

Low temperature detectors: physics and applications

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Outline of the lecture

1 – Broad introduction to Low Temperature Detectors

Basic principles and advantages of LTD

Driving science cases: astronomy, dark matter, neutrinos

2 – LTD technologies today

Who are the main competitors in the field?

An overview of the different options

3 – A detailed case: Kinetic Inductance Detectors

What makes them unique? (Apart from the fact that that's what I do!)

Why could other LTD technologies also profit of their development?

4 – KID activities in Grenoble

KID for astronomy: the NIKA and NIKA2 cameras

Applications as particle detectors and for fundamental physics

Introduction and main concepts of Low Temperature Detectors

The origins of LTD

First proposed in 1984:

- Fiorini and Niinikoski, *Nucl. Instr. Meth.* **224** (1984) 83

Application: particle physics

- Moseley, Mather and McCammon, *J. Appl. Phys.* **56** (1984) 1257

Application: X-Ray astronomy

In 30 years the field has passed from 'frontier physics' to 'widespread instrumentation' for two reasons: improvements in technology and ***intrinsic advantages*** of LTDs



Makes an experiment easier



Makes an experiment possible!

The fundamental advantage of LTDs

Low temperatures ($<1\text{K}$) give many advantages (dark current, Johnsons noise, superconductivity, etc...)

Although very nice, these can almost be regarded as 'side effects'..

The real advantage being that:

At low T, typical excitations have extremely low E!

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Gain in energy resolution

Let's assume your detector receives a large amount of energy E (say, 6keV)

Case 1: Si based photodetector

The excitations are the creations of e-h pairs: $\delta E = 1.2\text{eV}$

You create $N = \eta E / \delta E$ excitations $\eta \approx 1/3$

Poisson $\rightarrow dN = \text{sqrt}(N)$ [actually, it's $\text{sqrt}(FN)$, Fano factor $F \approx 0.1$]

Which gives

$$\Delta E_{rms} \approx 50\text{eV}$$

$$\Delta E_{FWHM} \approx 120\text{eV}$$

At low T, typical excitations have extremely low E!



Gain in energy resolution

Let's assume your detector receives a large amount of energy E (say, 6keV)

Case 2: low temperature photodetector

For the time being, we make just a very general assumption: $\delta E \approx k_b T$

Assume $T=1K \rightarrow \delta E \approx 0.1meV$

Which, if everything stayed the same (which it does not..) would give:

$$\Delta E_{rms} \approx 0.5eV$$

$$\Delta E_{FWHM} \approx 1.2eV$$

NOTE: the assumptions are quite rough, the result is surprisingly quite correct!

At low T, typical excitations have extremely low E!



Gain in lowest detectable energy

The THz part of the e-m spectrum is very elusive (low energy of each photon)

Coherent detectors

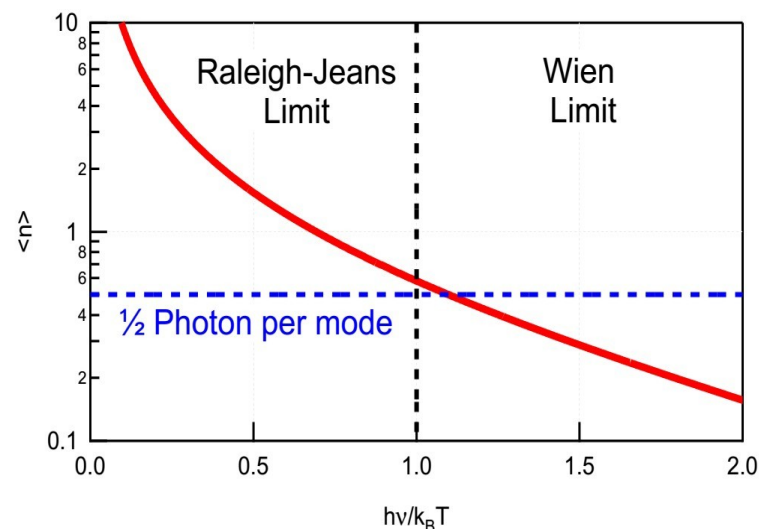
Mixer and amplifiers

Info on amplitude and phase

Add unavoidable quantization noise:

$$n_{qm} = h\nu/2 \text{ per mode}$$

Ok only for $\nu < k_b T_{bb}/h \approx 50\text{GHz}$ for $T_{bb}=3\text{K}$



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Semiconductor-based photodetectors

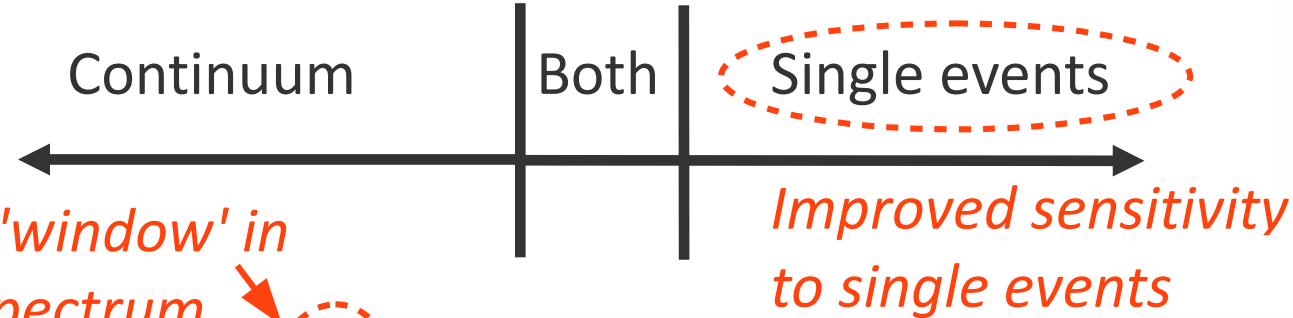
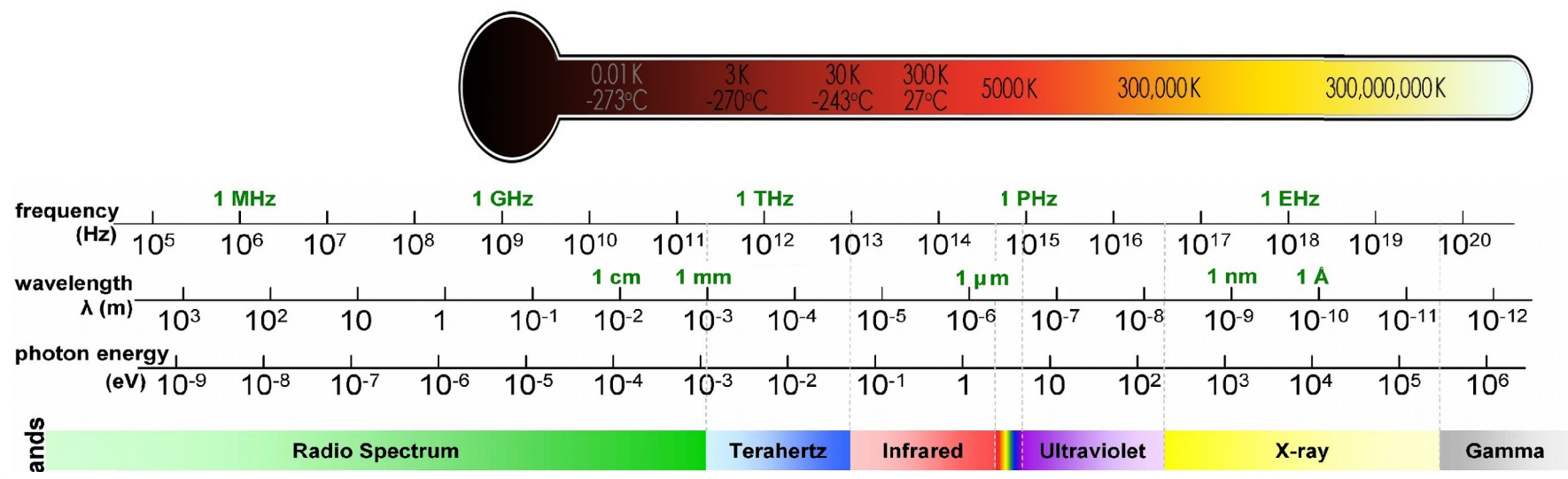
Need $h\nu > \delta E \approx 0.1\text{eV}$

So ok only for $\nu > \approx 50\text{THz}$

$50\text{GHz} < \nu < 50\text{THz} ?$

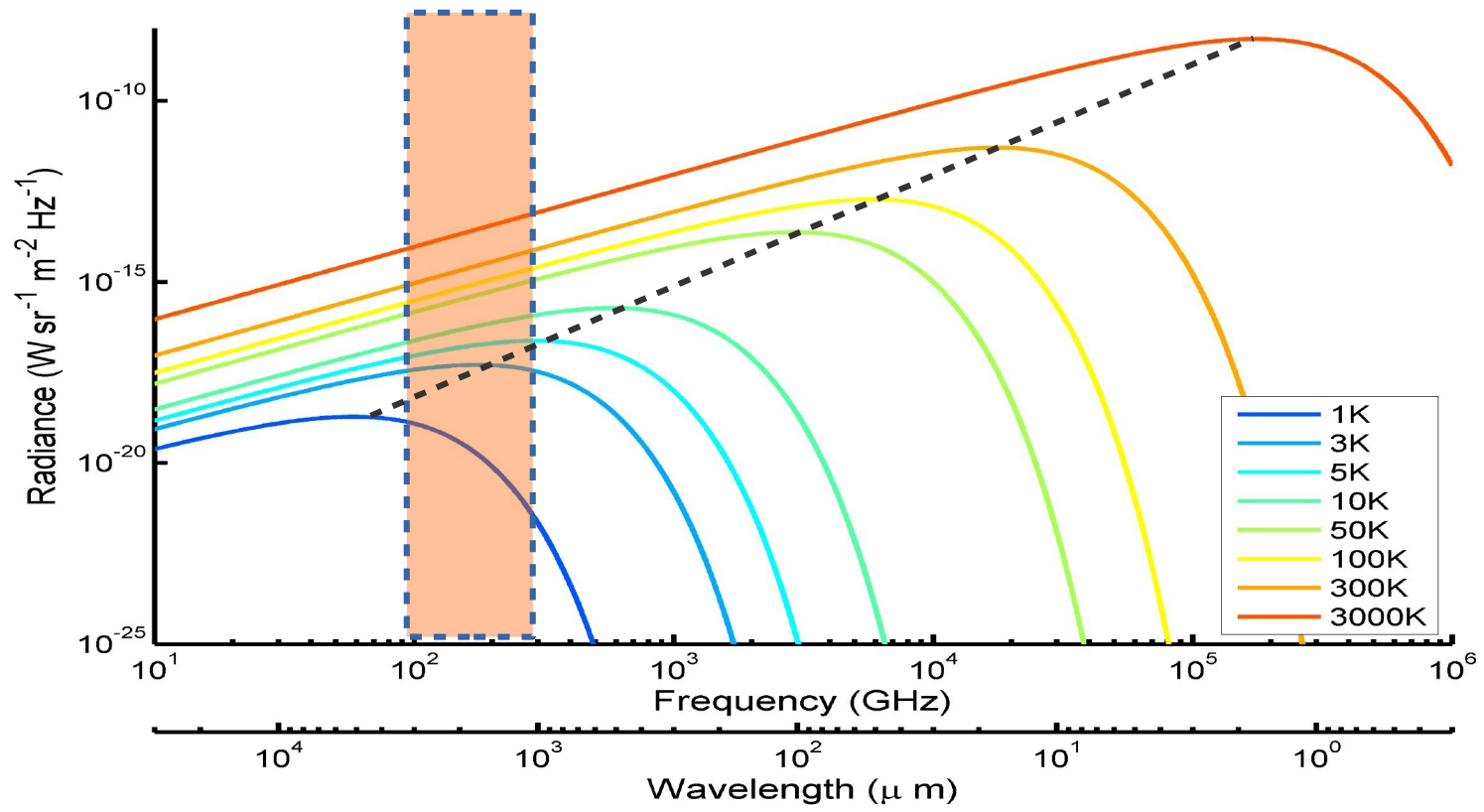
LTDs can fill this gap!

LTDs and the EM spectrum



This section compares four detection technologies. On the left, 'Heterodyne receivers' are shown as cylindrical units. In the center, 'Bolometers' are shown as a vertical stack of components labeled 'electronics' and 'optics'. On the right, 'CCD cameras' are shown as a flat detector array, and 'Scintillators + Photomultipliers' are shown as a circular detector with a lens. A red dashed oval encircles the Bolometers and CCD cameras.

Driving science: the 'cold' Universe



Wien's black-body law :

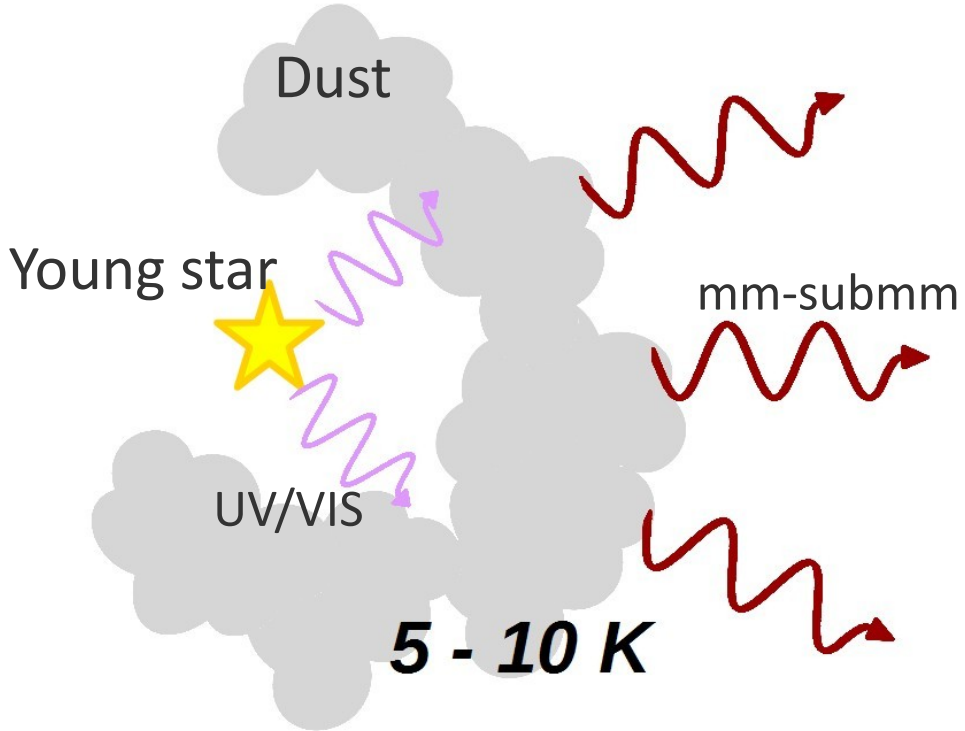
$$\lambda_{\text{max}} \approx (5/T) \text{ mm}$$



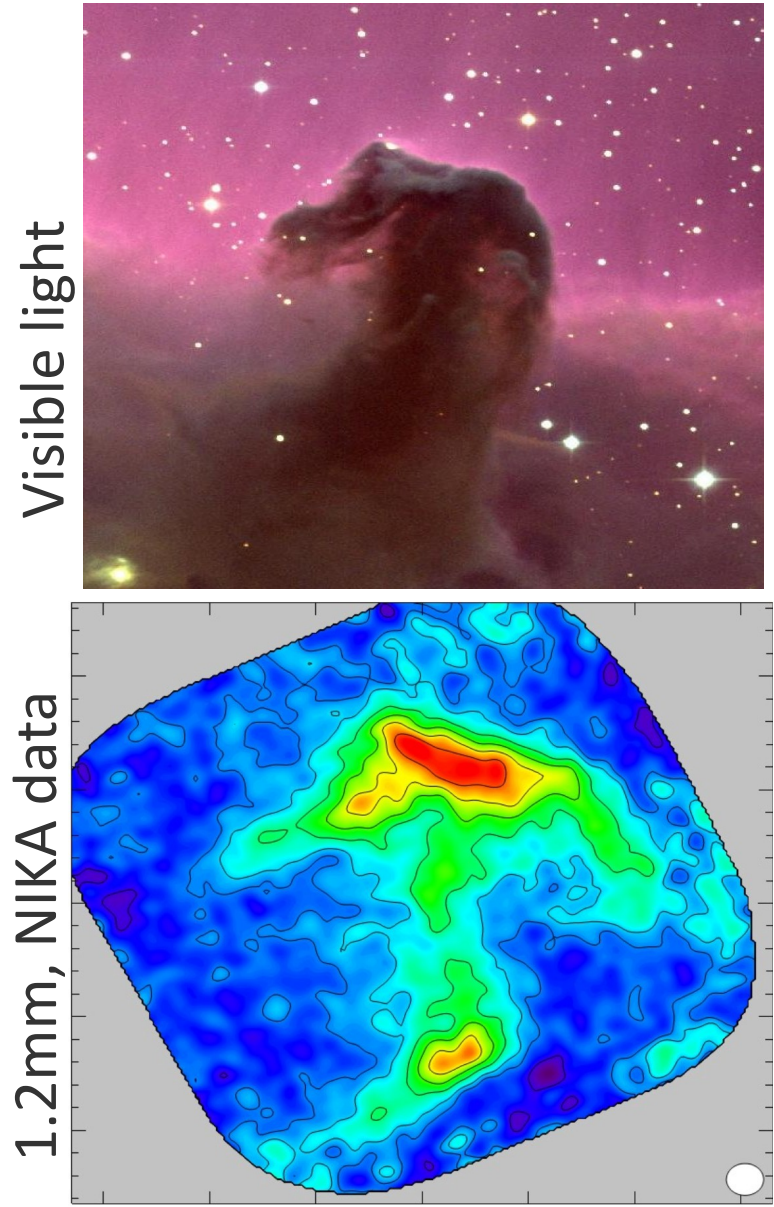
Astrophysics : structure formation

Cosmology : Big Bang science

Astrophysics : structure formation



Example: the Horsehead Nebula!



Cosmology : the Big Bang radiation (Cosmic Microwave Background)

Planck's satellite view of the mm sky :

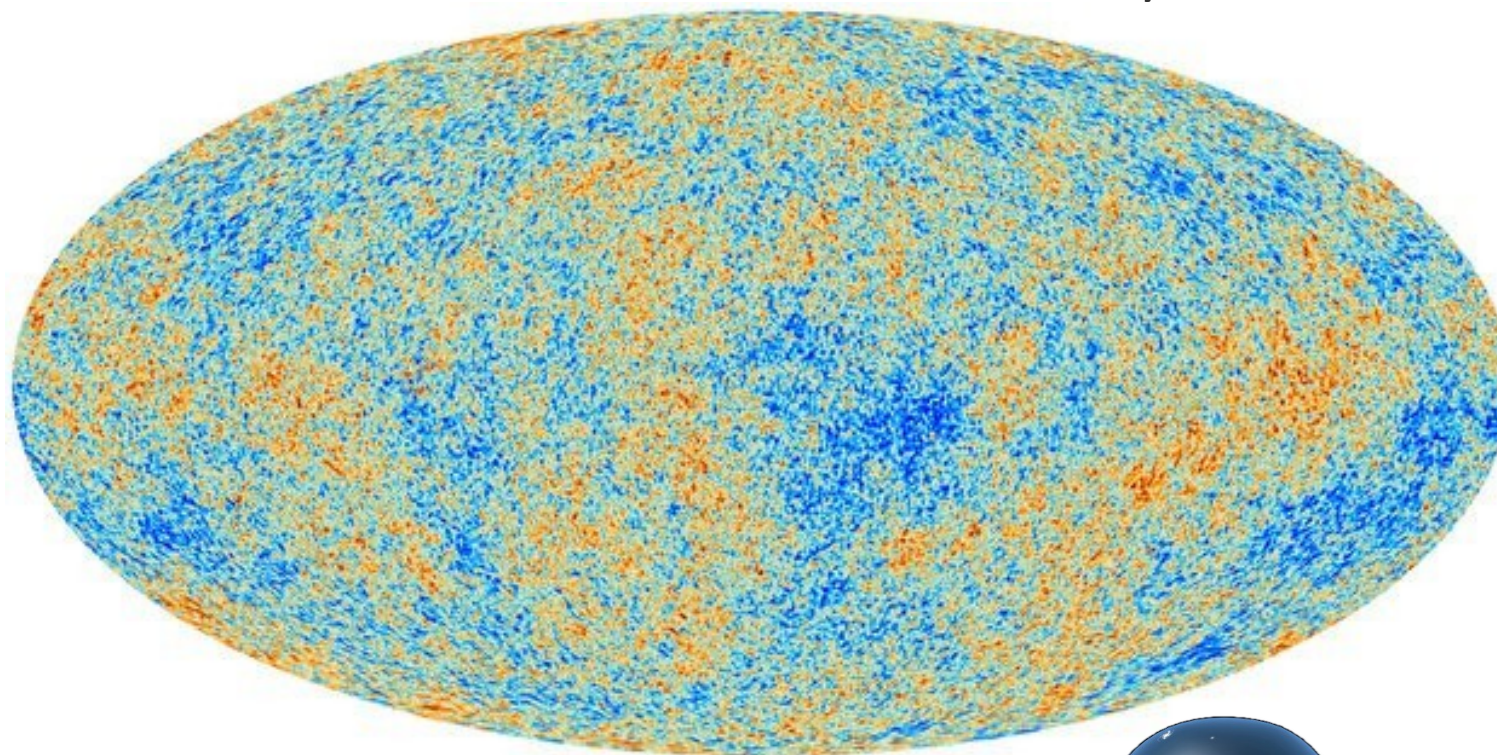
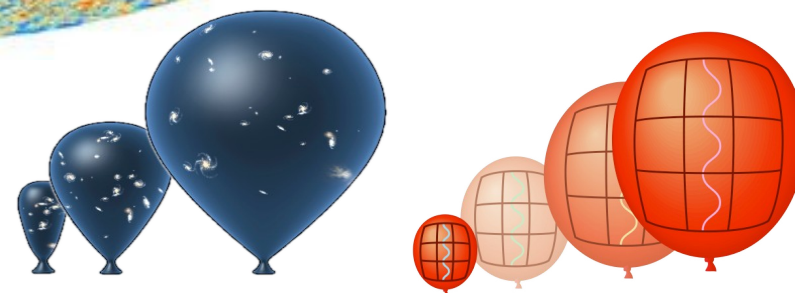


Image taken with LTDs!

Wavelength: $3\mu\text{m} \text{ -- } \rightarrow 3\text{mm!}$

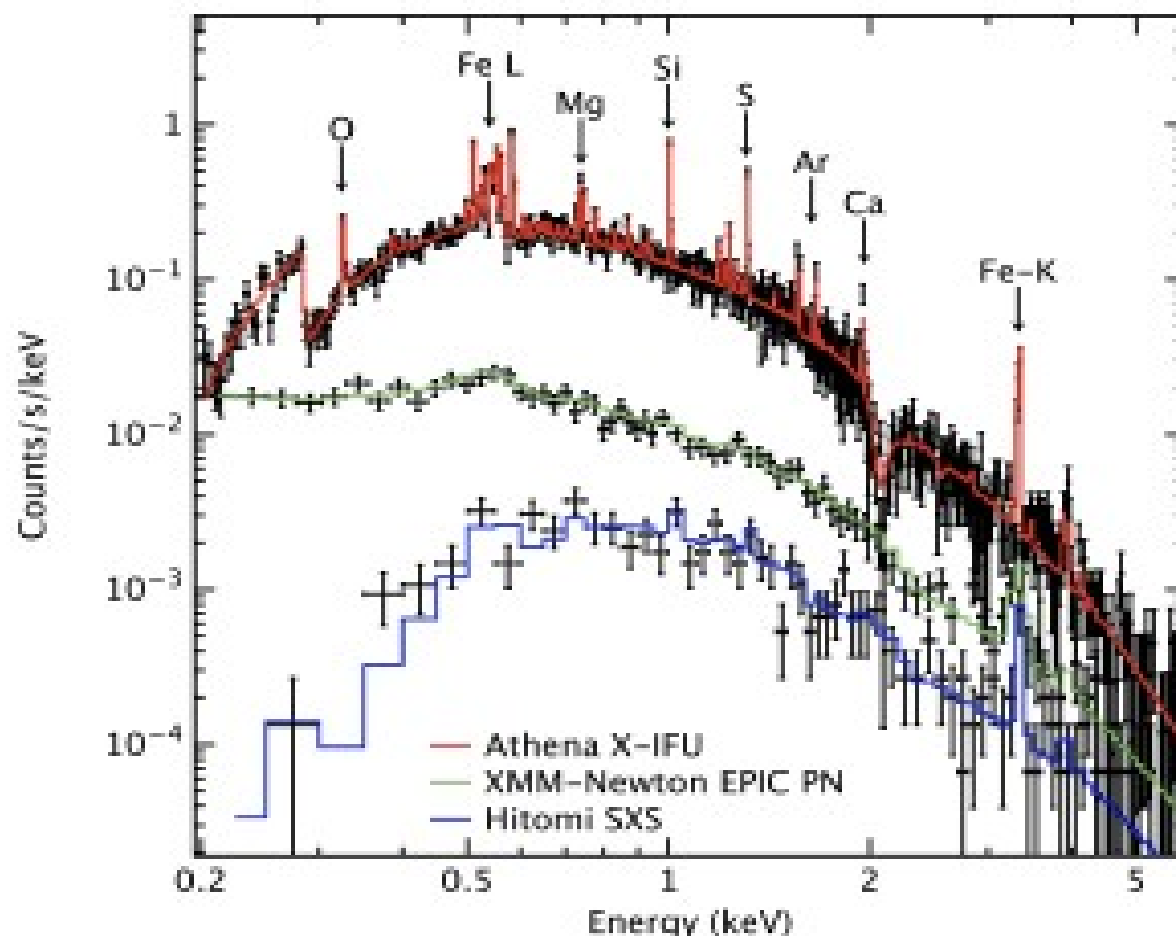


X-ray universe : study of the hot
intracluster gas

Line heights :
ion-per-ion abundances

Line widths :
velocity profiles

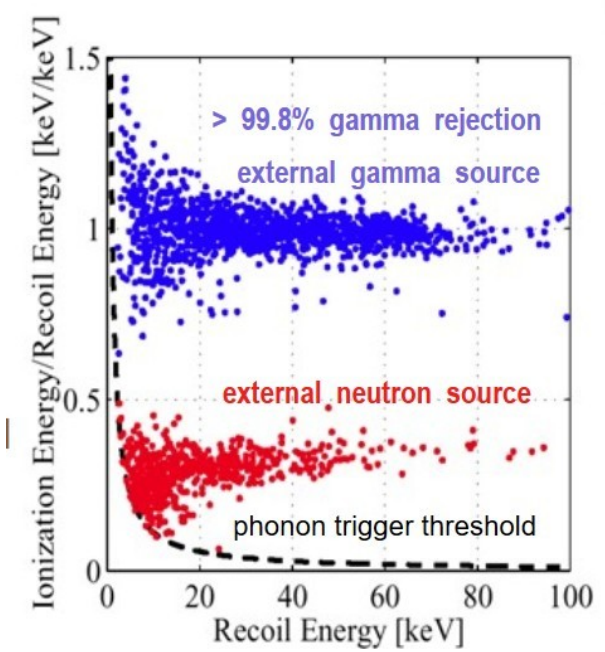
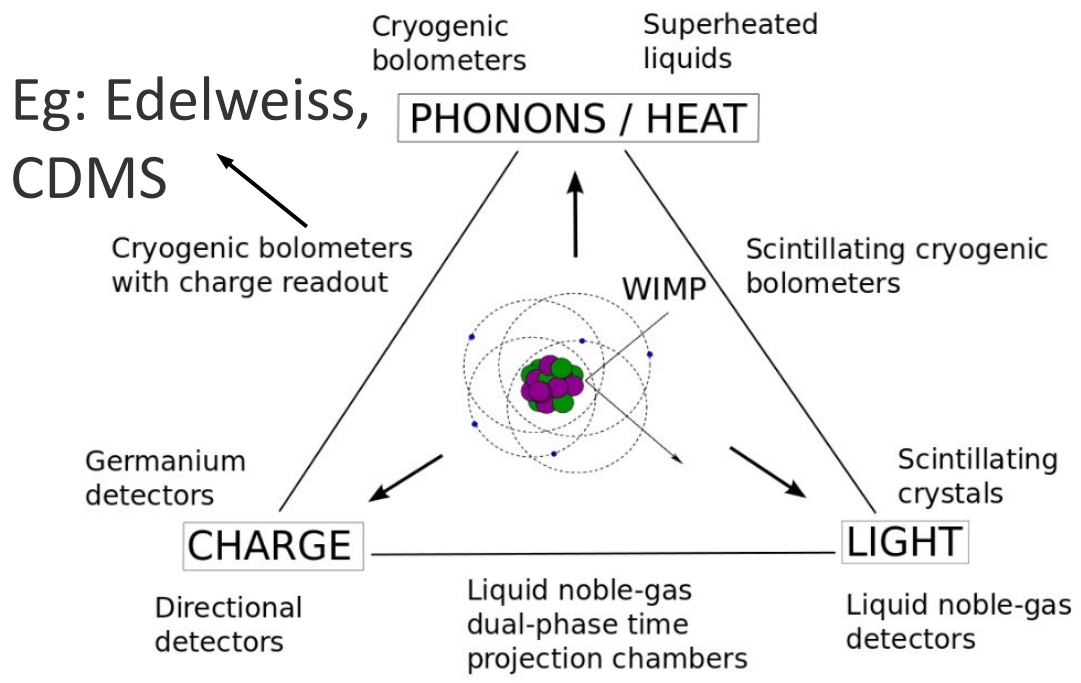
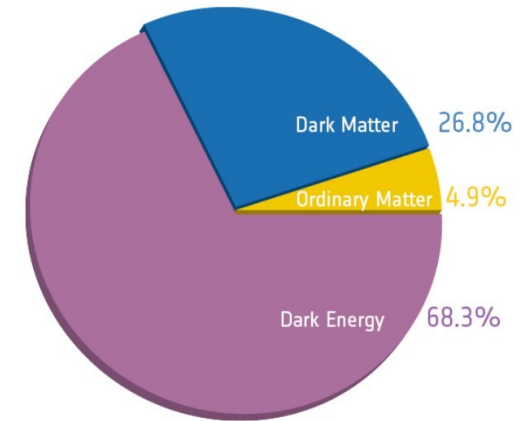
Galaxy cluster simulation
ATHENA+ satellite (2030)



Driving science: weak interactions

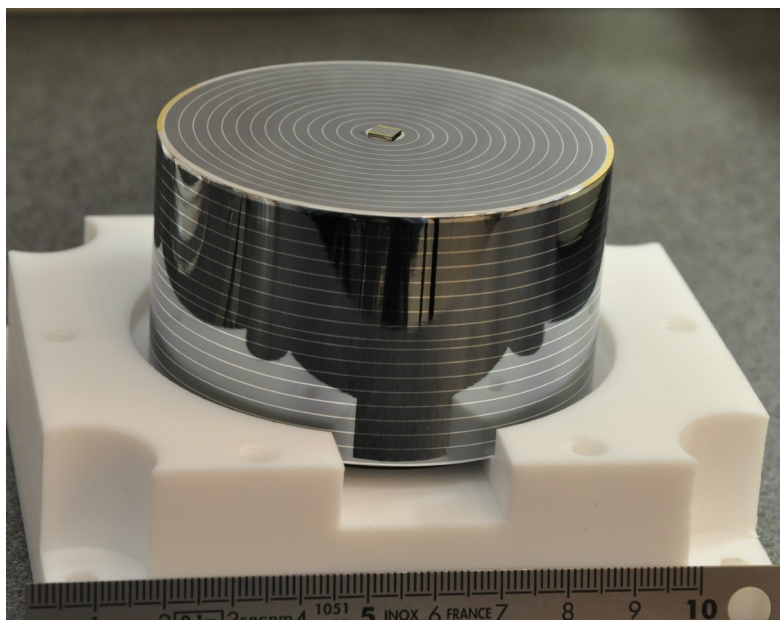
Dark matter : 5 times more abundant than 'ordinary' (barionic) matter!

