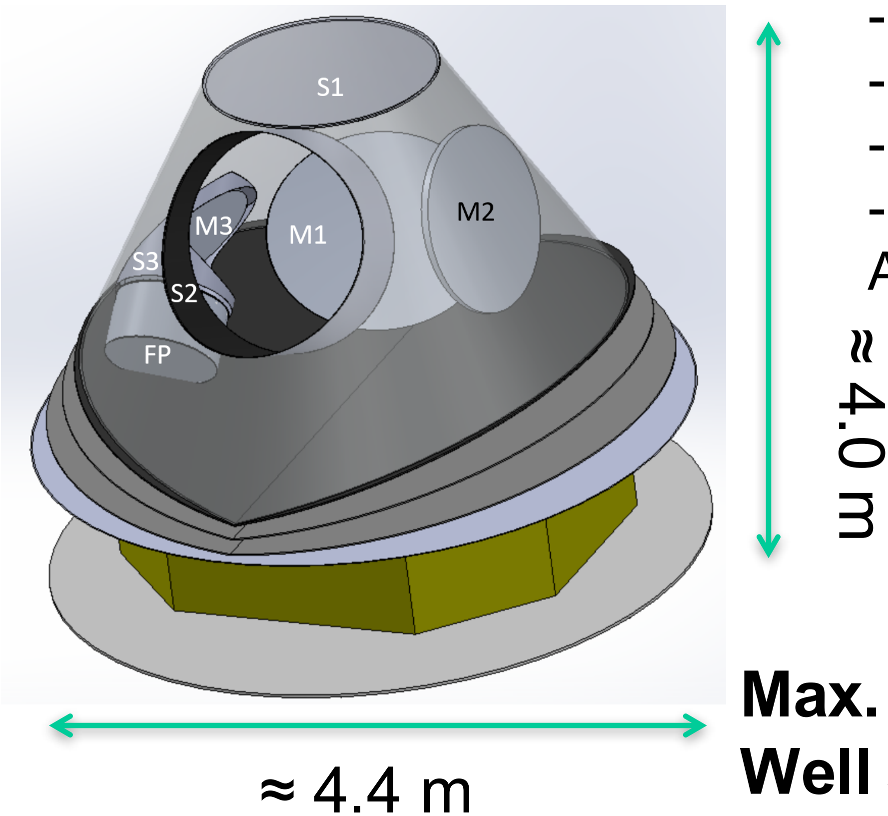
~6800 detectors

Sensitivity in CMB band: 1μK.arcmin

CMB-Bharat S/c Specs.

- 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

Chandrayaan-2 successful launch with GSLV-III July 22,2019

Indian technical contribution

Capabilities that are challenging, but nevertheless, may be readily achieved in India include:

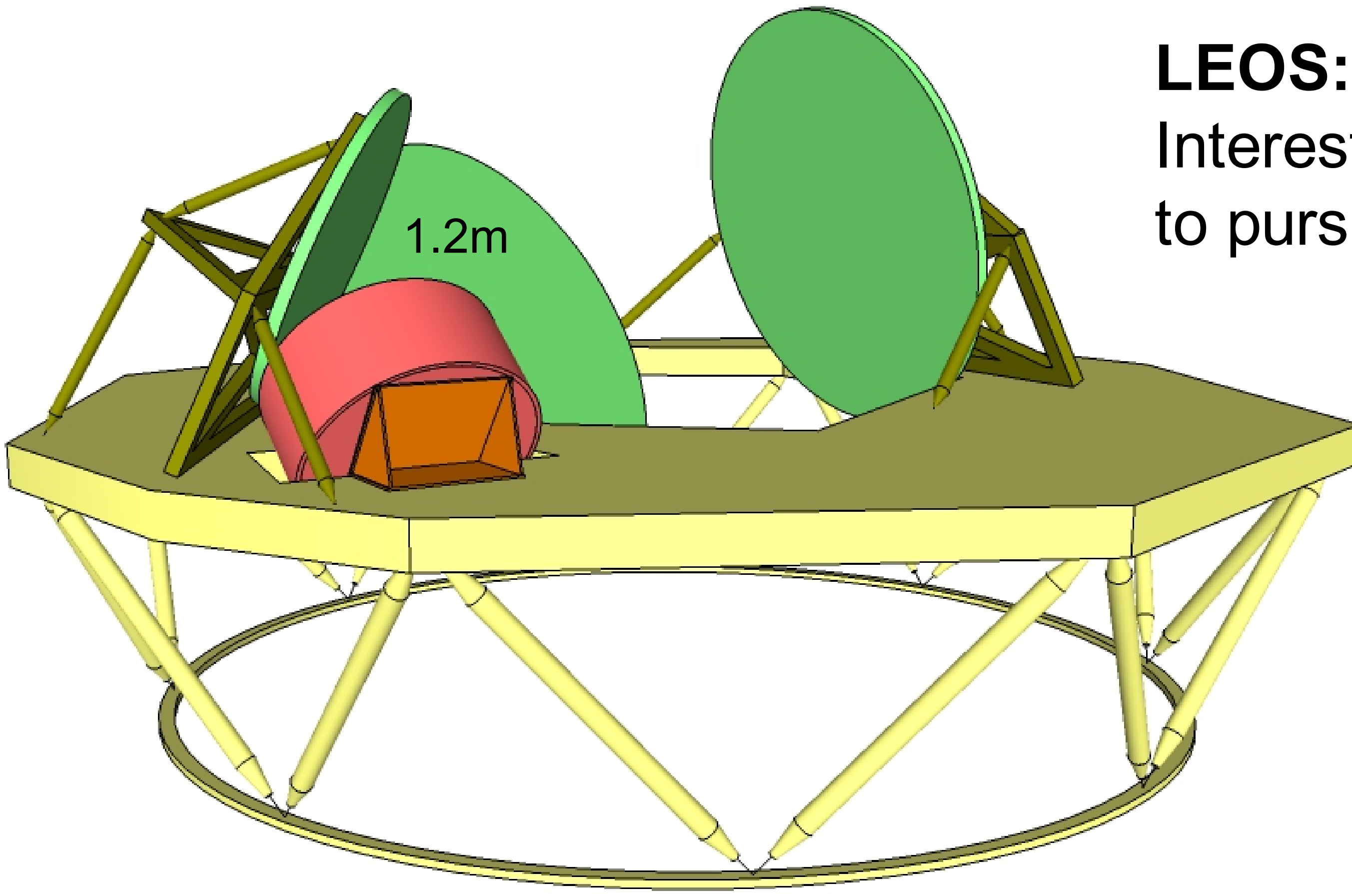
- Mission planning and operations;
- Launch to L2, tracking and control, orbit maintenance, science data downlink;
- Thermal infrastructure: design and fabrication of solar shield, hot-cold stage V-groove separator;
- Service module: design, fabrication, assembly and testing;
- Extensive modelling of instrument for calibrating systematic effects;
- Data products, analysis and science.

Indian technical contribution

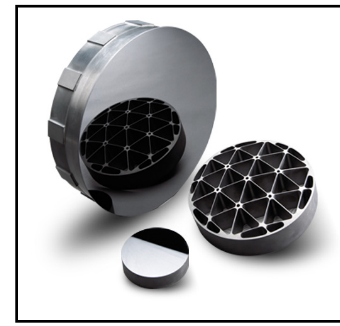
Capabilities achieved with modest planned investments

- Telescope and Optics **LEOS**
  - Design, fabrication, assembly, testing
  - Reflectors, baffling
  - Reimaging optics, filters
- Science Payload
  - Design, assembly, testing
- Thermal system: first stage coolers in the cryogenic cooling chain;

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*

TDP: Technology Development Program
LEOS: Laboratory for Electro-Optics Systems

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

Jan 21-22: fruitful meeting with SAC THz group on a aligned and concurrent Tech. Dev. Programme

Preferable route is to seek from international partner

However, time and manpower intensive **Detector testing & calibration facility** can be set up in one of many institutions coupled with faculty hiring of advanced Indian postdocs in CMB-Bharat (now working with top groups)

Action report 2019

Exploratory meetings

- **CMB-The next decade: An Indian perspective** Jan 24, 2019: ICTS Bangalore *All major CMB-Next gen plans and proposals around the world (USA, Europe, Japan, India): S&T Experts from ISRO and Indian labs*
- **Tera-Hertz detector technology workshop** Jan 21-22, 2019: SAC, Ahmedabad *Detector technology experts from Europe, US & India*

*** Presentation at Special Inter-Center team set up Chair ISRO**

Space Application Centre: May 10, 2019

Committee charged with identifying the technical dividend of future Astro mission proposals (primarily CMB-Bhārat)

- positive discussions: Ground based TRD leading to Space
- awaiting formal committee report (after all other proposals?).

