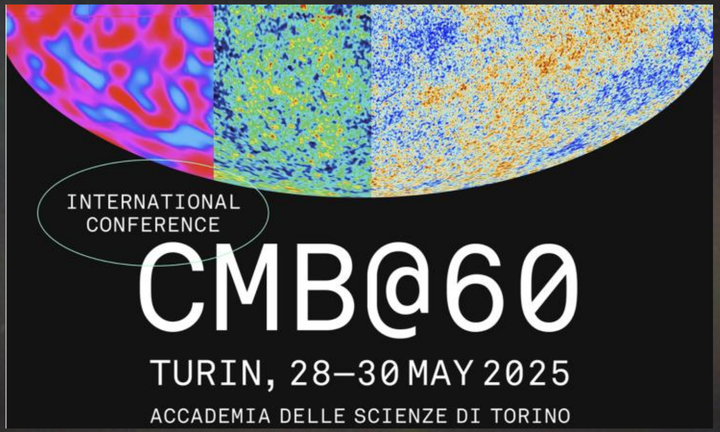
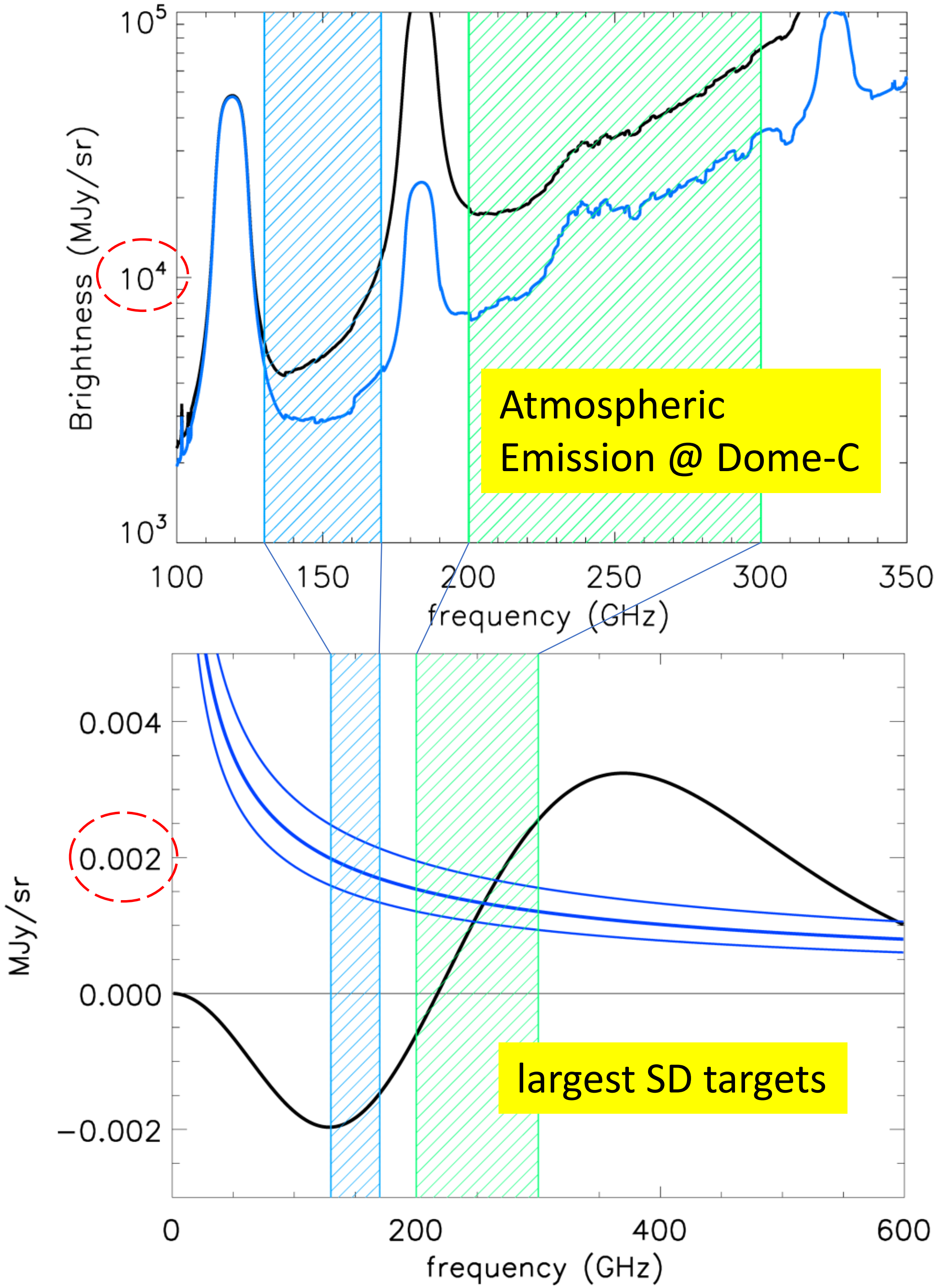
Sub-orbital spectral distortions : the *COSMO* program

P. de Bernardis, Sapienza, Roma, for the *COSMO* collaboration



Ground-based & Balloon-borne spectral distortion measurements

- *Isotropic* spectral distortions (SD) of the CMB are extremely faint, when compared to the CMB itself, and even more if compared to room-temperature emissions.
- Sub-orbital experiments face:
  - Atmospheric emission
  - Ground emission in the sidelobes
  - Receiver vacuum window emission
  - Electromagnetic interference
- All the above is reduced or absent in space-based instruments, which clearly represent the final stage to obtain high-quality SD measurements.
- However, sub-orbital experiments:
  - Are relatively cheap and can be deployed in a reasonable time scale. Can sample a significant frequency range using different atmospheric windows
  - Offer the opportunity to develop, test and optimize iteratively instrument configurations and analysis methods
  - Can detect the largest spectral distortions, still undetected.
- Here I focus on COSMO, a ground-based experiment aimed at measuring SDs in two mm bands.



COSMO (COSmic Monopole Observer)

G. Barbieri-Ripamonti, E. Battistelli, P. de Bernardis, M. Bersanelli, F. Cacciotti, A. Capponi, E. Catena, J. Chluba, S. Cibella, F. Columbro, A. Coppolecchia, I. Di Nitto, M. Bersanelli, M. De Petris, G. Fabbian, C. Franceschet, M. Gervasi, G. Isopi, A. Limonta, L. Lamagna, B. Maffei, E. Marchitelli, S. Masi, A. Mennella, F. Nati, A. Occhiuzzi, A. Paiella, A. Passerini, G. Pettinari, F. Piacentini, L. Piccirillo, G. Pisano, C. Tucker, M. Zannoni

Sapienza Università di Roma
CNR IFN Istituto di Fotonica e Nanotecnologie
Università degli Studi di Milano Bicocca
Universitas Studiorum Mediolanensis
IAS Orsay
Manchester 1824 The University of Manchester
Cardiff University Prifysgol Caerdydd

Fondo Italiano per la Scienza
MUR
PRIN Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale
Programma Nazionale di Ricerche in Antartide

https://cosmo.roma1.infn.it

Absolute spectroscopy approach

- The Martin-Puplett Fourier Transform Spectrometer (**MP-FTS**, the instrument used in COBE-FIRAS and being implemented in BISOU and PIXIE) has two input ports.
- The instrument is intrinsically ***differential***, measuring the spectrum of the difference of the brightness at the two input ports.
- During the sky measurement one port looks at the sky and the other one looks at an internal reference blackbody. The measured interferogram is (σ=wavenumber, 2x=optical path difference):

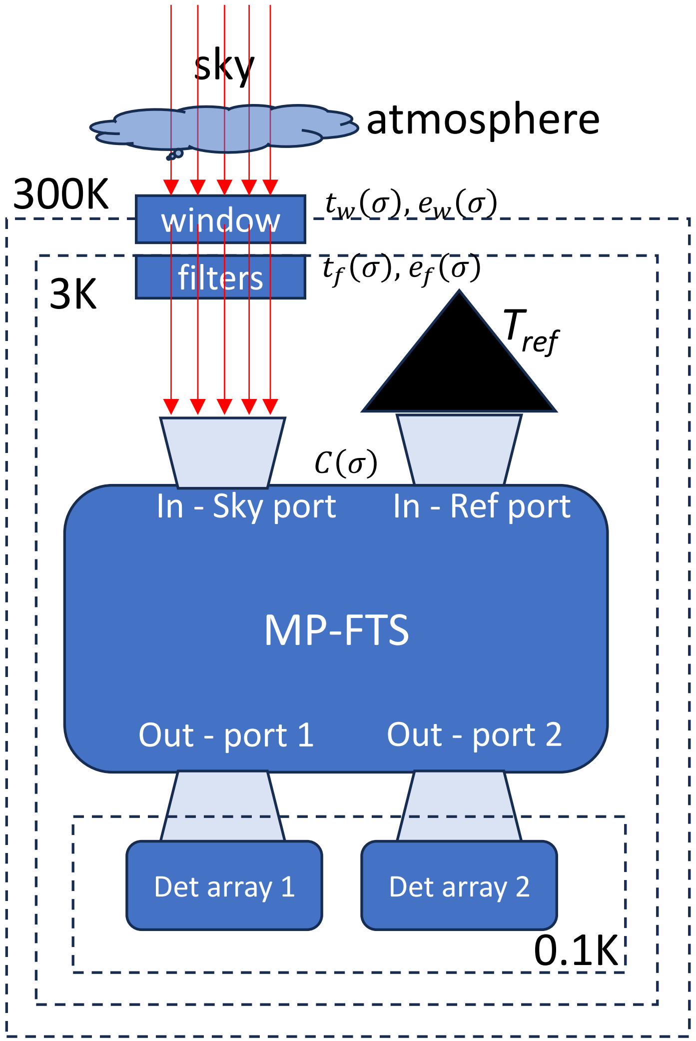
$$I_{SKYPORT}(x) = \int_0^{\infty} C(\sigma)\left[S_{SKYPORT}(\sigma) - B\left(T_{ref},\sigma\right)\right]\{1+\cos[4\pi\sigma x]\}d\sigma$$

where $S_{SKYPORT}(\sigma) = [S_{SKY}(\sigma)t_w(\sigma) + e_w(\sigma)]\, t_f(\sigma) + e_f(\sigma)$

- In order to measure the signal from the skyport we take the antitransform of the equation above and find

$$\left[S_{SKYPORT}(\sigma) - B\left(T_{ref},\sigma\right)\right] = \left[\int_{-\infty}^{+\infty} [I_{SKYPORT}(x) - \langle I\rangle] \cos[4\pi\sigma x]\, dx\right] \Big/ C(\sigma)$$

- In order to extract the sky signal $S_{SKY}(\sigma)$ from the skyport signal:
  - $C(\sigma)$ must be known, i.e. the FTS and detectors response must be calibrated
  - $B\left(T_{ref},\sigma\right)$, $t_w(\sigma)$, $e_w(\sigma)$, $t_f(\sigma)$, $e_f(\sigma)$, atmospheric emission and transmission etc. must be estimated and removed.

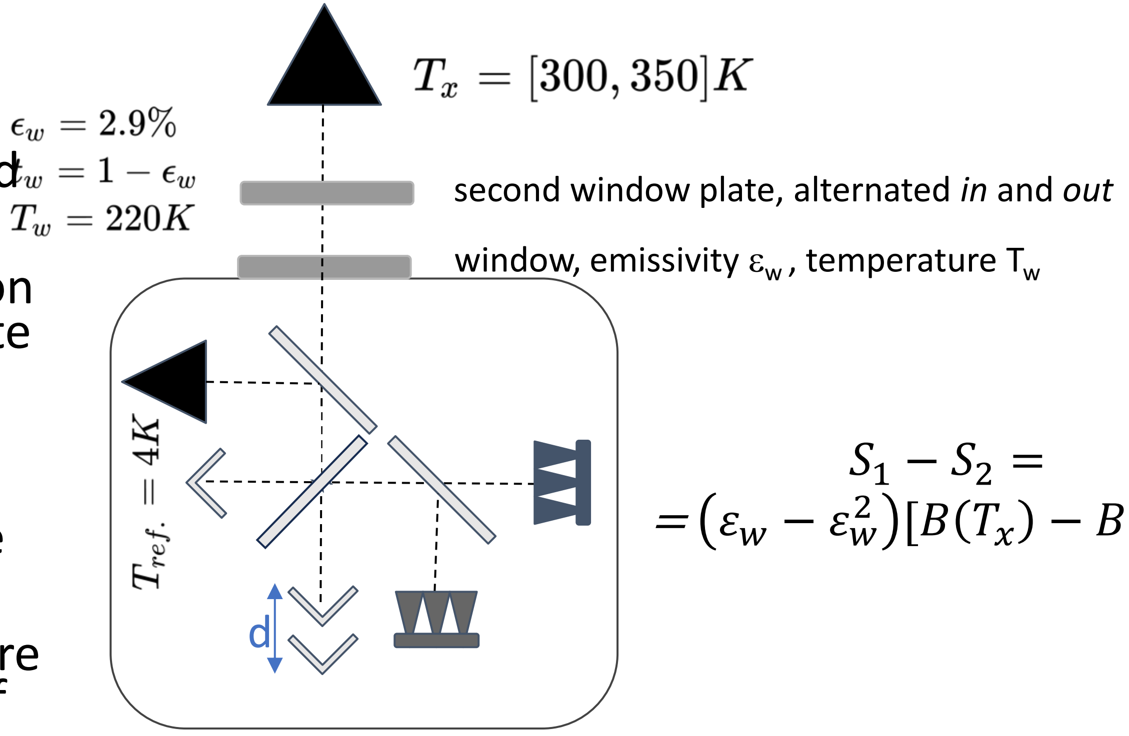


- In our case $C(\sigma)$ is obtained from the difference of two calibration signals, both with the skyport filled by a stable external reference mimiking the sky brightness, and corresponding to two different temperatures of the internal reference:

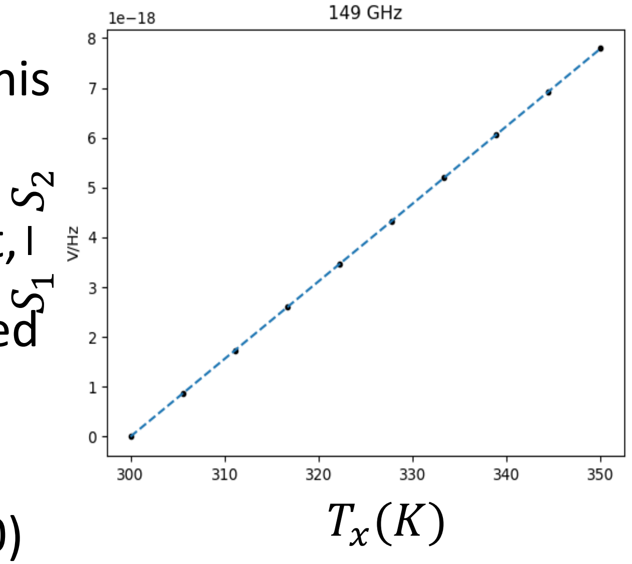
$$C(\sigma) = \left[\int_{-\infty}^{+\infty} \left[I_{cal,1}(x) - \langle I_{cal,1}\rangle - \left(I_{cal,2}(x) - \langle I_{cal,2}\rangle\right)\right] \cos[4\pi\sigma x]\, dx\right] \Big/ \left[B\left(T_{ref,2},\sigma\right) - B\left(T_{ref,1},\sigma\right)\right]$$

