Cryogenic Detectors & associated instrumentation.
- IN2P3 Overview -

GDR DI2I

-Détecteurs et Instrumentations pour les 2 Infinis-

SUBATECH 10-12 Juillet 20213 *https://indico.in2p3.fr/event/29808/*

Alex Juillard IP2I

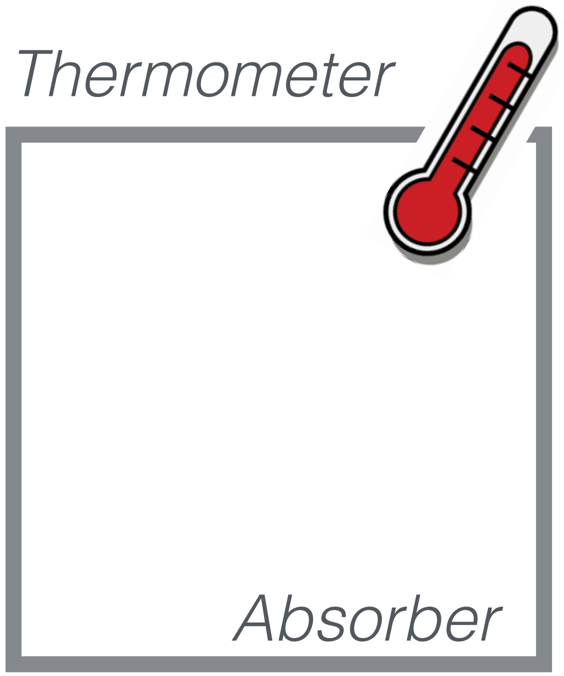
contribution from APC, IP2I, LPSC, IJCLab & Institut Néel

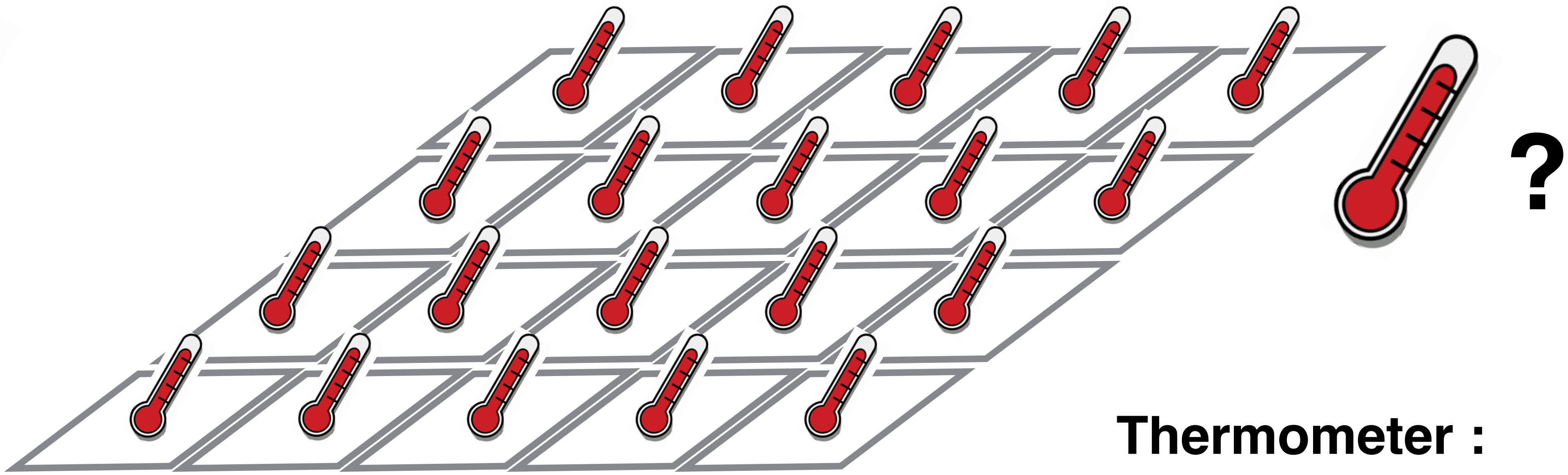
IN2P3
Institut national de **physique nucléaire**
et de **physique des particules**

iP2i LES 2 INFINIS LYON

- ✦ **Cryogenic Detector ?**
  - basics
- ✦ Examples of running **« large instrument »** (with IN2P3 involvement)
  - EDELWEISS
  - CUPID-Mo
  - NIKA2
  - QUBIC
- ✦ **Ongoing R&D** & next generation experiments
  - massive bolometer & matrix
- ✦ **Conclusion**

Cryogenic Detector ??





« massive » Bolometer:

- ✦ ~ g ➙ ~ kg
- ✦ Some of the fabrication step done *«by hand»*
- ✦ Particle detection « one by one »
- ✦ Main application : **Rare event detection**
  - Dark Matter
  - $0\nu\beta\beta$
  - CEνNS

Matrice de Bolomètre :

- ✦ 1 ➙ 100k « pixels »
- ✦ Some of the fabrication step done *«collectively»*
- ✦ Particle detection « one by one » or by flux
- ✦ Main application : **Astro**
  - Sub-mm (50-600 Ghz)
  - X

Thermometer :

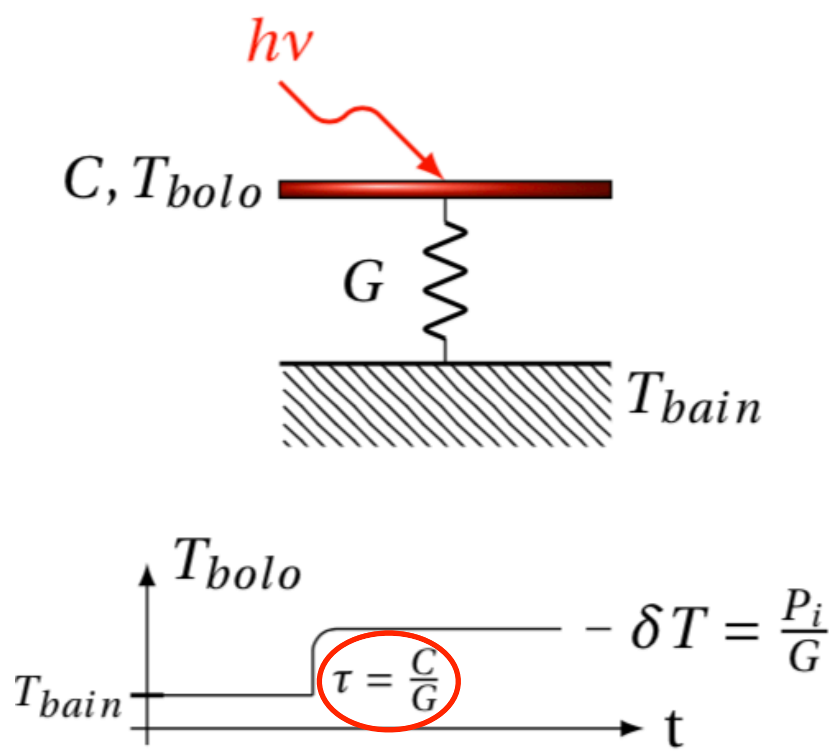
- ✦ T ➙ measurable value
- ✦ Resistive
  - superconductor
  - Metal InsulatorTransition
- ✦ Magnetic
- ✦ w/ out of equilibrium mediator
  - Copper pairs in SC material :
  - Kinetic Inductance vs dN_{qp}
  - Out of equilibrium phonon can brake Cooper Pairs

Link with Quantum sensor

Cryogenic Detector ??

D. Prêle DRTBT 2018

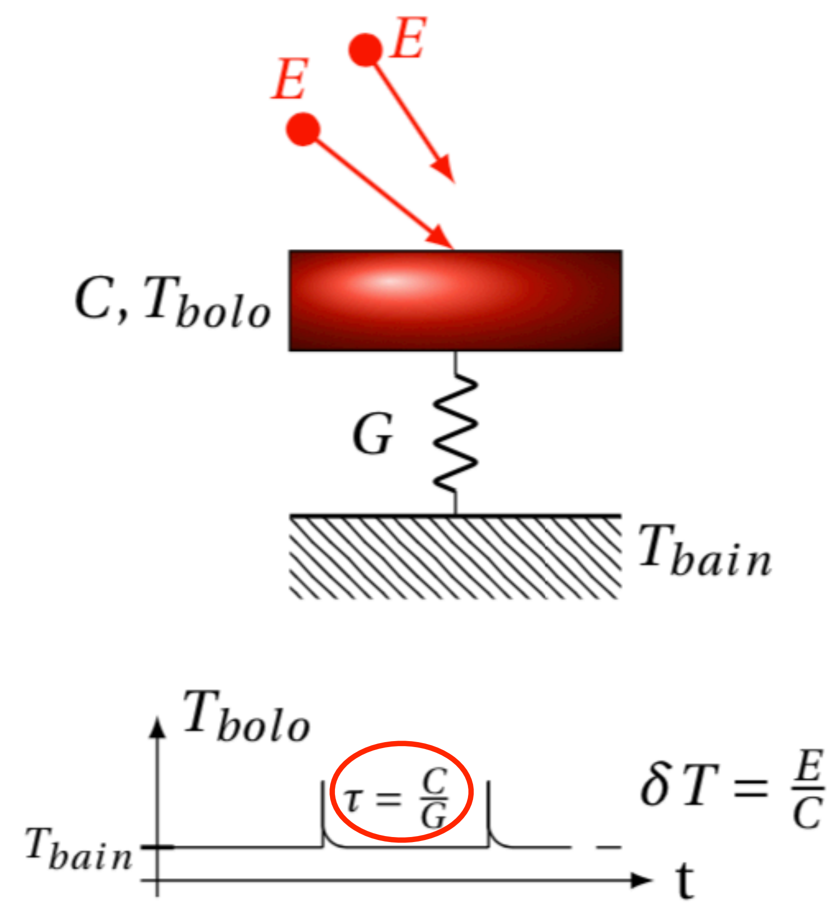
"background"/flux de photon



« Bolometer » Mode

- ✦ Response ~ C/G
- ✦ NEP = $\sqrt{4k_BT^2G}$ [W/√Hz]

photons>eV/particules



« Calorimeter » Mode

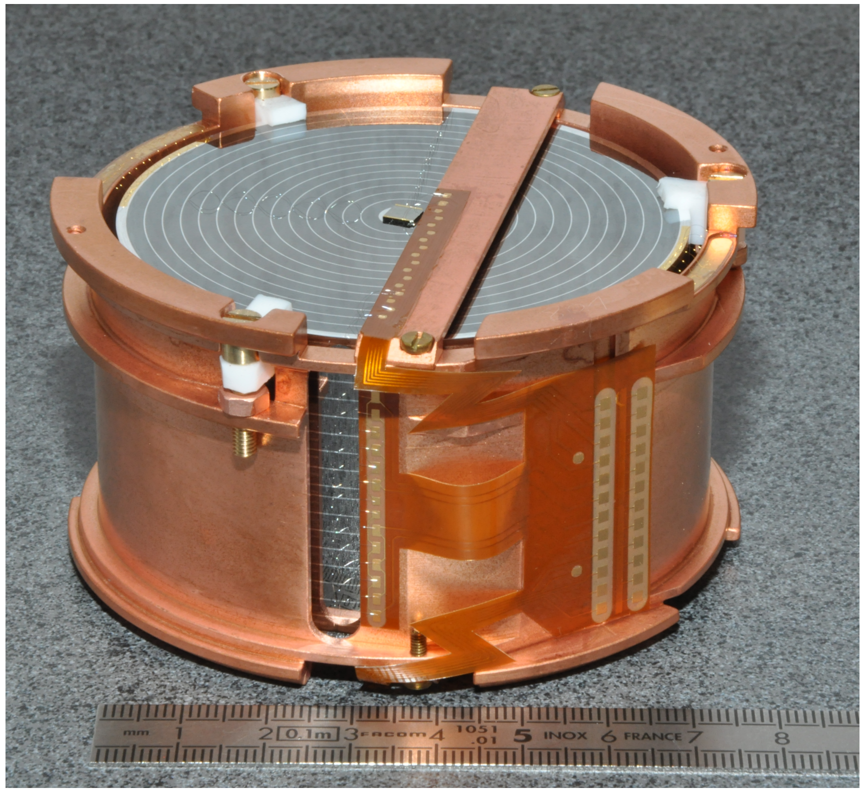
- ✦ Decay ~ C/G
- ✦ $\delta E = \sqrt{4k_BT^2C}$ [J]

Low Temperature → Sensitivity ↗ & Noise ↘

T_{bath} ~10 mK - 300 mK

R&D = absorber + thermometer + electronics (Z adaptation, gain, readout) + cryo environment

Ex. of instrument : EDELWEISS-III



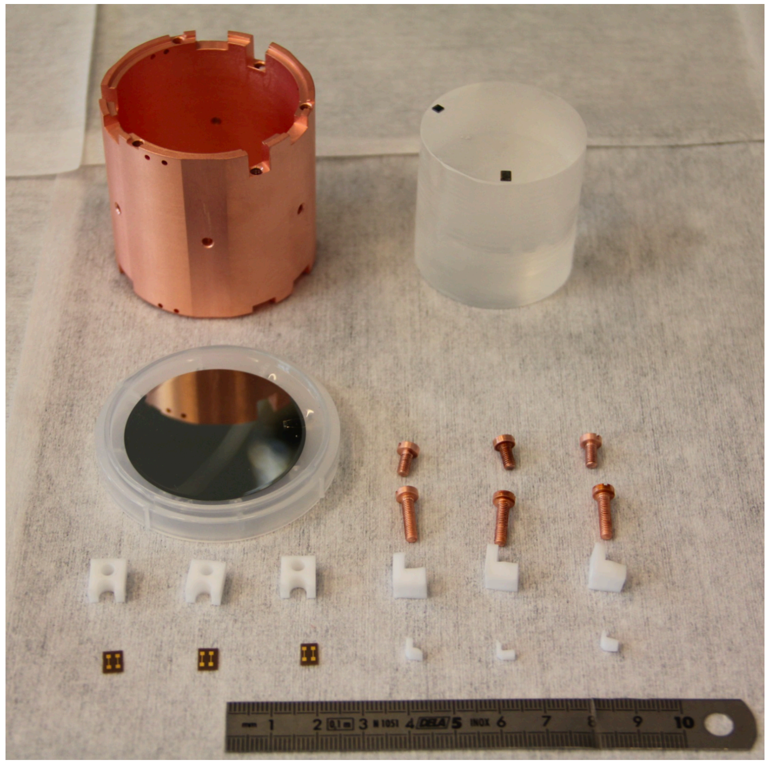
36 * FID-800

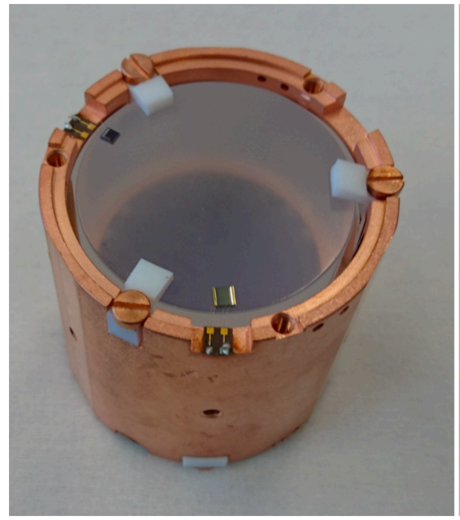
- ✦ **Ge 820 g**
- ✦ High impedance Ge-NTD thermometer (neutron doped Ge crystals)
- ✦ 4 sets of Al electrodes for charge collection
  - Simultaneous measurement of **ionization & heat**
  - Background active rejection

