Looking for spectral distortions of the Cosmic Microwave Background (CMB) from Antarctica

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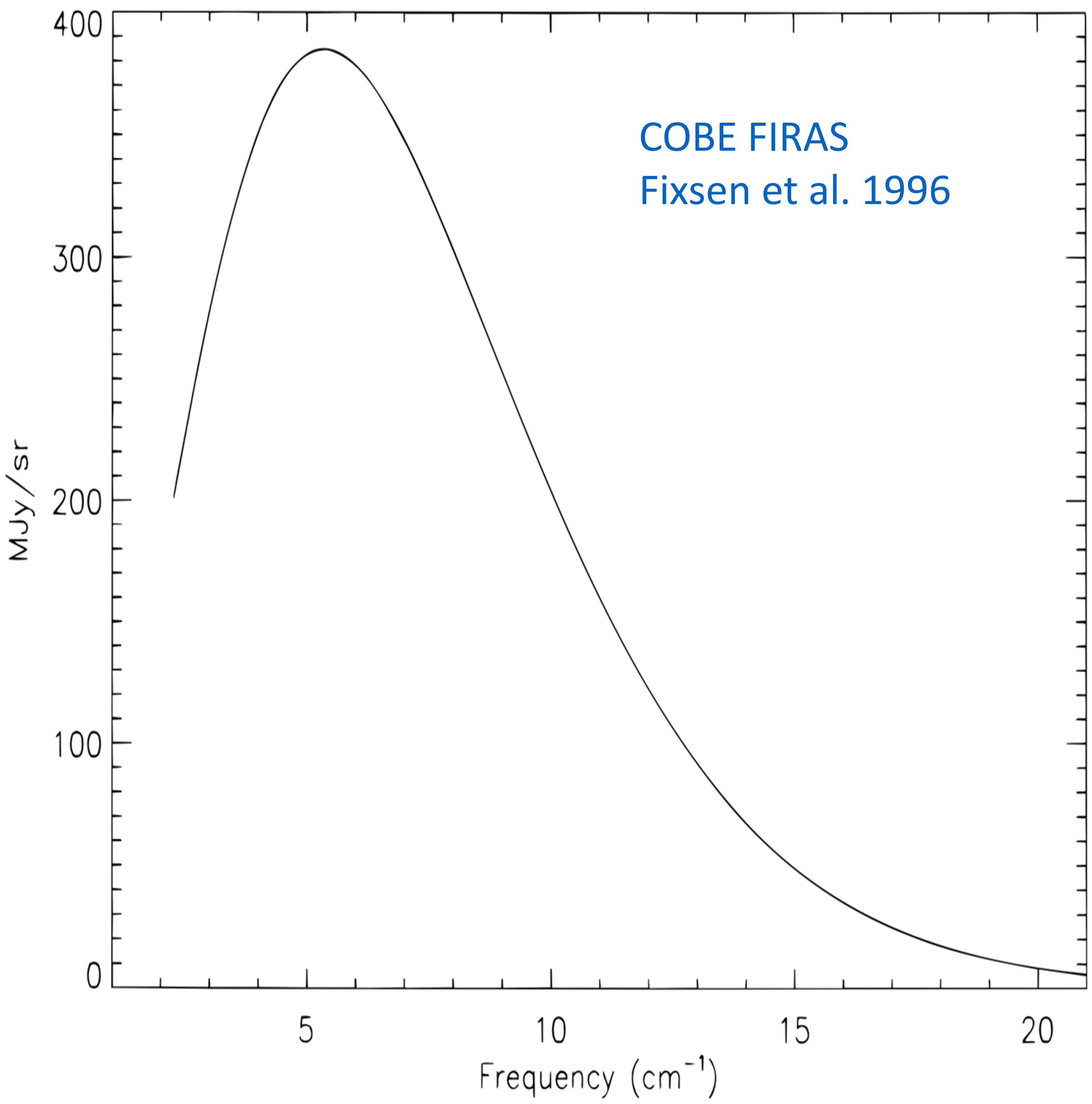
PNRA workshop

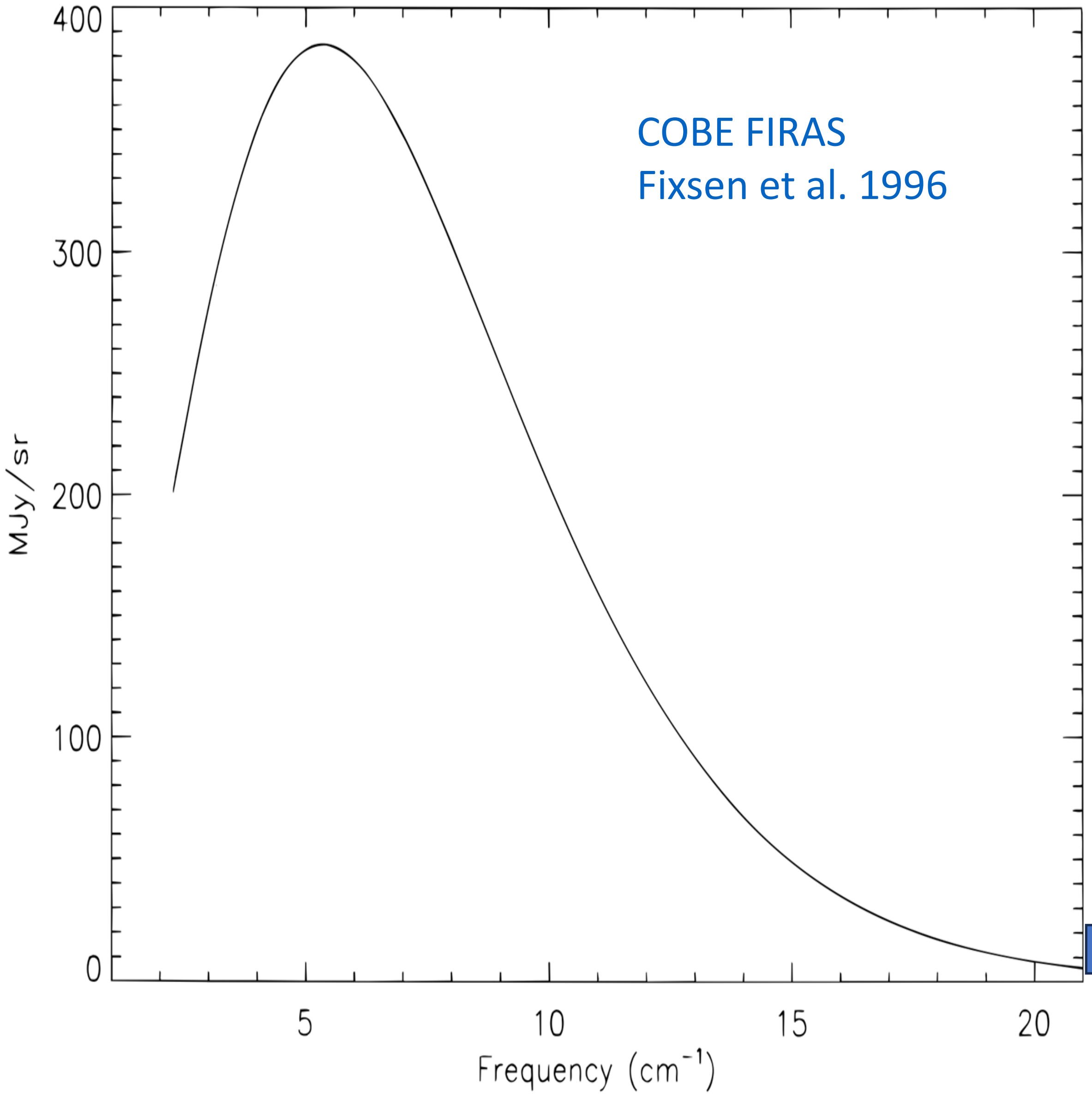
2023/12/04 Villa Torlonia, Roma

The CMB: a messenger of the early universe



- CMB photons were produced by matter-antimatter annihilation a few μs after the big bang.
- They were then thermalized in the primeval fireball.
- The expansion of the universe redshifted and diluted these photons, maintaining the blackbody spectrum.
- To first order, the CMB must be – and in fact is - a blackbody.
- Current CMB research:
  - CMB polarization, B-mode polarization expected to be generated at cosmic inflation, a split second after the big bang.
    Huge international effort, including >100M$ for South Pole Telescope, Bicep-Keck & in Antarctica
  - Spectral distortions of the CMB due to non-equilibrium phenomena, at various phases during the evolution of the universe. Strategic niche of research, opportunity for Italian scientists to exploit the assets provided by the Concordia station for a first implementation of a staged effort.

The CMB: an almost perfect blackbody



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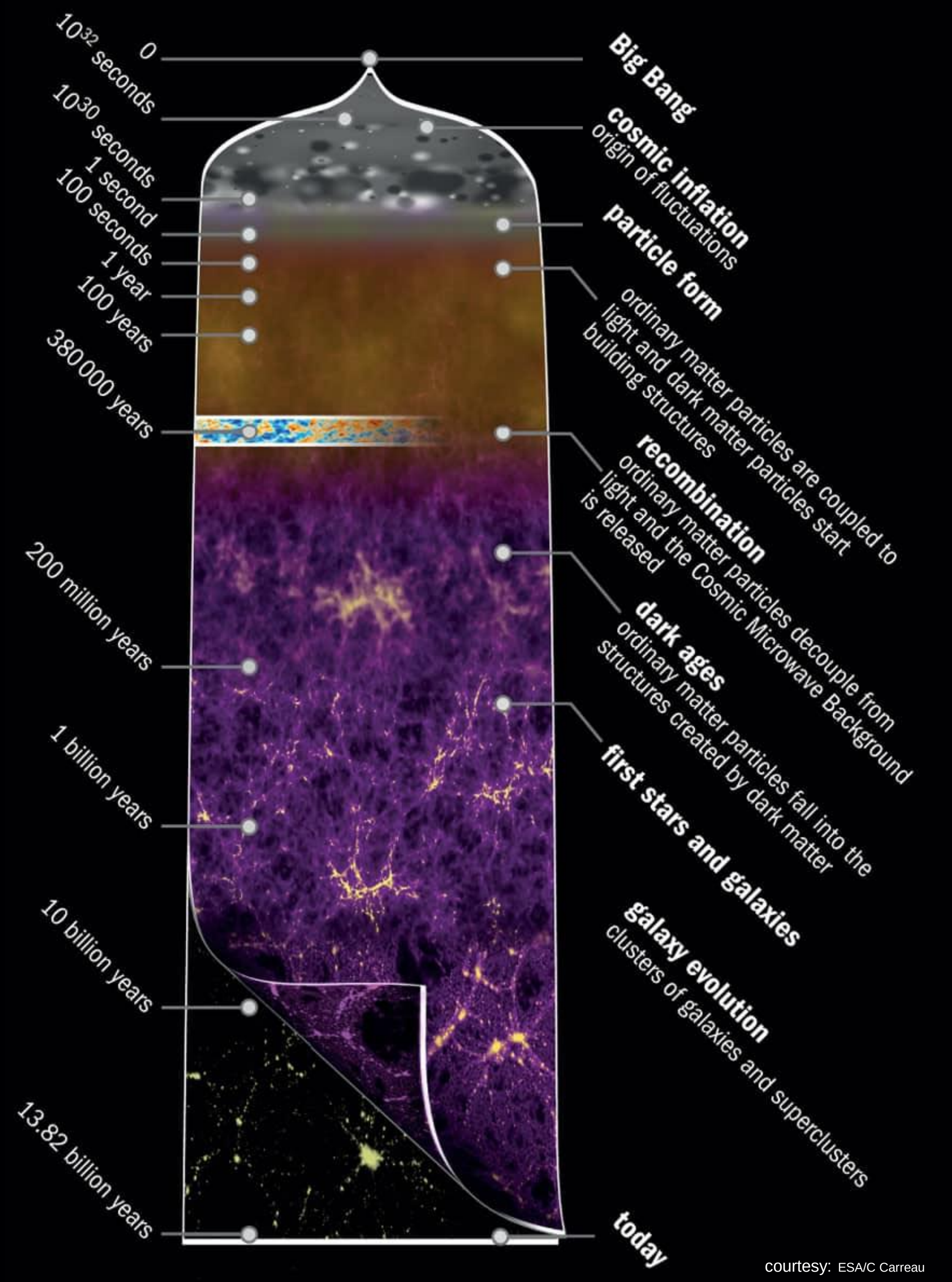
$$B(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1} = \frac{2h\nu^3}{c^2}\frac{1}{e^x-1}$$

$$B_{\mu}(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{x+\mu}-1}$$

$$B_y(\nu,T) = B(\nu,T)\left\{1 + y\frac{xe^x}{e^x-1}\left[x\coth\frac{x}{2} - 4\right]\right\}$$

$$y,\mu < 10^{-5}$$



courtesy: ESA/C Carreau

Spectral distortions of the CMB

Small departures from a perfect blackbody shape are expected, due to well known as well as exotic physical processes; and can provide information about processes that occurred before and after recombination. See e.g. :

