Polarization modulation for space application

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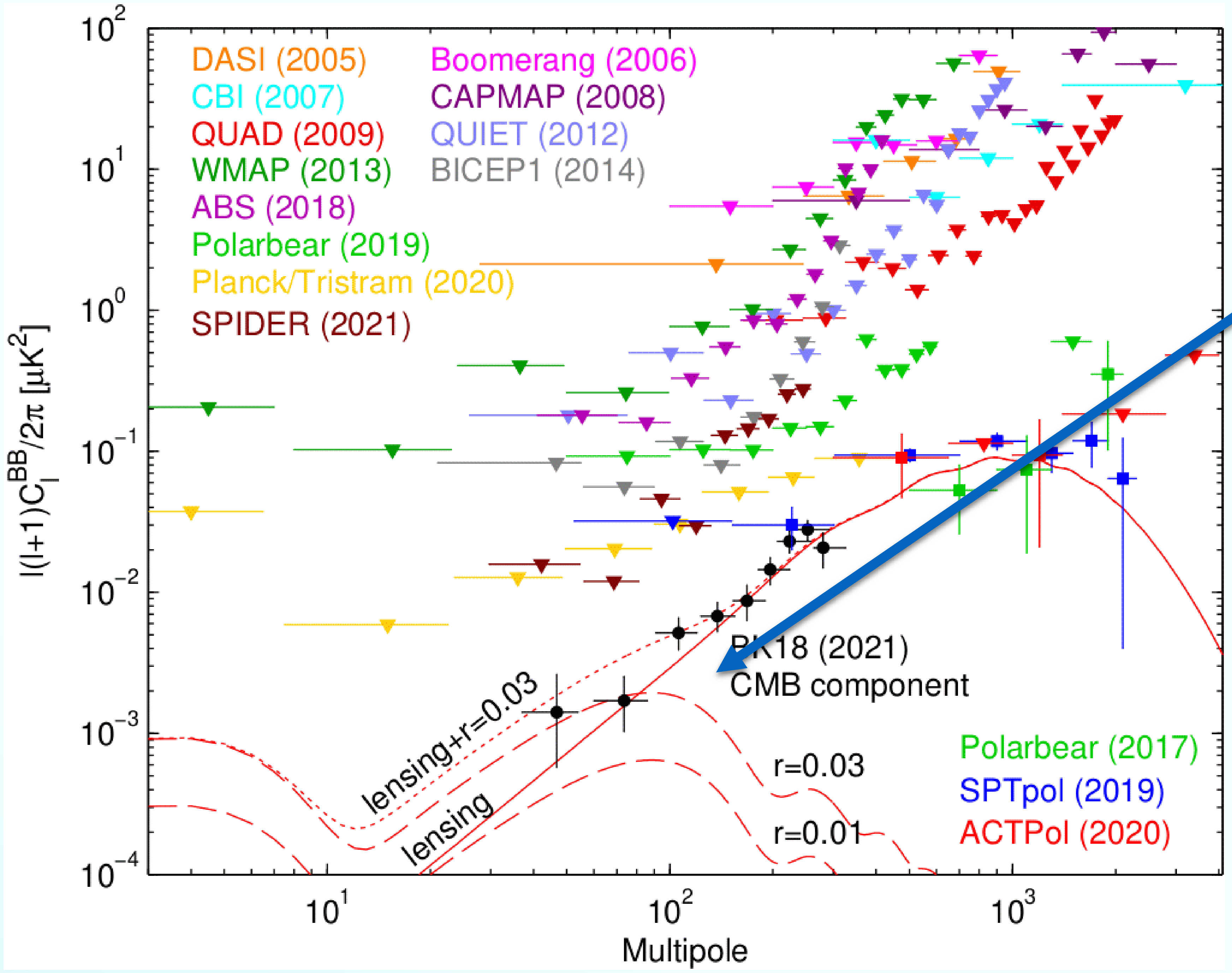
CMB-DAY 2 - 17/10/23

B-modes

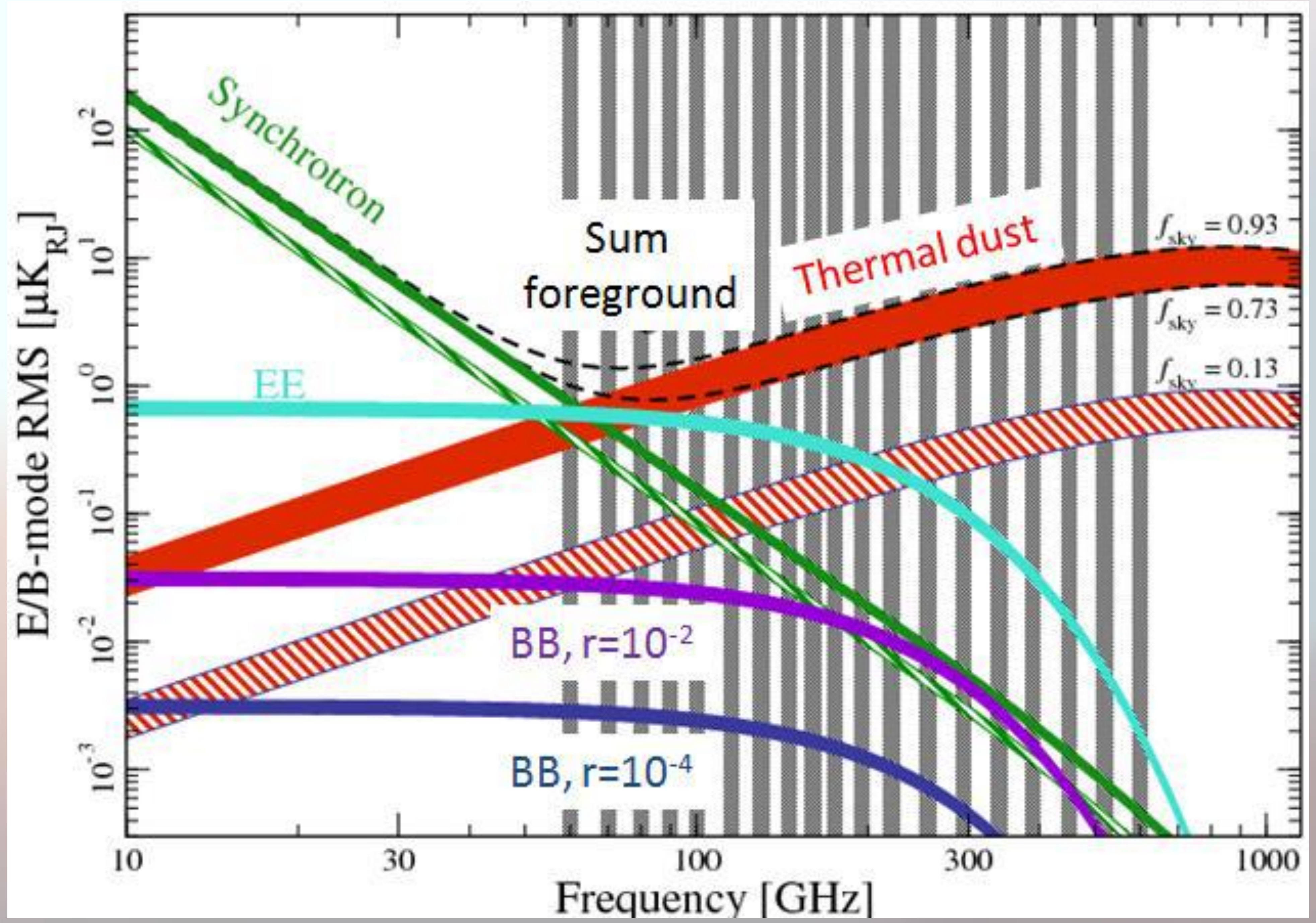


$$r = \frac{c_l^T}{c_l^S}|_{l=2} \propto 0.1\left(\frac{E_{inflation}}{2 \cdot 10^{16} GeV}\right)^4$$

Current r upper limit
~ 0.1

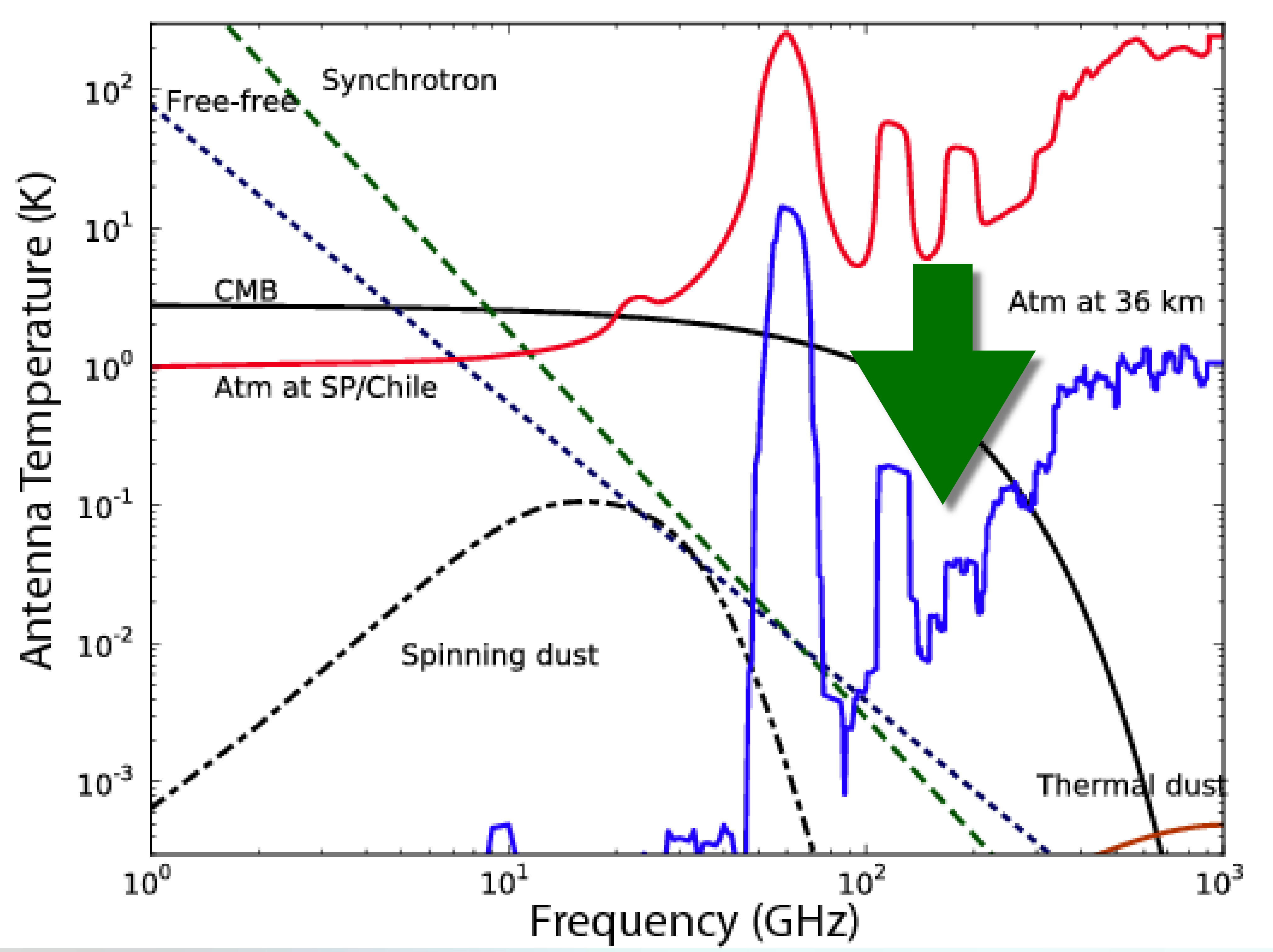
At l = 80, r = 0.05 corresponds to 50nK,
r = 0.001 to 8nK

Wide spectral coverage required to monitor the foregrounds (dust, synchrotron) and separate the CMB signal



CMB Experiments

Lot of experiments aim to measure the B-modes polarization with different approaches



BICEP3 / Keck Array	South Pole	-	-
CLASS	Atacama Desert	-	-
POLARBEAR-2	Atacama Desert	HWP	Continuous, 60K
QUBIC	Puma de Atacama	HWP	Step, 5K
Simons Observatory LAT	Atacama Desert	-	-
Simons Observatory SAT	Atacama Desert	HWP	Continuous, 50K
SPT-3G	South Pole	-	-
EBEX	Balloon	HWP	Continuous, 5K
LSPE-SWIPE	**Balloon**	**HWP**	**Continuous, 5K**
Spider-2	Balloon	HWPs	Step, 5K
LiteBIRD	**L2**	**HWPs**	**Continuous, 5K**

Ground

- Long observational time
- Possibility to upgrade/modify the instrument

Balloon

- Residual atmospheric emission
- “low” cost and “fast” development time

Space

- No atmosphere
- No Earth emission

CMB Experiments - Polarization Modulation

Polarization sensitive detectors

- No polarization systematics introduced by moving optical elements
- Easier instrument development

- The sky has to be mapped with different angles to fully reconstruct the polarization
- Beam knowledge is critical. Asymmetries can introduce systematics

Active optical element

Half-wave plate type:
- Metal-mesh
- Birefringent crystal (sapphire)