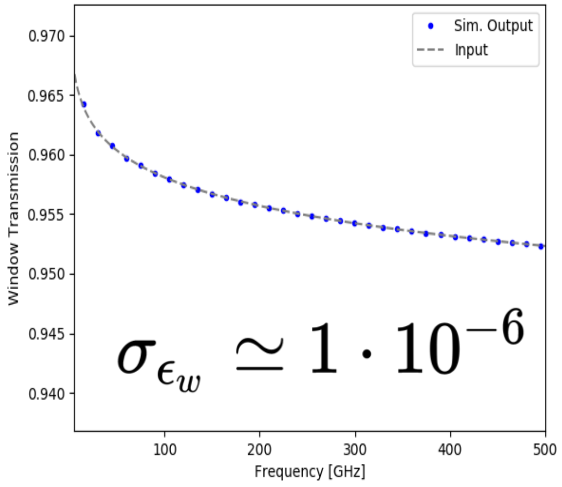
Coping with window emission

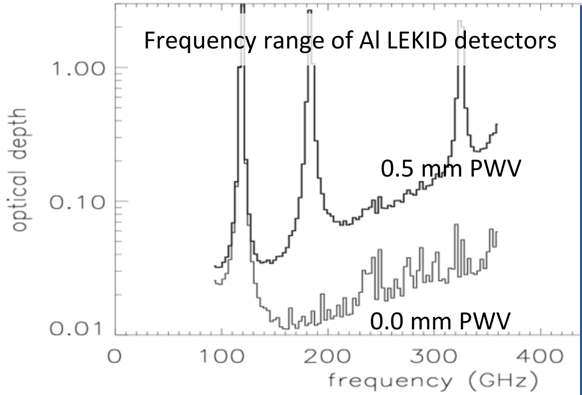
- Window **common mode emission** must be measured and removed with high accuracy.
- A special subtraction procedure, based on the comparison of the emission from 1 or 2 windows stacked and accurate temperature monitoring, has been studied (PhD thesis, Lorenzo Mele)
- **Preliminary results:** The window emission can be subtracted, and the expected residual is smaller than the target distortion (assuming *y* ~ 2x10^{-6}).
- This is relevant for the ground based measurement, where the window is HDPE, ~10 mm thick, to withstand 1 bar of atmospheric pressure.
- For a balloon-borne measurement (3 mbar), the window thickness can be reduced to a few tens of microns, and this issue becomes less important.
- Similar procedures must be carried out for **all other common mode emissions** (the window one is the largest, but we also have a filters chain and a cold lens), which **must be measured in advance vs temperature**, monitored and subtracted.
- To further mitigate the contributio of these smooth-spectrum contaminants, the FSD method (Mukherjee &, 2018) or/and ILC/moments method (Rotti & Chluba 2020) can be used.



$$S_1 - S_2 =$$
$$= (\varepsilon_w - \varepsilon_w^2)[B(T_x) - B(T_w)]$$





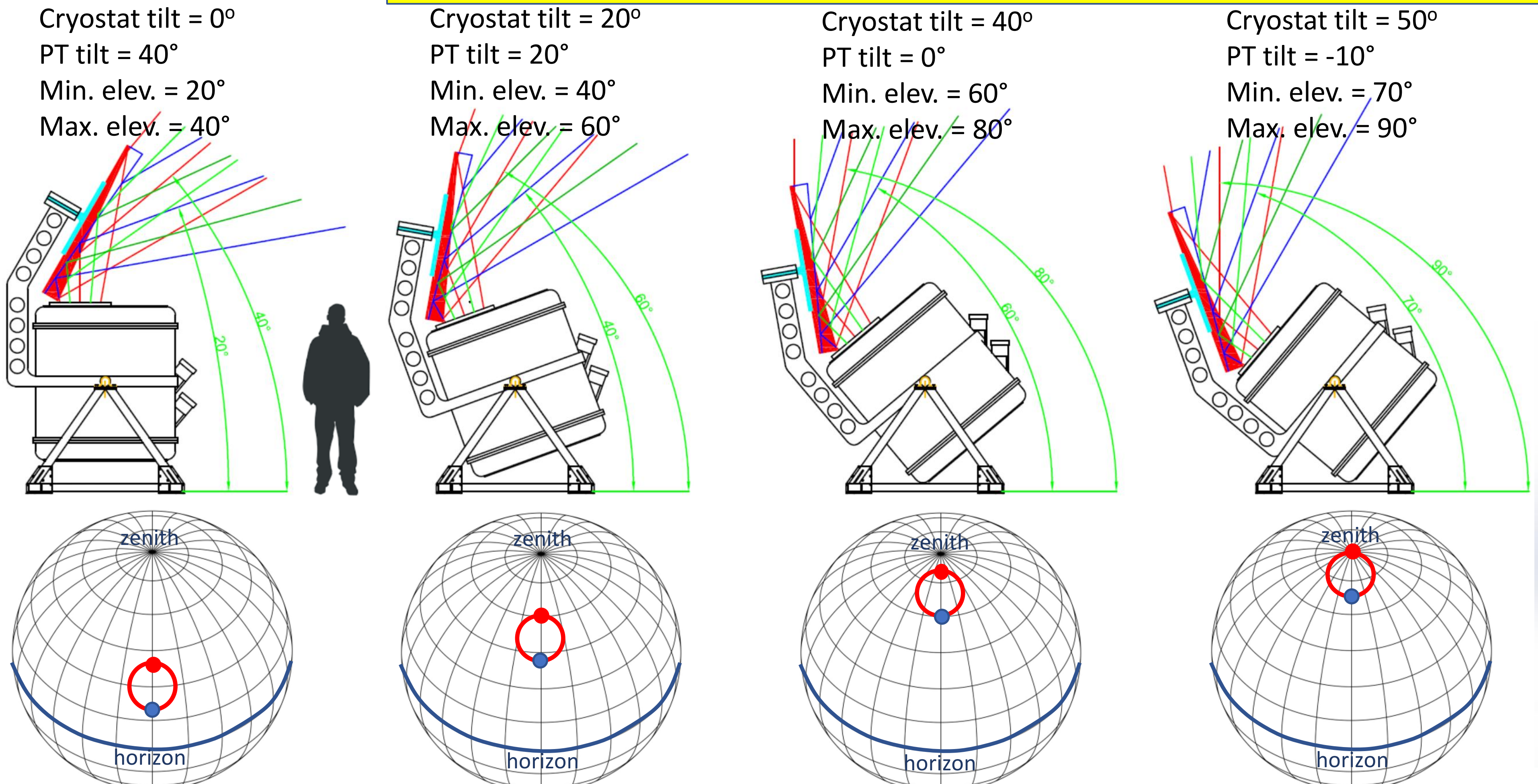


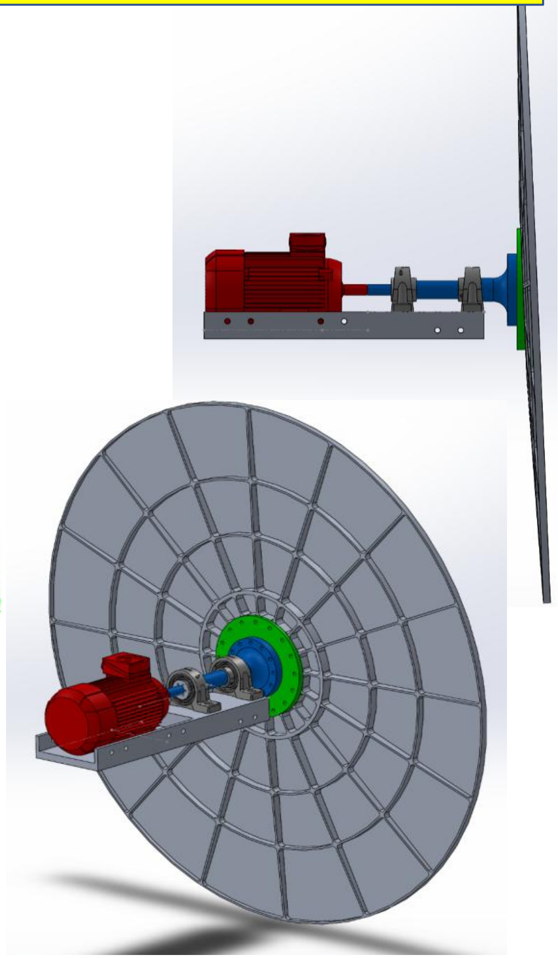
Coping with atmospheric emission

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.

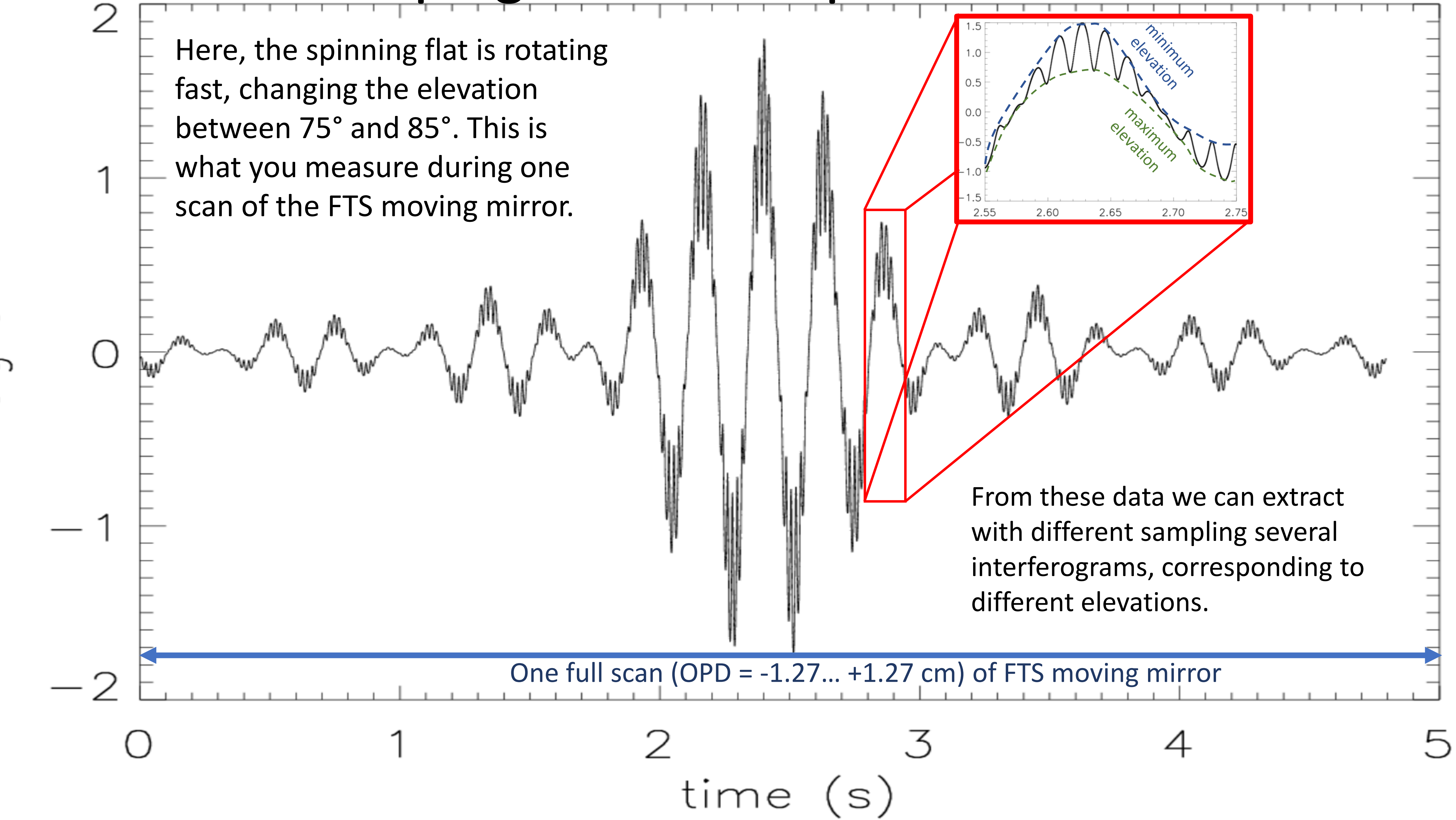
COSMO uses fast detectors (KIDs) and fast elevation scans to separate atmospheric emission and its long-term fluctuations from the monopole of the sky brightness.

A fast spinning wedge mirror (>1000 rpm!) steers the boresight direction on a circle, 20º in diameter, scanning a range of elevations (and corresponding atmospheric optical depths) while the cryogenic interferometer scans the optical path difference.





Coping with atmospheric emission

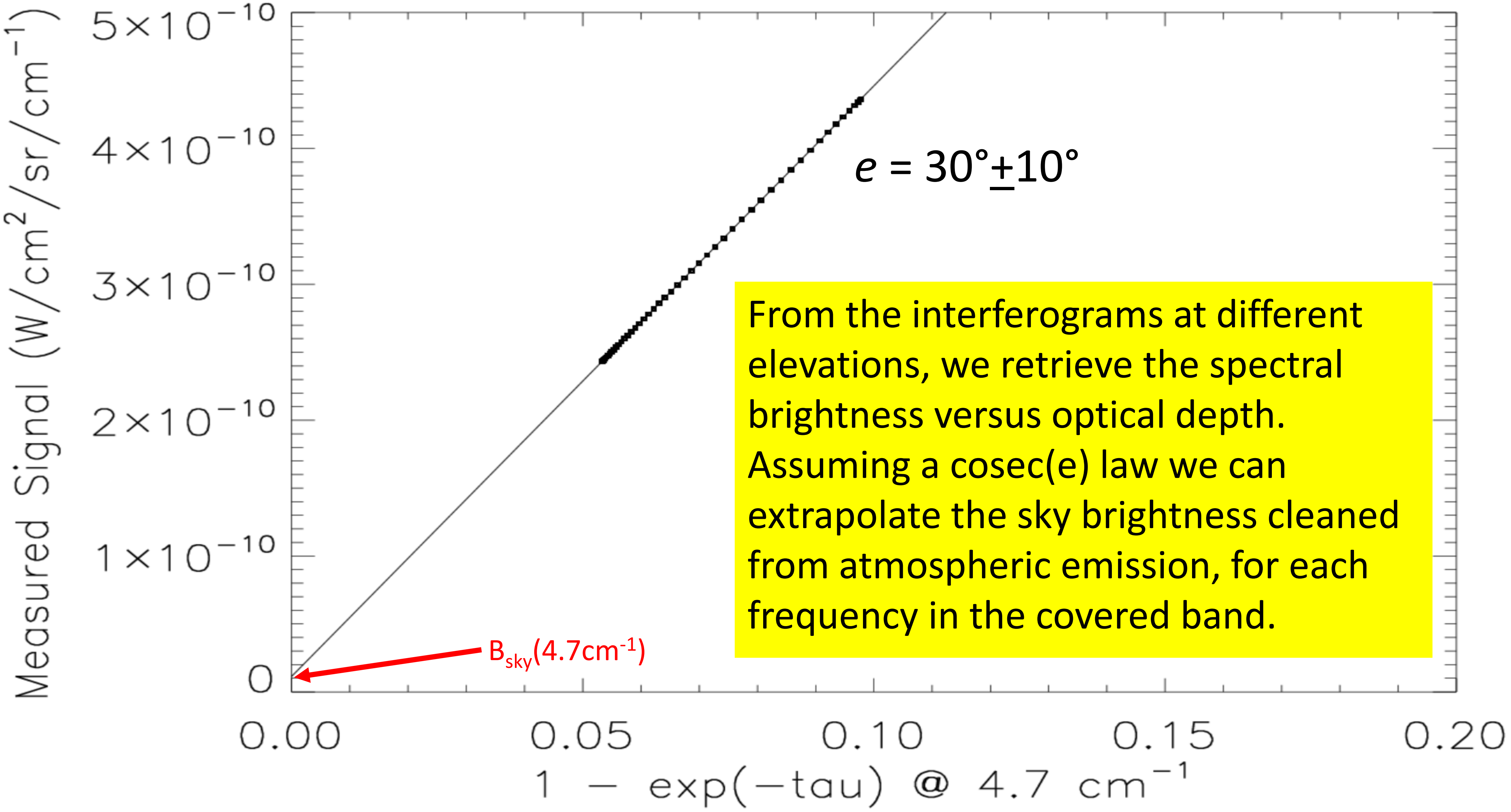


Here, the spinning flat is rotating fast, changing the elevation between 75° and 85°. This is what you measure during one scan of the FTS moving mirror.