*** (Souradeep) Invited to Human Resource Gen. Comm. for Sp. Science** Nov 23, 2019 : Planning growth Space Science in Academia: IISERs and IITs, Space tech Cell, Dept of Space Tech.

*** (Souradeep) Member: National Advisory Council for Dept of Space S&T at IIT Kanpur**

Identification of teams in Academia

- Mech. Engineering group IIT Kgp for space cryogenics.
- Couple of faculty in IIT Bombay for nano-fabrication.

TDPs can be pursued through their ISRO Space Tech cells

ISRO Special Inter-Center team meeting

Space Application Centre: May 10, 2019

CMB-Bhārat provides an opportunity to Indian laboratories to launch long term technology development in key areas of interest to ISRO

- Broadband photon-noise-limited sensors & readout for CMB frequency bands

- Cryogenic coolers at 100mK in space

Primary discussion point at this meeting:

- understand and refine aspirations of SAC THz detector program based on global status
- TDP for detector in the context of Ground based effort planned in Hanle high altitude Himalayan site (<2mm precipitable water vapour) for test of THz tech. developed --- 18MEu (~150 Cr INR) funds to set up 3 m dish
- **Need to align them with the TDP for proposed CMB space mission**

CMB-Bhārat: multi-faceted science

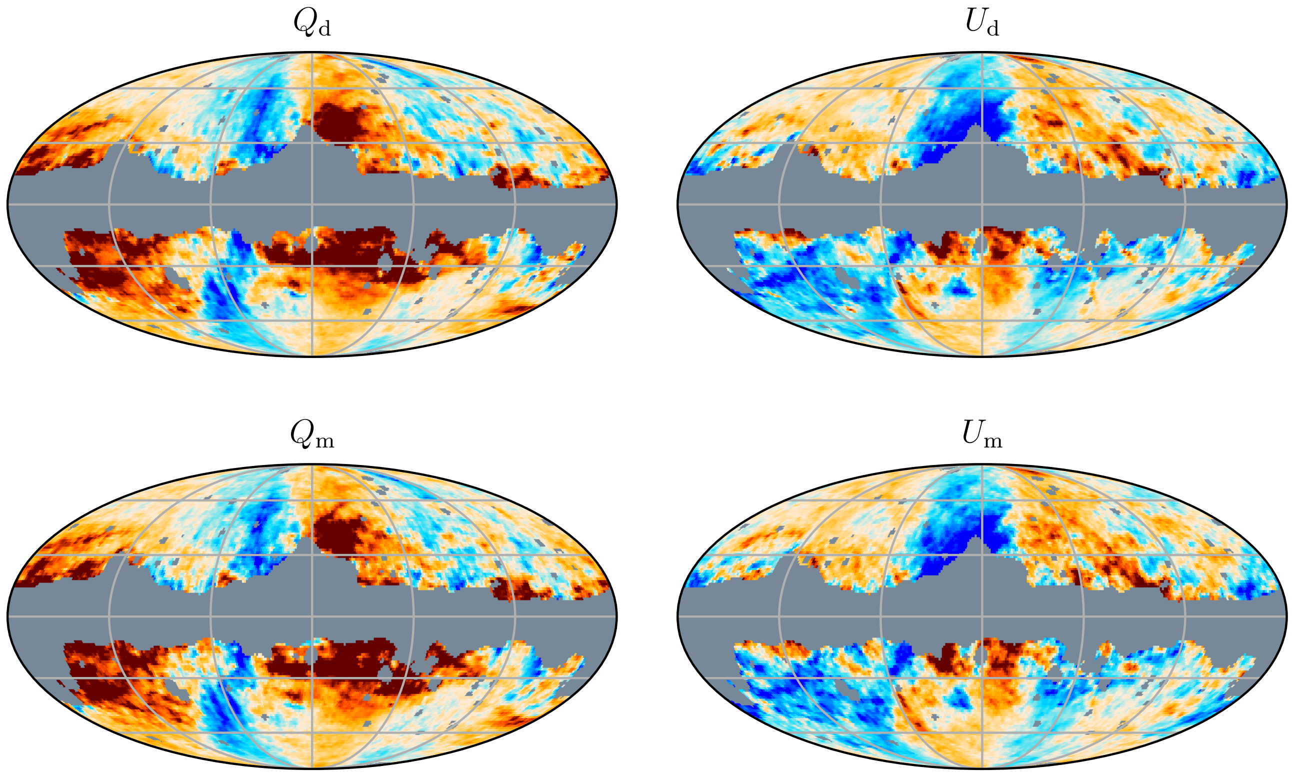
Indian Working groups

- ***Cosmological parameters:*** *Lead: Dhiraj Hazra (Bologna→ IMSc. Jan 2019,…)*
- ***Weak Lensing:*** *Lead: Suvodip Mukherjee (IAP → .. ?)*
- ***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-Bhārat: Research Glimpses

Generation of realistic dust simulations at the scales of CMB-Bhārat and CORE using polarization tensor approach

(T. Ghosh, A. Frolov, F. Boulanger, J.R. Bond +)



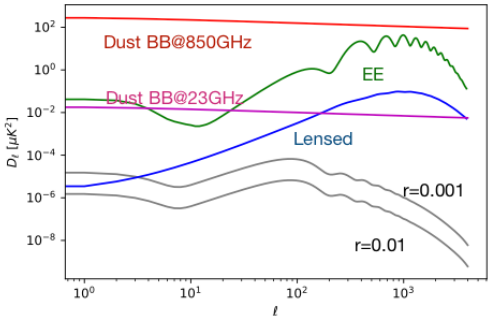
Top panel:
Planck data

Bottom panel:
Dust Realization

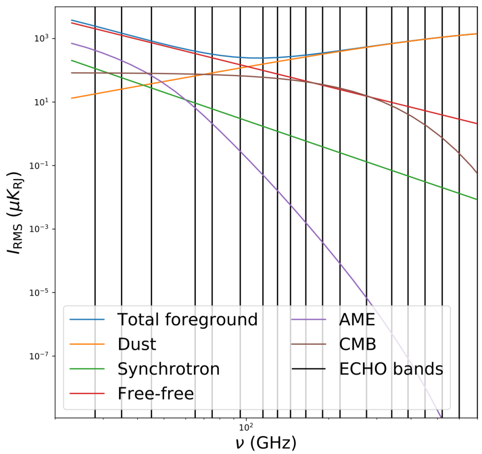
CMB-Bhārat: Research Glimpses

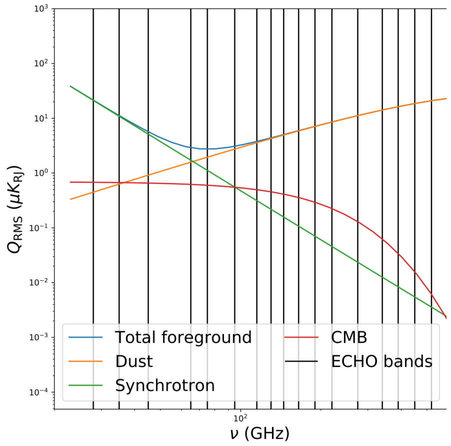
Test of the efficiency of the existing component separation methods on realistic foreground dust simulations (including dust decorrelation) for target r = 10^{-3} (CORE, CMB Bharat, CMB S4)

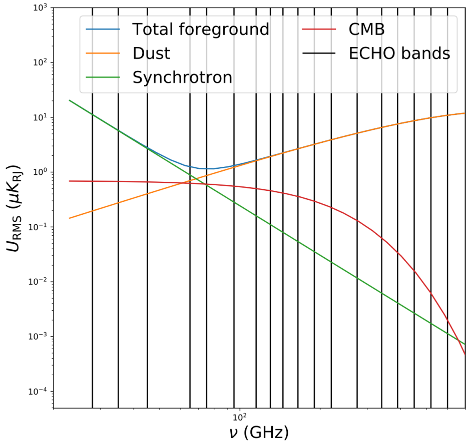
(D. Adak, T. Ghosh, S. Basak, T. Souradeep, A. Sen, J. Delabrouille +)



* PySM models for foreground simulations (full sky, Nside = 512)
* Clean Foregrounds using NILC and COMMANDER.
* Test tensor-to-scalar rato possible to recover.
* Residual Foreground in cleaned map.





