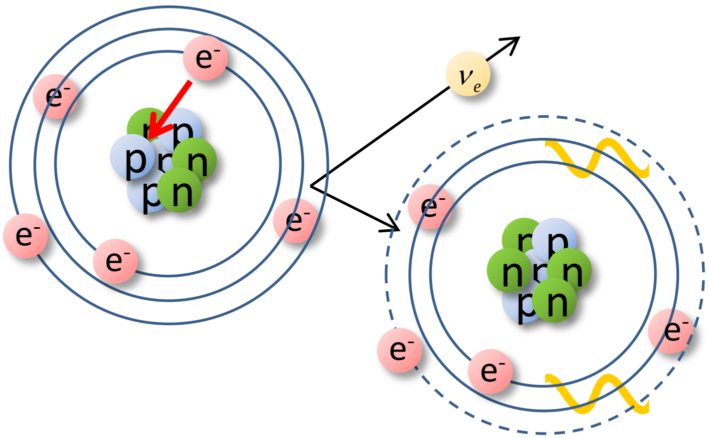
The Status of the ECHo experiment for investigation of keV sterile neutrinos

CLEMENS HASSEL

for the ECHo-Collaboration

ECHo

^{163}Ho and neutrino mass



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

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

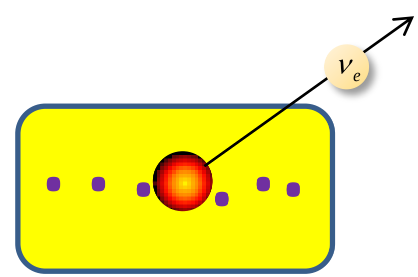
- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = (2.555 $\pm$ 0.016) keV *

*M. Wang, G. Audi et al., *Chinese Phys. C* **36**, 1603, (2012)

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

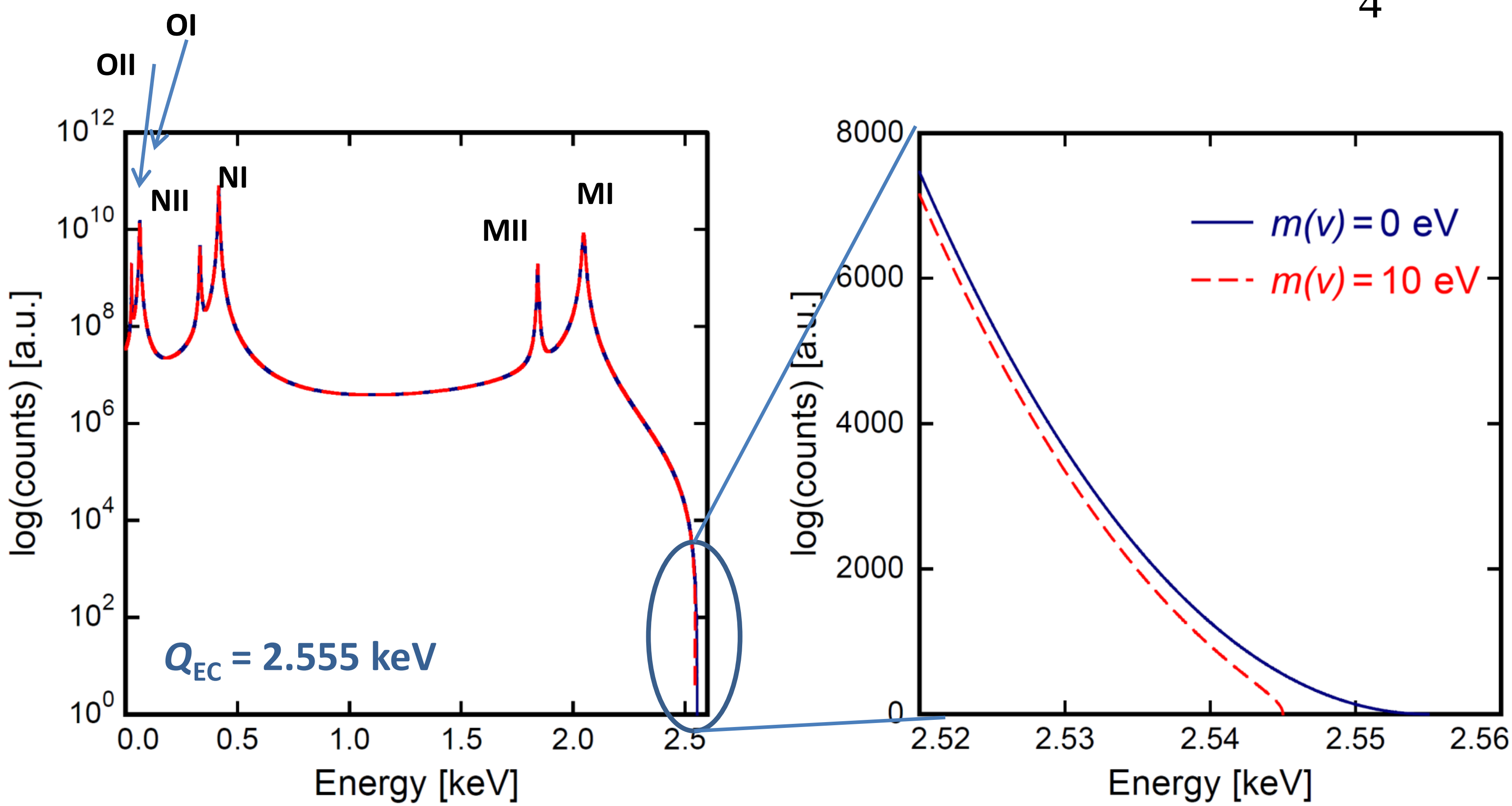
Atomic de-excitation:
- X-ray emission
- Auger electrons
- Coster-Kronig transitions

} Calorimetric measurement



^{163}Ho and neutrino mass

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



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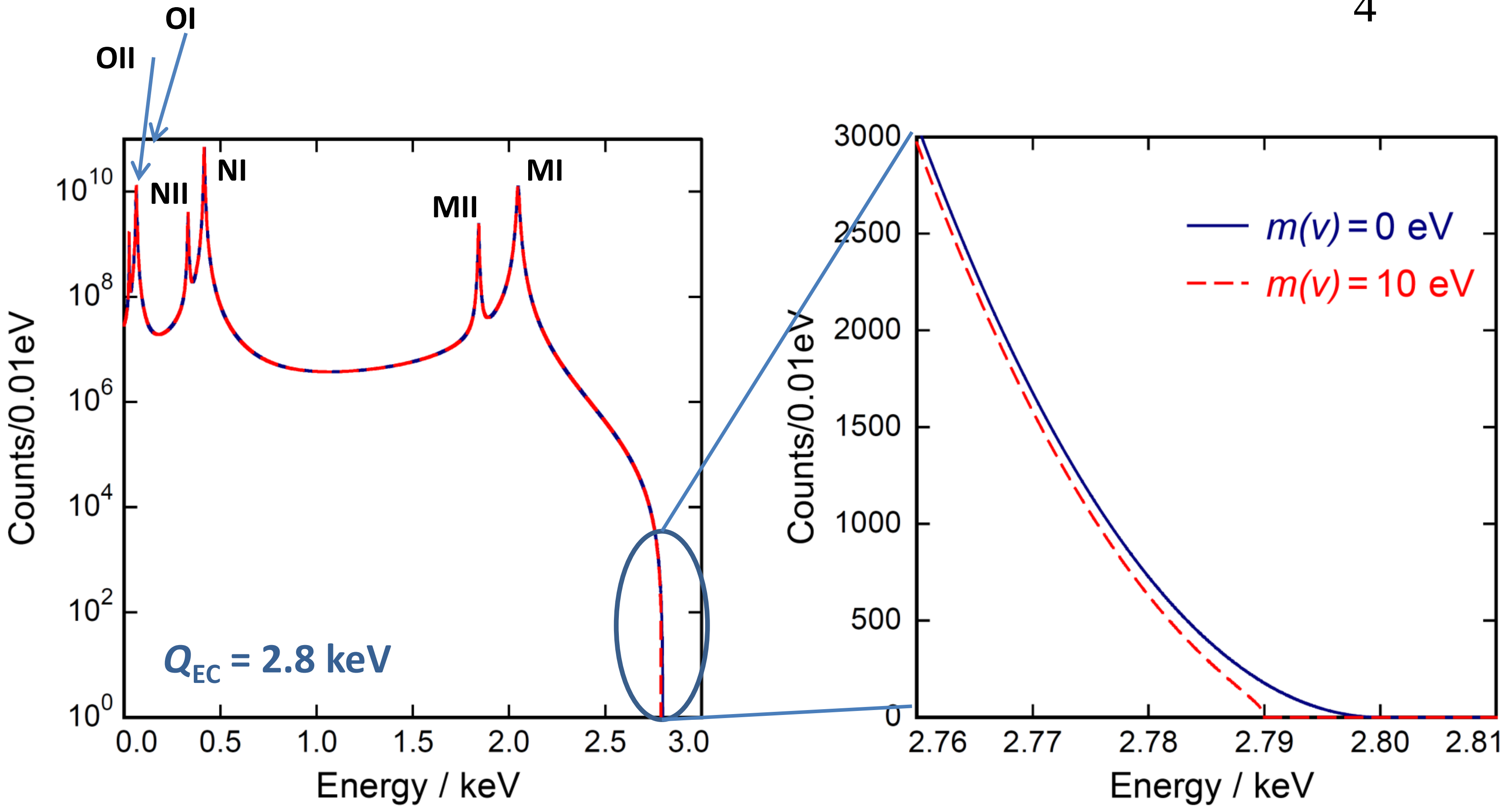
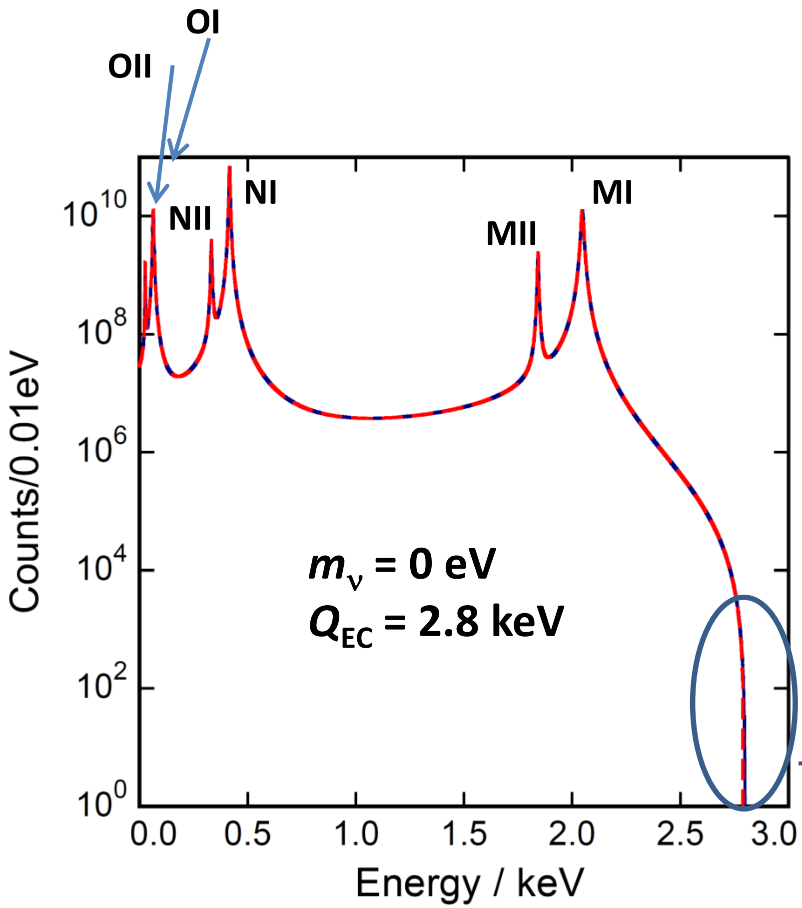
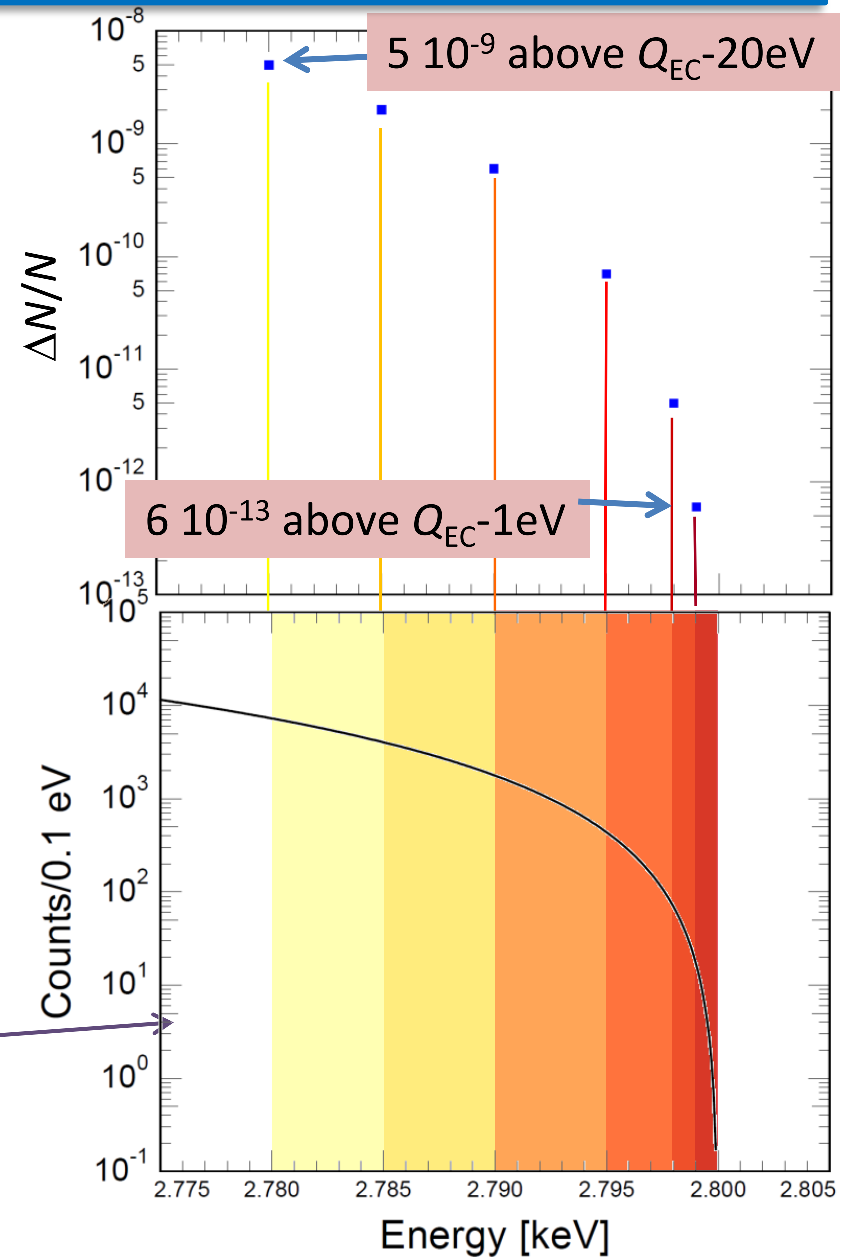


^{163}Ho and neutrino mass: sub-eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → $A \approx 1$ MBq





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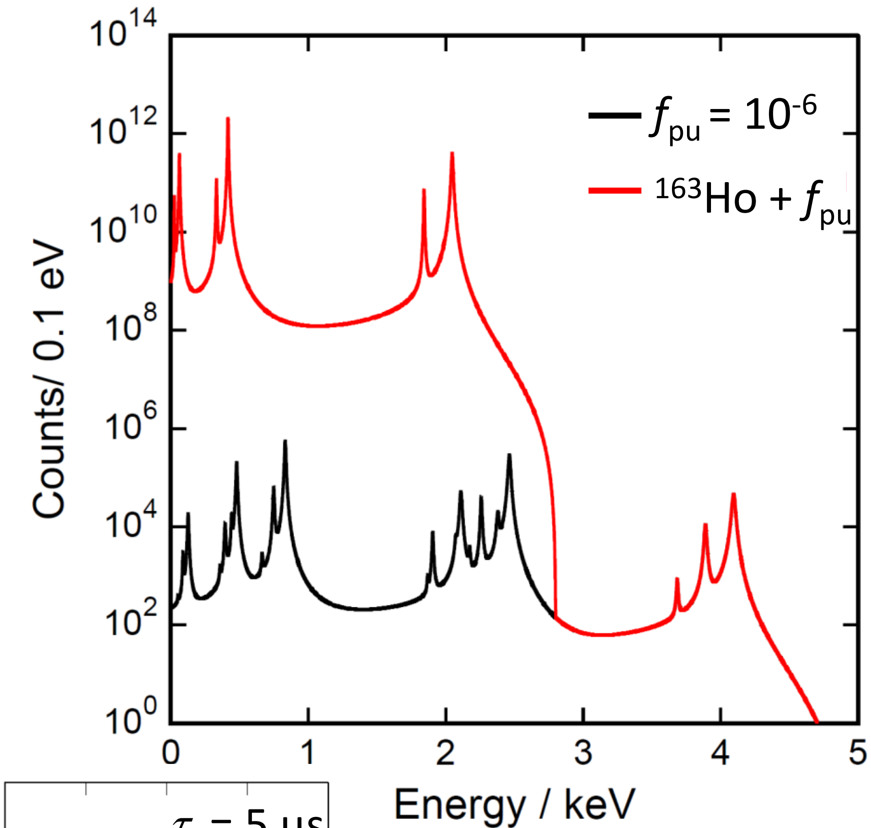
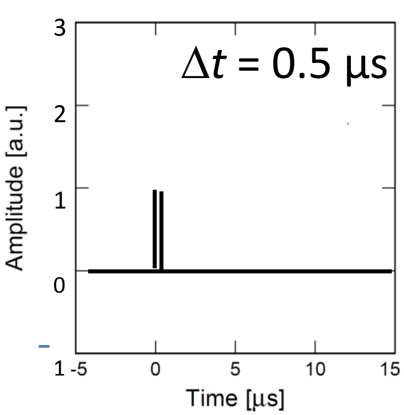
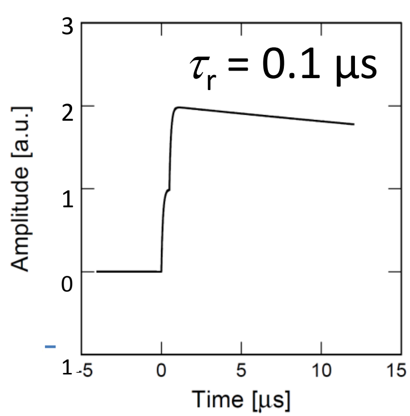
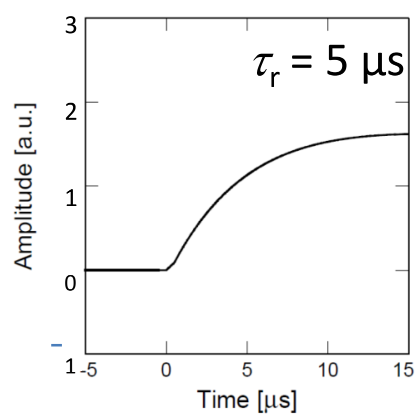
Unresolved pile-up ($f_{pu} \approx a \cdot \tau_r$)

