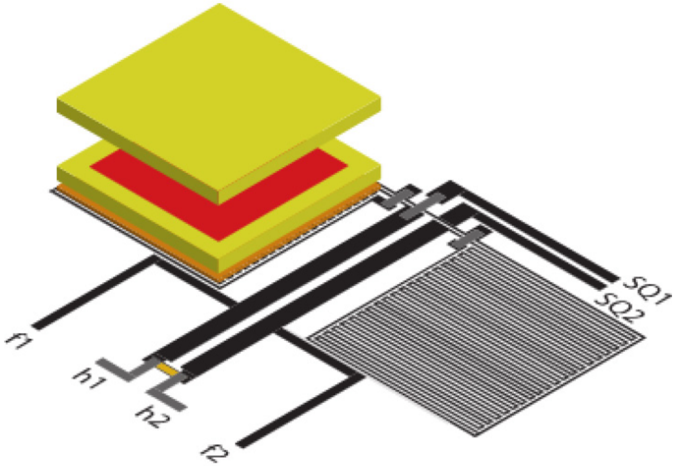
The Electron Capture ^{163}Ho experiment and sterile neutrino

Loredana Gastaldo
for the ECHo Collaboration

Kirchhoff Institute for Physics, Heidelberg University



Contents

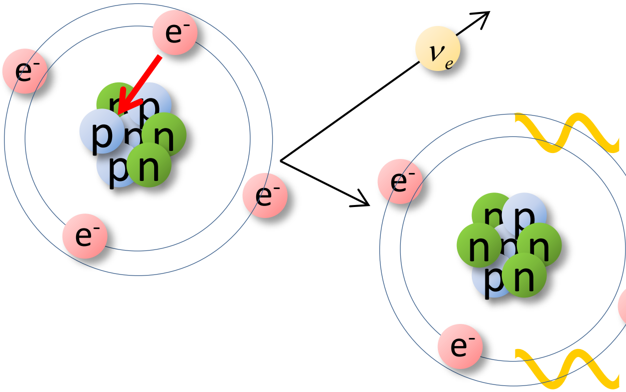
- Electron capture and electron neutrino mass
- The ^{163}Ho case
- The ECHo neutrino mass experiment
- Sensitivity to sterile neutrino in ECHo
- Electron capture and sterile neutrino
- Conclusions

Present limit:

$m(\nu_e) < 225$ eV (95% C.L.)

P.T. Springer et al., *Phys. Rev. A* **35**, 679 (1987)

Electron capture and electron neutrino mass



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

Atomic de-excitation:

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

Calorimetric measurement

$$\frac{dW}{dE_{\mathrm{C}}} = \mathrm{A}\left(Q_{\mathrm{EC}} - E_{\mathrm{C}}\right)^2 \sqrt{1 - \frac{m_\nu^{\,2}}{\left(Q_{\mathrm{EC}} - E_{\mathrm{C}}\right)^2}} \sum_{\mathrm{H}} B_H \varphi_{\mathrm{H}}^{\,2}(0) \frac{\frac{\Gamma_{\mathrm{H}}}{2\pi}}{\left(E_{\mathrm{C}} - E_{\mathrm{H}}\right)^2 + \frac{\Gamma_{\mathrm{H}}^{\,2}}{4}}$$

The case of ^{163}Ho

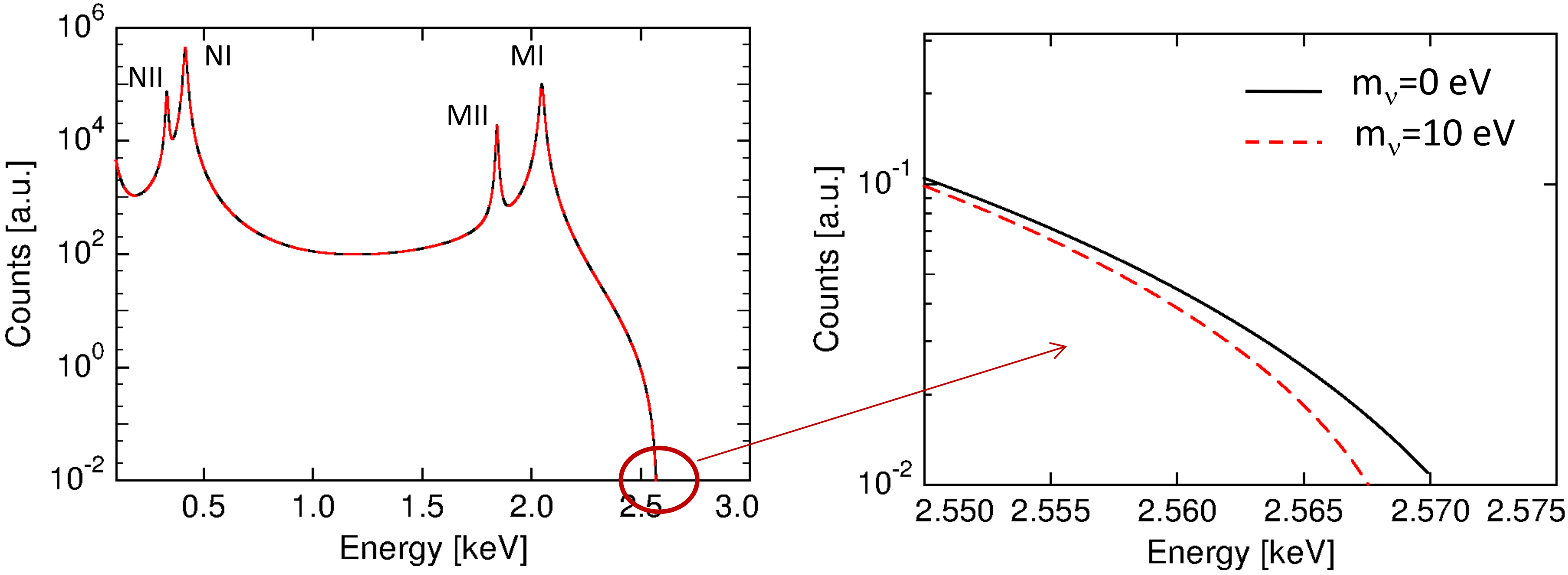
$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

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

- $\tau_{1/2} \cong$ 4570 years

  ($2 \cdot 10^{11}$ atoms 1 Bq)

- Q_{EC} = (2.555 ± 0.016) keV
  recomended value!?



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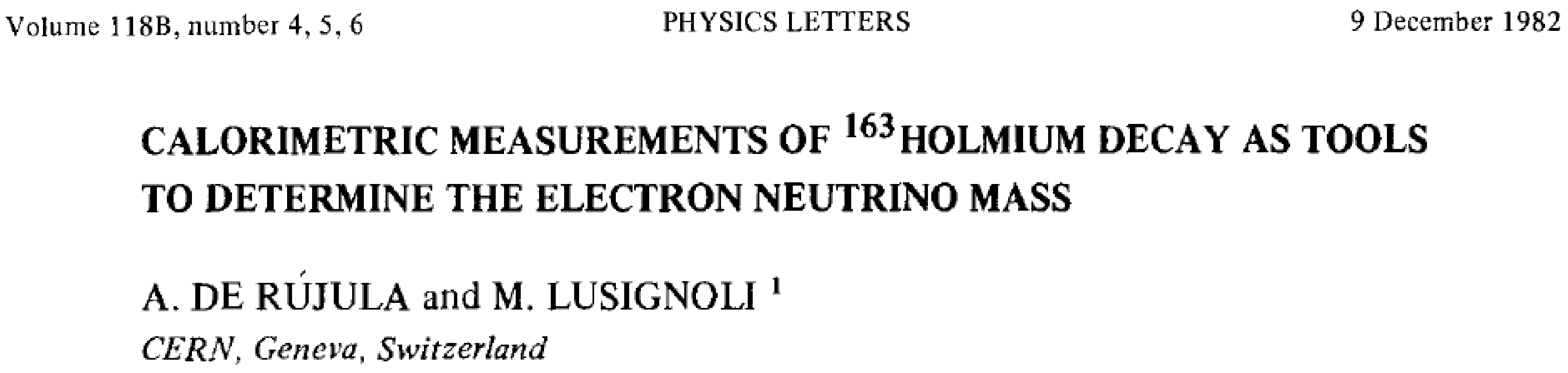


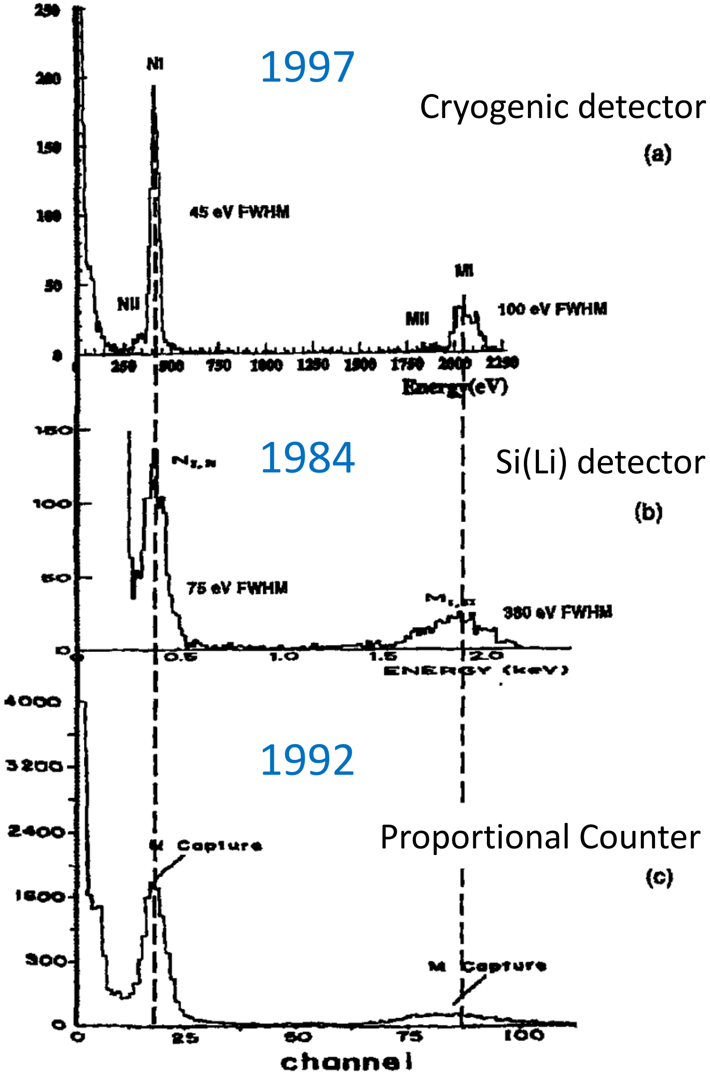
Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

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



1997

Cryogenic detector

1984

Si(Li) detector

1992

Proportional Counter

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.

The case of ^{163}Ho: Statistics

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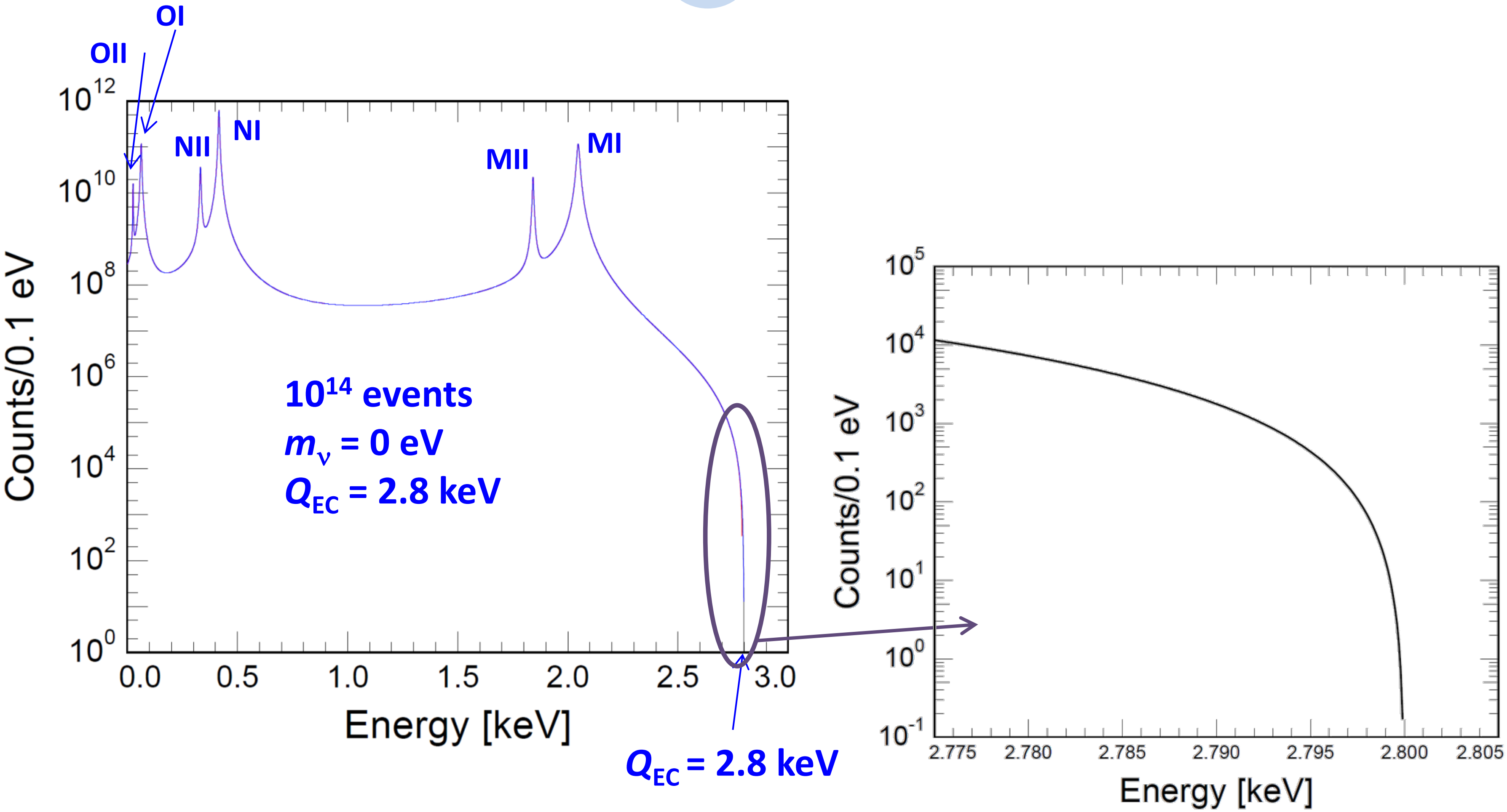

10^{14} events

m_{ν} = 0 eV

Q_{EC} = 2.8 keV

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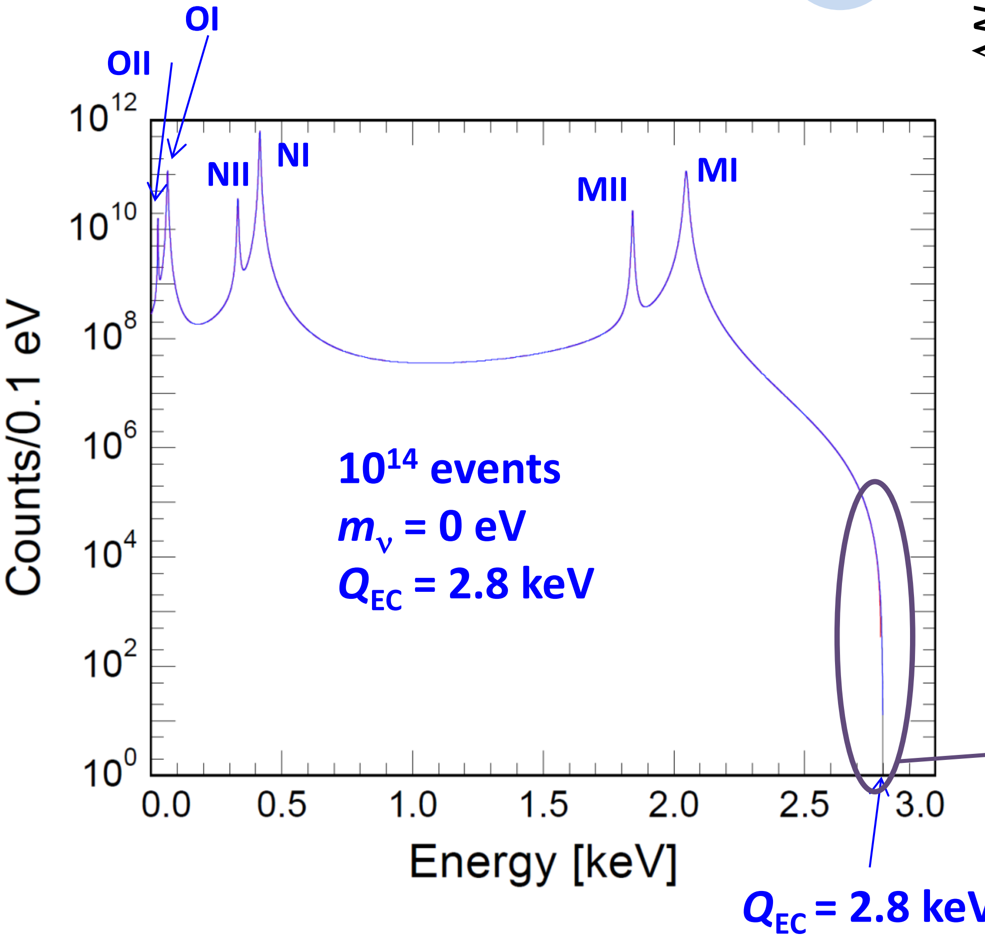

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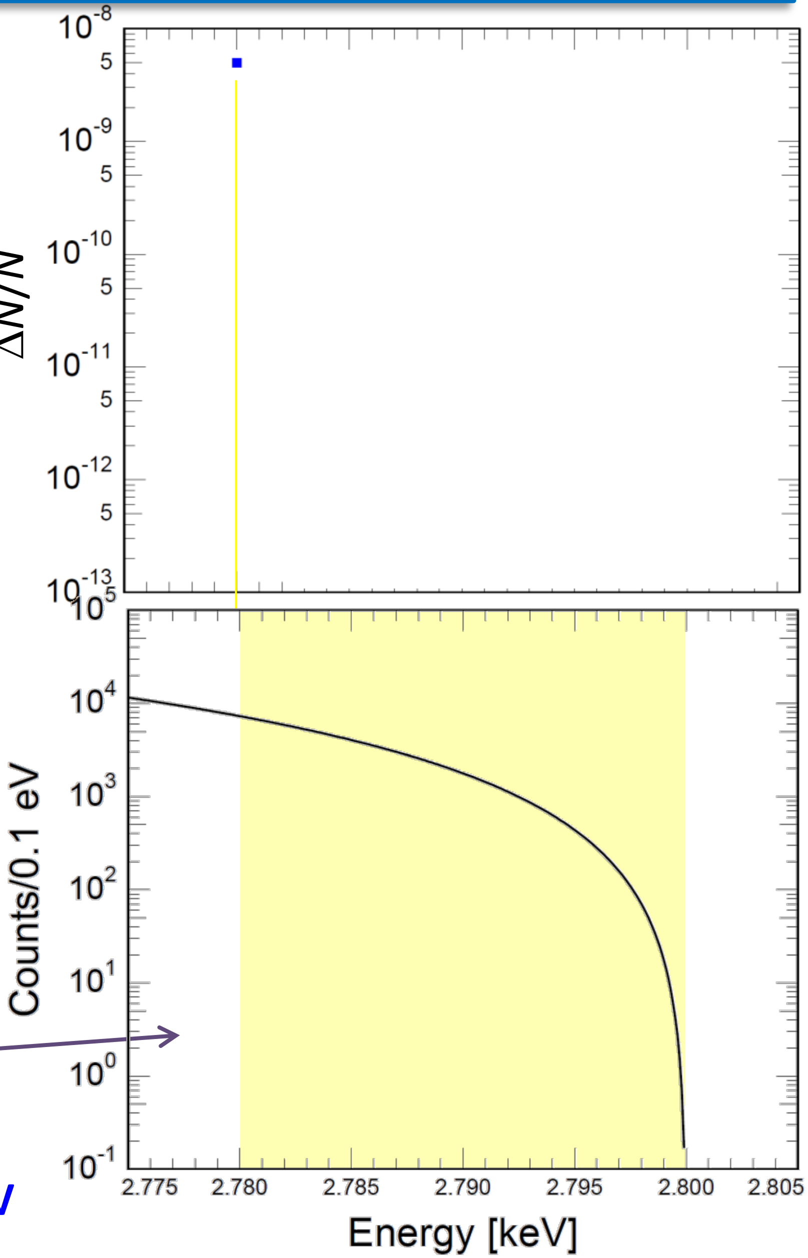

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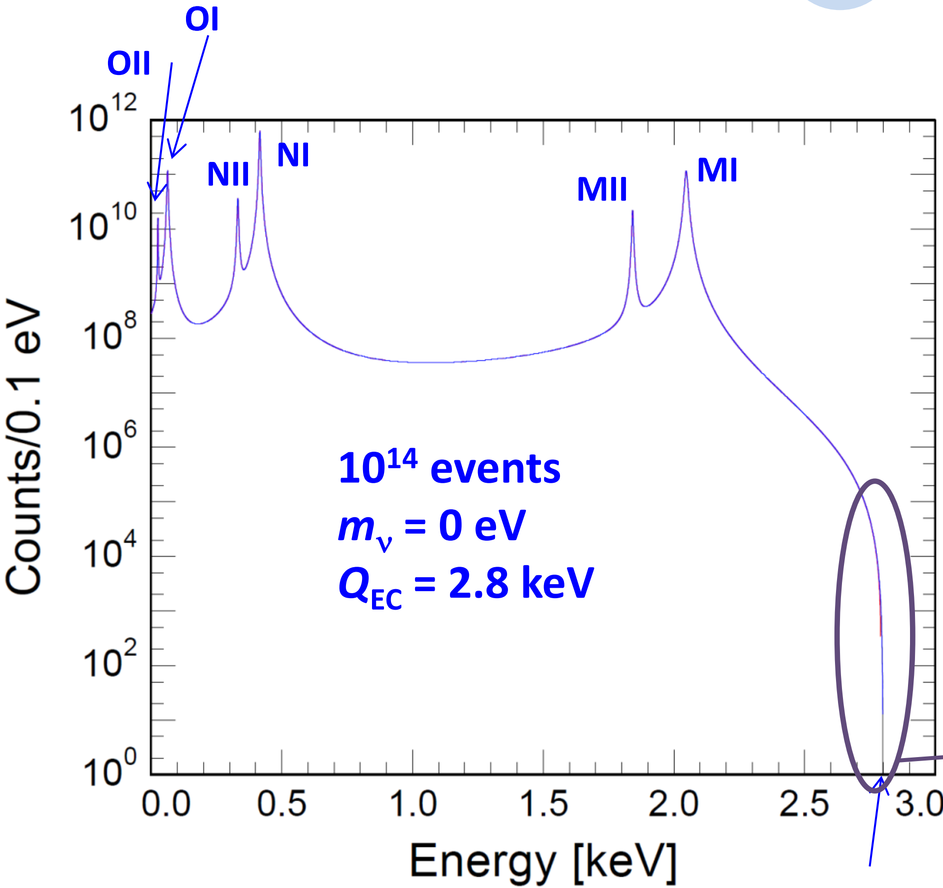

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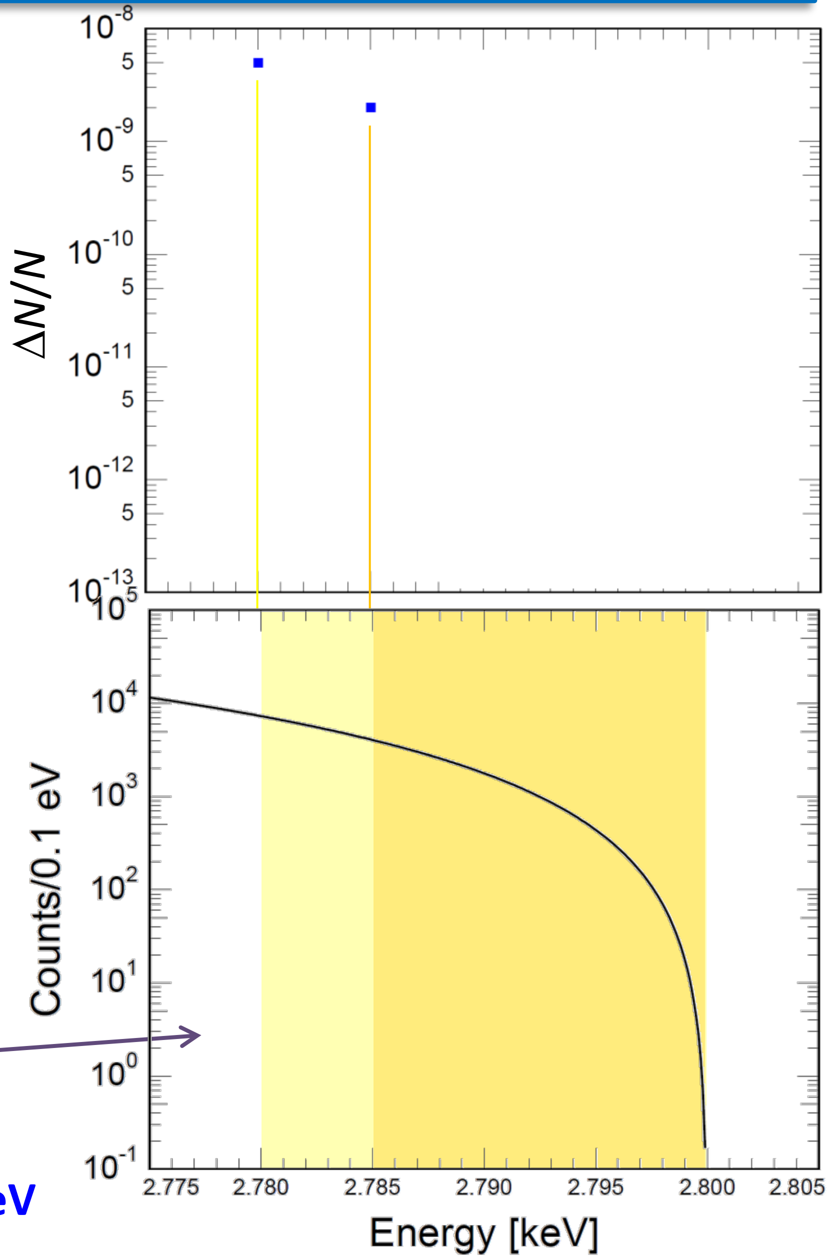

