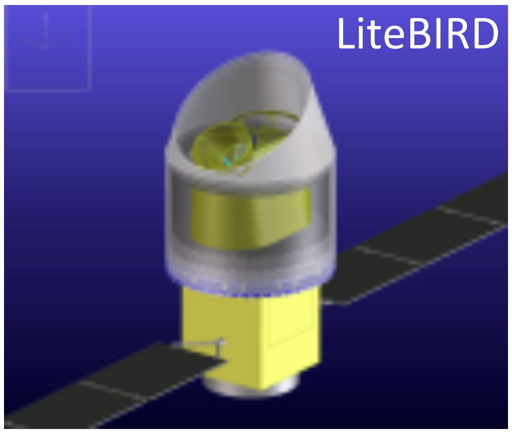
Future CMB space missions

Jacques Delabrouille
Laboratoire APC, Paris, France
on behalf of the CORE collaboration

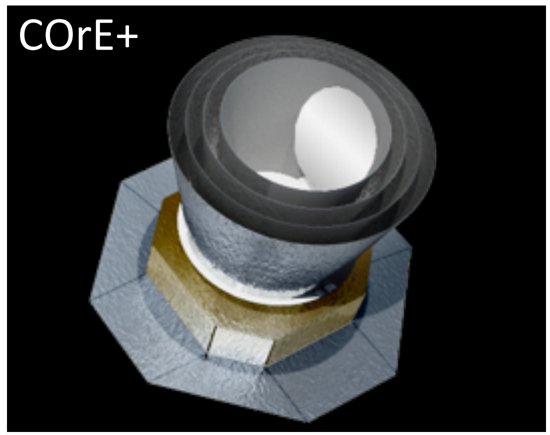
Recently proposed CMB missions

JAXA



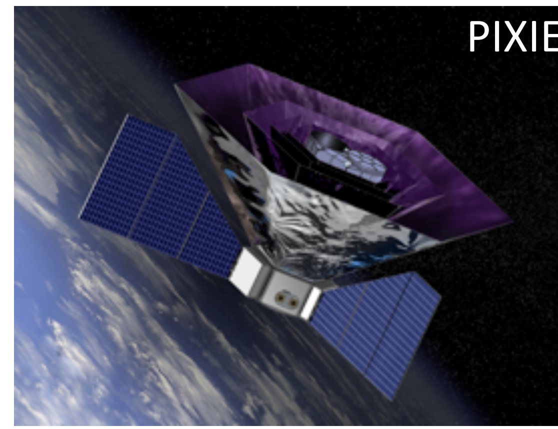
Primordial B-modes mission

ESA



Cosmic origins explorer

NASA



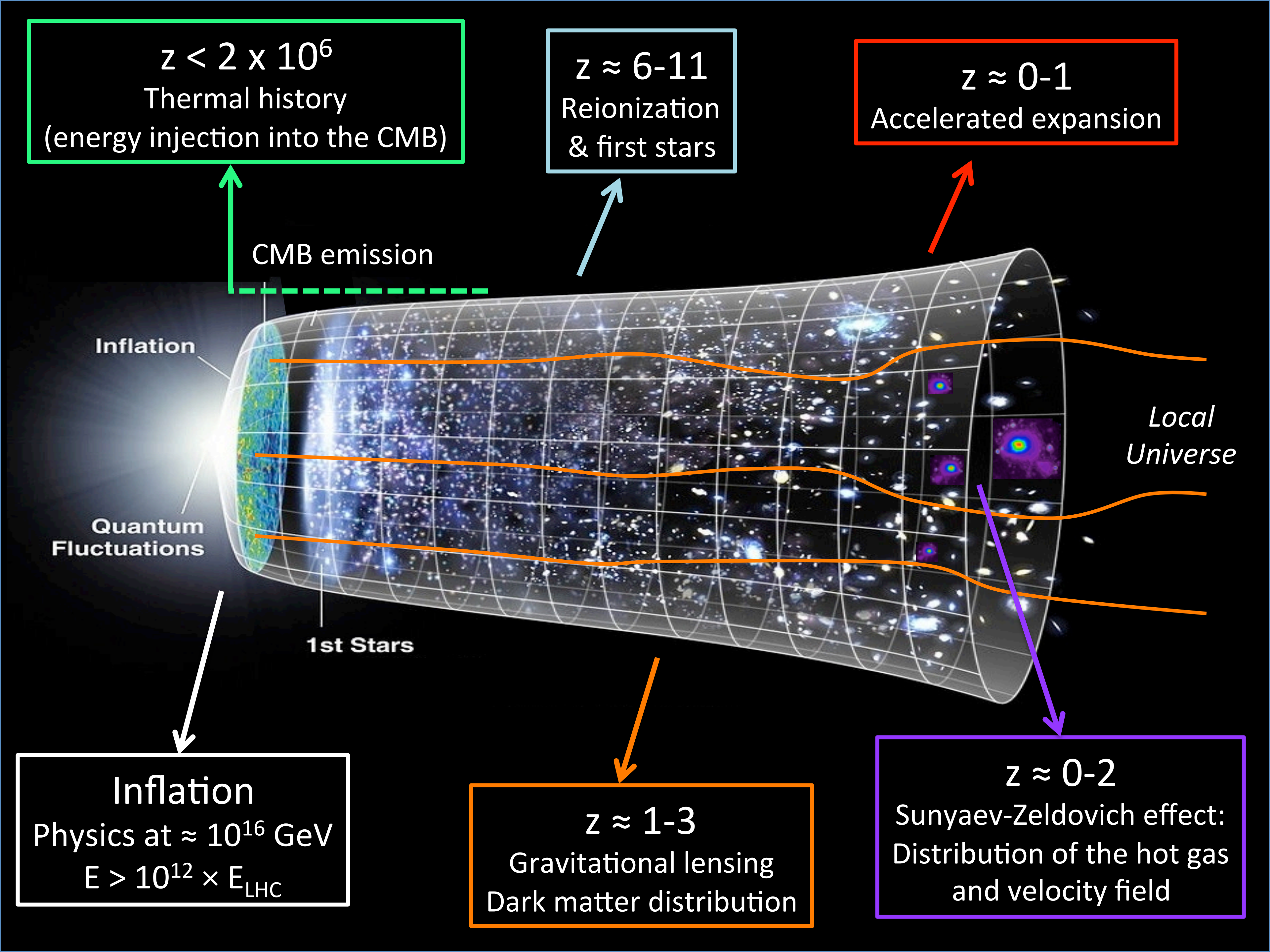
Absolute spectrophotometer

"LiteCOrE"

A joint ESA-JAXA CMB polarization imager ?

Outline

- Introduction
- CORE
- PIXIE
- LiteBIRD
- Discussion



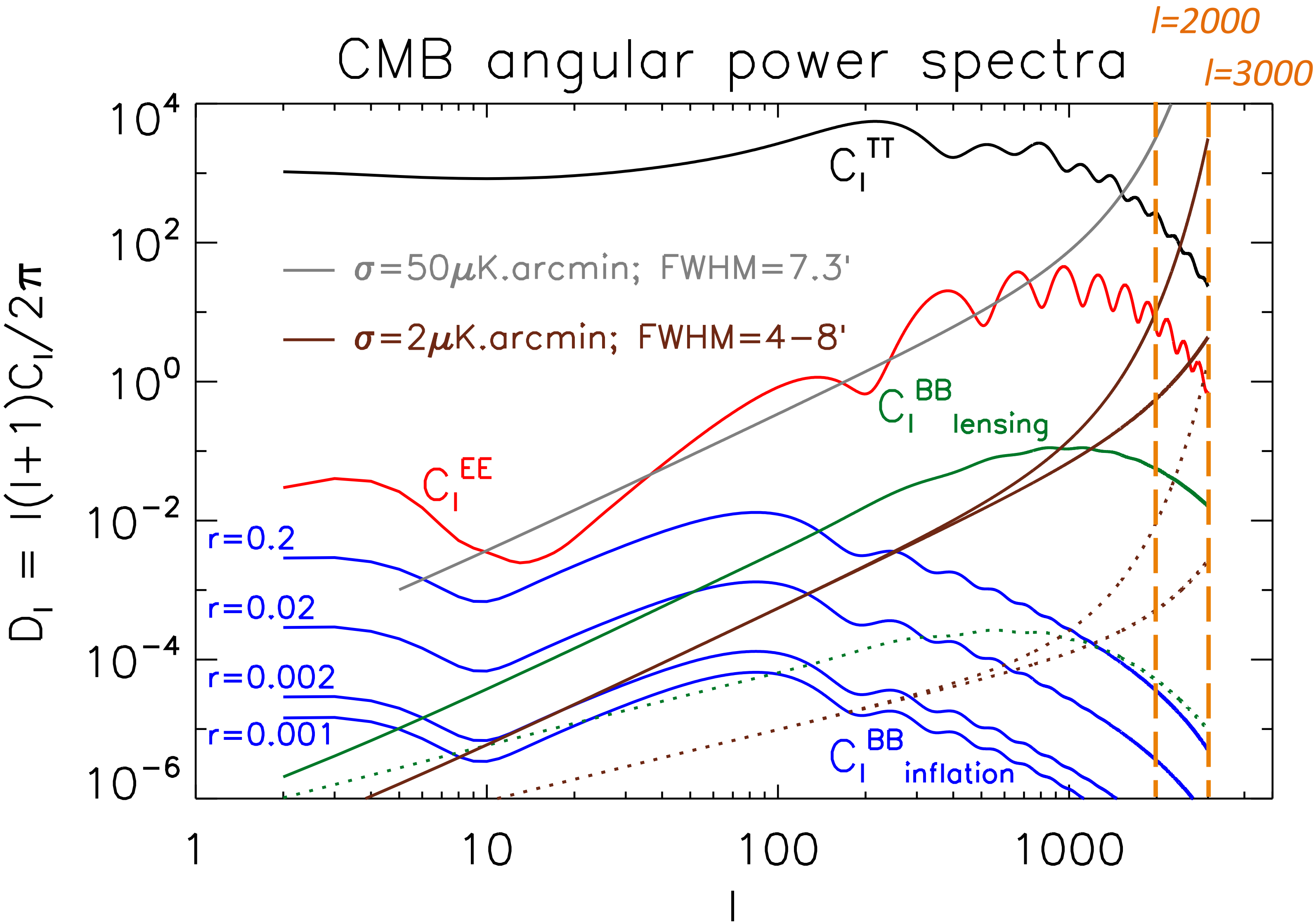
$z < 2 \times 10^6$
Thermal history
(energy injection into the CMB)
$z \approx 6\text{-}11$
Reionization
& first stars
$z \approx 0\text{-}1$
Accelerated expansion
CMB emission
Inflation
Quantum Fluctuations
1st Stars
Local Universe
Inflation
Physics at $\approx 10^{16}$ GeV
$E > 10^{12} \times E_{LHC}$
$z \approx 1\text{-}3$
Gravitational lensing
Dark matter distribution
$z \approx 0\text{-}2$
Sunyaev-Zeldovich effect:
Distribution of the hot gas
and velocity field

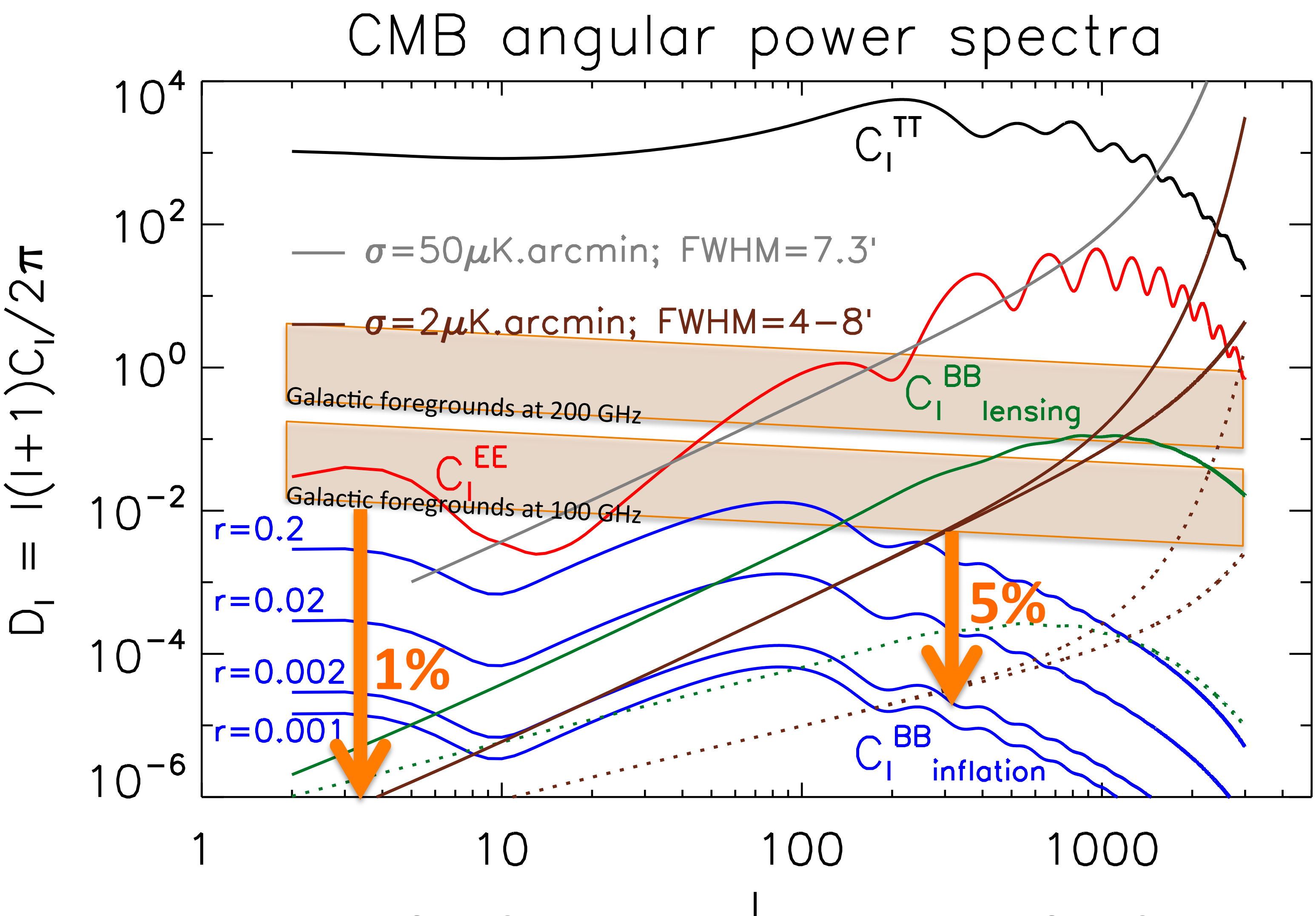
CMB science

- Inflation – *of course, but also…*
- A census of mass (CMB lensing)
- Cosmological parameters
- Detailed validation of the model
- A census of hot gas (thermal SZ)
- The cosmic velocity field (kinetic SZ)
- Thermal history / absolute spectrum
- Surprises

Requires us to resolve the CMB beam ≈ 4'

Requires us to resolve clusters beam ≈ 1'


l=2000
l=3000
CMB angular power spectra
$D_l = l(l+1)C_l/2\pi$
σ=50μK.arcmin; FWHM=7.3'
σ=2μK.arcmin; FWHM=4−8'
C_l^{TT}
C_l^{EE}
C_l^{BB} lensing
C_l^{BB} inflation
r=0.2
r=0.02
r=0.002
r=0.001
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
1
10
100
1000
l



1% in amplitude
= 10^{-4} in power

5% in amplitude
= 2.5 10^{-3} in power

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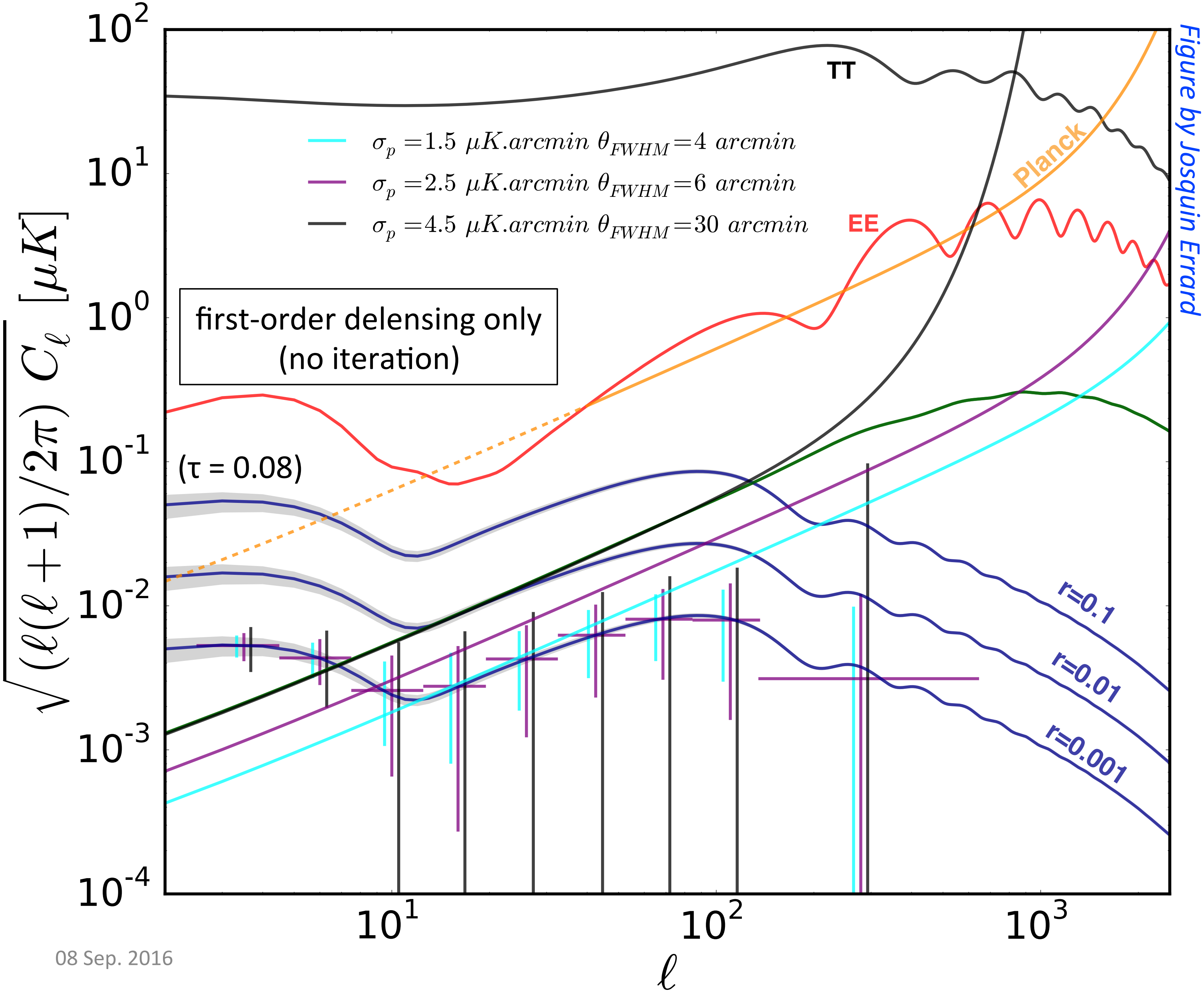

$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
$\sigma_p = 1.5\ \mu K.arcmin\ \theta_{FWHM} = 4\ arcmin$
$\sigma_p = 2.5\ \mu K.arcmin\ \theta_{FWHM} = 6\ arcmin$
$\sigma_p = 4.5\ \mu K.arcmin\ \theta_{FWHM} = 30\ arcmin$
TT
EE
Planck
first-order delensing only
(no iteration)
(τ = 0.08)
r=0.1
r=0.01
r=0.001
Figure by Josquin Errard

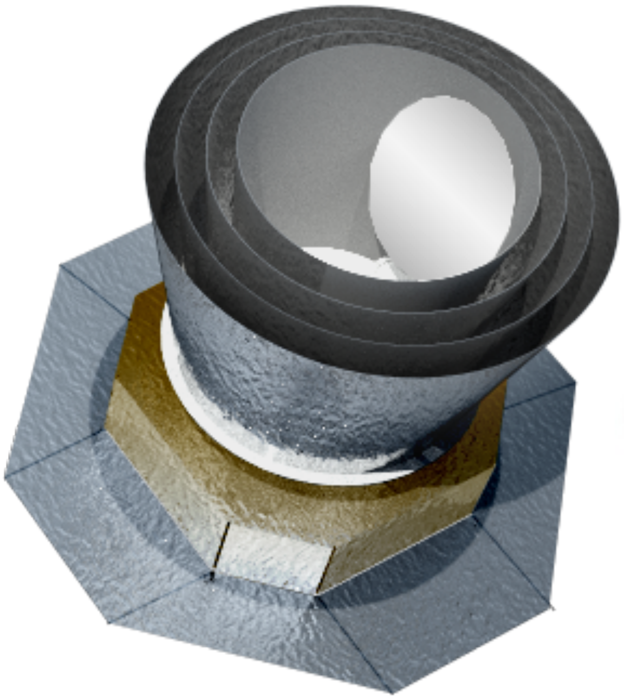
CORE concept and strategy

A near-ultimate CMB polarisation mission proposed to ESA.

