# Kinetic Inductance Detectors

- INTRINSICALLY MULTIPLEXABLE
- FABRICATION MUCH EASIER
- NEW CONCEPT, STILL TO BE STUDIED

**Which applications ?**

| | |
|---|---|
| - mm and sub-mm wave astronomy | DEFINITELY YES |
| - high energy resolution X-rays | PROBABLY NOT |
| - Optical Astronomy | POSSIBLE, but ... |
| - Dark matter and Neutrino | PROBABLY YES |
| - ....many others to be proposed... | SURE |

# Multiplexing schemes

## TIME-DOMAIN

Reading-out one detector at a time.

***Examples:***
- TES (NIST, APC, Germany)
- Semiconductor bolometers
e.g. CEA for Herschel, Néel for NbSi bolometers

**ADVANTAGE: simple**
**DRAWBACK: few, «slow» pixels***

*** Remark valid for LTDs only.**

## (RADIO) FREQUENCY-DOMAIN

Each detector is associated to a frequency $f_i$.

$f_i$; i=1,2 …. N

Each detector has a $\Delta f$ available (speed).
**→ N·$\Delta f$ is roughly the total band we need.**

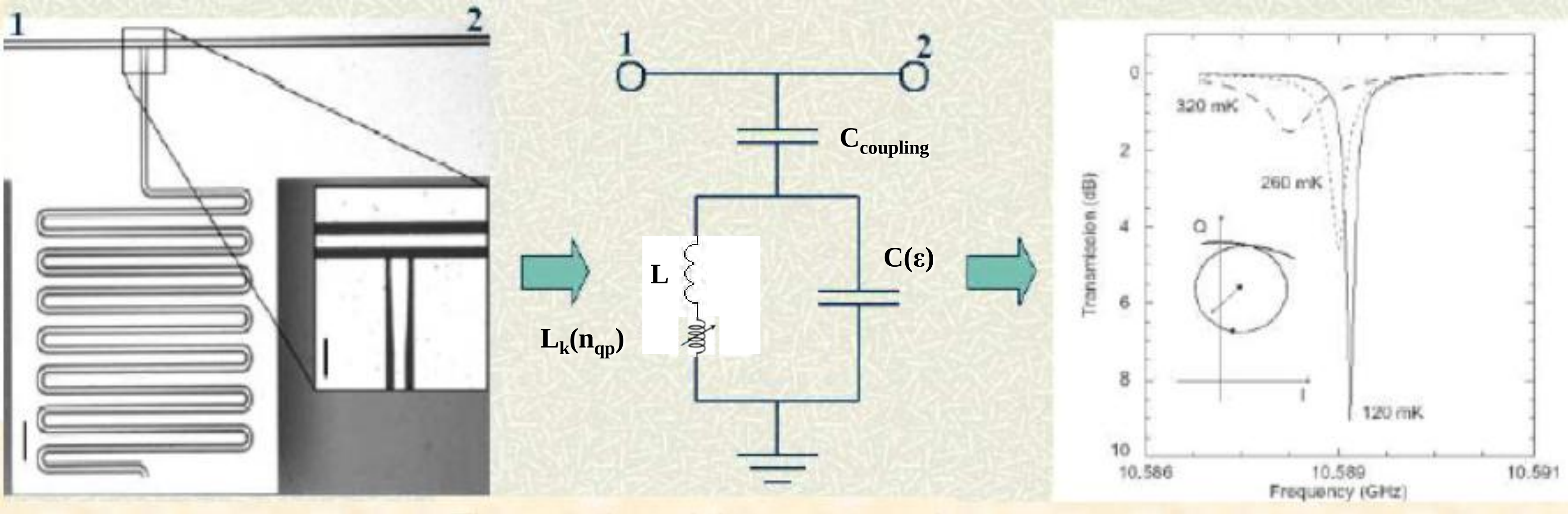
If N and/or $\Delta f$ is large (usually desired)
→ Need enough space in frequency domain
**→ RF (pixels broadcast)**

e.g. $\Delta f$ =1MHz, N=1000 → 1GHz

**ADVANTAGE: many, «fast» pixels**
**DRAWBACK: ?? Let see ??**

# High Quality Factor Superconducting Resonators

# Kinetic Inductance "Detectors"



**MULTIPLEXING FIRST !! RF and f-DOMAIN IS THE BEST OPTION. HOW ?**

**High MUX factor → closely packed in f →**

**Resonating structures (high Q) →**

**SUPERCONDUCTORS $T<<T_c$**

**Parallel C-coupled resonators ≡ MUX scheme ≠ Detectors**

**Can the MUX scheme be transformed into a Detector ? DEFINITELY !**

# Some typical dielectric waveguides

Comparison

← No cut-off frequency →

← homogenous

⇒ no dispersion

⇒ no impedance mismatch

inhomogenous →

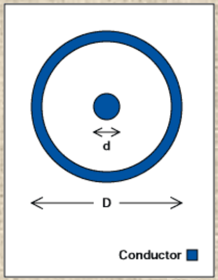
⇒ $\varepsilon_{eff}$ and $Z_0$ depend on frequency

⇒ dispersion and impedance mismatch

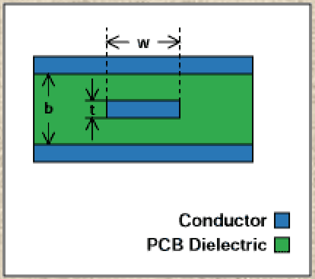
← Good isolation between adjacent traces can be achieved

Can be fabricated using planar technology →

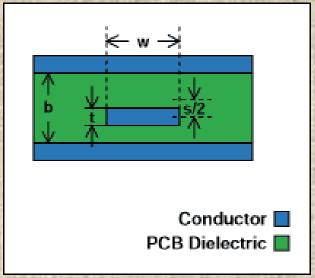
Are sensitive on the material above →



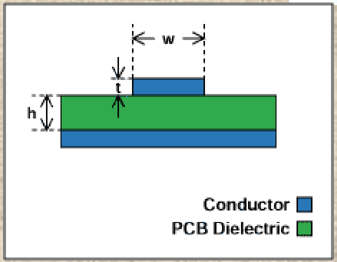
Coaxial line



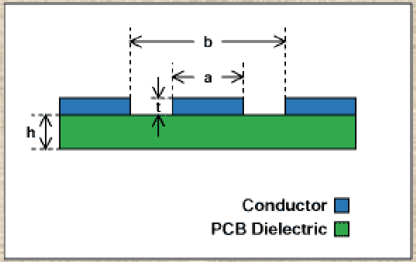
Centred stripline



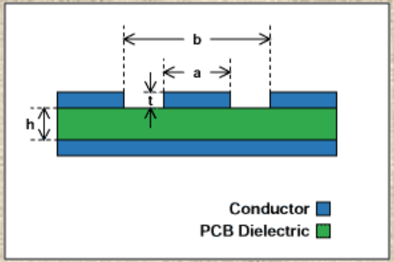
Off-centred stripline



Microstrip line



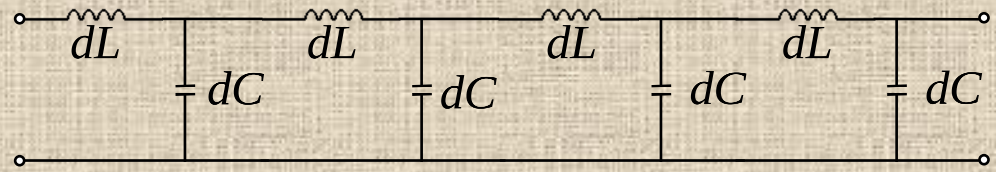
Coplanar waveguide



Grounded coplanar waveguide

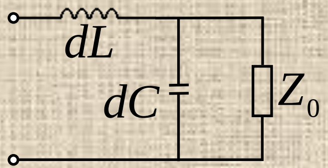
# Transmission lines

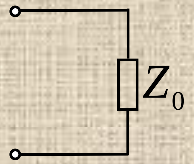
Each transmission line can be represented as series inductances and shunted capacitances



$$dL = \mathcal{L}\,dl,\ [\mathcal{L}] = \frac{H}{m}$$

$$dC = \mathcal{C}\,dl, [\mathcal{C}] = \frac{F}{m}$$





From this approximation we can extract some useful relations:

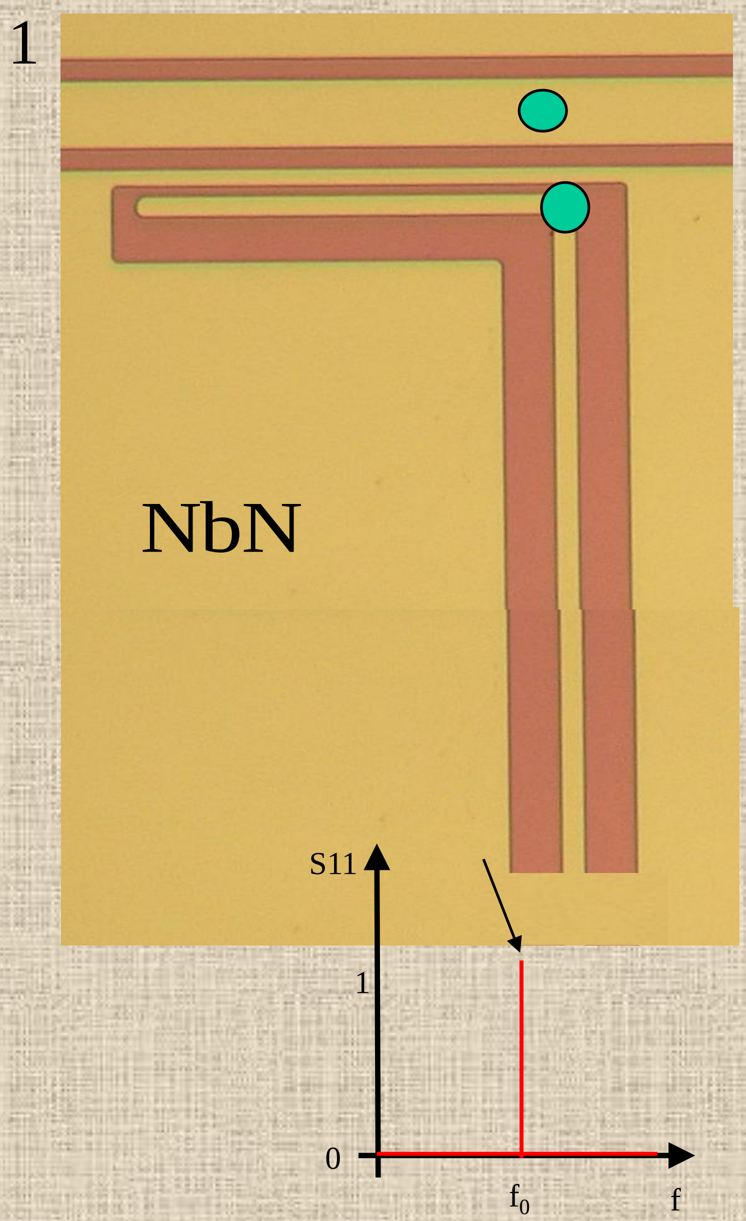
Characteristic impedance: $Z_0 = i\omega dL + \dfrac{1}{i\omega dC + {}^{1}\!/\!_{Z_0}} \Rightarrow \ Z_0 = \sqrt{\dfrac{\mathcal{L}}{\mathcal{C}}}$

Phase velocity: $v_{phase} = \dfrac{1}{\sqrt{\mathcal{L}\mathcal{C}}} = \dfrac{c}{\sqrt{\varepsilon_{eff}}} = \dfrac{\omega}{k}$

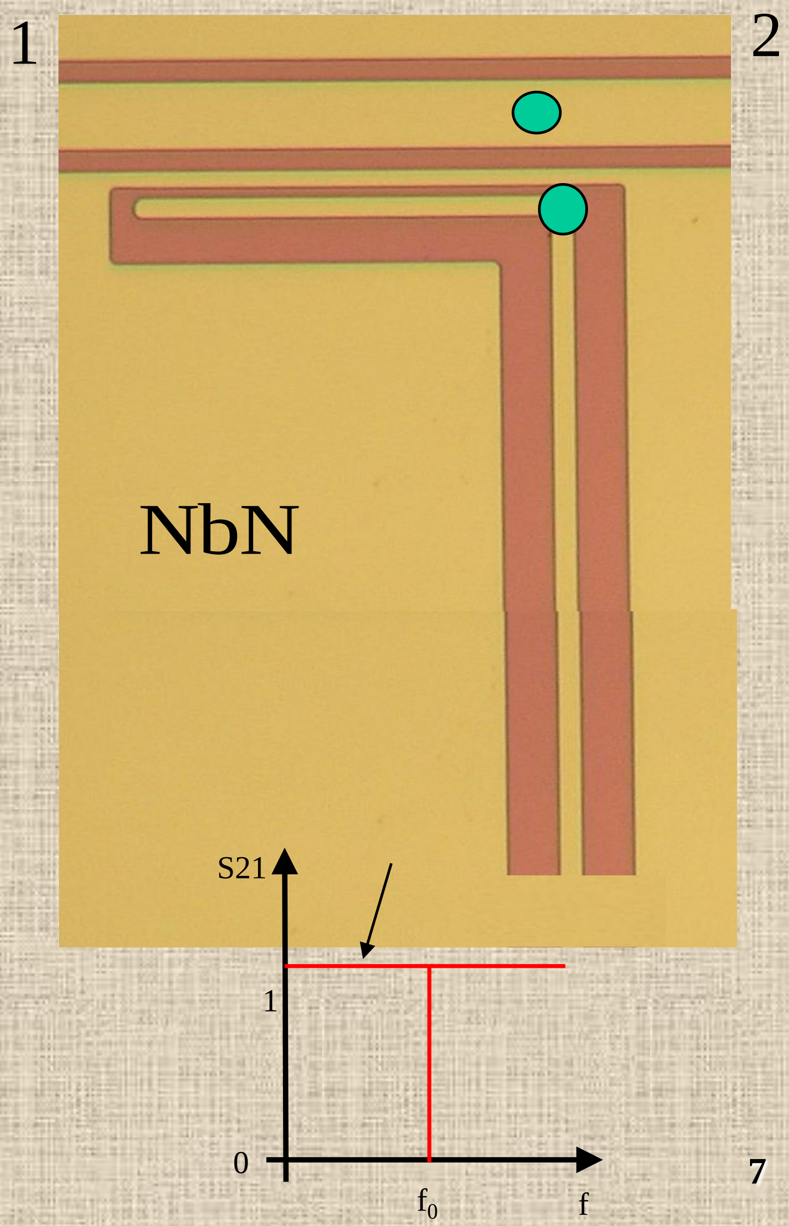
Some typical values: $\mathcal{L} \approx 250\,{}^{nH}\!/\!_{m}$ and $\mathcal{C} \approx 100\,{}^{pF}\!/\!_{m}$

$Z_0 = 50\Omega;\ v_{phase} = 2 \cdot 10^8 = 0{,}7c$

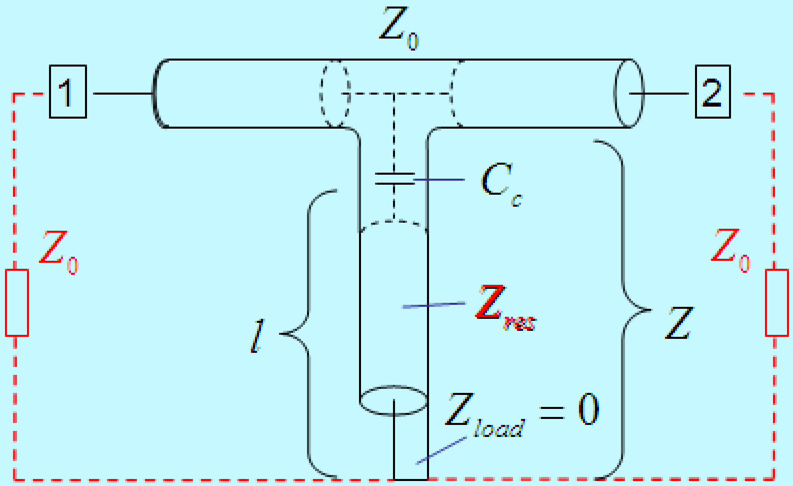
## ON RESONANCE: |S11|=1



## OFF RESONANCE: |S21|=1



# High-Q resonators



Dissipation of energy due to:

- Loss in the resonating transmission line (dielectric and superconductor) → $Q_i$
- The resistance $Z_0$ at both ports → $Q_C$

$$S_{21} = \frac{S_0 + 2iQ_0\delta x}{1 + 2iQ_0\delta x}.$$

$$Q_0 = \frac{Q_c Q_i}{Q_c + Q_i} \qquad S_0 = \frac{Q_c}{Q_c + Q_i}$$

**Total (measured) Q factor and minimum transmission.**

$$f_0 \cong \frac{1}{4l\sqrt{\underbrace{(L_K + L_G)}_{\mathrm{L_{tot}}}C(\epsilon)}},$$

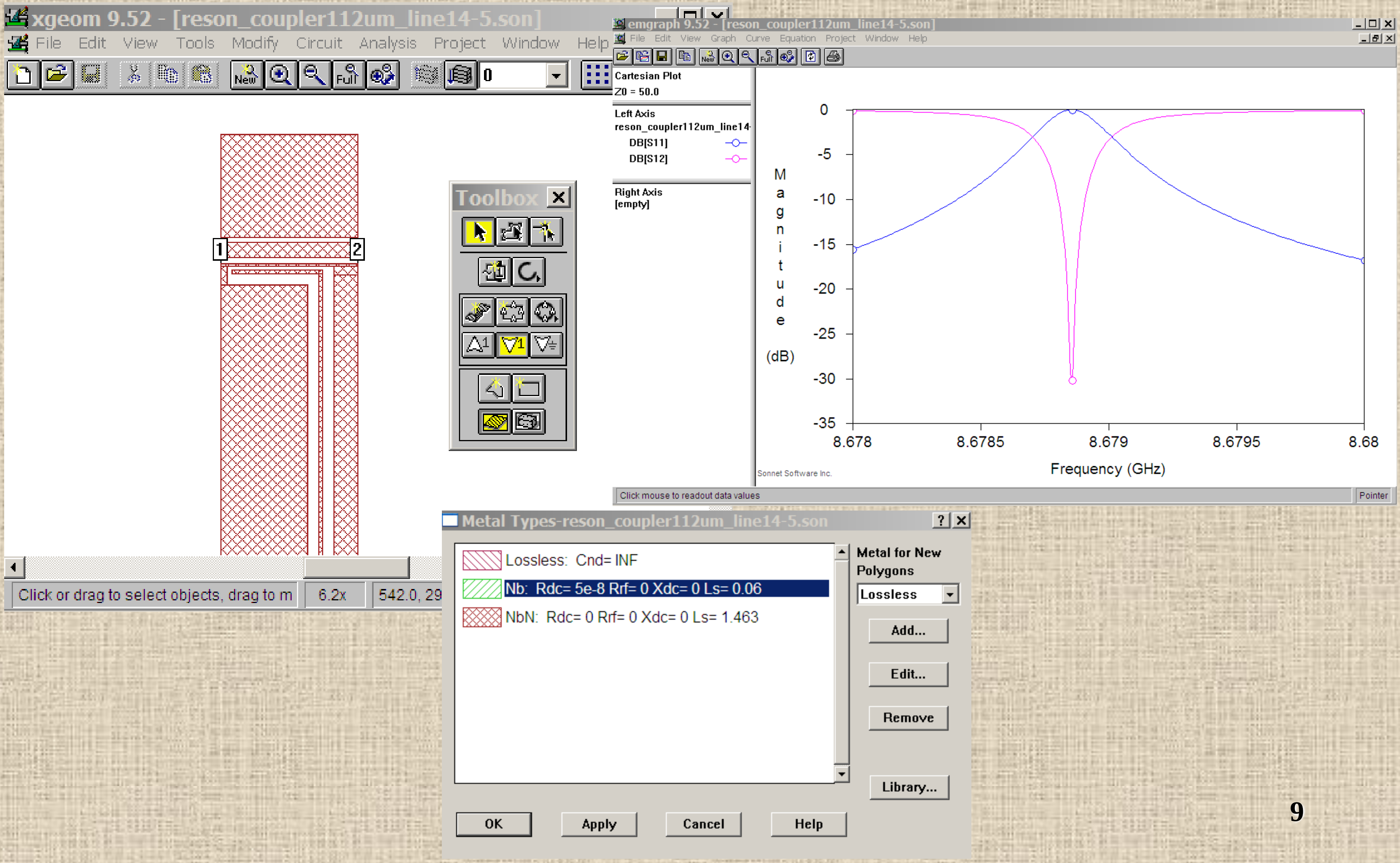
## Resonating frequency

Linear dependence on l. *Assuming:*

**$\Delta l/l = 10^{-4}$ ($\Delta l = 2\mu m$; $l = 20mm$) = $\Delta f/f$**

→ **$\Delta f$ = 0.4 MHz @ f = 4 GHz**

# Main design tool: SONNET



Click or drag to select objects, drag to m

6.2x

542.0, 29

Cartesian Plot

Z0 = 50.0

Left Axis

reson_coupler112um_line14

DB[S11]

DB[S12]

Right Axis

[empty]

Click mouse to readout data values

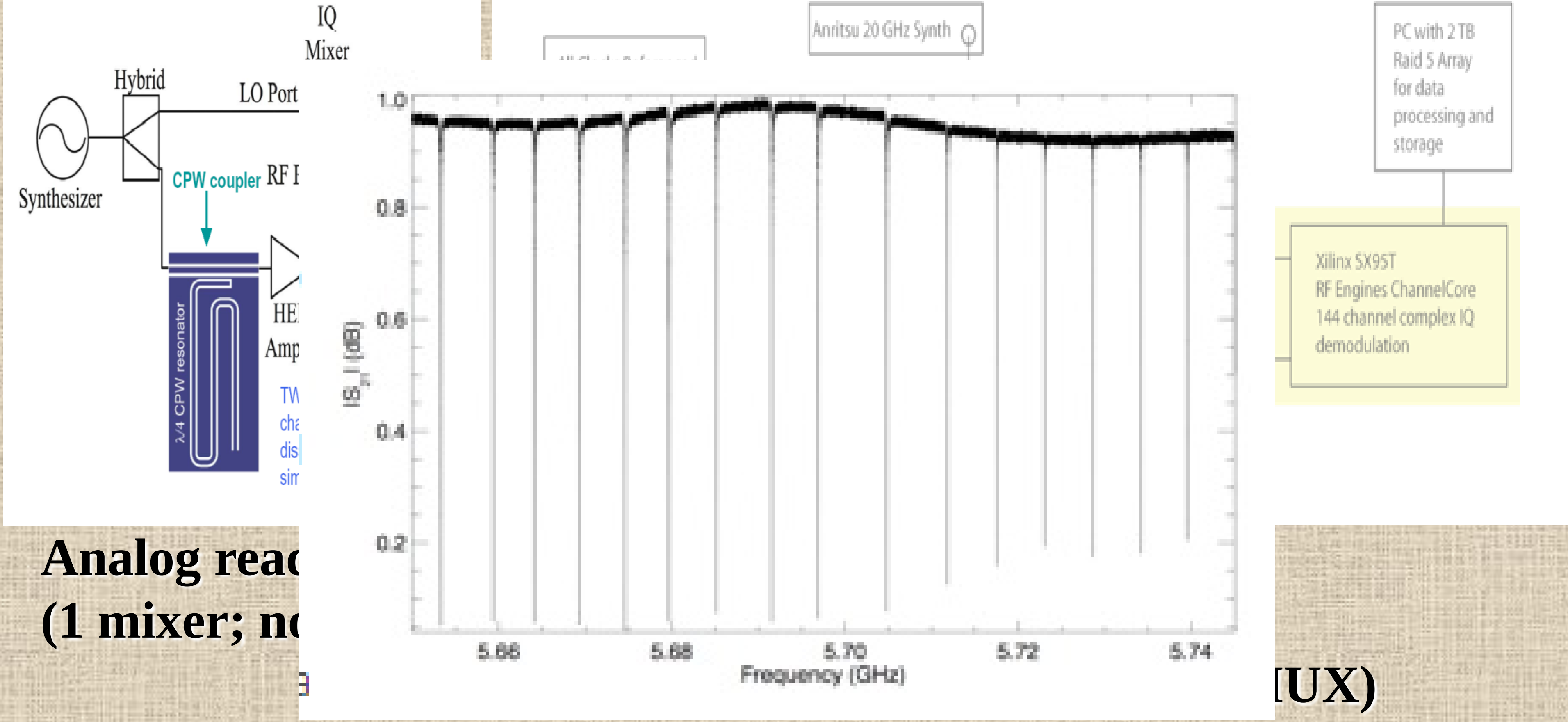
Lossless: Cnd= INF

Nb: Rdc= 5e-8 Rrf= 0 Xdc= 0 Ls= 0.06

NbN: Rdc= 0 Rrf= 0 Xdc= 0 Ls= 1.463

Metal for New Polygons: Lossless

# Readout



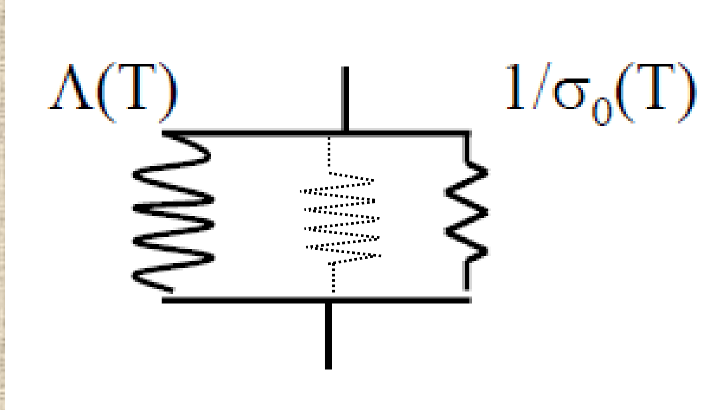
**Analog reac**
**(1 mixer; nc**

**UX)**

# KINETIC INDUCTANCE DETECTORS

# Two-fluid model

**Supercarriers** **Additional losses ($Q_i$)** **Normal carriers**



Supercarriers Normal carriers

Actually $N_n \sim e^{-\Delta/kT}$

Cooper pairs

« quasi-particles »
(un-paired electrons)

$$Z_{tot} = 1/(1/R_n + 1/i\omega L + 1/R_{losses})$$
$$Z_{tot} \rightarrow 0 \text{ if (and only if due to } R_{losses}\text{) } \omega \rightarrow 0$$

**Model:** two separate populations of current carriers co-exist in a finite T superconductor. So each superconducting strip is seen as a parallel of « normal resistance » (quasi-particles) and « super-inductance » (Cooper pairs).

In AC the « super-inductance » is no longer a zero impedance shunt

**→ Quasi-particles losses for any finite T superconductor in AC.**

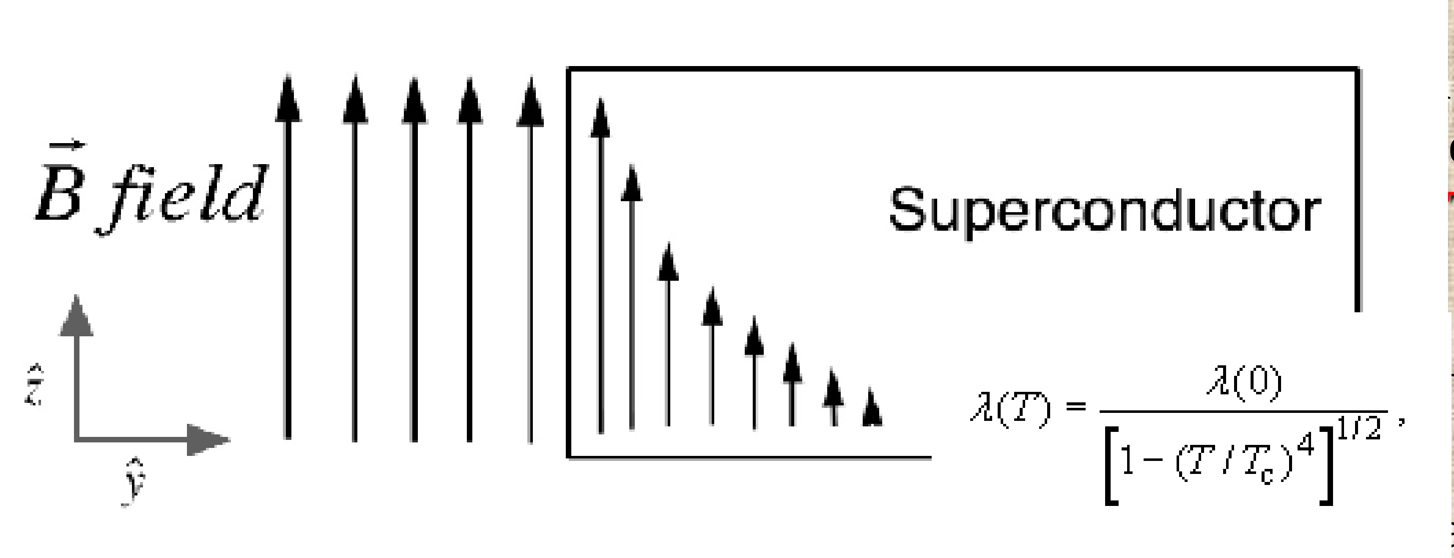
**→ Additional losses (e.g. dielectrics) always present to limit $Q_i$ even at T→0**

# Kinetic Inductance: we have a detector !!

**When** **the B**
**field (** **ed to**
**actua** **TIC**
**INDU**

$E$ $V$

**$L_k$ is** **anar**



$$L_K = \frac{\mu_0 \lambda(T)^2}{l} \int \frac{j_s^2}{I^2} dV, \approx \mu_0 \frac{\lambda(T)^2}{l \cdot t}$$

**lines), $L_k$ depends on the penetration length λ, the quasi-particles concentration and so, finally, the flux of Cooper-pair breaking photons hitting the slab.**

**→ MUX IS SEEING LIGHT**

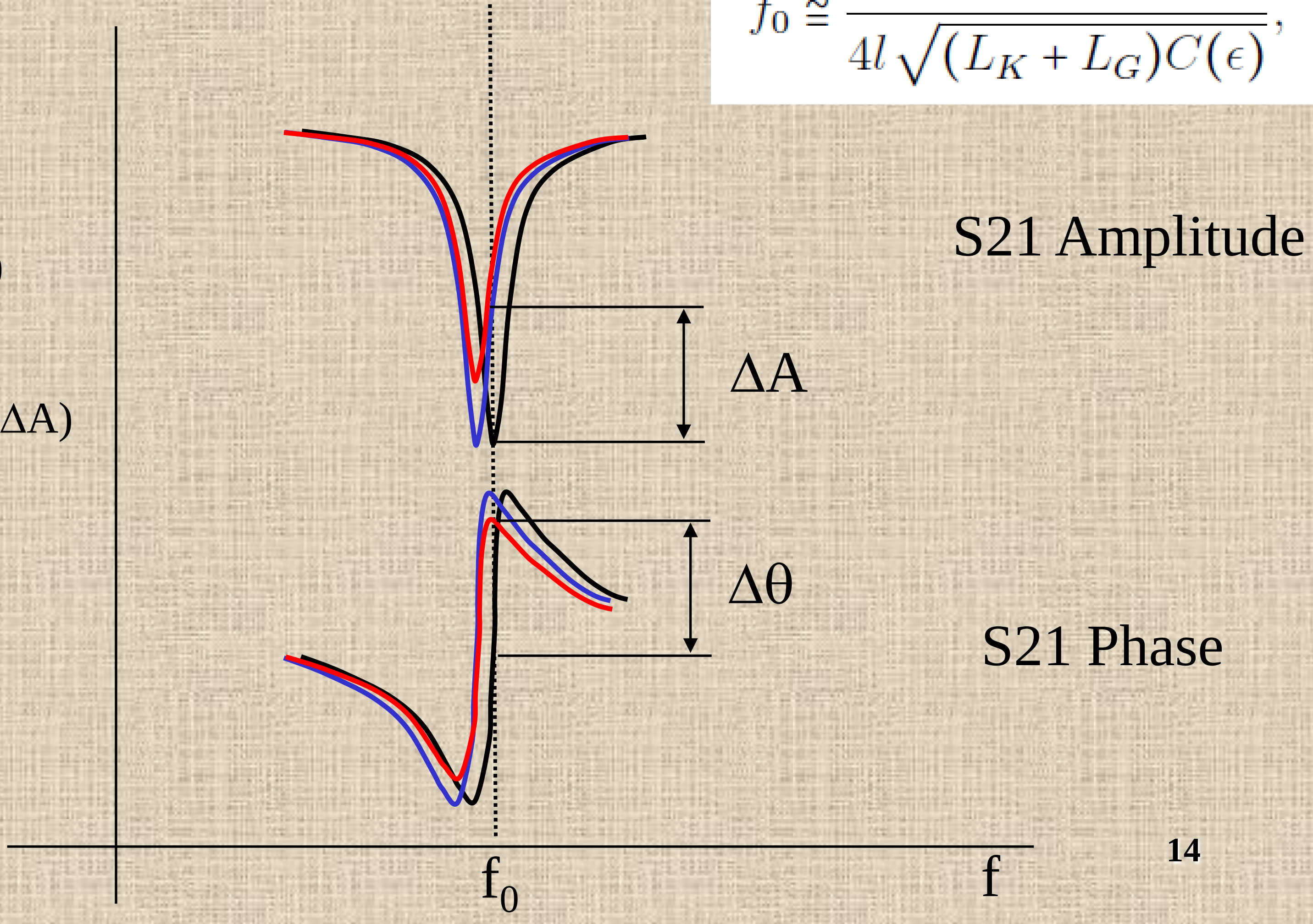
# Switch on the light

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

Dark, T<<Tc

Light: increase in $L_k$
Change in phase (Δθ)