Challenging to detect. Need high resolution and high cross section!



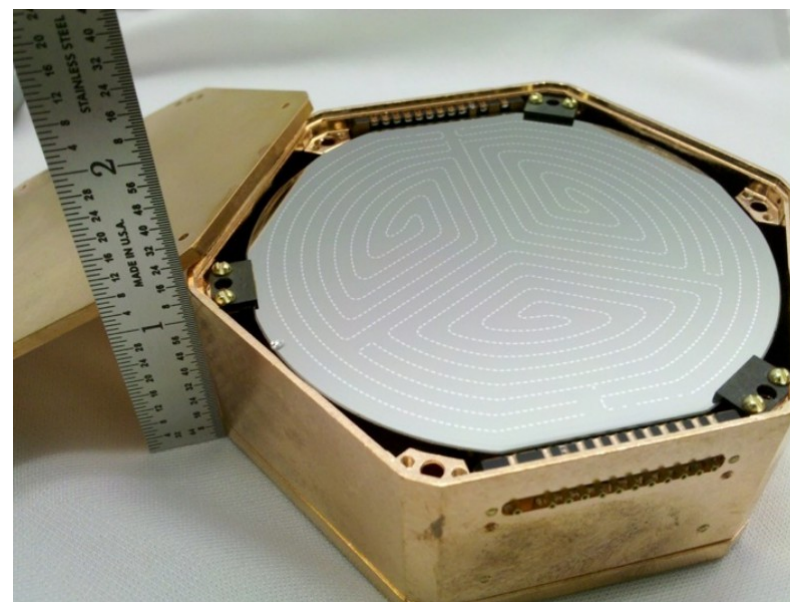
Note: one of the rare case in which **massive LTDs** are desirable (see later)
Design driven by the need for large cross sections!

Edelweiss III



Ge crystals + FID detectors
(NTD + charge collection)

SupedCDMS

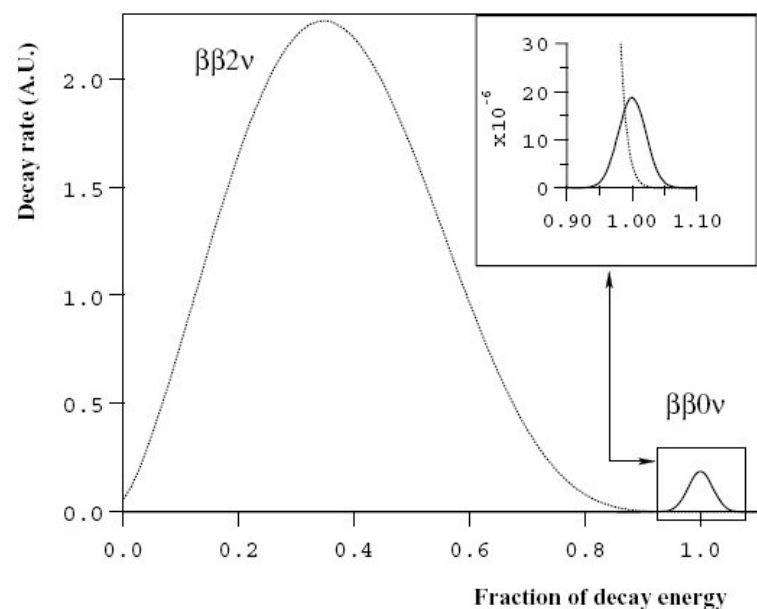


Ge crystals + iZip detectors
(Wu TES + charge collection)

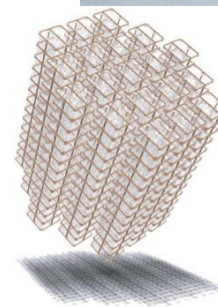
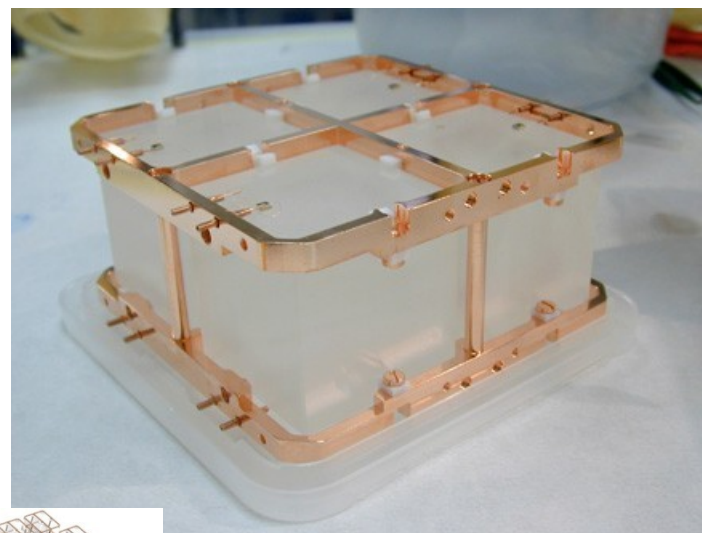
Neutrino physics : determine mass/nature of neutrinos

Eg: $0\nu\beta\beta$ decay experiments

Typically studying 'missing energy' so resolution (FWHM) is paramount!

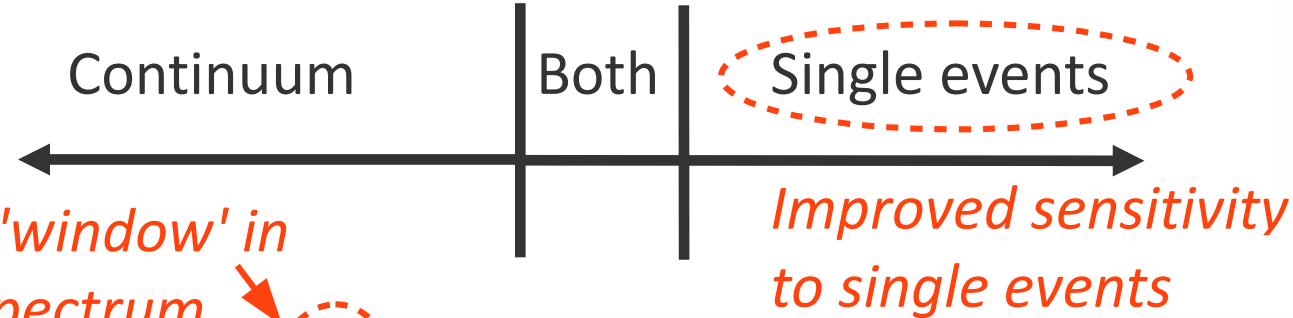
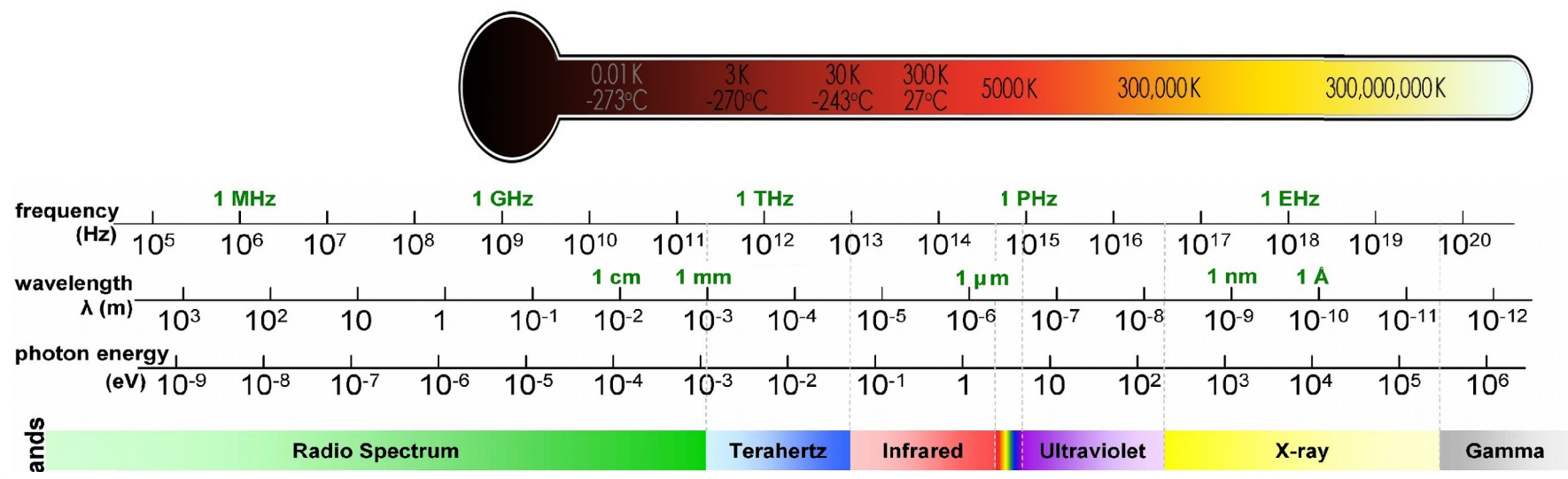


Eg: CUORE



~750kg TeO₂
crystal!

LTDs and the EM spectrum

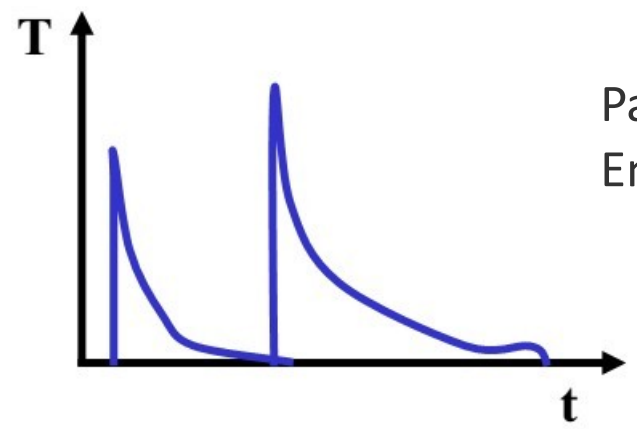
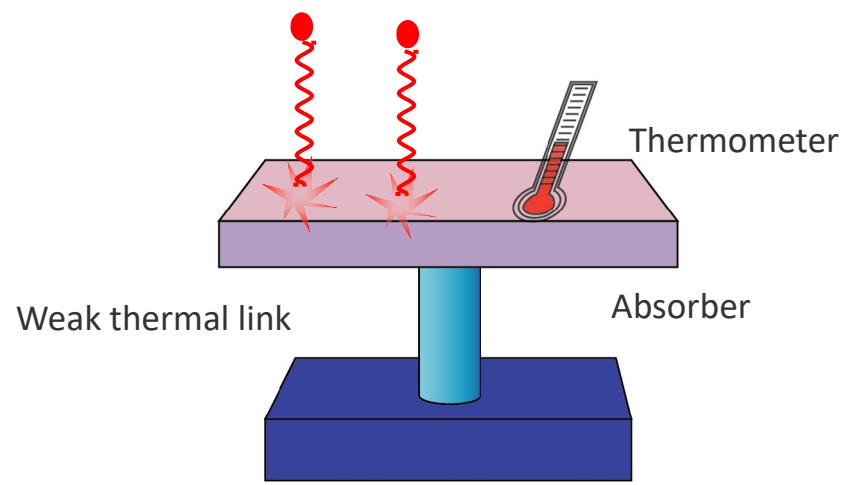


Four detection technologies are shown in a row, separated by vertical dashed lines:

- Heterodyne receivers:** Shown as five cylindrical units on a blue base.
- Bolometers:** A vertical grey bar with 'electronics' and 'optics' labels, circled in red.
- CCD cameras:** Shown as a flat detector array on a metal frame.
- Scintillators + Photomultipliers:** Shown as a circular detector with a central crystal and surrounding electronics.

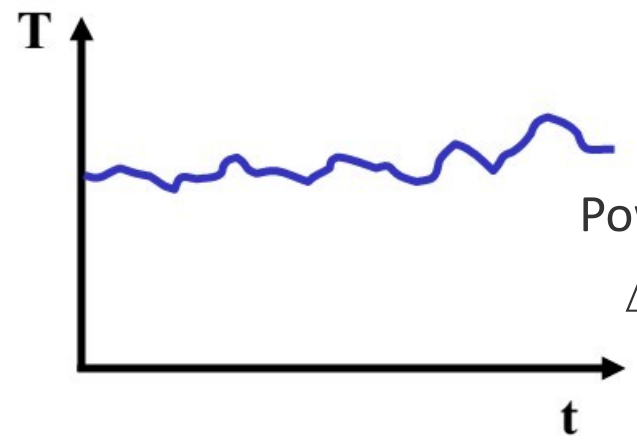
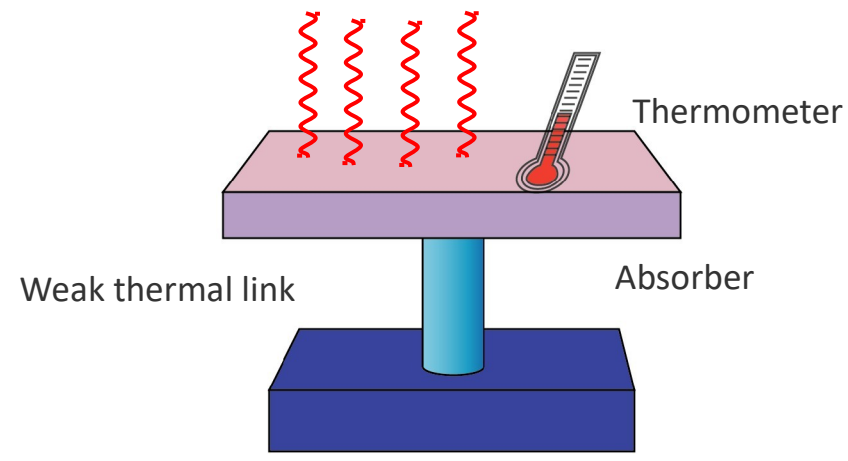
LTDs operating modes

A typical LTD has two 'operating modes':



Particle counting/
Energy measurement

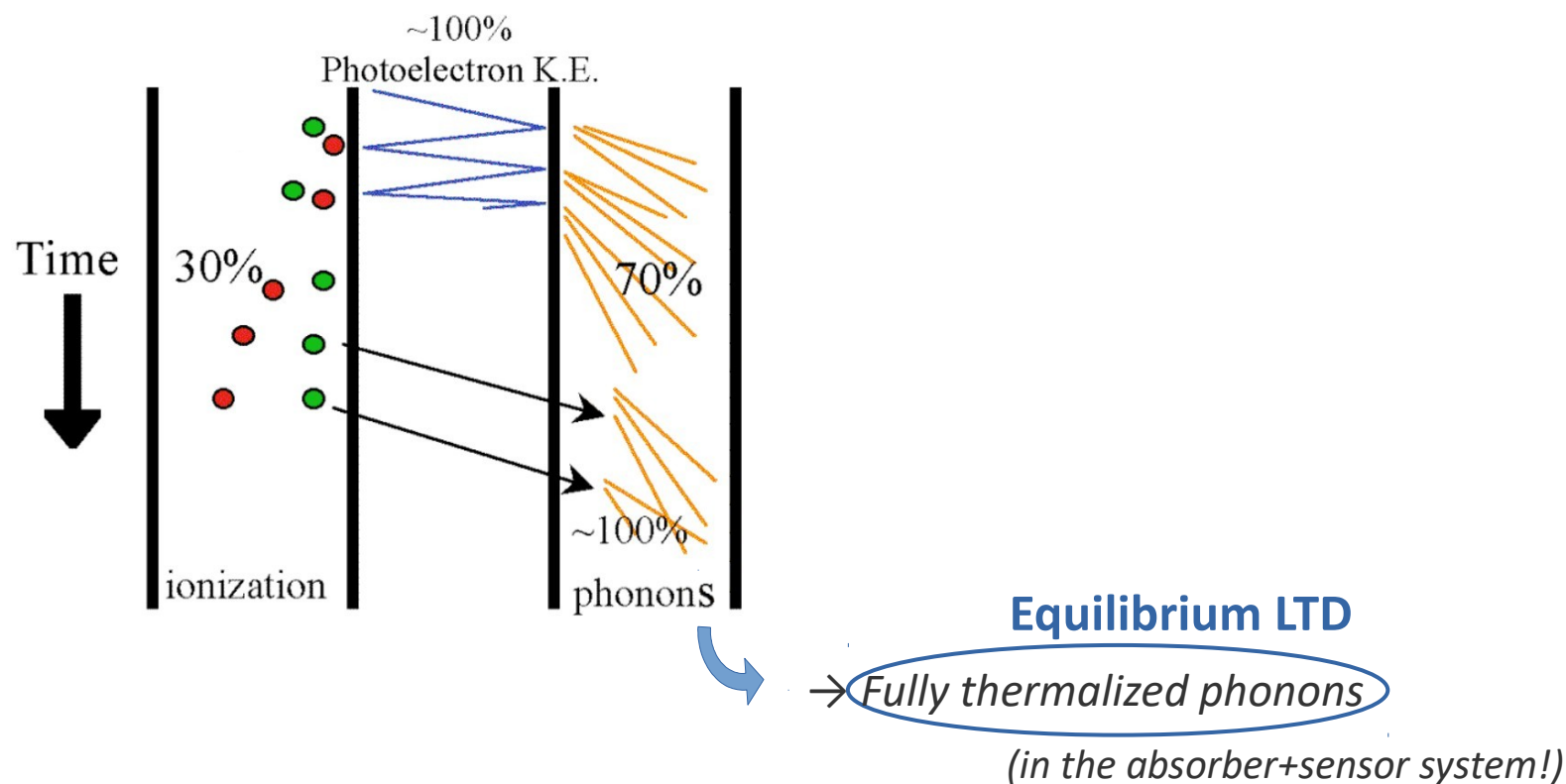
$$\Delta T = E/C$$



Power measurement

$$\Delta T = P \tau / C = P / G$$

Equilibrium LTDs



All the energy released in the absorber will in the end become phonons

→ **detection efficiency can approach 100% in equilibrium LTDs!**

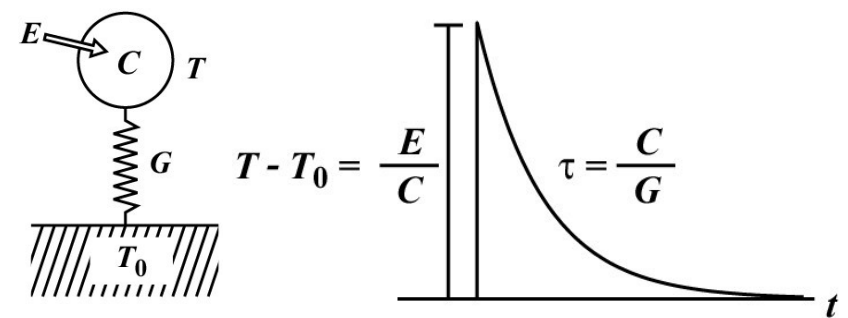
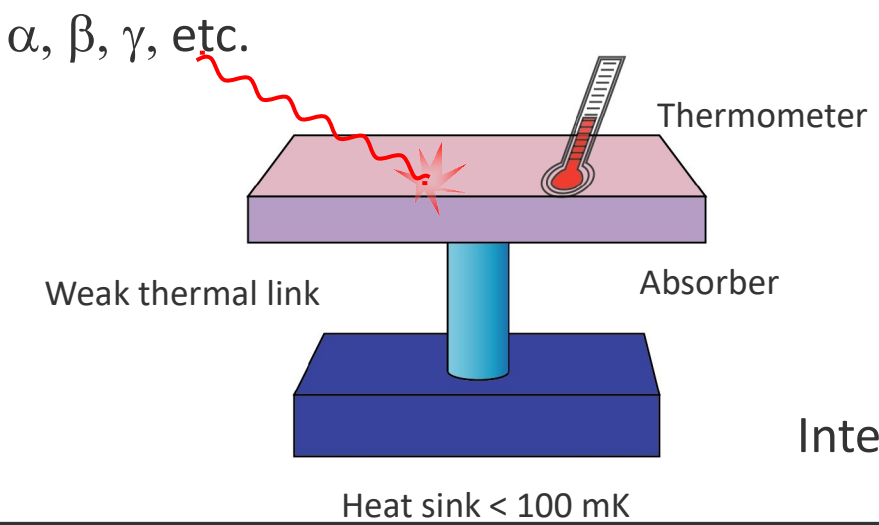
On the other hand, they are relatively slow. And, any phonon can be sensed!

Equilibrium LTDs

The energy is deposited in an absorber, weakly linked to a thermal bath
 The temperature increase is measured with an appropriate thermometer
 Assuming one has an ideal, noiseless thermometer, the energy resolution is determined by the background thermodynamical temperature fluctuations
 The Thermodynamic Fluctuations Noise (TFN) gives:

$$\Delta E_{rms} = \sqrt{k_b T^2 C}$$

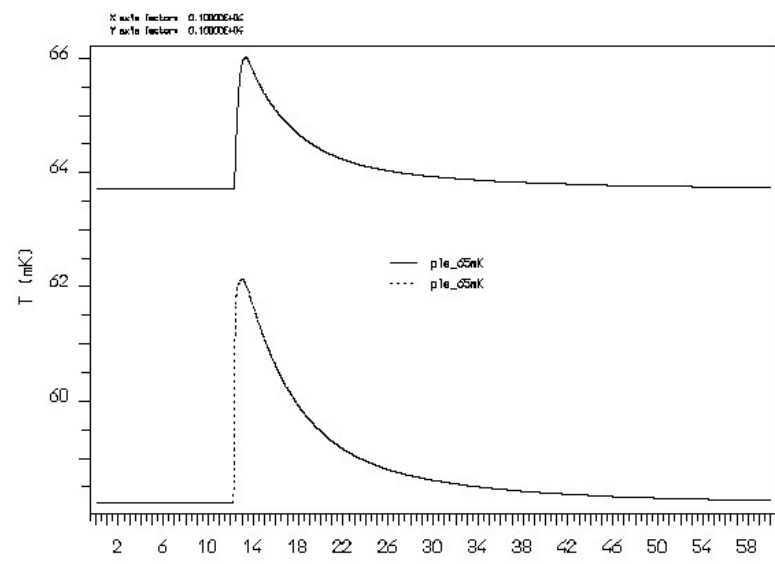
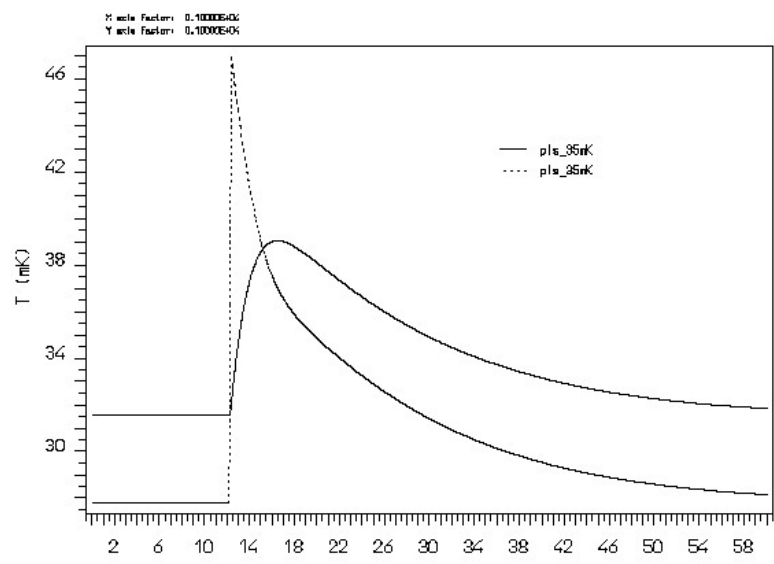
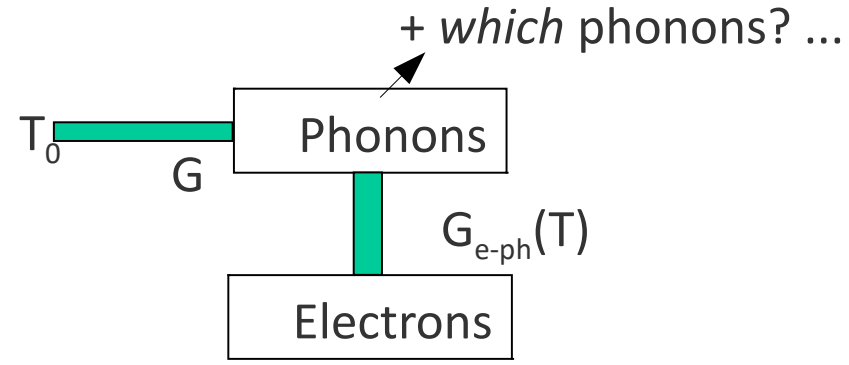
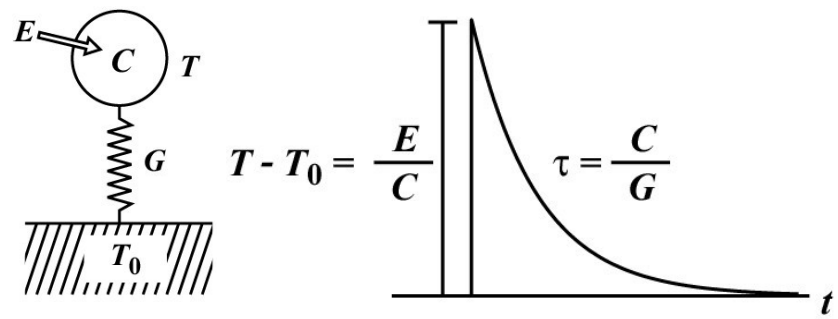
Excitation = **phonons!**
 $E = k_b T_{bath}$



Interest in low C → **cryogenic microcalorimeters!**

Equilibrium LTDs

Note: the reality is more complex than that....



Equilibrium LTDs

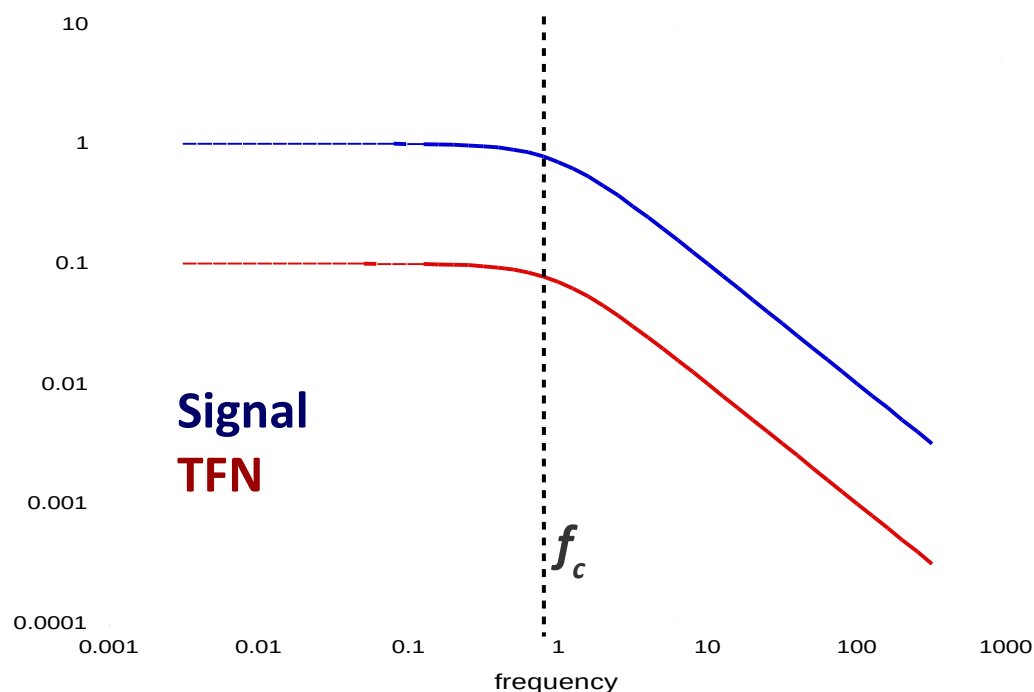
$$\Delta E_{rms} = \sqrt{k_b T^2 C}$$

The thermodynamic fluctuations have a timescale given by $\tau = C/G$

Their spectrum has a single pole roll-off at $f_c = G/(2\pi C)$

The signal has, in principle, the same spectrum

In an ideal world, could reach arbitrary energy resolution by increasing the bandwidth of the measurement (ie, sampling the temperature at very high rate)



$$\Delta E = \left(\frac{2\pi f_c}{\Delta f} \right)^{1/2} \sqrt{k_b T^2 C}$$

$$\Delta E = \left(\frac{t_{meas}}{\tau} \right)^{1/2} \sqrt{k_b T^2 C}$$

Equilibrium LTDs

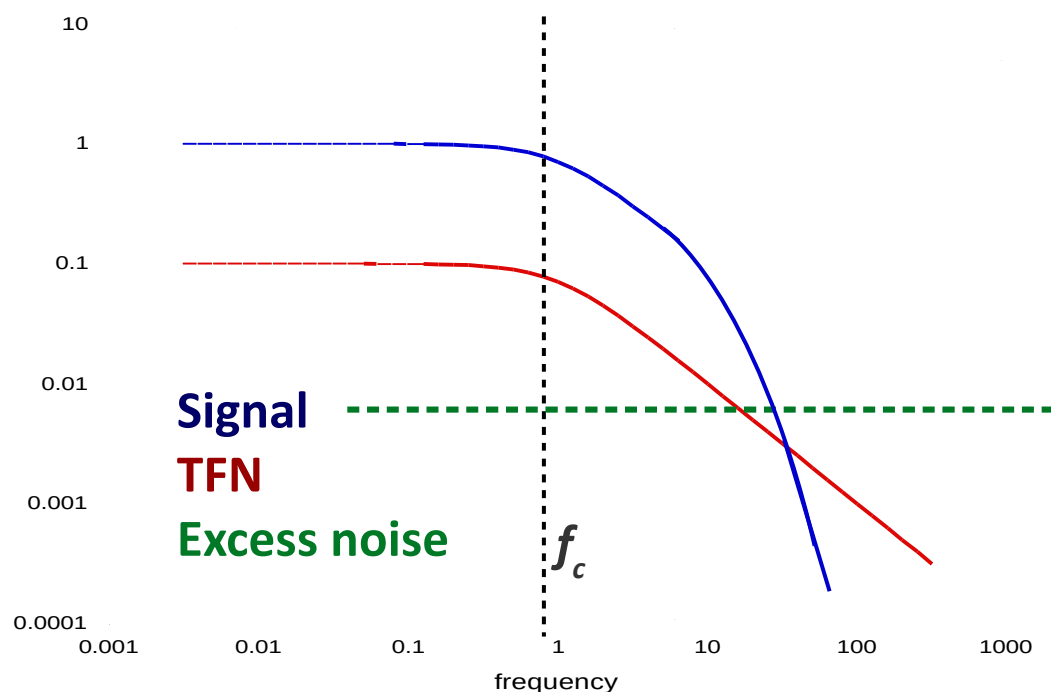
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The signal has, in principle, the same spectrum

$$\Delta E_{rms} = \sqrt{k_b T^2 C}$$

But the ideal world does not exist....