Temperature:
- 300K
- 40-50K
- 4-5K

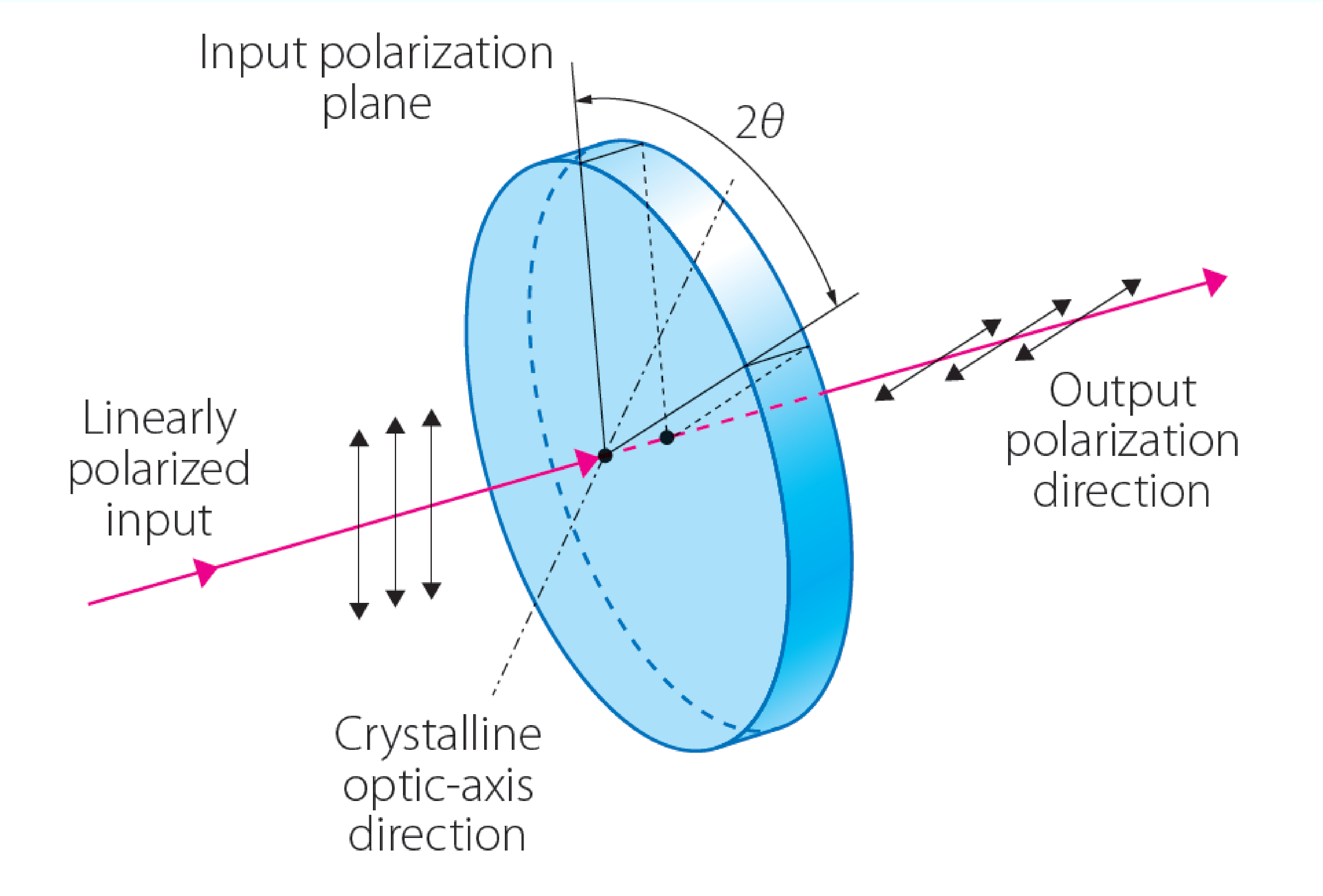
The emission of the HWP has to be compared with other systematics (atmospheric emission, …)

Strategy:
- Continuous
- Step

Faster is better (see next slide)

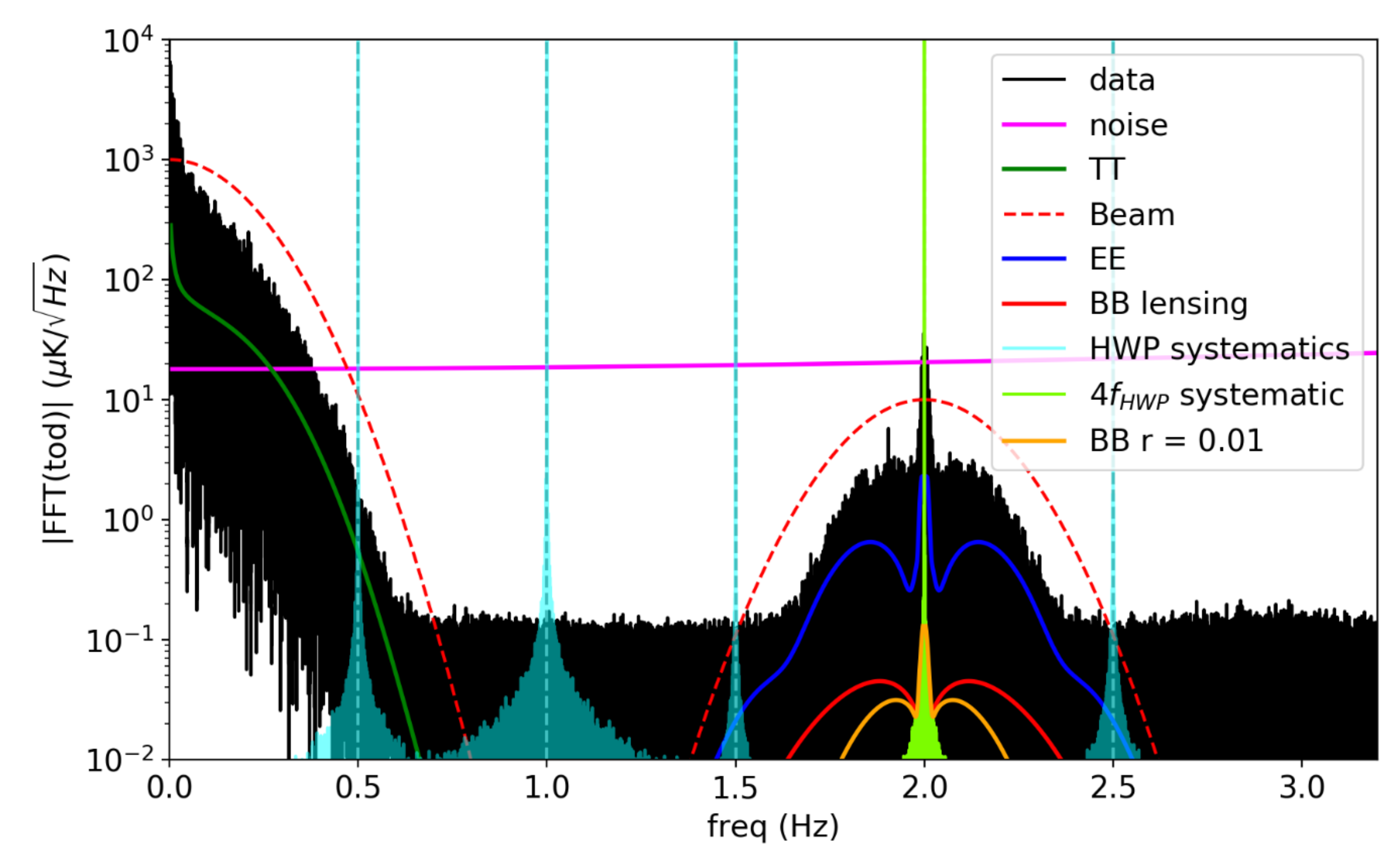
A Half-Wave Plate (HWP) as polarization modulator represents a powerful tool to minimize spurious contaminations

Stokes polarimeter



Performance of half (λ/2) waveplate

To be effective, HWPs must be rotated during the observation, either in stepped or (continuously) spinning mode



$$S(\theta) = \frac{1}{2}(I + Q\cos(4\omega t) + U\sin(4\omega t)) = \frac{1}{2}(I + Q\cos 4\theta + U\sin 4\theta)$$

A spinning HWP helps to:

- mitigate of 1/f noise (and atmospheric polarized signal if present)
- increase signal-to-noise ratio
- reconstruct the state of incoming polarized light (ideally with a single detector)
- mitigate detector gain variation
- neglect beam asymmetry

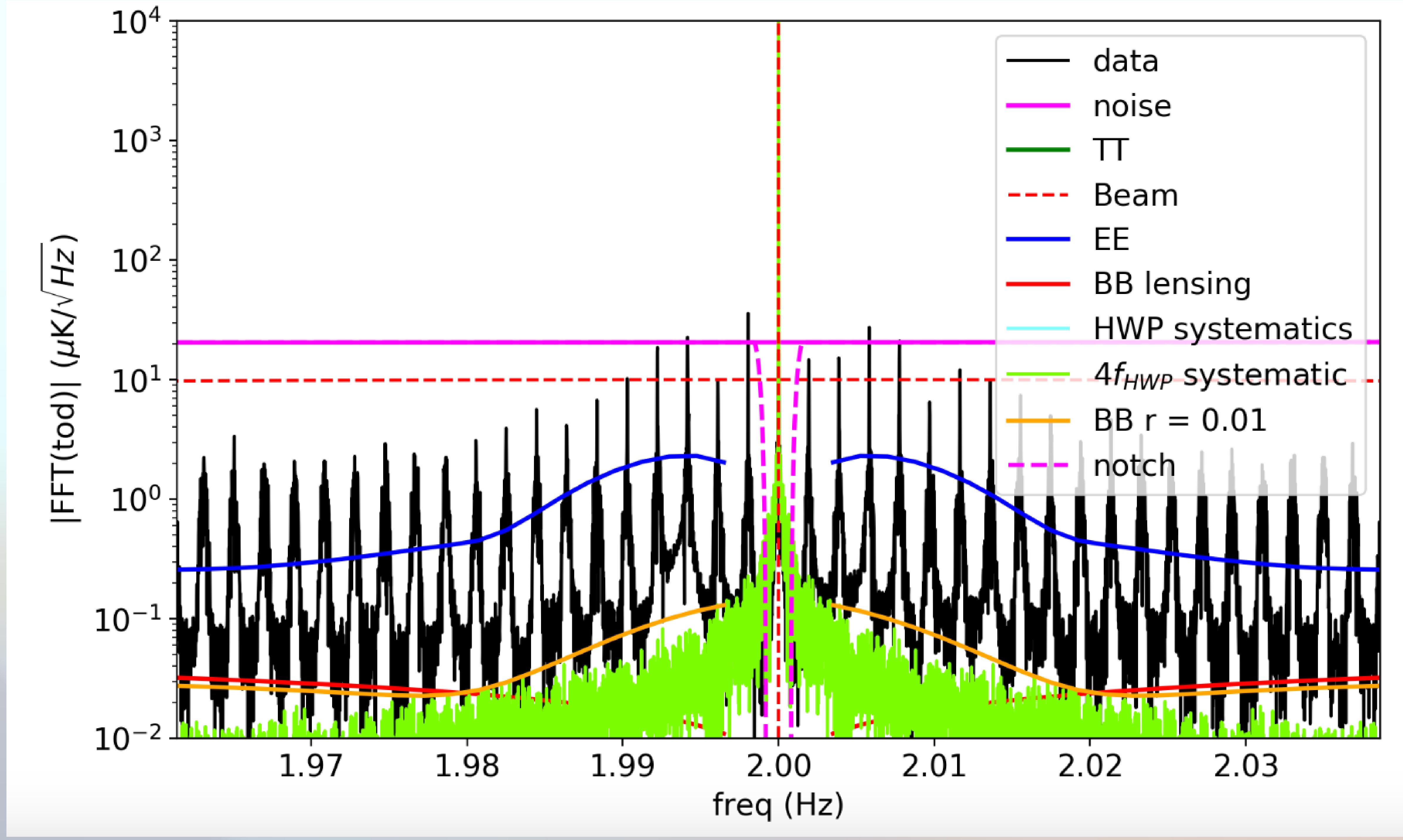
A spinning HWP introduces:

- power load produced by (cryogenic) continuous rotation
- spurious signals (1f, 2f, 3f, 4f, ….)