Light: increase in R
Change in amplitude (ΔA)



A superconducting resonator is very sensitive to

- **the kinetic inductance (strictly speaking KIDs)**

  → photon detection (ONLY if incident radiation $h\nu > 2\cdot E_{gap} \approx 3.6\cdot kT_c$)

  → temperature dependence (if $T > 0.2\cdot T_c$ … otherwise not so sensitive)

  → measurement of the penetration depth $\lambda_L$ (if T > 0.2·Tc … otherwise frozen at $\lambda_0$)

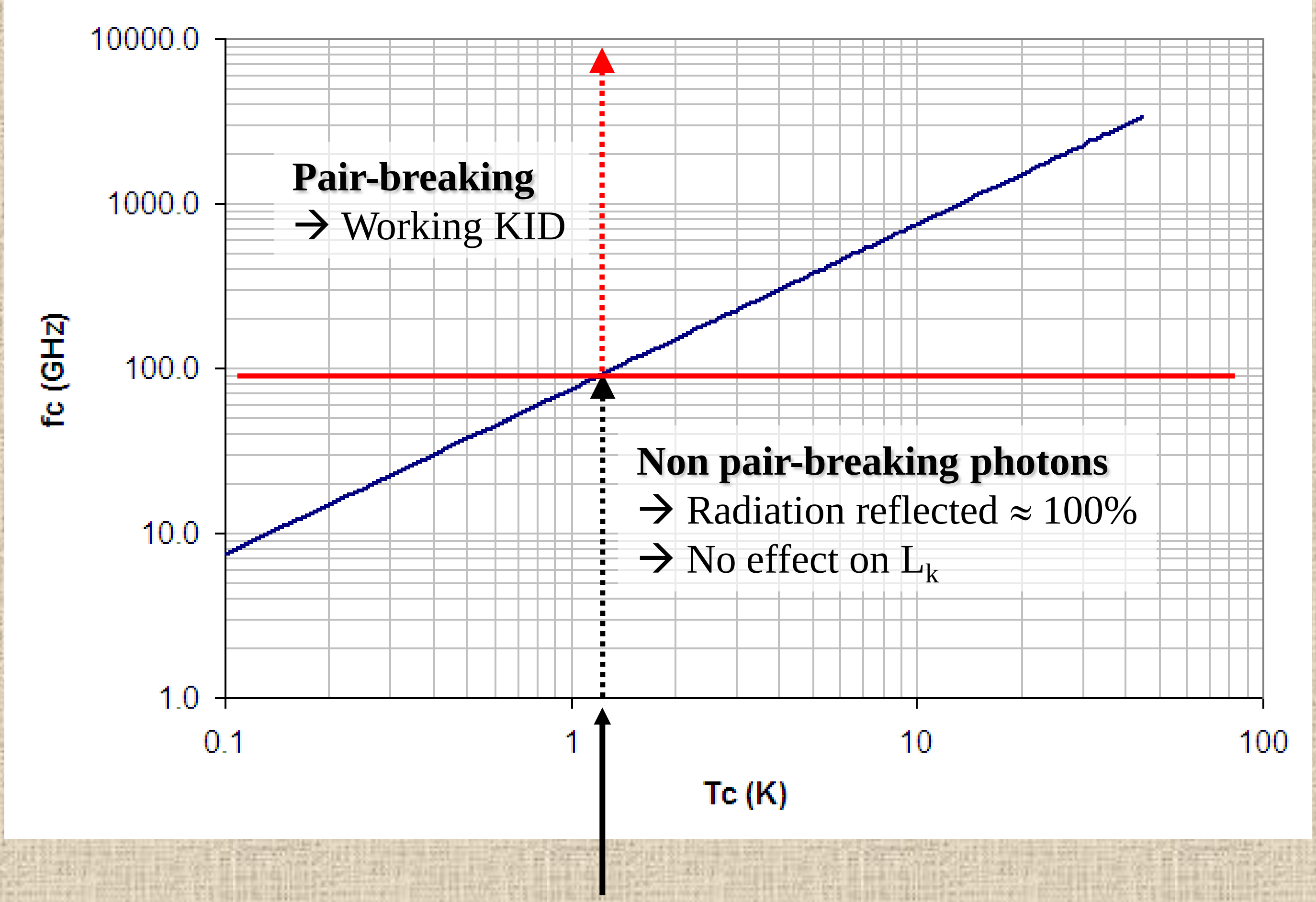
- **the EM environment**

  → characterization of materials and the change of $\varepsilon_r$ with temperature

  → measurement of the loss tan $\delta$ in the surrounding dielectric medium and of the attenuation constant $\alpha$. Sensitive to losses in the ground plane.

  → small changes in the geometry (e.g. nano-mechanics, hydrodynamics)

# MATERIALS FOR LOW-ENERGY PHOTON DETECTIONS



**Pair-breaking**
→ Working KID

**Non pair-breaking photons**
→ Radiation reflected ≈ 100%
→ No effect on $L_k$

**e.g. Al**

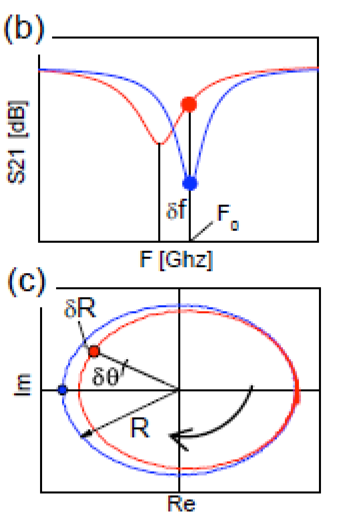
***Examples:***

Ti → $f_c \approx$ 40GHz
Al → $f_c \approx$ 90GHz
Re → $f_c \approx$ 130GHz
Ta → $f_c \approx$ 340GHz
Nb → $f_c \approx$ 700GHz
NbN → $f_c \approx$ 1.2THz
…

# Sensitivity

***__Two possible measurements on the complex S21 (transmission) plane:__***

**radius (amplitude) and azimuth (phase).**



$$\delta\theta = [2Q_i^2/(Q_i + Q_e)](\delta f/f_0) \cong 2\cdot Q\cdot(\delta f/f)$$

**The Q factor and the resonator volume determine directly the sensitivity.**

$$\frac{d\theta}{dN_{qp}} = 1.63 \times 10^{-7}\frac{\alpha Q}{V},$$

**Al**

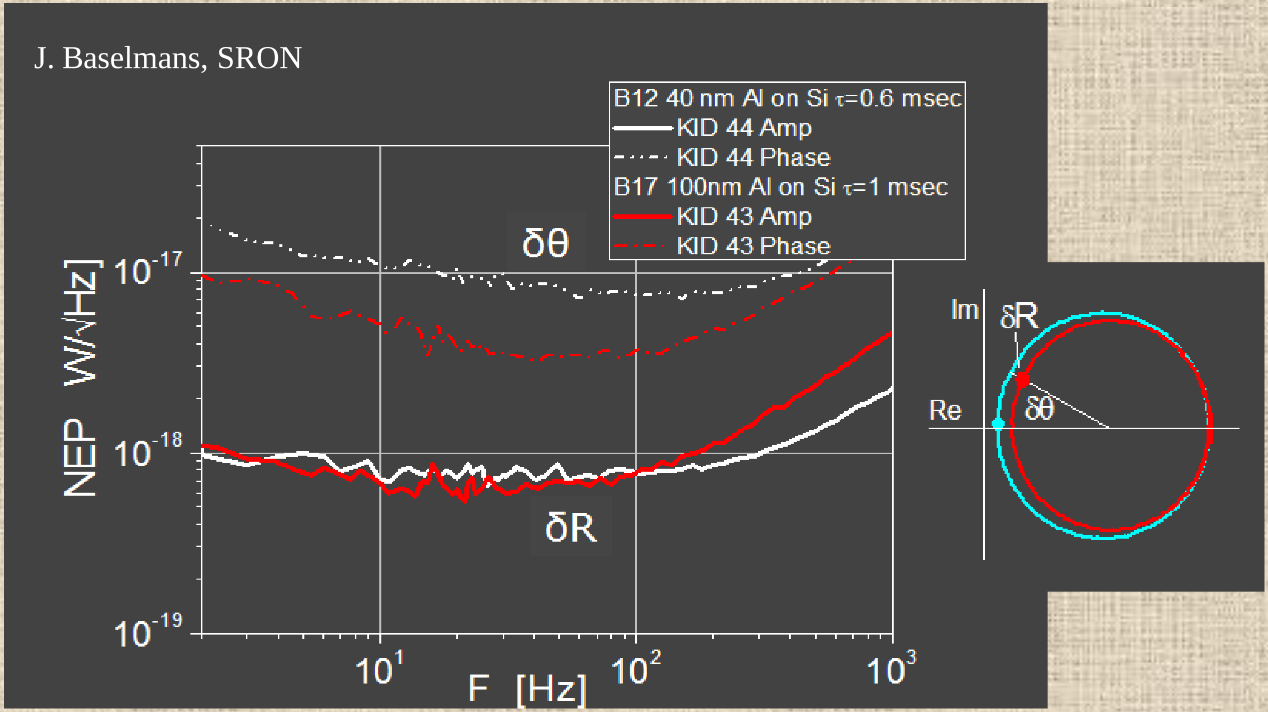
**B. Mazin, PhD thesis, Caltech 2004**

Noise Signal

$$\mathrm{NEP} = S_x(\omega)\cdot\left(\frac{\eta\tau_{qp}}{\Delta}\frac{\partial x}{\partial N_{qp}}\right)^{-1}\cdot\sqrt{1+\omega^2\tau_{qp}^2}$$

→ **high-Q (film quality, design), low V (design, technology), long $\tau_{qp}$ (film quality, impurities … still unclear)**

# Noise: phase vs. amplitude read-out

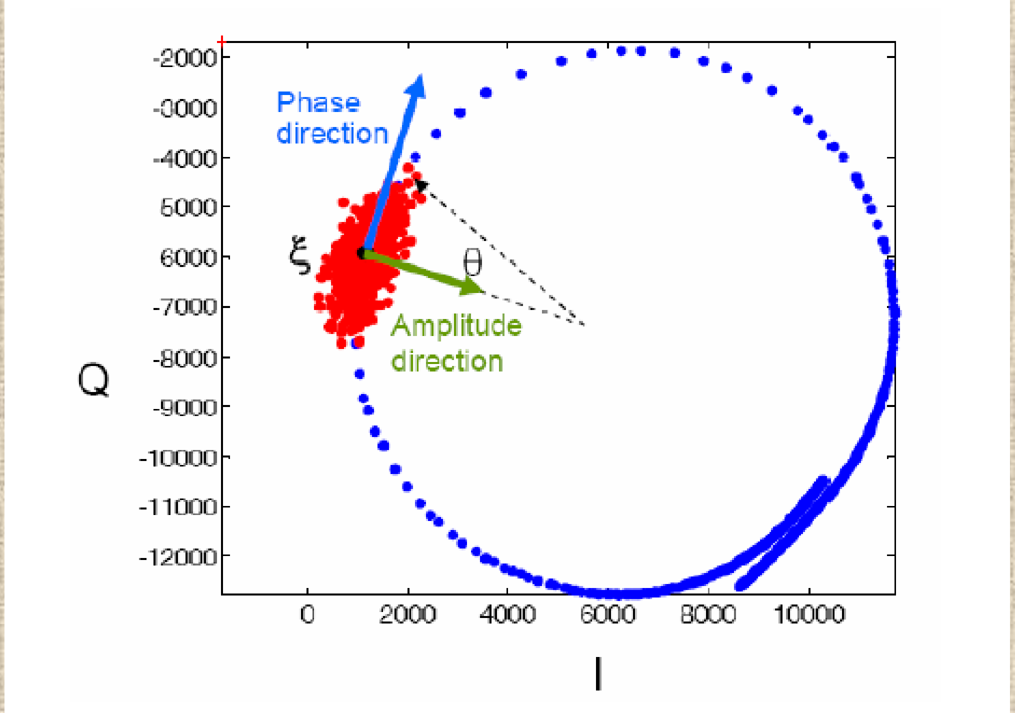


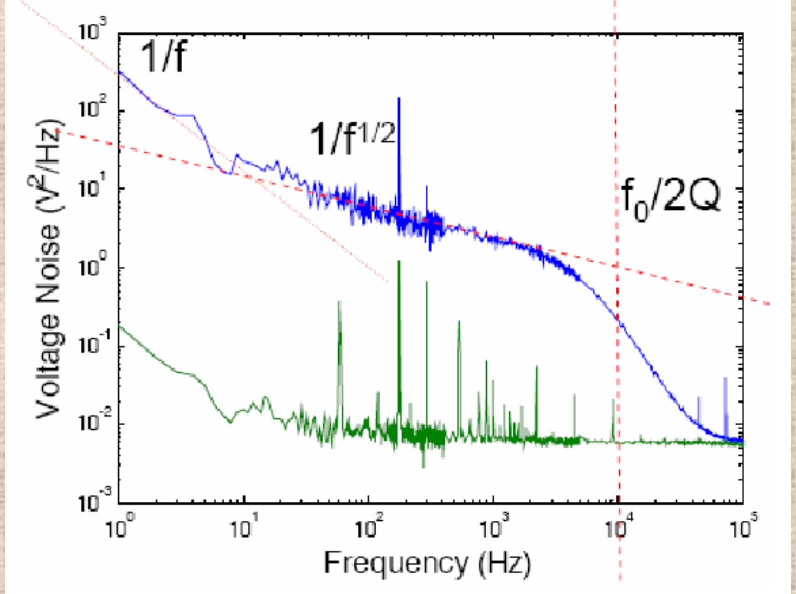
Still some **excess noise** in phase readout.
New results seem to indicate it's originating at the **metal/substrate interface** **(but where ?).**

Amplitude read-out already OK for many applications (e.g. ground-based)
However, for pushing S/N to the limit it is better to **understand and kill** the phase noise.