From these data we can extract with different sampling several interferograms, corresponding to different elevations.

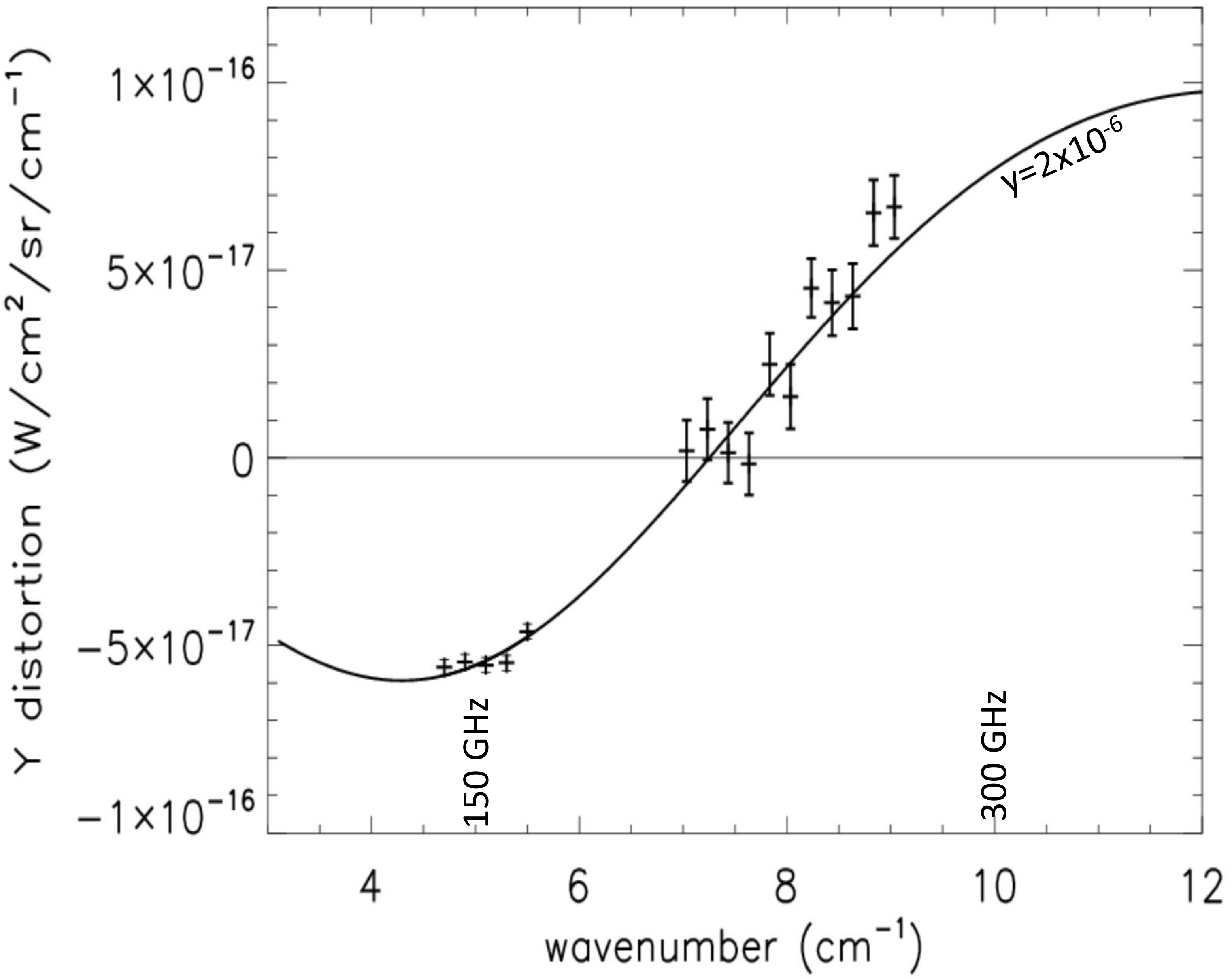
One full scan (OPD = -1.27... +1.27 cm) of FTS moving mirror

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



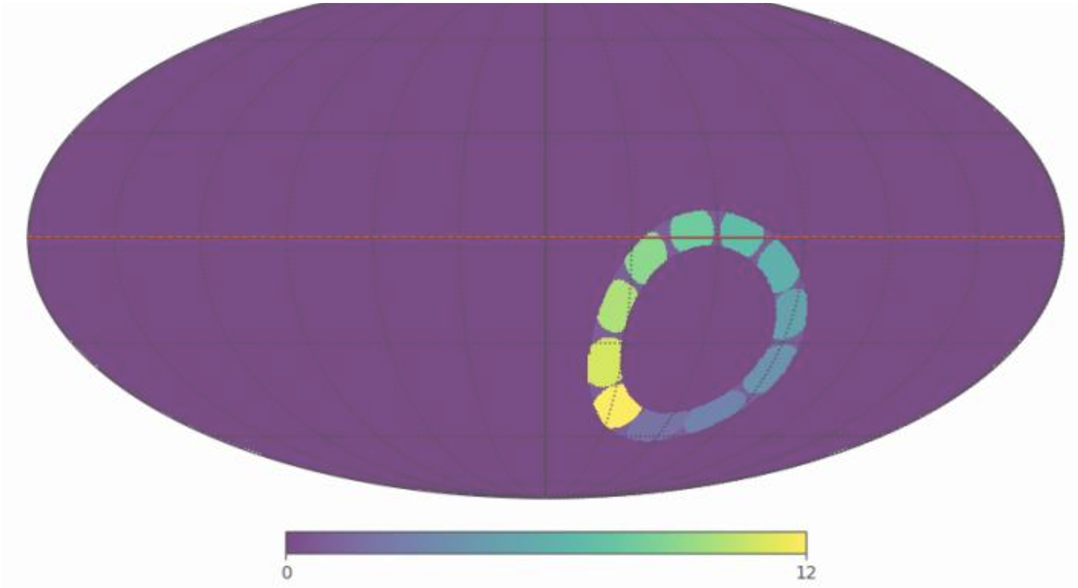
Covering about **1800 square degrees** of the sky in **2 years**, we expect to reach a **goal sensitivity** for the average spectral brightness:

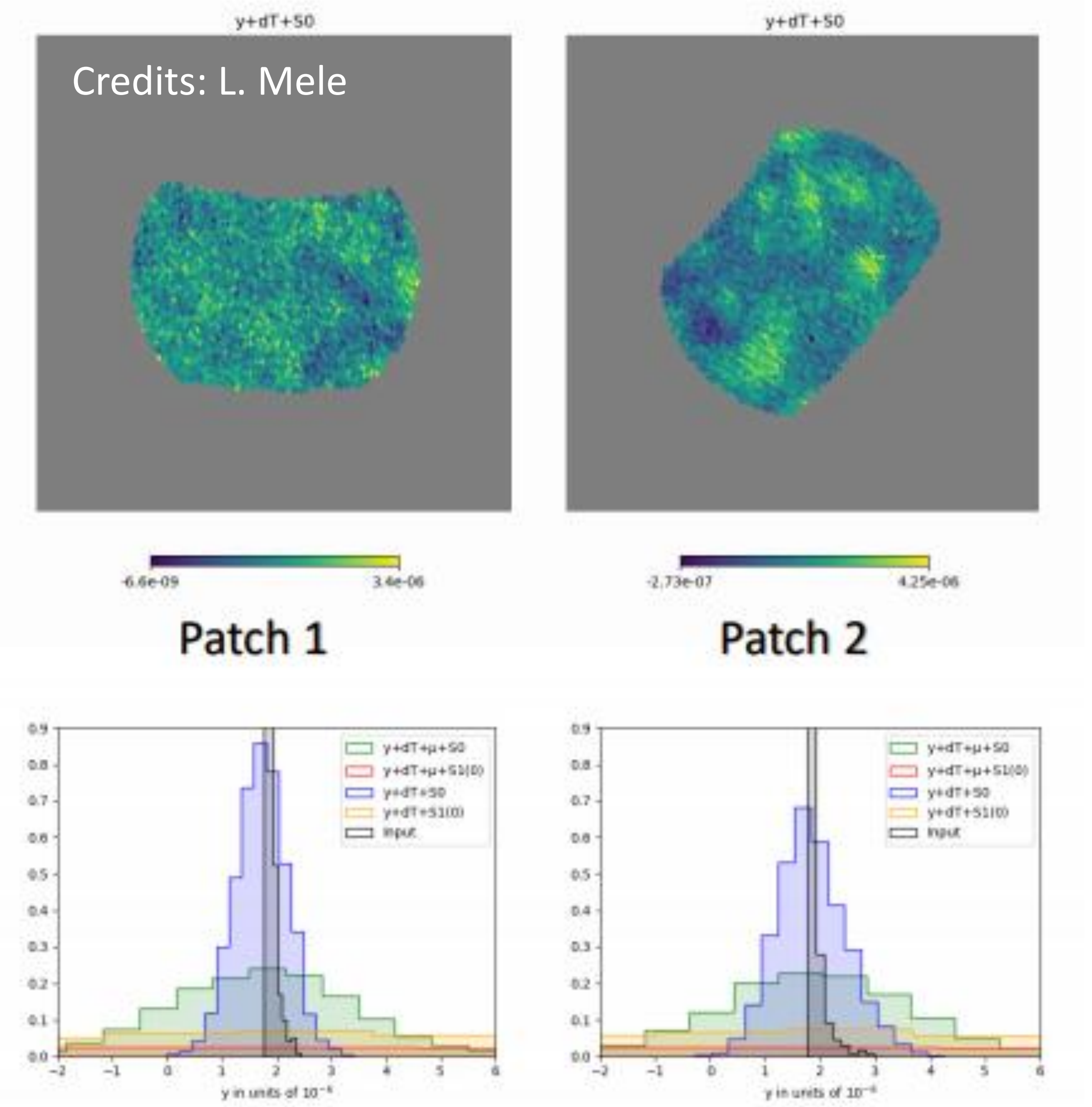
- **1×10^{-17} W/cm^2/sr/cm^{-1}** per spectral bin, in 10 spectral bins, **10 GHz** wide, within the 200-300 GHz atmospheric window;
- **3×10^{-18} W/cm^2/sr/cm^{-1}** per spectral bin in 5 spectral bins, **10 GHz** wide, within the 130-170 GHz atmospheric window

- Note: 3×10^{-18} W/cm^2/sr/cm^{-1} = 100 Jy/sr

Performance Forecast

- Assuming photon noise limited performance, dominated by the atmospheric emission (AM model) and cryostat window (with $\varepsilon = 1\%$)
- Observing site: Dome-C. Daily coverage of 11 sky patches at high elevation, 100 days of integration.
- ILC-based simulations: COSMO can extract the isotropic comptonization parameter (assumed to be $y = 1.77 \cdot 10^{-6}$) as $y = (1.76 \pm 0.26) \cdot 10^{-6}$ in the presence of the main Galactic foreground (thermal dust) and of CMB anisotropy, and assuming perfect atmospheric emission removal (L. Mele)

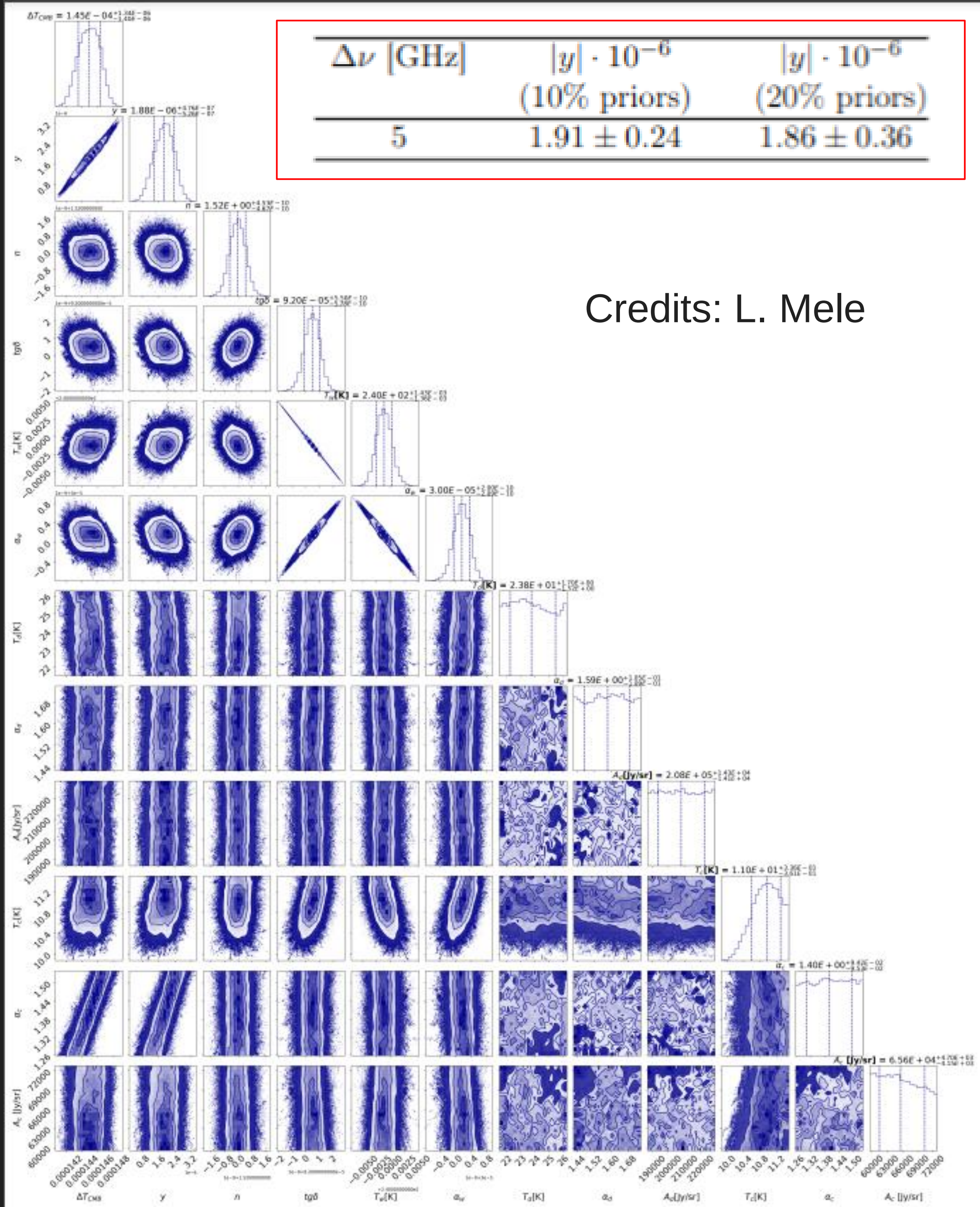




Simulations

- Monte Carlo Markov Chain (MCMC) fitting
- Photon noise limited performance (atmosphere + vacuum window)
- Separation from the Thermal dust emission from the Galaxy and the Cosmic Infrared Background (CIB) as the main foreground emissions
- Input distortion $|y| = 1.77 \cdot 10^{-6}$
- Different priors on foregrounds parameters
- Single sky-patches separation

