Low Temperature Detectors

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Presentation plan:

- Science cases
- Introduction to LTD
- Superconductivity
- Kinetic Inductance Detectors (KID)
- Applications (selected) and Technology

Science cases

Science case (I): the cold Universe

Blackbody's Wien law → $\lambda_{max} \approx (5 / T)$ mm

→ «Cold» radiation (λ = 1mm ≡ 5K ; λ = 2mm ≡ 2.5K)

Astrophysics :

Galaxies, stars and planets are born from cold gas and powder.

→ Early formation stages of small-scale structures

Cosmology :

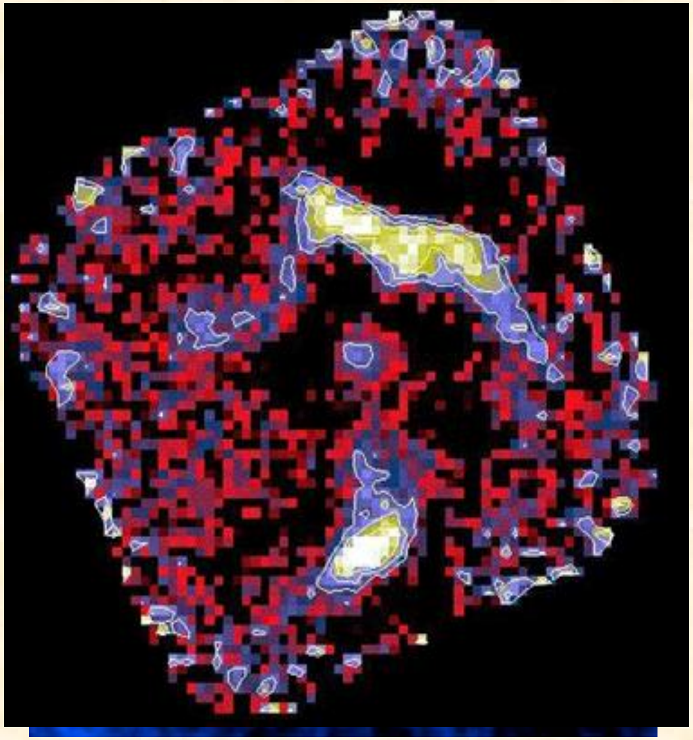
14 billions years ago, first H atoms formed from e^- and p^+ hot «soup».
A flash of UV light was emitted, at the same time, everywhere in the Universe.
Expansion → TODAY the Universe is cold (2.7K) and brightest in mm-wave.

→ Universe shape; large scale; primordial structures; inflation test

Science case (I): an example

Horsehead Nebula

- Thick dust (mm and sub-mm)
- Ionised H (UV-NIR)
- Young Stars (UV-NIR)
- Polarisation (all bands)

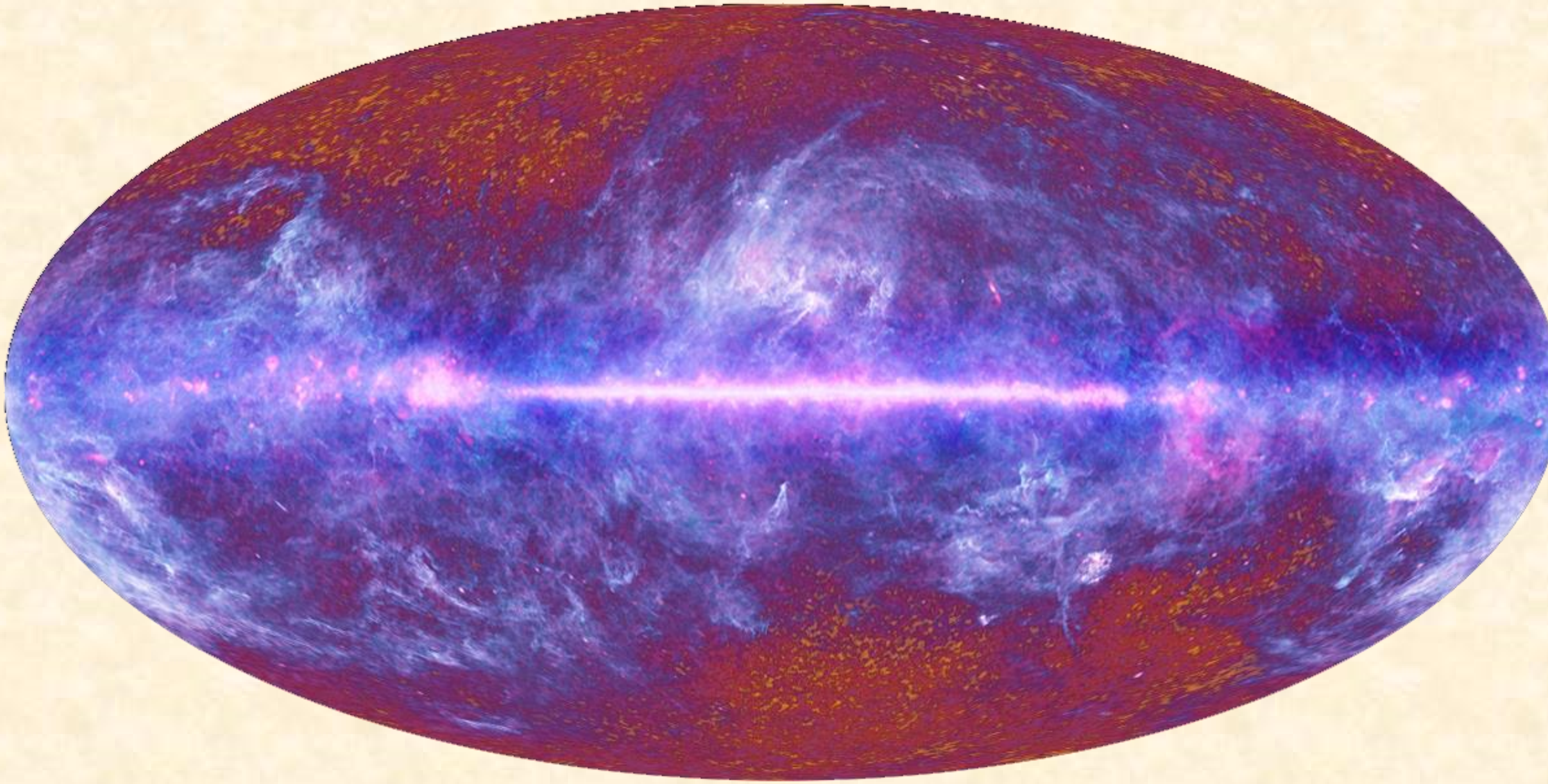


Multiwavelength required !!

Effect of redshift (z): wavelengths are stretched by a factor (z+1)

⇒mm-wave is the new fronteer to explore the Dark Ages
($z = 6 \div 20$)

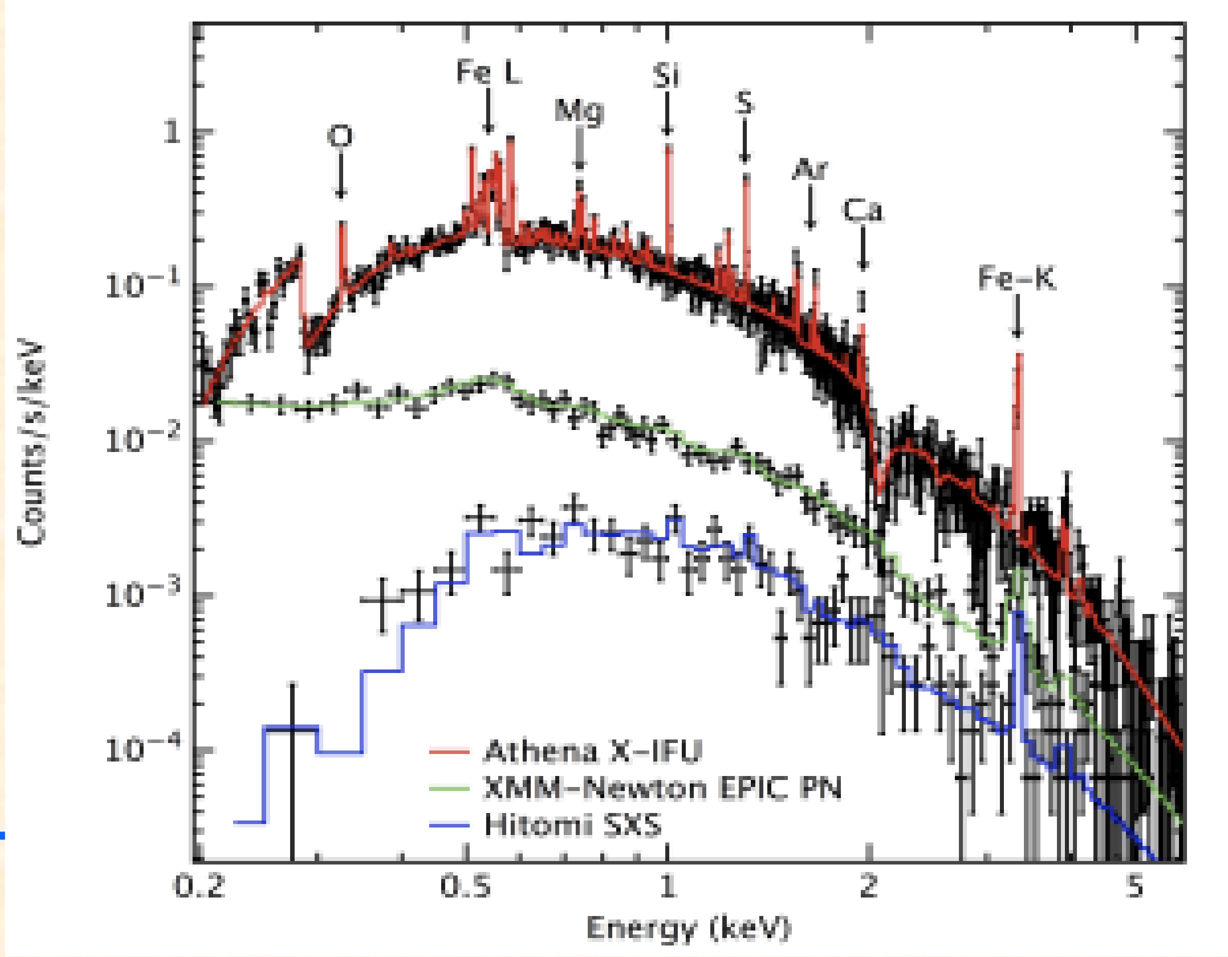
Science case (I): the whole Sky



Science case (II): the hot Universe

- ABUNDANCES (ion-per-ion)
- LINE PROFILES → velocity profiles

Galaxy cluster simulation
ATHENA+ satellite (2030)



Science case (III): weak interactions

- **Directly detecting Dark Matter**

Clear (but indirect) observational evidences → $M_{dark} > 5 \cdot M_{baryons}$!
The nature of M_{dark} is **100% unknown**.

- **Neutrino physics (e.g. double beta decay)**

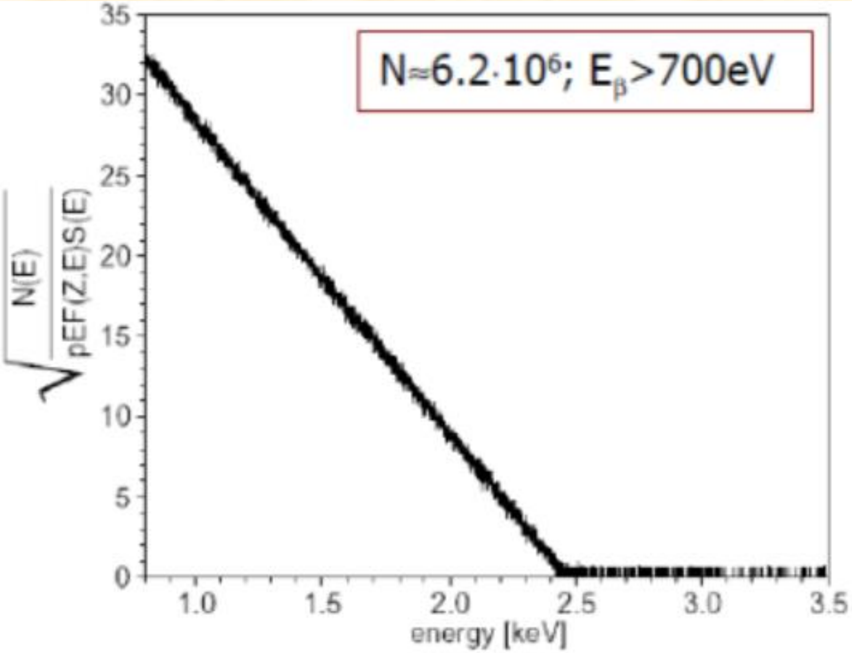
→ **Large cross - section Detectors (rare events)**

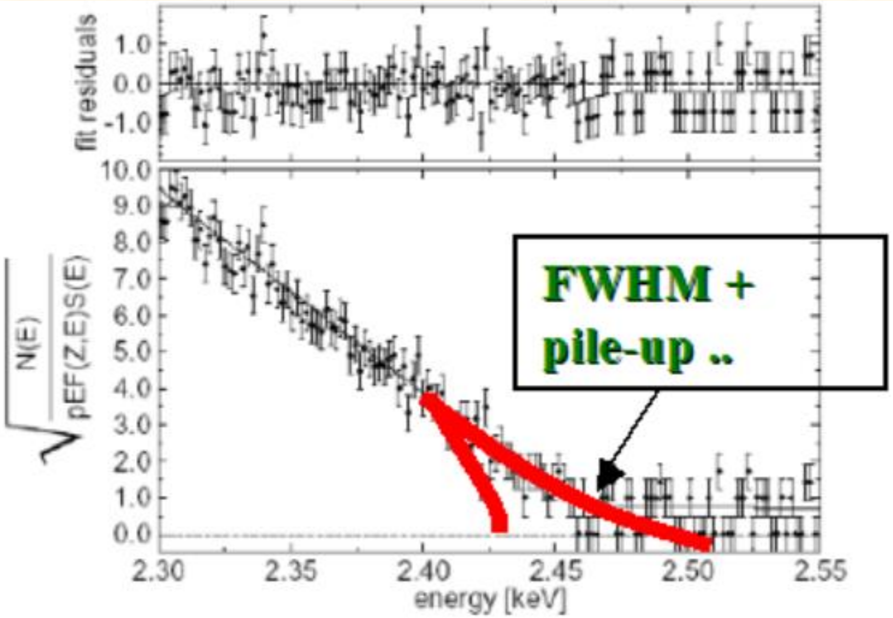
- **Neutrino(s) mass (single beta decay ^{187}Re, Electron Capture ^{163}Ho)**

→ **Smaller Detectors (higher energy resolution, faster)**

Science case (III): the neutrino mass

$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e \left(Q = 2466\,\mathrm{eV};\, T_{1/2} = 43.2\,\mathrm{Gyr}\right)$$





Now these experiments are **a bit outdated**, the ^{187}Re is replaced by ^{163}Ho and the beta decay is replaced by electronic capture.

LTD:
motivations and classification

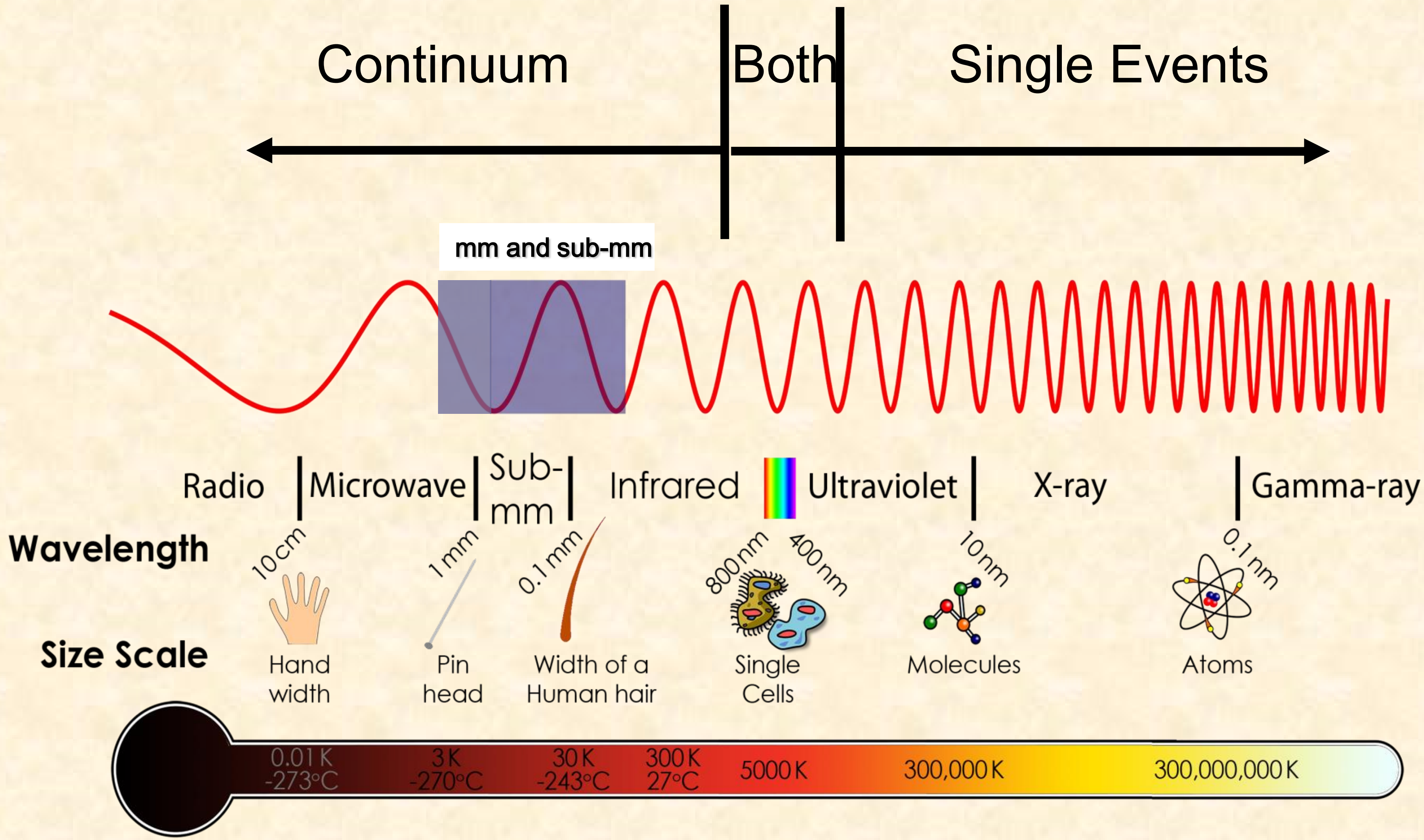
Low Temperature Detectors: a comment

http://ltd16.grenoble.cnrs.fr/#LTD-history

LTD are in general defined as just the **very-low-temperature** ones e.g. 95% of our community works at sub-Kelvin temperatures. Most of the sub-Kelvin cryogenics techniques have been developed and spread around by the LTD and Solid-State Physics community. **More than 90% of the « LTD » operate between 5 and 300mK.**

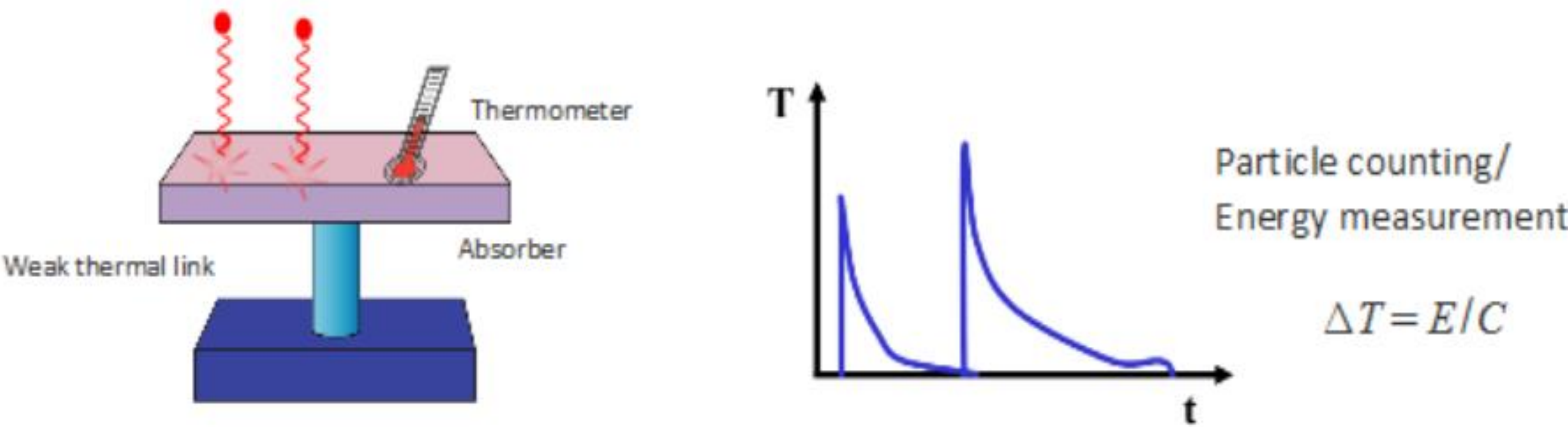
For example, we do not consider as LTD the IR semiconducting detectors that are cooled to LN2 temperature just to suppress the thermal noise

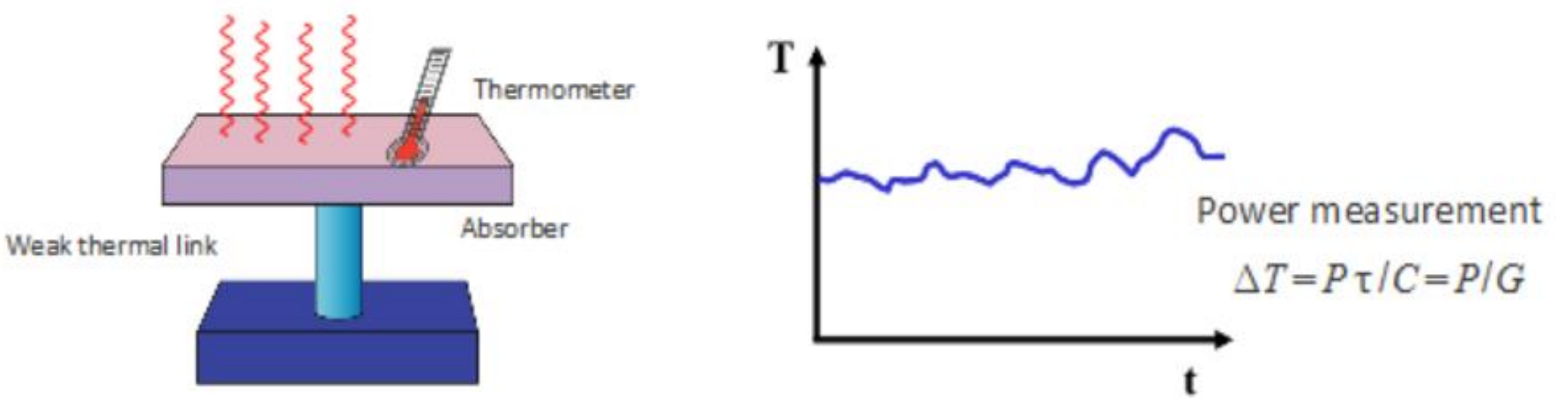
The EM spectrum: count vs record



Pulses versus time-traces

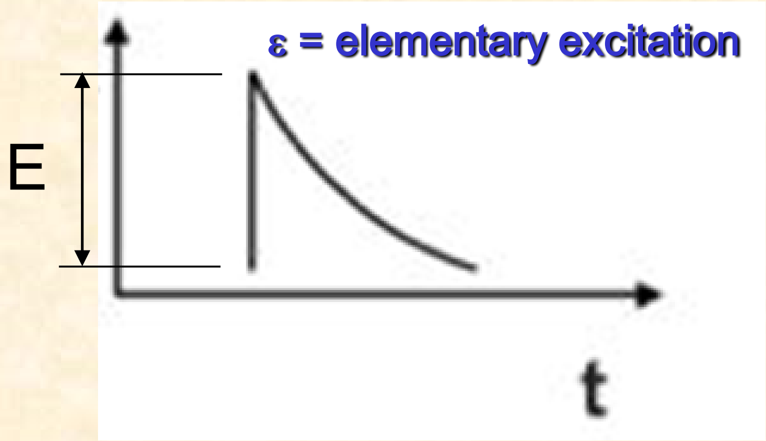
A typical LTD has two 'operating modes':





Low Temperature Detectors

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 $\approx 3.5 \cdot kT_c$)

→ 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

Low Temperature Detectors

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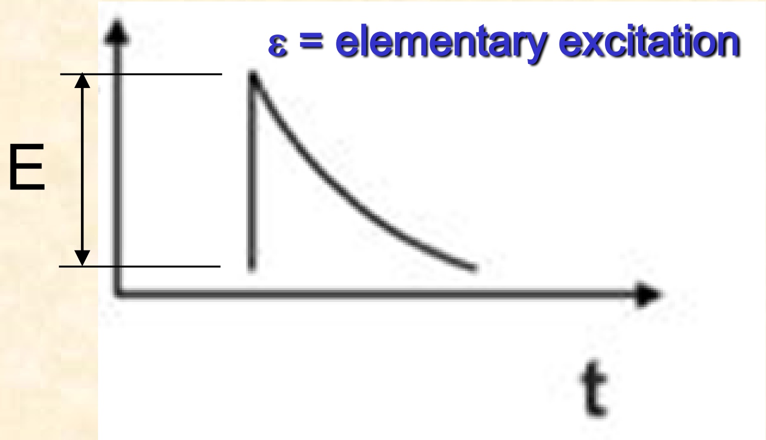

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→ Cooper-pair-breaking detectors (gap ≈ $3.5 \cdot kT_c$) $\boxed{T_{base} \ll T_c}$

→ Bolometers (phonon energy ≈ kT)

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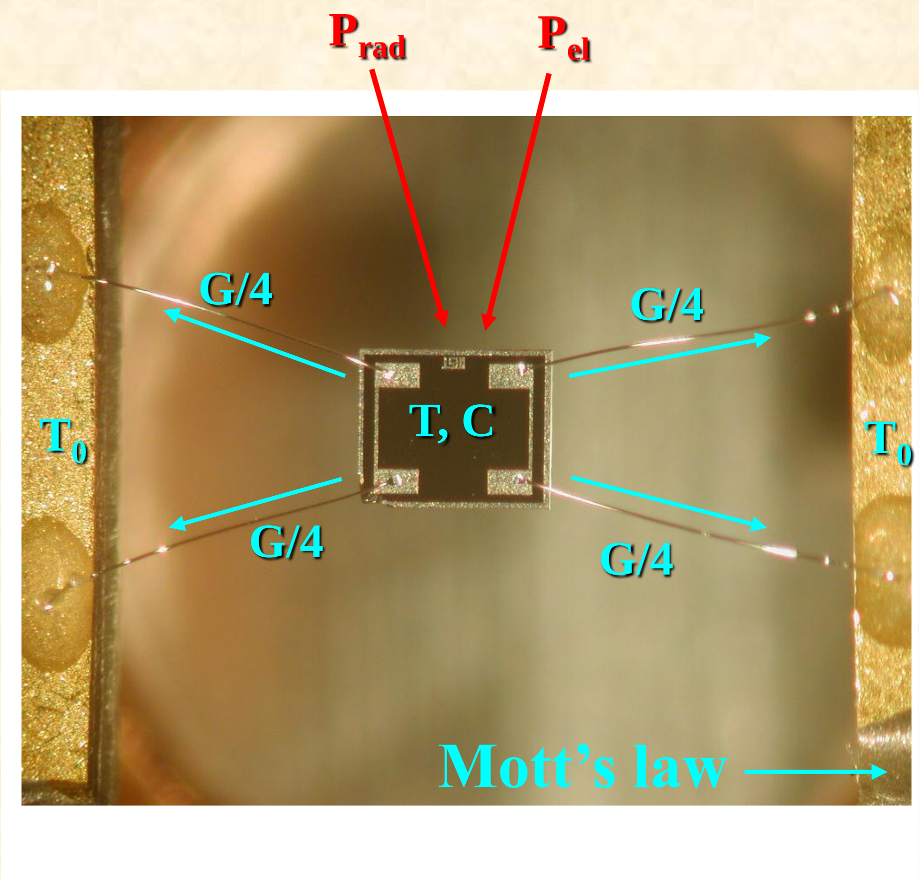
Bolometers: ideally simple



