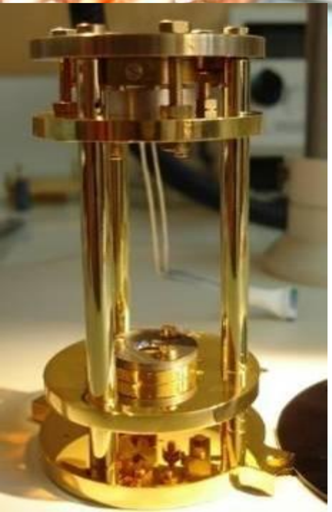
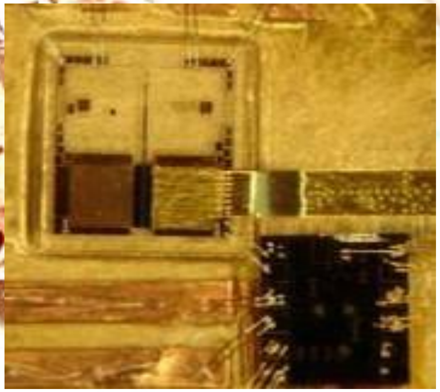
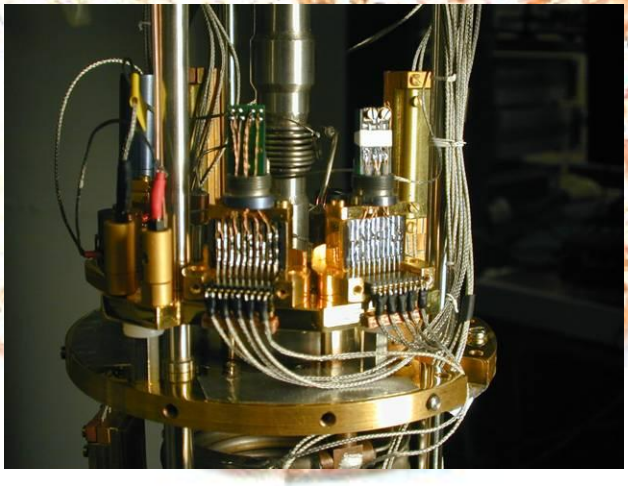
Metallic Magnetic Calorimeters for spectrometry applications

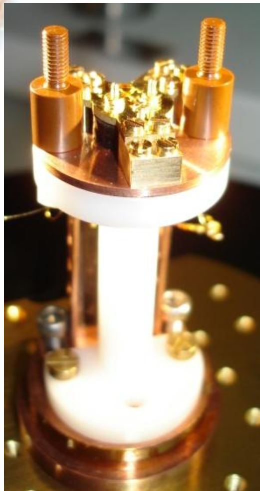
Matias Rodrigues
CEA-Saclay LNHB

DRTBT09 : 6ième école thématique
Perspectives des détecteurs cryogéniques









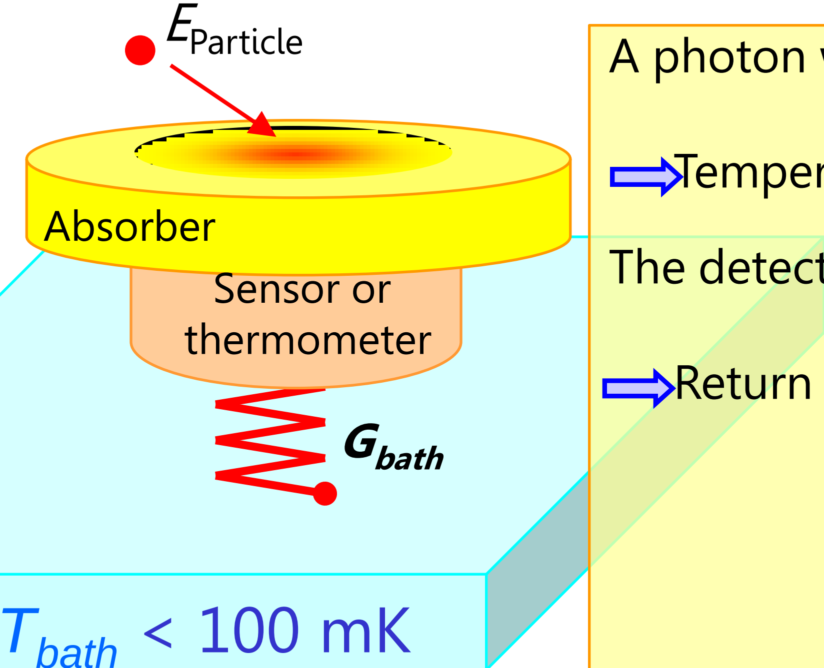
Metallic magnetic calorimeter

- Physical principle
  - Choice of the paramagnetic sensor
  - The calculation of signal size
  - Intrinsic sources of noise
- Detector read out
  - SQUID read out and performances
  - SQUID-detector coupling
- Optimizations
  - Signal to noise ratio
  - Fabrication and experimental set-up

- Applications
  - External sources
    - X ray spectrometry
    - Gamma ray spectrometry
  - Embedded source in the detector
    - Activity measurement
    - Beta spectrometry
    - MARE project

Physical principle of metallic magnetic calorimeters

Physical principle of calorimeters

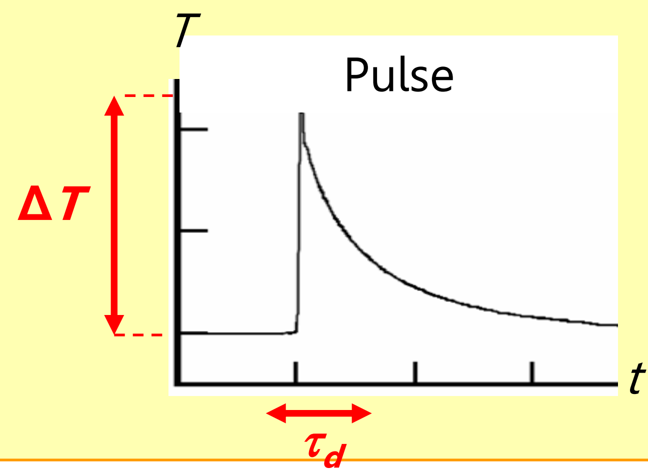


A photon with an energy ***E*** interacts in the absorber

⇨ Temperature rise : $\Delta T = E / C_{total}$

The detector is weakly thermally coupled to a thermal bath

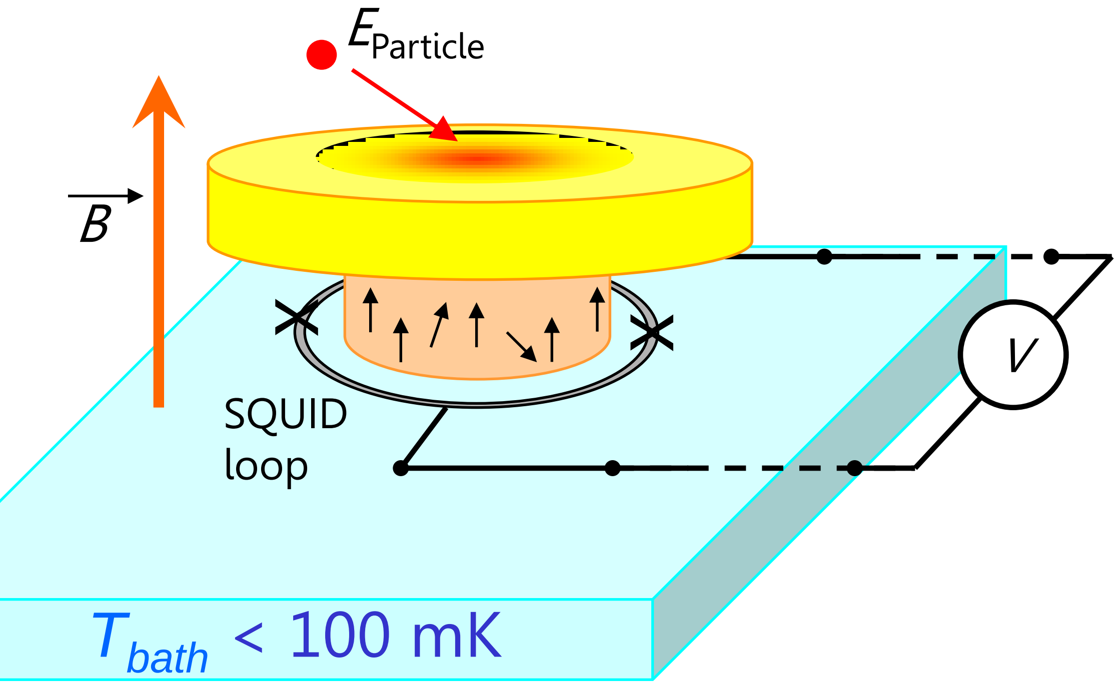
⇨ Return to the equilibrium temperature : $\tau_d = C_{total} / G_{bath}$



$$C_{absorber} = \begin{cases} C_{Electron} \propto T & \text{(Metal)} \\ C_{Phonon} \propto T^3 & \text{(Dielectric crystal, superconductor)} \end{cases}$$

⇨ **ΔT maximised at low T_{bath}**

Physical principle of magnetic calorimeters



The sensor is a paramagnetic material, magnetized by an external magnetic field ***B***

The sensor magnetization ***M*** is strongly dependent on the temperature

Absorption of a particle with the energy ***E*** leads to a temperature rise and a change of ***M***

A magnetization change induces a flux variation **ΔΦ** in the SQUID loop

$$\delta\Phi = \frac{G}{r_{loop}} \cdot \delta m = \frac{G}{r_{loop}} \cdot \mu_0 \cdot V_{sensor} \cdot \left(\frac{\partial M}{\partial T}\right) \frac{E_{particle}}{C_{sensor} + C_{absorber}}$$

Magnetic coupling factor

Thermodynamic quantities of paramagnetic material
$f(B, T, V_{sensor}, x)$

$\delta\Phi$ expressed in units of the magnetic flux quantum, Φ_0 = 2.07x10^{-15} A/m

Calculation of thermodynamics quantities using statistical physics

Example for localized spin of 1/2 interacting with *B*

Zeeman Hamiltonian $H^{Zeeman} = -\vec{\mu} \cdot \vec{B}$

Two eigen energies $\varepsilon_{\pm} = \pm \mu B \qquad \Delta E = \varepsilon_{+} - \varepsilon_{-}$

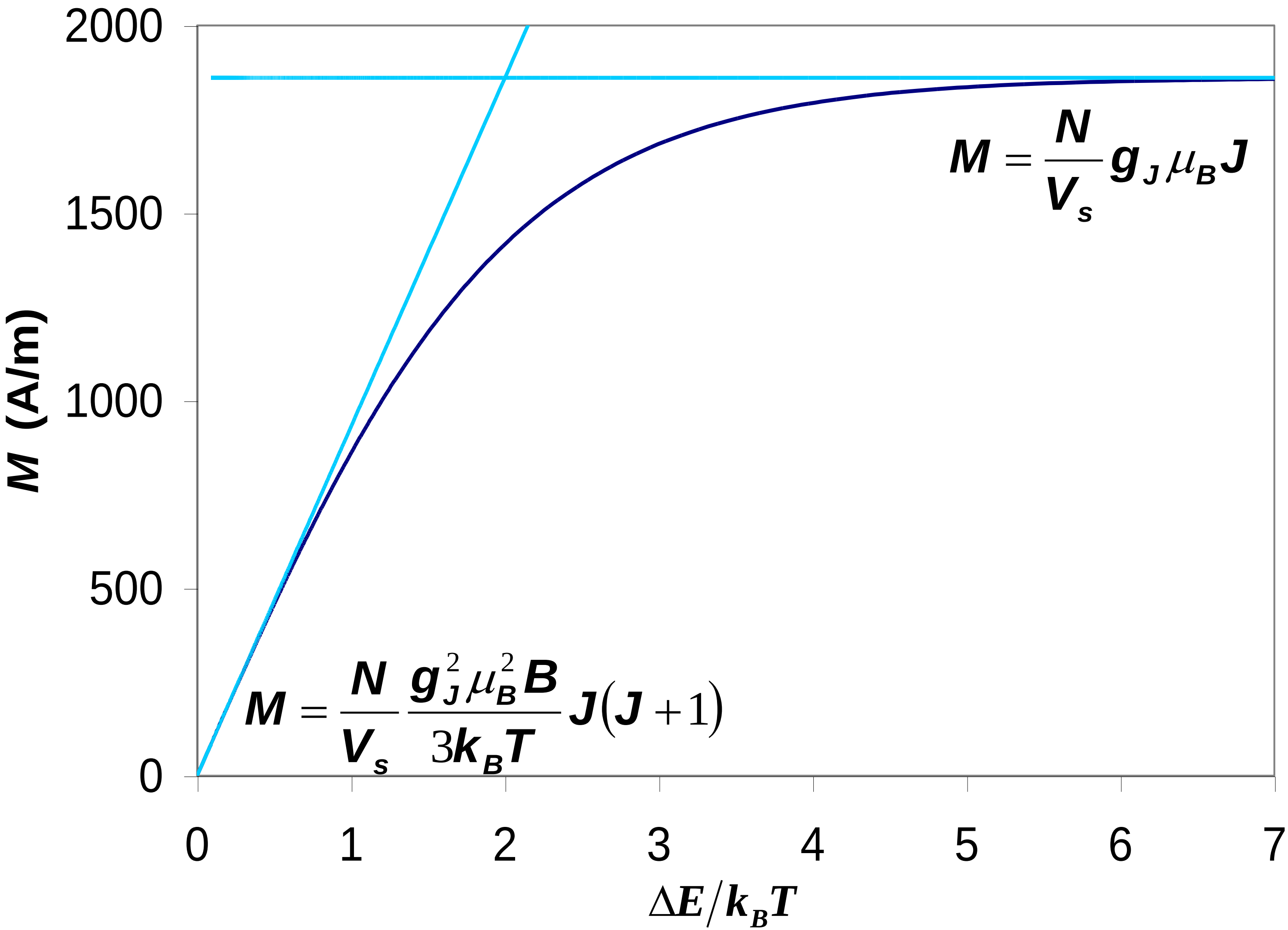
Partition function of a canonical ensemble $Z = \sum_{n=-J}^{J} e^{-\varepsilon_n / kT}$

Internal energy $\langle U \rangle = N \langle \varepsilon \rangle = N k_B T^2 \left(\frac{\partial \ln Z}{\partial T} \right)_B = -N \cdot \Delta E \tanh \left(\frac{\Delta E}{2 k_B T} \right)$

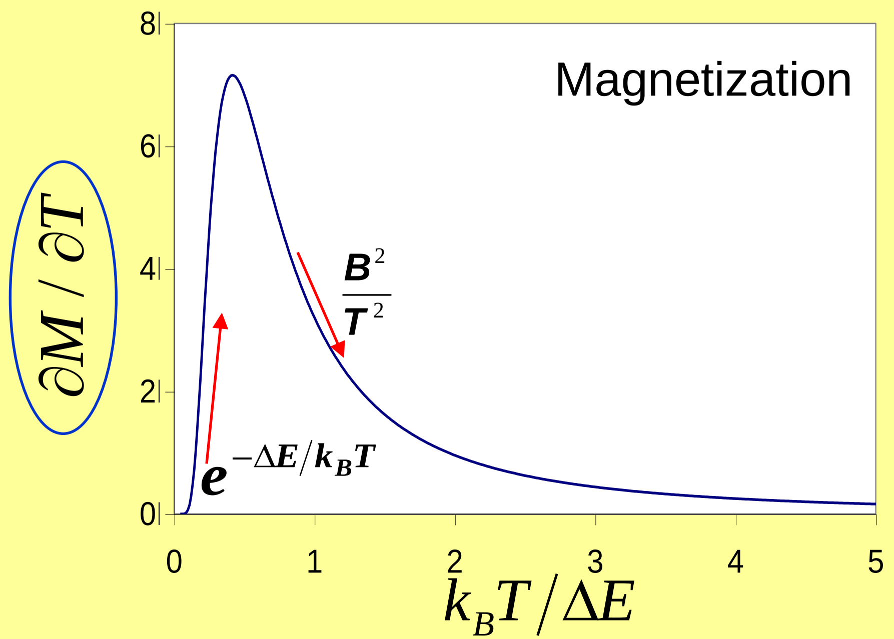
Magnetization $M = -\frac{N_{spin}}{V_{sensor}} \frac{\partial \langle U \rangle}{\partial B} = \frac{N_{spin}}{V_{sensor}} \frac{\Delta E}{2B} \tanh \left(\frac{\Delta E}{2 k_B T} \right)$

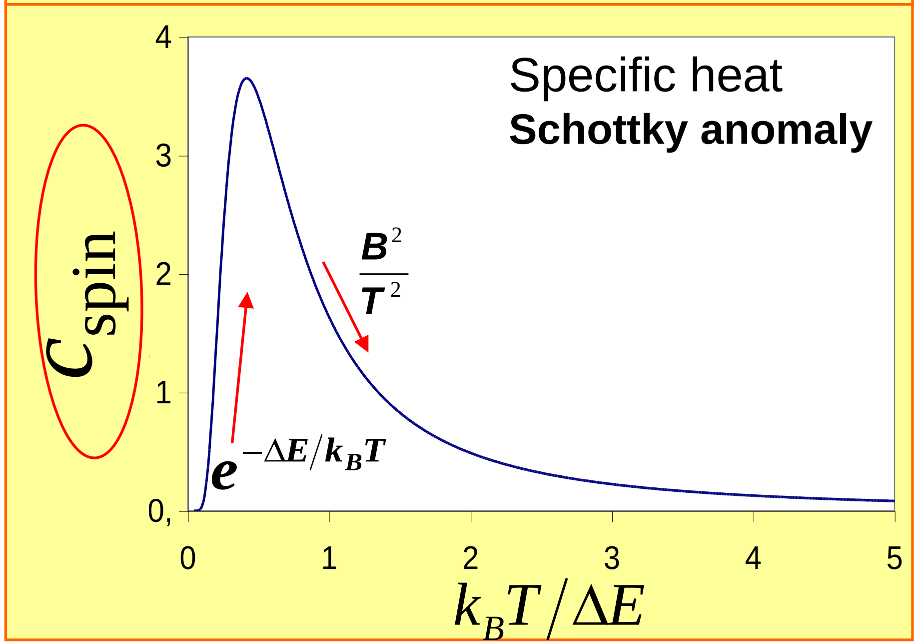
Spin heat capacity $C_{spin} = \left(\frac{\partial \langle U \rangle}{\partial T} \right)_V = N_{spin} k_B \left(\frac{\Delta E}{2 k_B T} \right)^2 \frac{1}{\cosh^2 \left(e^{\Delta E / 2 k_B T} \right)} \approx C_{sensor}$

Magnetization



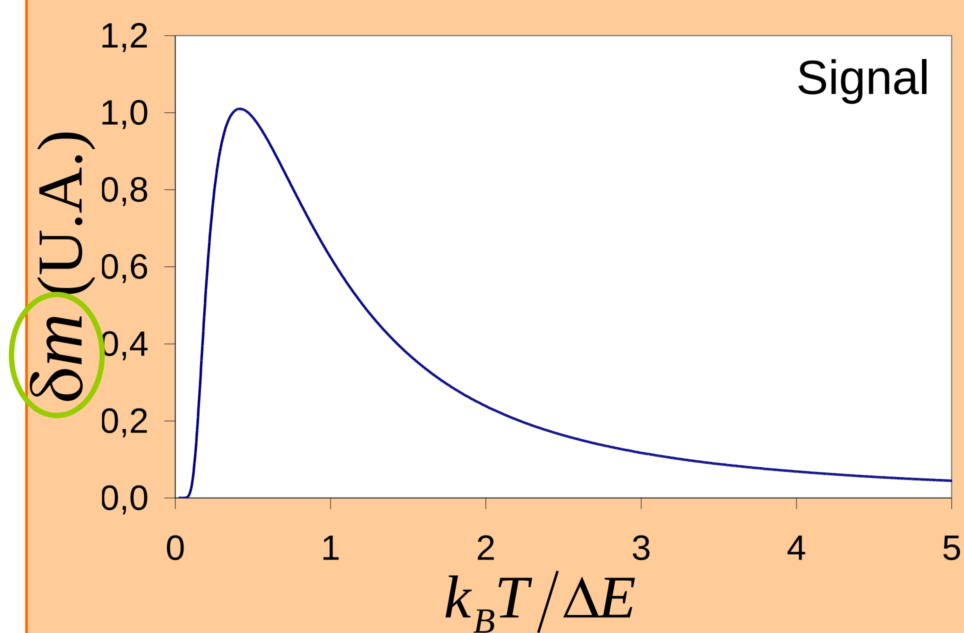
Thermodynamics quantities for the signal





$$\text{Signal} \propto \delta m = V_{sensor} \cdot \left(\frac{\partial M}{\partial T} \right) \frac{E}{N_{spin} c_{spin} + C_{absorber}}$$

$$V_{sensor} \cdot \left(\frac{\partial M}{\partial T} \right) \frac{1}{N_{spin} c_{spin}} = \text{cste}$$



(Ex. with $C_{absorber}$ fixed)

Possibility to use large C_{spin} and couple absorber with large $C_{absorber}$

Ideal magnetic calorimeters for spectrometry

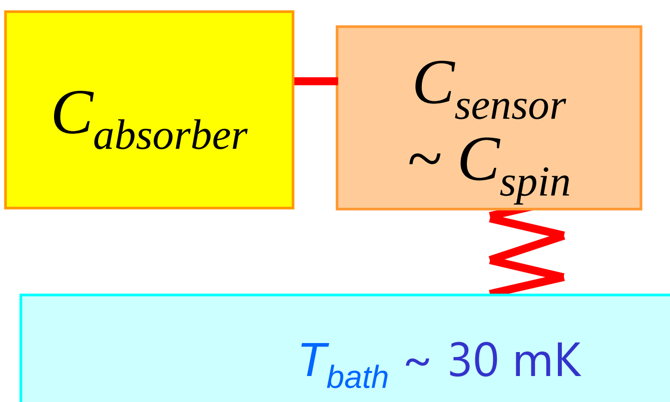
Each application requires a detection efficiency which fixes the absorber heat capacity.

One has to calculate the parameters B, T_{bath}, x, V_{sensor}, that maximize the Signal/Noise ratio.

For spectrometry applications one needs a fast rise time and high energy resolution.