Stokes polarimeter

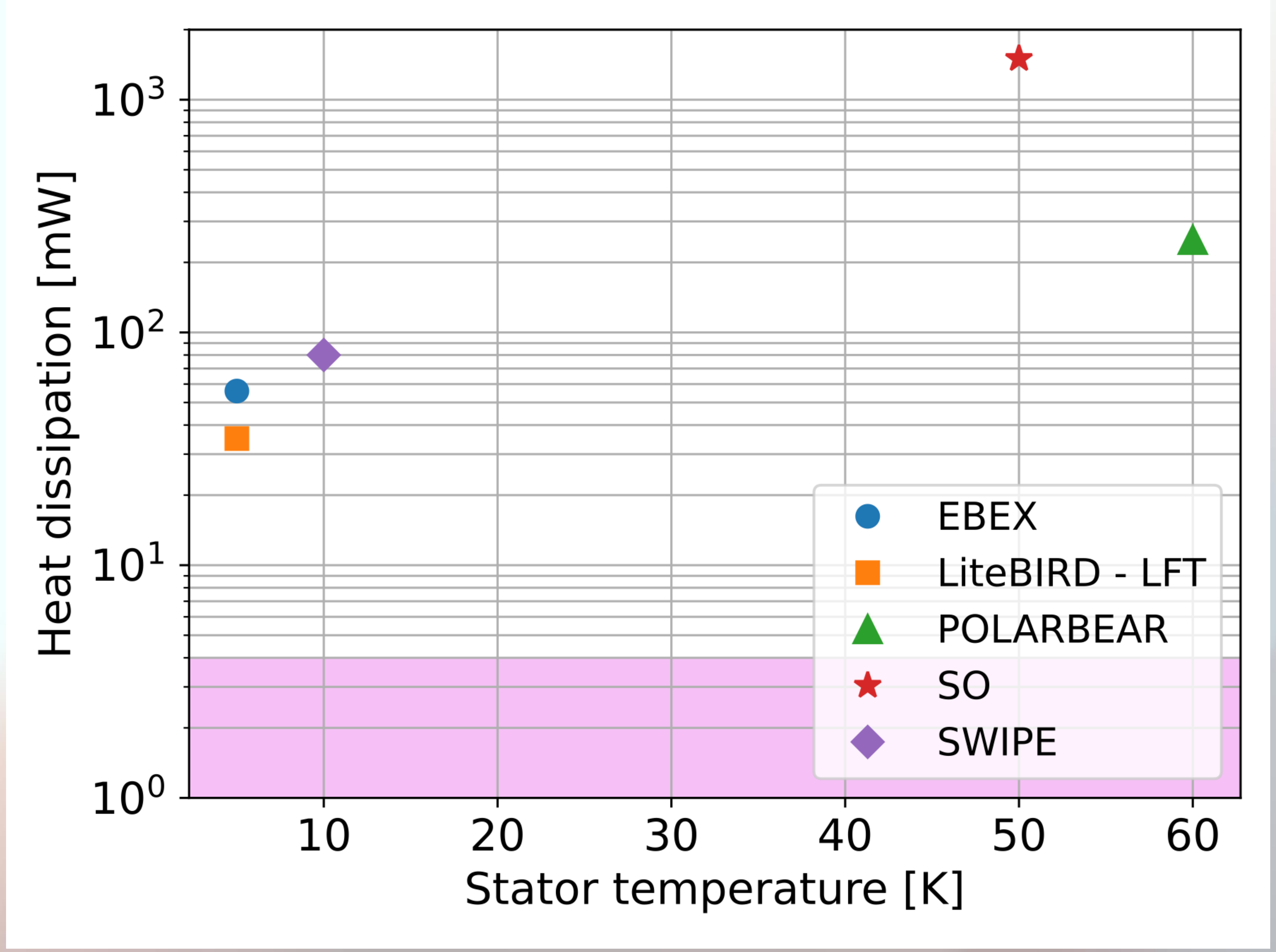
Systematics from HWP are not fully characterized yet:

- Angular accuracy reconstruction
- HWP harmonics
- HWP differential transmission
- …..



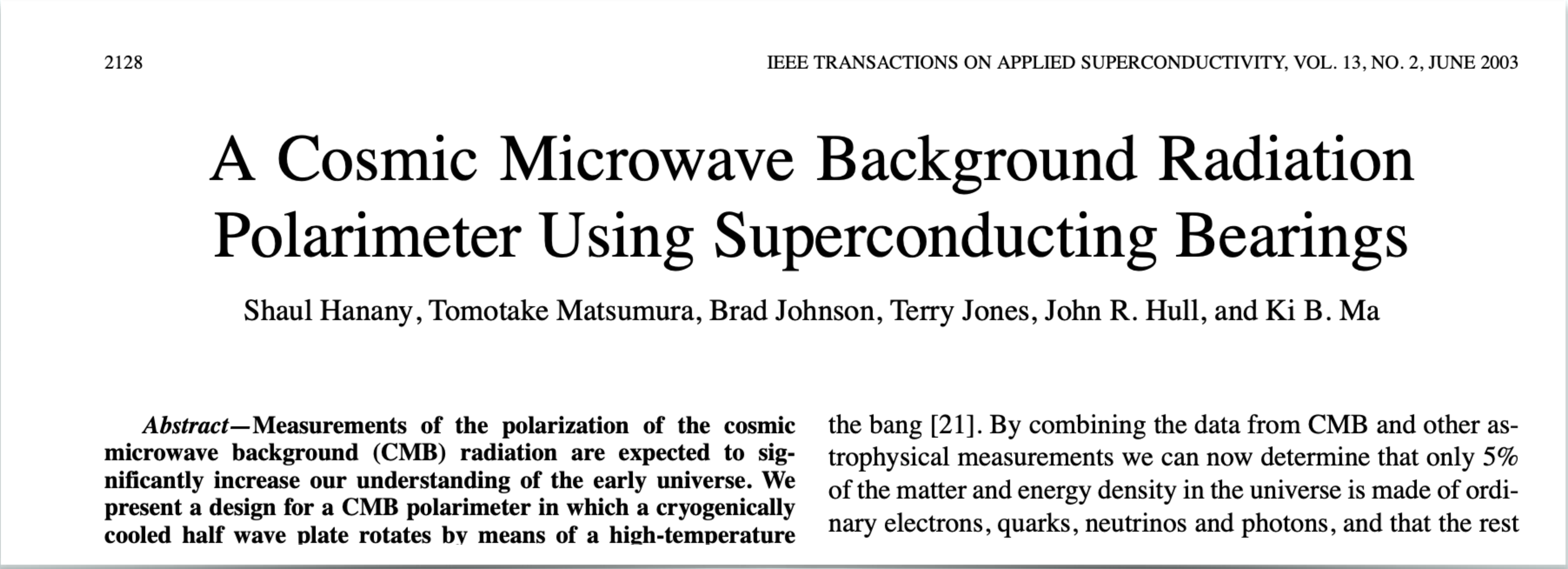
HWP and its rotation are far from ideality!

A typical cryogenic system for space missions (like LiteBIRD) has a power budget on the coldest stage of tens of mW. A small part of this budget is allocated to the PMU.



Heat loads normalized at 1Hz

PMUs - Overview



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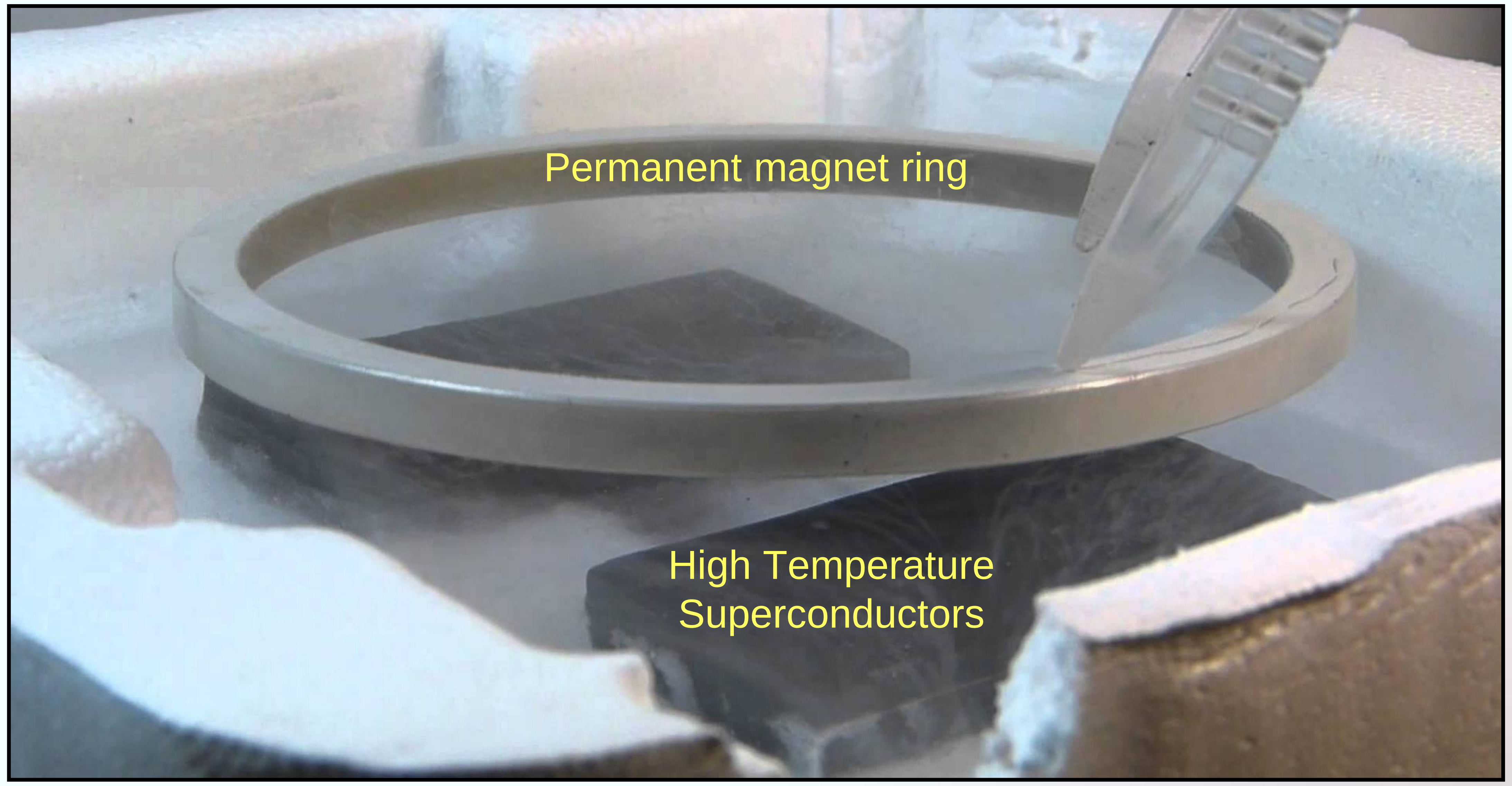
A Cosmic Microwave Background Radiation Polarimeter Using Superconducting Bearings

Shaul Hanany, Tomotake Matsumura, Brad Johnson, Terry Jones, John R. Hull, and Ki B. Ma

Abstract—**Measurements of the polarization of the cosmic microwave background (CMB) radiation are expected to significantly increase our understanding of the early universe. We present a design for a CMB polarimeter in which a cryogenically cooled half wave plate rotates by means of a high-temperature**

the bang [21]. By combining the data from CMB and other astrophysical measurements we can now determine that only 5% of the matter and energy density in the universe is made of ordinary electrons, quarks, neutrinos and photons, and that the rest