P_{rad} = radiation power
P_{el} = electrical power (needed)
P_{ev} = power flowing to the cryostat

$$\boxed{C(T)\frac{dT}{dt} = P_{rad}(t) + P_{el}(T) - P_{ev}(T)}$$

$$C(T) = a \cdot T^b \quad e.g. b = 3$$

$$P_{ev}(T) \approx G_0 \cdot \left(T^{\beta+1} - T_b^{\beta+1}\right)$$

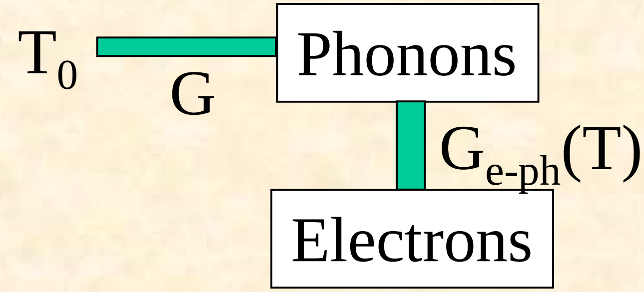
$$P_{el} = R(T) \cdot I^2$$

$$R(T) \overset{e.g.}{=} R_0 \cdot \exp\left[\left(T_0/T\right)^n\right] \quad e.g. n = 0.5$$

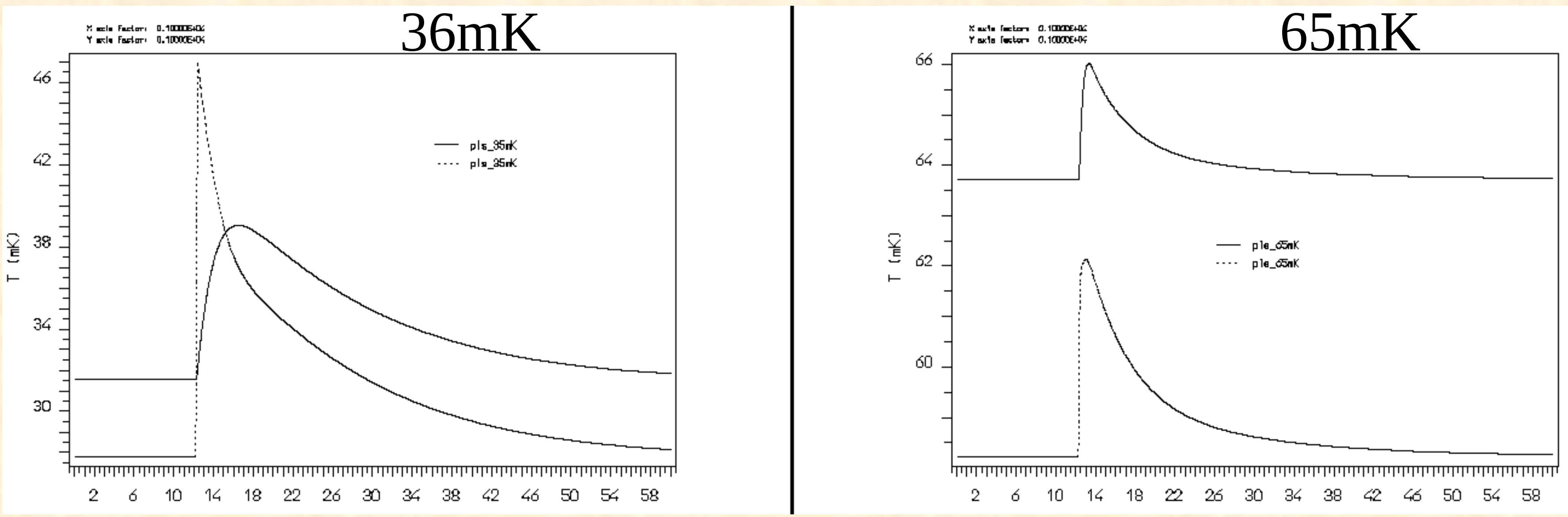
The R(T) shown here is verified for example in the case of doped semiconductors.

Real bolometers: more complicated

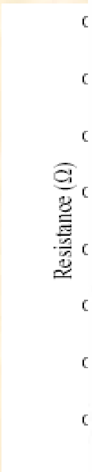
Experimental data require it behaves like:

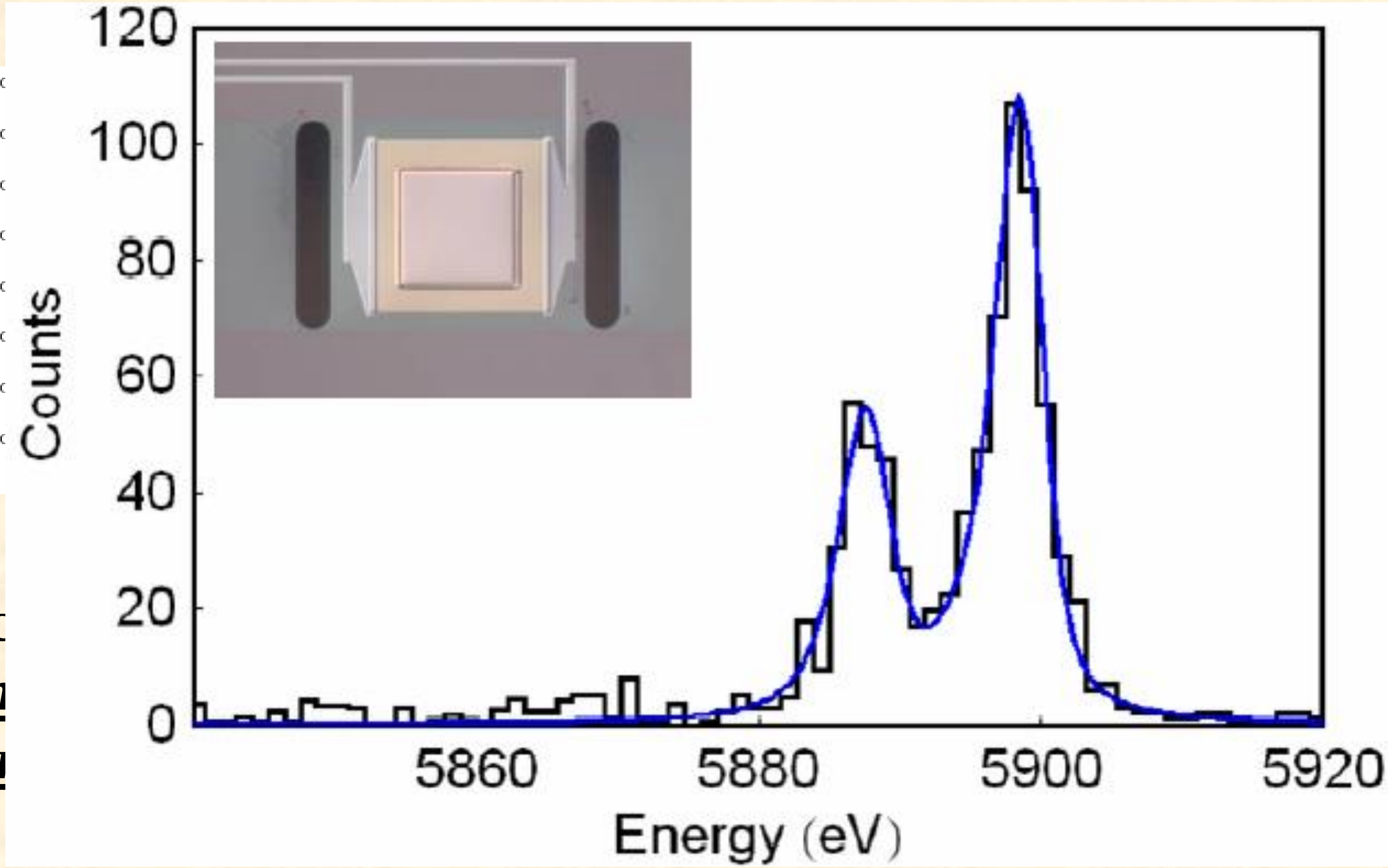


BUT: how can an electron know about the others “temperature” ?



Transition Edge Sensor - TES





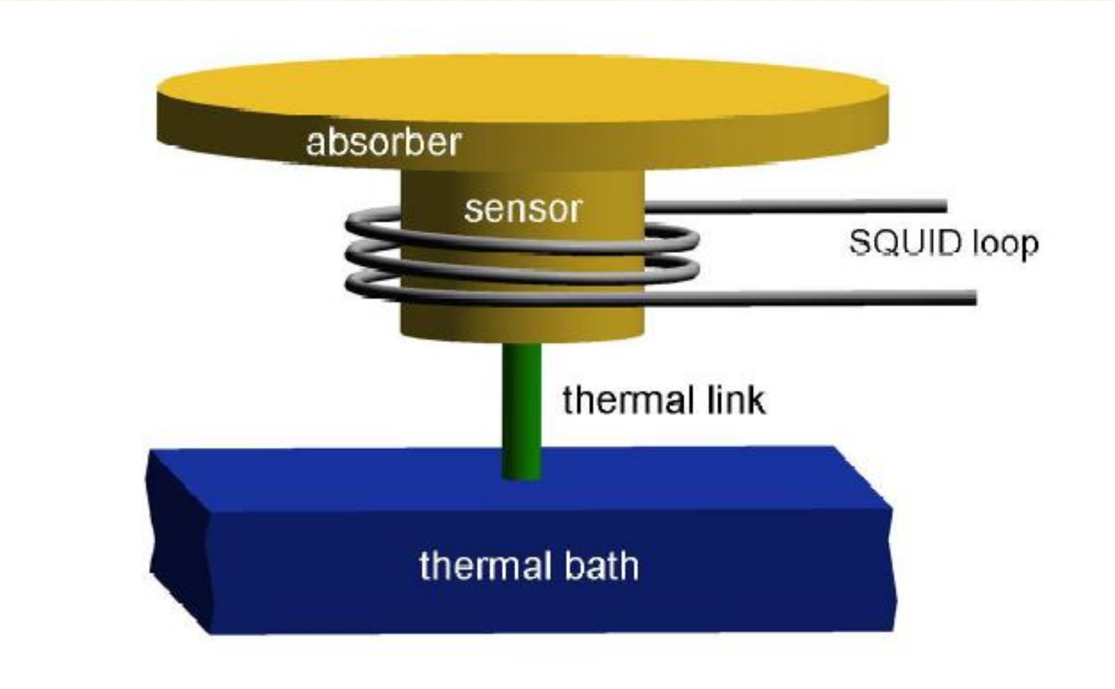
UID

Effec

I con ble

V co ⇒ **OK**

Magnetic Metallic Calorimeters - MMC



The radiation absorber is thermally coupled to a paramagnetic sensor that is actually the thermometer.

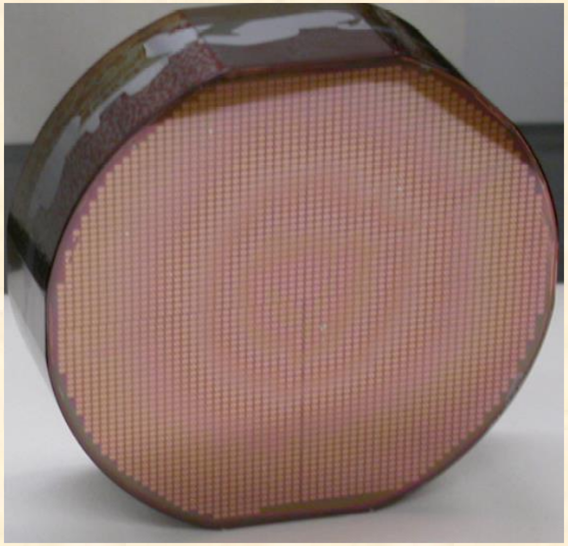
The magnetization is in fact temperature-dependent and is measured by means of a SQUID magnetometer.

The sensor is realized by implantation of paramagnetic ions into a metallic host (e.g. **Au:Eu**) that allows a sufficiently fast relaxation time.

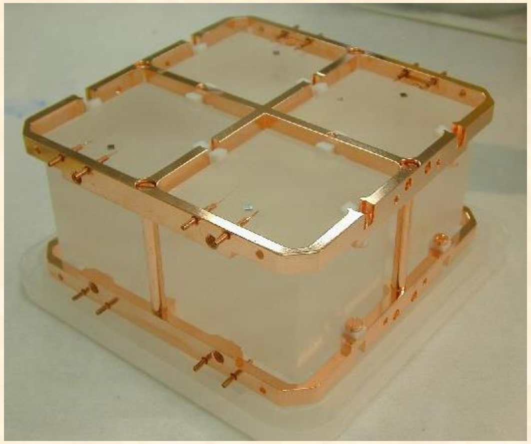
Macro-bolometers for rare events search

In this case, the detector (bolometer-absorber) has to be big !!

EDELWEISS-II 320gr Ge
Total mass: 40kg
Frejus - FRANCE



Super CDMS 350gr Ge+Si
Total mass: 25kg
Soudan - USA

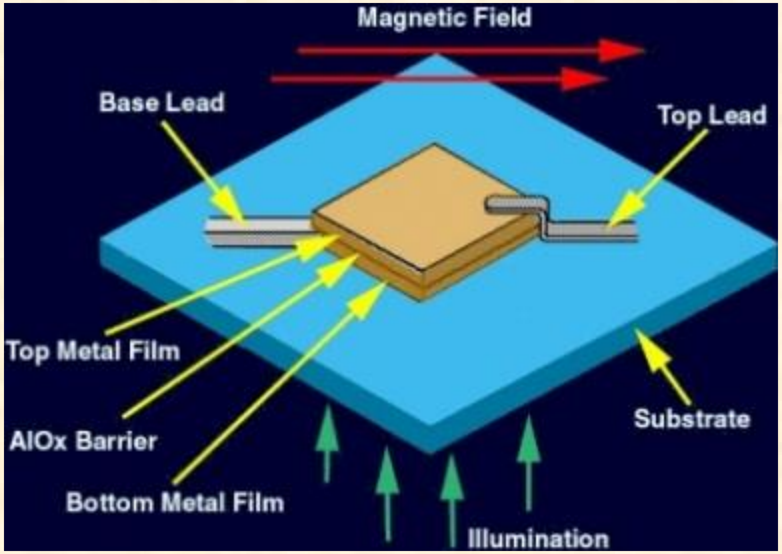


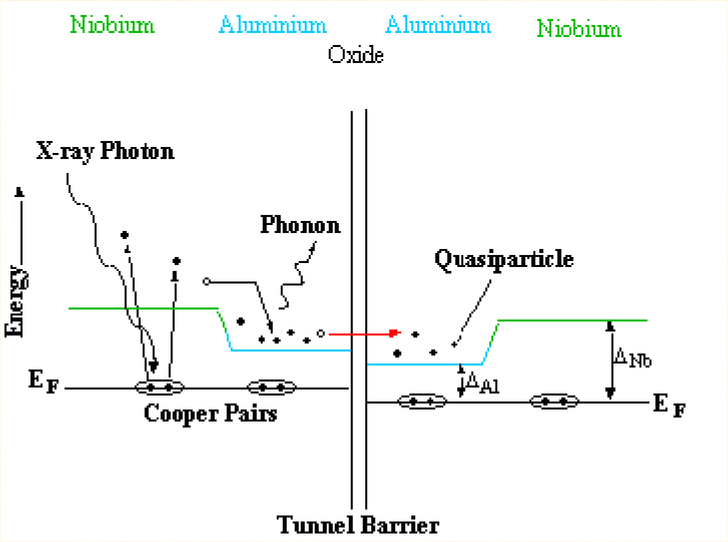
CUORE 750gr TeO_2
Total mass: 750kg
Gran Sasso - ITALIA

So far a list of bolometers equipped with different thermistors

What about Cooper-pair-breaking devices ?

Superconducting Tunnel Junction - STJ



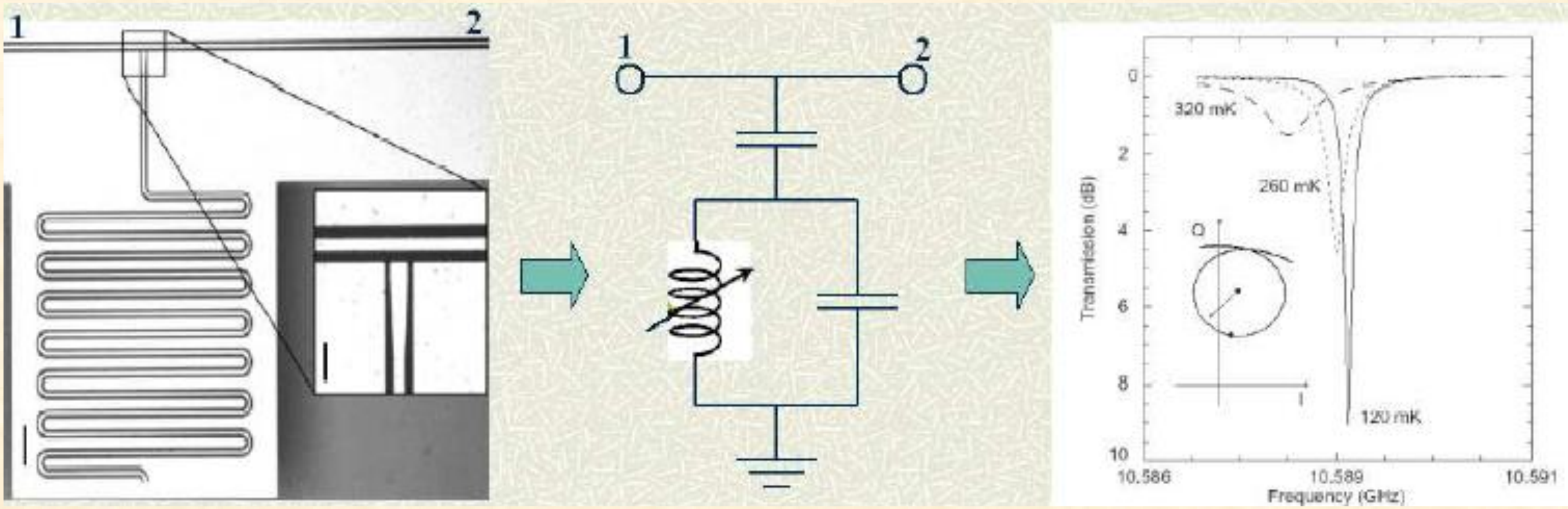


Pair-breaking detectors (not phonon-mediated)

Advantages: relatively fast, 300mK operations, position-sensitive.
Drawbacks: complexity, need of B field, resolution worse than others, ***not easily multiplexable.***

In the old days used to be the 1st choice for Astronomical applications (e.g. S-CAM).

Kinetic Inductance Detectors - KID

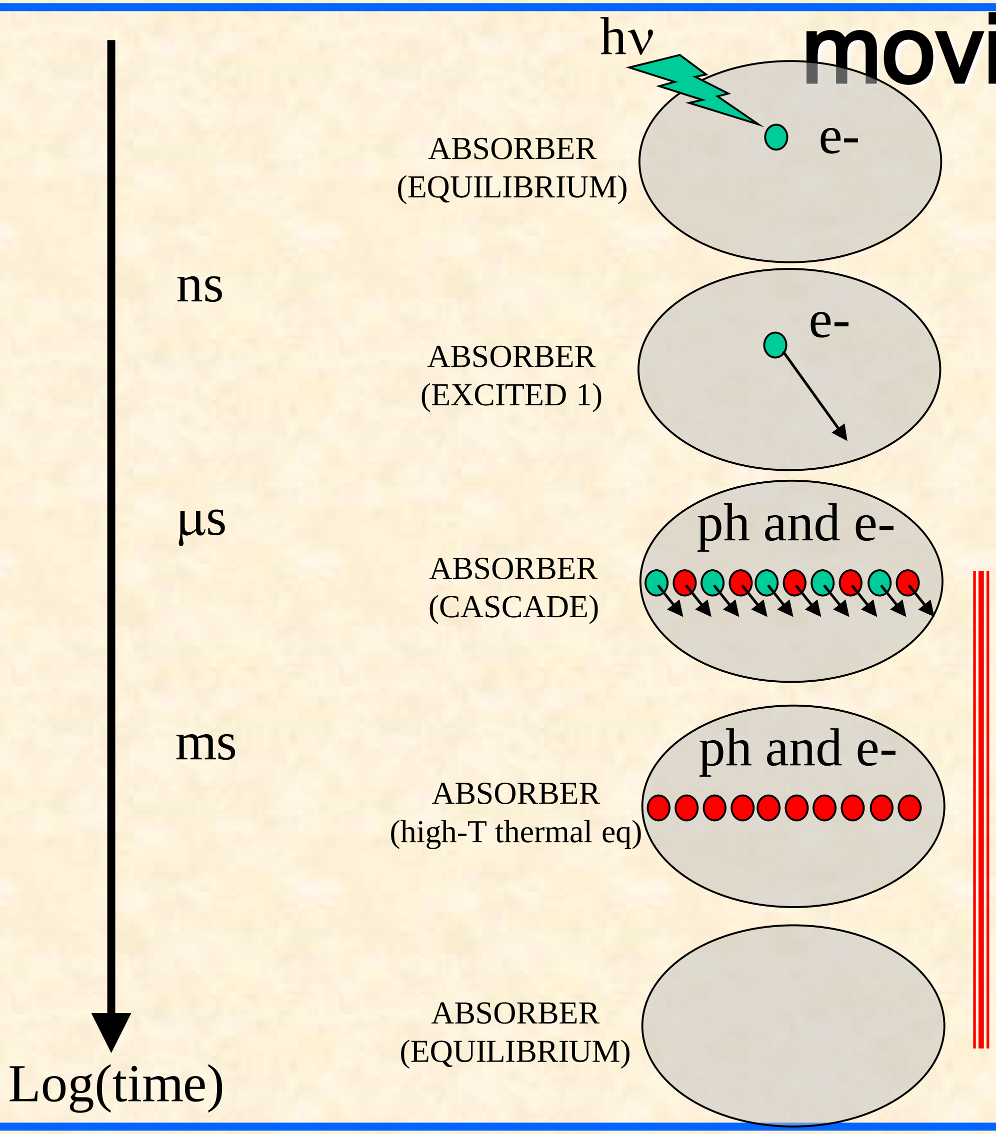


<u>BIG ADVANTAGE:</u> intrinsically multiplexable.

Seems a merely « technical » advantage, in reality VERY important.

<u>Old LTD workshops:</u> in 2005 only one talk on KID …
<u>LTD16 (Grenoble, 2015):</u> the number of abstract received concerning KID surclassed the bolometers for the first time.

Bolometers vs Pair-breaking: detection movie



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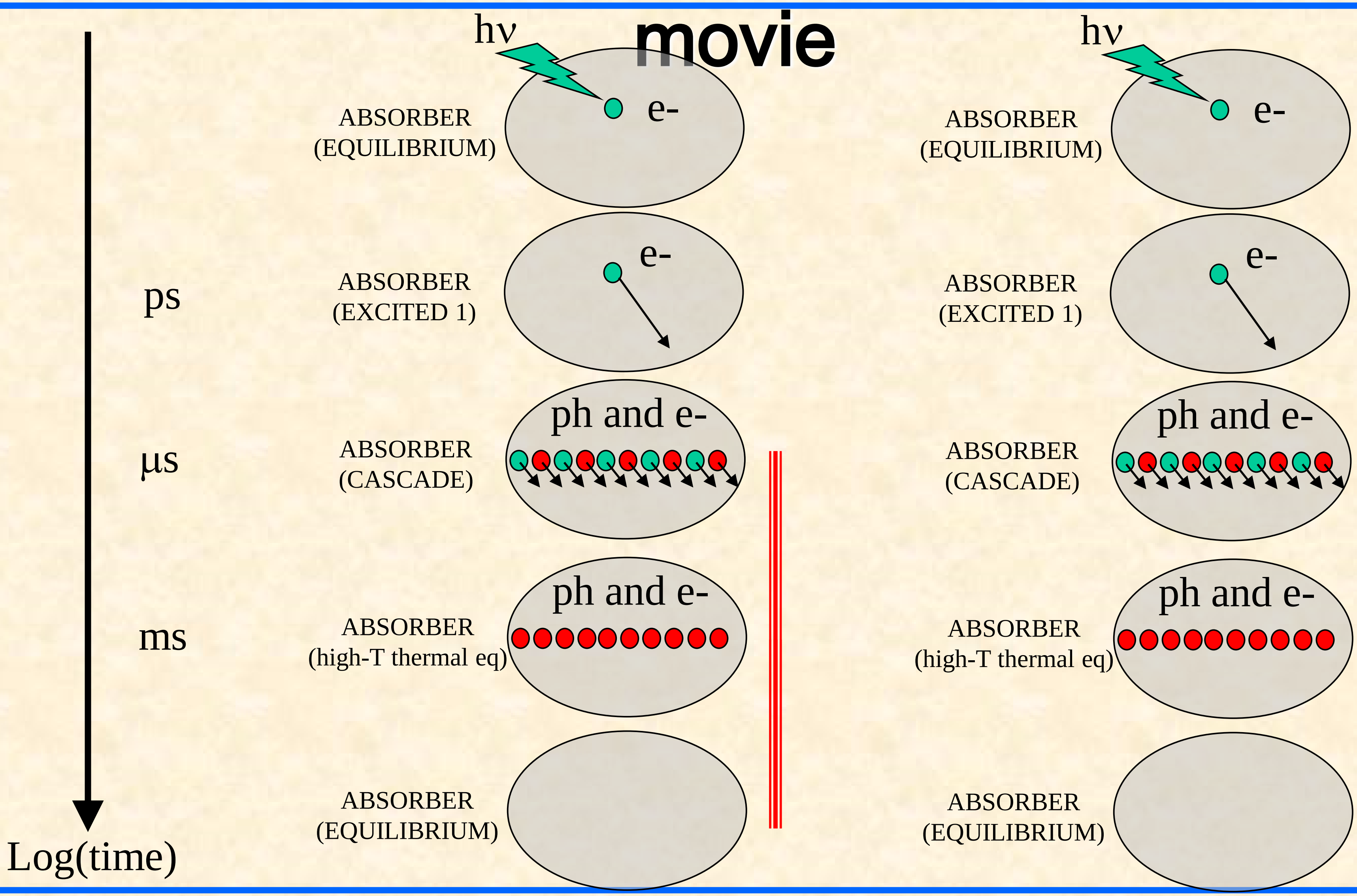


Bolometers vs Pair-breaking

Single events detection (counting/measuring):

- if the priority is the best energy resolution (very often the case for LTD), BOLOMETERS (e.g. TES) are the best choice.