Ideal magnetic calorimeters :

- Large signal ⟺ strong dependence of the magnetization on the temperature
  ⟺ No interaction between magnetic moments
  No additional heat capacities $C_{sensor} = C_{spin}$
- Fast rise time
  ⟺ Strong coupling between spins and the absorber heat capacity
  large $G_{sensor\text{-}absorber}$



Different choices of magnetic ions and host

- Dielectric host
  - TmAG:Er, YAG:Er
  - CMN, CDP

    High sensitivity but very long rise time due to a weak coupling between magnetic moments and phonons

- Metallic host
  - LaB_6:Er (large additional heat capacity at low *T*)
  - **Au:Er (well known, stable)**
  - Ag:Er

    Reduced sensitivity due to exchange interaction between magnetic moments **but fast rise time** due to strong coupling between magnetic magnetics moments and conduction electrons

- Semi metallic host (unstudied)
- Semiconductor (unstudied)
  - Bi_2Te_3 (E_g = 0,15 eV) doped with Er

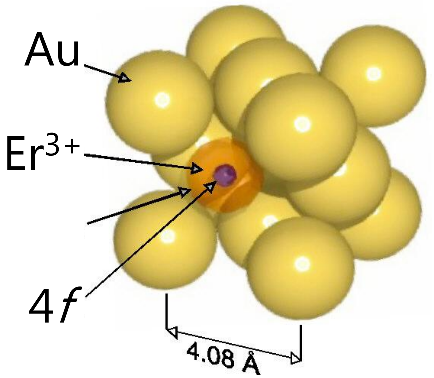
Signal size for Metallic Magnetic Calorimeter using Au:Er sensor

Magnetic properties of AuEr. Er in cubic symmetry

- Electronic Zeeman interaction

$J = 15/2 \qquad g_J = 6/5$

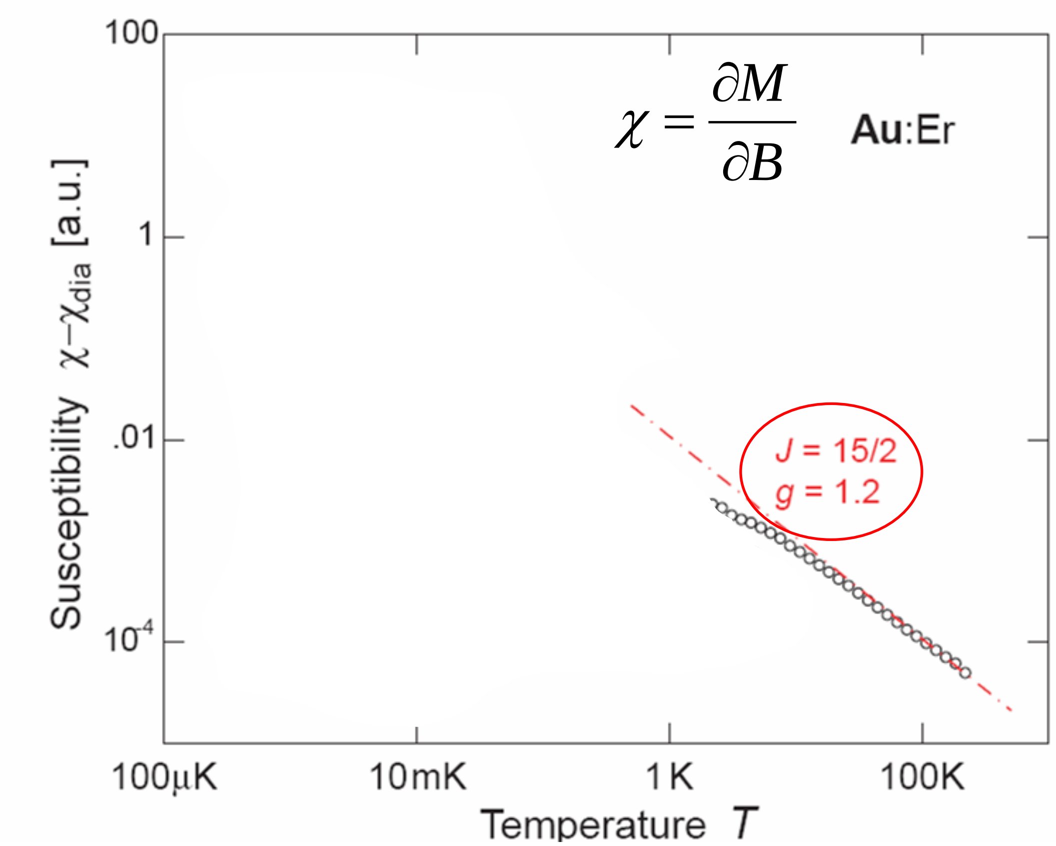
$$H^{Zeeman} = g_J \mu_B \vec{B} \cdot \vec{J}$$



$[\mathrm{Kr}]4d^{10}4f^{11}5s^2 5p^6$

$\langle r_{4f} \rangle \approx 0.3\,\mathring{A}$

$\langle r_{5p} \rangle \approx 1\,\mathring{A}$



Exchange interactions

Interaction between two localized spins S_i and S_j

• Dipole – Dipole interaction

Coupling between two localized magnet

$$H_{ij}^{Dipole} = \underbrace{\frac{\mu_0}{4\pi}(\tilde{g}\mu_B)^2(2k_F)^3}_{\Gamma_{\text{Dipole}}} \frac{\left(\vec{\tilde{S}}_i \cdot \vec{\tilde{S}}_j\right) - 3\left(\vec{\tilde{S}}_i \cdot \vec{r}_{ij}\right)\left(\vec{\tilde{S}}_j \cdot \vec{r}_{ij}\right)}{(2k_F r_{ij})^3}$$

• RKKY interaction (Ruderman - Kittel - Kasuya - Yosida)

Interaction between two localized magnetic moments mediates through the conduction electrons and their magnetic moment (itinerant electrons).

$$H_{ij}^{RKKY} = \underbrace{J_{sf}^2 \frac{\tilde{g}^2 (g_J - 1)^2}{g_J^2} \frac{4V_p^2 m_e^* k_F^4}{\hbar^2 (2\pi)^3}}_{\Gamma_{\text{RKKY}}} \left(\tilde{S}_i \cdot \tilde{S}_j\right) \frac{\cos(2k_F r_{ij}) - 1/2k_F r_{ij} \cdot \sin(2k_F r_{ij})}{(2k_F r_{ij})^3}$$

$\Gamma_{\text{RKKY}} = 5.\Gamma_{\text{Dipole}}$

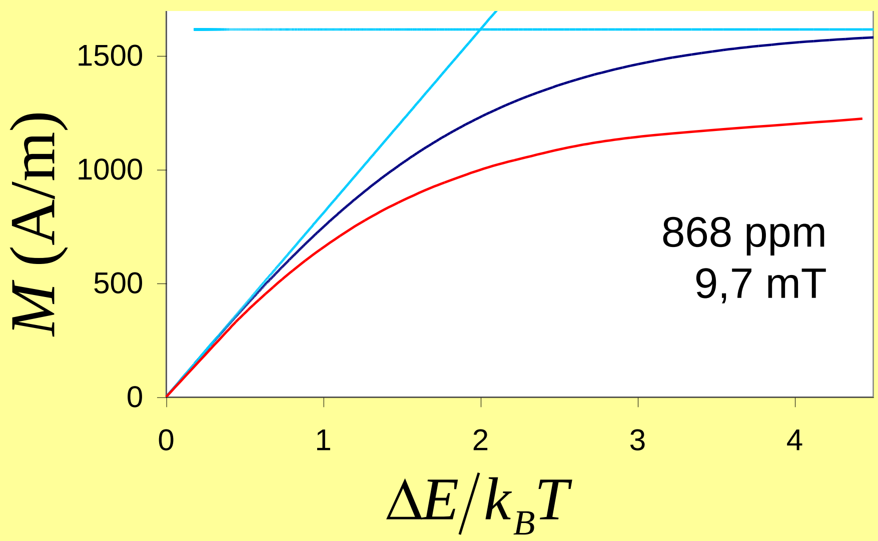
RKKY interaction leads to spin glass transition at ~ 1 mK with 300 ppm erbium

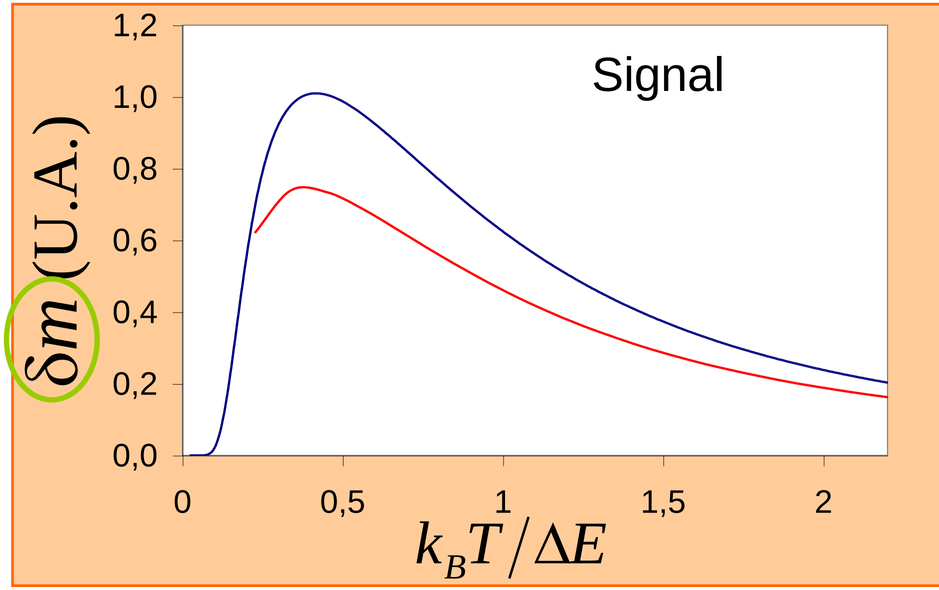
⇒ minimal T_{bath} ~ 10 mK

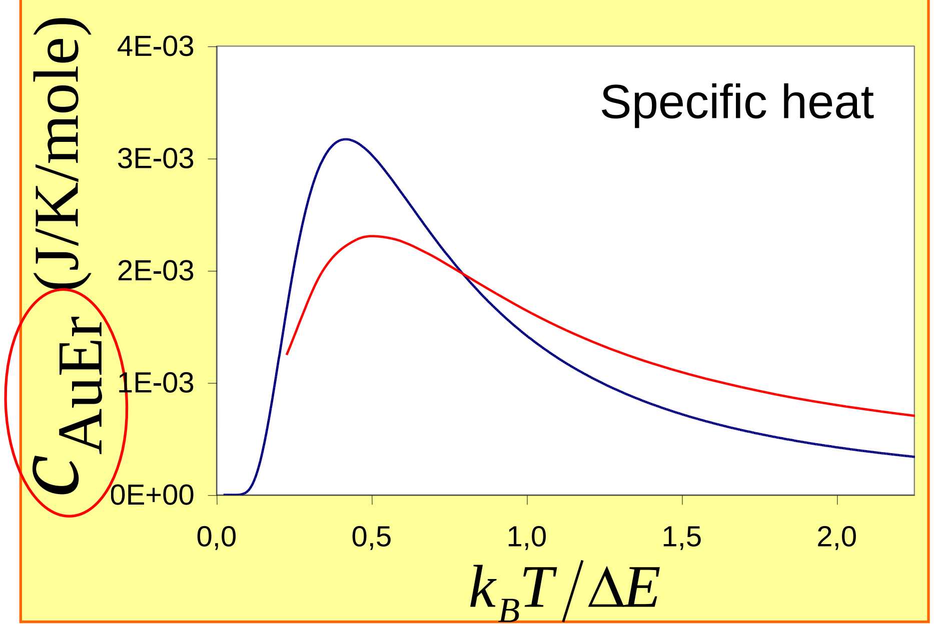
Thermodynamic quantities for the signal

AuEr w/o exchange
AuEr with exchange

$$\text{Signal} \propto \delta m = V_{sensor} \cdot \left(\frac{\partial M}{\partial T}\right) \frac{E}{N_{spin} c_{spin} + C_{absorber}}$$



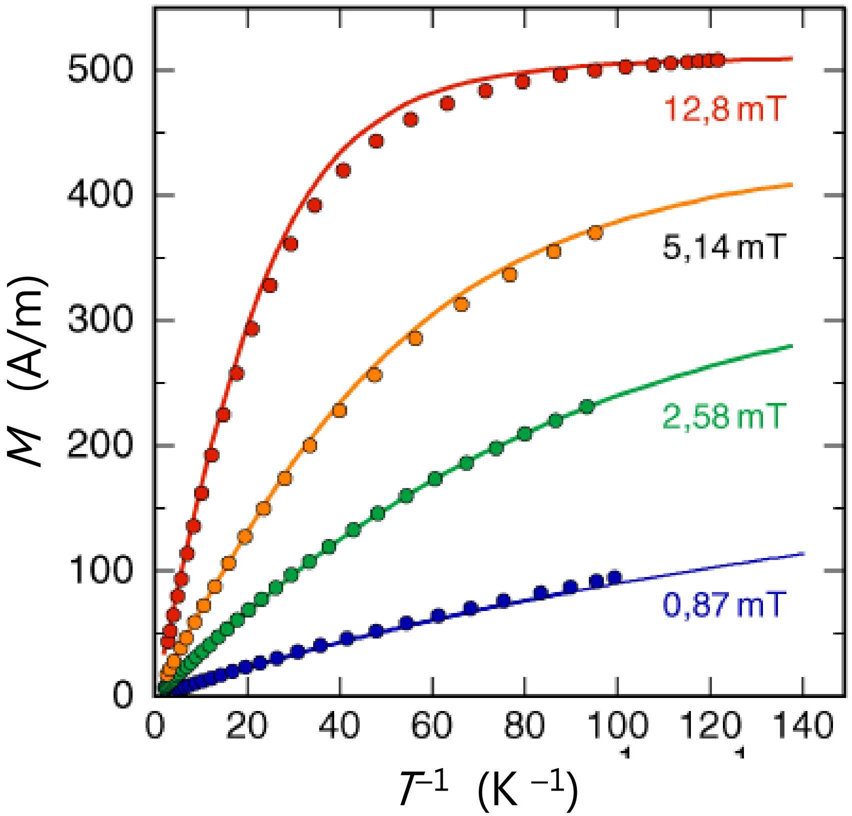




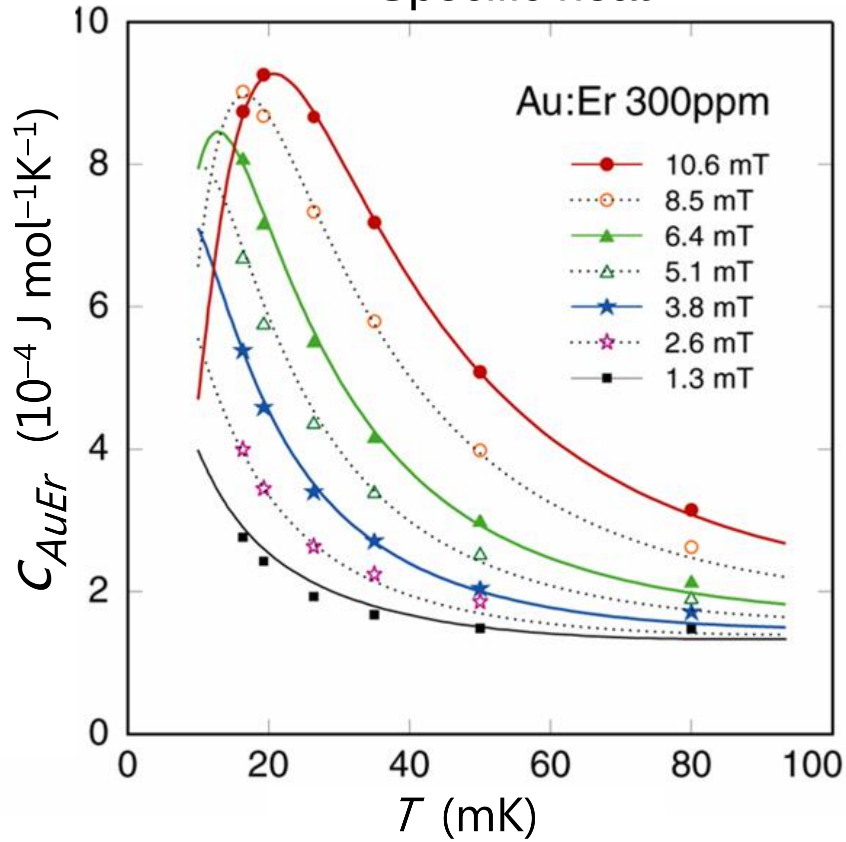
Exchange interactions lead to a reduced of the signal size

Thermodynamic properties of AuEr can be calculated by mean field approximations or with Monte Carlo simulations.

Magnetization



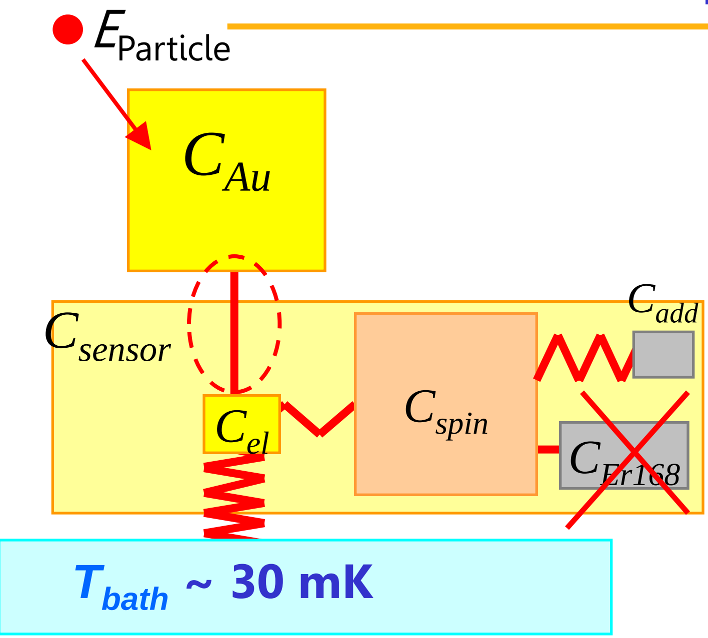
Specific heat



We can predict the signal size as a function of all the parameters

Time structure of the signal

Heat capacities and thermal conductances



If we use a gold absorber

- $C_{Au} = N\left(\gamma T + 234 \cdot k_B N_a \left(\frac{T}{\theta_D}\right)^3\right)$ $\gamma = 7.29.10^{-4}$ J/K^2/mole, $\theta_D = 162{,}4$ K
- C_{spin} electronic magnetic moments (Zeeman+exchange)
- C_{el} conduction electrons of Au:Er (~ 1% of C_{spin})
- C_{add} : interaction of the nuclear quadrupole moments of gold with the electric field gradient due to the presence of Er^{3+}
- C_{Er168} : hyperfine interactions of the nuclear magnetic moments of Er^{168}. Using of enriched Er^{166} or Er^{167}

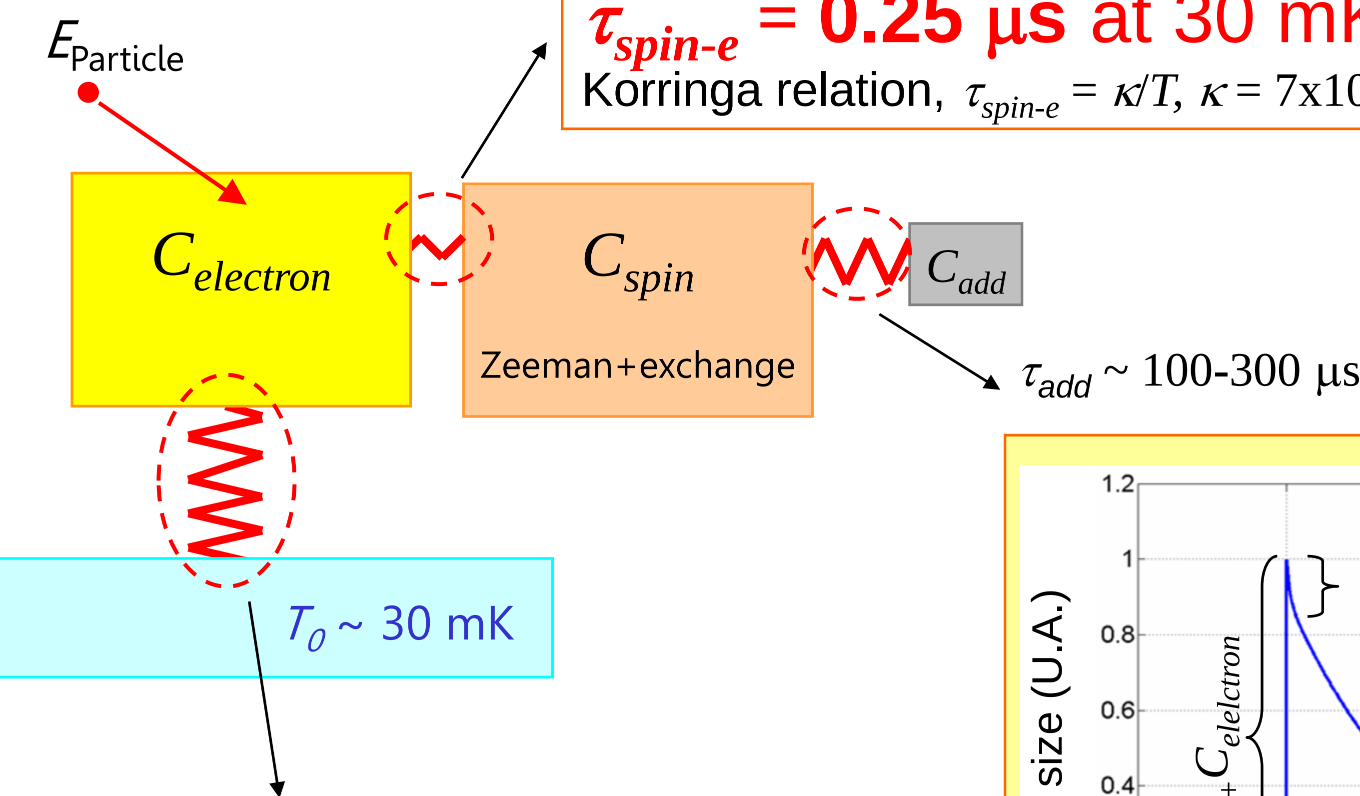
x = 900 ppm B ~ 5 mT	C_{Au} mJ/K/mole	C_{spin} mJ/K/mole	C_{add} mJ/K/mole
20 mK	0.015	1.8	~1/4 C_{spin}
30 mK	0.022	1.4	~1/5 C_{spin}

Thermalisation of the particle energy and pulse shape

We suppose heat diffusion through conduction electrons very fast

$\tau_{spin\text{-}e}$ **= 0.25 μs at 30 mK**

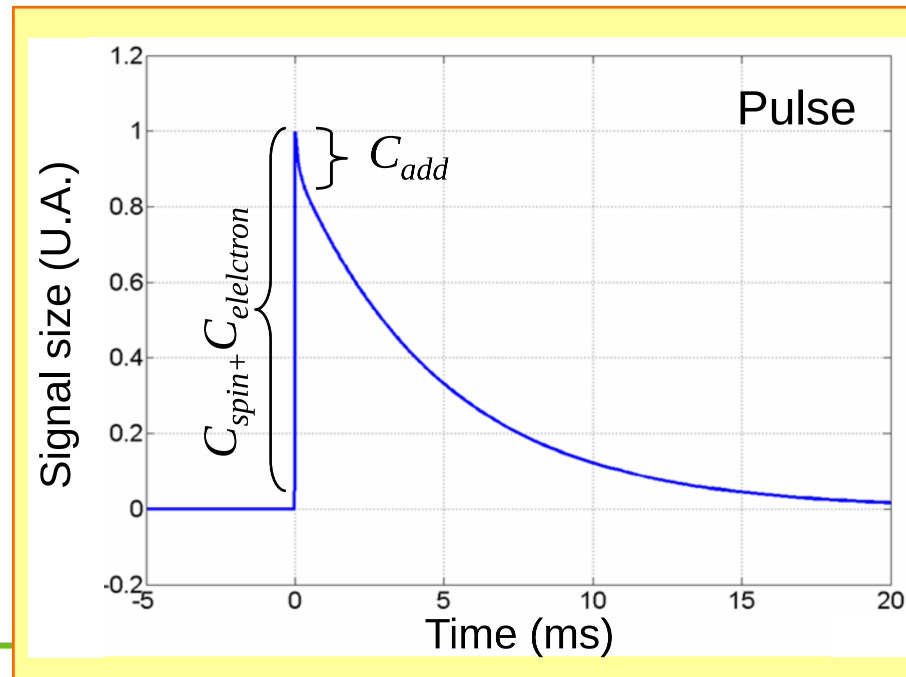
Korringa relation, $\tau_{spin\text{-}e} = \kappa/T$, $\kappa = 7\text{x}10^{-9}$ K.s



$\tau_d = C_{total} / G$

$G_{Kapitza}$ ~ 10 nW/K/mm² at 20 mK

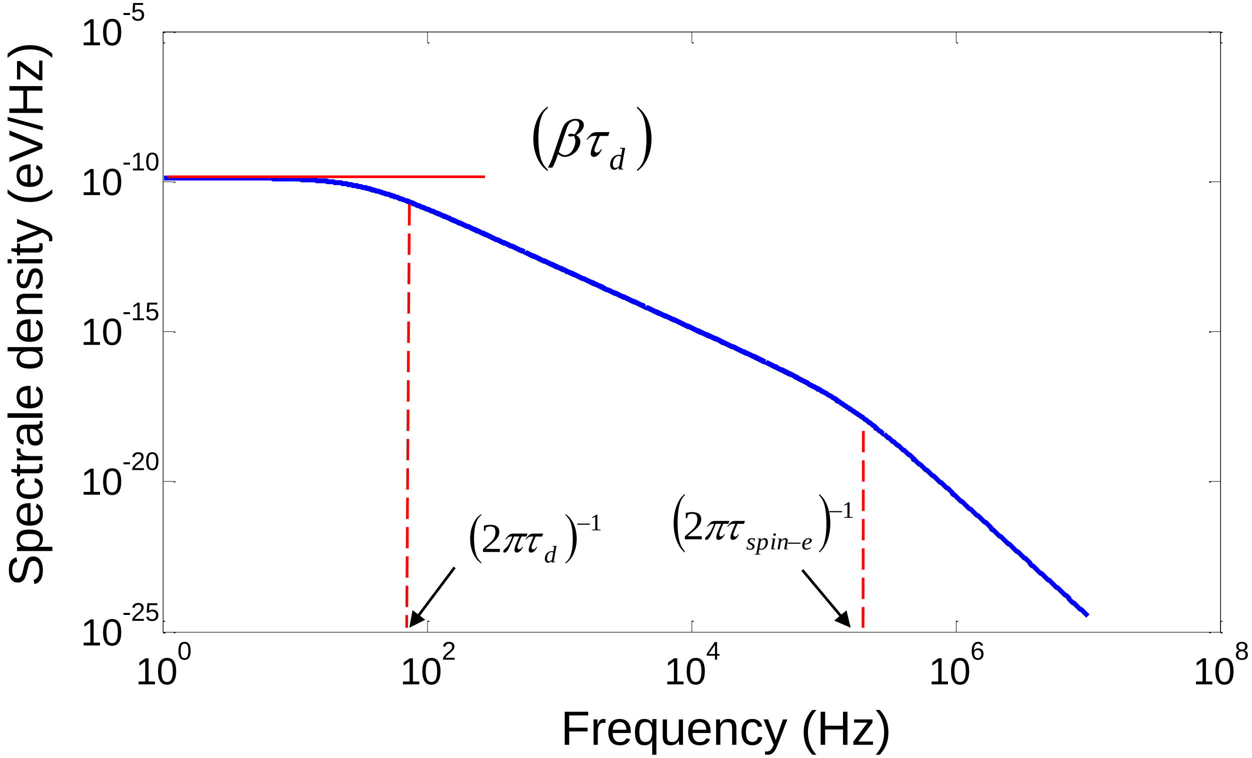
$G_{metal\text{-}metal}$ *preferable, >> $G_{Kapitza}$*



Fourier spectrum of the signal

$$S(f) = E\frac{(\beta\tau_d)}{\sqrt{\left(1+(2\pi f \tau_r)^2\right)\left(1+(2\pi f \tau_r)^2\right)}}$$

$$\beta = \frac{C_{spin}}{C_{spin}+C_{electron}}$$

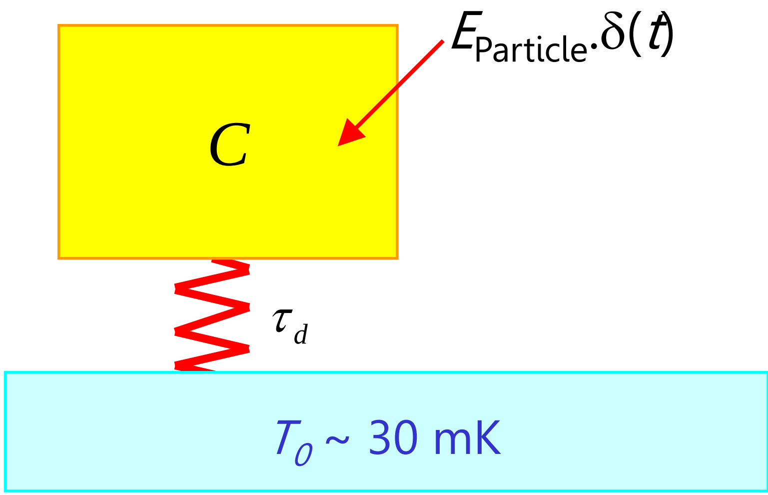


Intrinsic sources of noise

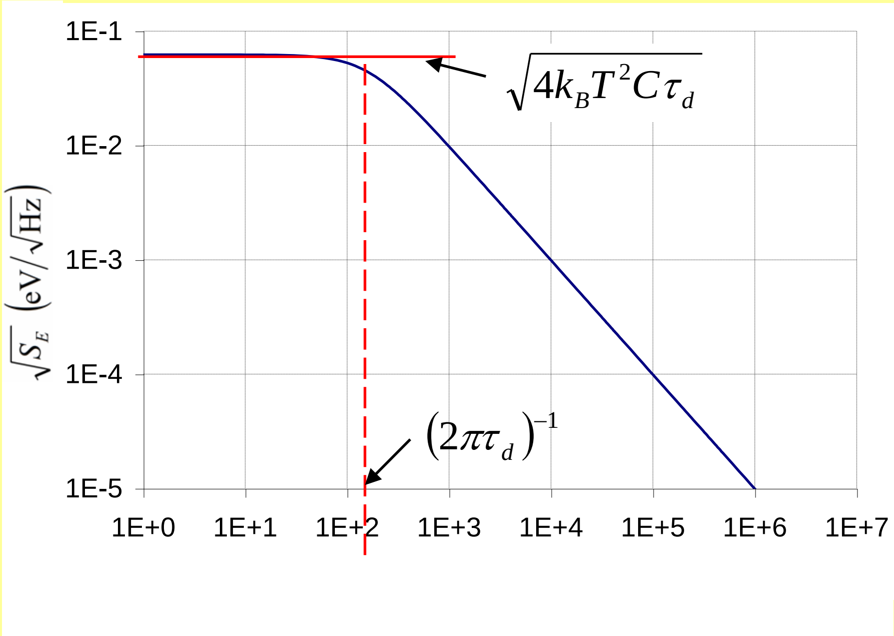
Thermodynamic fluctuations of the energy

A simple canonical ensemble with one system.

$$\Delta U = \sqrt{\langle U^2 \rangle - \langle U \rangle^2} = \sqrt{k_B T^2 \left(\frac{\partial \langle U \rangle}{\partial T} \right)} = \sqrt{k_B T^2 C}$$



⇨ **Low Temperature required!**



$$T = 30\,\text{mK}, C = 1\,\text{pJ/K}, \tau_d = 1\,\text{ms}$$

$$S_E = k_B C T^2 \frac{4\tau_d}{(1 + 2\pi f \tau_d)^2}$$

Thermodynamic fluctuations of the energy

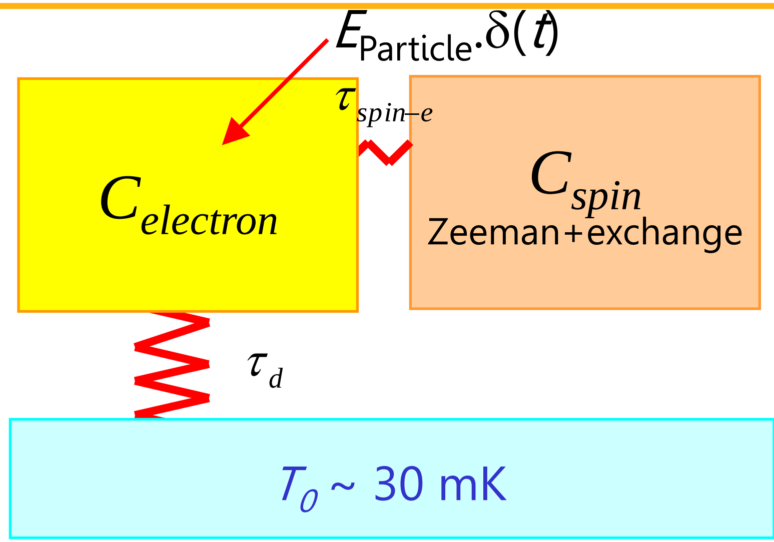
Canonical ensemble with two sub systems

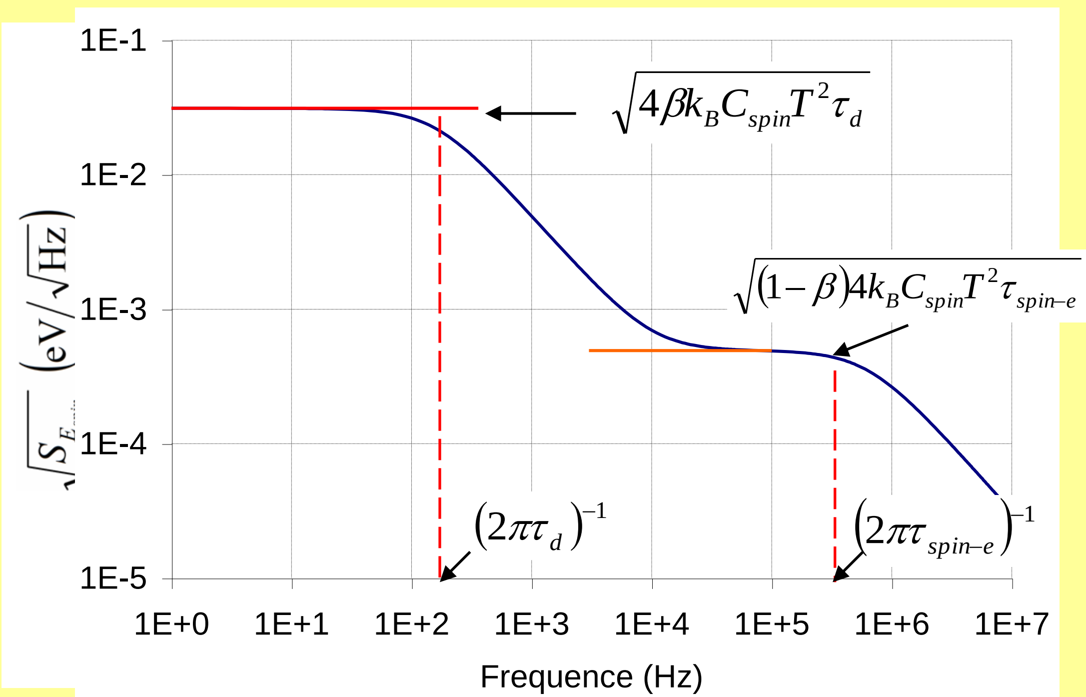
(C_{add} ignored).

$$\beta = \frac{C_{spin}}{C_{spin} + C_{electron}}, \; 0.1 < C_{spin}/\mathrm{C}_{\mathrm{electron}} < 10, \; \tau_{spin-e} << \tau_d$$

$$S_{spin} = k_B C_{spin} T^2 \left[(1-\beta) \frac{4\tau_{spin-e}}{1 + (2\pi f \tau_{spin-e})^2} + \beta \frac{4\tau_d}{(1 + 2\pi f \tau_d)^2} \right]$$

⇨ **Low Temperature required!**





$C_{electron} = C_{spin} = 0.5\,\mathrm{pJ/K}, T = 30\,\mathrm{mK},$

$\tau_{\text{spin-e}} = 0.25\,\mu\mathrm{s}, \tau_d = 1\,\mathrm{ms}$

Fundamental limits of metallic magnetic calorimeter :

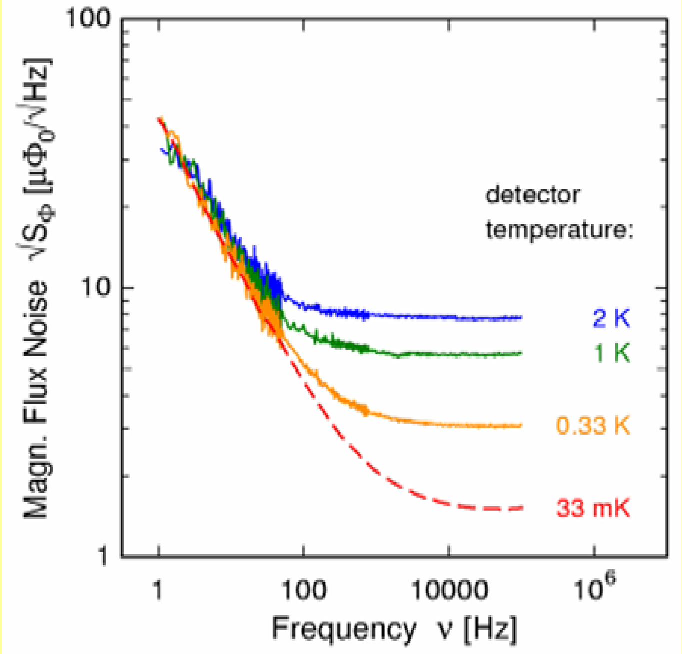
$$\Delta U_{spin} = \sqrt{4 k_B T^2 C_e} \left(\frac{1}{\beta(1-\beta)} \left(\frac{\tau_{spin-e}}{\tau_d} \right) \right)^{1/4}$$

Minimized for $C_{electron} = C_{spin}$

Other intrinsic sources of noise

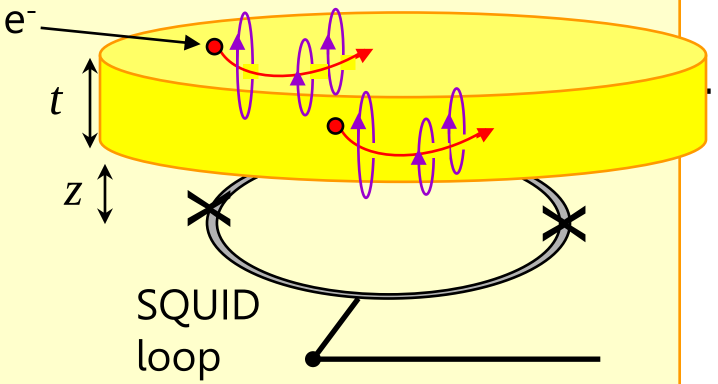
1/f noise of Au:Er sensor

Independent of temperature and proportional to erbium concentration

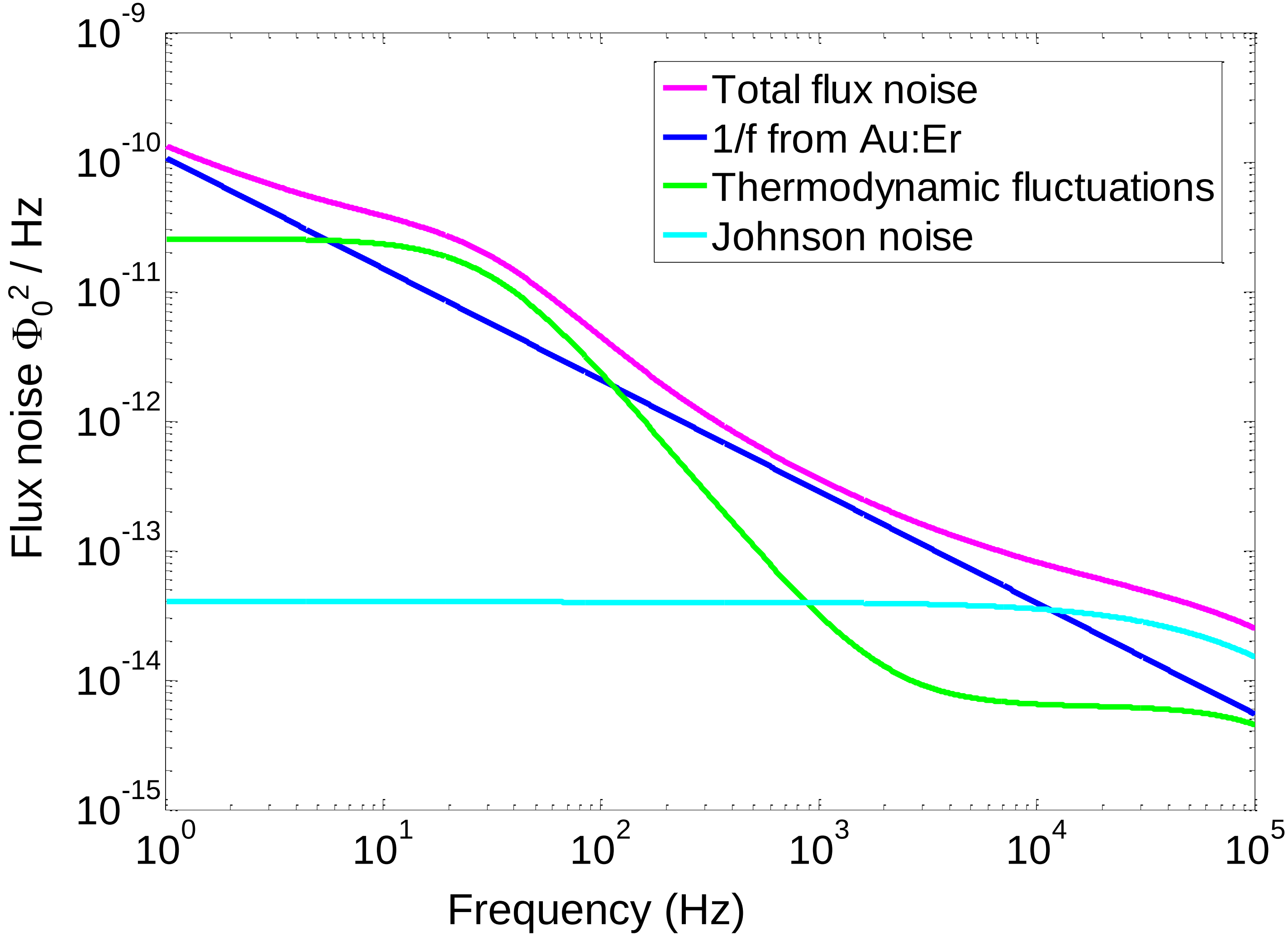


Magnetic Johnson noise, random motion of conduction electrons in metals from the sensor and the absorber

$$\sqrt{S_\Phi^{mag}} \approx \mu_0 \sqrt{\alpha \sigma k_B T V} \qquad f_c \approx \frac{1}{4 \cdot \mu_0 \cdot \sigma \cdot z \cdot t}$$



⇨ Depends strongly on the way the sensor is coupled to the SQUID



T = 30 mK

$C_{absorber}$ = 0.5 nJ/K

C_{AuEr} = 0.4 nJ/K

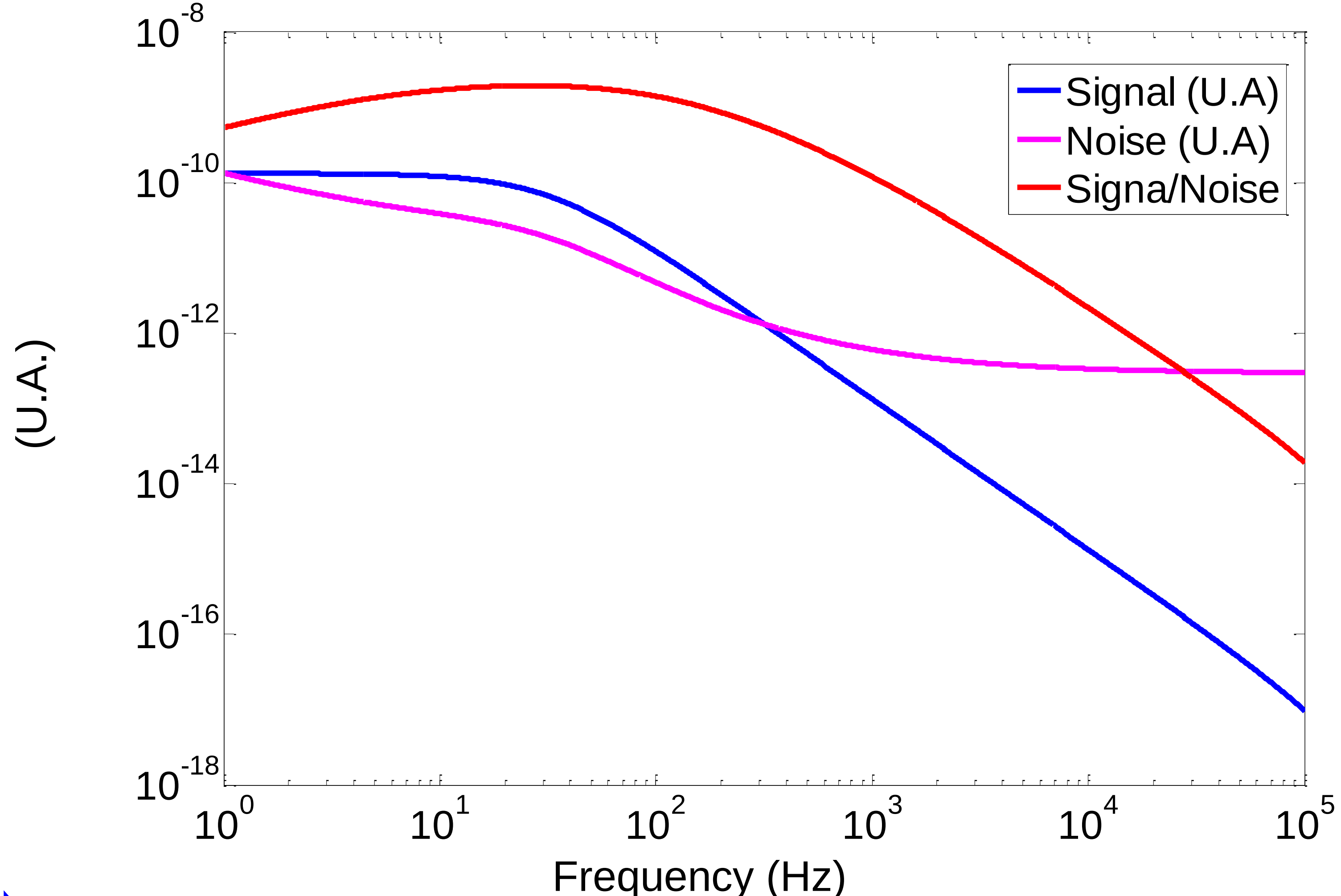
τ_r = 1 ms

τ_d = 5 ms

Signal size :

$d\Phi_0/dE$ = 1.7 $m\Phi_0$/keV

Signal to noise ratio

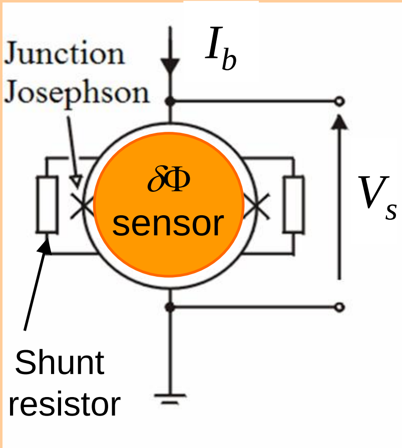


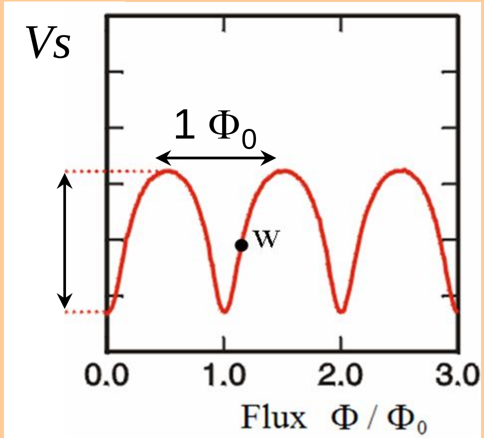
FWHM = 35 eV

(Fundamental limit from thermodynamic fluctuations FWHM = 24 eV)

How to read the magnetization of the sensor

SQUID





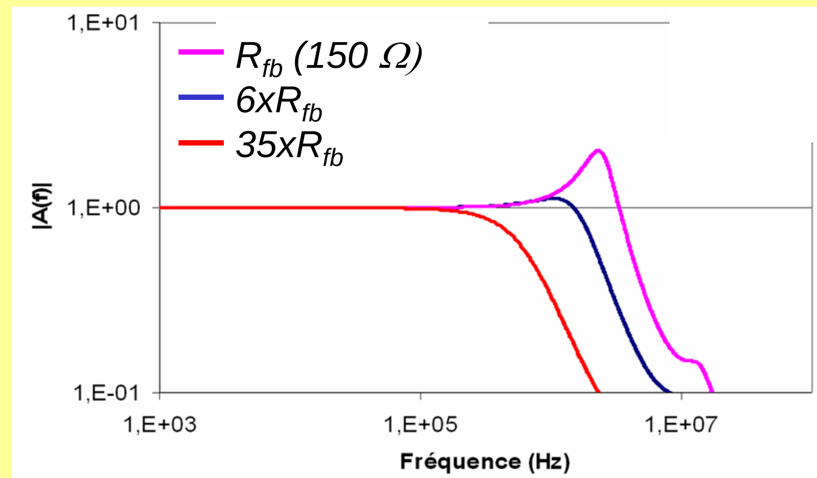
SQUID Noise

$$S_{\Phi,SQUID} \approx 32 \cdot k_B T \sqrt{L_{SQUID}^3 C_{SQUID}}$$

$$L_{squid} \approx 100\,\text{pH}, C_{squid} \approx 1\,\text{pF}, T_{\min} \approx 100 \ldots 300\,\text{mK}$$

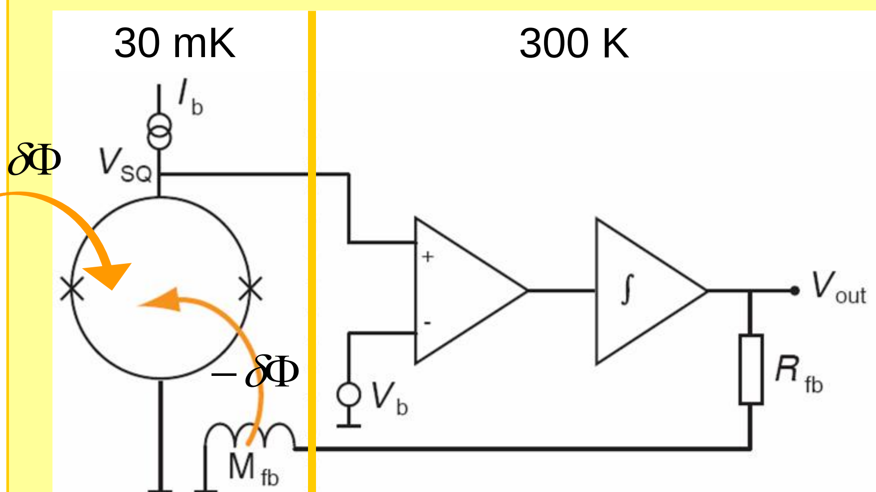
$$\Rightarrow \sqrt{S_{\Phi,SQUID}} \approx 0.15\,\mu\Phi_0/\sqrt{\text{Hz}}$$

Limited bandwidth ~ 1MHz



Slew rate < $1\Phi_0/\mu s$, rise time ~ 1 μs
Maximal signal size ~ $1\Phi_0$

Amplification and linearization

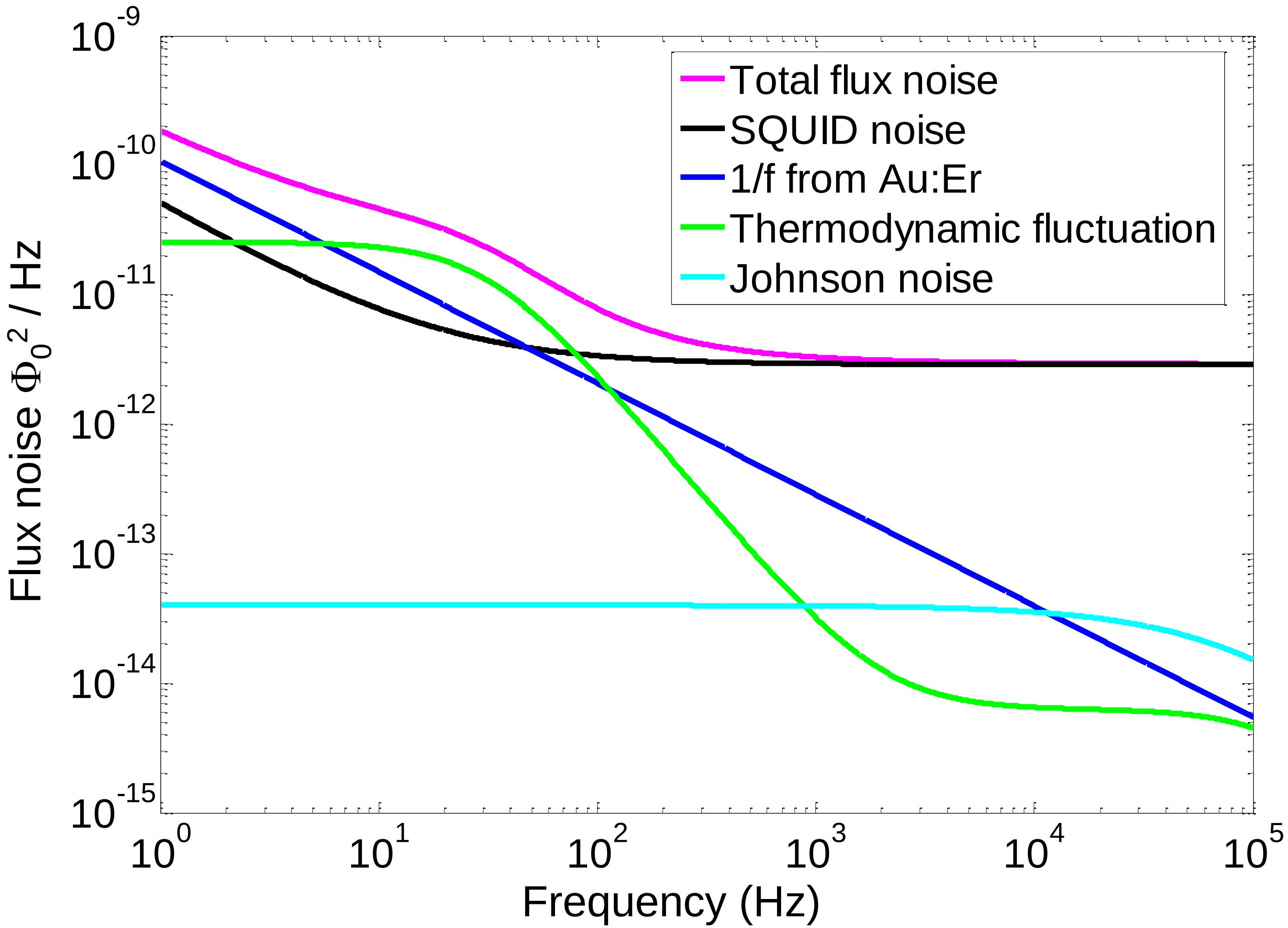


SQUID | Room temperature electronics

$0.15\,\mu\Phi_0/\sqrt{\text{Hz}}$

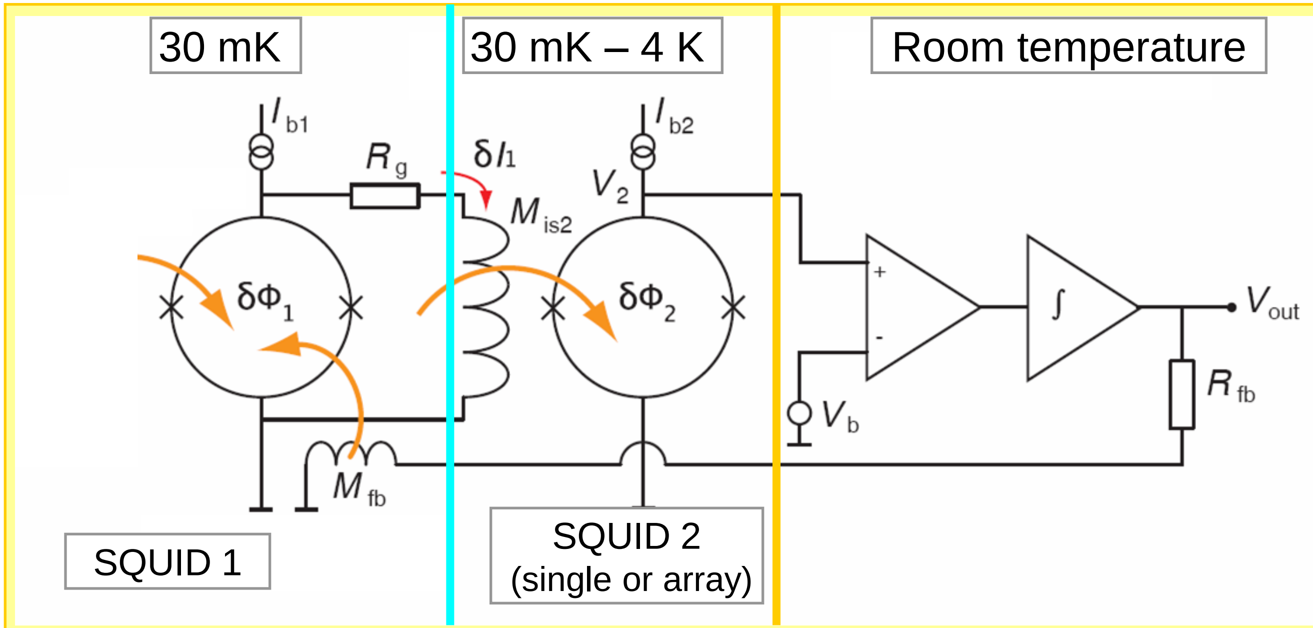
$\sqrt{S_{v,elec}} = 0.33\,\text{nV}/\sqrt{\text{Hz}} \Leftrightarrow \sqrt{S_{\Phi,elec}} = 1.7\,\mu\Phi_0/\sqrt{\text{Hz}}$

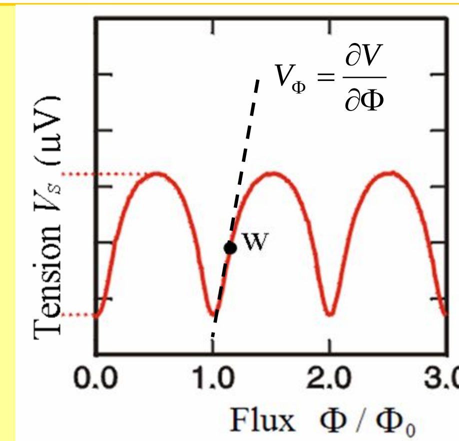
Noise limited by room temperature electronics



FWHM = 69 eV, SQUID electronics white noise of 1.7 $\mu\Phi_0$ / $Hz^{1/2}$
(FWHM = 35 eV with a noiseless electronics)

Two stage SQUID set up





$$V_\Phi = \frac{\partial V}{\partial \Phi}$$

$$G_\Phi = \frac{\delta\Phi_2}{\delta\Phi_1} \approx \frac{M_{is2}}{R_g + R_S} V_{\Phi,1}$$

$$S_{\Phi,SQUID} = \underbrace{S_{\Phi,1}}_{\left(0.15\times10^{-6}\right)^2} + \underbrace{\frac{4k_BTR_g}{V_{\Phi,1}^2}}_{<\left(2\cdot10^{-8}\right)^2} + \underbrace{\frac{S_{\Phi,2}}{G_\Phi^2}}_{\left(0.08\ldots0.7\times10^{-6}\right)^2} + \underbrace{\frac{S_{V,elec}}{V_{\Phi,2}^2 G_\Phi^2}}_{\left(0.6\times10^{-6}\right)^2}$$

$\sqrt{S_{\Phi,1}} \approx 0.15\,\mu\Phi_0/\sqrt{\text{Hz}}$

$\sqrt{S_{\Phi,2}} \approx 0.15\ \ldots\ 2\,\mu\Phi_0/\sqrt{\text{Hz}}$

$R_g \approx 1\ldots50\,\Omega$

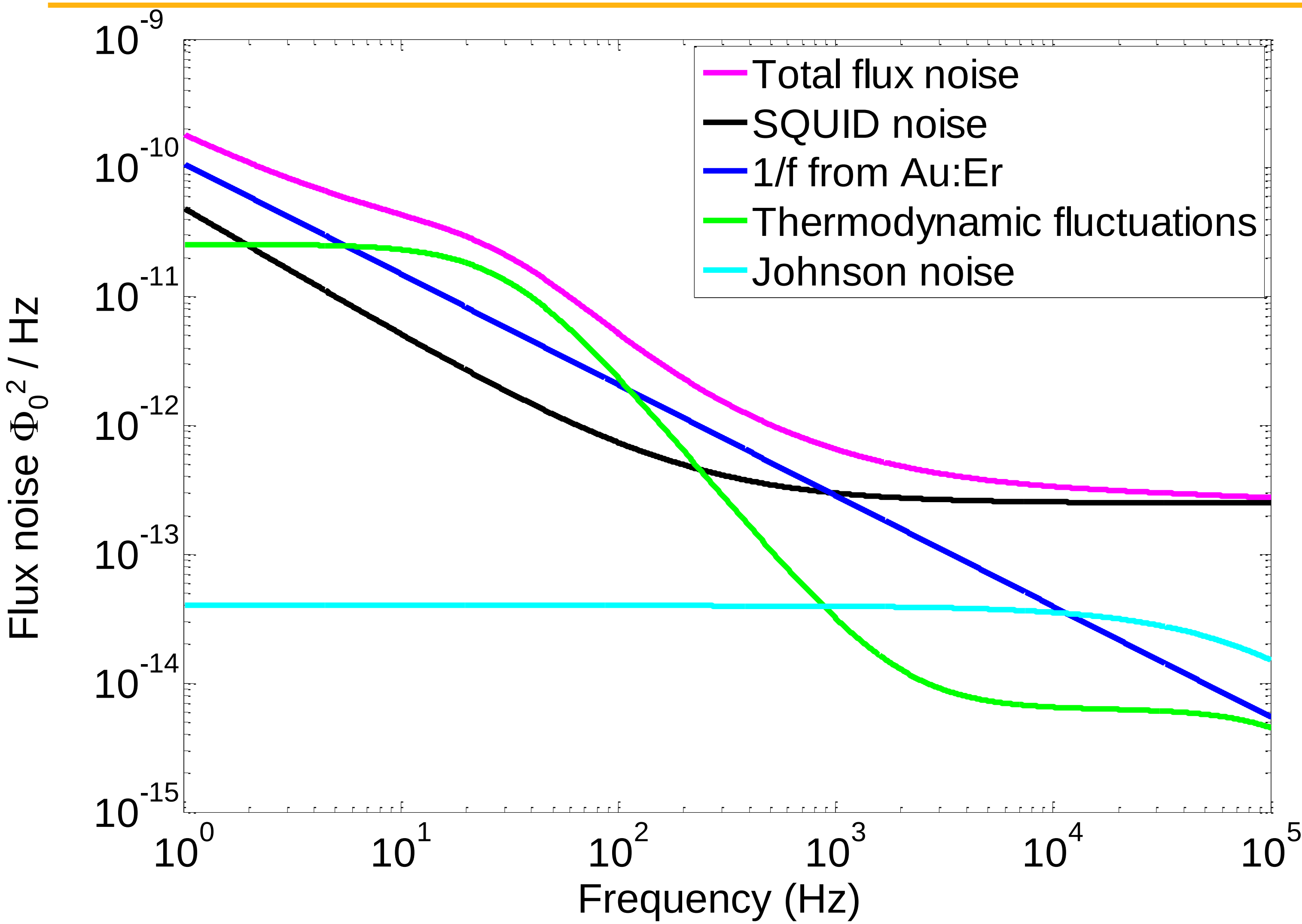
$\sqrt{S_{V,elec}} \approx 0.33\,\mu\text{V}/\sqrt{\text{Hz}}$

$V_{\Phi,2} \approx 200\,\mu\text{V}/\Phi_0,\ G_{\Phi,\max} \approx 3$

$$\sqrt{S_{\Phi,SQUID}} = 0.5\ \text{to}\ 1\,\mu\Phi_0/\sqrt{\text{Hz}}$$

$$\sqrt{S_{\Phi,SQUID_{1/f}}}(1\,\text{Hz}) \approx 8\,\mu\Phi_0/\sqrt{\text{Hz}}$$

Lower power dissipation in the SQUID1 shunts



FWHM = 45 eV, SQUID electronics white noise of 0.5 $\mu\Phi_0$ / $Hz^{1/2}$

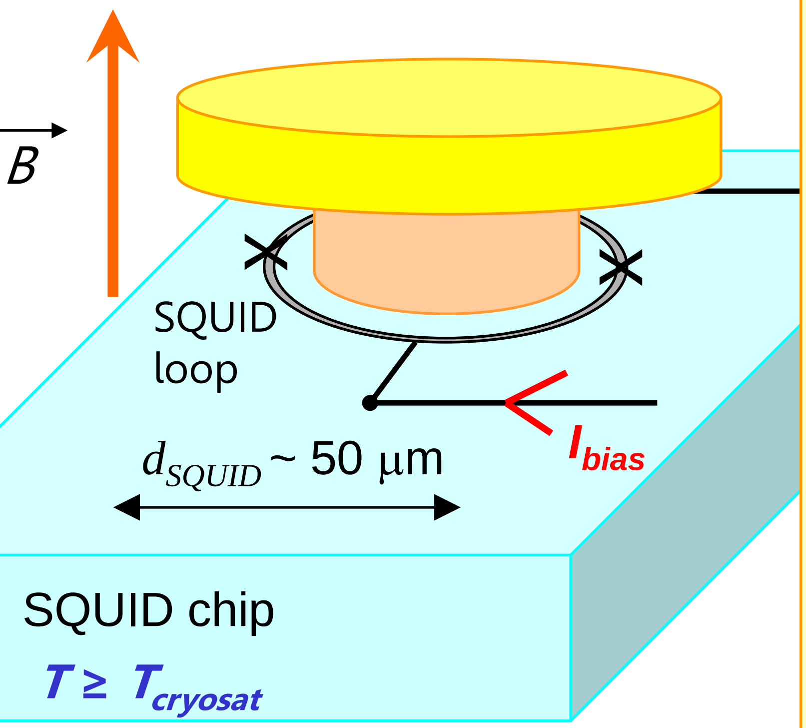
(FWHM = 35 eV with a noiseless electronics)

How to couple the magnetization of the sensor to the SQUID

Direct coupling

$$\delta\Phi = \frac{G}{r_{loop}} \cdot V_{sensor} \cdot \mu_0 \cdot \left(\frac{\partial M}{\partial T}\right) \frac{E}{C_{sensor} + C_{absorber}}$$

Magnetic coupling factor between the sensor and the SQUID loop

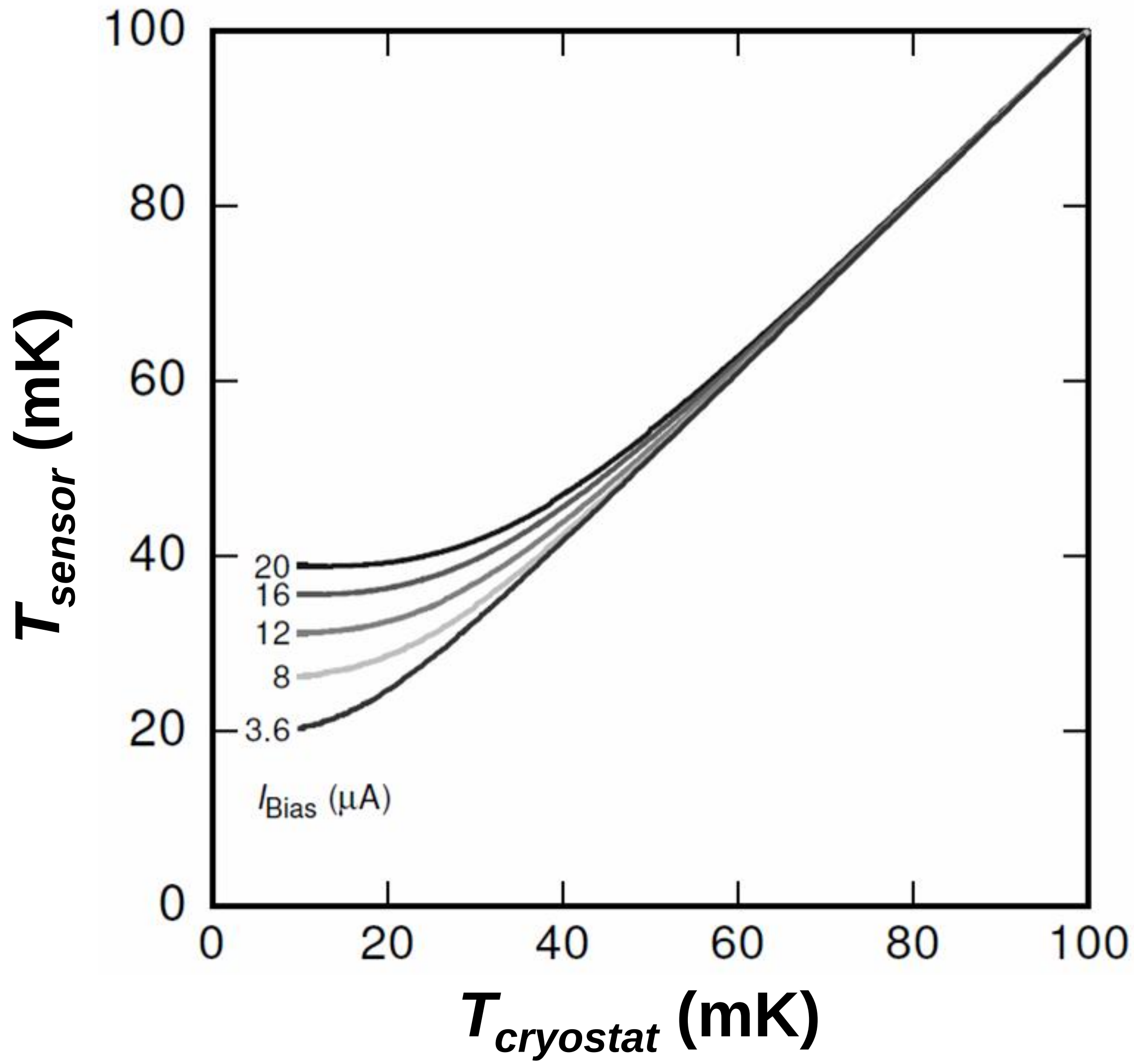


Advantage

- High coupling factor
- Easy to realize

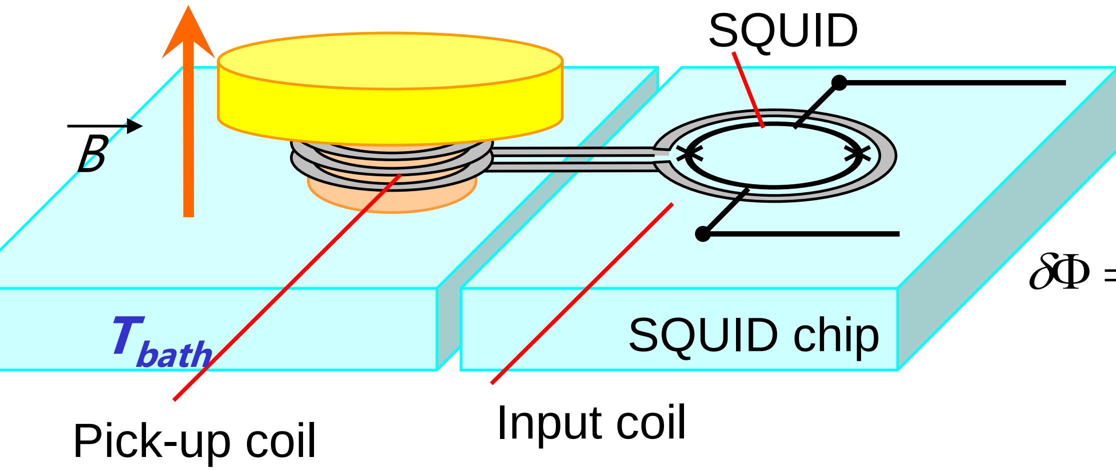
Disadvantage

- Josephson junctions are sensitive to B
  ⇒ Reduce the signal to noise ratio of the SQUID
- Thermal decoupling between bath and SQUID chip
- Sensor size and SQUID noise limited by SQUID loop radius $\sqrt{S_{\Phi,SQUID}} \propto L_{SQUID}^{3/4} \propto r_{SQUID}^{3/4}$
- Sensitive to magnetic Johnson noise