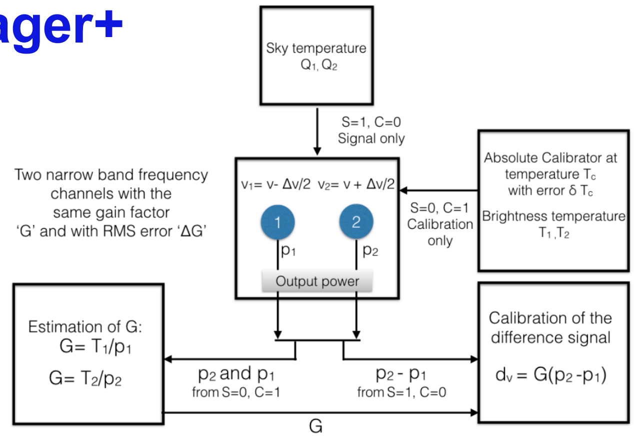


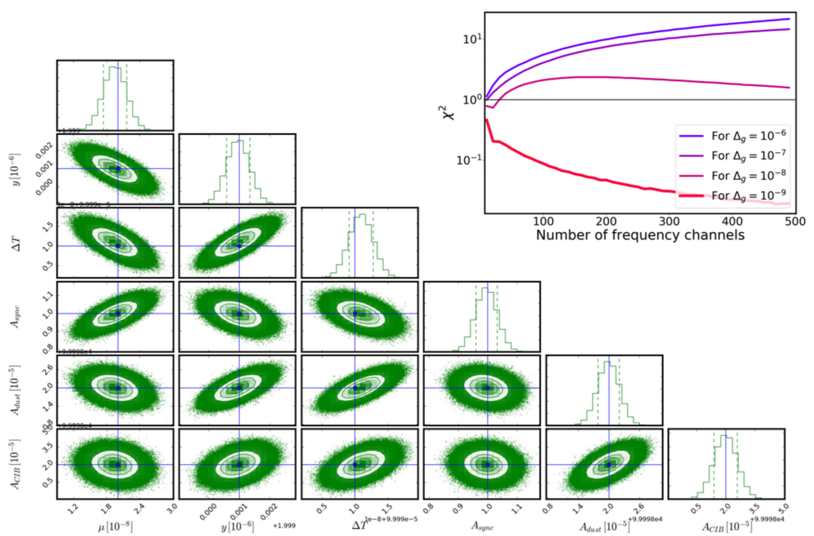
CMB-Bhārat: Research Glimpses

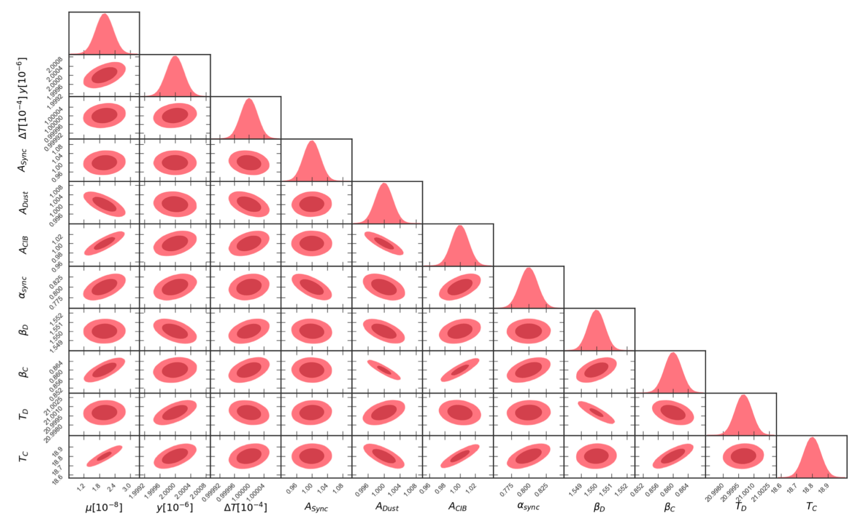
Measuring the CMB spectral distortions with an imager+ calibrator

