Bilaterale INFN - IN2P3

(SUB-KELVIN) CRYOGENIC DETECTORS IN FRANCE

MONFARDINI Alessandro
Institut Néel - CNRS
Grenoble

MENU

- MOTIVATIONS FOR SUB-KELVIN LTD (LOW TEMPERATURE DETECTORS)
- SCIENCE DRIVERS IN A NUTSHELL
- EXAMPLES OF FRENCH LTD
- ONGOING / FUTURE / IT-FR LINKS

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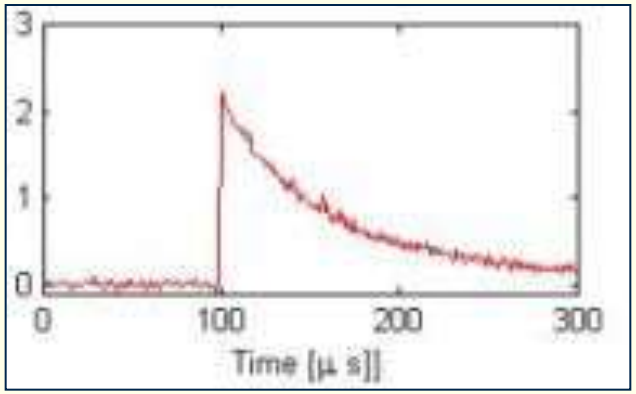
ENERGY/POWER versus TIME

Single Events:

- Photomultipliers
- **X-ray detectors**
- **Particles, Rare events ...**



Triggering

Both plots taken with the same detectors

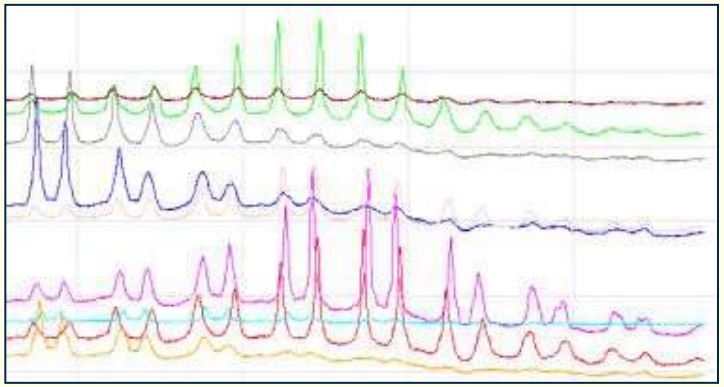
Characterised by:

- Detection threshold
- Speed (counting)
- Pulse(s) shape(s)
- **Energy resolution (ΔE or ΔE/E)**

CDD-like lie here

Continuum:

- IR cameras
- mm and THz



Recording

Characterised by:

- **NEP**
  (Noise Equivalent Power)
- Sampling rate
- 1/f knee ...

WHY SUB-KELVIN

- TO detect/measure **tiny amounts/variations** of power (aW/Hz$^{0.5}$), targeting the ultimate photon-noise limit → RECORD A TIMELINE

- TO measure **very precisely** small amounts of deposited energy, targeting the ultimate the phonon-noise limit → TRIGGER A PULSE

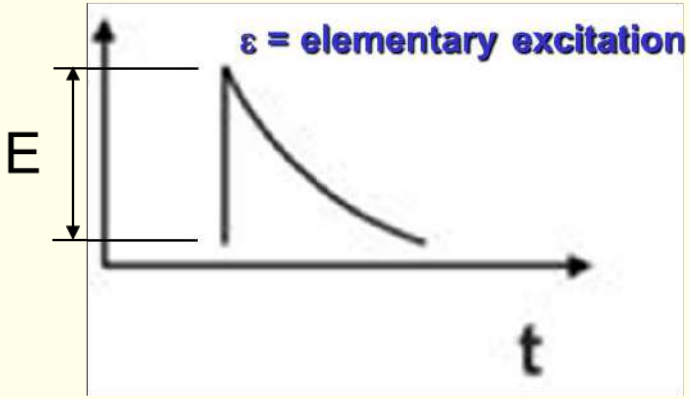
Both these ultimate limits have been achieved a long ago in several domains and on single detectors/pixels .. well not so long ago

HOWEVER:

- EVERY MODERN/FUTURE APPLICATION REQUIRES A LARGE NUMBER OF DETECTORS → **PARALLELISATION**
- NEW FUNCTIONALITIES ARE ADDED, e.g. **SMART PIXELS**

QUANTUM RULERS

Whole point is to **reduce the energy associated to the "elementary excitation".**



$\Rightarrow N = E/\varepsilon$

$\Rightarrow \sqrt{N} = \sqrt{E/\varepsilon}$

$\Rightarrow$ Energy Resolution $\propto \sqrt{\varepsilon}$

$\Rightarrow$ **ε to be MINIMIZED**

→ Cooper-pair-breaking detectors (gap $\approx 3.5 \cdot kT_c$) **$T_{base} << T_c$**

→ Bolometers (phonon energy $\approx kT$)

Big **advantage of bolometers**: working temperature is a "free" parameter

Big **advantage of pair-breaking detectors**: design not driven by thermal constrains

Independent "practical" limitation: multiplexing

OTHER REASONS TO GO SUB-K

THE MOST OBVIOUS, IF JOKING, ARE:

- BEING A LITTLE MASOCHIST
- POSSESSING BLUEFORS OR OXFORD SHARES

THE REAL MESSAGE IS:

“BEFORE DOING THINK TWICE .. DO I REALLY NEED IT ?”

KEY ENABLING TECHNOLOGIES

THE TECHNOLOGICAL CONDITIONS, IN FRANCE, PROVIDED FERTILE GROUND FOR OUR DEVELOPMENTS

IN PARTICULAR, among others:

- **CRYOGENICS**. Historically developed starting from the Grenoble area. Examples: Planck (CNRS/Air Liquide), Herschel (CEA), NIKA2 (CNRS), BICEP (CEA)

- **MICROFABRICATION**. Hubs in Saclay, Grenoble, Lille … The CNRS platforms are working as a single network (RENATECH). CEA-LETI is the biggest center in France and made the Herschel detectors.

- **ELECTRONICS**. Several excellence centers: Paris, Lyon, Grenoble, Toulouse, Bordeaux and others

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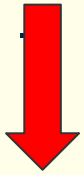
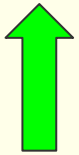


CRYOGENICS. Historically developed starting from the Grenoble area. Examples: Planck (CNRS/Air Liquide), Herschel (CEA), NIKA2 (CNRS), BICEP (CEA). *Conservation of Momentum ?*



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ELECTRONICS. Several excellence centers: Paris, Lyon, Grenoble, Toulouse, Bordeaux and others

SCIENCE DRIVERS: PARTICLE PHYSICS

A COUPLE KEY QUESTIONS TO BE ADDRESSED

- **What is the dark matter ?**
  Observable: unexplained events

- **The nature of the neutrino, the Physics beyond the Standard Model …**
  Observable: "forbidden" nuclear reactions, neutrino coherent interactions

e.g. DARK MATTER SEARCH → **EDELWEISS heritage**

e.g. NEUTRINOLESS DOUBLE-BETA → **CUORE heritage**

e.g. COHERENT NEUTRINO SCATTERING → **EDELWEISS heritage**

SCIENCE DRIVERS: ASTROPHYSICS

A COUPLE KEY QUESTIONS TO BE ADDRESSED

- **Did inflation occur soon after the Big Bang ?**
  Observable: the Cosmic Microwave Background polarised pattern (CMB, T = 2.7K)