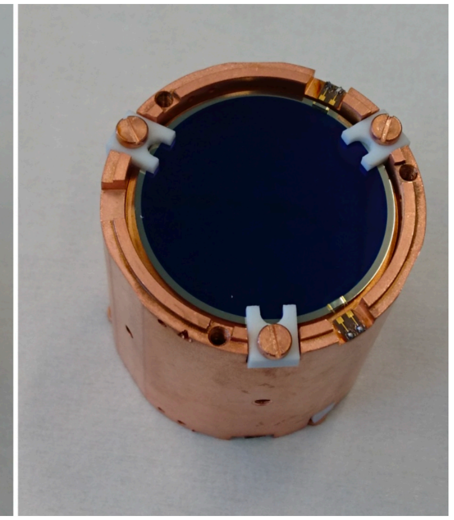
Running 2013-2023

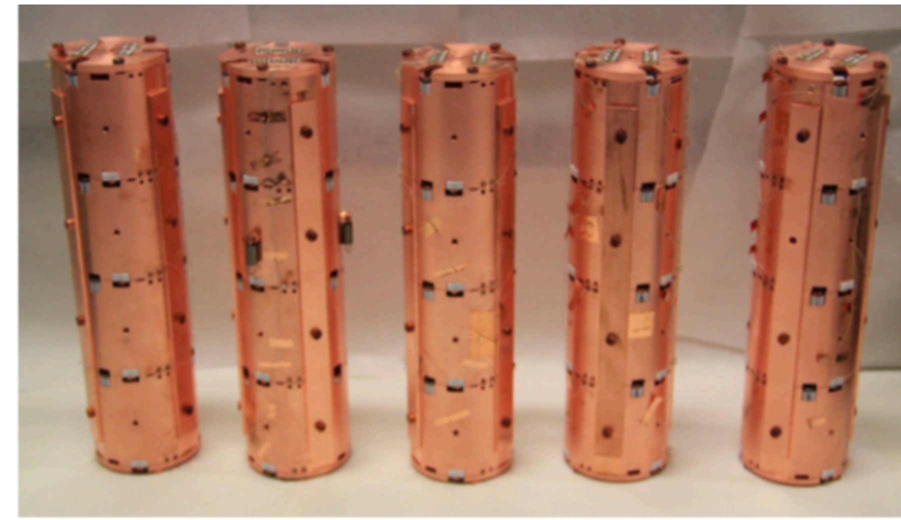
- ✦ **10mK Cryostat** + 40 tons of shielding (PE + Pb) @ LSM
- ✦ **3000 coax. cables (6 km)**
- ✦ **350 Si-JFET transistors@ 120K**
- ✦ 36*2 « Bolometers Boxes » @ 300K

Ex. of instrument : CUPID-Mo

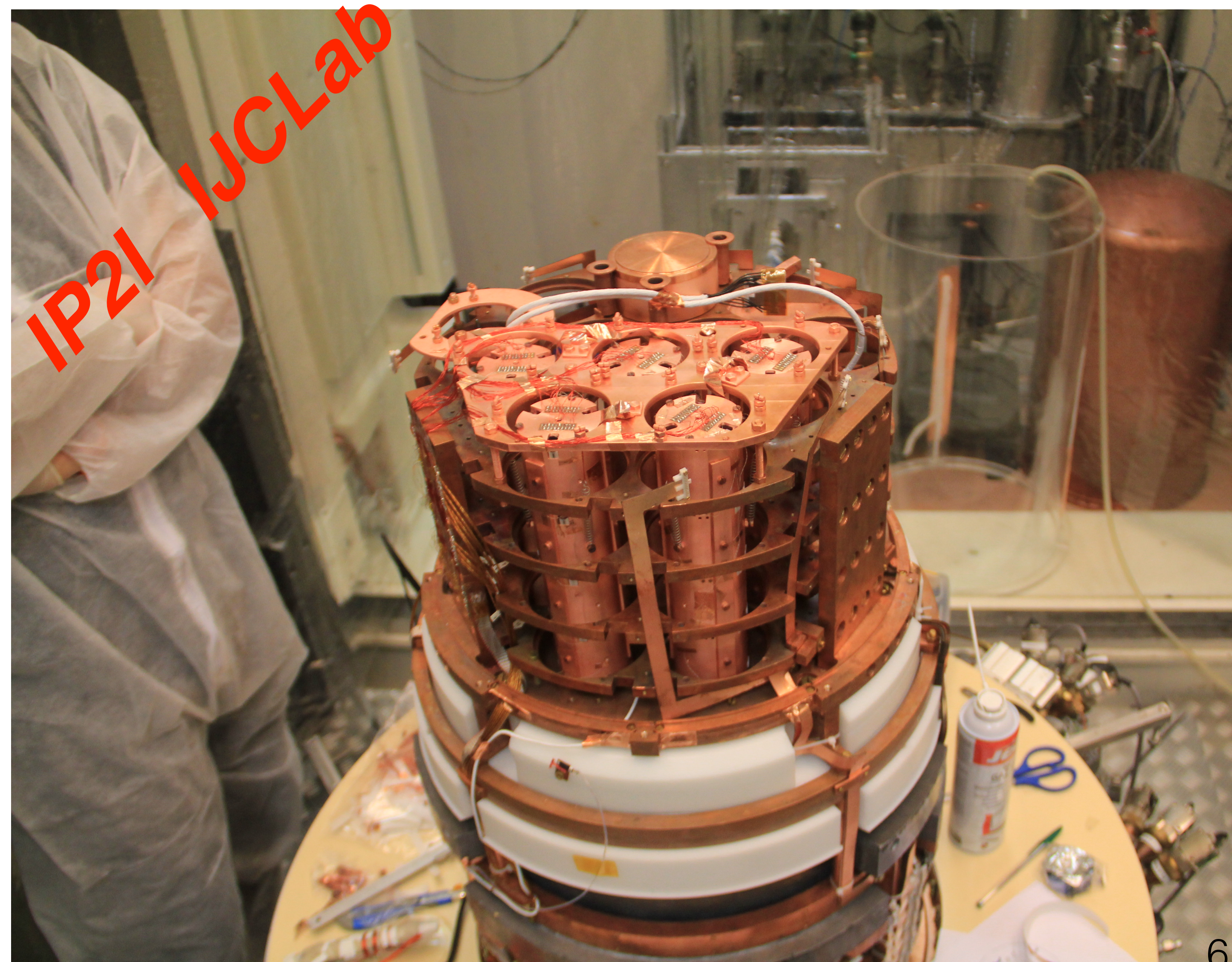








Eur. Phys. J. C **80**, 44 (2020)



5 towers of 4 detector (2018)

- Absorber **$Li_2{}^{100}MoO_4$**: Ø 43.8 x 45 mm, 210 g
- Light detector: Ge wafer Ø 44.5 mm x 170 μm with SiO coating
- Ge-NTD thermometer
- Simultaneous measurement of **ligh & heat** for alpha bkg discrimination
- Low radioactivity Cu

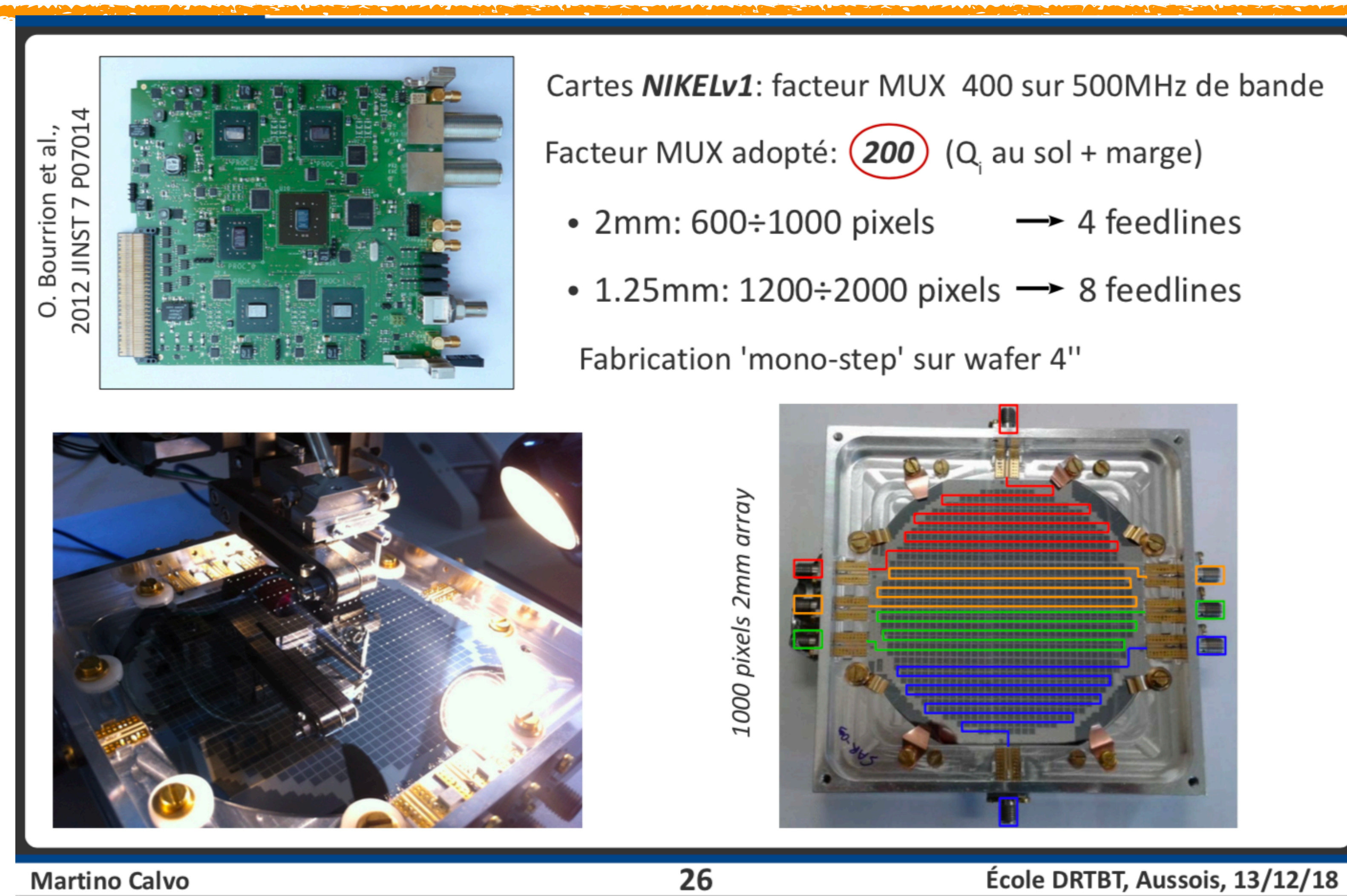
Cryostat, Electronics & DAQ = EDELWEIS-III

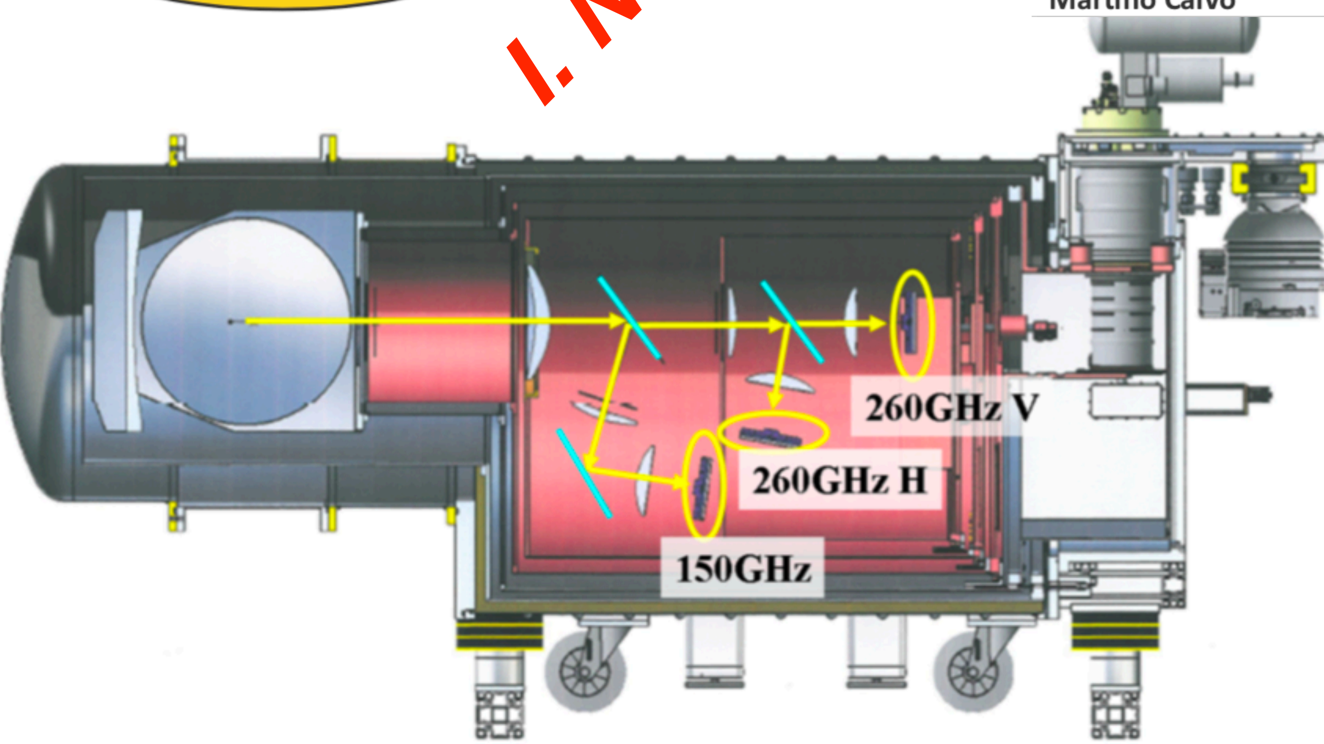
Ex. of instrument : NIKA2

A&A 609, A115 (2018)

Sierra Nevada (Spain)
@2900m a.s.l.

