CMB Polarisation Study

Summary Presentation

ESTEC, 15 April 2016

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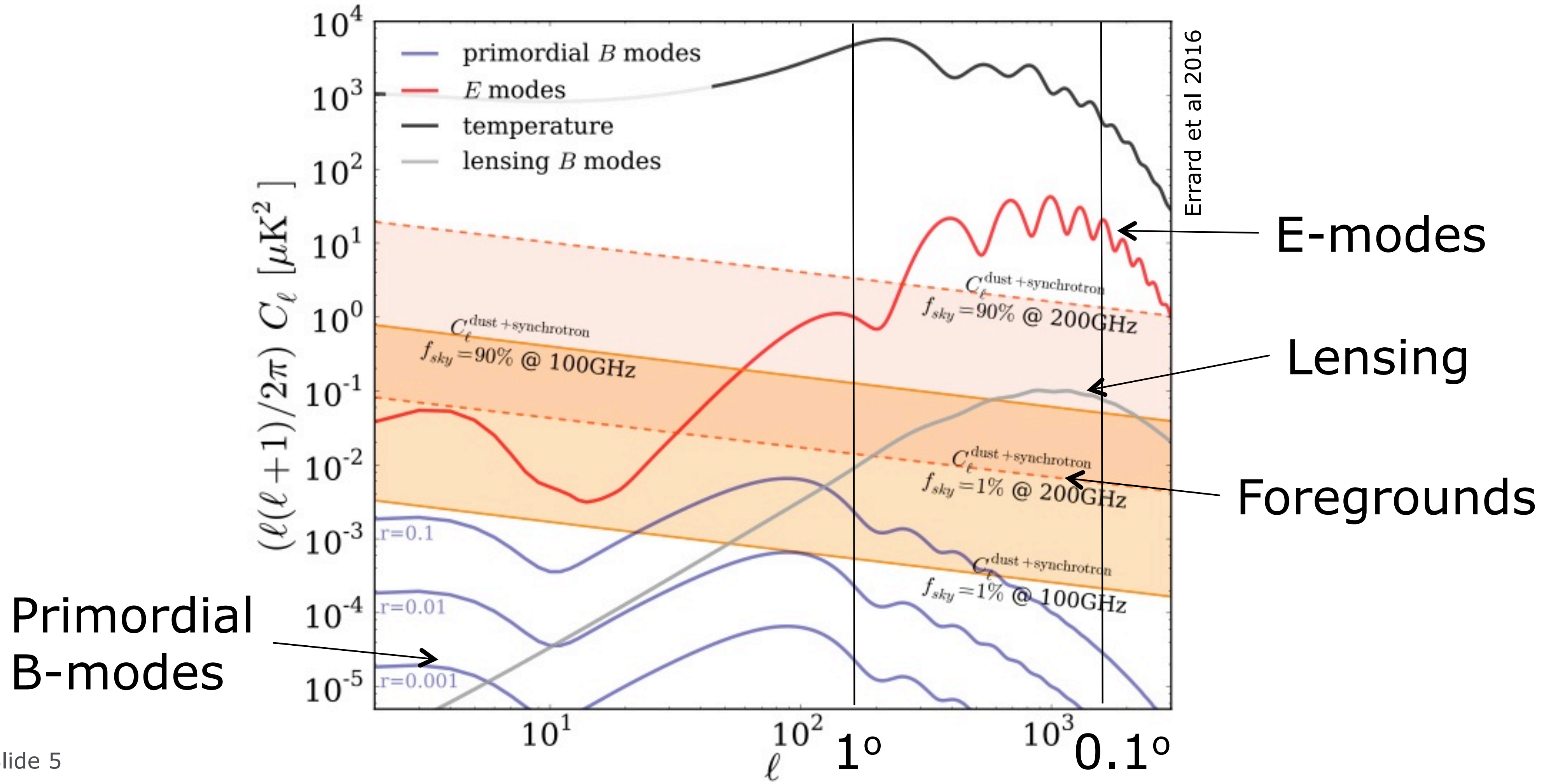
Context

- Cosmic Microwave Background
  - One of the main pillars of modern cosmology – providing the most "precise" estimates of cosmological parameters
  - Current frontier: detection of primordial gravitational waves via polarised CMB B-modes
- Experimental context
  - Sub-orbital: dozens of experiments starting from the 60's (Penzias and Wilson), both ground and balloon. Currently major experiments ongoing e.g. in Chile and South Pole, planning significant expansion to "Stage 4" level.
  - Space: COBE/DMR – WMAP – Planck
    - Next generation project under discussion in the scientific community for consideration by several agencies: ESA (Core+…); JAXA (Litebird); NASA (EPIC, PIXIE…)
- The aim of this (very short) CDF study was to investigate the technical feasibility of a potential collaborative project between JAXA and ESA in this field, to be proposed as a candidate for ESA's M5 opportunity

Mission Objectives - Experimental approach

- Goal of space proposals: observe B-modes at a level r ~0.01, implying $\sigma(r)$ ~0.001
- Main issues:
  - Instrumental systematic effects introduce low-frequency "noise"
    - Reduce by hardware, e.g. rotating Half-wave plate
    - Reduce by scanning strategy
  - Galactic and extra-galactic (B-mode) Foregrounds need to be removed
    - Require observations over a wide frequency range and with high(er) angular resolution
  - B-mode signals due to lensing of CMB E-modes need to be removed
    - Requires high(er) angular resolution

Mission Objectives - What we are trying to measure

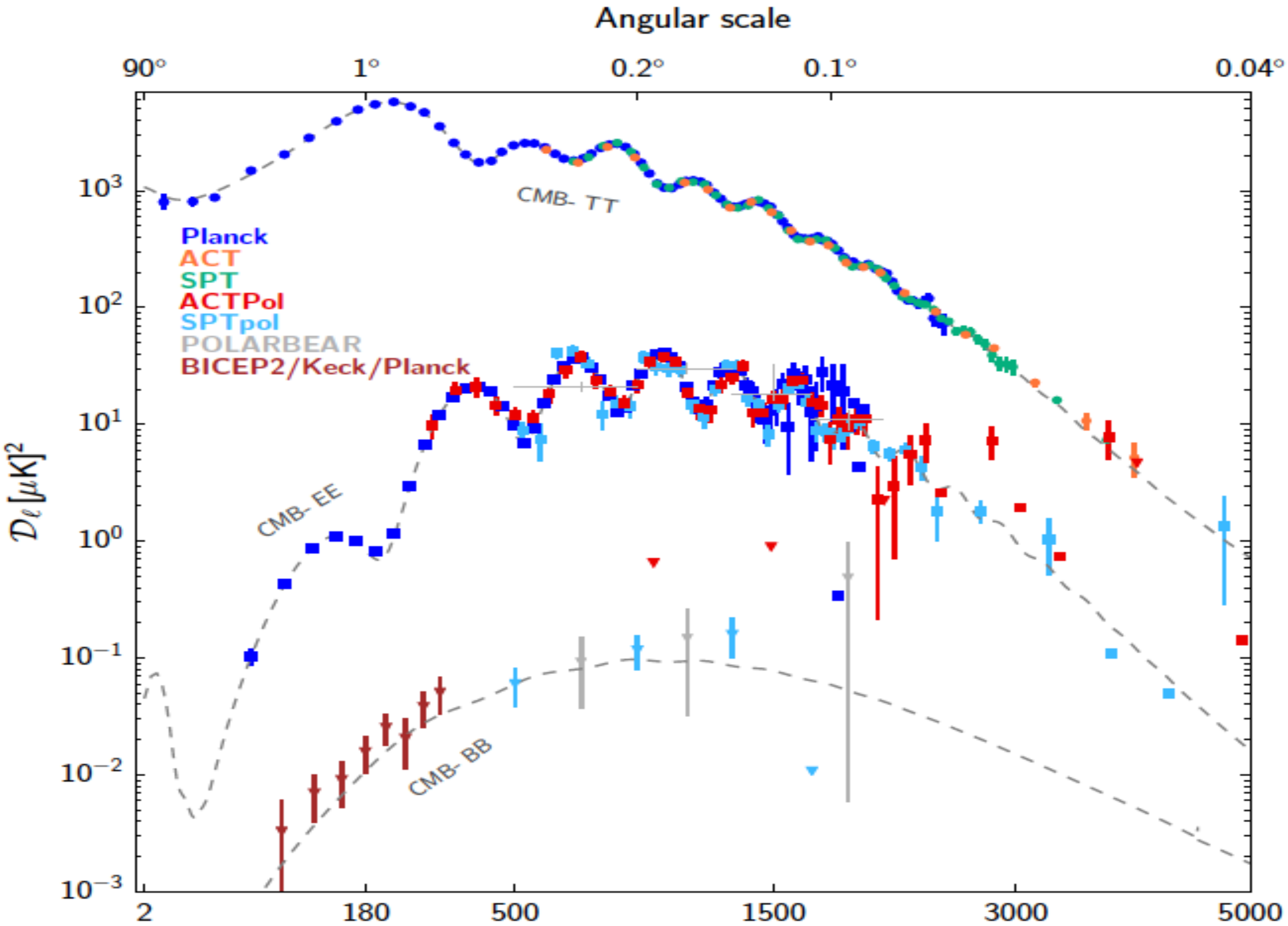


Mission Objectives - What has been measured

Current level:

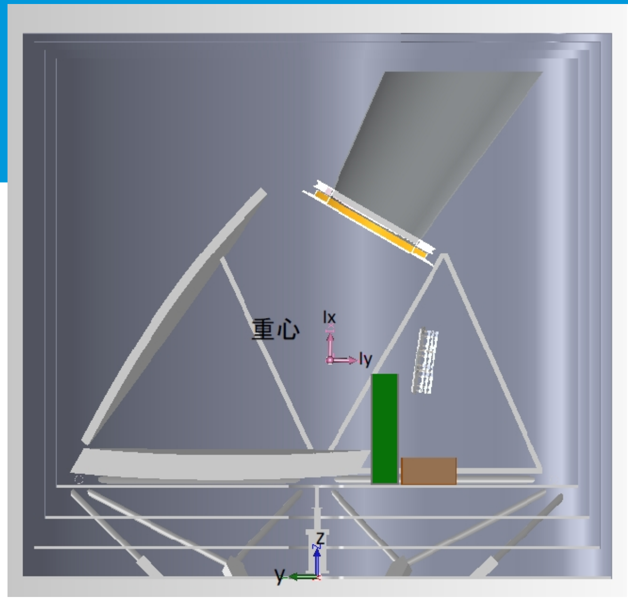
r < 0.07

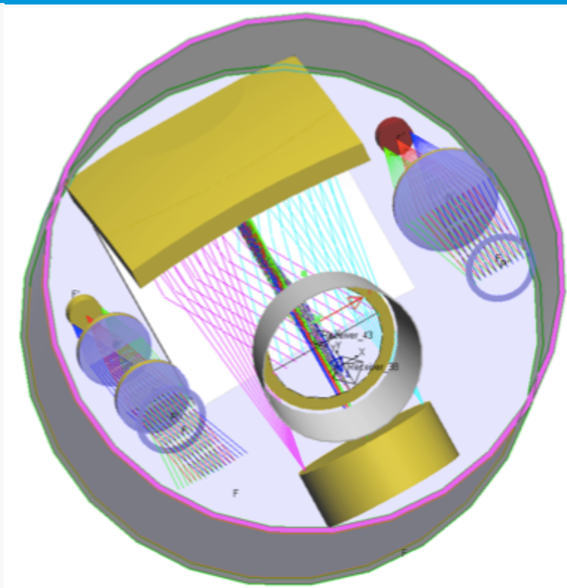
(Bicep2/Keck/ Planck 2016)

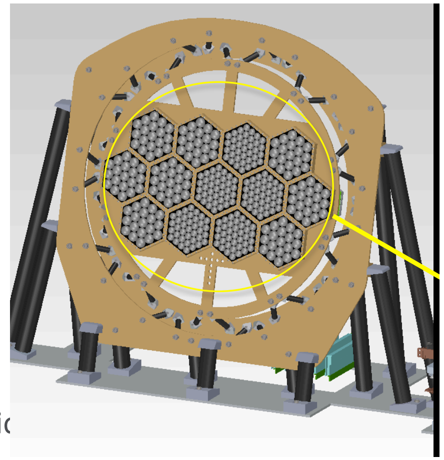


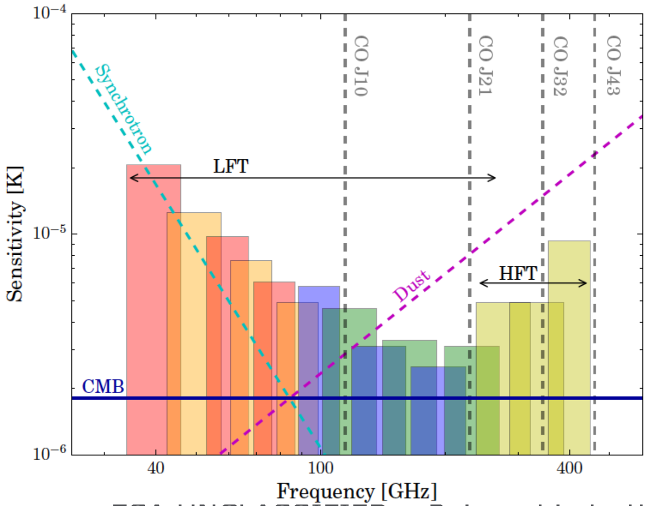
Litebird approach

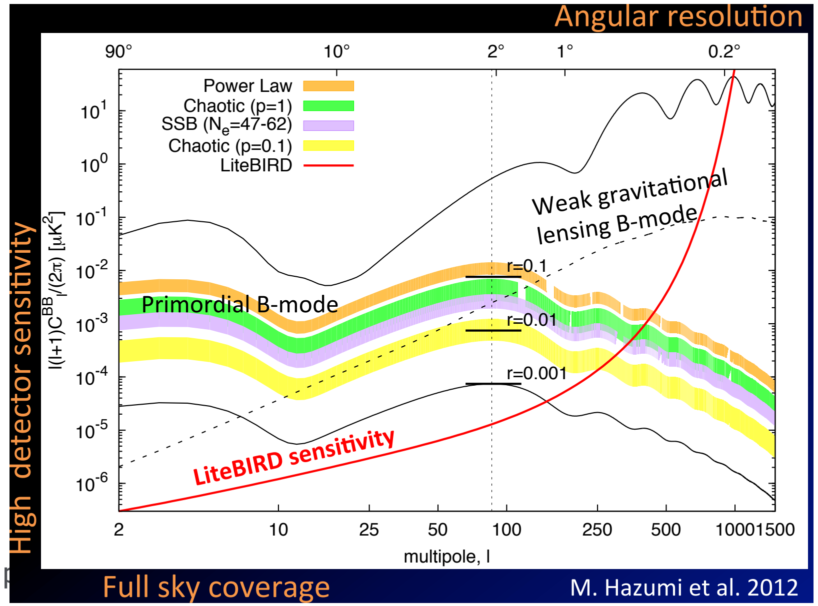
- Sensitivity ~2 μK-arcmin
  - TES or KIDs at 100 mK
- Use of rotating HWP (<50 cm diam) at ~5 K
- Angular resolution ~2°
- Freq range ~40-400 GHz
- 0.1 rpm spinner, 30° precession
- Launch ~2025





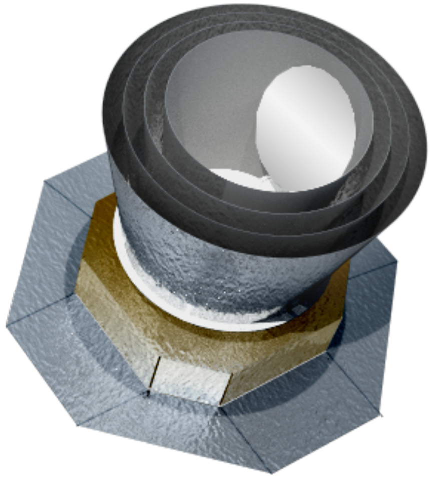


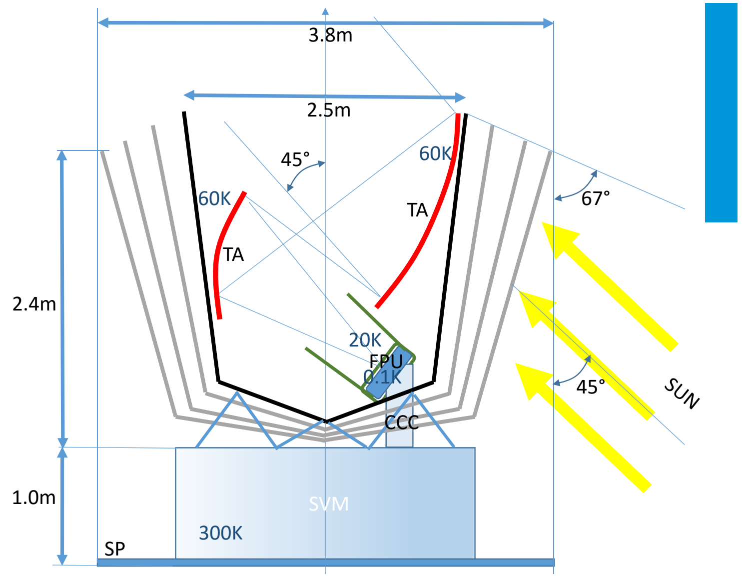


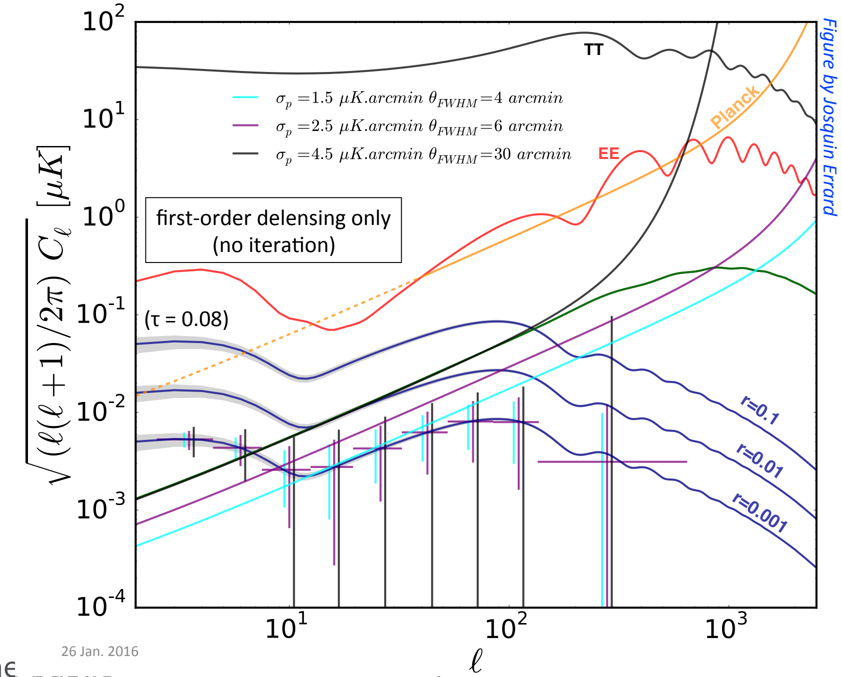


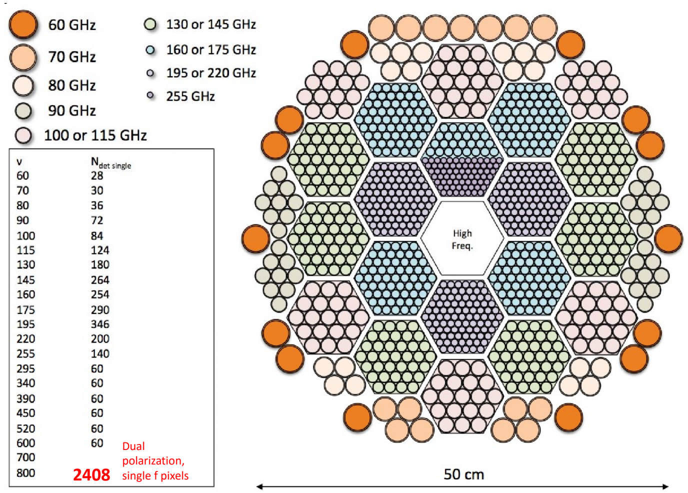
Core+ (M4) approach

- Sensitivity ~2 μK-arcmin
  - TES or KIDs at 100 mK
- No HWP (TBC)
- Angular resolution ~ 6′
  - Science beyond B-modes
- Freq range ~60-600 GHz
- 1 rpm spinner, 45° precession
- Launch >2028 (M5)









ν	$N_{det\ single}$
60	28
70	30
80	36
90	72
100	84
115	124
130	180
145	264
160	254
175	290
195	346
220	200
255	140
295	60
340	60
390	60
450	60
520	60
600	60
700	
800	2408

Dual polarization, single f pixels

CDF baseline

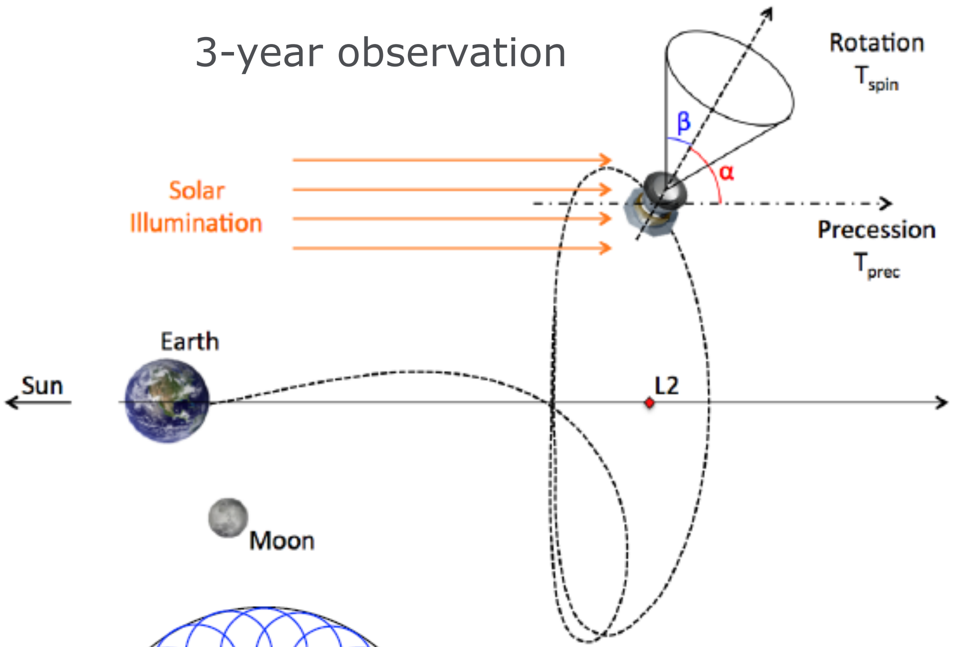
- use of cold HWP in front of telescope is a fundamental difference in Litebird and Core+ designs which is a design driver (e.g. limited angular resolution, frequency range)
  - Neither team convinced of need for HWP
    - resolution must be achieved by realistic simulations w/ and w/out HWP
    - Cannot be done within the timescale of the CDF
- Fundamental requirement of the European team is high angular resolution (aperture > 0.8 m), both for B-mode science and additional science
- it was agreed to study a single configuration with no HWP and an effective aperture ~1.2 m
  - Use prior knowledge as much as possible (Planck, NGCryoIRTel)
  - Assume use of European technology
  - Ignore details of focal plane (treat as "black box")
    - Allowing for reimaging optics inside black box
  - Include a cold baffle to reduce straylight and act as partial cold stop
  - high spin rate (2 rpm) to mitigate low frequency noise

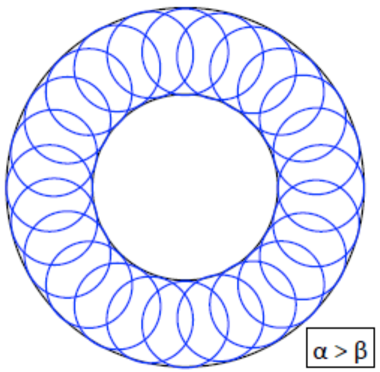
CDF Study

- 5-session study
- Reduced team of specialists covering the critical disciplines
- For other subsystems only system level assessment and reliance on NGCryo design
- Participation from European and Japanese scientists

