SAPIENZA UNIVERSITÀ DI ROMA
INFN Istituto Nazionale di Fisica Nucleare
CNR IFN Istituto di Fotonica e Nanotecnologie
INAF Istituto Nazionale di Astrofisica
PON Ricerca e Innovazione 2014 - 2020

MISTRAL: MIllimetric Sardinia radio Telescope Receiver based on Array of Lumped elements kids

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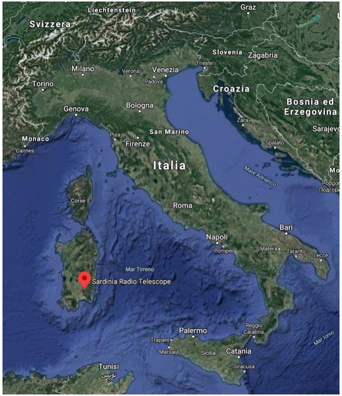
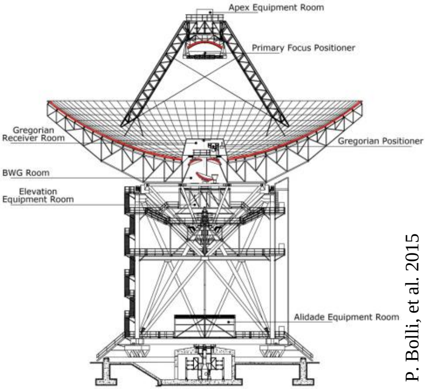
Photograph by Mike Peel (www.mikepeel.net)

The Sardinia Radio Telescope

The Sardina Radio Telescope (SRT) is an Italian radio telescope, located near Cagliari (Lat. 39°29′34″N, Long. 9°14′42″E, 600 m above the sea level), in Sardinia.

- Collaboration among three Research Structures of INAF:
  - Astronomical Observatory of Cagliari,
  - Institute of Radio Astronomy (Bologna),
  - Arcetri Astrophysical Observatory (Florence).
- SRT is a fully steerable radio telescope, with
  - a 64 m diam. primary mirror, equipped with 1116 actuators,
  - a 7.9 m diam. secondary mirror,
  - frequency coverage 0.3–116 GHz,
  - 6 focal positions: Primary, Gregorian, and 4 Beam Wave Guides,
  - a maximum of 14 receivers.





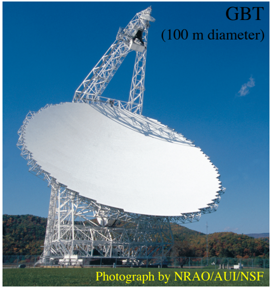
P. Bolli, et al. 2015

MISTRAL

In 2019, INAF won a call for proposals for grants aimed to enhance research infrastructures, published by MIUR in the context of PON (Programma Operativo Nazionale) – Research and Innovation 2014–2020.
In particular:

- the funded project concerns the *Enhancement of the Sardinia Radio Telescope for the study of the Universe at high radio frequencies*, divided in 9 work packages (WP),
- the WP–3 concerns the supply of a bolometric cryogenic W–band (80–110 GHz) kinetic inductance detector (KID) camera for the SRT Gregorian focus,
  - it has been awarded to *Sapienza*, Università di Roma (in collaboration with CNR–IFN and INFN),
  - this project has been named MISTRAL.
  - The MISTRAL camera will consist of a compact cryostat hosting the re–imaging optics, cooled at 4 K, and a 408–pixel array of photon–noise limited lumped element kinetic inductance detectors, cooled at a base temperature lower than 300 mK.
  - For high angular resolution observations in the W–band, SRT+MISTRAL will be very competitive with the state–of–the–art of such an instrument: GBT+MUSTANG–2:

Facility	Instantaneous FOV	Angular Resolution
SRT+MISTRAL	$2.4'/4'$	$12''/13''$
GBT+MUSTANG–2	$4'$	$9''$



Astrophysics in the W–band at high angular resolution

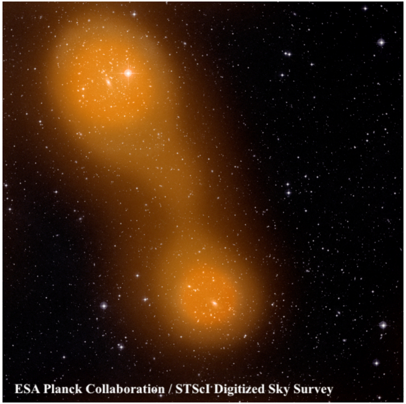
High angular resolution observations in the W-band allow to explore scientific targets which span from extragalactic astrophysics to solar system science.

For instance, through the Sunyaev–Zel'dovich (SZ) effect, surveys of galaxy clusters can be obtained as well as information about their physics, dynamics and morphology, and the filaments connecting them.

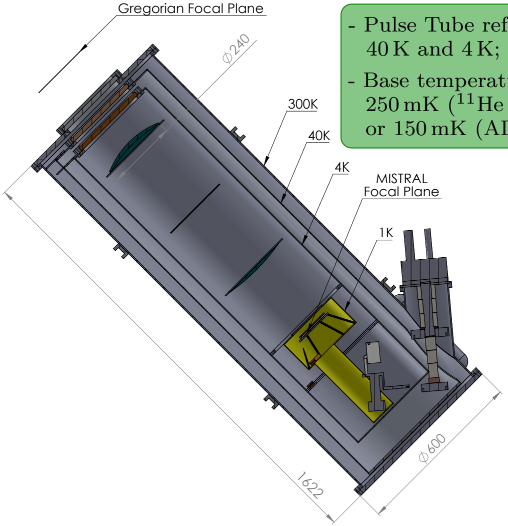
- Surveys would improve the constraints on the evolution of dark energy by measuring the abundance of clusters as a function of redshift.
- Since the SZ effect provides a measure of the integrated electron pressure along the line of sight, resolved measurements can identify intracluster medium discontinuities such as cold fronts or shocks (the presence of which was revealed by X–ray observations), which are related to cluster mergers.
- Filaments consist of diffuse warm/hot plasma (warm–hot intergalactic medium WHIM), less dense and hot than that of galaxy clusters, which can be detected through the SZ effect and forms along the cosmic web connecting galaxy clusters and surrounding cosmic voids, following the gravitational potential well of dark–matter filaments.

SZ effect

CMB photons crossing the hot gas of clusters of galaxies, acquire energy via inverse Compton scattering, and their spectrum is perturbed.

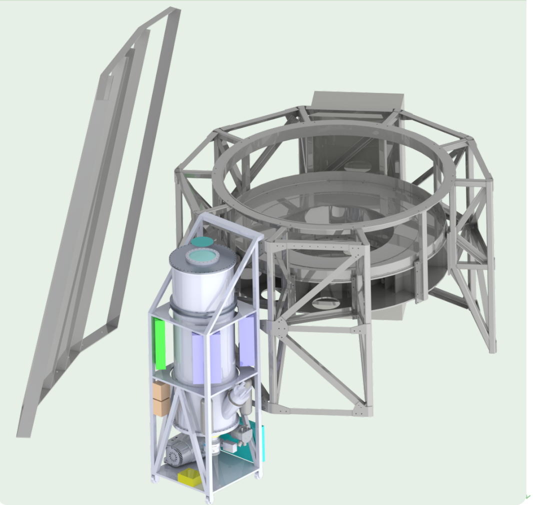


The Instrument
Cryogenic System



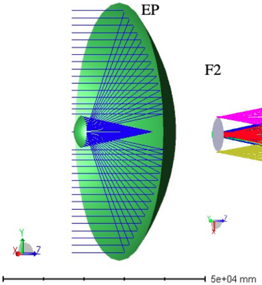
- Pulse Tube refrigerator: 40 K and 4 K;
- Base temperature: 250 mK (^{11}He fridge) or 150 mK (ADR).

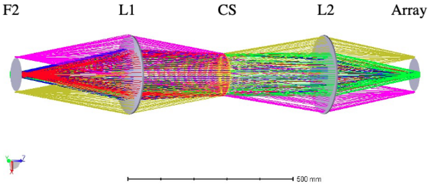
MISTRAL @ SRT Gregorian Focus



The Instrument
Optical System

- Telescope: Shaped Gregorian config.
- Angular resolution @ 3.3 mm: $12''/13''$
- Entrance Pupil diameter: 60 m
- DLFOV: $2.4'/4'$





Quasi–optical elements

A chain of filters will be assembled inside the cryostat to ensure cryogenic operation and efficient radiation selection of the interesting frequency band.

Optics requirements

The main reasons to introduce a relay optics between the Gregorian focal plane and the KID array plane are the following:

- to possibly rescale the Gregorian telescope focal plane → the same scale for $2.4'$ / f–number ratio 1.8 for $4'$;
- to insert a cold aperture stop (CS) in order to resize the EP to 60 m in diameter to avoid wavefront distortion induced by shaped surfaces;
- to provide a gaussian wavelength independent beam telescope configuration → almost satisfied, after optimisation of L2
- to provide a telecentric optics.

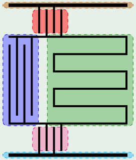
The Instrument
Detectors

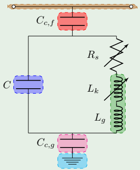
Kinetic Inductance Detectors

- Low–temperature, fast ($\sim 100\,\mu s$), superconductive detectors.
- Radiation with energy greater than the binding energy of the Cooper Pairs of the superconductor can break them, producing a change in the in the kinetic inductance, L_k.

Readout Scheme

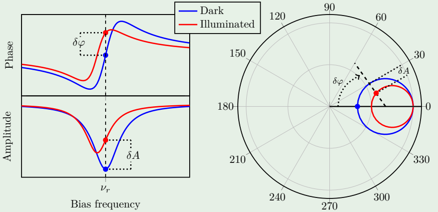
- In the lumped element configuration, a superconducting strip is shaped and sized to perform as a radiation absorber as well as an inductor, which is coupled to a capacitor to form a high–Q (R)LC resonator, fed and read out thanks to a feedline.





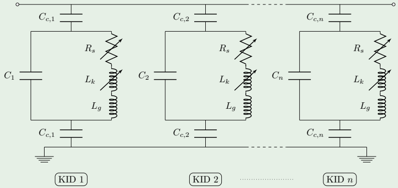
Readout Procedure

- The change ok L_k (ν_r and Q) can be sensed by measuring the change in the amplitude and phase of the bias signal, transmitted past the resonator.



Multiplexing & Readout electronics

- High values of Q allow to multiplex thousands of KIDs, with different ν_r, all coupled to the same feedline.



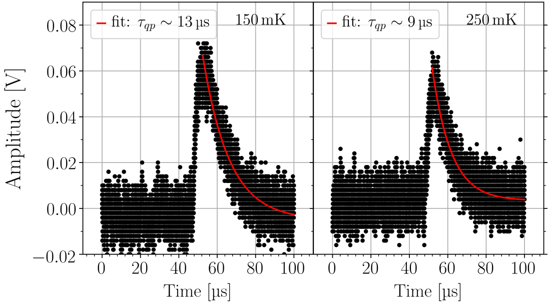
- ROACH–based readout electronics able to generate up to 1000 tones over a 512 MHz bandwidth.

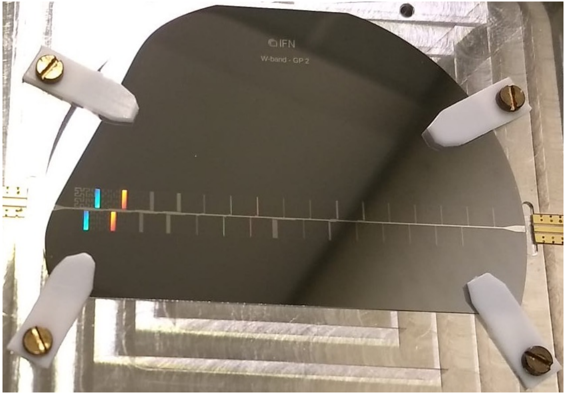
The Instrument

Detectors: MISTRAL prototype

- We tested a prototype: 31–pixel array made of Ti–Al bilayer 10+30 nm thick on a 235 µm thick Si substrate.
- We measured the critical temperature of the superconductor film: $T_c \sim 945\,\text{mK} \Rightarrow \nu_{min} \sim 70\,\text{GHz}$.
- We measured the dark (electrical) performance:

		Operation Temperature	
		150 mK	250 mK
τ_{qp} [µs]		13	9
NEP_{dark}	Avg.	1.05×10^{-16}	3.40×10^{-16}
$\left[\text{W}/\sqrt{\text{Hz}}\right]$	Best	0.33×10^{-16}	1.98×10^{-16}
	Worst	2.15×10^{-16}	6.87×10^{-16}





Expected noise @ SRT in the W–band due to atmospheric turbolence: $\sim 5 \times 10^{-15}\,\text{W}/\sqrt{\text{Hz}}$, to be compared with $\text{NEP}_{\text{dark}}/\eta$ with $\eta \sim 0.25$ (expected optical efficiency).

Conclusion

- MISTRAL: MIllimetric Sardinia radio Telescope Receiver based on Array of Lumped elements kids will enhance SRT allowing high angular resolution observations in the W–band.
- MISTRAL will provide a wide field ($2.4'$ to $4'$ diameter, approximately Nyquist sampled at the diffraction limit of $14''$ FWHM) continuum receiver for the W–band, complementing the multi–beam coherent spectroscopic receiver for the same band.
- This camera will be available as a facility instrument for the radio–astronomy community.
- With the expected atmospheric–limited sensitivity in the 95 GHz window < 0.4 MJy/sr in 1 s of integration, for each of the 400 pixels, MISTRAL will allow continuum surveys of the mm–wave sky with a variety of scientific targets.

Timeline