Kirchhoff-Institut für Physik

# Search for $0\nu2\beta$ decay of $^{100}$Mo with AMoRE

Loredana Gastaldo
for the AMoRE Collaboration

Heidelberg University

# AMoRE Collaboration (since 2009)

# Dream of zero background…

**Sizable background case ;**

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

*b* = background index in cts/(keV kg y)

$\Delta E$ = FWHM energy resolution at $Q_{\beta\beta}$ in keV

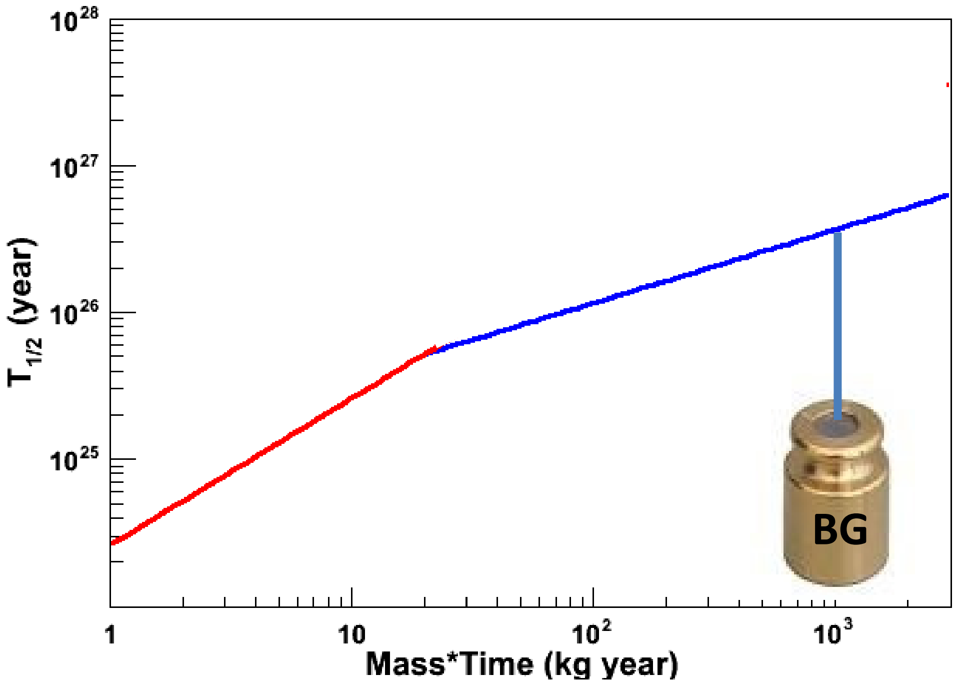
*M* = mass of detector in kg

*A* = mass number of candidate material

ε = detection efficiency at $Q_{\beta\beta}$

*A* = ββ isotope fraction (Enrichment)

*T* = measured time in years



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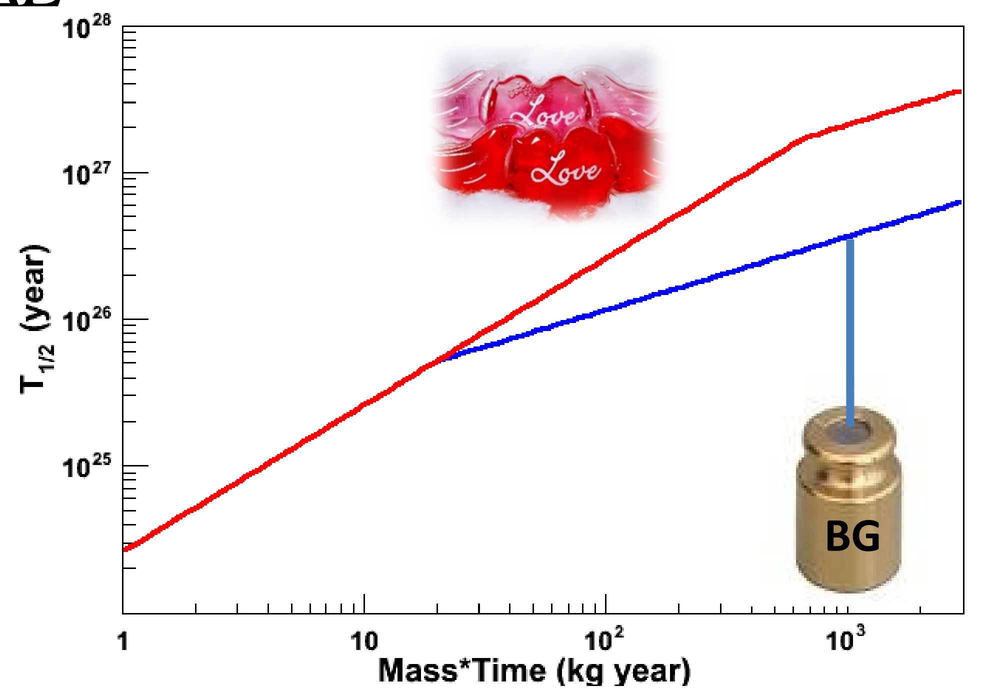


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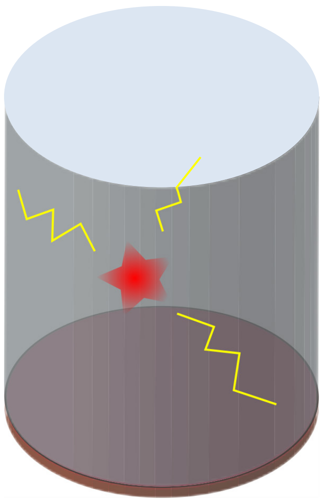
**"Zero" background case ;**

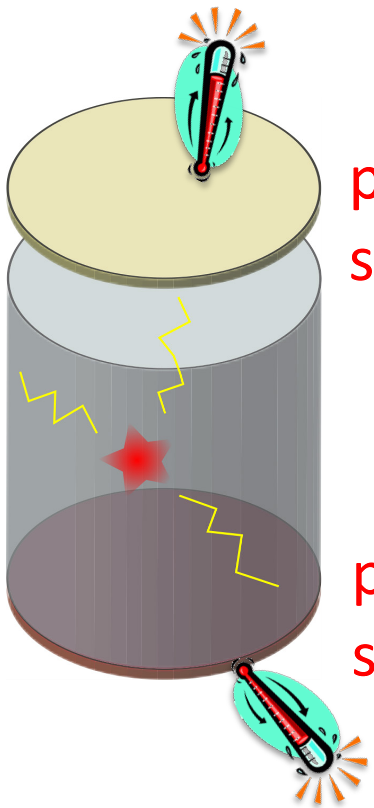
$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$

# Scintillating crystals



- The energy of an interacting particle is converted into **heat** and **light**
- The fraction of light depends on the **mass** of the particle

# Scintillating crystals

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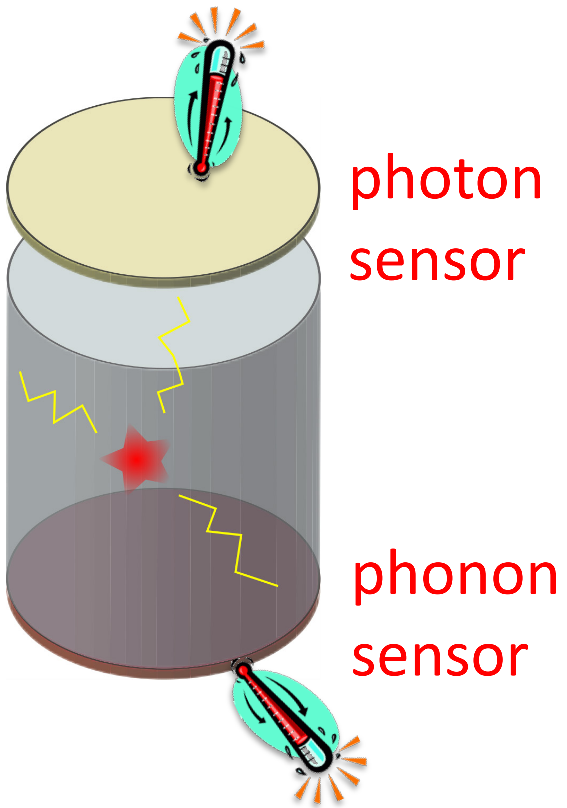
- The fraction of light depends on the **mass** of the particle
- Measure **both** fractions of energy
  → discrimination
  → rejection of background events

# Scintillating crystals

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- The fraction of light depends on the **mass** of the particle
- Measure **both** fractions of energy
  → discrimination
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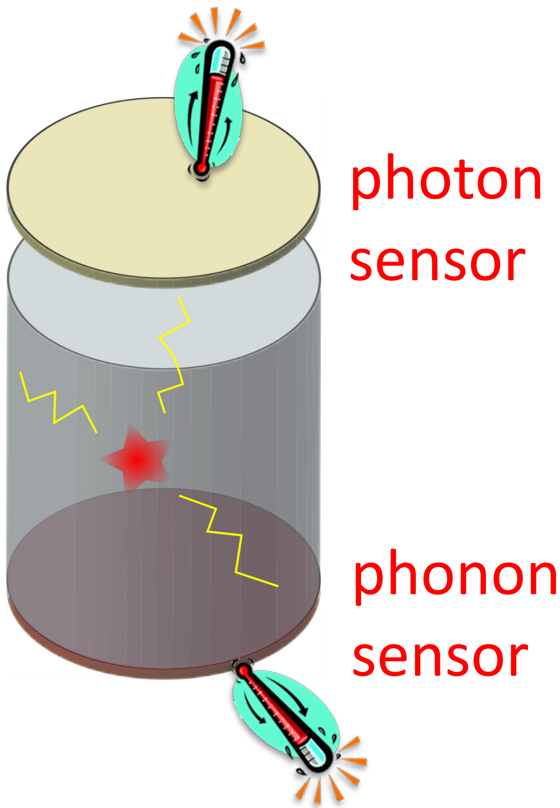
$$^{100}Mo \rightarrow ^{100}Ru + 2e^- + (2\overline{\nu}_e)$$

$Q_{\beta\beta}$ = 3.034 MeV
$a$ = 10%

# Scintillating crystals

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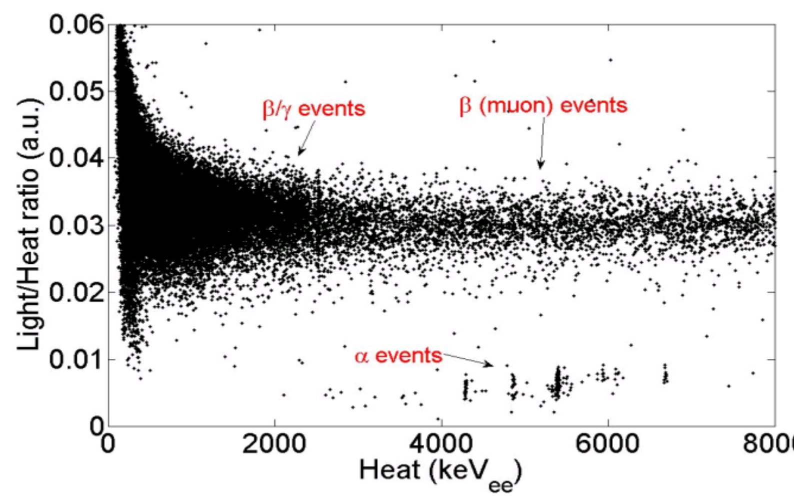
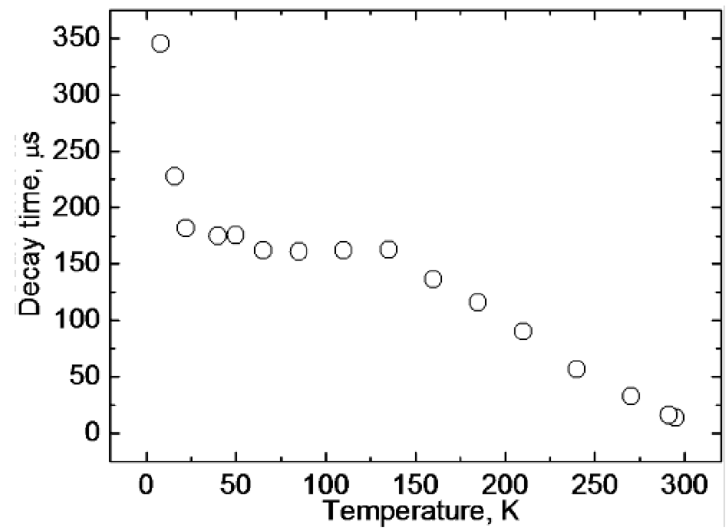
$^{40}Ca^{100}MoO_4$
+ MMCs thermal sensors



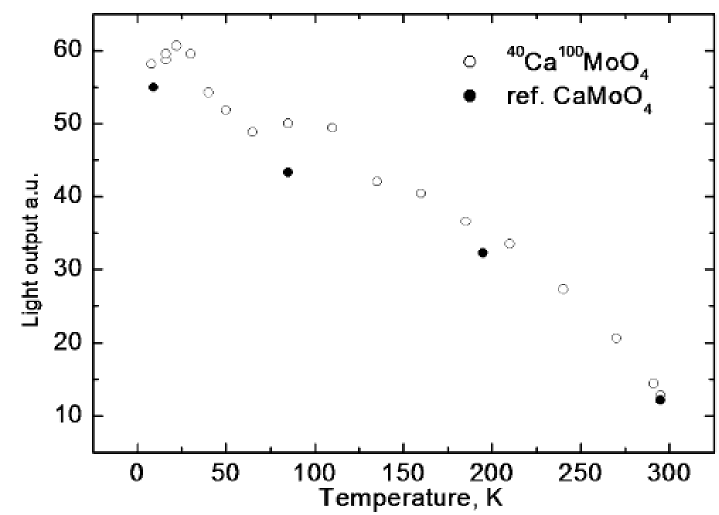
# $^{40}Ca^{100}MoO_4$ crystals

- Enrichment of $^{100}Mo$ (natural abundance : 9.6%)
  - Gas-centrifuge method
  - Enrichment of $^{100}Mo$ is higher than 96%.

- Depletion of $^{48}Ca$ (natural abundance : 0.157%)
  - Electromagnetic separation
  - Composition of $^{48}Ca$ is less than 0.001 %.



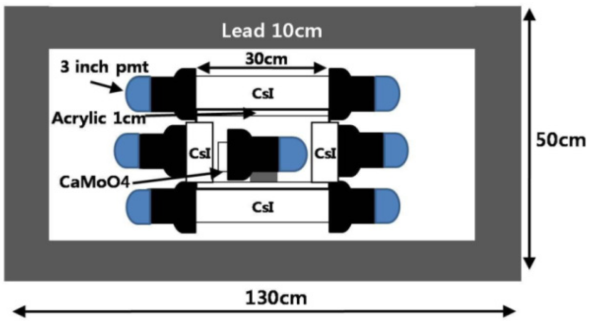





*Ref. Crystal research and Technology, 1-6(2011)*

# $^{40}Ca^{100}MoO_4$ crystals

4π gamma veto system




Measured at YangYang underground Laboratory (depth : 700 m )