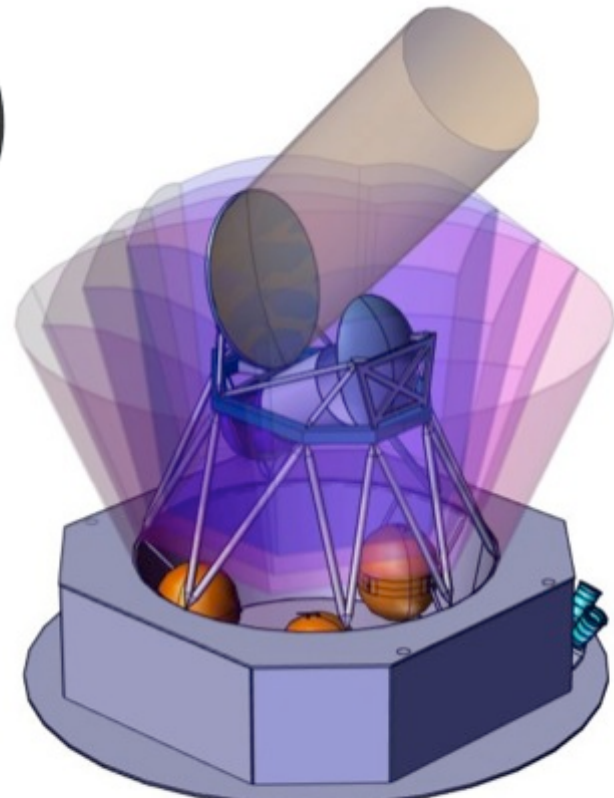
- *guaranteed CMB science (full exploitation of CMB polarization information)*
- *strong legacy value and discovery potential for many areas of science*

Performance / requirement	***Solution***
Resolve the CMB for exhaustive CMB science ≈ 4'-6' resolution or better	Class 1.2-1.5 m telescope or better ≈ 6-8' at 135 GHz; ≈ 4-5' at 200 GHz
Signal dominated data (S/N >2-3 for B_{lens}) σ_P = 1.5-2.5 μK.arcmin on ≈ 100% sky	from ≈ 2000 (base) to 5000 (extension) detectors at ≈ 100 mK
Control of systematic effets for polarisation measurements	L2 orbit; Redundancy and polarisation modulation by scanning strategy
Control/separation of polarised (and intensity) foregrounds	15-20 frequency bands (or more) covering ≈ 60-600 GHz (or more)

Spacecraft (from M4 to M5 concept)

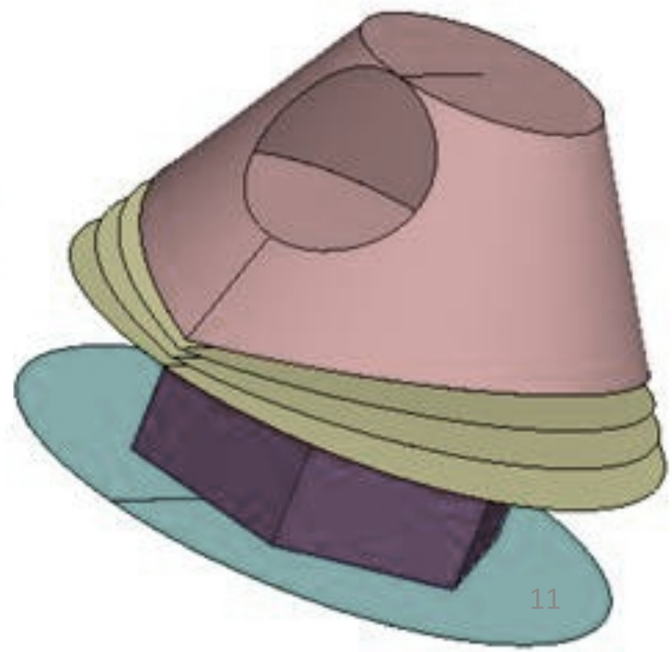


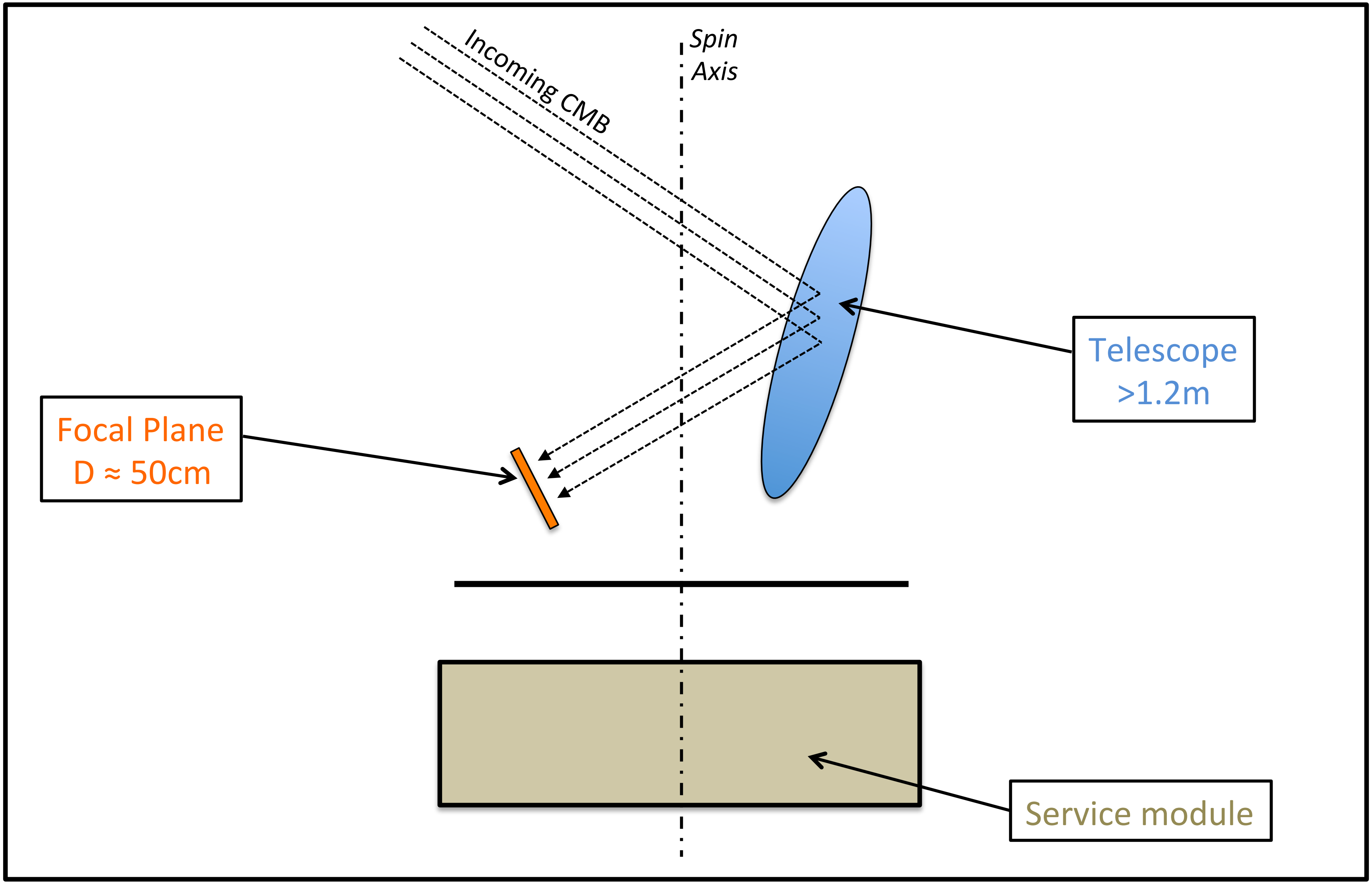
M4 proposal

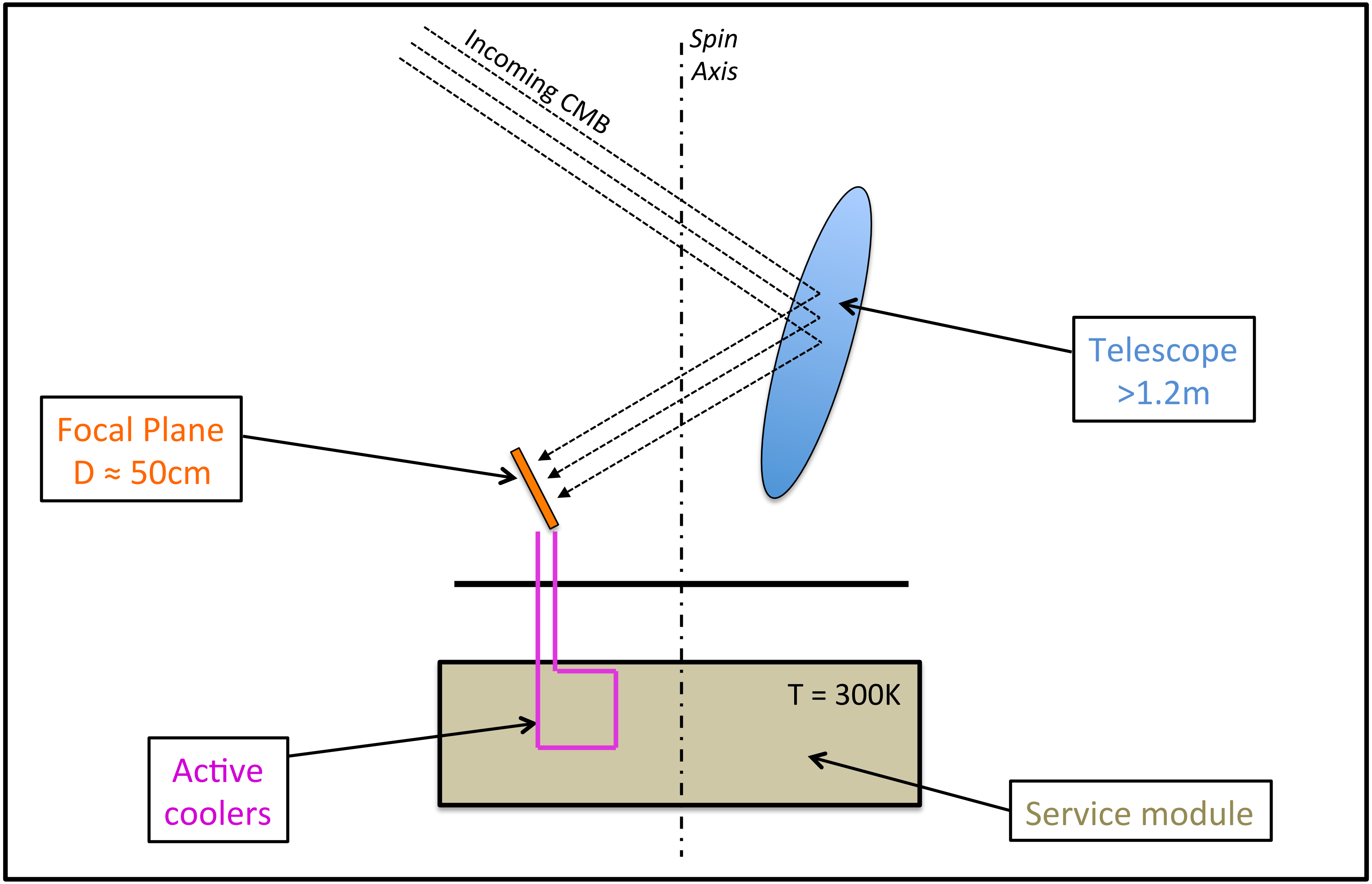


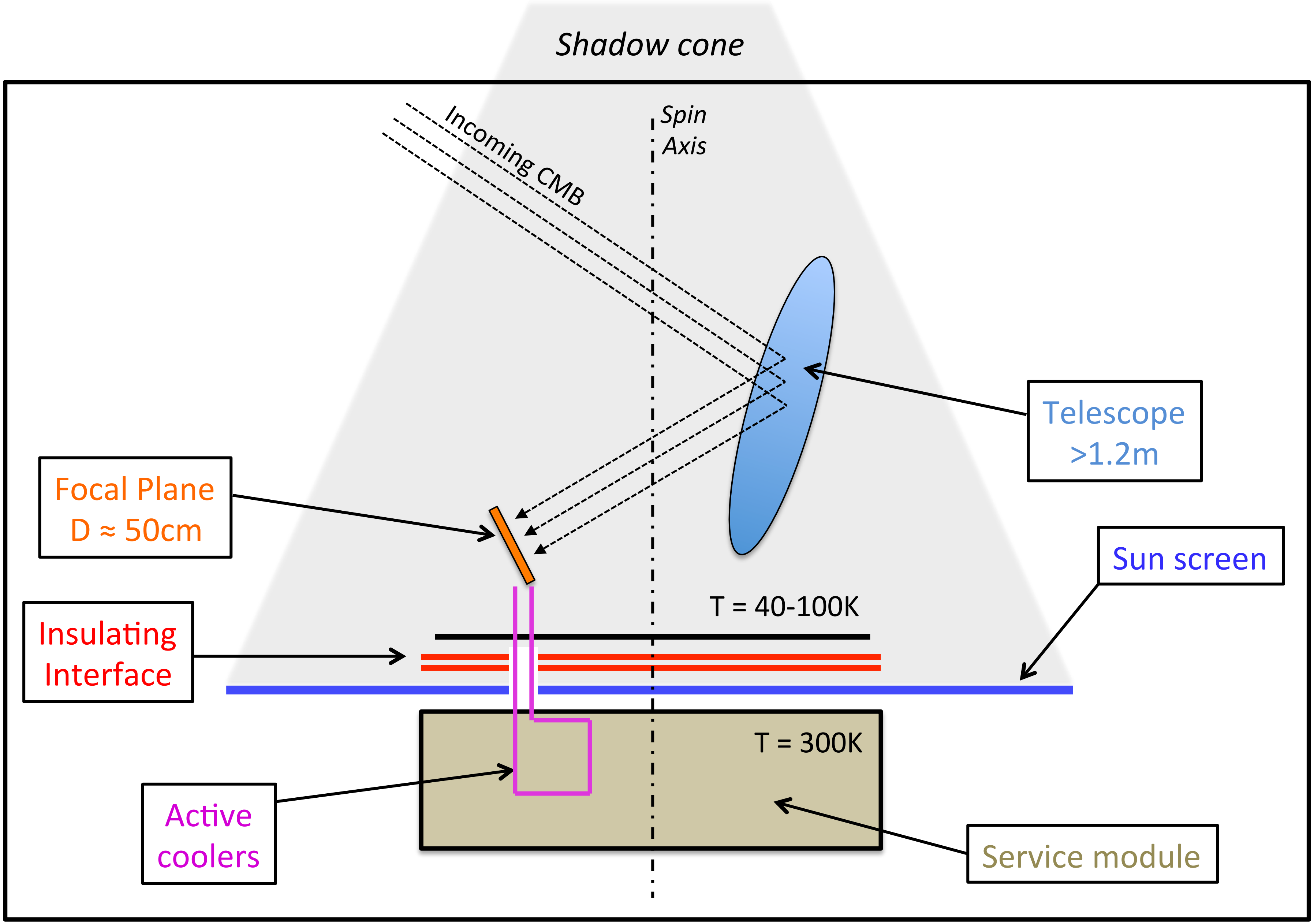
ESA CDF

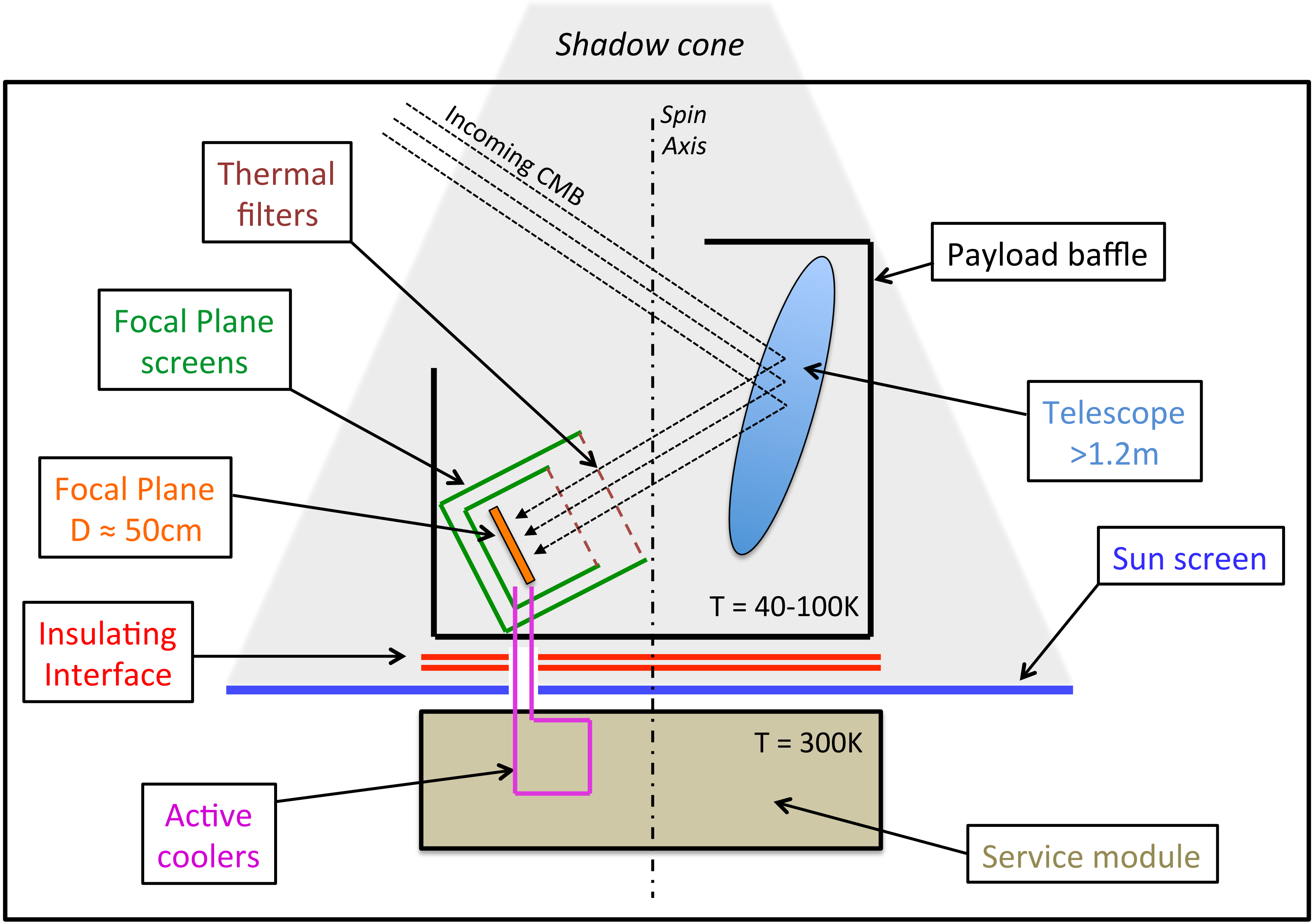
M5 proposal (TBC)