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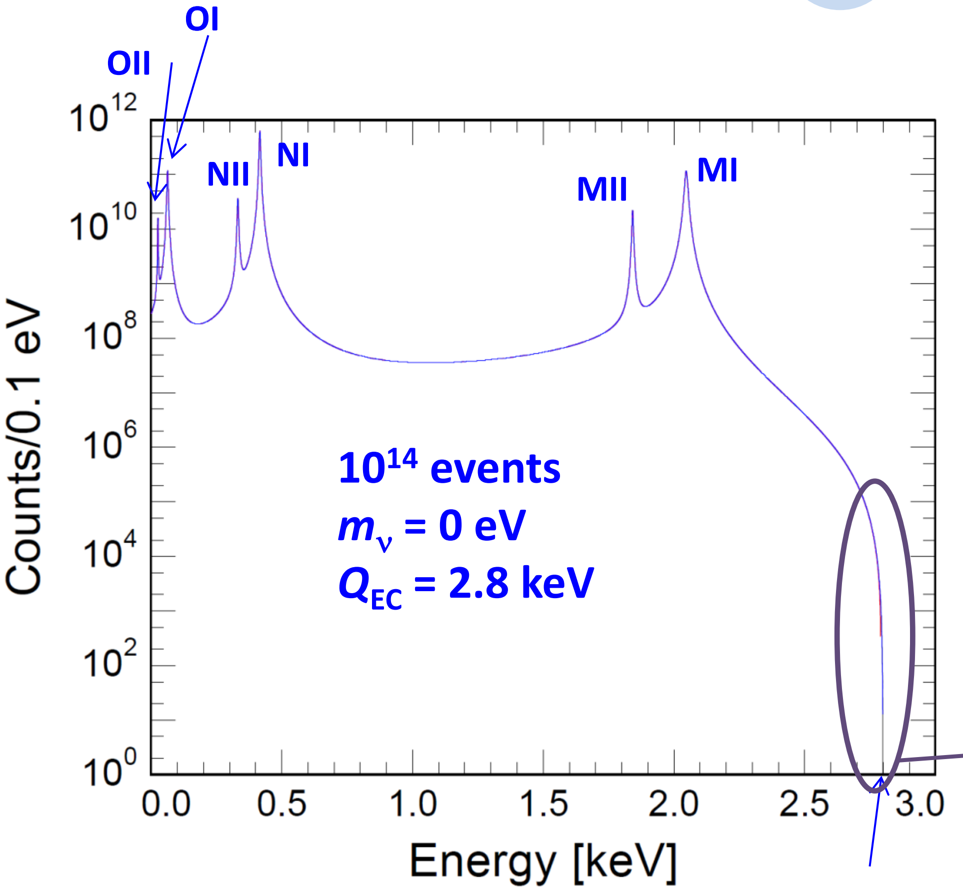

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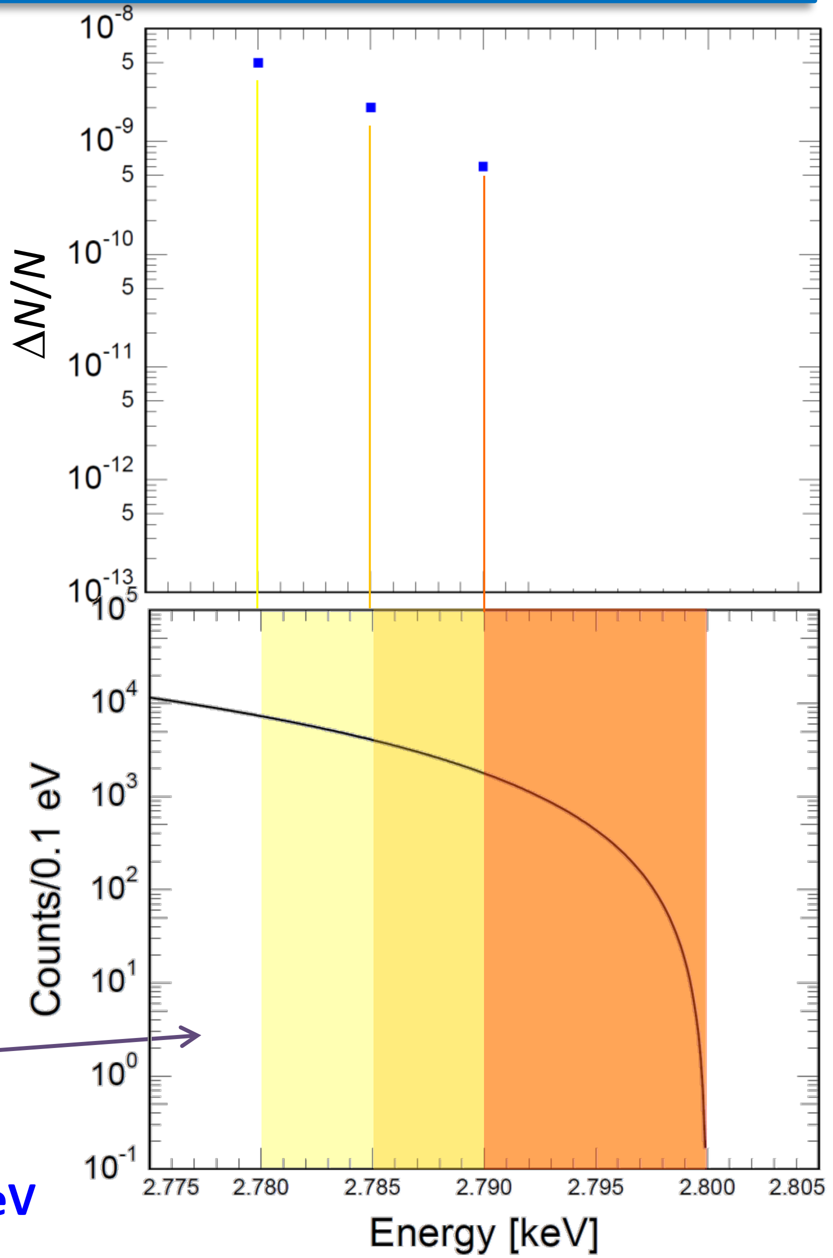

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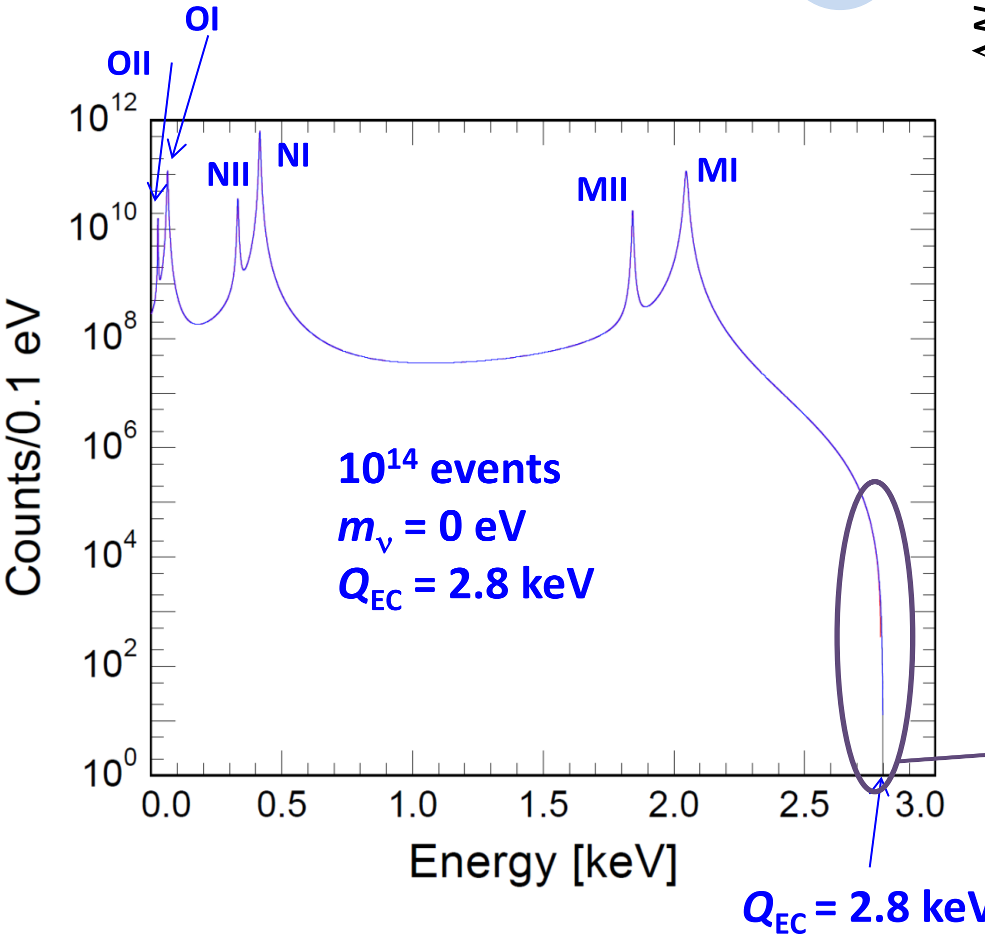

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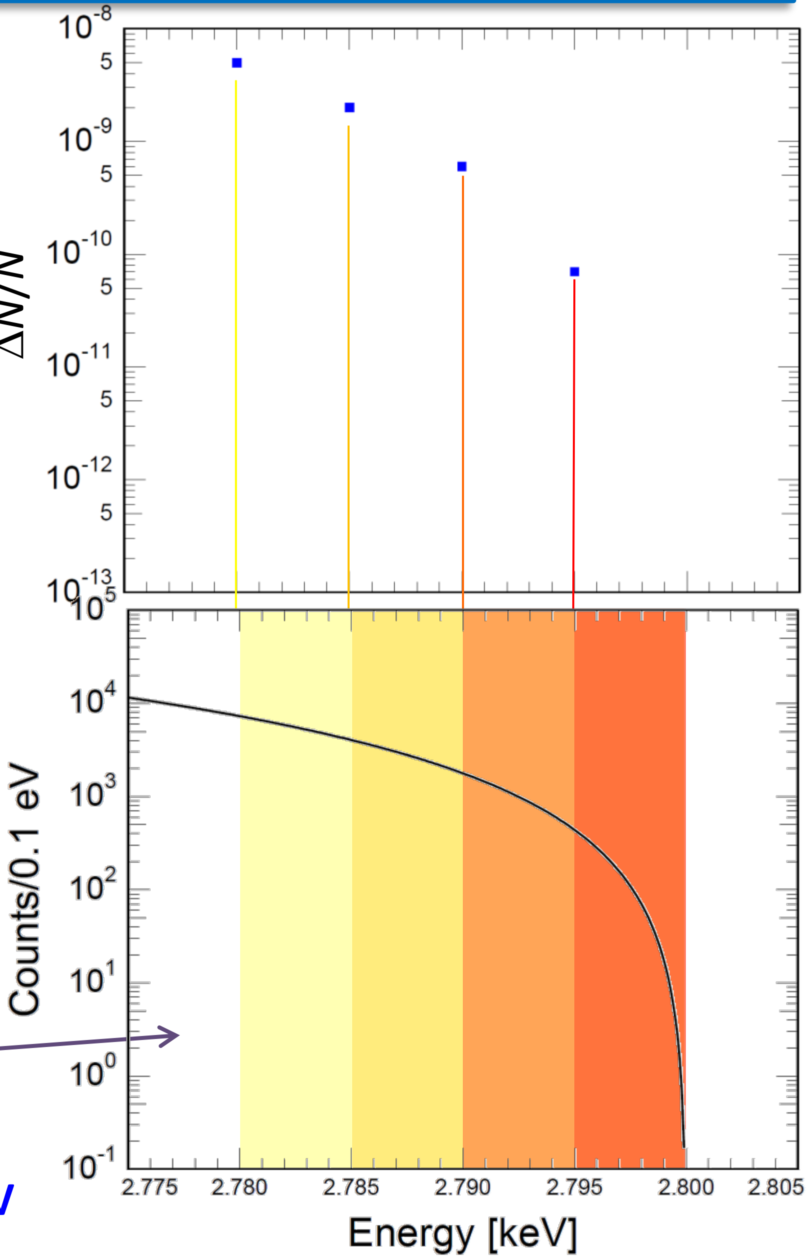

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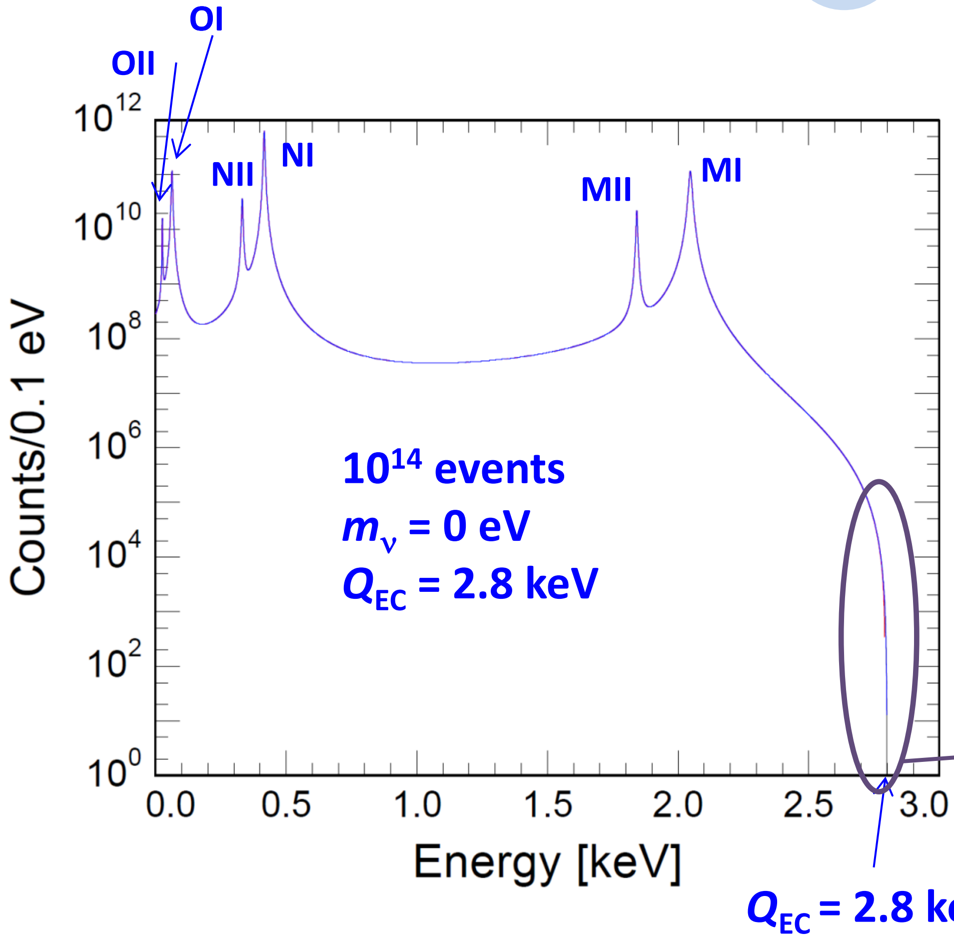

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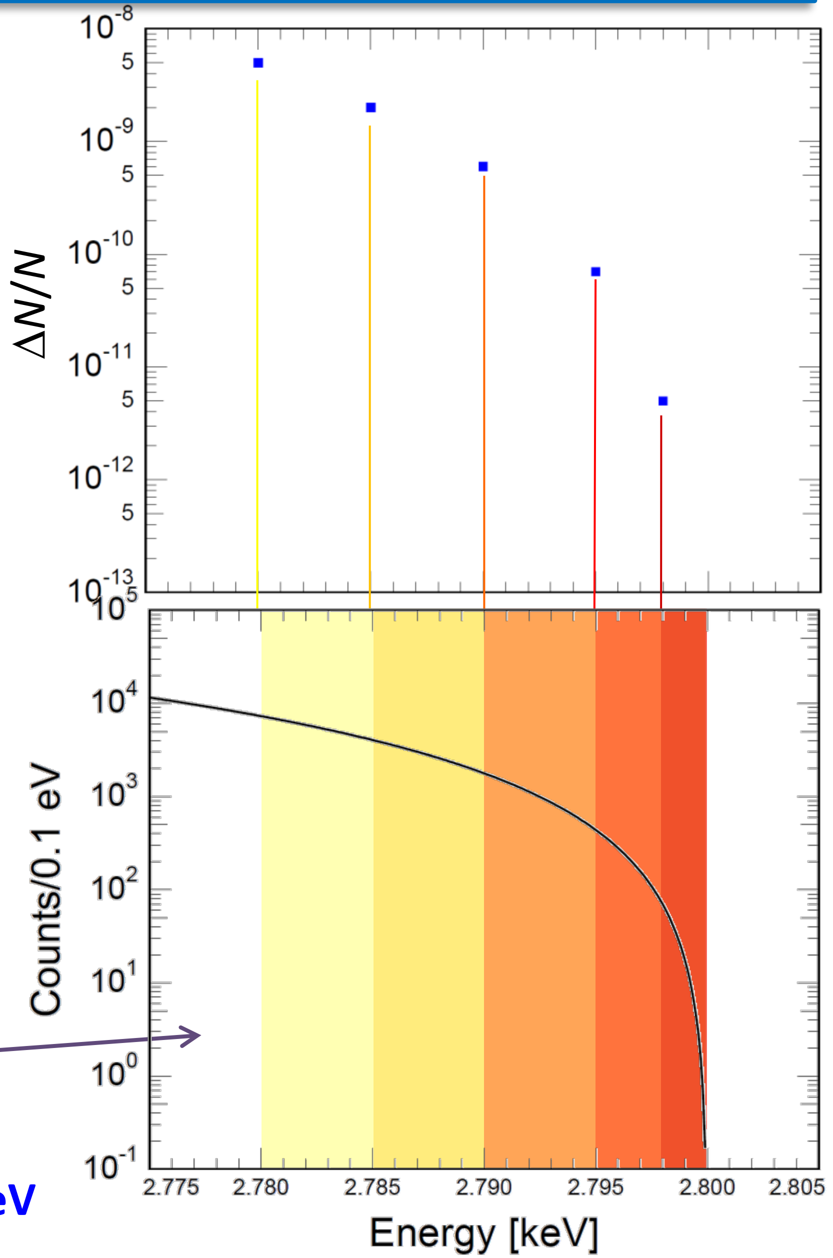

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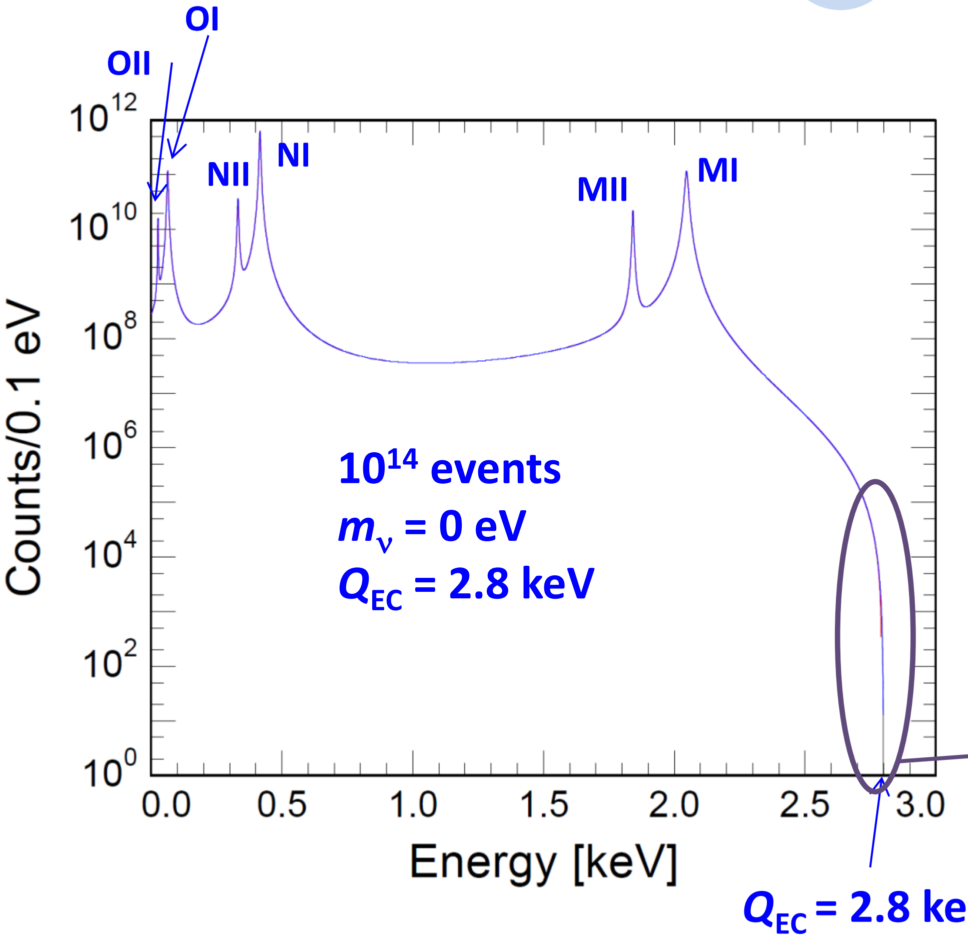

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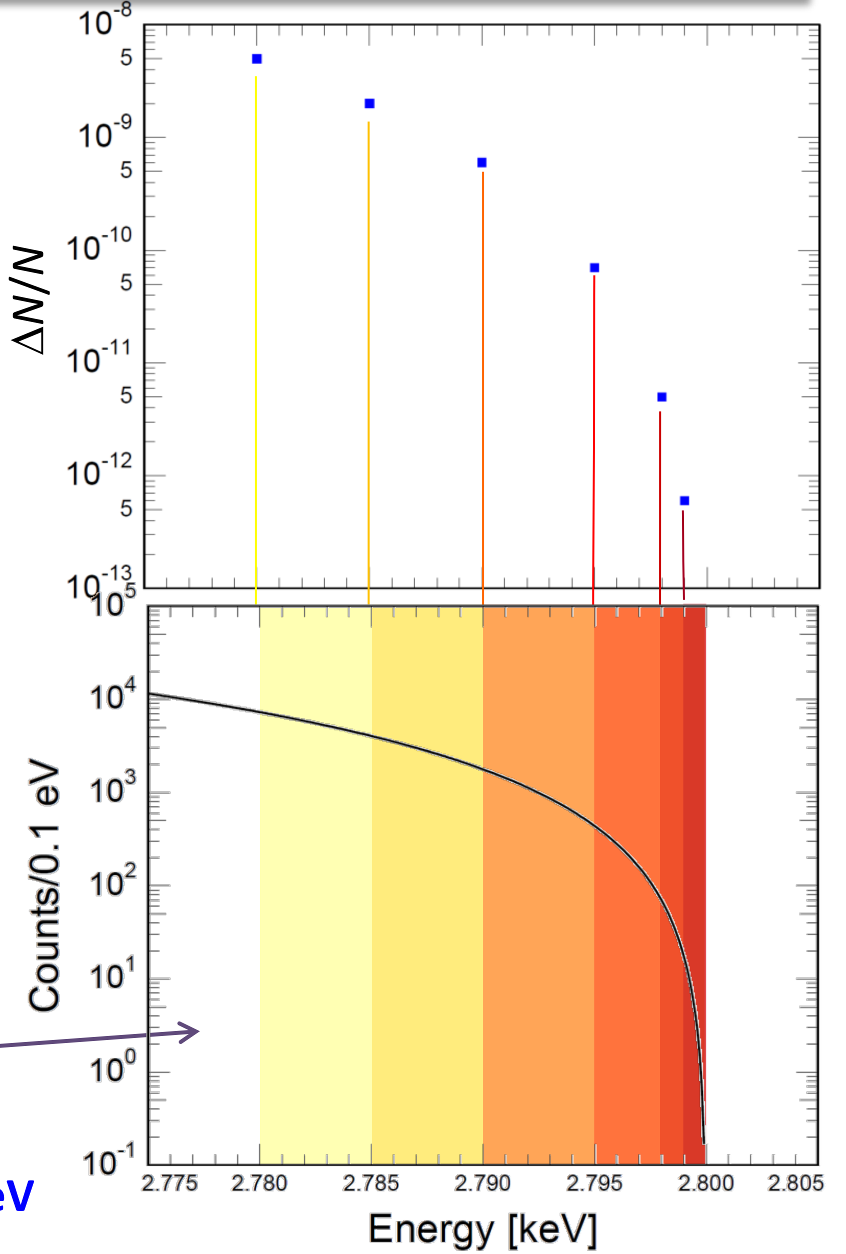