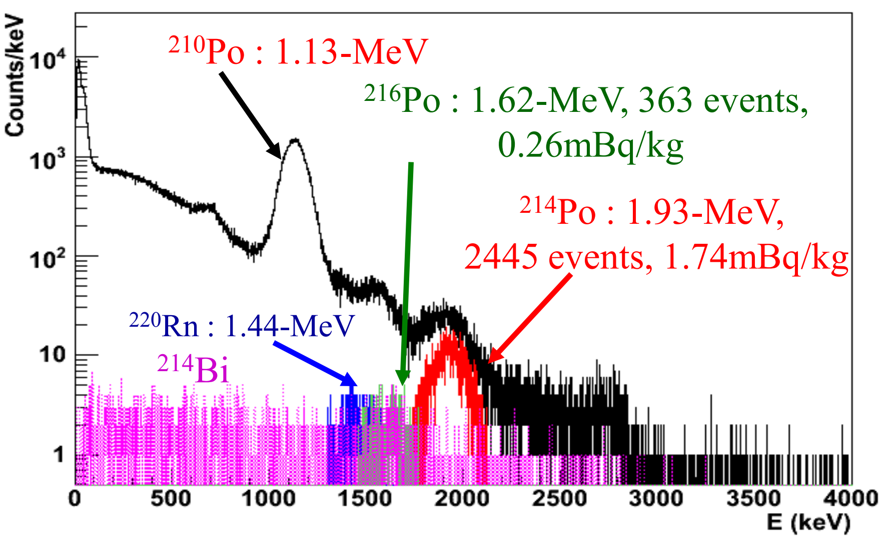
*β*-*α* decay in $^{238}U$

$^{214}Bi$ (Q-value : 3.27-MeV) → $^{214}Po$ (Q-value : 7.83-MeV)→ $^{210}Pb$

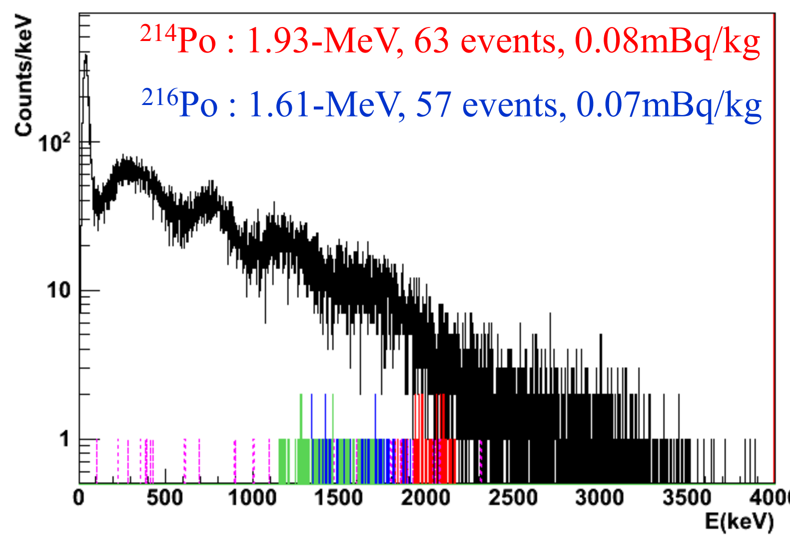
*α*-*α* decay in $^{232}Th$

$^{220}Rn$ (Q-value : 6.41-MeV) → $^{216}Po$ (Q-value : 6.91-MeV)→ $^{212}Pb$

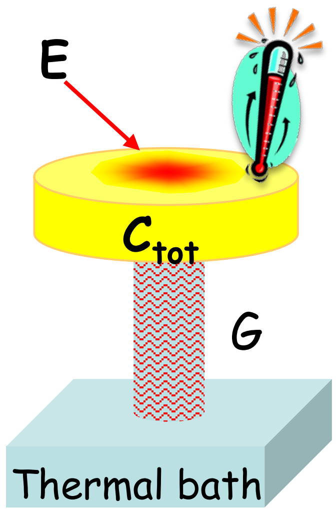
Crystal S35



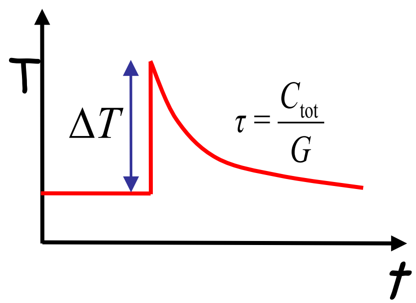

Crystal SB28



# Low temperature micro-calorimeters




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



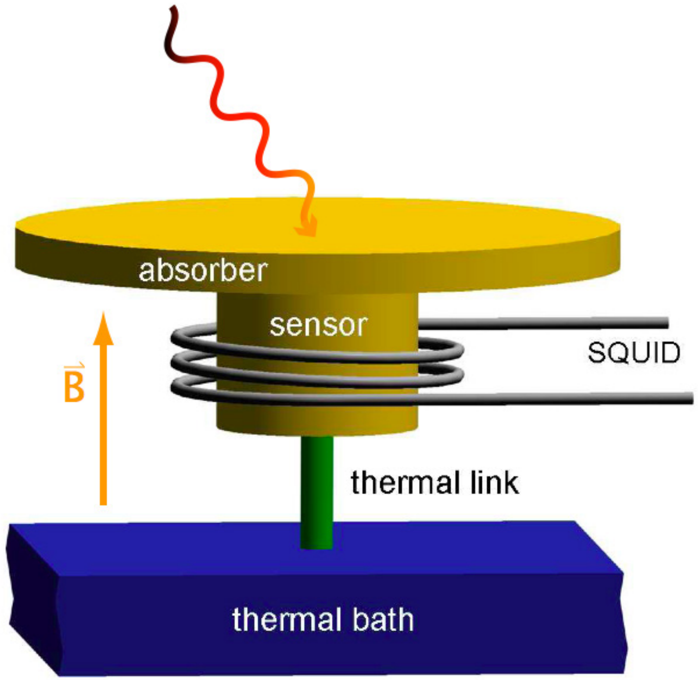

***E* = 1 MeV**

***C*$_{tot}$ = 1 nJ/K**

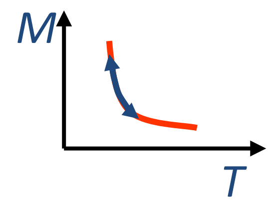
**→ ~ 0.1 mK**

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

# 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**

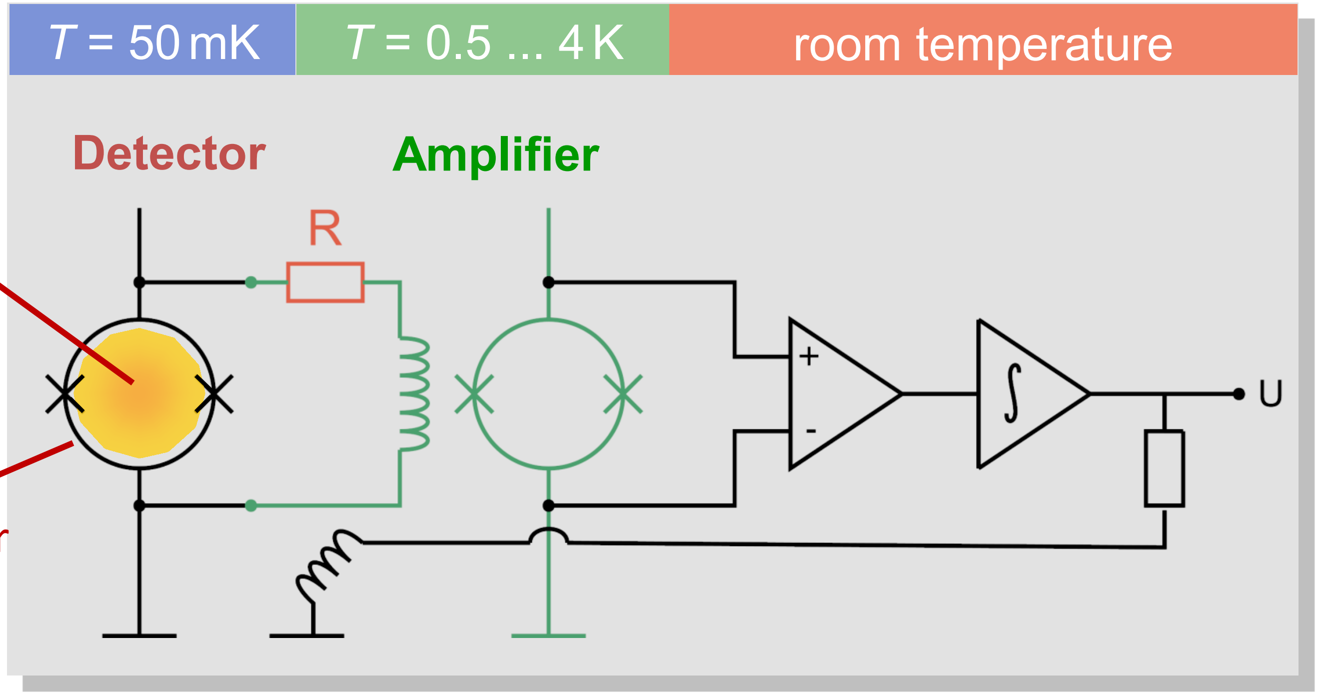
**no dissipation in the sensor**

**no galvanic contact to the sensor**

# MMCs: Readout

paramagnetic sensor

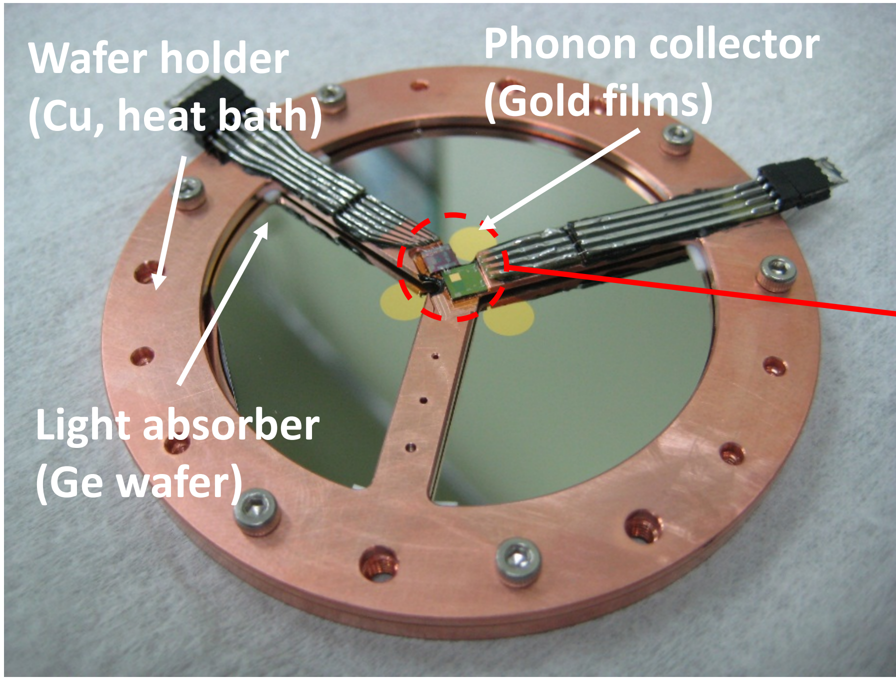
SQUID magnetometer

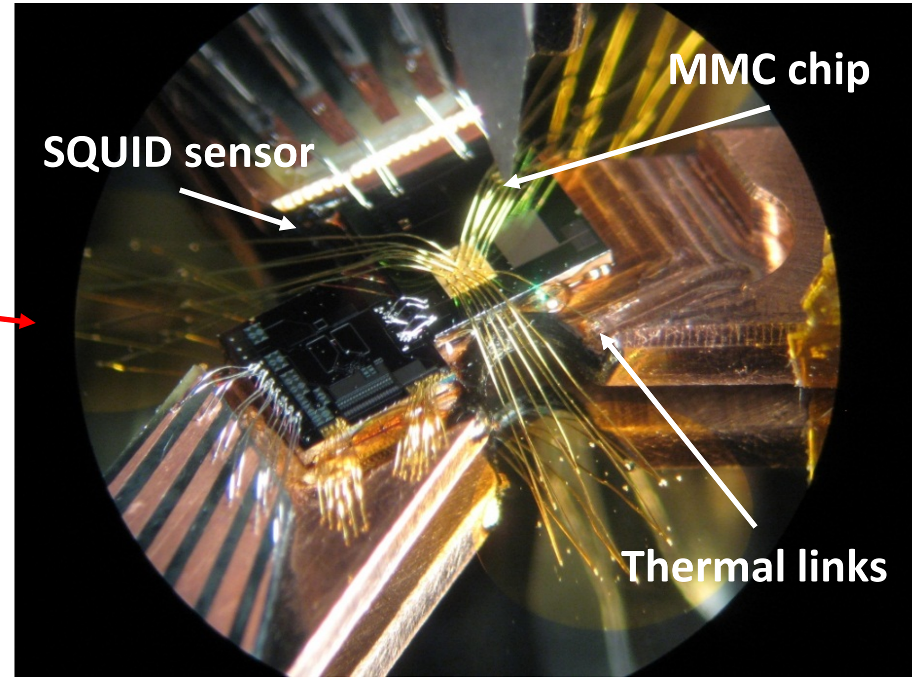



Two-stage SQUID setup  with flux locked loop to linearize the first stage SQUID allows for:

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

# Photon detector



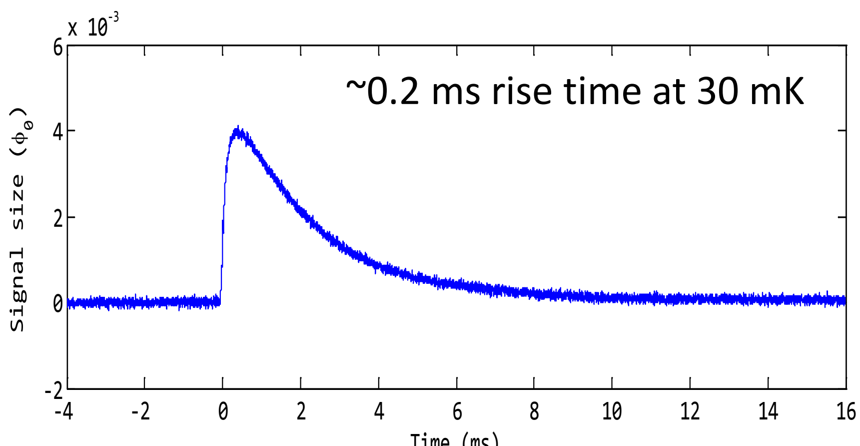



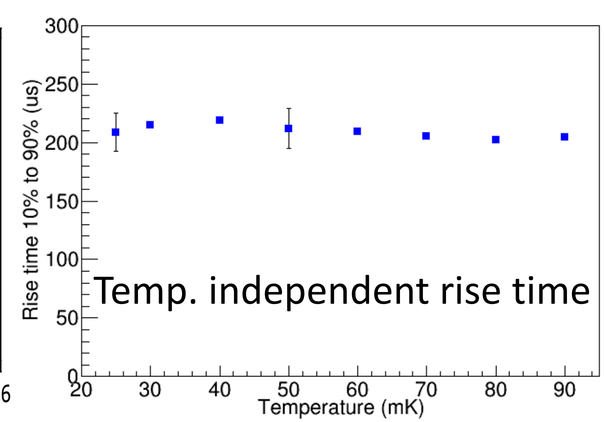

**# Three gold patterns**

- Thickness : 320 nm
- Diameter : 5 mm

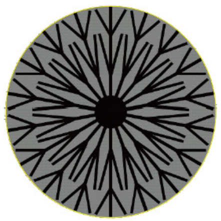
**# Ge wafer**

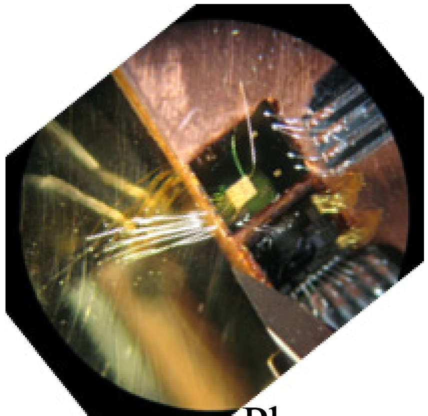
- Thickness : 500 *mm*
- Diameter : 2 inch



# Detector Assembly using $^{40}Ca^{100}MoO_4$ crystal

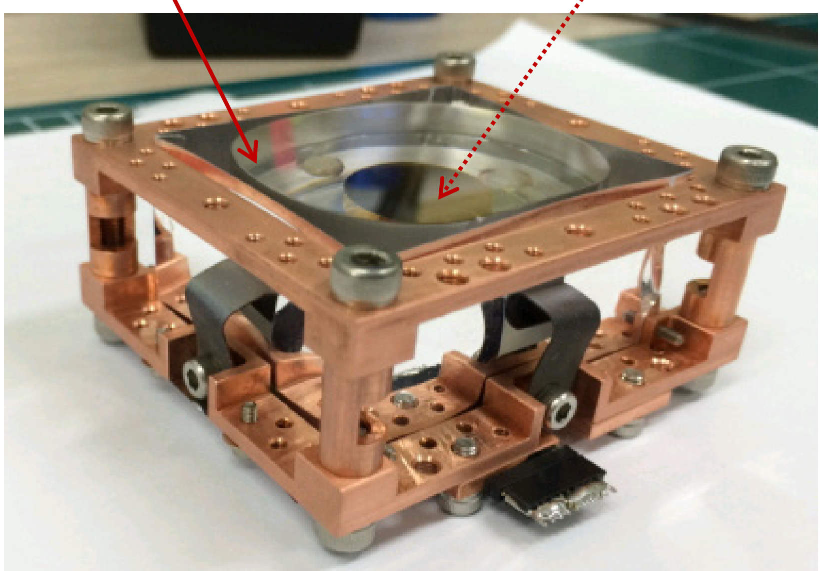


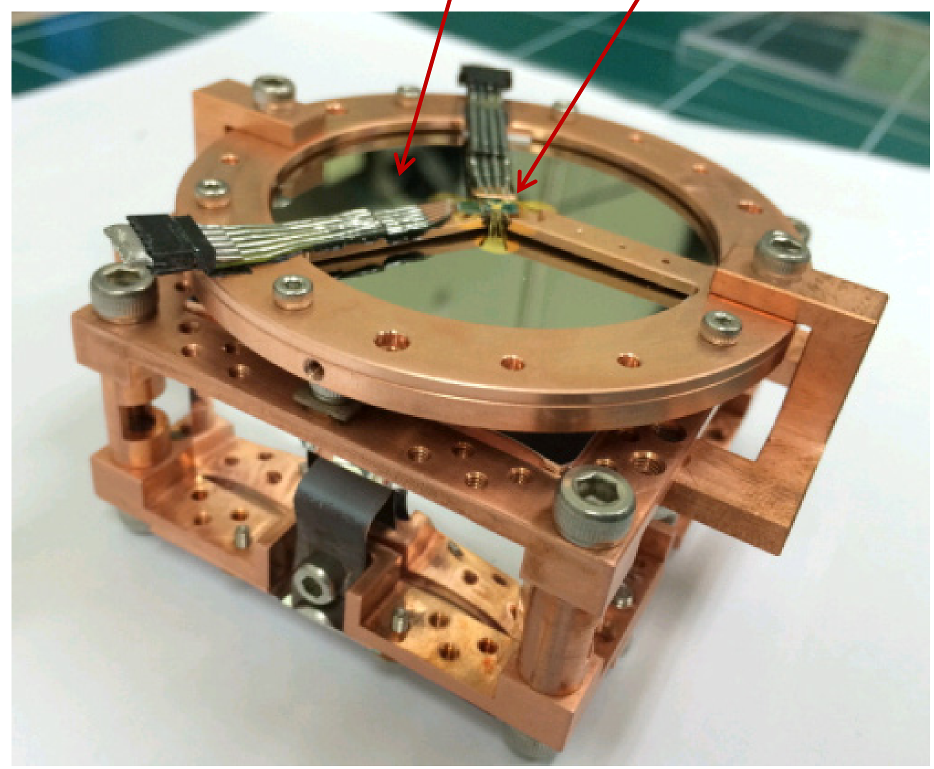


Light detector
2 inch Ge wafer + MMC

Phonon collector film
on bottom surface

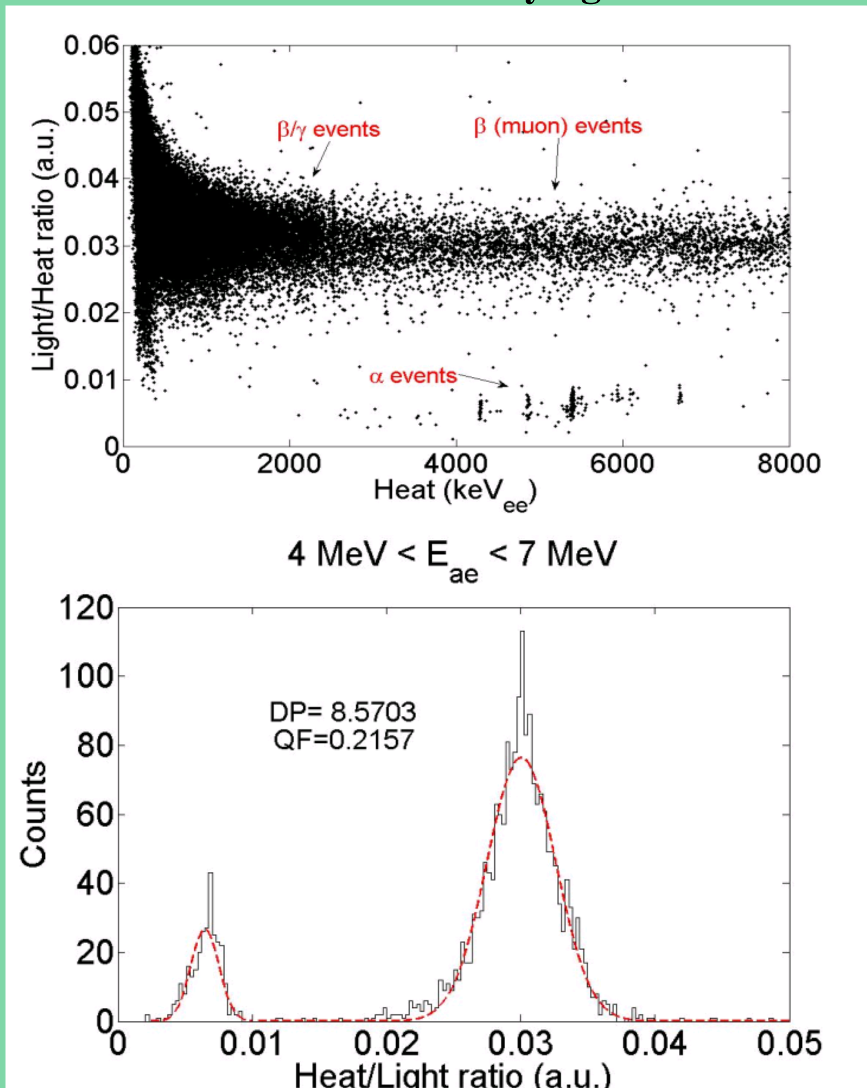
196 g $^{40}Ca^{100}MoO_4$
(doubly enriched crystal)