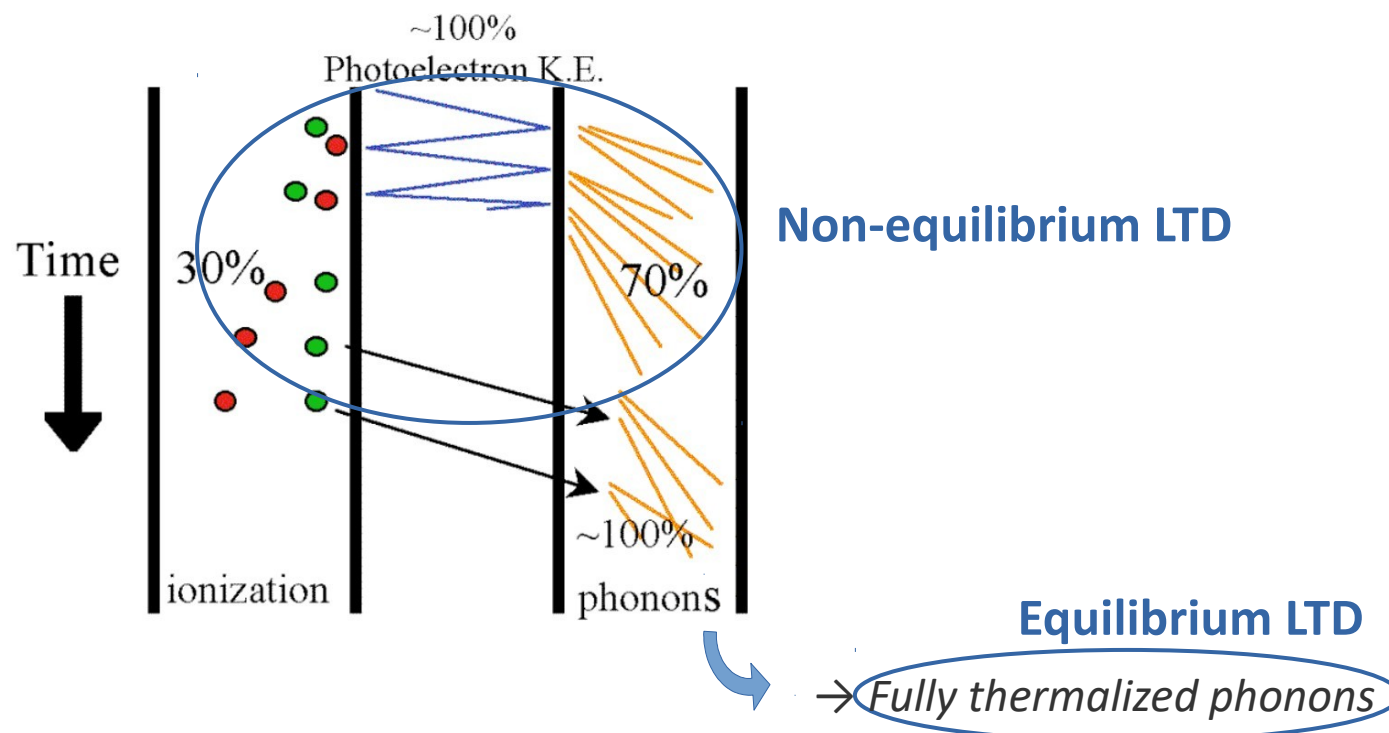


- t_{meas} is not arbitrarily small
- Additional noise always present (typically in the sensor)

$$\Delta E = \xi \cdot \sqrt{k_b T^2 C}$$

ξ is sensor-dependant and can be less than 1!

Non-equilibrium LTDs



Only part of the energy is sensed. 'Excitation counting'.

→ detection must be fast, and precise (lowest possible quanta of E)

Faster than equilibrium LTD, different limitations/experimental constraints.

Non-equilibrium LTDs

The energy absorbed creates quantized excitations (analog to photodiodes!)

The excitations have energy δE well above kT (they are 'decoupled')

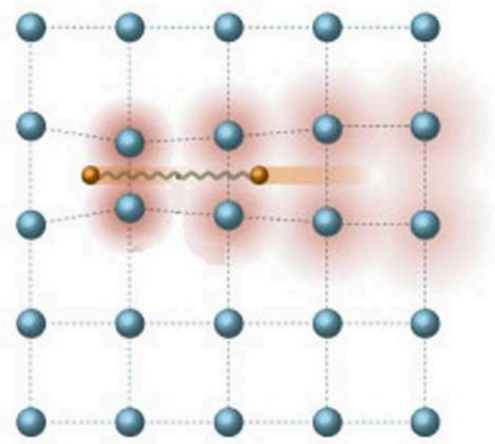
The energy is split between different channels, so in this case (as we have seen before) it's the counting statistics that determines the energy resolution

$$\Delta E_{rms} = \delta E \sqrt{N} = \delta E \sqrt{E/\delta E} \propto \sqrt{\delta E}$$

To have a good energy resolution we want non-thermal excitations with a very low energy. Ideal candidates are the **quasi-particles!**

Superconductivity reminder (I)

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



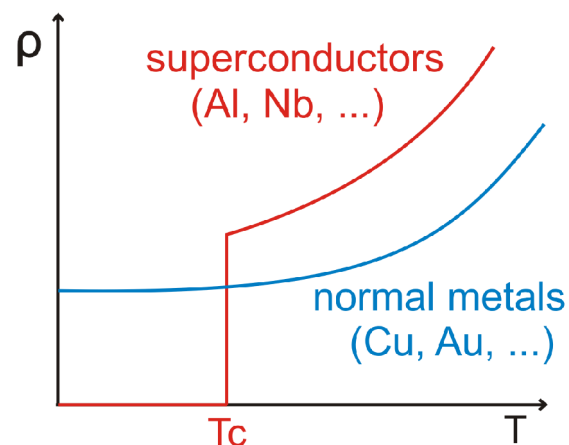
The binding energy of a Cooper Pair is given by :

$$2\Delta = 3.5 k_b T_c$$

This corresponds to typically few meV.

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

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



Excitation = **quasiparticles!**

$$E = 3.5 k_b T_c$$

Non-equilibrium LTDs

However small, the energy gap decouples the superconductor from the bath

The time evolution is not governed by thermal processes but by **QPs dynamics**

So:

Non-thermal detectors can be **very fast!**

Working temperatures typically need to be well below T_c

For the same T_{bath} , the excitation δE quanta are:

{	$\delta E \propto k_b T_{bath}$	<u>Thermal LTD</u>
}	$\delta E \propto k_b T_c > k_b T_{bath}$	<u>Non-thermal LTD</u>

A very (very!) broad indication therefore is

Need high energy resolution → Thermal



High count rate/fast events → Non-thermal

(Disregarding any instrument-related considerations..)



Current implementations of LTD detectors

Overview of main LTD types

- **Equilibrium LTDs:**

- Measure T through $R(T)$*  Semiconductor bolometers (NTD, doped Si...)
 Superconductor bolometer (TES)
- Measure T through $M(T)$*  Magnetic Metallic Calorimeters (MMC)

- **Non-Equilibrium (pair-breaking) LTDs:**



- Measure n_{qp} through $i(E)$*  Superconducting Tunnel Junctions
- Measure n_{qp} through $L(E)$*  Kinetic Inductance Detectors

- **Not treated today: many!**



Superconducting Nanowire Single-Photon Detectors, Quantum Capacitance Detectors,

Overview of main LTD types

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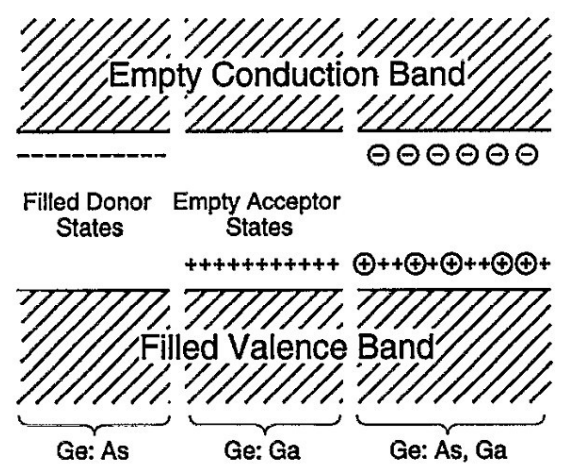
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- Measure n_{qp} through $i(E)$*  Superconducting Tunnel Junctions
- Measure n_{qp} through $L(E)$*  Kinetic Inductance Detectors

Semiconductor bolometers

This has been the first kind of cryogenic detector to be developed
 Standard (impure) semiconductors are not viable: $R = R_0 \exp(\Delta/T)$
 with Δ of order 100K \rightarrow way too resistive at low T!

Solution is to dope the semiconductor to near to the metal to insulator transition



Conduction get in VRH regime, which gives:

$$R = R_0 \exp((T_0/T)^{0.5}) \quad T_0 \text{ adjusted with dopant}$$

Main fabrication techniques:

- Ion implantation in Si
- Neutron transmutation of Ge (\rightarrow Ga, As)

(used since 1961! But at room T.)

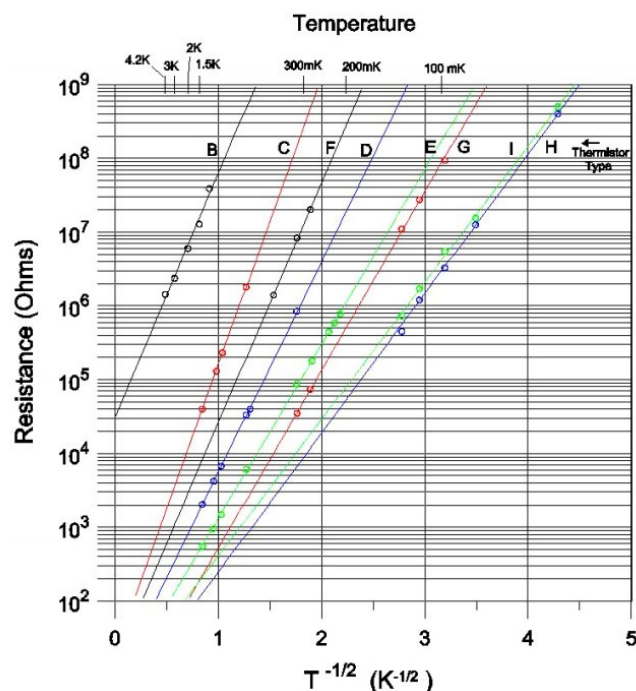
Semiconductor bolometers

The fundamental parameter of a thermometer based on $R(T)$ is

$$\alpha = \frac{T}{R} \frac{dR}{dT}$$

Typically, the larger $|\alpha|$ the better. With semiconductors, $\alpha \approx -1 - -10$

Resistance vs. $T^{-1/2}$ for H-B NTD Germanium
Samples, Size = 250 x 250 x 250 Microns



Negative $\alpha \rightarrow$ current bias

$$T \uparrow \Rightarrow R \downarrow \Rightarrow P_{elec} = RI_{bias}^2 \downarrow \Rightarrow T \downarrow$$

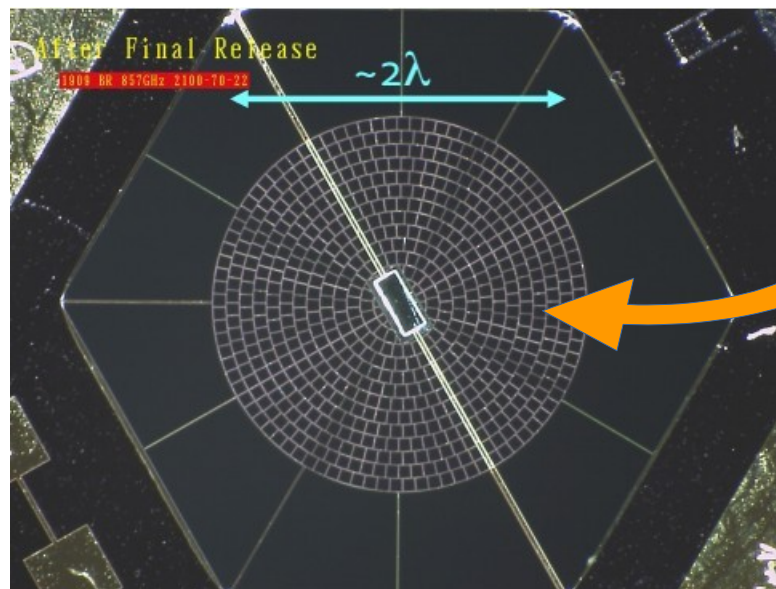
Semiconductors-based bolometers are limited by the moderate α

Plus, Johnson noise:

$$P_V = 4 k_b T R$$

Yet, have achieved a lot!

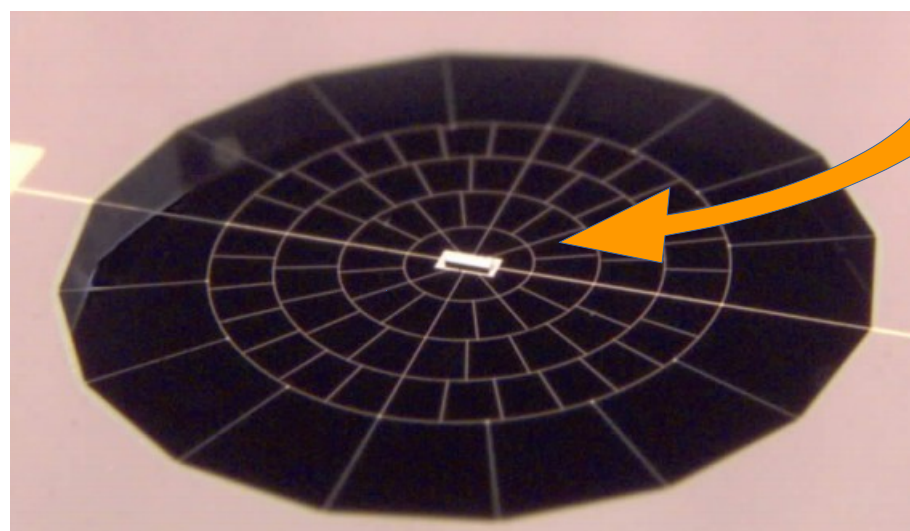
NTD bolometers of Planck



Gold-plated spider web absorber

Couples high cross section to radiation to low heat capacity C

4um * 1um!



NTD Ge thermistor

During Planck flight, achieved CMB photon noise!

@300mK: $NEP = 1,5 \cdot 10^{-17} \text{ W/Hz}^{1/2}$
= 11ms C = 1pJ/K

@100mK: $NEP = 1,5 \cdot 10^{-18} \text{ W/Hz}^{1/2}$
= 1,5ms C = 0,4pJ/K

NTD bolometers of Planck

Planck's satellite view of the mm sky :

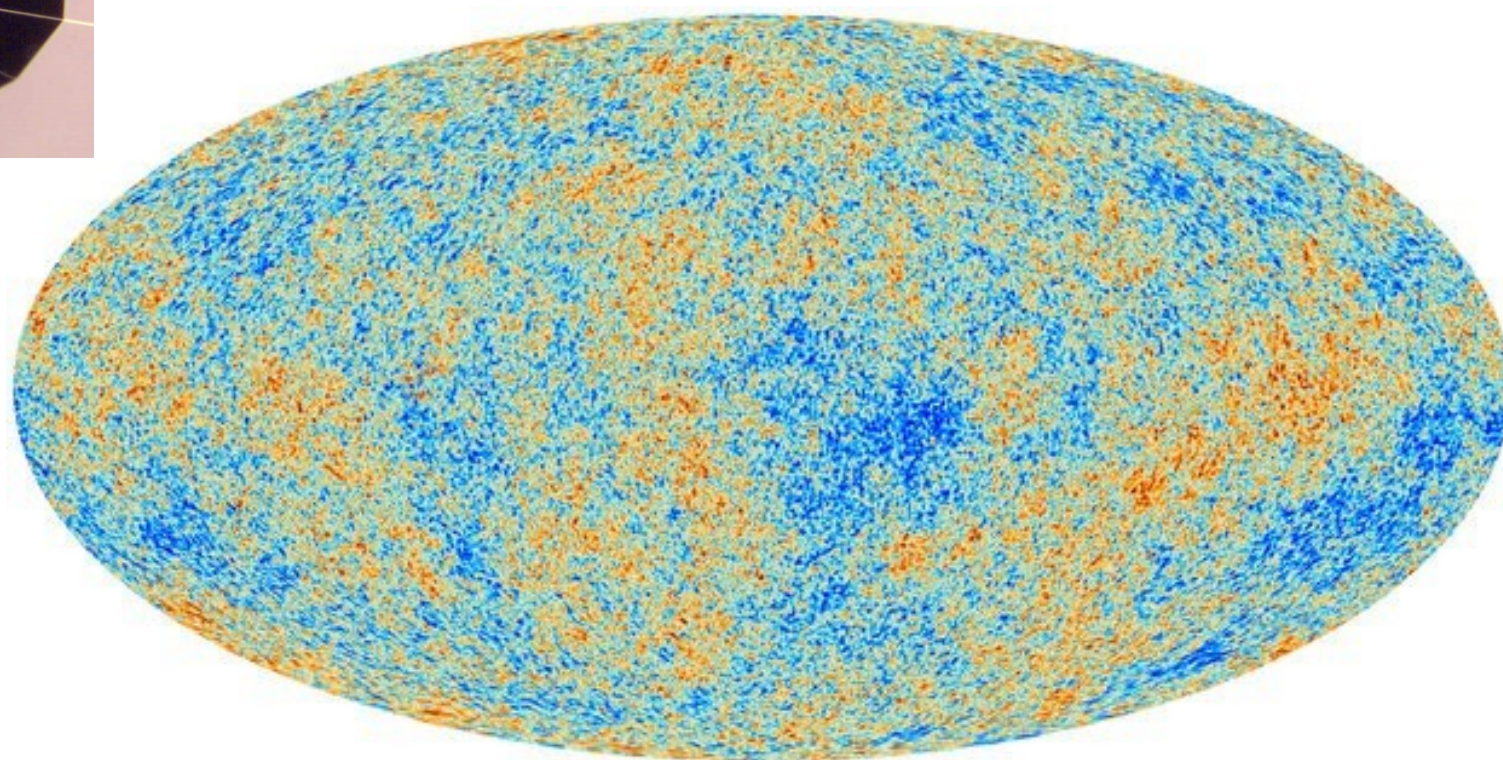
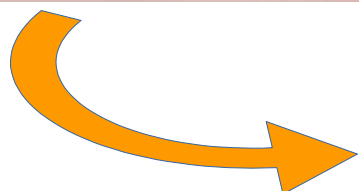
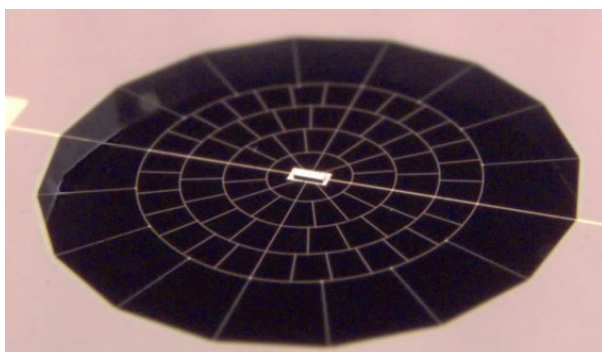
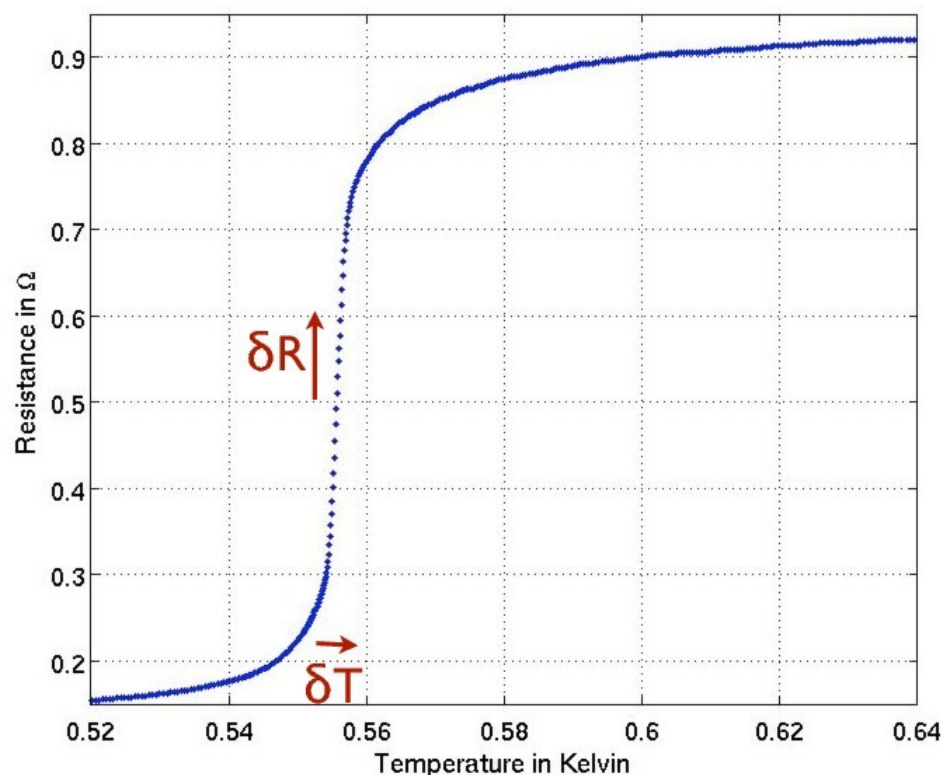


Image taken with LTDs!

Transition Edge Sensors

At cold temperature, we can take advantage of another steep $R(T)$ relation..



$$\alpha = \frac{T}{R} \frac{dR}{dT}$$

$$\alpha \approx 100 - 1000$$

Could be a great thermometer!

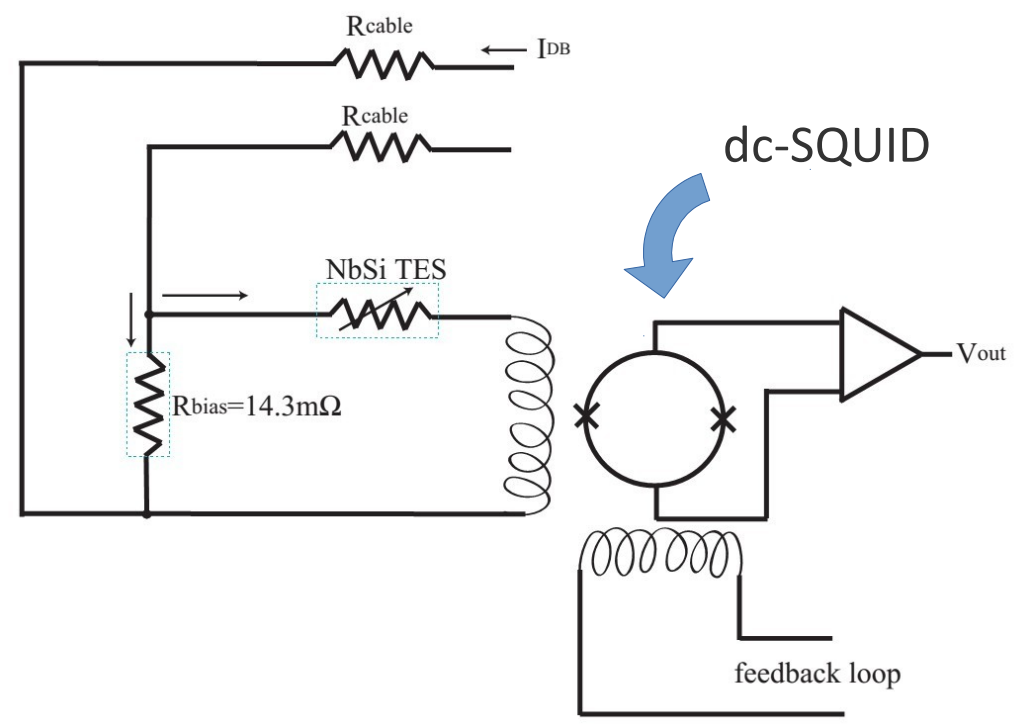
But :

$$T \uparrow \Rightarrow R \uparrow \Rightarrow P_{elec} = RI_{bias}^2 \uparrow \Rightarrow T \uparrow$$

The idea is actually pretty old. The problem was mainly technological!
(lack of appropriate current sensor, so current biasing)

Transition Edge Sensors

The solution: replacing a JFET with a SQUID to enable **voltage biasing** !



Signal:

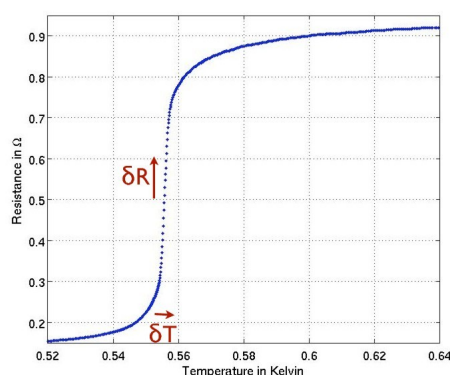
$$I(t) = V_{bias} / R(t)$$

$$T \uparrow \Rightarrow R \uparrow \Rightarrow P_{elec} = V_{bias}^2 / R \downarrow \Rightarrow T \downarrow$$

Transition Edge Sensors

Voltage-biasing → strong Electro-Thermal Feedback (ETF) !

$$T \uparrow \Rightarrow R \uparrow \Rightarrow P_{elec} = V_{bias}^2 / R \downarrow \Rightarrow T \downarrow$$



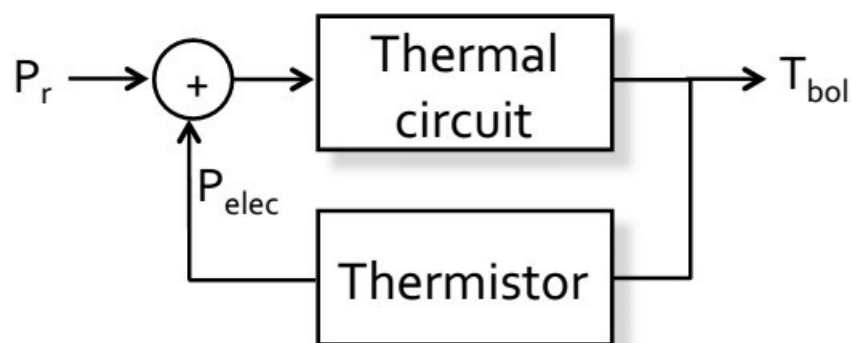
- Auto-tuning of working point
- Increased speed of operation :

$$\tau_{eff} = \frac{\tau_0}{1 + \alpha/n}$$

with $n = 5$ (electro-phonon thermal coupling)

- But mind the saturation!

$$C \approx E / dT \propto \alpha E / T$$

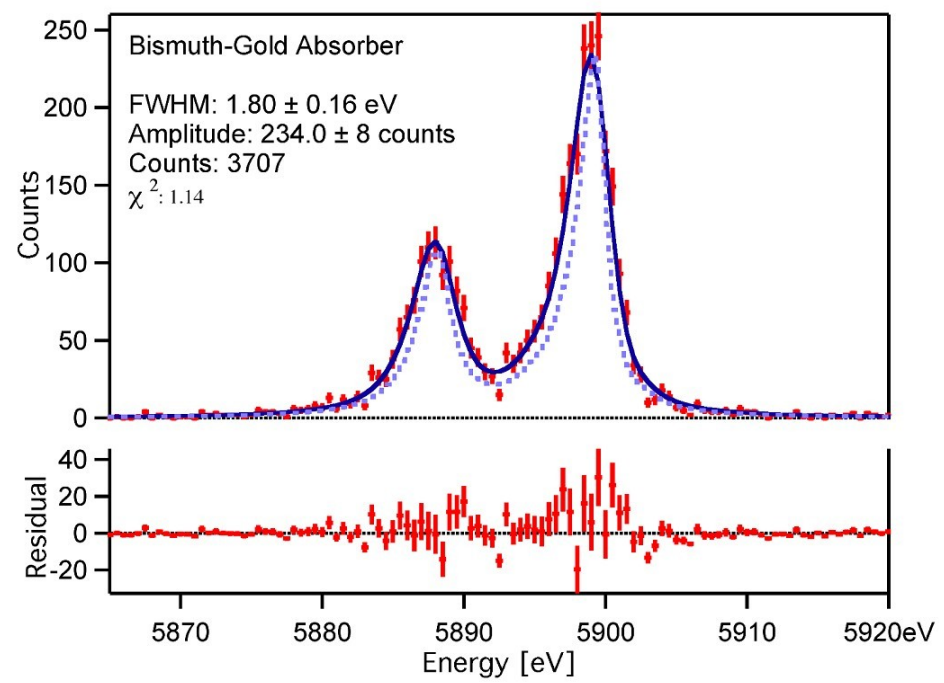


TES achievements

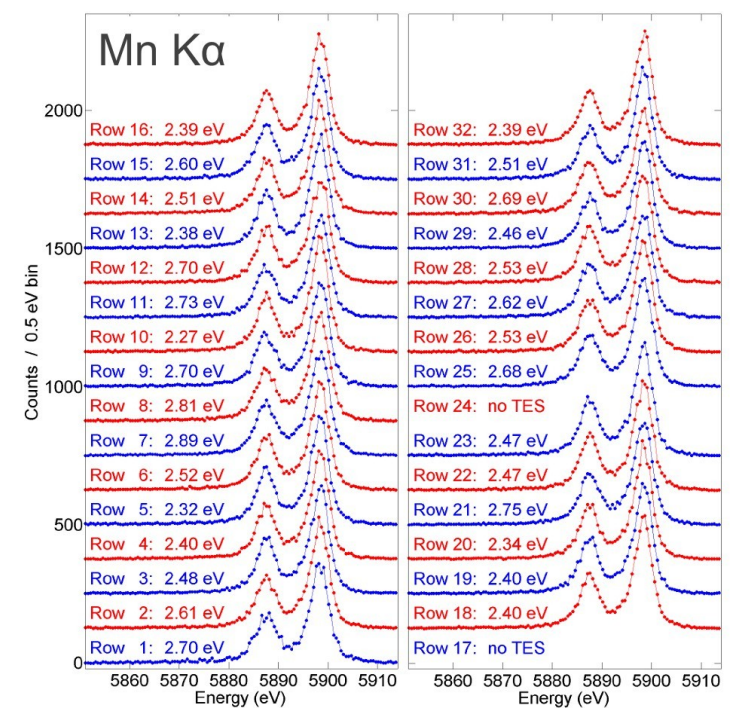
Fundamental resolution limit :

$$\Delta E = \xi \cdot \sqrt{k_B T^2 C} \longrightarrow \Delta E_{FWHM} = 2.355 \sqrt{4 k_B T_e^2 C \sqrt{\frac{n}{2}} / \alpha}$$

@ 6keV = 0.8eV



C. Kilbourne, Proc. of SPIE 668606-7

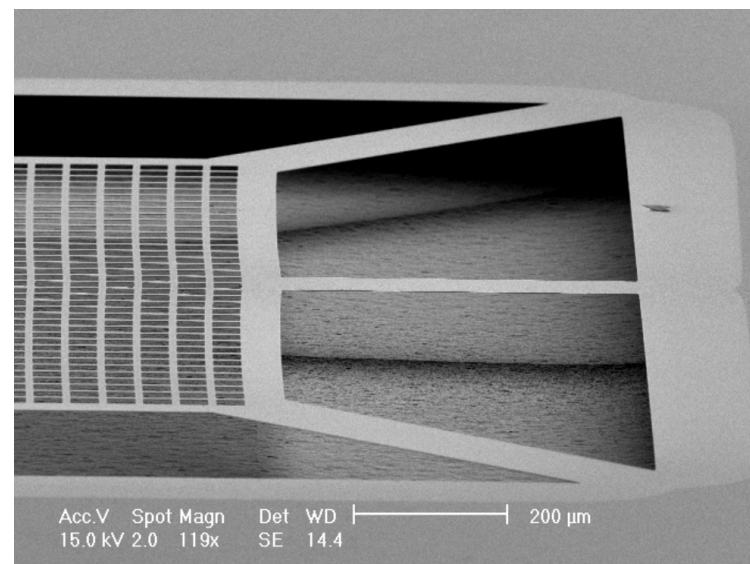
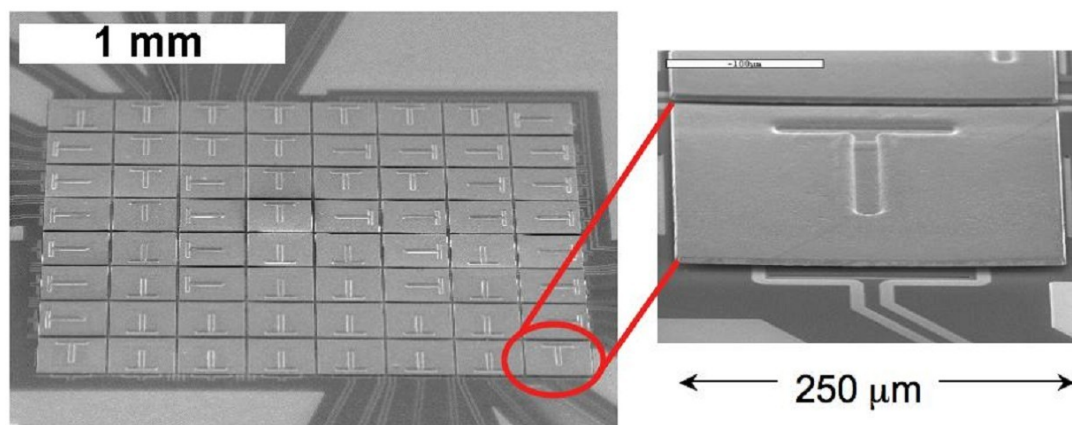


R. Doriese, Proc. LTD 16

TES disadvantages...