Low energy photons detection (recording):

- if the priority is be sensitive and maximizing the number of pixels (very often the case for LTD) KID are the best choice

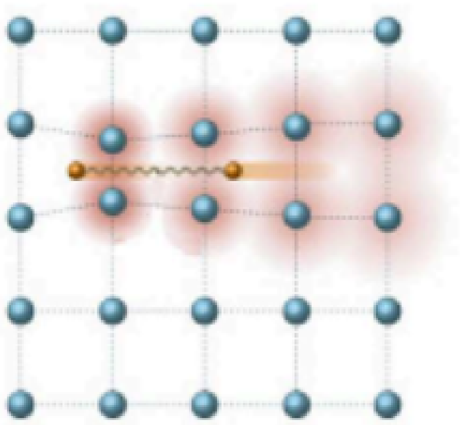
THESE CONCLUSIONS ARE OBVIOUSLY TOO SIMPLE AND SCHEMATIC. MANY EXCEPTIONS CAN BE FOUND !!!!

TO BE CONSIDERED: response speed, sensitivity to B fields, microphonics, readout electronics, environment, technology availability etc. etc.

Superconductivity and high-Q resonators

Superconductivity (I)

At low T the electrons have very little thermal energy, and can bind to form **Cooper Pairs** through a phonon-mediated interaction



The binding energy of a Cooper Pair is given by :

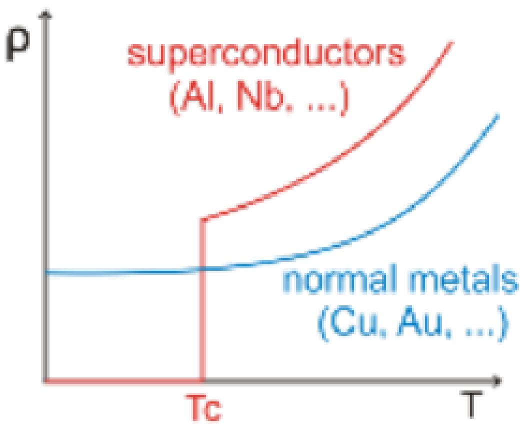
$$\boxed{2\Delta = 3.5\ k_b T_c}$$

QUANTUM MECHANICS

This corresponds to typically few meV.

The Cooper Pairs are bosons → perfectly ordered motion, $\rho = 0$

Electrons that remain unbound are called quasi-particles. $\rho \neq 0$



Excitation = **quasiparticles!**

$E = 3.5 k_b T_c$

Superconductivity (II)

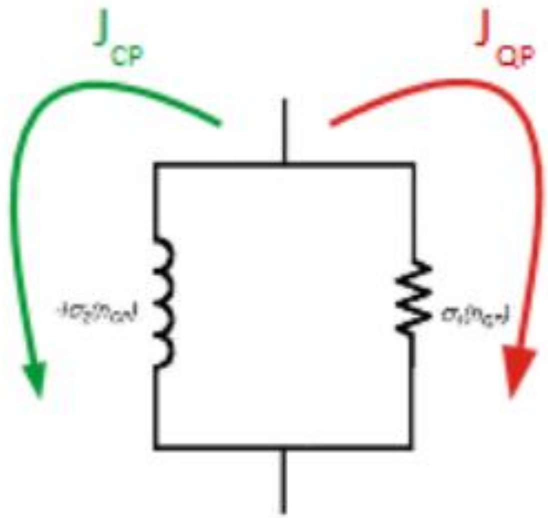
We can describe the conductivity of a superconductor starting from the behavior of CPs and QPs two families:

- **Cooper Pairs :**

  Non-dissipative

  Reactance!

  Proportional to ω



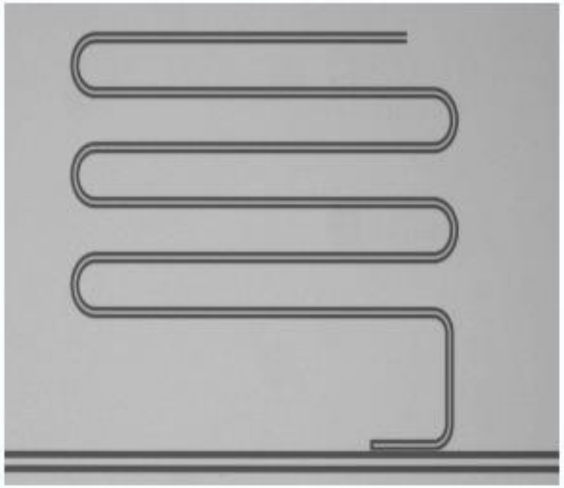
- **Quasi-Particles :**

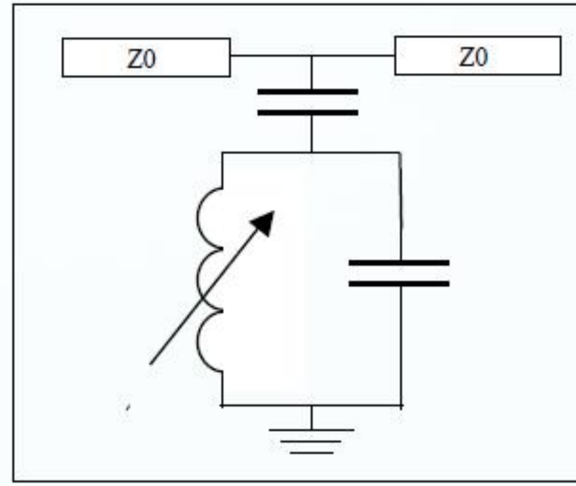
  Dissipative

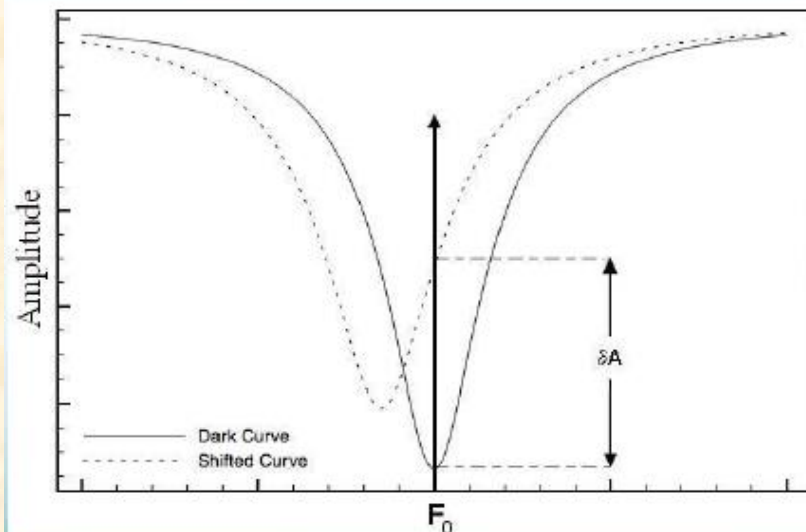
  Resistance

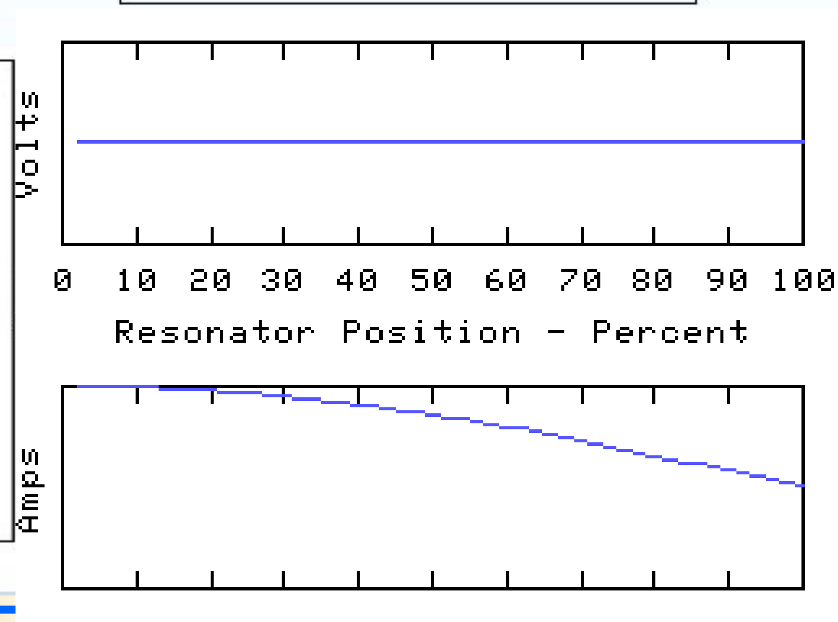
- DC field : zero impedance (→ 'classical' superconductivity)
- AC field : non-zero impedance!

The distributed (λ/4) planar resonator

1  2

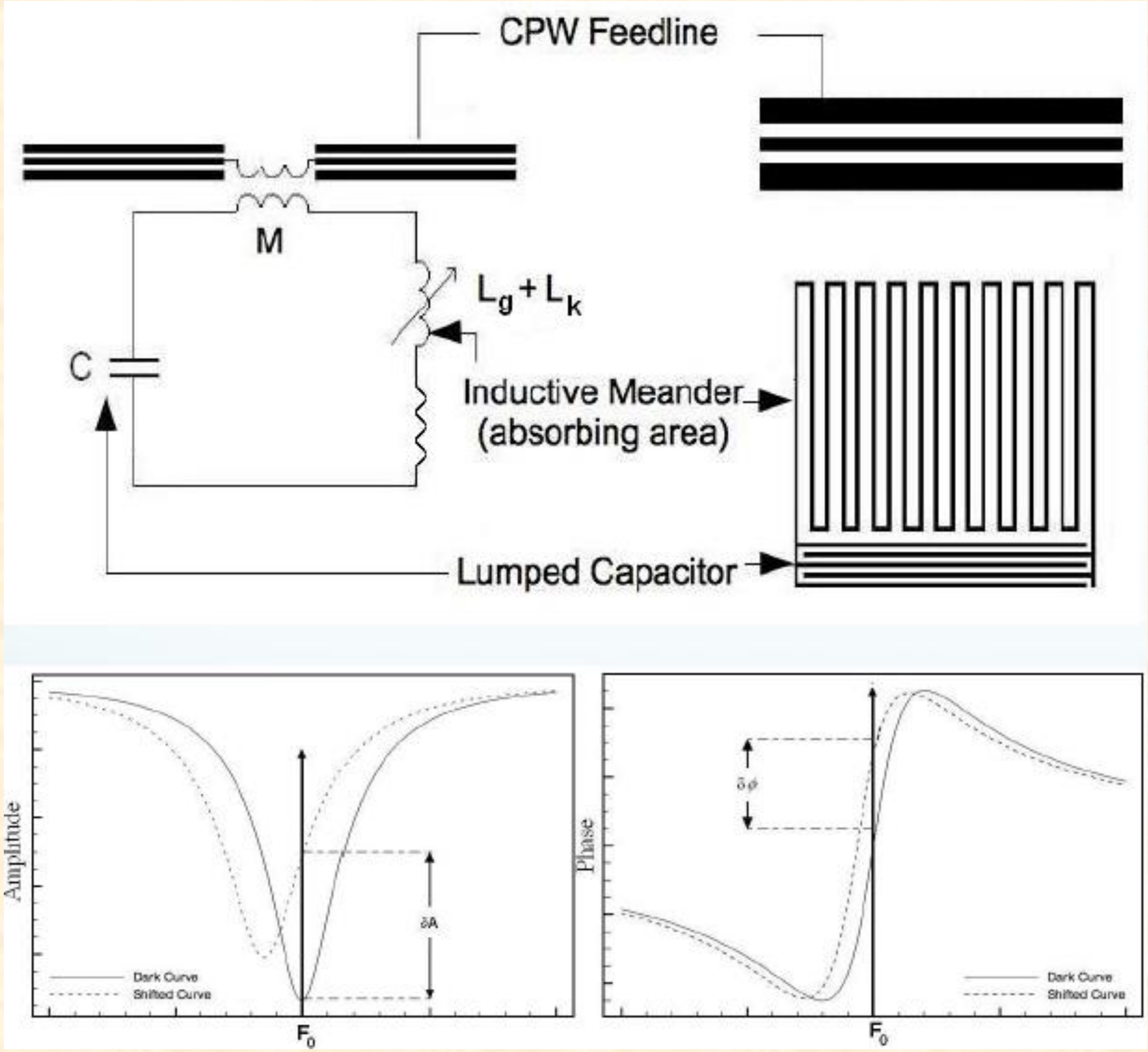


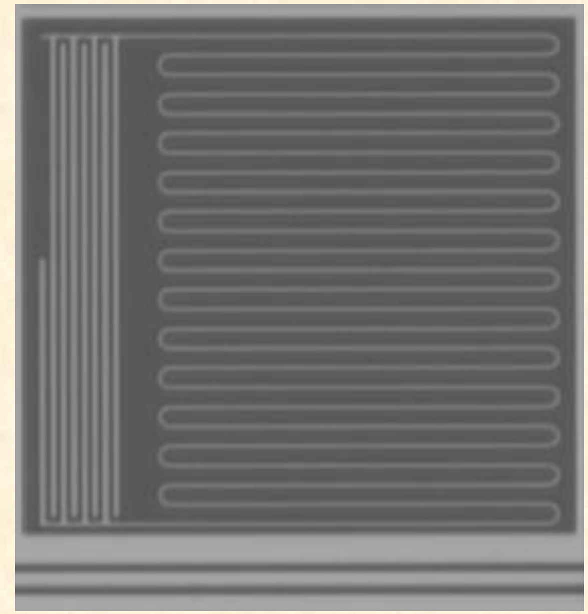




$$f_0 \cong \frac{1}{4l\sqrt{(L_K + L_G)C(\epsilon)}},$$

The “lumped elements” planar resonator



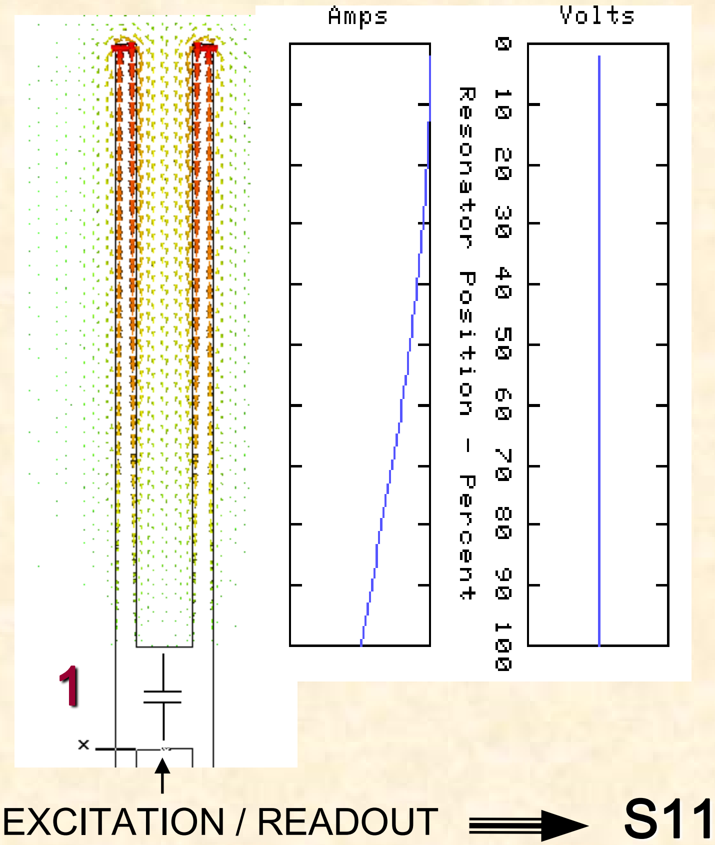


The resonator is ready to become a radiation detector

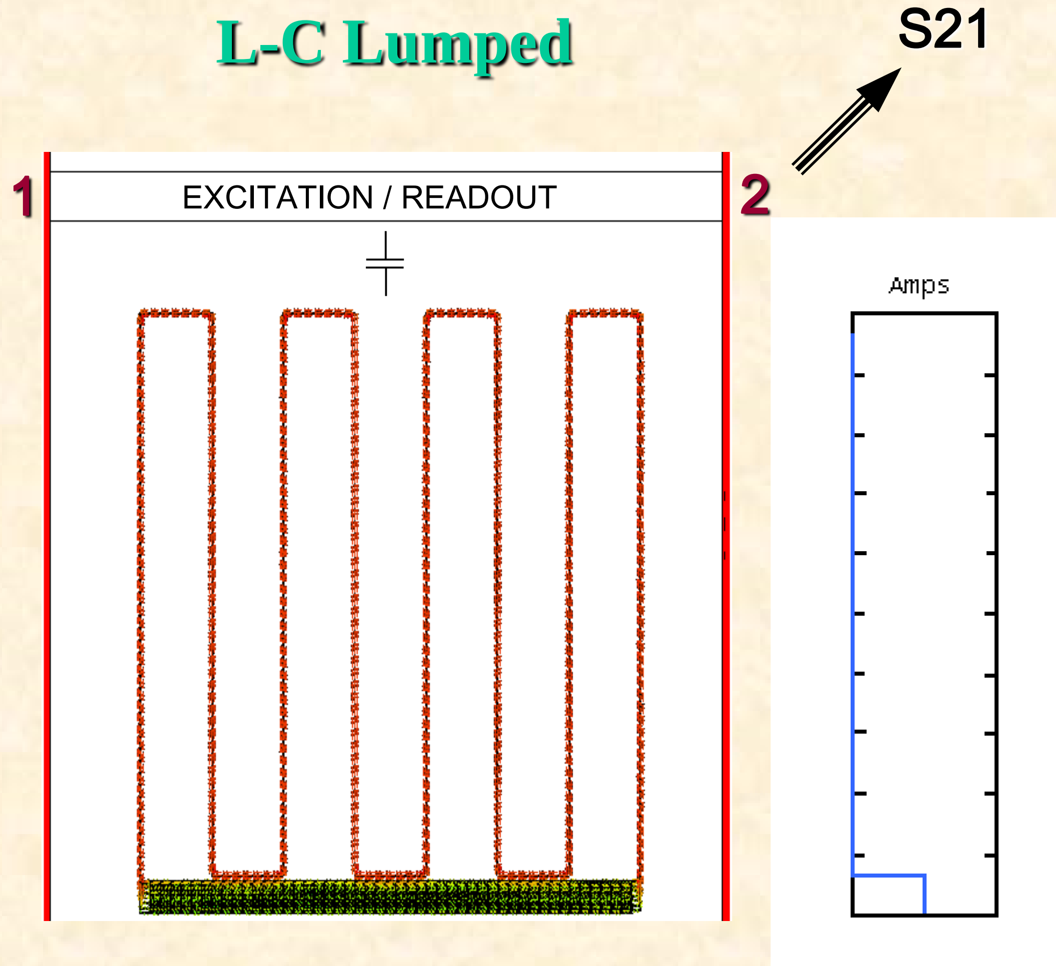
Credit: S. Doyle

Distributed vs. Lumped

L-C distributed (λ/4)



L-C Lumped



Additional ingredient from superconductivity

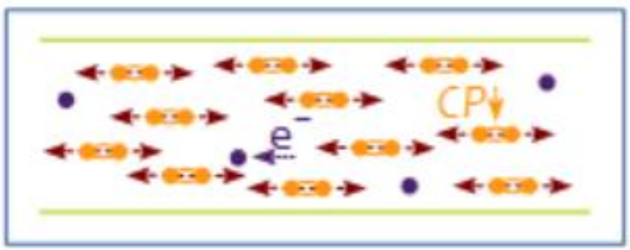
The reactance of the CP is due to their *acceleration*!

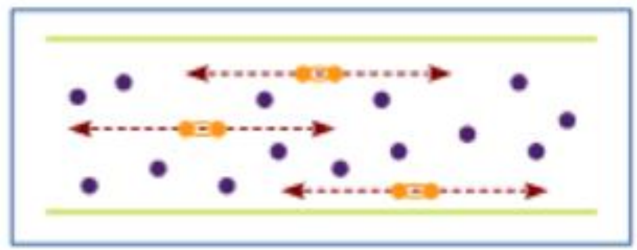
When moving, the CP store energy:

- Magnetic field → magnetic inductance, L_m
- Kinetic energy → $\boxed{\text{kinetic inductance, } L_k}$

L_k

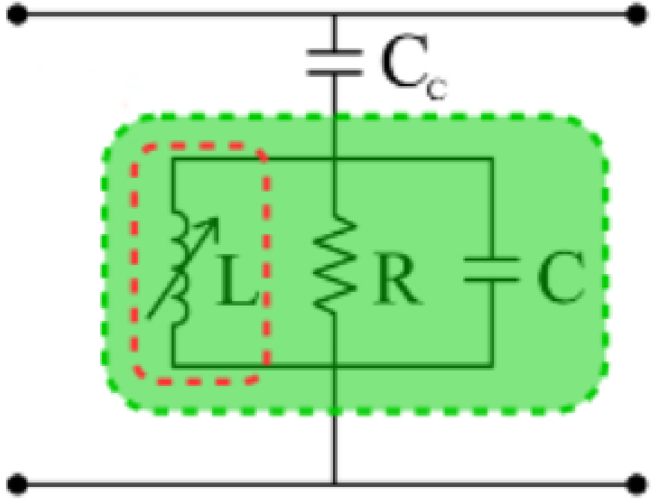
L_k depends on the desity of Cooper Pairs, $\boldsymbol{n_{CP}}$:





$\boxed{n_{CP} \searrow \quad \Rightarrow \quad L_k \nearrow}$

Integrate the L_k into the circuit



- A variable inductance

  (→ *superconductivity*)

- A resonating circuit

Sensitive devices

Quality factor: $Q \equiv \Delta f / f_0$ (typ. $10^3 - 10^7$) **superconductivity**

Q is a kind of « internal gain ». *Best Q is application-dependent.*

An LC(R) resonator is sensitive to L, C and (R) changes. **Obvious.**

Quarter Wave Electrical Measurable:

Transmission (complex) (S21) $\Rightarrow$ I,Q **(projections on complex plane)**

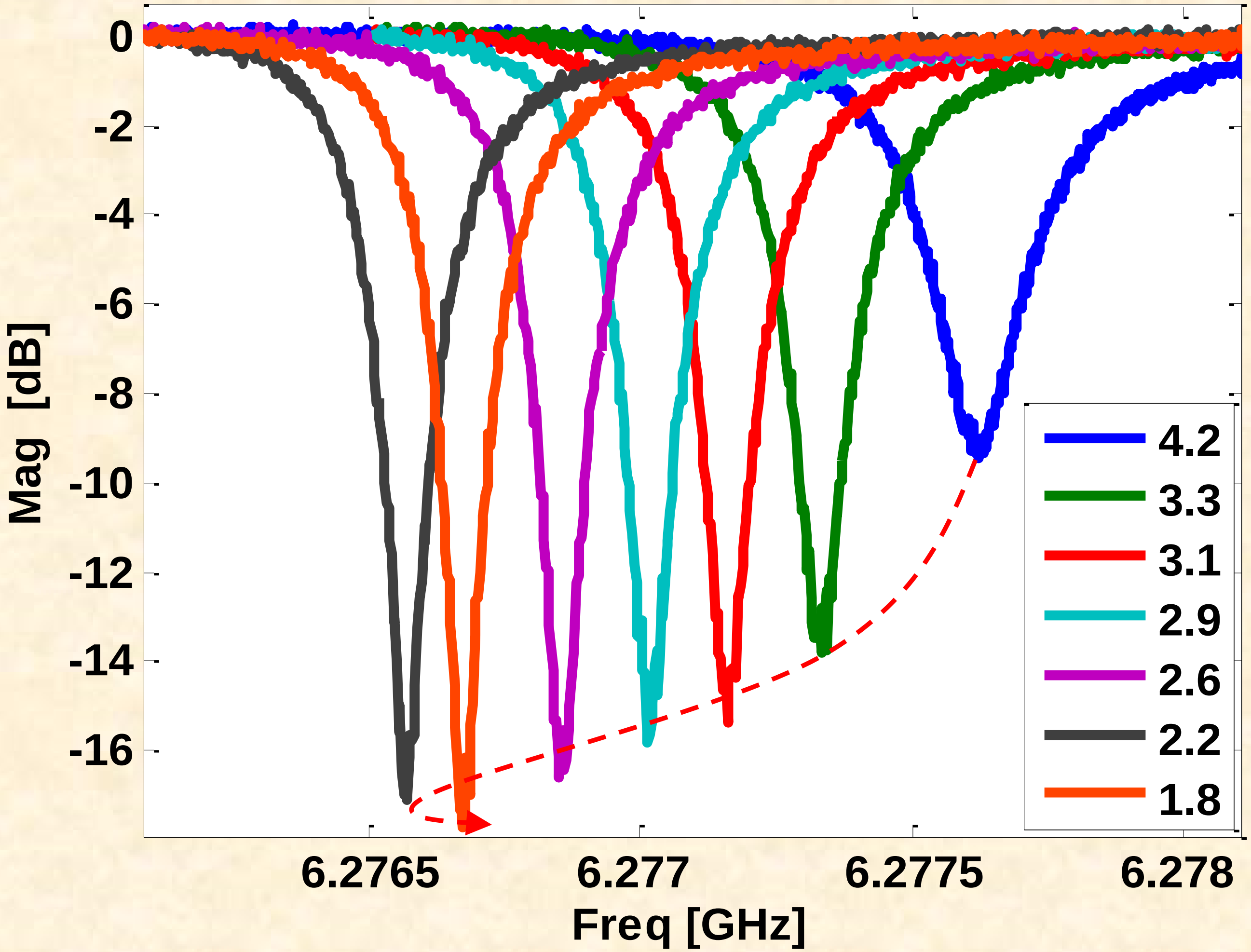
Physically interesting quantity:

Frequency shift $\Rightarrow \delta f \propto$ power (L.J. Swenson et al., APL 96, Issue 26, 263511 (2010))

EM environment (C): dielectrics + geometry

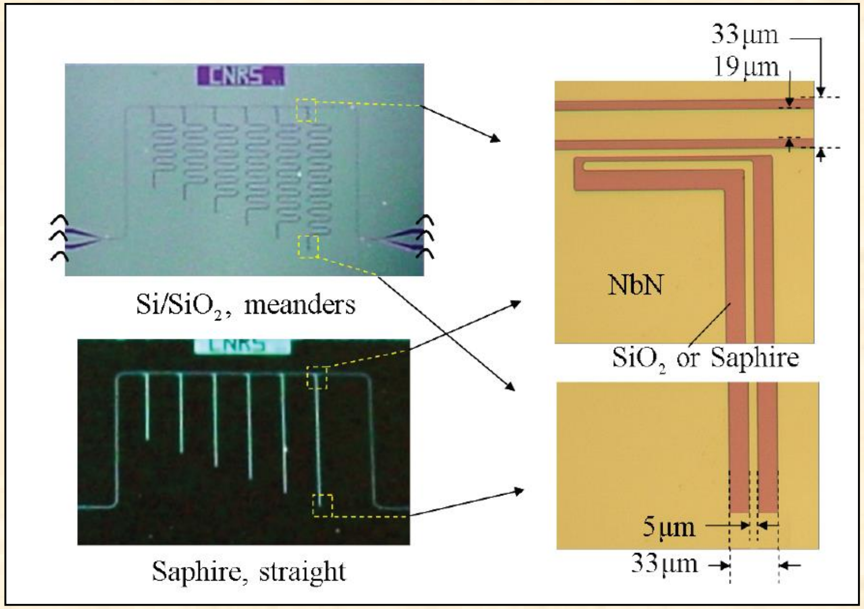
Quasi-particles (or Cooper pairs) density (L,R): KID