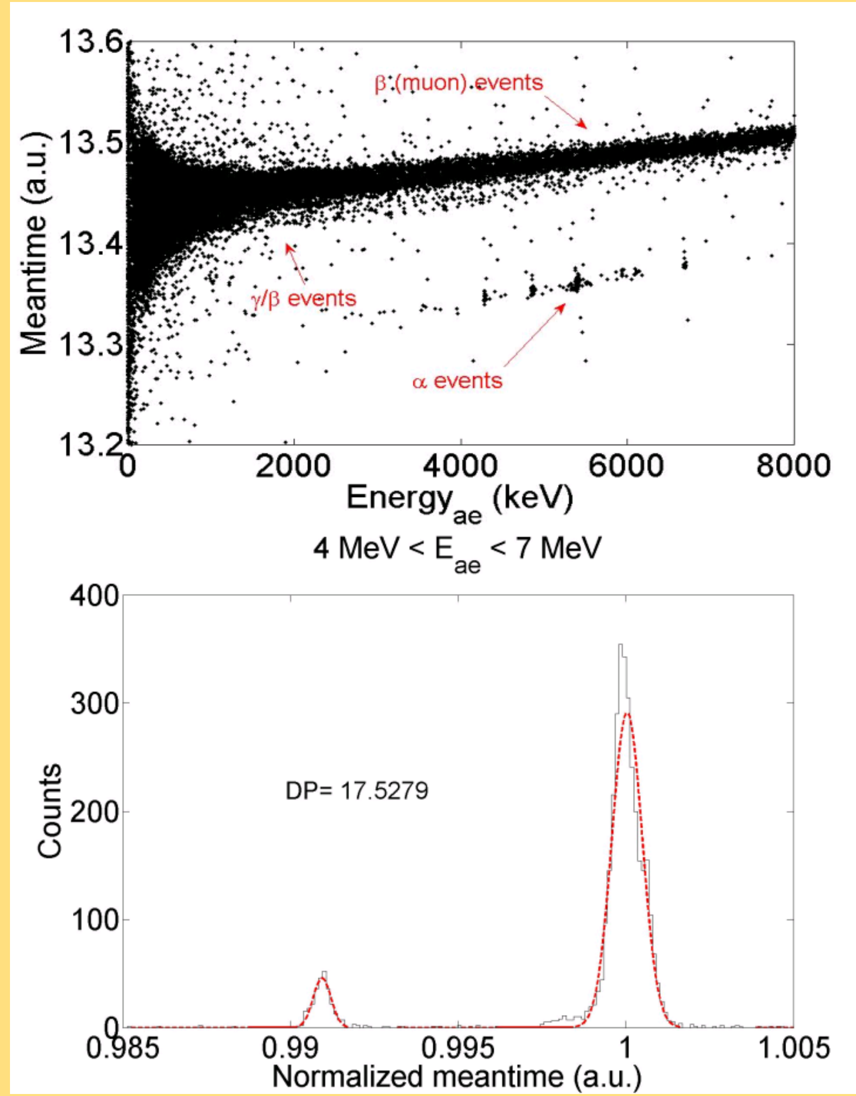


# Particle discrimination

## Particle discrimination by light heat ratio

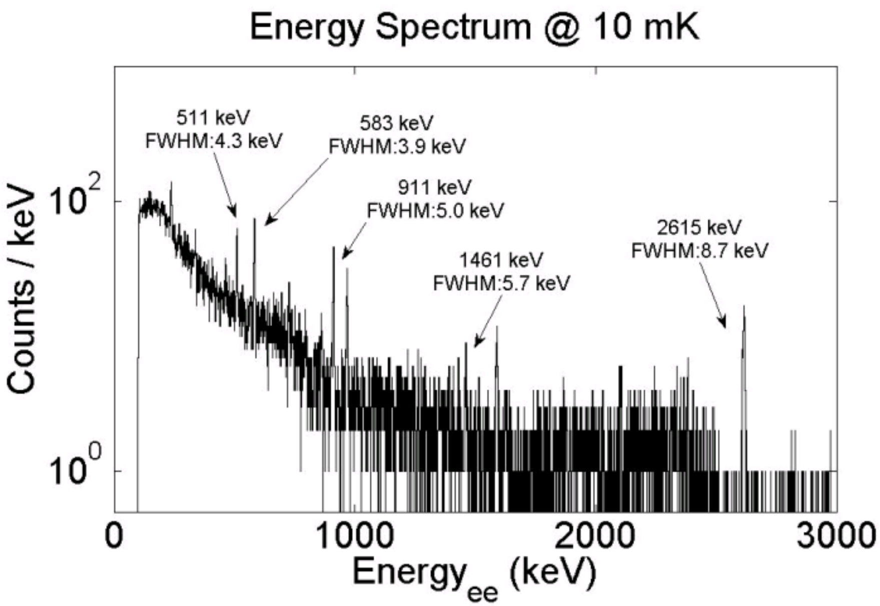



## Phonon pulse shape discrimination (PSD)

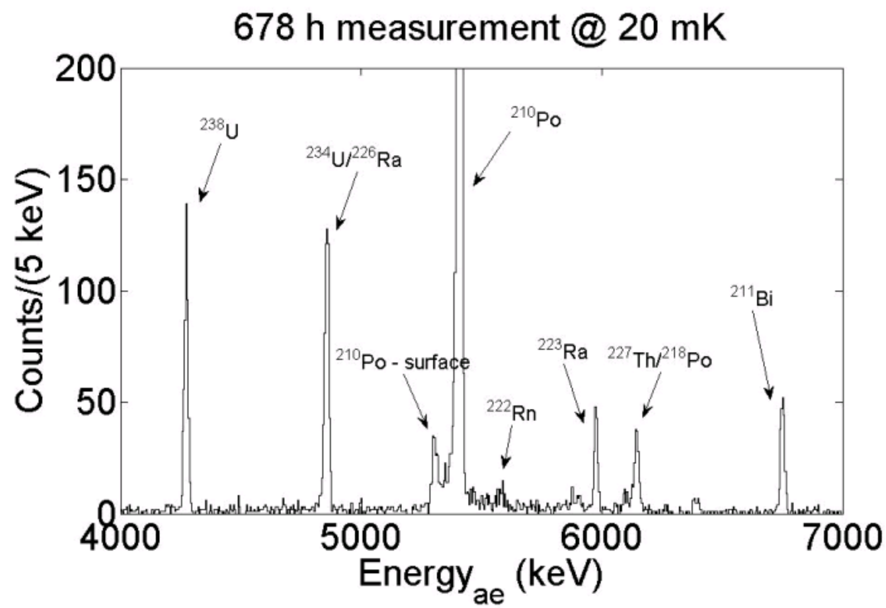


# Energy spectrum (Phonon above ground)

**Gamma background events**



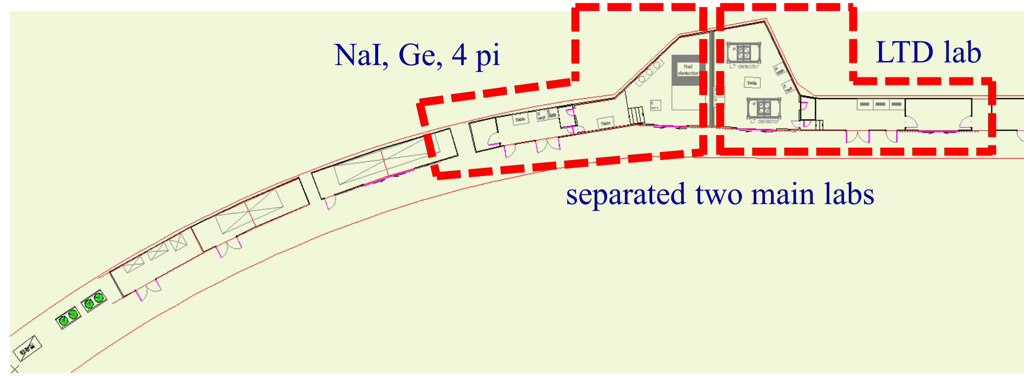

**Selected alpha events**

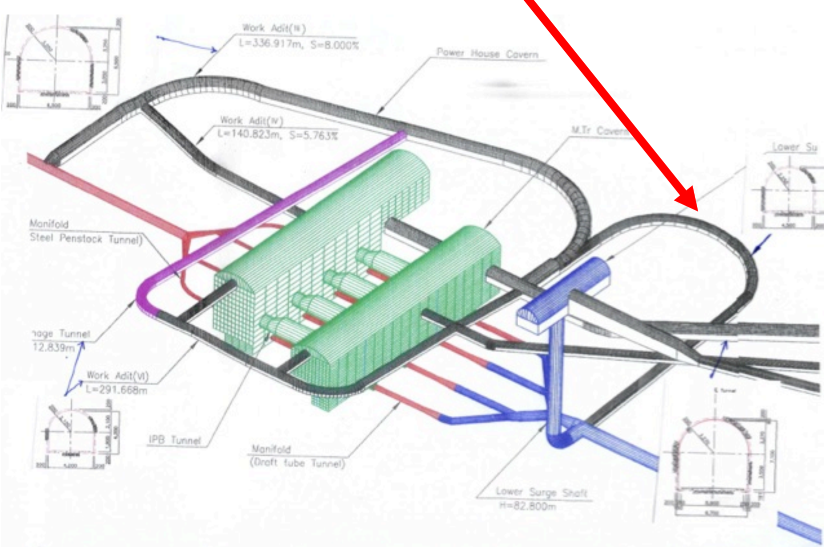



- Better than 10 keV energy resolution was obtained at 10 mK temperature.
- Internal alpha background levels of each isotopes were calculated successfully.

# YangYang underground laboratory (Y2L)


AMoRE-pilot and AMoRE-10 will be run at Y2L.
AMoRE-200 will be run at other place. (New underground lab.)




Yangyang pumped storage Power Plant

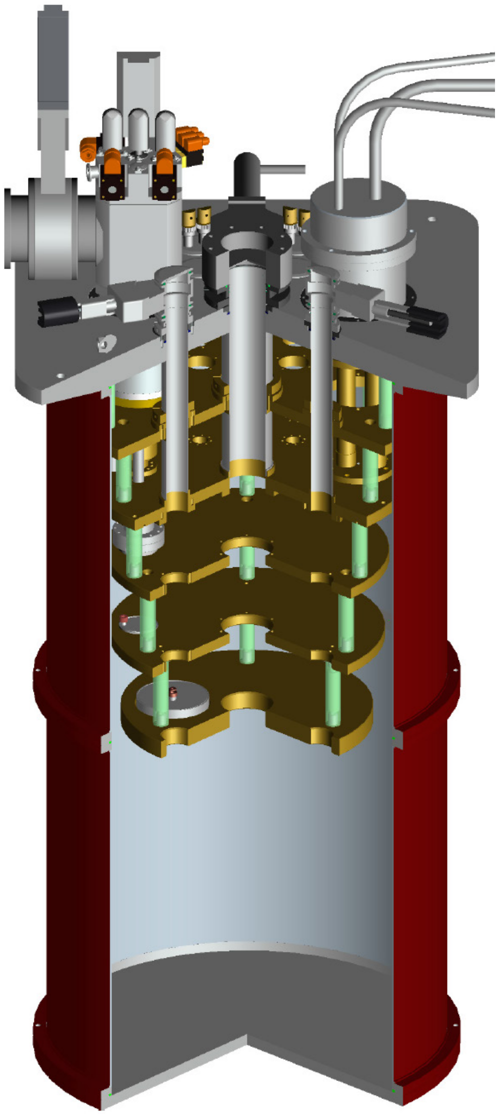
Minimum vertical depth : 700 m

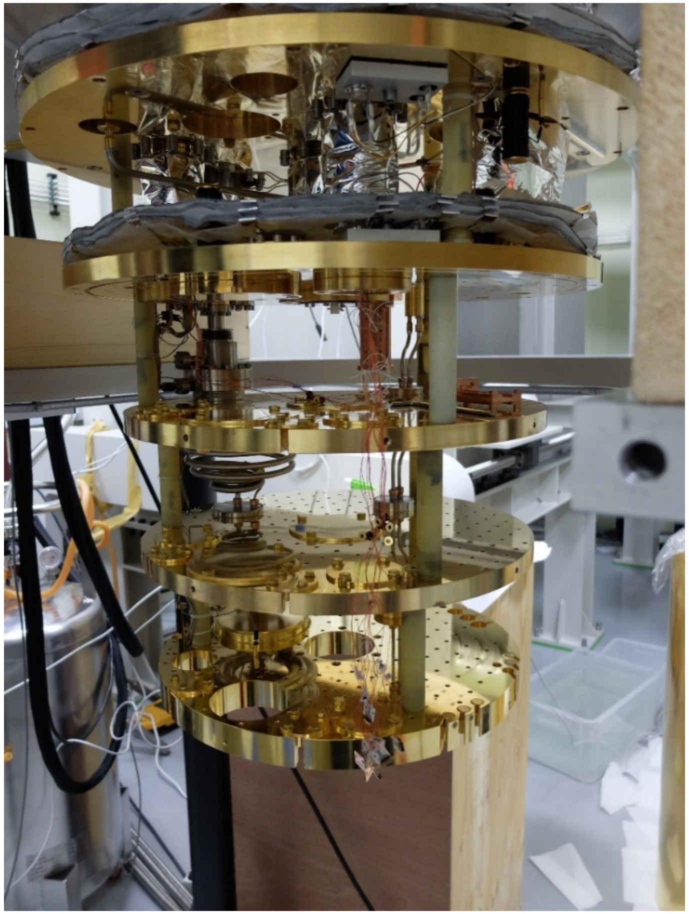
Access to the lab by car : around 2 km

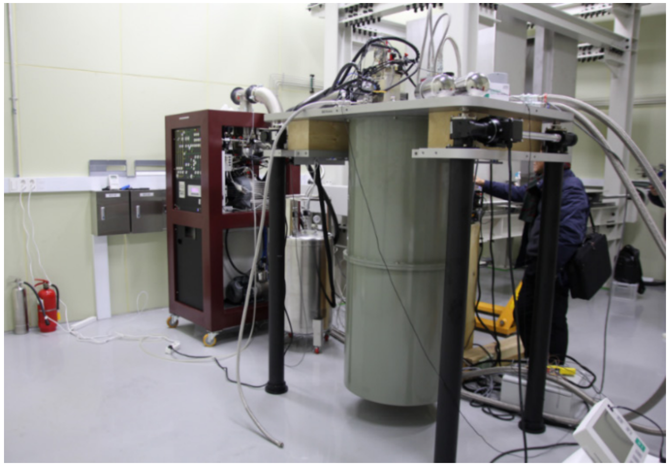
Experiments

- KIMS : dark matter search experiment
- AMoRE : 0$\nu$ $\beta\beta$ decay search experiment

# Cryostat : Cryogen Free Dilution Refrigerator





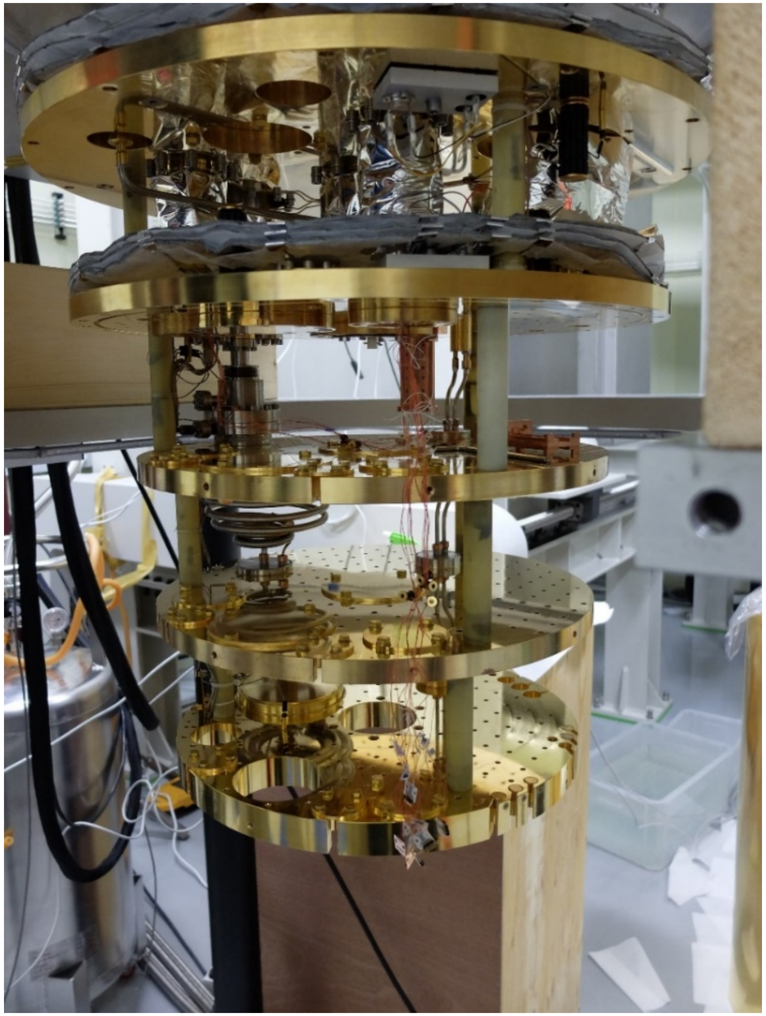


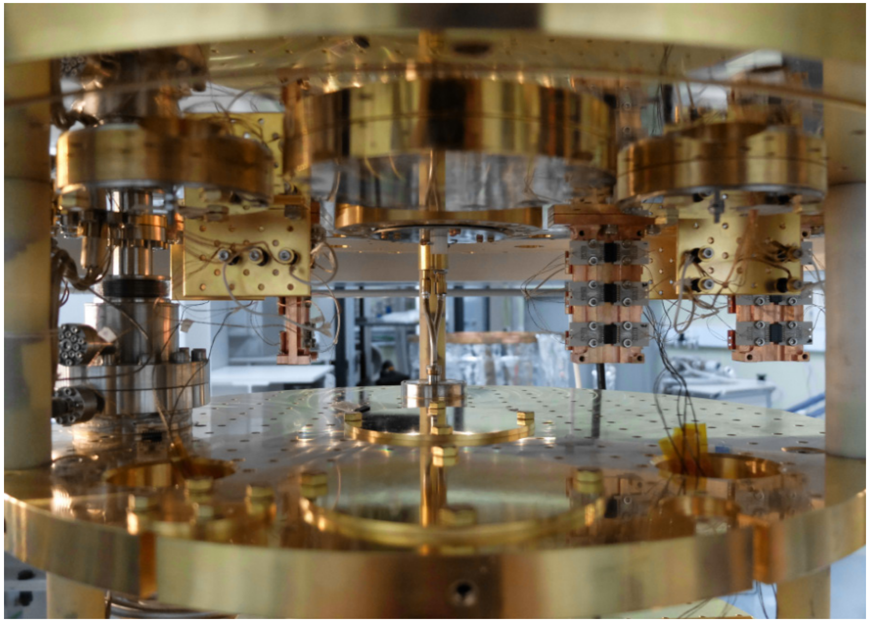
- CFDR for AMoRE-pilot and 10
- Leiden : CF-1200-maglav
- 50 K, 3 K, 1 K, 50 mK, and 10 mK
- 1.4 mW at 120 mK.
- Volume : (D) 408 mm x (H) 690 mm
- IVC : OFE Cu
- $T_{min}$ : 8.7 mK as tested.
- $t_{cooling}$ : 34 h without load

  43 h with 30 kg of Pb and Cu

# Cryostat : Cryogen Free Dilution Refrigerator

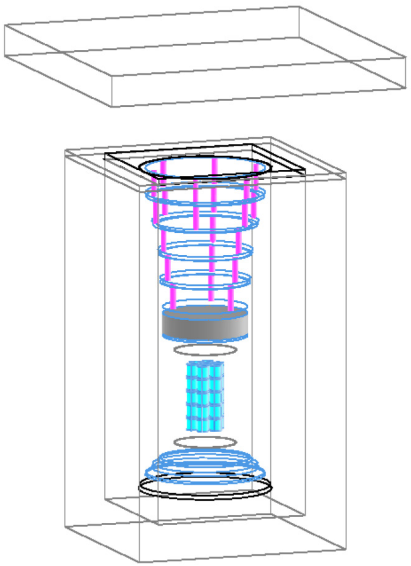
The background of materials are measuring ICP-MS and HPGe.



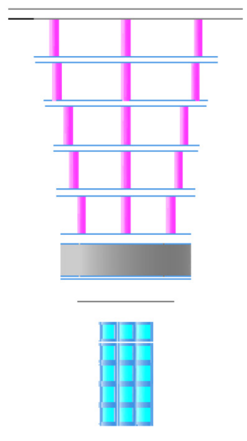


- There are so many parts in the CFDR.
  - Wires (NbTi, CuNi), Phosphor-Bronze support, G-10 support, bolts, Iron (Gantry), OFE Cu (IVC), NOSV Cu (holder), and so on.
- Most of the materials have been measured the background level.
- The results have been used for GEANT4 simulation.

# Simulation for expected background in ROI

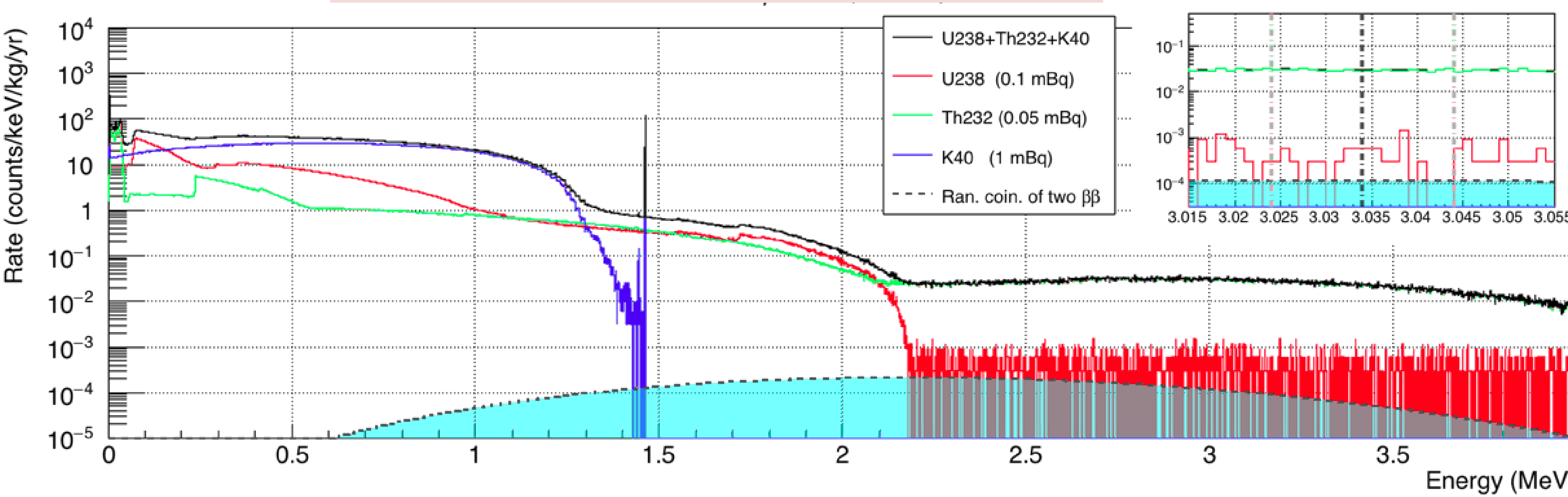


## External BG for AMoRE-10



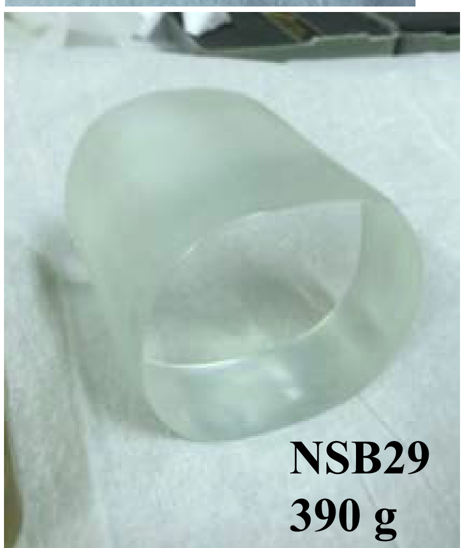
- The measured impurity level has been used for MC simulation.
- The external background can not give any events to AMoRE-10.
- We need more consideration about materials for AMoRE-200.
- The internal background of CMO crystals have been measure at Y2L.
- The most effective background is caused by $^{208}Tl$ in the crystals.