Incoming CMB
Spin
Axis
Telescope
>1.2m
Focal Plane
D ≈ 50cm
Service module

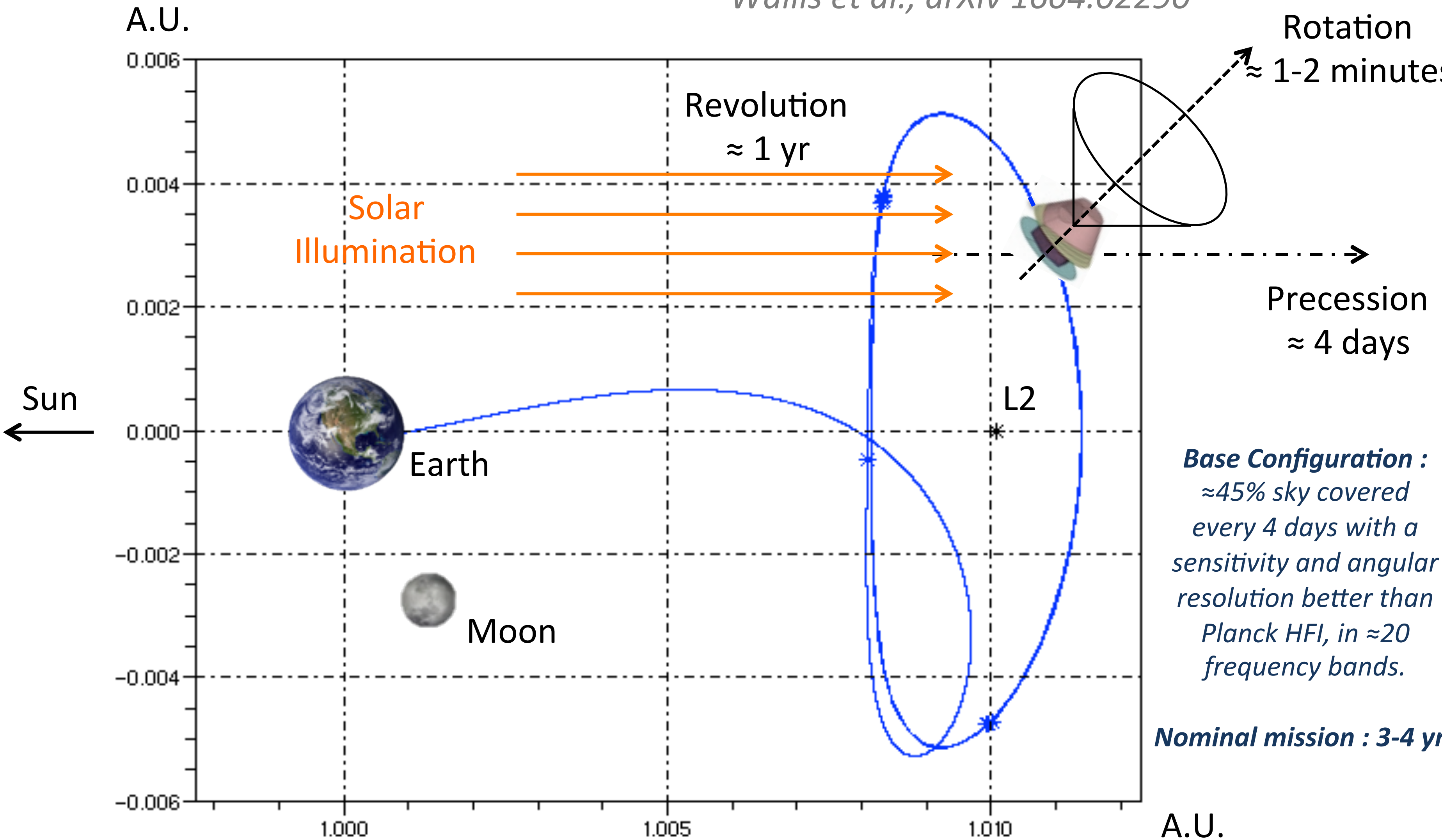

Incoming CMB
Spin Axis
Telescope >1.2m
Focal Plane D ≈ 50cm
T = 300K
Active coolers
Service module


Shadow cone
Incoming CMB
Spin Axis
Telescope >1.2m
Focal Plane D ≈ 50cm
Sun screen
T = 40-100K
Insulating Interface
T = 300K
Active coolers
Service module


Shadow cone
Spin
Axis
Incoming CMB
Thermal
filters
Payload baffle
Focal Plane
screens
Telescope
>1.2m
Focal Plane
D ≈ 50cm
Sun screen
T = 40-100K
Insulating
Interface
T = 300K
Active
coolers
Service module

Orbit and Scan strategy

Wallis et al., arXiv 1604.02290

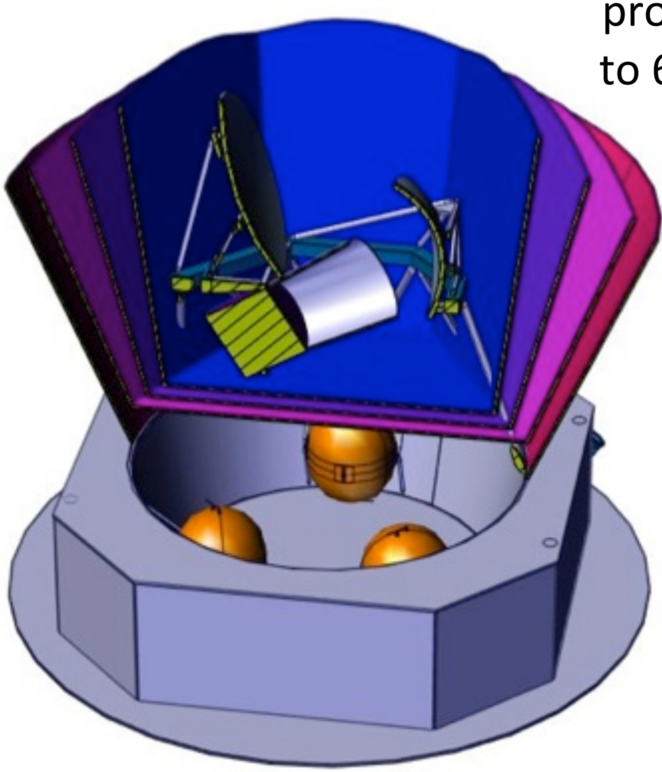


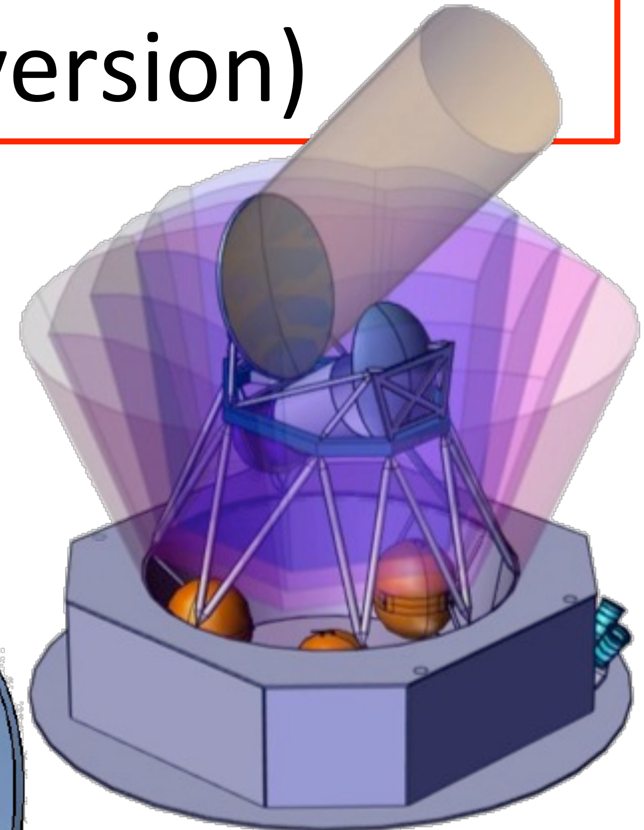
Base Configuration :
≈45% sky covered every 4 days with a sensitivity and angular resolution better than Planck HFI, in ≈20 frequency bands.

Nominal mission : 3-4 yrs

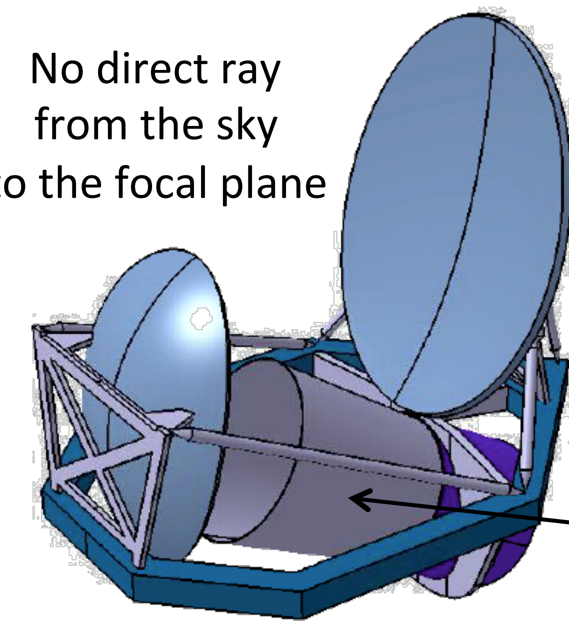
Spacecraft (ESA CDF version)

Tulip-shaped V-grooves
provide passive cooling
to 60K even with α≈45°





No direct ray
from the sky
to the focal plane



>1.2m aperture;

Cold shield <20K

+ 4K stage
+ Baffle <1K

http://sci.esa.int/trs/57795-cmb-polarisation-mission-study/

Conclusions of the ESA CDF

Summary

- Baseline CDF design
  - No specific technical show-stoppers identified, but some technology developments needed
  - Difficult to increase the aperture (>1.5 m cannot be accommodated)
  - Preliminary cost above M5 envelope
  - Suitable for collaboration (>20% level)
- Options identified to reduce complexity and cost of baseline design
  - Reduce spin rate (to 0.5 – 1.0 rpm)
  - Reduce pointing reconstruction error (to 5-6”)
  - Increase telescope temperature (to ~100 K)

Conclusions of the ESA CDF

Criticalities

esa

Mission drivers:

- Large precession: large Sun aspect angle more complex cryo-architecture, additional solar panels, complex TT&C, complex AOCS, | Reduce α to 30°
- Cryogenic cooling FPU @100 mK, only free design parameter is Telescope temperature | Nothing we can do on FPU but flexibility on telescope
- Fairing size and precession law: limiting maximum telescope size

Open points:

- Technology maturity of detector arrays (TRL 3-4). Clear Development plan required in the proposal
- Need of Half Wave Plate. Consensus from community required for a credible proposal

Address these two points in the proposal and in companion papers

Conclusions of the ESA CDF

Cost

esa

- The costs of the mission is above the limit of a M-class mission, requiring either:
  - Substantial contribution from the member states
  - International cooperation

Actively discussed

- Cost/risk reduction could be achieved by :

1. Reducing spin rate to 1 rpm

   OK! That was our M4 baseline … checking ½ RPM

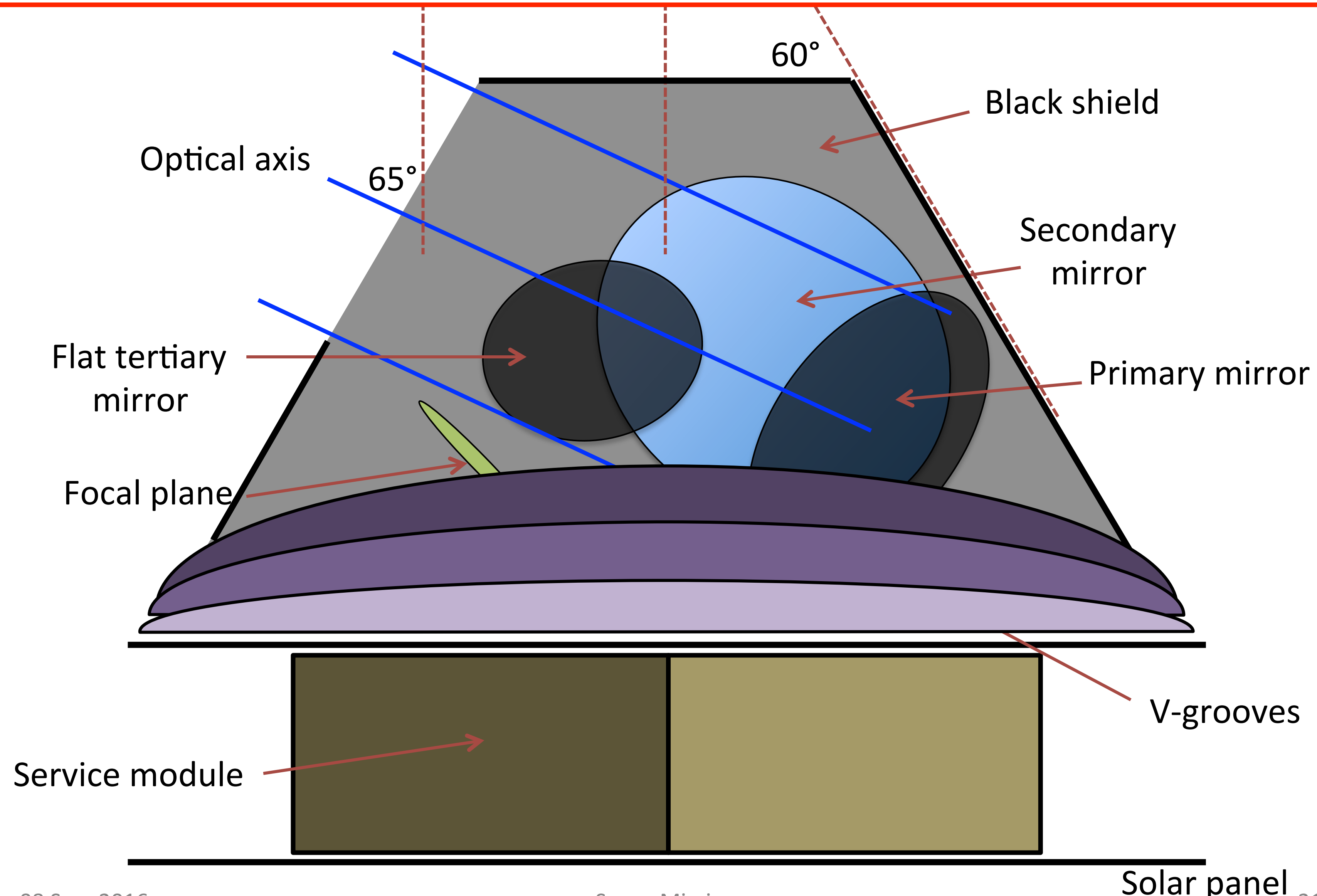
   - RW based AOCS possible
   - Lower data-rate: smaller data storage
   - Less power or less time for data download (X-band still not feasible)
   - Simpler Propulsion System
2. No passive cooling at 60K cryo-architecture

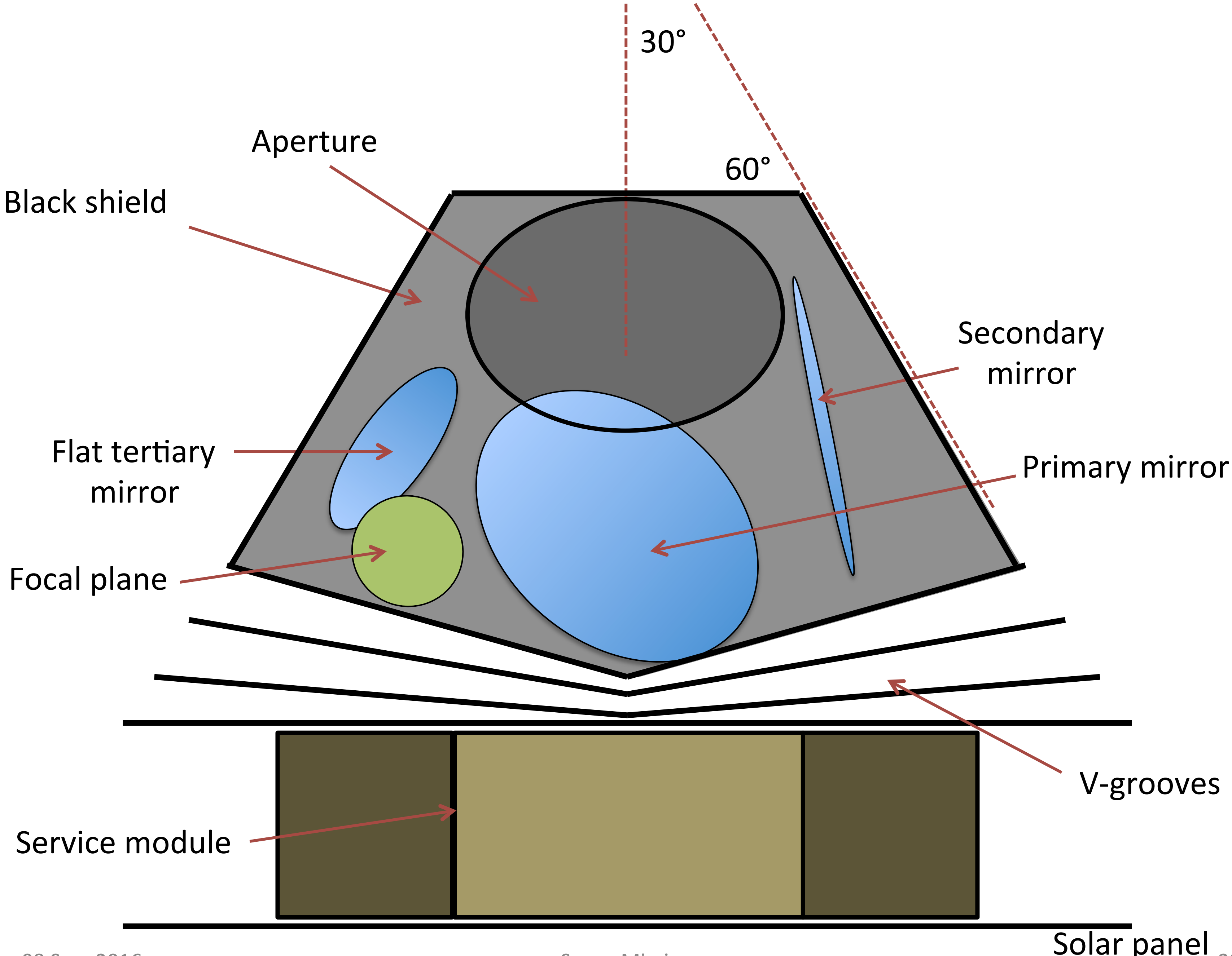
   OK, but maybe building more on Planck heritage is still better.

