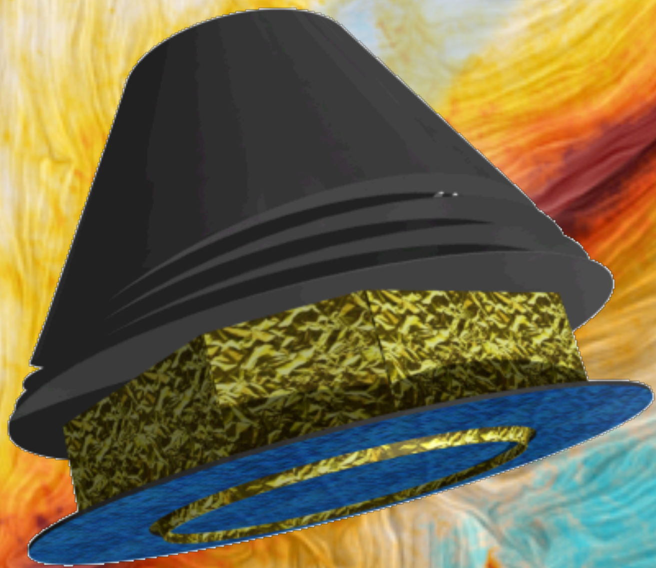
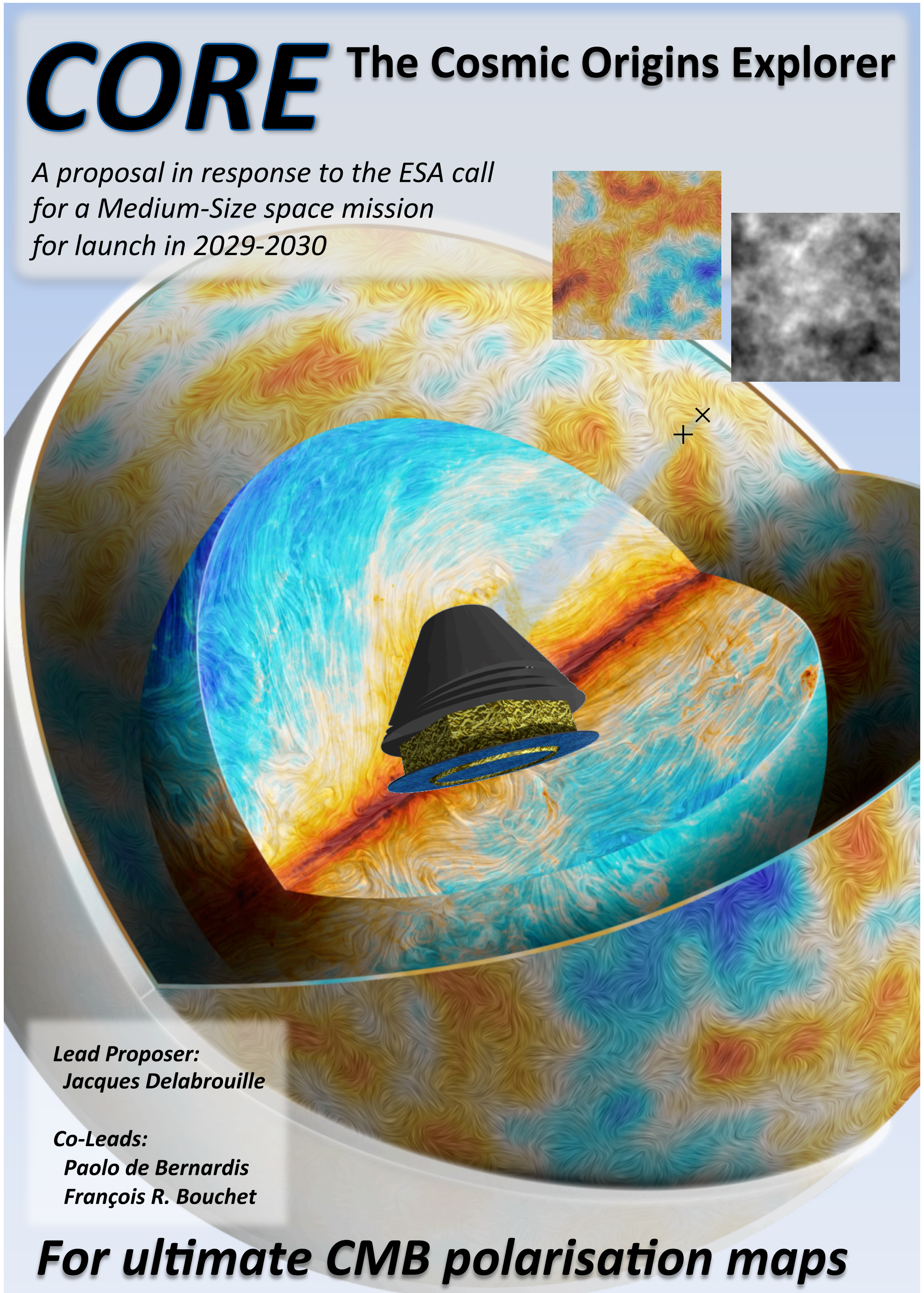
The Cosmic Origins Explorer and the CMB-Bharat proposal

Jacques Delabrouille, APC (Paris)

On behalf of the CORE collaboration





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350 proposers mostly from Europe

CORE status and context for follow-up

- CORE is designed as a "near-ultimate" CMB polarization mission (as Planck was a "near-ultimate" CMB temperature anisotropy mission).
- In spite of strong support from the community (and from major national space agencies in Europe), the proposed mission concept did not pass the initial technical and programmatic screening by ESA in January 2017.
- The main issue was cost and, to a lesser extent, the TRL of enabling technology in Europe alone (detectors, cooling chain).
- ESA encouraged the CORE consortium to consider a joint proposal with a major international partner.