Sky patch #	$\lvert y\rvert \cdot 10^{-6}$ (10% priors on CIB and Dust)	$\lvert y\rvert \cdot 10^{-6}$ (20% priors on CIB and Dust)
1	1.96 ± 0.57	1.99 ± 0.88
2	1.88 ± 0.62	1.59 ± 0.83
3	2.16 ± 0.77	1.95 ± 0.87
4	2.19 ± 2.36	2.62 ± 1.87
5	2.56 ± 2.91	2.94 ± 2.26
6	2.98 ± 3.21	2.66 ± 2.45
7	3.68 ± 2.56	3.29 ± 2.28
8	2.04 ± 1.00	1.76 ± 1.28
9	1.86 ± 0.55	1.90 ± 0.88
10	1.84 ± 0.53	1.93 ± 0.97
11	1.88 ± 0.55	1.87 ± 0.90

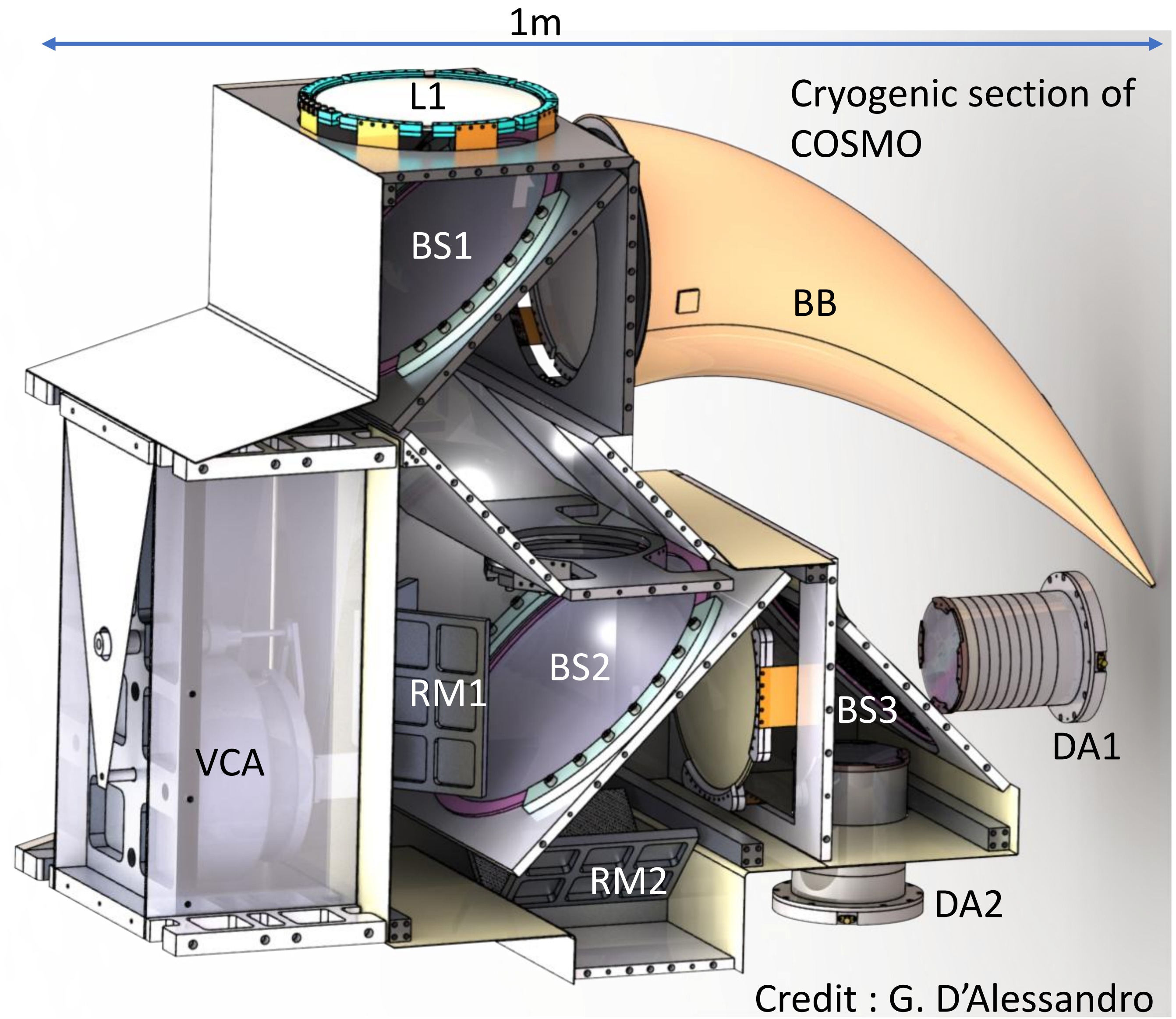


$\Delta\nu$ [GHz]	$\lvert y\rvert \cdot 10^{-6}$ (10% priors)	$\lvert y\rvert \cdot 10^{-6}$ (20% priors)
5	1.91 ± 0.24	1.86 ± 0.36

Credits: L. Mele

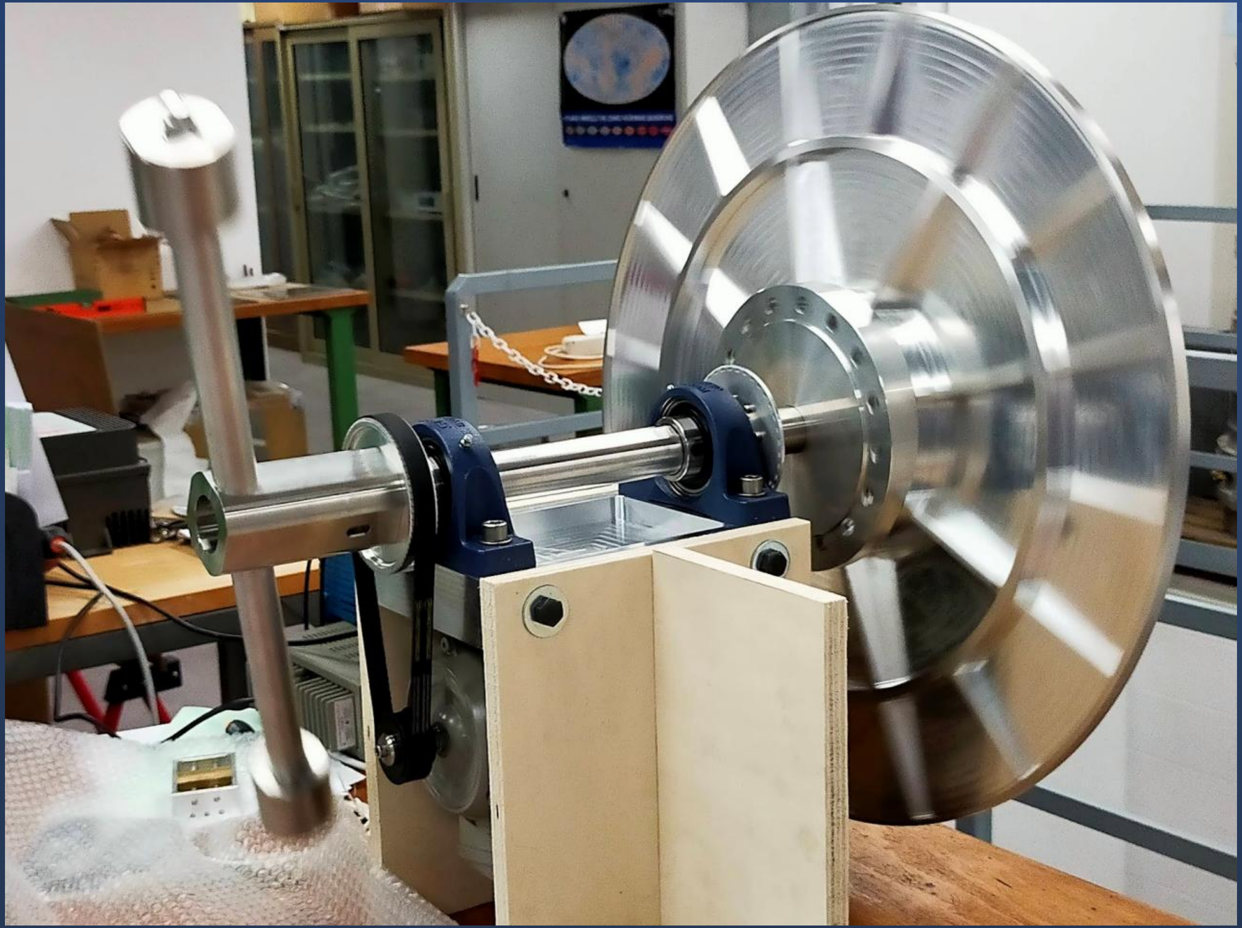
COSMO in a nutshell

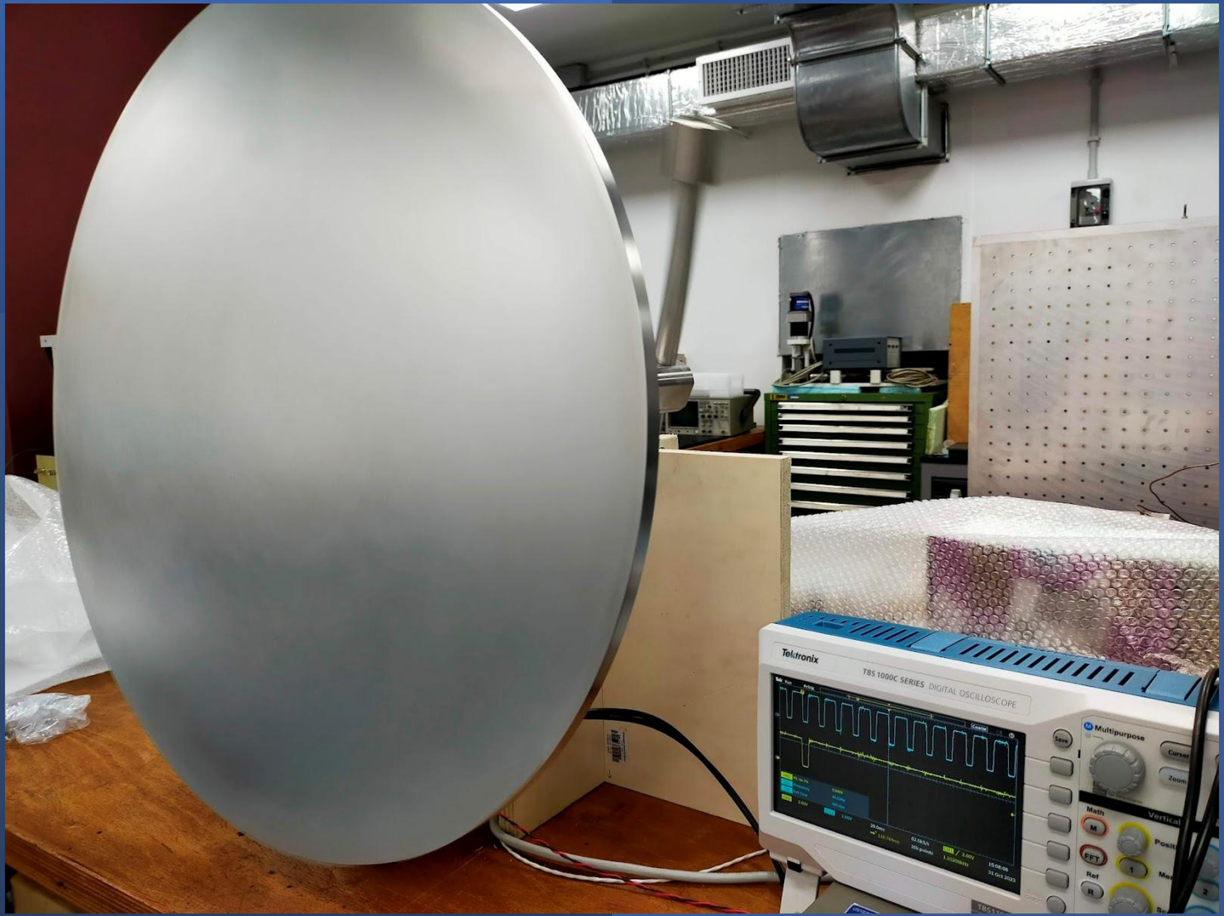
- **COSMO** is a pathfinder experiment, ground-based in the first implementation, balloon-borne in its second step.
- A cryogenic **Differential Fourier Transform Spectrometer**, comparing the sky brightness to an internal blackbody (configuration similar to COBE-FIRAS)
- Operation from the Concordia 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 3K…5K;
- A continuous and **fast** (few seconds) **interferogram scan** is achieved moving the roof mirror with a voice-coil.
- Several **10ºx10º** sky patches are observed with **1º 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**.