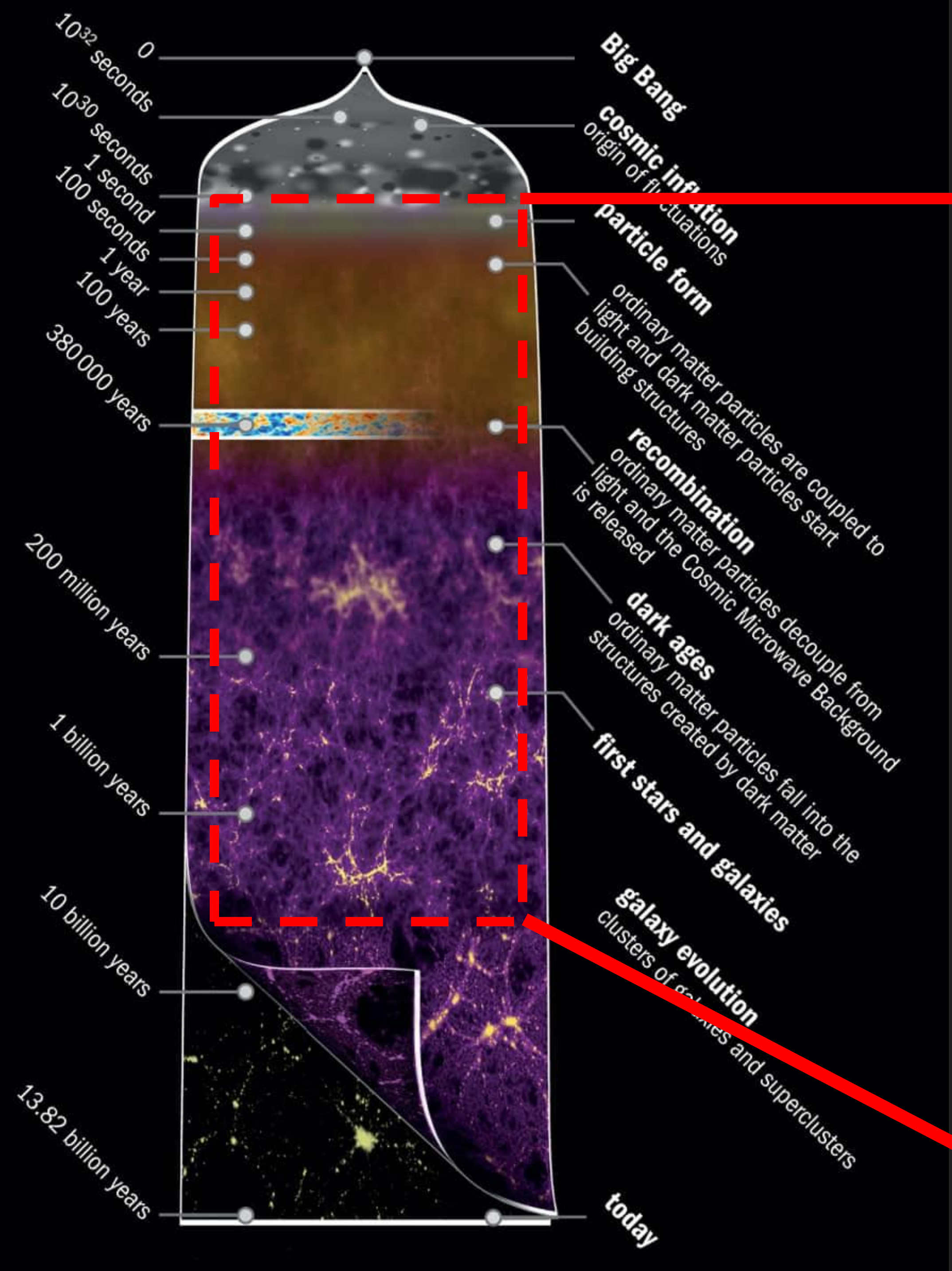
- Reionization and structure formation (De Zotti et al., 2016)
- Adiabatic cooling of baryons and electrons (Chluba and Sunyaev, 2012)
- Damping of small scale acoustic modes -> inflationary power spectra (Chluba et al., 2011)
- Cosmological recombination radiation (Dubrovich, 1975, Sunyaev and Chluba 2008)
- Decaying and annihilating particles (Acharya and Kharti 2019)
- …… and many more

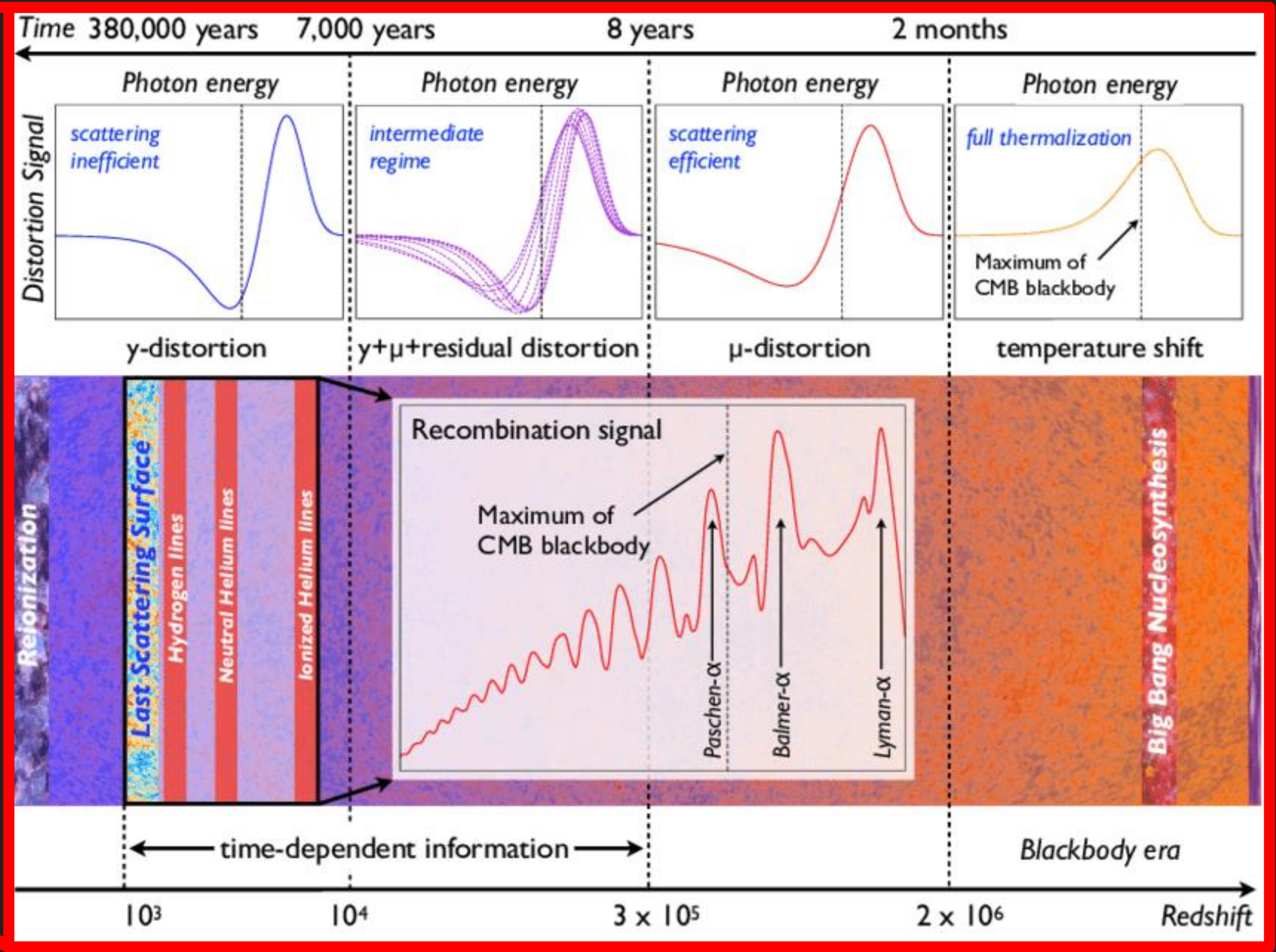
Current upper limits for the comptonization parameter *y* and for the chemical potential μ are still close to the ones from COBE/FIRAS :

$$y, \mu < 10^{-5}$$

Spectral distortions of the CMB

Expected from ΛCDM: $\mu \simeq 2 \times 10^{-8}$ $y \simeq 1.77 \times 10^{-6}$

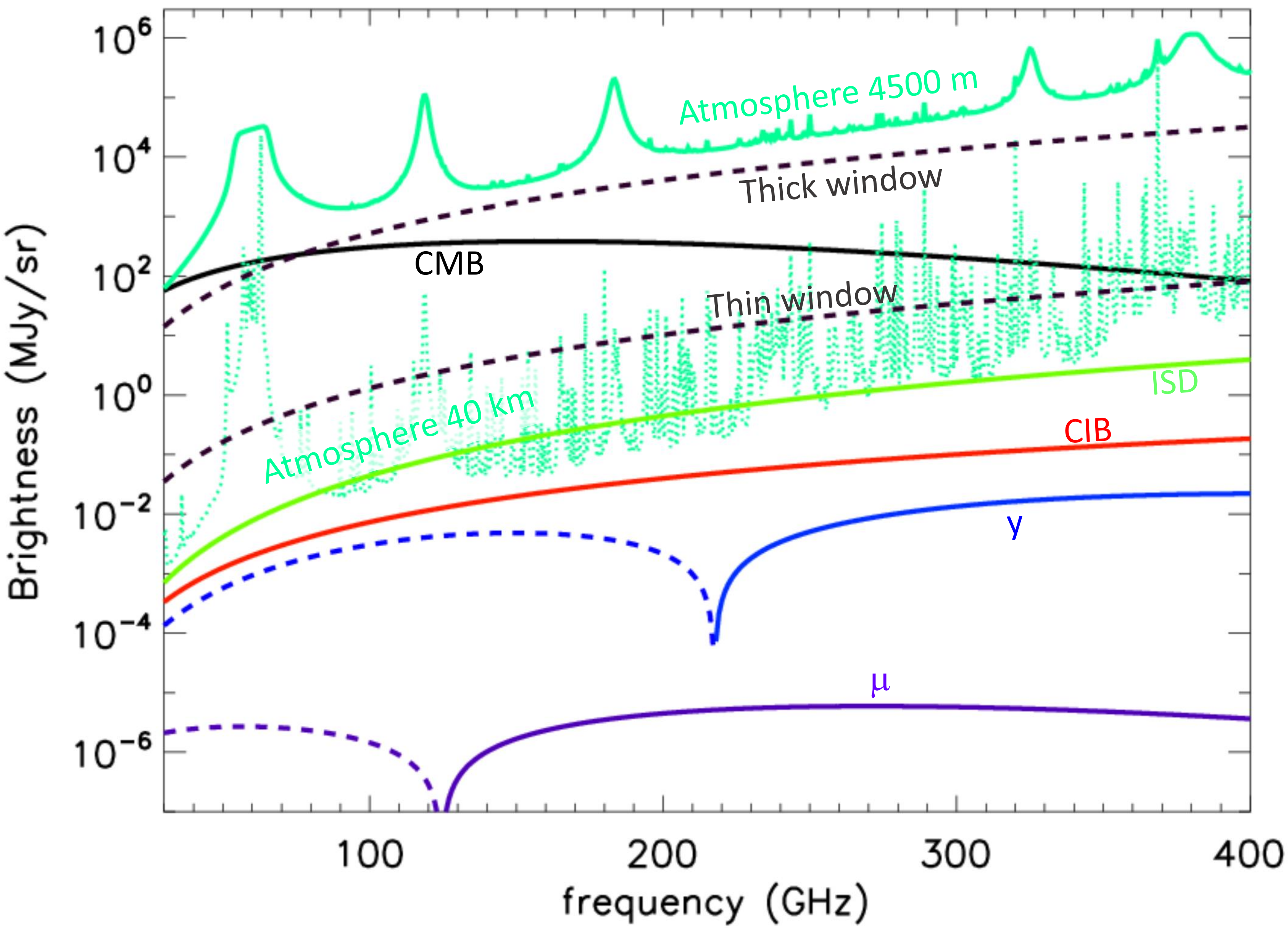




Chluba et al. 2019

Spectral distortions at mm wavelengths

- y, μ, and mixed distortions.
- Post-recombination y is the strongest distortion at a level $y \sim 2 \times 10^{-6}$.
- Pre-recombination y at least 1 order of magnitude smaller.
- μ even smaller.
- Smooth spectra in the mm range, to be compared to complex atmospheric emission spectra.
- Atmospheric and window emissions are the main foregrounds for ground-based experiments.
- Atmospheric emission can be monitored by means of sky dips



COSMO (COSmic Monopole Observer)

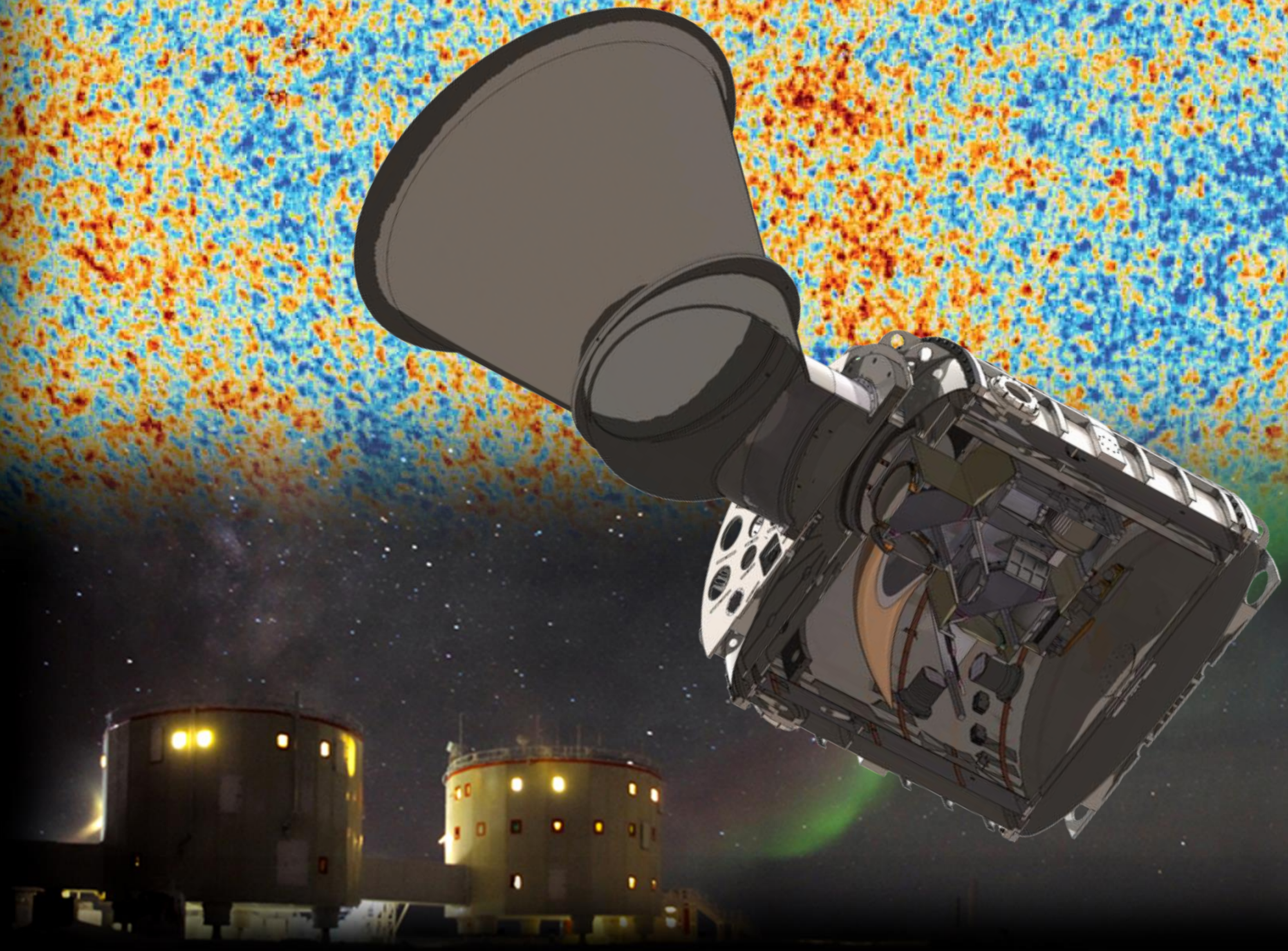
SAPIENZA UNIVERSITÀ DI ROMA

CNR IFN Istituto di Fotonica e Nanotecnologie

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

MANCHESTER 1824 The University of Manchester

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD



E. Battistelli, P. de Bernardis, F. Cacciotti, J. Chluba, S. Cibella, F. Columbro, G. Conenna. A. Coppolecchia, M. Bersanelli, G. D'Alessandro, M. De Petris, C. Franceschet, M. Gervasi, A. Limonta, L. Lamagna, E. Manzan, E. Marchitelli, S. Masi, L. Mele, A. Mennella, A. Passerini, A. Paiella, G. Pettinari, F. Piacentini, L. Piccirillo, G. Pisano, S. Realini, C. Tucker, M. Zannoni

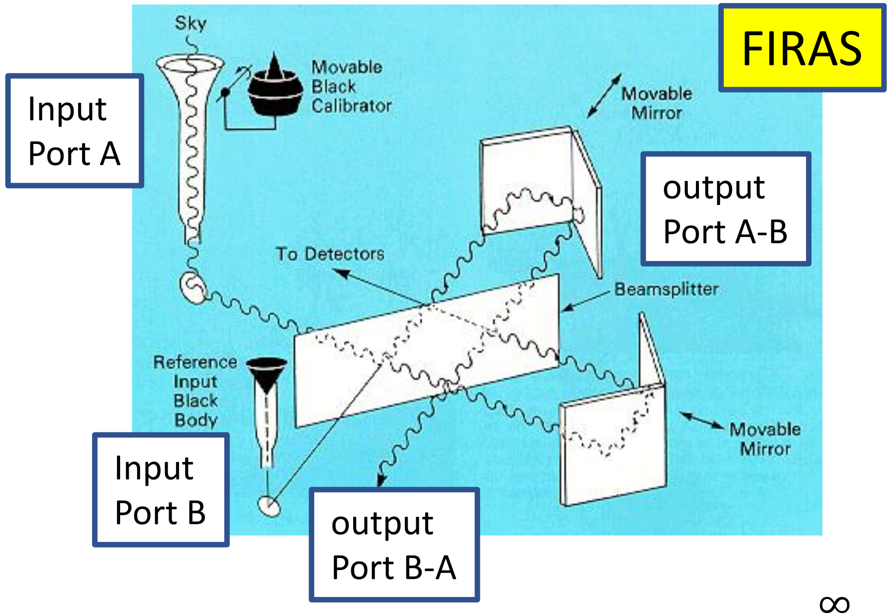
https://cosmo.roma1.infn.it

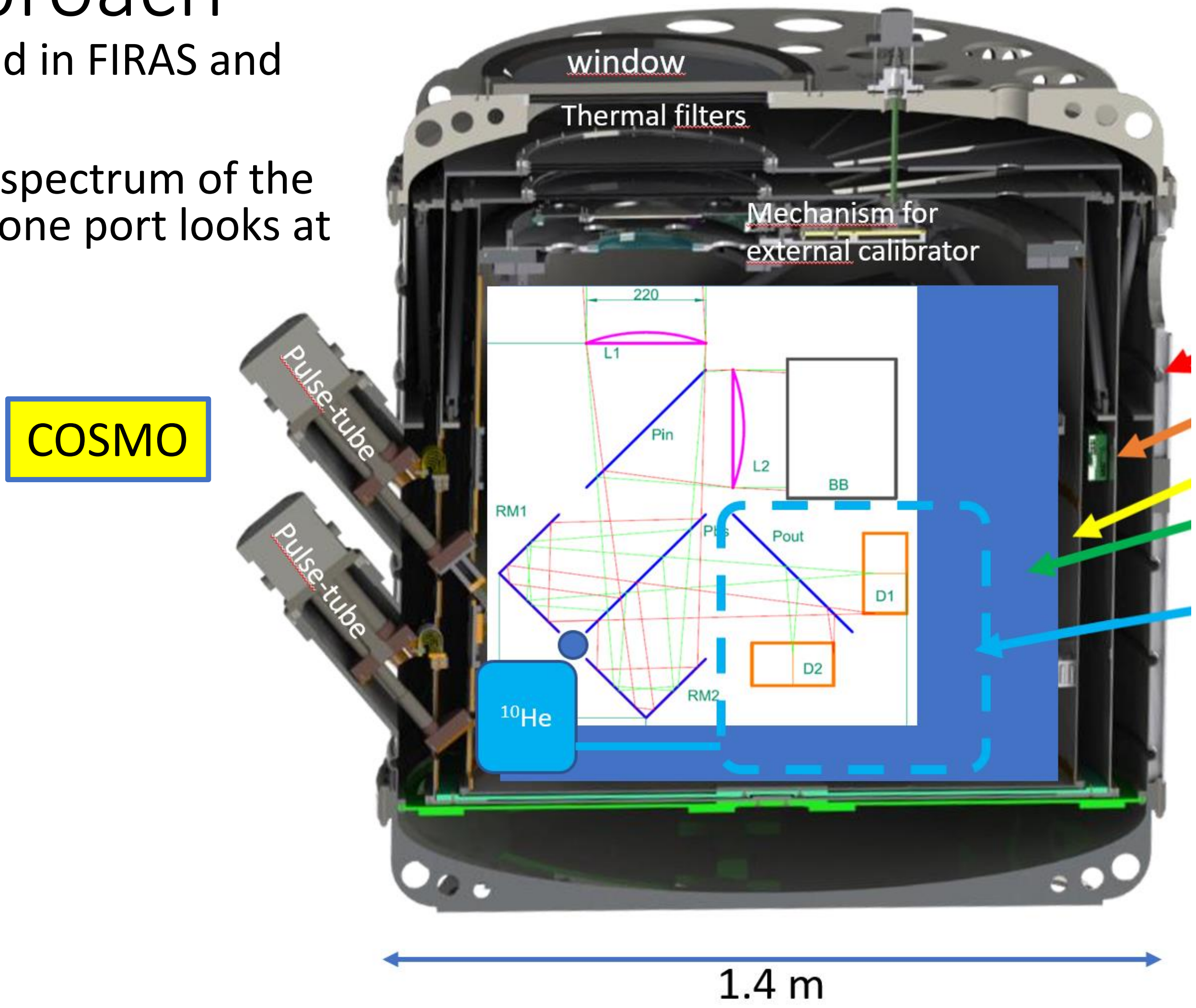
PRIN Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale

PROGRAMMA NAZIONALE DI RICERCHE IN ANTARTIDE ITALIANTARTIDE

Absolute measurement approach

- The Martin-Pupplett Fourier Transform Spectrometer used in FIRAS and PIXIE has two input ports.
- The instrument is intrinsically differential, measuring the spectrum of the difference in brightness at the two input ports. Normally one port looks at the sky, the other one at an internal reference blackbody.
- For calibration, a movable blackbody fills the sky port.





Sky measurement

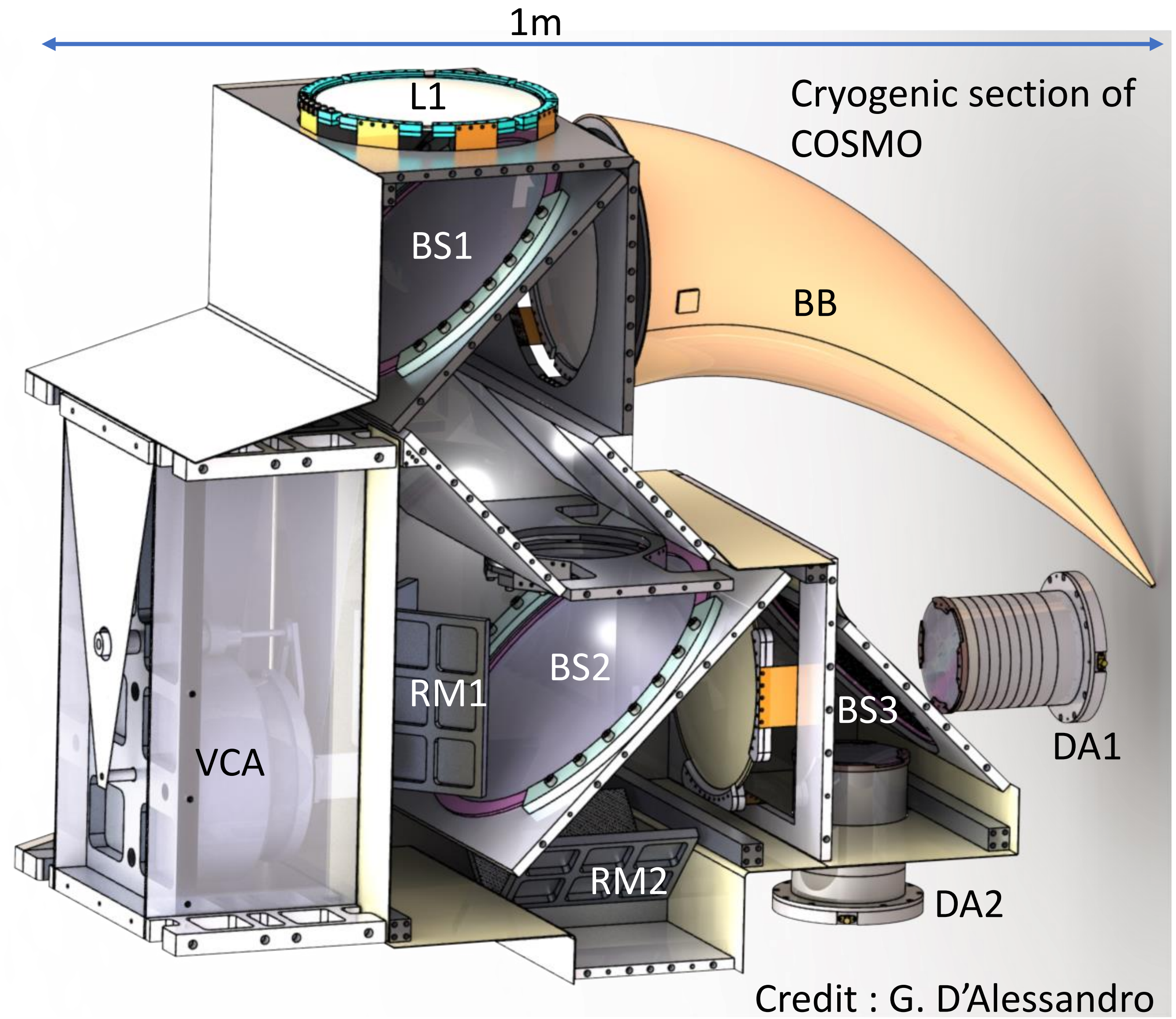
$$I_{SKY}(x) = C\int_0^\infty [S_{SKY}(\sigma) - S_{REF}(\sigma)]rt(\sigma)\{1+\cos[4\pi\sigma x]\}d\sigma$$

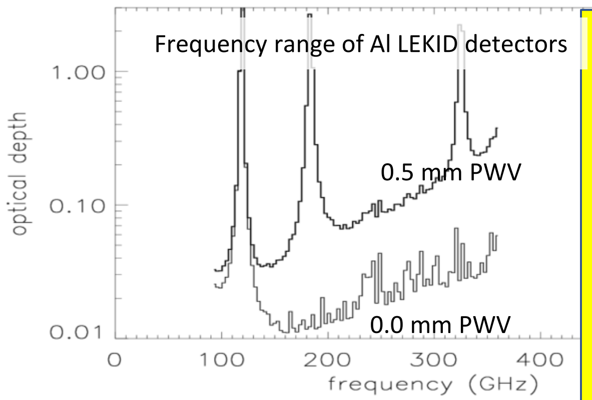
Calibration measurement

$$I_{CAL}(x) = C\int_0^\infty [S_{CAL}(\sigma) - S_{REF}(\sigma)]rt(\sigma)\{1+\cos[4\pi\sigma x]\}d\sigma$$

COSMO in a nutshell

- **COSMO** is a pathfinder experiment, ground-based in the first implementation, balloon-borne in its second step.
- A cryogenic **Differential Fourier Transform Spectrometer**, comparing the sky brightness to an internal blackbody (configuration similar to COBE-FIRAS)
- Operation from the Concordia French-Italian base in **Dome-C, Antarctica**. Average PVW of 210µm, T < -60C, stable weather in the winter season (*Tremblin et al. A&A, 2011*). Atmospheric emission strongly reduced wrt mid latitude sites.
- High transmission bands: **125-175 GHz** (ySD<0) and **200-285 GHz** (ySD>0) ~**5 GHz** resolution.
- Uses fast detectors (multi-mode KIDs, τ=60 μs) so that **fast sky-dips** are continuously performed to measure and reject atmospheric emission and its slow fluctuations.
- The FTS is cryogenically cooled @3K;
- The reference blackbody can be tuned to 2.5-4 K;
- A continuous and **fast** (few seconds) **interferogram scan** is achieved via a voice-coil actuator.
- Several **10°x10°** sky patches are observed with **1° resolution**, in the southern sky and with varying levels of galactic signals.
- In **100 days of integration** in the Antarctic winter, the *y SD* can be detected at **5σ**.





Coping with atmospheric emission

COSMO will operate from the Concordia French-Italian base in Dome-C (Antarctica) … the best site on Earth, extremely cold and dry ! But still has to cope with some atmospheric emission.

COSMO uses fast detectors (KIDs) and fast elevation scans to separate atmospheric emission and its long-term fluctuations from the monopole of the sky brightness.

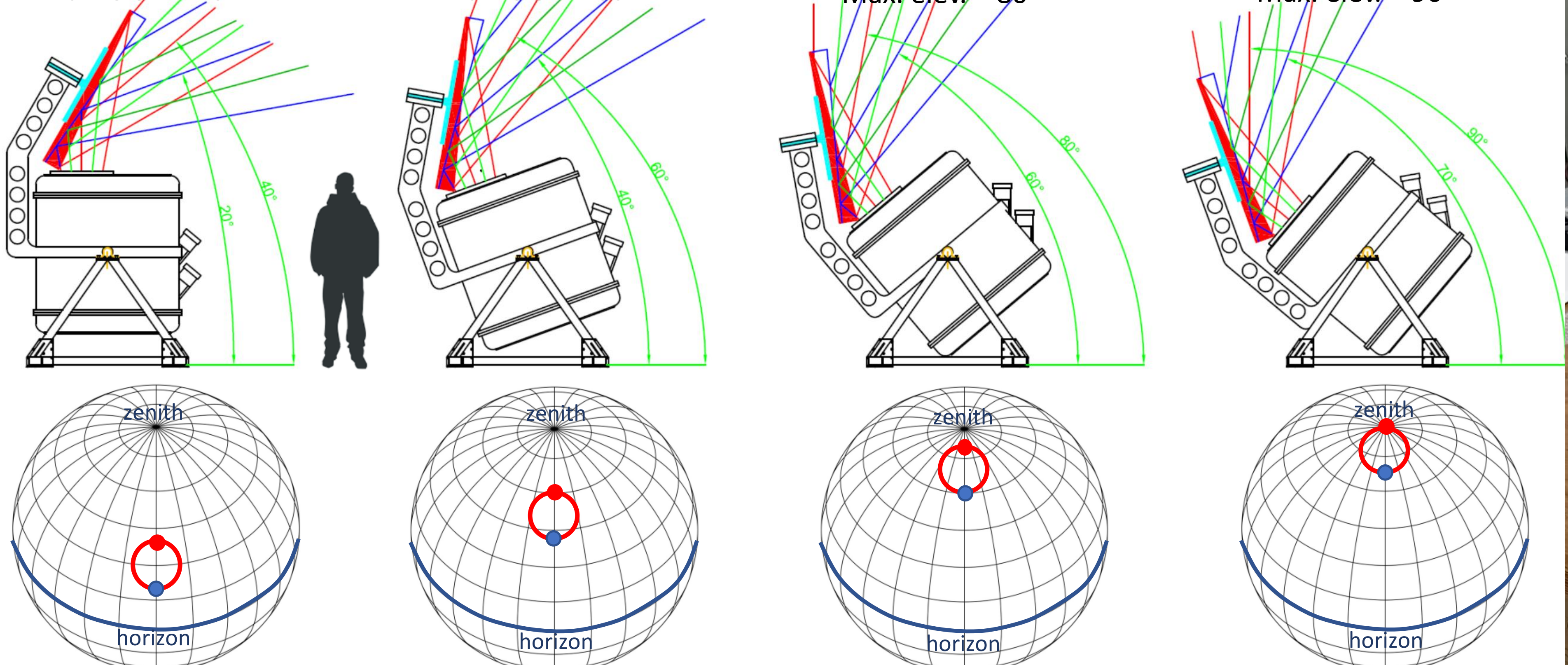
A fast spinning wedge mirror (>600 rpm!) steers the boresight direction on a circle, 20^o in diameter, scanning a range of elevations (and corresponding atmospheric optical depths) while the cryogenic interferometer scans the optical path difference.

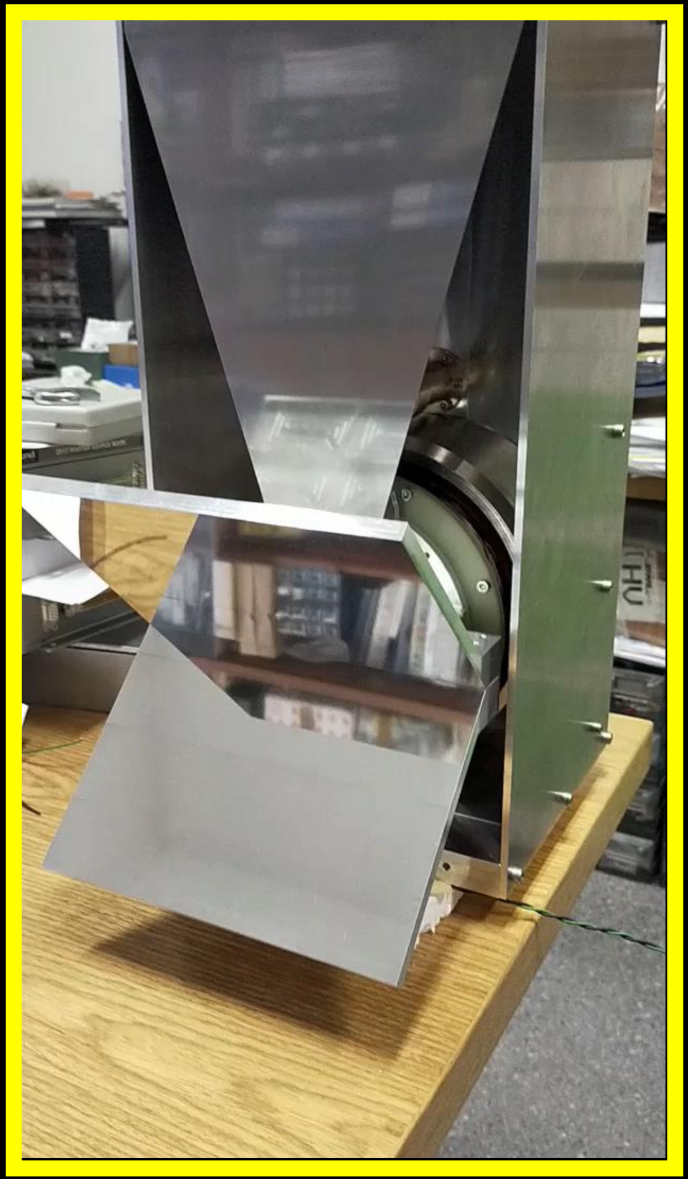
Cryostat tilt = 0^o
PT tilt = 40°
Min. elev. = 20°
Max. elev. = 40°

Cryostat tilt = 20^o
PT tilt = 20°
Min. elev. = 40°
Max. elev. = 60°

Cryostat tilt = 40^o
PT tilt = 0°
Min. elev. = 60°
Max. elev. = 80°

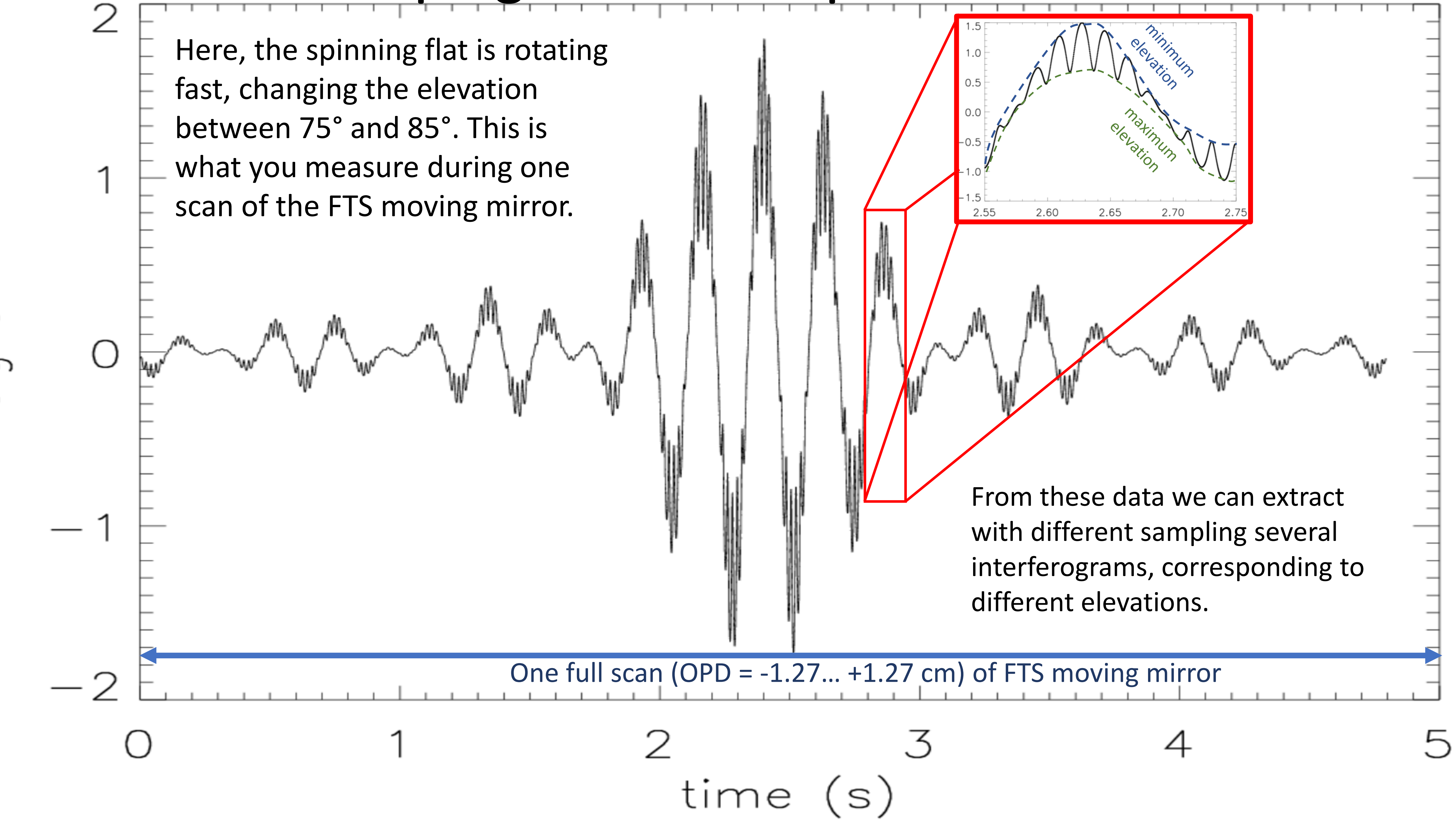
Cryostat tilt = 50^o
PT tilt = -10°
Min. elev. = 70°
Max. elev. = 90°



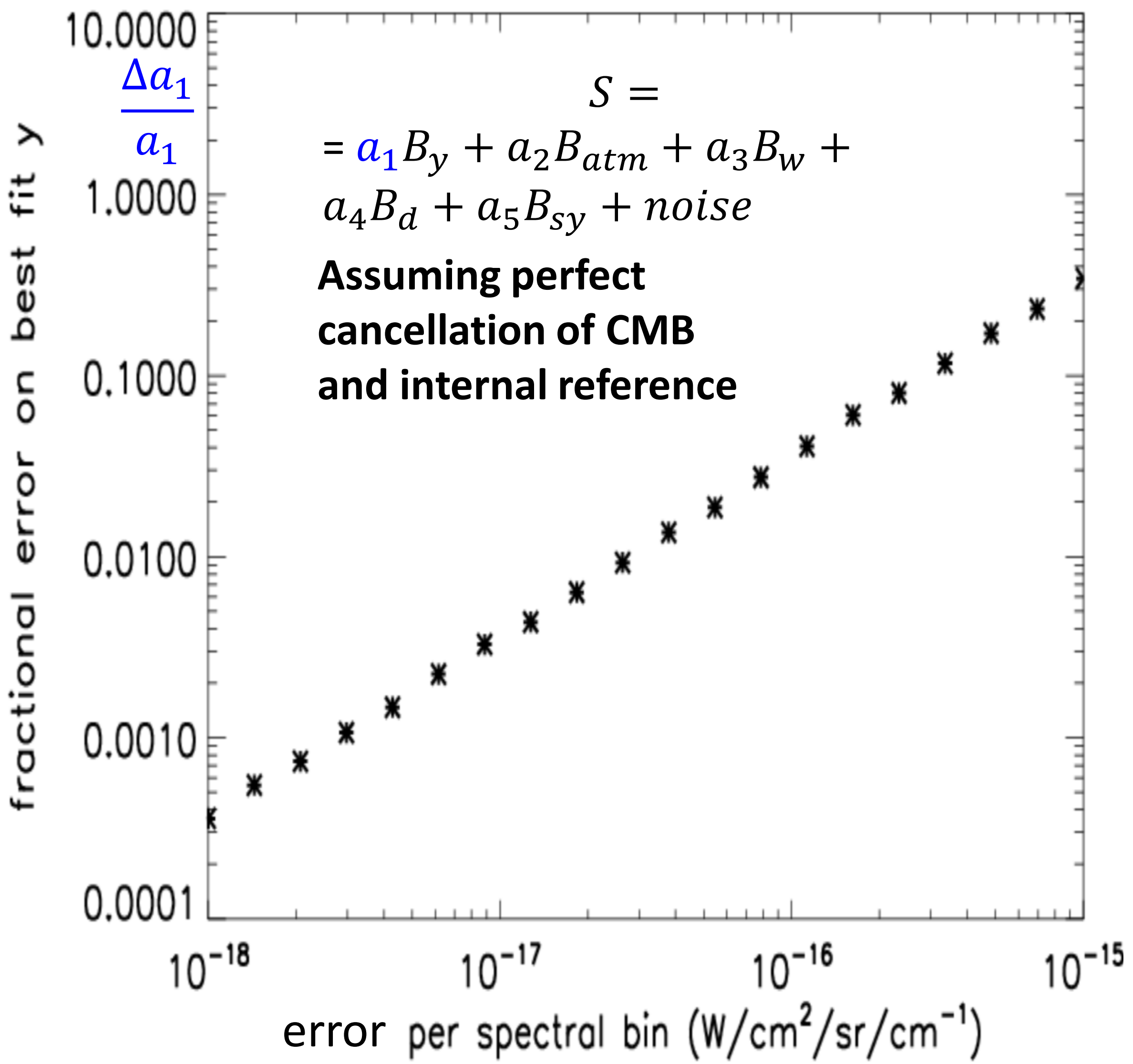


Combination of spatial and spectral modulations
to extract the spectral distortions signal

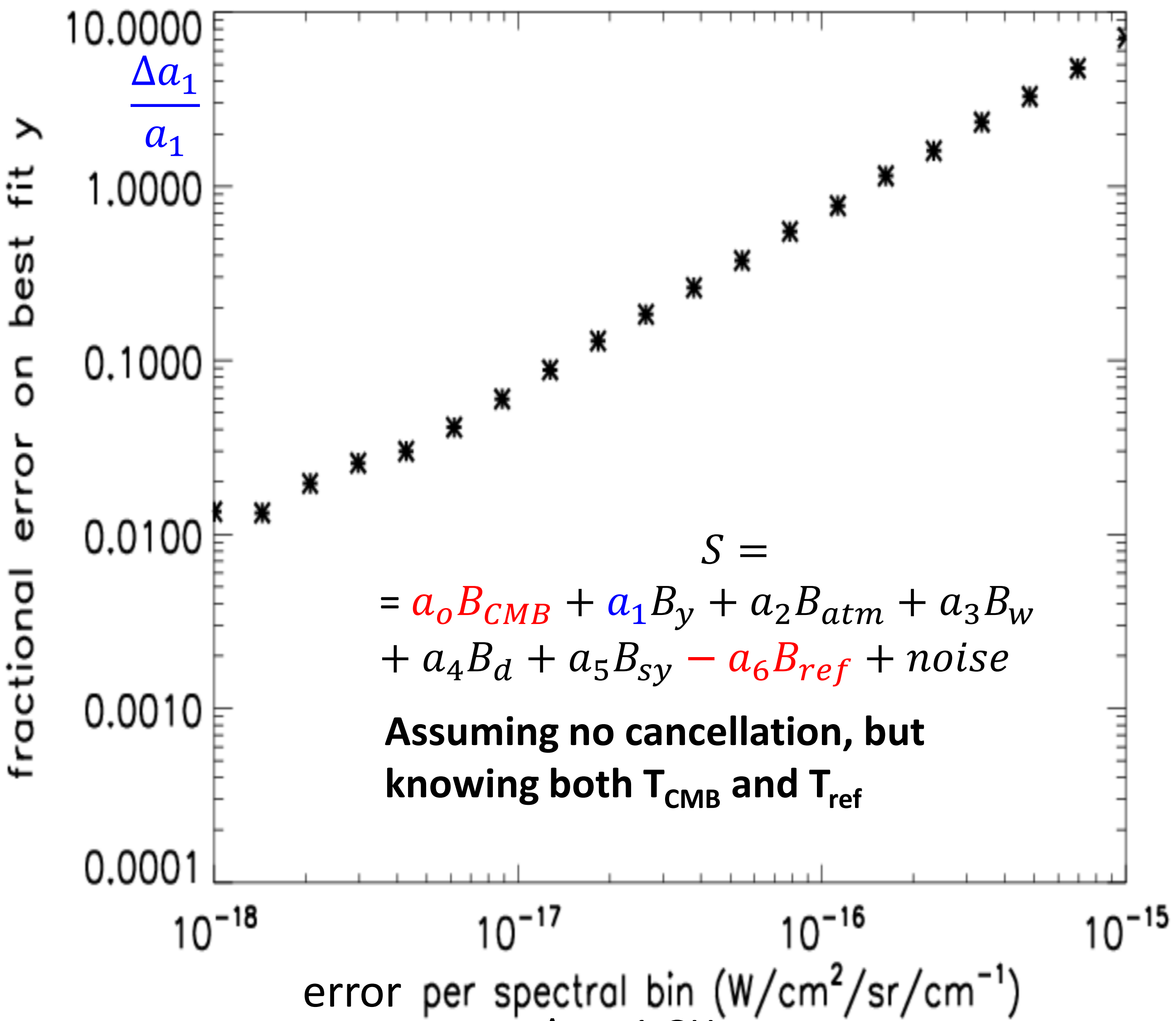
Coping with atmospheric emission



Naïve simulations



$\Delta\nu$ = 1 GHz



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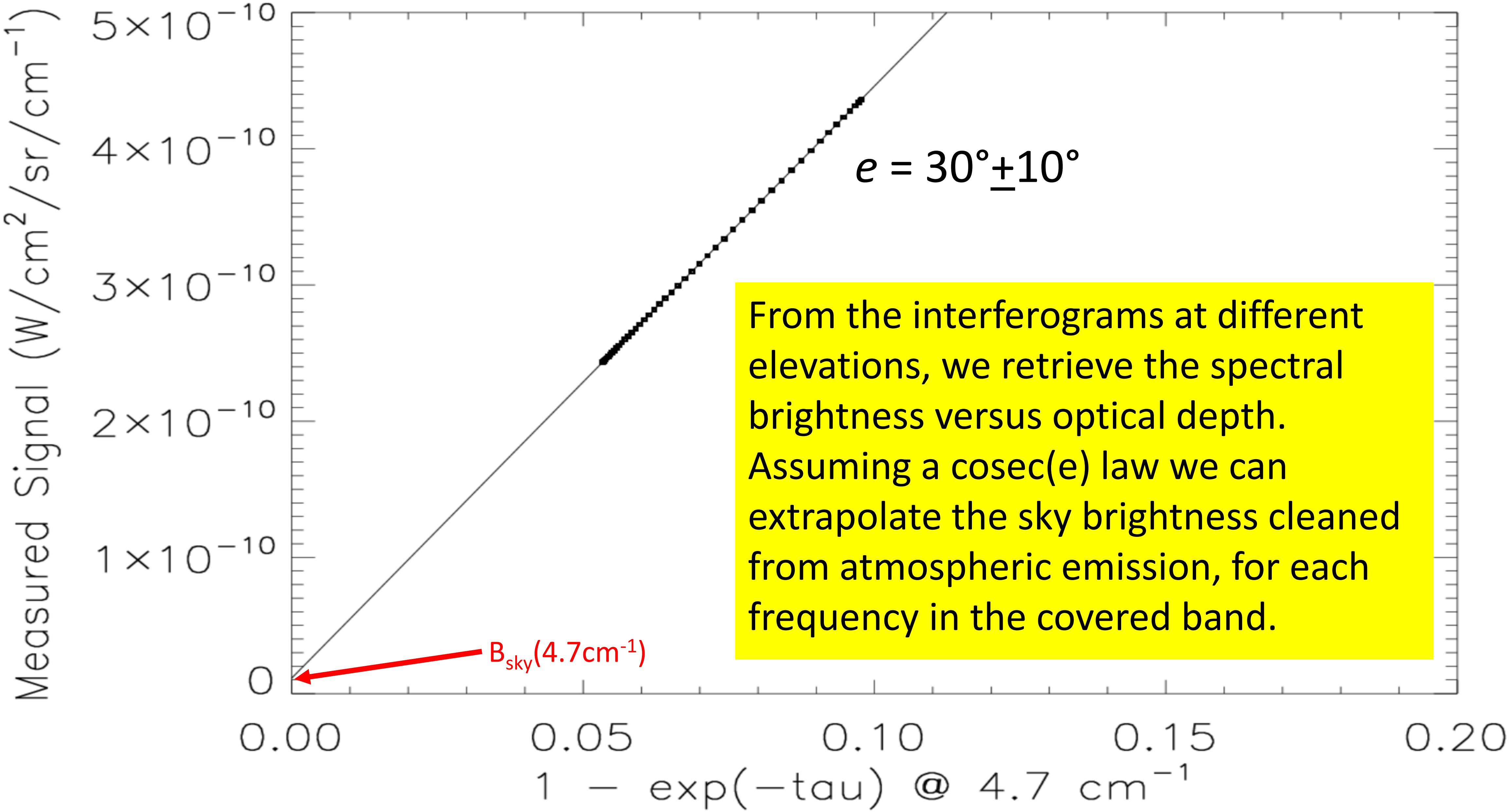
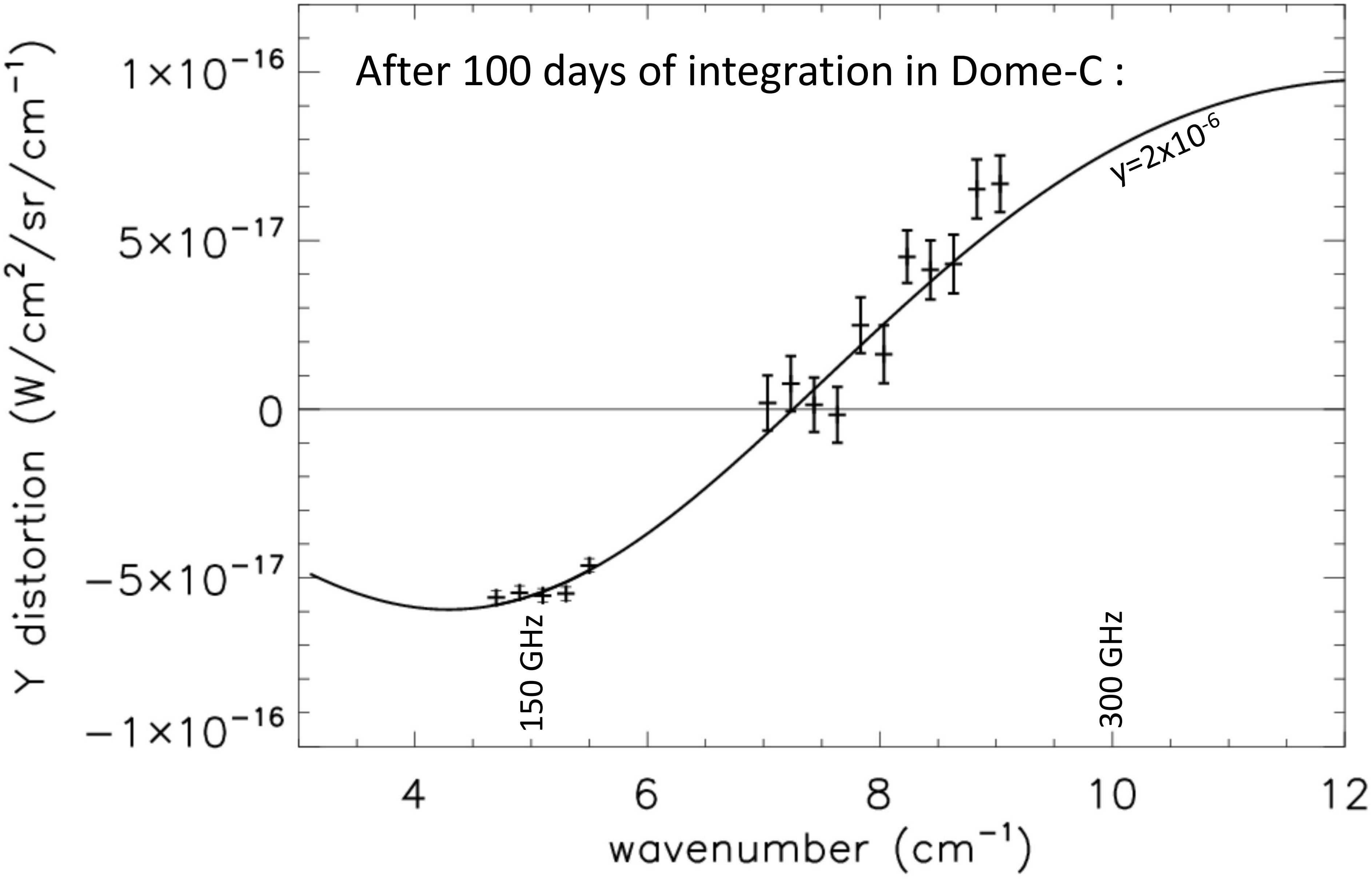
Coping with atmospheric emission

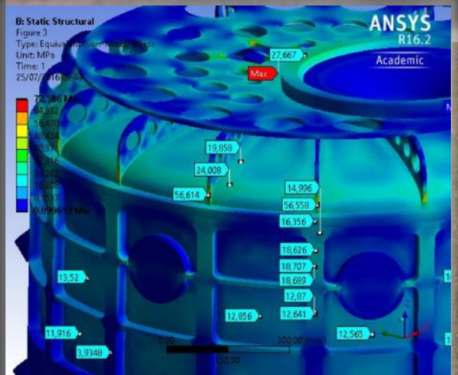


From the interferograms at different elevations, we retrieve the spectral brightness versus optical depth. Assuming a cosec(e) law we can extrapolate the sky brightness cleaned from atmospheric emission, for each frequency in the covered band.

Simplistic Forecast

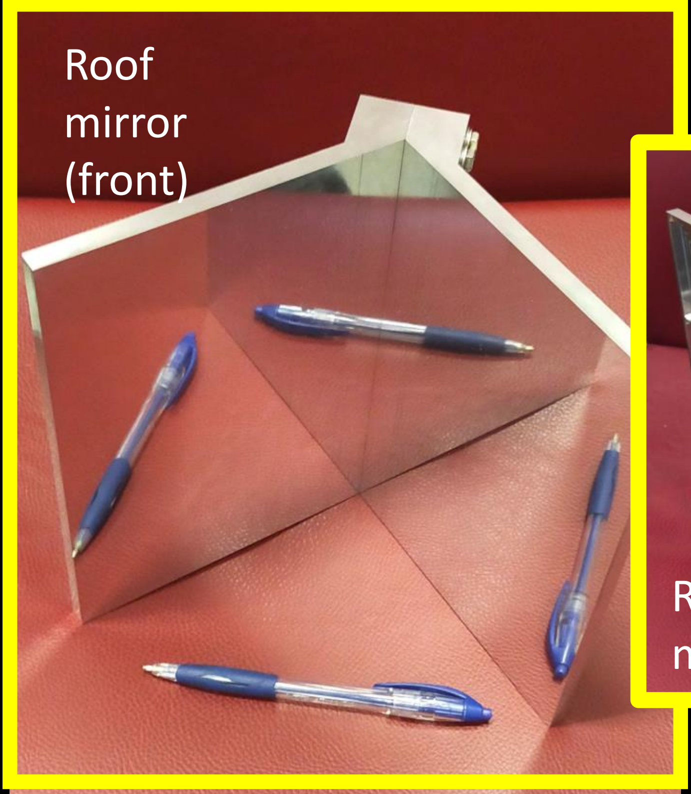


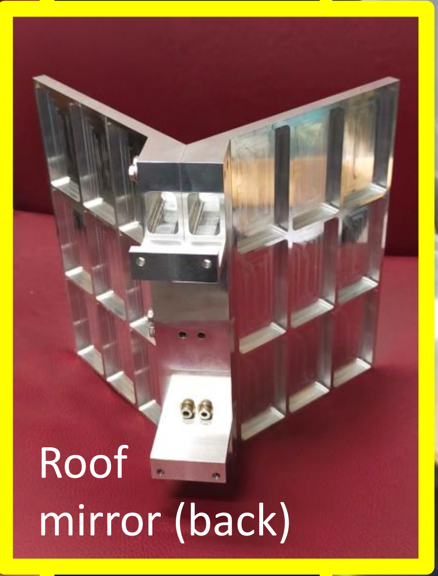
COSMO hardware

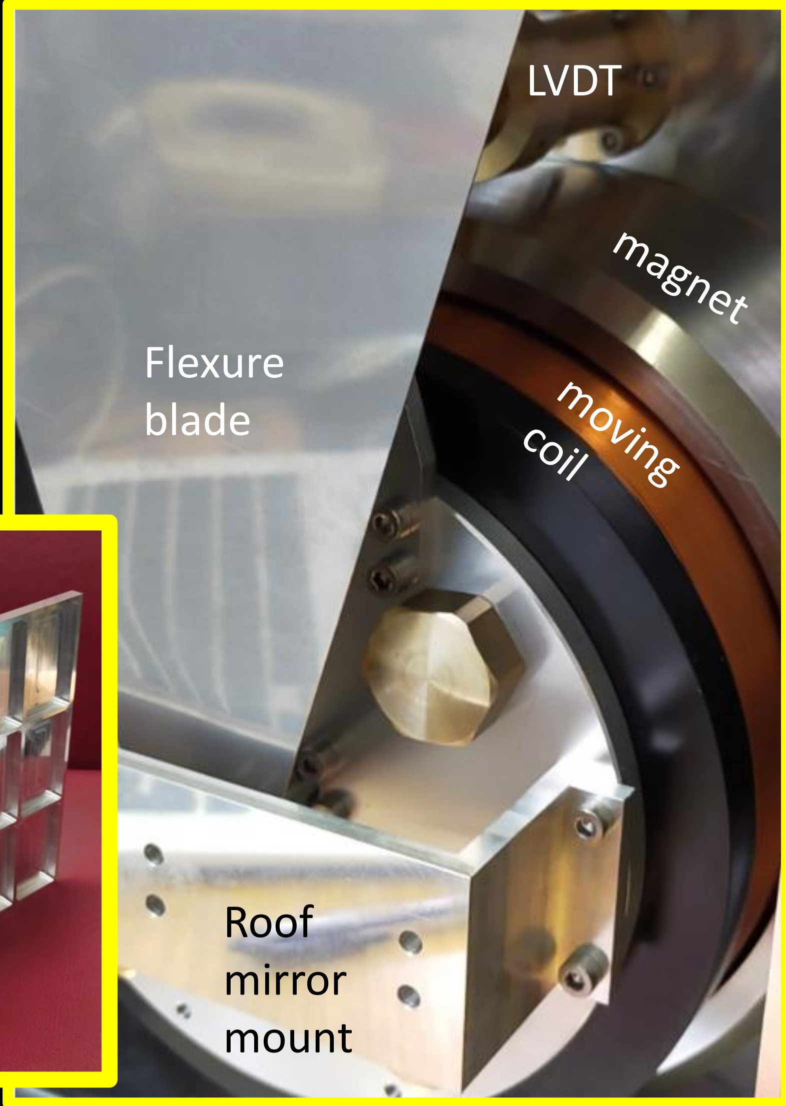


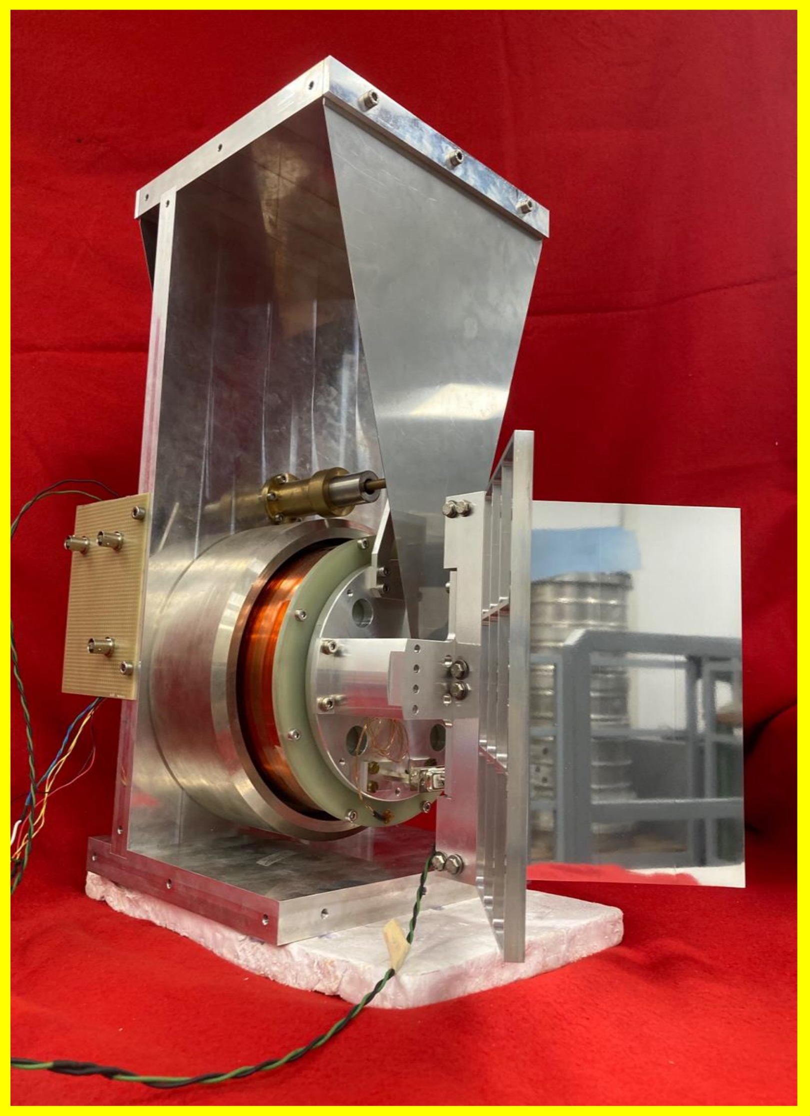
Variable Delay Line for the FTS

- Cryogenic operation – frictionless design to minimize heat load
- Based on a powerful voice coil with steel flexure blades support, to move one roof mirror. up to 0.2 cm/s.
- Voice coil delivered, assembly built.
- Eddy currents in moving coil support minimized by means of a dielectric coil support.
- Electronics developed (E. Marchitelli)



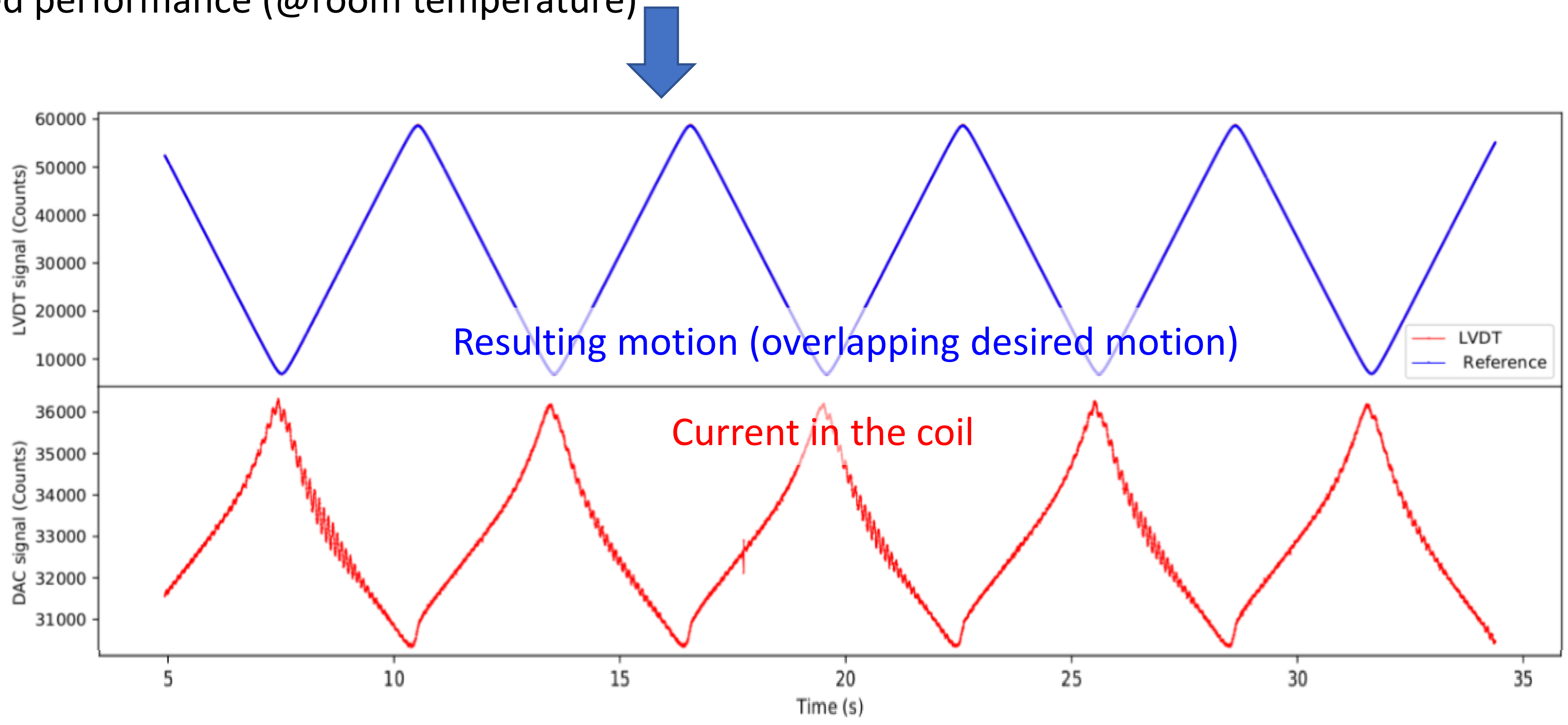






Cryogenic Roof Mirror Transport Mechanism

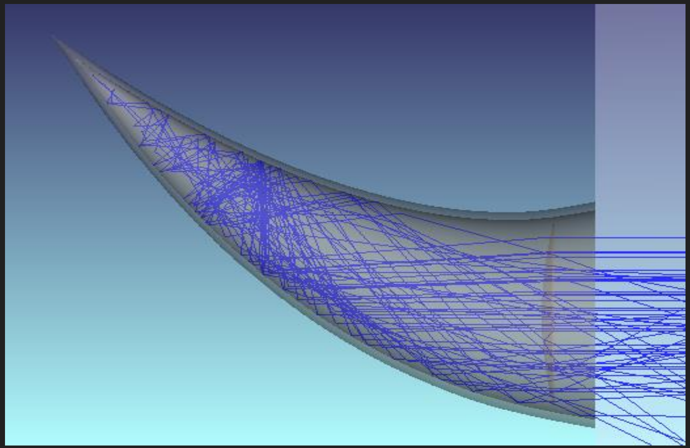
- Based on harmonic steel flexure blades supporting a large voice coil
- Drive electronics based on digital generator, DAC, current pump, coil, LVDT sensor, ADC, digital PID feedback loop.
- Auxiliary NIR FP interferometer for precision position readout (< 1 μm) procured.
- Measured performance (@room temperature)

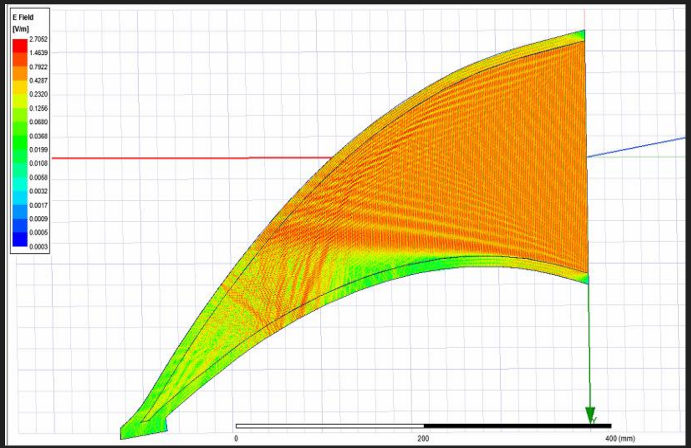


Credits: E. Marchitelli

Reference Blackbody

- A parabolic cavity providing an emissivity very close to unity
- Thermal gradients <1mK (FEM simulation in Comsol Multiphysics, assuming a single compact element)
- Ray-Tracing simulations have been performed to maximize of the # of reflections with the absorbing coating (Emerson & Cuming CR-110)
- HFSS simulations provide a residual reflectance of 1×10^{-6} @ 120 GHz
- A prototype of the calibrator has been assembled





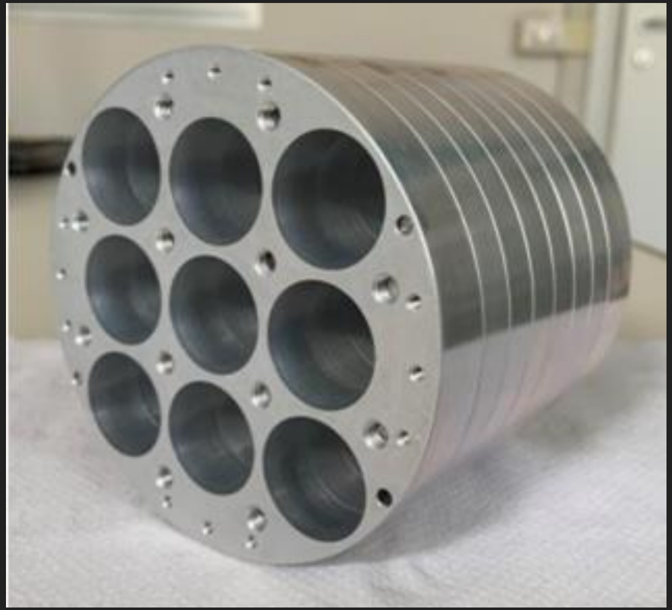
External Al mould

Teflon master mould to shape the absorbing coating

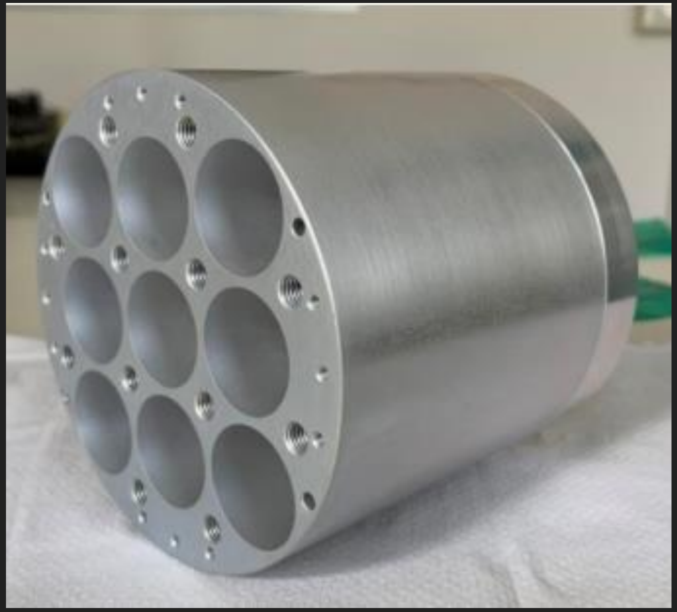
Credit: L.Mele

Feedhorns Arrays

- Multi-mode 3×3 horn antenna arrays feed the multimode KIDs arrays
- Each horn has a 24 mm aperture diameter and a waveguide diameter of 4.5 mm and 4.0 mm for the 150 GHz and the 220 GHz horn-arrays respectively
- The 150 GHz array is made of 7 platelets to build a Winston cone to model a parabolic internal profile
- The 220 GHz horn-array is made of a linear single profile
- Made of aluminum and machined through a CNC milling machine
- Electromagnetic simulations have been carried out to provide the expected performance. From 10 to 19 modes are included for the 150 GHz simulation, and from 23 to 42 modes are included in the 220 GHz simulation



E. Manzan, University of Milan

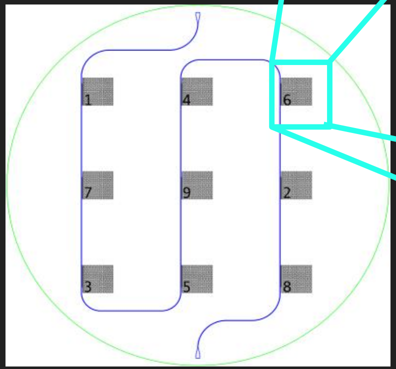


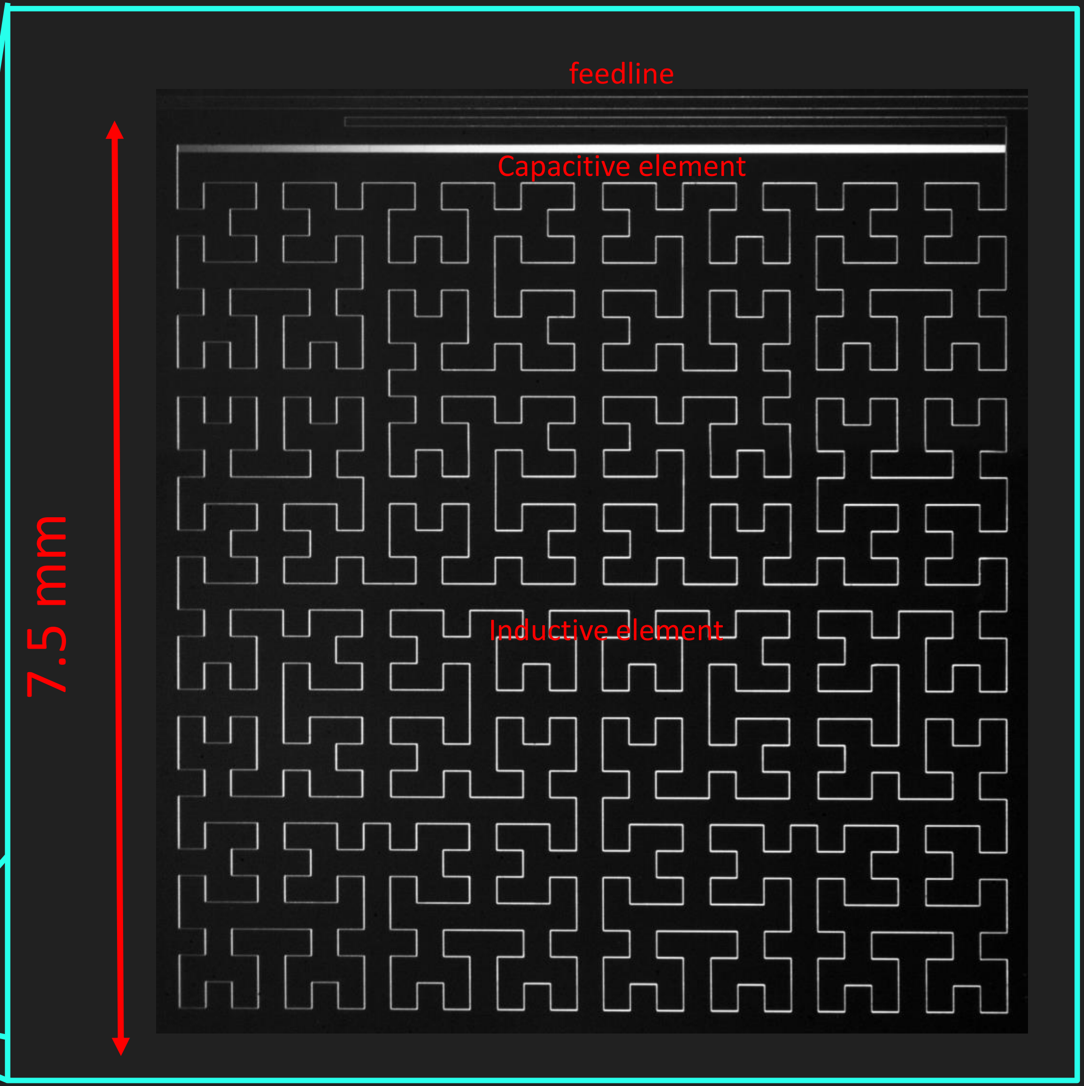
Kinetic Inductance Detector Arrays

- The throughput of the system, which includes the cryogenic differential MPI, is limited by the available room in the cryostat, and the angular resolution required by the measurement is modest (~1°)
- For these reasons the two focal planes, sensitive in the 150GHz and 250GHz bands, are filled with just 9 multimode feed-horns, each feeding one large Kinetic Inductance Detector (KID) fabricated with the same process developed for the OLIMPO ones (Paiella et al. 2019, Masi et al. 2019).
- Nine 7.5mm x 7.5mm pixels accommodated on a 4" Si wafer
- Photon noise limited performance, (scales as $N_{modes}^{1/2}$)
- 150GHz prototype currently under test

Index	n_c	C [pF]	ν_r [MHz]	Q_c
1	16	6.80	85.1	13 700
2	15	6.35	88.1	12 400
3	14	5.89	91.4	11 100
4	13	5.44	95.1	9800
5	12	4.99	99.4	8600
6	11	4.53	104.2	7500
7	10	4.08	109.9	6400
8	9	3.63	116.5	5300
9	8	3.17	124.6	4400

Low resonance frequencies to cope with lumped condition





A. Credits: A. Paiella, F. Cacciotti, G. Isopi, E. Marchitelli (Sapienza) G. Pettinari (IFN-CNR)

Kinetic Inductance Detector Arrays

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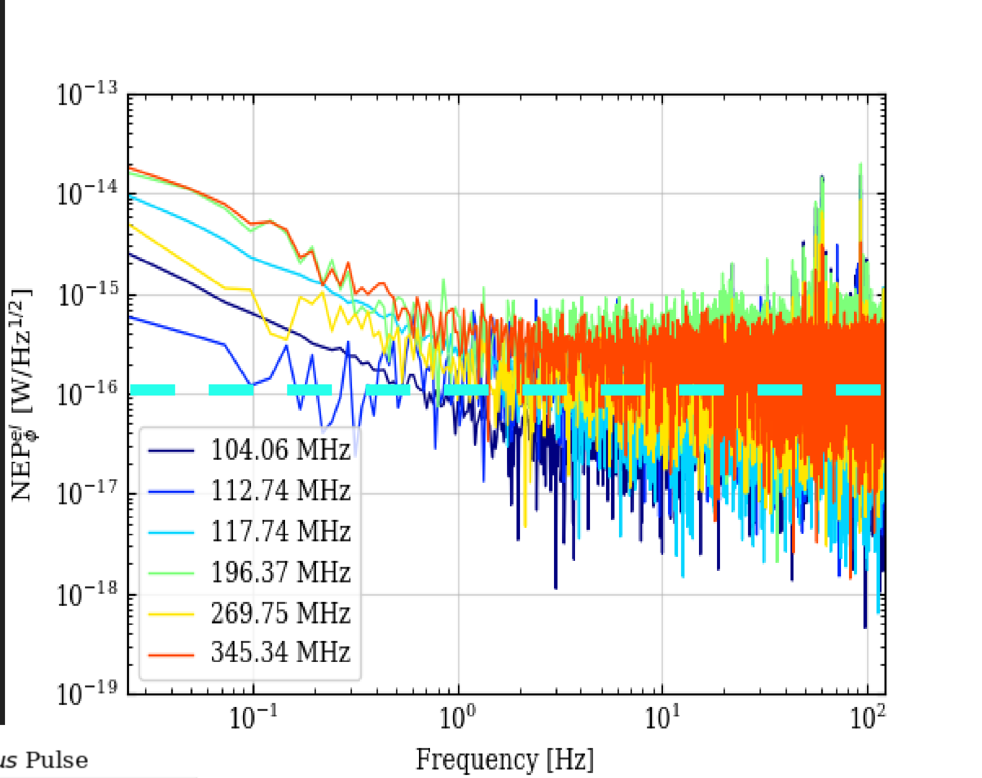
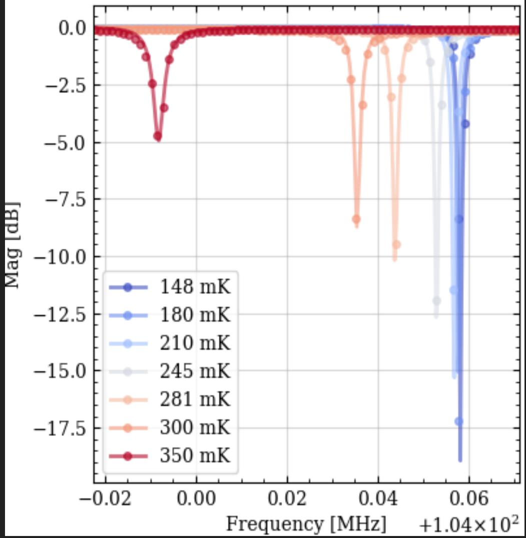
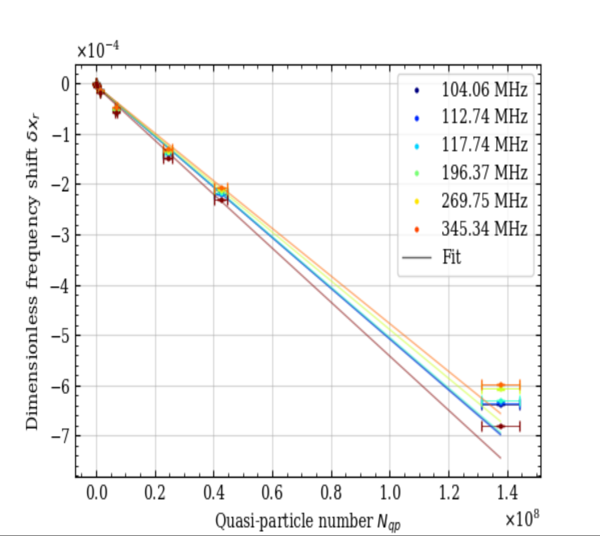
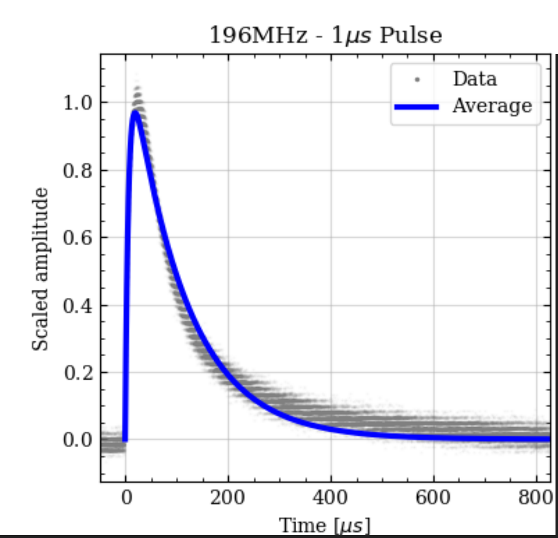