I. Néel LPSC



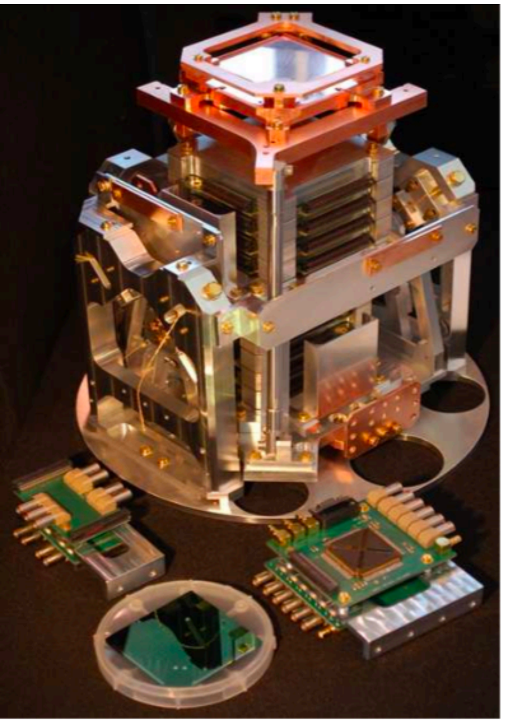


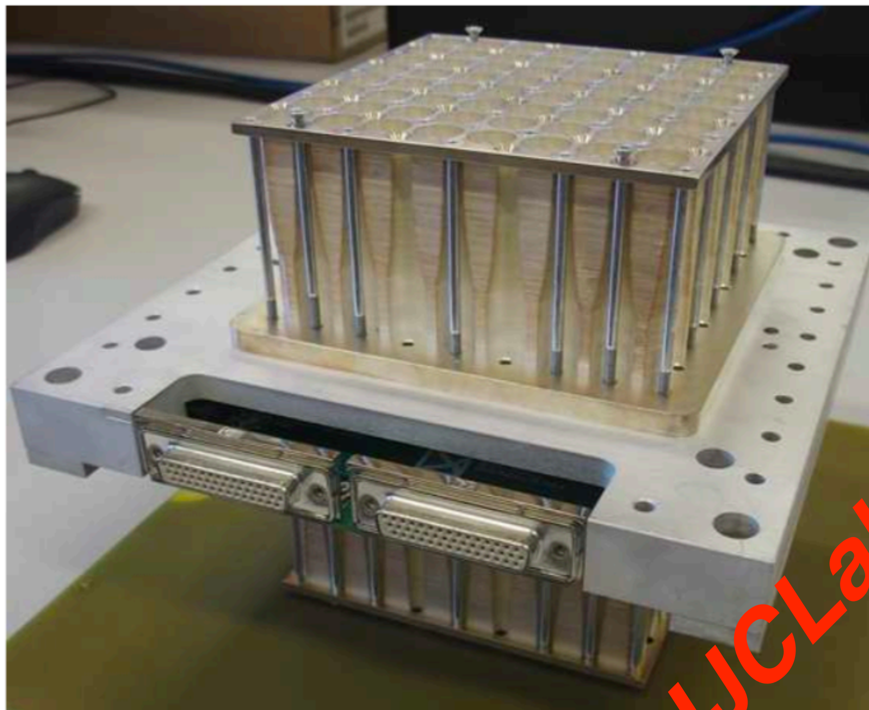
Band	Number of KIDs	Wavelength	Bandwidth
NIKA2 2 mm/150 GHz	616	2.00 mm	125-170 GHz
NIKA2 1 mm/260 GHz	2x1140	1.15 mm	240-280 GHz

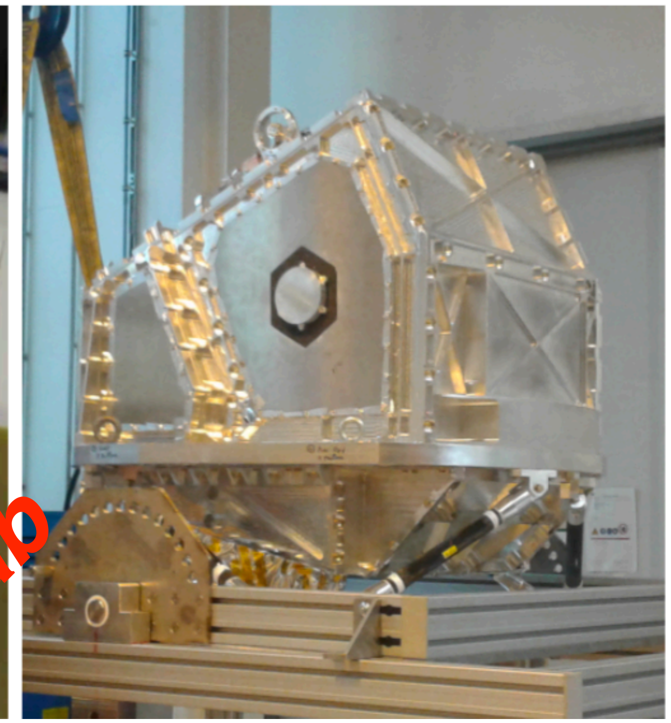
3 KIDs Matrices (kinetic inductance det.)

- ✦ data taking since 2018
- ✦ 150mK Cryostat
- ✦ **3000 pixels. 150 & 260 GHz**
- ✦ **Only 20 feed lines and 20 HEMT LNA@4K !**
- ✦ LPSC 300K elec.

Ex. of instrument : QUBIC

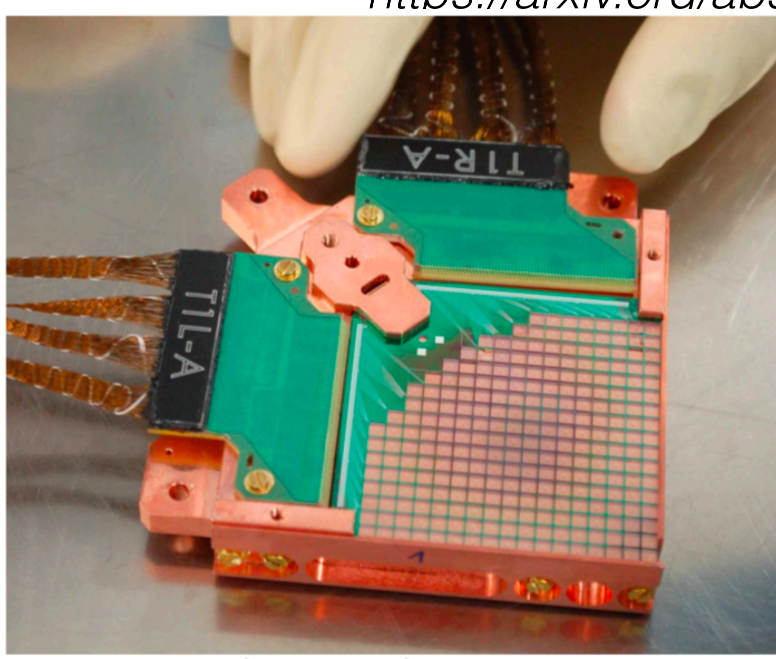




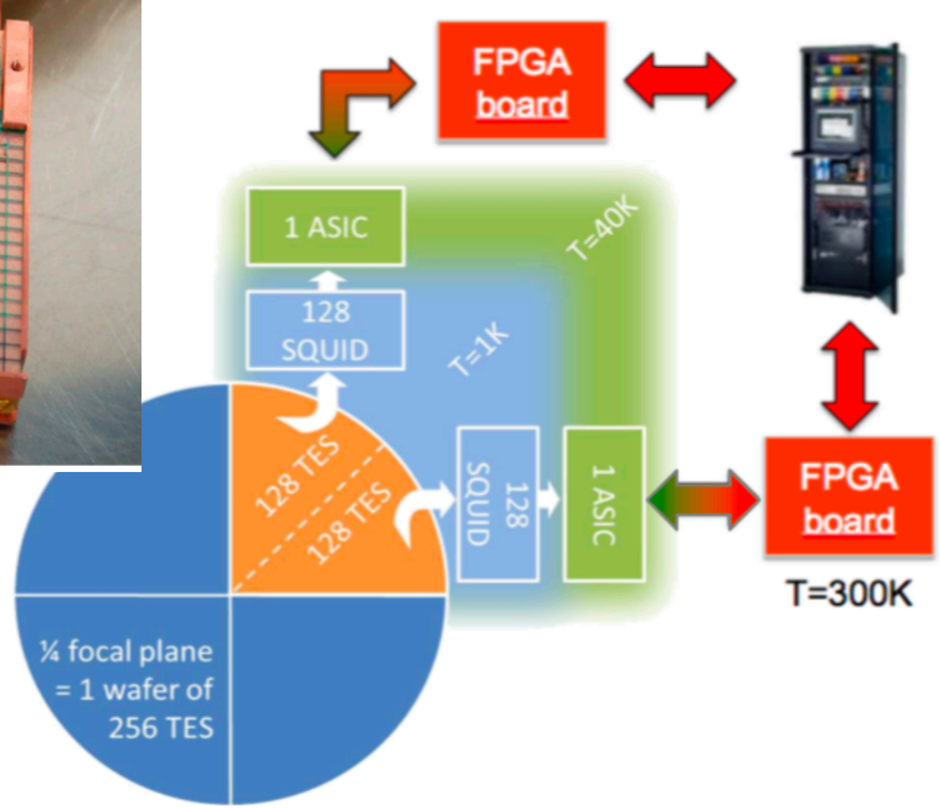


https://arxiv.org/abs/1812.00785

APC IJCLab



NbSi TES Matrix
(IJCLab)



Technology Demonstrator @APC

- Commissioning started in Argentina (2023)
- Bolometric Interferometer
- **300 mK Cryostat**
- **248 pixels NbSi supra** (2000 on final Inst.).
- **150 GHz** (+ 220 GHz on final Instr.)
- **Custom squids + ASIC cold elec** (AMS 0.35 SiGe)
- **128:1 multiplexing**

Ex. of instrument : QUBIC

QUBIC on site near San Antonio de los Cobres, Argentina, at 5000m a.s.l. (inaugurated Nov. 22nd 2022)

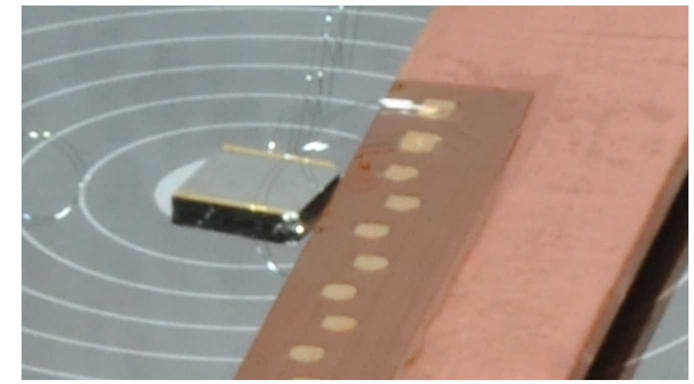
9

R&D : Ge-NTD thermal sensors

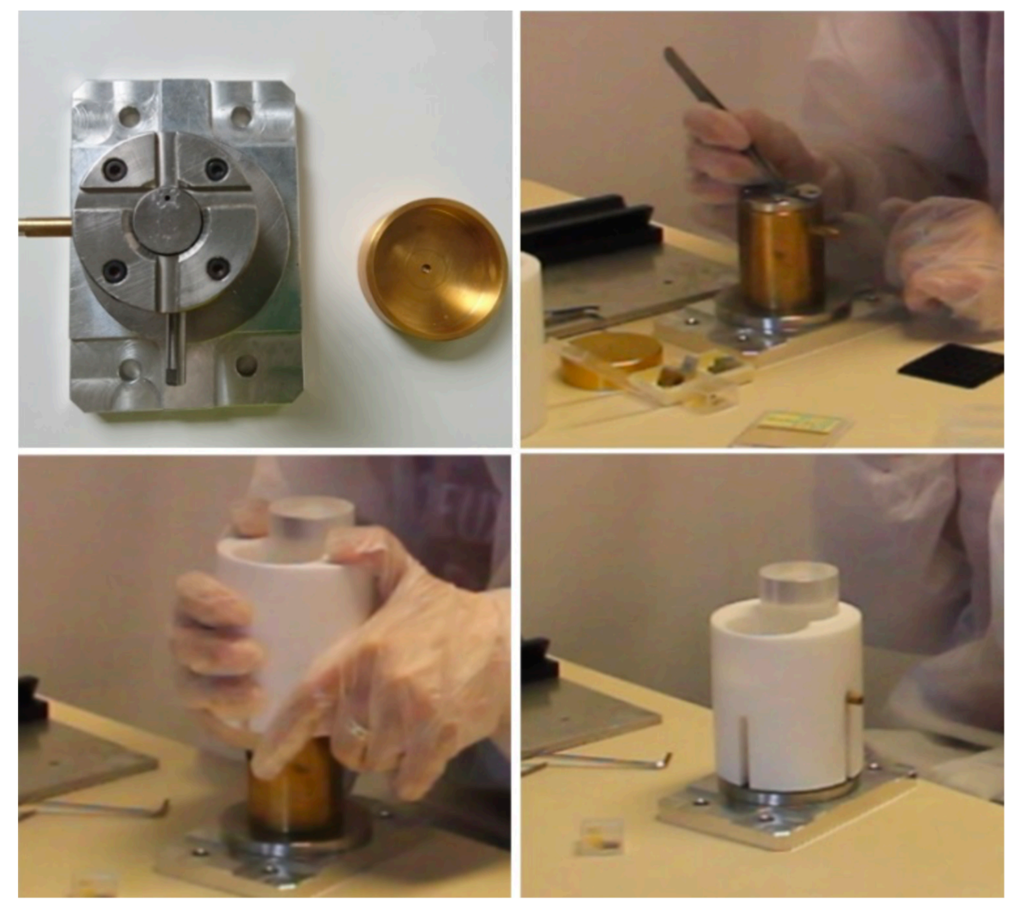
Ge-NTD **(IJCLab, IP2I)**

Neutron doped semiconductor. Near Metal Insulator Transition.

- ✦ NTD production on french reactor feasible in France
- ✦ Production (2015) during the LUMINEU ANR (CSNSM - CEA)
- ✦ No new production planed. Contact w/ other producer.
- ✦ **R&D : Optimization**
  - cutting, electrodes metallization. Gluing.
  - Massive test for selection and extra noise measurement
  - **need = few 1000s of NTDs over the next decade**



EDELWEISS FID800 det.



