The Spanish Contribution to the Medium and High Frequency Telescopes (MHFT) of LiteBIRD

Temperature Monitoring and Control System (TMCS) for the 5 to 0.1 K cryogenic stages

F. J. Casas on Behalf of the Spanish LiteBIRD Collaboration

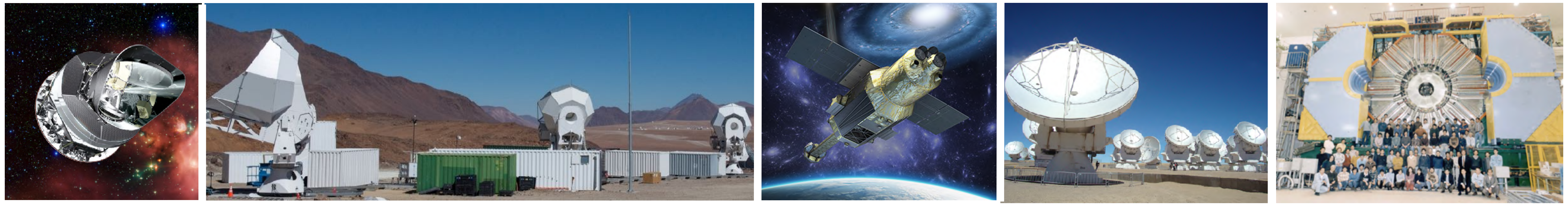
Summary

- LiteBIRD Space Mission
  - Mission overview: JSGs, and *B*-modes
  - Spacecraft and scanning strategy
  - Telescopes and focal planes
  - Cryogenic system
  - Spanish community and contribution
- TMCS: The Spanish Contribution
  - Purpose of the TMCS
  - Activities and participants
  - Resources (funding, people and technical)
  - Thermal noise budget
  - Thermal modelling and stability
  - Architecture and technical budget
  - Cryogenic infrastructure application
- Additional slide: IFCA refrigerator DM applications

LiteBIRD Joint Study Group

Over 400 researchers from **Japan**, **North America** and **Europe**

Team experience in CMB experiments, X-ray satellites and other large projects (ALMA, HEP experiments, …)

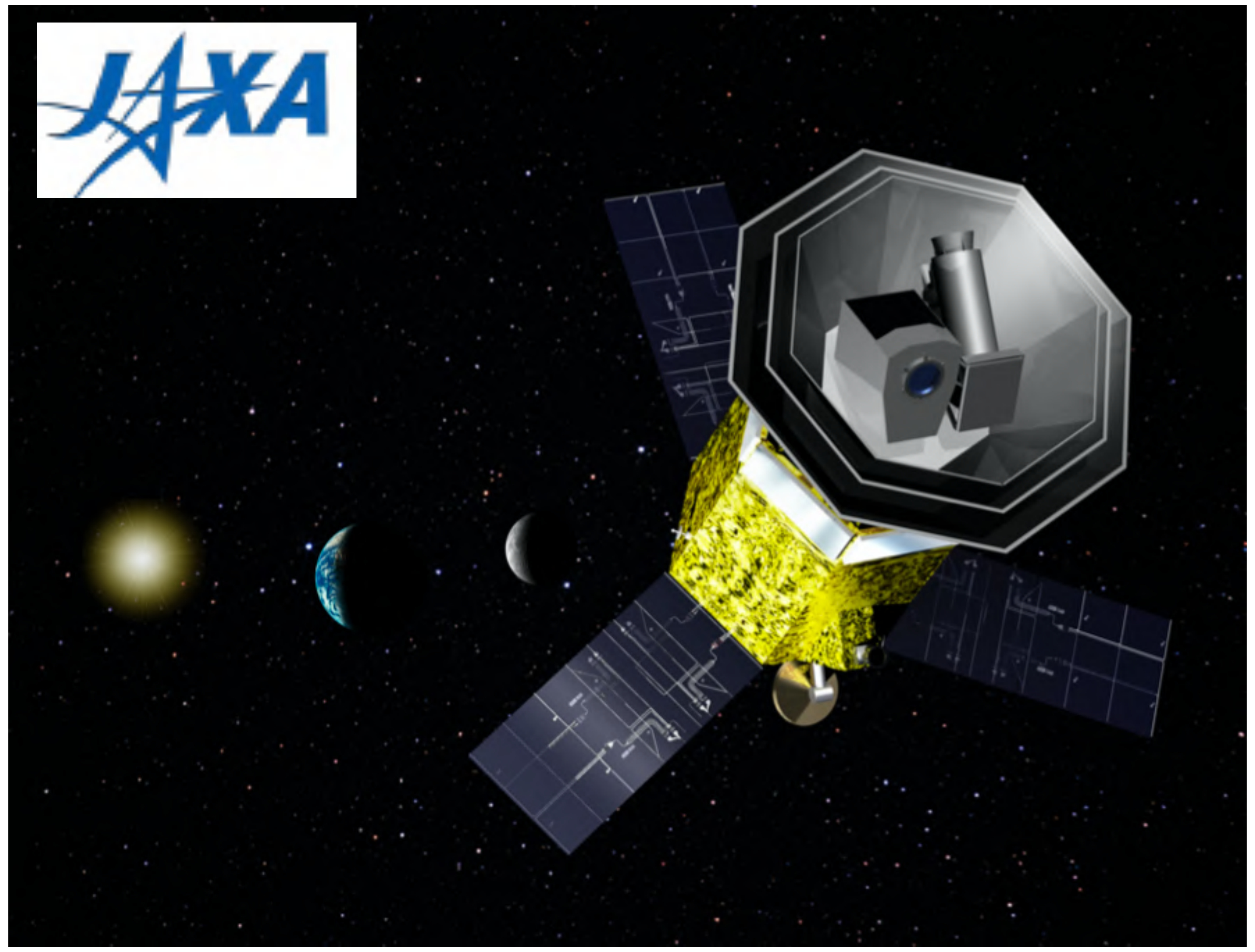


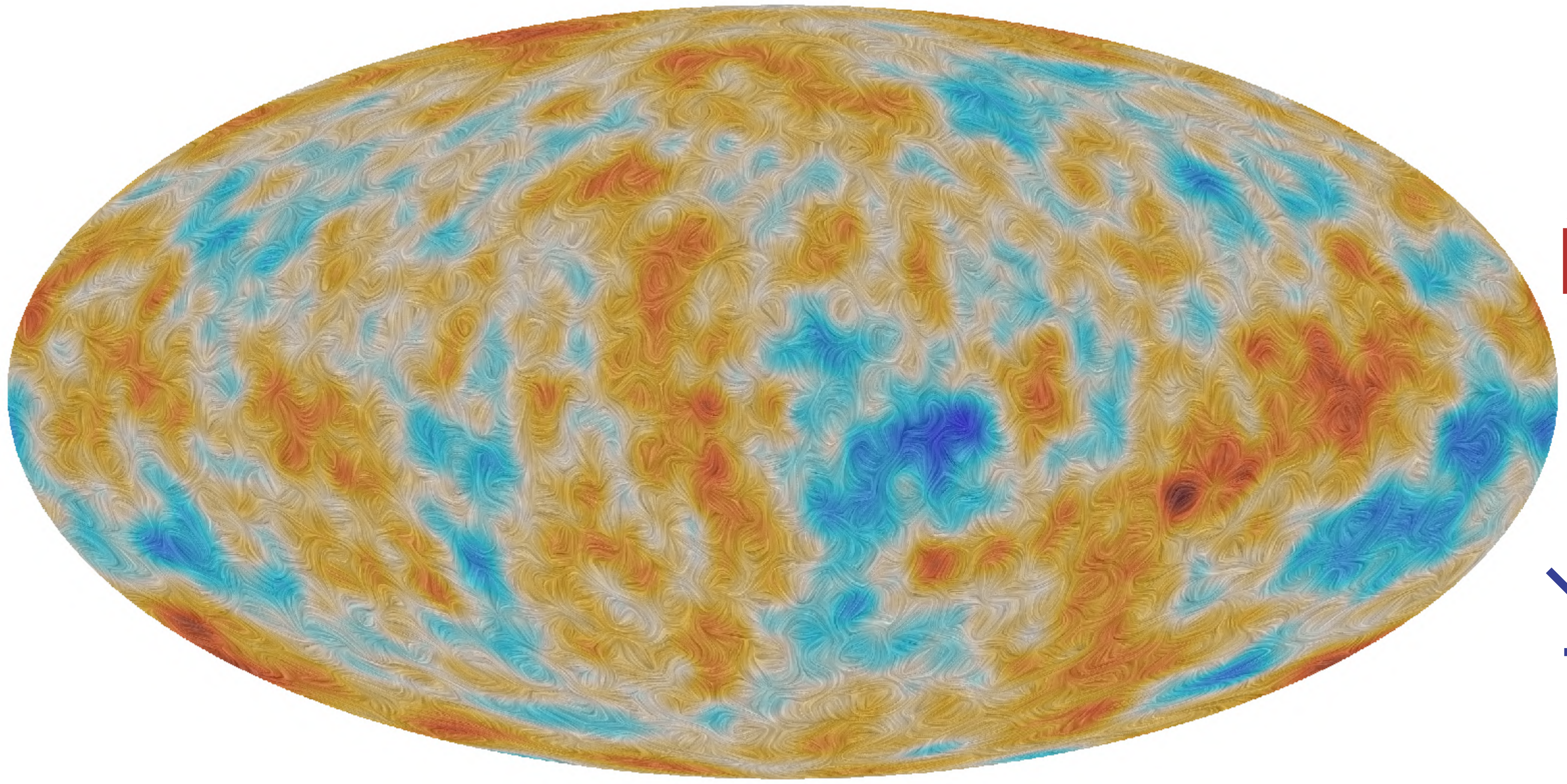
LiteBIRD Global F2F meeting
Sep 28 - Oct 1, 2023 at Elba

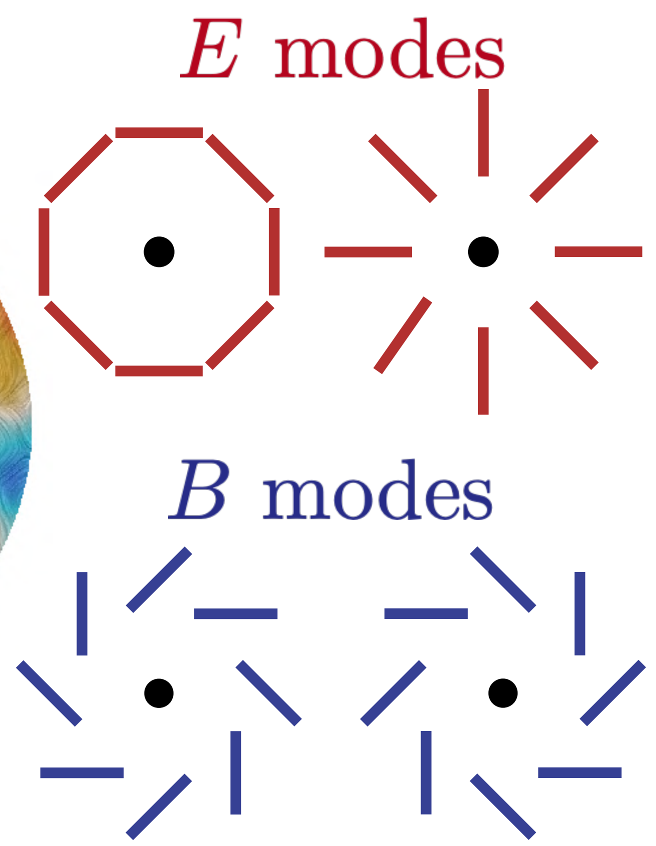
LiteBIRD overview

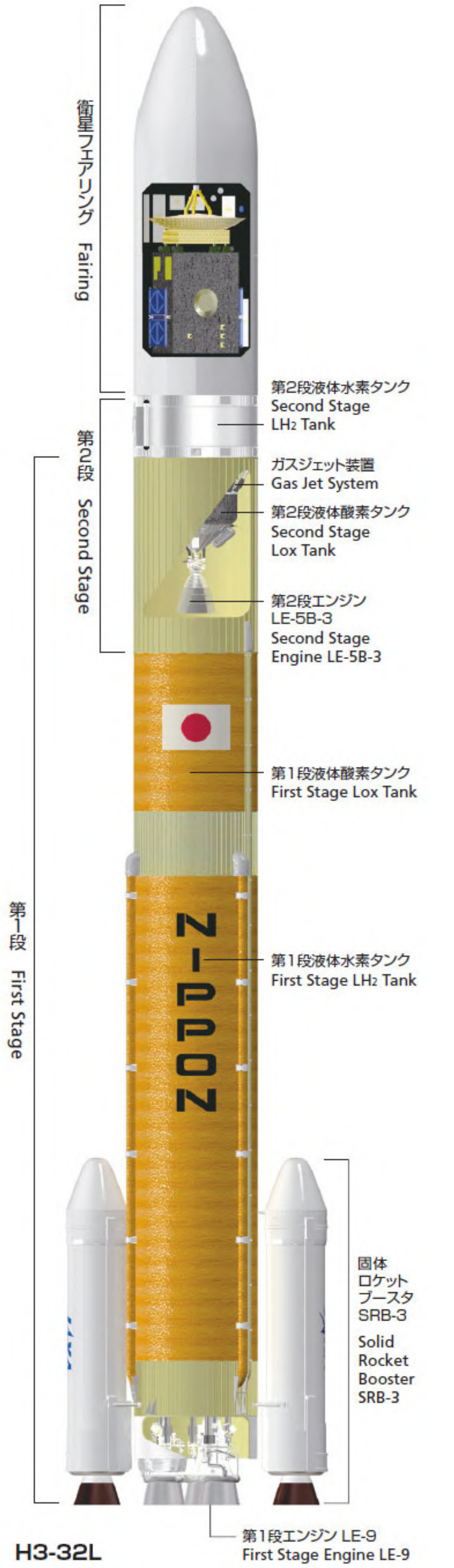
📖 LiteBIRD collaboration PTEP 2023

- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in **JFY 2032** with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**









The challenge of B-modes detection

- The *B*-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- The inflationary (i.e. primordial) B-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: r < 0.032 (95% C.L.) (📖 Tristram et al. 2022, combining BK18 and Planck PR4)
- LiteBIRD is targeting a sensitivity level in polarization ~30 times better than Planck (*r* improvement by a factor ~50)
- Needs exquisite control of:
  1. **Instrument systematic** uncertainties
  2. **Galactic foreground** contamination
  3. **"Lensing B-mode signal"** induced by gravitational lensing
  4. Observer biases