TES are great, and very widespread. Nonetheless:

- Fabrication very challenging!



- Issues of T_c uniformity (bi-layers, thin films...)
- Need of SQUID
- Power dissipation

TES multiplexing

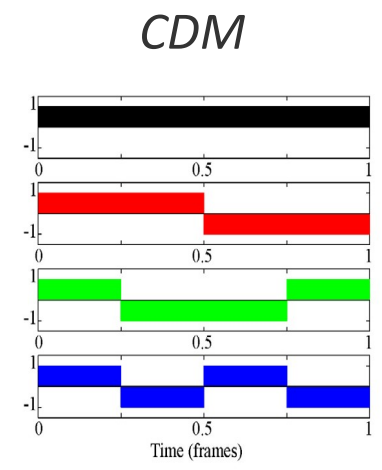
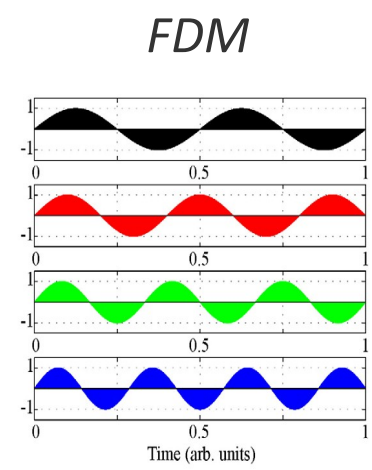
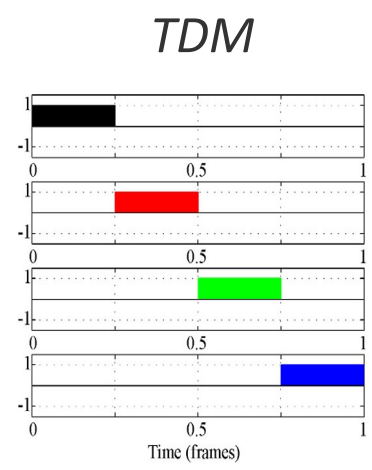
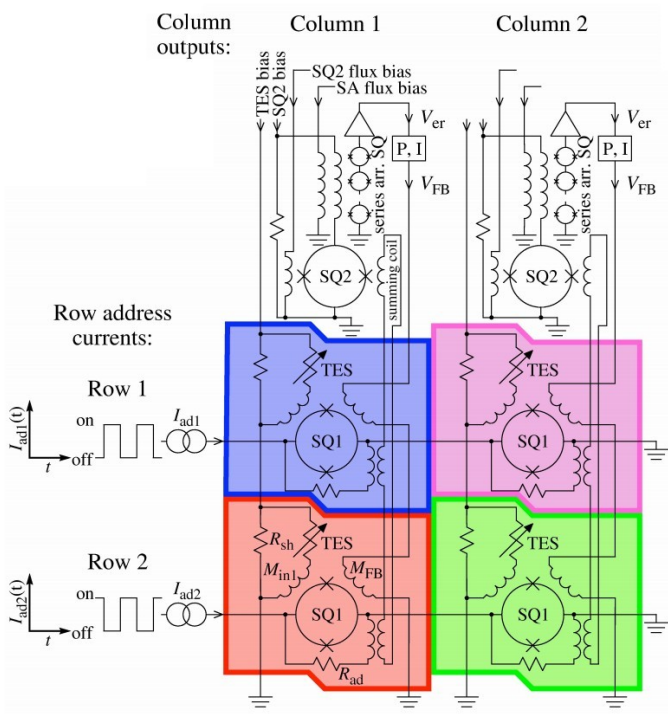
People get greedy and want large pixel counts !

(not an exclusivity of digital cameras market!)

Multiplexing becomes paramount!

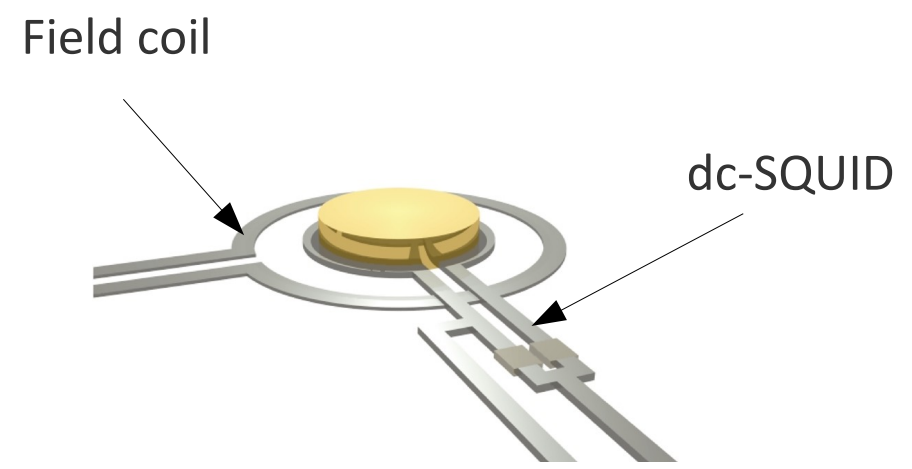
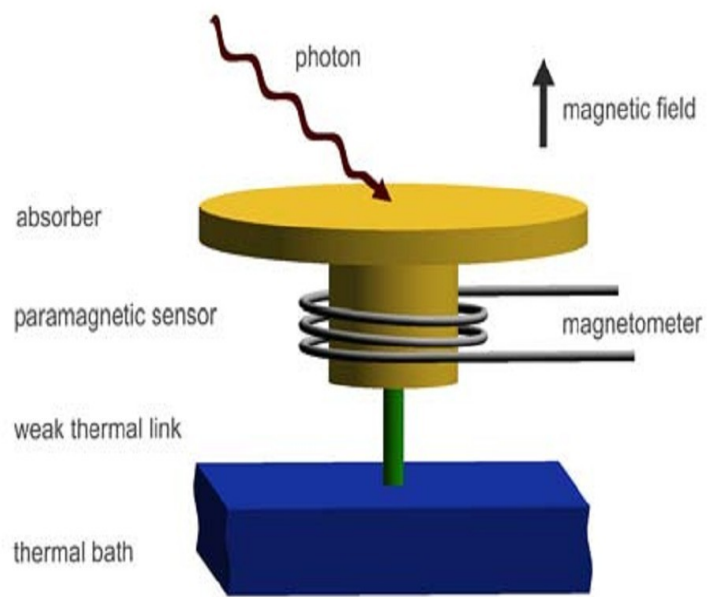
Semiconductor based bolometers → very difficult (+ not worth the effort, really..)

TES → easier ... but still difficult!

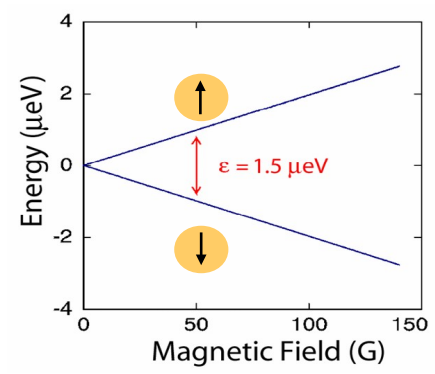


Magnetic Metallic Calorimeters

Another type of thermal detectors, based on the dependance of magnetization M from T



Er^{3+} magnetic ions in B field



$$\Delta\Phi \propto \frac{\partial M}{\partial T} \Delta T = \frac{\partial M}{\partial T} \frac{E}{C} = \frac{\partial M}{\partial T} \frac{E}{C_a + C_s}$$

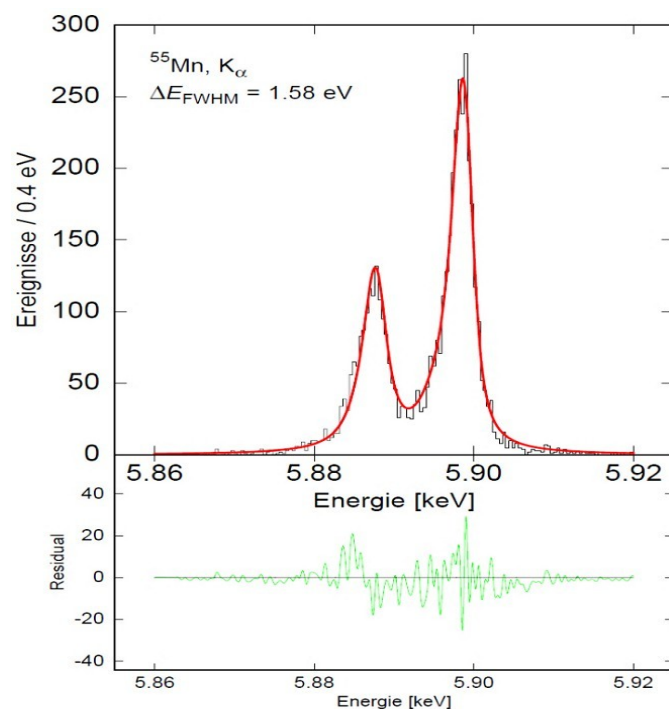
Magnetic Metallic Calorimeters

First tests: magnetic ions (Er) implanted in dielectric material

Problem: way too slow! (spin-phonon relaxation = seconds at low T)

Solution: **Magnetic Metallic Calorimeters**

Use of metallic host speeds up the response time. Typical material is **Au:Er**_{10~1000 ppm}



L. Gastaldo, LTD16 proceedings (2016)

Theoretical limit:

$$\Delta E_{FWHM} = 2.35 \sqrt{4k_B C_a T^2 \left(\frac{1}{\beta(1-\beta)} \frac{\tau_0}{\tau_1} \right)^{1/4}}$$



sub-eV!

MMC: pros and cons



- No threshold temperature so less stringent limits on C_{abs}
- Increasing τ_1 can reach very high E resolution (but, slower detector!)
- **The readout is dissipationless! (dissipation only at SQUID stage)**
 - an advantage for very large arrays?
- Multiplexing difficult but possible (similar approach as for TES)

BUT:



- No dissipation means no ETF → slower than TES
- Small primary signal so need extremely low noise SQUID
- A lot less 'manpower' and later start → lower TRL!

Overview of main LTD types

- **Equilibrium LTDs:**

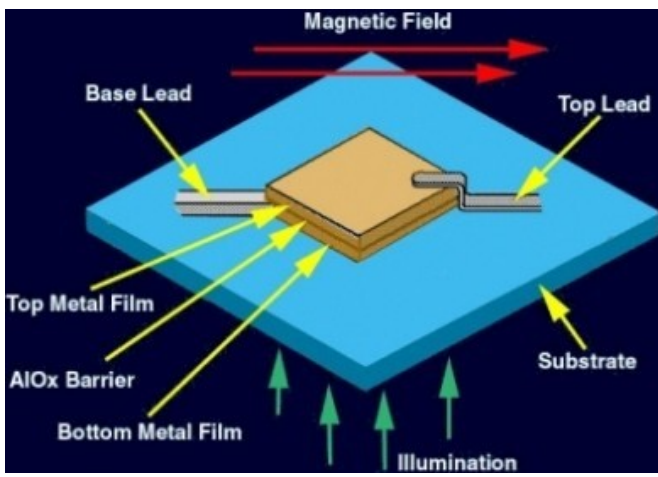
- Measure T through $R(T)$*  Semiconductor bolometers (NTD, doped Si...)
 Superconductor bolometer (TES)
- Measure T through $M(T)$*  Magnetic Metallic Calorimeters (MMC)

- **Non-Equilibrium (pair-breaking) LTDs:**

- Measure n_{qp} through $i(E)$*  Superconducting Tunnel Junctions
- Measure n_{qp} through $L(E)$*  Kinetic Inductance Detectors

Superconducting Tunnel Junctions

The absorbed energy generates excess QPs which tunnel through a thin insulating junction giving a current signal.



$$I \propto N_{qp} \propto E$$

Theoretical limit is not far from TES/MMC

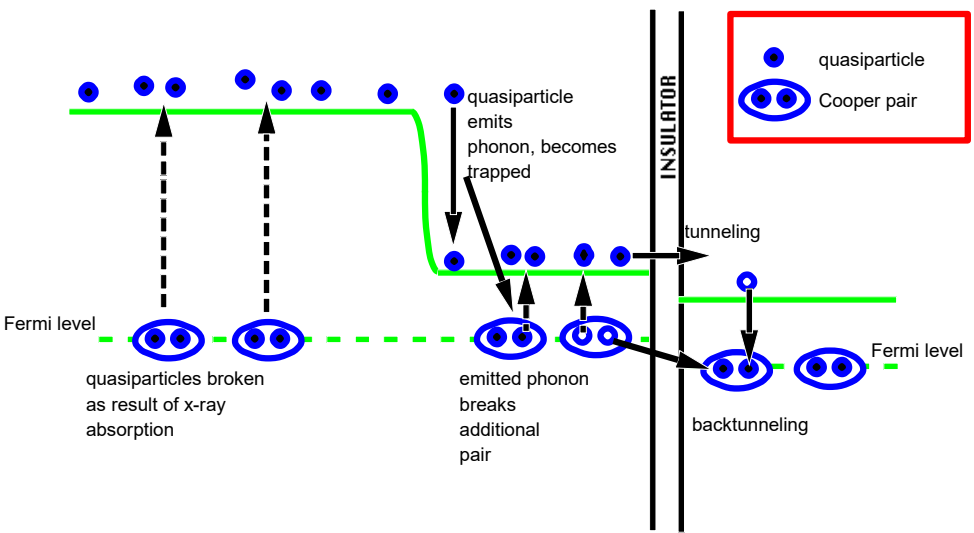
$$\Delta E_{FWHM} = 2.355 \sqrt{1.7 E \cdot (F+G) \cdot 1.76 k_b T_c}$$

But:

Backtunneling $\rightarrow G = 1 + 1 / \langle n \rangle$

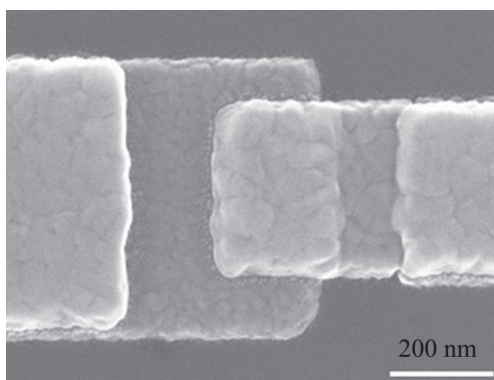
Assuming $T_c = 1K, G=1$

@ 6keV = 3.5eV

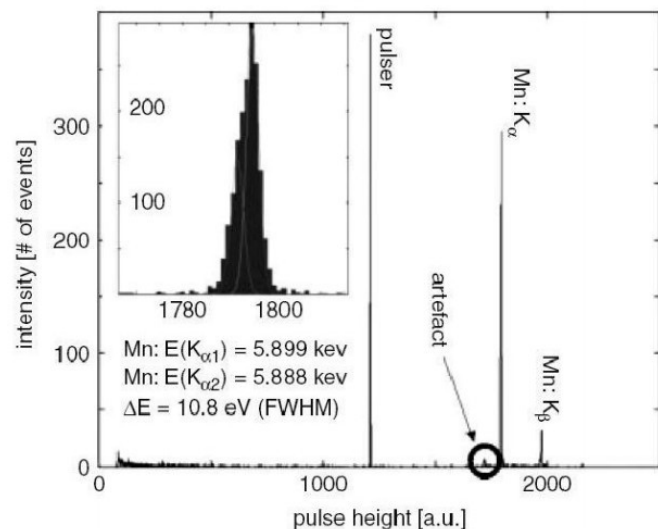


STJ pros and cons

- Intrinsically fast (non-thermal LTD)
- No membranes for thermal isolation needed



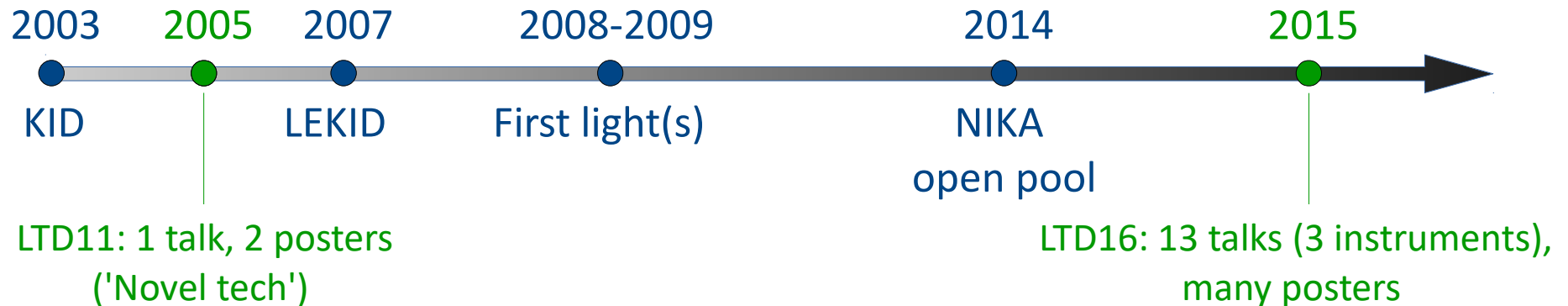
- Very thin and uniform barriers
- Need B to suppress CP Josephson current
- Multiplexing unclear (no real solution right now..)



Not the best choice for large arrays!

Kinetic Inductance Detectors

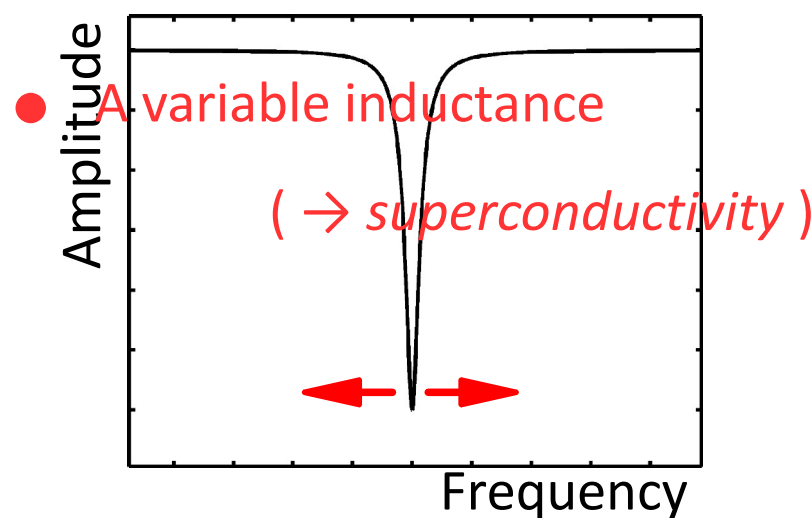
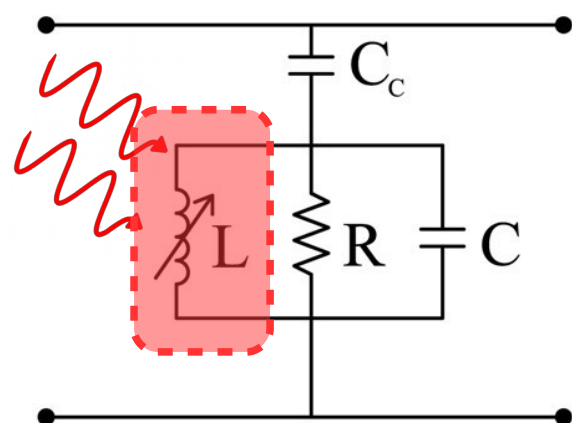
A (relatively) new technology, but very fast development



- 2003** Kinetic Inductance Detectors are first proposed (P. Day et al, 2003)
- 2007** Lumped Element KID are first proposed (S. Doyle et al, 2007)
- 2008** First (single pixel) light using KID at CSO (US) (J. Schlaerth et al, 2008)
- 2009** First multiplexed astronomical observations: NIKA (A. Monfardini et al, 2009)
- 2014** NIKA open to external astronomers. First 'real' KID based instrument (A. Catalano et al, 2014)

KID operating principle

Simply put, a KID is a **superconducting resonator** whose resonant frequency depends on the absorbed power



We measure the shift of the resonance (or any other variable related to it) and get the power :

$$\delta P \propto \delta f_0$$

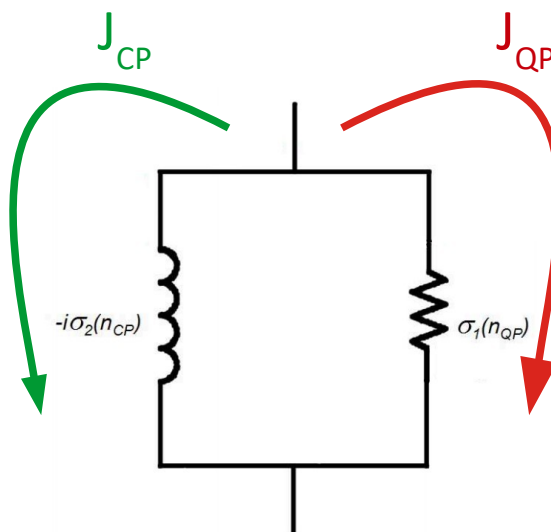
We can describe the conductivity of a superconductor starting from the behavior of CPs and QPs two families:

- **Cooper Pairs :**

Non-dissipative

Reactance!

Proportional to ω



- **Quasi-Particles :**

Dissipative

Resistance

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

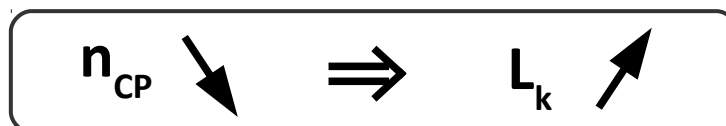
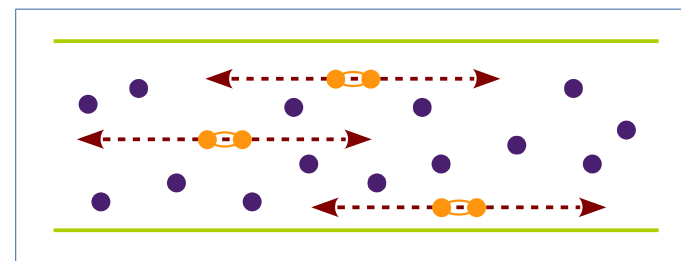
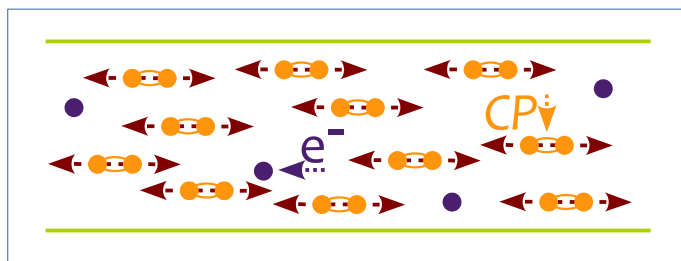
Kinetic Inductance

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

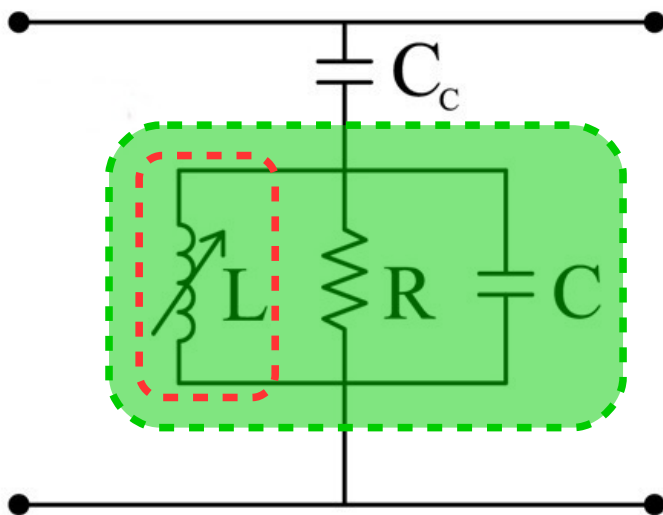
When moving, the CP store energy:

- Magnetic field \rightarrow magnetic inductance, L_m
- Kinetic energy \rightarrow kinetic inductance, L_k

L_k depends on the density of Cooper Pairs, n_{CP} :



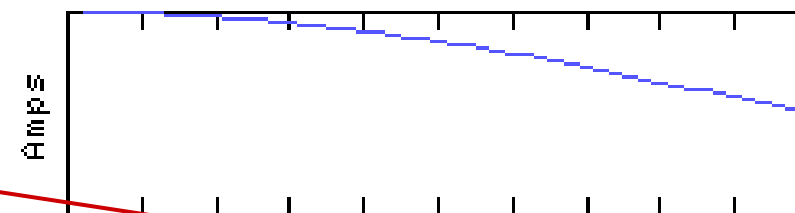
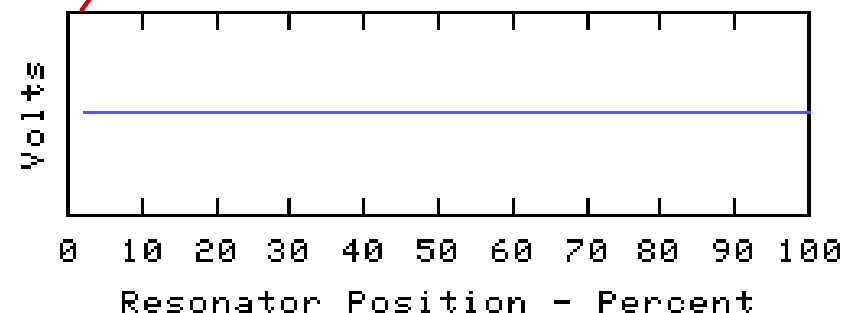
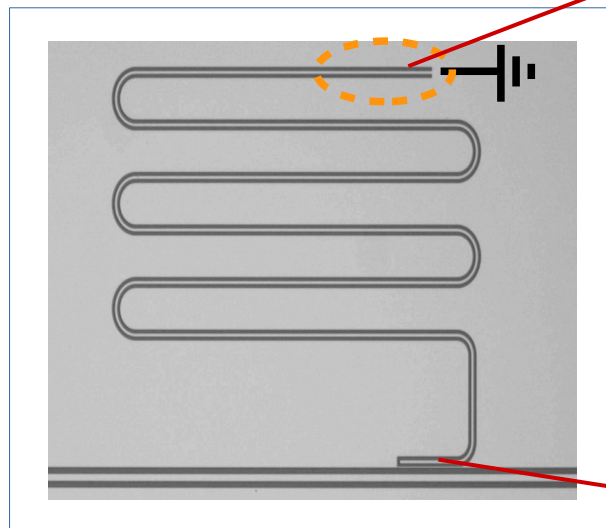
Superconducting resonators



- A variable inductance
(\rightarrow *superconductivity*)
- A resonating circuit

- First option: simply take a strip of superconductor!

The first KID to be proposed, so simply “Microwave KID”, or “Distributed KID”



The resonator is $\lambda/4$ long ('quarter wavelength')

The current is *distributed* !

$$f_0 = c_{eff} / \lambda = c_{eff} / 4l$$

- Second option: 'old-style' RLC!

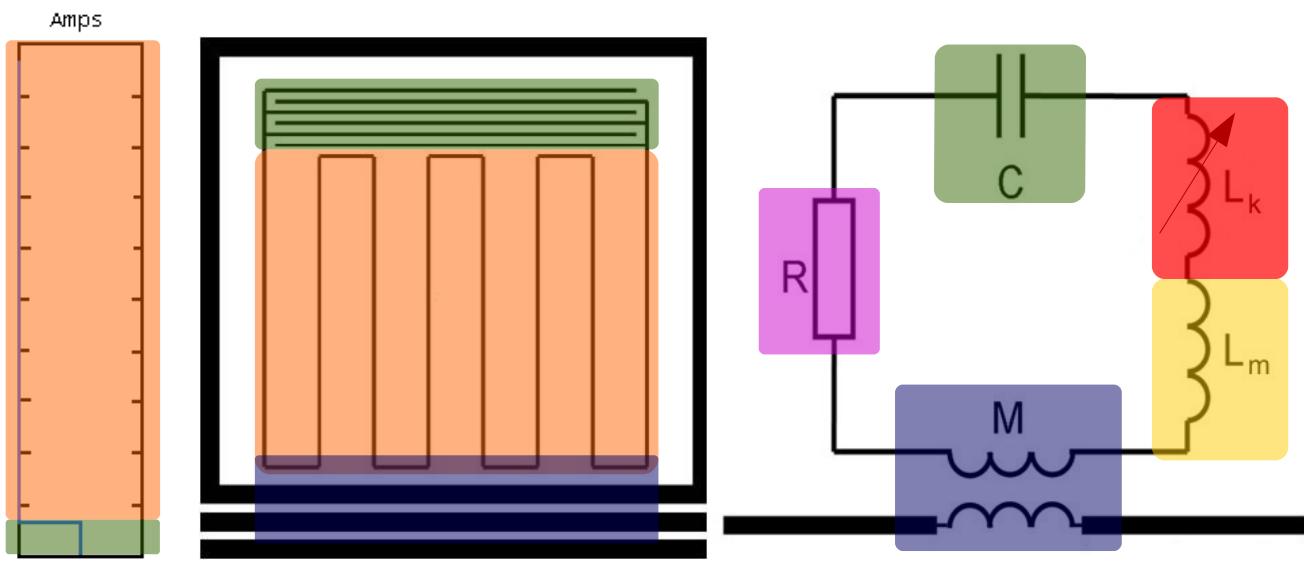
Lumped electrical components (dimensions smaller than the wavelength)



Superconducting resonators: LEKID

- Second option: 'old-style' RLC!