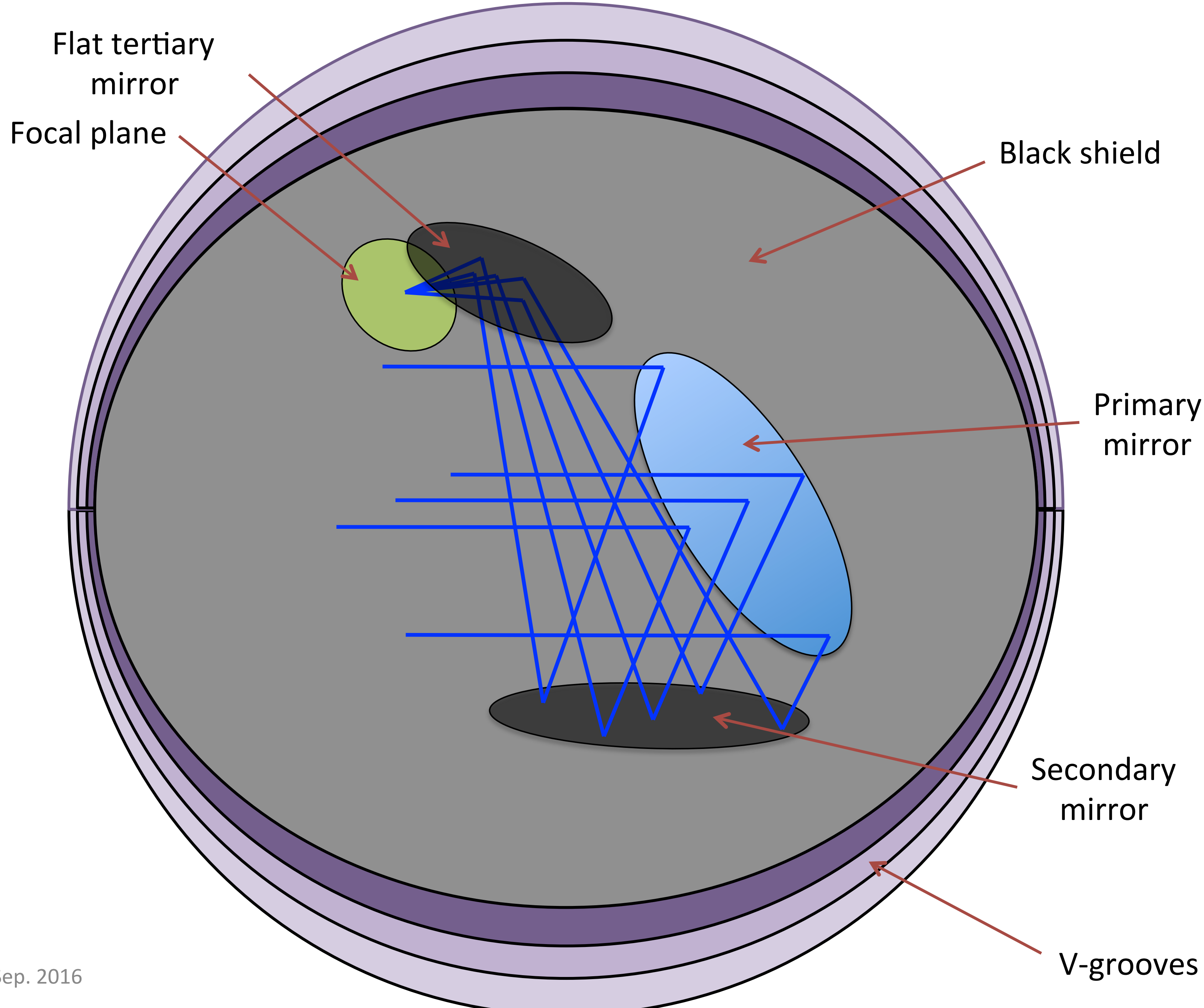
   - Avoids use of He shrouds test chamber
   - Smaller/warmer telescope

   OK, test impact on science

Spacecraft (M5 concept)



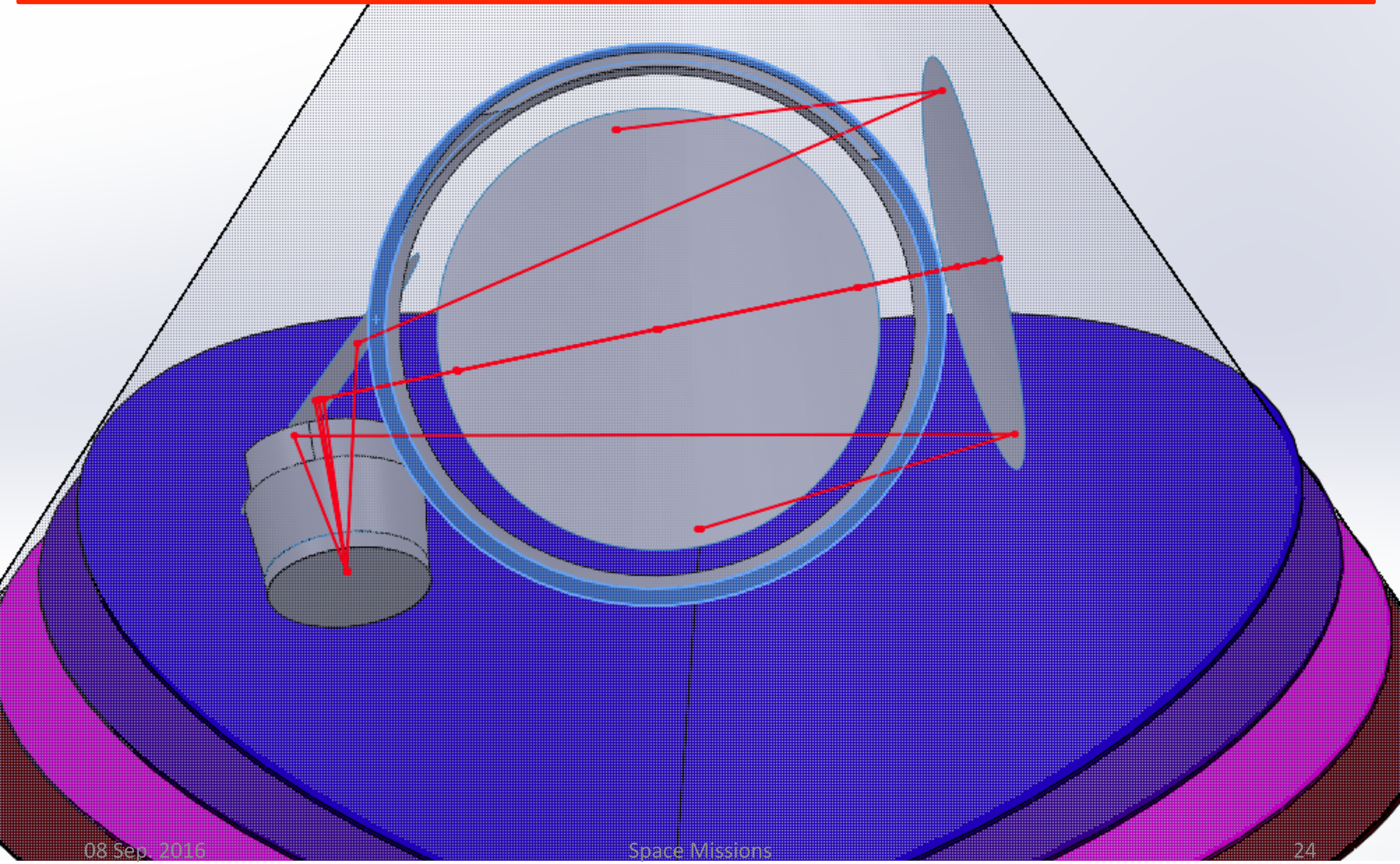

30°
60°
Aperture
Black shield
Secondary mirror
Flat tertiary mirror
Primary mirror
Focal plane
V-grooves
Service module
Solar panel



Flat tertiary mirror
Focal plane
Black shield
Primary mirror
Secondary mirror
V-grooves

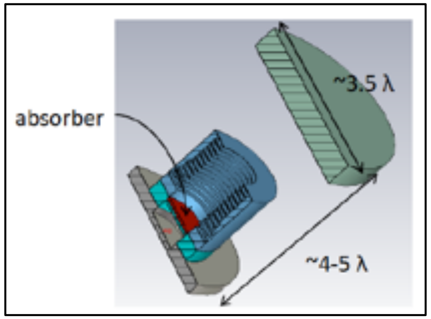
08 Sep. 2016

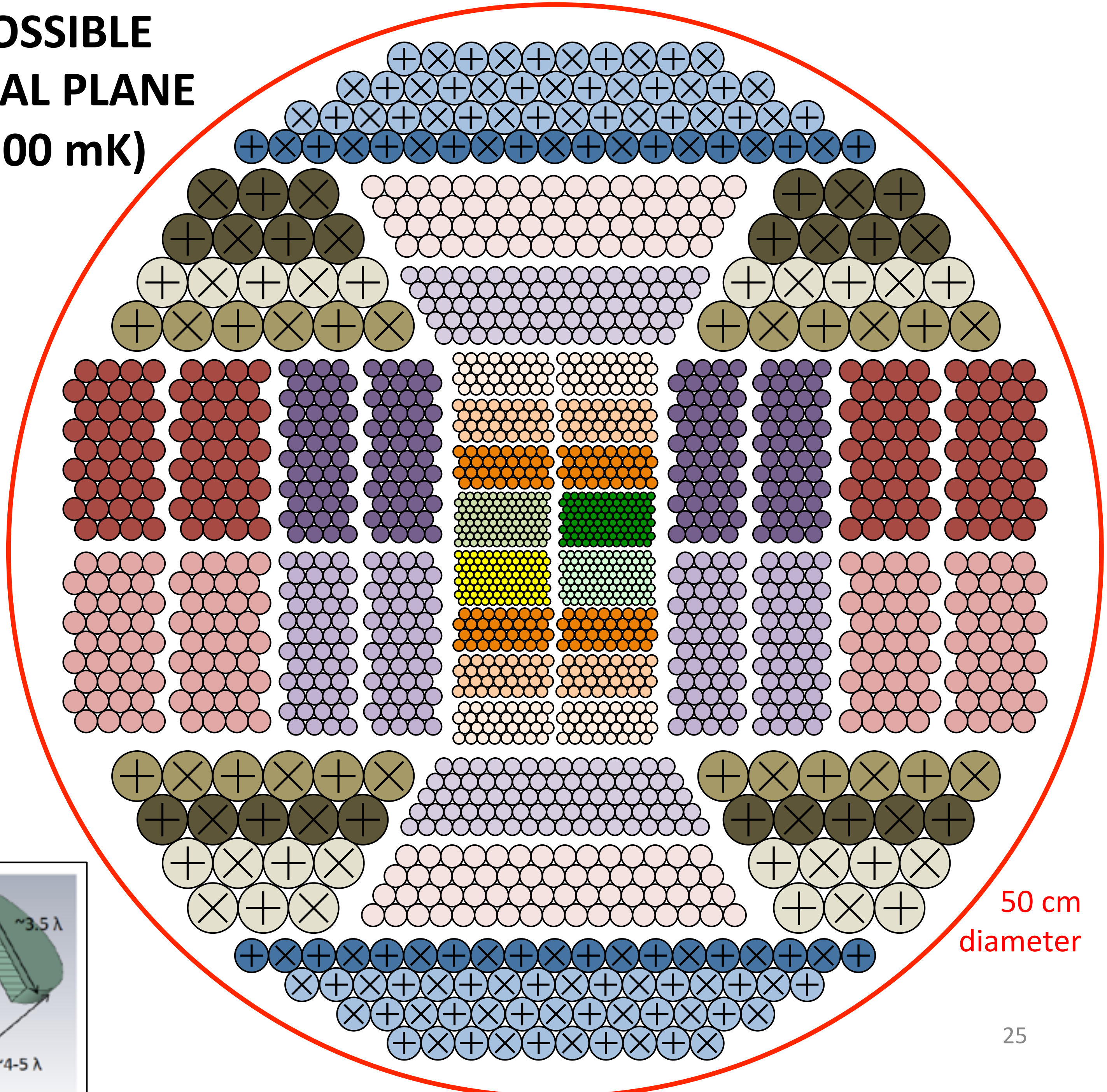
View from boresight



POSSIBLE FOCAL PLANE (100 mK)

GHz	N_{det} (M5)
60	24×2
70	24×2
80	24×2
90	39×2
100	39×2
115	38×2
130	124
145	144
160	144
175	160
195	192
220	192
255	128
295	128
340	128
390	96
450	96
520	96
600	96
TOTAL	2100

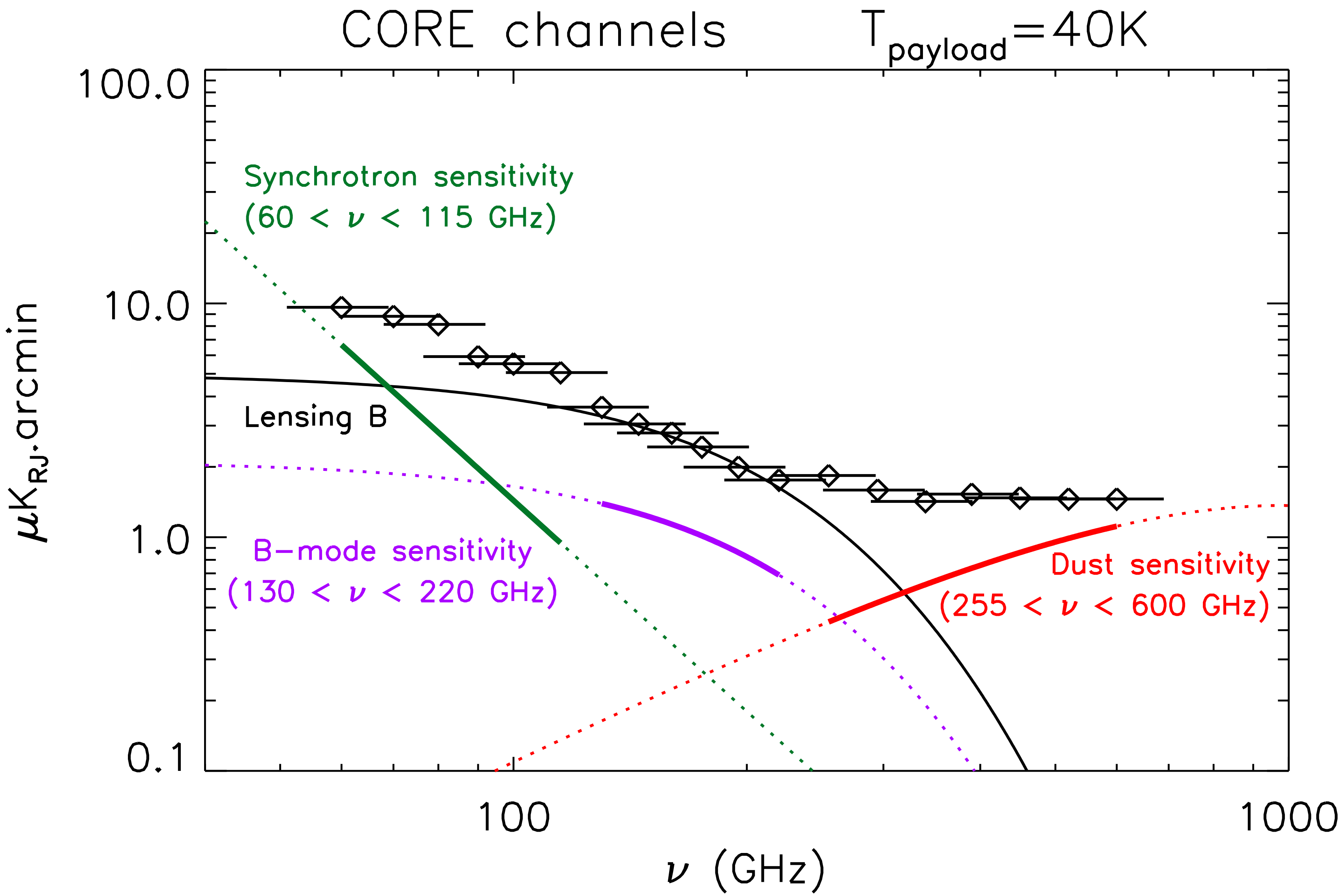




channel GHz	beam arcmin	$N_{\rm det}$	ΔT μK.arcmin	ΔP μK.arcmin	ΔI $\mu K_{\rm RJ}$.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ $y_{\rm SZ}$.arcmin	PS (5σ) mJy	FP area %
60	17.87	48	7.5	10.6	6.81	0.75	-1.5	5.0	8.23
70	15.39	48	7.1	10	6.23	0.94	-1.5	5.4	6.19
80	13.52	48	6.8	9.6	5.76	1.13	-1.5	5.7	4.85
90	12.08	78	5.1	7.3	4.19	1.04	-1.2	4.7	6.38
100	10.92	78	5.0	7.1	3.90	1.2	-1.2	4.9	5.29
115	9.56	76	5.0	7.0	3.58	1.45	-1.3	5.2	4.03
130	8.51	124	3.9	5.5	2.55	1.32	-1.2	4.2	10.64
145	7.68	144	3.6	5.1	2.16	1.39	-1.3	4.0	10.25
160	7.01	144	3.7	5.2	1.98	1.55	-1.6	4.1	8.69
175	6.45	160	3.6	5.1	1.72	1.62	-2.1	3.9	8.31
195	5.84	192	3.5	4.9	1.41	1.65	-3.8	3.6	8.34
220	5.23	192	3.8	5.4	1.24	1.85	-	3.6	6.84
255	4.57	128	5.6	7.9	1.30	2.59	3.5	4.4	3.57
295	3.99	128	7.4	10.5	1.12	3.01	2.2	4.5	2.79
340	3.49	128	11.1	15.7	1.01	3.57	2.0	4.7	2.17
390	3.06	96	22.0	31.1	1.08	5.05	2.8	5.8	1.26
450	2.65	96	45.9	64.9	1.04	6.48	4.3	6.5	0.95
520	2.29	96	116.6	164.8	1.03	8.56	8.3	7.4	0.71
600	1.98	96	358.3	506.7	1.03	11.4	20.0	8.5	0.53

Table 1: Proposed CORE frequency channels. The sensitivity is calculated assuming $\Delta\nu/\nu = 30\%$ bandwidth, 60% optical efficiency, total noise of twice the expected photon noise from the sky and the optics of the instrument at 40K temperature.

