~~Future of~~ CMB B-modes & CMB-Bhārat

CMB BHĀRAT: AN INDIAN COSMOLOGY CONSORTIUM

Physics of the Early Universe
(an online precursor)

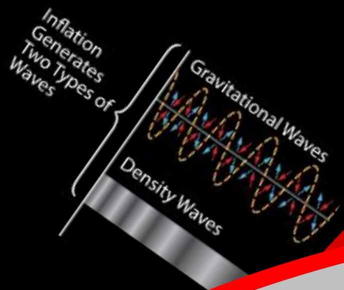
ICTS-TIFR, Bangalore

Aug. 31-Sep. 3, 2020

Tarun Souradeep
IISER-Pune, India

IISER PUNE

Cosmic "Super–IMAX" theater



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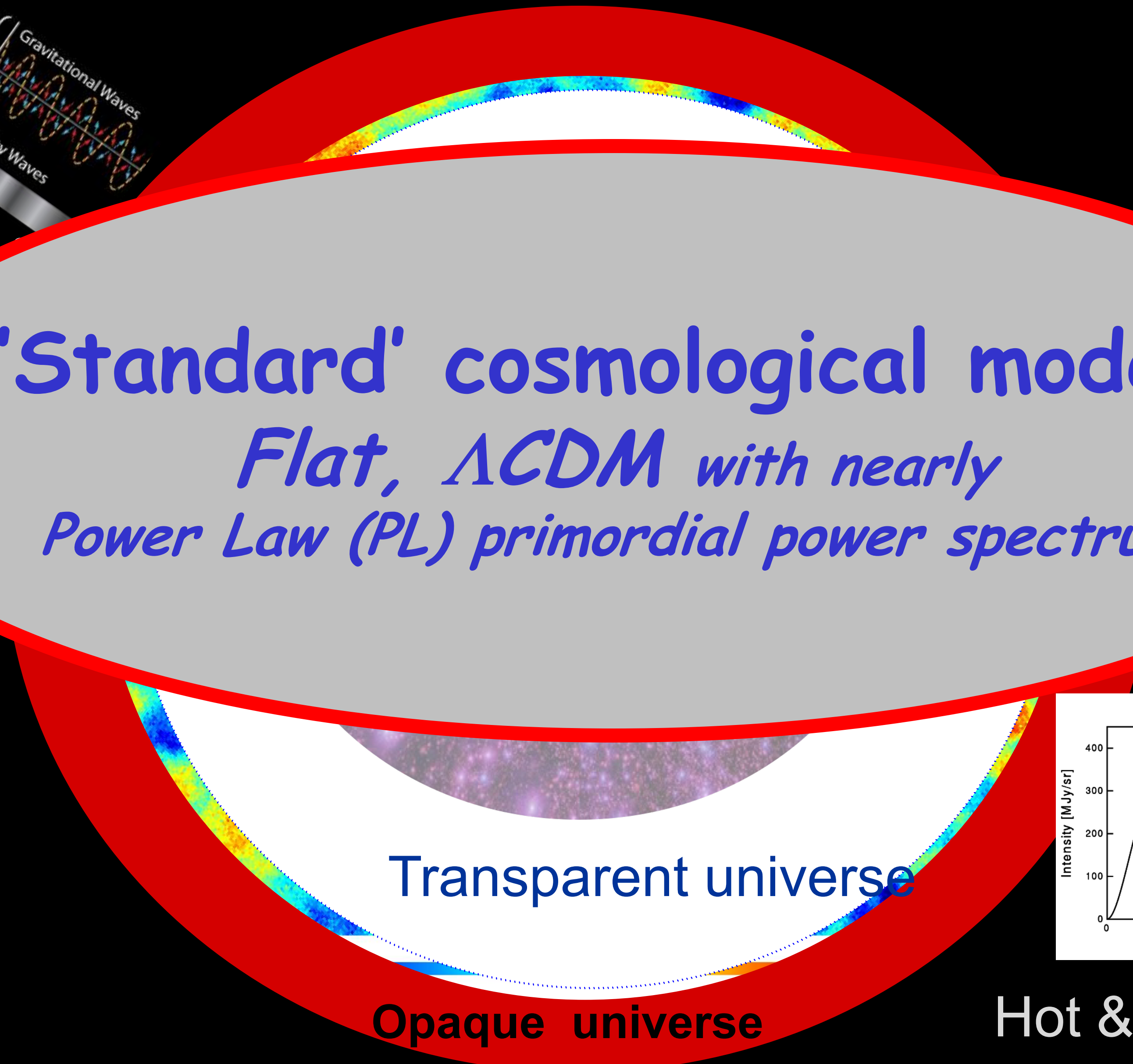
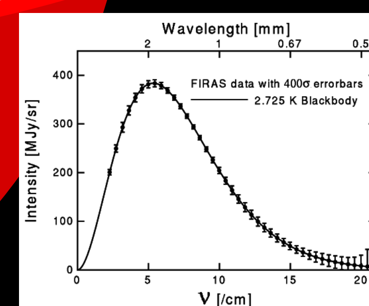


'Standard' cosmological model:

***Flat, ΛCDM** with nearly*

Power Law (PL) primordial power spectrum



Hot & dense origin

Cosmic GW background From Inflation

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

To/Must-Do for cosmology !!!!