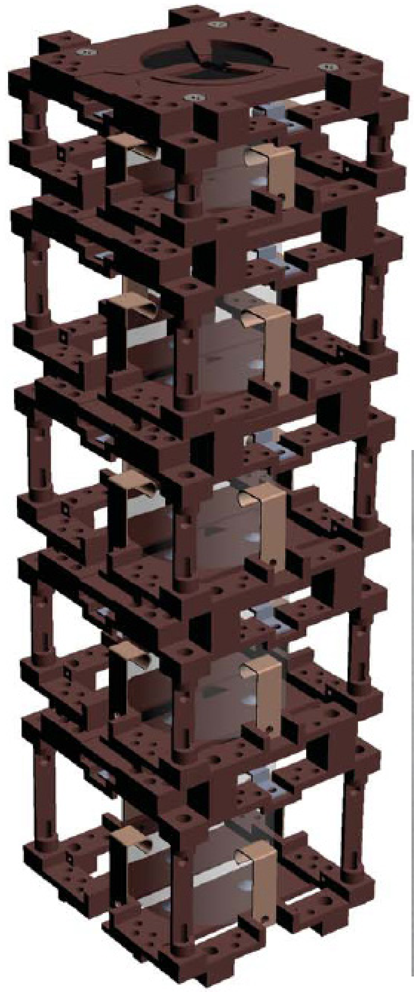
## Internal BG of CMO crystals for AMoRE-10

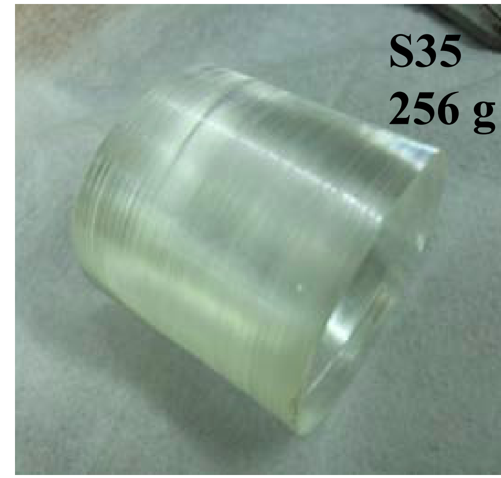


# $^{40}Ca^{100}MoO_4$ crystals for AMoRE-pilot

Total mass of crystals ~ 1.5 kg

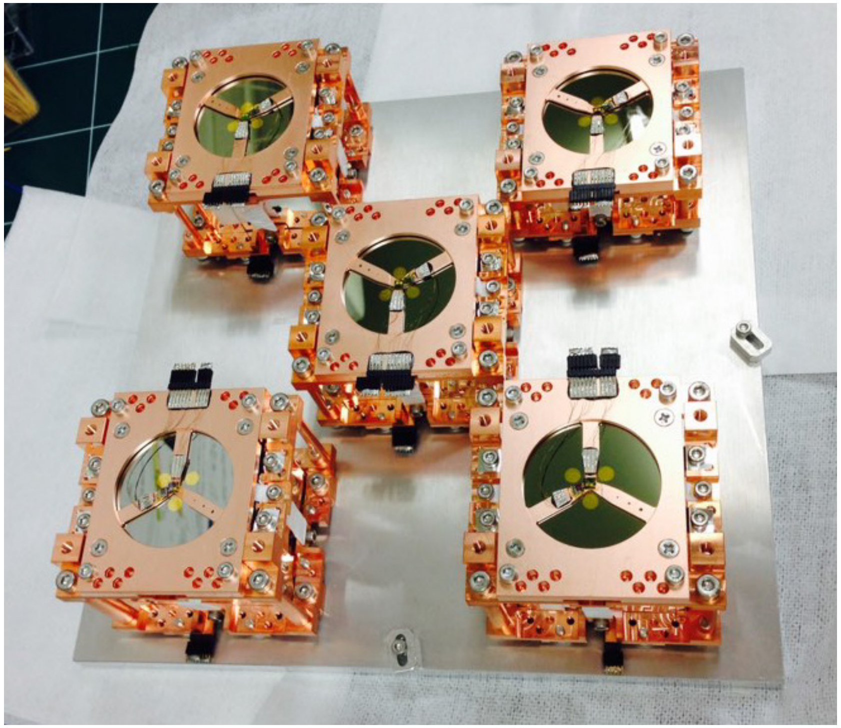



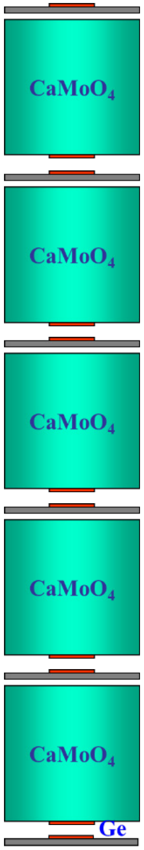



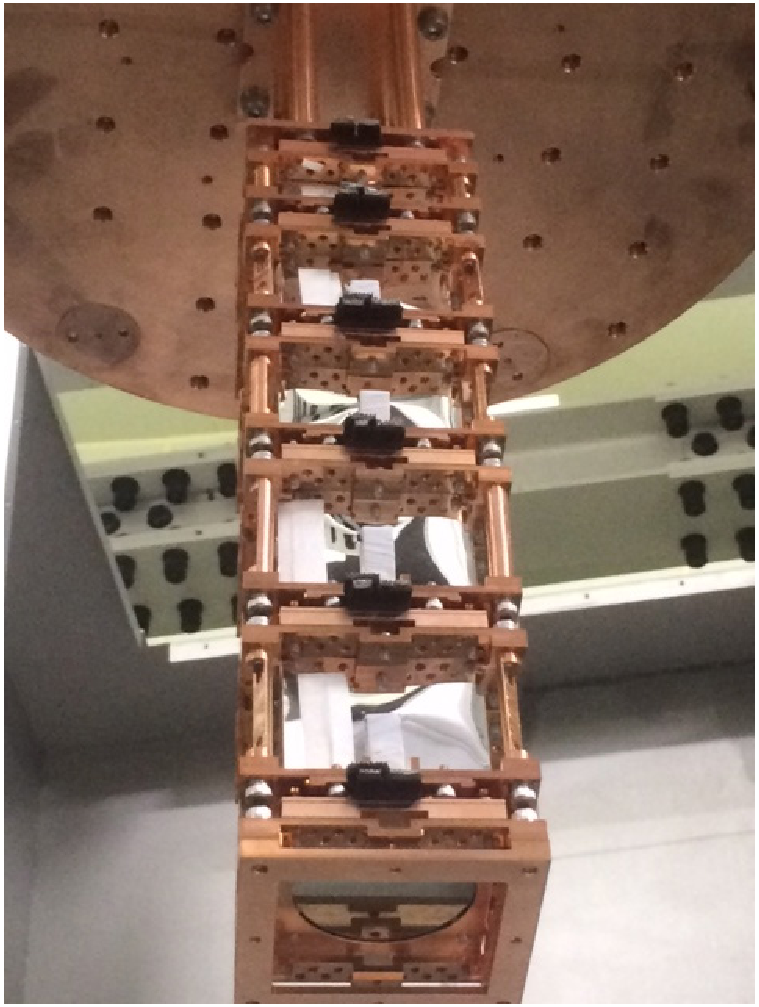




# Scintillating crystals ready to be measured

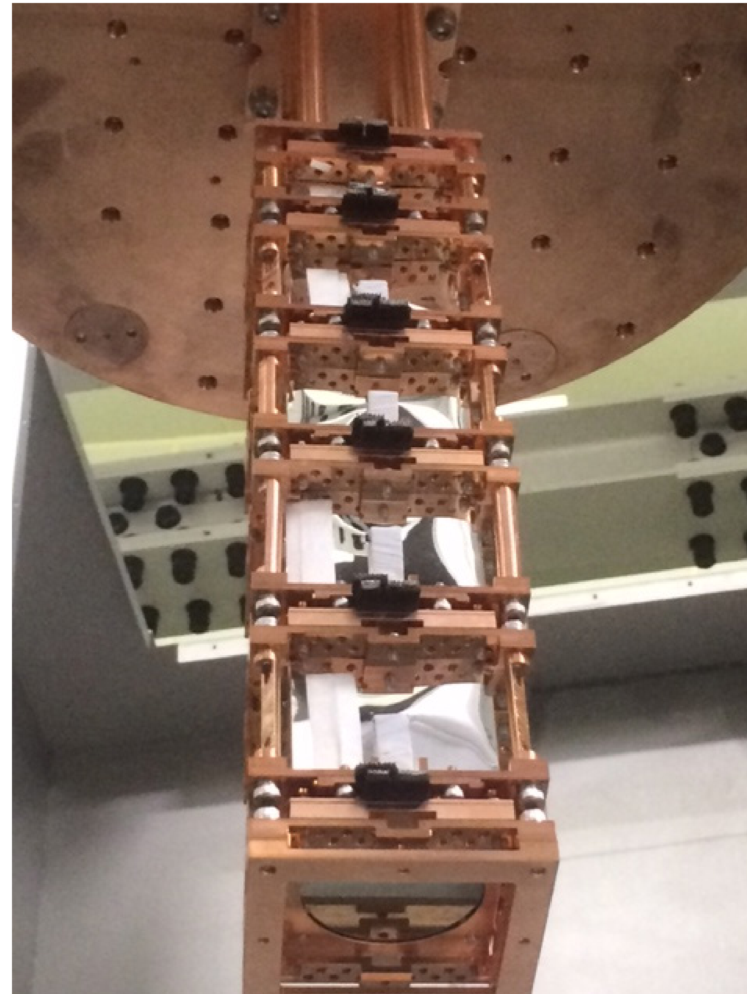




- 5 detectors cells have been assembled last week.
- installed in the cryostat with inner Pb shielding.
- We will start to measure soon!!!

# Scintillating crystals ready to be measured



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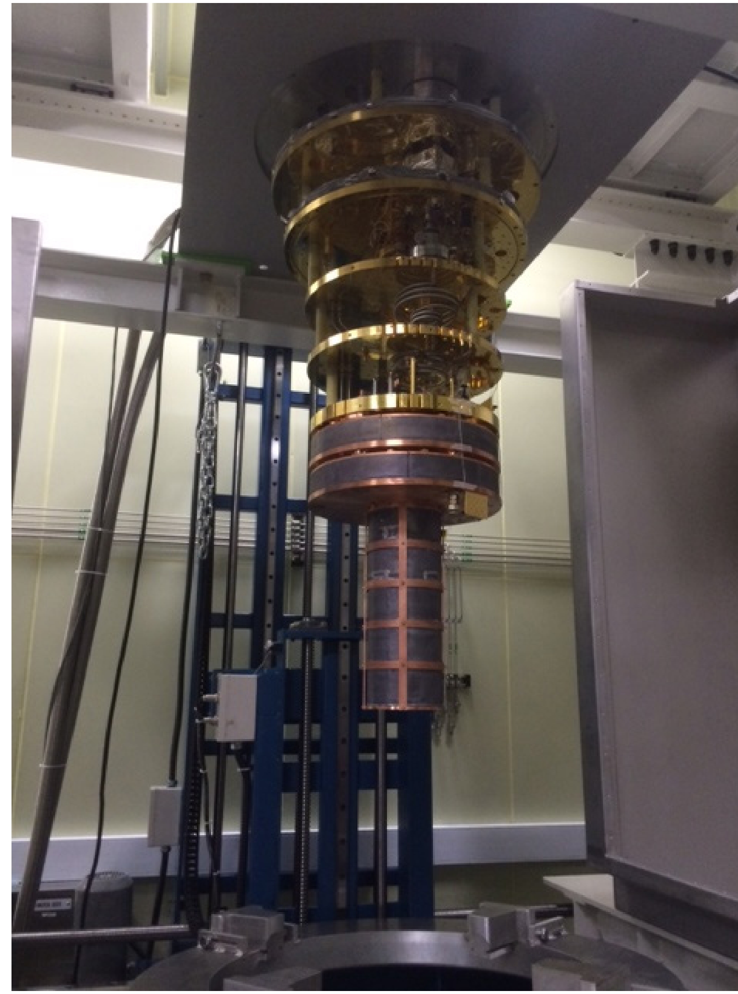

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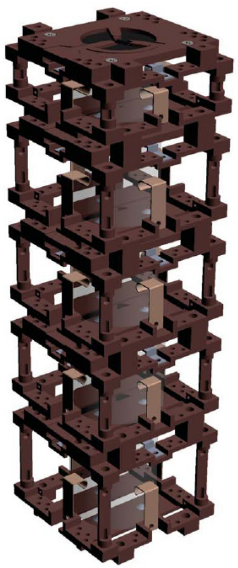
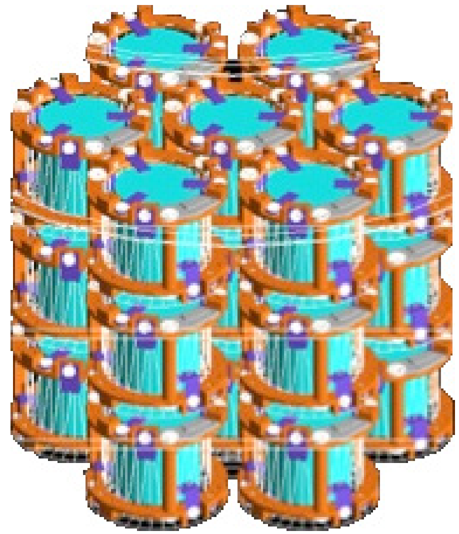
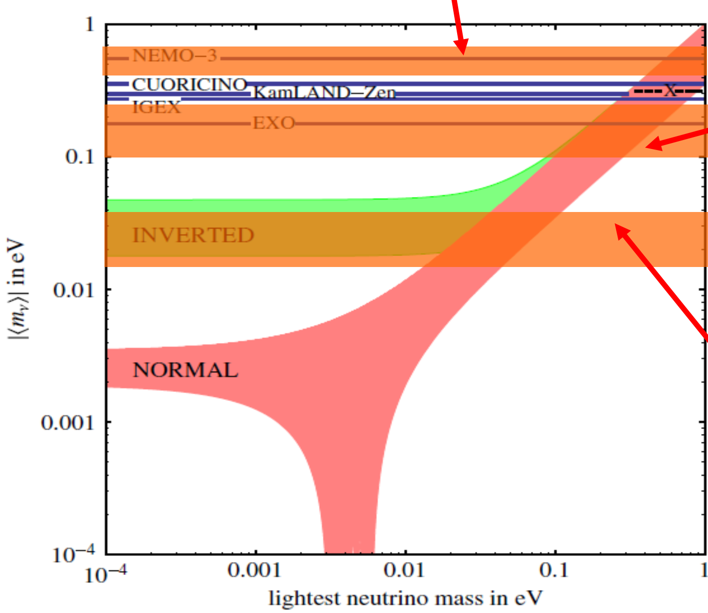
# Present and Future of AMoRE



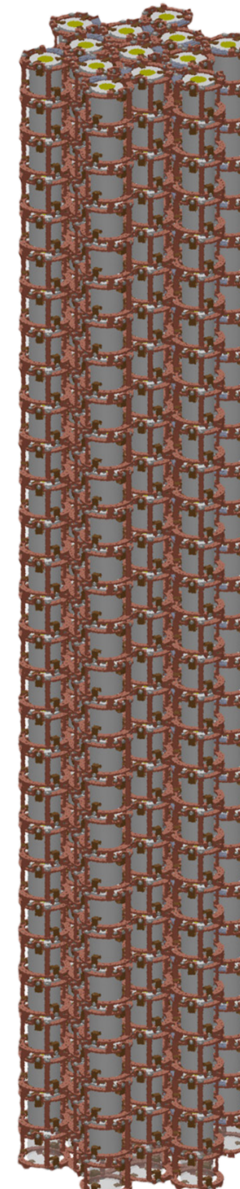
AMoRE-pilot (Now)
1.5 kg of $^{40}Ca^{100}MoO_4$
(2015~)



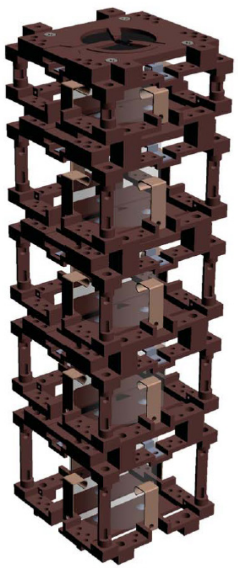
AMoRE-10
10 kg of $^{40}Ca^{100}MoO_4$
(2016~2018)




AMoRE-200
$^{40}Ca^{100}MoO_4$ (D=50mm, H=60mm, 506g)
30 layers(2.4 m height)-13 columns
or 20 layers(1.6 m height)-19 columns
Total mass of $^{40}Ca^{100}MoO_4$ : 200 kg
(2018~2022)



# Present and Future of AMoRE



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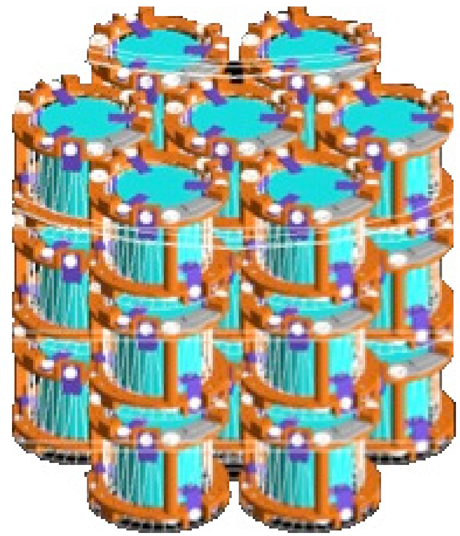
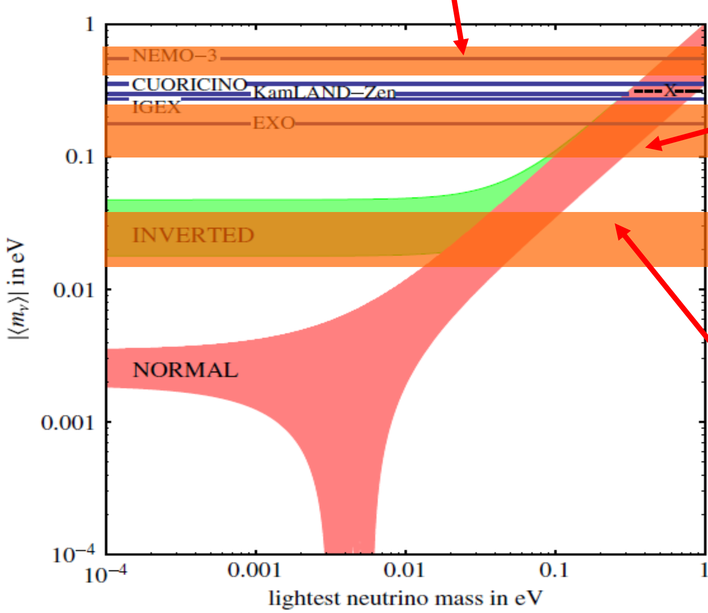


AMoRE-10
10 kg of $^{40}Ca^{100}MoO_4$
(2016~2018)




Thank you!