Lumped electrical components (dimensions smaller than the wavelength)



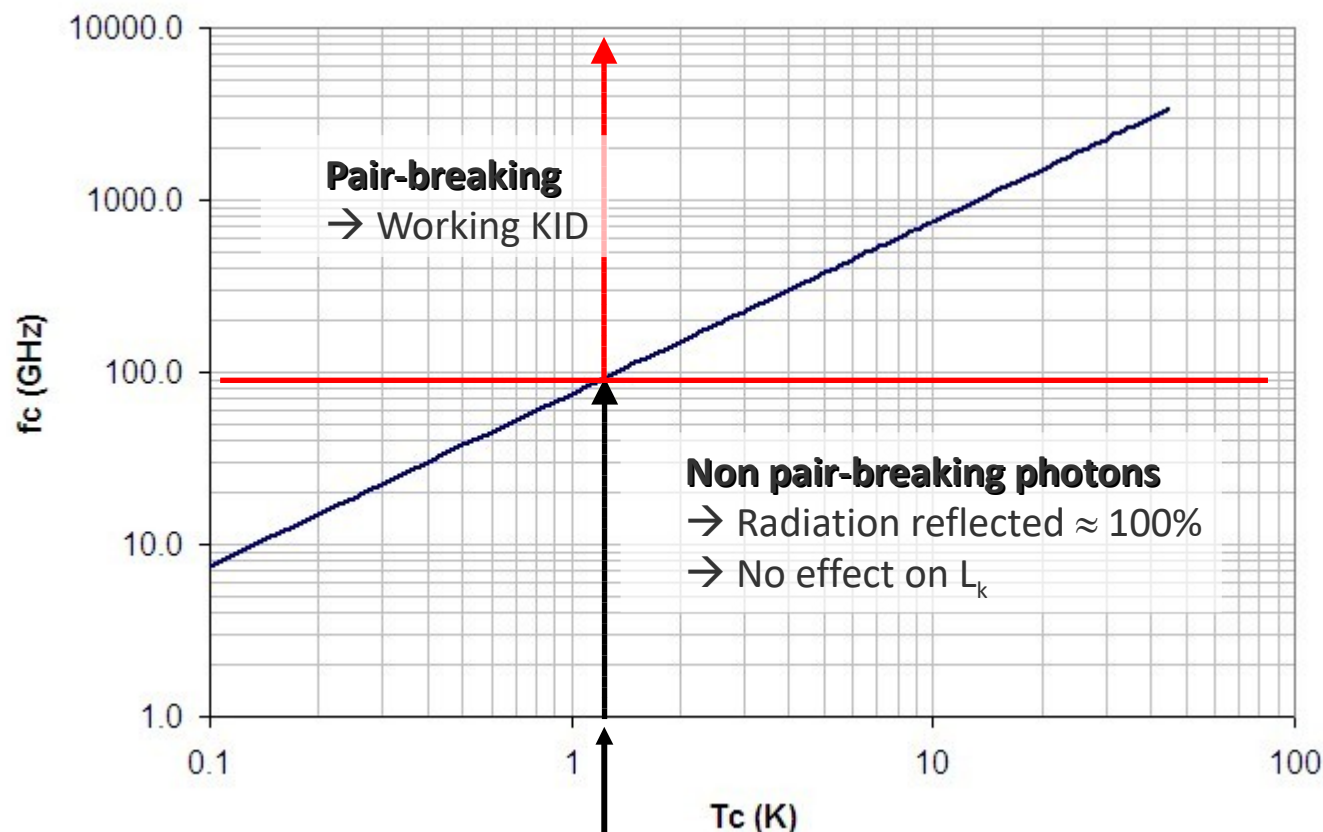
- Kinetic Inductance (CP)
- Geometric Inductance
- ID Capacitor
- Residual R (QP)
- Coupling (mag/capa)

$$f_0 = 1/\sqrt{(L_k + L_m) \cdot C}$$

KID response to light

Light can break Cooper Pairs, *if it has enough energy*

Some typical examples materials



e.g. Al, our best friend !!

Ti $\rightarrow f_c \approx 40$ GHz

Al $\rightarrow f_c \approx 100$ GHz

Re $\rightarrow f_c \approx 130$ GHz

Ta $\rightarrow f_c \approx 340$ GHz

Nb $\rightarrow f_c \approx 700$ GHz

NbN $\rightarrow f_c \approx 1.2$ THz

...

TiN_x \rightarrow adjustable

Nb_xSi \rightarrow adjustable

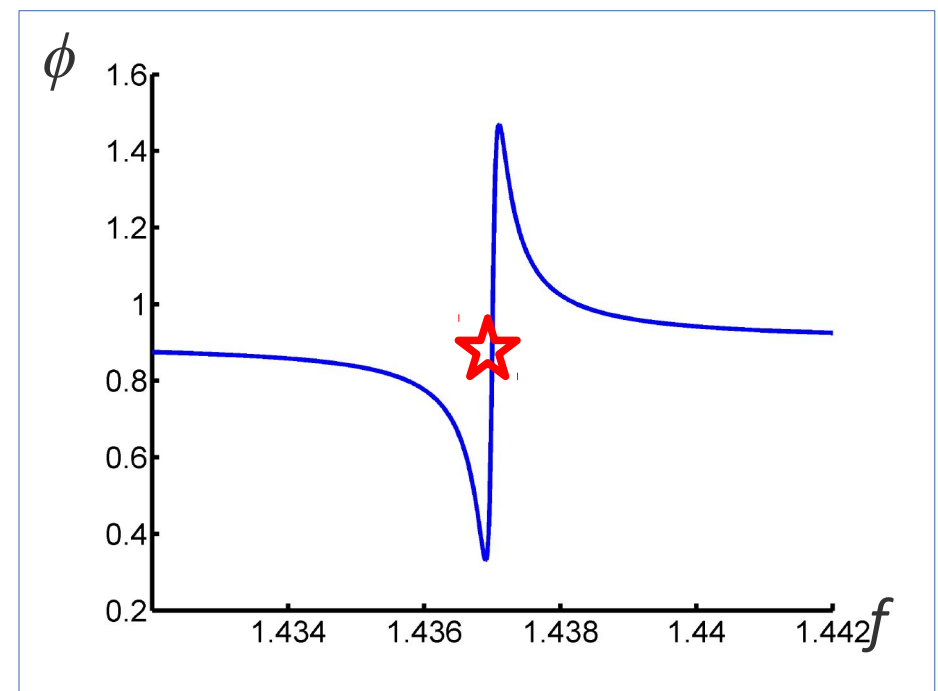
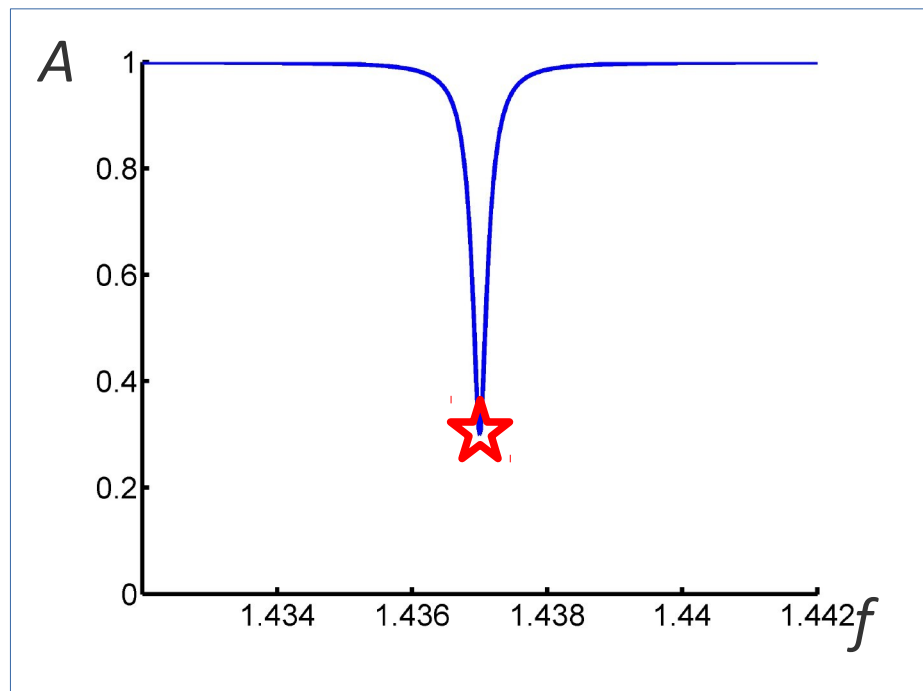
TiV_x \rightarrow adjustable

Multilayers \rightarrow adjustable

KID response to light

S_{21} is the signal transmitted past the resonator

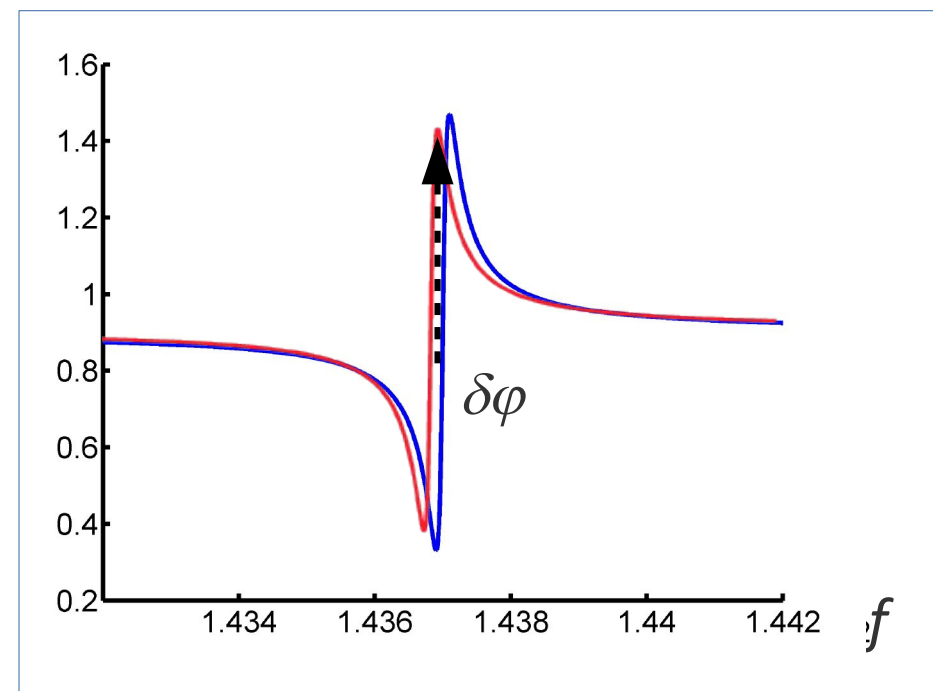
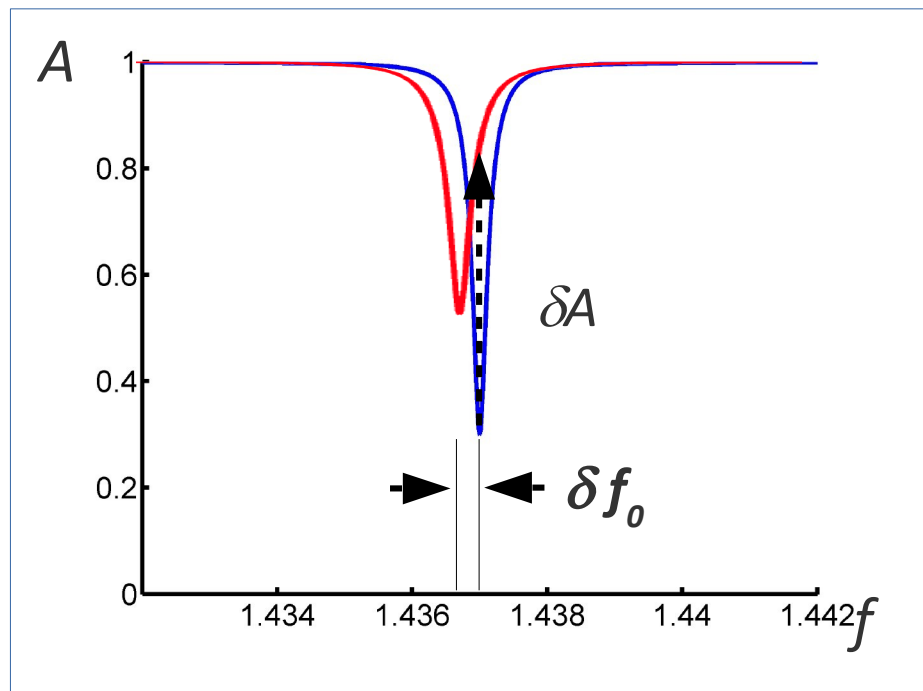
S_{21} is complex \rightarrow possible to study in Amplitude and/or Phase



KID response to light

Absorbed light \rightarrow change in n_{qp} \rightarrow change in L_k \rightarrow change in phase + f_{reso}

Absorbed light \rightarrow change in n_{qp} \rightarrow change in R \rightarrow change in amplitude



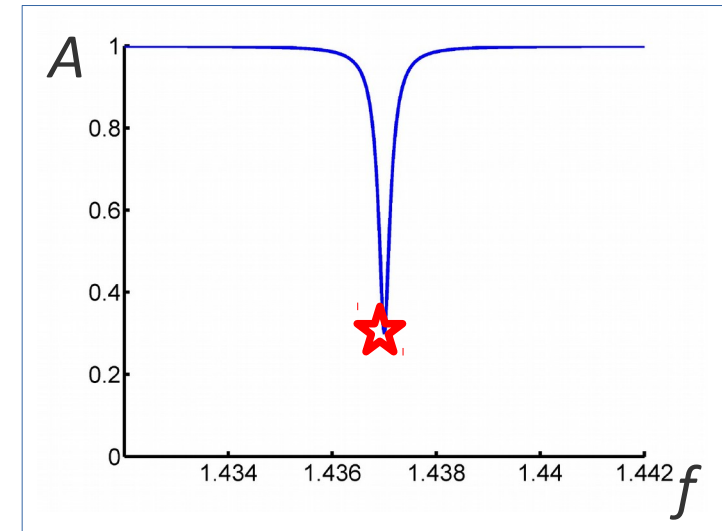
$$\delta\phi \propto \delta f_0 \propto \delta P_{abs}$$

KID: 'intrinsic' multiplexing

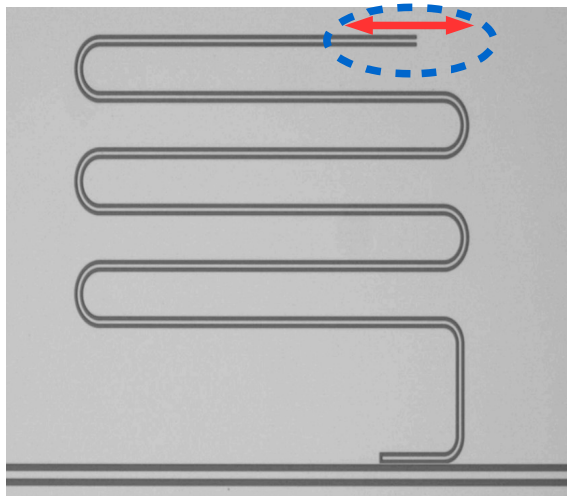
Superconducting resonators \rightarrow very high Q ($10^3 - 10^7$!)

The high Q has a double advantage:

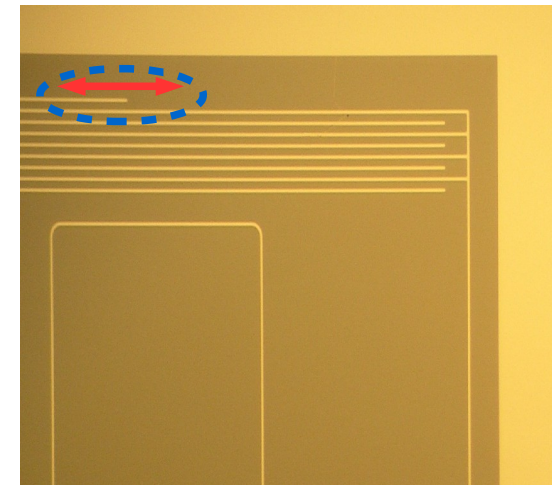
- Acts as an 'internal amplification gain'
- Readout line affected only very near to f_0
 \rightarrow KID can be 'intrinsicly multiplexable'!



$$\text{MKID} : \Delta \rightarrow \Delta f_0$$



$$\text{LEKID} : \Delta C \rightarrow \Delta f_0$$



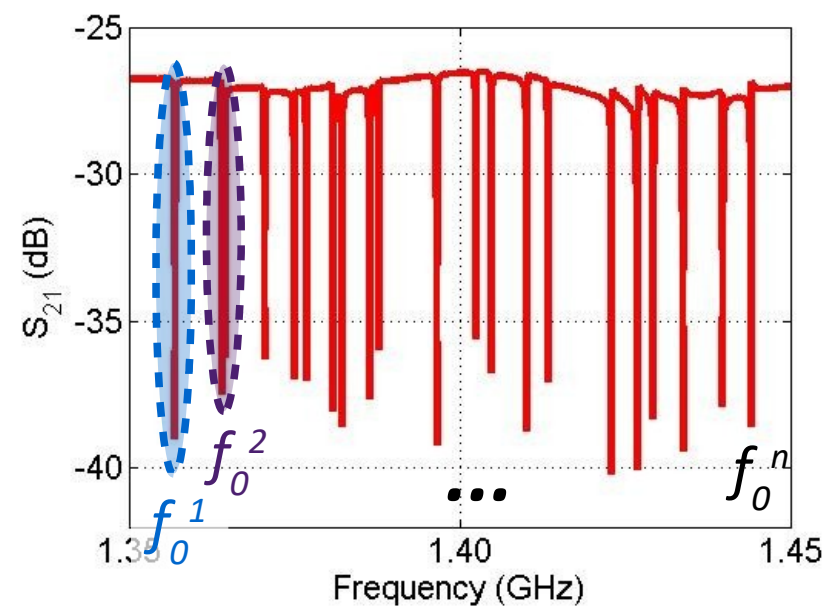
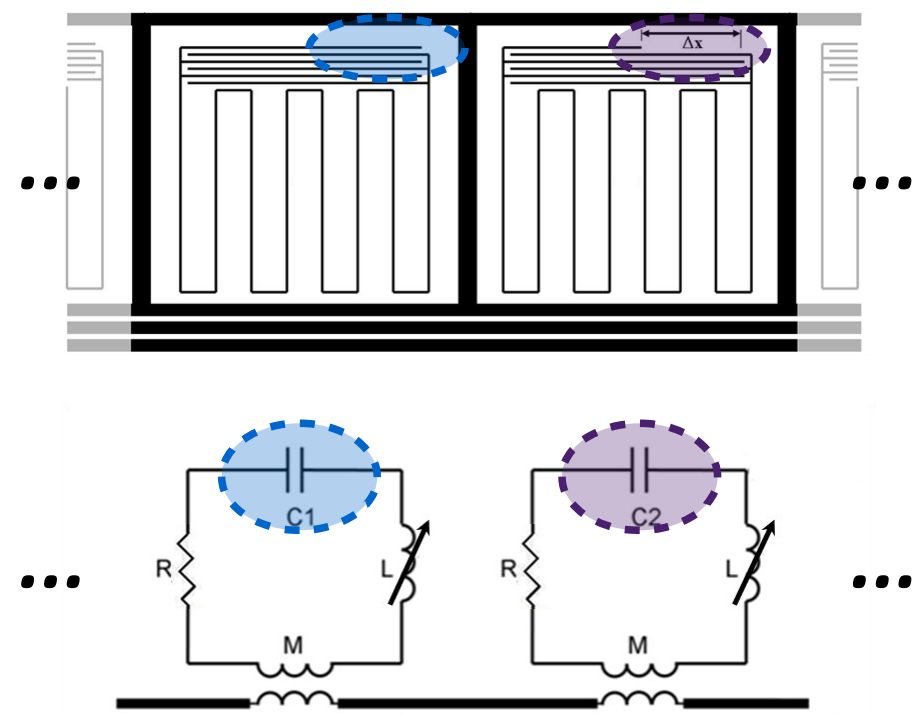
KID: 'intrinsic' multiplexing

Superconducting (\rightarrow very high Q) resonators

Readout line affected only very near to f_0

f_0 can be easily tuned lithographically

100s to 1000s KID per line !



Cold electronics: 1 low-noise HEMT per line!

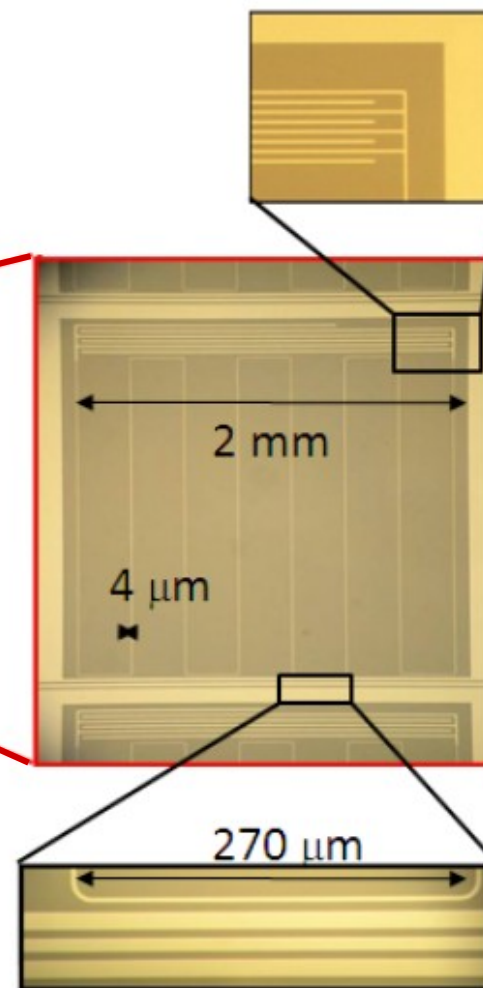
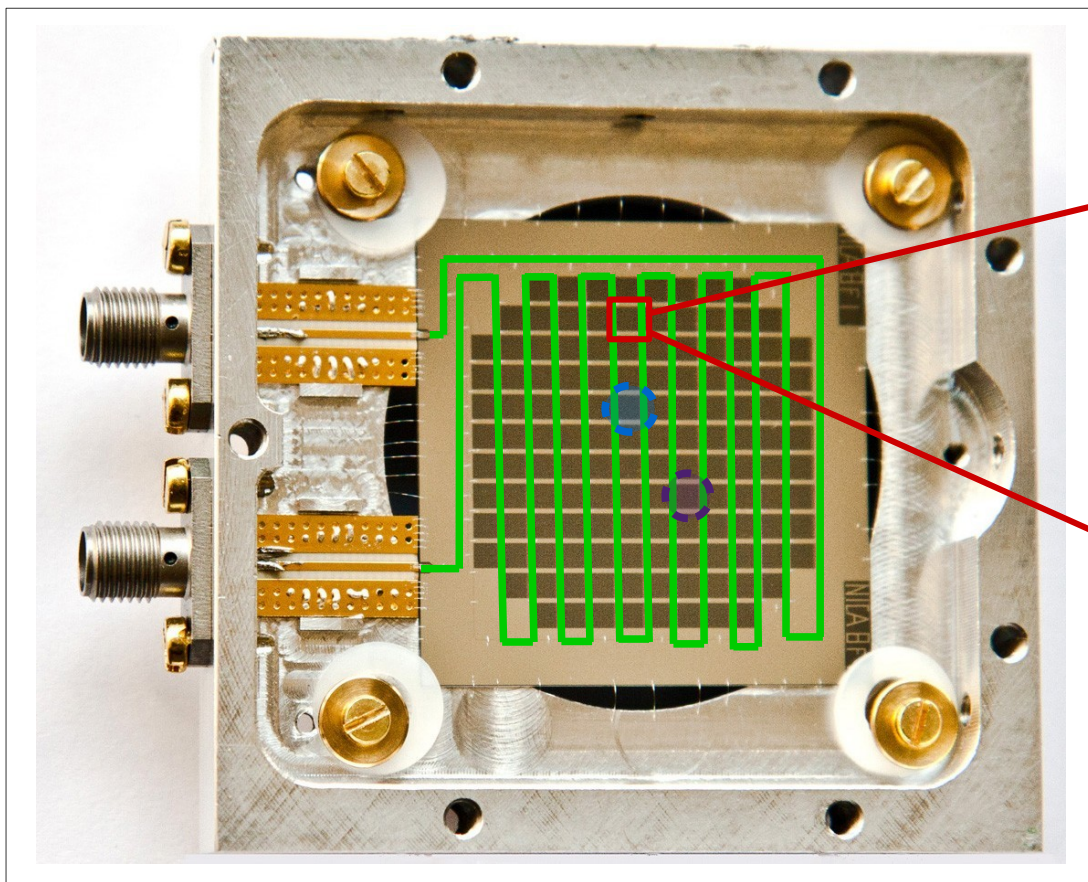
KID: 'intrinsic' multiplexing

Superconducting (\rightarrow very high Q) resonators

Readout line affected only very near to f_0

f_0 can be easily tuned lithographically

100s to 1000s KID per line !

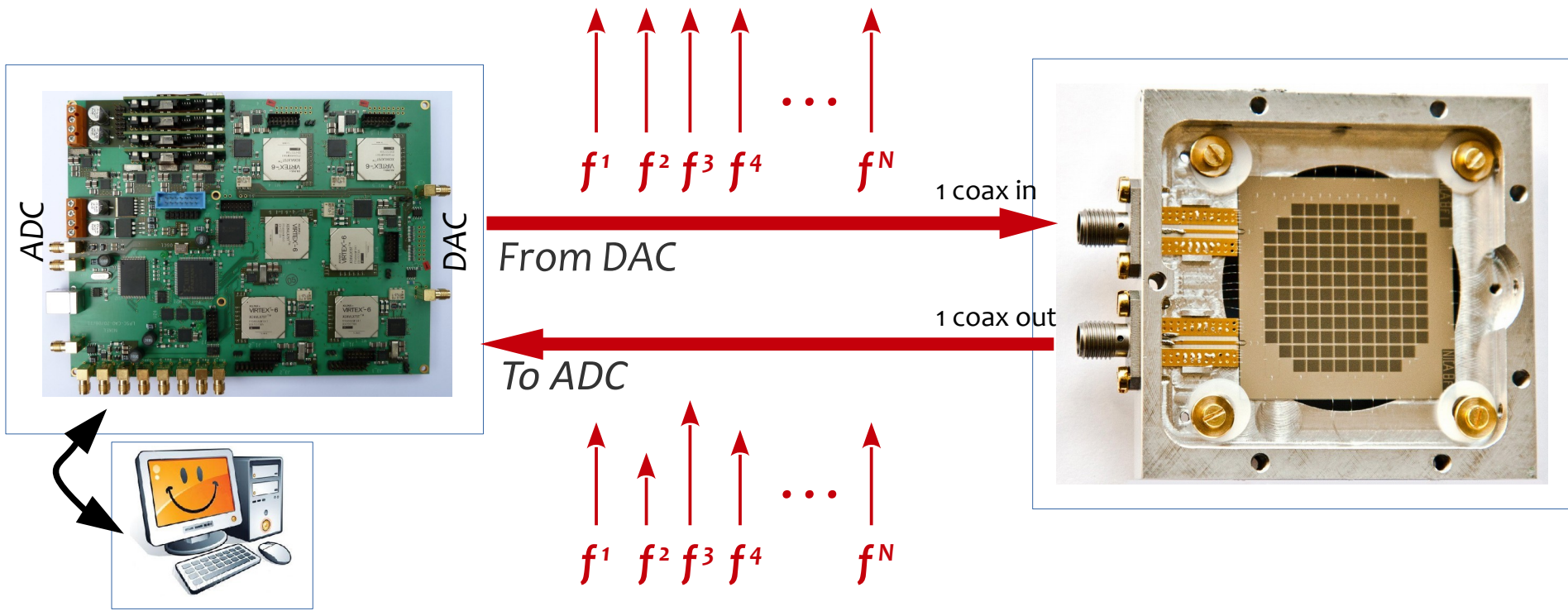


KID multiplexed readout system

To readout the pixels, the superposition of many excitation tones is fed to the readout line (one tone at each f_0)

Each resonator affects **only** the tone corresponding to its own f_0 !

The comb of tones is generated, acquired and deconvoluted using a dedicated high speed electronics board (FPGA)



KID advantages

- In both MKID and LEKID, fabrication is quite simple (decoupled from phonons!)
- *Multiplexing comes essentially for free!*

KID are pair-breaking detectors: the quanta of energies have

$$\delta E = 3.5k_b T_c$$

At $T \ll T_c$, basically no phonons have energy $> \delta E$



The KID is thermally decoupled from the surrounding environment

No need of complex and delicate structures for thermal isolation

Almost insensitive to variations in the temperature of the thermal bath

Could be an advantage for space missions (Cosmic Rays)

Again, not really suited as thermometers: $\Delta E_{FWHM} = 2.355 \sqrt{1.7 E \cdot F \cdot 1.76 k_b T_c}$

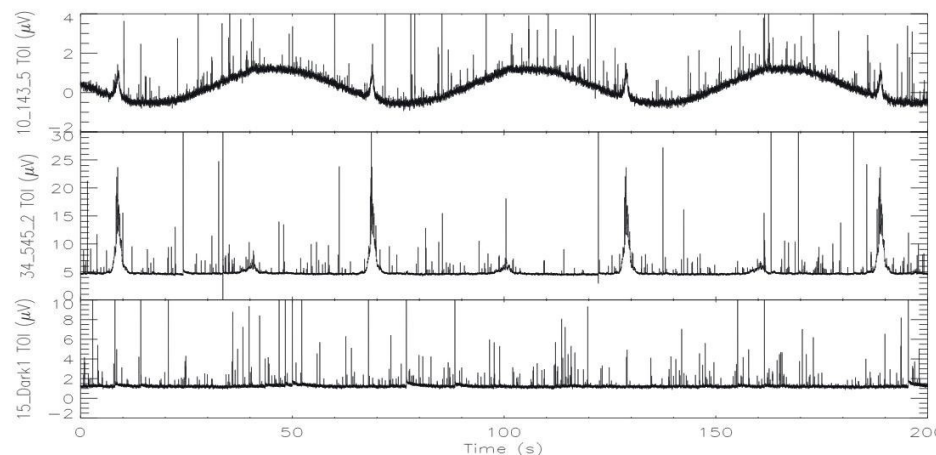
Cosmic Rays effect on KID



Space-based missions are exposed to an intense flux of high-energy particles, known as Cosmic Rays (CR)

CR can reach focal plane giving an unwanted *glitch*, masking the scientific signal

Planck:
≈ 20% of data loss!



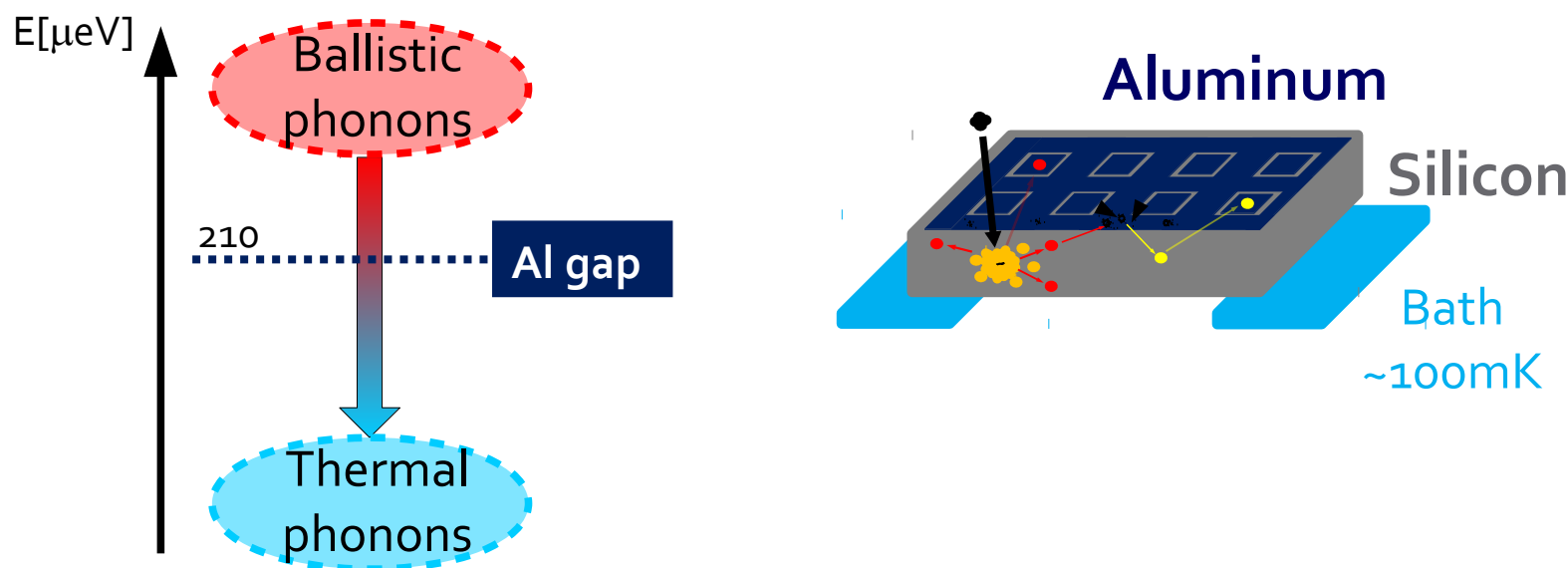
The effect of long range 'ballistic' phonons was larger than expected

KID could help a lot!

