13th Pisa meetings on Advanced Detectors

Kinetic Inductance Detectors for kilopixel intruments at Radiotelescopes

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Outline

1 - Introduction

Superconductivity and Kinetic Inductance

2 – KID theory

What is a KID and how to make it

3 – KID applications

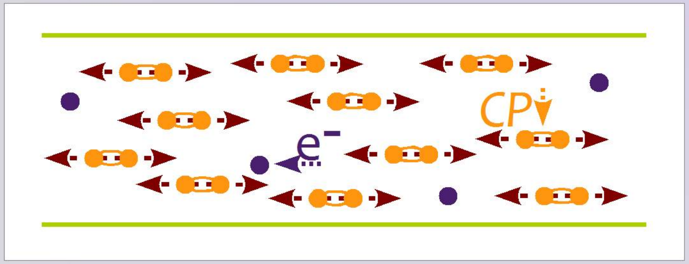
The advantages of KID detectors and their applications

4 – The NIKA2 camera

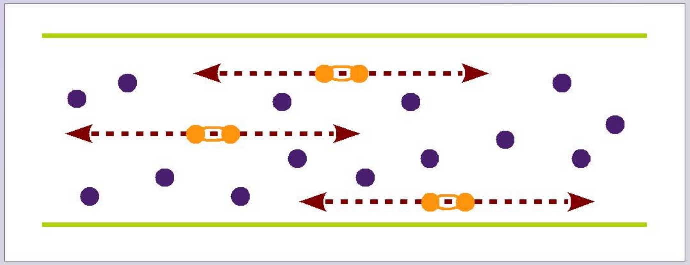
A kilopixel camera for mm astronomy

The Kinetic Inductance

- In a superconductor below T_c, two different types of charge carriers coexist:
  - ***Cooper Pairs*** : paired electrons. ***Reactive***
  - ***Quasi-Particles*** : the standard, unbound electrons. ***Resistive***
- When moving, the CP store energy, and show an inertia to changes in it
  - ***Magnetic field*** → magnetic inductance, L_m
  - ***Kinetic energy*** → kinetic inductance, L_k



n_{cp} ↓ E_k

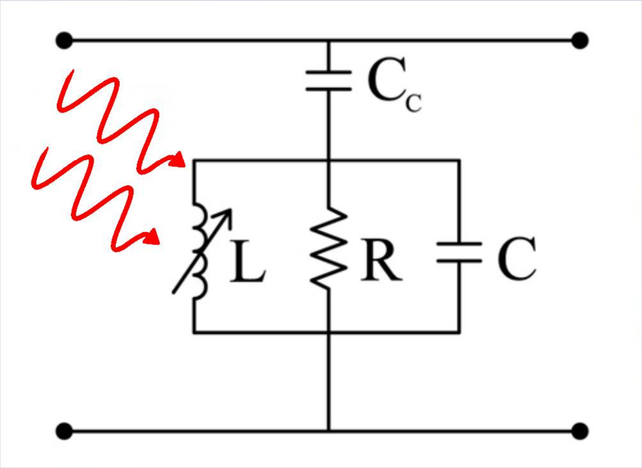


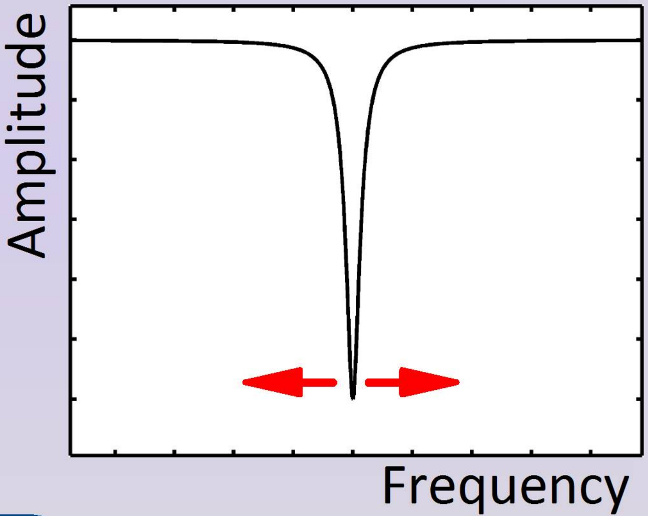
$n_{cp}/2$ ↓ $2E_k$

$n_{CP} \searrow \;\Rightarrow\; L_k \nearrow$ (and $R \nearrow$)

Kinetic Inductance Detectors

- Simply put, a KID is a **superconducting resonator** in which the kinetic inductance is used as sensitive element
- The absorbed power induces a variation of L_k and thus of the resonant frequency, $\boldsymbol{f_0}$





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

- 'The' paper: P. Day et al., *Nature*, 425, 817 (2003)

The Lumped Element KID ('LEKID')

- A very easy and effective way of making a KID

  Based on 'lumped element' components (dimensions << wavelength)

  Basically, a 'standard' RLC circuit

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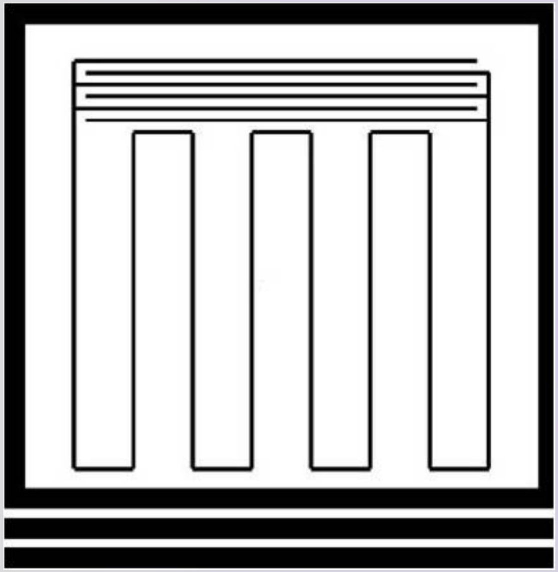