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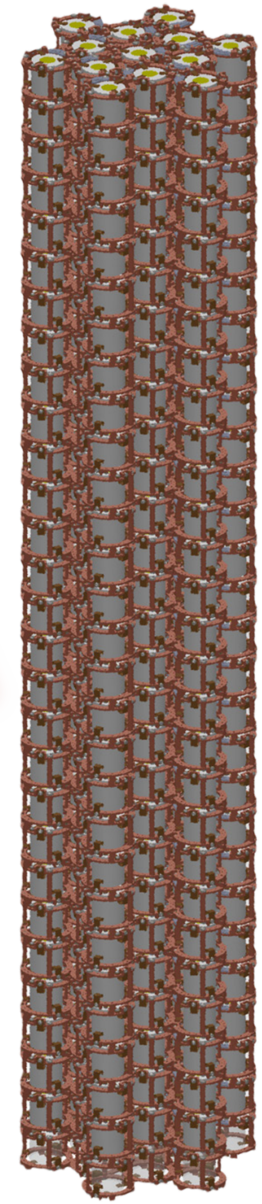
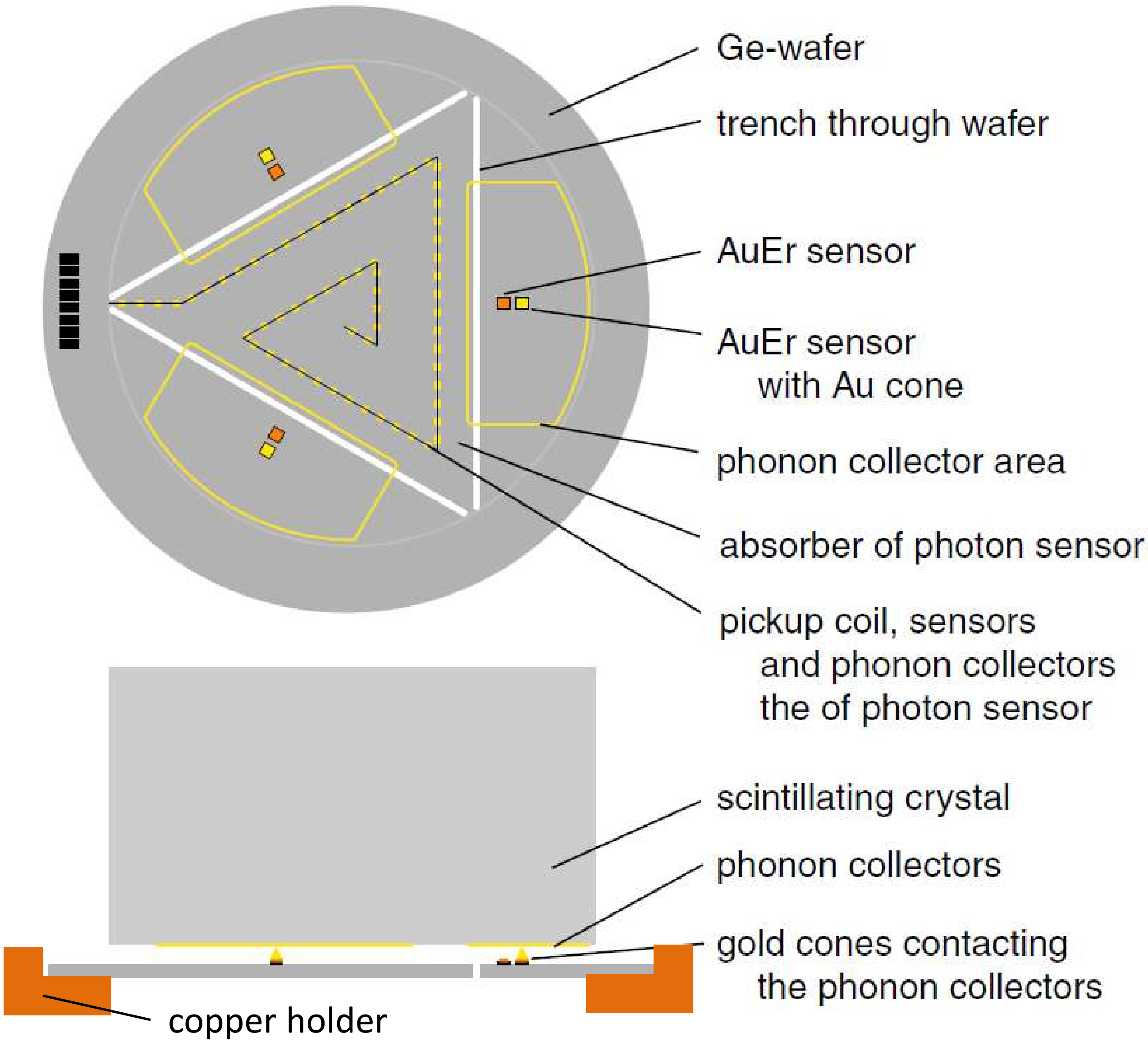
Total mass of $^{40}Ca^{100}MoO_4$ : 200 kg
(2018~2022)

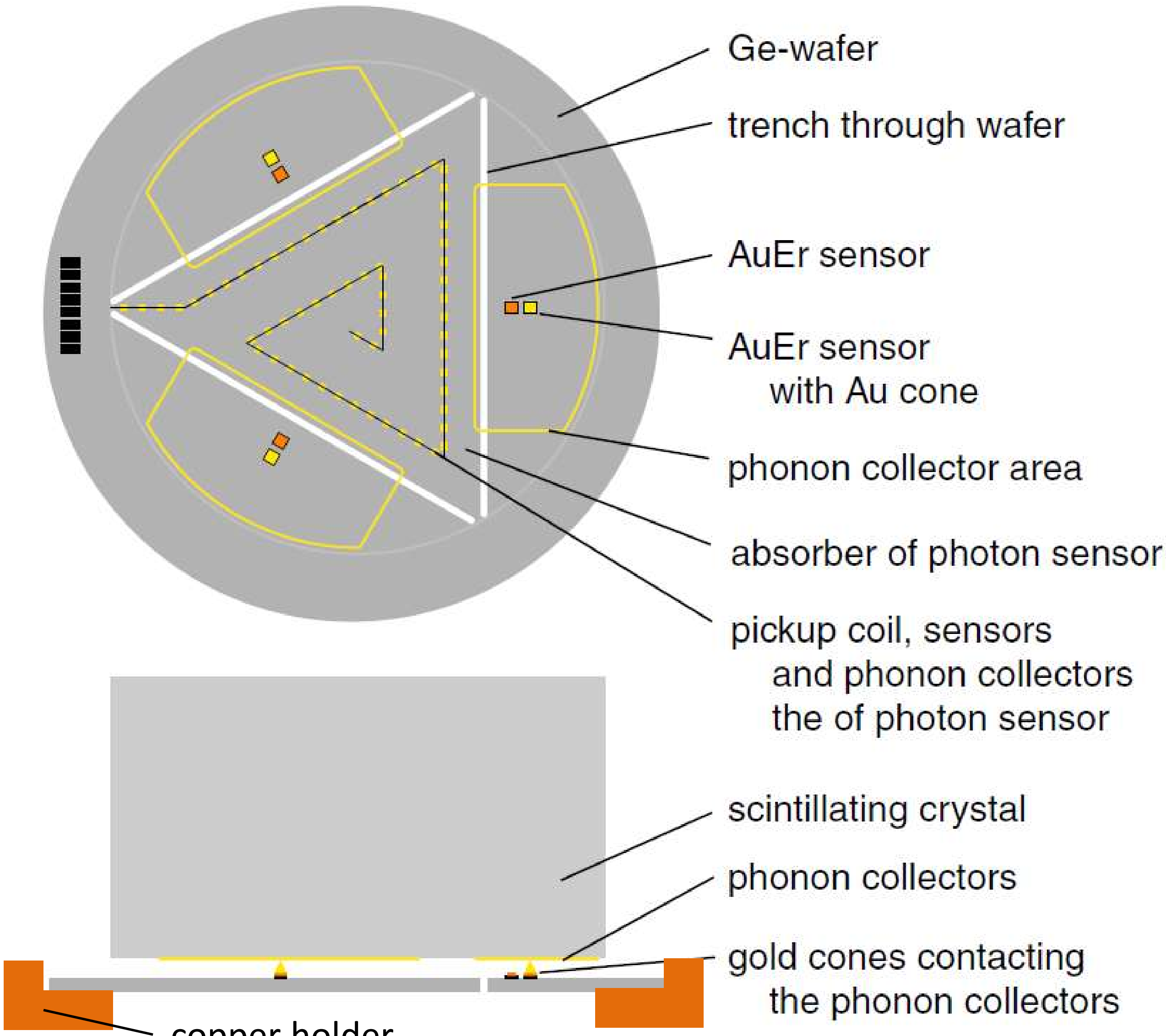


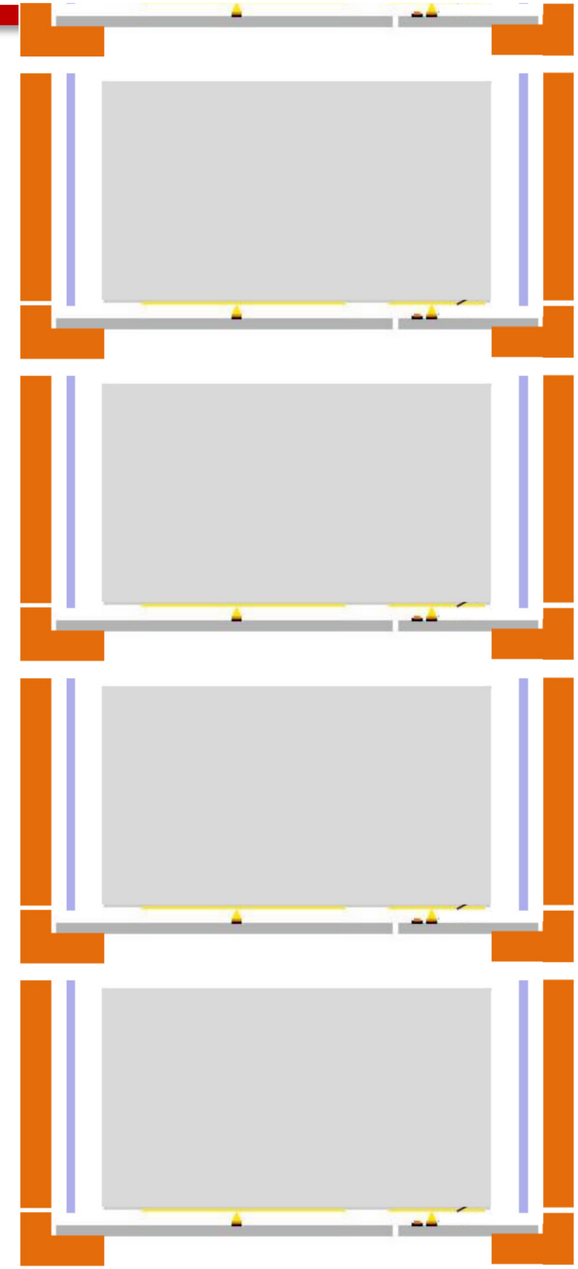
# Present and Future of AMoRE

# Combined photon and phonon detector: P2



# Combined photon and phonon detector: P2

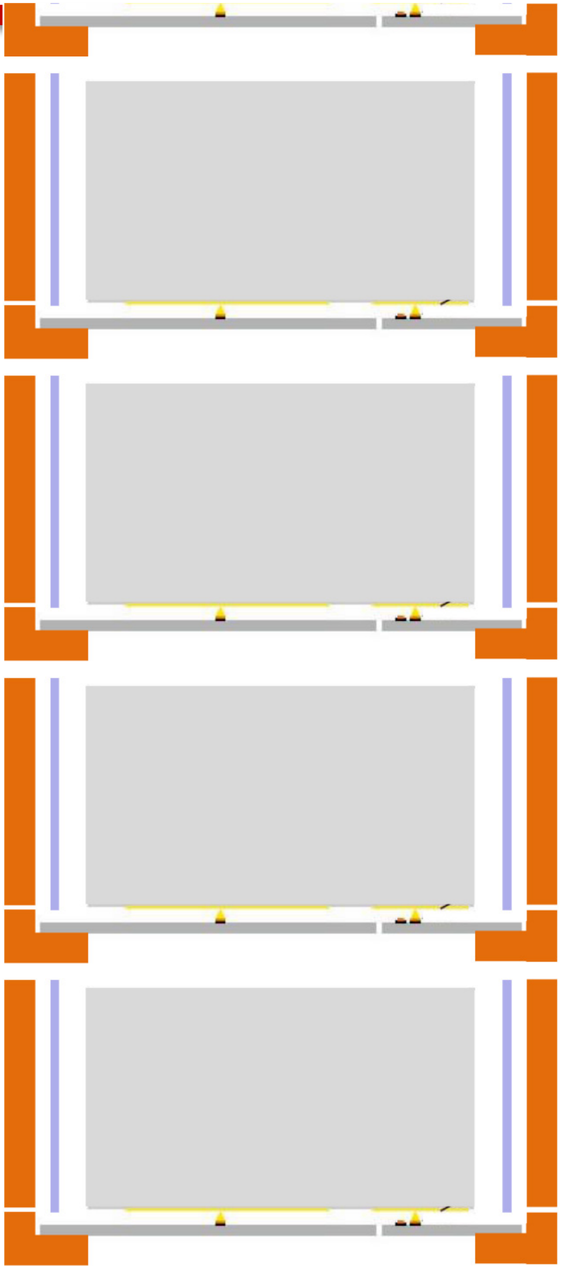


# Combined photon and phonon detector: P2

- Phonon detector:
  - energy resolution $\Delta E_{FWHM}$ = 50 -100 eV
  - rise time $\tau$ < 200 µs
- Photon detector:
  - energy resolution $\Delta E_{FWHM}$ = 3 -10 eV
  - rise time $\tau$ < 50 µs
- A minimum of (contaminated?) parts
- Two light detectors per crystal
- Position sensitivity, if wanted

→ reduce and discriminate
intrinsic contamination background



# Combined photon and phonon detector: P2

- Phonon detector:
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- A minimum of (contaminated?) parts
- Two light detectors per crystal
- Position sensitivity, if wanted

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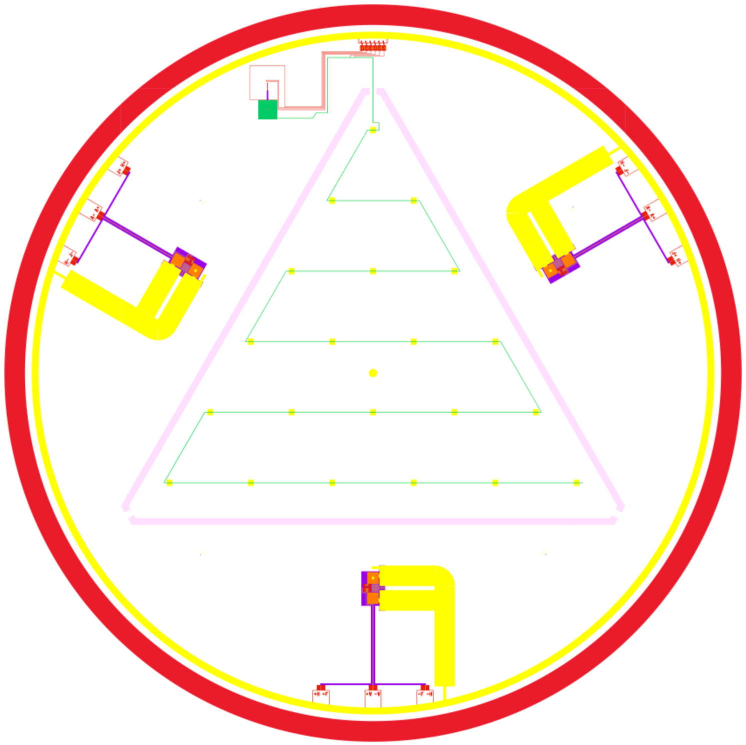
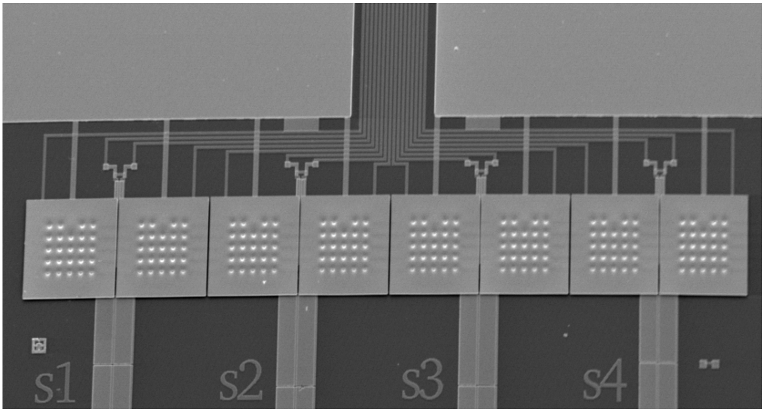
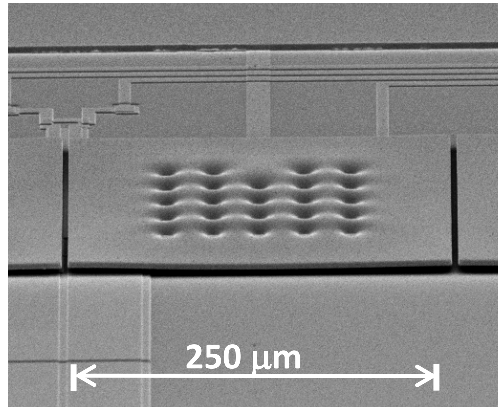
intrinsic contamination background