- **How the Universe structures formed ?**
  Observable: early evolution stages of galaxies, stars, planets (cold dust and gas)

e.g. MILLIMETRE ASTRONOMY

Blackbody's Wien law **(λ = 1mm ≡ 5K)**

- **mm-waves ≡ «Cold» radiation**

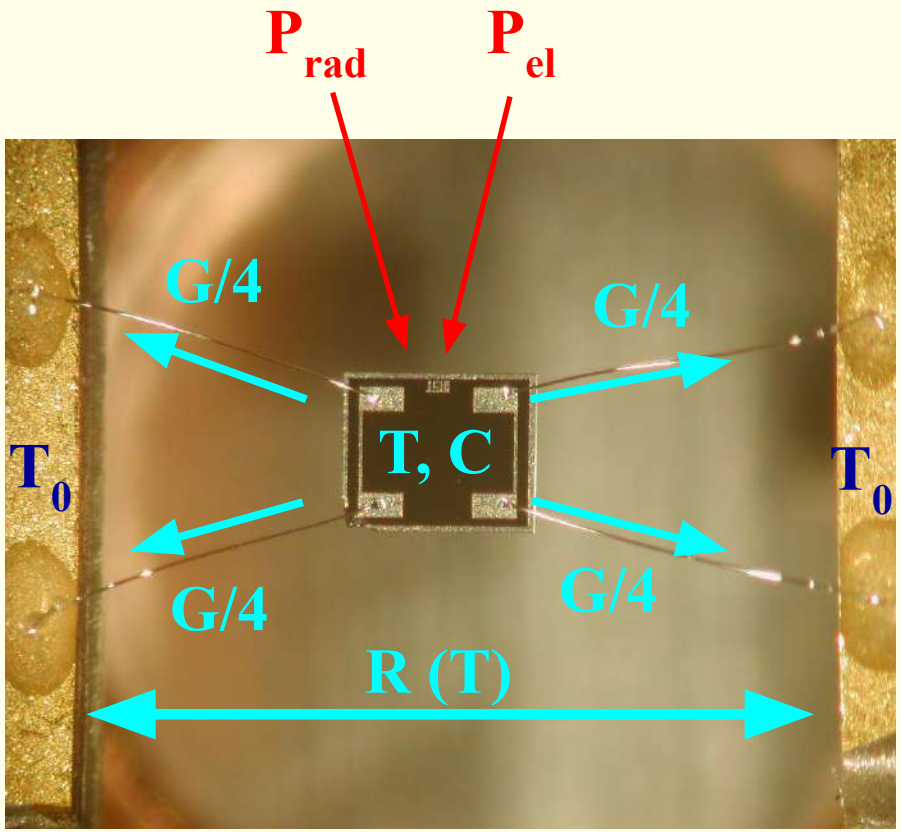
The millimetric Sky surveyed by Planck

BOLOMETERS (MIS, TES, MMC)

Measurable: R
(or any other electrical quantity function of T)

CALIBRATION

End result P_{rad}



A real « vintage » bolometer from the 90s

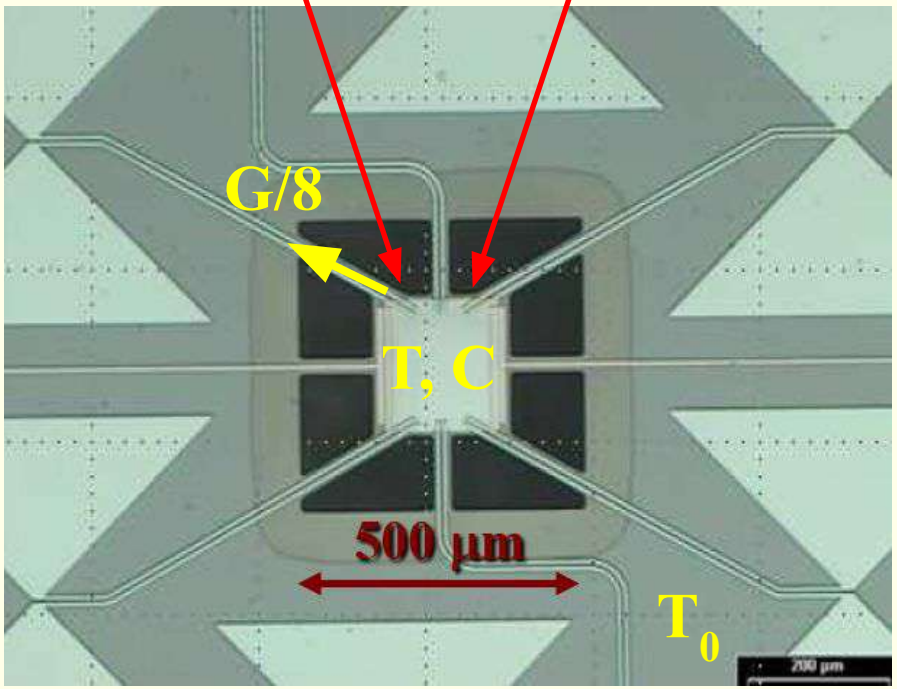
P.S. Reality is MUCH more complicated than that.

BOLOMETERS (MIS, TES, MMC)

Measurable: R
(or any other electrical quantity function of T)

CALIBRATION

End result P_{rad}

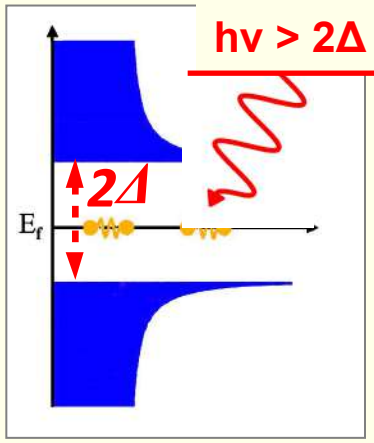


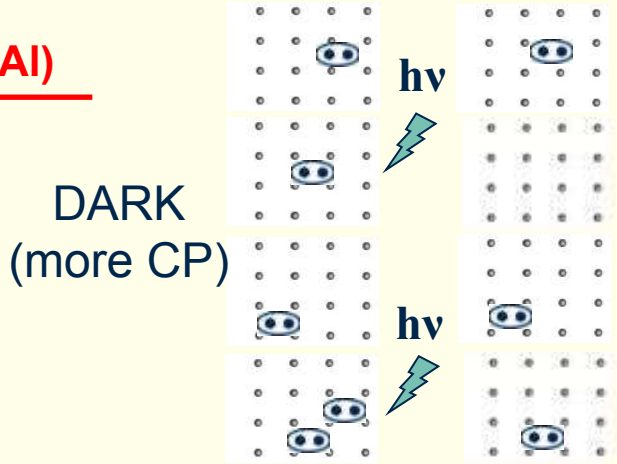
From the 2000s … microfabricated

P.S. Reality is EVEN more complicated than that.