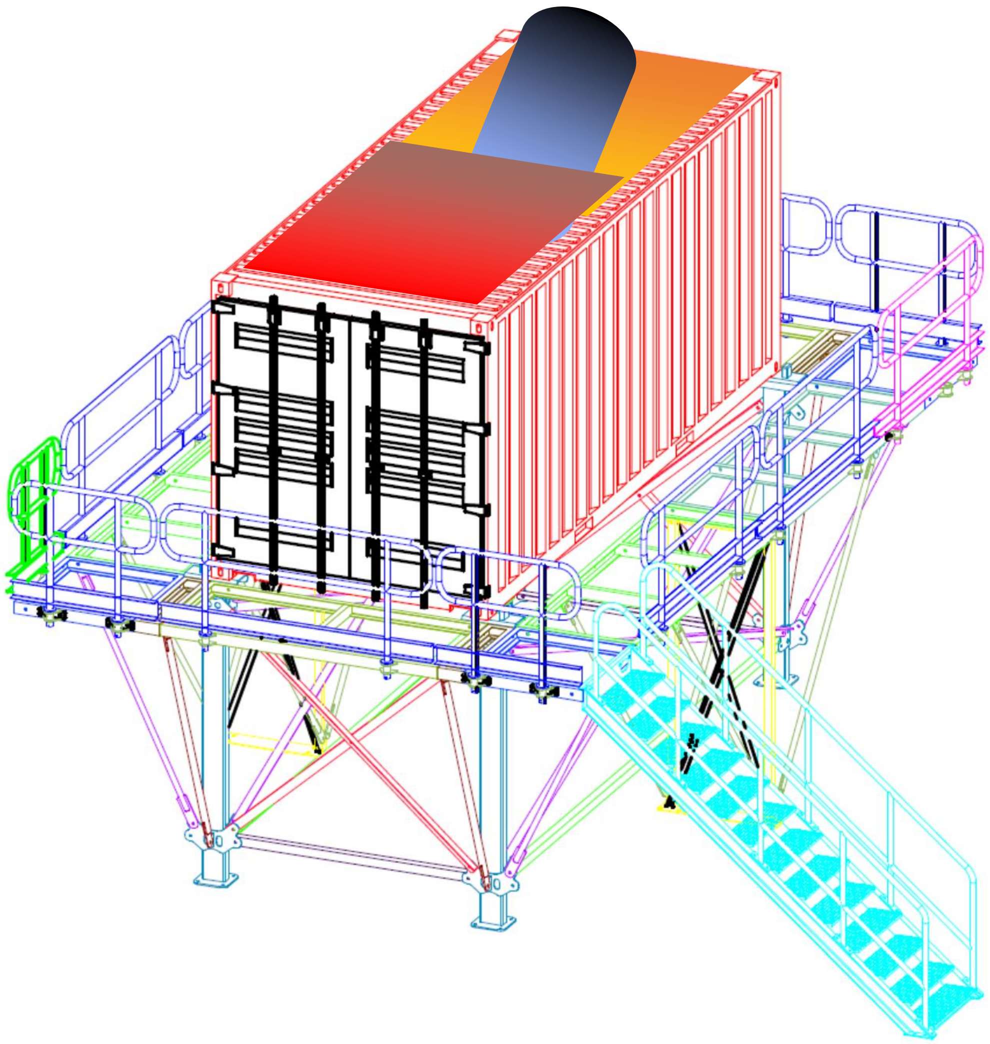






- Non-linearities and harmonics present, due to lumped condition not perfectly met.
- Average performance close or better than photon noise limit (depending on chosen resonance)

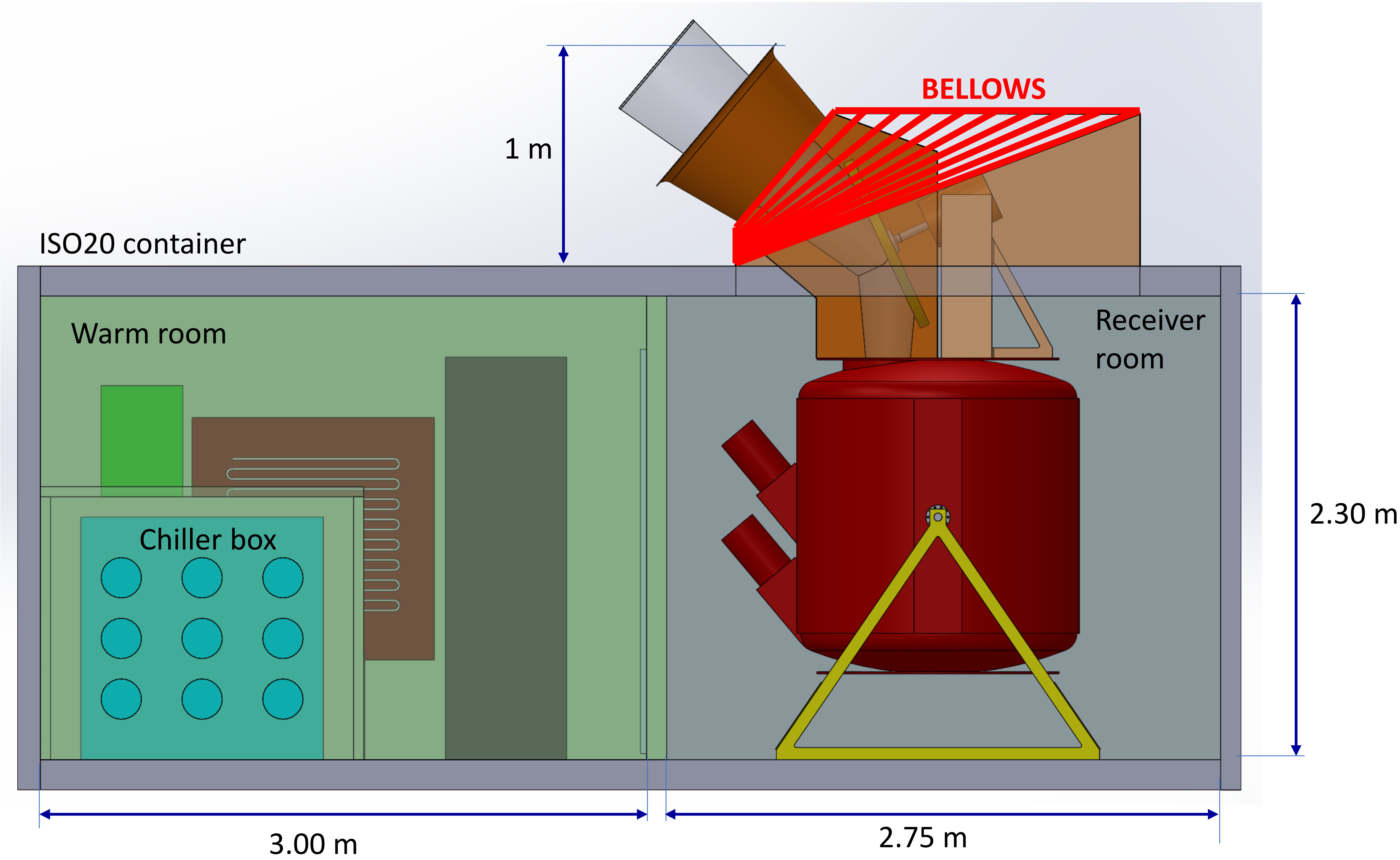
COSMO on-site implementation



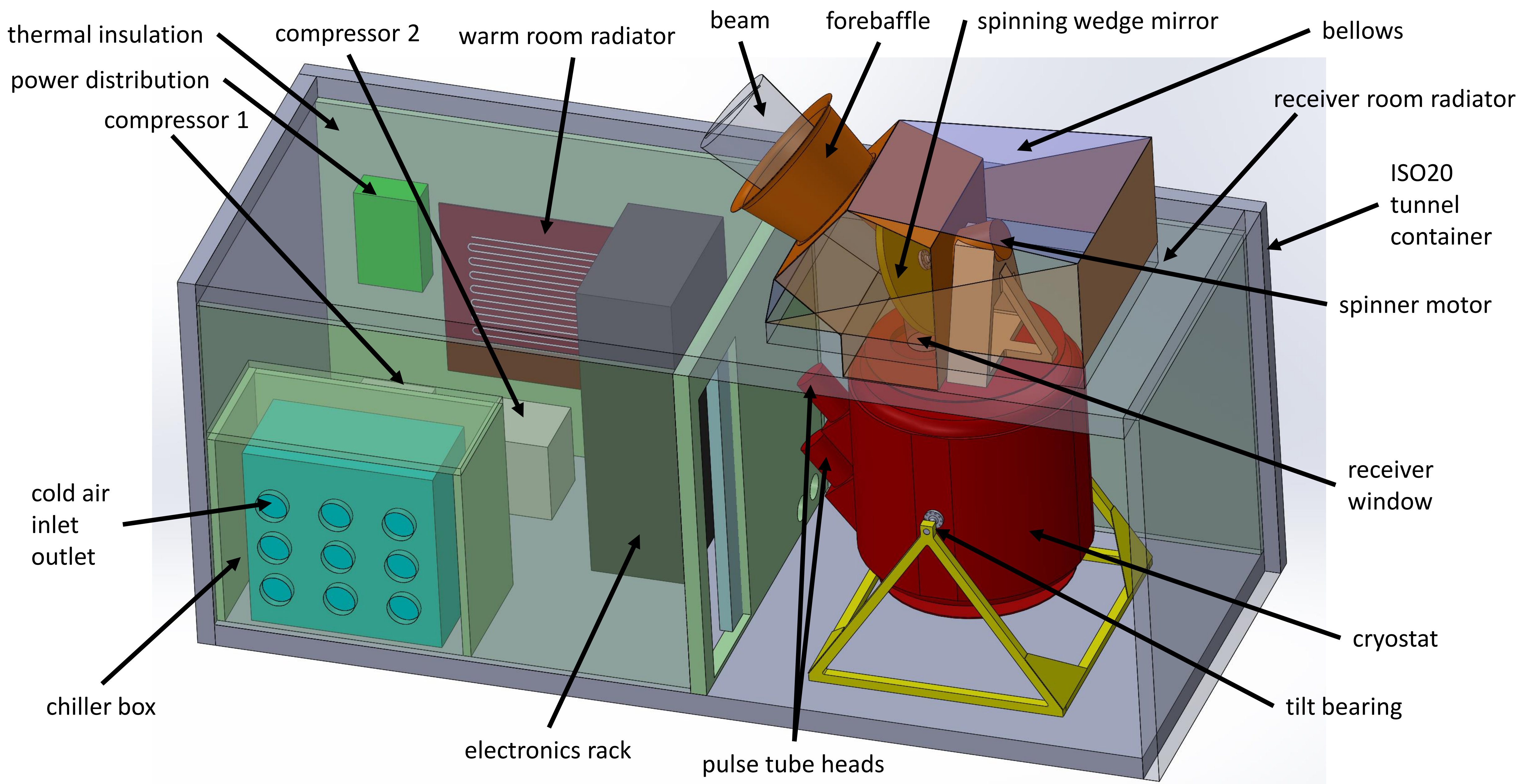
- Experiment in a thermally insulated container
- Warm section with electronics and compressors.
- Cold section with receiver. No window. Shields.
- The same container used for tests and shipment
- Palafitte as usual in Dome-C (e.g. superDARN)
- Installation site: near astronomy lab
- Energy needed: 20 kW for 100 days

Thanks to Gianluca Bianchi-Fasani for palafitte dwg.

COSMO on-site implementation – main concept

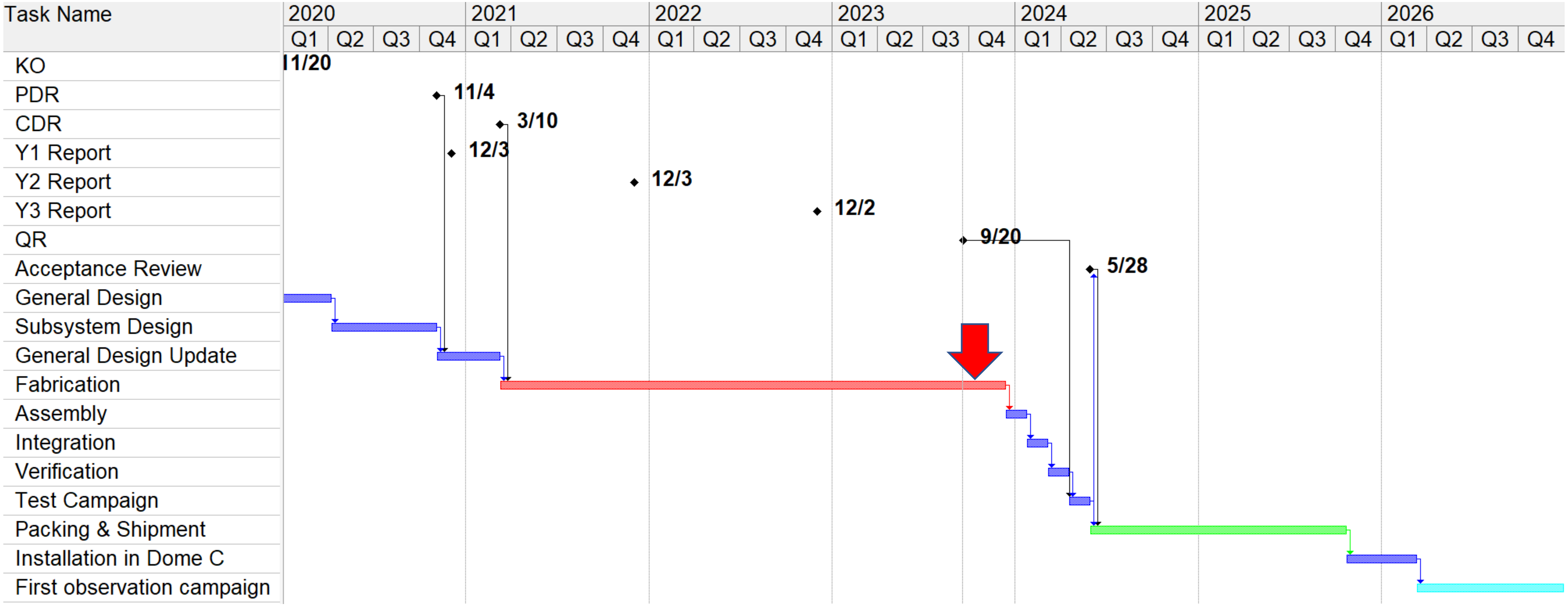


COSMO on-site implementation – location of main components



COSMO - Top Level Schedule

- We are currently near the end of the subsystems fabrication phase.
- In the current schedule, the first Antarctic winter observation campaign in Dome-C will be in 2026



Conclusions

- COSMO is a first attempt to measure the spectral distortions of the CMB monopole from the ground.
- It beats atmospheric noise and measures atmospheric emission using fast modulation and detectors.
- If this strategy is effective, the sensitivity is enough to measure the largest spectral distortion, arising from comptonization at recombination / reionization / ionized baryons in the universe.
- It paves the way to more accurate measurements with the same approach, to be carried out with COSMO on a stratospheric balloon (see also the synergic proposal BISOU)
- Synergic to low-frequency *monopole* spectral distortion measurements (e.g. The Tenerife Microwave Spectrometer (TMS) and the Array of Precision Spectrometers for the Epoch of RecombinAtion (APSERa) to enter the detection era of SD.