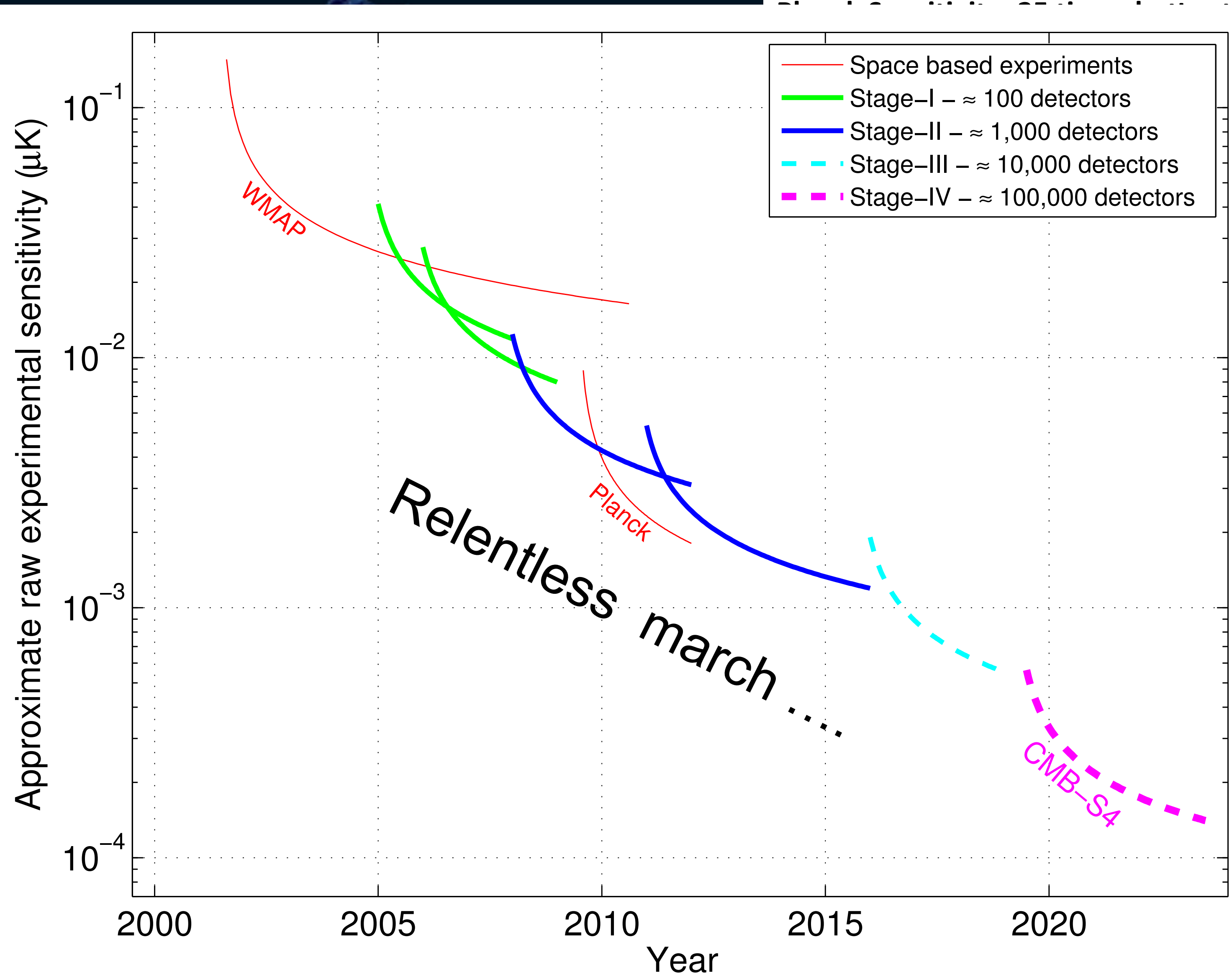
a… …GW

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

Currently, r < 0.07

CMB measurements

1st, 2nd and the 3rd decade



ian WMAP
an WMAP
times better than COBE
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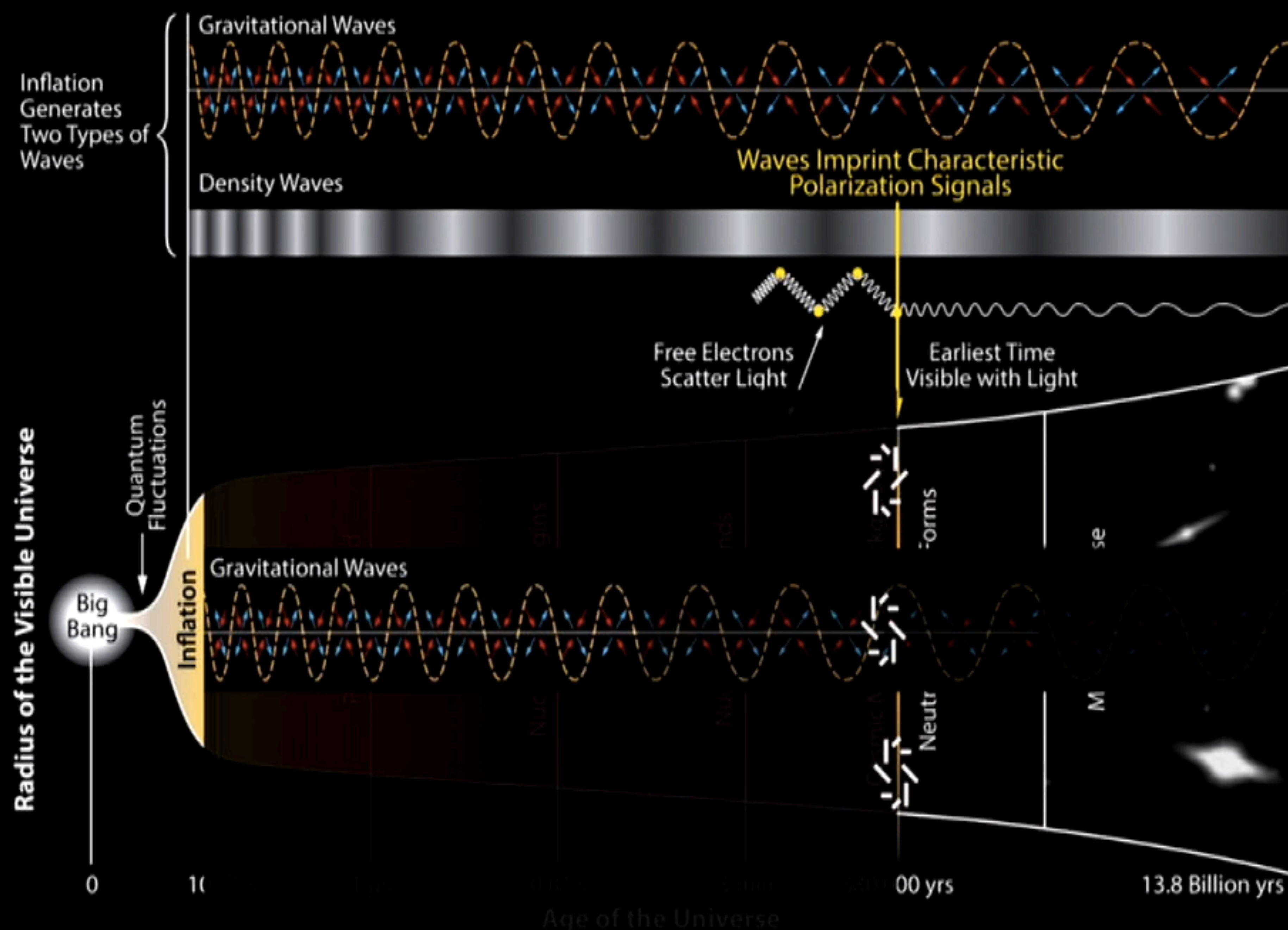
xt Gen.
2025+

History of the Universe



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**

  And, no significant addition on CMB spectral information since COBE

Scientific promise:

•**ULTRA- HIGH: Reveal signature of primordial GW from inflation -- first clear signature of QFT in curved spacetime and ultra-HEP in the very early universe**

•**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'($z<2 \times 10^6$) thermal history of the universe**

Next CMB space mission?

Spectral distortions (Absolute Calibration)

B-modes

Low resolution

PRISTINE (ESA)

√ LITEBIRD (JAXA)

PIXIE (NASA)

2020-01-30 LiteBIRD is selected as one of 31 highest-priority large projects by the Science Council of Japan.

ECHO (ISRO)?

CORE (ESA)

High resolution

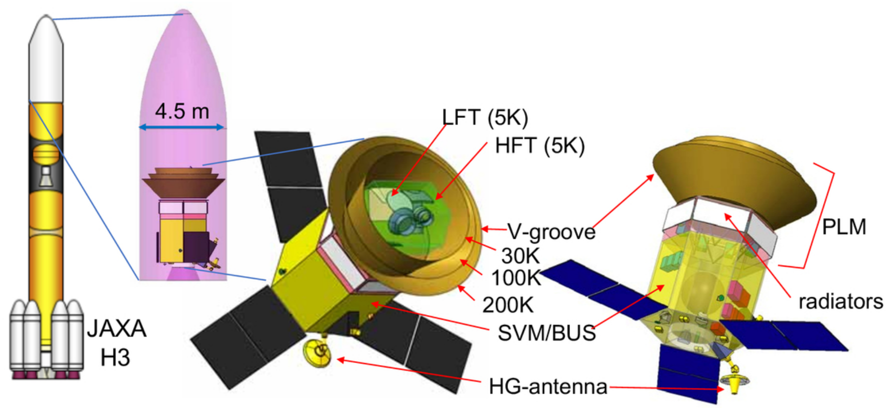
PICO (NASA)

ECHO (ISRO)

PRISM (ESA)

Adapted from slide from Rishi Khatri

LiteBIRD: a brief tour



Sekimoto et al. SPIE Proc. 2018

The basic concept of LiteBIRD is as follows:

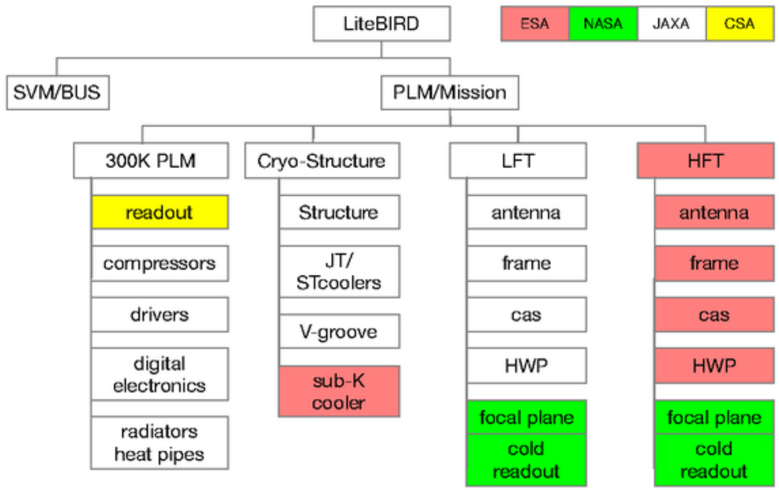
1) **Design a satellite optimized for CMB polarization B mode detection on large angle scales. Without compromise on sensitivity, verify definitely the focused target.**
2) **Design a lightweight, compact satellite without requiring angular resolution of less than 1 degree. This will increase the chance of launch.**

LiteBIRD website http://litebird.jp/

Major specifications are shown below:

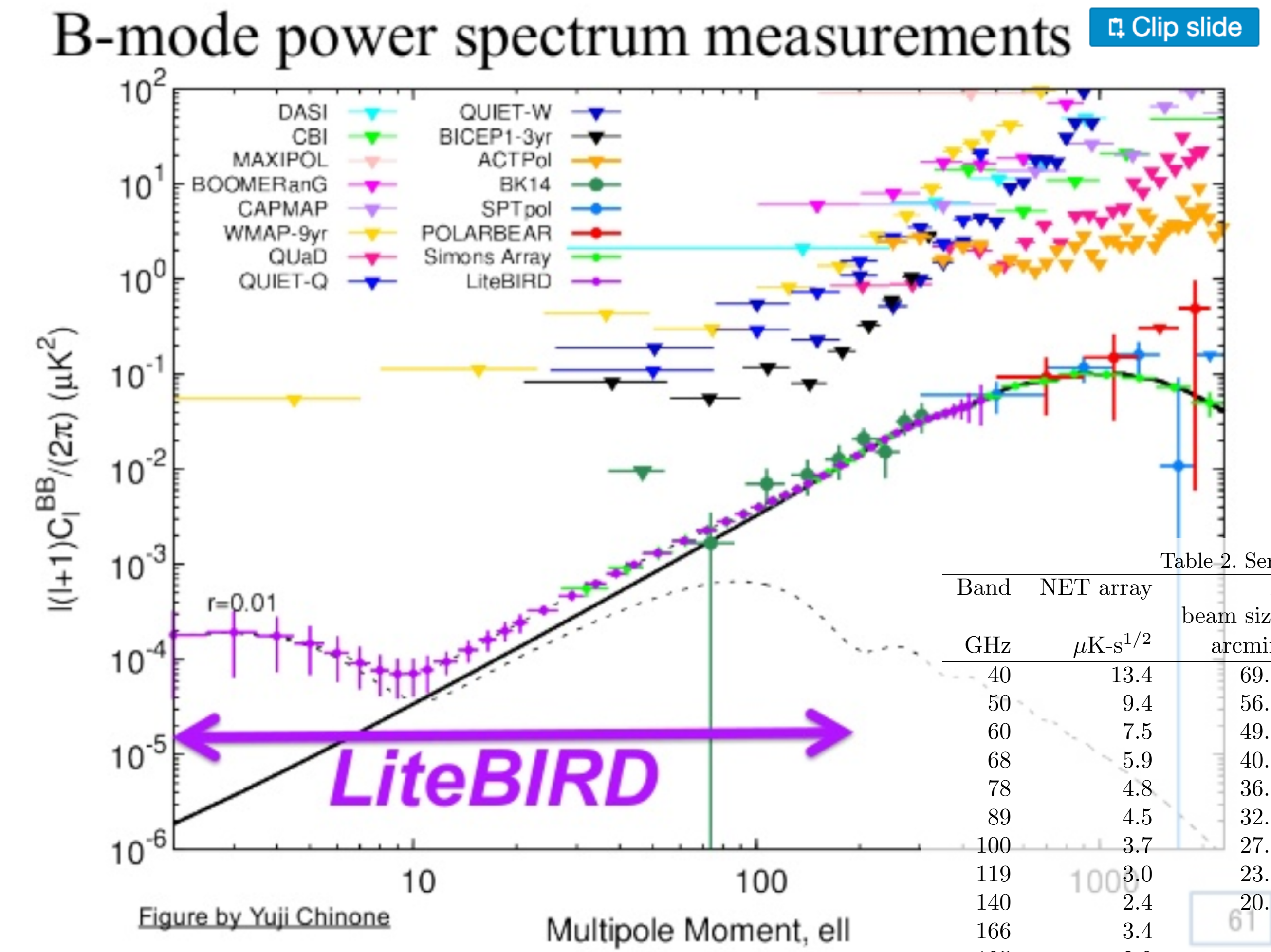
Item	Specification
Observation duration	3 years
Orbit	Sun–Earth L2
Cooling system	Similarly to pre-cooling method of infrared astronomical satellite SPICA, use radiative cooling and mechanical refrigerators (Stirling and JT) without cryogen. Cool in space after launch. CCDR or ADR is used to cool the focal plane down to 0.1 K.
Focal-plane detector	Multi-chroic superconducting detector (TES) array with more than 3000 bolometers
Sensitivity	3 micro-Kelvin x arcmin
Observing frequencies	15 bands between 34 and 448 GHz
Modulation	Satellite spin and half-wave-plate modulation

LiteBIRD website



Sekimoto et al. SPIE Proc. 2018

LiteBIRD: a brief tour



Hazumi talk Sep 2020

Table 2. Sensitivity and beam size of LiteBIRD

Band	NET array	LFT		HFT		polarization
		beam size	NET_{array}	beam size	NET_{array}	sensitivity
GHz	μK-s$^{1/2}$	arcmin	μK-s$^{1/2}$	arcmin	μK-s$^{1/2}$	μK-arcmin
40	13.4	69.2	13.4			27.9
50	9.4	56.9	9.4			19.6
60	7.5	49.0	7.5			15.6
68	5.9	40.8	5.9			12.3
78	4.8	36.1	4.8			10.0
89	4.5	32.3	4.5			9.4
100	3.7	27.7	5.9	37.0	4.6	7.6
119	3.0	23.7	4.6	31.6	4.1	6.4
140	2.4	20.7	4.4	27.6	2.9	5.1
166	3.4			24.2	3.4	7.0
195	2.8			21.7	2.8	5.8
235	3.8			19.6	3.8	8.0
280	4.4			13.2	4.4	9.1
337	5.5			11.2	5.5	11.4
402	9.4			9.7	9.4	19.6