TOTAL NUMBER OF DETECTORS = 2100
TOTAL NUMBER OF CMB DETECTORS FROM 130 TO 220 GHz = 956 (45.5%)
TOTAL SYNCHROTRON POLARISATION EQUIVALENT SENSITIVITY AT 130 GHz = 0.994 $\mu K_{\rm CMB}$
TOTAL DUST POLARISATION EQUIVALENT SENSITIVITY AT 220 GHz = 1.091 $\mu K_{\rm CMB}$
TOTAL CMB POLARISATION SENSITIVITY (from 130 to 220 GHz)= 2.046 $\mu K_{\rm CMB}$
TOTAL CMB POLARISATION SENSITIVITY (full array)= 1.710 $\mu K_{\rm CMB}$
5 SIGMA Y SZ SENSITIVITY (x 1e4)= 0.152
DATA RATE = 1132.0 kbit/s
DATA RATE = 156.13 x Ns.Nb.sin(beta).(60s/Tspin)) (kbit/s)



CMB polarization sensitivity	2.05 uK.arcmin
Synchrotron extrapolation at 130 GHz	1.00 uK.arcmin
Dust extrapolation at 220 GHz	1.10 uK.arcmin

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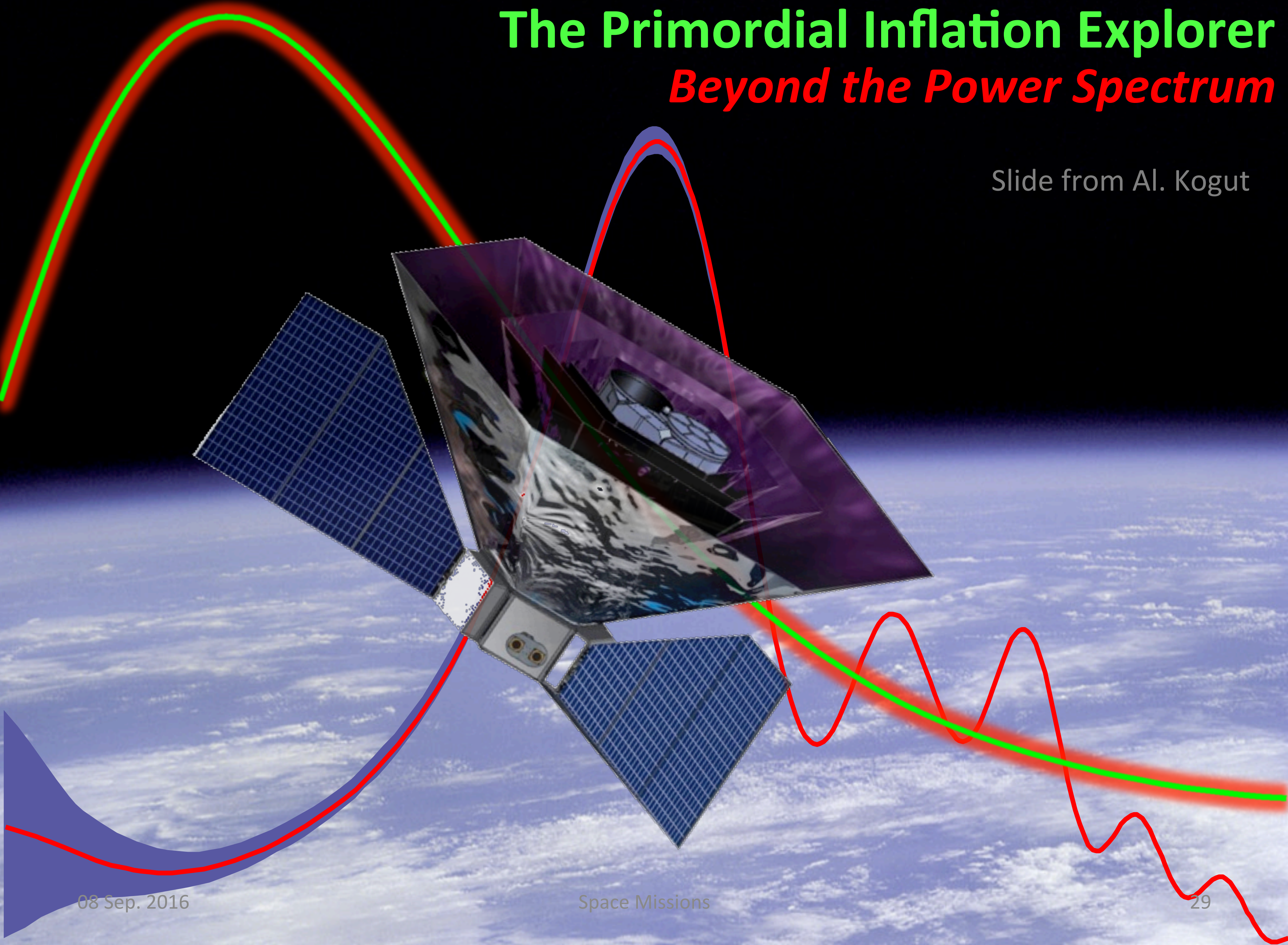
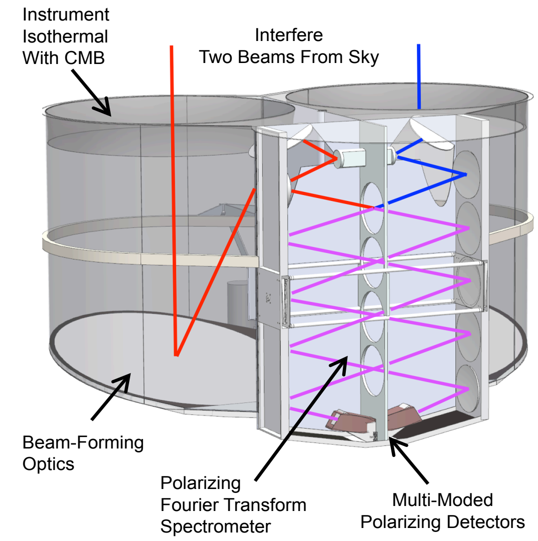
The Primordial Inflation Explorer
Beyond the Power Spectrum

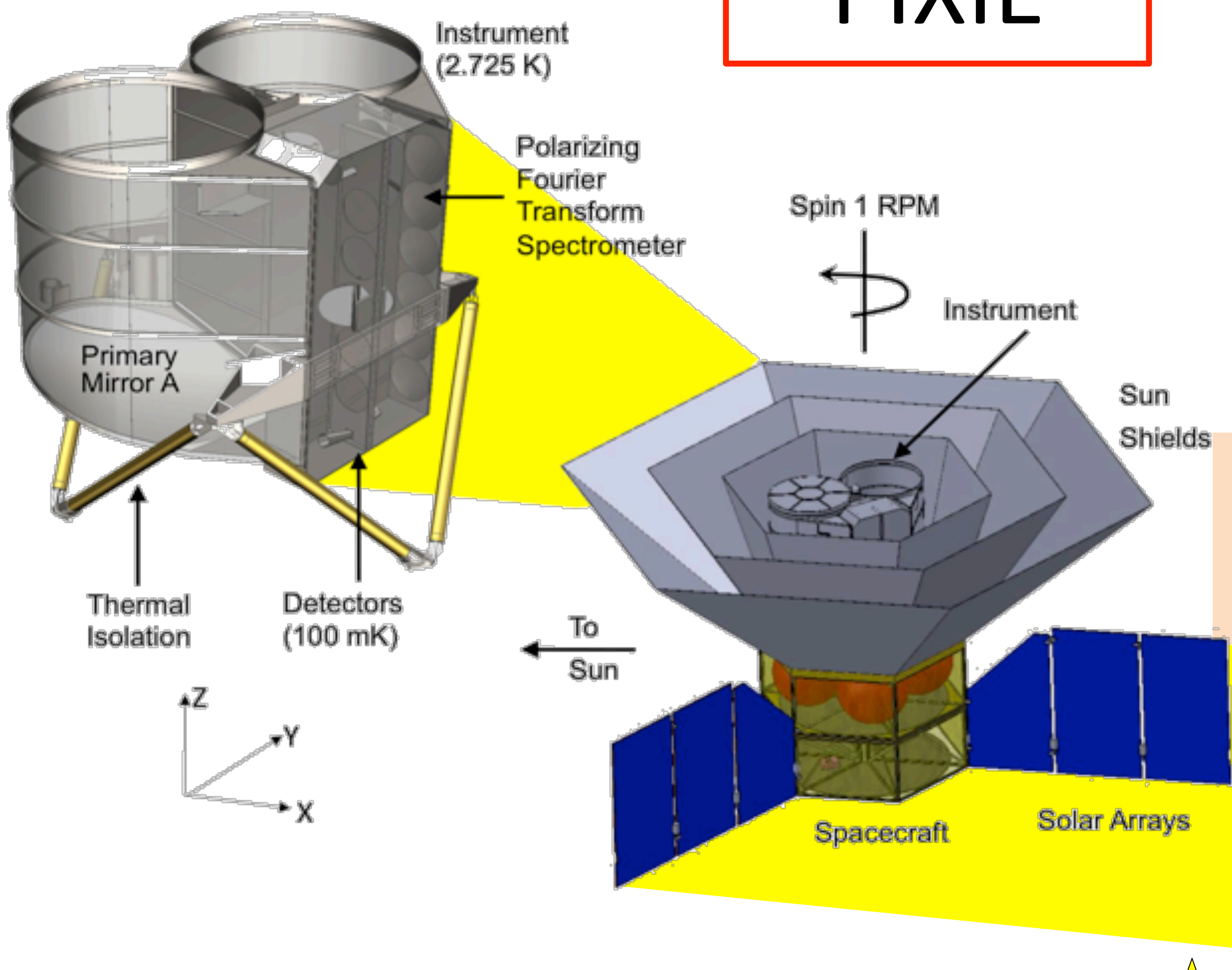
Slide from Al. Kogut



Slide from Al. Kogut

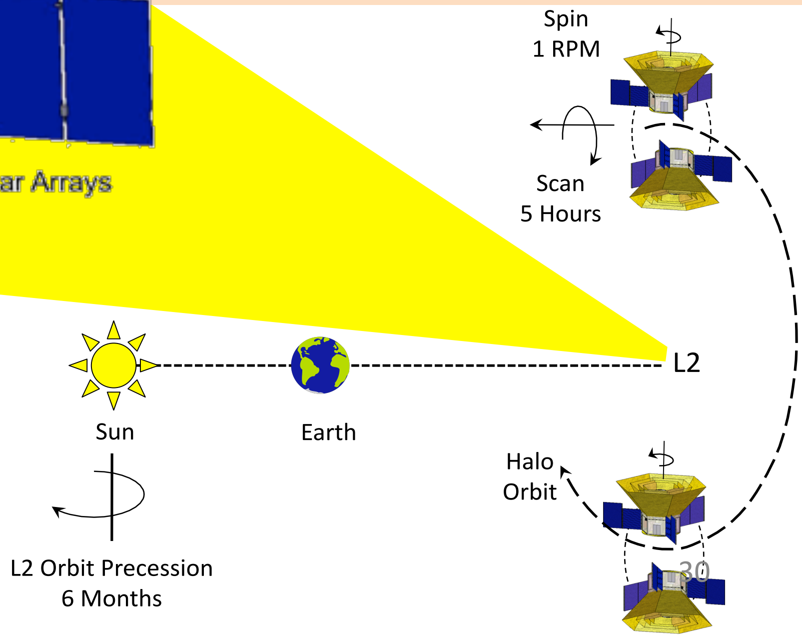
PIXIE





Cryogenic instrument at L2 halo orbit

- Spin at 1 RPM
- Precession 5 hours about sun line

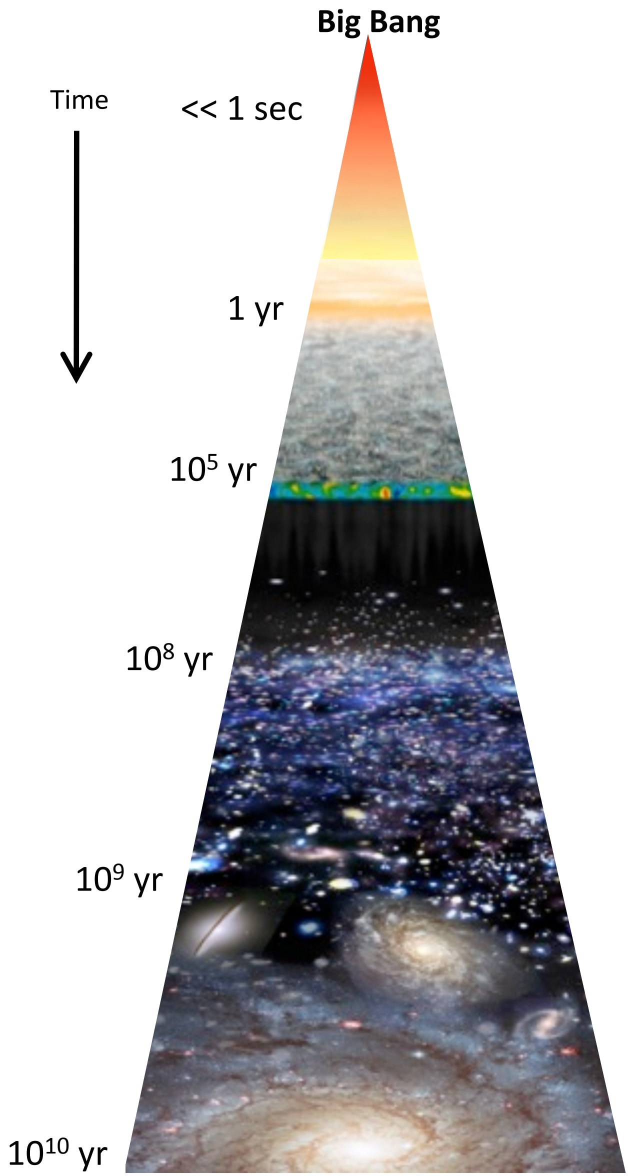


L2 Halo Orbit

- Spin axis 91 deg to sun line
- Precess scan plane to follow sun line
- Full-sky coverage every 6 months

Slide from Al. Kogut

PIXIE Samples History of the Universe



Big Bang Cosmology
- Inflation
- Grand Unification physics
- Quantum gravity

Early Universe
- Dark matter decay/annihilation
- Primordial density perturbations

Reionization and First Stars
- Detection of neutrino mass
- Nature of first stars

Large-scale Structure
- Cosmic tomography
- Star formation history

Galactic Structure
- Assembly history of the Galaxy
- Dust & chemical separation

All this science with single instrument

Questions specifically called out in Astro-2010 Decadal Survey

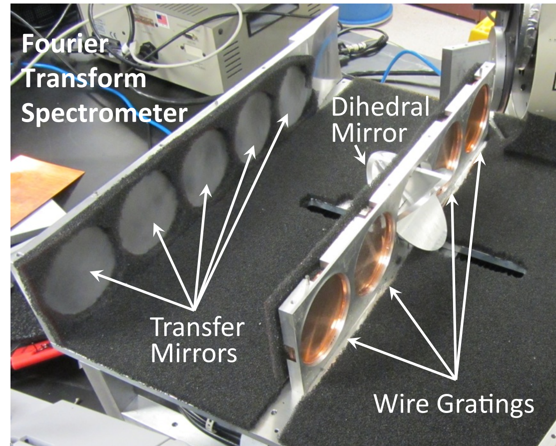
Slide from Al. Kogut

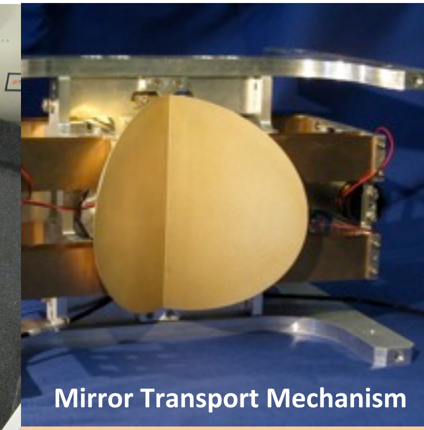
NASA Explorer Program

Small PI-led missions
- 22 full missions proposed Feb 2011
- $200M Cost Cap + launch vehicle

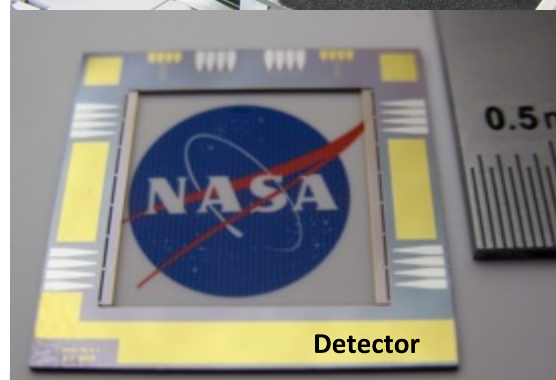
PIXIE not selected; urged to re-propose
- Top (Category I) science rating
- Broad recognition of science appeal

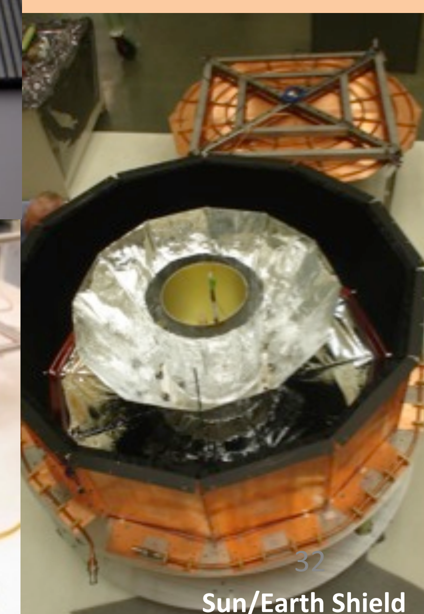
Re-propose to next MIDEX AO (2016)
- Technology is mature
- Launch early next decade