Mission description

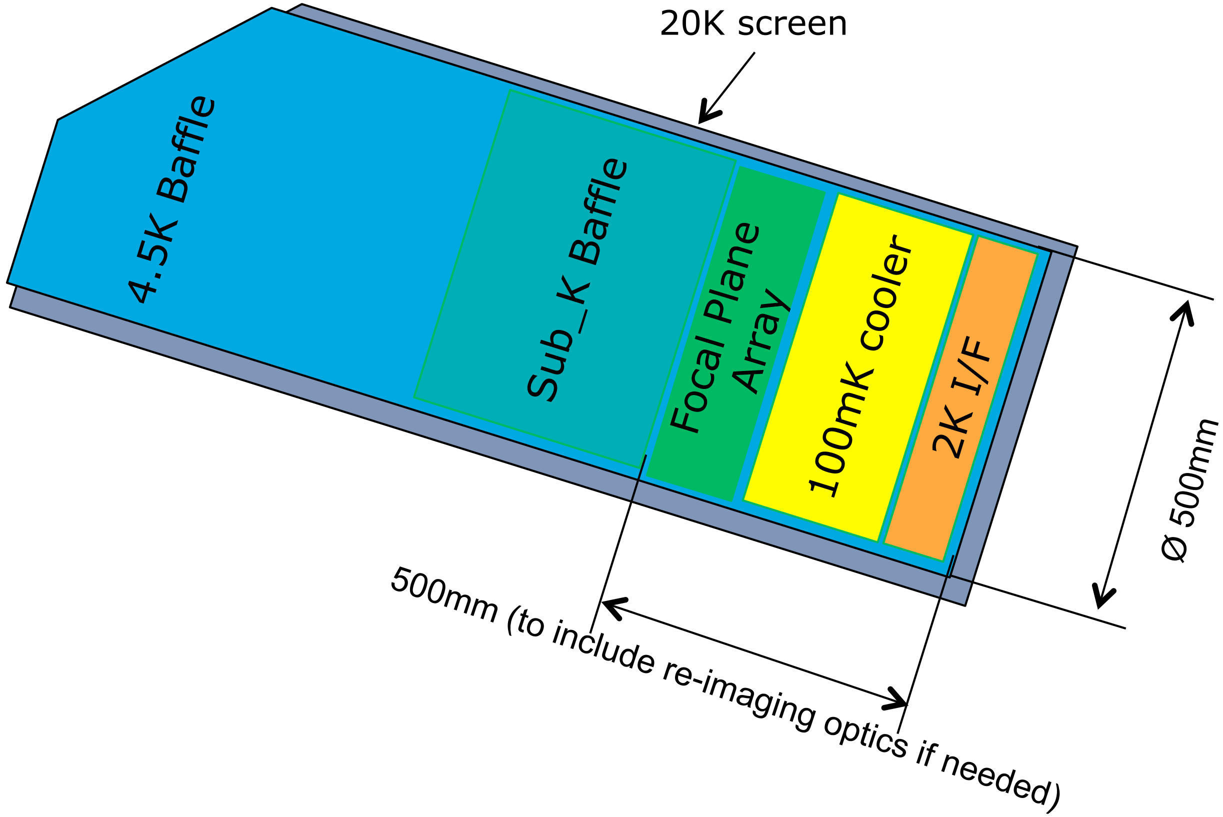
- Orbit: Large amplitude Halo orbit around L2 (like Herschel). No scientific need for a small amplitude Lissajous orbit (like Planck)
- Launch Vehicle:
  - H-II/H-III launcher, sizing for fairing volume (4.6 m Ø X ~4 m h cylindrical part)
  - Ariane 6.2 sizing for mass performance to L2.
- Full sky coverage with scanning law consisting of three combined rotations:
  - Spin @ 2 RPM around axis at β = 45 deg wrto optical axis
  - 4-day Precession of spin axis with α = 50 deg wrto Sun line
  - Daily Sun-SC line rotation





Focal Plane Unit (FPU)

- Assumed as a "black box"
- Ø 550 mm diameter Focal Plane Array assumed sufficient to accommodate enough detectors
- 500 mm height required to accommodate the coolers
- A 4.5K baffle mounted in front of the FPU to open up the possibility to use lenslets or flat arrays instead of a horn based solution
- In addition to a 4.5K I/F, a 2K I/F can be made available for the FPU



Detectors

- Both TES and KIDS technology possible:
- Heat load baseline for the study was a KID filled FPA to limit the number of read-out channels (large multiplexing factors already shown) and to define a reference harness design
- KID's detectors in Europe: TRL 3-4
- Use of cold baffles for straylight control and partially as cold stop (no horns assumed but it may be investigated in the future)

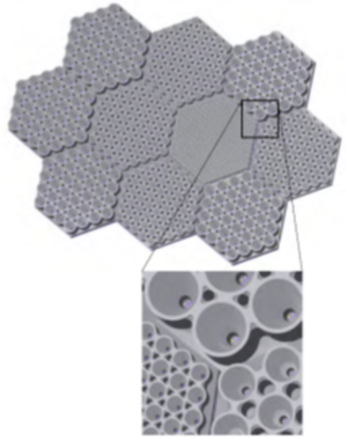


Figure 3. Conceptional design of an MKID focal plane array with direct machined corrugated horn arrays for LiteBIRD

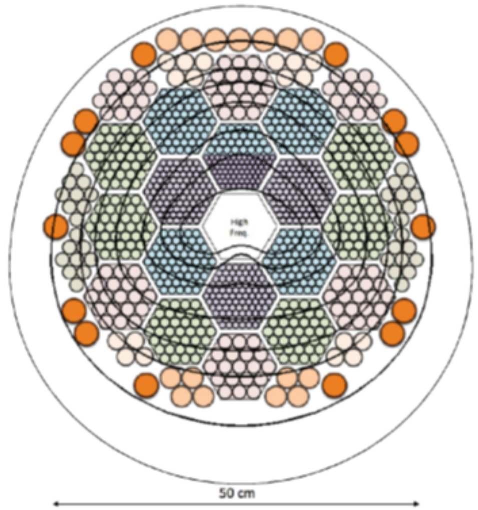
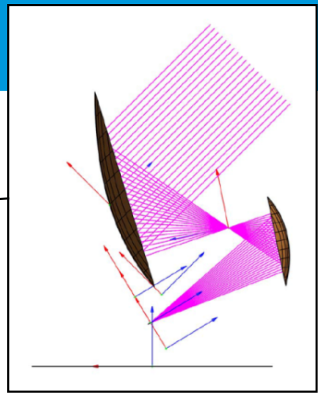


Figure 3: Sketch of the focal plane of COrE+ Light. Contours are Strehl= 0.8 for 60, 90, 130, 160, 220, 340, 450, and 600 GHz. The small colored circles correspond to feedhorns at these frequencies.

Telescope configuration trade-off

Four configurations considered:

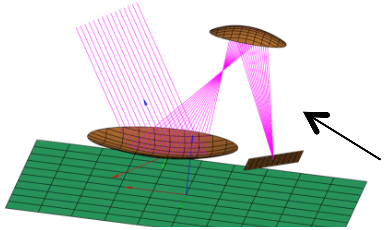
- Gregorian option 1
- Gregorian option 2
- Open Dragone
- Cross-Dragone
  with F~2



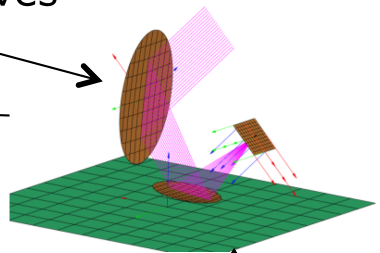
Selected option:

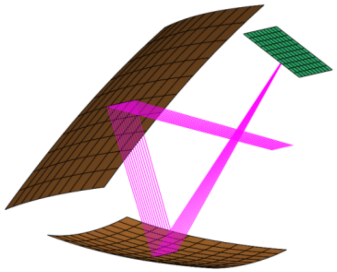
Fits in V-Grooves

and can easily be mounted



Does not fit in V-Grooves





Focal plane too high.

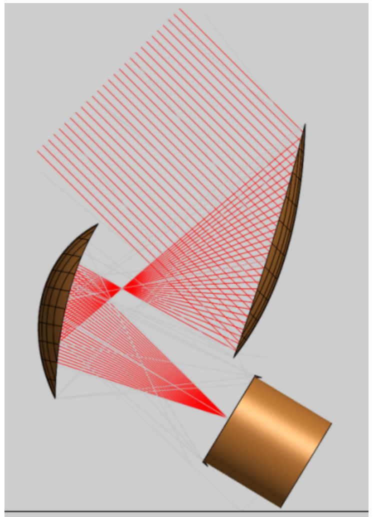
Complex Thermo-Mechanical accommodation

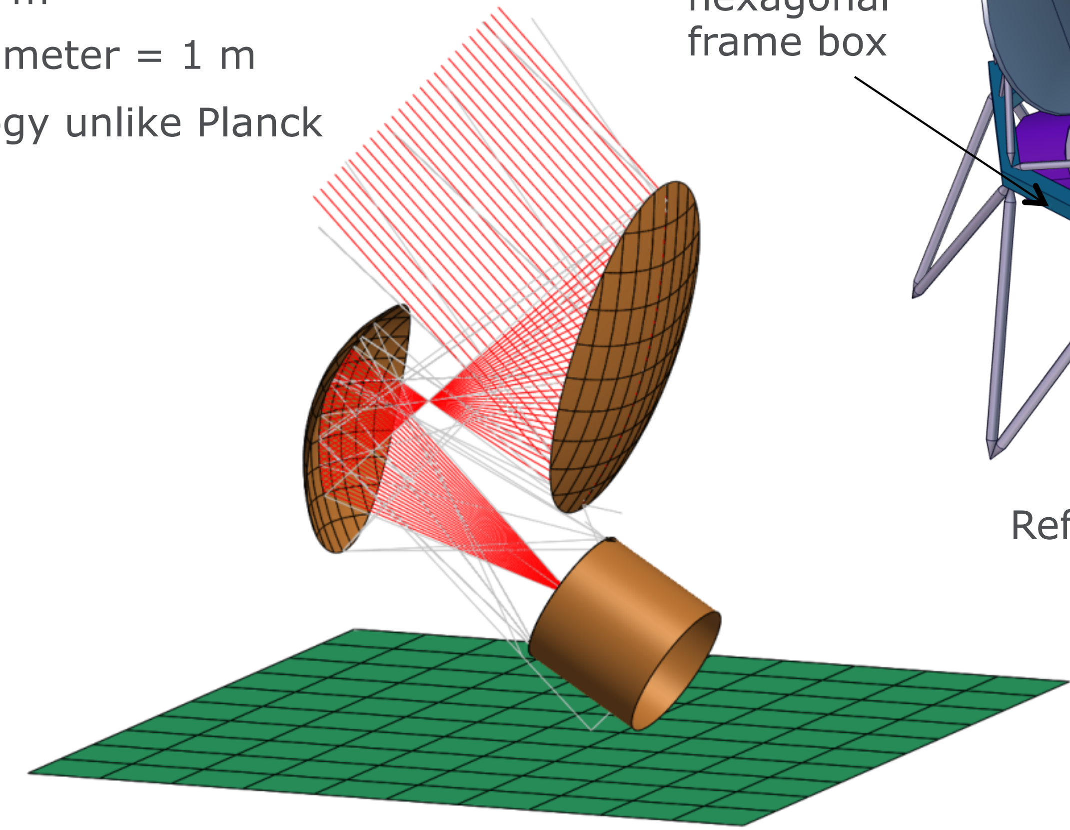
Large secondary mirror

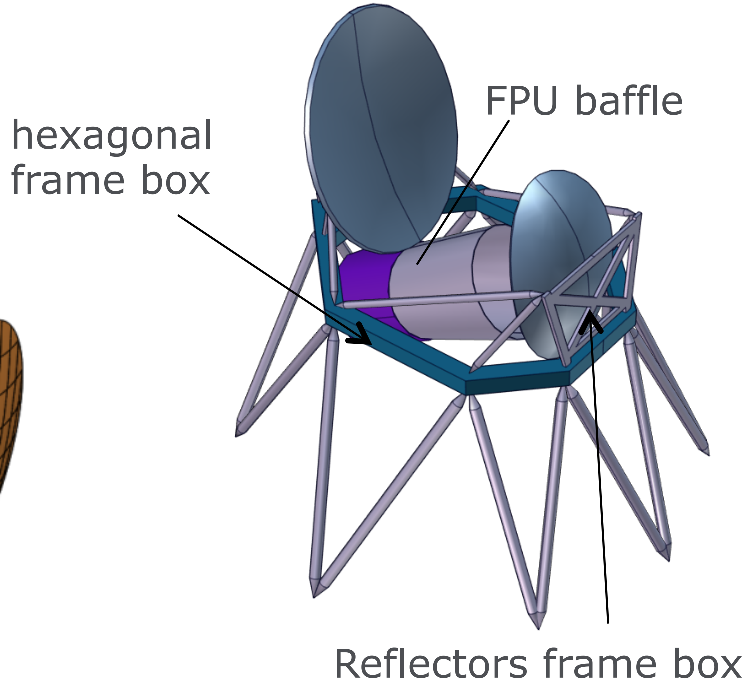
Telescope baseline

Gregorian configuration:

- Aperture =1.2 m - F/D ~ 2.
- Primary Mirror 1.5X1.2 m
- Secondary reflector diameter = 1 m
- Monolithic SiC technology unlike Planck







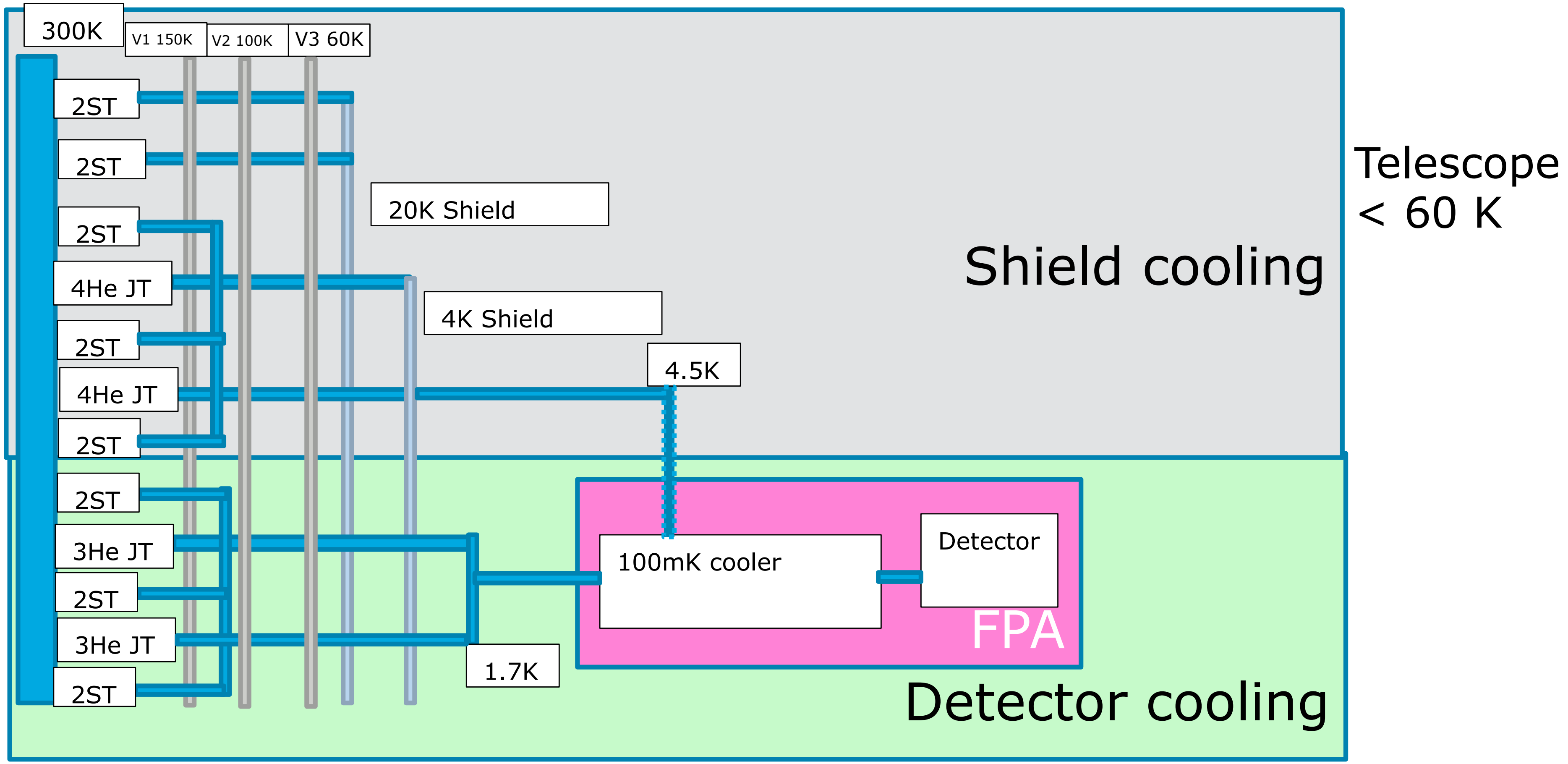
Cryogenic architecture

- Requirements: Detectors at 100mK, ~1µW cooling power at Detector level +
- additional dissipations at intermediate temperature

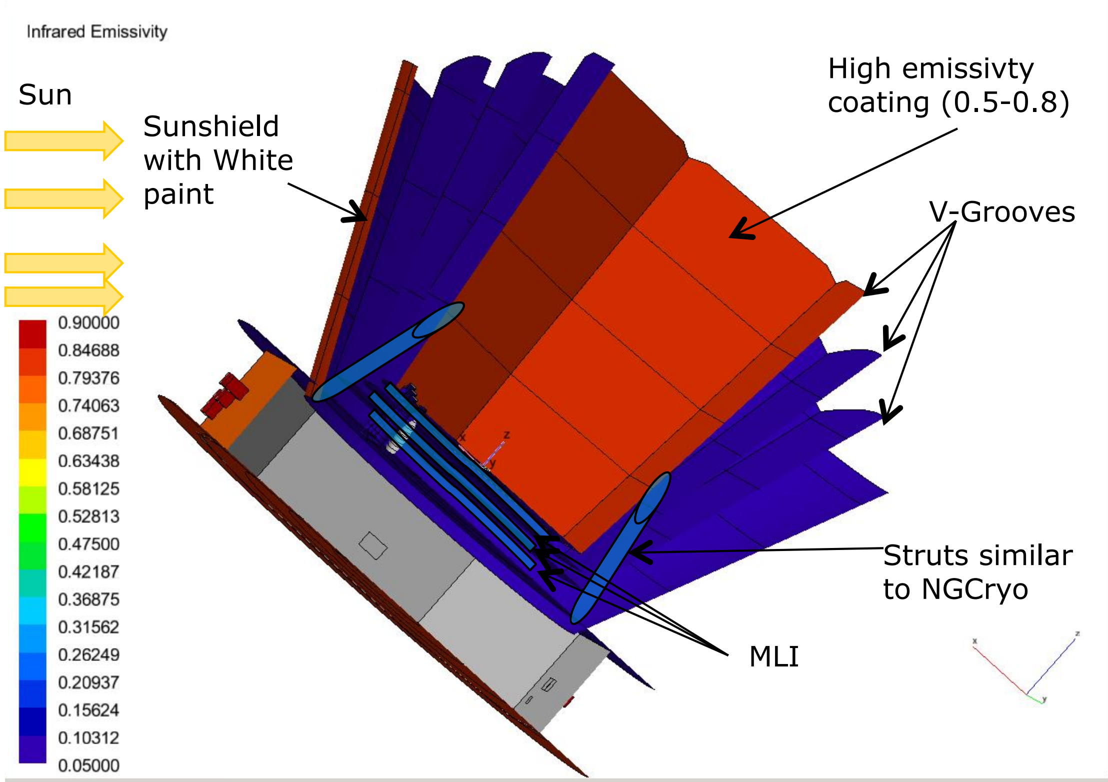
- Focal Plane cooling: 100mK achieved using either CCDR or tandem ADR/ Sorption
  - Requiring 1.7 K and/or 4K pre-cooling using JT coolers
  - JT coolers require in turn pre-cooling between 15-20K
  - 4K shields and 20K shields required to intercept load at higher temperatures and to reduce load at lower temperatures

- Baseline: Telescope @ <60 K by Sun shield + V-grooves Series of shields
- Two additional options studied for the chain down to focal plane:
  1. Passively cooled external shield @150 K + 2 actively cooled shields @80 K and 30 K by Pulse Tube coolers
  2. 100K telescope

Cryogenic architecture – Baseline



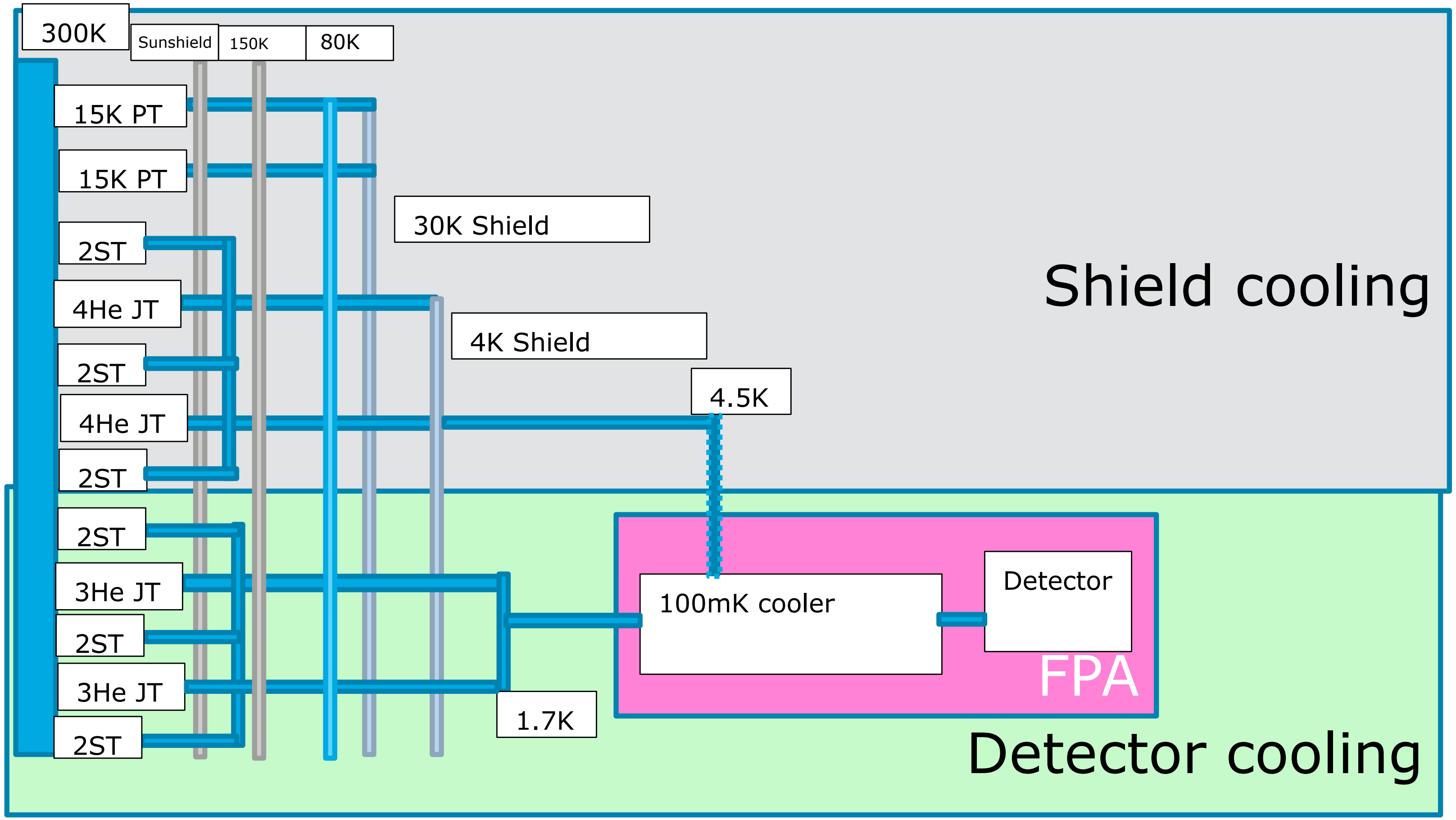
Cryogenic architecture – Baseline



- \+ Payload available volume: ~2m diam / 2m height
- \+ Has more heritage (Planck), predicted V-Groove temp ~45K
- – Requires cryo-testing with Helium shrouds (high cost)

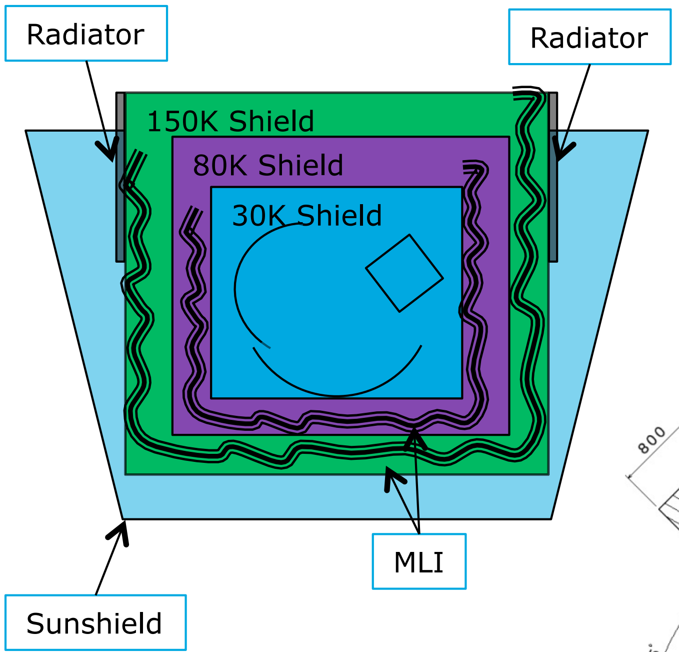
Active cooling looks feasible, but low margins on 4K/2K cooling stages → further optimisation will be required

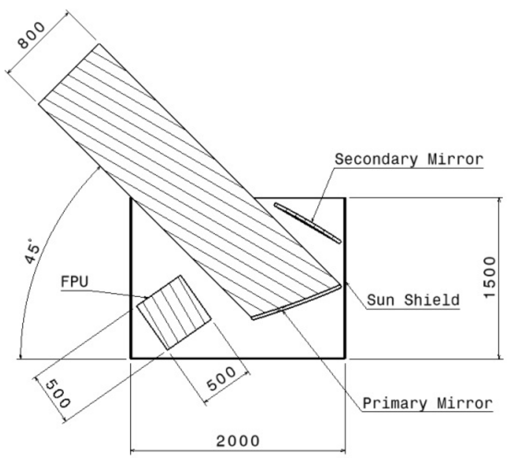
Cryogenic architecture – option 1



Telescope
~ 30 K

Cryogenic architecture – option 1





Cross Dragone Concept

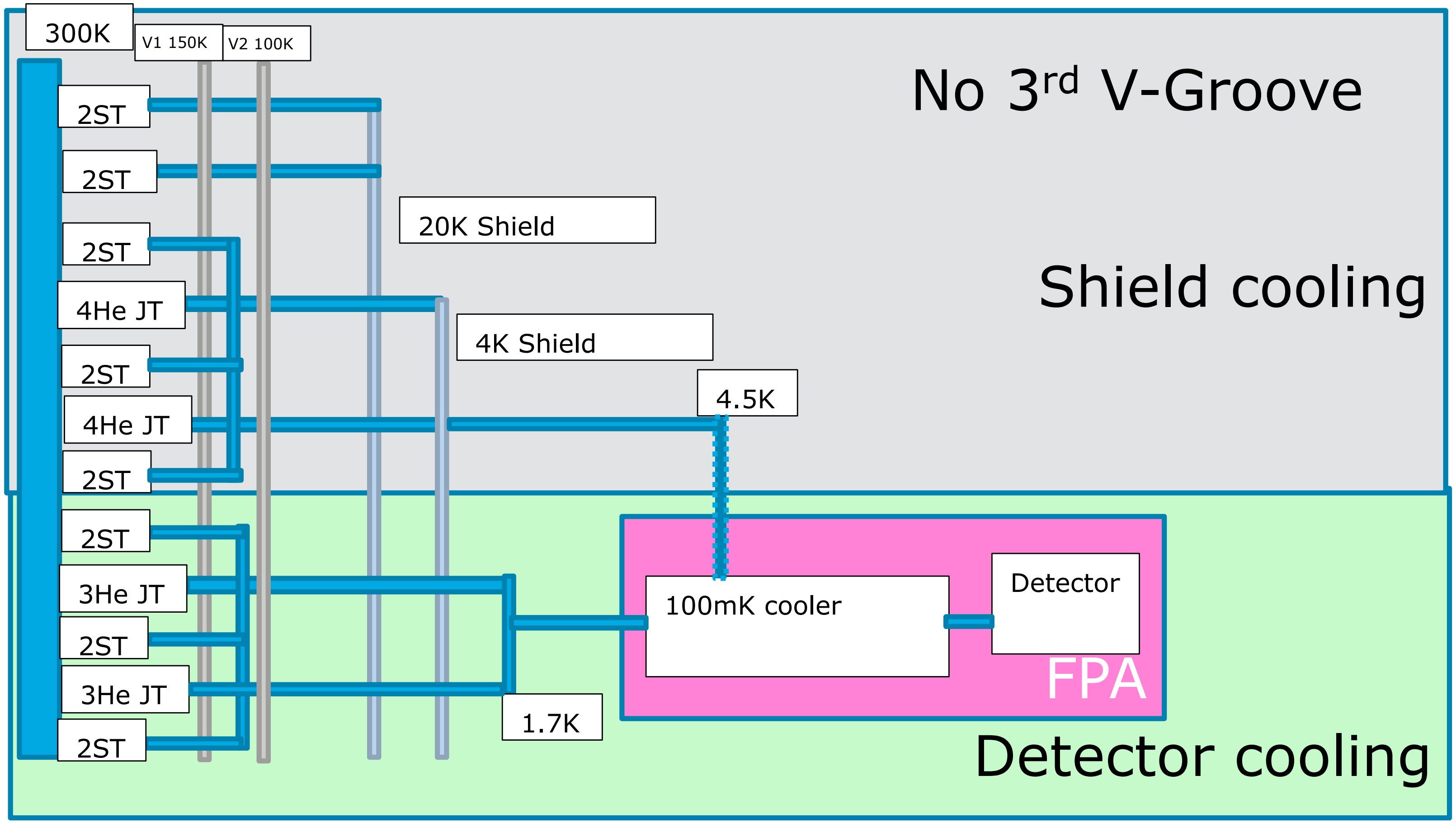
- − Limits Payload available volume to ~2m diam / 1.5 m height

  Max aperture ~ 80 cm
- + Does not Require System level cryo-testing with Helium shrouds
- − Telescope testing @30 K required
- − Requires ~300 W additional cooling power vs option 1
- − Requires dis-connectible support structure

  Relies on 15 K Pulse Tube qualification (ATHENA)

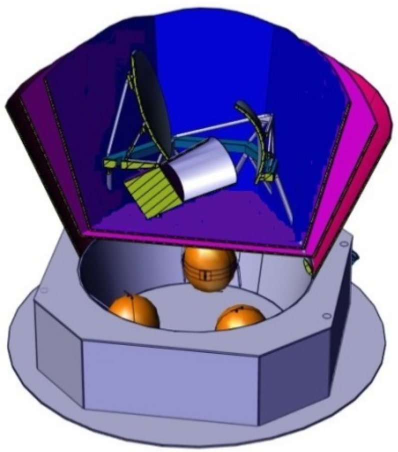
  Cooling power marginal vs heat load; requires optimisation

Cryogenic architecture – option 2



Telescope
~100 K

Cryogenic architecture-option 2



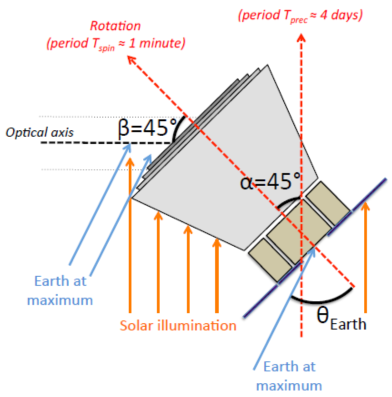
- Two V-grooves, passive cooling down to 100K only ➔

+ No testing required in LHe chamber in CSL (Telescope and System)

– Higher Telescope temperature ➔ higher background

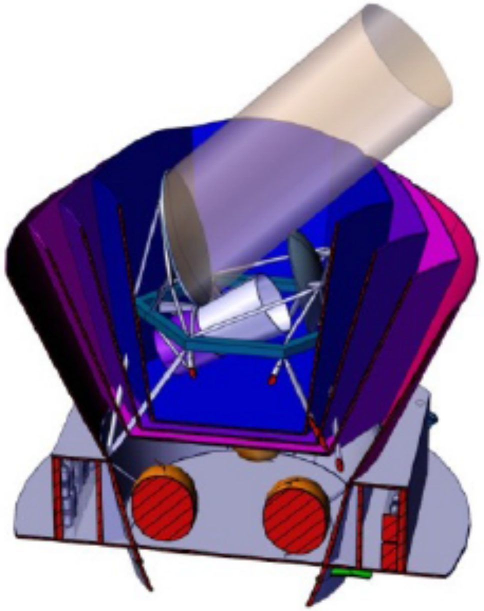
- Load on the active cooling at 20K increased ➔ additional 20K JAXA shield cooler or ESA 15K PT might be required
- Active cooling looks feasible, but still low margins on 4K/2K cooling stages ➔ further optimisation will be required

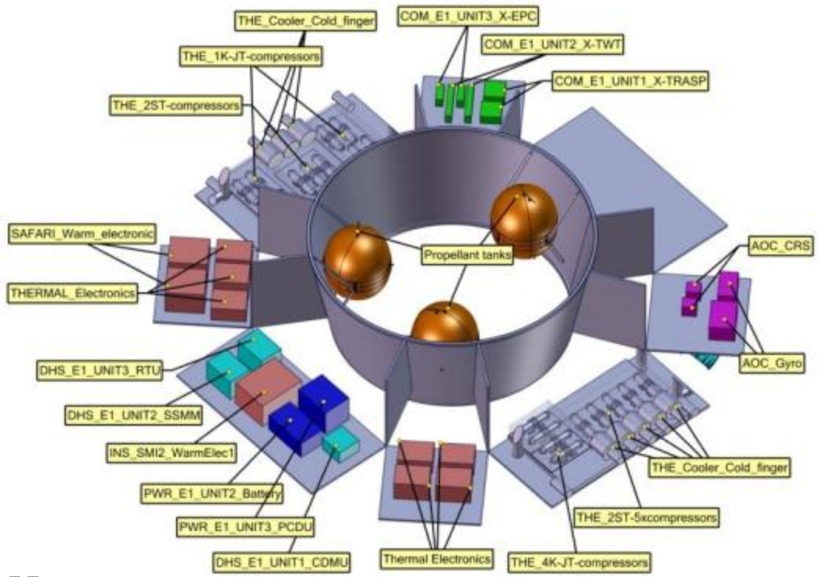
Configuration



Large Earth and Sun aspect angles to cope with

Need of 2360 IF: not standard in Ariane 6





Limited growth potential due to fairing volume limitations

AOCS design

Two options to comply with scanning law:

1. Momentum exchange based - only if 1 RPM spin:

Use of reaction wheel assembly to cancel the spacecraft momentum and to move the spin axis about the precession cone.

- Momentum of the spacecraft about 420 Nms if spin=2 RPM. Very large wheel required (not available). Stack of wheels
- Additionally, four 70 Nms reaction wheels in tetrahedral configuration

2. Thruster based (mandatory above 1 RPM)

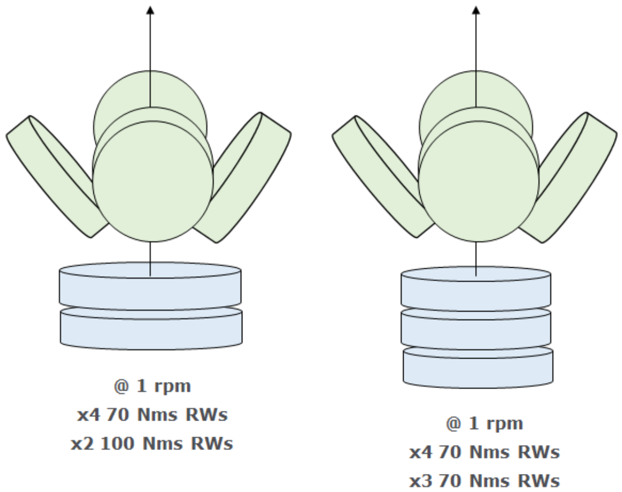
Small and very frequent (every spin period) pulses of about 0.23 N (considering 1 m arm) throughout the whole mission

About 11 500 pulses are needed to achieve 1 complete precession (about 3 200 000 for all mission). Considering that 1-N thrusters are qualified for 375 000 pulses, 10 units are needed to achieve lifetime

Estimated propellant consumption: 250 kg

Very complex system without heritage

A hybrid approach (wheels+thrusters) may also be possible but this has not been studied



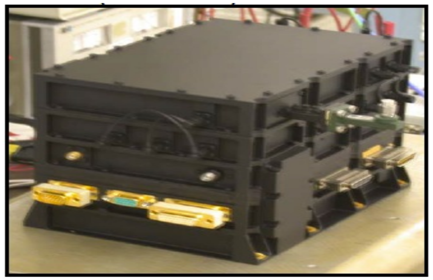
AOCS Performance

- Requirement from science of ~ 1 arcsec (1–sigma) attitude knowledge error
- Simulation has shown that 6 arcsec (3-sigma) could be achieved using gyrostellar estimator technique: combination of Star Tracker @6 arcsec + high accuracy gyro
- Issue: Star tracker (A-STR) able to operate at 12 deg/s (using TDI technique) is out of production. Present high accuracy Star Trackers provide required performance only up to 6-8 deg/sec rate (beyond image smear)
- Need of Star Tracker re-development

STR	STR with TDI
Tracking rate up to 6÷8 deg/s (1 ÷ 1.3 rpm)	Tracking rate up to 60 deg/s (10 rpm)
Accuracy* pitch/yaw (NEA) 71.67 arcsec @ 6 deg/s	Accuracy* pitch/yaw (NEA) 8.76 arcsec @ 6 deg/s 11.57 arcsec @ 12 deg/s
Attitude estimation error* (STR @10 Hz) (gyrostellar estimator) 13.91 arcsec @ 6 deg/s	Attitude estimation error* (STR @10 Hz) (gyrostellar estimator) 2.82 arcsec @ 6 deg/s 3.49 arcsec @ 12 deg/s
Non stringent mounting alignment requirement	Stringent mounting alignment requirement
Available off the shelf	Not available off the shelf (TRL 3÷4 due to need of re-development but flight-proven)

Communication

- Science Data Volume (includes compression of factor 4)
  - Option 1 (O1) (2 RPM): 4.8 [Mbps] → 414.72 [Gbit/day]
  - Option 2 (O2) (1 RPM): 2.4 [Mbps] → 207.36 [Gbit/day]
- Too high for X-band (band limited to 10 MHz), K-band downlink required (as Euclid)
- 4h downlink/day assumed with 35-m Cebreros, data rate ~15 Mbps
- 0.2 m Parabolic K-band HGA
- Mechanical steering required as Electrical steering will imply too high power
- 15 W RF power and TWT-based amplifiers

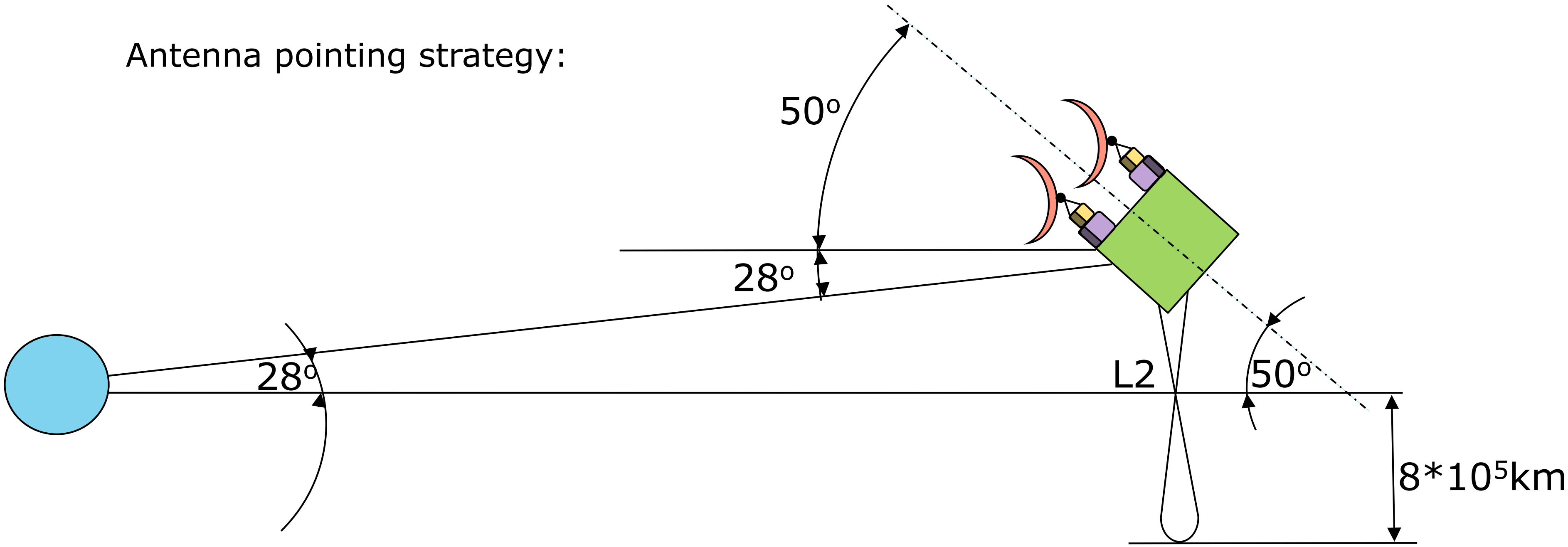


X/X/Ka DS TRSP

K-Band TWT

Antenna Mechanisms

Antenna pointing strategy:



- Rotation range azimuth stage: continuously rotates to de-spin the antenna;
- Rotation range elevation stage: +/-78°.
- Lifecycle (for 2RPM, duty cycle: 4h out of 24h, 3 years): 525600 revolutions;
- Continuous rotation applications require power and signals be carried over the rotating interface, therefore can integrate pointing mechanisms with slip ring;
- Requires specific development

Service Module

- Planck heritage but with significant modifications:
  - Bottom-mounted Solar array not sufficient given the large Sun aspect angle: additional deployable solar panels required
  - AOCS requires specific angular momentum management strategy and Technology developments
  - Specific antenna pointing mechanism to be developed
  - TT&C: heritage from Euclid

S/C Mass Budget		Mass [kg]
Dry Mass PLM		**372.91**
Dry Mass SVM		**1151.51**
System Margin	20%	304.88
Dry Mass incl. System Margin		**1829.30**
CPROP Propellant Mass		318.00
CPROP Propellant Margin	2%	6.36
CPROP Pressurant Mass		5.20
CPROP Pressurant Margin	2%	0.10
Total Wet Mass		**2158.97**

Power (W)	P_mean
PLM (Payload Module)	**0.00**
SVM (Service Module)	**1931.26**
AOGNC	37.50
COM	39.96
CPROP	1.00
DH	80.80
INS	222.00
MEC	15.00
TC	1535.00
Grand Total	**1931.26**

Summary

AIV/T and schedule

Protoflight approach but with specific qualification models:

- Cryogenic Qualification Model (CQM) (@CSL)
  - P/L QM, with a full structure (as for Planck), SVM dummy with fittings for the PLM coolers and "PLM warm units‟, to be used for the cryogenic test qualifying the chain of cryo stages
- SVM Avionics Model (AVM)
- Optical QM (refurbished CQM) (assumed @CSL but required space may be an issue) Mirror models:
  - QM, SM and FM: QM for the CQM and then the Optical QM
- Videogrammetry test with PFM PLM and QM mirrors (tbc)
- Spin test
- Implementation Phase: ~6 years+ margin from B2/C/D KO (~end 2021 in current M5 plan)
- Instrument QM shall be ready 4 years in advance of launch
- P/L PFM on the critical path as it starts only after CQM is finished

Cost

- The costs of the mission is above the limit of a M-class mission, requiring either:
  - Substantial contribution from the member states
  - International cooperation
- Cost/risk reduction could be achieved by :

1. Reducing spin rate to 1 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
   - Avoids use of He shrouds test chamber
   - Smaller/warmer telescope

Criticalities

Mission drivers:

- Large precession: large Sun aspect angle more complex cryo-architecture, additional solar panels, complex TT&C, complex AOCS,
- Cryogenic cooling FPU @100 mK, only free design parameter is Telescope temperature
- 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

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)
- Alternative design (cryo-option 1)
  - Actively cooled shields
  - Aperture <0.8 m
  - Not studied at same level of detail. Cost savings uncertain