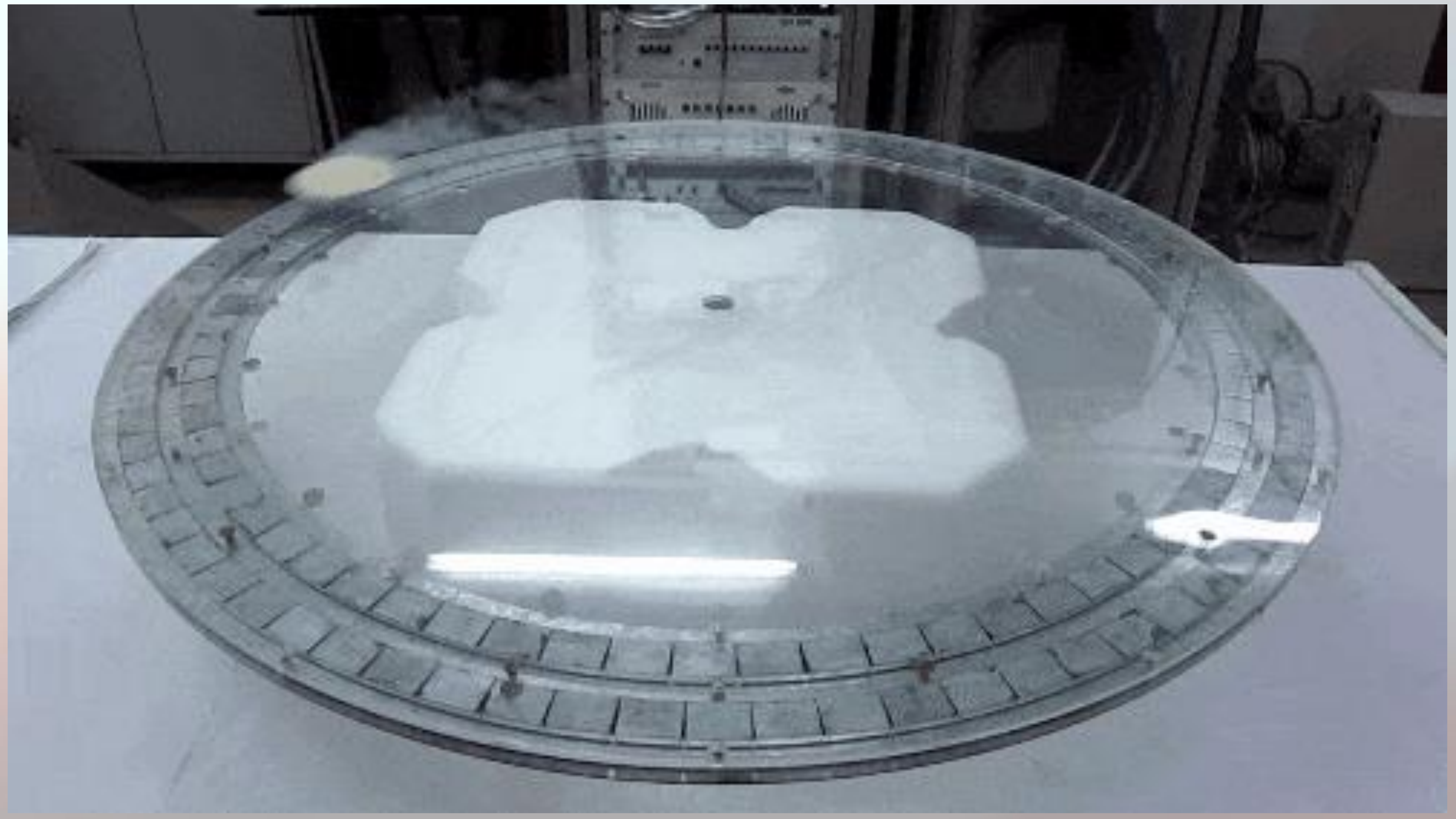


Pros

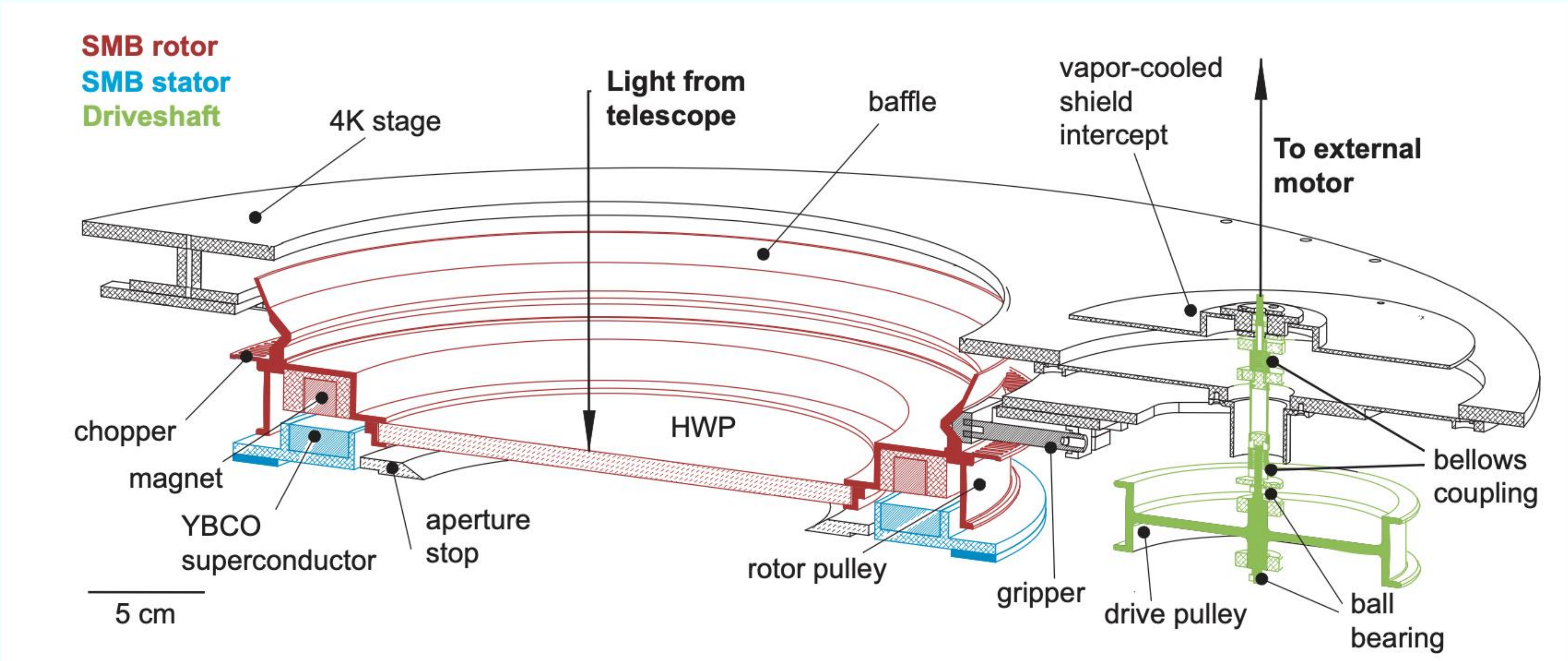
- NO stick-slip friction
- NO extra-effort to cool HTSs
- Passive stable levitation
- Low Coefficient of friction
- Continuous rotation (0-10Hz)

Cons

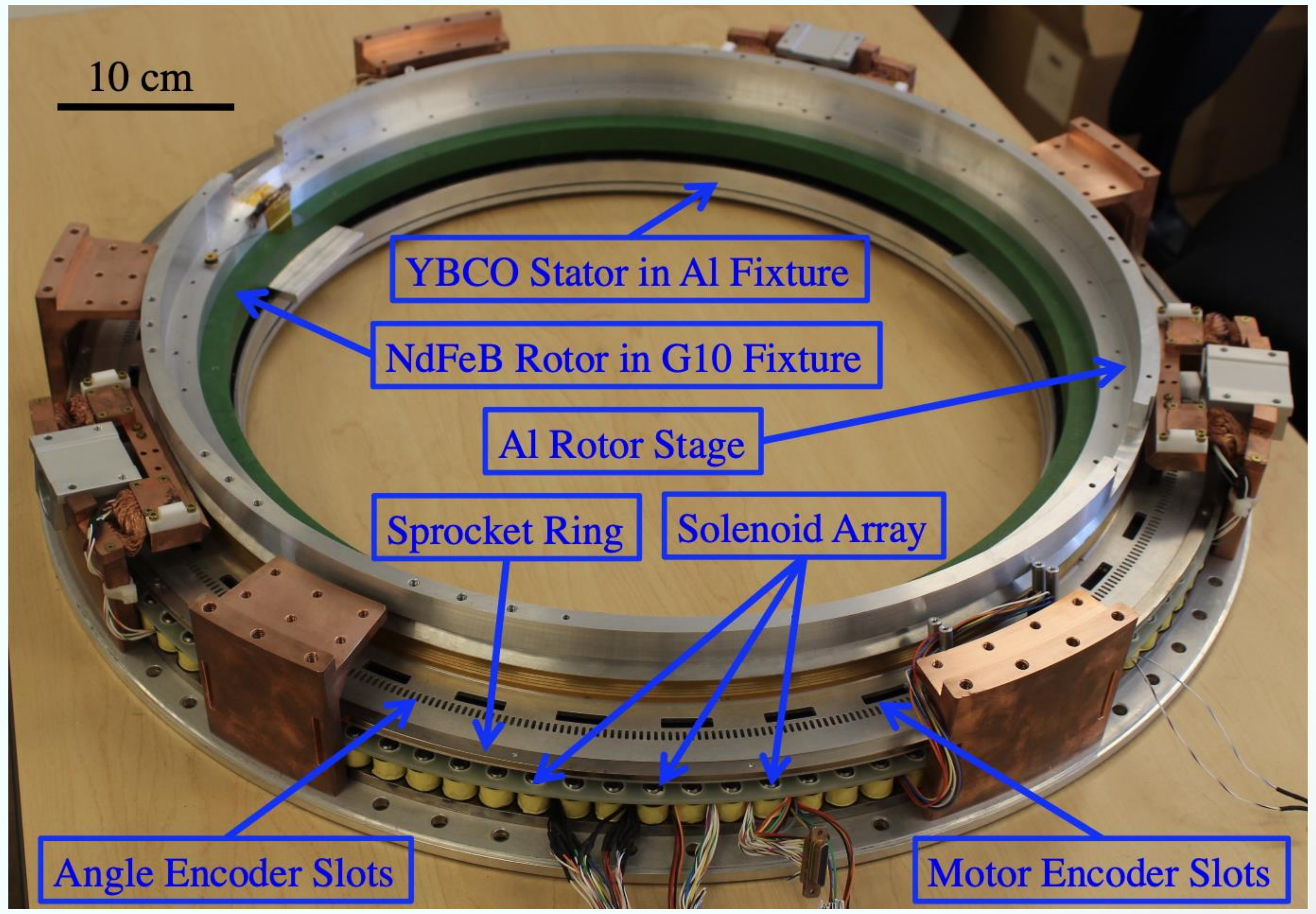
- Variable magnetic field
- Clamp mechanism at 4K