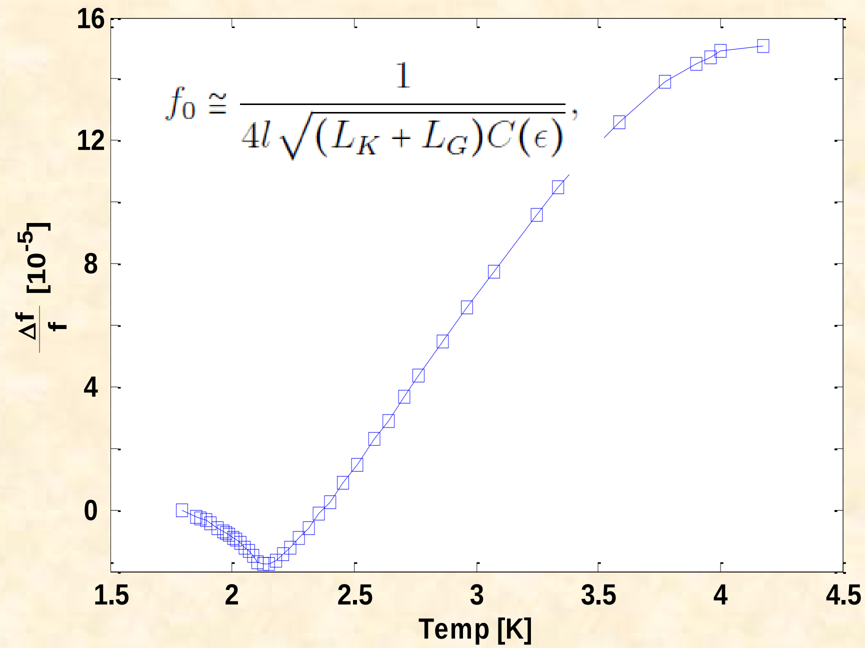
Cooling down in LHe .. strange effect



Pumped He
« green » cryo

LHe dielectric constant





NbN λ/4 resonators

(collaboration J.C. Villegier – CEA Grenoble)

$Q_i \approx 2\cdot 10^5$ at 2K

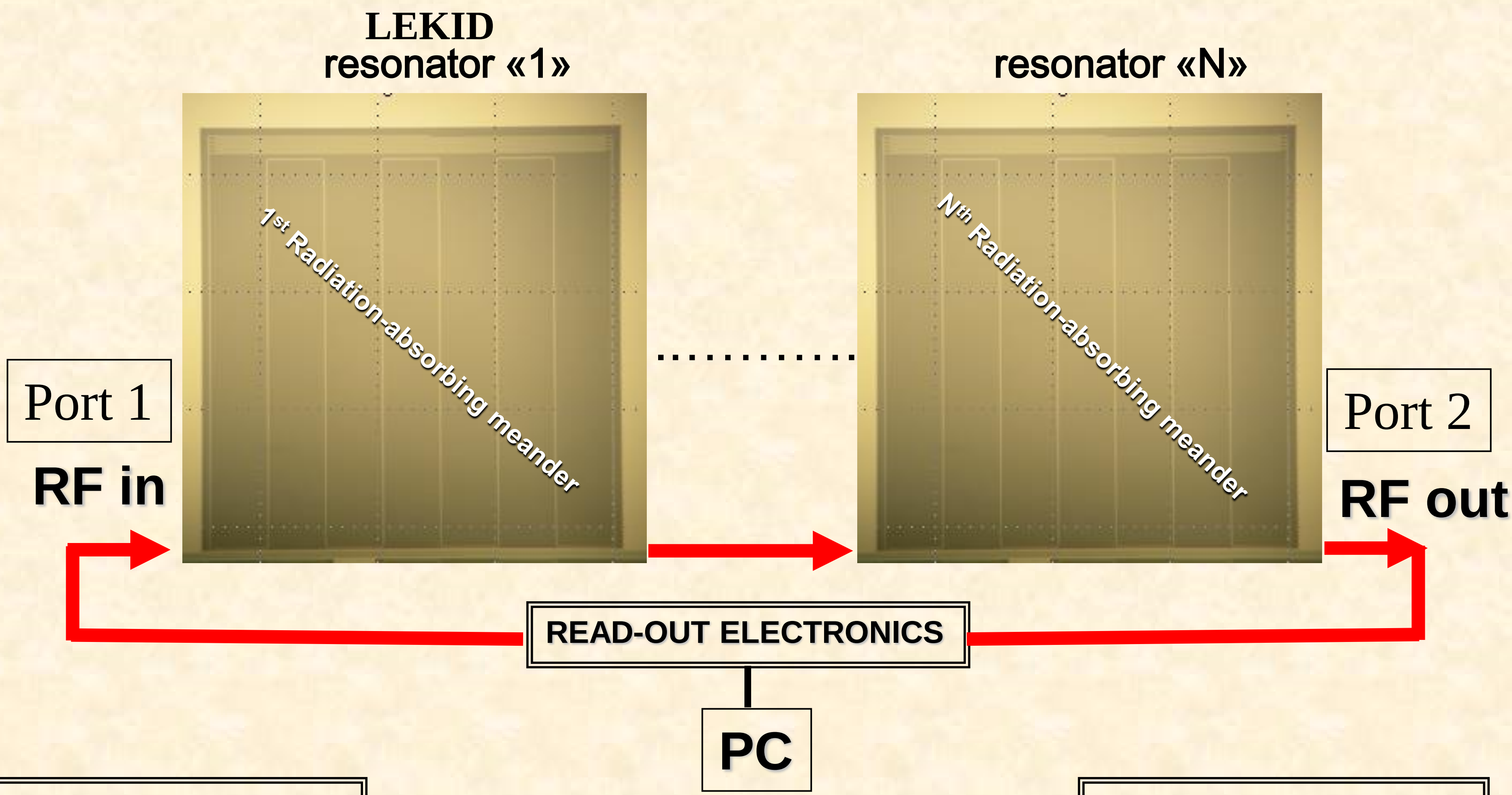
Applied Physics Letters 93, Issue 13, 134102 (2008)

Sensitivity to ε_r measurement:

$$\boxed{10^{-13}\ \epsilon_0/\mathrm{Hz}^{1/2}}$$

Kinetic Inductance Detectors (KID)

Kinetic Inductance Detectors MUX



N ≈ 100 ÷ 1000

Measurable: S21 = V_2^- / V_1^+

RF ≈ 0.1-10GHz

Kinetic Inductance Detectors : how it works

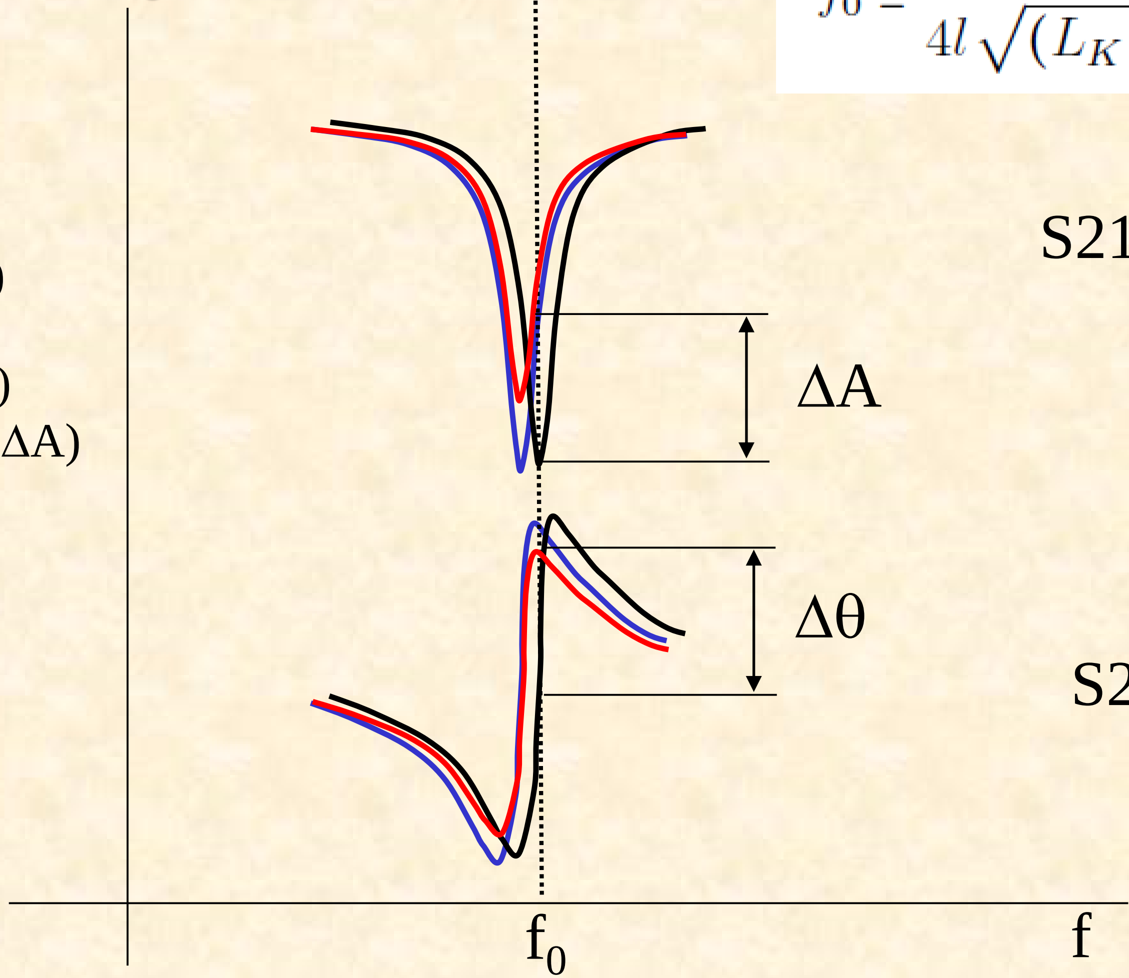
WHY : MULTIPLEXING !!
HOW : Superconducting RF Resonators

$$f_0 \cong \frac{1}{4l\sqrt{(L_K + L_G)C(\epsilon)}},$$

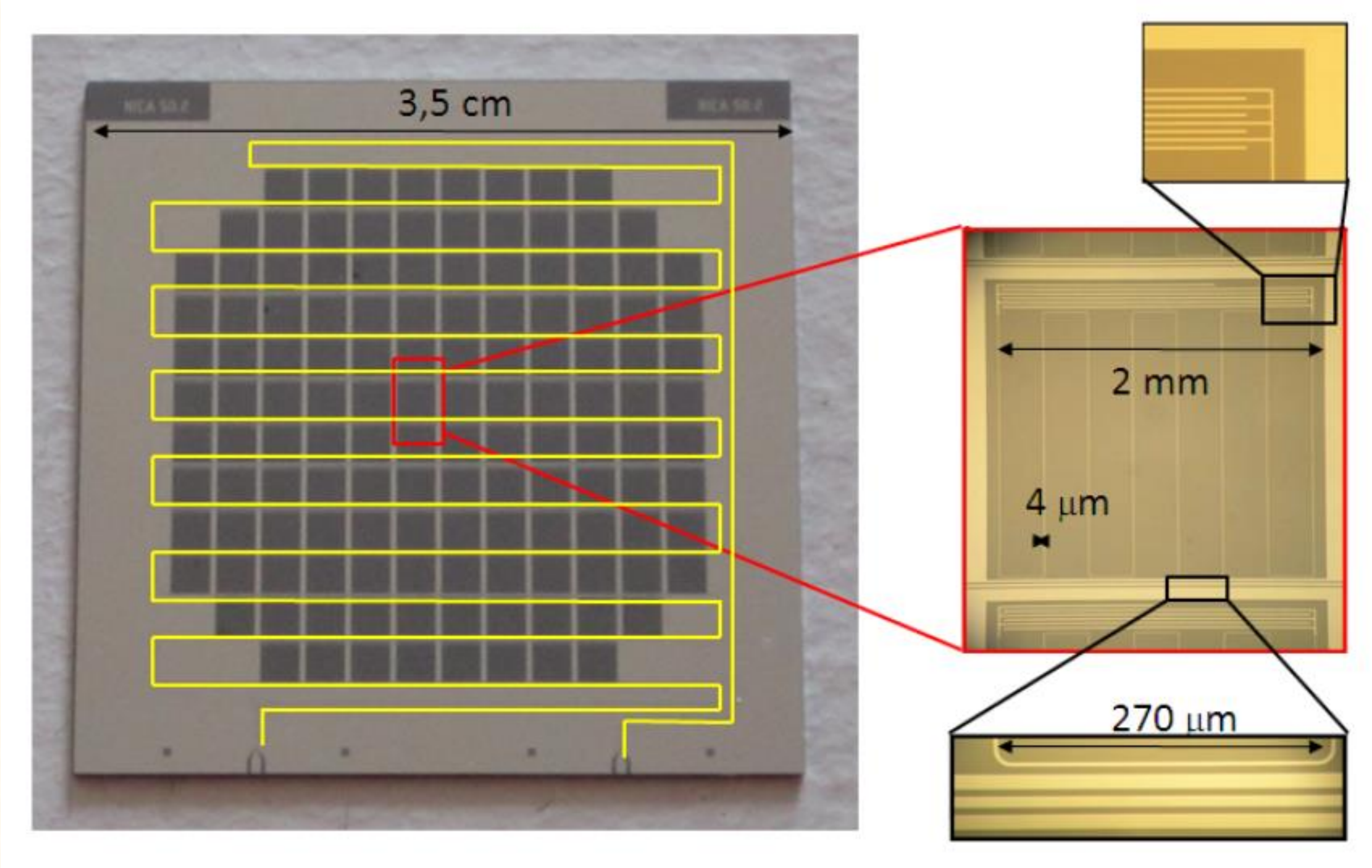
Dark, $T << T_c$

Photons: more L_k
Change in phase ($\Delta\theta$)

Photons: more qp (R)
Change in amplitude (ΔA)



A real array



LEKID intuitive model – take it with care

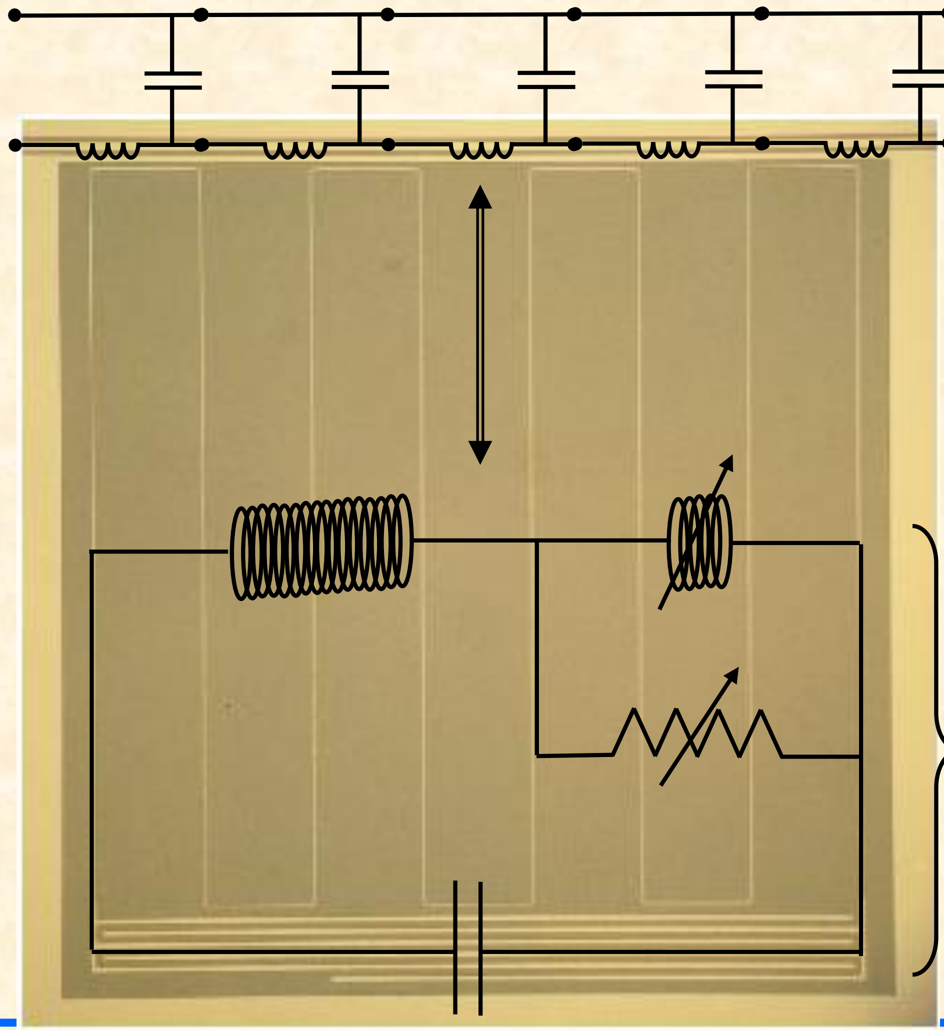
Coplanar Feedline (50Ω)

Mutual inductance M
and coupling C

Inductive meander $L_G + L_K$

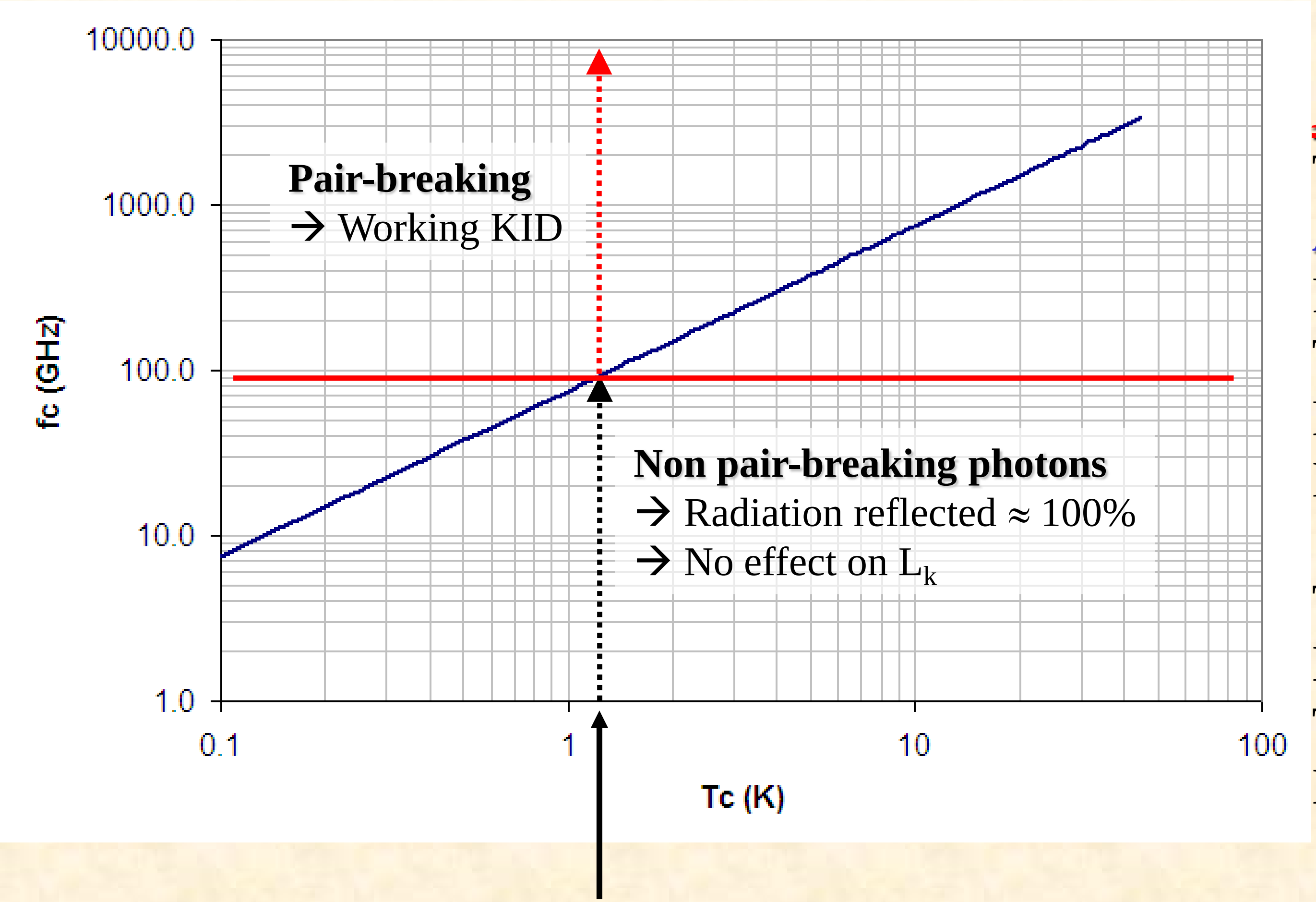
Resistance R (quasi-particles)
Metal IS SUPERCONDUCTING
at 1.5 GHz !!

Capacitor C



LRC
resonator

“Classical” films for KID



Examples:

Ti → $f_c \approx$ 40 GHz

Al → $f_c \approx$ 100 GHz

Re → $f_c \approx$ 130 GHz

Ta → $f_c \approx$ 340 GHz

Nb → $f_c \approx$ 700 GHz

NbN → $f_c \approx$ 1.2 THz

…

TiN_x → adjustable

Nb_xSi → adjustable

TiV_x → adjustable

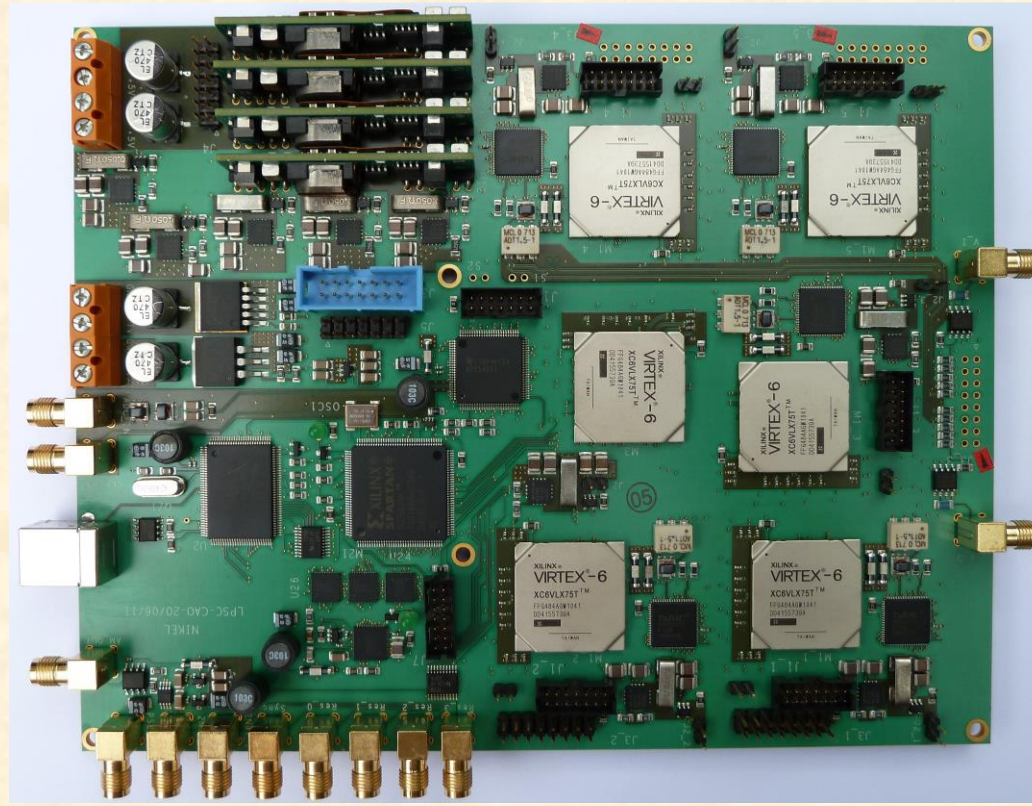
Multilayers → adjustable

e.g. Al, our best friend !!

