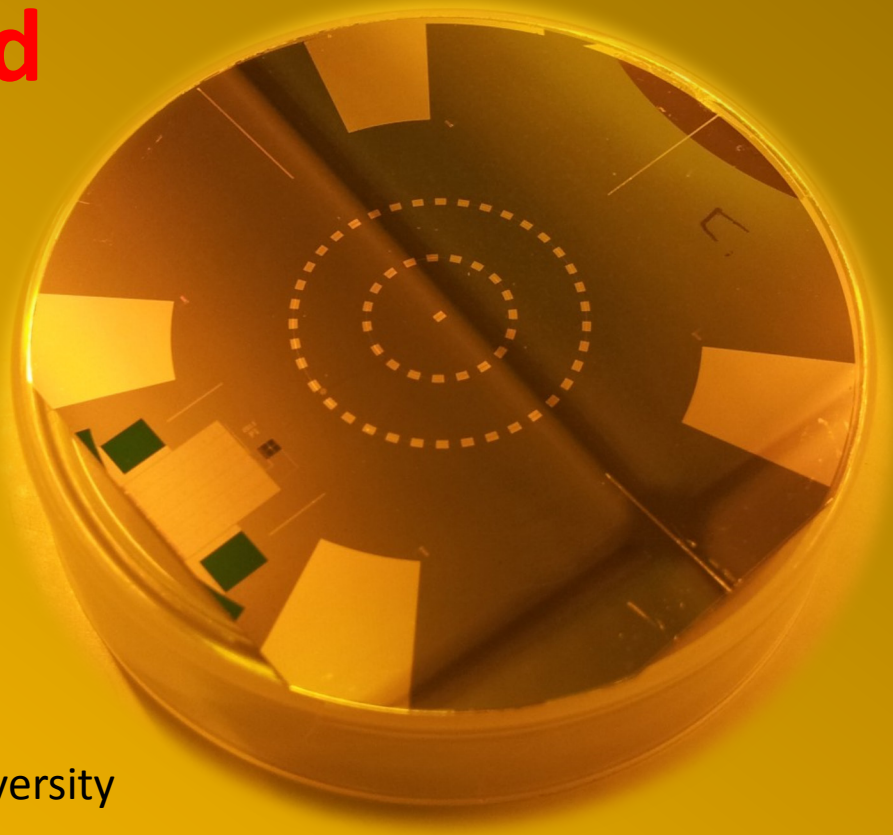
Integrated phonon and photon detector to search for rare events in scintillating crystals



Loredana Gastaldo
Kirchhoff Institute for Physics, Heidelberg University

LUMINEU

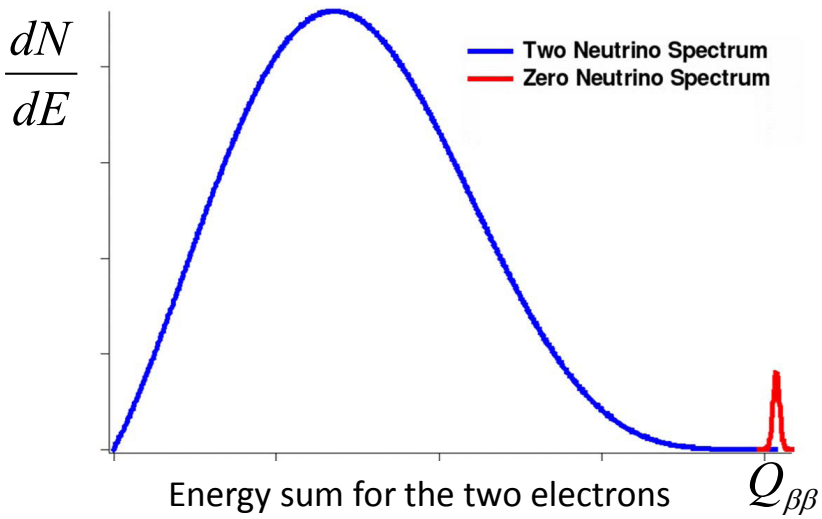
$\beta\beta\ 0\nu$

AMoRE

KIP, Uni-Heidelberg, Germany
CEA, Saclay, France
IBS, Daejon Republic of Korea

Neutrinoless double beta decay

If conservation rules don´t allow simple beta decay:



$2\nu\beta\beta$: $(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$\tau_{1/2} \geq 10^{19}$ years

If $\nu = \bar{\nu}$:

$0\nu\beta\beta$: $(A,Z) \rightarrow (A, Z+2) + 2e^-$

$\tau_{1/2} > 10^{25}$ years

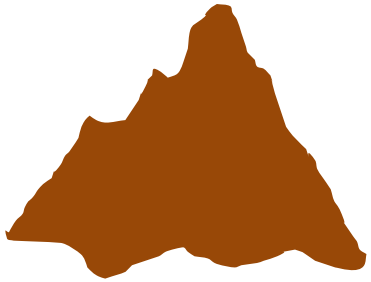
Measured for several nuclides

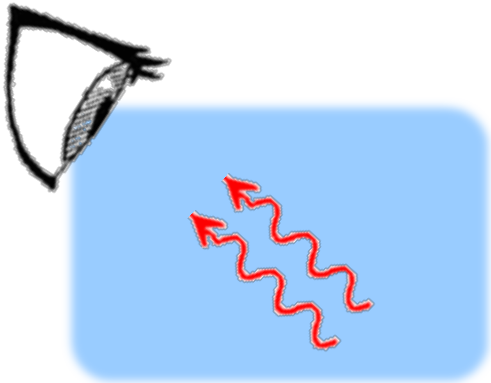
Never observed

Very rare events!

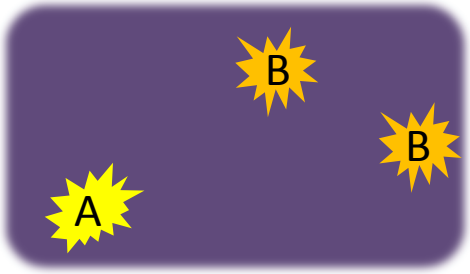
Fight against background

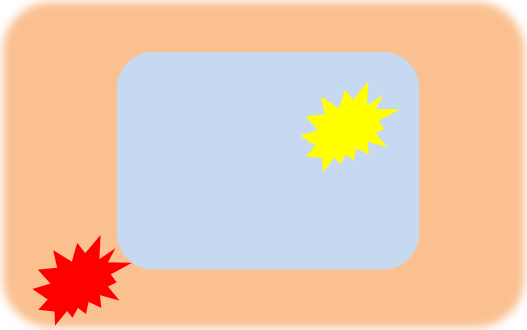
Direct reduction of background activity

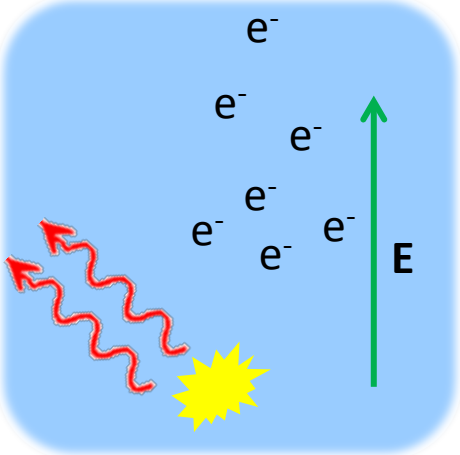


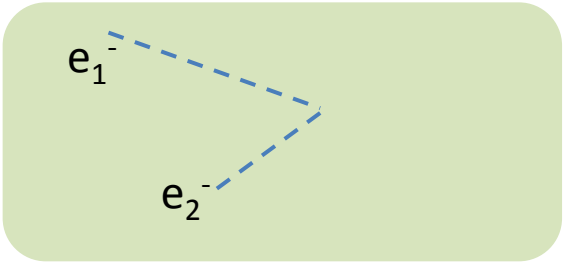


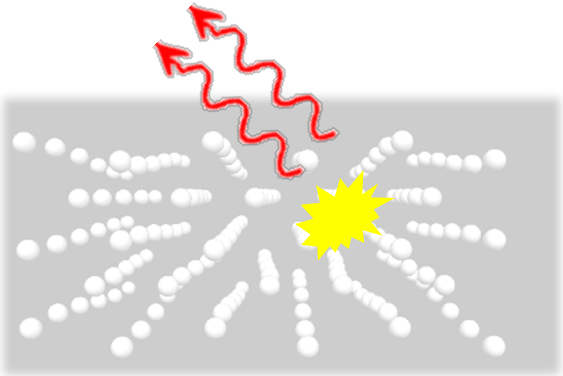
Discrimination techniques











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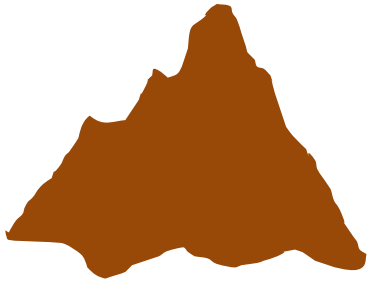
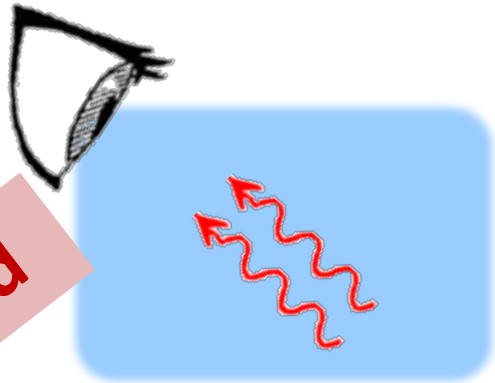
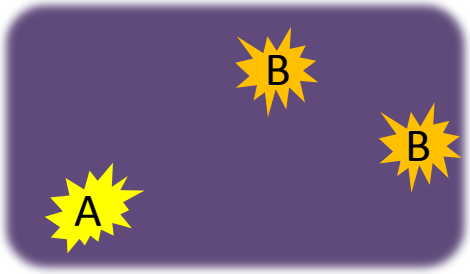
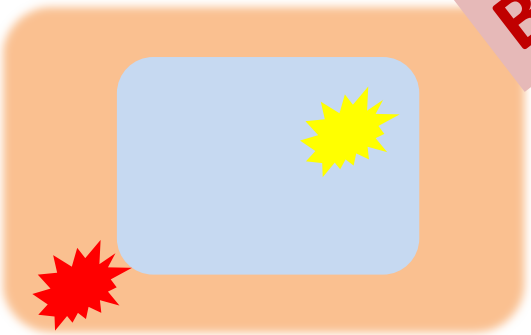


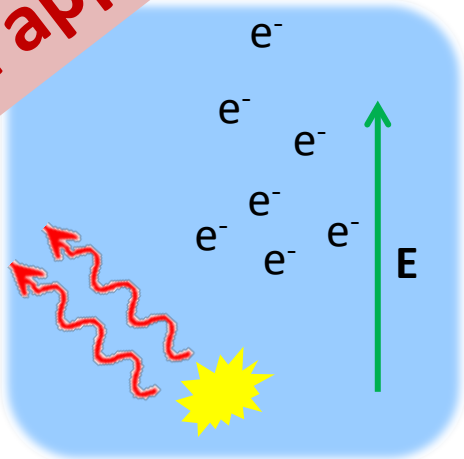


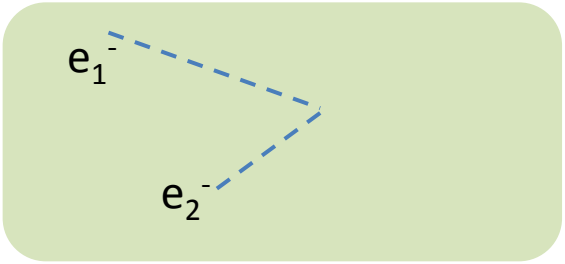
Both approaches are needed

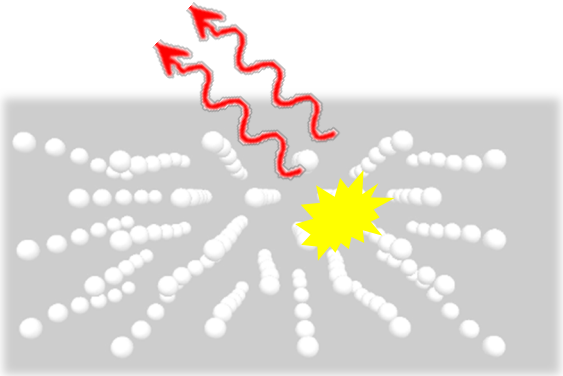
Discrimination techniques



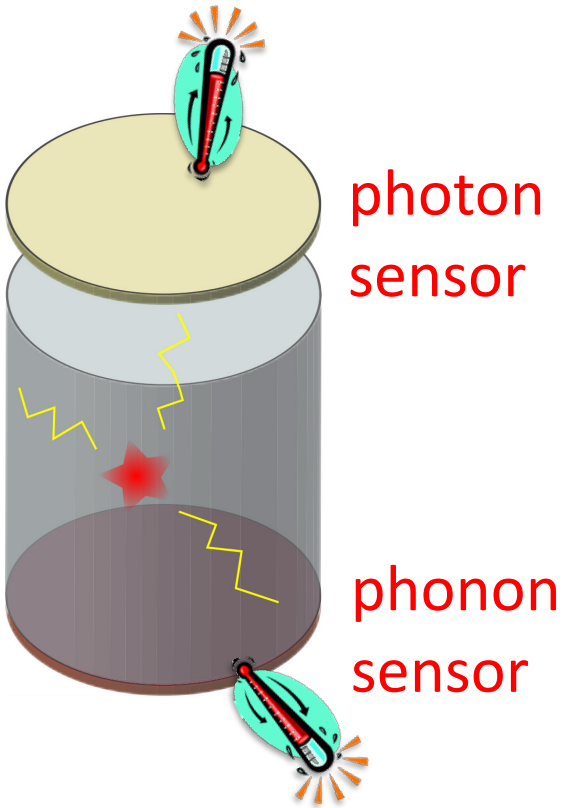


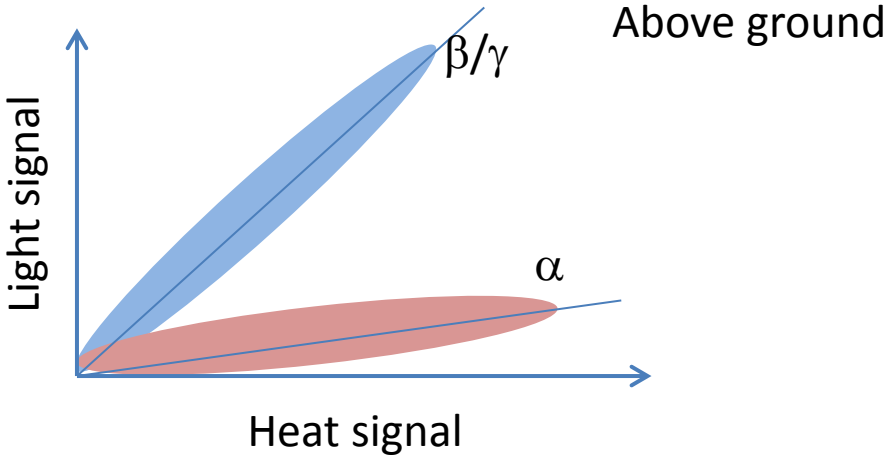




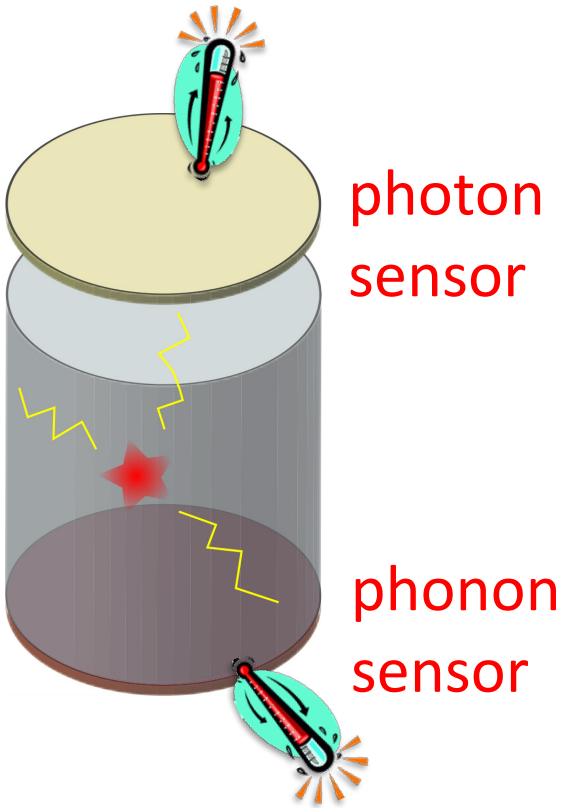


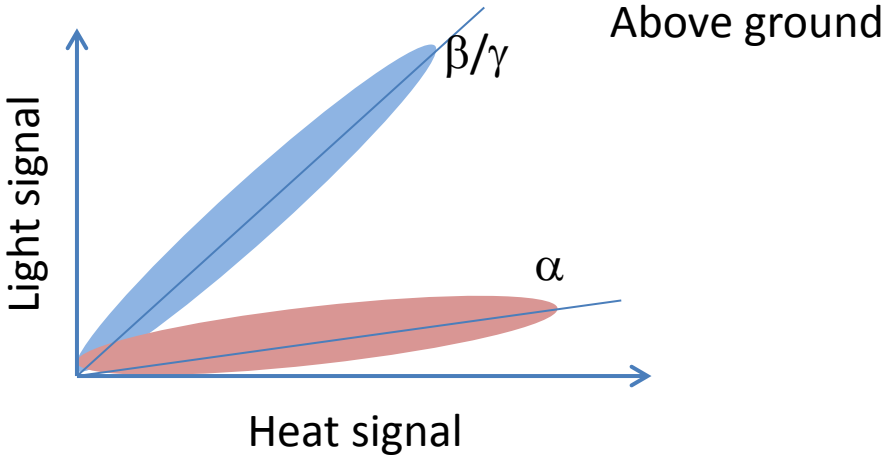
Promising technologies - Scintillating crystals

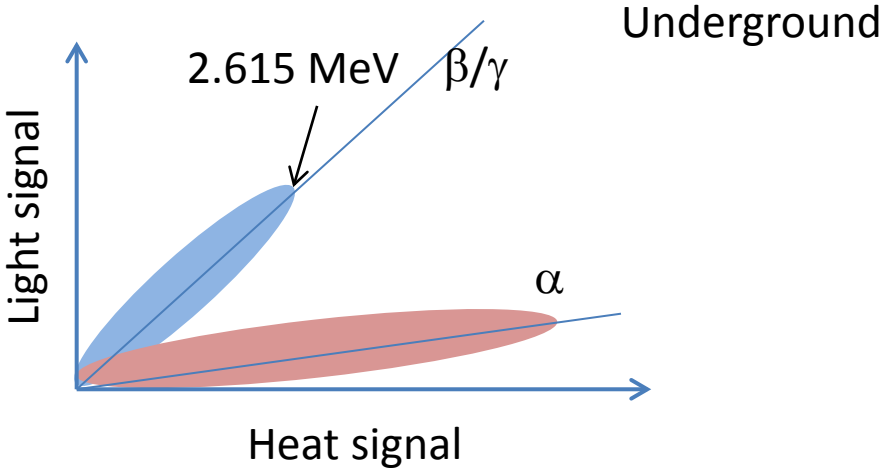




Promising technologies - Scintillating crystals

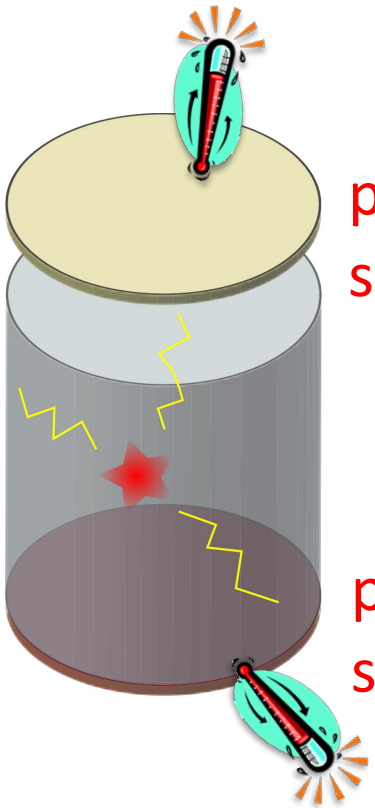






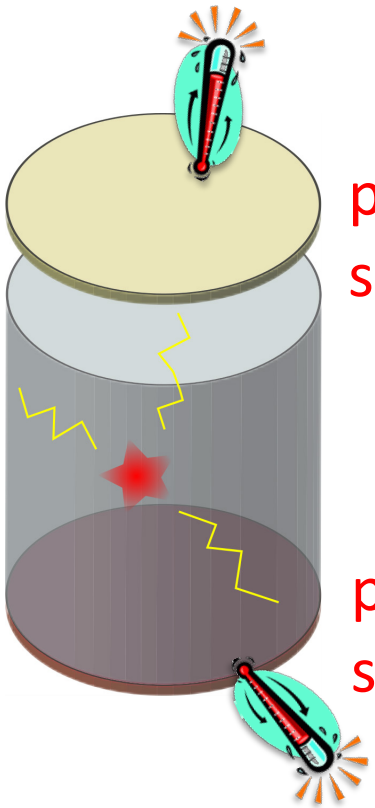
Background due to α particle can be removed

Promising technologies - Scintillating crystals



transition	$G^{01}(E_0, Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)
$^{150}Nd \rightarrow {}^{150}Sm$ ←	26.9	3.667	6
$^{48}Ca \rightarrow {}^{48}Ti$ ←	8.04	4.271	0.2
$^{96}Zr \rightarrow {}^{96}Mo$ ←	7.37	3.350	3
$^{116}Cd \rightarrow {}^{116}Sn$ ←	6.24	2.802	7
$^{136}Xe \rightarrow {}^{136}Ba$	5.92	2.479	9
$^{100}Mo \rightarrow {}^{100}Ru$ ←	5.74	3.034	10
$^{130}Te \rightarrow {}^{130}Xe$	5.55	2.533	34
$^{82}Se \rightarrow {}^{82}Kr$ ←	3.53	2.995	9
$^{76}Ge \rightarrow {}^{76}Se$	0.79	2.040	8

Promising technologies - Scintillating crystals



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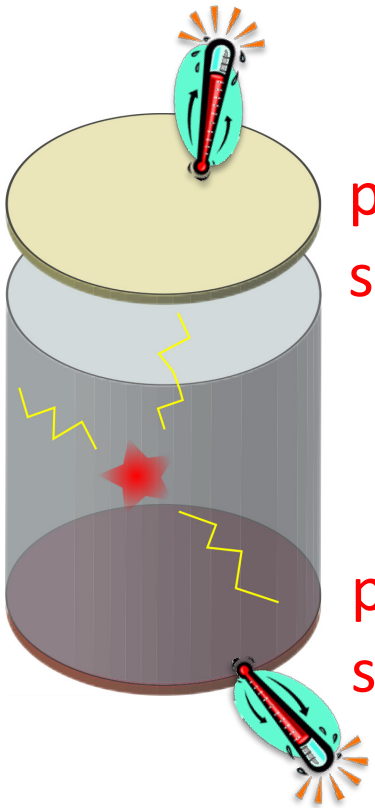
Temperature signal: $\Delta T \cong \dfrac{\Delta E_{phonon}}{C}$