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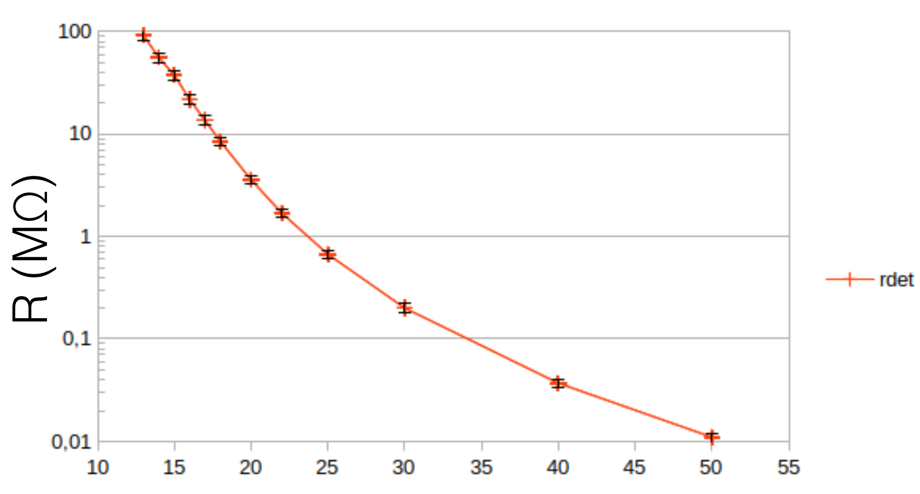
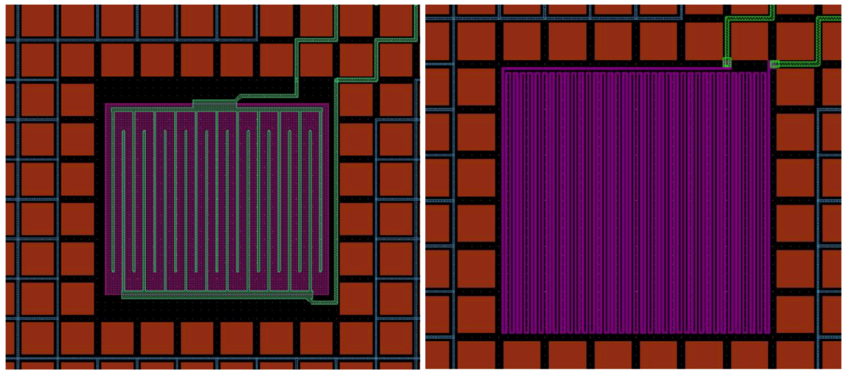


R&D : NbSi thermal sensor



Low Impedance High Impedance

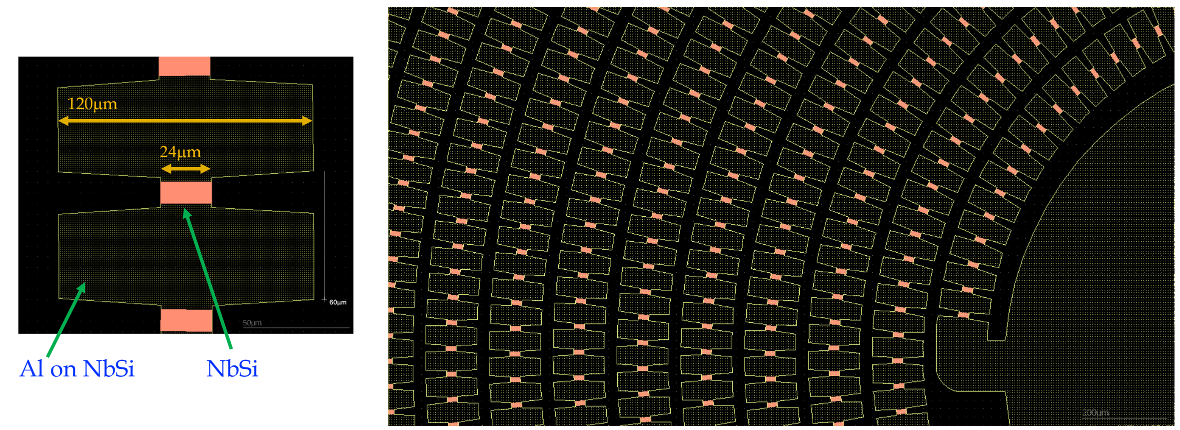
Nb_xSi_{1-x} **(IJCLab)**

Alloy near the Metal Insulator Transition or superconductor

- > 20 ans of development. Co-evap of thin film.
  - see S. Sengupta talk
- Best result in the superconducting mode (high or low Z)
- **Micro-lithography** (CNRS/C2N) for both **detectors matrices** (QUBIC) **and massive bolometers** (EDELWEISS, Ricochet).
- **R&D :**
  - Specific heat minimization ➞ Phonon traps
  - Low threshold « metastable »state for heat only event discrimination (**Superconducting Single-Electron Device** -SSED-, CryoSEL ANR project)
  -

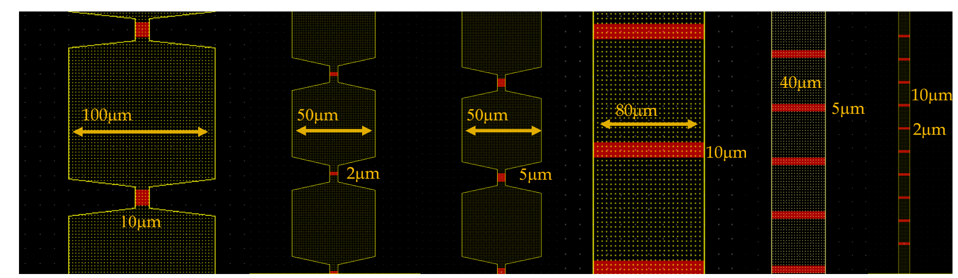
The NbSi phonon-trap design

17000 NbSi-Al cells in series to form a spiral

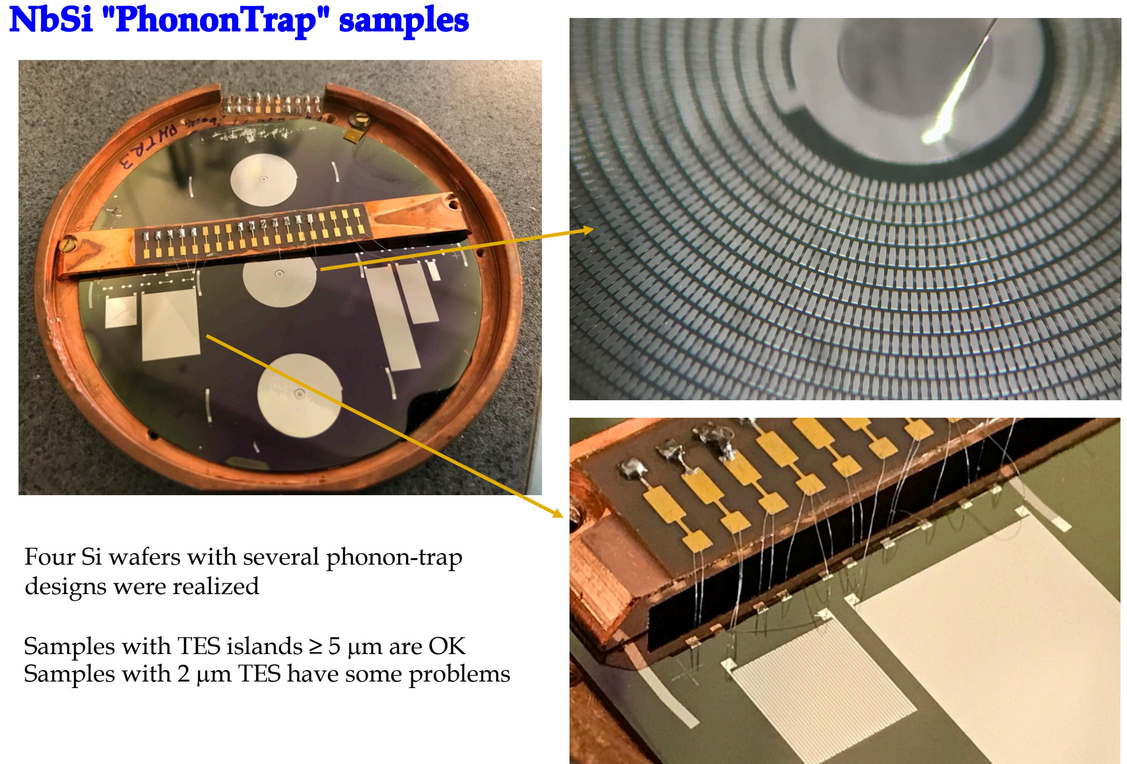


Other tested designs …

10 µm, 5 µm and 2 µm TES



NbSi "PhononTrap" samples



Four Si wafers with several phonon-trap designs were realized

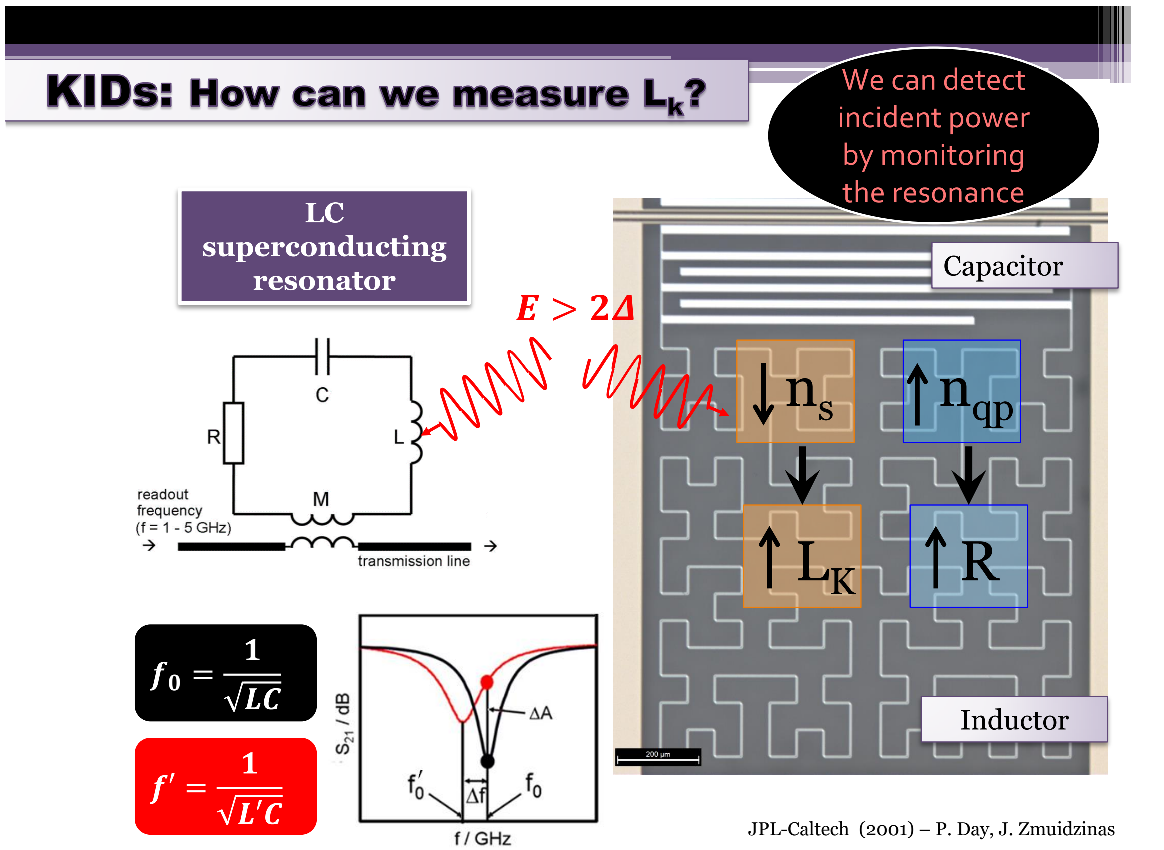
Samples with TES islands ≥ 5 µm are OK
Samples with 2 µm TES have some problems

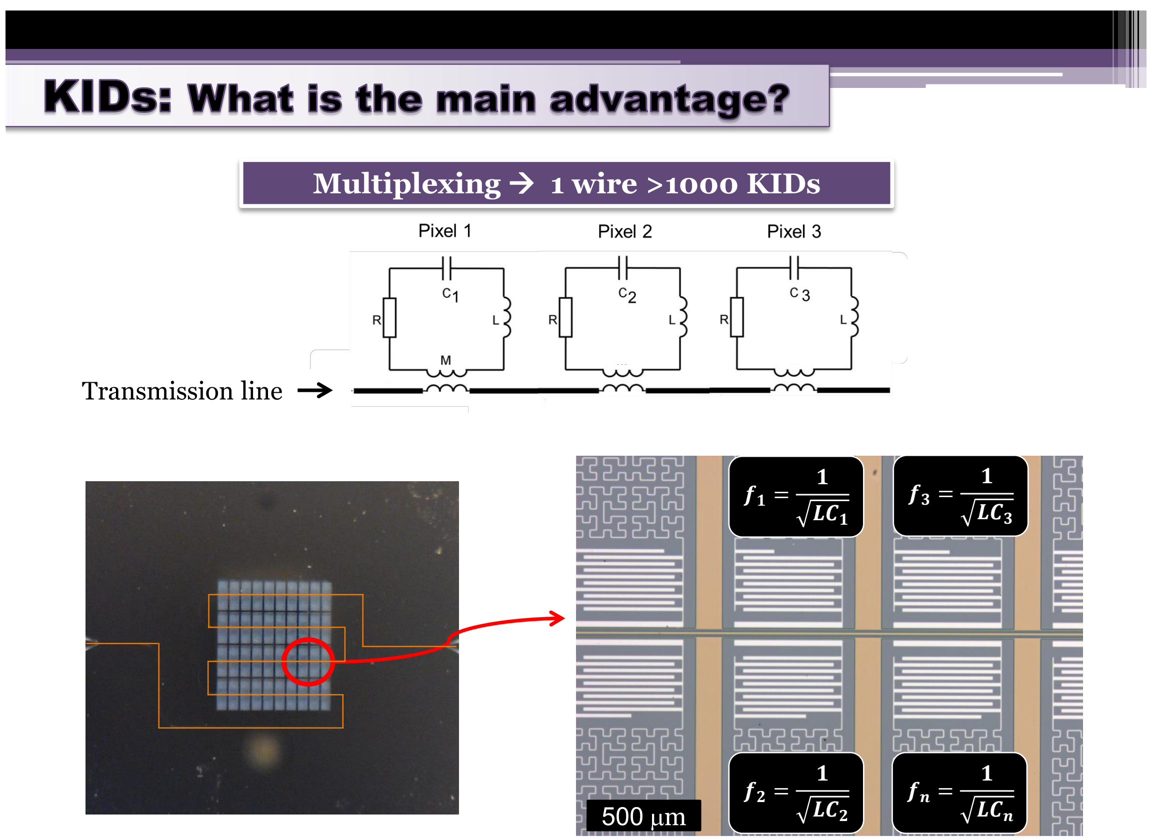
Stefanos Marnieros & IJCLab

R&D : KIDs sensor

Kinetic Inductance Detector
(I. Néel, LPSC, APC)
= superconducting resonator

- ✦ Resonance depends on the Cooper pairs density : **sensitive to all interaction w/E>Δ_s**
- ✦ **Started in 2000** by Caltec/JPL groups
- ✦ Main player in France : **NIKA2, LPSC & Néel**
  - ➡ **see S. Savorgnano talk**
- ✦ **R&D :**
  - Integration : **more pixels !**
  - Al techno is mature but the bandwidth is limited (by the superconducting gap)
  - Goal : **enhance the BW to 50 - 650 GHz**
    - ➡ **lower Tc** (Tc Al = 1.4K)
    - ➡ Al-Ti or other materials
  - Phonons sensitivity
    - ➡ **Particule** detection (**IP2I-Néel**)
    - ➡ **BullKid** project (**Néel**)
- ✦ **SPIAKID** Project for visible and near IR photon detection (**APC**)
  - ➡ **see J. Hu talk**





Alicia Gomez DRTBT2018

R&D : Massive Bolometer

3 major scientific goals :

- **$0\nu2\beta$** (double beta desintegration w/o neutrino emission) :
  - Prepare the future of CUORE = **CUPID**
  - ➡ **CUPID-Mo** @ LSM is **a major input for CUPID**
  - ➡ Goal = 1 ton of detector with bkg discrimination
- **Dark Matter** « crisis » : no direct detection so far + no new physics at LHC
  - ➡ « dead » of the « standard » few GeV SUSY WIMPs candidate
  - ➡ Focus on low mass and ALPs (Axion Like Particle)
  - ➡ EDELWEISS-SubGeV, **TESSERACT** proposal @ LSM
- **Search of New Physics** with precision **CEνNS** **(Coherent Elastic neutrino-nucleus scattering)** measurement
  - ➡ Push the discrimination at very low threshold
  - ➡ **RICOCHET installation started @ ILL**
- Many other application:
  - ➡ Fast neutron spectroscopy, rare decay observation, metrology, etc.

R&D : CUPID

CUPID

CUORE Upgrade with Particle Identification

- ✦ 30 institut., 100s of people
- ✦ Long **process of R&D selection**
  - *https://arxiv.org/abs/1504.03612*
- ✦ French R&D (**CUPID-Mo**, IJCLab-IP2I + CEA) **selected as the CUPID baseline**
  - *https://arxiv.org/abs/1907.09376*
  - *Luke Neganov Ge **Light detectors will be produced by IJCLab***
- ✦ dedicated « small » underground R&D project : CROSS, BINGO ERC project
- ✦ **lots to be done over the next 3 decades**

https://arxiv.org/abs/1712.07995

Parameter	CUPID	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV kg y))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 meV
discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

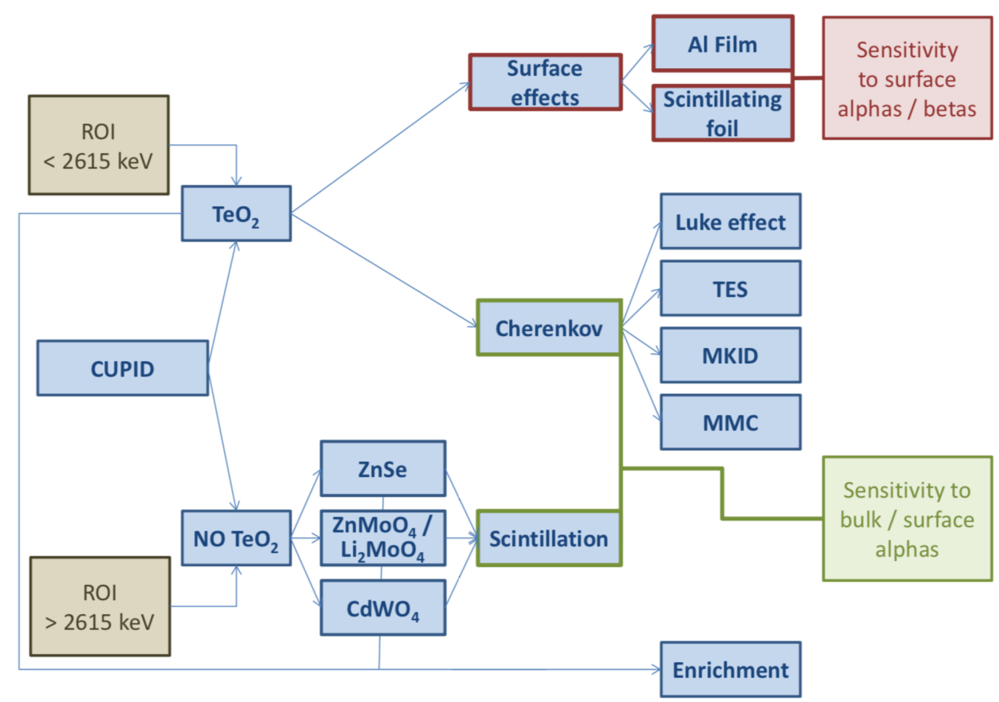


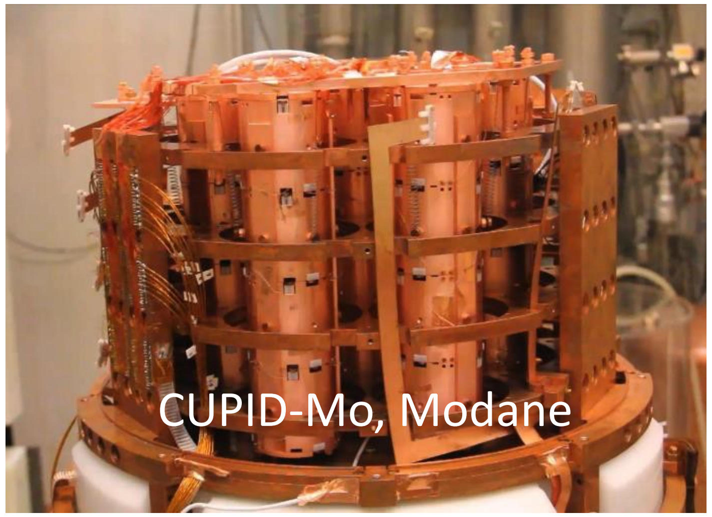
FIG. 1: Scheme of the R&D detector activities for CUPID

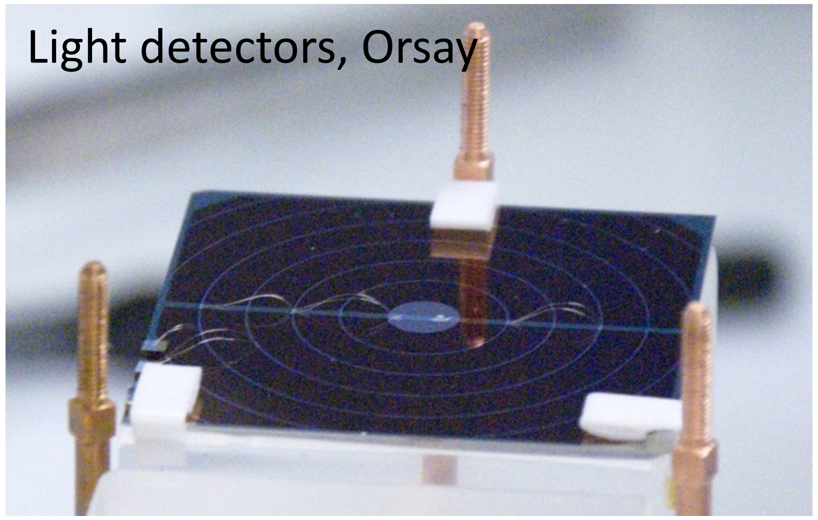
https://arxiv.org/abs/1504.03612

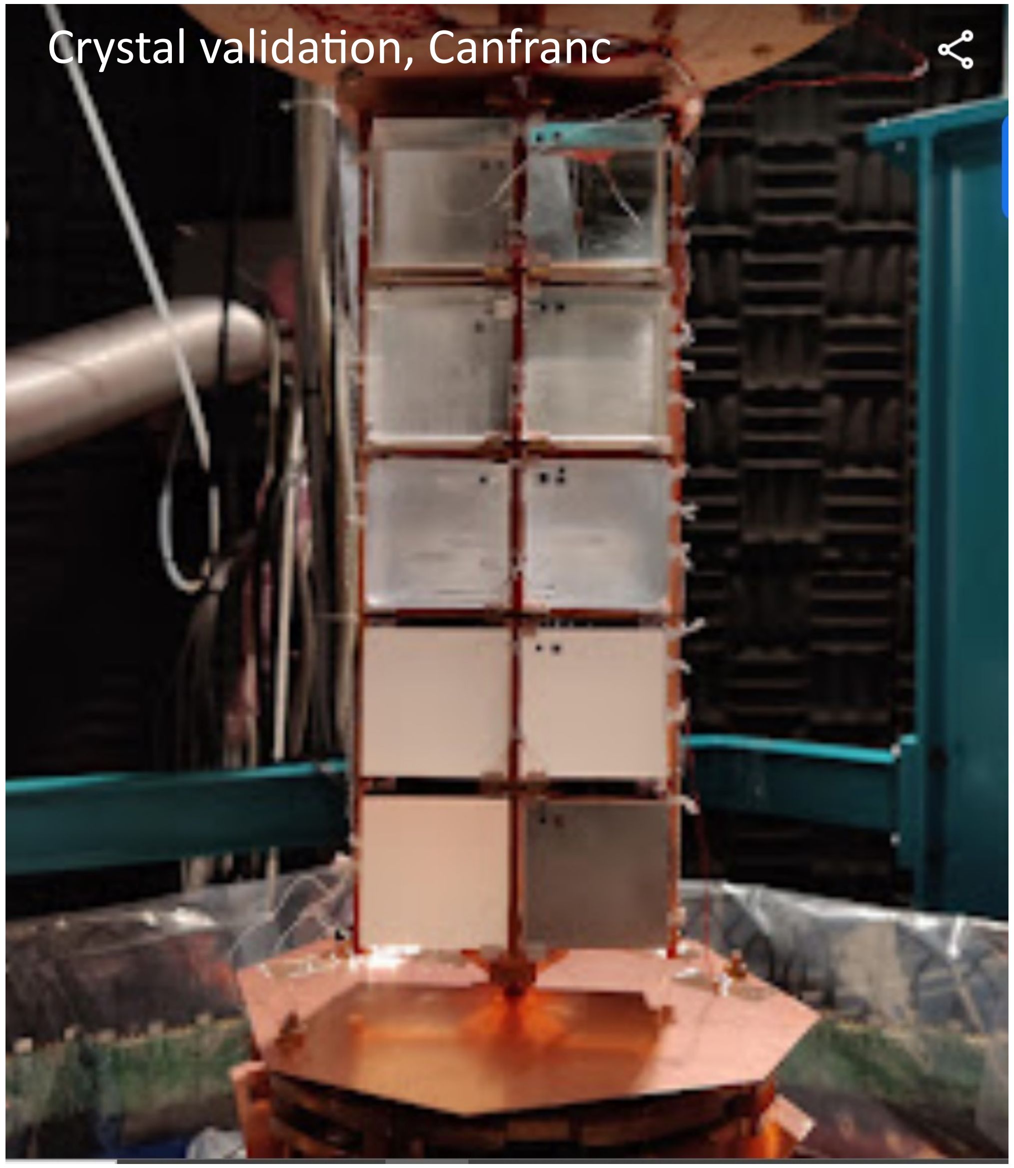
CUPID – French contribution

Main French contributions to CUPID (IJCLab, IP2I, CEA/IRFU):

- Development of the Li_2MoO_4 technology (CUPID-Mo, LSM)
- Adoption of light detectors based on the Neganov-Trofimov-Luke effect for more effective background reduction (see BINGO experiment)
- Preliminary tests of crystals in the Canfranc underground facility (see CROSS experiment)
- Substantial contibutions in assembly, electronics, low radioactivity, background simulations
- Li_2MoO_4 crystallization studies (SiMAP Grenoble)







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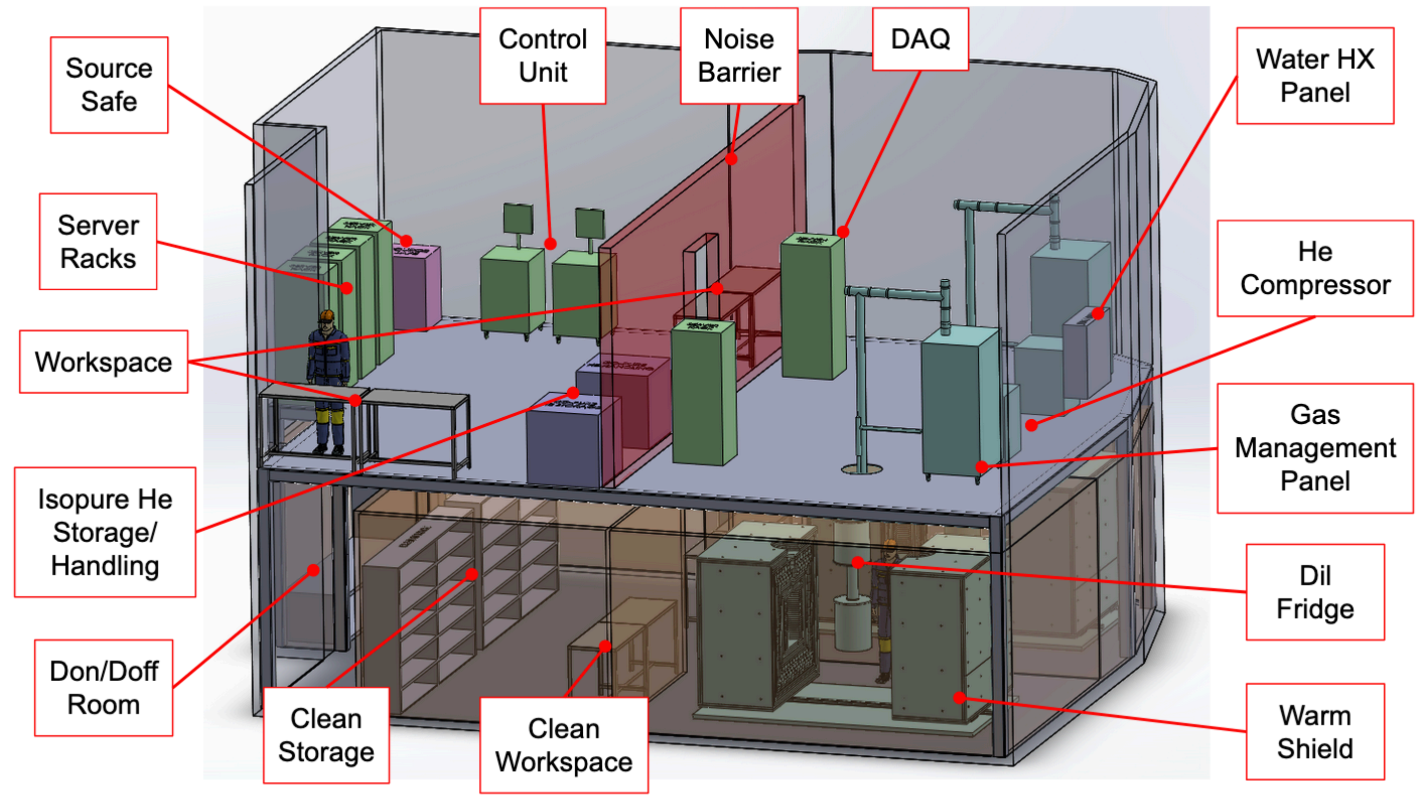
R&D : Tesseract project @ LSM

EDELWEISS room at LSM (May 2023)



