Performance validation tests

Paolo de Bernardis, Silvia Masi & the Rome LB team
Dipartimento di Fisica, Sapienza

LiteBIRD EU detector KO workshop
Pisa, 20260108

SAPIENZA
UNIVERSITÀ DI ROMA

Test ID	Type	Test	Expected output
T_1	Electrical	Functionality (on/off)	Number of active TES
T_2	Electrical	I-V curves	I-V curve for each TES in the FPSA
T_3	Electrical	Noise	Dark Noise Equivalent Power (NEP) estimation
T_4	Electrical	Electrical responsivity	Estimation of responsivity from electrical measurement
T_5	Electrical	Saturation power	Electrical power for transition to normal
T_6	Thermal	Time-constant	Time constant of the device
T_7	RF	**Optical efficiency**	Estimation of optical efficiency of the system
T_8	RF	**Angular response**	2D optical response of the radiation coupling system
T_9	RF	**Spectral response**	Frequency response of the TES + Horn + four probes + on-chip filter
T_10	RF	**Out-of-band rejection**	Sensitivity to radiation at frequency higher and lower of the nominal band
T_11	RF	**Polarimetry**	Polarization angle and polarization efficiency as a function of frequency and incident direction
T_12	Magnetic	Magnetic susceptibility	Sensitivity of TES to magnetic field variations (coupling coefficient to magnetic field)
T_13	Thermal	Thermal susceptibility	Sensitivity of TES to temperature of the supporting wafer (coupling coefficients to wafer temperature)
T_14	Electrical	Electrical crosstalk	Cross-talk matrix for electrical impulse to each TES in the FPSA
T_15	RF	**Optical crosstalk**	Cross-talk matrix for RF signal to each TES on the FPSA
T_16	Electrical	**NEP**	Noise Equivalent Power (NEP) estimation, with different optical loads
T_17	RF	**Responsivity / NET**	Conversion factor from optical signal to detector output and estimation of the Noise Equivalent Temperature with different optical loads, that is one of the main elements to verify detector performance.
T_18	RF	**Stability and 1/*f* noise**	Measurement of the power spectrum of the noise on timescales of the order of 30 minutes or longer (frequencies below 0.5mHz)

In the following we focus on the optical tests

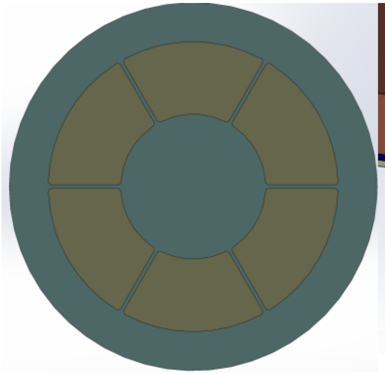
General considerations

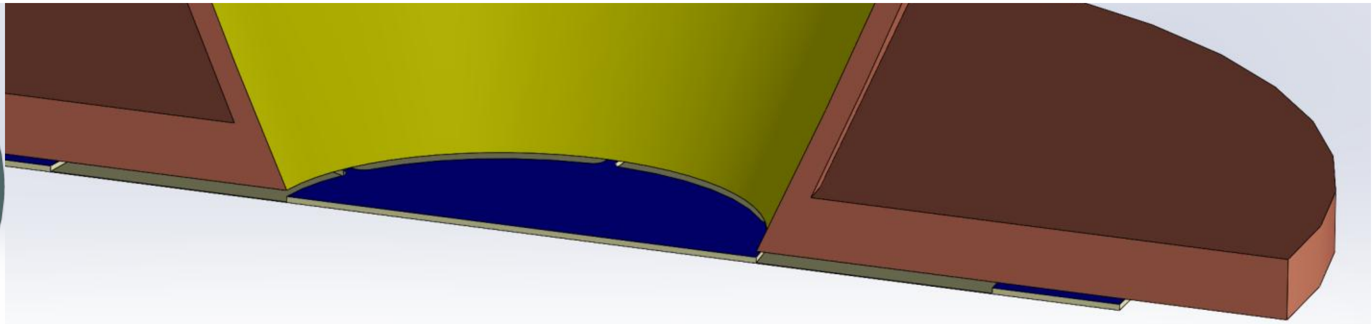
- *Electrical* tests must be carried out in a representative cryogenic environment
  - Testbed cryostat must reach 0.1K with at least a few μW of cooling power
- *Optical* tests must be carried out in a representative radiative environment
  - A 2.7K enclosure surrounding the 0.1K detection stage is needed
  - Blackbody signals
    - This is a practical way to produce a well calibrated brightness at the pixel input, i.e. to perform *optical responsivity* and *optical efficiency* tests.
    - BB signals can be generated inside the 2.7K enclosure using a blackbody with sufficient throughput.
    - The source must be *modulated* to produce a usable calibration signal. To achieve fast modulation
      - Reduce the heat capacity of the emitter (inverted bolometer source) or ..
      - Chop between two cryogenic blackbodies at slightly different temperatures
  - Monochromatic signals
    - If properly calibrated, these signals are useful to test the frequency response, particularly important for dichroic pixels.
    - Must be injected from external sources (VNA) by means of suitable window, waveguides or light-pipes, low-pass filter stacks …
    - … or can be produced locally by Josephson Junctions based oscillators
    - in both cases the big issue is the a-priori knowledge of the brightness at the pixel input as a function of frequency
  - A cryogenic DFTS with two BB sources at the two input ports would allow for *simultaneous* optical efficiency and spectral response measurements. However, for the required throughput, the DFTS is cumbersome, and difficult to squeeze in the available 2.7K volume.