- $f_{pu} < 10^{-5}$
- τ_r < 1 µs → a ≈ 10 Bq









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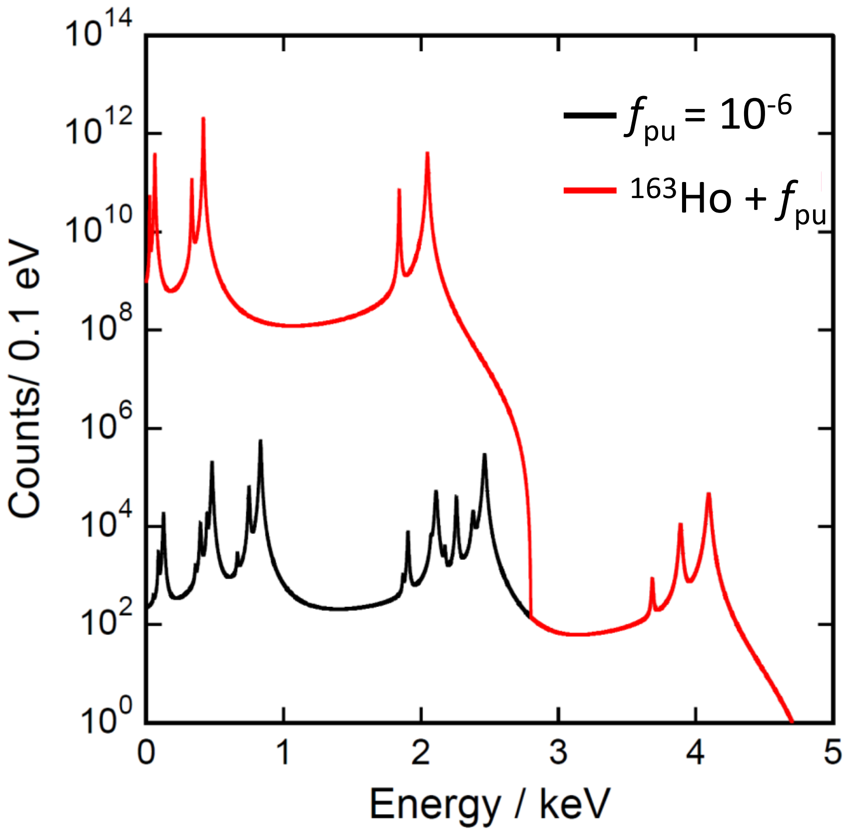
- **10^5 pixels**



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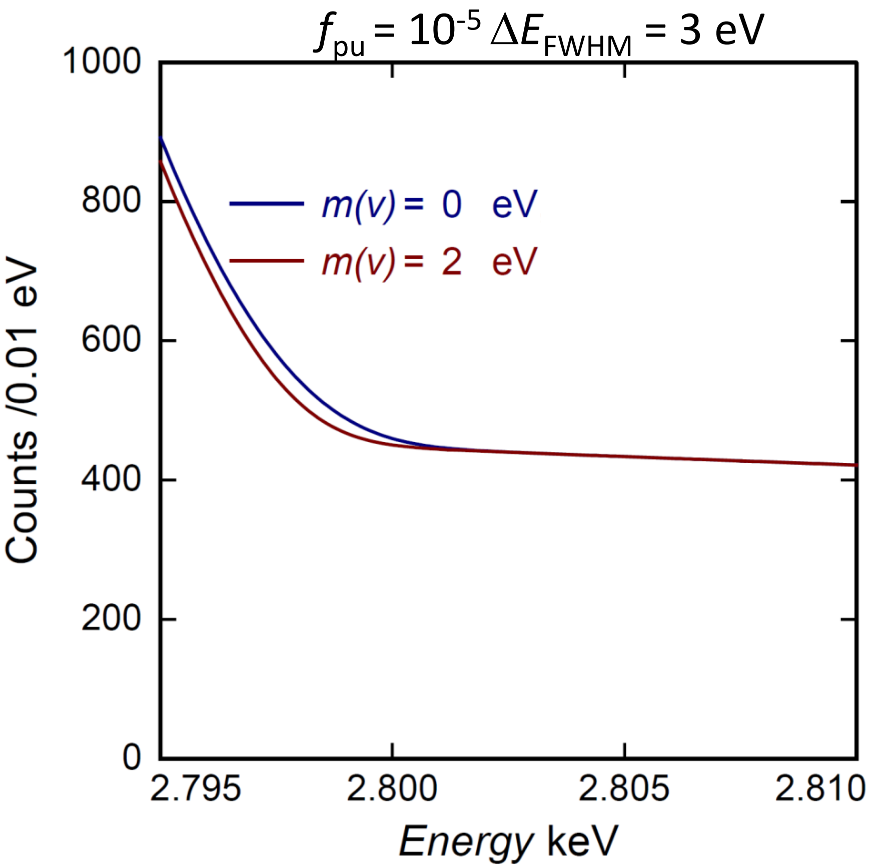
Precision characterization of the endpoint region

- $\Delta E_{FWHM} < 2$ eV



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Precision characterization of the endpoint region

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Metallic Magnetic Calorimeters
and
Microwave multiplexing
fullfil all the requirements

^{163}Ho and neutrino mass: sub-eV sensitivity

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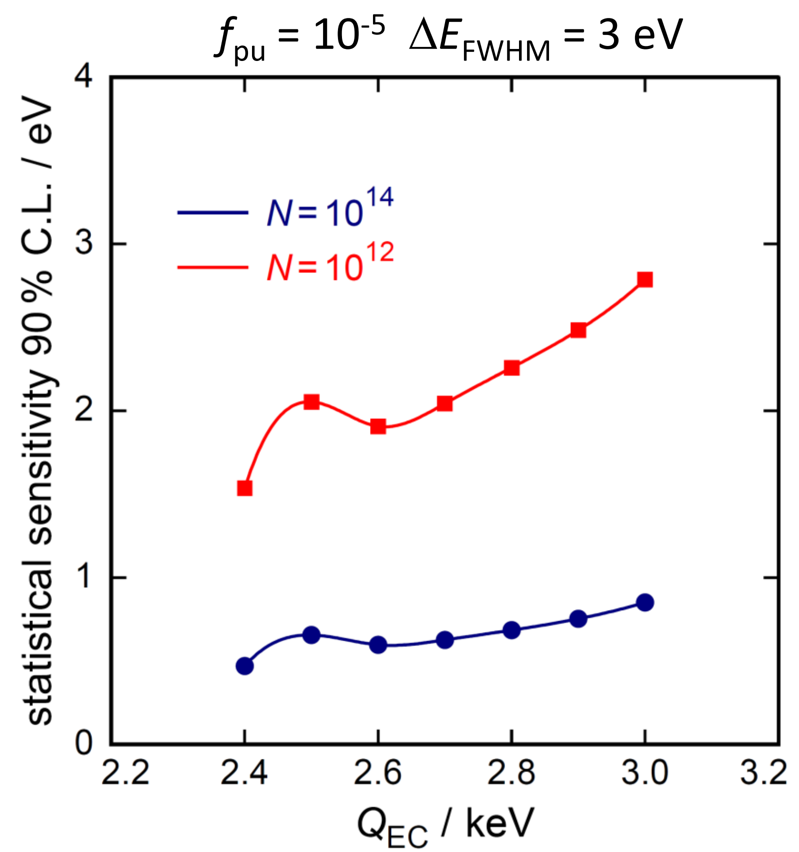


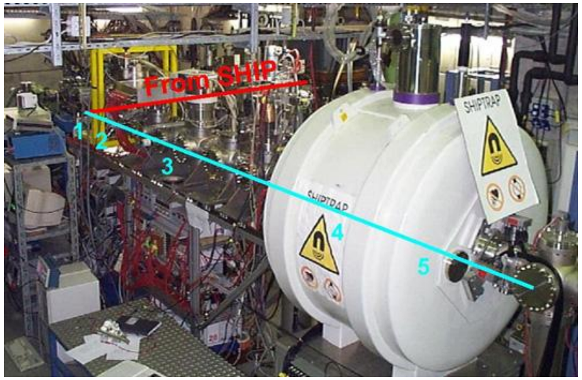
Q_{EC} determination of ^{163}Ho

Penning Trap mass spectrometry

- First experiments at TRIGA-TRAP (Uni-Mainz) in 2014 *
  - Development of efficient Ho ion source using laser ablation
  - Uncertainties on ^{163}Dy and ^{163}Ho mass reduced by a factor of 2
  - Know-how to be applied in SHIPTRAP

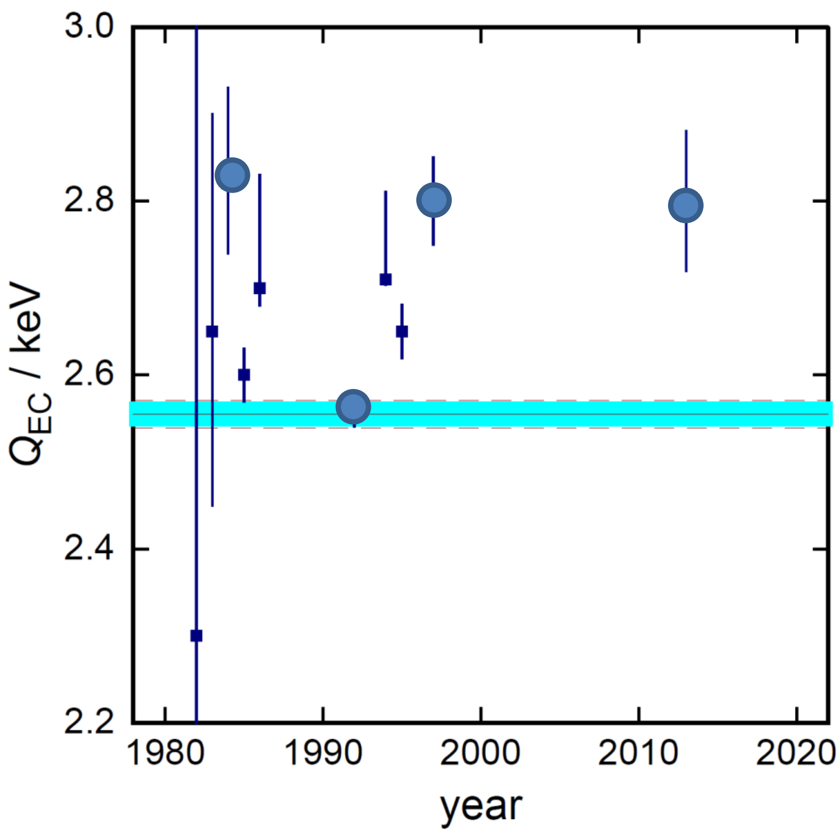
*Preparatory studies for a high-precision Penning trap measurement of the ^{163}Ho electron capture Q-value
F. Schneider et al., submitted to EPJ

- Presently: SHIPTRAP (GSI) **
  - Q_{EC} determination with smaller uncertainties
  - Define scale of the experiment



** Direct measurement of the mass difference of ^{163}Ho and ^{163}Dy as prerequisite to a determination of the electron neutrino mass
S. Eliseev et al., submitted to PRL

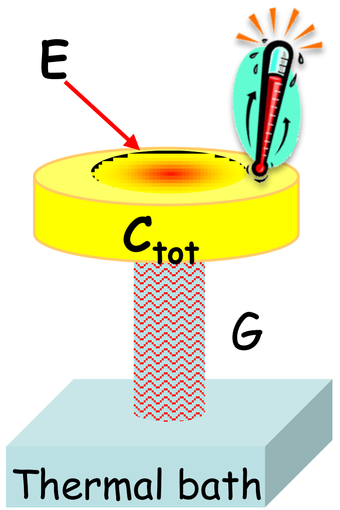
Q_{EC} determination of ^{163}Ho



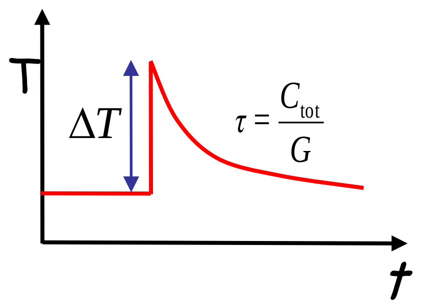
- Calorimetric measurements
- Other methods

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

Low temperature micro-calorimeters



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



E = 10 keV

C_{tot} = 1 pJ/K

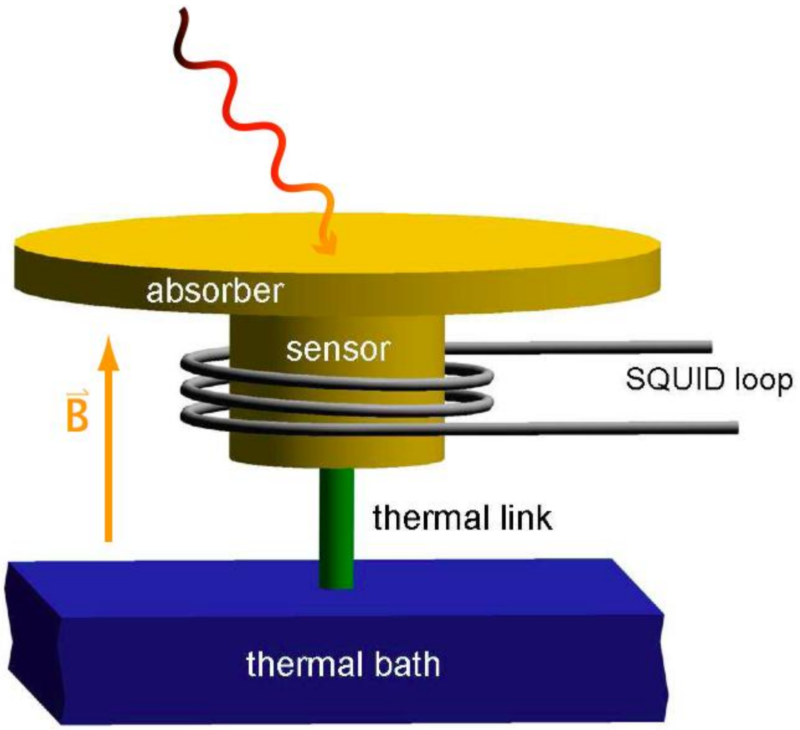
→ ~ 1 mK

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

Metallic Magnetic Calorimeters - MMC

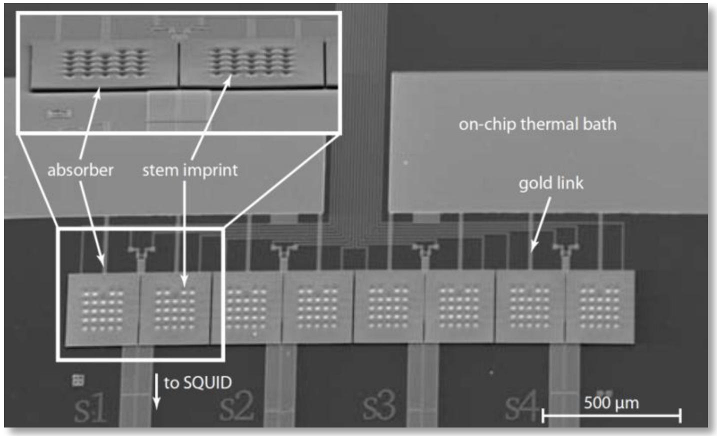
A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

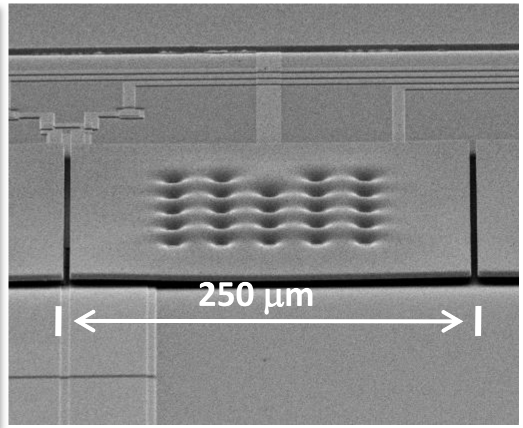
- Paramagnetic sensor: Au:Er



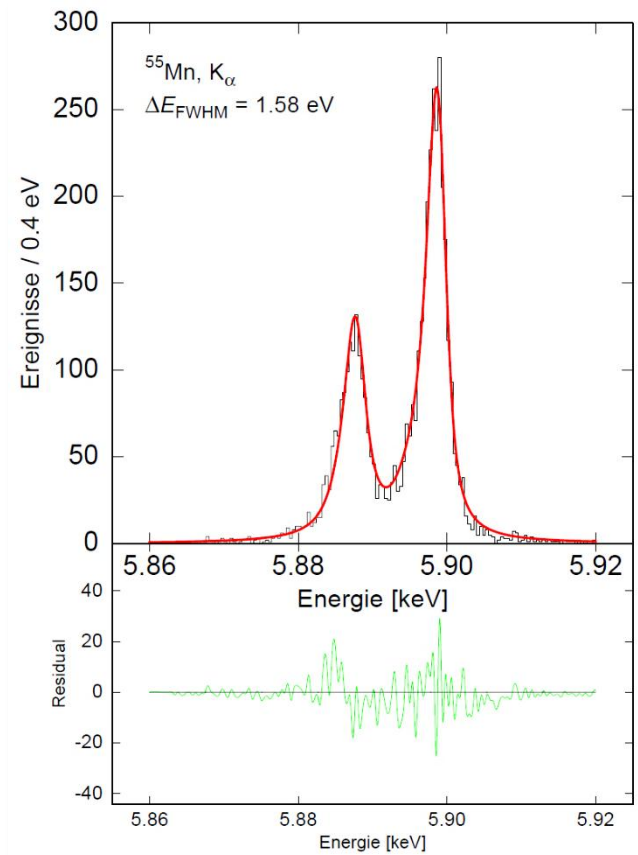
$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

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

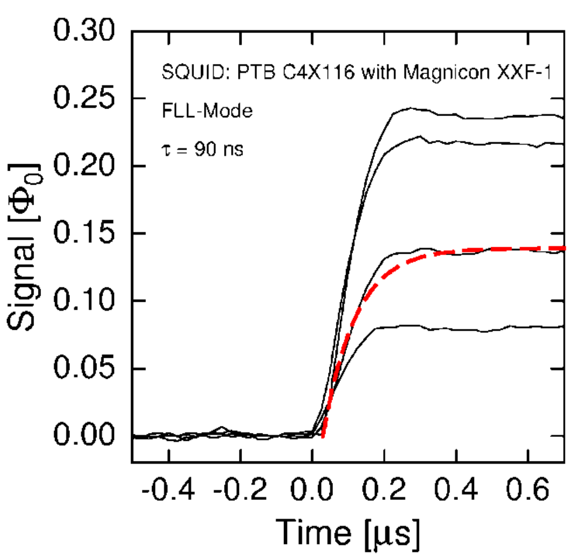




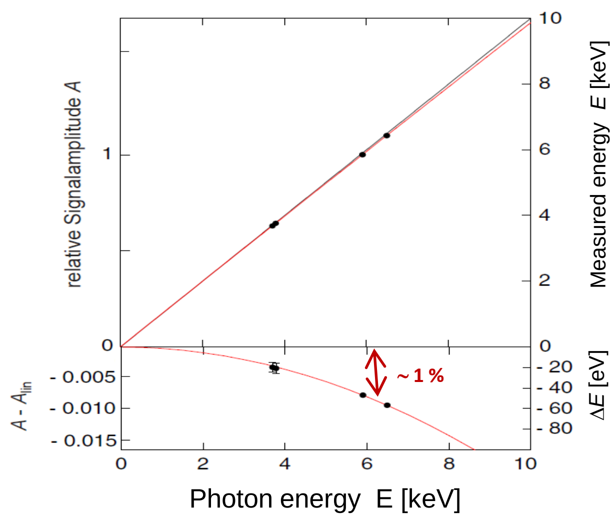
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



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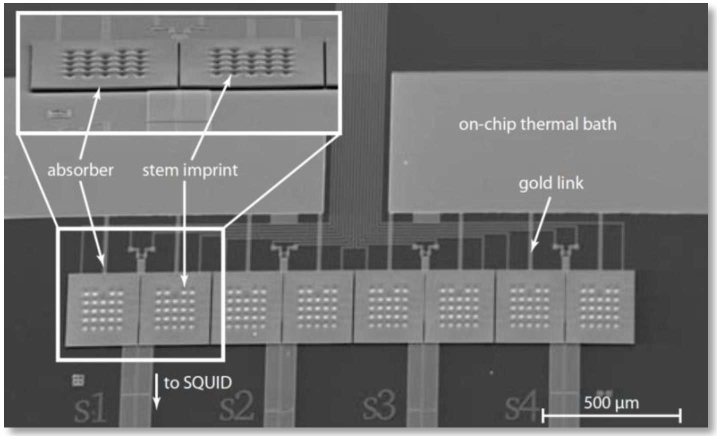

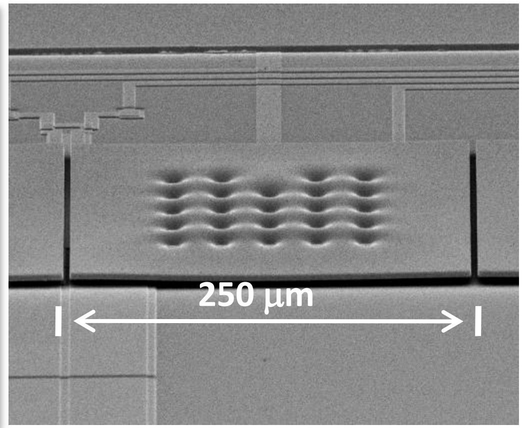

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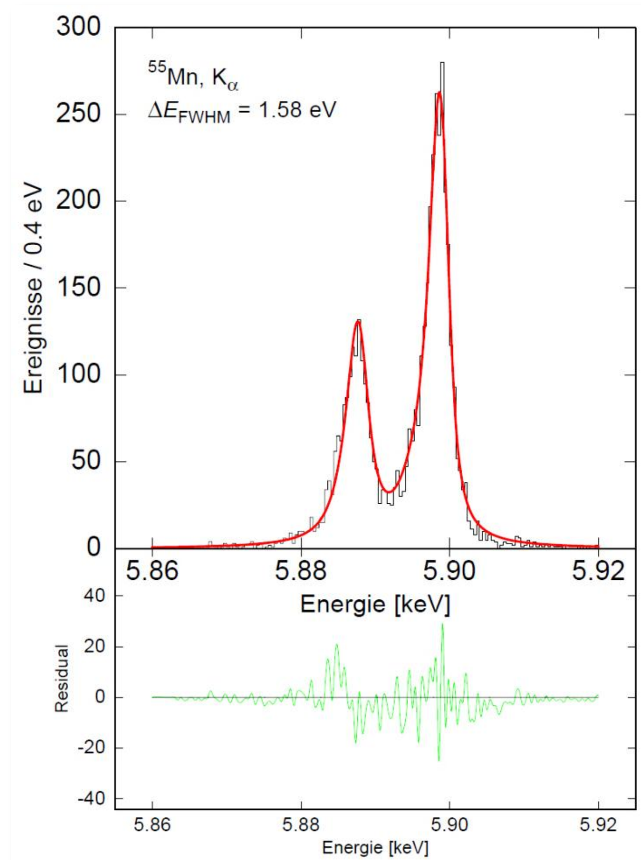

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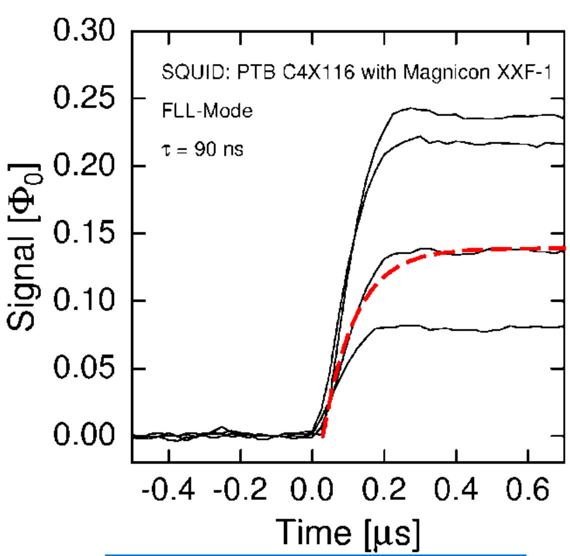

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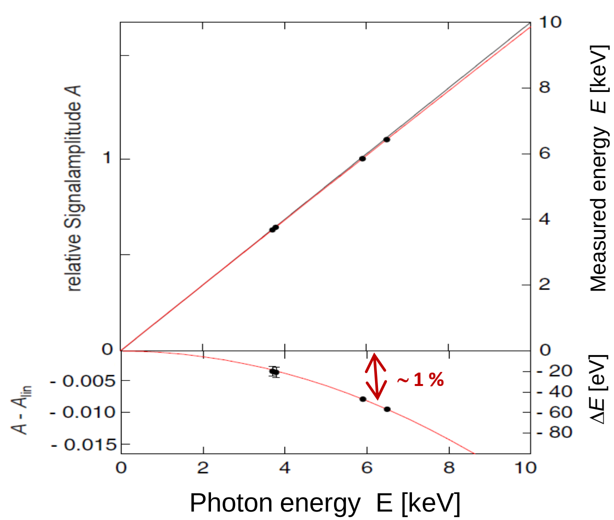

Reduction un-resolved pile-up

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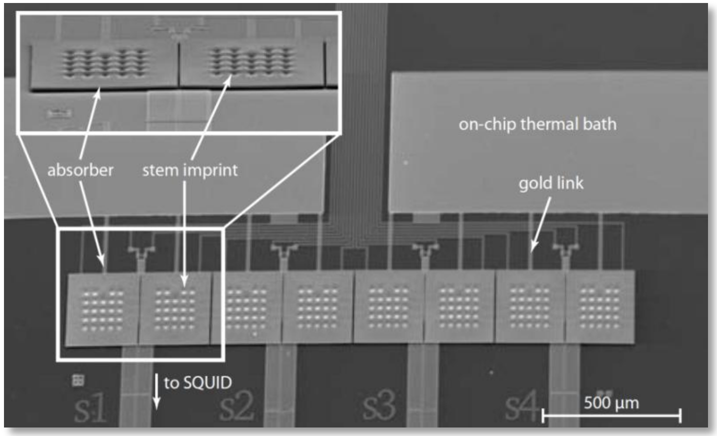

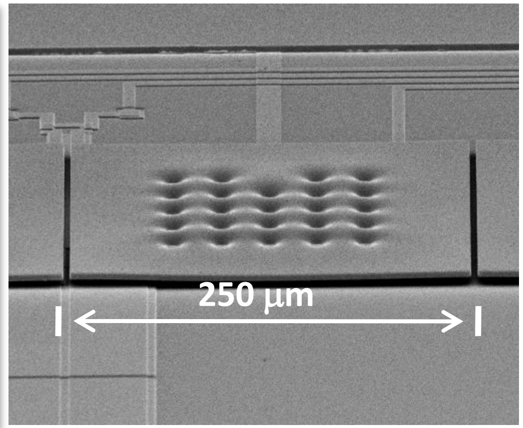

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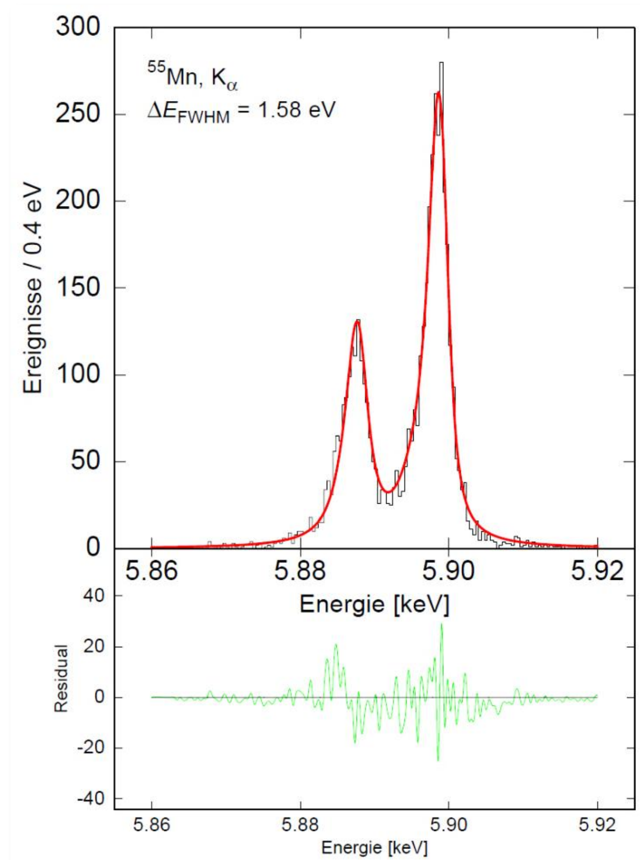

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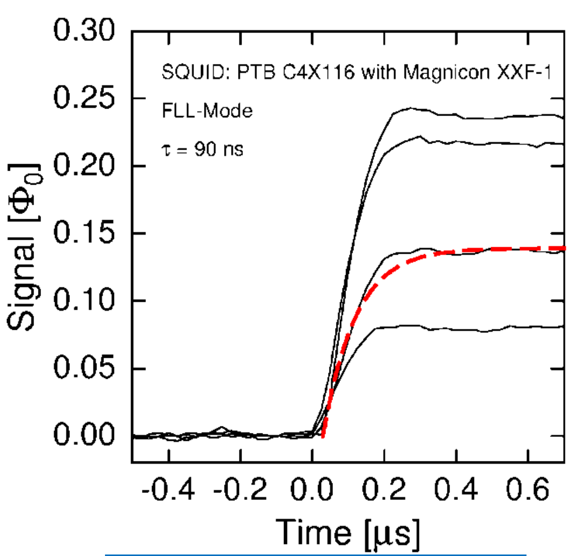

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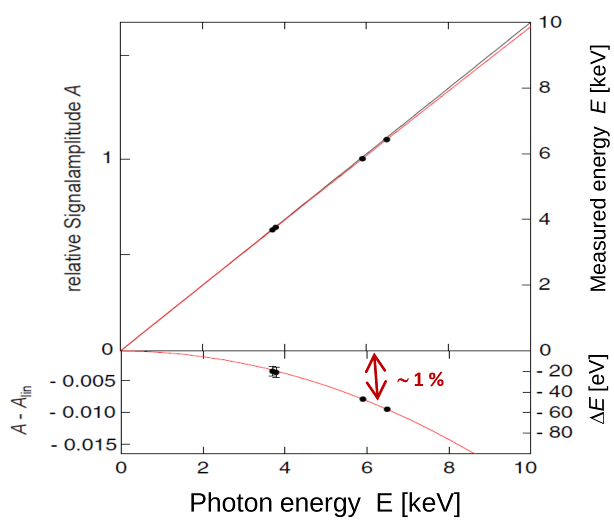
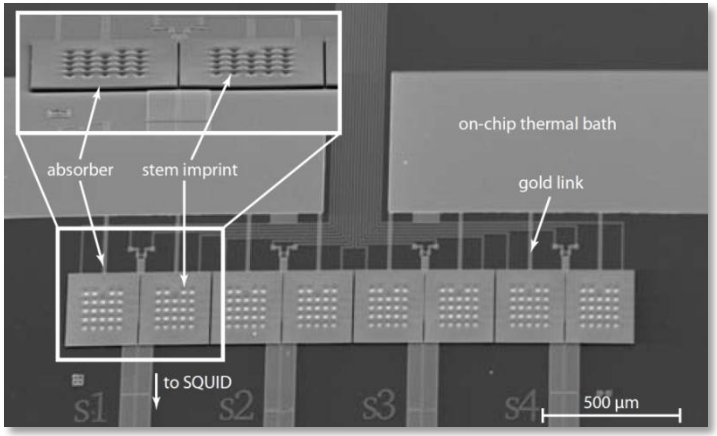
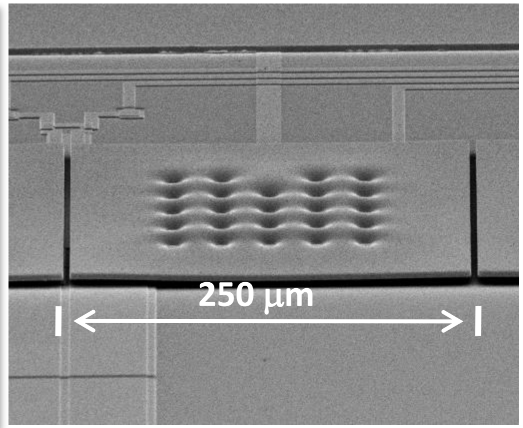


Reduction un-resolved pile-up

Definition of the energy scale

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





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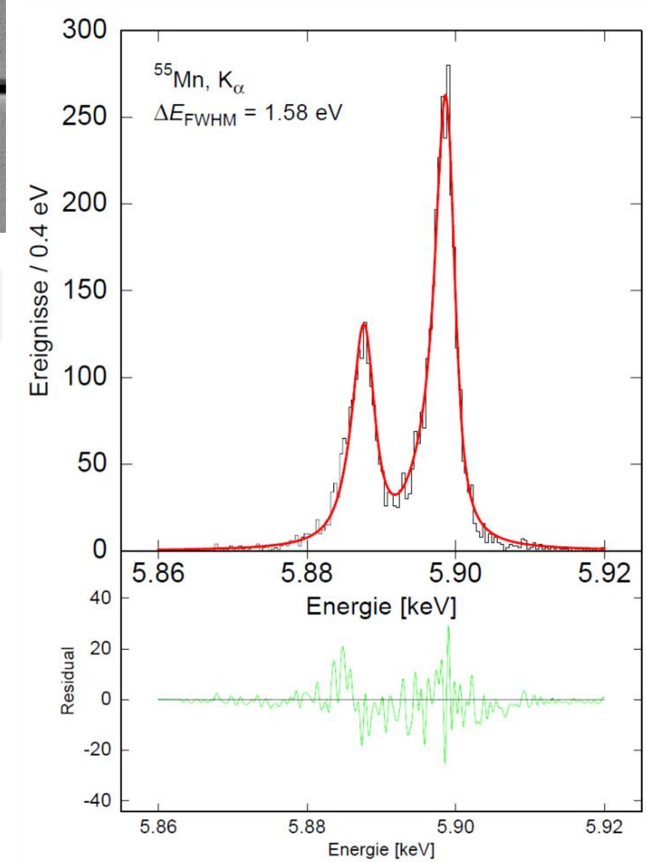

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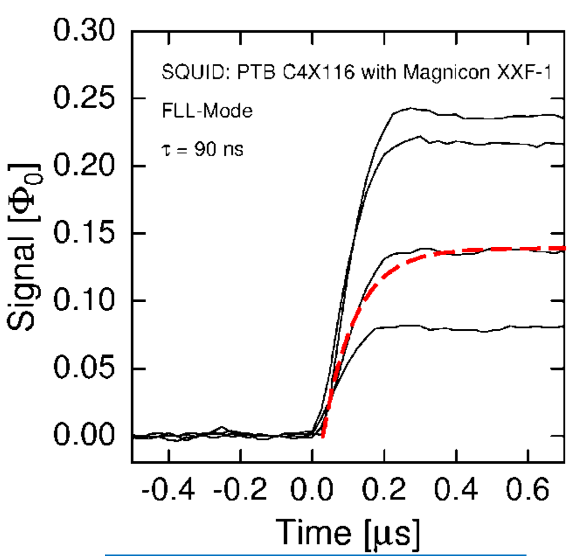

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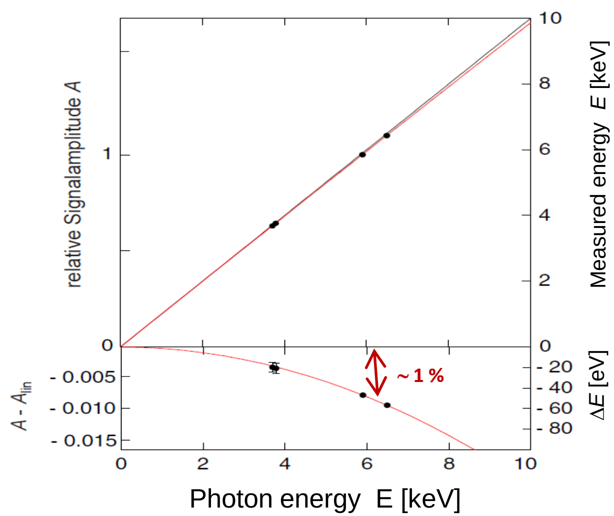


Reduction
un-resolved pile-up

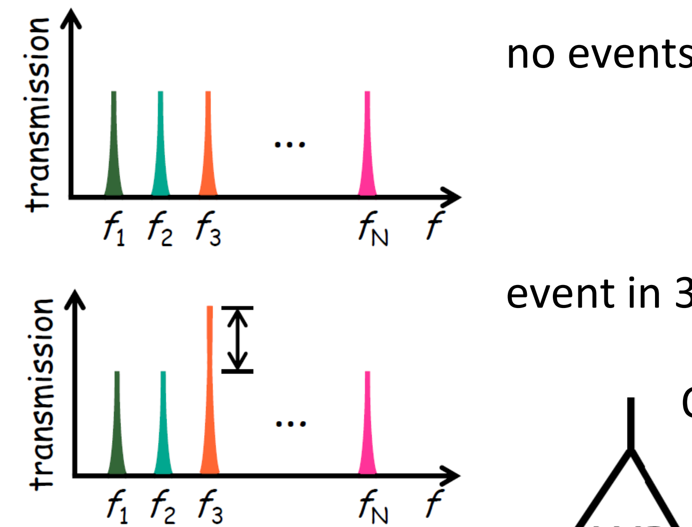
Definition
of the energy scale

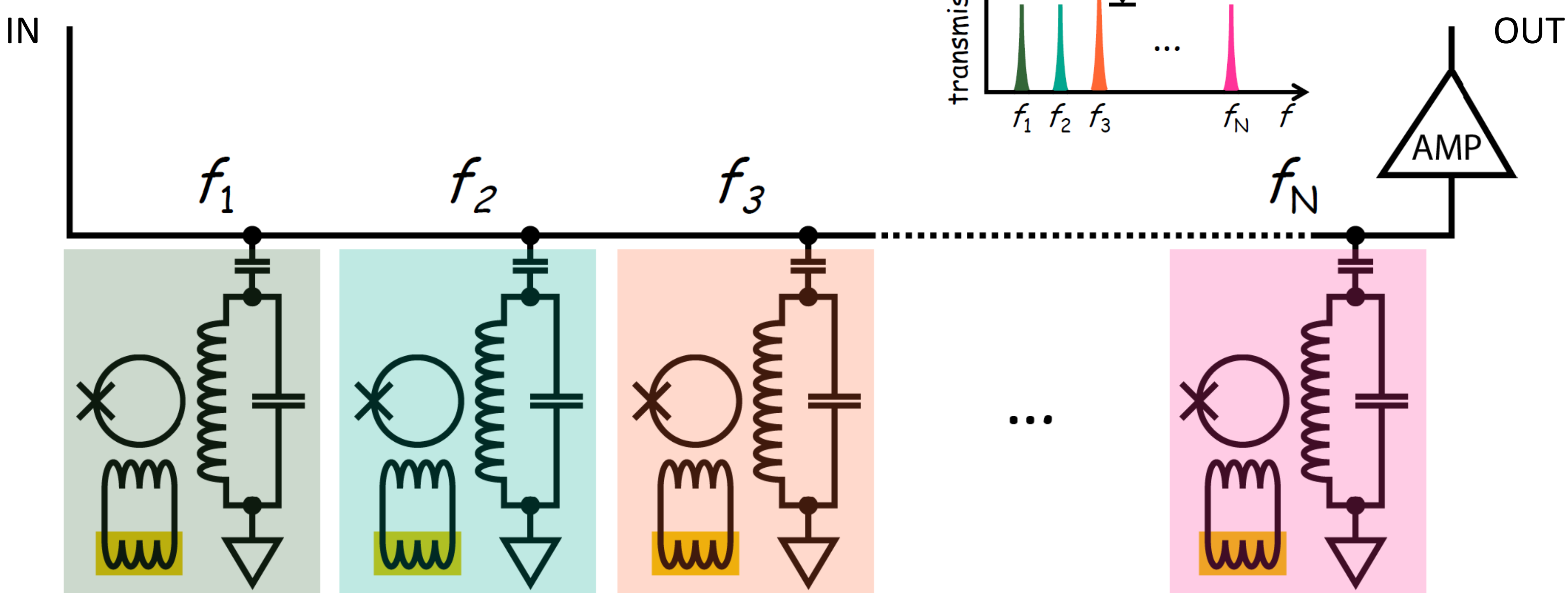
Reduced smearing
in the end point region

MMCs: From single pixels to arrays

Microwave SQUID multiplexing

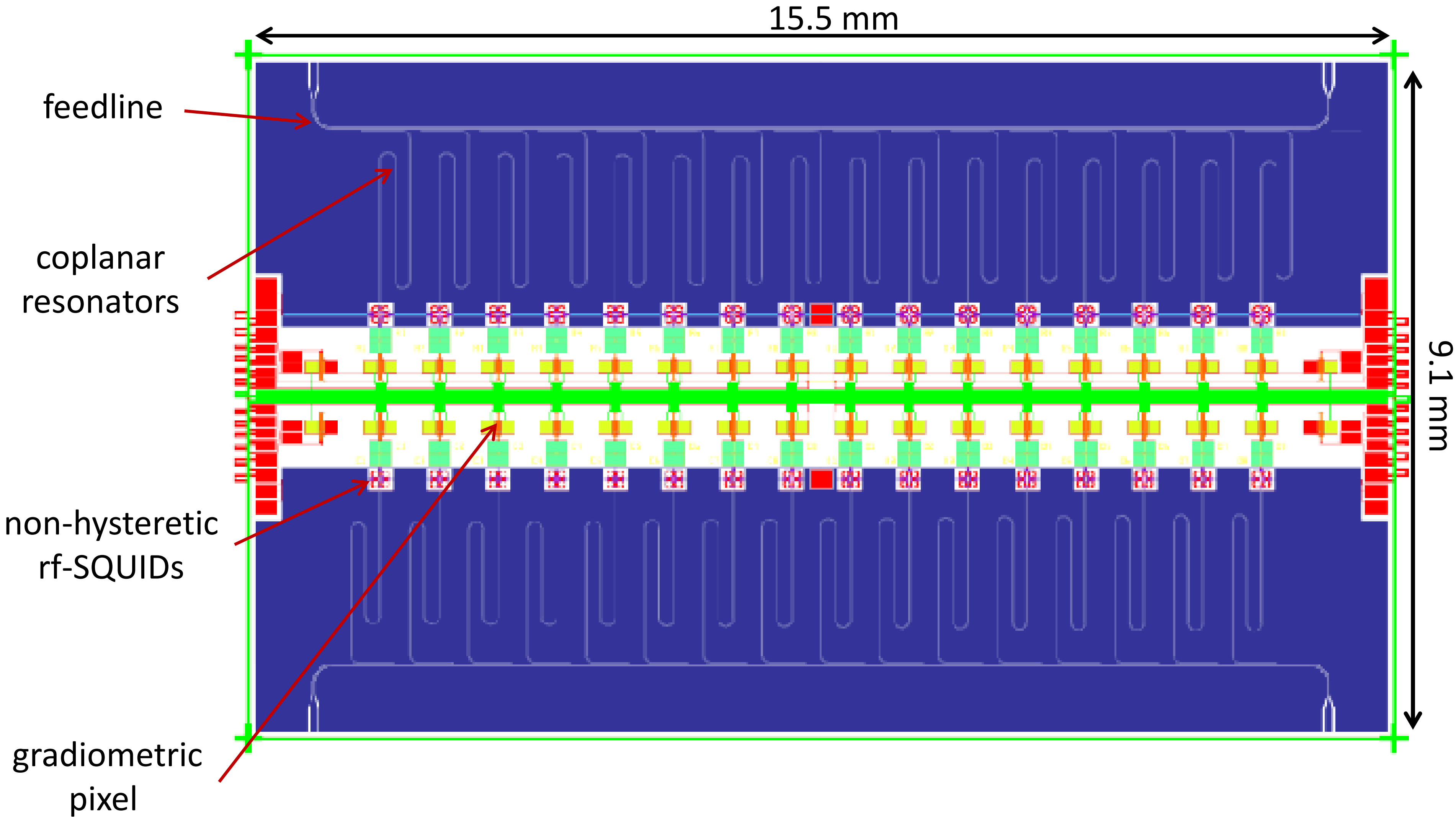
single HEMT amplifier and 2 coaxes
to read out 100 - 1000 detectors



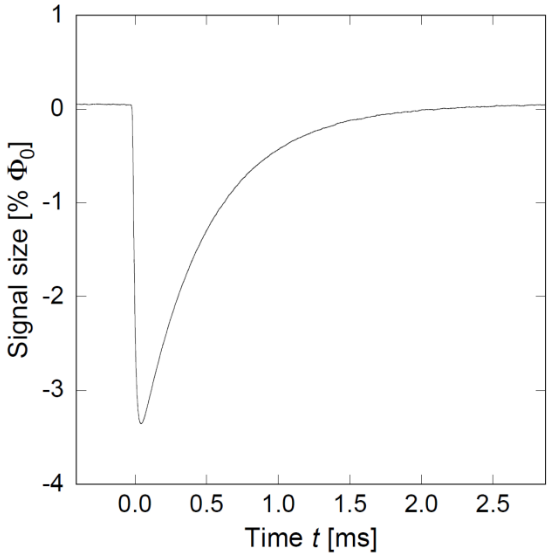


Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

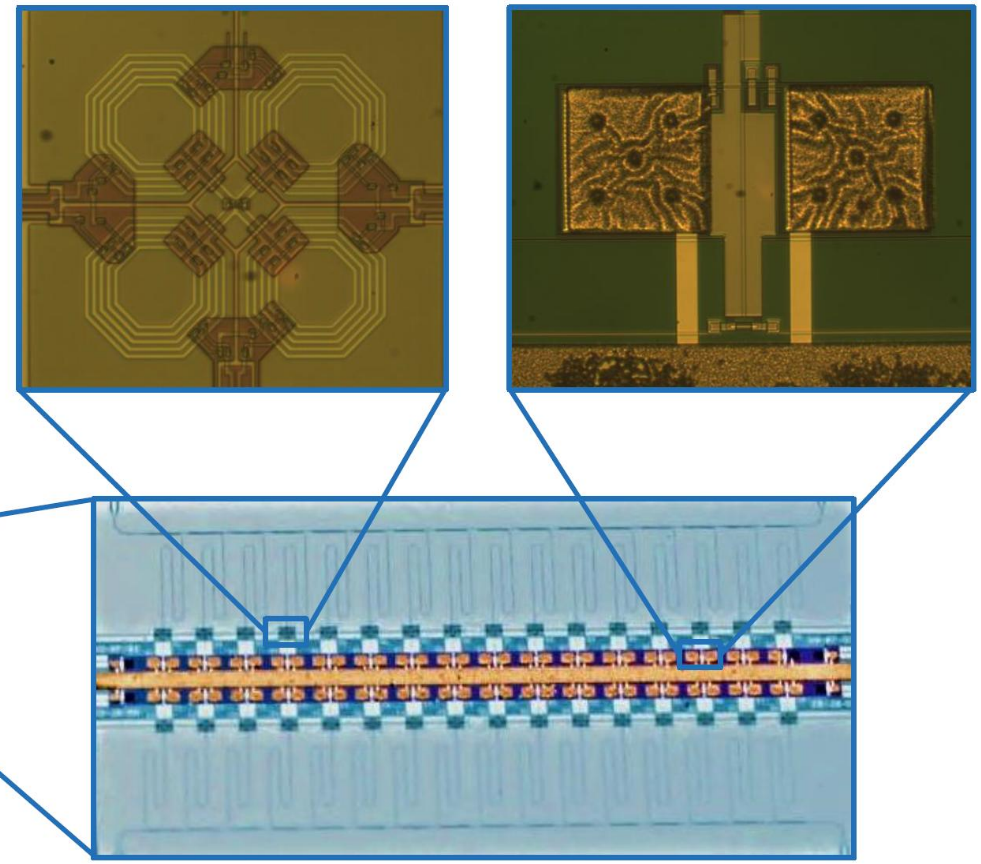
MMCs: 64 pixel array

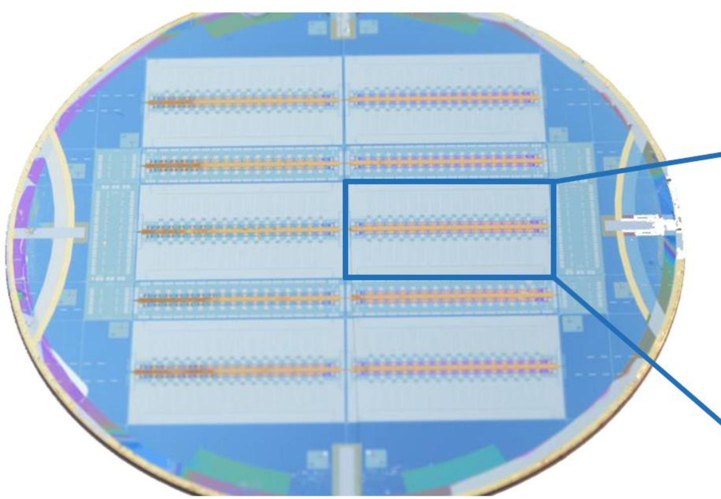


MMCs: Microwave SQUID multiplexing



Successful production and test of the first prototype





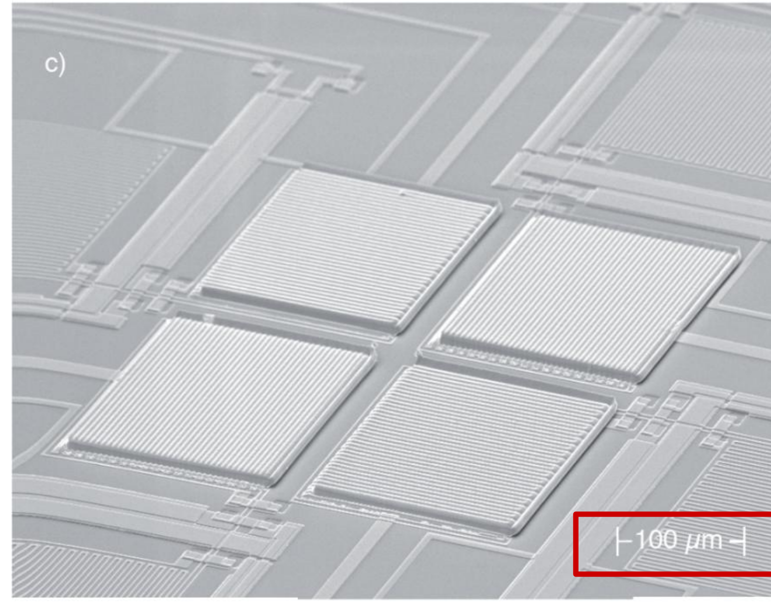
M. Wegner et al., in preparation

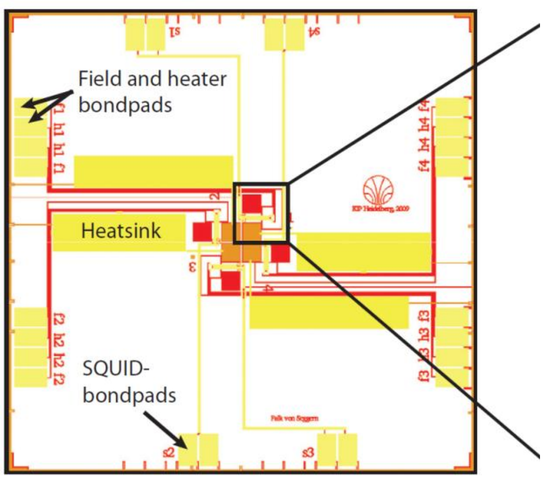
First detector prototype

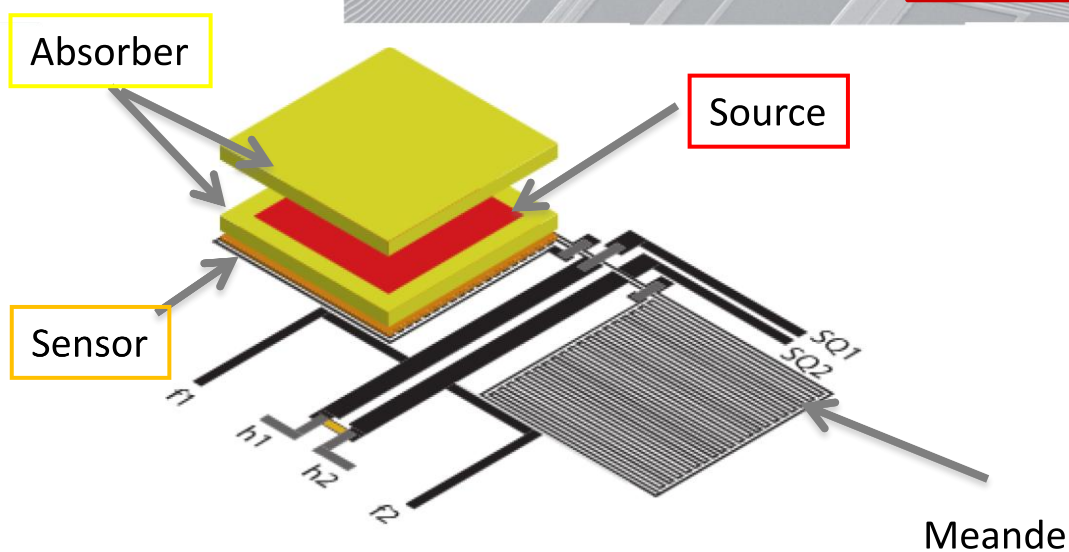
- Absorber for calorimetric measurement
  → ion implantation @ ISOLDE-CERN

- About 0.01 Bq per pixel

- Two pixels have been simultaneusly measured







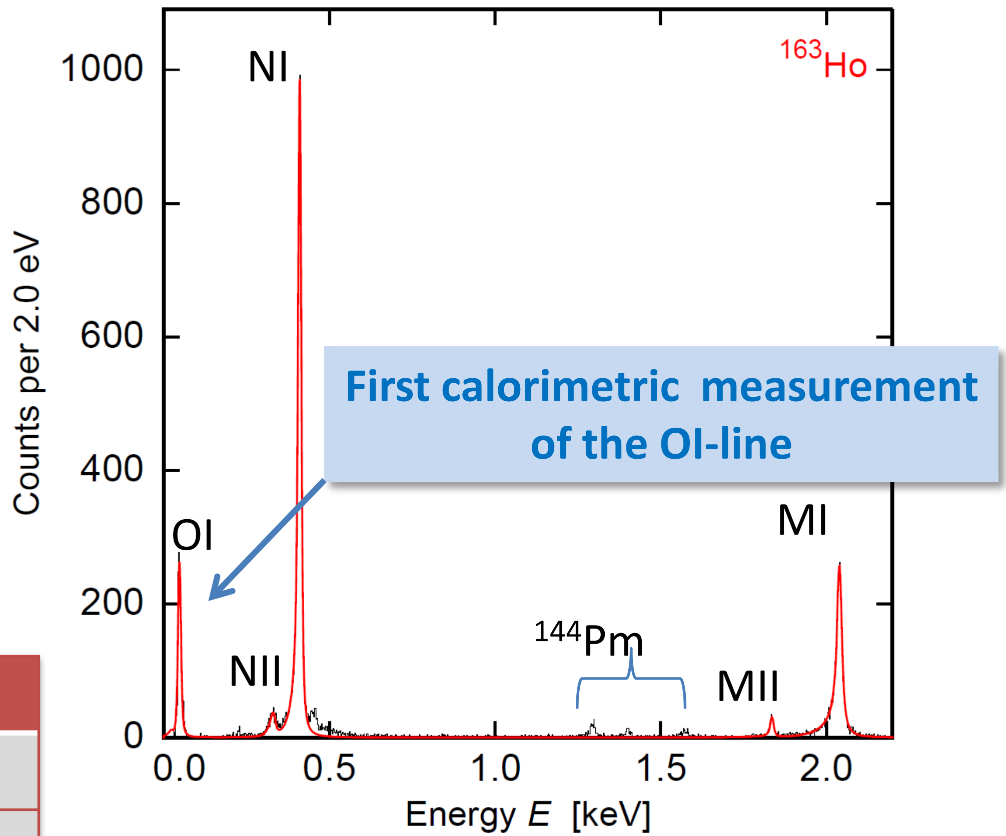
L. Gastaldo et al.,
Nucl. Inst. Meth. A, 711 (2013) 150

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)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels
- Presently most precise ^{163}Ho spectrum

	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



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

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

Detector design and fabrication:

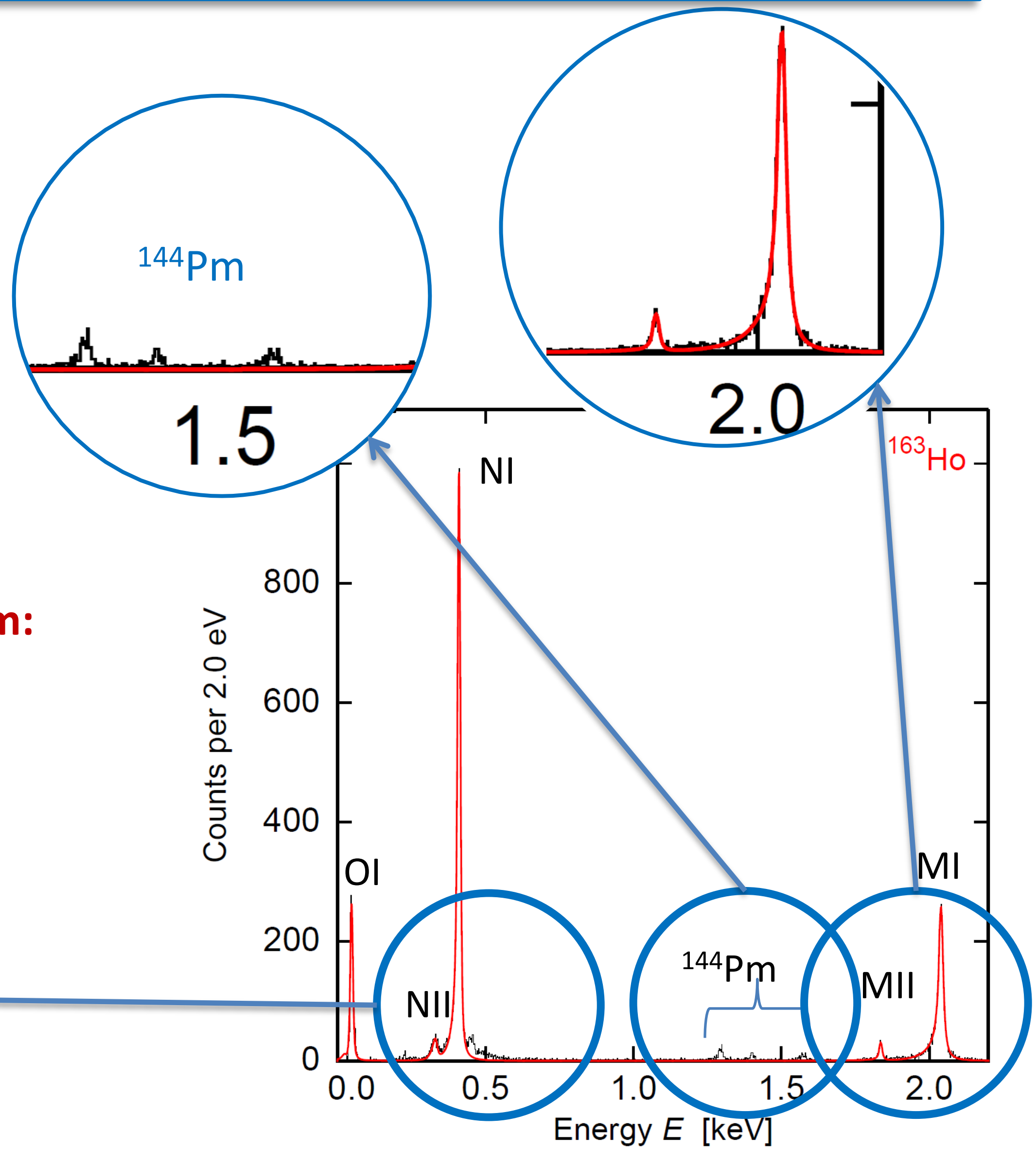
- Increase activity per pixel
- Remove low energy tail

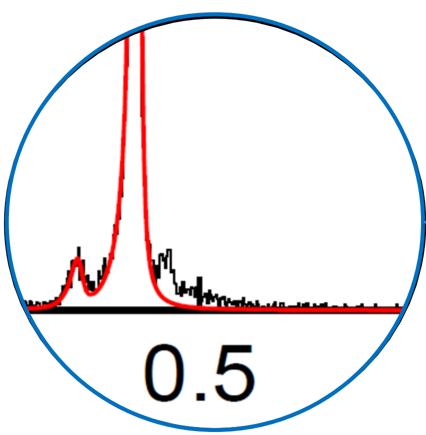
High purity ^{163}Ho source:

- Background reduction

Understanding of the ^{163}Ho spectrum:

- Investigate undefined structures





High purity ^{163}Ho source

(n,γ)-reaction on 30% enriched ^{162}Er

Thermal neutron flux (Φ): $1.3\text{x}10^{15}$ $cm^{-2}s^{-1}$

NEUTRONS FOR SCIENCE

γ spectrum of the 30 mg sample after chemical separation:

$\Rightarrow$ only ^{166m}Ho visible

Mass separation

- Use of the RISIKO mass-separator@Uni-Mainz
  → First successful test with ^{165}Ho
- Separation at CERN/ISOLDE December 2014
  → new chips to test!

Goal: $^{166m}Ho/^{163}Ho \leq 10^{-9}$

maXs–20: 16 pixel detector arrays for soft x-rays

ISOLDE

→ higher activity per pixel ≈ 1 Bq

→ no radioactive contaminants

→ better energy resolution

New detector ready for first tests….

At 18 mK since last Wednesday…..

NI

preliminary

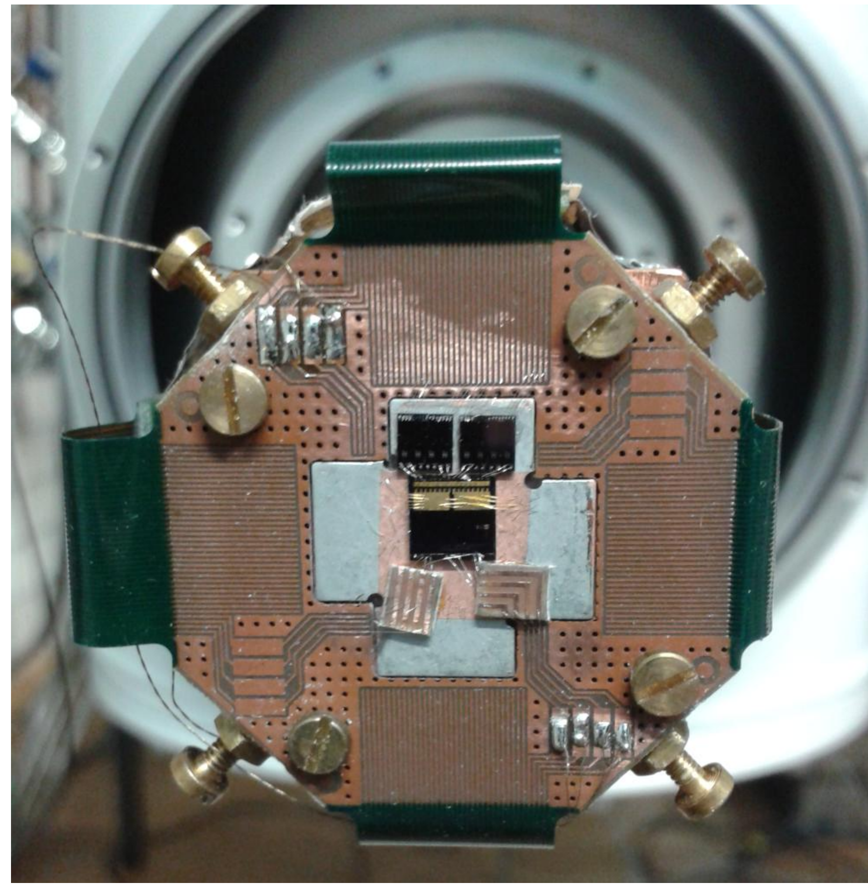
OI

MI

NII

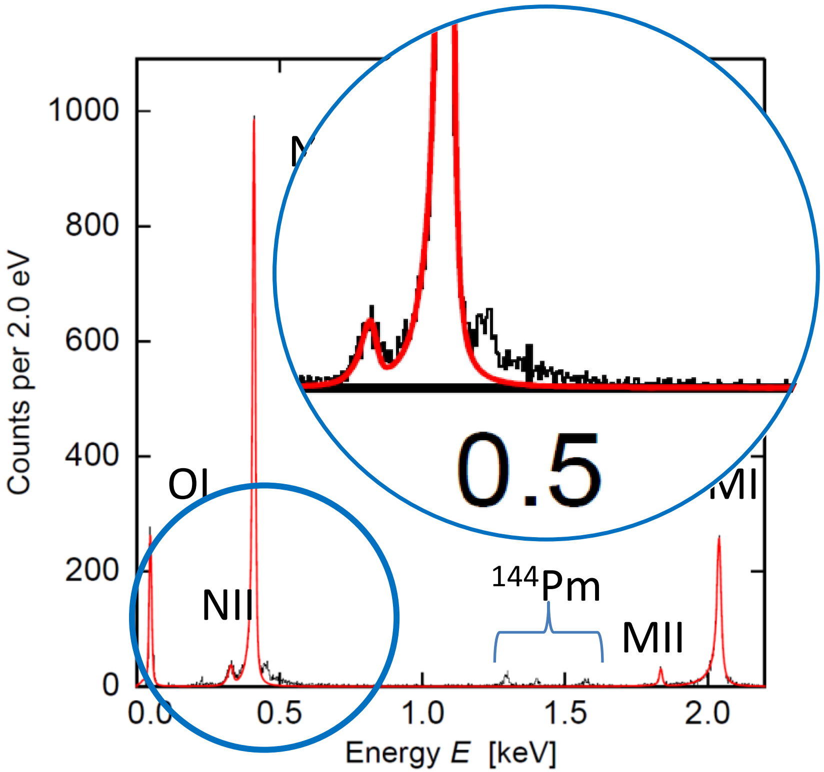
MII

Mounted on a cold arm of a dry cryostat



- Activity per pixel : $A \sim 0.2$ Bq
- Baseline resolution : $\Delta E_{FWHM} = 5$ eV
- No evidence of strong radioactive contamination in the source

Characterisation of spectral shape



Estimate the effect of

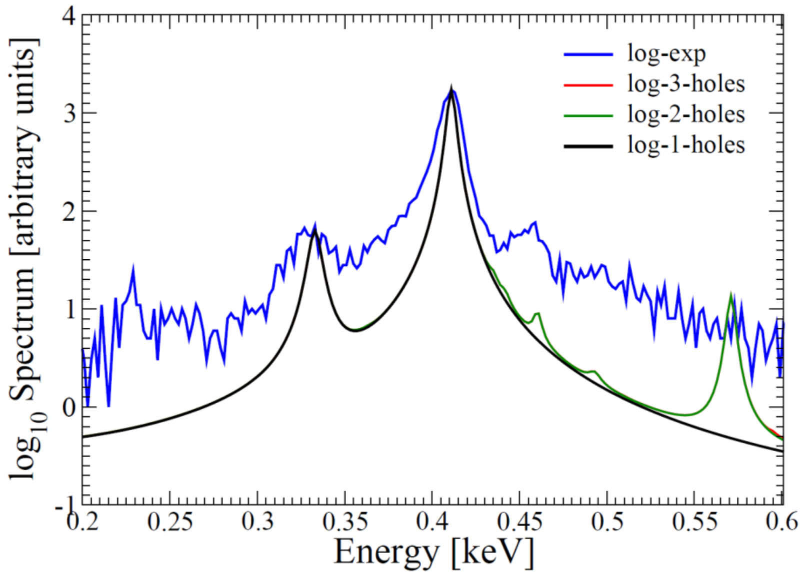
- Higher order excitation in ^{163}Dy
- ^{163}Ho ion embedded in Au

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)



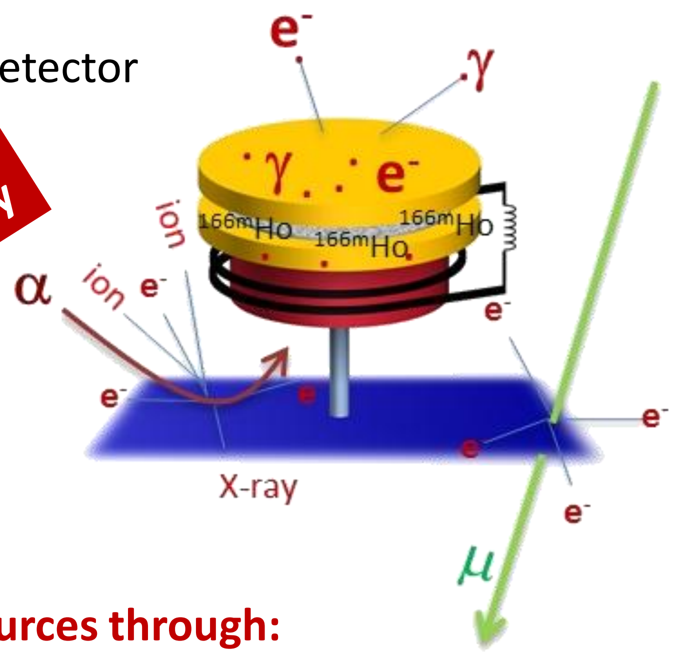
EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Background

Background sources:

- Environmental radioactivity → Material screening
- Cosmic rays → Underground labs
- Induced secondary radiation by cosmic rays → μ-Veto
- Radioactivity in the detector

Background level
5×10^{-5} counts/eV/det/day



Underground measurements in Modane

Study of background sources through:

- Monte Carlo simulations
- Dedicated experiments

Screening facilities
- Uni-Tübingen
- Felsenkeller

ECHo overview

- Prove scalability with medium large experiment **ECHo-1k**
  - A ~ 1000 Bq — High purity ^{163}Ho source (produced at reactor)
  - $\Delta E_{FWHM} < 5$ eV
  - $\tau_r < 1$ µs
  - multiplexed arrays → microwave SQUID multiplexing
  - 1 year measuring time → 10^{10} counts = Neutrino mass sensitivity $m_\nu < 10$ eV

Just approved

Research Unit FOR 2202/1

„Neutrino Mass Determination by Electron Capture in Holmium-163 – ECHo“

DFG Deutsche Forschungsgemeinschaft

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

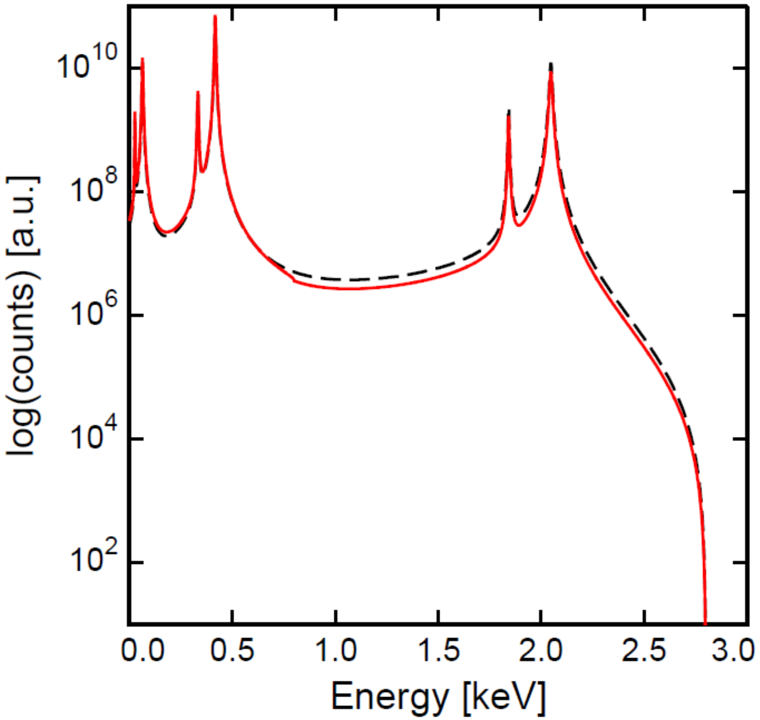
Sterile Neutrino and ^{163}Ho

Sterile Neutrino and ^{163}Ho

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

Sterile Neutrino and ^{163}Ho

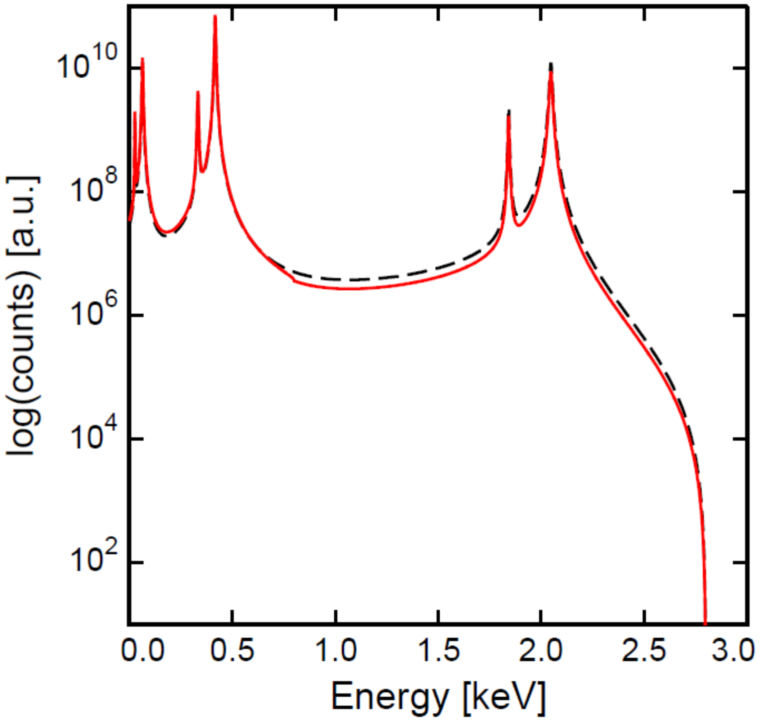
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$



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

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

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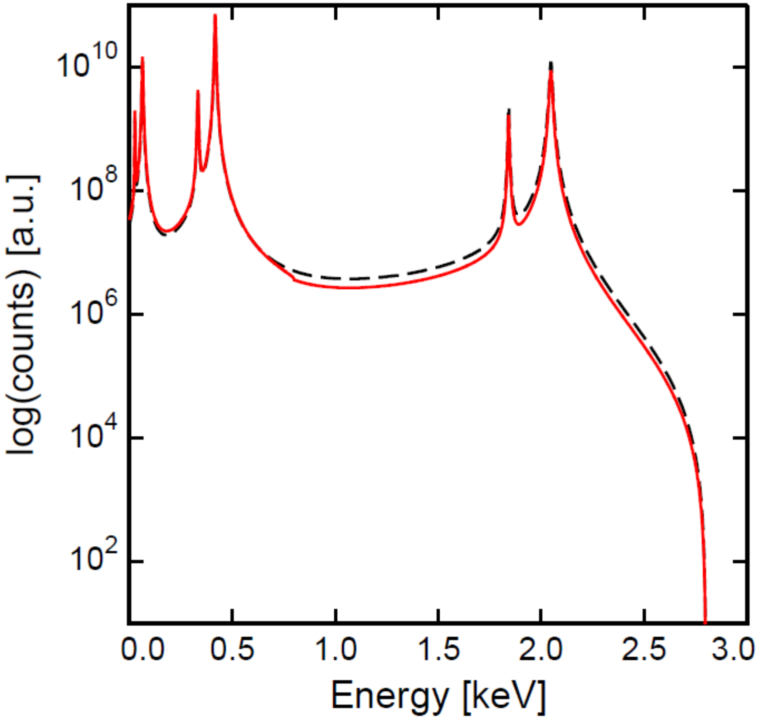

Sterile Neutrino and ^{163}Ho

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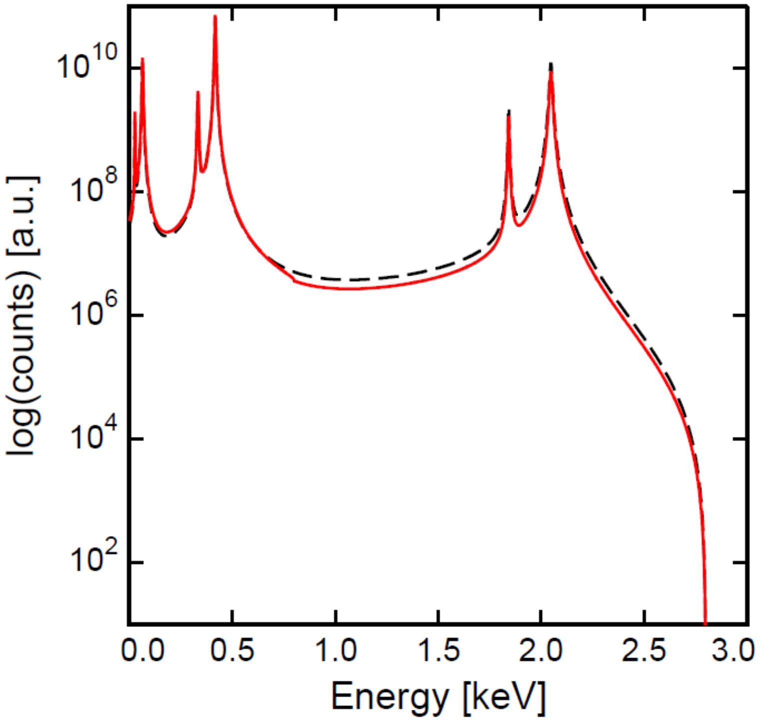

Assume:

$$m_a = 0$$

$$m_s \neq 0$$

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

$$m_4 \neq 0$$

$$m_4 \approx keV$$

Sterile Neutrino and ^{163}Ho

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

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

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

Sterile Neutrino and ^{163}Ho

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

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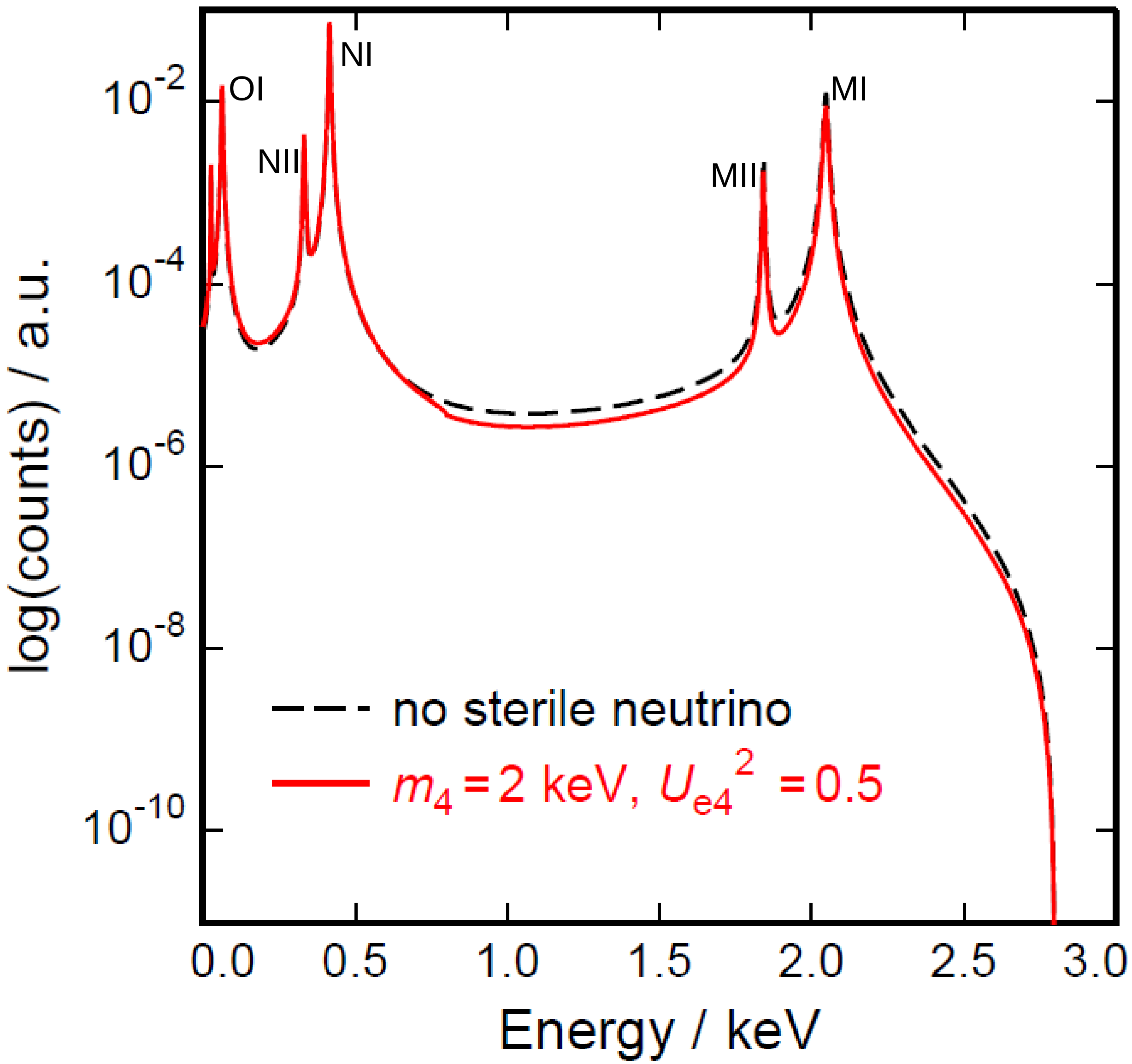
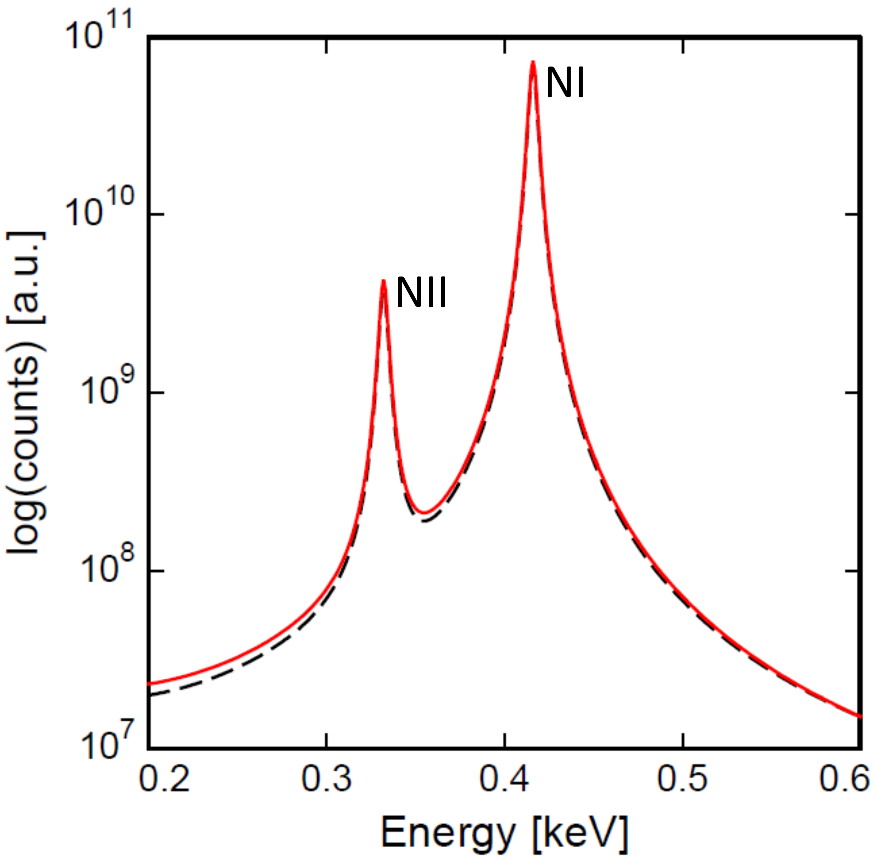
No contribution for $Q_{EC} < m_4$

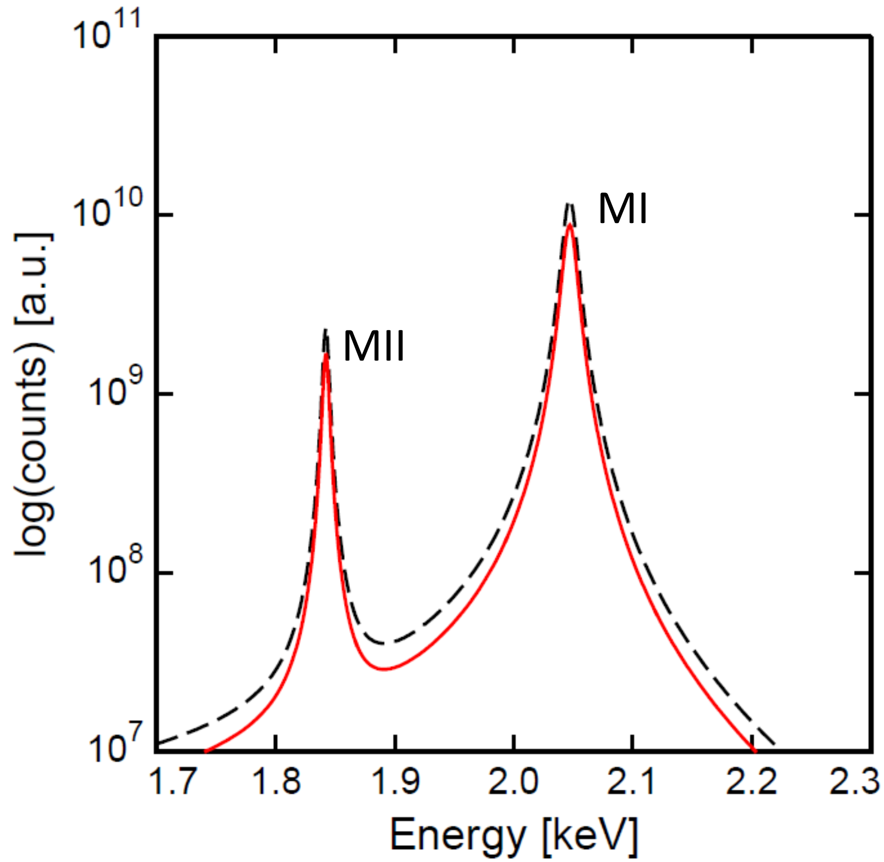
Sterile Neutrino and ^{163}Ho



Sterile Neutrino and ^{163}Ho

m_4=2 keV, U_{e4}^2=0.5
no sterile neutrino





Sterile Neutrino and ^{163}Ho

- Amplitude of the line H for only active neutrinos

$$W_{Ha} = A\left(Q_{EC} - E_H\right)^2 B_H \varphi_H^{\ 2}(0)$$

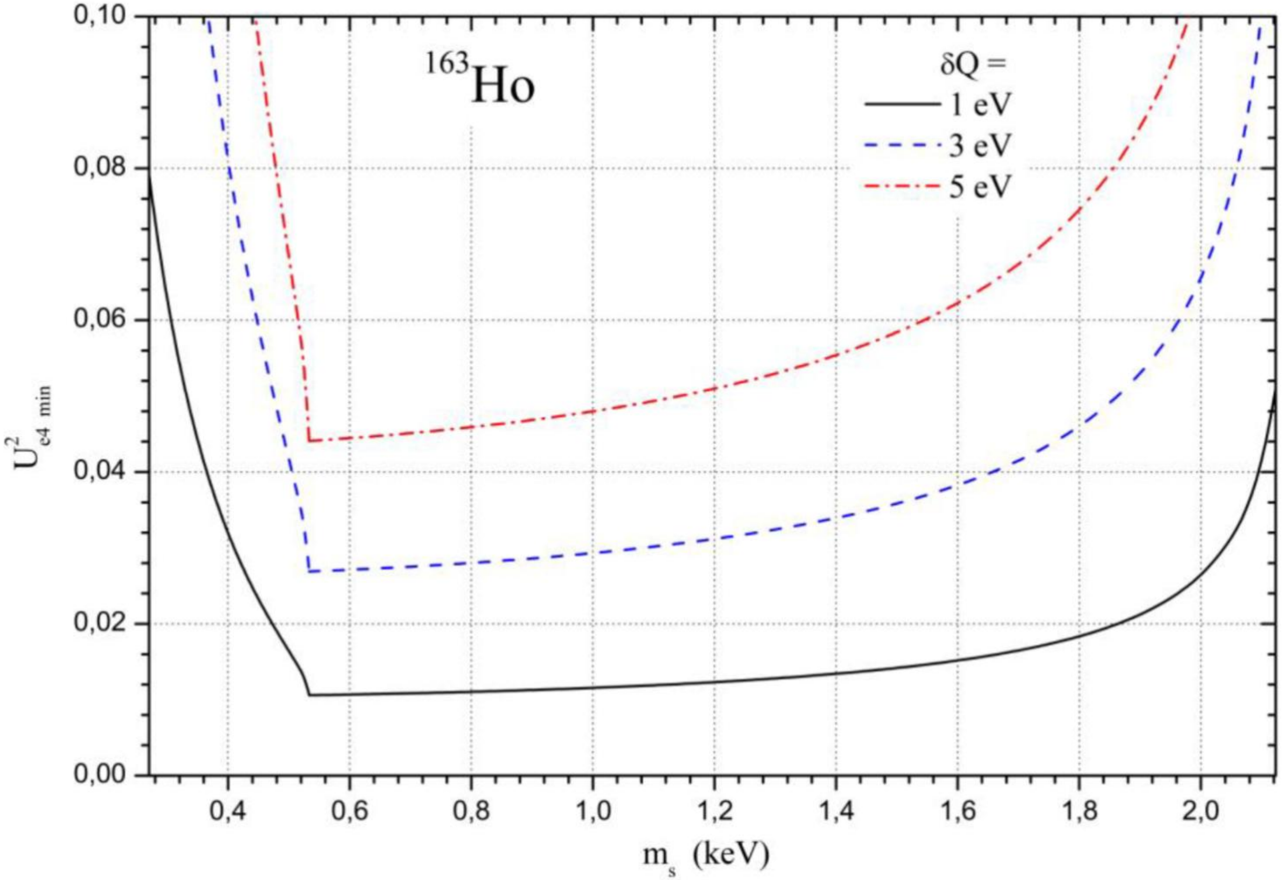
- Amplitude of the line H for 3+1 model in case of m_a = 0 eV

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

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

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

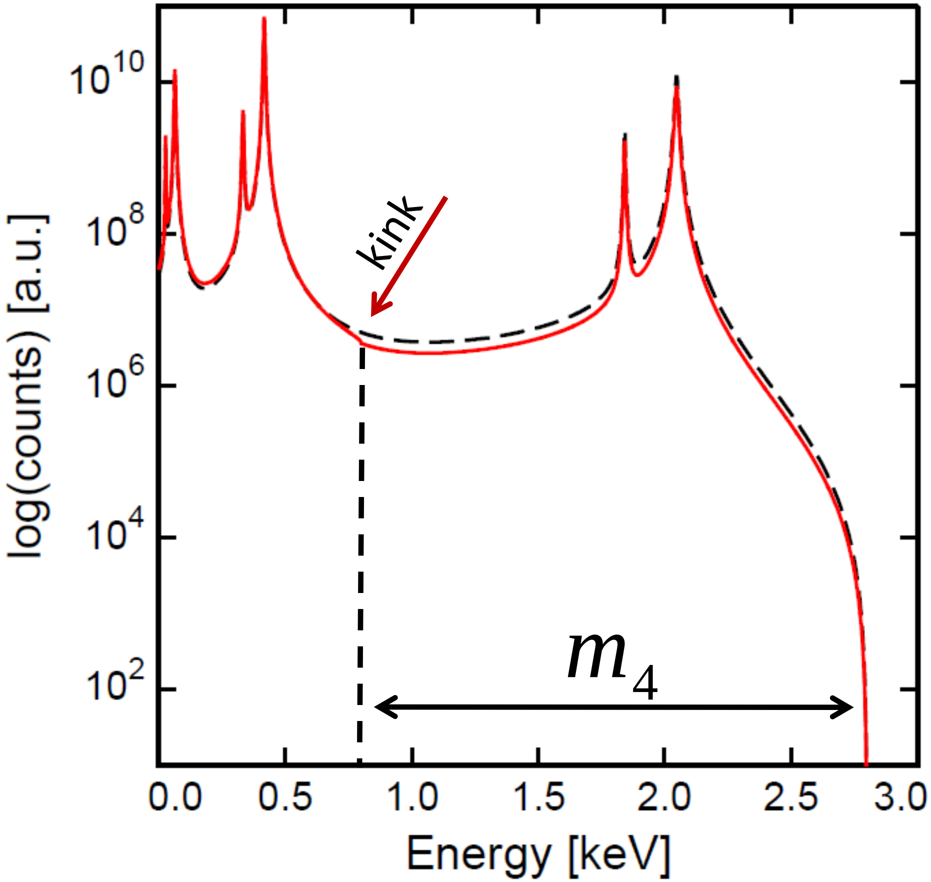
Sterile Neutrino and ^{163}Ho



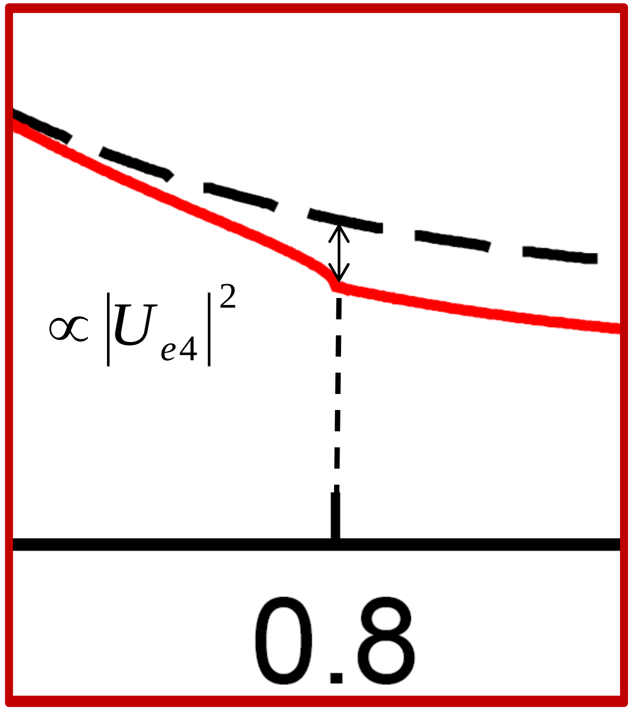
Sensitivity to the mixing matrix element at 90% CL as a function of the sterile neutrino mass achievable with about 10^{10} events in the full EC spectrum.

P. Filianin et al. arXiv: 1402.4400

Sterile Neutrino and ^{163}Ho

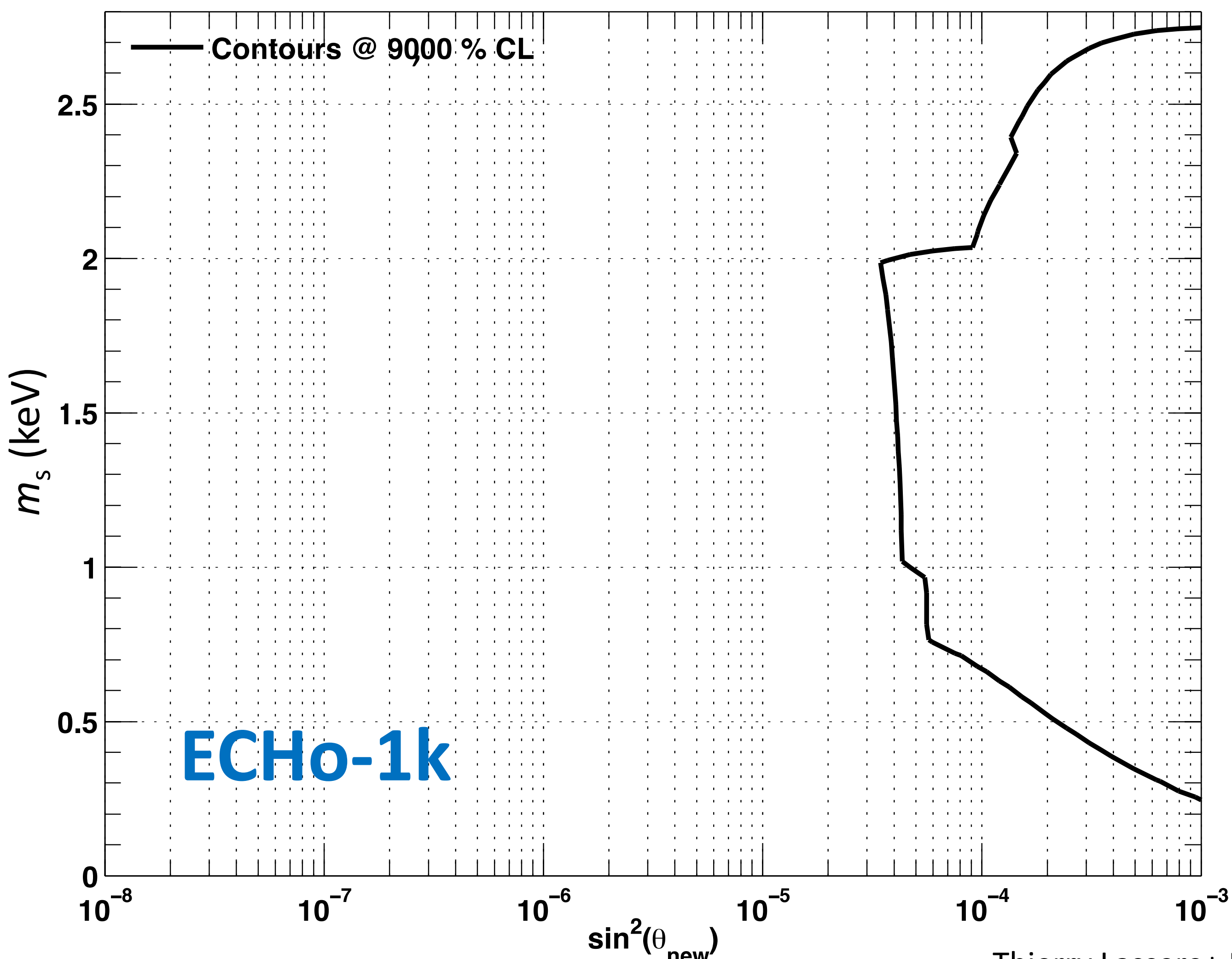


- postion of kink => m_4
- depth of kink => $|U_{e4}|^2$



Sterile Neutrino and ^{163}Ho

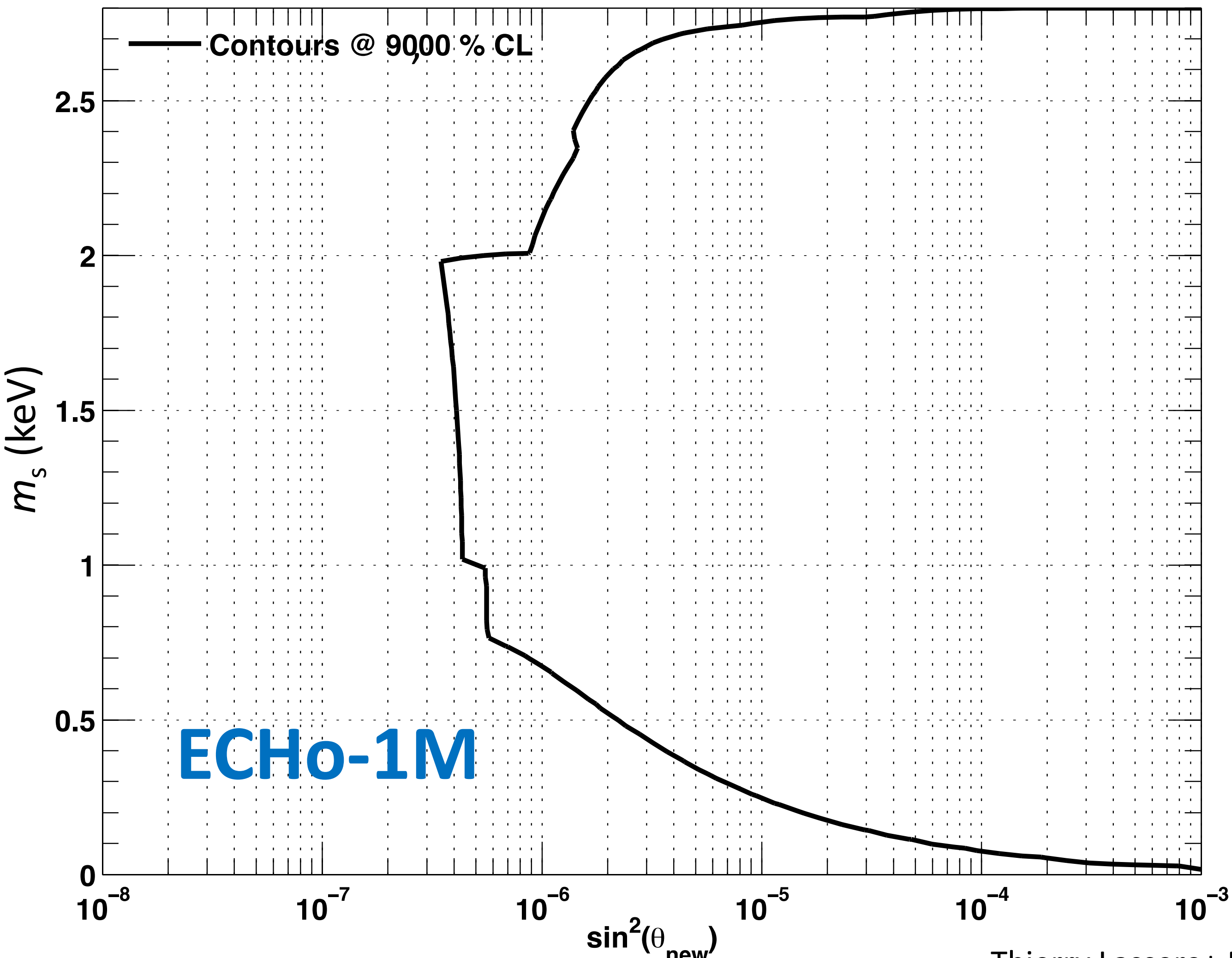
Statistical Fluctuation – No Pile Up – Counts = 1e10
Theoretical Spectrum Supposed to be perfectly known



Thierry Lassere+ ECHo, in progress

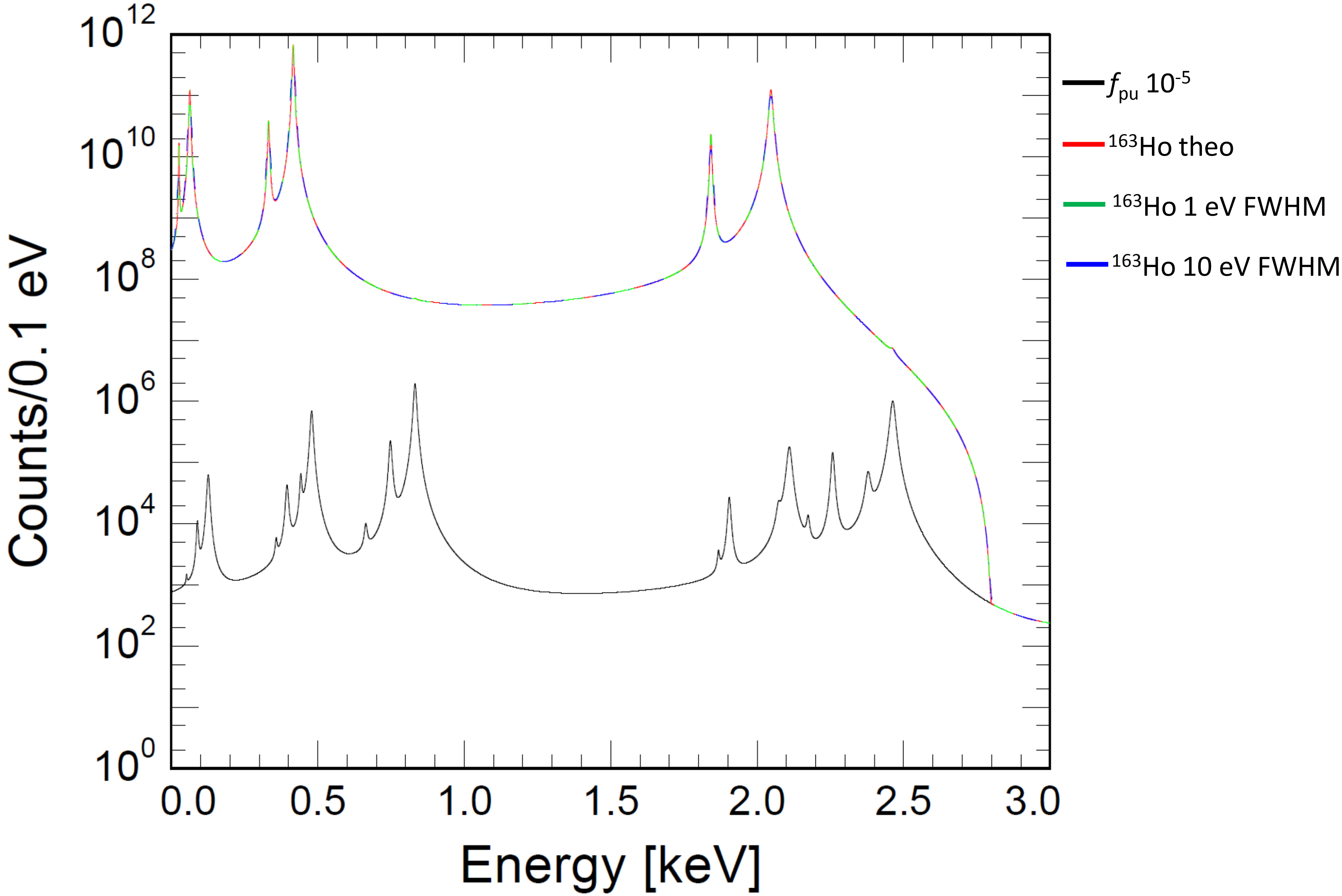
Sterile Neutrino and ^{163}Ho

Statistical Fluctuation – No Pile Up – Counts = 1e14
Theoretical Spectrum Supposed to be perfectly known



Thierry Lassere+ ECHo, in progress

Pile-up and energy resolution



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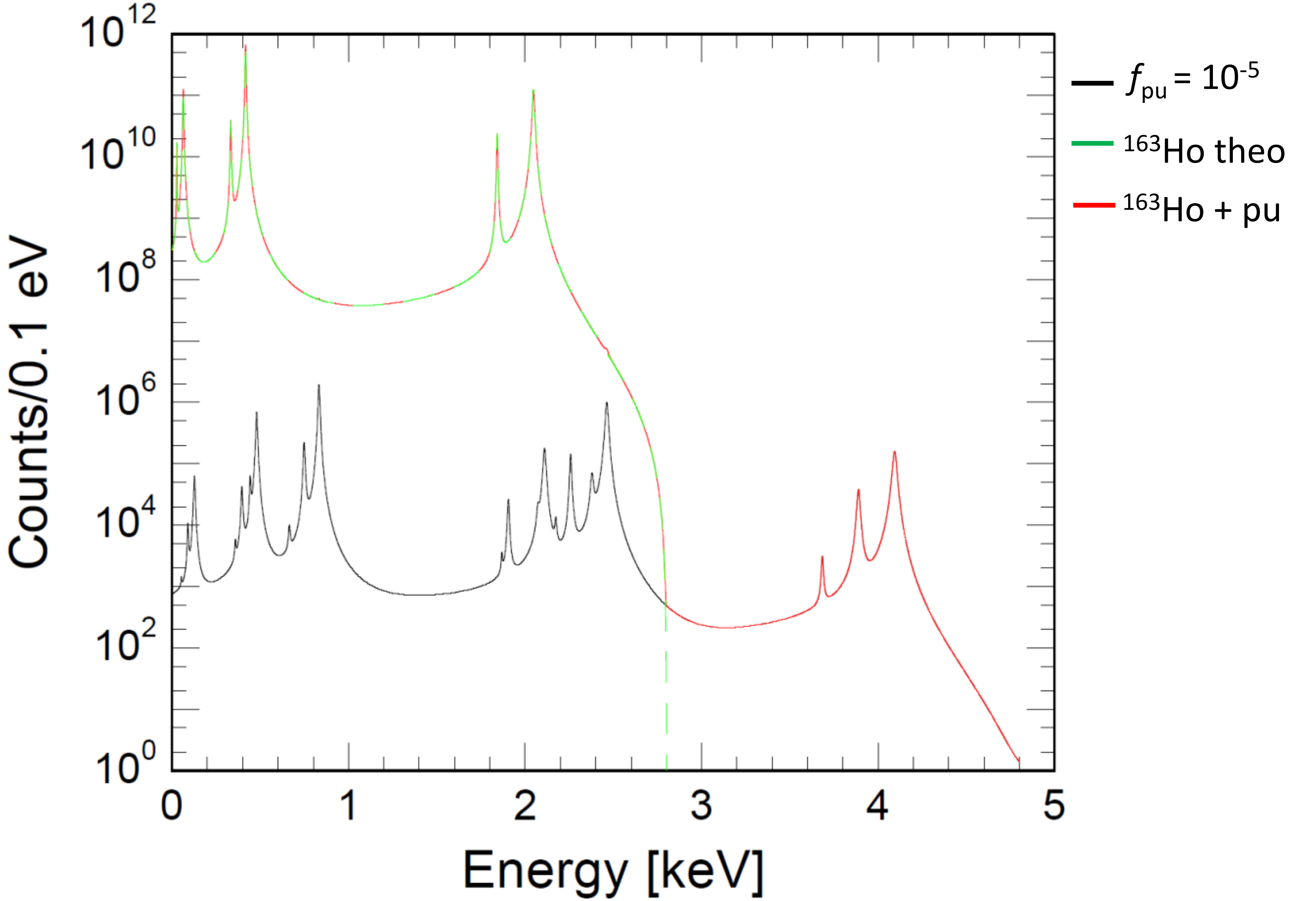

Sterile Neutrino (keV) and Electron Capture

Other candidates 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]	$\|\psi_i\|^2/\|\psi_j\|^2$	$Q-B_i$ (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. arXiv: 1402.4400

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

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

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

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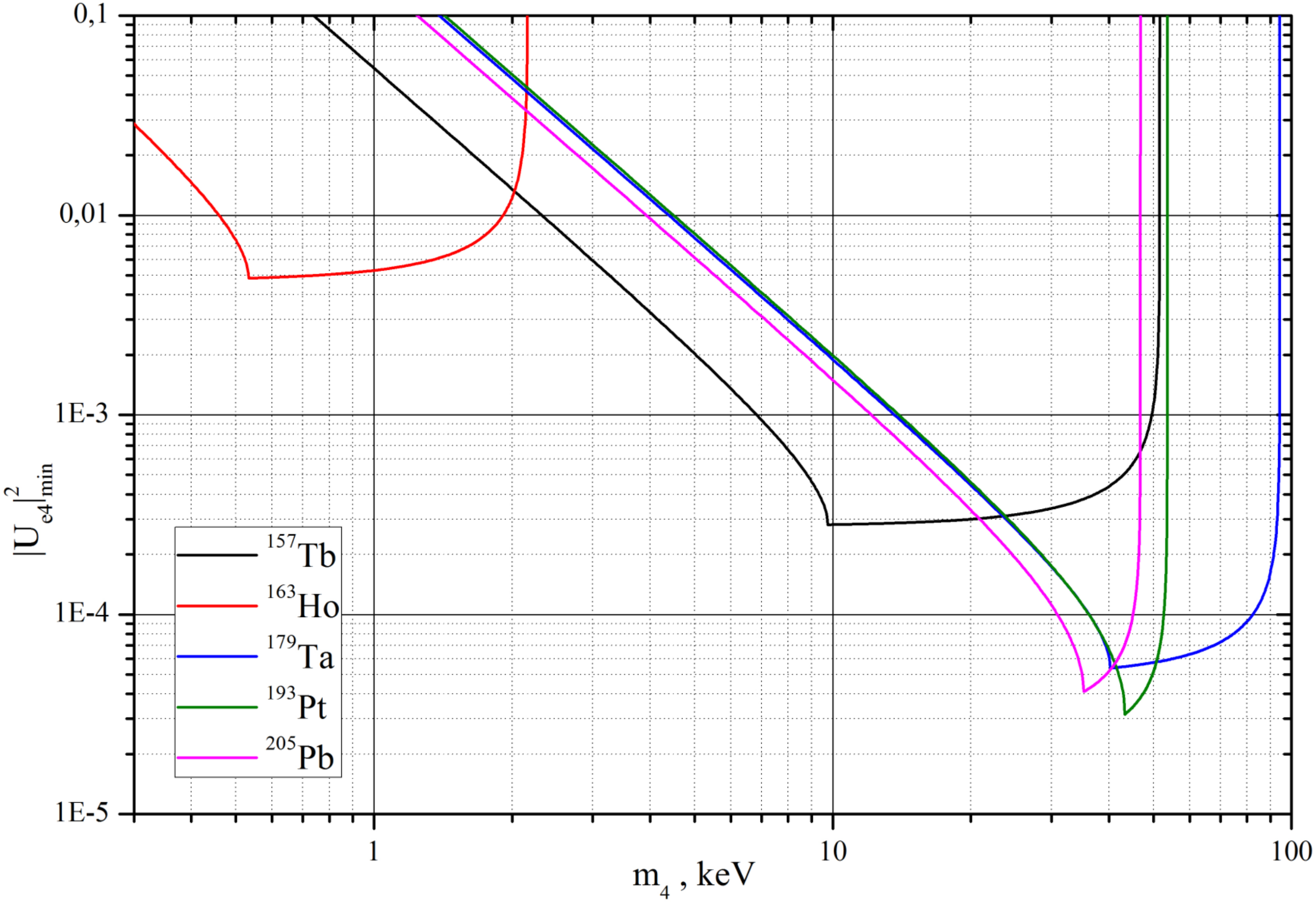
$$\left(\frac{W_{H1}}{W_{H2}}\right)_s = \left(\frac{W_{H1}}{W_{H2}}\right)_a \frac{\left|U_{e4}\right|^2 \left[H(Q_{EC} - E_1 - m_4)\sqrt{1 - \frac{m_4^{\ 2}}{\left(Q_{\mathrm{EC}} - E_1\right)^2}} - 1\right] + 1}{\left|U_{e4}\right|^2 \left[H(Q_{EC} - E_2 - m_4)\sqrt{1 - \frac{m_4^{\ 2}}{\left(Q_{\mathrm{EC}}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

Sterile Neutrino (keV) and Electron Capture



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

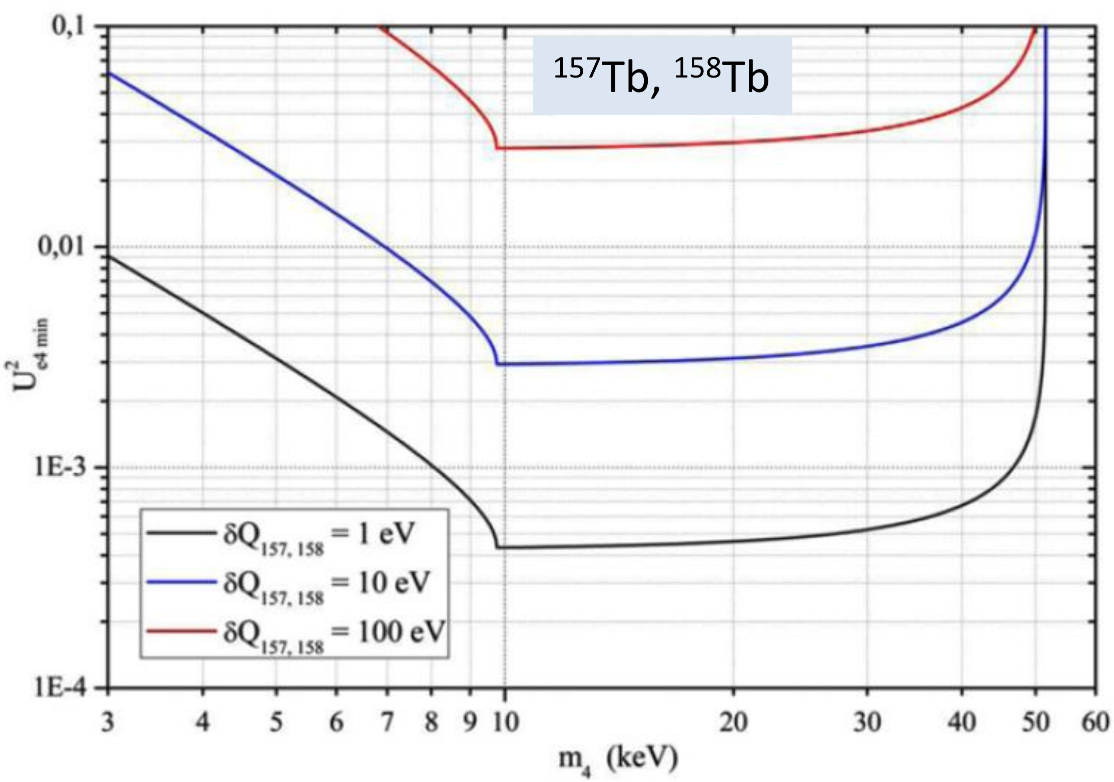
Sterile Neutrino (keV) and Electron Capture

Two EC isotopes of the same element:

$$\zeta_{\text{st}} \equiv \frac{\left(\lambda_i/\lambda_j\right)_1}{\left(\lambda_i/\lambda_j\right)_2} = \zeta_{\text{act}} \frac{\left[1-U_{e4}^2\left(1-\omega_{i1}\right)\right]\left[1-U_{e4}^2\left(1-\omega_{j2}\right)\right]}{\left[1-U_{e4}^2\left(1-\omega_{i2}\right)\right]\left[1-U_{e4}^2\left(1-\omega_{j1}\right)\right]}$$

$$\omega_{lk} \equiv \mathrm{H}\left[\left(Q_k - B_l\right) - m_s\right] \cdot \sqrt{1-\left(\frac{m_s}{Q_k - B_l}\right)^2}$$

$$\zeta_{\text{act}} = \left[\frac{\left(Q_1 - B_i\right)\left(Q_2 - B_j\right)}{\left(Q_2 - B_i\right)\left(Q_1 - B_j\right)}\right]^2$$



P. Filianin et al. arXiv: 1402.4400

Conclusions

- The ECHo experiment can investigate the electron neutrino mass in sub-eV range
- The sensitivity of ^{163}Ho- based experiment to the sterile neutrino is limited to $m_s < Q_{EC.}$
- Other candidates can be found in the EC sector. They can cover a larger sterile neutrino mass range.

Thank you!

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Goethe Universität Frankfurt am Main
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Susanta Lahiri

ECHo