# Spectral Distortions of the Cosmic Microwave Background: the COSMO Experiment

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**G31 Experimental Cosmology Group**

**Retreat della Sezione INFN di Roma**
**14/06/2022**

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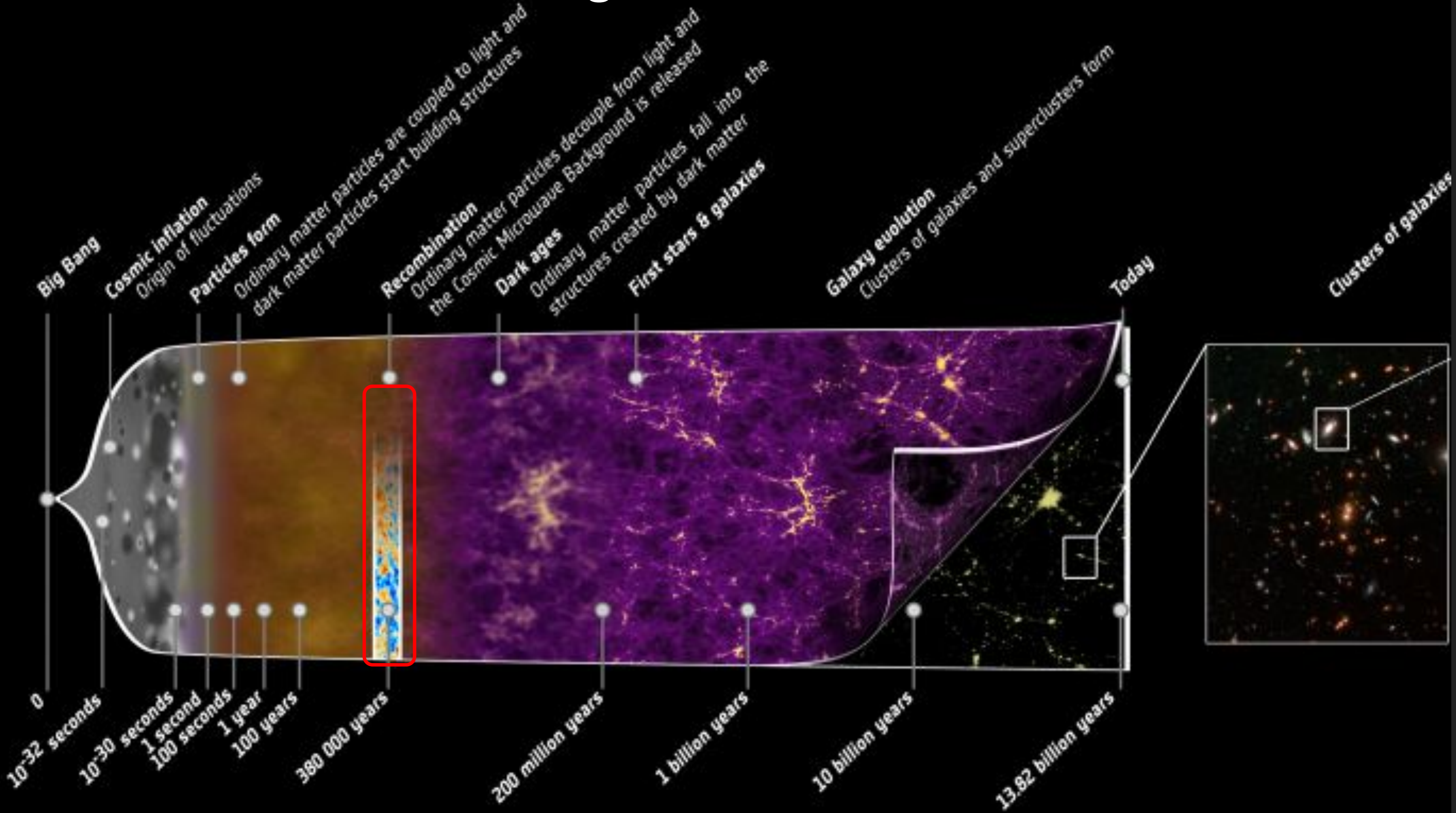
# The Cosmic Microwave Background



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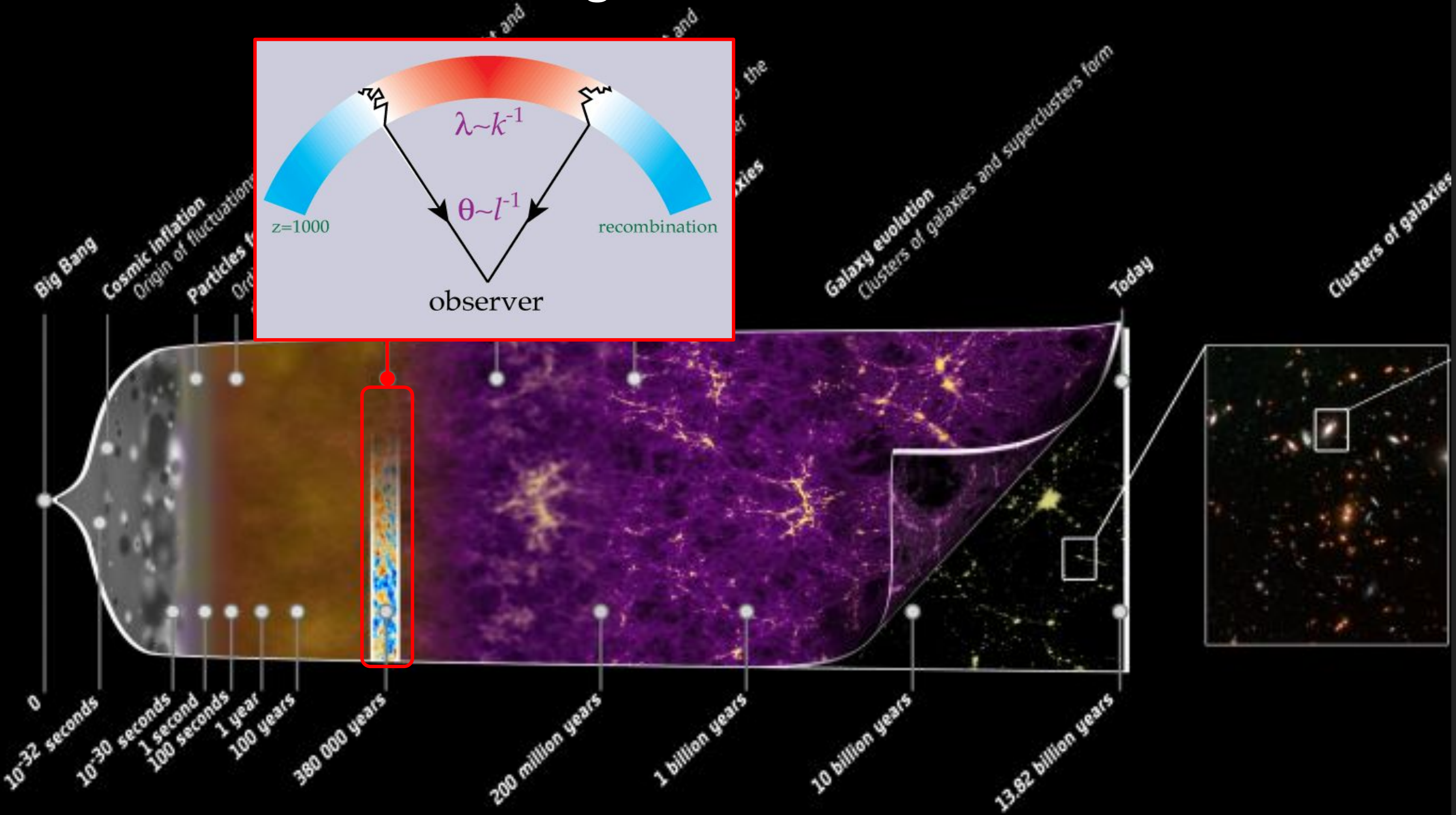

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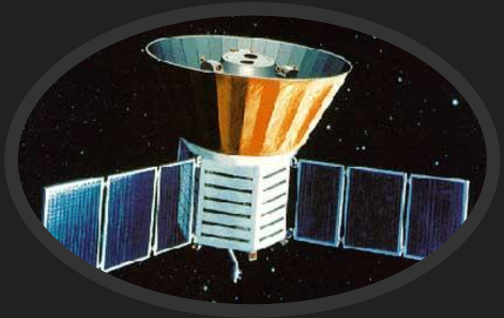
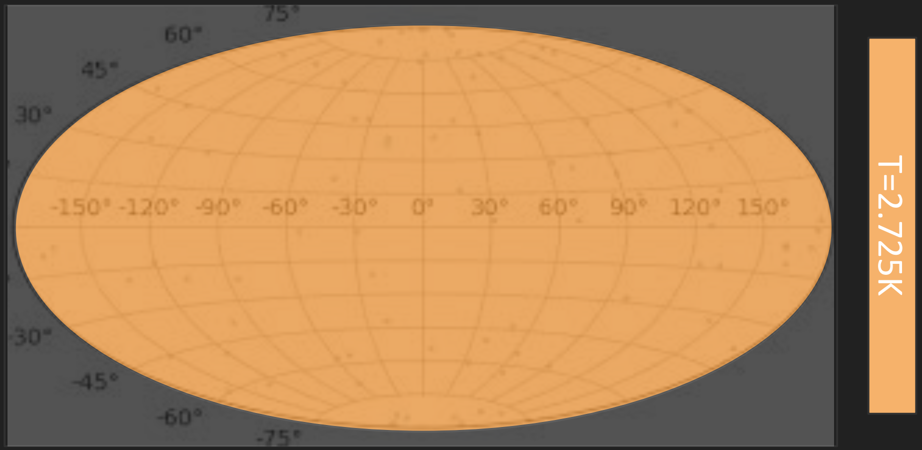
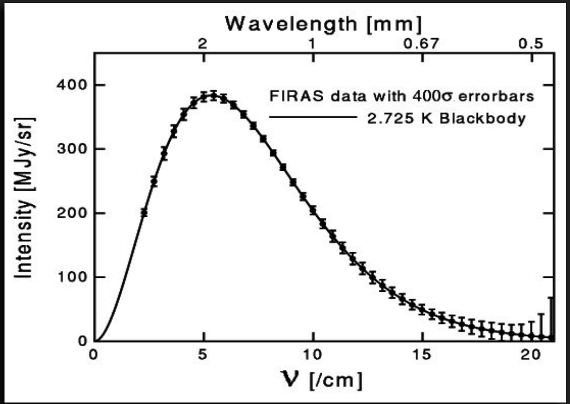
A direct look at the early-Universe (at Recombination phase, 380000 years after the Big Bang):

- Almost a perfect blackbody at T=2.725K
- Temperature Anisotropies ΔT/T= $10^{-5}$



**COsmic Background Explorer (COBE, 1989)**
**Far InfraRed Absolute Spectrometer (FIRAS)**
**&**
**Differential Microwave Radiometer (DMR)**



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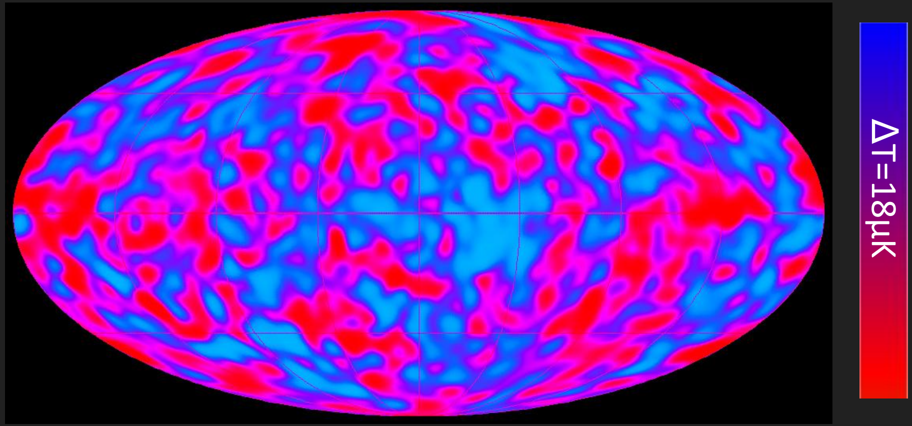


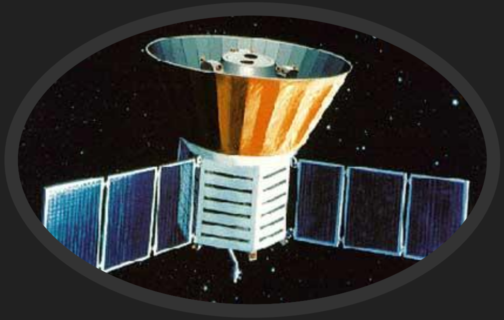

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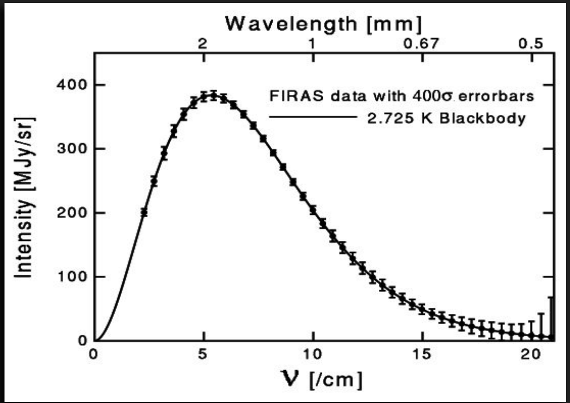

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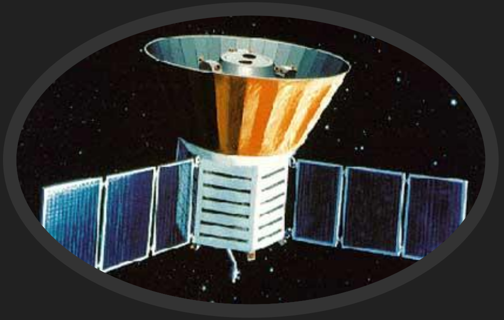
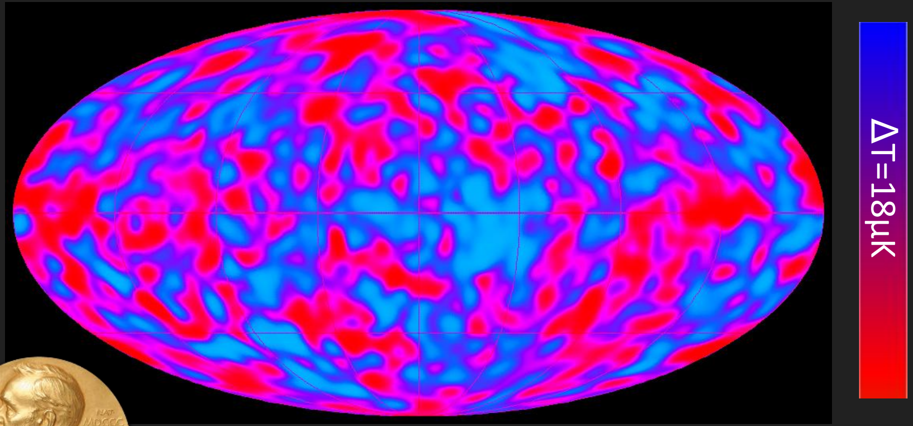
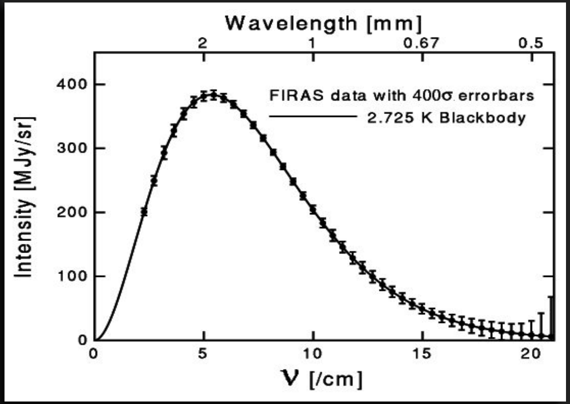





**Nobel Prize**
in Physics
2006

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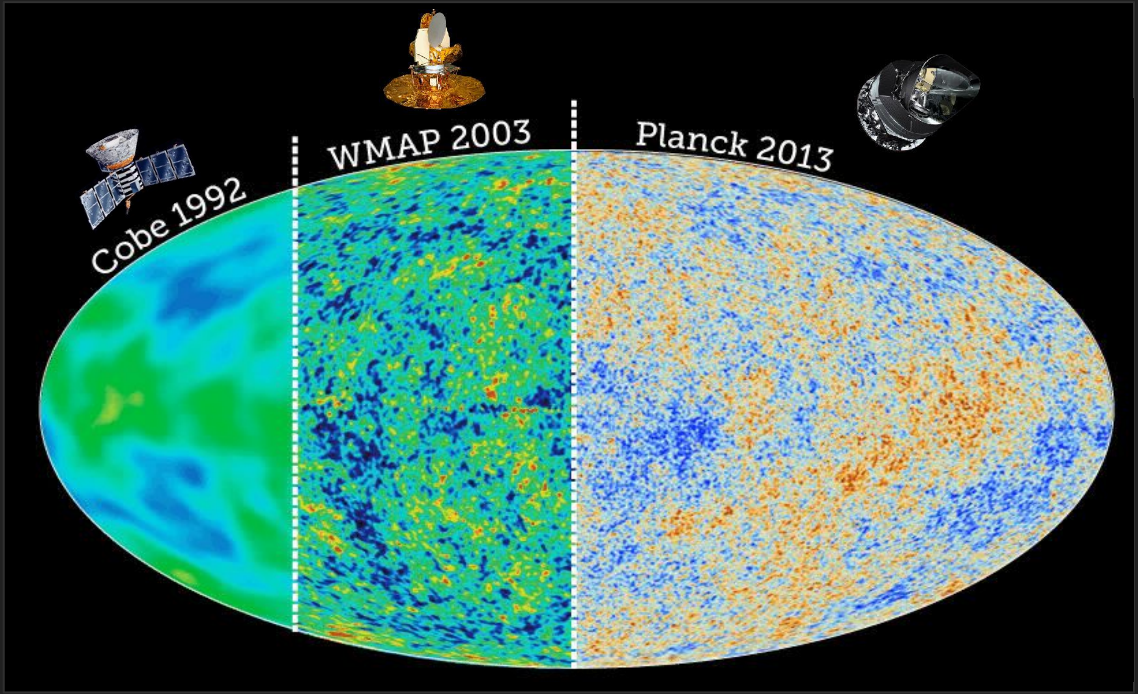
| | | |
|---|---|---|
| COBE | 7° | [31.5, 53, 90 ]GHz |
| WMAP | 0.25° | [22,30,40, 60,90]GHz |
| Planck | 0.08°-0.16° | [30, 44, 70, 100, 143, 217, 353, 545, 857] GHz |



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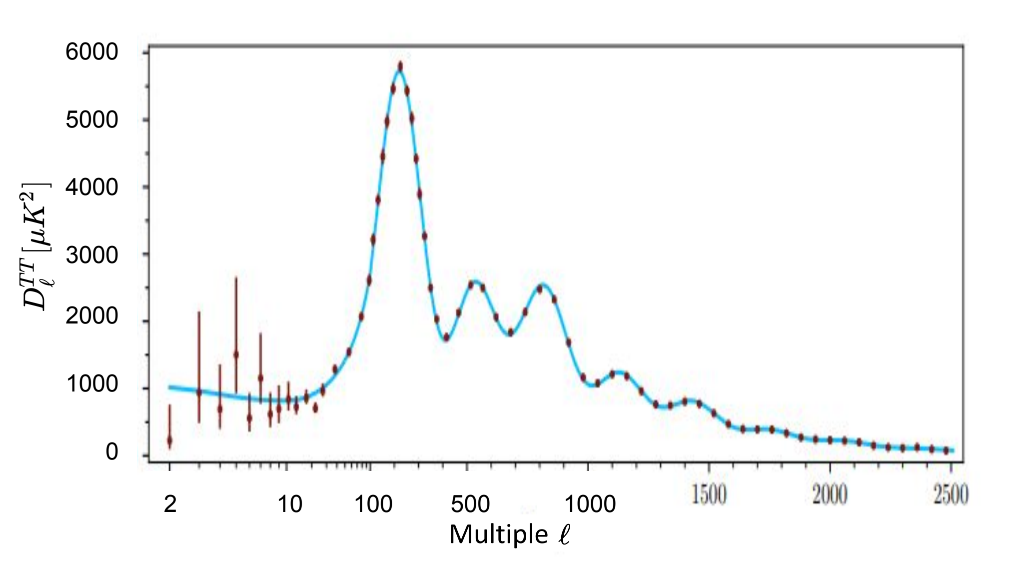
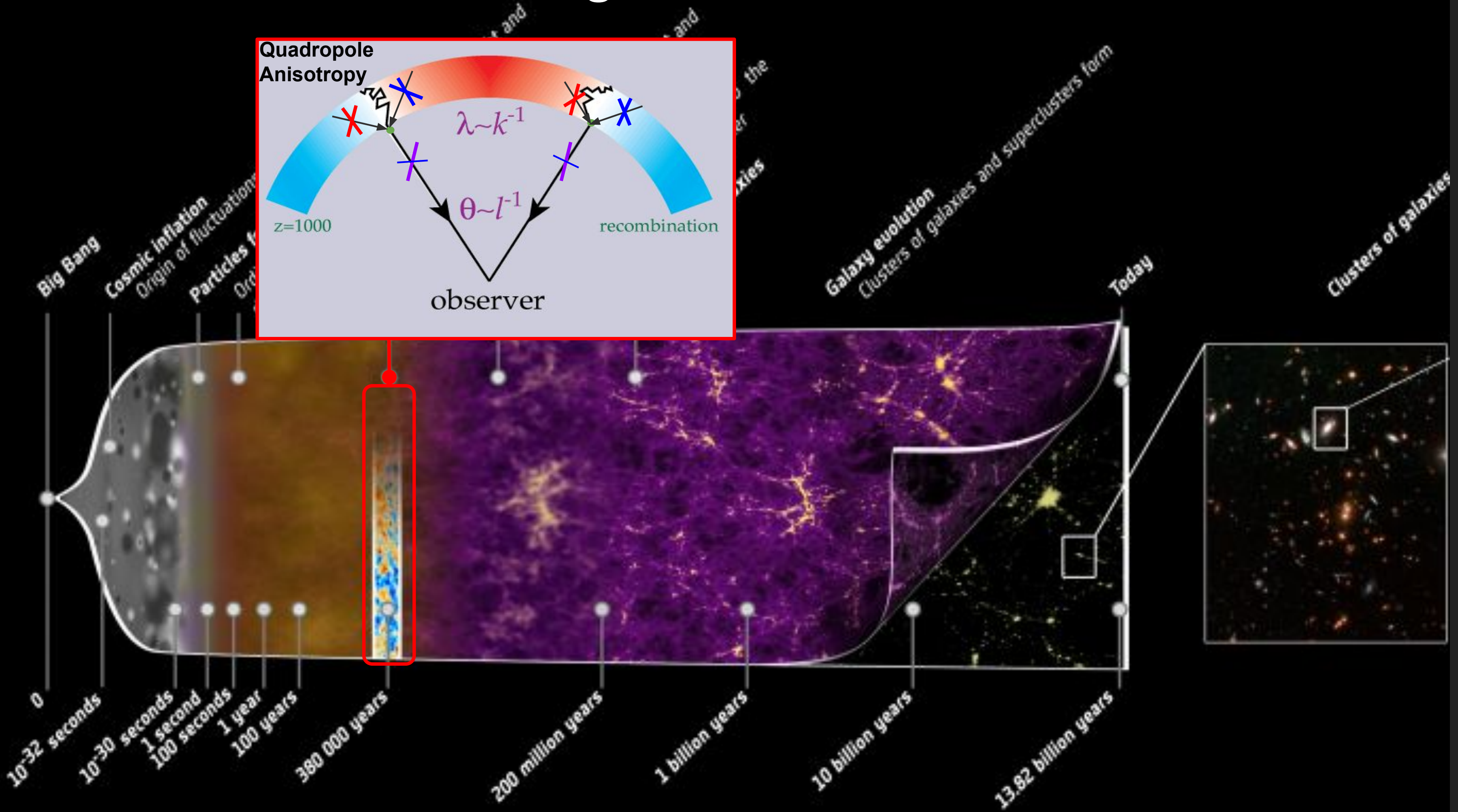
| Parameter | *Planck* alone |
|---|---|
| $\Omega_b h^2$ | 0.022383 |
| $\Omega_c h^2$ | 0.12011 |
| $100\theta_{MC}$ | 1.040909 |
| $\tau$ | 0.0543 |
| $\ln(10^{10} A_s)$ | 3.0448 |
| $n_s$ | 0.96605 |
| $H_0$ [km s$^{-1}$Mpc$^{-1}$] | 67.32 |
| $\Omega_\Lambda$ | 0.6842 |
| $\Omega_m$ | 0.3158 |
| $\Omega_m h^2$ | 0.1431 |
| $\Omega_m h^3$ | 0.0964 |
| $\sigma_8$ | 0.8120 |
| $\sigma_8(\Omega_m/0.3)^{0.5}$ | 0.8331 |
| $z_{re}$ | 7.68 |
| Age [Gyr] | 13.7971 |

ΛCDM fundamental parameters




*Planck Collaboration: Planck 2018 results. I.*

# The Cosmic Microwave Background



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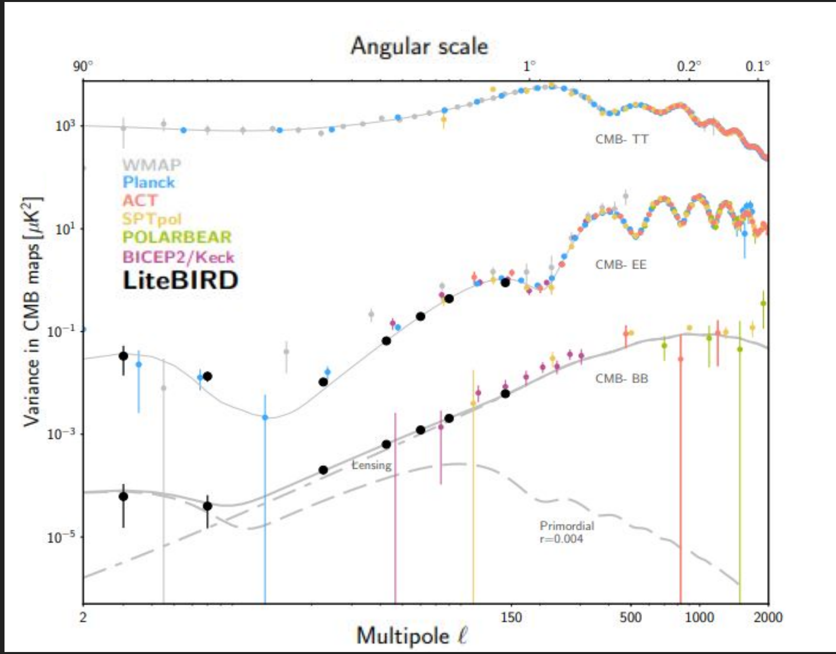
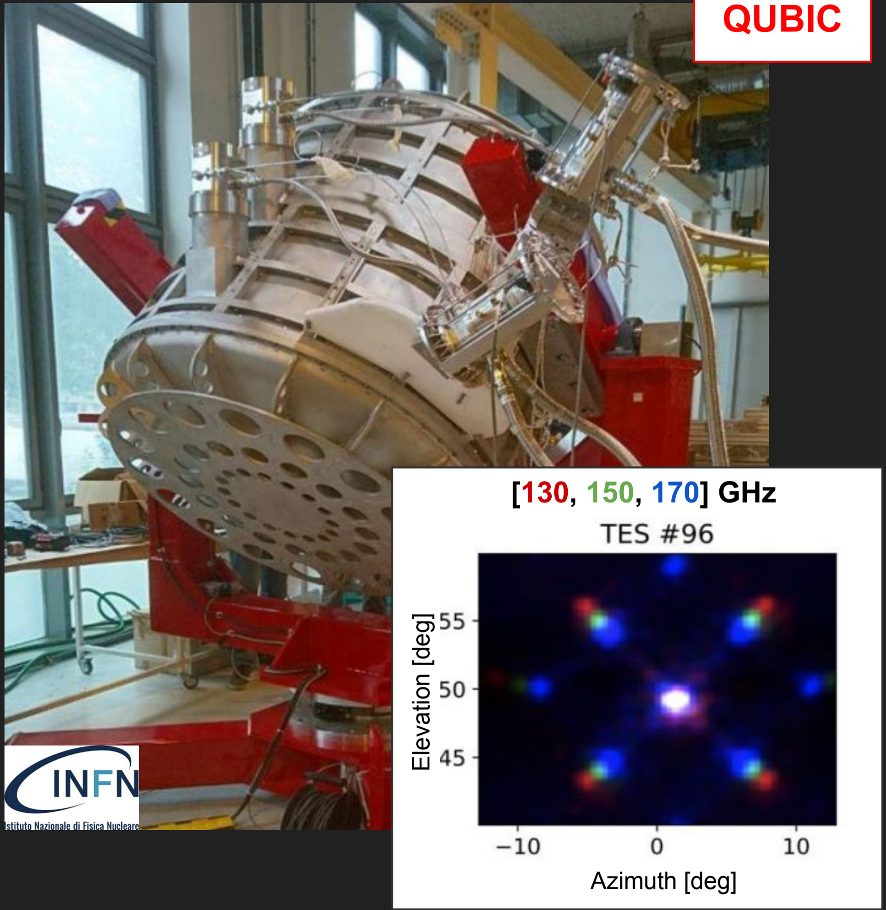
- Almost a perfect blackbody at T=2.725K
- Temperature Anisotropies ΔT/T= $10^{-5}$
- Polarized signal from anisotropic Thomson scattering with free electrons (quadrupole anisotropies)
- The polarization pattern in the sky can be decomposed into 2 components
- Curl-free component (E-mode) principally generated by density fluctuation
- Grad-free component (B-mode) principally generated by primordial gravitational waves
- CMB B-modes as indirect probe for an early *cosmic inflation*

Tensor-to-scalar ratio r < 0.032 (95% C.L.) (M. Tristram et al. 2021, combining Bicep2/Keck 2018 and Planck PR4 data set)

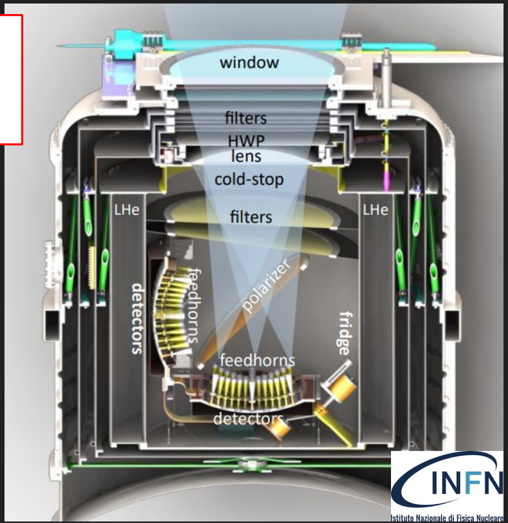


# The Cosmic Microwave Background

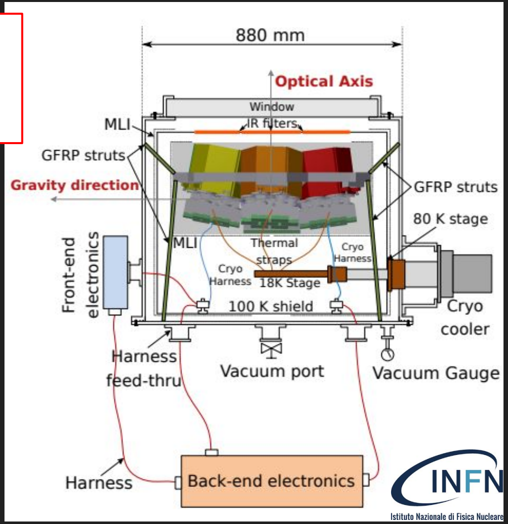
**QUBIC**




**LSPE SWIPE**



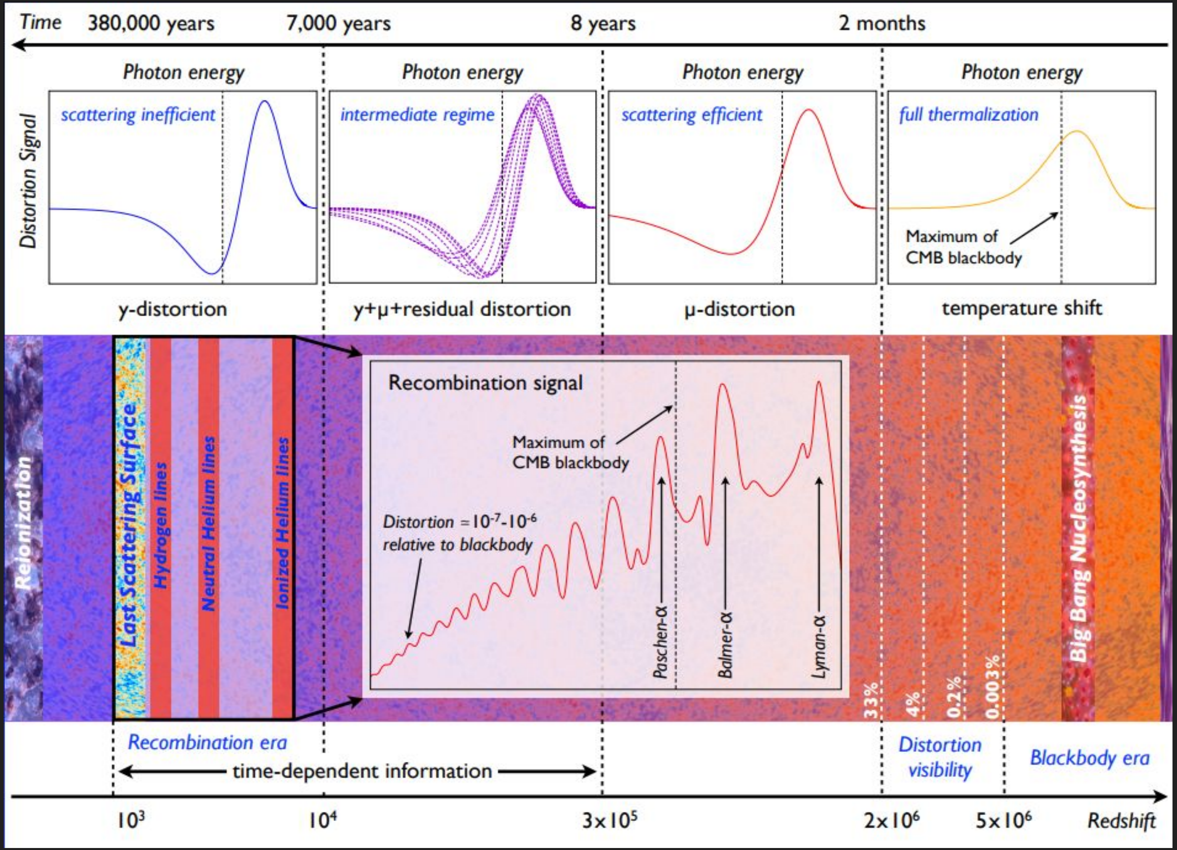

**LSPE STRIP**



# CMB Spectral Distortions

Departures from the blackbody shape are predicted by the current cosmological model (energy injection/ extraction or photon production/ destruction):

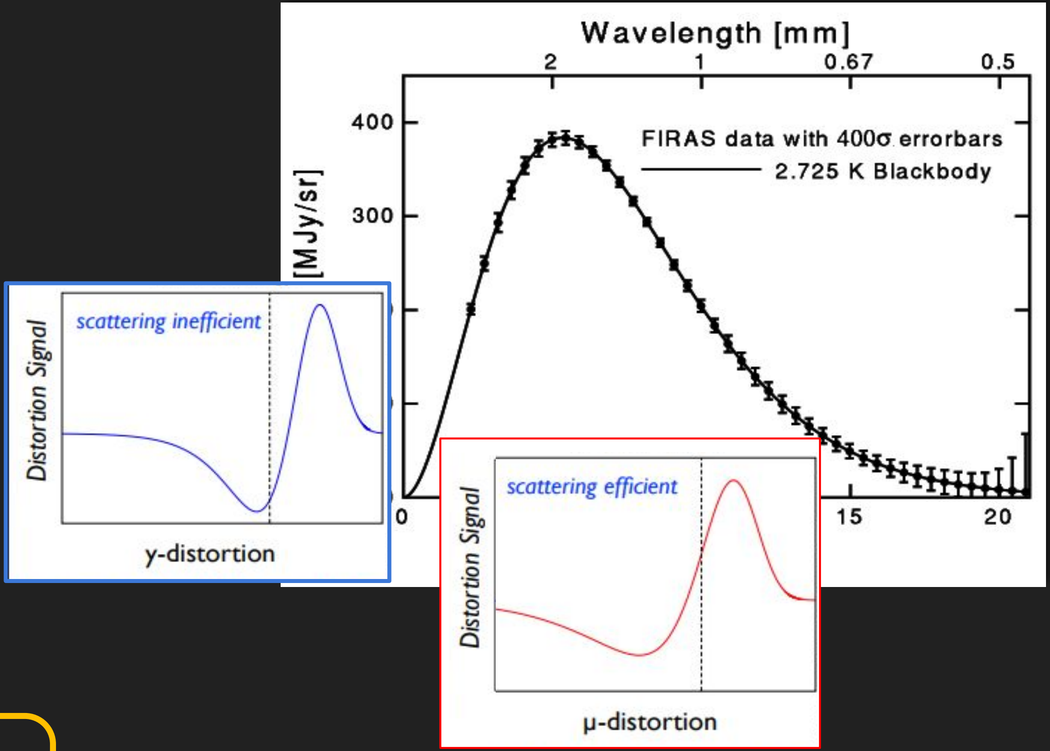
- New tests of particle/dark matter physics
- Signals from the reionization and recombination eras
- Complementarity and synergy with CMB anisotropy studies



# CMB Spectral Distortions

Departures from the blackbody shape are predicted by the current cosmological model (energy injection/ extraction or photon production/ destruction):

- Reionization
- Structure formation shocks
- Adiabatic cooling of baryons
- Damping of small-scale fluctuations
- Sunyeav-Zel'dovich effect (anisotropic)
- Cold dark matter annihilation
- Cosmological recombination radiation
- Particles decay




**Spectral Distortions carry complementary information about processes in the early-Universe!**

But also about fundamental physics!

# CMB Spectral Distortions

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| Experiment | Instrument Concept | Distortion Measurement |
|---|---|---|
| COBE-FIRAS | Satellite (1989) Interferometer 30-2910GHz Δν=13.6GHz | $\|y\| < 1.5 \cdot 10^{-5}$ (95% C.L.)<br>$\|\mu\| < 9 \cdot 10^{-5}$ (95% C.L.) |
| ARCADE-II | Balloon (2006) Absolute radiometers [3,5,8,10]GHz | $\|\mu\| < 6 \cdot 10^{-5}$ (95% C.L.) |
| TRIS | Ground (2008) Absolute radiometers [0.6,0.8,2.4]GHz | $\|\mu\| < 6 \cdot 10^{-5}$ (95% C.L.) |
| TMS | Ground (2022) Interferometer 10-20GHz Δν=250MHz | - |
| **COSMO** | Ground (2023) Interferometer 150-250GHz bands Δν=5GHz | - |
| APSERa | Ground Radio receivers 2-6GHz | - |
| BISOU | Balloon (2026) Interferometer 60-600GHz Δν=15GHz | - |

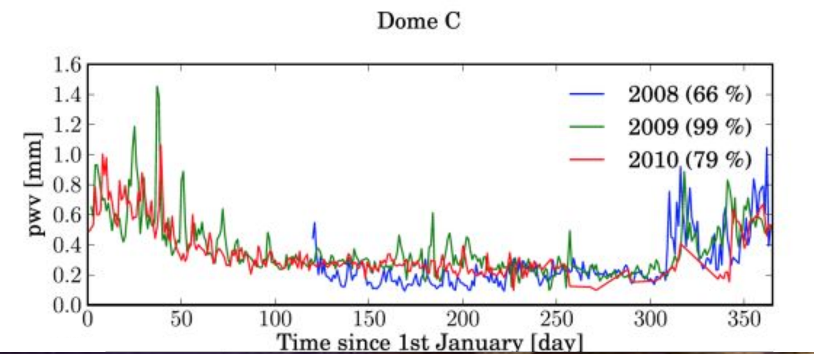
# The COSmic Monopole Observer

- PI: Silvia Masi
- Webpage: http://cosmo.roma1.infn.it/
- Pathfinder experiment to observe the isotropic y-distortion
- Martin-Puplett Interferometer (MPI) to measure the difference between the sky brightness and a reference internal blackbody calibrator
- Two arrays of fast (τ~60μs, NEP~3.8 · $10^{-17} W/\ Hz$) Multi-mode Kinetic Inductance Detectors (KIDs)
- KIDs coupled with the MPI output with multi-mode horn arrays
- Frequency coverage [125-280]GHz - Δν ≥ 5GHz
- Fast sky modulation with a rotating wedge-mirror, data collection at different elevations in a single interferogram

# The COSmic Monopole Observer

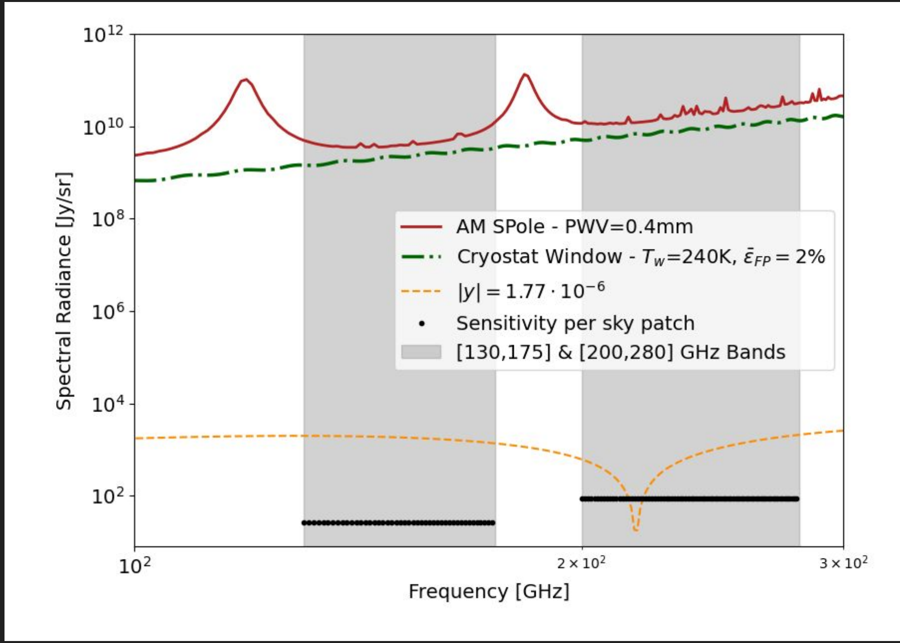
- COSMO will operate from the French-Italian base Concordia in Antarctica, one of the best logistically supported sites on Earth for CMB measurements

- Water Vapour Content <0.4mm PWV (~75% of the time) and an average of 210μm PVW in the winter season (*Tremblin et al. A&A, 2011*)



# The COSmic Monopole Observer

- Still have to cope with atmospheric emission and its fluctuations to remove the dominant contribution to the measurements
- Fast KIDs detectors and fast elevation scans are required to separate the atmospheric emission from the monopole of the sky brightness
- The fast spinning wedge (~1000r.p.m.) mirror modulates the elevation while scanning the interferogram
- Scanning the sky at different elevations we can interpolate the signal per spectral bin at null air-mass, that is the sky brightness



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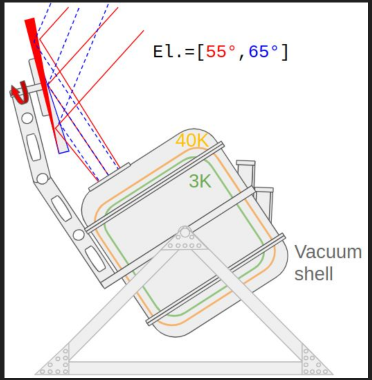


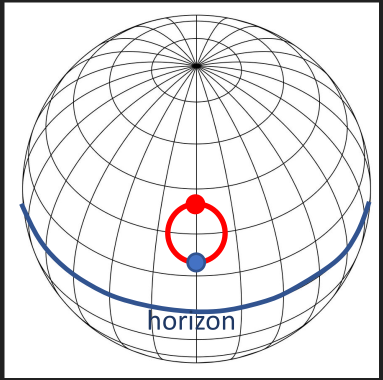


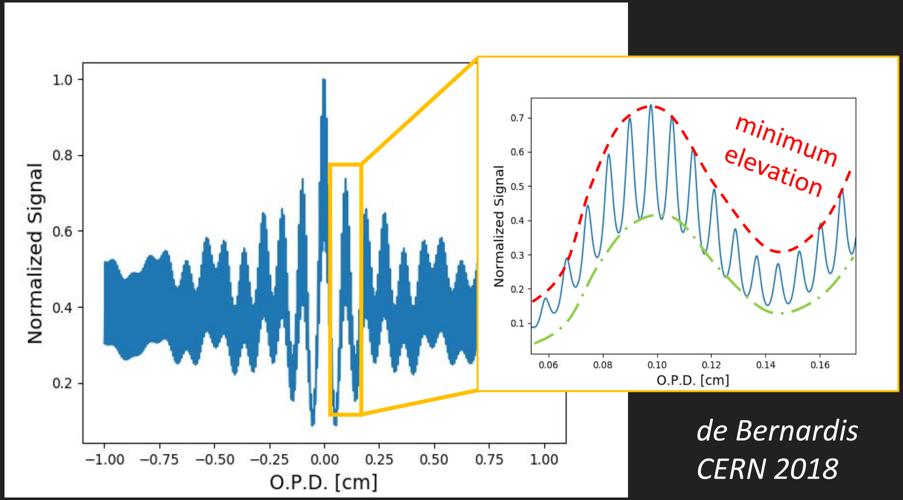


*de Bernardis CERN 2018*

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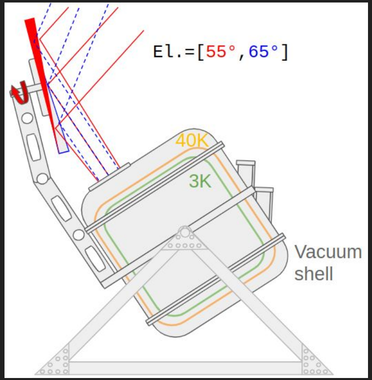
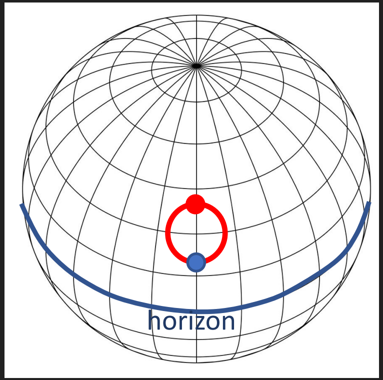
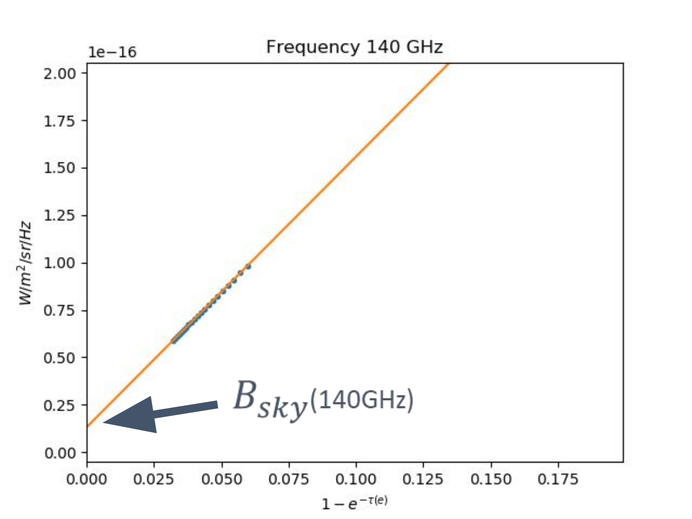
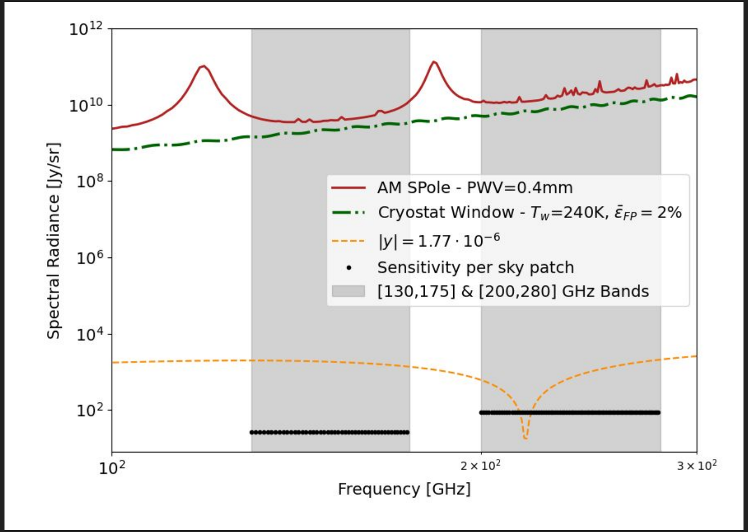


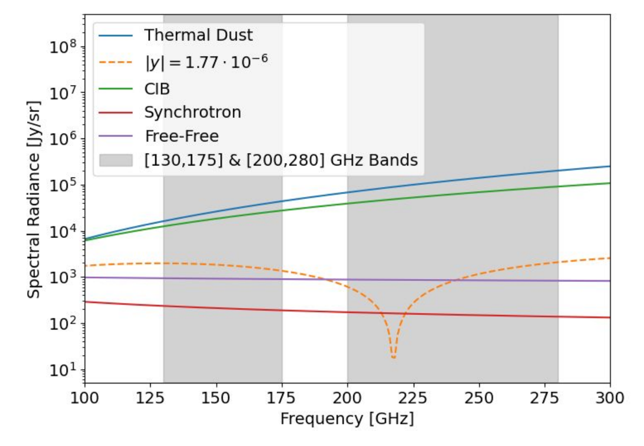



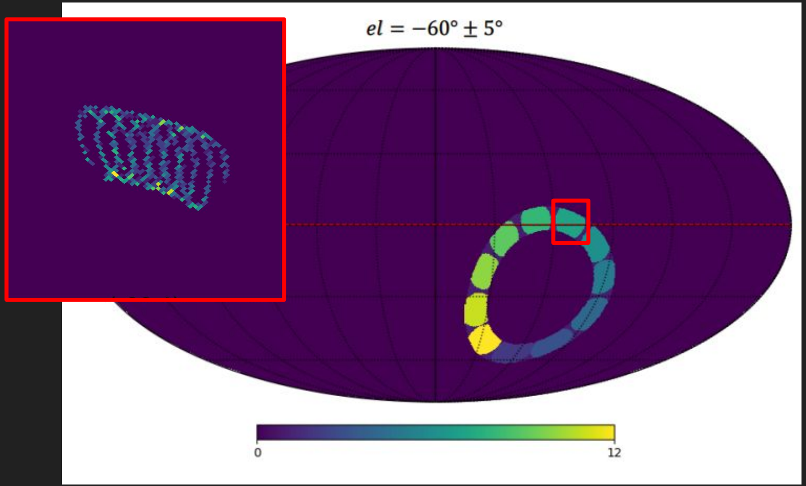



# The COSmic Monopole Observer

- 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



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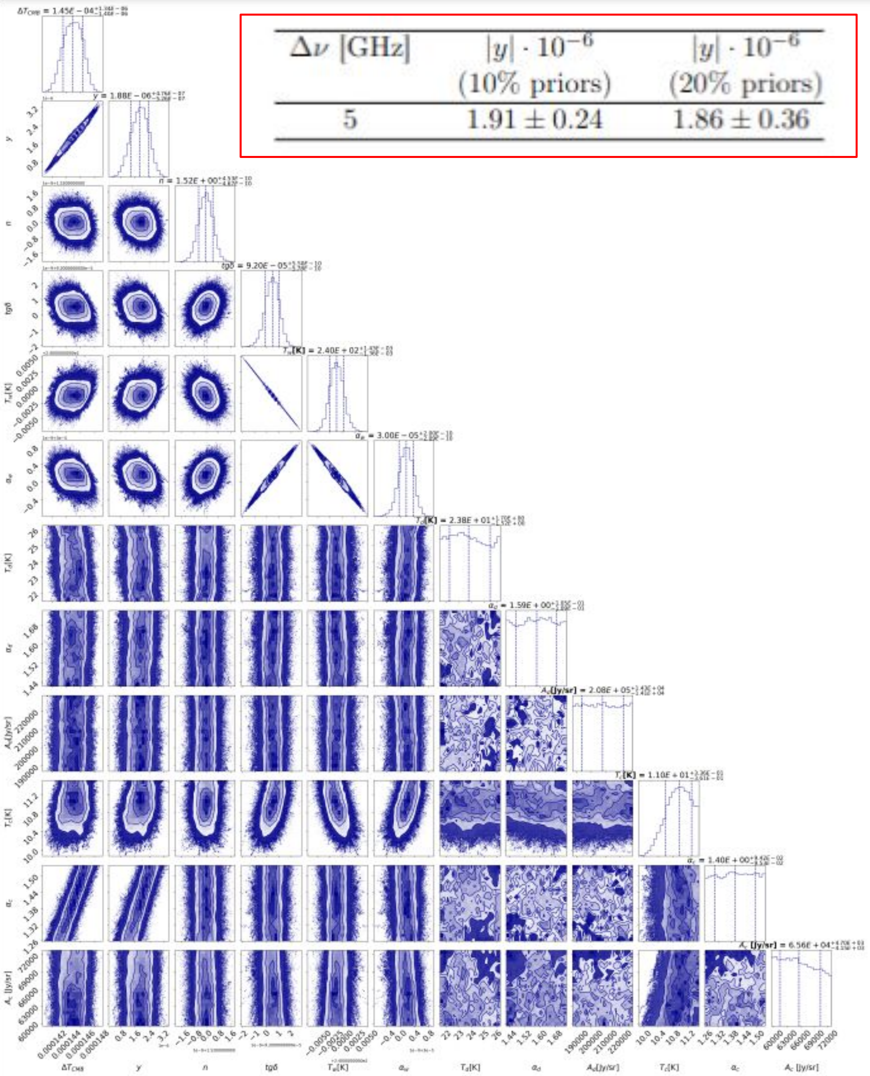
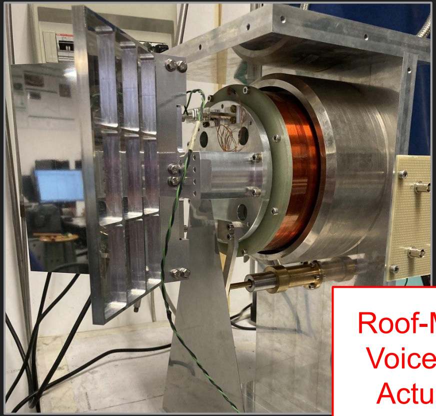
| Sky patch # | $\|y\| \cdot 10^{-6}$ (10% priors on CIB and Dust) | $\|y\| \cdot 10^{-6}$ (20% priors on CIB and Dust) |
|---|---|---|
| 1 | $1.96 \pm 0.57$ | $1.99 \pm 0.88$ |
| 2 | $1.88 \pm 0.62$ | $1.59 \pm 0.83$ |
| 3 | $2.16 \pm 0.77$ | $1.95 \pm 0.87$ |
| 4 | $2.19 \pm 2.36$ | $2.62 \pm 1.87$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

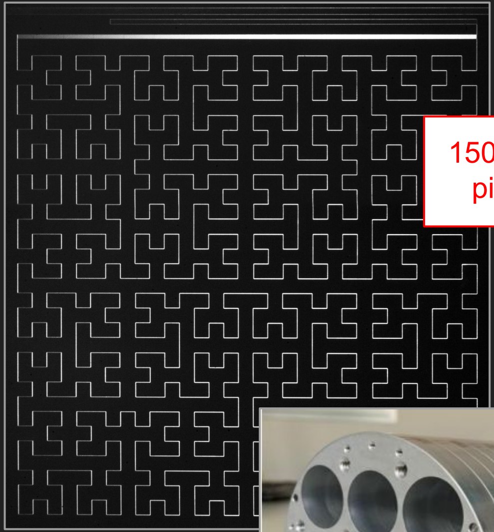


| $\Delta\nu$ [GHz] | $\|y\| \cdot 10^{-6}$ (10% priors) | $\|y\| \cdot 10^{-6}$ (20% priors) |
|---|---|---|
| 5 | $1.91 \pm 0.24$ | $1.86 \pm 0.36$ |

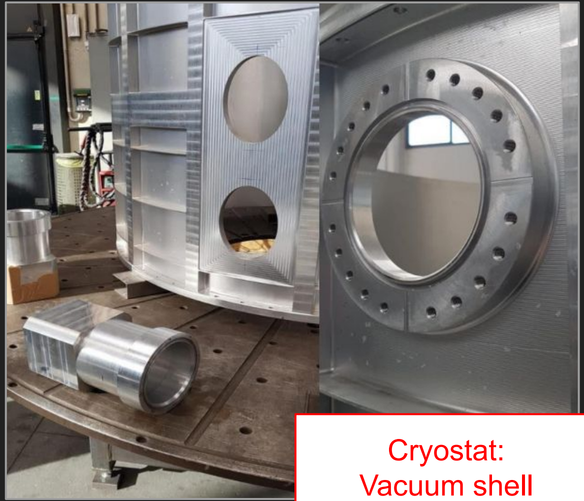
# The COSmic Monopole Observer



Roof-Mirror Voice Coil Actuator

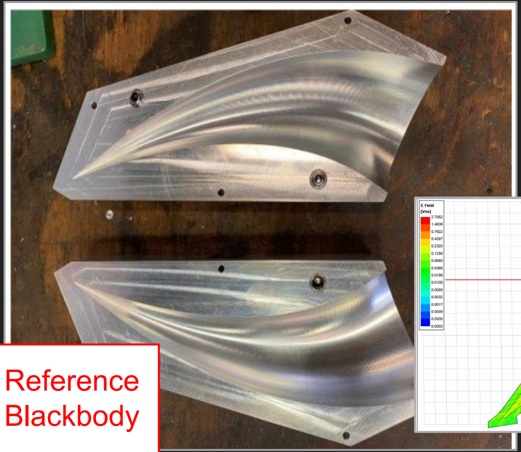


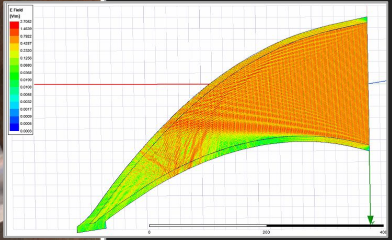
150GHz pixel



Cryostat: Vacuum shell Intermediate 40K, 4K shields

150GHz horn array





Reference Blackbody

# Conclusions

- Measurements of CMB spectral distortions represent an independent source of information about processes in the Universe, complementary to CMB temperature and polarization anisotropies

- Representing also a window to the early-Universe physics, interaction with dark matter particles, particle decays, ...

- The ground-based version of the COSMO experiment can provide a detection of the largest isotropic y-distortion (related to post-recombination era), with a S2N~5 assuming 1 year of observation and assuming to be dominated by the photon noise of the main sources from the sky and from the instrument

- The future balloon-borne version of COSMO will provide further constraints on CMB spectral distortions related to the pre-recombination era

# Backup

# The COSmic Monopole Observer

Cryostat:

- Vacuum shell (1.4m x 1.55m)

- 40K and 4K intermediate stages as thermal shields
- Cooled down by two Pulse Tubes (PTs)

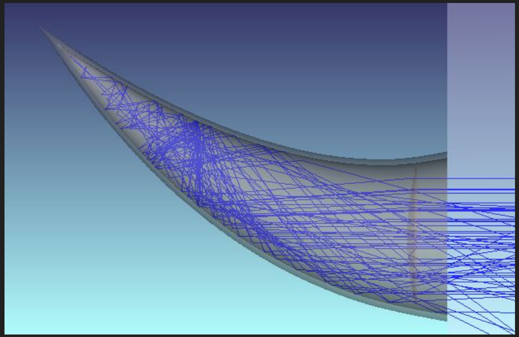
- The PTs heads are connected to the 40 K and 4 K shields with elastic copper interfaces (two copper plates with thin golden copper strips providing flexibility and good heat conduction)

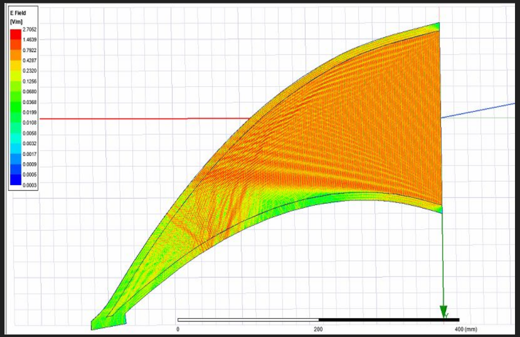
- Cryostat on delivery!

# The COSmic Monopole Observer

Cold Blackbody:

- A parabolic cavity providing an emissivity 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 $3.2 \cdot 10^{-6}$ @ 120 GHz
- A scaled version prototype of the calibrator is currently being assembled!





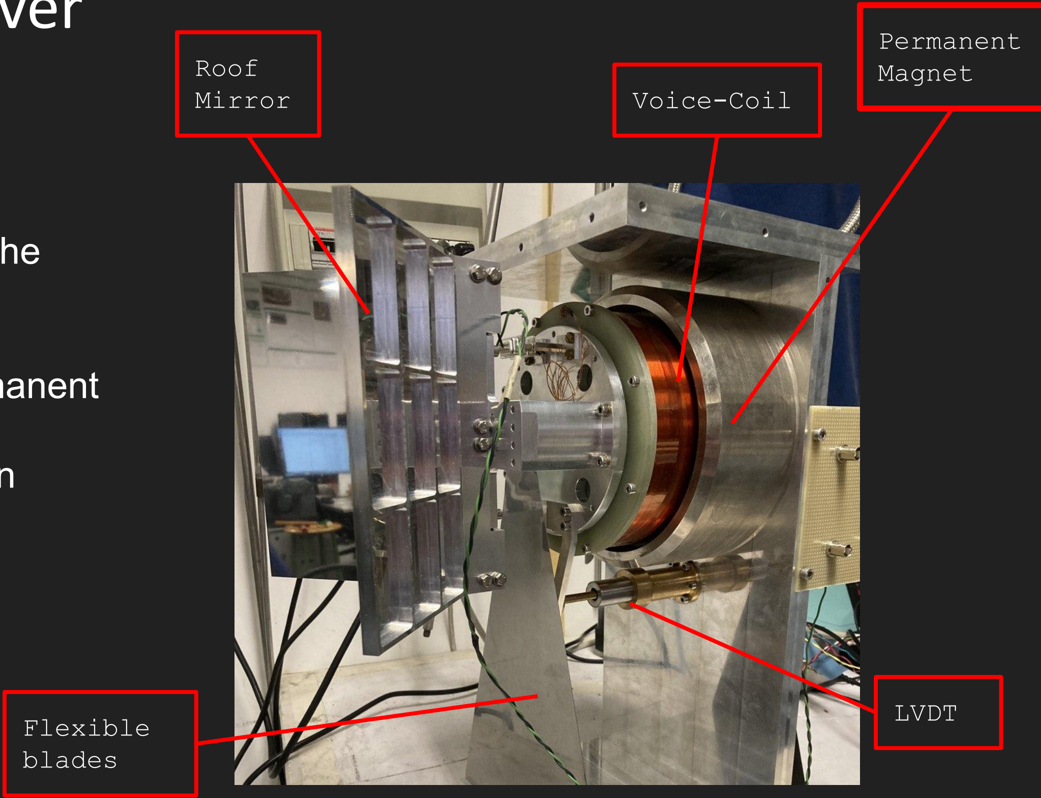
External Al. frame


Teflon master to shape the absorbing coating

# The COSmic Monopole Observer

Roof-Mirror Modulator:

- Intrinsically frictionless device to produce the interference at the focal planes
- Based on a powerful voice coil and a permanent magnet (B~1 T) with steel flexure blades supports, providing smooth and fast motion
- The heat load during cryogenic operations (at ~4 K) is minimized
- Cryogenic tests soon!

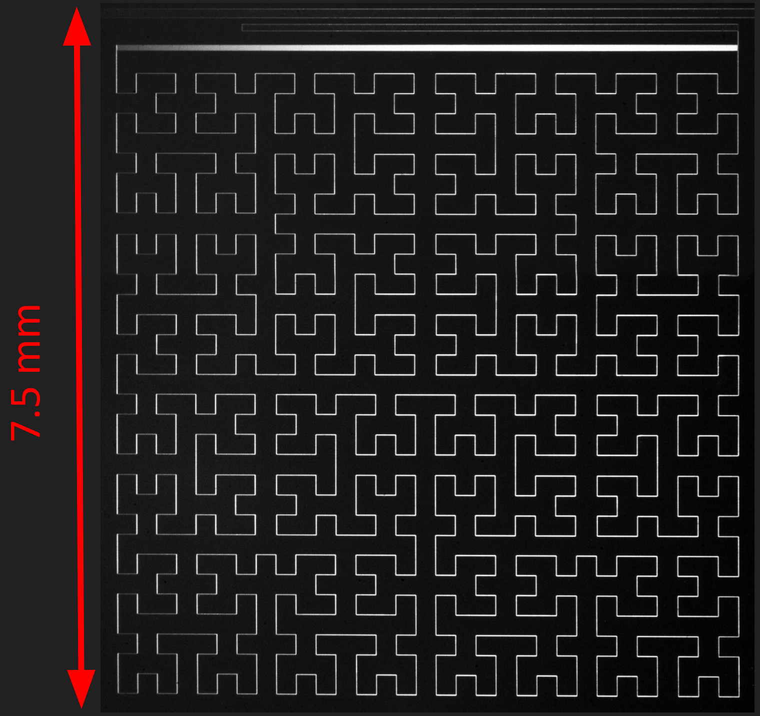



P. de Bernardis, S. Masi, E. Marchitelli

# The COSmic Monopole Observer

KIDs 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 @ 150 GHz and 250 GHz bands, are filled with 9 multimode feed-horns and Kinetic Inductance Detectors (KIDs)
- 7.5mm x 7.5mm pixels accommodated on a 4" Si wafer
- Easily achieving the photon noise limited performance as the sensitivity scales as $N_{modes}^{1/2}$
- 150 GHz prototype currently under test!

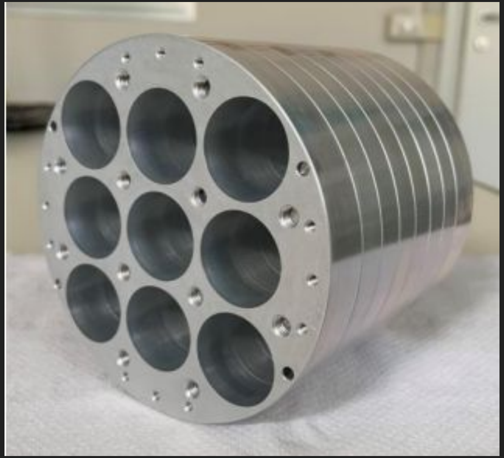



A. Paiella, F. Cacciotti, G. Isopi, E. Marchitelli

# The COSmic Monopole Observer

Horn-arrays:

- Multi-mode 3×3 horn antenna arrays feed the multimode KIDs arrays
- Each horn has a 24 mm aperture diameter and with 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 to provide the expected performance. From 10 to 19 modes are included for the 150 GHz simulation, and from to 23 to 42 modes are included in the 220 GHz simulation



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