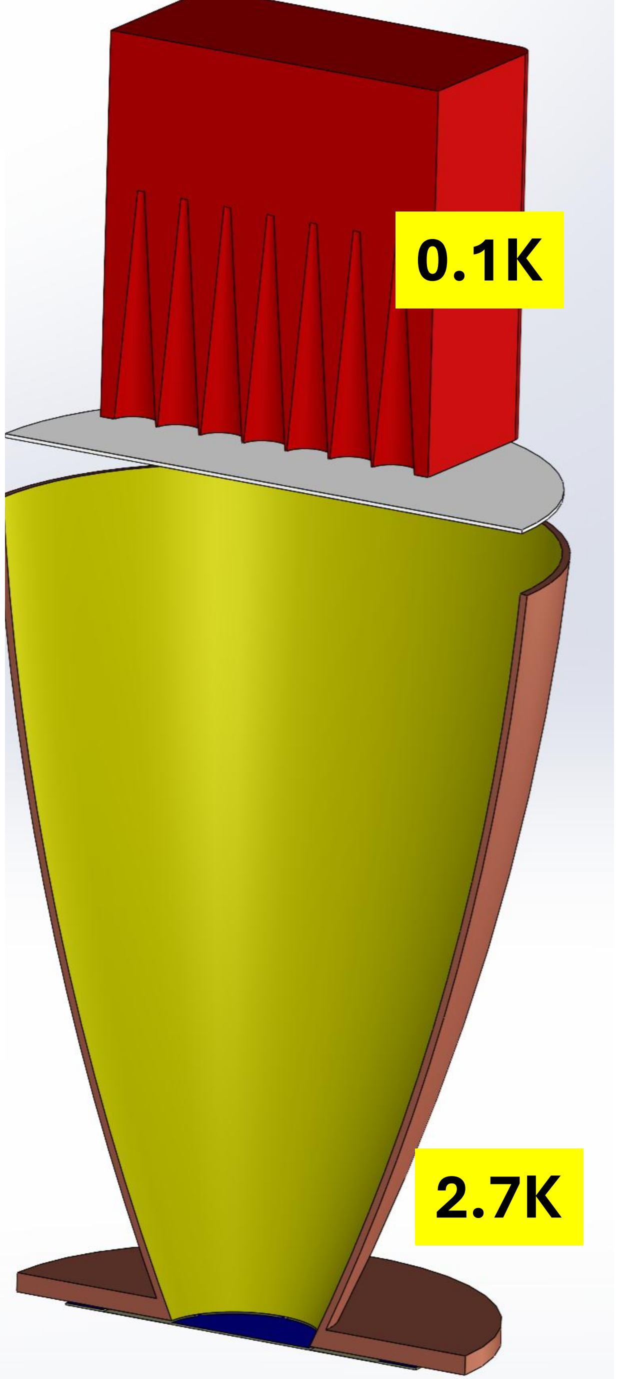
Optical efficiency measurements

Efficiency measurement for the entire array

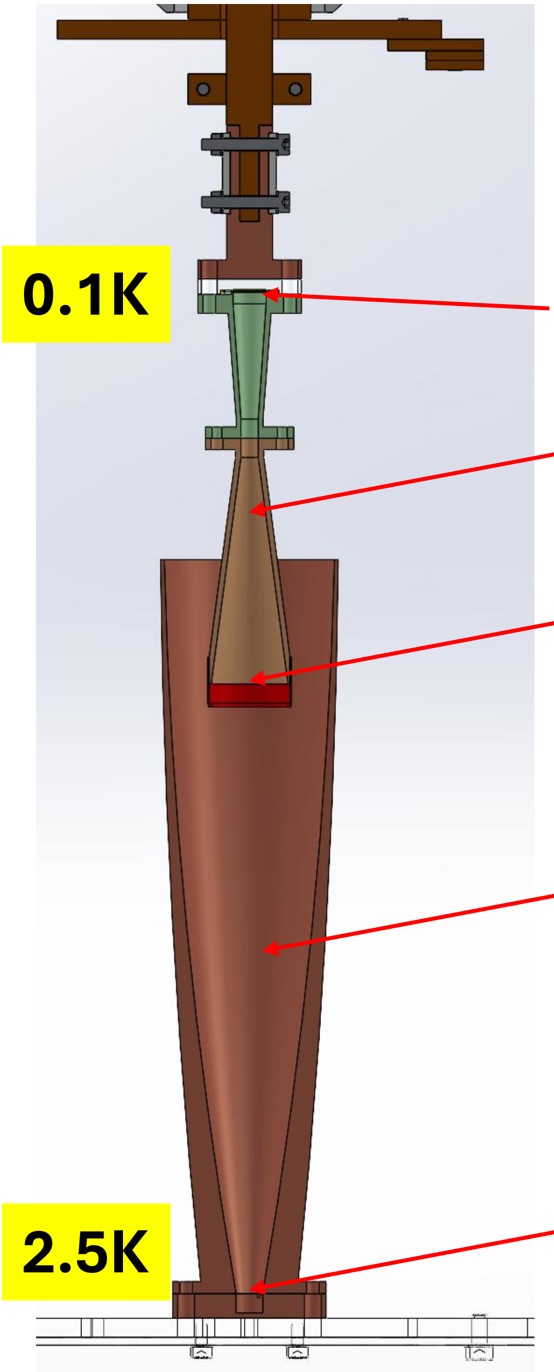
- Either
  - Mechanical scanning mechanism moving the source for sequential calibration of all the detectors ..
- ... or
  - set of 64 sources (one per pixel)
- ... or
  - *Compact* large throughput source for simultaneous illumination of all the detectors. In this case:
    - Array area $A_a \cong 9.5 \times 9.5\ cm^2$
    - Solid angle of main beam $\Omega_d \cong 0.2\ sr$ (basically twice the main beam Ω)
    - Required source throughput $A\Omega \cong 20\ cm^2 sr$
    - Transfer optics can be non-imaging (e.g. Winston)
    - If $\Omega_s \cong 1.5\pi\ sr\ \rightarrow\ A_s \cong 4\ cm^2$ (lower limit)
    - Concept drawing:
    - 45" Si wafer 500 μm thick, 4 cm diam blackened (Bi film) center disk, thermally insulated from periphery ring via **50 μm** thick membrane. Heater layer deposited on the opposite side. $\tau \cong 5\ ms$, $G \cong 2\ mW/K$
    - Winston cone: gold plated Cu, 15 cm output dia, 4 cm input dia, 20.4 cm length, $\theta_{HWHM} \cong 25^o$
    - 14 cm diameter polarizer (photolitographed) with cryo rotation mechanism (e.g. Salatino A&A 2011)