Mukherjee, Silk, Wandelt

Phys.Rev. D100 (2019) no.10, 103508







CMB-Bhārat: Research Glimpses

Ranajoy Banerji
Post-doc researcher
ITA, University of Oslo

Current Projects

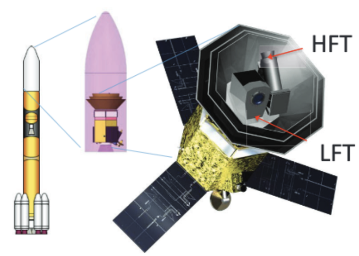
- **LiteBIRD**: CMB polarisation space mission to detect primordial B-modes at large scales.
- **BeyondPlanck**: End-to-end Bayesian analysis of CMB data, starting with Planck LFI. To include multi-frequency serveys in the future.

Expertise

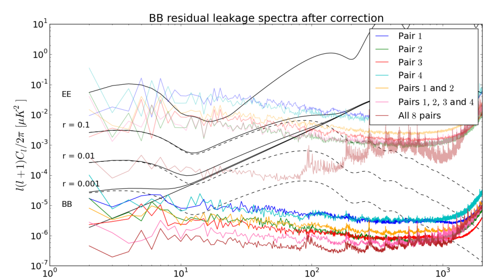
- Modelling Instrumental systematics and mitigation
- Foreground estimation
- TOD simulation and analysis

Important Publication/Software

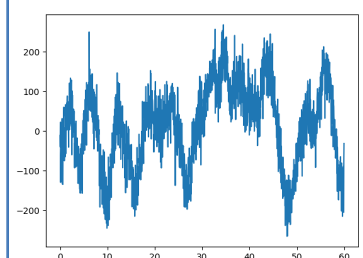
- Bandpass mismatch error for satellite CMB experiments II: Correcting for the spurious signal
- https://github.com/ranajoy-cosmo/genesys.git



De-striping systematics correction



Beyond PLANCK



$$
\begin{aligned}
s^{i+1} &\leftarrow P(s|f^i, \beta^i, g^i, d, \ldots) \\
f^{i+1} &\leftarrow P(f|s^{i+1}, \beta^i, g^i, d, \ldots) \\
\beta^{i+1} &\leftarrow P(\beta|s^{i+1}, f^{i+1}, g^i, d, \ldots) \\
g^{i+1} &\leftarrow P(g|s^{i+1}, \beta^{i+1}, f^{i+1}, d, \ldots) \\
&\vdots
\end{aligned}
$$

Parameter
n_s . . . . .
H_0 . . . . .
Ω_Λ . . . . .
Ω_m . . . . .
$\Omega_b h^2$ . . . .
$\Omega_c h^2$ . . . .
σ_8 . . . . .
z_{re} . . . . .
Age/Gyr .

CMB-Bhārat: Summary

- **CMB-Bhārat alive, not kicking yet !!! Needs a trigger!**
  - Continues to be on the shortlist post ADCOSS – Advisory comm. on Space Science – ISRO's highest advisory body (Dec 2018) *(Meanwhile, ADCOSS replaced by an Apex committee - with better coordination between recommendation and implementation?)*
  - ISRO Intercenter team to identify tech dividends to ISRO from Astro missions. CMB-Bhārat features prominently in the charge document.

- **ISRO seeks higher share of responsibilities for payload to be taken up in the academic institutions (not burden ISRO labs).**
  - Apex committee has set up sub-committee to evolve HRD plans
  - Enhance scope of ISRO Space Science Technology centers/cells in academic institutions , in particular, IITs & IISERs. Willingness to fund.
  - IITs & IISERs interested in creating Astro, Space S&T departments.

- CMB-Bhārat community is steadily building up more coordinated, focused research efforts for a next generation CMB space mission.

- **Clear signs of high aspirations in ISRO**

Planck launch 2009

Next (to next ?) Gen 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.

THUS the explorations of space end on a note of uncertainty. And necessarily so. We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary—the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial.

The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation.

Edwin Hubble, The Realm of the Nebulae, 1936