Barends et al., Applied Physics Letters, 92, Issue 22, 223502 (2008)

# Excess Phase Noise





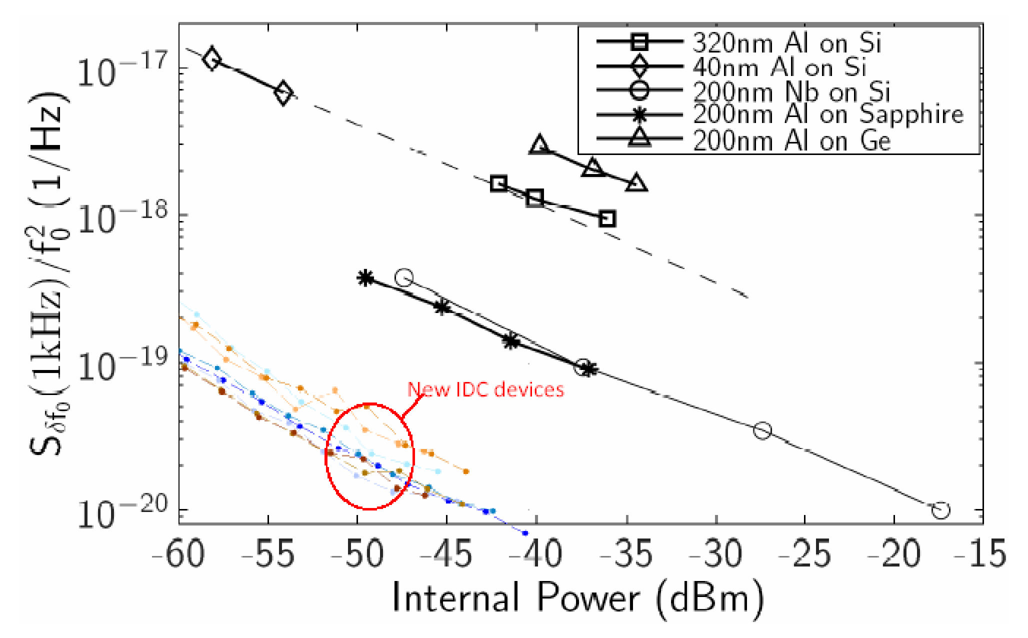
*Credit: Omid Noroozian, Caltech (2008)*

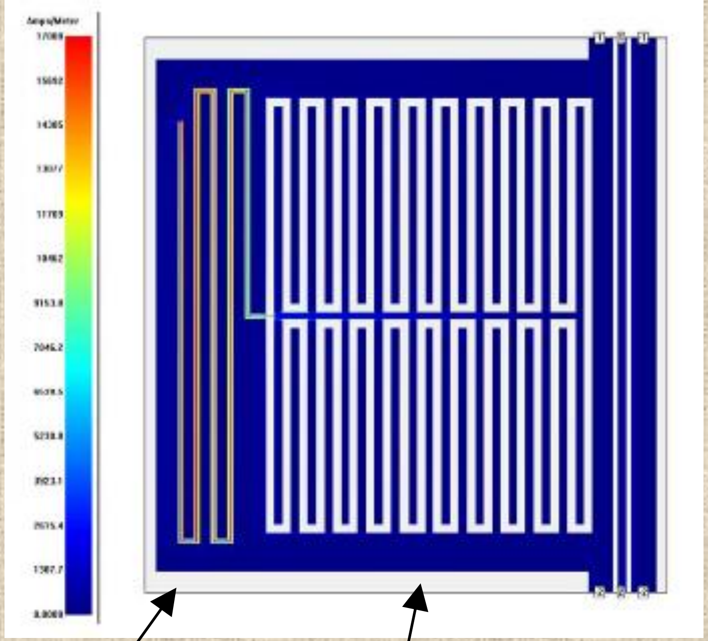
**A semi-empirical model now available !!**
**Work mainly carried out in the US.**

# Excess Phase Noise: first hints

To reduce ***noise***: make **fat** CPW near the coupler end.

To maintain high ***sensitivity***: make **narrow** CPW near short circuit to have higher sensitivity.



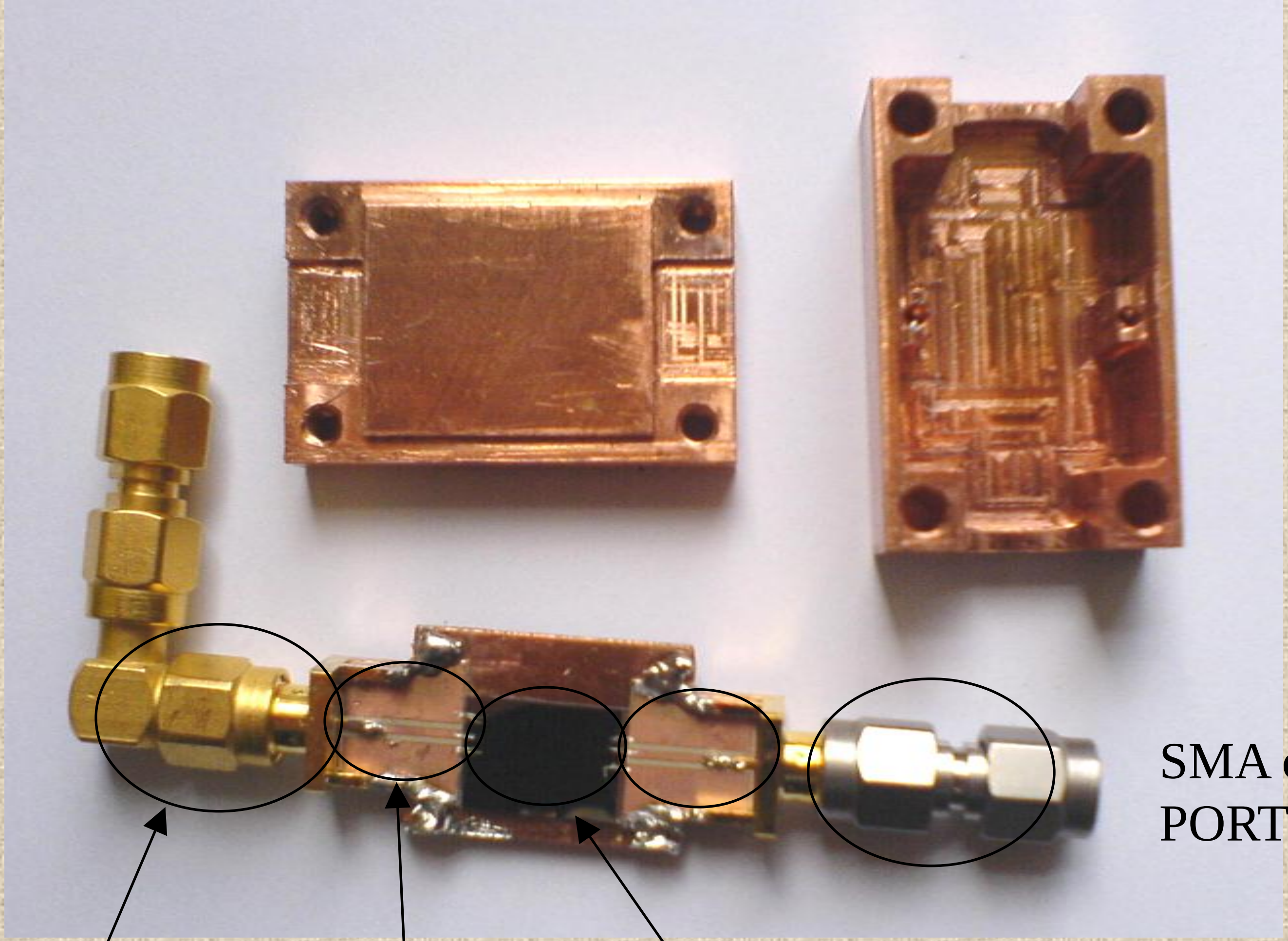


*Credit: Omid Noroozian, Caltech (2008)*

λ/4 resonator

Interdigitate C

# KIDs packaging



SMA connector
PORT 2

SMA connector
PORT 1

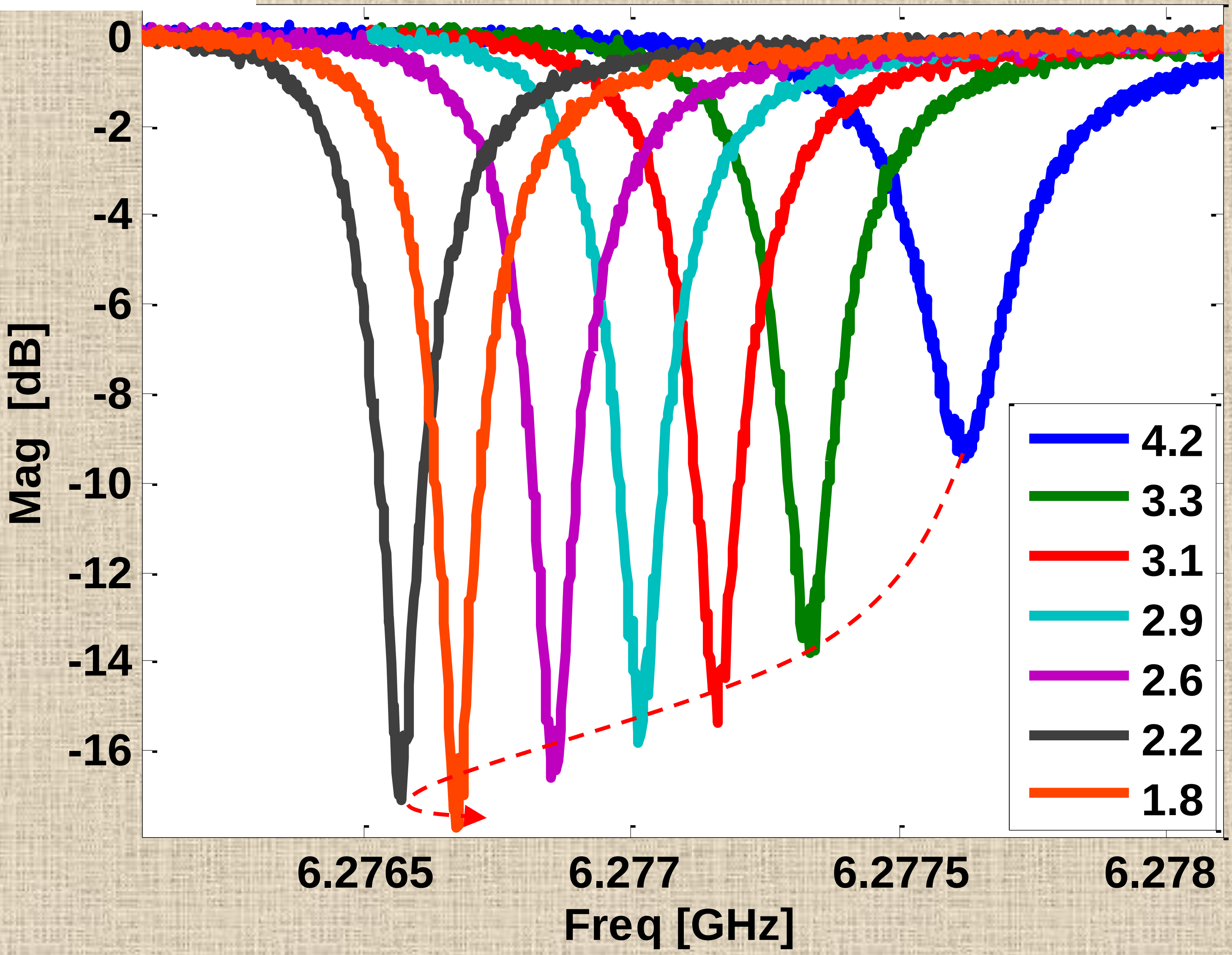
50Ω launcher
(coax-to-planar transition)

Chip with many resonators

# NbN resonators on Sapphire ( 1.8 K < T < 4.2 K )

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

Mag vs. Freq, in dependence of Temp



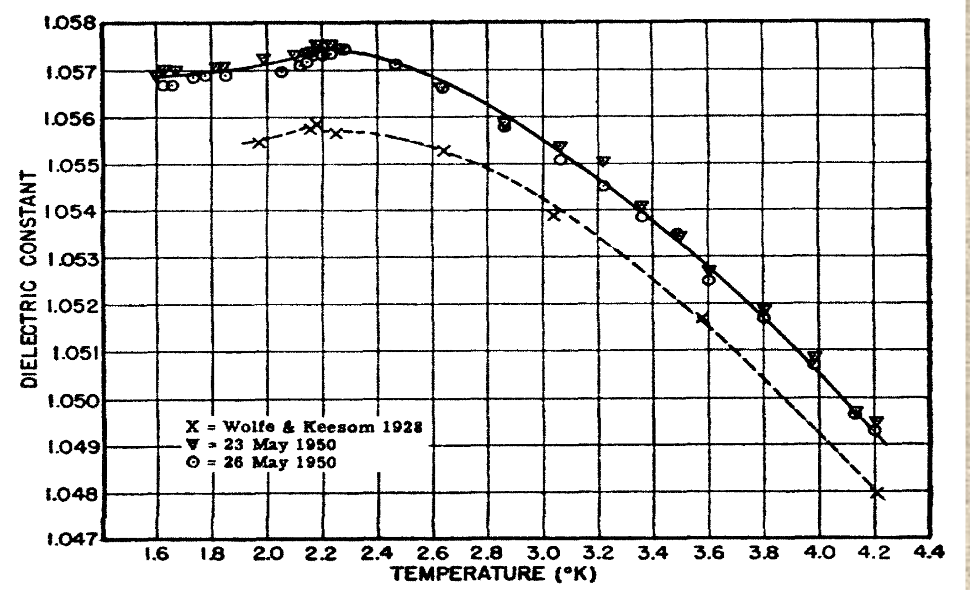
# A very interesting effect

The amplitude and the different quality factors don’t show anything special.

But the frequency points clearly an effect.

Solution: Let’s see what people did in 1950 (Phys. Rev.,Vol.80 Nr.8 Page 89,1950)

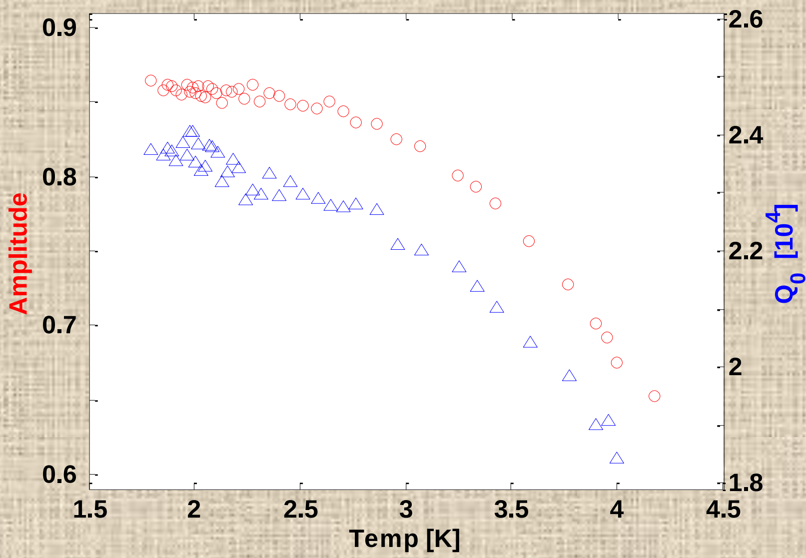
**The Dielectric Constant of Liquid Helium**



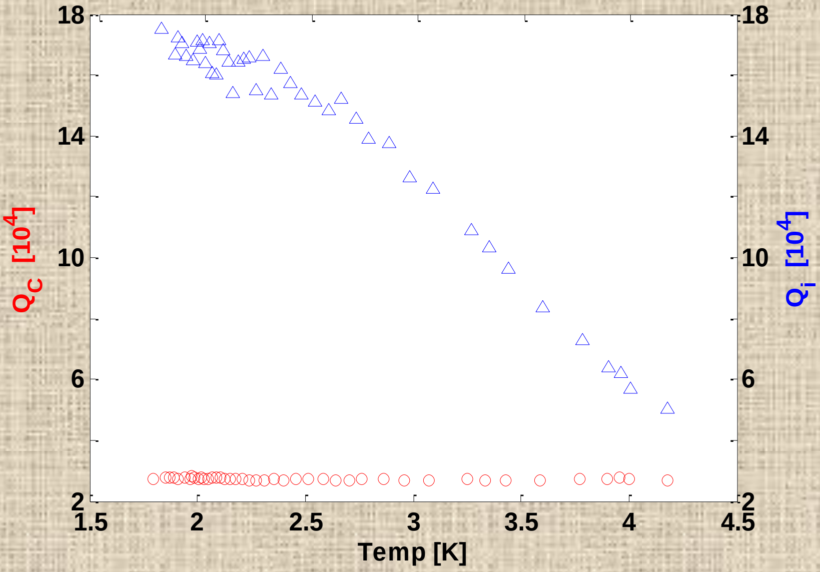
- During decreasing temperature ε increases
- At 2.17 K helium gets superfluid → first order phase transition
- Below this critical temperature ε starts to decrease