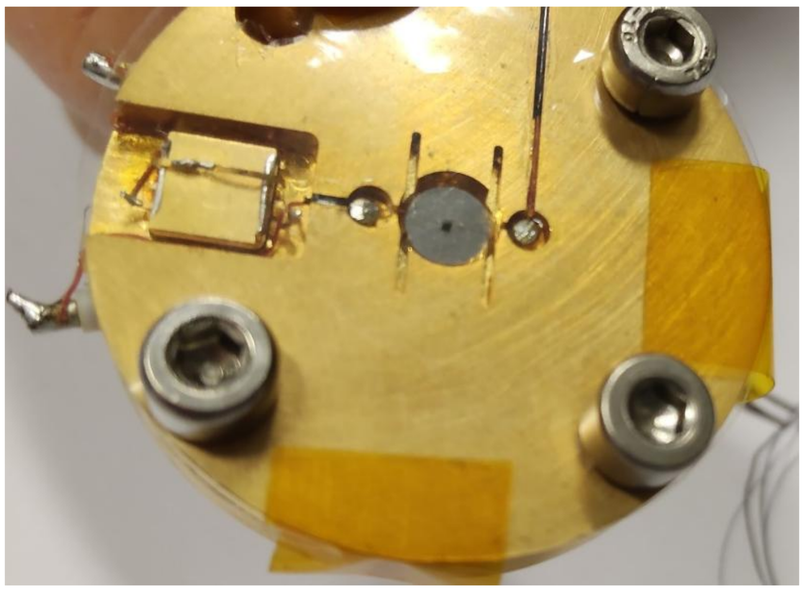




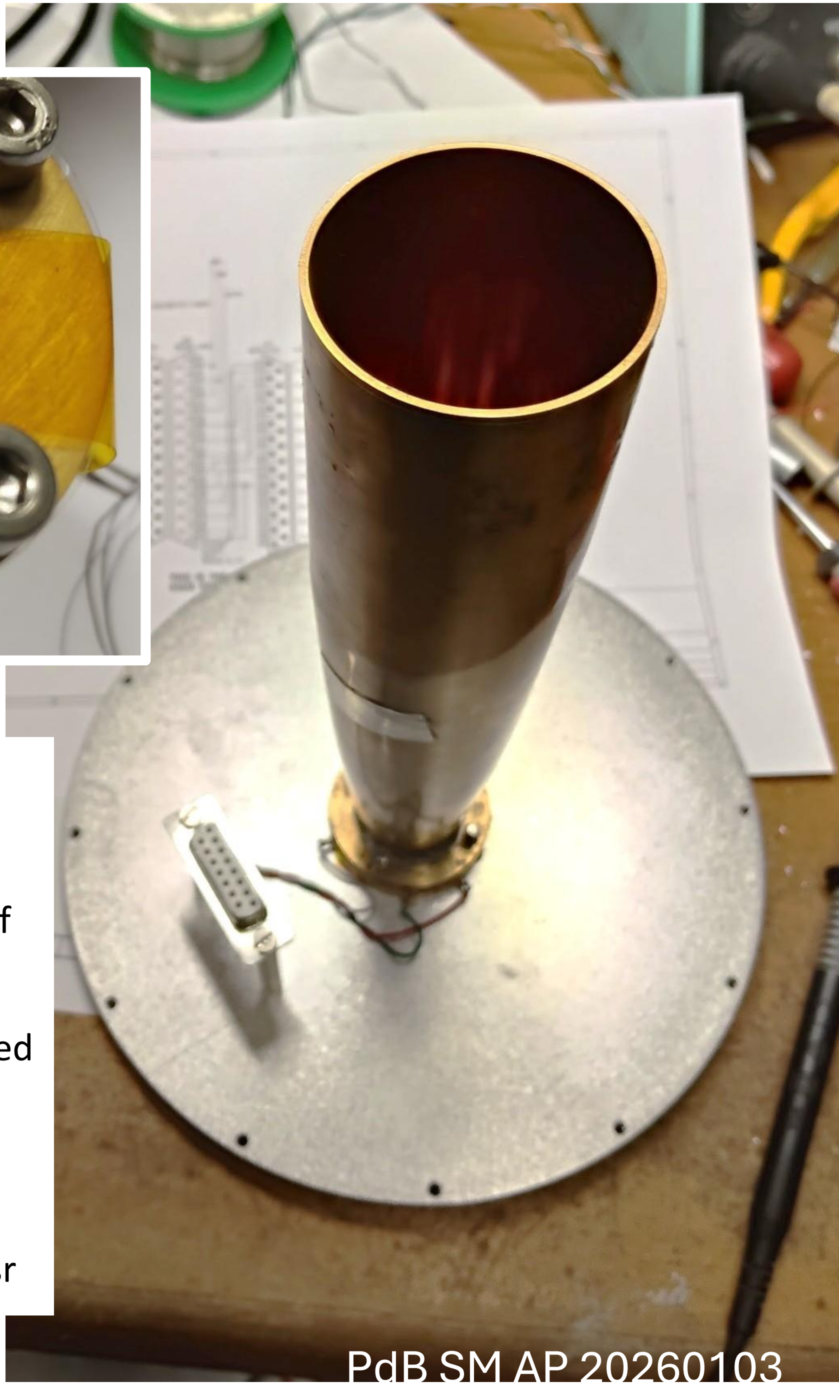


bolometer optical test

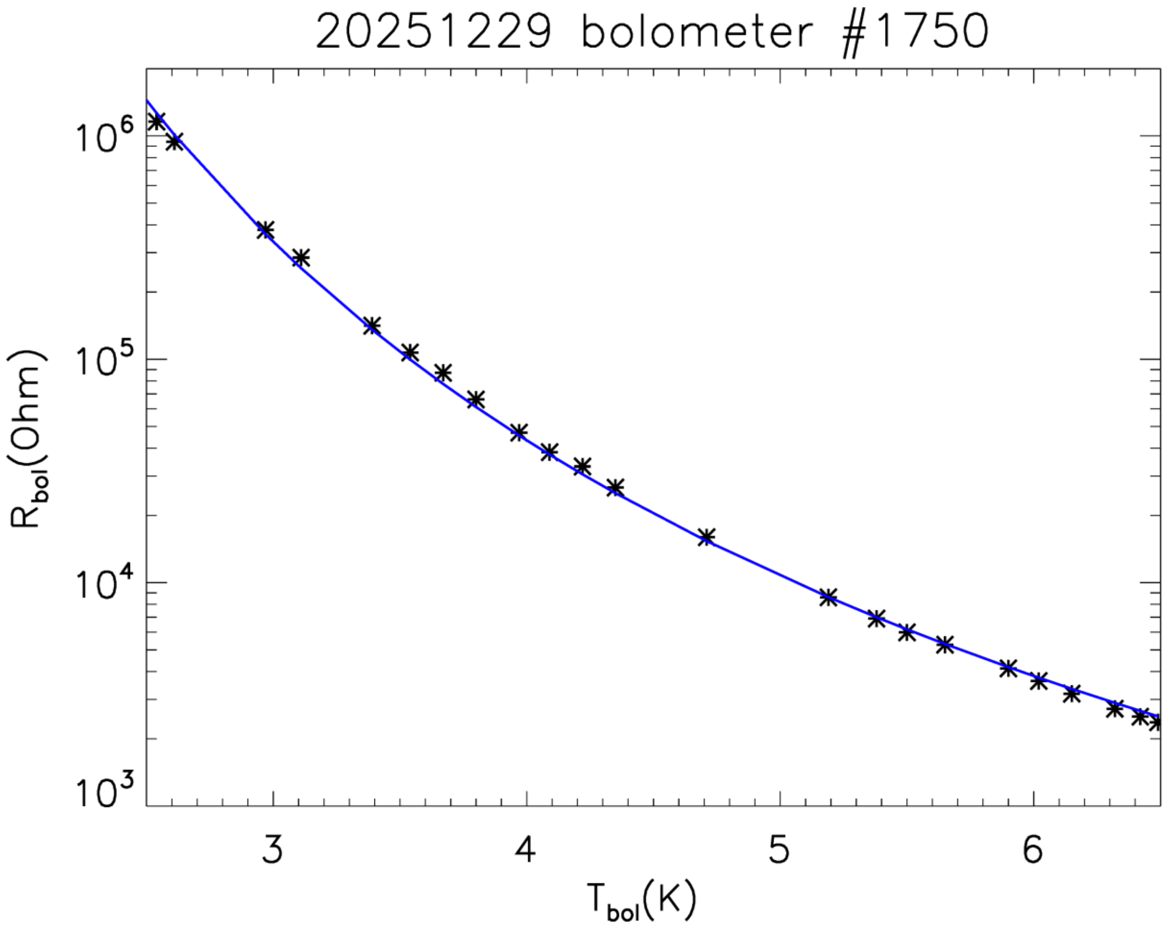


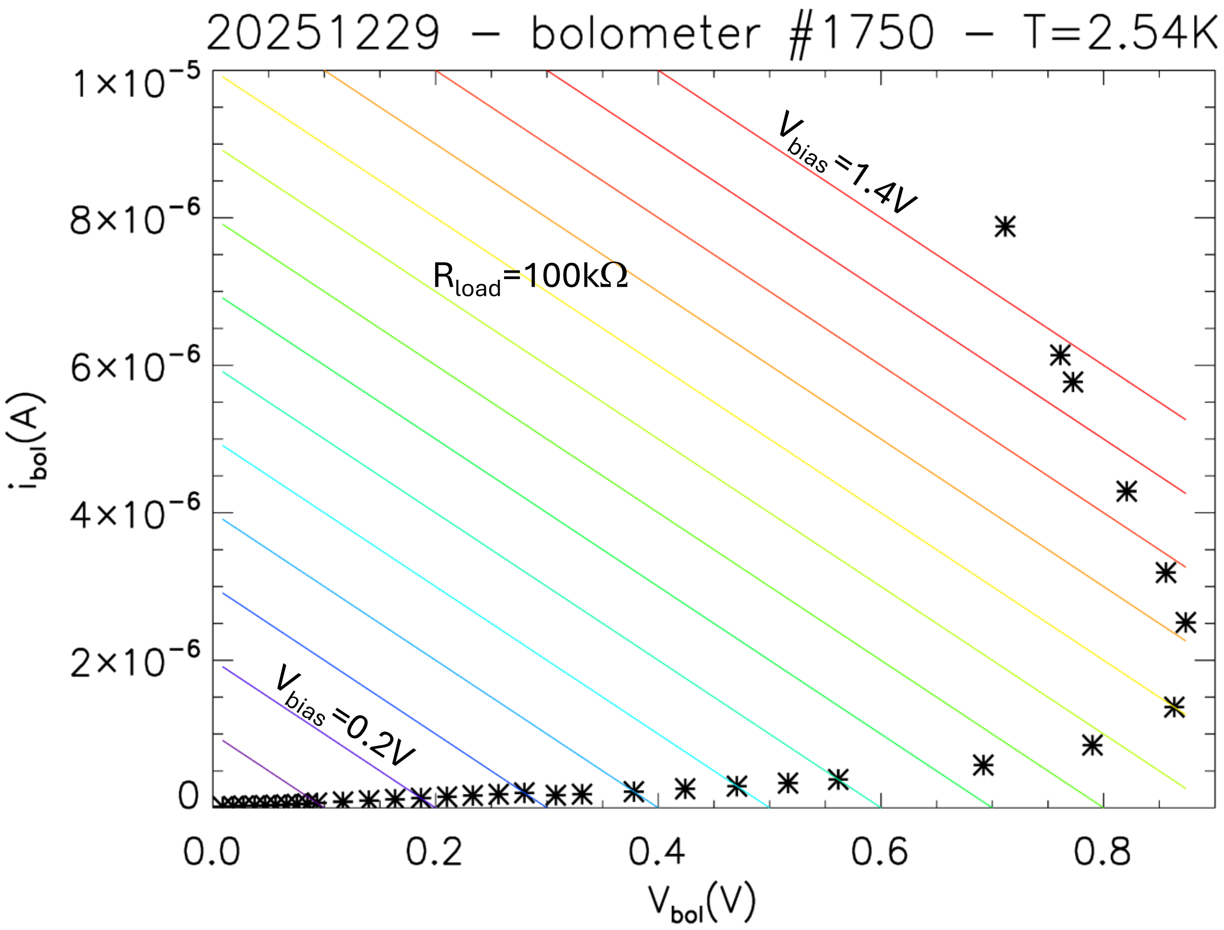


- The thermal source is a metalized sapphire absorber, 4.5mm in diameter, suspended in a cavity.
- The absorber temperature is modulated between 2.5K and 6.5K at a frequency of 230 mHz to ensure prompt response of the source
- The Winston cone conveys the modulated absorber brightness to the 20 mm aperture of the SWIPE feedhorn
- The SWIPE bolometer signal at the modulation frequency is measured
- $A\Omega_{source} \cong 1\ cm^2 sr > A\Omega_{SWIPE} \cong 0.6\ cm^2 sr$



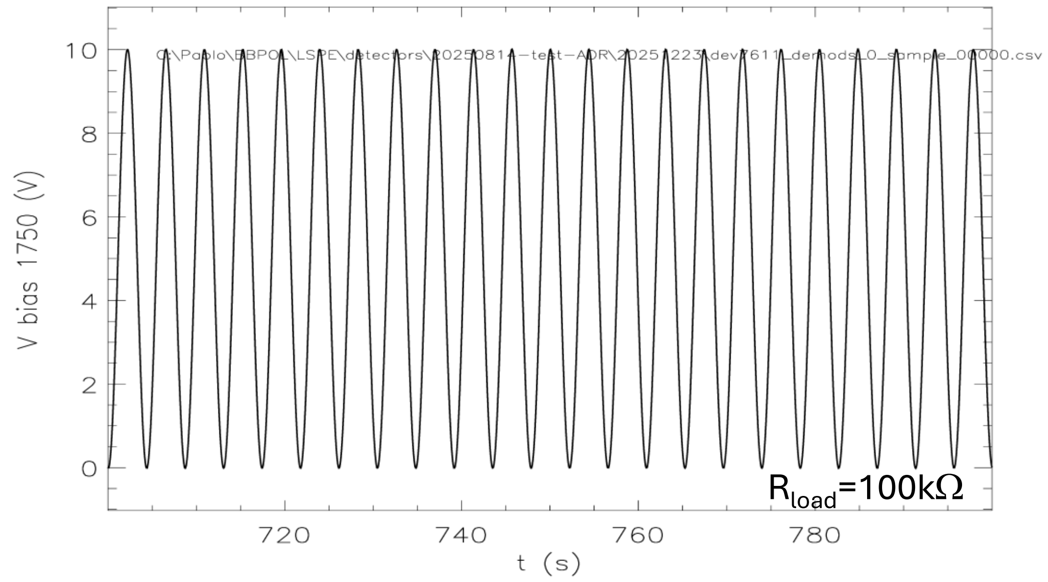
Source bolometer characterization

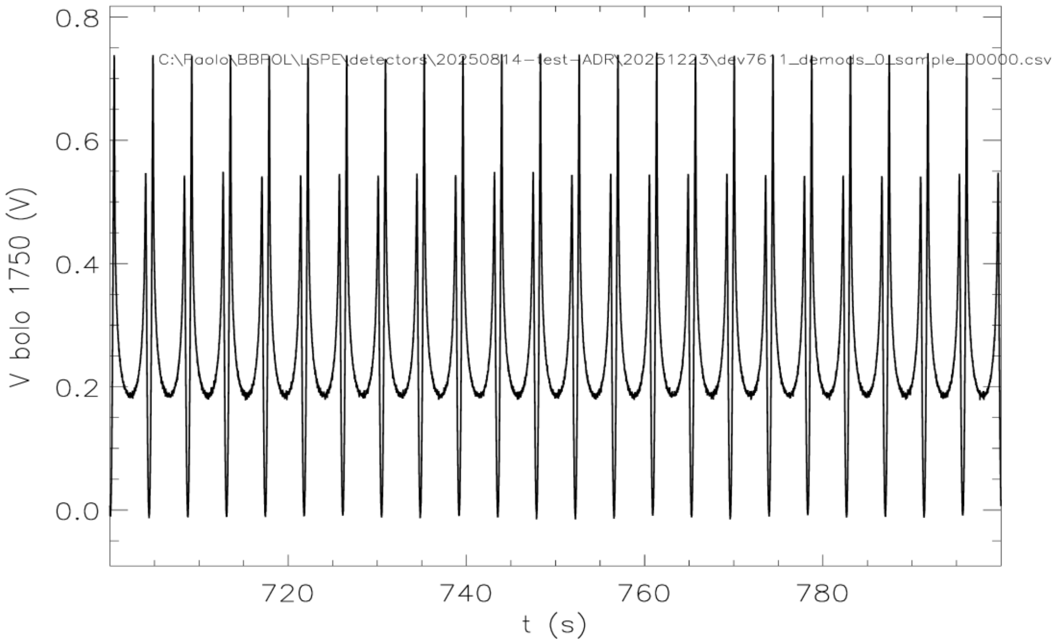


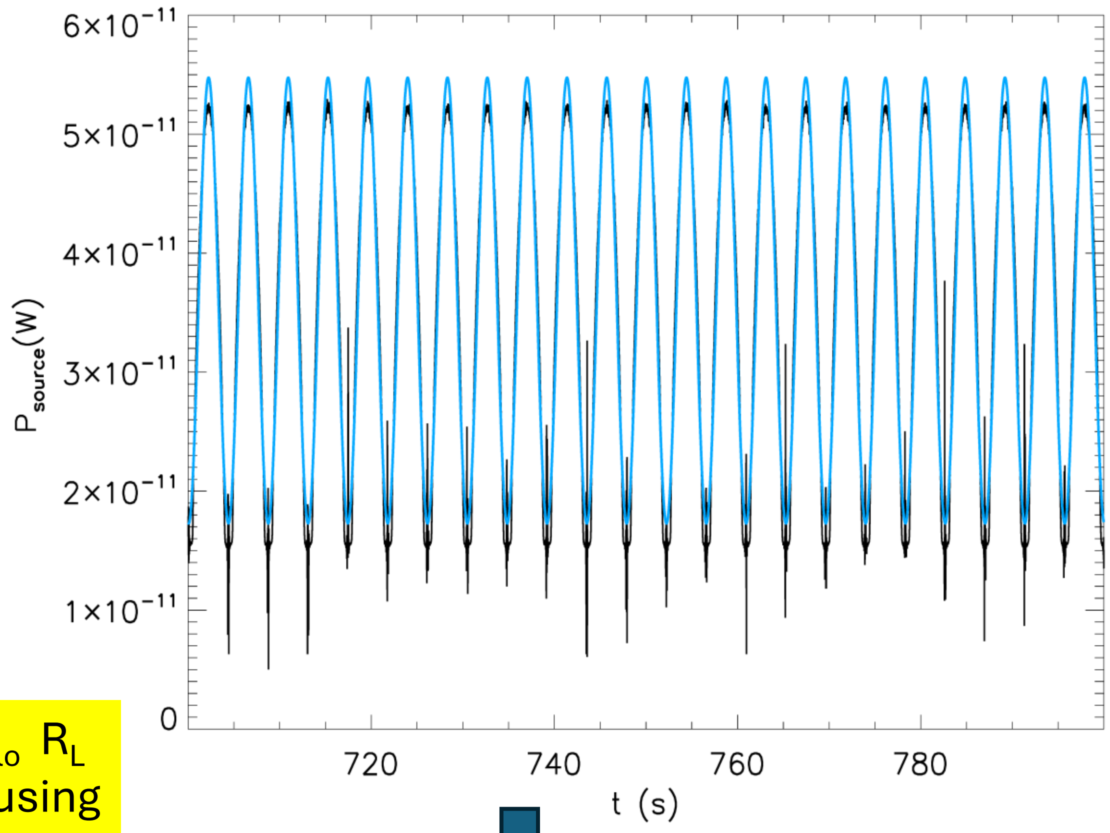


PdB SM AP 20260103

Source bolometer signals





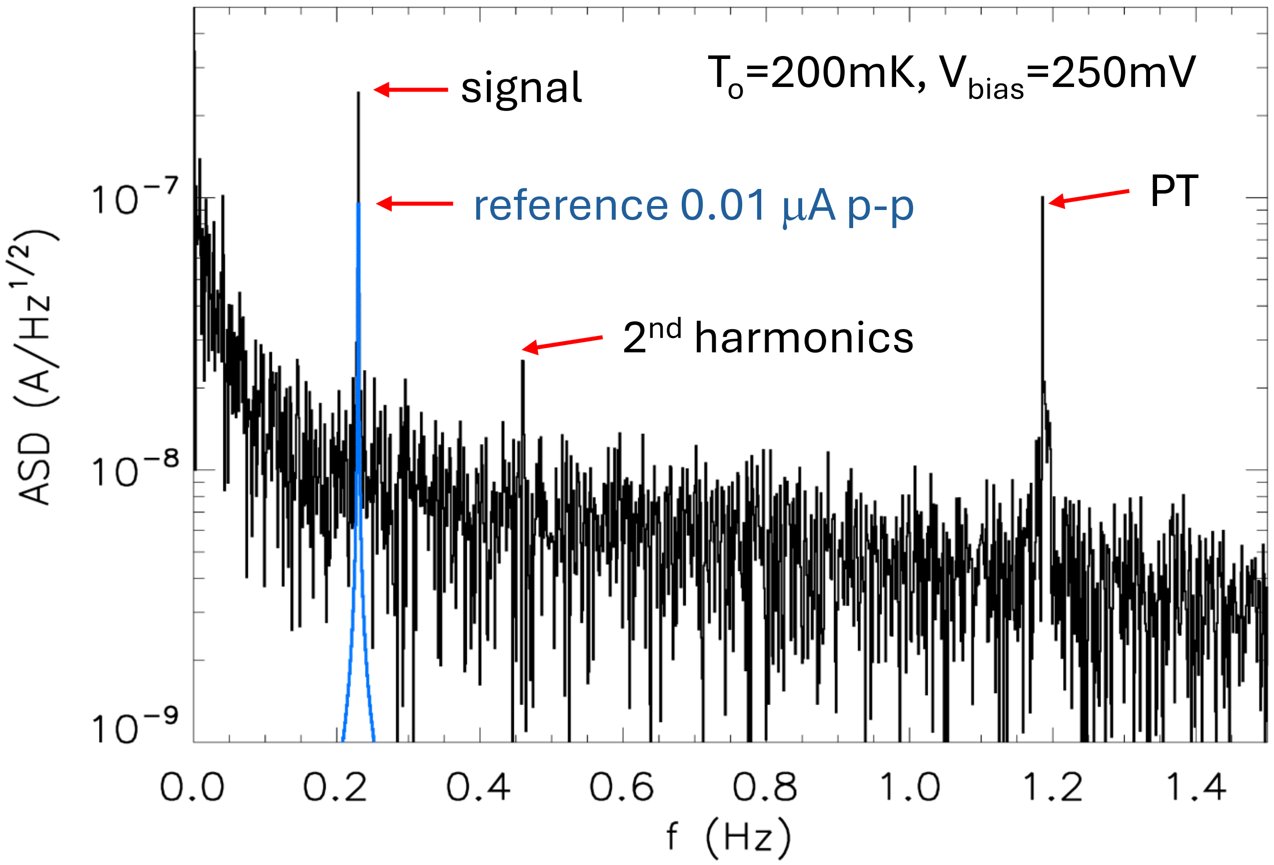


From V_{bias} V_{bolo} R_L compute R_s ; using R(T) calibration compute T_s, and from that compute P_{source} using assumed $\Delta\nu$, $A\Omega$

$\Delta P_{source\ p\text{-}p} = 3.7 \times 10^{-11}$ W

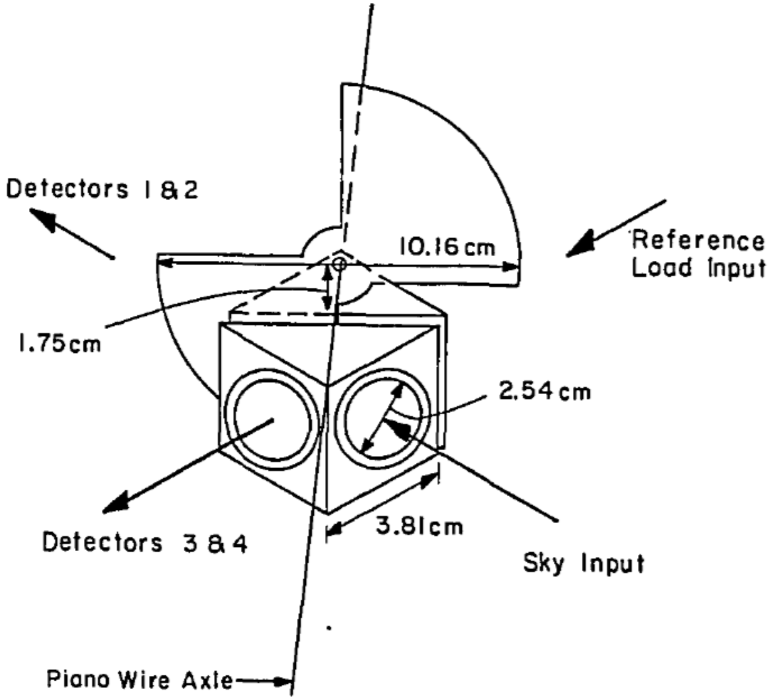
PdB SM AP 20260103

Corresponding detecting bolometer signal

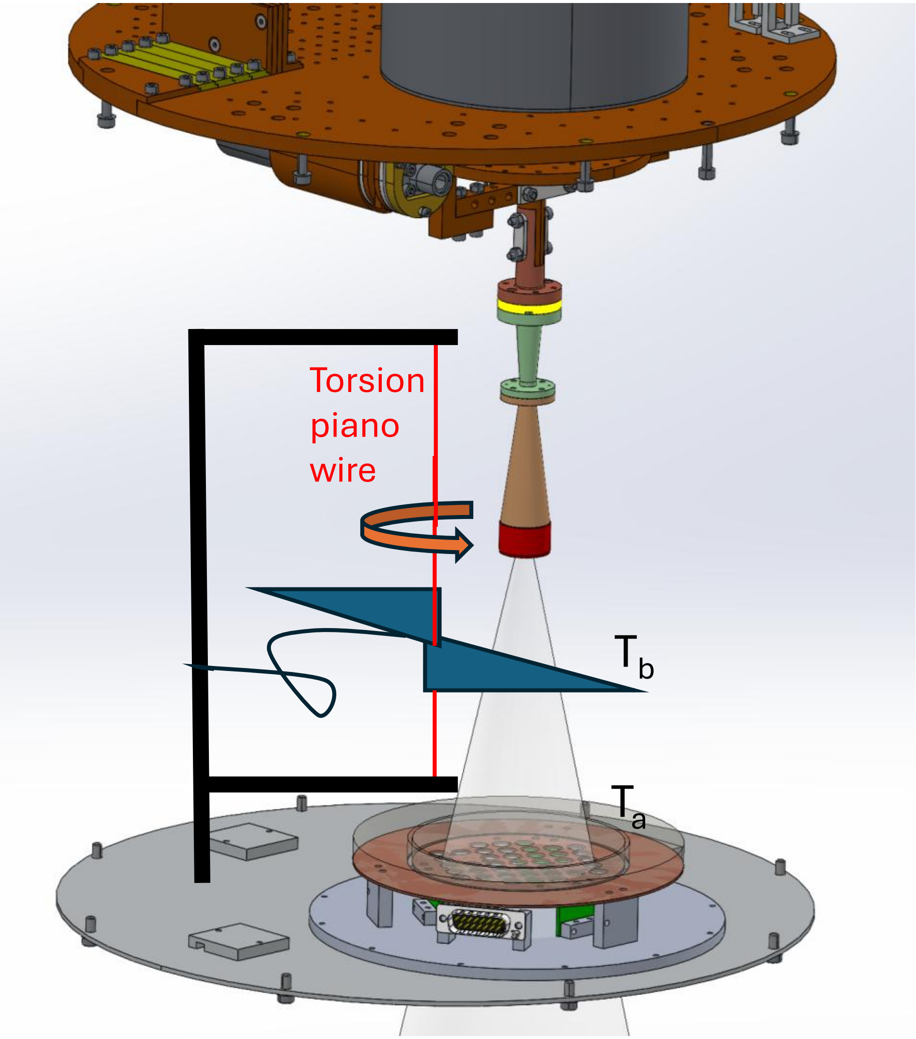


Another option

- "Large" tunable BB sources + mechanical resonant chopper (see e.g. Page & 1992)
- Advantage: Absolute source, switching between two beam-filling BB sources with directly measured temperatures
- Issues:
  - Dimensions challenging ; significant effort to produce working chopper
  - Low modulation frequency (most likely < 0.1..1 Hz)



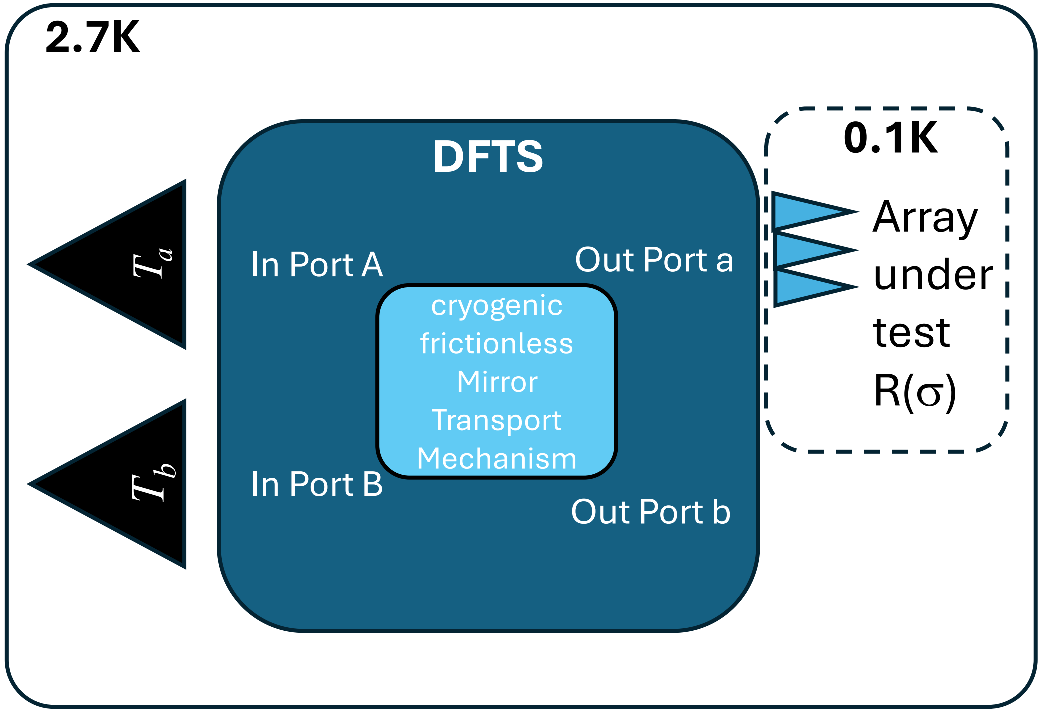
Concept sketch



Spectral measurements for dichroic pixels validation

several options

In principle :



Modulation frequency (with MTM) $f = 2\sigma\dot{x}$

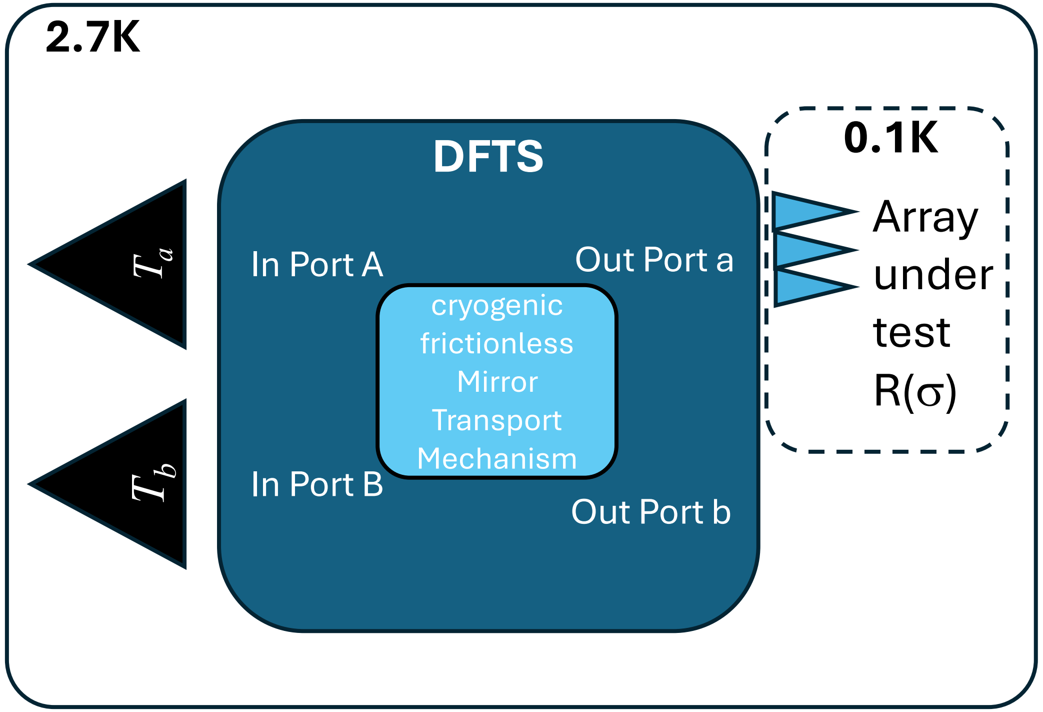
$$B(x) = \int_0^\infty R(\sigma)[B(T_a,\sigma) - B(T_b,\sigma)]\,\{1 + \cos[4\pi\sigma x]\}d\sigma$$

$$R(\sigma) = \left[\int_{-\infty}^{+\infty} [B(x) - \langle B\rangle] \cos[4\pi\sigma x]\, dx\right] \Big/ [B(T_a,\sigma) - B(T_b,\sigma)]$$

$R(\sigma)$ includes FTS response (flat in the band of interset ?)

In principle this approach would provide both
efficiency and spectrum validations

In principle :



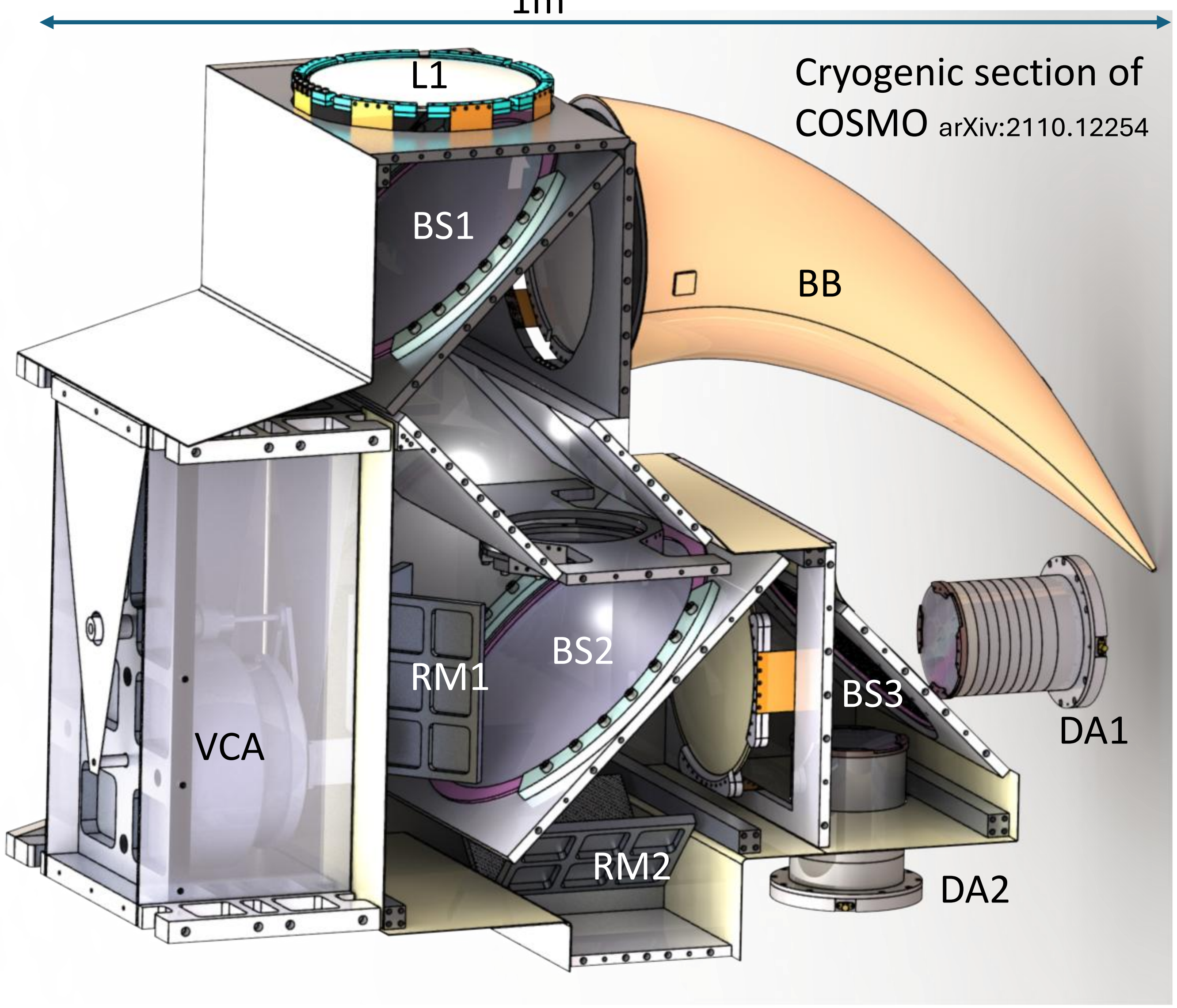
Modulation frequency (with MTM) $f = 2\sigma\dot{x}$

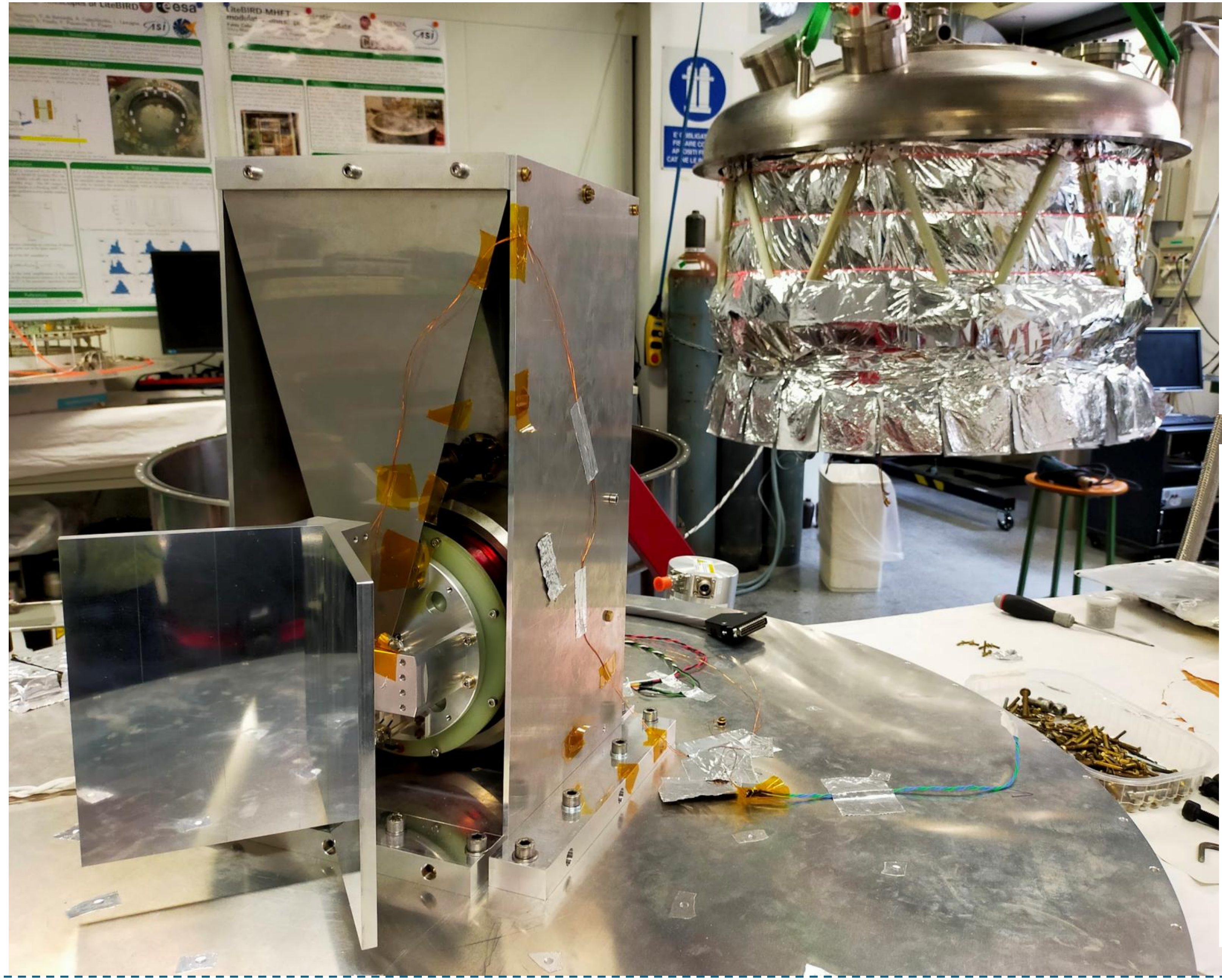
$$B(x) = \int_0^\infty R(\sigma)[B(T_a,\sigma) - B(T_b,\sigma)]\{1 + \cos[4\pi\sigma x]\}d\sigma$$

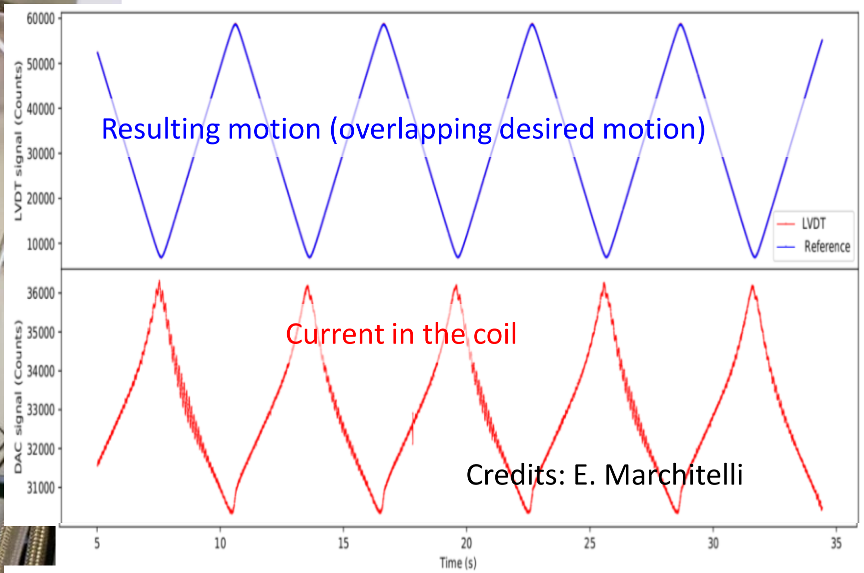
$$R(\sigma) = \left[\int_{-\infty}^{+\infty} [B(x) - \langle B\rangle]\cos[4\pi\sigma x]\,dx\right] \Big/ [B(T_a,\sigma) - B(T_b,\sigma)]$$

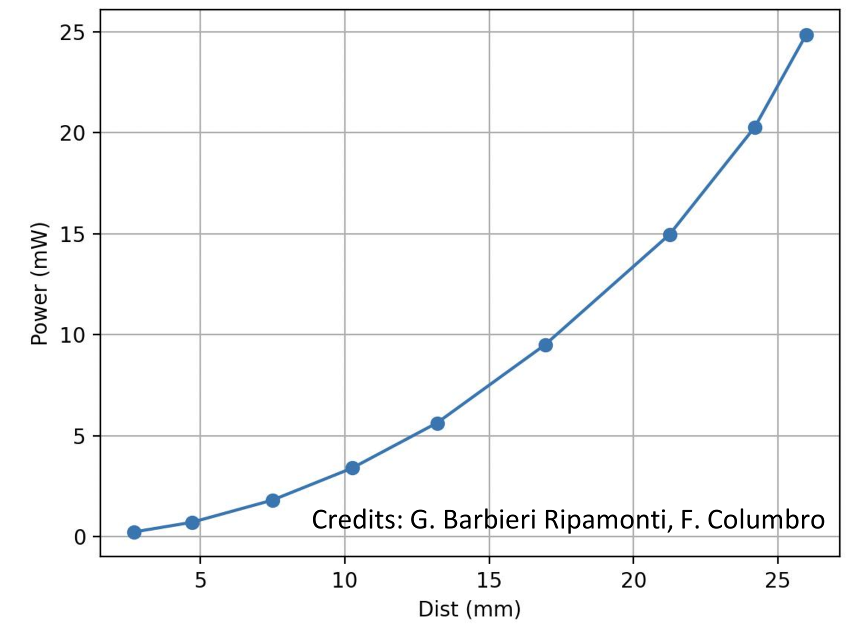
$R(\sigma)$ includes FTS response (flat in the band of interset ?)

In practice, for a 20 cm^{2}sr throughput:



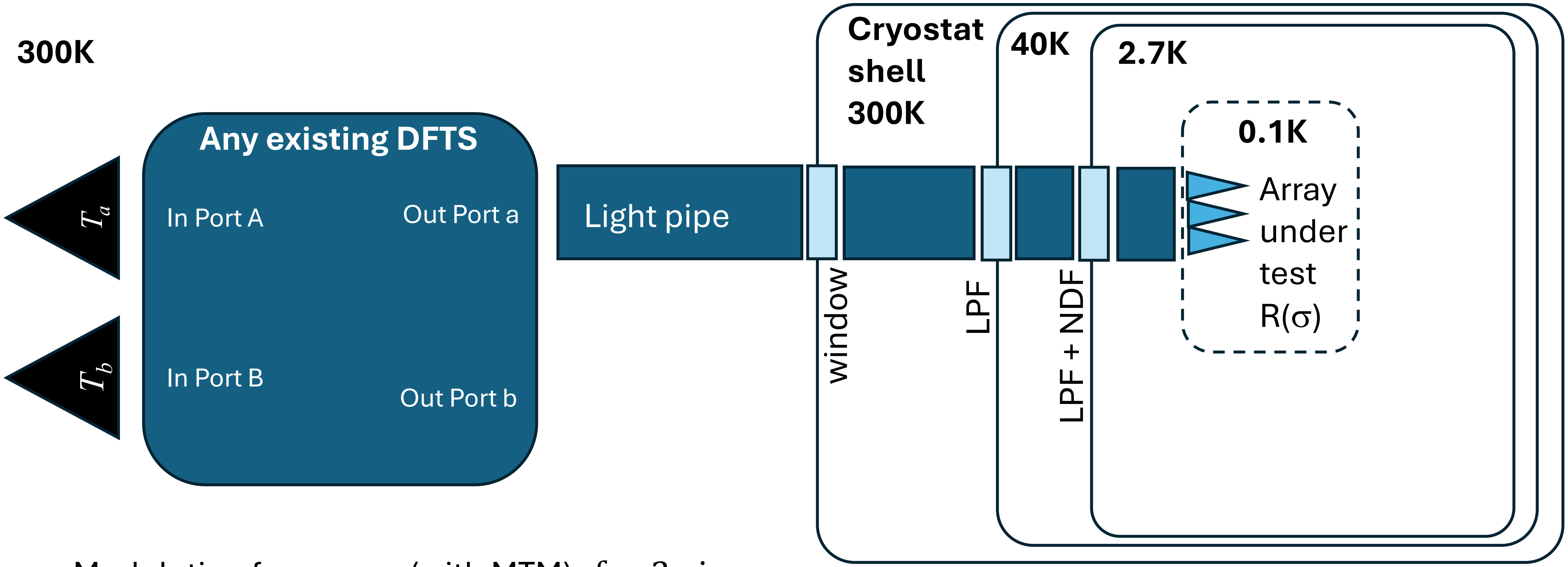






May be a much smaller throughput system to calibrate just the center detector ?

In alternative



Modulation frequency (with MTM) $f = 2\sigma\dot{x}$

$$B(x) = \int_0^{\infty} R(\sigma)t(\sigma)[B(T_a,\sigma) - B(T_b,\sigma)]\{1 + \cos[4\pi\sigma x]\}d\sigma$$

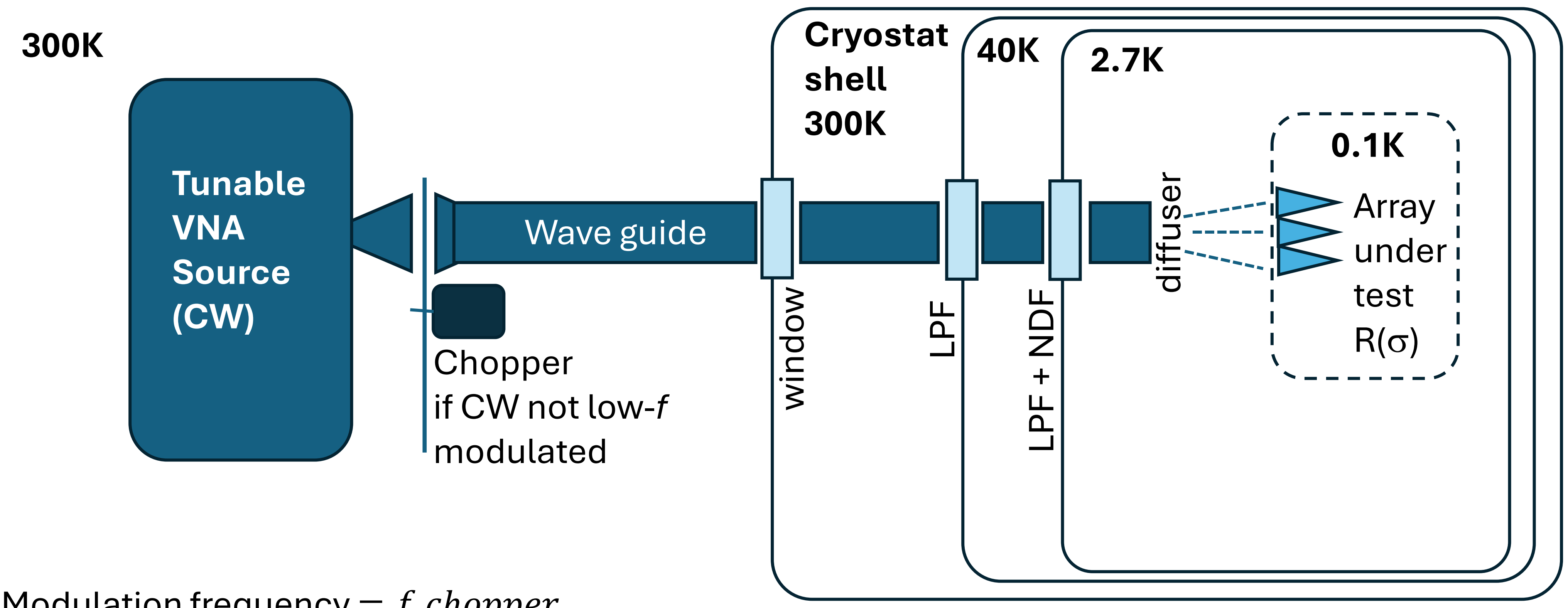
$$R(\sigma)t(\sigma) = \left[\int_{-\infty}^{+\infty} [B(x) - \langle B\rangle]\cos[4\pi\sigma x]\,dx\right] \Big/ [B(T_a,\sigma) - B(T_b,\sigma)]$$

$$T_a = 300K, T_b = 77K$$

Requires custom cold NDF

$t(\sigma)$ (due to window, LPF, NDF, light pipe) must be calibrated separately (not easy)

Or ...



Modulation frequency $= f\ chopper$

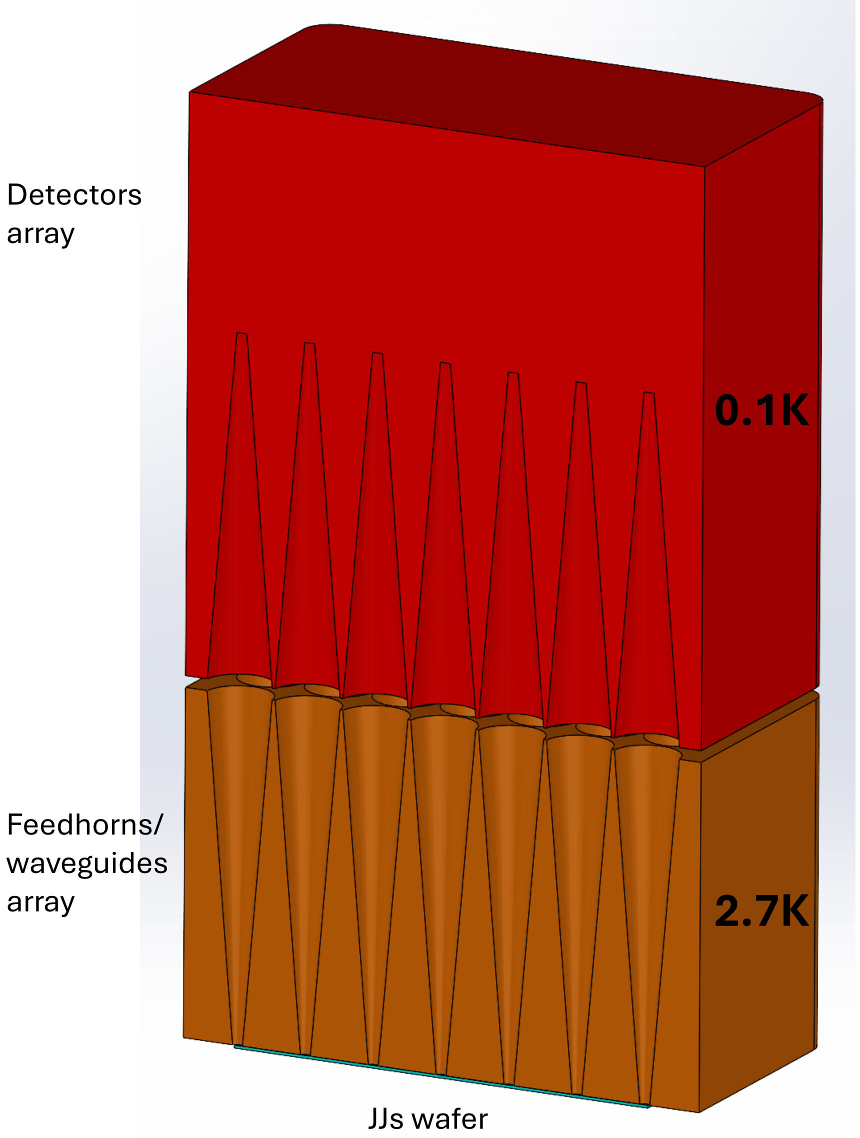
$T_a = 300K, T_b = 77K$

$t(\sigma)$ (due to VNA, window, LPF, NDF, waveguide, diffuser) must be calibrated separately (not easy)

Or even ...

- Josephson junctions array:
- $f = \frac{2e}{h} V \rightarrow 145\mu V \,..\, 372\mu V \;\leftrightarrow\; 70\ GHz \,..\, 180\ GHz$
- $P_{max} \cong \frac{I_c^2 R_n}{2}$

  for $I_c = 10\mu A$ and $R_n = 10\Omega \rightarrow P_{max} \cong 0.5\ nW$
- Looks appealing. However
  - Mismatch to the load will kill the power, so careful connection to waveguide/horn or any other free space adaptor is needed
  - Calibration of $P(f)$ is a big issue (as above)
  - JJ array wafer feasibility and cost to be investigated
- See e.g.
  - Revin et al. 2024, https://www.beilstein-journals.org/bjnano/articles/15/3
  - Revin et al. 2020, Appl Sci, 10 (21) (2020), p. 7667



To follow:

- Consolidation of requirements for FPSA *optical efficiency* and *spectral response* accuracy needs (0.1% ? 1% ? 10% ? ...)
- *Then*, selection of measurement options, based on study of
  - *systematic effects*
  - *feasibility* in the project timeframe (also related to available infrastructure, personnel and funds resources)