A real MUX electronics

Board specs:

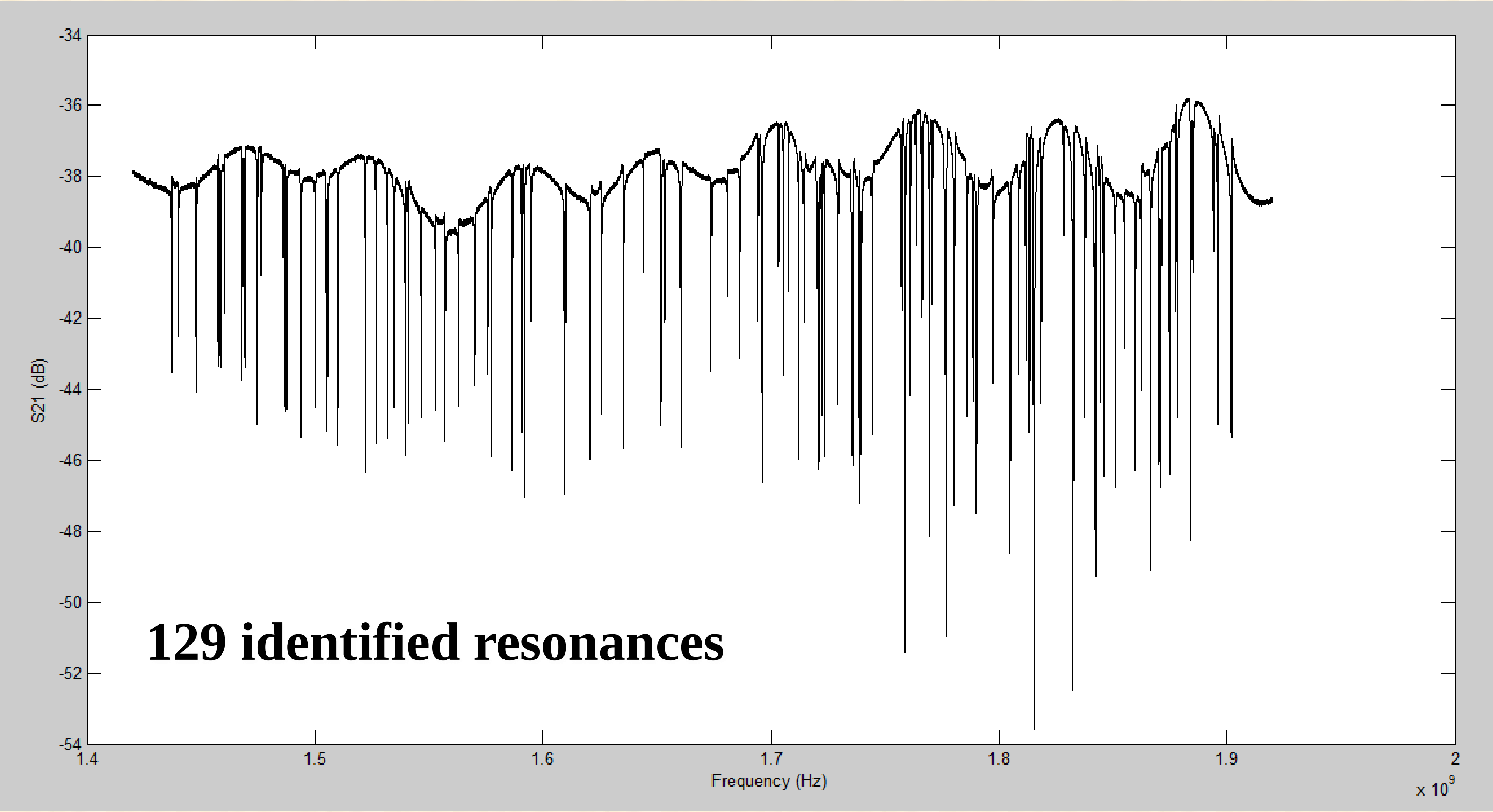
500 MHz, 400 channels
- ADC 12 bits 1GSPS
- DAC 16 bits 1GSPS
- FPGA Xilinx Virtex-6



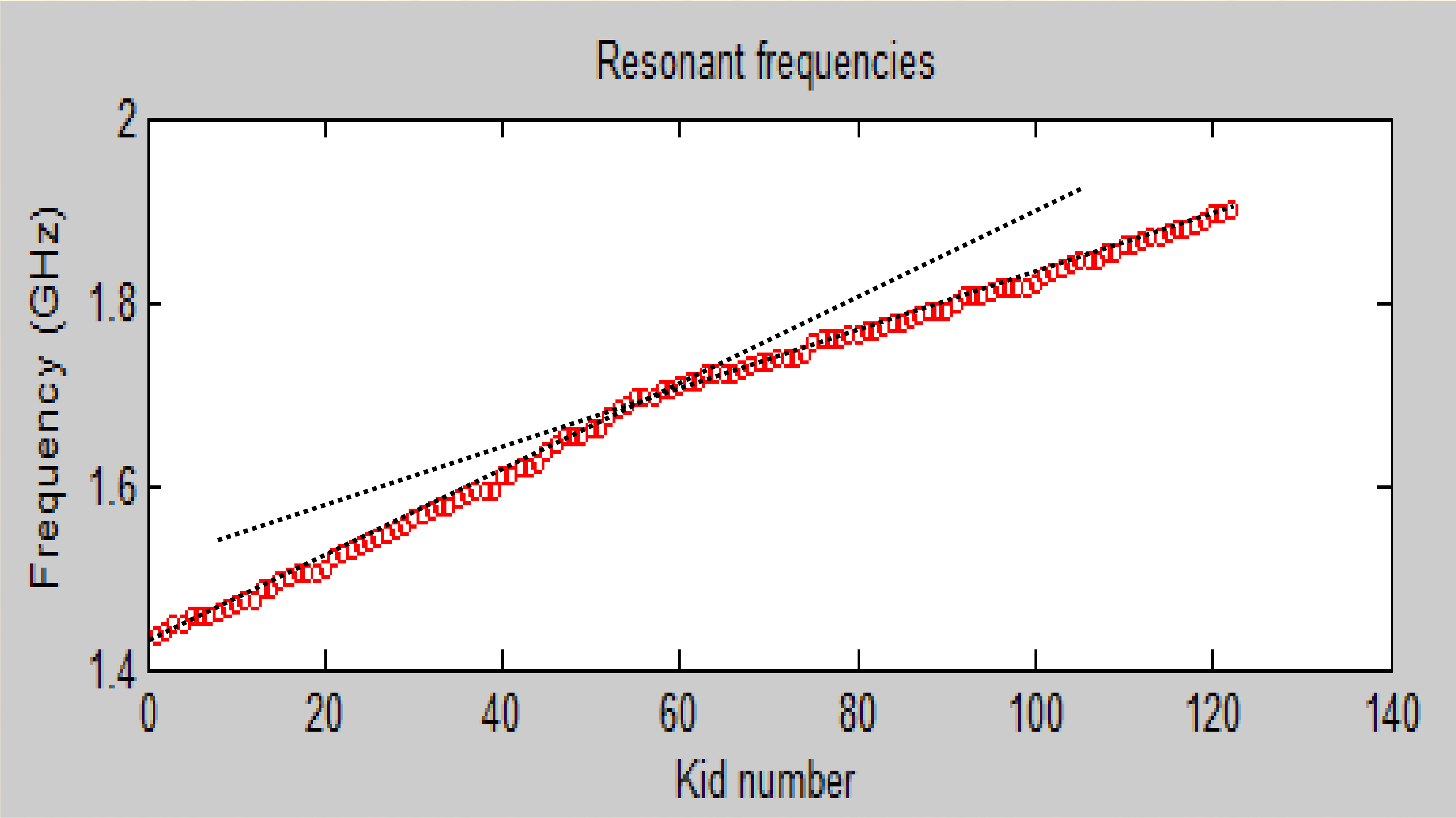
Board functions:
- Excitation tones
- Up-and-down conversion
- Digital mixing
- mini-PC integrated, ethernet to DAQ

For full details: ***O. Bourrion et al., Journ. of Instrum. 7, P07014 (2012)*** arXiv:1204.1415

Transmission of a (good) 132 pixels array



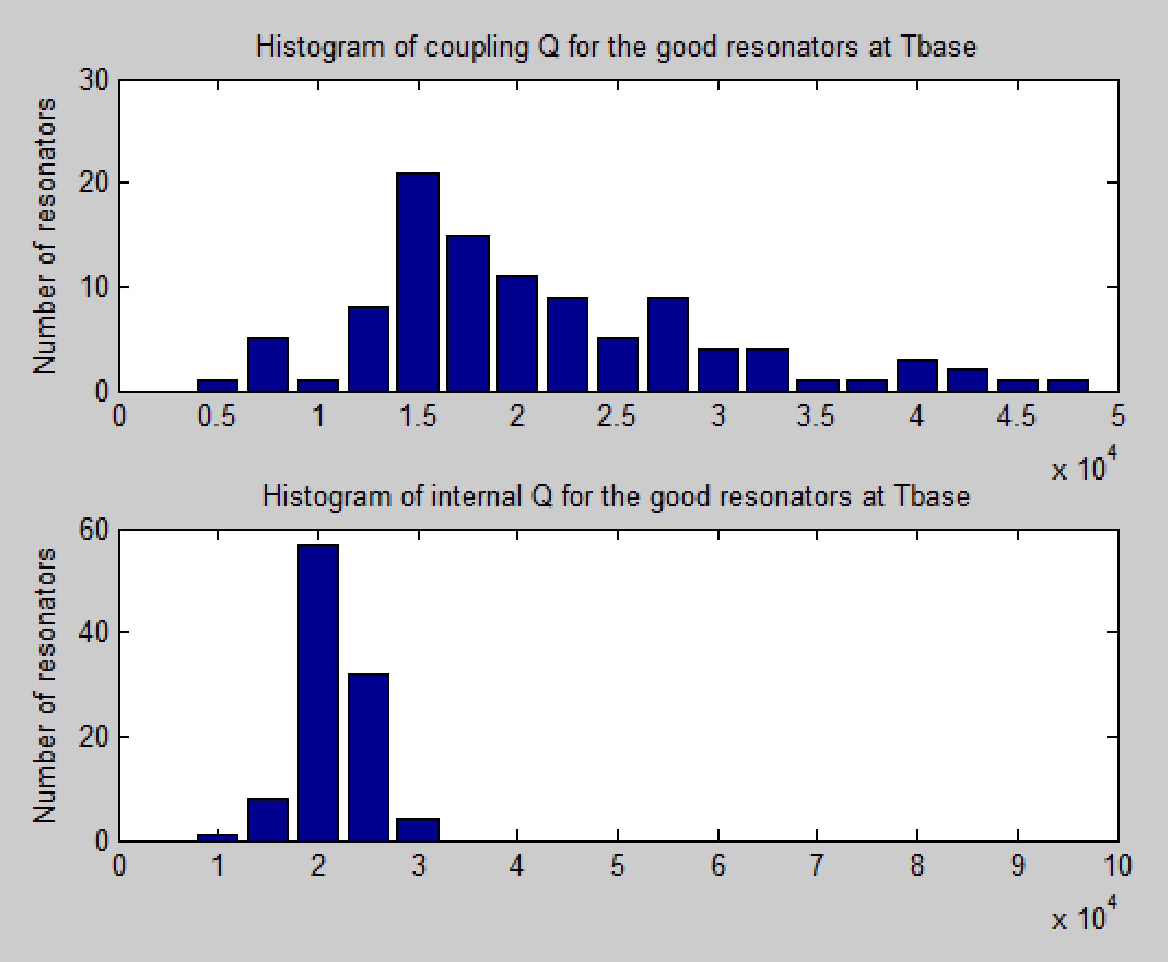
Frequency-space occupation



Quality factors statistics

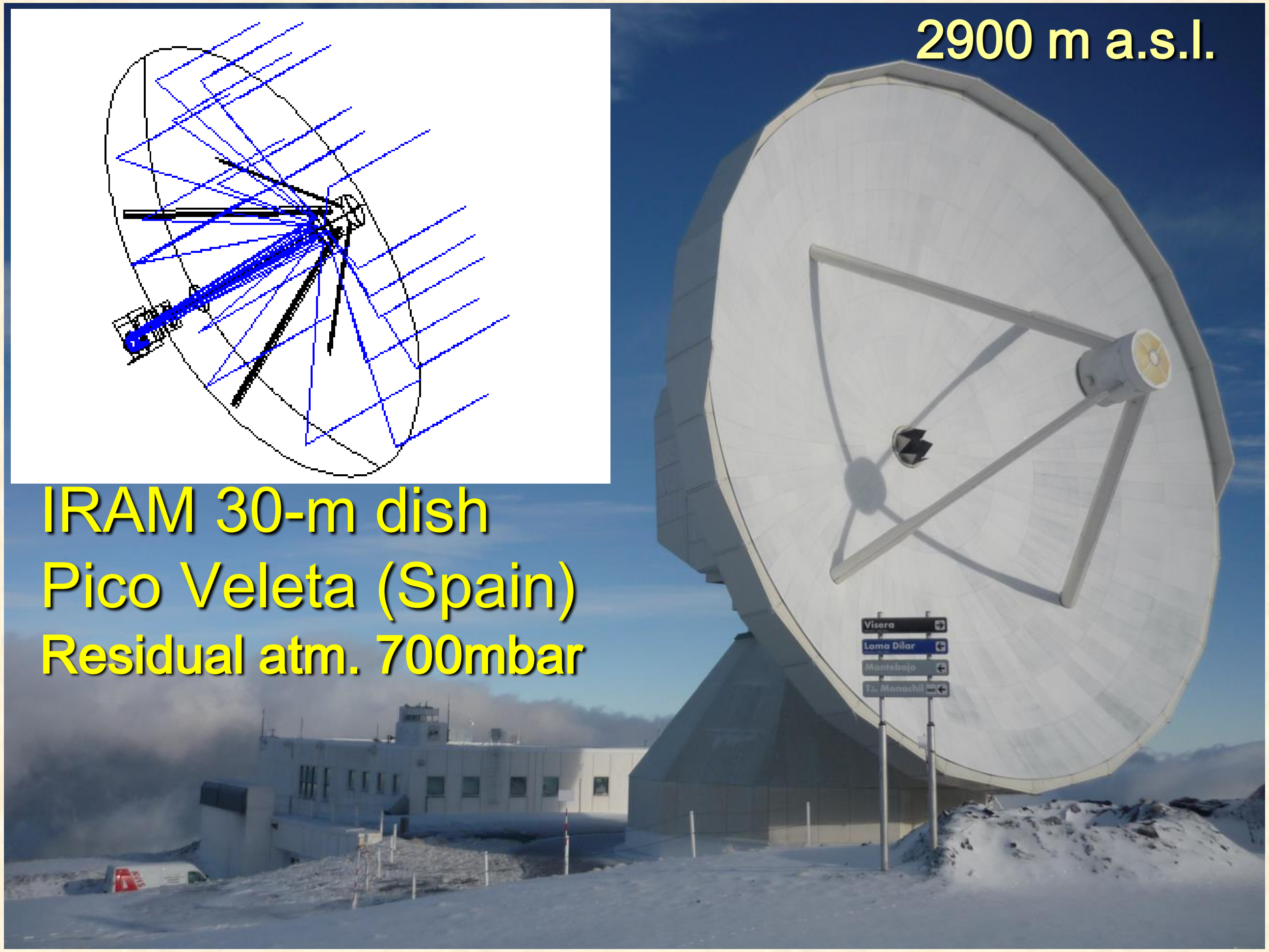
$$Q_c^{(fitOk)} = 21.0 \pm 8.9 \cdot 10^3$$

$$Q_i^{(fitOk)} = 21.6 \pm 3.1 \cdot 10^3$$



Selected (example) application of KID: mm-wave astronomy

The biggest mm-wave telescope around



Working Bands:

3mm (100GHz)
2.05mm (146 GHz)
1.25mm (240 GHz)
0.87mm (345 GHz)

IRAM, based in Grenoble, was founded in 1979 by the French CNRS, the German MPG (Max-Planck-Gesellschaft) and the Spanish IGN (Instituto Geográfico Nacional).

IRAM = Institute for Millimetric RadioAstronomy

New IRAM KID Arrays (NIKA)

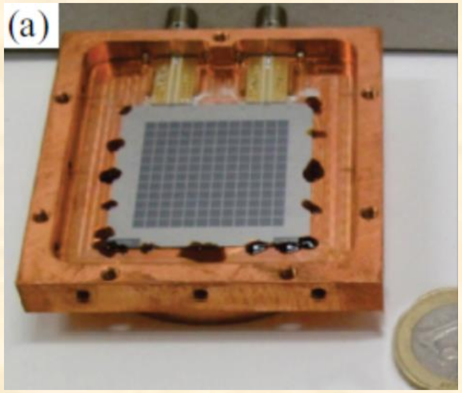
NIKA (until 2015)

- **Dualband (1.25mm and 2mm)**
- LEKID Arrays Detectors:
  - **132 pixels @ 2mm (150 GHz)**
  - **224 pixels @ 1.25mm (240 GHz)**
- NIKEL Read-Out Electronics
- State-of-the-art sensitivity (even compared to TES)
- PIs: A. Benoit & A. Monfardini
- Ten successful observing runs at the telescope (2009-15) … celebrated our 100th day on top of the Sierra Nevada
- **Fully justifying NIKA2 !!**

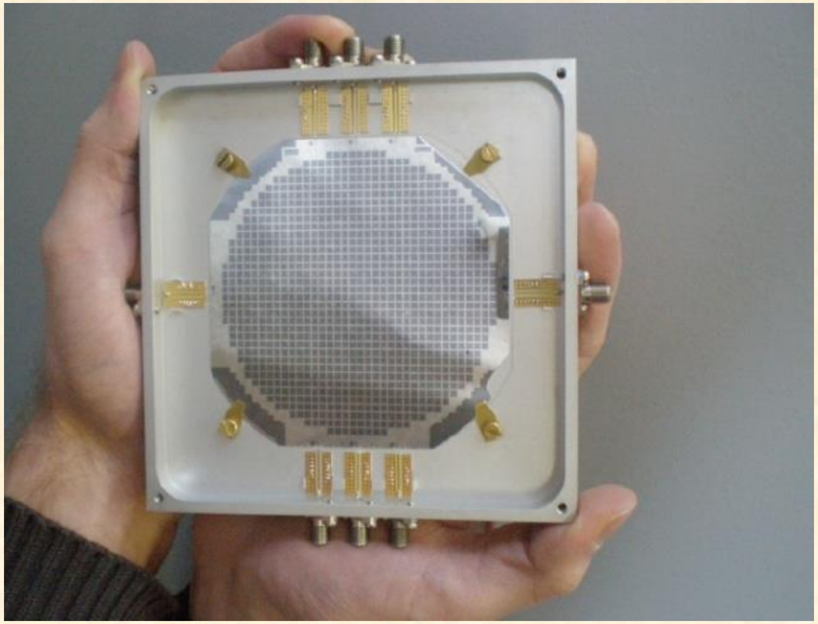
From NIKA0 to NIKA2 arrays evolution

2009

2010-2013



2014



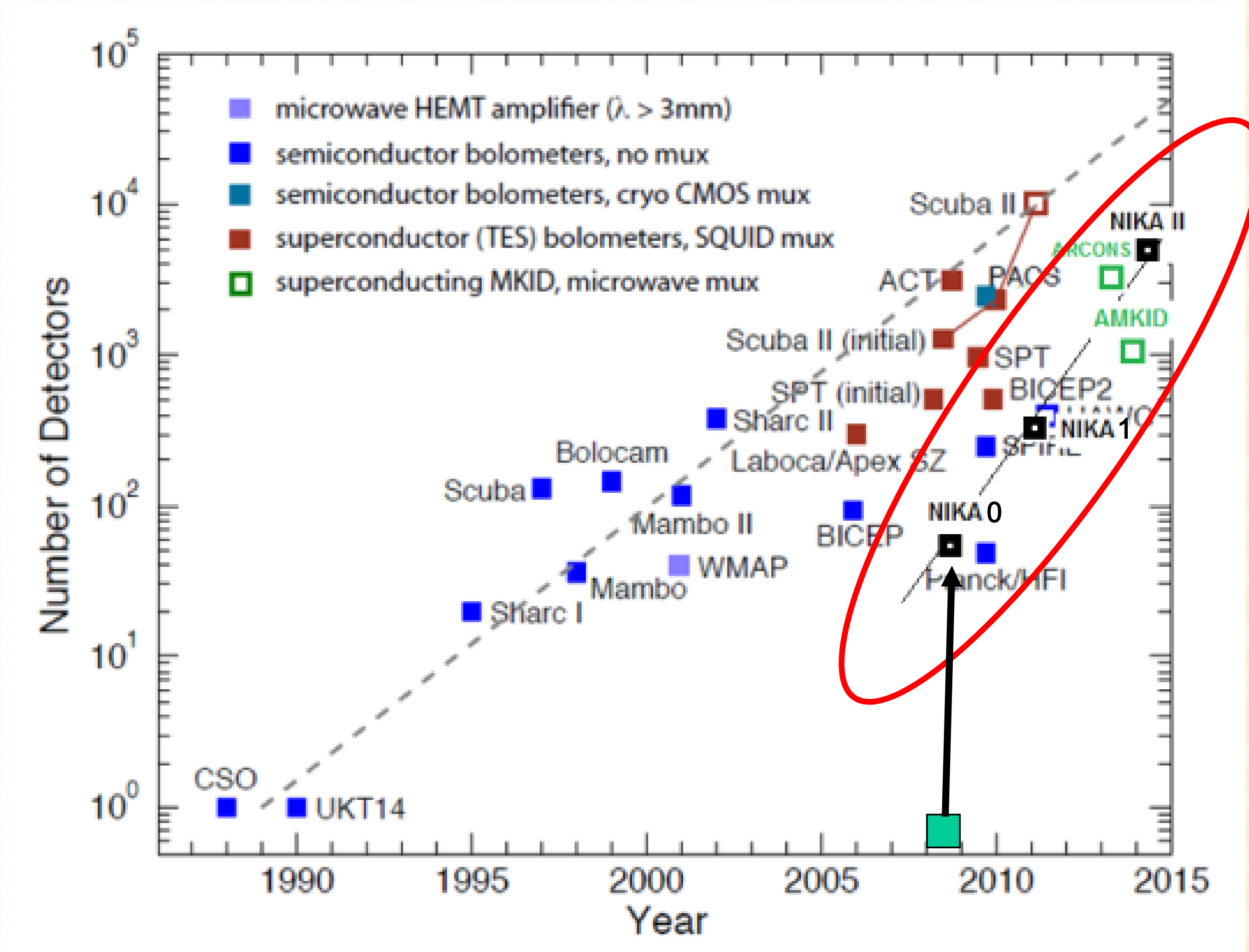
2009:

- 30 pixels, detectors noise limited

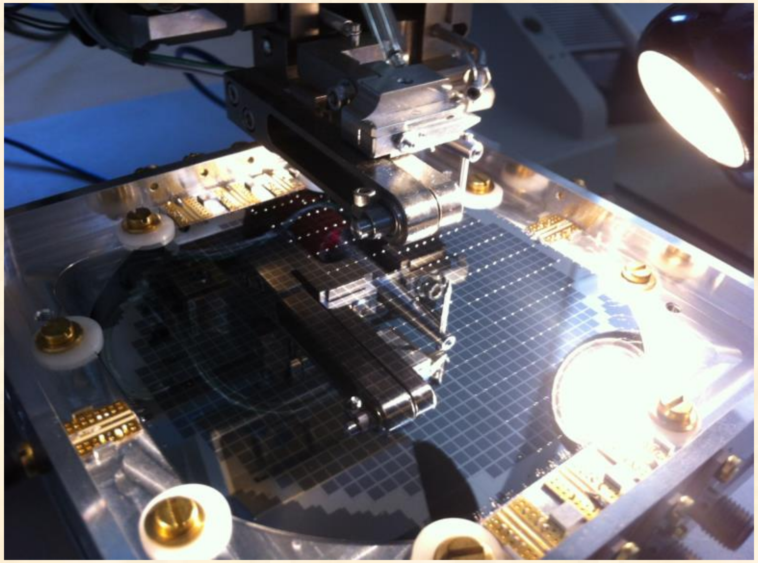
2014:

- kpixels, photon-noise limited
- large area (full 4 inches)
- Readout line 2.5 m long !!

NIKA on the Moore plot !!



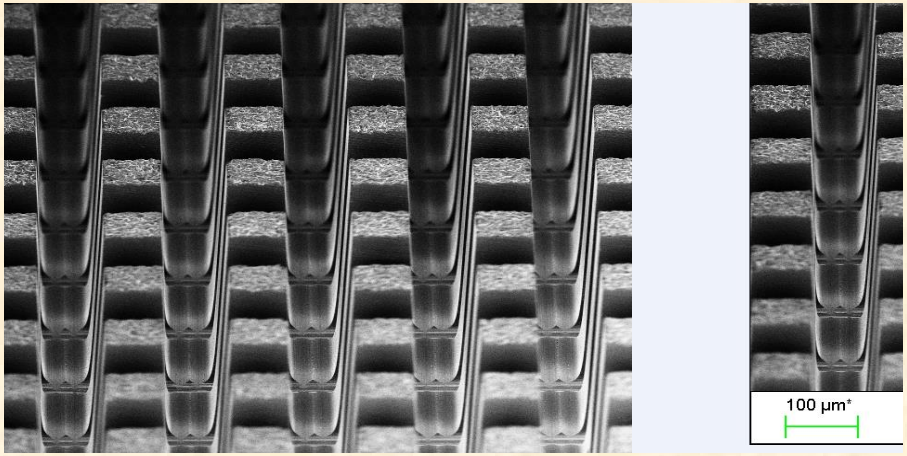
The NIKA2 arrays technology

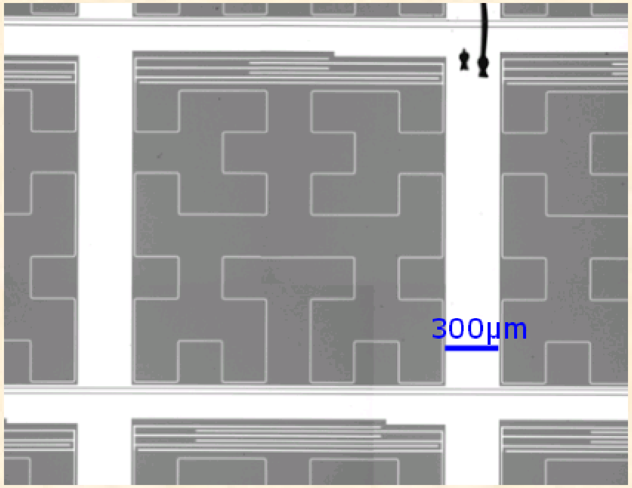


- Pixels are fractal Hilbert-shaped LEKID
- Films: thin Al (18 – 25 nm)
- Different arrays designed/fab/tested:

No AR layer ⟷ AR layer (dicing, etching)

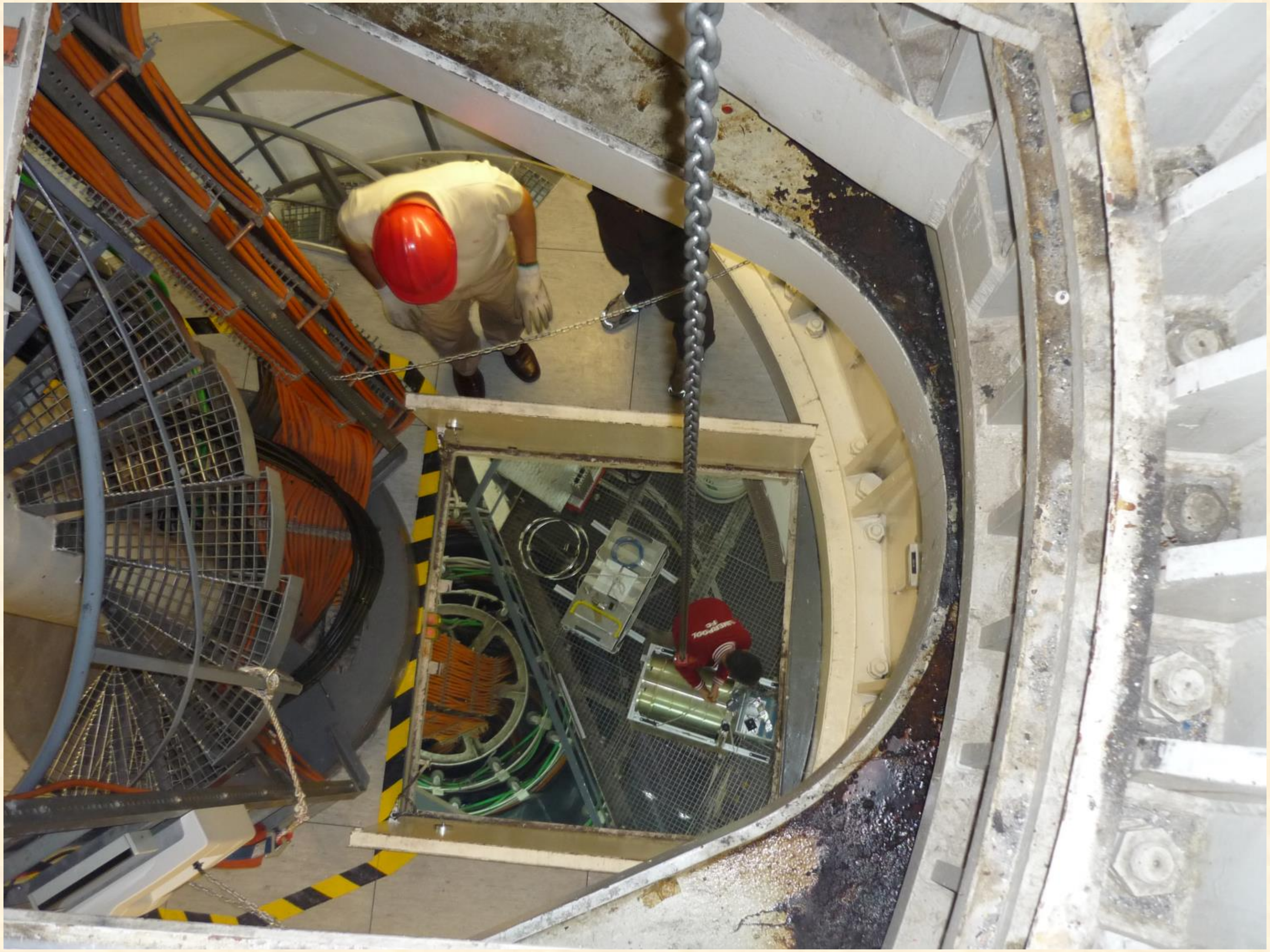
CPW feedline ⟷ **MS feedline**



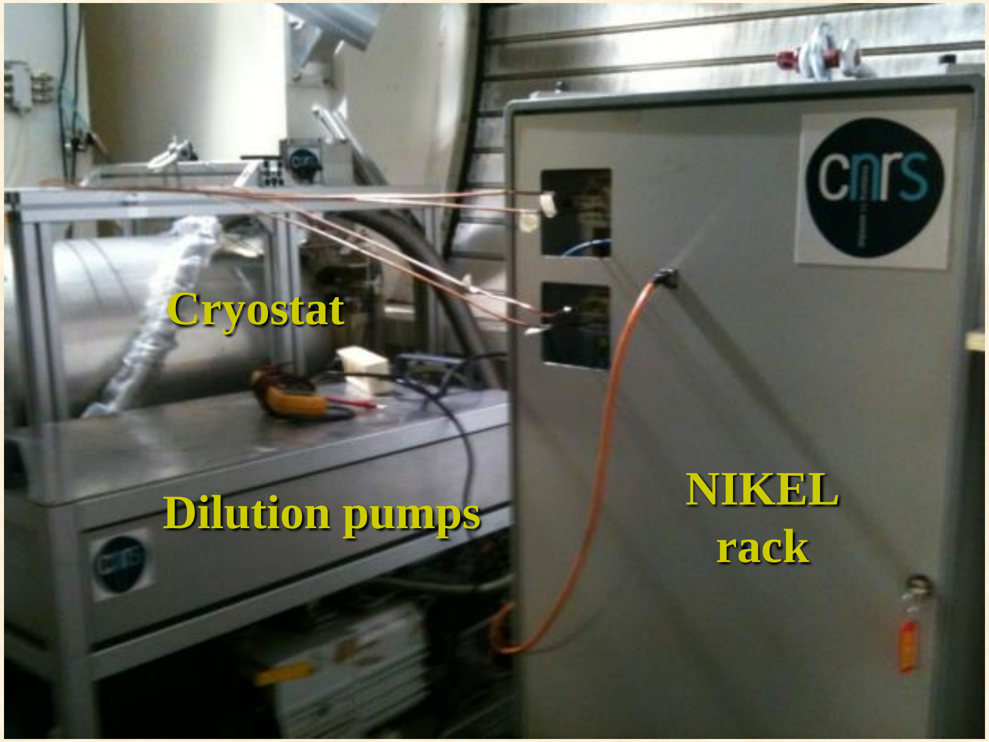


http://ltd16.grenoble.cnrs.fr/IMG/UserFiles/Images/06_GOUPY-LTD16.pdf

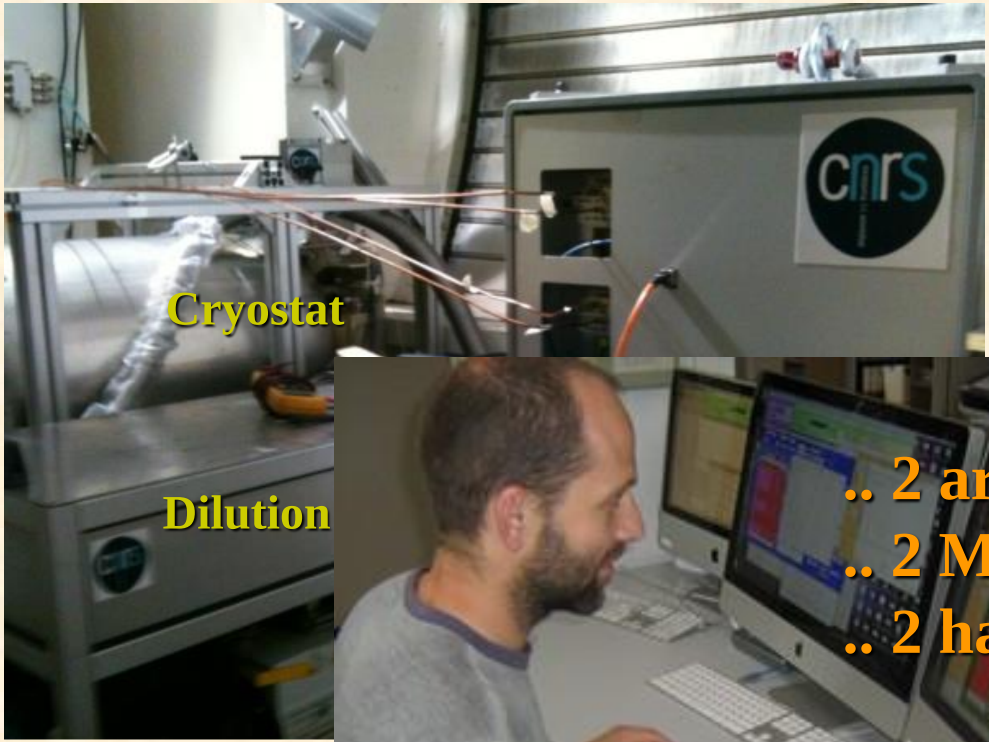
... not in clean-room today ?



NIKA at the 30m



NIKA at the 30m



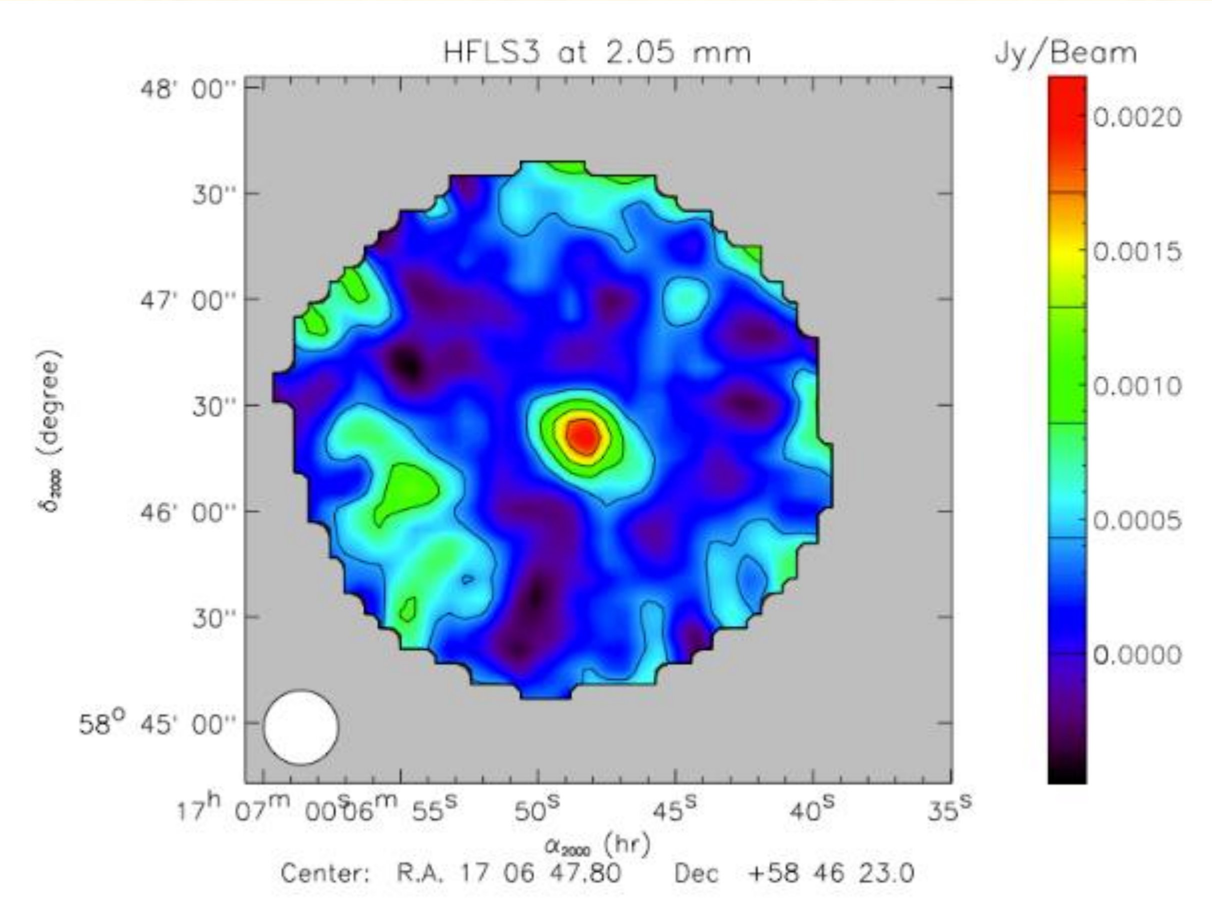
NIKA seeing glows in the Dark Age

$z \approx 6.34$

Intense starbust galaxy

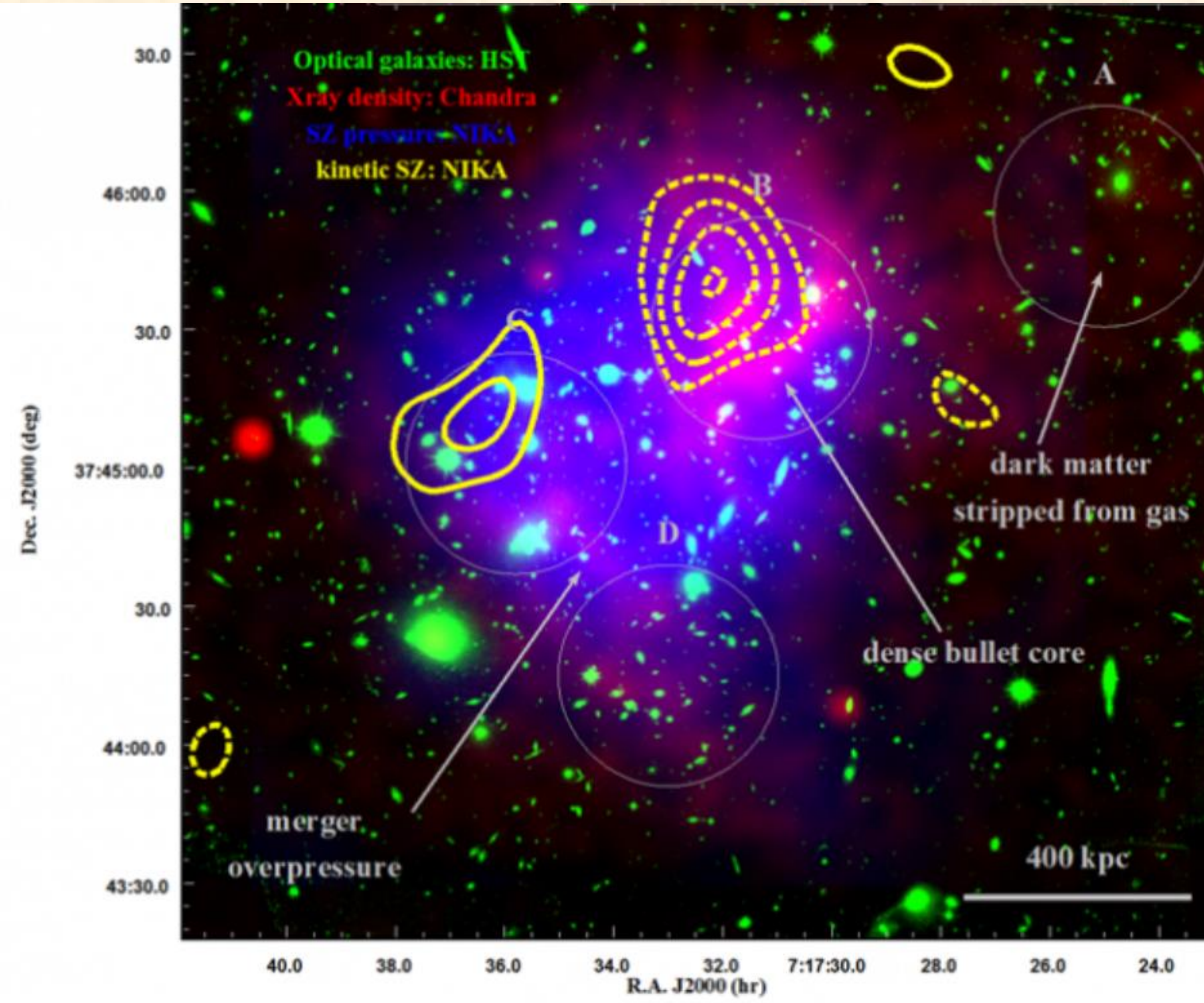
Producing
3000 $M_\odot$ per year

Milky Way ≈ 1 Sun per year



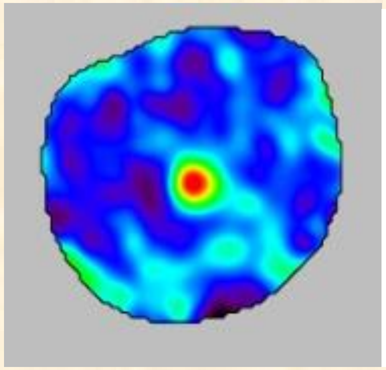
Looking 13 billions years in the past !! Universe only 0.88 Gyr old.

Mapping the intergalactig medium kinetics

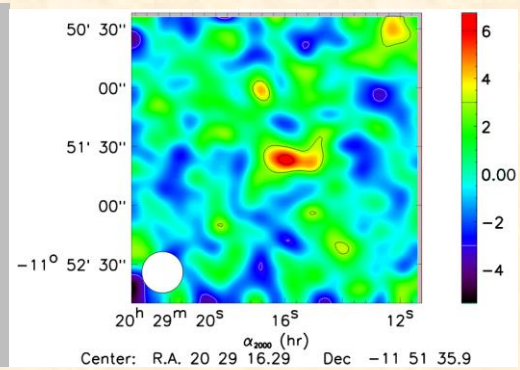


The largest g-bound objects, building blocks of our Universe, are the **clusters of galaxies**. They are mainly made of **dark matter and hot ionized gas**. Only a few percent of the mass is contained in galaxies. These mergers are **the most energetic events since the Big Bang** and they are fundamental to understand.

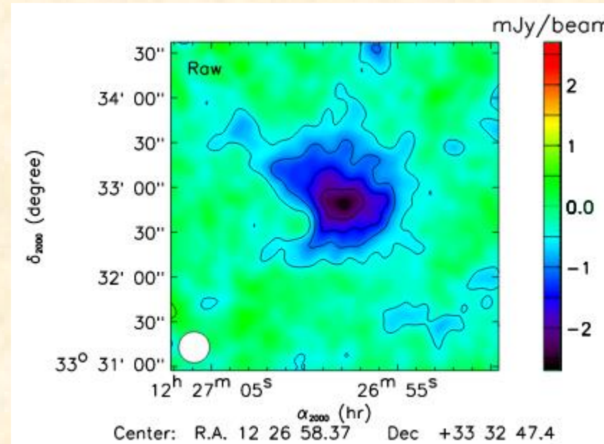
Selected NIKA images



Pluto at 150GHz

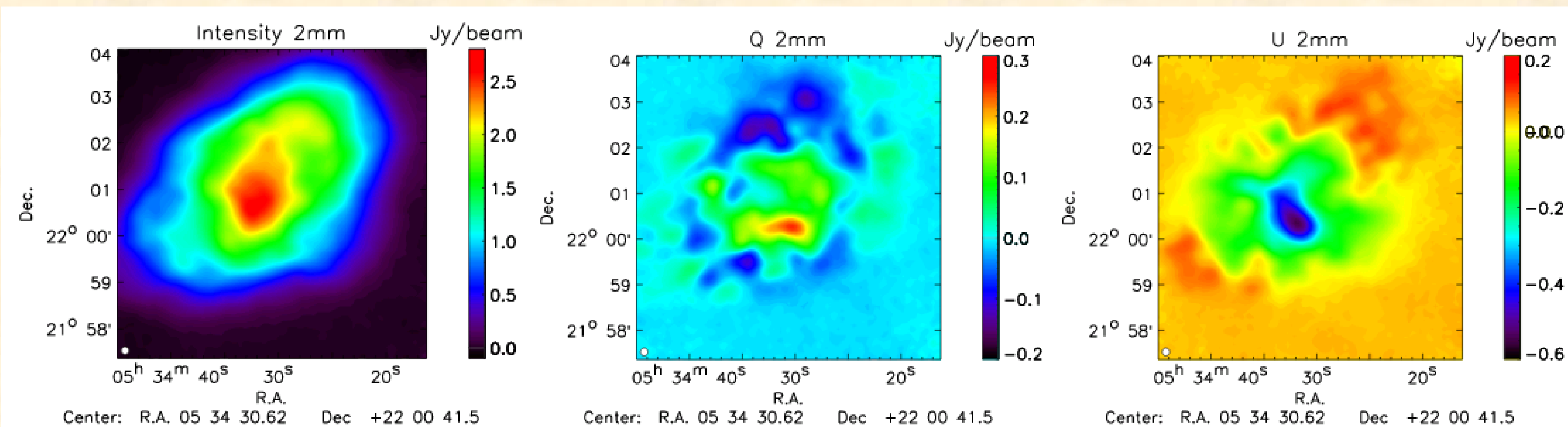


GRB121123A



CL J1226.9+3332
(z = 0.89)

Adam et al., A&A 576, A12 (2015)

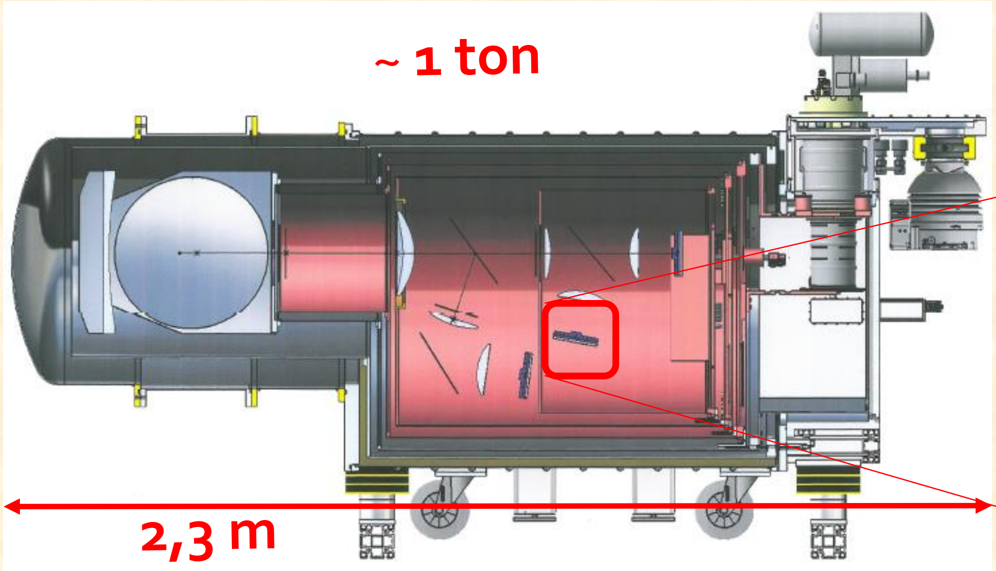


The Crab nebula – Intensity and polarisation (A. Ritacco et al., arXiv:1508.00747)

NIKA2 fabrication in Grenoble (2013-15)

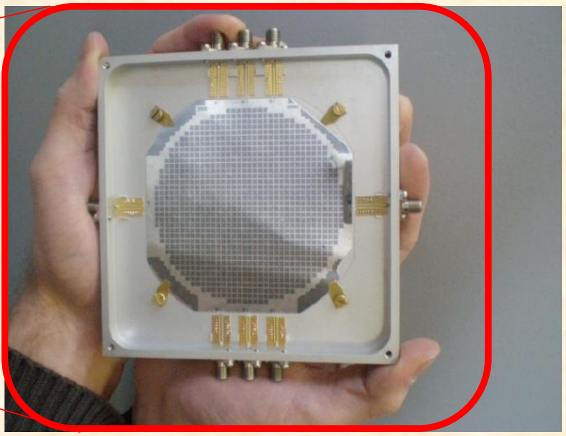
Goals et Varia

- 6.5 arc-min FoV (≡ IRAM 30m)
- Close to background-limited
- Dual-band imaging + polarization
- Derived from NIKA R&D



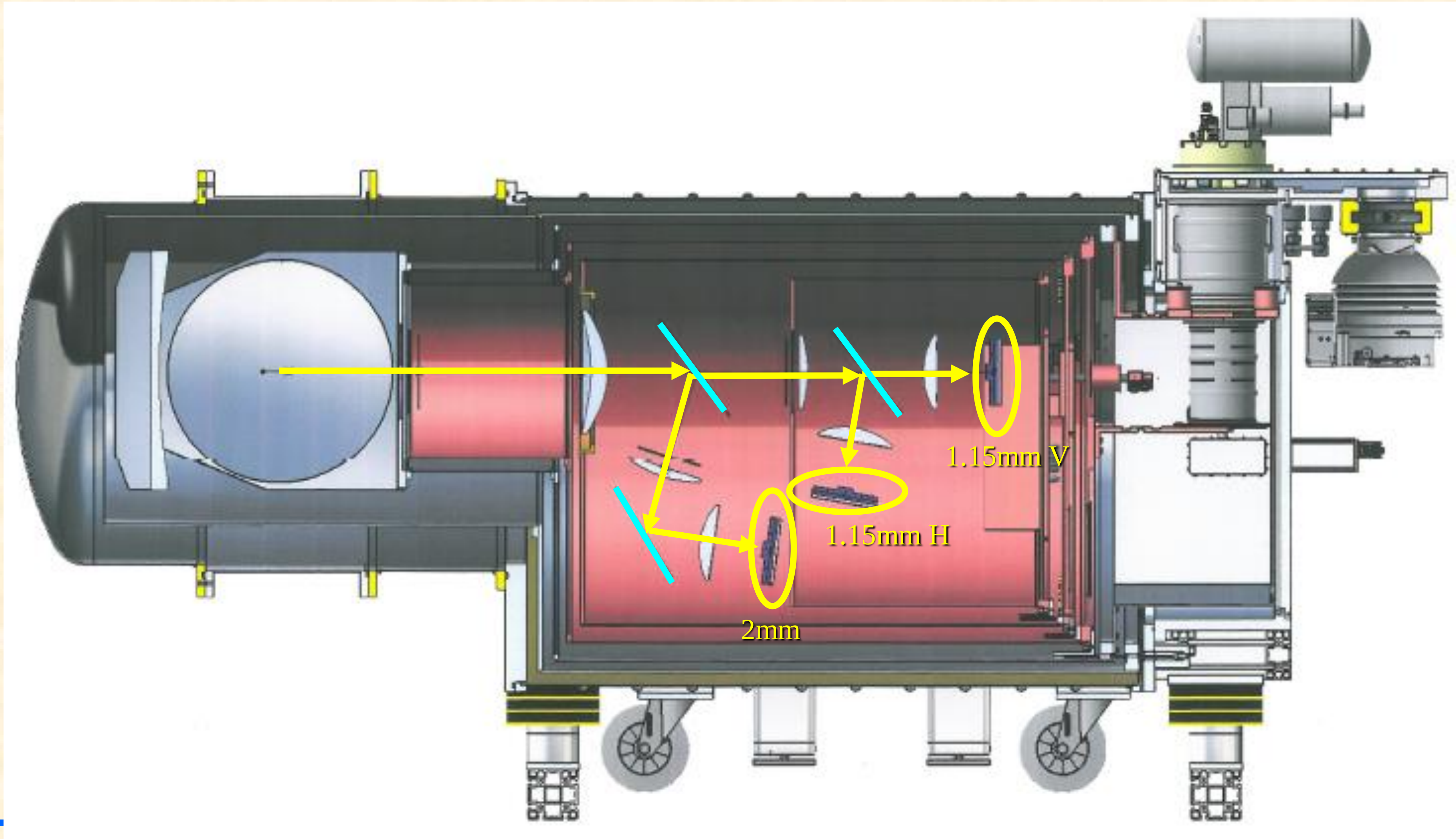
Characteristics

- **Dual-band (1.25mm and 2mm)**
- **Polarization @ 1.25mm**
- KID Arrays Detectors:
  - **1000 pixels @ 2mm**
  - **2 × 1200 pixels @ 1.15mm**
- NIKEL Read-Out Electronics

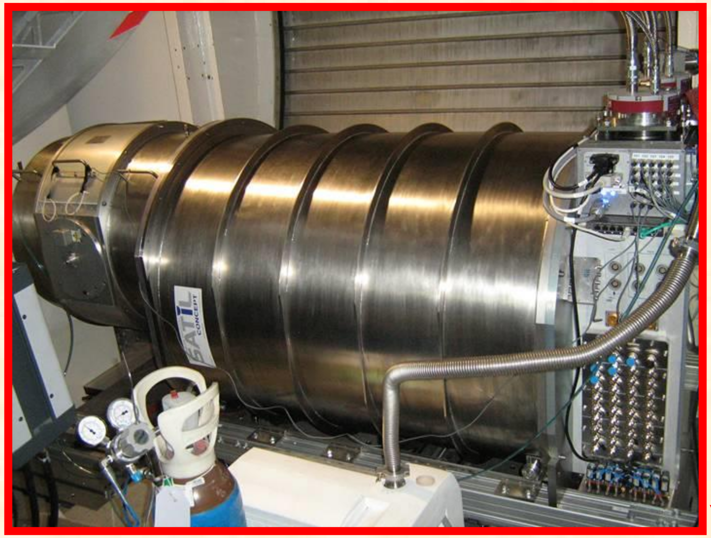


A. Monfardini et al., arXiv:1310.1230

NIKA2 cross-section



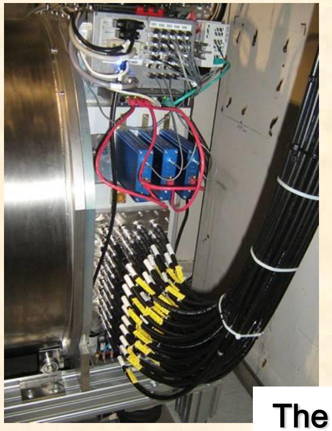
NIKA2 is installed (10/2015) !!



