

Low Temperature Detectors for Astrophysics

Cryocourse 2011

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PLAN

- Introduction
- LTD overview
- Selected applications

What is a good detector ?

- It is a device that converts a physical quantity into an electrical signal...
- High efficiency
- Sensitivity (high Signal/Noise)
- Calibration
- Compatible with electronics
- Fabrication (arrays)

=> don't reduce it to the physical principle...

Why using low temperatures ?

- Low temperature means low energy :

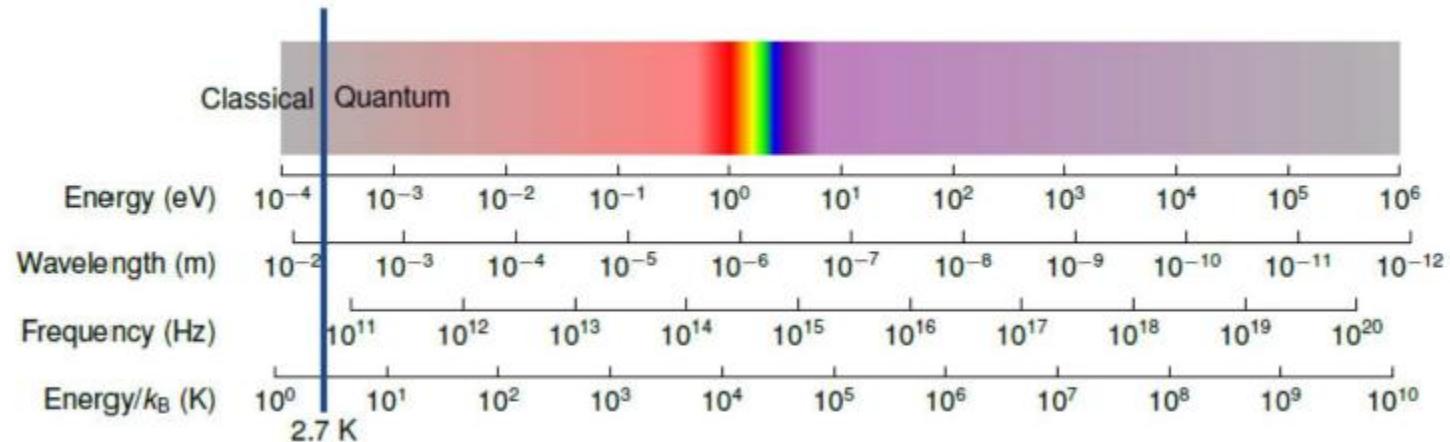
$$E = k_B T \Rightarrow 0.086 \text{ meV} @ 1K$$

- Energy gap in superconductors

$$\begin{aligned} E_g &= 1.76 k_B T \\ \Rightarrow h f &> 2 \cdot E_g \\ f &> 64 \text{ GHz/K} \end{aligned}$$

⇒ *High energy resolution in X-ray*

⇒ *Detectors for millimeter and submilleter*



Photons : mm & sub mm, X-rays (1-10 keV)

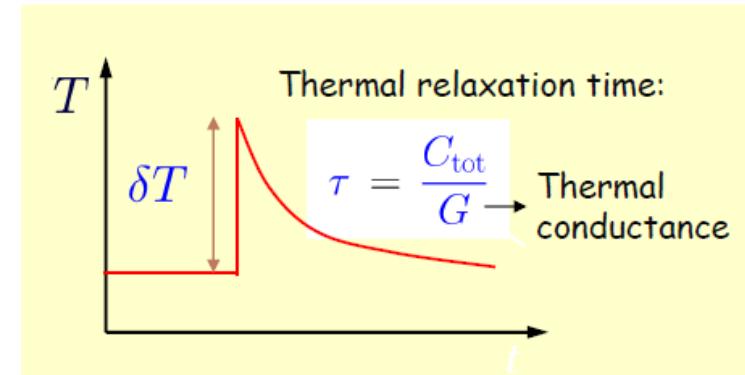
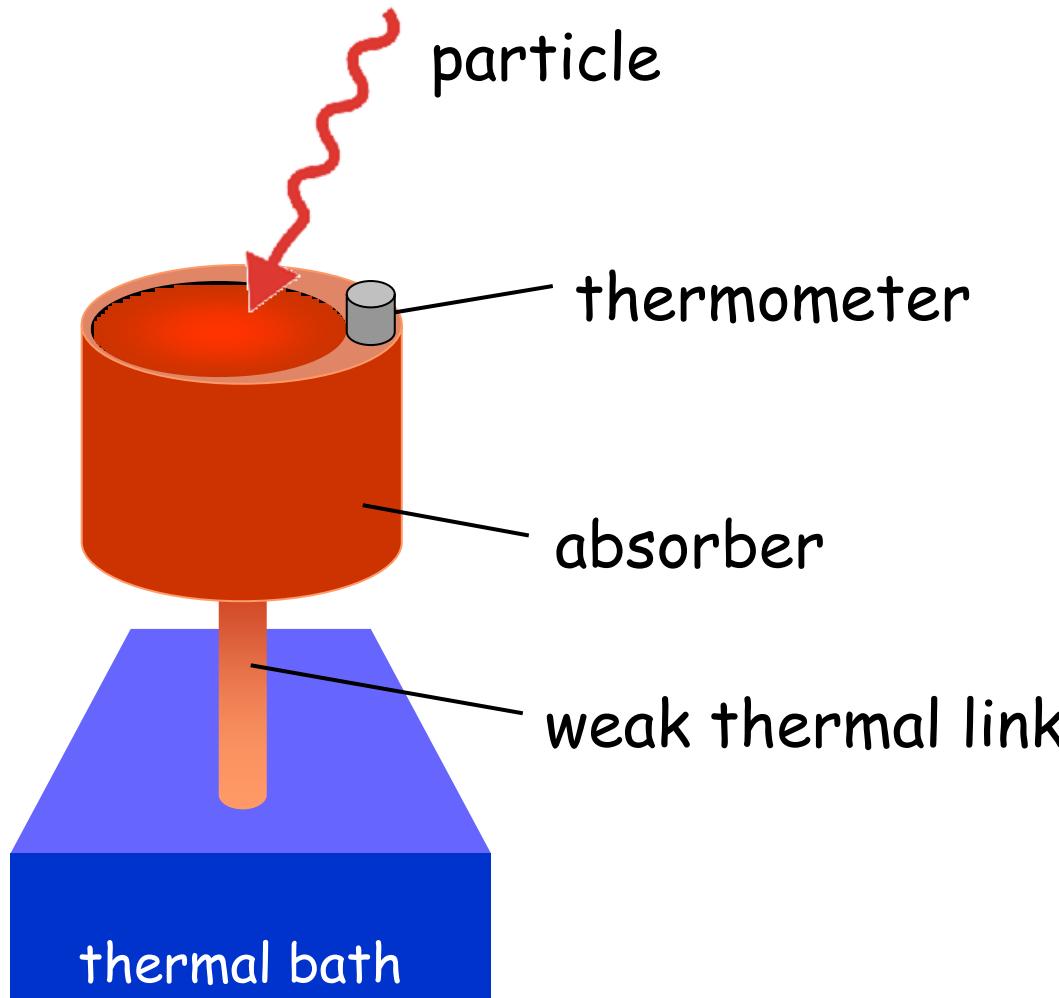
Matter : Mass spectrometry, heavy ion, α particles, β particles,...

Astroparticles : Neutrinos, Dark Matter (WIMPs)

LTDs Overview :

Selected topics

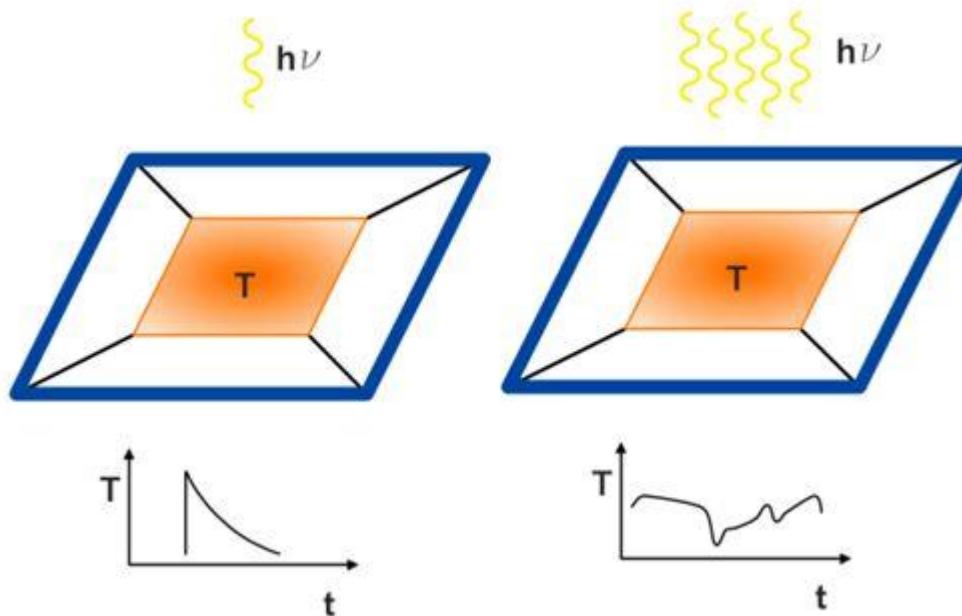
Calorimeter principle



$$\delta T = \frac{E}{C_{\text{tot}}}$$

Phonons
Electrons
Spins
Tunneling states
Quasi-particles

Calorimeter or Bolometer ?



$$\Delta T = \frac{E}{C}$$

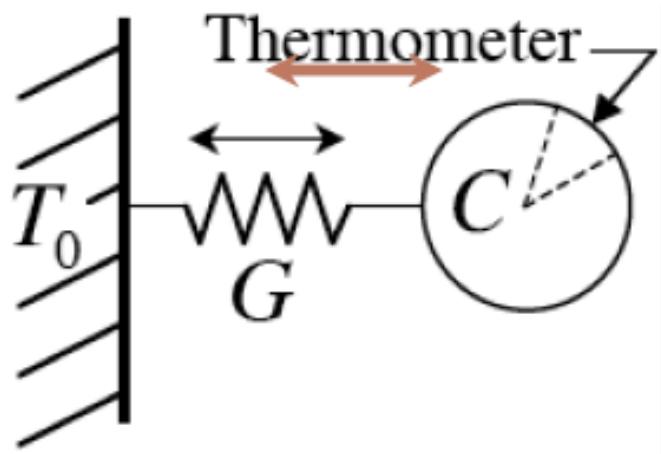
$$\Delta T = \frac{P}{g}$$

$$\tau = \frac{C}{g}$$

C decrease with T !

The absorber depends on the application
Needs a good thermometer

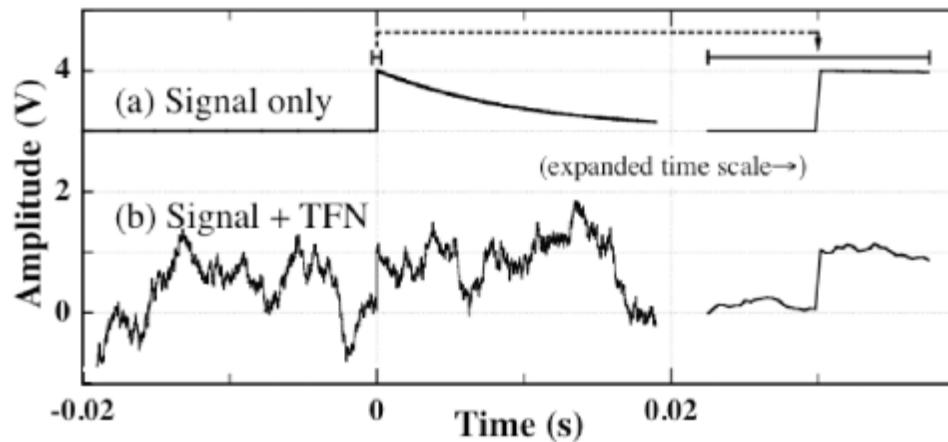
Fundamental thermal noise



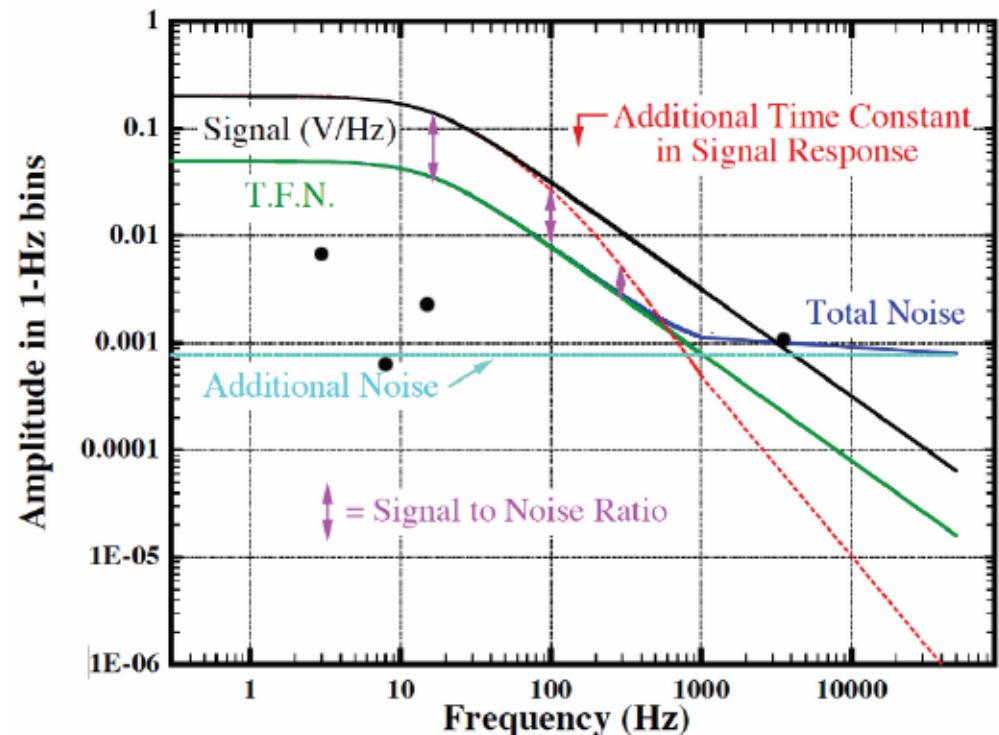
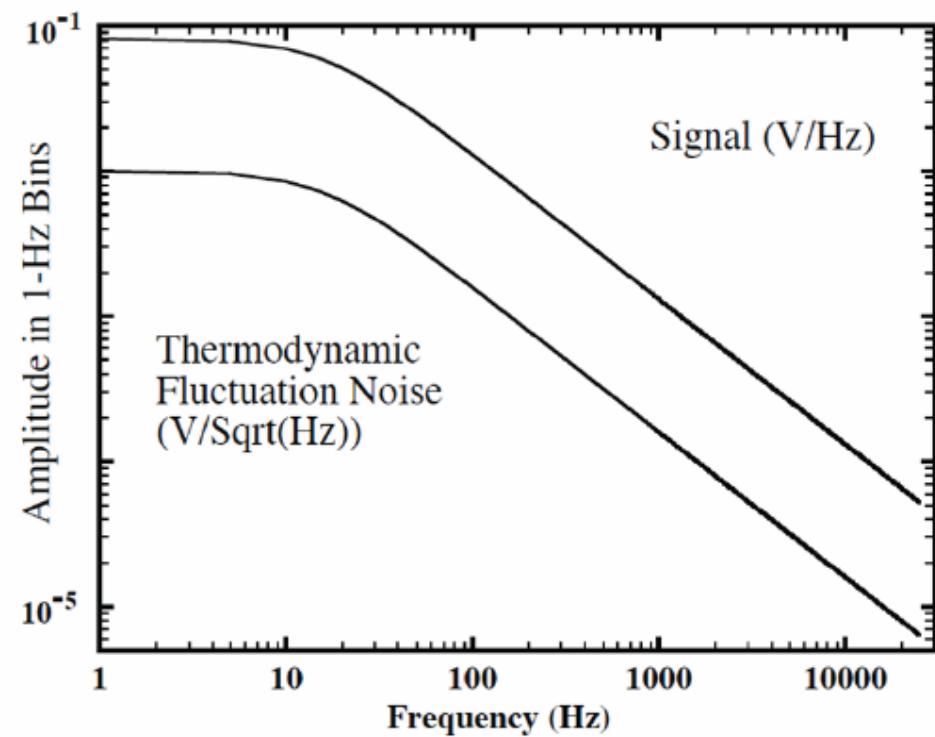
$$\sigma_E^2 = k T^2 C$$

$$N \approx \frac{CT}{kT}, \quad \Delta E_{rms} = \sqrt{N} \cdot (kT) = \sqrt{kT^2 C}$$

Poissonian statistics



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



The energy resolution is given by the readout electronics

Temperature measurement

$$\frac{dV}{dT} = i \cdot \frac{dR}{dT}$$

$$e_N = \sqrt{4 \cdot k_B \cdot R \cdot T}$$

$$\Rightarrow NET = \sqrt{\frac{4k_B \cdot T^3}{P_j} \cdot \frac{1}{A^3}}$$

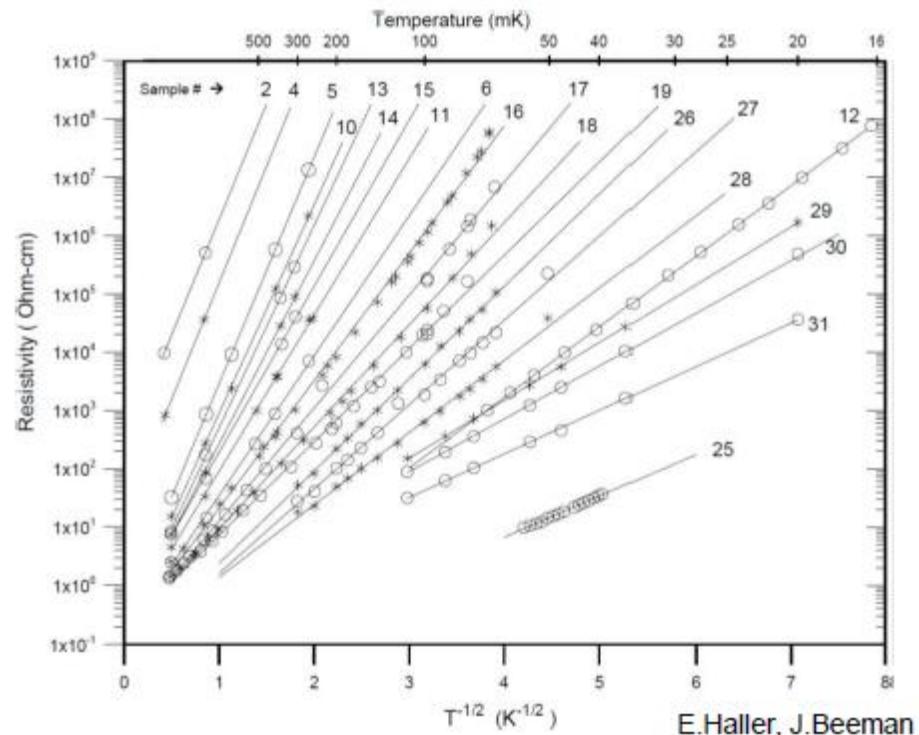
- A resistive thermometer needs to dissipate some power
- Look for high sensitivity (A)
- Essential to be close to the fundamental Johnson noise

NTD-Ge / Doped Si / NbSi

VRH systems

$$R(T) = R_0 T^q \exp\left(\frac{T_0}{T}\right)^p$$

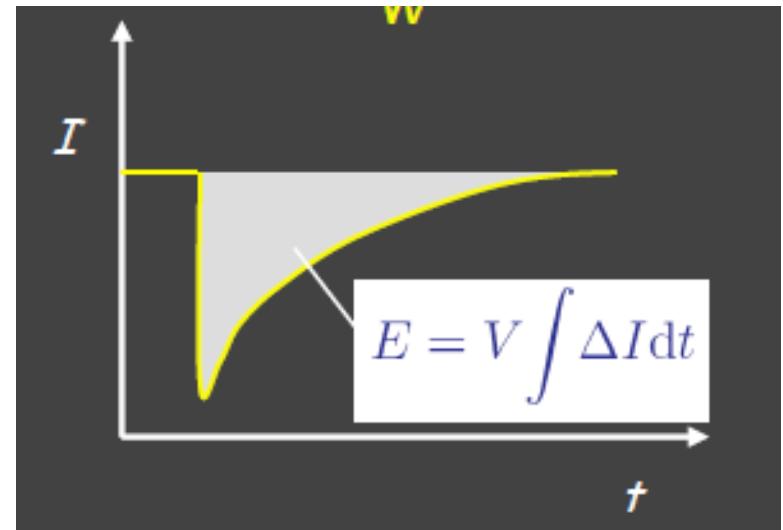
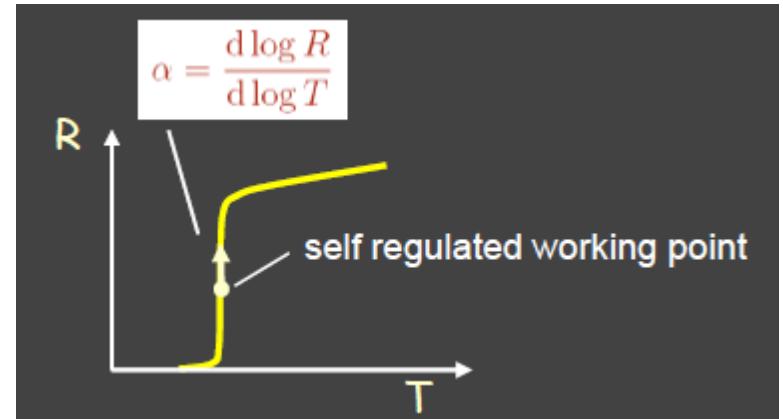
- Neutron transmutation doped Germanium
- Doped silicon Si:P:B
- Amorphous alloys (excess noise !?)



$A = -3 \dots -15$
Large resistance adjustment ($k\Omega$ - $G\Omega$)

TES

- Sharp resistance variation at transition ($A = 50 \dots 1000$)
- Strong electro-thermal feedback ($P_j = V^2/R$)
- Voltage – biased
- Pure metal (W), bi-layer Mo/Cu, Mo/Au, Ir/Au, Ti/Au or alloys NbSi
- Low impedance ($m\Omega$)



Needs a detailed understanding

- Electrothermal Feedback
 - Voltage bias intrinsically stable

$$C \frac{dT}{dt} = \frac{V_B^2}{R} - \sum (T_e^n - T_{ph}^n), \quad n = 5$$

- Fast response

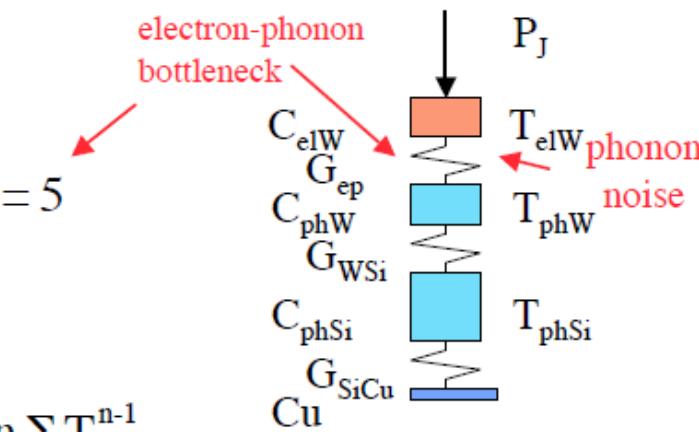
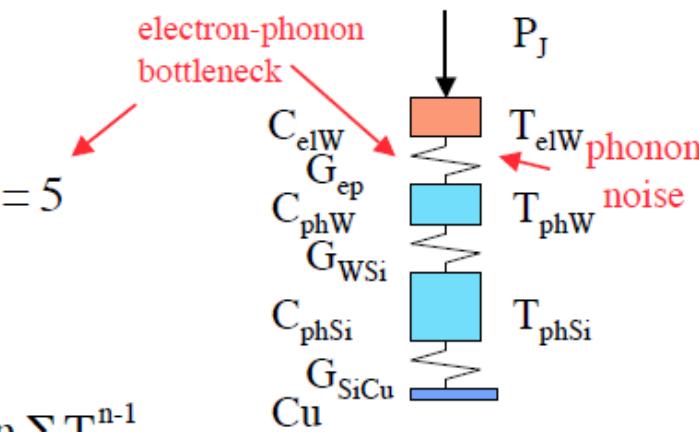
$$\tau_{etf} = \frac{\tau_0}{1 + \alpha/n}, \quad \tau_0 = \frac{C}{g}, \quad g = n \sum T_e^{n-1}$$

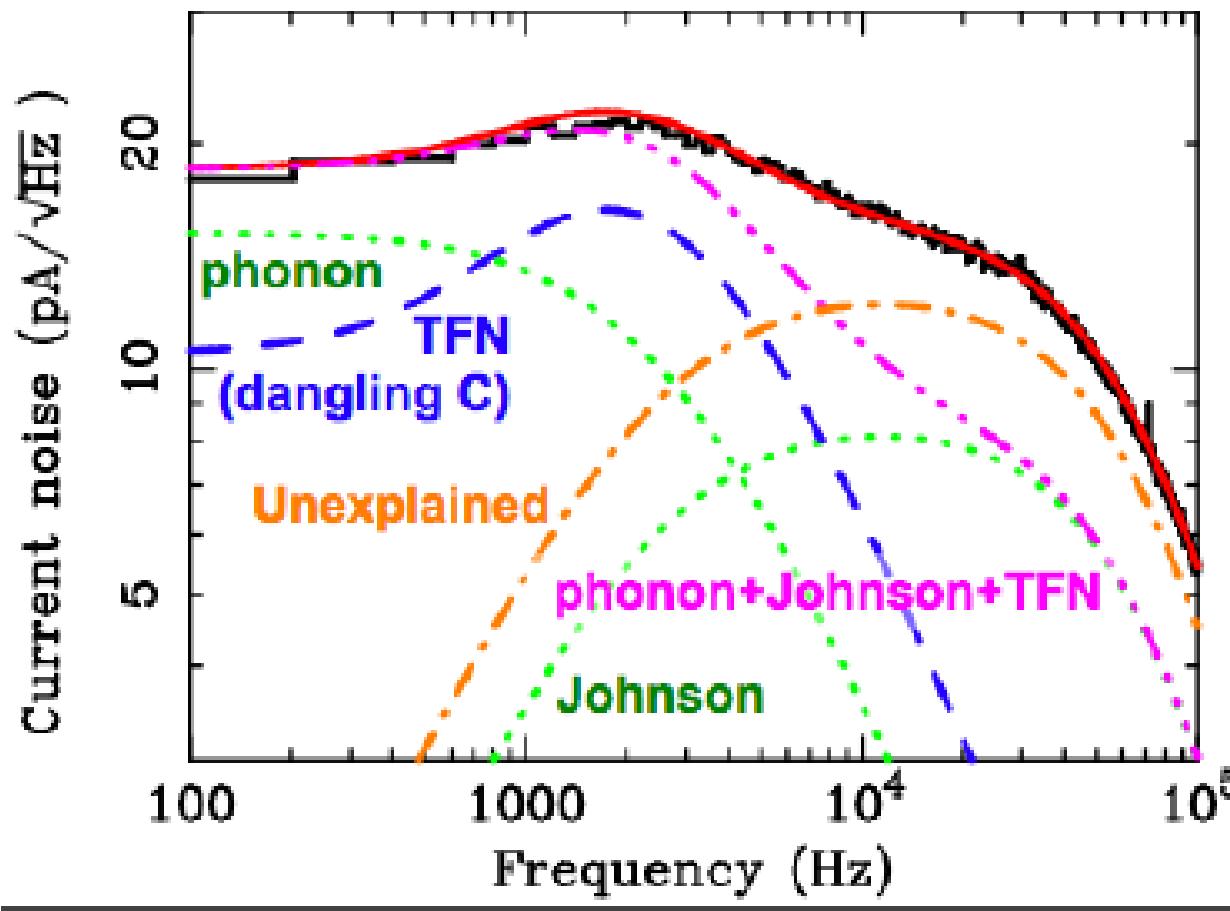
- High Sensitivity

$$\Delta E_{FWHM} = 2.355 \sqrt{4 k_B T_e^2 C \sqrt{\frac{n}{2}} / \alpha} = 2.355 \sqrt{4 k_B T_e P_J \tau_{etf} \sqrt{\frac{n}{2}}}$$

For $E_{sat} (\sim C T_e / \alpha = P_J \tau_{etf}) = 10 \text{ keV}$ then $\Delta E_{FWHM} = 1.1 \text{ eV}$

For $E_{sat} (\sim C T_e / \alpha = P_J \tau_{etf}) = 1 \text{ eV}$ then $\Delta E_{FWHM} = 11 \text{ meV}$

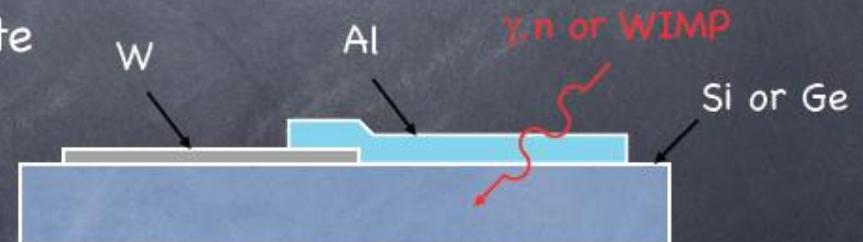
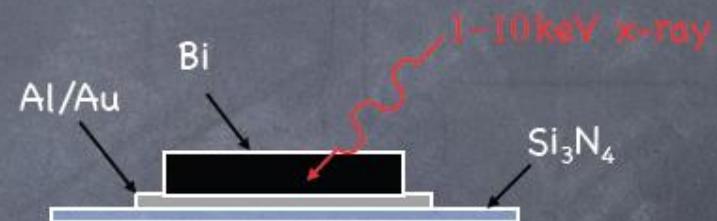
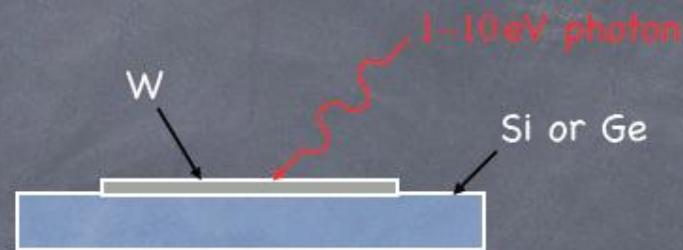




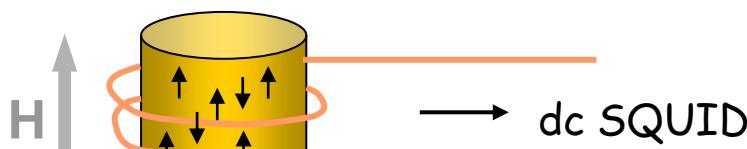
Agreement on the TES-microcalorimeter model after several years (K.Irwin...)

Types of TES Detectors

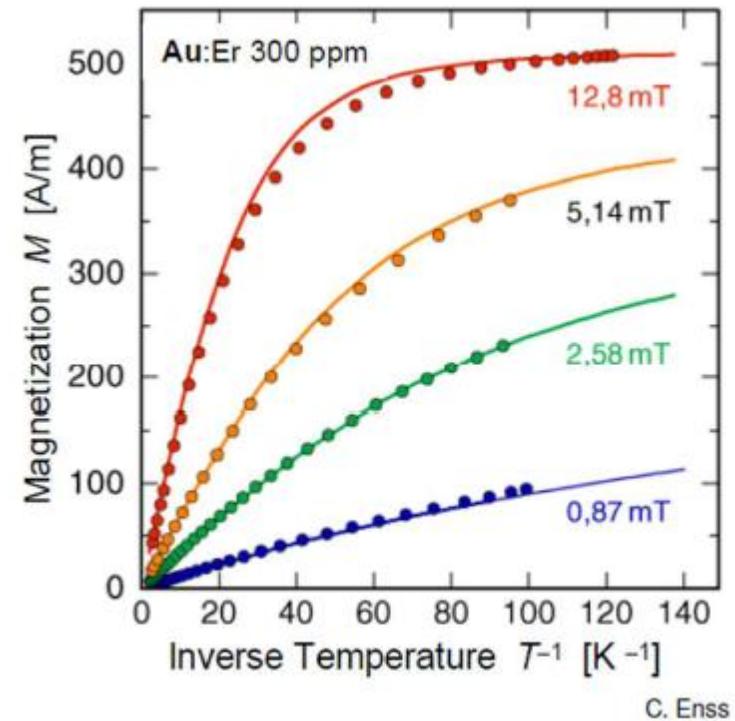
- Direct absorption of photon into TES
(e. g., optical photon detectors)
- Photon absorber in electrical contact with TES
(e. g., x-ray detectors)
- Large mass absorbers generate phonons which are converted into quasiparticles which diffuse to the TES
(e. g., dark matter detectors)



Metallic Magnetic Calorimeter

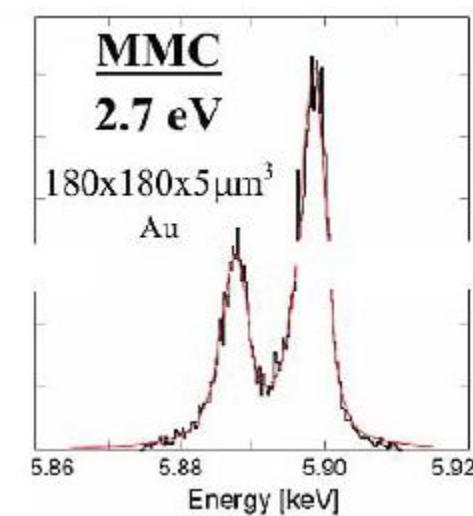
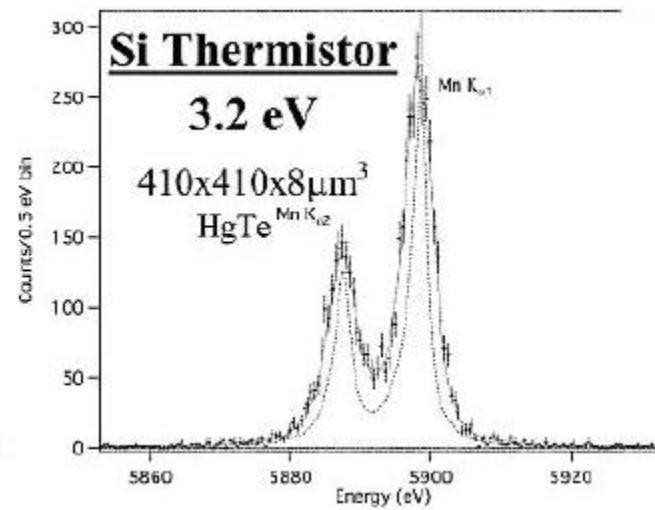
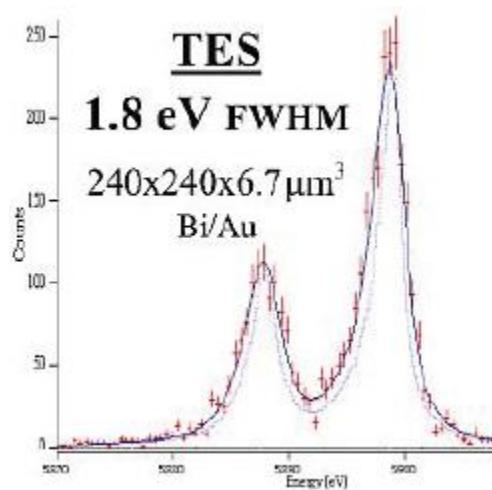


Au:Er
Au:Yb
Ag:Er
Bi₂Te₃:Er
PbTe:Er
LaB₆:Er



- Non dissipative thermometer
- Contactless

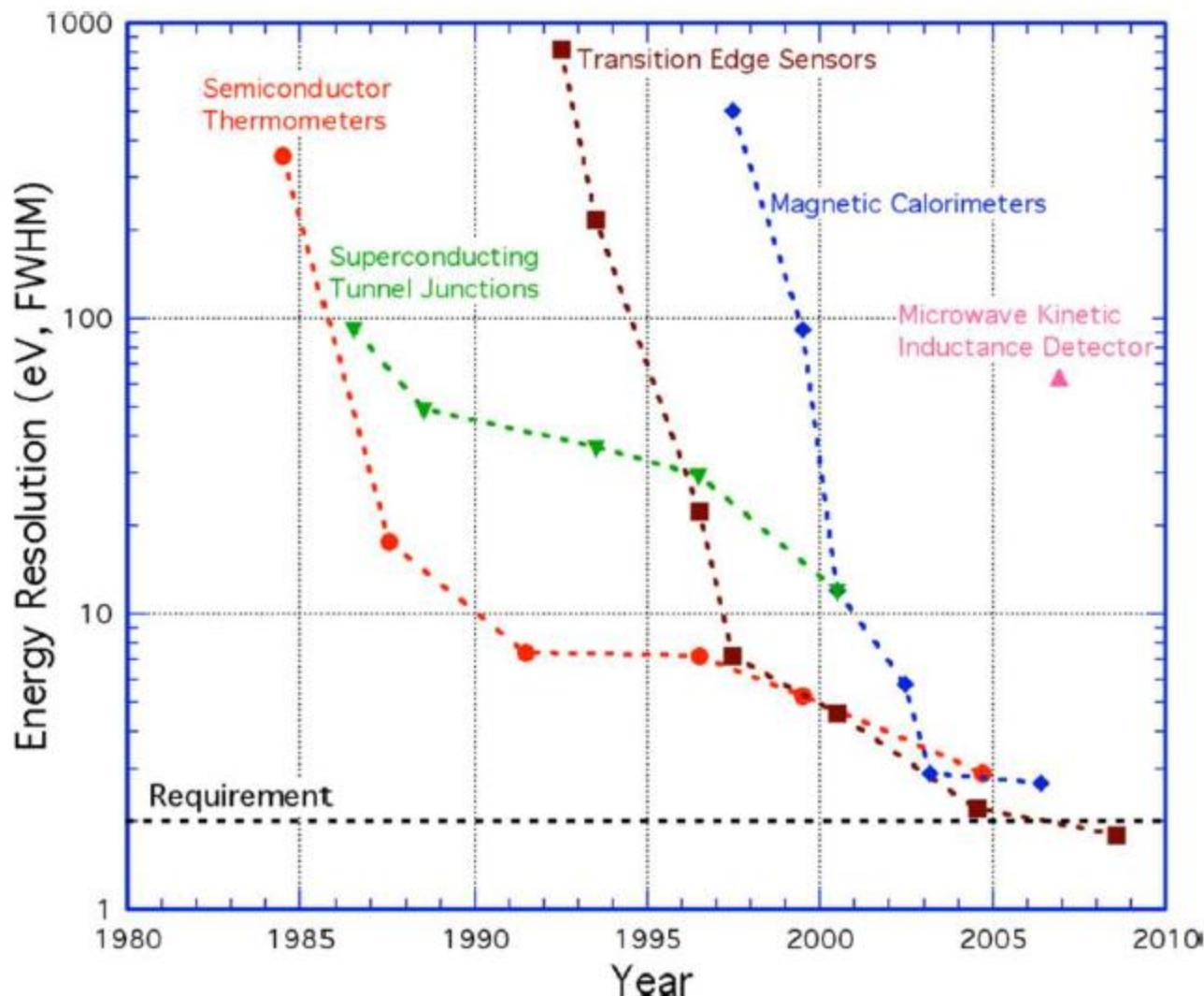
State of the art for X-ray energy resolution



$$(\Delta E)_{rms} = \sqrt{k_B T^2 C} \frac{(40)^{1/4}}{\sqrt{\alpha}}$$

$$(\Delta E)_{rms} = \sqrt{k_B T^2 C} \frac{4}{\sqrt{\alpha}}$$

$$(\Delta E)_{rms} = \sqrt{k_B T^2 C} \sqrt{8} \left(\frac{\tau_0}{\tau_1} \right)^{1/4}$$



Bolometer version

Noise Equivalent Power :

$$NEP = \sqrt{4 \cdot k_B \cdot g \cdot T^2} \quad (W/H_z^{1/2})$$

Relation with the energy resolution :

$$\Delta E = NEP \cdot \sqrt{\tau}$$

Detector design :

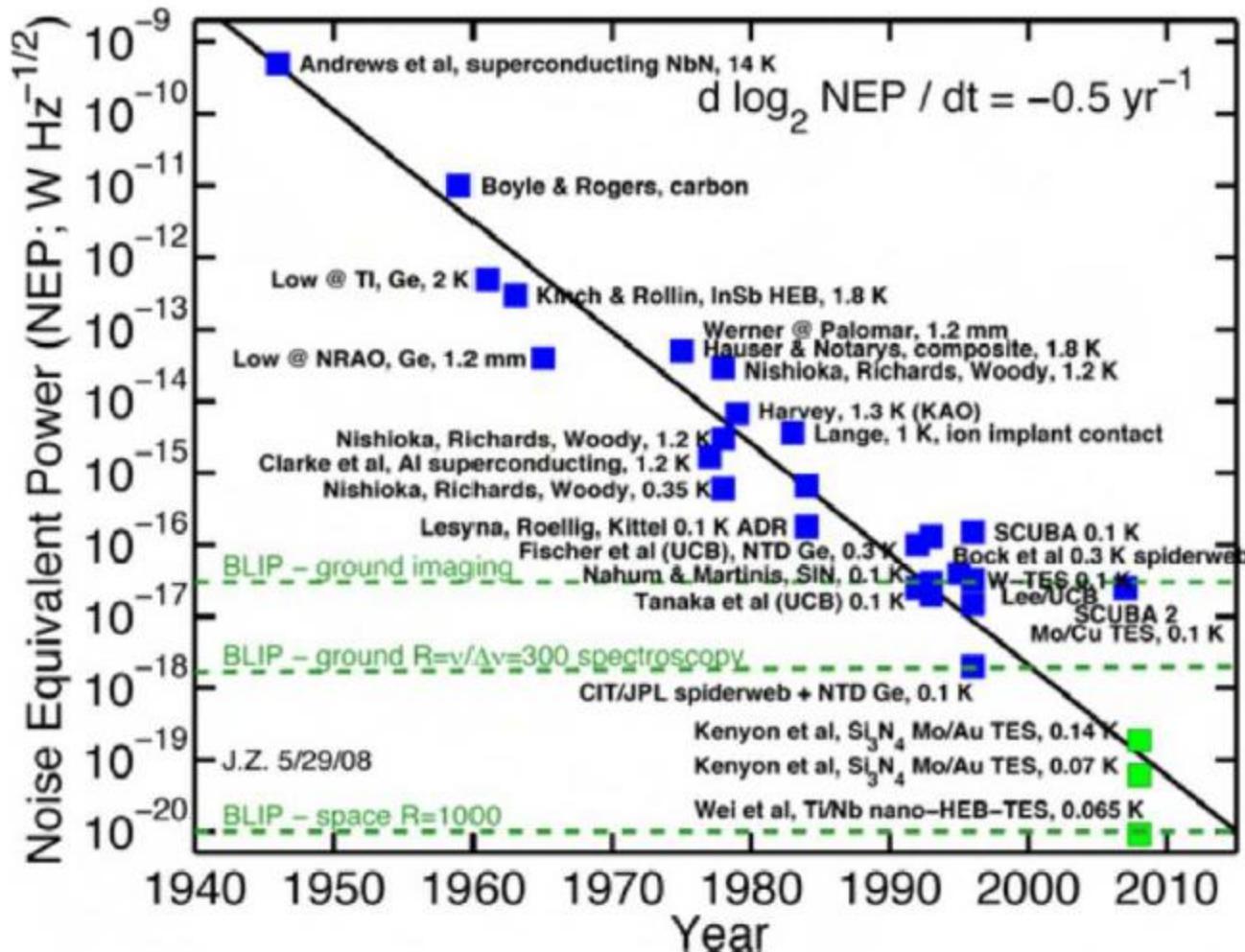
$$g \cong \frac{P}{T}$$

Low fluxes => low-g

BLIP condition :

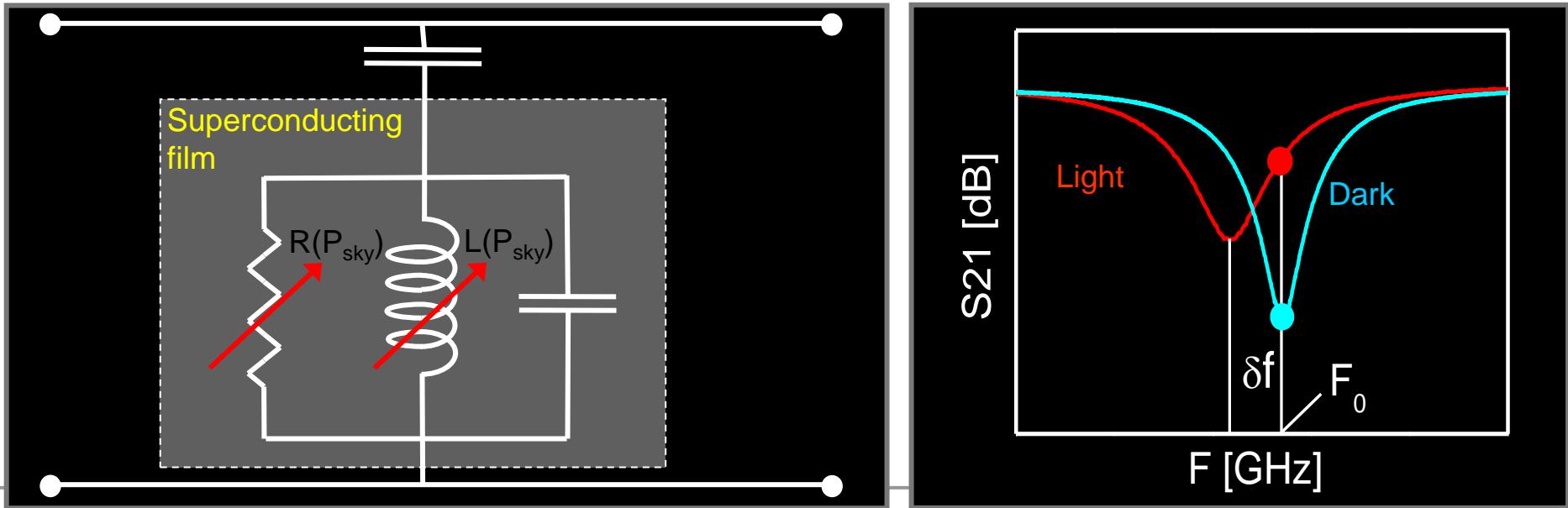
Low freq. => low temperature

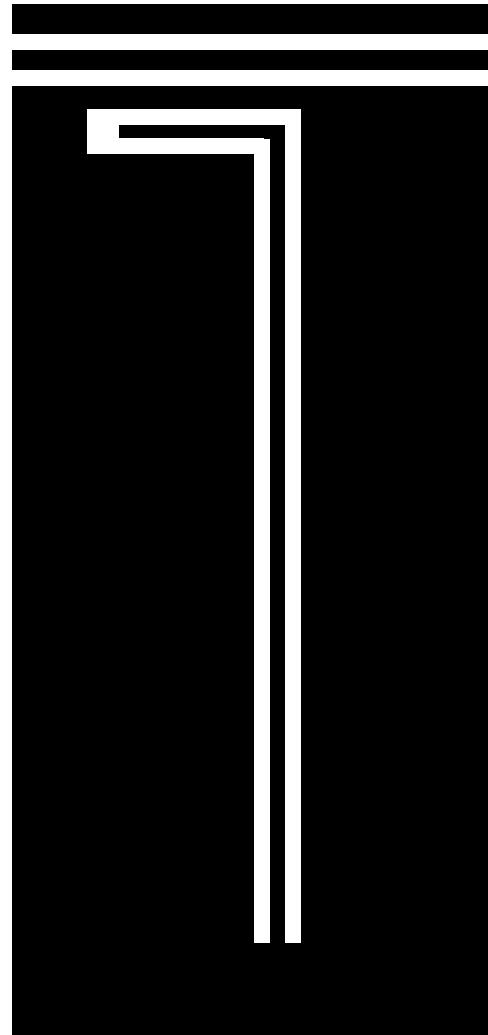
$$\begin{aligned} \sqrt{4 \cdot k_B \cdot g \cdot T^2} &= \sqrt{P \cdot h\nu} \\ \Rightarrow T &\approx \frac{h\nu}{4 \cdot k_B} \end{aligned}$$



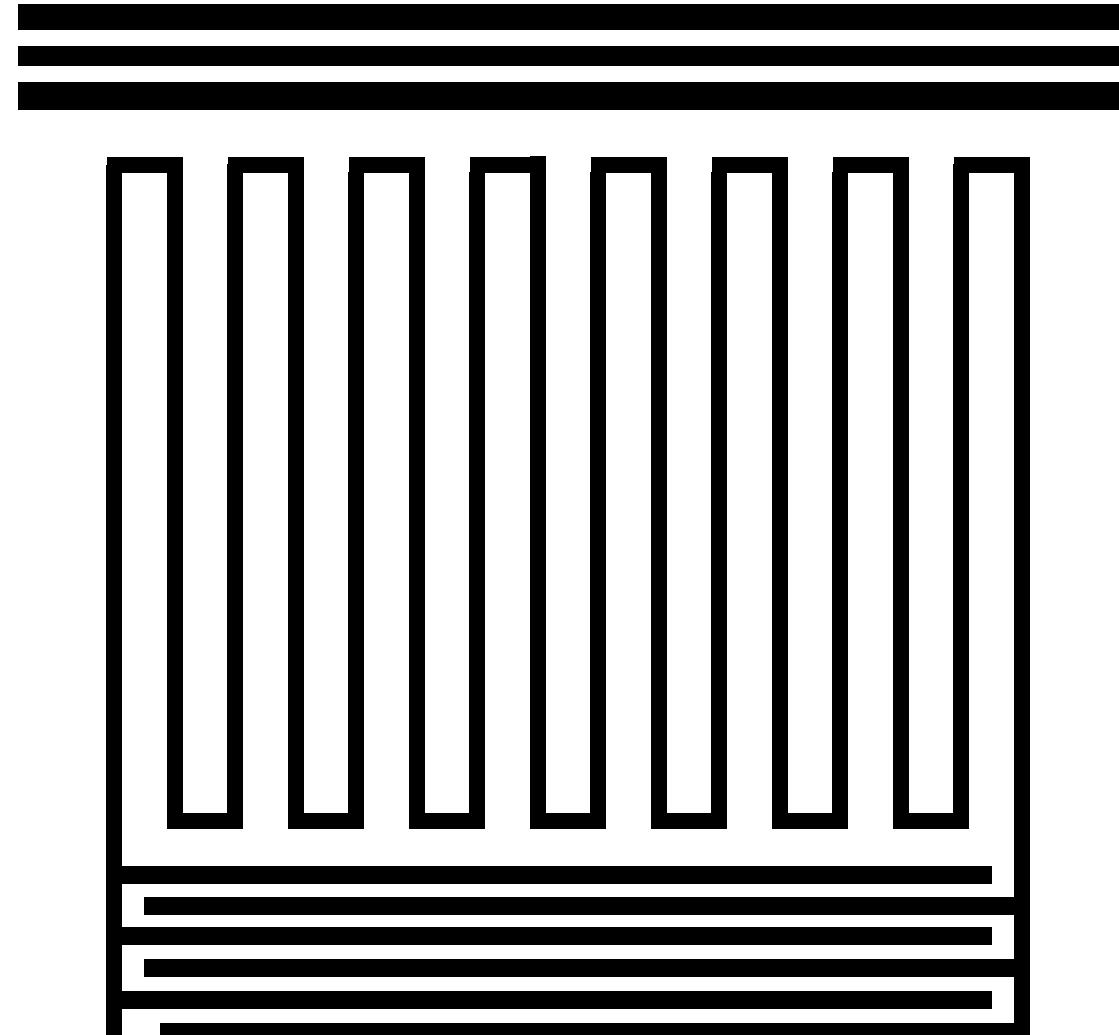
Kinetic Inductance Detectors

- Principle proposed by J.Zmuidzinas (Caltech, 2002)
- Measure QP generated in superconducting films





$\lambda/4$ CPW resonator

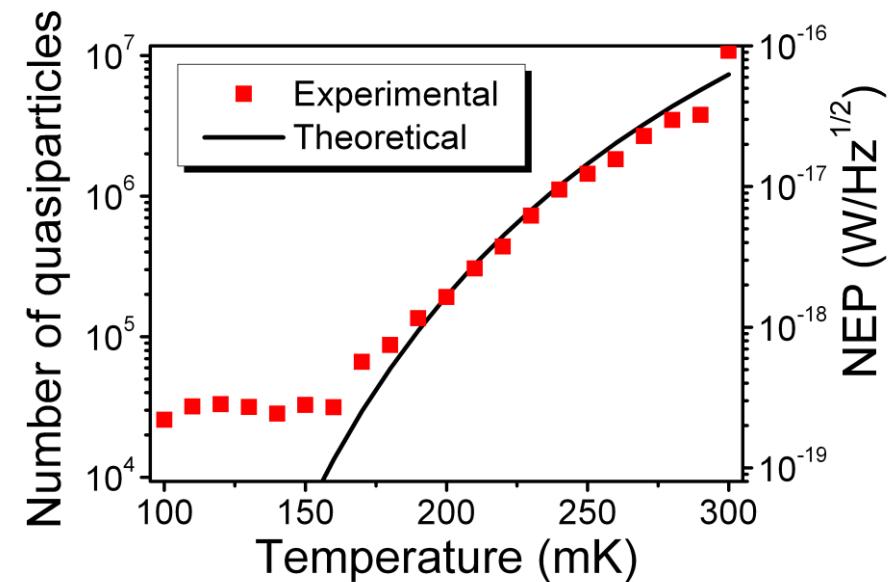
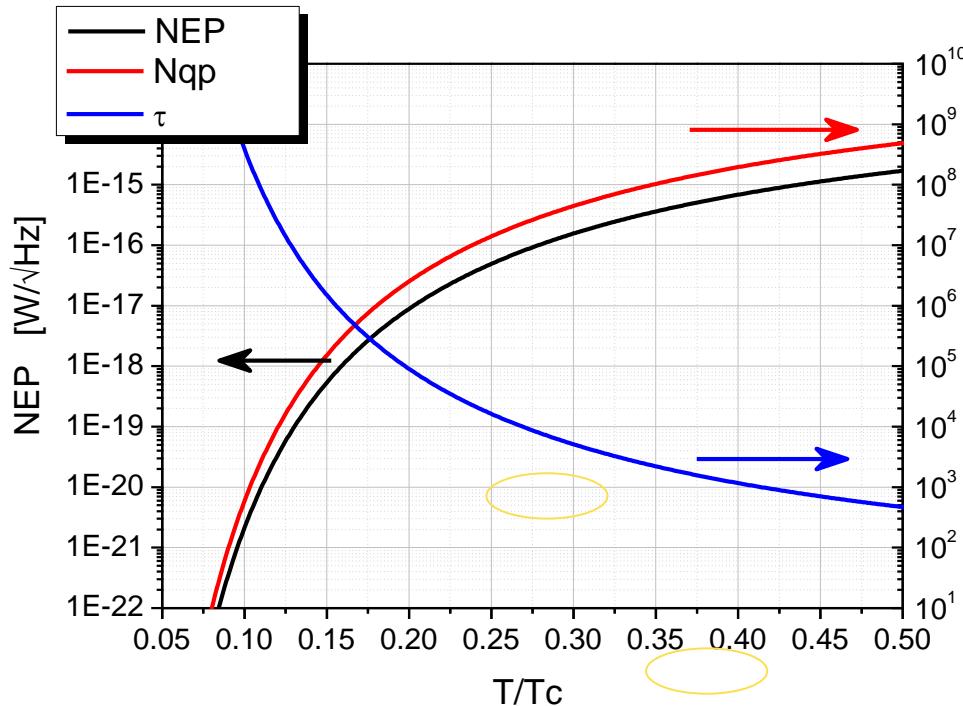


Lumped Element Kinetic Inductance Detector

quasiparticles

quasiparticle lifetime

$$NEP = 2\Delta/\eta \cdot \sqrt{N_{qp}/\tau_{qp}} \propto \exp\left[-\frac{\Delta}{k_B T}\right]$$

100 nm Al 6 GHz $\lambda/4$ CPW resonator

- Looking for the best materials (Al, Ta, TiN, TaN...)
- A very active field of research in the next years

TES versus STJ or KID

Intrinsic resolutions are similar because non-equilibrium detectors have excitations given by gap which is $\sim kT_c$ whereas thermal detectors have quanta with average $\sim kT_c$

TES

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

$n = 5$ electron-phonon coupling
 $T_e = T_c$ and $E_{sat} = T_c C / \alpha$

$$\Delta E_{FWHM} = 2.355 \sqrt{6.4 k_B T_c E_{sat}}$$

$$\Delta E_{FWHM} \approx 15 \text{ meV} \left(\frac{E_{sat}}{1 \text{ eV}} \right)^{1/2} \left(\frac{T_c}{70 \text{ mK}} \right)^{1/2}$$

STJ or L_K

$$\Delta E_{FWHM} = 2.355 \sqrt{E \epsilon_0 (F + G)}$$

$\epsilon_0 \approx 1.7 \Delta \approx 1.7(1.76 kT_c) = 3kT_c$
 $F = 0.2$ is Fano; $G = 0 - 2$ (tunneling noise)

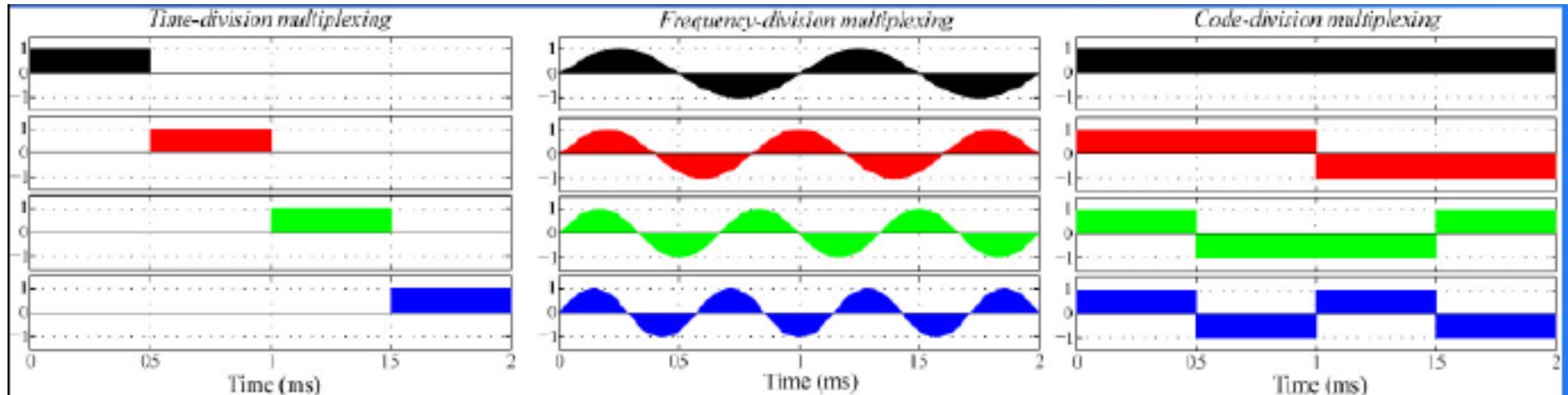
$$\Delta E_{FWHM} = 2.355 \sqrt{0.6 k T_c E}$$

$$\Delta E_{FWHM} \approx 18 \text{ meV} \left(\frac{E}{1 \text{ eV}} \right)^{1/2} \left(\frac{T_c}{1 \text{ K}} \right)^{1/2}$$

Making Arrays

Multiplexing techniques : put several signals into a single line ?

- Time division
- Frequency division
- Code division

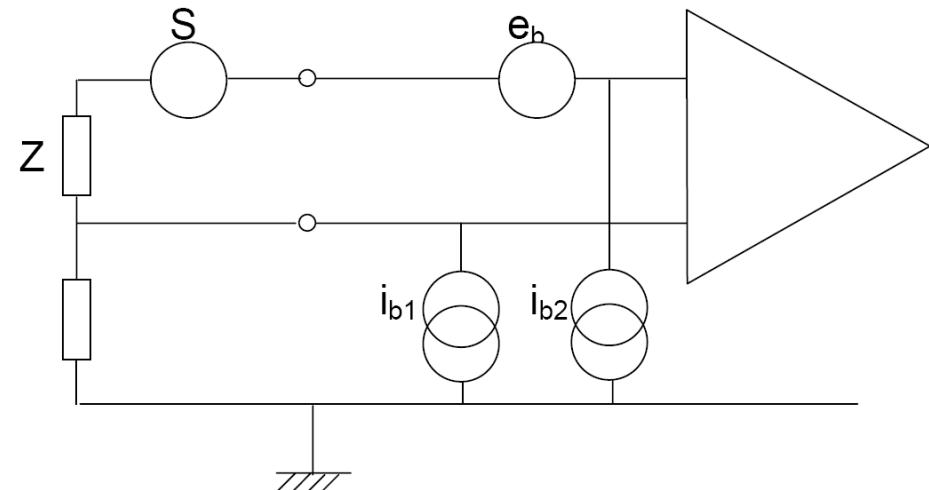


Amplifier noise

$$\overline{b^2} = \overline{e_b^2} + \overline{Z^2} \cdot \overline{i_b^2}$$

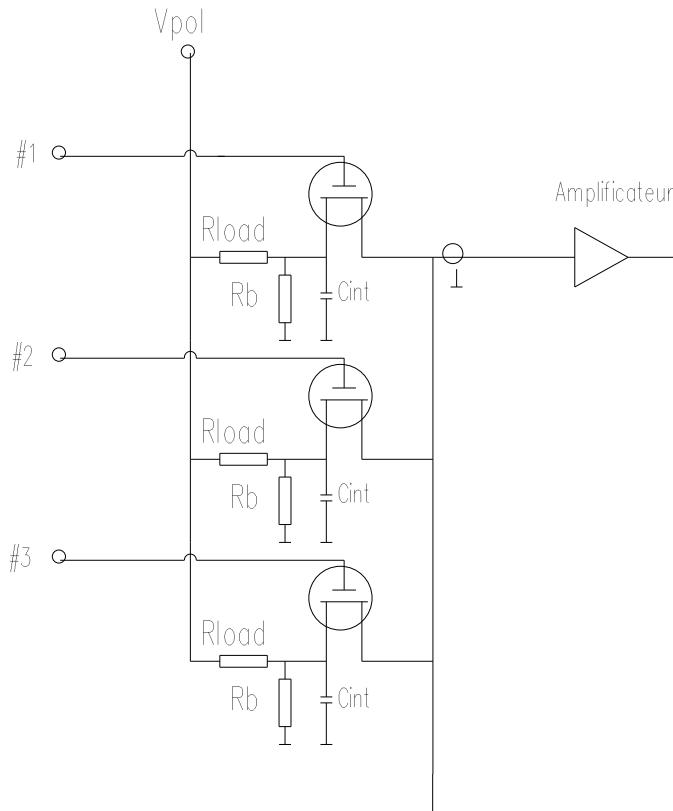
$$Z_o = e_b / i_b$$

$$T_{min} = (e_b \cdot i_b) / 2 \cdot K$$



AMPLI	T _{ut}	S _V (100Hz) V/Hz ^{1/2}	S _I A/Hz ^{1/2}	T _{BRUIT} =S _V *S _I /k _B	R [*] =S _V /S _I
BIPOLAIRE	300 K	1 nV	1 pA	2 K	1 kΩ
JFET Si	300 K	1 nV	1 fA	20 mK	1 MΩ
JFET Si	150 K	1 nV	0.1 fA	2 mK	10 MΩ
MOSFET Si	4 K	1 μV	<<0.1fA	200 mK	>>100 GΩ
FET AsGa	4 K	1 nV	1 fA	2 mK	1 MΩ
SQUID	4 K		1 pA	20 μK	1 mΩ

High Impedance Temporal MUX



$$R_b = 10M\Omega$$

$$C_{int} = 1nF$$

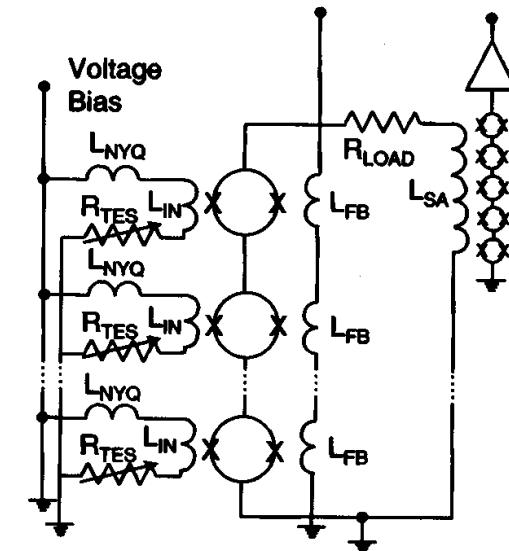
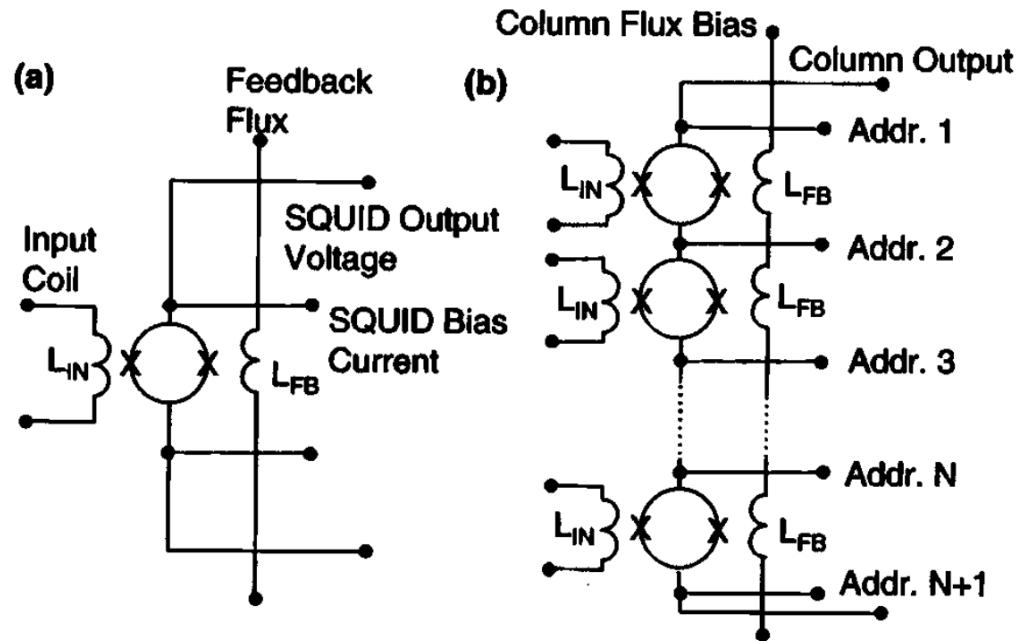
$$f_{RC} = 16Hz$$

$$N = 8$$

$$F = 256Hz$$

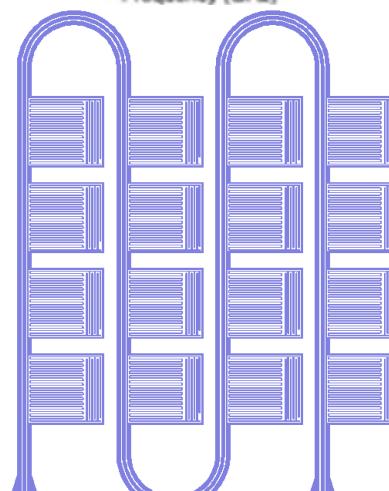
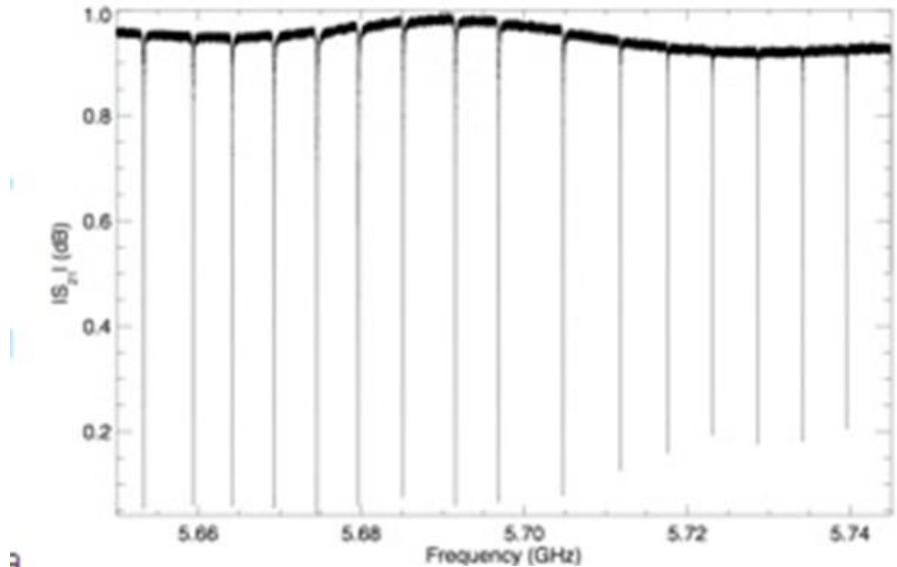
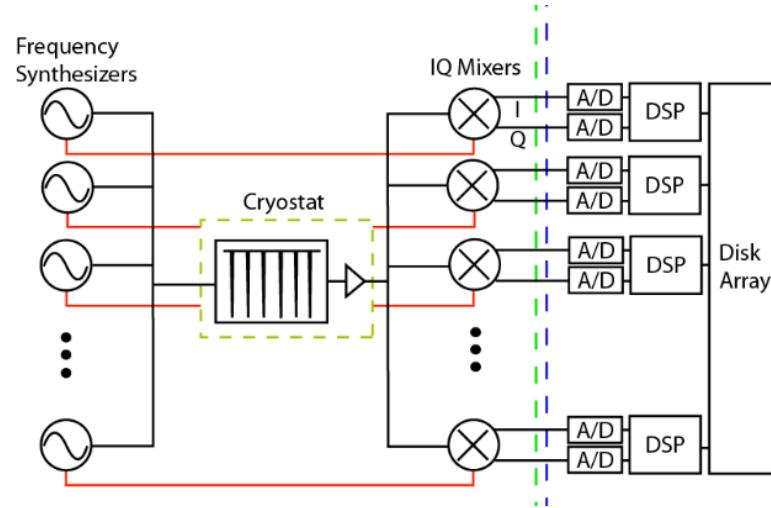
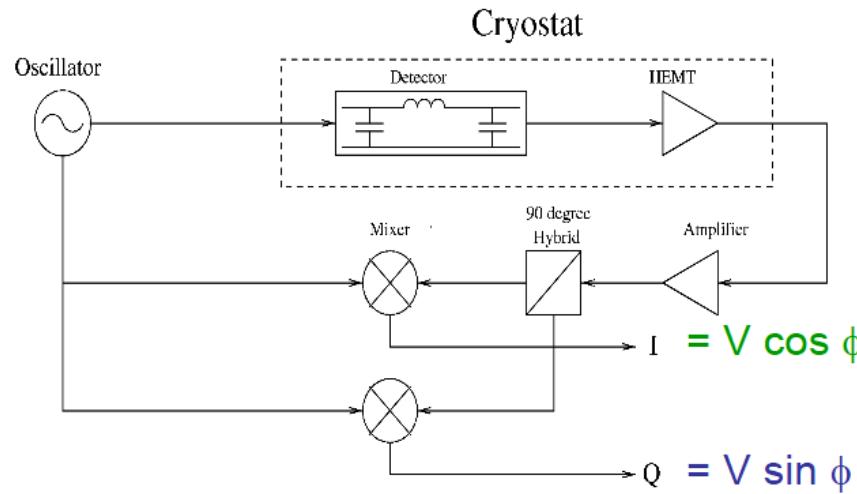
$$E_{amp} = 1.6nV/Hz^{1/2}$$

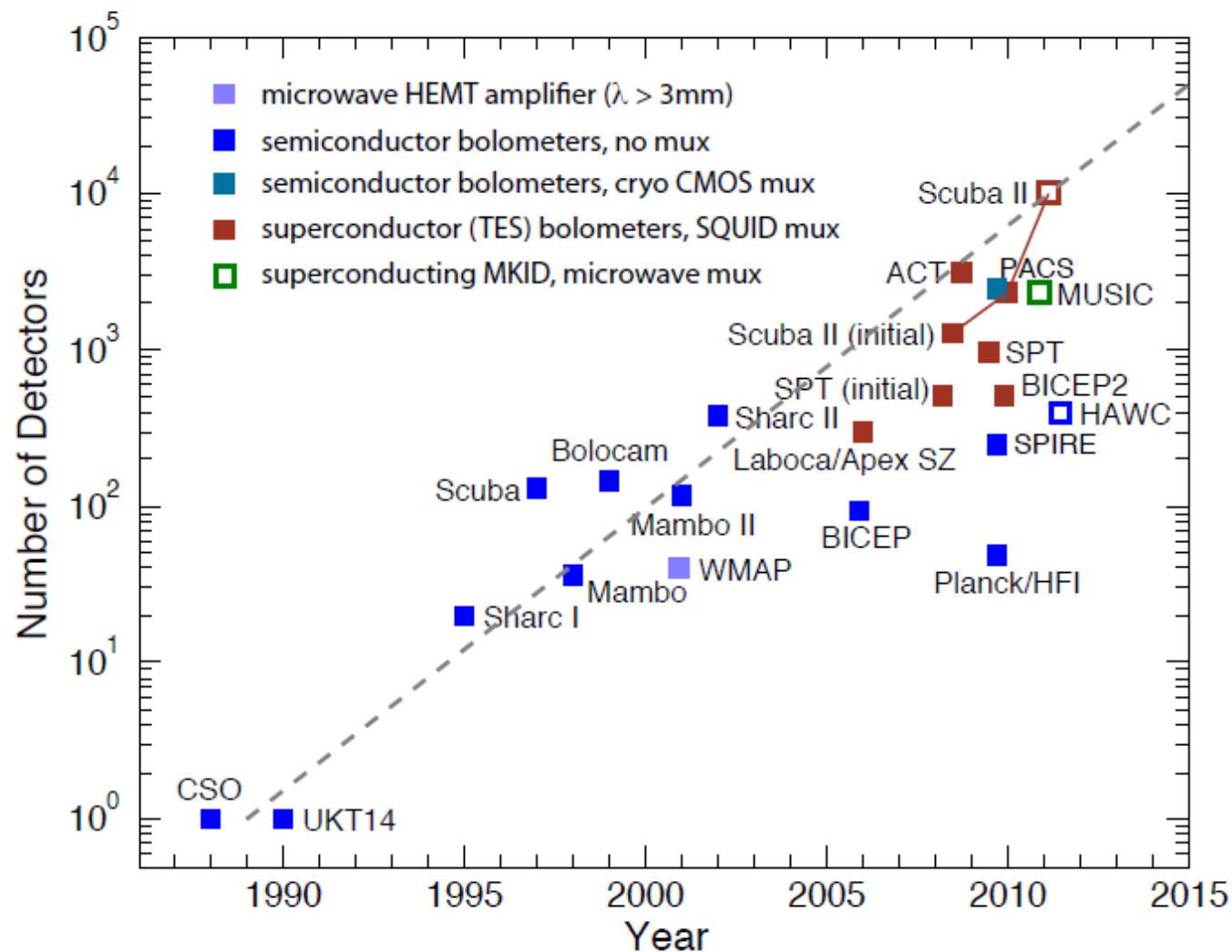
Low Impedance Temporal MUX



Nyquist LC filter
BW 20 Hz, MUX 8:1

KIDs frequency multiplexer



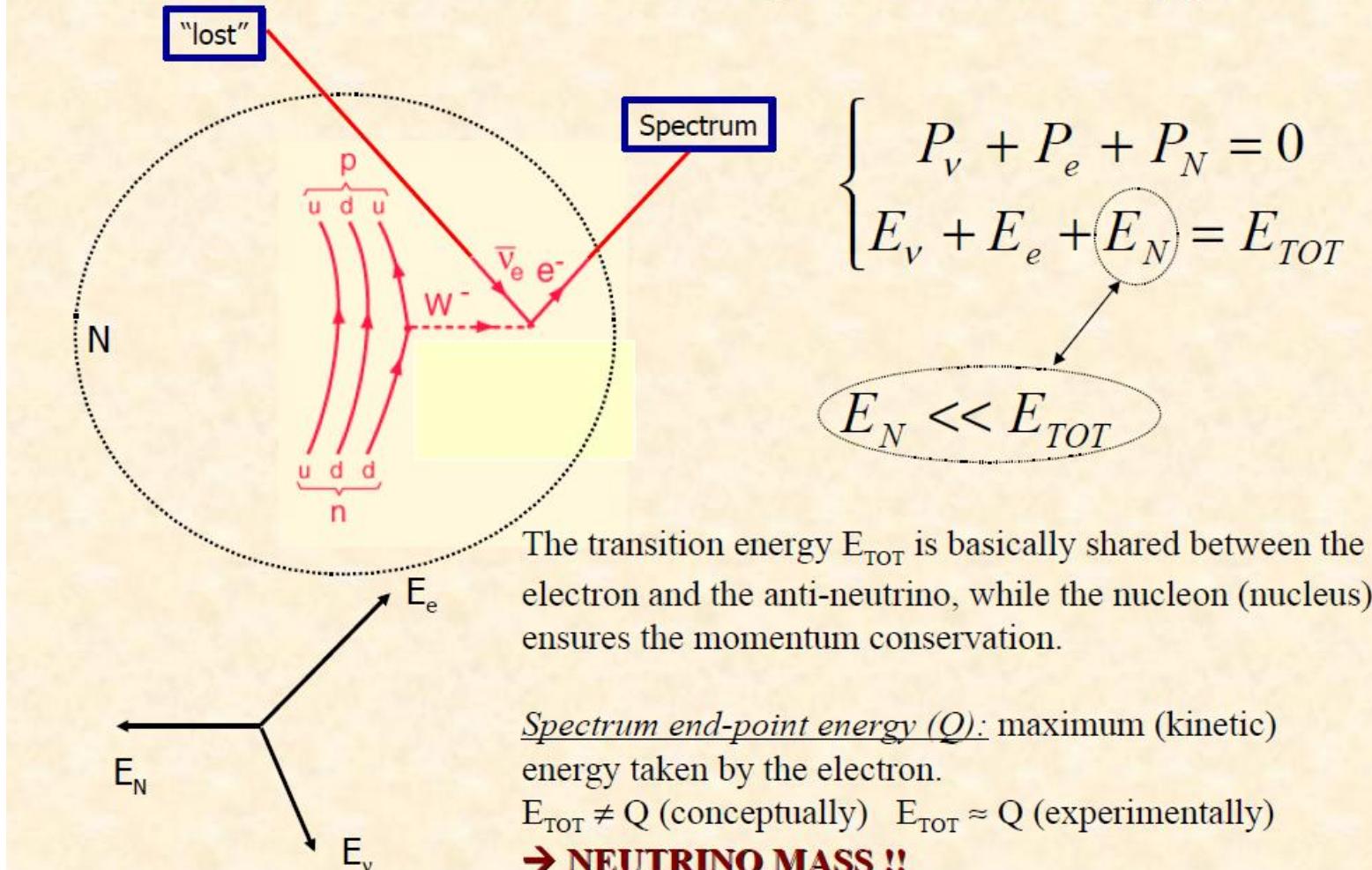


Selected Applications

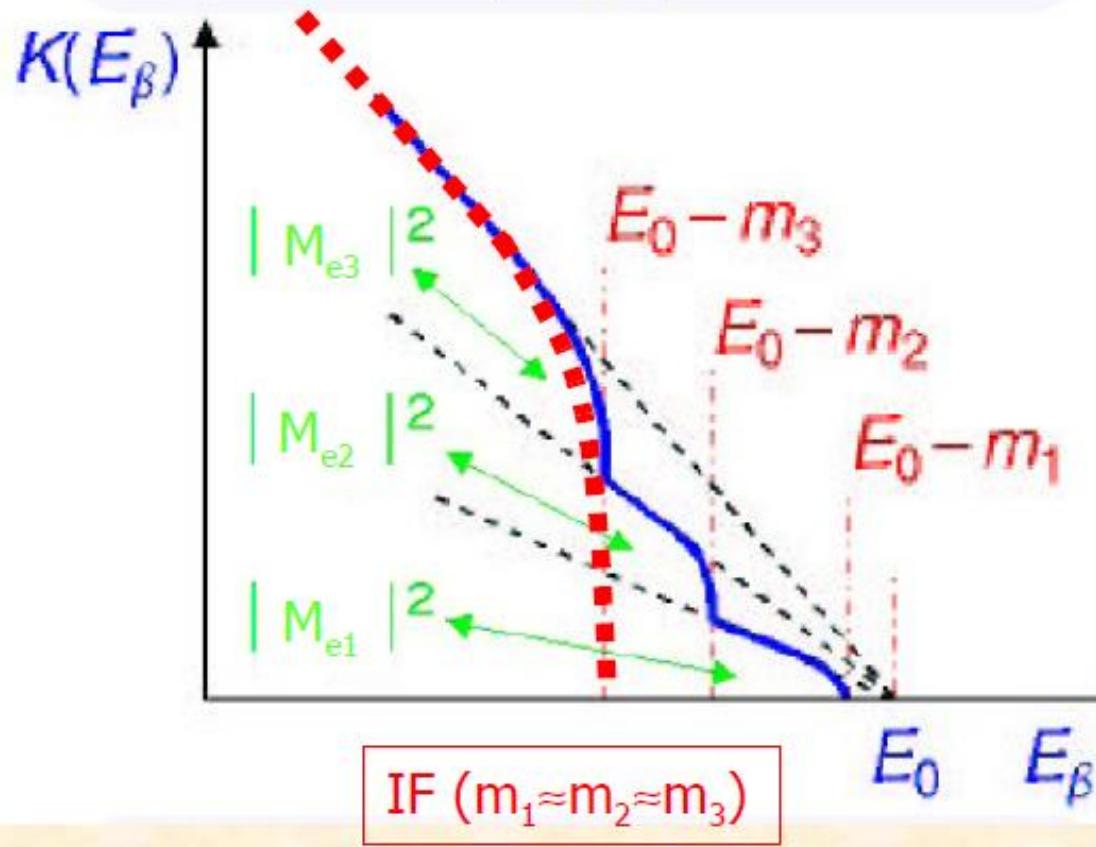
- The neutrino mass
- LTD in space : Planck/Herschel mission and future
- Dark matter search by cryogenic methods

Neutrino mass

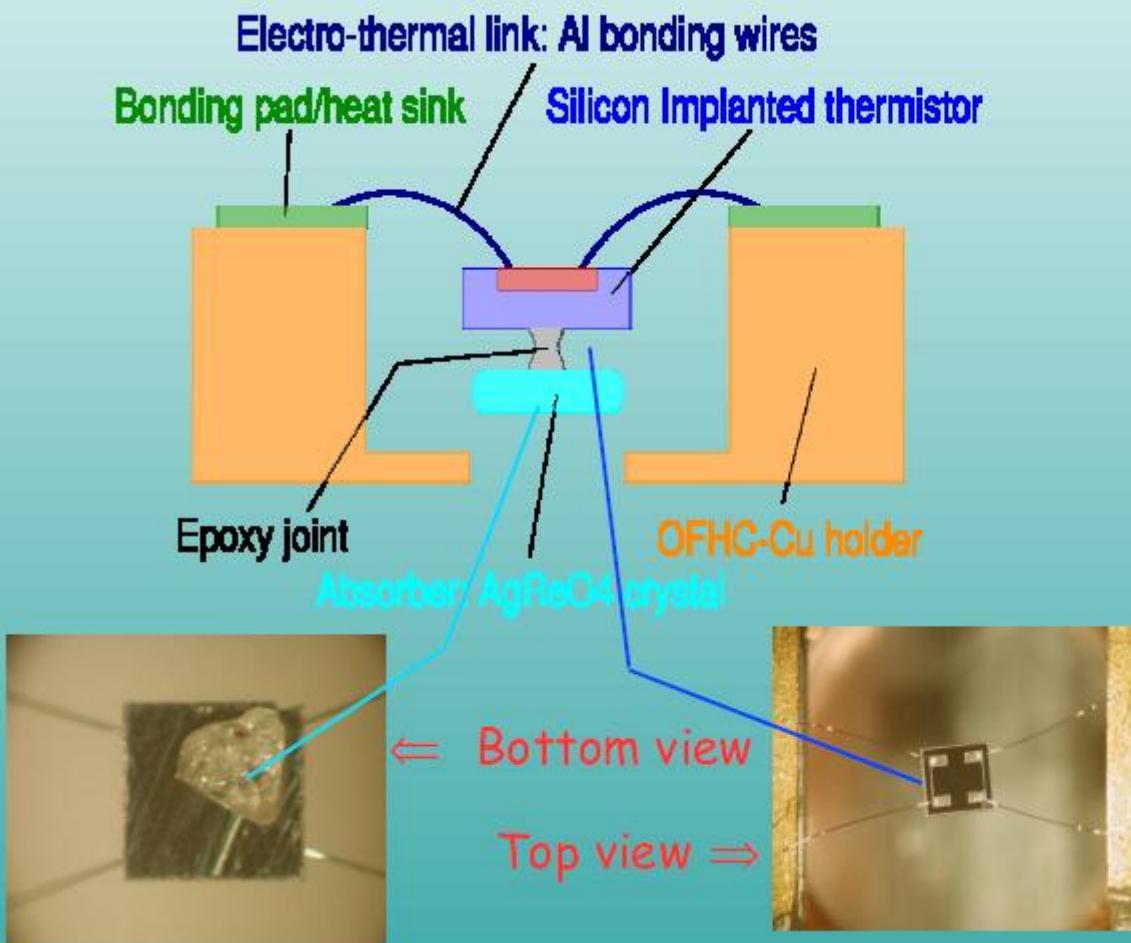
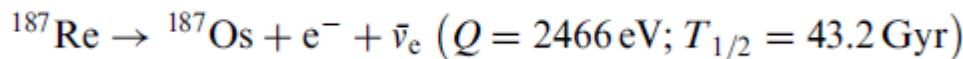
Kinematics of beta decay: "direct" approach



Y. Farzan *et al.*, hep-ph/0105105



Mibeta calorimeter



Absorbers

AgReO₄ single crystals

¹⁸⁷Re fraction ~0.32

$A_B \approx 5.4 \times 10^{-4} \text{ Hz}/\mu\text{g}$

Mass 250 ~ 300 μg

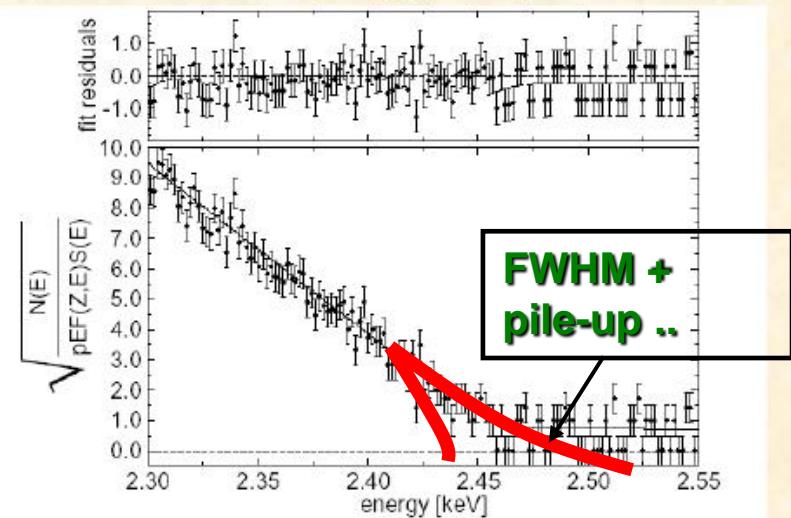
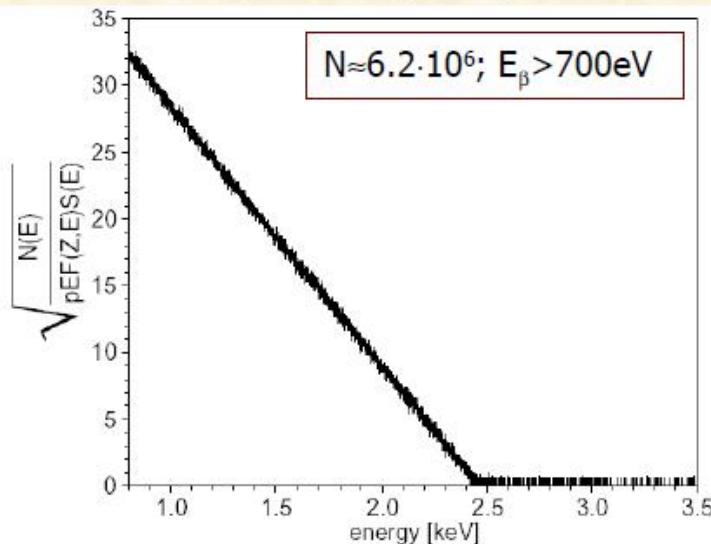


Intense detectors development in **Milano and IRST** in the 90s.

Side-product result: first $\Delta E_{FWHM} \approx 5\text{eV}$ ever achieved on 6keV X-ray Mn K calibration lines.

Ref. PRL, 82-3, 513 (1999)

Details: small array of 8 AgReO₄ micro-detectors (1 year data taking, $m_{TOT} \approx 2\text{mg}$).

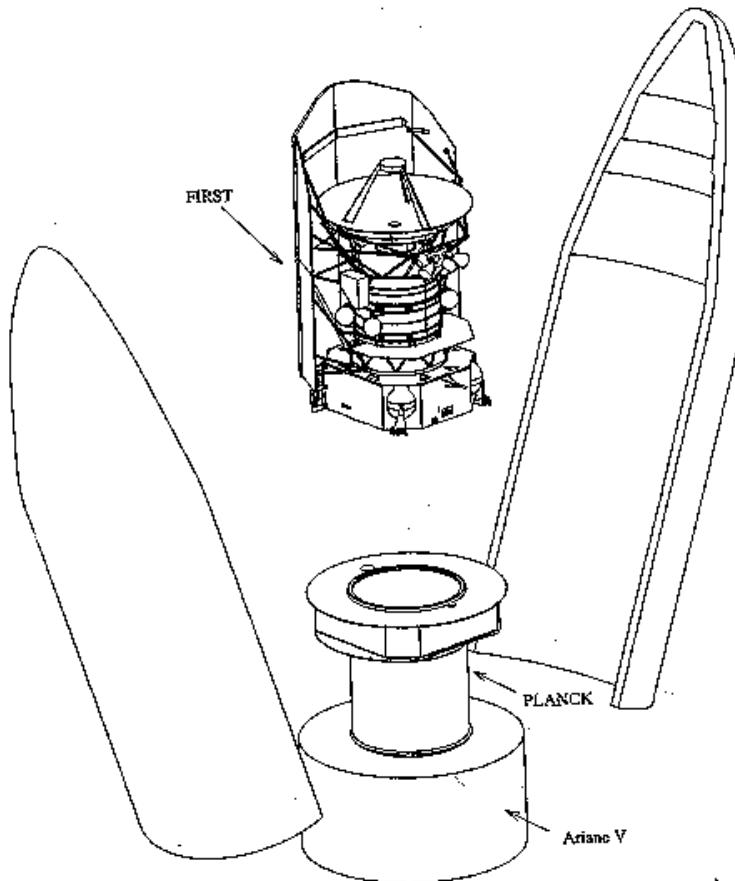


$$\left\{ \begin{array}{l} m_v < 15\text{eV} \text{ (90\% C.L.)} \\ Q = 2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{sys}} \text{ eV} \\ T_{1/2} = 43.2 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}} \text{ Gyr} \\ + BEFS \text{ (see next)} \end{array} \right.$$

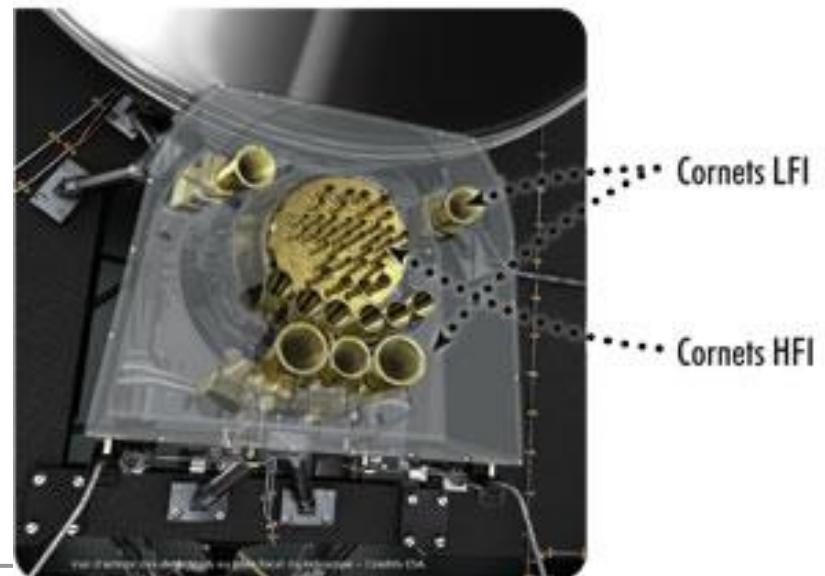
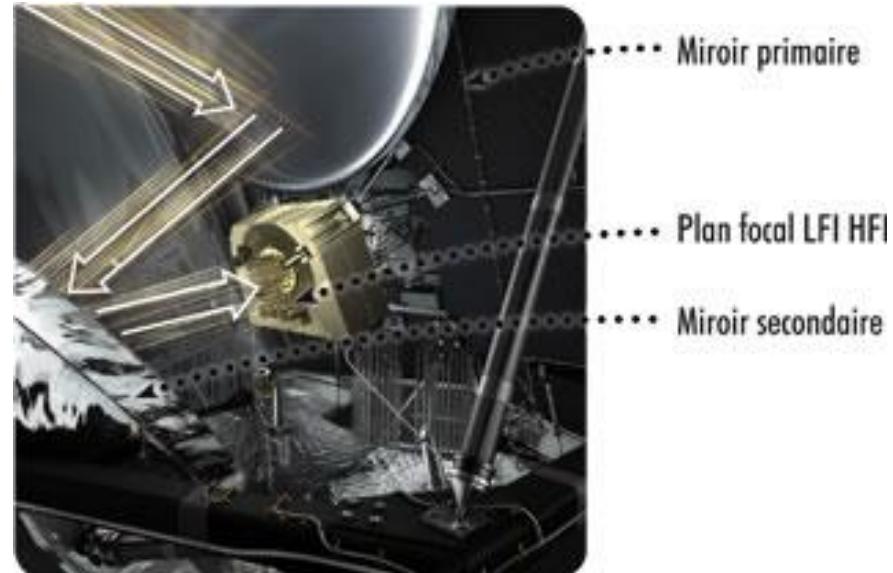
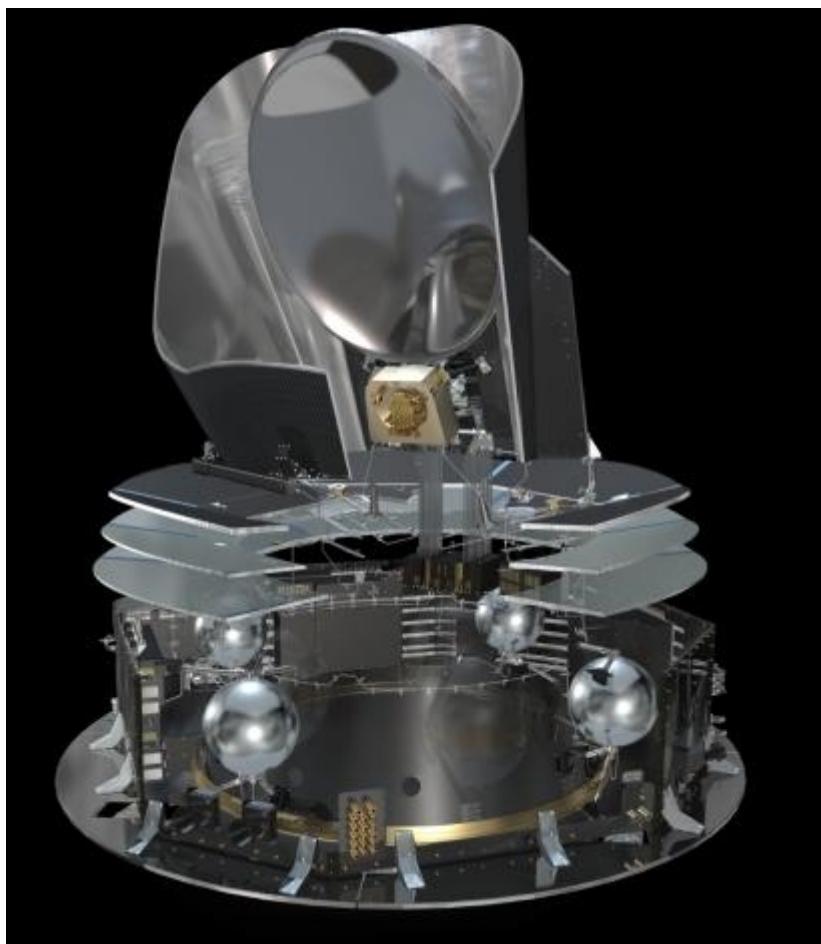
Thermistors: IRST doped(P)/compensated(B) silicon kept in **VRH** (Variable Range Hopping).

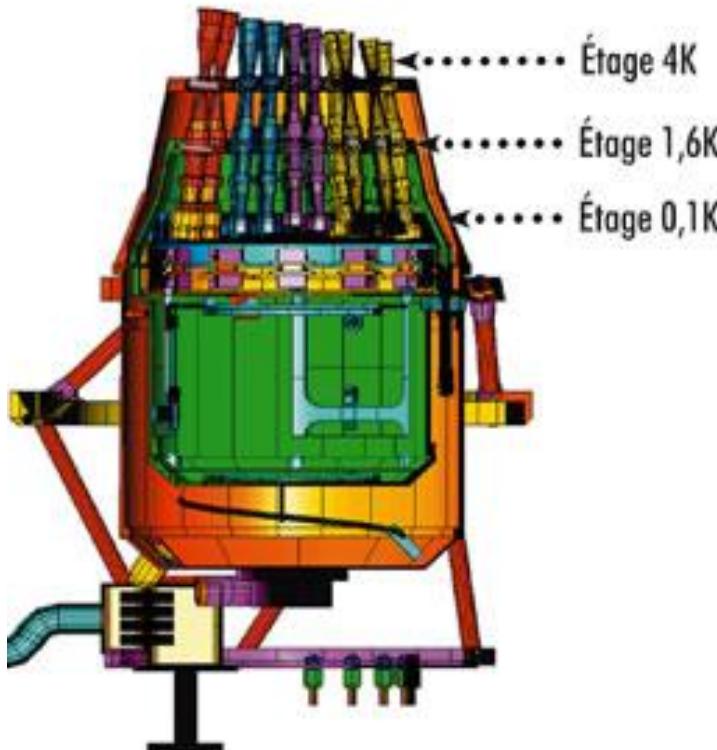
$$R(T) = R_0 \cdot e^{\left(\frac{T_0}{T}\right)^{\gamma}}$$

Cryogenic detectors in Space : the Planck / Herschel missions

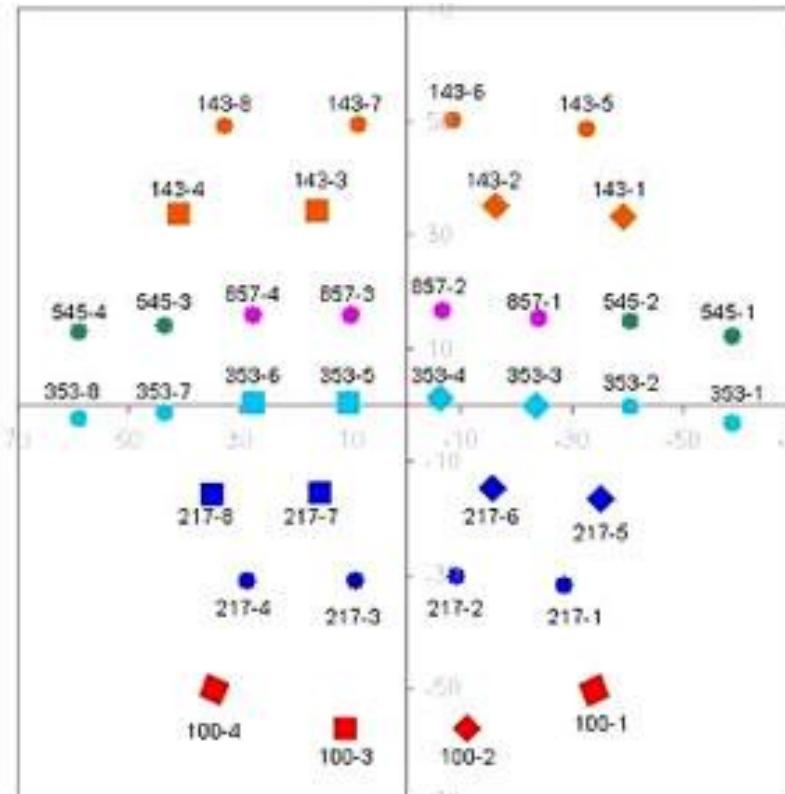


Launched in May 2009

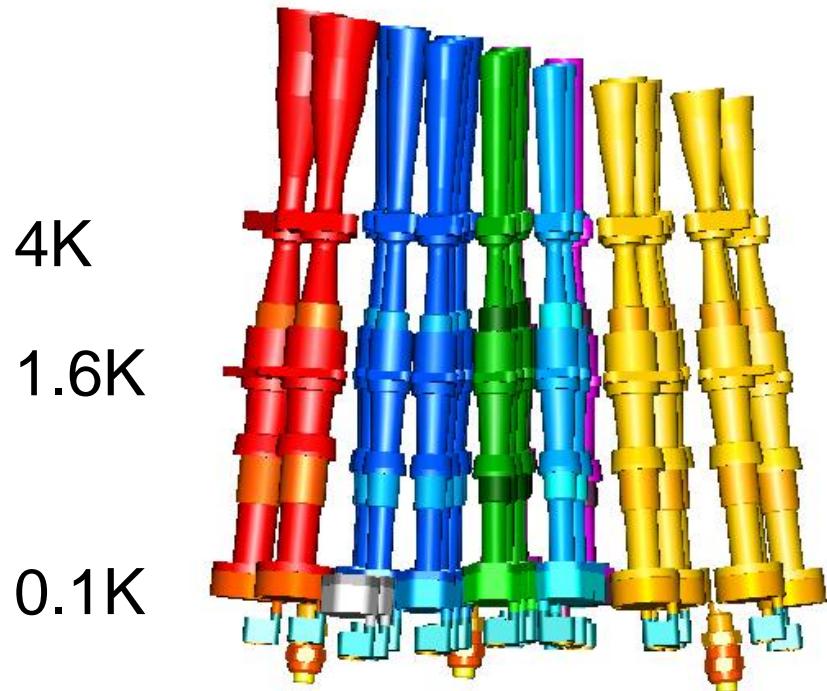




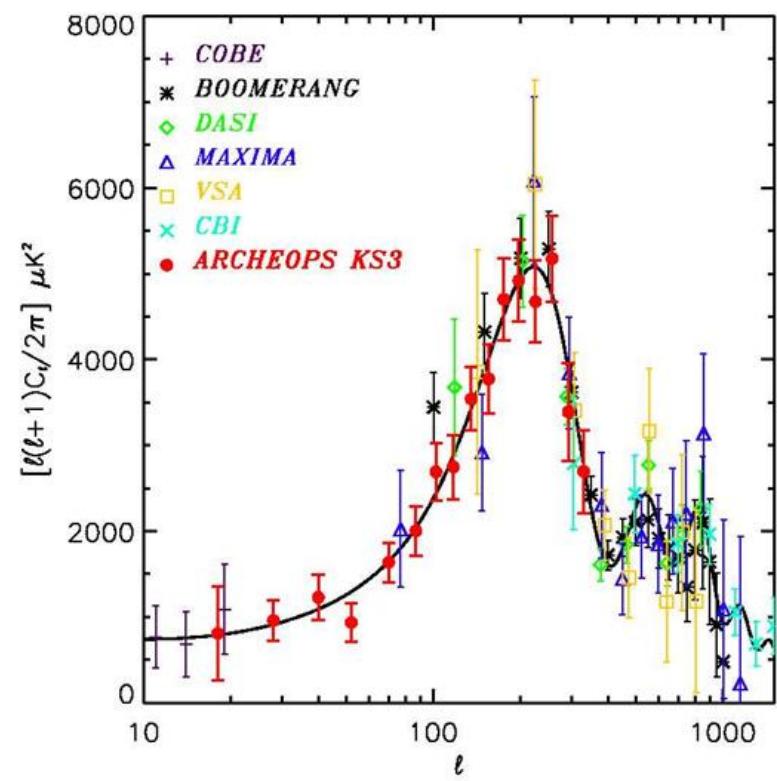
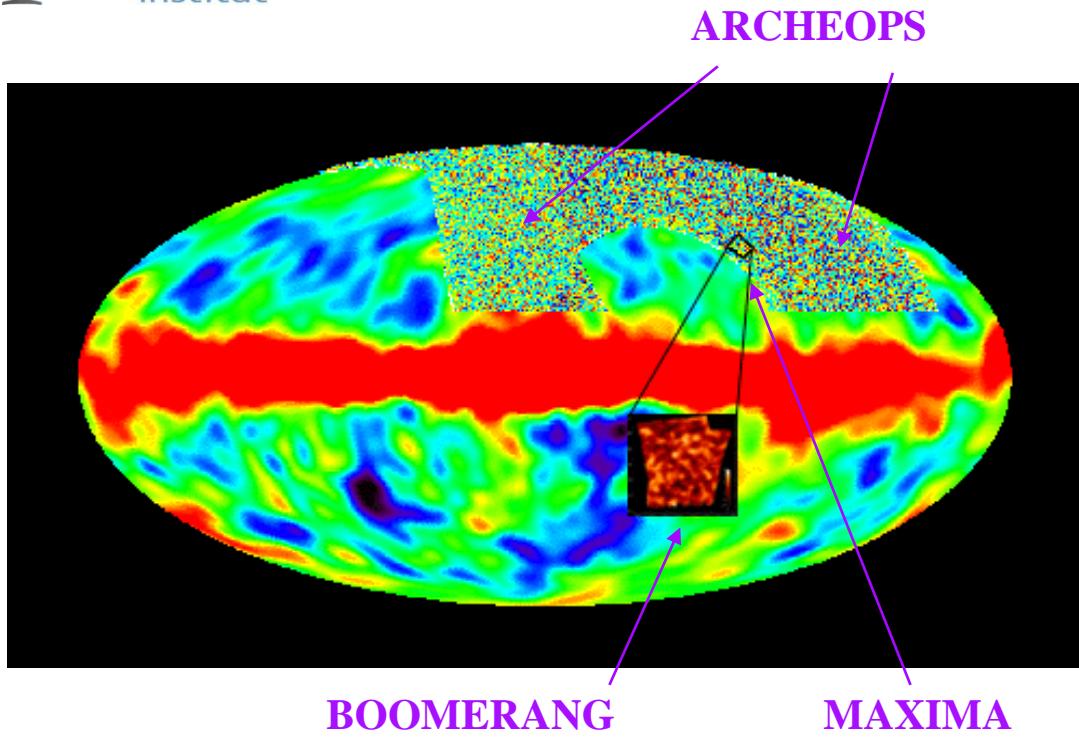
Plan de coupe HFI

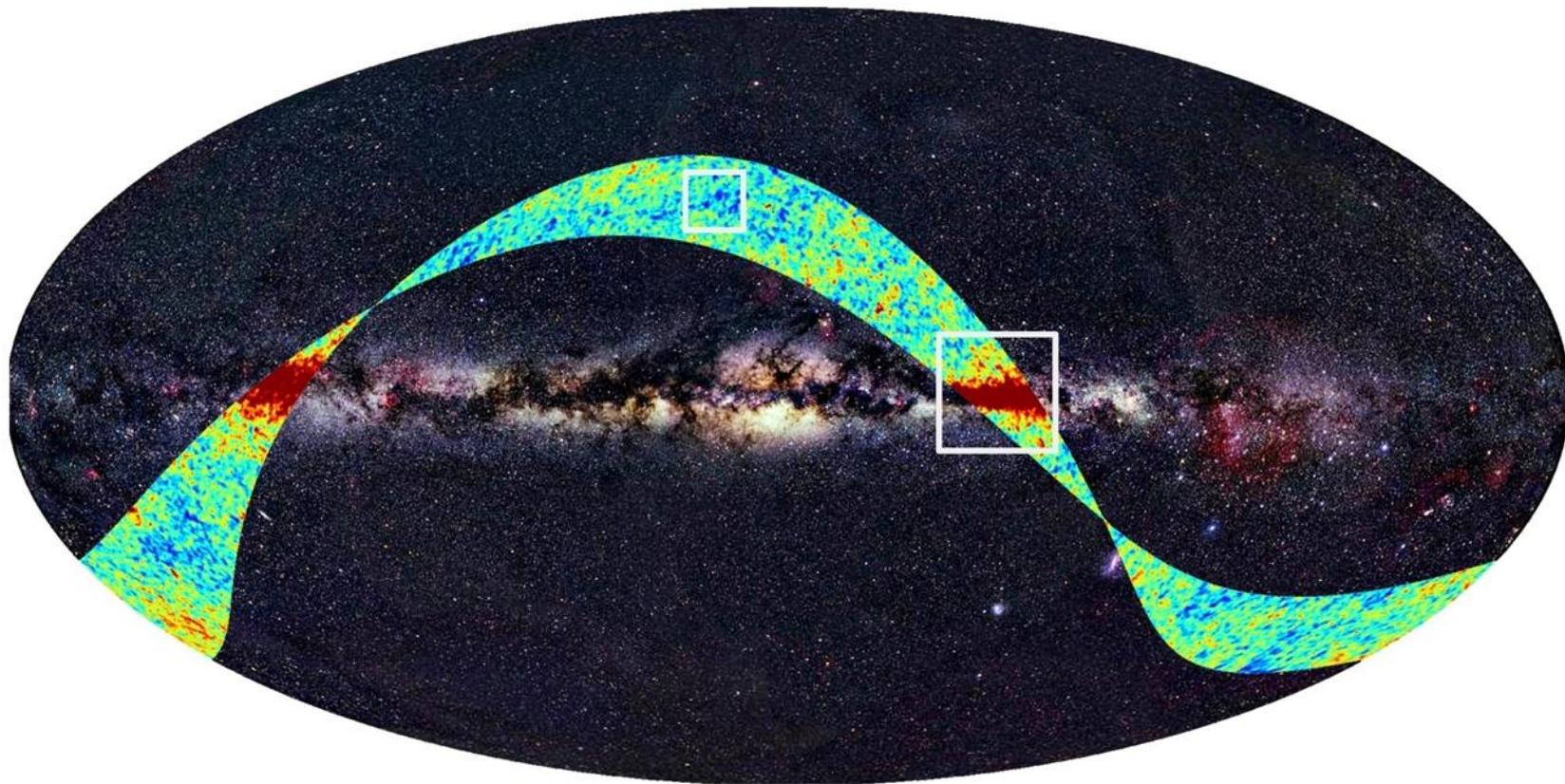


Vue de dessus : arrangement des pixels
 Les cercles représentent les voies non-polarisées
 Les carrés représentent les voies polarisées.



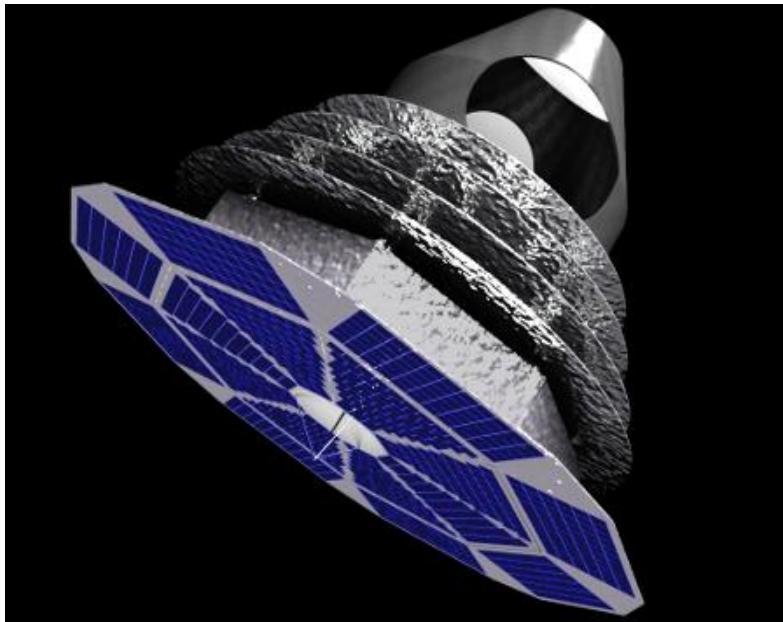
NTD-Ge sensor, NEP = 10^{-17} W/Hz $^{1/2}$ @ 100mK





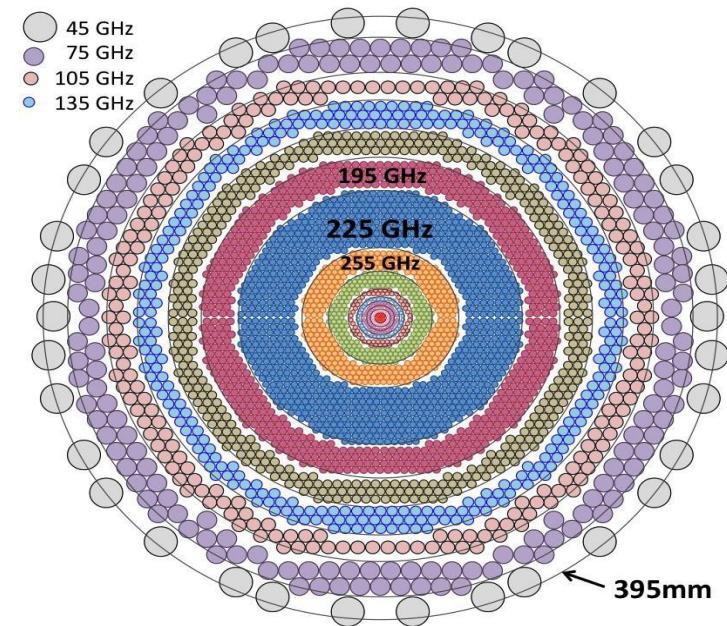
End of mission in January 2012

After Planck...



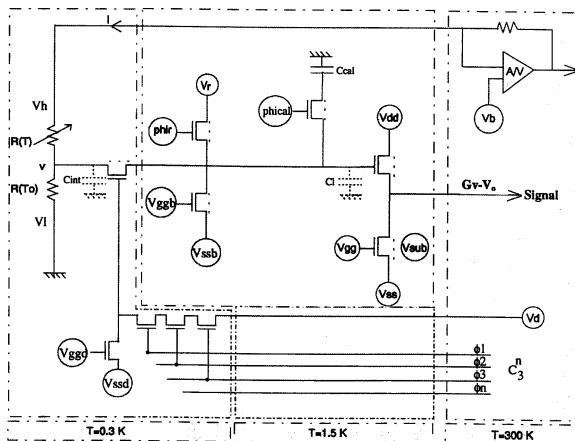
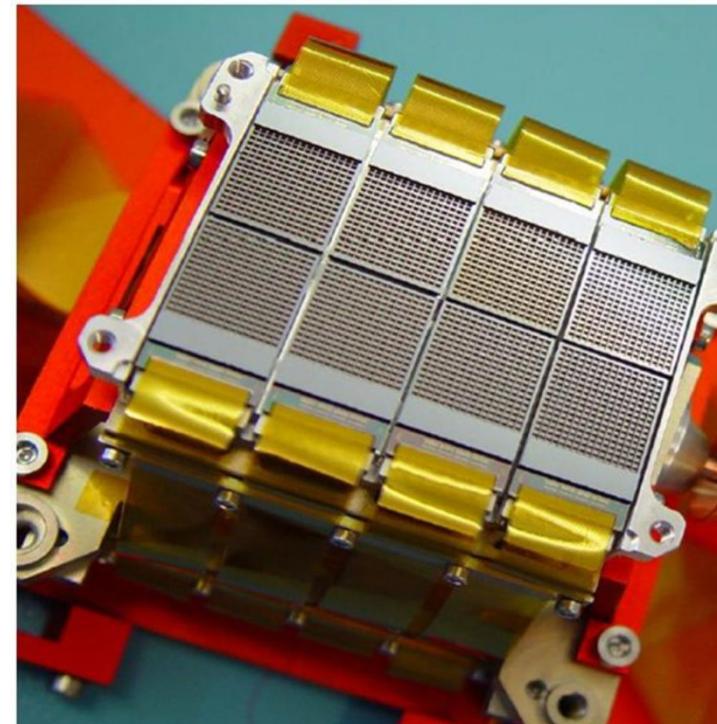
CORE Concept (ESA)

- Mapping the CMB polarization
- Information on the inflation phase
- Needs an increased number of detectors (52 => 10000)



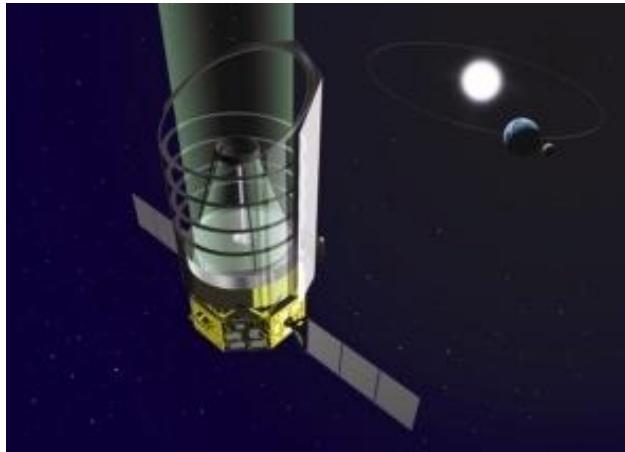
Focal plane at 50 mK

Herschel Detectors

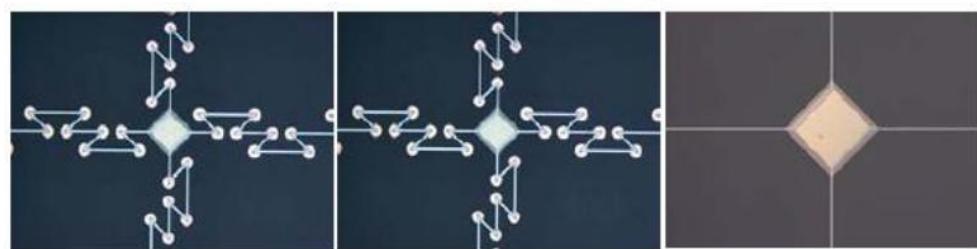
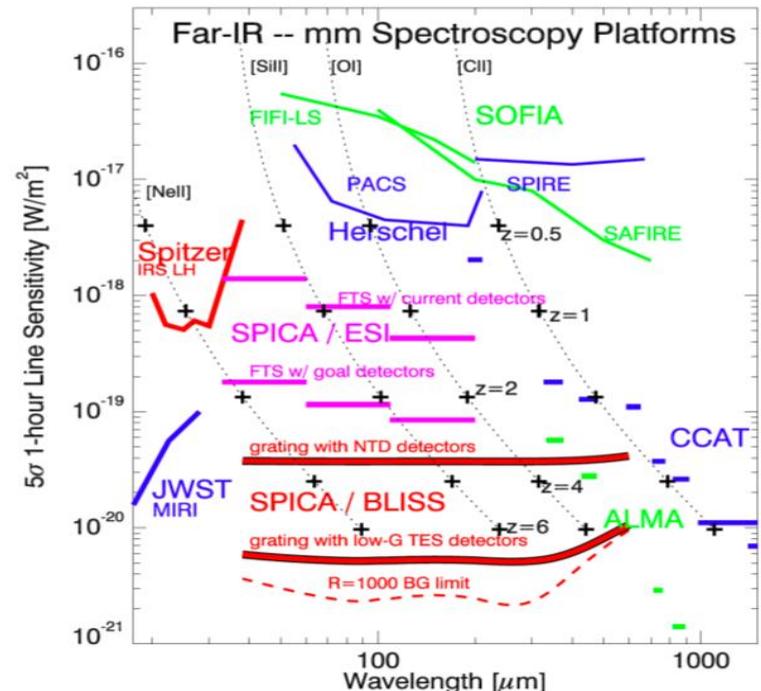
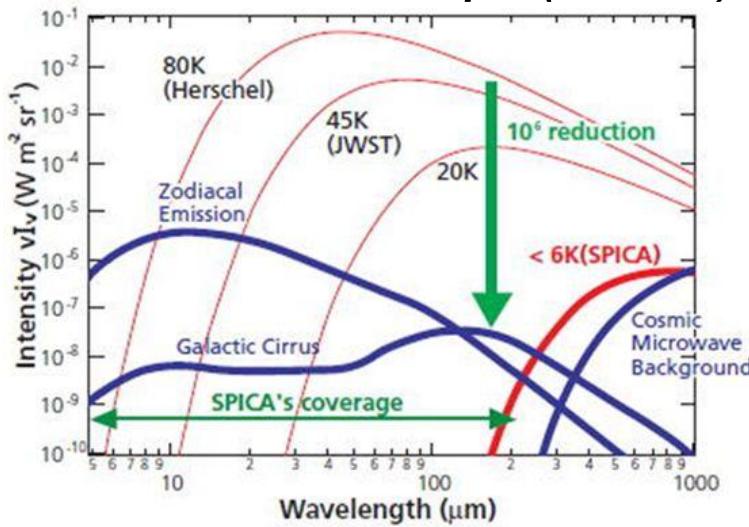


- PACS Instrument 256 pixels arrays (300mK)
- Integrated MUX with CMOS

After Herschel



SPICA Concept (JAXA)



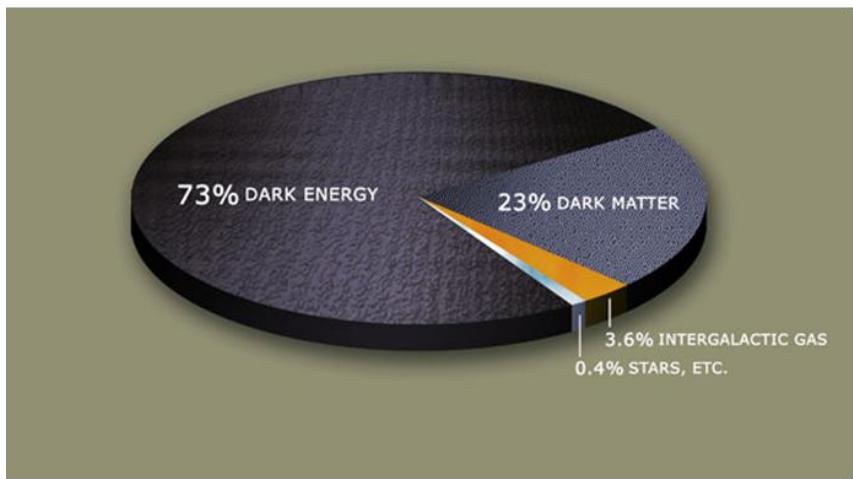
Low g design for 70 pW, 50mK

Dark Matter

Concordant Λ CDM model

Dark Matter and
Dark Energy

$$\Omega \approx 1$$

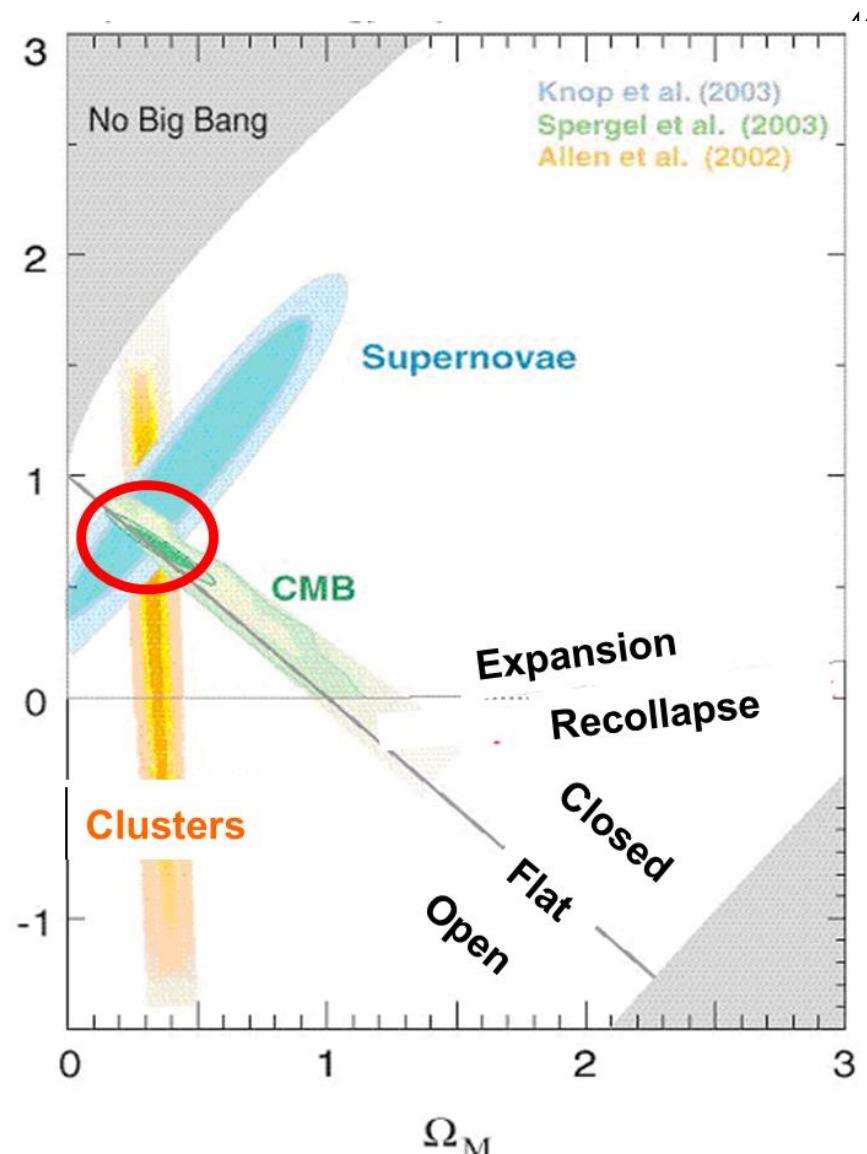


$$\Omega_m = \Omega_{\text{Baryons}} + \Omega_{\text{Dark}}$$

$$\Omega_{\text{Baryons}} = \Omega_{\text{visible}} + \Omega_{\text{invisible}}$$

$$\Omega_{\text{visible}} \approx 0.01$$

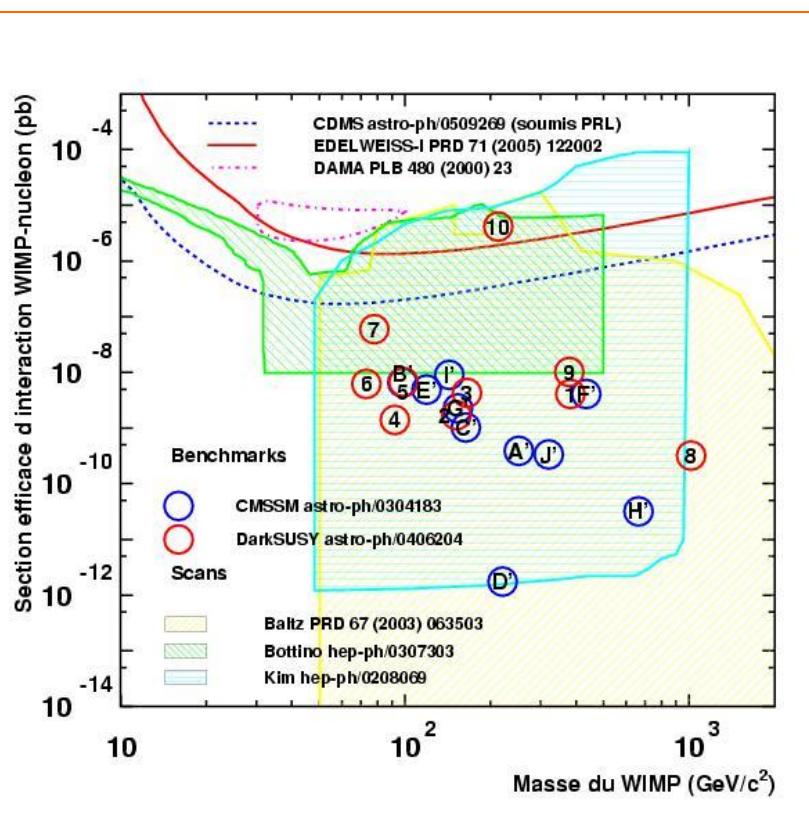
$$\Omega_{\text{Baryons}} \approx 0.047 \text{ (primordial nucleosynthesis)}$$



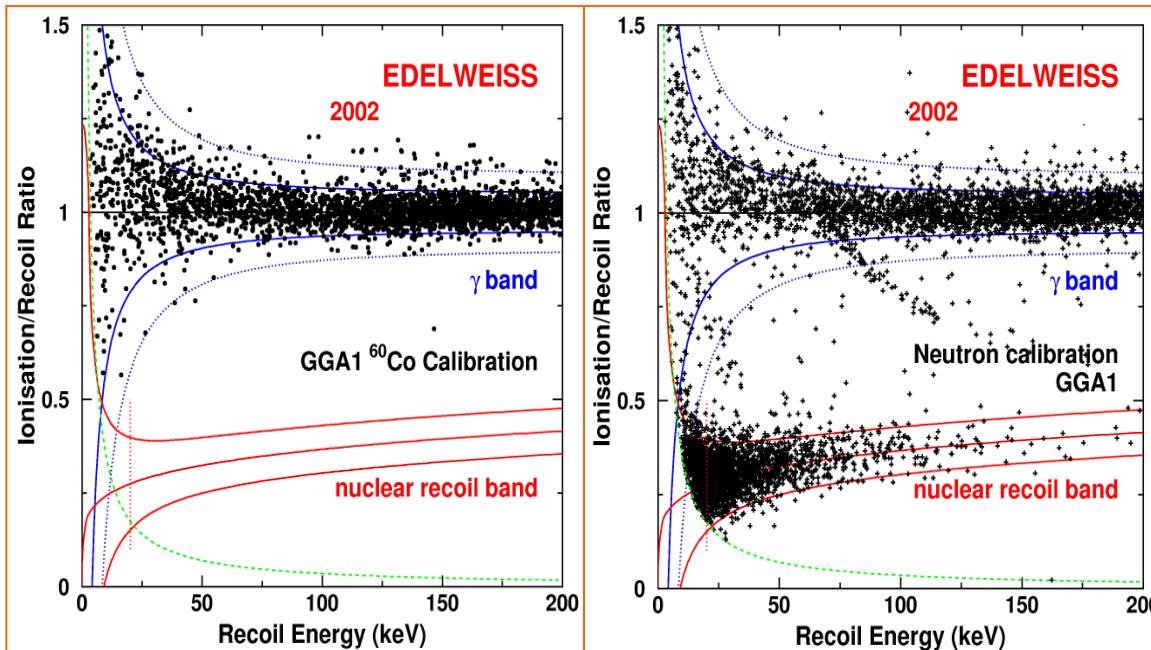
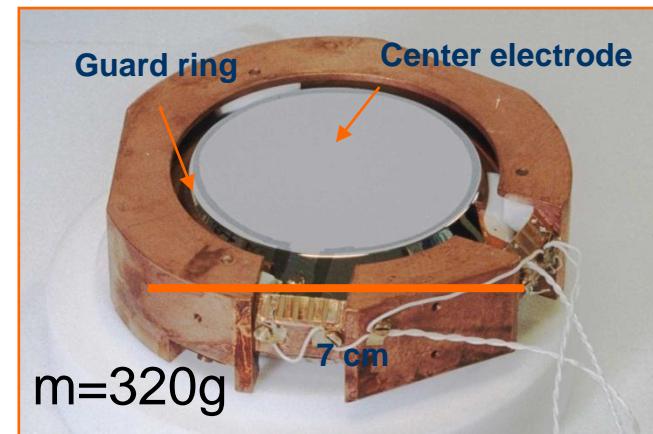
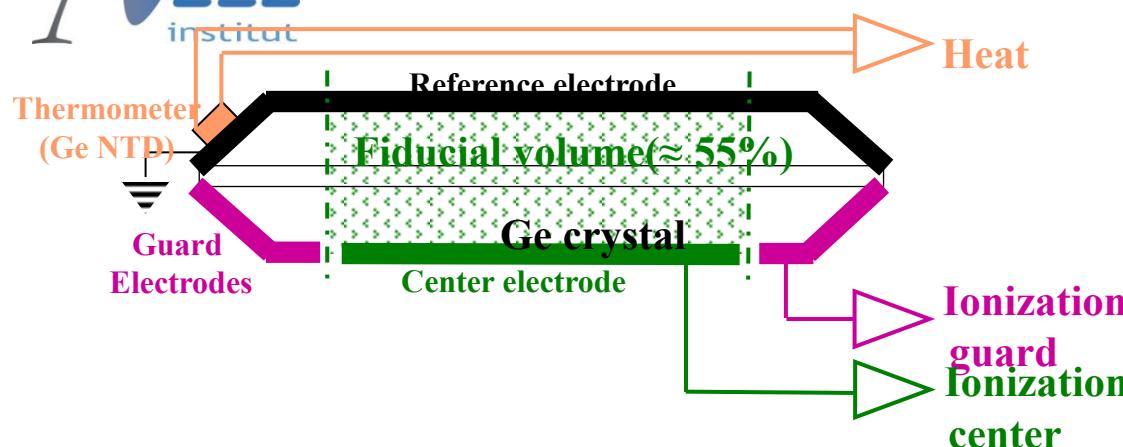
Goobar (2004)

Detection of WIMPs by the nuclear recoil (energy deposition)

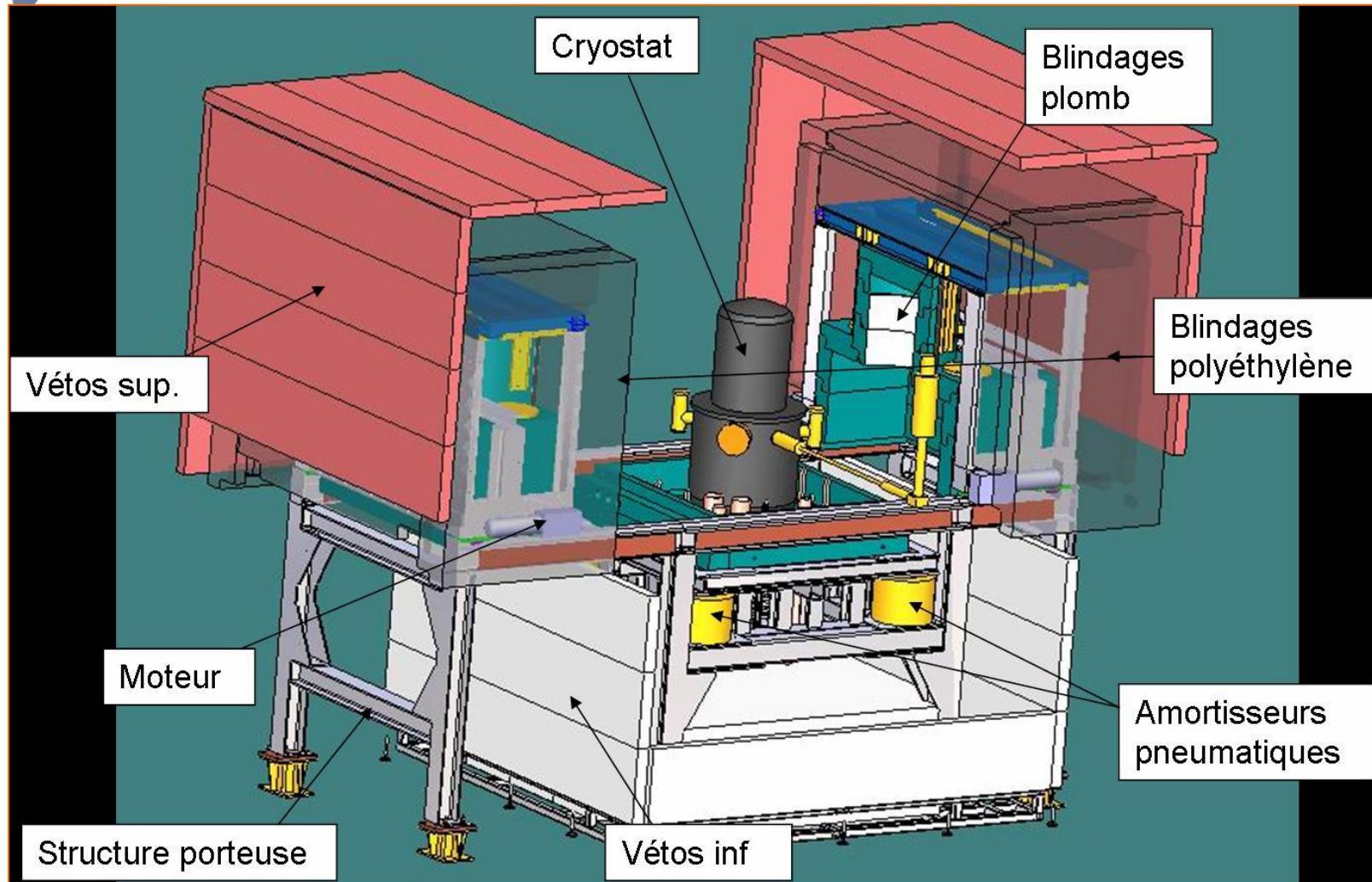
- ⇒ WIMPs energy
- ⇒ WIMP cross section (very low...)



- ◆ Cryogenic detectors provide best WIMP limit. Already sensitive to SUSY models
- ◆ Threshold and resolution \approx ok
- ◆ Future gains in sensitivity will depend on improvements on different backgrounds discrimination : **R&D !!**
- ◆ Improve the mass :
 - EDW-II \approx 40 kg for $\sigma_{w-n} \approx 10^{-8}$ pb
 - EURECA \approx 1 ton for $\sigma_{w-n} \approx 10^{-10}$ pb



- ◆ Mesure simultanée
 - Chaleur @ 17 mK avec thermomètre Ge/NTD
 - Ionisation @ qq V/cm avec électrodes Al
- ◆ Identification Evt par evt du type de recul
- ◆ $Q = \text{Ionisation/Erecul}$
 - $Q=1$ pour recul électronique (radioactivité ambiante)
 - $Q \approx 0.3$ pour recul nucléaire (Wimps et neutron)



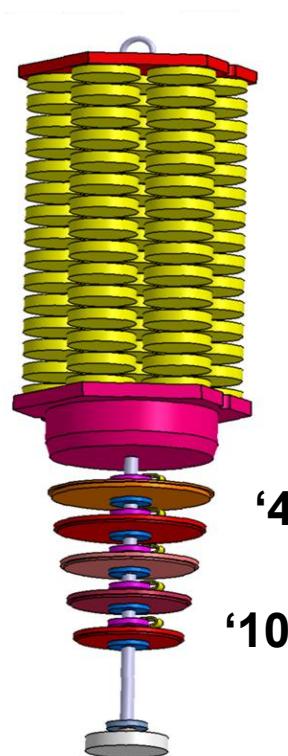
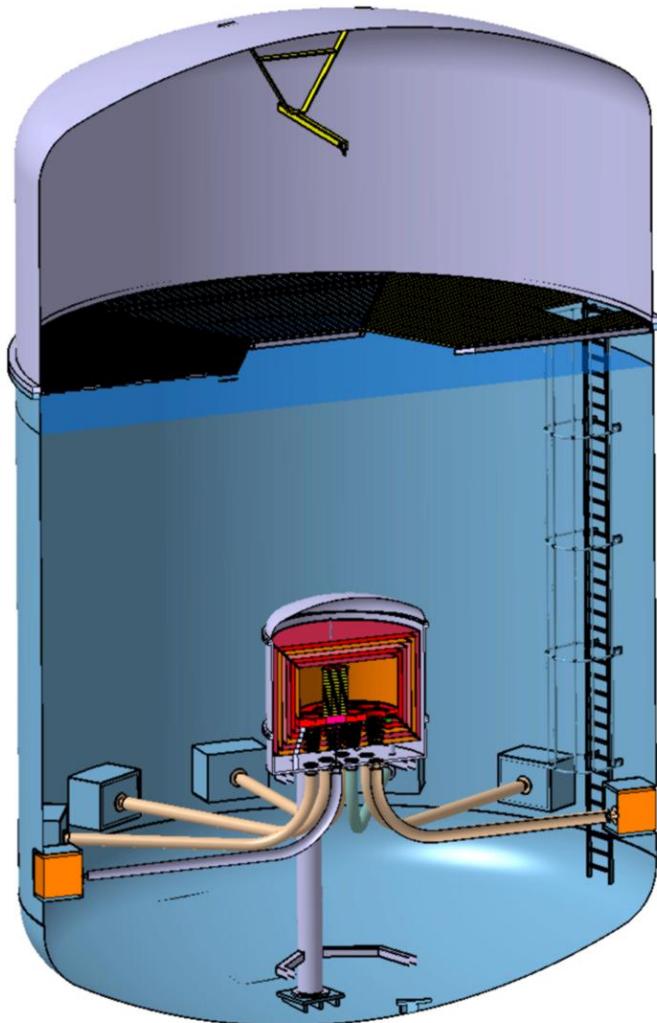
Structure : 10 tonnes

Blindage Pb : 35 tonnes

Pour qq kg de détecteurs...

Blindage PE : 35 tonnes

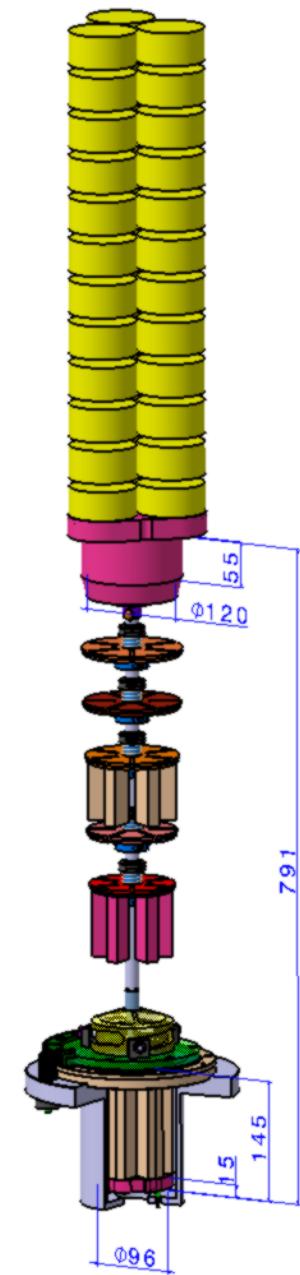
EURECA 1T

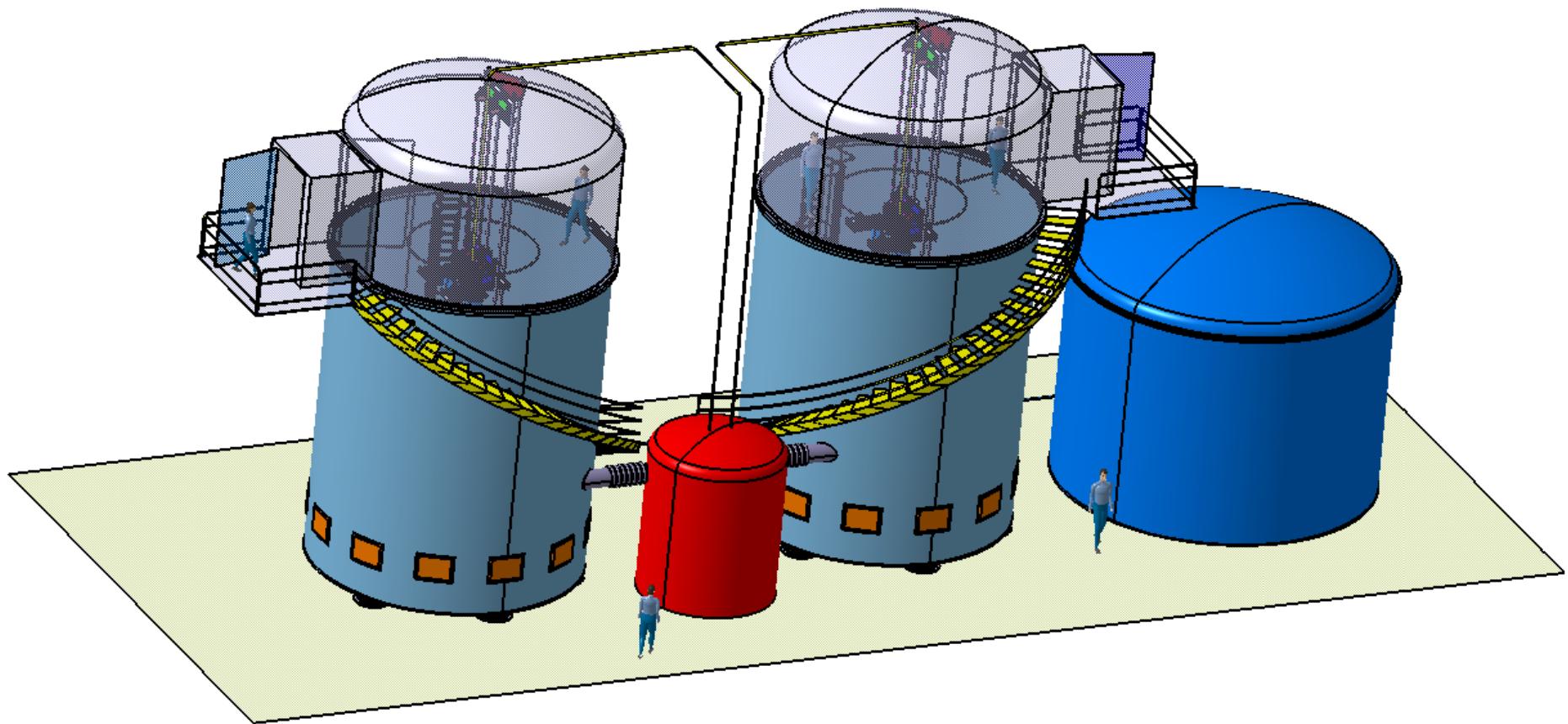


'4K' electronics

'100K' electronics

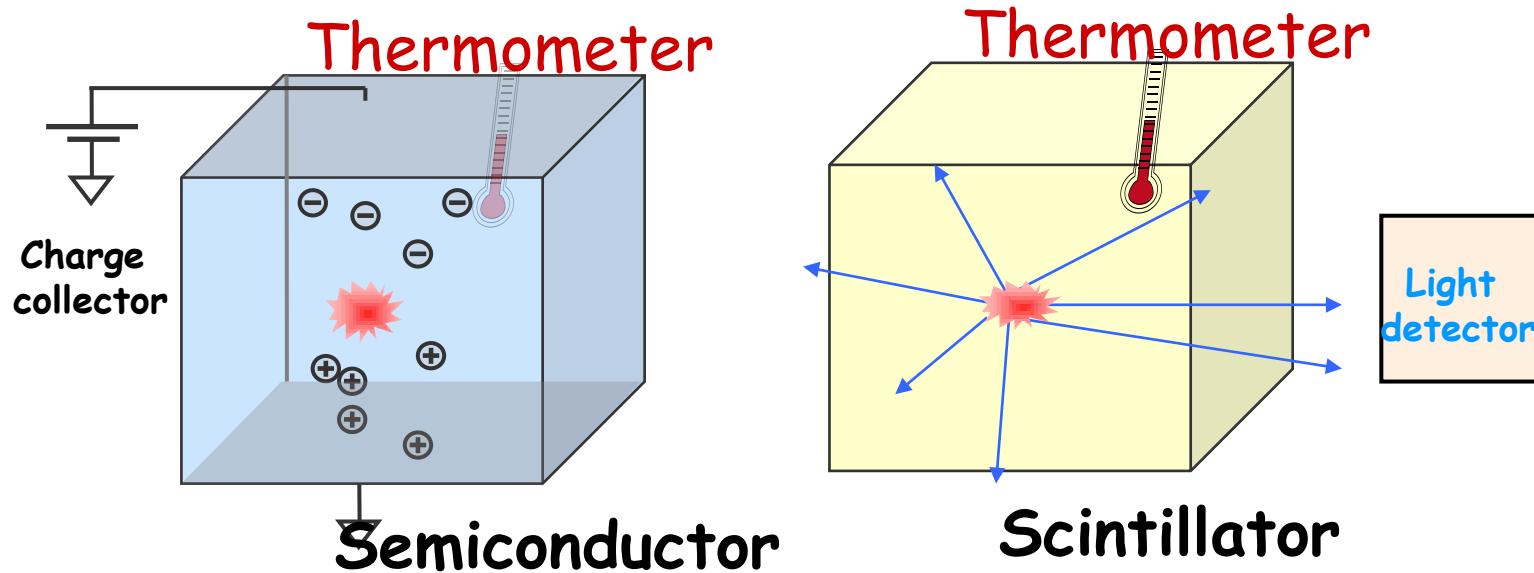
'300K' electronics



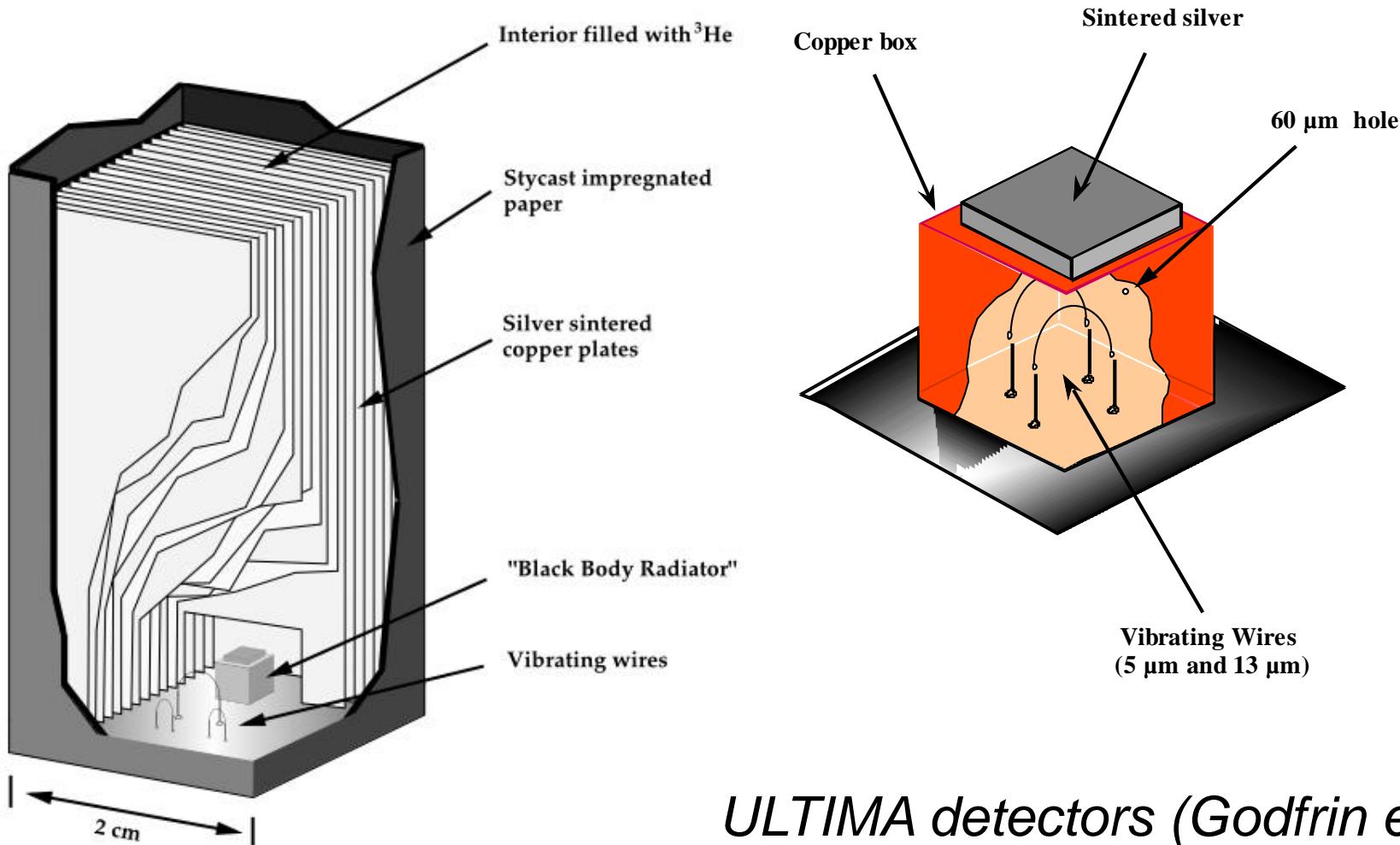


Heat is a nice way of detecting particles...

But other “channels” are often used and needed:
charge and light, for instance (ionization, scintillation)



Density of quasiparticles measured directly by damping of micro vibrating wire



ULTIMA detectors (Godfrin et al.)

Conclusion

- LTD are essential for high sensitivity instruments in astrophysics
- Wide range of techniques and application
- Progress in manufacturing make them ready for applications in other fields of science and industry
- Needs a low-temperature cryogenics

References

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Cryogenics Particle Detection,
Springer (2005)
- LTD Conferences (1987-2011)
<http://ltdorg.kip.uni-heidelberg.de/>
- DRTBT
<http://www-ecole-drtbt.grenoble.cnrs.fr/>