Mature technology





"PIXIE's spectral measurements alone justify the program"
-- NASA review panel

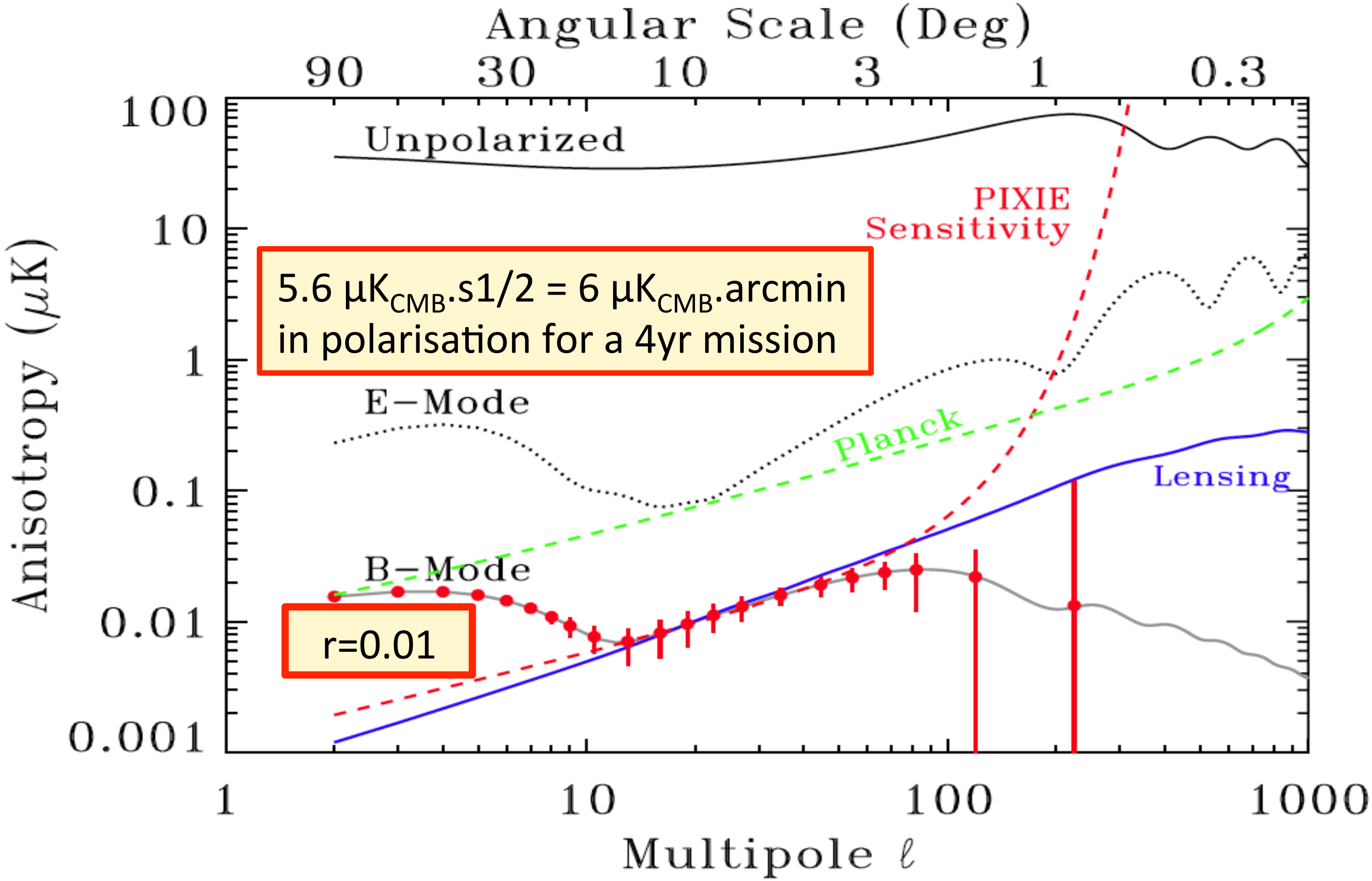
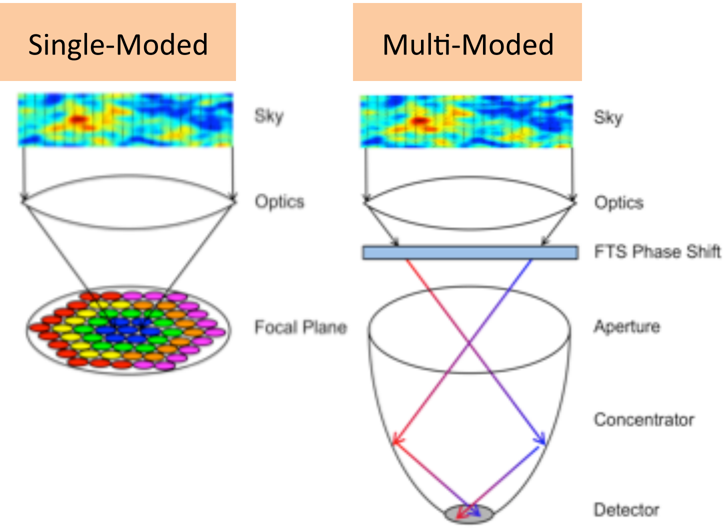


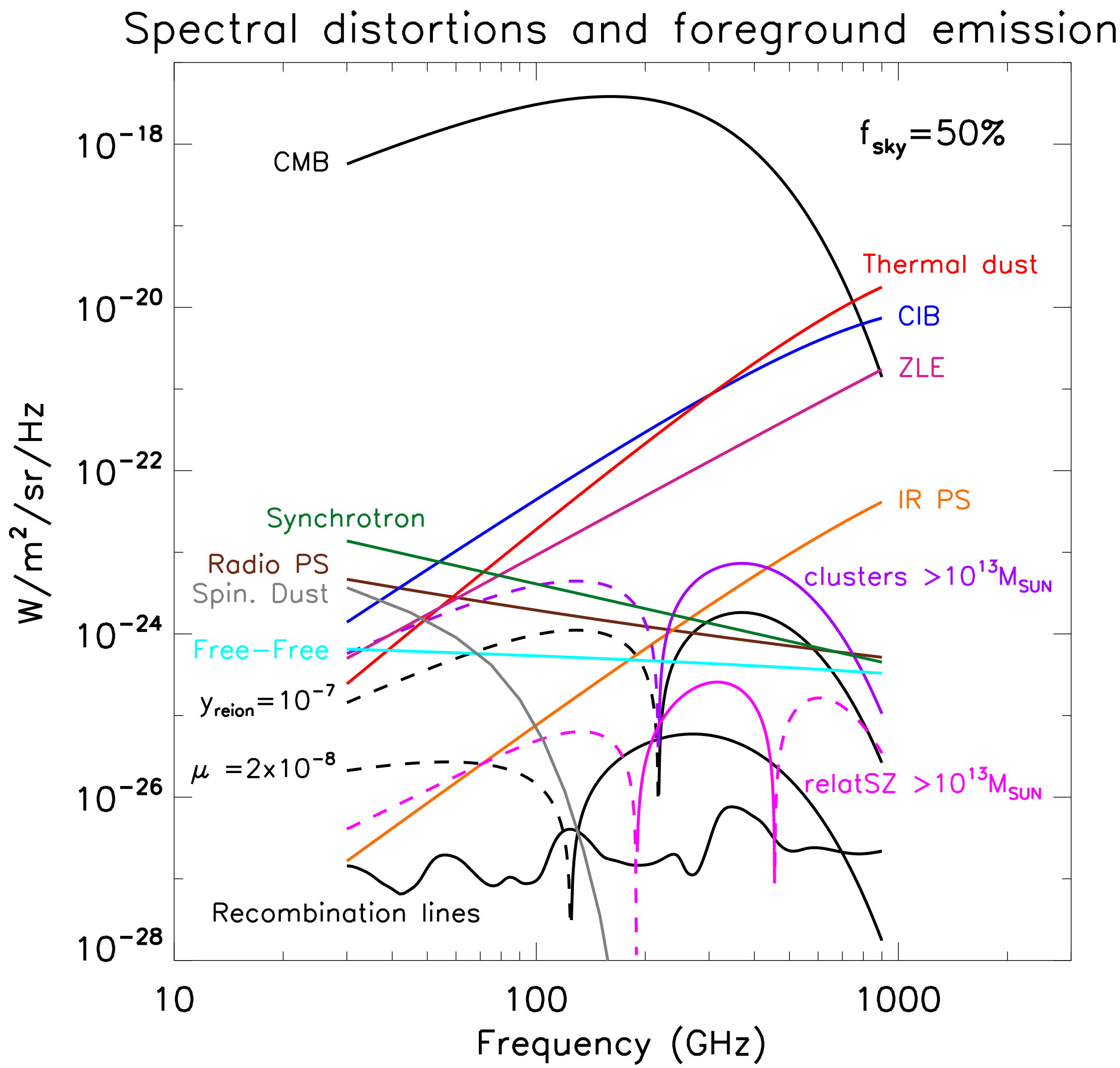
Figure 1. Angular power spectra for unpolarized, E-mode, and B-mode polarization in the cosmic microwave background. The dashed red line shows the PIXIE sensitivity to B-mode polarization at each multipole moment $\ell \sim 180°/\theta$. The sensitivity estimate assumes a 4-year mission and includes the effects of foreground subtraction within the cleanest 75% of the sky combining PIXIE data at frequencies $\nu < 600$ GHz. Red points and error bars show the response within broader ℓ bins to a B-mode power spectrum with amplitude $r = 0.01$. PIXIE will reach the confusion noise (blue curve) from the gravitational lensing of the E-mode signal by cosmic shear along each line of sight, and has the sensitivity and angular response to measure even the minimum predicted B-mode power spectrum at high statistical confidence.



Main limitations of PIXIE

1) Beam size 2.6°

2) Foreground emission



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JAXA
T. Dotani
H. Fuke
H. Imada
I. Kawano
H. Matsuhara
T. Matsumura
K. Mitsuda
T. Nishibori
K. Nishijo
A. Noda
A. Okamoto
S. Sakai
Y. Sato
K. Shinozaki
H. Sugita
Y. Takei
S. Utsunomiya
T. Wada
R. Yamamoto
N. Yamasaki
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K. Yotsumoto

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S. Takakura
K. Takano

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K. Kimura
H. Ogawa
N. Okada

Okayama U.
T. Funaki
N. Hidehira
H. Ishino
A. Kibayashi
Y. Kida
K. Komatsu
S. Uozumi
Y. Yamada

NIFS
S. Takada

Kavli IPMU
K. Hattori
N. Katayama
Y. Sakurai
H. Sugai

KEK
M. Hazumi (PI)
M. Hasegawa
N. Kimura
K. Kohri
M. Maki
Y. Minami
T. Nagasaki
R. Nagata
H. Nishino
S. Oguri
T. Okamura
N. Sato
J. Suzuki
T. Suzuki
O. Tajima
T. Tomaru
M. Yoshida

Kansei Gakuin U.
S. Matsuura

Kitazato U.
T. Kawasaki

Konan U.
I. Ohta

NAOJ
A. Dominjon
T. Hasebe
J. Inatani
K. Karatsu
S. Kashima
T. Noguchi
Y. Sekimoto
M. Sekine

Saitama U.
M. Naruse

NICT
Y. Uzawa

SOKENDAI
Y. Akiba
Y. Inoue
H. Ishitsuka
Y. Segawa
S. Takatori
D. Tanabe
H. Watanabe

U. Tsukuba
M. Nagai

TIT
S. Matsuoka
R. Chendra

U. Tokyo
S. Sekiguchi
T. Shimizu
S. Shu
N. Tomita

Tohoku U.
M. Hattori

Nagoya U.
K. Ichiki

Yokohama Natl. U.
T. Fujino
F. Irie
H. Kanai
S. Nakamura
T. Yamashita

RIKEN
S. Mima
C. Otani

APC Paris
R. Stompor

Cardiff U.
G. Pisano

Paris ILP
J. Errard

CU Boulder
N. Halverson

McGill U.
M. Dobbs

MPA
E. Komatsu

NIST
G. Hilton
J. Hubmayr

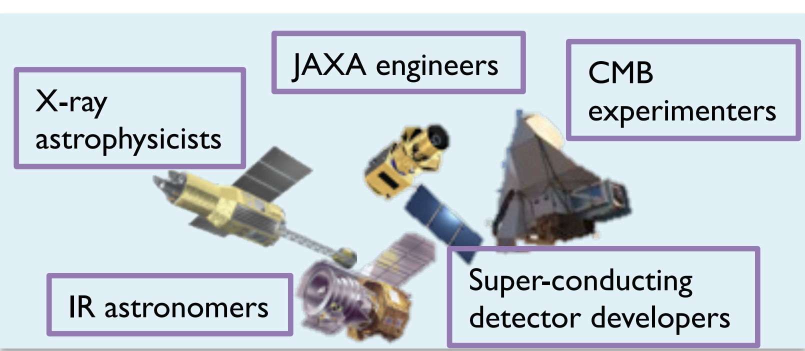
Stanford U.
S. Cho
K. Irwin
S. Kernasovskiy
C.-L. Kuo
D. Li
T. Namikawa
W. Ogburn
K. L. Thompson

U. Wisconsin
K. Arnold

UC Berkeley / LBNL
D. Barron
J. Borrill
Y. Chinone
A. Cukierman
T. de Haan
N. Goeckner-wald
P. Harvey
C. Hill
W. Holzapfel
Y. Hori
O. Jeong
R. Keskitalo
T. Kisner
A. Kusaka
A. Lee(US PI)
E. Linder
P. Richards
U. Seljak
B. Sherwin
A. Suzuki
P. Turin
B. Westbrook
N. Whitehorn

UC San Diego
T. Elleot
B. Keating
G. Rebeiz

LiteBIRD working group

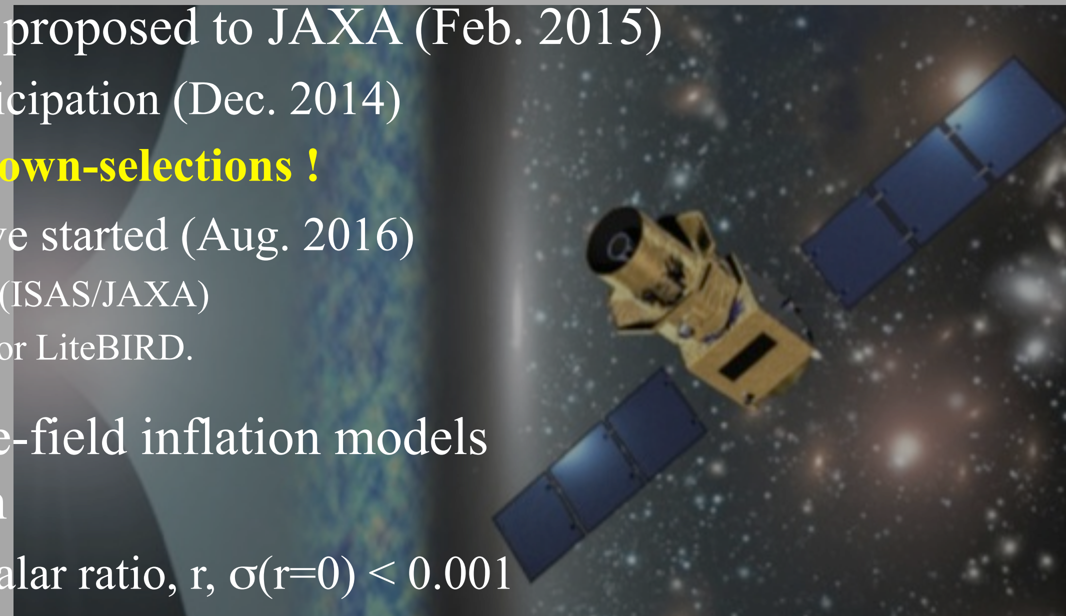


139 members, international and interdisciplinary (as of May 1, 2016)

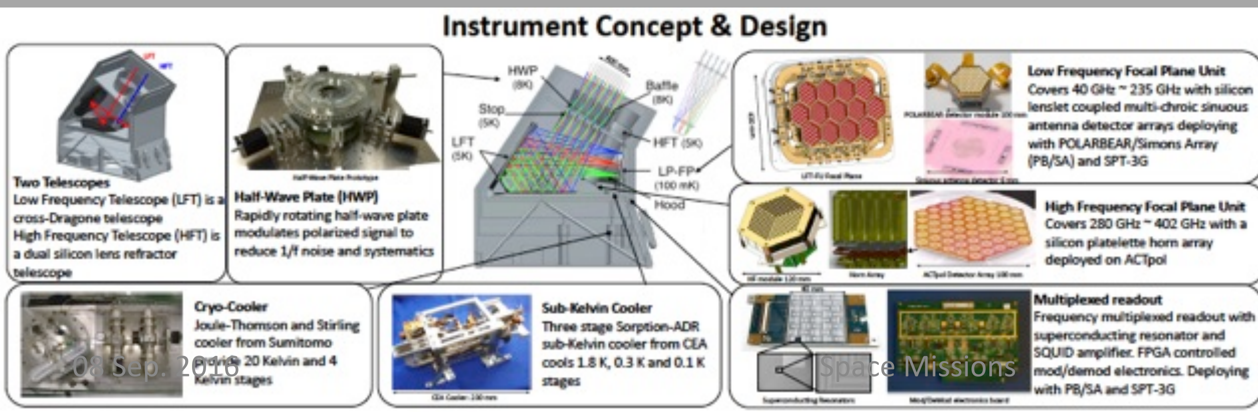
Slide from Masashi Hazumi

LiteBIRD

Lite (Light) *Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection*



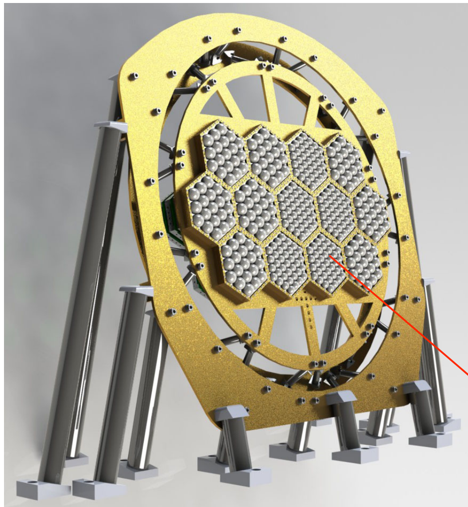
- CMB polarization all-sky survey proposed to JAXA (Feb. 2015)
  - Also to NASA MO for U.S. participation (Dec. 2014)
  - **Both proposals passed initial down-selections !**
  - ISAS/JAXA Phase-A studies have started (Aug. 2016)
    - ISAS team leader: Tadayasu Dotani (ISAS/JAXA)
    - ISAS is also hiring a full professor for LiteBIRD.
- Clear mission : to test major large-field inflation models and quantum gravity behind them
  - Total uncertainty on tensor-to-scalar ratio, r, $\sigma(r=0) < 0.001$
  - Multipole coverage: $2 \leq \ell \leq 200$
- Launch in ~2025 w/ JAXA's H3 for 3-year observations at L2
  - Currently the only CMB polarization space project in Phase-A status



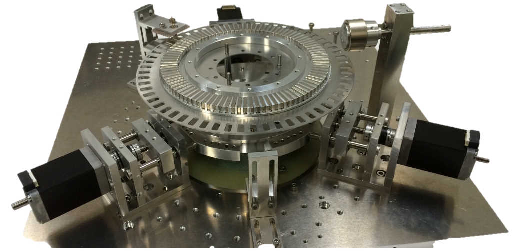
Slide from Masashi Hazumi

LiteBIRD Instrument

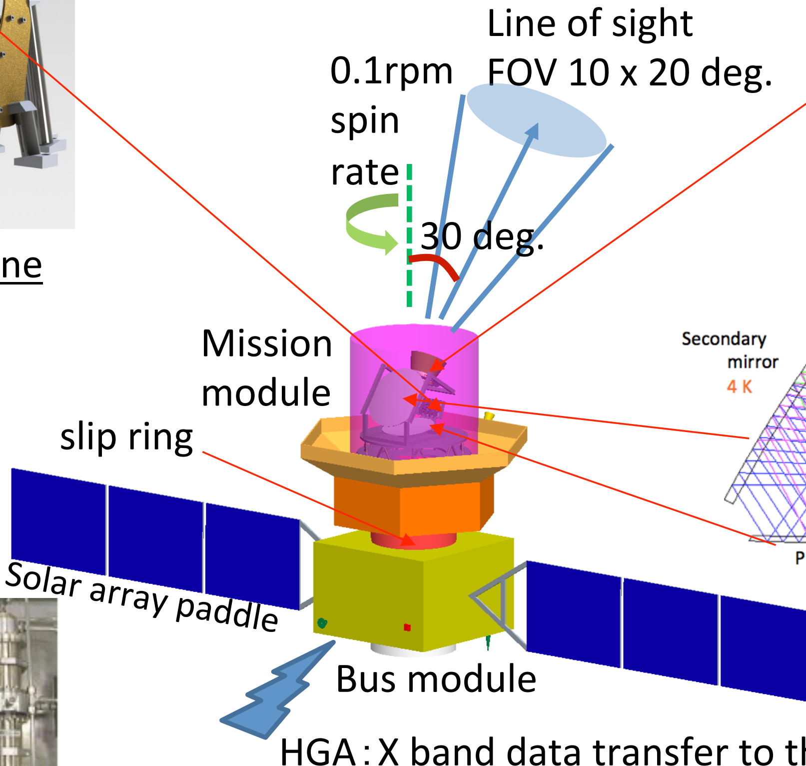
Slide from Adrian Lee

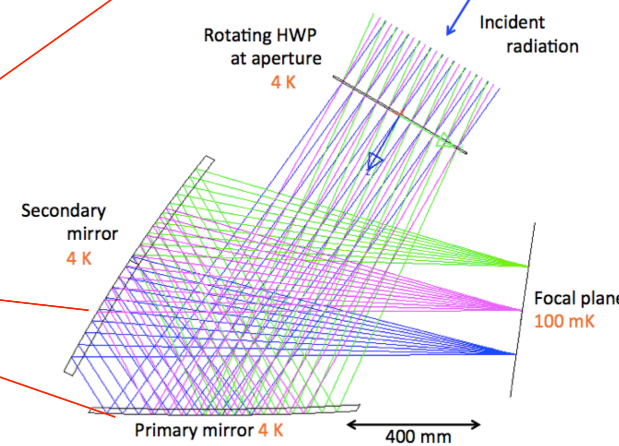


Multi-chroic focal plane



Continuously-rotating half wave plate (HWP)

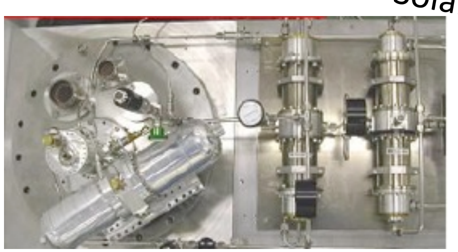




Mirrors at 4K

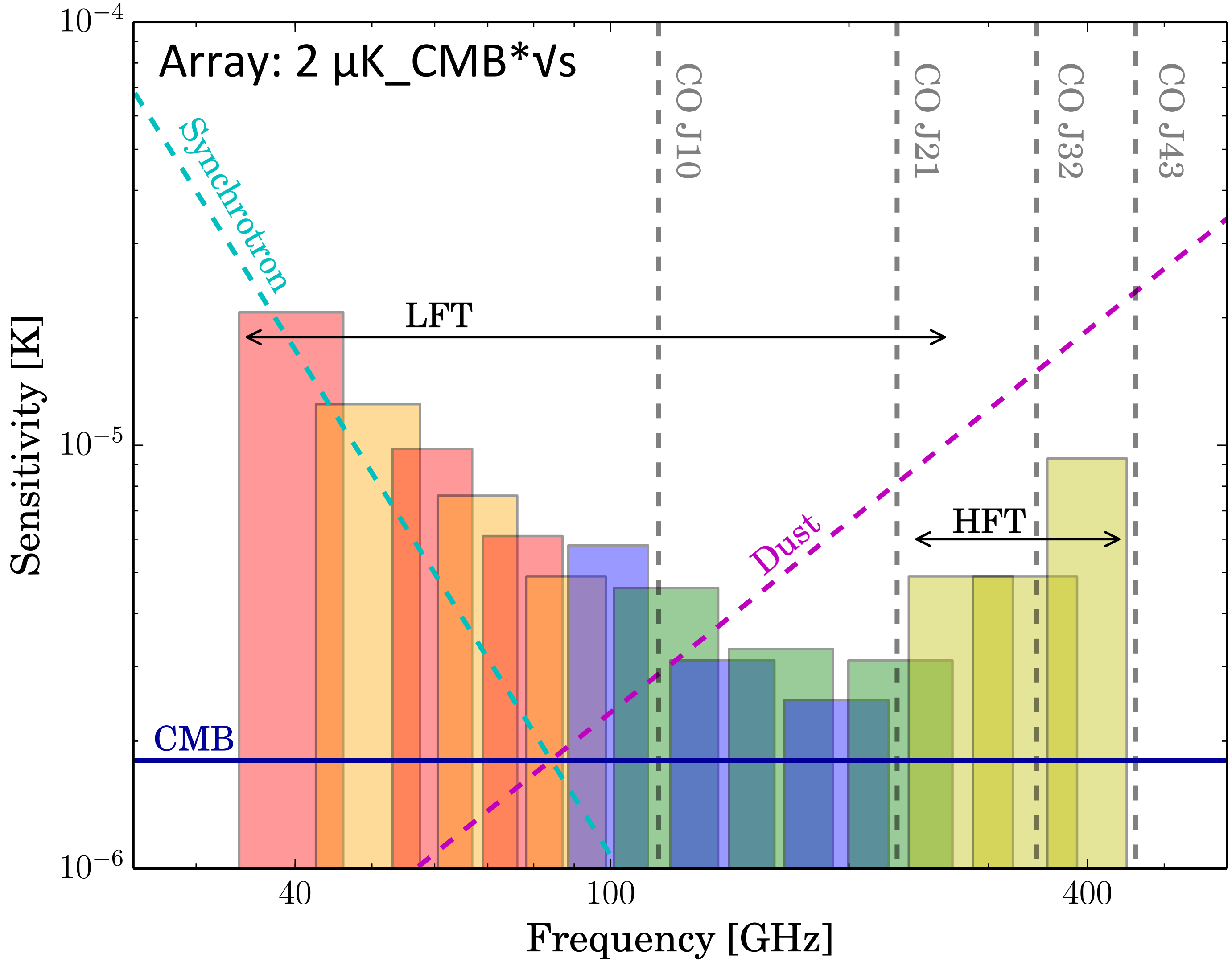
Cryogenics

- JT/ST and ADR (Astro-H heritage)

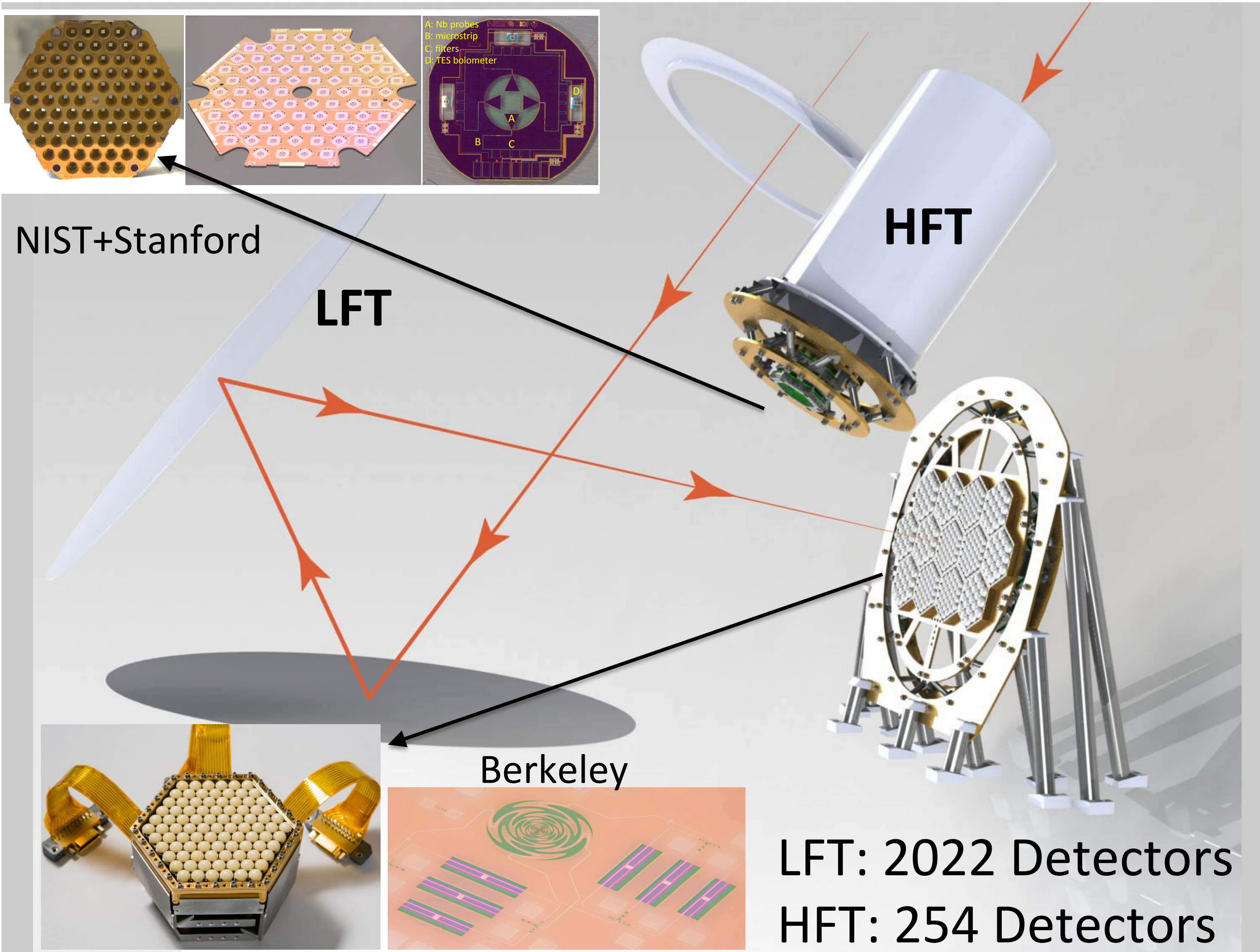


4

15 frequency bands



Slide from Adrian Lee



Slide from Adrian Lee

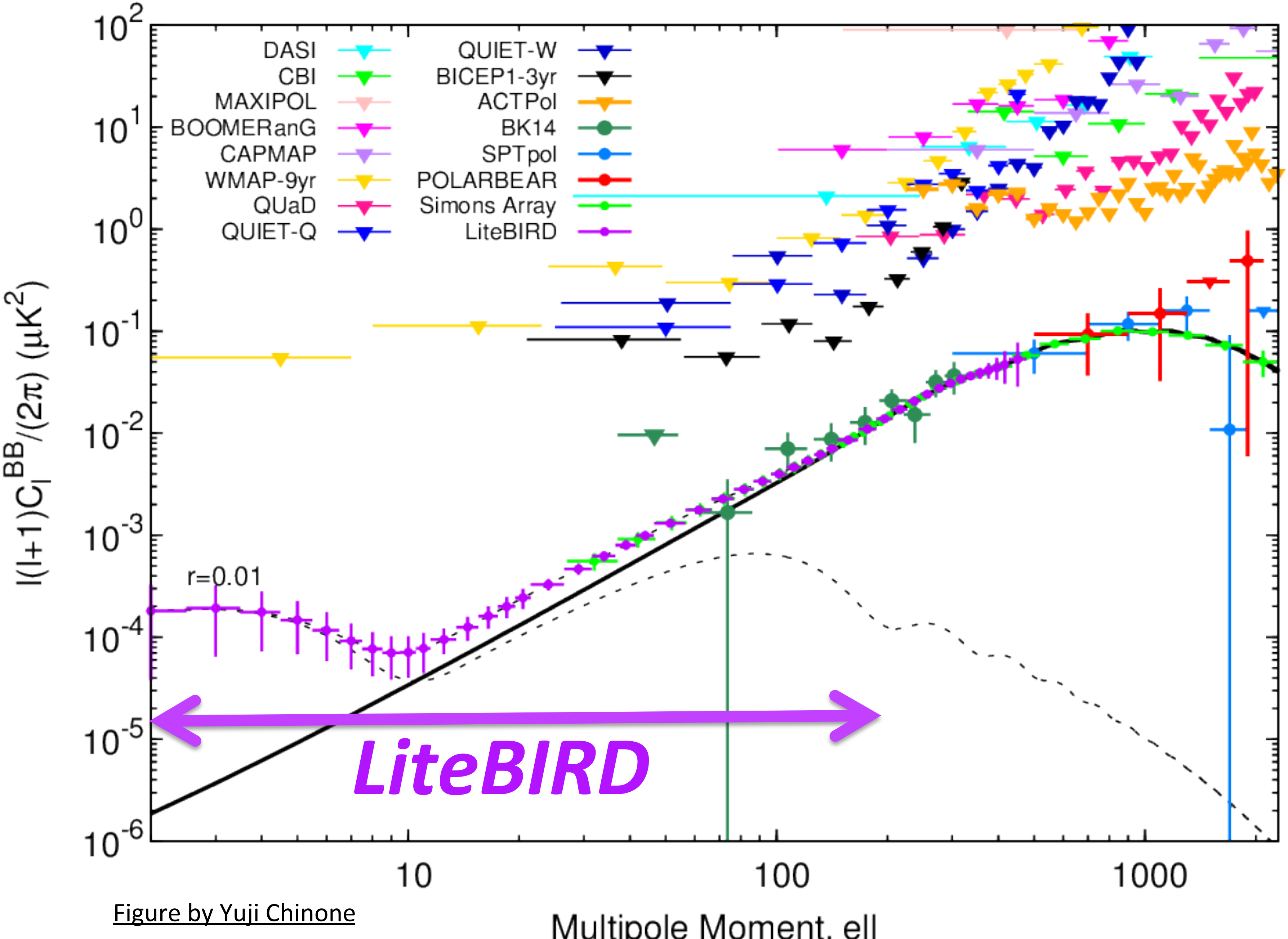
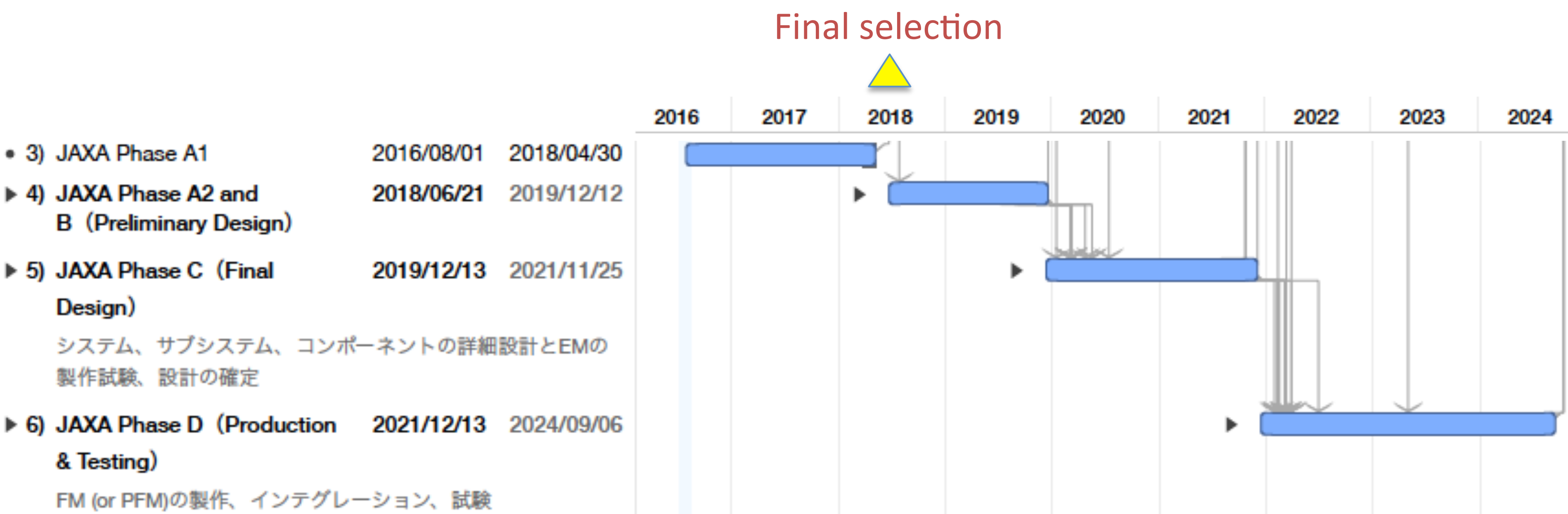


Figure by Yuji Chinone

Slide from Masashi Hazumi

LiteBIRD schedule

- To be consistent with the launch in 2025, we need to finish detailed engineering studies in 2016-2021 (Phase-A/B/C) and start flight model production in 2022 (Phase D).
- 5-year extension of Kavli IPMU is well aligned to the overall schedule of LiteBIRD.



Slide from Masashi Hazumi

The ESA-JAXA CDF study

future missions office

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Missions
- Show All Missions

Future Missions Office
- Introduction to the Office

Astrophysics & Fundamental Physics Missions

Solar System & Robotic Exploration Missions

Payload Instruments

Payload Technology Validation

CMB POLARISATION: COSMIC MICROWAVE BACKGROUND POLARISATION MISSION

ESA's Concurrent Design Facility (CDF) has completed a short study of a Cosmic Microwave Background Polarisation mission (CMB Polarisation). The purpose of this study is to support the European and Japanese science community in defining a collaborative mission studying the Polarisation of the Cosmic Microwave Background for calls for Cosmic Vision Medium-sized mission. A brief outline of the mission is given here, while further details can be found in the CDF presentations: CMB Polarisation mission - summary and CMB Polarisation mission - full presentation.

MISSION JUSTIFICATION

The highly successful ESA Planck space mission has demonstrated the capability of precision Cosmic Microwave Background (CMB) observations to constrain models of fundamental physics in the primordial Universe. Planck was primarily designed as the near-ultimate space mission for measuring the angular power spectrum of CMB temperature anisotropies, and has also made the most constraining measurements so far of E-mode polarisation. However, much remains to be learned from CMB polarisation, especially with regard to the much fainter B-modes, which are the signature of gravitational waves generated during inflation.

