Kirchhoff-Institut für Physik

ECHo Experiment

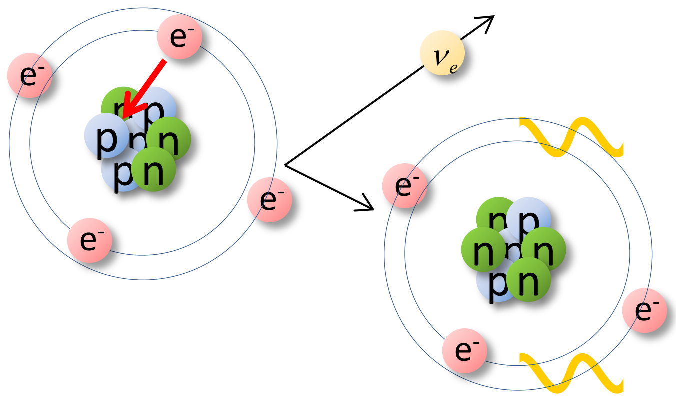
Loredana Gastaldo
for the ECHo collaboration

Heidelberg University

Contents

- Electron capture process: The case of ^{163}Ho
- Metallic Magnetic Calorimeters
- Recent results
- ECHo experiment

Electron Capture



A non- zero neutrino mass affects the de-excitation energy spectrum

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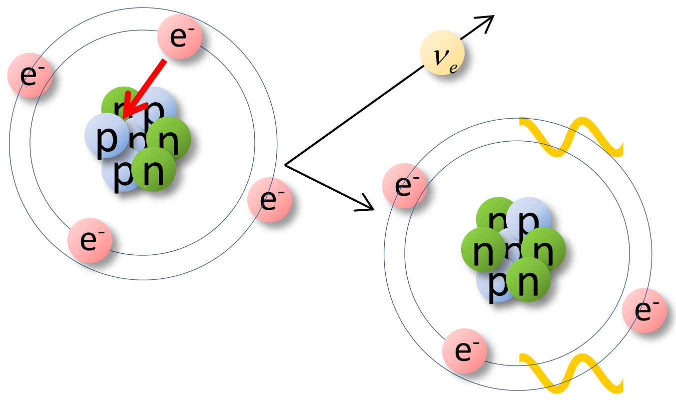

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Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions

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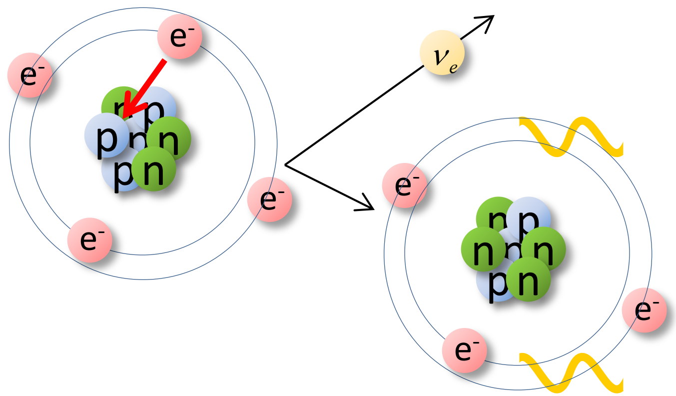

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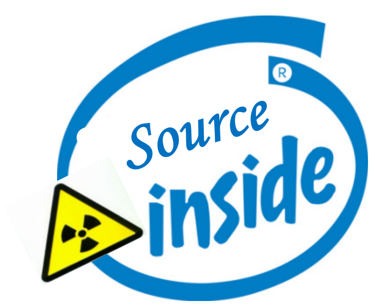
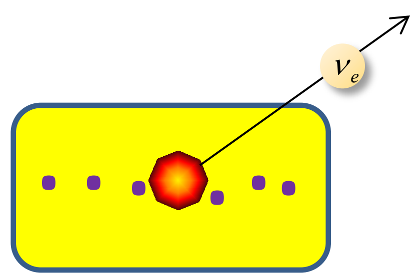
} Calorimetric measurement





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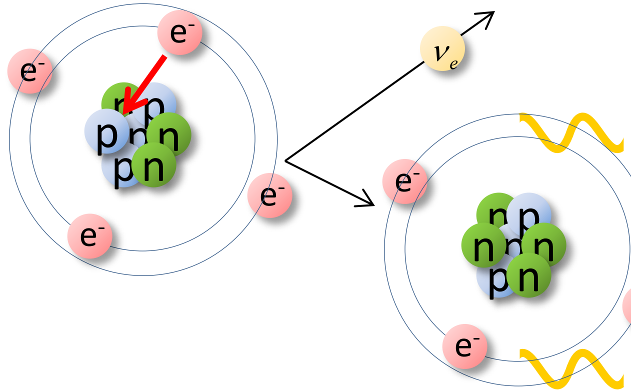

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Atomic de-excitation:
- X-ray emission
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Calorimetric measurement

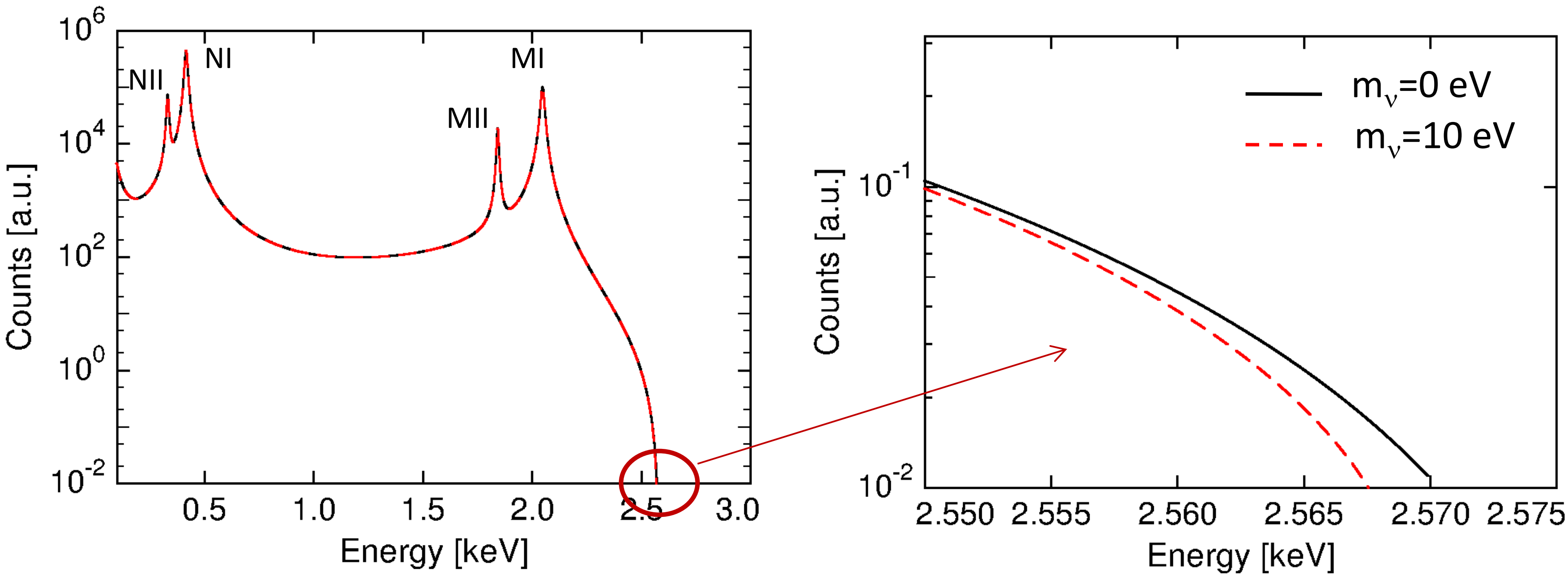
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\ 2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\ 2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\ 2}}{4}}$$

The case of ^{163}Ho

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

- $Q_{EC} \cong 2.5$ keV
- $\tau_{1/2} \cong 4570$ years



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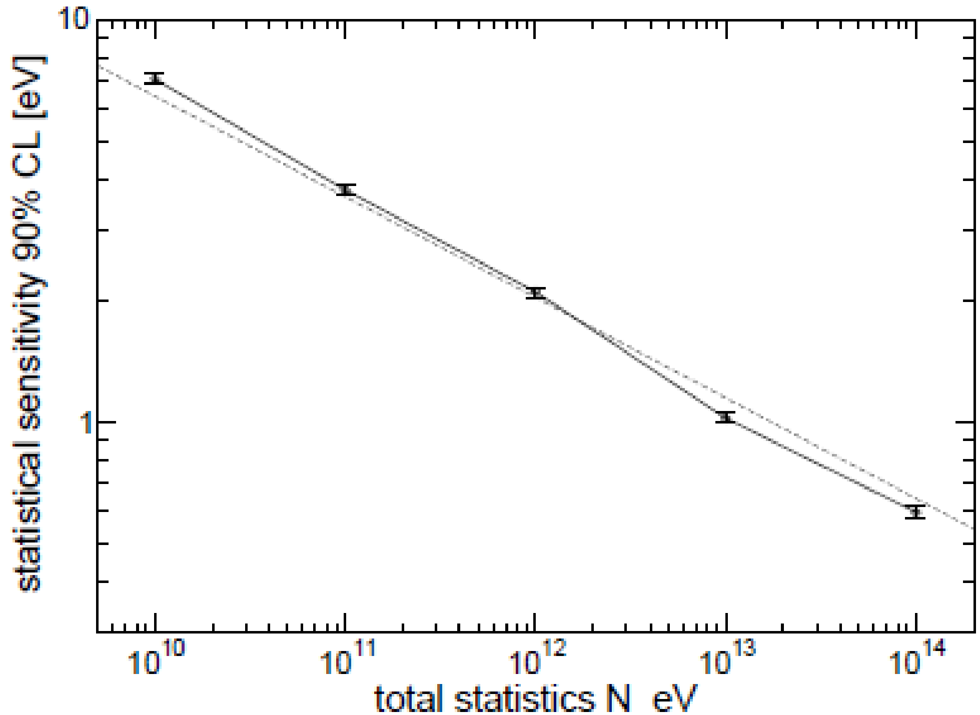
Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

CALORIMETRIC MEASUREMENTS OF ^{163}HOLMIUM DECAY AS TOOLS TO DETERMINE THE ELECTRON NEUTRINO MASS

A. DE RÚJULA and M. LUSIGNOLI [1]
CERN, Geneva, Switzerland

The case of ^{163}Ho: Sub-eV sensitivity

Statistics



ΔE_{FWHM} = 1 eV, $f_{pp} = 10^{-5}$, Q_{EC} = 2600 eV

From M. Galeazzi et al., arXiv:1202.4763v2 [physics.ins-det]

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$N_{ev} > 10^{14}$

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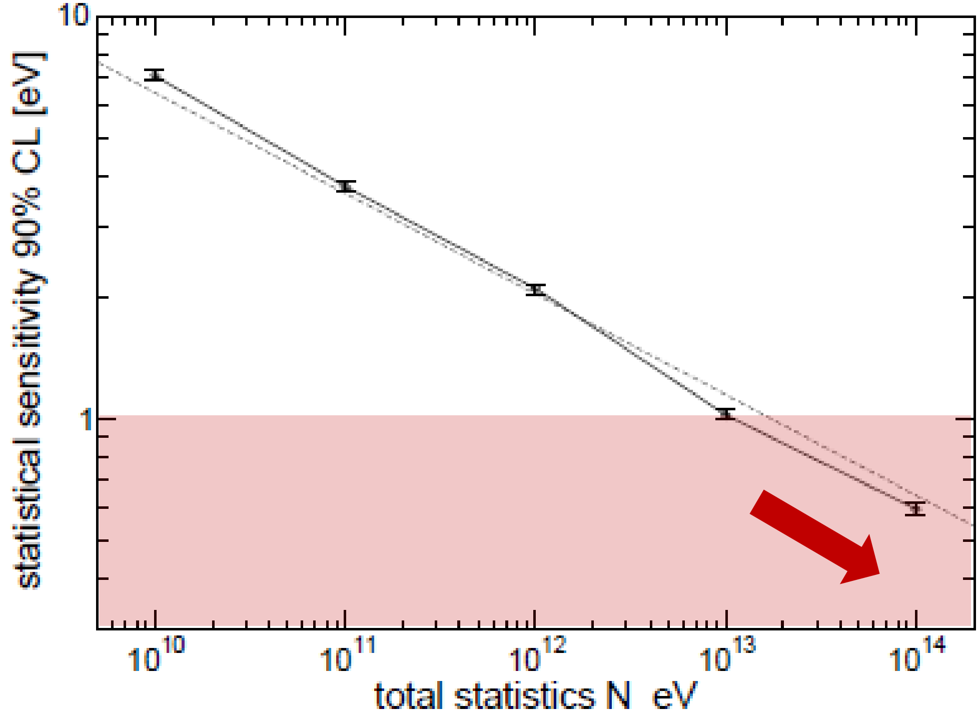

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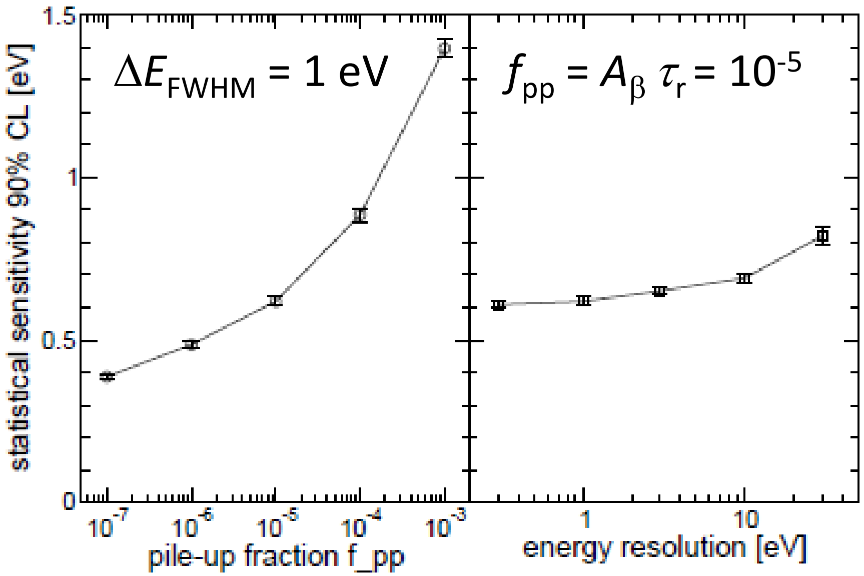
Detector performance



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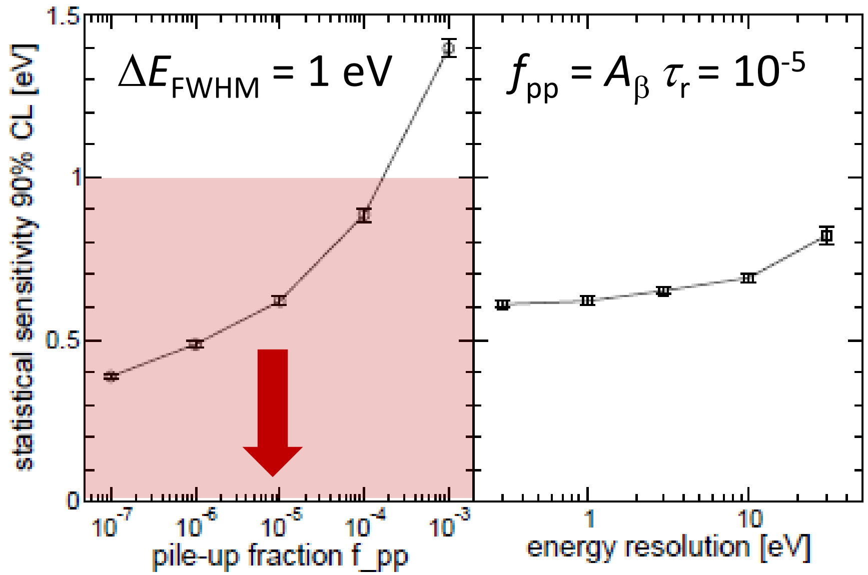

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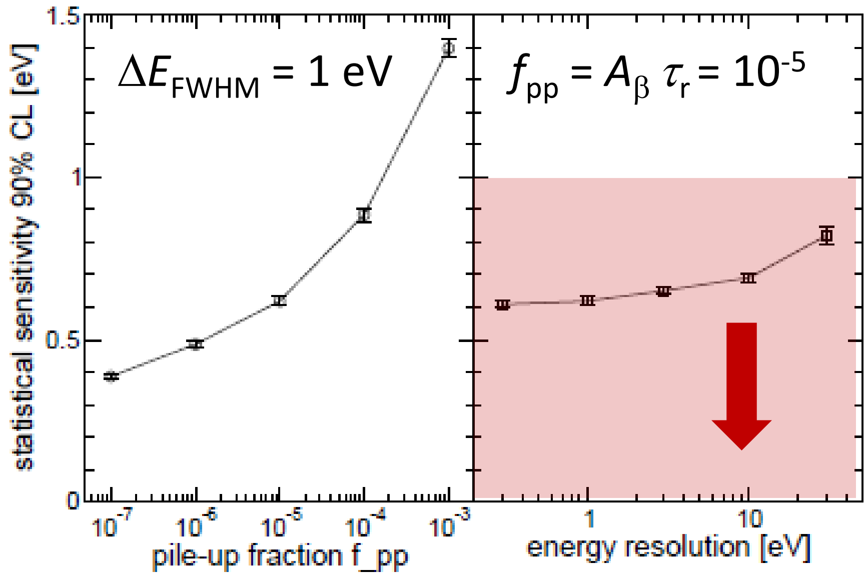

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⟶

$\tau_r \sim 0.1\ \mu s$
$A_\beta \approx 10\ s^{-1}$

⟶

$\geq 10^5$ detectors

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→

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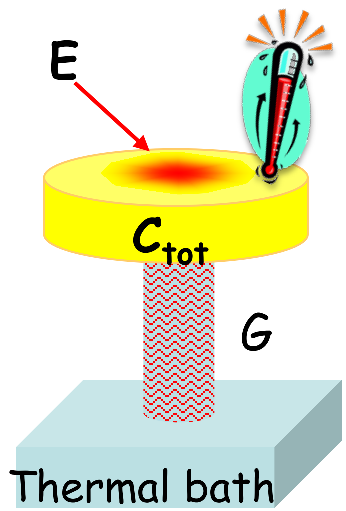
→

$\geq 10^5$ detectors

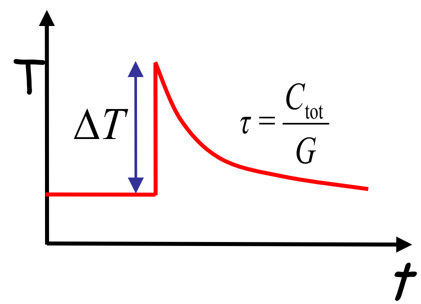
Low temperature

Metallic Magnetic Calorimeter

MMCs: Concept



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



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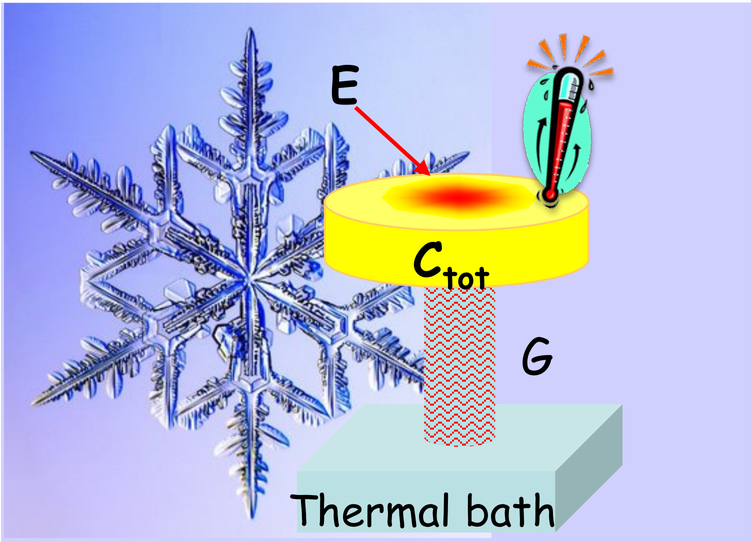

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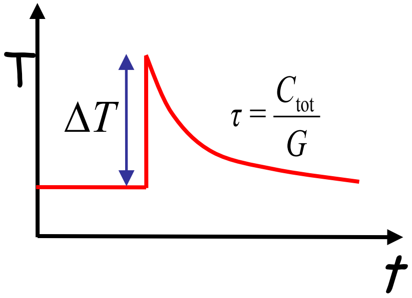


- Working temperature below 100 mK

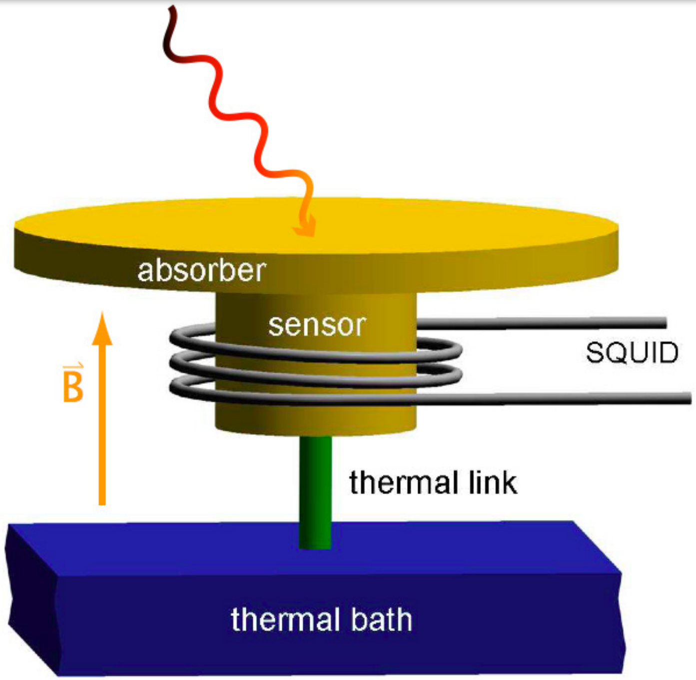
  small specific heat

  large temperature change

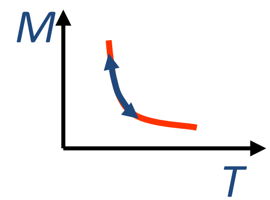
  small thermal noise

- Very sensitive temperature sensor

MMCs: Concept



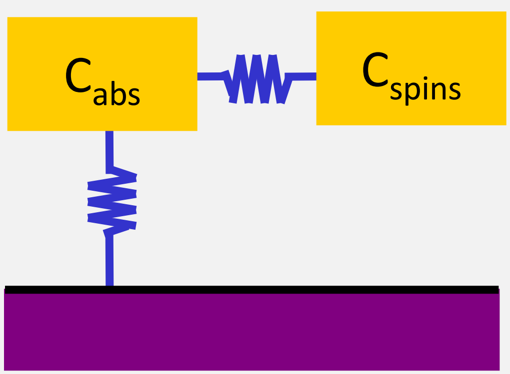
Paramagnetic sensor: **Au**:Er_{500ppm}



Signal size:

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

Energy resolution --- Why ‚micro'-calorimeter

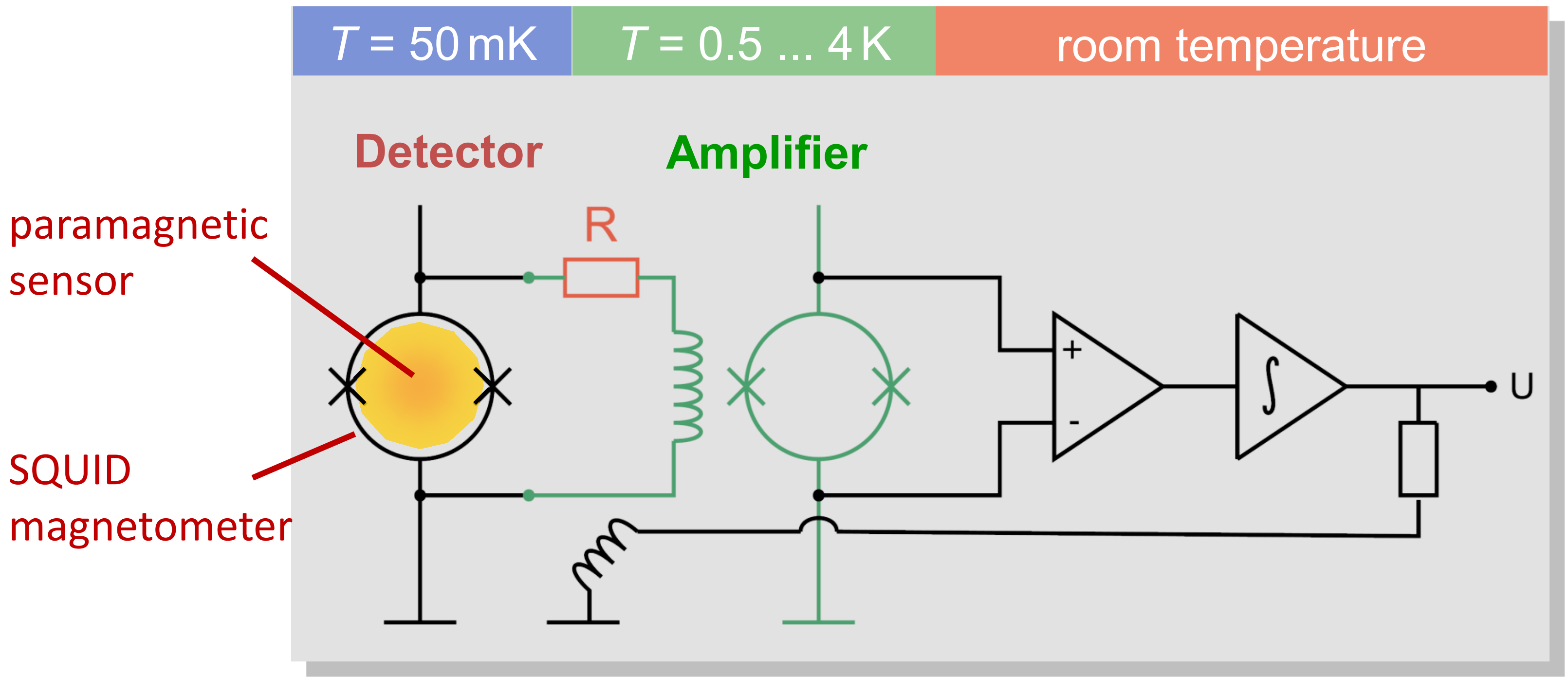


Thermal fluctuations of energy
between absorber, thermometer and bath lead to

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

e.g. **1eV** for C = 1 pJ/K at T = 50 mK

MMCs: Readout



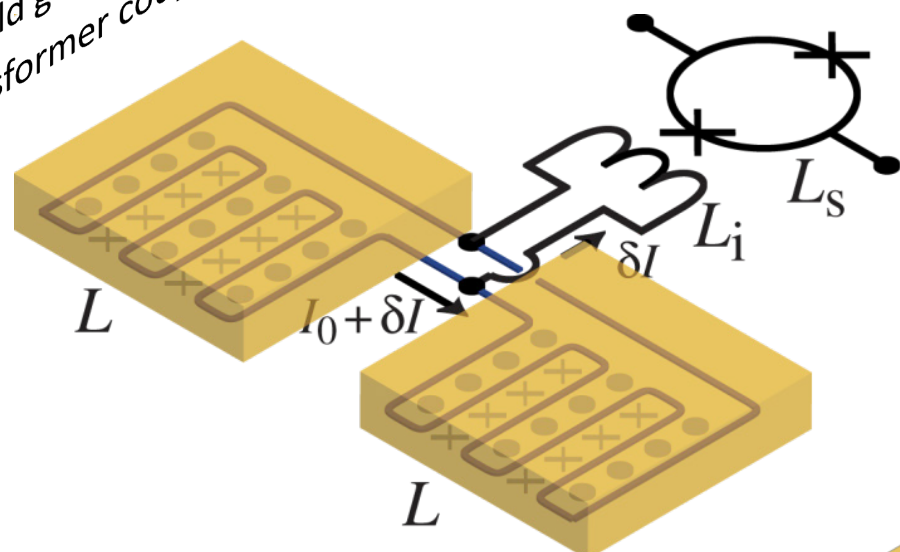
Two-stage SQUID setup with flux locked loop to linearize the first stage SQUID allows for:

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

MMCs: Geometries

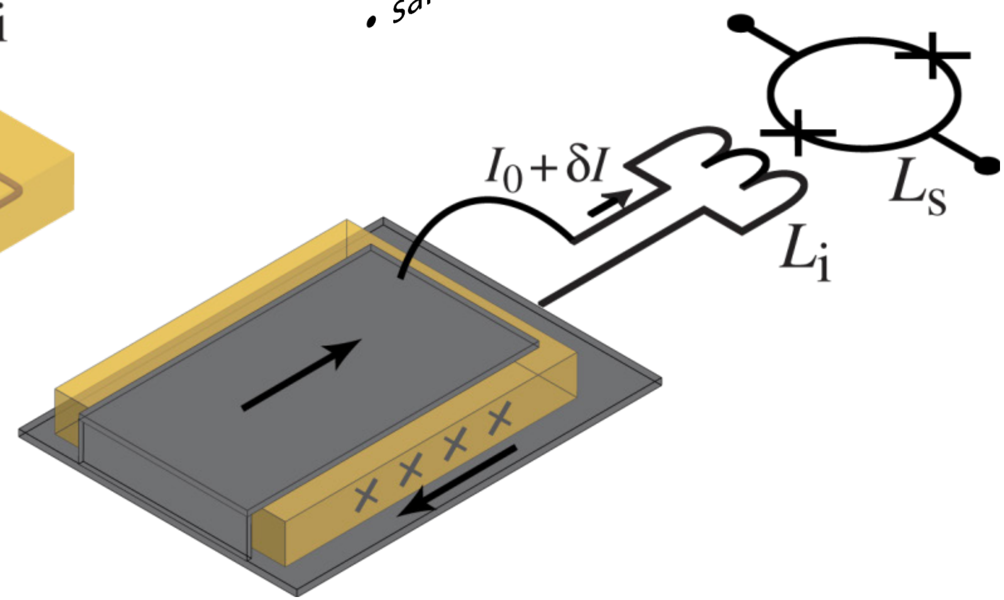
Well established:

- *planar T-sensor*
- *superconducting meander shaped pickup loop*
- *B-field generated by persistent current*
- *transformer coupled to SQUID*



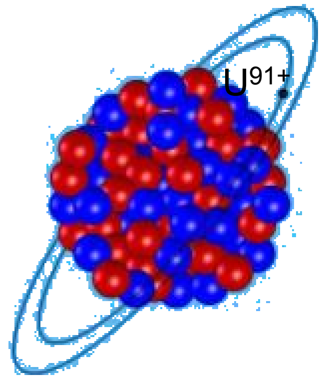
New sandwich geometry:

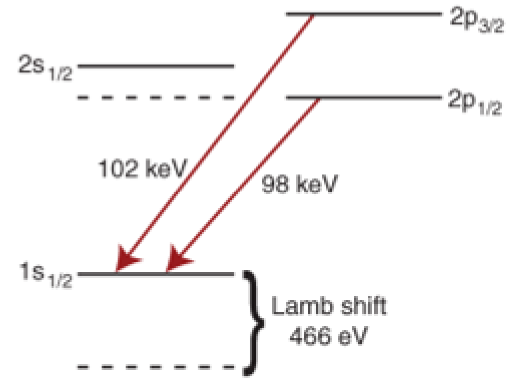
- *best magn. flux coupling,*
- *planar sensor*
- *sandwiched between stripline*

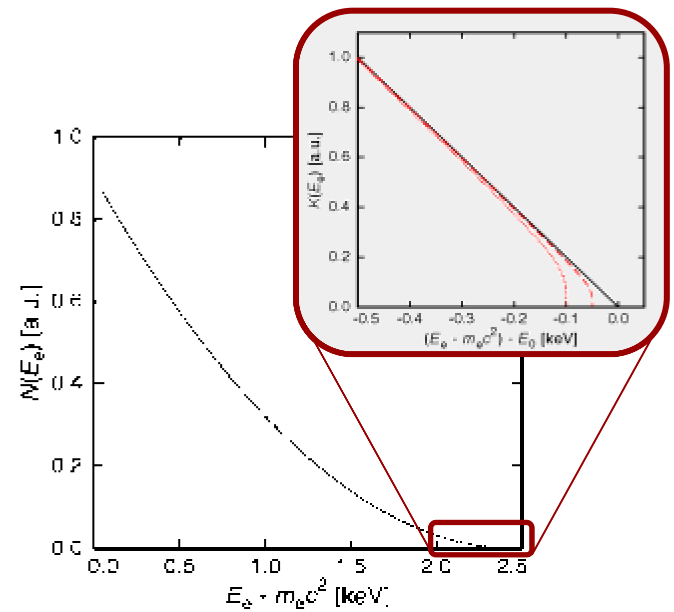


MMCs: Applications

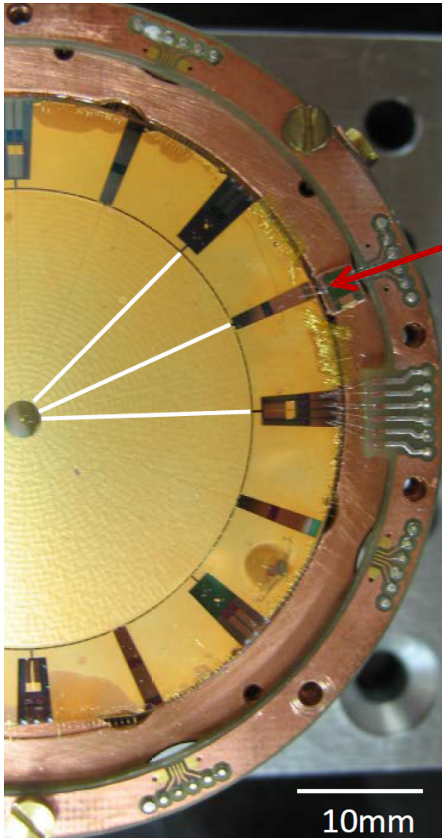
- X-ray spectroscopy
  - atomic physics
  - astronomy
- X-ray imaging
  - large MMC arrays
  - microwave SQUID multiplexing
- Detection of molecular fragments
- Radiation standards for metrology
- Experiments for neutrino physics
  - β decay of ^{187}Re (MARE)
  - EC of ^{163}Ho (ECHo)
  - 0ν2β (AMoRE & LUMINEU)





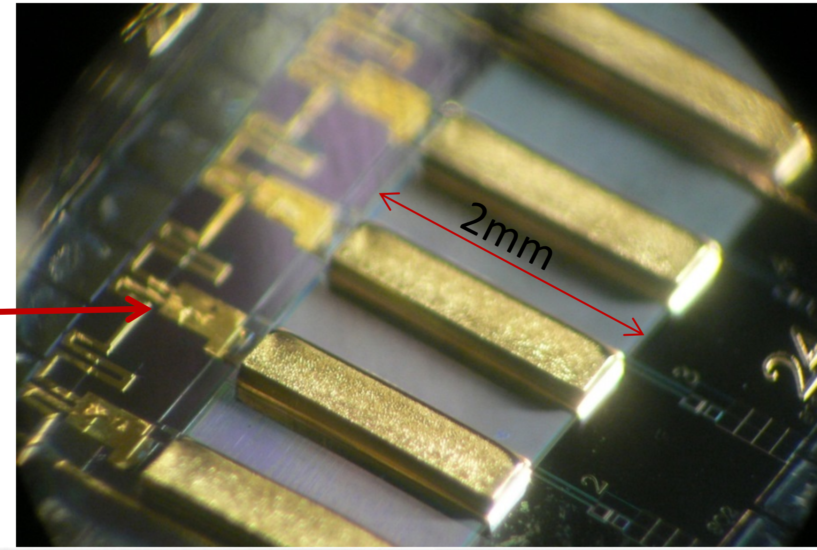


MMCs: Examples

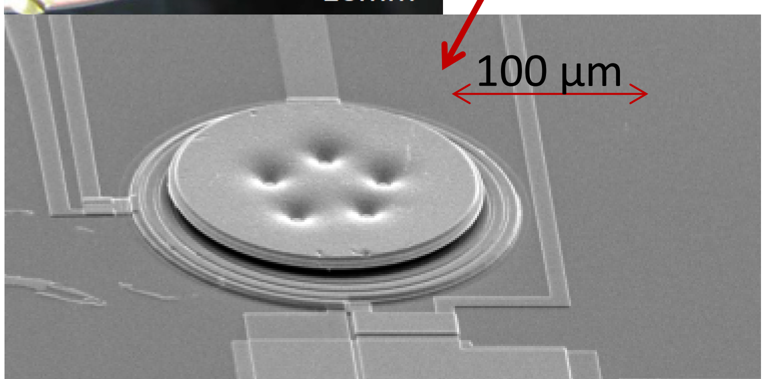


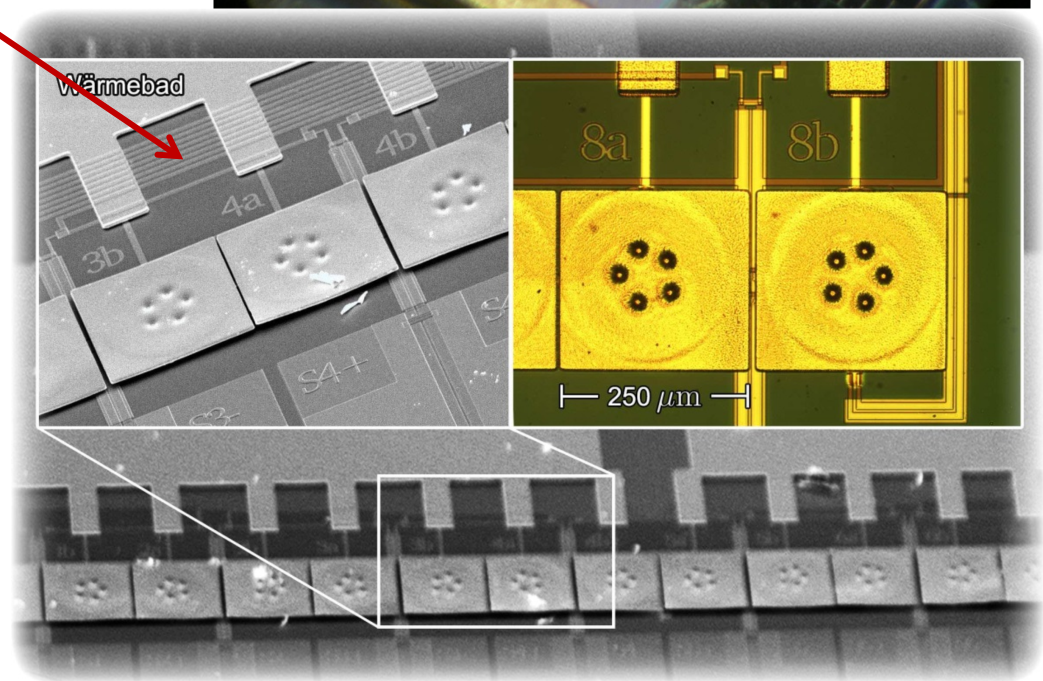
Pizza detector
for molecular fragments

Hard x-rays detectors

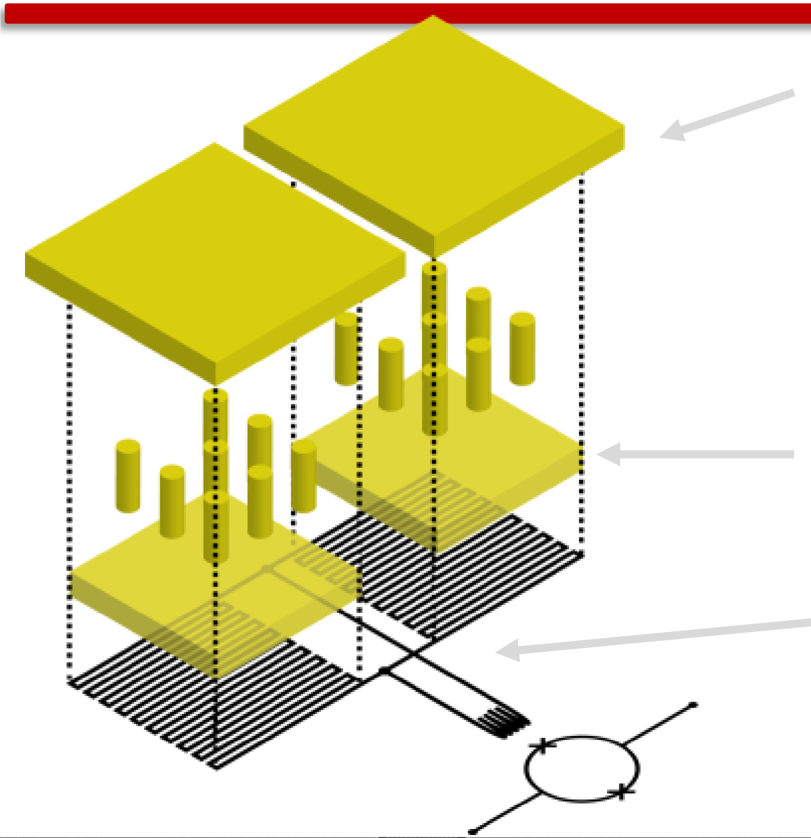


Soft x-rays
detectors

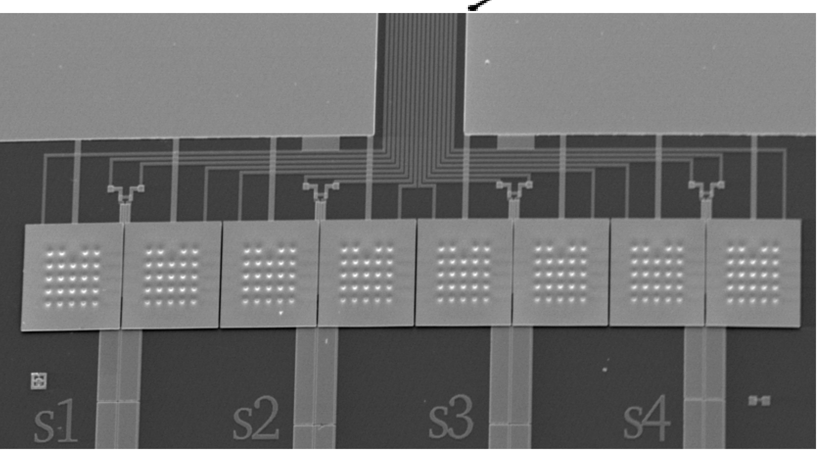


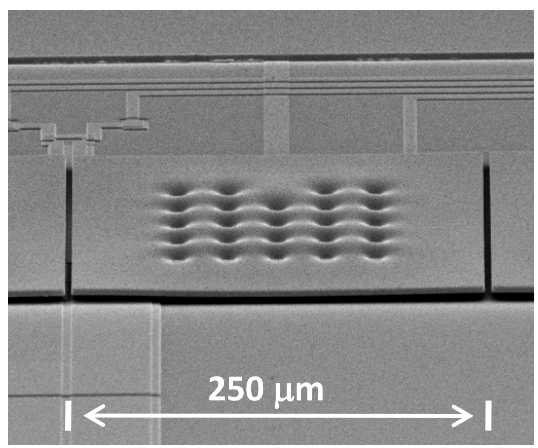


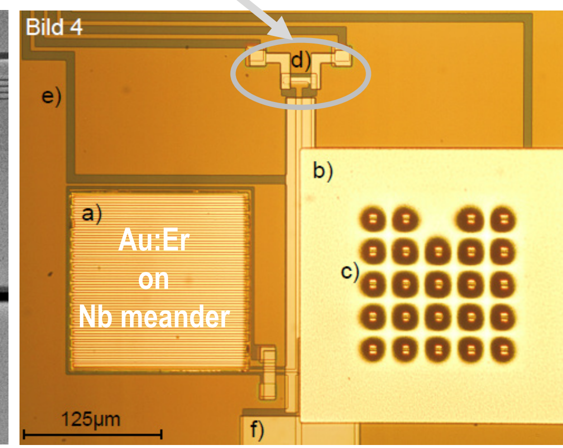
maXs: 1d-array for soft x-rays



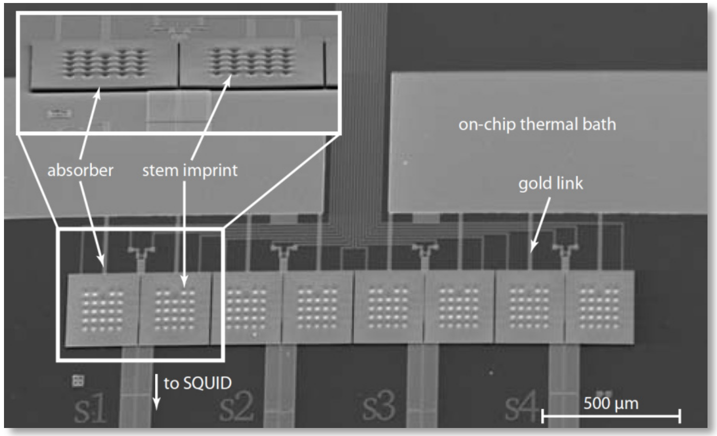
- **1×8 x-ray absorbers**
  - **250µm×250µm** gold**, 5µm thick**
  - >**98%** Qu.-Eff. @ 6 keV
  - electroplated into photoresist mold (RRR>15)
  - **mech/therm contact to sensor by stems** to prevent loss of initial hot phonons
- **Au: ^{166}Er$_{300ppm}$ temperature sensors**
  - co-sputtered from pure Au and high conc. AuEr target
- **Meander shaped pickup coils**
  - 2.5 µm wide Nb lines, ~400 nm thick
  - $I_c \approx$ 100mA
- **On-chip persistent current switch** (AuPd)

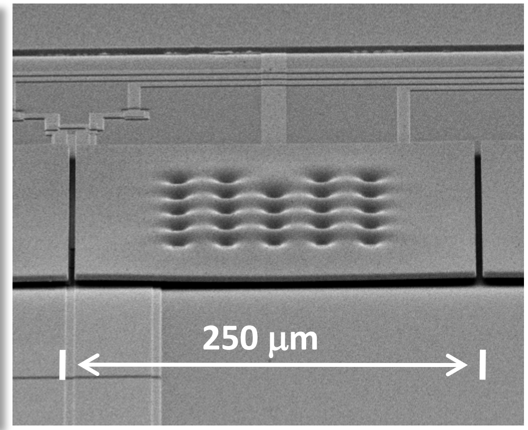




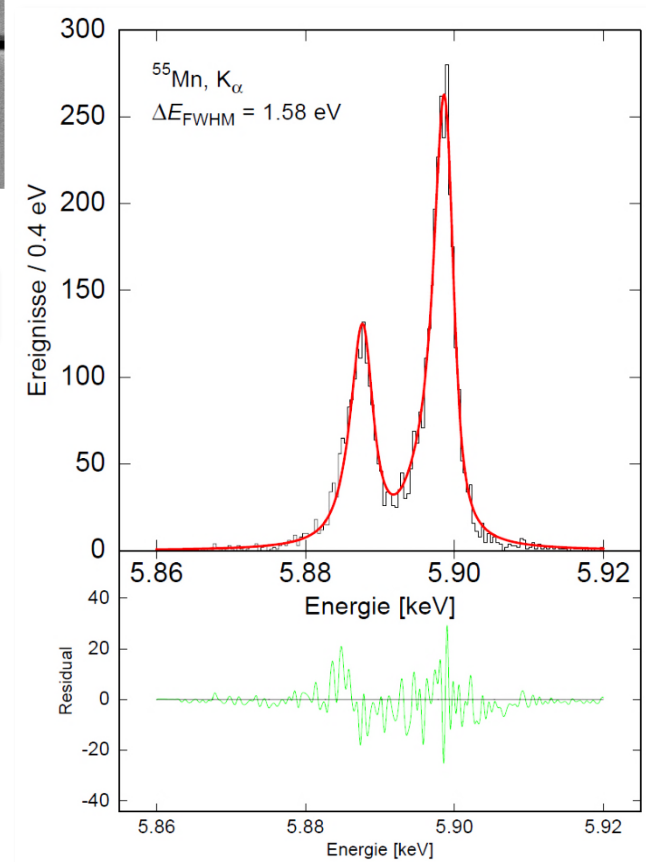


maXs: 1d-array for soft x-rays (T=20 mK)

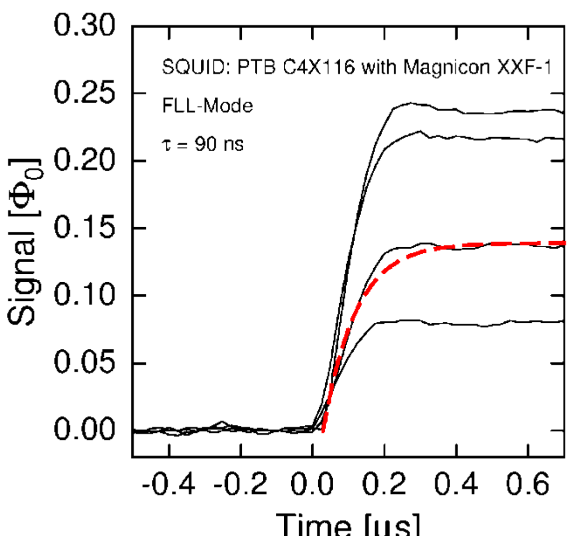




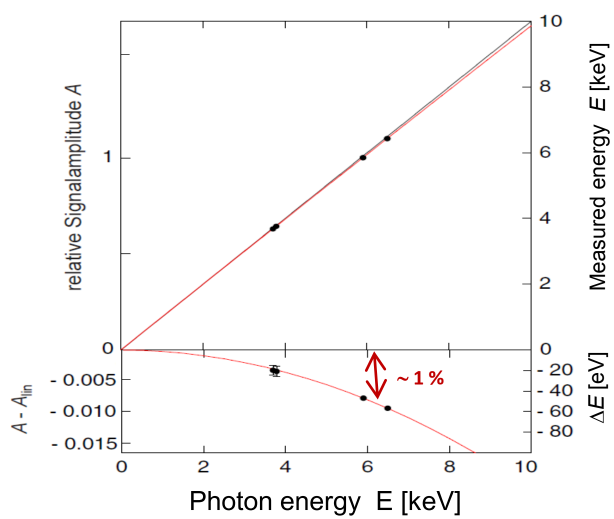
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



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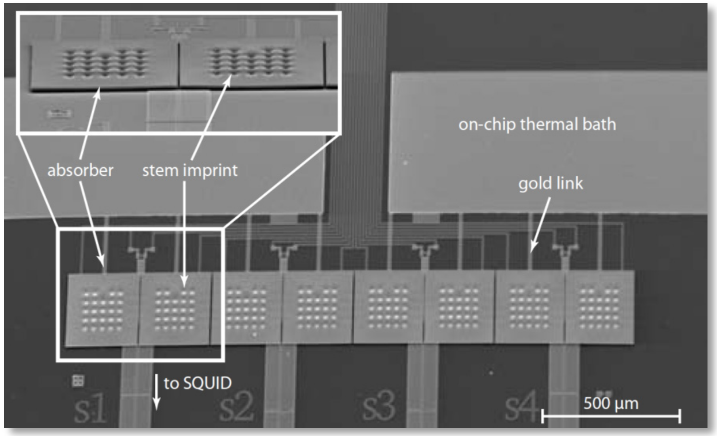

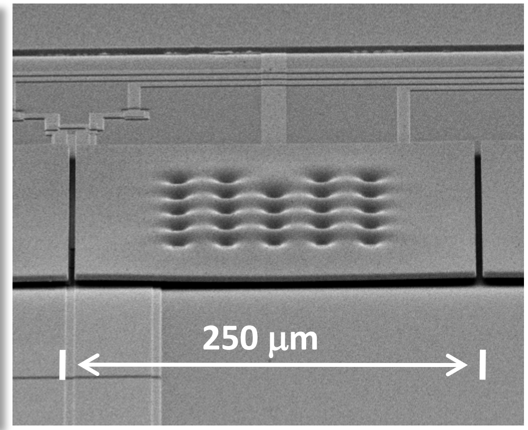

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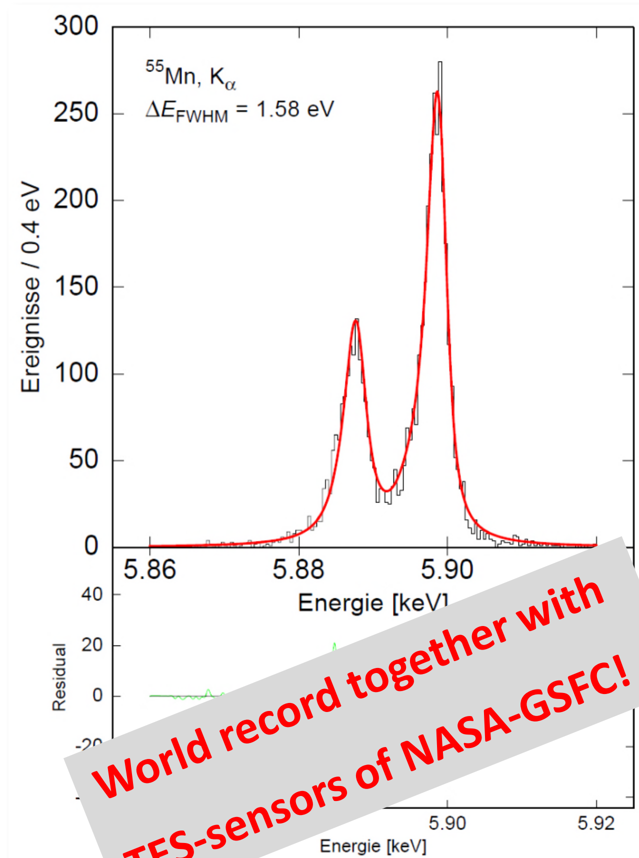

World record together with TES-sensors of NASA-GSFC!