Light signal is also detected as $\Delta T \cong \dfrac{\Delta E_{photon}}{C}$ of a suitable photon detector

Promising technologies - Scintillating crystals



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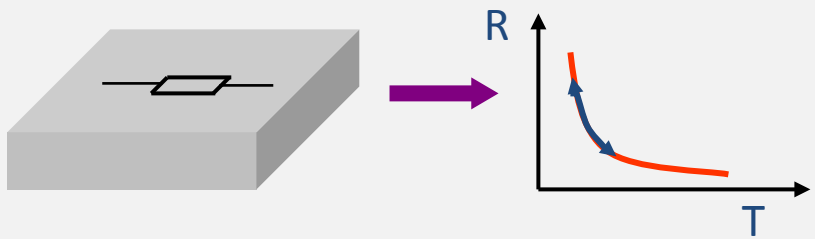
Low T thermal detectors are the best candidate for these measurements

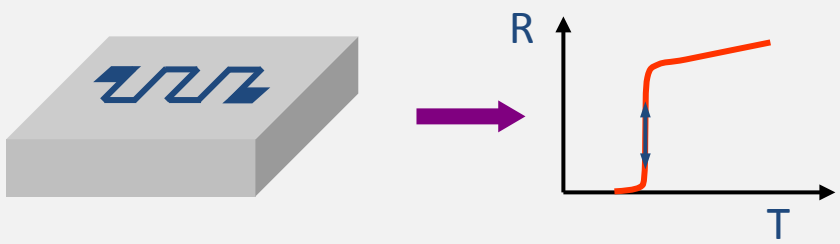
Temperature sensors

Resistance of highly doped semiconductors



- τ_{rise} ~ 1 ms
- τ_{decay} ~ 10 ms

Resistance at superconducting transition,TES



- τ_{rise} ~ 1 μs intrinsic
- τ_{decay} ~ ms intrinsic

Magnetization of paramagnetic material, MMC

- τ_{rise} < 1 μs intrinsic
- τ_{decay} ~ ms intrinsic

Scintillating crystal based experiments

$$^{82}Se \rightarrow {}^{82}Kr + 2e^- + (2\nu_e)$$

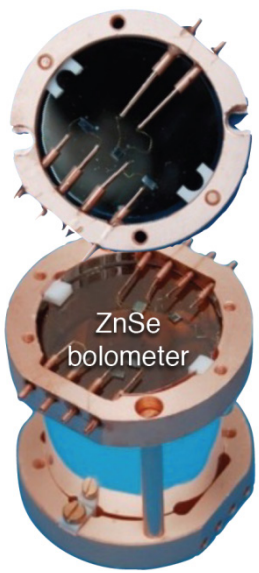
$$Q_{\beta\beta} = 2995 \text{ keV}$$

$$^{100}Mo \rightarrow {}^{100}Ru + 2e^- + (2\nu_e)$$

$$Q_{\beta\beta} = 3034 \text{ keV}$$

LUCIFER

ZnSe

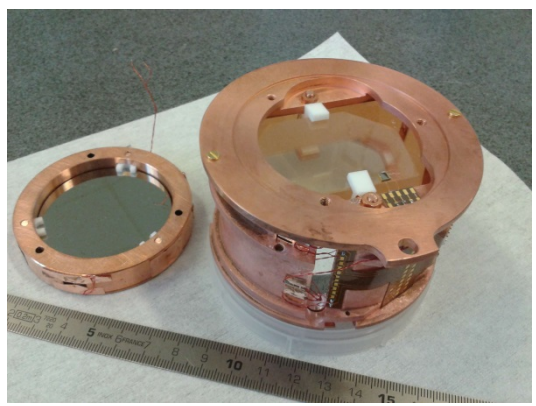


NTD-Ge baseline for photon and phonon channel

LUCIFER, http://arxiv.org/abs/1303.4080
JINST 8 (2013) P05021

LUMINEU

$ZnMoO_4$, $LiMoO_4$

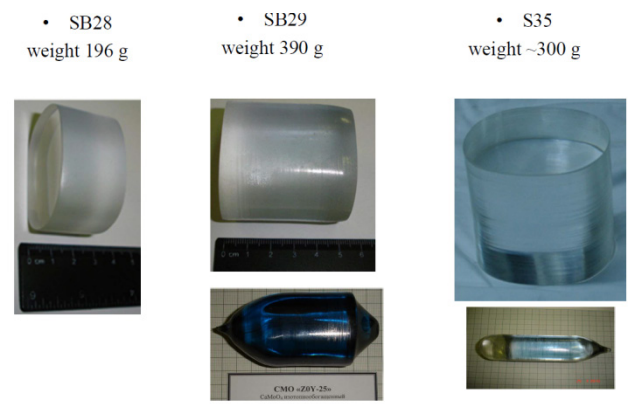


NTD-Ge baseline for photon and phonon channel
MMC R&D for photon channel

LUMINEU arXiv:1704.01758
Submitted to EPJC

AMoRE

$CaMoO_4$



MMC for photon and phonon channel

Technical Design Report for the AMoRE 0*νββ* Decay Search Experiment
arXiv:1512.05957 [physics.ins-det]

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LUCIFER

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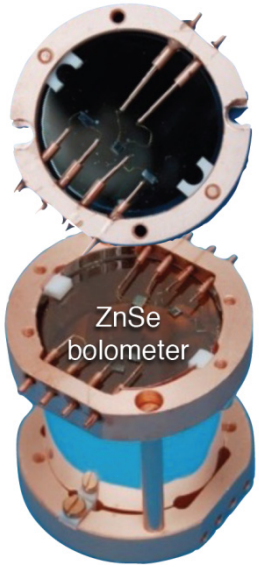

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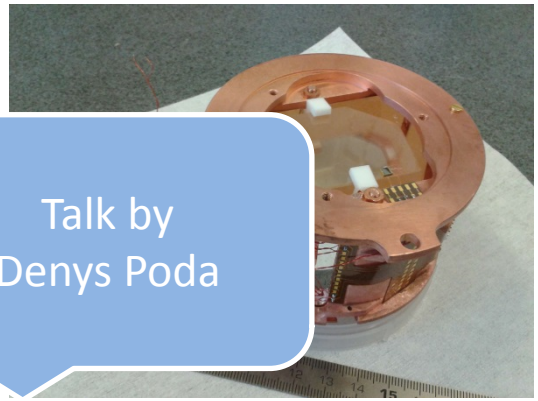

Talk by
Denys Poda

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LUCIFER

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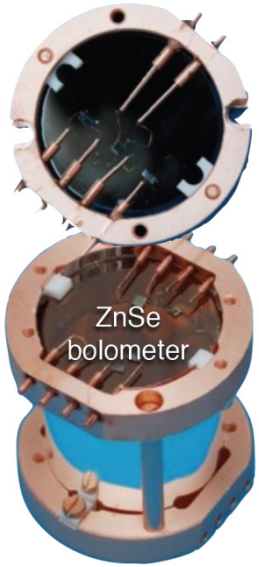

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LUMINEU

$ZnMoO_4$, $LiMoO_4$

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Denys Poda

NTD-Ge
and pho
MMC R&D fo photon channel

CUPID
Talk by
Ezio Previtali

LUMINEU arXiv:1704.01758
Submitted to EPJC

AMoRE

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Talk by
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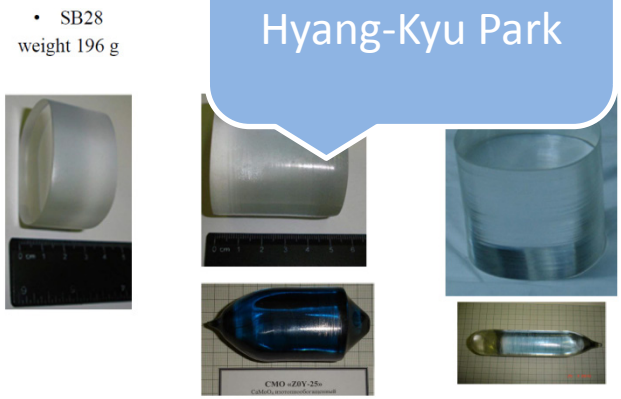

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LUCIFER

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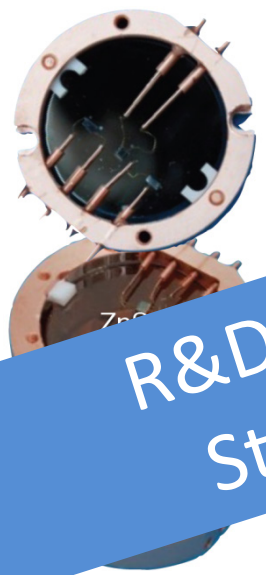

LUMINEU

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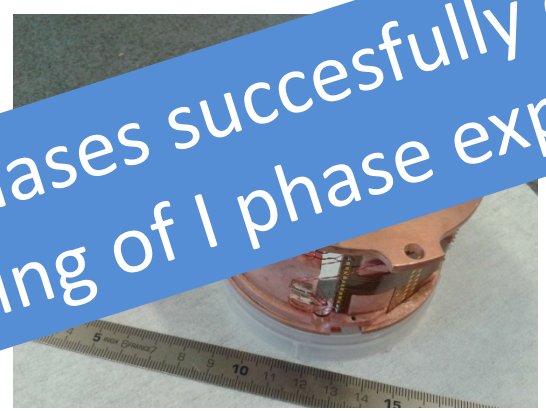

AMoRE

R&D phases succesfully concluded
Starting of I phase experiments

NTD-Ge baseline for photon and phonon channel

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MMC R&D for photon channel

MMC for photon and phonon channel

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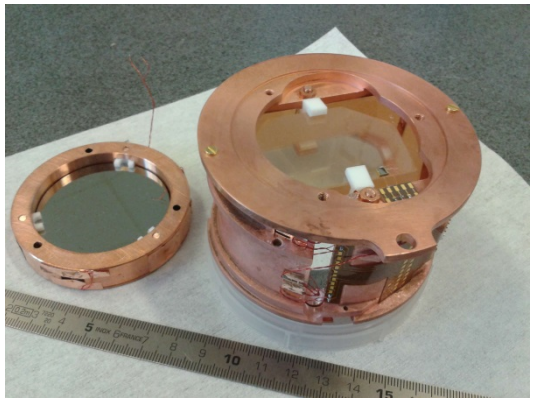
Detector performance

LUMINEU

$ZnMoO_4$, $LiMoO_4$



$$\tau_r^{light} = 2.3 - .. - 5.2 \text{ ms}$$

$$\tau_d^{light} = 2.6 - .. - 24 \text{ ms}$$

$$\tau_r^{heat} = 6.4 - .. - 38 \text{ ms}$$

$$\tau_d^{heat} = 18 - .. - 414 \text{ ms}$$

$$\Delta E_{FWHM}^{2615keV} = 3.8 - .. - 22 \text{ keV}$$

NTD-Ge baseline for photon and phonon channel
MMC R&D for photon channel

LUMINEU arXiv:1704.01758
Submitted to EPJC

Detector performance

$$\tau_r^{light} \approx 0.2 \text{ ms}$$

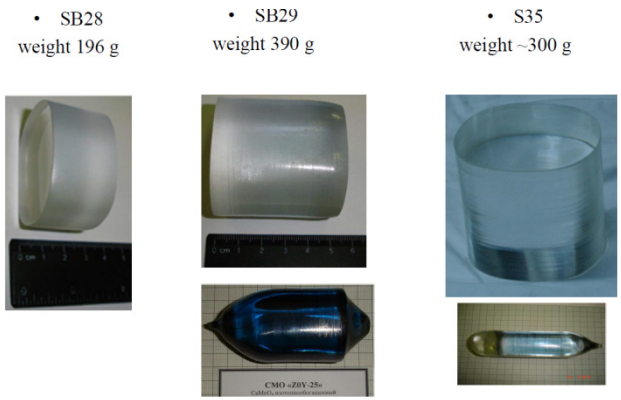
$$\tau_d^{light} \approx 4 \text{ ms}$$

$$\tau_r^{heat} \approx 1 \text{ ms}$$

$$\Delta E_{FWHM}^{2615keV} \approx 11 \text{ keV}$$

AMoRE

$CaMoO_4$



MMC for photon and phonon channel

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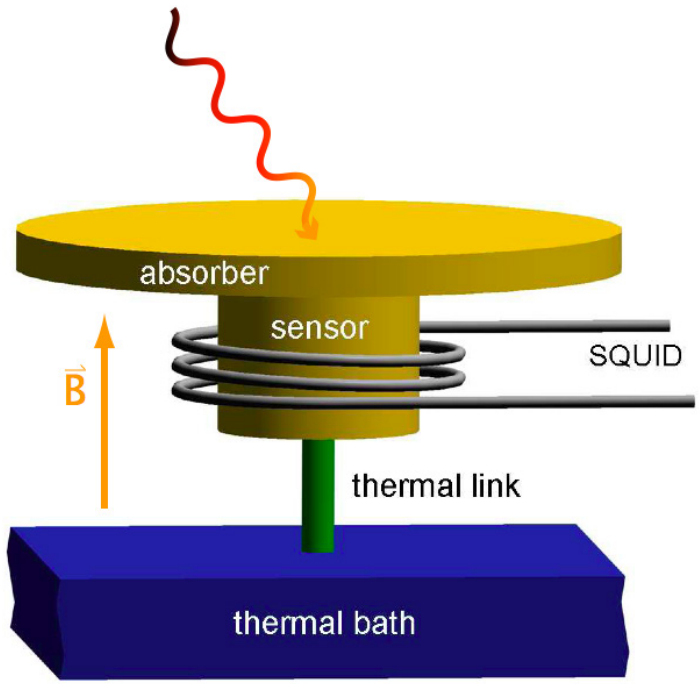
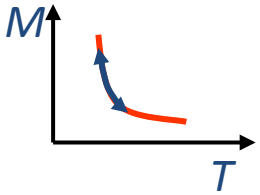
Metallic Magnetic Calorimeters - MMC



Paramagnetic sensor: **Au**:Er_{500ppm}



Signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$

main differences to calorimeters with resistive thermometers

no dissipation in the sensor

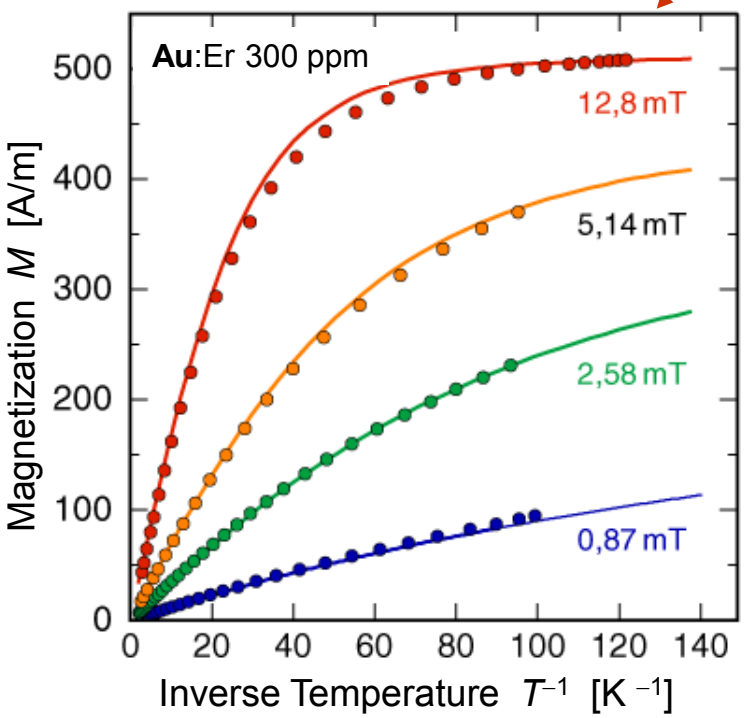
no galvanic contact to the sensor

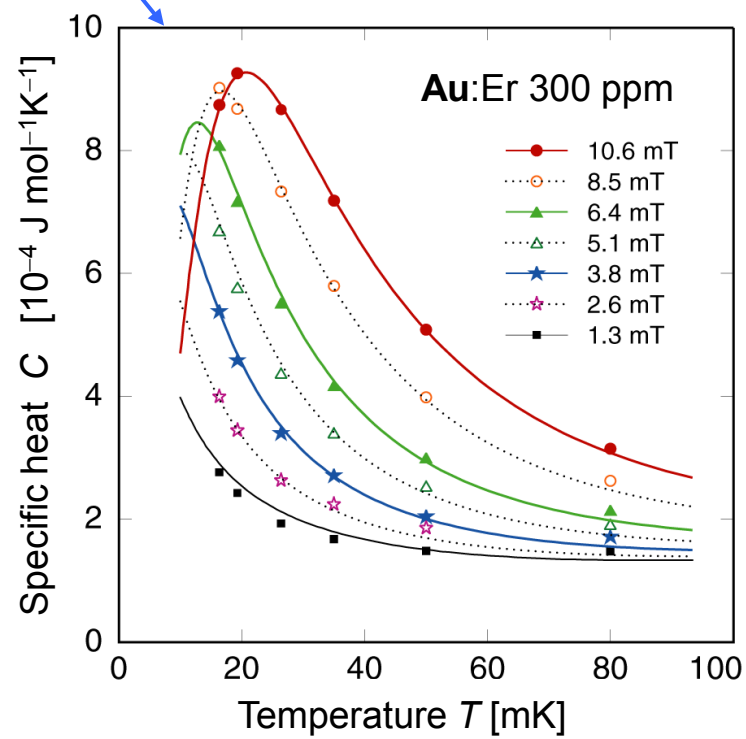
A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

MMC: signal size

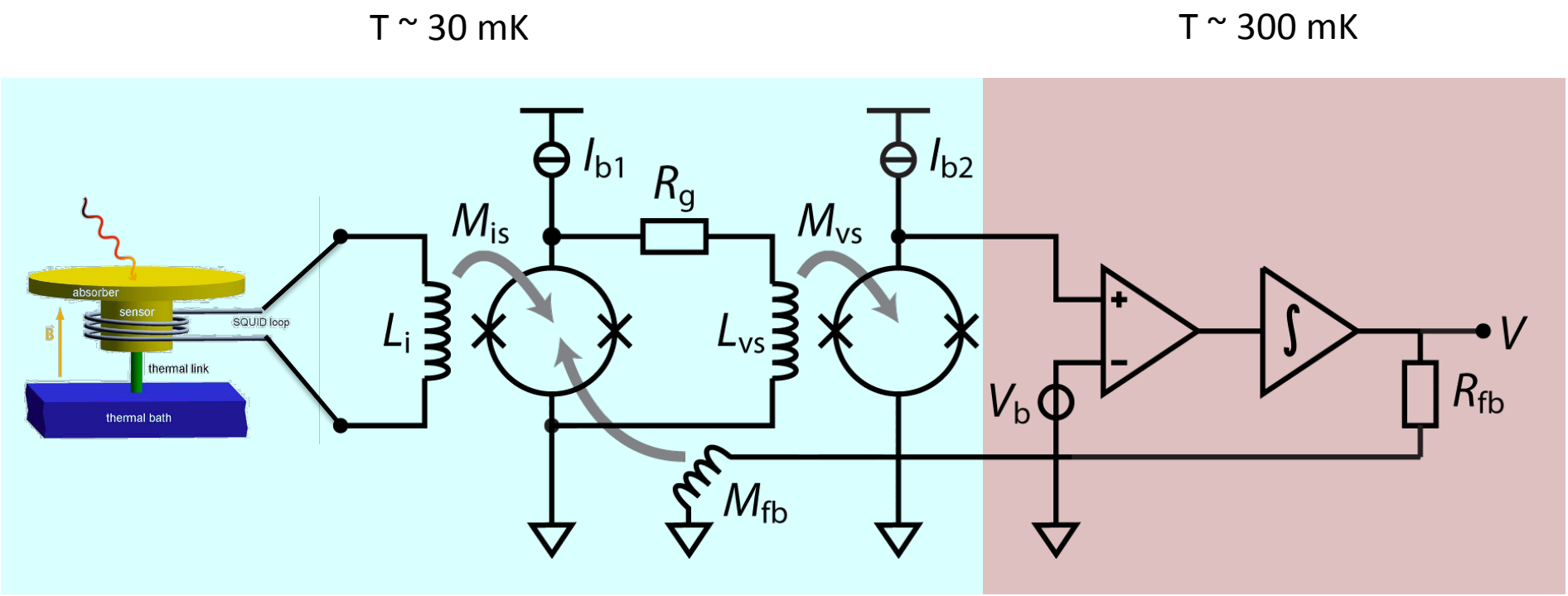
Numerical calculations based on mean field approximation are used to describe thermodynamical properties of interacting spins (RKKY)

$$\delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{1}{C_{tot}}\delta E$$





MMCs: Readout

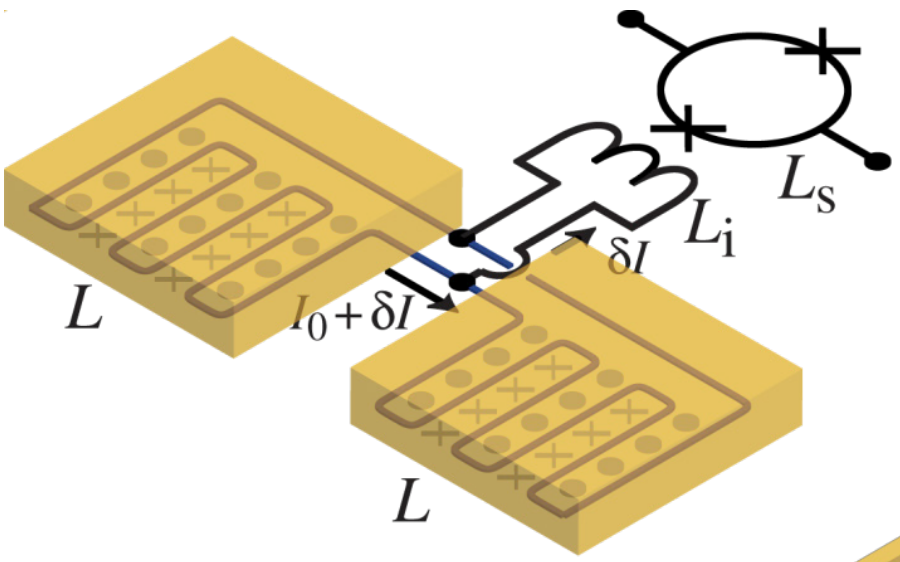


Two-stage SQUID setup with flux locked loop allows for:

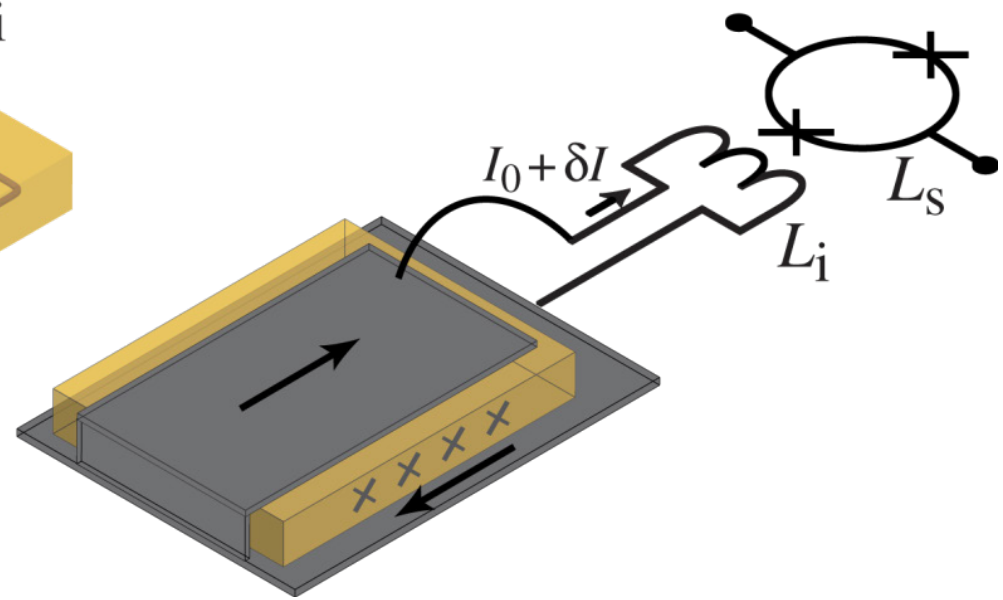
- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)

MMCs: Planar Geometries

- Planar temperature sensor
- B-field generated by persistent current
- transformer coupled to SQUID



Sandwich design:
Filling factor ~1



Meander-shaped pick-up coil:
Filling factor ~0.5

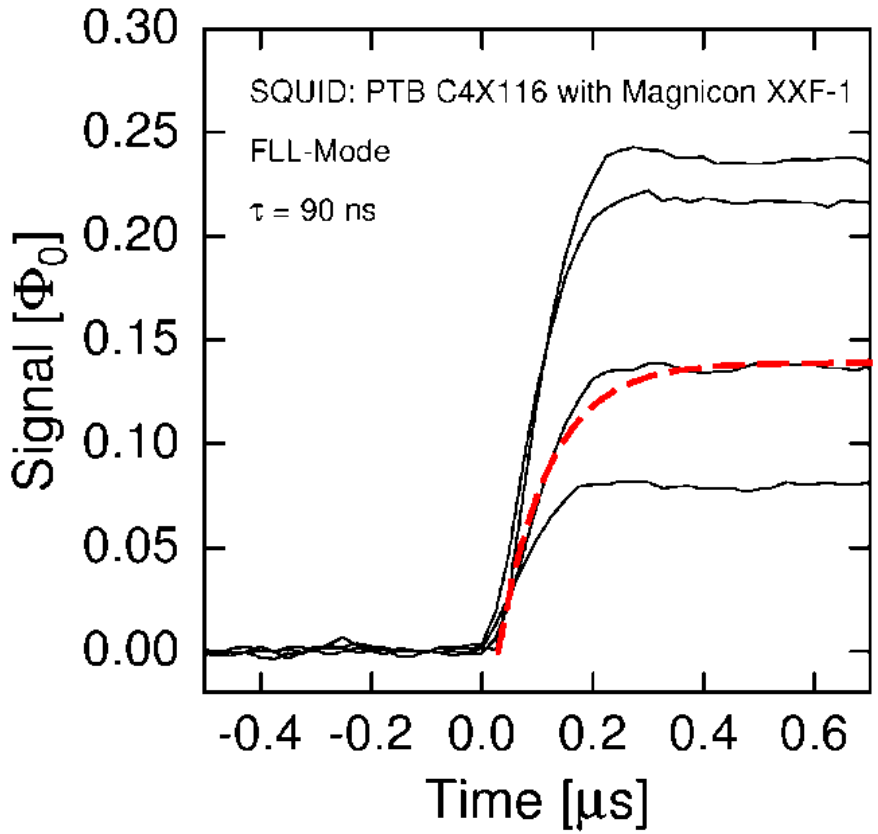
maXs20: 1d-array for soft x-rays

- **rise time: 90 ns** @ 30 mK,

  as expected for the **spin-electron-relaxation**

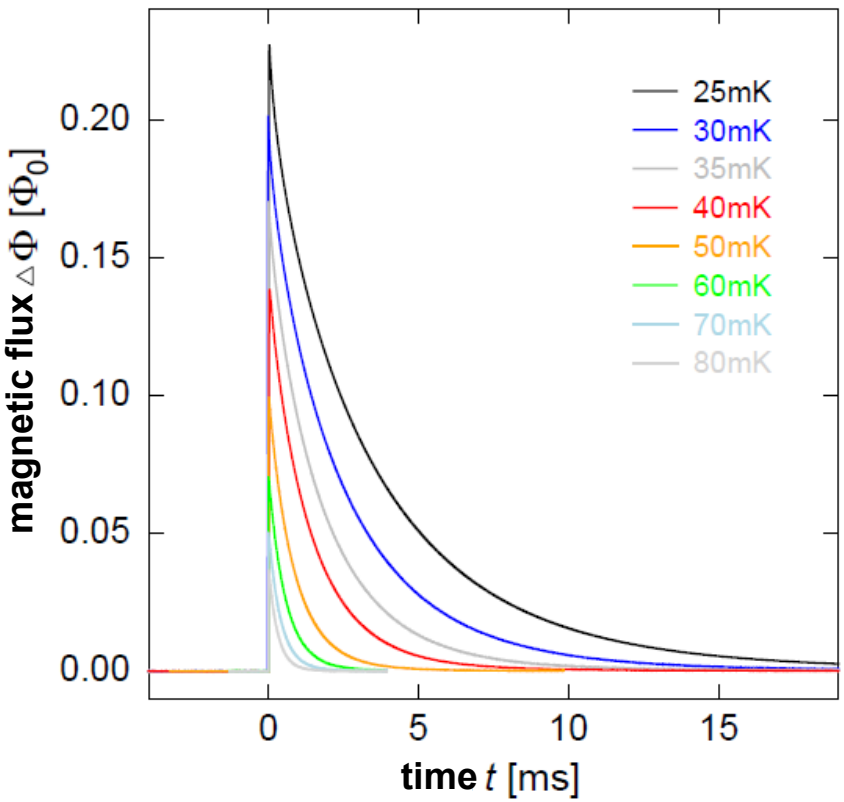
  from Korringa-constant of Er in Au

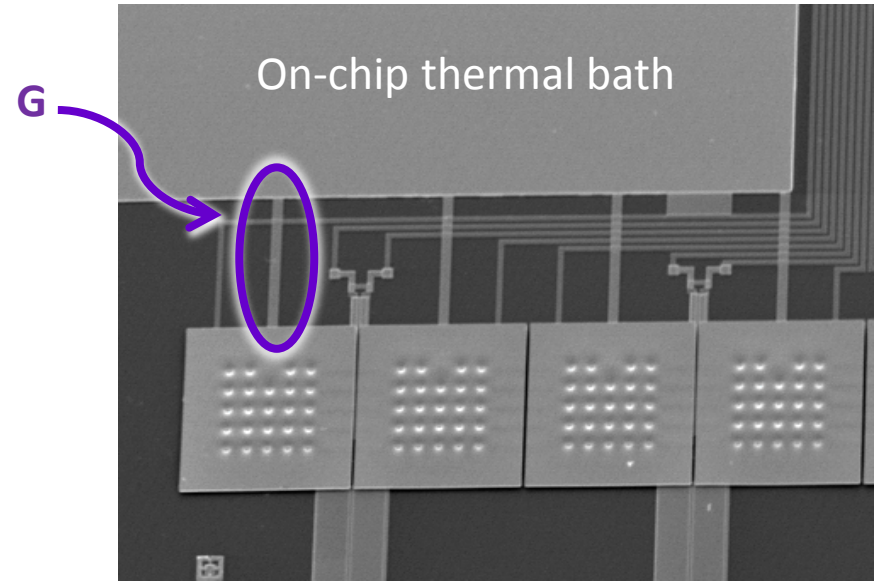
Fastest rise-time among µ-cal for x-ray detection



maXs20: 1d-array for soft x-rays

- **decay time** here: **3 ms @ 30 mK**
- nearly single exponential decay



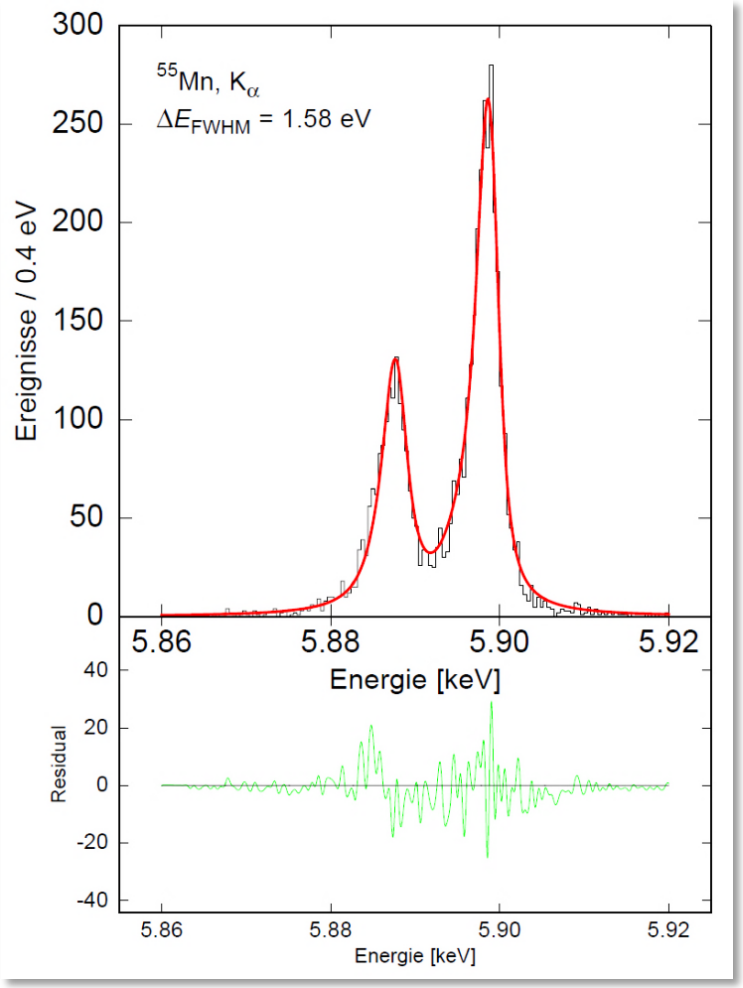


adjusted by sputtered thermal link (Au)

maXs20: 1d-array for soft x-rays (*T*=20 mK)

- Very good energy resolution

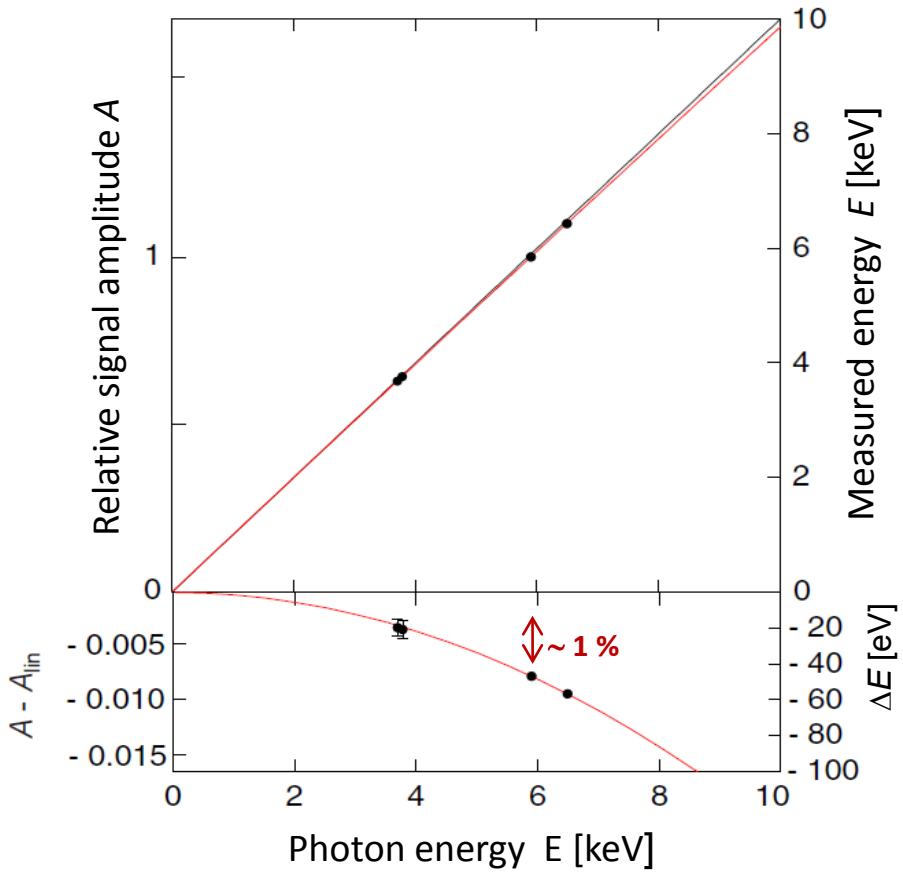
ΔE_{FWHM}= 1.6 eV @ 6 keV



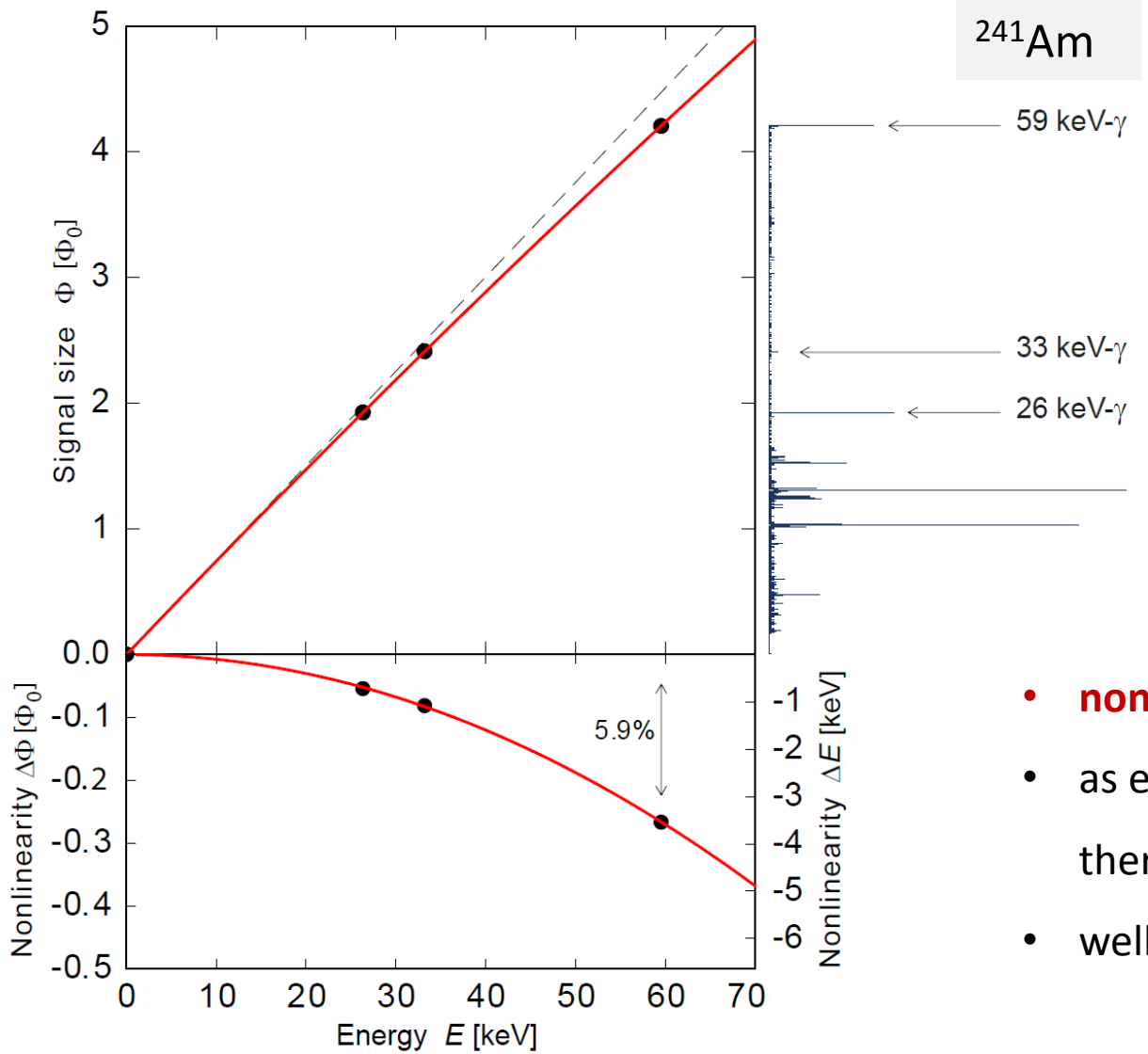
maXs20: 1d-array for soft x-rays

- **non-linearity: 1%** at **6 keV**
- as expected from thermodynamical properties
- well described by quadratic term

The energy scale is defined with high precision



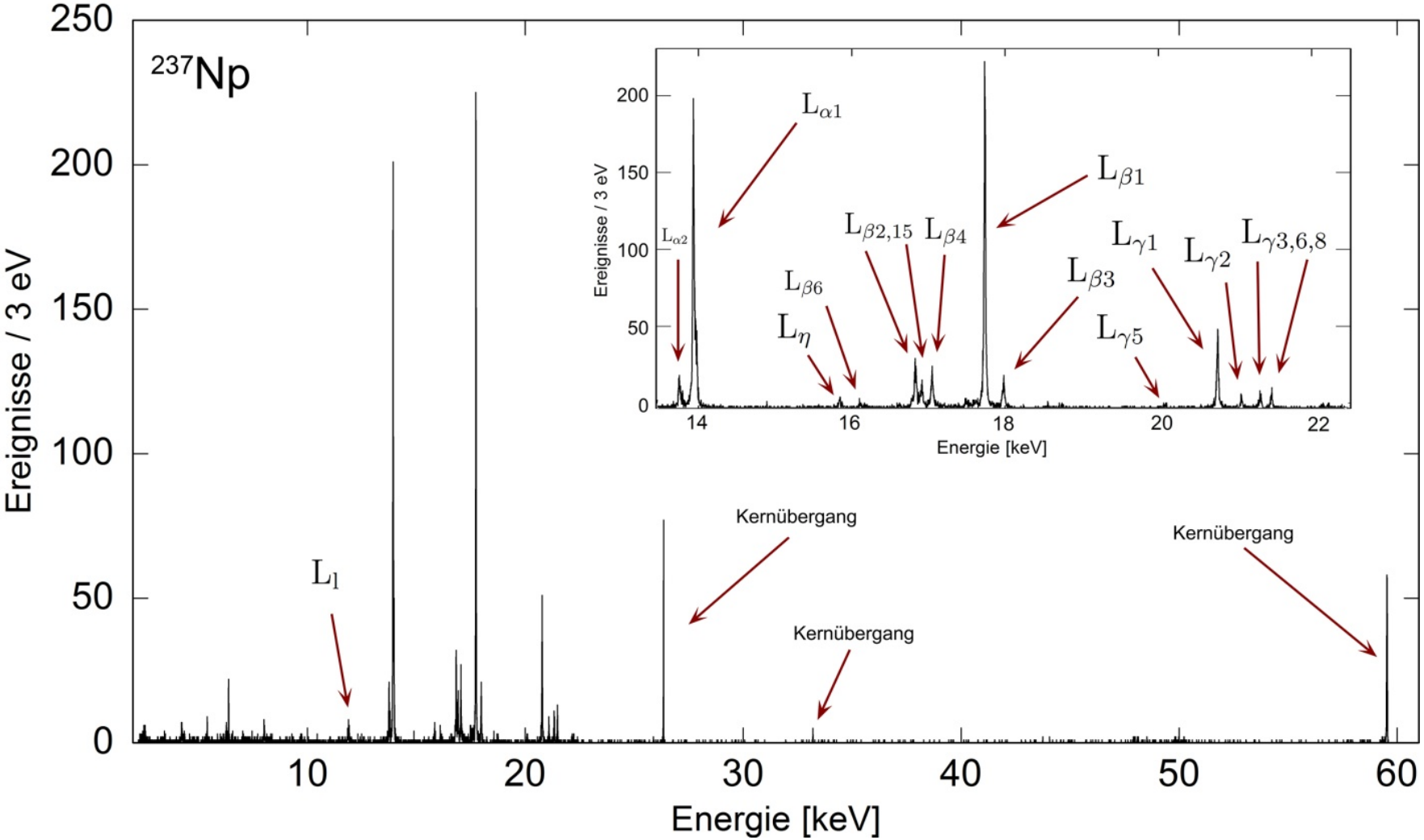
maXs20: 1d-array for soft x-rays



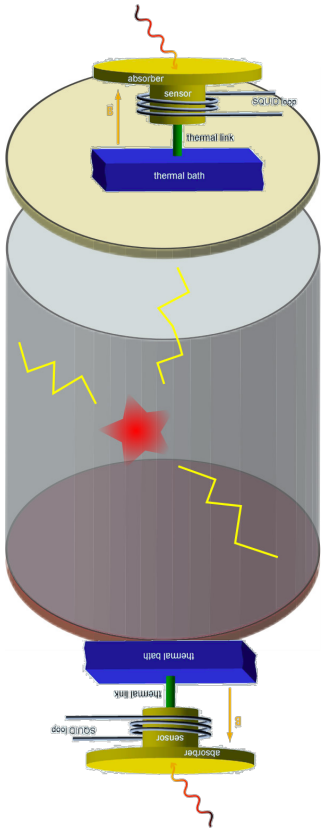
- **non-linearity: 6% at 60 keV**
- as expected from thermodynamical properties
- well described by quadratic term

maXs20: 1d-array for soft x-rays (*T*=20 mK)

- Large dynamic range



Scintillating crystals with MMCs



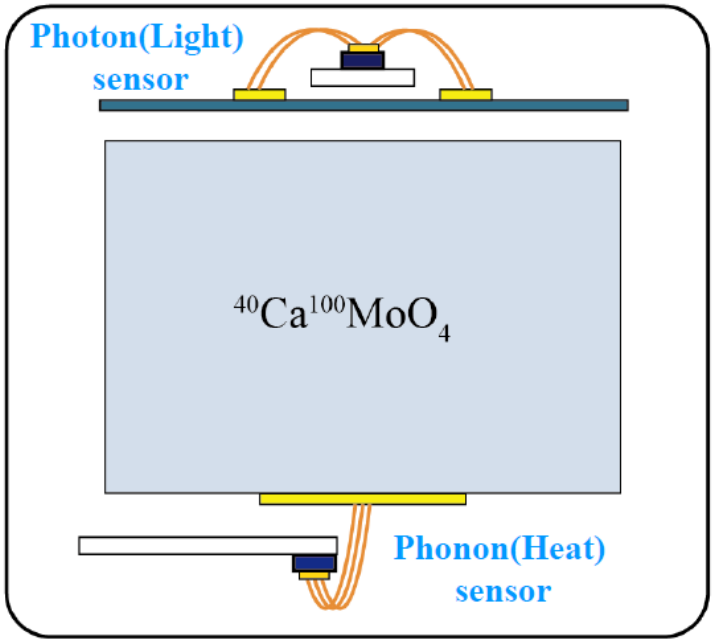
photon sensor

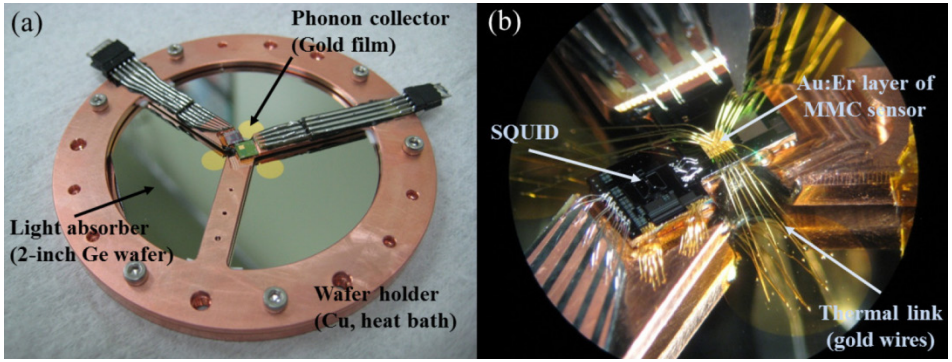
phonon sensor

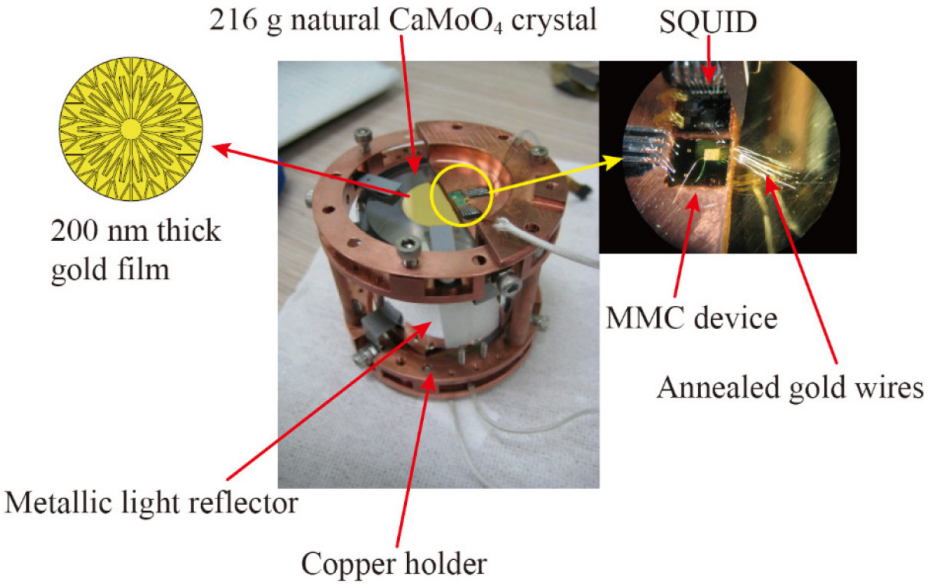
- How to couple MMC to scintillating crystals
- Learn how the thermalization of energy in the crystal affects the detector response

Approach used in AMoRe

Technical Design Report for the
AMoRE 0*νββ* Decay Search Experiment
arXiv:1512.05957 [physics.ins-det]







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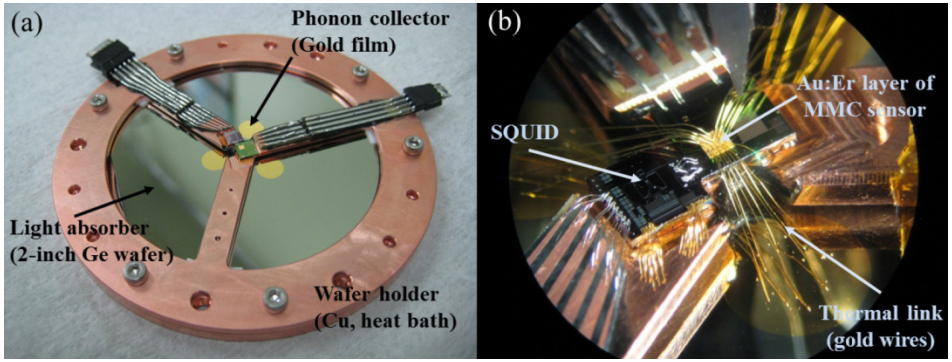
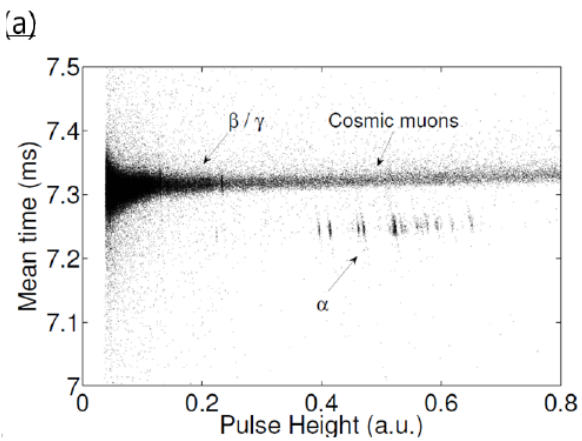
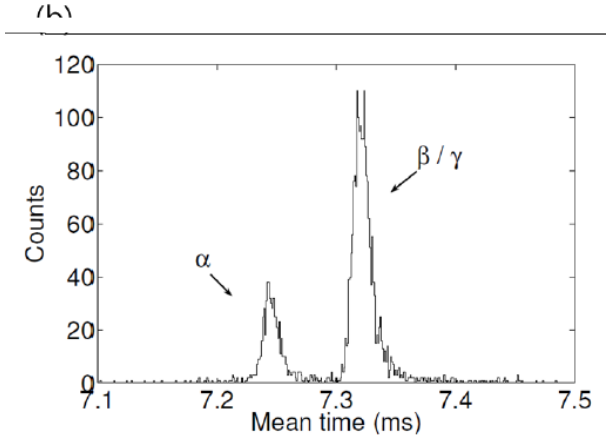
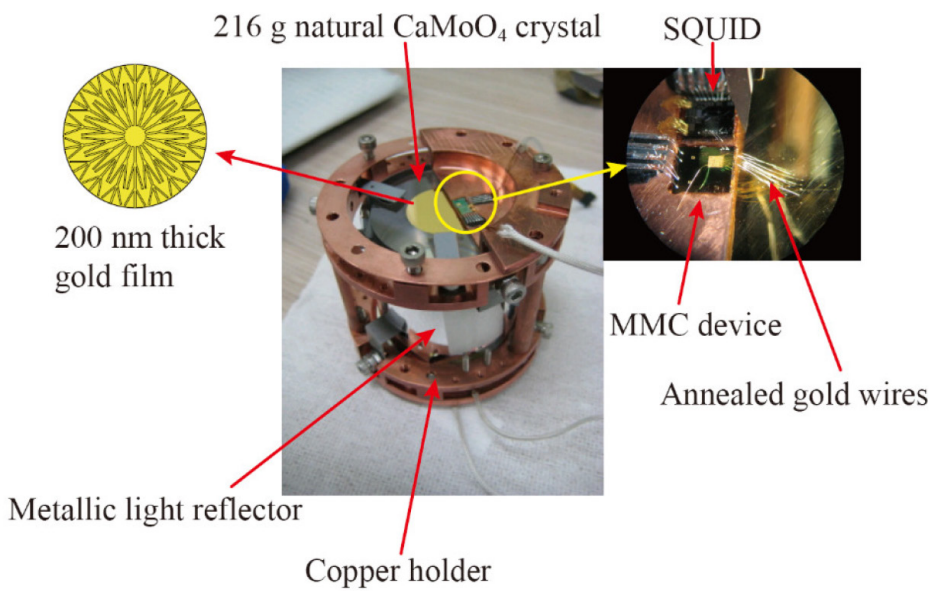


545 eV @ 6 keV



11 keV @ 2615 keV
6.5 keV @ 583 keV



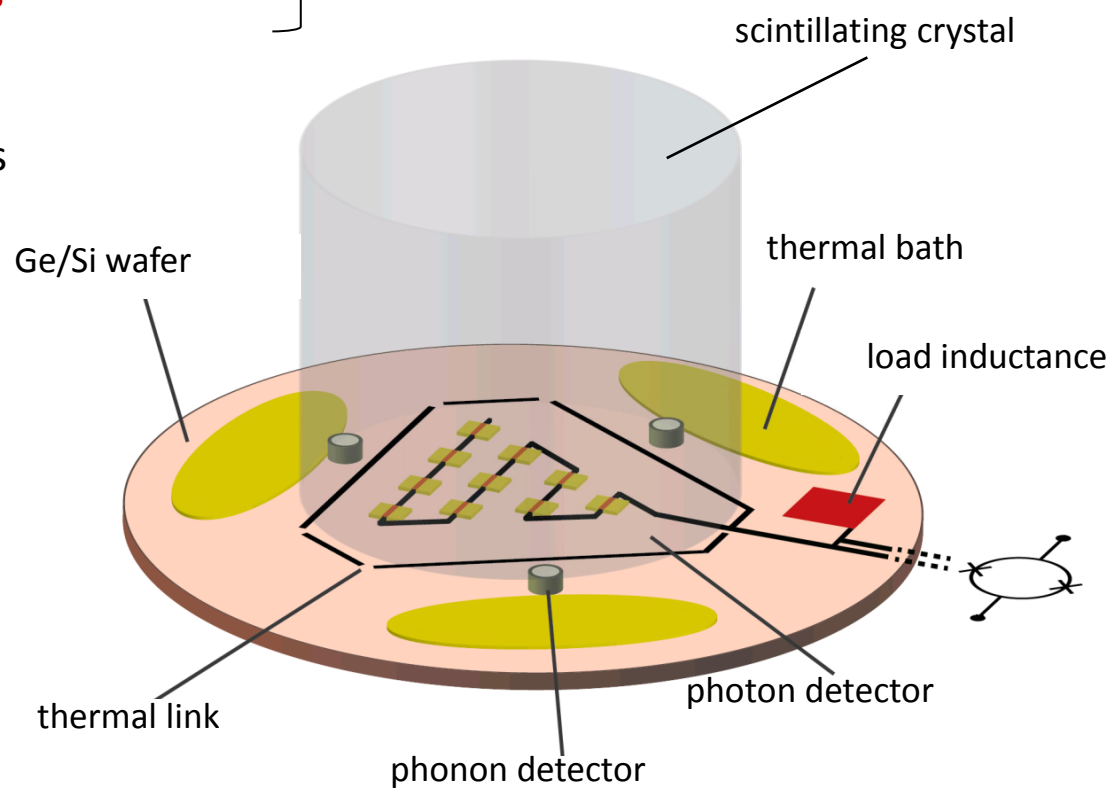


Combined Photon and Phonon Detector: P2

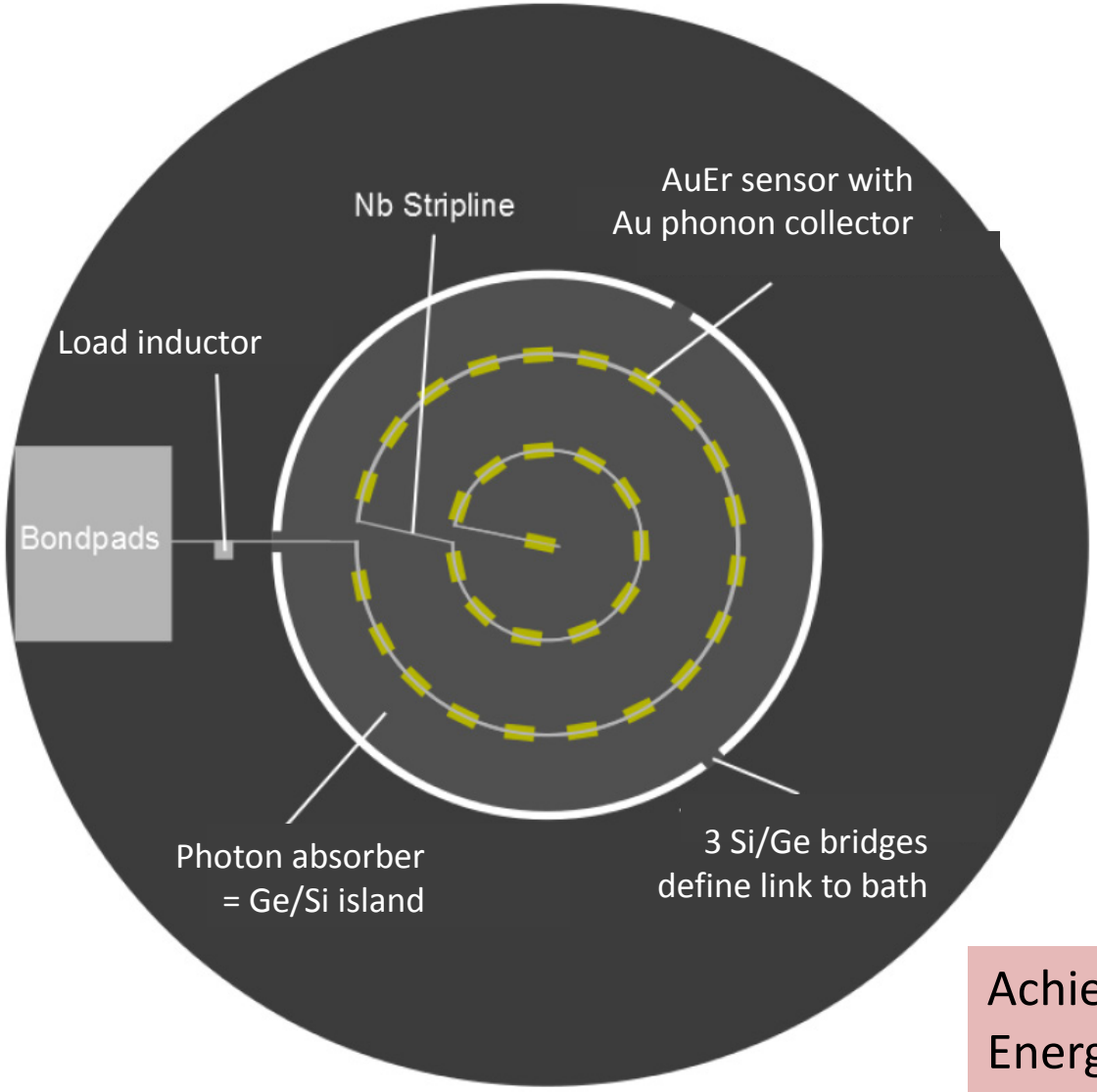
- Phonon detector:
  - energy resolution $\Delta E_{FWHM} < 100$ eV
  - rise time $\tau < 200$ µs
- Photon detector:
  - energy resolution $\Delta E_{FWHM} < 10$ eV
  - rise time $\tau < 50$ µs

Substrate: Ge or Si 3‘‘ wafer

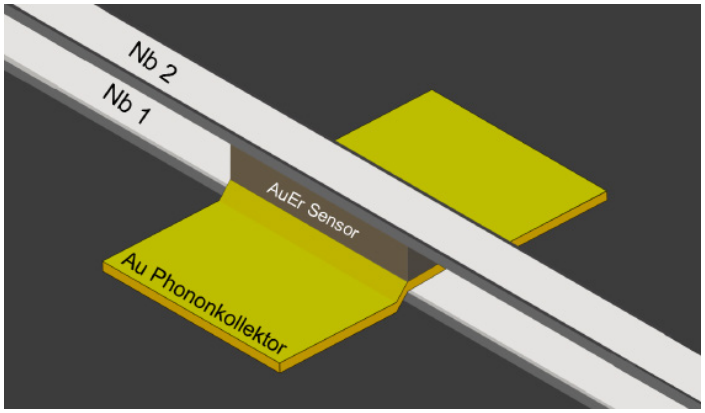
- A minimum of (contaminated?) parts
- Position sensitivity possible



MMC-based photon detector



Substrate: Ge or Si
2´´ wafer

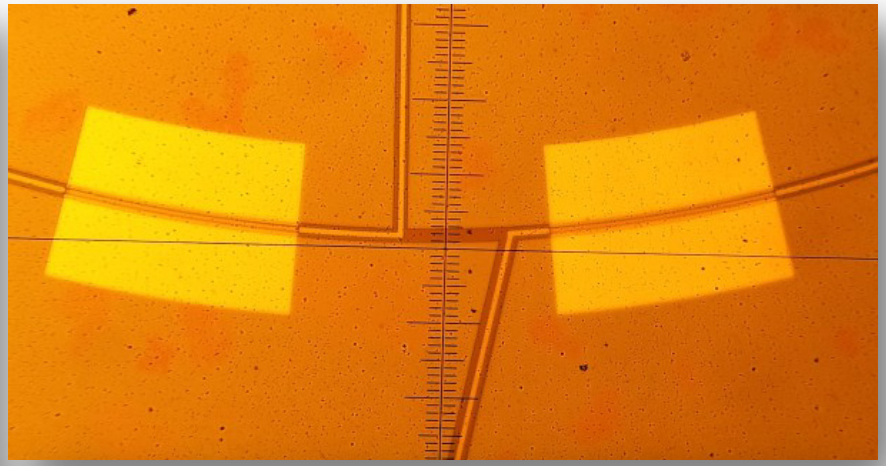


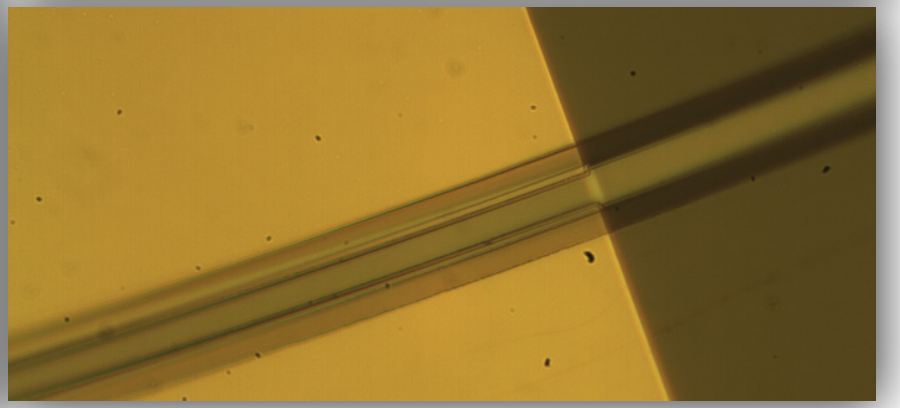
Achievable:

Energy resolution $\Delta E_{FWHM} < 10$ eV

Rise time $\tau_R < 50$ µs

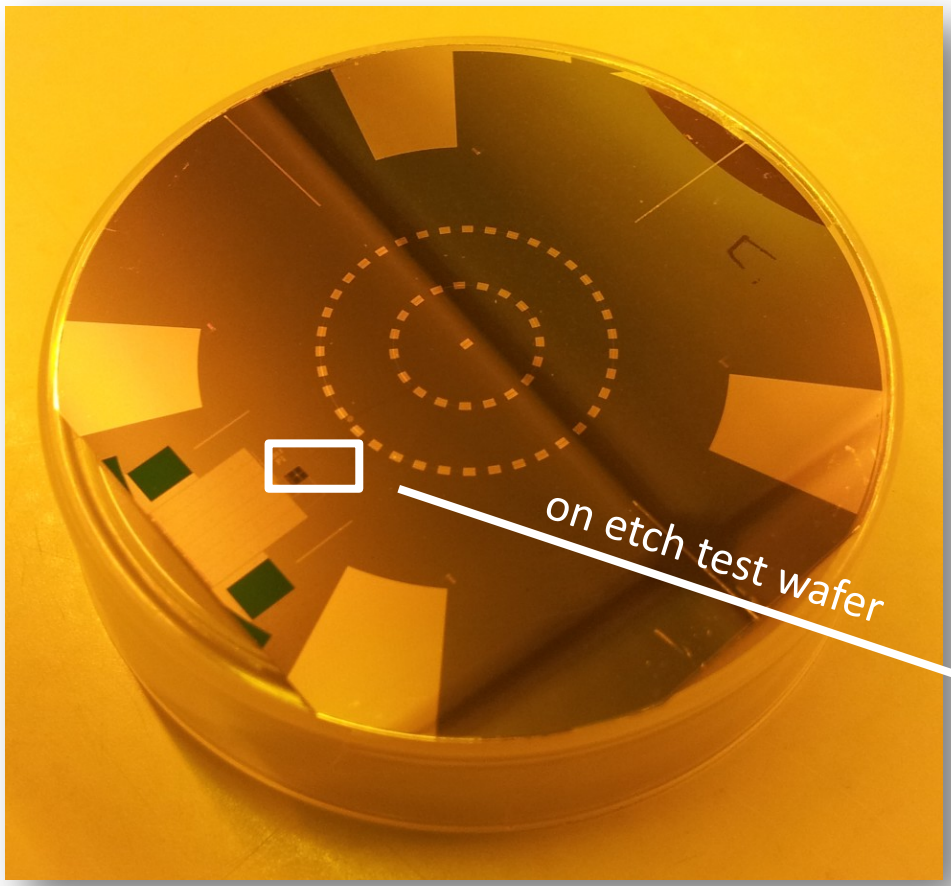
MMC-based photon detector: P1 design

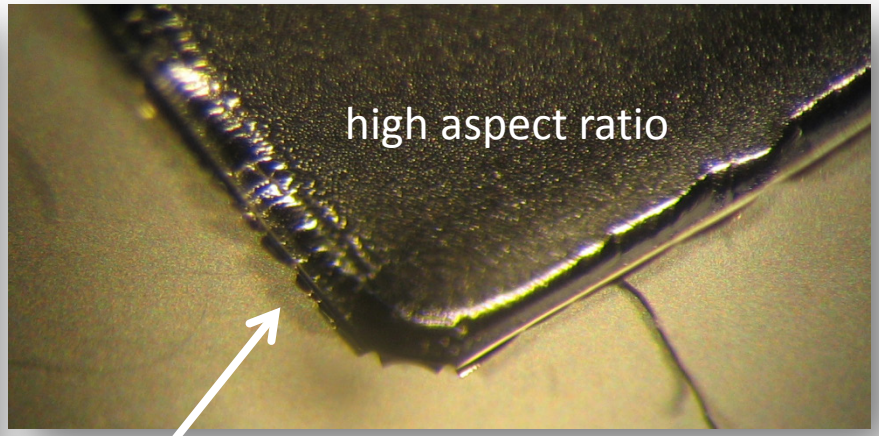


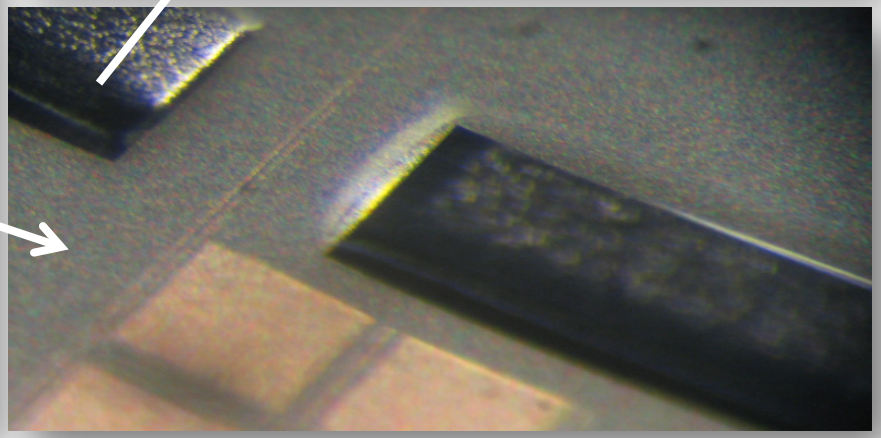


First produced P1 have well defined steps across the sensors

MMC-based photon detector: P1 design







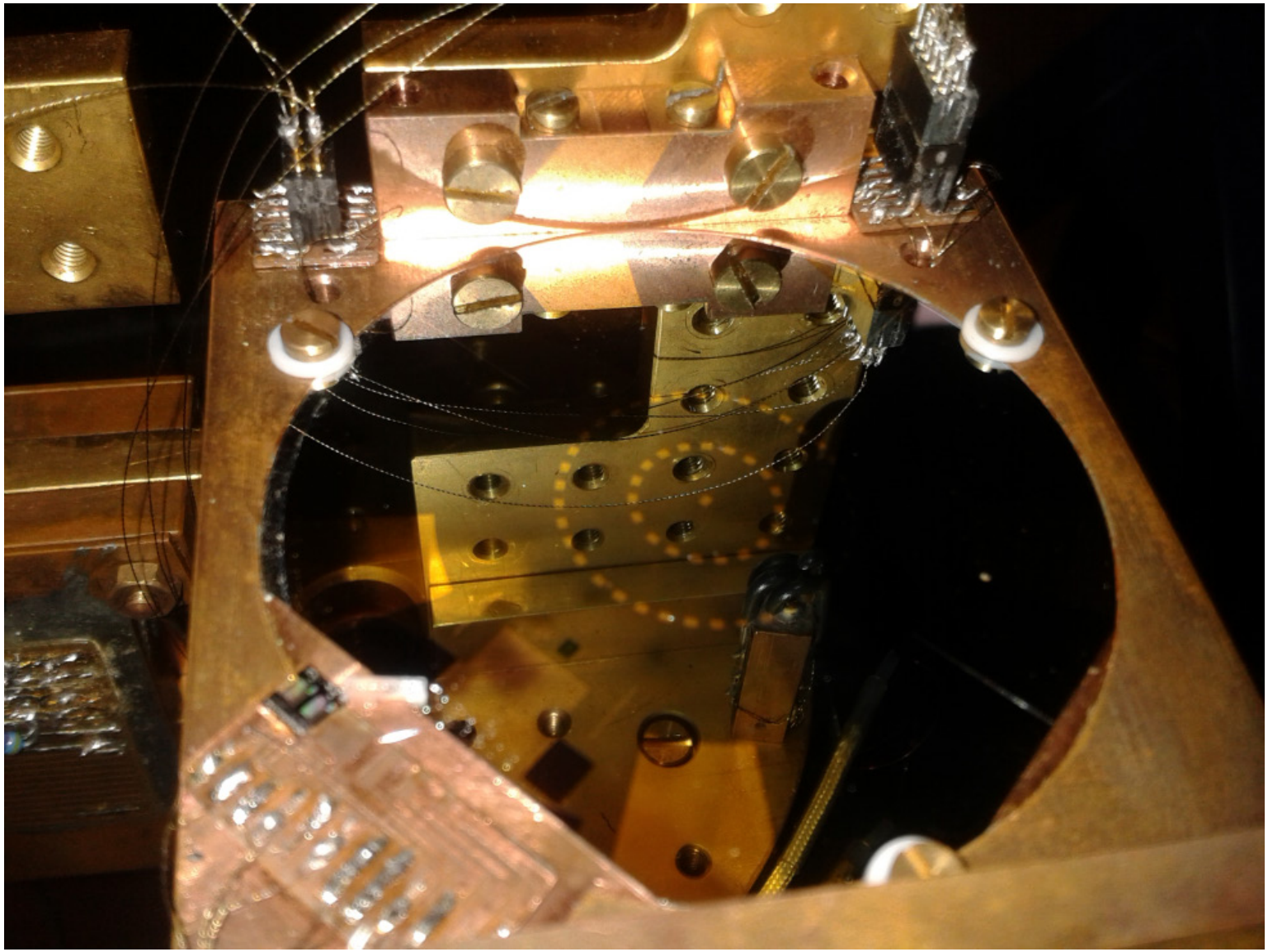
First tests for etching trenches were promising:

- recipe already tested:

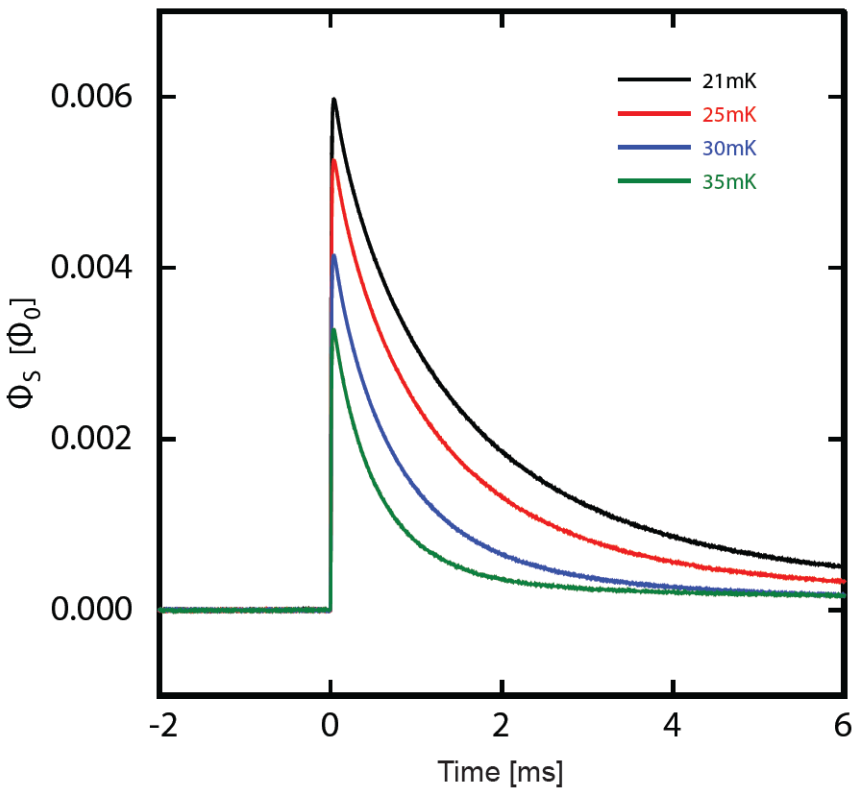
3 hours of $SF_6 + O_2$ (14:1), T = -90 °C, and 500W ICP power

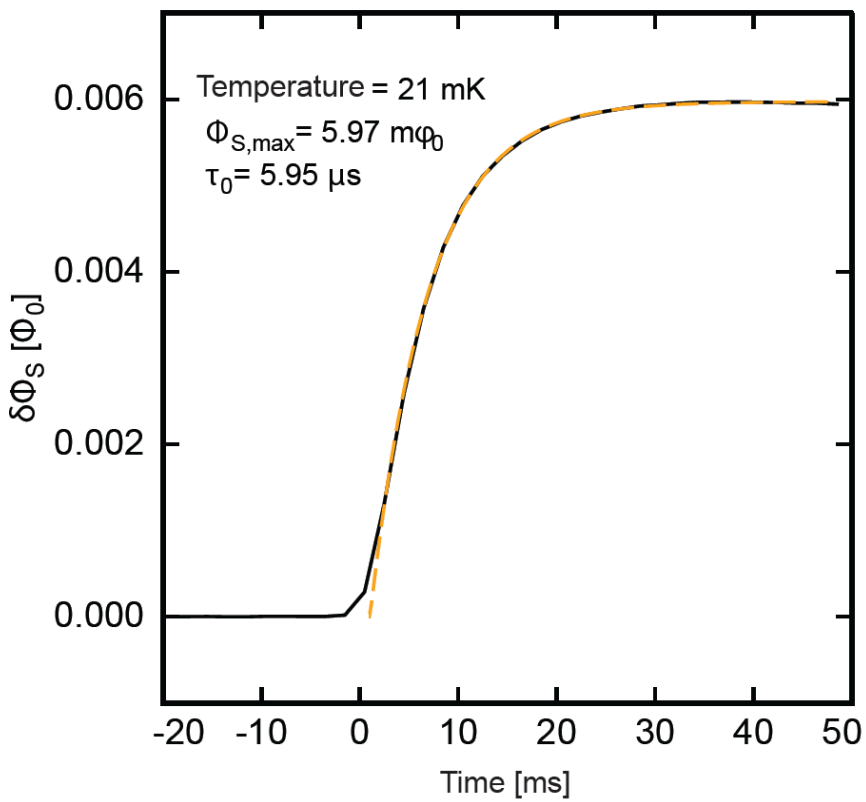
….but not stable.

Tests with LED and x-rays in HD



Photon detector: First tests with 6keV x-rays

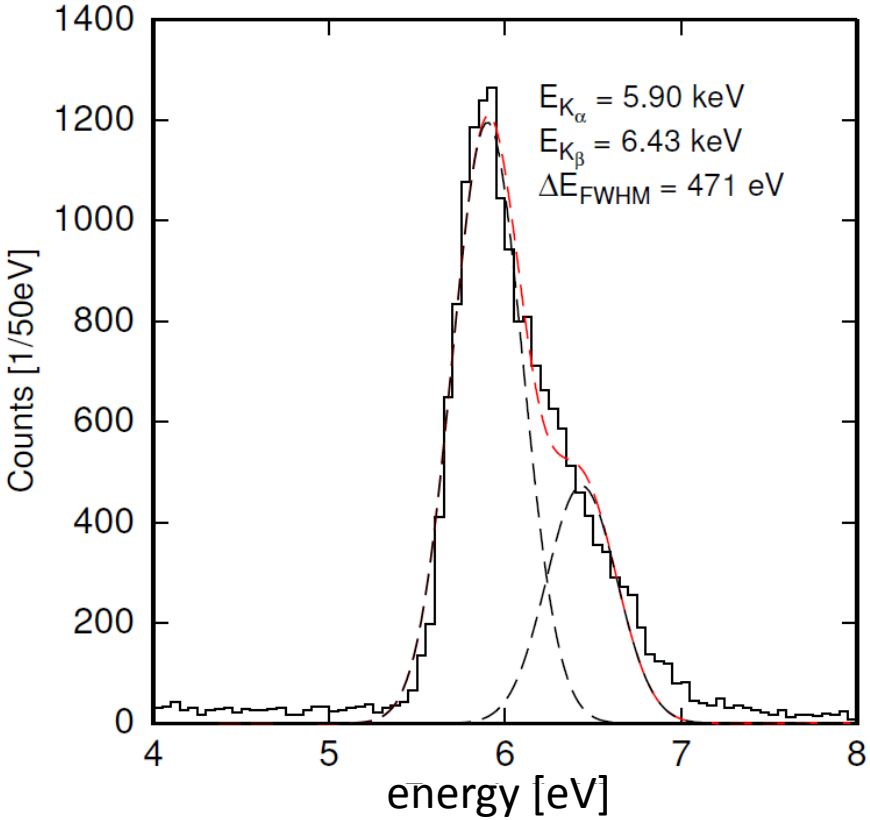


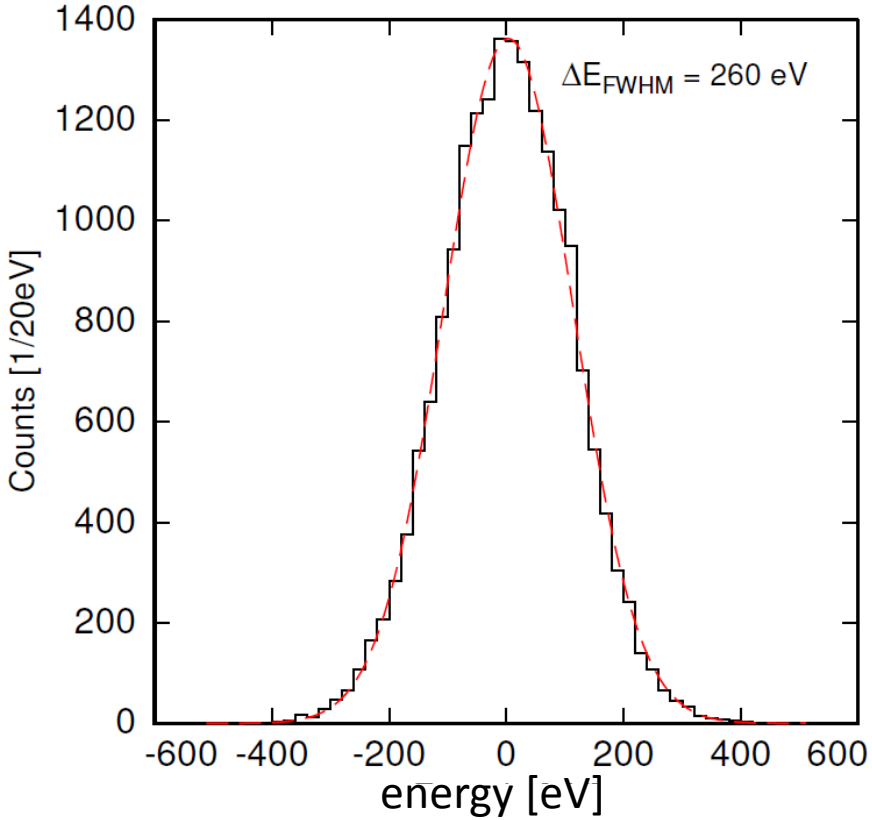


Risetimes:	**direct x-rays**	**~ 6 µs**
	for scintillation light	~ 250–350 µs (Saclay)

D. Gray et al., JLTP 184 3-4 (2016) 904

Photon detector: First tests with 6keV x-rays





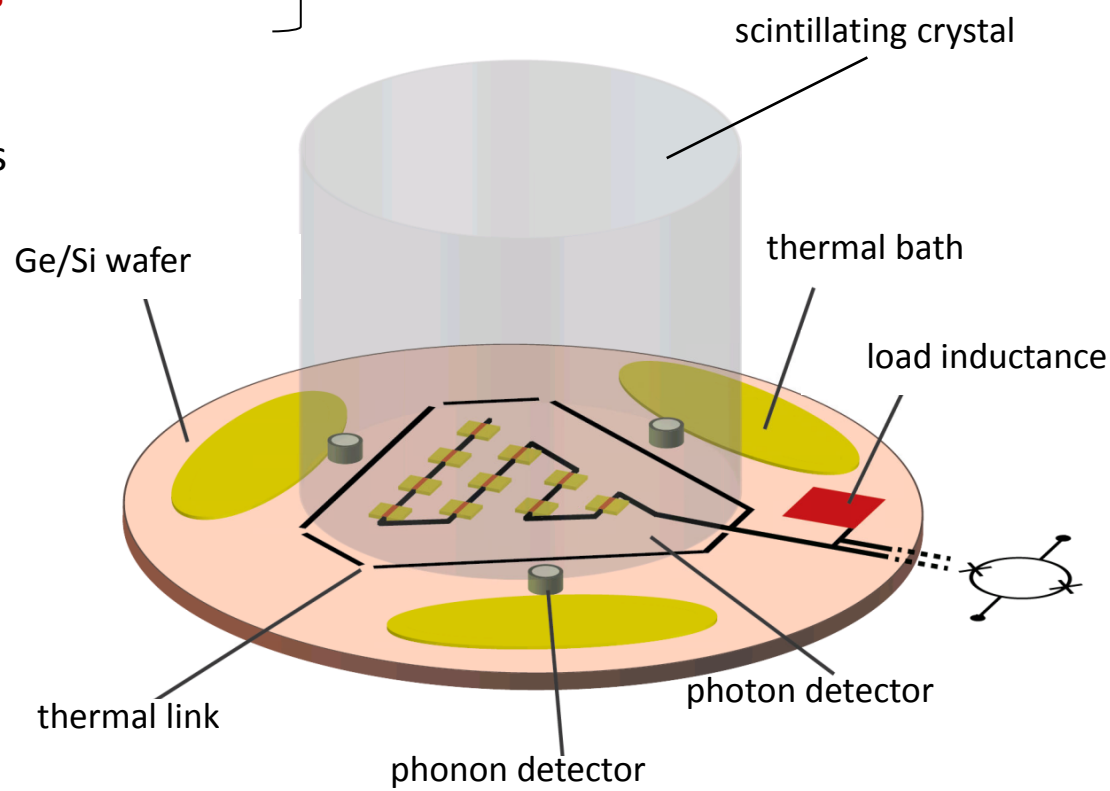
- Numerical simulation: $E_{\mathrm{FWHM}} < 10\ \mathrm{eV}$
- Possible reasons for discrepancy: low signal size

Combined Photon and Phonon Detector: P2

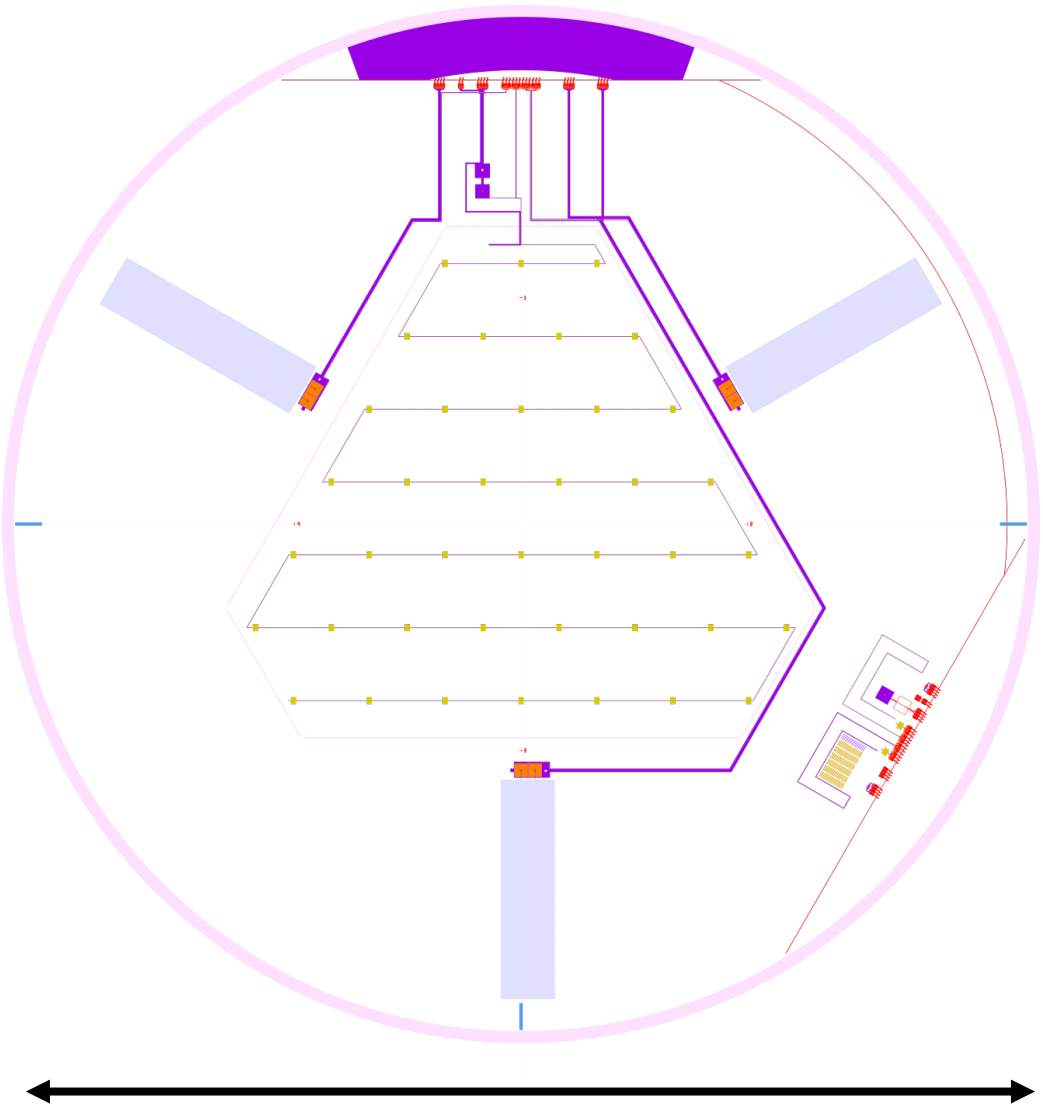
- Phonon detector:
  - energy resolution $\Delta E_{FWHM} < 100$ eV
  - rise time $\tau < 200$ µs
- Photon detector:
  - energy resolution $\Delta E_{FWHM} < 10$ eV
  - rise time $\tau < 50$ µs

Substrate: Ge or Si 3‘‘ wafer

- A minimum of (contaminated?) parts
- Position sensitivity possible

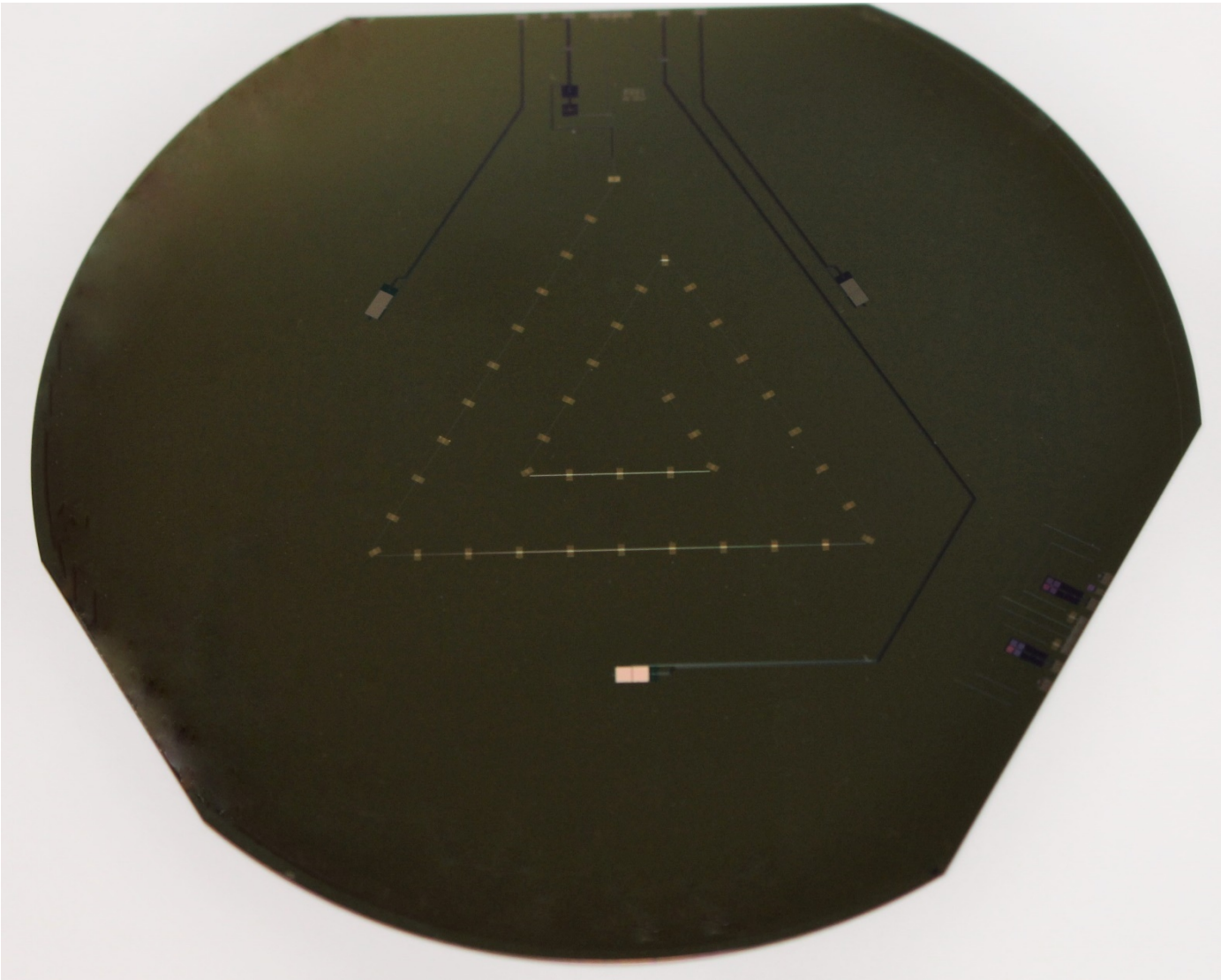


Integrated light and heat detectors P2

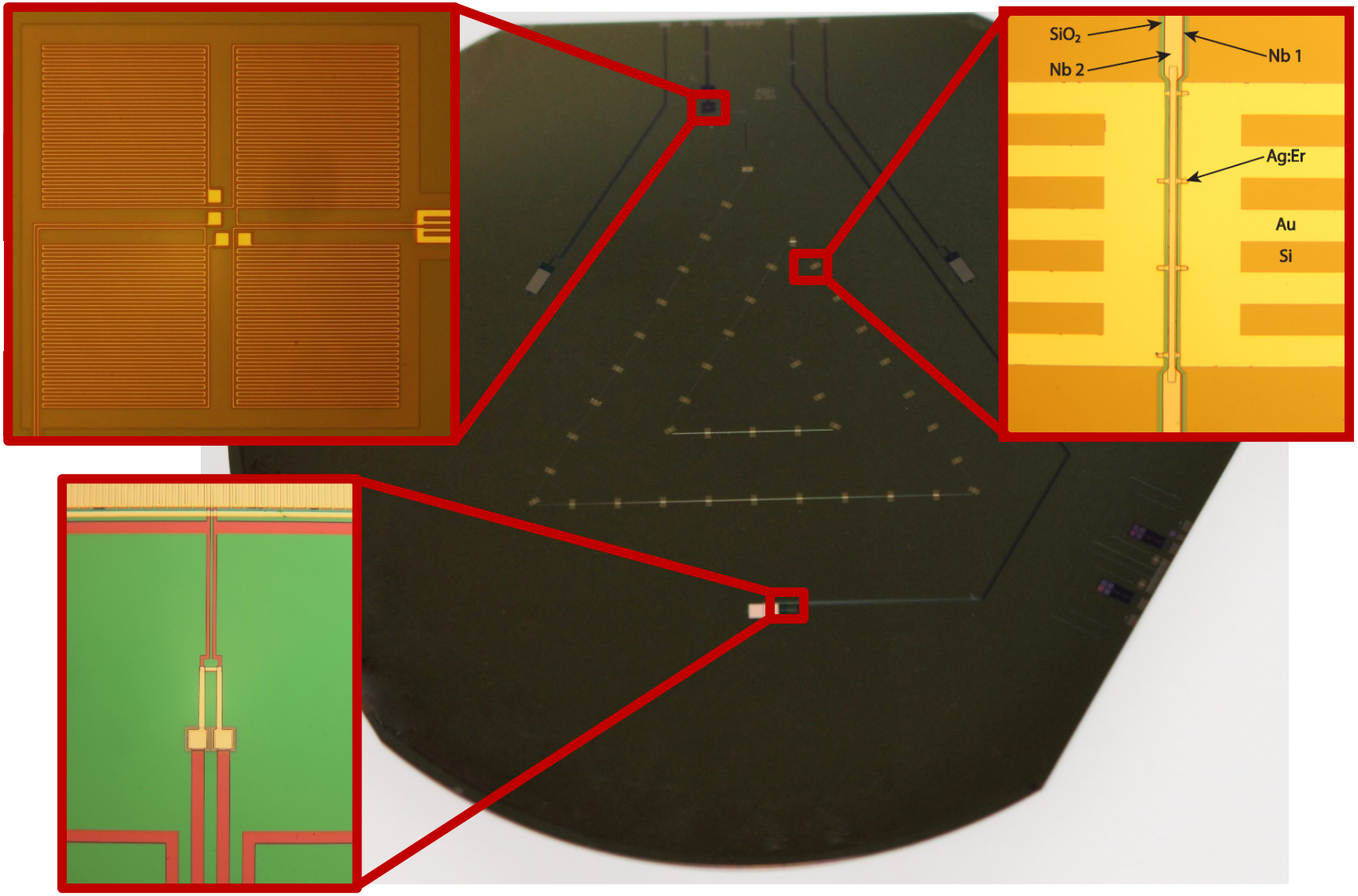


76,2 mm

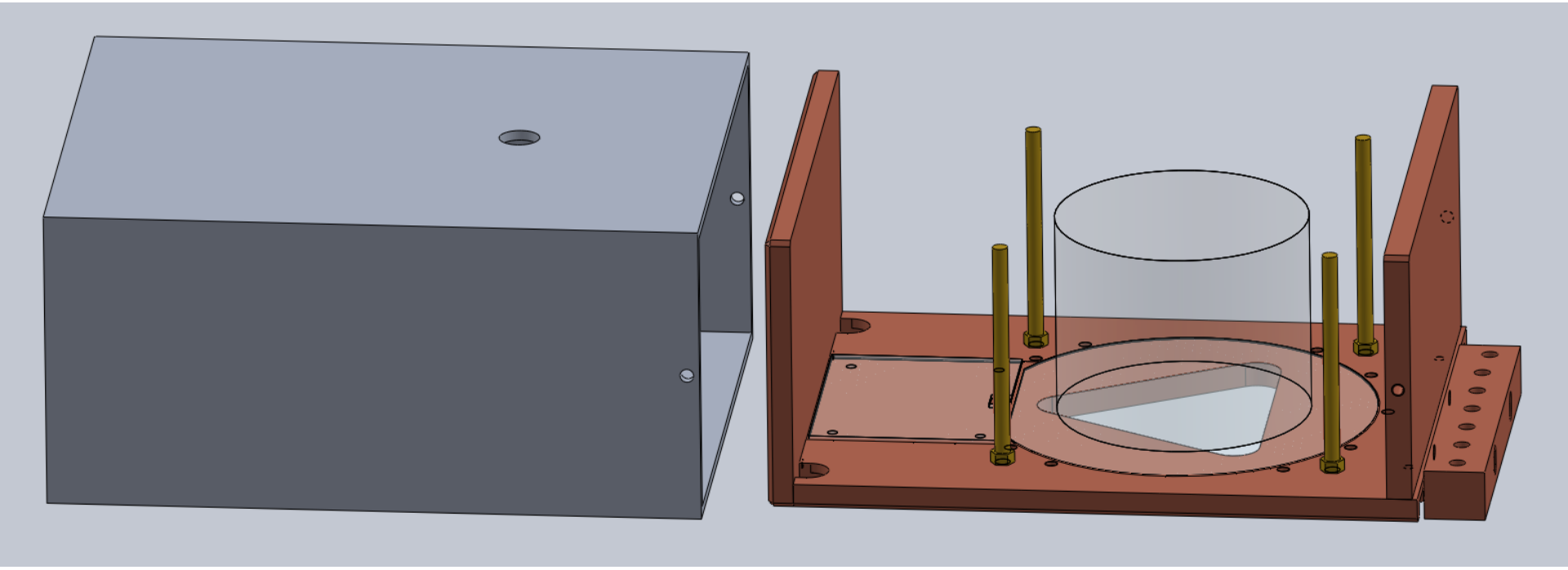
Integrated light and heat detectors P2



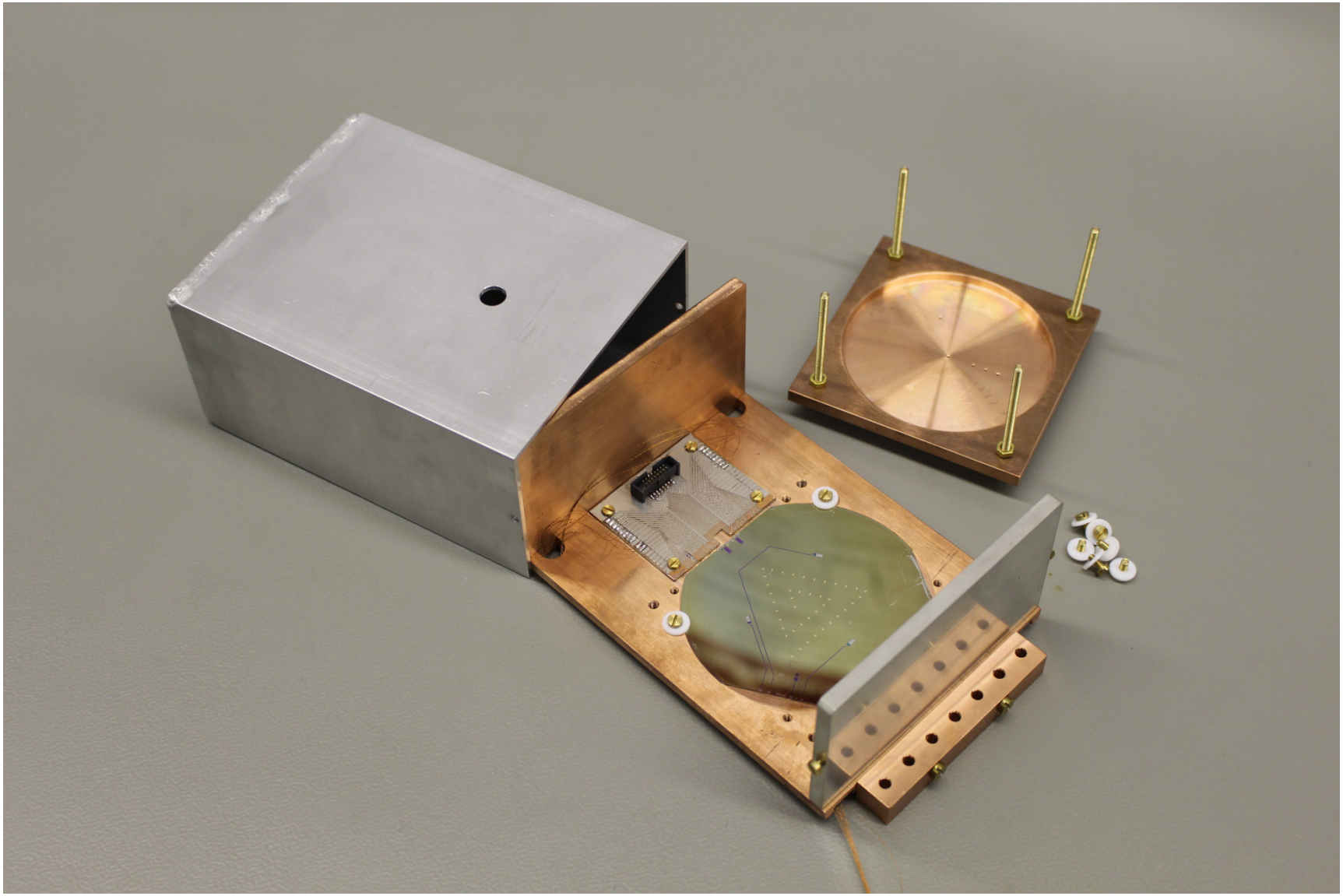
Integrated light and heat detectors P2



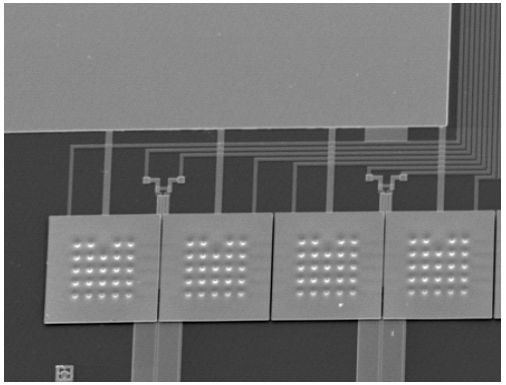
Experimental set-up for P2

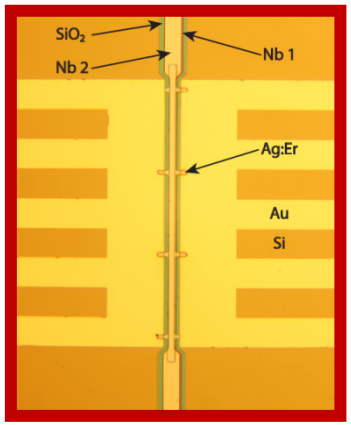


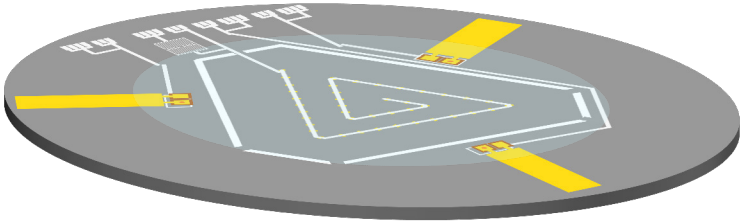
Experimental set-up for P2



Summary and Outlook







Metallic magnetic calorimeters

- are versatile low temperature detectors
- high resolution for all kinds of particles
- wide range of energies
- Fast signal rise time
- could bring significat benefit for large mass Mo-100 based DBD experiment

Photon detector

- Segmented paramagnetic sensor
- Challenges in fabrication solved

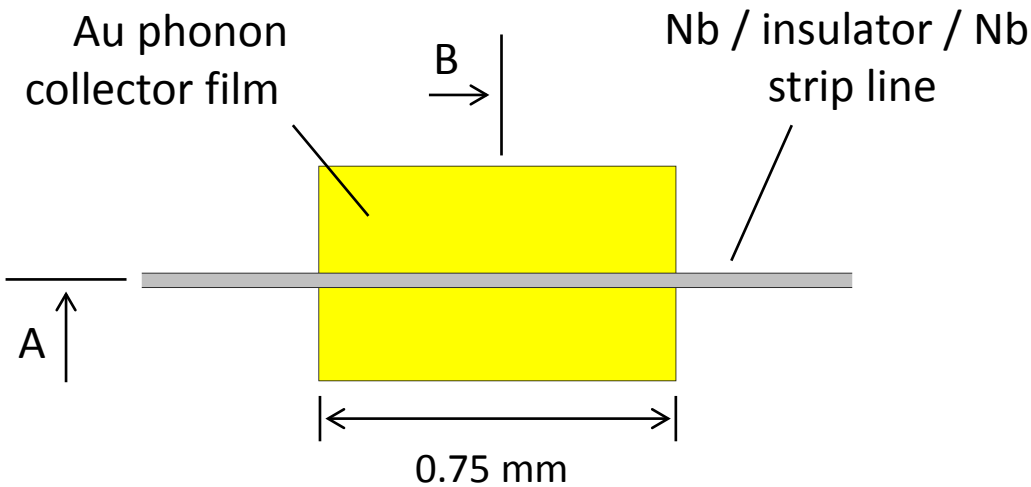
Combined photon and phonon detector

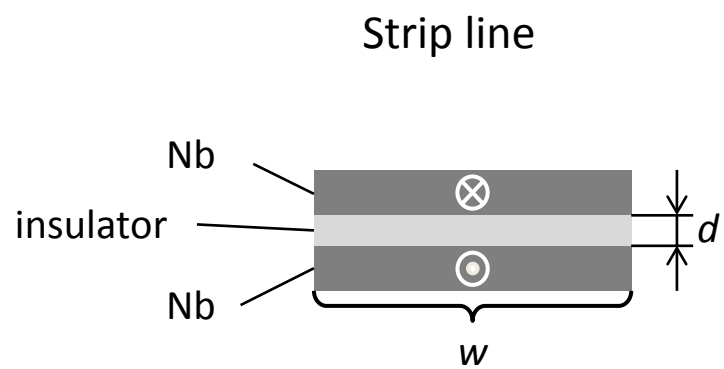
- New design on 3‘‘ wafer
- First tests on going

Thank you !

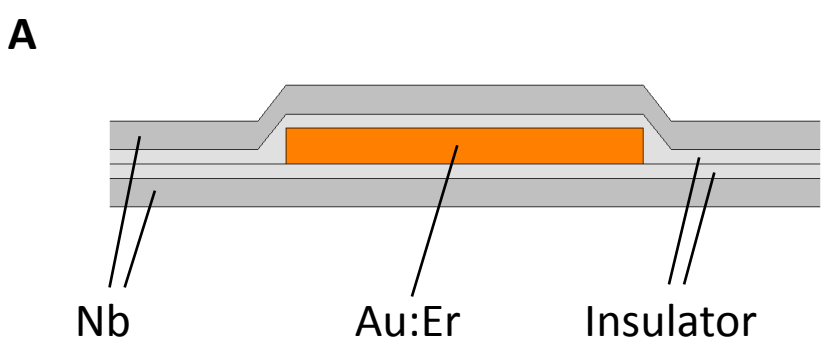
First prototype of photon detector

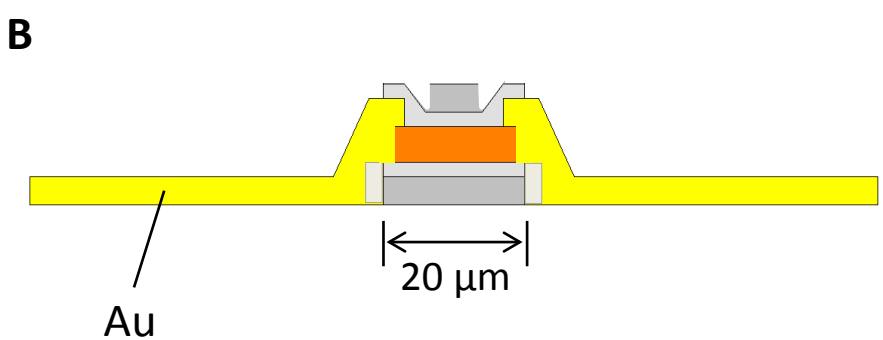
Top view:



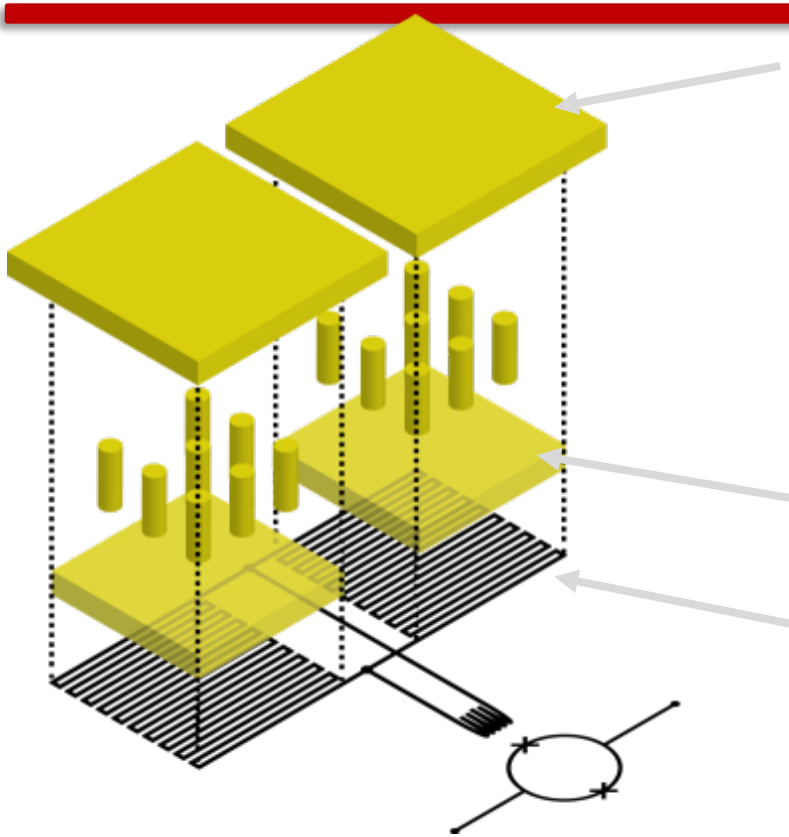


Cross section:

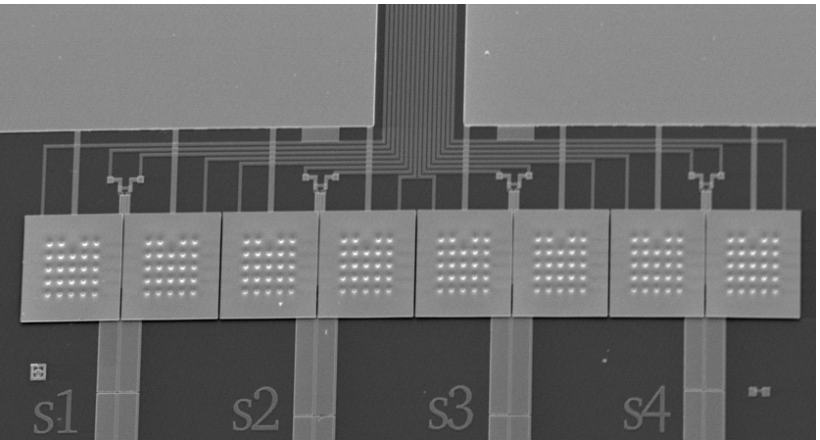


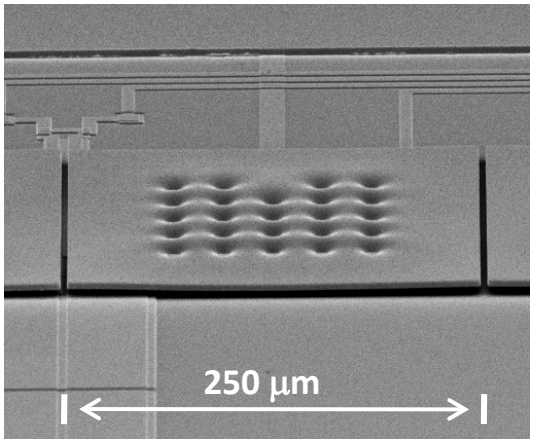


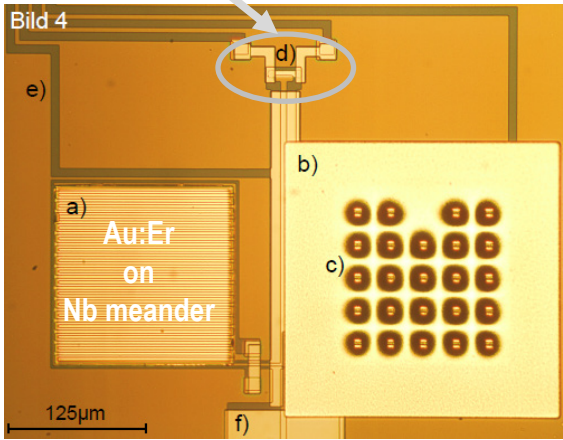
maXs20: 1d-array for soft x-rays



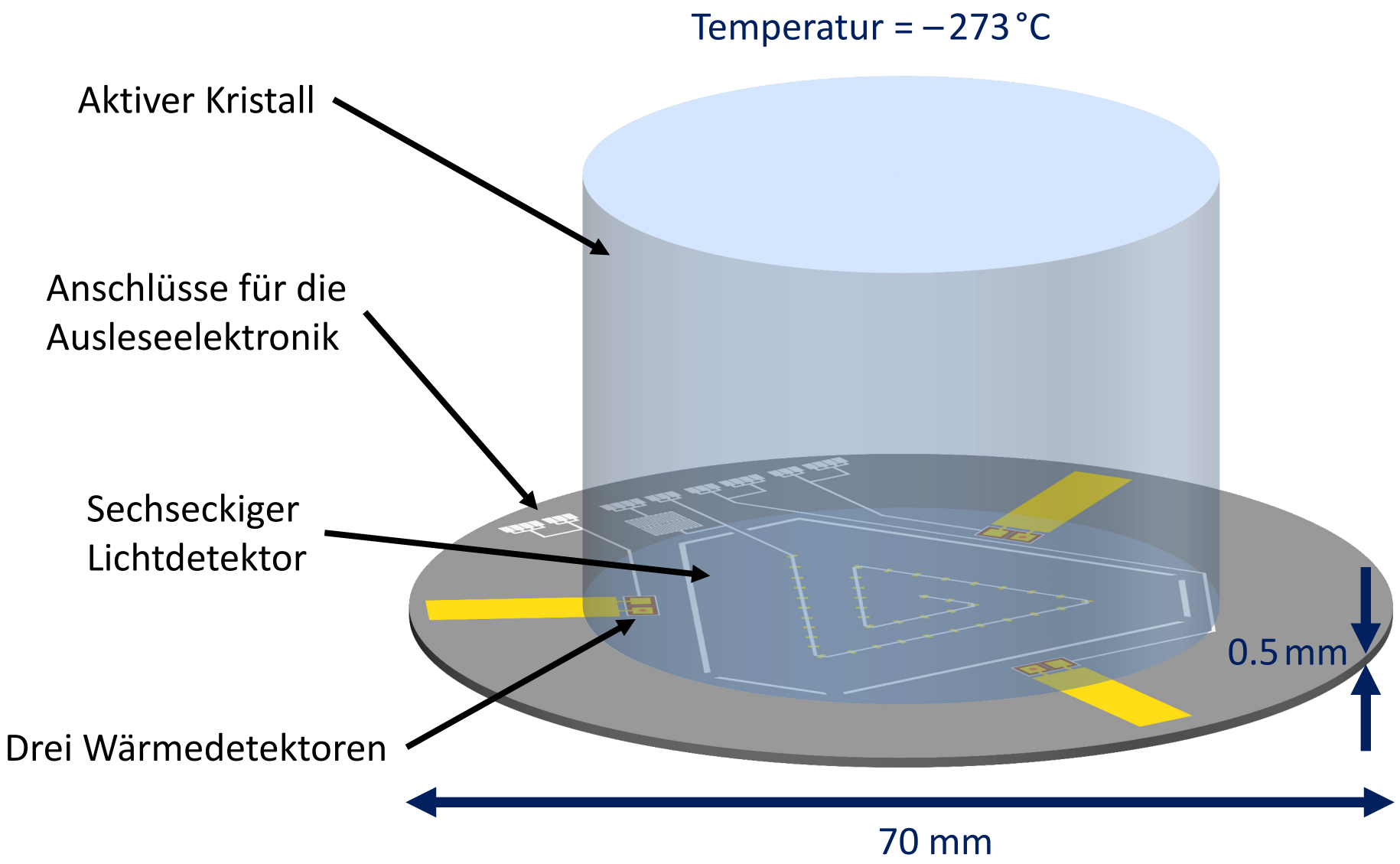
- **1×8 x-ray absorbers**
  - **250μm×250μm** gold**, 5μm thick**
  - **98%** Qu.-Eff. @ 6 keV
  - electroplated into photoresist mold (RRR>15)
  - **mech/therm contact to sensor by stems** to prevent loss of initially hot phonons
- **Au:^{166}Er$_{300ppm}$ temperature sensors**
  - co-sputtered from pure Au and high conc. AuEr target
- **Meander shaped pickup coils**
  - 2.5 μm wide Nb lines
  - **I_c ≈ 100mA**
- **On-chip persistent current switch** (AuPd)





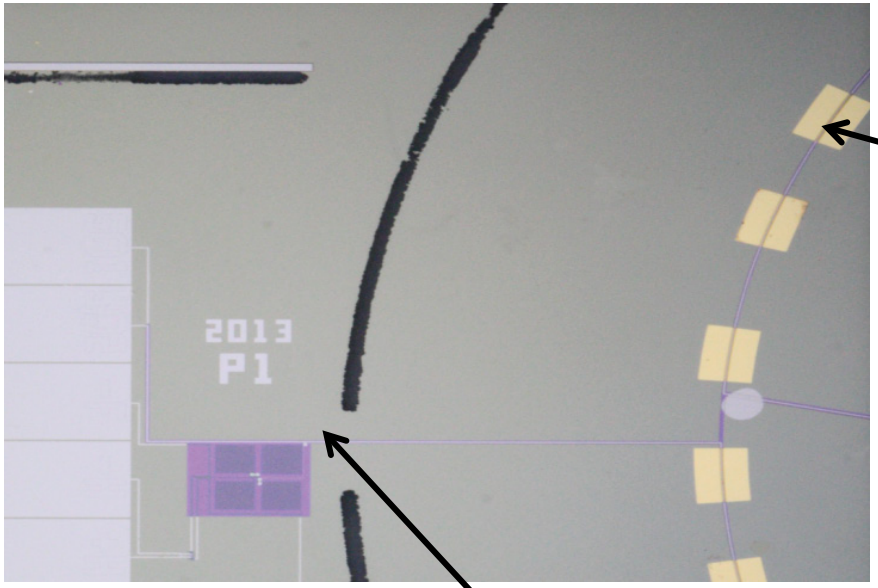


Wärme- & Lichtdetektor



Cleanroom issues

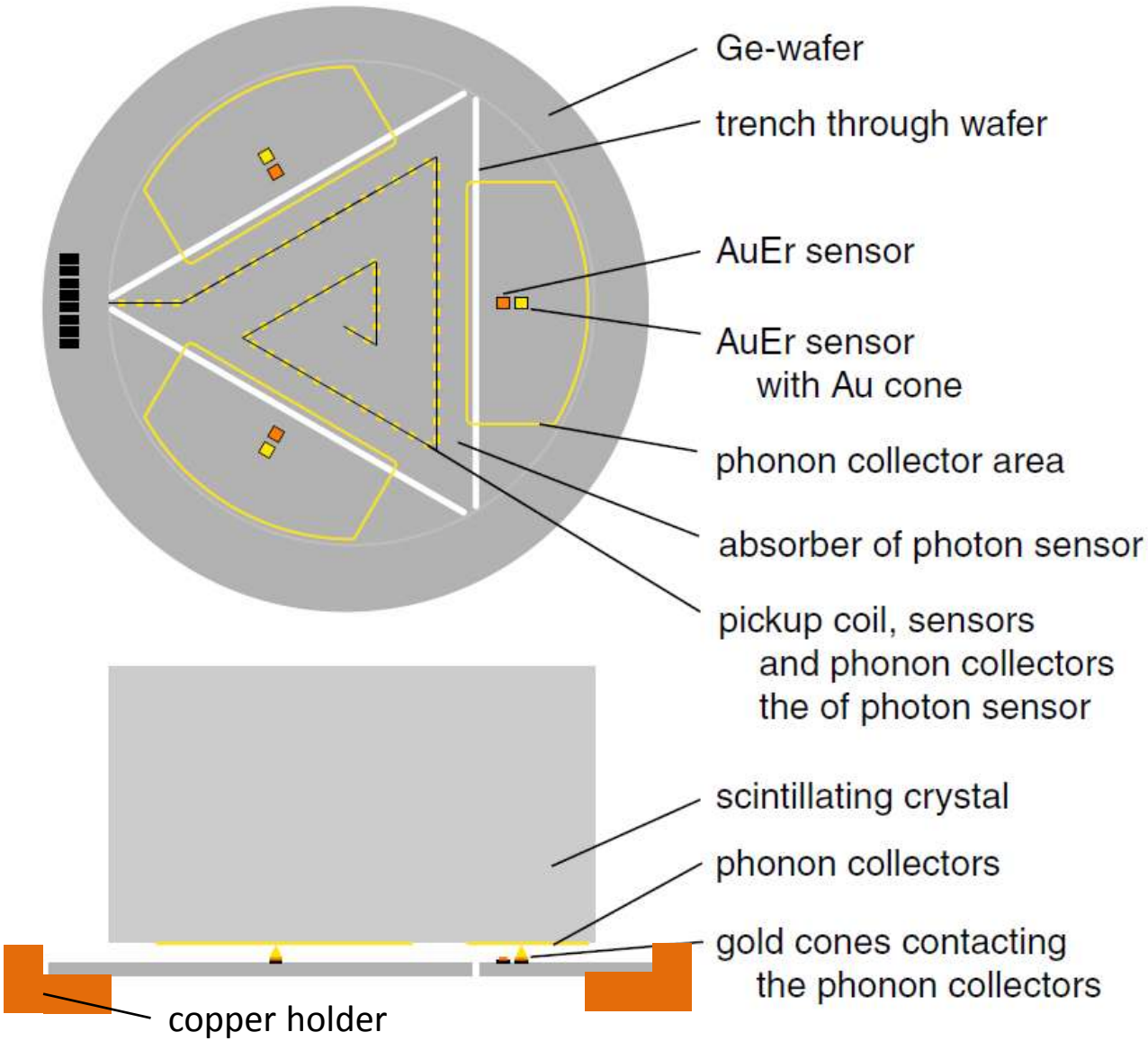
deep etching the trenches:
.... we discovered, that the DRIE machine
was not installed correct when delivered



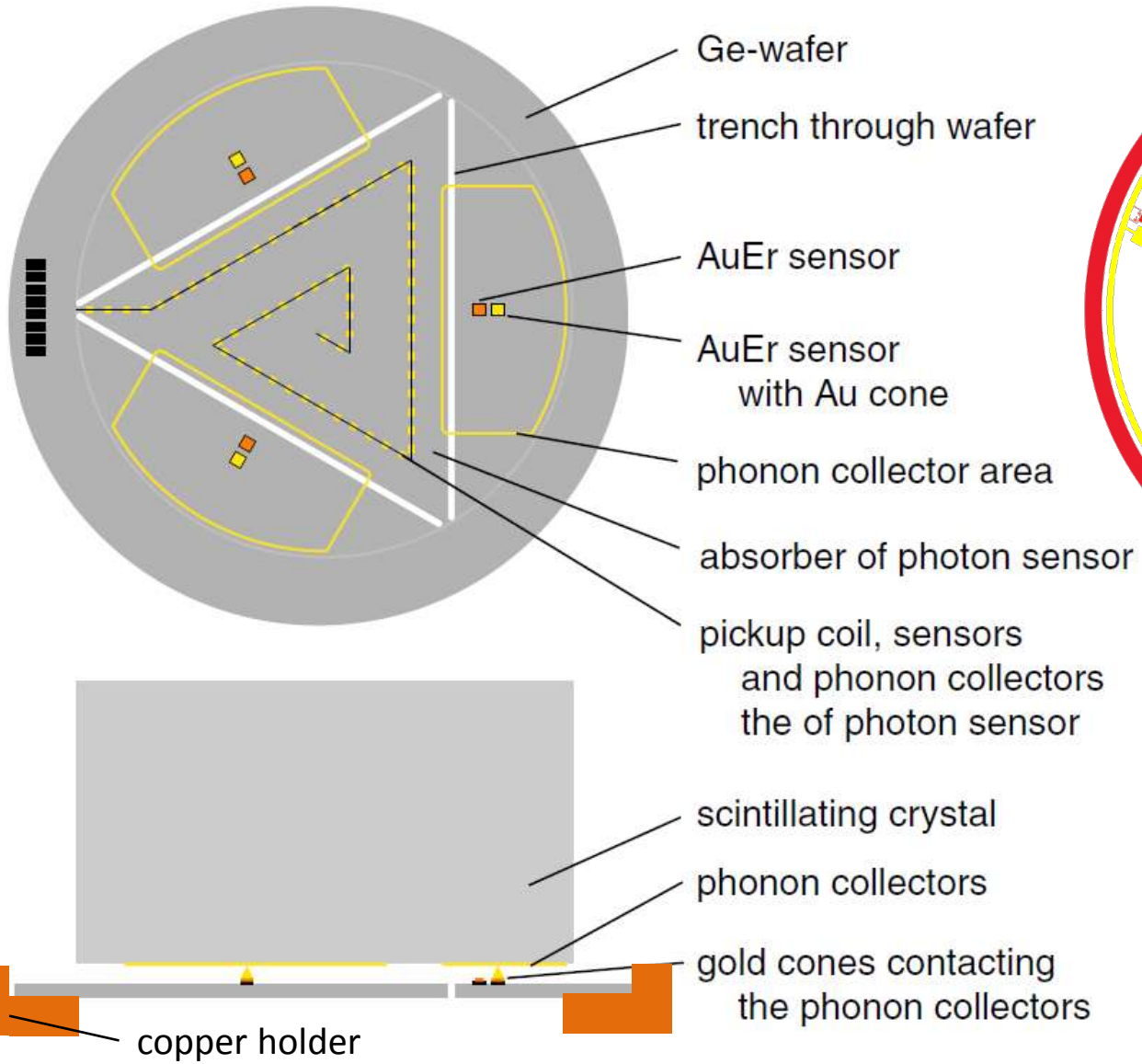
switching from Au:Er to Ag:Er
... affected sticking etc of succeeding layers

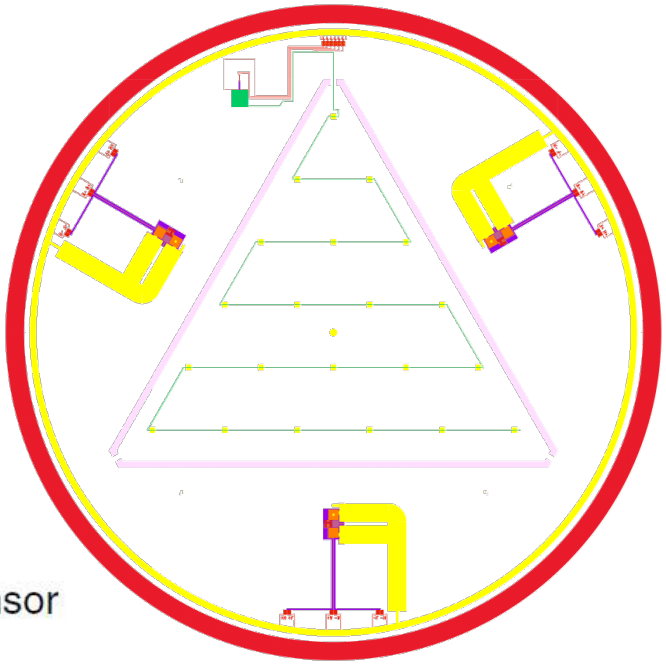
switching from MA to Direct Laser Lithography (MLA)
... switched photoresist
... new step shape of insulating SiOx layer
... bad electrical contact at VIAs

Combined photon and phonon detector: P2

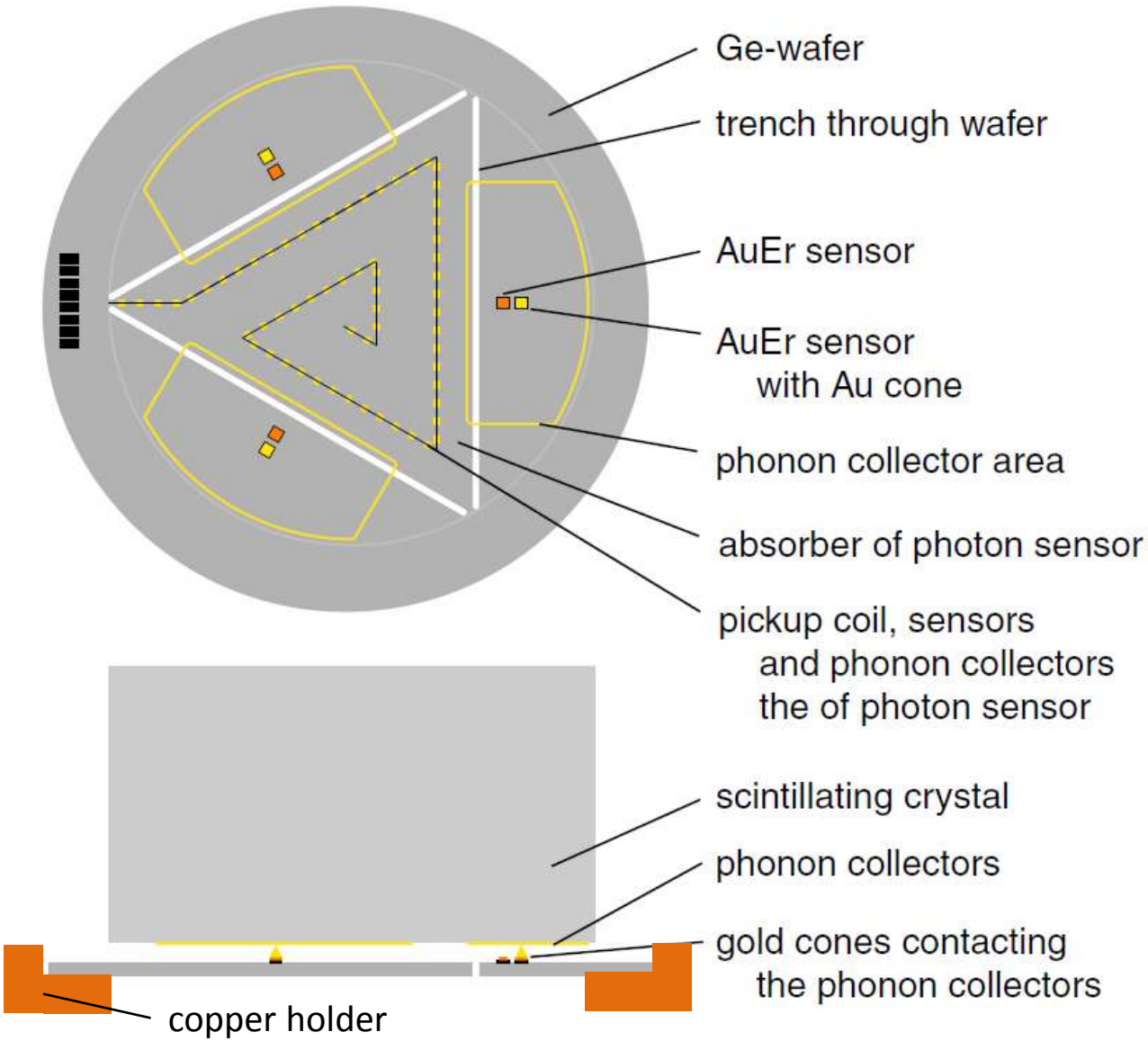


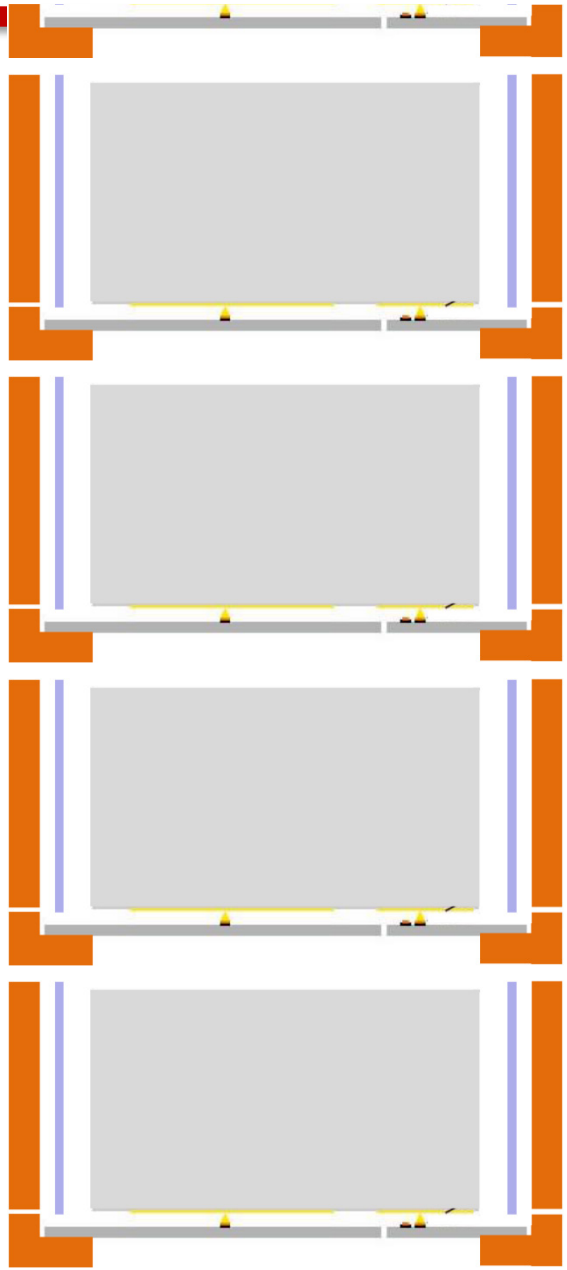
Combined photon and phonon detector: P2



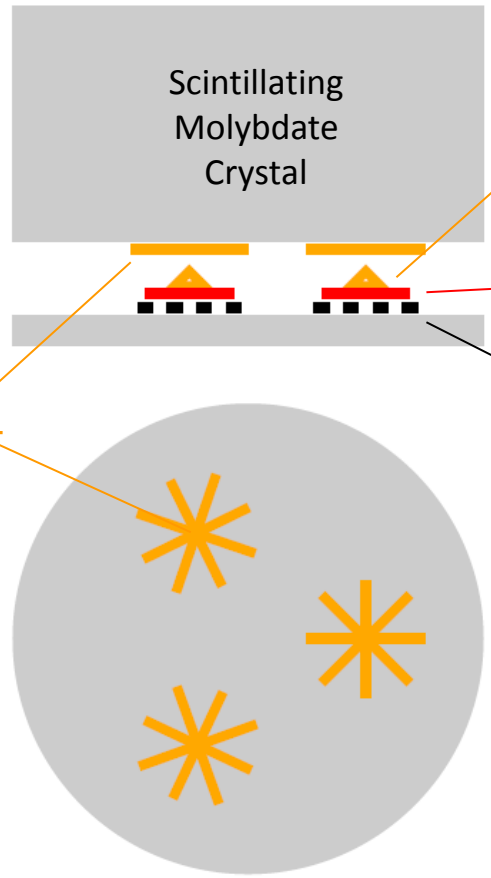


Combined photon and phonon detector: P2





MMC-based phonon sensors



3 micro-fabricated gold cones:

- mechanical support of crystal
- thermal contact to sensors

3 AuEr temperature sensors

- about 1nJ/K

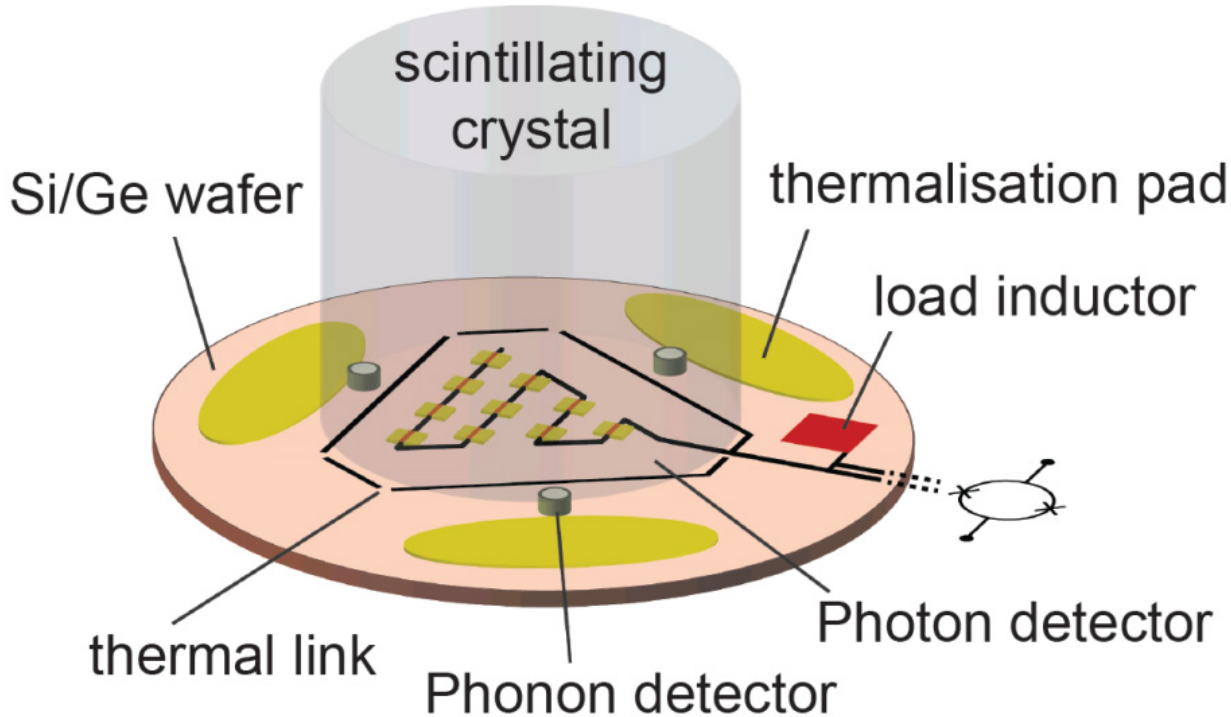
1-3 independent Nb pickup coils

Phonon collectors:
evaporated Au

Achievable:

Energy resolution	ΔE_{FWHM} = 50 -100 eV
Rise time	τ_R < 200 µs

Integrated light and heat detectors P2

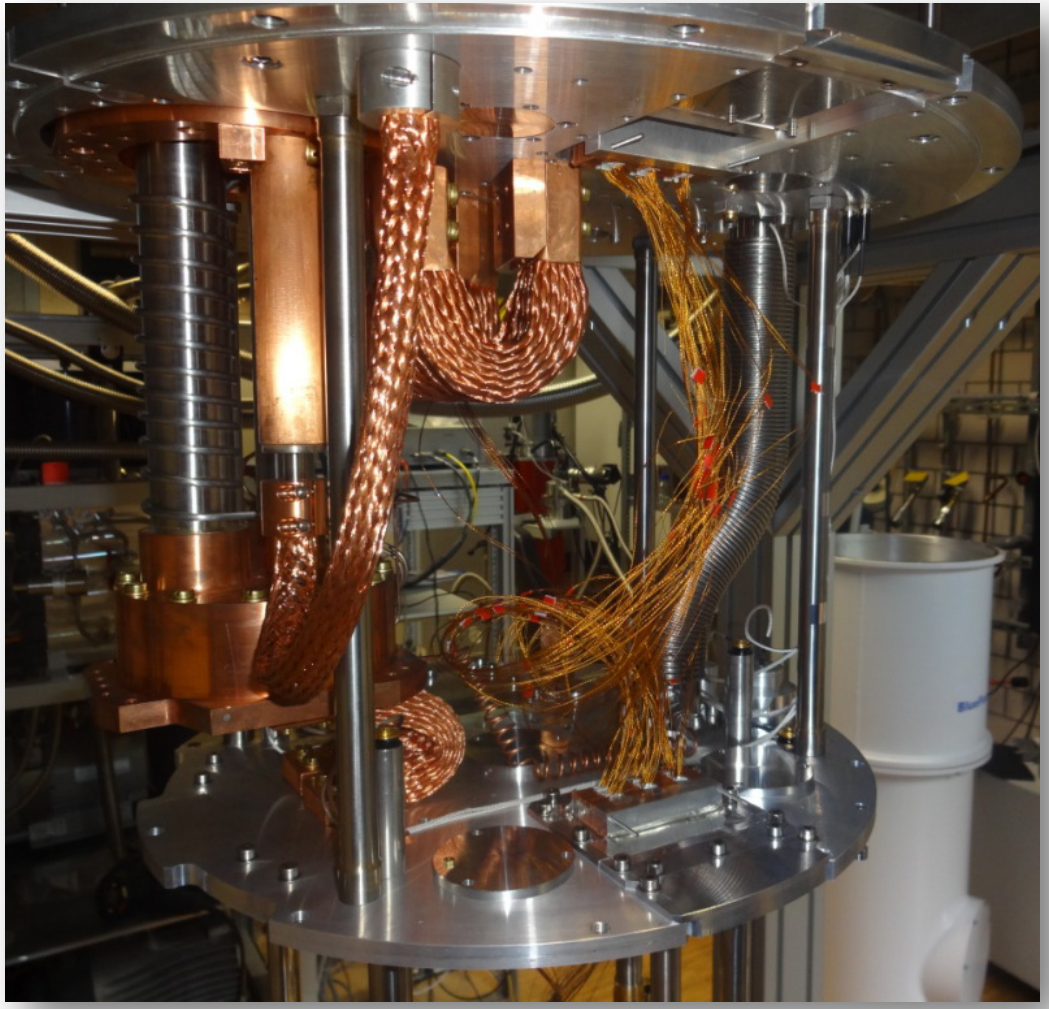


- Crystal is resting on 3 rigid temperature sensors
- Photon detector read out by highly segmented sensors for speed

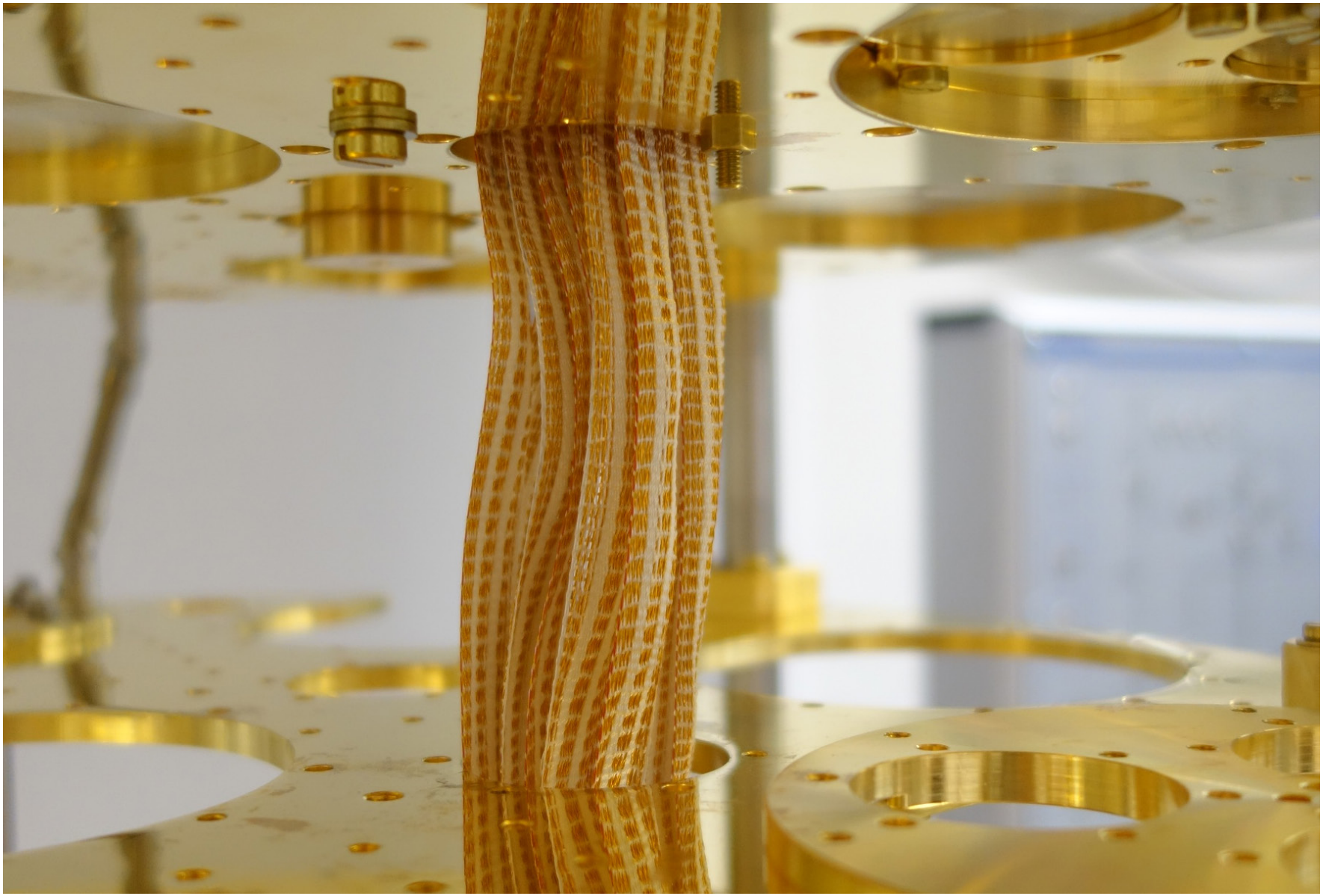
maXs: system integration

vibrations no problem

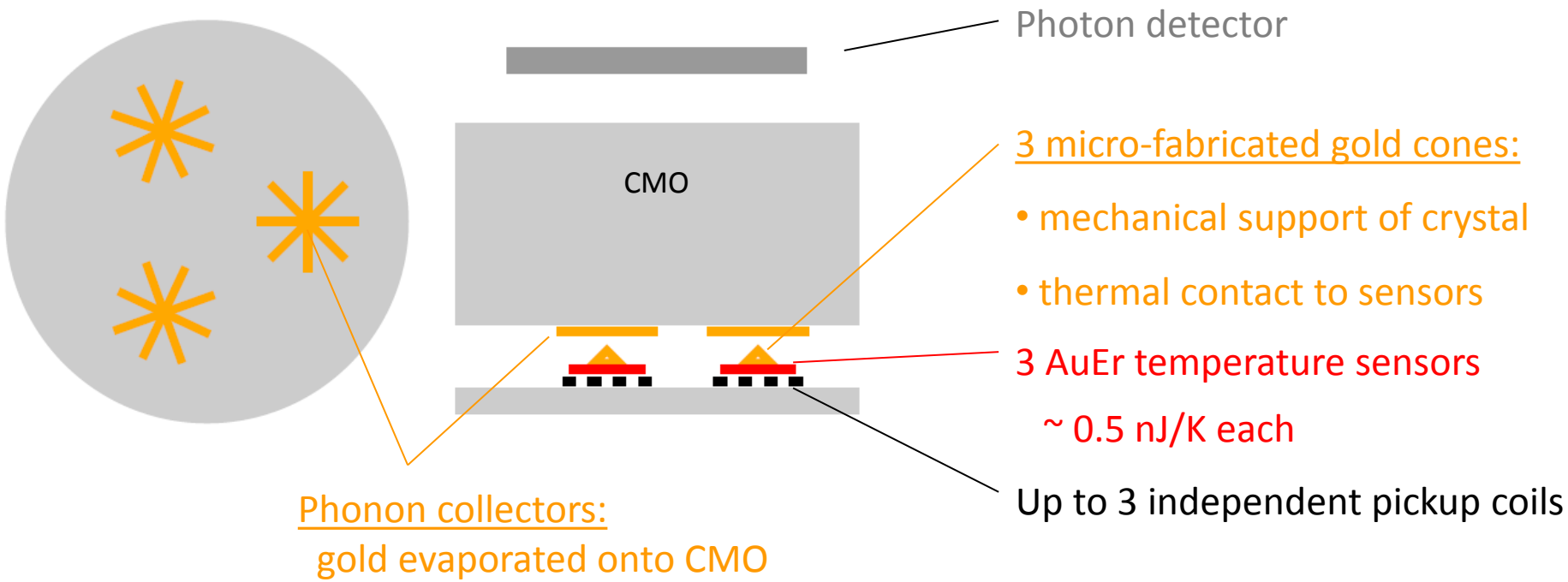
but: for >100 channels you want a multiplexing scheme



what about kilo-pixel arrays?

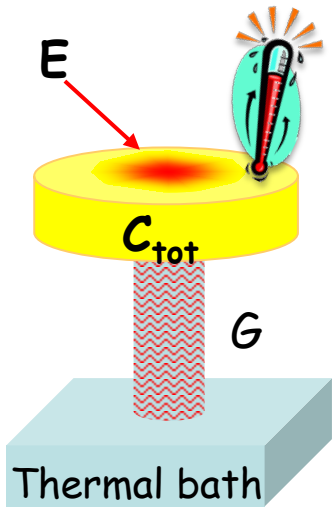


phonon detector

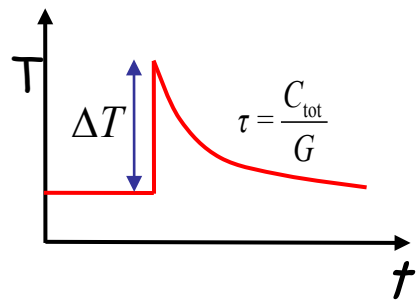


- Energy should be proportional to integral of summed temperature pulse
- Allows for some position discrimination (e.g. support-event suppression)
- $\Delta E_{FWHM} < 200$ eV
- rise time < 200 μs

Low temperature micro-calorimeters



$$\Delta T \cong \frac{E}{C_{tot}}$$



E = 10 keV
C_{tot} = 1 pJ/K
→ ~ 1 mK

- Very small volume
- Working temperature below 100 mK
  small specific heat
  small thermal noise
- **Very sensitive temperature sensor**

P1 photon detector in Saclay and Heidelberg

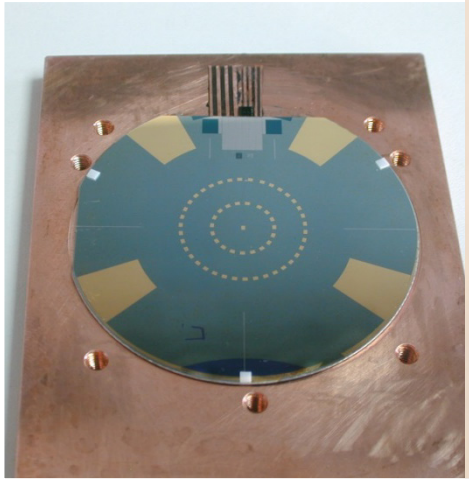
Copper holder developed for detectors with trenches

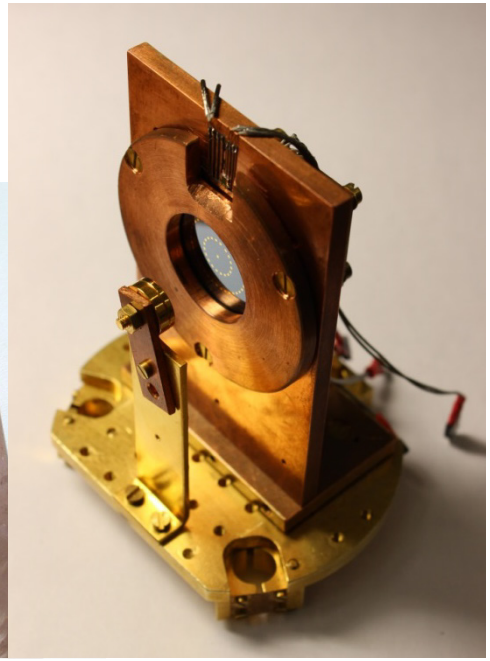
Saclay

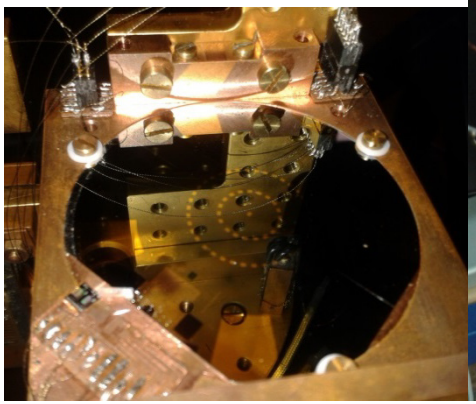
- ^{55}Fe calibration source
- LED light
- Coupled to a $ZnMoO_4$ small crystal

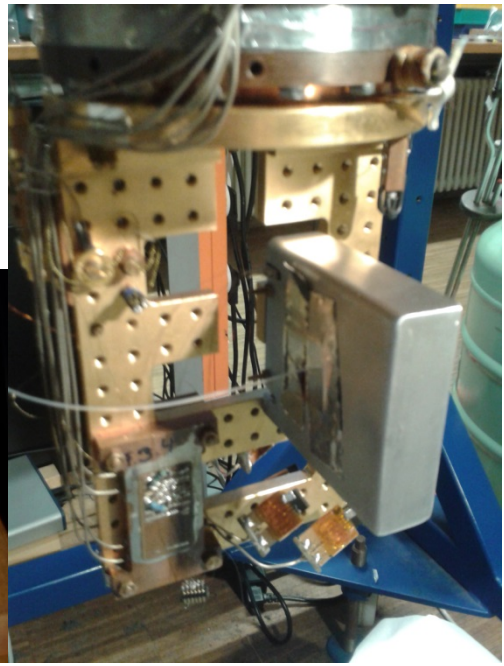
Heidelberg

- ^{55}Fe calibration source
- LED light



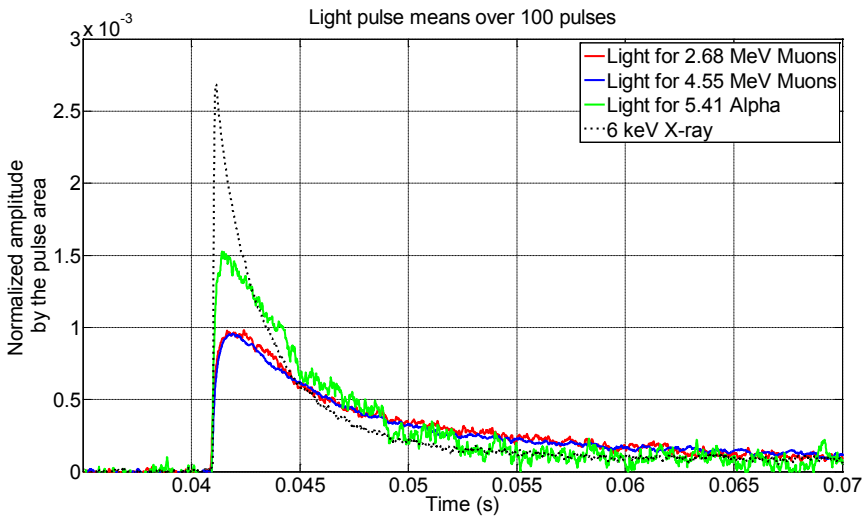


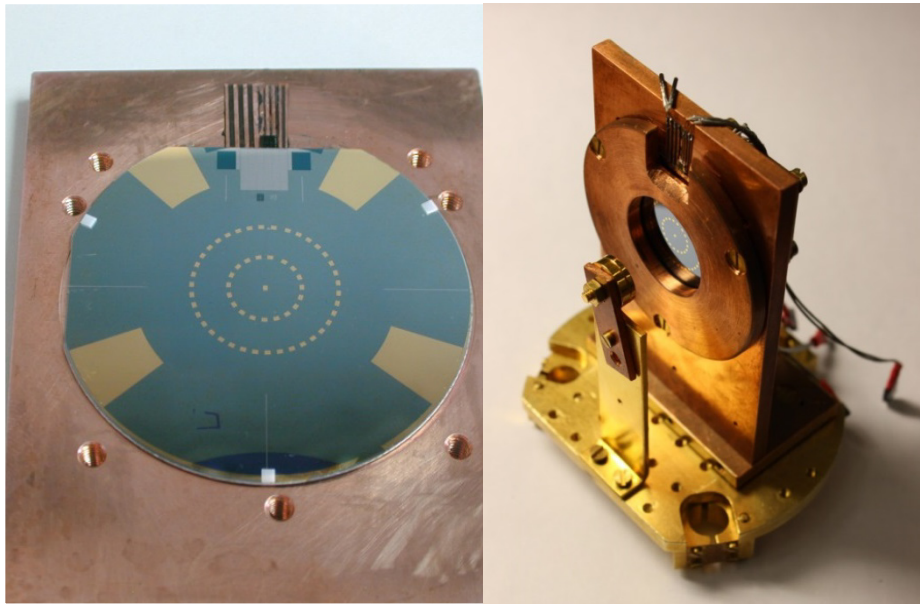




P1 photon detector in Saclay

α and muons particles give a different scintillation pulse shape to X-ray pulse





X-ray rise time ~ 25-30 µs

Light rise time ~ 250–350 µs

Measurement of the scintillation time constant