Cosmic Rays effect on KID

The superconducting gap gives 2 advantages

- As soon as the phonons have $E < 2\Delta$, they become 'invisible'
→ glitches are faster → less data lost
- We can further improve adding films with lower T_c

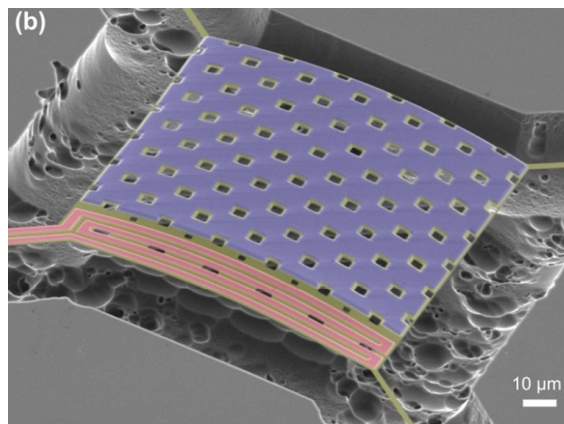


KID advantages

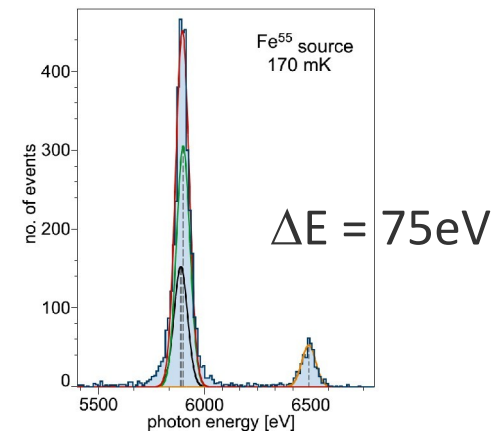
- In both MKID and LEKID, fabrication is quite simple (decoupled from phonons!)
- *Multiplexing comes essentially for free!*
- Ideal for space missions (hopefully...)
- **Not ideal** for energy resolution
- Technology gaining a lot of interest and in rapid expansion!

Innovative KID applications

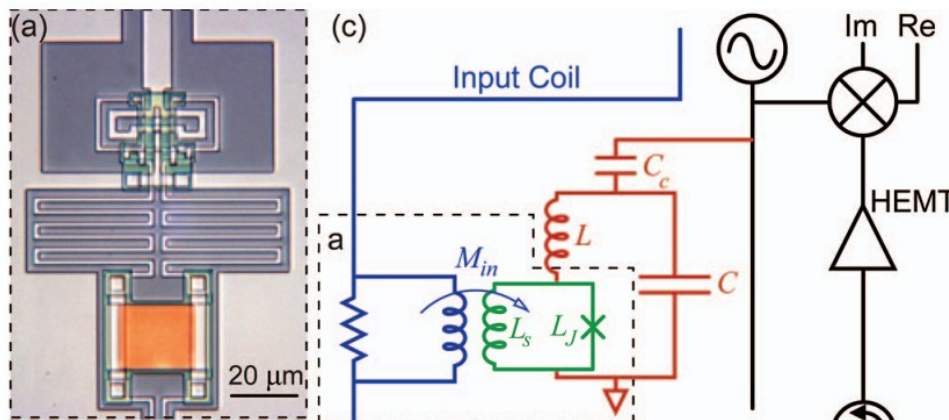
- Originally conceived mainly for astronomy
- But expanding rapidly!



TKID: thermal KID
(but I disagree..)



Superconducting resonator for TES/MMC multiplexing!



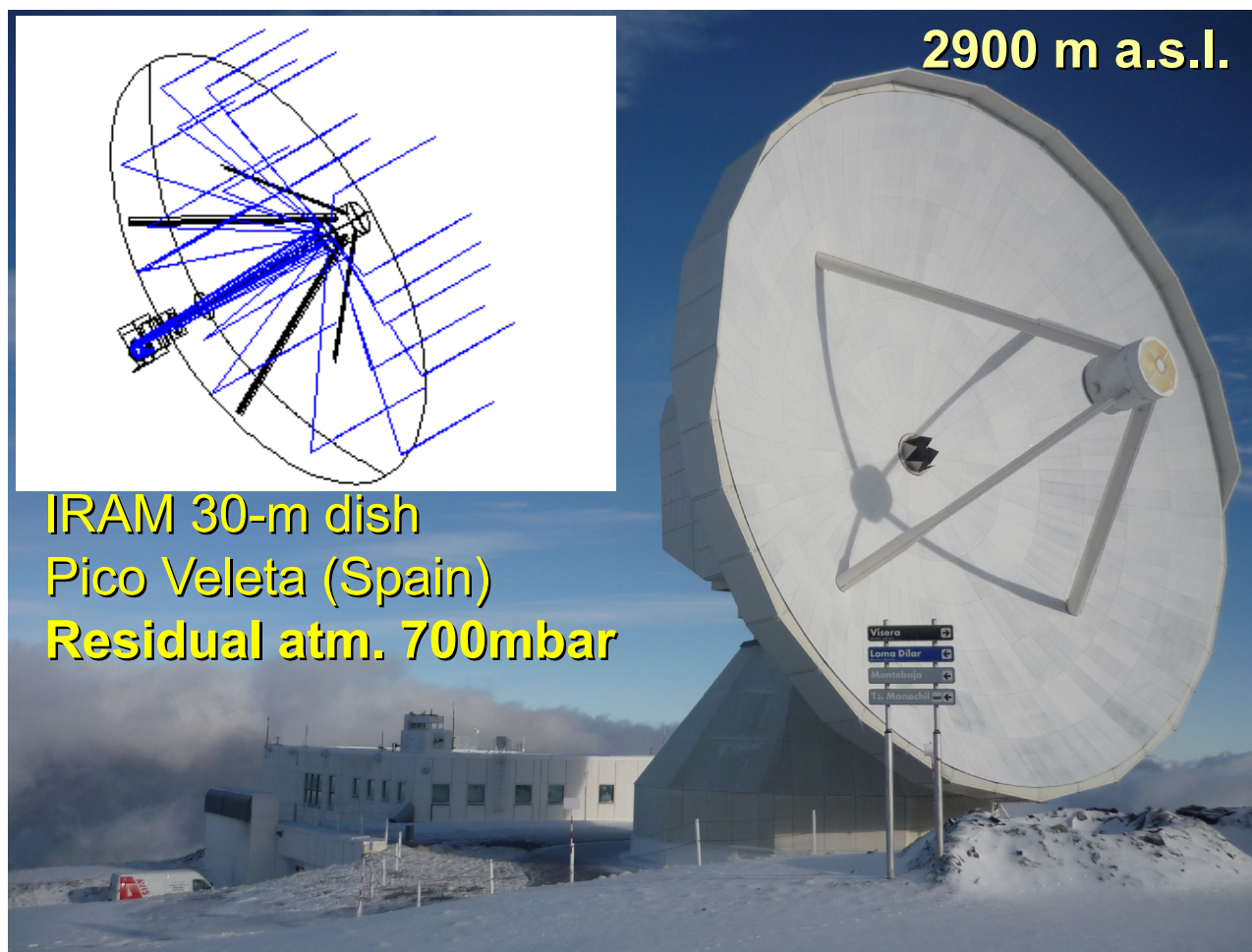
OLEKID, Spectrometers on chip, CALDER...

Main KID-based projects in Grenoble: astronomy and beyond

The first driver: the IRAM telescope

IRAM = Institut de Radio Astronomie Millimetrique

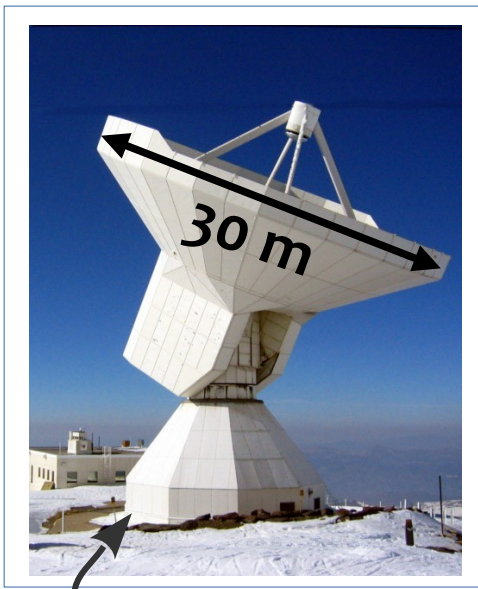
The largest mm-wave telescope in the world today!



The NIKA/NIKA2 experiments

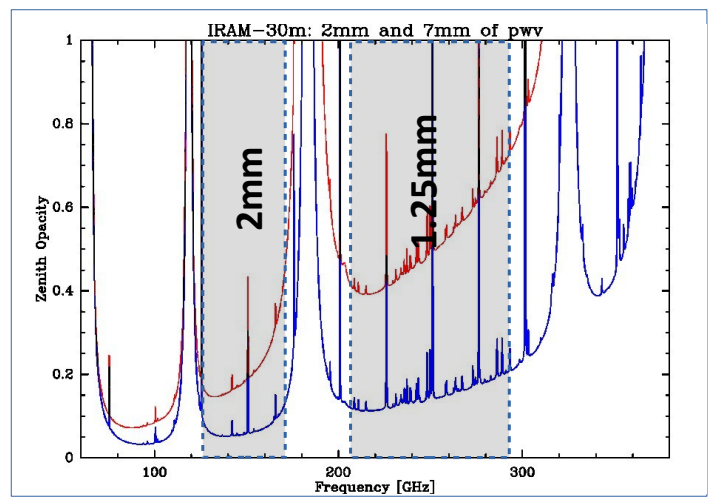
NIKA2: New IRAM KID Array 2

NIKA2 will be the new photometric instrument of the IRAM 30m telescope



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

- 30 m aperture $\left\{ \begin{array}{l} 17 \text{ arcsec @ 2mm} \\ 12 \text{ arcsec @ 1.25mm} \end{array} \right.$
- Correct Field Of View up to 6.5 arcmin
- Multi-bands measurements



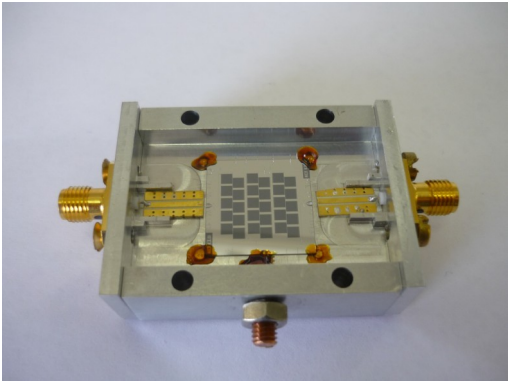
Thousands of pixels at 100 to 200GHz

Ideal KID 'playground'!

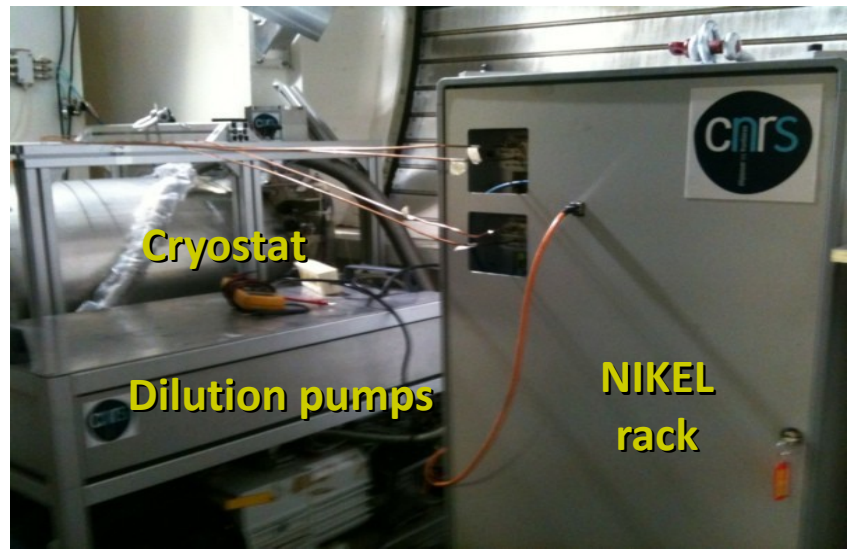
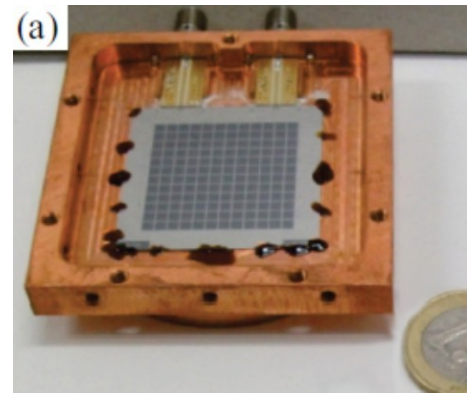
NIKA, the first KID camera

A step backwards: NIKA, 10's → 100's of pixels

2009

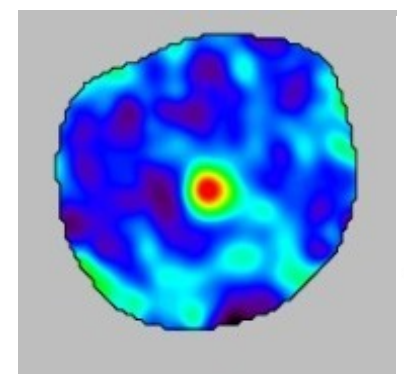


2010-2013

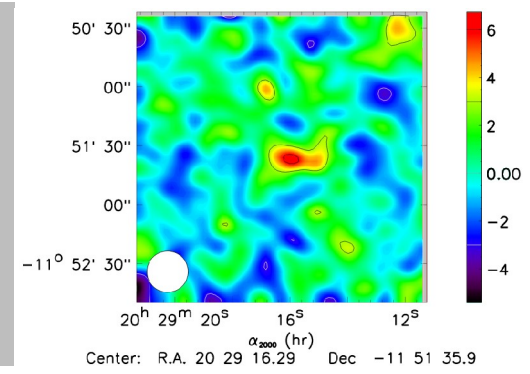


A NIKA picture gallery

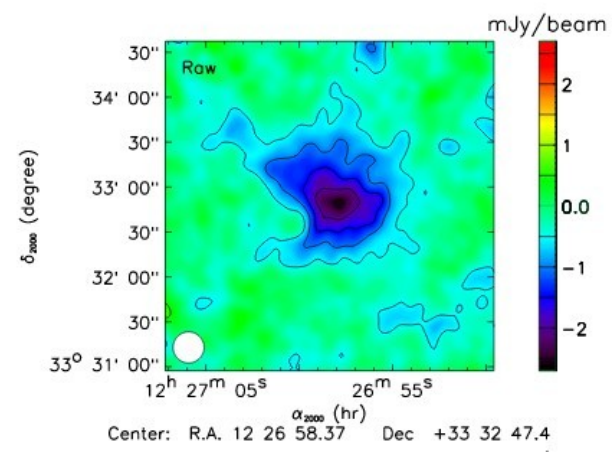
A few selected images:



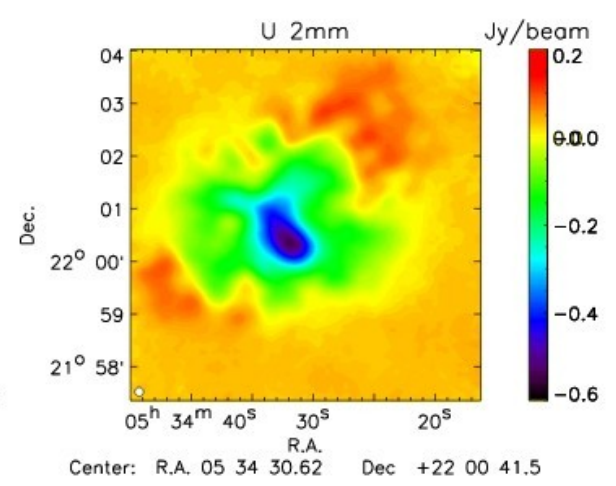
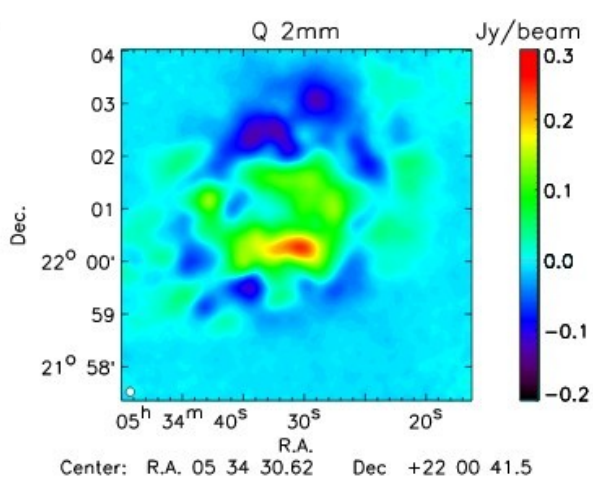
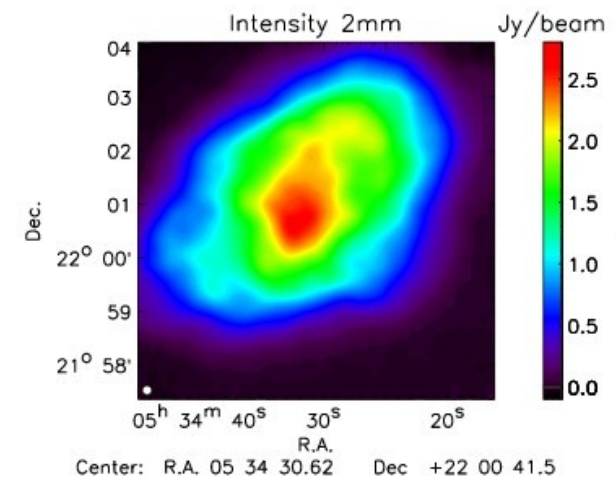
Pluto at 150GHz



GRB121123A

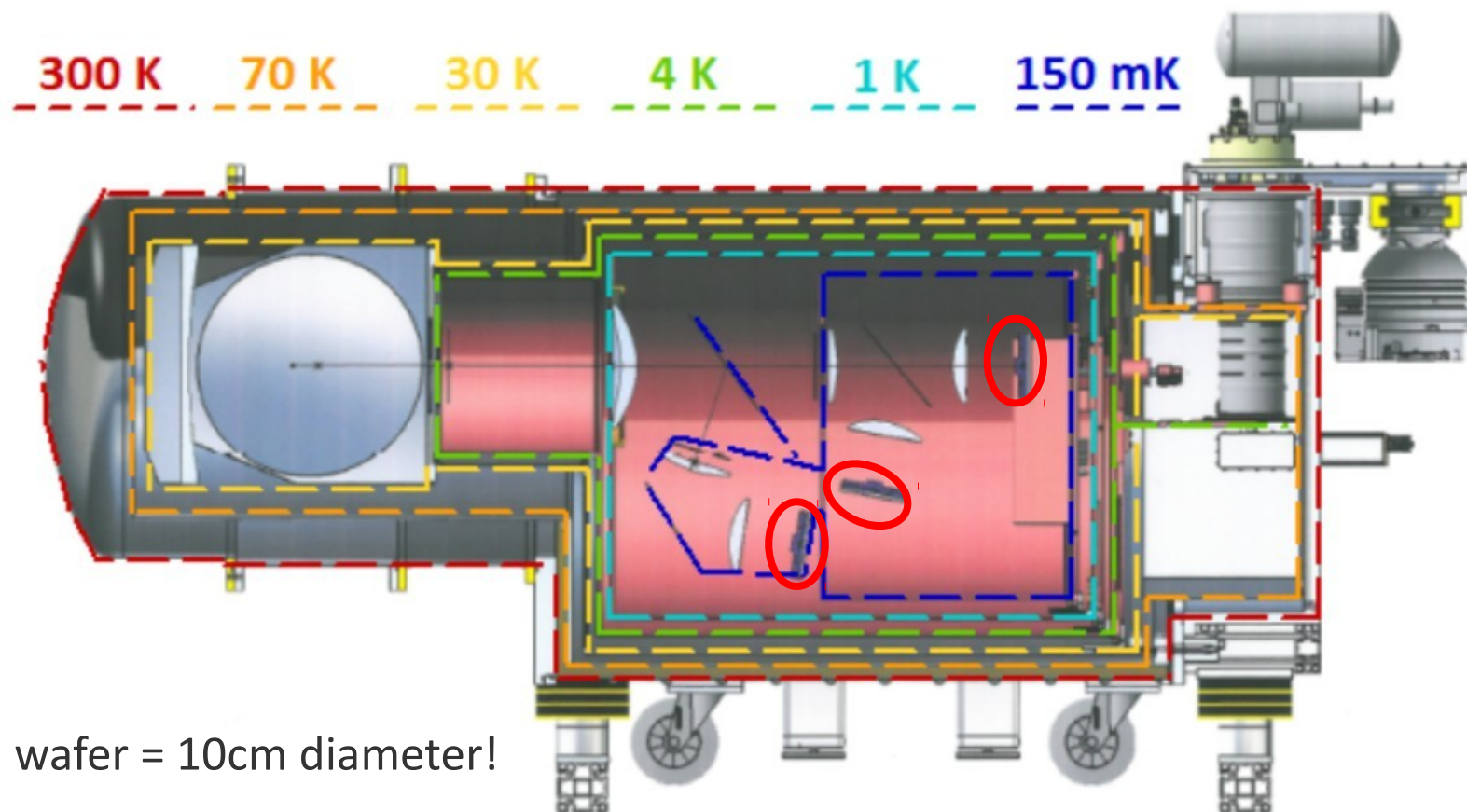


**Adam et al.,
 A&A 576, A12
 (2015)**



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

Going full-scale: NIKA2!



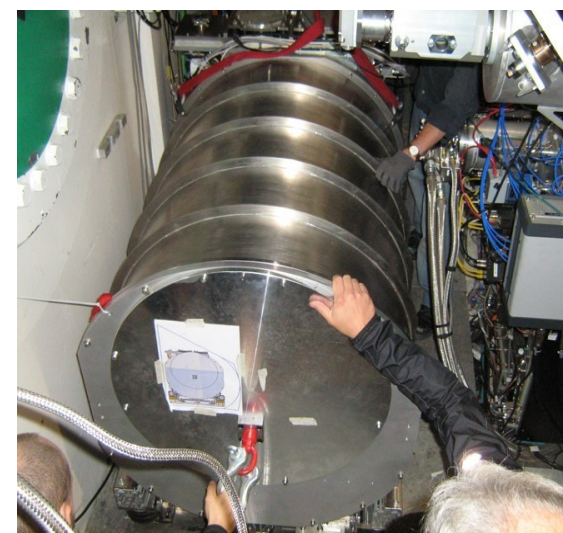
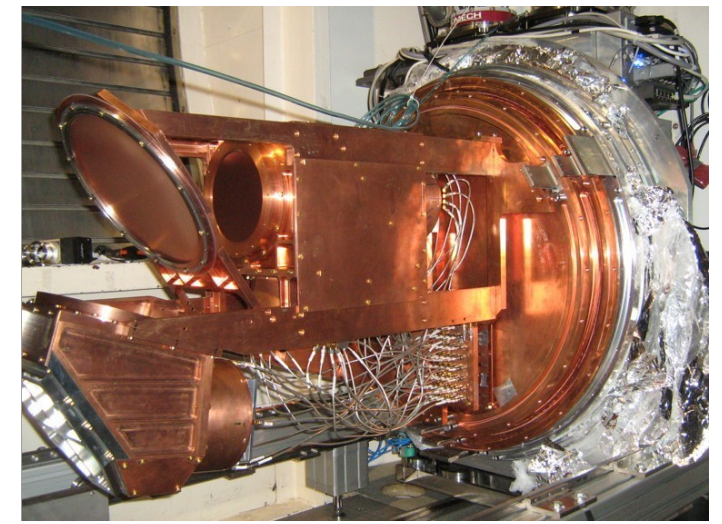
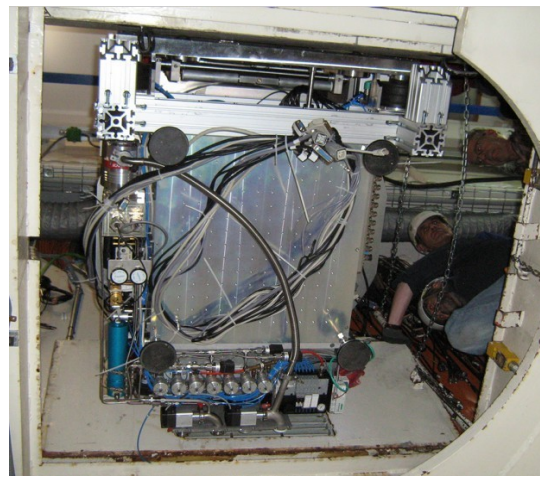
3x **array**, 4" wafer = 10cm diameter!

NIKA2 key 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 \approx 100 mK

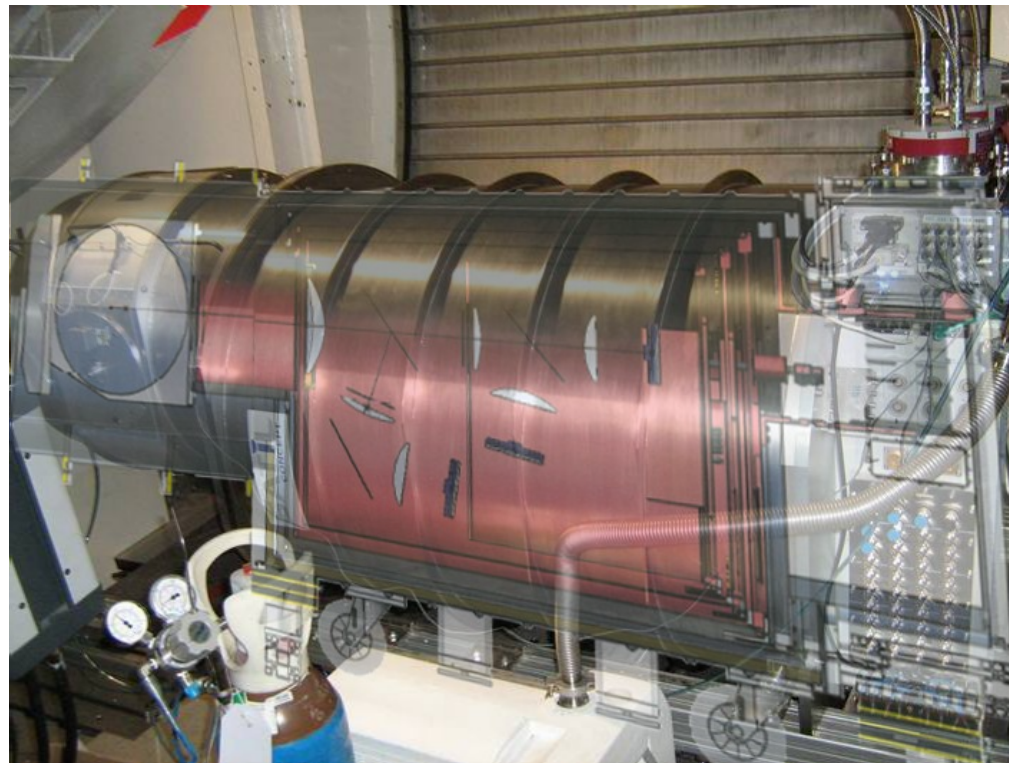
Going full-scale: NIKA2!

A lot of effort... and hard 'intellectual' work



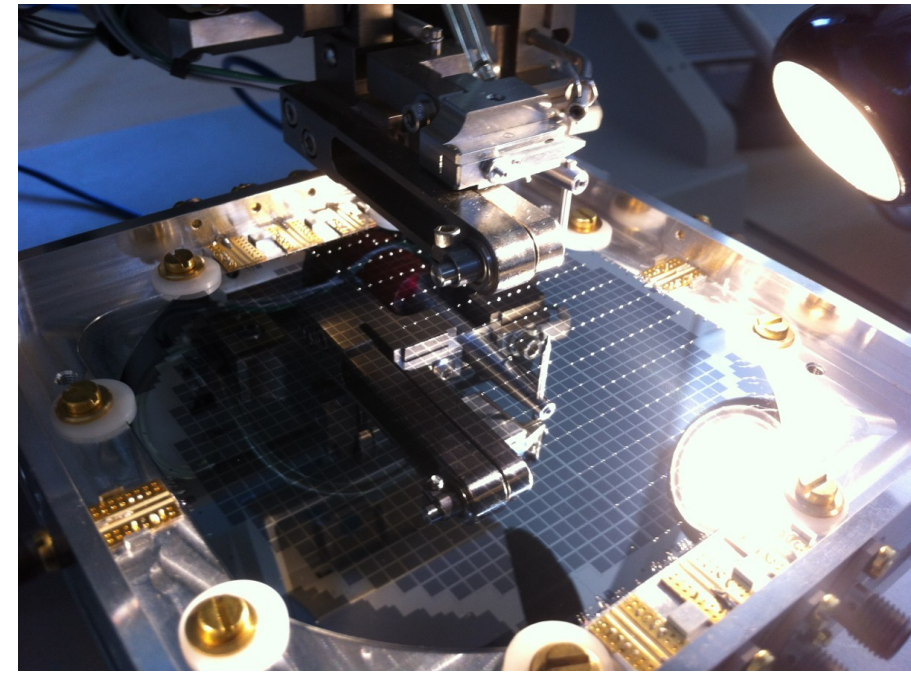
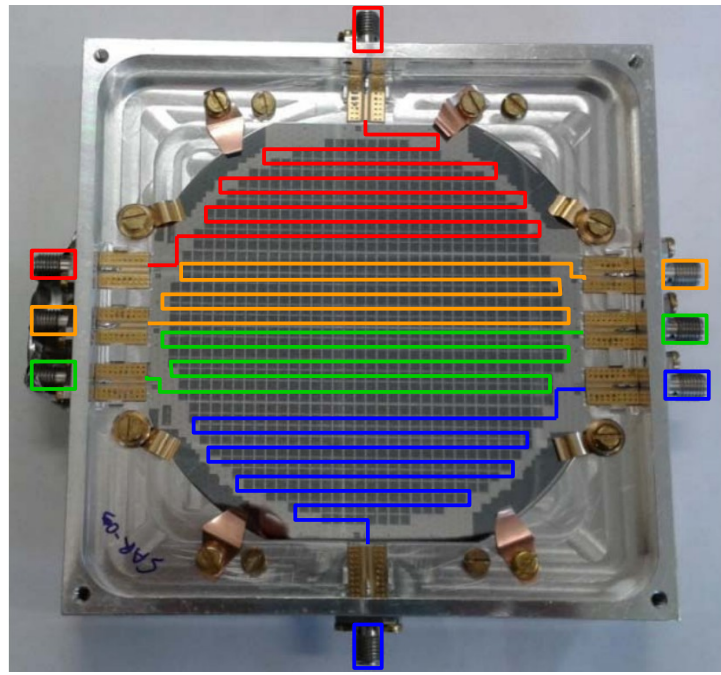
Going full-scale: NIKA2!

A lot of effort... and hard 'intellectual' work

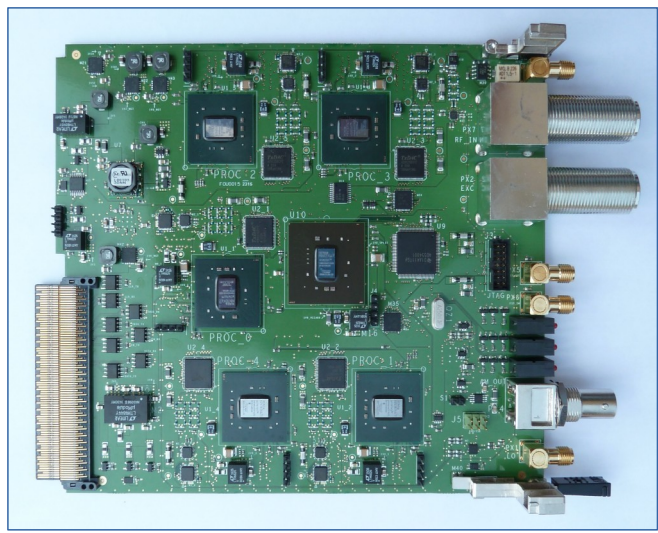


Going full-scale: NIKA2!

1000 pixels 2mm array



O. Bourrion et al.,
2012 JINST 7 P07014



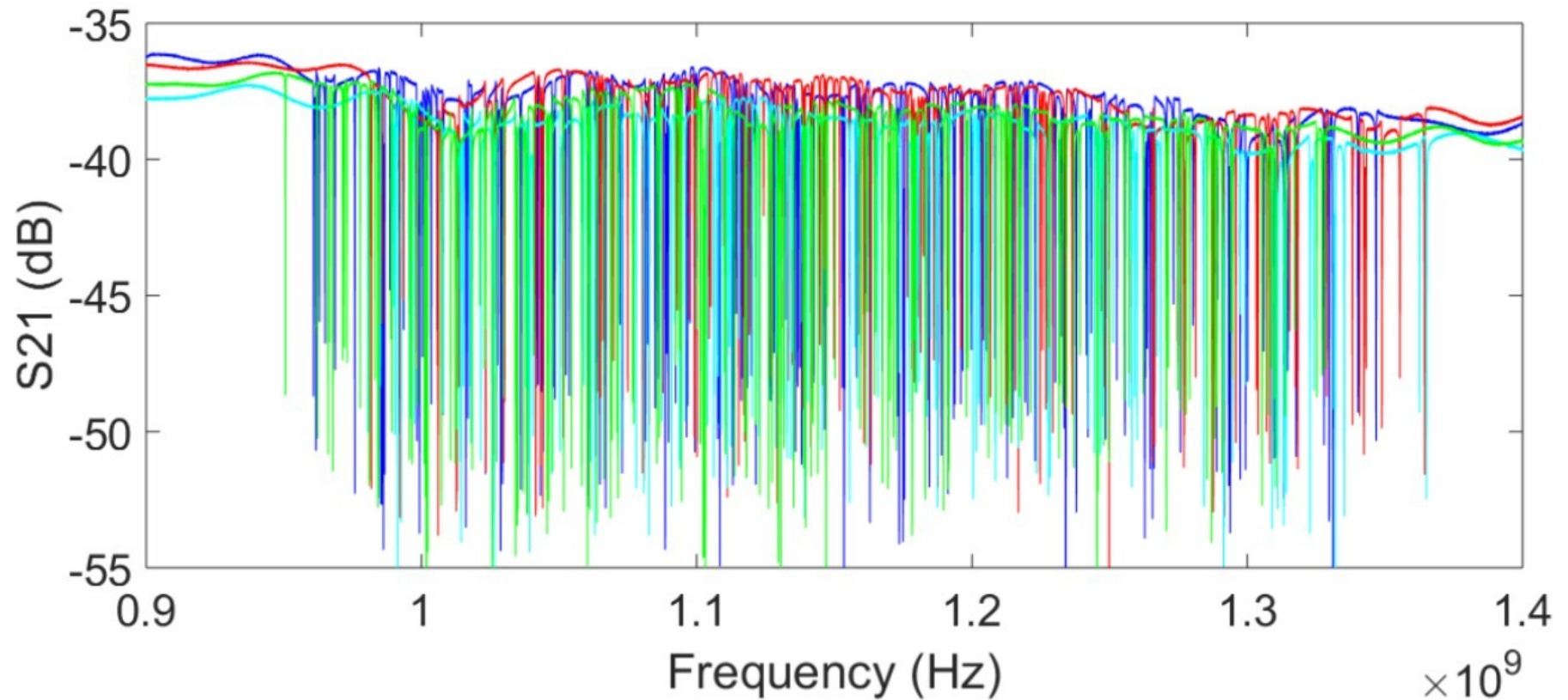
- 2mm: $600 \div 1000$ pixels \rightarrow 4 feedlines
- 1.25mm: $1200 \div 2000$ pixels \rightarrow 8 feedlines

Single 4" wafer fabrication

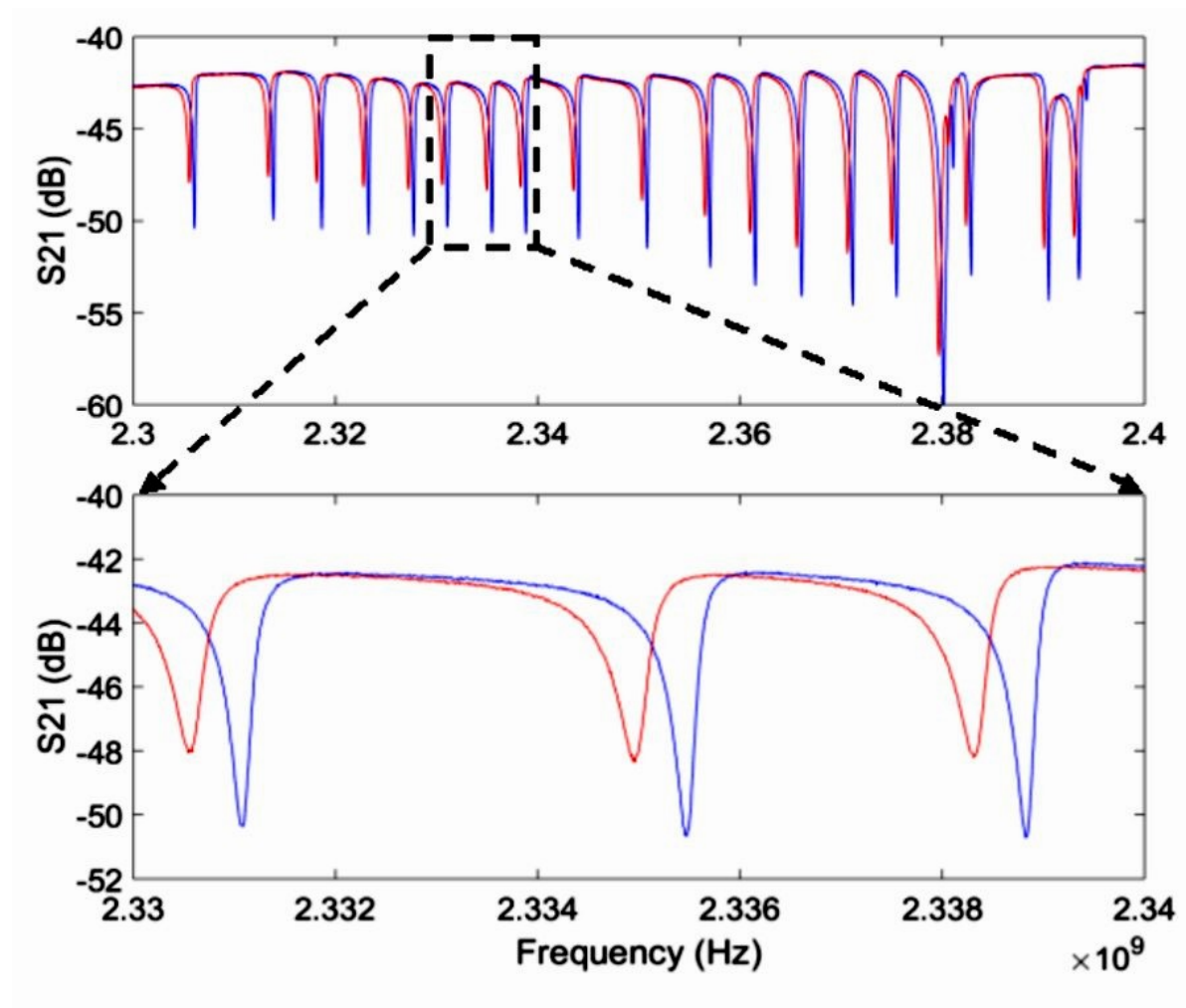
NIKELv1 boards: MUX factor 400 over 500MHz band

Current MUX factor: **250** (for safety + Q_i on ground!)

Going full-scale: NIKA2!



Going full-scale: NIKA2!



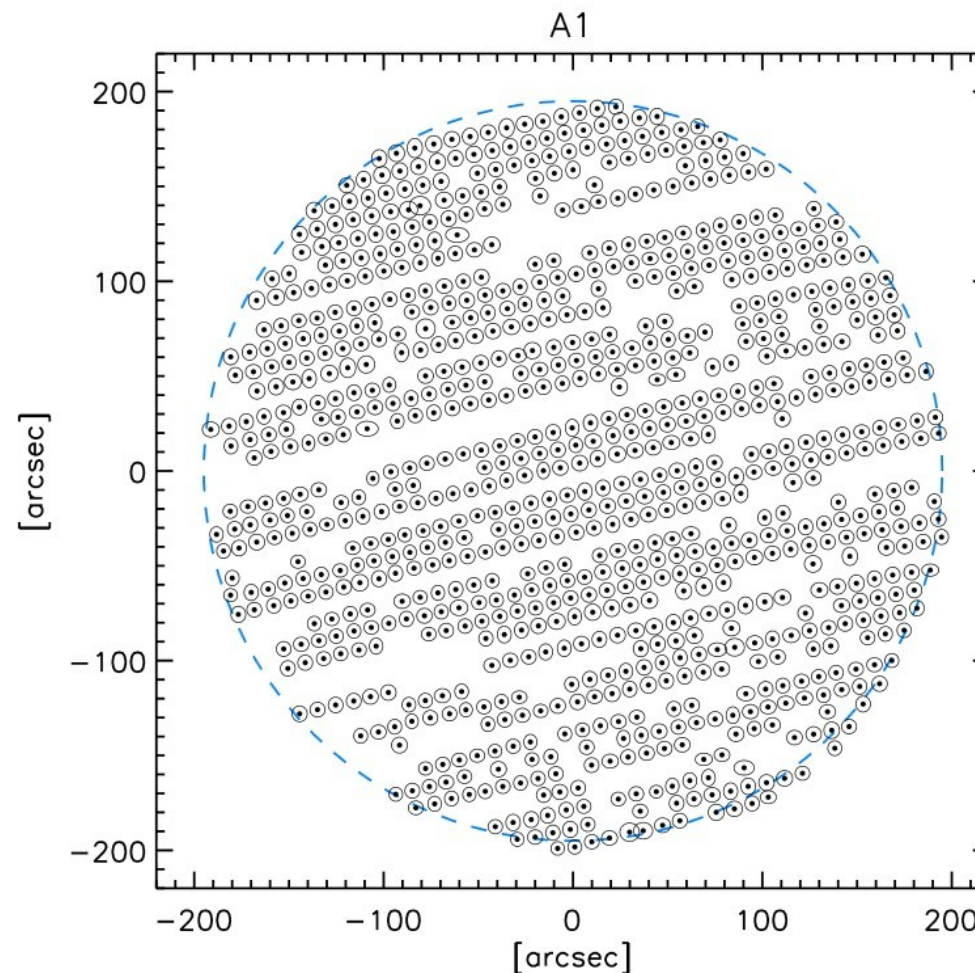
Going full-scale: NIKA2!

Footprint of a NIKA2 1mm array:

Yield 70% to 90%!

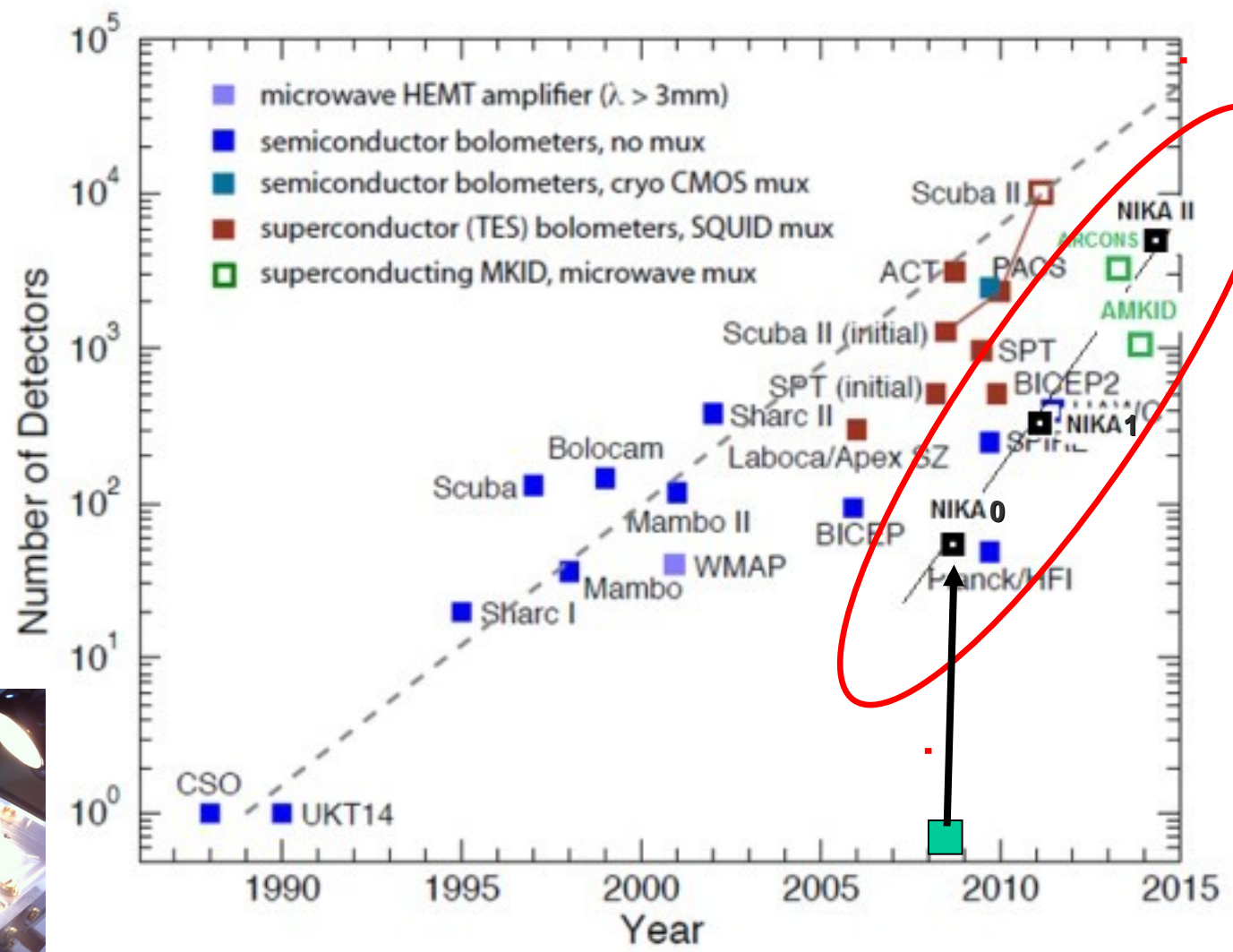
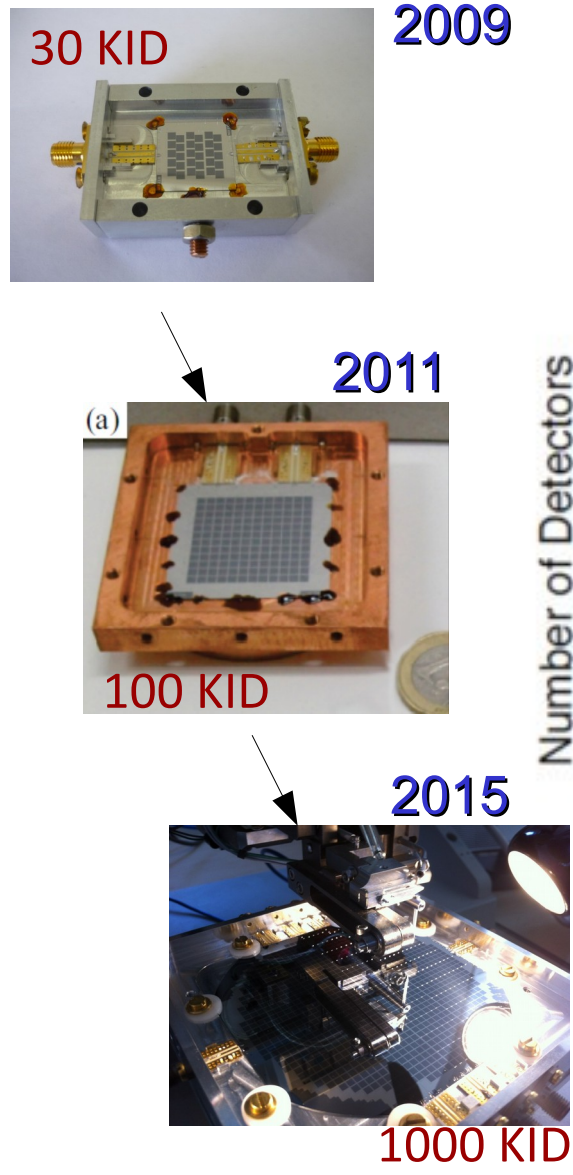
Used

Existing pixels



See Adam et al, A&A 609, A115 (2018) (arXiv: 1707.00908)

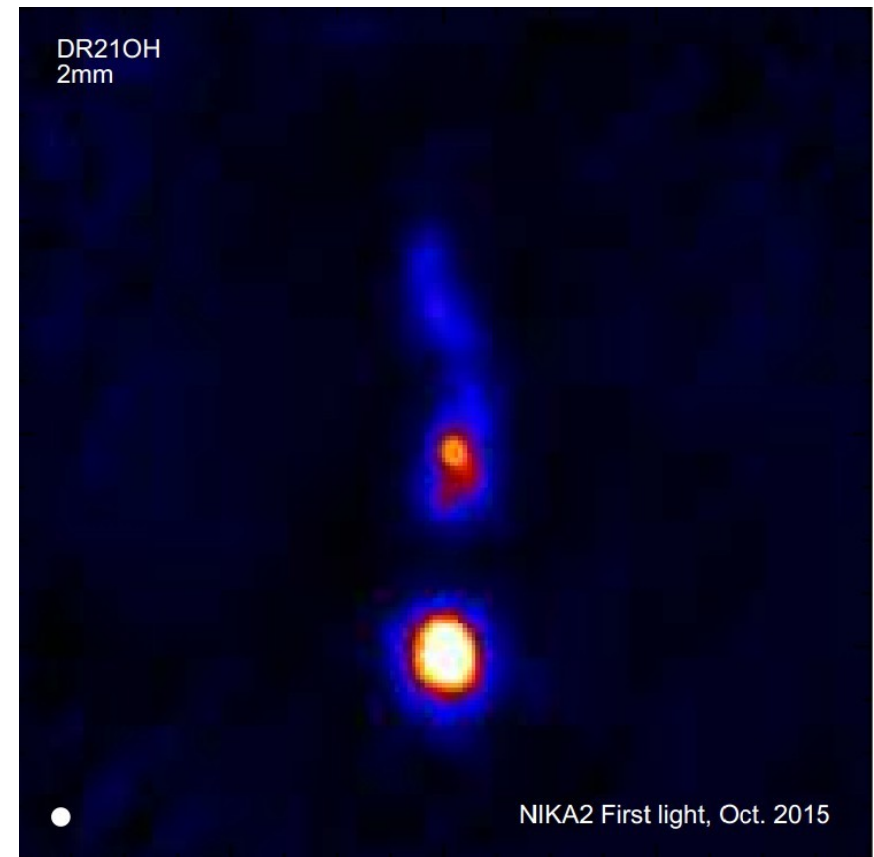
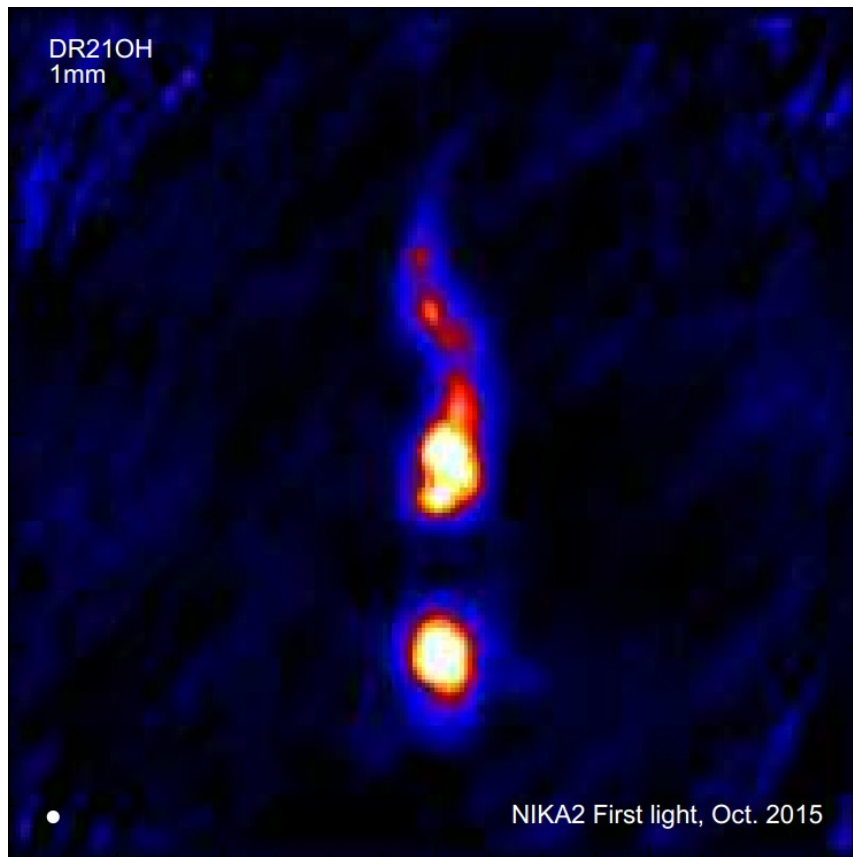
NIKA2 on the Moore plot!



The NIKA2 experiment

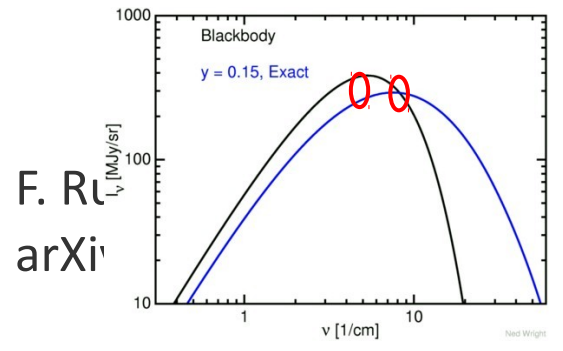
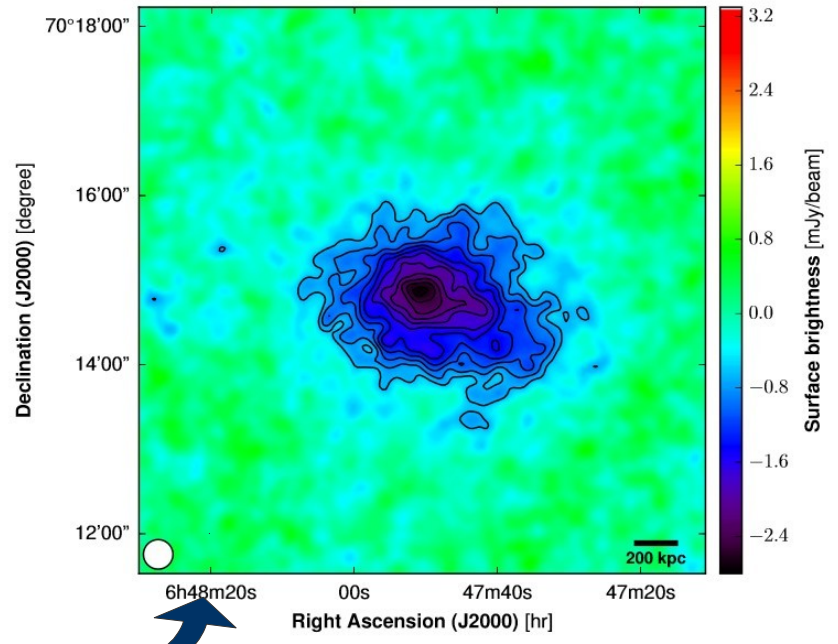
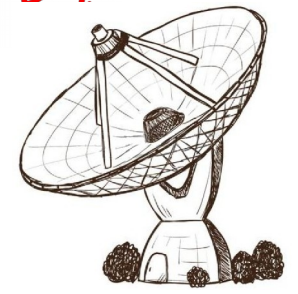
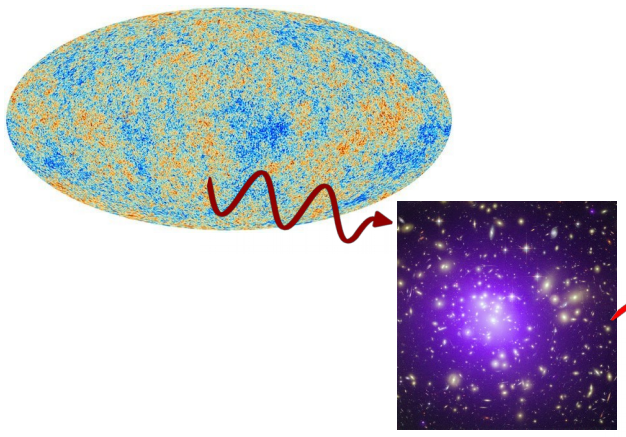
- A small, and preliminary, picture gallery:

DR210H star forming region:



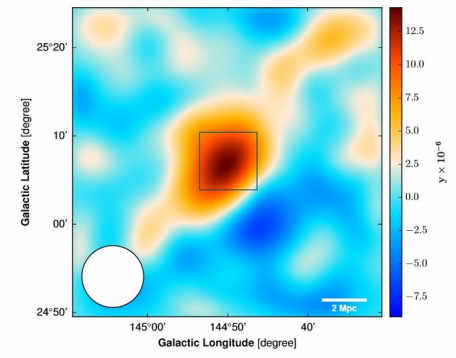
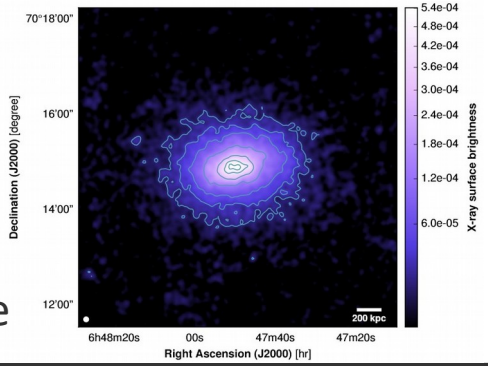
The NIKA2 experiment

- First detection of *SZ effect* with NIKA2: PSZ2 G144.83+25.11



For comparison... :

XMM X-ray satellite



Planck satellite

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



Altitude : 5100m

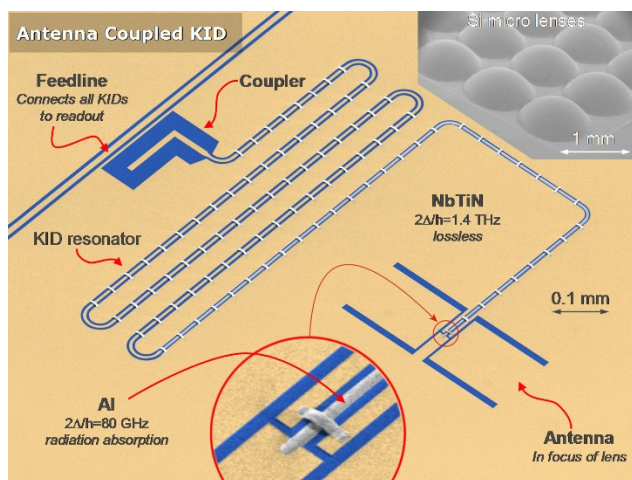
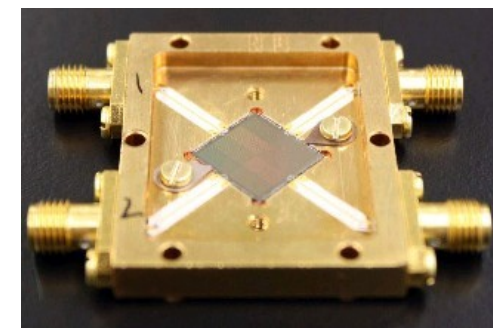
Plenty of activity ongoing, both on current and planned experiments!

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

ARCONS (US)

5 m Palomar telescope (visible)
Counting/measuring visible photons
Lumped Element KID:
2,024 pixels



And also :

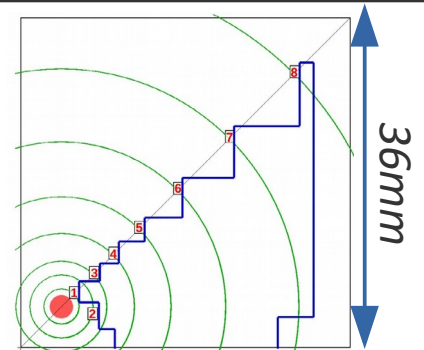
Deshima spectrometer (Delft – SRON – Japan)
US balloons

Gran Telescopio Milimetrico (UK – Mexico)

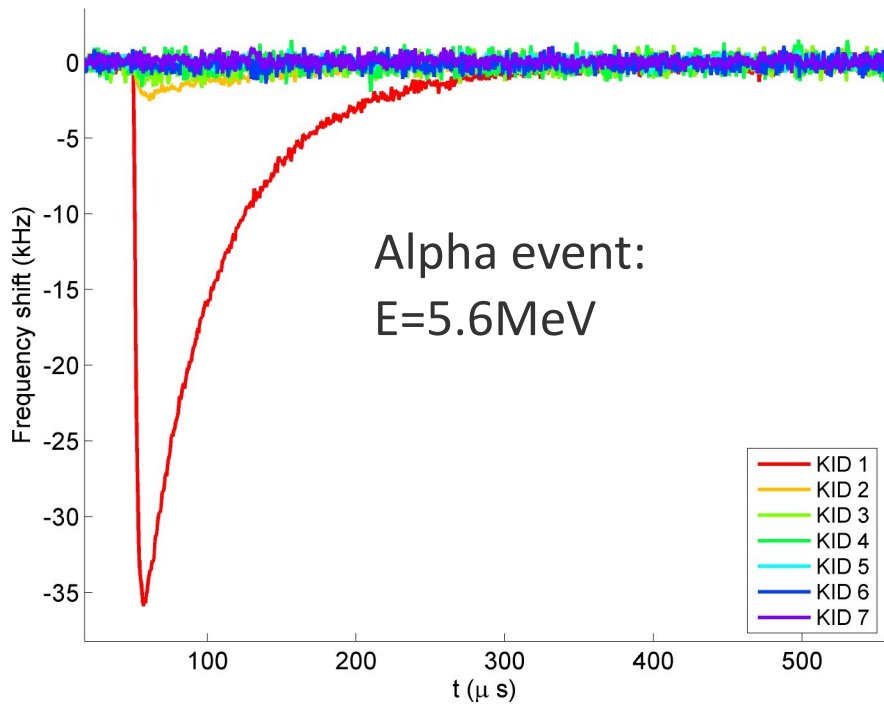
Large future telescopes (Caltech + JPL in US)

Other KID activities in Grenoble

Trying to avoid high energy phonons (space applications)...
But we might also like to see them!



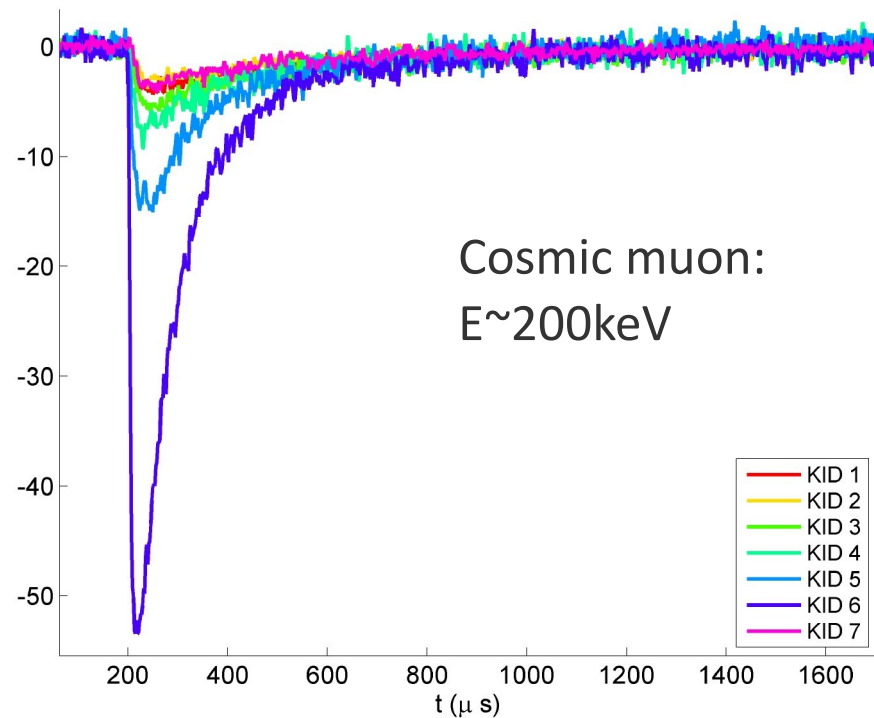
Event 8, array SPK3-01-GND, Ti on back, alphas 150mK, all traces



Alpha event:
 $E=5.6\text{MeV}$

Hot phonons suppressed
(use of low-Tc layer)

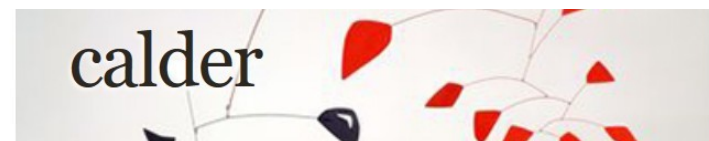
Event 11, array SPK3-02-BAR, cosmics 125mK, all traces



Cosmic muon:
 $E\sim 200\text{keV}$

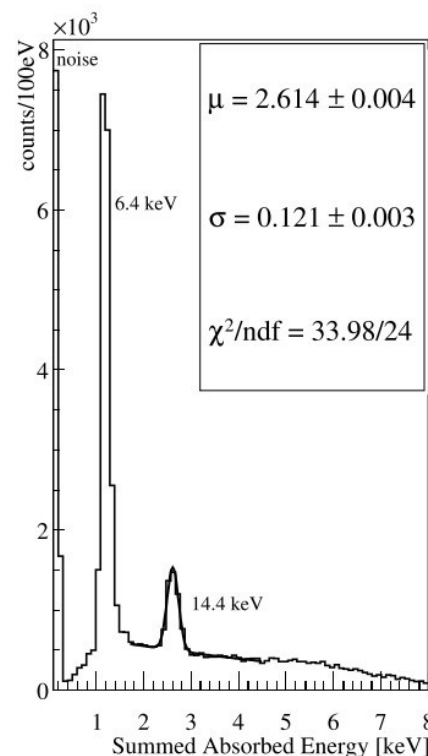
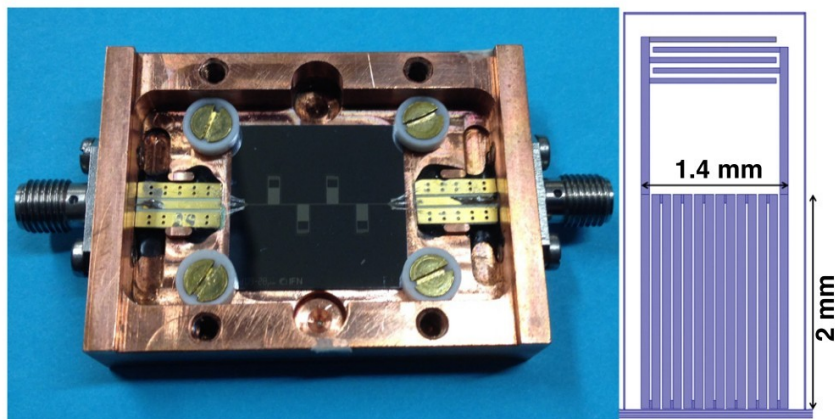
Hot phonons preserved
(minimum metal deposition)

CALDER project (collaboration with INFN – Rome)



Use of KID detectors for sensing Cerenkov light in TeO₂ scintillators for CUORE

This approach is pushed to the extreme (with promising results!)



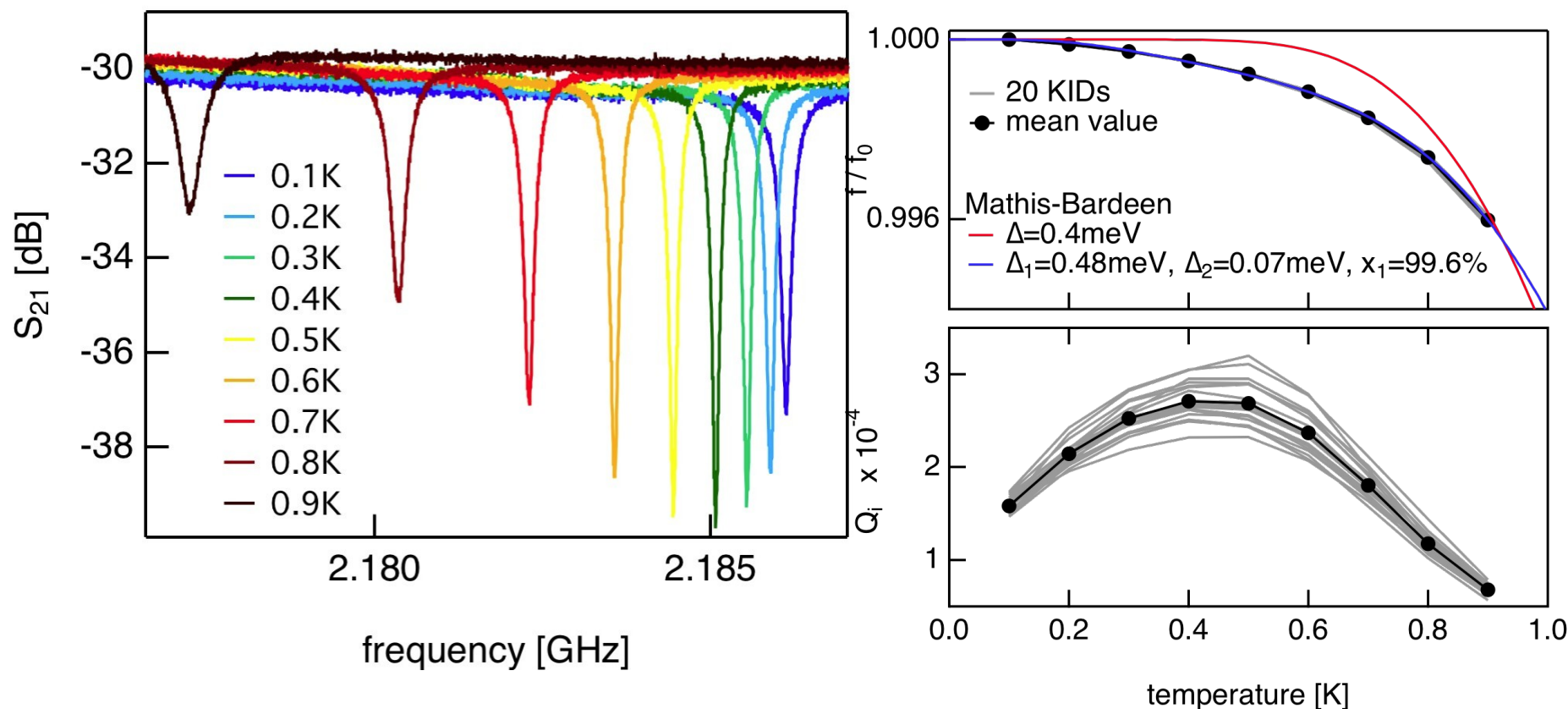
Resolution better than **30eV**
for phonon-mediated
UV/VIS light detection!

Cardani et al, arXiv: 1801.08403.pdf

Other KID activities in Grenoble

Study of material properties in disordered materials (InOx, GrAl, ...)

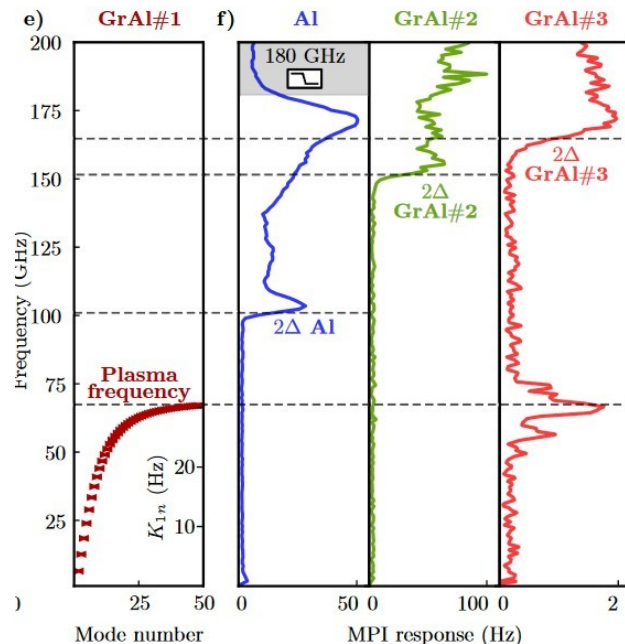
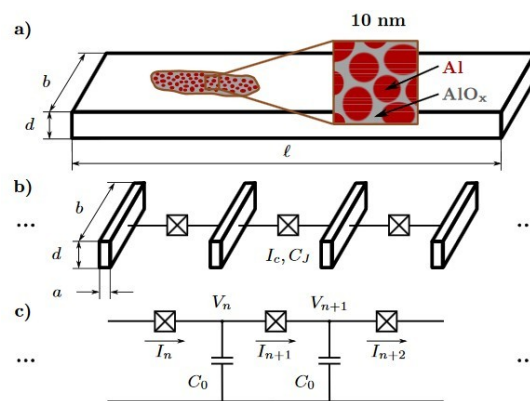
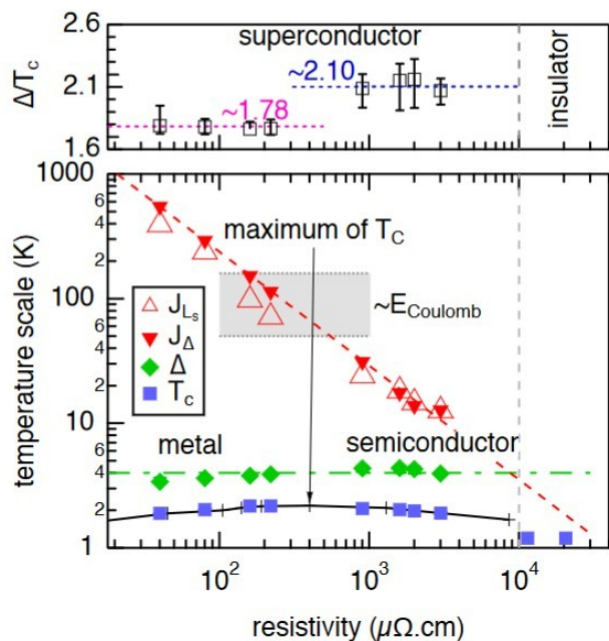
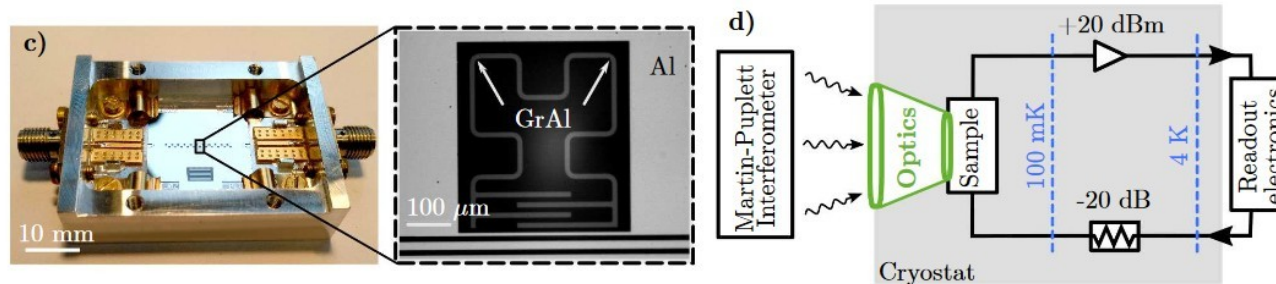
The detector itself gives plenty of information on superconductivity



Can be used for detectors as well! See Dupre et al, SUST 30 (2017)

Study of material properties in disordered materials (InOx, GrAl, ...)

GrAl: effect of QP dynamics

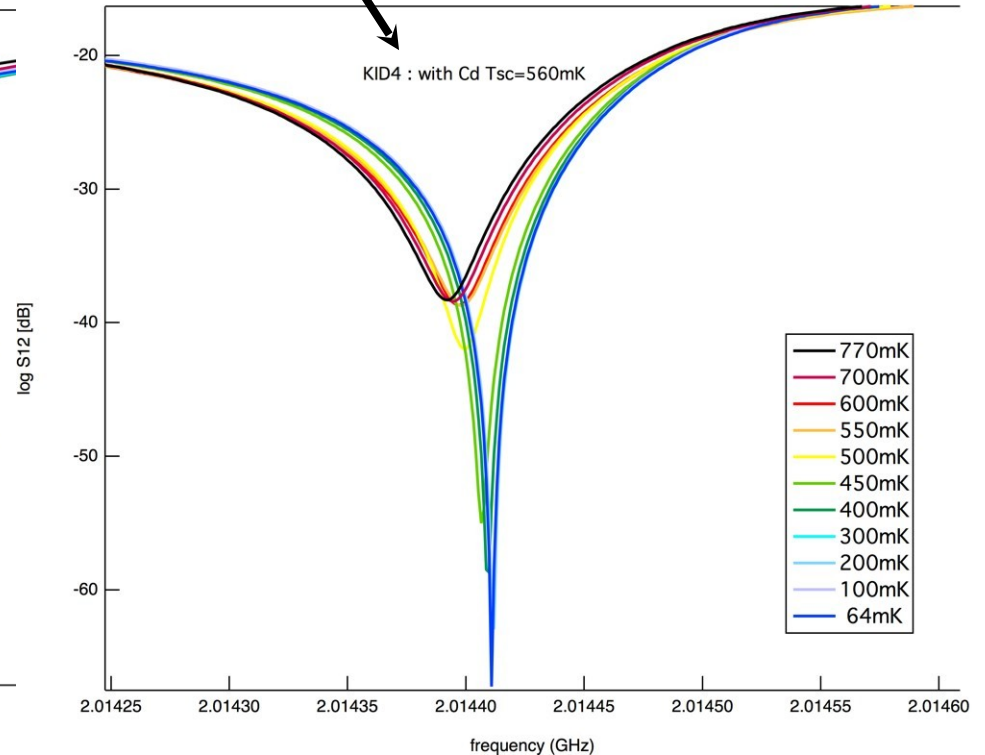
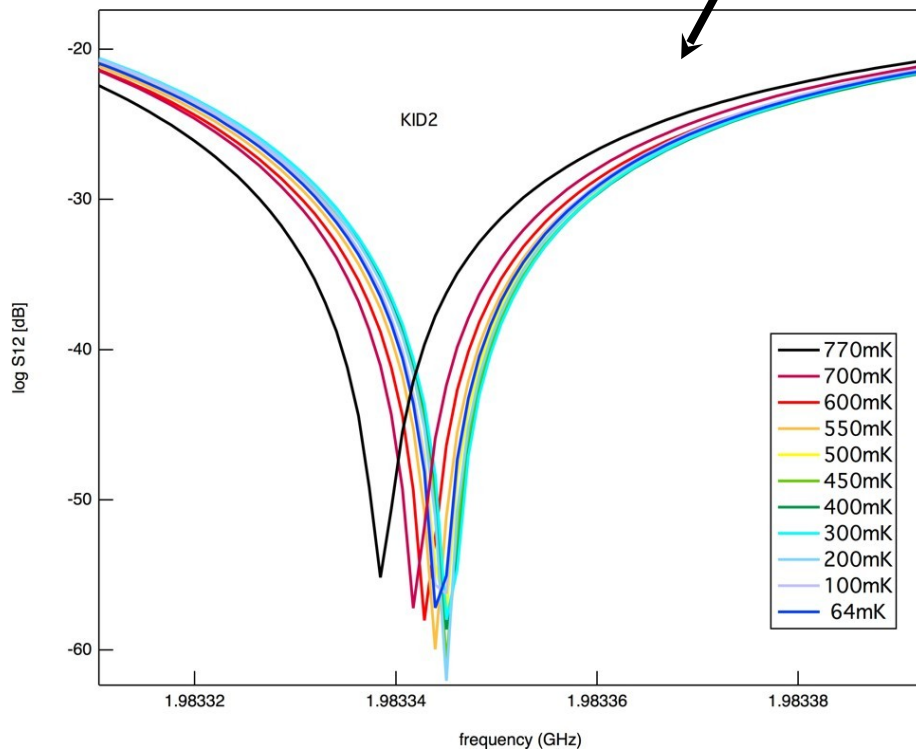
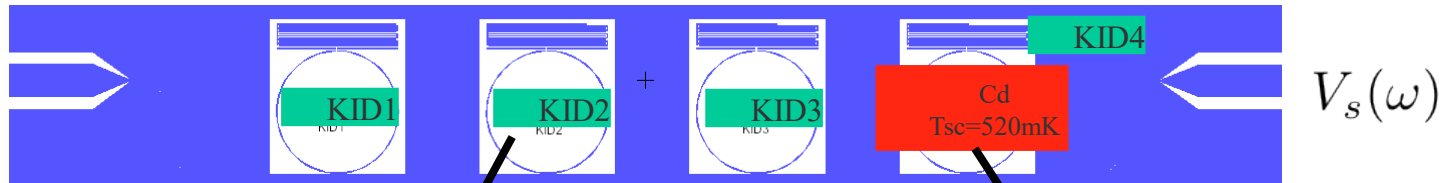


Levy et al, submitted to SUST

Maleeva et al, arXiv: 1802.01859.pdf

Other KID activities in Grenoble

KID as London penetration depth sensors ('Omega-Lambda KID')



Conclusions

- LTD have great performances, and a lot of potential still to exploit
- As of now, main actors are probably TES (+MMC?) and KID
- Accessory technologies (coolers, microfabrication, ...) have evolved a lot
- They are today common tools for physicists
- So don't be afraid to go for them! (*ok, not if you don't need them..*)

And, especially:

Many thanks to you and to the organizers!

References

C. Enss, *Physical principle of Low Temperature Detectors*

D. Martin and P. Verhoeve, *Superconducting Tunnel Junctions*

K. Irwin and G. C. Hilton, *Transition-Edge Sensors*

L. Fleischmann et al., *Metallic Magnetic Calorimeters for X-ray Spectroscopy*

P. Richards, *Bolometers for Infrared and Millimetre Waves*

Many presentations: A. Monfardini, M. Piat, C. Kilbourne, B. Cabrera, ...

(Many thanks to all these sources as well...)

Coupling energy to a MKID

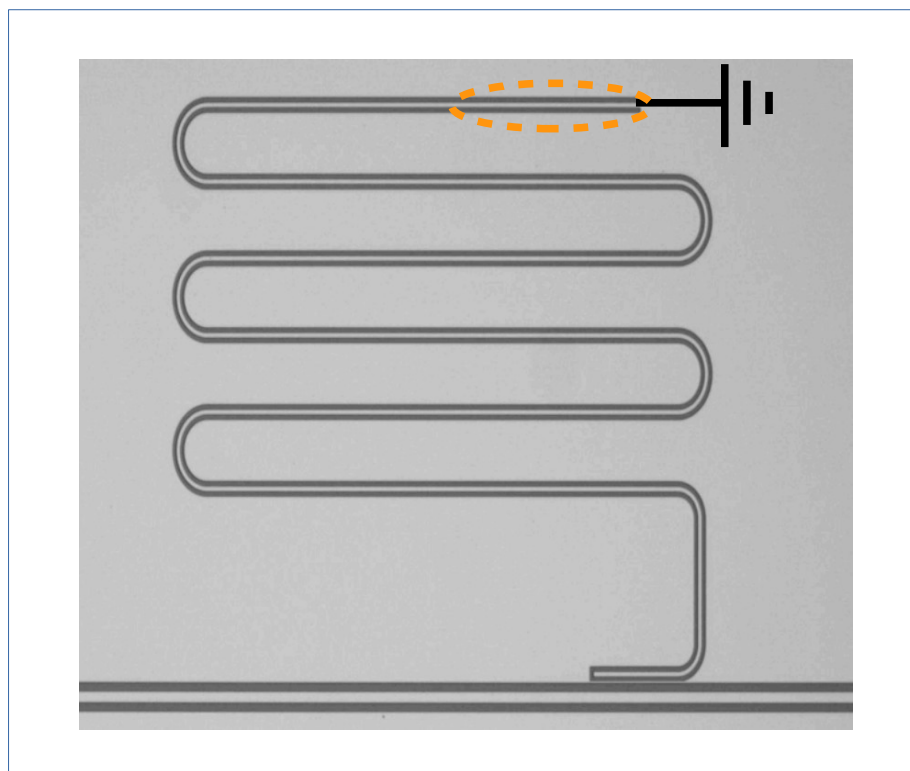
In a distributed KID, the current (ie, the sensitivity!) is maximum at the shorted end

One needs therefore:

A **lens** (focusing)

An **antenna** (impedance matching)

A quasi-particle trap



Coupling energy to a MKID

In a distributed KID, the current (ie, the sensitivity!) is maximum at the shorted end

One needs therefore:

A **lens** (focusing)

An **antenna** (impedance matching)

A quasi-particle trap

Pros :

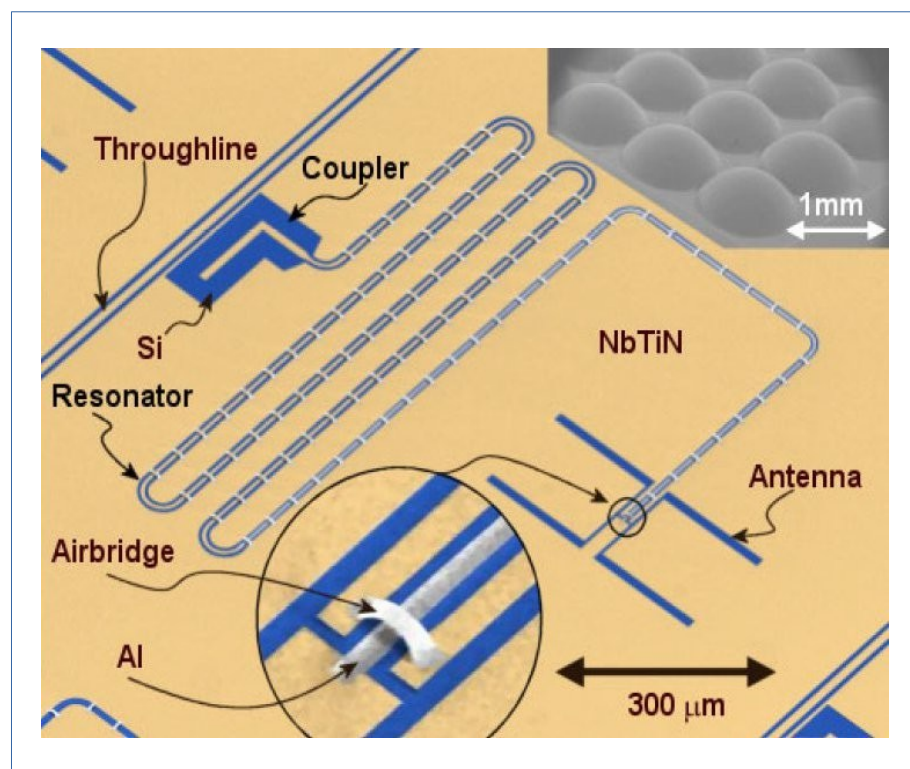
More flexible approach

Can easily add planar elements (filters, polarization etc)

Cons :

Fabrication is more complex

Difficult to tightly control all the steps



Coupling energy to a LEKID

In a LEKID, the current is uniform in the whole meander

Therefore, *the meander itself can be used as an absorber!*

The meander shape can be adjusted to get $Z_{\text{eff}} \approx Z_0$



$\lambda \gg s, w :$

Pros :

- Extremely simple system
- Easy fabrication

Cons :

- Tighter constraints
- Less flexible

Cosmic Rays absorbing layers

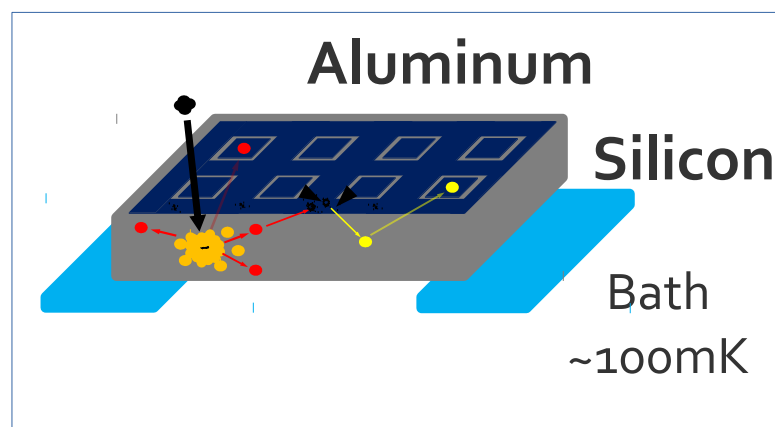
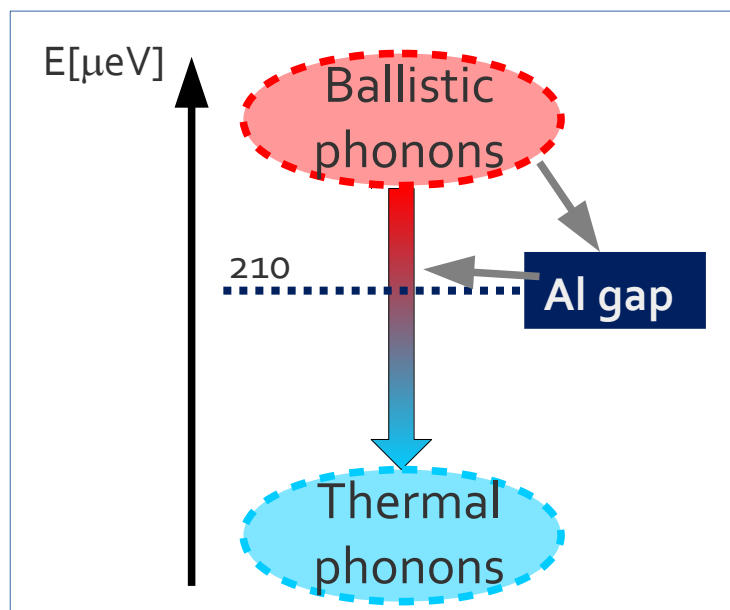
Studies have started to investigate the CR effect

(any detector will have to do this step!)

The superconducting gap gives us 2 advantages

- As soon as the phonons have $E < 2\Delta$, they become 'invisible'

→ glitches are faster → less data lost



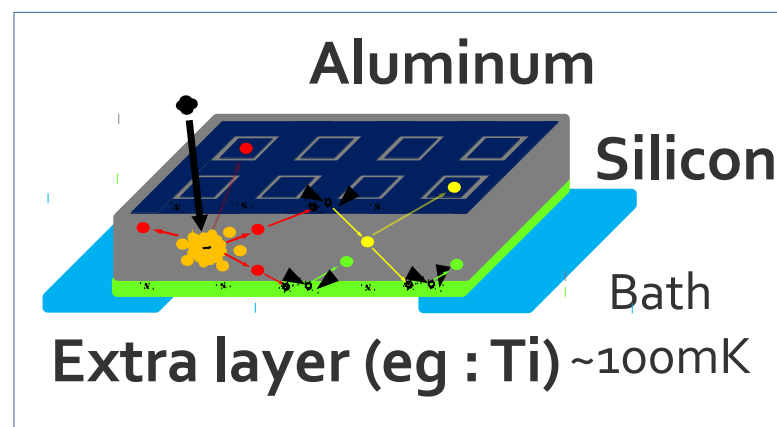
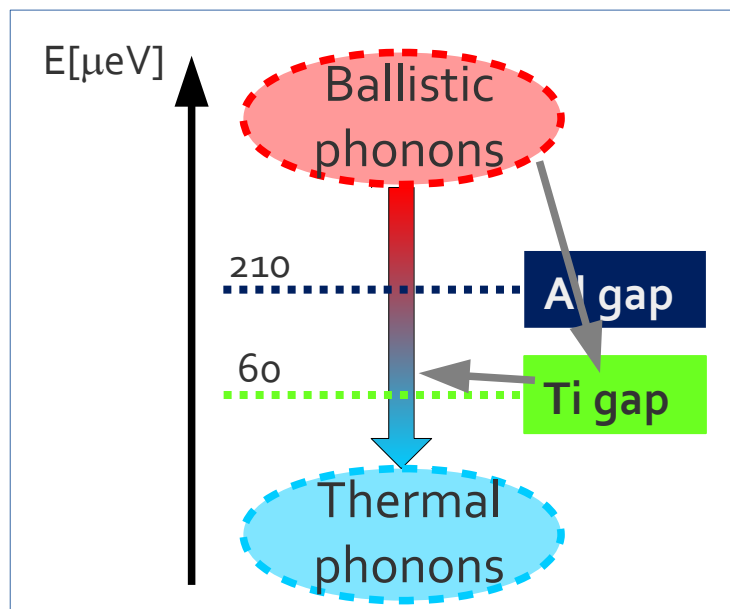
First results are **very promising!**

Studies have started to investigate the CR effect

(any detector will have to do this step!)

The superconducting gap gives us 2 advantages

- As soon as the phonons have $E < 2\Delta$, they become 'invisible'
→ glitches are faster → less data lost
- We can further improve adding films with lower T_c



First results are **very promising!**