100
80
60
40
20
0
20
16
12
8
3.6
I_{Bias} (µA)
0
20
40
60
80
100
T_{sensor} (mK)
$T_{cryostat}$ (mK)

Flux transformer



$$\delta\Phi = \frac{G_{mag} G_{in}}{r_{pick-up}} V_s \cdot \mu_0 \cdot \left(\frac{\partial M}{\partial T}\right) \frac{E}{C_{sens} + C_{abs}}$$

$$G_{in} = N_{turn} \frac{M_{in-SQ}}{L_{pick-up} + L_{input} + L_w}$$

Optimised for

$$L_{pick-up} = L_{input}$$

$$L_w \rightarrow 0$$

$$\sqrt{S_{\Phi,SQUID}^{pick-up}} \propto \sqrt{L_{pick-up}}$$

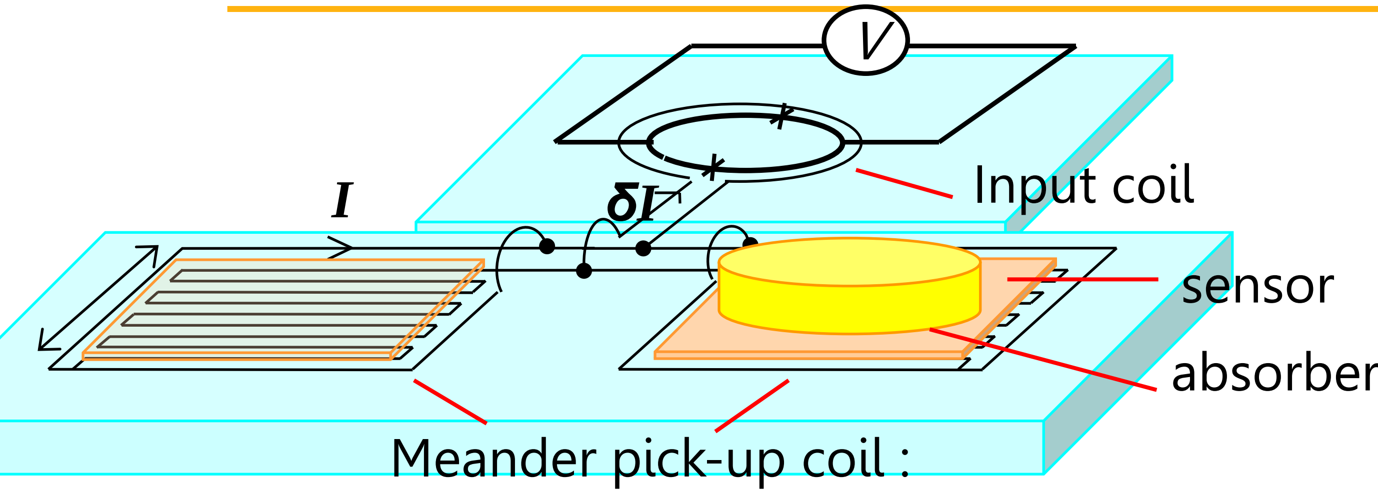
Advantage

- Sensor thermally decouple from SQUID chip
- Possibility to read large sensor, required for applications needing a large absorber

Disadvantage

- Signal to SQUID noise ratio is smaller by a factor 2 at least
- Sensitive to magnetic Johnson noise

Flux transformer with meander shaped pickup coil



$$G_{in} = \frac{M_{in-SQ}}{2L_{meander} + L_{input}}$$

$$L_{meander} \propto \frac{A_{meander}}{p}$$

G_{mag} ?

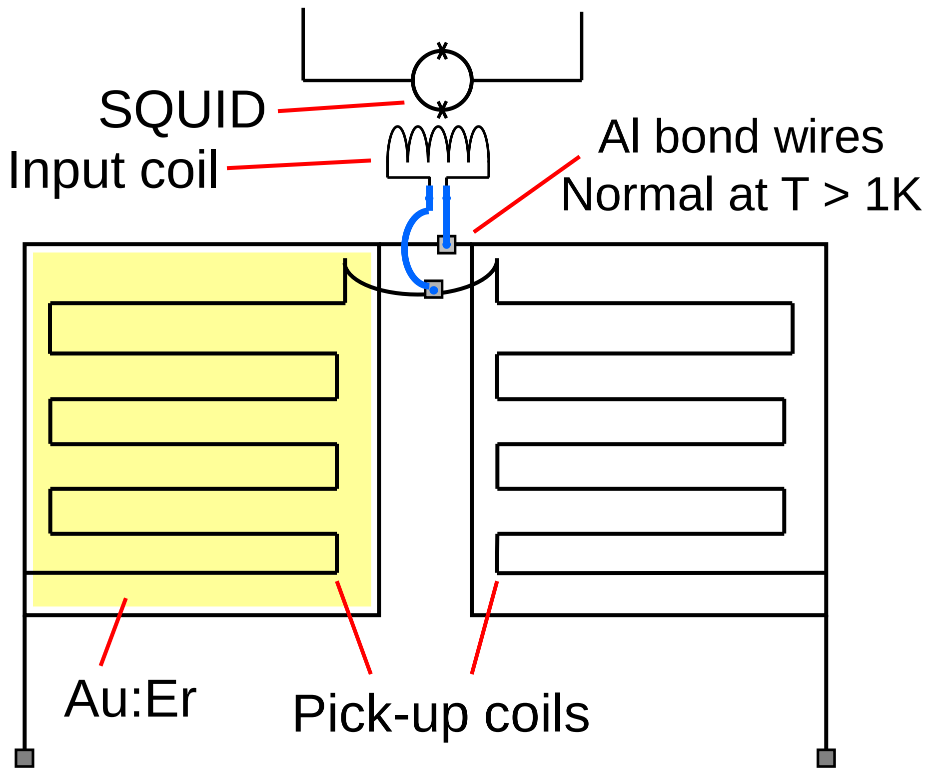
B ?

Advantage

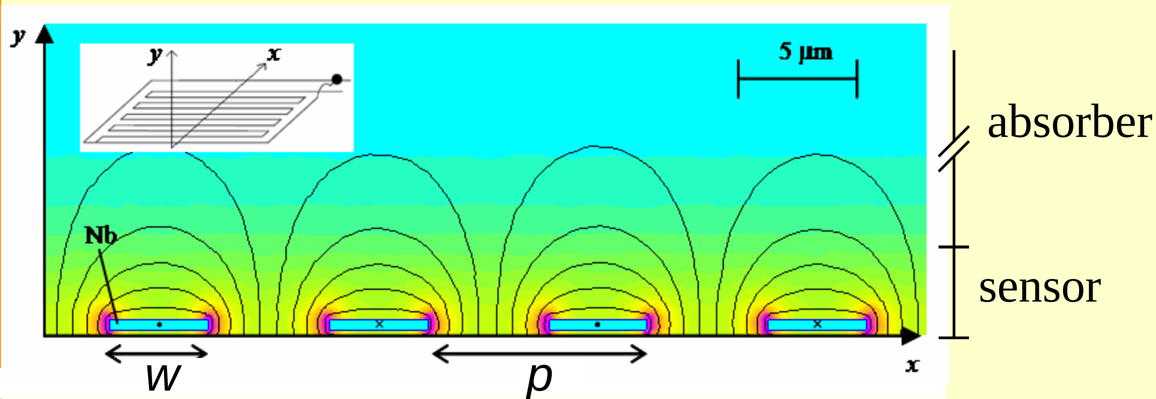
- Advantages of a flux transformer
- Insensitive to external magnetic field, Johnson magnetic noise
- No external field coil
- Gradiometric
- Microfabrication (reproducible, serial)

Disadvantage

- Large current in the SQUID input coil
- Microfabrication (expensive equipements)
- Signal size reduced



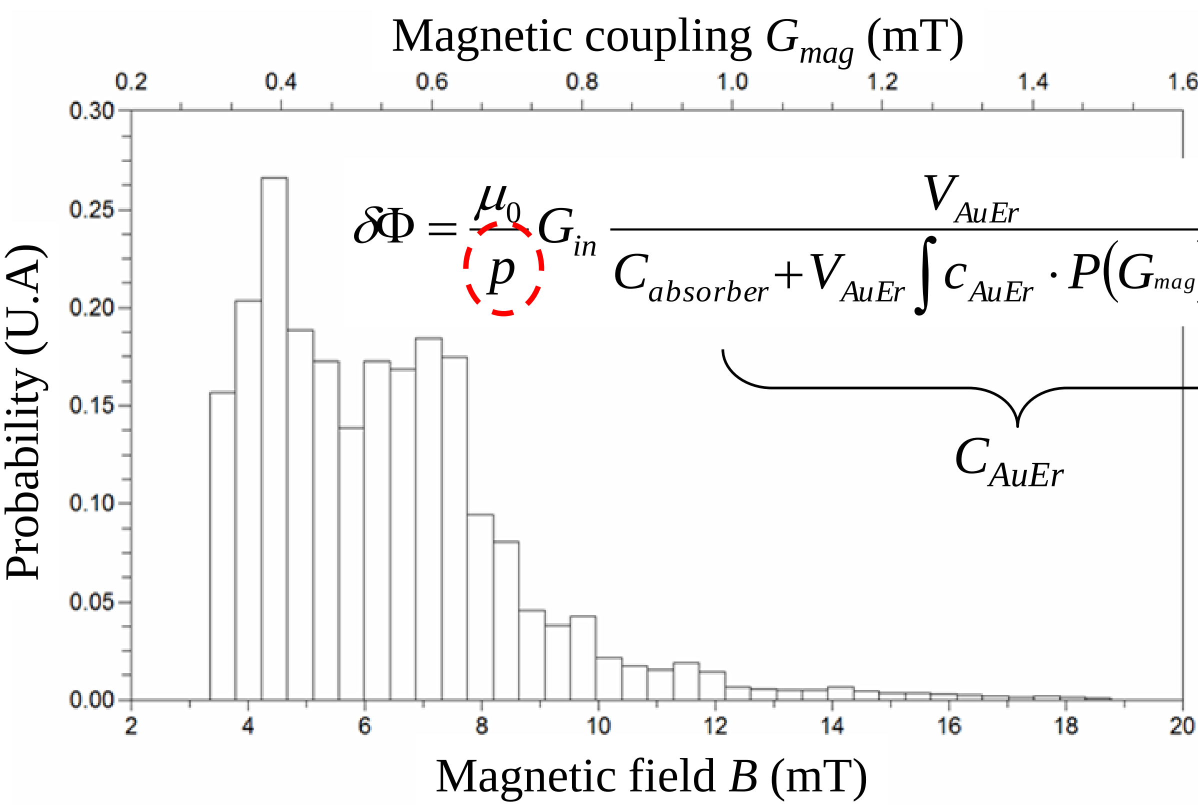
Field distribution



Inhomogeneous magnetic field B

$$G_{mag} = Bp/\mu_0 I$$

w = 2 … 5 µm
p = 5…10 µm



$$\delta\Phi = \frac{\mu_0}{p} G_{in} \frac{V_{AuEr}}{C_{absorber} + V_{AuEr}\int c_{AuEr}\cdot P(G_{mag})\cdot dG_{mag}} \int G_{mag}\cdot\frac{\partial M}{\partial T}\cdot P(G_{mag})\cdot dG_{mag}$$

C_{AuEr}

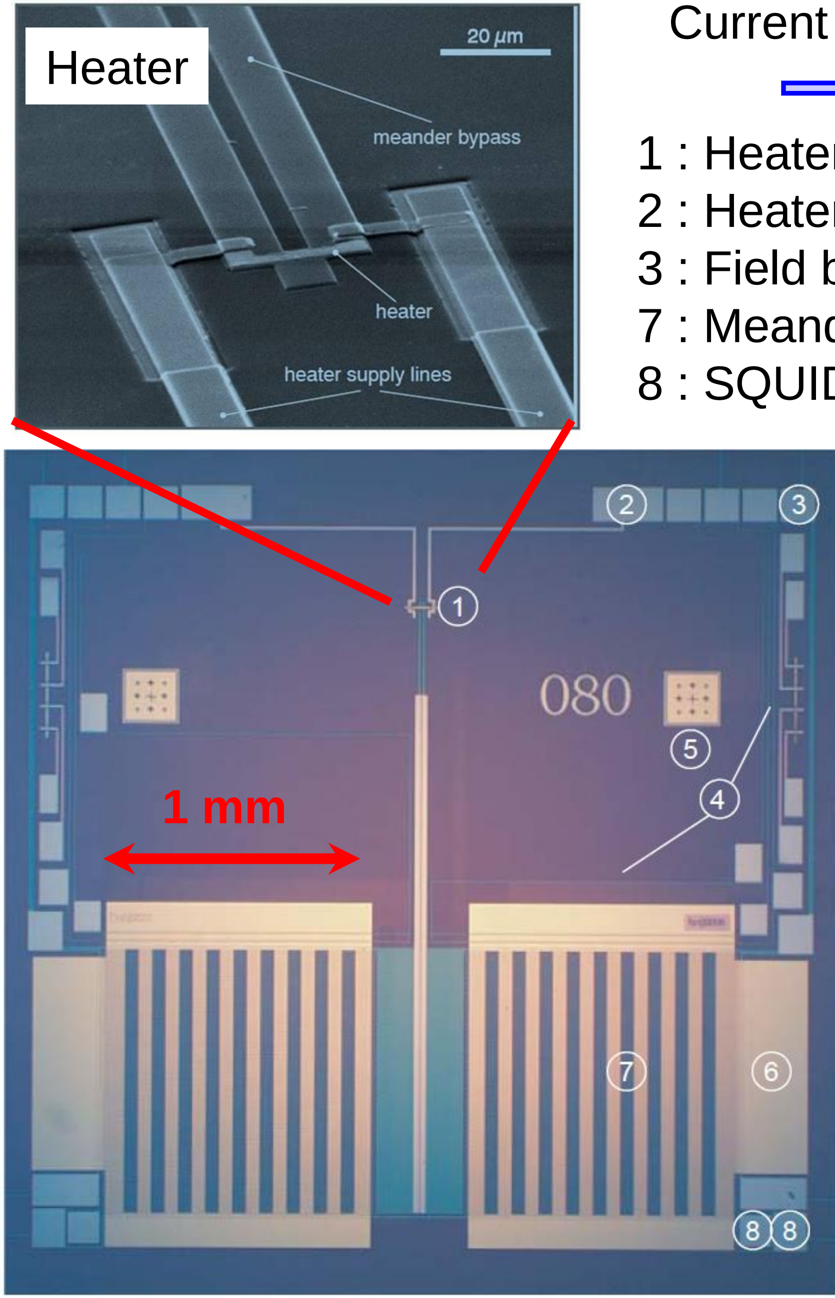
Magnetization

Optimization, fabrication and experimental set-up

Optimization

- T_{bath} as low as possible but > 10 mK and fixed by the cryostat
- $C_{absorber}$ as small as possible but fixed by the application
- Signal size as large as possible but < 1 Φ_0 in the SQUID loop
- τ_d as long as possible but limited by the count rate
- $B_{opt} \propto T_{bath}$
- $x_{opt} \propto T_{bath}$
- $\mathrm{Signal} \propto C_{absorber}^{1/3}$

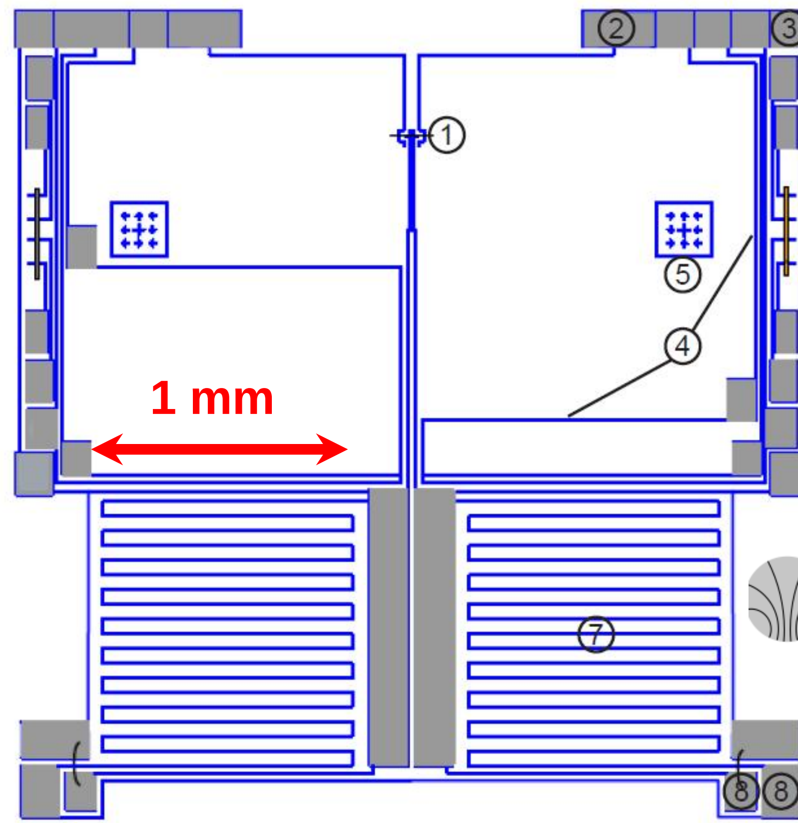
Meander shaped pick-up coil



Current of 100 mA required in the meander

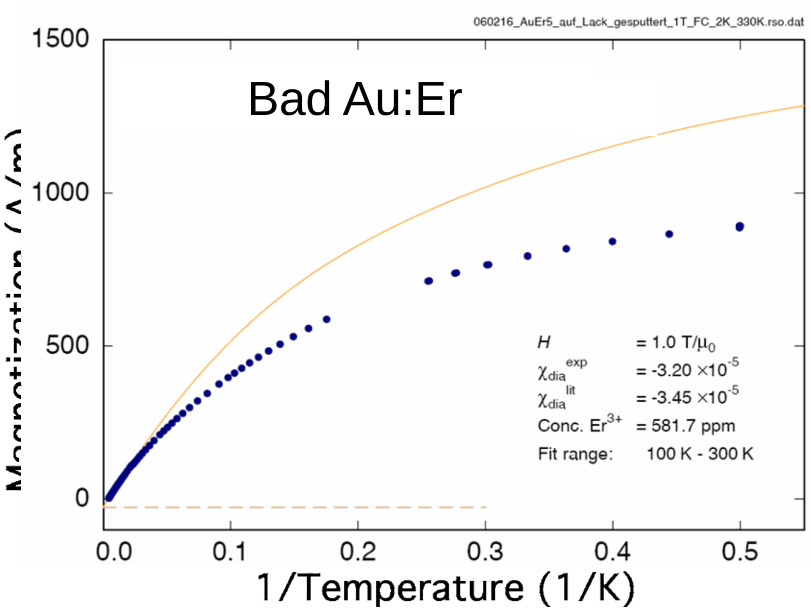
⇒ Good niobium film quality

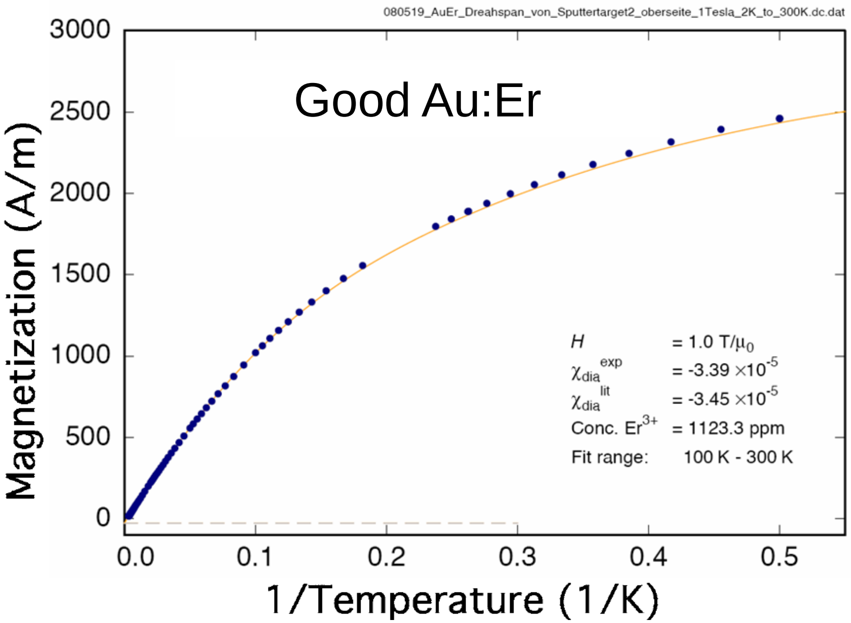
1 : Heater
2 : Heater bond pads
3 : Field bond pad
7 : Meander pick-up coil made of Nb
8 : SQUID input coil bond pads

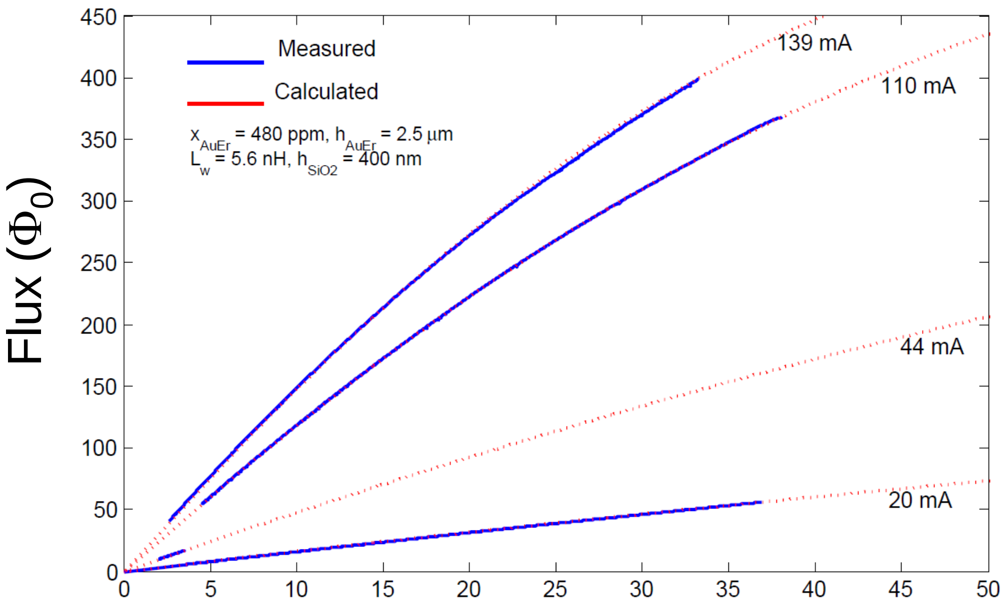


AuEr sensor

Sputtering of the AuEr



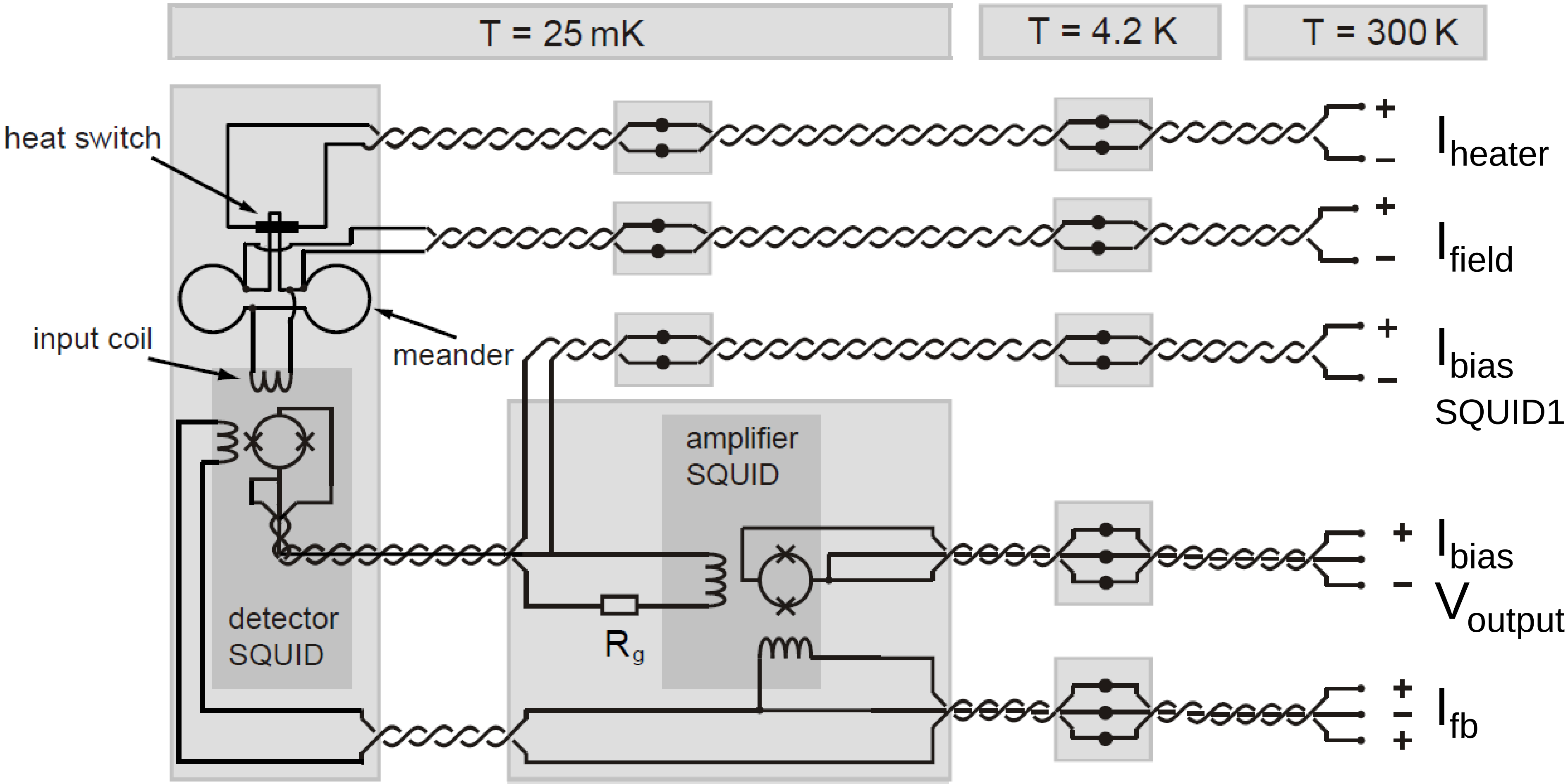




Good Au:Er at low T

UHV required < 10^{-8} Torr

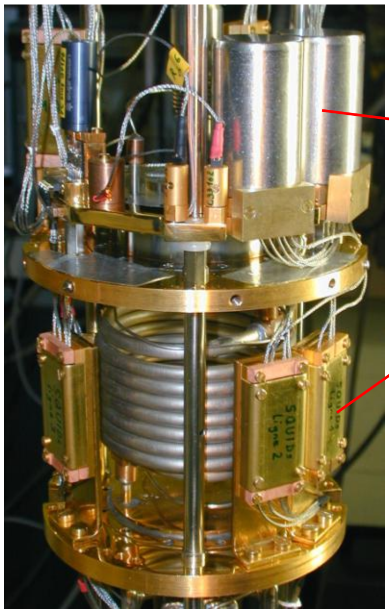
Wiring

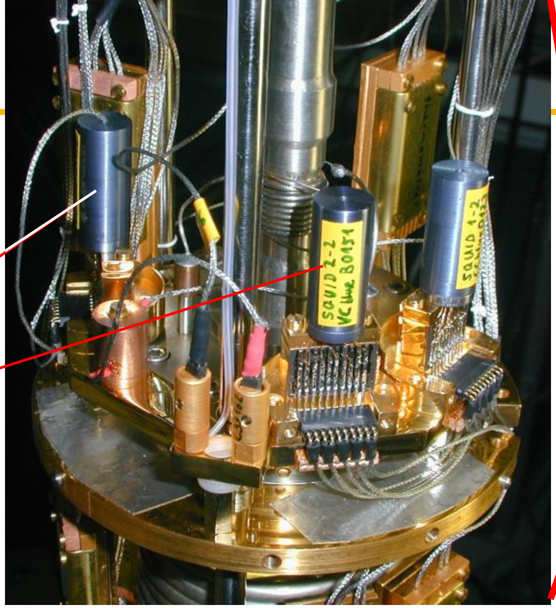


T = 25 mK
T = 4.2 K
T = 300 K
heat switch
input coil
meander
detector SQUID
amplifier SQUID
R g
+
–
I heater
I field
I bias
SQUID1
V output
I fb

In the cryostat

Dilution or ADR cryostat





SQUIDs of preamplification :
T reguled between 1.5 and 4.2 K

Thermalisation of the wires and filters

Detector stages.
Temperature regulation
with a PID at 15 to 20 mK ± few µK

KIRCHHOFF
INSTITUT
FÜR PHYSIK

NIST

Application
External sources

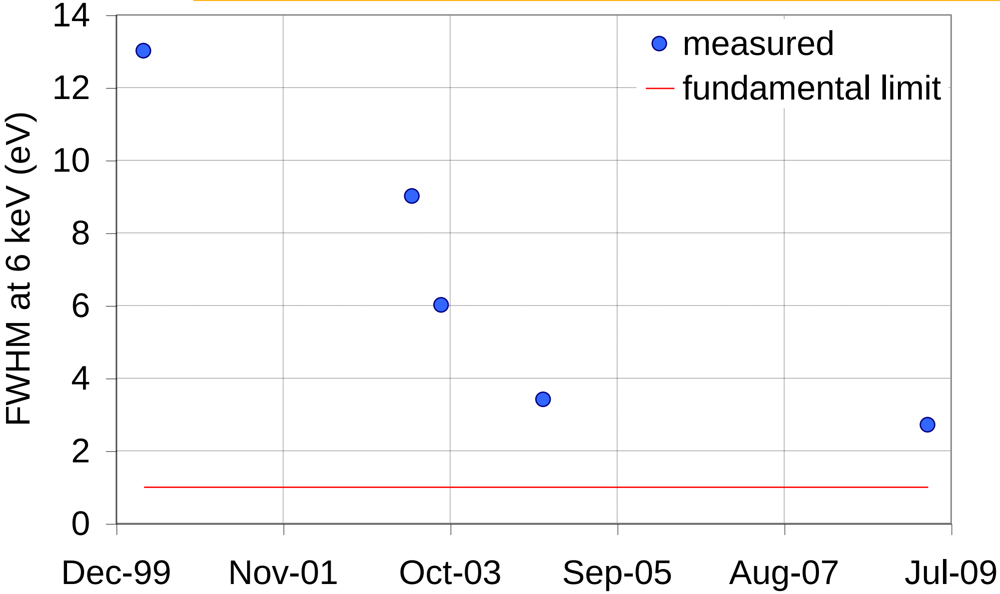
KRISS KOREA RESEARCH INSTITUTE OF STANDARDS AND SCIENCE

LNE
Le progrès, une passion à partager

NASA

IN DEO SPERAMUS

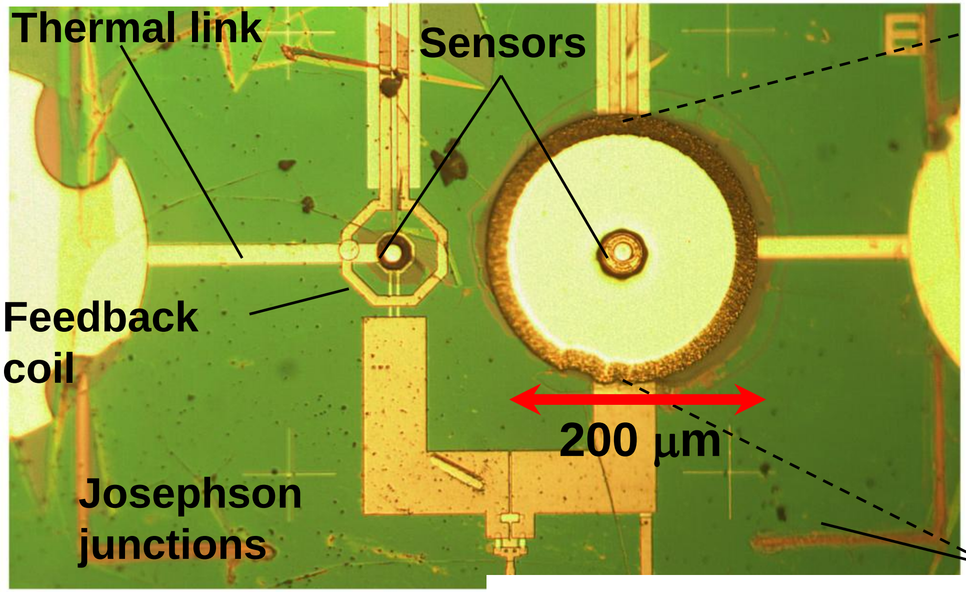
X ray spectrometry

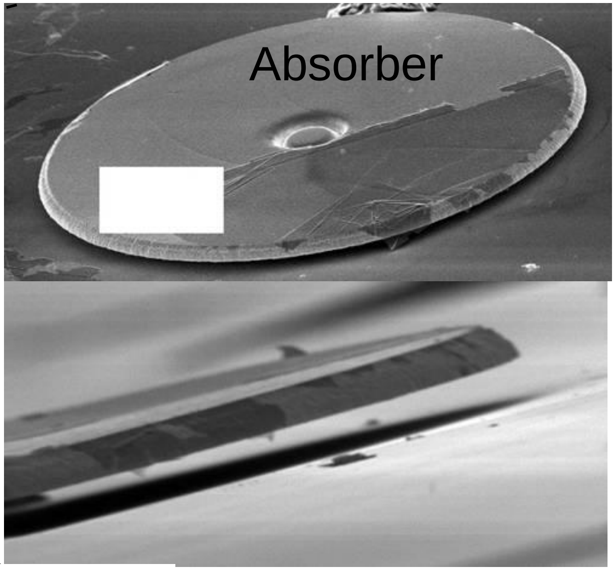


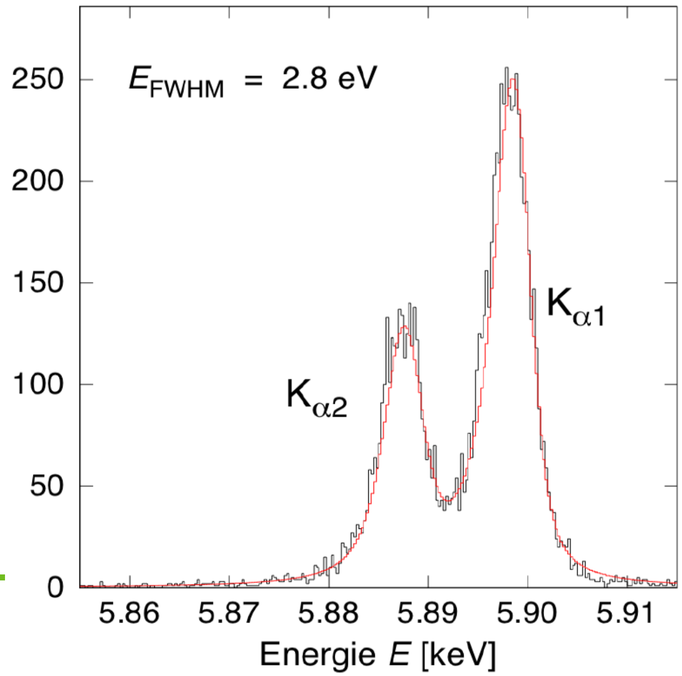
T	$C_{absorber}$ (pJ/K)	C_{sensor} (pJ/K)	β	B (mT)	$\delta\Phi$/6 keV (Φ_0)	SQUID noise $\mu\Phi_0/Hz^{1/2}$	FWHM (eV)
30 mK	0.11	0.073	0.39	8	1.4	0.6	**0.94**
50 mK	0.19	0.067	0.26	12	0.65	0.6	2.2

Absorber: πx150x150x3 µm3 ⇒ 95 % detection efficiency at 6 keV

X ray spectrometry



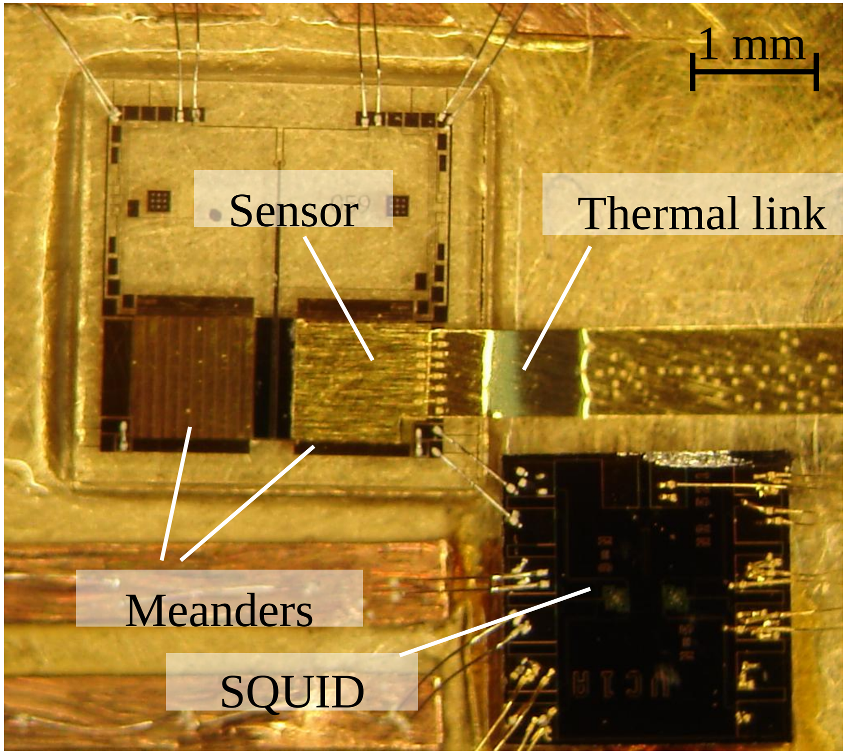


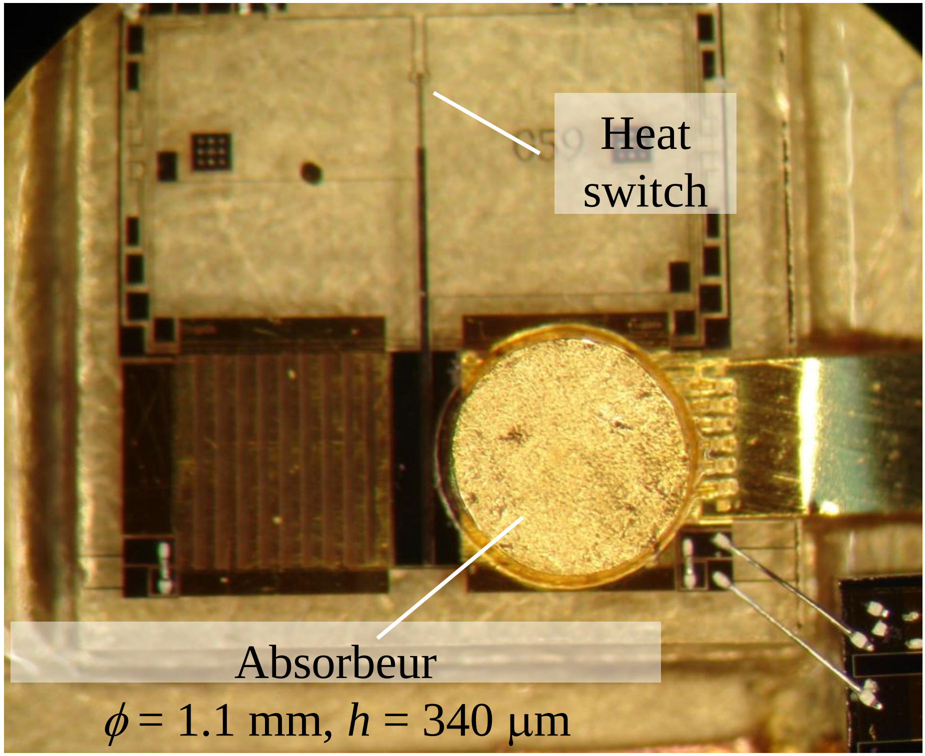


Gamma spectrometry

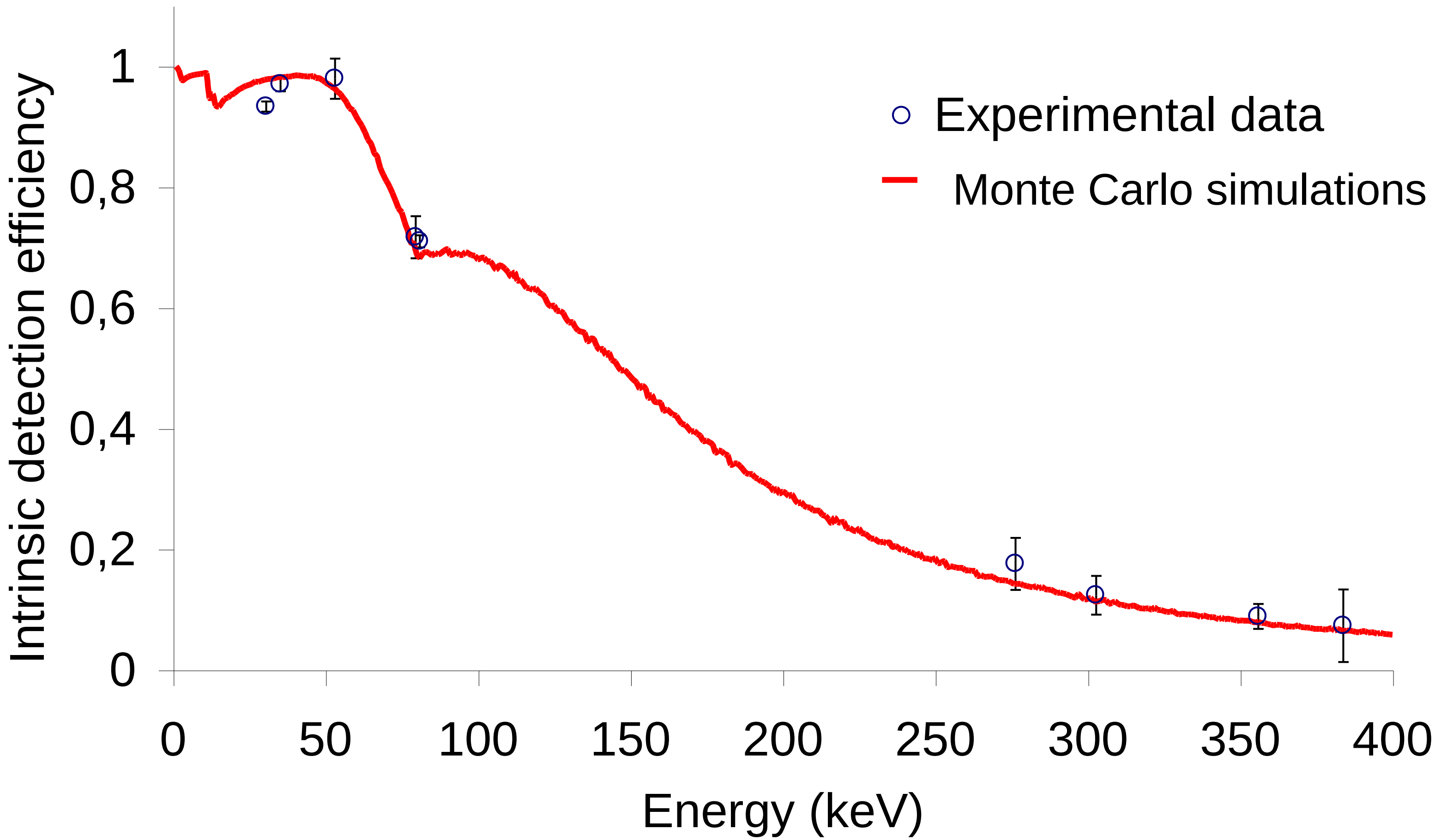
T	$C_{absorber}$ (nJ/K)	C_{sensor} (nJ/K)	β	*I* (mA)	$\delta\Phi$/100 keV (Φ_0)	SQUID noise $\mu\Phi_0/Hz^{1/2}$	FWHM (eV)
30 mK	0.5	0.41	0.45	80	0.17	0.5	**45**