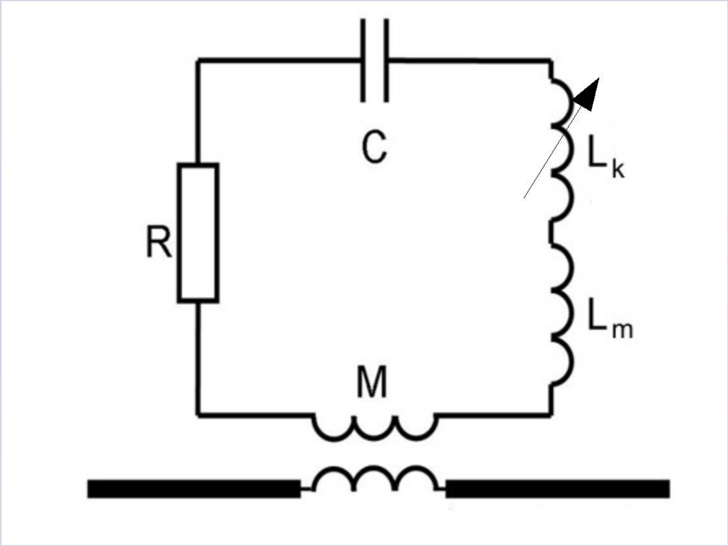

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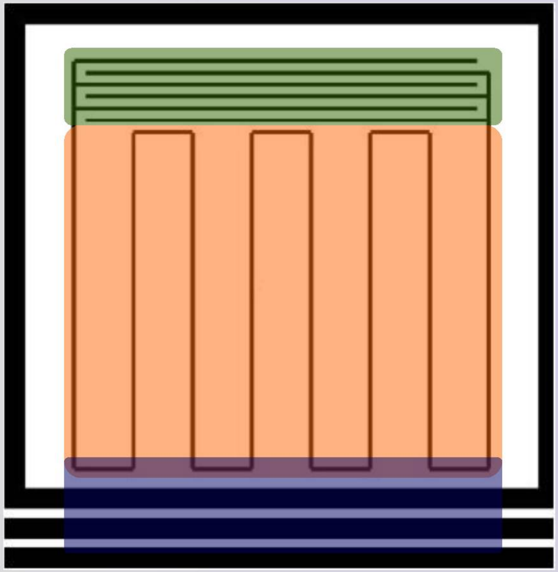
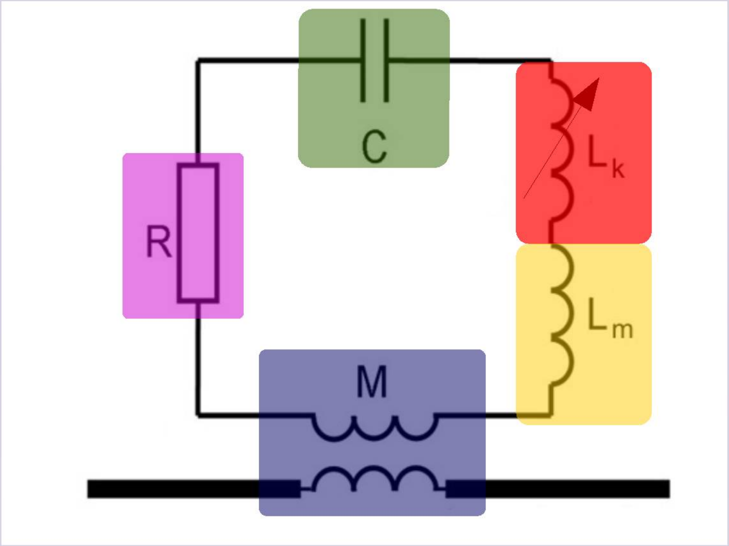




- Kinetic Inductance (CP)
- Geometric Inductance
- ID Capacitor
- Residual R (QP)
- Coupling (mag/capa)

The current is *uniform* in the whole meander

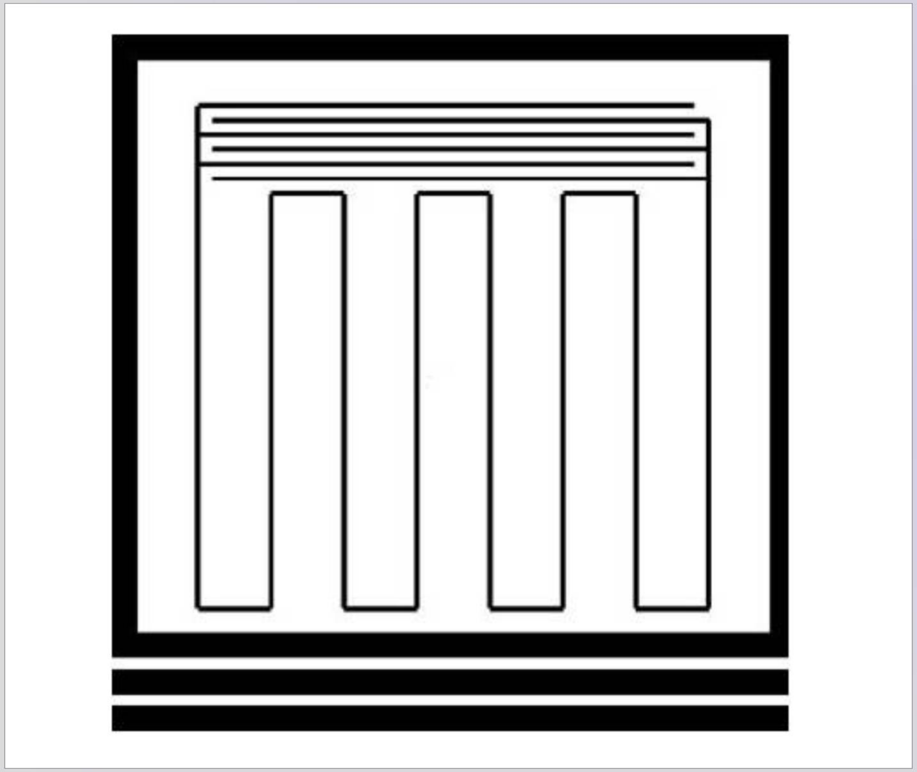
$$f_0 = 1/\sqrt{(L_k + L_m)\cdot C}$$

Coupling radiation to a LEKID

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

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

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



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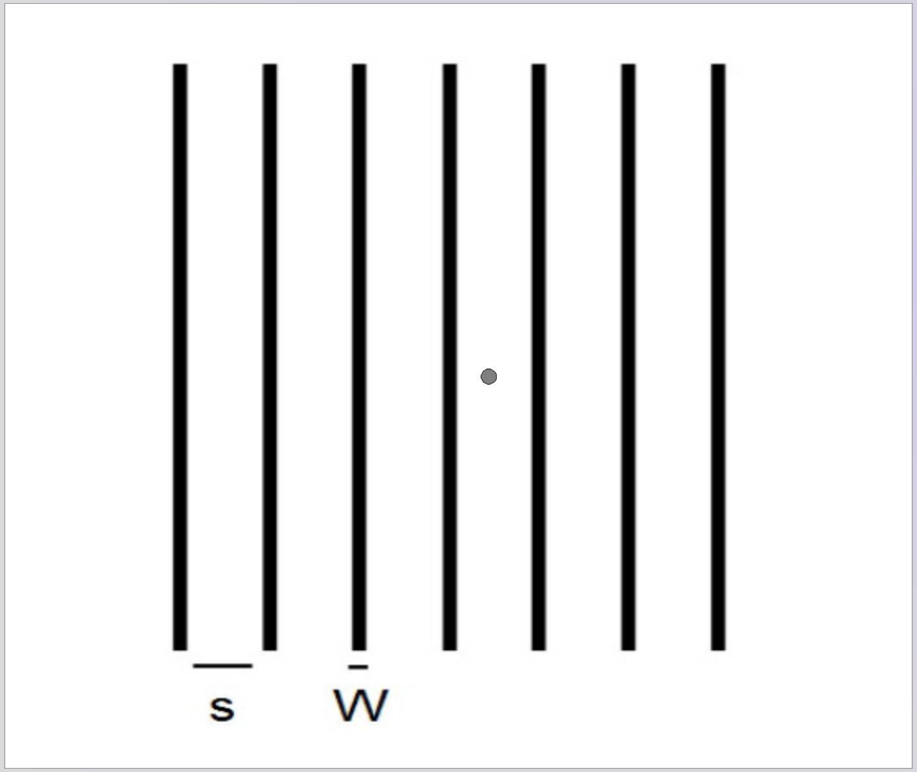

$\lambda << s, W$

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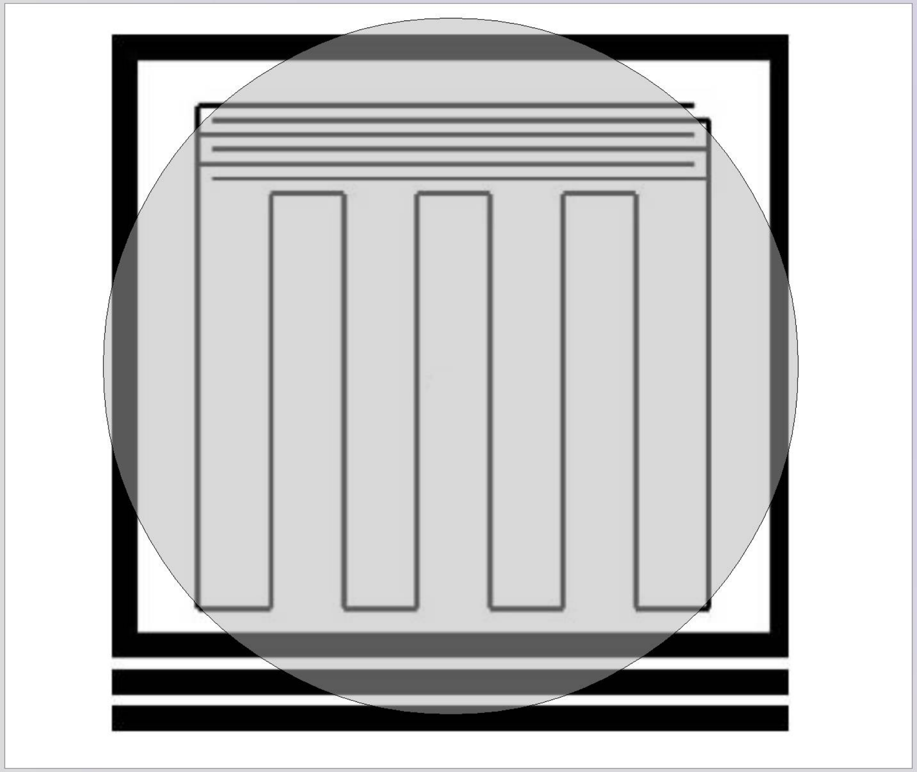

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$\lambda >> s$

Pros :

- Extremely simple system
- Easy fabrication

Cons :

- Less flexible than other solutions

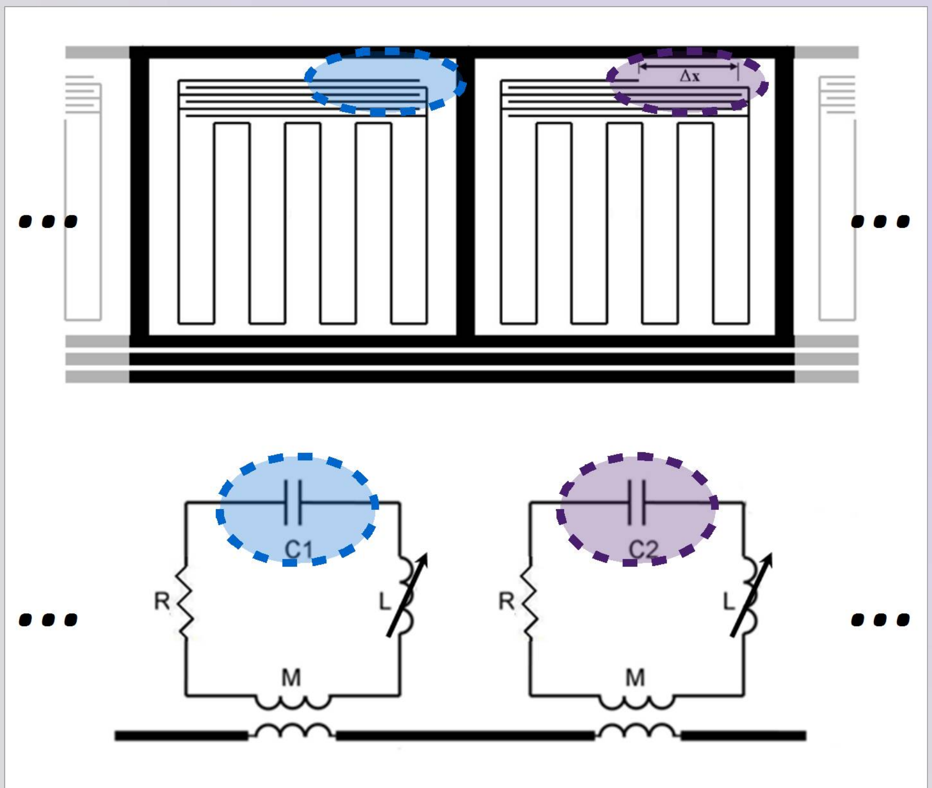
Frequency Domain Multiplexing

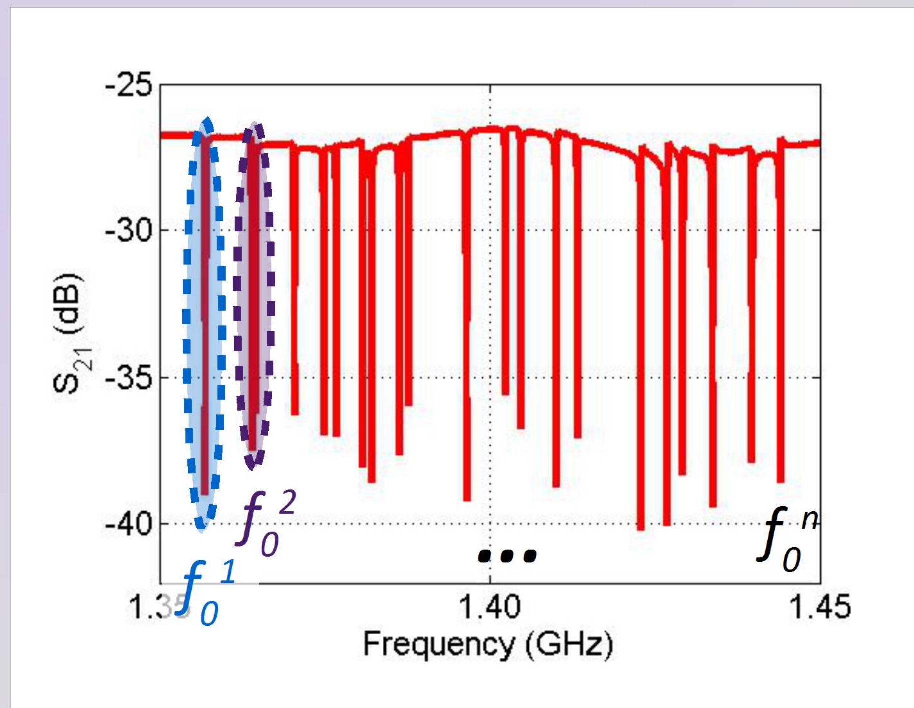
A KID is a very high Q resonator

The f_0 can be varied lithographically (e.g. in a LEKID, $\Delta C \rightarrow \Delta f_0$)

Many resonators can be coupled to a single readout line!

100s to 1000s!

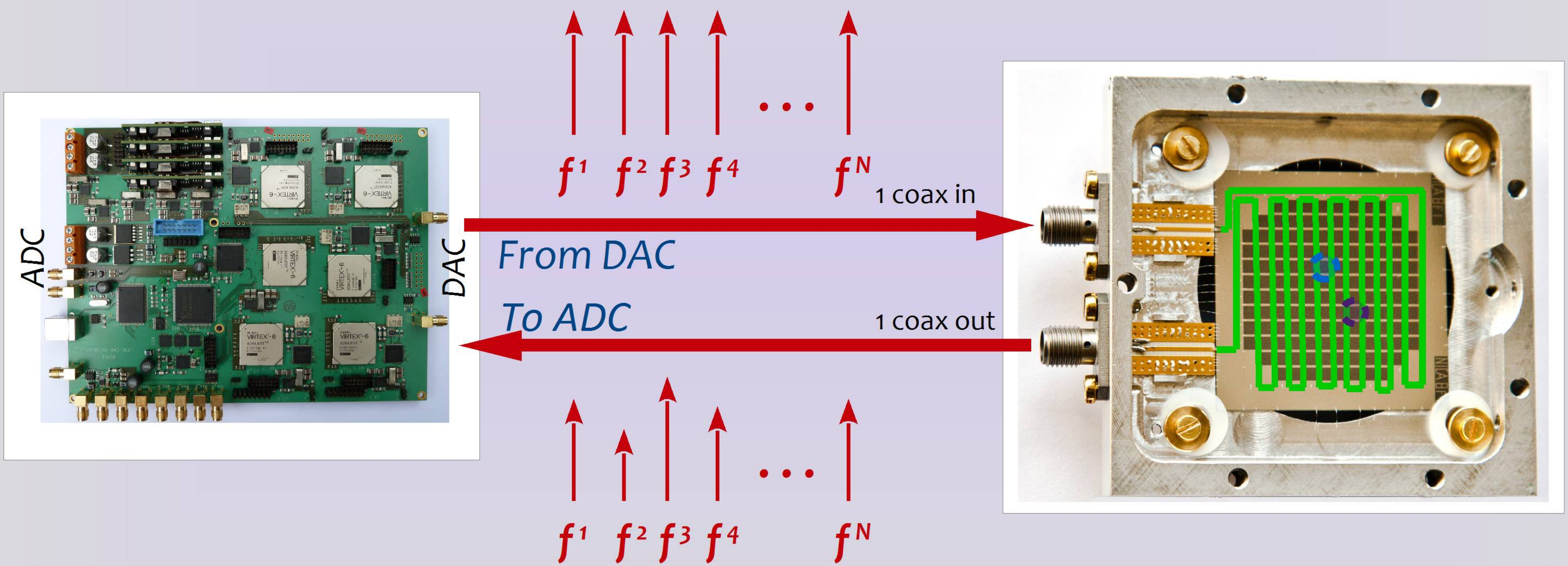




Frequency Domain Multiplexing

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 !



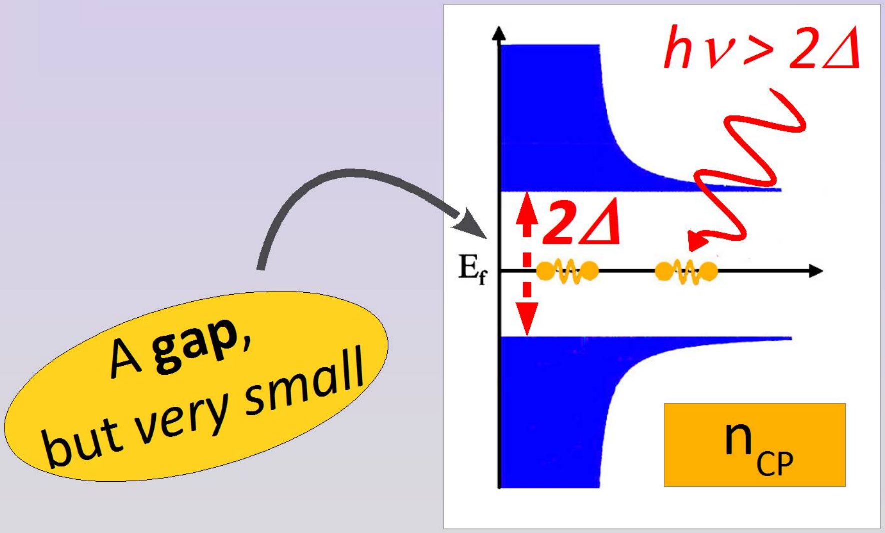
KID are ***intrinsically multiplexable*** in the frequency domain

Effects of the energy gap

- A KID is a **pair-breaking detector**
- The binding energy of a Cooper Pair is given by: $2\Delta = 3.5\, k_b T_c$

→ Quanta of energy lower than the gap do not affect it

- The gap in a superconductor is typically just ***a fraction of a meV***, 1000 times smaller than in a semiconductor

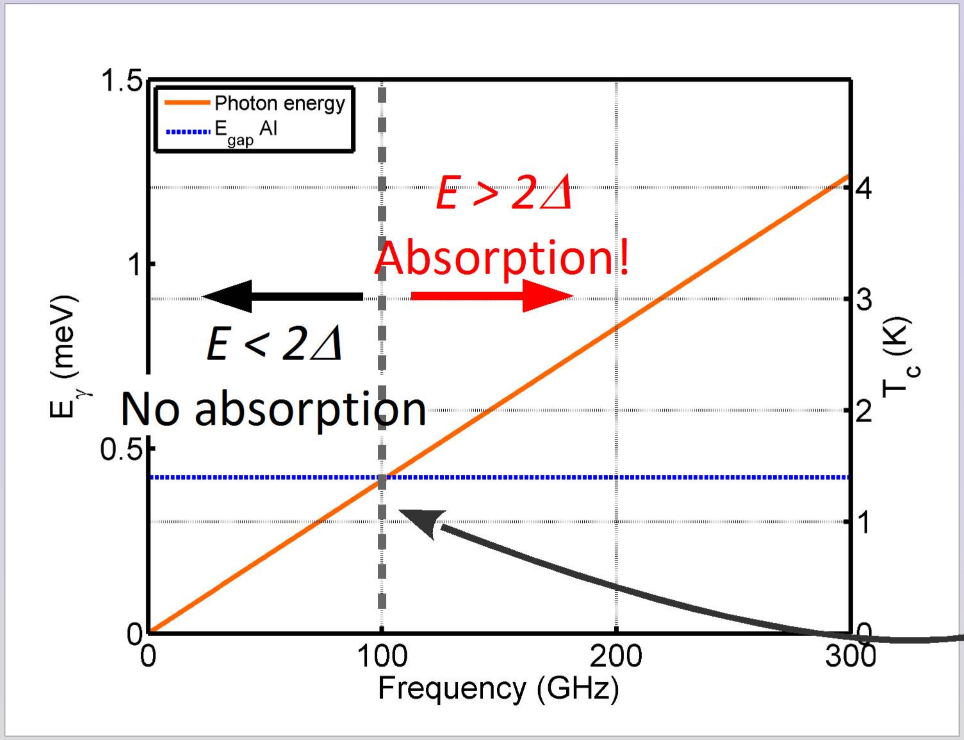


Effects of the energy gap

- A KID is a **pair-breaking detector**

  → Quanta of energy lower than 2Δ do not affect it

- Optically : Photons with $\nu < \nu_{cutoff}$ = $\mathbf{3.5k_bT_c/h}$ are not absorbed



$\nu_{cutoff} \approx$ **75GHz · (T_c/K)**

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  - KID are viable for frequencies **above ~50GHz**

  - Can use different superconductors to make integrated circuits

Effects of the energy gap

- A KID is a **pair-breaking detector**

→ Quanta of energy lower than 2Δ do not affect it

- Thermally : at $T \ll T_c$, almost no phonons have energy $>2\Delta$

The KID is thermally decoupled from the sorrounding environment

- No need of complex and delicate structures for thermal isolation

→ *Easy fabrication*

- Almost insensitive to variations in the temperature of the thermal bath

→ *Not prone to microphonics, thermal 1/f, …*

- **Fast response**, determined by the QP recombination time (τ_{qp})

→ *Tens of μs up to few ms*

Ideal fields of application

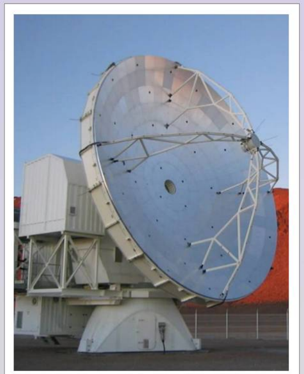
- KID are perfectly suited for ***large arrays of ultresensitive detectors***
- But mind: *cryogenics is a must*!

Astronomy

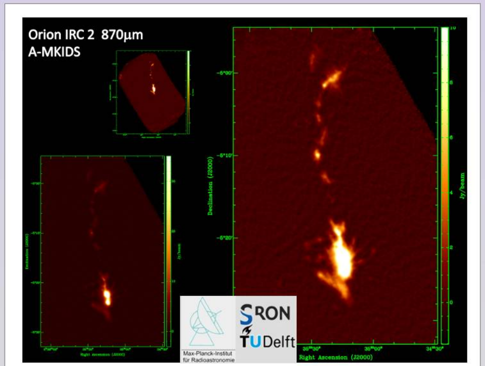
Photon-noise limit → large number of detectors needed

On-going developments for many bands

NIKA+NIKA2



AMKID



MUSIC

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Astronomy

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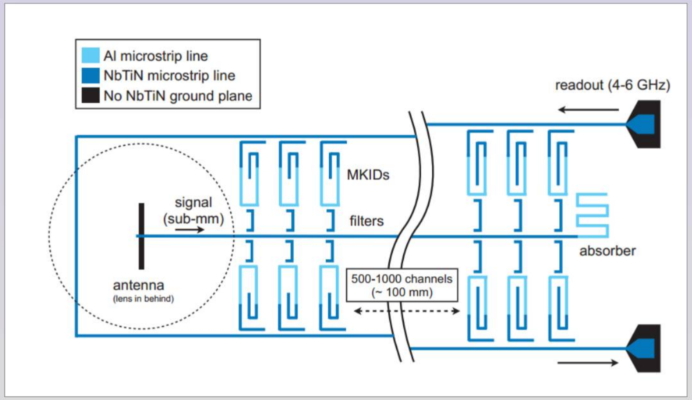
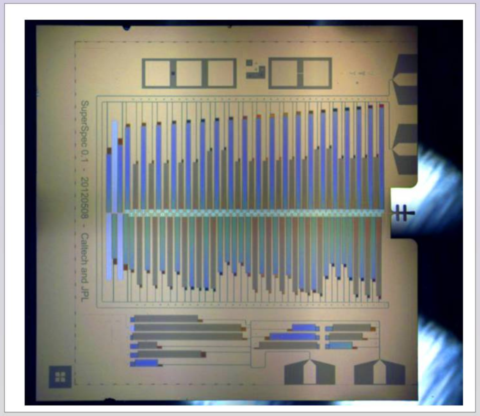
On-going developments for many bands

The next step: integrated planar spectrometers or polarimeters

DESHIMA



SUPERSPEC



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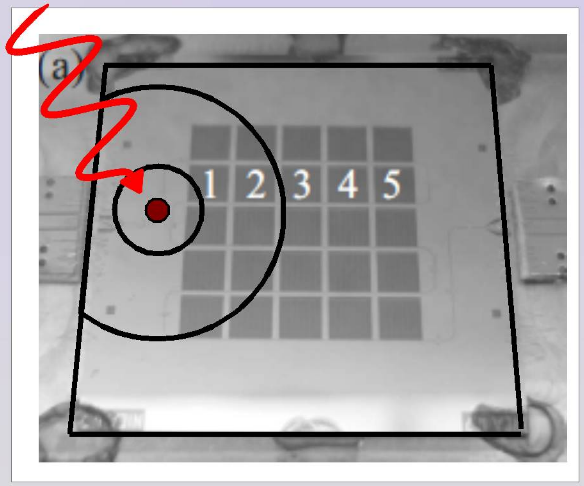
Phonon mediated detection

High energy particles hitting the substrate generate a cascade of athermal phonons

These can be then sensed using KID



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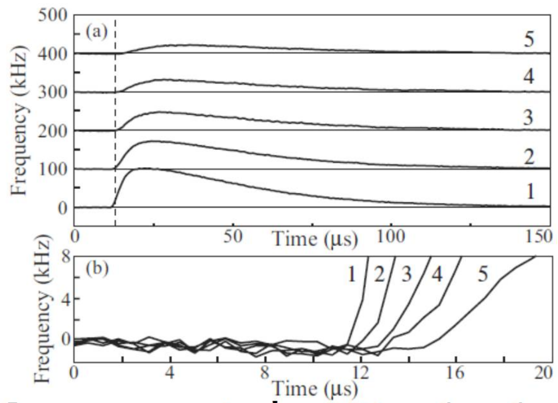


L. Swenson et al., APL 96, 263511

Info on delays + peak amplitude

↓

Reconstruct particle E and impact point

Rare events searches → ***CALDER***

KIDs on satellites → ***SPACEKIDS***

Ideal fields of application

- KID are perfectly suited for ***large arrays of ultresensitive detectors***
- But mind: *cryogenics is a must*!

Material properties

Can get information on the behaviour of materials at 100s of GHz

The KID resonances shape is determined by L_k and the residual R

→ gives info on penetration depth, losses...

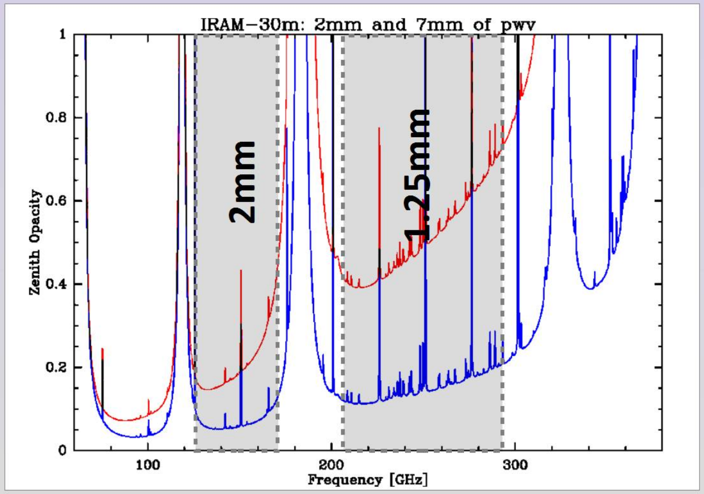
The NIKA 2 project

NIKA2: New IRAM KID Array 2

Aim: build an instrument to get the maximum out of the IRAM 30m telescope

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

- 30 m aperture → 17 arcsec @ 2mm; 10.5 arcsec @ 1.25mm
- Correct Field Of View up to 6.5 arcmin (NIKA: 2.5 arcmin)
- Measurements in multiple bands possible



One of the best telescopes for mm-wave astronomy!

The NIKA 2 project

Fully deploying the potential of the IRAM telescope means:

- Fully sampled 6.5 arcmin correct FOV
- Highest possible resolution
- Dual band operation (1.25 and 2 mm)
- Detectors at or near the photon noise limit
- Polarization sensitive at 1.25 mm

Pixels count:
1000 @ 2mm
2x 2000 @ 1.25mm

1000s of ultrasensitive pixels at millimetric wavelengths =

The ideal playground for KID!

A small step back: NIKA

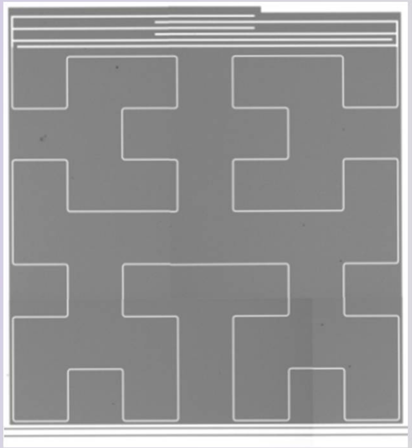
NIKA: a pathfinder instrument before going 'full scale'

2008-2012 NIKA development. KID improving rapidly!

2013 Commissioning of the instrument in its final configuration:

- *dual band (2mm and 1.25mm)*
- *total of > 300 pixel*
- *LEKID based on the Hilbert fractal geometry (2-pol)*

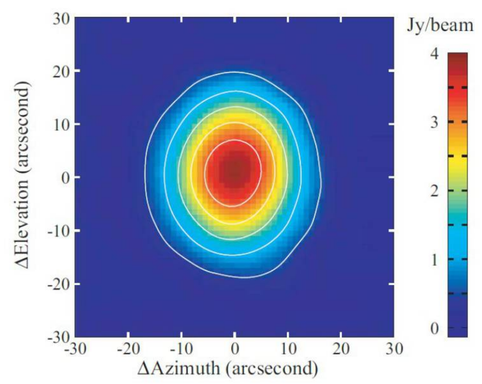
NEFD: 10 mJy $s^{0.5}$ @ 2mm, 35 mJy $s^{0.5}$ @ 1mm



2014 **NIKA is the world's first KID camera to open to external astronomers!**

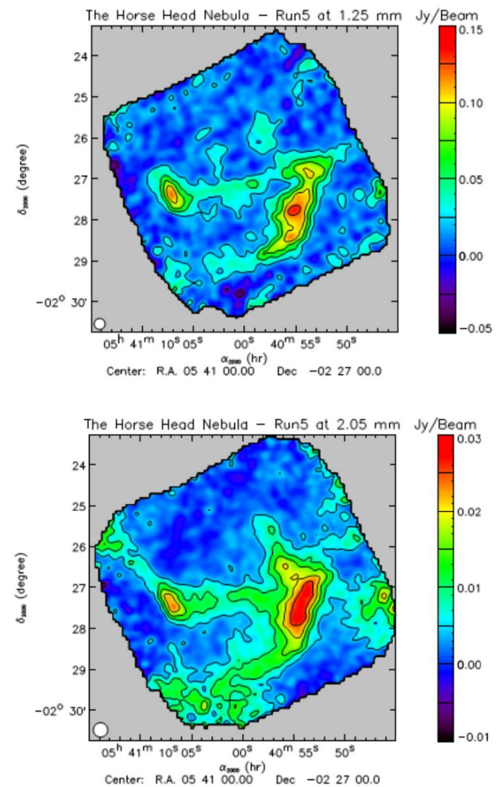
The NIKA history in images

2009



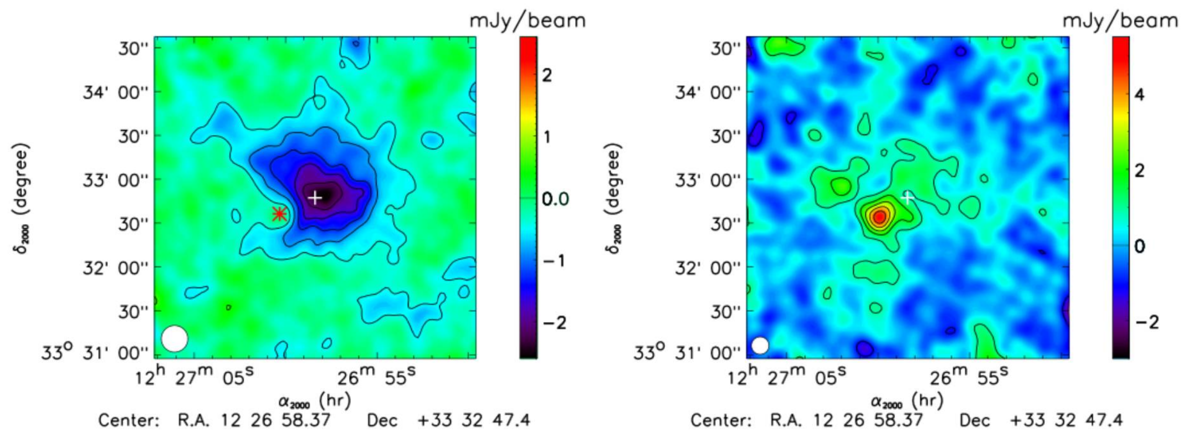
3c345 @ 2mm

2012



Horsehead nebula @ 1 and 2mm

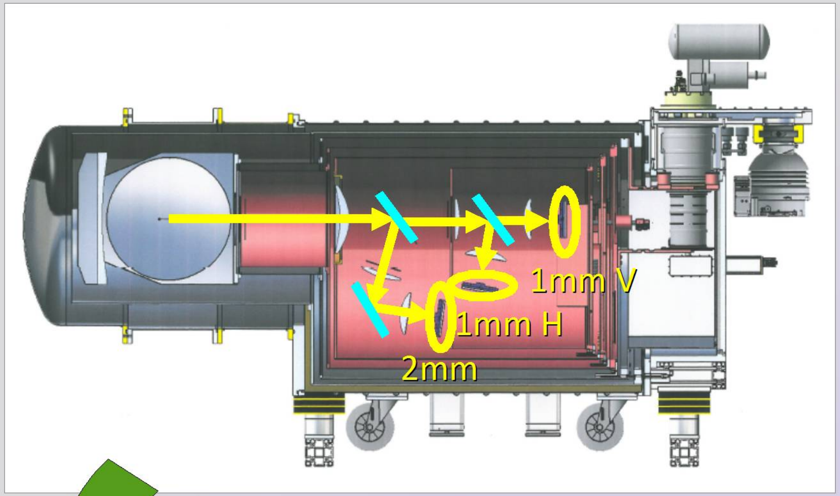
2014



S-Z galaxy cluster CL J1226.9+3332

R. Adam et al., A&A 576 A12, 2015

Current status of NIKA2: cryostat

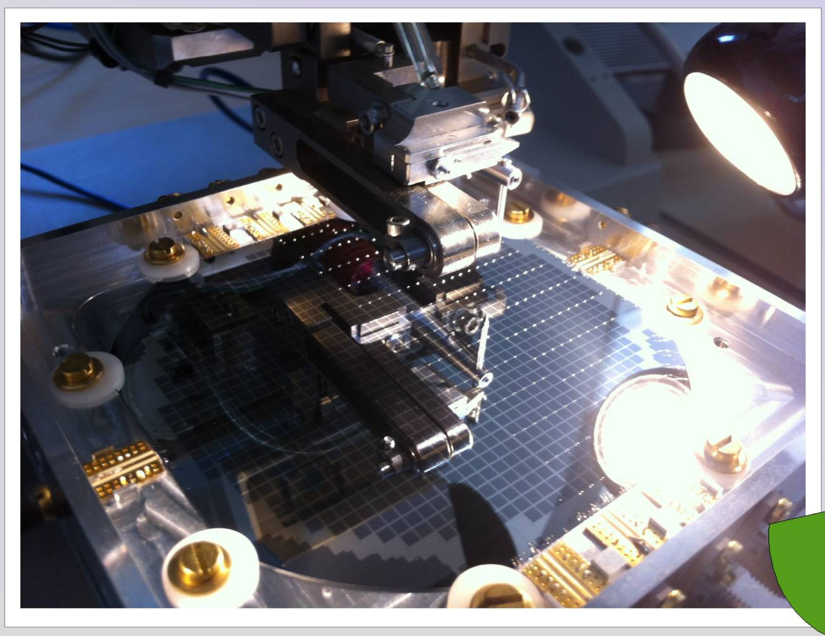


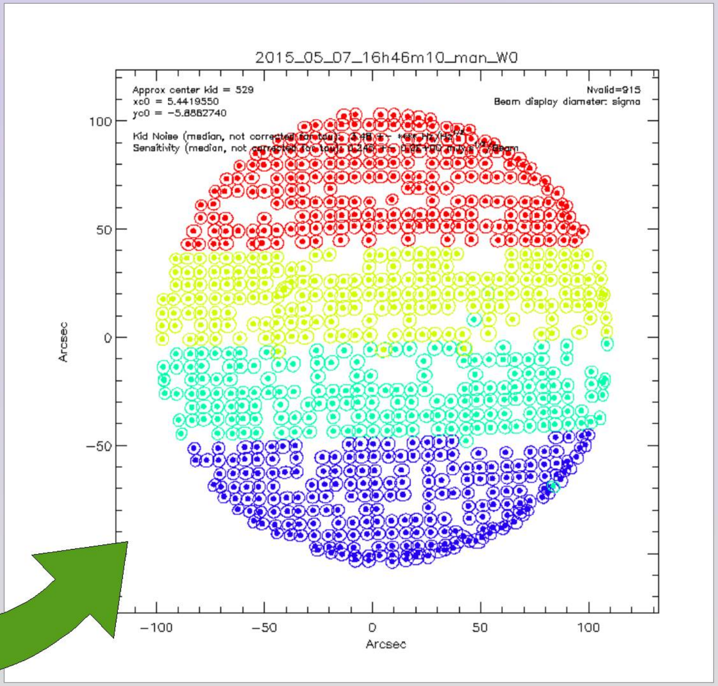
- Large focal plane → large cryostat
- ***2.3m length, 1m diameter, >1ton!***

- Already >20 cooldowns
- 'Debug phase' done
- All optics installed
- ***Cryostat ready!***

Current status of NIKA2: detectors

- Already many arrays fabricated, for both bands
- 20 RF lines installed and fully functional
- New electronics board under final development (more compact and less power hungry wrt NIKA1)
- Optical test of the arrays in the final configuration are ongoing





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Everything looks **very** promising! Taking care of final details...

09/2015 Installation at IRAM!

(Perfectly on time...)

Conclusions

- KID have evolved very fast since their proposition in 2003
- In little over 10 years, they have already reached a very good maturity level
- Today, KID represent a viable alternative for many applications looking for large format arrays of cryogenic detectors
- They are 'cheap, rugged and easy to make'
- NIKA and NIKA2 are preminent example of what can be achieved using KID arrays
- So, if they are good for your application, ***why not going for it?***

Thank you!

If you want to read further...

Theses (just a few samples) :

B. Mazin, *Microwave Kinetic Inductance Detectors*
S. Doyle, *Lumped Element Kinetic Inductance Detectors*
P. de Viesser, *Quasiparticles dynamics in Aluminum superconducting resonators*
A. D'Addabbo, *Applications of KID to astronomy and particle physics*

Review papers :

J. Zmuidzinas, *Superconducting Microresonators,* Ann Rev Cond Mat Phys (2012)
J. Baselmans, *Kinetic Inductance Detectors,* J Low Temp Phys (2012)

NIKA+NIKA2 :

A. Monfardini et al., *Latest NIKA Results and the NIKA-2 Project,* JLTP 176, 787
M. Calvo et al., *Improved mm-wave photometry for KID,* A&A 551, L12
A. Catalano et al., *Introduction to Superconductivity,* A&A 569, A9