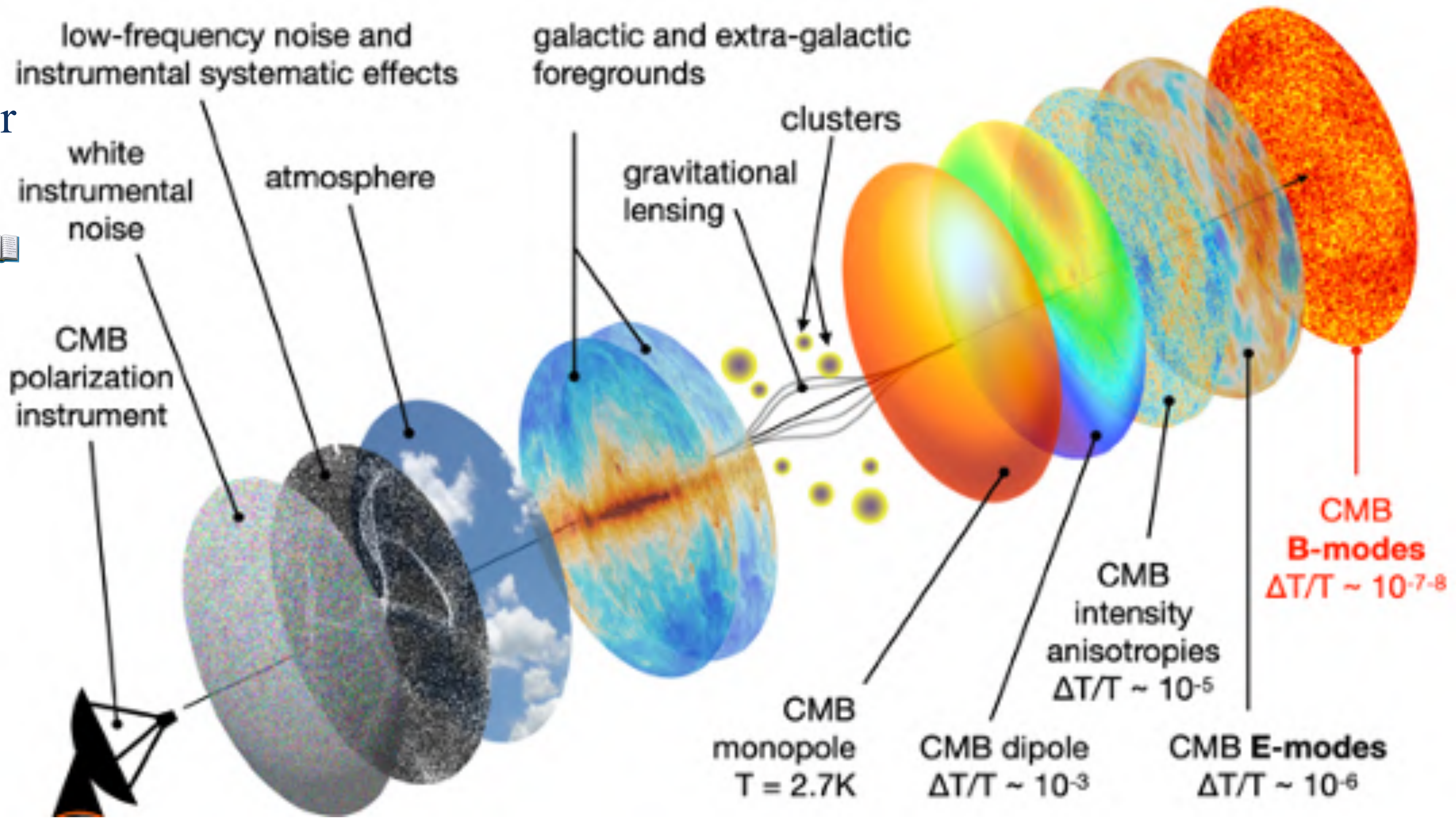
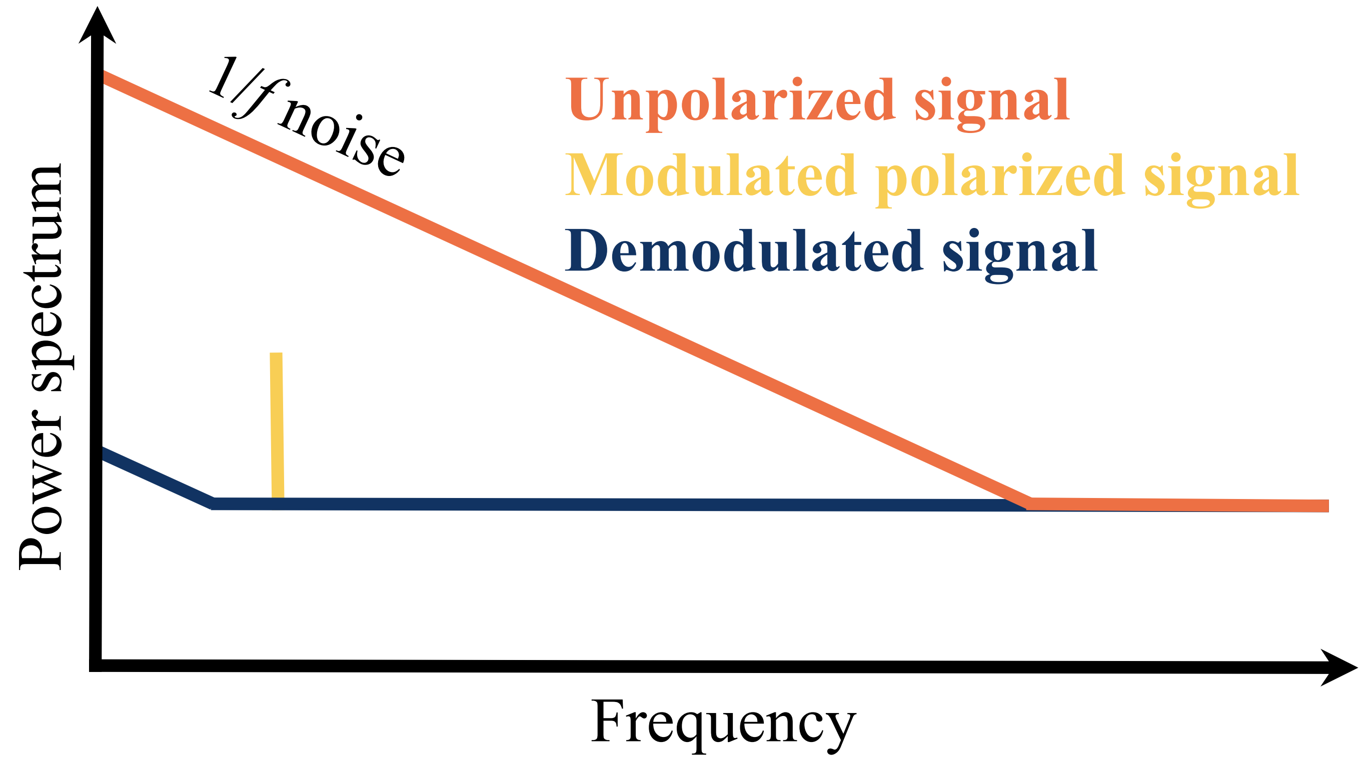


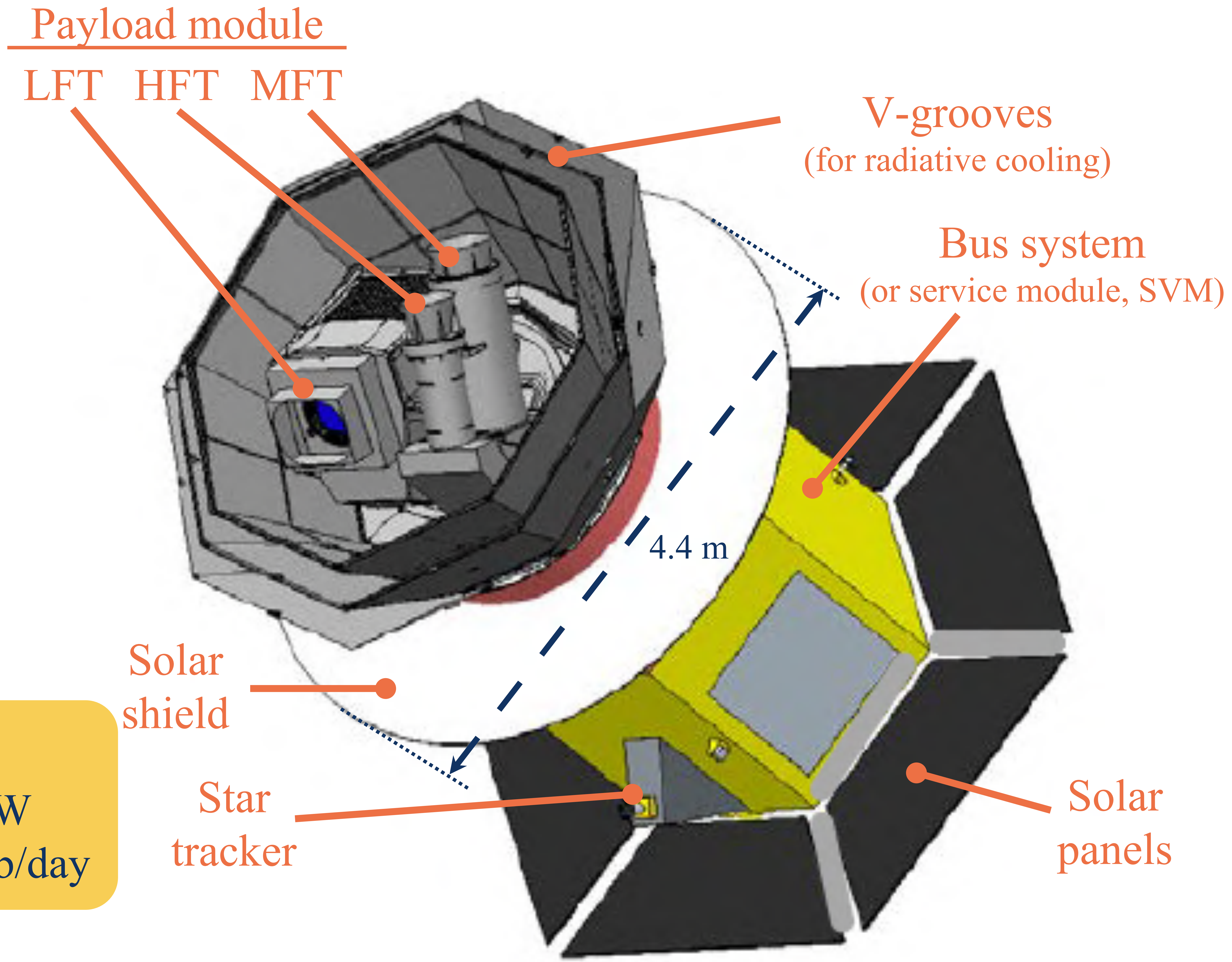
Image credit: Josquin Errard

LiteBIRD spacecraft overview

- **3 telescopes** are used to provide the **40-402 GHz** frequency coverage
  1. **LFT** (low frequency telescope)
  2. **MFT** (middle frequency telescope)
  3. **HFT** (high frequency telescope)
- Multi-chroic transition-edge sensor (TES) **bolometer arrays** cooled to **100 mK**
- Optics cooled to **5 K**
- Polarization modulation unit (PMU) in each telescope with **rotating half-wave plate** (HWP), for $1/f$ noise and systematics reduction

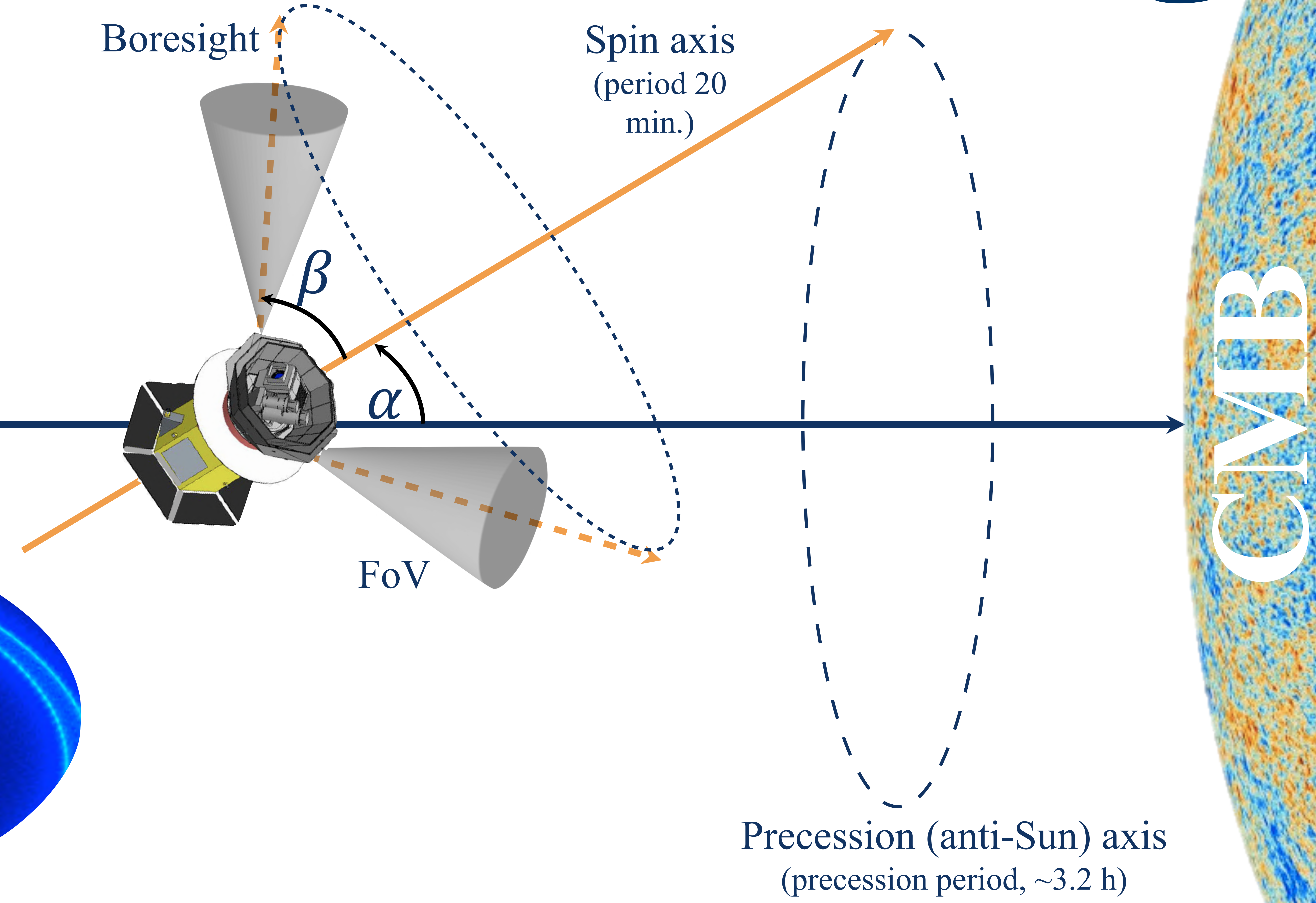


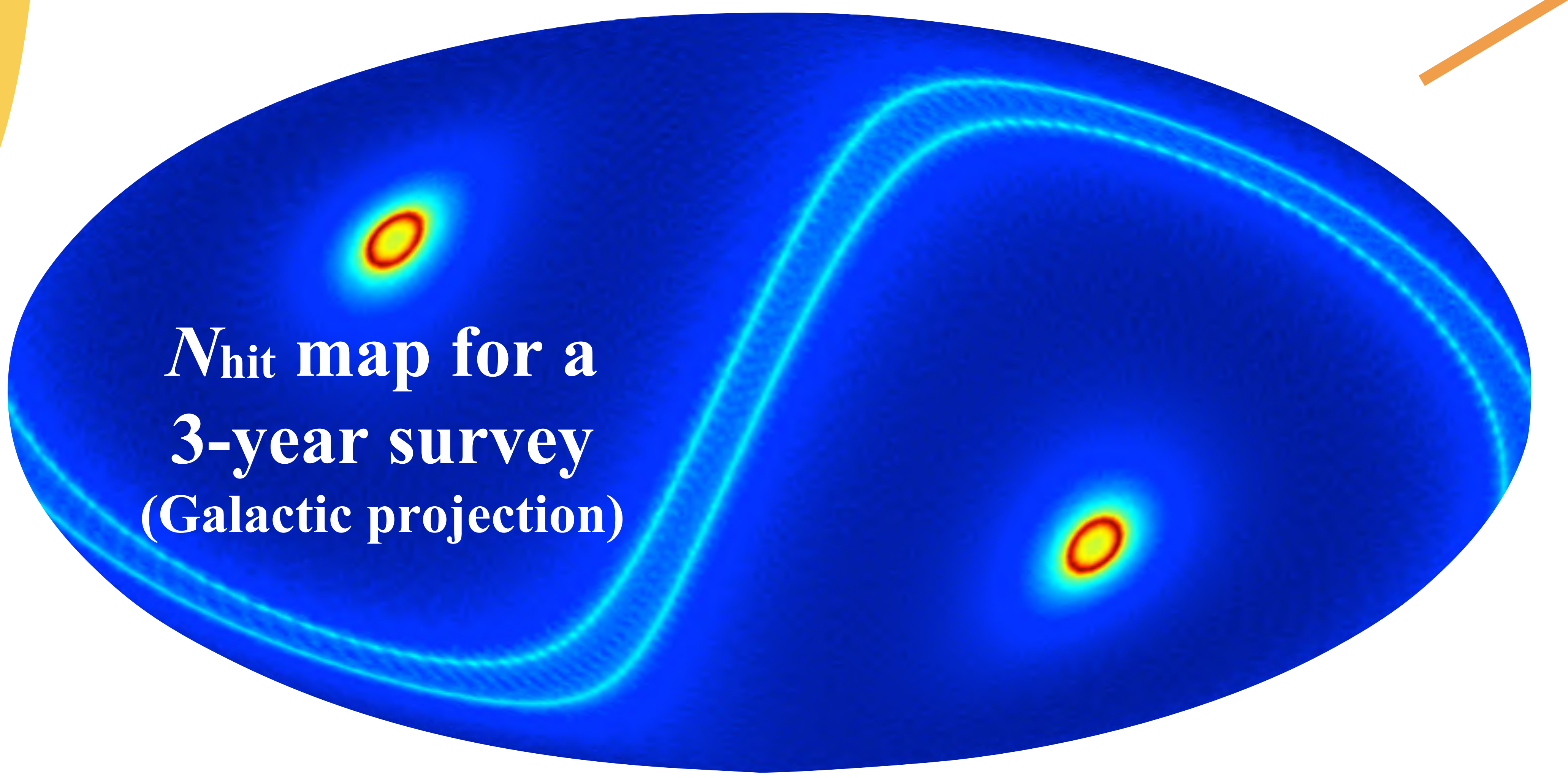
- Mass: 2.6 t
- Power: 3.0 kW
- Data: 17.9 Gb/day



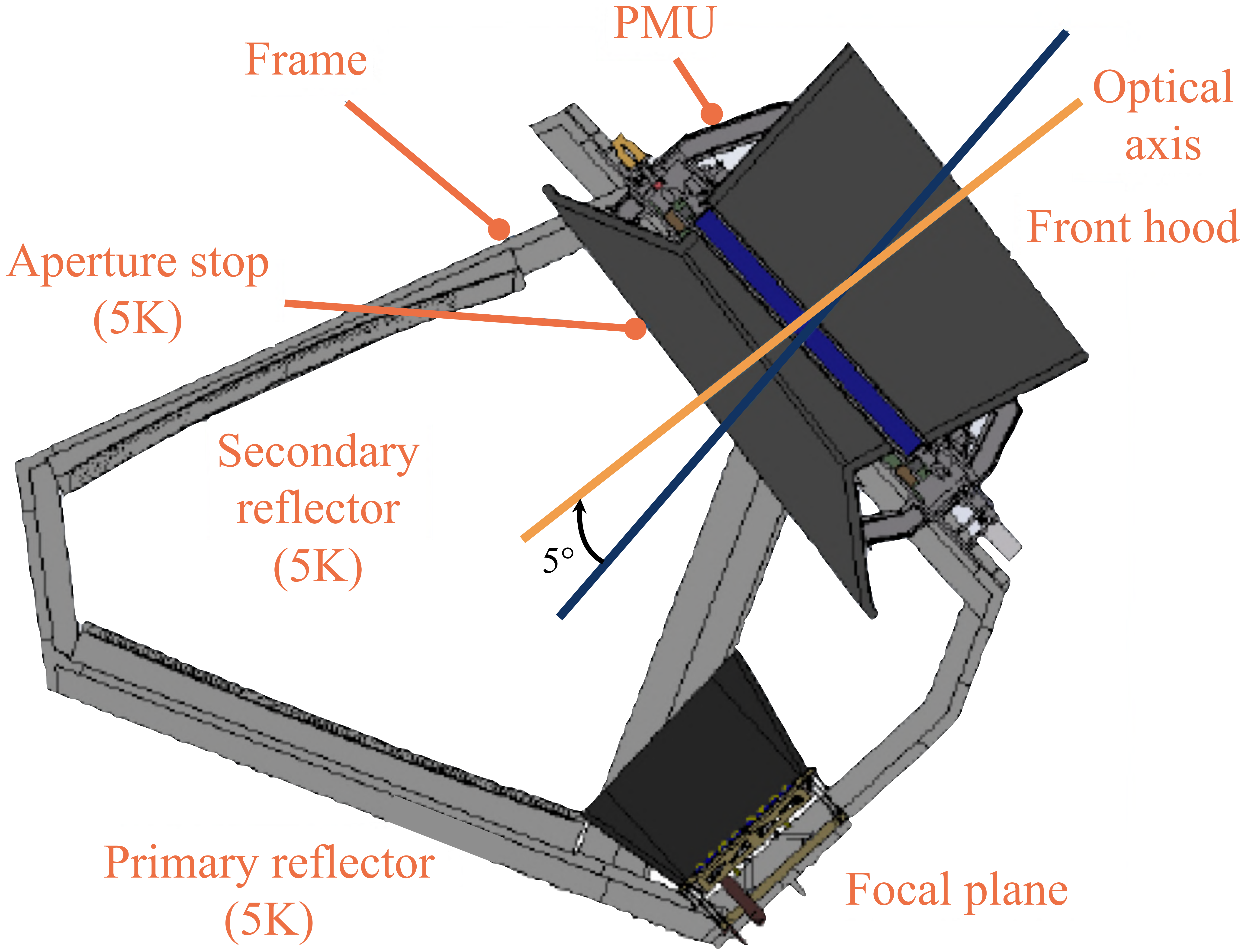
LiteBIRD scanning strategy

- 3-year survey, Sun-Earth L2 Lissajous orbit
- Precession angle: $\alpha = 45°$
- Spin angle: $\beta = 50°$





Low Frequency Telescope (LFT)



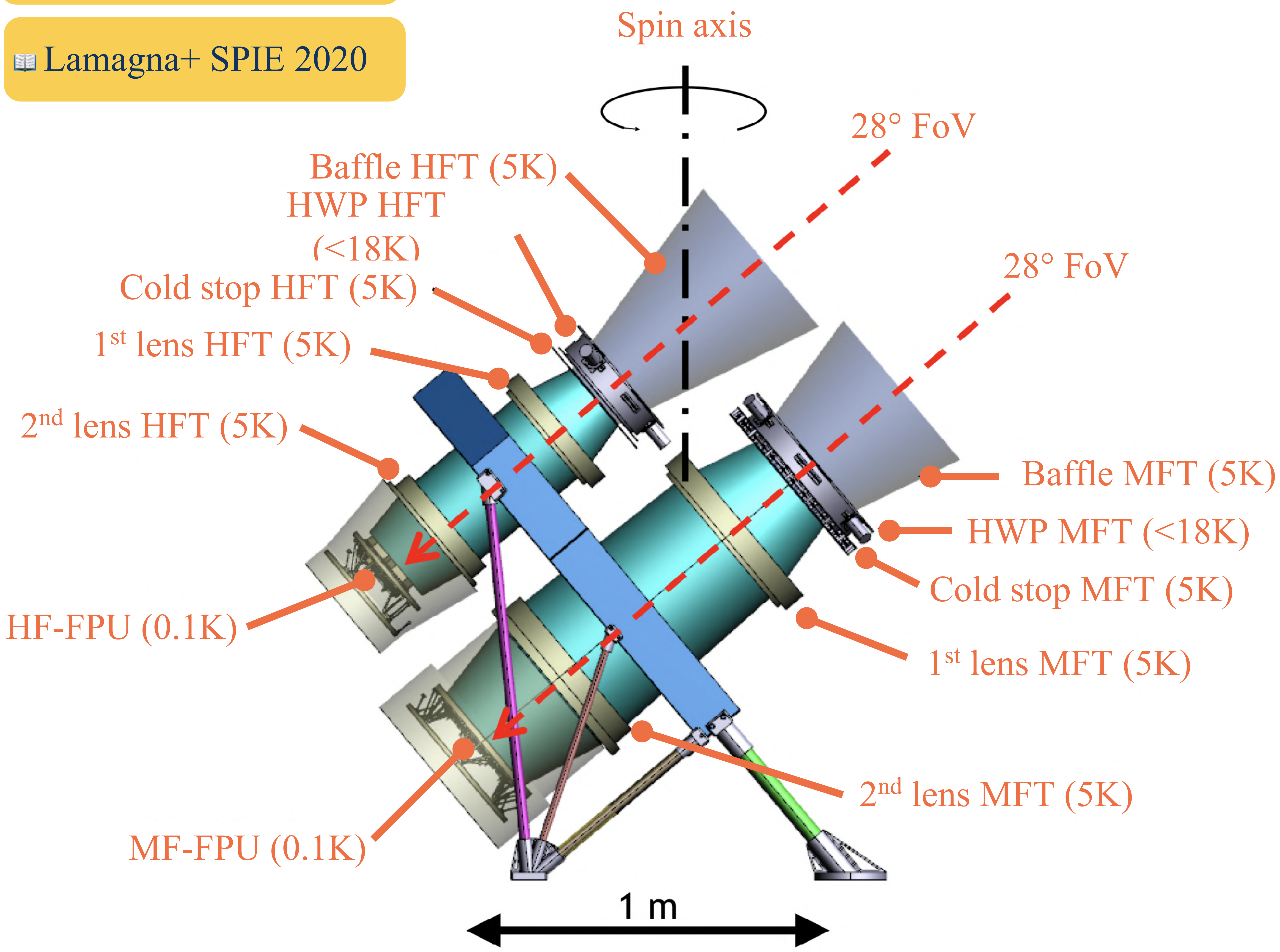
- Polarization Modulation Unit (PMU) as the first sky-side optical element
- **Crossed-Dragone** design
  - Made of aluminium
- Field of view: **18°×9°**
- Strehl ratio > 0.95 (@ 161 GHz)
- Aperture diameter: **400 mm**
- Frequency range: **40-140 GHz**
- Angular resolution: **70-24 arcmin**
- F#3.0 & cross angle of 90°
- Cross-polarization < **-30 dB**
- Rotation of the polarization angle across the FoV < ±1.5°
- Weight < 200 kg

📖 Sekimoto+ SPIE 2020

Middle-High Frequency Telescopes (MFT/HFT)

📖 Montier+ SPIE 2020

📖 Lamagna+ SPIE 2020



- Refractive optics
- Each telescope has PMU with a half-wave-plate (HWP)
- Field of view: **28°**
- Simple and high heritage from ground experiments
- Compact (mass & volume)
- Simplified design for filtering scheme
- PP lenses + ARC
- Weight 180 kg

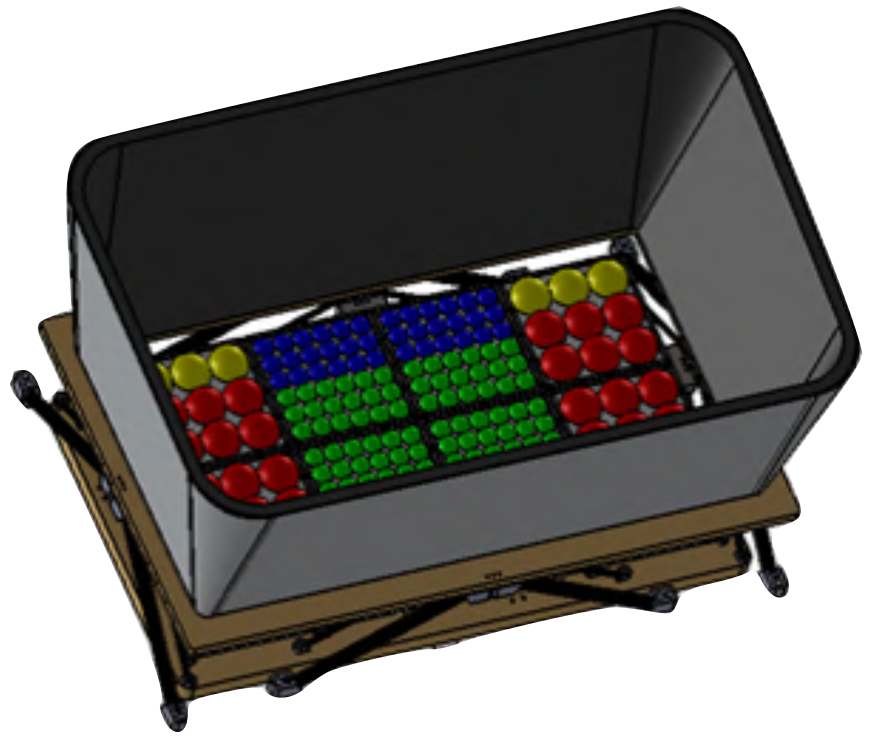
	MFT	HFT
ν (GHz)	**100-195**	**195-402**
Ap. diameter (mm)	**300**	**200**
Ang. res. (arcmin)	**38-28**	**29-18**

Focal plane configuration

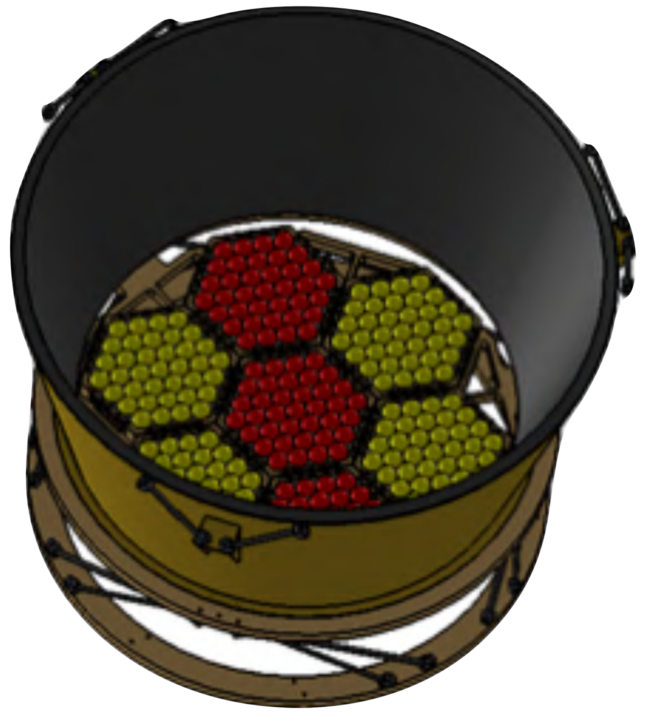
- Transition-Edge Sensor (TES) arrays
- Multichroic detectors
- Number of detectors: 4508
- 15 bands including overlap between instruments

Rule of thumb: 1000 detectors in space = 100 000 detectors on ground

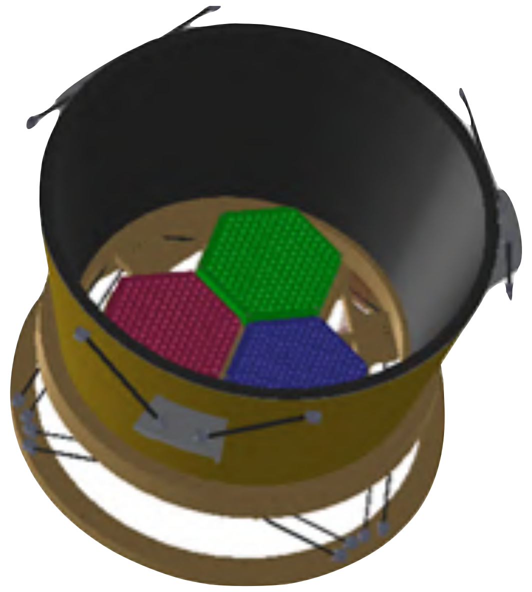
LFT



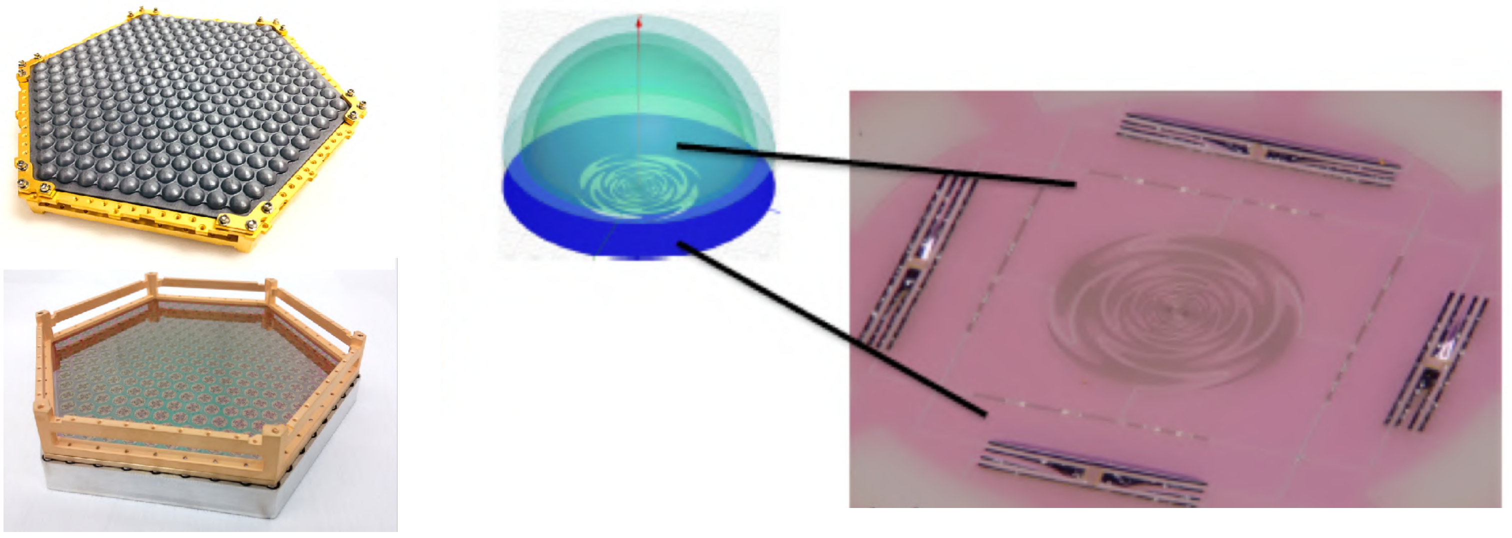
MFT



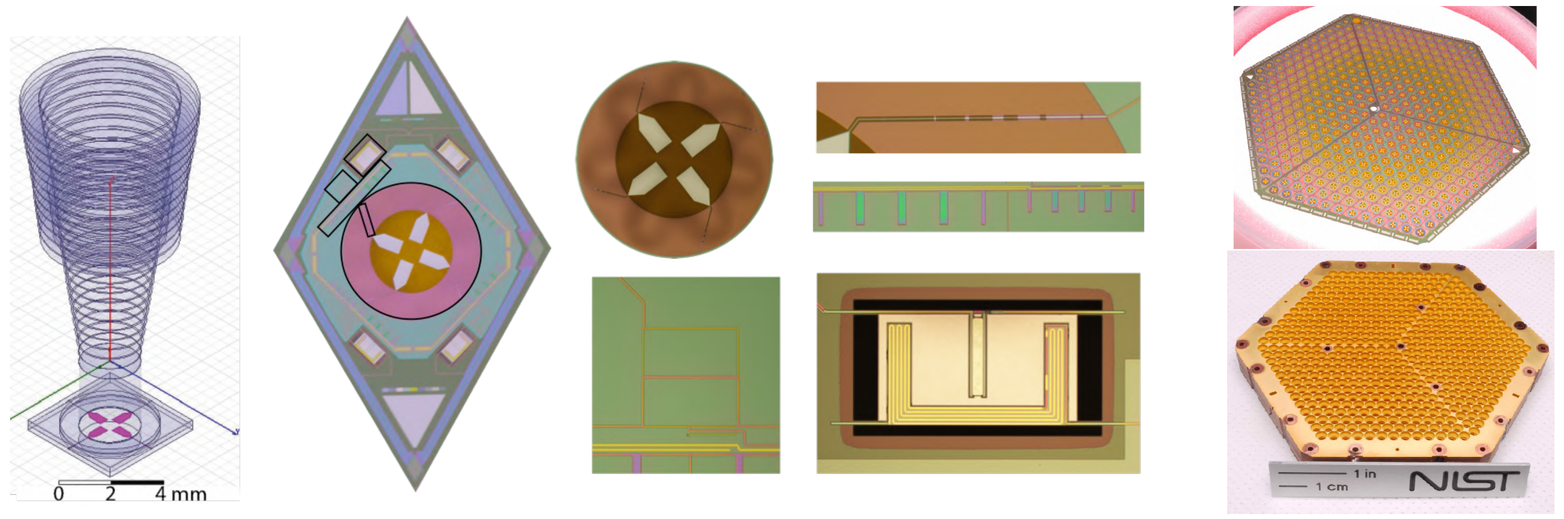
HFT



Lensed coupled detectors
Lenslets



Horn coupled detectors
Platelets



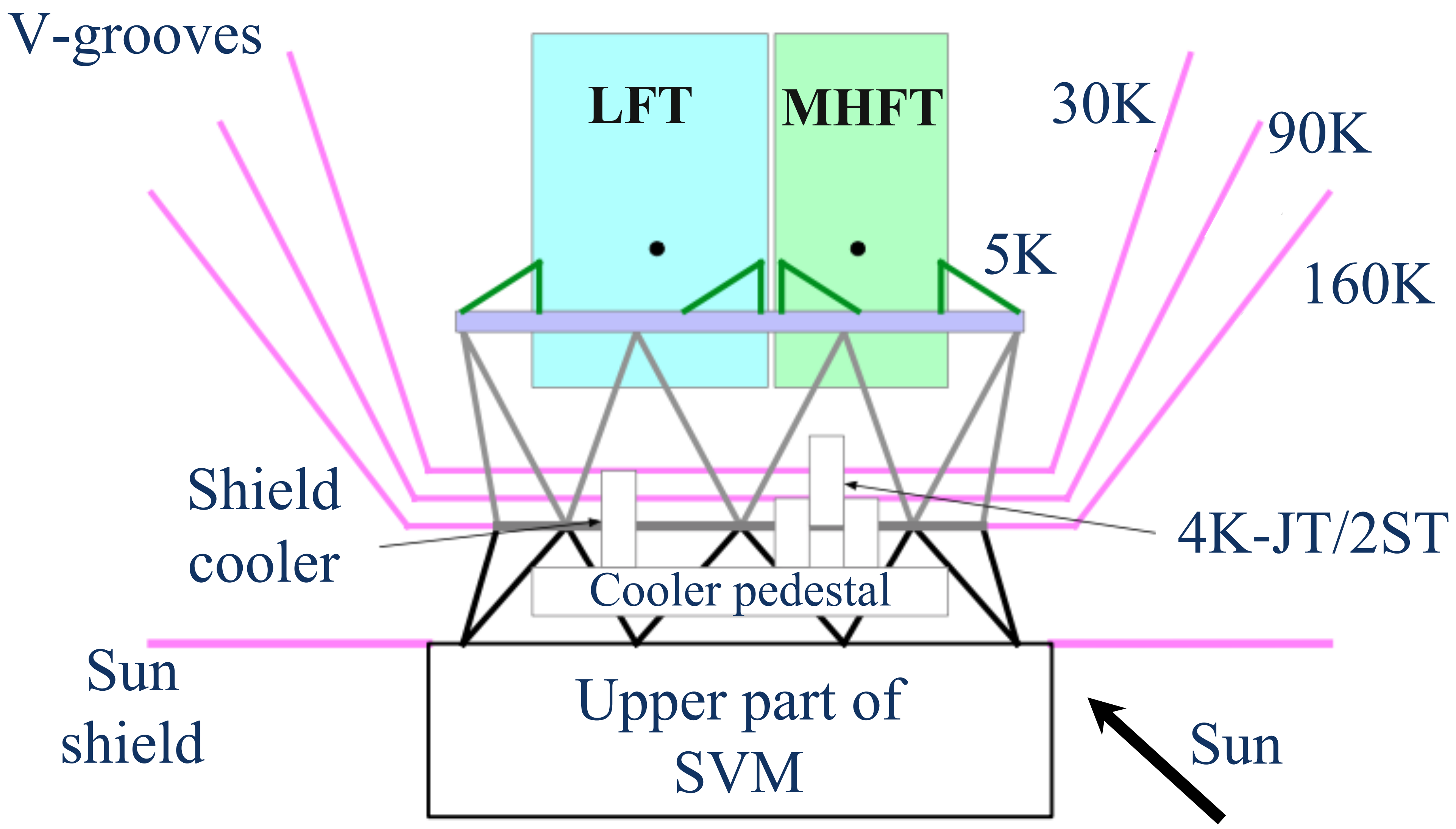
Westbrook+ SPIE 2020

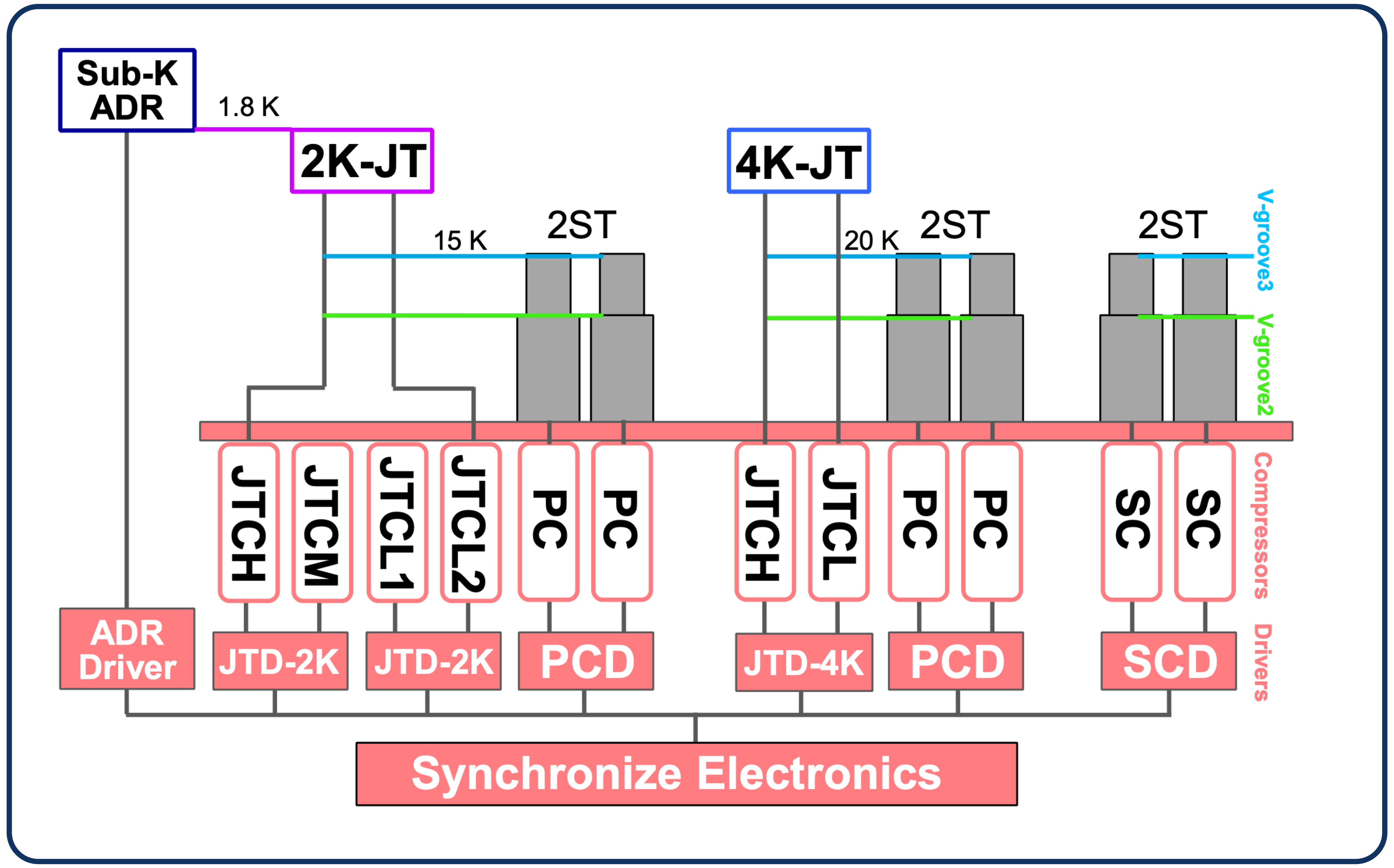
MFT (2.5:1)
89GHz — 225 GHz
2074 detectors
2 x 183 Trichroic TES
2 x 244 Dichroic TES
100 | 119 | 140 | 166 | 195

LFT (5.7:1)
34GHz — 161 GHz
40 | 50 | 60 | 68 | 78 | 89 | 100 | 119 | 140
68 | 78 | 89
1080 detectors
2 x 180 Trichroic TES

HFT (2.7:1)
166 GHz — 448 GHz
195 | 235 | 280 | 337 | 402
1354 detectors
2 x 254 Dichroic TES
2 x 169 Monochromatic TES

LiteBIRD cryogenic system





- Optimized to ensure **maximum stability** of the focal planes and of the optical elements of the telescopes
  - Radiative cooling to 30 K with V-grooves
  - Two 2ST are used for cooling V-grooves 2 and 3
  - A 4K-JT and two 2ST are used to cool the LFT and the MHFT
  - A 2K-JT, two 2ST, and a sub-K ADR are used for cooling the focal plane down to **100 mK**

LiteBIRD Spanish Community

- The Spanish scientific and technical community involved in LiteBIRD is summarised here:

  - Instituto de Astrofísica de Canarias **(IAC)**:
    - Debabrata Adak, Jose Javier Diaz-García, Ricardo Génova-Santos, Raul Gonzalez, Gabriel González Rial, Carlos Hernandez-Monteagudo, Jose Alberto Rubiño-Martín, Diego Tamayo Guzmán.
  - Instituto de Física de Cantabria **(IFCA)**:
    - R. Belén Barreiro, Francisco J. Casas Reinares, Laura Castelló-Gomar, Jyothis Chandran, Elena de la Hoz López-Collado, Patricia Diego Palazuelos, Christian Gimeno-Amo, Diego Herranz, Enrique Martínez-González, Felice A. Martire, Guillermo Pascual-Cisneros, Mathieu Remazeilles, Miguel Ruiz Granda, P. Vielva.
  - Instituto Universitario de Microgravedad "Ignacio de Riva"/Universidad Politécnica de Madrid **(IDR/UPM)**:
    - Juan Bermejo, Javier Cubas, Ignacio Torralbo.
  - Universidad Europea de Madrid/European Space Astronomy Center **(UEM/ESAC)**:
    - Marcos López-Caniego.

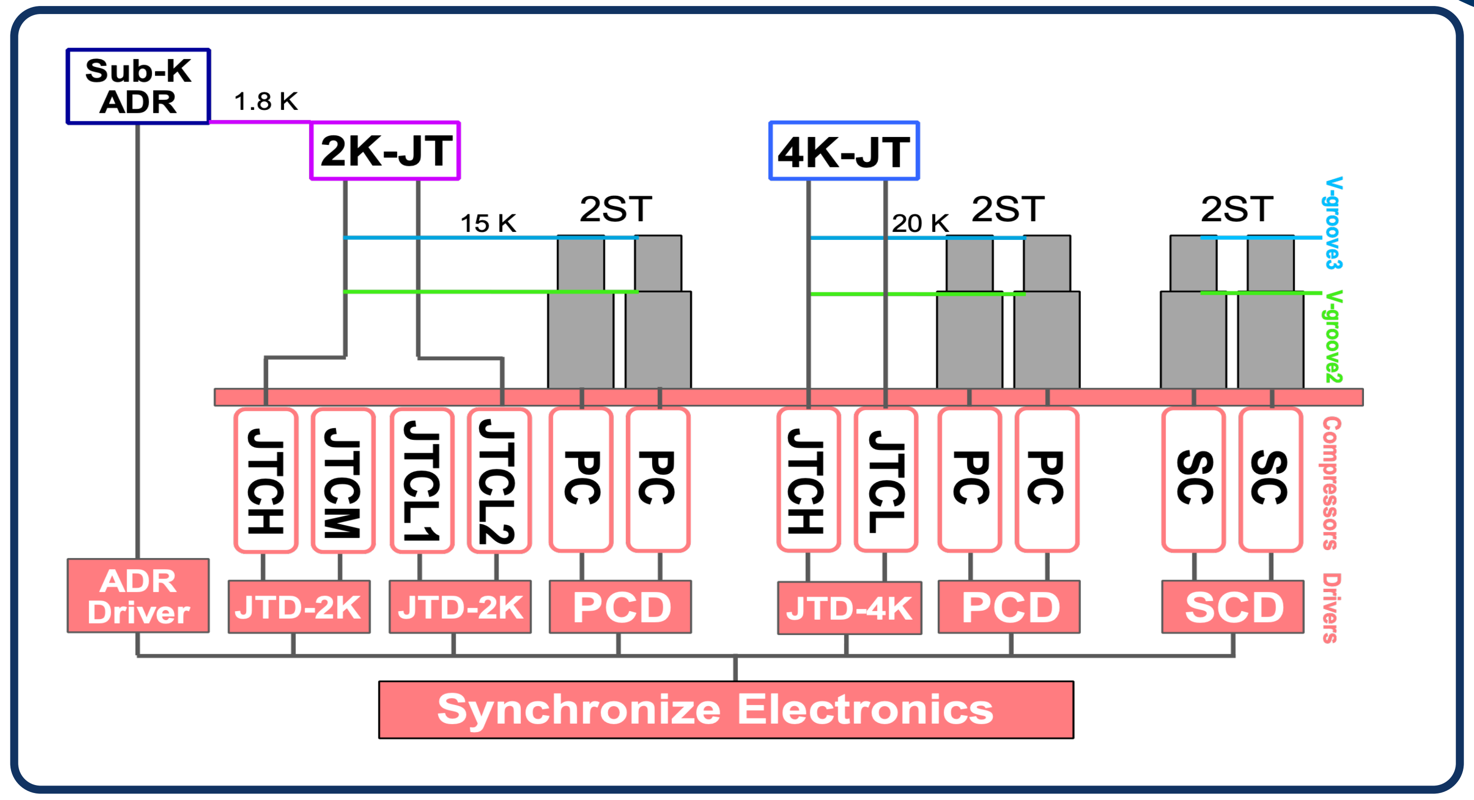
LiteBIRD Spanish Contribution

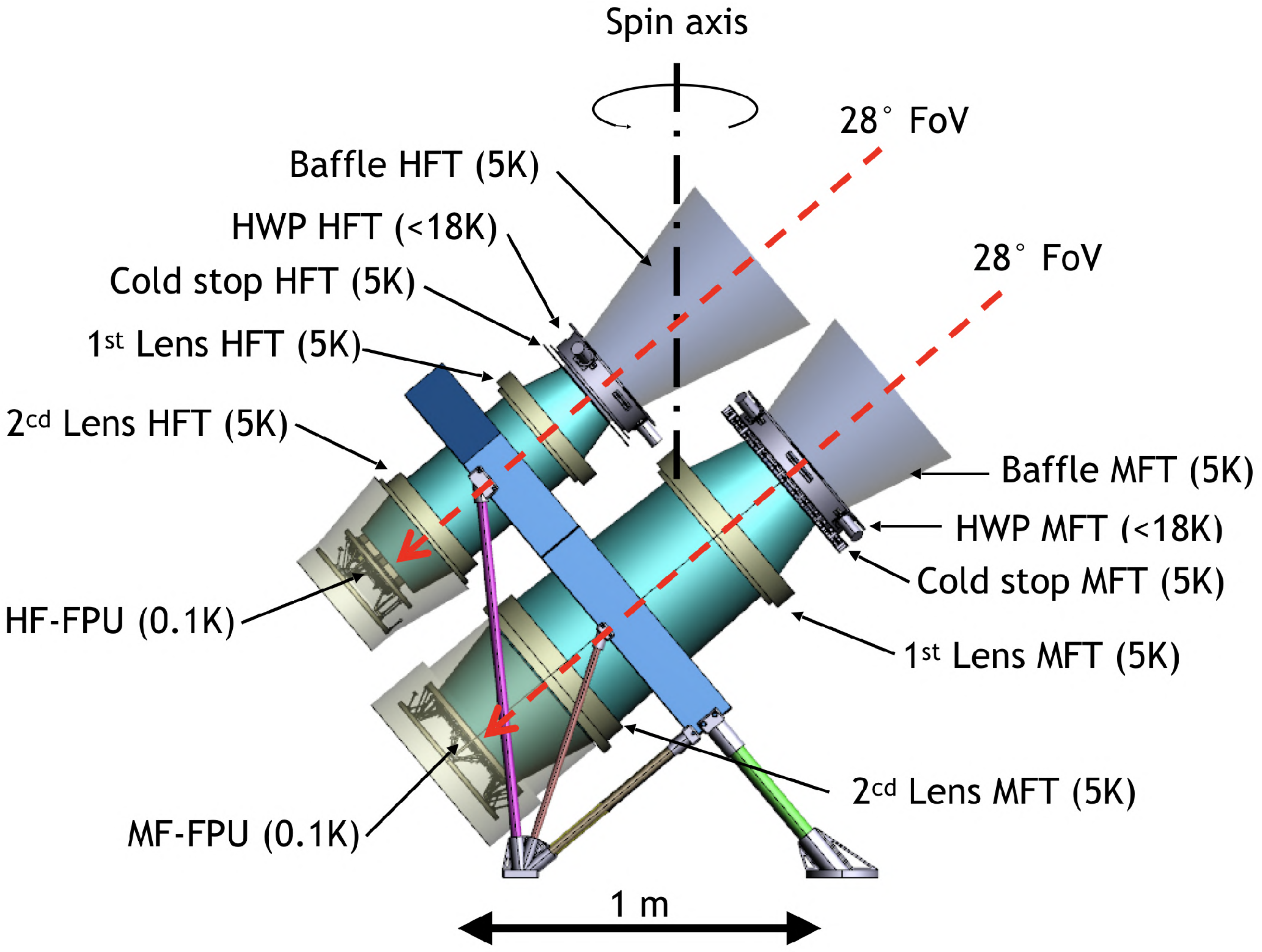
- The overall contribution of Spain to the LiteBIRD mission is summarised here:
  - **TMCS** (Temperature Monitoring and Control System):
    - Payload subsystem critical for the monitorization of the instrumentation lowest temperatures (5, 2, 0.4 and 0.1 K cryogenic stages) and for the compensation of lowest-frequencies temperature fluctuation of the focal plane.
    - It is composed by a set of temperature sensors, heaters, cables (harness) and electronics boxes for monitoring and active control.
  - **Data Center**:
    - IFCA is expected to host one of the nodes of the mission Data Center, which will be distributed between the three continents (Asia, America and Europe).
  - **Preparation for Science exploitation**:
    - Spain contributes to different working groups (Joint Study Groups) like the ones of Calibration, and Systematics and contribute also to Forecast activities.
  - **Mission governance representation**:
    - Spain is represented in the most important governance bodies: Interim Governance Body, European Steering Committee, Project Office of the MHFT (Medium and High frequency Telescopes, of European responsibility), Speaker Selection Committee and Interim Publication Board.

TMCS: Purpose

- Purpose of the **TMCS** (Temperature Monitoring and Control System)
  - **Monitor** the temperature of the MHFT 5, 2, 0.4 and 0.1 K stages
  - **Compensate** low frequency thermal fluctuations in the 100 mK (T_0) focal plane introduced by factors not controllable by design like:
    - Sky background
    - Cosmic rays
  - Considering the **thermal loading budget at T_0**:
    - $\mathbf{P_{l\_0} = P_l + P_{ext}}$
    - P_{l_0} is the required constant thermal load
    - P_l is the thermal load provided by the heater of the control system
    - P_{ext} is the thermal load from sky background, cosmic rays, etc.

- No thermal control of higher (5, 2, and 0.4 K) temperature stages is necessary





TMCS: Activities and participants

- Engineering activities
  - Requirements
  - TMCS electronics design
  - Temperature sensors validation (Cernox & RuOx)
  - Design and provide a Validation Test Bench (GSE for the TMCS models)
  - High frequency temperature fluctuation compensation by post processing
  - Cosmic rays and sky background modelling and evaluation of thermal effects at T_0 stage (0.1 K)

- Participant institutions
  - Instituto de Astrofísica de Canarias (IAC)
  - Instituto de Física de Cantabria, Consejo Superior de Investigaciones Científicas - Universidad de Cantabria (IFCA, CSIC-UC)
  - Instituto Ignacio Da Riva at Universidad Politécnica de Madrid (UPM/IDR)

TMCS: Resources (funding and people)

Institution/People	Funding
Instituto de Astrofísica de Canarias (IAC)	
• José Javier Díaz García • Ricardo Génova Santos • Gabriel González Rial • J. Alberto Rubiño Martín • + Part time Senior engineer and junior engineer (expected 1Q 2025)	• 2020-2023 PNAYA + CDTI • 2024 IAC Internal funds (Severo Ochoa) + PNAYA • 2024 Submitted research project (3 years). • 2024 PRODEX Call (1-2 Years)
Instituto de Física de Cantabria (IFCA)	
• Francisco Javier Casas • Enrique Martínez-González • Guillermo Pascual Cisneros • Laura Castelló Gomar (starting Doctor-FC contract)	• Funded research projects (Ref. PID2022-139223OB-C21) MCIN/AEI/10.13039/501100011033 • EU-funded “Recovery, Transformation and Resilience Plan – NextGenerationEU” / AstroHEP-PPCC • 2024 PRODEX Call (1-2 Years)
Universidad Politécnica de Madrid. Instituto Ignacio Da Riva (UPM/IDR)	
• Javier Cubas • Ignacio Torralbo	• Funded research project (ref. PID2022-139223OB-C22);

TMCS: Resources (technical)

Institution/Technical Resources
Instituto de Astrofísica de Canarias (IAC)
• Sub-K cryostat (ADR) • Temperature monitoring and control equipment • RuOx and Cernox Sensors • Prototyping boards for flight like electronic functions validation (ADC, DAC) • Thermal modelling tools
Instituto de Física de Cantabria (IFCA)

• Cryo-lab infrastructure with dilution refrigerator (operations will start Q1 2025)
• Computation facilities (cosmo-cluster) for:
    • Cosmic Rays and Sky Background modelling and simulation
    • High frequency thermal noise effects compensation analysis and post processing implementation methods

Universidad Politécnica de Madrid. Instituto Ignacio Da Riva (UPM/IDR)
• Thermal modelling tools

TMCS: Thermal noise budget

$$\delta r < 10^{-3} \Rightarrow \delta r^2 = \delta r^2_{Stat} + \delta r^2_{Syst}$$

δr^2_{Stat}: 7.1×10^{-4} — δr^2_{Syst}: 7.1×10^{-4}

$$\delta r_{Syst} = \Sigma \Delta r_i$$

Each systematics should be 1% of the Systematics budget

$$\Delta r_i < 7.1 \times 10^{-6}$$

- Thermal noise (induced by thermal fluctuations) must contribute with less than 5% of the detector total noise (NEP).
- Thermal stability requirements are derived from the noise contribution due to thermal fluctuations.

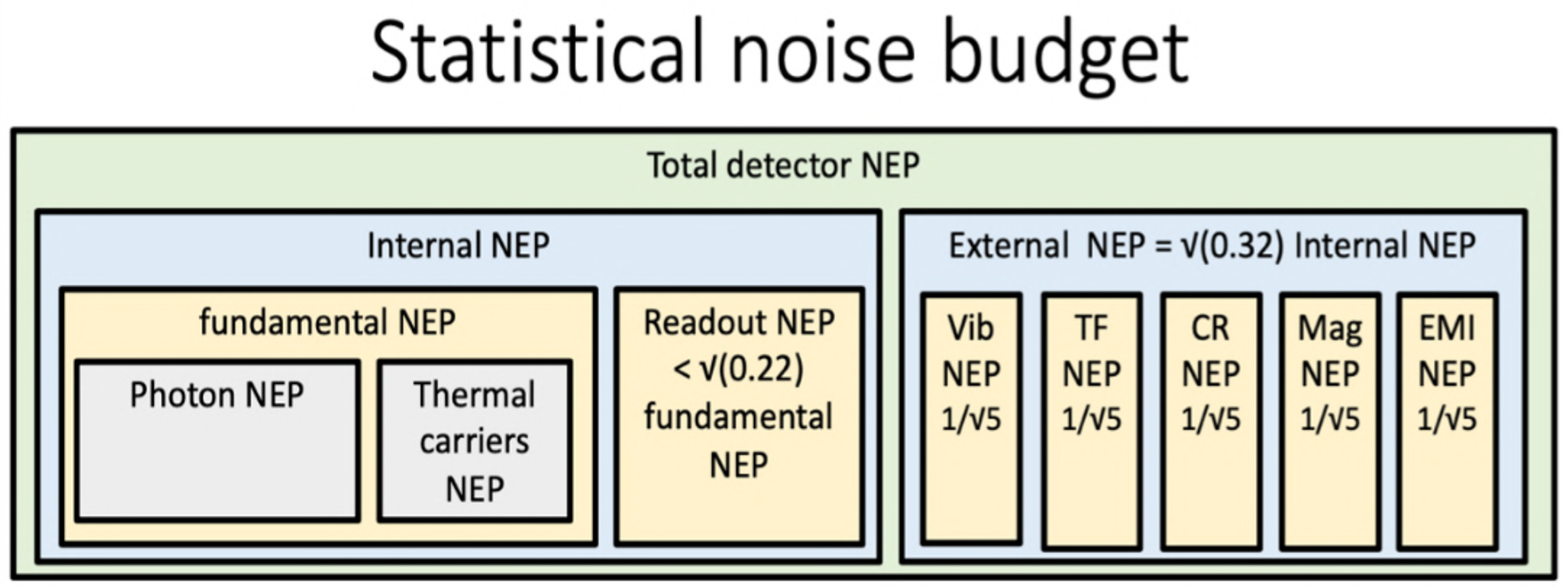
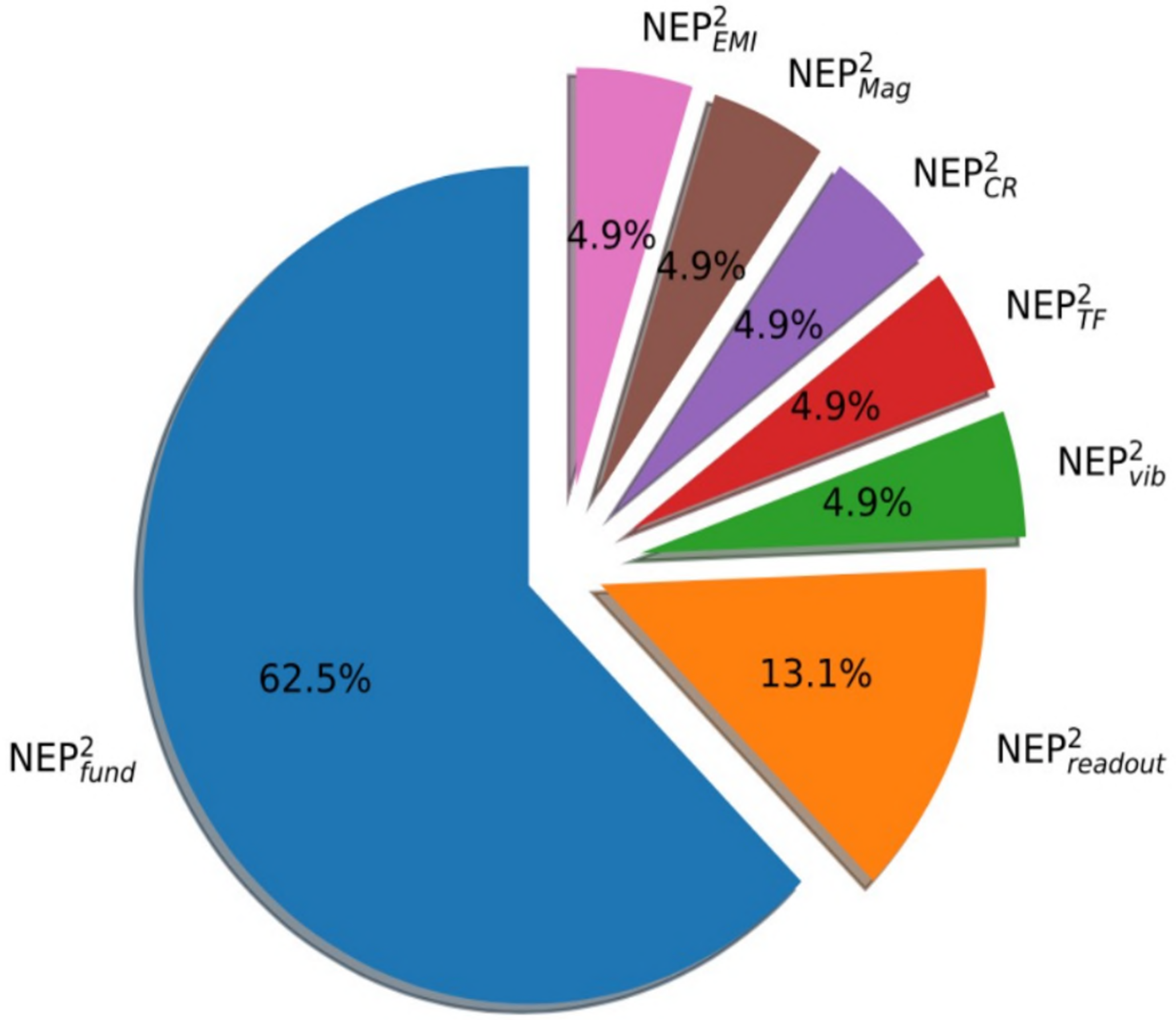
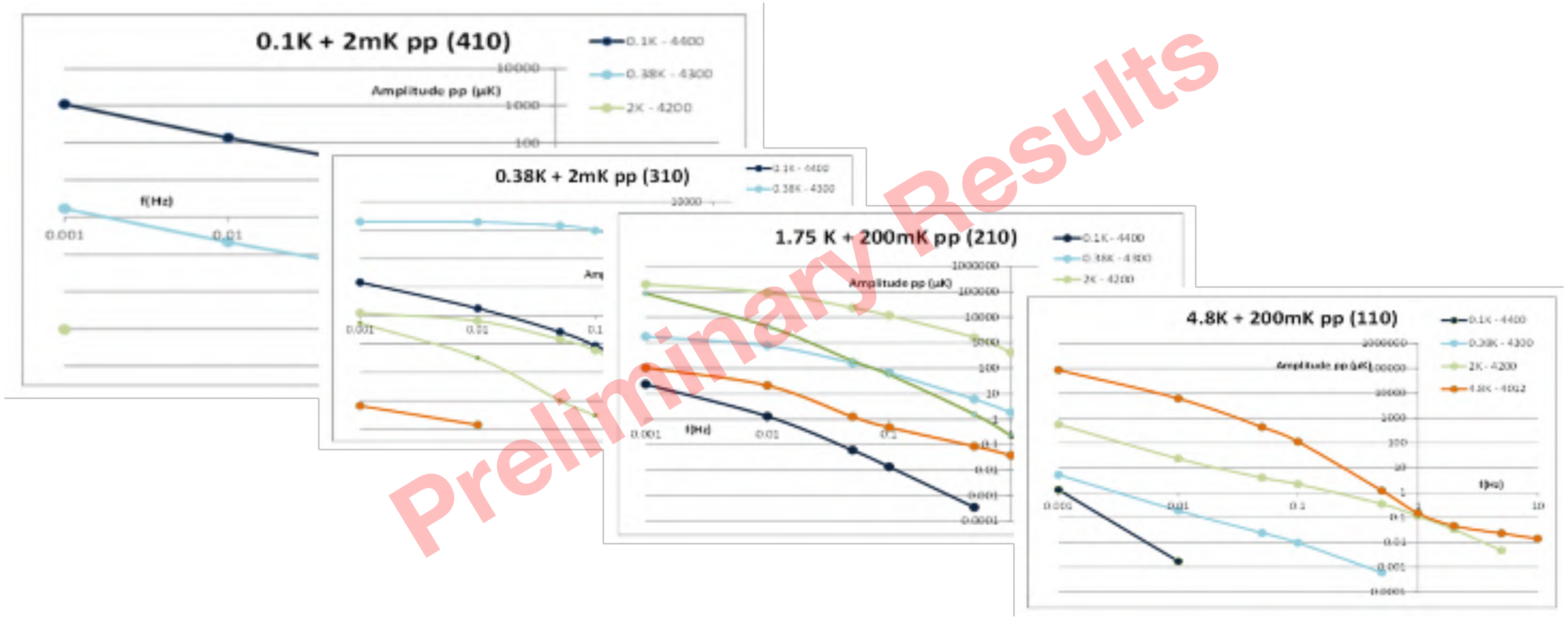


Figure 1: LiteBIRD statistical noise budget.



TMCS: Thermal modelling and stability

- Temperature stability analysis by the LiteBIRD Thermo-Mechanical Group (APC & CEA/DSBT, France).
  - Max Peak to Peak oscillations for T_0 (0.1 K)-T_4 (5 K).



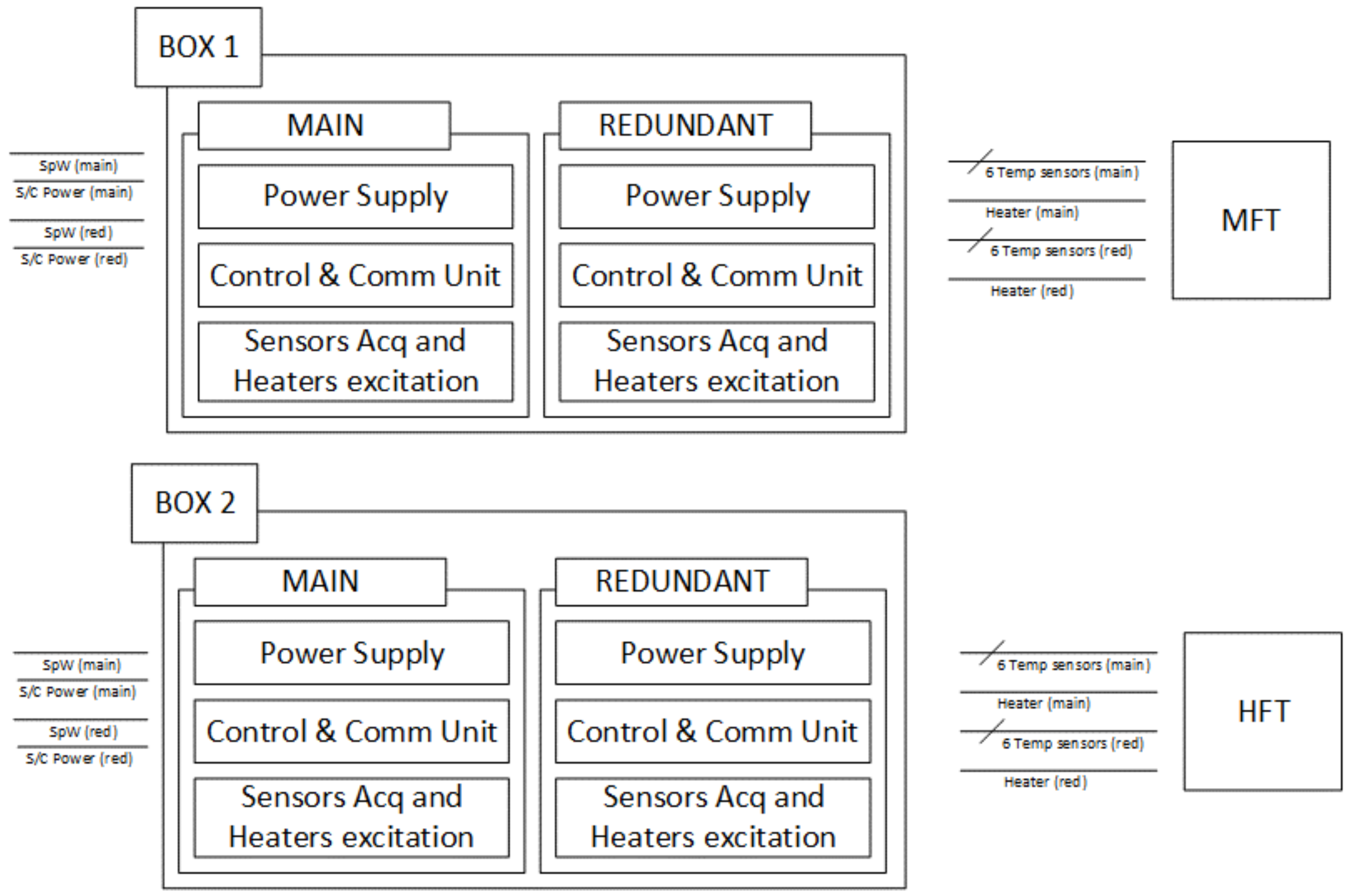
TMCS: Thermal modelling and stability

- The most relevant requirements are those at low frequencies (<1e-3 Hz) and related to T_0 stage
  - At frequencies > 1Hz passive mitigation of thermal fluctuations is enough to accomplish stability requirements

- Still under discussion.
  - Low-frequency temperature stability requirements relaxation can be assumed relying in different techniques (considering foregrounds cleaning).
  - ADR includes its own temperature control that must be complementary to that of the TMCS, which should cover only the frequency ranges not compensated by the ADR thermal control (the control loops must be isolated to avoid thermal instabilities produced by mutual interferences).
  - In the thermal analysis, the assumed level of perturbation (mK) seems too high (a kind of worst-case scenario).
    - CR contribution has been preliminary estimated orders of magnitude lower (uK level)

TMCS: Architecture and technical budget

- TMCS Electronics Architecture
  - 2 x Electronics Boxes (One per Telescope) with N&R sections. No X-strapping.

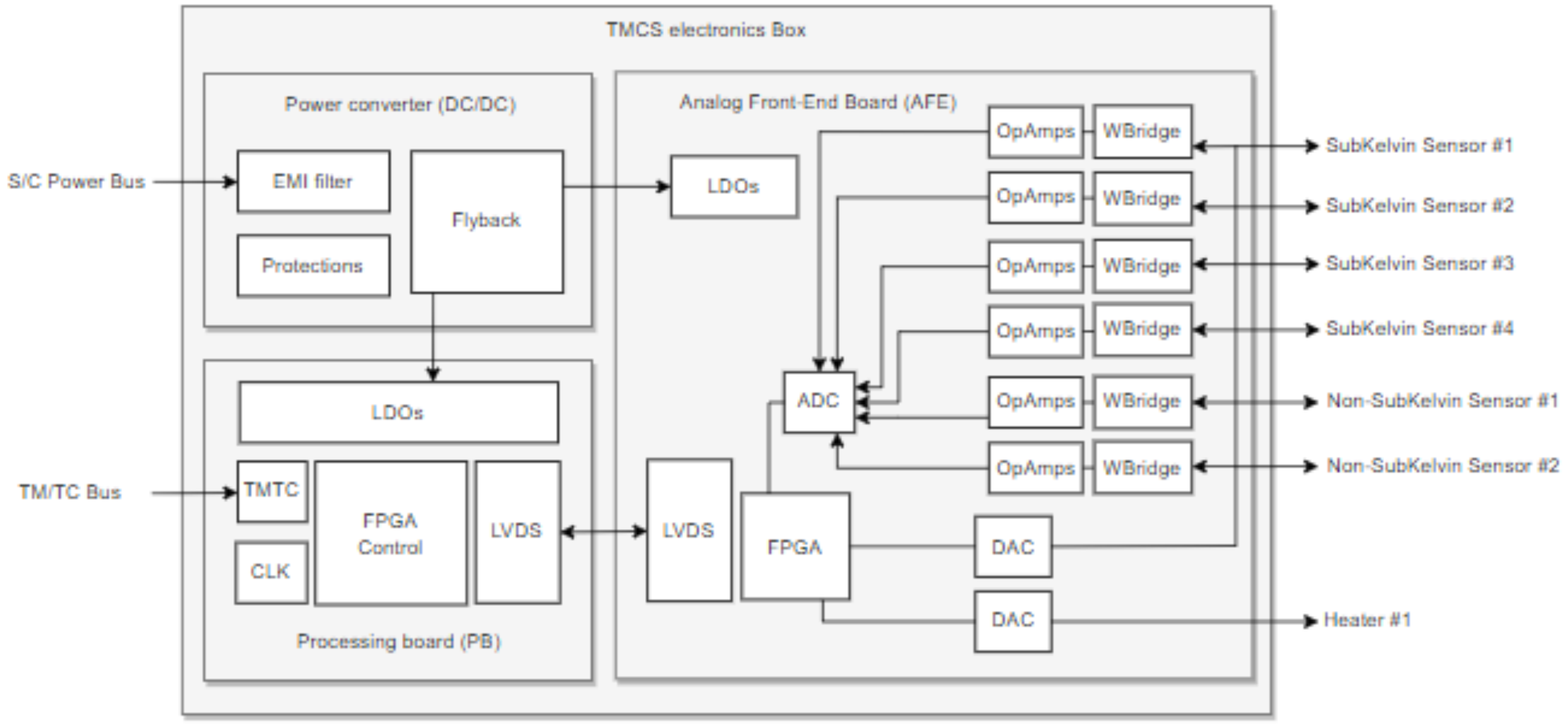


- Budgets:

Preliminary Values

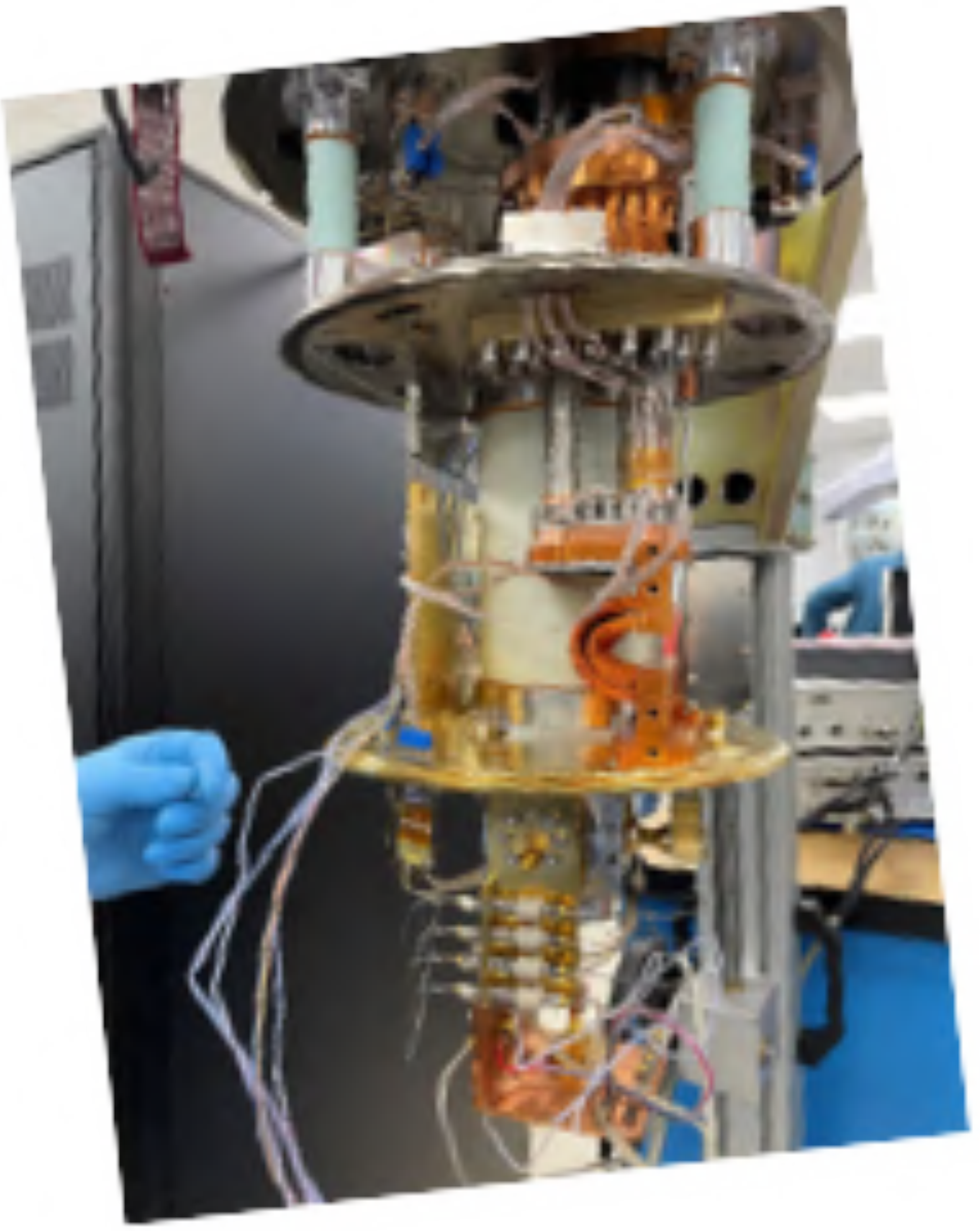
Magnitude	Value	Unit
Height	192	mm
Width	215	mm
Length	175	mm
Volume	7.22	dm^3
+20% Margin	8.67	dm^3
Weight	6.40	Kg
+20% Margin	7.68	Kg

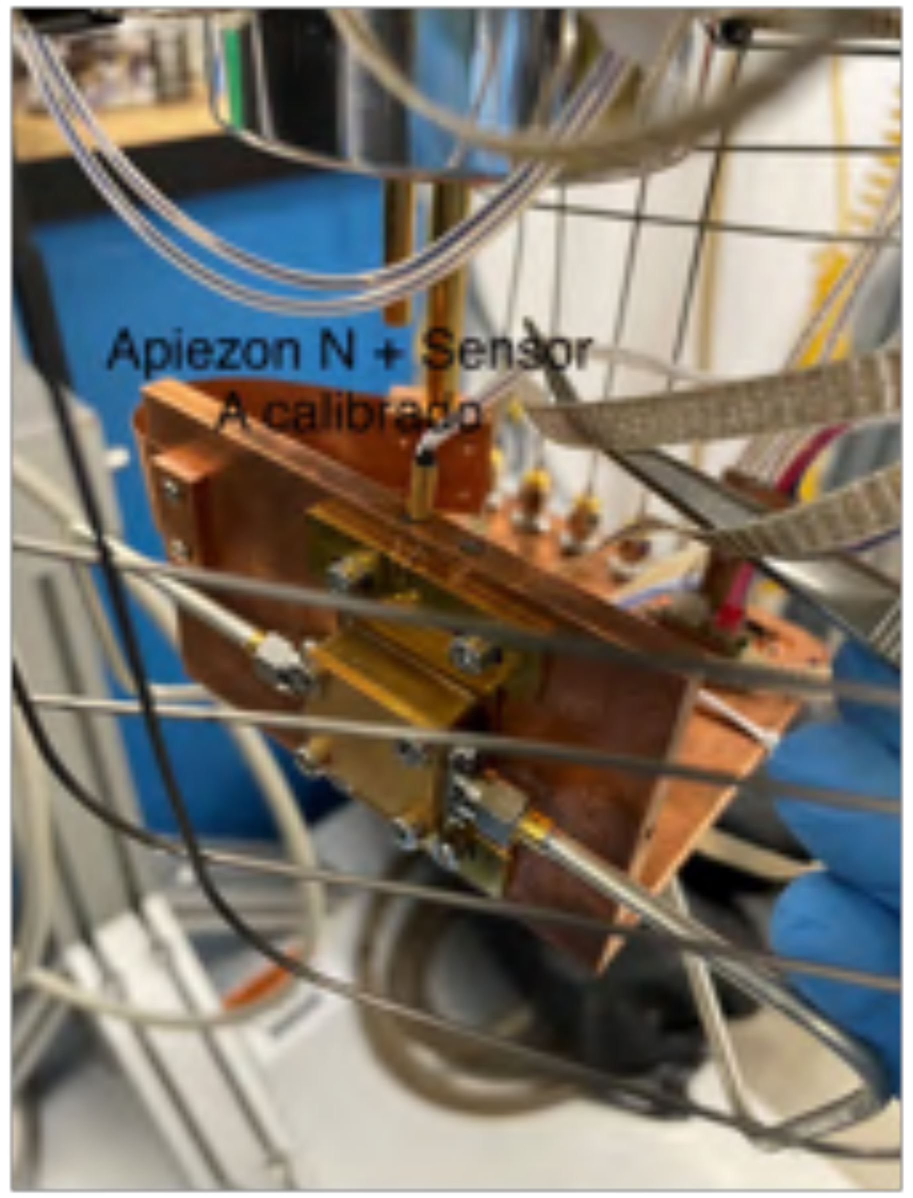
Board	Value	Unit
AFE Board	1.23	W
Processing Board	2.26	W
Total	3.49	W
+DC/DC Eff (85%)	4.11	W
+20% Margin	4.9	W
+EoL	5.4	W

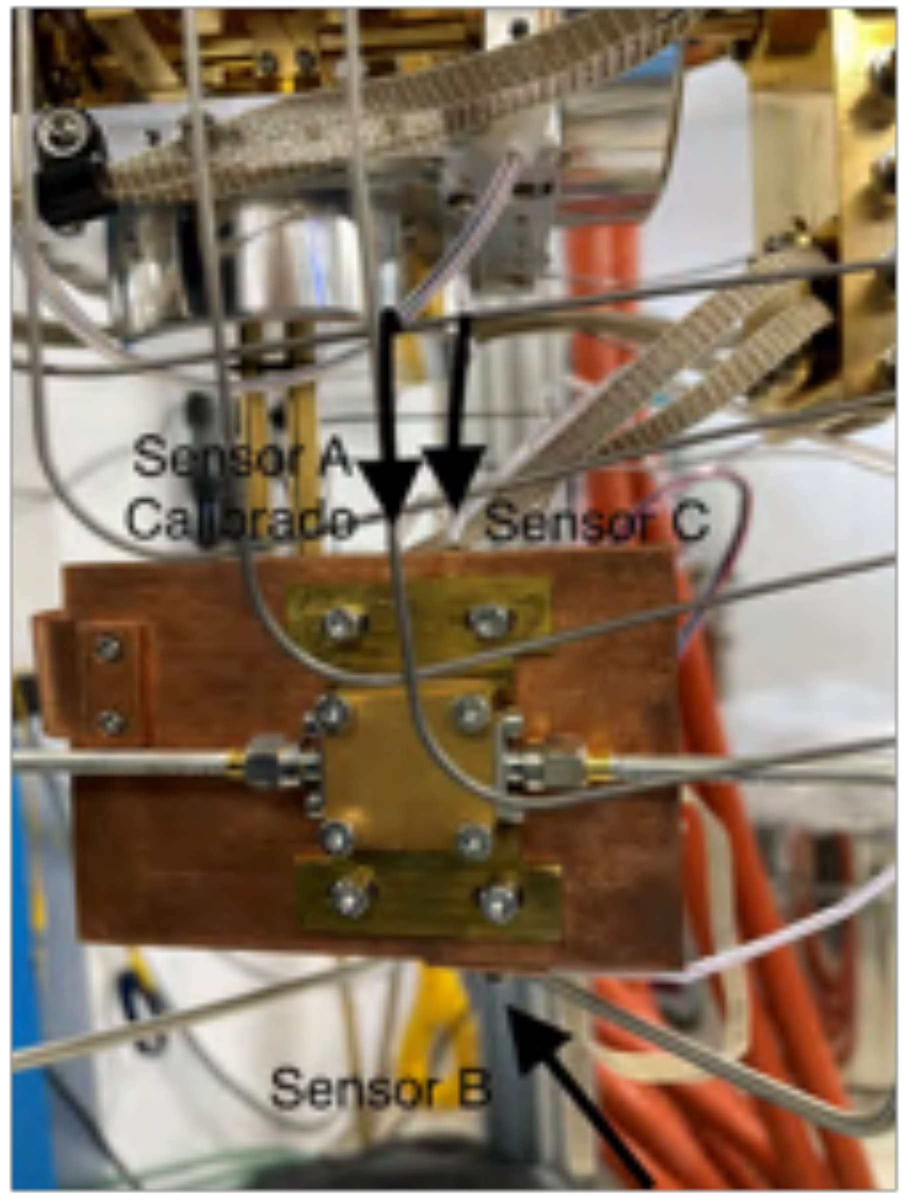


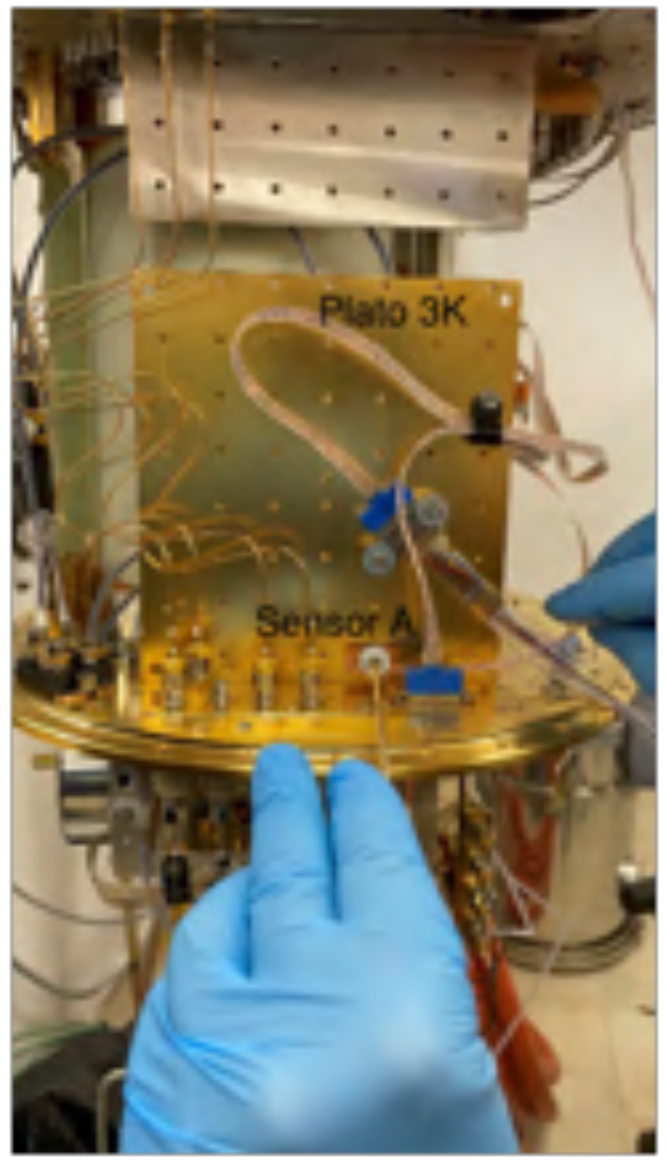
TMCS: Cryogenic infrastructure application

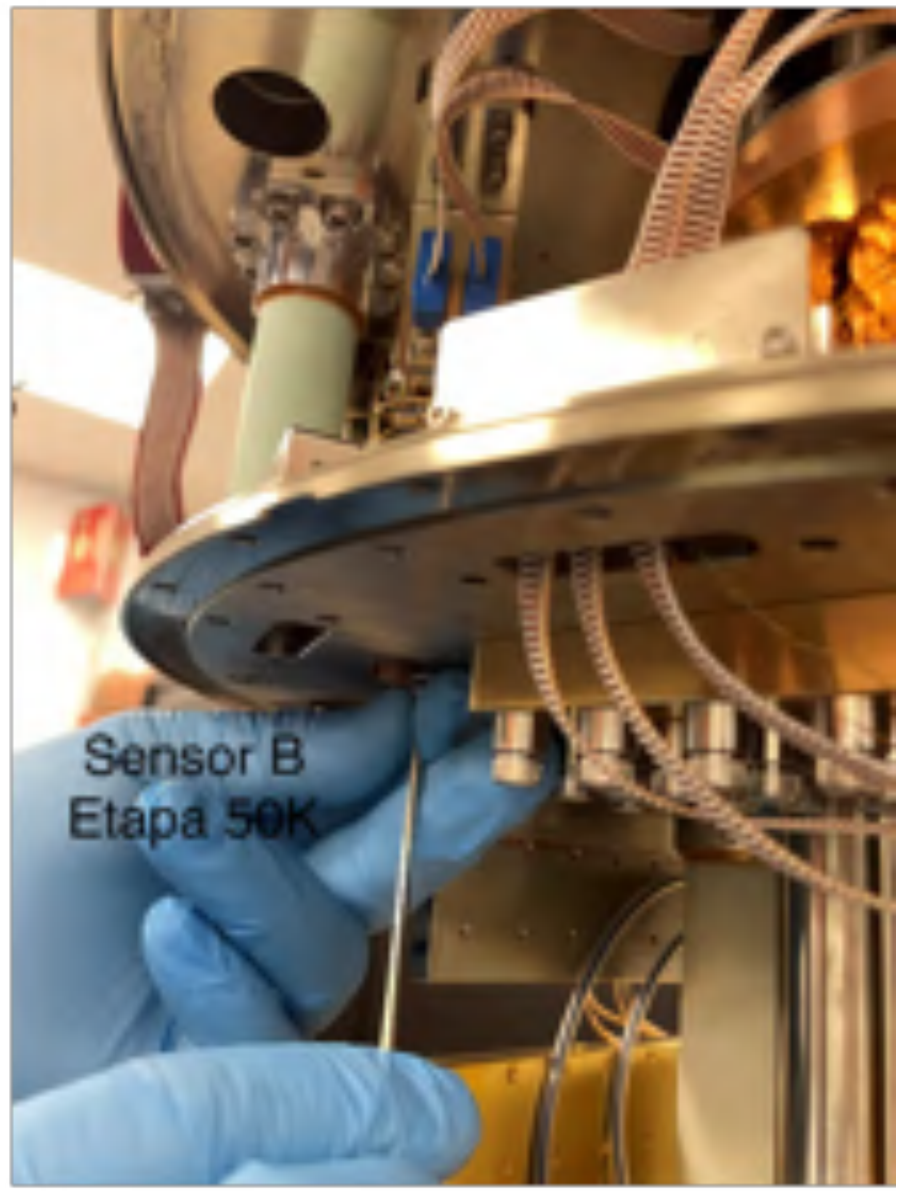
- IAC
  - Temperature sensors validation (Cernox & RuOx).
  - Design and provide a Validation Test Bench (GSE for the TMCS models).





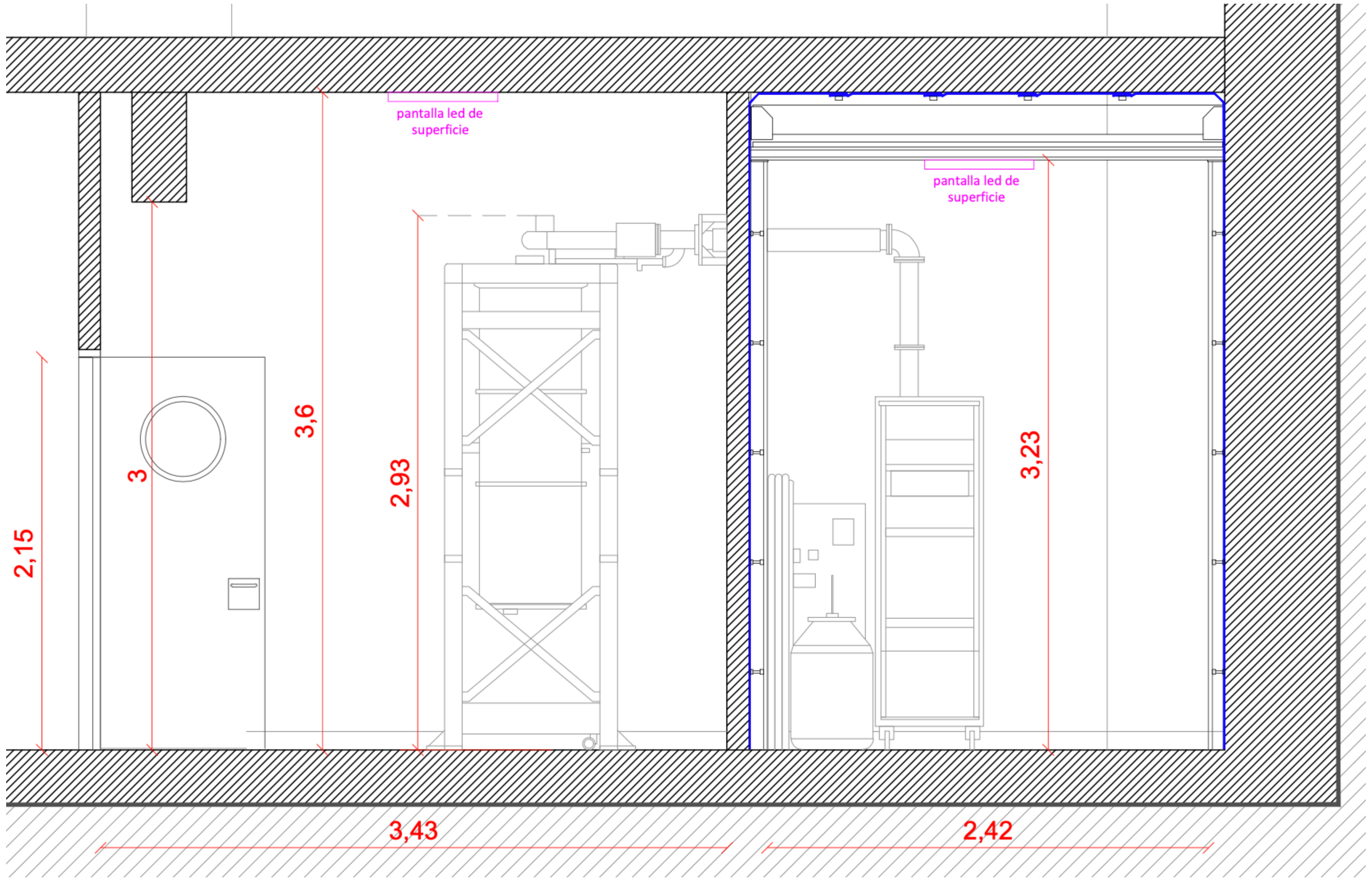


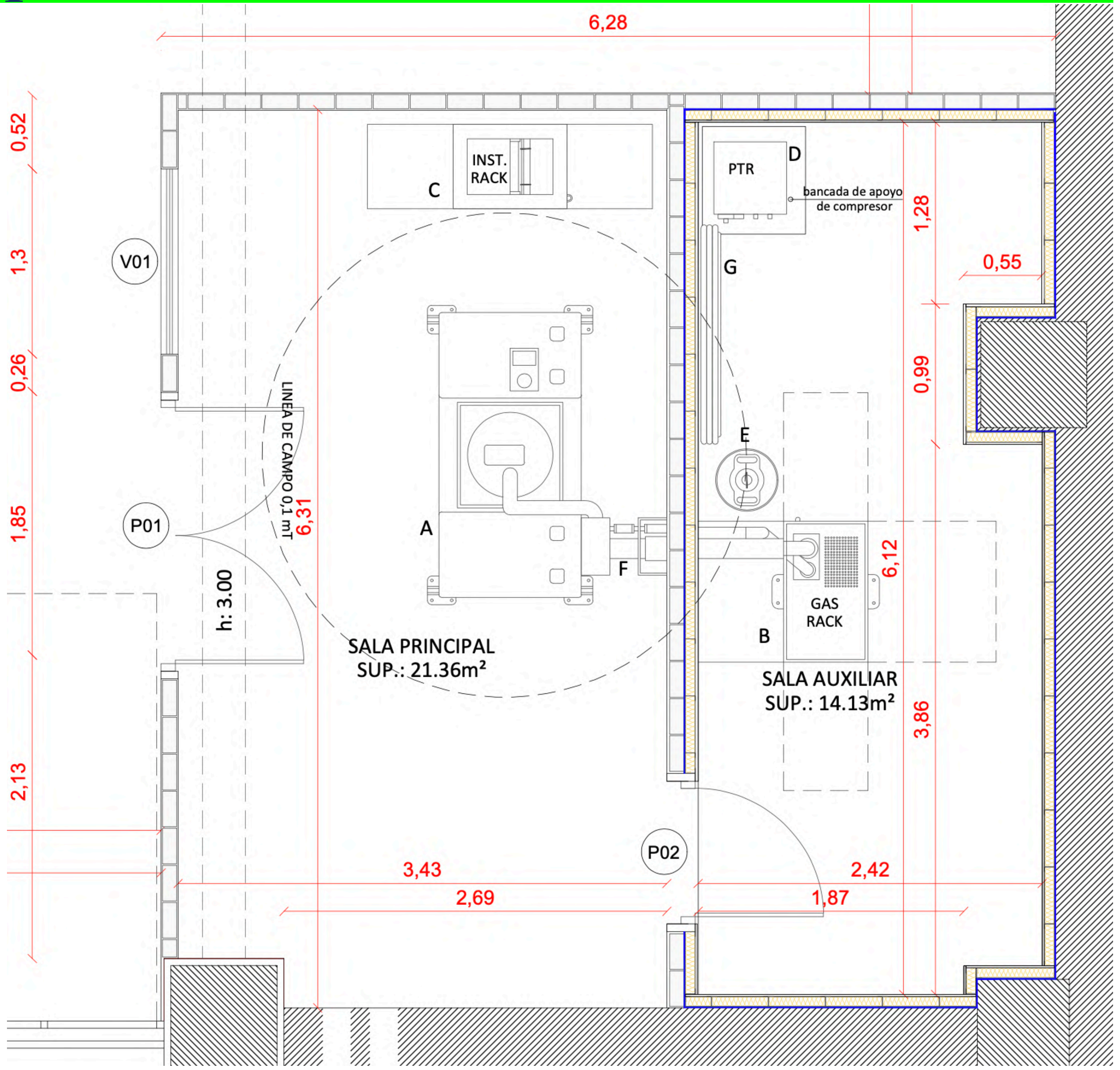




TMCS: Cryogenic infrastructure application

- IFCA
  - High frequency temperature fluctuation compensation by post processing
    - Allows to relax thermal stability requirements
    - Involves the use of dark sensors (Low-resistance thermometers or dark TES)
    - One of the utilities of the "cryo-lab" will be the development and test of this kind of sensors.





APC
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BERKELEY LAB
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
cea
Centre Pierre Binétruy CNRS • Berkeley
cnes
cnrs
CSA ASC Canada

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CSL CENTRE SPATIAL DE LIÈGE
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NASA Goddard Space Flight Center
GSSI GRAN SASSO SCIENCE INSTITUTE
INSTITUTO DE ASTROFISICA DE CANARIAS IAC
IAP
IAS Institut d'Astrophysique Spatiale Orsay
IFCA Instituto de Física de Cantabria
ifpU
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

INFN
INAF ISTITUTO NAZIONALE DI ASTROFISICA
IPMU
IPNS 素粒子原子核研究所 Institute of Particle and Nuclear Studies
irap astrophysique & planétologie
JAXA
NASA Jet Propulsion Laboratory California Institute of Technology

NATIONAL INSTITUTE OF TECHNOLOGY KAGAWA COLLEGE 香川高専
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Stockholm University
公立諏訪東京理科大学 Suwa University of Science
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

UCL
UBC THE UNIVERSITY OF BRITISH COLUMBIA
UC UNIVERSIDAD DE CANTABRIA
Università di Catania
University of Colorado Boulder
Science and Technology Facilities Council
UK RI
ULB UNIVERSITÉ LIBRE DE BRUXELLES
Universidad de La Laguna

MANCHESTER 1824 The University of Manchester
UiO University of Oslo
UNIVERSITY OF OXFORD
UNIVERSITÀ DI PISA
Università degli Studi di Ferrara
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI PADOVA
THE UNIVERSITY OF TOKYO
UNIVERSITY OF TORONTO

IFCA refrigerator DM applications

- IFCA
  - Another main application will be focused on the search of Dark Matter (DM) particles (Axions).
    - IFCA participates in DM search collaborations like CADEx.
    - It can be used to test and calibrate different parts of the experimental set-up under strong magnetic field conditions
      - Resonators, and waveguide components
      - Optical components (mirrors, lenses…)
      - Detectors (magnetic shield req.)
  - Also, the "cryo-lab" will be used for the development and test of new sensors and technologies with the aim of improving the current sensitivity values increasing the viability and probability of success of both kind of experiments (CMB polarization and DM search).