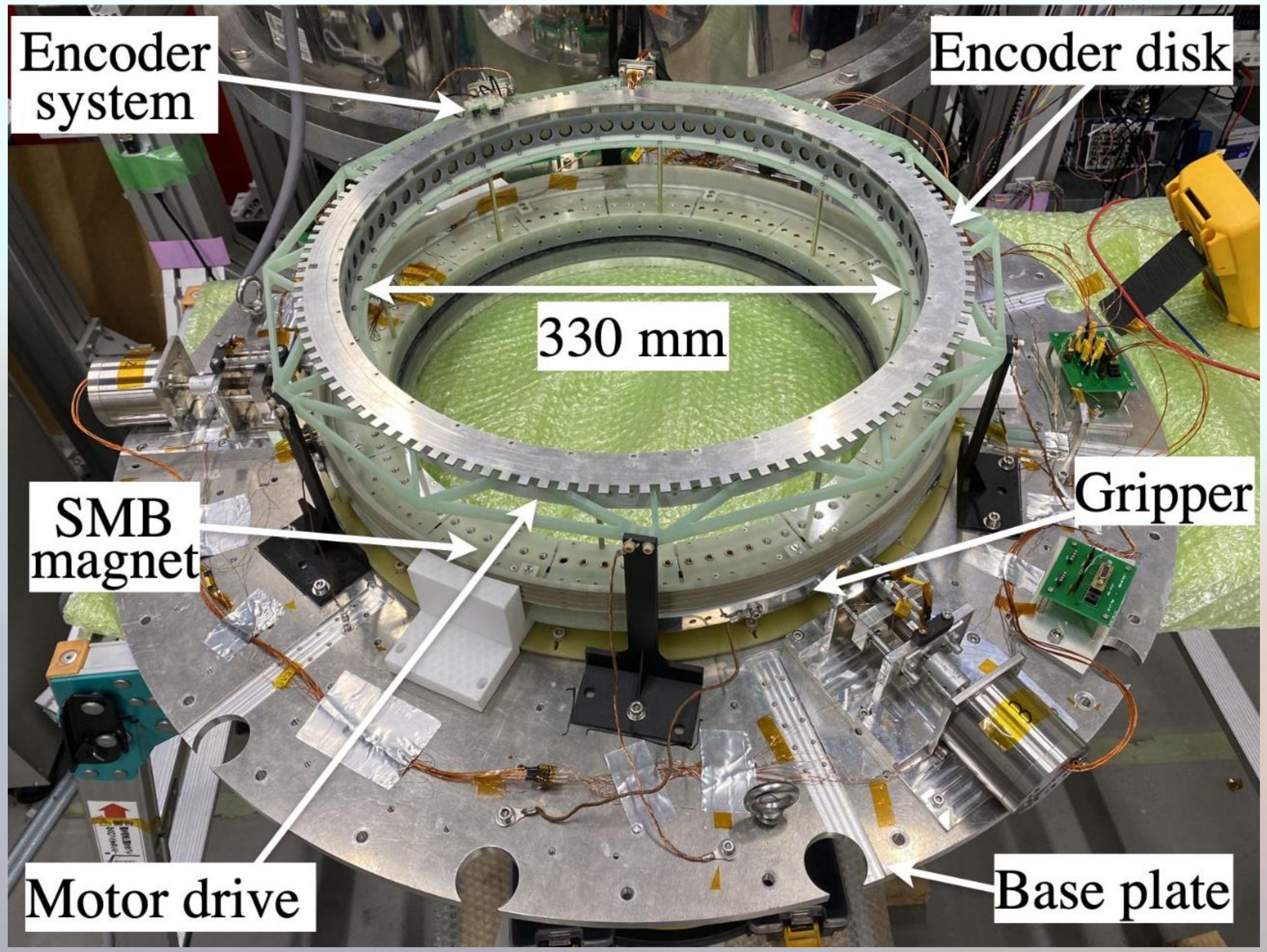
PMUs - Overview



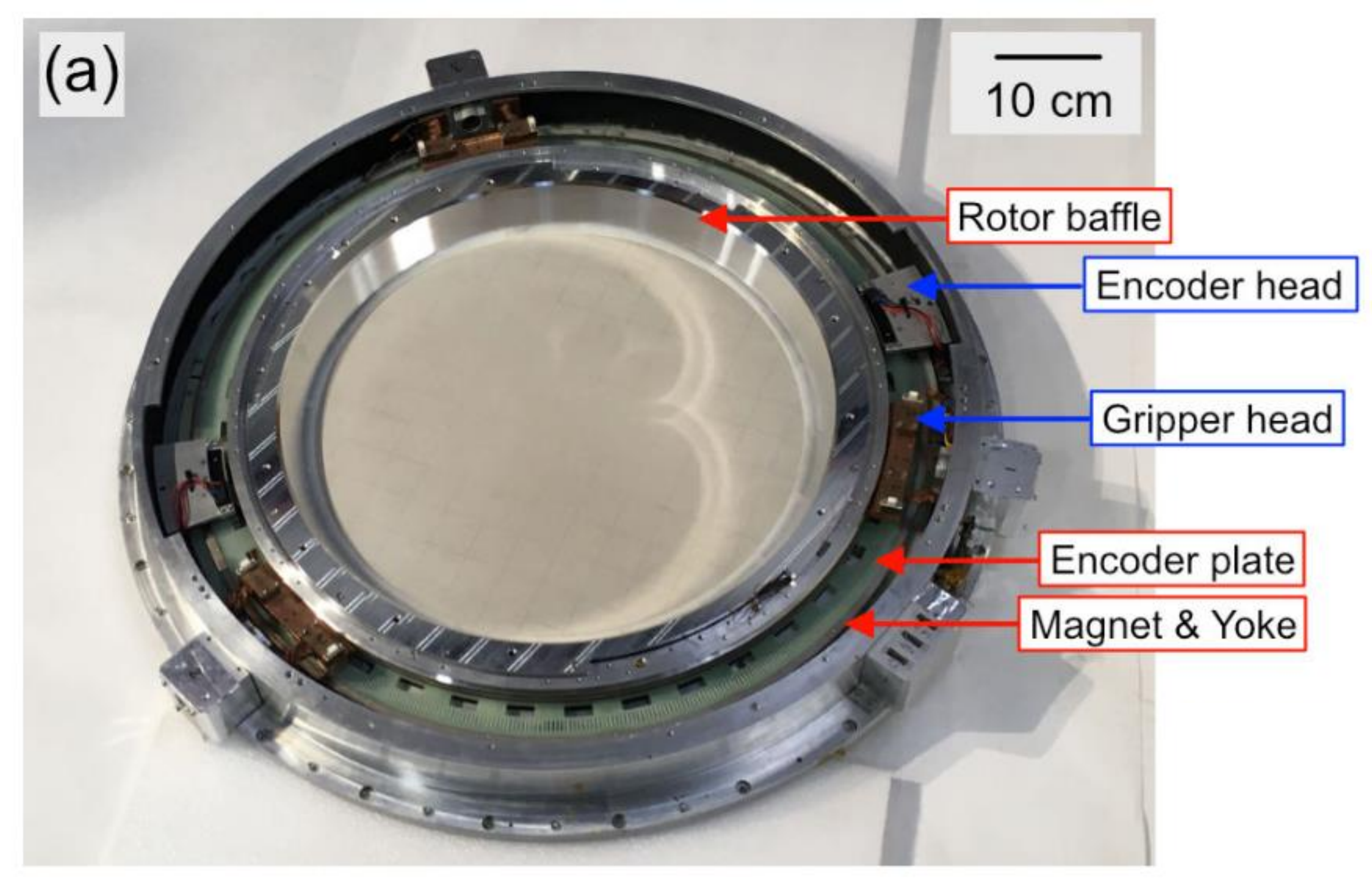
EBEX - Klein et al. 2017



Polarbear - Hill et al. 2019



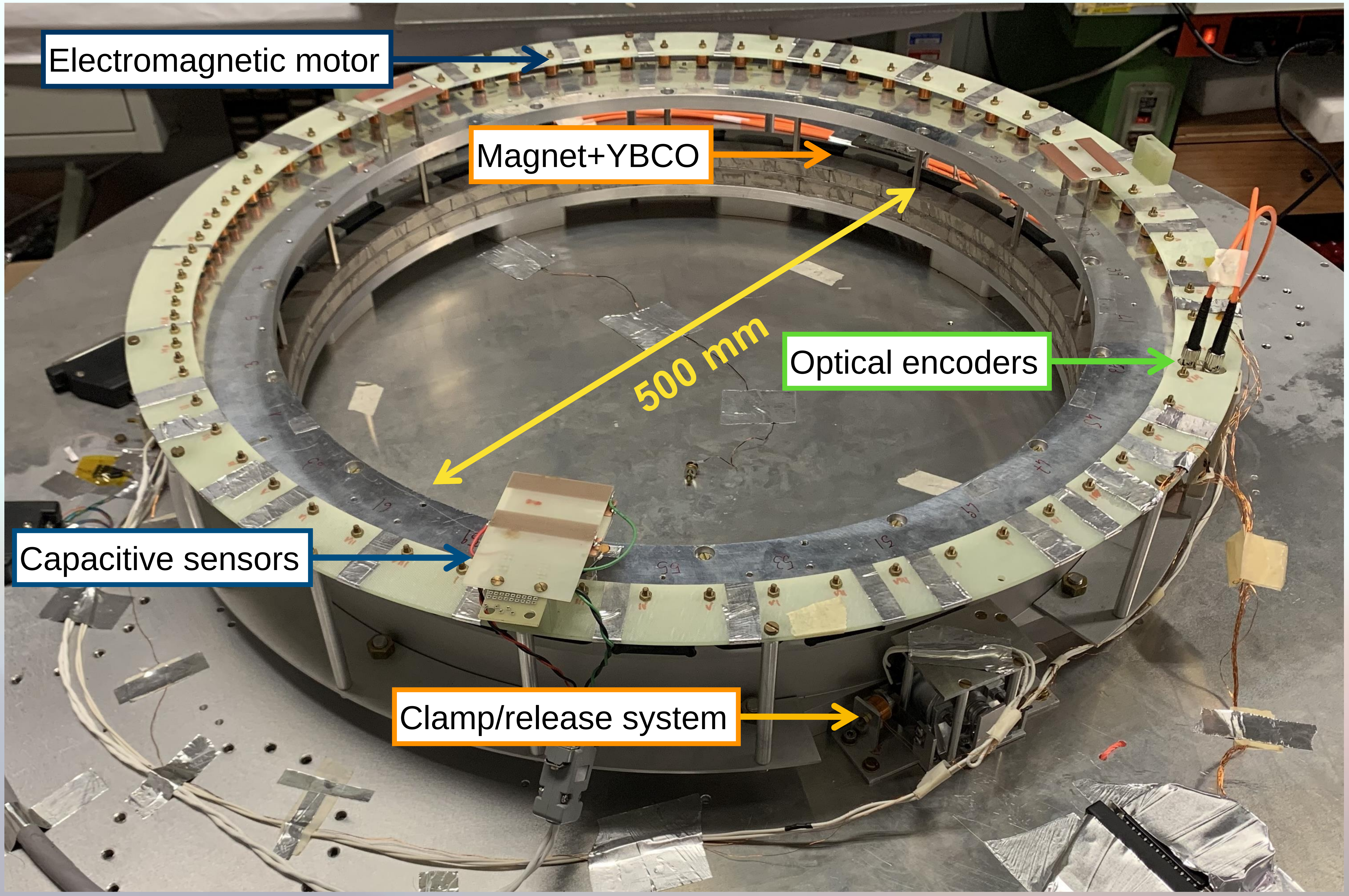
LiteBIRD LFT - Sakurai et al. 2022

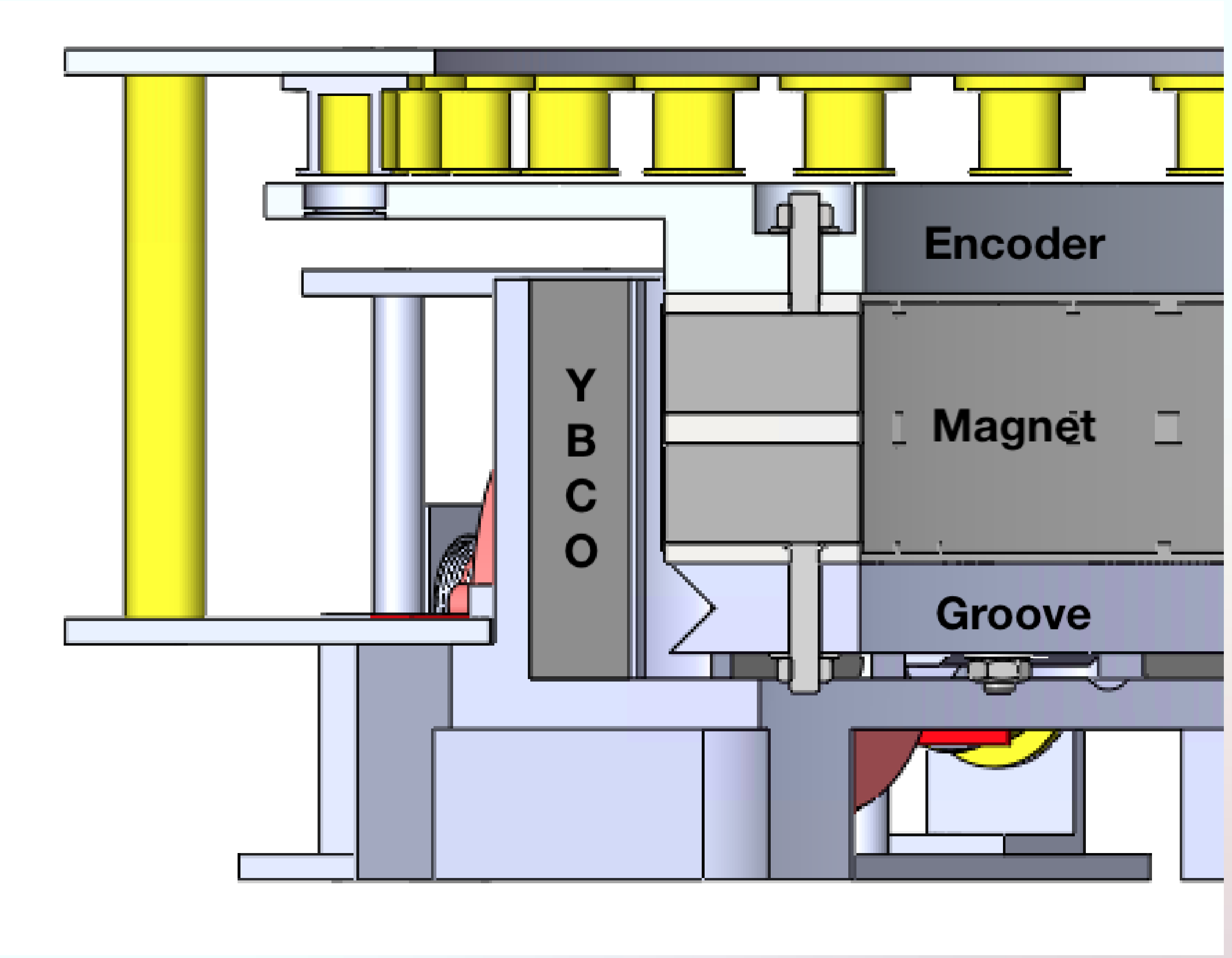


SO - Yamada et al. 2023

PMU - Sapienza

The breadboard design is based on the PMU (metal-mesh HWP) developed by our team for the SWIPE balloon-borne instrument.



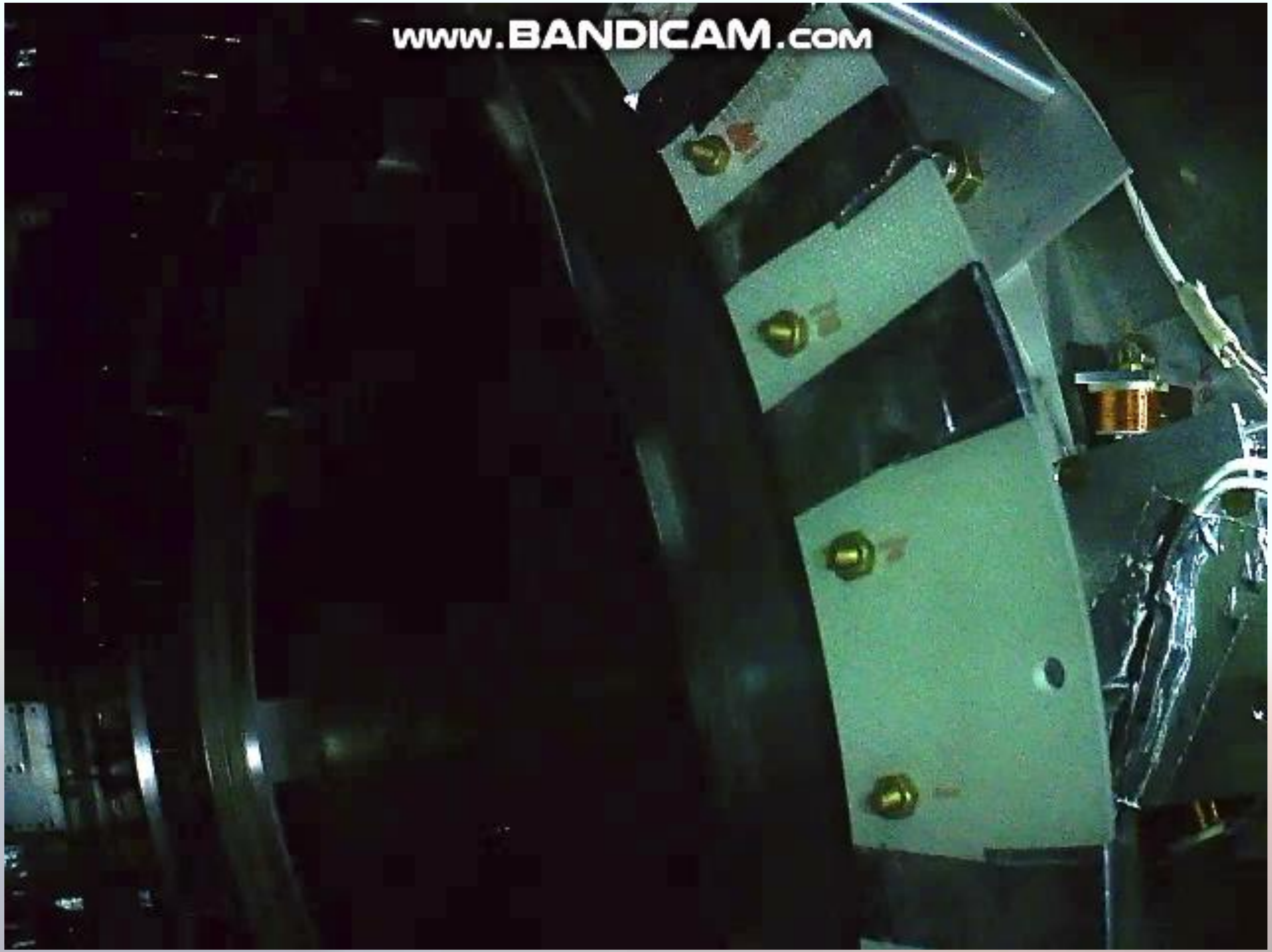


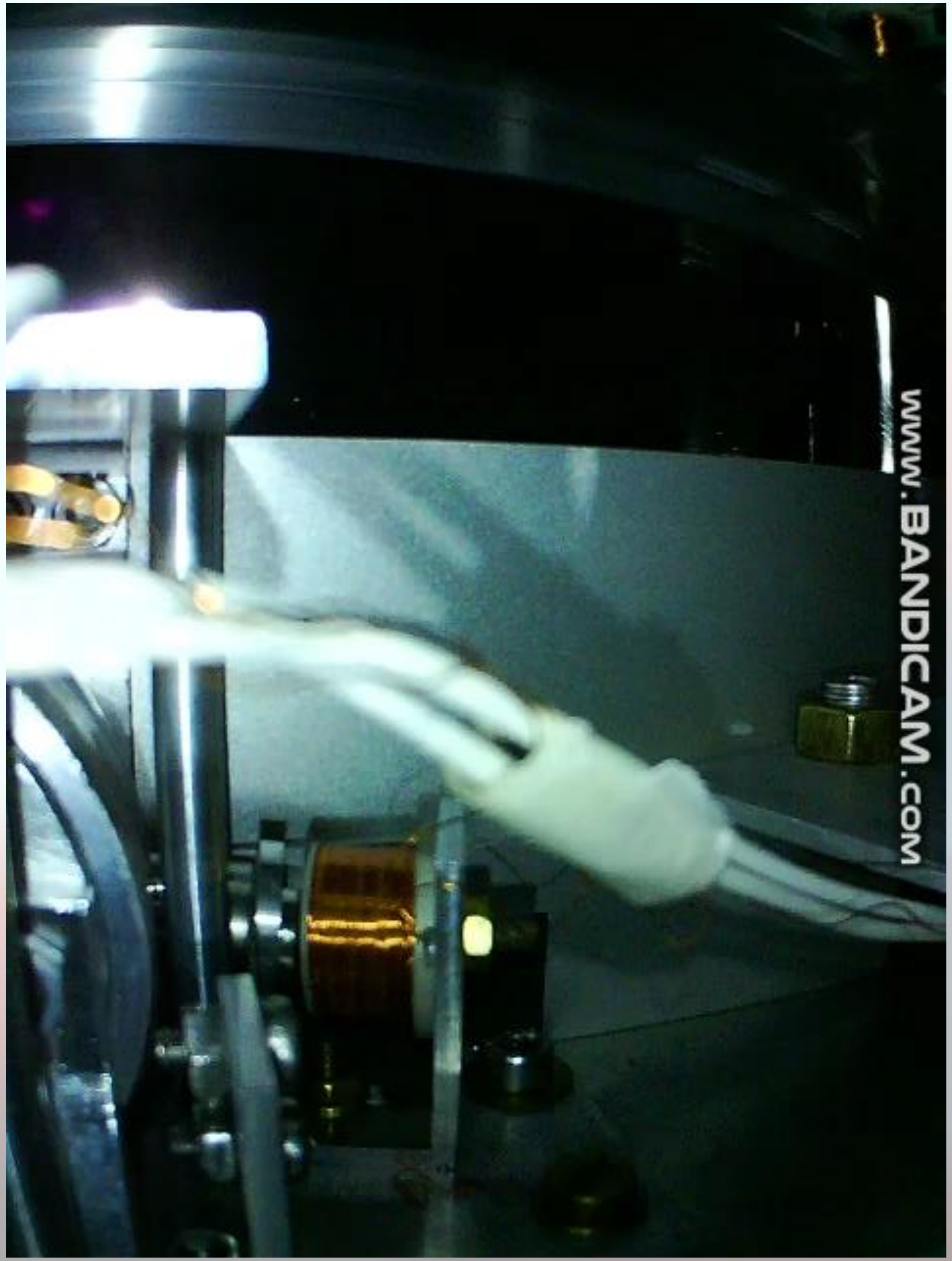
Subsystems:

- 18 YBCO bulks
- 2 segmented NdFeB rings + 3 iron yokes
- Homemade clamp/release system
- 64 coils (8-phase) + 8 coils (start)
- 8 magnets
- Optical encoders
- Capacitive sensors
- Hall sensors
- 2 cryogenic webcams

PMU - Sapienza

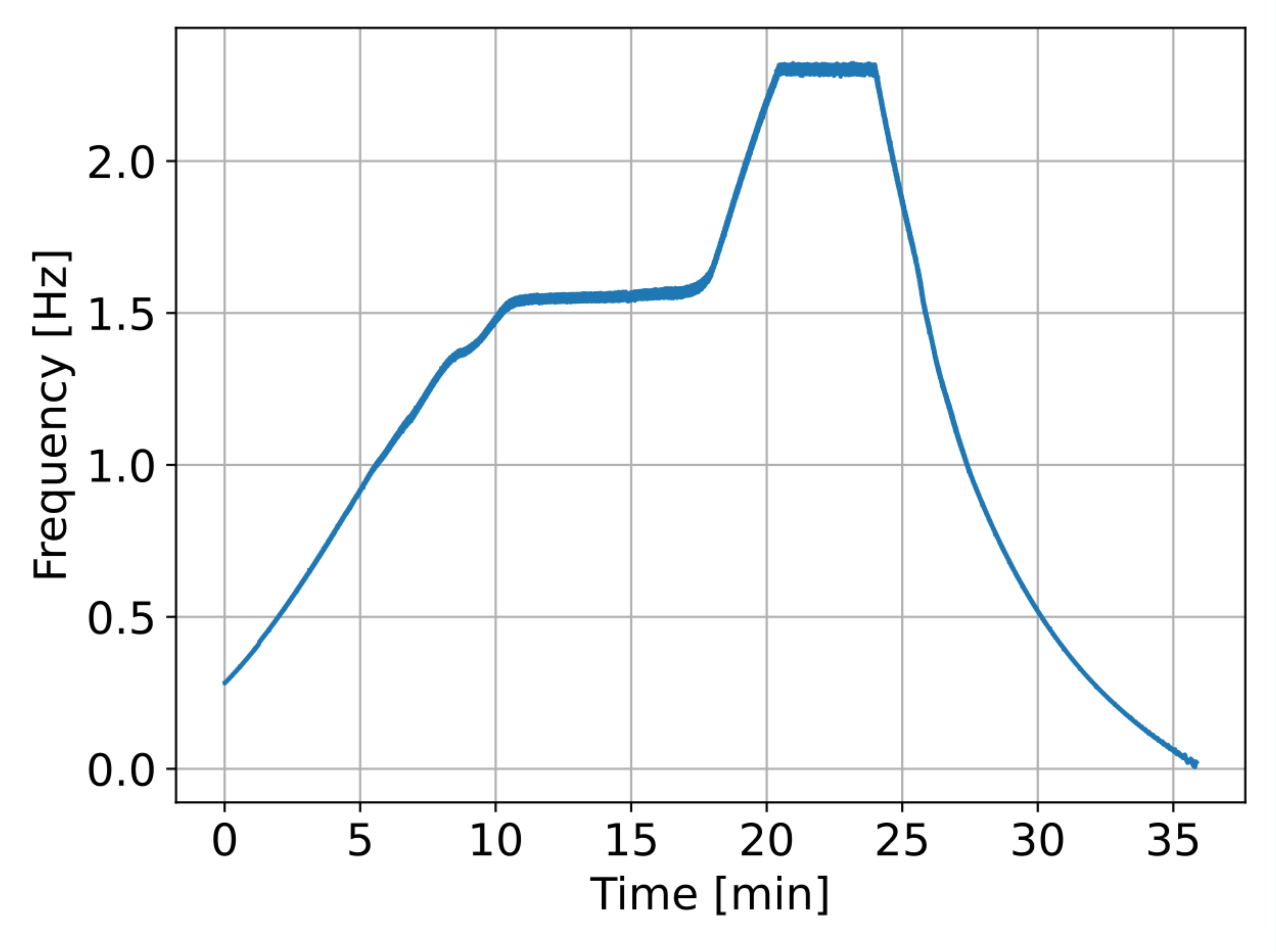
Stable rotation at ~10K!

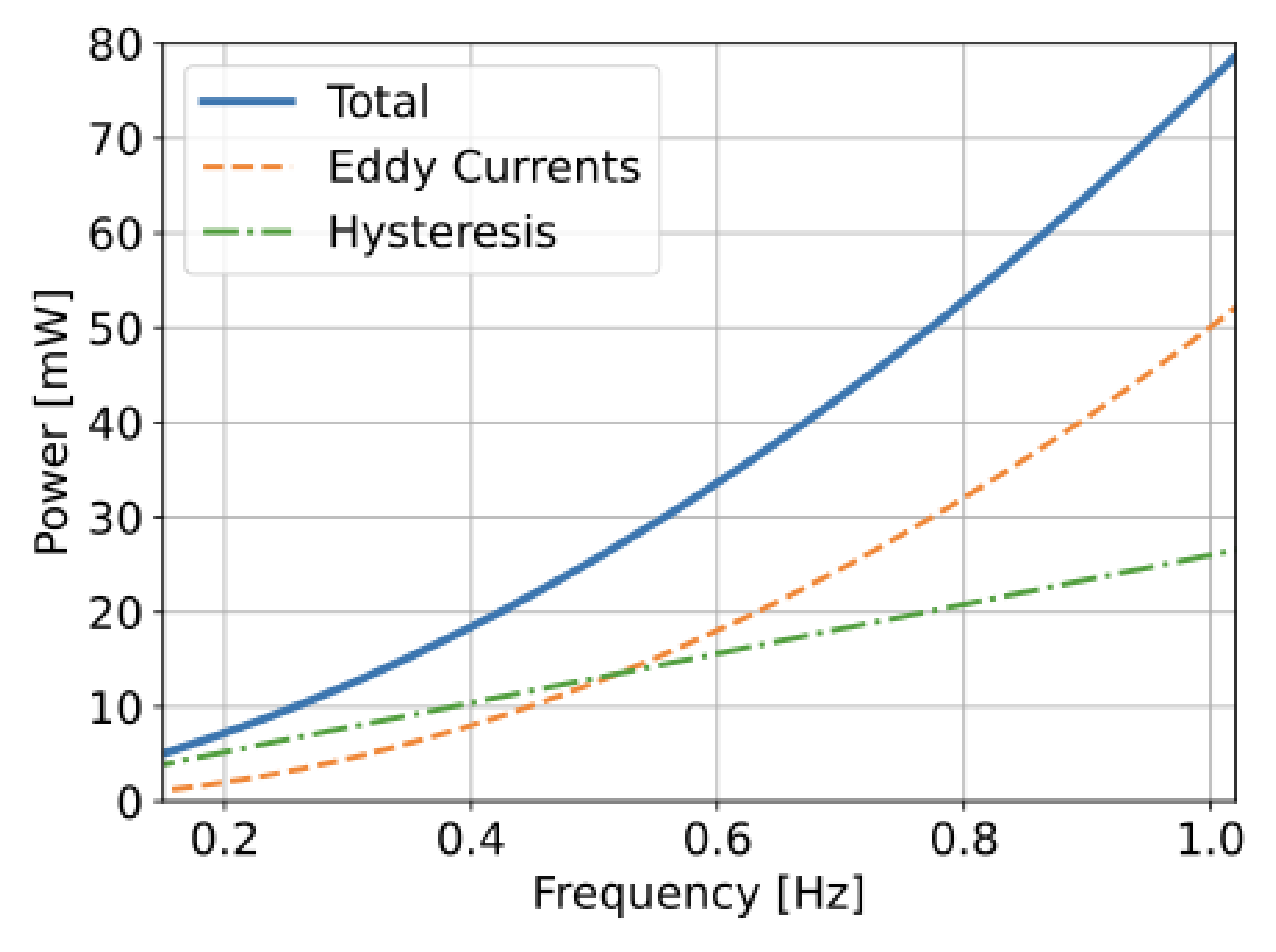




PMU - Sapienza

$$P(\omega) = -\omega I \frac{d\omega}{dt} = -2\pi f I \frac{d\omega}{dt} = -2\pi f I(\alpha_0 + 2\pi\alpha_1 f)$$



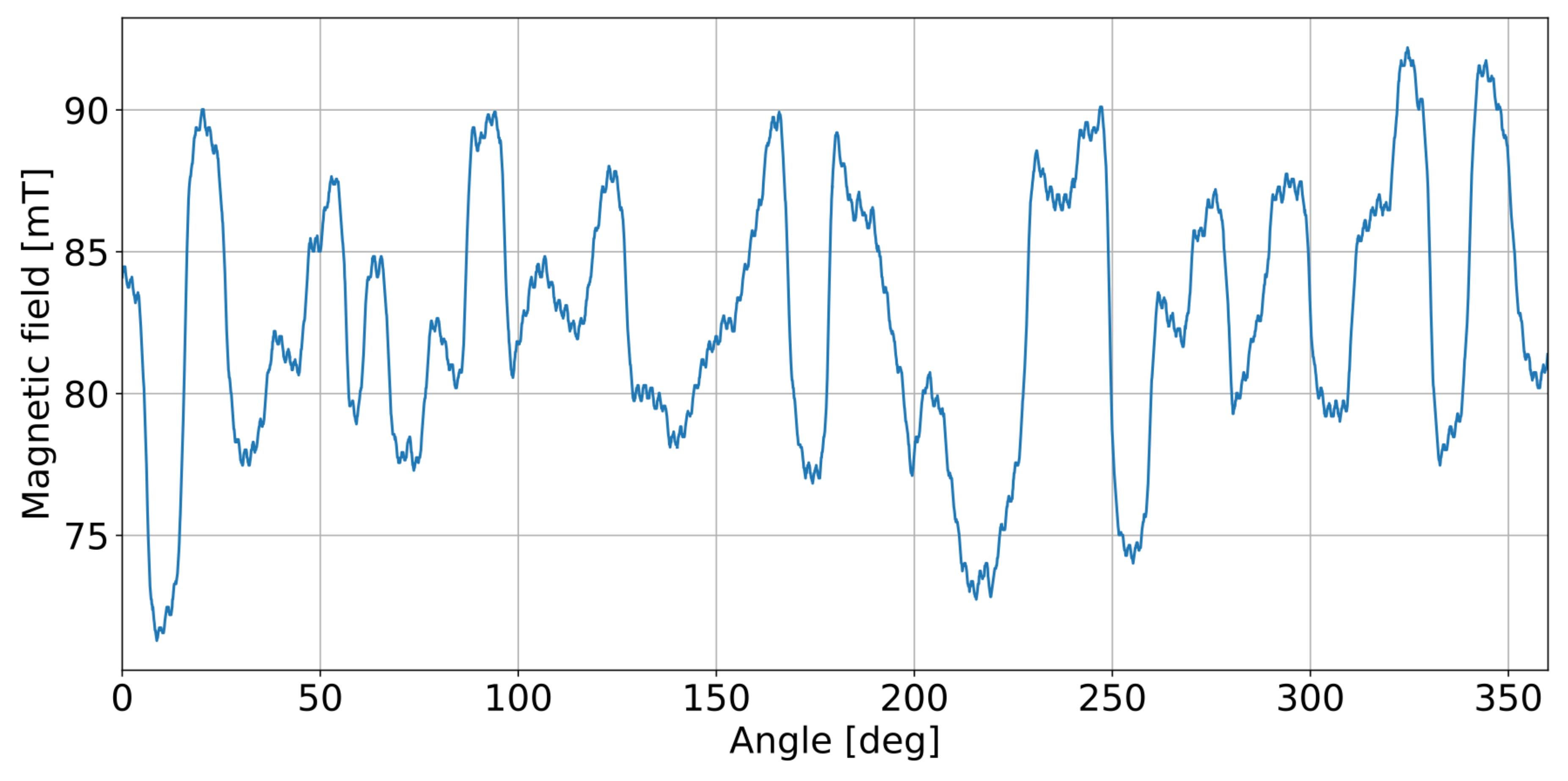


Hysteresis

$\alpha_0 = 2.11 \times 10^{-3} rad/s^2$

$\alpha_1 = 3.38 \times 10^{-3} 1/s$

Eddy currents



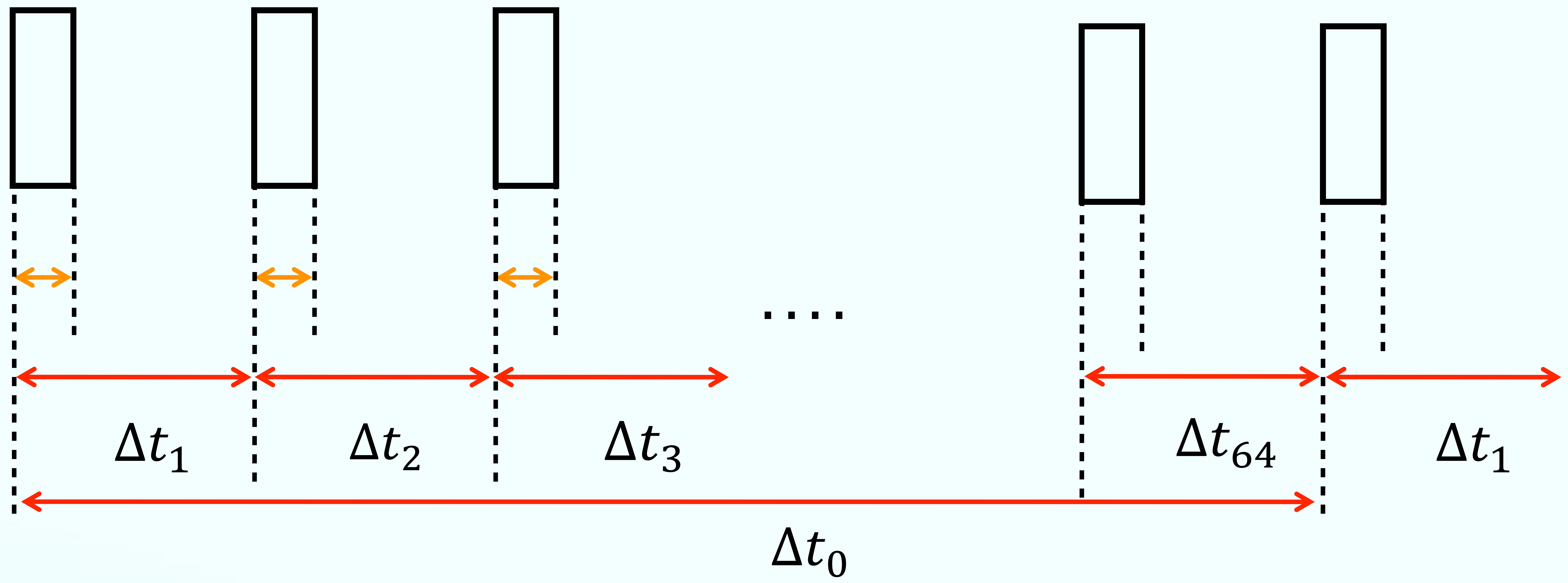
$$\frac{\Delta B}{\overline{B}} = 5.9\%$$

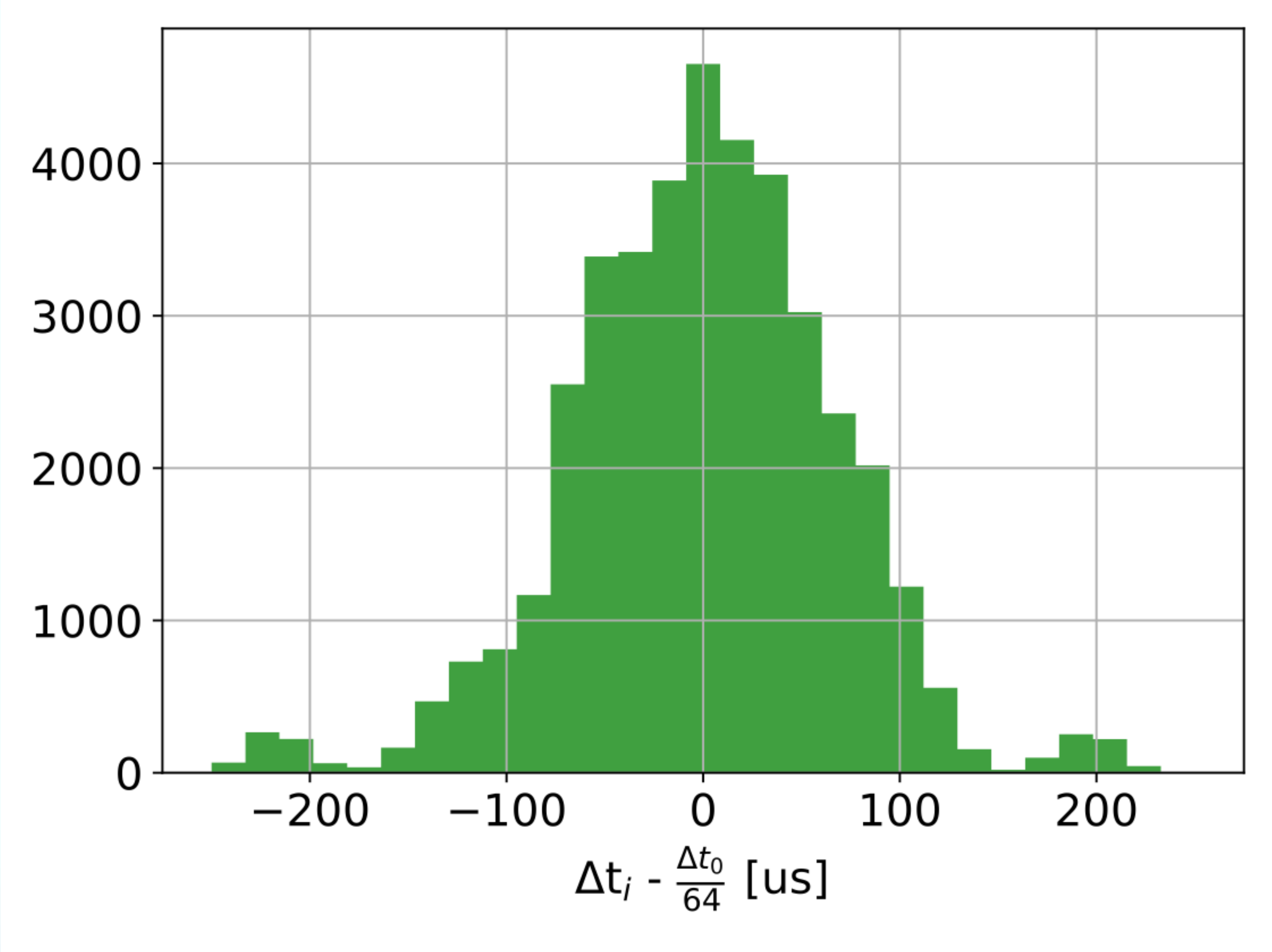
$$P_e \propto \Delta B^2$$

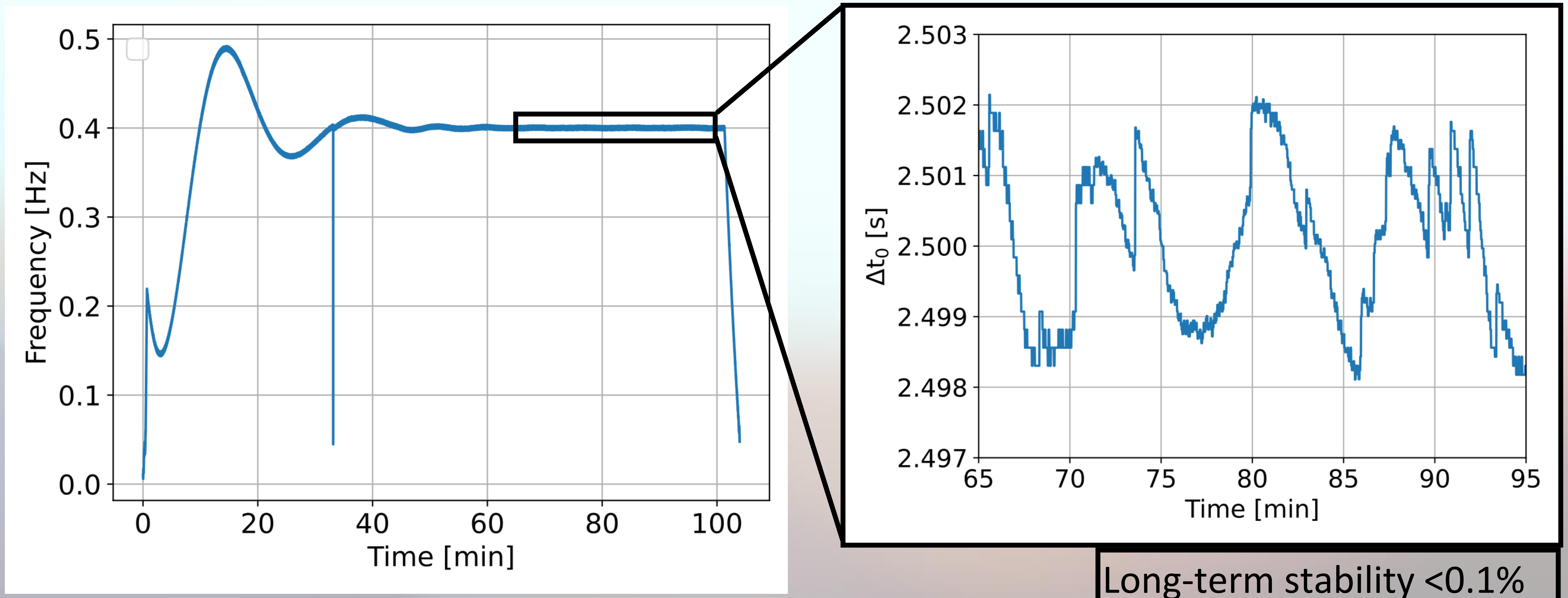
Eddy currents must be minimized

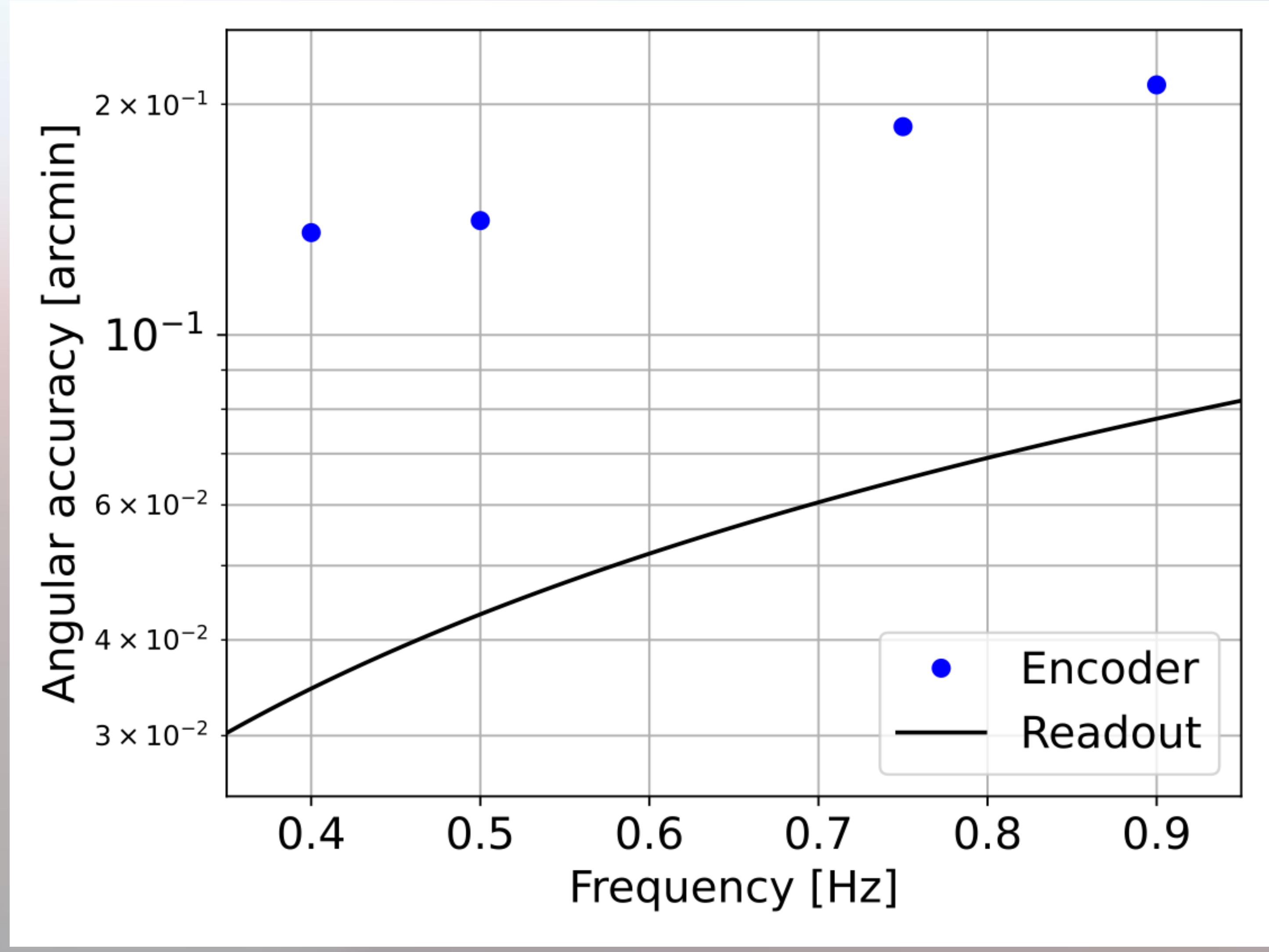
PMU - Sapienza

- Absolute encoder Δt_0
- Relative encoder $\Delta t_i i = 1, \ldots, 64$



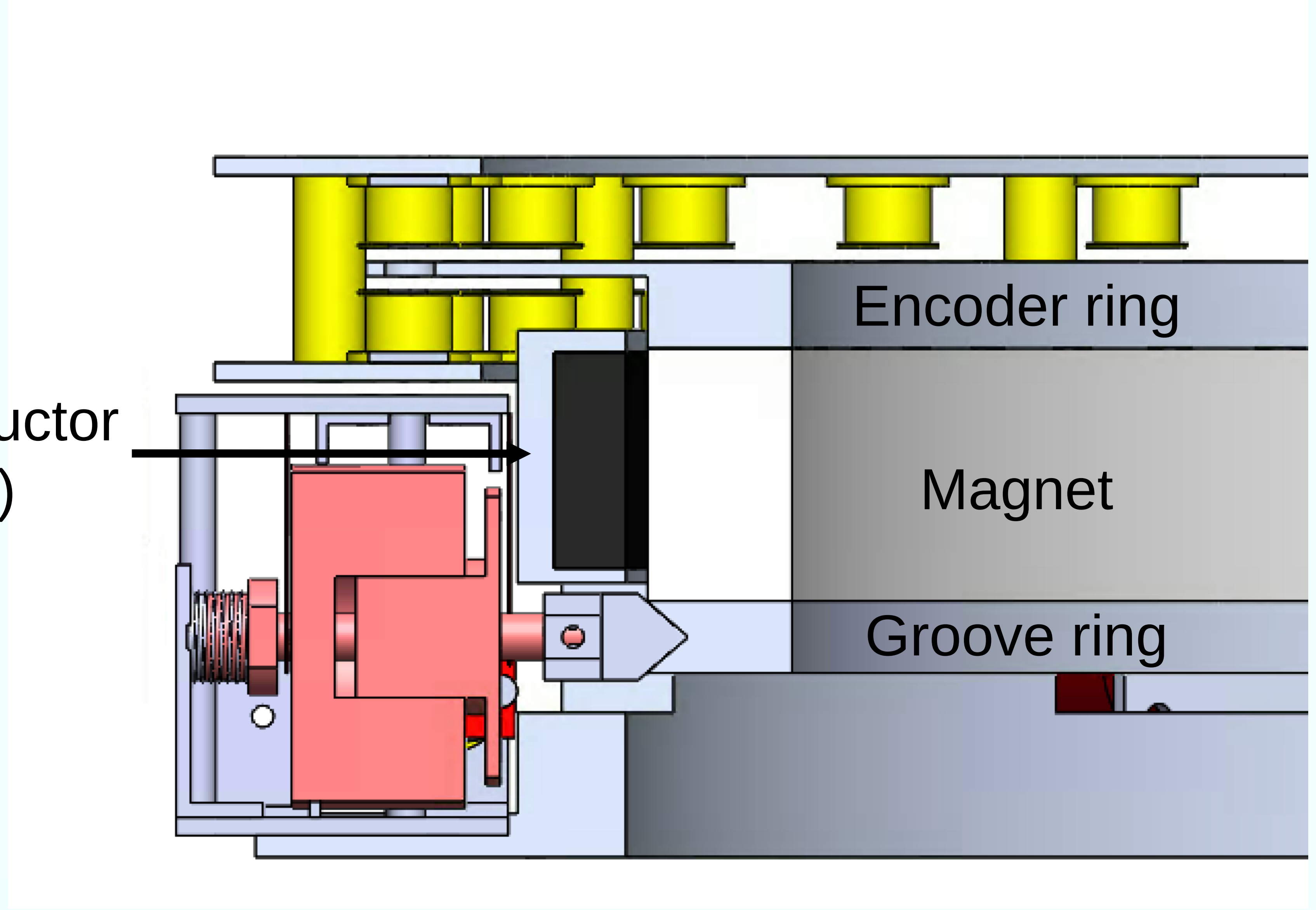


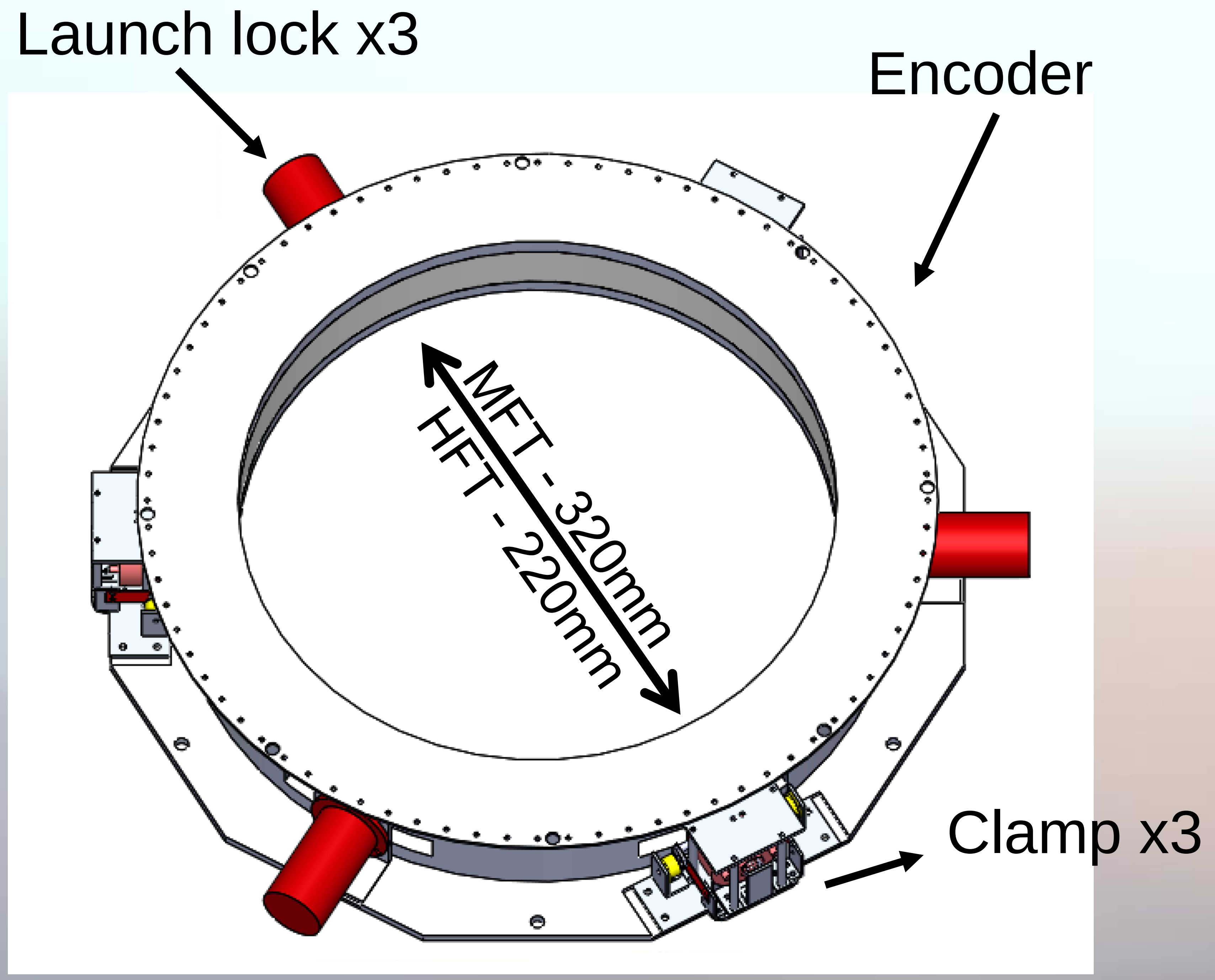




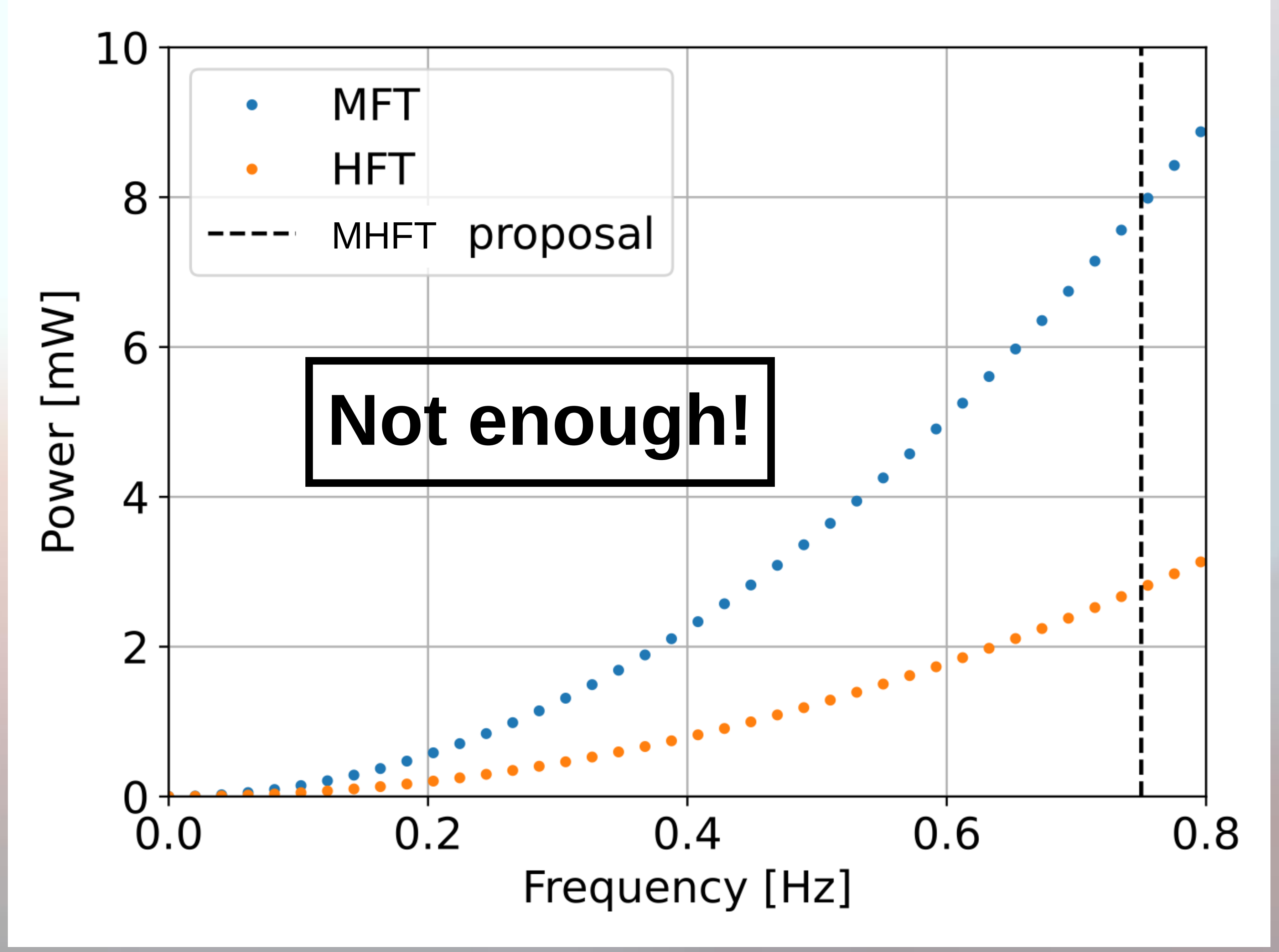
Long-term stability <0.1%

PMU - LiteBIRD MHFT





	MFT	HFT
HWP diameter	320 mm	220 mm
HWP temperature	< 20 K	< 20 K
PMUs dissipation	< 4 mW	
Rotation frequency	45 rpm	45 rpm
Angular accuracy	< 1’	< 5’
Lifetime	> 3 years	> 3 years
Total mass	< 20 Kg	



Conclusions

The SMB technology is ready to be used for space application.
The heat loads **must** be reduced by:

- reducing the inhomogeneity of the main magnet
- Improving the purity of the copper wire

Strong interaction with the manufacturers is needed.

Space companies must be involved in the qualification process in order to raise the SMB-TRL and to qualify each component of the system.

Level of HWP-Mueller matrix characterization is still an open issue.