CORE: Some references

Space mission: "Exploring Cosmic Origins (ECO) papers" (special issue of JCAP)

DESIGN

- Mission: Delabrouille, de Bernardis, Bouchet et al. arXiv:1706.04516
- Instrument: de Bernardis, Ade, Baselmans et al. arXiv:1705.02170

SCIENCE

- Inflation: Finelli, Bucher, Achucarro et al. arXiv:1612.08270
- Lensing: Challinor, Allison, Carron et al. arXiv:1707.02259
- Parameters: Di Valentino, Brinckmann, Gerbino et al. arXiv:1612.00021
- Clusters: Melin, Bonaldi, Remazeilles et al. arXiv:1703.10456
- Velocity: Burigana, Carvalho, Trombetti et al. arXiv:1704.05764
- Sources: De Zotti, Gonzalez-Nuevo, Lopez-Caniego et al. arXiv:1609.07263

PROCESSING

- Foregrounds: Remazeilles, Banday, Baccigalupi et al. arXiv:1704.04501
- Systematics: Natoli, Ashdown, Banerji et al. arXiv:1707.04224

A lot of amazing work from many people , many of whom are present at this workshop !

http://iopscience.iop.org/journal/1475-7516/page/extraproc1

Outline

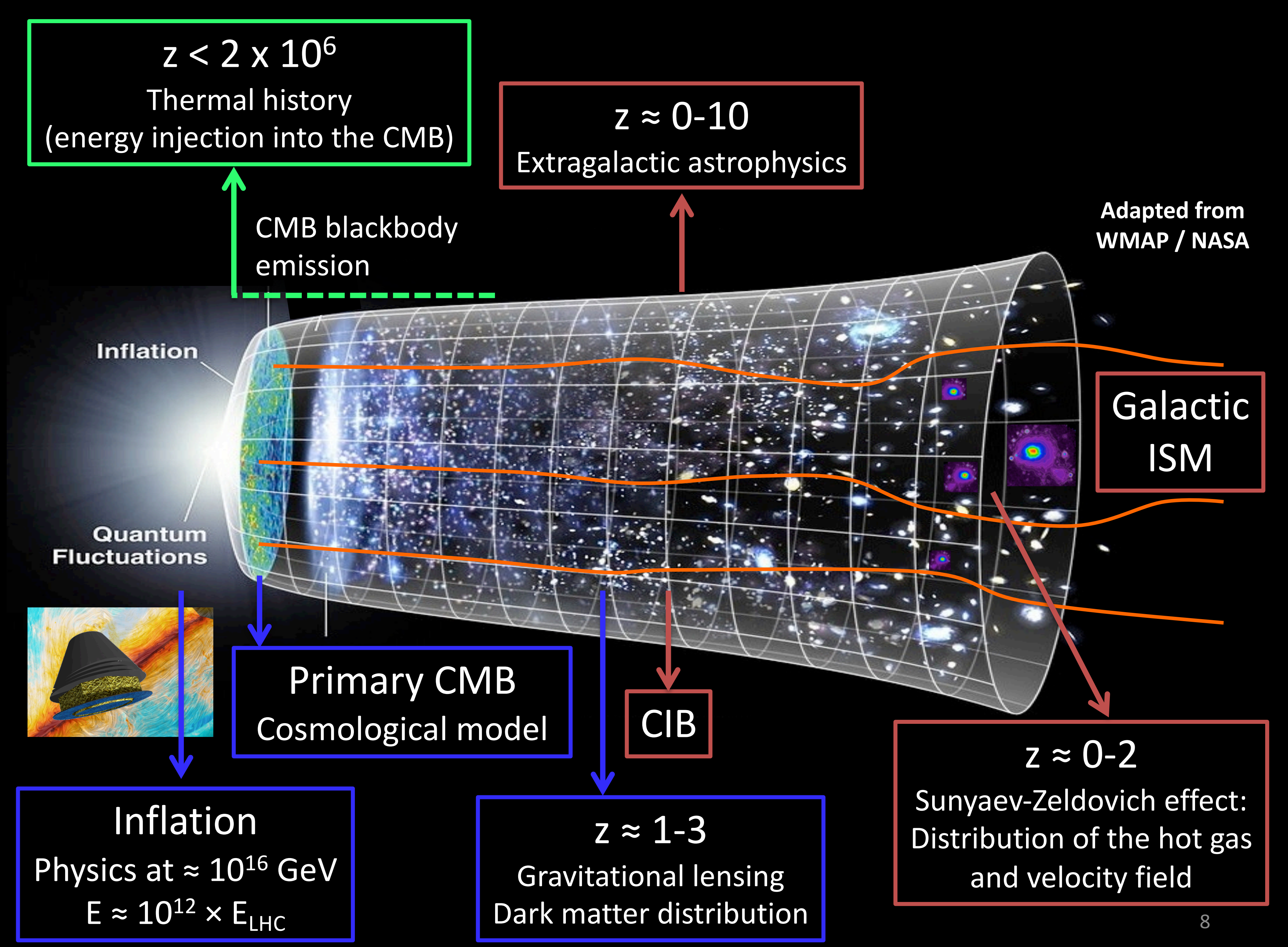
- CORE science requirements and goals
- Mission requirements and design
- ESA evaluation of the M5 proposal
- The CMB-Bharat proposal to ISRO
- Summary and perspective

Standard paradigm

- A standard model of Cosmology has emerged: ΛCDM
- Compatible with many cosmological observables ("concordance")
- The CMB is the main observable that established the paradigm and determined its main parameters to percent accuracy (with improvements still possible: $\tau, \Sigma m_{\nu}$…)
- A phenomenological model fits the data well, but we must verify if it survives a detailed scrutiny at the fundamental limits of what the CMB can teach us.
- Indeed many open questions remain, which testify that we are far from being done yet !
  - **Inflation?** Did it happen? At what energy scale? What drives inflation? What inflation?
  - **Dark matter?** What is it? Does it interact? Does it decay? …?
  - **Dark Energy?** Cosmological constant? Why? Dynamical DE? Modifications to gravitation?
  - **Anomalies in the CMB?** Low low multipoles, NS asymmetry? Kinks, outliers, etc…?
  - **Tensions (H_0, σ_8…)?** Will they survive decreasing error bars? Will new tensions emerge?

CORE science case in a nutshell

- Scrutinize the CMB some more to look for answers to these questions
- Design driver: comprehensive polarisation science
  - Primordial B-modes at the limit of astrophysical/cosmic confusion;
  - Map CMB lensing with high S/N at all scales > 15';
  - Constrain ΛCDM and extensions at the CMB cosmic variance limit;
- Comes "for free" but of major scientific interest
  - Map the hot baryons through SZ effect
  - Extragalactic sources
  - Astrophysical foreground emissions
  - Galactic magnetism
  - Very rich data set for many fields of astrophysics!


z < 2 x 10^6
Thermal history
(energy injection into the CMB)
CMB blackbody
emission
z ≈ 0-10
Extragalactic astrophysics
Adapted from
WMAP / NASA
Inflation
Quantum
Fluctuations
Galactic
ISM
Primary CMB
Cosmological model
CIB
z ≈ 0-2
Sunyaev-Zeldovich effect:
Distribution of the hot gas
and velocity field
Inflation
Physics at ≈ 10^16 GeV
E ≈ 10^12 × E_LHC
z ≈ 1-3
Gravitational lensing
Dark matter distribution

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CORE space mission key requirements

1) Noise ≈ 2 μK.arcmin or better
- need signal-dominated maps
- lensing B modes ≈ 5μK.arcmin

2) All primary CMB scales
- cover from $l = 1$ to $l \approx 2500$
- angular resolution $\approx 5'$

3) Full sky
- for testing stationarity, redundancy
- for lowest possible cosmic variance

4) 15 frequencies or more

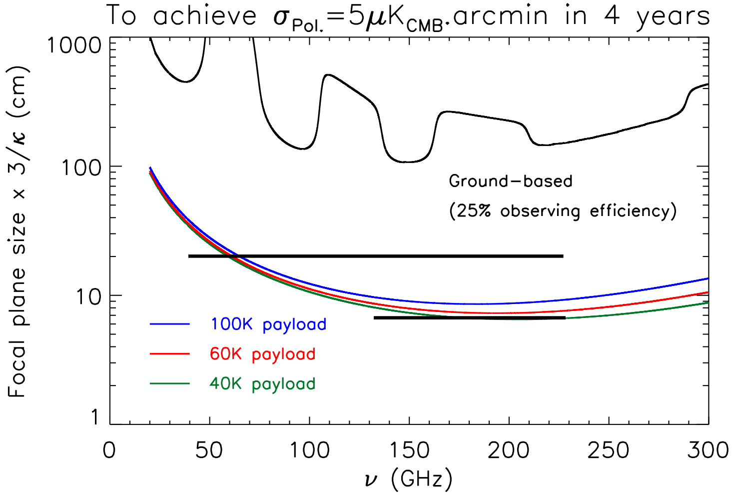
Foregrounds!
- to understand/model the foregrounds
- for redundant CMB obs. at $\neq \nu$

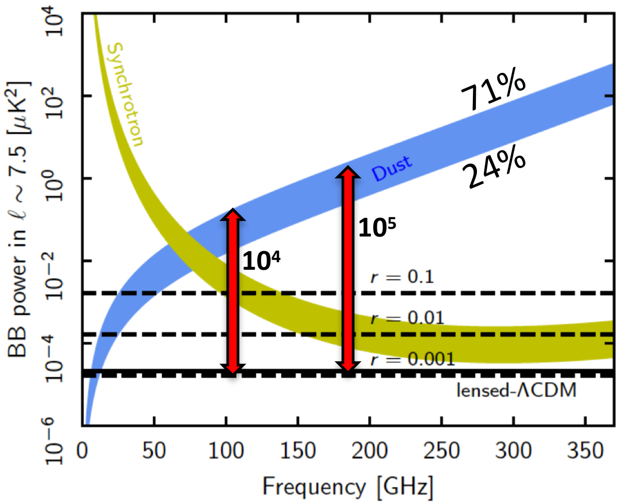
5) Instrumental stability

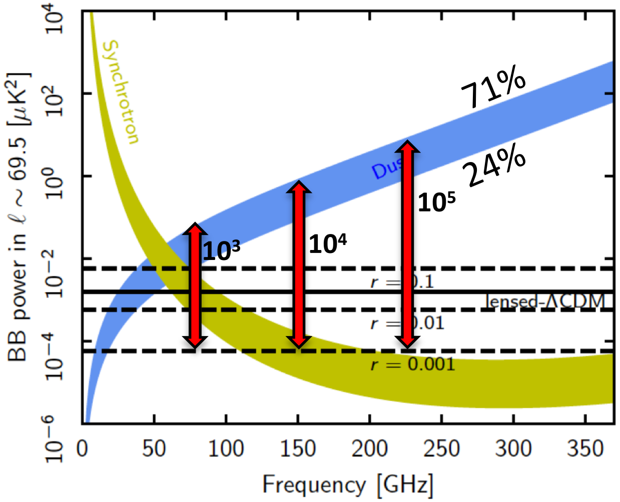
Systematics!
- to understand/model the instrument

6) Multiple redundancy
- to assess is the origin of the signal

Frequency range: 60-600 GHz







Planck 2018: Polarized foregrounds

Best CMB sensitivity from space around 200 GHz

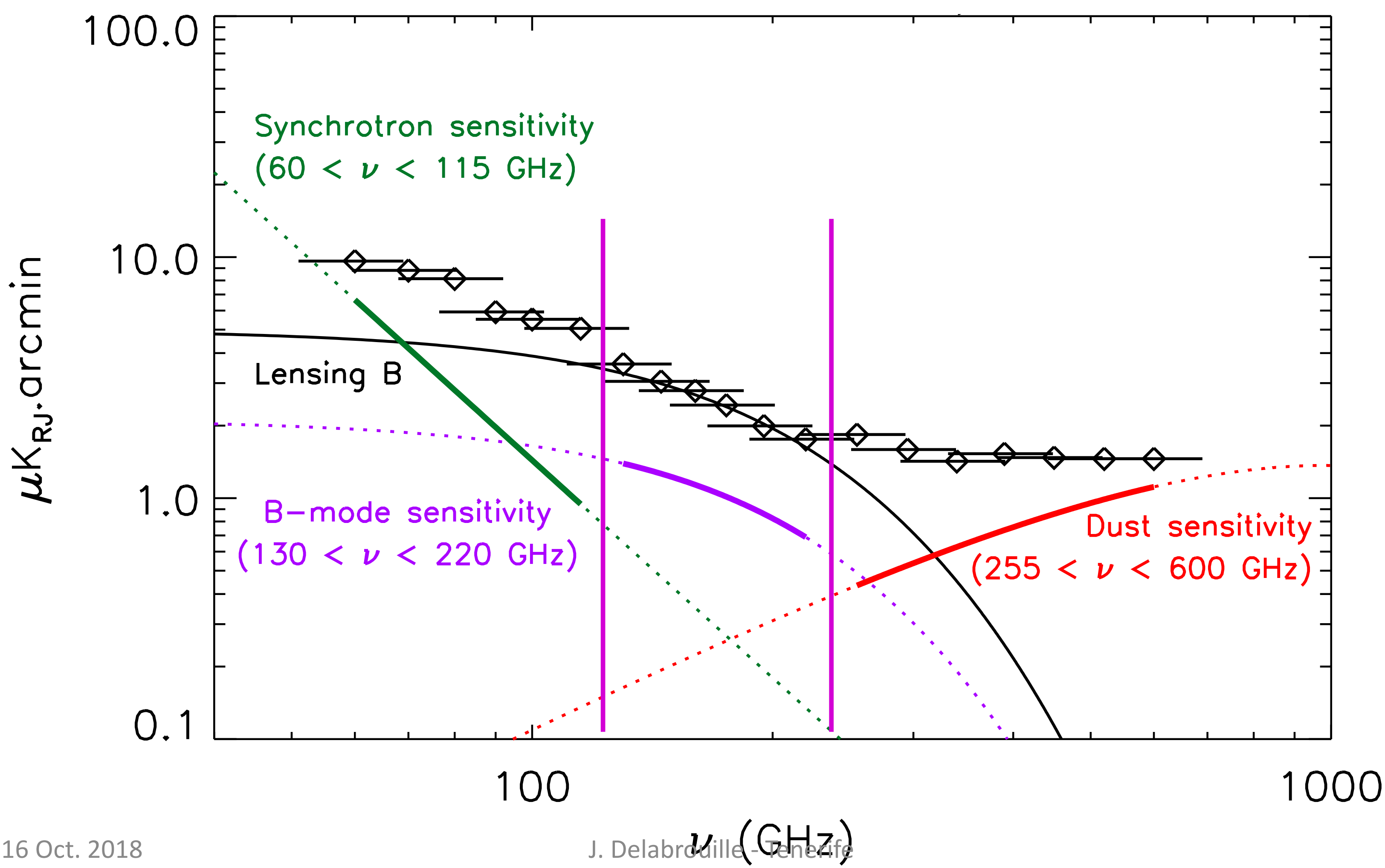
Mapping speed ≈ 10 times worse at 60 GHz than 200 GHz
Foregrounds ≈ 10 times worse at 200 GHz than at 60 GHz
Beam size ≈ 3 times worse at 60 GHz than 200 GHz

COMPROMISE NEEDED

CORE channels

channel GHz	beam arcmin	$N_{\rm det}$	ΔT μK.arcmin	ΔP μK.arcmin	ΔI $\mu K_{\rm RJ}$.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ $y_{\rm SZ}$.arcmin	PS (5σ) mJy
60	17.87	48	7.5	10.6	6.81	0.75	-1.5	5.0
70	15.39	48	7.1	10	6.23	0.94	-1.5	5.4
80	13.52	48	6.8	9.6	5.76	1.13	-1.5	5.7
90	12.08	78	5.1	7.3	4.19	1.04	-1.2	4.7
100	10.92	78	5.0	7.1	3.90	1.2	-1.2	4.9
115	9.56	76	5.0	7.0	3.58	1.45	-1.3	5.2
130	8.51	124	3.9	5.5	2.55	1.32	-1.2	4.2
145	7.68	144	3.6	5.1	2.16	1.39	-1.3	4.0
160	7.01	144	3.7	5.2	1.98	1.55	-1.6	4.1
175	6.45	160	3.6	5.1	1.72	1.62	-2.1	3.9
195	5.84	192	3.5	4.9	1.41	1.65	-3.8	3.6
220	5.23	192	3.8	5.4	1.24	1.85	-	3.6
255	4.57	128	5.6	7.9	1.30	2.59	3.5	4.4
295	3.99	128	7.4	10.5	1.12	3.01	2.2	4.5
340	3.49	128	11.1	15.7	1.01	3.57	2.0	4.7
390	3.06	96	22.0	31.1	1.08	5.05	2.8	5.8
450	2.65	96	45.9	64.9	1.04	6.48	4.3	6.5
520	2.29	96	116.6	164.8	1.03	8.56	8.3	7.4
600	1.98	96	358.3	506.7	1.03	11.4	20.0	8.5
Array		2100	1.2	1.7			0.41	

CORE channels



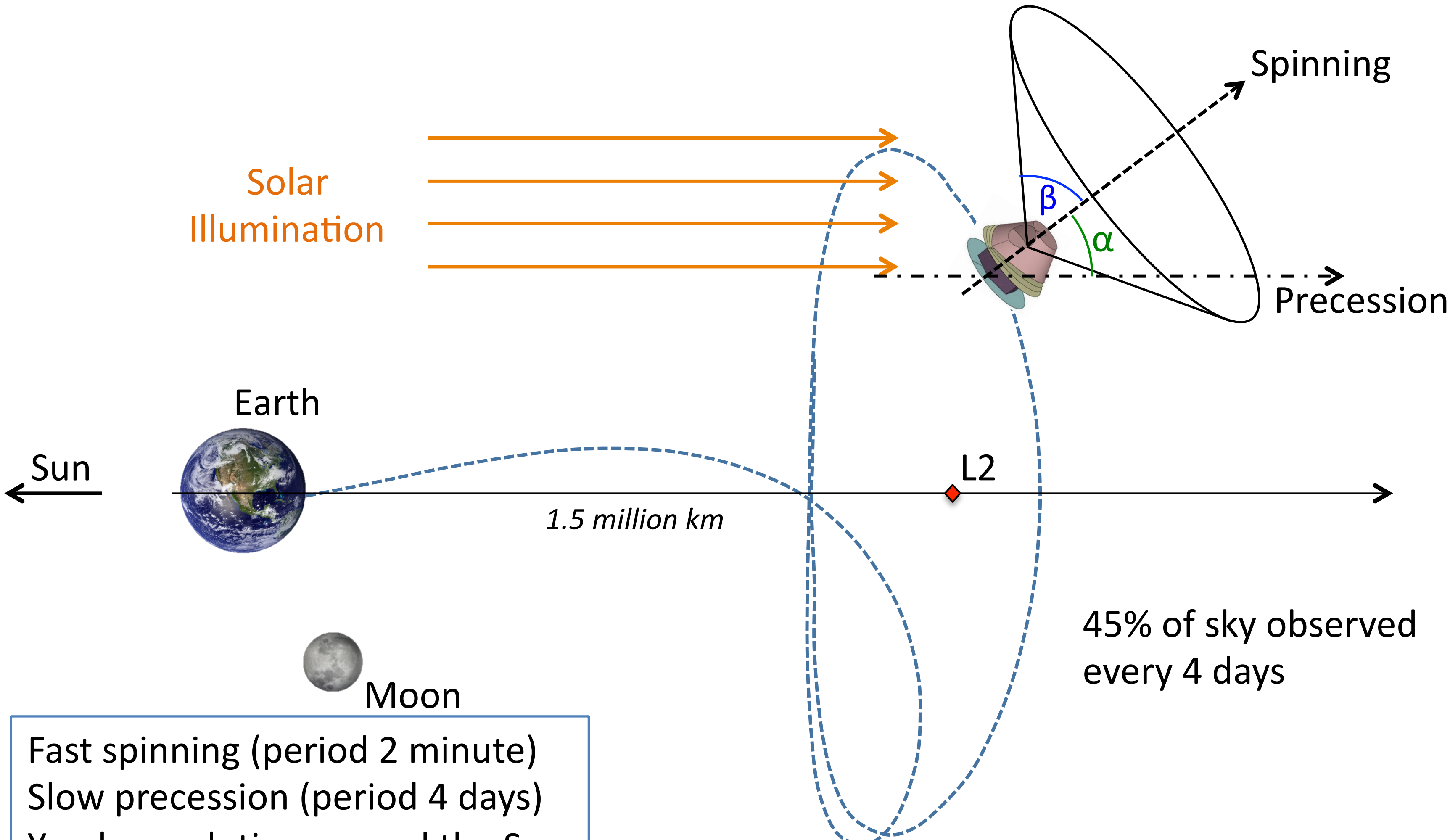
Observing strategy

Space offers a unique observing environment

- Access to all frequencies (for astrophysical foregrounds)
- Very stable environment (for systematics)
- Flexibility to observe large patches of sky
- Flexibility to observe distant points in short timescales

CORE is design to fully exploit these advantages

Orbit and scan strategy



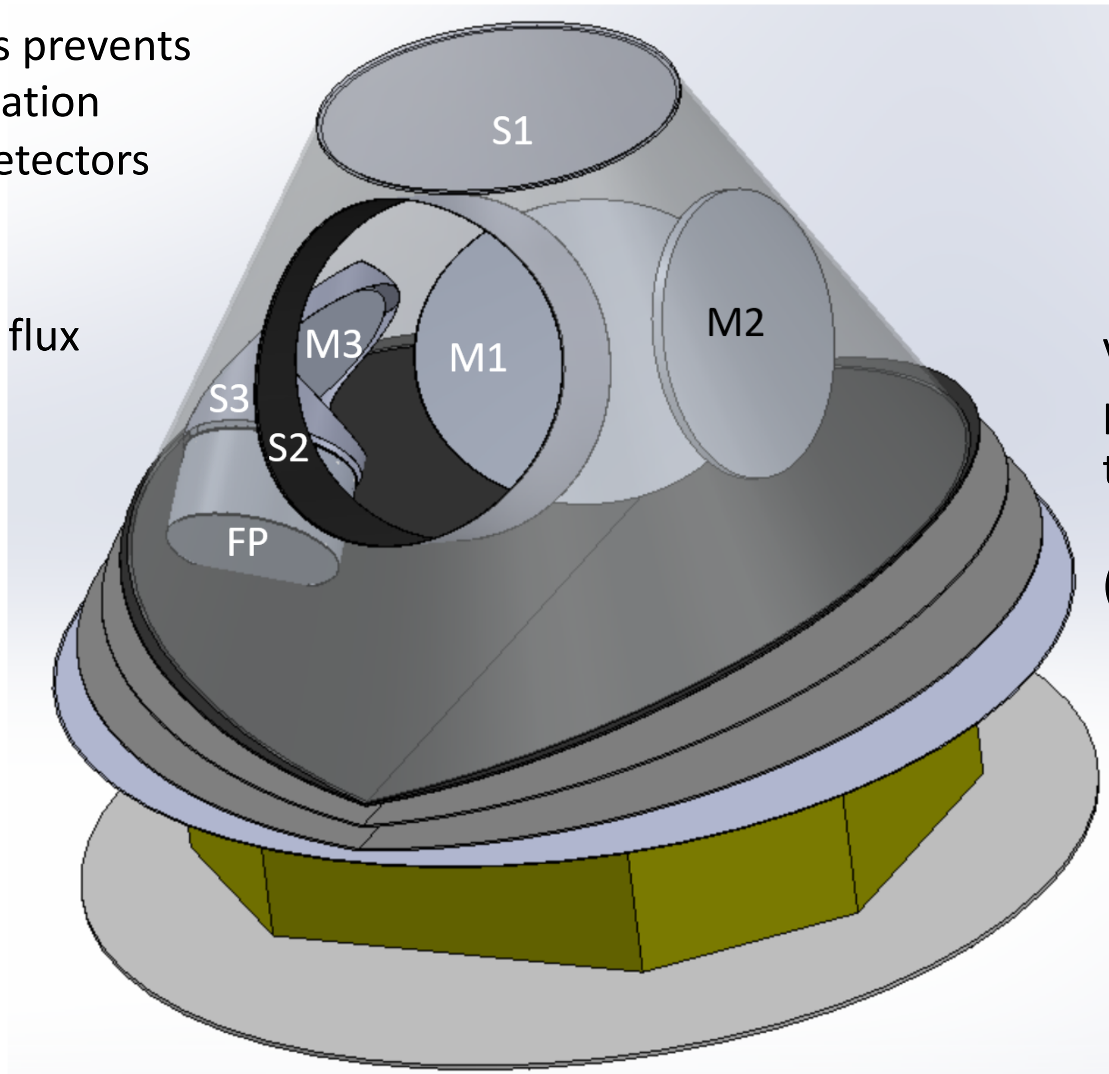
Fast spinning (period 2 minute)
Slow precession (period 4 days)
Yearly revolution around the Sun

Geometry, shielding and V-grooves

A set of shields prevents
unwanted radiation
to reach the detectors

Constant solar flux
on payload

No moving
parts



V-grooves provide
passive cooling of
the payload to 40K

(Planck heritage)

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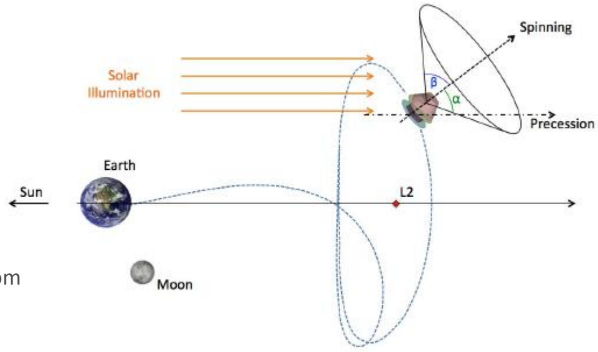
Evaluation by ESA (1/3)

22 CORE (Description)

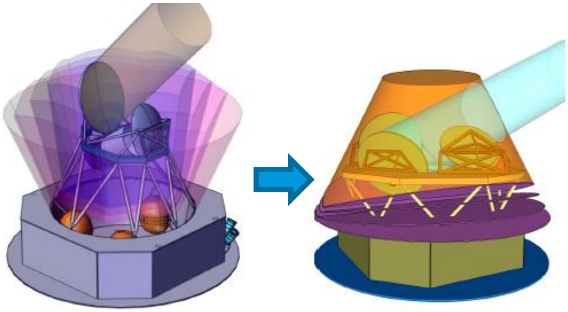
Main science objectives:
- Measurement of B-mode polarisation of Cosmic Microwave Background

Mission profile:
- Ariane 6.2 single launch into L2 transfer (3 ton performance). Potential need of larger LV-IF (2624 vs 1780 available)
- L2 large halo orbit
- Full sky survey mission with defined scanning law (see picture right), 4 years observation



Spacecraft (1 S/C, ~2000 kg, ~2000 W):
- Configuration as Planck/CDF NGCryo, PLM isolated from SVM by V-grooves. Different PLM layout
- Single S/C, spin stabilised 0.5 RPM, precession: 4 days period. Tilt of 30° wrt. Sun direction, Fixed Solar panel at the bottom
- Cryogenic PLM with Telescope @ ~40-50 K (passive cooling)
- Cryo-chain: Focal Plane 1st shield: 15K by 3x 5PTC, 2nd shield: 4 K by 2x JT4K, 3rd shield: 1.7 K by 2x JT1.7K
- Total mass: 1998 kg (dry 1845), Power:~2000 W (1300 W of cryo-cooling), 4.4 m diam. x ~4 m height
- 100 Gbit/day data volume at the limit of X-band TT&C capability (~9 Mbps)

Payload (mass, power, one instruments):
- Telescope: 1.2 m projected aperture Cross-Dragone configuration with M3 folding mirror and f/2.5
  M1: 1.5 x 1.3 m, M2= 1.4 x 1.3 m
- **Single Instrument**: Polarimeter with 2100 KIDS detectors (60-600 GHz range) in 19 frequency bands.
- Cooling @100 mK by Closed-Cycle Dilution Refrigerator (CCDR) He_3
- Required performance: sensitivity: 2μK*arcmin (30x better than Planck), angular resolution: 6 arcmin @ 150 GHz (driven by lensing)
- MKIDS detectors: Photon noise~ 10^{-17} W/Hz$^{-0.5}$
- Optional Half wave plate



Implementation scheme & ESA contribution:
- **Role of ESA**: Overall Mission + SVM, telescope and PLM shielding + cryo-chain down to 1.7 K
- **Role of Member States:** Focal Plane + electronics + dilution cooler
- **Role International Partner(s):** None

Evaluation by ESA (2/3)

22 CORE (Evaluation)

S/C Major challenges & critical issues:

- Complex cryo-chain and associated AIT
- Non-standard AOCS with large wheels required for momentum canceling to allow S/C precession (2x 70Nms)
- If K-band (32 GHz) science data downlink required, potential spurious signals to instrument

P/L Major challenges & critical issues:

- Large telescope
- Complex filter geometry to adapt to Focal plane frequency partition
- Large Focal Plane: cooling more difficult

Qualification status (S/C and P/L):

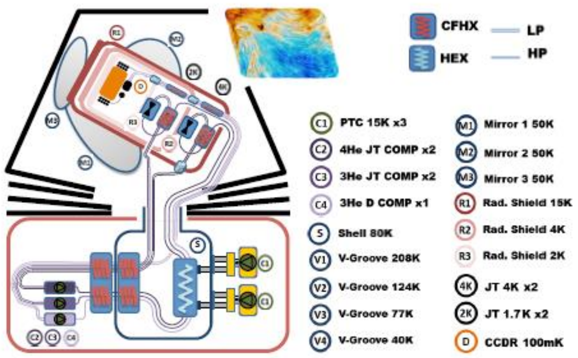
- S/C: all TRL6; STR for 0.5 RPM (TDA development ongoing)
- Dilution cooler: TRL3-4 (Breadboard tested in 2014 with JAXA DM compressor). Requires immediate investment from MS (activities described in the proposal), but high risk.
- KIDS detectors: Development under FP7 project (SPACEKIDS):
  - TRL5 (f>110 GHz), used on Ground telescopes, and radiation tested
  - TRL3 (f<110 GHz), require immediate MS investment for space qualification (activities described in the proposal)
- Demonstration of yield for KIDS detectors

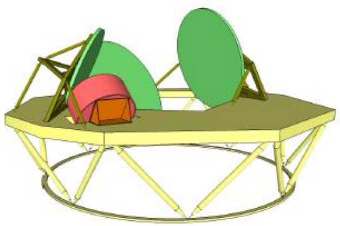
Programmatic aspects:

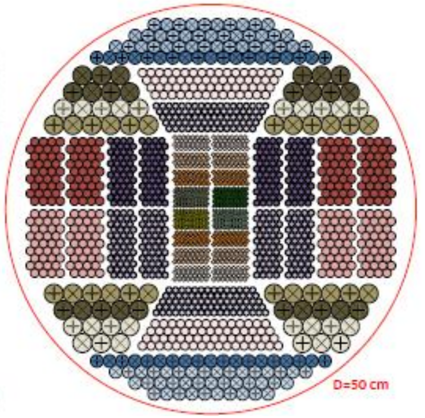
- Much larger share of PLM on ESA compared to M4 (Core+)
- 5 De-scoping options proposed but impact on total mission cost is minor:
  1) single polarization detectors @115 GHz,
  2) halving no. of detectors,
  3) replace KIDS at low frequency with high TRL detectors,
  4)Telescope aperture to 1 m,
  5) PLM T @ 100 K

Clarity of implementation scheme, split of responsibilities and interfaces:

- Clear responsibility allocation
- Instrument Phase A tasks and allocations among partners described







Evaluation by ESA (3/3)

22 CORE (Summary)

Increase TRL →

Too costly →

Summary Evaluation		Comment
Mission profile	G	o.k.
Spacecraft design	G	Standard SVM
Spacecraft TRL	G	All cryocoolers on ESA can be based on existing development (ATHENA)
Payload design	Y	Complex cryogenic design of Focal Plane, 2100 detectors
Payload TRL	Y/R	TRL6 by 2021 doubtful for the dilution cooler and feasible for the KIDS only if MS pursue immediate development.
GS & Science Ops.	G	Survey mission, 4 yrs ops
Programmatic / Cost	R	Cost exceeding>550 M€ target. De-scoping options saving: ~30 Meuro max (mainly option 5)
Implementation Scheme	Y	too much on ESA, need for a strong international partner
General summary	R	**Significantly above cost target**

Sharing of Responsibility

Element	ESA	MS / (SL)		Int. Partner / SL		comment
Launcher	X					
S/C	X					
P/L	X	X				ESA in charge of: whole PLM including AIV/T and cryo-chain down to 1.7 K. MS responsible of instrument + dilution cooler
G/S & OPS	X	X				In proposal, role of ESAC reduced (Pipeline on SDC). However, ESA cost assessment based on standard ESAC services
other						

<u>Conclusion of Evaluation:</u>

1: Mature mission profile and spacecraft design, doubtful for dilution cooler (required for continuous operations)
2: Low TRL of payload elements (KIDS detectors and dilution cooler) requiring immediate commitment of MS funding for development
3: Cost above M5 target and not recoverable by de-scoping options (plus risk of increased cost due to optimistic SOC assumption).
Success oriented proposed schedule for reaching TR:5-6 by mission selection (~ 2 years) → would require substantial MS investment before mission selection.

Measures taken since then

- TRL increase of key technologies in Europe
  - Developments for other instruments / space missions
    - Cooling chain for Athena
    - Cooling chain: Participation to LiteBIRD phase A; Design study of PRISTINE
    - Balloons: Olimpo has been flown, LSPE being assembled
    - Sub-orbital programme in Europe (NIKA2, QUBIC, STRIP, QUIJOTE, C-BASS,…)
  - Specific developments with CNES support
    - European KIDs tested in the lab for the full CORE frequency range (Grenoble)
    - Development of closed cycle dilution fridge (IAS and Grenoble)
- Identification of potential international partners
  - Contribution to PICO study (USA) funded by NASA
  - Initiated work with CMB-Bharat consortium (India) and ISRO

Outline

- CORE science requirements and goals
- Mission requirements and design
- ESA evaluation of the M5 proposal
- ➡ The CMB-Bharat proposal to ISRO
- Summary and perspective

Indian proposal: context and calendar

- 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. Identified convergence of interests.
- Meeting at ISRO-HQ on Jan 8-9, 2018 to demonstrate an Indian community capable of taking on the science.
  - **CMB-Bharat:** Cross-institutional Indian cosmology consortium

  Set up formally on Jan 9th at ISRO HQ meeting: ~ 90 members from ~15 institutions/laboratories (and growing)
- **Suggestion by ISRO to respond to AO issued in India as next step**
- **Proposal by CMB-Bharat consortium to ISRO on Apr 16, 2018.**
- **Future Astro AO review, SSPO, ISRO HQ, Bangalore, July 8, 2018**

Dr. K. V. Sriram (LEOS)
Dr. P. Upadhya (LEOS)
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Dr. L. Sriramkumar (IIT Madras)
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ECHO: Exploring Cosmic History and Origin

Next generation comprehensive CMB space mission

भारत

CMB BHĀRAT: AN INDIAN COSMOLOGY CONSORTIUM

Future Astro AO review

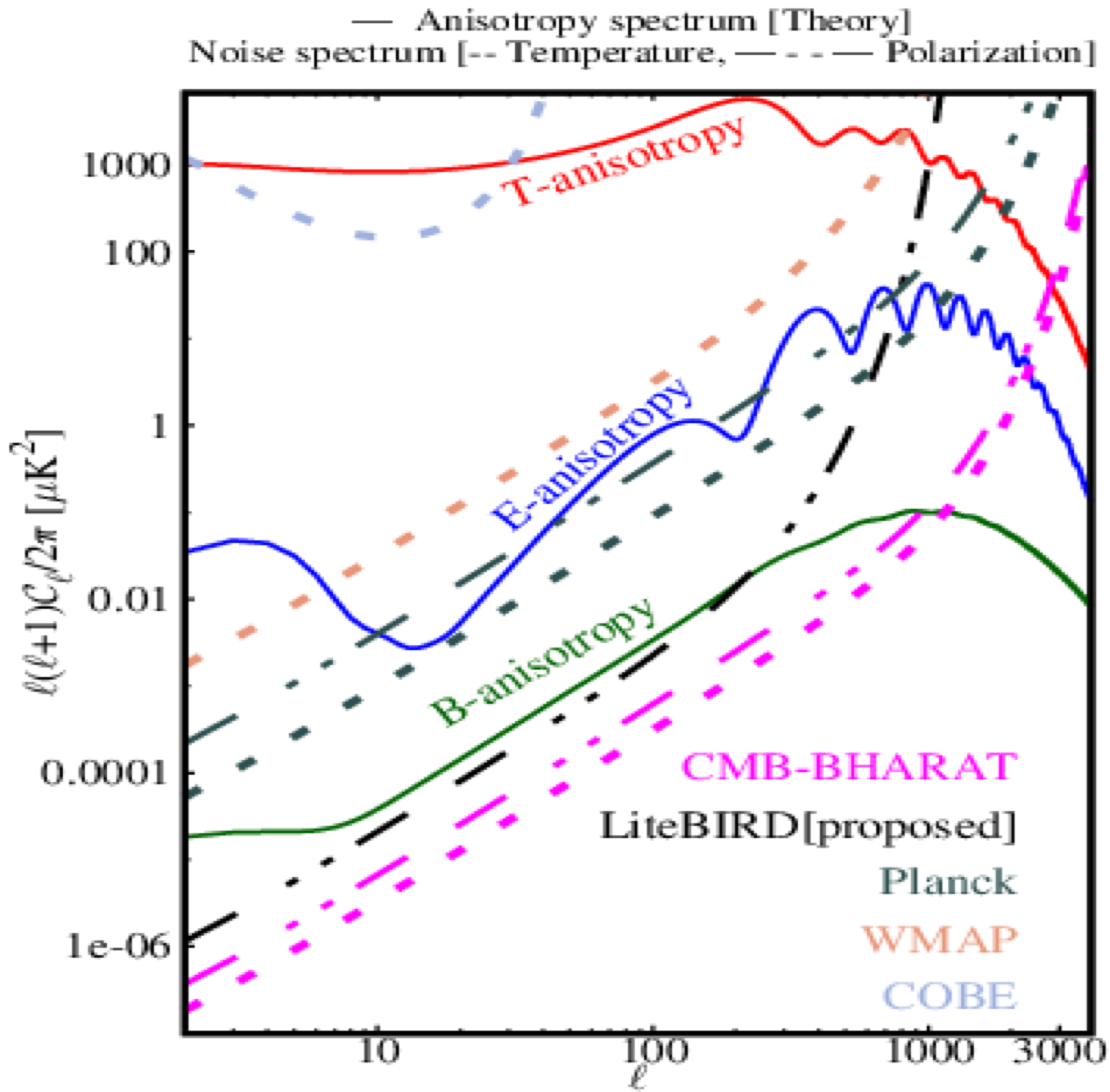
SSPO, ISRO HQ, Bangalore

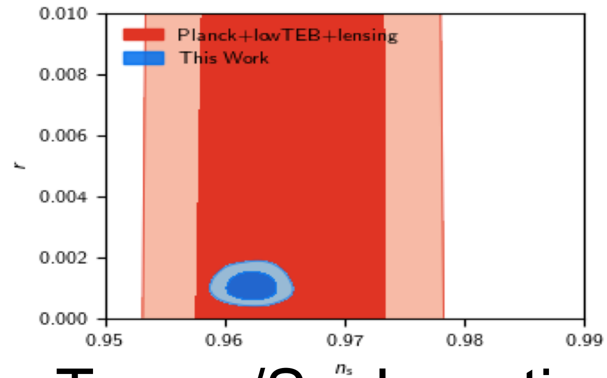
July 6, 2018

Tarun Souradeep
IUCAA

On behalf of CMB-Bharat

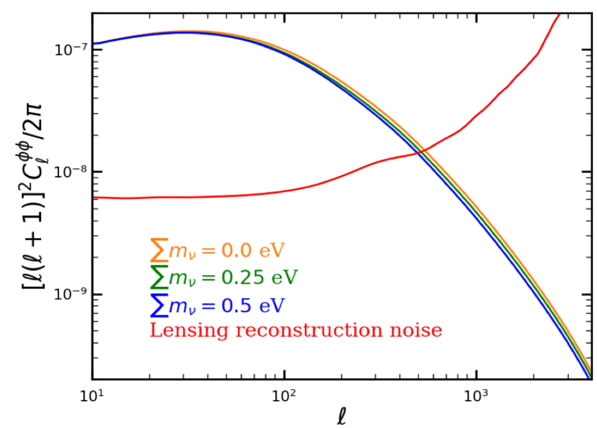
(An Indian Cosmology consortium)





Tensor/Scalar ratio

Lensing



Main goals, observations, differences with CORE

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

SIMILAR TO CORE

But also two interesting extensions (to be optimised in study phase):

- ***Enhanced spectral characterisation***
  (FT Spectrometer: 36-3000 GHz, sensitivity 100x FIRAS, ≈3 deg. beam)

Cosmic variance limited τ from EE; Detect the y distortion
Absolute calibrator for the imager + Zero-level of intensity maps
Polarisation maps at 100's of frequencies on large scale (l<80)

- ***Observatory mode (2 years) after survey (4 years)***

Deep patches of selected sky (e.g. low FG, CMB-S4 deep field)

Outline

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The CMB is unique !

It brings us an image of the Universe at $z \approx 1000$.

It is a probe of very early universe physics.

It is a source plane that shines on structures
in the whole universe and allows us to probe them.

We must ultimately learn everything it can tell us.

CORE and CMB-Bharat are designed for this goal.