- Potential layout in Modane

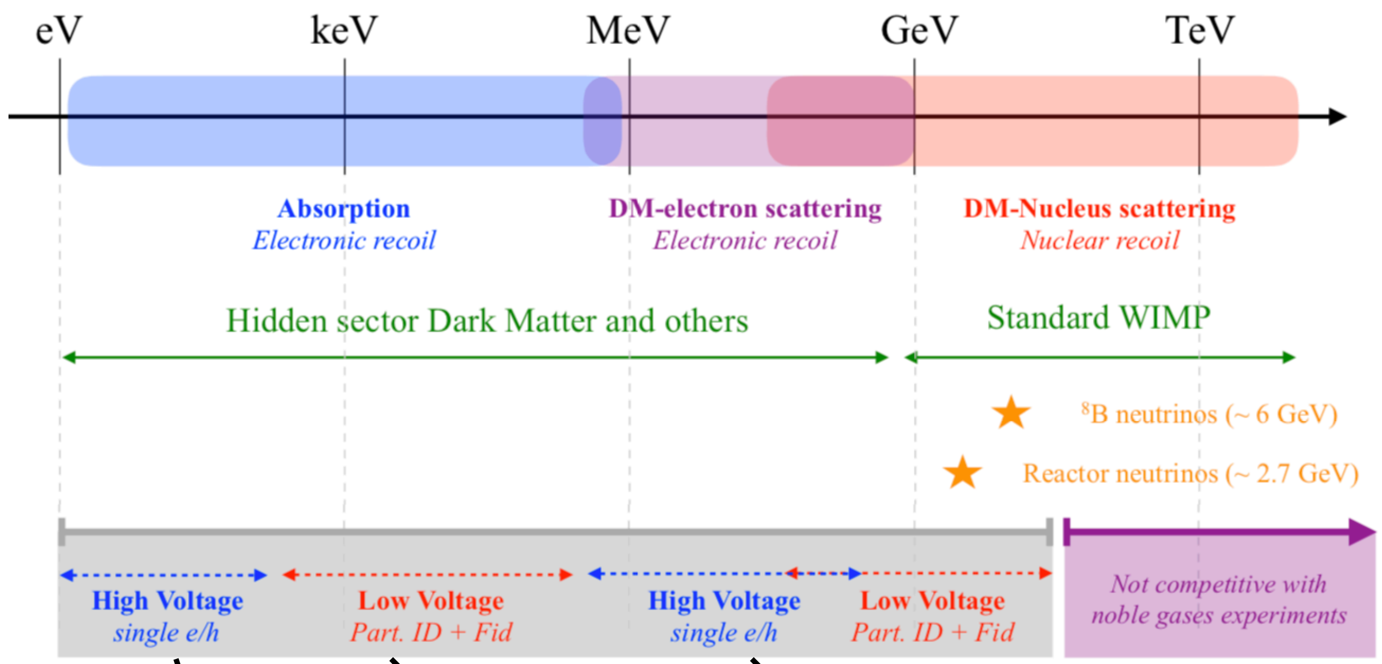
- Potential **TESSERACT** layout in Modane accommodating the BINGO cryostat in the **former EDELWEISS space**
  - Work ongoing between US and IN2P3 TESSERACT partners
- Ideally two cryostats would be needed tom combine short (R&D) and long (DM search) cycles simultaneously
- Significant emphasis on vibrational and EM noise suppression
- Integration of dedicated low energy NR and ER calibration sources

R&D : Low Mass Dark Matter

« small is beautiful ! »

- ✦ No observation of « standard » WIMPs (M> few GeV) w/ interaction rate < 1 evt/ton.year !
- ✦ Cryogenic detector no more competitive in this region
- ✦ Focus at low mass (resolution & threshold)
- ✦ If DM = Sub-GeV WIMPs then there are a lot of them !
  - **1 kg of good detector is competive**
- ✦ Axion & ALPs : Electronic Recoils
  - **main background = Heat Only excess at low E**
- ✦ **R&D goals:** IPNL IJCLab (+ CEA)
  - HV withstand (w/o current leakage) for Luke Neganov « **boost** »
  - Discrimination down to a single **e-/h+ pair**
  - **New transistor technology**
    - ➡ Si-JFET ➛ **HEMT** (C2N/CNRS)
- ✦ **> 10 years program**

✦ **Coming experiment will use the EDELWEISS space (now dismantled) at LSM**



« HEMT » R&D common w/ Ricochet

CryoSEL @LSM (On BINGO cryostat)

Luke Neganov « boost », single pair sensitivity

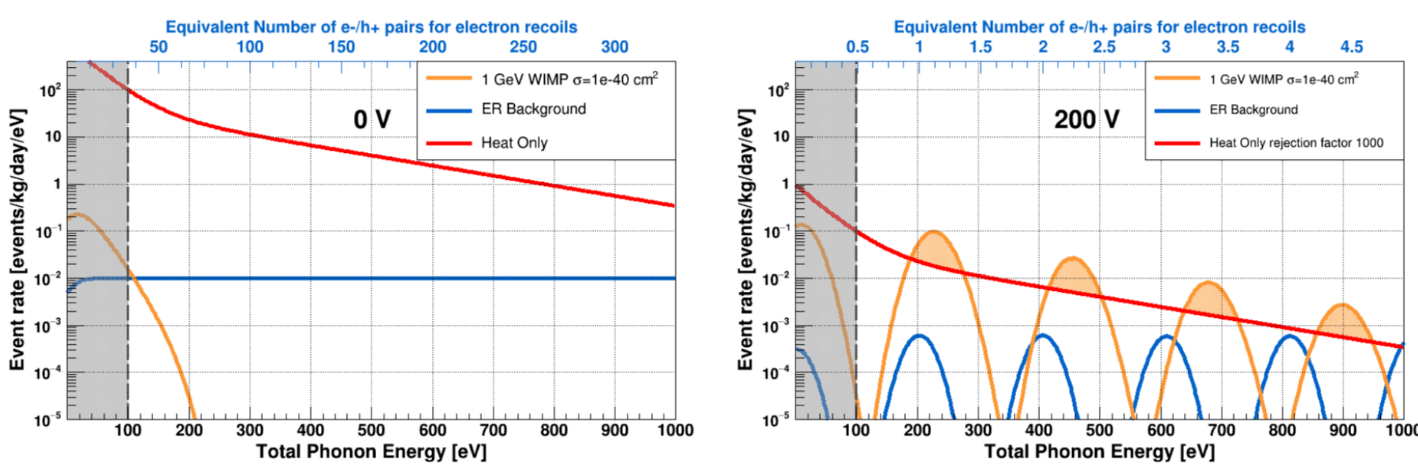


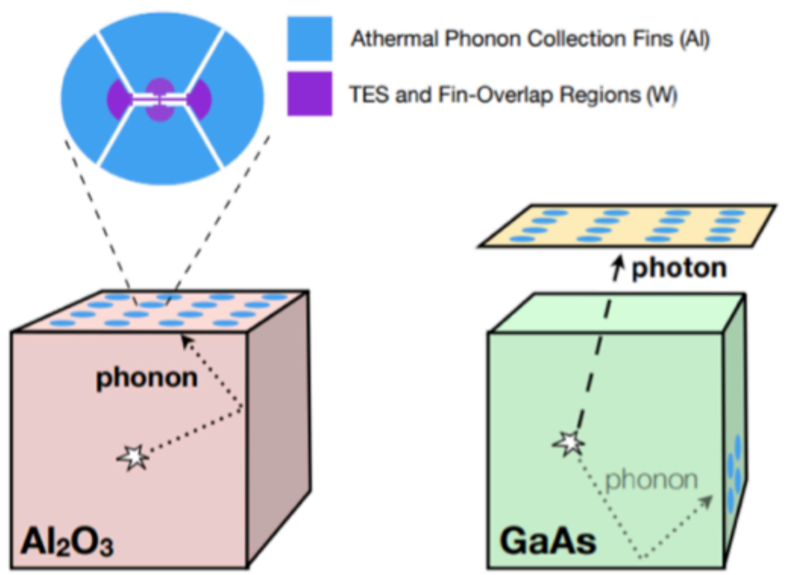
Figure 1: Response of the CRYOSEL detector operated at 0 V (left) and 200 V (right). Orange: expected NR signal for a 1 GeV/c² WIMP with a scattering cross-section of 10^{-40} cm². The blue and red lines correspond to the ER and heat-only backgrounds observed in EDELWEISS detectors. The shape of the NR response is sensitive to the actual quenching factor and straggling effects for this type of interaction. In right panel a rejection factor of 1000 is considered for HO events.

TESSERACT: *Proposal experiment at LSM*

TESSERACT

***T**ransition **E**dge **S**ensors with **S**ub-**E**v **R**esolution **A**nd **C**ryogenic **T**argets*

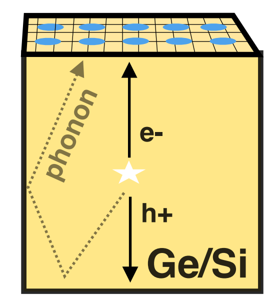
Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project



- DOE Funding for R&D and project development began in June 2020 (Dark Matter New Initiative)
- One experimental design, and different target materials with complementary DM sensitivity, all using TES
- Includes SPICE (Al_2O_3 and GaAs) and HeRALD (LHe)
- ~40 people from 8 institutions
- **Actively searching for an underground lab**

Berkeley Lab, Berkeley University of California, Caltech, Florida State, Texas A&M University, University of Michigan, Argonne National Laboratory, UMass Amherst

TESSERACT @ LSM



LSM

- Adding Ge/Si semiconductors with TES (heat) and electrodes (ion) readout
- Benefit from EDW+Ricochet Ge bolometer expertise and low-background cryogenic setup
- Ongoing discussions with IN2P3 Ricochet and EDW partners (LPSC, IJCLab, IP2I)
- **Actively looking for a future cryogenic DM experiment**

iP2i Les 2 Infinis Lyon, IJCLab Irène Joliot-Curie, LPSC Grenoble

Prospective R&D : Ricochet

Precise Measurement of a known signal

IP2I, IJCLab, LPSC, I. Néel, ILL

- ✦ Change of philosophy wrt Dark Matter
- ✦ **CEνNS measurement for ν MeV** (measured in 2018 @ 30 MeV)
- ✦ Specifications goals
  - **1 kg Ge (27*38g)**
  - **20 eV ioni + 10eV chal**
- ✦ some of the R&D (HEMT transistors) common w/ EDELWEISS

60 MW reactor @ ILL / Grenoble

- ✦ Ricochet installation started in 2022
- ✦ **5-10 years program**

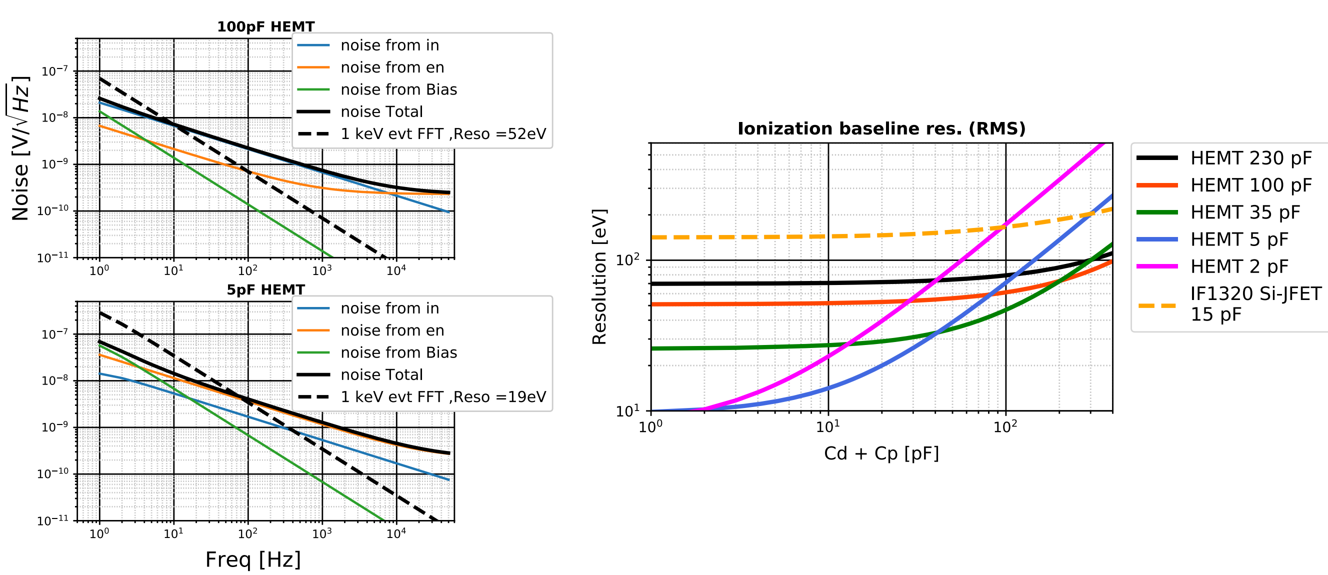


Fig. 5 *Left:* Contribution to the ionization resolution of the voltage noise, current noise, bias resistor (10 GΩ @ 20 mK). The total detector + cabling capacitance is 20 pF. 5 pF and 100 pF geometries have been studied. FFT of 1 keV event are shown. *Right:* Evolution of the resolution with the detector+cabling capacitance for the 5 HEMT geometries and the IF1320 Si-JFET from InterFET. Noise of the bias resistor is included. (Color figure online.)

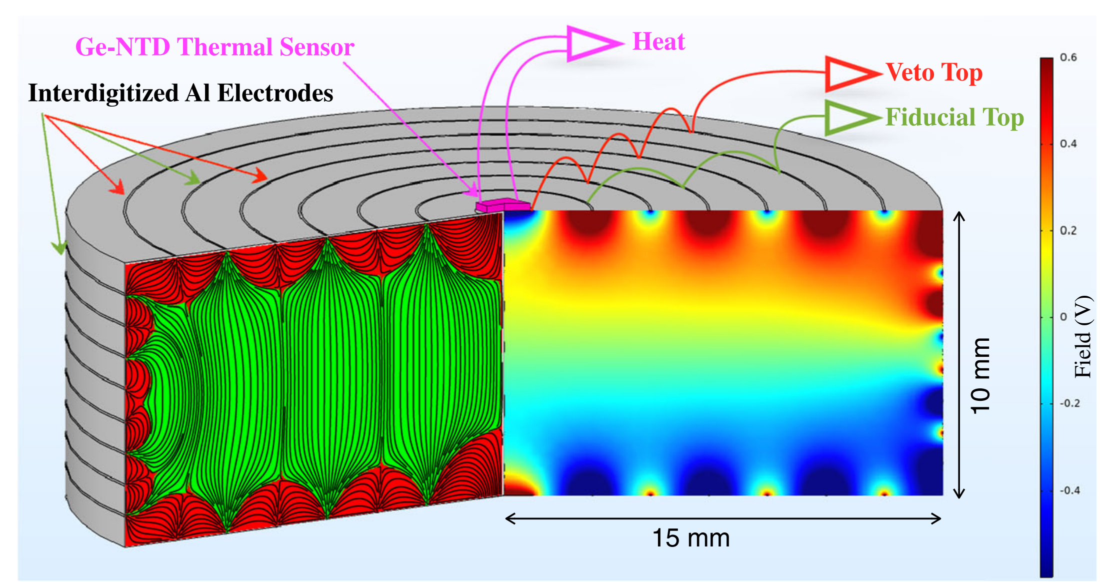


Fig. 6 Electrostatic simulation of a Full Inter-Digitized electrodes scheme on a 38 g germanium crystal (Φ = 30 g, h = 10 mm). The crystal is surrounded at 2 mm distance by a chassis connected to the ground (not shown). The capacitance of the 4 electrodes with respect to the ground is about 20 pF (Color figure online.)