The cryostat in the receivers cabin

60 meters of pipes

The dilution gas handling in the basement

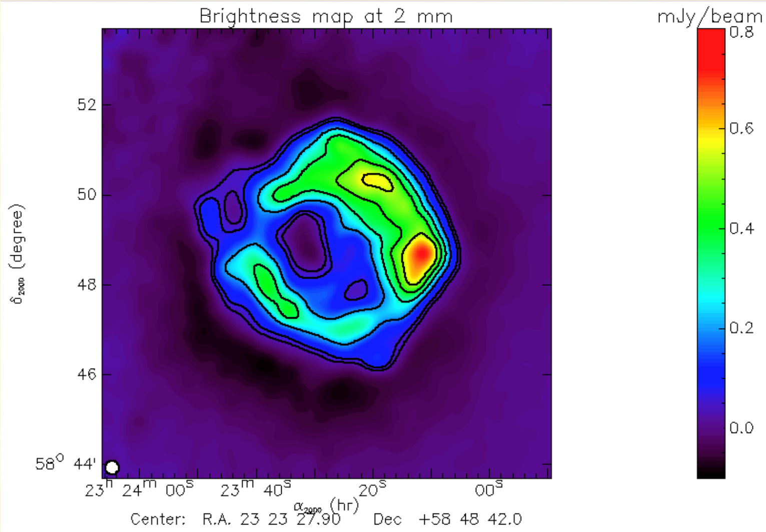


The 40 COAX cables

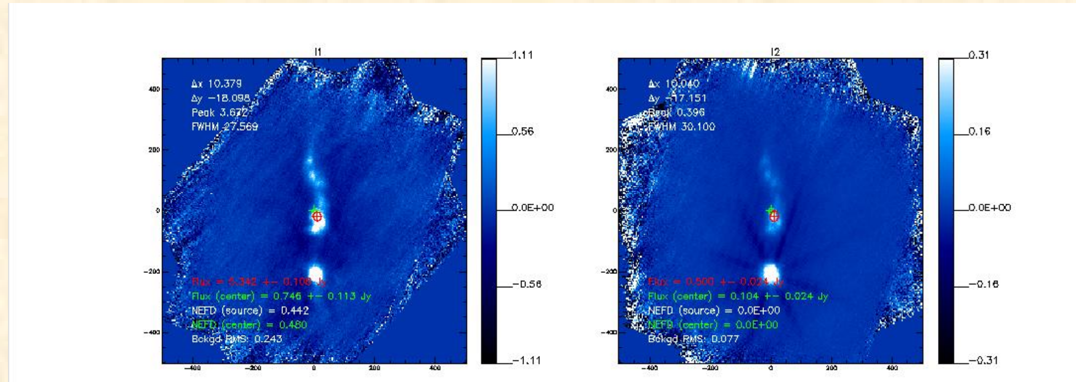
NIKA2 figures:

- 3300 pixels over 3 arrays
- 1.2 tons; 2.5 m long; 3000 pieces
- Two Pulse Tubes
- Fully remote control
- Completely cryogen free
- Base T ≈ 100 mK

NIKA2 preliminary (technical run 1) results

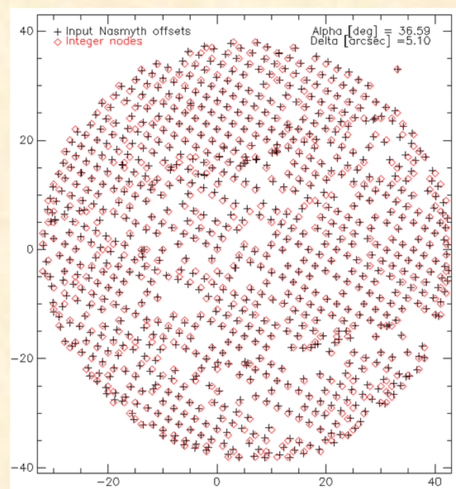


CasA at 150GHz
(only 14 minutes telescope time !!)



DR21OH at 260GHz (left) and 150GHz (right)

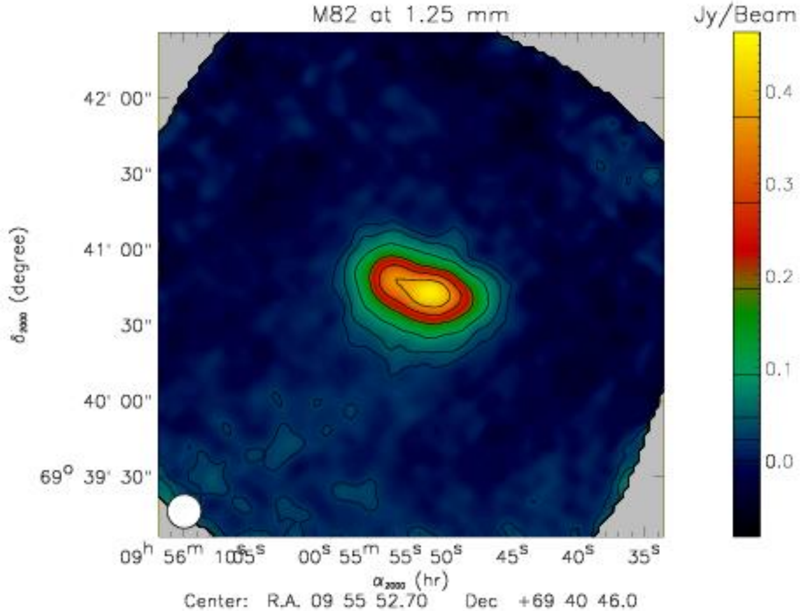
- Faint sources down to the mJy (10^{-29} W/m²/Hz) level detected despite preliminary status of the instrument and the data analysis software.
- Started (well ahead schedule) polarisation tests.

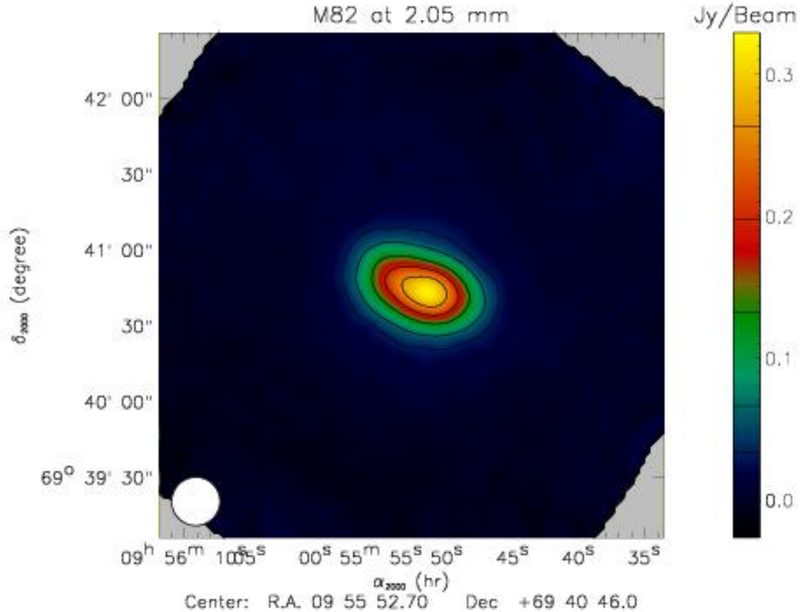


Beam maps of the 2mm array (1020 pix).

Nearby galaxies mapping/spectrum

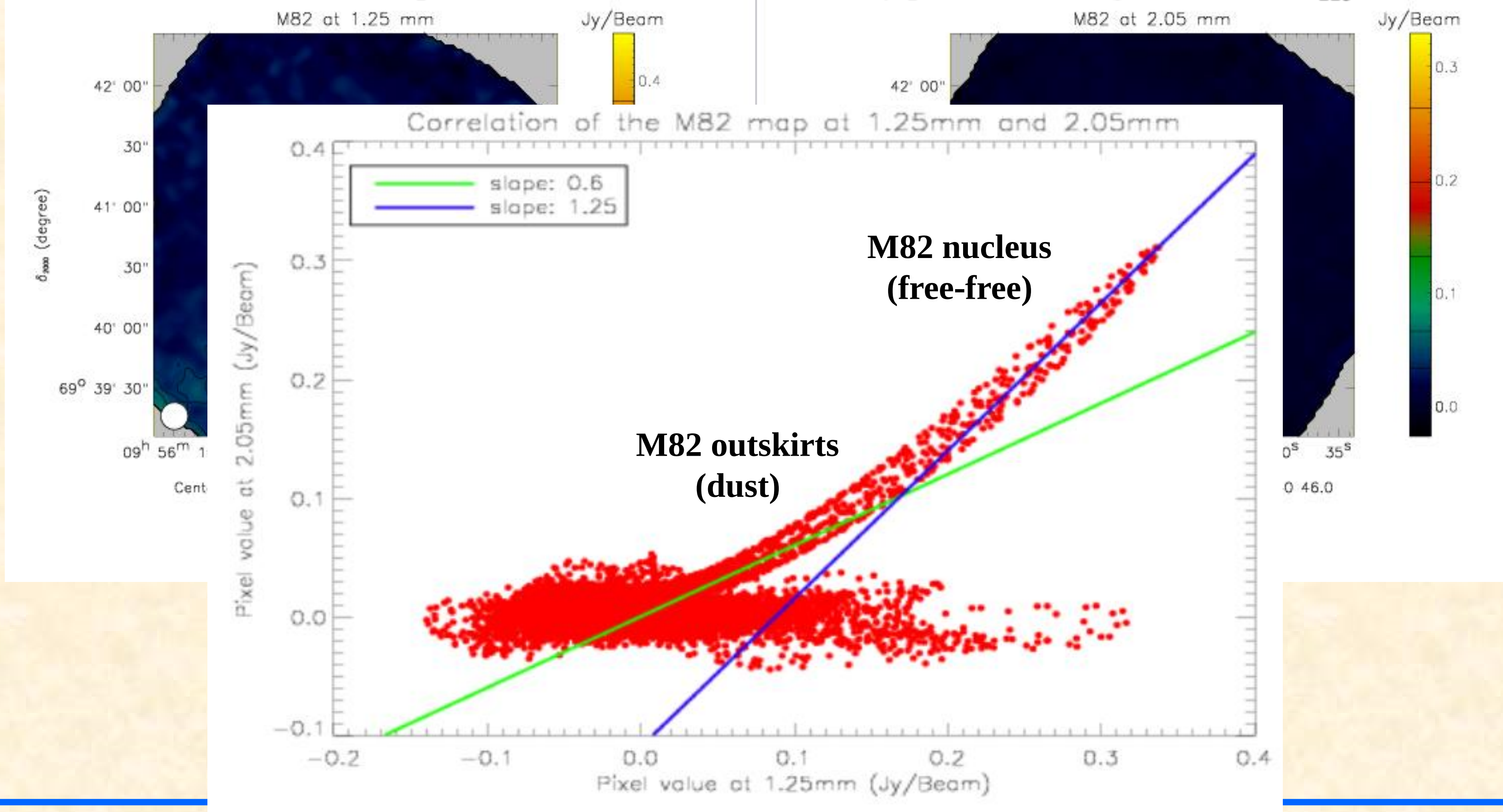
June 2013 – run 6 **Exposure time ≈ 18 min. under very poor observing conditions (τ_{225} = 0.8)**





Nearby galaxies mapping/spectrum

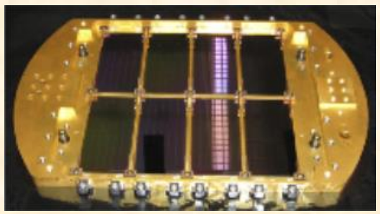
June 2013 – run 6 **Exposure time ≈ 18 min. under very poor observing conditions (τ_{225} = 0.8)**



More instruments using KID

MUSIC and MAKO (US)

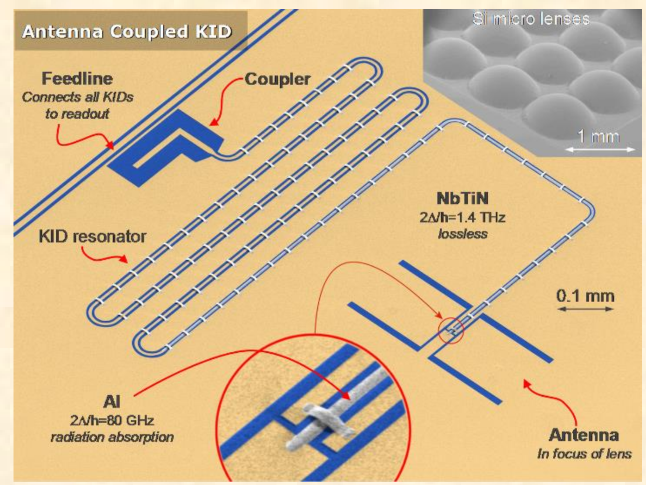
- **10.4 m CSO telescope (Hawaii)**
- **Mm and sub-mm (MAKO) bands**
- Antenna-coupled (MUSIC) and LEKID (MAKO):



  - **2,304 pixels (MUSIC)**
  - **100s pixels (MAKO)**

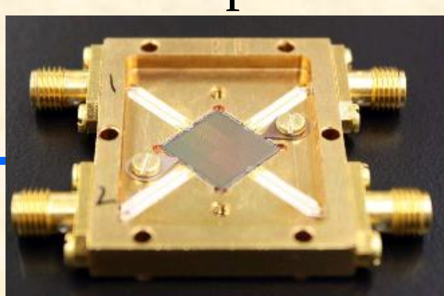
A-MKID (EU)

- **12 m APEX telescope (Chili)**
- **Two sub-mm bands (350 and 850 GHz)**
- Antenna-coupled KID:
  - **3,500 pixels @ 0.85mm**
  - **20,000 pixels @ 0.35mm (PLANNED)**
  - Bonn FFTS read-out



ARCONS (US)

- **5 m Palomar telescope (visible)**
- **Counting/measuring visible photons**
- Lumped Element KID:



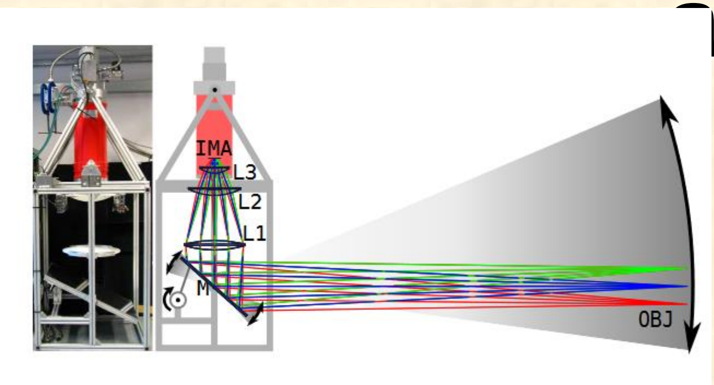
2,024 pixels

A lot more in fabrication or planned

- Deshima spectrometer (Delft – SRON – Japan)
- OLIMPO balloon (Italy – USA)
- QUBIC (France – UK – Italy – Argentina)
- US balloons
- GMT (Gran Telescopio Milimetrico) – Cardiff, Mexico
- Large future telescopes (Caltech, JPL)
- etc.

Further (selected) applications of KID

Passive THz cameras for security applications

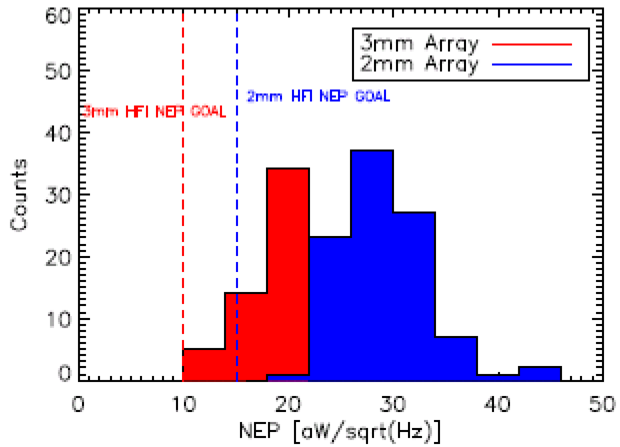


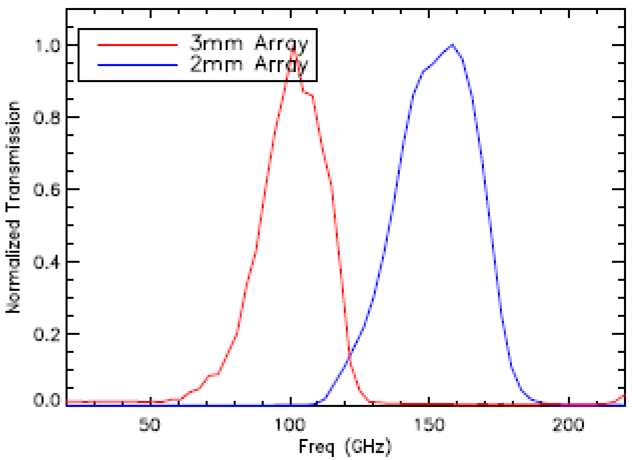
Operating at 350GHz, sweeps a Human body with a moving mirror

A: a wallet
B: a pistol
C: a few pounds for a beer

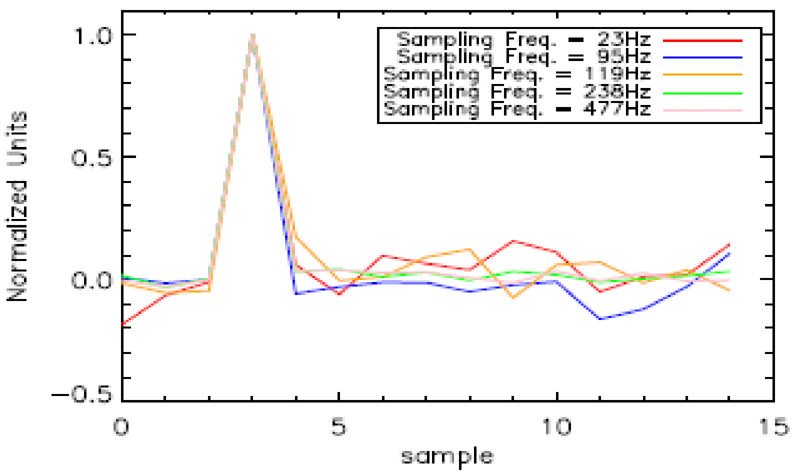
S. Rowe et al., Review of Scientific Instruments 87, Issue 3, 033105 (2016)

LEKID arrays for Space





132-pixels arrays designed for NIKA (New IRAM KID Arrays) exhibit Planck-like sensitivity at both 100 and 150 GHz.

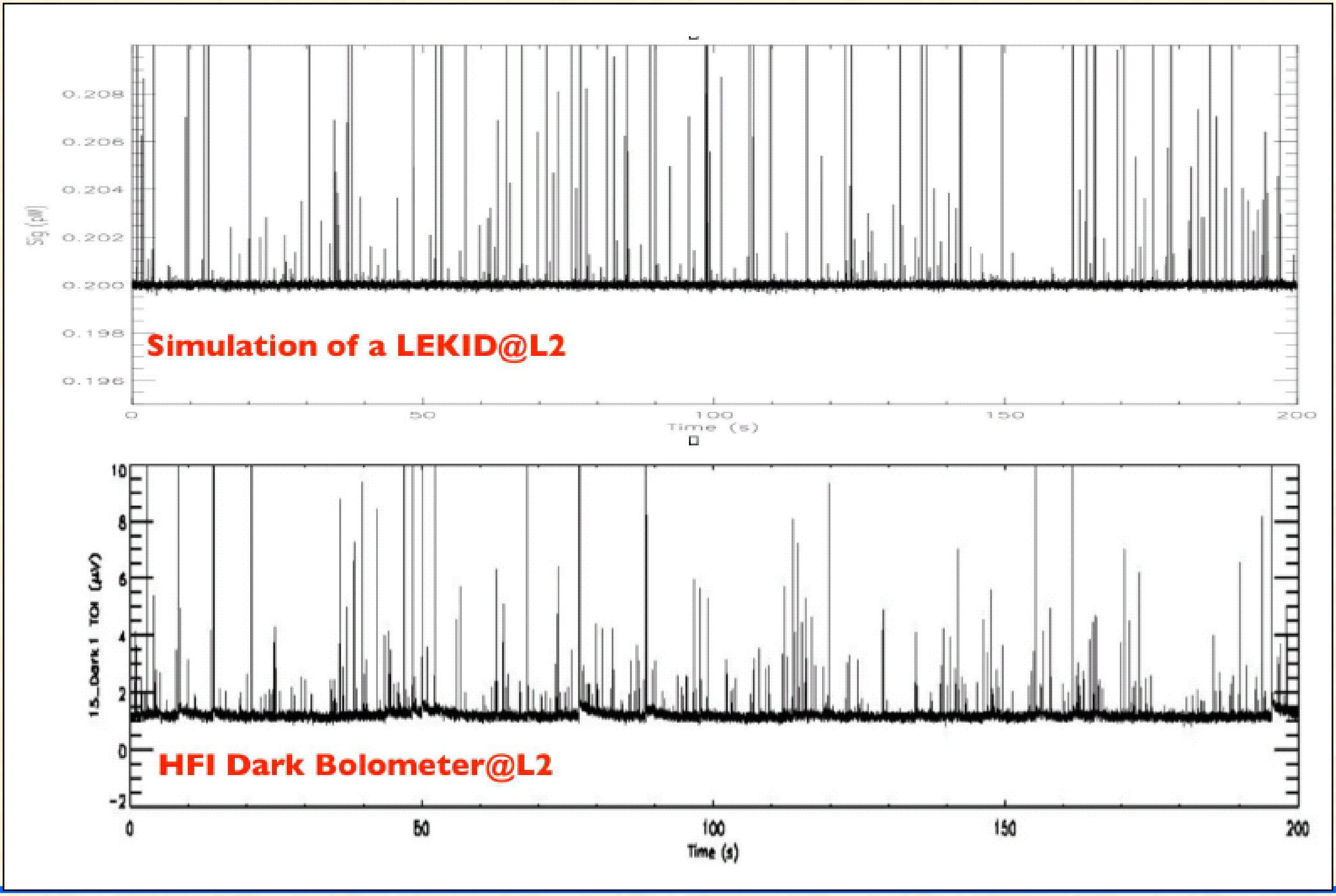


One such arrays, under realistic background conditions (0.5 pW/pix) and sensitivity (10^{-17} W/Hz$^{0.5}$), irradiated with 630-keV alphas.

For any useful sampling frequency only one sample is affected.

A. Catalano, A. Benoit, O. Bourrion, M. Calvo, G. Coiffard, A. D'Addabbo, J. Goupy, H. Le Sueur, J. Macìas-Perez and A. Monfardini, arXiv:1511.02652, submitted to A&A (11/2015)

A 132-pixels array at L2 (simulation)



Main results:

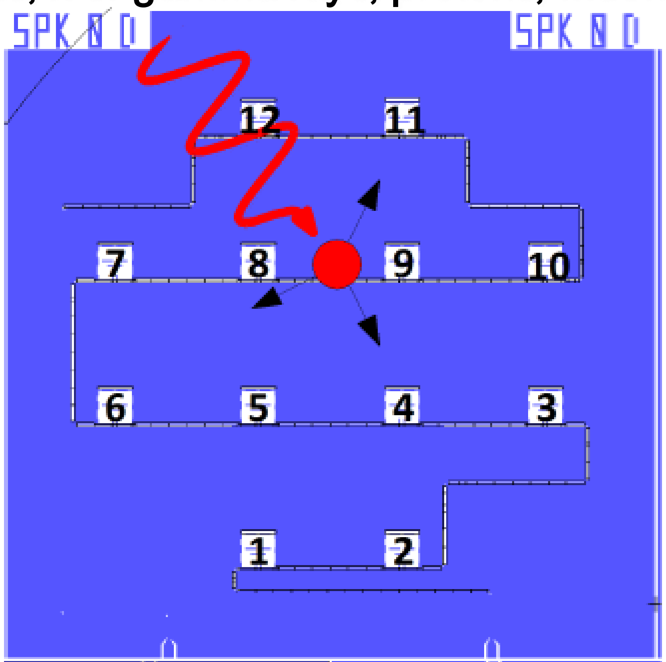
- Data-loss of the order of 1%

- Negligible effect on RMS

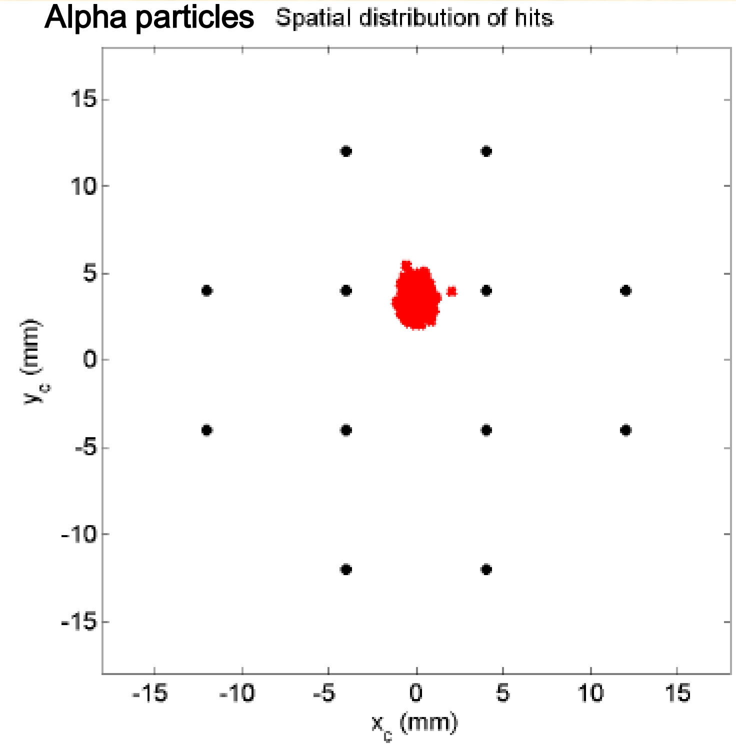
- Gaussian noise behaviour preserved on the on-the-sky maps

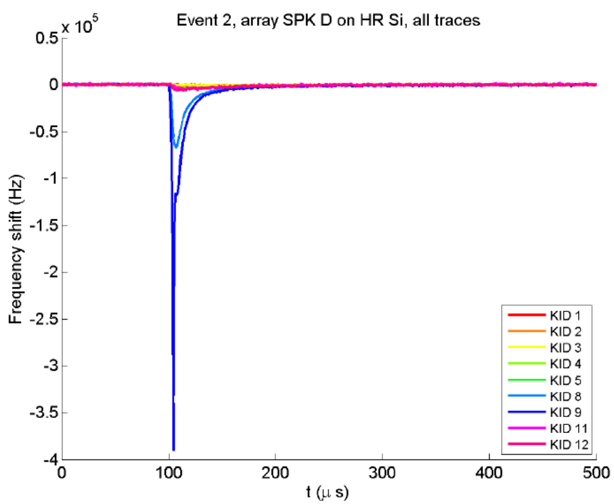
Phonons-mediated particles imaging

Alphas, x or gamma rays, protons, muons etc.



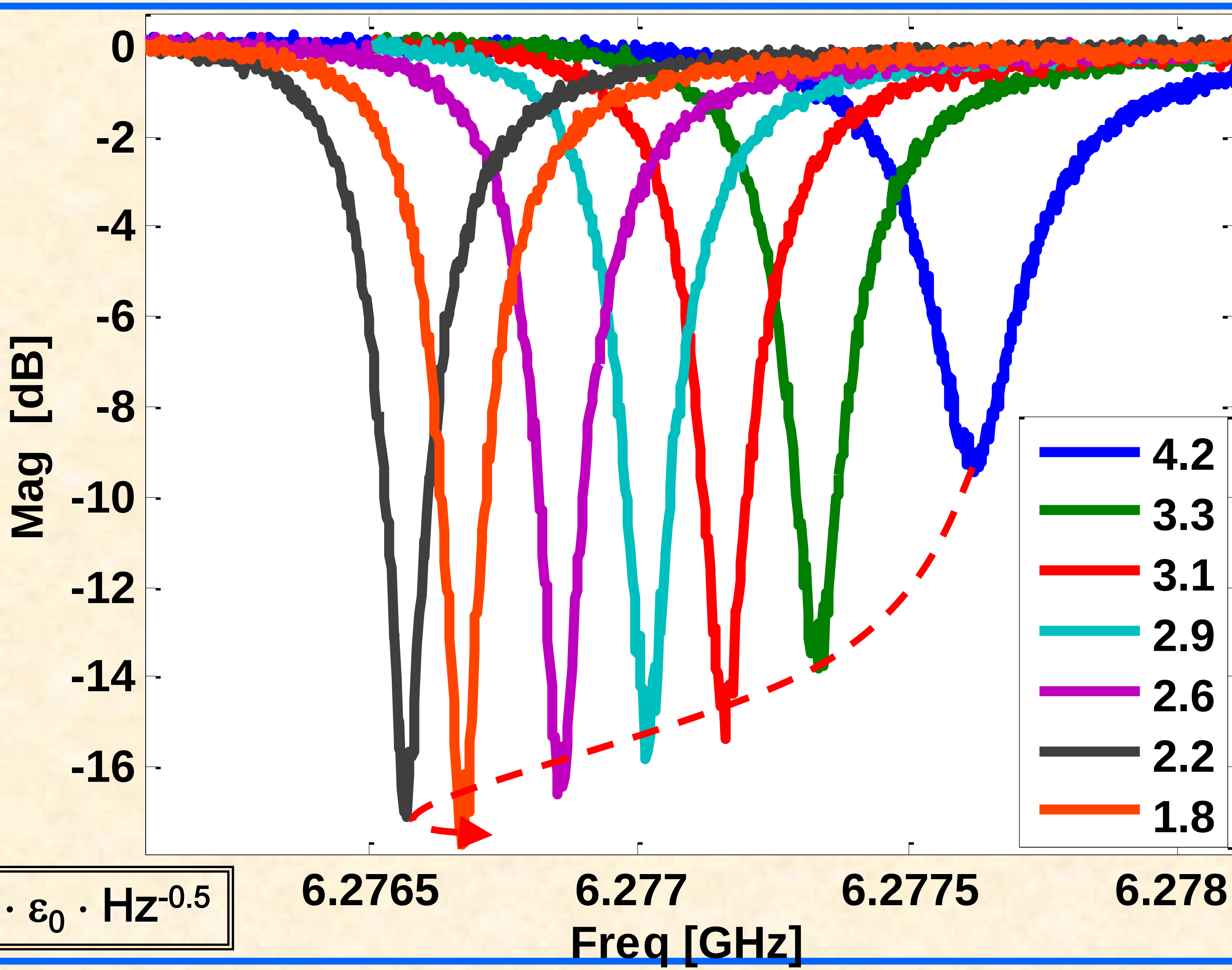
Alpha particles





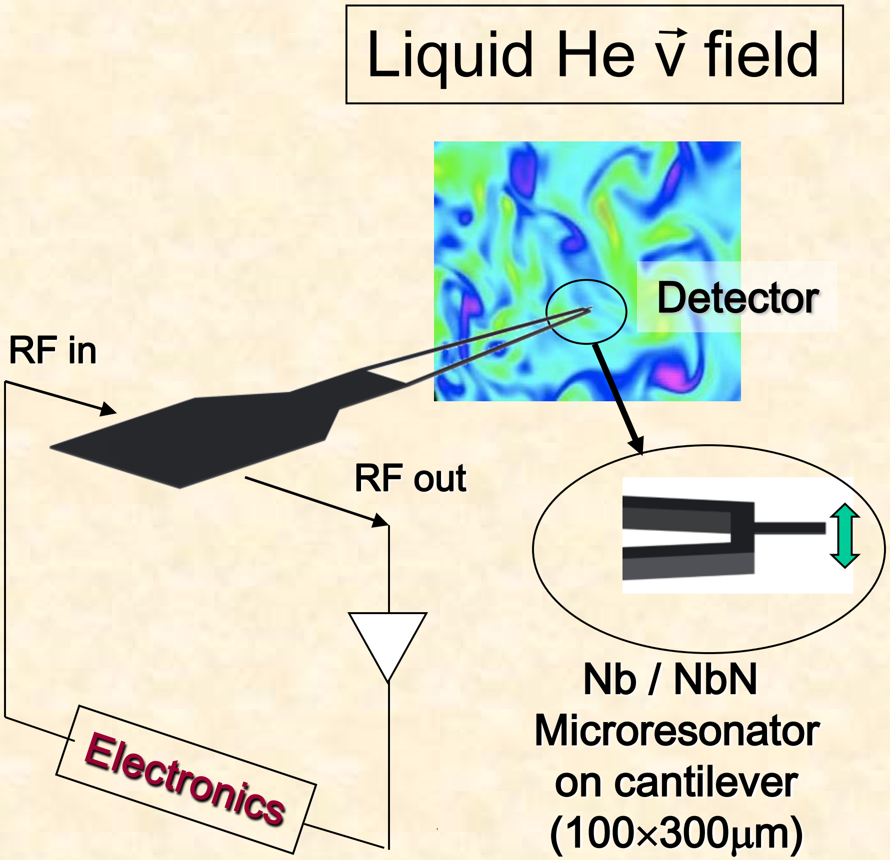
EM sensitivity: NbN resonators in LHe

G. Grabovski et al., APL (2008)



$\varepsilon_r \approx 10^{-11} \cdot \varepsilon_0 \cdot Hz^{-0.5}$

LHe Hydrodynamics with resonators



Motivations:

The very low viscosity of cryogenic Helium offers unique opportunities for turbulence studies (μ(LHe) < μ(water)/100).

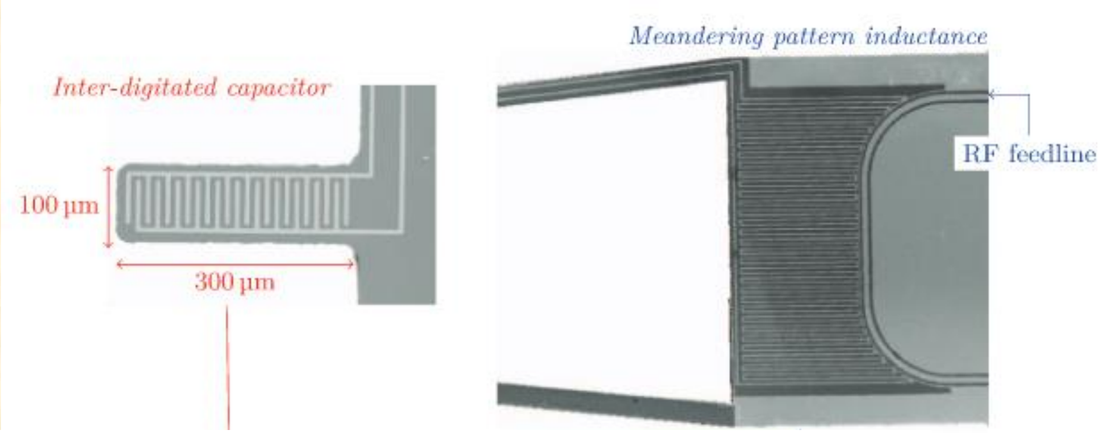
Beside, the superfluid state (T < 2.17K) allows to explore quantum turbulence.

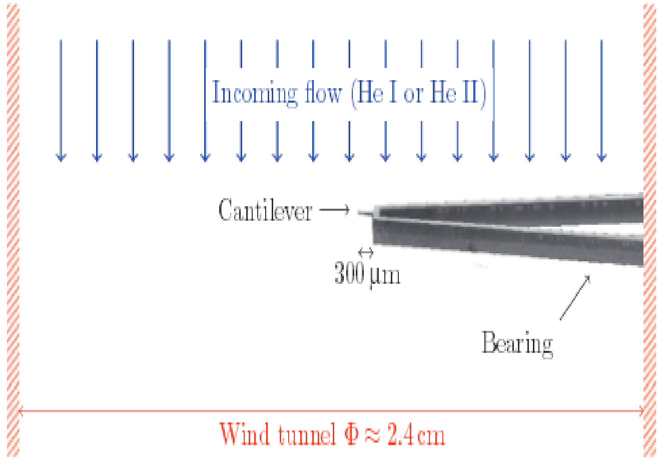
A specific instrumentation is needed.

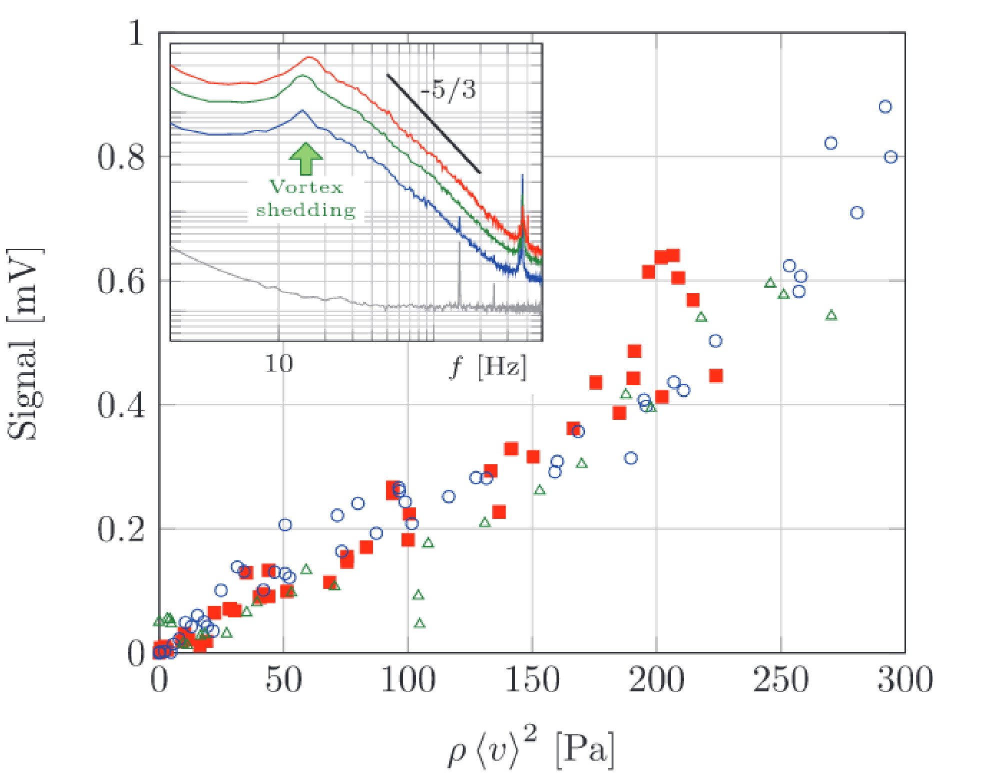
Advantages:

- Spatial resolution (≈ 100 μm)
- Robust to static pressure fluctuations
- Normal AND Superfluid (inertial force)

Superfluid LHe turbulence

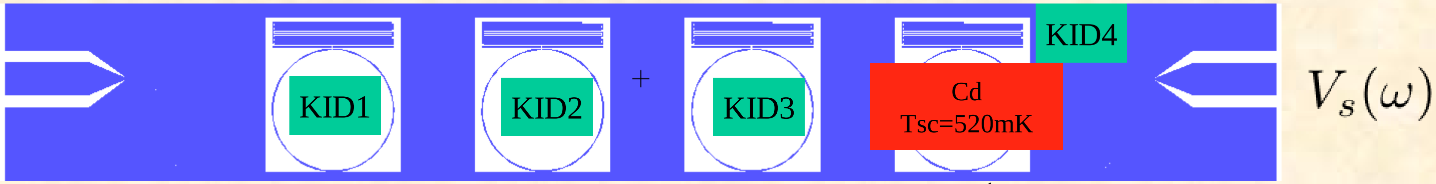


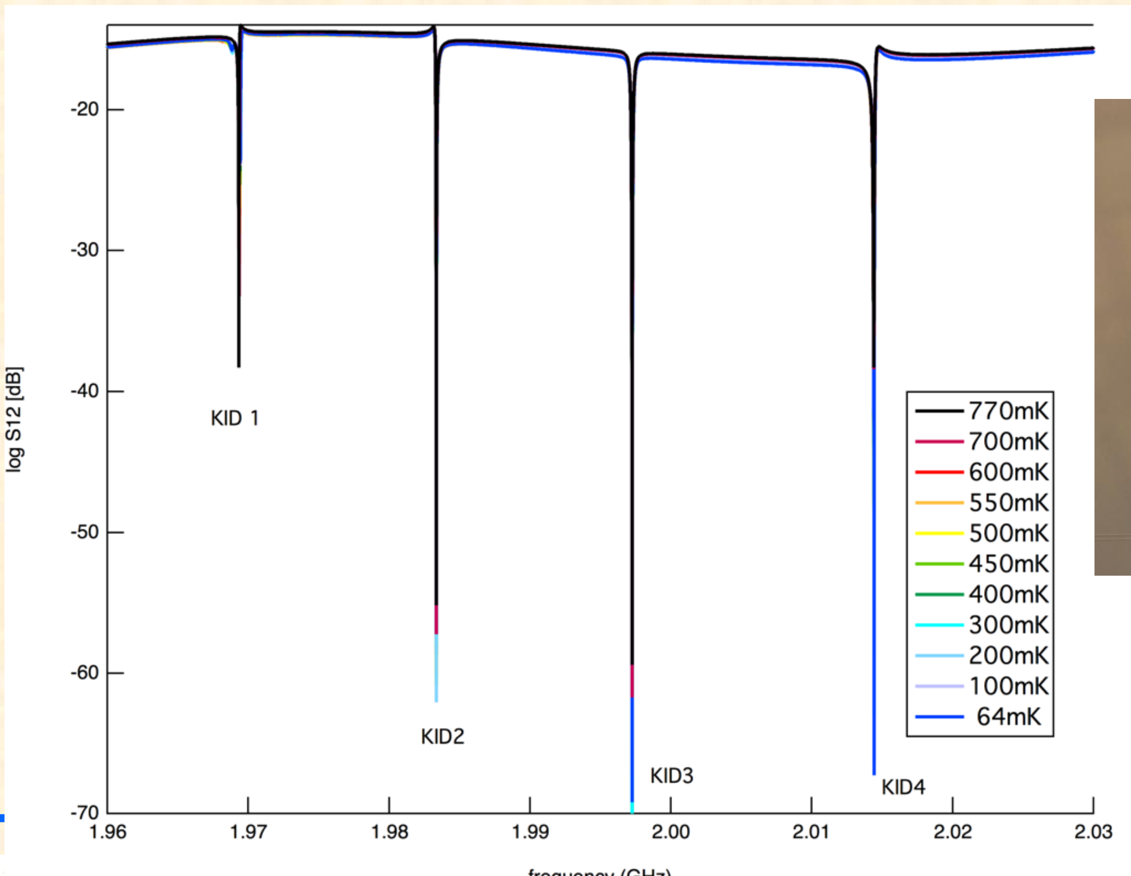


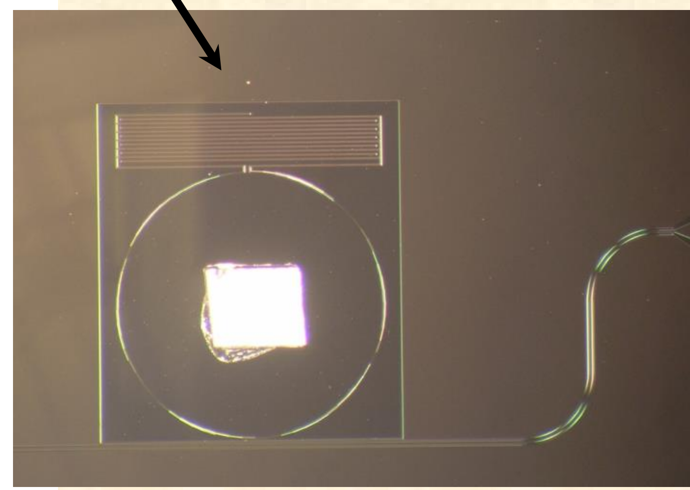


J. Salort, A. Monfardini and P.-E. Roche, Rev. Sci. Instrum. 83, 125002 (2012)

Resonators as London depth sensors

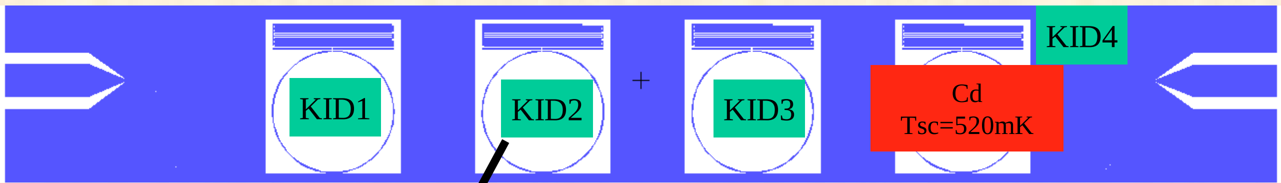




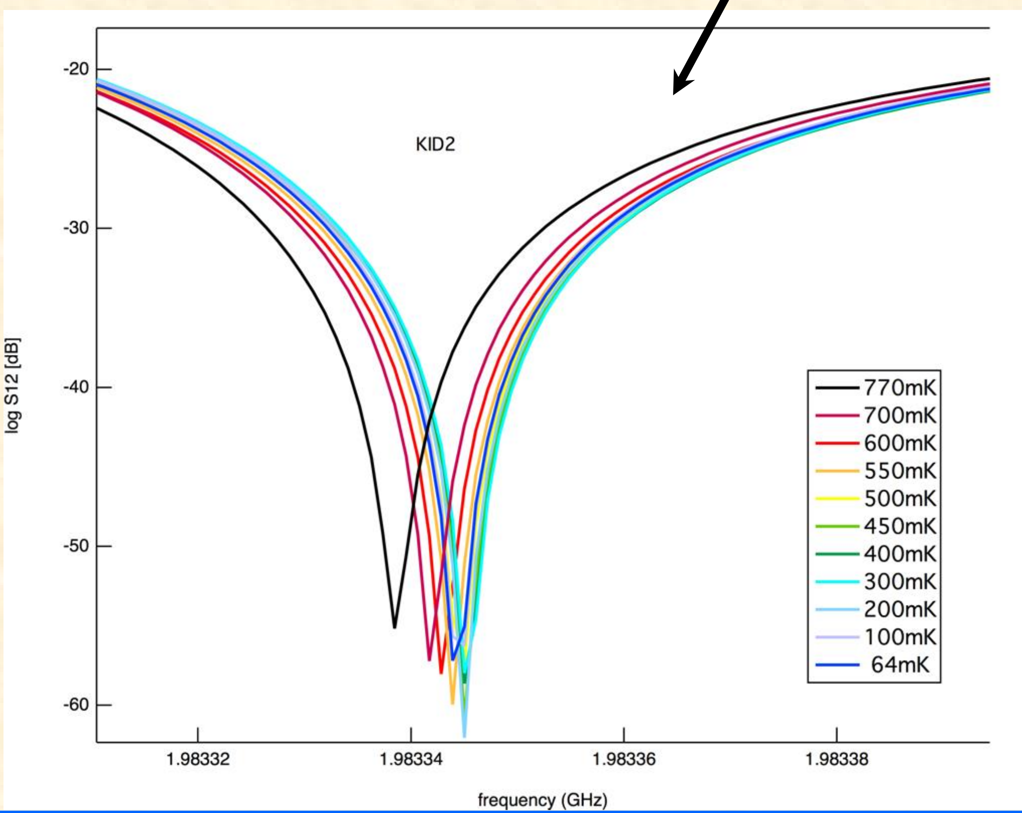


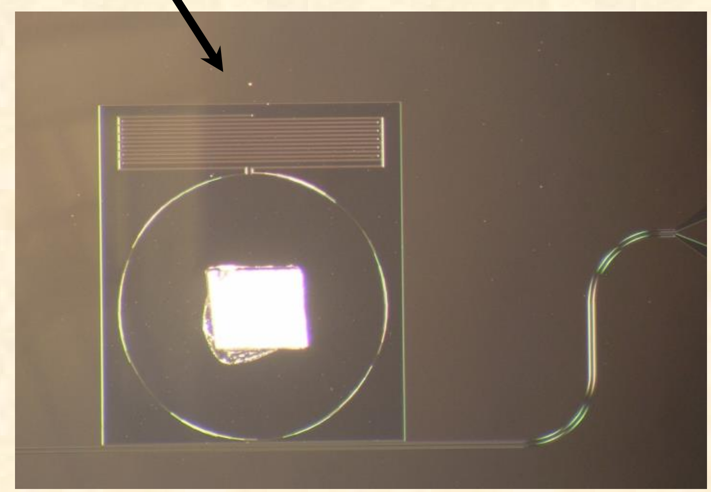
Collaboration with
P. Rodiere, F. Levy-Bertrand
Institut Néel

Resonators as London depth sensors

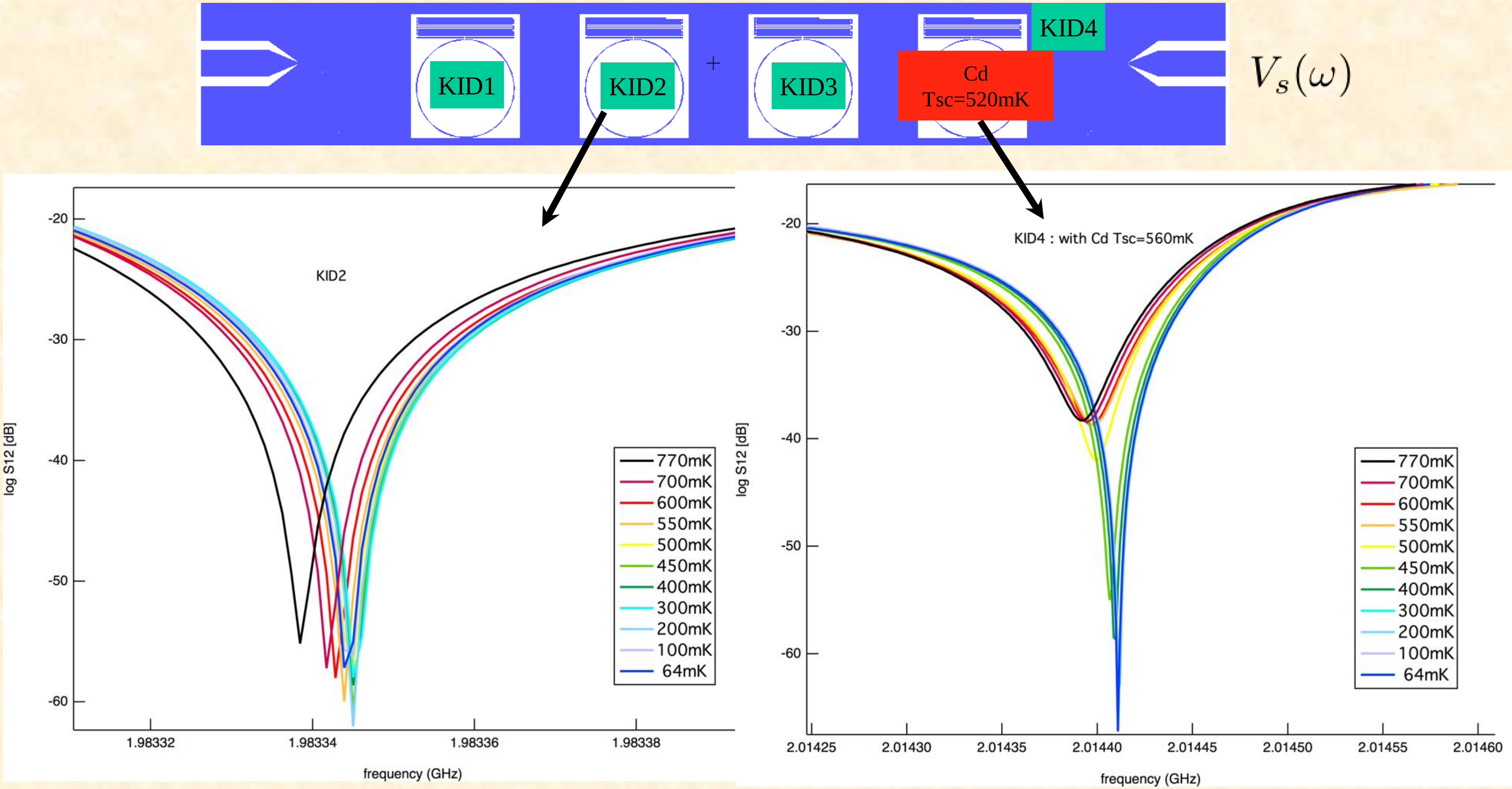


$V_s(\omega)$

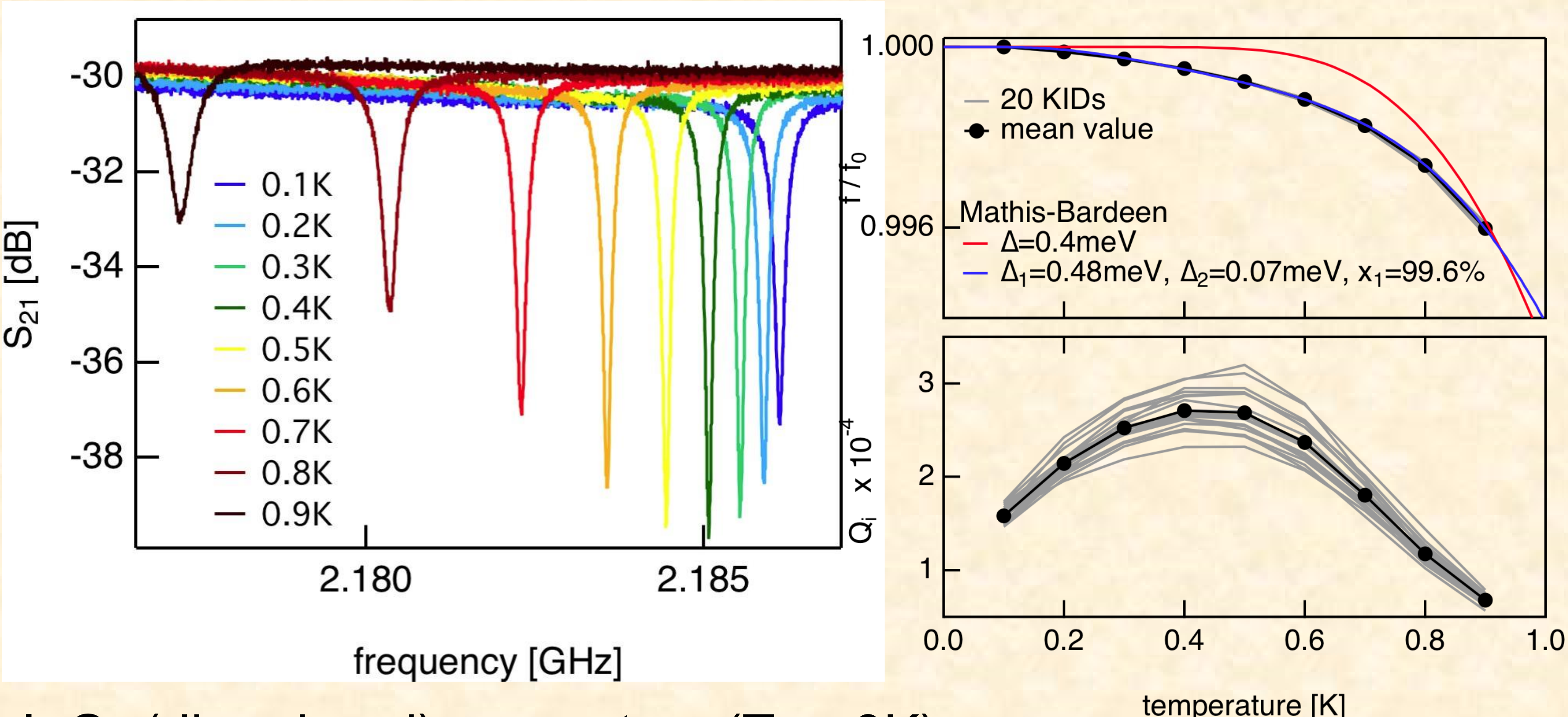




Resonators as London depth sensors



Superconductor films fundamental studies



InO_x (disordered) resonators ($T_c \approx 3$K)
Study of fundamental superconducting thin films properties
(collaboration with B. Sacepe, F. Levy-Bertrand – Institut Néel)

Thank you for your attention !!