# Resonances on Sapphire ( 1.8 K < T < 4.2 K )

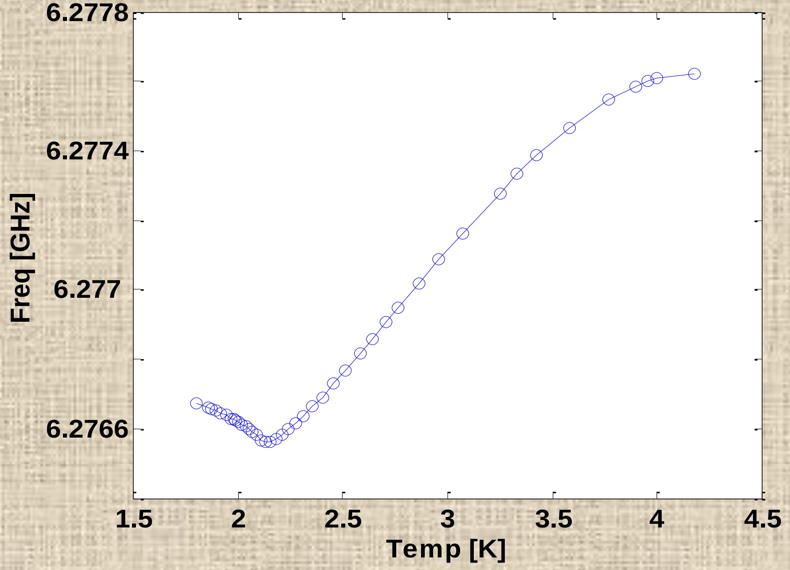
Amplitude, Q - factor



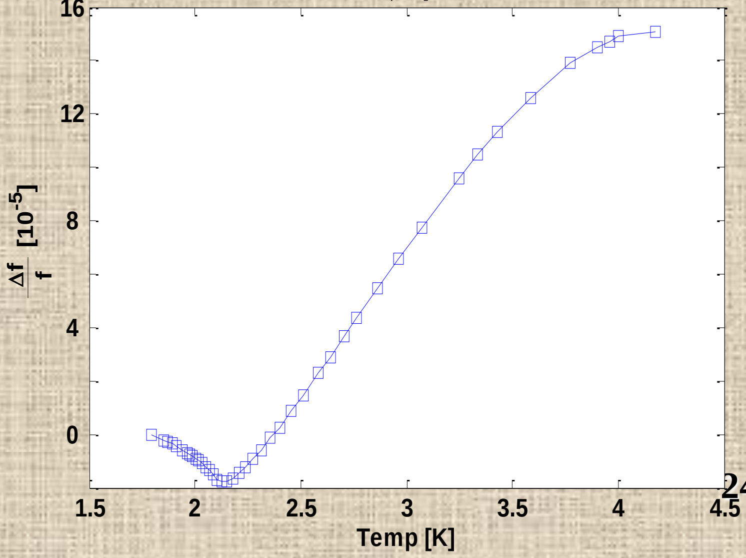
$Q_C$, $Q_i$



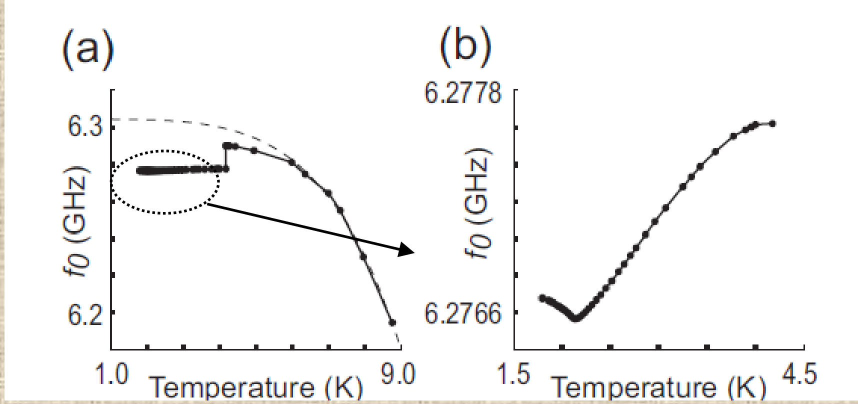
Frequency



$\Delta f / f$



# Helium Detectors (Grenoble)

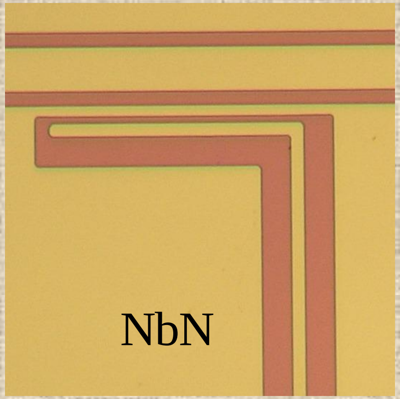


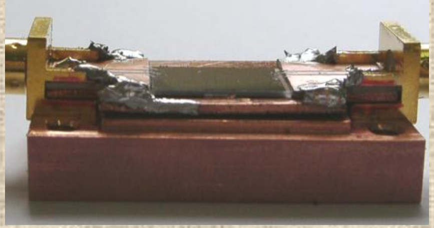
- Designed, fabricated and tested high-Q ($10^5$) NbN resonators
- Demonstrated a highly sensitive LHe detector for hydrodynamics applications (**APPLIED PHYSICS LETTERS 93, 134102**)
- In progress ..

$$\delta\epsilon_{He}^{min} \cong 2\epsilon\sqrt{\frac{k_B T_n}{2P_s}\left(\frac{Q_i+Q_e}{Q_i^2}\right)}$$

***Achievable sensitivity:***

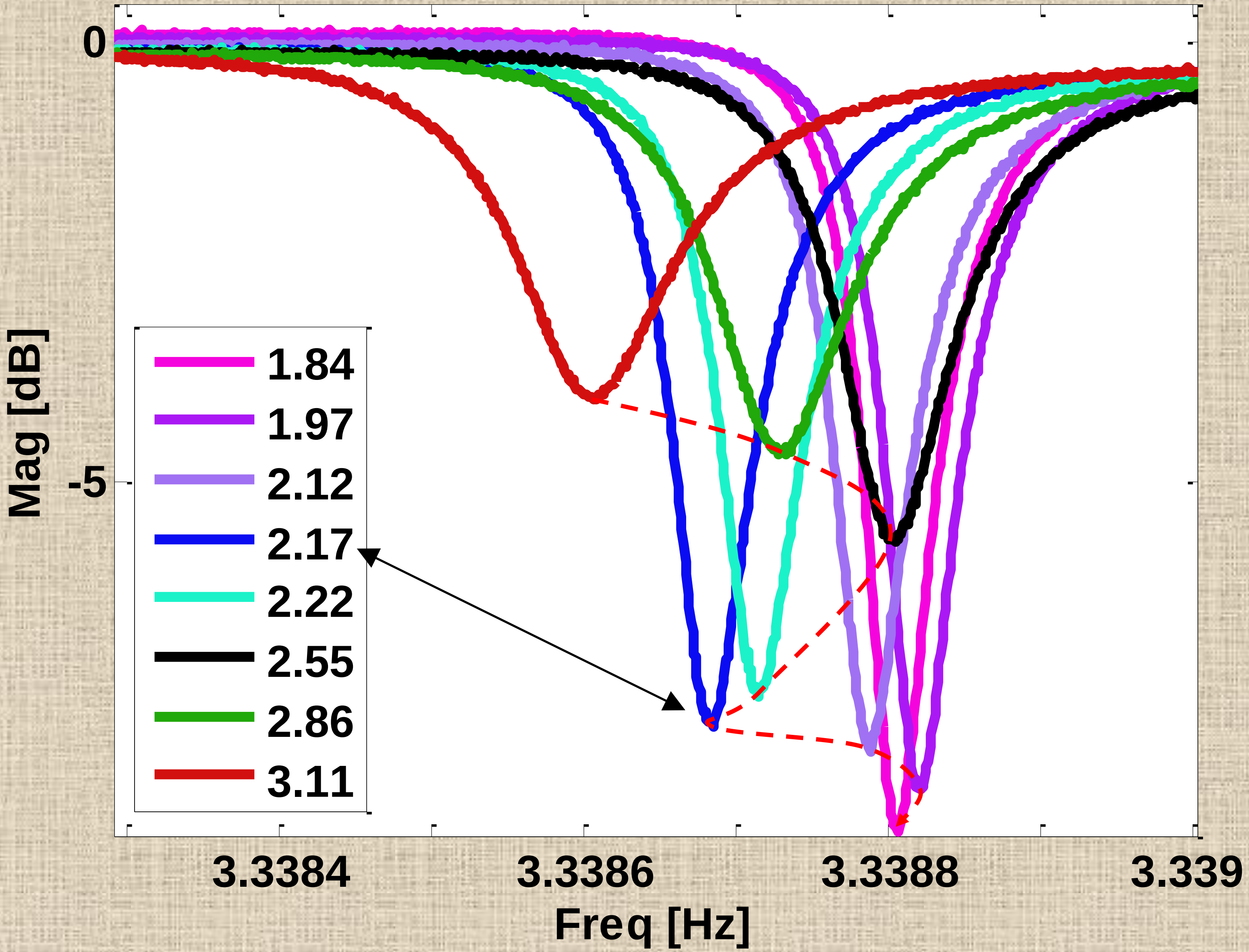
$10^{-10}\varepsilon_0/\mathrm{Hz}^{1/2}$ !!





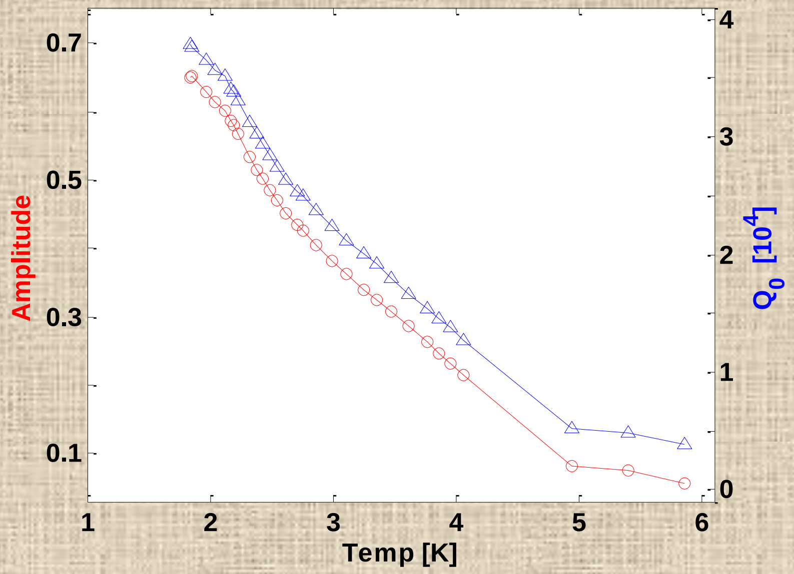
# NbN resonators on Si+SiO$_2$ ( 1.8 K < T < 4.2 K )

Mag vs. Freq, in dependence of Temp

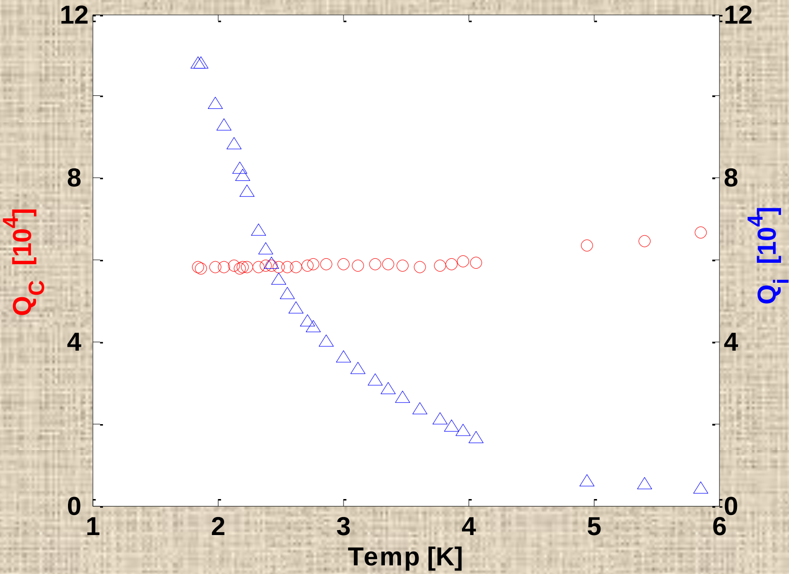


# Resonances on Si/SiO$_2$ in dependence of temperature

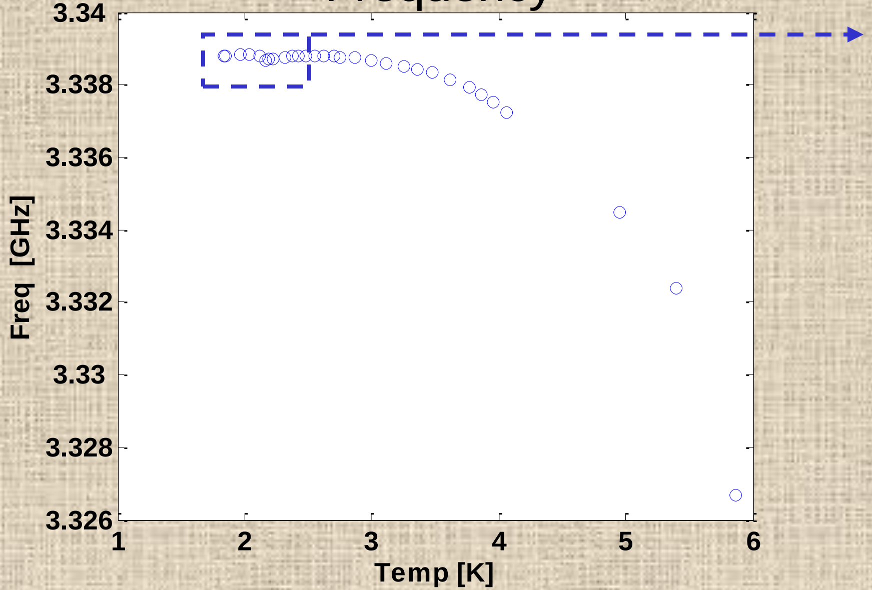
## Amplitude, Q - factor



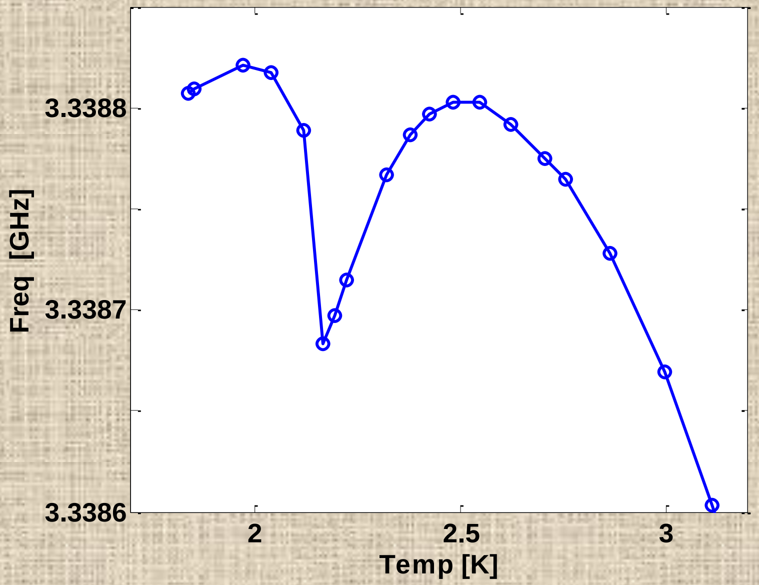
## Q$_C$, Q$_i$



## Frequency



## Frequency



# Materials for MKIDs

| | | |
|---|---|---|
| **- Al** | **$T_c = 1.2$ K** | **mm-wave detection (down to 90GHz)** |
| **- Ti** | **$T_c = 0.5$ K** | **mm-wave (down to 40GHz)** |
| **- Nb** | **$T_c = 9$ K** | **THz detection (from 700GHz), transmission lines, filters** |
| **- NbN** | **$T_c = 16$ K** | **Hydrodynamics, THz** |
| **- Re** | **$T_c = 1.7$ K** | **Neutrino mass, mm-wave detection, X-rays** |
| **- Ta** | **$T_c = 4.5$ K** | **X-rays absorber, visible-NIR single photons** |

- **SPUTTERING or UHV EVAPORATION**
- **BETTER IF HEPITAXIALS (substrate matching)**

# Bolometers vs KIDs

***Bolometers:***

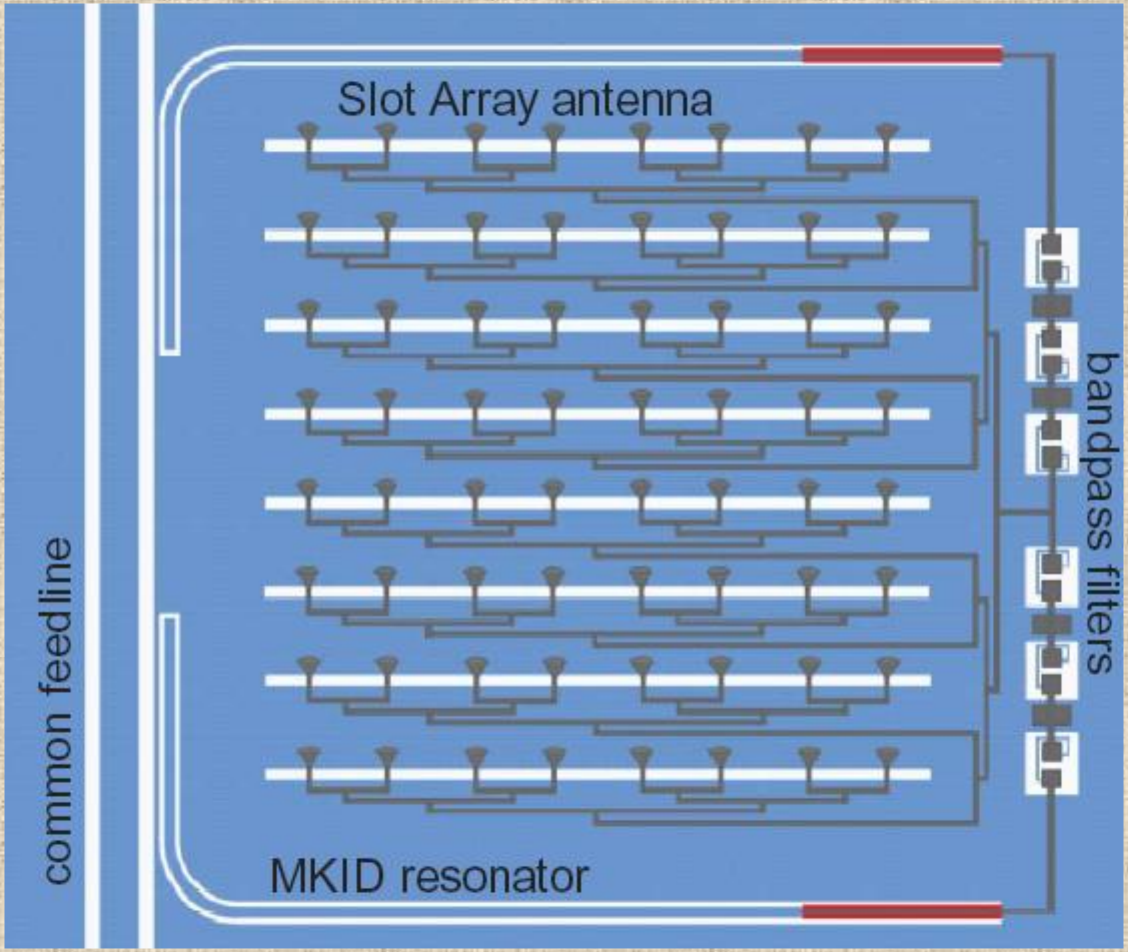
- Sensitivity depends on thermal decoupling, so it's IN PRINCIPLE adjustable
- Easier to decouple the absorber from the thermistor (particularly important for higher energy spectroscopy applications)
- Big arrays made by weak multiplexing and brute force
- Complicated fabrication processes
- Heavy, expensive, complicated low-T electronics (SQUIDs, JFETs, MUX …)
- ……

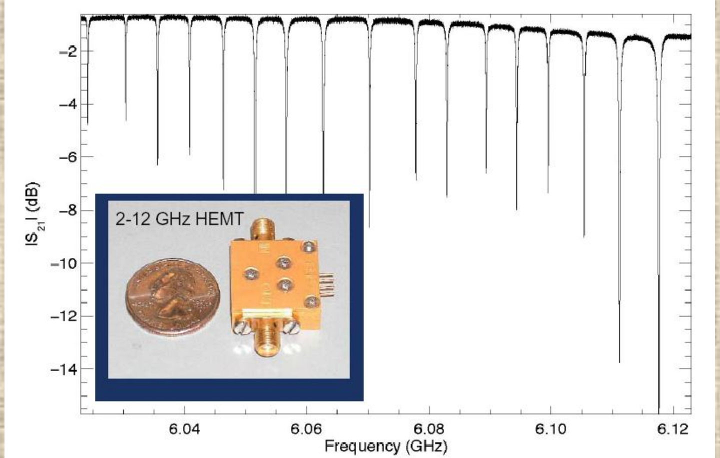
***KIDs:***

- Sensitivity is limited by quasi-particles lifetime (not yet under control)
- Quasi-particles transport still difficult (see STJs)
- Better suited for giant arrays
- Easier to fabricate, extremely robust
- Less sensitive to T fluctuations; in principle doesn't requires very low $T_{base}$
- Tumultuous R (big) & D (small) phase ongoing (more fun..)
- ……

# A look around
# (mm-wave astronomy)

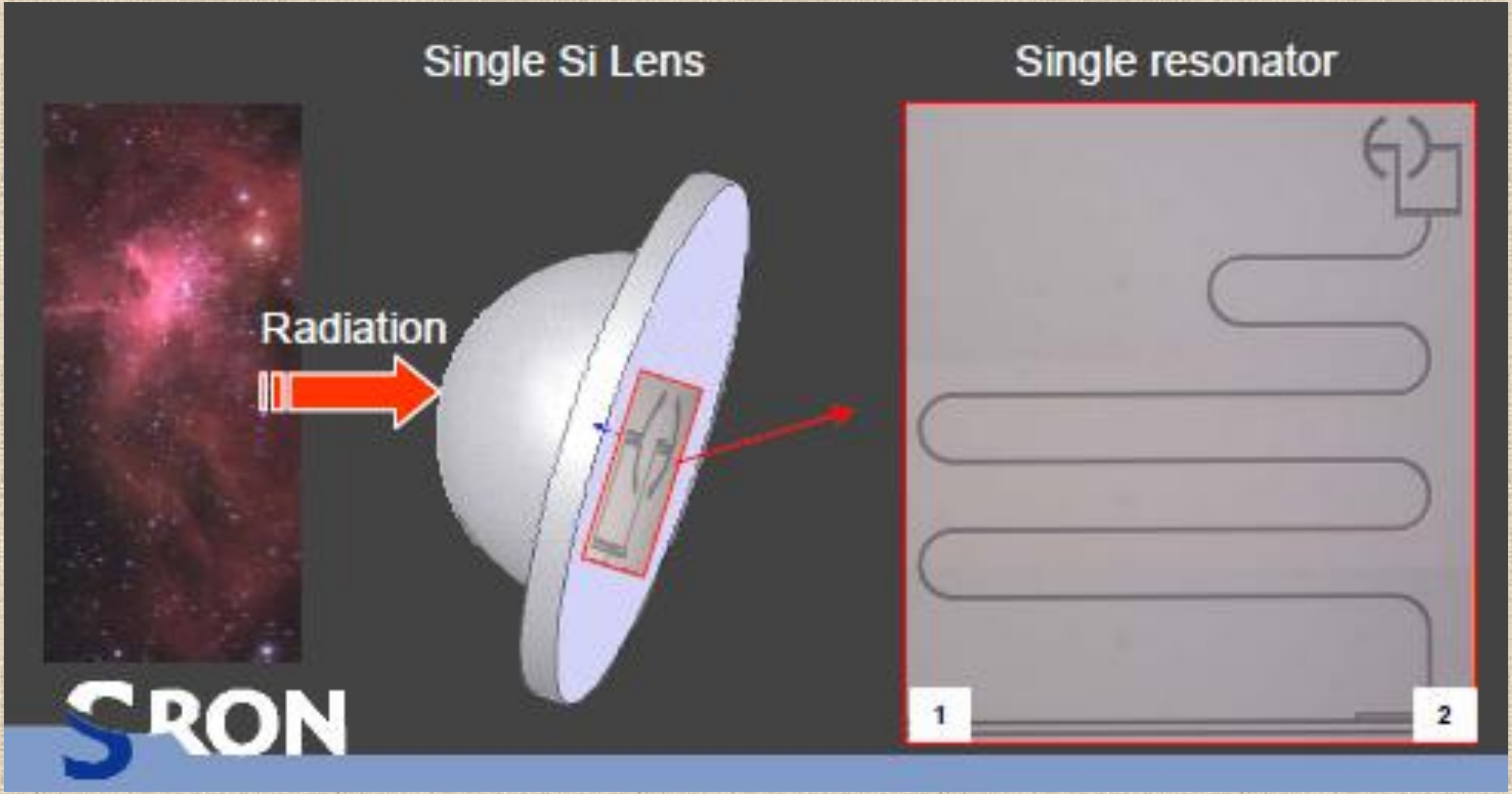
# Lossy line over the resonators (USA)





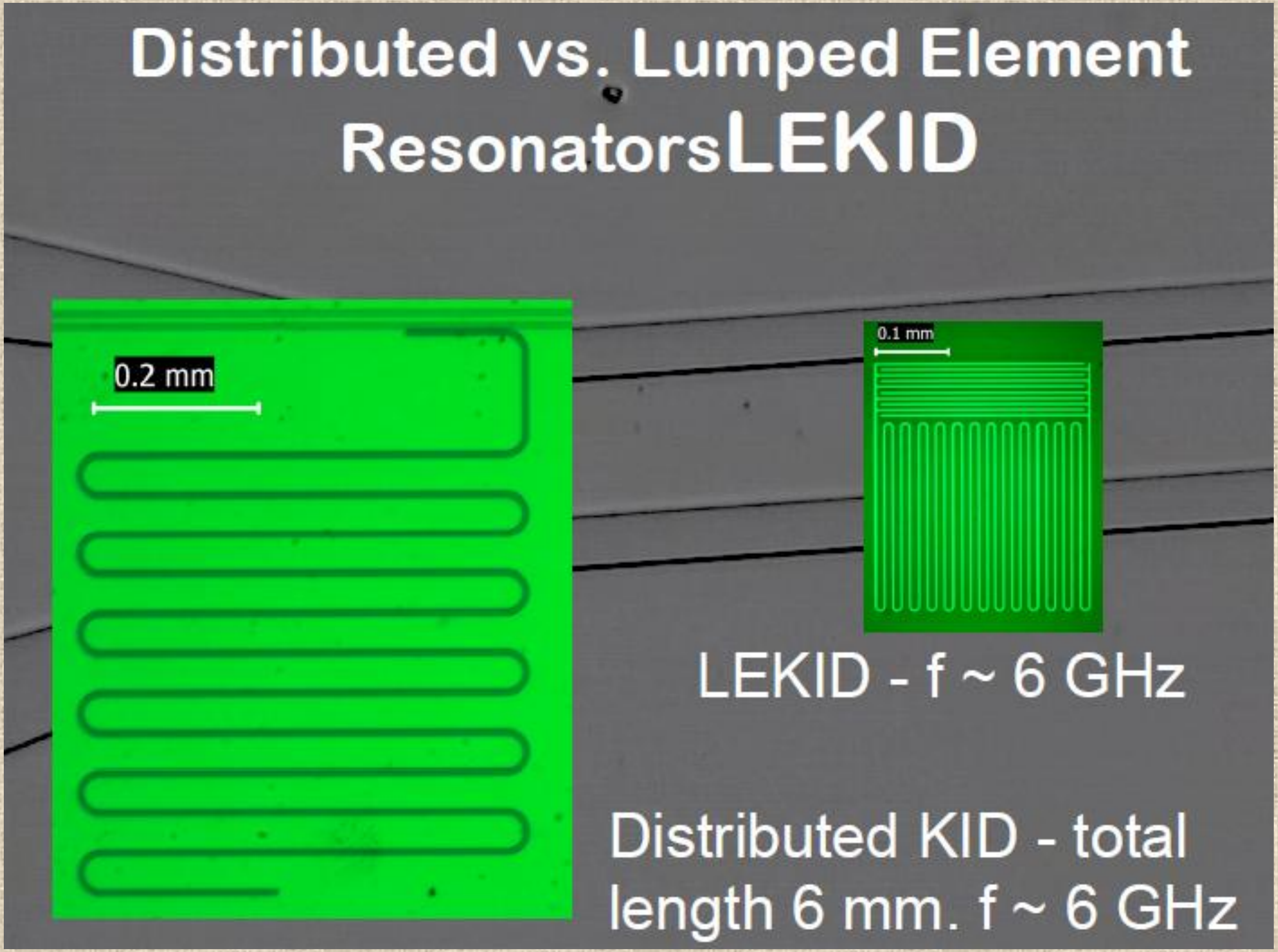
**MKIDCAMERA for the Caltech Sub-mm Observatory (CSO)**

# Antenna IN THE resonator (SRON 2005-)



Being developed for SPICA satellite (200um), NIKA-IRAM (2mm) and now also APEX (1mm)

# Lumped Element KIDs (Cardiff, Grenoble, Roma)



NICA : the Neel IRAM Cardiff Array !!!

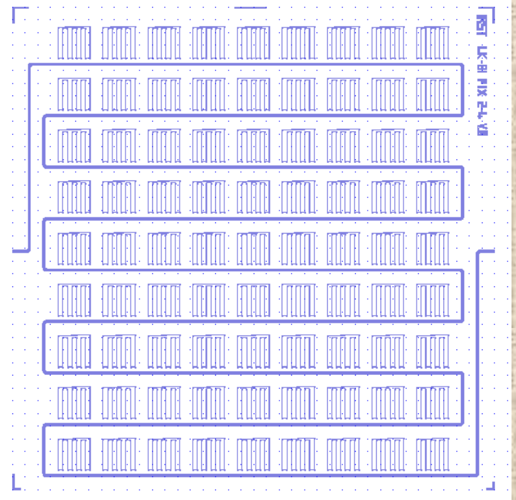
# A KIDs European Camera for IRAM: the Nèel Iram KIDs Array

# “NIKA”

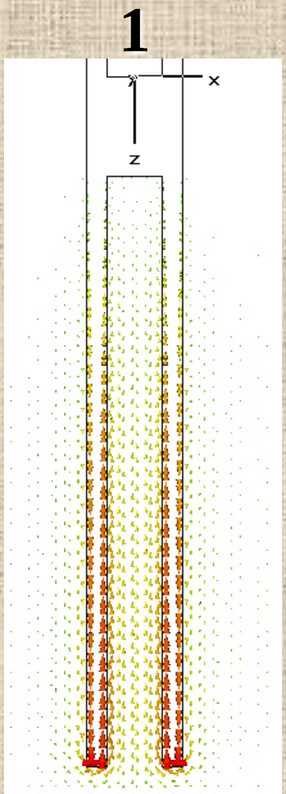
**Target: Summer 2009**

# LEKIDs design for IRAM (v.0)

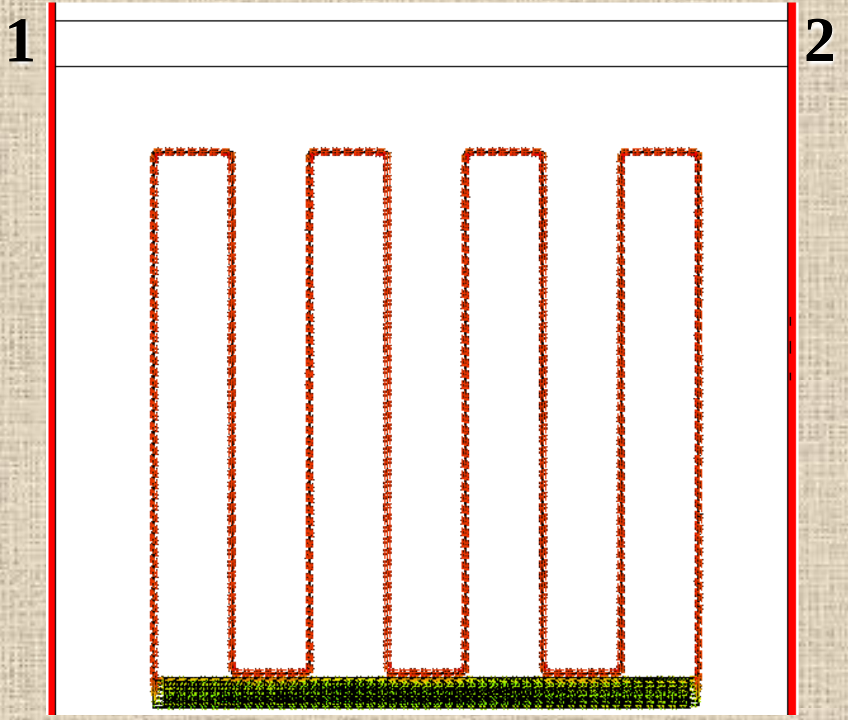
**81 pixels LEKIDs array. Now we're at version 1 (CPW and 196 pixels).**
**Measured preliminarly optical NEP around $10^{-15}$W/Hz$^{0.5}$, limited by poor film quality and excess phase noise → the pixel is absorbing the 2mm radiation !!**



## λ/4 (distributed)

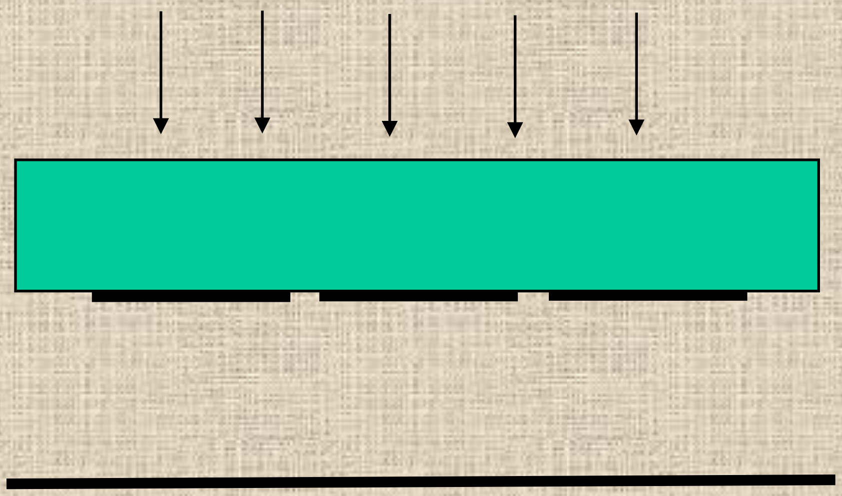


## Lumped Element



**3-D simulation**

# LEKIDs (1st order) radiation coupling



Incoming radiation

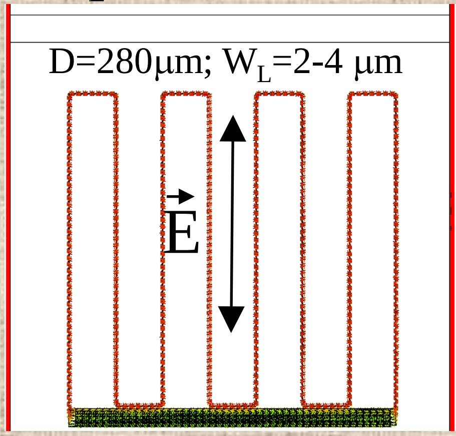
***Si substrate $t \approx \lambda_{Si}/4$***

***Cavity $d \approx \lambda_{vacuum}/4$***

**Backshort (SC)**

D = distance between lines

$W_L$ = meander line width



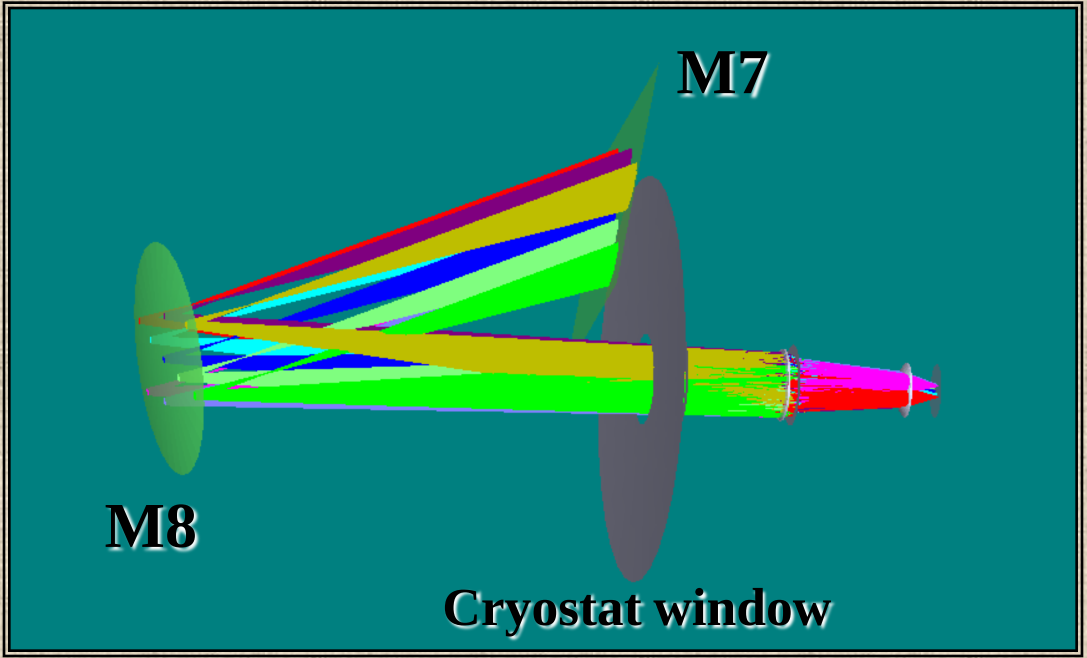
$R_\square \approx$ 1-2Ω for 40nm Al at low-T

The incoming wave is « terminated » with an effective $Z = R_\square \cdot D/W_L$ that can be $\approx Z_{Si} = 377/\varepsilon_r^{0.5} \approx 100\Omega$

Mean Optical Absorption over 125-170GHz can reach 80% even without an additional AR coating.

*See S. Doyle PhD thesis for more details and 2nd order effects (e.g. meander inductance…)*

# NIKA goals



***On the cryostat (horizontal):***

*- M7 (flat)*

*- M8 (x-y $2^{nd}$ degree polyn.)*

*at the IRAM focal plane (f/10)*

***In the cryostat:***

*- 4 K HDPE lens*

*- 100 mK HDPE lens*

| | |
|---|---|
| ***Pixel pitch:*** | 1.6 mm ($\lambda$ = 2.05mm, f/1.7 optics → Nyquist) |
| ***Array dimensions:*** | 32×32 $\text{mm}^2$ |
| ***Number of pixels:*** | 20×20 (2.4×2.4arc-min, pixels spacing 7.2 arc-sec) |
| ***Read-outs:*** | REALLY low-cost FPGA (up to 32 channels)<br>FFTS (SRON, “best efforts basis”): all the 400 channels |

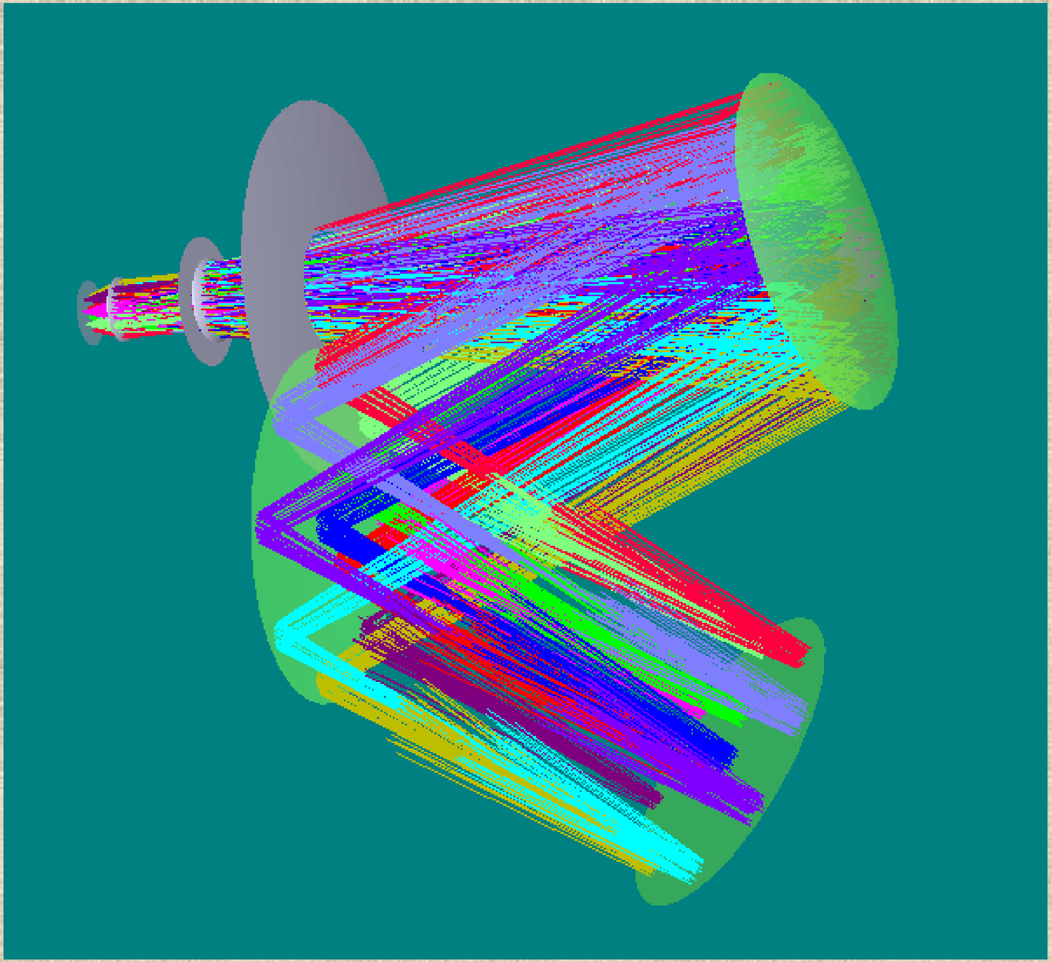
***Number of cables from the cryostat: 2 coax (f < 8 GHz), 3 for preamplifier bias.***

# Perspectives: large FoV

IRAM is going to **increase the 30-m field-of-view.** Several options, with different complexities and costs, are under study. From 12’ downwards.

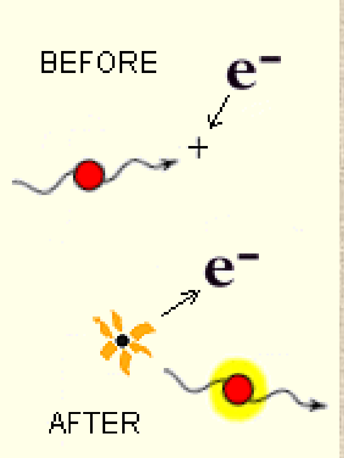
The “NèelCam”, with the **present IRAM optics**, could take **up to 6’** (requires to reduce a bit the IRAM focal length for fitting the 6’ on the existing, small M3)

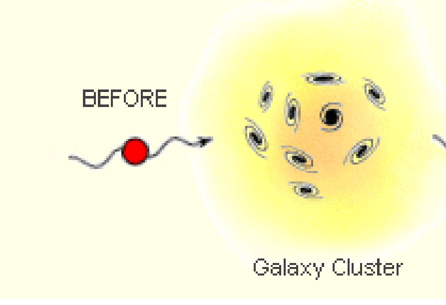
That will require, for Nyquist at 2 mm, a **48×48 (2000 pixels) array**. If the FFTS read-out is working, feasible with a total of 4 coax cables.



***BUT … we’ll see …***

# S-Z in clusters of galaxies





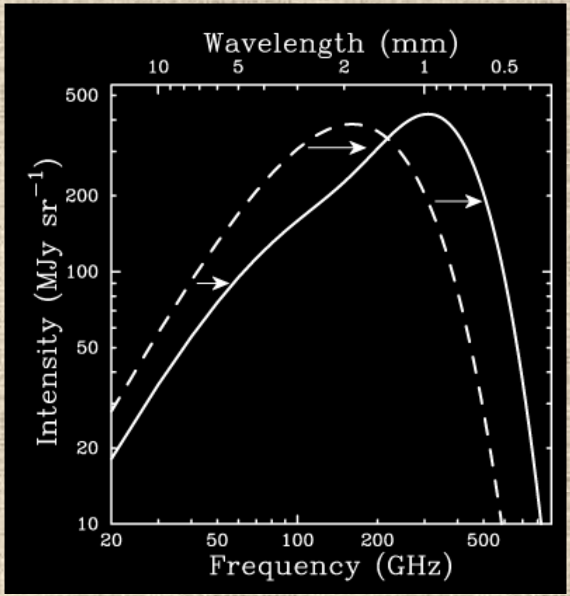
$R_{eff} \sim 5\text{Mpc}$
$n \sim 10^{-3}\text{cm}^3$

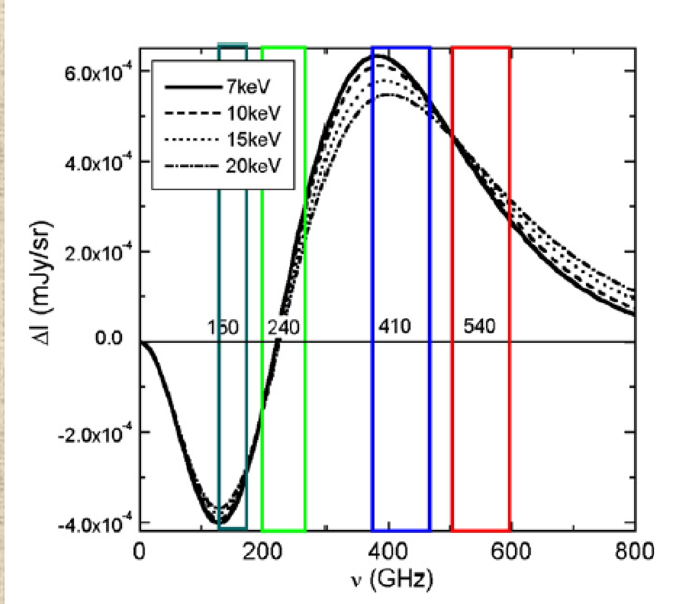
**Electrons are really hot:**

$$k_B T_e \approx \frac{GMm_p}{2R_{eff}} \approx 7\,(M/3\times10^{14}M_\odot)\,(R_{eff}/\text{Mpc})^{-1} \quad \text{keV}$$

***Basic mechanism:***

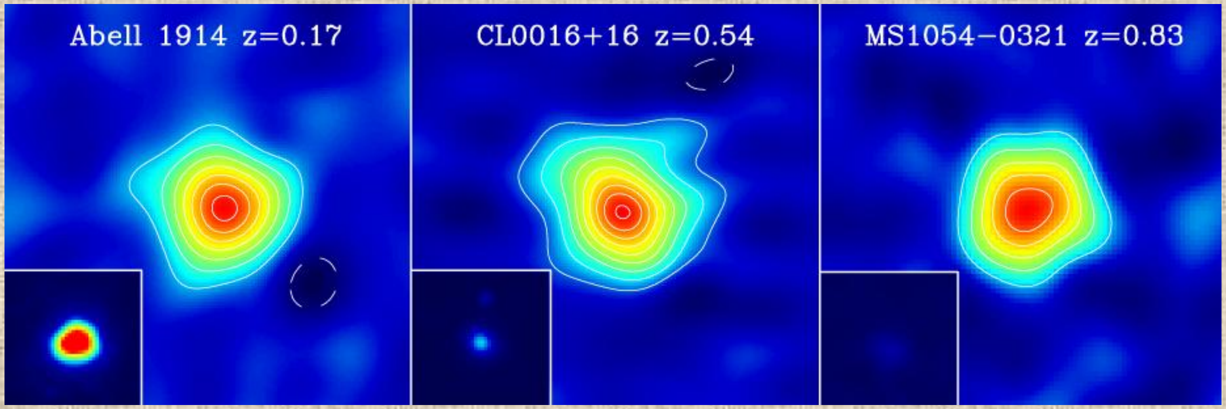
Compton scattering on hot electrons (IC)





# S-Z for the deep Universe

SZ contours are 0.75 μK and X-ray scales are the same.



Z = 0.17 Z = 0.54 Z = 0.83

SZ particularly important for deep studies (z > 1).
Formation and evolution of clusters, Cosmology.

Mohl 2002. X-rays from ROSAT, SZ from interferometric surveys

# IRAM 30-m

***DATA SHEET ON-A-STAMP***

- 30 m dish at Pico Veleta (2850m)
- PSF OK down to 0.8 mm
- Hetherodyne and Bolometers
- **MAMBO2** -117 pixels. f = 240GHz Horn-coupled; HPBW =11",

pixel spacing = 20".

*Brand new* ***European consortium*** *for a KIDs 2-mm demonstrator at IRAM:*

**FRANCE:** Grenoble (Nèel, LAOG, IRAM). Cryostat, optics, LEKID, digital readout electronics (32 channels), detectors design and fabrication.
**UK:** AIG Cardiff. Filters, LEKID, digital electronics.
**Holland:** SRON Utrecht and Groningen: antenna-coupled KIDs design + fabrication
**Italy:** La Sapienza Roma: LEKID design, software.

# ***Other Applications:***

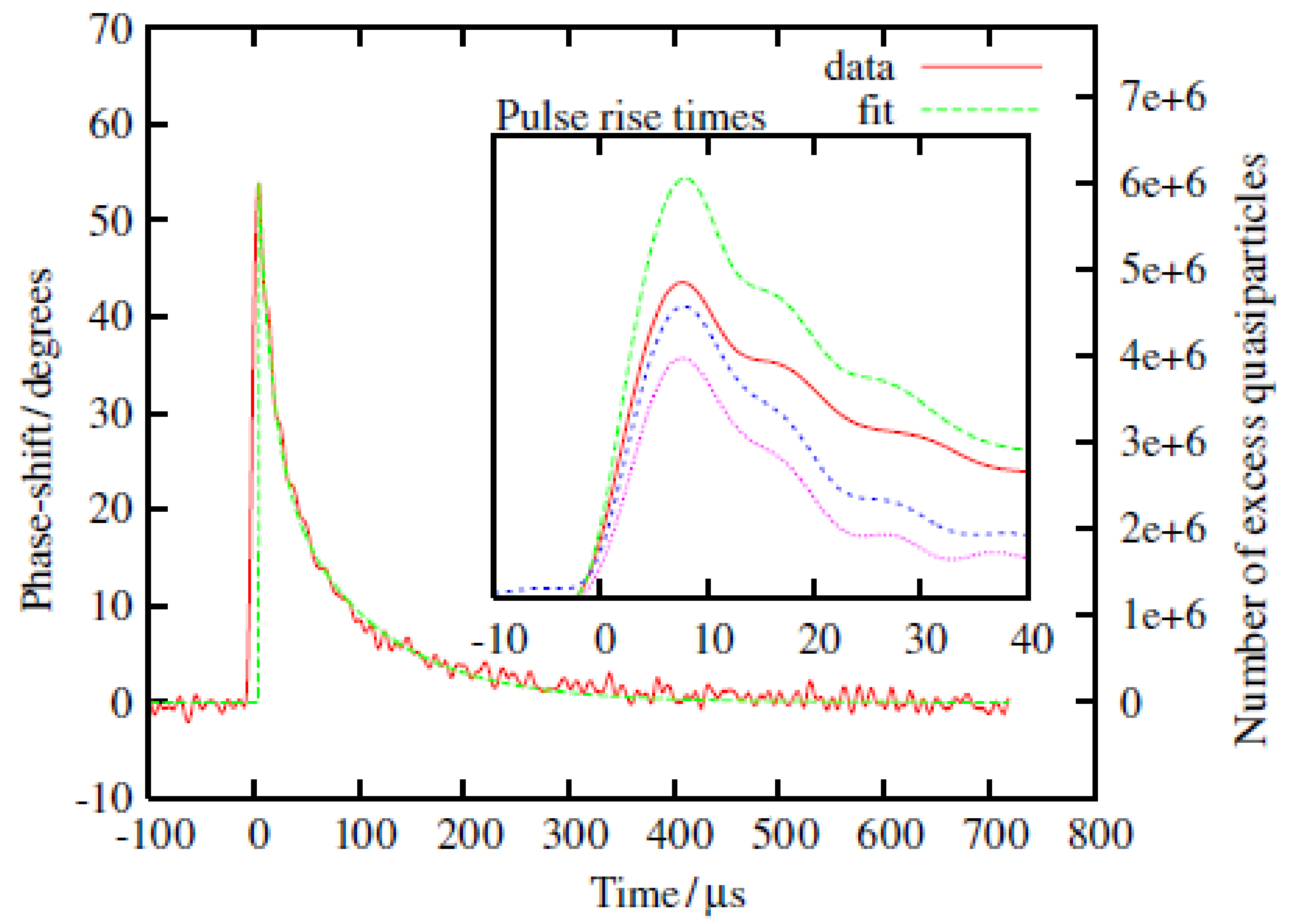
**High energy resolution X-rays**

**Optical/NIR**

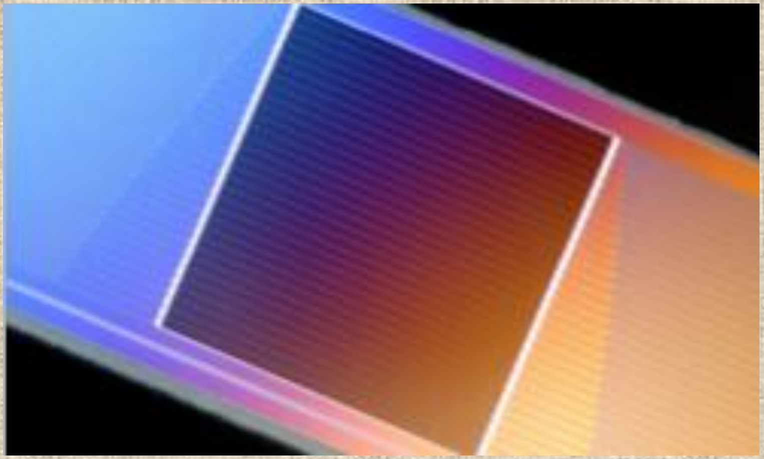
**Neutrino mass**

**…..**

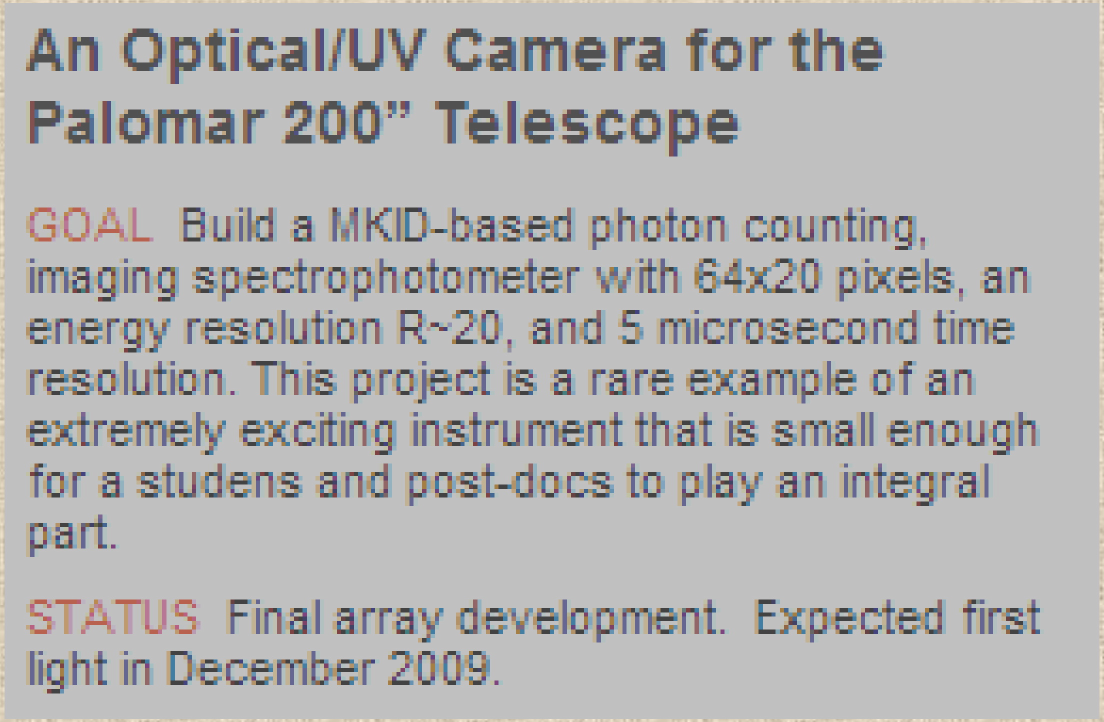
# X-rays (Caltech, Cambridge)



# Optical Camera (UCSB)



From B. Mazin website



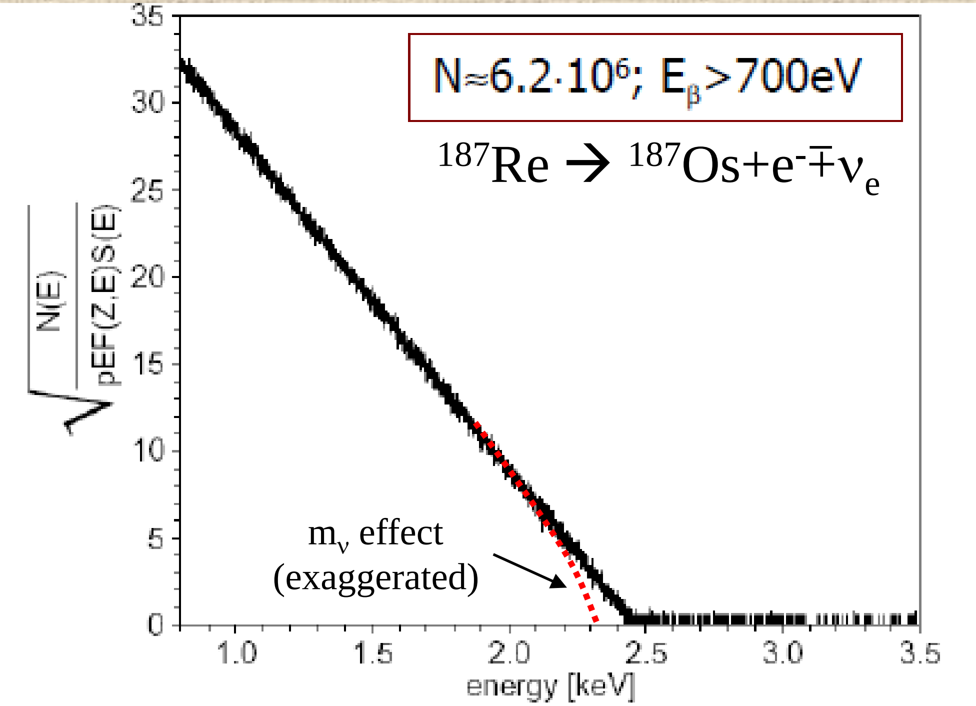
**An Optical/UV Camera for the Palomar 200" Telescope**

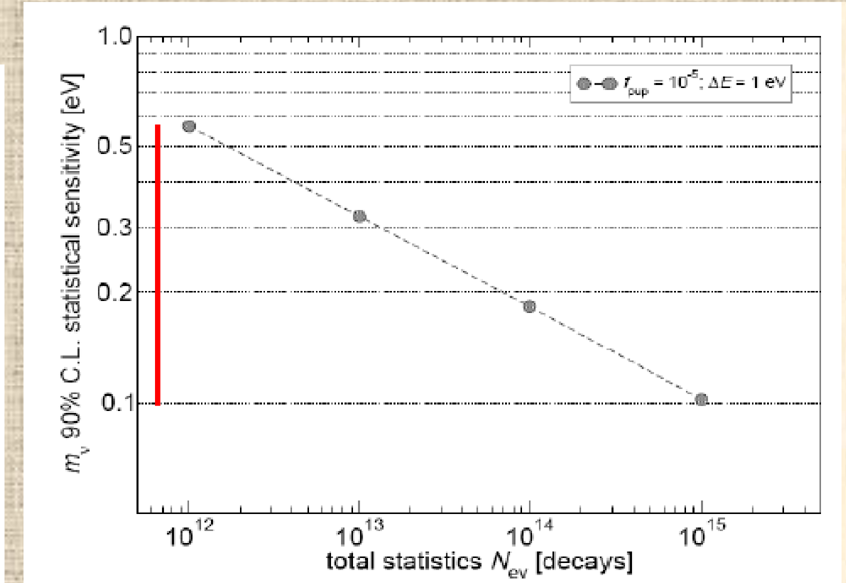
GOAL Build a MKID-based photon counting, imaging spectrophotometer with 64x20 pixels, an energy resolution R~20, and 5 microsecond time resolution. This project is a rare example of an extremely exciting instrument that is small enough for a studens and post-docs to play an integral part.

STATUS Final array development. Expected first light in December 2009.

Possible science case: GRB fast follow-up. Competing with AMICI prisms + CCD instruments …. (e.g. REM, …).
ADVANTAGE: photon-counting

# MARE – Microcalorimeters Arrays for a Rhenium Experiment





- ~ $10^{14}$ beta decays required
- $f_{pup}$ ~ $10^{-5}$ is required
- $\Delta E < 5$eV is enough

Growing interest in Grenoble to develop high-quality Re resonators for MARE and q-bits. Epitaxial Re on Shappire → hopefully very high Q (in progress)

SOME NEW IDEAS FOR MARE (version « resonators » ≠ KIDs)

WE'RE SLOW DUE TO NIKA … HOPEFULLY BETTER FROM SEPTEMBER 2009 …

# Conclusions: KIDs or not KIDs ?

- Groups in Europe REALLY working on KIDs (to my knowledge)

| | |
|---|---|
| - SRON Holland | 3 full-time researchers |
| - University of Cardiff | 1 full-time researcher |
| - Grenoble Néel | 1.5 full-time researchers |
| - Roma La Sapienza | 1 full-time post-doc + 1 PhD |
| - Cambridge | ??? But not a lot of people |
| - Karlsrhue | 1-2 full-time |

- In any case less than 10 people. Largely “inexpert” researchers.
- Not to mention the financial resources ..

Despite that, strongly competing in the mm and sub-mm domain with the long-developed (and expensive) bolometers (TES, doped Si, NbSi etc.).