Sekimoto et al. SPIE Proc. 2018

Indian response

- **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**

CMB-Bhārat: Exploring Cosmic History & Origin

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

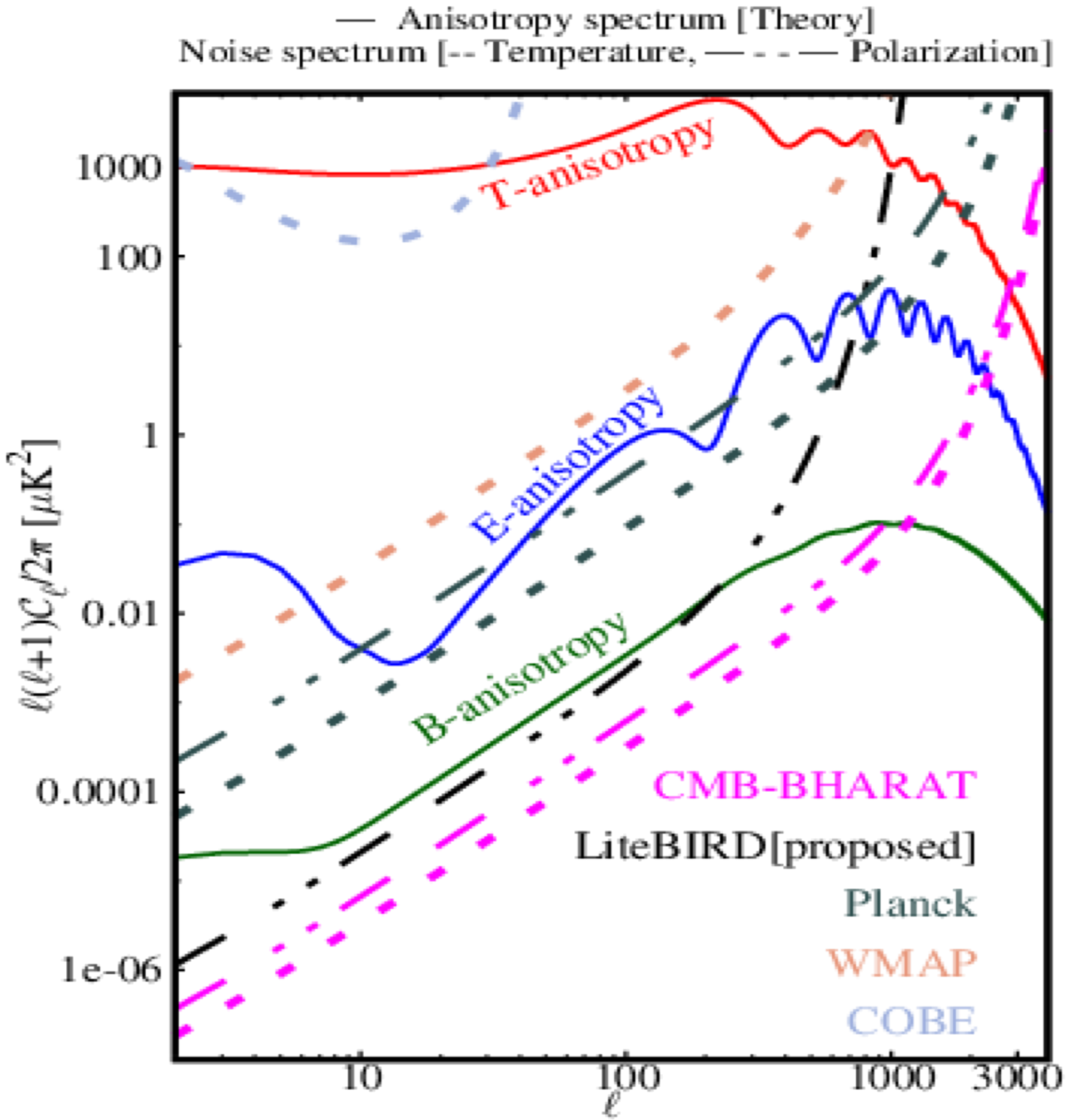
- **Proposal explicitly envisages International collab.**
- **Projected full costing of mission with launch**

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

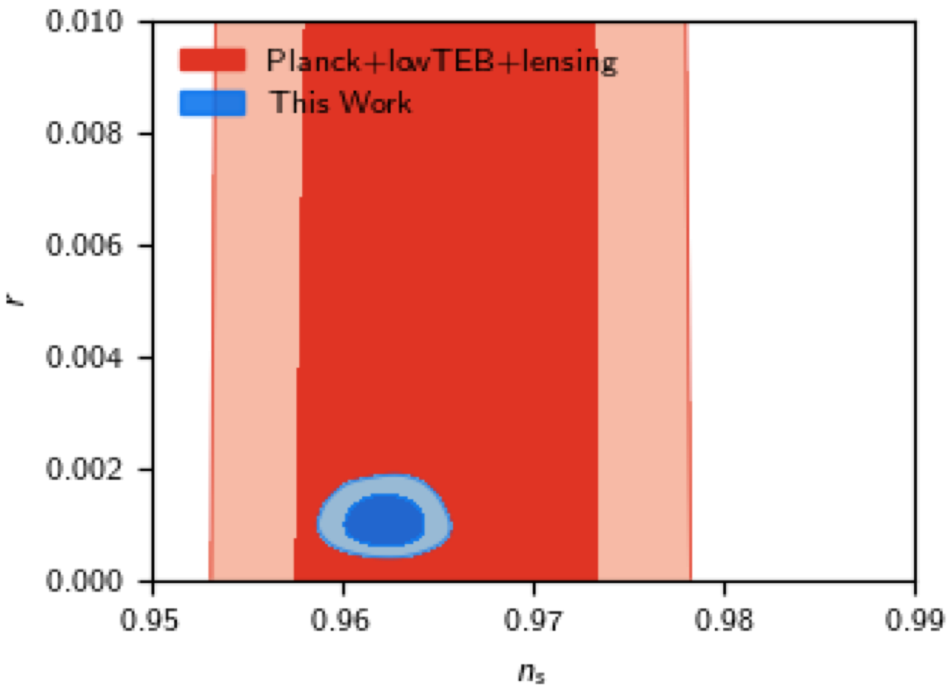
PI's of CORE and PiXIE are listed as international POC in the Proposal

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

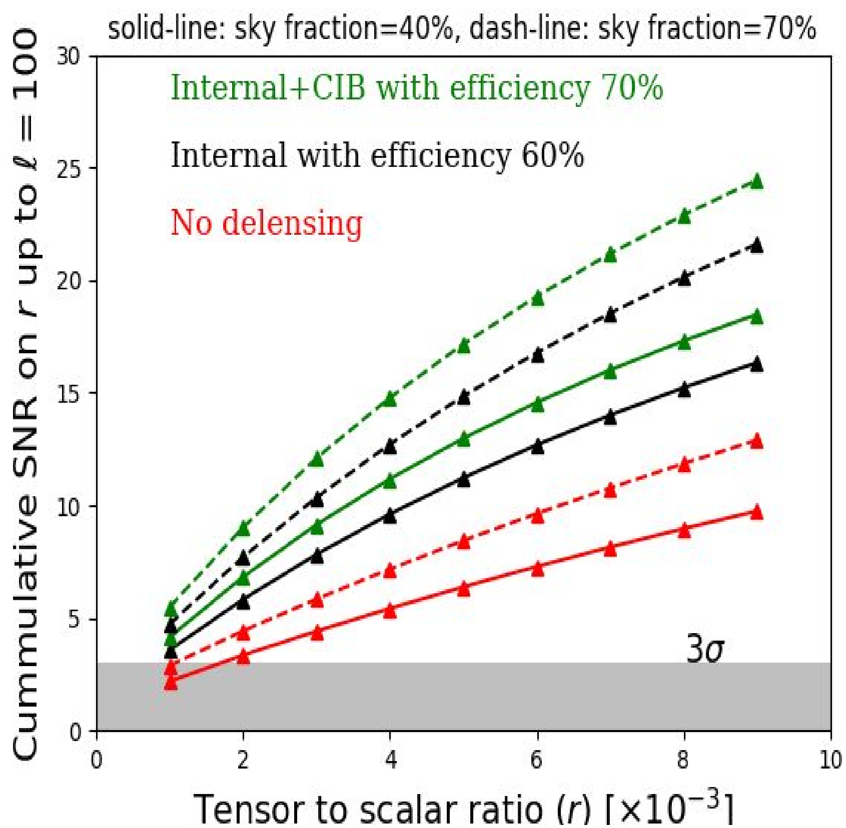
CMB Polarization



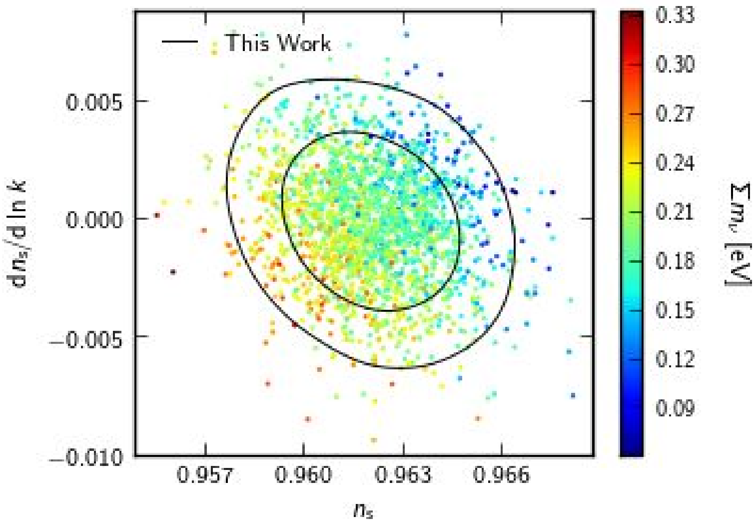
CMB Polarization: ultra-high dividend

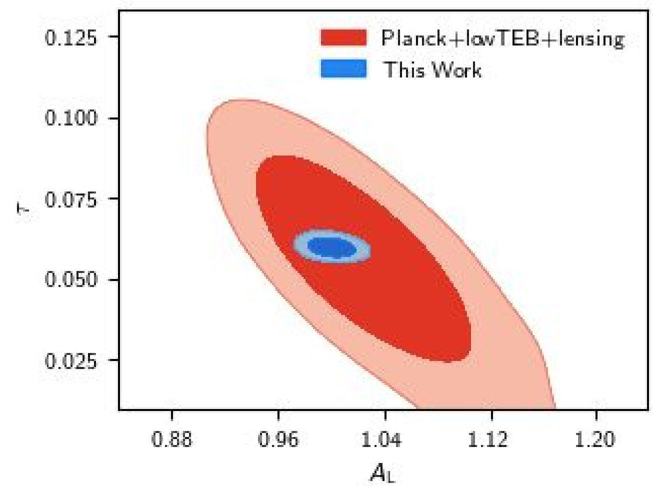


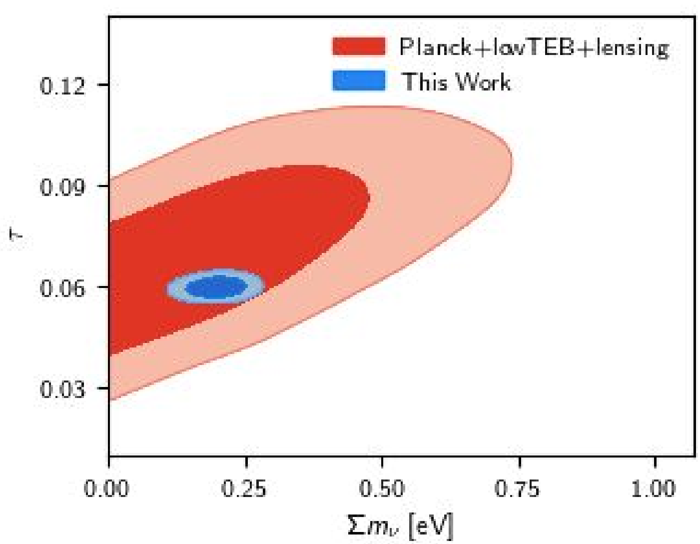
Primordial GW from Inflation
Tensor/Scalar ratio

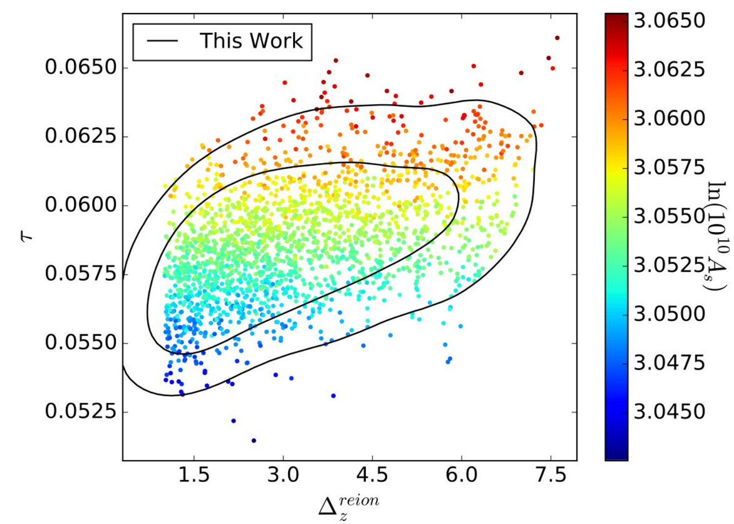


CMB Polarization: high dividend

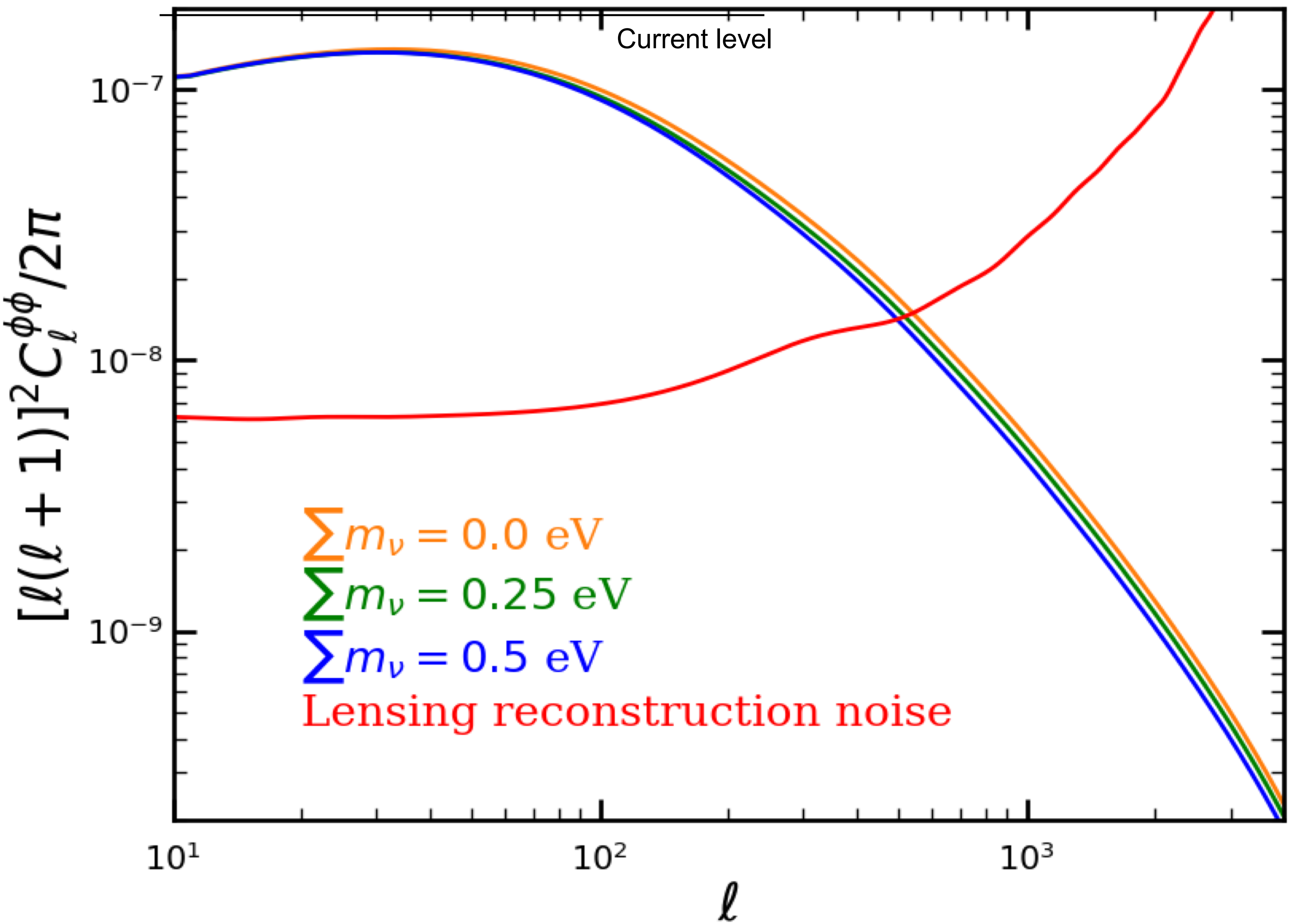








Projected Lensing potential from Planck



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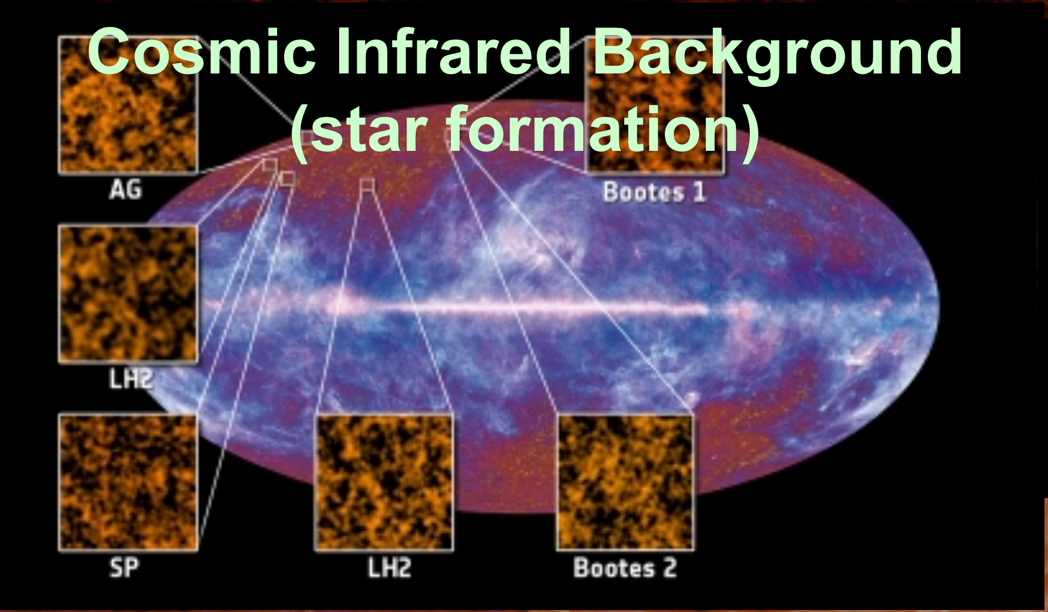
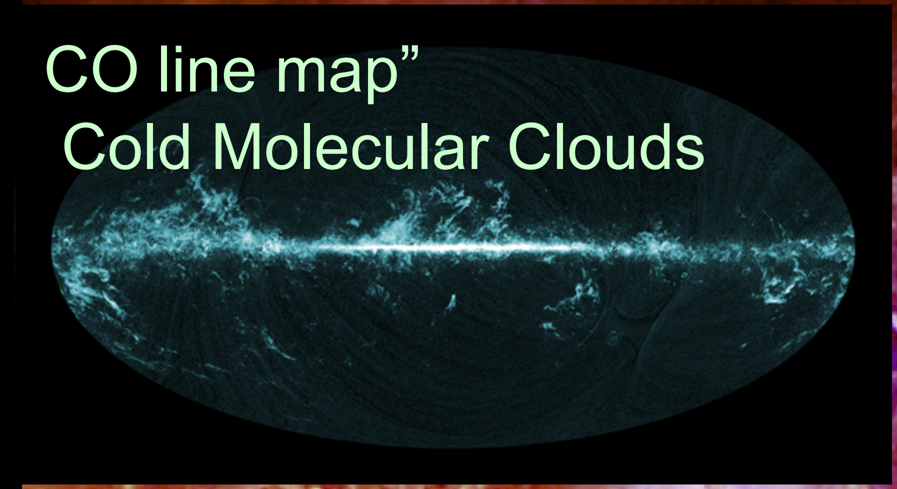
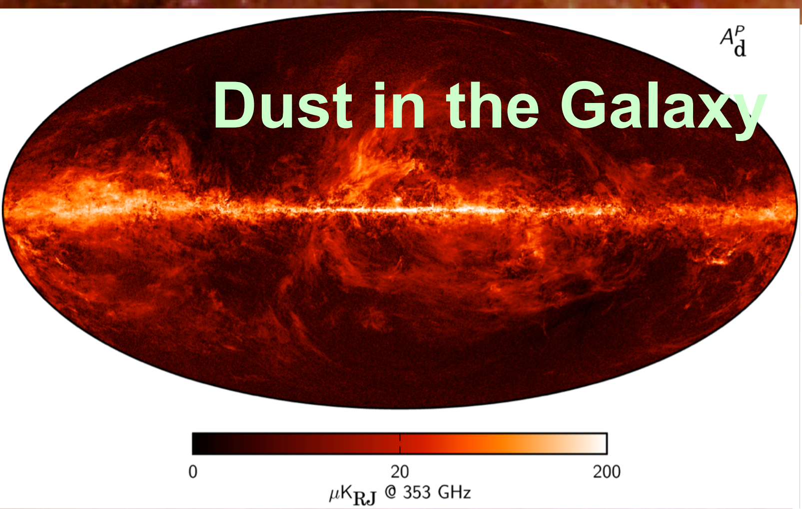
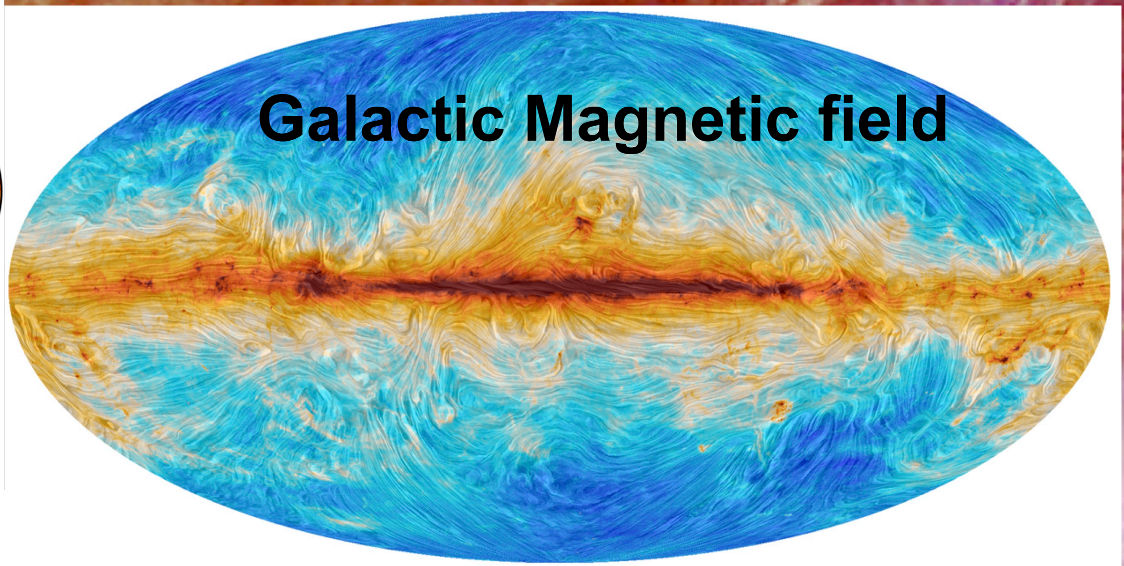
CMB Foregrounds : Rich A&A science
(600-900GHz)

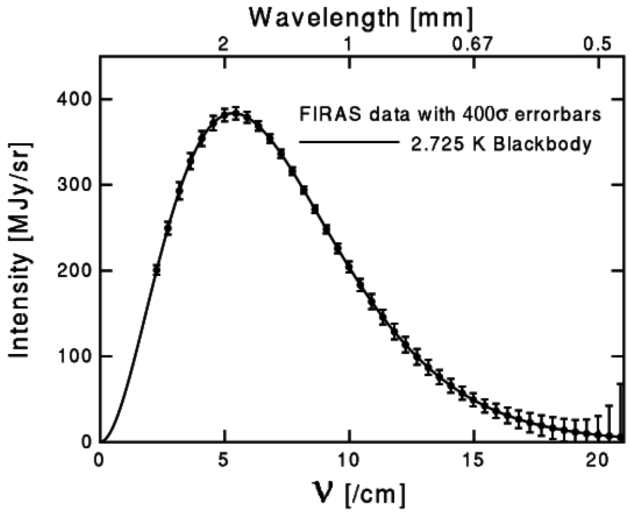


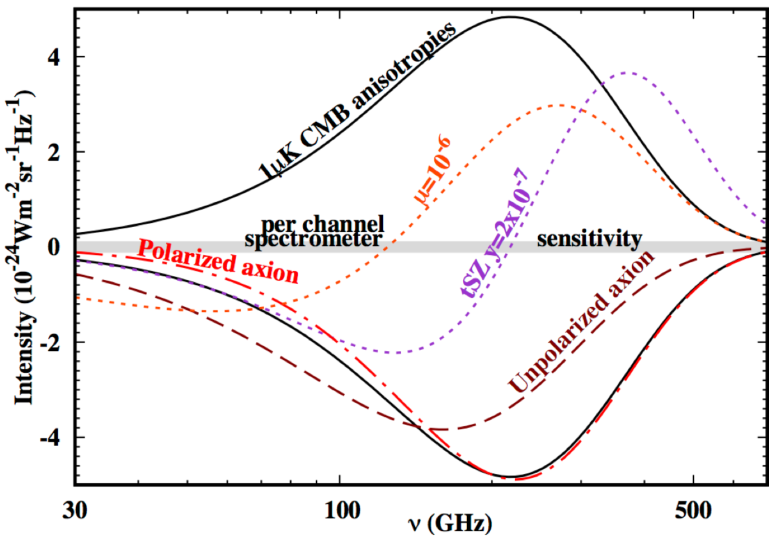






CMB Spectral distortion

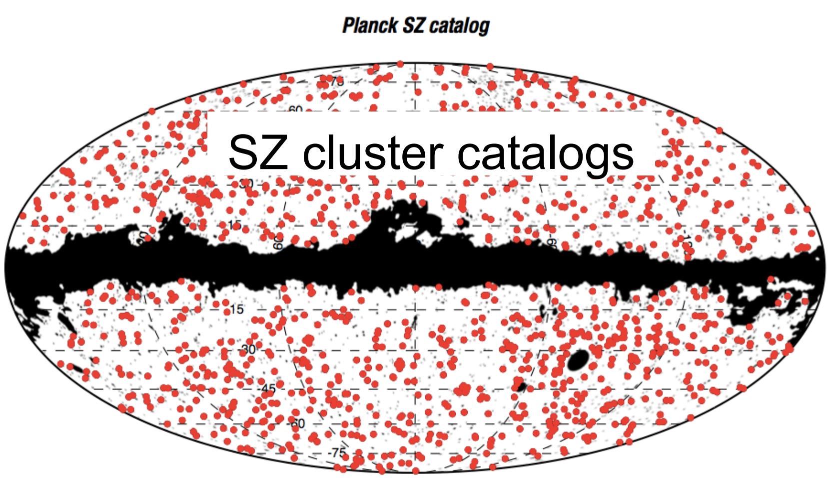




- Cosmic thermal history

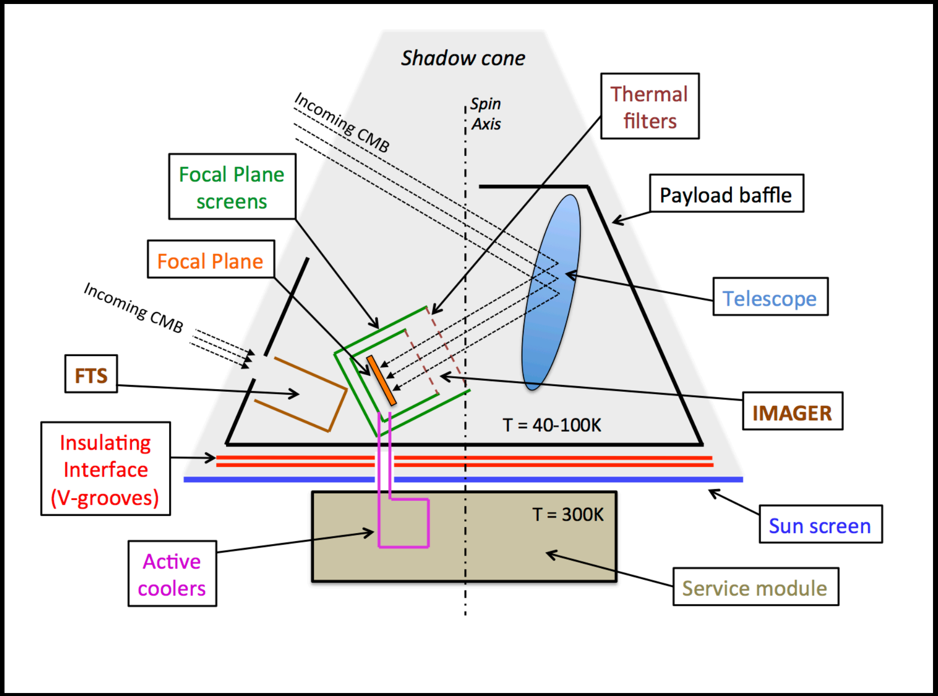
Any Energy injection (1100 <z<2.10^6)

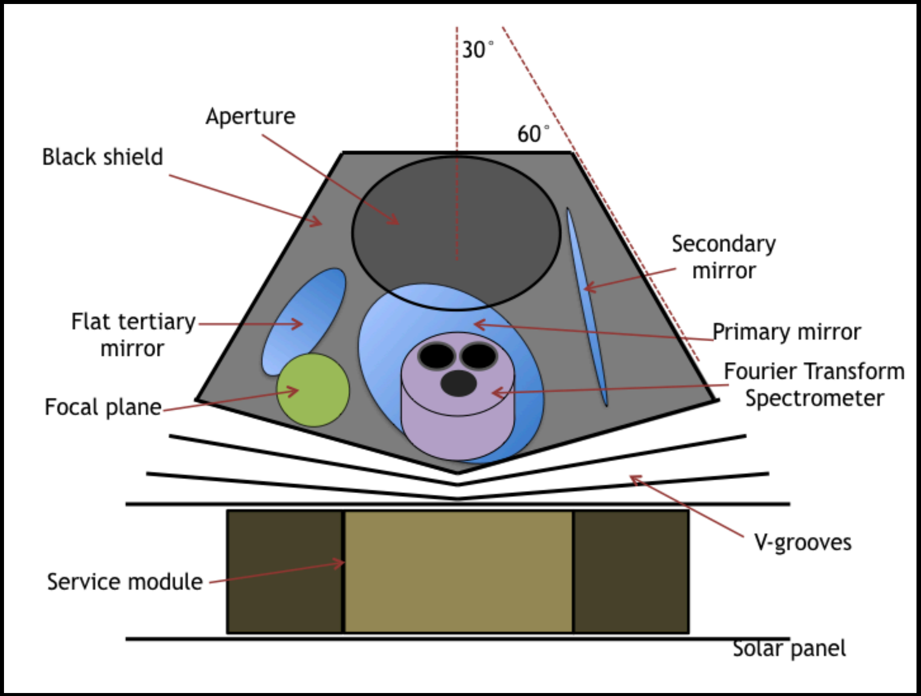
- Global SZ signal - cosmic web
- Decaying dark matter
- Axions
- Primordial Black holes
- Decaying topological defects



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.

CMB-Bharat S/c Specs.

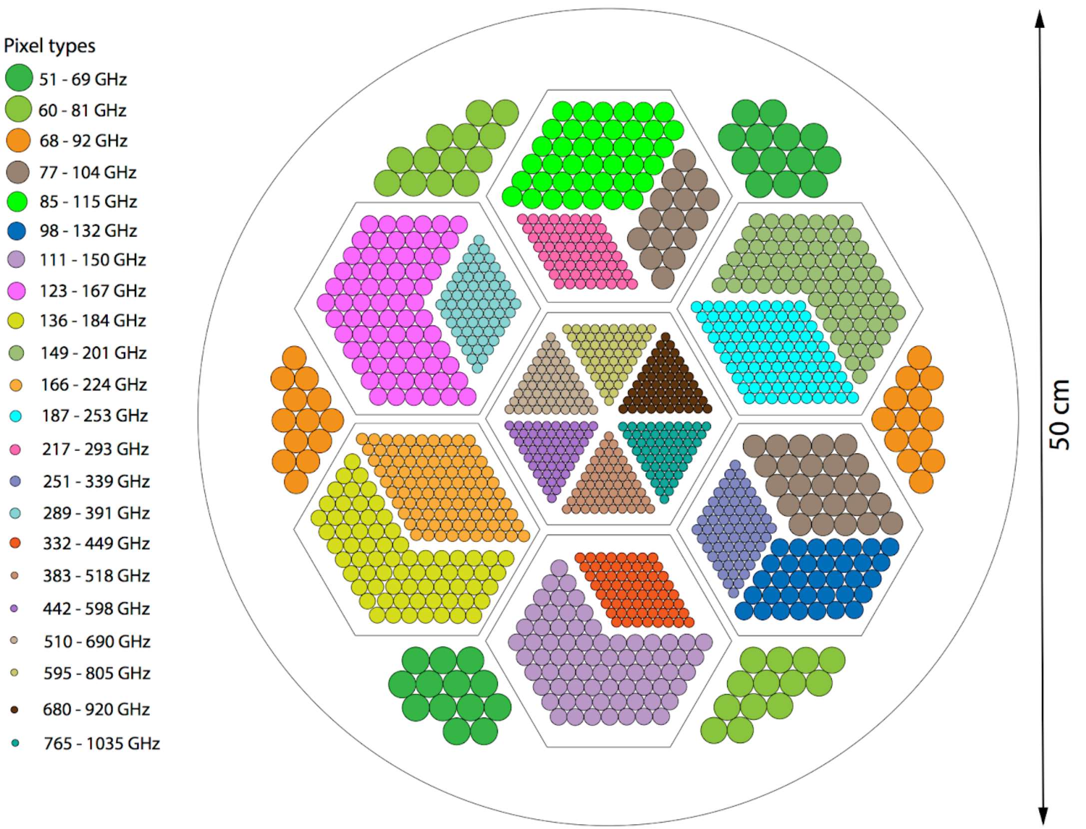
Subsystem	Mass (kg)	Margin (%)	Allocated (kg)
Telescope Optics			
Primary mirror	50	20	60
Secondary mirror	45	20	54
Tertiary mirror	18	20	22
Telescope structure	75	20	90
Subtotal Telescope Optics	188	20	226
Passive Cooling and Shielding			
Sunshield with supports	180	20	216
Telescope baffles/shields	50	20	60
V-grooves	90	20	108
Subtotal Passive Cooling and Shielding	320	20	384
Active Cooling			
Pulse tube coolers	85	20	102
Joule Thomson coolers	90	20	108
Closed cycle dilution refrigerator	30	20	36
Aluminum shells	40	20	48
Thermal/IR filters and supports	20	20	24
Subtotal Active Cooling Subsystem	265	20	318
Focal Plane Array			
Feed-horn coupled detector array	20	20	24
Cryogenic readout and harnesses	10	20	12
Support structure	10	20	12
Subtotal Focal Plane Array	42	20	48
Cabling	50	20	60
Warm readout electronics	30	20	36
Subtotal Payload	910	20	1100
Attitude Control System	80	30	104
Command and Data Handling	30	20	36
Power units	60	20	72
Cabling	50	20	60
Spacecraft Antenna with amplifier	15	20	18
Miscellaneous structures and mechanisms	200	20	240
Total dry mass	1340		1610
Propellant	150	100	300
Total spacecraft wet mass	1500		1900

Item	Power (Watt)	Margin (%)	Allocated (Watt)
Detectors and readout	150	20	180
Data processing	75	20	90
Cooling chain	1300	20	1560
Subtotal Payload	1525	20	1830
Attitude control	100	20	120
Command and data handling	80	20	96
Communication	40	20	48
Other mechanisms	30	20	36
Total Power	1775	20	2130

Mirror diameter	1.5m
Focal plane radius	26 cm
Total # of detectors	2388
CMB detectors 130 to 220 GHz	956 (40%)
CMB Pol. Sensitivity (130 to 220 GHz)	2.0 μK_{CMB}
Total CMB Pol. Sensitivity (full array)	1.7 μK_{CMB}
Data rate of FPU	2050 kbit/s

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

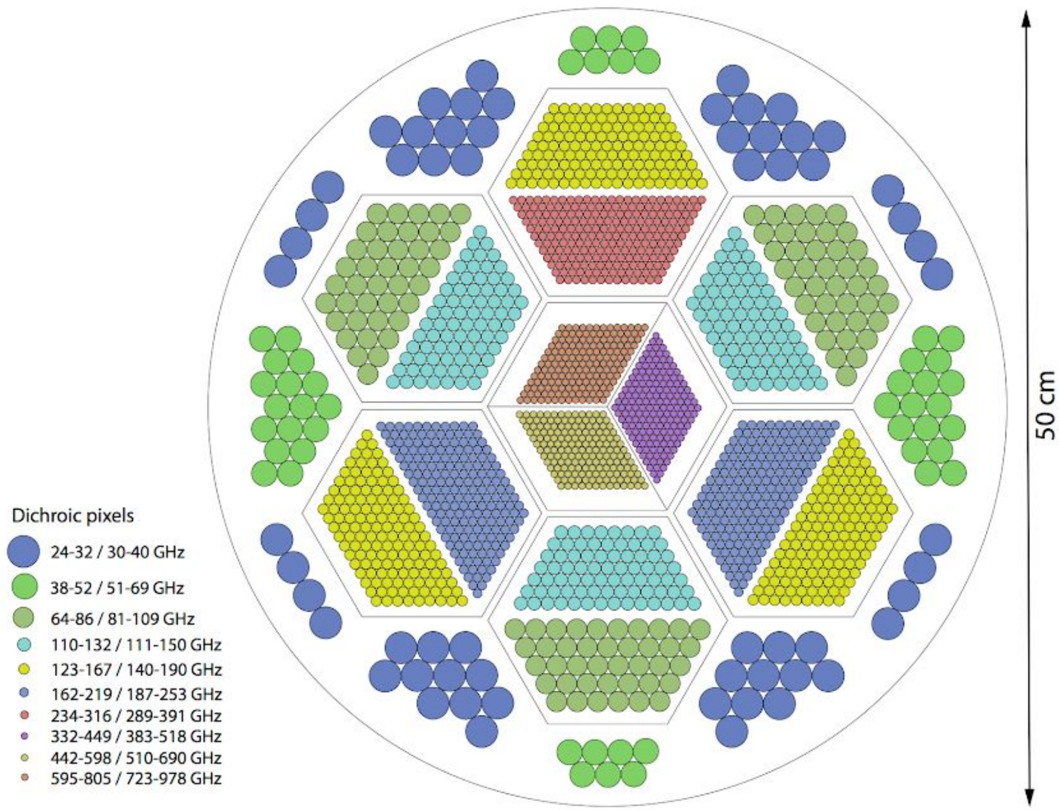


Extended CORE
700, 800, 900GHz

~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



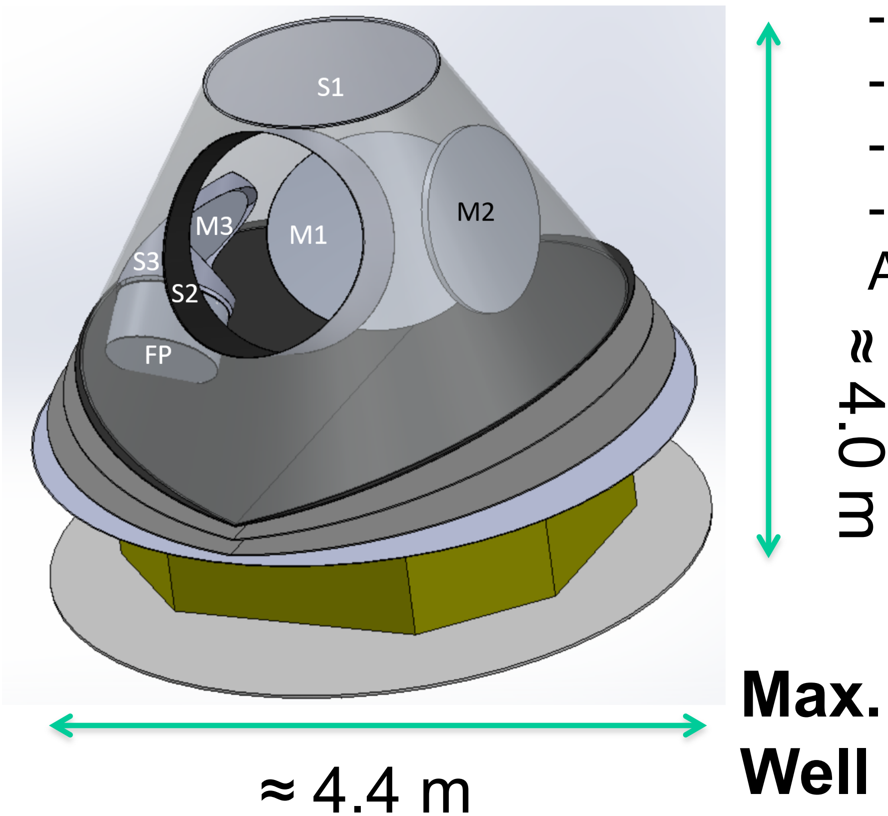
Ground expt inspired

Readout challenging

~6800 detectors/polarisation

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

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?).

*** 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.

*** Member: National Advisory Council for Dept of Space S&T at IIT Kanpur** Oct. 31, 2019

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 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

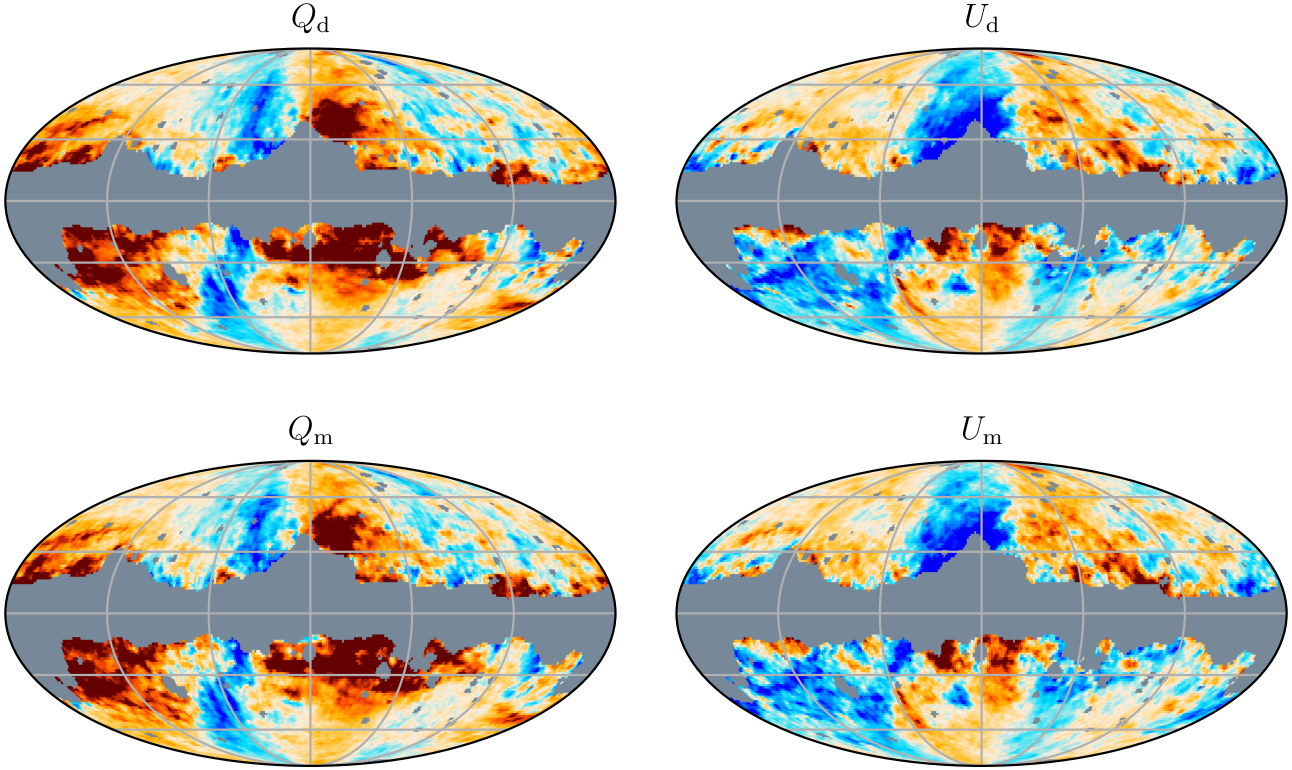
Indian Working groups

- ***Cosmological parameters:*** *Lead: Dhiraj Hazra (Bologna→ IMSc. Jan 2019,…)*
- ***Weak Lensing:*** *Lead: Suvodip Mukherjee (IAP, CCA, IAP, Nikhef ,→ .. ? India)*
- ***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 +)



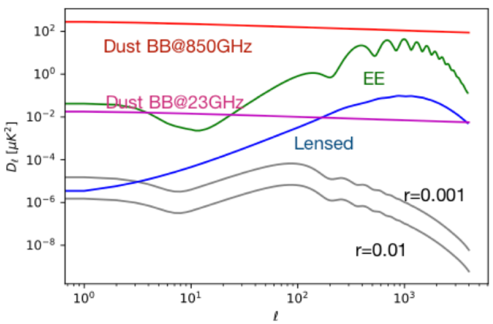
Top panel:
Planck data

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 +)

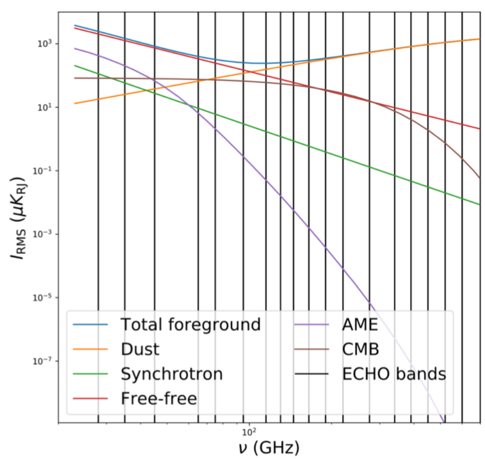


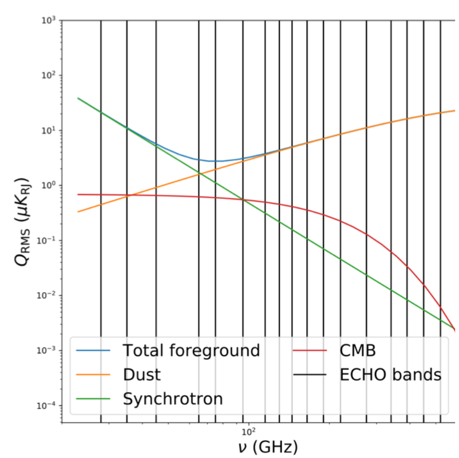
* PySM models for foreground simulations (full sky, Nside = 512)

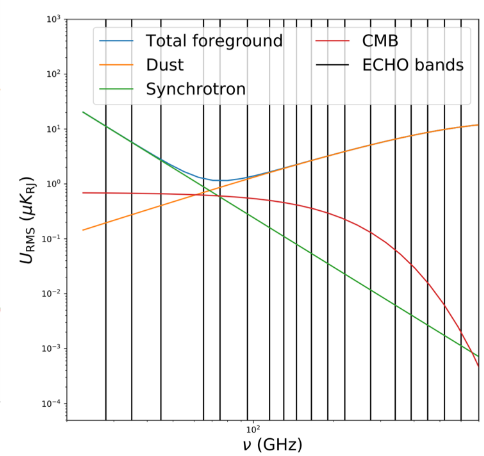
* Clean Foregrounds using NILC and COMMANDER.

* Test tensor-to-scalar rato possible to recover.

* Residual Foreground in cleaned map.



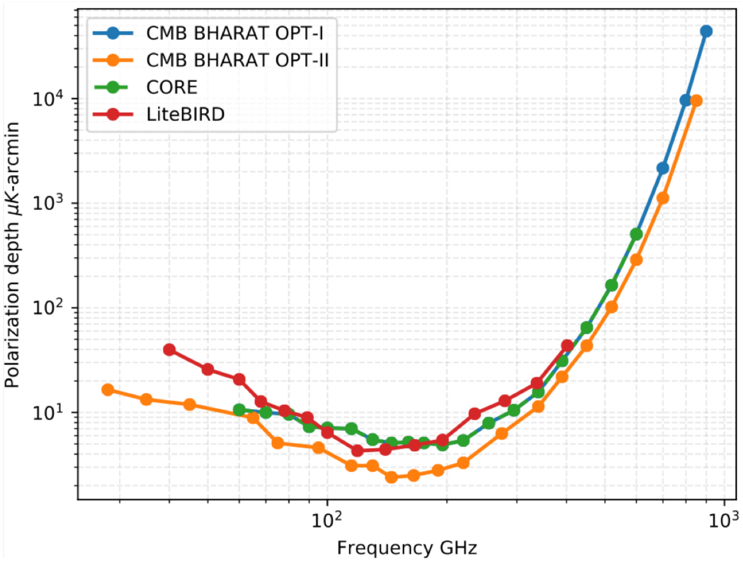




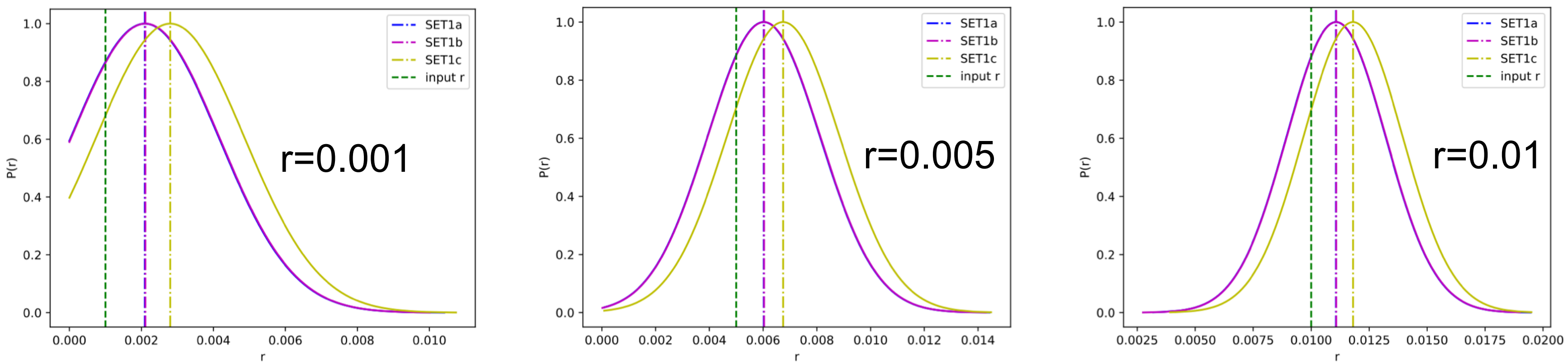
CMB-Bhārat: Research Glimpses

Efficiency of the existing component separation methods for B-Mode

(D. Adak, T. Ghosh, S. Basak, A. Sen, J. Delabrouille, G. Marť ınez-Solaeche, TS)



- **OPT-I is extended in high frequency side compared to CORE**
- **OPT-II extended in both side of frequencies compared to CORE**

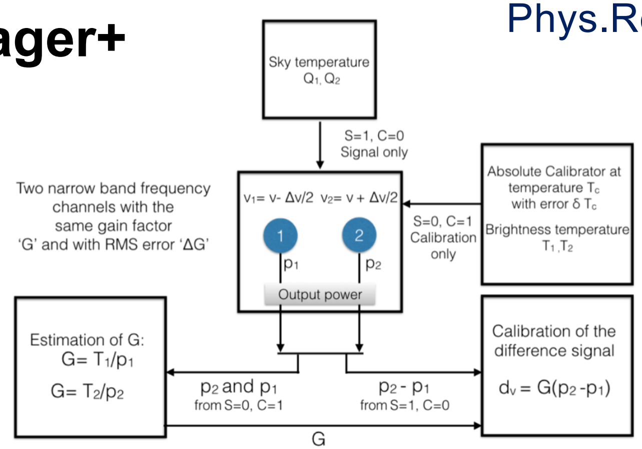


CMB-Bhārat: Research Glimpses

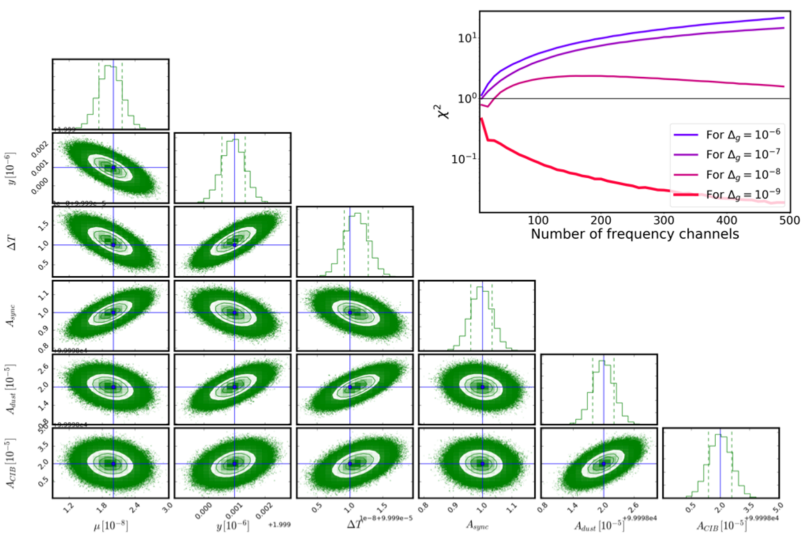
Measuring the CMB spectral distortions with an imager+ calibrator

Mukherjee, Silk, Wandelt

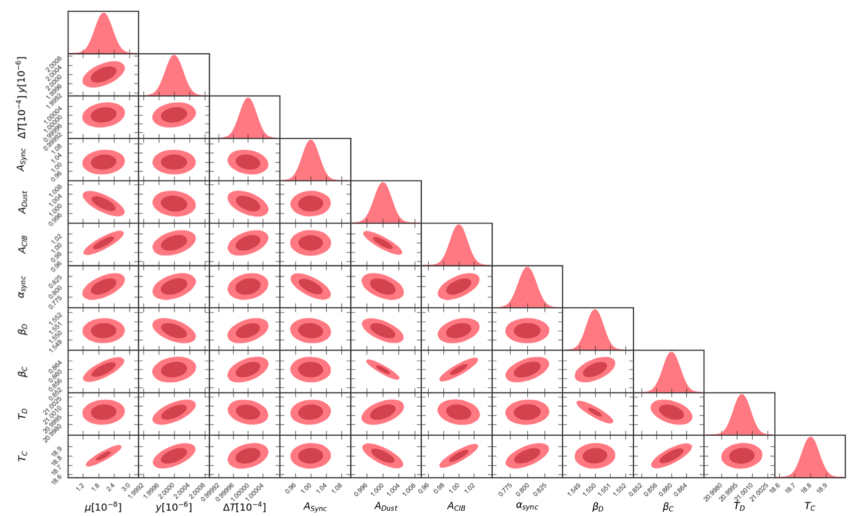
Phys.Rev. D100 (2019) no.10, 103508



MCMC analysis



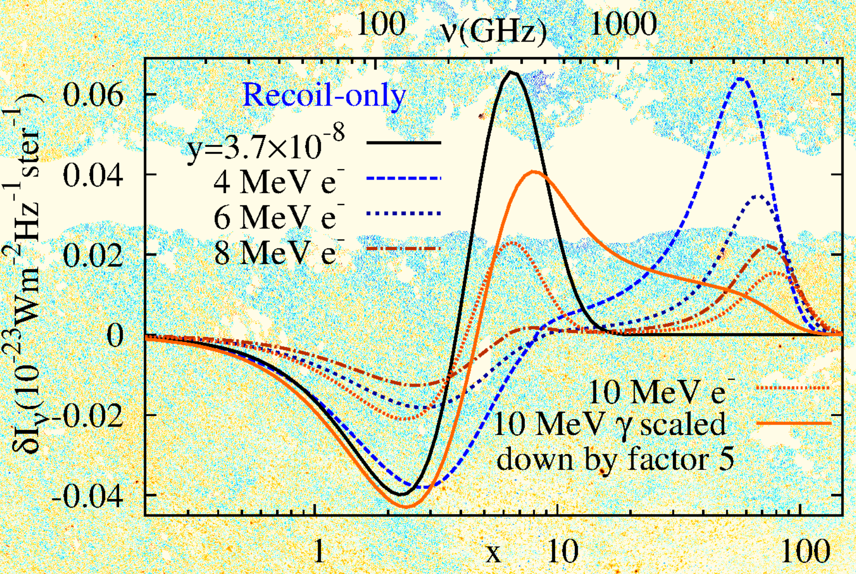
Fisher analysis



CMB-Bhārat: Research Glimpses

The information hidden in the shape of the CMB spectral distortions

Rishi Khatri
Group leader at TIFR, Mumbai



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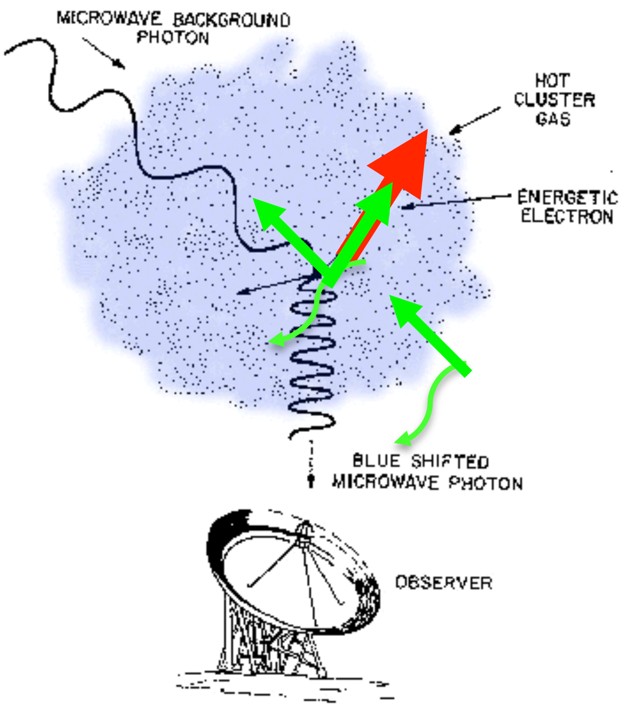
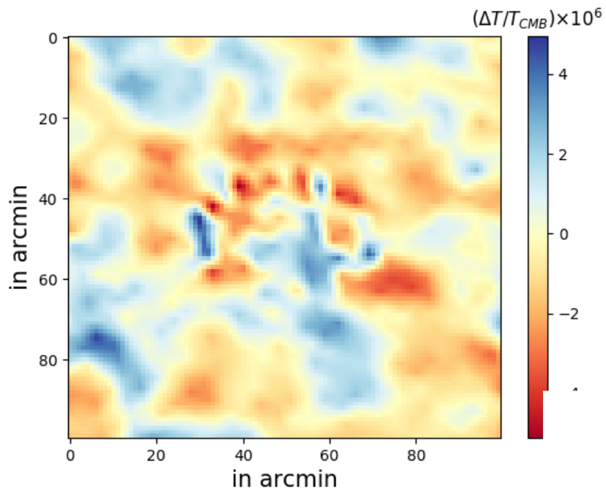
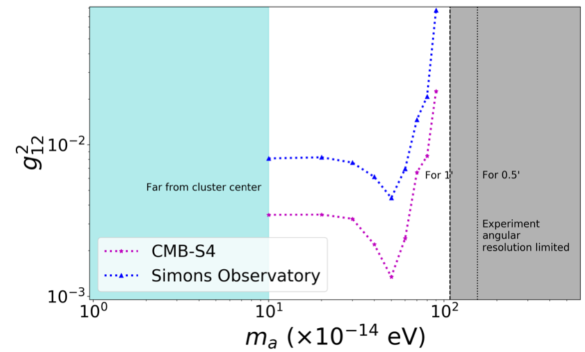
CMB-Bhārat: Research Glimpses

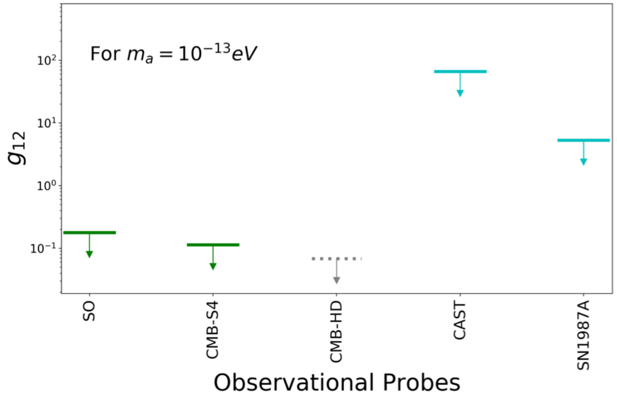
ALPs constraints from the future CMB missions
Distortion around a galaxy cluster in the polarization map

Mukherjee, Spergel, Khatri, Wandelt.
arXiv:1908.07534









CMB-Bhārat: Research Glimpses

Ranajoy Banerji
Post-doc researcher
ITA, University of Oslo

Current Projects

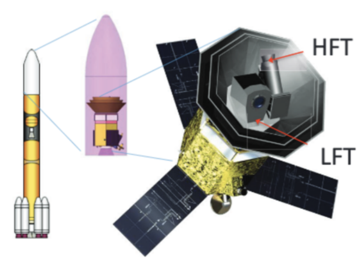
- **LiteBIRD**: CMB polarisation space mission to detect primordial B-modes at large scales.
- **BeyondPlanck**: End-to-end Bayesian analysis of CMB data, starting with Planck LFI. To include multi-frequency serveys in the future.

Expertise

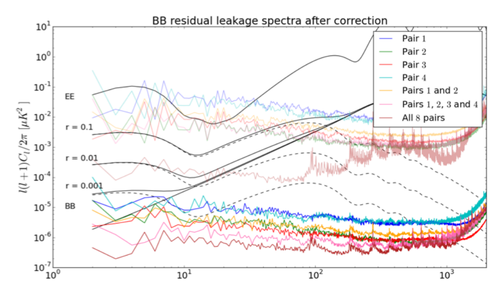
- Modelling Instrumental systematics and mitigation
- Foreground estimation
- TOD simulation and analysis

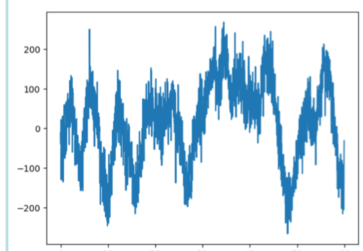
Important Publication/Software

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



De-striping systematics correction





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

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 in ISRO womb, 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.

- **Hard gestation period but clear signs of high aspirations in ISRO**

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

https://www.isro.gov.in/chandrayaan2-home-0

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 !!!