Kirchhoff-Institut für Physik

ECHo Experiment

Loredana Gastaldo

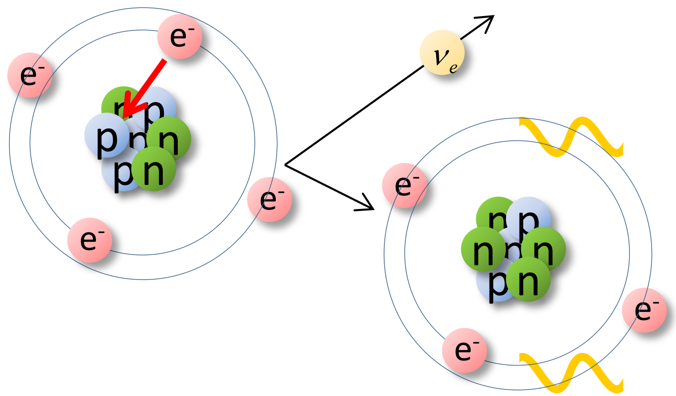
for the ECHo collaboration

Heidelberg University

Contents

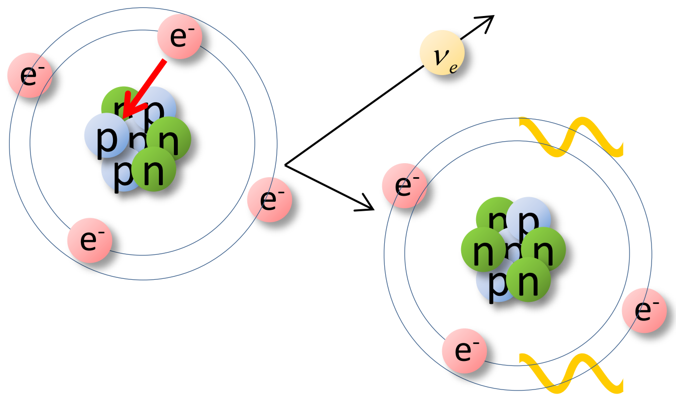
- Electron capture process: The case of ^{163}Ho
- Metallic Magnetic Calorimeters
- Recent results
- ECHo experiment

Electron Capture



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

Electron Capture



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

Atomic de-excitation:

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

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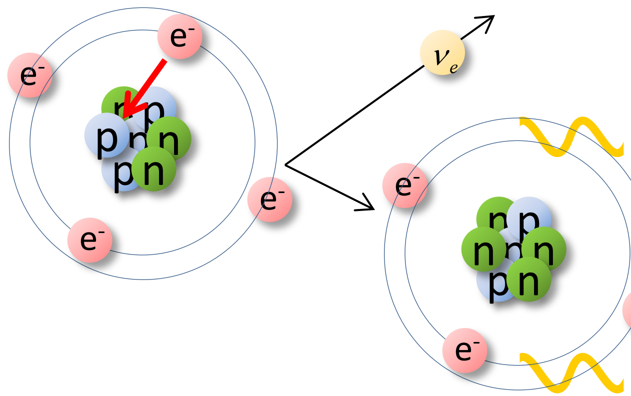

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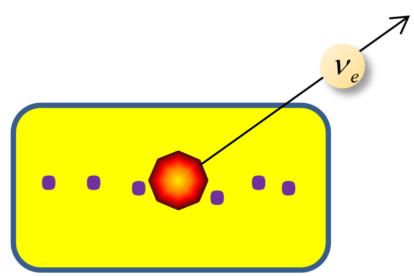
Calorimetric measurement



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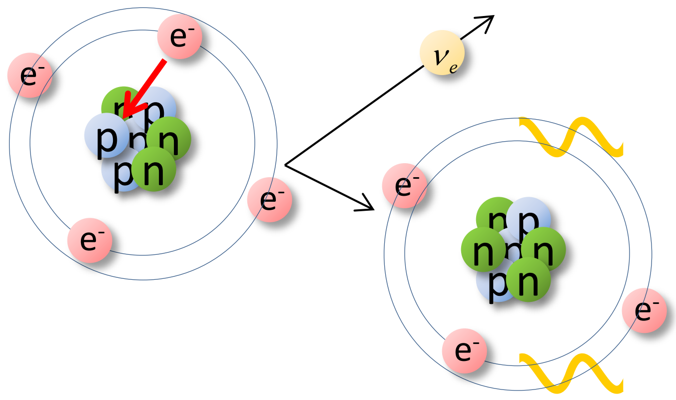

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Atomic de-excitation:

- X-ray emission
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Calorimetric measurement

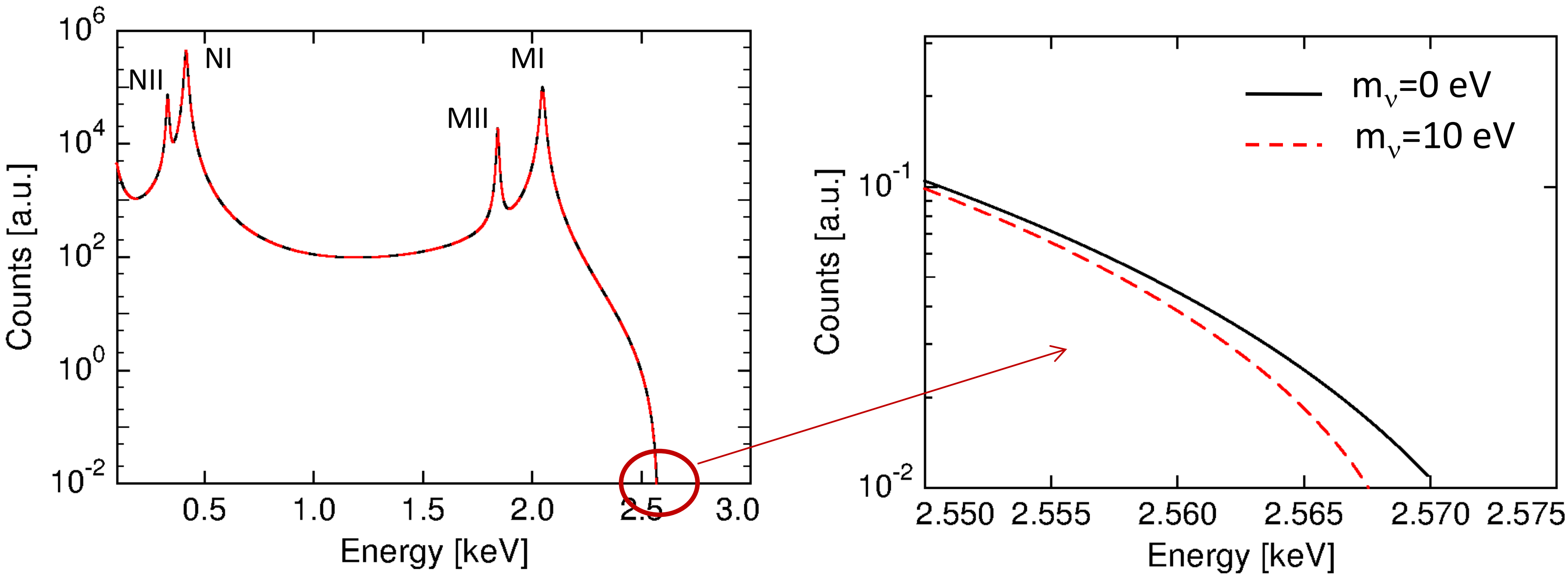
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\ 2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\ 2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\ 2}}{4}}$$

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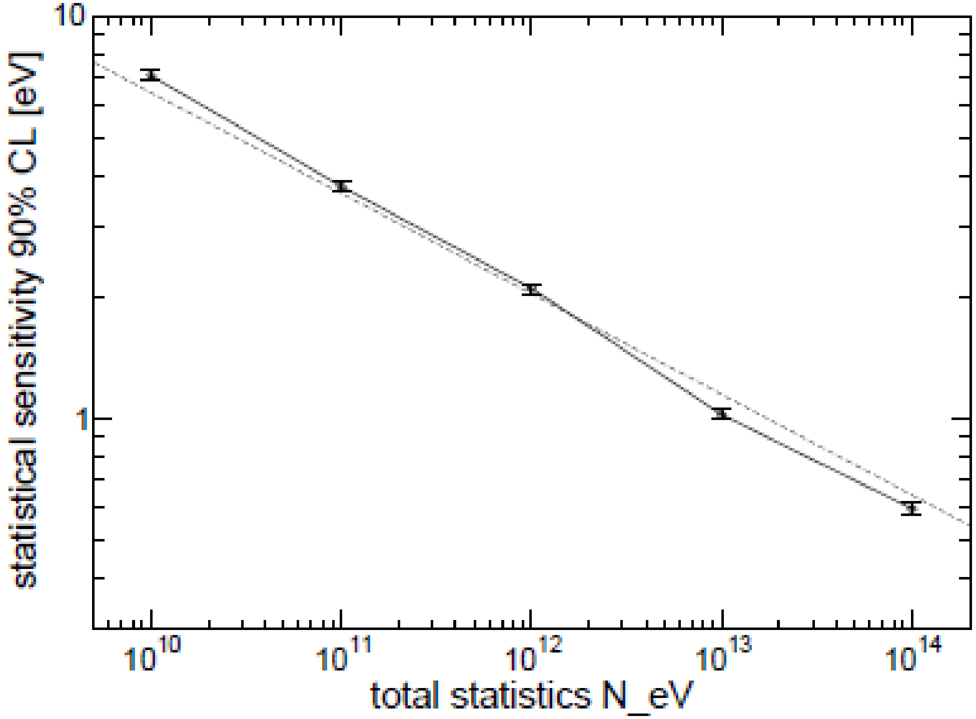
Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

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

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

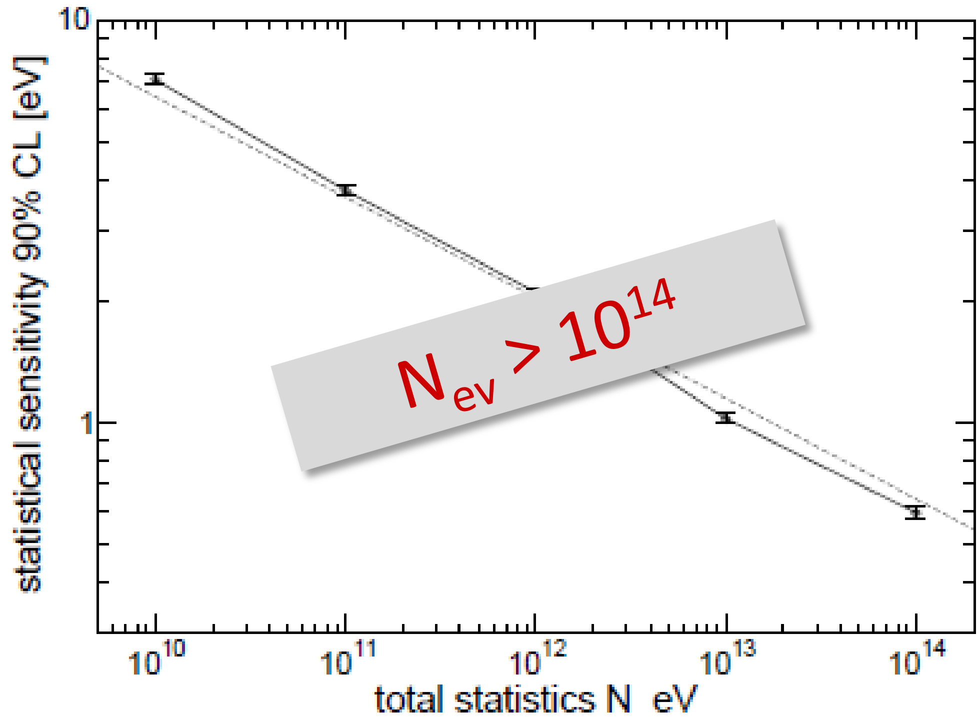
Neutrino mass sensitivity



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

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

Neutrino mass sensitivity



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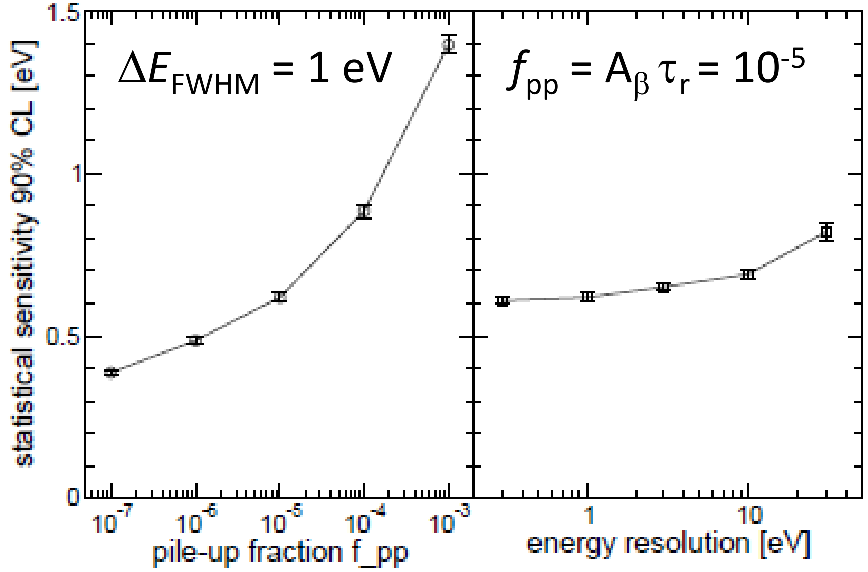

$N_{ev} = 10^{14}$, Q_{EC} = 2600 eV

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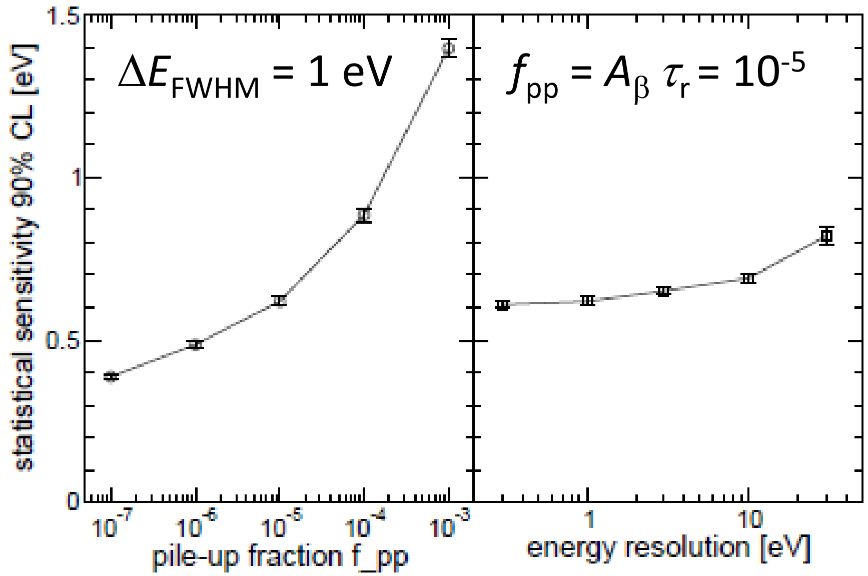

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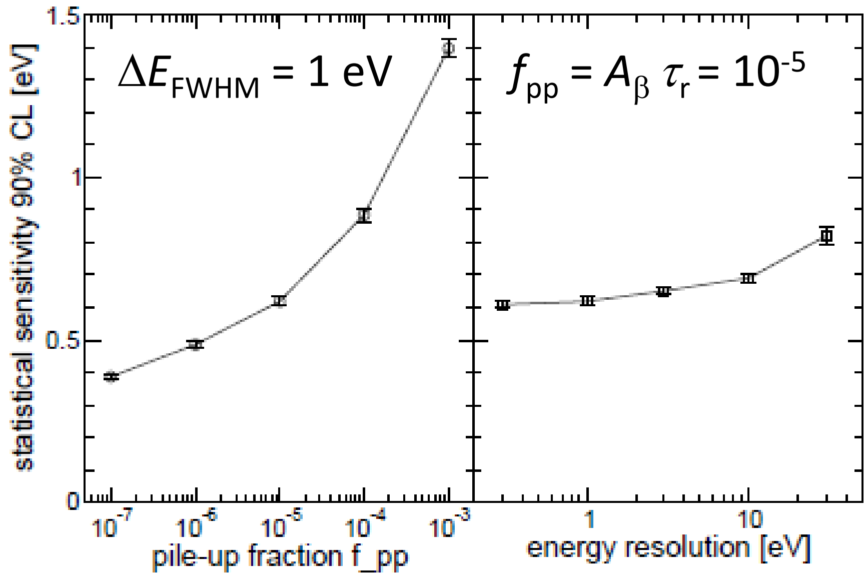

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ΔE_{FWHM} < 10 eV

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Neutrino mass sensitivity

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

$\Delta E_{FWHM} < 10$ eV

$\tau_r \sim 0.1$ μs

$A_\beta \approx 10 \text{ s}^{-1}$ ⟶ $\geq 10^5$ detectors

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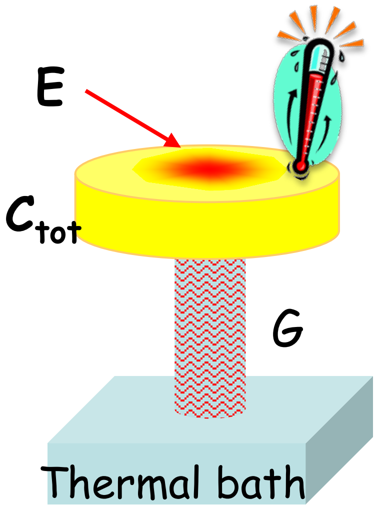
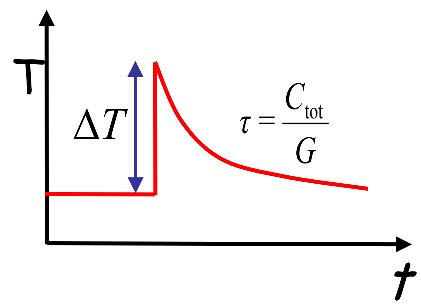
Low temperature

Metallic Magnetic Calorimeter

MMCs: Concept



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



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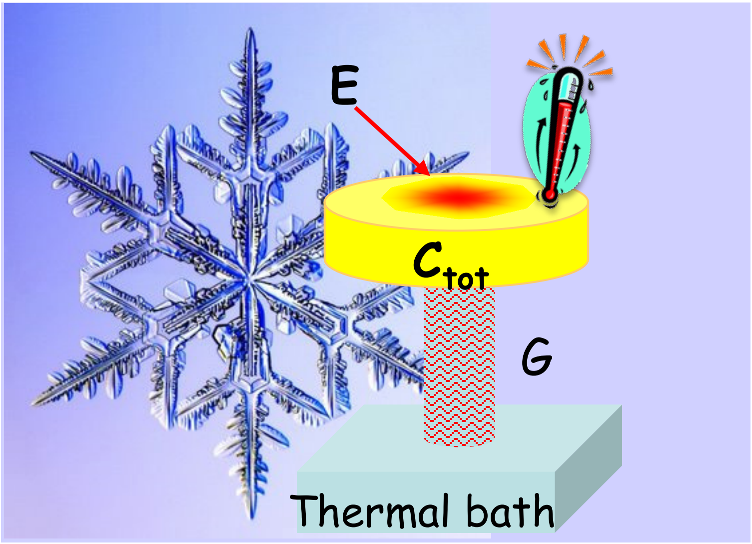

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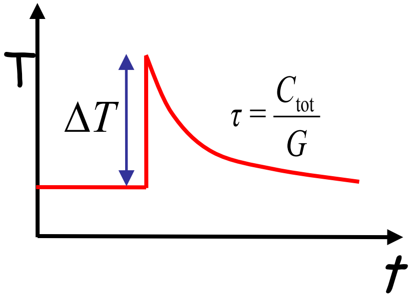
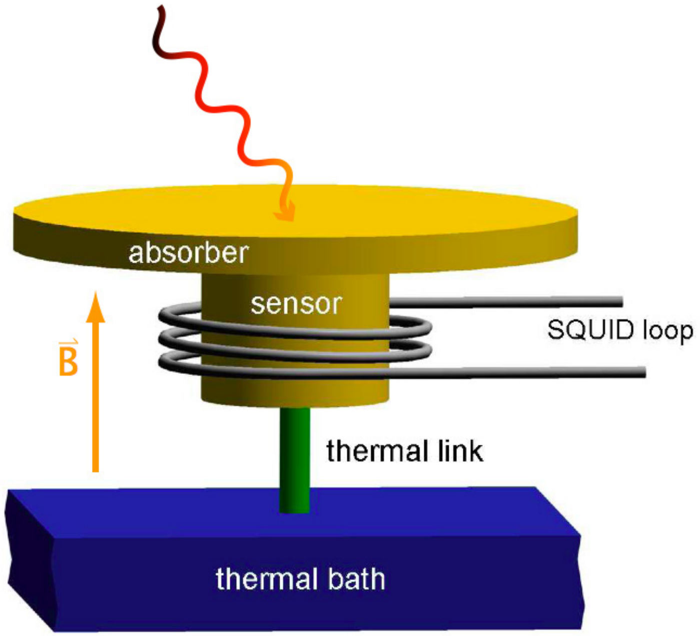


- Working temperature below 100 mK
  - small specific heat
  - large temperature change
  - small thermal noise

- Very sensitive temperature sensor

MMCs: Concept

- Paramagnetic Au:Er sensor



$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

MMCs: Concept

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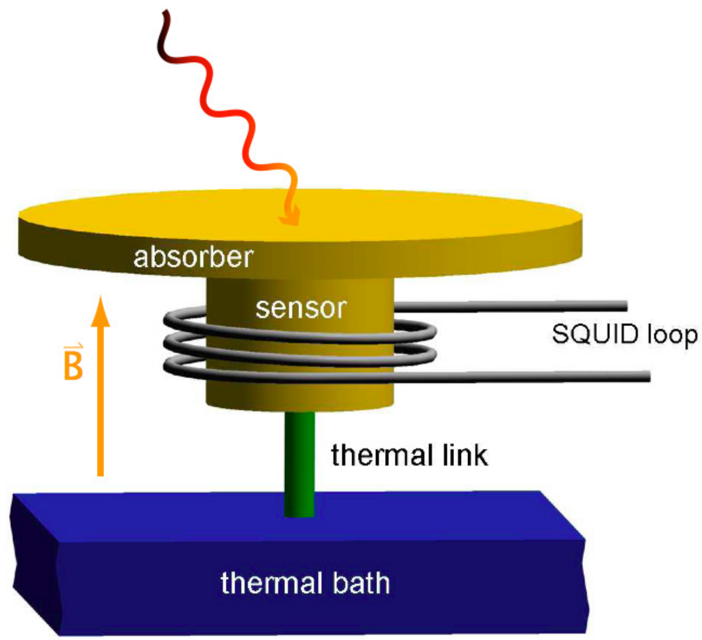

Talk of Philipp Ranitzsch

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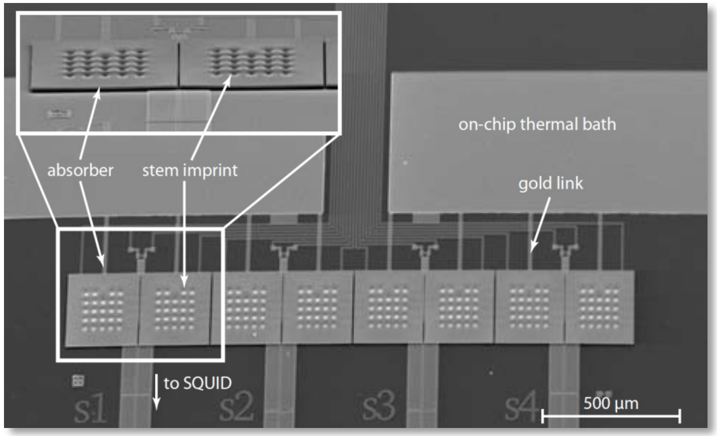
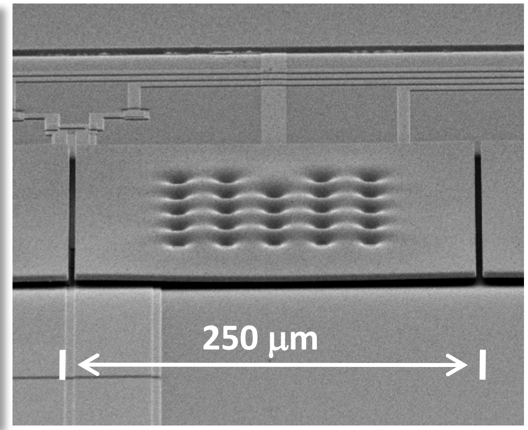
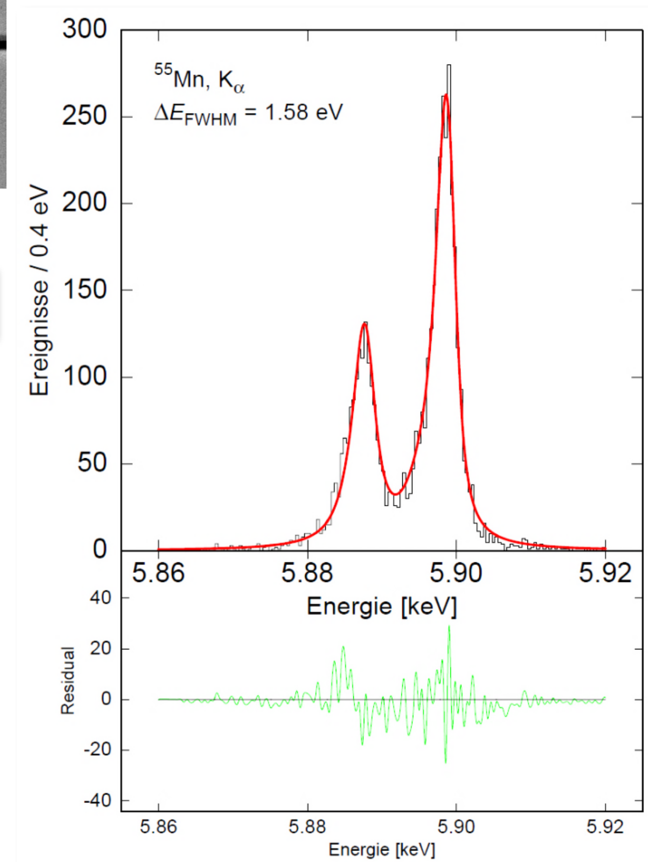
maXs: 1d-array for soft x-rays (T=20 mK)

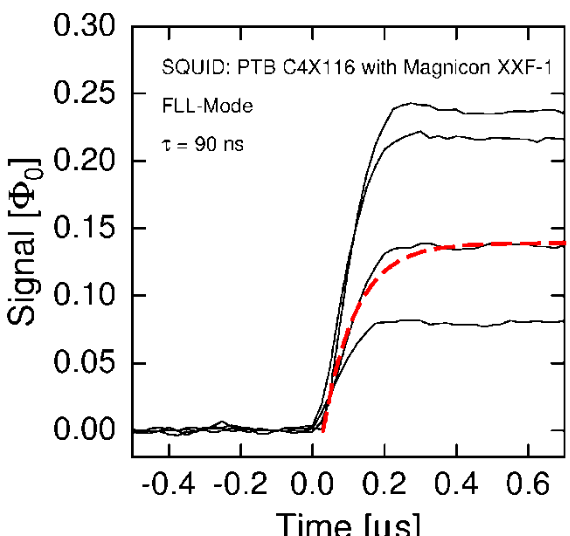




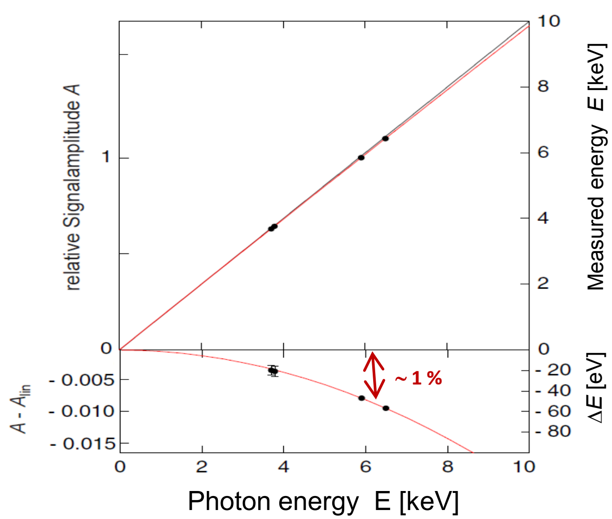
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



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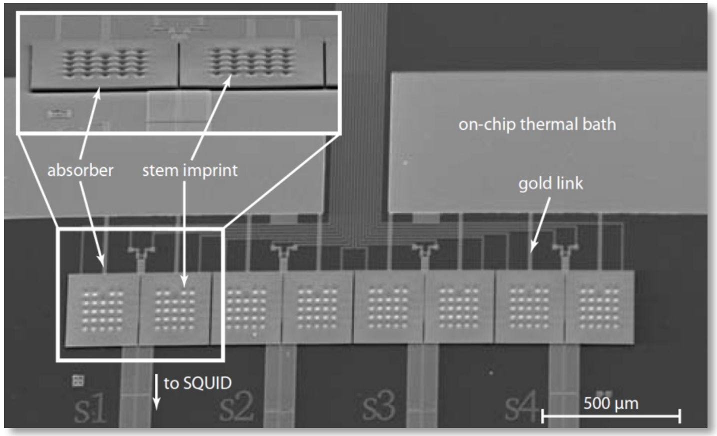

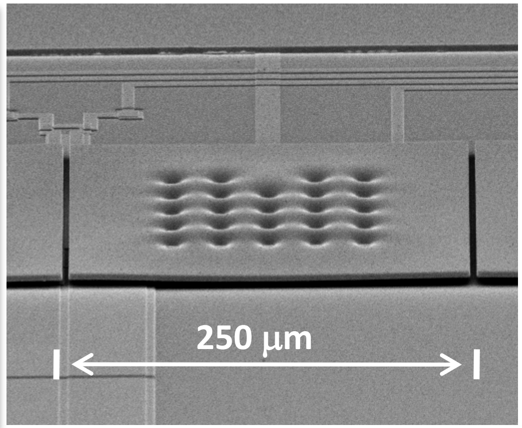

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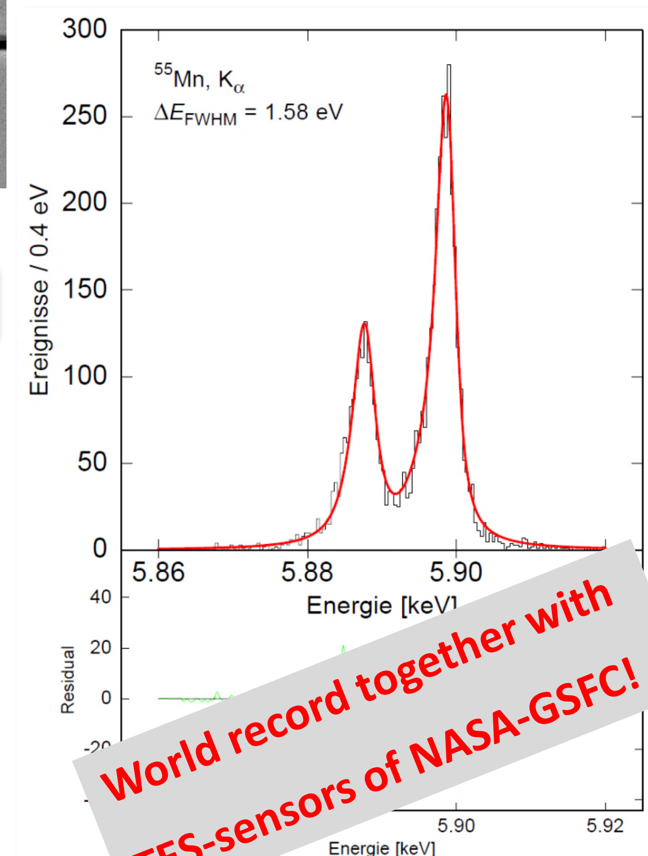

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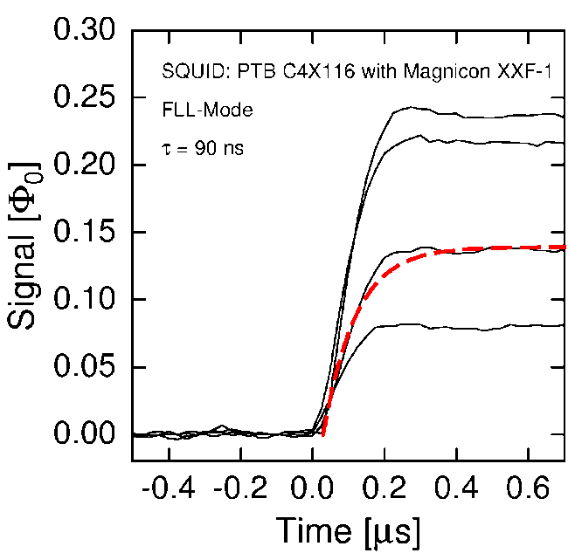

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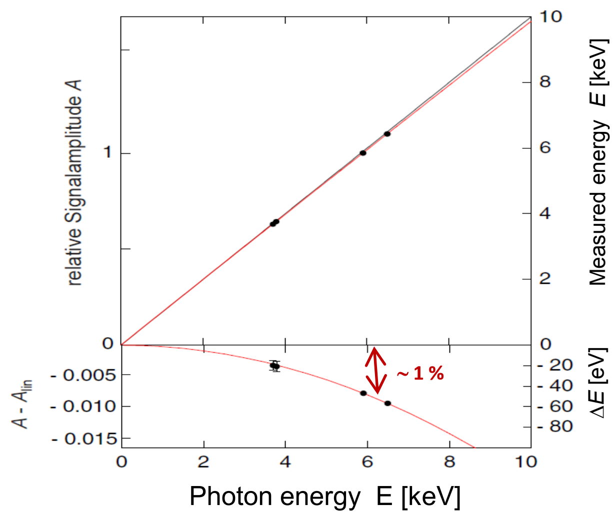
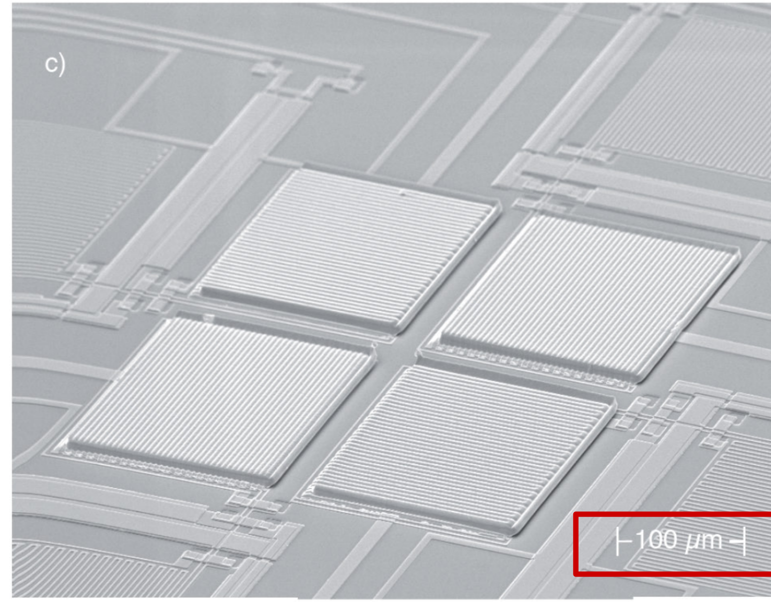
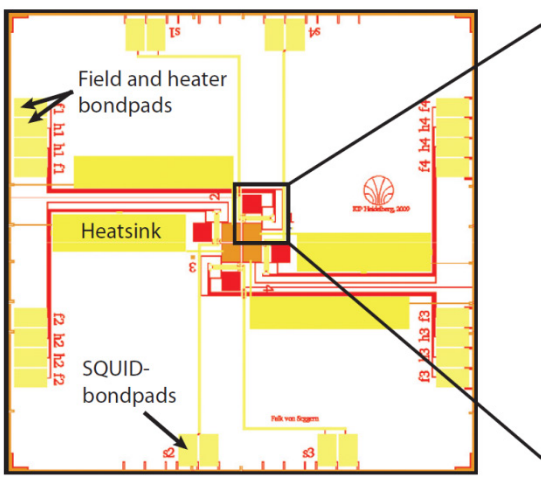


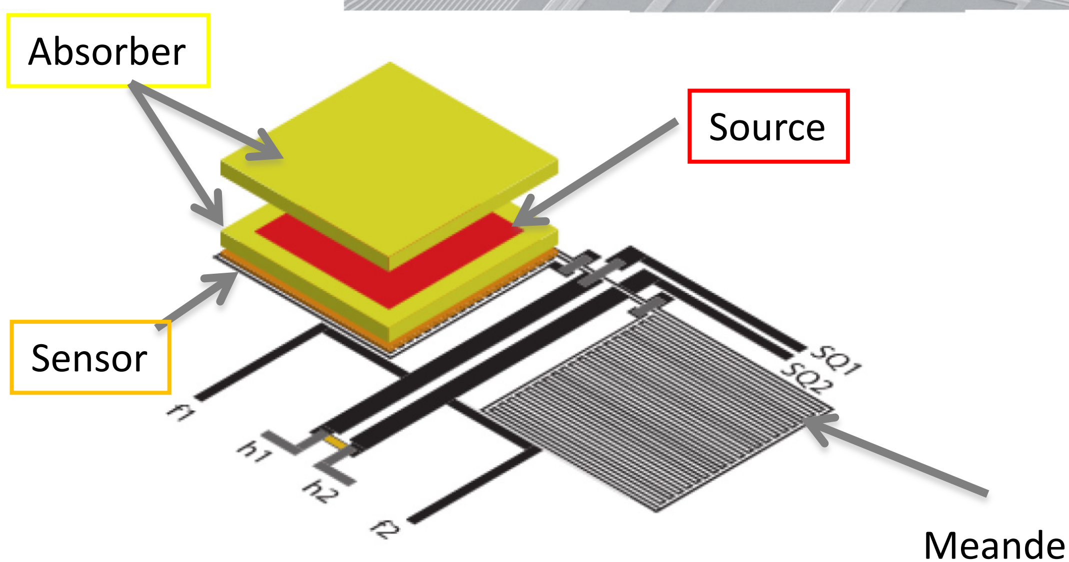
World record together with TES-sensors of NASA-GSFC!

ECHo experiment: First detector 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

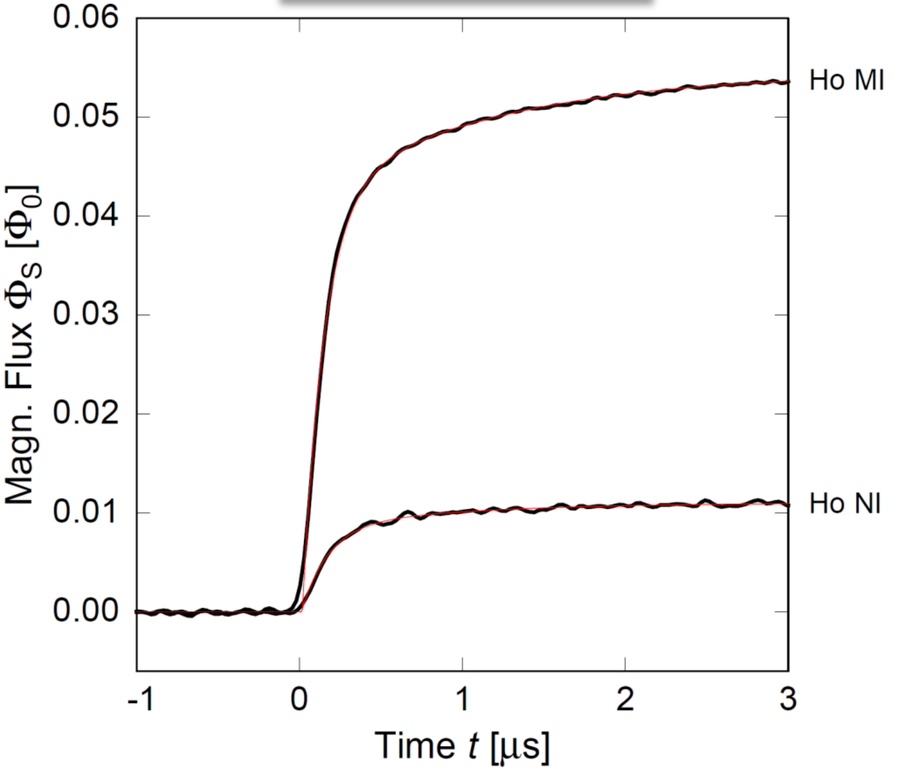






ECHo experiment: Calorimetric spectrum

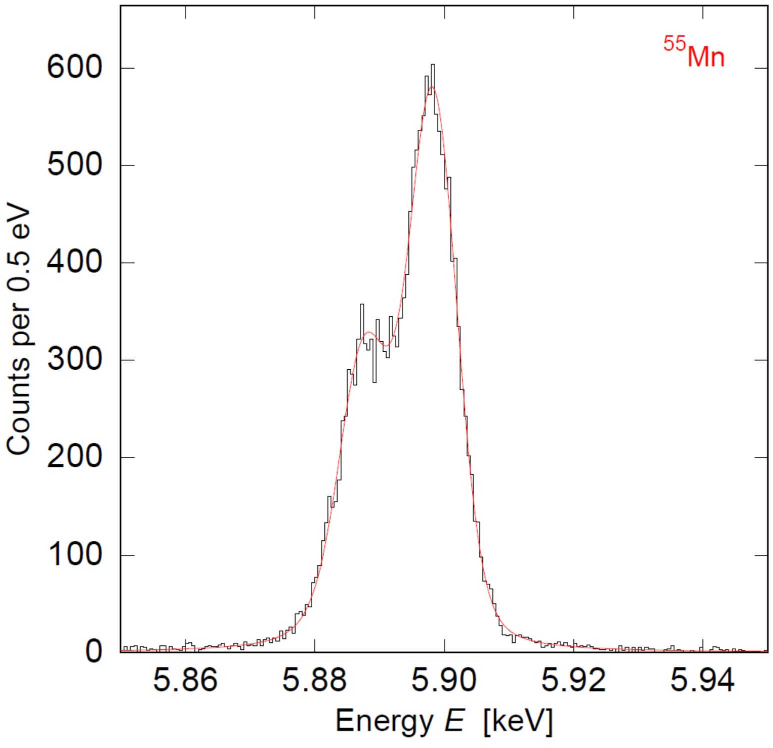
Rise Time ~ 130 ns



ECHo experiment: Calorimetric spectrum

- **Rise Time ~ 130 ns**

ΔE_{FWHM} = 7.6 eV @ 6 keV



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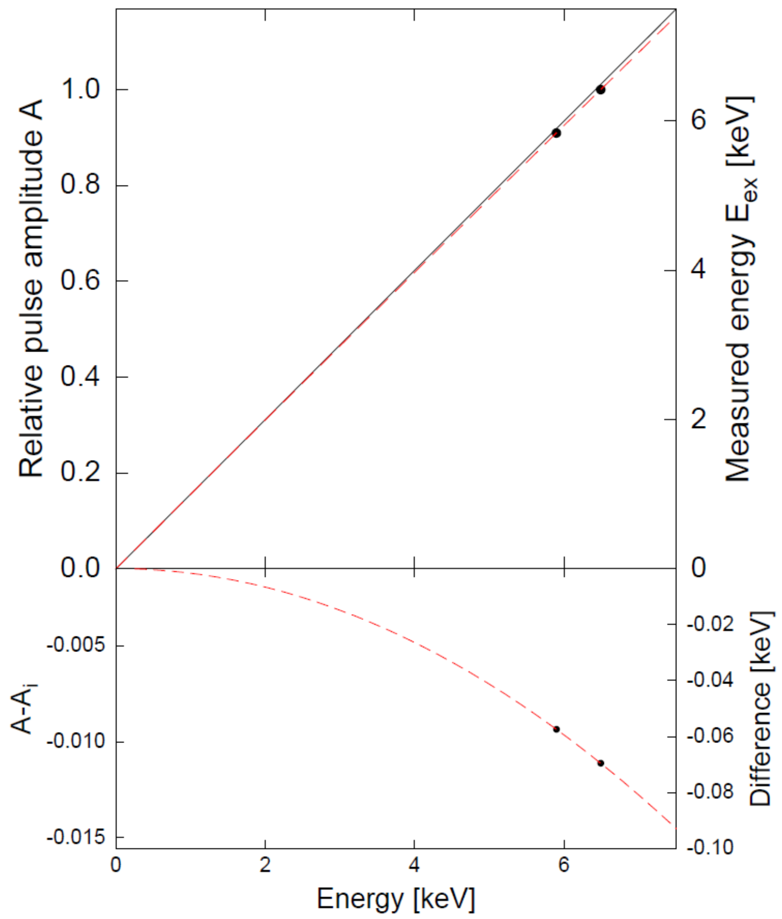

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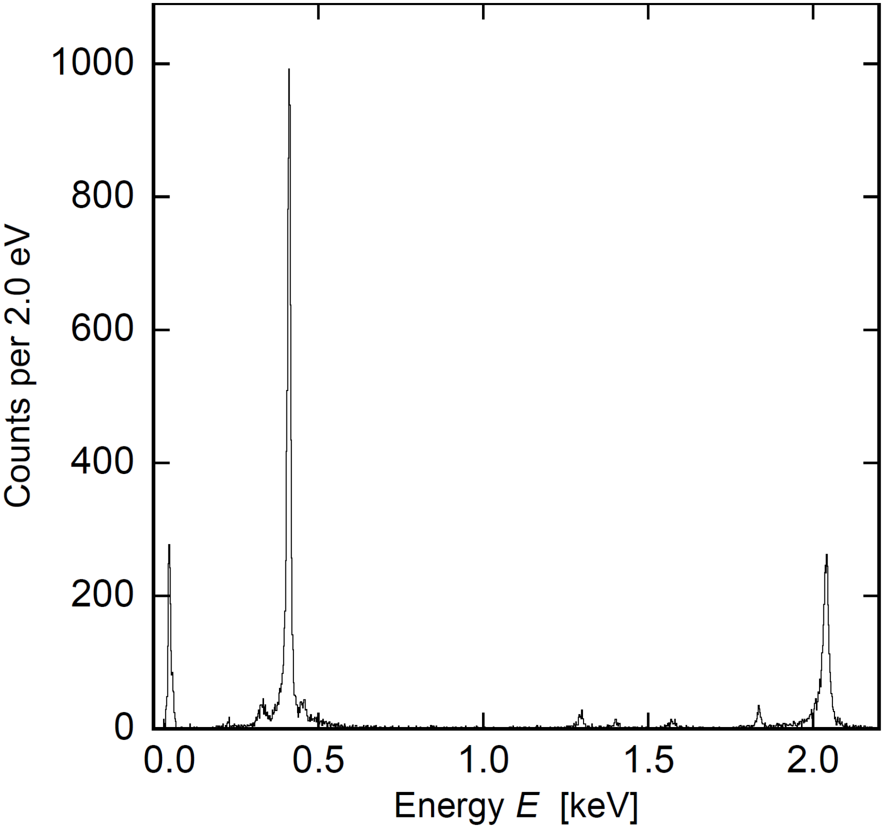
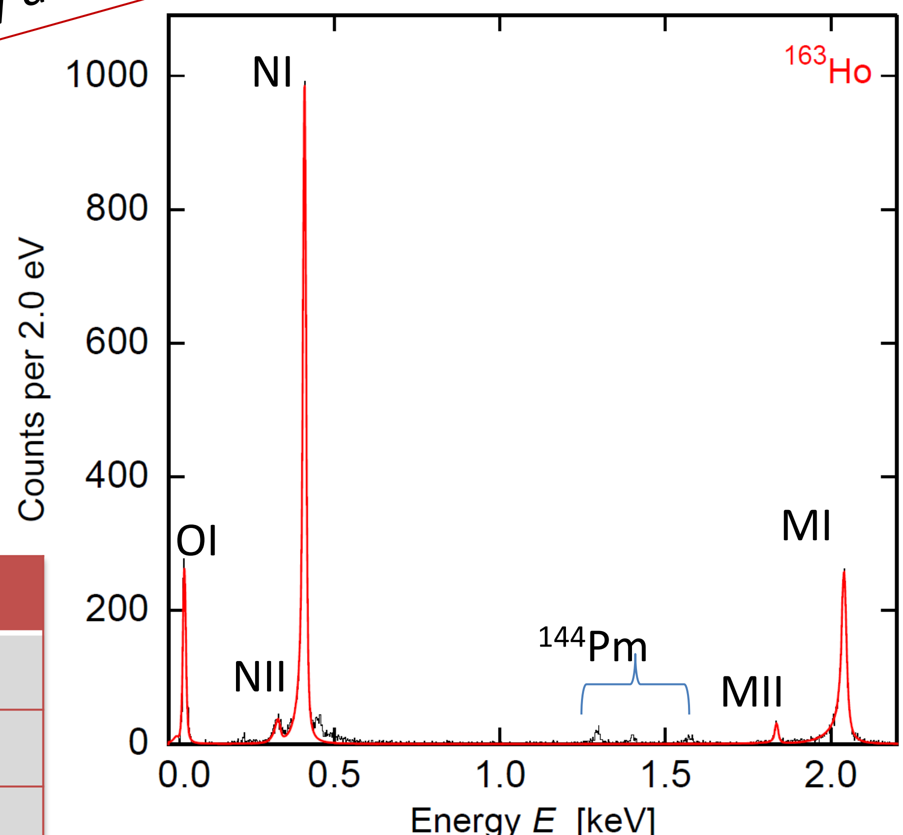


ECHo experiment: Calorimetric spectrum

- **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

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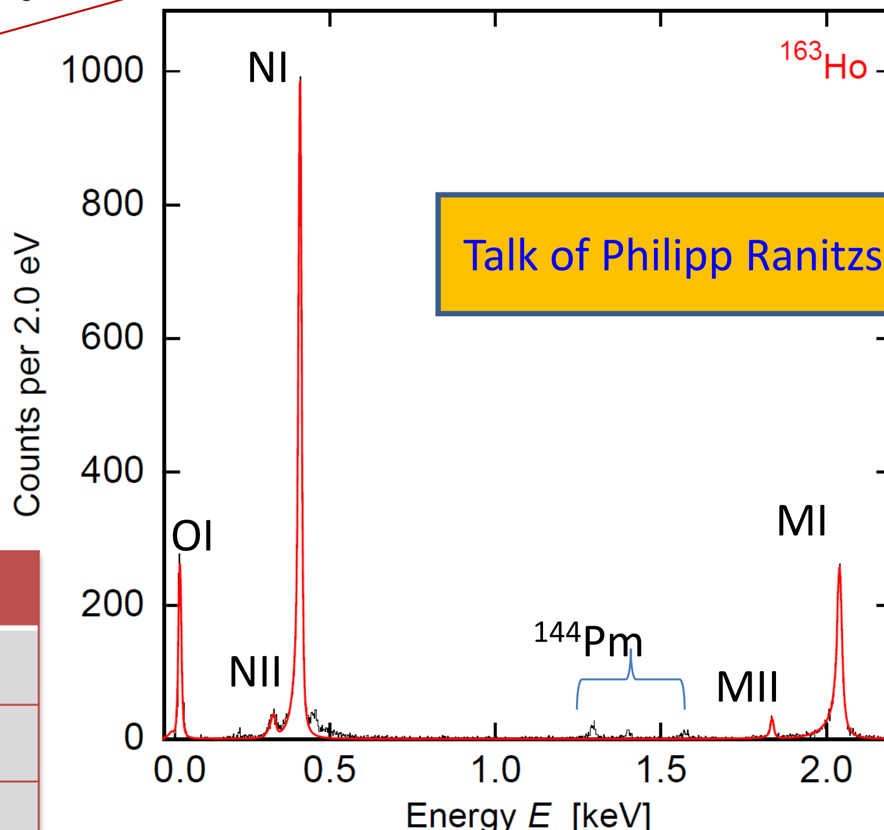

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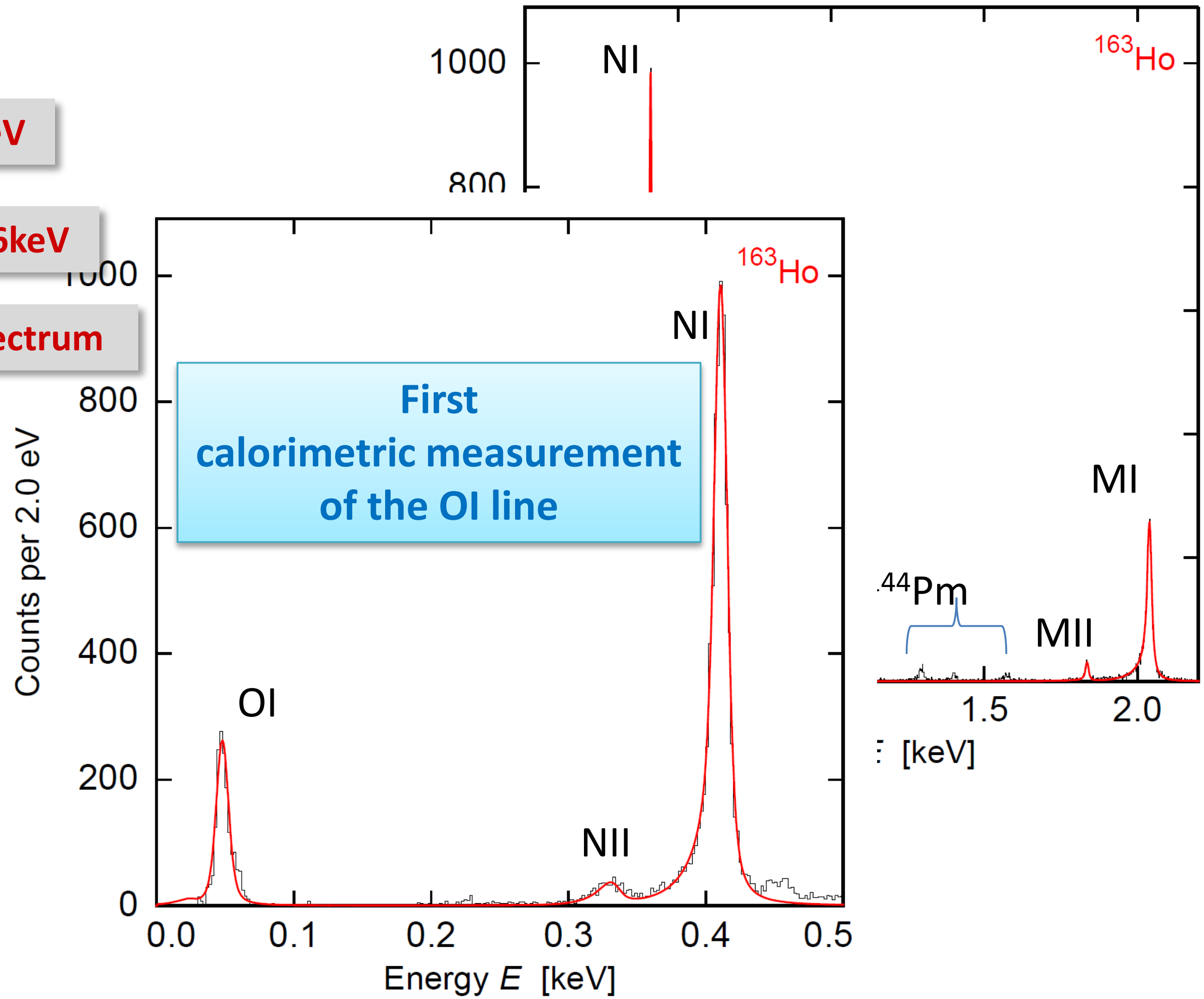

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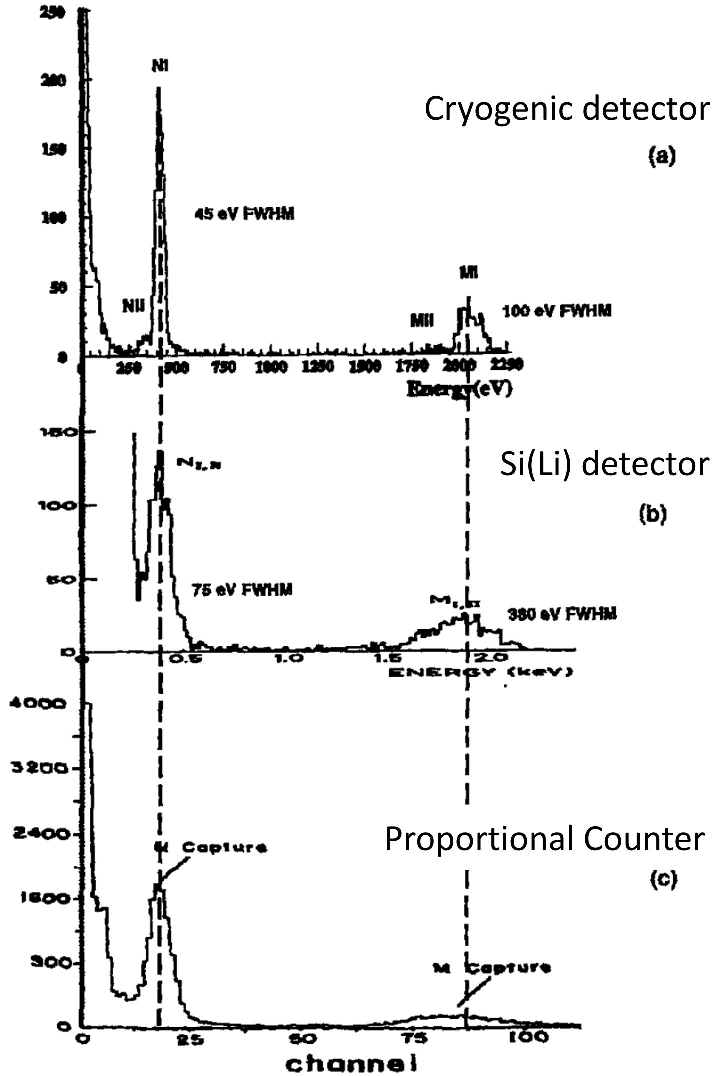
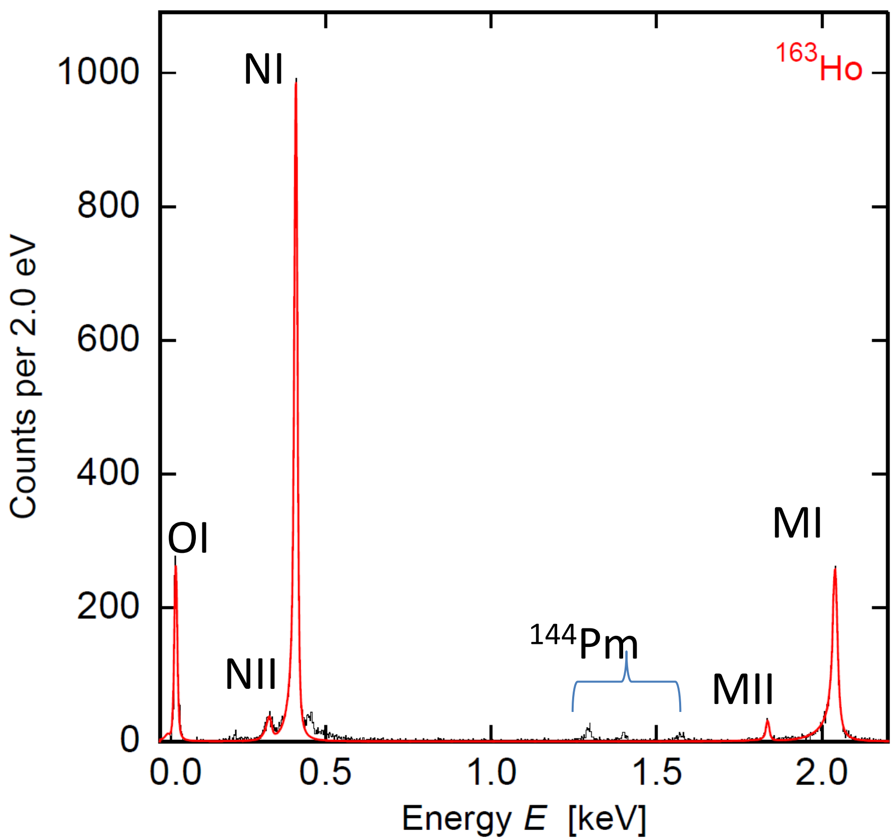


F. Gatti et al., Physics Letters B 398 (1997) 415-419



(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.

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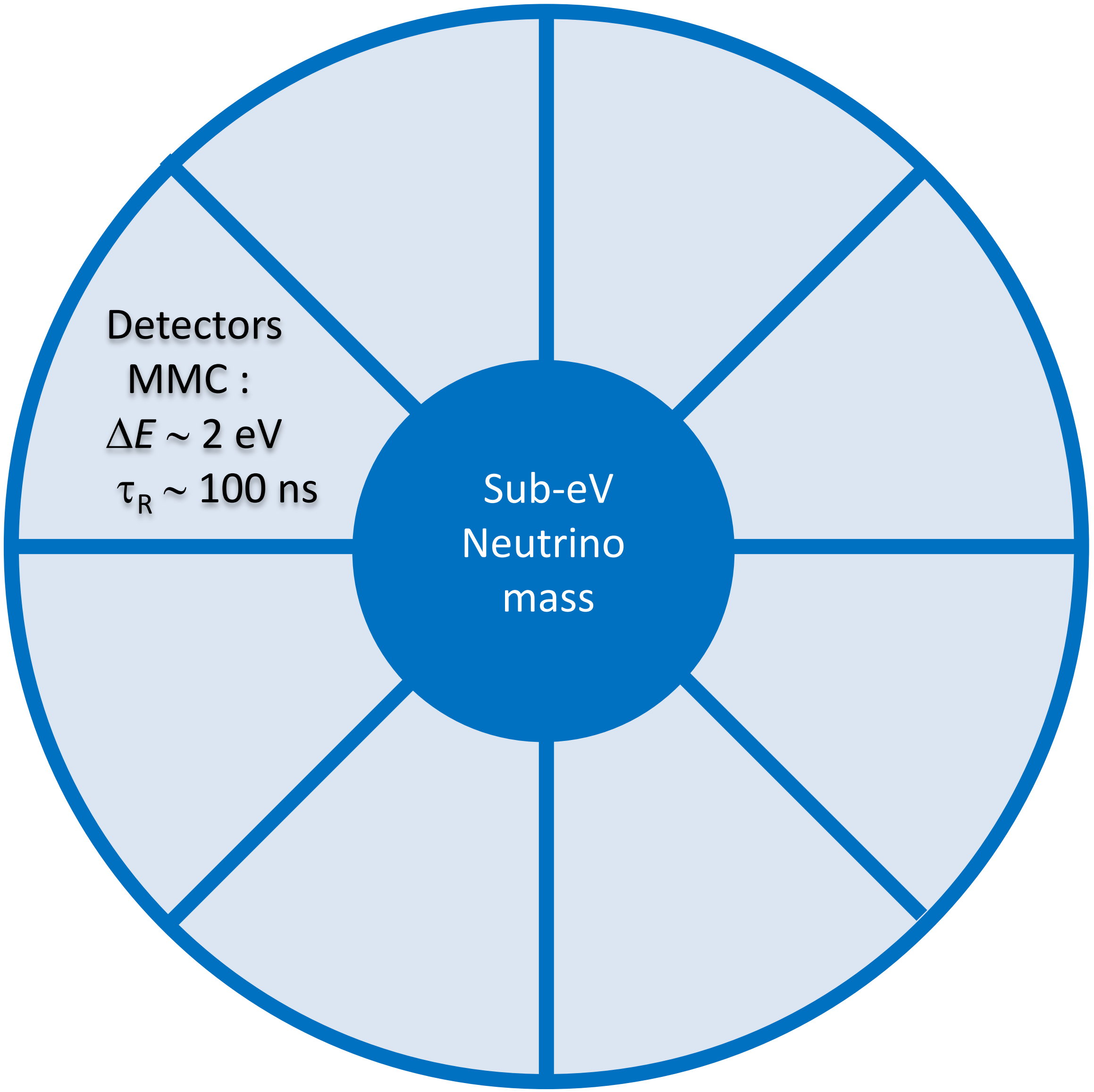

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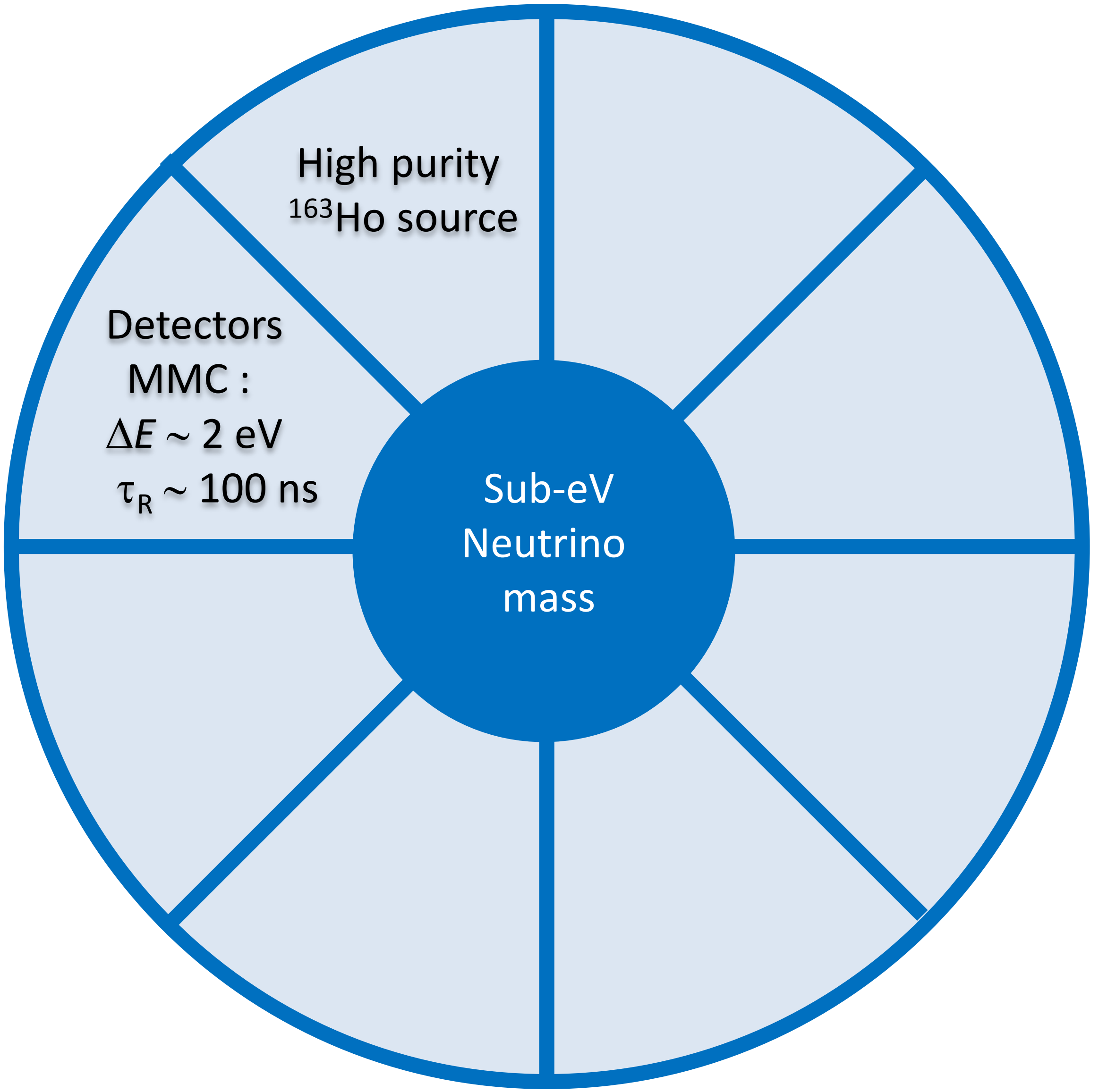

ECHo experiment: ^{163}Ho source

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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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➢ ^{163}Ho can be produced by via (n,γ)-reaction on ^{162}Er

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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^{nat}Dy(α, xn) ^{163}Er (ε) ^{163}Ho

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

➢ ^{163}Ho can be produced by via (n,γ)-reaction on ^{162}Er

Two sources already produced
- ✓ Helmoltz Zentrum Berlin
- ✓ Institut Laue-Langevin in Grenoble

ECHo experiment: ^{163}Ho source

- Required activity in the detectors: Final experiment → $>10^{6}$ Bq → $>10^{17}$ atoms

➢ ^{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

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Two sources already produced
✓ Helmoltz Zentrum Berlin
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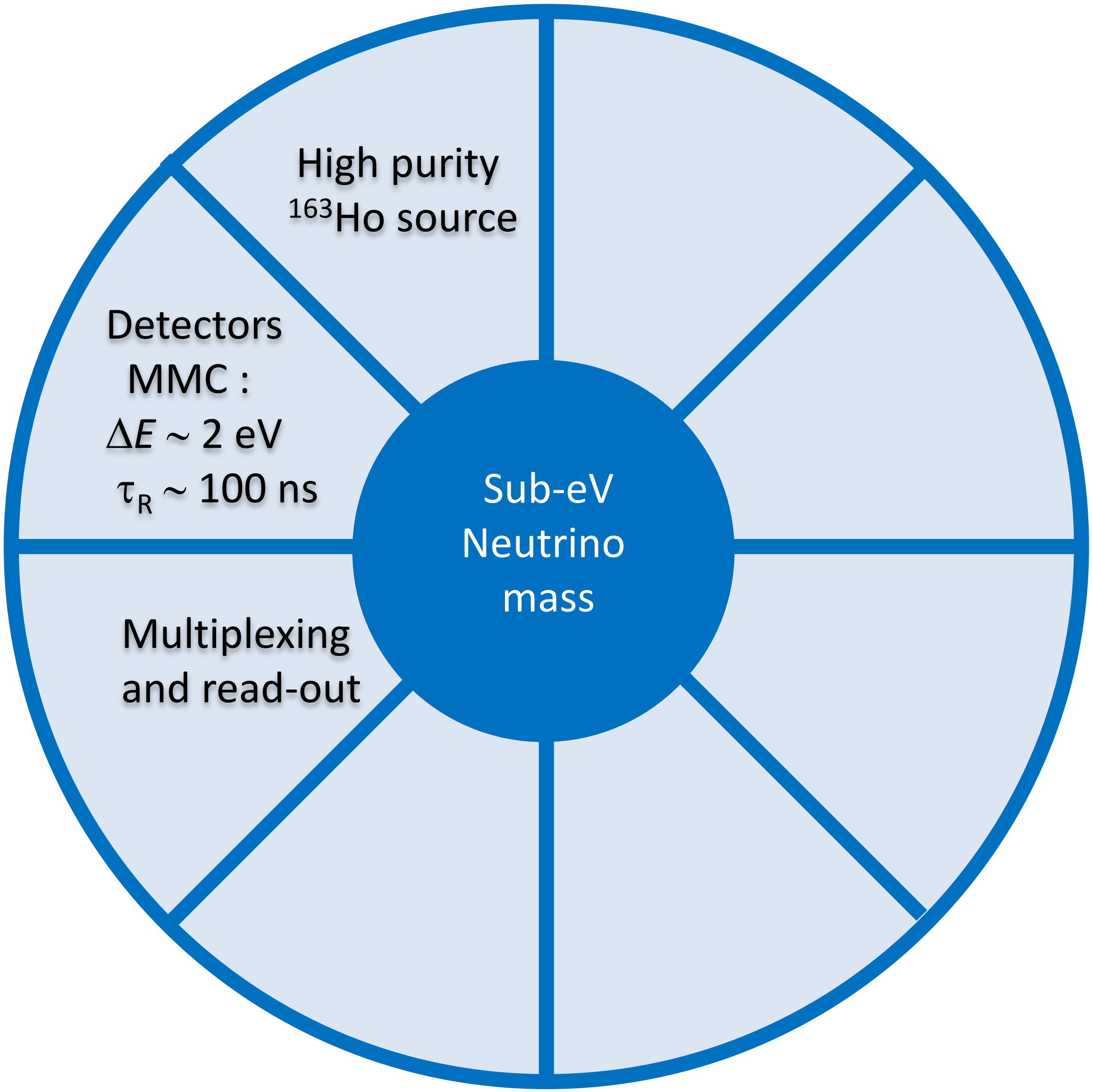
- Purity: No radioactive contaminants and removed target material

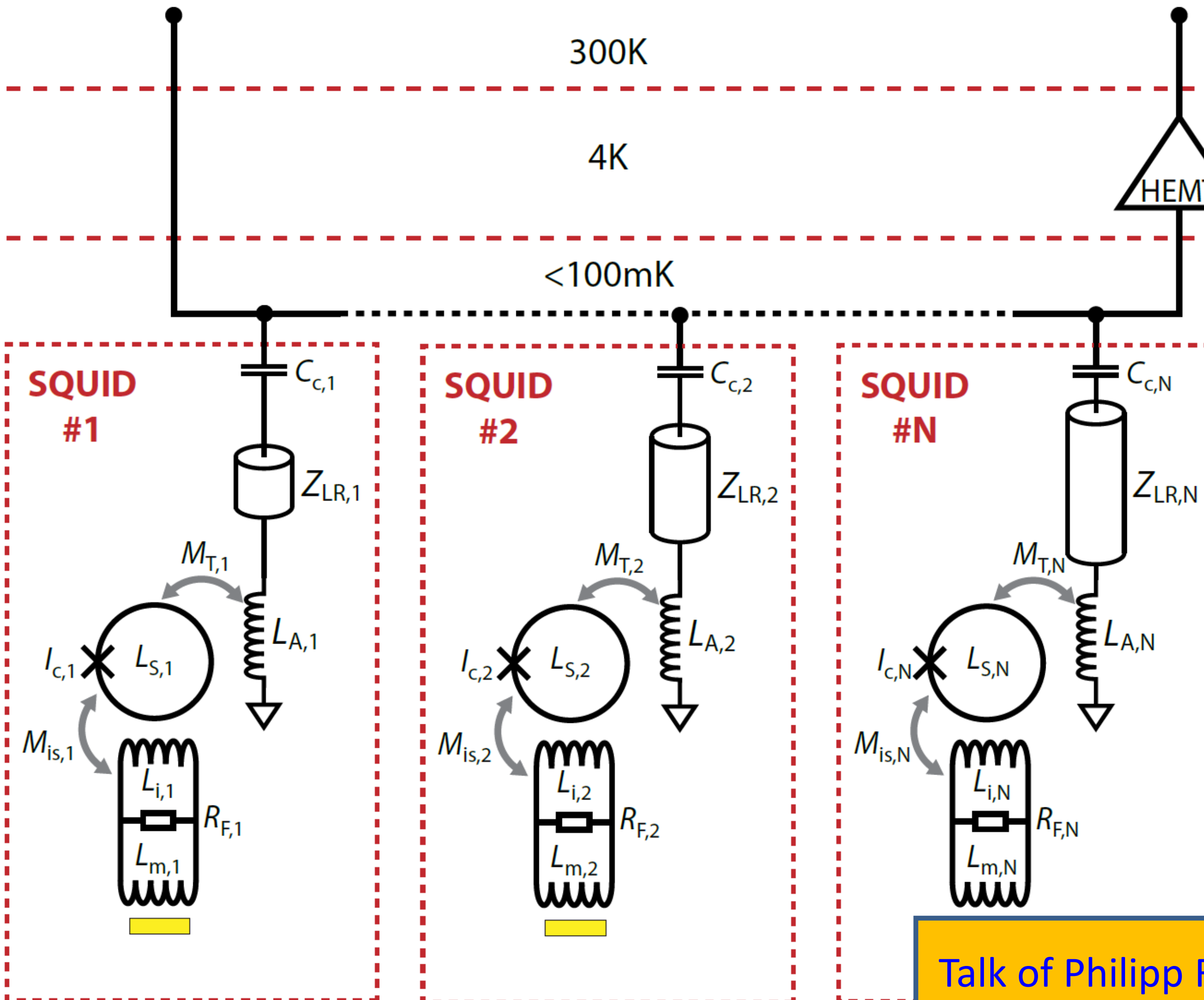
➢ High efficiency purification methods

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

ECHo experiment

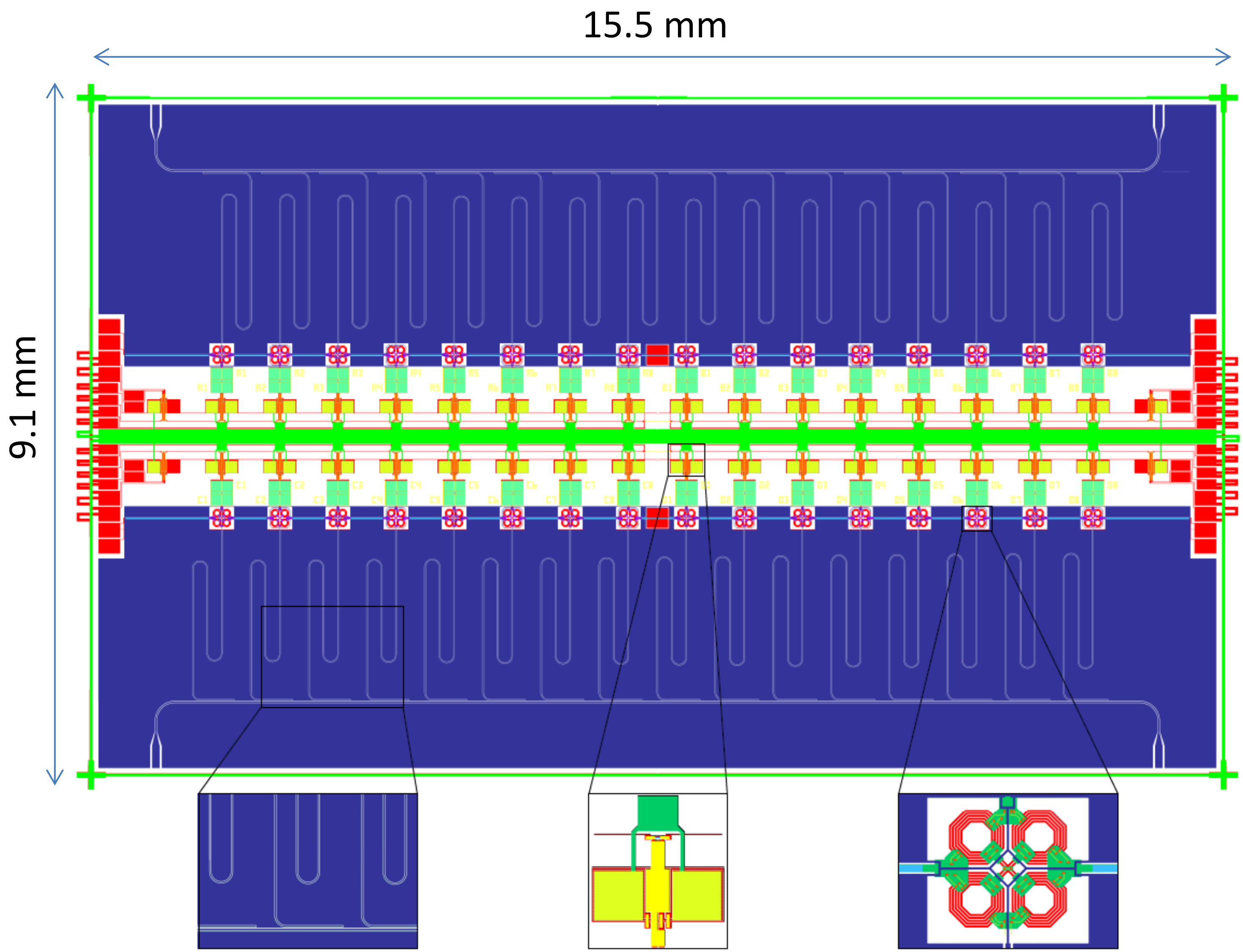


ECHo experiment: µ-wave multiplexing

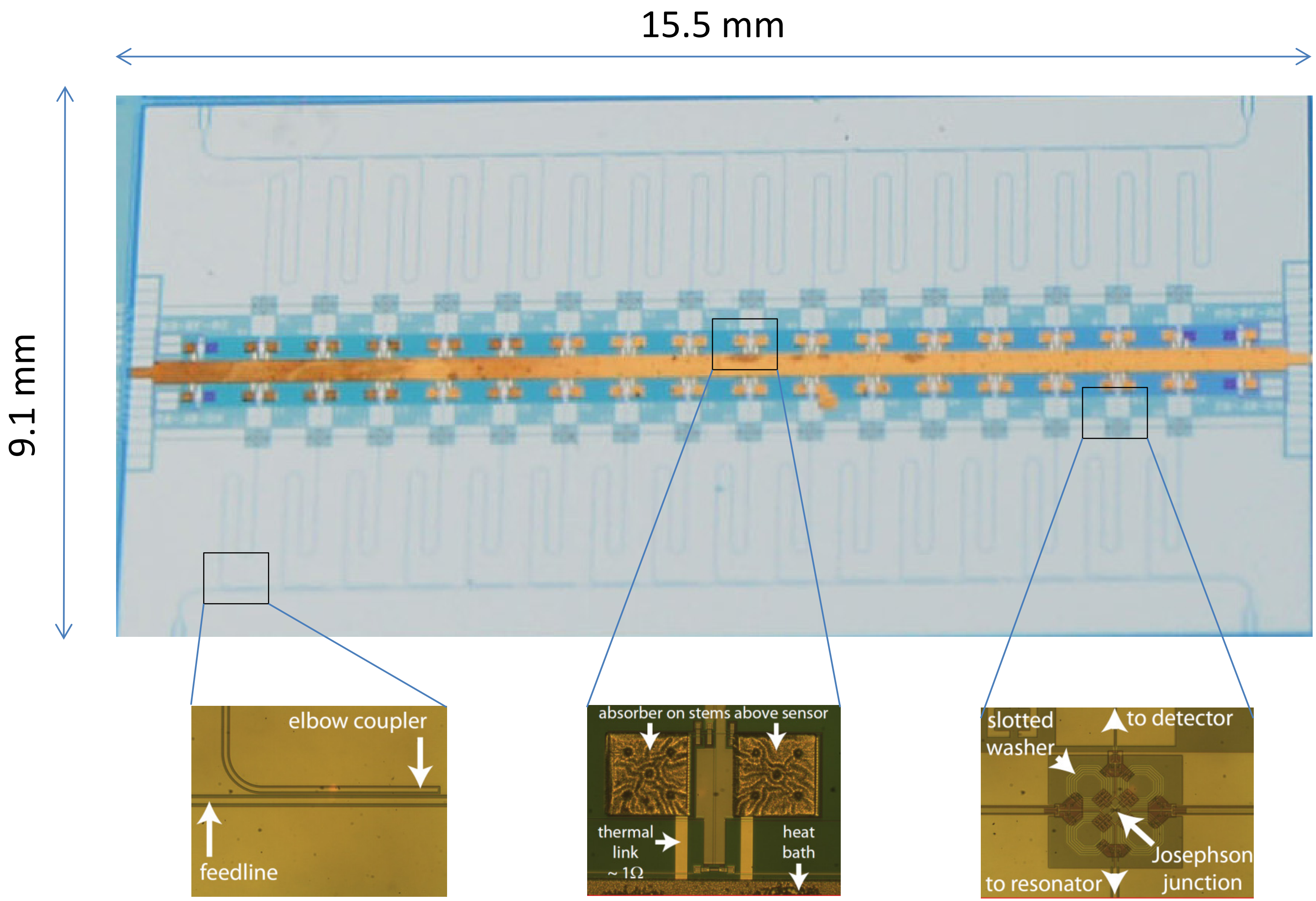


Talk of Philipp Ranitzsch

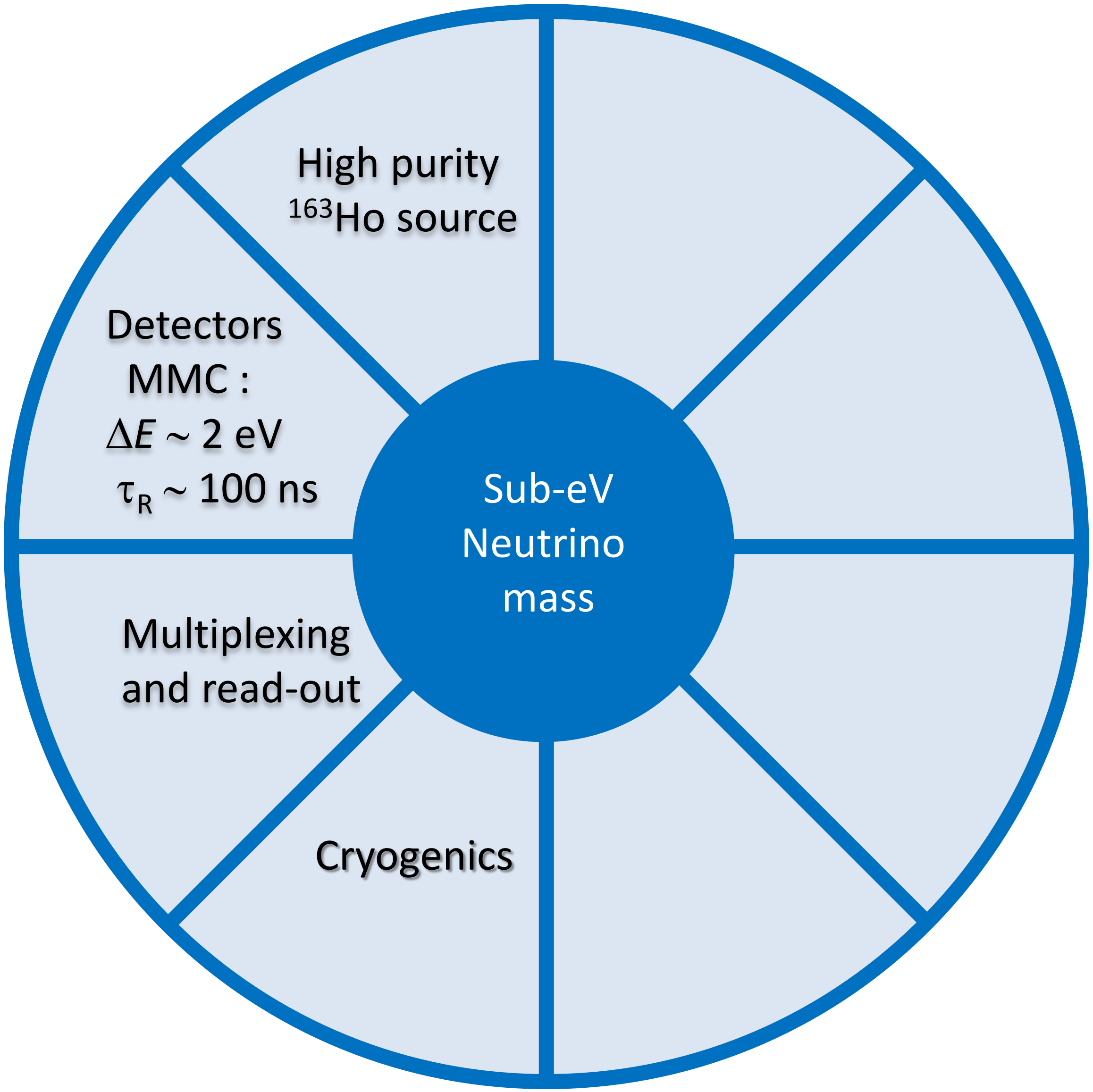
ECHo experiment: 64-pixel chip



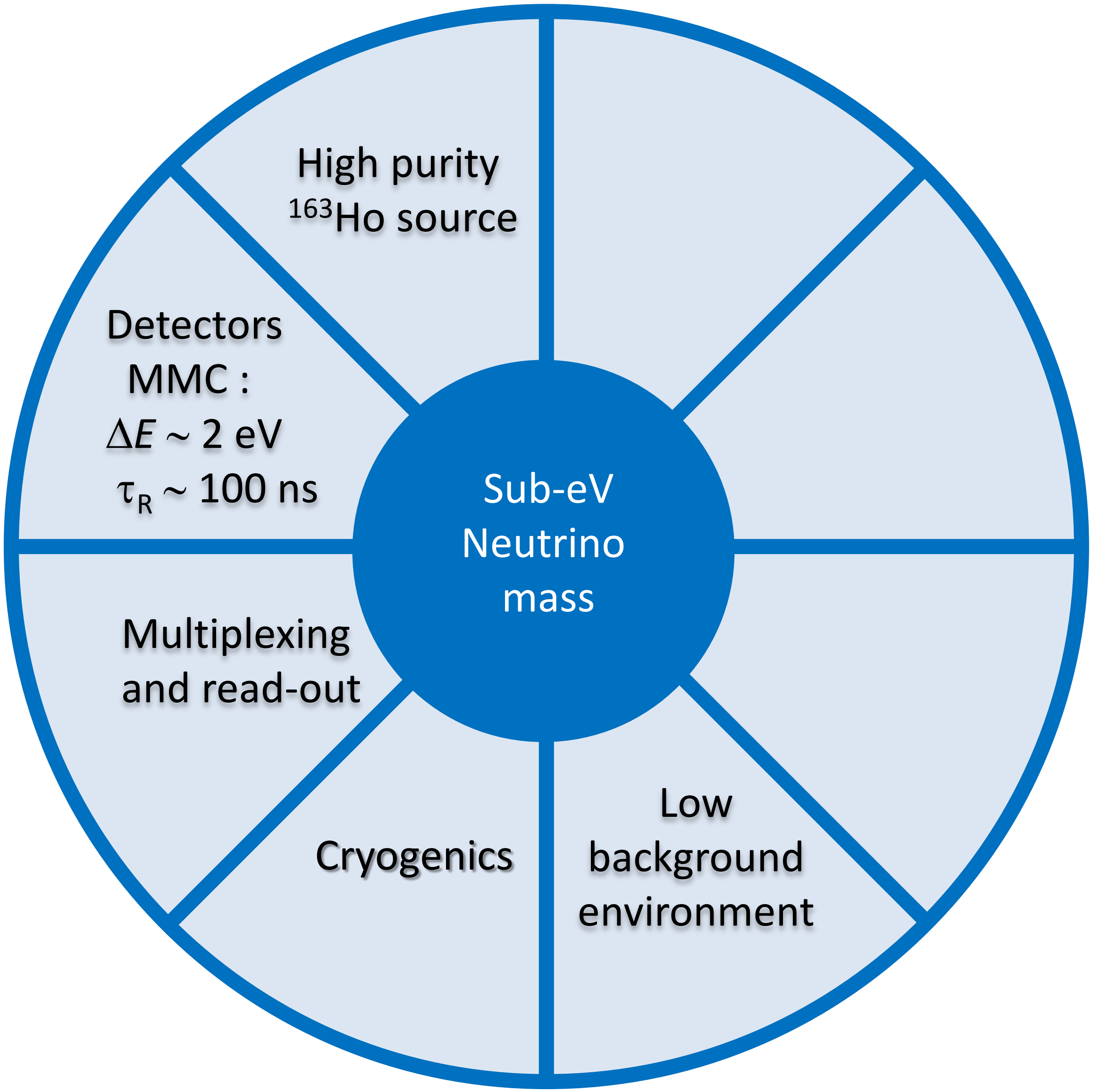
ECHo experiment: 64-pixel chip



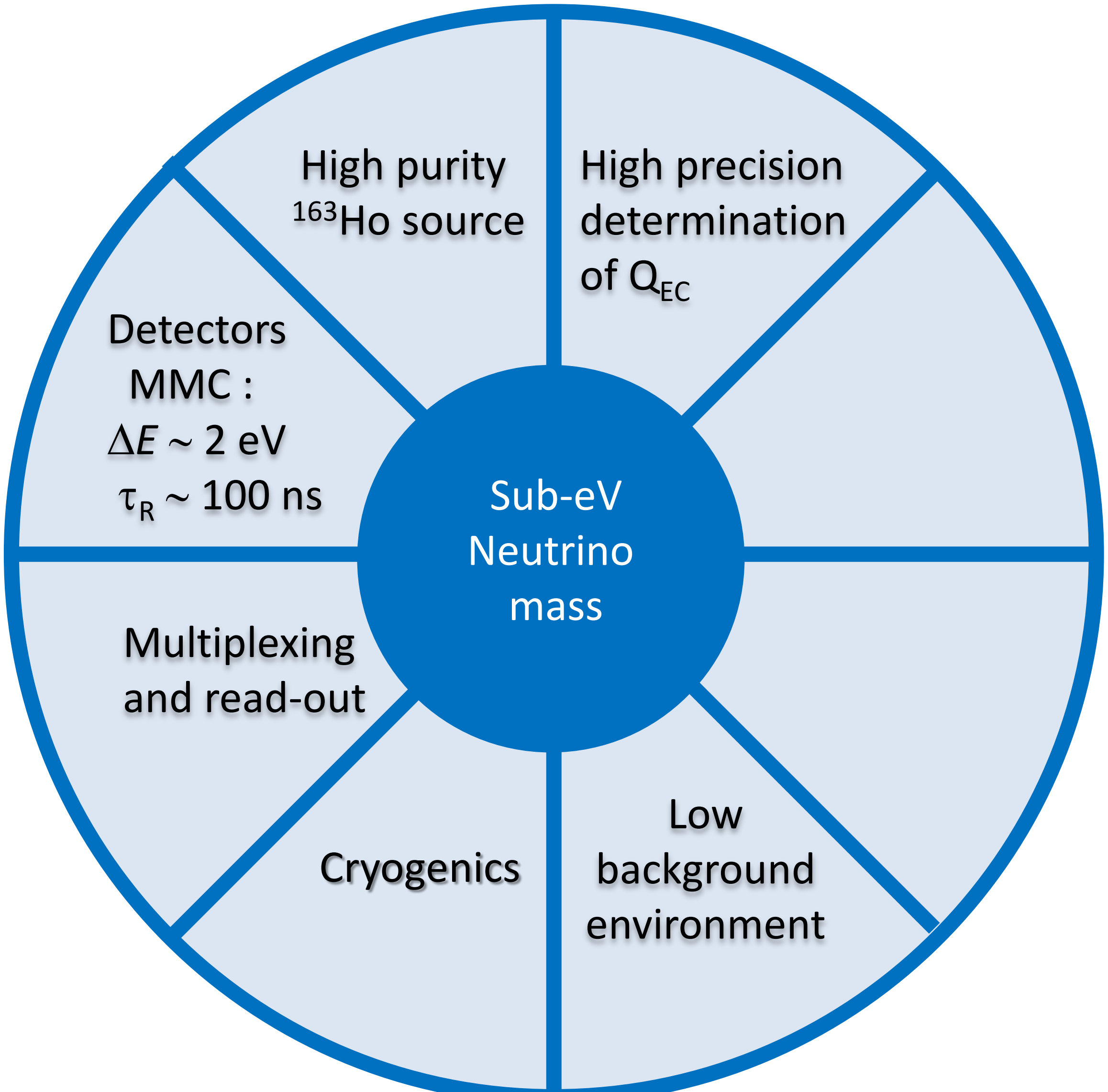
ECHo experiment



ECHo experiment

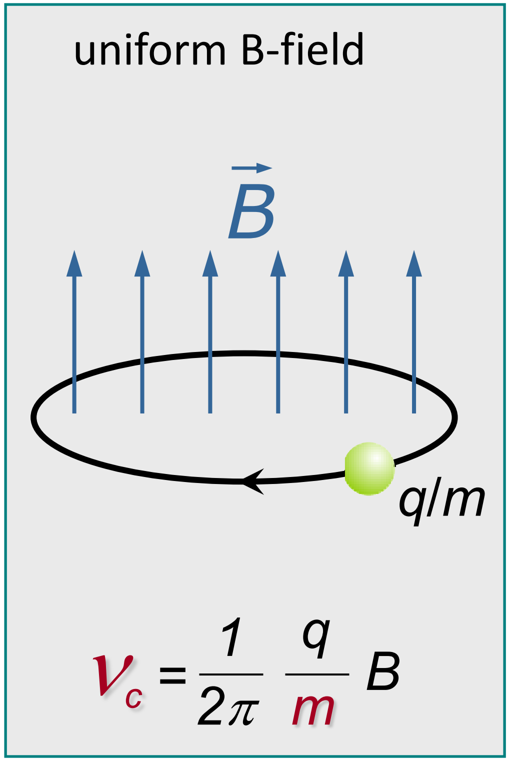


ECHo experiment



ECHo experiment: Q_{EC} determination

Penning Trap mass spectroscopy



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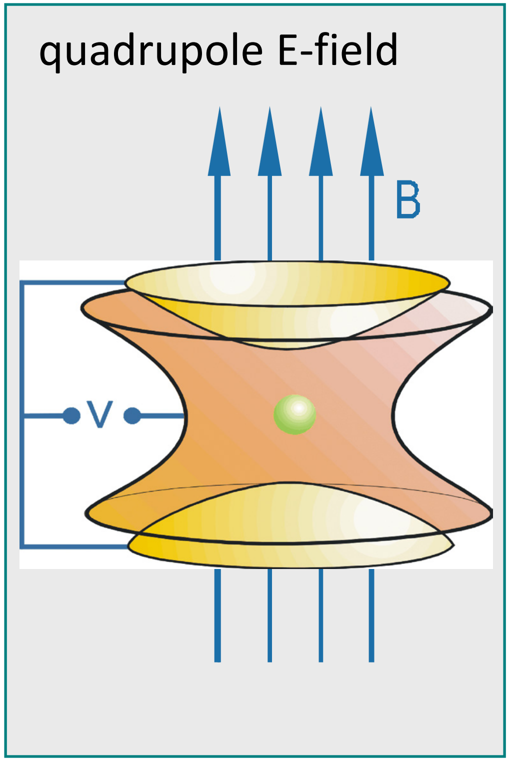

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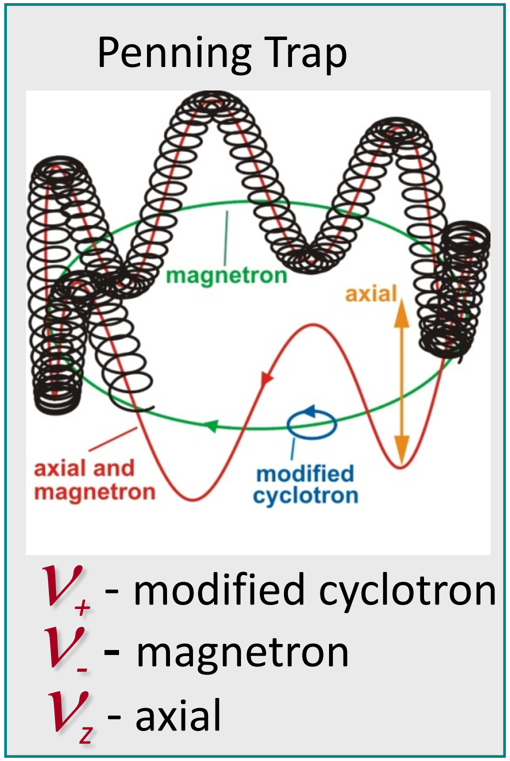
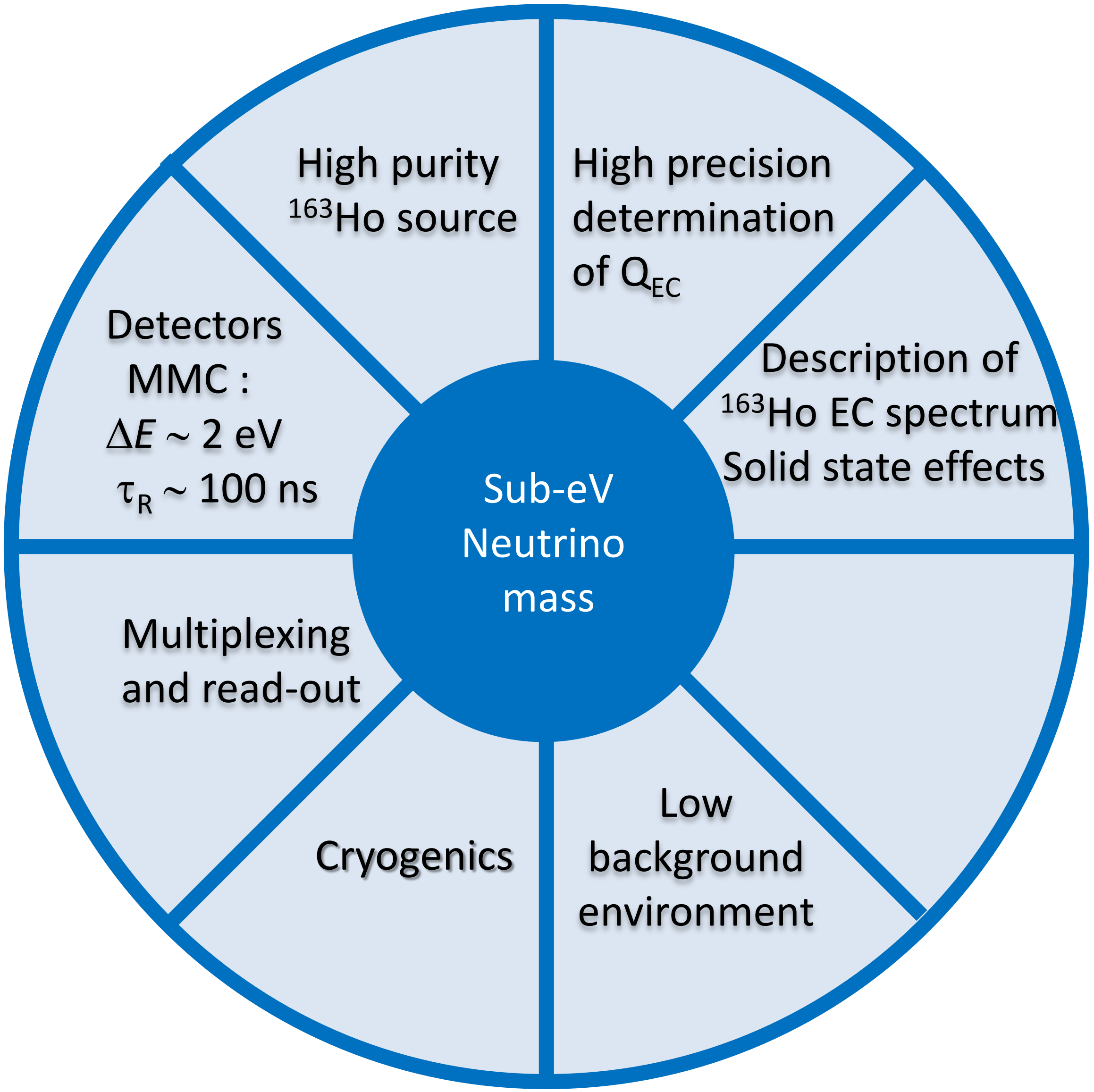


Next future : SHIPTRAP (GSI) → Q_{EC} determination within 100 eV

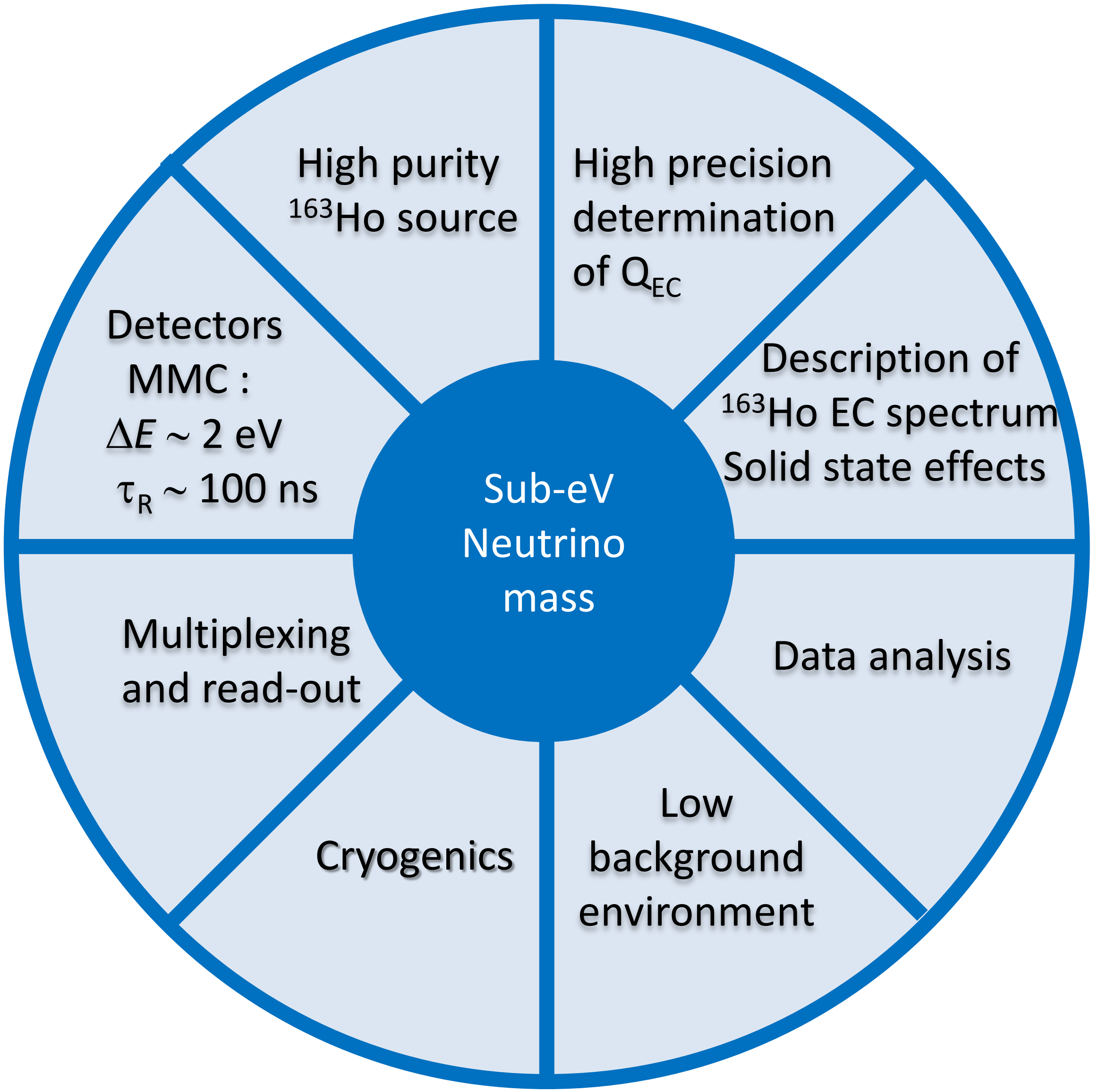
In few years: PENTATRAP (MPI-K HD) → Q_{EC} determination within 1 eV

Courtesy S. Eliseev, MPI-K HD

ECHo experiment



ECHo experiment



^{163}Ho experiments

ECHo

- 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

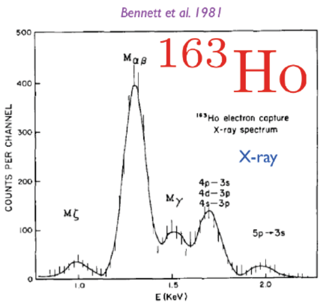

FIG. 5: IBEC spectrum in ^{163}Ho decay [22], showing prominent X-ray lines.

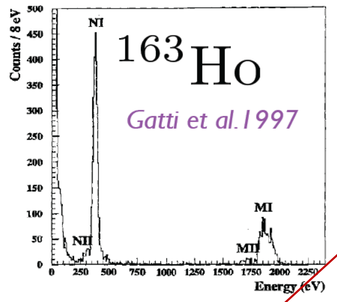

FIG. 6: Results of an early ^{163}Ho calorimetric spectrum [25].

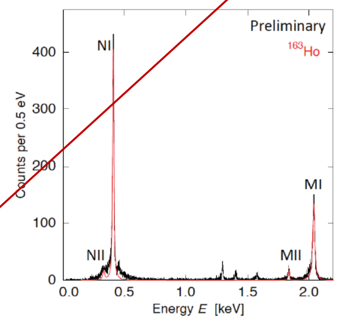

FIG. 7: Test results of ECHo [27] for the calorimetric spectrum of ^{163}Ho decay. The unlabeled impurities are ^{144}Pm. The continuous (red line) theory [5] is based on Eq. (9).

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:

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

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 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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Klaus Blaum, Andreas Dörr, Sergey Eliseev
Petersburg Nuclear Physics Institute, Russia
Yuri Novikov
Saha Institute of Nuclear Physics, Kolkata, India
Susanta Lahiri

Sandwiched sensor

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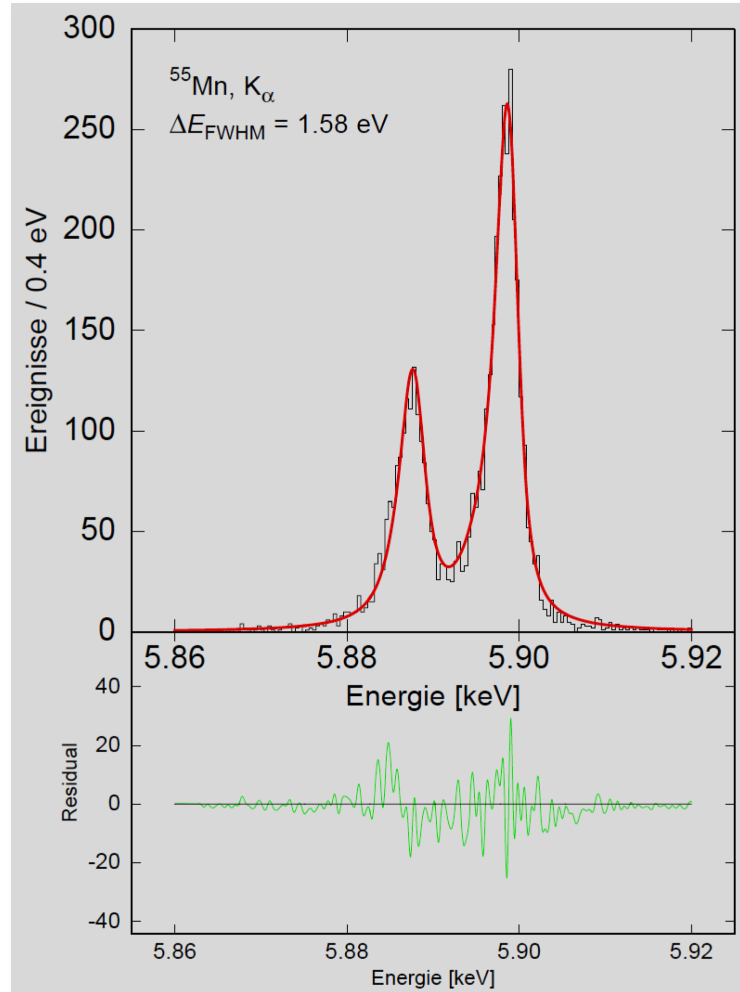


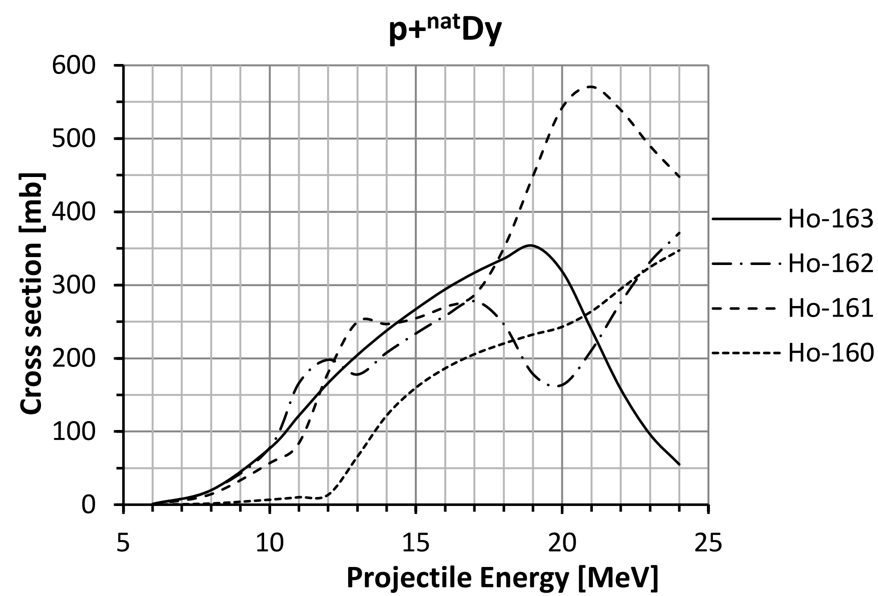
ΔE_{FWHM} = 1.6eV @ 6 keV

Proton induced reaction

Calculations by Maiti et al.

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

σ ~350 mb at 19 MeV



Contributors:

^{163}Dy (24.9%)(p,n)^{163}Ho (σ~0.4 mb)

^{164}Dy (28.2%)(p,2n)^{163}Ho (σ~1254 mb)

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
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

$\alpha + Dy_2O_3$

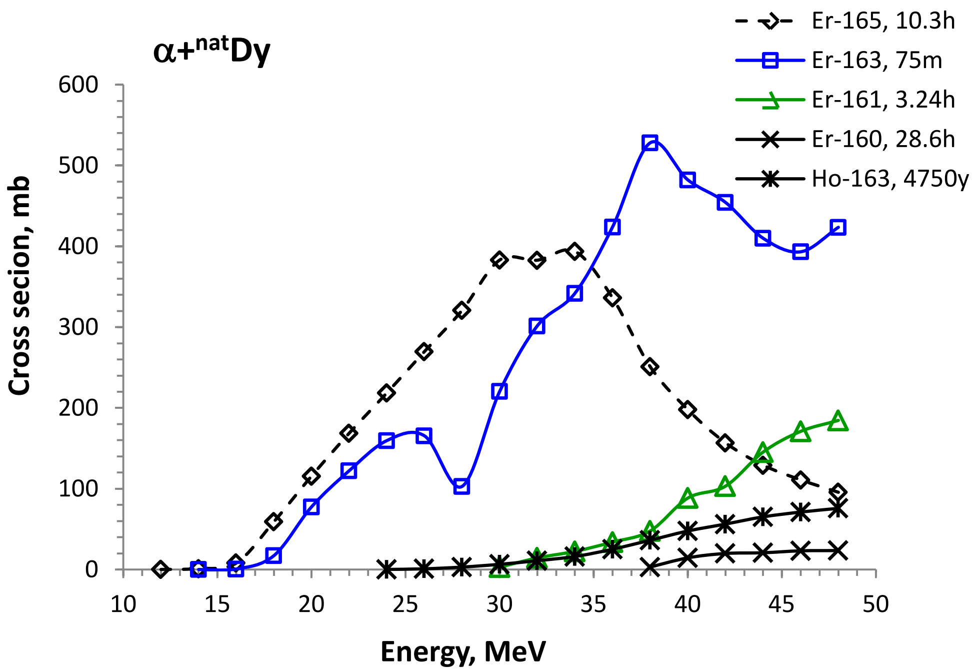
Irradiation parameters:

Projectile : α

E_P = 40 MeV

first target: 1 µA, 7 h irradiation

second target: 3 µA, 11 h irradiation



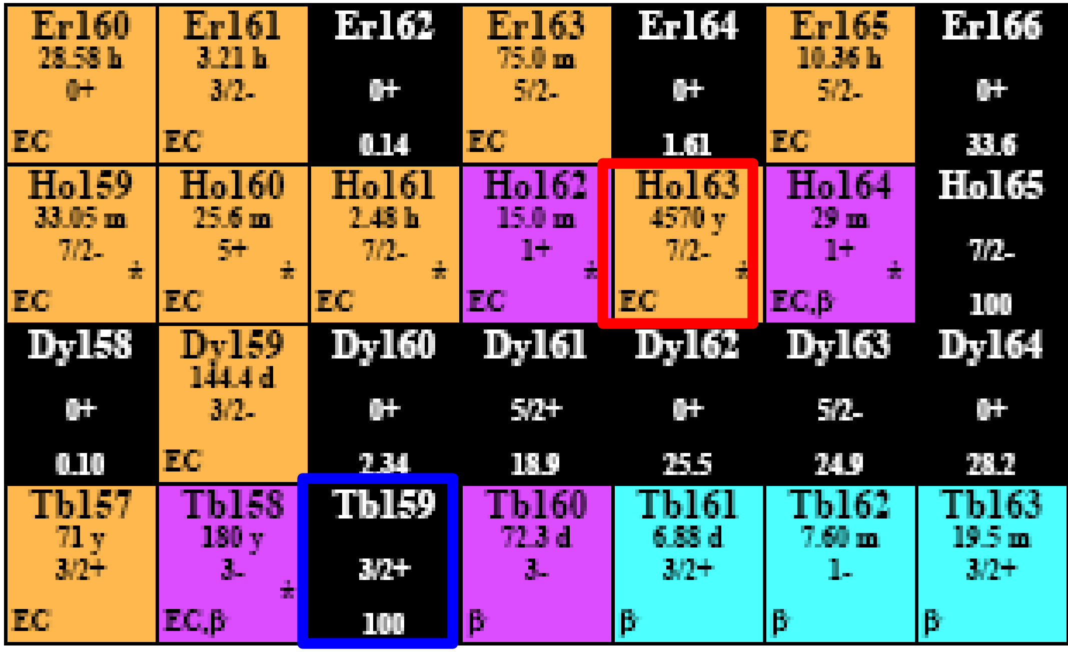
$^{nat}Dy(\alpha, xn)\ ^{163}Er\ (\varepsilon)\ ^{163}Ho$
(σ ~500 mb at 40 MeV)

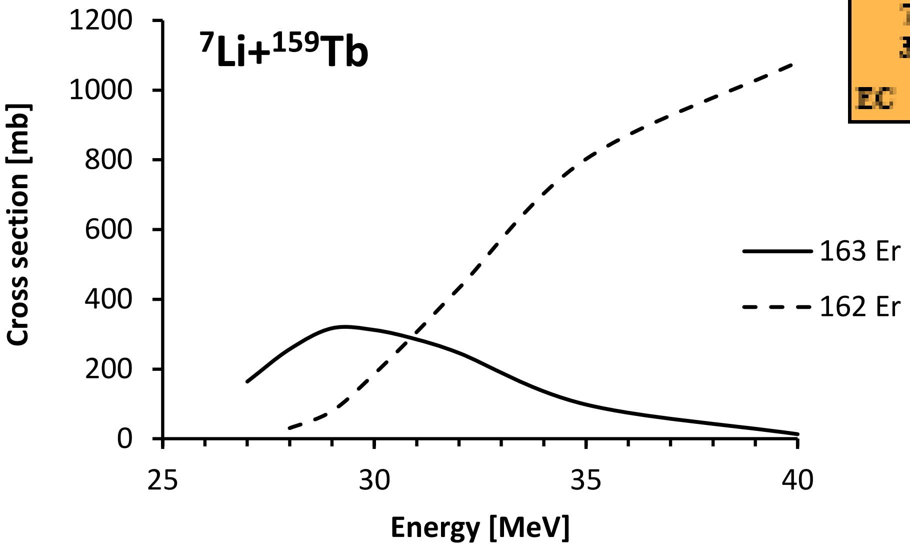
Exhaustive Chemistry !!

Experiment and Calculations by Maiti et al.

Li-induced reaction

$^{159}Tb(^{7}Li, 3n)\,^{163}Er$
(σ ~312 mb at 31 MeV)

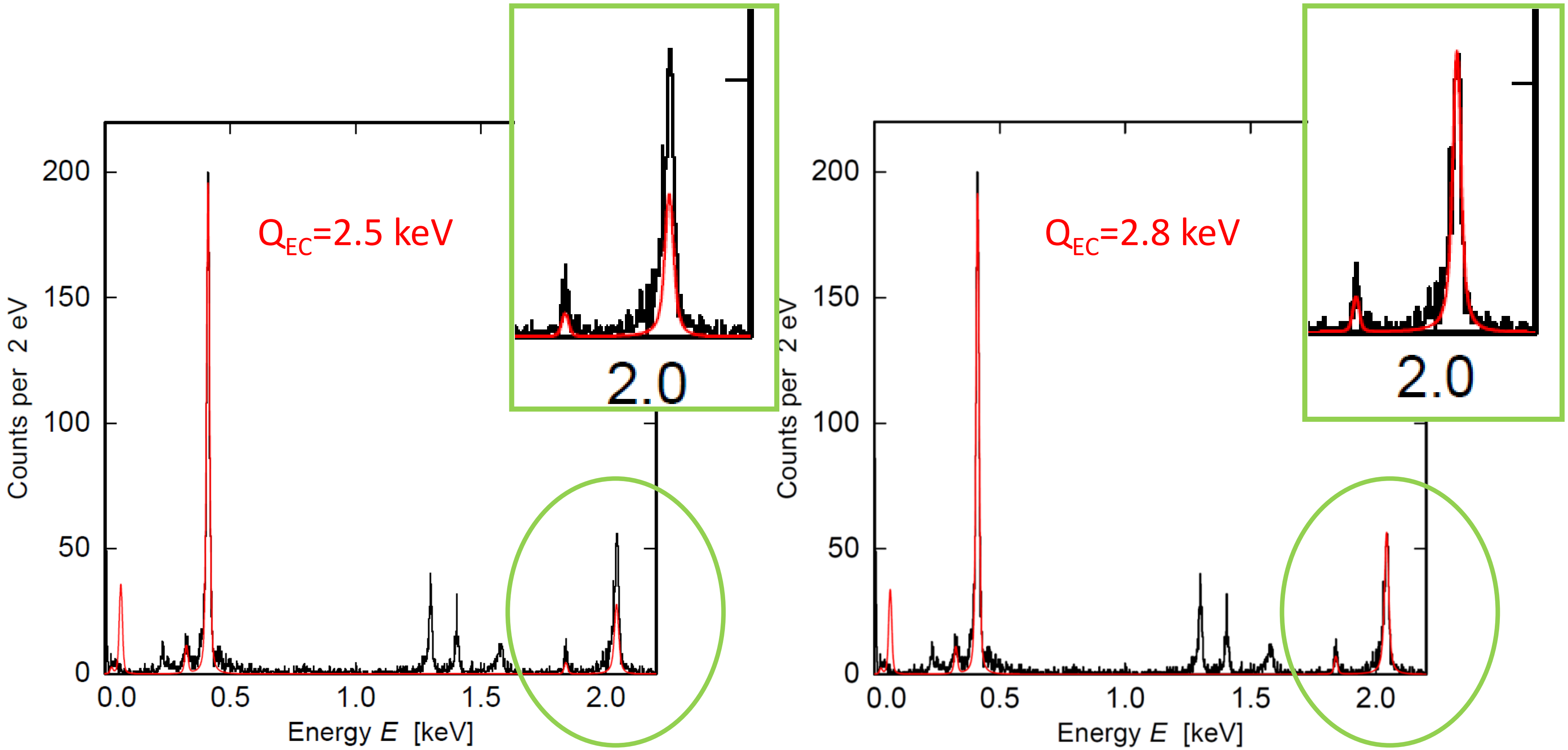




Calculations by Maiti et al.

^{163}Ho experiment: Calorimetric spectrum

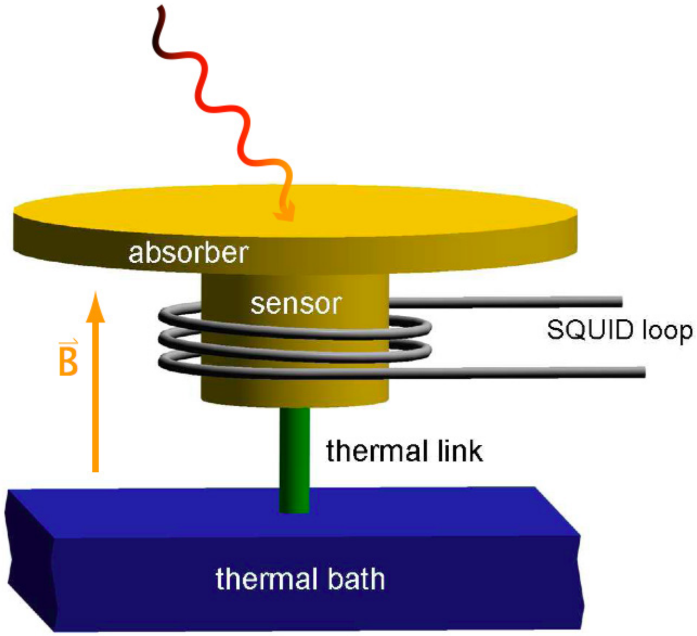
Determination of the Q_{EC} value from the intensity of the lines for m_ν=0:

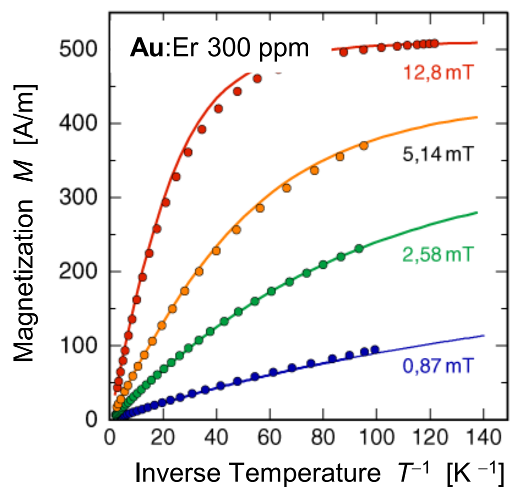


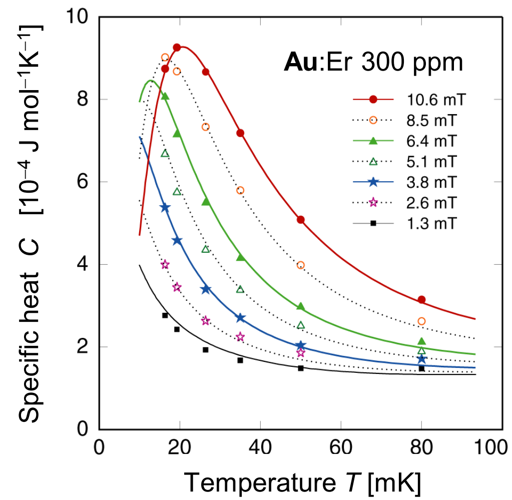
MMCs: Concept

- Paramagnetic Au:Er sensor

$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$







Main differences to calorimeters with resistive thermometers

no dissipation in the sensor

no galvanic contact to the sensor