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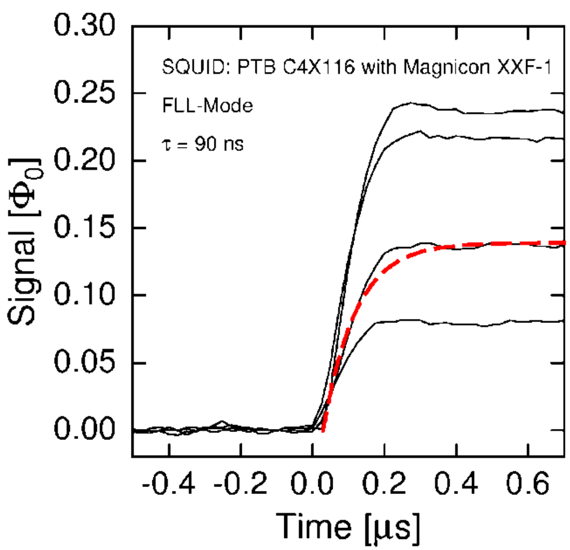

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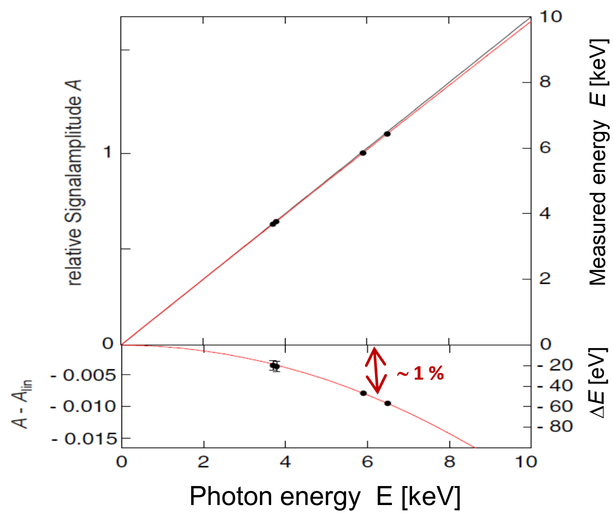
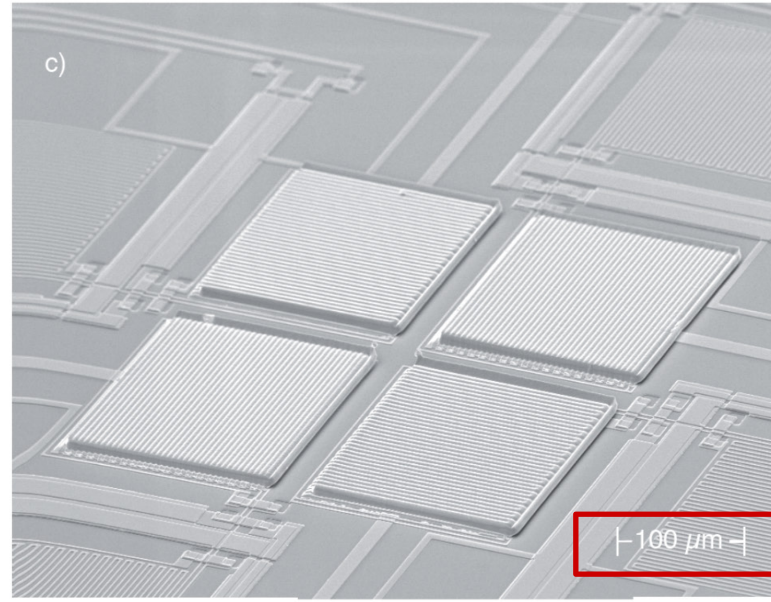
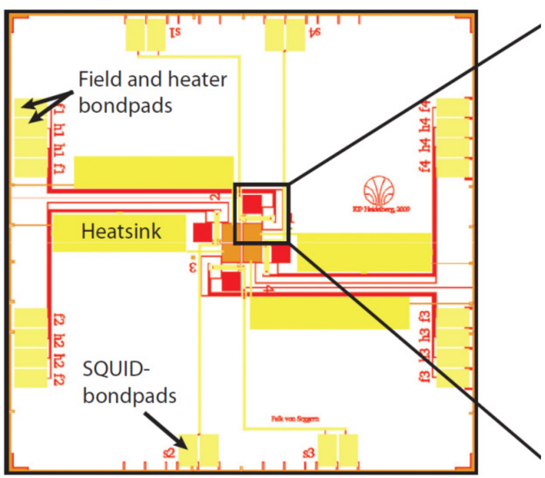
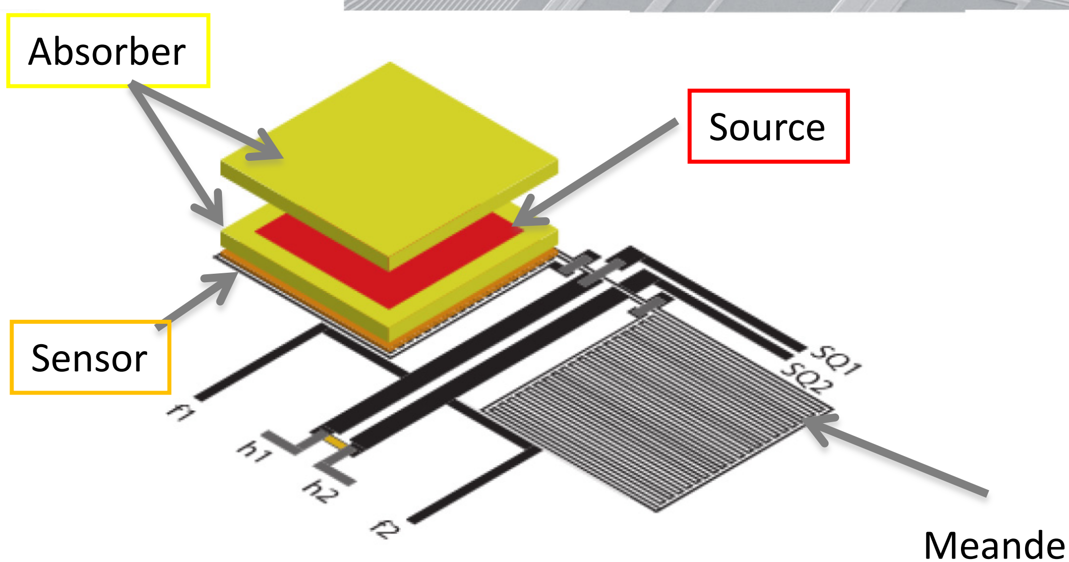


^{163}Ho Detector: First prototype

- Absorber for calorimetric measurement → ion implantation @ ISOLDE-CERN
- Two pixels have been simultaneusly measured
- ^{55}Fe calibration source was collimated only on one pixel







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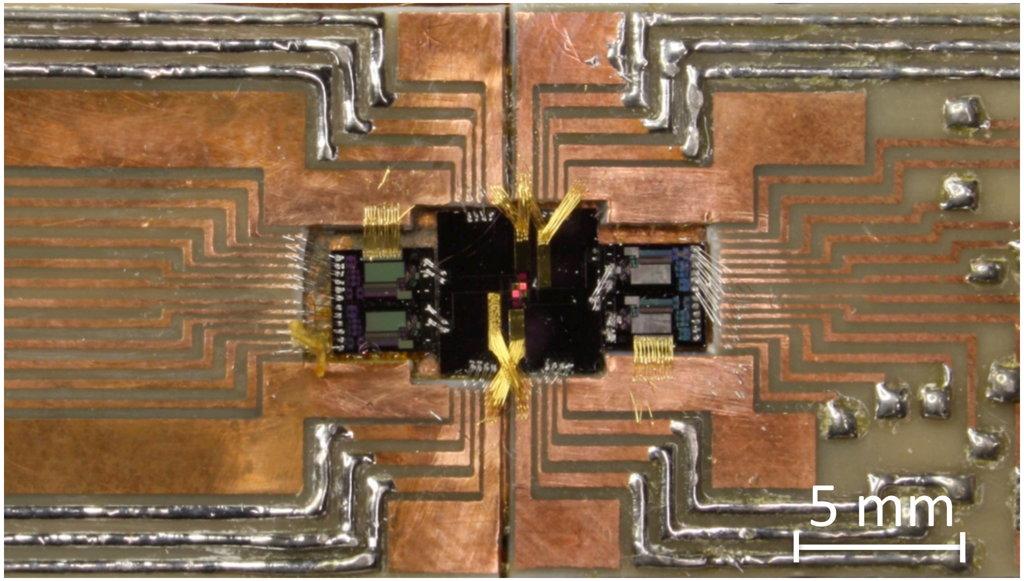
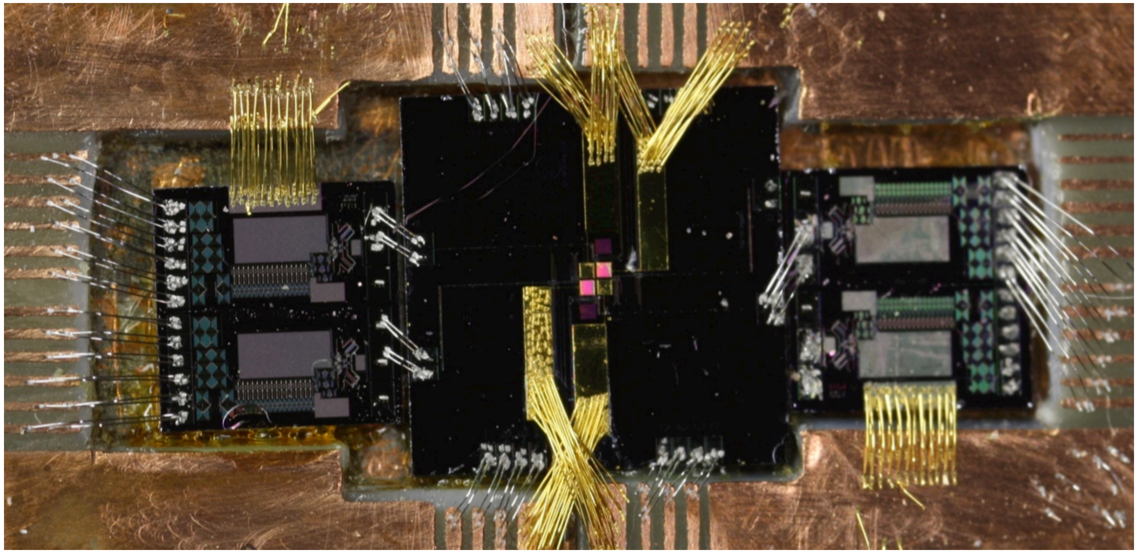
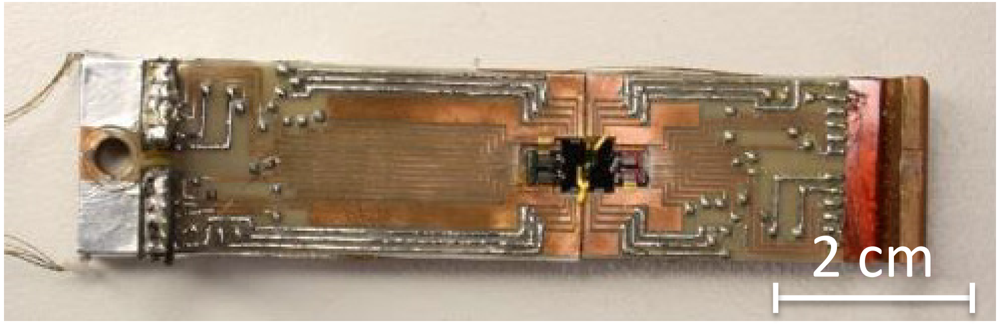


- Newest generation C6X114W SQUIDs (PTB Berlin)
  ➔ best noise performance

- **Al** bonding wires for electrical connections
- **Au** bonding wires for thermal connections

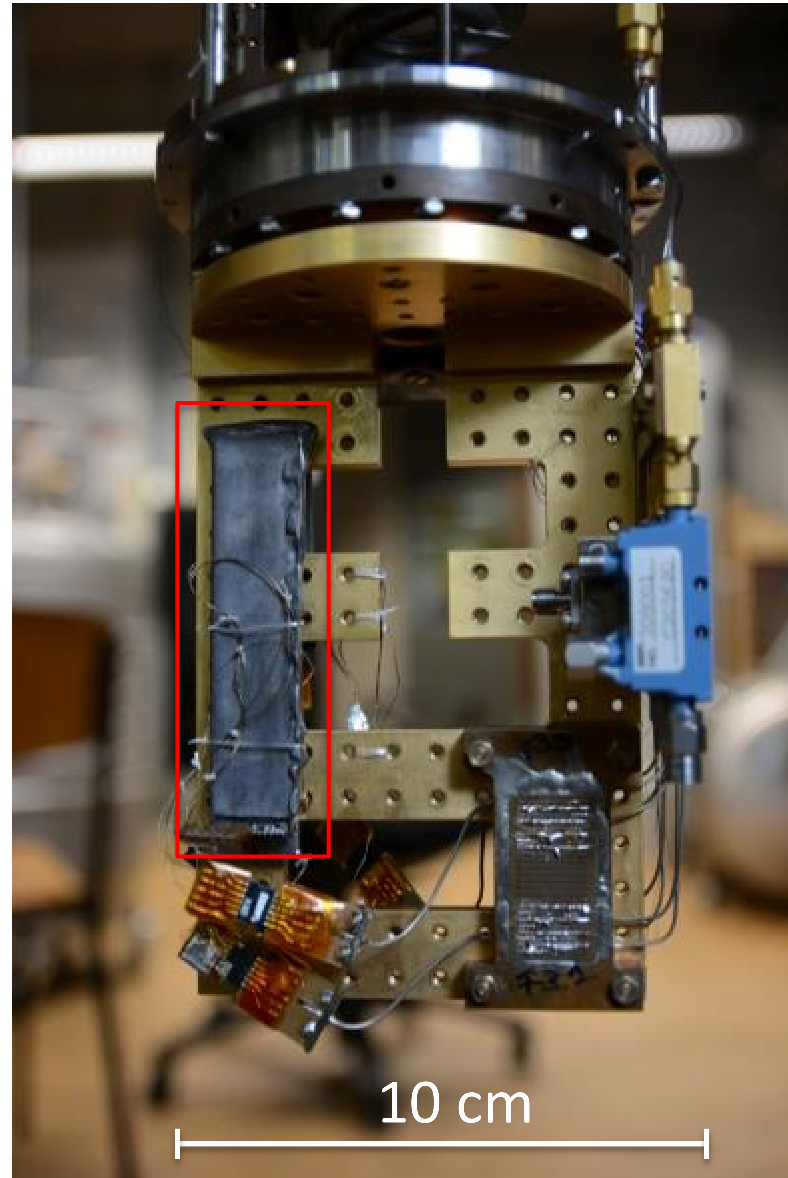


^{163}Ho Detector: Experimental environment



- Cu holder
- CuFlon circuit board
- Pb shielding

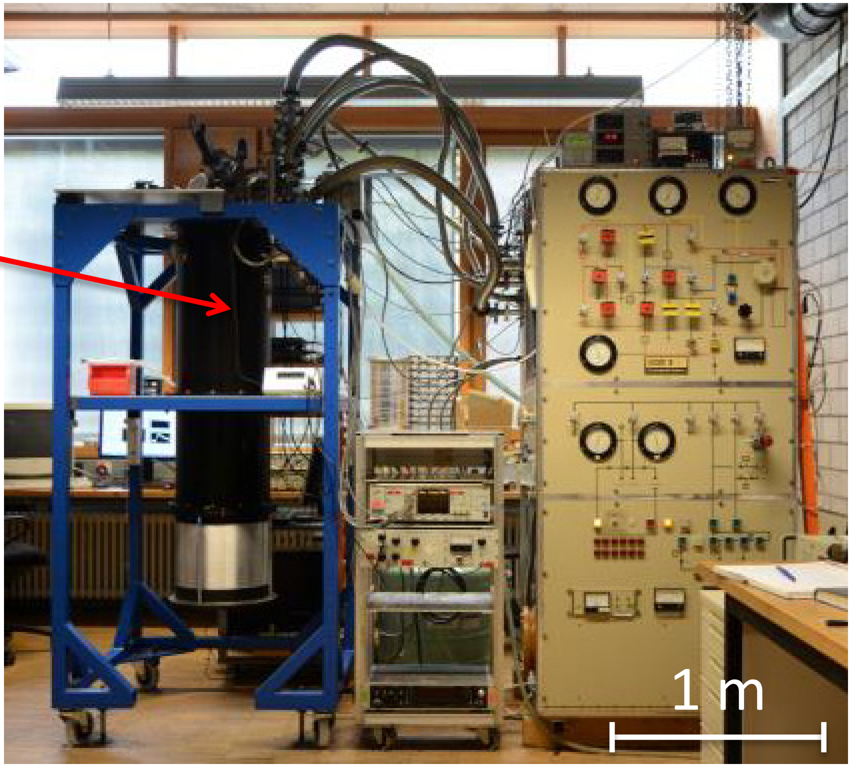
- ^{3}He/^{4}He dilution refrigerator (Oxford instruments)
- Cu experimental platform (Au plated)
- T ≈ 20 mK

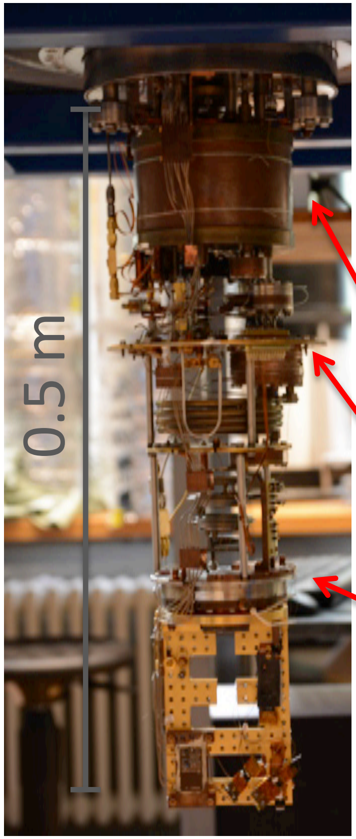


^{163}Ho Detector: Experimental environment

Layered precooling:

- Liquid N_2 ~ 77 K
- Liquid ^{4}He ~ 4.2 K



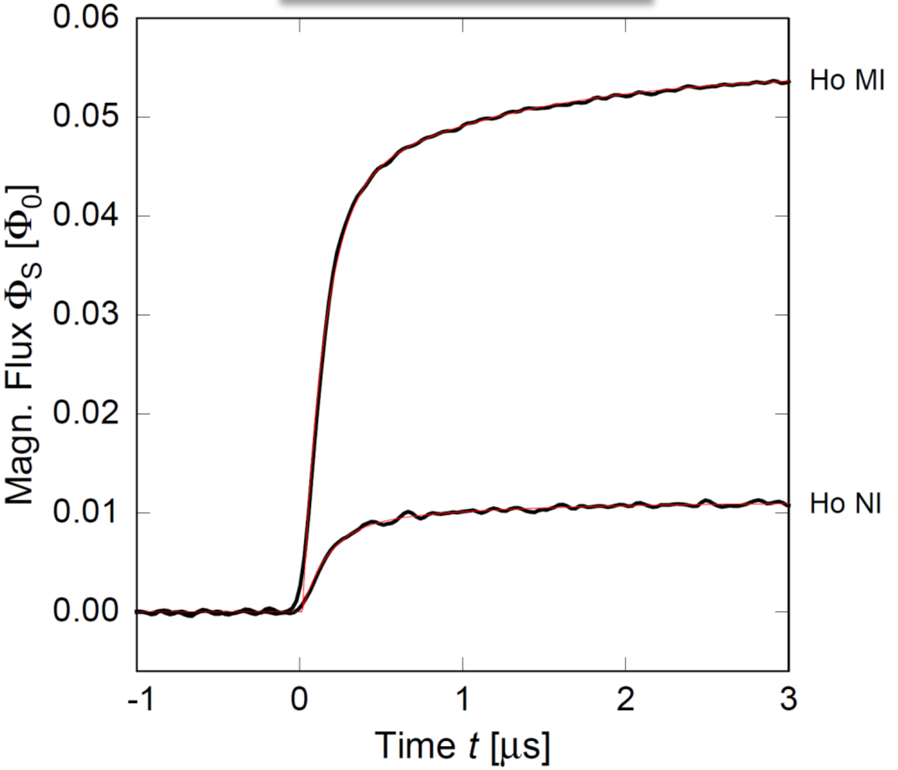


Dilution unit

- 1st stage ~ 1.5 K
- 2nd stage ~ 0.6 K
- Experimental platform ~ 20 mK

^{163}Ho Detector: Calorimetric spectrum

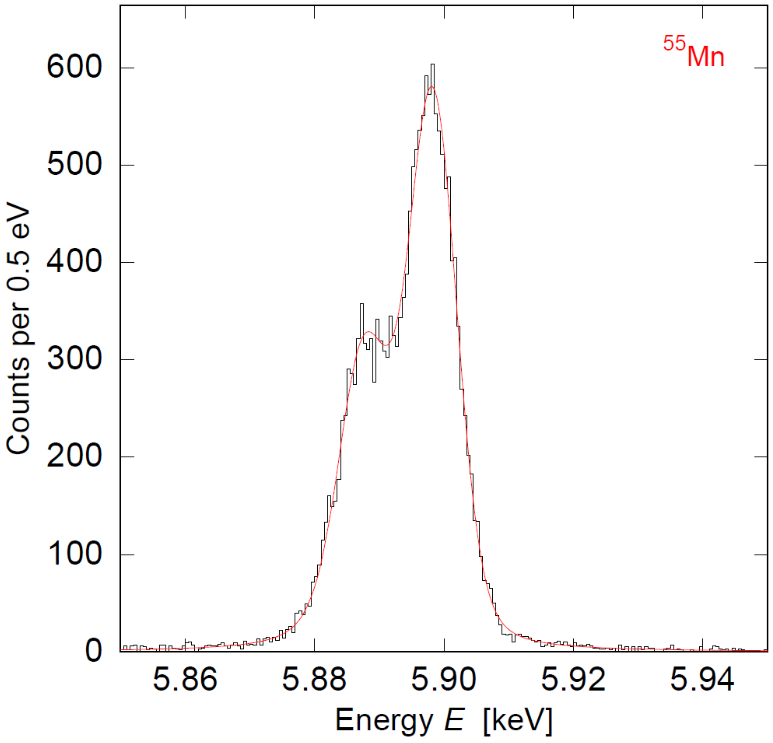
Rise Time ~ 130 ns



^{163}Ho Detector: Calorimetric spectrum

- **Rise Time ~ 130 ns**

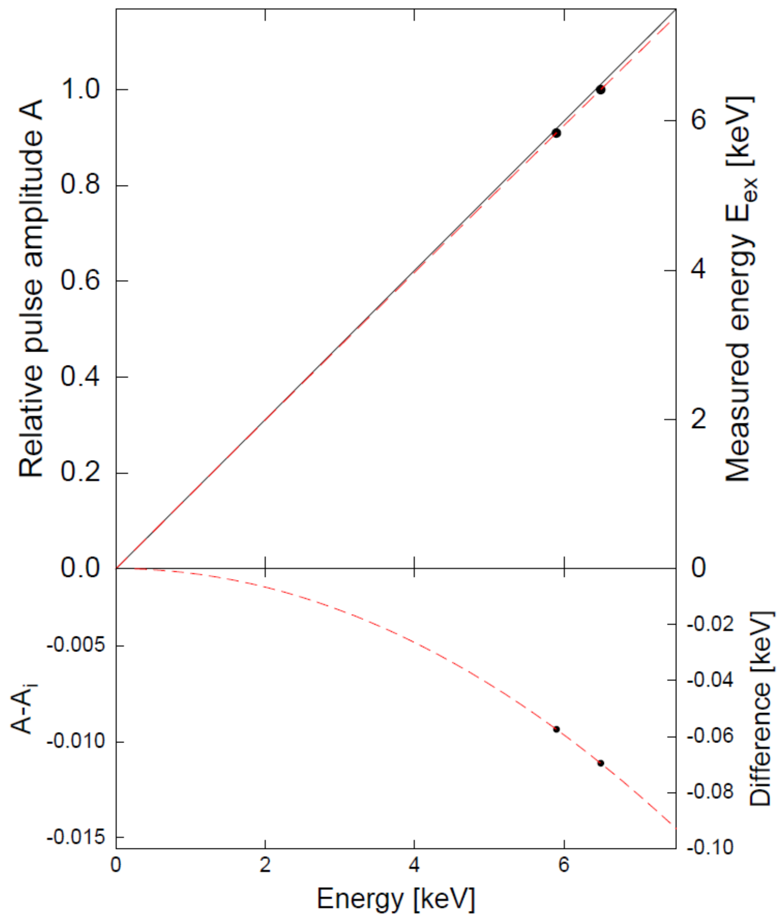
ΔE_{FWHM} = 7.6 eV @ 6 keV



^{163}Ho Detector: Calorimetric spectrum

- **Rise Time ~ 130 ns**
- **ΔE_{FWHM} = 7.6 eV @ 6 keV**

Non-Linearity < 1% @6keV



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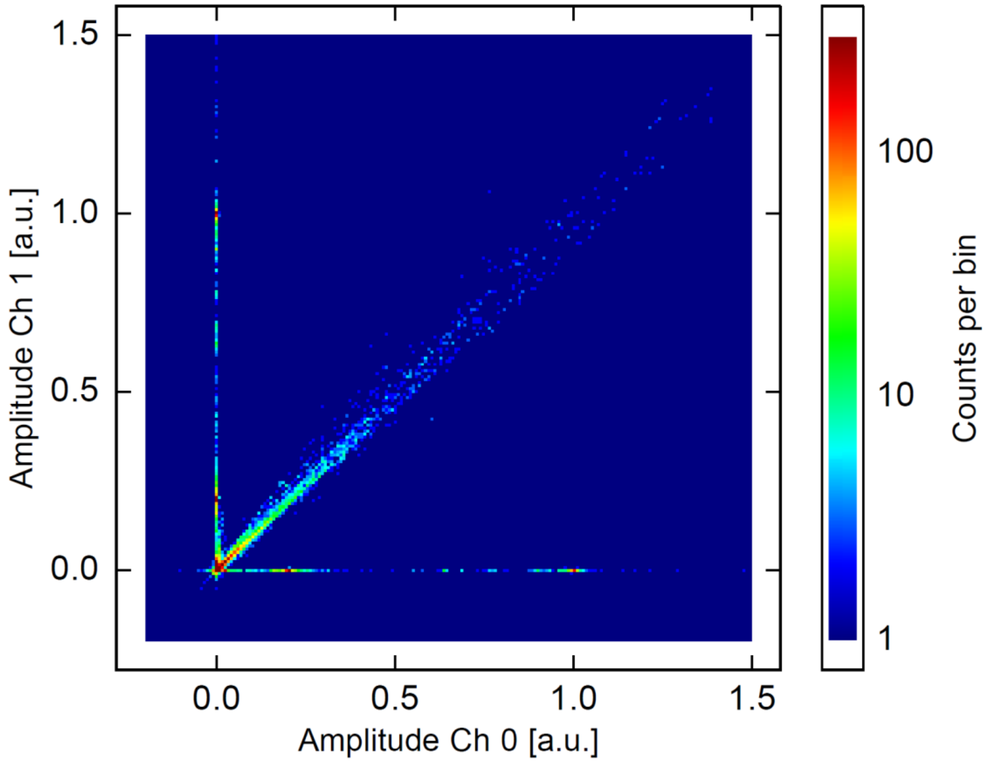

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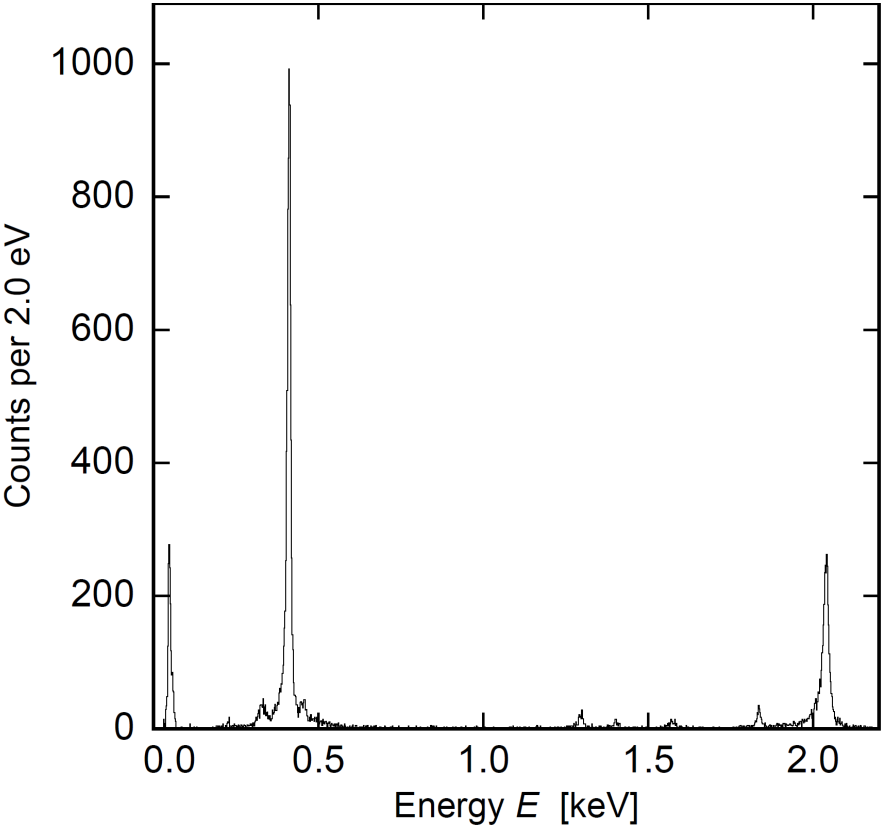
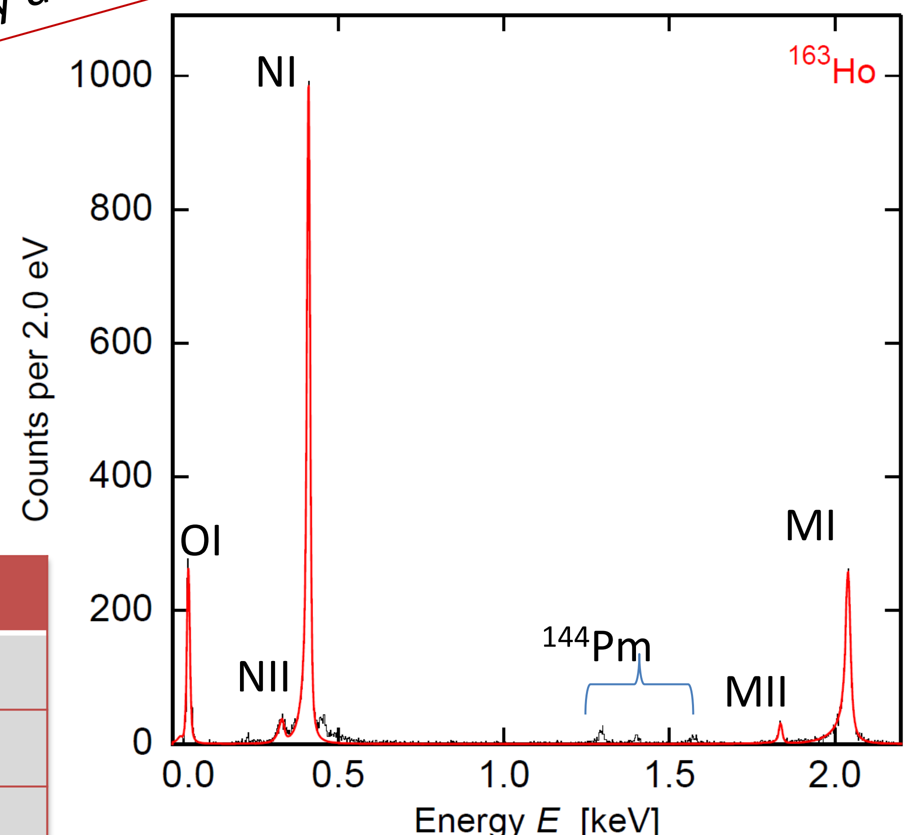


^{163}Ho Detector: Calorimetric spectrum

- **Rise Time ~ 130 ns**
- **ΔE_{FWHM} = 7.6 eV @ 6 keV**
- **Non-Linearity < 1% @6keV**
- **Most precise ^{163}Ho spectrum**

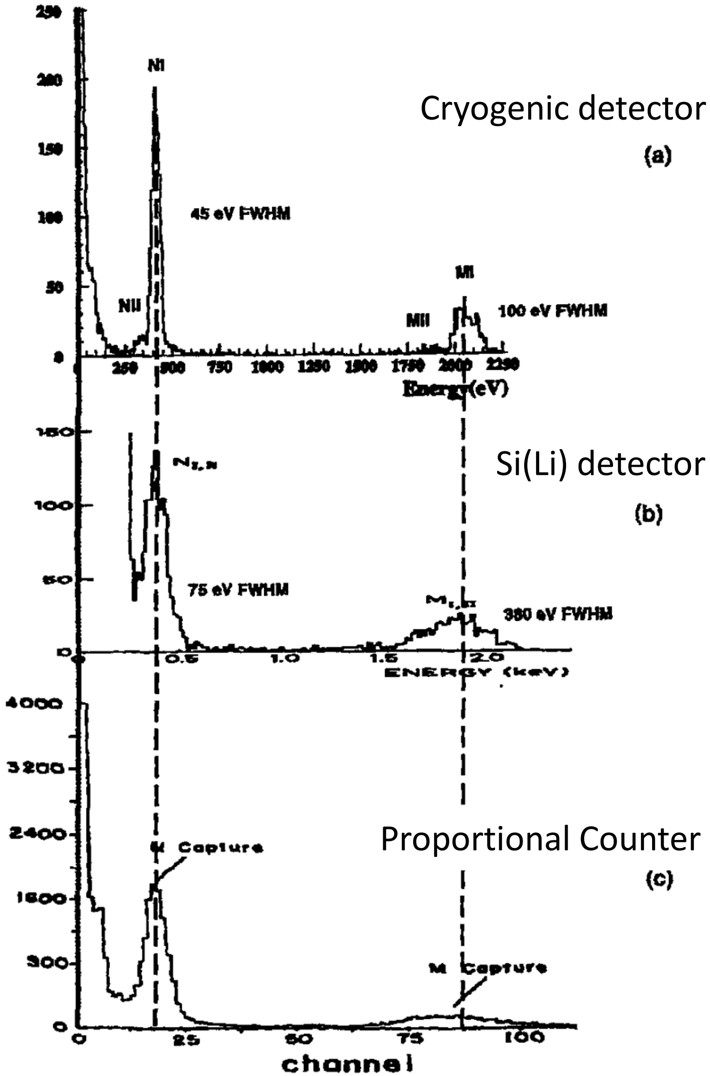
Preliminary analysis



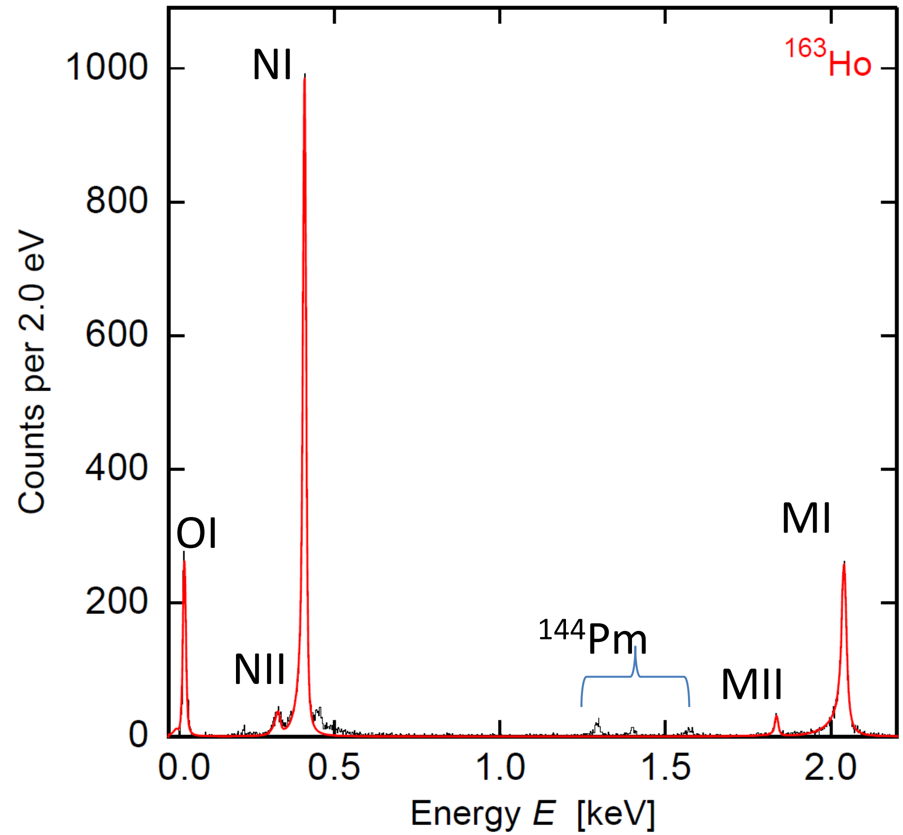
	E_H lit.	E_H exp.	Γ_H lit.	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

Q_{EC} =(2.80±0.08) keV

^{163}Ho Detector: Calorimetric spectrum



F. Gatti et al., Physics Letters B 398 (1997) 415-419

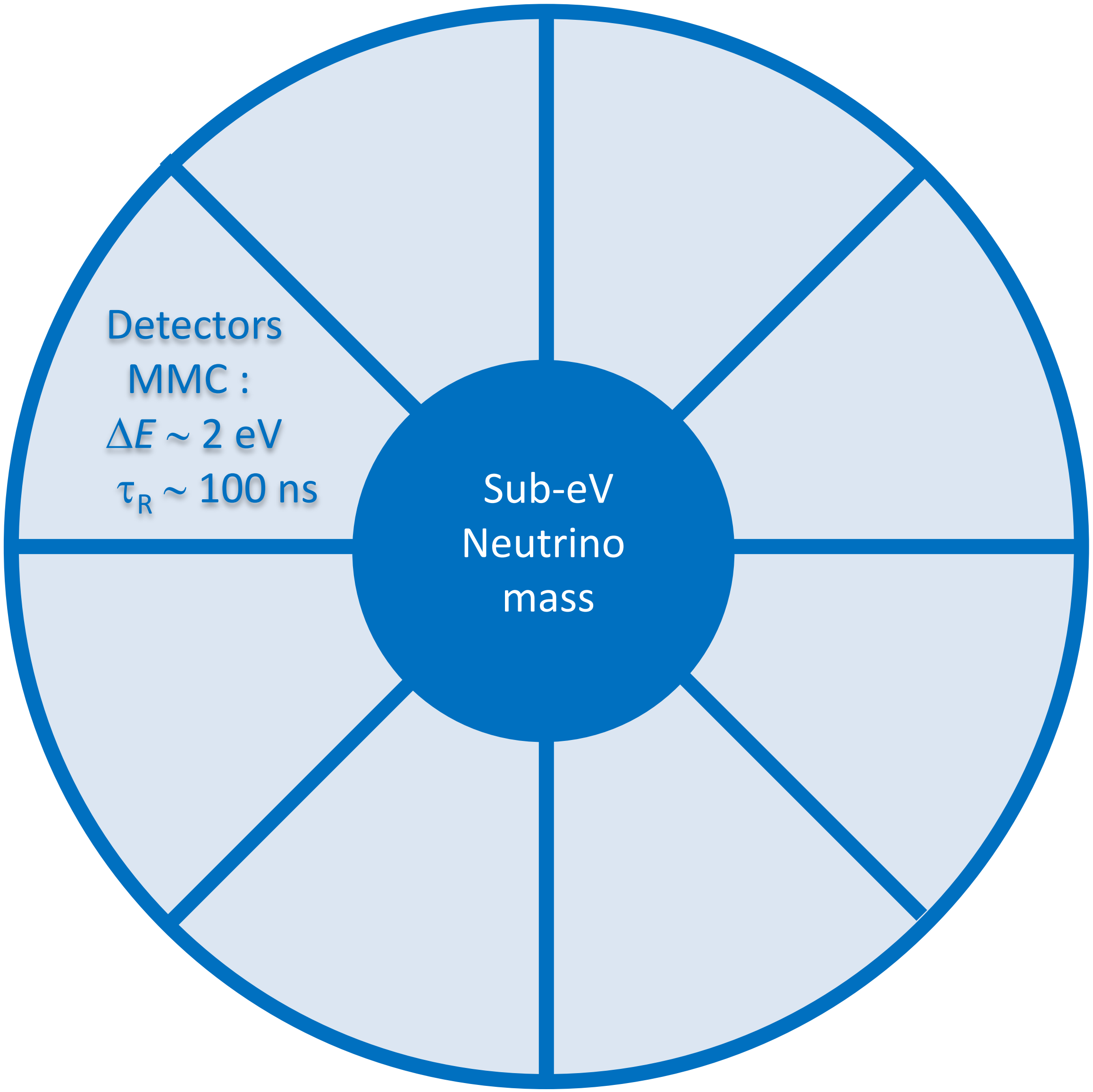


(a) F. Gatti et al., Physics Letters B 398 (1997) 415-419

(b) E. Laesgaard et al., Proceeding of 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), (1984).

(c) F.X. Hartmann and R.A. Naumann, Nucl. Instr. Meth. A 3 13 (1992) 237.

ECHo experiment



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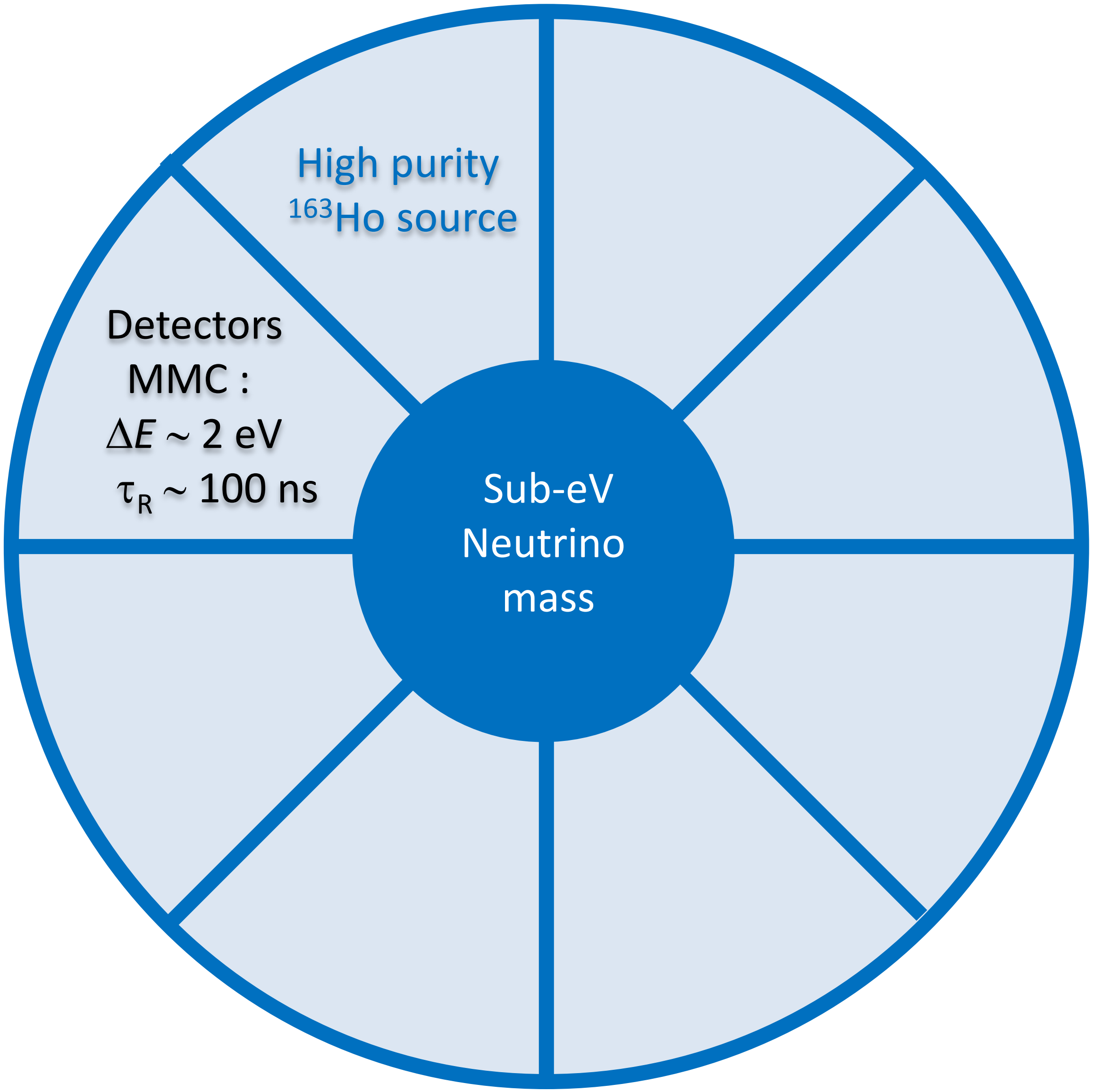

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➢ ^{163}Ho can be produced by charged particle activation through direct or indirect way

^{nat}Dy(p,xn) ^{163}Ho

^{nat}Dy(α, xn) ^{163}Er (ε) ^{163}Ho

^{159}Tb(^{7}Li, 3n) ^{163}Er (ε) ^{163}Ho

Er155 5.3 m 7/2- C,α	Er156 19.5 m 0+ EC	Er157 18.65 m 3/2- * EC	Er158 2.29 h 0+ EC	Er159 36 m 3/2- EC	Er160 28.58 h 0+ EC	Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho154 11.76 m (2)- * C,α	Ho155 48 m 5/2+ EC	Ho156 56 m (4+) * EC	Ho157 12.6 m 7/2- EC	Ho158 11.3 m 5+ * EC	Ho159 33.05 m 7/2- * EC	Ho160 25.6 m 5+ * EC	Ho161 2.48 h 7/2- * EC	Ho162 15.0 m 1+ * EC	Ho163 4570 y 7/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100
Dy153 6.4 h 7/2(-)	Dy154 3.0E+6 y 0+ α	Dy155 9.9 h 3/2- EC	Dy156 0+ 0.06	Dy157 8.14 h 3/2- * EC	Dy158 0+ 0.10	Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb152 17.5 h 2- * C,α	Tb153 2.34 d 5/2+ EC	Tb154 21.5 h 0 * EC,β-	Tb155 5.32 d 3/2+ EC	Tb156 5.35 d 3- * EC,β-	Tb157 71 y 3/2+ EC	Tb158 180 y 3- * EC,β-	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-

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Dy153 6.4 h 7/2(-)	Dy154 3.0E+6 y 0+ α	Dy155 9.9 h 3/2- EC	Dy156 0+ 0.06	Dy157 8.14 h 3/2- * EC	Dy158 0+ 0.10	Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb152 17.5 h 2- * C,α	Tb153 2.34 d 5/2+ EC	Tb154 21.5 h 0 * EC,β-	Tb155 5.32 d 3/2+ EC	Tb156 5.35 d 3- * EC,β-	Tb157 71 y 3/2+ EC	Tb158 180 y 3- * EC,β-	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-

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Two sources already produced

✓ Helmoltz Zentrum Berlin

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Two sources already produced

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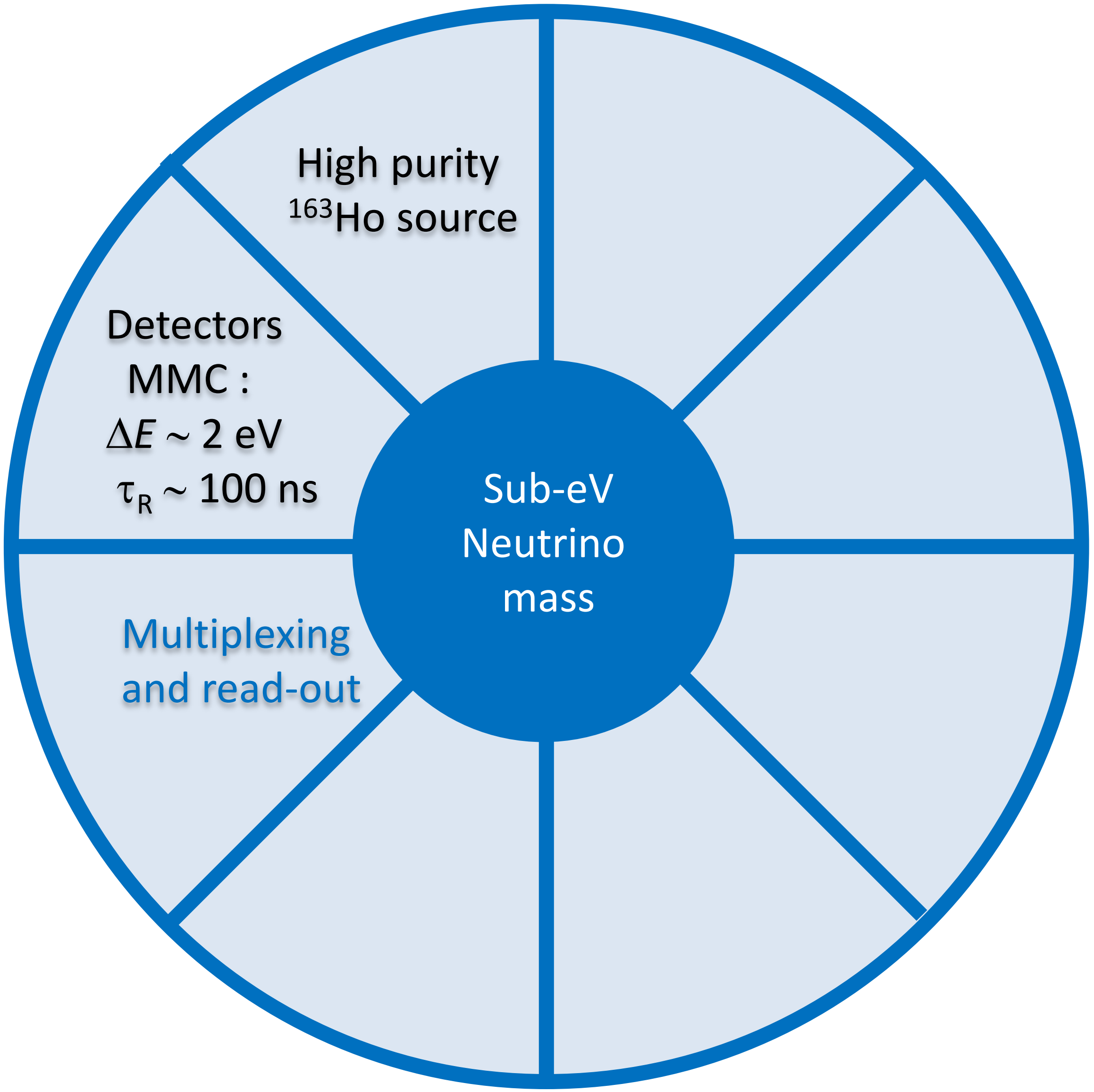
- Purity: No radioactive contaminants and removed target material

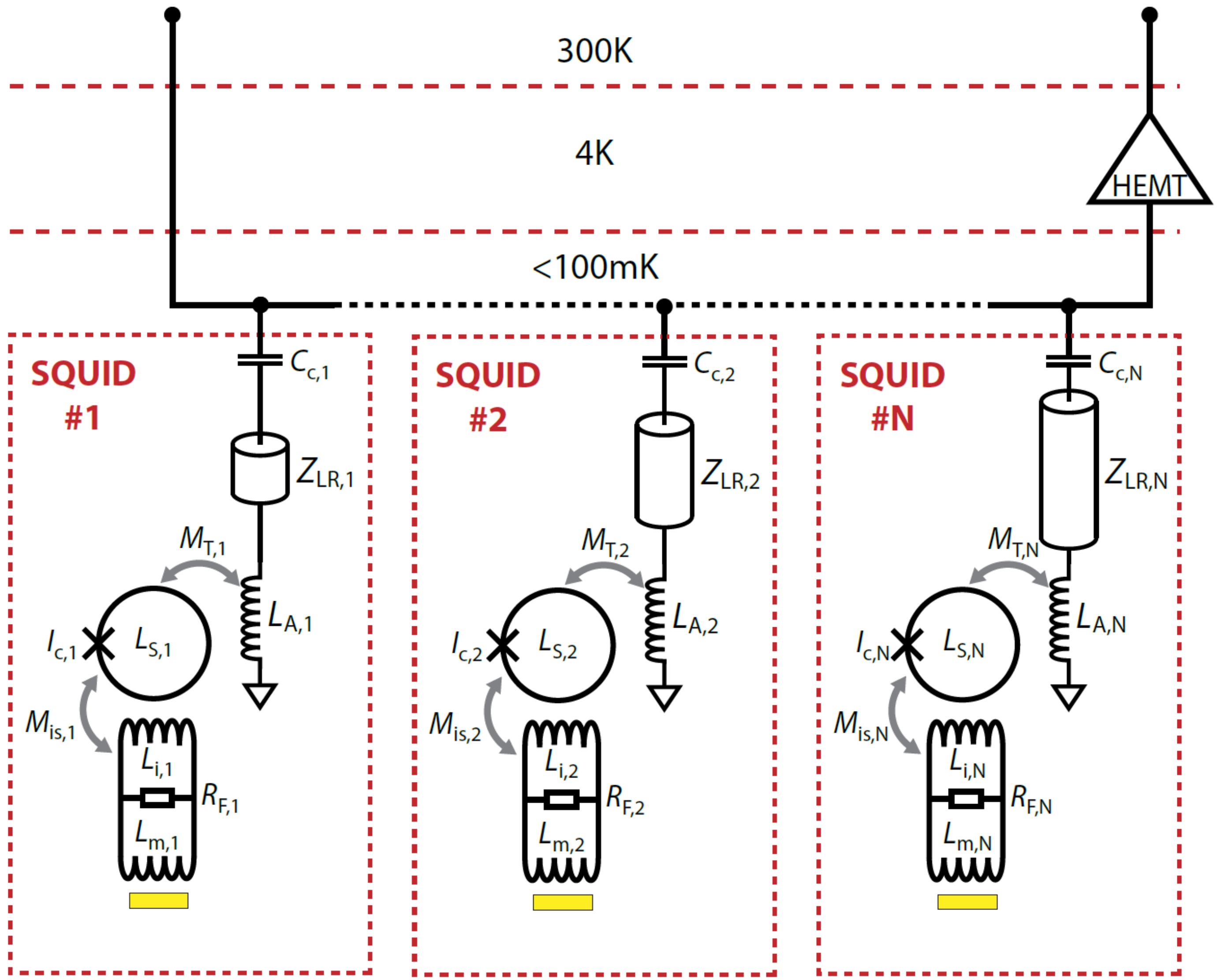
➢ High efficiency purification methods

- Chemical form: depends on the absorber preparation (ion implantation, dilute alloys)

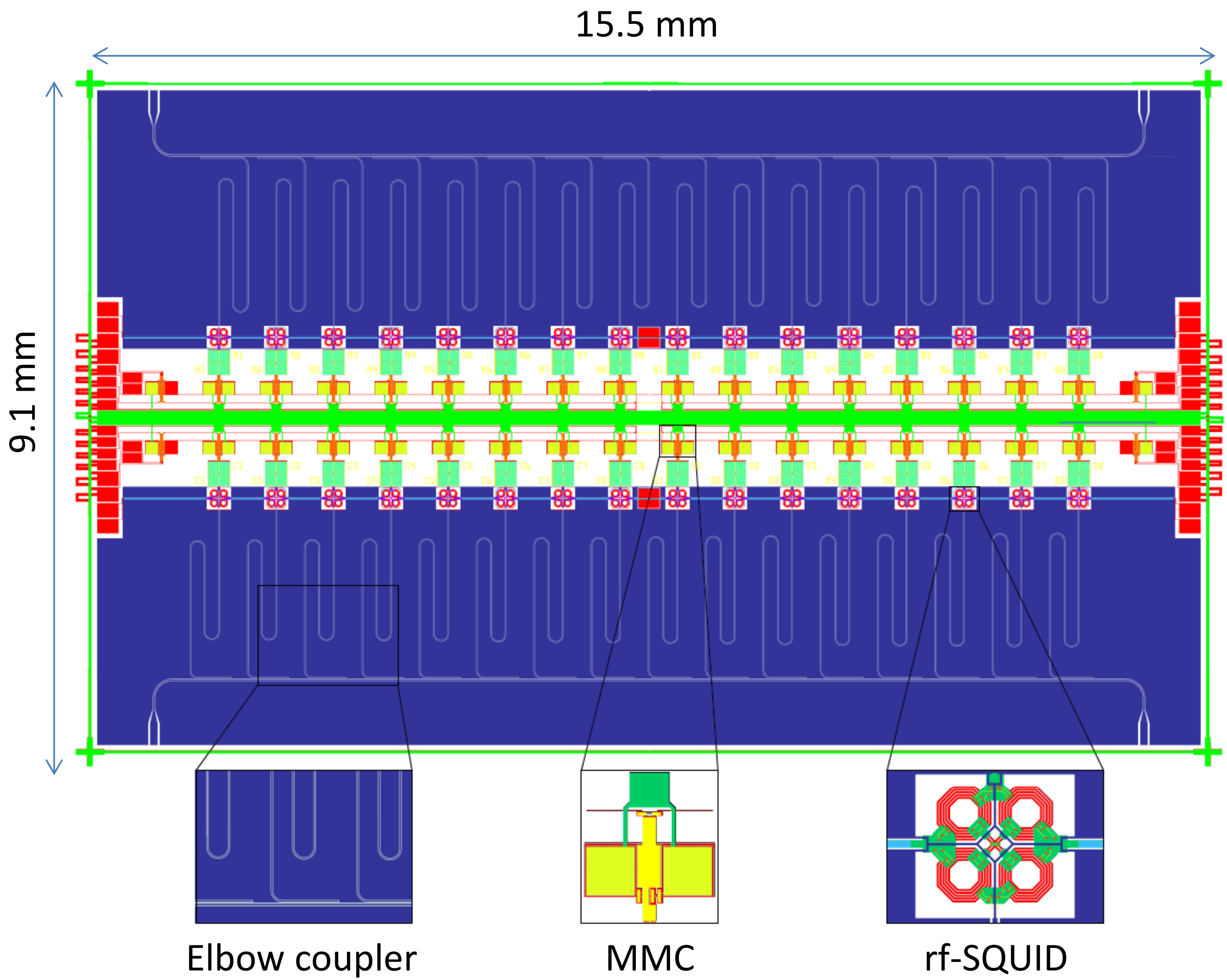
ECHo experiment



ECHo experiment: µwave SQUID multiplexing



ECHo experiment: 64-pixel chip



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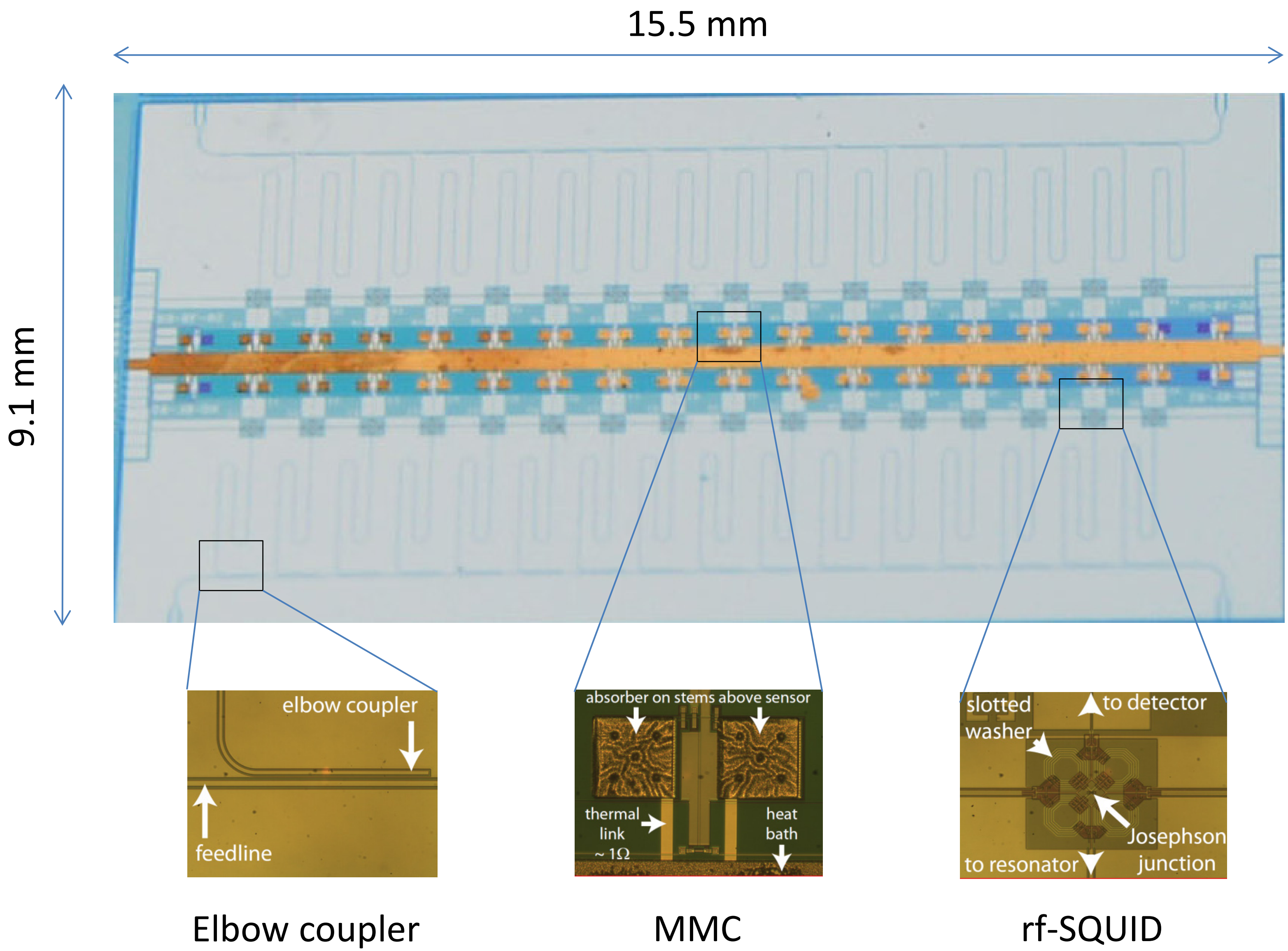
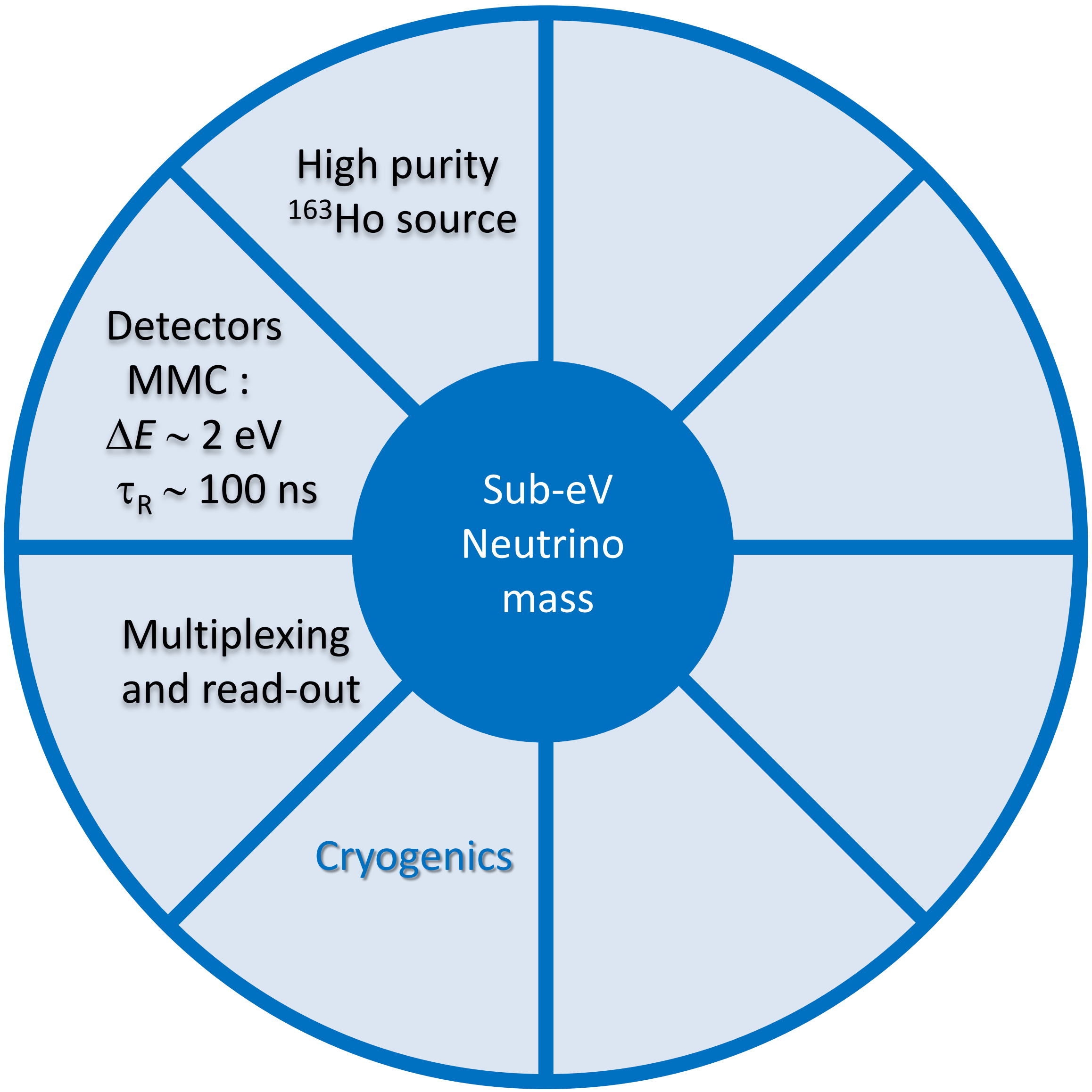
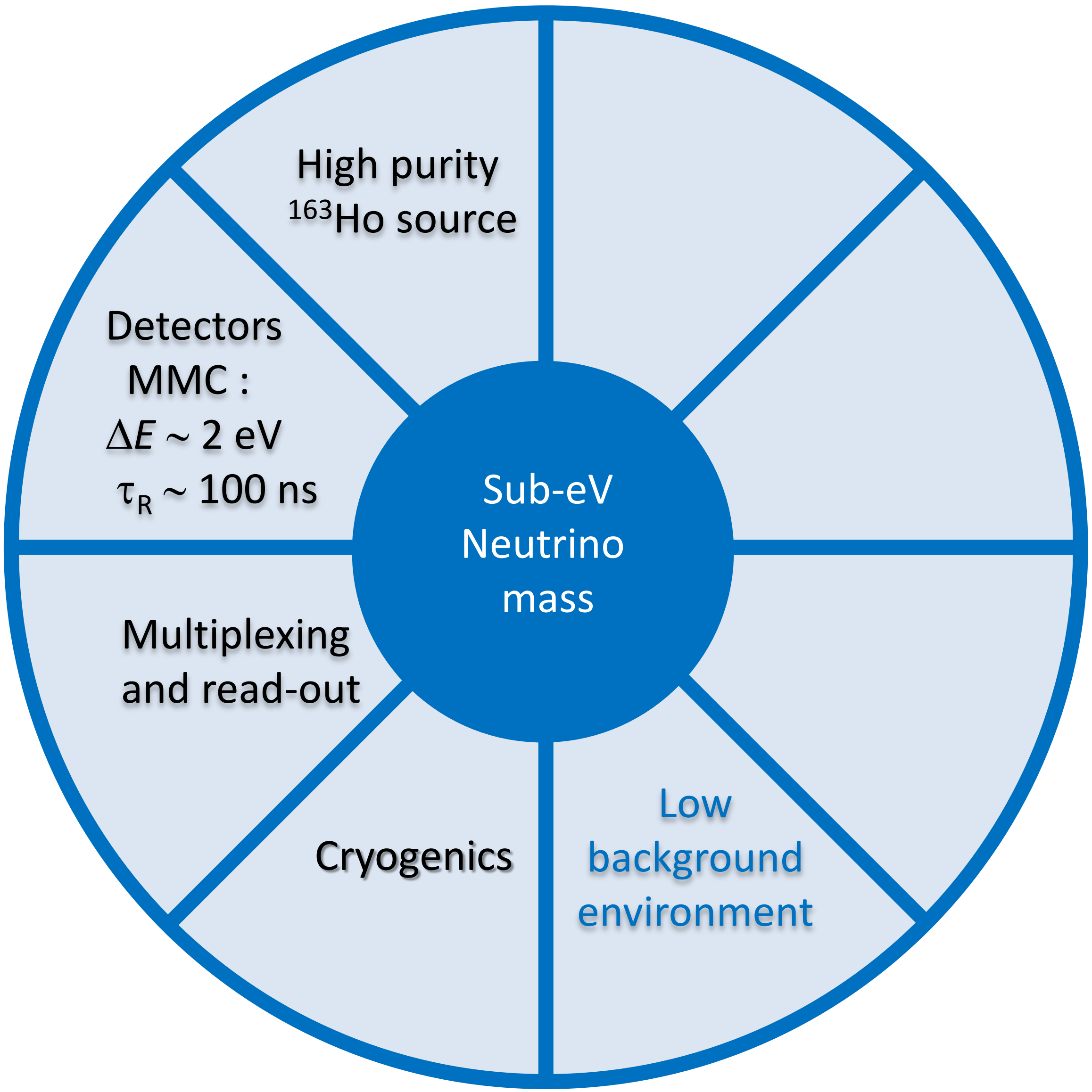


ECHo experiment



ECHo experiment



ECHo experiment: Low background

Background sources:

- Contamination of the source→ ^{166m}Ho
- Environmental radioactivity
- Induced secondary radiation by cosmic rays

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Dedicated experiments

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First measurements underground in Modane winter 2013

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- Environmental radioactivity
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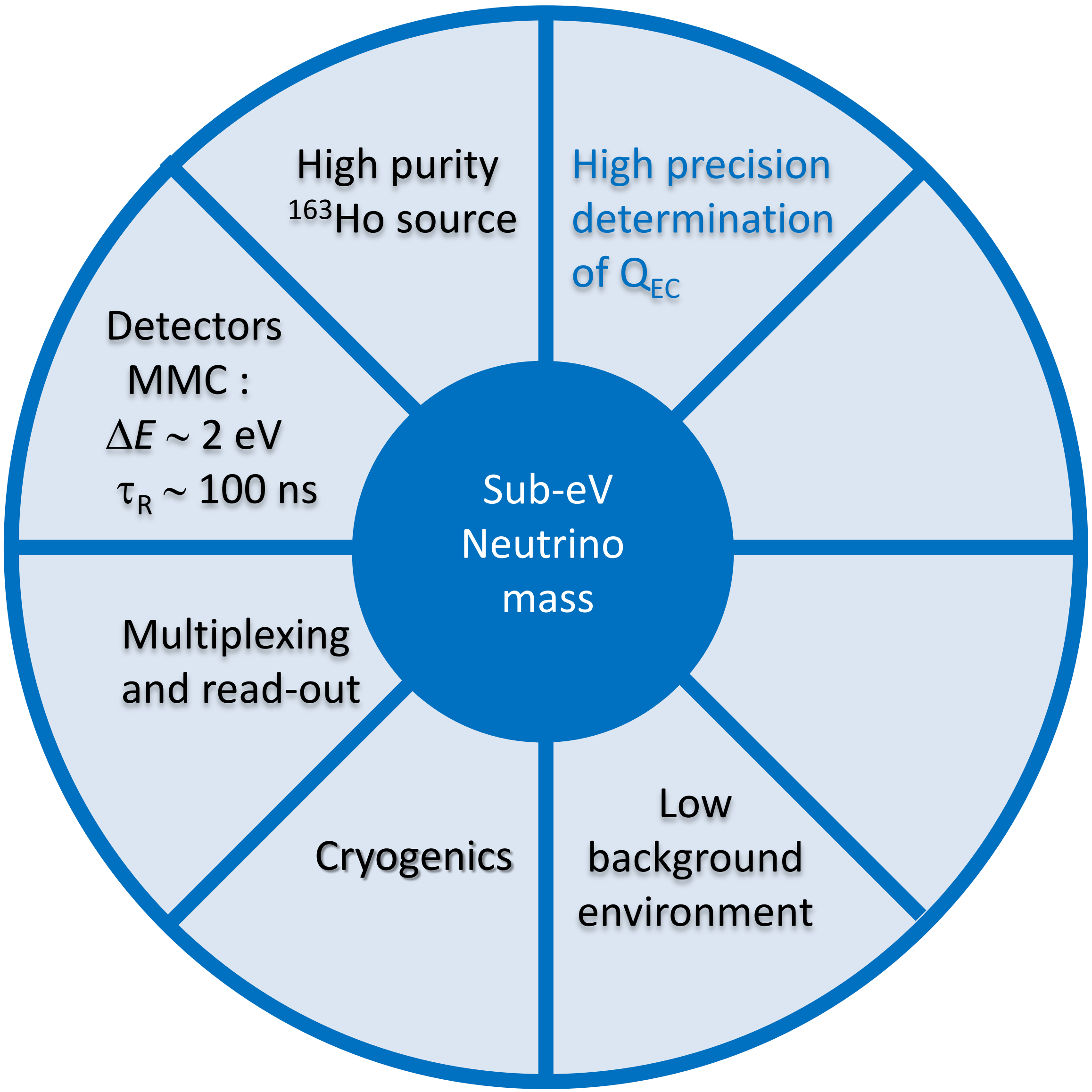
→

Monte Carlo simulations
Dedicated experiments

First measurements underground in Modane winter 2013

- ✓ Selection of materials for the experimental set-up
- ✓ Definition of detector design →veto
- ✓ Designs for the shielding

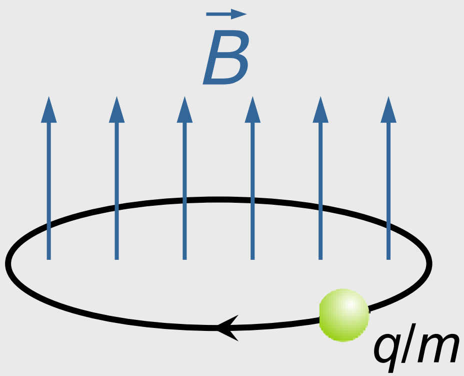
ECHo experiment



ECHo experiment: Q_{EC} determination

Penning Trap mass spectroscopy

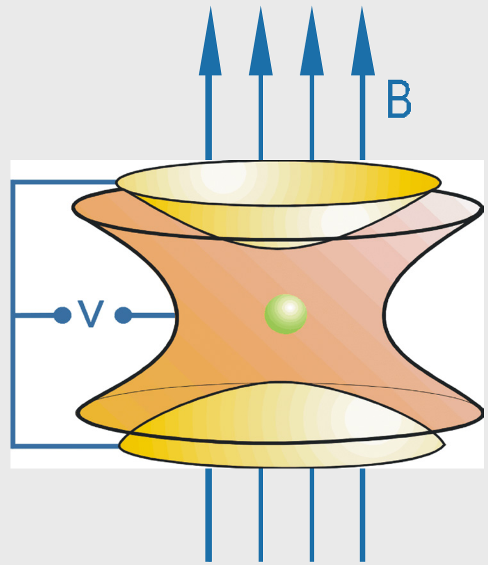
uniform B-field



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

+

quadrupole E-field



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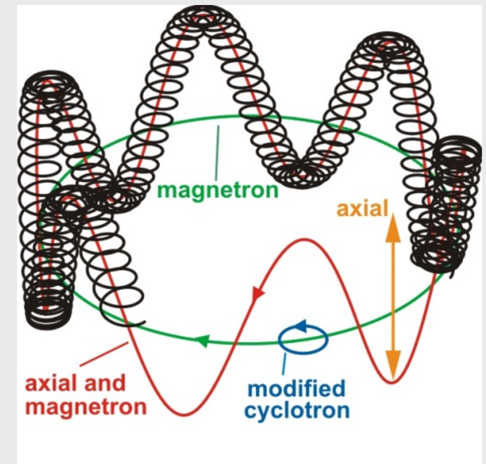
Penning Trap



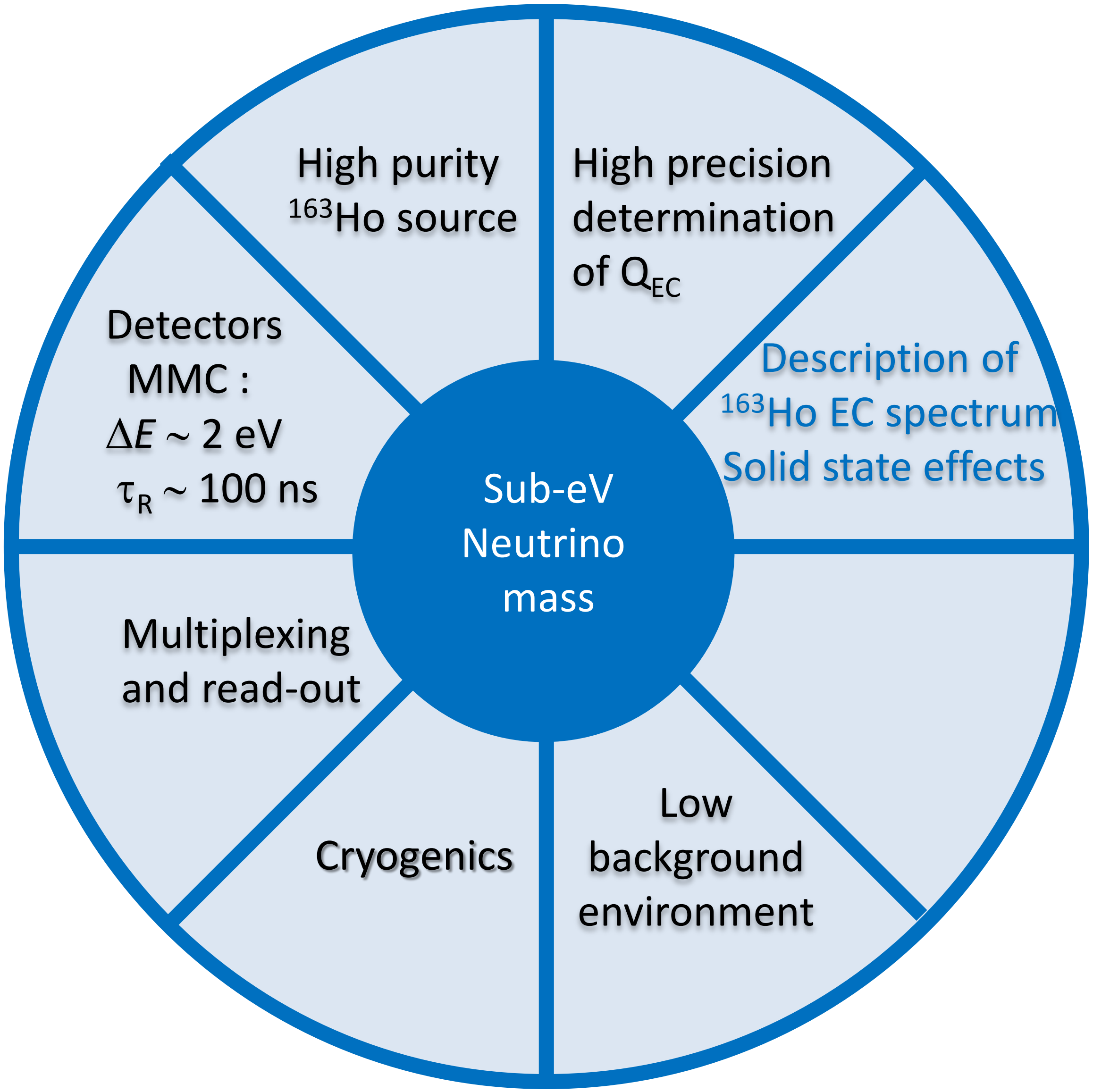
ν_+ - modified cyclotron
ν_- - magnetron
ν_z - axial

Next future : SHIPTRAP (GSI) → Q_{EC} determination within 100 eV

In few years: PENTATRAP (MPI-K HD) → Q_{EC} determination within 1 eV

Courtesy S. Eliseev, MPI-K HD

ECHo experiment



ECHo experiment: spectral shape

How precise do we know the calorimetric spectrum of ^{163}Ho?

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

Density Functional Theory (DFT) & Quasiparticle Random Phase Approximation (QRPA)

SOLID STATE EFFECTS

Experimental investiations:
^{163}Ho implanted in different materials
Simple ^{163}Ho molecules implanted in Au

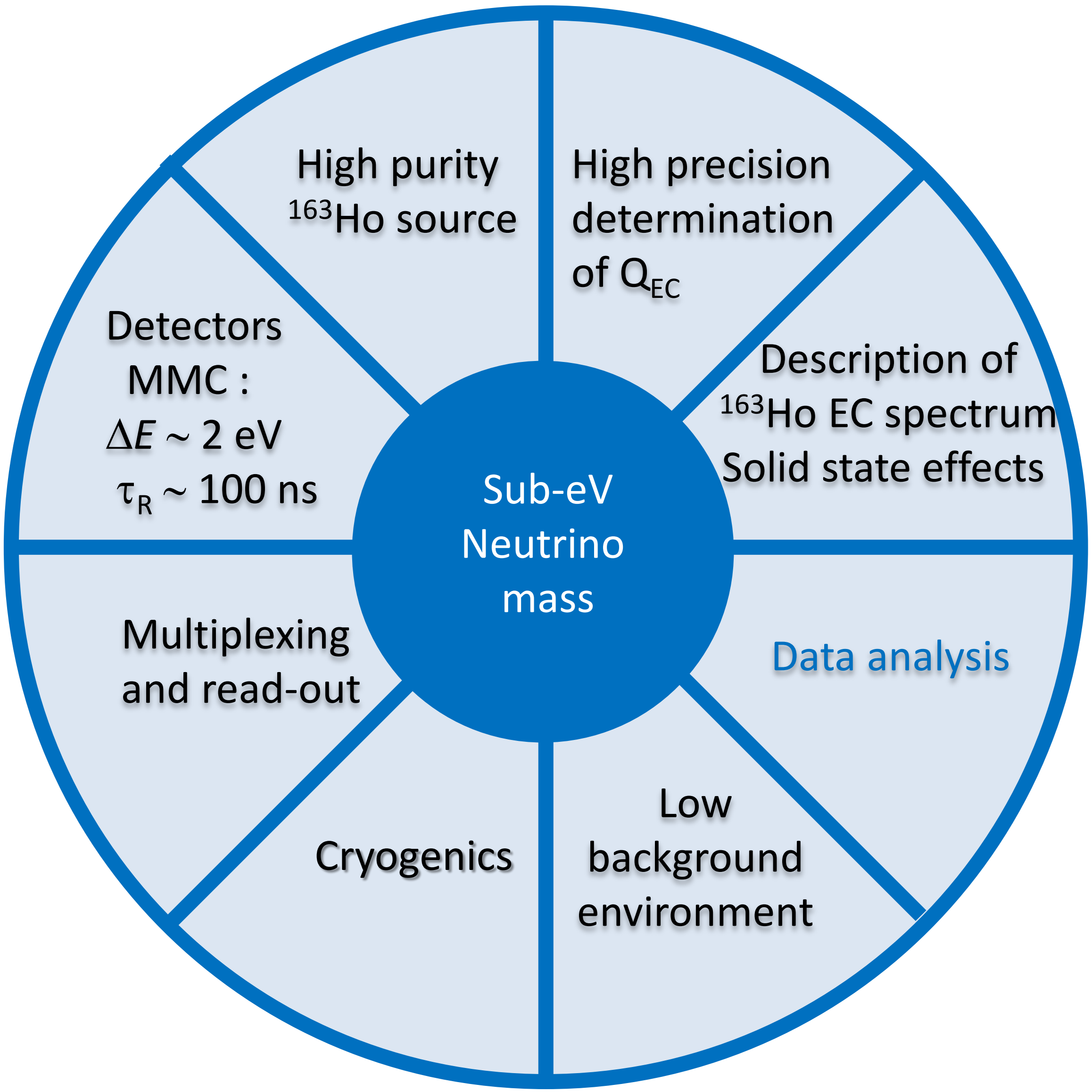
Core Level binding energy Shift (CLS):
calculated using the complete
screening approximation of DFT

Sensitivity to:

keV sterile neutrino

Cosmic neutrino background

ECHo experiment



^{163}Ho experiments

- Started R&D in 2011
- Small scale experiment with ~100 pixels within the next three years
- Large scale experiment to reach sub-eV sensitivity to neutrino mass

http://www.kip.uni-heidelberg.de/echo/

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HOLMES

- Established in 2013 (ERC Advanced Grants for Prof. S. Ragazzi)
- Some R&D done already within the MARE experiment

http://artico.mib.infn.it/nucriomib/general-infos/holmes-approved

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OTHERS

- **LANL + NIST** (last two years)
  - investigation for source production
  - detector developement for calorimentric measurements

http://conference.ipac.caltech.edu/ltd-15 (Kunde, Schmidt, Croce, Fowler)

Conclusion

A. De Rujula
arXiv:1305.4857v1 [hep-ph] 21 May 2013

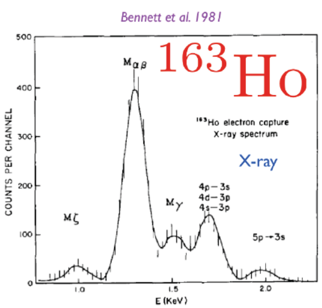

FIG. 5: IBEC spectrum in ^{163}Ho decay [22], showing prominent X-ray lines.

Some early measurements with a ^{163}Ho source [22, 23] were based on IBEC (Internal Bremsstrahlung in Electron Capture), the first-principle theory of which is fiendishly complex both above [24] and –more so– below [4] the energies coinciding with X-ray resonances. One example is shown in Fig. 5. Other measurements were calorimetric [25], see Fig. 6. The most stringent of the early mass limits, from [23] and [26] were, respectively:

$$m_\nu < 225\,\mathrm{eV}\ \text{at}\ 95\%\ \mathrm{CL}, \qquad m_\nu < 490\,\mathrm{eV}\ \text{at}\ 68\%\ \mathrm{CL}. \quad (8)$$

The recent progress may be illustrated by comparing Fig. 6 [25] with the preliminary results shown in Fig. 7, from the incipient experiment ECHo [27], which employs MMCs (Magnetic Metallic Calorimeters). The unlabeled peaks in Fig. 7 are due to ^{144}Pm, an impurity accompanying ^{163}Ho at the implantation stage at ISOLDE-CERN, an early test of source-preparation techniques.

One cannot resist the temptation of showing a scheme and a picture of the set of four MMCs in the ^{163}Ho detector prototype of ECHo [27]: Figs. 8 and 9. There is satisfaction associated with the possibility of measuring a tiny quantity –the neutrino mass– with nano-scale detectors. Even with the associated cryogenics and electronics, the apparatuses are still table-top.

V. THE THEORY OF EC IN ^{163}Ho

The EC process, all by itself, does not yield any information on the neutrino mass, or on anything else, for that matter. The mere information that "it happened" is

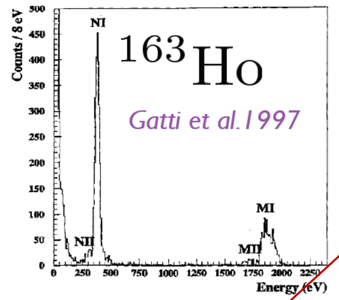

FIG. 6: Results of an early ^{163}Ho calorimetric spectrum [25].

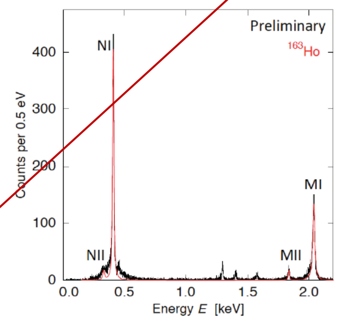

FIG. 7: Test results of ECHo [27] for the calorimetric spectrum of ^{163}Ho decay. The unlabeled impurities are ^{144}Pm. The continuous (red line) theory [5] is based on Eq. (9).

provided by the fact that the daughter atom, and sometimes its nucleus, are unstable. The hole in an atomic shell, for instance, results in observable X-rays, as the outer electrons cascade inwards, see Fig. 5.

The measured $Q = M(^{163}\mathrm{Ho}) - M(^{163}\mathrm{Dy})$ is so small that EC is only energetically allowed from ^{163}Ho orbitals with principal quantum number $n > 2$. The emission of X-rays from holes in such external shells is negligible compared to that of atomic de-excitations involving electron emission (in the classical parlance, the "fluorescence yields" are tiny). The electron-emitting transitions have

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Thank you!

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Yuri Novikov
Saha Institute of Nuclear Physics, Kolkata, India
Susanta Lahiri

ECHo