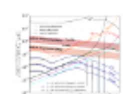
Search here

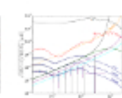
16-May-2016 22:33 UT

Shortcut URL

http://sci.esa.int/jump.cfm?oid=57795

Images And Videos





- CMB Polarisation mission - sensitivity to B-modes
- CMB Polarisation mission - orbit and scan strategy

http://sci.esa.int/trs/57795-cmb-polarisation-mission-study/

	CDF study	LiteBIRD
Orbit	L2	L2
Launch year	>2026 at the earliest anticipated: 2029	target: 2025
Observation time	3 years	3 years
Mass	2.2 tons	2.2 tons
Power	2.2 kW	2.5 kW
Main telescope	Gregorian, 1.2m aperture, 60K passive	Cross Dragone 40cm aperture, <10K active
Secondary telescope + instrument	No	Yes
Frequencies	≈ 60-600 (15-20 bands)	≈ 40-400 (12+3 = 15 bands)
Detectors	2420 single band, 100mK One focal plane	2276, 100 mK Two focal planes
Cooling system	ST/JT/CCDR or ADR	ST/JT/ADR or CCDR
Data size	100-400 Gbit/day	4 Gbit/day
Moving parts in PLM	none	2 CRHWPs, cooled to <10K Slip ring between PLM and SVM
Moving parts in SVM	Deployable solar panels Steerable antenna	Deployable solar panels Steerable antenna
Sensitivity	2 μK.arcmin	3 μK.arcmin (assumes 0.8 yield + 25% margin)
Angular resolution	10' @ 100 GHz	30' @ 100 GHz

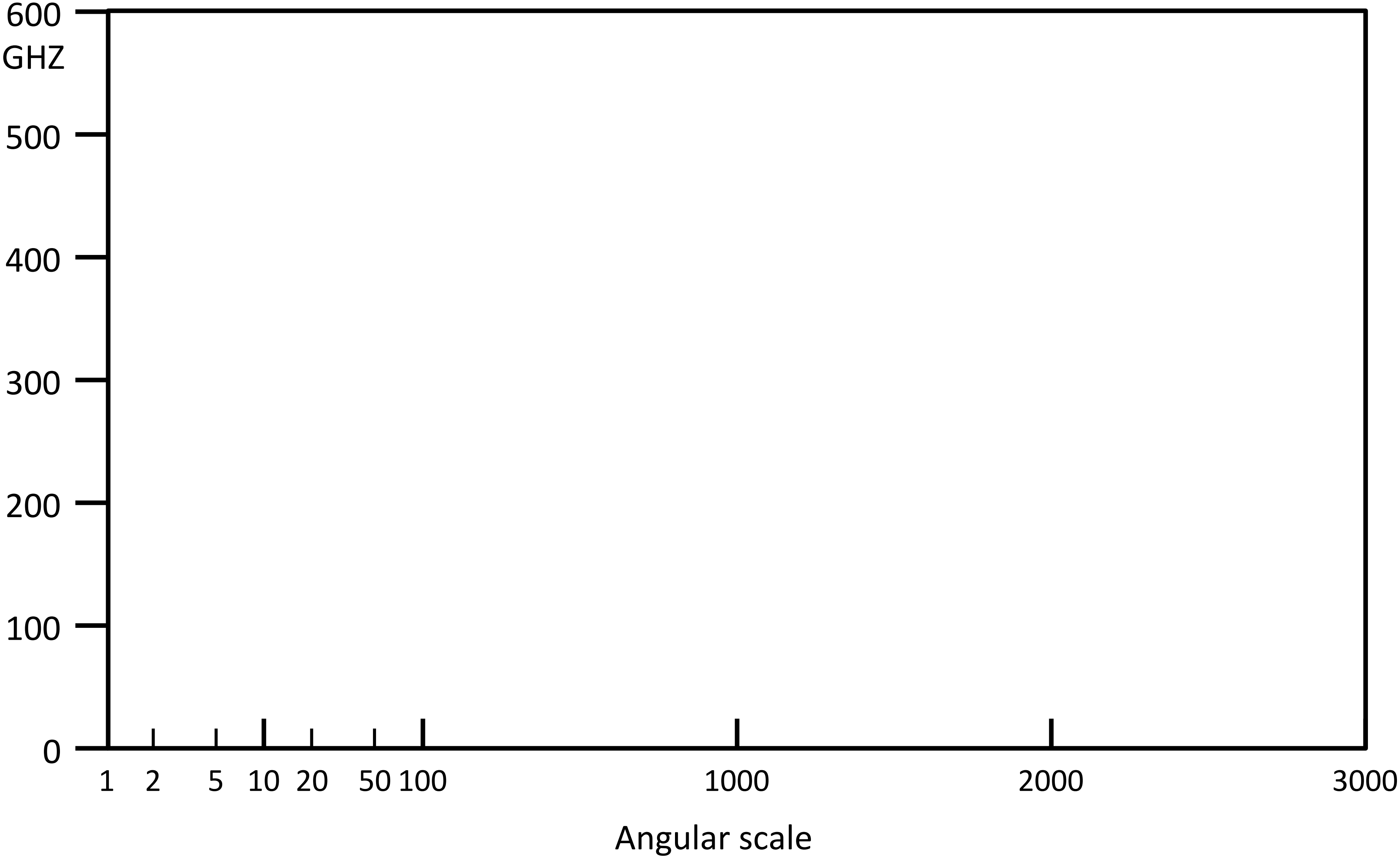
Outline

- Introduction
- CORE
- PIXIE
- LiteBIRD
- Discussion

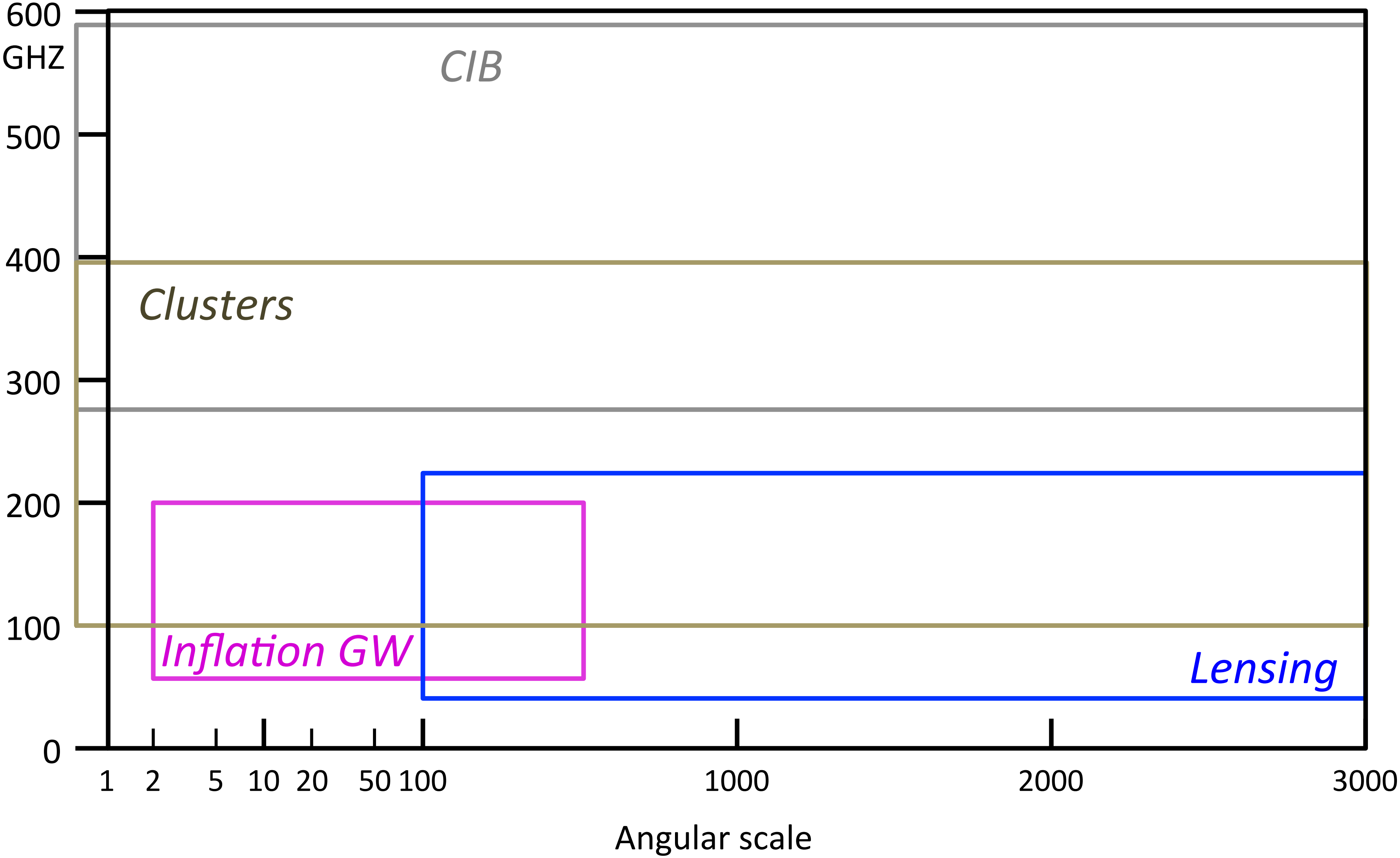
Comparison

	CMB resolution	CMB l_{max}	CMB Sensitivity μK.arcmin	Number of channels	% modes up to 2000 up to 3000
LiteBIRD	25'	400	2-3	15	4% 2%
PIXIE	2.5°	80	6	400	0.16% 0.07%
CORE	5'	2000	2	19	100% 50%

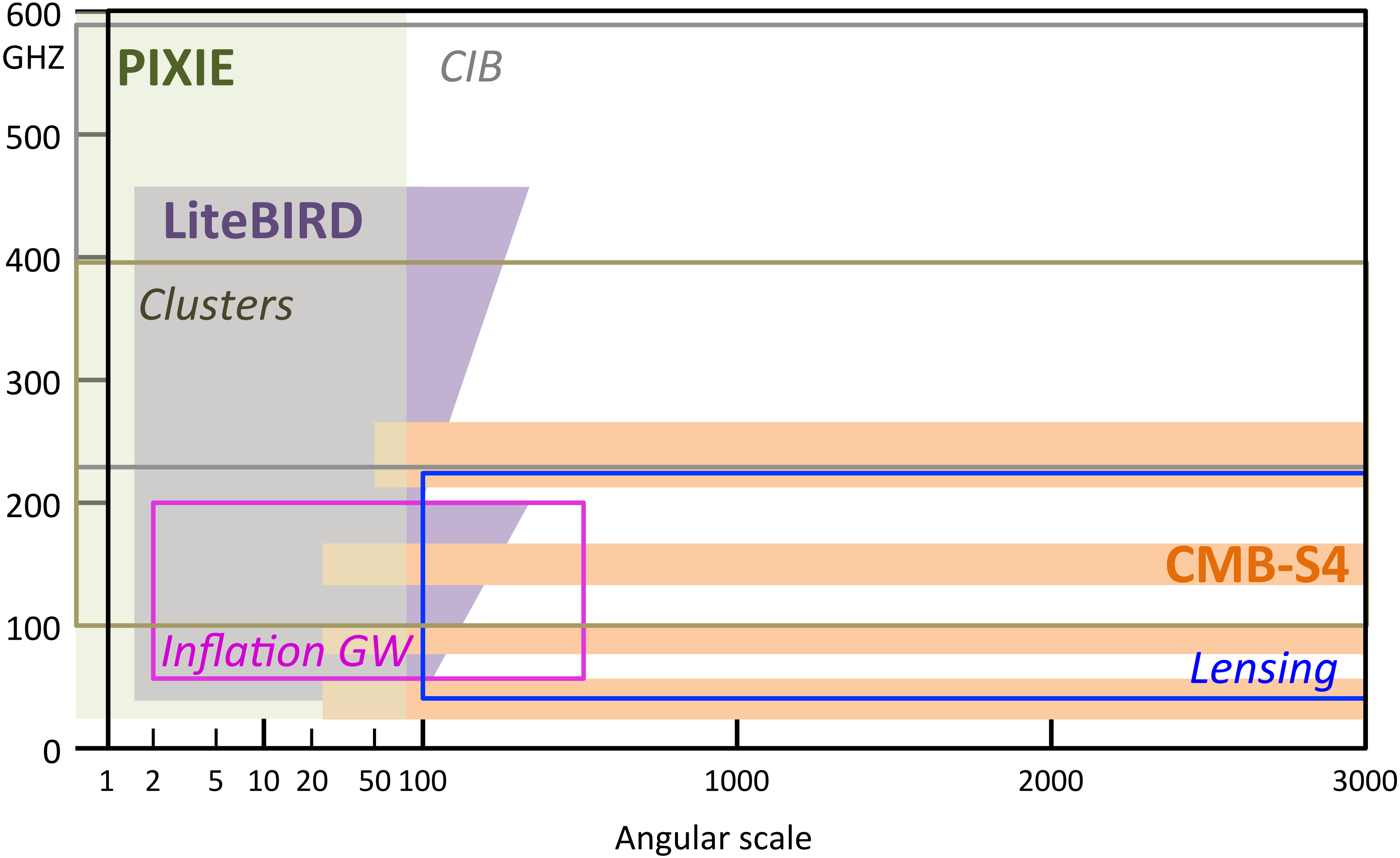
Complementarity



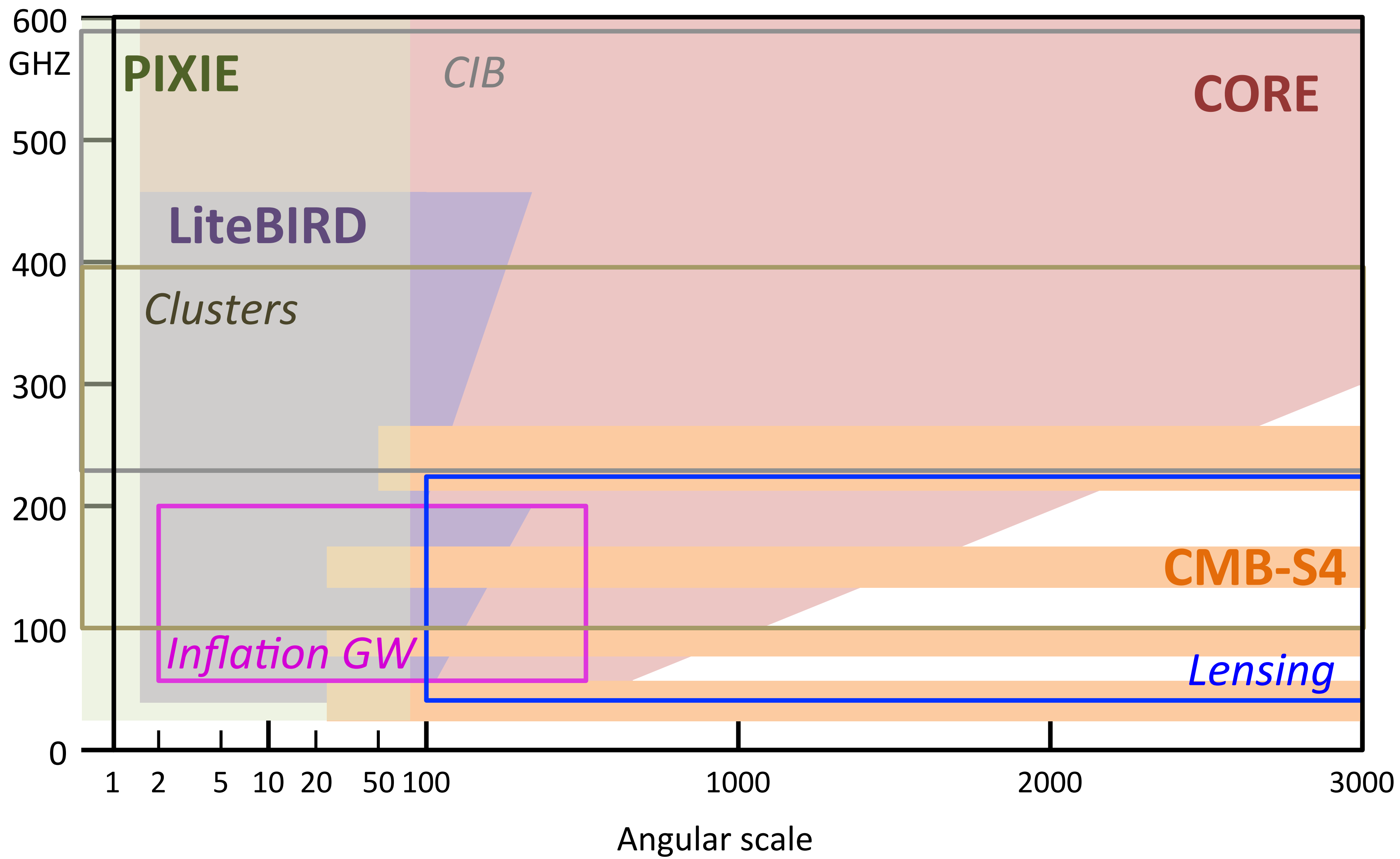
Complementarity



Complementarity



Complementarity

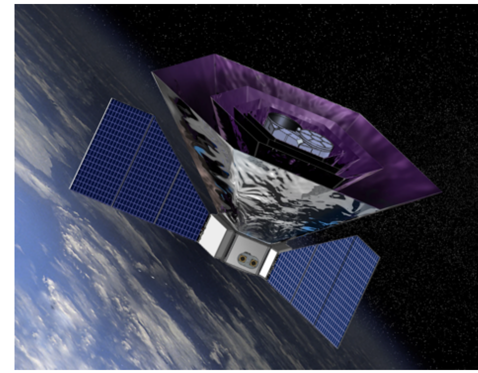


Synergy

The CMB spectrum

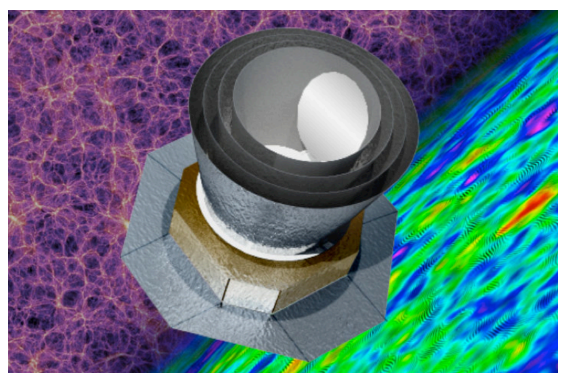

The suborbital roadmap

High resolution maps at ν < 200 GHz



Absolute spectrophotometry

Polarization from space

UNIQUE:
resolve CMB with:
- **many frequencies**
- **full sky**
- **systematics control**

High sensitivity multi-channel differential polarimetry

NASA : proposals for probe-scale mission studies

- Similar to CMBPol study (2007)
- Probe-scale = 400M$-1B$
- Planning for next decadal
- Call for mission *studies* (not mission proposals)
  - e.g. The CMBPol study for decadal 2010
  - Proposals due Nov. 15 2016, selection Feb. 2017
  - Study duration 18 months (Mar. 2017 – Sep. 2018)
  - Funding 100-150 k$ + cost of design studies +cost assessment