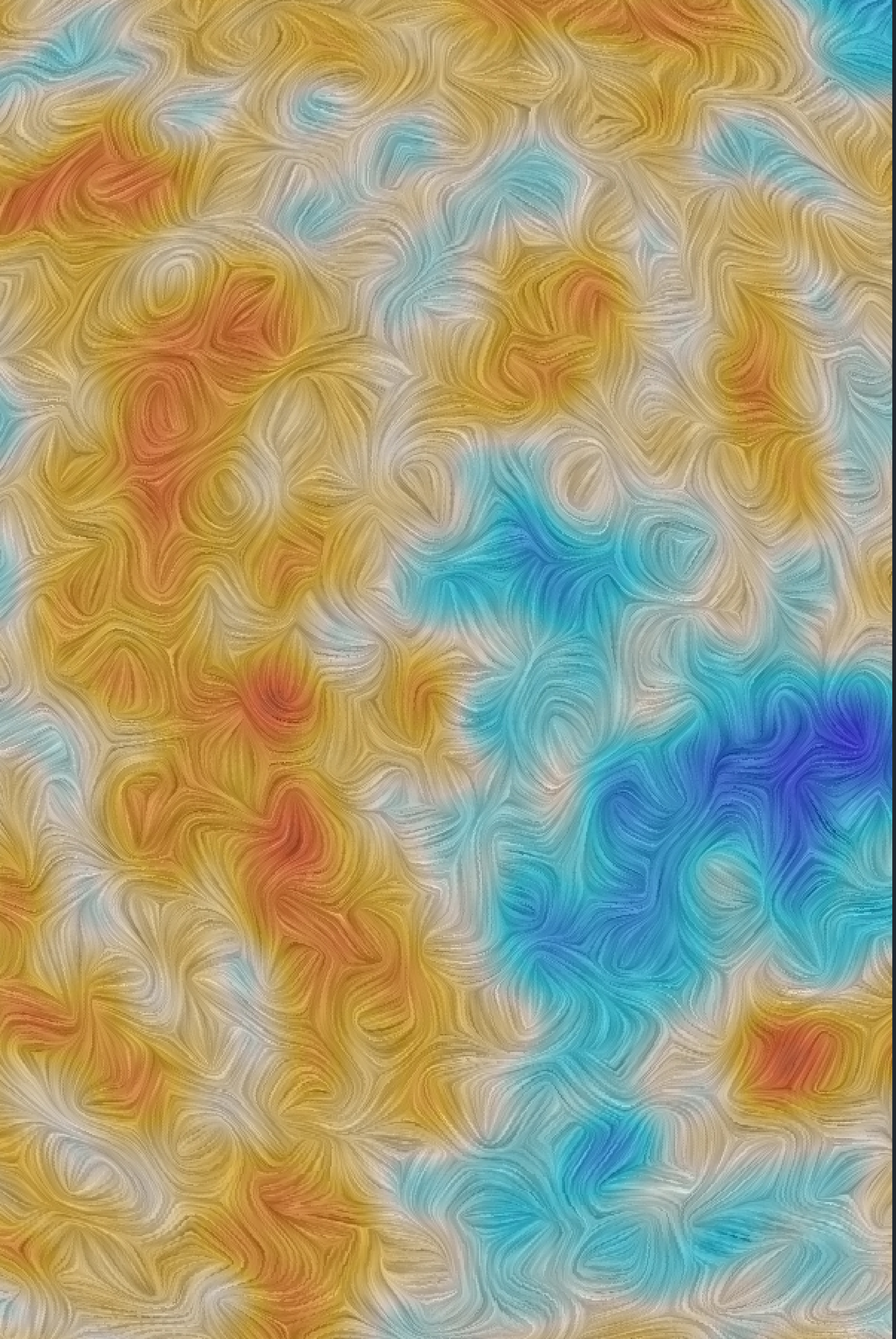
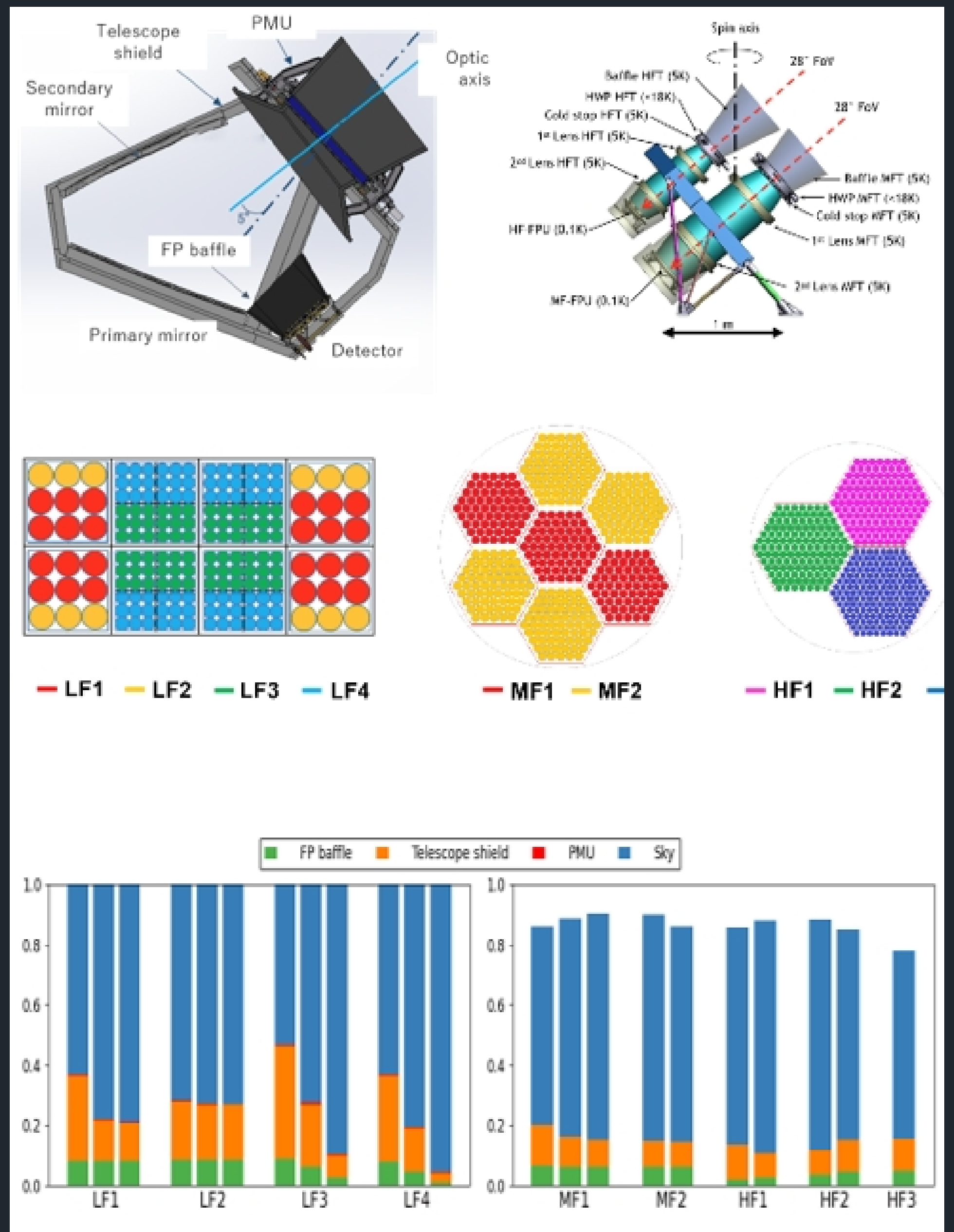


Instrument Design for CMB Space Mission

Takashi Hasebe

My Recearch Topics



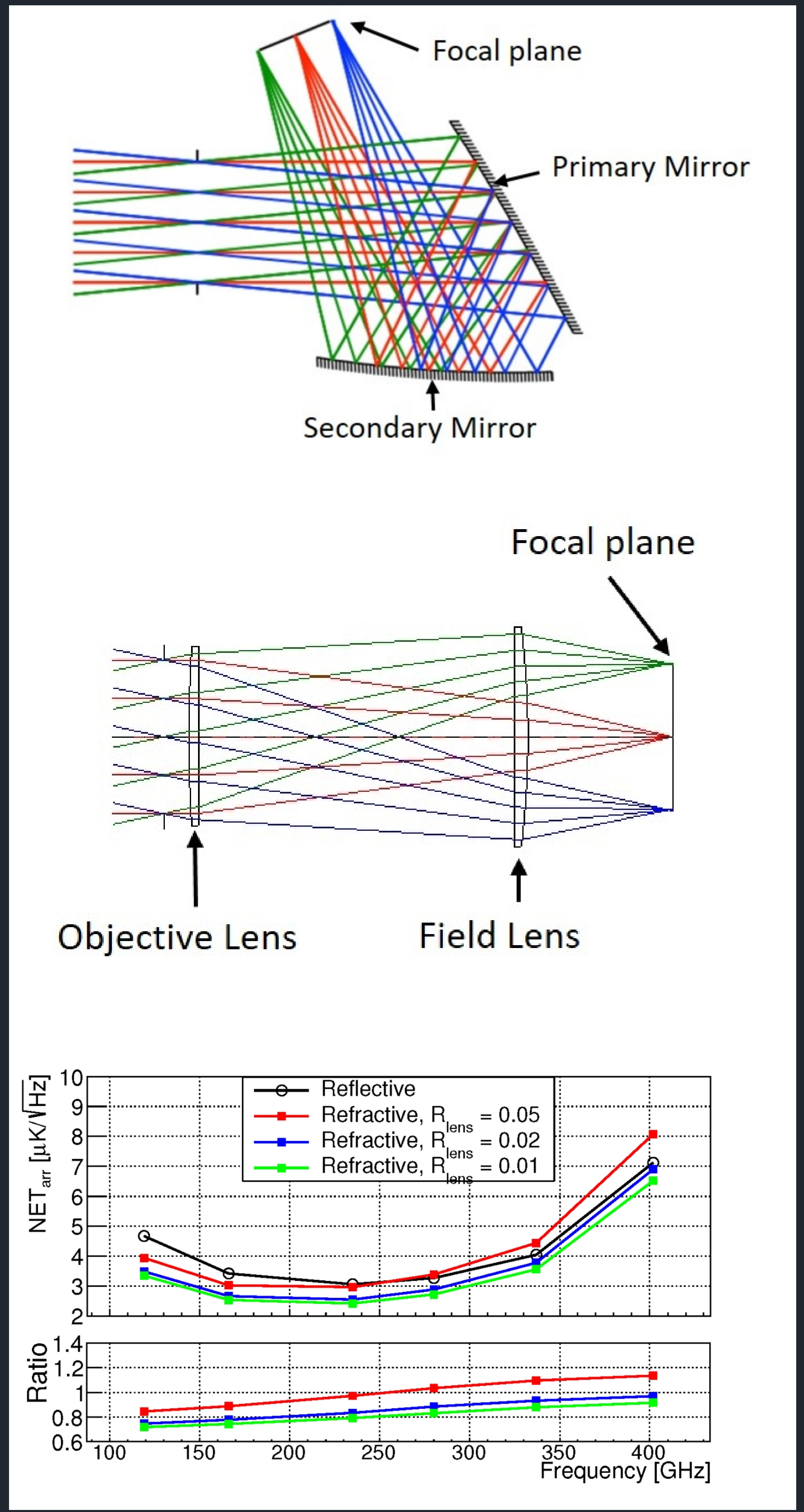
Center frequency (GHz)	End-to-end optical efficiency	NEP_{ph} ($aW/\sqrt{Hz}$)	NEP_{g} ($aW/\sqrt{Hz}$)	NEP_{read} ($aW/\sqrt{Hz}$)	NEP_{ext} ($aW/\sqrt{Hz}$)	NEP_{det} ($aW/\sqrt{sec}$)	NET_{det} ($\mu K\sqrt{sec}$)	NET_{arr} ($\mu K\sqrt{sec}$)
40	0.32	5.44	3.95	2.67	4.09	8.31	114.63	18.5
60	0.49	5.26	3.59	2.43	3.86	7.84	65.28	10.54
78	0.49	5.98	3.79	2.57	4.26	8.65	58.61	9.46
50	0.43	5.72	4.04	2.74	4.25	8.64	72.48	16.54
68	0.46	5.81	3.8	2.58	4.19	8.51	68.81	15.7
89	0.46	6.58	3.97	2.69	4.61	9.36	62.33	14.22
68	0.33	6.58	4.18	2.83	4.69	9.53	105.64	9.84
89	0.46	6.85	4.11	2.78	4.79	9.72	65.18	6.07
119	0.56	8.18	4.48	3.04	5.55	11.27	40.78	3.8
78	0.39	6.76	4.18	2.83	4.77	9.69	82.51	7.69
100	0.51	6.97	4.04	2.74	4.81	9.78	54.88	5.11
140	0.59	8.45	4.36	2.95	5.63	11.44	38.44	3.58
100	0.43	7.62	4.36	2.95	5.24	10.64	71.7	4.19
119	0.45	8.92	4.84	3.28	6.03	12.25	55.65	2.82
140	0.46	9.27	4.74	3.21	6.16	12.52	54	3.16
166	0.47	9.56	4.57	3.09	6.24	12.68	54.37	2.75
195	0.46	9.78	4.37	2.96	6.29	12.77	59.61	3.48
195	0.5	13.23	5.79	3.93	8.46	17.19	73.96	5.19
235	0.53	12.31	5.01	3.4	7.76	15.77	76.06	5.34
280	0.52	11.91	4.49	3.04	7.4	15.04	97.26	6.82
337	0.48	11.58	4	2.71	7.1	14.42	154.64	10.85
402	0.43	10.85	3.43	2.32	6.57	13.34	385.69	23.45

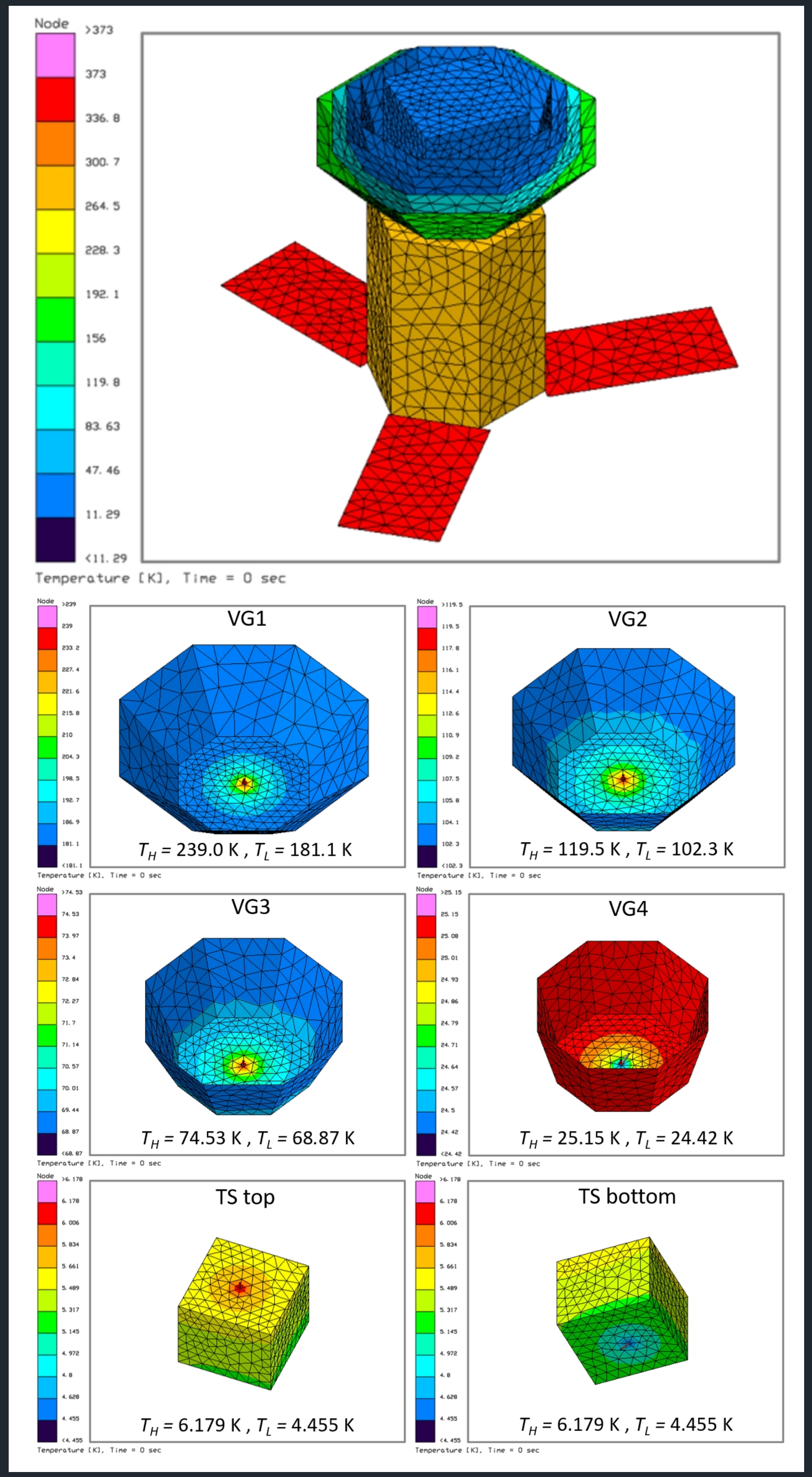
Sensitivity estimation for CMB space mission