Absorber: πx0.5x0.5x0.3 mm^3 ⇒ 60 % intrinsic detection efficiency at 100 keV



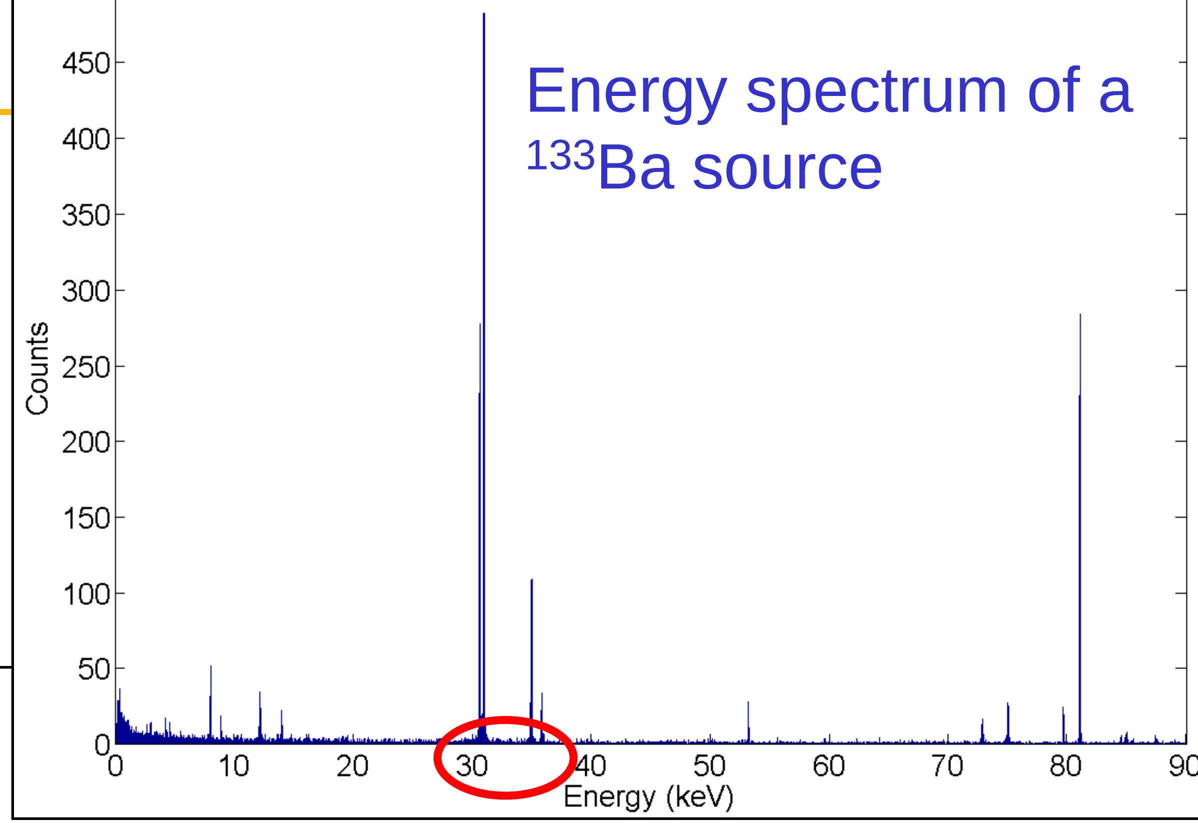


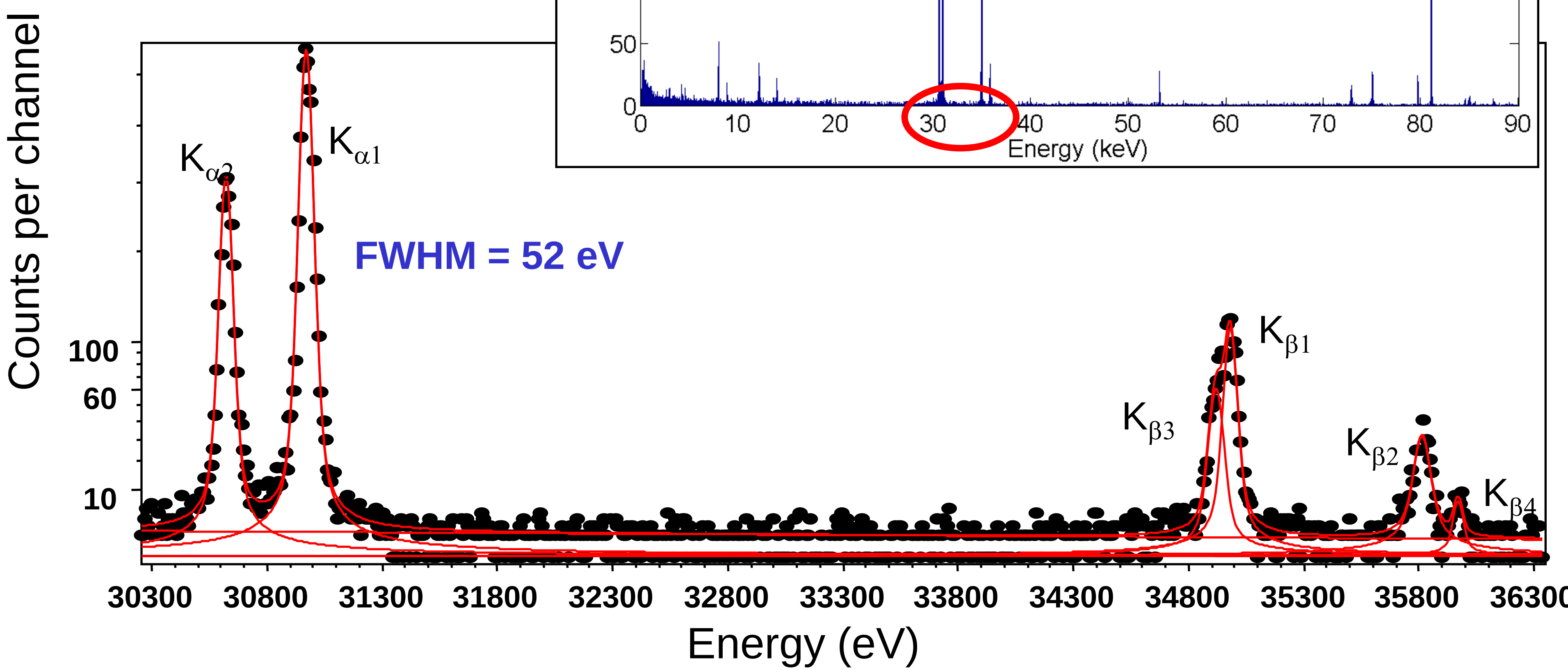
Gamma spectrometry



Le progrès, une passion à partager

FWHM of
52 eV at 30 keV
and 58 eV at 81 keV
T = 13 mK





Application

Embeded sources

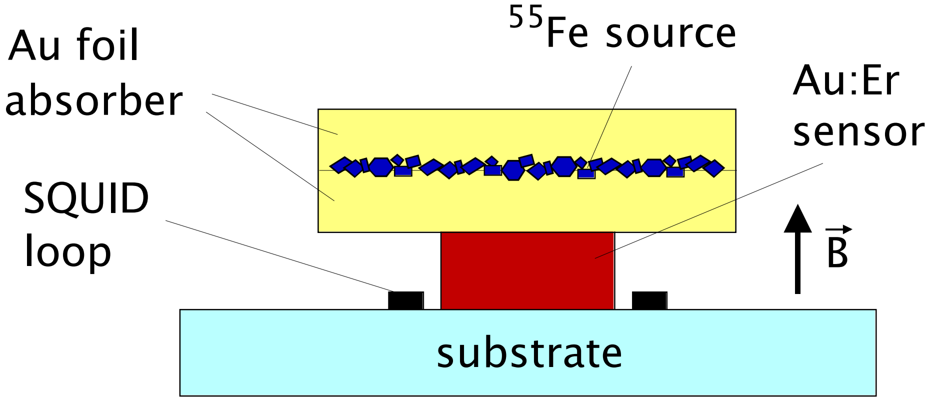
Absolute activity measurement of ^{55}Fe

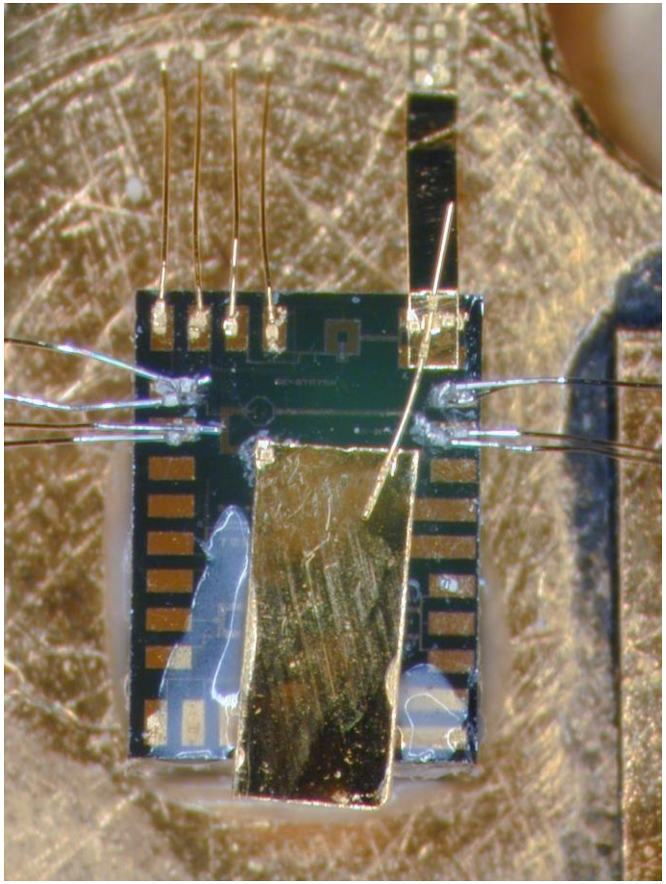
Source enclosed inside the absorber

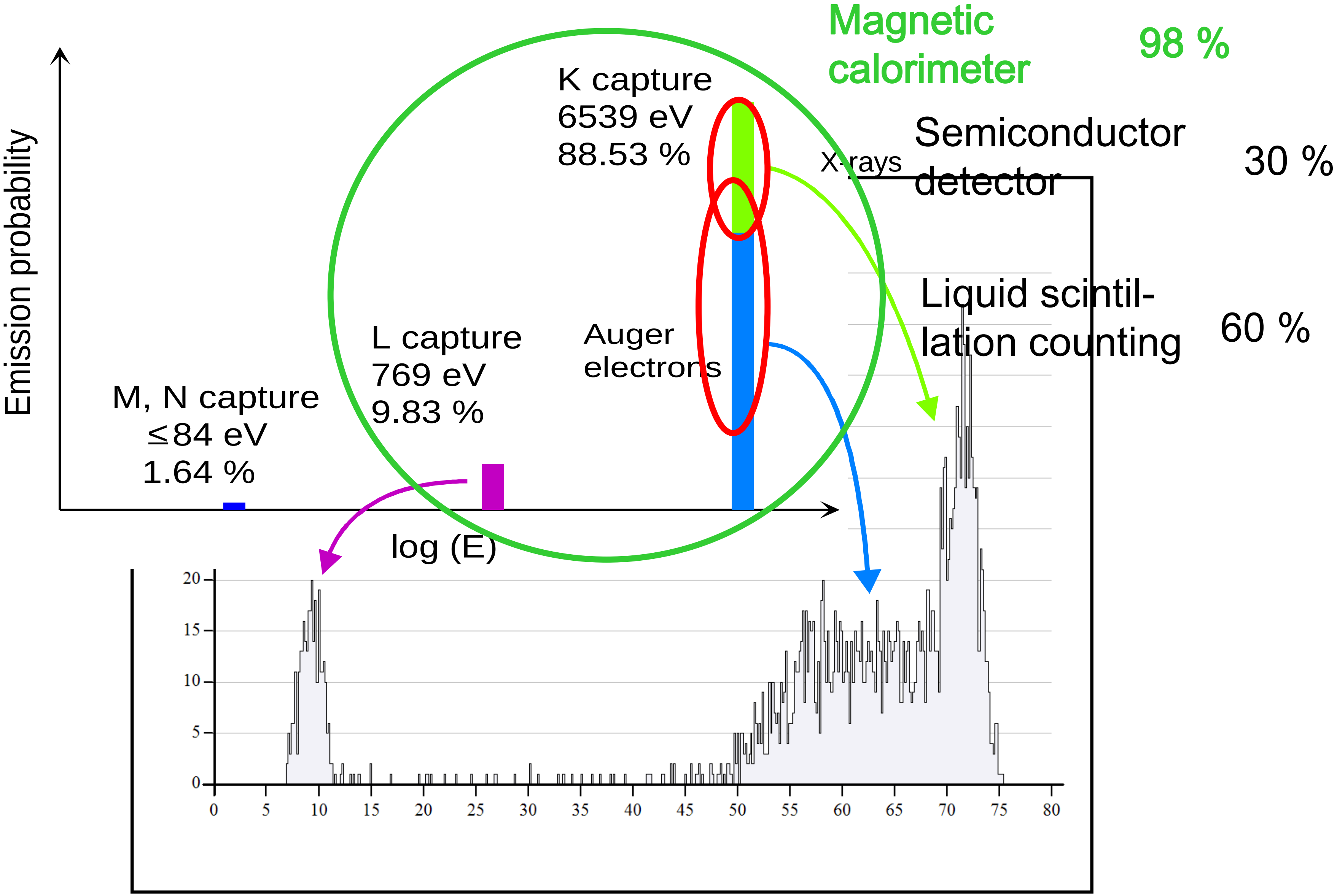
→ 4 p detection geometry

Gold absorber: high stopping power
thickness 12 µm: ≥ 99.9 % absorption
for electrons and photons up to 6.5 keV

→ high detection efficiency





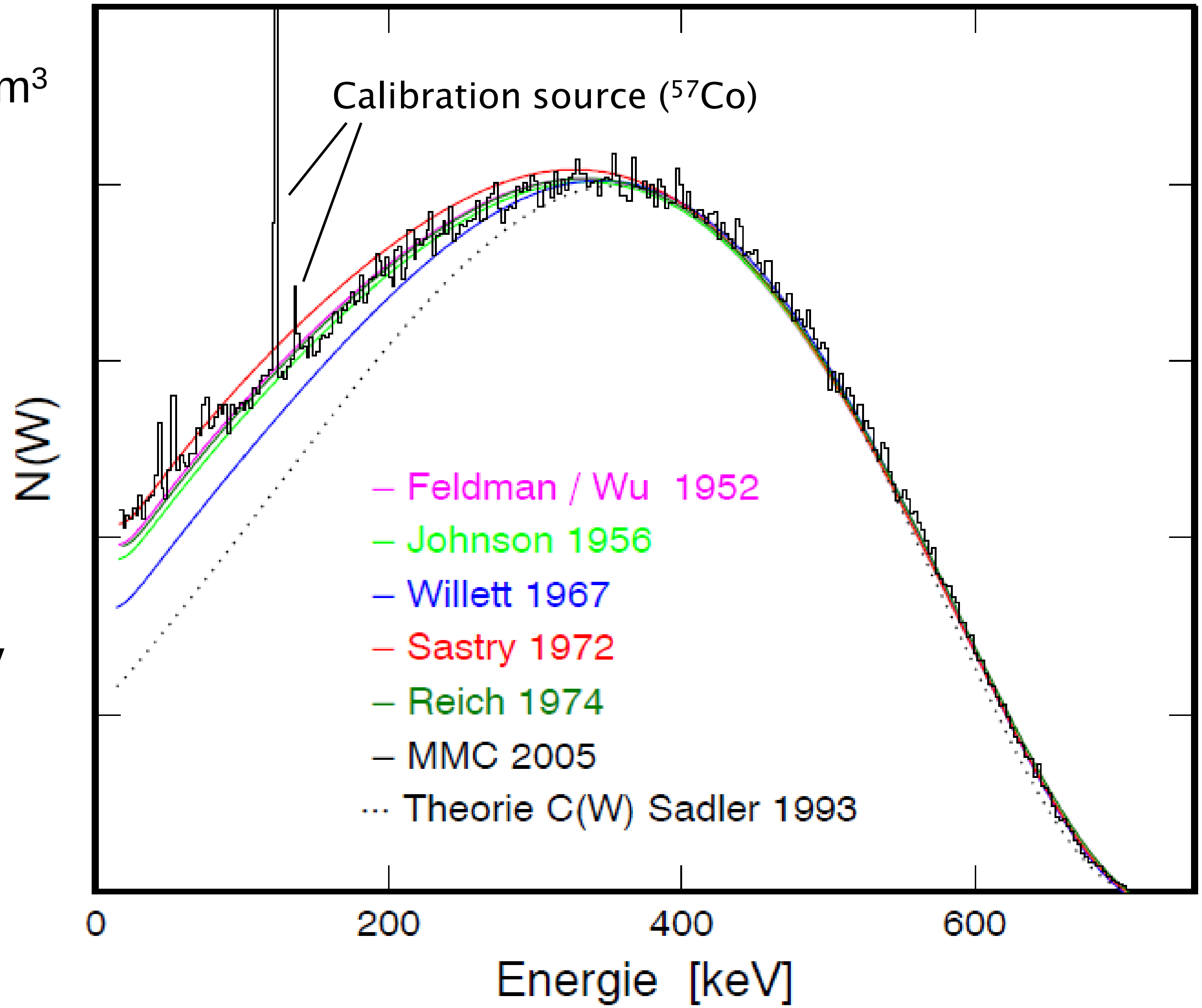

Magnetic calorimeter
98 %
K capture
6539 eV
88.53 %
X-rays
Semiconductor detector
30 %
Liquid scintil-lation counting
60 %
Auger electrons
L capture
769 eV
9.83 %
M, N capture
≤84 eV
1.64 %
Emission probability
log (E)
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

Beta spectrometry

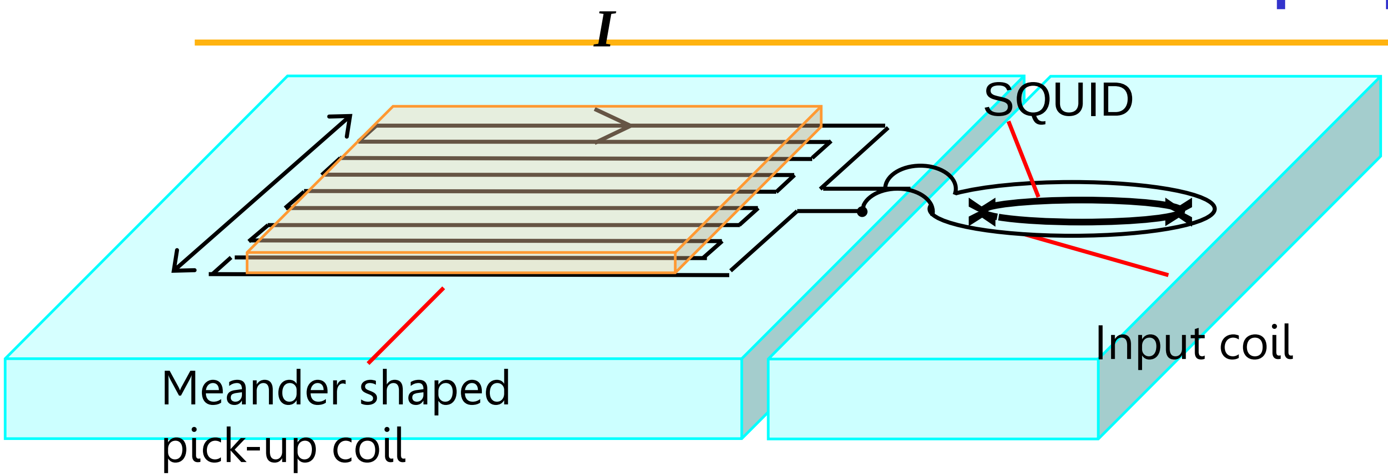
Using 1x1 mm² meander pick-up coil
Absorber 800x800x500 μm³

750 000 counts
(3.2 cps)

ΔE = 750 eV à 122 keV



Flux transformer with meander shaped pickup coil



$$G_{in} = \frac{M_{in-SQ}}{L_{meander} + L_{input}}$$

$$L_{meander} \propto \frac{A_{meander}}{p}$$

$$G_{mag}\ ?$$

$$B\ ?$$

Advantage

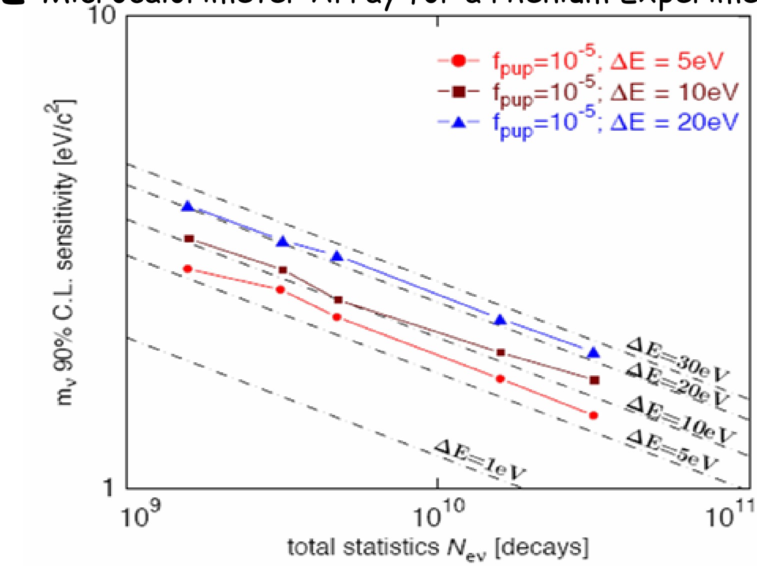
- Advantages of a flux transformer
- No external field coil
- Insensitive to external magnetic field, Johnson magnetic noise
- Microfabrication of arrays

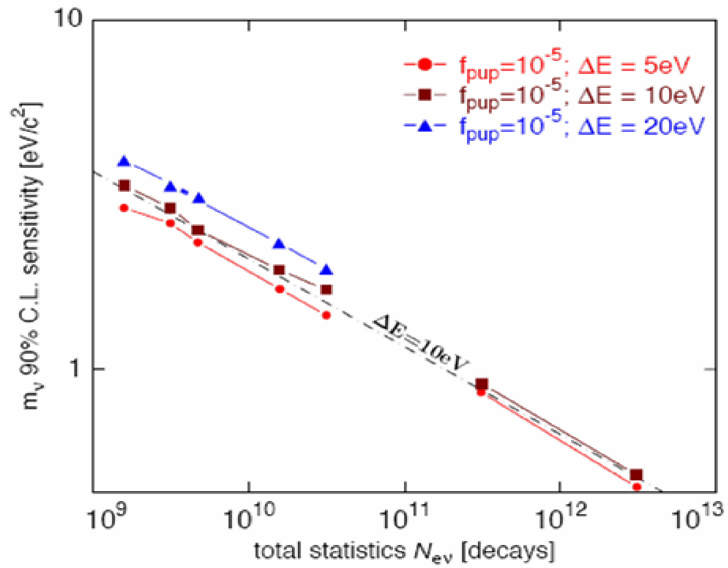
Disadvantage

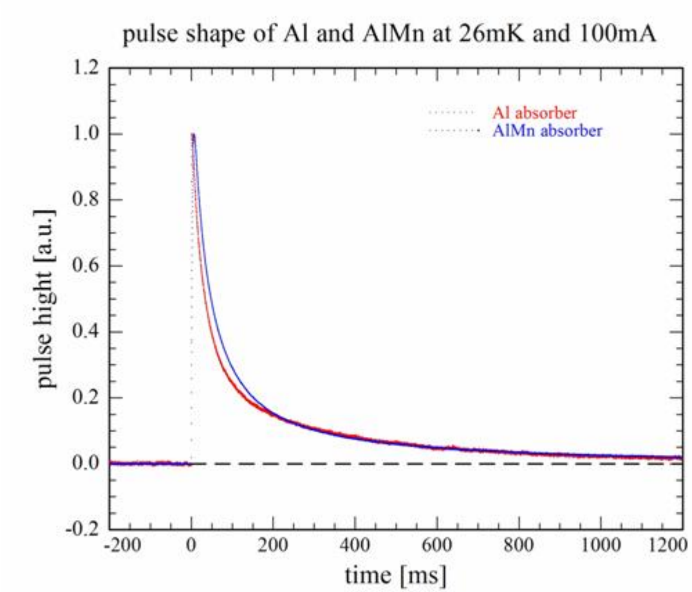
- Large current in the SQUID input coil
- Microfabrication

MARE project, neutrino mass

MARE Microcalorimeter Array for a rhenium Experiment





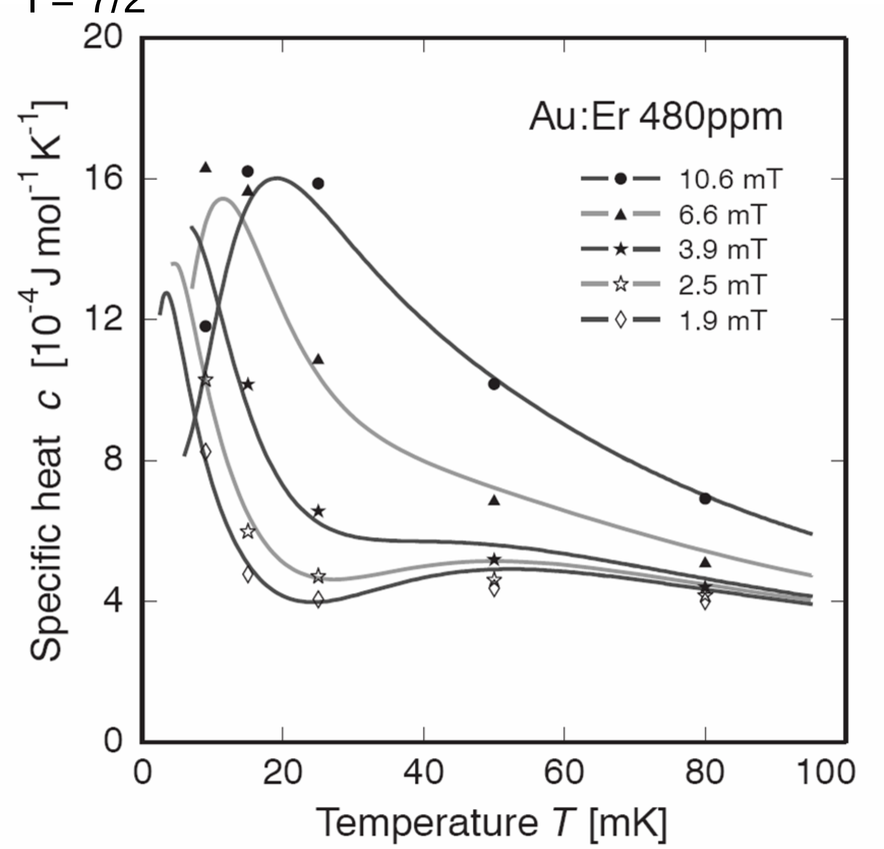


KIRCHHOFF INSTITUT FÜR PHYSIK

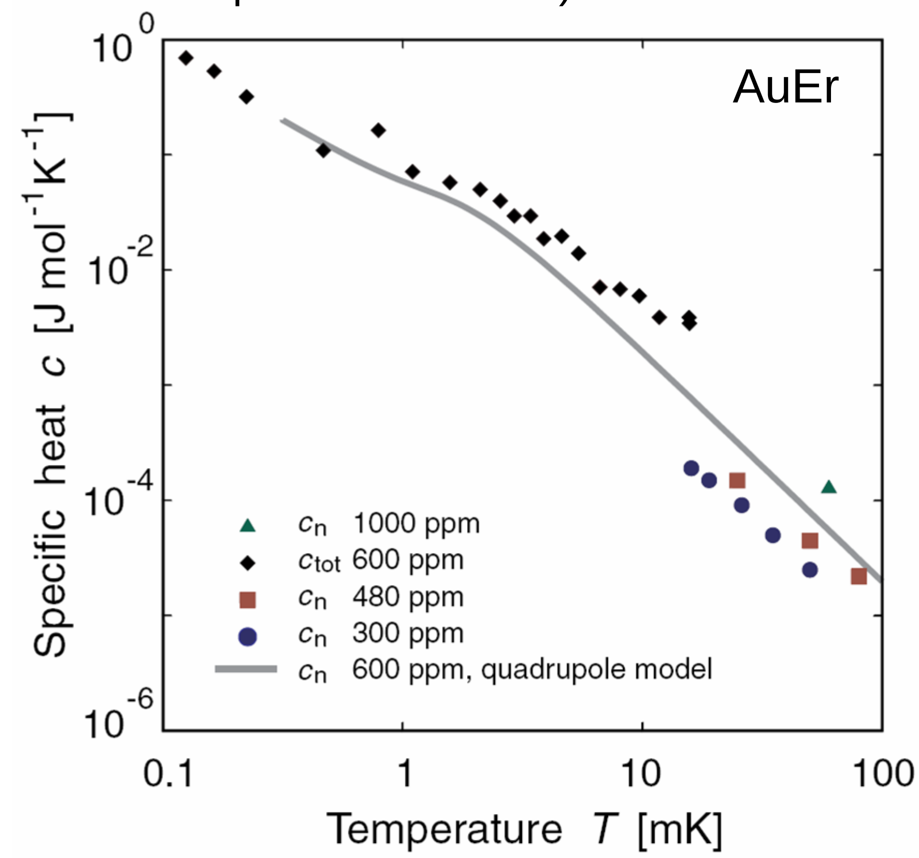
Superconducting absorbers

Thank you for attention

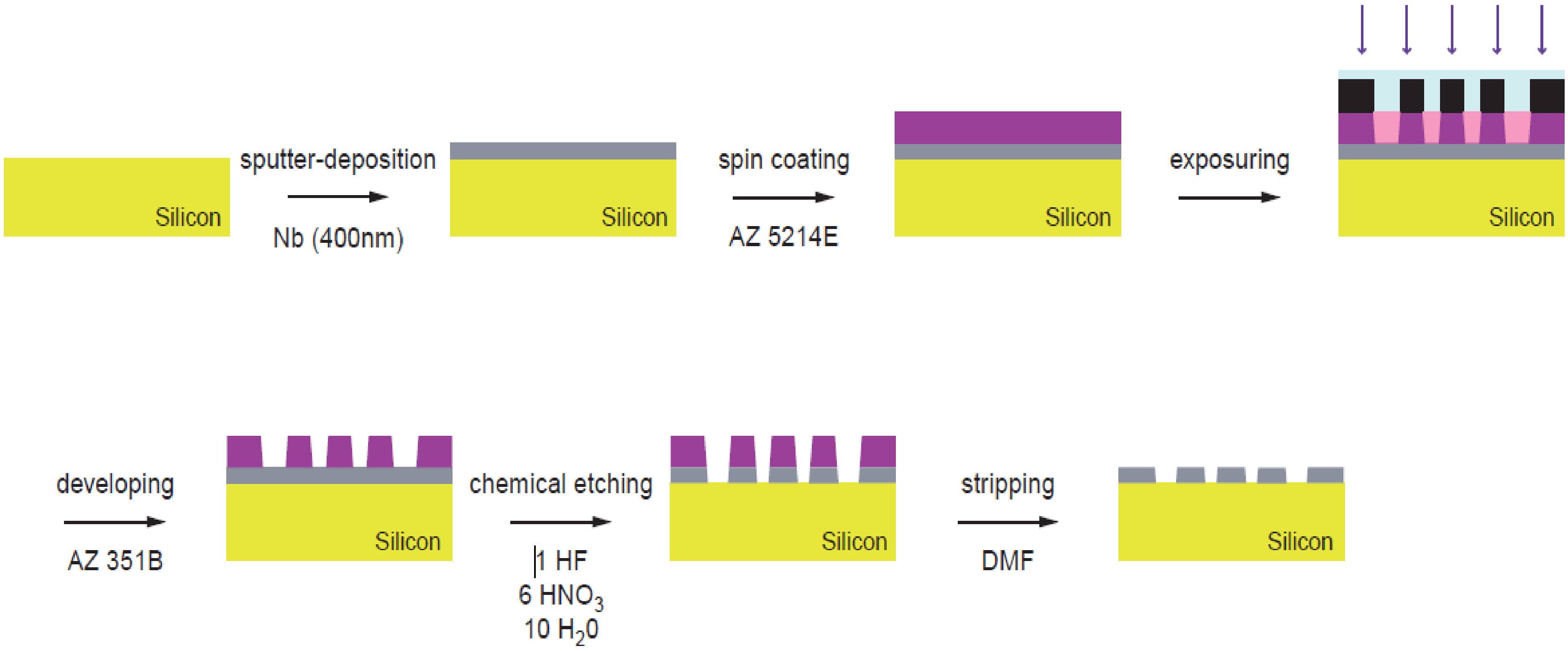
C_{add}' (hyperfine interactions between the nuclear magnetic moments of Er^{168})
I = 7/2

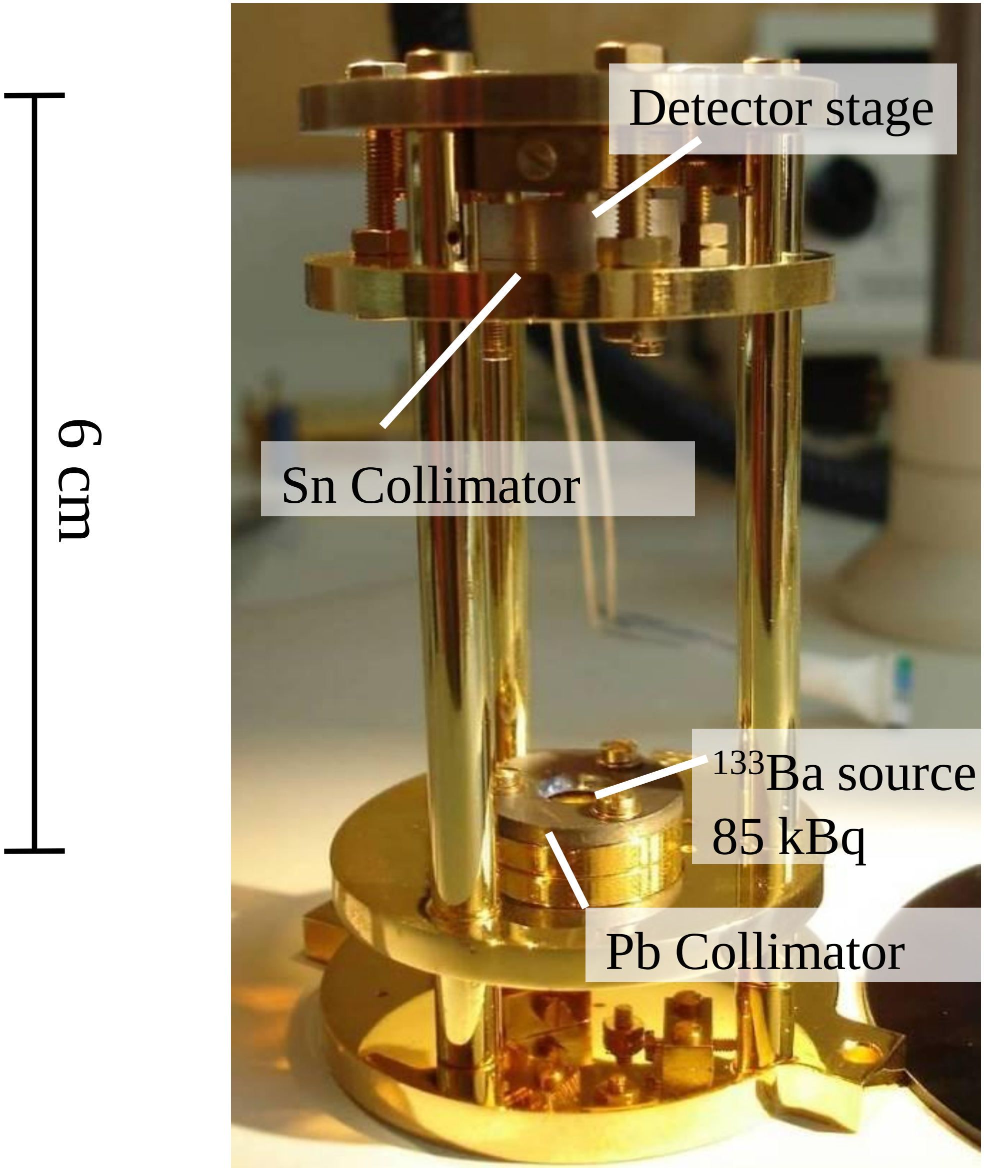


C_{add} (interaction between the quadrupole moments of gold and the electric field gradient due to the presence of Er3+)

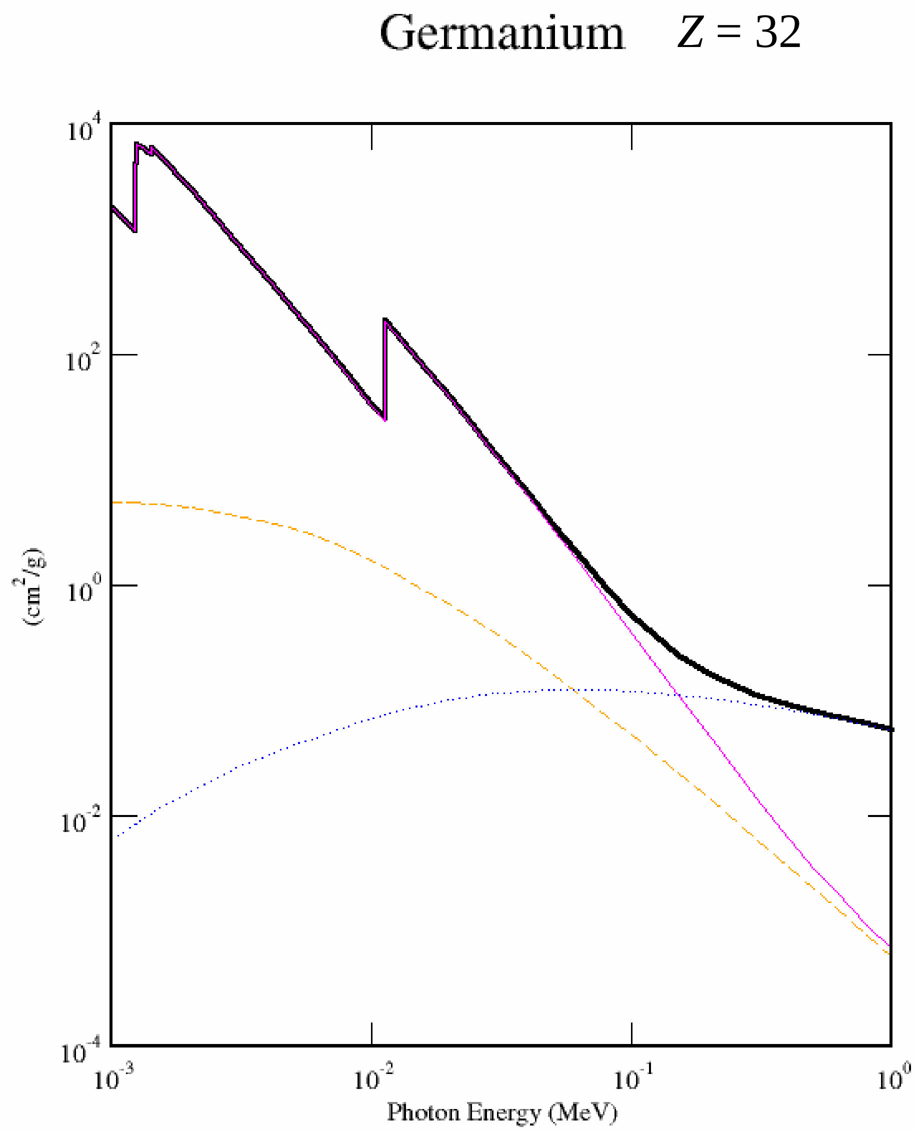


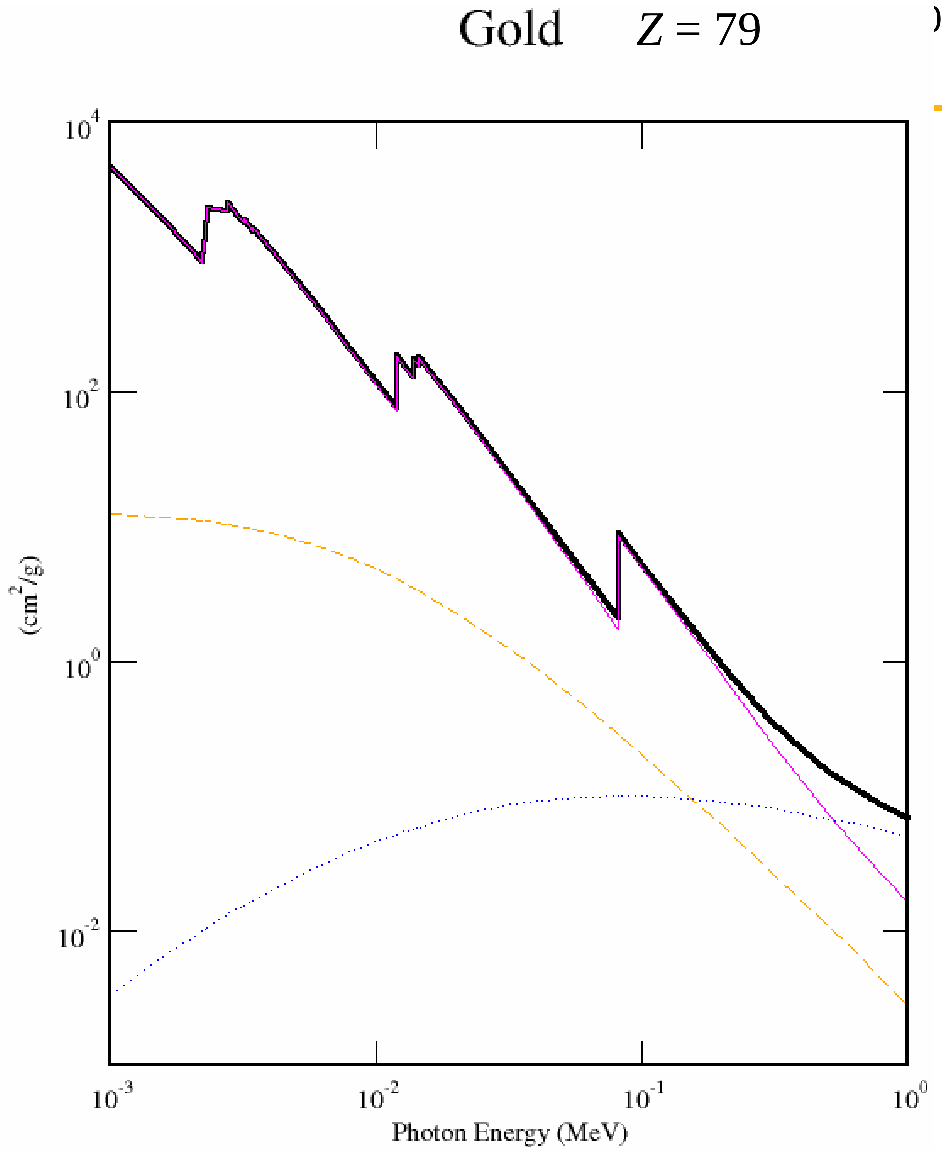
AgEr could be a better choice below 20 mK even if the RKKY interaction is stronger than for AuEr

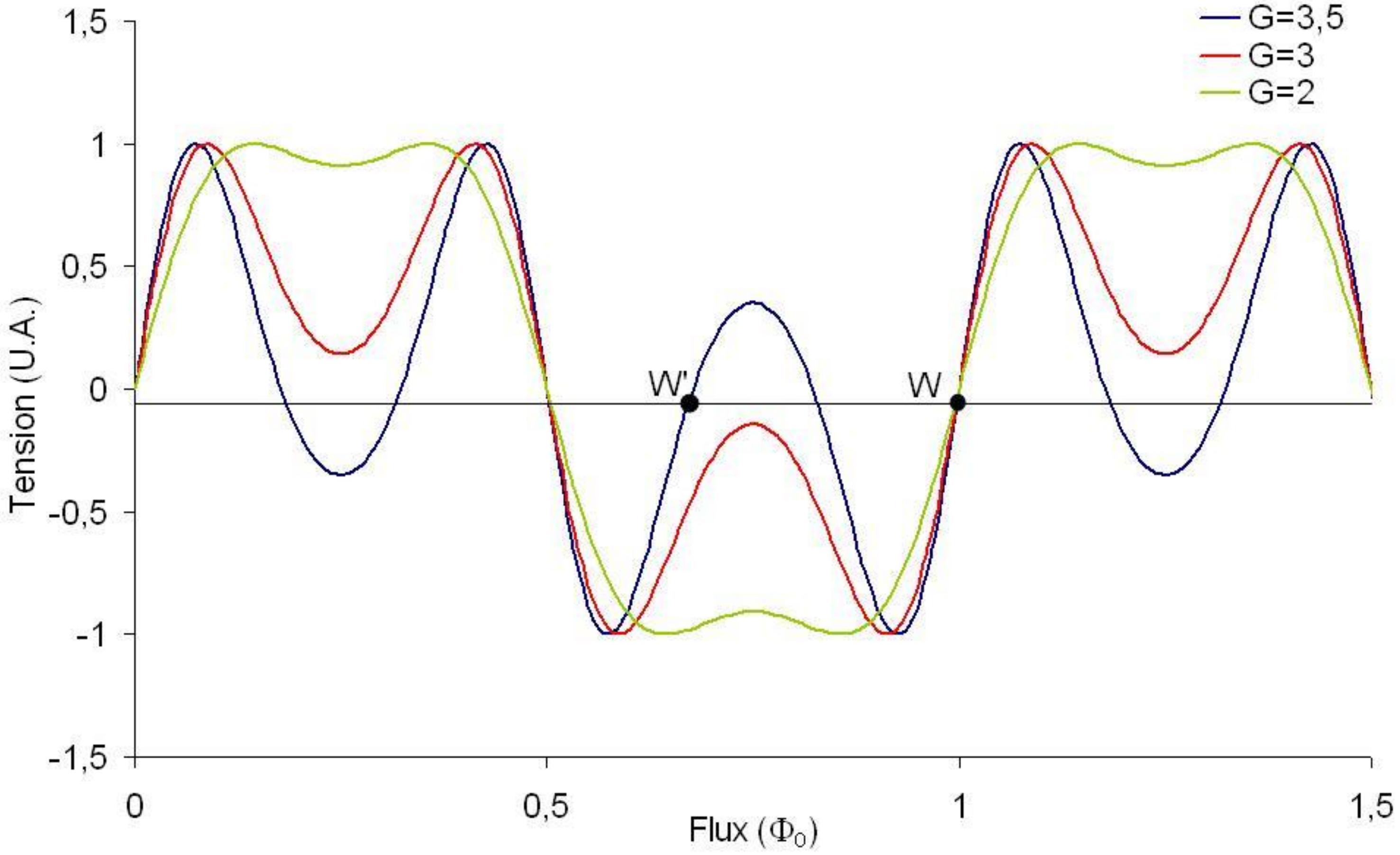

Silicon
sputter-deposition
Nb (400nm)
Silicon
spin coating
AZ 5214E
Silicon
exposuring
Silicon
developing
AZ 351B
Silicon
chemical etching
1 HF
6 HNO3
10 H20
Silicon
stripping
DMF
Silicon



The activity of the source was measured with a HPGe detector


Germanium Z = 32
(cm²/g)
10⁴
10²
10⁰
10⁻²
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
Photon Energy (MeV)


Gold Z = 79
(cm²/g)
10⁴
10²
10⁰
10⁻²
10⁻³
10⁻²
10⁻¹
10⁰
Photon Energy (MeV)


G=3,5
G=3
G=2
1,5
1
0,5
0
-0,5
-1
-1,5
Tension (U.A.)
W'
W
0
0,5
1
1,5
Flux (Φ_0)