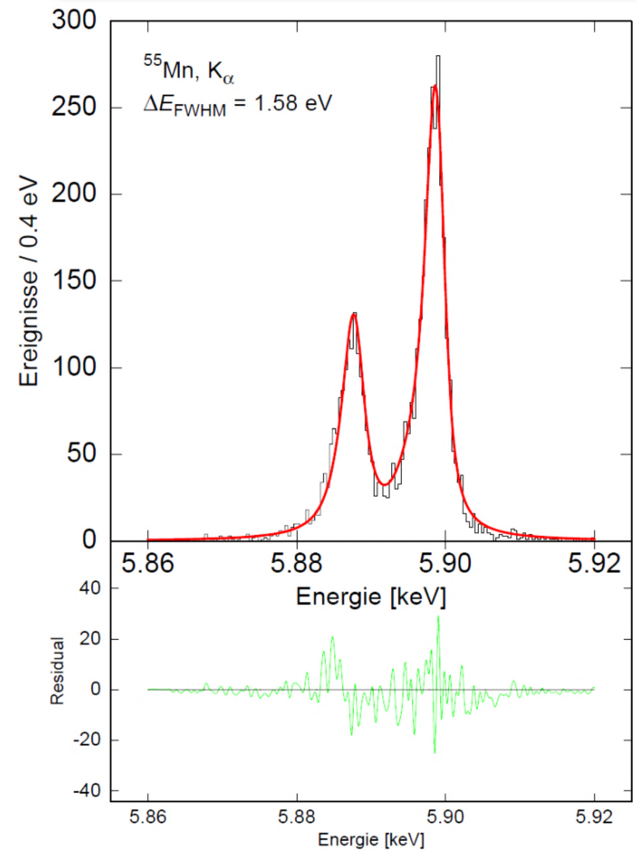


# MMCs: performance

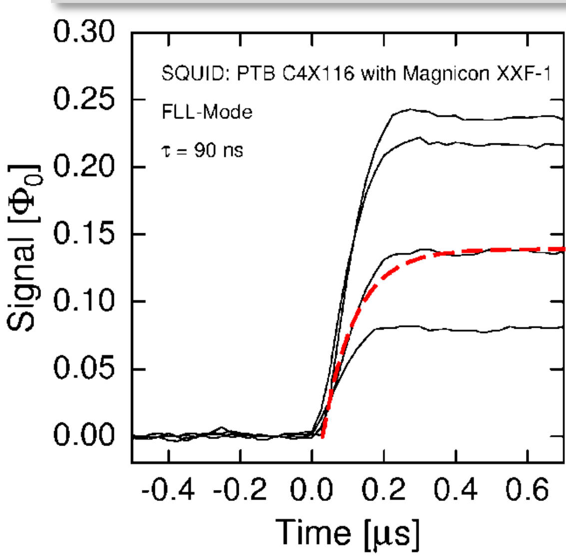


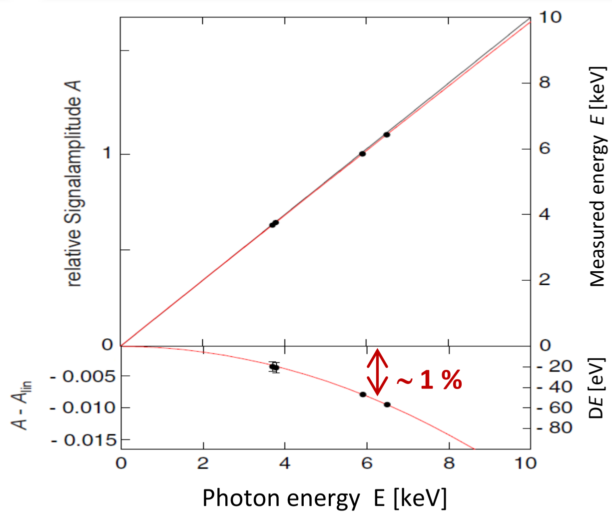

**$\Delta E_{FWHM}$ = 1.6 eV @ 6keV**




**Rise Time: 90 ns**

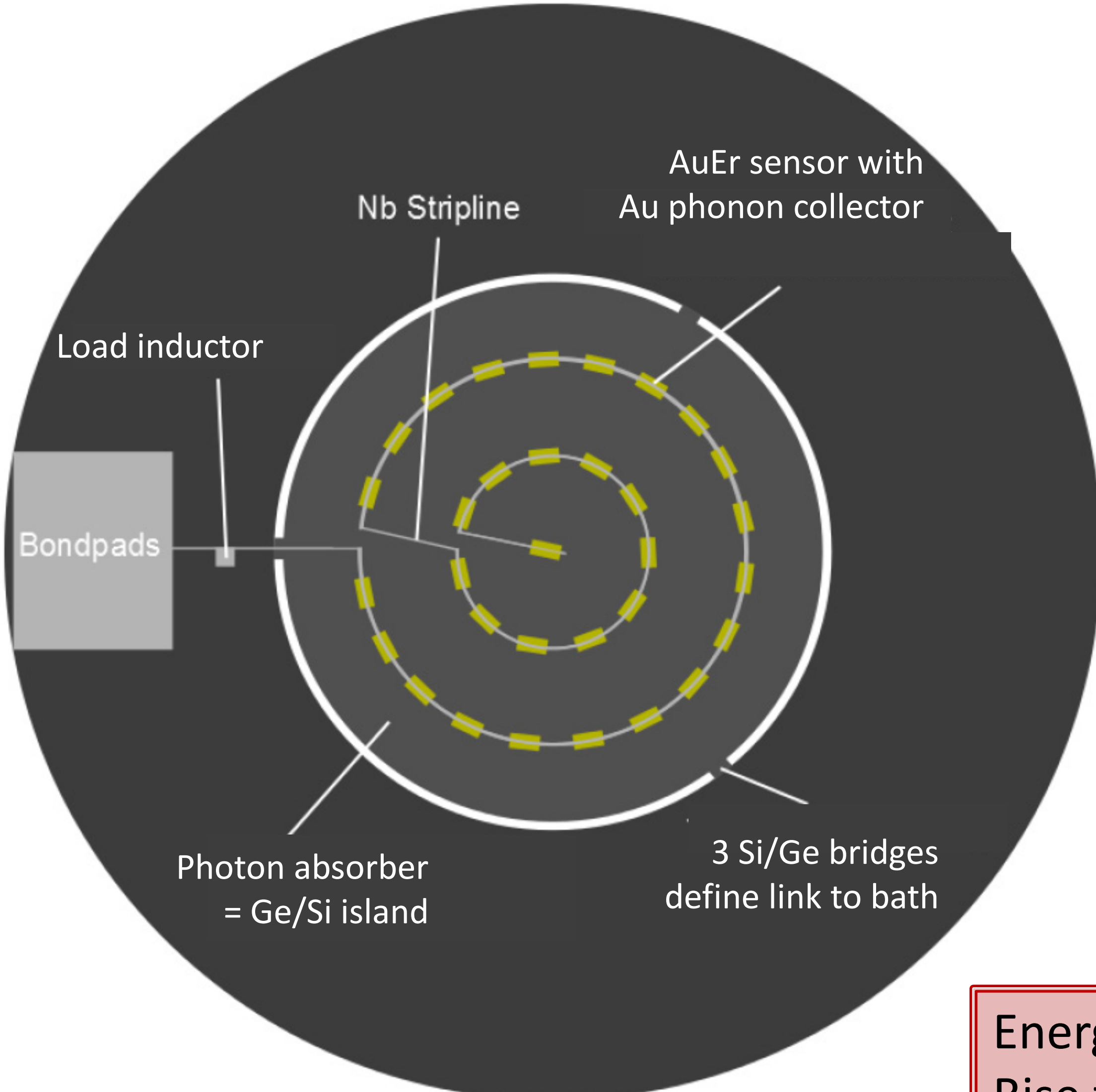



**Non-Linearity<1% @6keV**

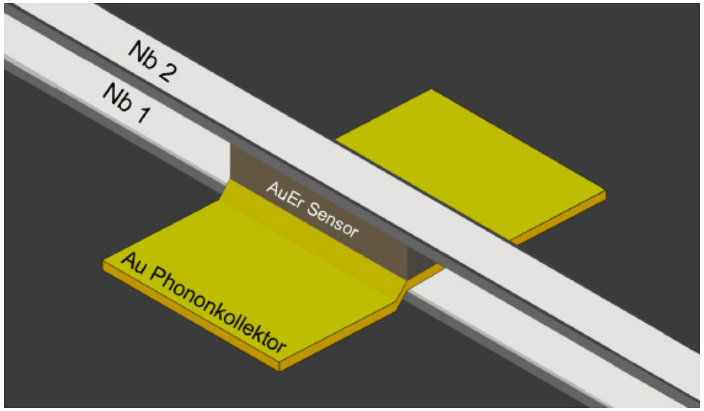



Background identification and better endpoint region analysis

# MMC-based photon detector: P1 design

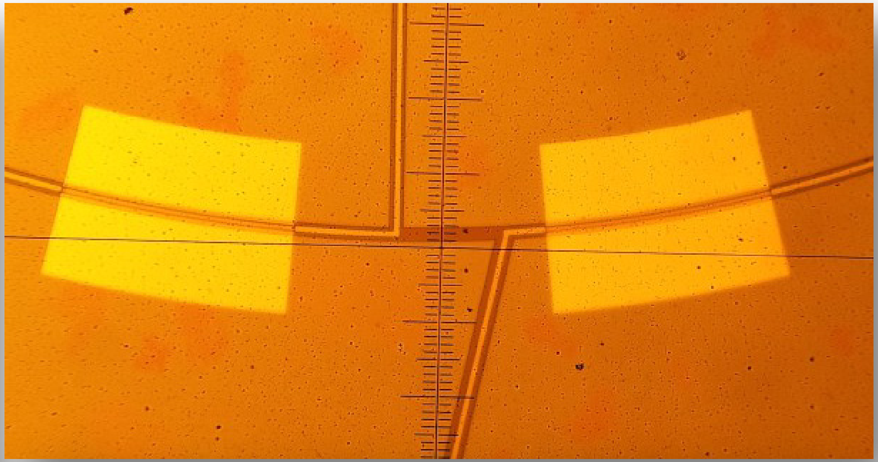


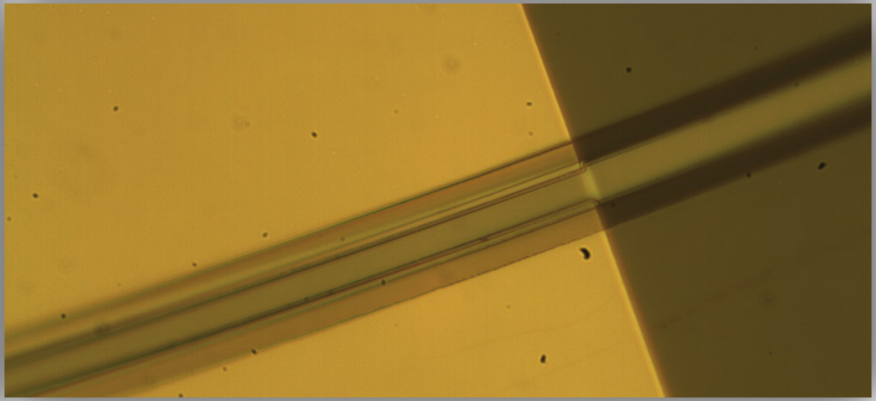

Substrate: Ge or Si
2´´ wafer




Energy resolution $\Delta E_{FWHM}$ = 3 -10 eV
Rise time $\tau_R$ < 50 µs

# MMC-based photon detector: P1 design



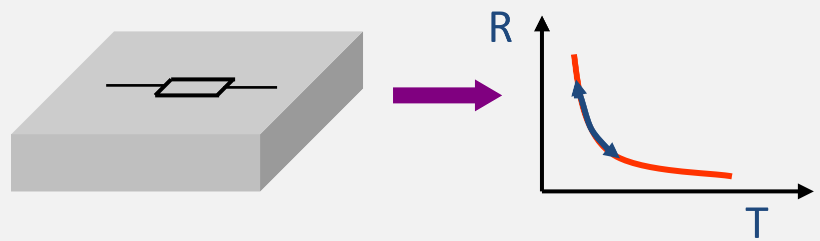


To be done: - dry-etching of trenches to define absorber island
- recipe already tested:
3 hours of $SF_6 + O_2$ (14:1), $T$ = -90 °C, and 500W ICP power

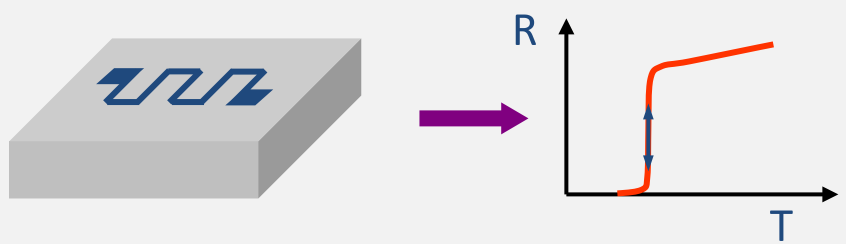
2 wafers without trenches tested in Heidelberg and Saclay

# Temperature sensors

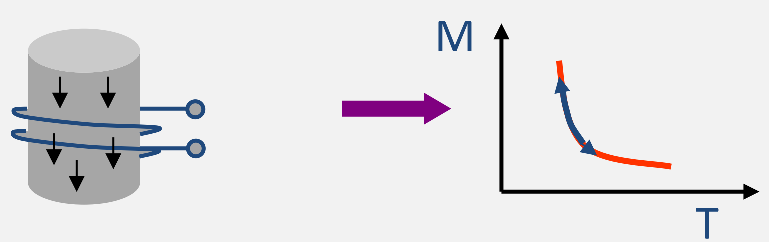
Resistance of highly doped semiconductors



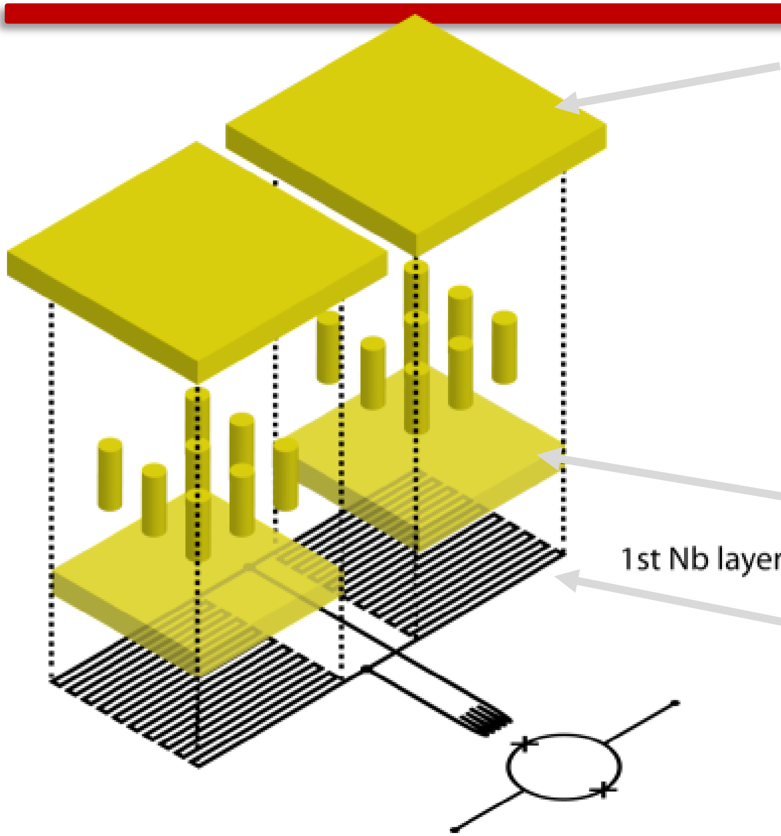

Resistance at superconducting transition,TES



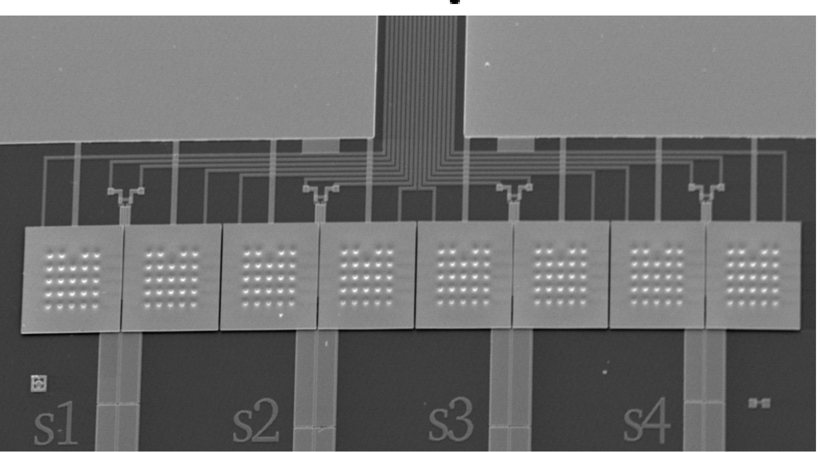

**Magnetization of paramagnetic material**

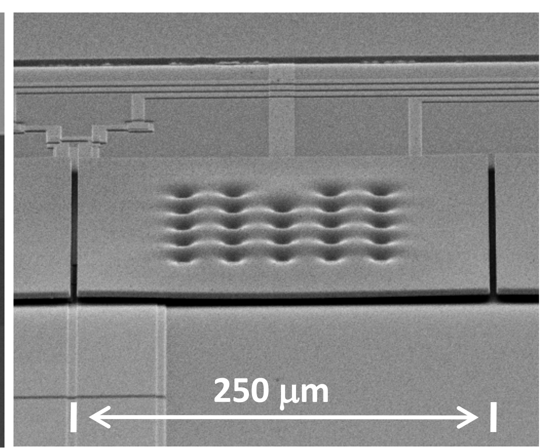


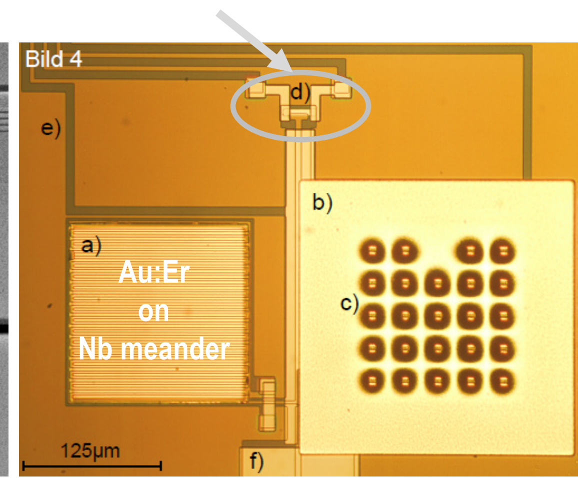
# **maXs20:** 1d-array for soft x-rays




- **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)

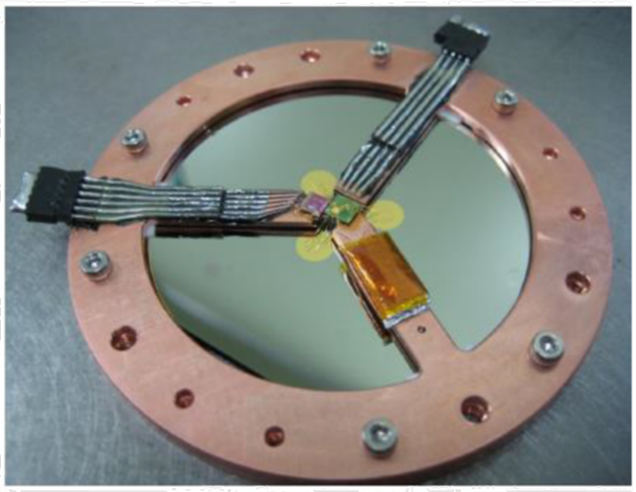


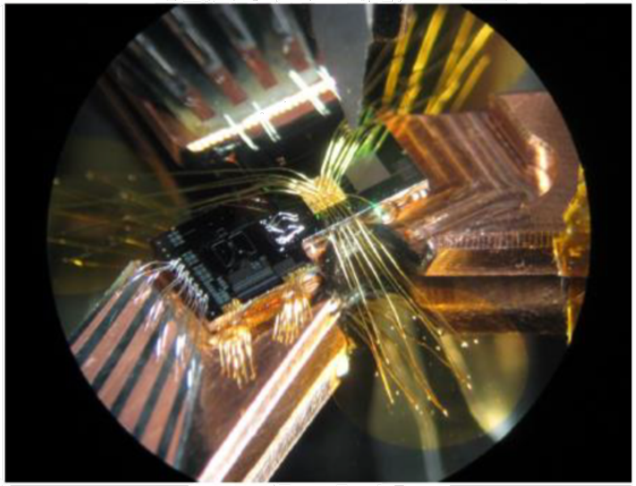



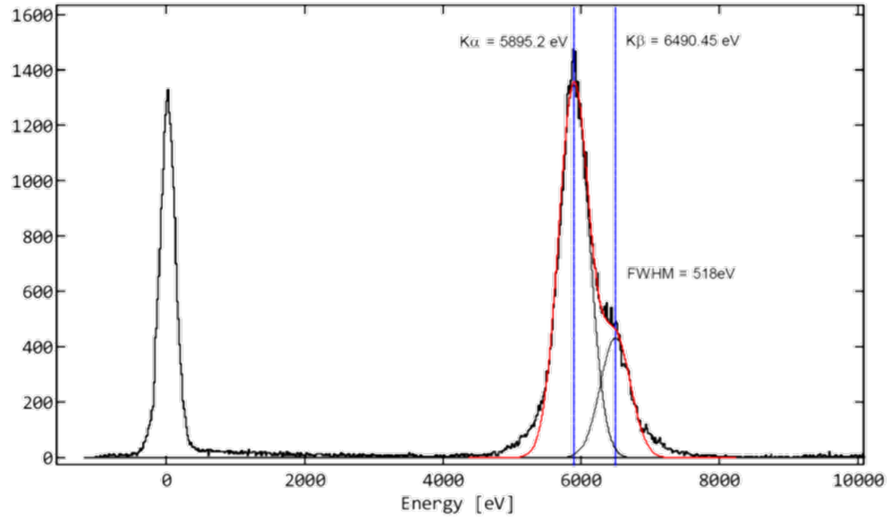
# First test of MMC-based photon sensors (KRISS)