T.Hasebe et al, LTD 2021

Trade study of LiteBIRD instuments

T.Hasebe et al, JLTP 2018



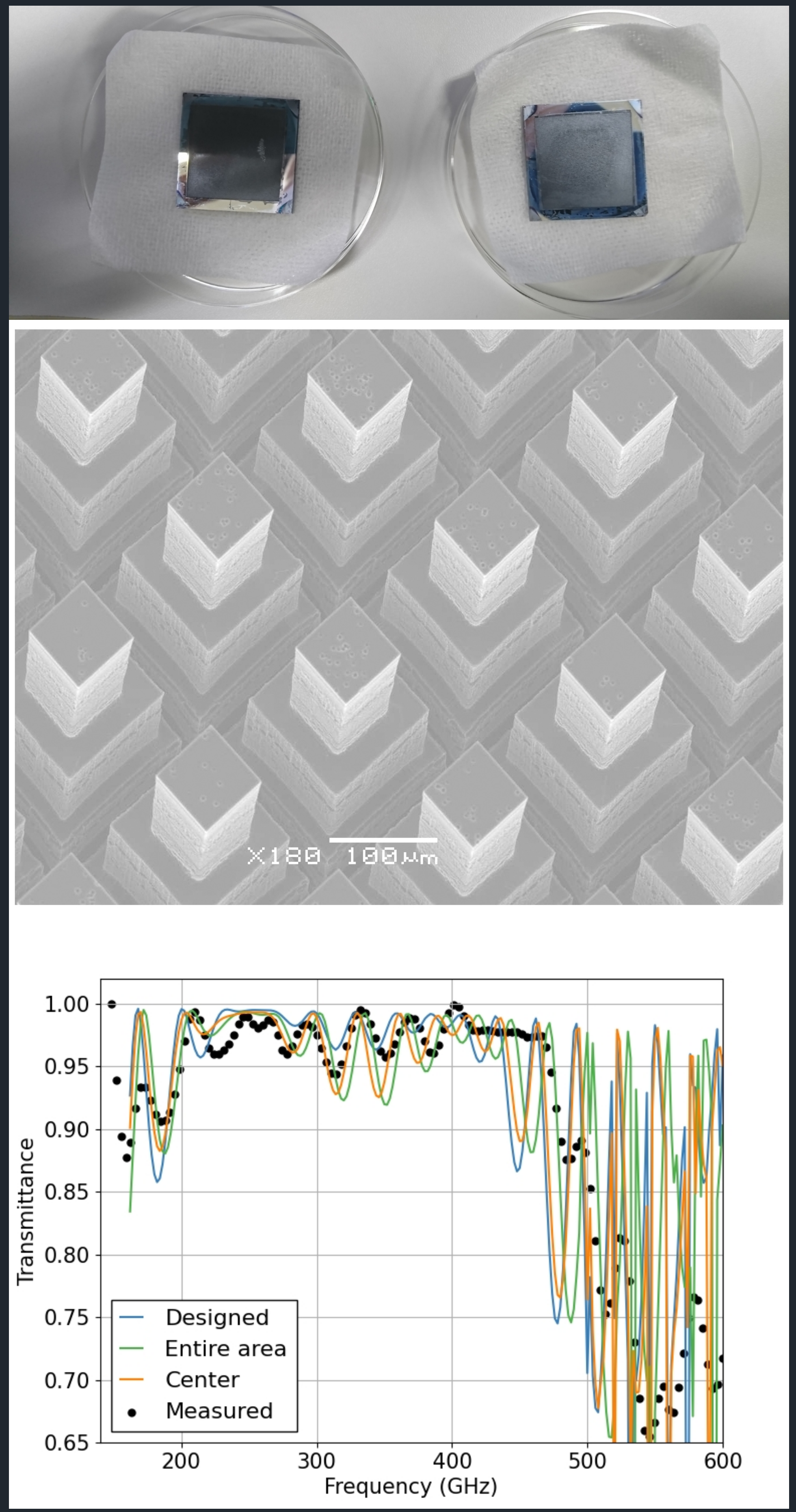


Thermal design of LiteBIRD satellite

T.Hasebe et al, JATIS 2019

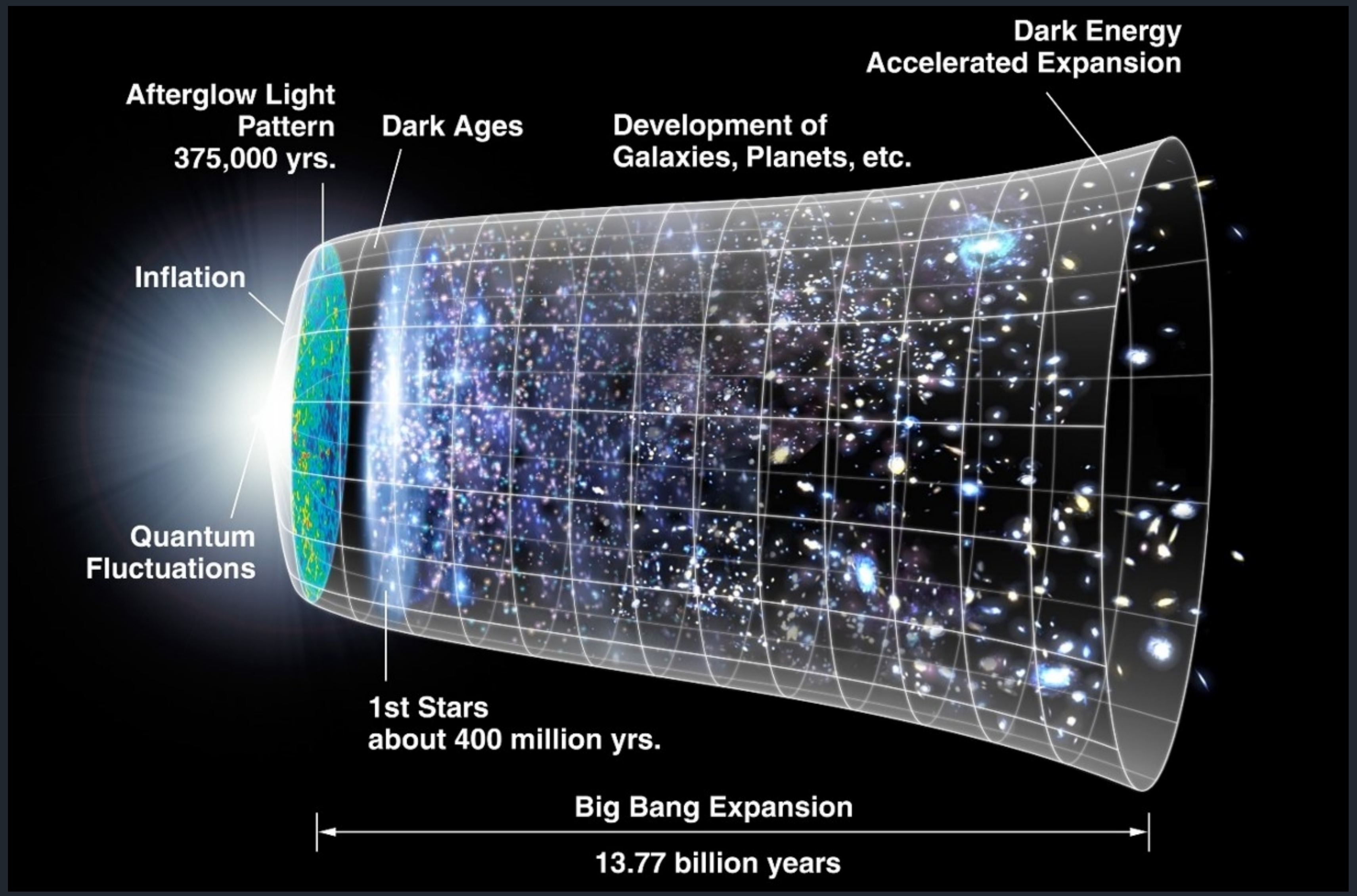
Development of broadband CMB optical devices

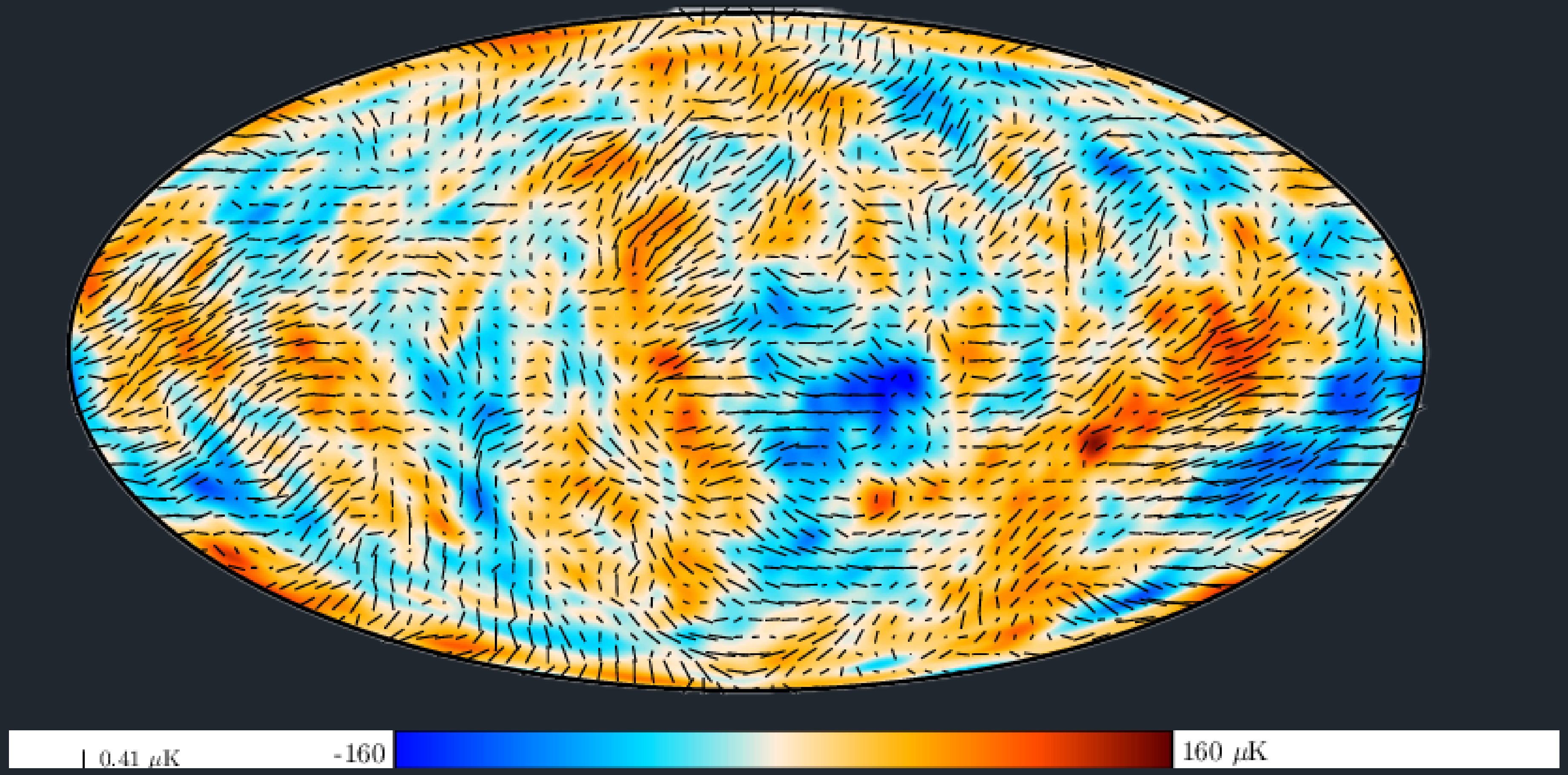
T.Hasebe et al, submitted



CMB Polarization and Cosmology

- Problems behind Big Bang model
- Inflation Phypothesis
- Gravitational wave
- CMB B-mode (parity-odd) polarization





Planck 2018 polarization data

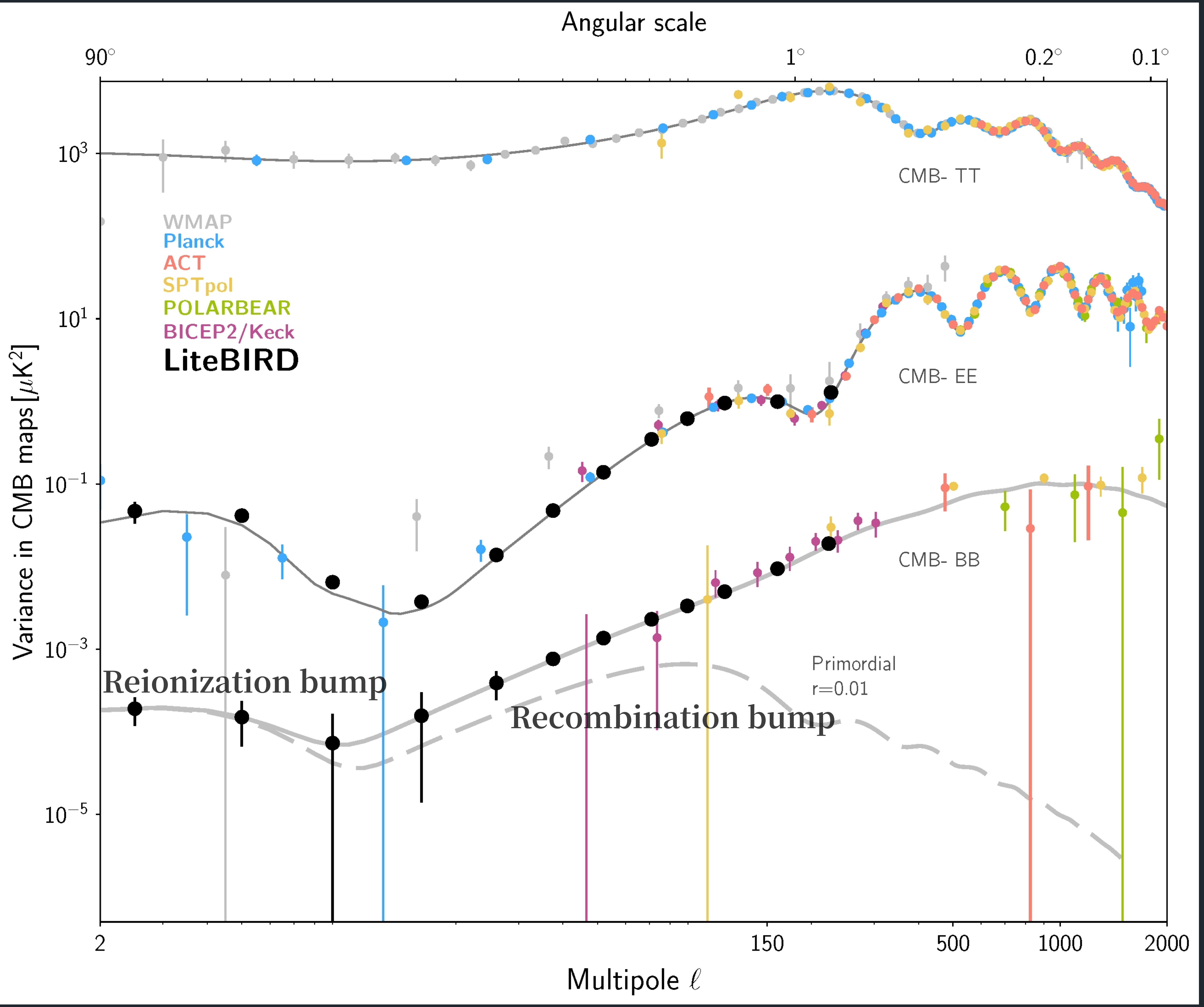
CMB Polarization Observations

Space mission

Ground experiment

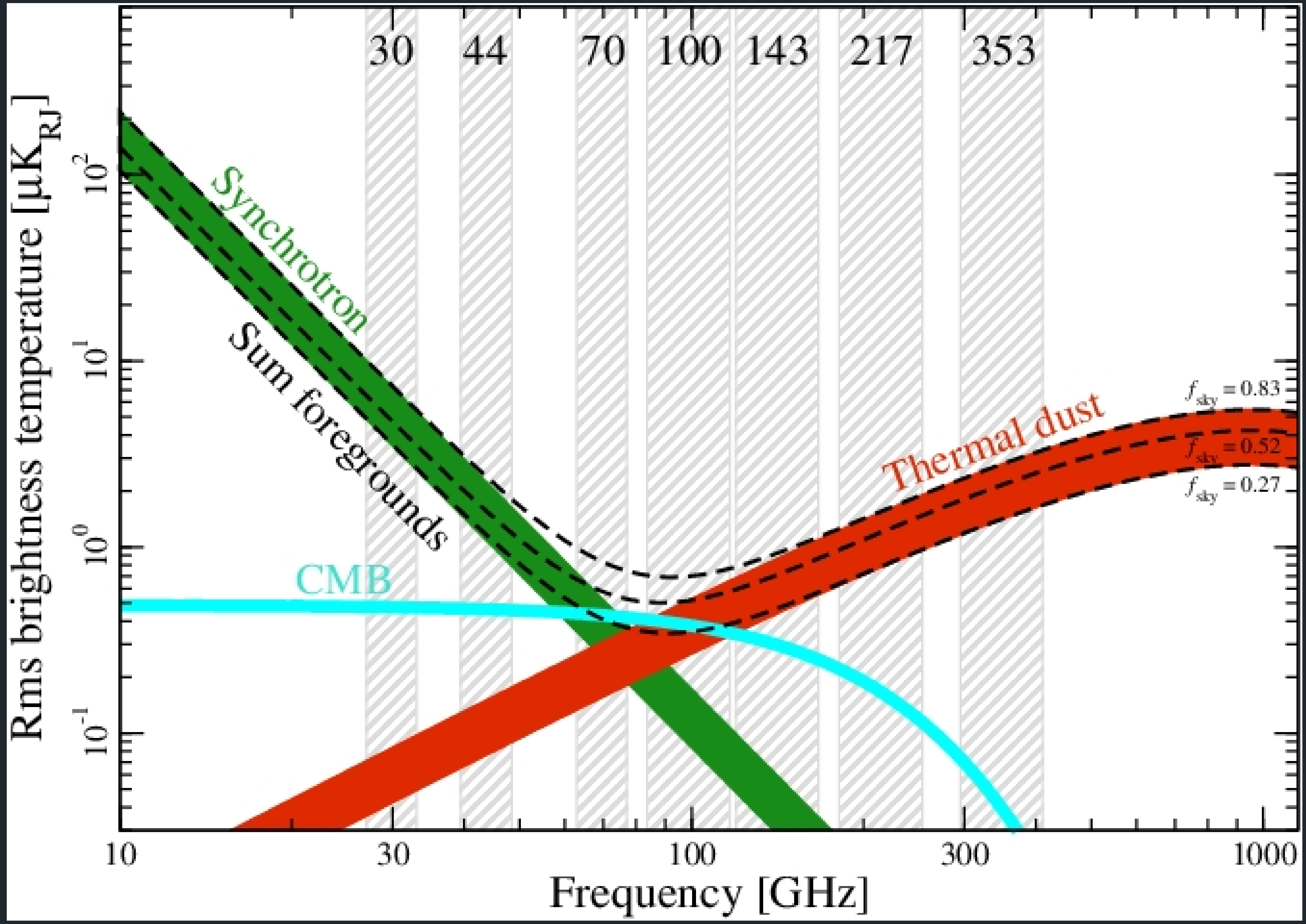
Why Space Mission?

- **Large anglar scale observation**
  Direct mesurement of Reionization bump
- **No atomospheric absorption**
  Higher observation efficiency
  No limitation of observation frequency choice
- **Stable thermal environment**
  Constant thermal radiation from the Sun
  Stable instrument performance

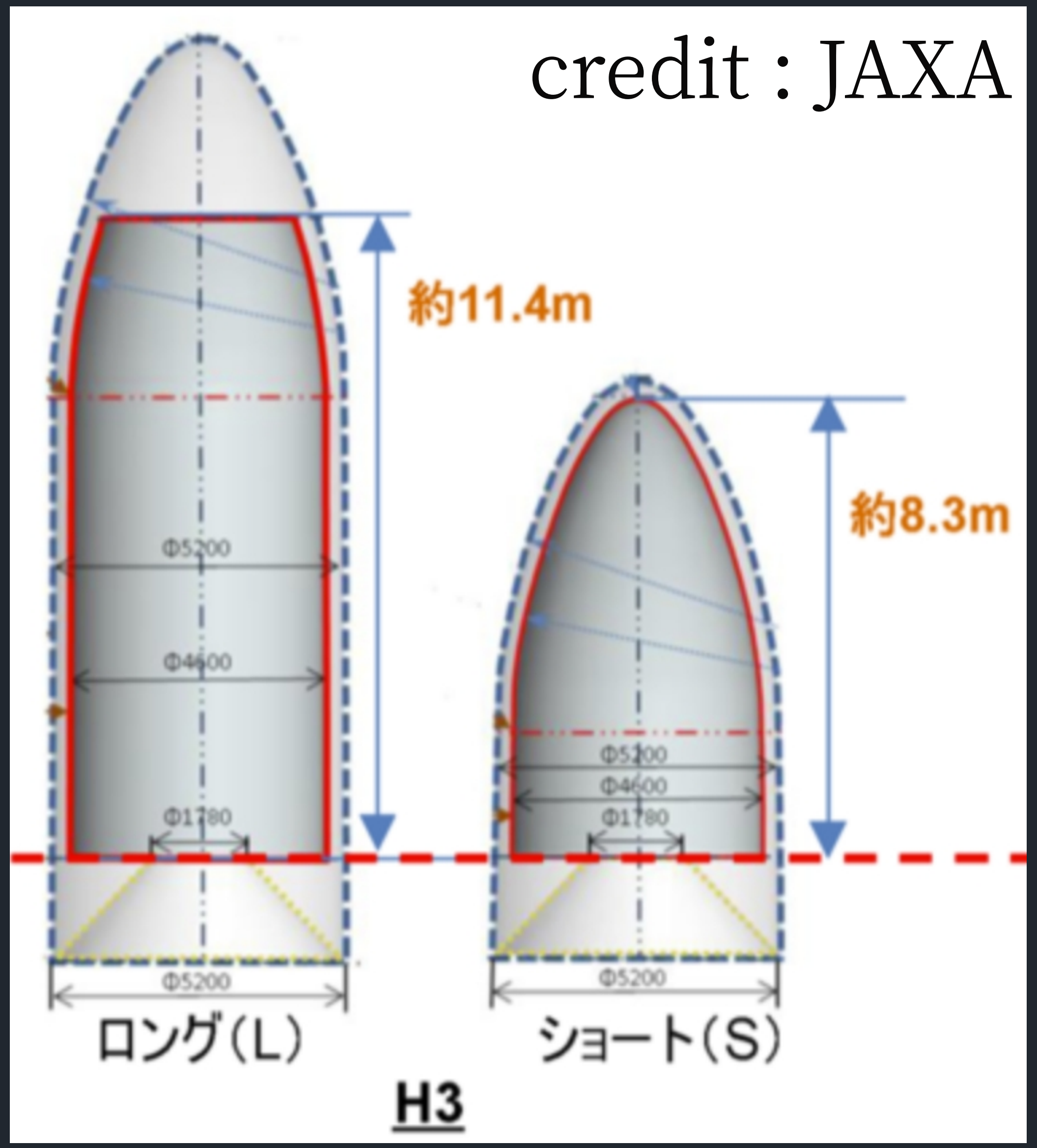


Wide Frequency Range Observation

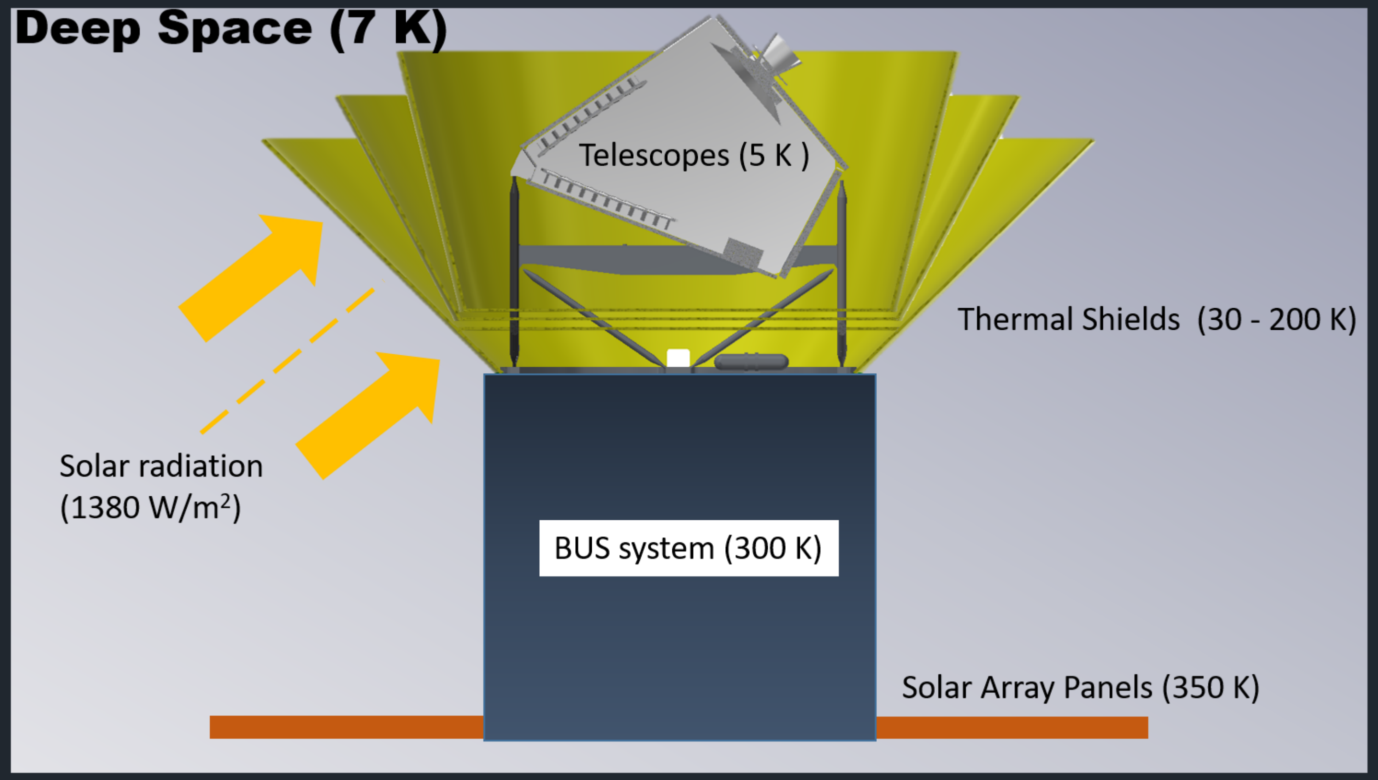
- Foregrounds (synchrotron radiation, thermal dust emission, and etc…) are fake signals of CMB.
- Foreground subtraction accuracy depens on frequency coverage and sensitivity of observation bands.
- A key develpment for CMB space mission is…
  How to develop a broadband and high-sensitivity observation syatem with limited resources.

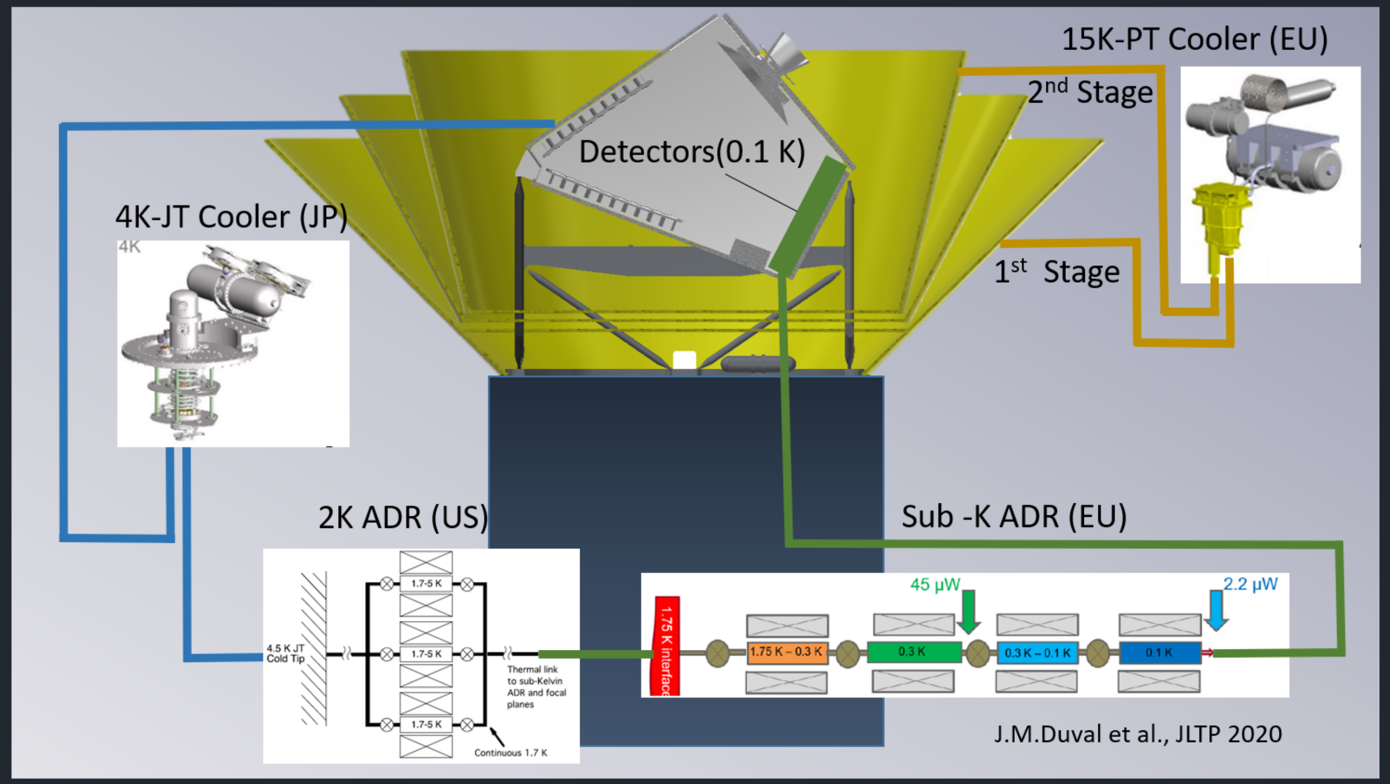


Design Constraints

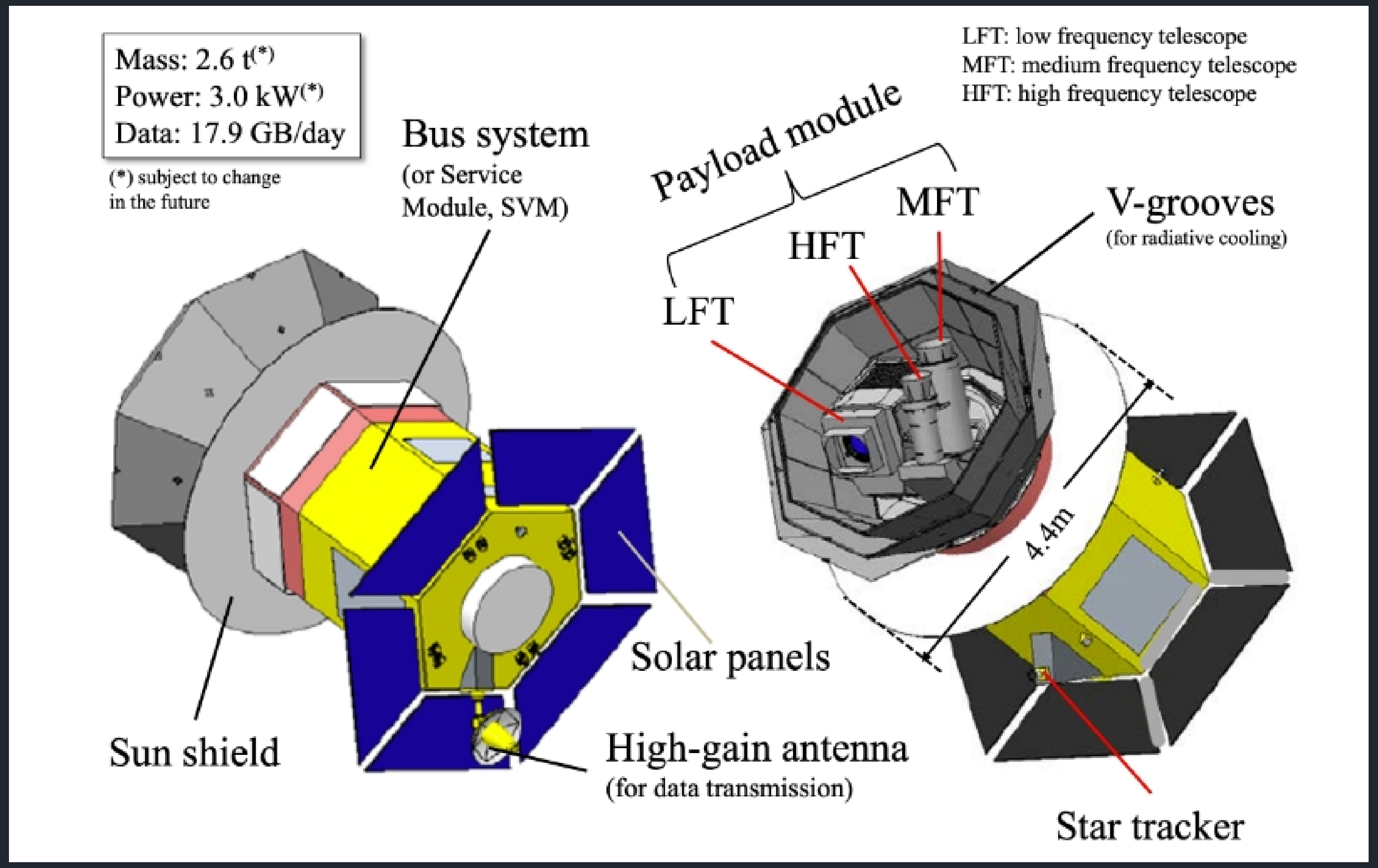


Launch vehicle →
Instument size





Mechanical & Thermal →
Instument mass and temperature



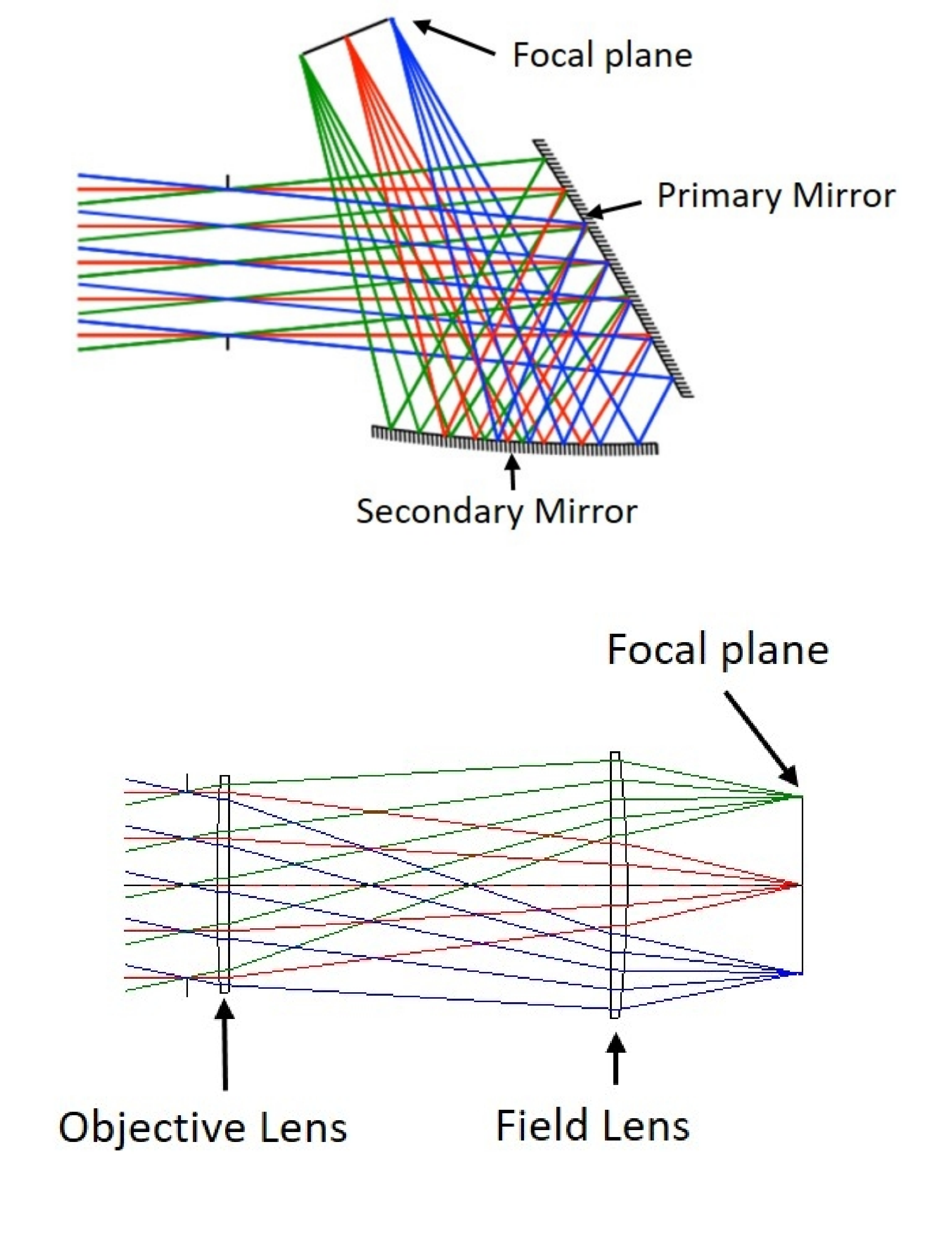
Electric power, Telecommunication →
Readout system,
Number of detector channnels

and Cost is a big factor

Consept Design Study

Key requiments

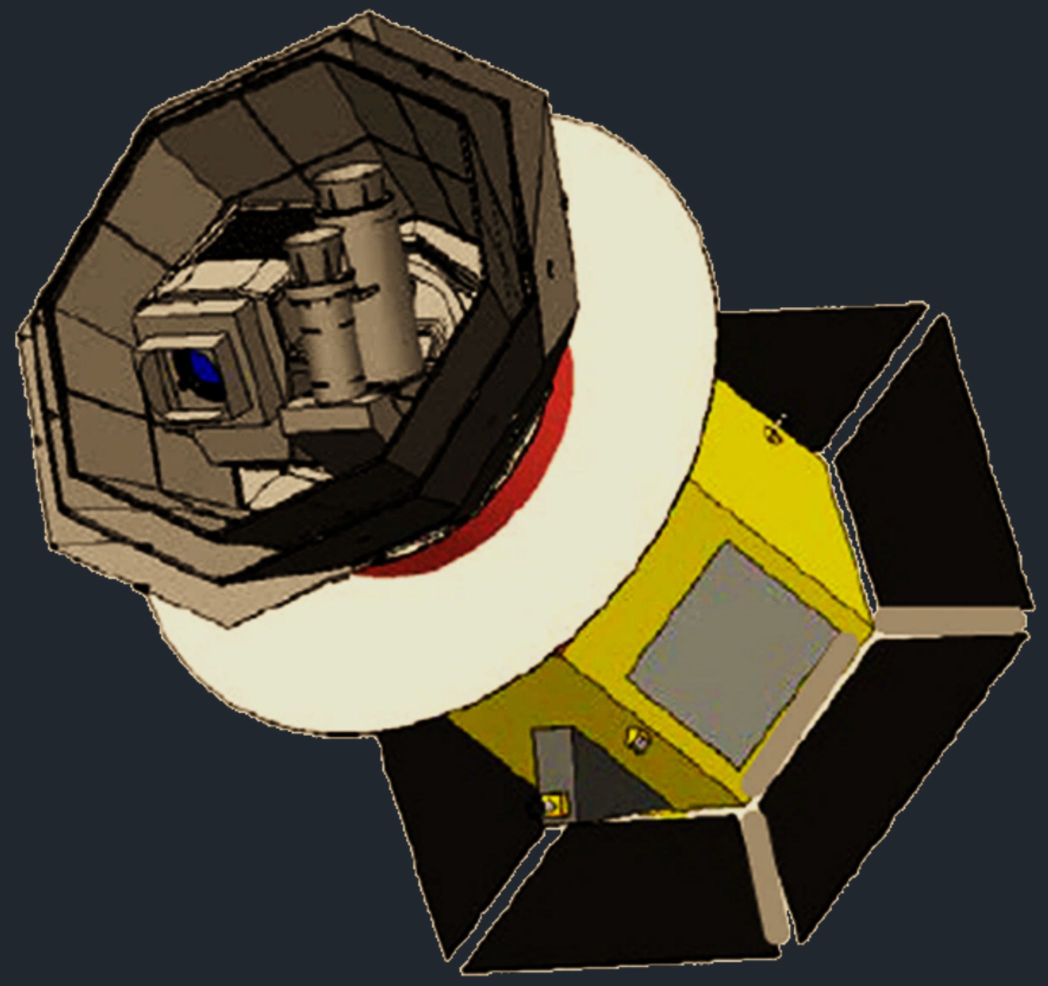
- L1 : Sience requirements
  - The mission shall measure the tensor-to-scalar ratio r with a total uncertainty of $\delta r < 1 \times 10^{-3}$.
- L2 : Mesurement requirements
  - The number of observing bands shall be 15.
  - The observing frequency range shall be between 40 GHz and 402 GHz.
- L3 : Integrated system requirements
  - The 5K enclosure + instruments shall fit within the mechanical envelope of 1.7m x 1.7m x 1.4m.



→ ## Design trade study

- Telescope Type
  - Reflective (mirror-type) : less gohsting but isseus of stray-light and large volume
  - Refractive (lens-type) : small valume but issues of optical gohsting
- Frequency coverage
  - Transmittance of optical elements
  - Detector arrangements
- Number of telescopes
  - Volume allocation
  - Mechanical requiements (including thermal)

LiteBIRD Telescope Design

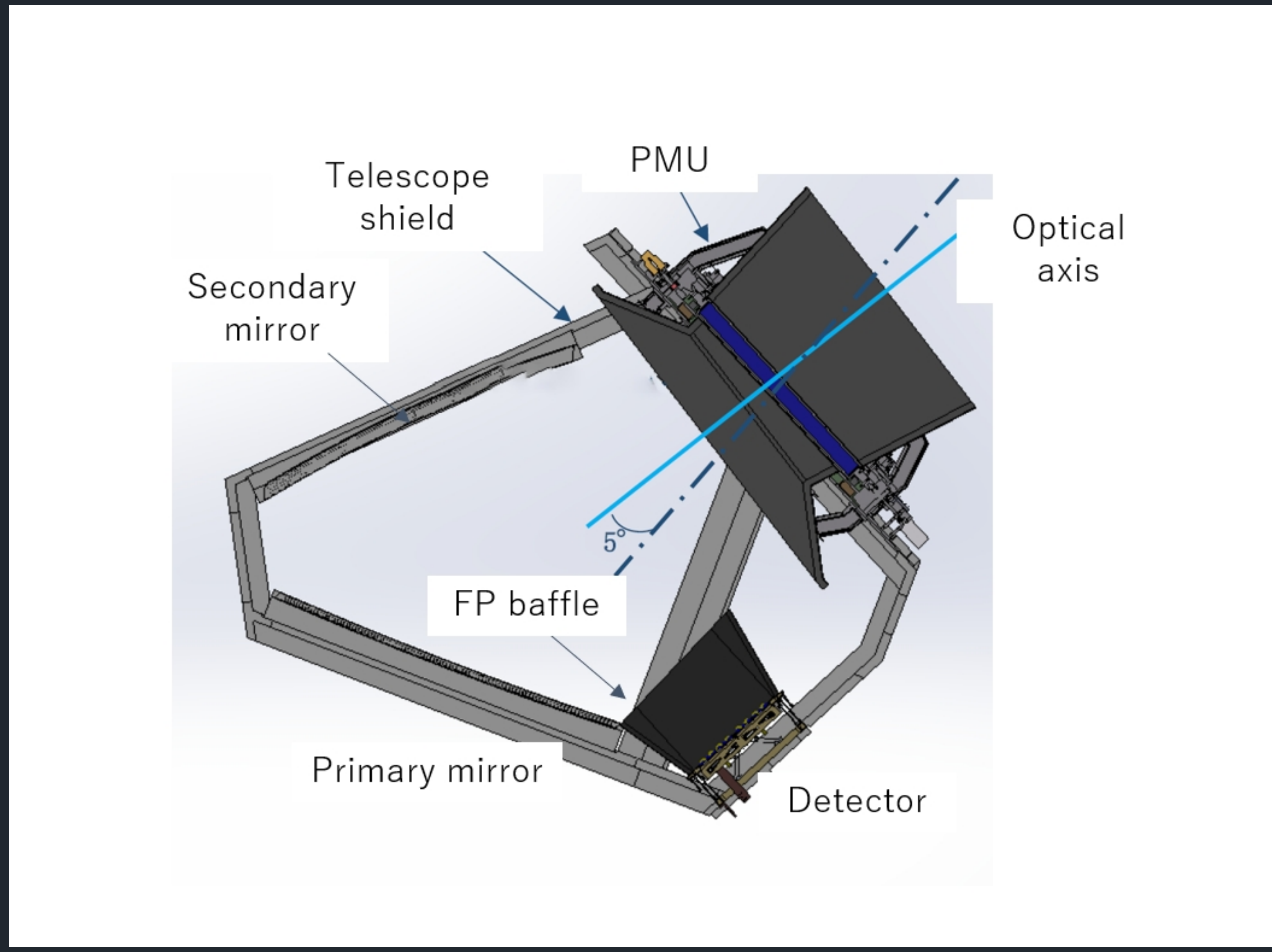


LiteBIRD observation frequency 34 - 450 GHz

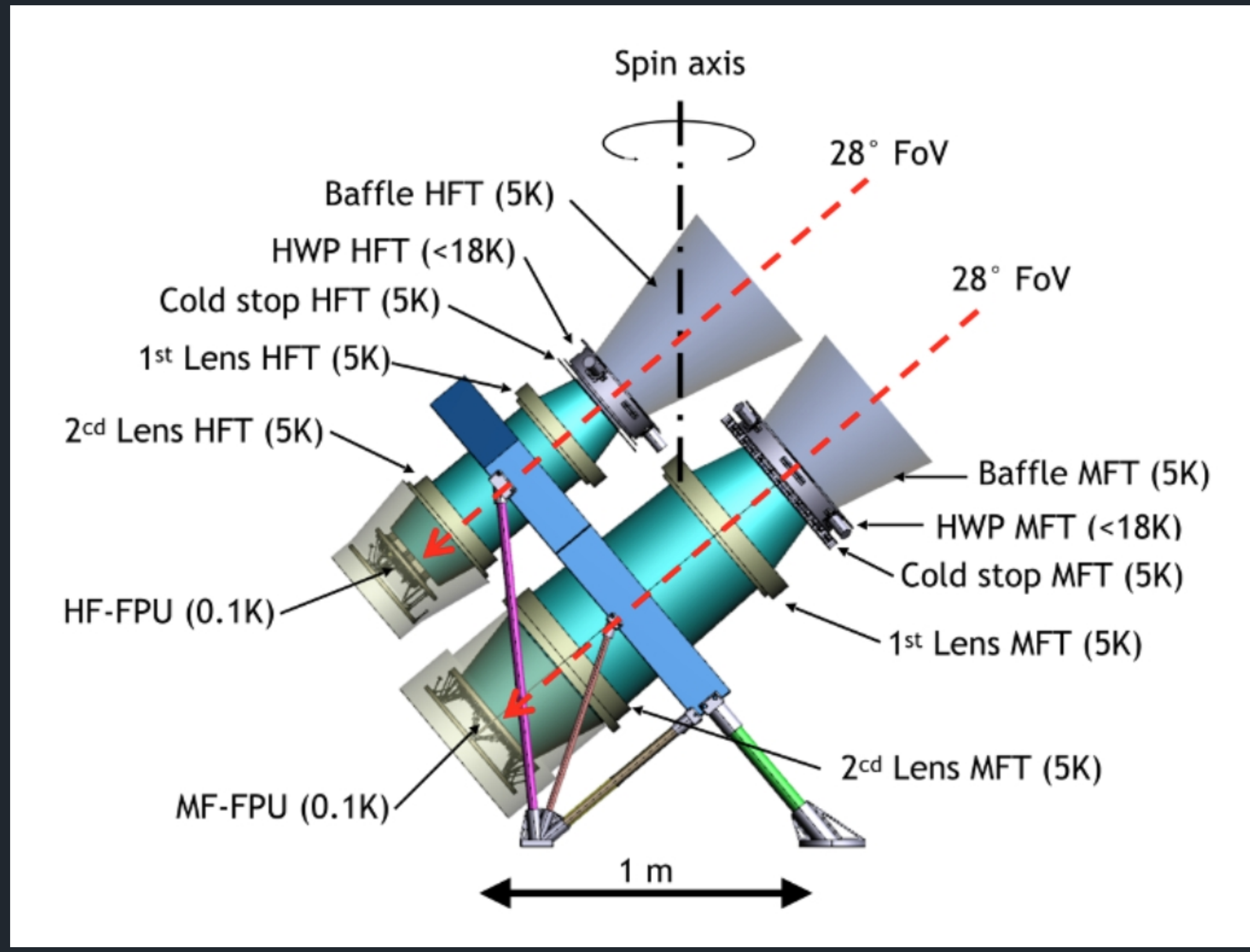
- Low Frequency Telescope (LFT) : 34 - 160 GHz
- Middle Freqency Telescopt (MFT) : 88 - 190 GHz
- High Freqency Telescopt (HFT) : 224 - 450 GHz

Frequency coverages are determined by bandwidth of transmissive optics (filter, window, lens).
In the case of LiteBIRD, bandwidths of the HWPs are key driver for telescope design.

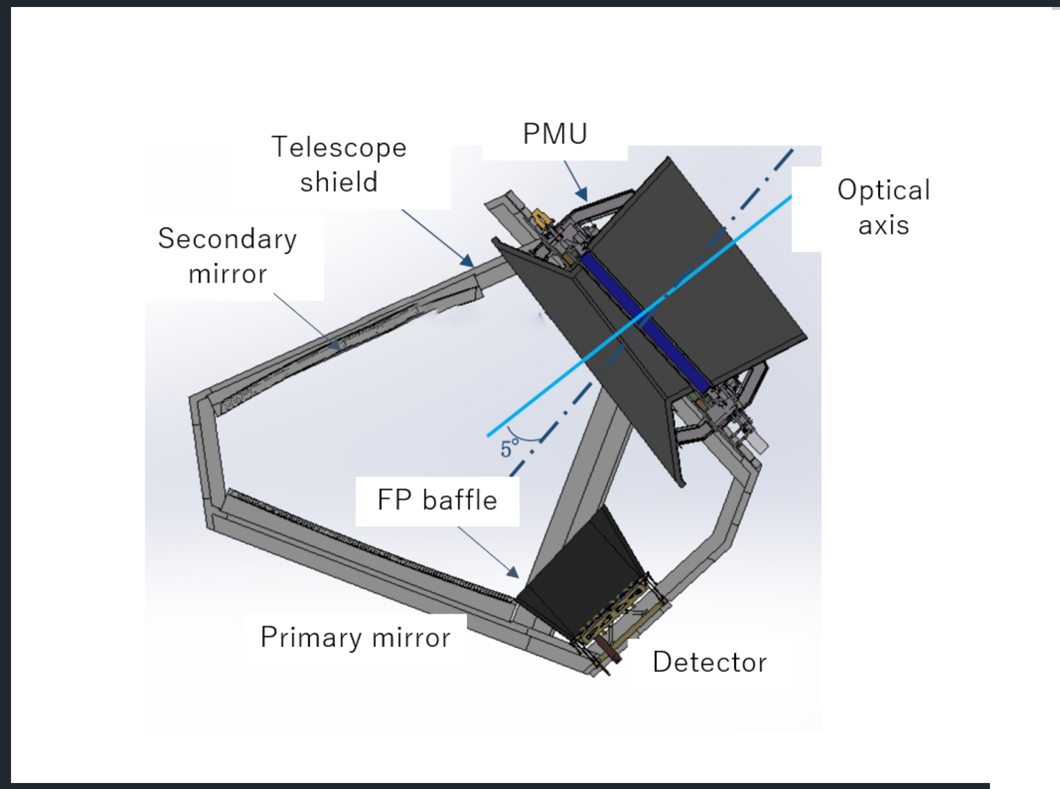
LFT

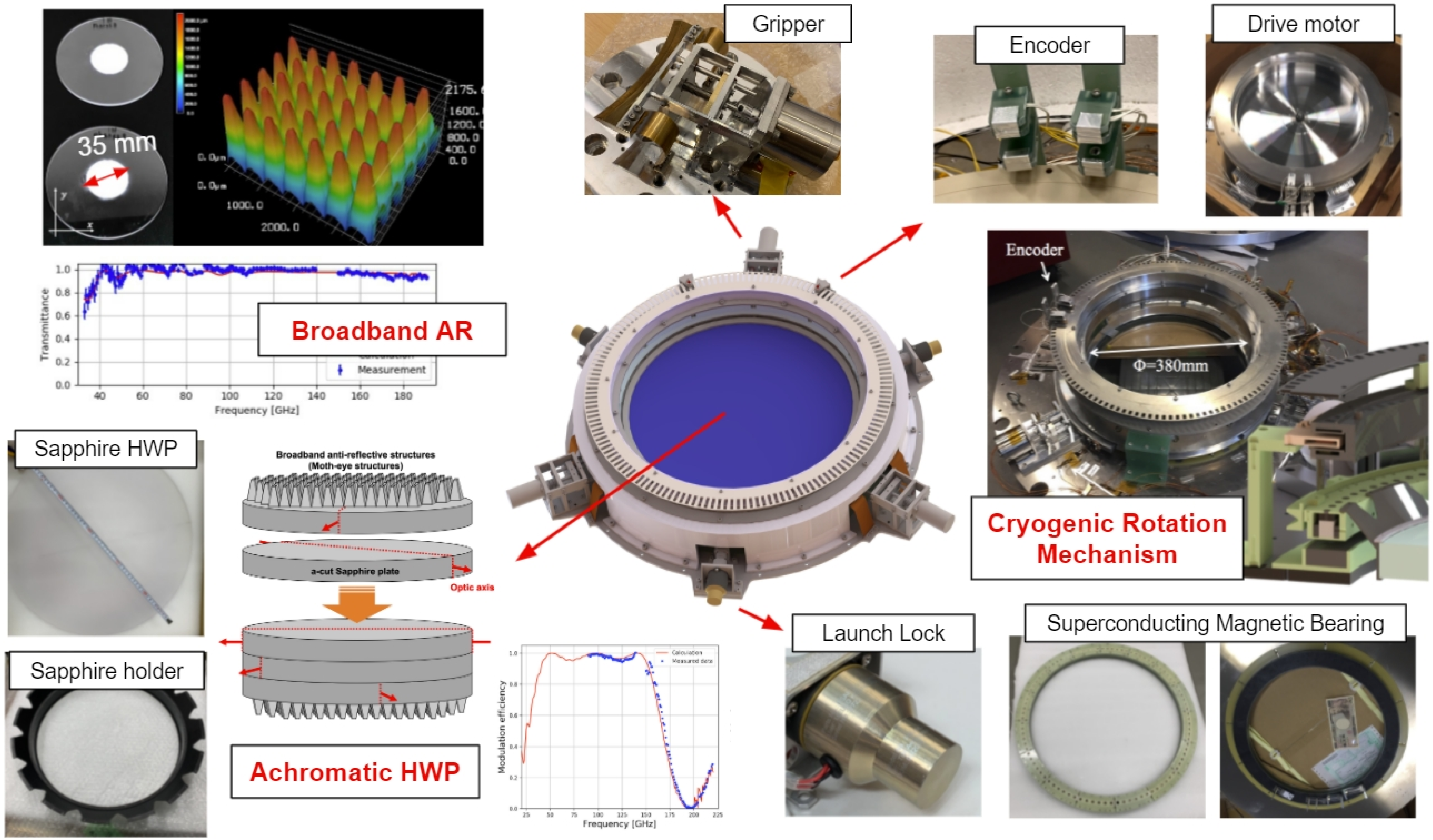


M,HFT



Development of Polarization Modulation Unit at IPMU





Related papers

K. Komatsu et al, JATIS 2021

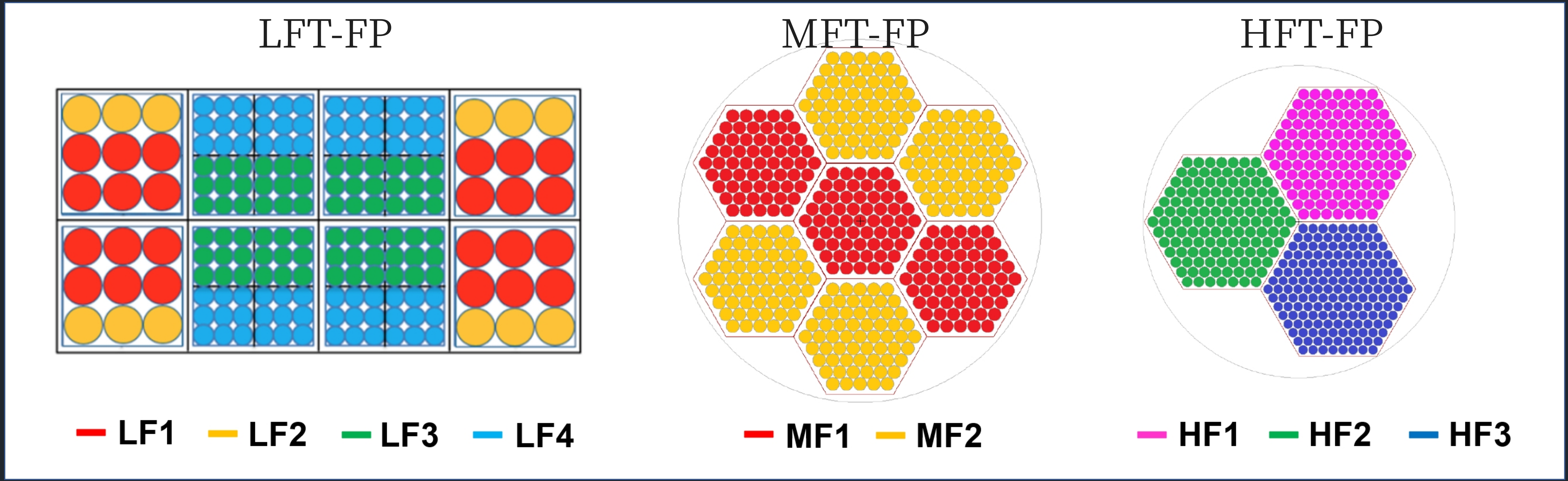
Y. Sakurai et al, SPIE 2020

S. Sugiyama et al, SPIE 2020

R. Takaku et al, SPIE 2020

etc…

Detctor Array Design



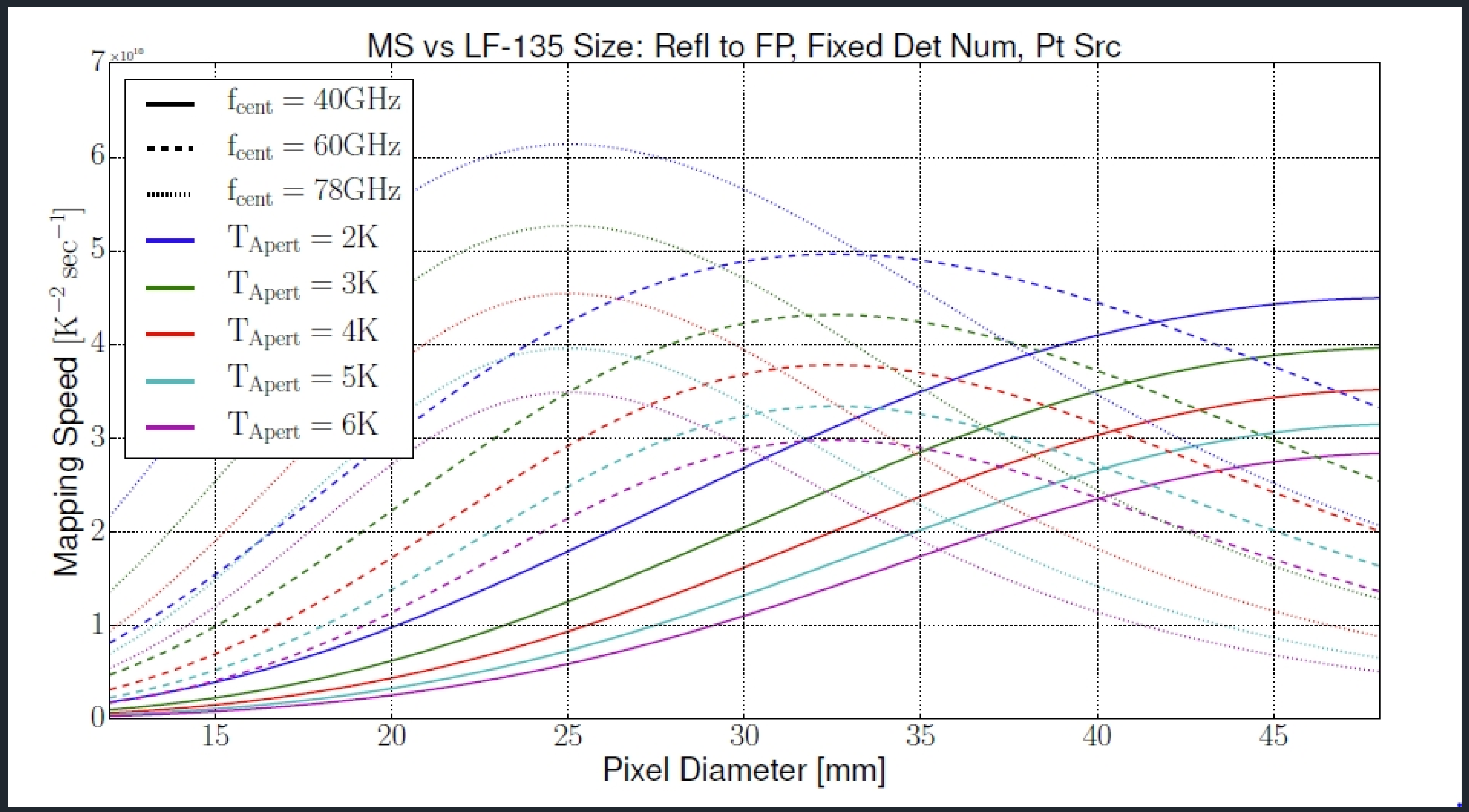
Module	f_{center} (GHz)	Fraction of band width	Pixel size (mm)	Number of pixels	Number of detectors
LF1	40	0.30	32.0	24	48
	60	0.23	32.0	24	48
	78	0.23	32.0	24	48
LF2	50	0.30	32.0	12	24
	68	0.23	32.0	12	24
	89	0.23	32.0	12	24
LF3	68	0.23	16.0	72	144
	89	0.23	16.0	72	144
	119	0.30	16.0	72	144
LF4	78	0.23	16.0	72	144
	100	0.23	16.0	72	144
	140	0.30	16.0	72	144
Total					1080

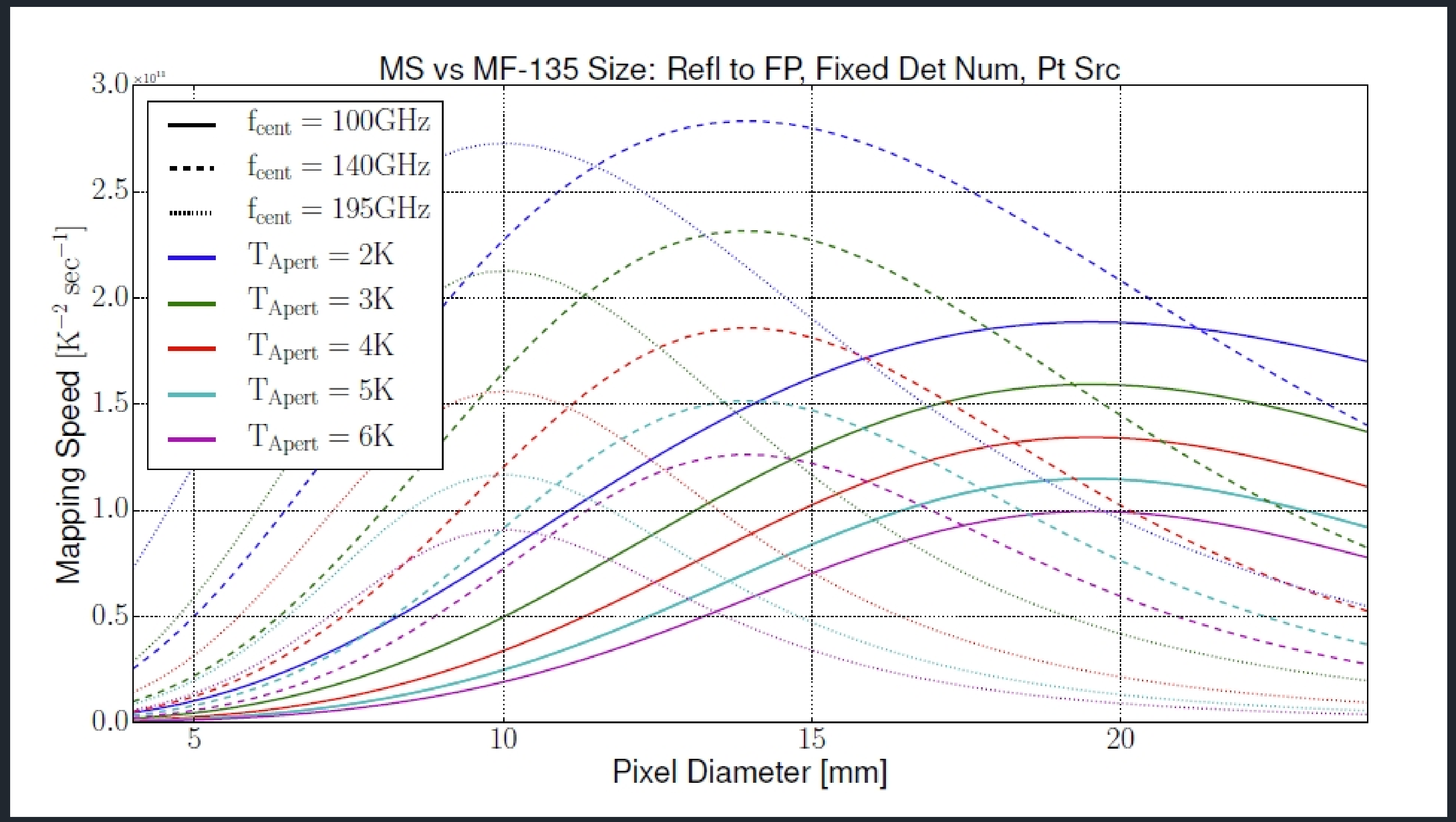
Apertute efficiency of single detector

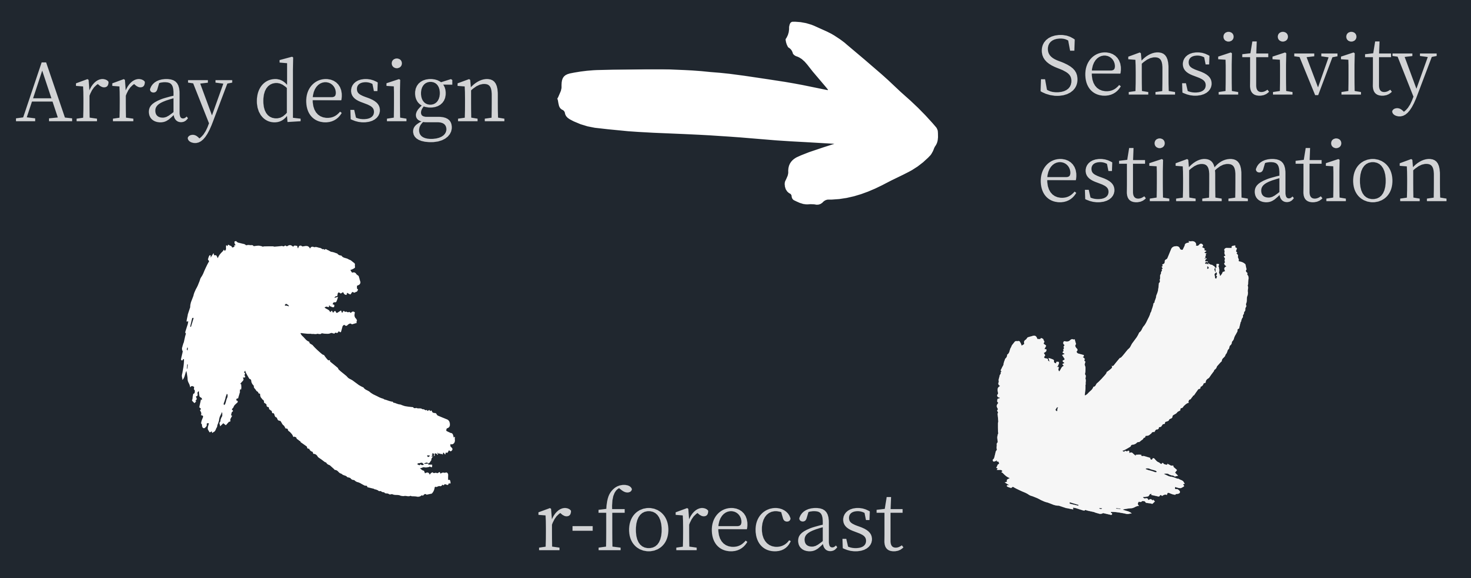
$$\eta_{Apt,LFT} = 1 - \exp\left[-\frac{\pi^2}{2}\left(\frac{D}{w_f\, F\, \lambda}\right)^2\right]$$

Large D : better efficiency, less N_{det}
Small D : worse efficiency, more N_{det}

Module	f_{center} (GHz)	Fraction of band width	Pixel size (mm)	Number of pixels	Number of detectors
MF1	100	0.23	12.0	183	366
	140	0.30	12.0	183	366
	195	0.30	12.0	183	366
MF2	119	0.30	12.0	244	488
	166	0.30	12.0	244	488
HF1	195	0.30	7.0	127	254
	280	0.30	7.0	127	254
HF2	235	0.30	7.0	127	254
	337	0.30	7.0	127	254
HF3	402	0.23	6.1	169	338
Total					3428



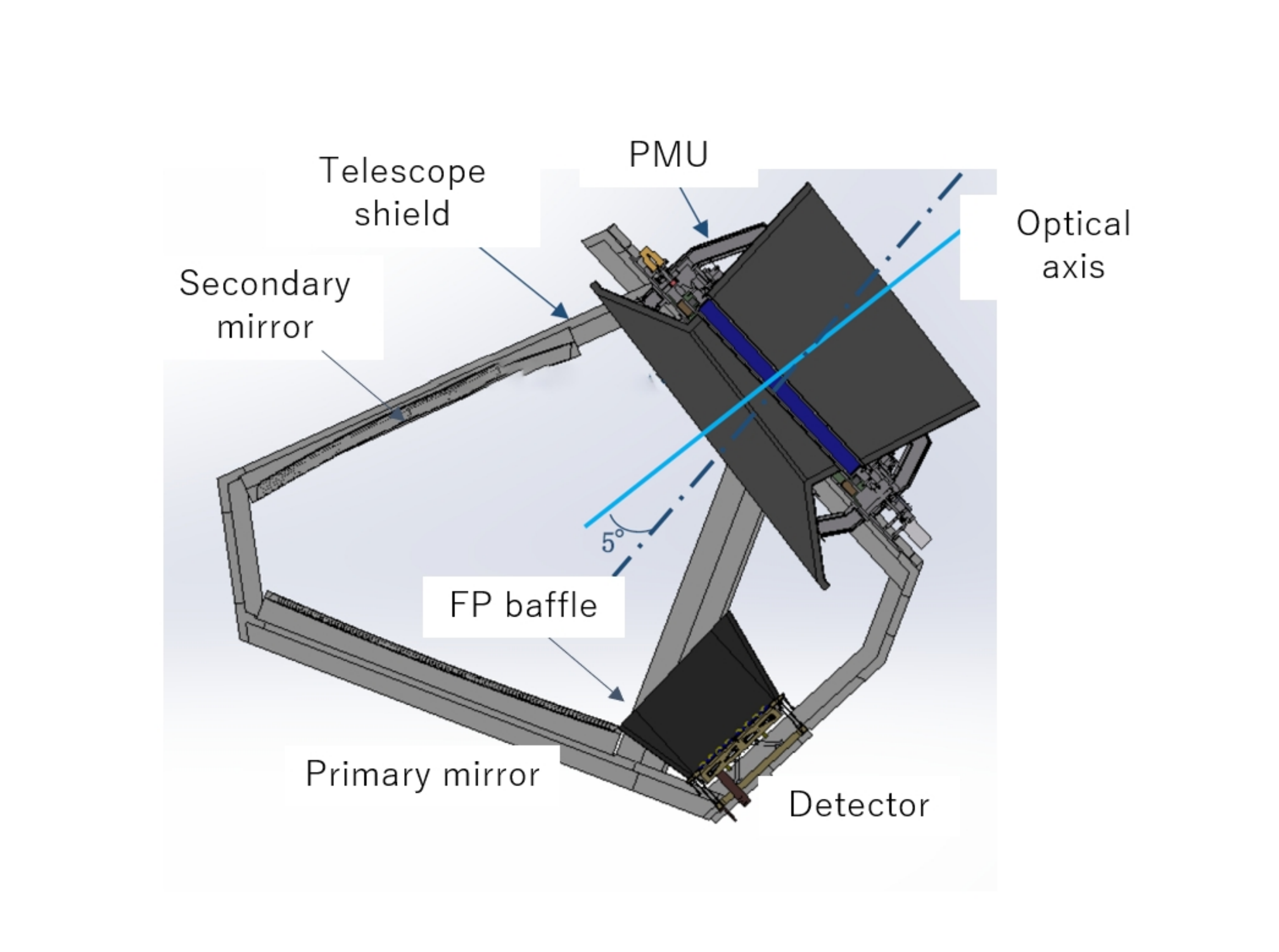


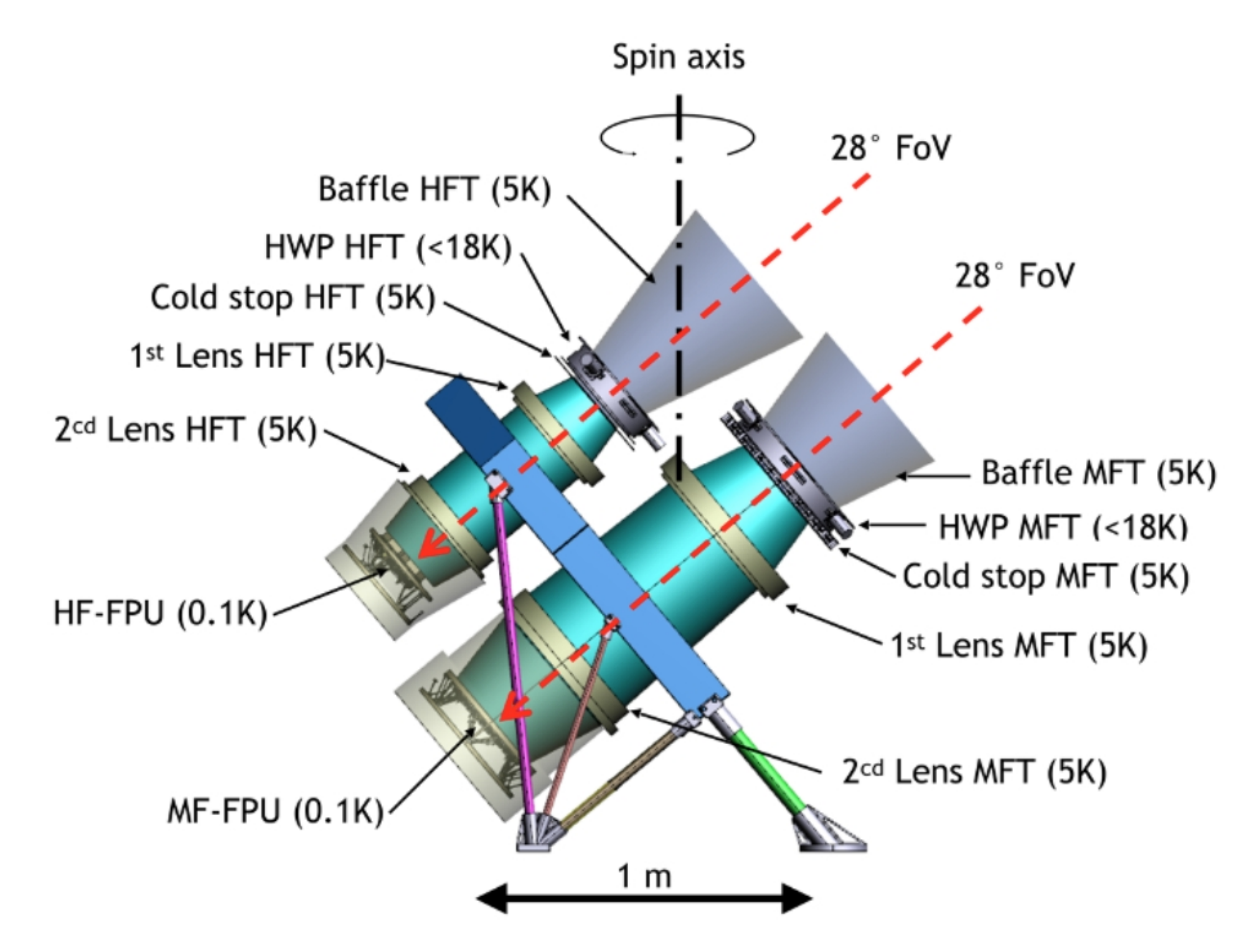


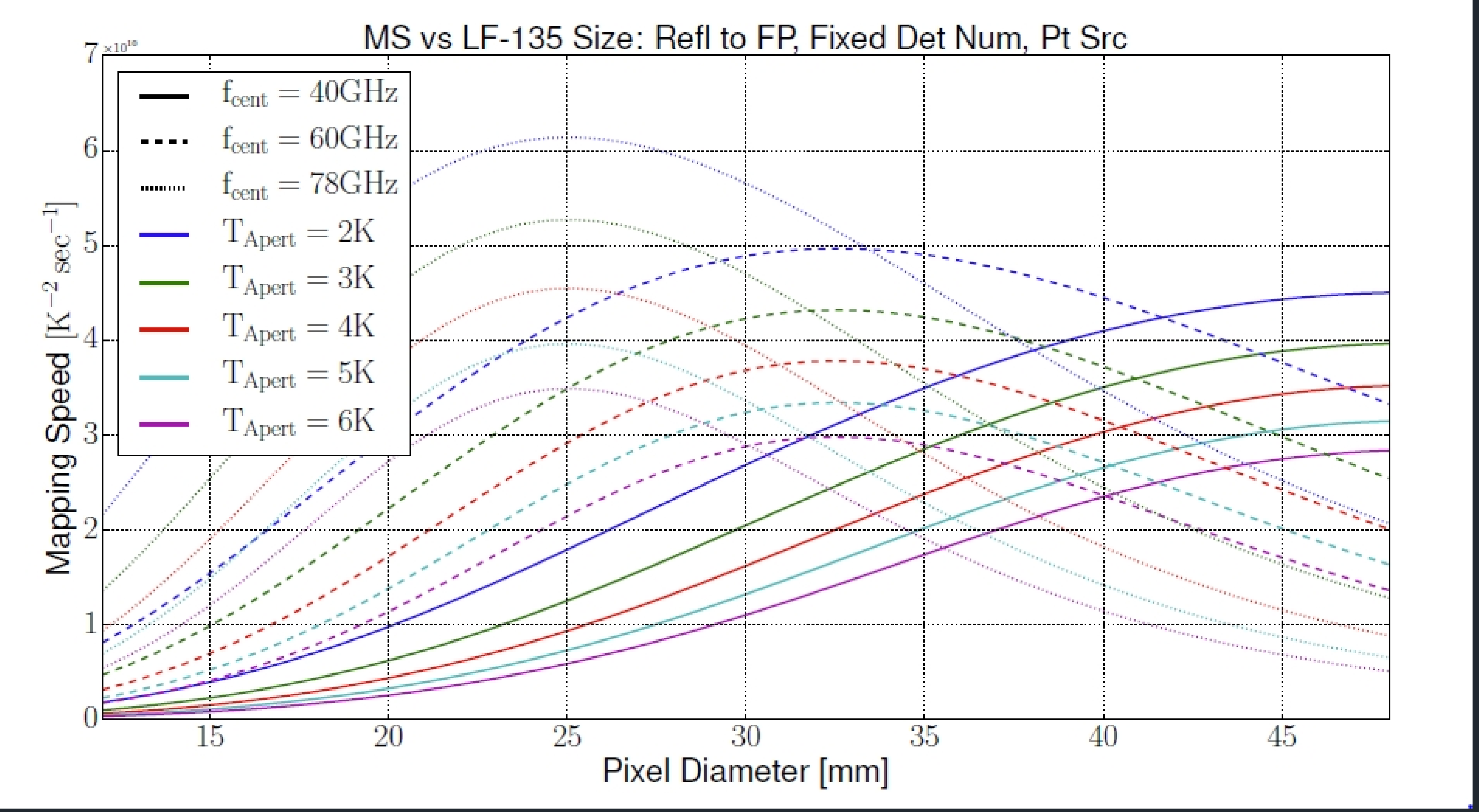
Cryogenics

LFT

MHFT







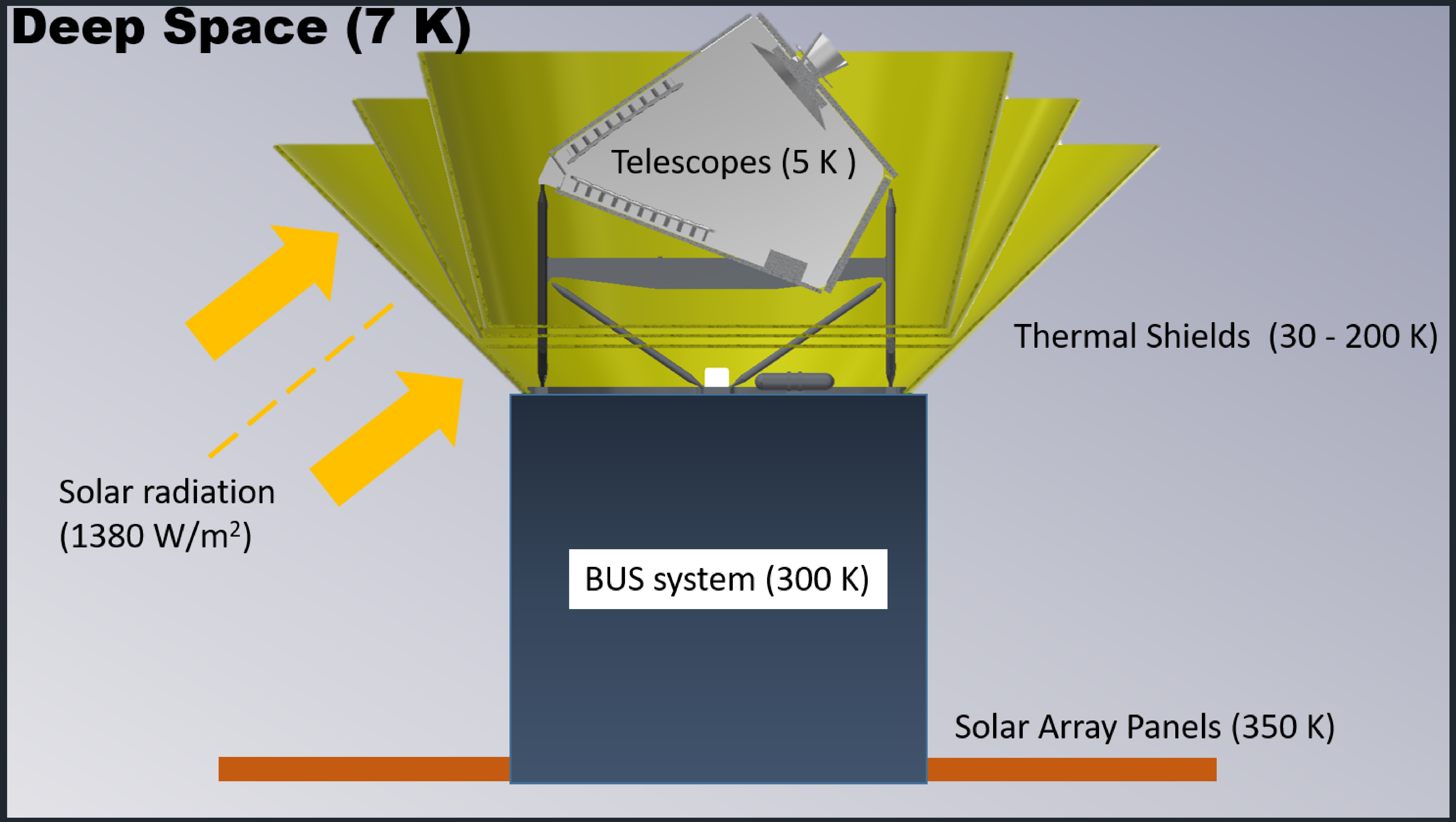
LFT Component	LFT T (K)	MHFT Component	MHFT T (K)
PMU	20.0	PMU	20.0
Telescope shield	5.0	Telescope shield	5.0
Primary mirror	5.0	First lens	5.0
Secondary mirror	5.0	Second lens	5.0
FP baffle	2.0	FP baffle	2.0
Thermal filter	2.0	Thermal filter	2.0
Detector	0.1	Detector	0.1

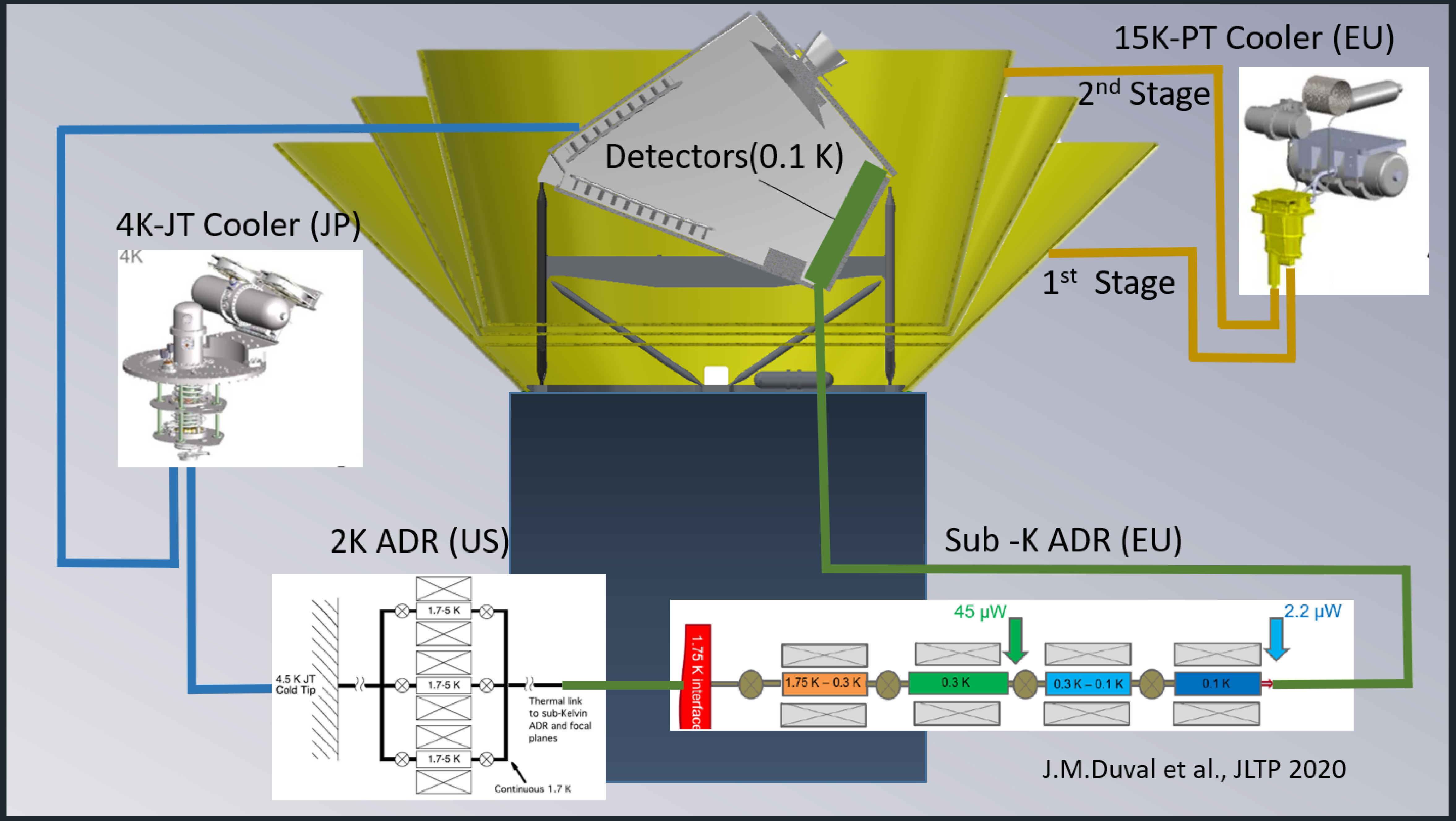
Science outcome of CMB space mission

↕

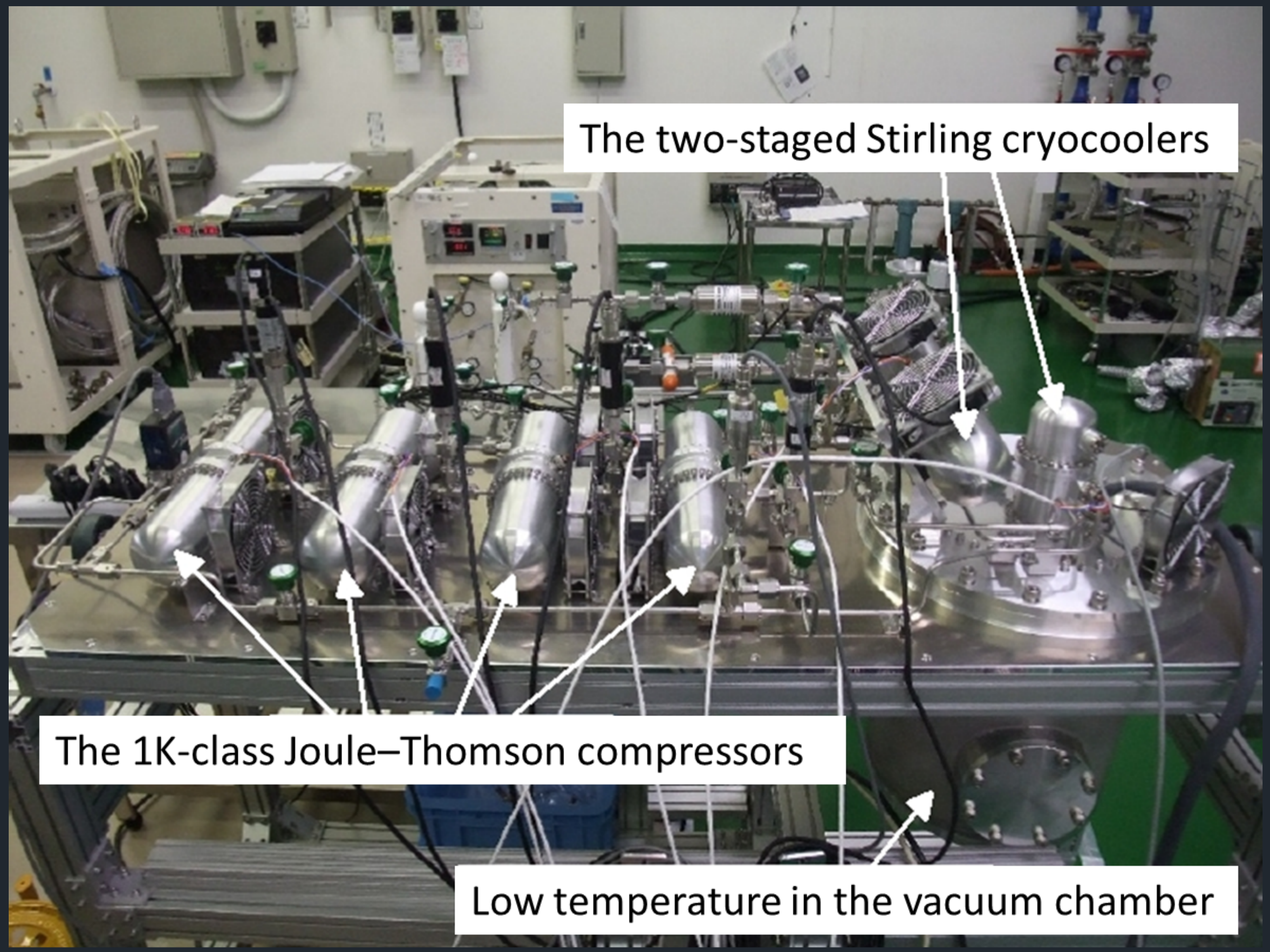
Technical maturity of space cryogenics

Thermal Design

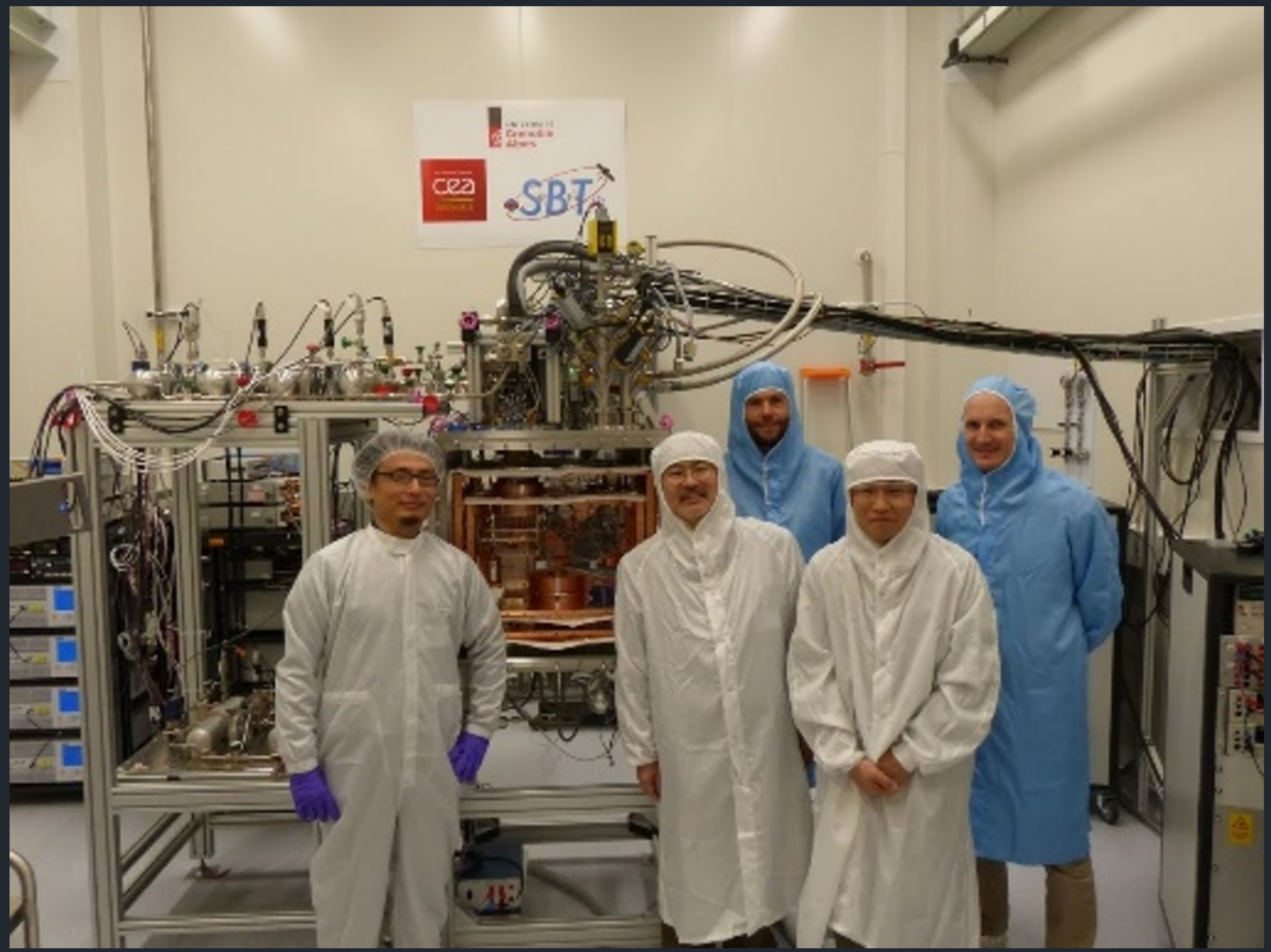




Space Cryocoolers



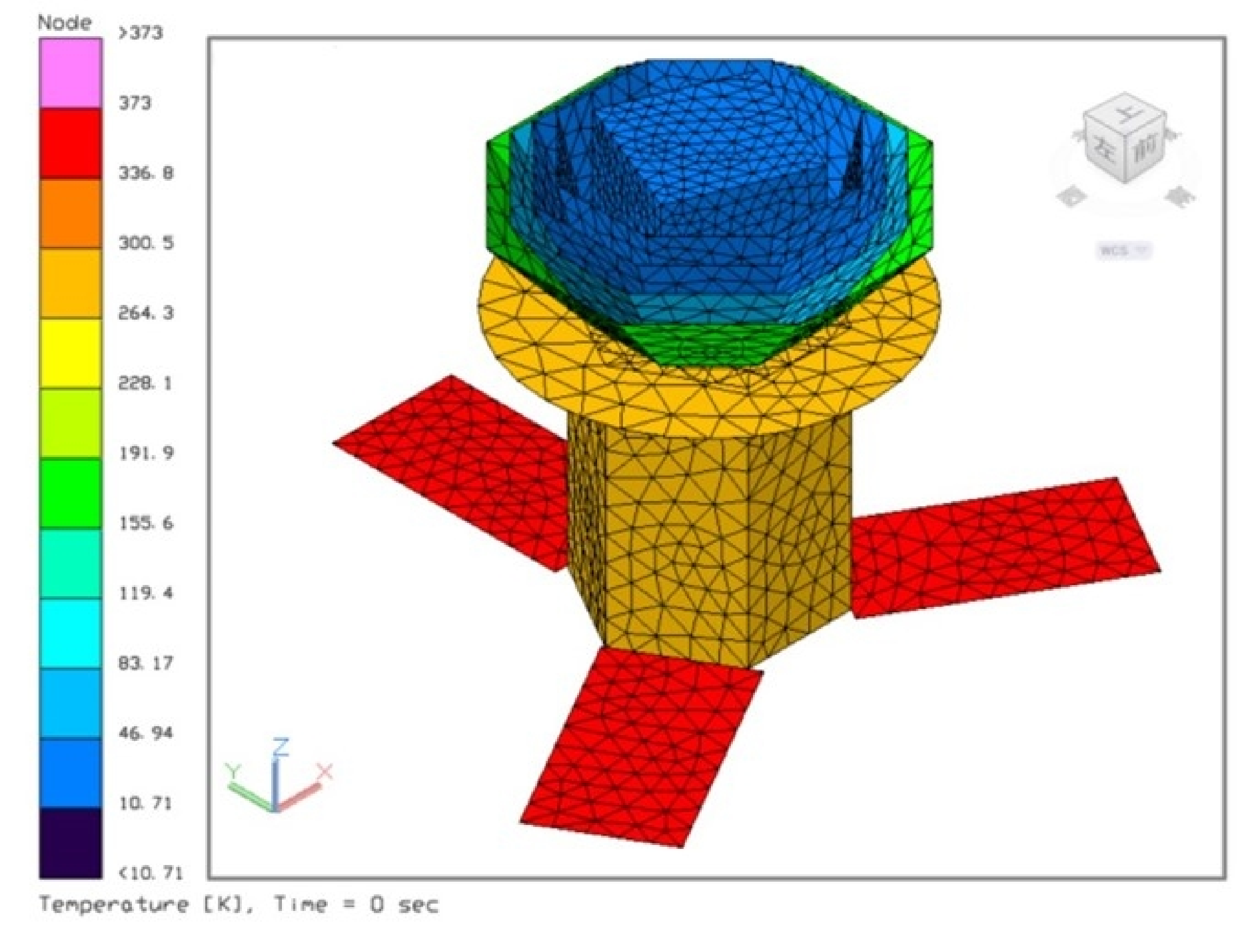
Y. Sato et al, Cryogenics 2016

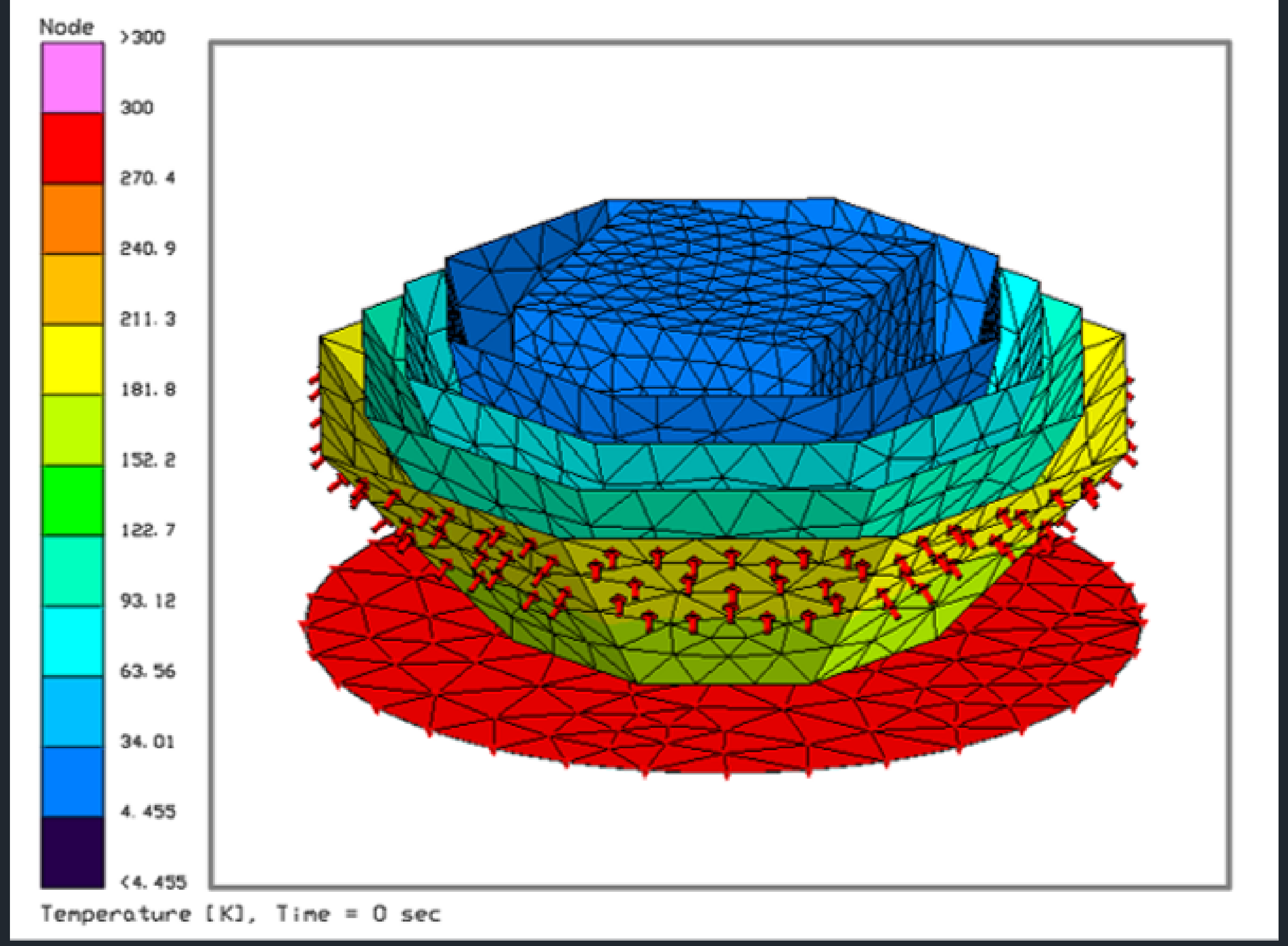


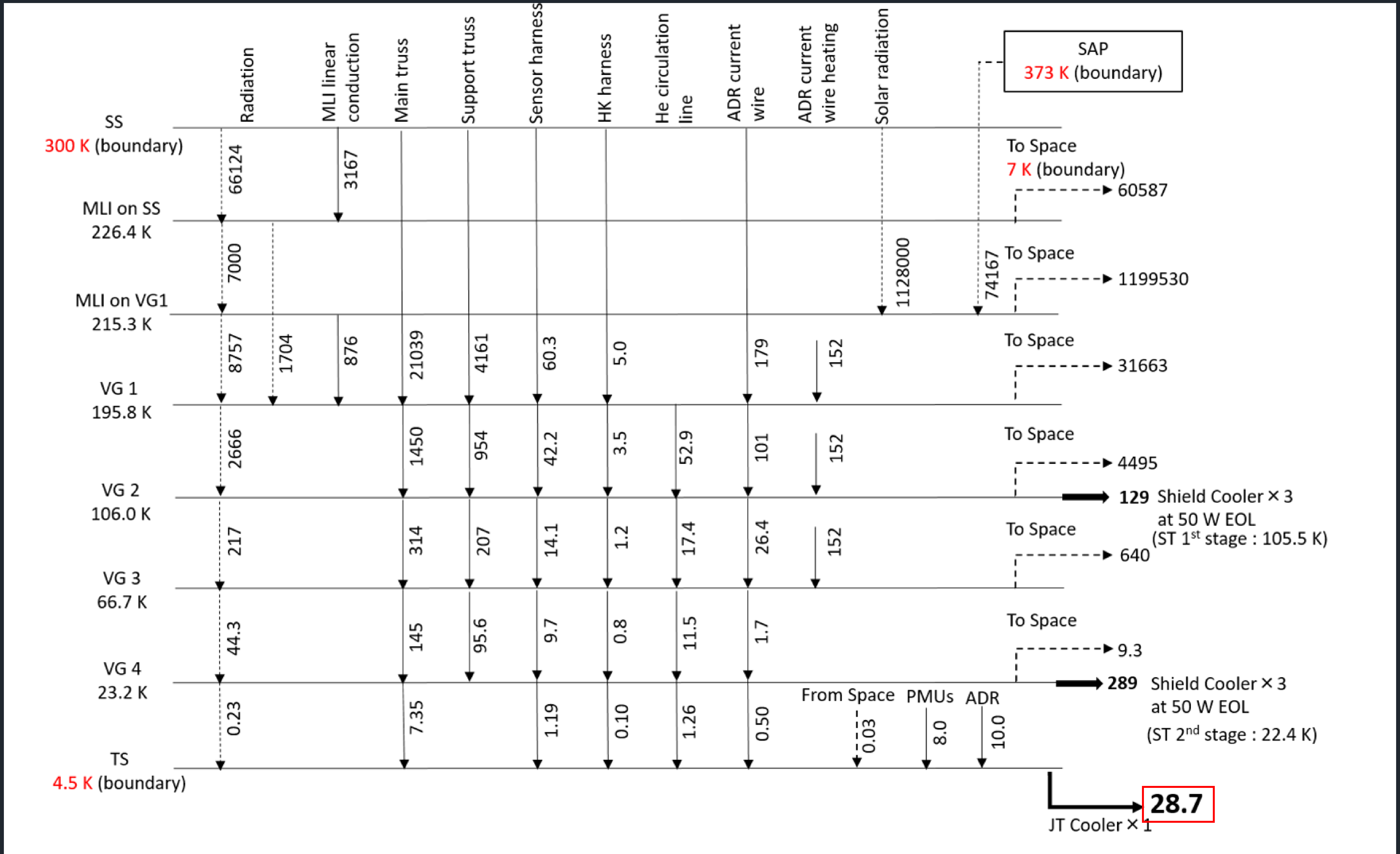
50 mK cooler test facility in Grenoble

- **Long-term (more than a decade) R&D**
  many moving parts, lifetime-test
- **Limited cooling capability**
  4K JAXA cooler : 40 mW @ 4 K
- **High cost**
  cold heads, compressors, drivers

Thermal Analysis







T. Hasebe et al, JATIS 2019

Other Challenges

- **Test campains**
  - About 100 test campains for each system
  - Test items and achievment should be clealy identified in each campain
- **System robustness and redundancy**
  - Failure system never be recovered after launch
  - Resonable margin allocation
  - Redundancy should be well considered

Summary

- **Key components for CMB satellite mission**
  - Broadband and high-sensitivity instruments (optics, detector)
  - Cryogenic systems

- **Design constrains**
  - Instrument size
  - Mechanical & Thermal resorces
  - Electrical power

- **Challenges**
  - Many test campains
  - Margin allocation
  - Robustness & redundancy
  - Cost