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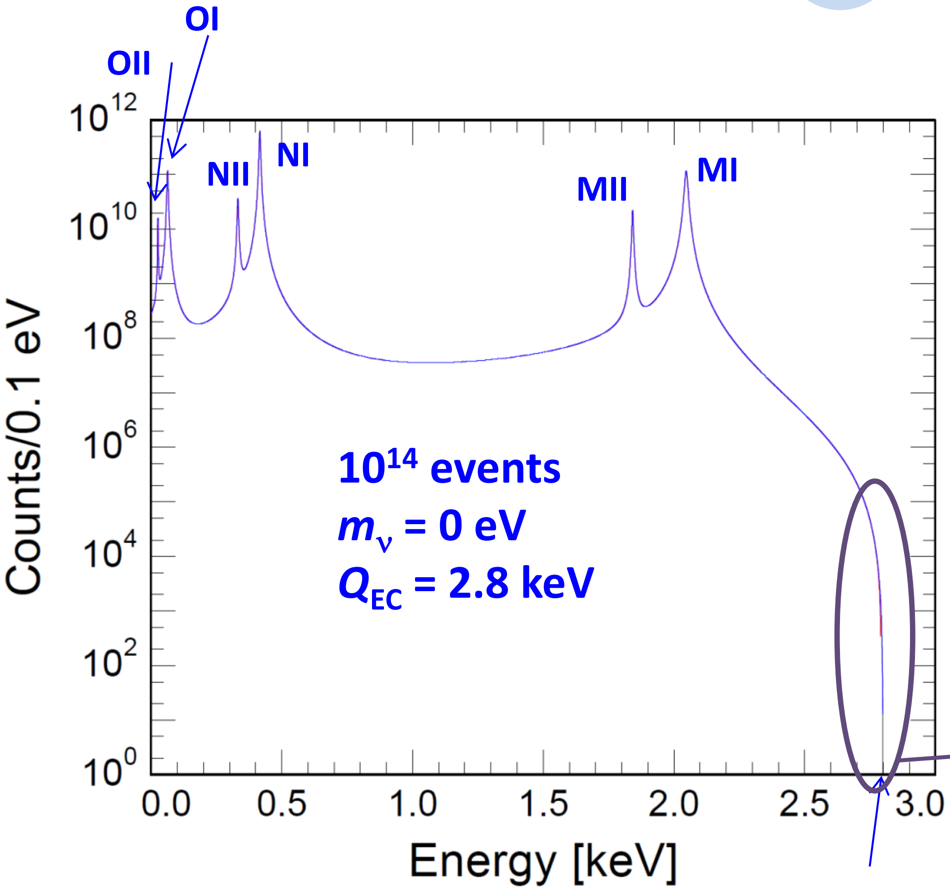

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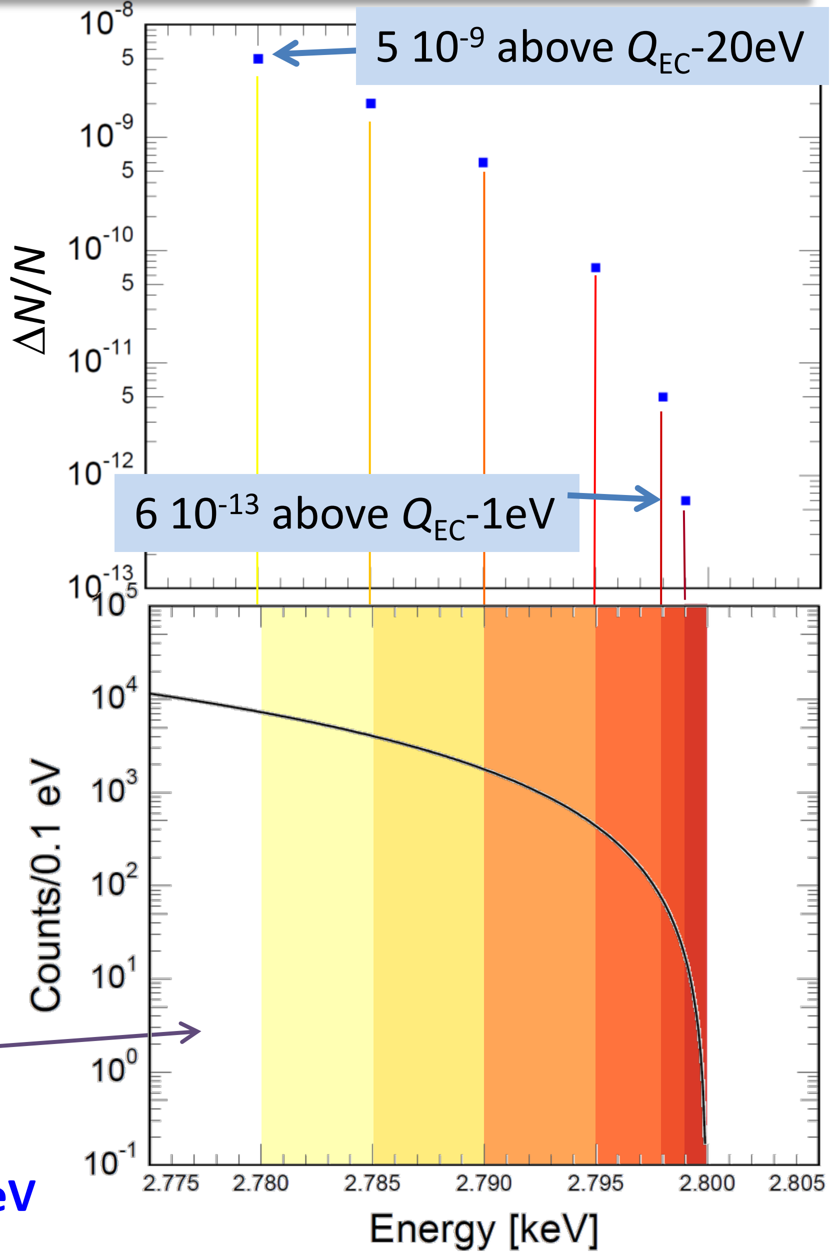
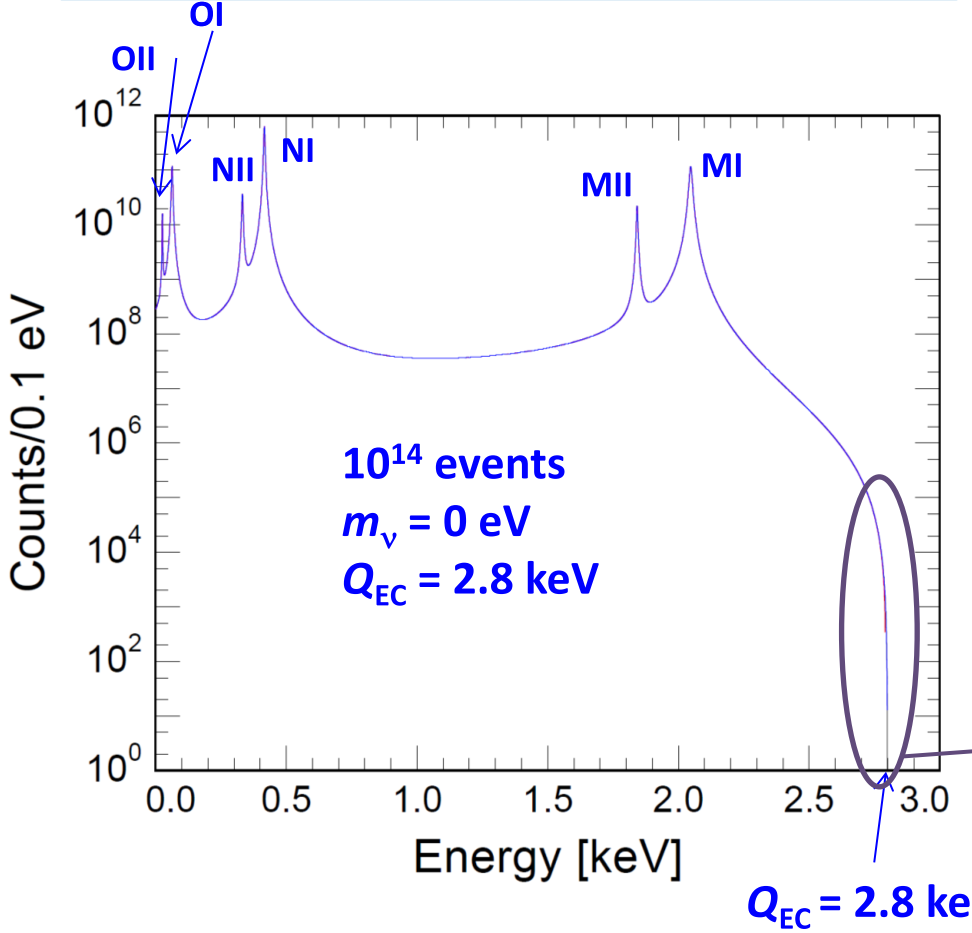


5 10^{-9} above Q_{EC}-20eV

6 10^{-13} above Q_{EC}-1eV

The case of ^{163}Ho: Statistics

More than 10^{14} events
→ A ~ MBq



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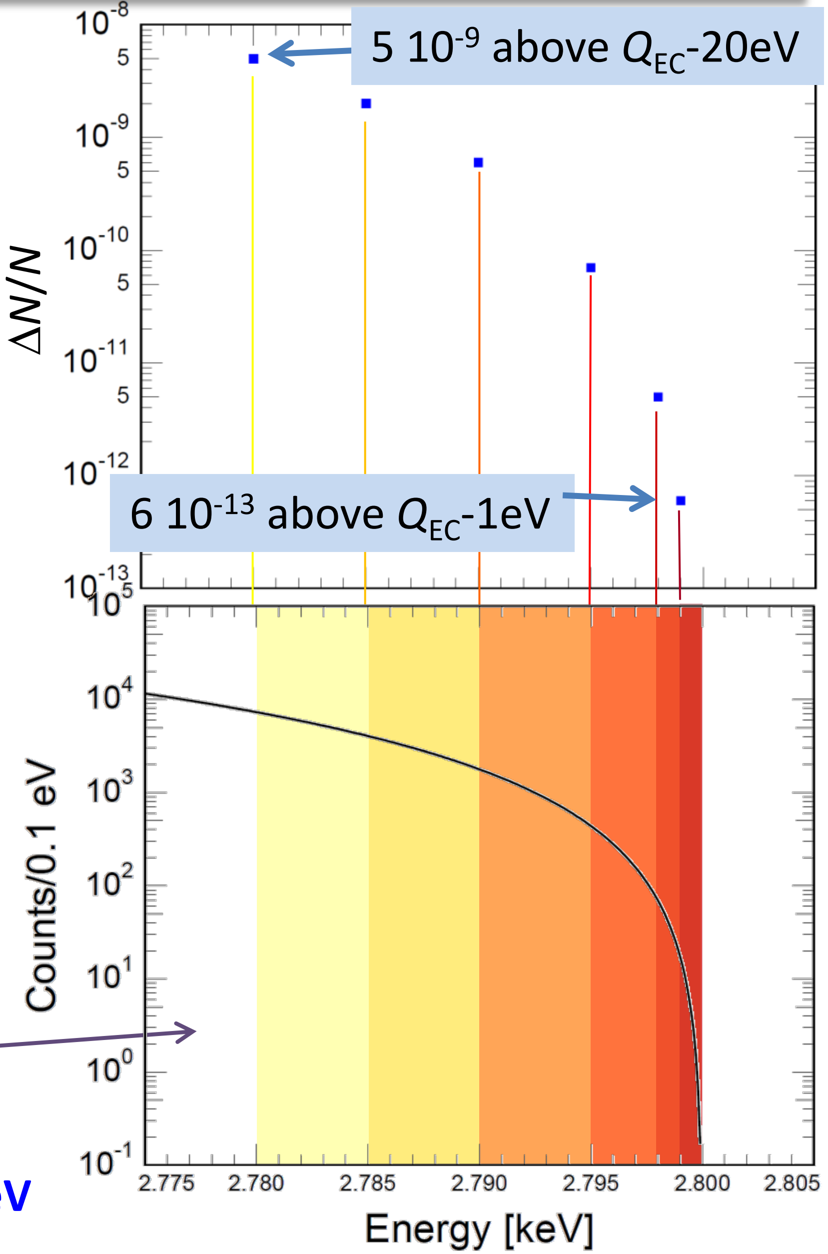

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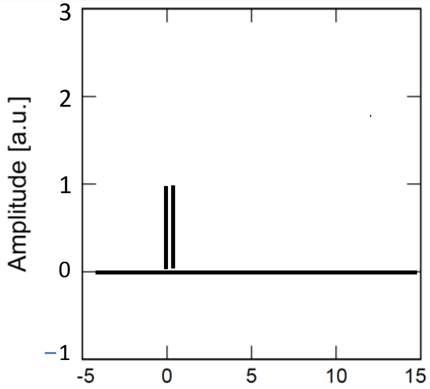
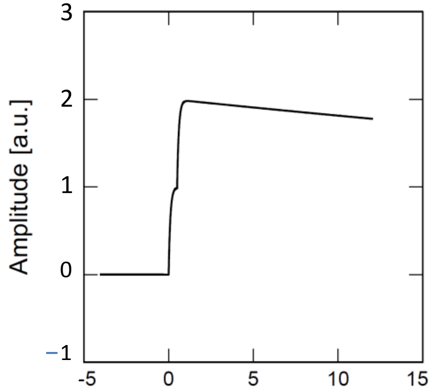
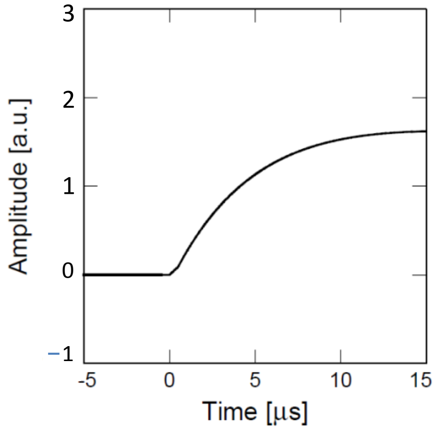
The case of ^{163}Ho: Unresolved pile-up



Δt = 0.5 μs

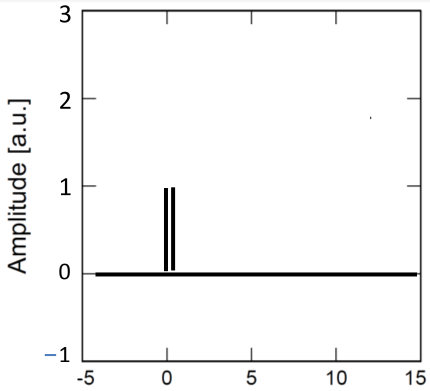


τ_r = 0.1 μs



τ_r = 5 μs

The case of ^{163}Ho: Unresolved pile-up



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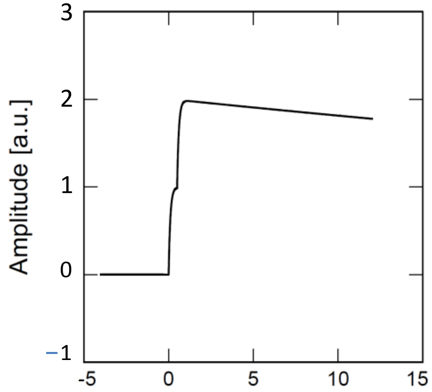

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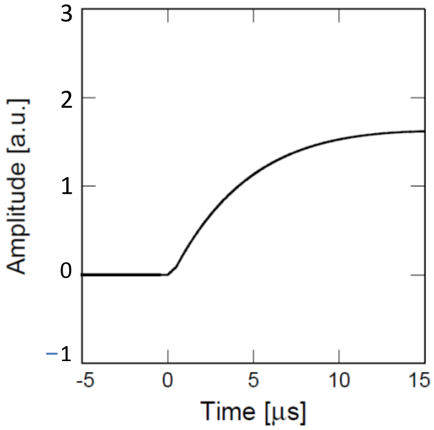

τ_r = 5 μs

$$f_{pu} \approx A\tau_r$$

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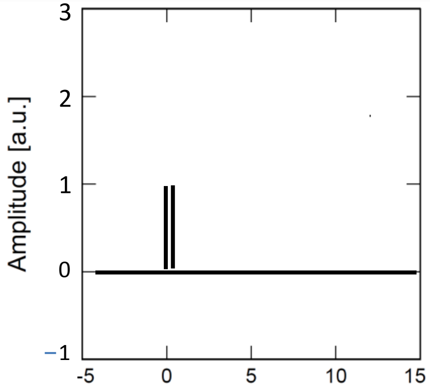

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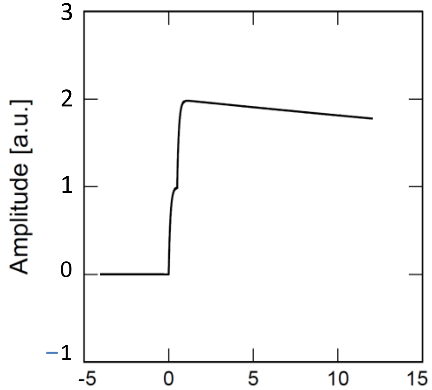

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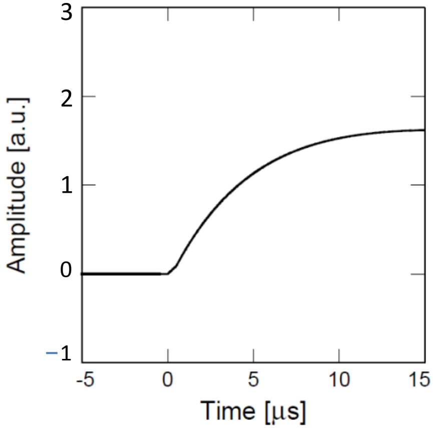

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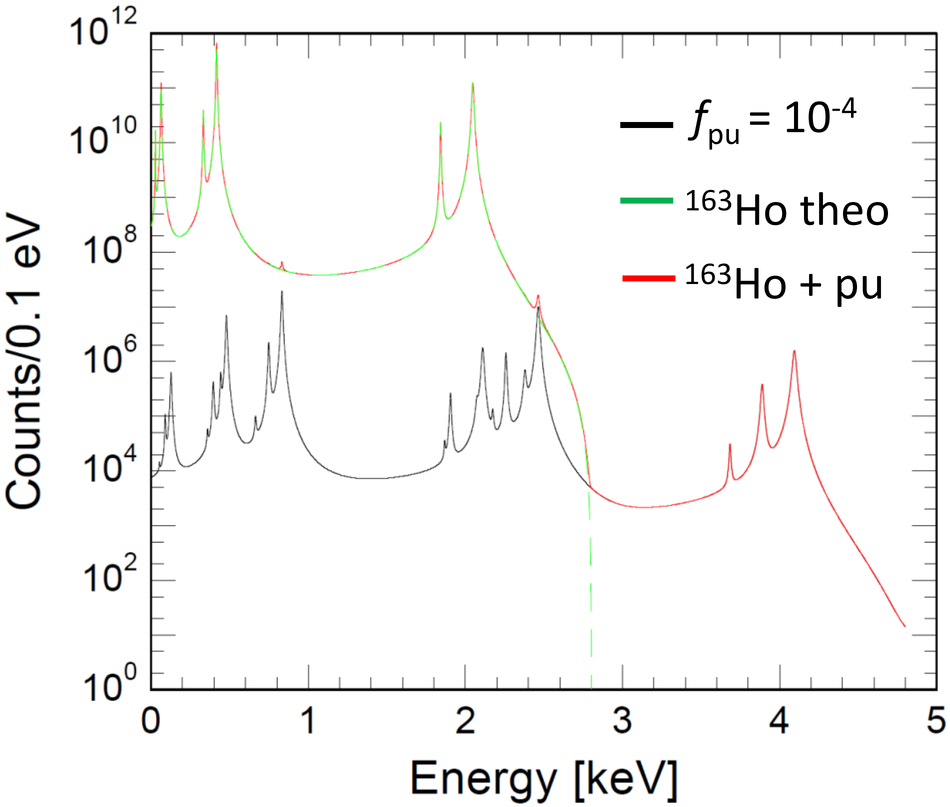

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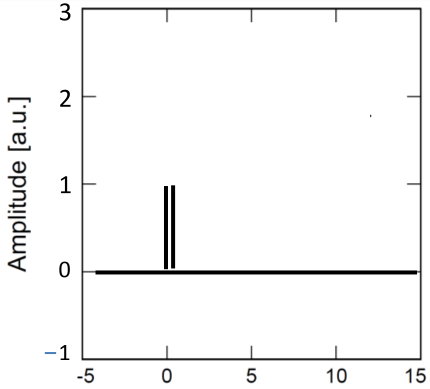

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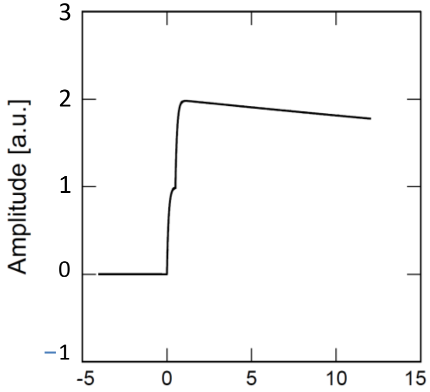

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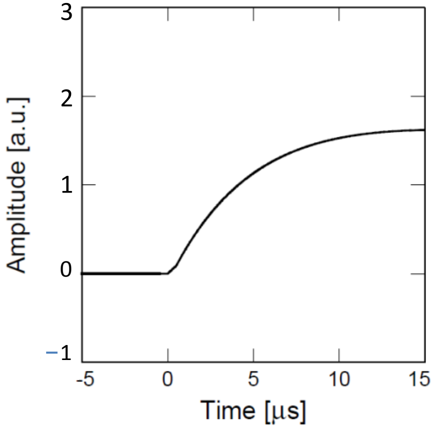

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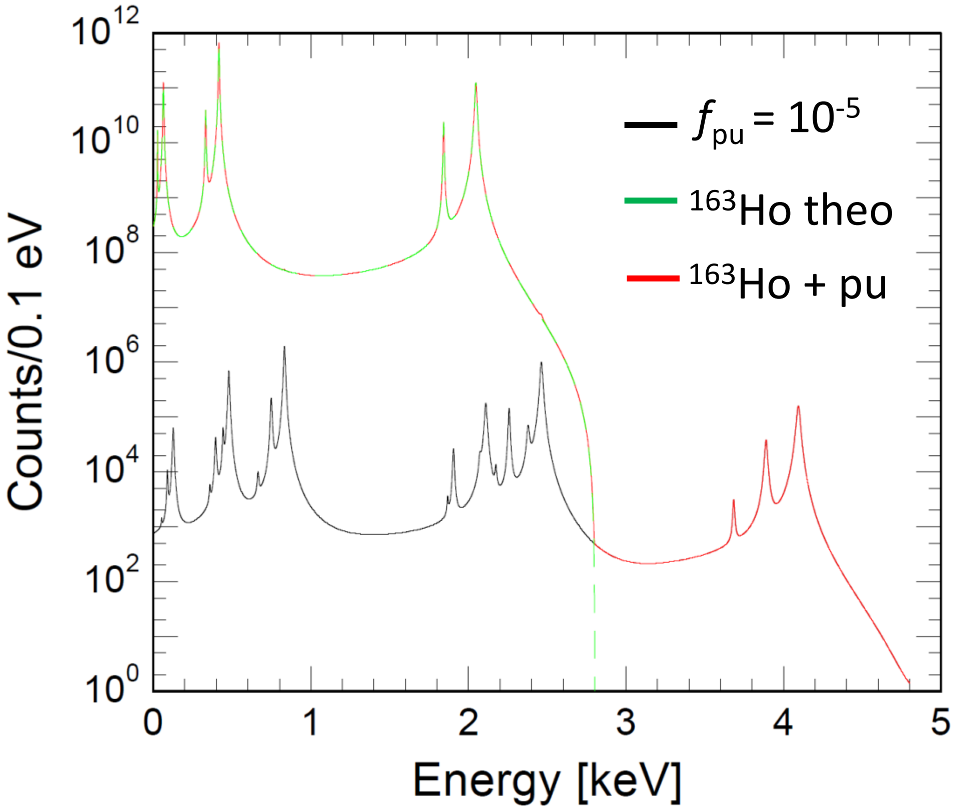

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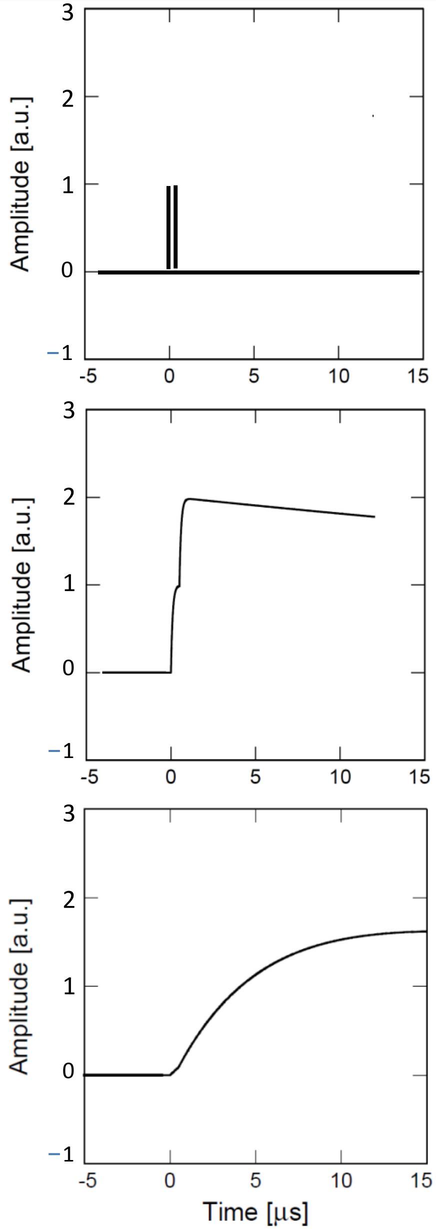

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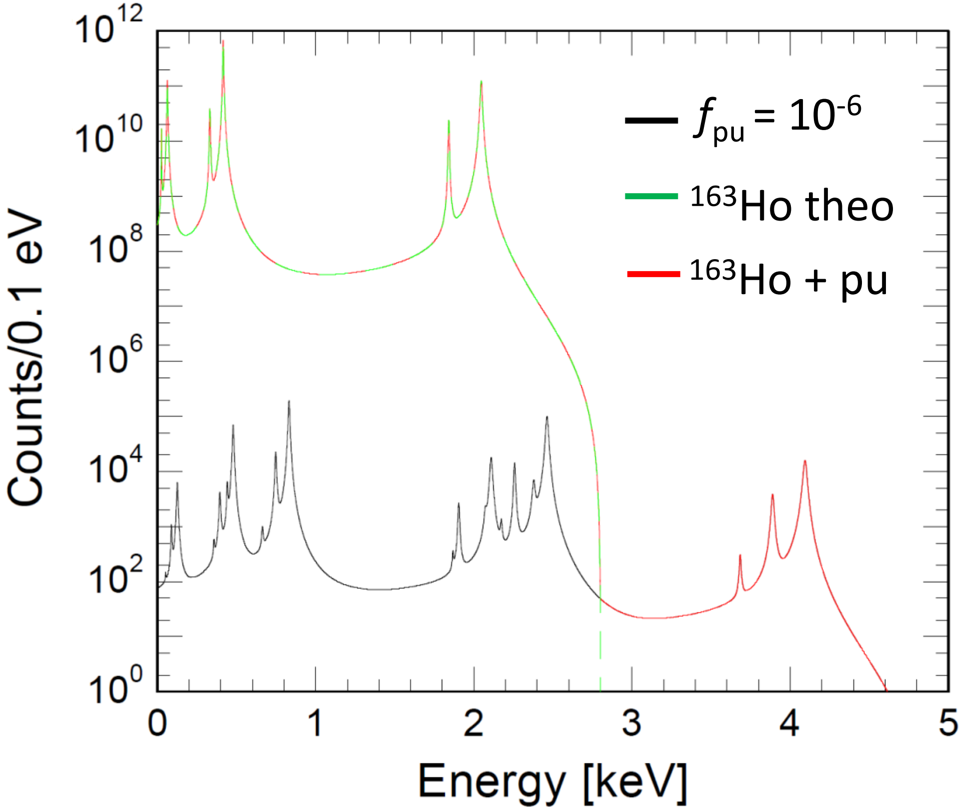

$\boldsymbol{f_{pu} = 10^{-6}}$

$\tau_r = 10^{-6}$ s → A = 1 Bq

10^6 Bq → **10^6 detectors**

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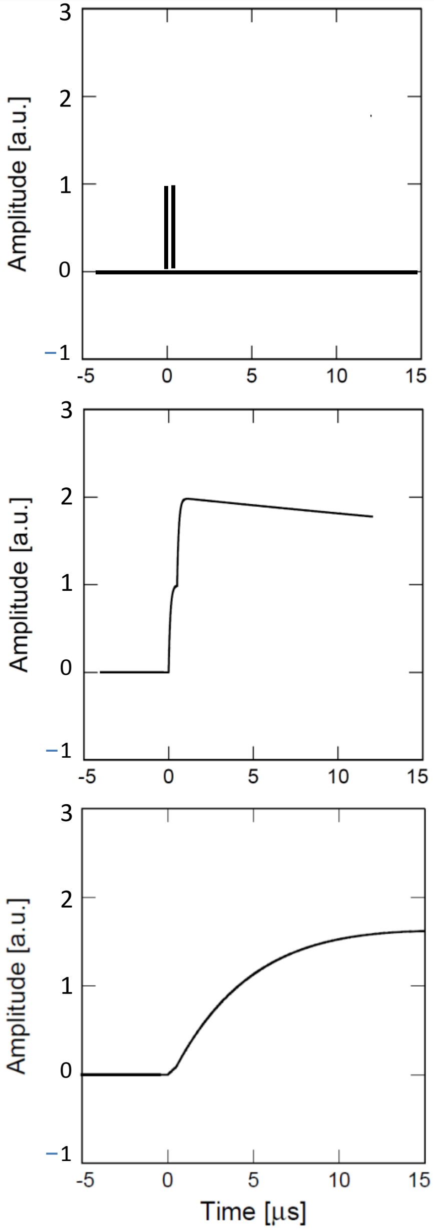

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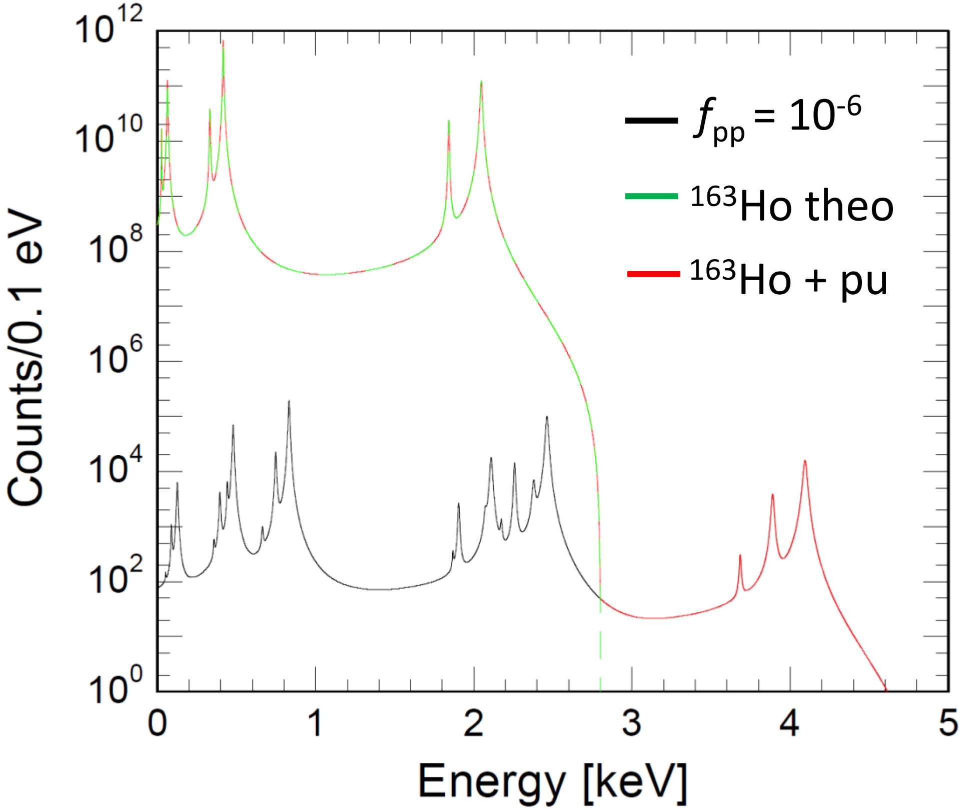

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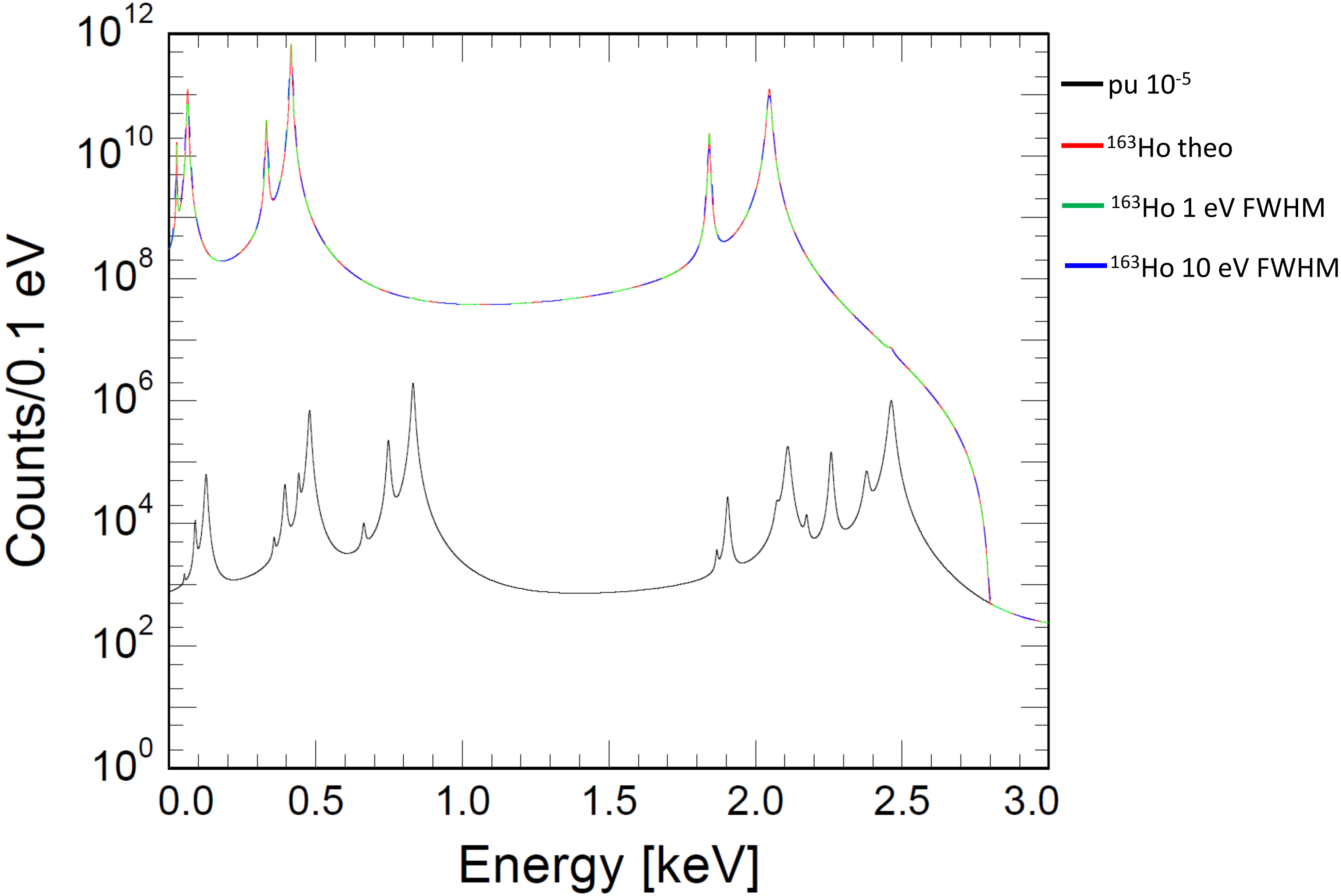
Fast detectors

The case of ^{163}Ho: Energy resolution



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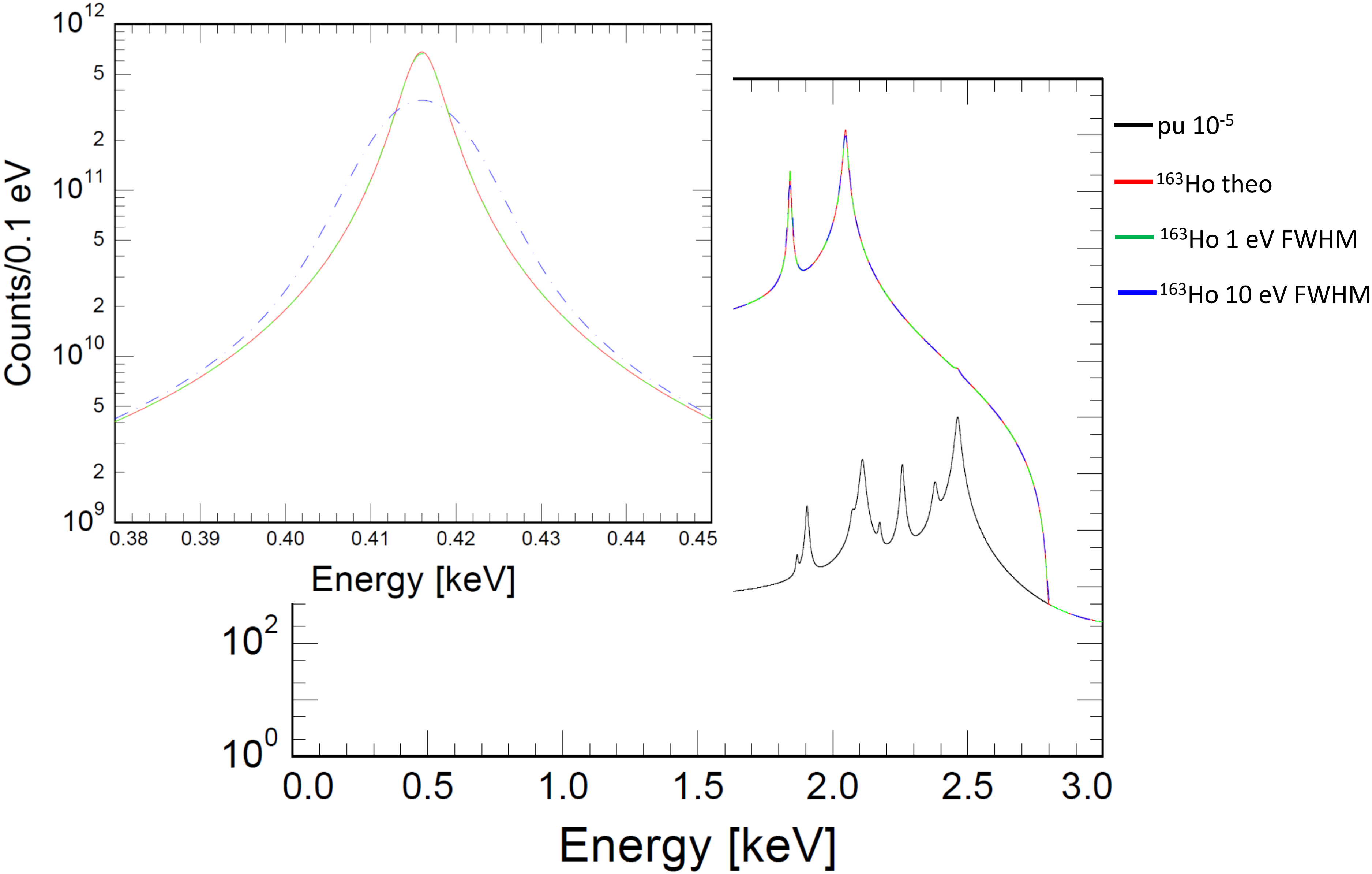

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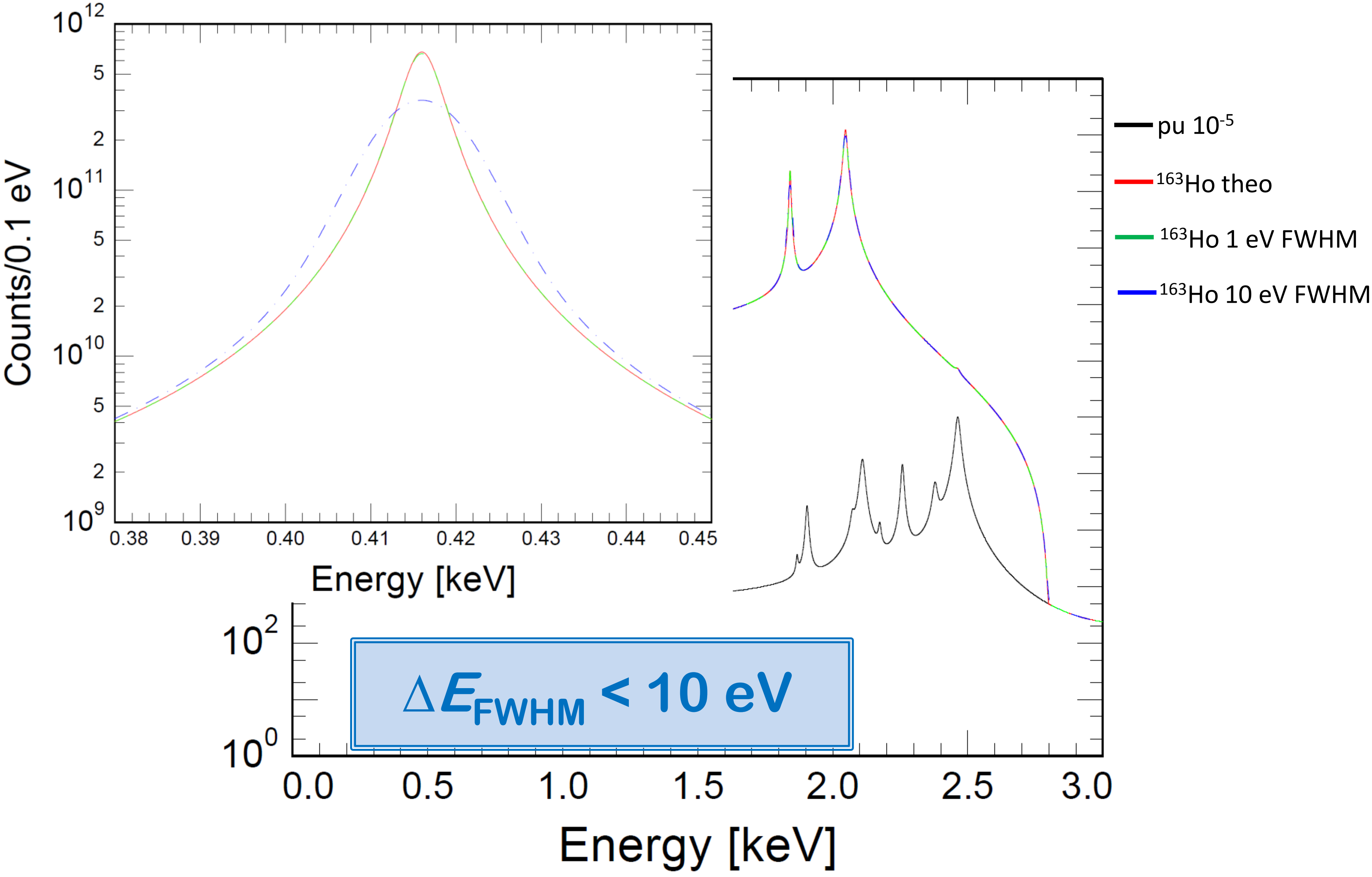

$\Delta E_{\mathrm{FWHM}} < 10$ eV

Sub-eV sensitivity

$N_{\mathrm{ev}} > 10^{14}$
$f_{\mathrm{pu}} < 10^{-5}$
$\Delta E_{\mathrm{FWHM}} < 10\ \mathrm{eV}$

$\longrightarrow$

$\tau_{\mathrm{r}} \sim 0.1\ \mu\mathrm{s}$
$\Delta E_{\mathrm{FWHM}} = 2\ \mathrm{eV}$
$A_{\beta} \approx 10\ \mathrm{s}^{-1}$

$\longrightarrow$

$\geq 10^{5}$ detectors

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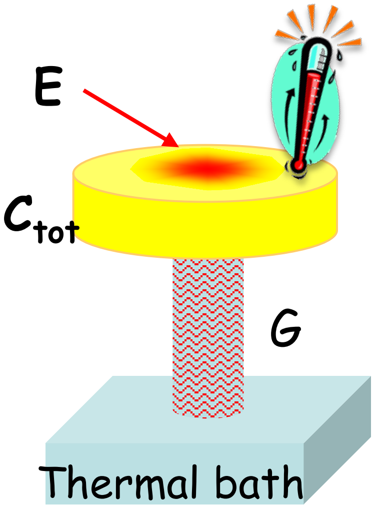
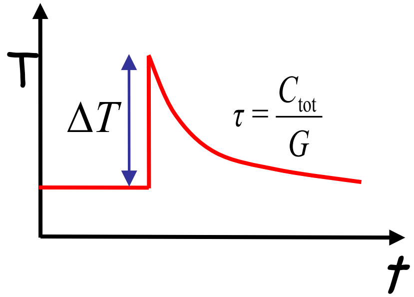
Low temperature
Metallic Magnetic Calorimeter

MMCs: Concept



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



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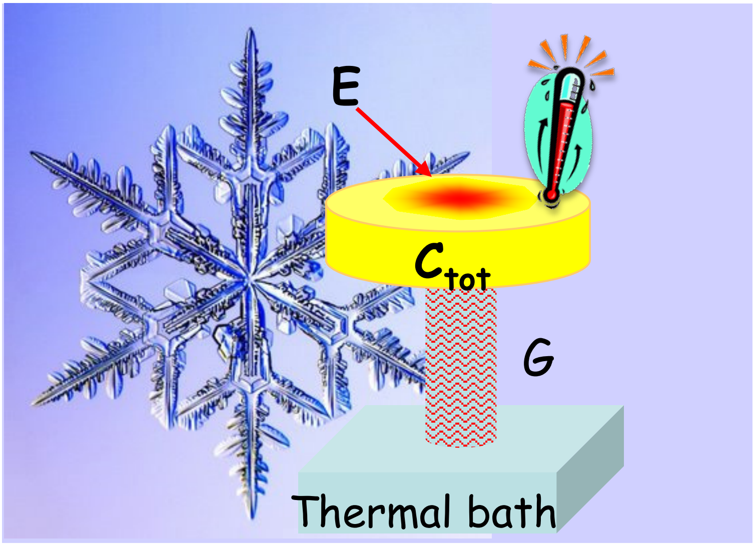

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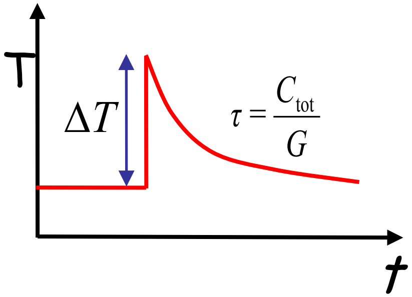


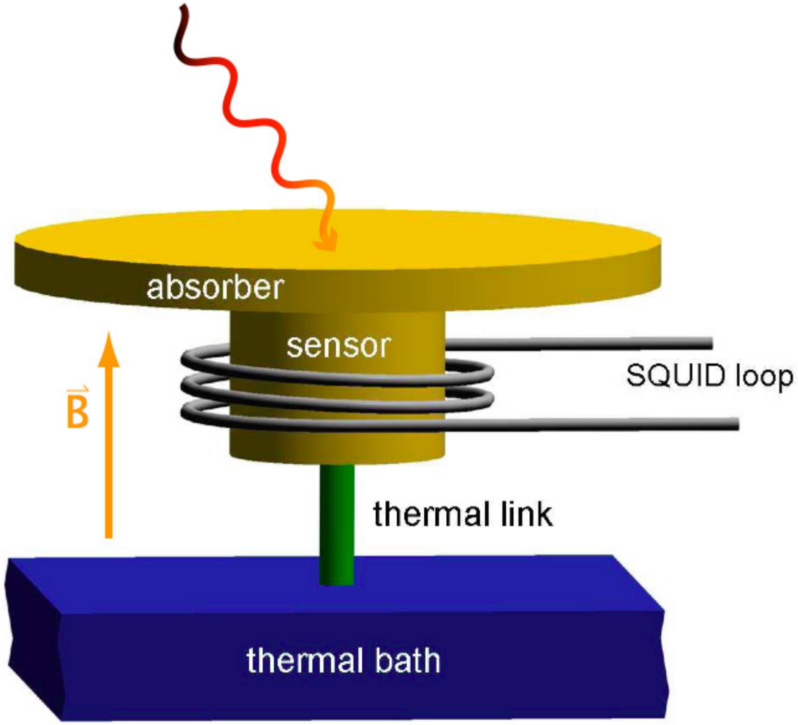
- Working temperature below 100 mK
  - small specific heat
  - large temperature change
  - small thermal noise

- Very sensitive temperature sensor

MMCs: Concept

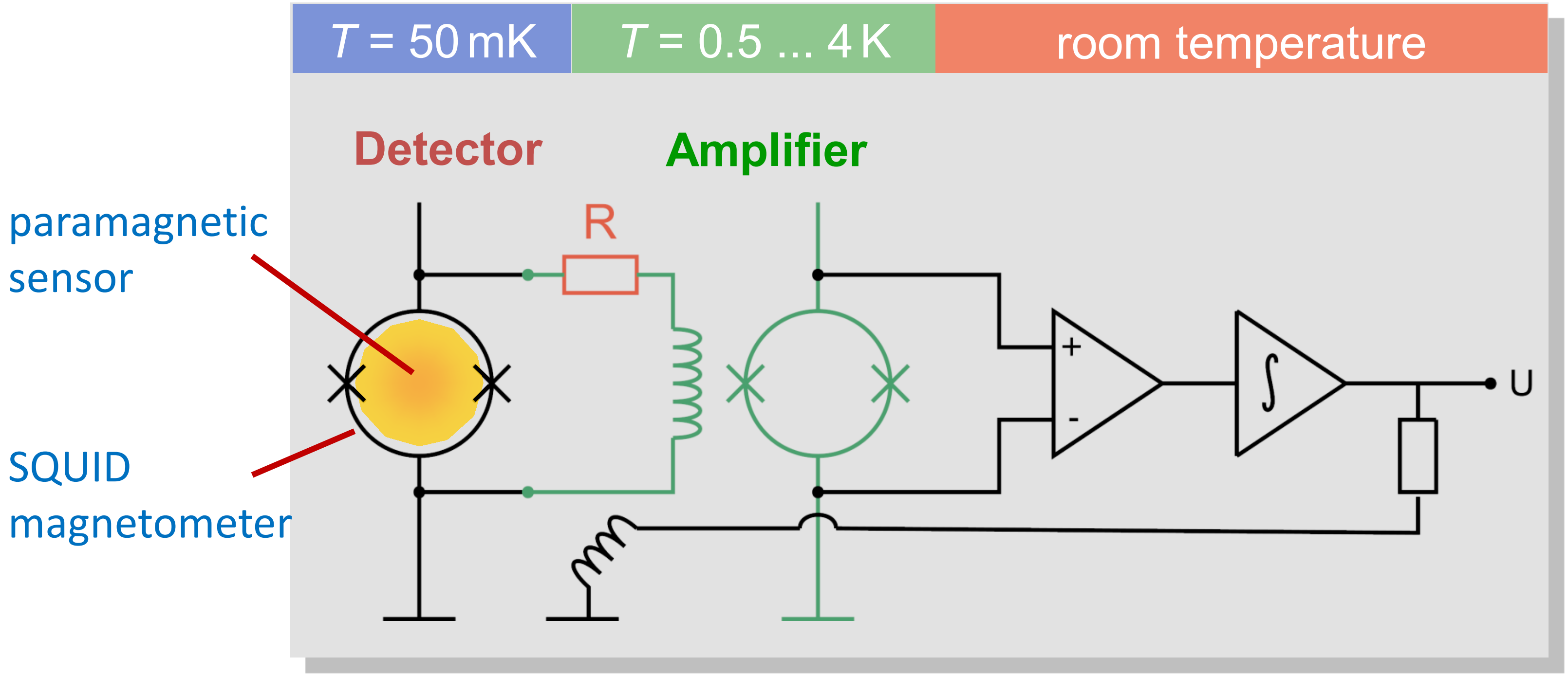
A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

- Paramagnetic Au:Er sensor



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

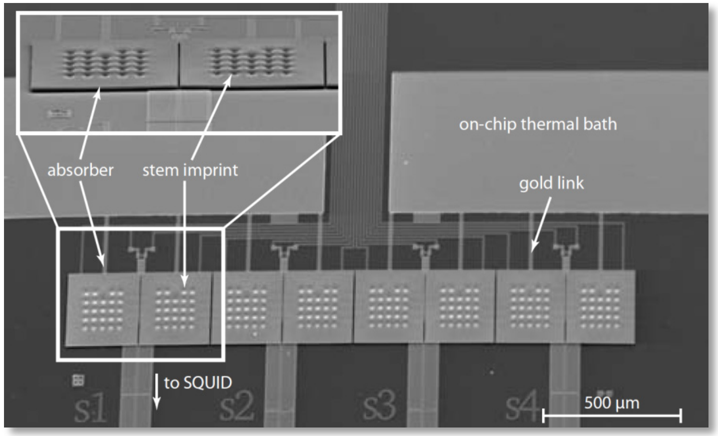
MMCs: Readout

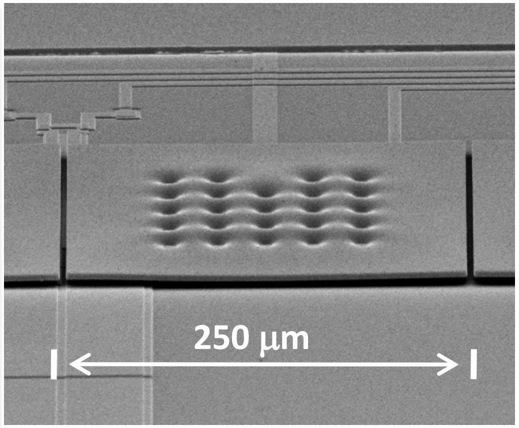


Two-stage SQUID setup with flux locked loop to linearize the first stage SQUID allows for:

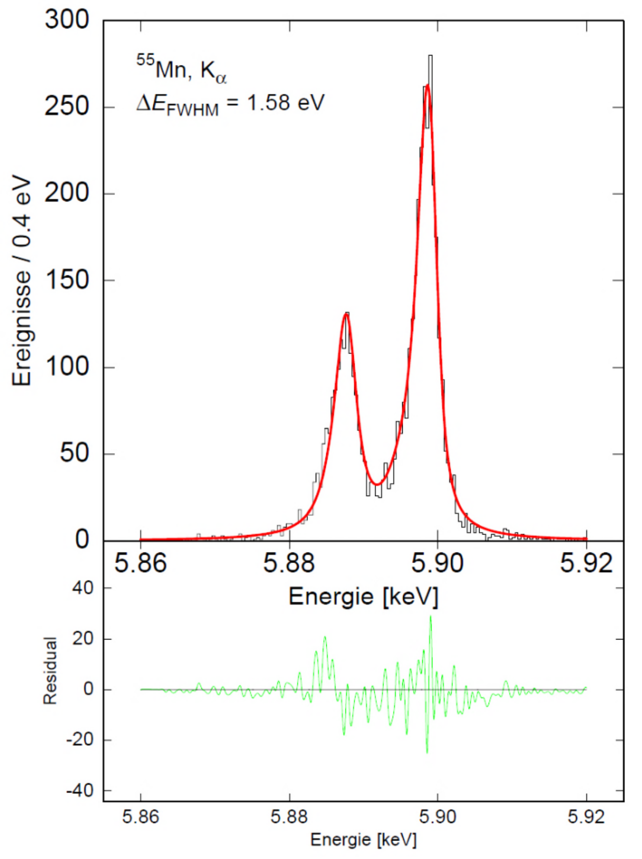
- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)

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

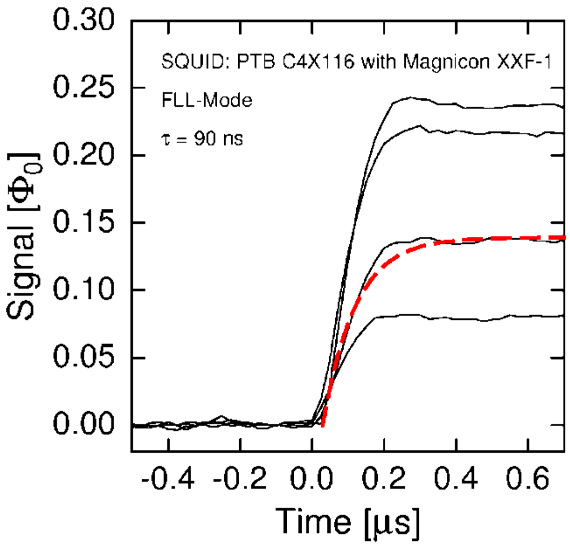




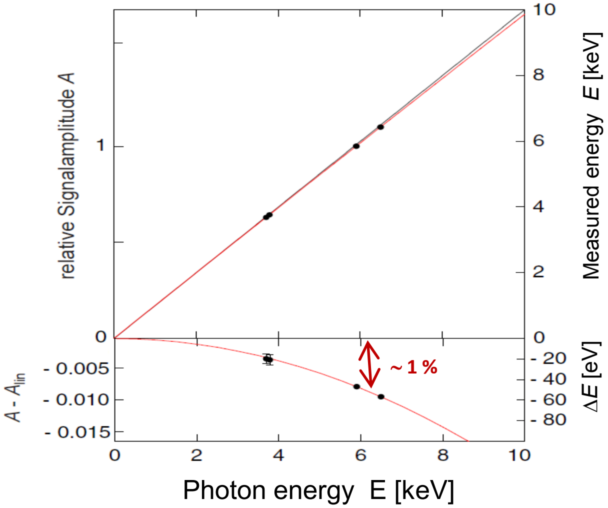
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns

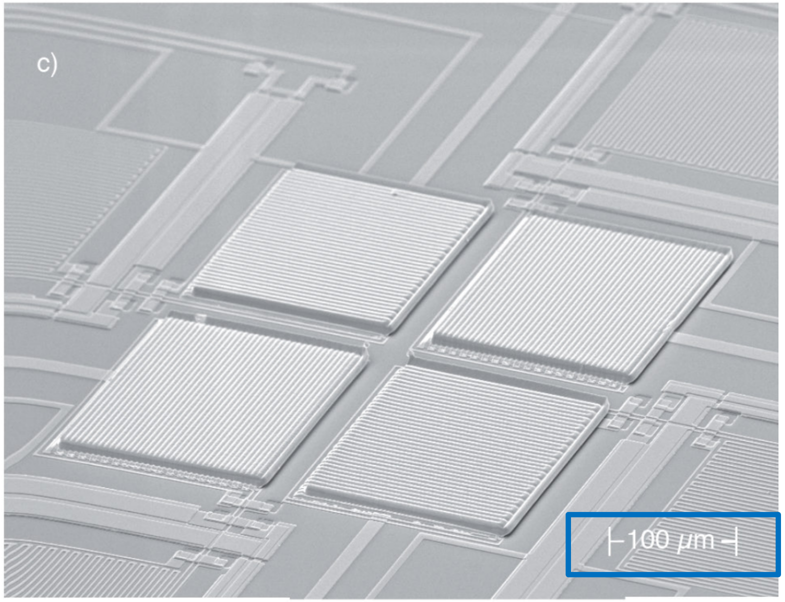


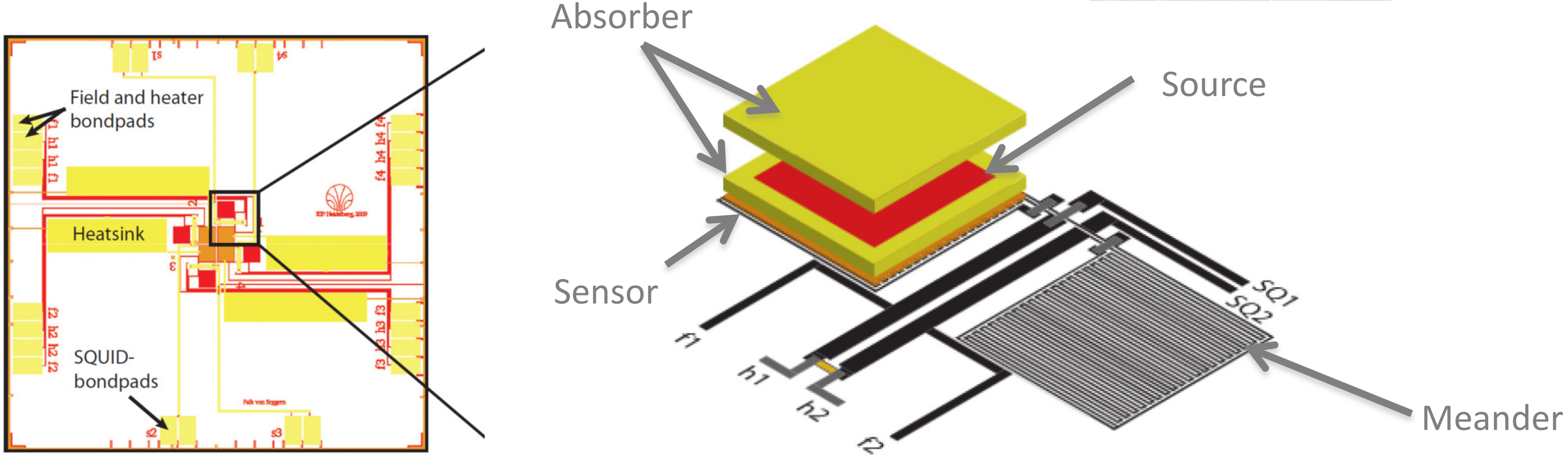
Non-Linearity < 1% @6keV



ECHo: First detector prototype

- Low temperature metallic magnetic calorimeters
- Embedding of ^{163}Ho source:
  → ion implantation @ ISOLDE-CERN
- About 0.01 Bq per pixel
- Two pixels have been simultaneusly measured

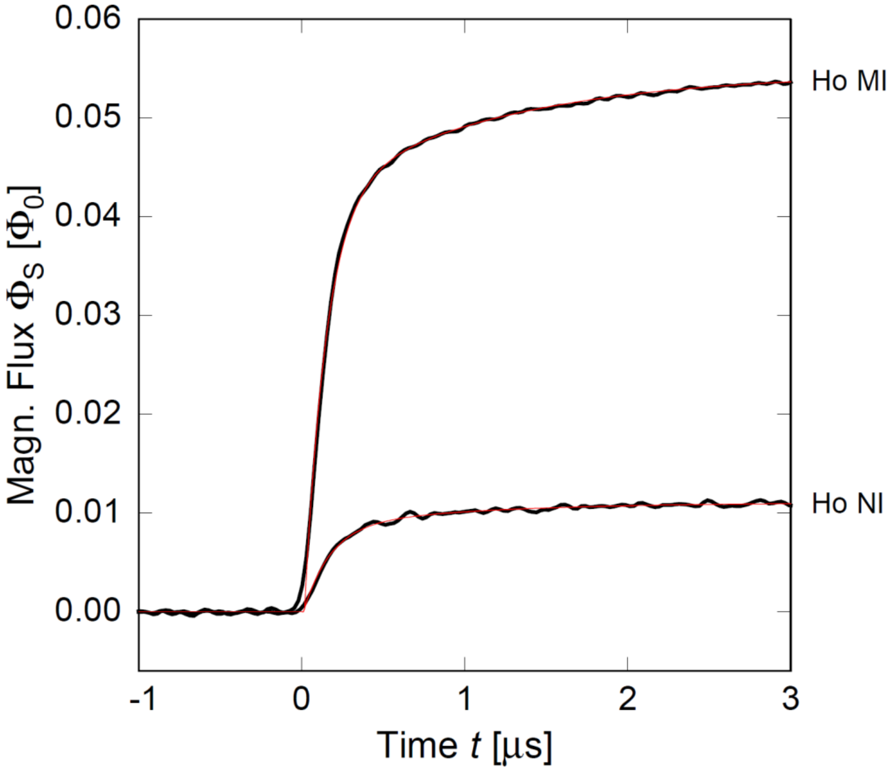




L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

ECHo: Calorimetric spectrum

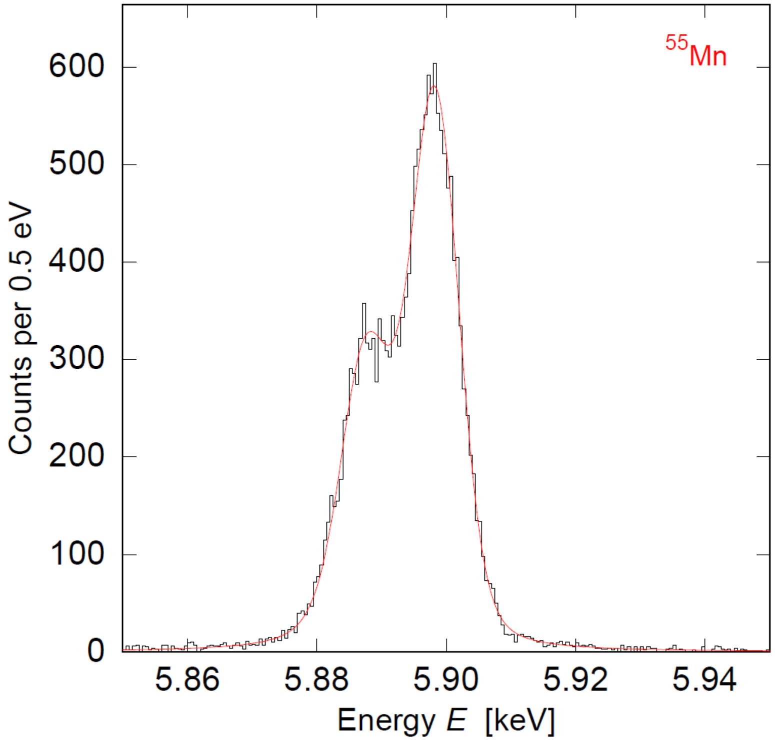
- Rise Time ~ 130 ns



ECHo: Calorimetric spectrum

- Rise Time ~ 130 ns

- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 4.7 eV @ 6 keV (2014)

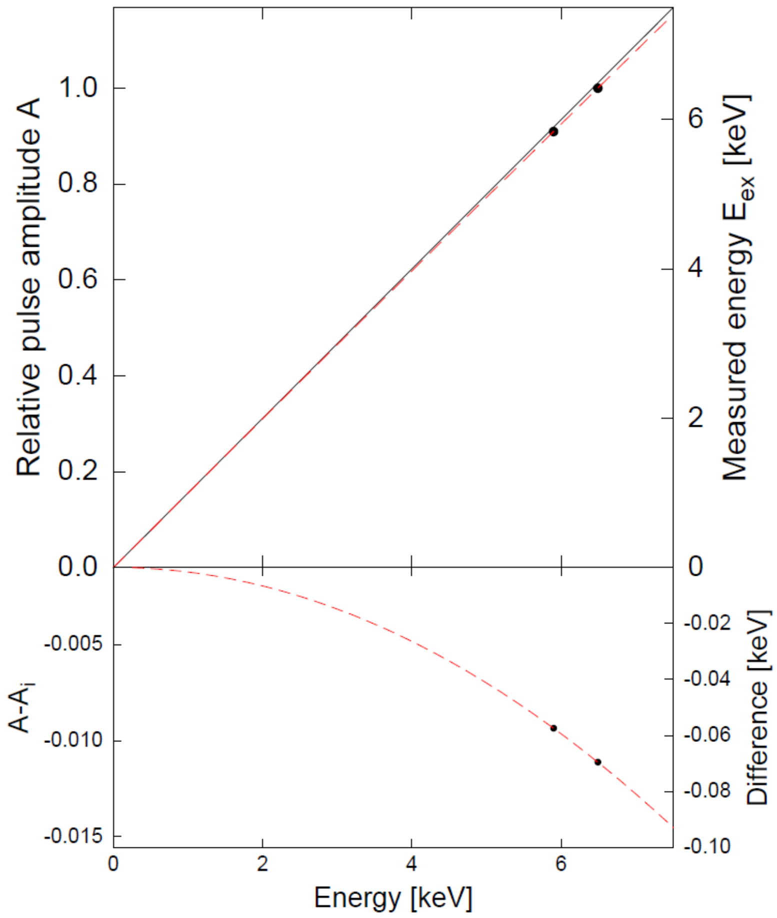


ECHo: Calorimetric spectrum

- Rise Time ~ 130 ns

- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 4.7 eV @ 6 keV (2014)

- Non-Linearity < 1% @ 6keV

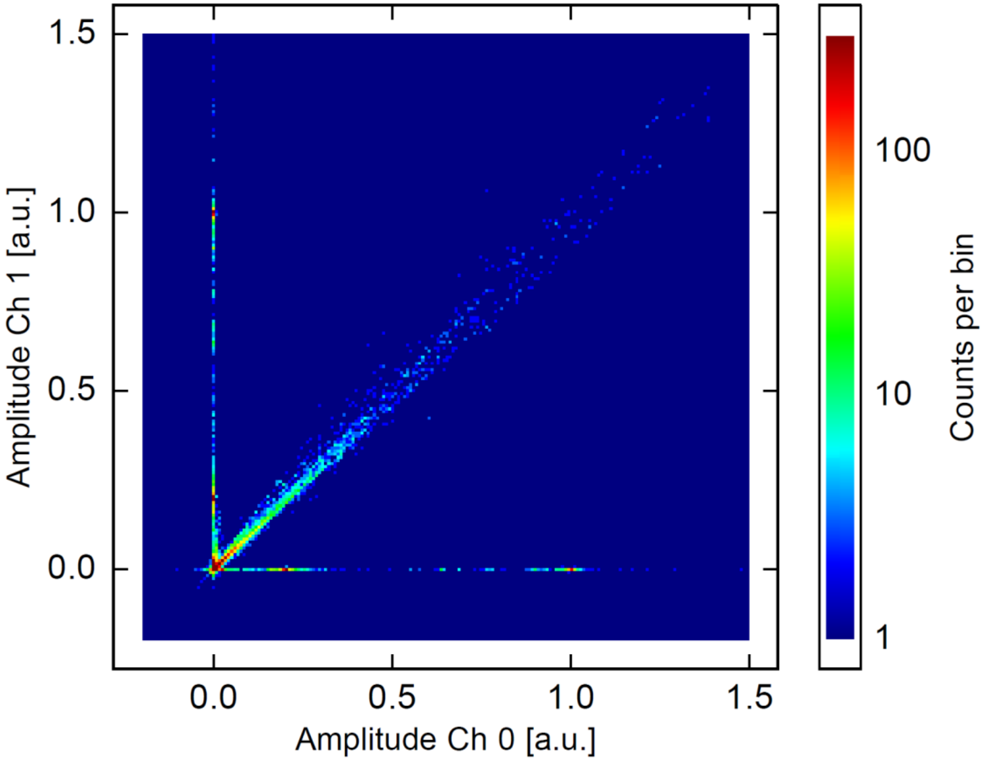


ECHo: Calorimetric spectrum

- Rise Time ~ 130 ns

- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 4.7 eV @ 6 keV (2014)

- Non-Linearity < 1% @ 6keV

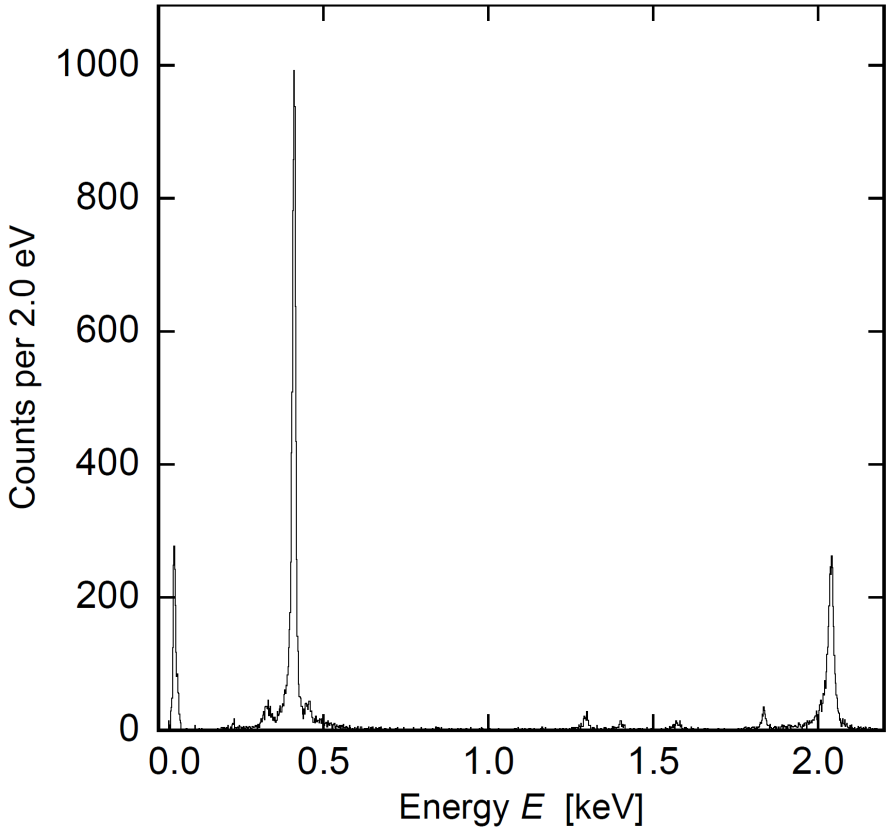


ECHo: Calorimetric spectrum

- Rise Time ~ 130 ns

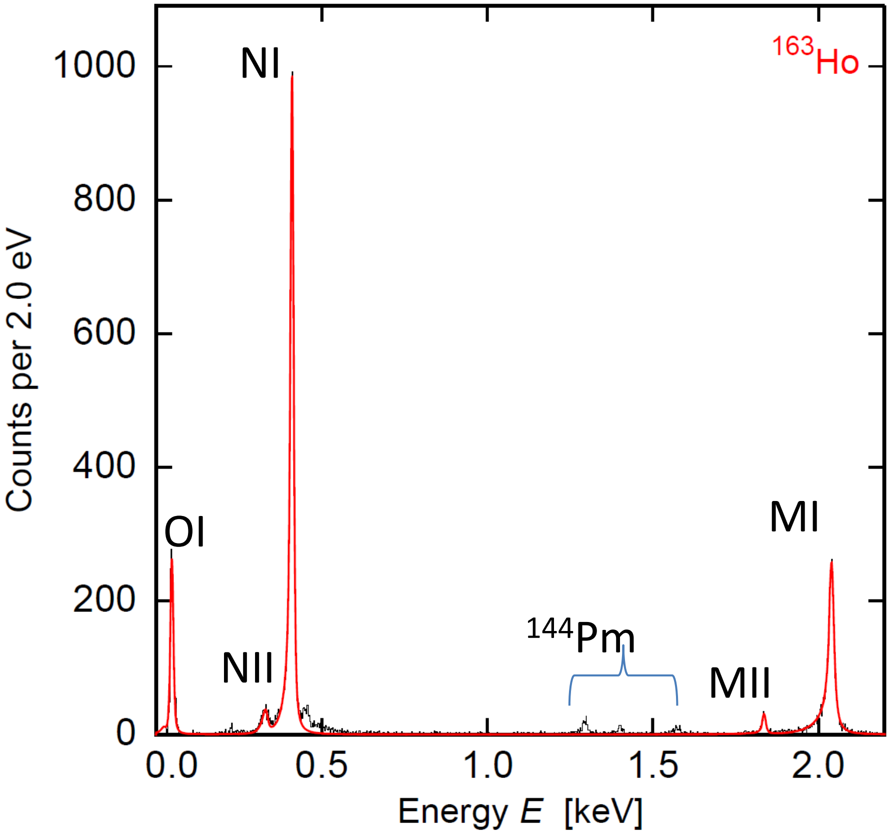
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 4.7 eV @ 6 keV (2014)

- Non-Linearity < 1% @ 6keV



ECHo: Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 4.7 eV @ 6 keV (2014)
- Non-Linearity < 1% @ 6keV
- Presently most precise ^{163}Ho spectrum



ECHo: Calorimetric spectrum

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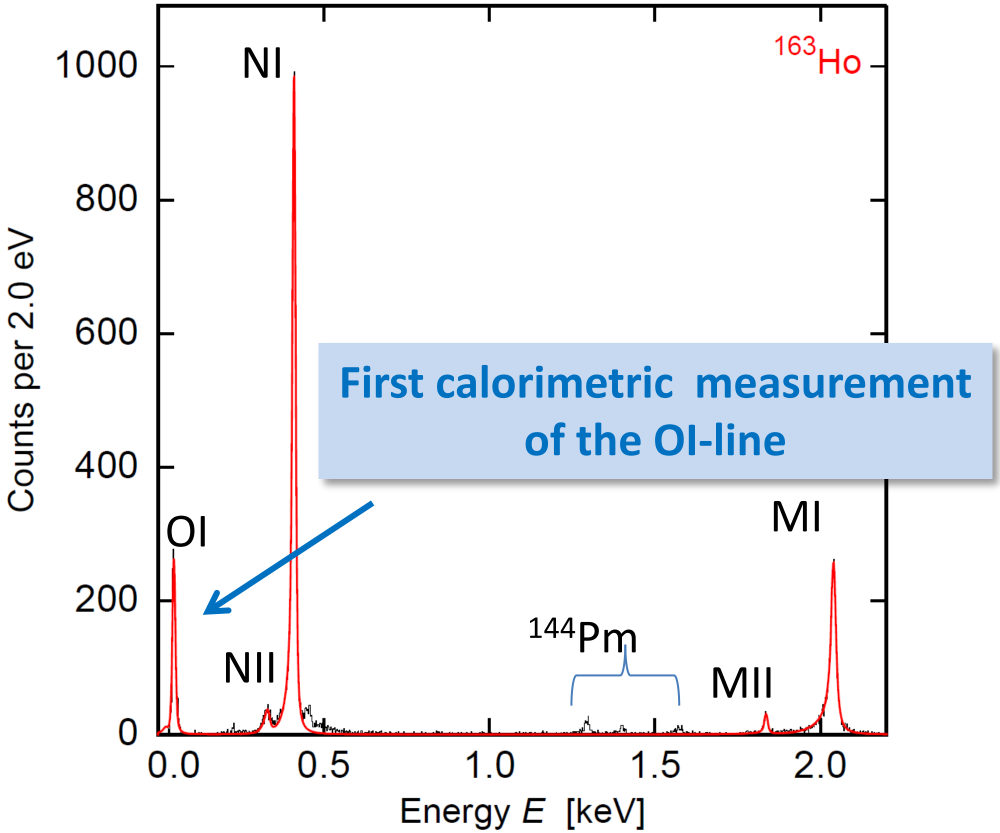
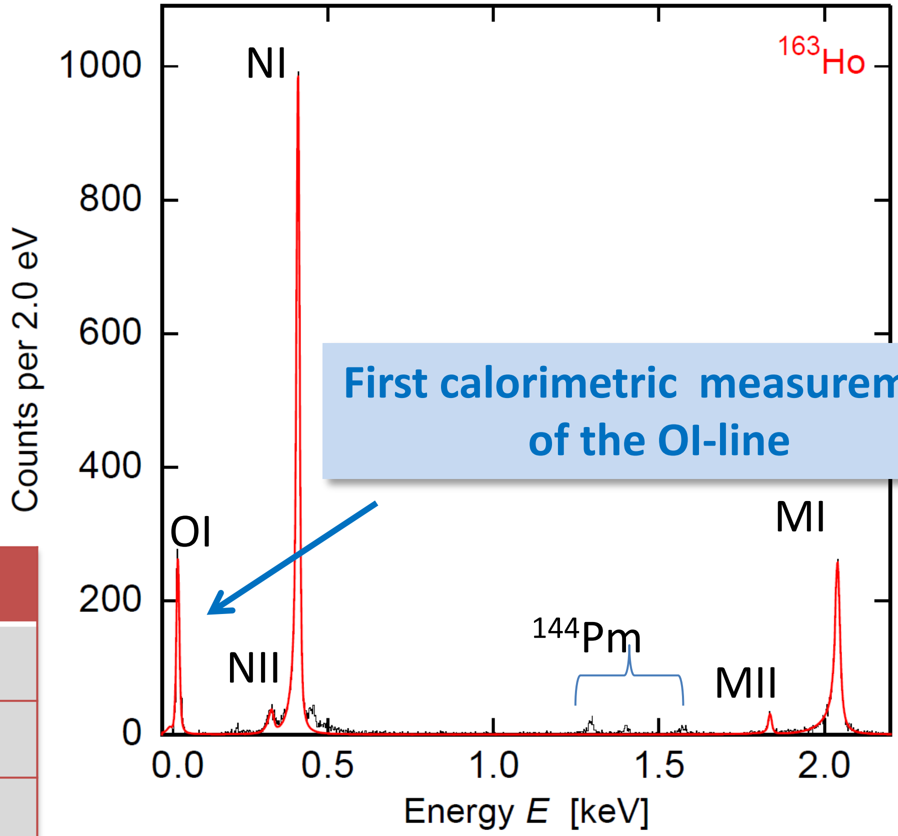


First calorimetric measurement of the OI-line

ECHo: Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 4.7 eV @ 6 keV (2014)
- Non-Linearity < 1% @ 6keV
- Presently most precise ^{163}Ho spectrum

	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



First calorimetric measurement of the OI-line

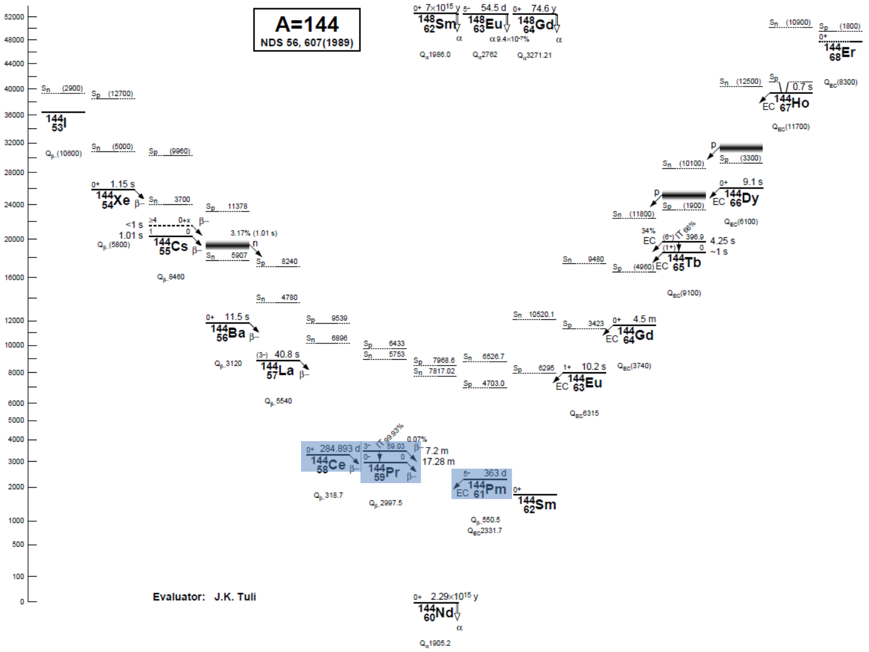
Q_{EC} =(2.80±0.08) keV

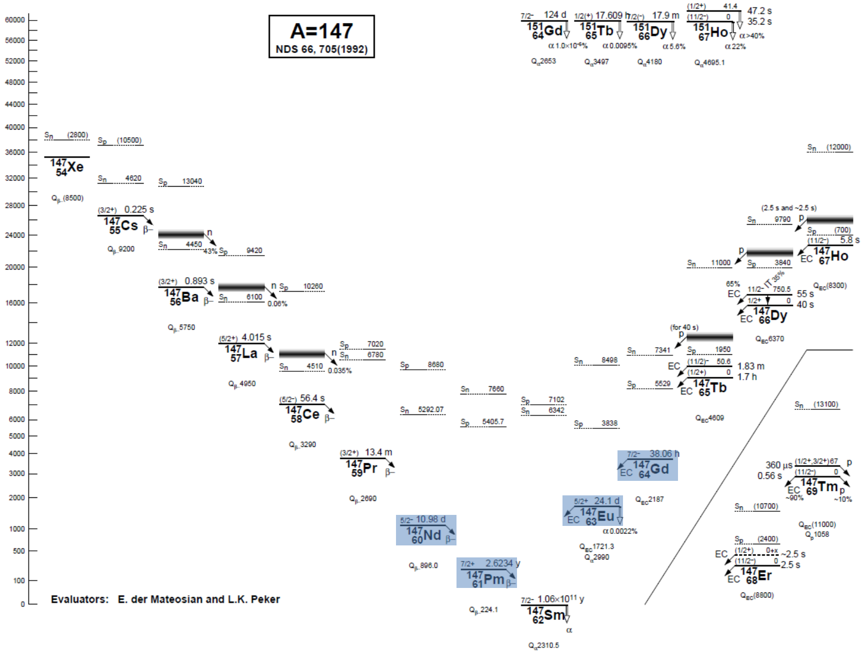
P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

ECHo : ^{163}Ho source

- First microstructured MMC → ^{163}Ho implanted in on-line process @ISOLDE
  proton on Ta-W target

- Purity of the beam: presence of ^{147}Gd chain (^{147}Gd→ ^{147}Eu→ ^{147}Sm) and ^{144}Pm→ ^{144}Nd
  maybe also ^{147}Nd→ ^{147}Pm→^{147}Sm and ^{144}Ce→^{144}Pr→^{144}Nd





ECHo : ^{163}Ho source

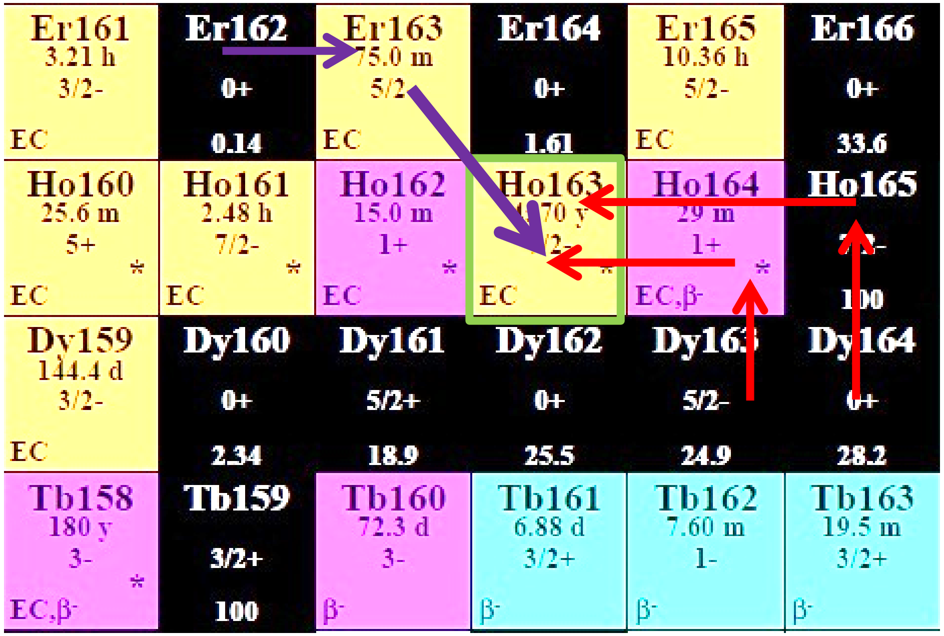
Required activity in the detectors: Final experiment → $>10^{6}$ Bq → $>10^{17}$ atoms

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

  High cross-section

  Radioactive contaminants



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
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
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
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-

- Charged particle activation

  ^{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

  Small cross-section

  Few radioactive contaminants

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

June 2012 : one irradiation at BER II Research Rector Berlin :

-Irradiate 5 mg Er for 11 days ⇒ $1.5 \bullet 10^{16}$ atoms ^{163}Ho

Summer 2013: Two irradiations at ILL

- Treatment of Er prior to irradiation:
  all elements lighter than Er separated

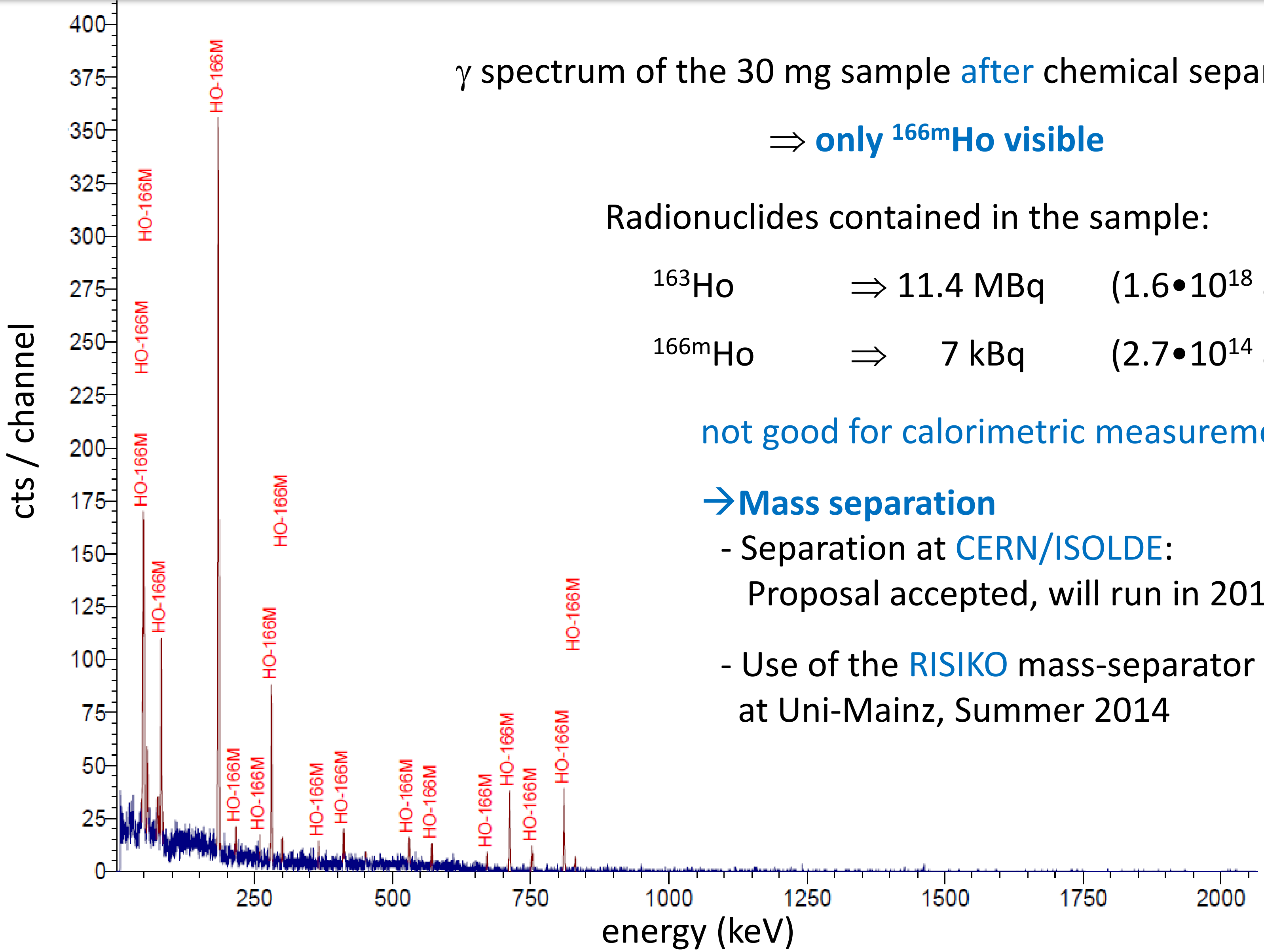
- Treatment of Er after irradiation:
  all elements heavier than Ho are separated

- 30 mg for 55 days	⇒ $1.6 \bullet 10^{18}$ atoms ^{163}Ho
- 7 mg for 7 days	⇒ $1.4 \bullet 10^{16}$ atoms ^{163}Ho

Thermal neutron flux
(Φ): 1.3×10^{15} cm^{-2}s^{-1}

NEUTRONS
FOR SCIENCE

ECHo : ^{163}Ho source - Purification of ^{163}Ho at PSI



γ spectrum of the 30 mg sample after chemical separation:

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

Radionuclides contained in the sample:

^{163}Ho	$\Rightarrow$ 11.4 MBq	($1.6 \bullet 10^{18}$ atoms)
^{166m}Ho	$\Rightarrow$ 7 kBq	($2.7 \bullet 10^{14}$ atoms)

not good for calorimetric measurement

→Mass separation

- Separation at CERN/ISOLDE:
  Proposal accepted, will run in 2014
- Use of the RISIKO mass-separator
  at Uni-Mainz, Summer 2014

ECHo : Background reduction

Background sources:

- Environmental radioactivity → Material selection
- Cosmic rays
- Induced secondary radiation by cosmic rays

→ Underground labs / Veto

↓

First measurements underground in Modane during 2014

Study of background sources through:

- Monte Carlo simulations
- Dedicated experiments → ^{166m}Ho implanted in MMC detectors

ECHo : Parameterization of the spectrum

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

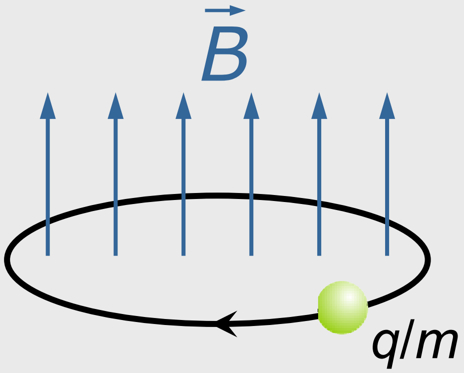
$$\frac{dW}{dE_C} = A\left(Q_{EC} - E_C\right)^2 \sqrt{1 - \frac{m_\nu^{\;2}}{\left(Q_{EC} - E_C\right)^2}} \sum_H B_H \varphi_H^{\;2}(0) \frac{\frac{\Gamma_H}{2\pi}}{\left(E_C - E_H\right)^2 + \frac{\Gamma_H^{\;2}}{4}}$$

- Determination of the Q_{EC} at 1 eV uncertainty
  by means of Penning Trap mass spectroscopy

ECHo : Q_{EC} determinetion

Penning Trap mass spectroscopy

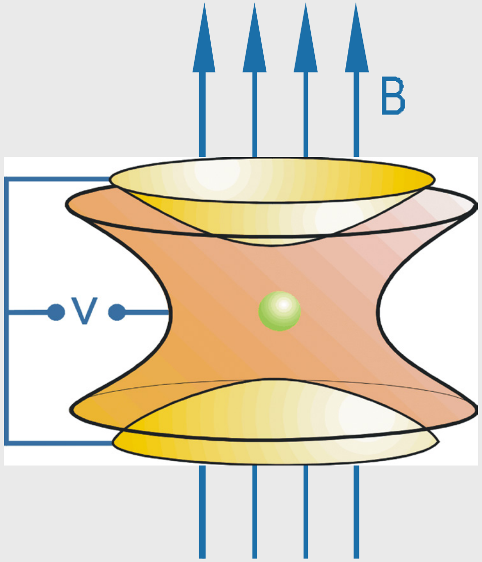
uniform B-field



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

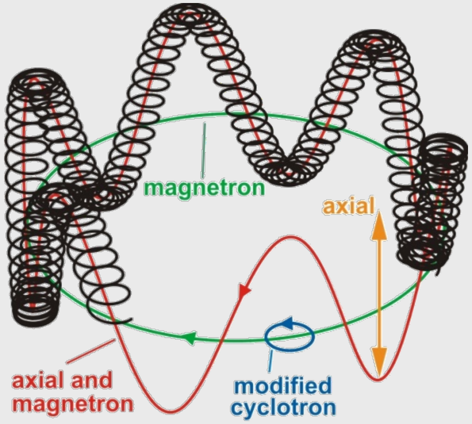
+

quadrupole E-field



=

Penning Trap



ν_+ - modified cyclotron

ν_- - magnetron

ν_z - axial

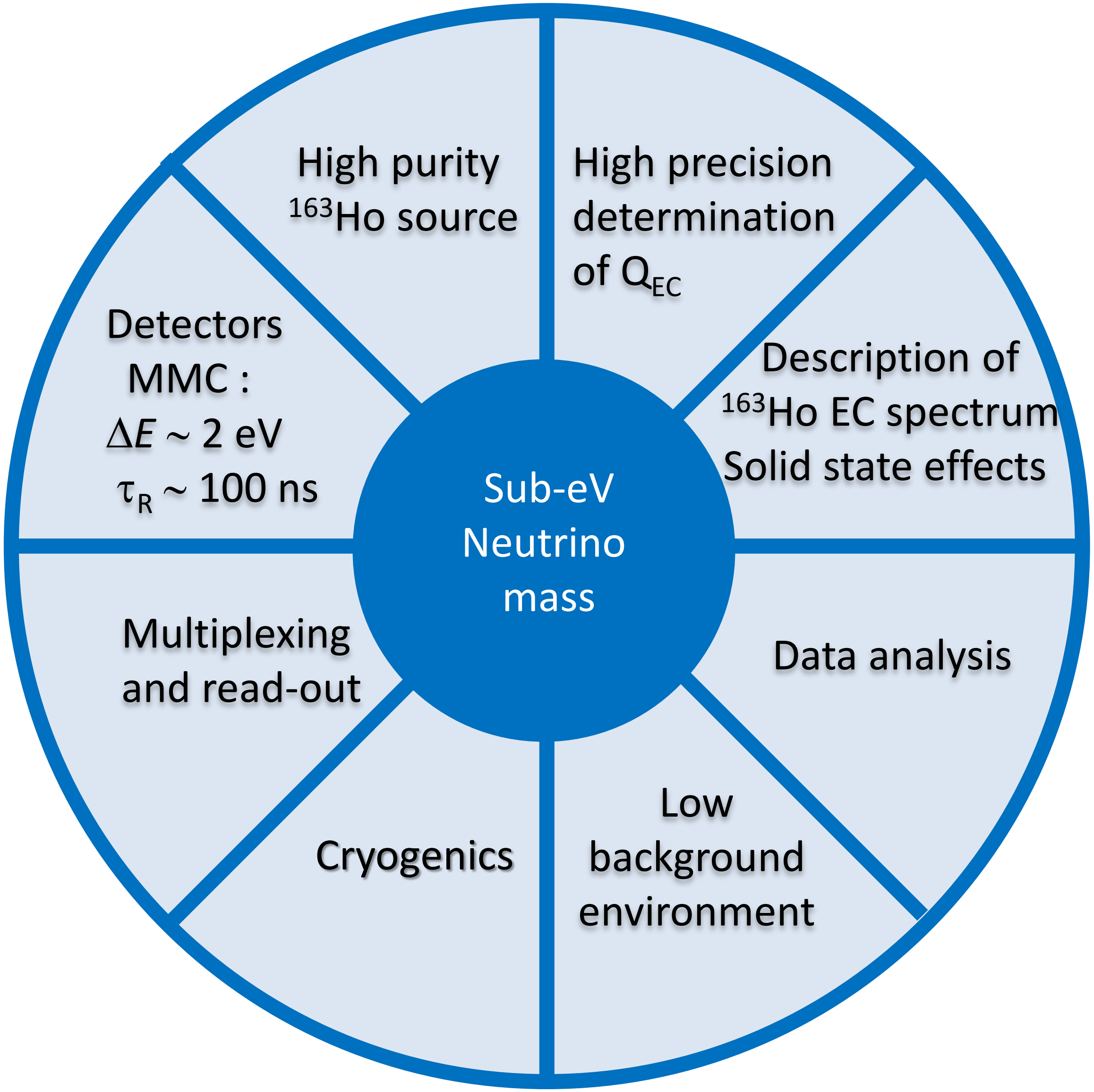
ECHo : Parameterization of the spectrum

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

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

- Determination of the Q_{EC} at 1 eV uncertainty by means of Penning Trap mass spectroscopy
  - 2014: TRIGATRAP - SHIPTRAP → Q_{EC} determination within 30 - 100 eV
  - In few years: PENTATRAP (MPI-K HD) → Q_{EC} determination within 1 eV
- Density Functional Theory (DFT) and Quasiparticle Random Phase Approximation (QRPA)
- Solid state effects like core level binding energy shift: theoretical and experimental approaches

ECHo : Overview



High purity ^{163}Ho source

High precision determination of Q_{EC}

Description of ^{163}Ho EC spectrum
Solid state effects

Data analysis

Low background environment

Cryogenics

Multiplexing and read-out

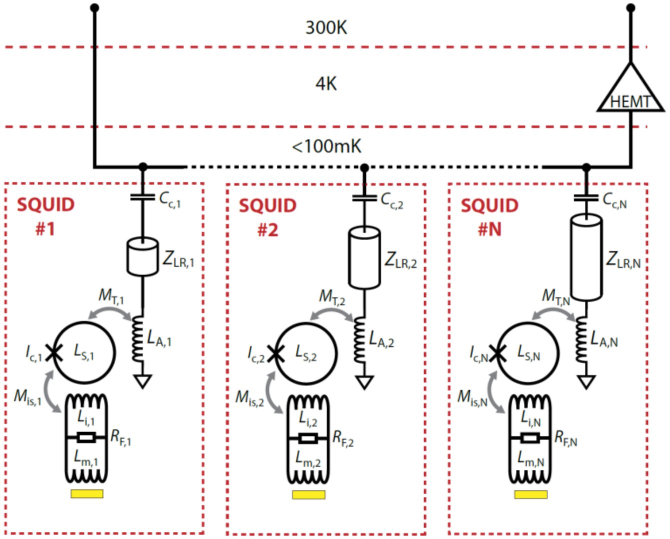
Detectors
MMC :
$\Delta E \sim 2$ eV
$\tau_R \sim 100$ ns

Sub-eV Neutrino mass

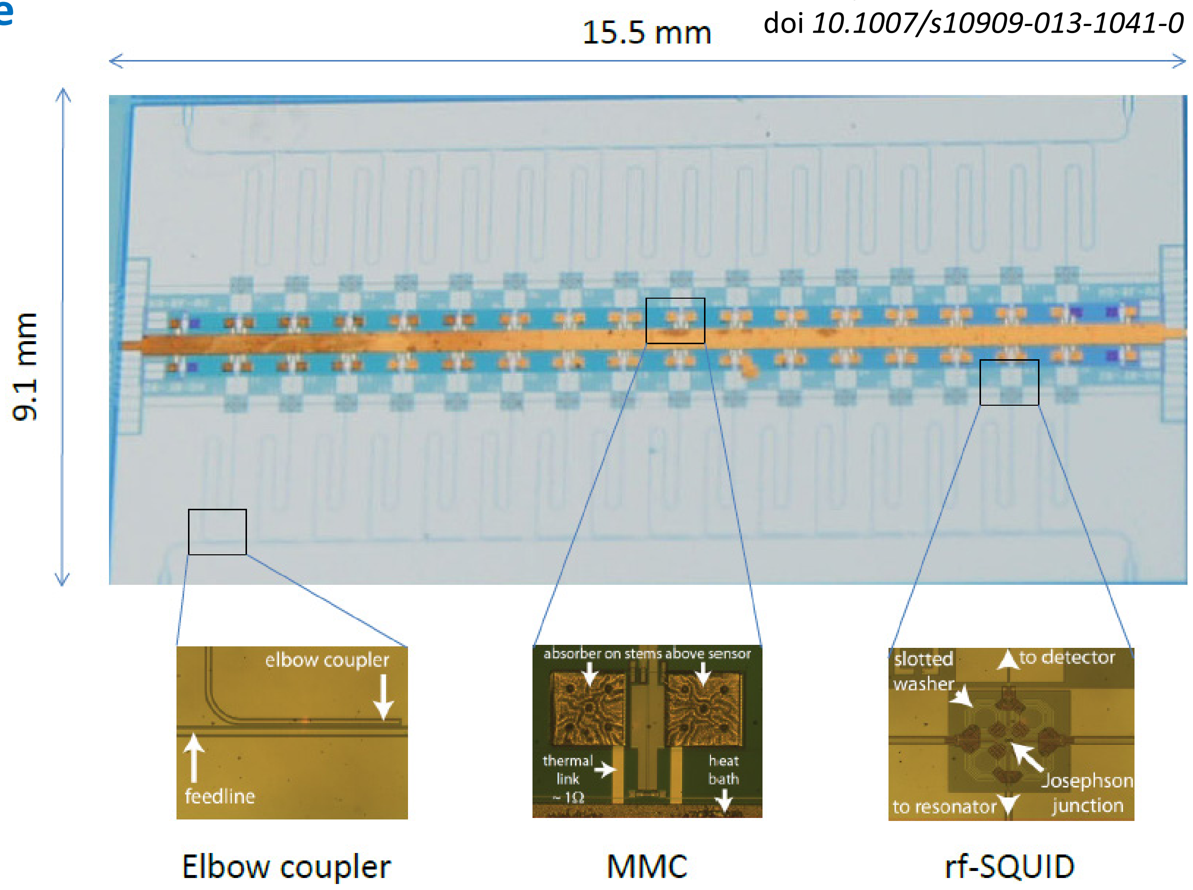
ECHo : next step

Microwave multiplexing technique

1 HEMT amplifier
+ 2 coaxes
= 100 - 1000 detectors



S. Kempf et al, JLTP online first
doi *10.1007/s10909-013-1041-0*



- 64 pixels, ΔE_{FWHM} = 5 eV, 10 Bq/pixel
- 2 chips

<10 eV m_ν sensitivity
Prove scalability

keV Sterile Neutrino

Single Neutrino Branch, m_{ν} :

$$\frac{dW}{dE_C}(m_\nu) = A\cdot(Q-E_C)^2\left(1-\frac{m^2{}_\nu}{(Q-E_C)^2}\right)^{1/2}\sum_H B_H\phi_H{}^2(0)\frac{\Gamma_H/2\pi}{(Q-E_C)^2+\Gamma_H{}^2/4}$$

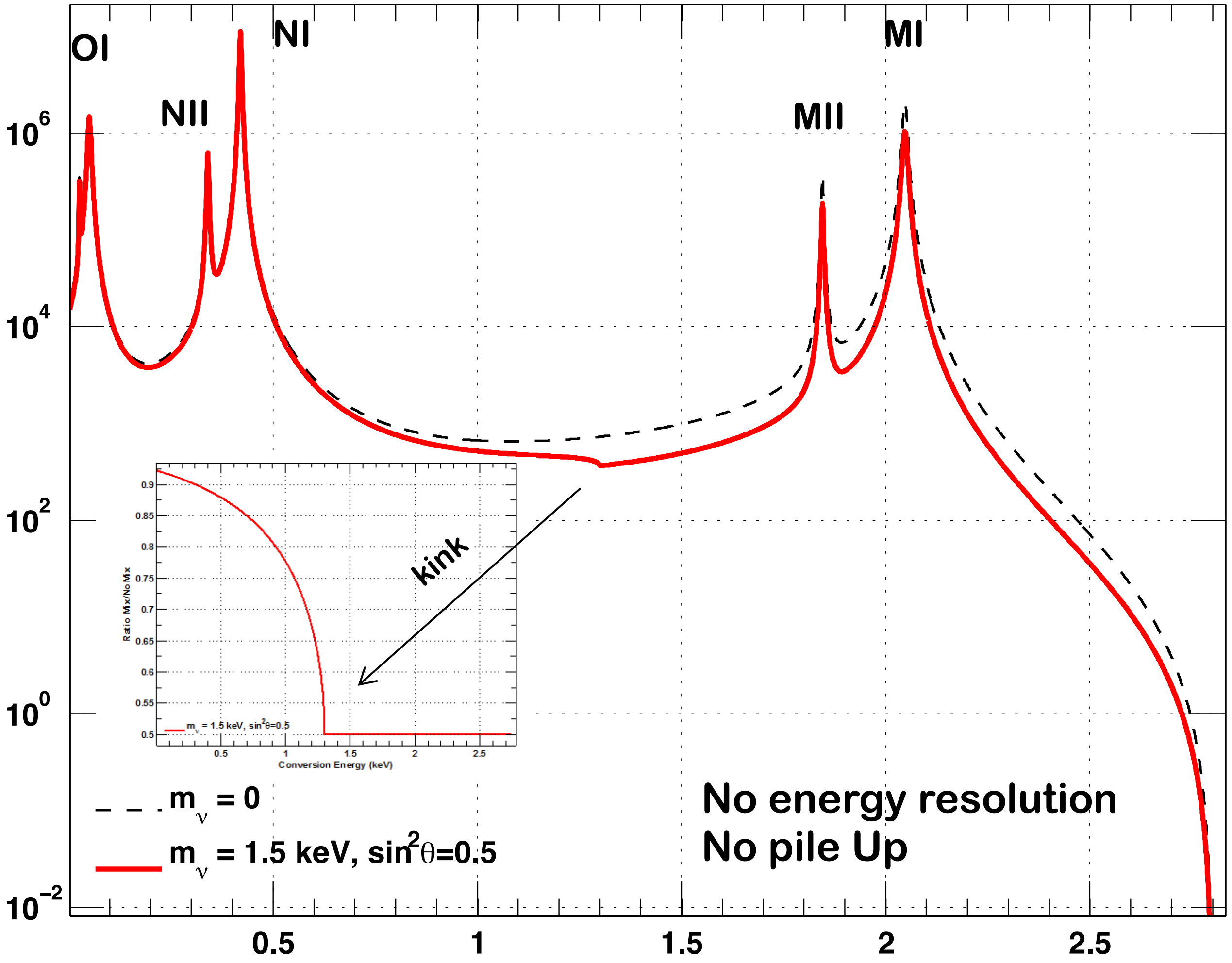
Two Neutrino Branches, m_{light} & m_{heavy}

$$\frac{dW}{dE_C}(\mathrm{m}_{light},\mathrm{m}_{heavy}) = \cos^2(\theta)\cdot\frac{dW}{dE_C}(m_{light})+\sin^2(\theta)\cdot\frac{dW}{dE_C}(m_{heavy})$$

Two Neutrino Branches, $\mathrm{m}_{light}=0$ & m_{heavy}

$$\frac{dW}{dE_C}(\mathrm{m}_{heavy}) = \cos^2(\theta)\cdot\frac{dW}{dE_C}(0)+\sin^2(\theta)\cdot\frac{dW}{dE_C}(m_{heavy})$$

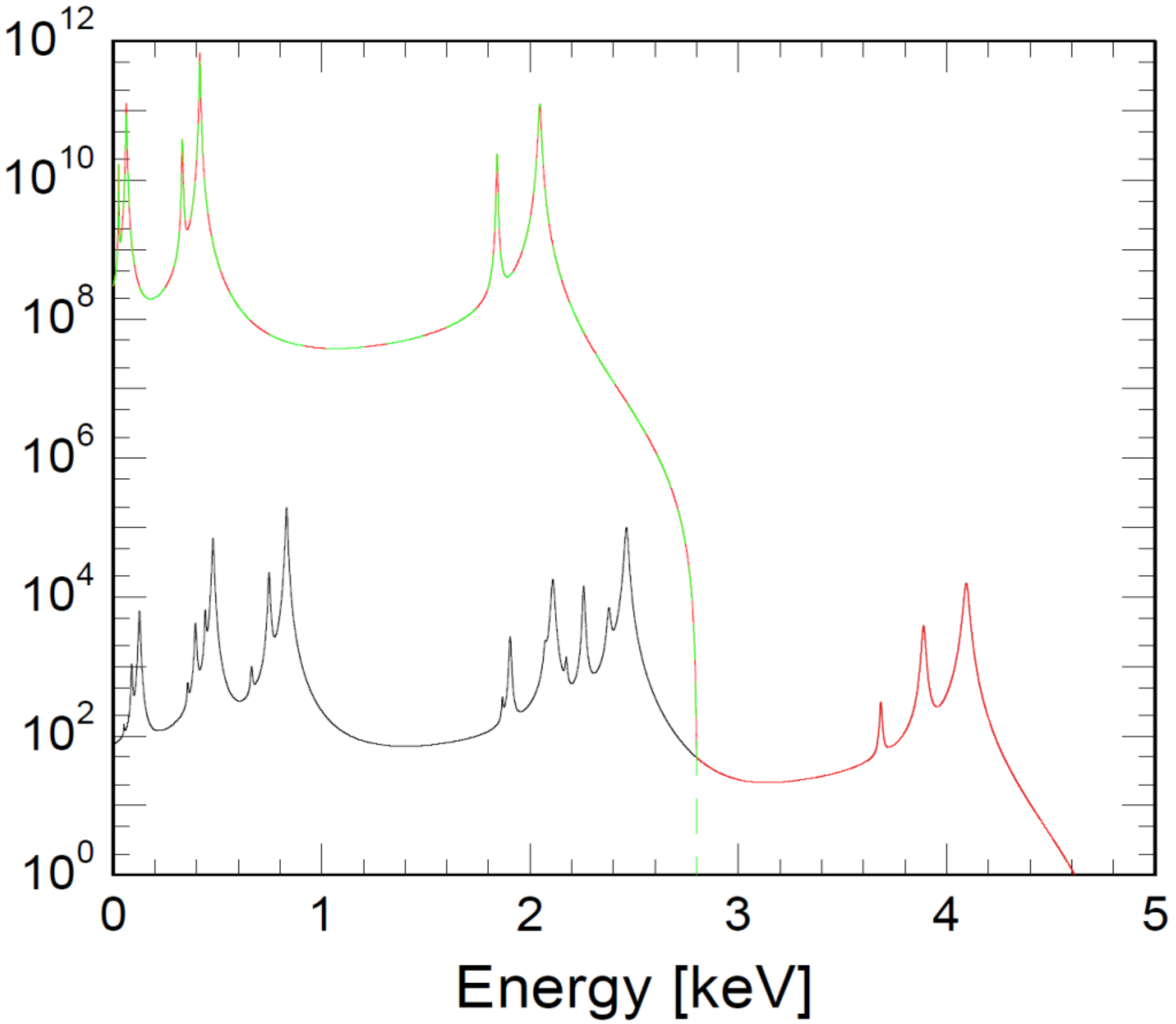
keV Sterile Neutrino



No energy resolution
No pile Up

keV Sterile Neutrino

Reminder: pile-up spectrum



keV Sterile Neutrino

In case of no sterile neutrino:

$$\lambda_i = \frac{G^2}{4\pi^2} C_i \left(Q - B_i\right)^2$$

In case of sterile neutrino:

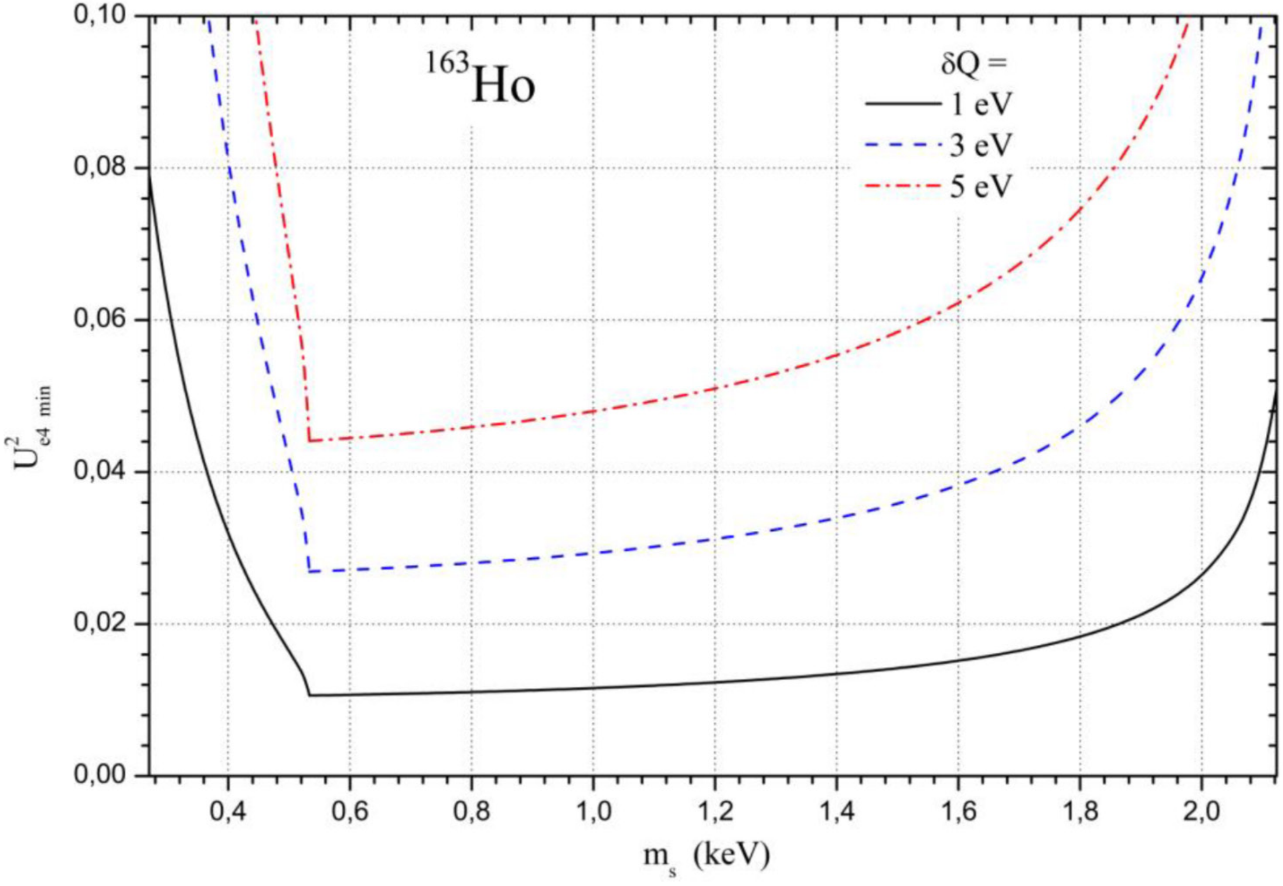
$$\lambda_i = \frac{G^2}{4\pi^2} C_i \left\{(1 - U_{e4}^2)(Q - B_i)^2 + U_{e4}^2 (Q - B_i)\sqrt{(Q - B_i)^2 - m_s^2}\right\}$$

Ratio between two lines of EC spectra in case of sterile neutrino:

$$\left(\frac{\lambda_i}{\lambda_j}\right)_{\mathrm{st}} = \left(\frac{\lambda_i}{\lambda_j}\right)_{\mathrm{act}} \cdot \frac{U_{e4}^2\left(\mathrm{H}\left[(Q - B_i) - m_s\right] \cdot \sqrt{1 - m_s^2 / (Q - B_i)^2} - 1\right) + 1}{U_{e4}^2\left(\mathrm{H}\left[(Q - B_j) - m_s\right] \cdot \sqrt{1 - m_s^2 / (Q - B_j)^2} - 1\right) + 1}$$

P. Filianin et al. arXiv: 1402.4400

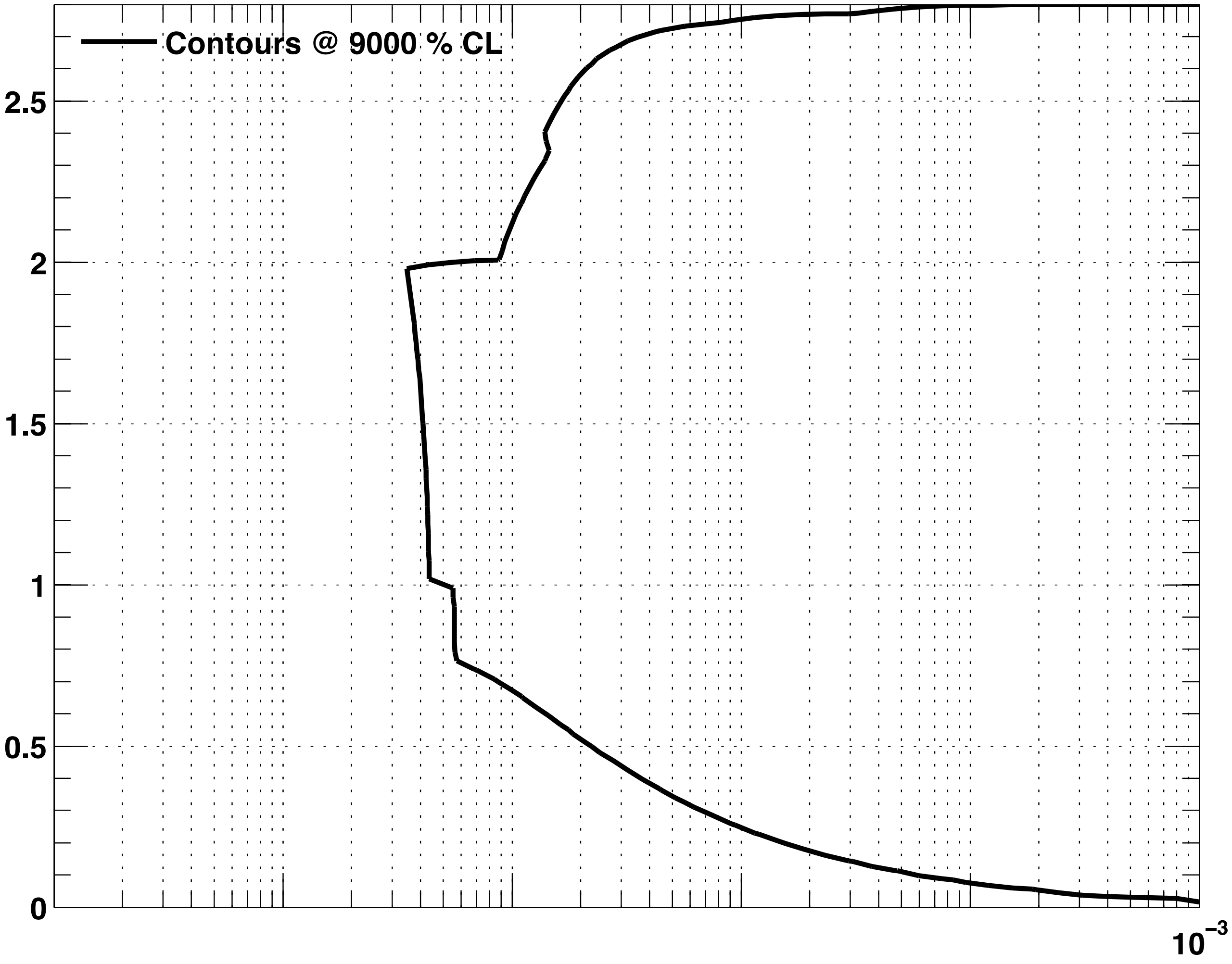
keV Sterile Neutrino



P. Filianin et al. arXiv: 1402.4400

keV Sterile Neutrino

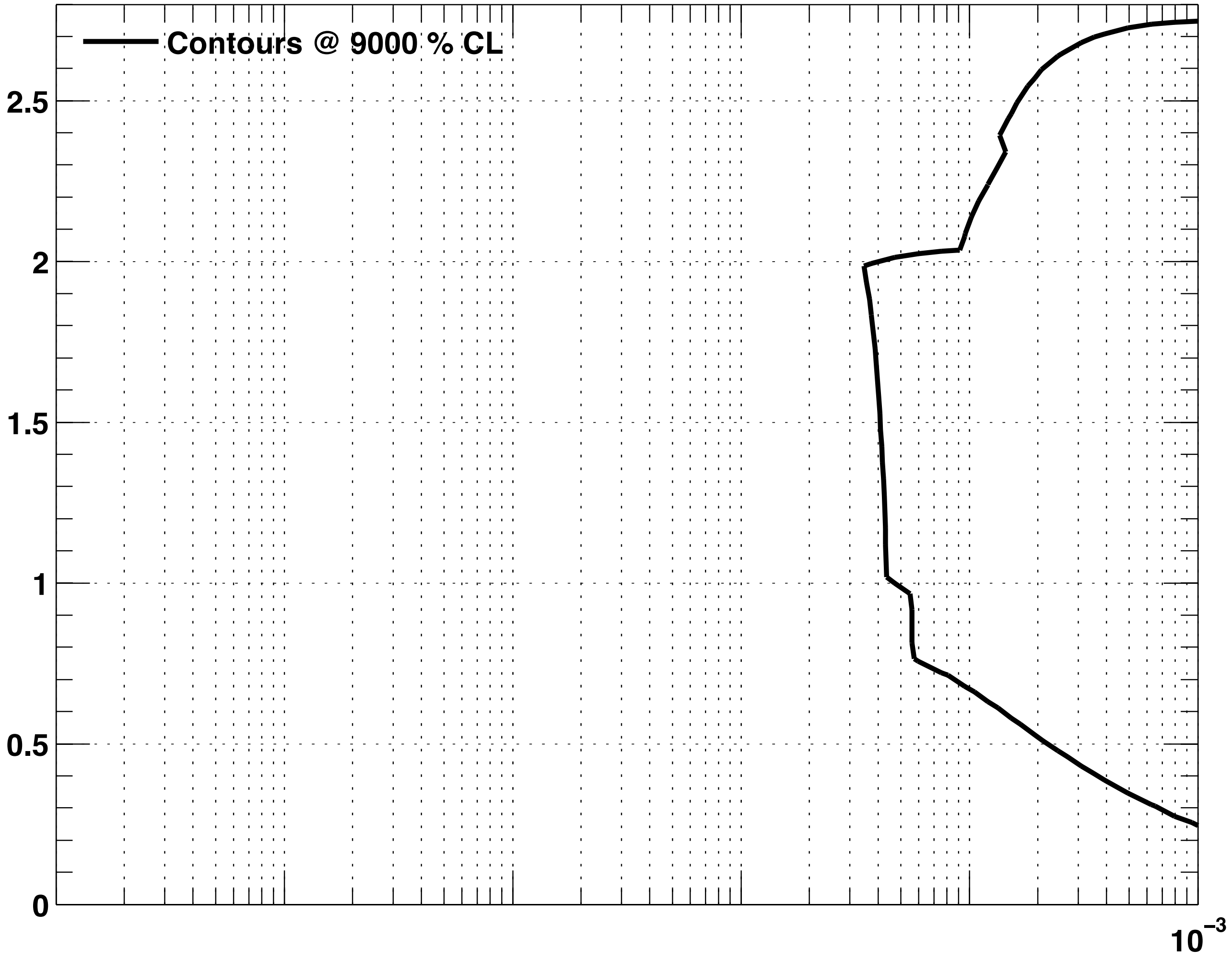
Statistical Fluctuation – No Pile Up – Counts = 1e14
Theoretical Spectrum Supposed to be perfectly known



