The Kinetic Inductance Detectors for the MISTRAL Instrument: installation and characterization at the Sardinia Radio Telescope

A.Paiella, F. Cacciotti, G. Isopi, E. Barbavara, E. S. Battistelli, P. de Bernardis, V. Capalbo, A. Carbone, E. Carretti, F. Columbro, A. Coppolecchia, A. Cruciani, G. D'Alessandro, M. De Petris, F. Govoni, L. Lamagna, P. Marongiu, A. Mascia, S. Masi, E. Molinari, M. Murgia, A. Navarrini, A. Novelli, A. Occhiuzzi, A. Orlati, G. Pettinari, F. Piacentini, T. Pisanu, S. Poppi, I. Porceddu, A. Ritacco, M. R. Schirru

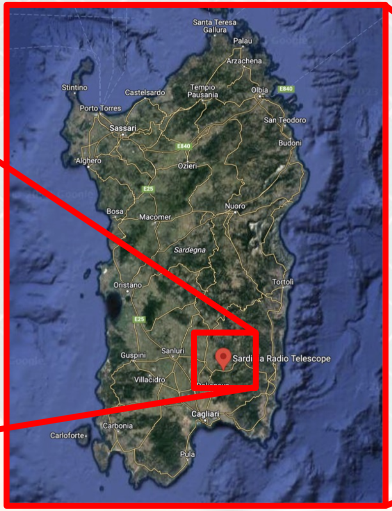
Photograph taken by G. Isopi

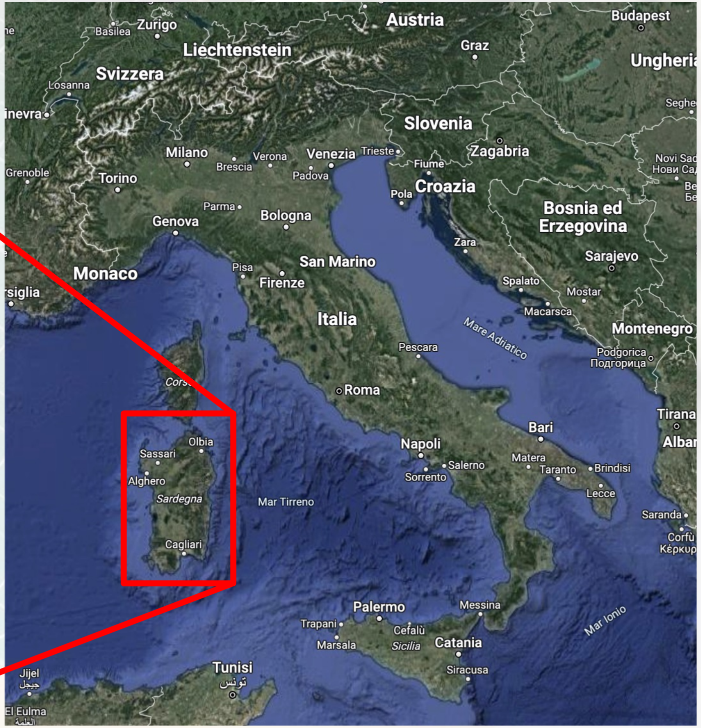
16TH PISA MEETING ON ADVANCED DETECTORS La Biodola, Isola d'Elba, May 26-June 1, 2024

MISTRAL @ SRT

MISTRAL: MIllimeter Sardinia radio Telescope Receiver based on Array of Lumped element KIDs

- MISTRAL is a cryogenic camera that houses ~ 400–pixel array of lumped element kinetic inductance detectors (LEKIDs) operating in the W–band (77–103 GHz) and cooled down below 250 mK.
- The Sardinia Radio Telescope (SRT) is an Italian radio telescope, located near Cagliari in Sardinia.





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- The Sardinia Radio Telescope (SRT) is an Italian radio telescope, located near Cagliari in Sardinia.
- SRT is a fully steerable radio telescope, with a 64 m diameter primary mirror, allowing high–angular–resolution observations in the frequency band 0.3–116 GHz.
- MISTRAL+SRT features a high–angular–resolution of 12’’ and a wide (instantaneous) field–of–view (FOV) of 4.2’.

Instrument	Frequency [GHz]	Resolution ["]	Instantaneous FOV [']
MUSTANG-2 @ GBT (100 m)	90	9	4.25
MISTRAL @ SRT (64 m)	90	12	4.2
Nobeyama (45 m)	100	14.4	3
NIKA2 @ IRAM (30 m)	150/260	11/17.5	6.5
Toltec @ LMT (50 m)	150/220/280	9.5/6.3/5	4

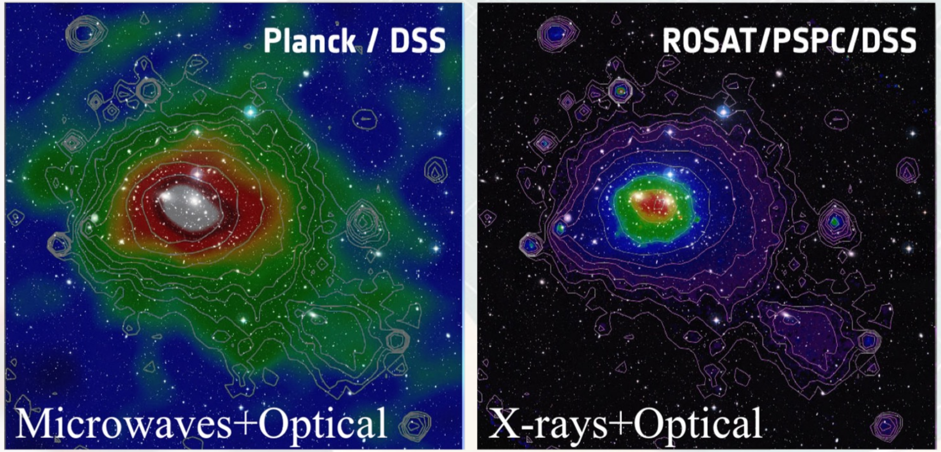
Photograph taken by G. Isopi

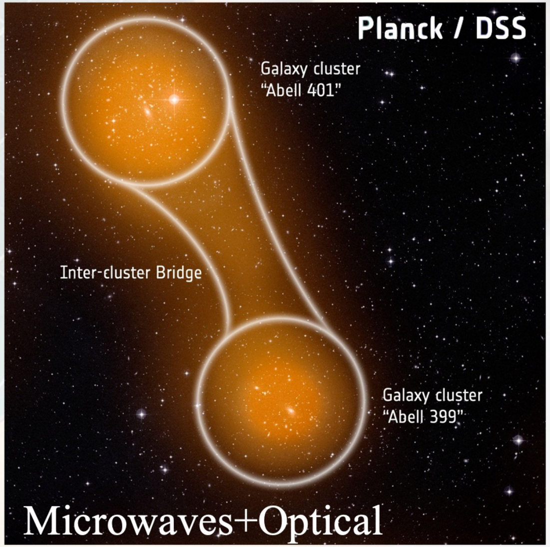
High–Angular–Resolution Astrophysics Observations

The main astrophysical targets of high–angular–resolution observations in the microwaves, including the W–band, are

- **Cosmic Microwave Background (CMB)**: Detailed mapping of the CMB anisotropies and Galactic foregrounds at small angular scales.
- **Galaxy Clusters**: Study of the intracluster medium (ICM), shock and merger phenomena.
- **Large-Scale Structures**: Investigation of the cosmic web, including filaments, voids and warm–hot intergalactic medium (WHIM).
- **Galactic Populations**: Characterization of star–forming regions, molecular clouds, and Galactic magnetic fields.
- **Extragalactic Sources**: Observations of active galactic nuclei (AGN), quasars, and radio galaxies.
- Study of **missing baryons** and their distribution.

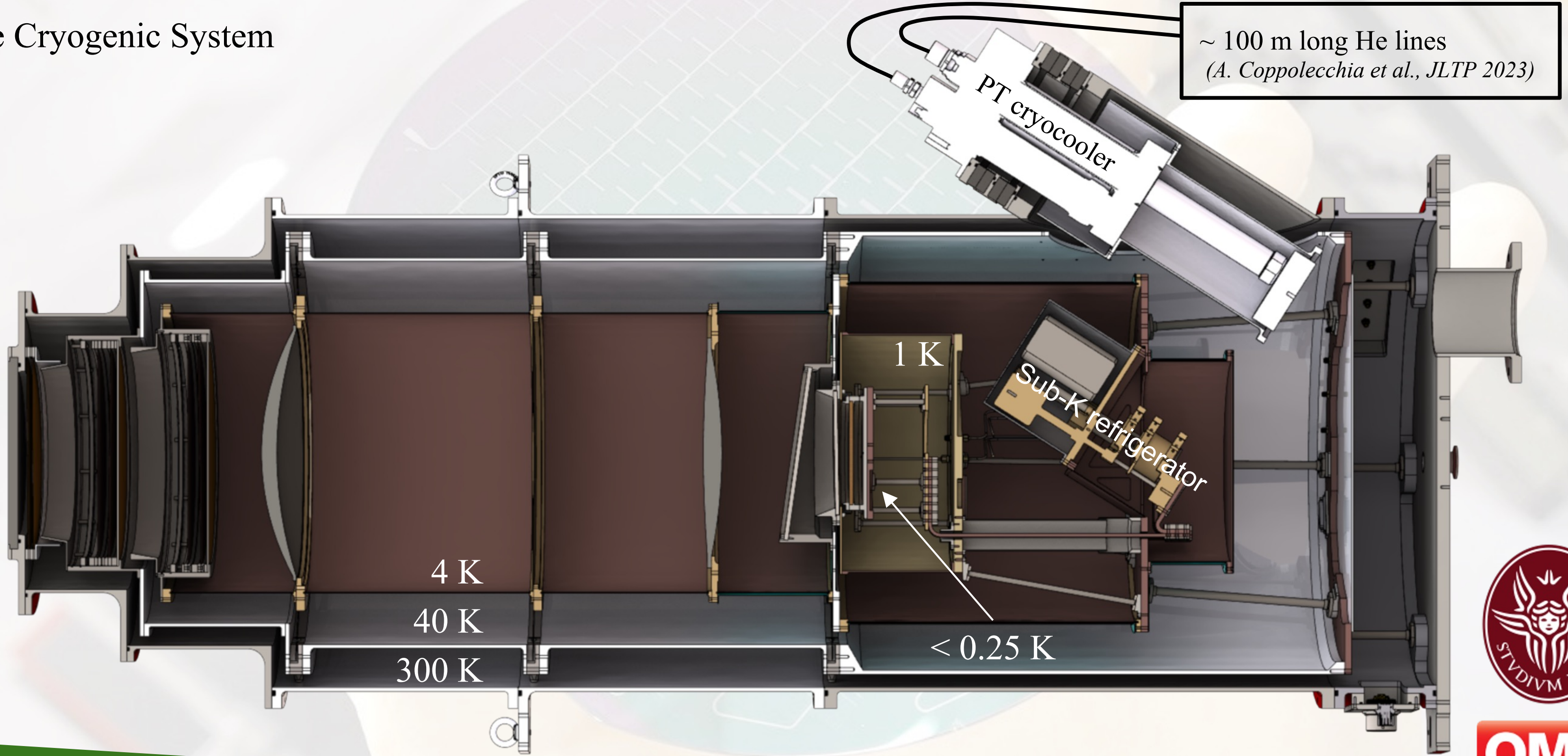
Coma Cluster





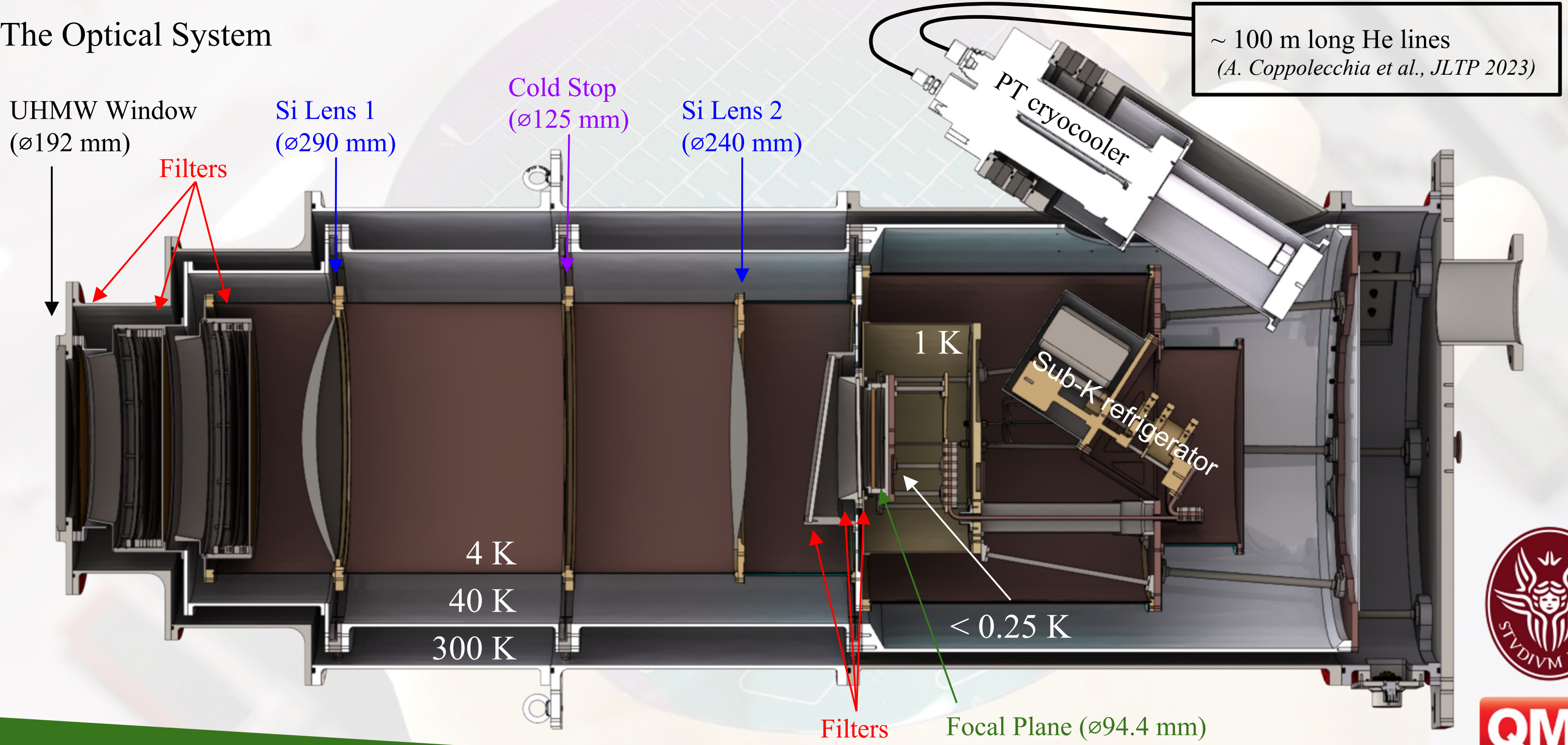
The Instrument

The Cryogenic System



The Instrument

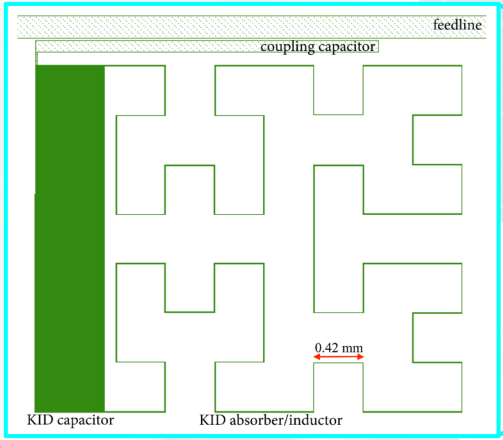
The Optical System

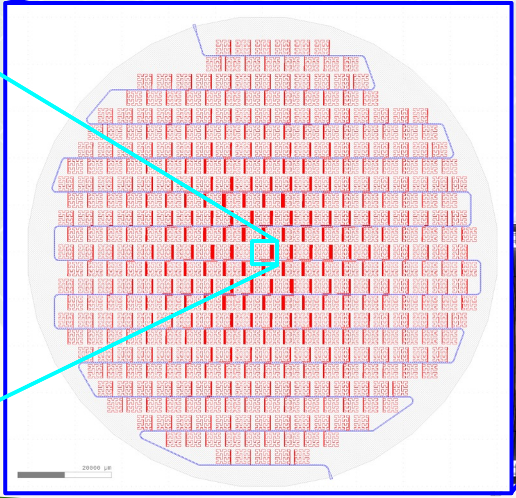


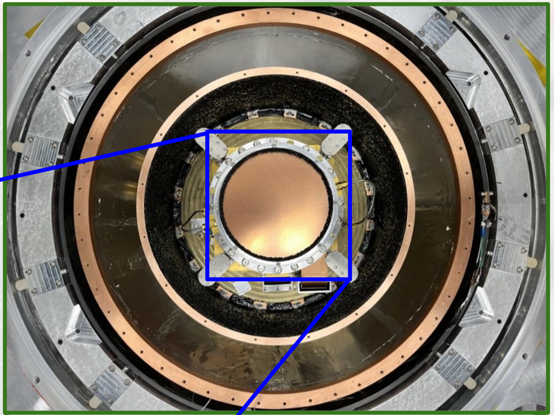
The Instrument

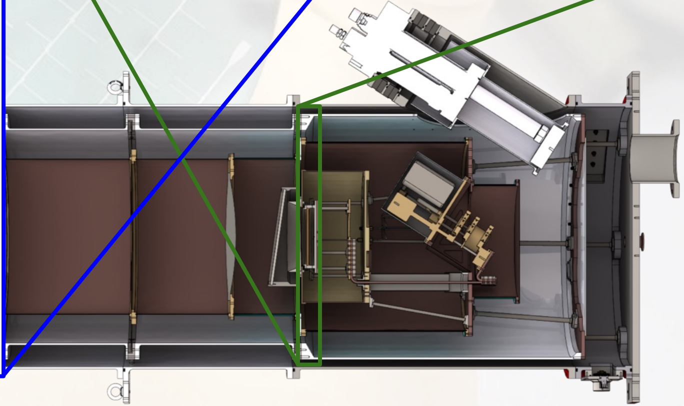
The Detector Array *(A. Paiella et al., JLTP 2022)*

- 415 lumped element kinetic inductance detectors in Ti–Al 10+30 nm thick ($T_c \sim 945$ mK), with a microstrip Al feedline 21 nm thick ($T_c \sim 1.35$ K);
- 3 mm ✕ 3 mm absorbers, separated by 4.2 mm: pixel separation of 10.6'';
- Pixel design: third order Hilbert inductor, interdigitated KID capacitor, capacitive coupling to the feedline.



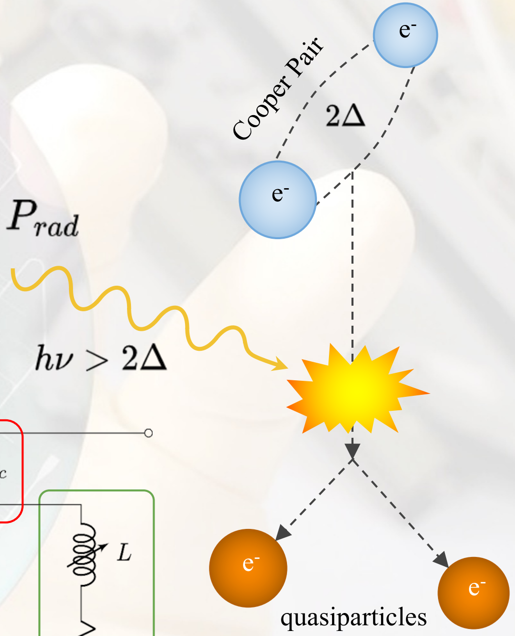






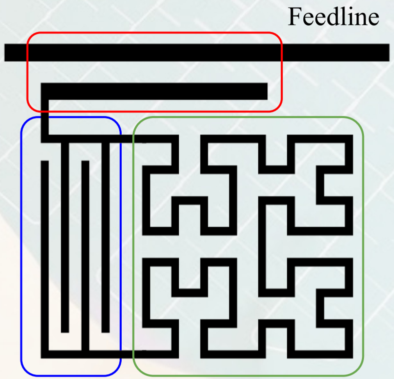
Kinetic Inductance Detectors – KIDs

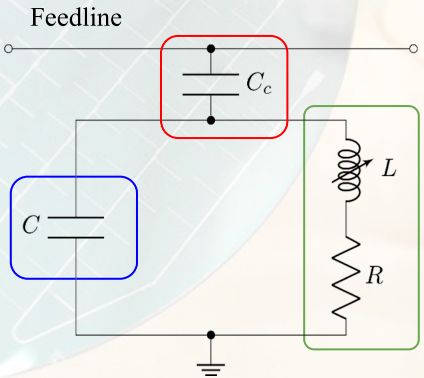
- KIDs are low–temperature, fast, superconductive detectors, where the radiation is detected by sensing changes of the kinetic inductance.
- A superconductor, cooled below its critical temperature T_c, presents two populations of electrons: quasiparticles and Cooper pairs (binding energy $2\Delta \approx 3.5 k_B T_c$).
- Pair–breaking radiation, $h\nu > 2\Delta$, can breaks Cooper pairs, producing a change in the population relative densities, and thus in the kinetic inductance.
- To detect the change in kinetic inductance, a superconducting film is configured to serve as the inductor in a high–quality factor (R)LC resonant circuit, realized on a dielectric wafer.



Lumped Element configuration

LEKID: the inductor acts also as the radiation absorbers





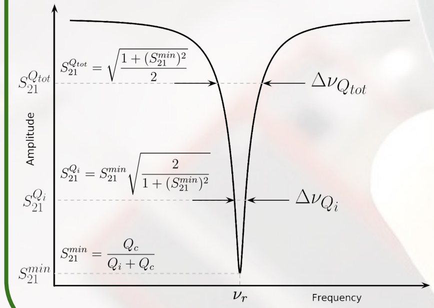
Kinetic Inductance Detectors – KIDs

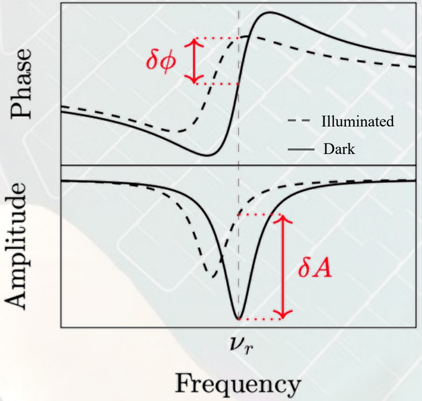
Readout Scheme

- The change in the kinetic inductance produces a change in the resonant frequency, ν_r, and in the quality factor, Q.
- They can be sensed by measuring the change in the amplitude and phase of the bias signal of the resonator, transmitted past the resonator through a feedline.

$$S_{21}(\nu) = 1 - \frac{Q_{tot}/Q_c}{1 + 2jQ_{tot}(\nu - \nu_r)/\nu_r}$$

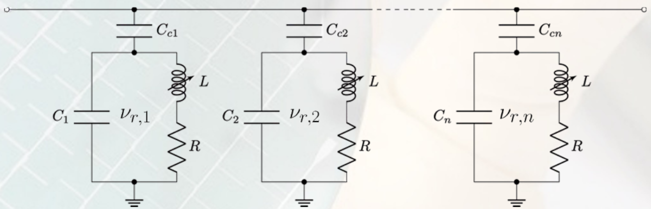
$$Q_{tot}^{-1} = Q_i^{-1} + Q_c^{-1}$$

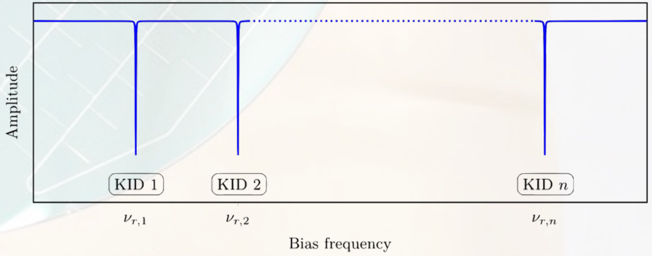


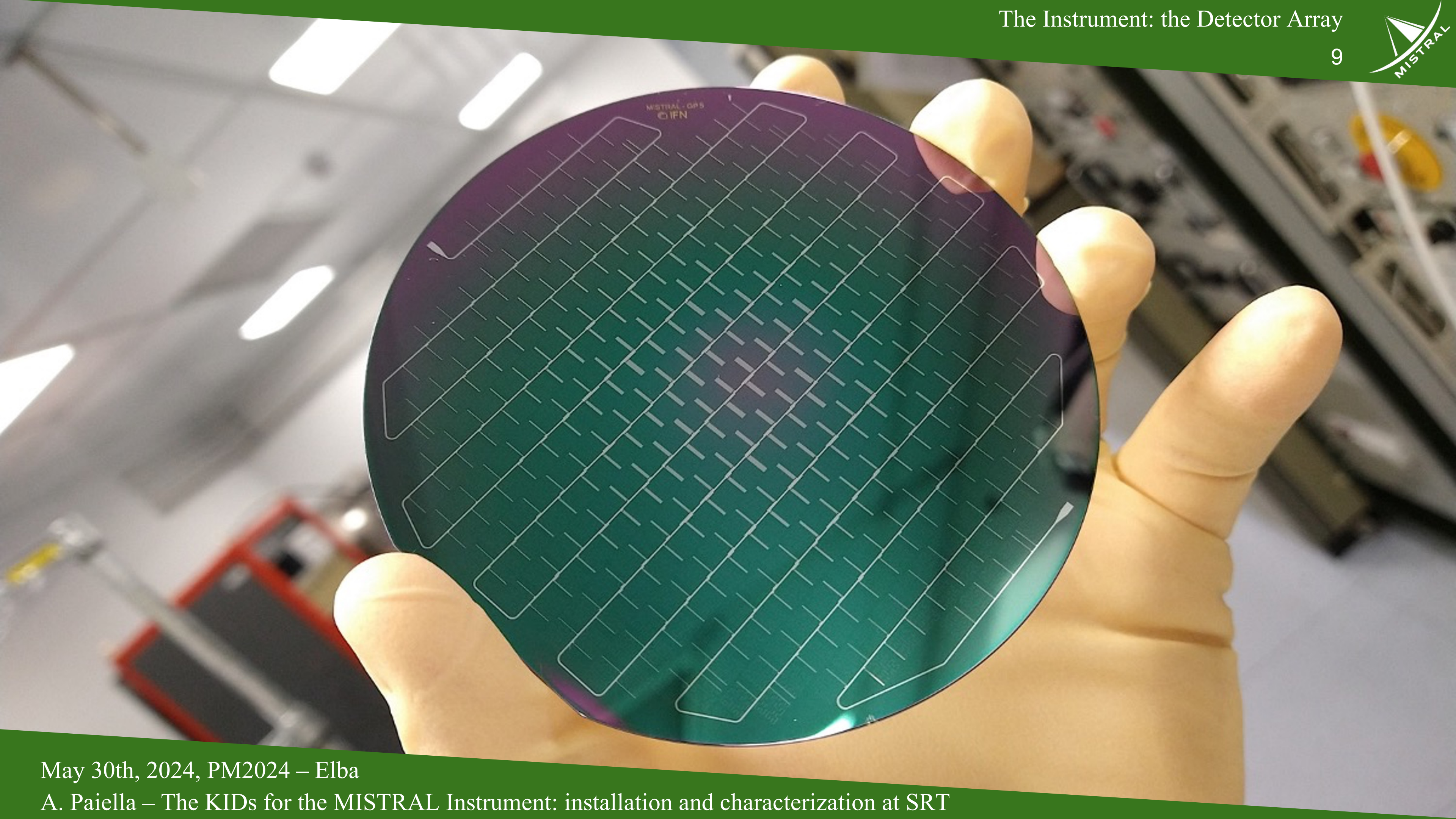


Multiplexing

- Multiplexing in the frequency domain: hundreds of KIDs, with different ν_r, all coupled to the same feedline (→ high sensitivities and small thermal load).
- FPGA–based multi–tone modulation and demodulation readout electronics.






MISTRAL - GPS
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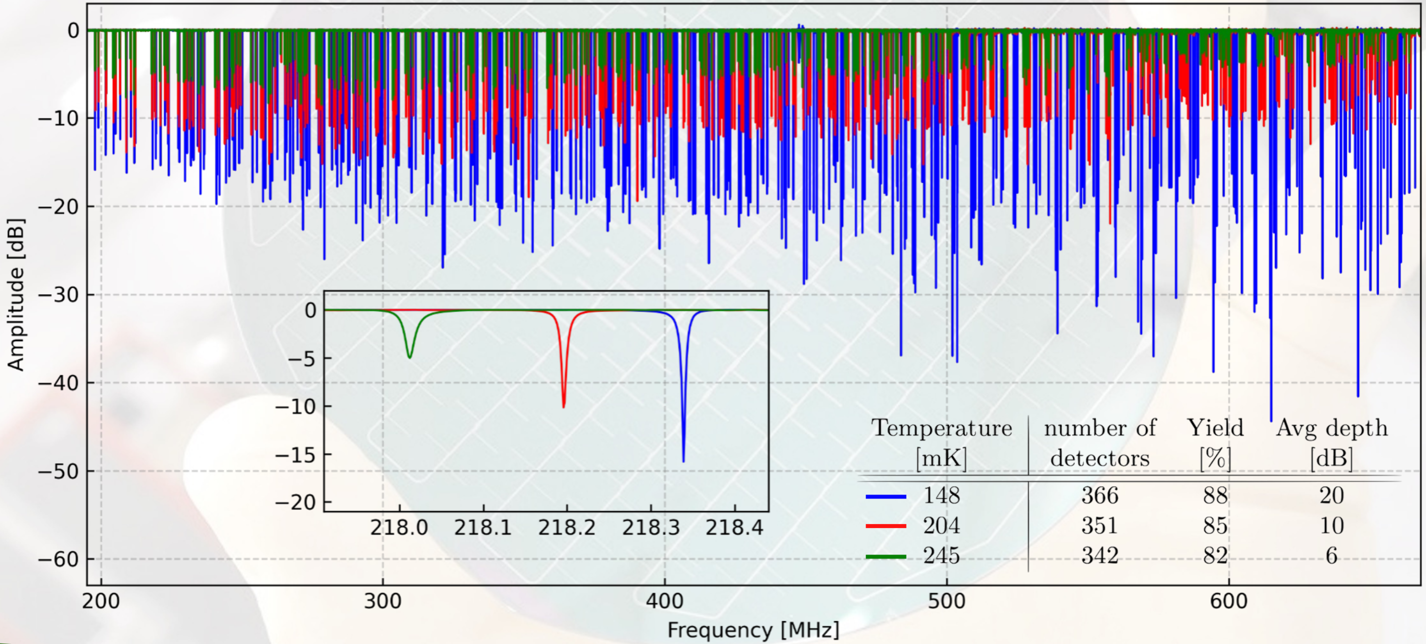
Detector Characterization in the laboratory

Dark Characterization *(F. Cacciotti, et al. submitted to JLTP)*

- high detector yield ~82%.

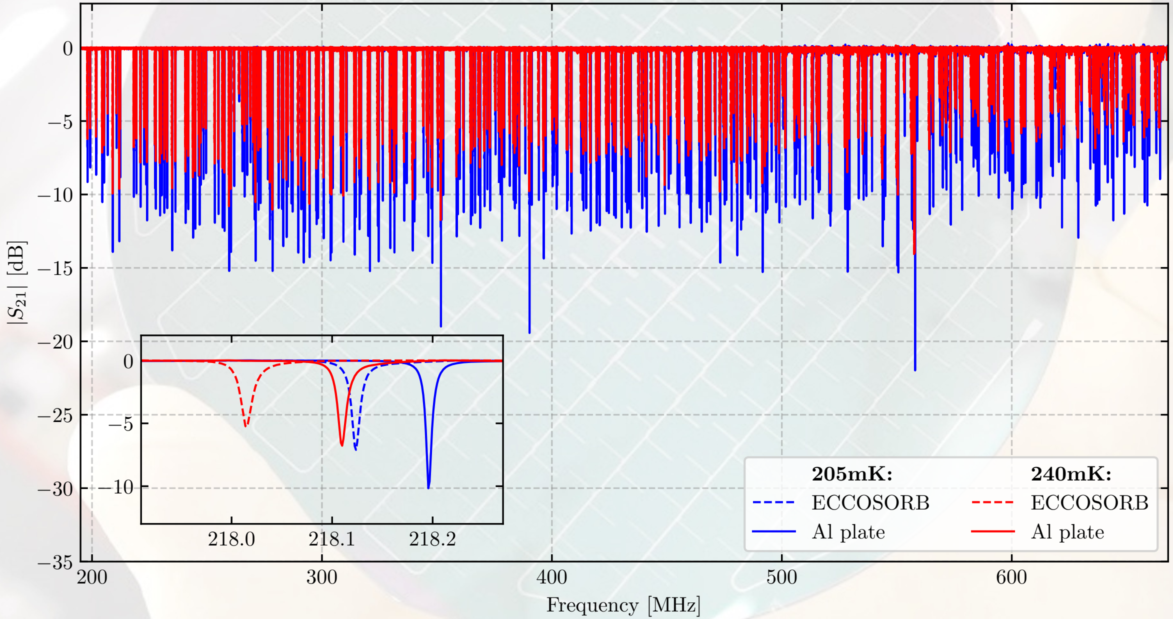


Temperature [mK]	number of detectors	Yield [%]	Avg depth [dB]
148	366	88	20
204	351	85	10
245	342	82	6

Detector Characterization in the laboratory

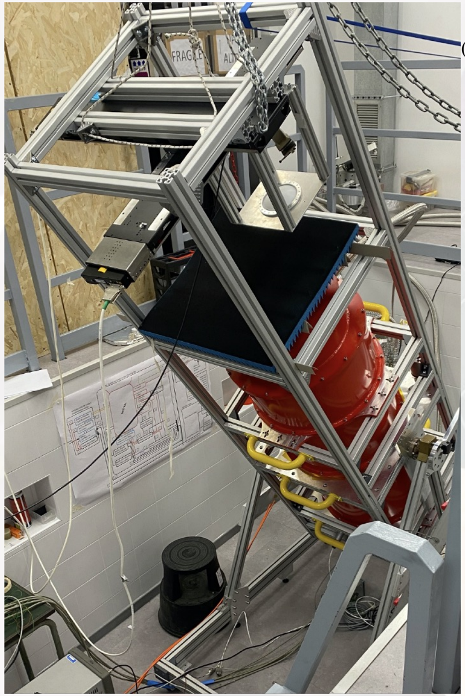
Optical Characterization

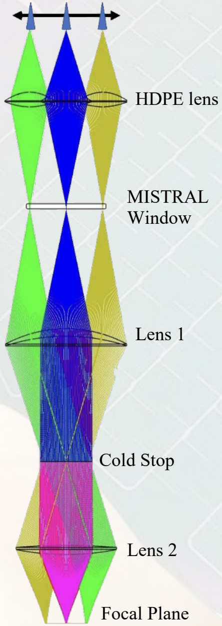
- resonances move under different radiative background loads due to the breaking of Cooper pairs of the superconductor.



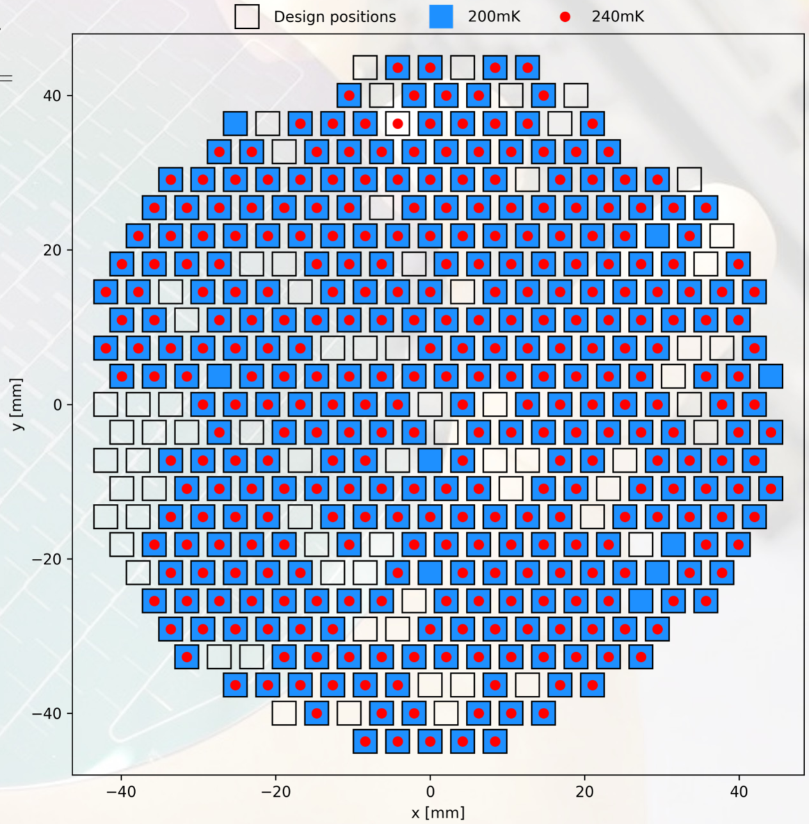
Detector Characterization in the laboratory

Pixel Identification





Temperature [mK]	number of detectors
200	343
240	336



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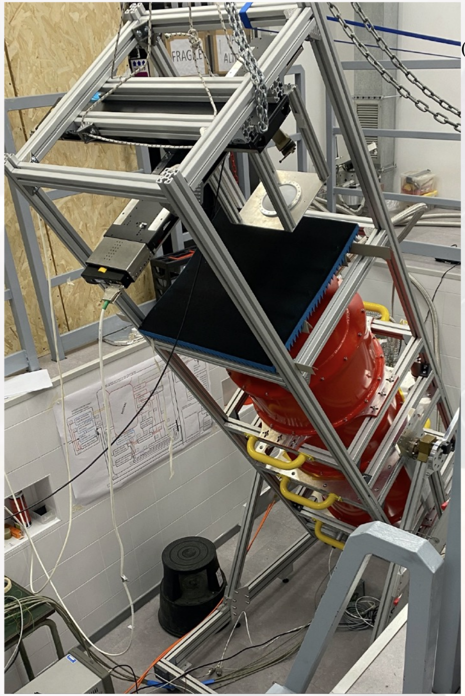
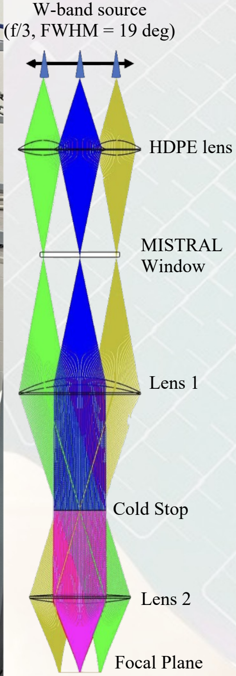
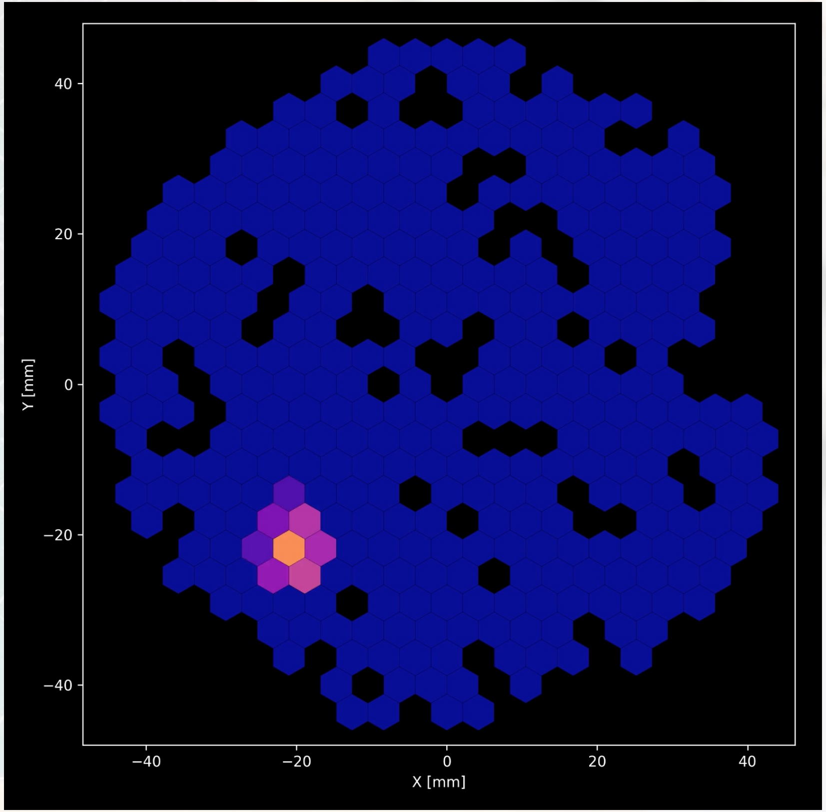
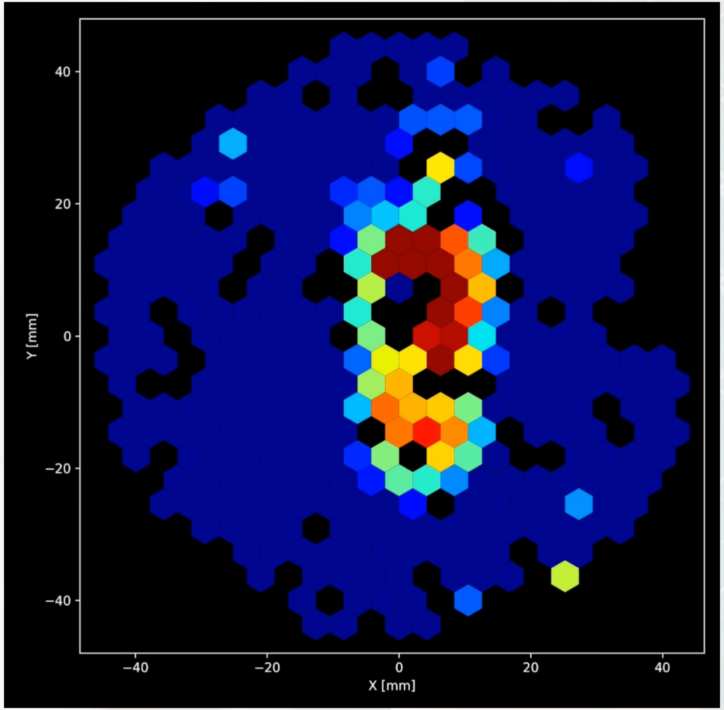






Detector Characterization in the laboratory

Imaging of strange (Astro)physical objects with MISTRAL:



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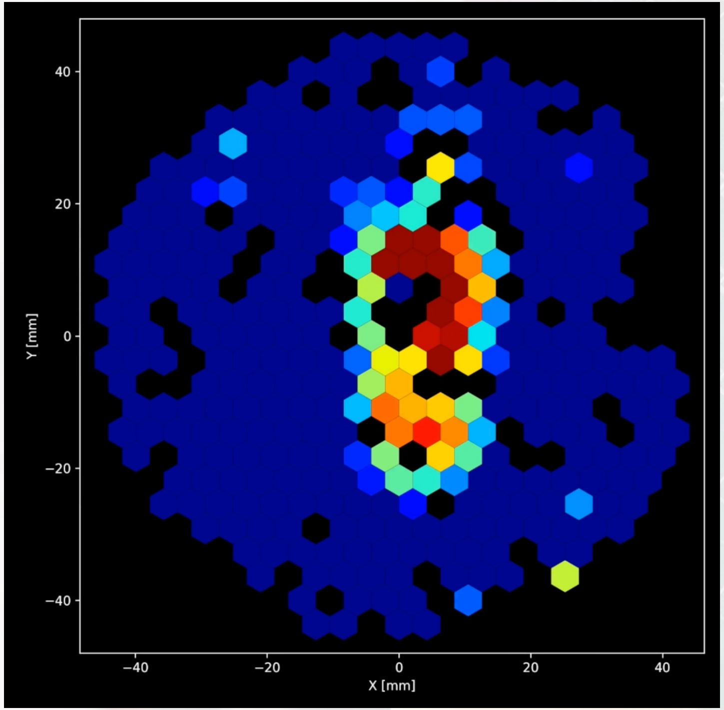

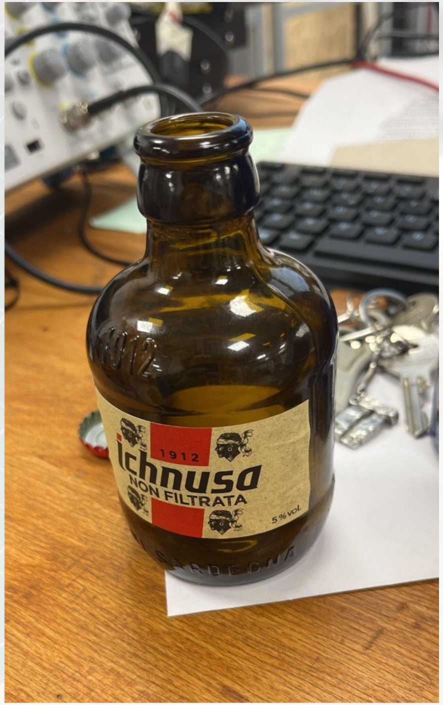

very tasty Sardinian beer!

Detector Characterization in the laboratory

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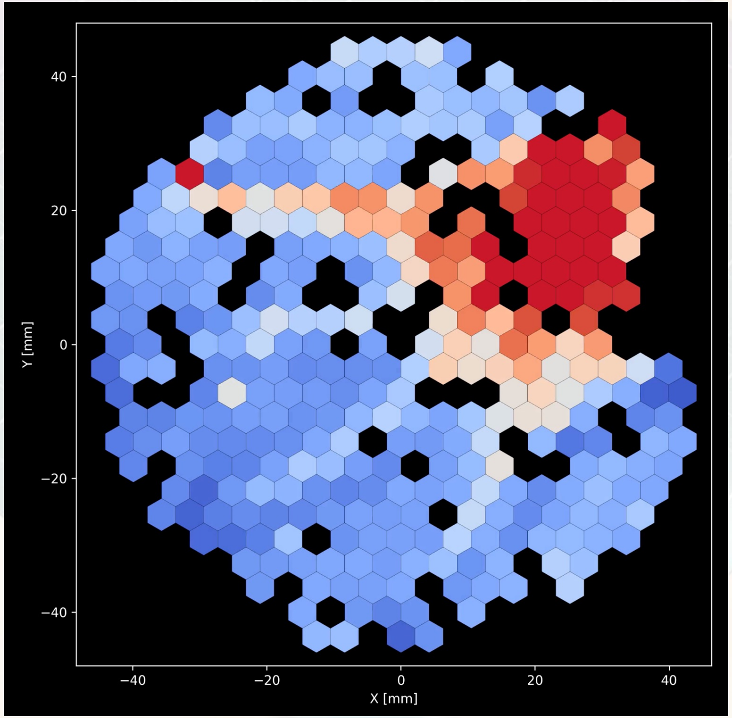
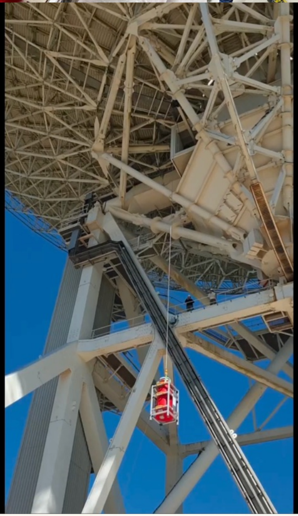


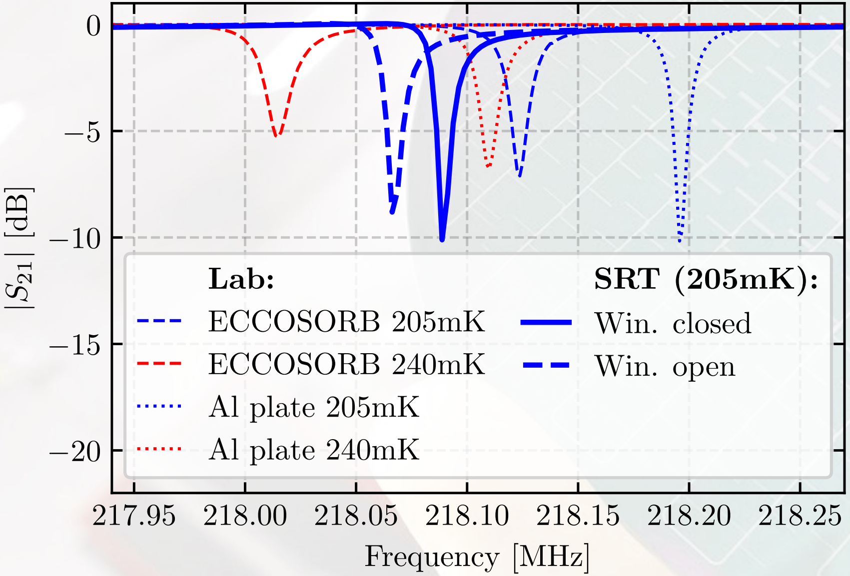
Installation Campaign at SRT

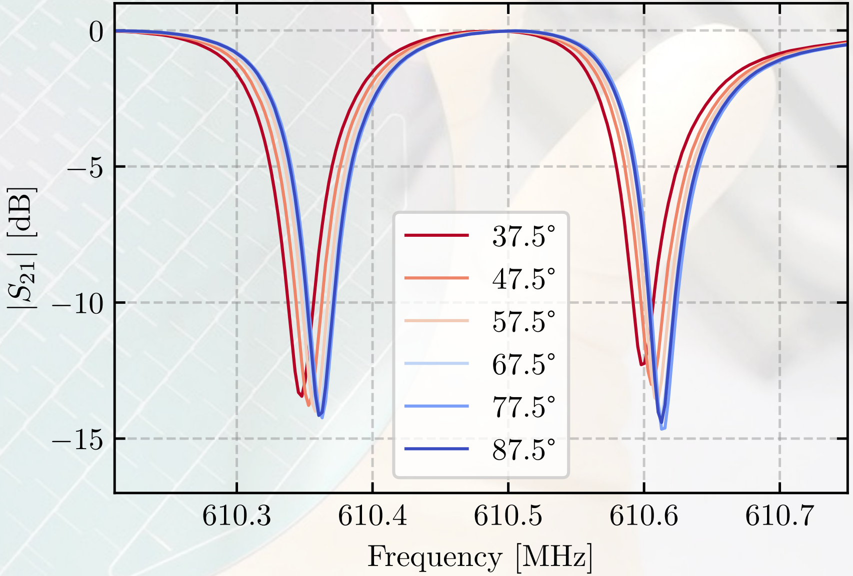


Detector Characterization at the telescope

Preliminary on-sky measurements:

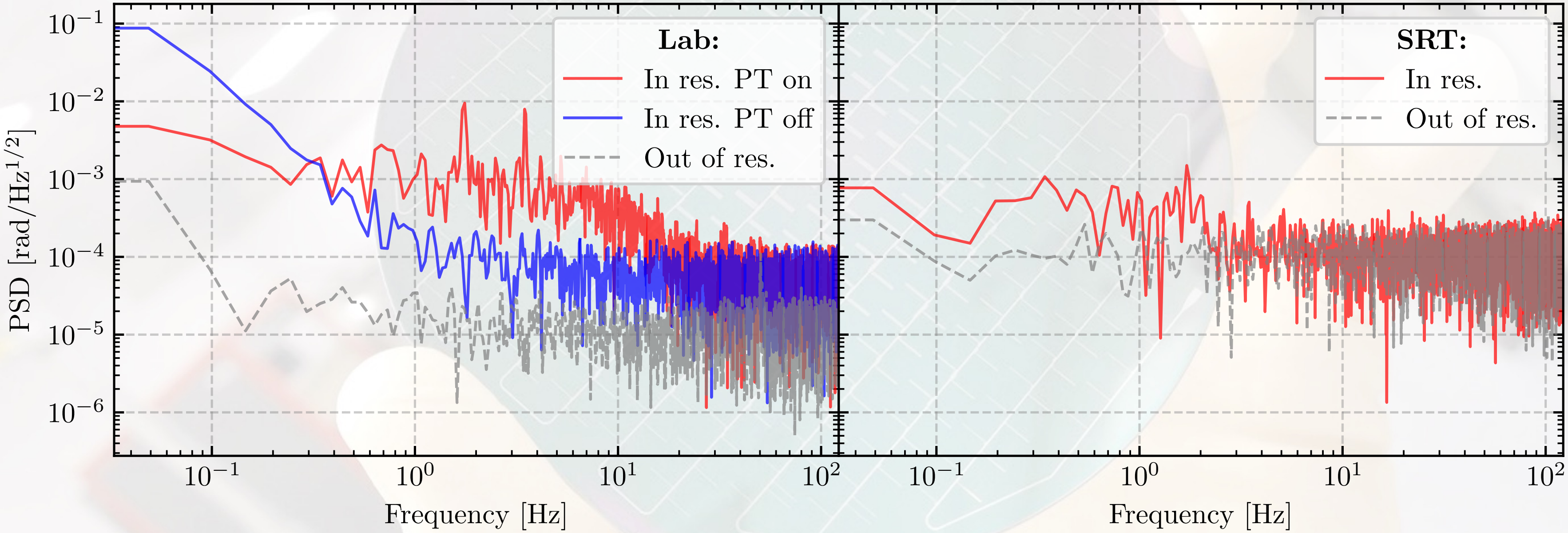
- Different radiative background loads.





Detector Characterization at the telescope

Noise level measurements:



Conclusion

- MISTRAL is a wide instantaneous field–of–view (~ 4’) W–band camera with a ~ 400–pixel LEKID array for high–angular–resolution (~12’’) observations at the Sardinia Radio Telescope.
- The MISTRAL camera will be available as a facility instrument to the community.
- Laboratory measurements have shown expected performance.
- Preliminary on-sky measurements have shown no significant degradation in performance. Noise analysis at the telescope suggests that further optimization of the readout electronics could enhance the instrument's performance.
- With the expected (measured in lab.) overall sensitivity in the W–band (NEFD) ~ 2.8 mJy in 1 s of integration and a mapping speed ranging from 170 to 1700 $\mathrm{arcmin}^2/\mathrm{mJy}^2/\mathrm{h}$,
    - MISTRAL will enable continuum surveys of the microwave sky, targeting various astrophysics cases;
    - MISTRAL could contribute to address open challenges, including the quest for missing baryons.