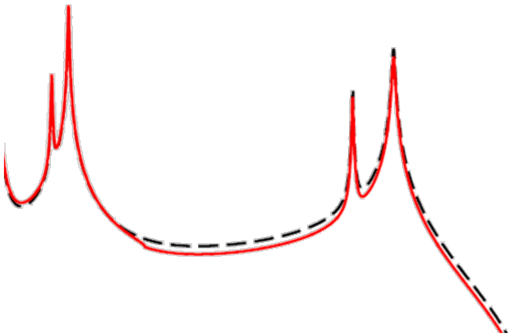
Search for keV Sterile Neutrinos with the ^{163}Ho Electron Capture experiment

Loredana Gastaldo
for the ECHo Collaboration

Kirchhoff Institute for Physics, Heidelberg University



Contents

- ^{163}Ho and electron neutrino mass
- The ECHo neutrino mass experiment
- keV sterile neutrinos and ECHo
- Conclusions and outlook

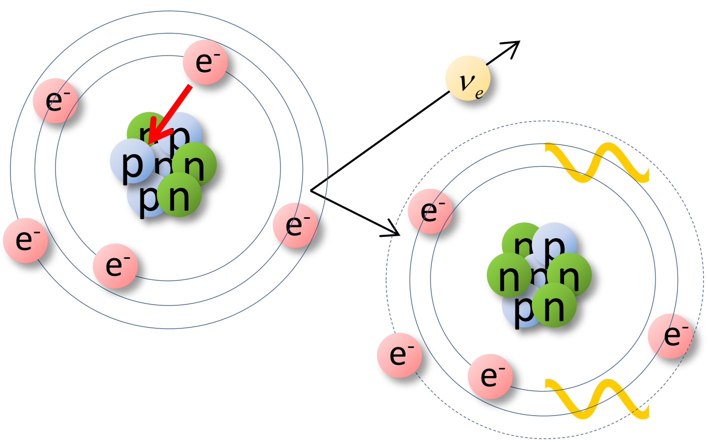
^{163}Ho and neutrino mass

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

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

- $\tau_{1/2} \cong 4570$ years (2*10[11] atoms for 1 Bq)
- $Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

S. Eliseev et al., *Phys. Rev. Lett.*, 115, 062501 (2015)

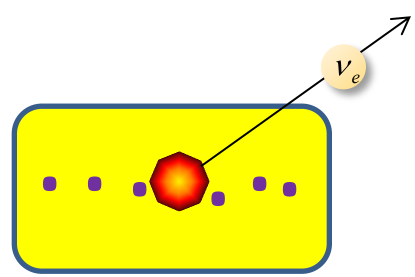


A non- zero neutrino mass affects the de-excitation energy spectrum

Atomic de-excitation:

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

} Calorimetric measurement



^{163}Ho Q_{EC}-value

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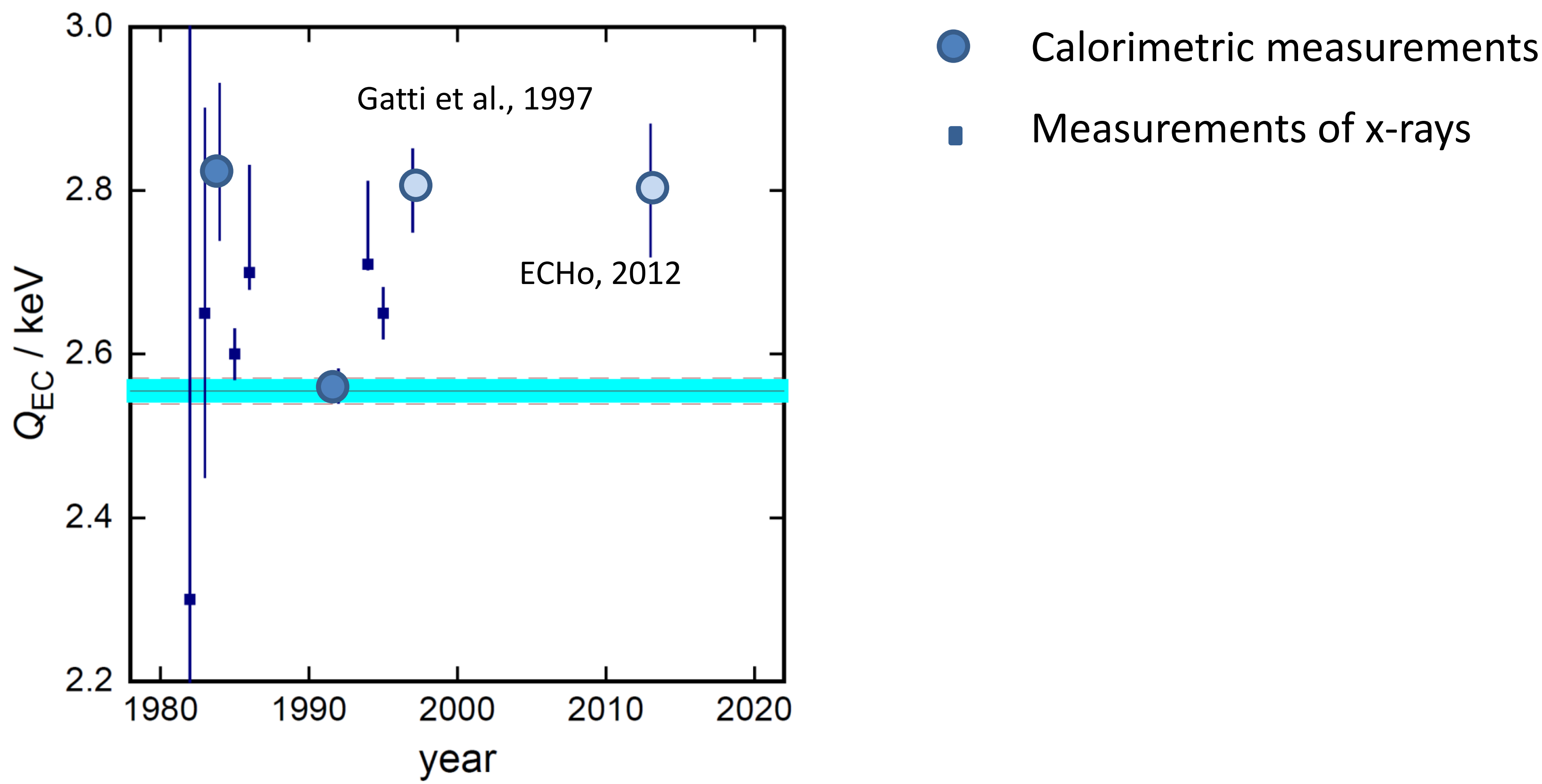

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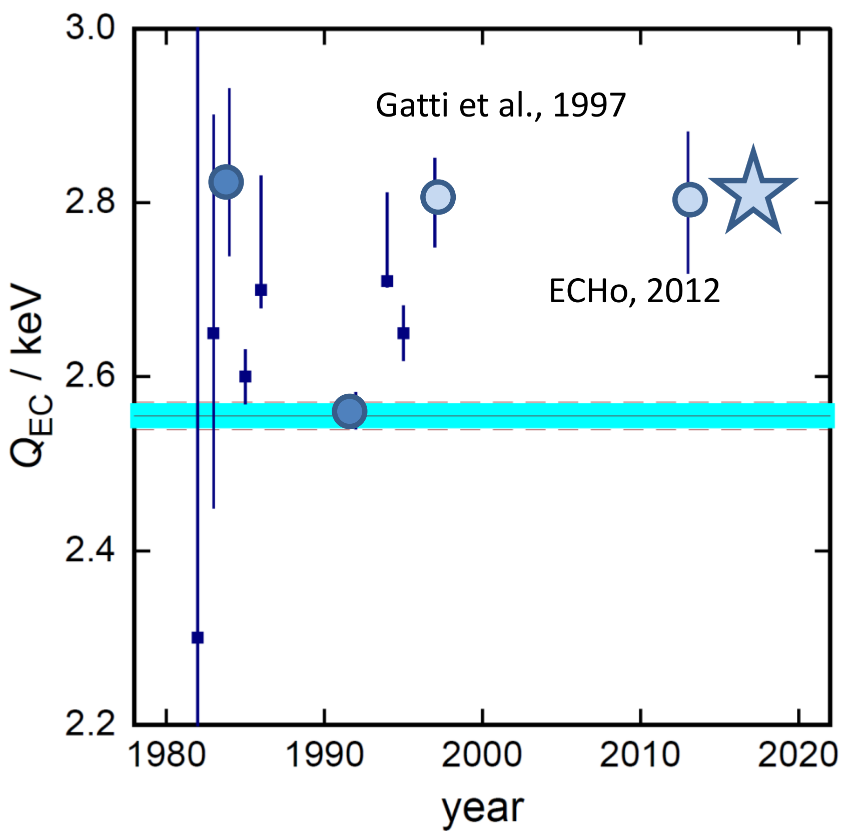

Calorimetric measurements

Measurements of x-rays

Independent of ^{163}Ho decay parameters

Penning Trap Mass Spectroscopy @SHIPTRAP GSI

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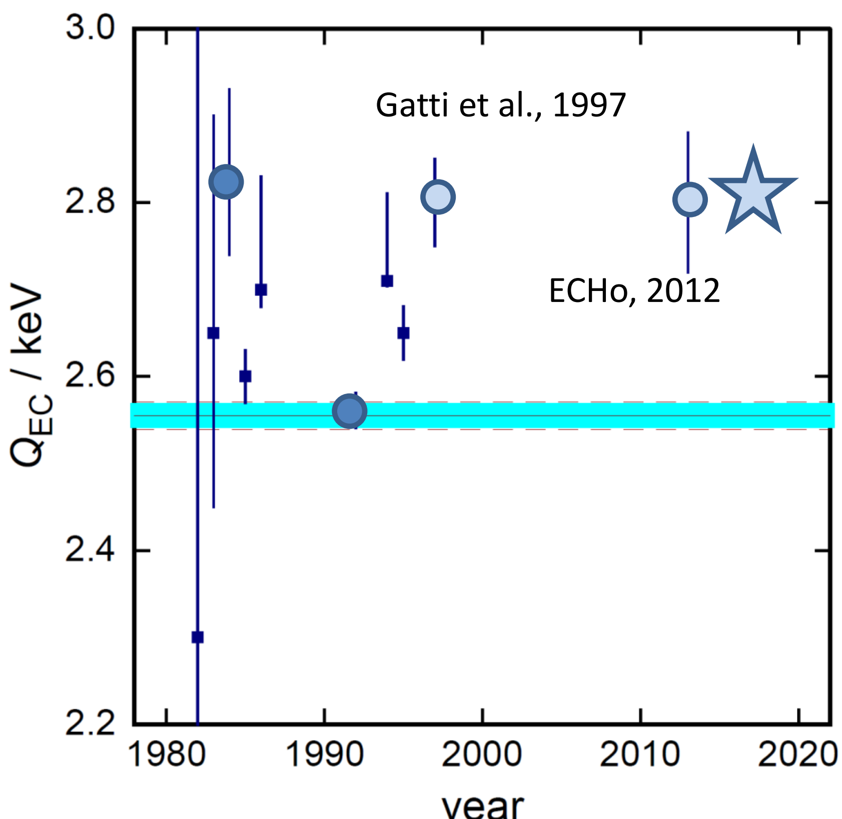


Calorimetric measurements

Measurements of x-rays

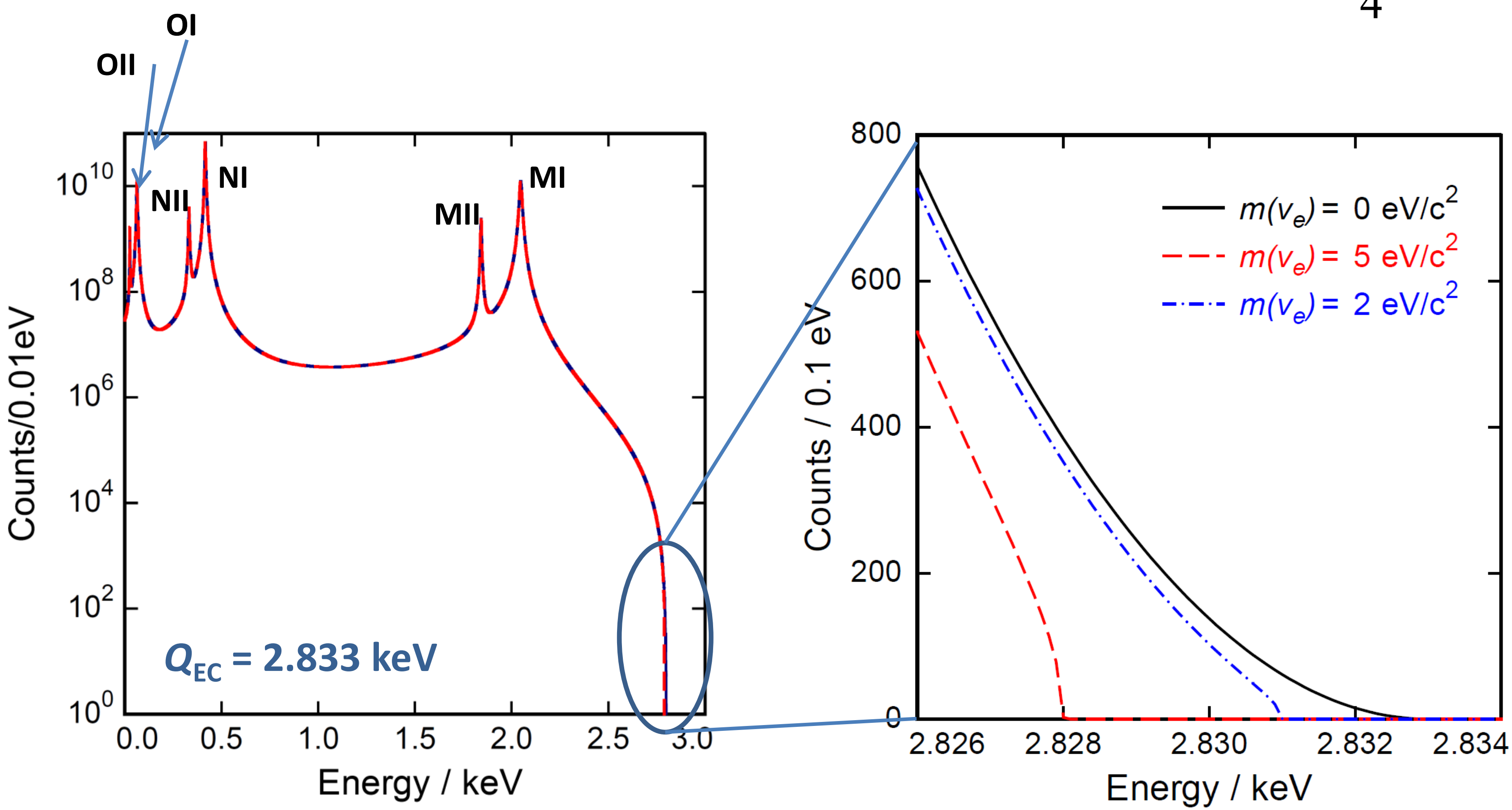
Independent of ^{163}Ho decay parameters

Penning Trap Mass Spectroscopy @SHIPTRAP GSI

To reduce uncertainties in the analysis:
Q_{EC} determination within **1 eV**
→ **PENTATRAP (MPIK HD)**

^{163}Ho Q_{EC}-value

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



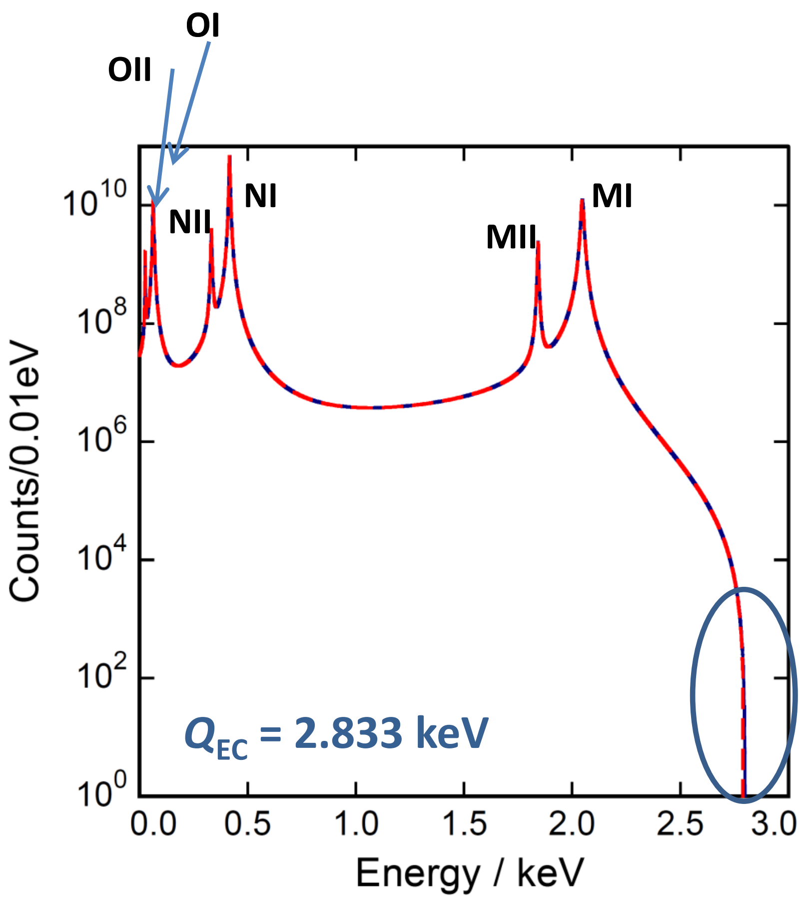
Requirements for sub-eV sensitivity in ECHo

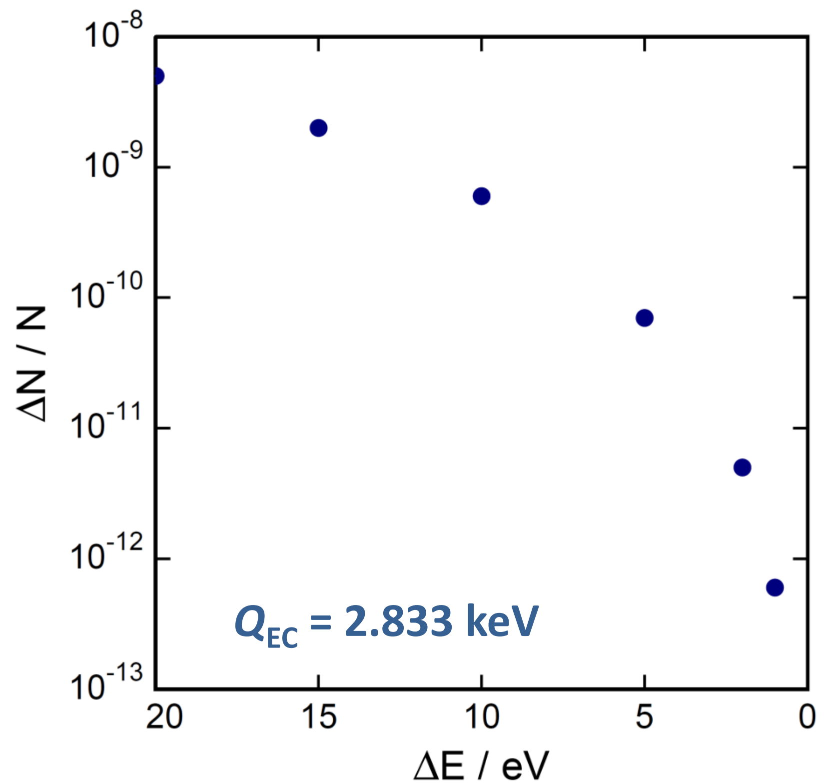
Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Fraction of events at endpoint regions

- In the interval 2.832 -2.833 keV only **6×10^{-13}**





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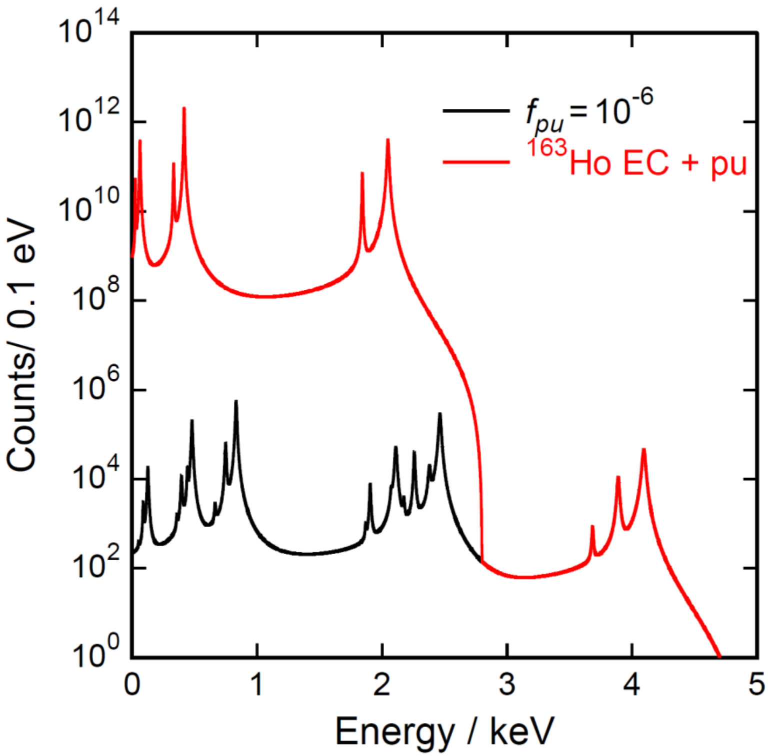
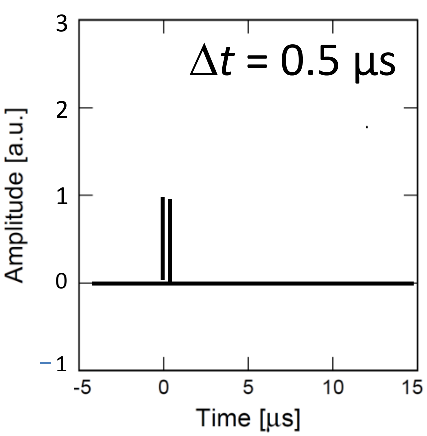
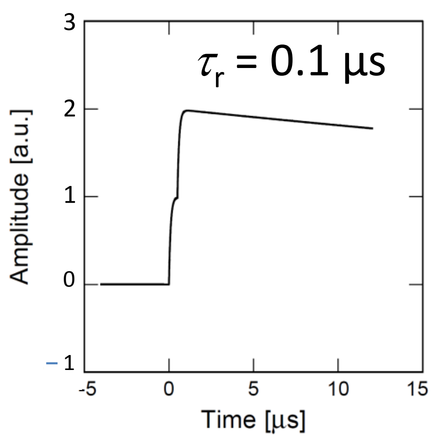
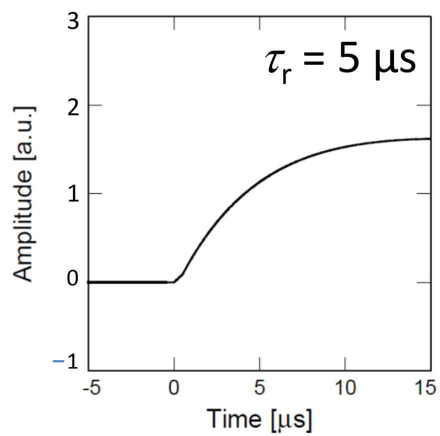
Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

- ***f_{pu}* < 10^{-5}**
- τ_r < 1 µs → a ~ 10 Bq
- 10^5 pixels









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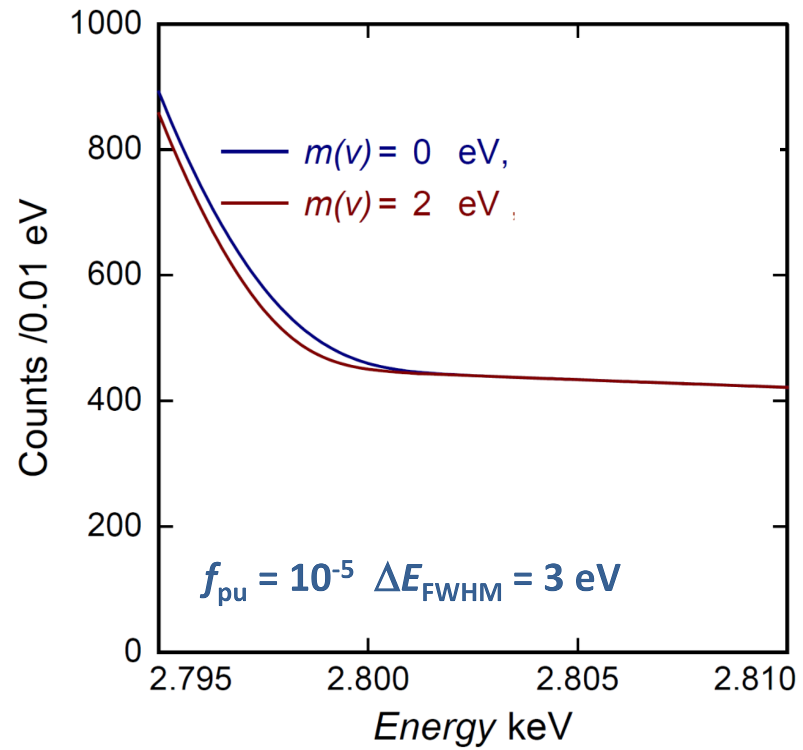
Precision characterization of the endpoint region

- $\boldsymbol{\Delta E_{FWHM} < 3}$ **eV**



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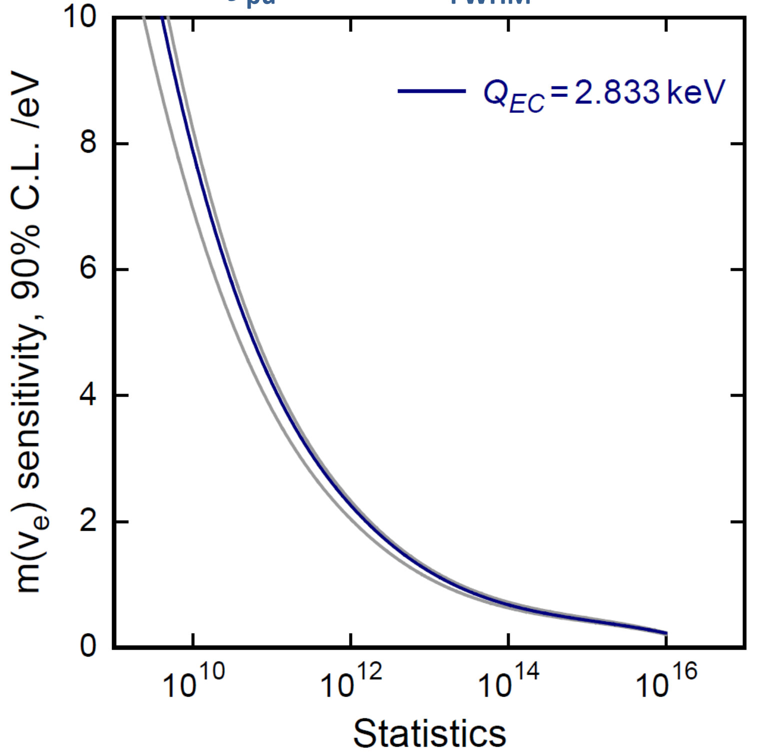
Background level

- **< 5∗10^{-5} events/eV/det/day**

$\boldsymbol{f_{pu} = 10^{-6}}$ $\boldsymbol{\Delta E_{FWHM} = 3}$ **eV**



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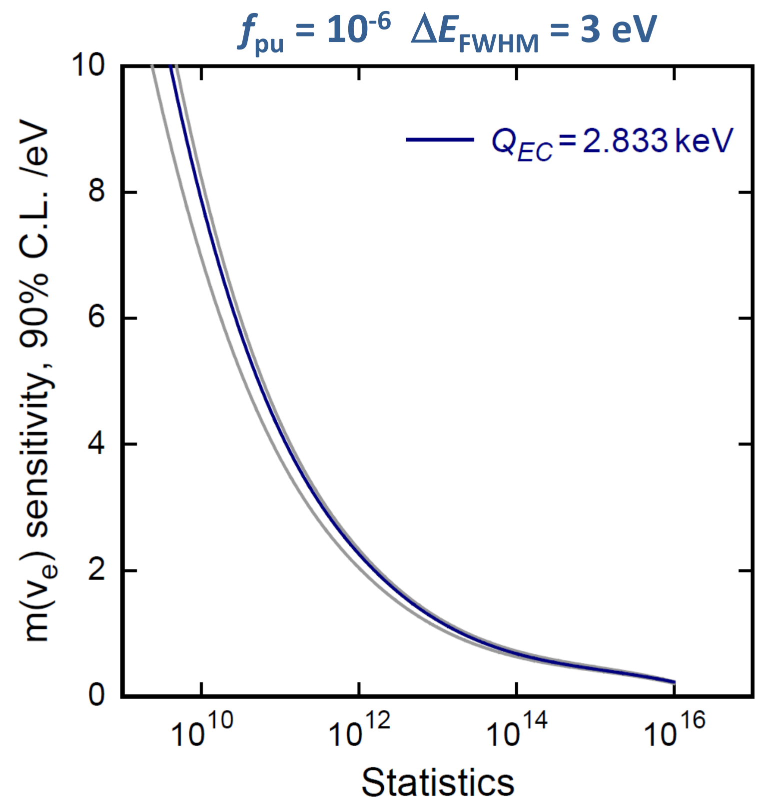


Low temperature

Metallic Magnetic Calorimeter

ECHo timeline

- Prove scalability with medium large experiment **ECHo-1K**

  - $A \sim 1000$ Bq
  - $\Delta E_{FWHM} < 5$ eV
  - $\tau_r < 1$ µs

  - 1 year measuring time → 10^{10} counts = Neutrino mass sensitivity $m_\nu < 10$ eV

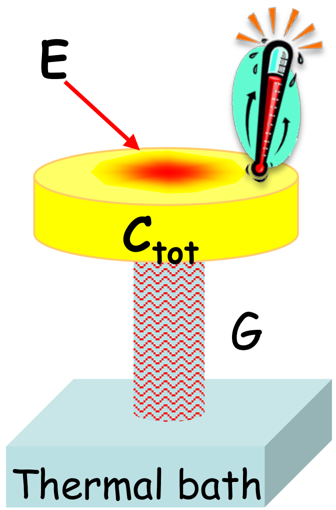
  Supported by

  Research Unit FOR 2202/1
  „Neutrino Mass Determination by Electron Capture in Holmium-163 – ECHo“

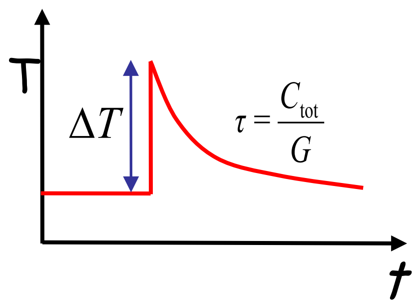
  DFG Deutsche Forschungsgemeinschaft

- **ECHo-1M** towards sub-eV sensitivity

Low temperature micro-calorimeters



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



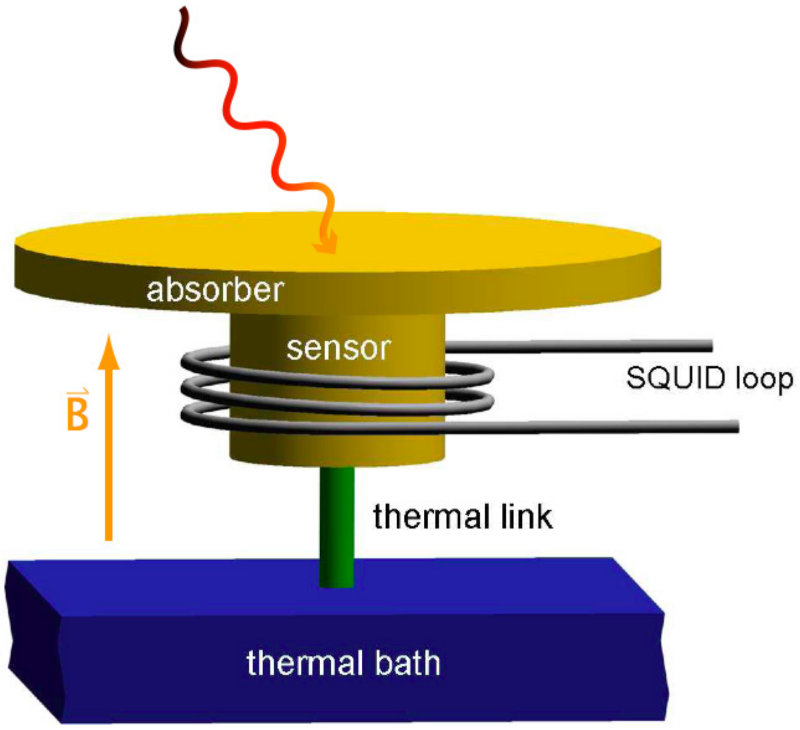
***E* = 10 keV**
***C*$_{tot}$ = 1 pJ/K**
→ ~ 1 mK

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

Metallic magnetic calorimeters (MMCs)

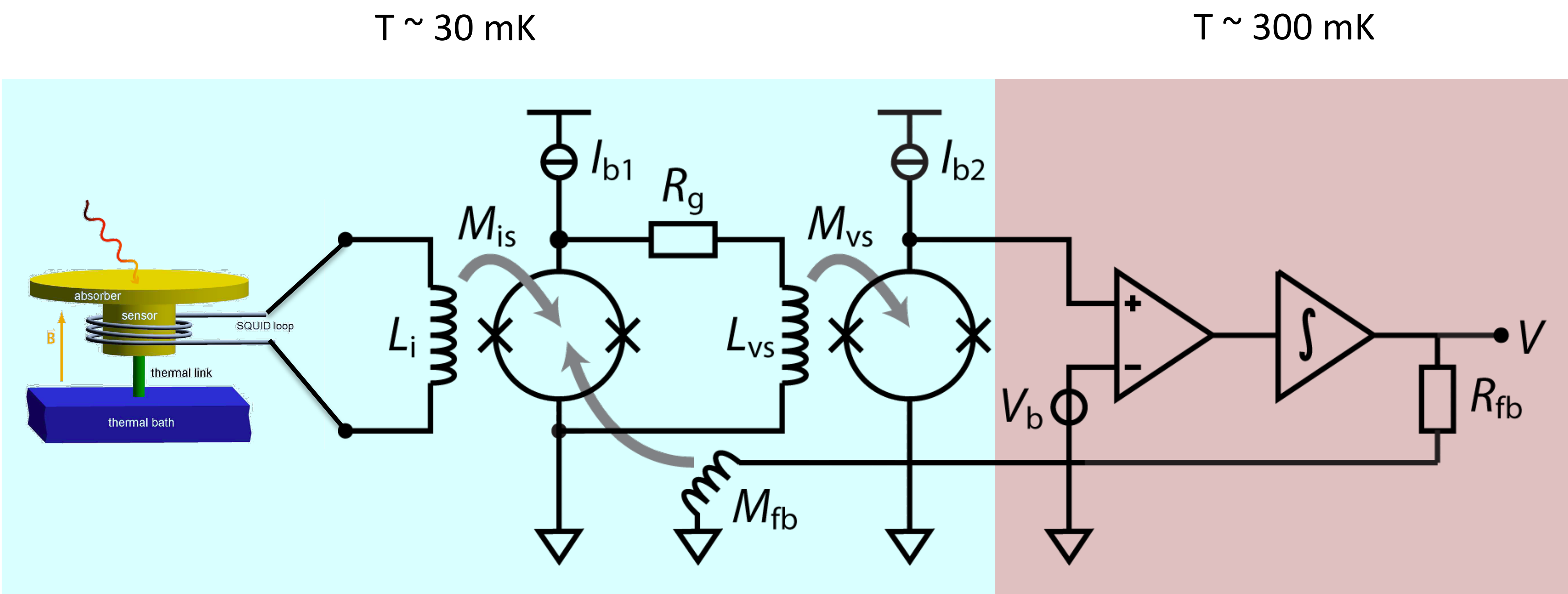
A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

- Paramagnetic Au:Er sensor
  Ag:Er



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

MMCs: Readout

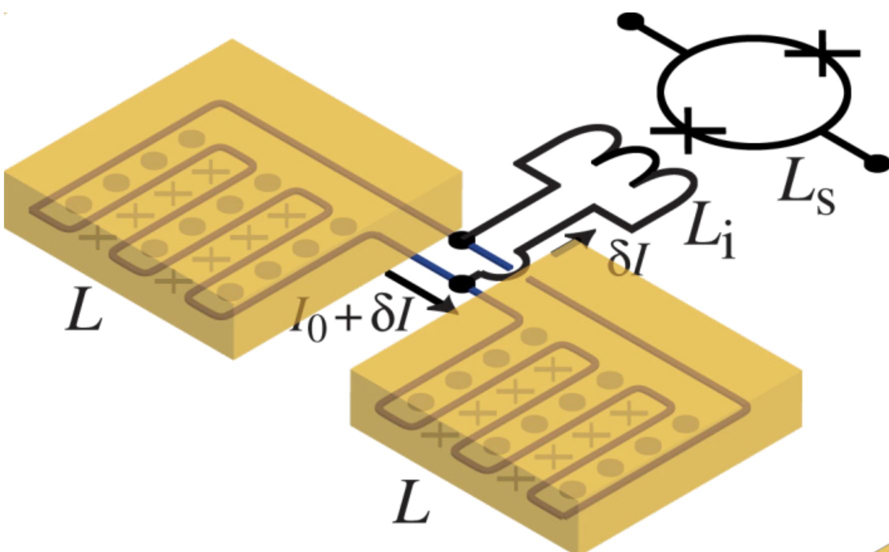


Two-stage SQUID setup with flux locked loop allows for:

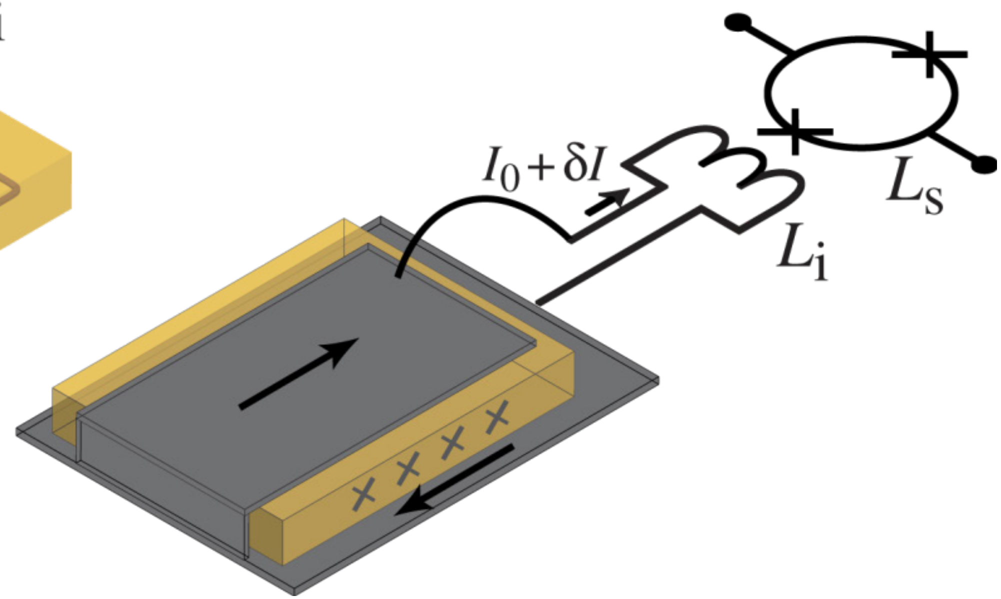
- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)

MMCs: Planar geometries

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

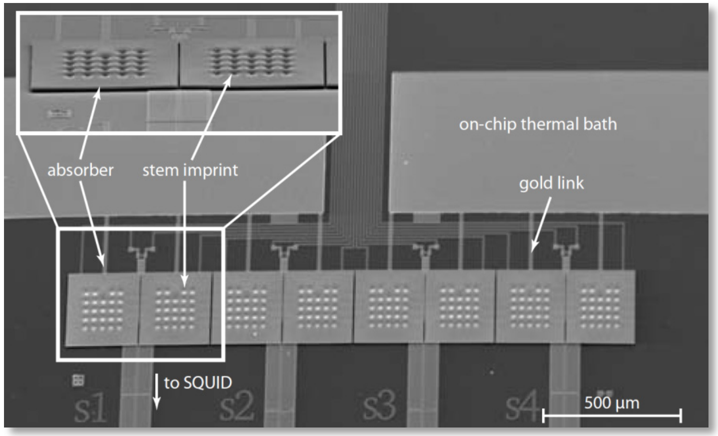


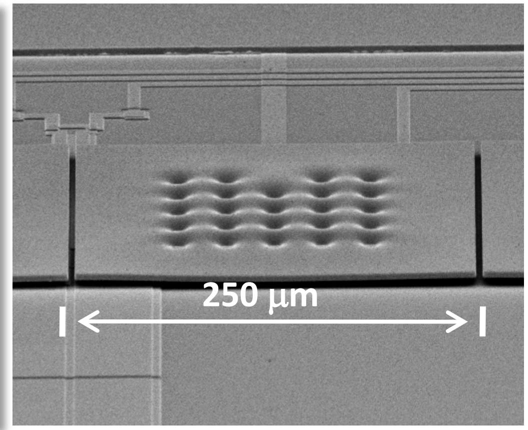
Meander-shaped pick-up coil



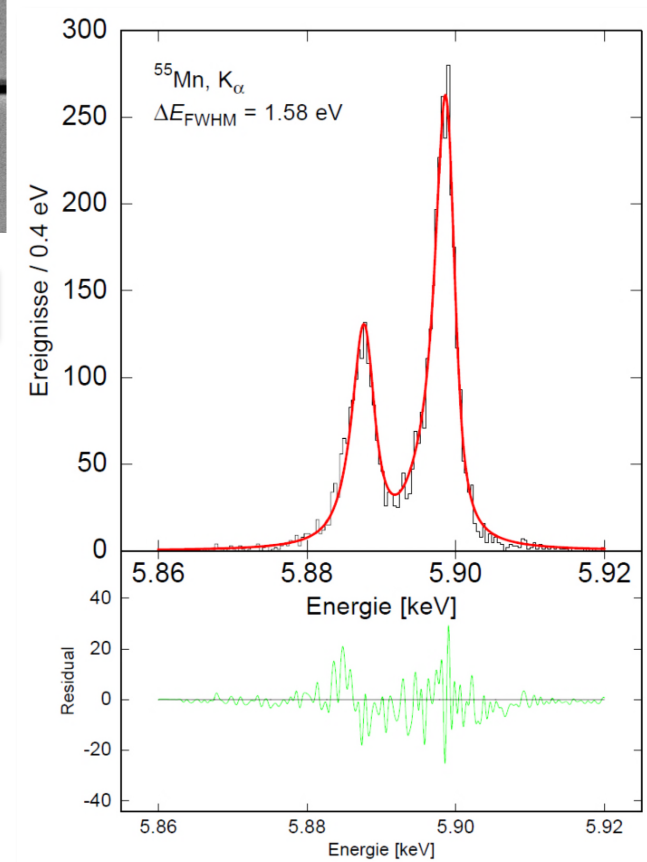
Sandwich design

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

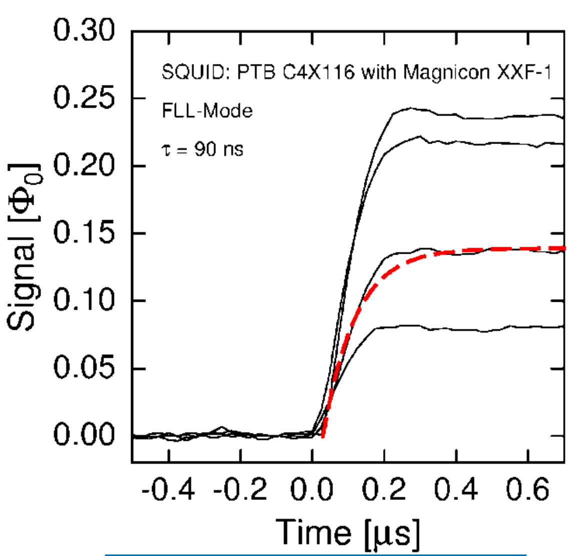




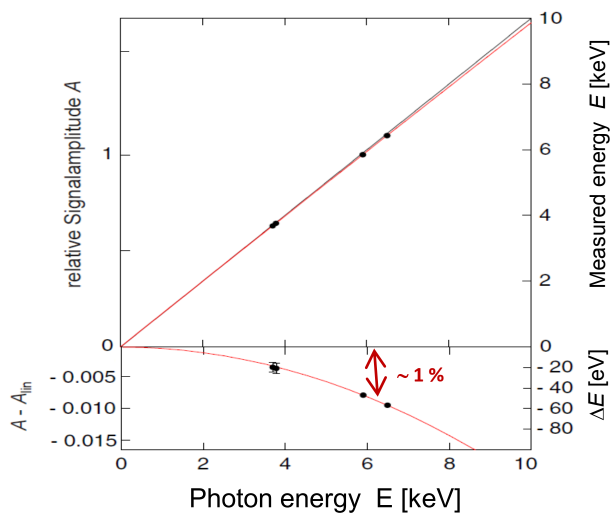
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



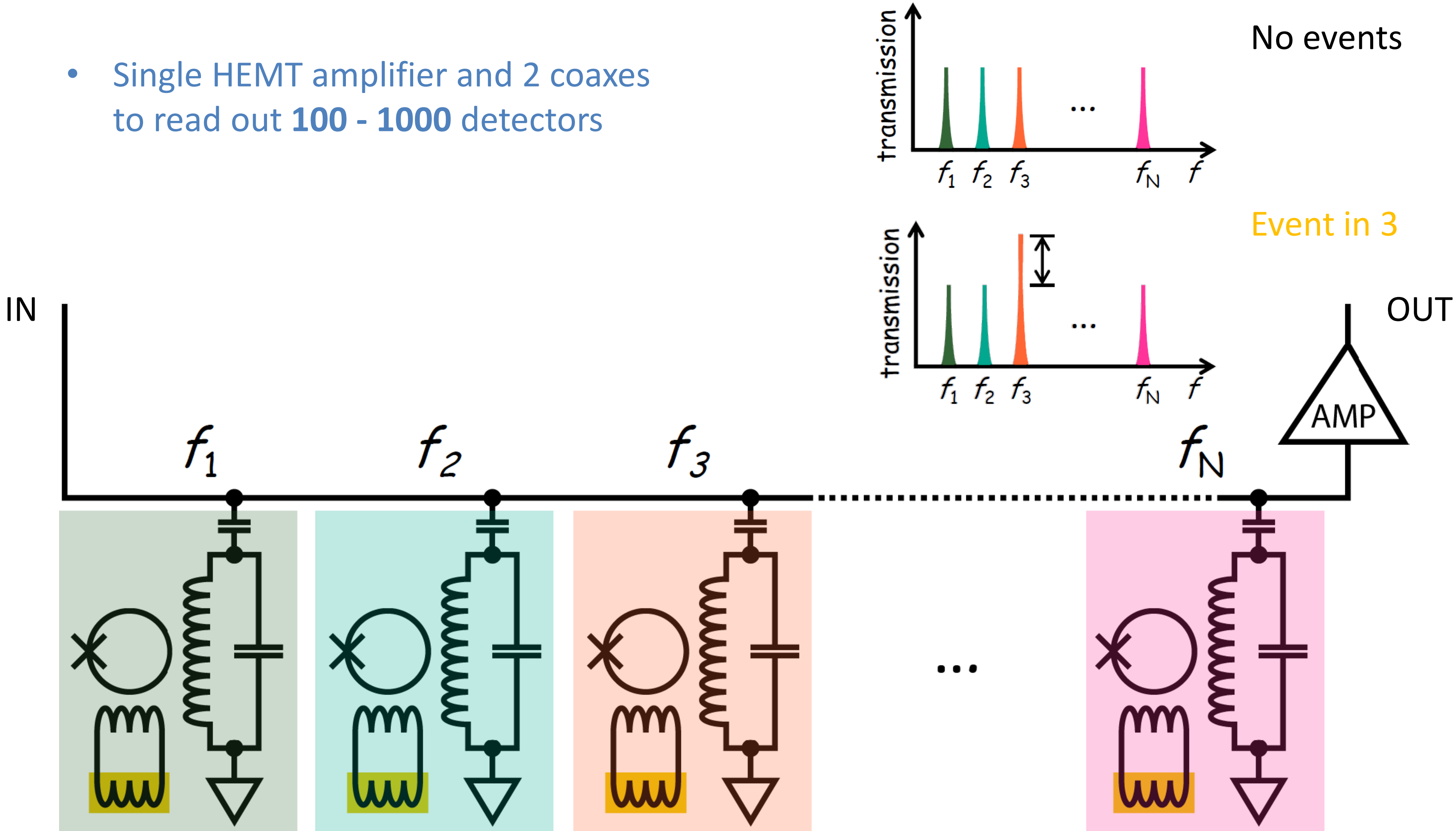
Reduction un-resolved pile-up

Definition of the energy scale

Reduced smearing in the end point region

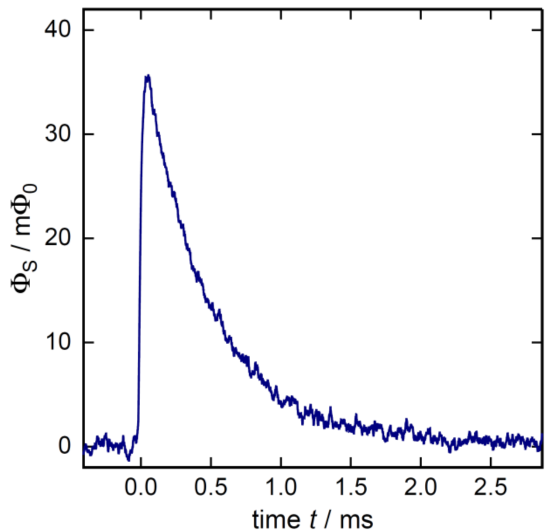
MMCs: Microwave SQUID multiplexing

- Single HEMT amplifier and 2 coaxes to read out **100 - 1000** detectors

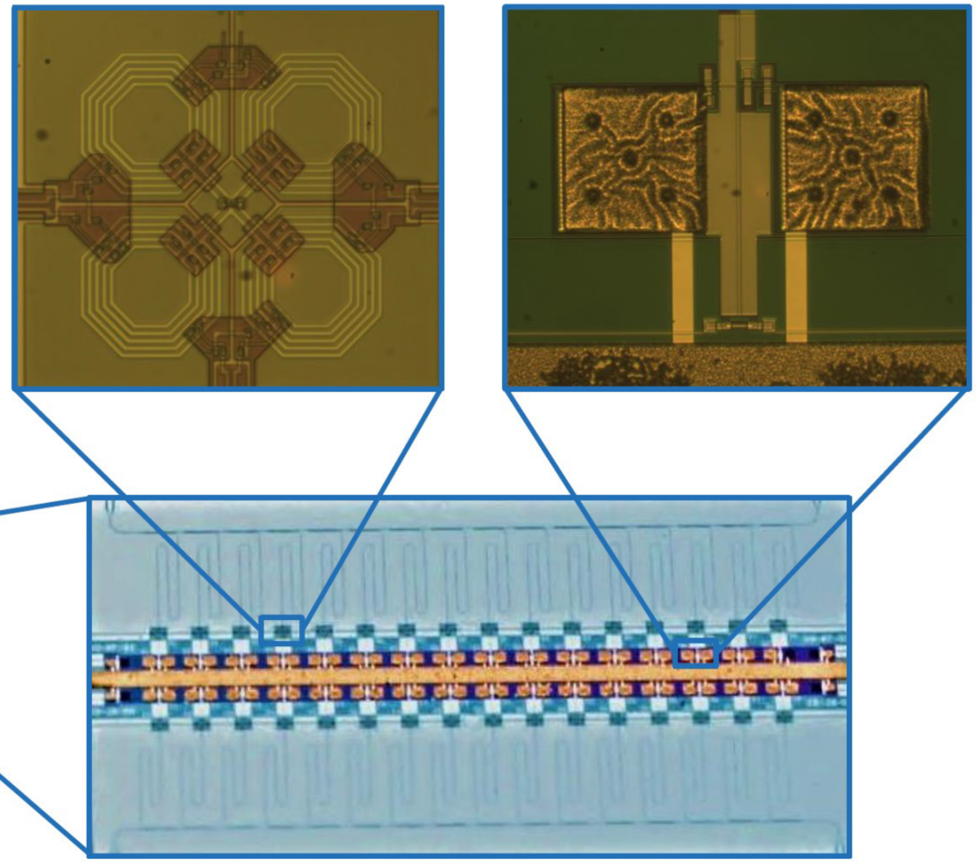


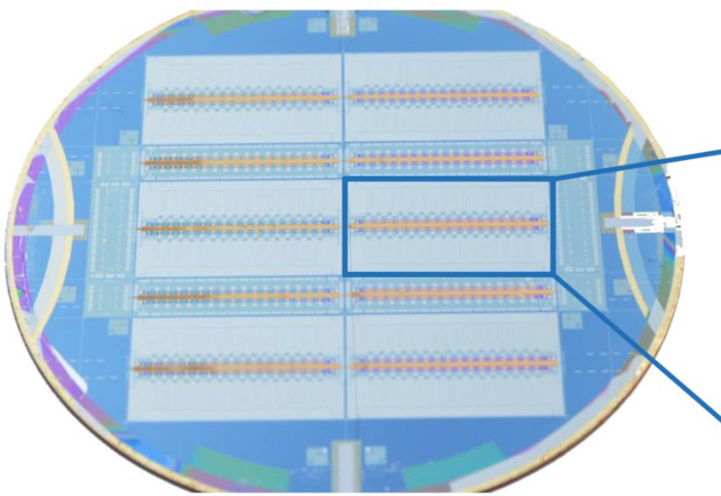
Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

MMCs: Microwave SQUID multiplexing



Successful production and test of the first prototype





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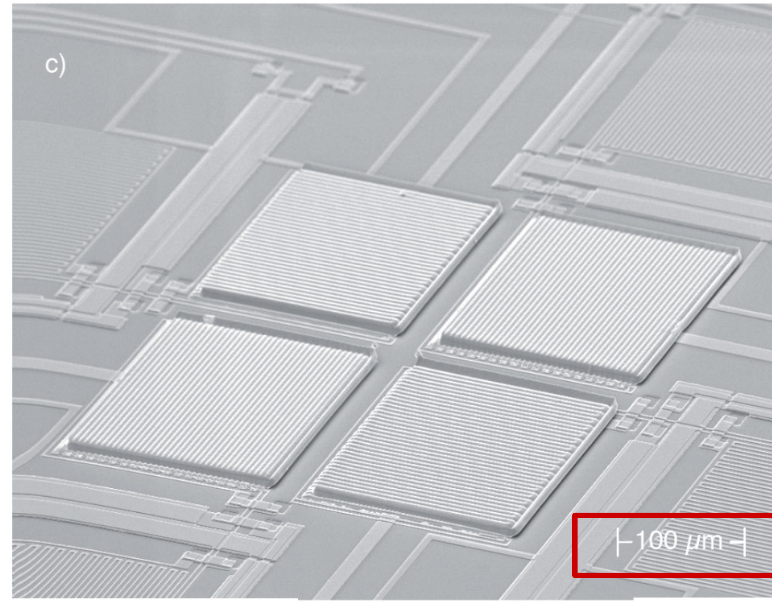
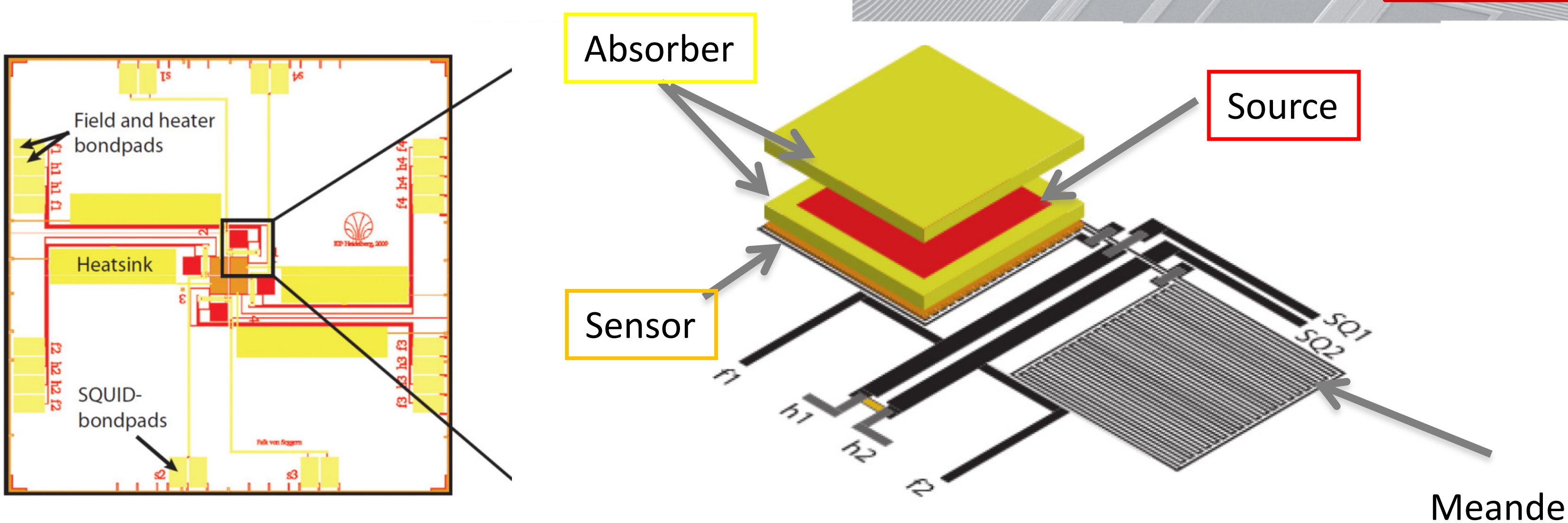
First detector prototype for ^{163}Ho

- Absorber for calorimetric measurement
  → ion implantation @ ISOLDE-CERN in 2009
  on-line process
- About 0.01 Bq per pixel
- Operated over more than 4 years



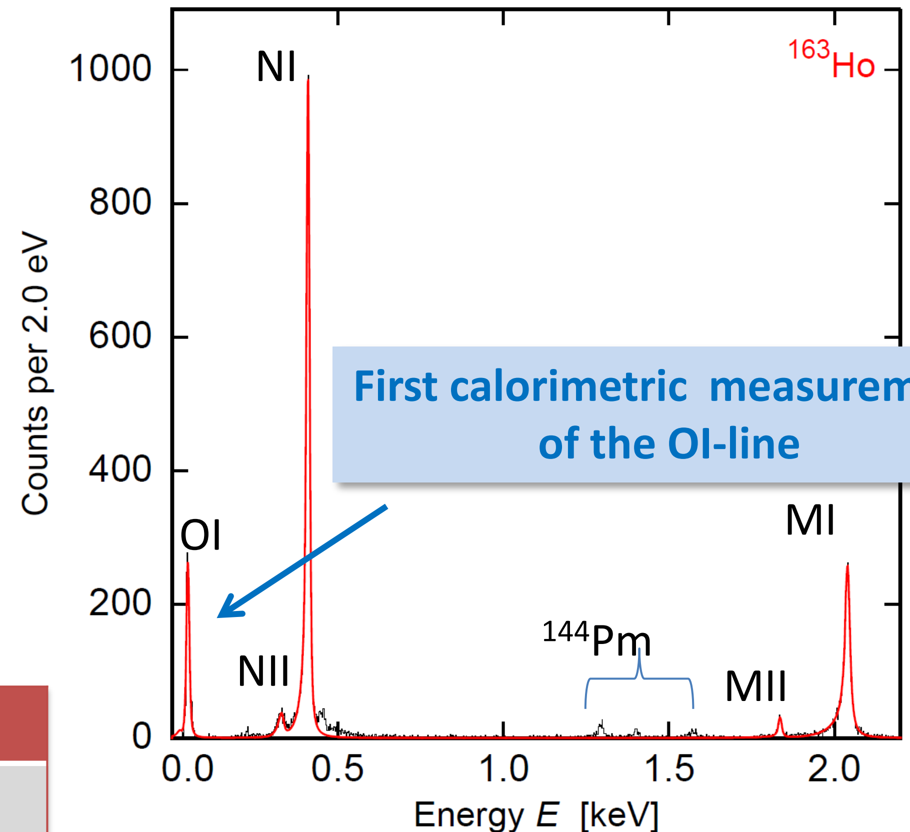


L. Gastaldo et al.,
Nucl. Inst. Meth. A, 711 (2013) 150

P. C.-O. Ranitzsch et al.,
http://arxiv.org/abs/1409.0071v1

Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels



First calorimetric measurement of the OI-line

	E_H bind.	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

$Q_{EC} = (2.843 \pm 0.009^{stat} \pm 0.06^{syst})$ keV

P. C.-O. Ranitzsch et al ., http://arxiv.org/abs/1409.0071v1)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

Where to improve

High purity ^{163}Ho source:

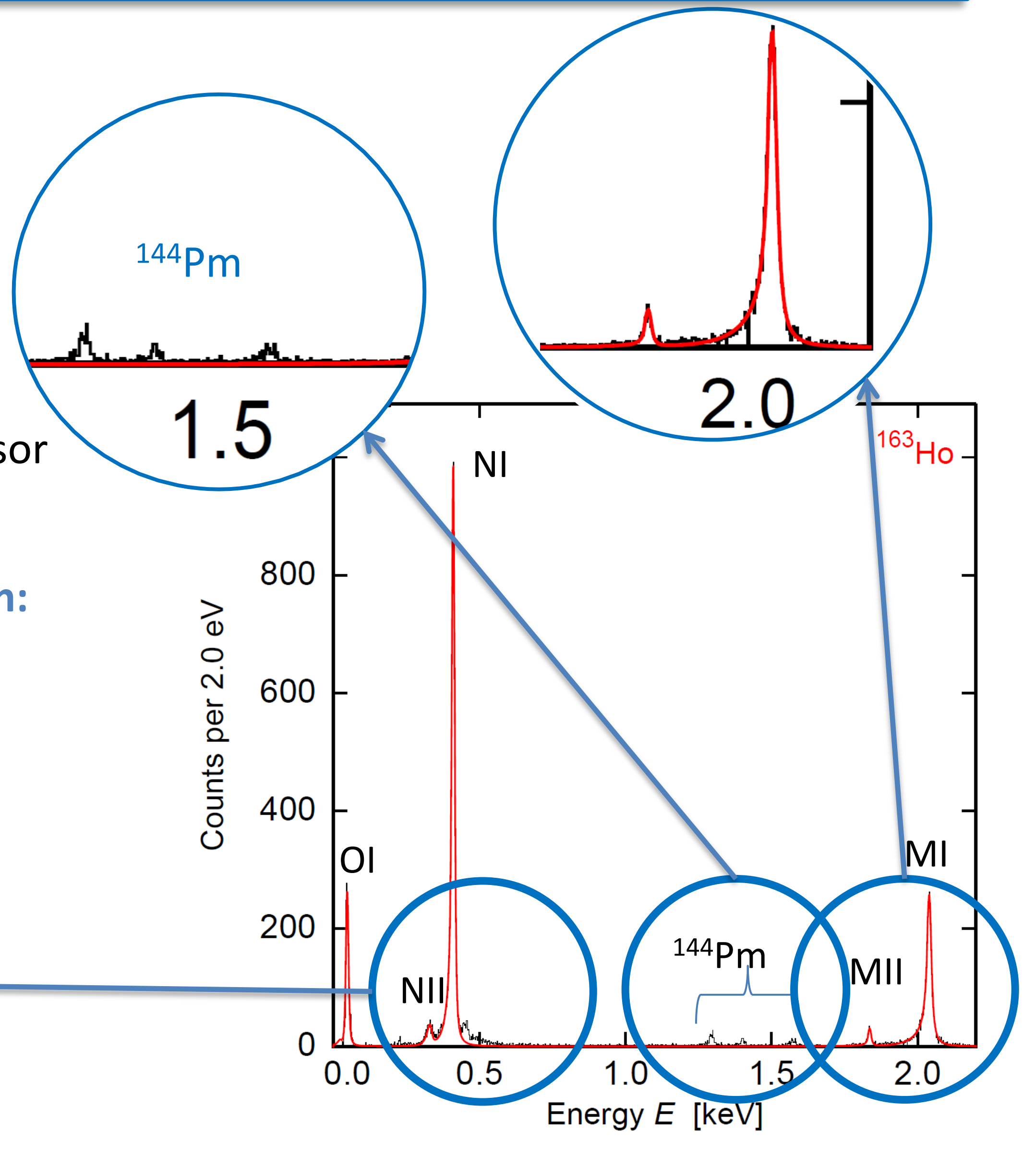
- Background reduction

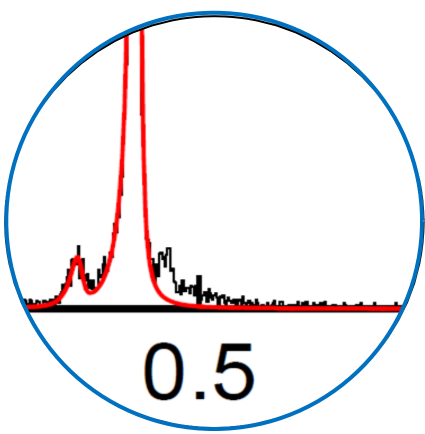
Detector design and fabrication:

- Increase activity per pixel
- Stems between absorber and sensor

Understanding of the ^{163}Ho spectrum:

- Investigate undefined structures

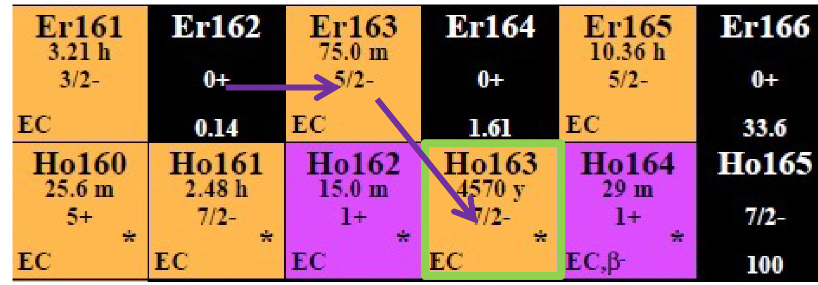




High purity ^{163}Ho source: (n,γ)-reaction on ^{162}Er

Requirement : >10^6 Bq → >10^{17} atoms

- (n,γ)-reaction on ^{162}Er
  - High cross-section
  - Radioactive contaminants



- Excellent chemical separation

  Only ^{166m}Ho

ECHo requirements:

^{166m}Ho/ ^{163}Ho < 10^{-9}

Offline mass separation:

RISIKO, Mainz University

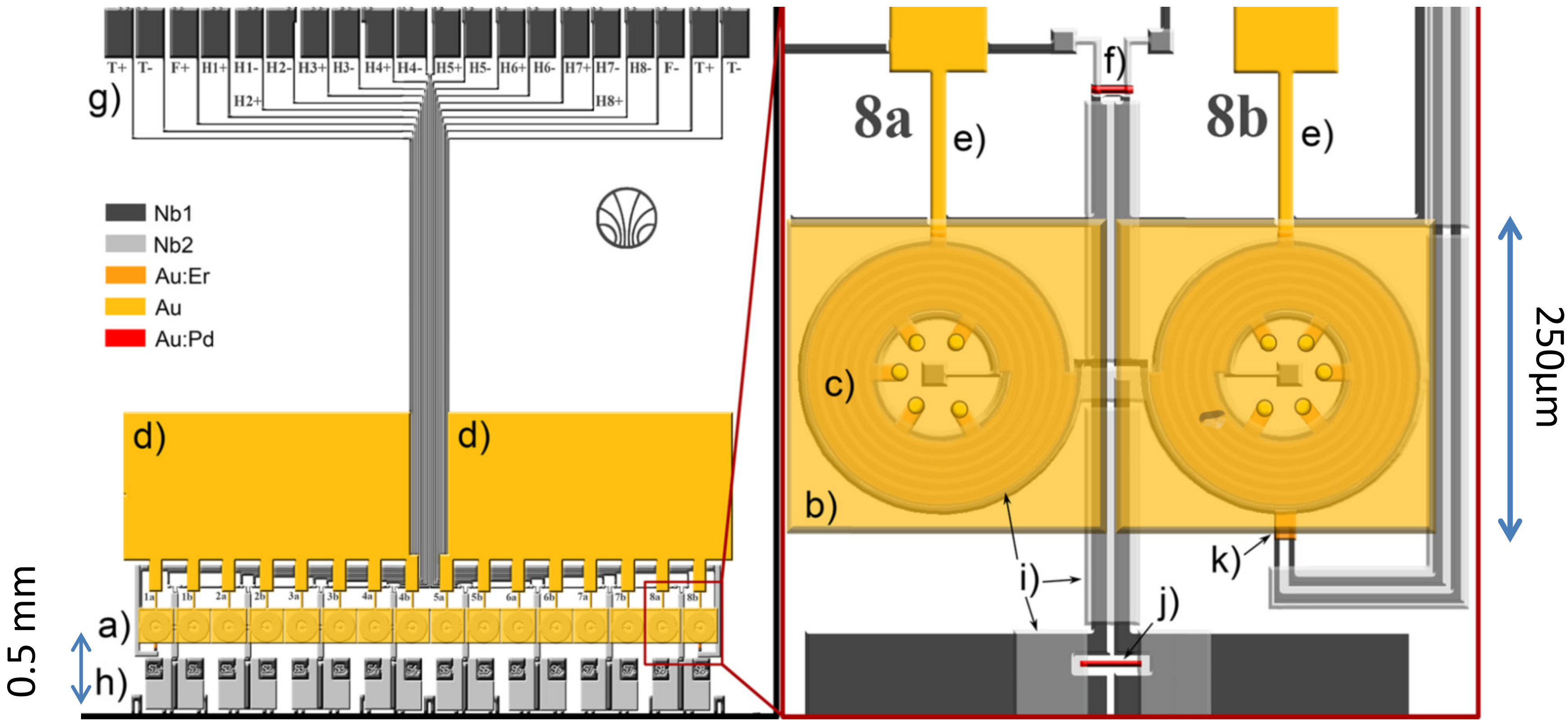
ISOLDE-CERN

- Available ^{163}Ho source:

  ~ 10^{18} atoms

Detector chip for second ^{163}Ho implantation

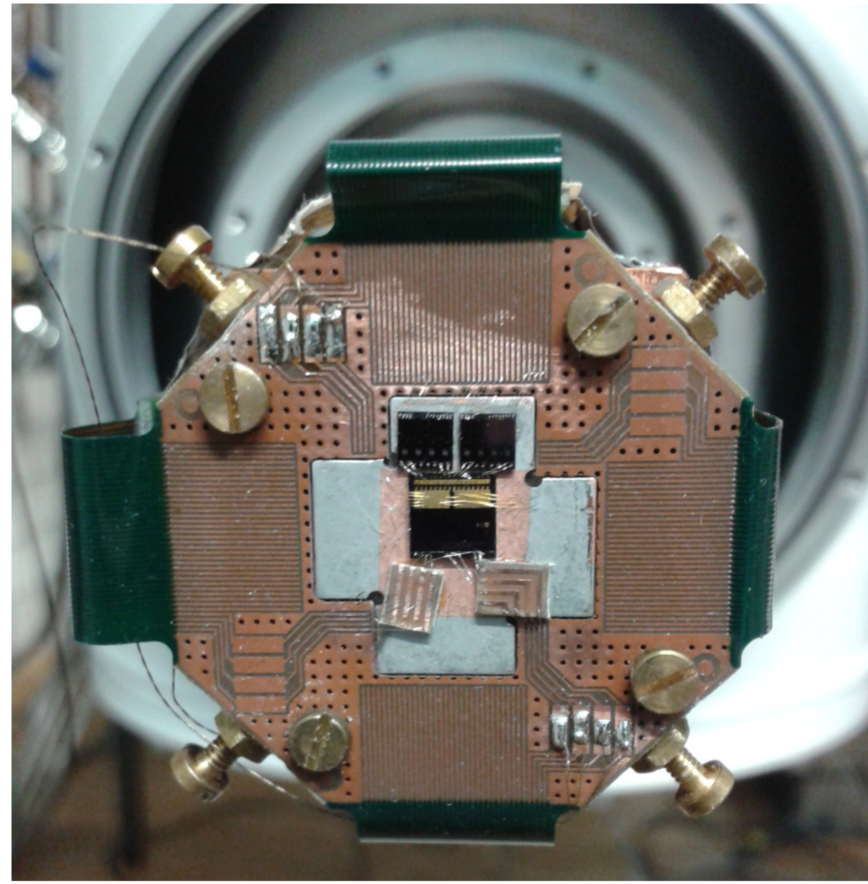
- maXs-20:
  - sandwich sensor design
  - absorber connected to sensor through stems
  - 16 pixels



- Chemically purified ^{163}Ho source
- Offline implantation @ISOLDE-CERN using GPS and RILIS (December 2014)

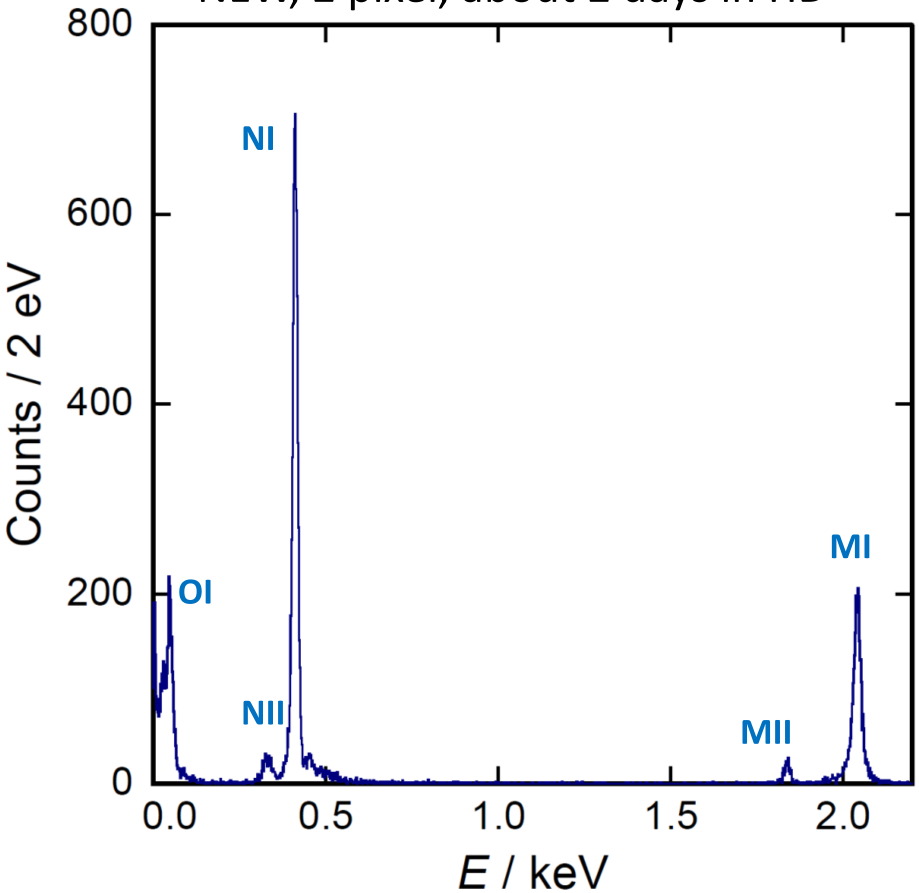
New detectors ready for …

Mounted on a cold arm of a dry cryostat



… first results

NEW, 2 pixel, about 2 days in HD



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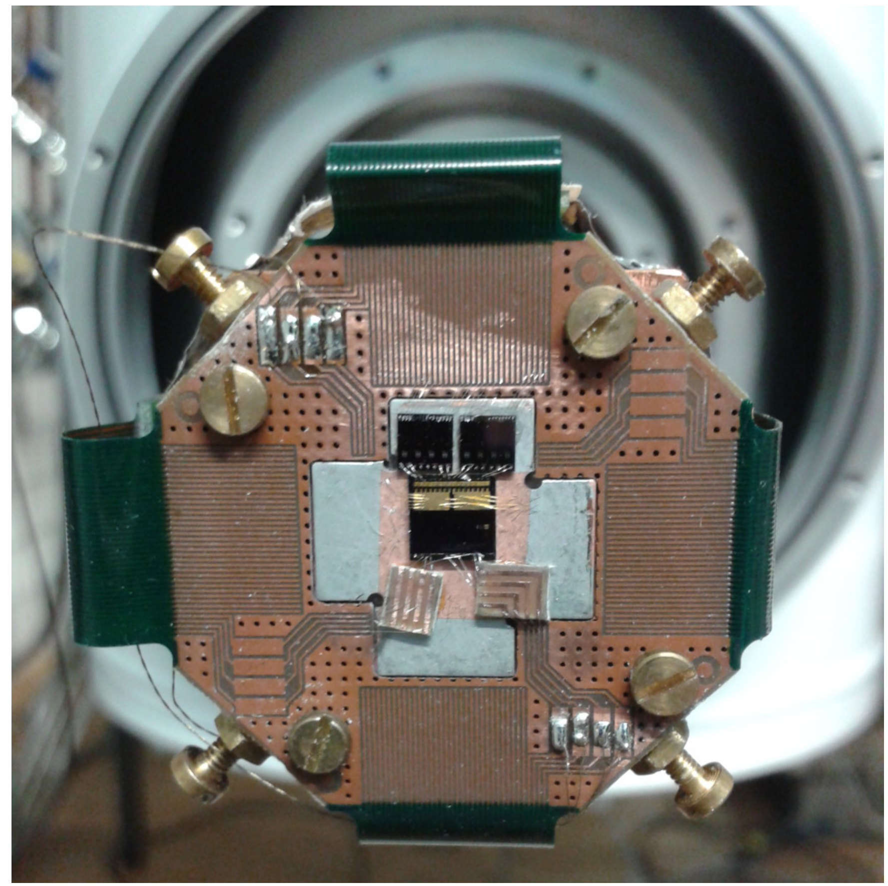

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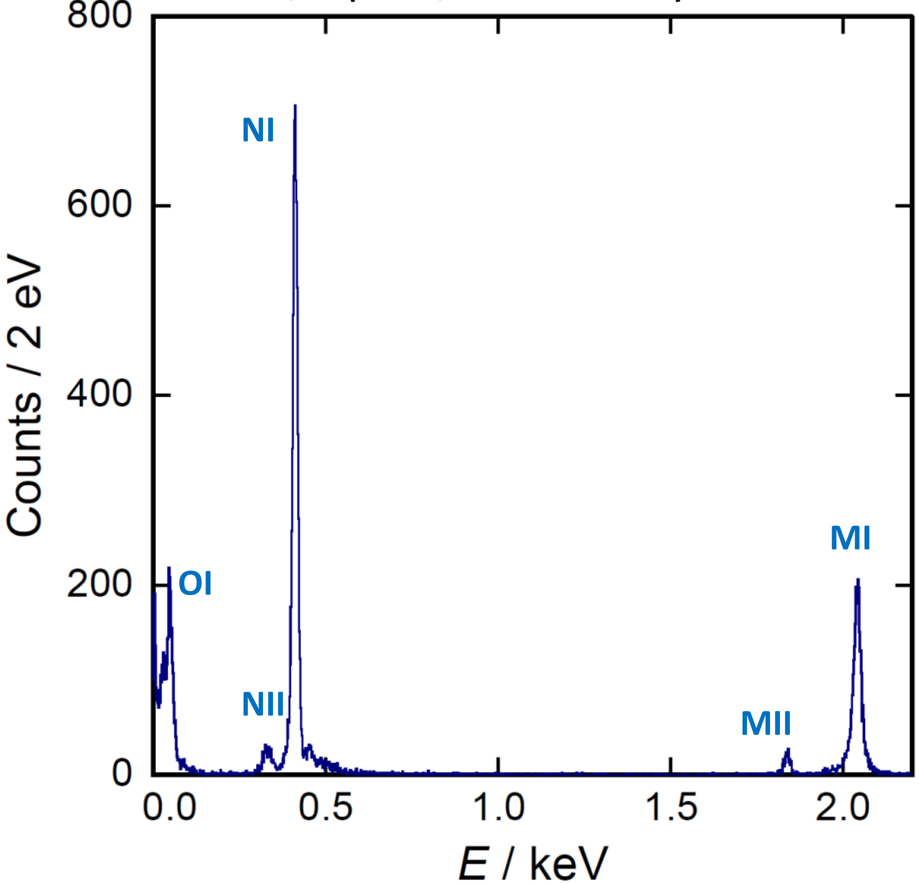
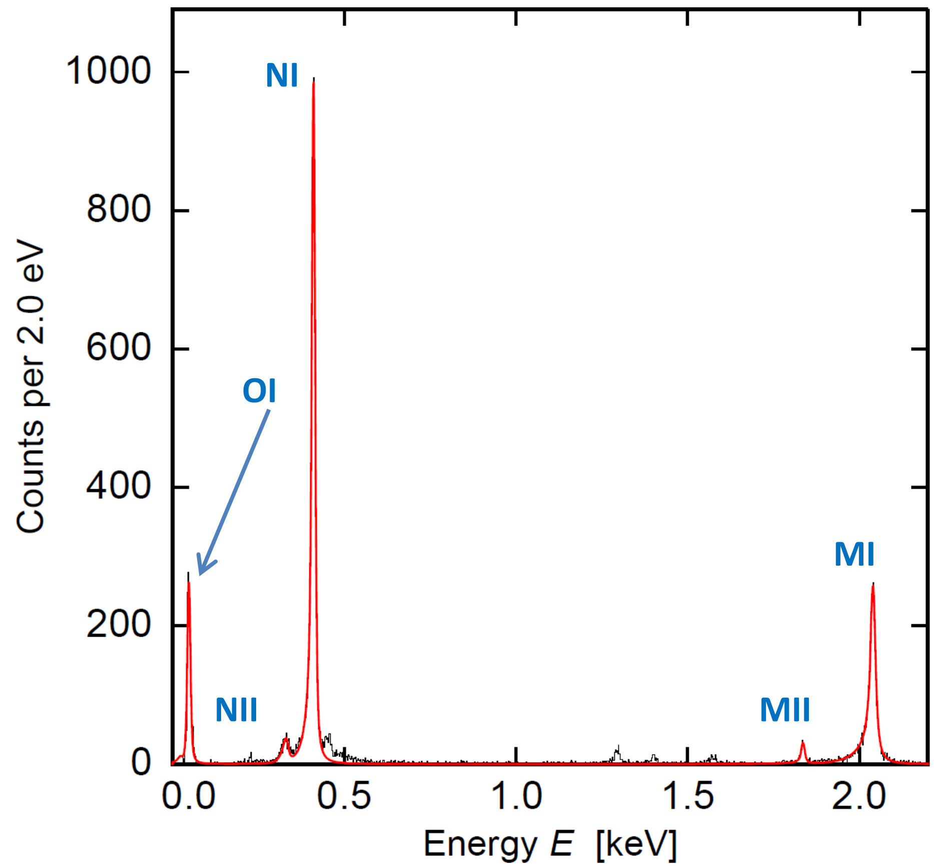
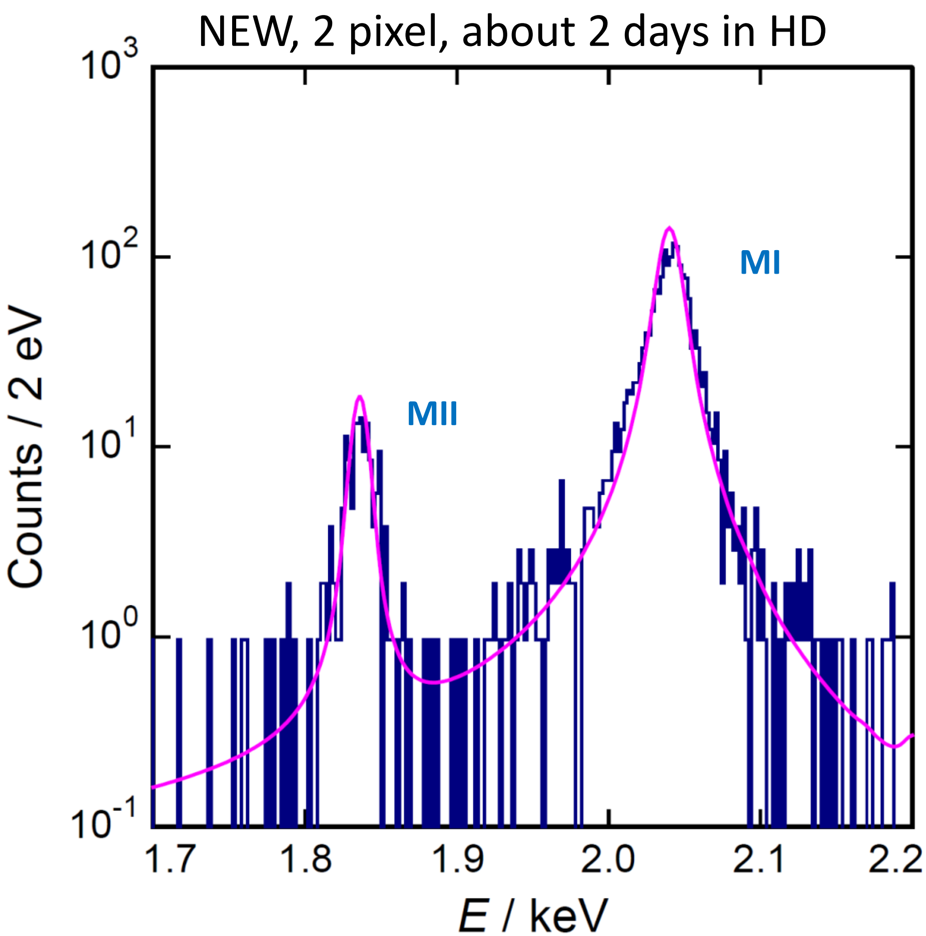


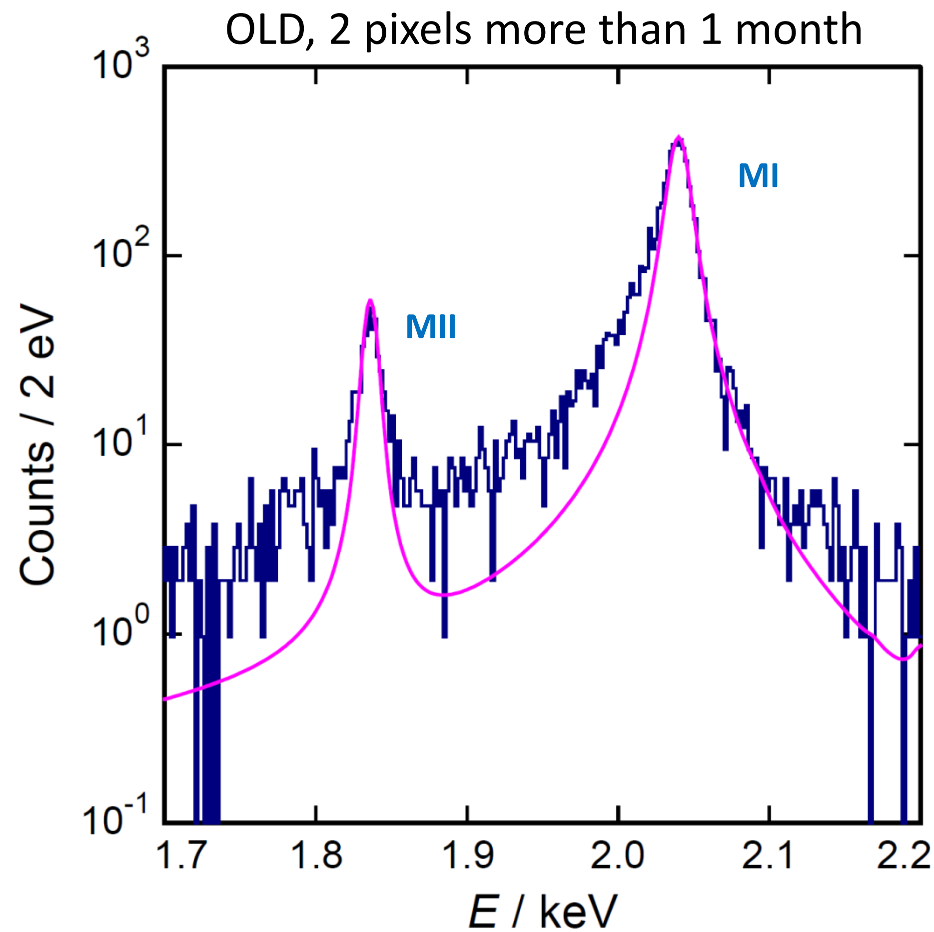
OLD, 2 pixels more than 1 month



- Activity per pixel $A \sim 0.1$ Bq
- Baseline resolution $\Delta E_{FWHM} \sim 5$ eV
- No strong evidence of radioactive contamination in the source

… first results

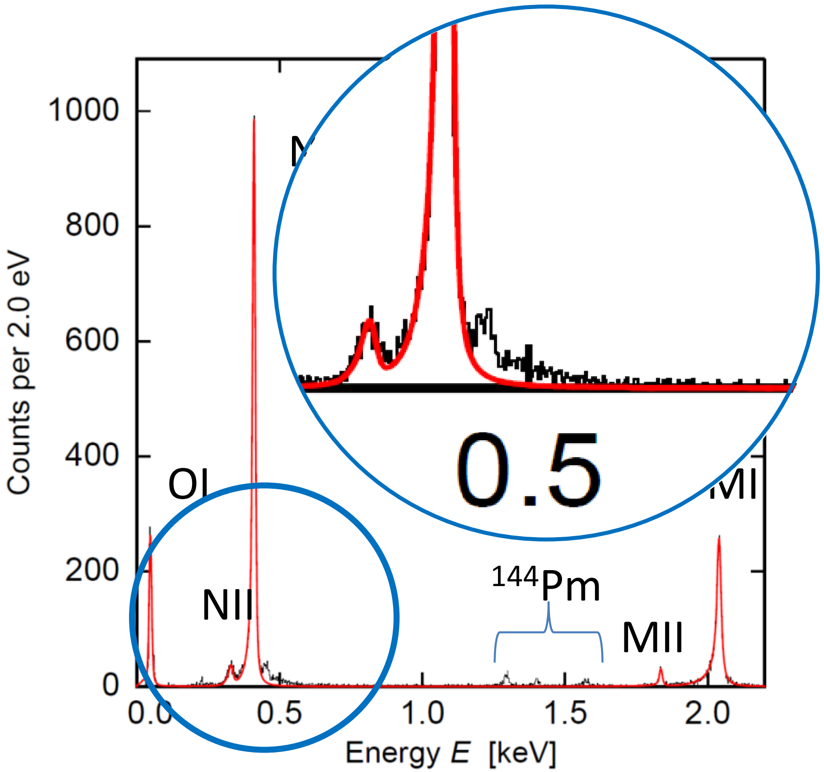




- Activity per pixel — A ~ 0.1 Bq
- Baseline resolution — ΔE_{FWHM} ~ 5 eV
- No strong evidence of radioactive contamination in the source
- Symmetric detector response

C. Hassel et al., submitted to JLTP (2015)

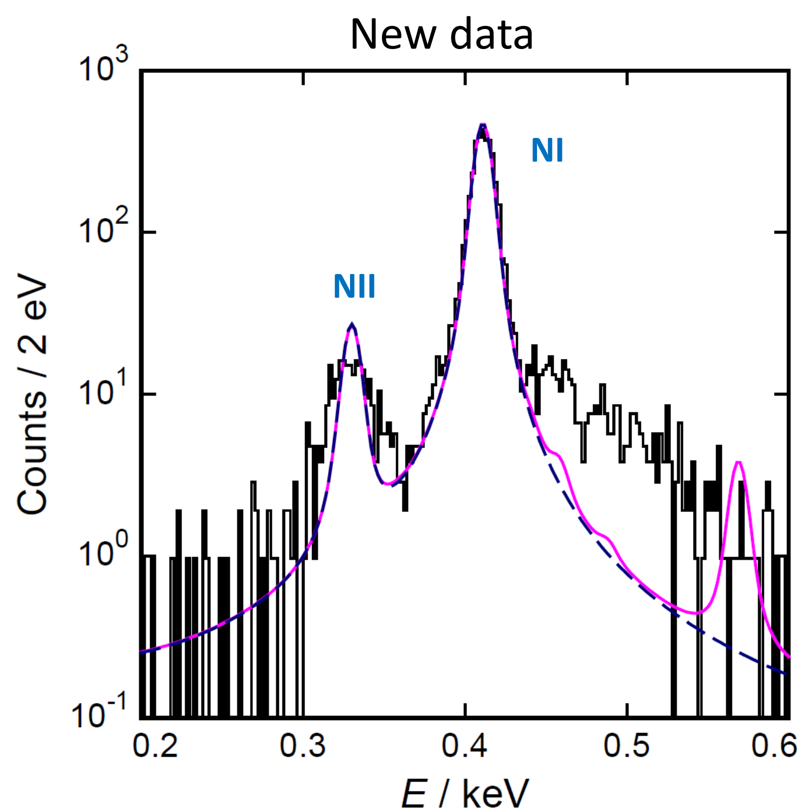
Characterisation of spectral shape



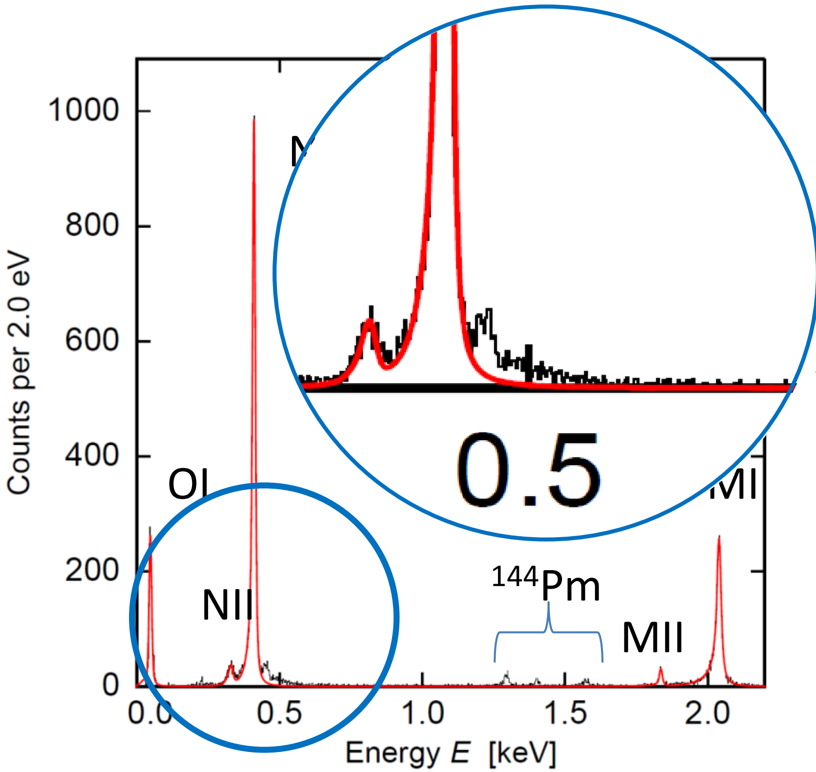
- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- **A. Faessler et al.**
  Phys. Rev. C 91, 045505 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula et al.
  http://arxiv.org/pdf/1510.05462.pdf

Estimate the effect of

- Higher order excitation in ^{163}Dy
- ^{163}Ho ion embedded in Au



Characterisation of spectral shape



Estimate the effect of

- Higher order excitation in ^{163}Dy
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- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 045505 (2015)
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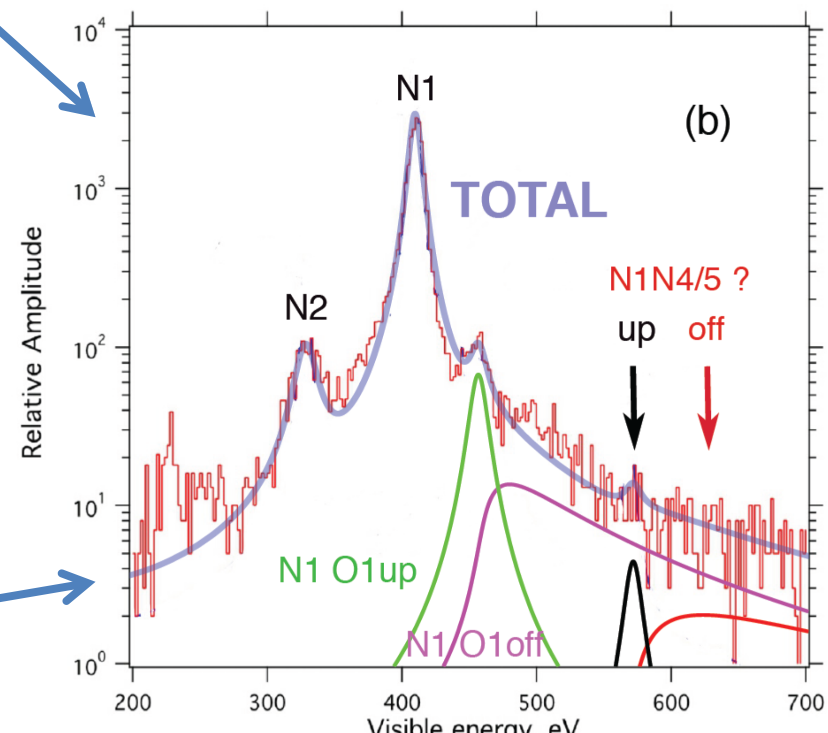
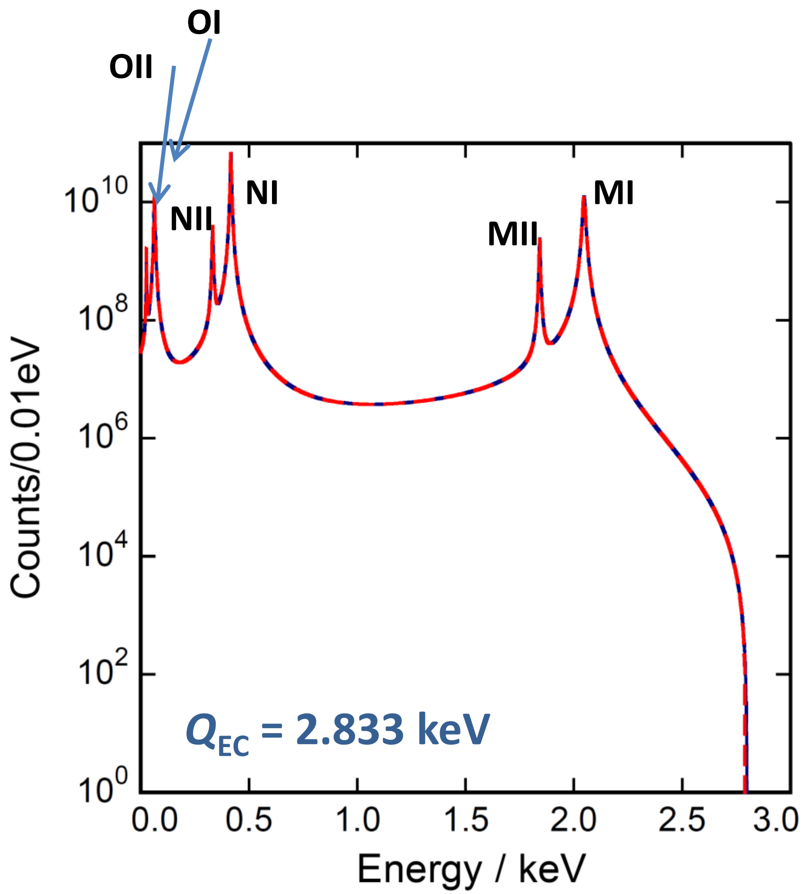


Sterile Neutrino and ^{163}Ho

How does
the existence of sterile neutrino
affect the EC spectrum?

Sterile Neutrino and ^{163}Ho

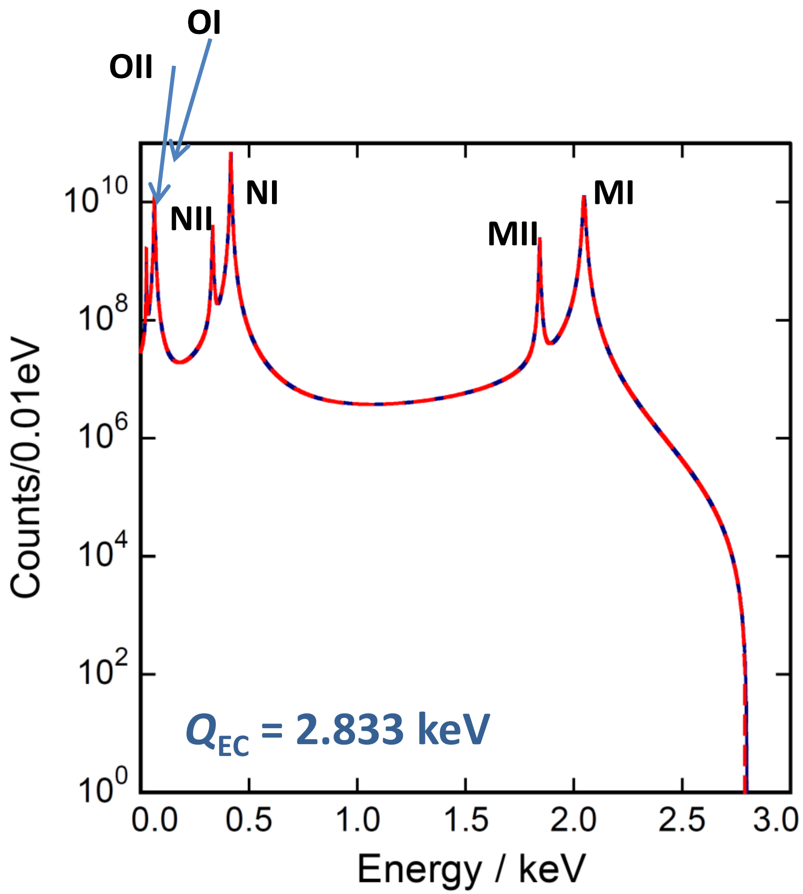
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\,2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\,2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\,2}}{4}}$$



Sterile Neutrino and ^{163}Ho

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

$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$



Sterile Neutrino and ^{163}Ho

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

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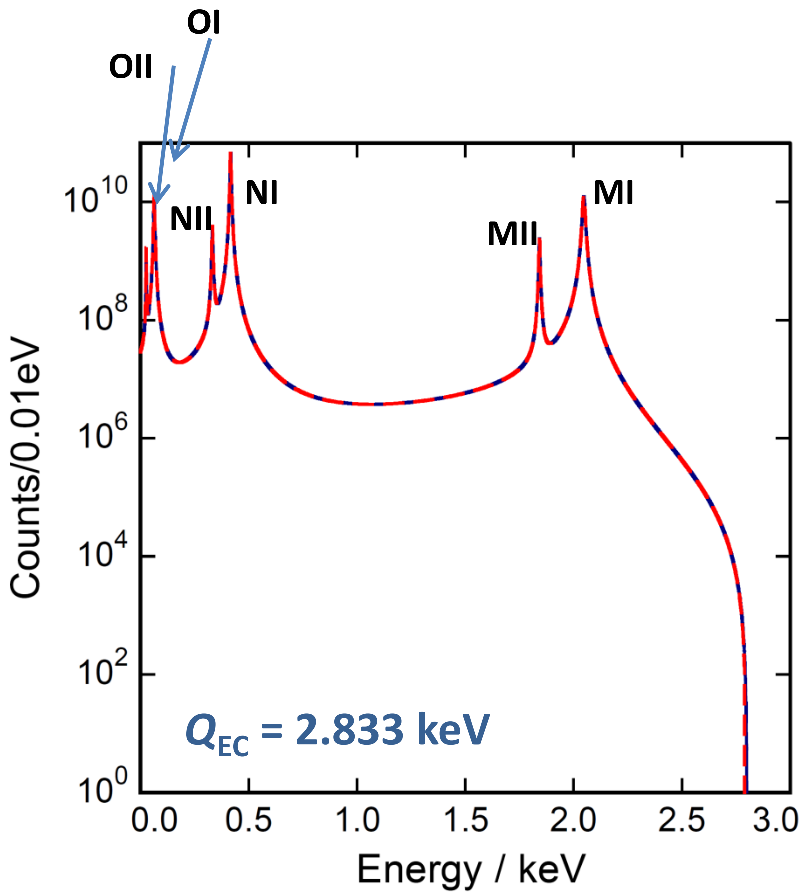


Sterile Neutrino and ^{163}Ho

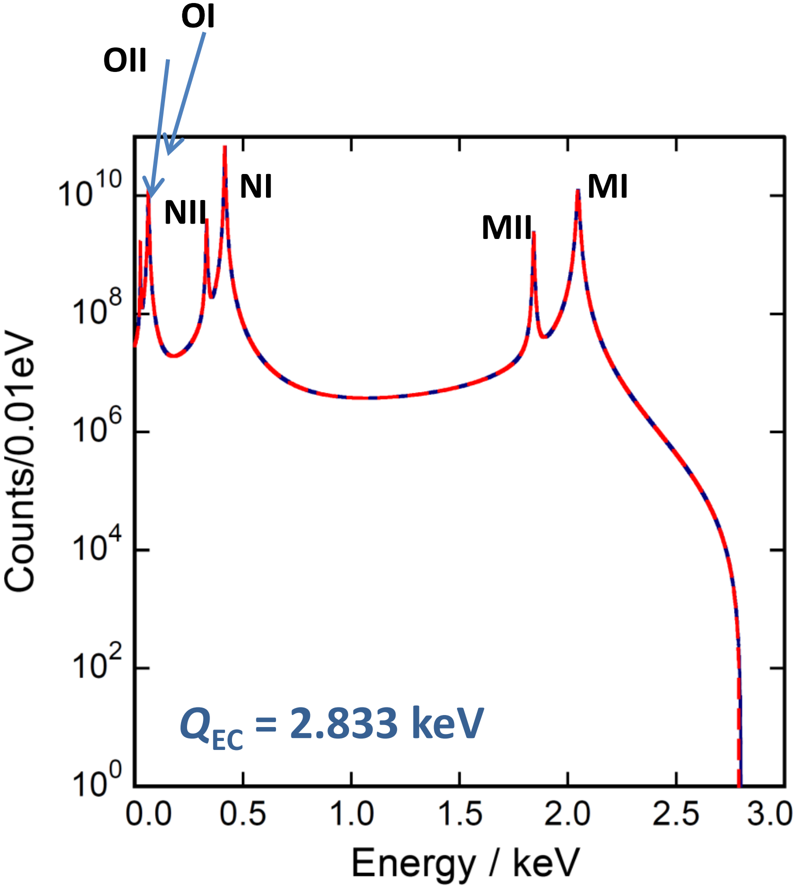
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \left[\left(1 - |U_{e4}|^2\right) + |U_{e4}|^2 \sqrt{1 - \frac{m_4^{\,2}}{(Q_{EC} - E_C)^2}} H(Q_{EC} - E_c - m_4) \right] \sum_H B_H \varphi_H^{\,2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\,2}}{4}}$$

$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$

$$m_{1,2,3} = 0$$

$$m_4 \neq 0$$

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} |\nu_i\rangle + U_{e4} |\nu_4\rangle$$



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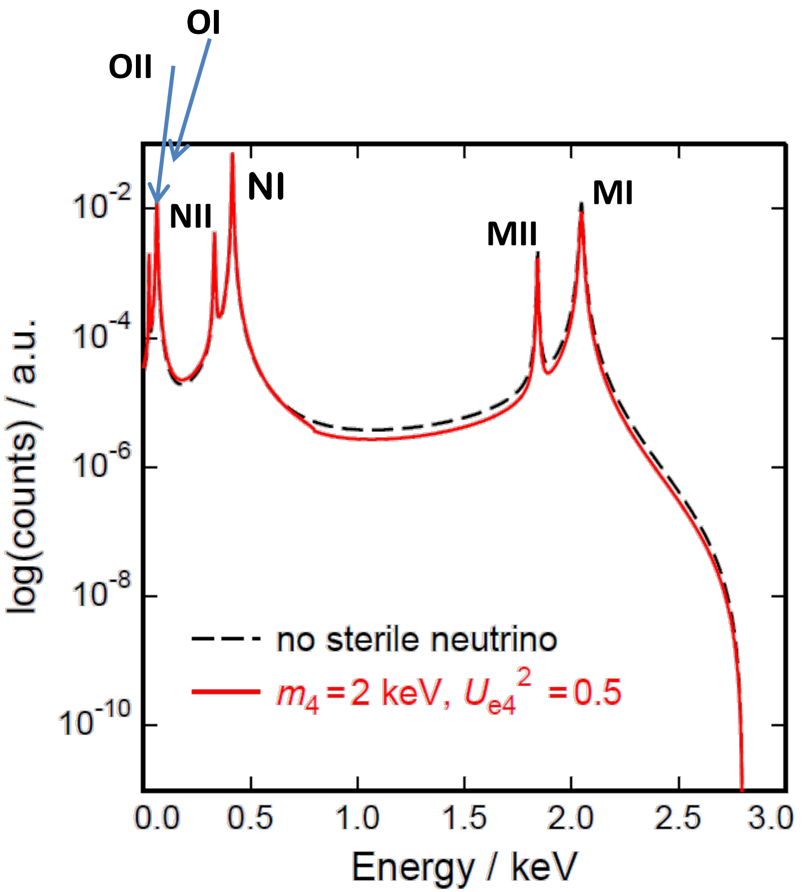
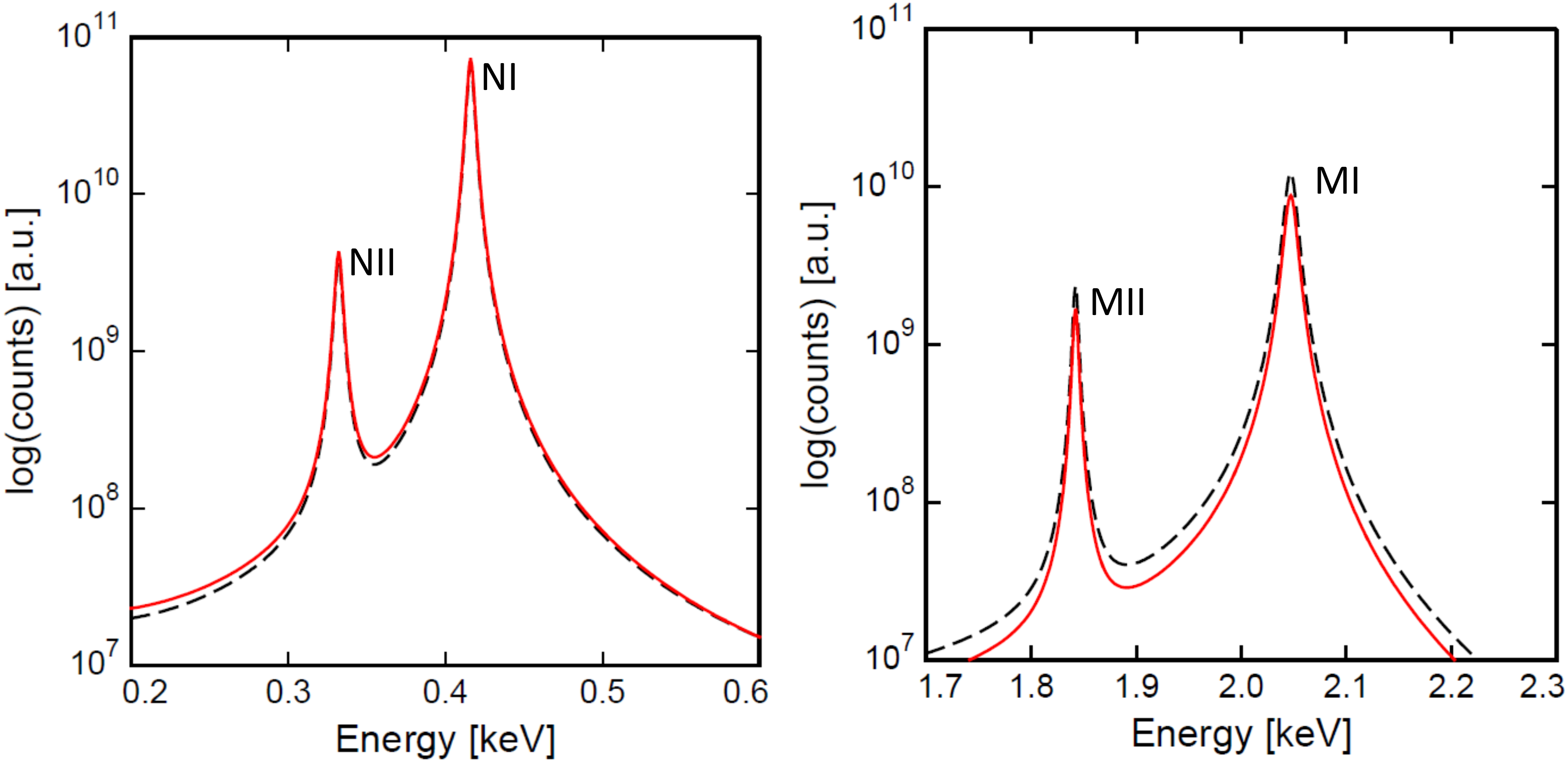


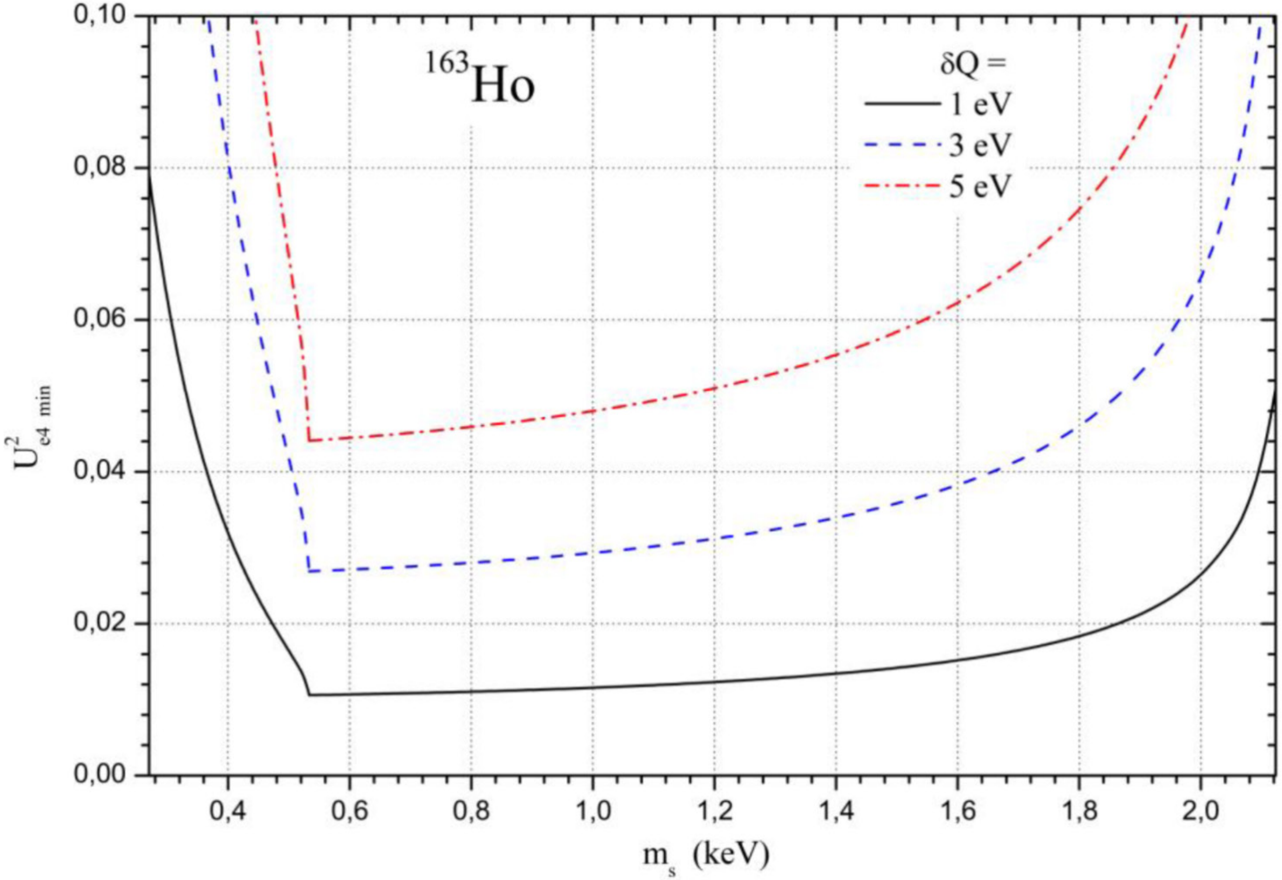
Sterile Neutrino and ^{163}Ho

m_4=2 keV, $U_{e4}{}^2$=0.5

no sterile neutrino



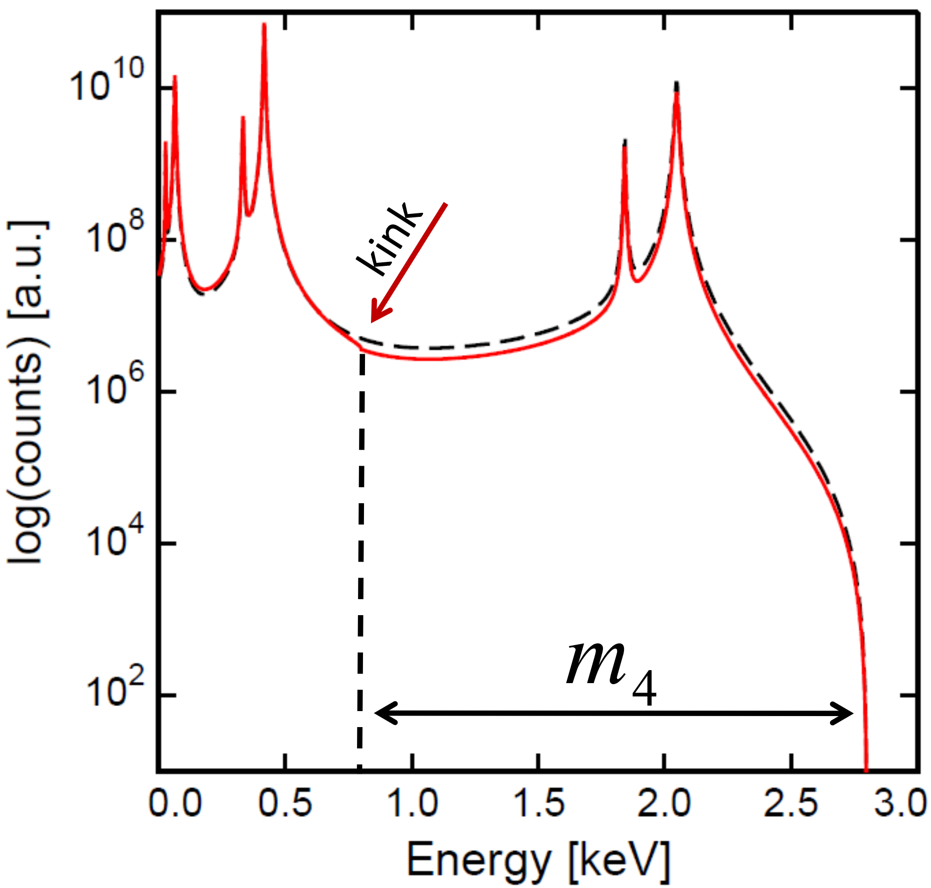
Sterile Neutrino and ^{163}Ho



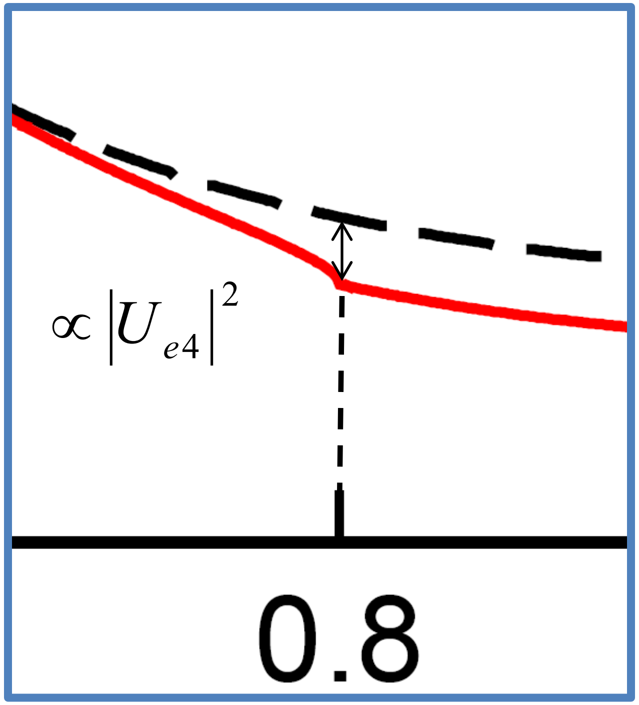
Sensitivity to the mixing matrix element at 90% CL as a function of the sterile neutrino mass achievable with about 10^{10} events in the full EC spectrum.

P. Filianin et al. arXiv: 1402.4400

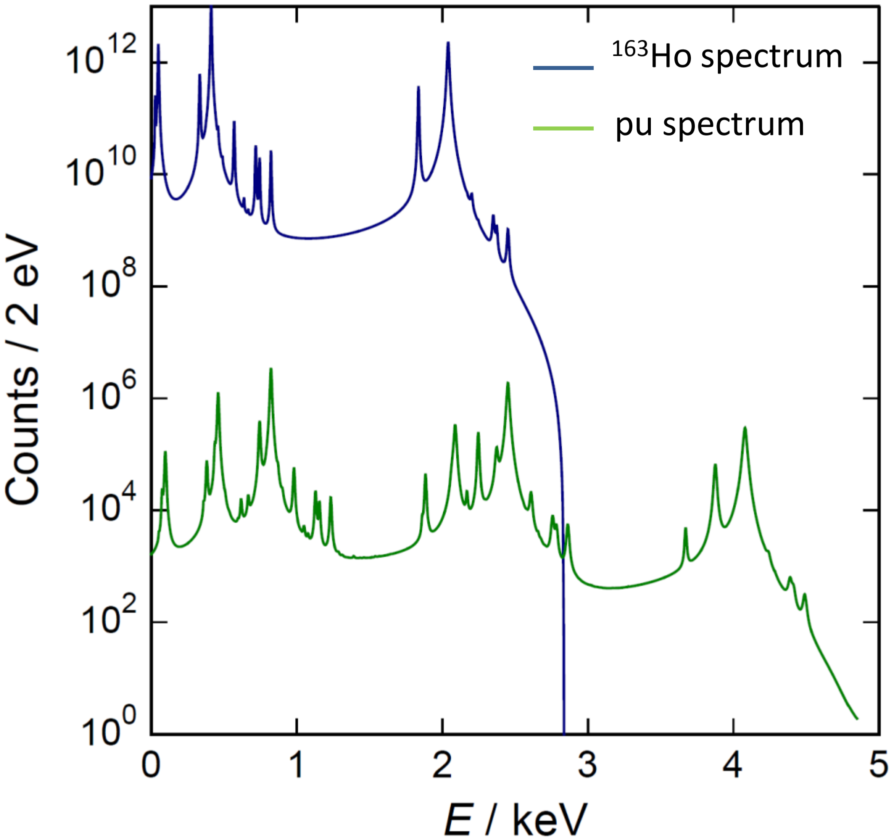
Sterile Neutrino and ^{163}Ho



- postion of kink => m_4
- depth of kink => $|U_{e4}|^2$

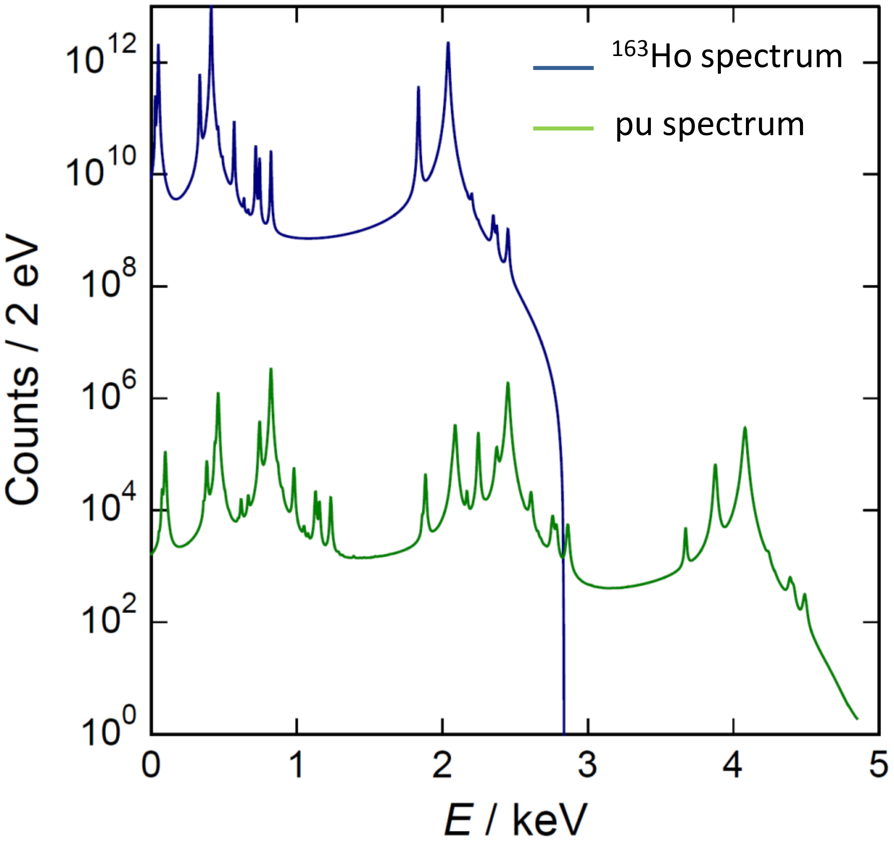


Other small structures on the ^{163}Ho spectrum



Many peaks due to higher order excited states in ^{163}Dy and the corresponding structures in the pile up spectrum

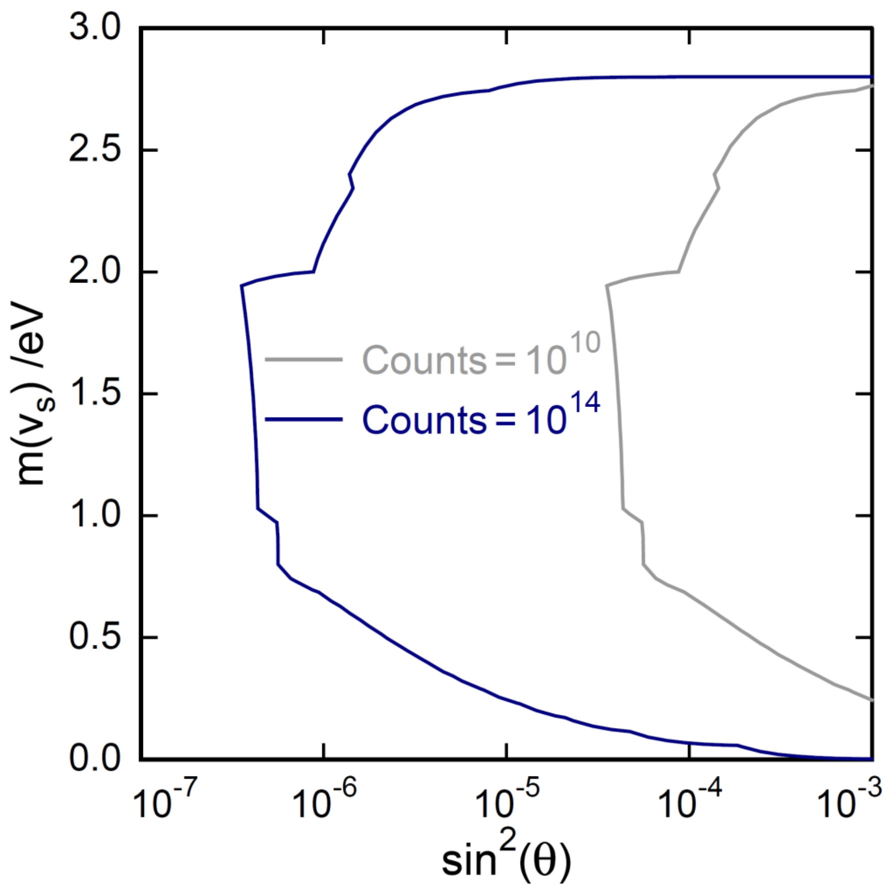
Other small structures on the ^{163}Ho spectrum



Many peaks due to higher order excited states in ^{163}Dy and the corresponding structures in the pile up spectrum

Identification of sterile neutrinos signatures could be limited by the complex structure of the ^{163}Ho spectrum

Sterile Neutrino in ECHo



- **Statistical Fluctuation**
- **No Pile Up**
- **Theoretical Spectrum supposed to be perfectly known**

A White Paper on keV Sterile Neutrino Dark Matter arXiv:1602.04816v1

Sterile Neutrino (keV) and Electron Capture

Other condidates in the EC branch:

- Q_{EC} < 100 keV
- Reasonable halflife

Nuclide	$T_{1/2}$	EC-transition	Q (keV) [22]	B_i (keV) [23]	B_j (keV) [23]	$\lvert\psi_i\rvert^2/\lvert\psi_j\rvert^2$	Q–B_i (keV)
^{123}Te	$>2\cdot10^{15}$ y	?	52.7(16)	K: 30.4912(3)	L_I: 4.9392(3)	7.833	22.2
^{157}Tb	71 y	$3/2^+\rightarrow3/2^-$	60.04(30)	K: 50.2391(5)	L_I: 8.3756(5)	7.124	9.76
^{163}Ho	4570 y	$7/2^-\rightarrow5/2^-$	2.555(16)	M_I: 2.0468(5)	N_I: 0.4163(5)	4.151	0.51
^{179}Ta	1.82 y	$7/2^+\rightarrow9/2^+$	105.6(4)	K: 65.3508(6)	L_I: 11.2707(4)	6.711	40.2
^{193}Pt	50 y	$1/2^-\rightarrow3/2^+$	56.63(30)	L_I: 13.4185(3)	M_I: 3.1737(17)	4.077	43.2
^{202}Pb	52 ky	$0^+\rightarrow2^-$	46(14)	L_I: 15.3467(4)	M_I: 3.7041(4)	4.036	30.7
^{205}Pb	13 My	$5/2^-\rightarrow1/2^+$	50.6(5)	L_I: 15.3467(4)	M_I: 3.7041(4)	4.036	35.3
^{235}Np	396 d	$5/2^+\rightarrow7/2^-$	124.2(9)	K: 115.6061(16)	L_I: 21.7574(3)	5.587	8.6

P. Filianin et al. *J. Phys. G: Nucl. Part. Phys.* **41** (2014) 095004

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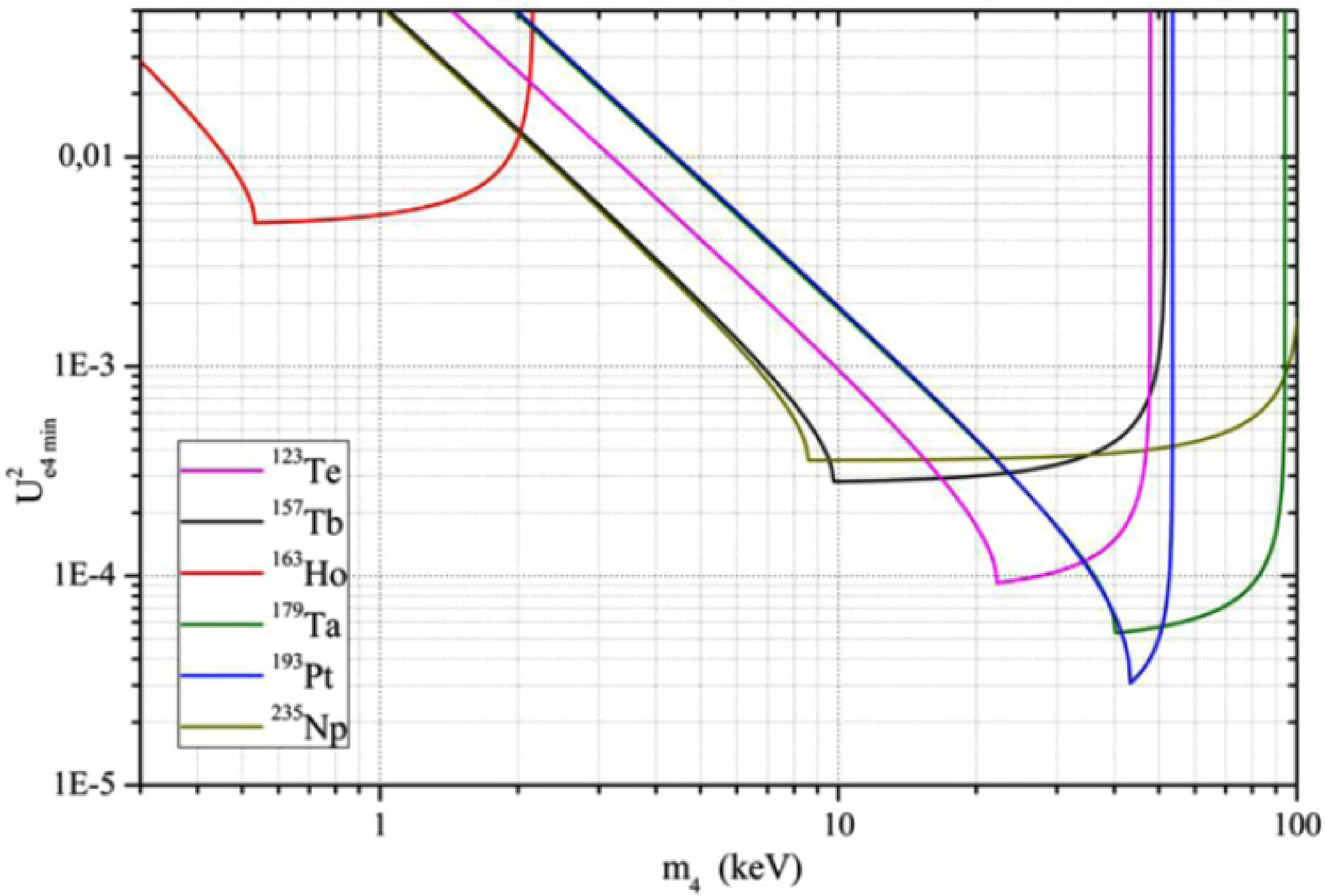


Same statistics + including errors : ($\delta\ \psi_{i,j} = 0$) δQ_{EC} = 1 eV $\delta E_{i,j}$ = 0.1 eV.

P. Filianin et al. *J. Phys. G: Nucl. Part. Phys.* **41** (2014) 095004

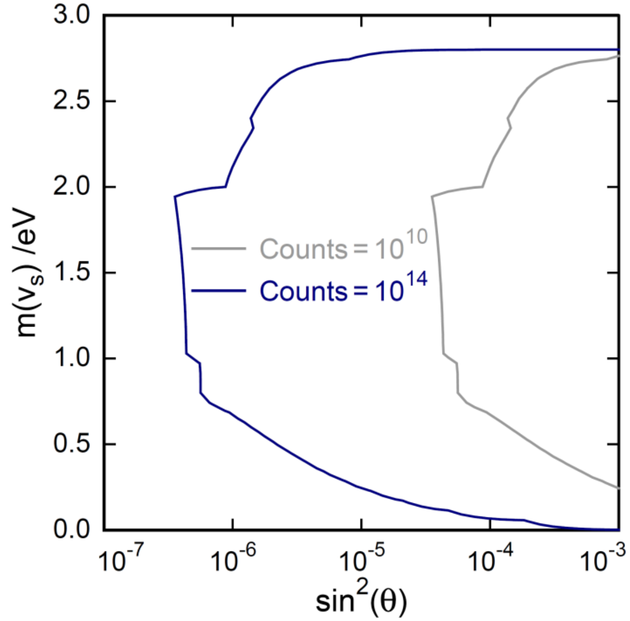
Conclusions and outlook

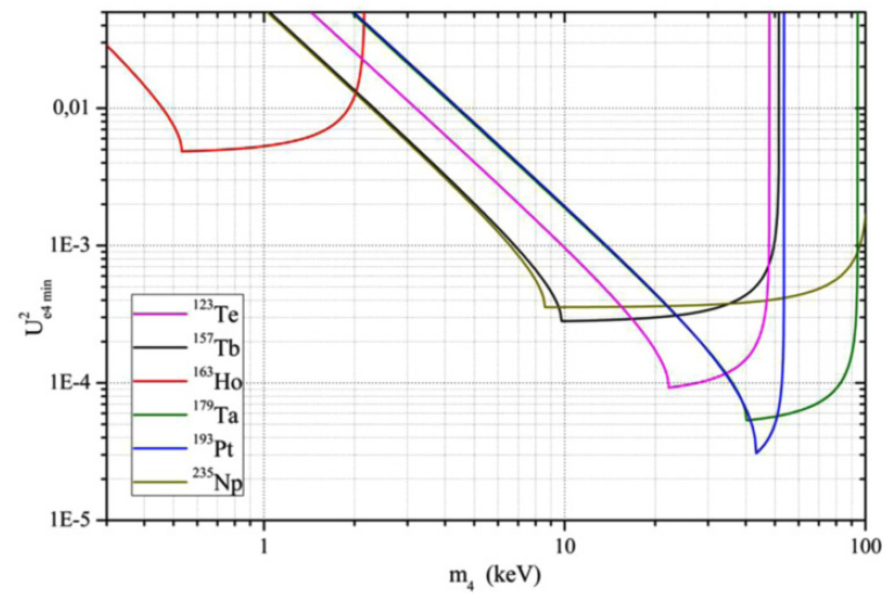
- ECHo is designed to investigate the electron neutrino mass in the sub-eV range:

ECHo-1k:	10^3 Bq	$m(\nu_e)<10$ eV 90% C.L.
ECHo-1M:	10^6 Bq	$m(\nu_e)<1$ eV 90% C.L.

- Possibility to investigate the existence of keV sterile neutrinos:
  - Limited mass range
  - presence of resonances complicate the analysis

- Other EC candidates could open larger mass range to be tested





Thank you!

Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
Fedor Simkovic
Department of Physics, Indian Institute of Technology Roorkee, India
Moumita Maiti
Goethe Universität Frankfurt am Main
Udo Kebschull, Panagiotis Neroutsos
Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz
Christoph E. Düllmann, Klaus Eberhardt, Holger Dorrer, Fabian Schneider
Institute of Nuclear Research of the Hungarian Academy of Sciences
Zoltán Szúcs
Institute of Nuclear and Particle Physics, TU Dresden, Germany
Kai Zuber
Institute for Physics, Humboldt-Universität zu Berlin
Alejandro Saenz
Institute for Physics, Johannes Gutenberg-Universität
Klaus Wendt, Sven Junck, Tom Kieck
Institute for Theoretical Physics, University of Tübingen, Germany
Amand Fäßler
Institut Laue-Langevin, Grenoble, France
Ulli Köster
ISOLDE-CERN
Marsh Bruce, Day Goodacre Tom, Johnston Karl, Rothe Sebastian,
Stora Thierry, Veinhard Matthieu
Kirchhoff-Institute for Physics, Heidelberg University, Germany
Christian Enss, Loredana Gastaldo, Andreas Fleischmann,
Clemens Hassel, Sebastian Kempf, Mathias Wegner
Max-Planck Institute for Nuclear Physics Heidelberg, Germany
Klaus Blaum, Andreas Dörr, Sergey Eliseev, Mikhail Goncharov,
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Petersburg Nuclear Physics Institute, Russia
Yuri Novikov, Pavel Filianin
Physics Institute, University of Tübingen, Germany
Josef Jochum, Stephan Scholl
Saha Institute of Nuclear Physics, Kolkata, India
Susanta Lahiri

Sterile Neutrino and ^{163}Ho

- Amplitude of the line H for only active neutrinos

$$W_{Ha} = A\left(Q_{\mathrm{EC}} - E_{\mathrm{H}}\right)^2 B_H \varphi_{\mathrm{H}}^{\ 2}(0)$$

- Amplitude of the line H for 3+1 model in case of m_a = 0 eV

$$W_{Hs} = A\left(Q_{\mathrm{EC}} - E_{\mathrm{H}}\right)^2 \left[\left(1 - \left|U_{e4}\right|^2\right) + \left|U_{e4}\right|^2 \sqrt{1 - \frac{m_4^{\ 2}}{\left(Q_{\mathrm{EC}} - E_{\mathrm{C}}\right)^2}} H\left(Q_{EC} - E_c - m_4\right)\right] B_H \varphi_{\mathrm{H}}^{\ 2}(0)$$

- Ratio between amplitudes of two lines in the spectrum for 3+1 model in case of m_a = 0 eV

$$\left(\frac{W_{H1}}{W_{H2}}\right)_s = \left(\frac{W_{H1}}{W_{H2}}\right)_a \frac{\left|U_{e4}\right|^2 \left[H\left(Q_{EC} - E_1 - m_4\right)\sqrt{1 - \frac{m_4^{\ 2}}{\left(Q_{\mathrm{EC}} - E_1\right)^2}} - 1\right] + 1}{\left|U_{e4}\right|^2 \left[H\left(Q_{EC} - E_2 - m_4\right)\sqrt{1 - \frac{m_4^{\ 2}}{\left(Q_{\mathrm{EC}} - E_2\right)^2}} - 1\right] + 1}$$

Sterile neutrino effect on ^{163}Ho spectrum