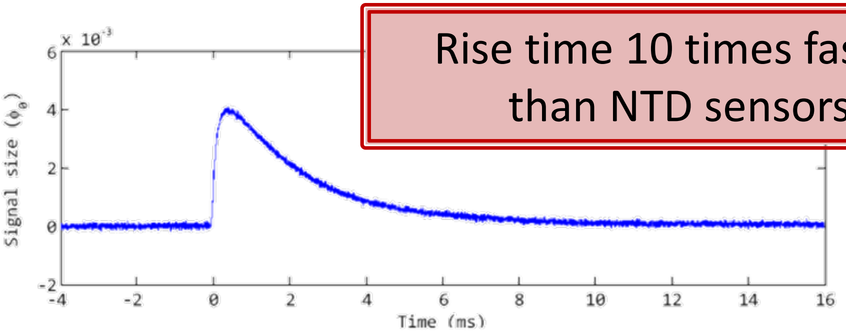
**0.5mm x 2 inch Ge wafer**





**~500eV FWHM**



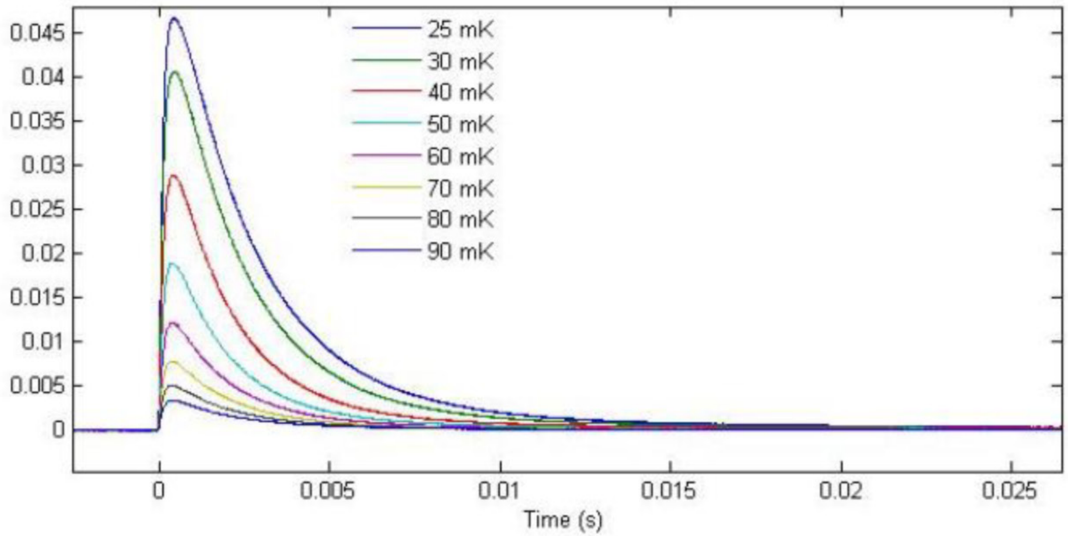



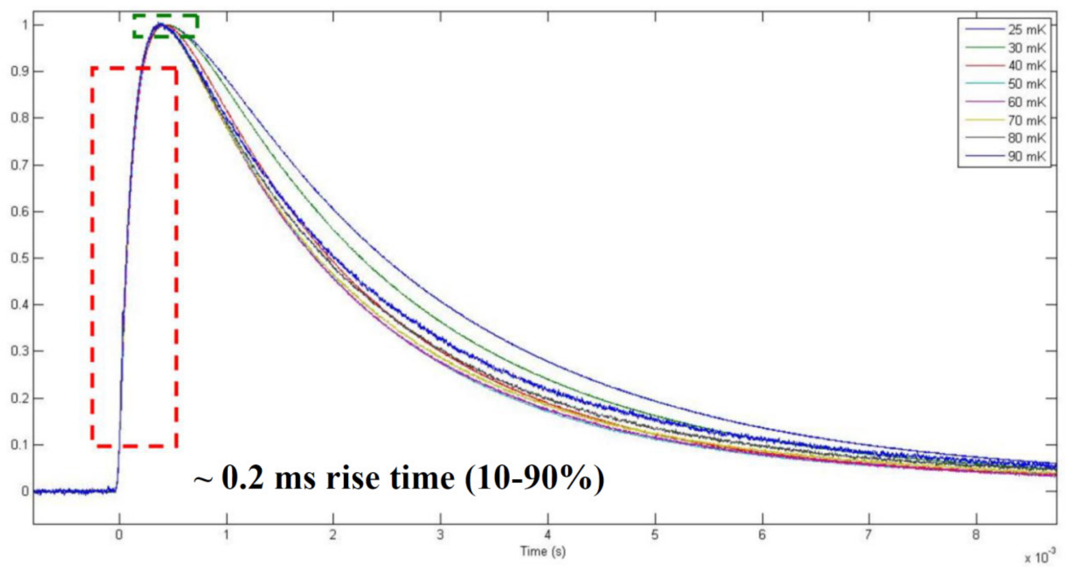

Rise time 10 times faster than NTD sensors

**6keV signal**

**0.2 ms rise time**

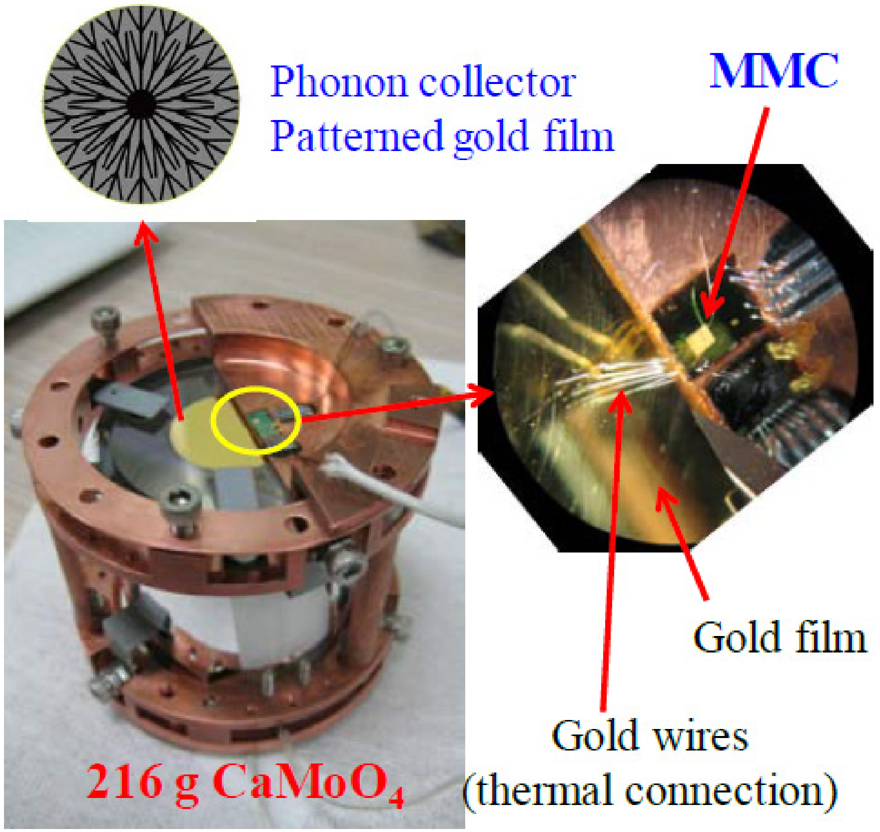
# First test of MMC-based photon sensors (KRISS)

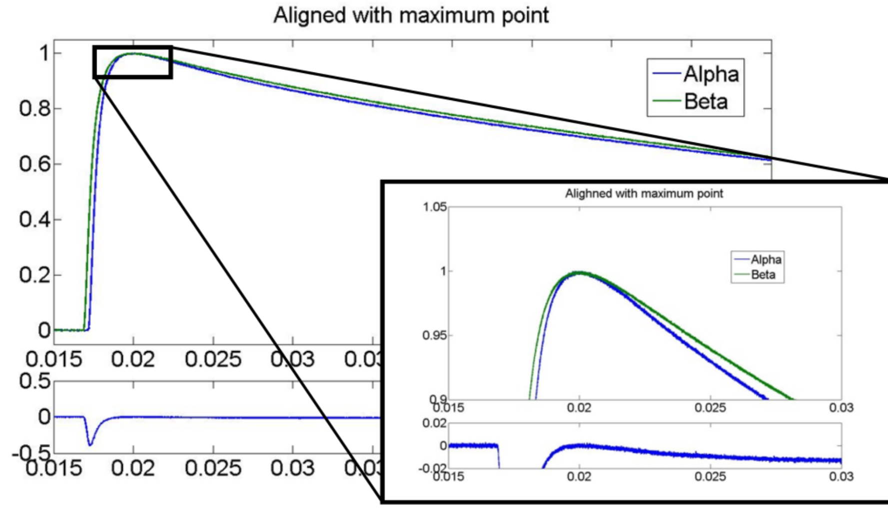


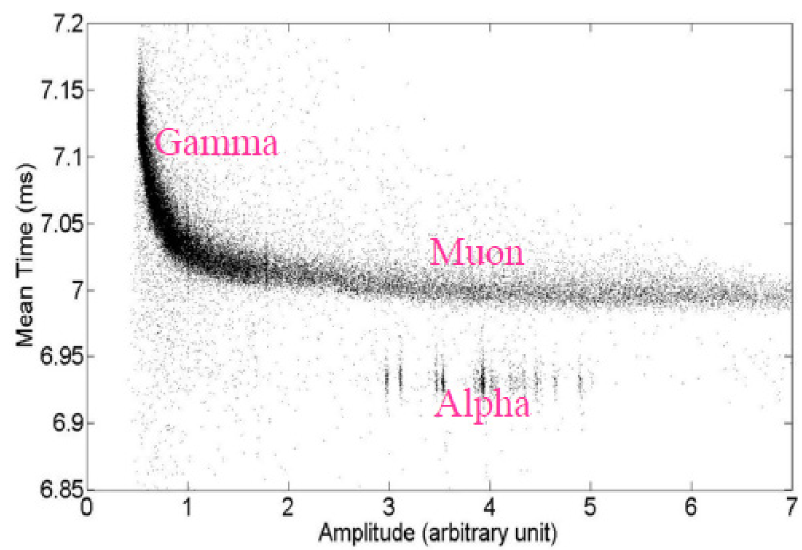




Very fast rise time

# MMC phonon sensor and $CaMoO_4$ @ KRISS



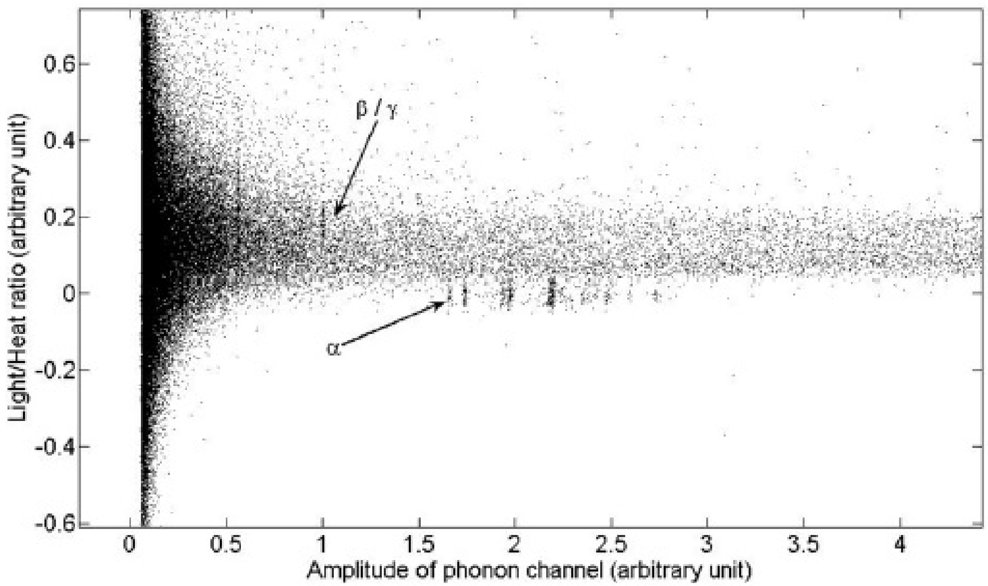



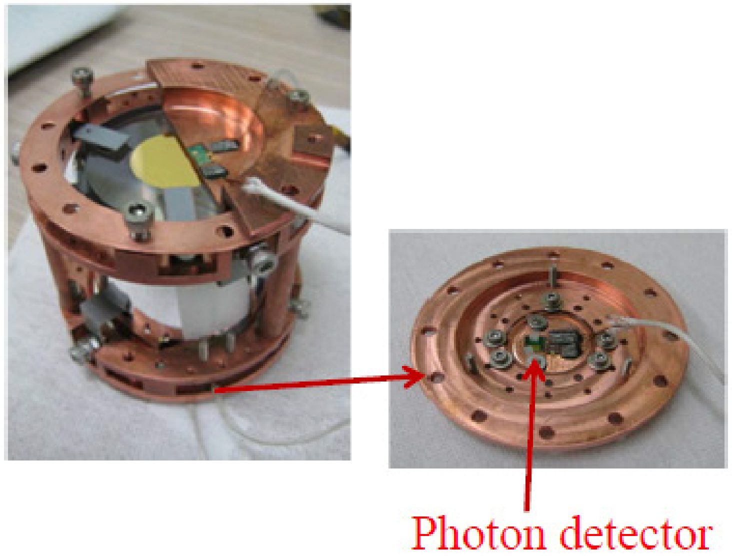




Particle discrimination
in the phonon channel

# Test of $CaMoO_4$ crystals with MMC @ KRISS

Phonon sensor + small photon sensor




Small assorbing area for photons ~ 20 mm$^2$ $\alpha$ and $\beta/\gamma$ discrimination already good

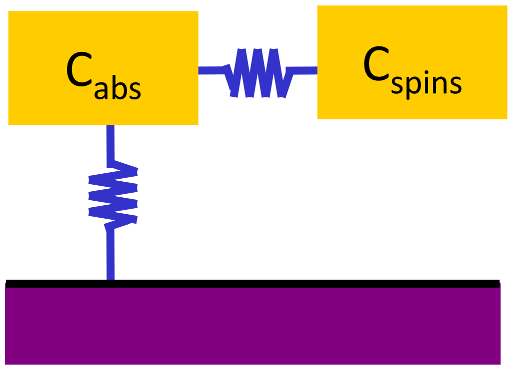
The new photon sensor will improve the discrimination

# Energy resolution

- fluctuations of energy between sub-systems

$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

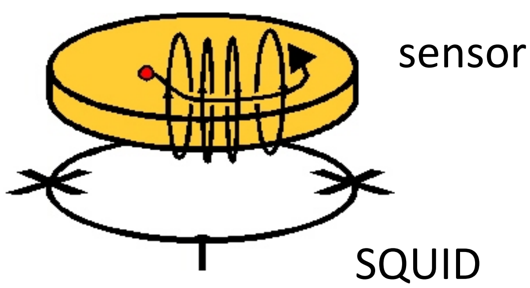
(optimum for $C_{abs} = C_{spins}$)




- flux noise of SQUID-magnetometer

$S_\Phi = 2\,\varepsilon\,L$, required: $\varepsilon < 50\,\hbar\,..\,300\,\hbar$

- magnetic Johnson noise
  - thermal currents in the metallic components
  - marginal in all present detectors




- excess noise $S_\Phi \sim N_{\mathbf{Er}}$

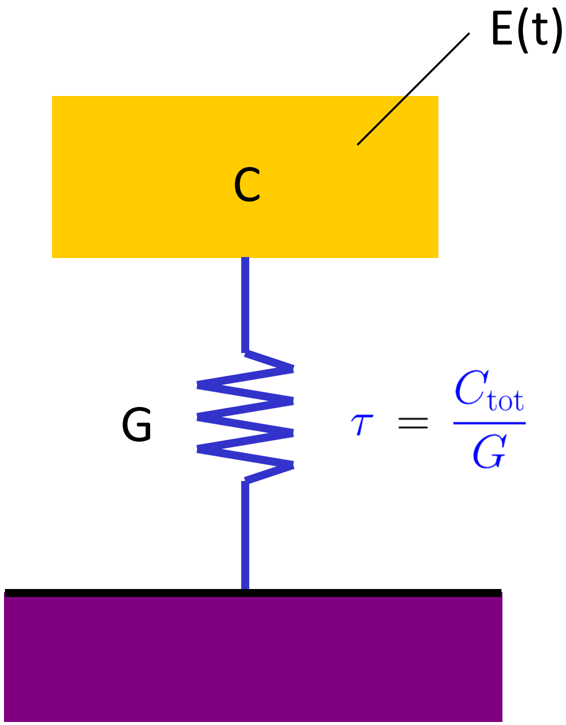
$S_\Phi \sim 1/f$, $S_m|_{1Hz} \approx 0.023\ \mu_{Er}^2/\mathrm{Hz}$

temperature independent (20mK – 4K)

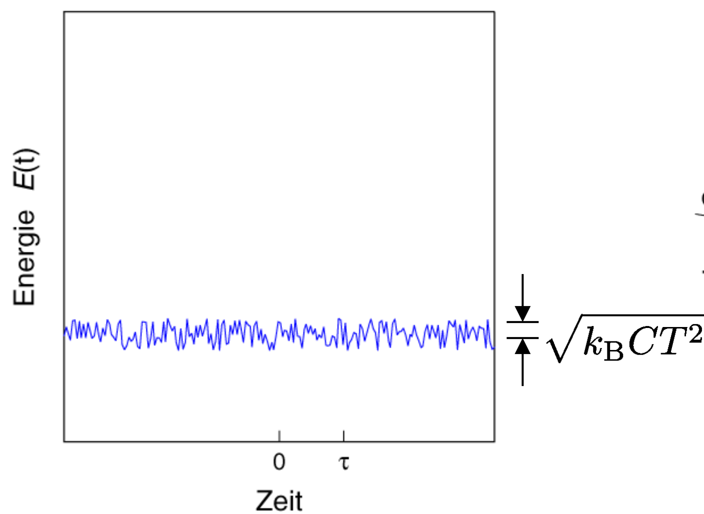
# Energy resolution

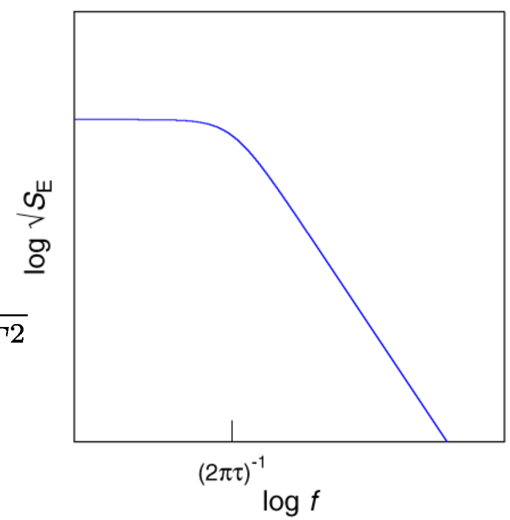
Is there an intrinsic limit?

- canonical ensemble
- ideal measurement of energy content E(t)
    - arbitrarily fast
    - noise-free




$$\tau = \frac{C_{\mathrm{tot}}}{G}$$



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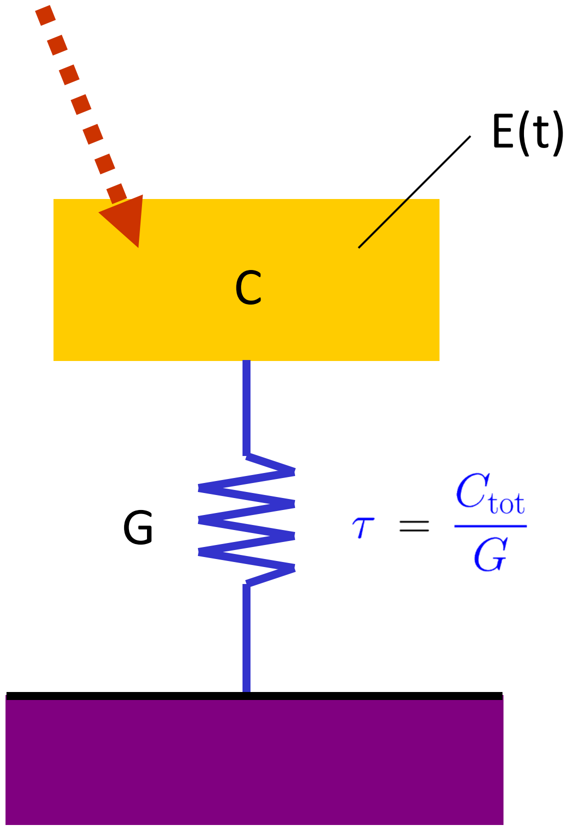


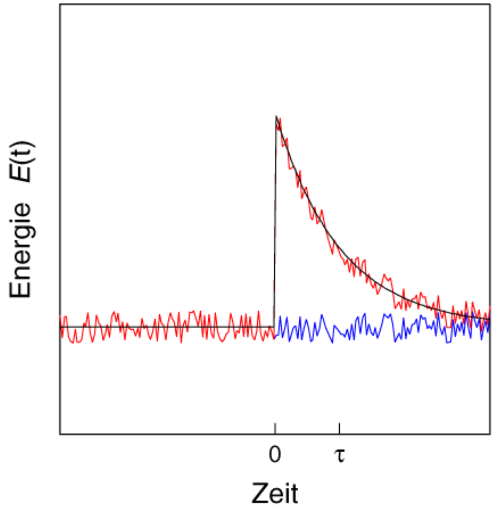


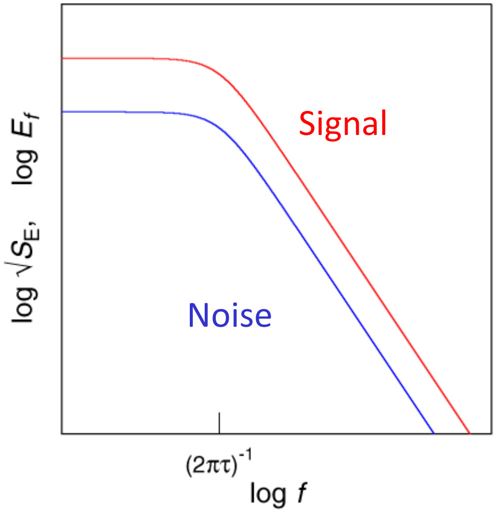

# Energy resolution

Is there an intrinsic limit?
- Simple model → NO

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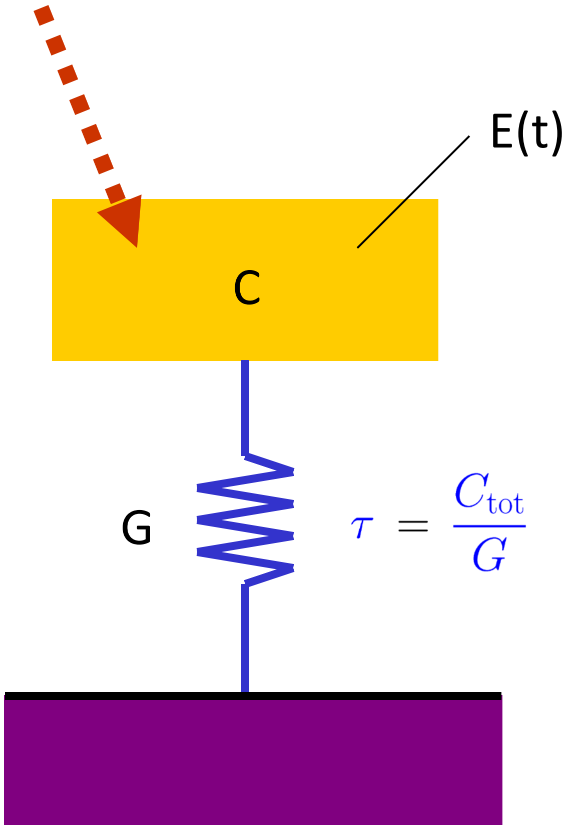