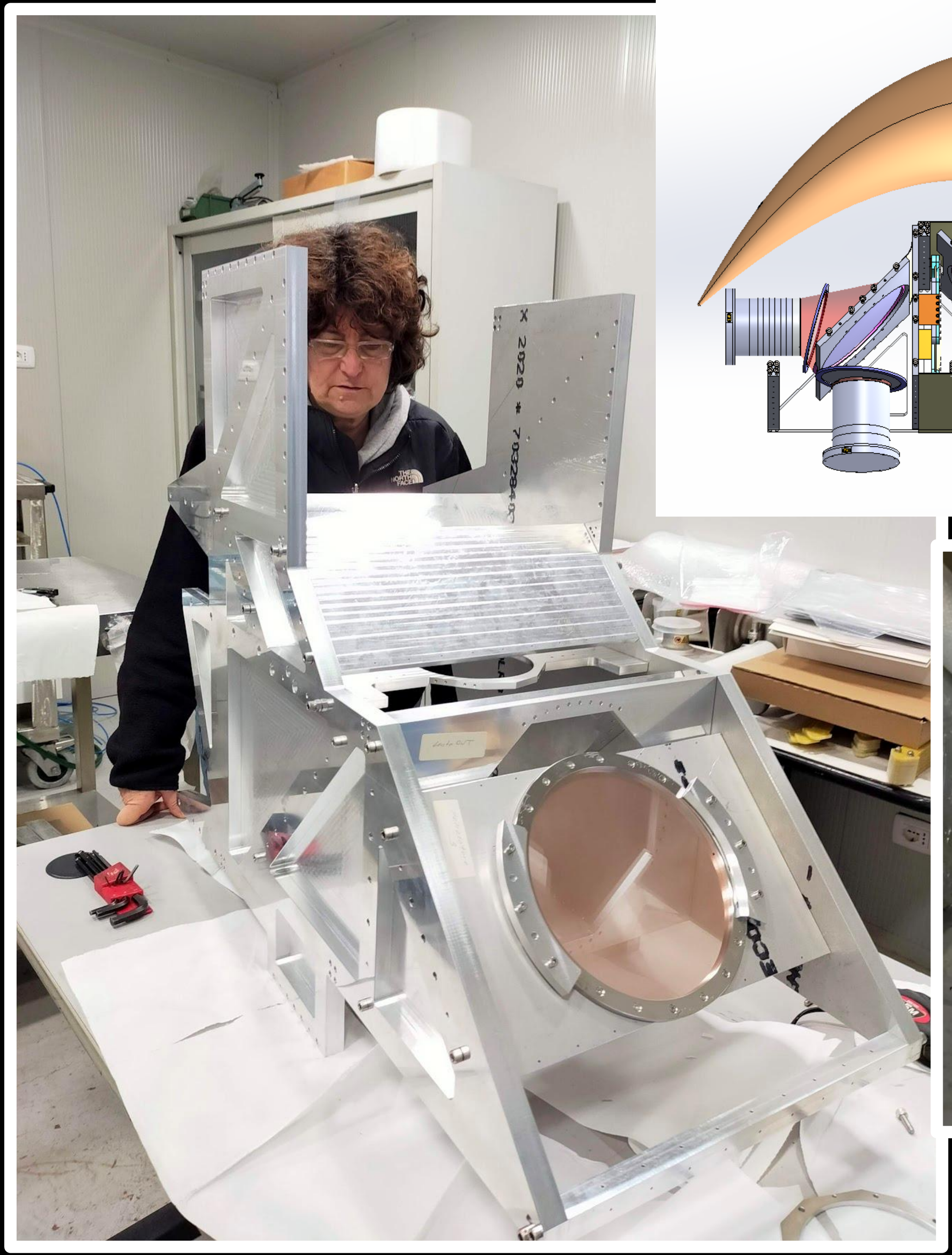
Credit : G. D'Alessandro

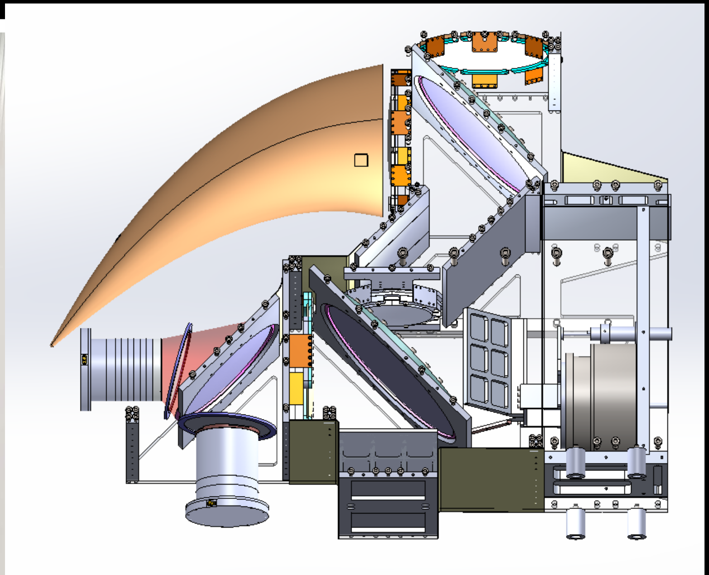
COSMO sky scanner

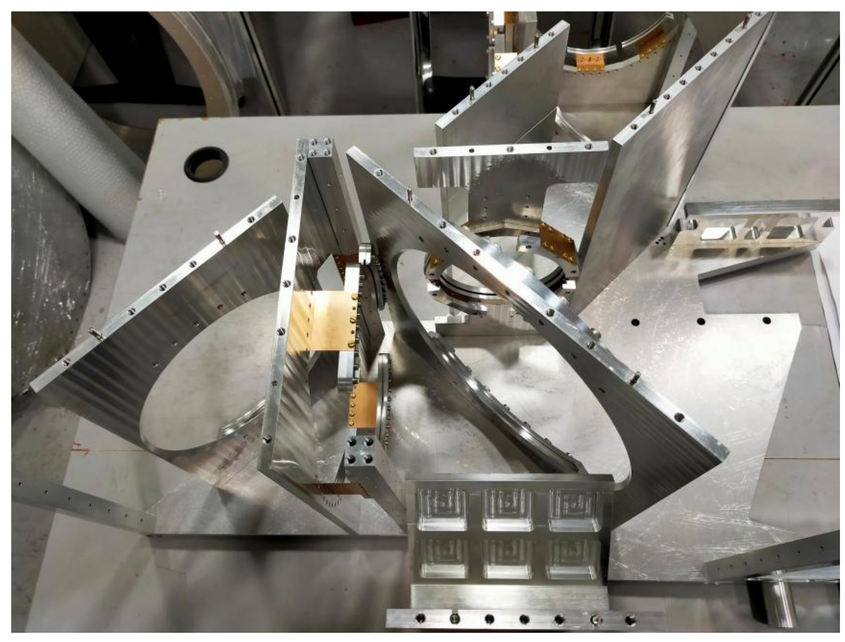


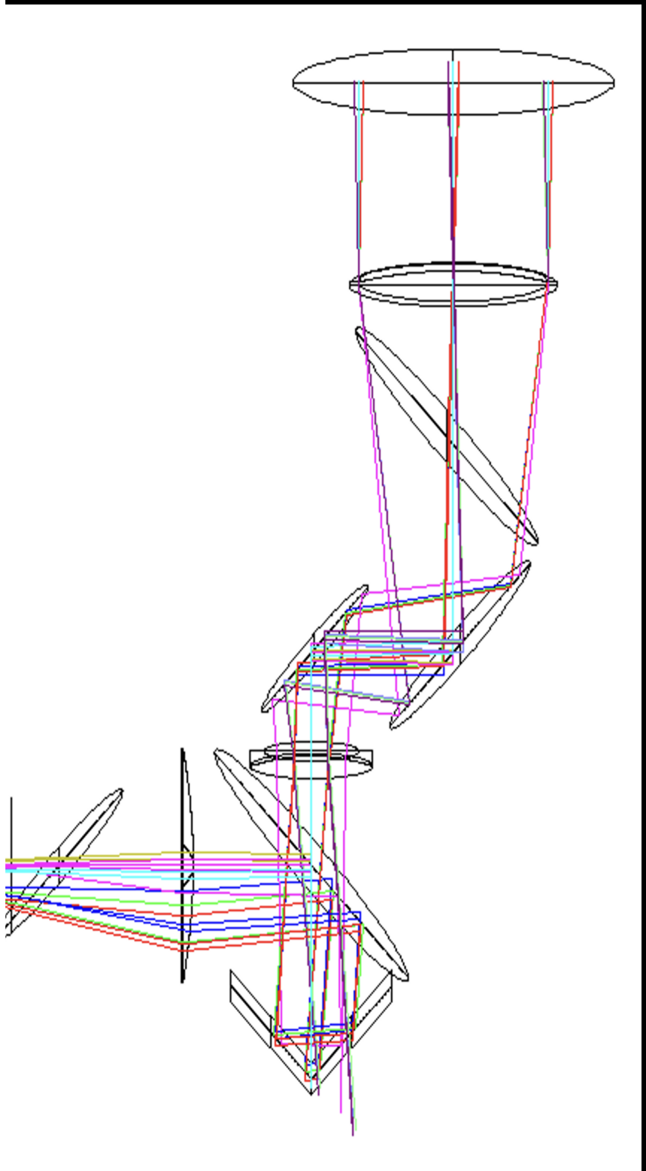


COSMO cryostat





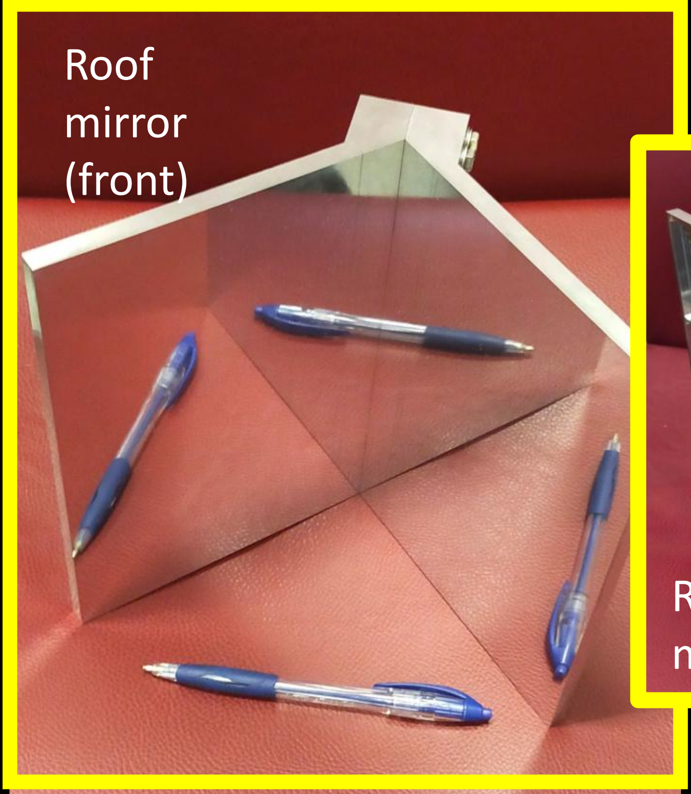


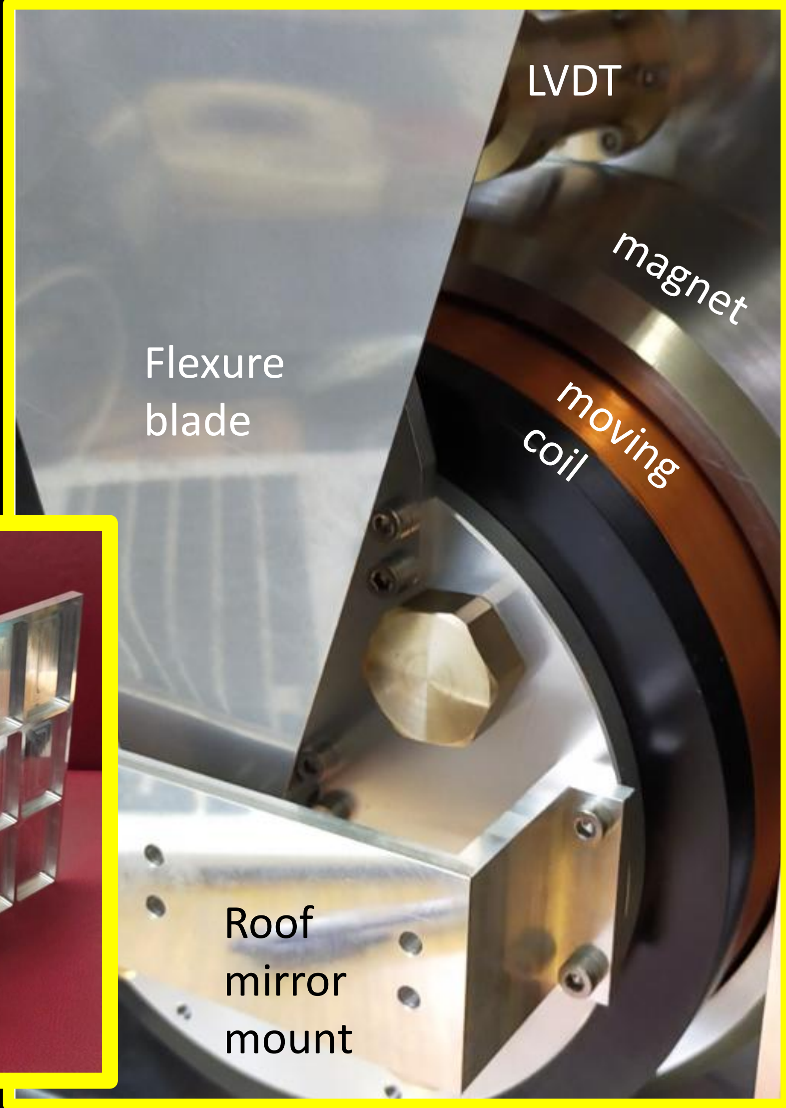


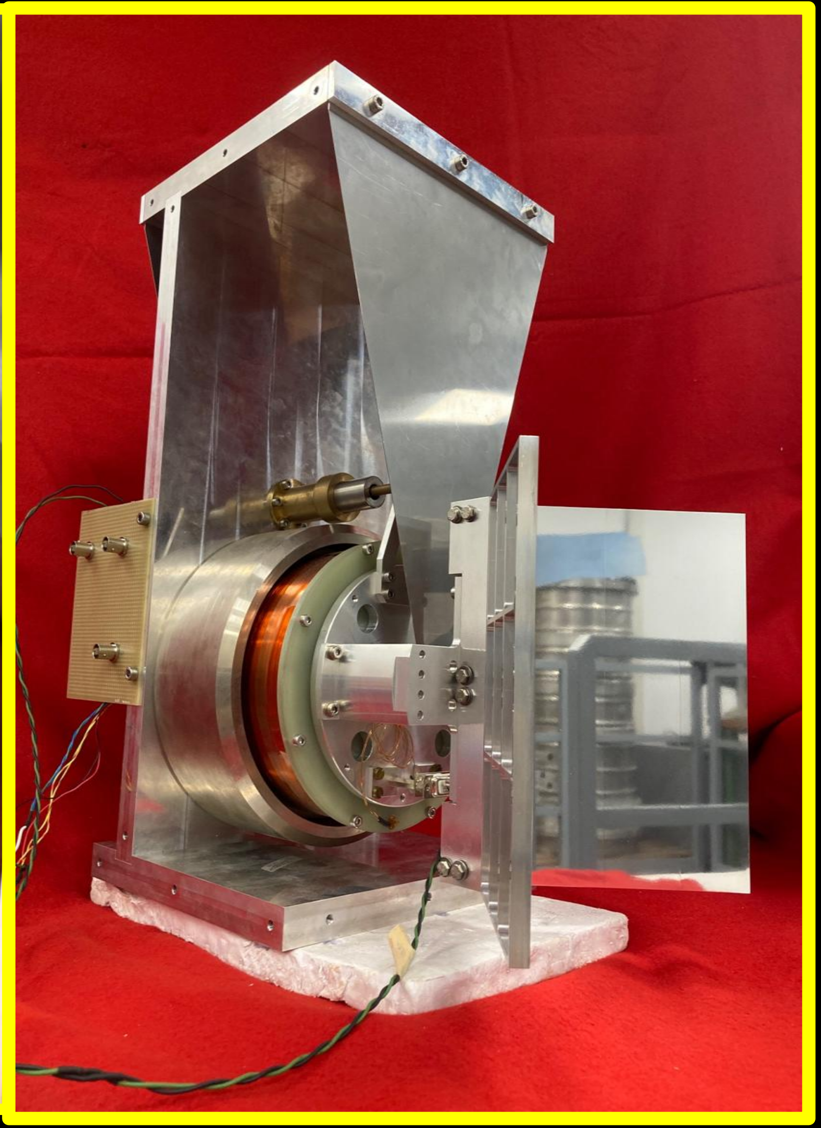
COSMO interferometer

COSMO Variable Delay Lines

- 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.
- Eddy currents in moving coil support minimized by means of a dielectric coil support.

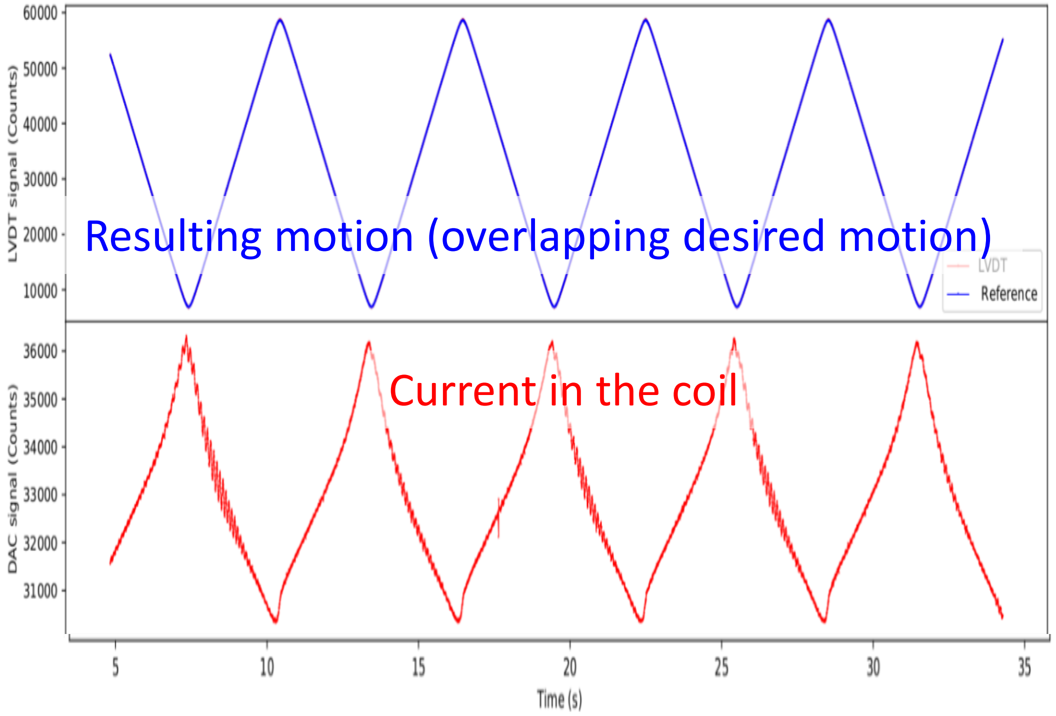




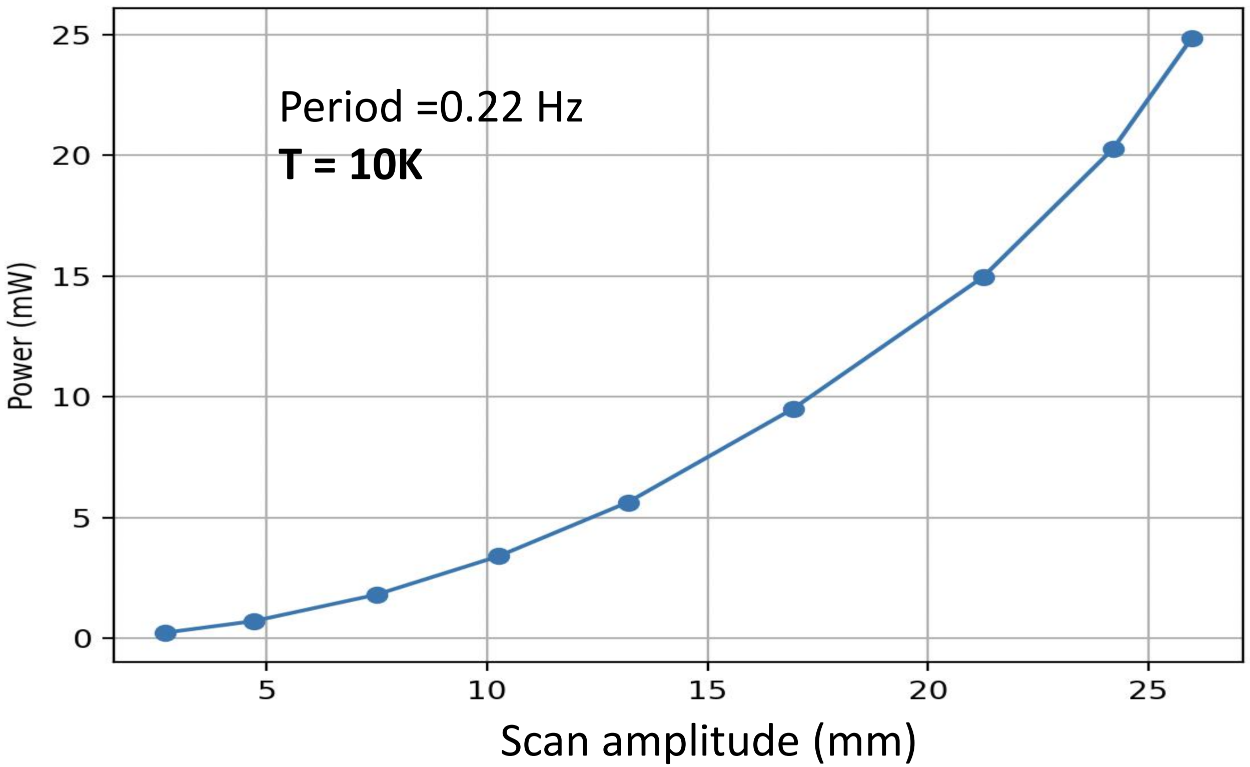


COSMO: Cryogenic Roof Mirror Transport Mechanism

- 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.
- Good measured performance (@room temperature and, recently, **at cryogenic temperature**)



Credits: E. Marchitelli

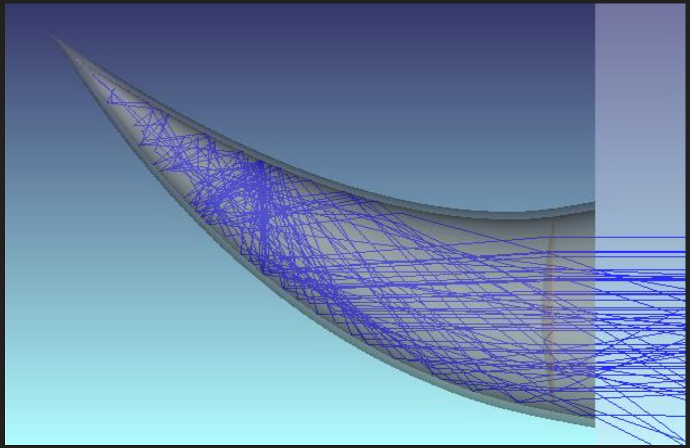


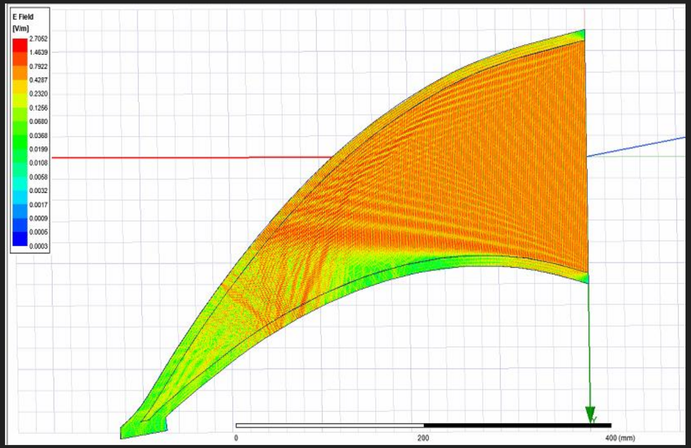
Credits: G. Barbieri Ripamonti, F. Columbro

COSMO: 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 and tested.

Credits: L.Mele, A. Capponi



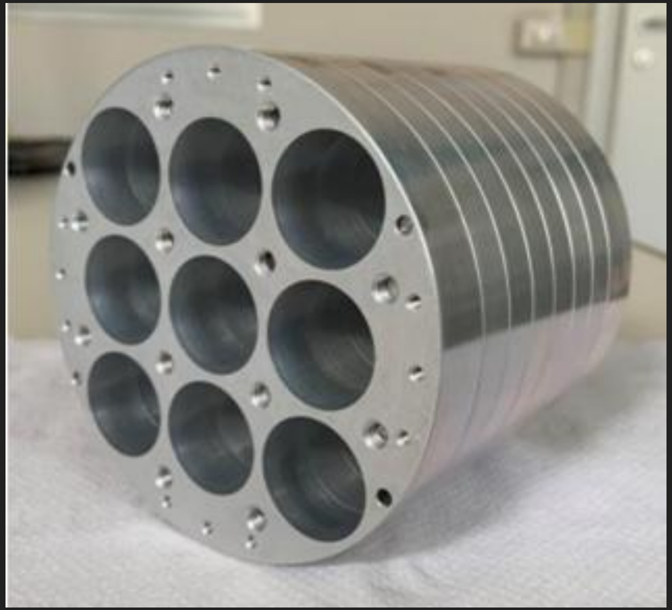


External Al mould

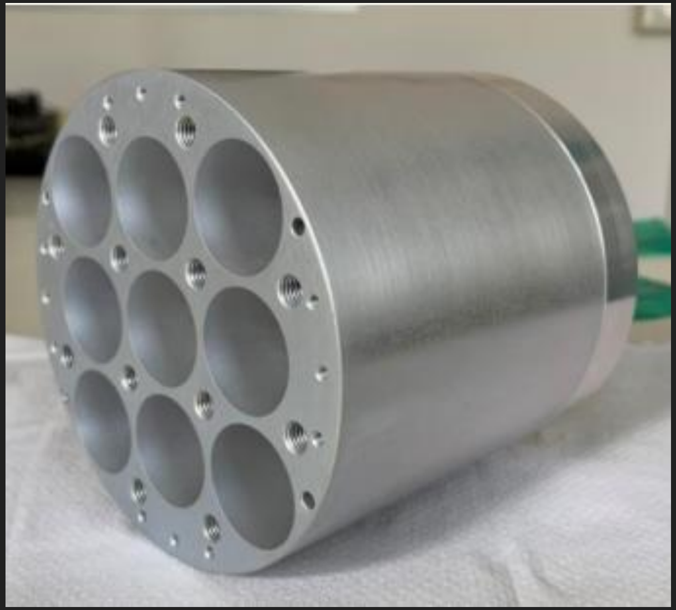
Teflon master mould to shape the absorbing coating

Feedhorns Arrays

- Multi-mode 3×3 horn antenna arrays, developed at UniMI (A. Mennella &) 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

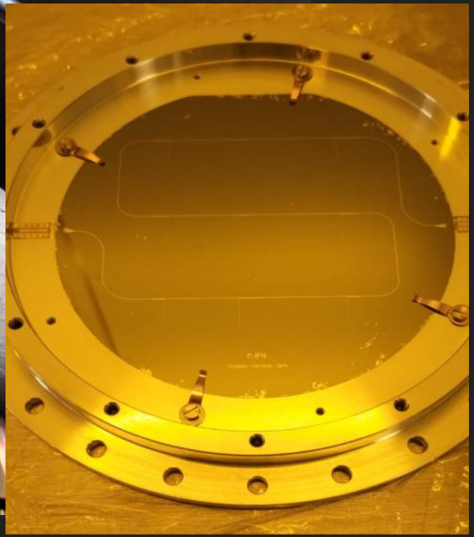


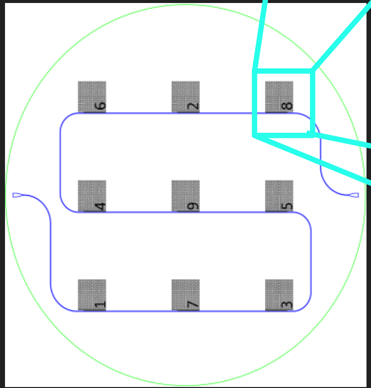
D. Mennella, E. Manzan, U. Milano

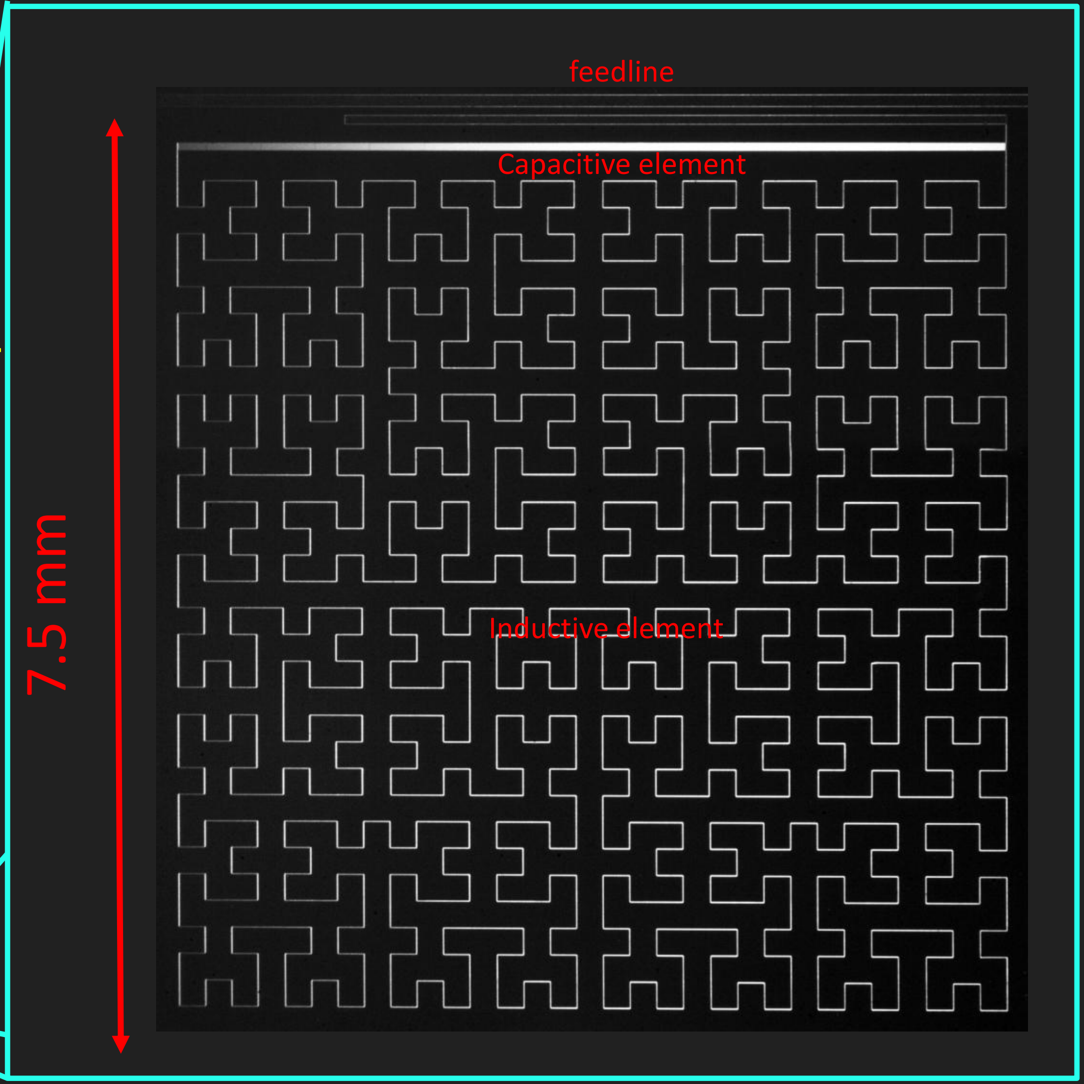


Kinetic Inductance Detector Arrays

- 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 (~1.5°FWHM)
- 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 (Paiella et al. 2019, Masi et al. 2019) and MISTRAL ones (Paiella et al. 2022).
- 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:



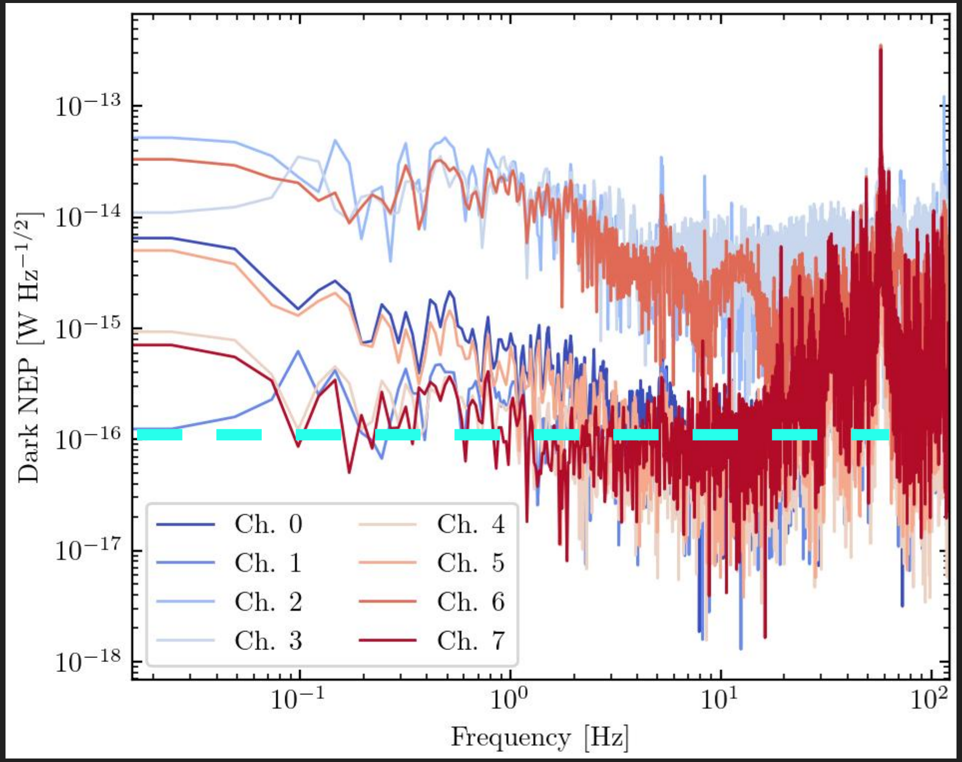


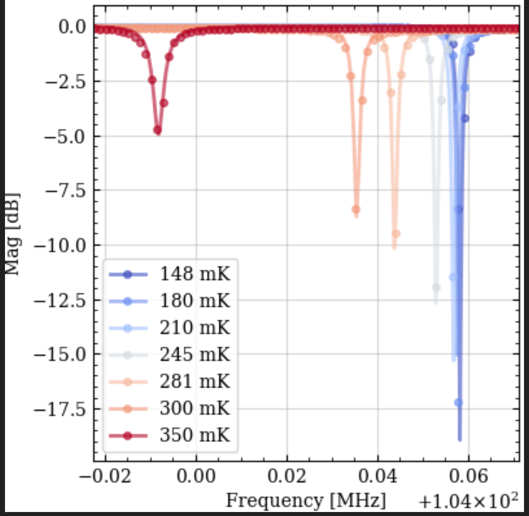


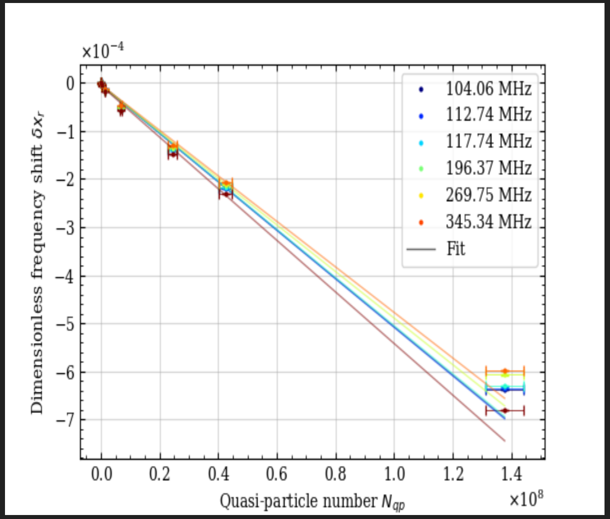
A. Credits: A. Paiella, F. Cacciotti, A. Capponi (Sapienza) G. Pettinari (IFN-CNR)

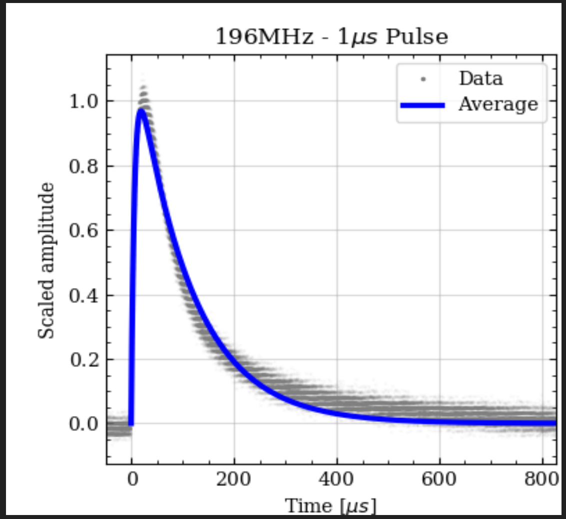
Kinetic Inductance Detector Arrays

- 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 (~1.5°FWHM)
- 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 (Paiella et al. 2019, Masi et al. 2019) and MISTRAL ones (Paiella et al. 2022).
- 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:



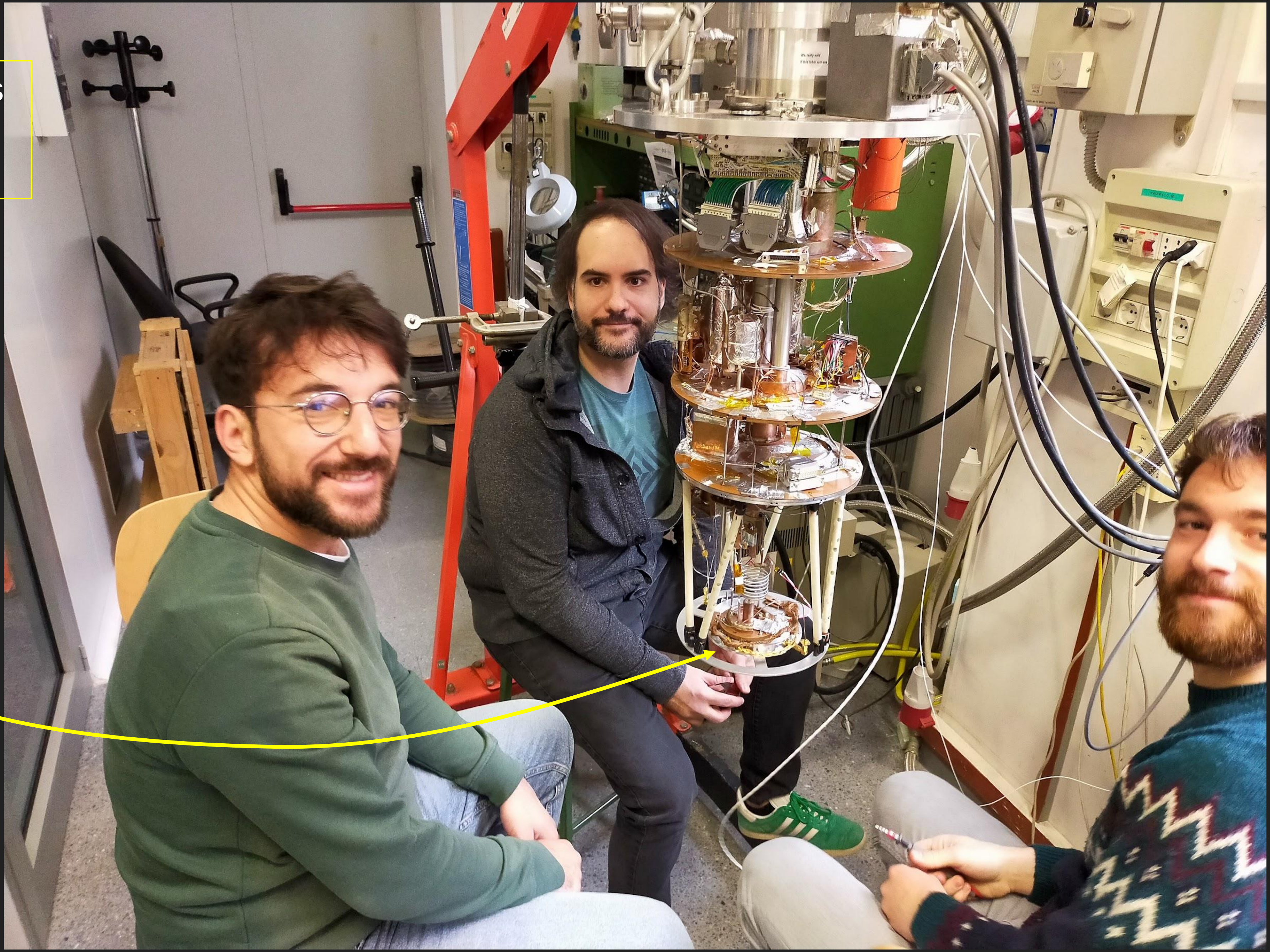






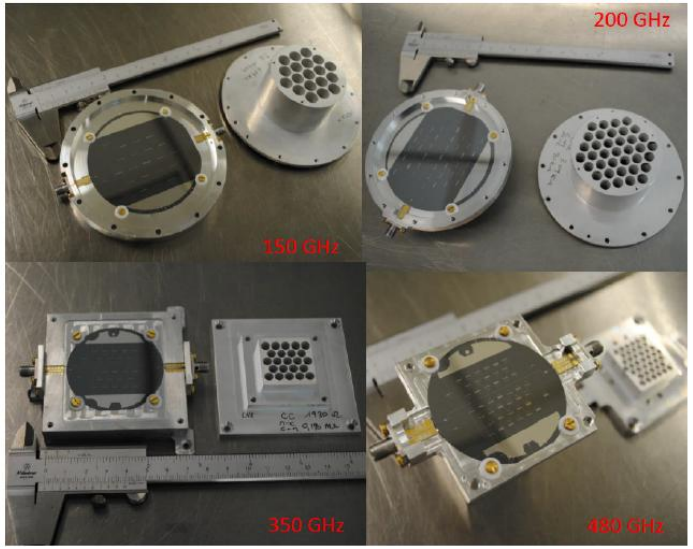
- Non-linearities and harmonics present, due to lumped condition not perfectly met.
- Average performance close or better than photon noise limit (depending on chosen resonance)

2nd gen. COSMO detectors under test as we speak (G31 lab)



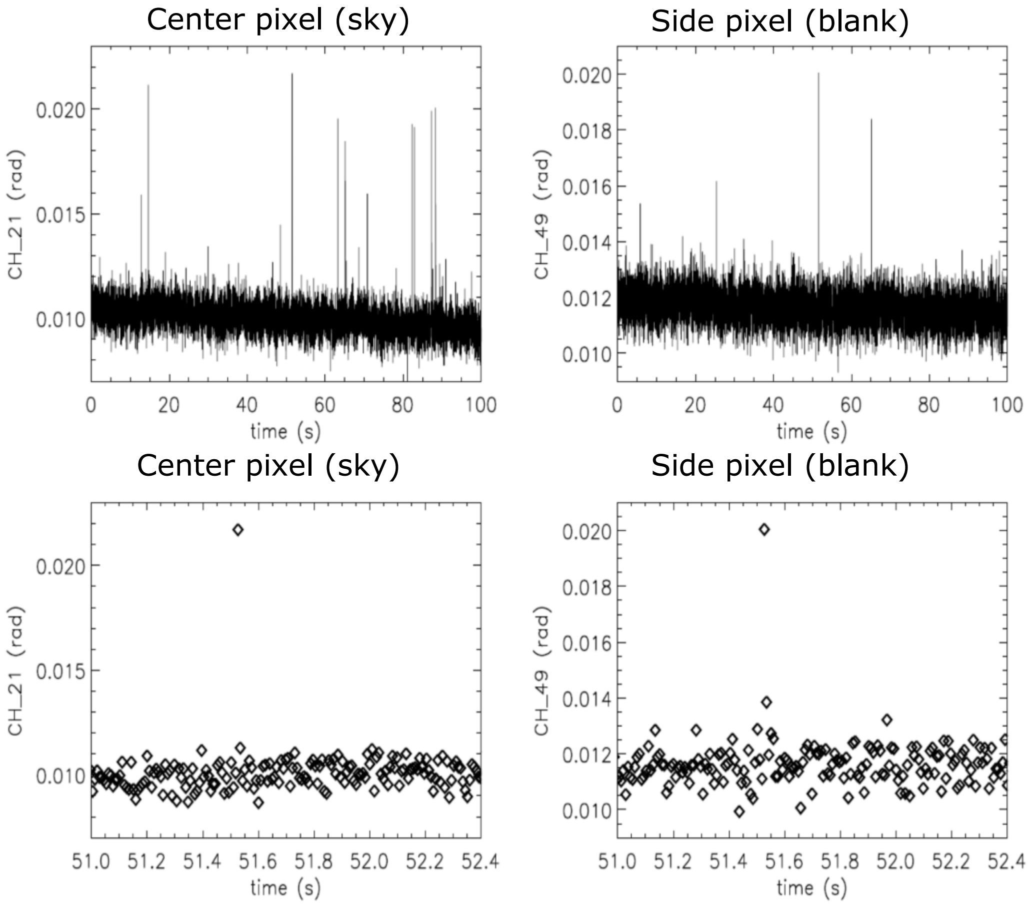
A. Capponi
A. Paiella
F. Cacciotti

Kinetic Inductance Detectors : in-flight performance



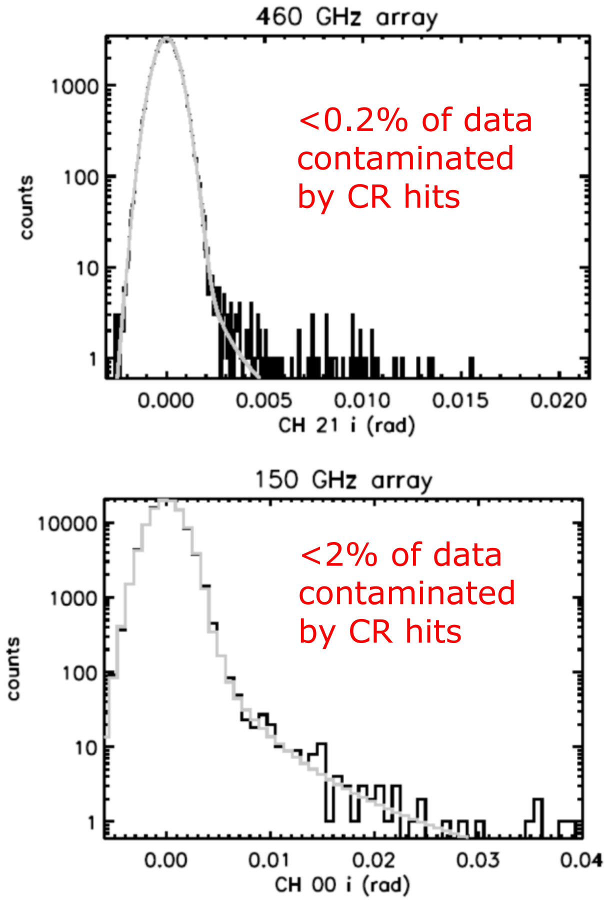
Response of KIDs to cosmic rays in the stratospheric environment – first test ever