SUPERCONDUCTING COOPER-PAIRS COUNTING

2Δ (Al) ~ 0.8 meV → A single "red photon" brakes ~ 10^3 CP





GOAL: count the Cooper pairs … to deduce how many are missing

HOW: measure their total kinetic energy

- MEASURE THE INDUCTANCE OF A FILM

Kinetic Inductance Detectors (KID)

KINETIC INDUCTANCE DETECTOR

DARK:

- $T << T_c \sim 1$ K
- deep & sharp resonance
- frequency □ f_0

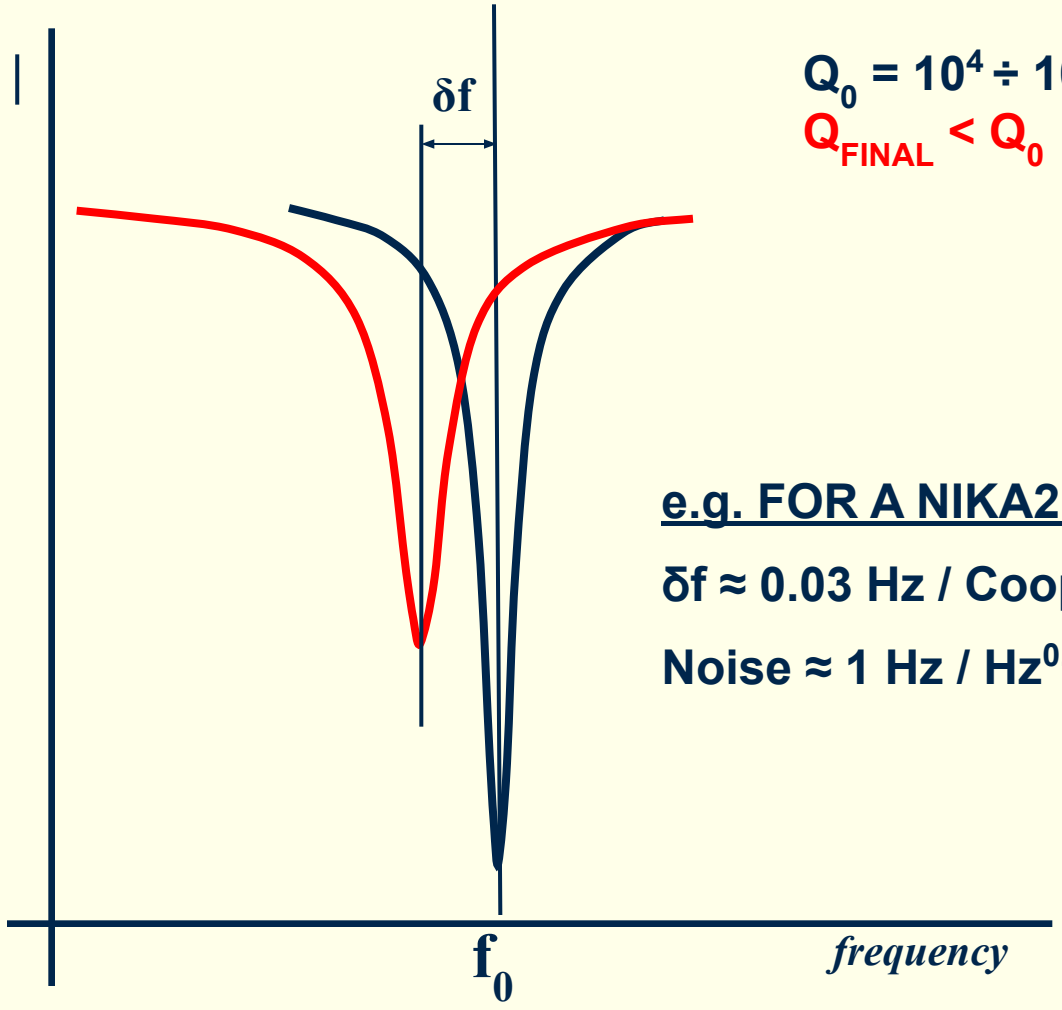
LIGHT:

- shallow & broad resonance
- frequency □ $f_0 - \delta f$

Large dynamics (linear!):

$$\delta f \propto \delta L_K \propto \delta P$$

APL 96, Issue 26, 263511 (2010)



$Q_0 = 10^4 \div 10^6$

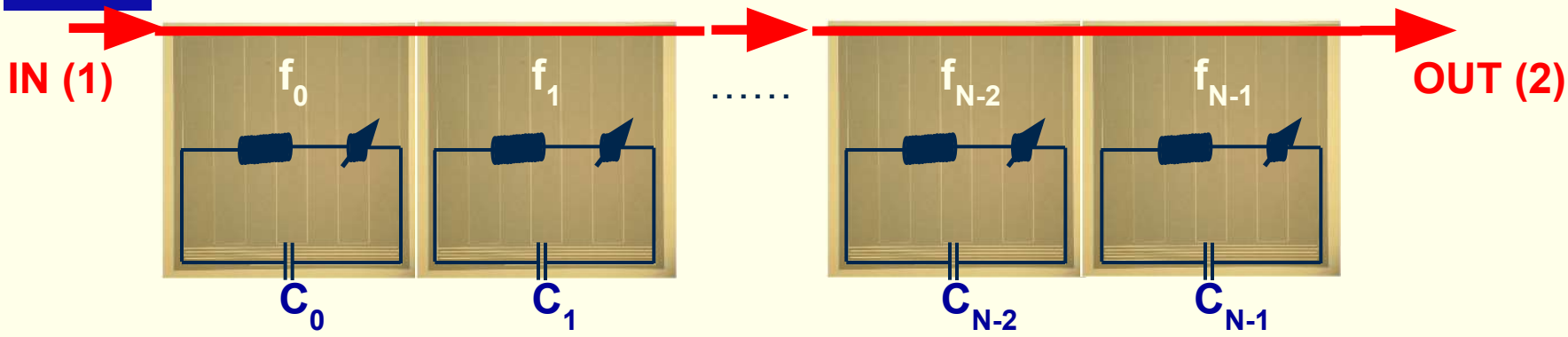
$Q_{FINAL} < Q_0$

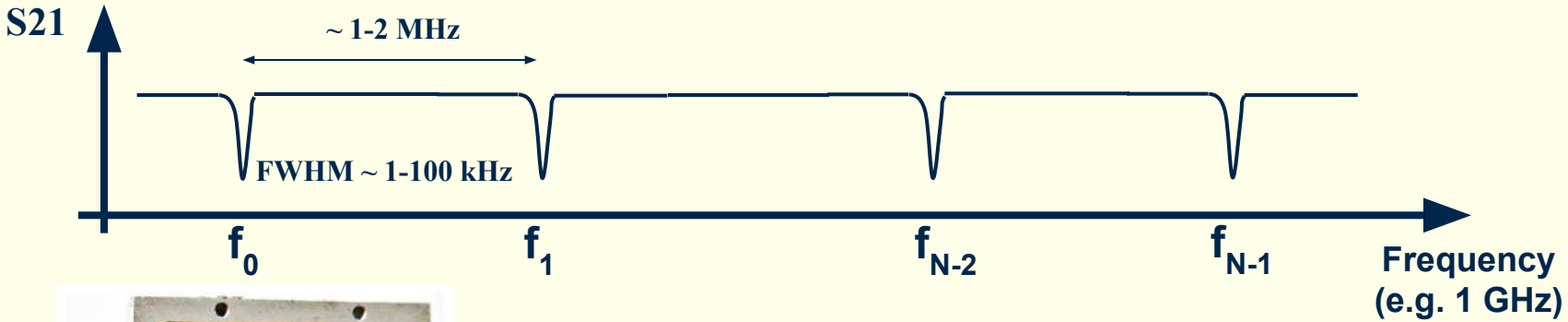
e.g. FOR A NIKA2 KID:

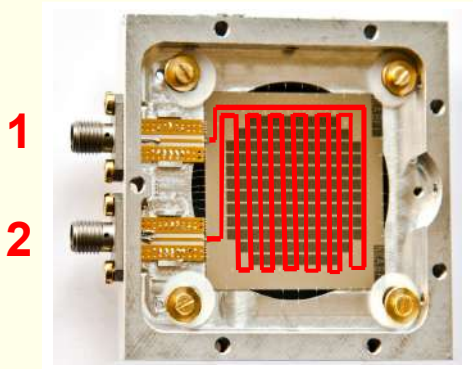
δf ≈ 0.03 Hz / Cooper Pair

Noise ≈ 1 Hz / $Hz^{0.5}$

RF MULTIPLEXING
(APPLICABLE TO KID & BOLOMETERS)







- Natural f-domain multiplexing
- High MUX factor (hundreds-thousands)

ALL THIS IN FRANCE

BOLOMETERS	PAIR-BREAKING
SINGLE EVENTS	
High-impedance (Si:P:B, NTD*)	KID (TiN, Ti)
TES (NbSi)	KID (Al, AlTiAl)
MMC (Au/Ag:Er*)	
High-impedance TES (NbSi)	
CONTINUUM	
MIS (Si:P:B)	KID (Al, TiAl, …)
TES (NbSi)	

* Commercial or "from collaborations" thermistors

… FOR THESE APPLICATIONS

PARTICLE PHYSICS

Dark Matter search, e.g. $m_{DM} \sim$ n,p
Neutrinoless Double Beta Decay
Coherent Neutrino scattering

ASTROPHYSICS

VIS-NIR, e.g. Dwarf galaxies
Sub-mm, e.g. Interstellar dust
Millimeter, e.g. Cosmology
X-rays, e.g. Compact objects

OTHER:

Metrology-Standards (gamma/x energy references)

……

DEPLOYED EXPERIMENTS

PARTICLE PHYSICS

France (ILL-RICOCHET)
France (LSM-EDELWEISS)
France/Spain (Canfranc-CROSS)
Italy (Gran Sasso-BULLKID-DM)
Italy (Gran Sasso-CUPID)

DEEP UNDERGROUND REACTOR (NEUTRINOS)

ASTROPHYSICS

Deep Space (Herschel)
Spain (NIKA, NIKA2)
Argentina (QUBIC)
Chile (Artemis, CONCERTO)
Tenerife (KISS)
Japan (Tsukuba-Grenoble)
High atmosphere (PILOT)

HIGHEST PLATEAUX BALLOONS & SPACE

TECHNOLOGY PLATFORMS

BOLOMETERS

CEA-LETI (MIS, SUB-MM & X)
ICJLAB* (MIS-TES, DM, ν, CMB)
C2N-ICJLAB (TES, CMB)
NANOFAB-NEEL (MIS et al.)
OTHERS ?

KID

PTA-GRENOBLE (MM-WAVE & DM)
PARIS OBSERVATORY (VIS-NIR)
IEMN-LILLE (MM-WAVE)
NANOFAB-NEEL (MM-WAVE)
IRAM (MM-WAVE)

* Non-standard processing, e.g. side-lithography

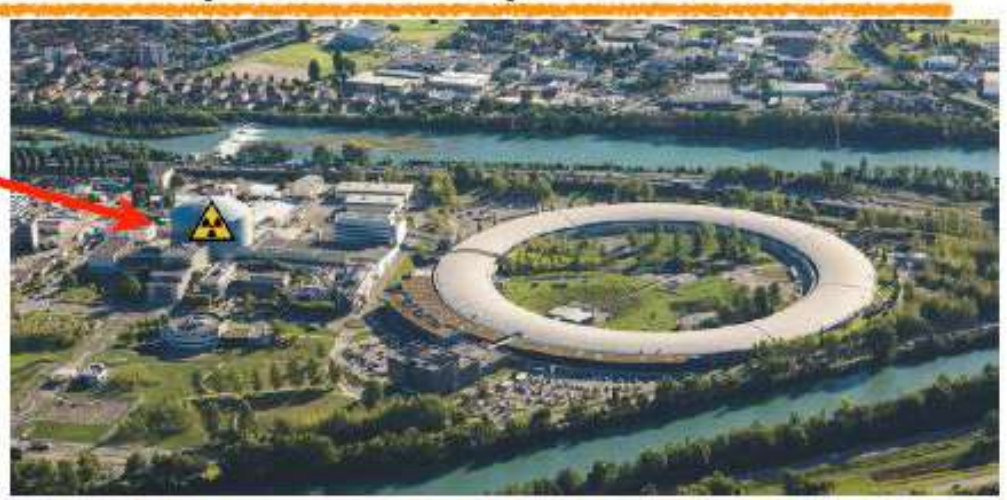
FOCUS ON DETECTORS FABRICATION

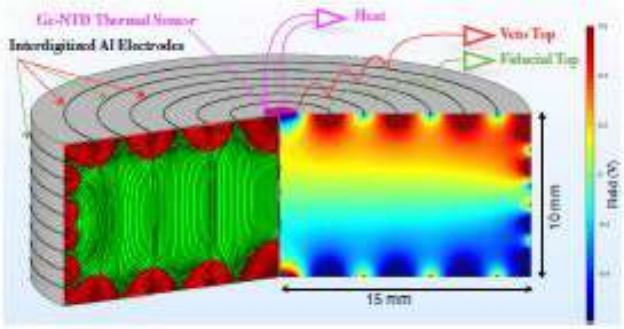
OTHER LABS LIKE IP2I LYON, CEA-SACLAY, APC-PARIS, LPSC, IRAP ET AL. ARE MORE INVOLVED IN DESIGN, PACKAGING, ELECTRONICS, SYSTEM IN GENERAL AND SCIENCE EXPLOITATION.

→ THE FULL CHAIN IS NEEDED

Ricochet @ ILL (Grenoble)

- Coherent Elastic Neutrino Nucleus Scattering (**CEνNS**) measurement
- ~**5 MeV** ν from 60 MW Reactor @ ILL
- ~**100 eV nuclear recoil** in Ge
- Installed end of 2023. **Sclence Runs started summer 2005 for 2 years**
- Heat-and-ionization **cryogenlc Ge** detectors from EDELWEISS legacy





J Low Temp Phys 199, 798–806 (2020)

Fig. 6 Electrostatic simulation of a Full Inter-Digitized electrodes scheme on a 38 g germanium crystal (ϕ=30 g, h=10 mm).

- **France - US - Russla - Canada coll.**

RICOCHET
Coherent Neutrino Scattering Program

Background mltlgatlon based on :

- Electronic/Nuclear **recoll dlscrlmlnatlon**
- 22 tons 300K and 1K **Pb & PE shleldlng**
- 35 m² **Full muon veto** coverage (incl. cryo veto @ 4K)
- Reactor ON/OFF cycles

→ *Commissioning paper arXiv:2507.22751 (accepted in PRD)*

NEUTRINO-LESS 2β DECAY

See Pia Loaiza talk

CUPID – CUORE Upgrade with Particle IDentifications

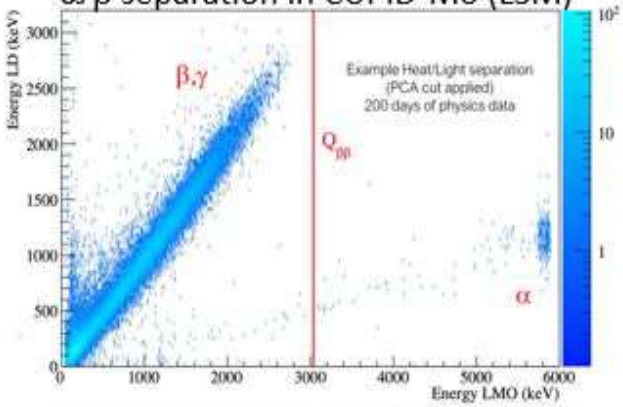
- **CUPID** – next generation experiment to search for neutrinoless double beta decay
- Investigate the candidate ^{100}Mo embedded in enriched $Li_2{}^{100}MoO_4$ crystals
- Based on scintillating bolometers of Li_2MoO_4 with powerful rejection of α background
- Built on the successful **CUORE** and **CUPID-Mo** experiments
- CUORE will provide the cryogenic infrastructure at LNGS (INFN), CUPID-Mo have demonstrated the technology at LSM
- About 1600 detectors containing 240 kg of ^{100}Mo → realistic expansion to 1 ton

Major collaboration with INFN within the CUPID international collaboration

INFN: cryogenic infrastructure, assembly line, electronics, cleaning and other major components

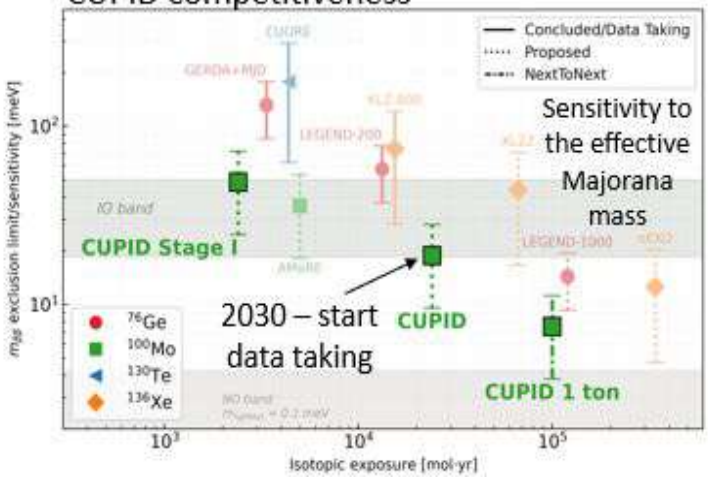
France (IJCLab+IRFU): light detectors, assembly elements (storage, gluing), part of electronics

α/β separation in CUPID-Mo (LSM)



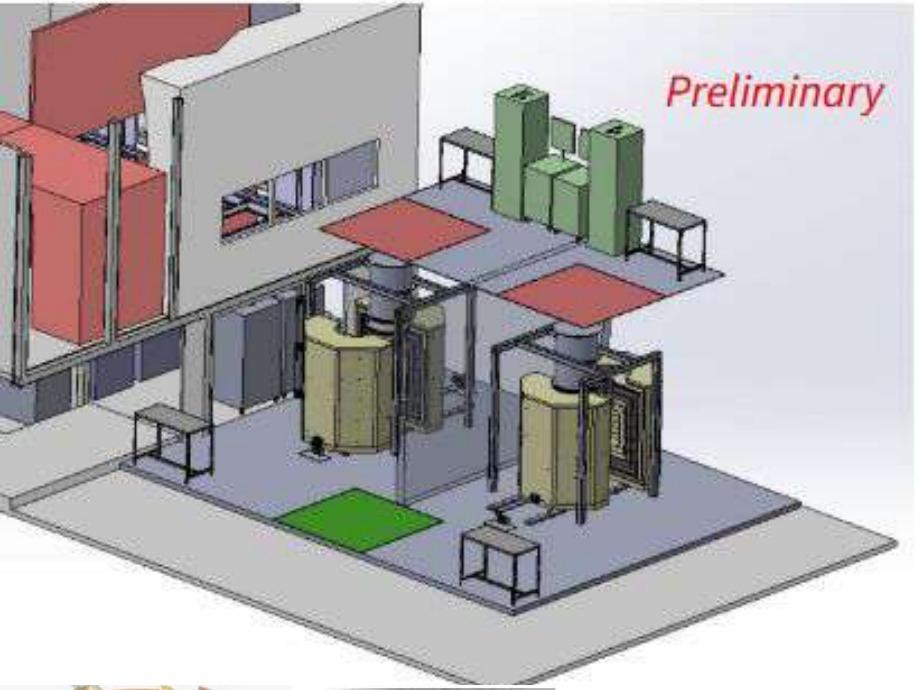
> 99.9% α particles rejection efficiency

CUPID competitiveness



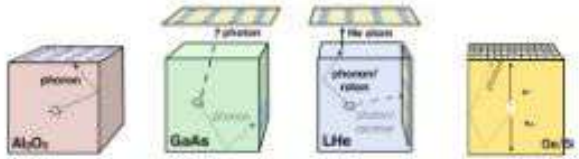
DARK MATTER: TESSERACT

Transition Edge Sensor with Sub-Ev Resolution And Cryogenic Targets



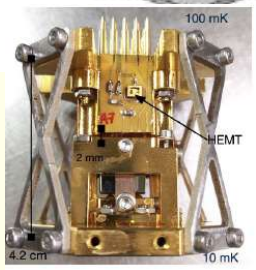
One experimental design, two cryostats, several targets :

- SPICE (Al_2O_3 and GaAs)
- HeRALD (LHe)
- Ge/Si bolometers



All equipped with new generation TES

Complementary DM sensitivity
Commissioning at Laboratoire Souterrain de Modane

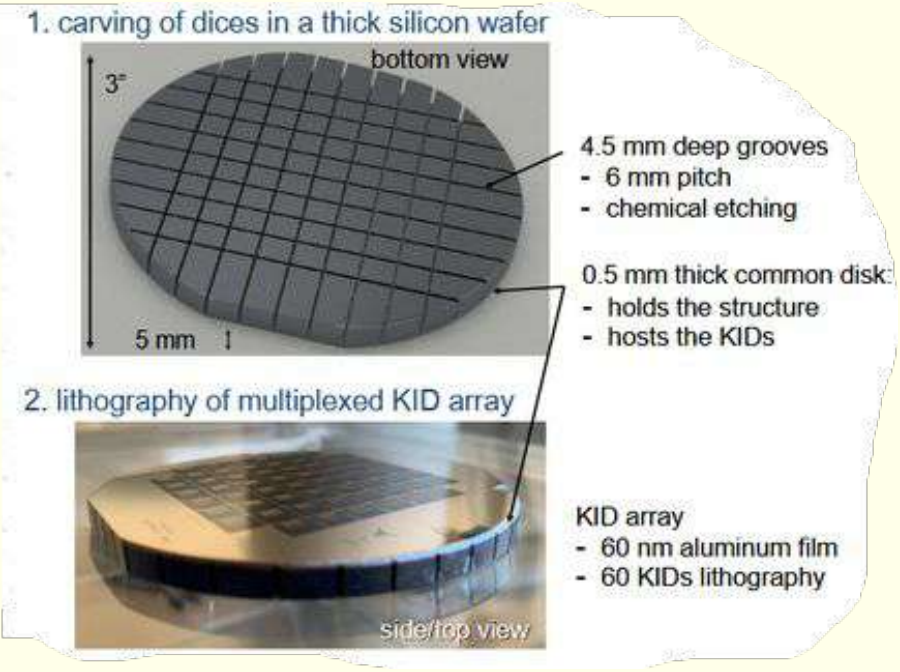


The French TESSERACT technologies

- HV with single-e/h sensitivity for electron-recoil DM search
- LV with dual phonon-ionization readout for nuclear-recoil DM search

See Paul Vittaz talk

DARK MATTER: BULLKID-DM



PROTOTYPE WILL BE INSTALLED IN GRAN SASSO. See Giorgio's talk later.

OUR **BIG HOPE**: REDUCED LOW-ENERGY "HEAT-ONLY" EXCESS THANKS TO THE SUPERCONDUCTING GAP "QUANTUM SHIELD".

LET SEE … ALONE, A GOOD REASON TO DO THE EXPERIMENT.

HIGH-ENERGY ASTRONOMY

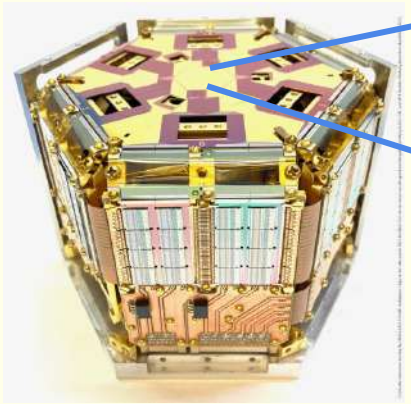
The NewAthena space observatory (X-IFU)

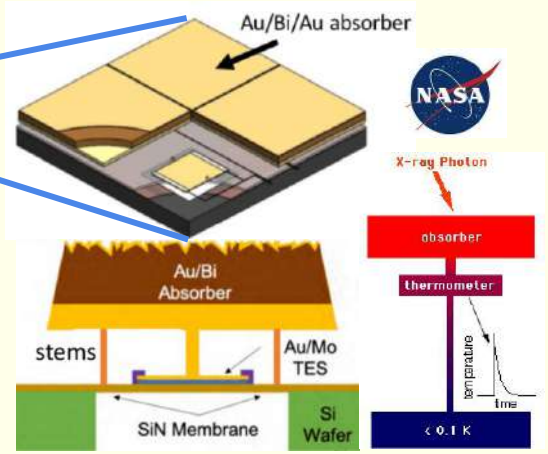
Large class ESA mission. Launch: 2037

X-ray integral field unit (X-IFU):

- **1500 TES** µ-calorim @ 50 mK
- ΔE < 4 eV @ 6 keV (**first demo 2025 <2.5 eV**)
- Time-division multiplexing (Mux 48)

Warm Readout developed in France



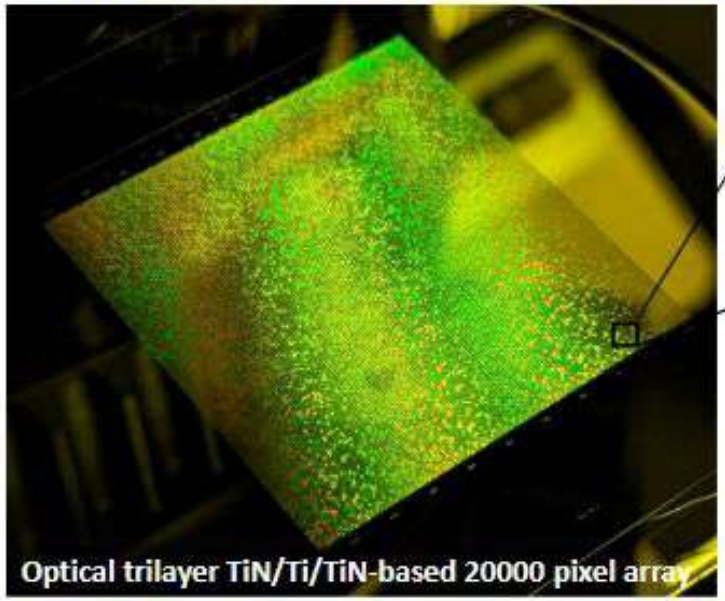


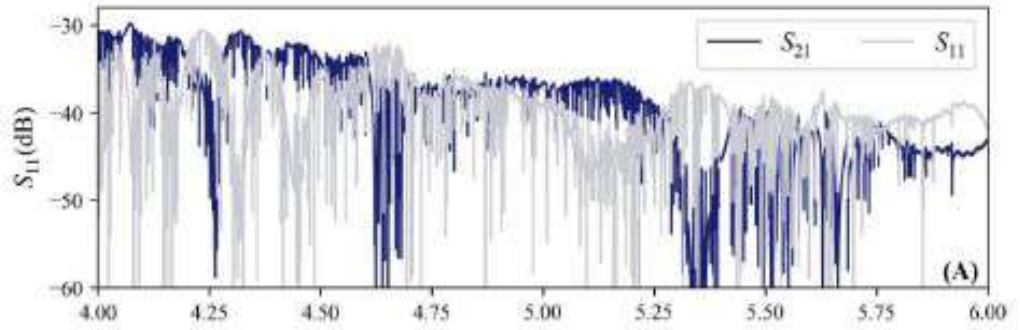
AwaXe SiGe ASIC family developed for X-IFU warm front-end (WFEE)

50mK test bench in IRAP-Toulouse

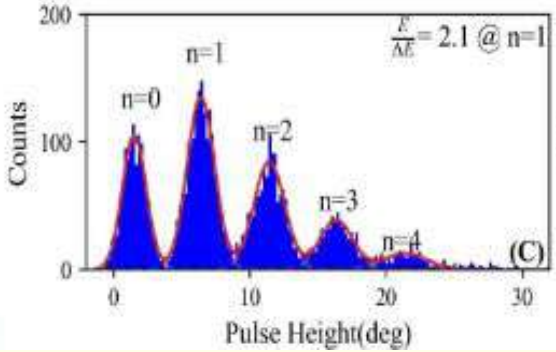
VIS-NIR ASTRONOMY

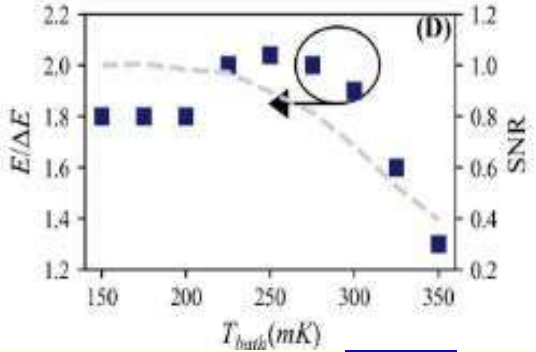
Project: SPIAKID (Spectro-Photometric Imaging in Astronomy with Kinetic Inductance Detectors)





- Based on Sapphire
- Pixel distance: 180um
  - Angular resolution of 0.45"
- Meander size about 35x35 um
- Change of finger length larger than 1 um
- Frequency: 4-8GHz
- 2000 pixels per readout line
- Q_c~50000

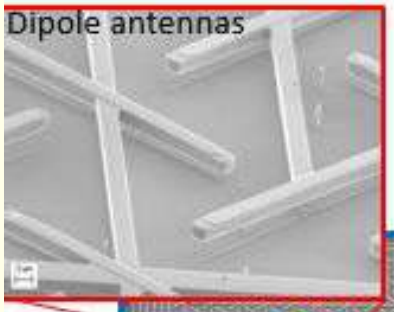


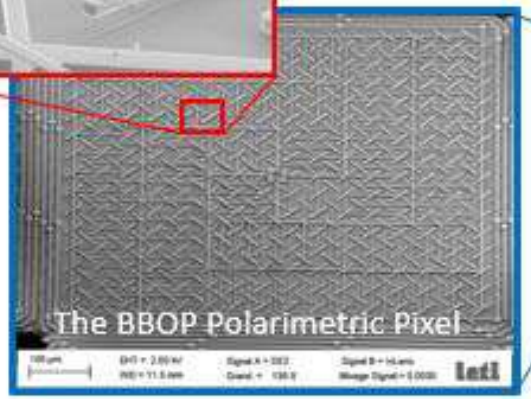


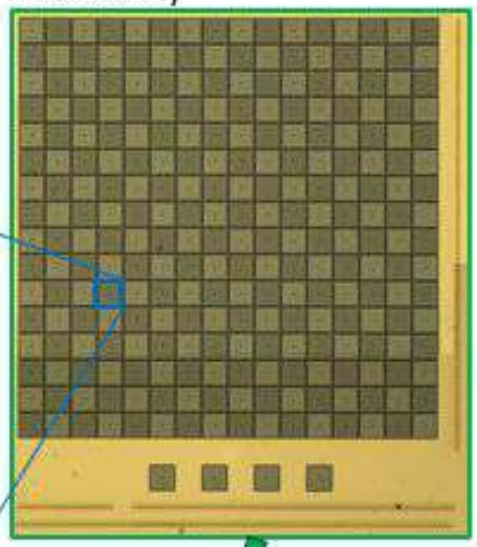
J. Low Temp. Physics, **2024**
Applied Physics letters, **2024**

SUB-MM ASTRONOMY

Bolometers for submillimeter astrophysics





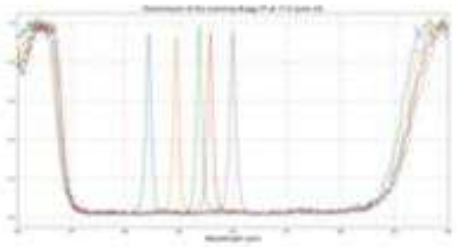


Development of High-sensitivity Silicon bolometers with polarimetric capacity

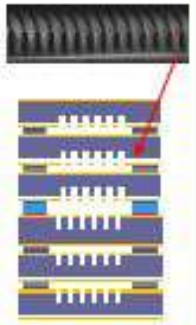
- Development initiated as part of the ESA SPICA Space Mission (2017 – 2021) for the BBOP imaging polarimeter
- BBOP detectors are intrinsically sensitive to the polarization of light : 2 independant networks of antenna per pixel detect 2 orthogonal components of polarized light, no need for a rotating HWP for modulation.
- We are developing the POLARYS camera at APEX telescope, that will use BBOP detectors at 350 µm.

Development of on-chip spectroscopy in the submillimeter range

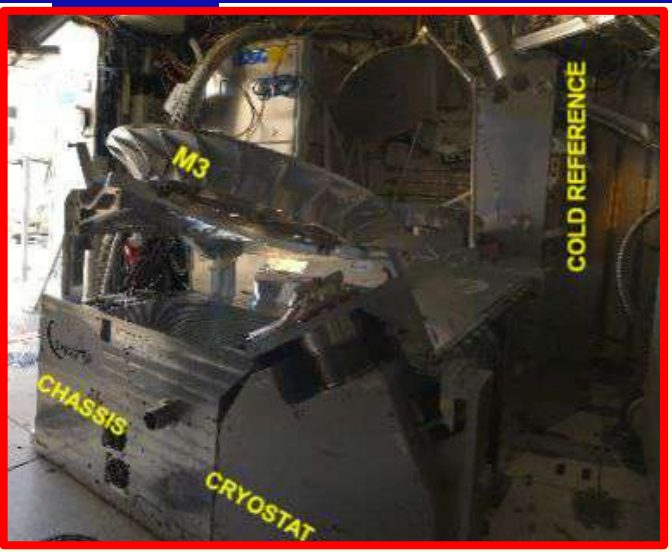
Cryogenic Silicon Fabry Perot



Stationary array of Fabry-Perot made of microstructured Si

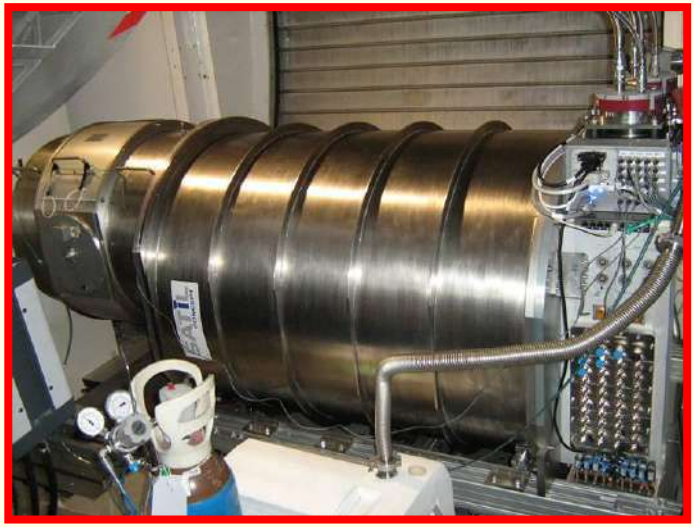


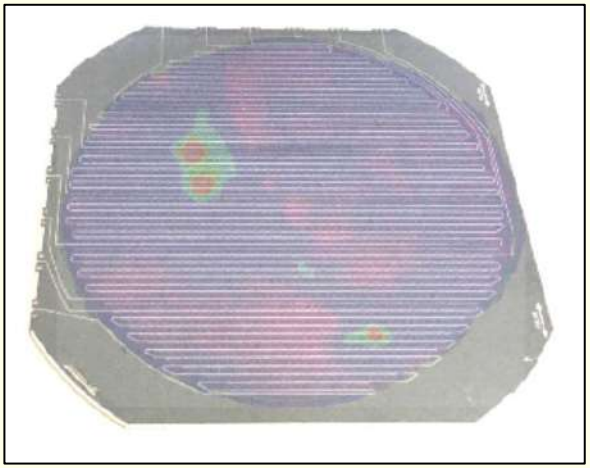
MM-WAVE ASTRONOMY & COSMOLOGY



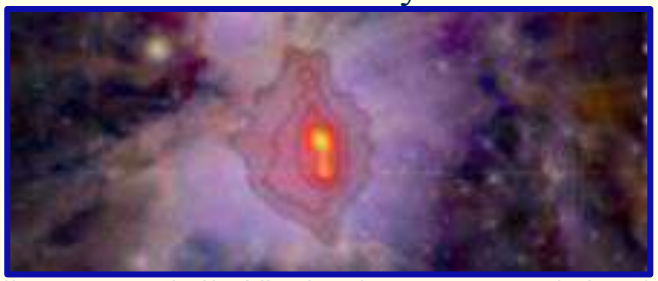
NIKA2@30-m (right) is, since 2015, mapping with unprecedented resolution and depth patches of the Sky at 150 and 250 GHz. *"Vanta innumerevoli tentativi d'imitazione"*.

CONCERTO@APEX (left) has carried out, in the period 2021-23, the first LIM of the high-z [CII] line. Setting a first upper limit to be (hopefully) improved by second generation instruments, e.g. CCAT/FYST, NIKONA, TIME, TIFUUN, SPT-SLIM and many others.

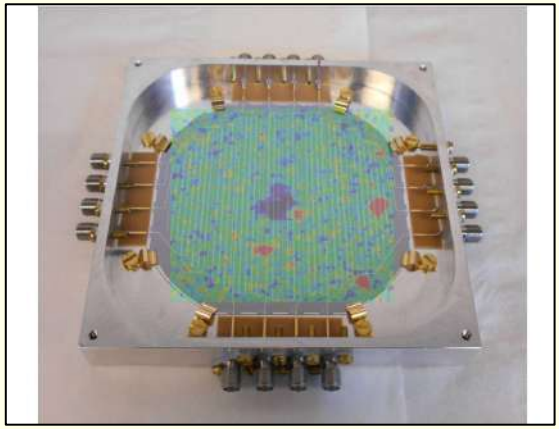




CONCERTO 2,152 pixels arrays (APEX telescope, 2021-2023)



https://www.eso.org/sci/publications/announcements/sciann17736.html

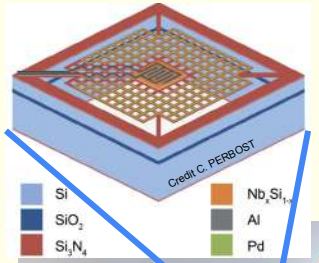


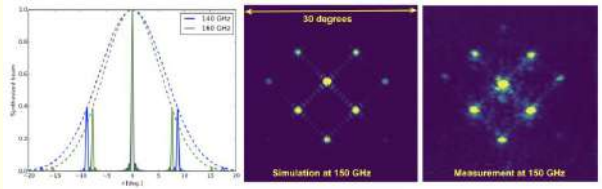
NIKA2 mapping a high-z galaxy cluster. 30-m IRAM telescope Pico Veleta)

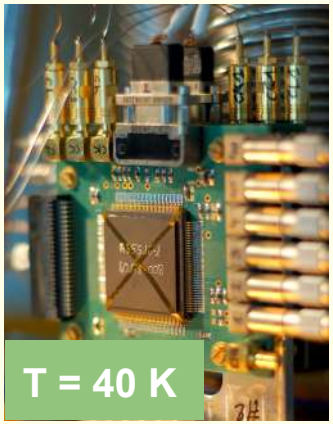
CMB POLARISATION

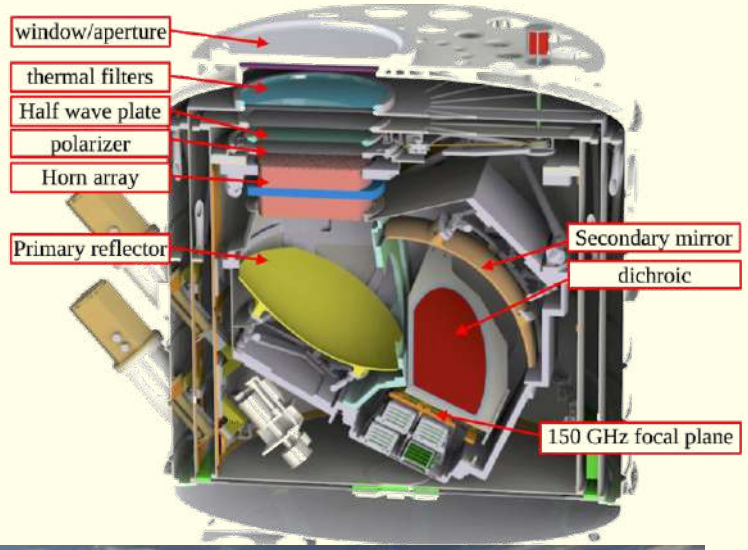
QUBIC (QU Bolometric interferometer for cosmology)

- **Spectral information** from interference side lobes
- **256 NbSi TES** @ 150 GHz currently deployed (¼ of FI)
- Time division multiplexing (MUX 128) with **cold ASIC**



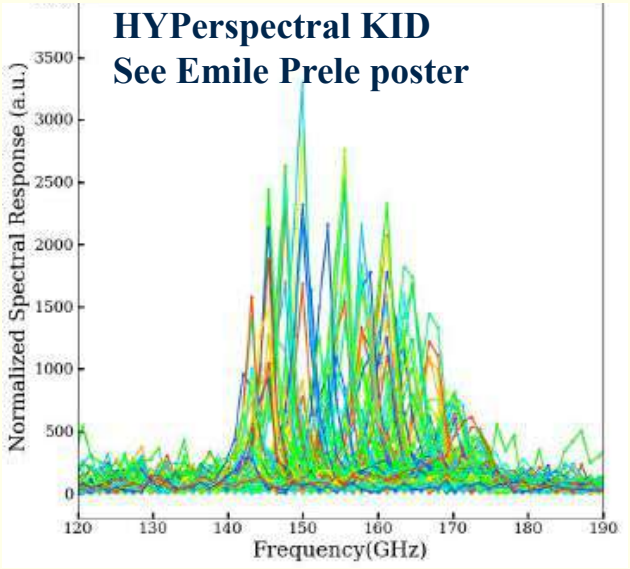




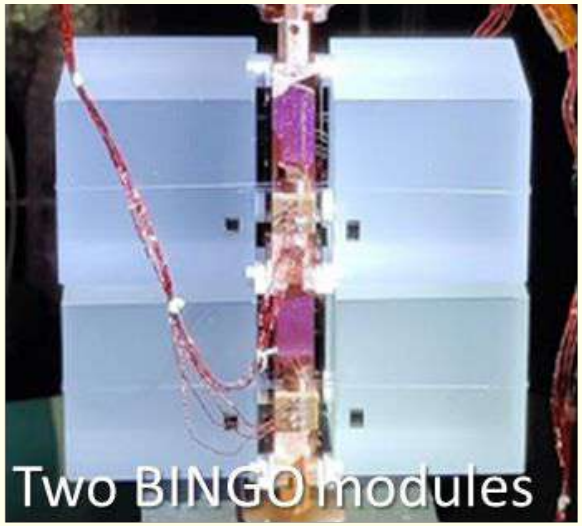


ON-GOING* .. JUST A SMALL TASTE

Line Intensity Mapping



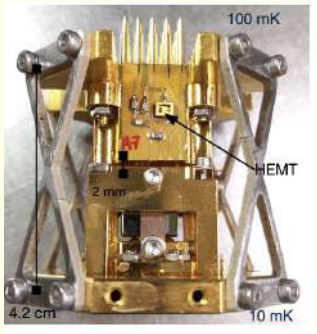
DOUBLE-BETA

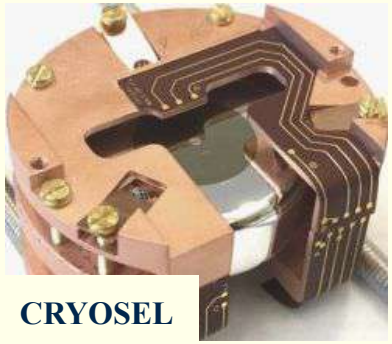


CMB

Simons Observatory
KAIROS

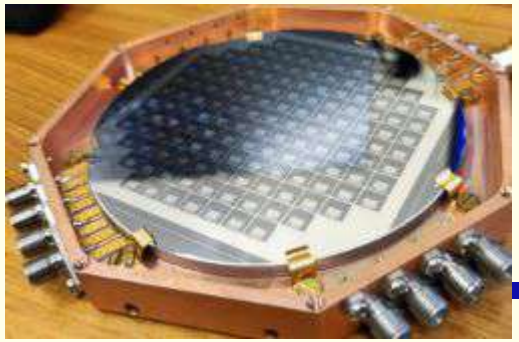
TESSERACT





CRYOSEL

BULLKID-DM



See G. Del Castello and Paul Vittaz talks

CONCLUSIONS AND THANKS

The border between Italy and France is extremely porous.

→ SYNERGIES & CONSTRUCTIVE COMPETITION

The **French LTD community** is positively (hopefully) contaminated. The dopants are Claudia Nones, Silvia Scorza, Valentina Novati, Martino Calvo, Andrea Giuliani+Catalano, Emiliano Olivieri, myself, and others (sorry !)

A number of **Italian LTD researchers** have on the other hand worked in France. They brought a bit of France across the Alps. Andrea Tartari, Angelo Cruciani, Antonio D'Addabbo, Daniele Delicato, and so many others (sorry !)

FIND THE ERROR .. AND THANKS FOR YOUR ATTENTION !!