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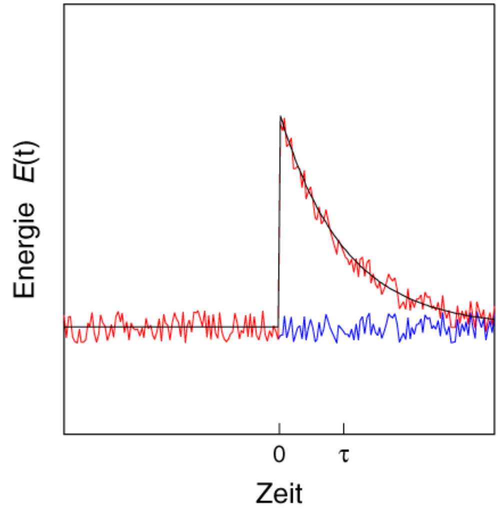
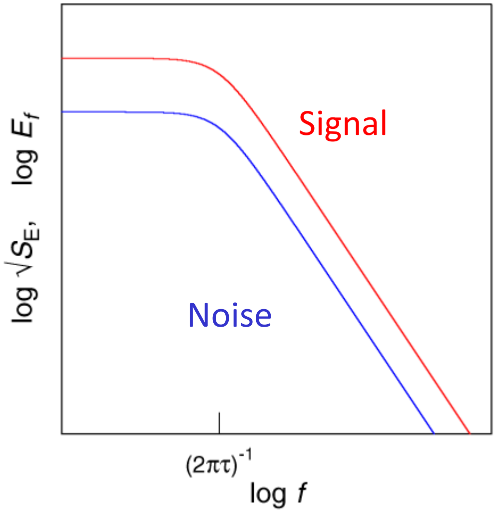


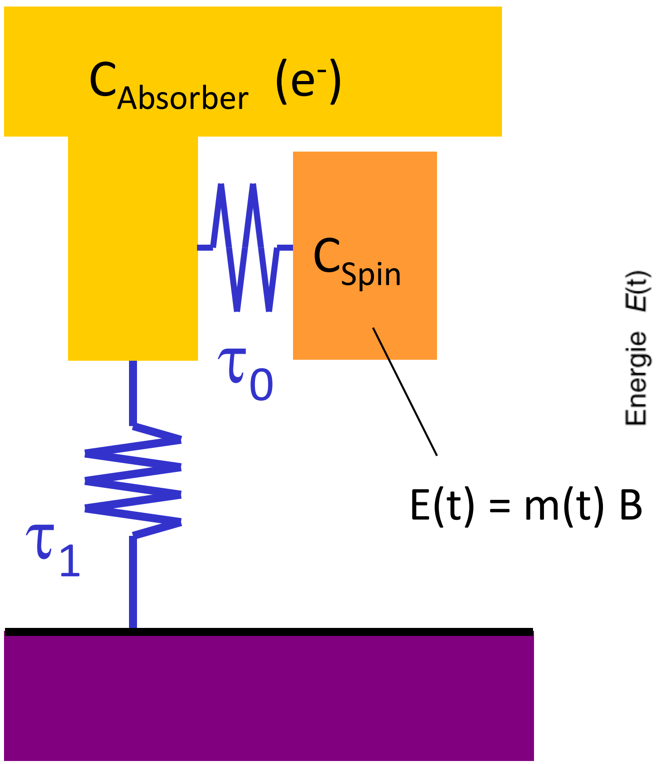

- Signal-to-Noise independent of frequency
- **Bandwidth → ∞ ⇒ ΔE → 0**

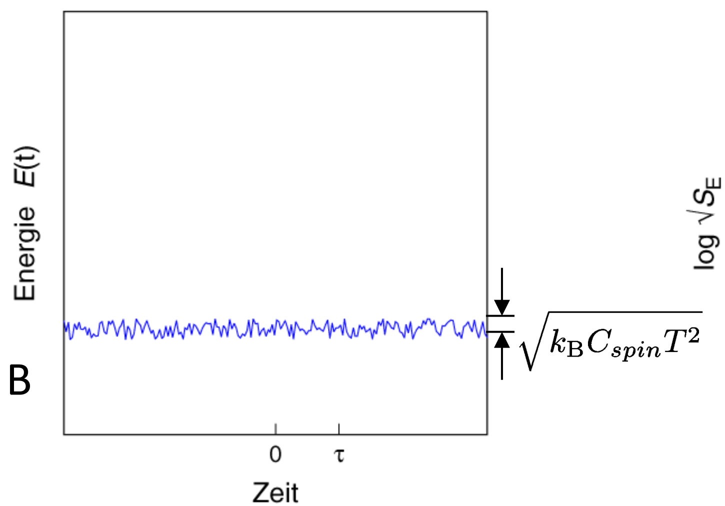
# Energy resolution

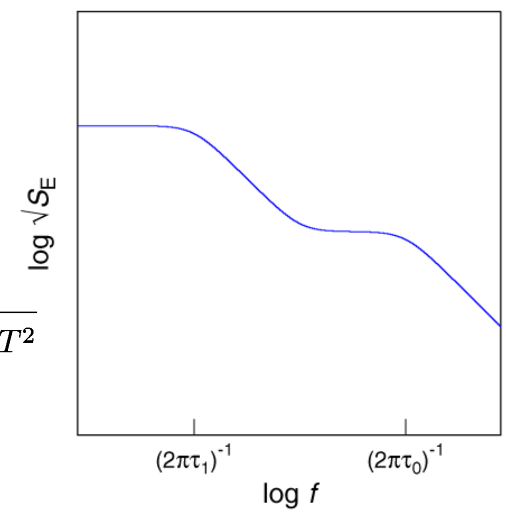
Is there an intrinsic limit?

- Simple model → NO
- Realistic model

- Absorber and thermometer are separate systems
- Thermalization within the absorber is fast ($t$ < 100ns)
- Relaxation time absorber-thermometer finite!



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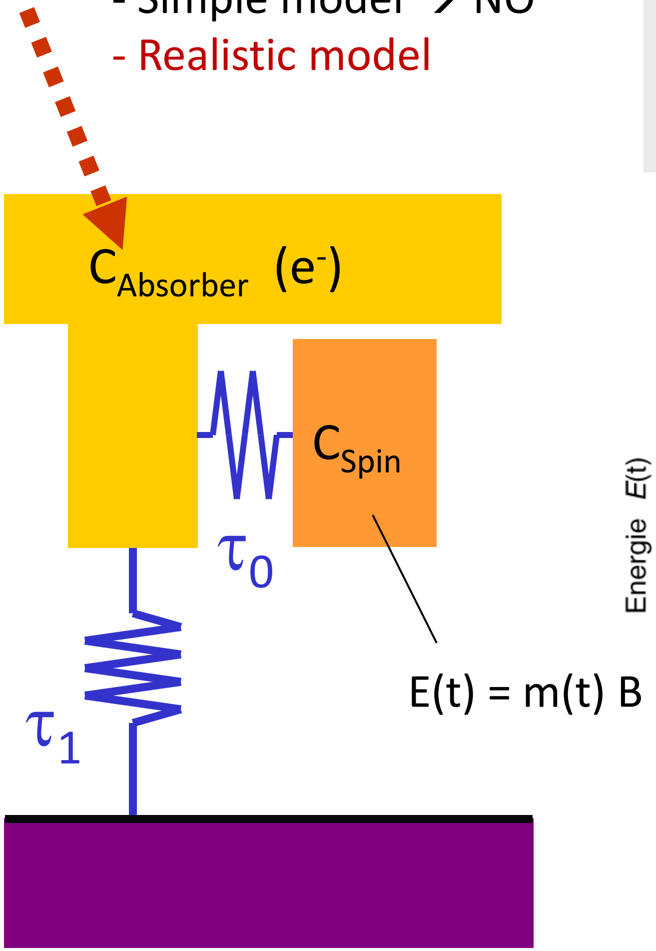
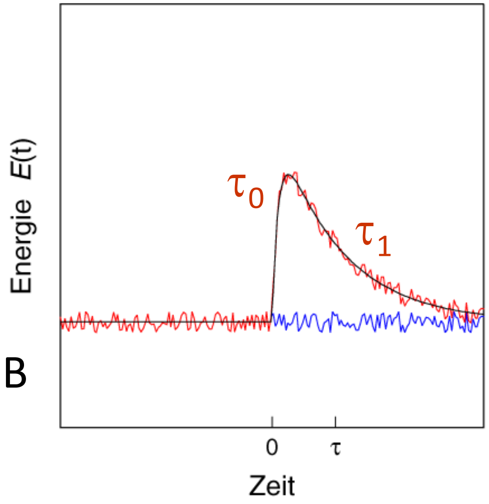
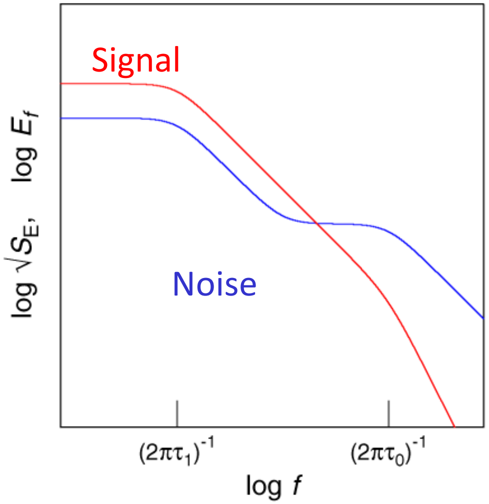
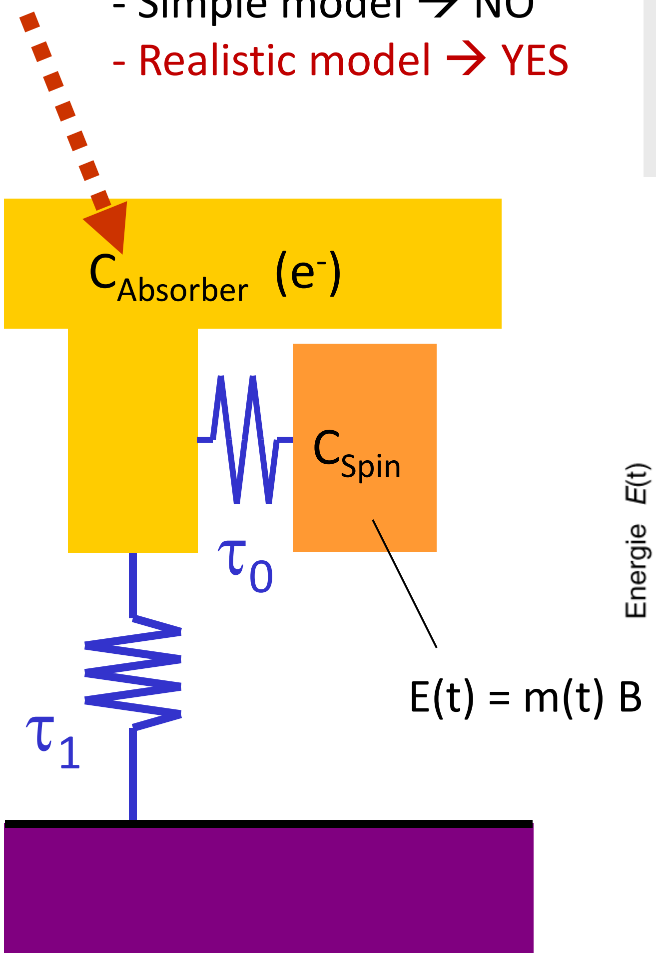


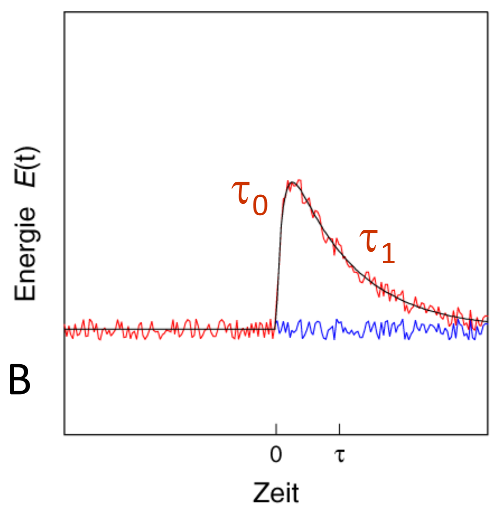
# Energy resolution

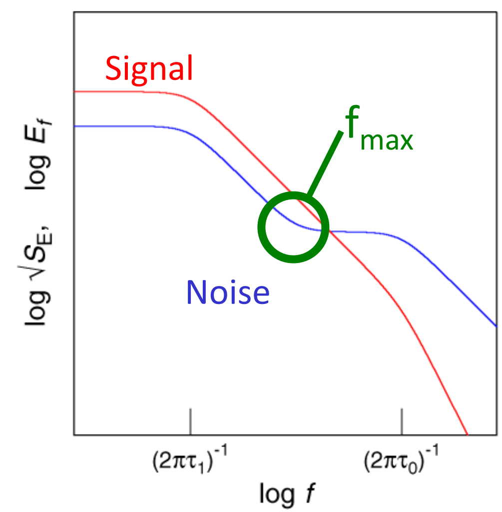
Is there an intrinsic limit?
- Simple model → NO
- Realistic model → YES




- Absorber and thermometer are separate systems
- Thermalization within the absorber is fast ($t$ < 100ns)
- Relaxation time absorber-thermometer finite!

Signal-to-noise is not constant!

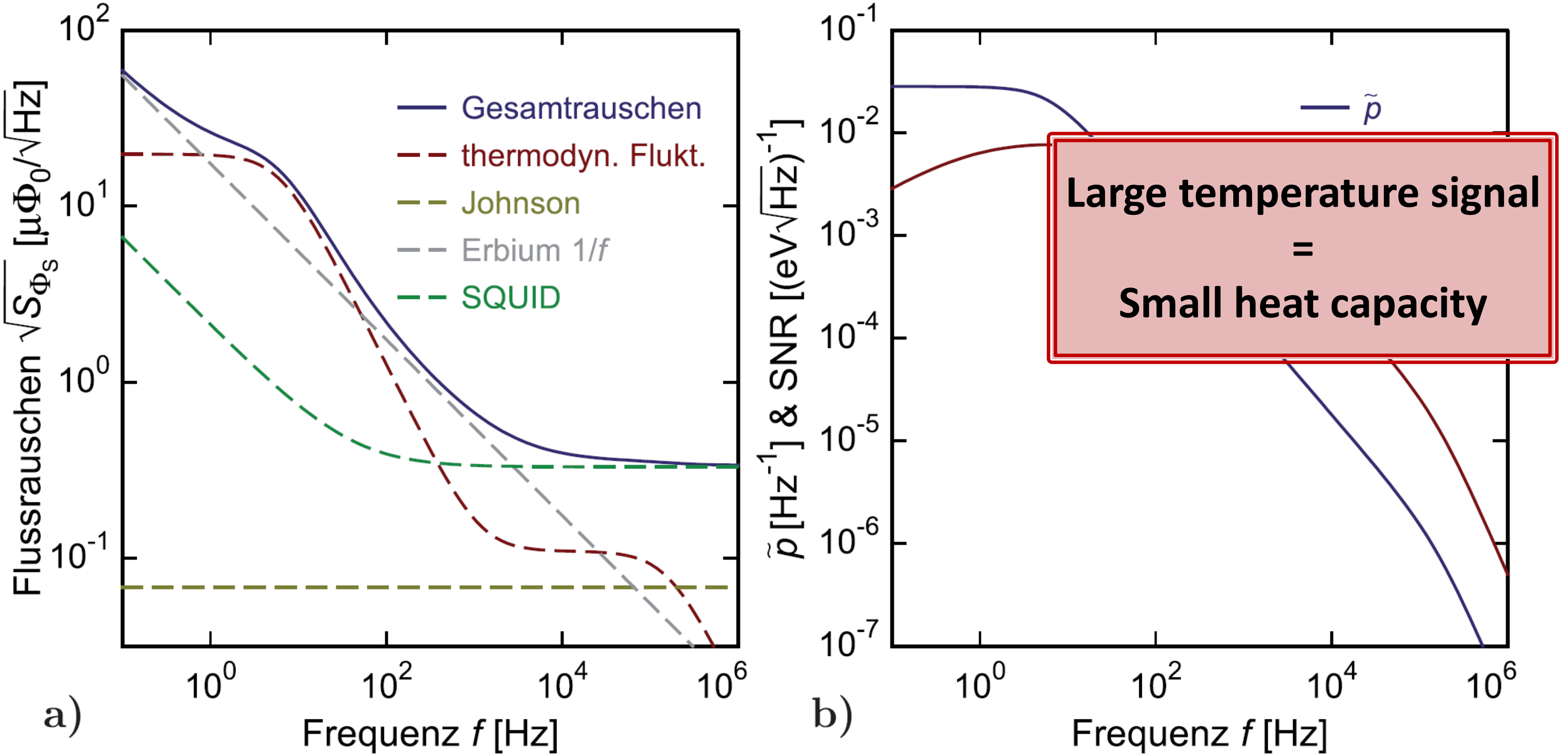



- **Optimum bandwidth $f_{max}$ is finite**

$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

# Energy resolution



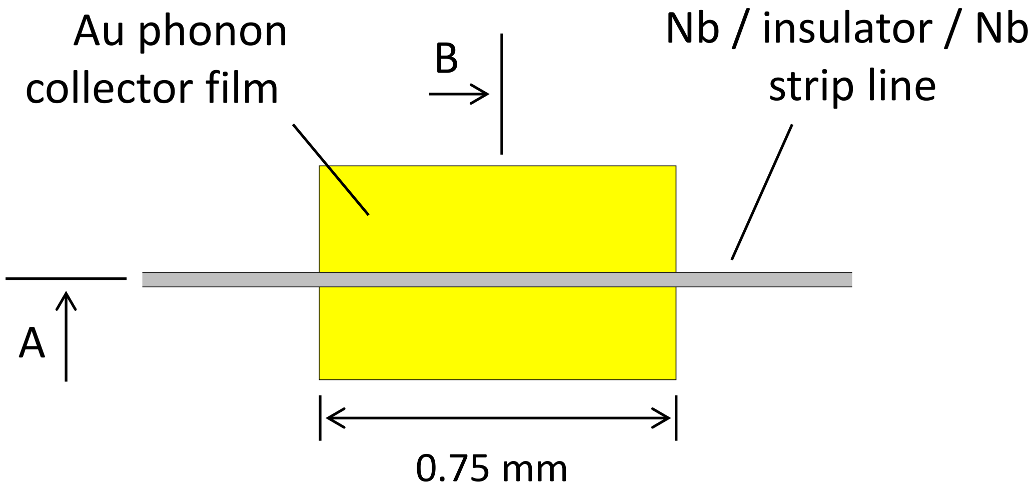

**Large temperature signal**

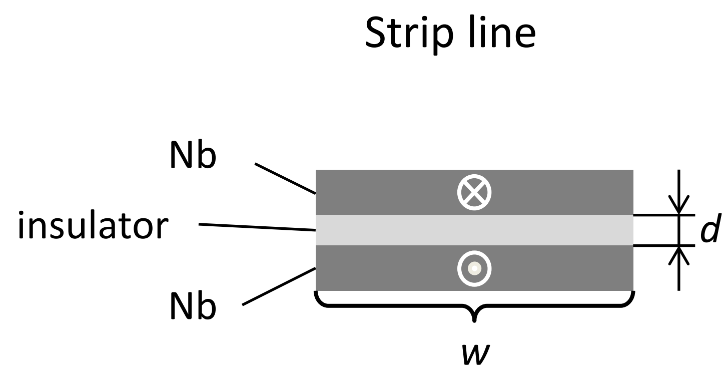
**=**

**Small heat capacity**

# First prototype of photon detector

Top view:




Cross section: