

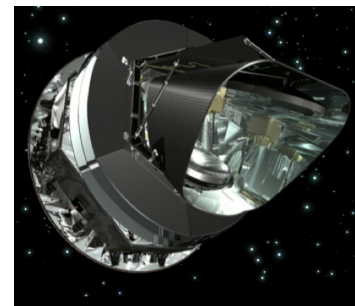
Cosmic Origins Explorer (COrE+)

An overview

(DRAFT – 24 Oct. 2014)

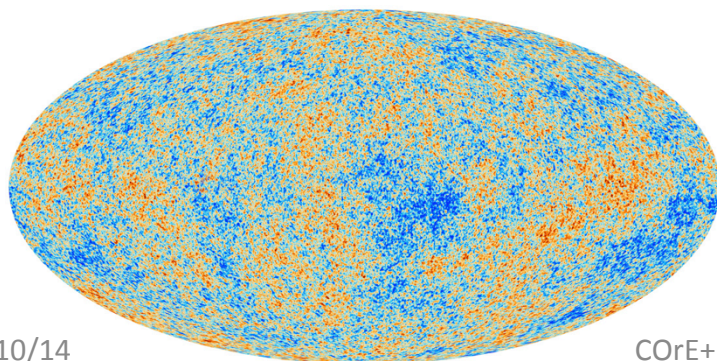
The COrE+ collaboration

The Planck legacy



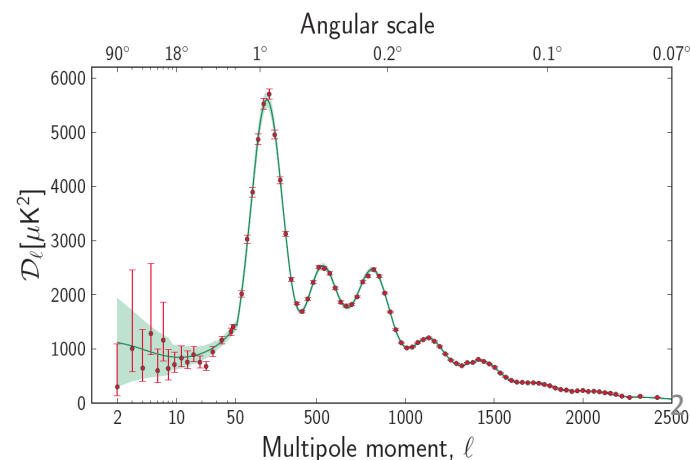
- **Planck: a great success**

- (top and 5 out of the 10 most cited papers in physics, astronomy and archive-eprint , as given by SAO/NASA ADS, over the period Jan. 2013 – Dec. 2013).
- near-ultimate CMB temperature anisotropies mission
- good measurement of the power spectrum of polarization anisotropies caused by density perturbations (E-modes).
- much science beyond the primary anisotropy C_l spectrum and parameters
 - CMB science: lensing; anomalies; primordial non-gaussianity
 - Non CMB cosmology: galaxy clusters; Cosmic Infrared Background...
 - Astrophysics: interstellar medium
 - Non-CMB science: 3/4 of the science papers, 1/2 of the citations



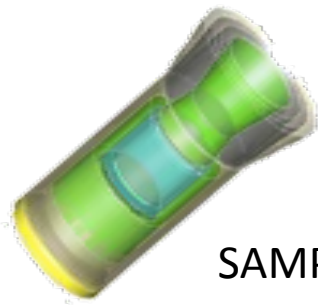
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COrE+ overview (DRAFT)

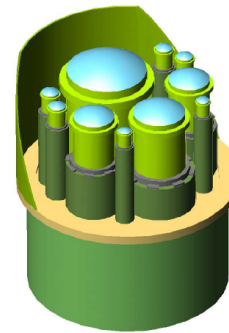


Future : A CMB polarization mission

- Several European proposals for CMB polarization between 2005 and now (and similar proposals in the US and in Japan)
 - Initially focussed mostly on inflationary B modes (SAMPAN, BPol)



SAMPAN (CNES) $\approx$ 2005



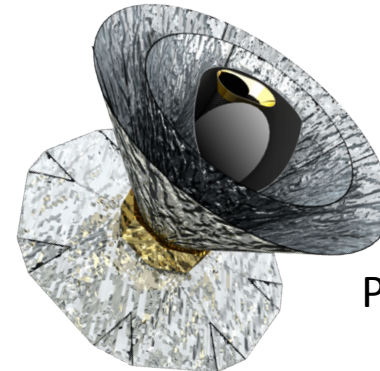
BPOL (ESA) $\approx$ 2007

- ***Concept evolving***: the case for polarization from space is very strong for astrophysics, cosmology, and fundamental physics (COrE, PRISM)



COrE (ESA) $\approx$ 2010

COrE+ overview (DRAFT)



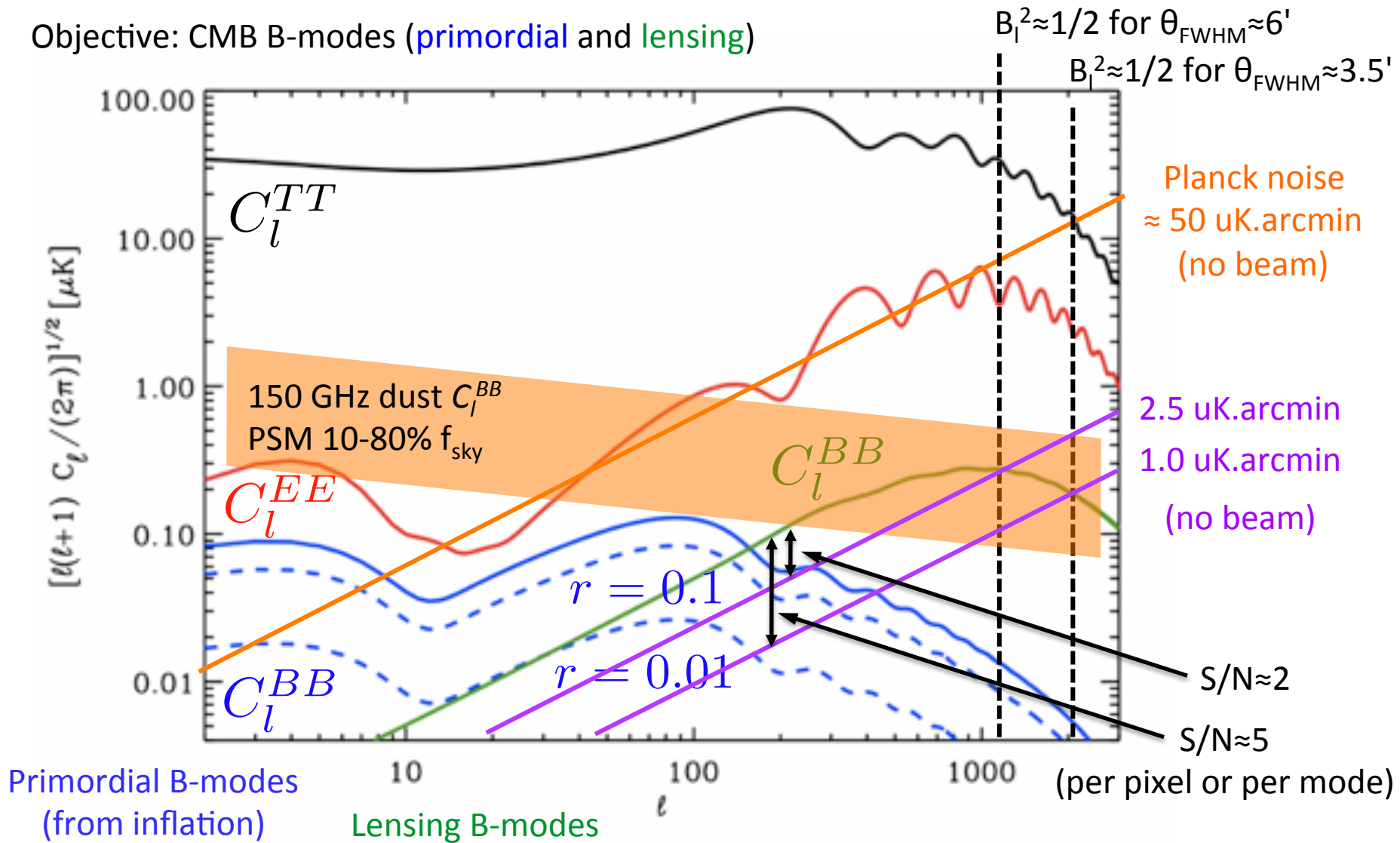
PRISM (ESA) $\approx$ 2013

COrE+, the near-ultimate CMB polarization measurement

- Strong interest and support in European countries for such a future CMB mission, e.g.
 - CMB polarization top in France prospective plan for space science;
 - PRISM evaluation: " The SSC was fully convinced of the great importance of the core CMB science and encourages the CMB community to consider proposing this science for a future M-class mission."
- ESA M4 call for a medium mission.
 - Budget 450 M€ (ESA) + National contributions for the science payload (including international contributions, e.g. from NASA);
 - Call issued August 19th, 2014; Proposal due January 15th, 2015;
 - If pre-selected, definition phase from 2015 to 2018.
 - Selection in 2018; Launch in 2025.
- Primary objectives:
 - primordial B-modes,
 - N_{eff} , Σm_ν , Y_{He} , all extensions to the standard model of cosmology impacting CMB maps or spectra.

Scientific requirements

Objective: CMB B-modes (primordial and lensing)



Sensitivity and case for a space mission

SENSITIVITY

- In space, the noise level in CMB channels is about $\approx 50 \mu\text{K.s}^{1/2}$.
- Full-sky observations: 1.5×10^8 arcminutes on the sky
- For a 3-year mission (10^8 seconds), about 5000 CMB detectors are required to reach $1 \mu\text{K.arcmin}$ sensitivity (about 2500 for $1.5 \mu\text{K.arcmin}$).

WHY SPACE?

- **Superior instrument sensitivity:** even in the atmospheric windows at 150 and 220 GHz, 100 to 1000 ground-based detectors are required to reach the raw sensitivity of one single spaceborne detector (assuming close to 100% observing efficiency).
- **Measurements Over the Full Sky:** Properly characterizing the inflationary signal requires sensitivity on the largest angular scales. A satellite provides full, cross-linked, sky maps, a feature that is difficult to achieve with sub-orbital platforms.
- **Broad Frequency Band Coverage:** Planck demonstrated that high fidelity characterization of the properties of galactic dust is an imperative for measurements of CMB B-mode polarization. Operating above all atmospheric emission sources, a satellite has unimpeded view of the Galaxy and the Universe over the broadest range of frequency bands.

COMPLEMENTARITY

- Ground-based instruments can observe with large telescopes. This can be used to extend the CORe+ angular resolution to 1' - 2' in atmospheric windows (≈ 90 , ≈ 160 and ≈ 220 GHz) and match the angular resolution of the space mission at higher frequencies, for superior CMB lensing and extragalactic science.

COrE+ options

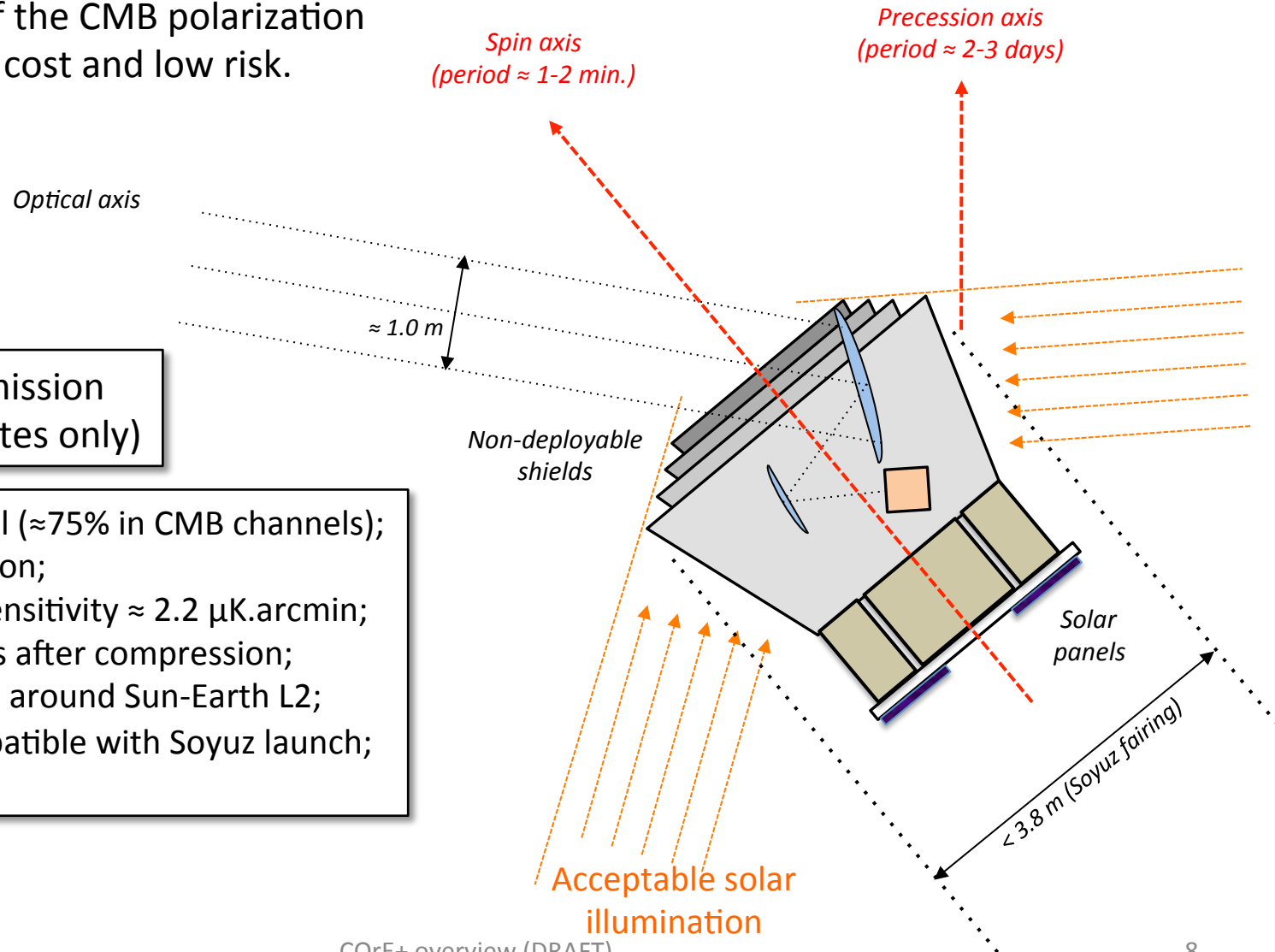
- **COrE+ light concept** *(baseline for a purely European mission)*
 - CMB B-modes + lensing science for cosmology and fundamental physics.
 - $\approx 6'$ resolution at 200 GHz, $\approx 1\text{m}$ aperture telescope;
 - $\approx 2.5\ \mu\text{K. arcmin}$ CMB polarization sensitivity after foreground subtraction;
 - Many bands (at least ≈ 15) for component separation covering at least $\approx 100\text{-}600$ GHz;
 - budget: ≈ 550 M€ (450 M€ ESA + 100 M€ European countries)
- **COrE+ extended concept** *(baseline with international partners)*
 - Near-ultimate CMB polarization space mission;
 - Extensive astrophysical cosmology (clusters) and extragalactic astrophysics; superior ISM science (with full sky resolution bridging with Herschel in small fields, at highest frequencies);
 - $\approx 3'$ to $4'$ resolution at 200 GHz, ≈ 1.5 (baseline) to 2m aperture telescope;
 - $\approx 1.5\ \mu\text{K.arcmin}$ CMB polarization sensitivity after foreground subtraction;
 - Extended frequency coverage $\approx 60\text{-}1200$ GHz;
 - budget: ≈ 700 M€ (450 M€ ESA + 250 M€ European and non-European countries).

COrE+ light

OBJECTIVE: Most of the CMB polarization science, at reduced cost and low risk.

OPTION: ESA mission
(ESA member states only)

2040 detectors total ($\approx 75\%$ in CMB channels);
3 years of observation;
CMB polarization sensitivity $\approx 2.2 \mu\text{K} \cdot \text{arcmin}$;
Data rate $\approx 3 \text{ Mbit/s}$ after compression;
Large lissajous orbit around Sun-Earth L2;
Mass and size compatible with Soyuz launch;
Budget 550 M€.



COrE+ light (possible configuration)

Core CMB science mission						
Freq	beam	N _{det}	per arcmin ² pixel		5σ PS or SZ	
GHz	arcmin		σ _p μK _{CMB}	σ _l kJy/sr	5σ _p mJy	5σ _l 10 ⁵ ×Y _{SZ}
60	21.0	10	29.1	2.1	16.3	38.6
70	18.0	10	28.0	2.6	17.7	33.0
80	15.8	20	19.2	2.3	13.4	20.7
90	14.0	30	15.4	2.2	11.6	15.5
100	12.6	50	11.8	2.0	9.4	11.3
115	11.0	100	8.3	1.7	7.0	7.7
130	9.7	160	6.6	1.6	5.8	6.2
145	8.7	240	5.5	1.5	4.9	5.4
160	7.9	260	5.5	1.6	4.9	6.1
175	7.2	300	5.4	1.7	4.6	7.2
195	6.5	350	5.4	1.8	4.4	11.9
220	5.7	200	8.1	2.8	5.9	-

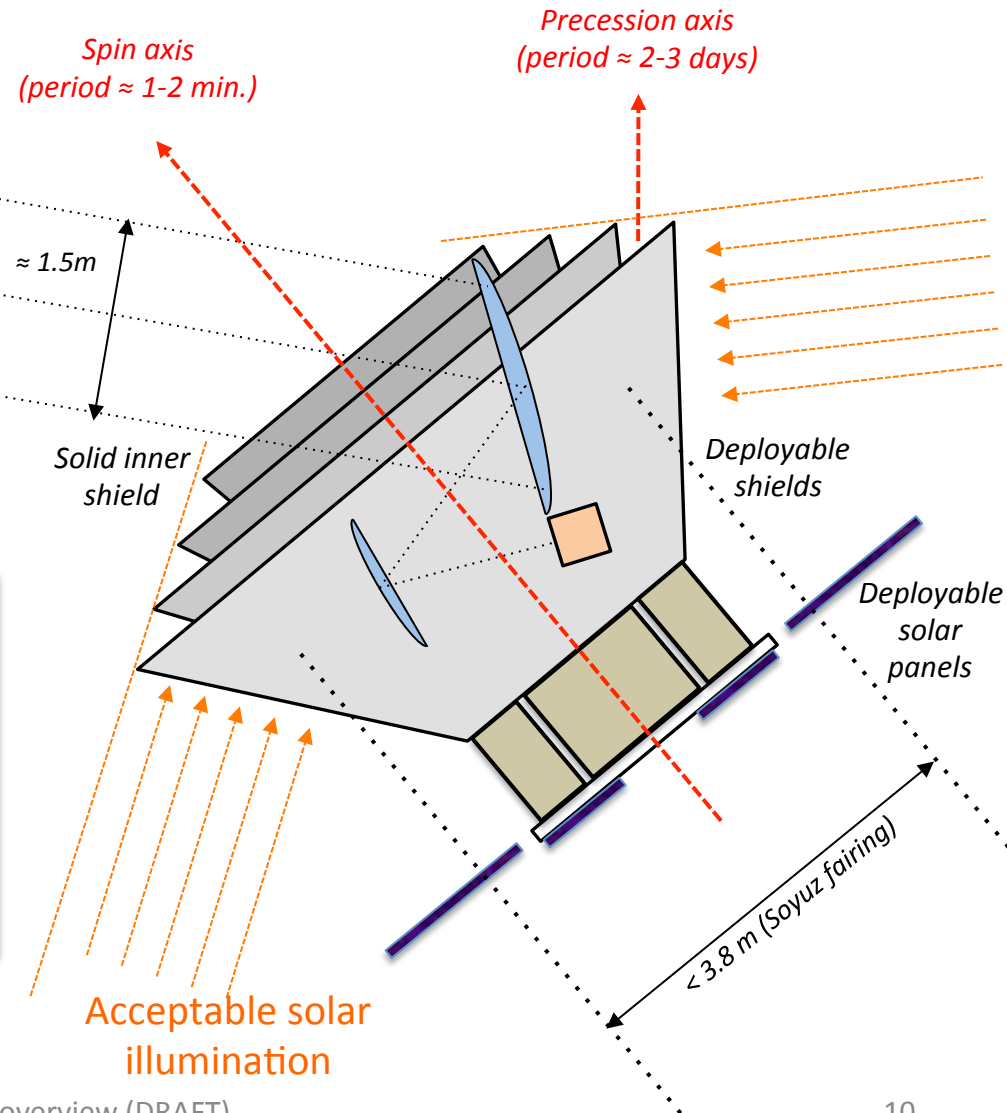
Core CMB science mission						
Freq	beam	N _{det}	per arcmin ² pixel		5σ PS or SZ	
GHz	arcmin		σ _p μK _{CMB}	σ _l kJy/sr	5σ _p mJy	5σ _l 10 ⁵ ×Y _{SZ}
255	5.0	120	13.1	4.3	8.0	12.6
295	4.3	60	25.8	7.4	11.8	10.1
340	3.7	40	49.0	11.1	15.5	10.3
390	3.2	30	98.7	16.0	19.4	12.7
450	2.8	20	252.3	25.2	26.5	20.7
520	2.4	20	632.1	32.8	29.8	34.1
600	2.1	20	1902	42.8	33.7	69.9
700	-	-	-	-	-	-
800	-	-	-	-	-	-
950	-	-	-	-	-	-
1100	-	-	-	-	-	-
1250	-	-	-	-	-	-

COrE+ extended

OBJECTIVE: Ultimate CMB polarization mission, and extensive non-CMB science.

OPTION: ESA mission with substantial international contribution, e.g. NASA

5800 detectors total ($\approx 65\%$ in CMB channels);
3 years of observation;
CMB polarization sensitivity $\approx 1.3 \mu\text{K} \cdot \text{arcmin}$;
Data rate $\approx 15 \text{ Mbit/s}$ after compression;
Large lissajous orbit around Sun-Earth L2;
Mass and size compatible with Soyuz launch;
Budget 700 M€.



COrE+ extended (possible configuration)

Extended science mission						
Freq	beam	N _{det}	per arcmin ² pixel		5σ PS or SZ	
GHz	arcmin		σ _p μK _{CMB}	σ _l kJy/sr	5σ _l mJy	5σ _l 10 ⁵ ×Y _{SZ}
60	14.0	20	20.5	1.5	7.7	18.2
70	12.0	40	14.0	1.3	5.9	11.0
80	10.5	80	9.6	1.1	4.5	6.9
90	9.3	130	7.4	1.1	3.7	5.0
100	8.4	200	5.9	1.0	3.1	3.8
115	7.3	360	4.4	0.92	2.5	2.7
130	6.5	600	3.4	0.83	2.0	2.1
145	5.8	650	3.4	0.92	2.0	2.2
160	5.3	700	3.4	1.0	2.0	2.5
175	4.8	700	3.5	1.1	2.0	3.1
195	4.3	700	3.8	1.3	2.1	5.6
220	3.8	450	5.4	1.9	2.6	-

Extended science mission						
Freq	beam	N _{det}	per arcmin ² pixel		5σ PS or SZ	
GHz	arcmin		σ _p μK _{CMB}	σ _l kJy/sr	5σ _l mJy	5σ _l 10 ⁵ ×Y _{SZ}
255	3.3	250	9.1	3.0	3.7	5.8
295	2.9	230	13.2	3.8	4.0	3.4
340	2.5	150	25.3	5.7	5.3	3.6
390	2.2	130	47.4	7.7	6.2	4.1
450	1.9	90	118.9	11.9	8.3	6.5
520	1.6	70	337.9	17.5	10.6	12.2
600	1.4	50	1203	27.0	14.2	29.5
700	1.2	40	5610	40.2	18.1	93.0
800	1.1	40	24400	51.2	20.2	292
950	0.9	40	-	69.5	23.0	-
1100	0.76	40	-	89.4	25.6	-
1250	0.67	40	-	110	27.8	-

Proposed COrE+ collaboration

- **Institutions from ESA member states:**

- **France** (CNES): APC Paris, CEA Saclay and Grenoble, IAP Paris, IAS Orsay, Institut Néel Grenoble, IPAG Grenoble, IRAP Toulouse, LAL Orsay, LPSC Grenoble, LPT Orsay.
- **Italy** (ASI): Dipartimento di Fisica e Scienze della Terra, Università di Ferrara; Dipartimento di Fisica, Università di Genova; Dipartimento di Fisica, Università di Milano; Dipartimento di Fisica, Università di Milano Bicocca; Dipartimento di Fisica e Astronomia, Università di Padova; Dipartimento di Fisica, Università di Roma La Sapienza; Dipartimento di Fisica, Università di Roma Tor Vergata; Dipartimento di Fisica, Università di Trieste; INAF-IASF Bologna; INAF-IRA; INAF - Osservatorio Astronomico di Padova; INAF - Osservatorio Astronomico di Trieste; SISSA Trieste.
- **United Kingdom** (UKSA): Cardiff University; University of Cambridge; University of Manchester; Rutherford Appleton Laboratory; University of Edinburgh / UK ATC; University of Oxford; Imperial college London; University College London; University of Sussex;
- **The Netherlands** (SRON): University of Groningen; Radboud University Nijmegen; University of Leiden; NIKHEF; SRON Netherlands Institute for Space Research.
- **Germany** (DLR): MPIfR Bonn; LMU Munich; MPA Garching; RWTH Aachen University.
- **Spain**: Instituto de Astrofísica de Canarias; Instituto de Física de Cantabria (CSIC-UC); Institut de Ciències del Cosmos de la Universitat de Barcelona; Universidad de Oviedo ; Centro de Estudios de Física del Cosmos de Aragón; Universidad de Granada.
- **Poland**: CBK PAN, Warsaw; NCBJ, Warsaw; Jagiellonian University, Cracow; Silesian University, Katowice; Nicolaus Copernicus University, Torun; CFT PAN, Warsaw; Jan Kochanowski University, Kielce; CAMK PAN, Warsaw.
- **Finland**: University of Helsinki.
- **Norway**: Institute of Theoretical Astrophysics, University of Oslo.
- **Denmark**: Niels Bohr Institute and Discovery Center; DTU Space Research Center.
- **Ireland**: Maynooth
- **Switzerland**: Departement Physik, Universität Basel; Laboratoire d'Astrophysique, EPFL; Département d'Astronomie, Université de Genève ; Département de Physique Théorique, Université de Genève.
- **Austria**: TBD
- **Portugal**: Institute of Astrophysics and Space Sciences, Porto and Lisbon ; University of Evora ; Institute of Telecommunications.

- **Participation of USA:**

- Caltech/JPL; Goddard Space Flight Center; UC Berkeley; LBNL/NERSC; Stanford University; University of Minnesota; NIST.