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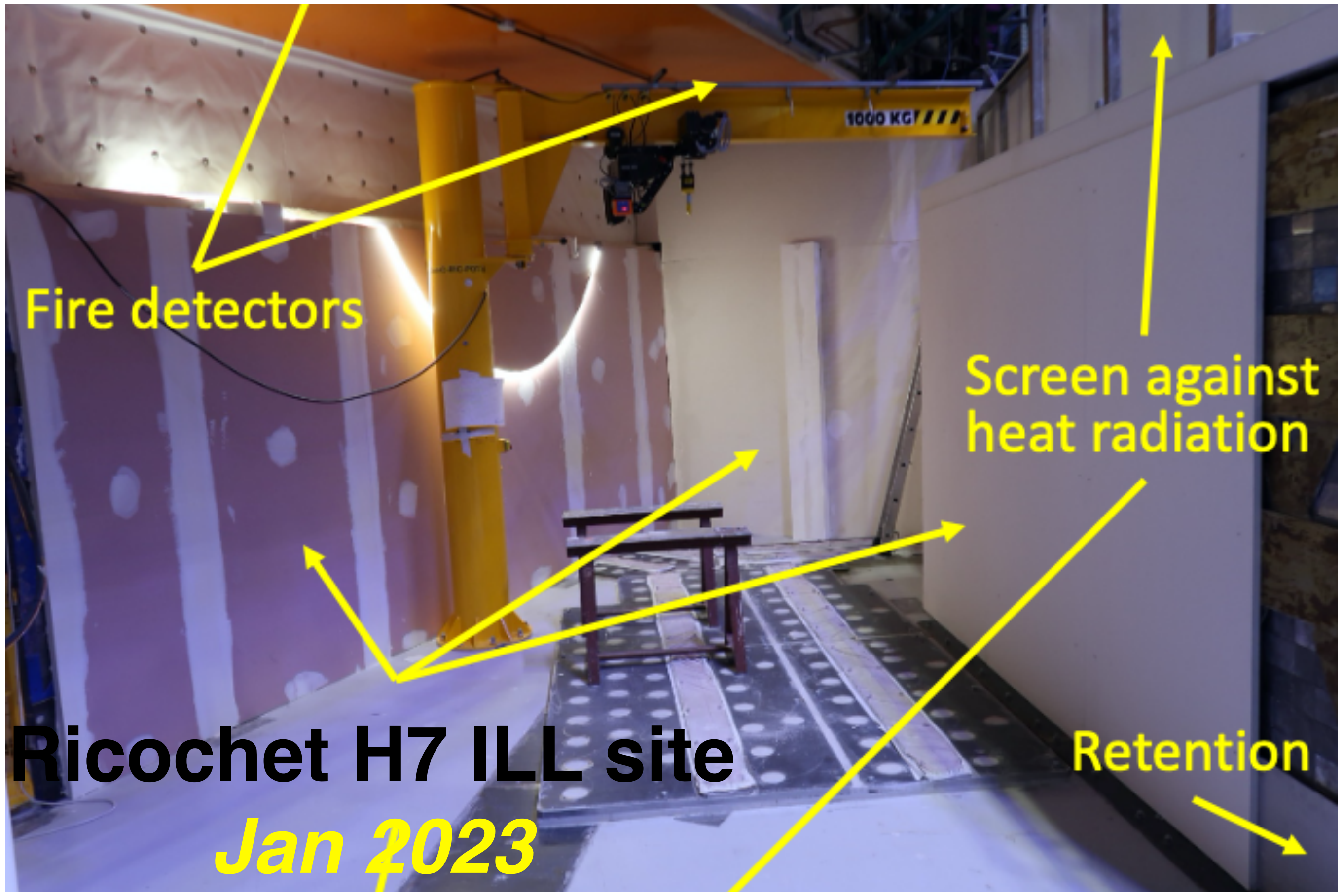
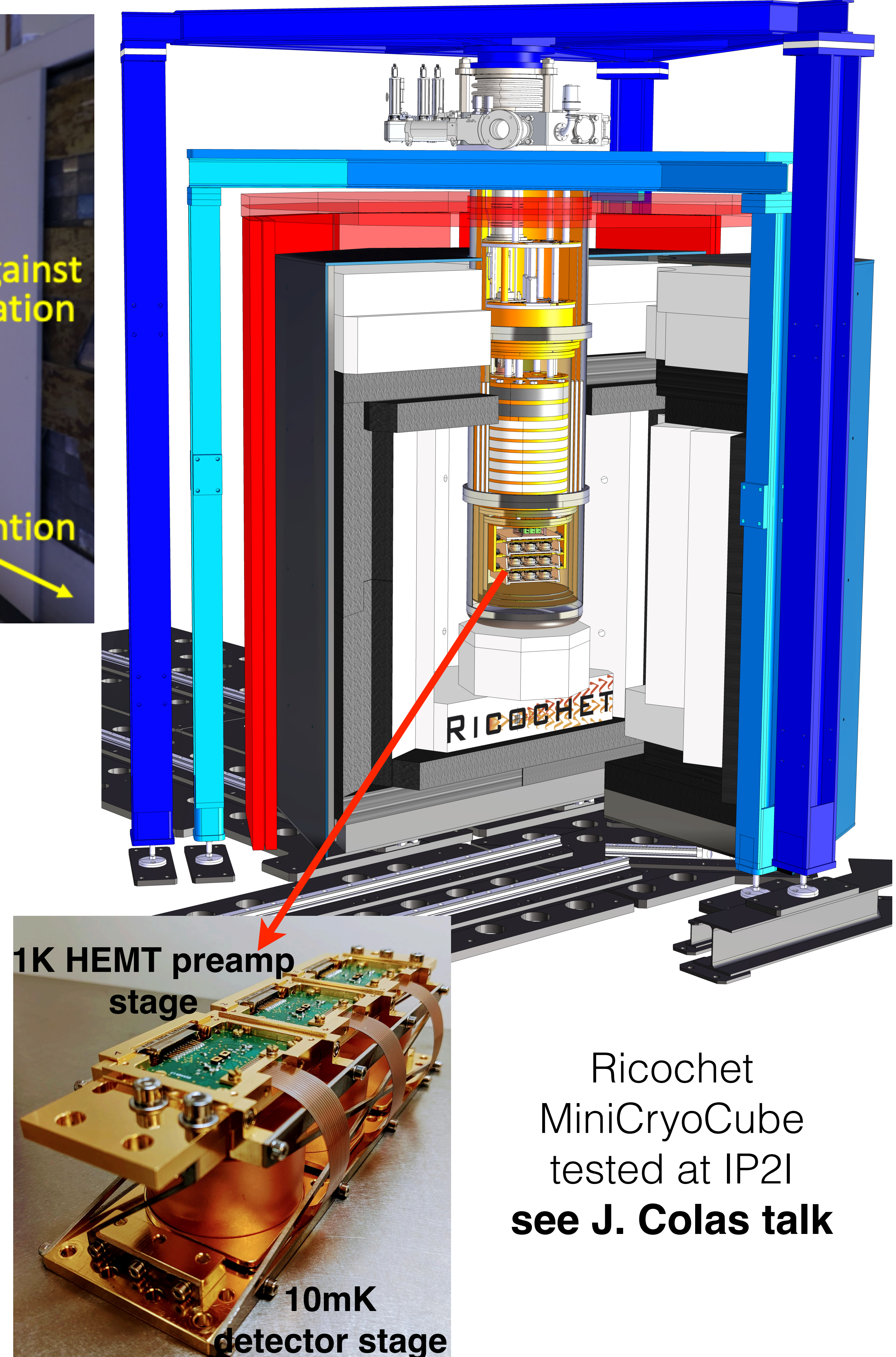




Ricochet MiniCryoCube tested at IP2I
see J. Colas talk

R&D : Sub-mm astro instruments

Prospective IN2P3 GT05 :

✦ Short-term goal (2019-2020):

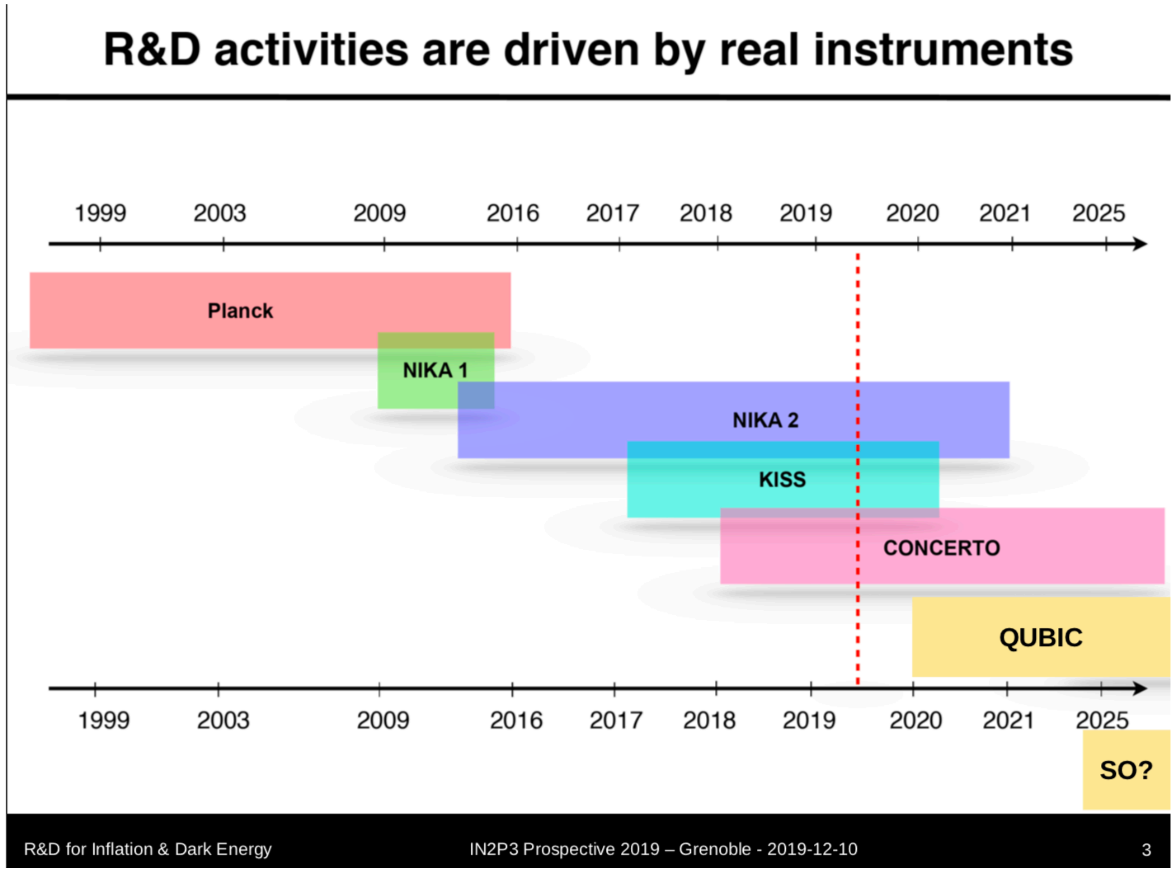
- Maintain **KID activity** with **existing instrument NIKA2 and KISS** ensuring upgrades to increase the performance.
- **Install QUBIC** at 5000m site in Salta province, Argentina. Demonstrate Bolometric Interferometry on sky data

✦ Mid-term goal (2020-2024):

- **installation of CONCERTO** (KIDs, 2021). Maintain the observations for several years.
  Begin studying the design for S4-like instruments.
- **Data taking with QUBIC Technical Demonstrator**.
  Upgrades: Multimode horns, 400 horn array, additional focal plane for 220GHz

✦ Long-term goal (2024-2030):

- be ready to **answer to the expectations of the S4 network**. Be a valid candidate for covering the focal plane of the **next generation space mission** devoted to the CMB
- Large QUBIC-like instrument with KID detector array, proposed as part of the S4 collaboration
- Bolometric Interferometer in the focal plane of LLAMA



2023 Updates :

- ✦ NIKA2 (3000 pixel) still running on the 30m. Dedicated time for NIKA team ended. Observation proposals on the open time. Discussion ongoing for a NIKA3
- ✦ KISS has been running over the 2018-2021 period as a CONCERTO (4300 pixels) pathfinder
- ✦ CONCERTO installed mid-2021. Data taking up to end 2022. Data analysis ongoing
- ✦ QUBIC commissioning ongoing
- ✦ Budget to complete the focal plane and horn array obtained (ANR2024)
- ✦ Both APC and Grenoble teams are working on S4/SO (Simons Observatory) proposals (future telescope network, attacama & South Pole)

Prospective R&D : QUBIC

Universe 2019, 5, 42

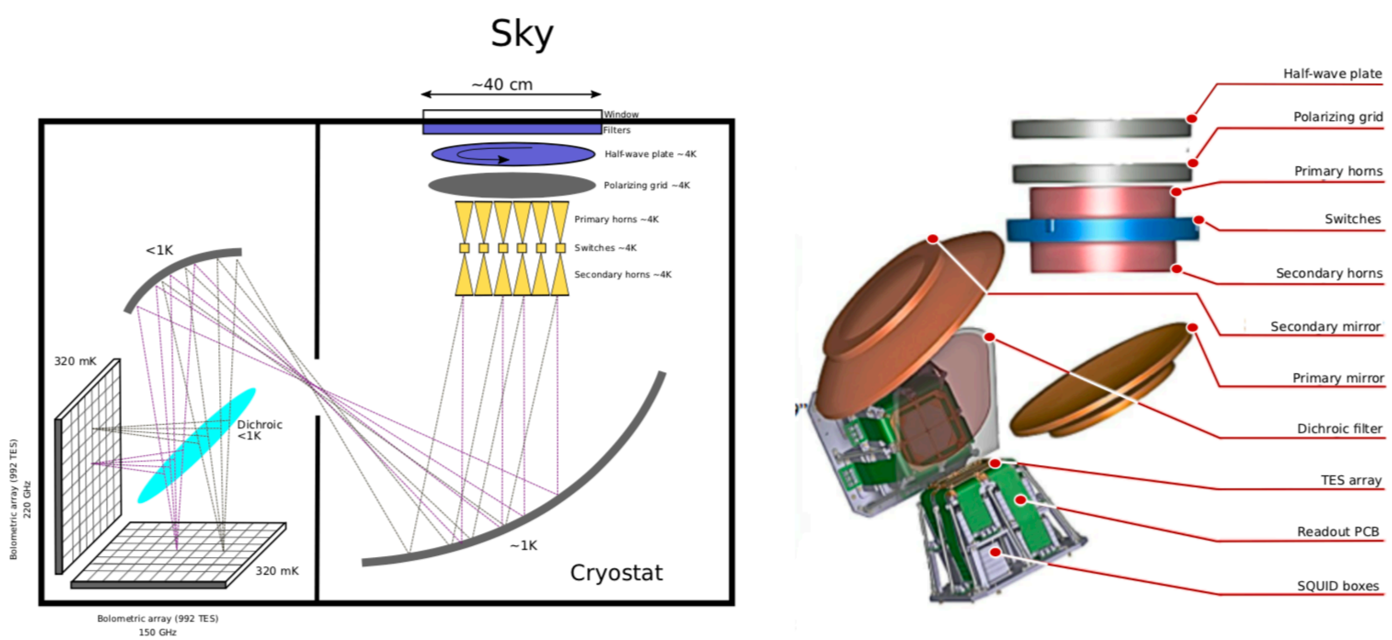


Figure 1. (**Left**) Schematic of the QUBIC instrument. The window aperture is about 40 cm; the cryostat is about 1.41 m in diameter and 1.51 m in height; (**right**) 3D rendering of the inner part of the cryostat. TES, Transition Edge Sensor.

Technological Demonstrator

= **1/8 Instrument Final @ La Puna (Argentina)**

✦ **programme à ~ ? ans**

JLTP 2019

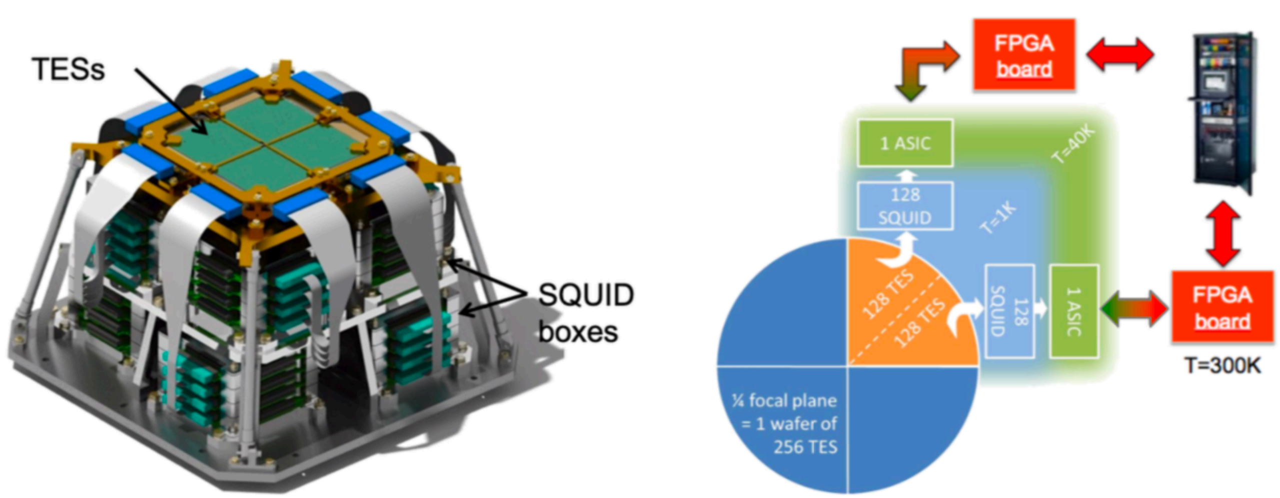
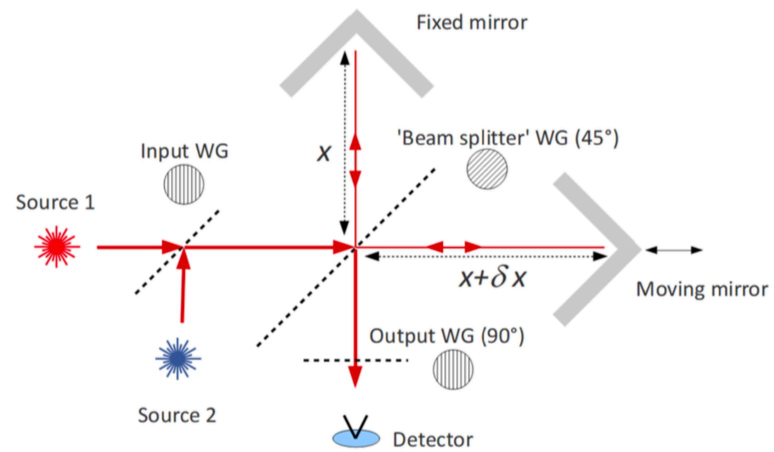


Fig. 2 *Left*: QUBIC cryo-mechanical structure which supports one TES focal plane at 350mK on top and the SQUID boxes at 1K below. *Right*: Architecture of the QUBIC detection chain for one focal plane of 1024 channels. (Color figure online.)

R&D : KISS & Concerto

Alternative : spectrométrie MPI

- Avantage : côté détecteurs simplifiée, grands plans focaux possibles
- Problèmes : vitesse, course, échantillonnage...



- Approche choisie pour KISS et CONCERTO !

KISS : étude détaillé du SZ

Installed end of 2018

- NIKA2 : 2 bandes → • KISS : ~100 bandes !

Installation sur le télescope QUIJOTE à Tenerife

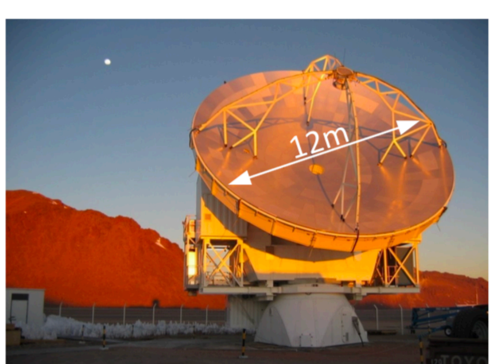
2.5m diamètre, 2300 mètres d'altitude

CONCERTO et la cartographie du CII

Installed mid-2018

- CONCERTO : un spectromètre dédié à la cartographie du CII
- ~100 bandes entre 200 et 360GHz
- Nécessite un télescope et un site exceptionnelle → **APEX**

Atacama Pathfinder Experiment APEX



Altitude : 5100m

KISS « Pathfinder pour CONCERTO et spectre

Averaged sky angular resolution	3.5 arcmin	Number of KIDS	500
Spectral range GHz	80 - 250 GHz	Frequency resolution δ_ν	1.5 GHz
Quijote telescope size	2.5m	Round FOV, Diameter	1 deg
End-to-end optical efficiency	0.3	^{3}He-^{4}He dilution cryostat	100 mK
# of expected observed clusters	10	Expected integration time	3000 hours

CONCERTO Installation 2021

Averaged sky angular resolution	27 arcsec	Number of KIDS	1500
Spectral range GHz	200 - 360 GHz	Frequency resolution δ_ν	1.5 GHz
LLAMA telescope size	12 m	Round FOV, Diameter	12 arcmin
End-to-end optical efficiency	0.3	^{3}He-^{4}He dilution cryostat	100 mK
[CII] survey field size	2 deg^2	[CII] survey integration time	1500 hours

➡ **see S. Savorgnano talk**

R&D Readout : discrete & ASICs

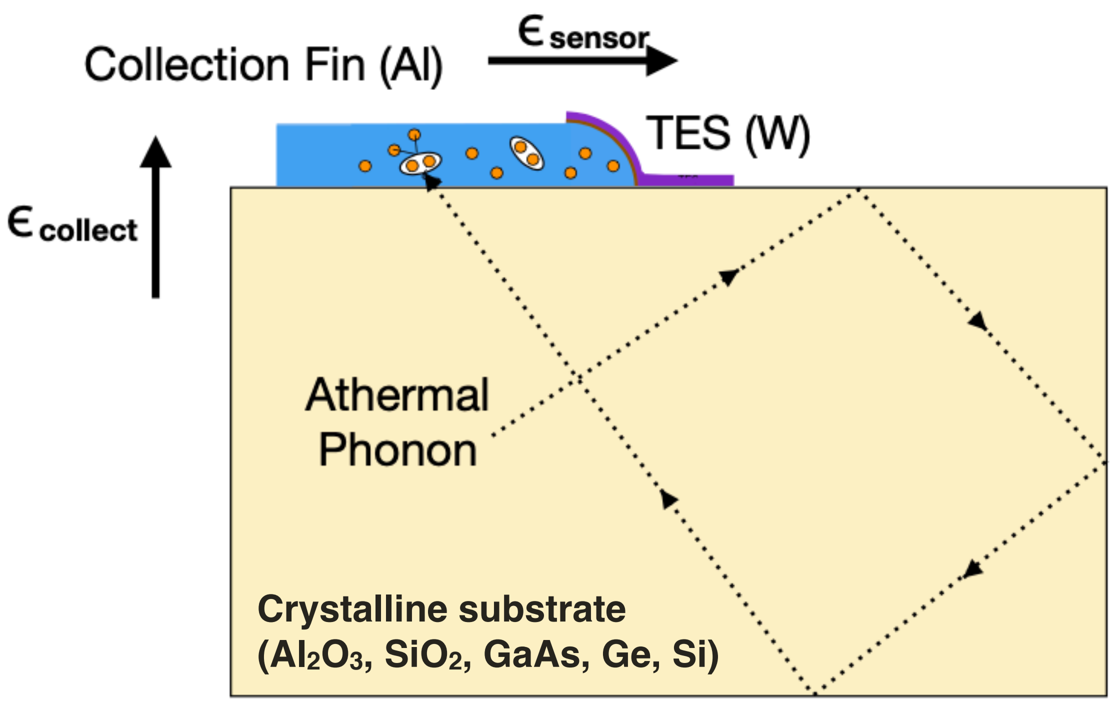
- ✦ Cryogenic detectors need a **special readout electronics** **(cryo + 300K)**
- ✦ **Discrete component** Development (HEMT, JFET, SQUID)
  - **1K HEMT readout** for Ricochet & Tesseract **(IP2I-Néel-LPSC, ➛J. Colas talk)**
  - **KIDs readout** (cryo amp few K) **(LPSC ➛C. Hoarau talk)**
  - **CUPID readout (300K) : 1000s of SiJFET (italian group)**
- ✦ **Dedicated ASICs** working at low T
  - **Multiplexing** CMOS AMS 0.35 **T<1K** for IR astronomy (SPICA - IRFU)
  - **Multiplexeur** BiCMOS SiGe AMS0.35 **T=2.5-15K** for X astronomy (IRFU)
  - **Multiplexing** BiCMOS SiGe AMS 0.35 (➛ST 130nm) **T=4-40K** for mm astronomy (**QUBIC - APC**)
  - **Control and low noise Readout at 300K** (outside cryostat) of a cryogenic chain BiCMOS SiGe AMS 0.35 (➛ST 130nm) (**APC**)
  - characterization of CMOS 130nm at low T (<4K) for Ricochet (**LPSC-Néel**)
- ✦ **Technology obsolescence** could be an issue : ex **AMS 0.35um for ATHENA.** **➛ see M. Gonzales talk**
- ✦ Multiplexing technology. **MicroWave Multiplexing -> GHz band**
  - ➚ pixels number, **same readout for KIDs & TES**

Conclusion

- **Cryogenic detectors** have reached **maturity** and are **integrated into complex instruments** and demanding sites (underground labs, balloons, satellites, telescopes, etc.)
- **Few well identified projects** with high IN2P3 contributions over tte next decades
- Many other projects not mentioned here
    - ➡ GRAAL, DALPs, wifiKIDs, BULLKIDs, etc.

TESSERACT: *New generation TES phonon sensors*

TES based athermal phonon sensor technology:

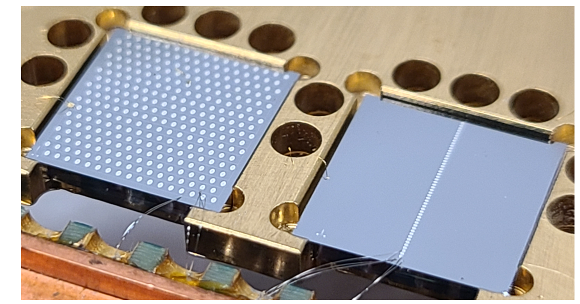


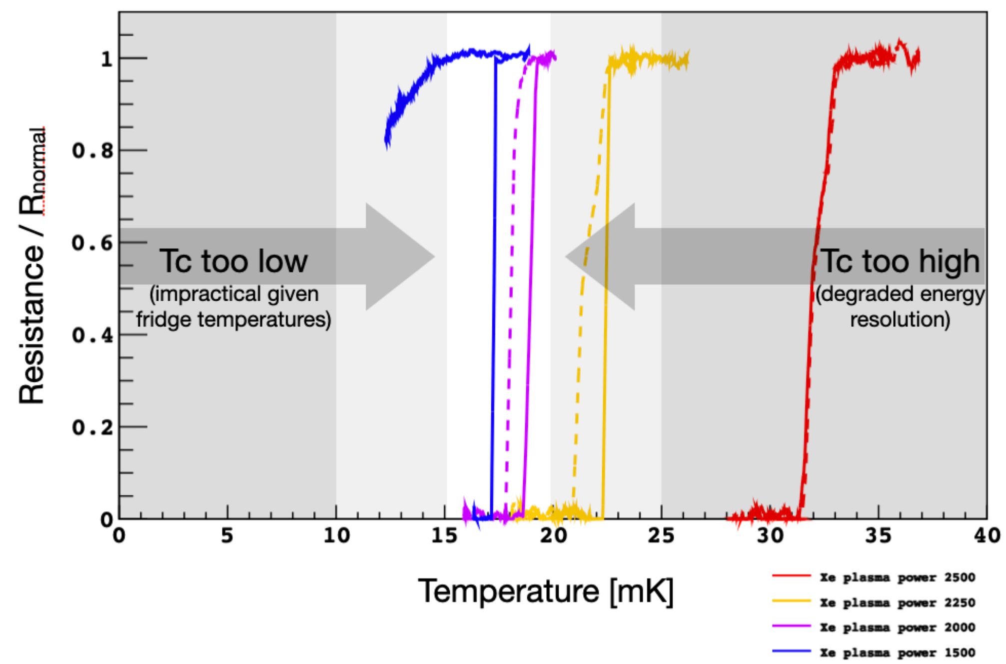
$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

$$\sigma_E \propto V_{det}^{1/2} T_c^3$$

Energy threshold decreases with detector mass

Energy threshold decreases **very quickly** with Tc





- 3.5 eV (RMS) already achieved with a 10g Si detector and Tc = 41 mK
- Targeted Tc around 15-20 mK recently achieved !
  - **~100 meV threshold achievable**
- **Next challenge:** parasitic power (vibrations, EMI, IR photons) needs to be <aW to fully reach TES sensitivity