Time ordered data



460 GHz array

Histograms

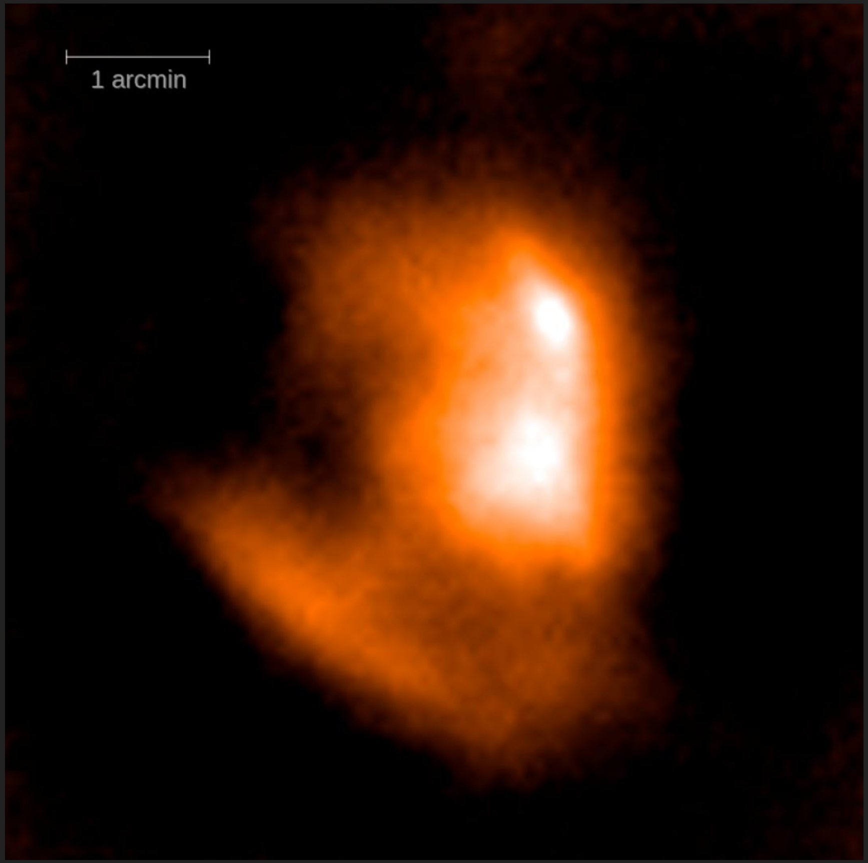


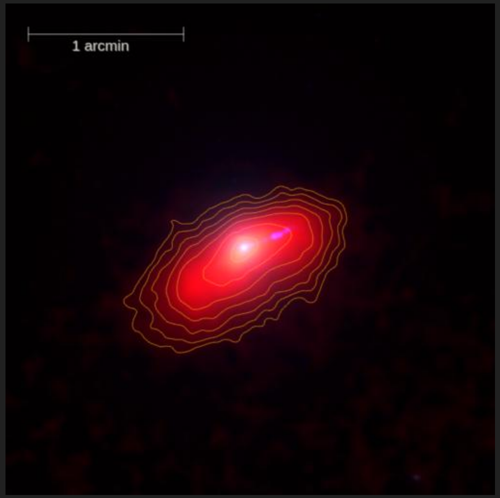
See Masi et al. JCAP 1907 (2019) arXiv:1902.08993

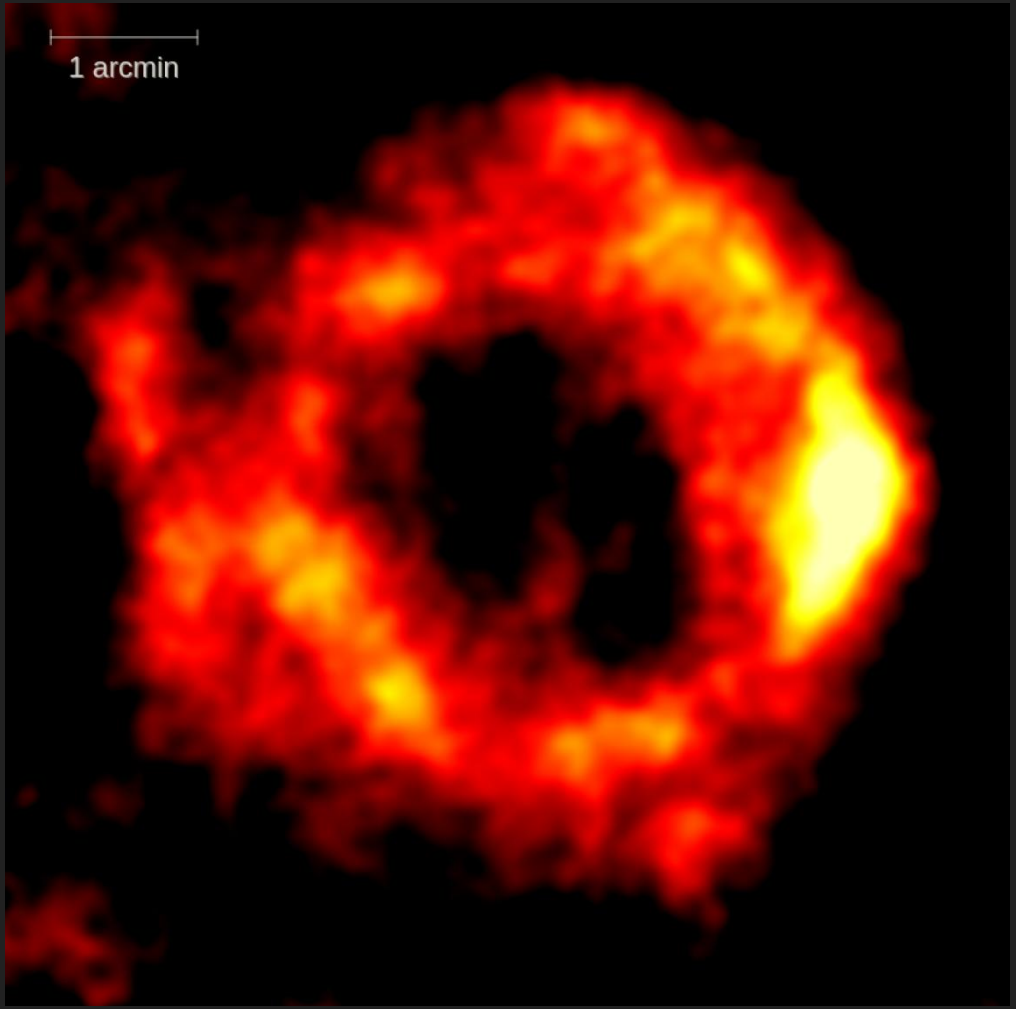
MISTRAL @ SRT

https://www.media.inaf.it/2025/05/29/mistral-ricevitore-osservazioni-srt/
https://www.phys.uniroma1.it/it/mistral-wind-change-srt-observations

90 GHz



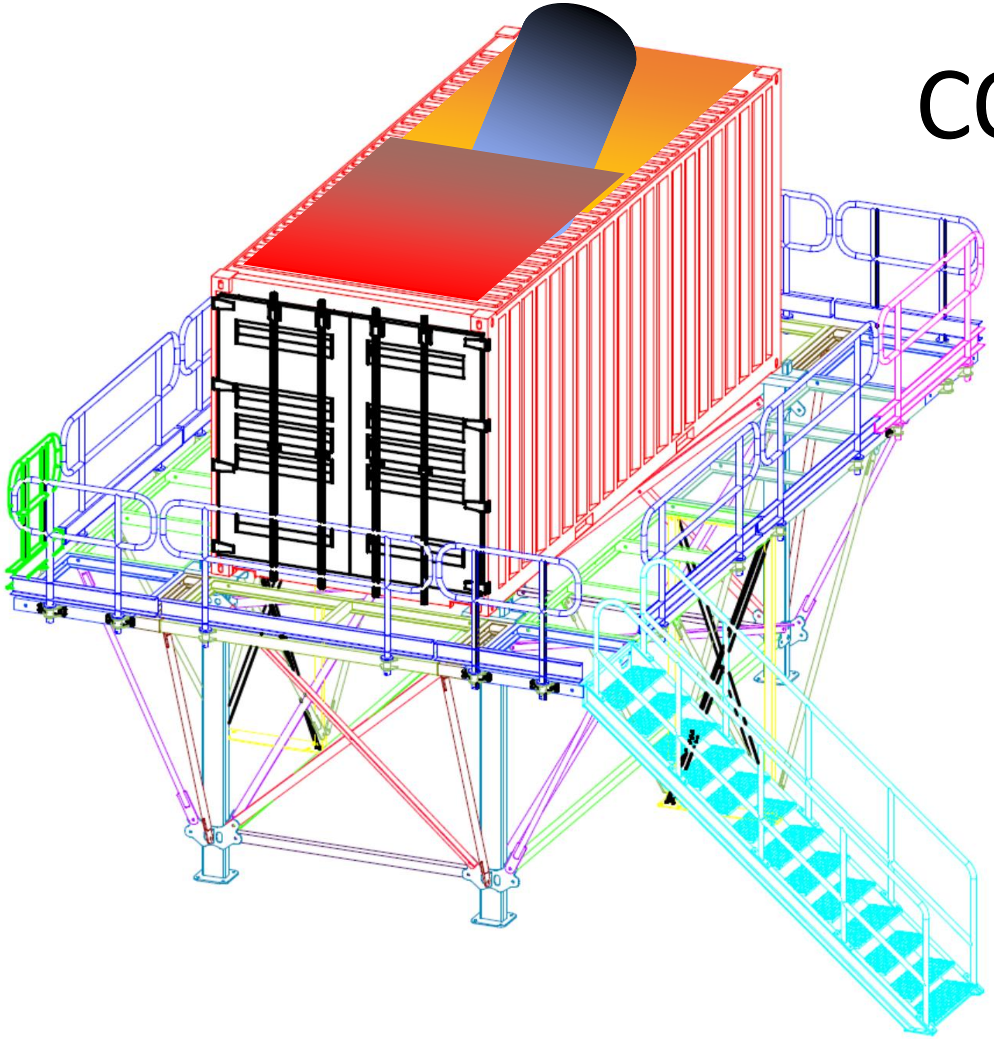




https://www.media.inaf.it/2025/05/29/mistral-ricevitore-osservazioni-srt/
https://www.phys.uniroma1.it/it/mistral-wind-change-srt-observations

We were recently funded by the "Italian Fund for Science" (FIS2, start 10/2025) to develop and test a "portable" version of the instrument.

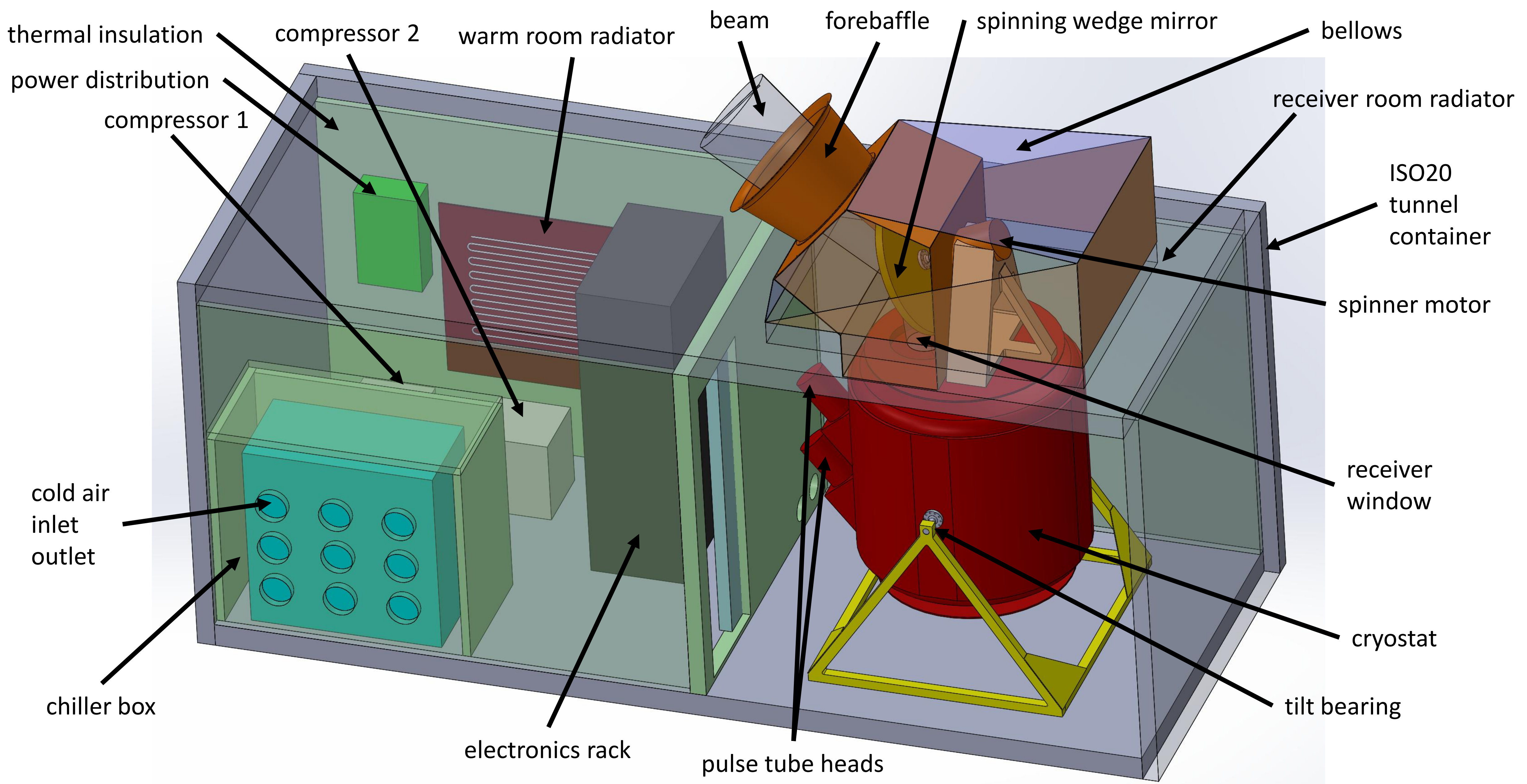
COSMO on-site implementation



- 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 – location of main components




Campo Imperatore Station
INAF, 2200 m, -20C
2026

Dome-C - Antarctica
PNRA-IPEV, 3200m, -80C
PNRA proposal recently approved.
2028-29 ?

Picture Credits: Marco Buttu

Short conclusions / issues to discuss:

- A phased development (high-mountain, antarctica, stratospheric balloon, space) allows us to optimize a very ambitious measurement. Such a program will take some time.
- Dome-C based measurements with COSMO at mm wavelengths will optimize:
  - Instrument HW:
    - Detector arrays
    - Filters stack, vacuum window
    - Sky scanner, cryogenic interferogram scanner
    - Blackbody reference
    - …
  - Sky measurement strategy (fast sky-dips vs slow interferogram scan, cosec-law atmospheric removal)
  - Calibration procedure ($\mathcal{R}A\Omega(\nu)$, two temperatures of internal reference, external reference vs internal, …)
  - Data analysis procedures (data cubes, apodization, resolution, components separation …)
- All that is complementing low frequency measurements like TMS …
- … is very useful in view of a forthcoming SD balloon-borne mission like BISOU, …
- … and can be sensitive enough to detect the largest SDs:
  - the high frequency tail of the "ARCADE excess"
  - the y-distortion due to post-recombination plasmas (reionization, LSS)
- As complimentary outcomes, COSMO will provide:
  - Full characterization of Dome-C as an astronomical site for millimeter-wave astronomy
  - Continuous monitoring of ozone concentrations and ultra-low levels of water vapor content in the Antarctic atmosphere during the winter: two original and environmentally important diagnostic tools.

Measurements based on two modulations (optical path difference + fast sky scan)

Optimal

sky scan fast		
circle radius	5	deg
circle length	31.4	deg
beam size	1	deg
number of samples per circle (3 per beam)	94	
time per beam	2.50E-04	s
time for 2 sky dips (downwards + upwards)	2.36E-02	s
wedge mirror rotation rate	2546	rpm
interferogram scan slow		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	6.032	s
interferograms per second	0.2	
mirror scan mechanism period	12.06	s
sky stability required for	6.03	s

Certainly Feasible

sky scan fast		
circle radius	5	deg
circle length	31.4	deg
beam size	0.5	deg
number of beams per circle	63	
time per beam	2.00E-04	s
time for 2 sky dips (downwards + upwards)	1.00E-01	s
wedge mirror rotation rate	600	rpm
interferogram scan slow		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	25.600	s
interferograms per second	0.0	
mirror scan mechanism period	51.20	s
sky stability required for	25.60	s