Thierry Lassere, LG Work in progress

keV Sterile Neutrino

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

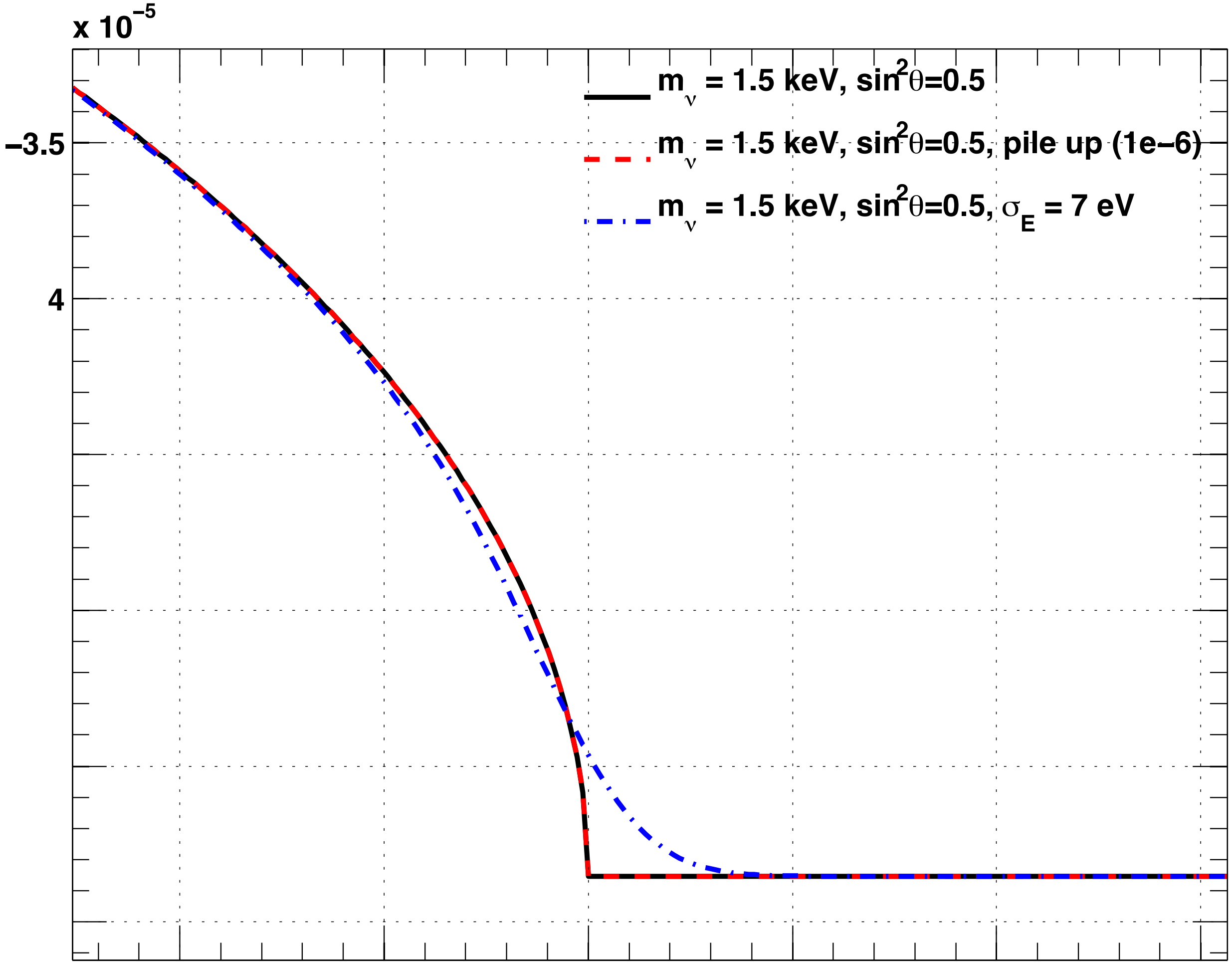


Thierry Lassere, LG Work in progress

keV Sterile Neutrino

No impact of the pile up, if <u>exactly</u> known

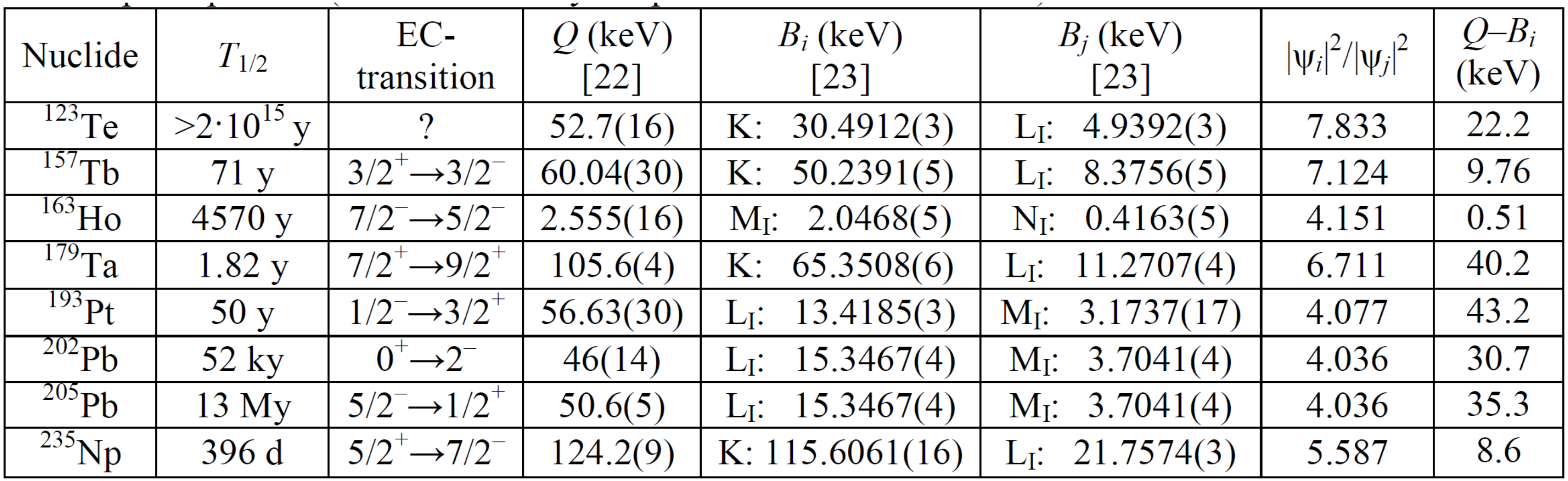
Weak impact on the energy resolution for keV neutrino kink search



Thierry Lassere, LG Work in progress

keV Sterile Neutrino

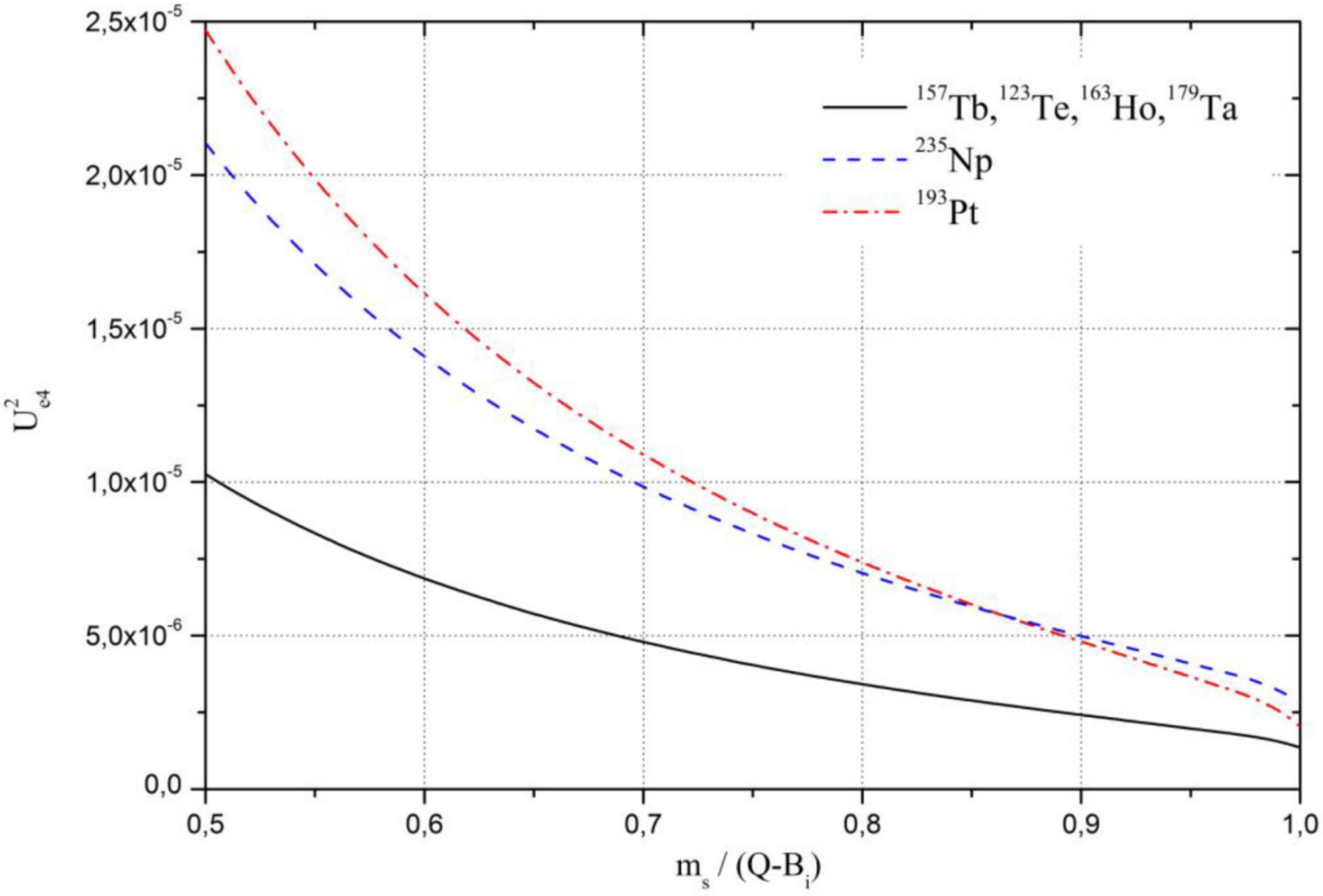
Other condidates in the EC branch:



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. arXiv: 1402.4400

keV Sterile Neutrino



P. Filianin et al. arXiv: 1402.4400

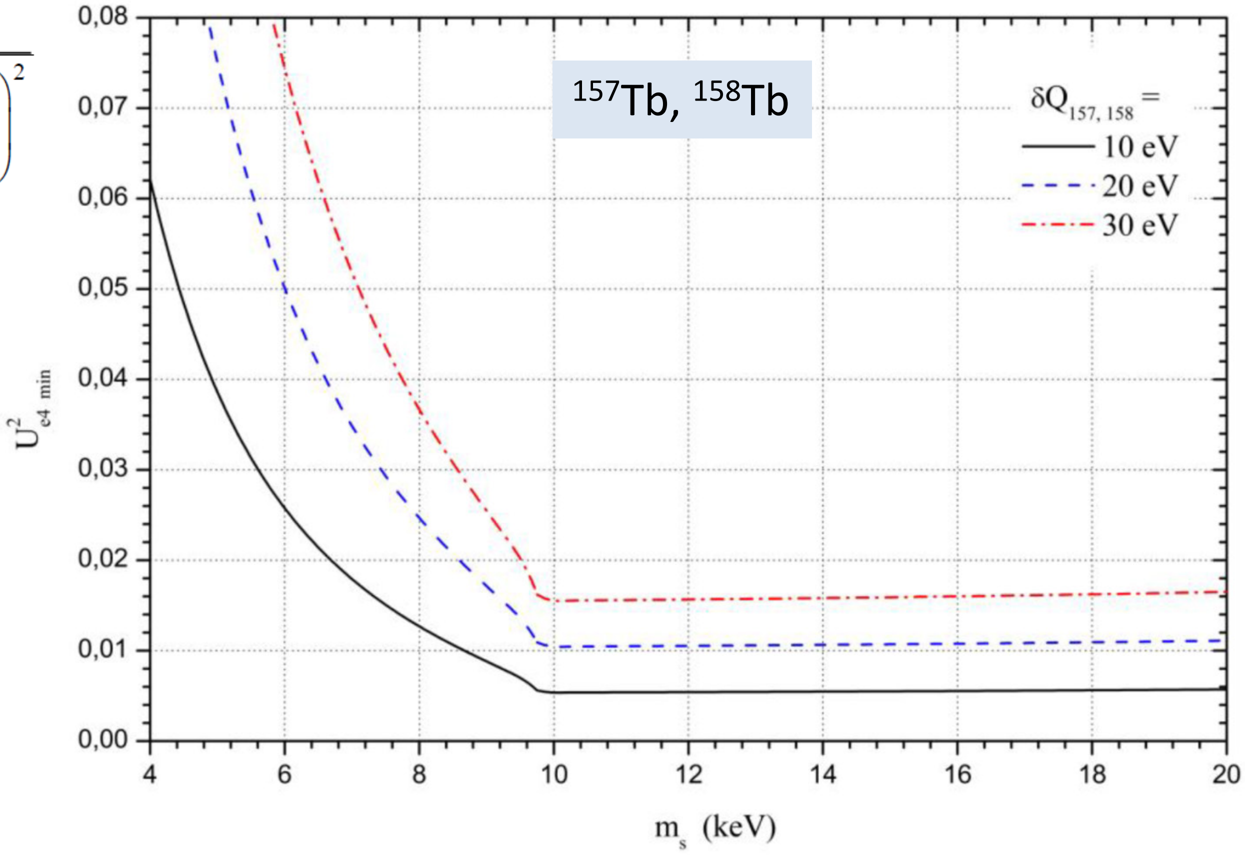
keV Sterile Neutrino

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 $m_s < 3$keV
- Other candidates can be found in EC sector which can cover a larger sterile neutrino mass range

Thank you!

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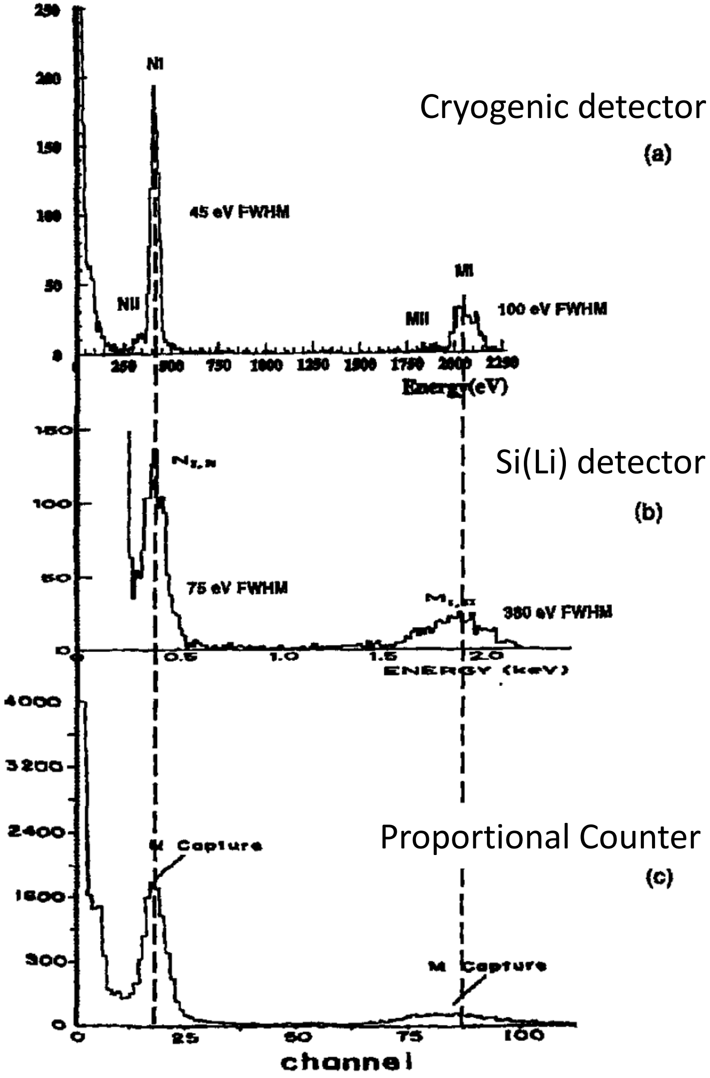
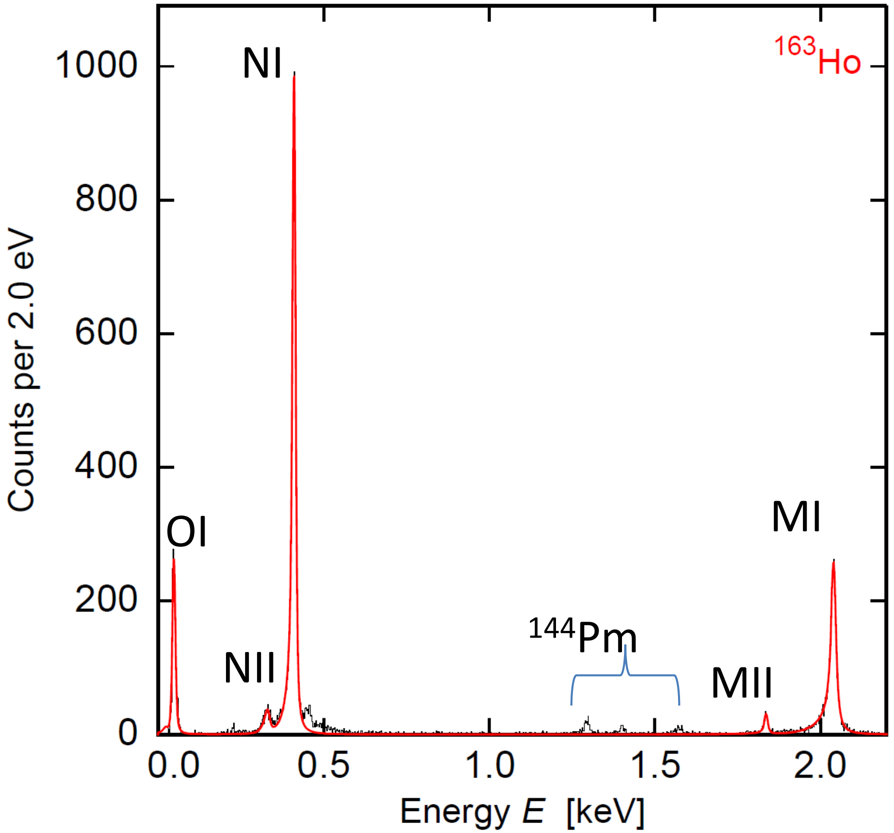
Susanta Lahiri

ECHo: Calorimetric spectrum



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



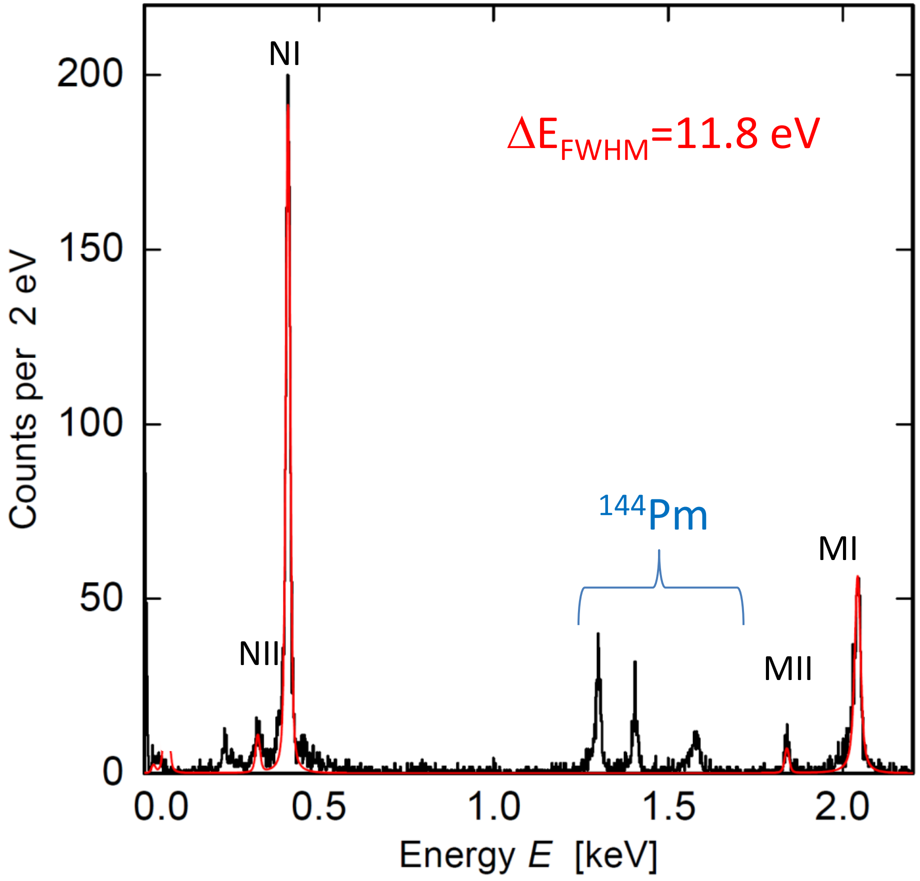
(a) F. Gatti et al., Physics Letters B 398 (1997) 415-419

(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: Calorimetric spectrum

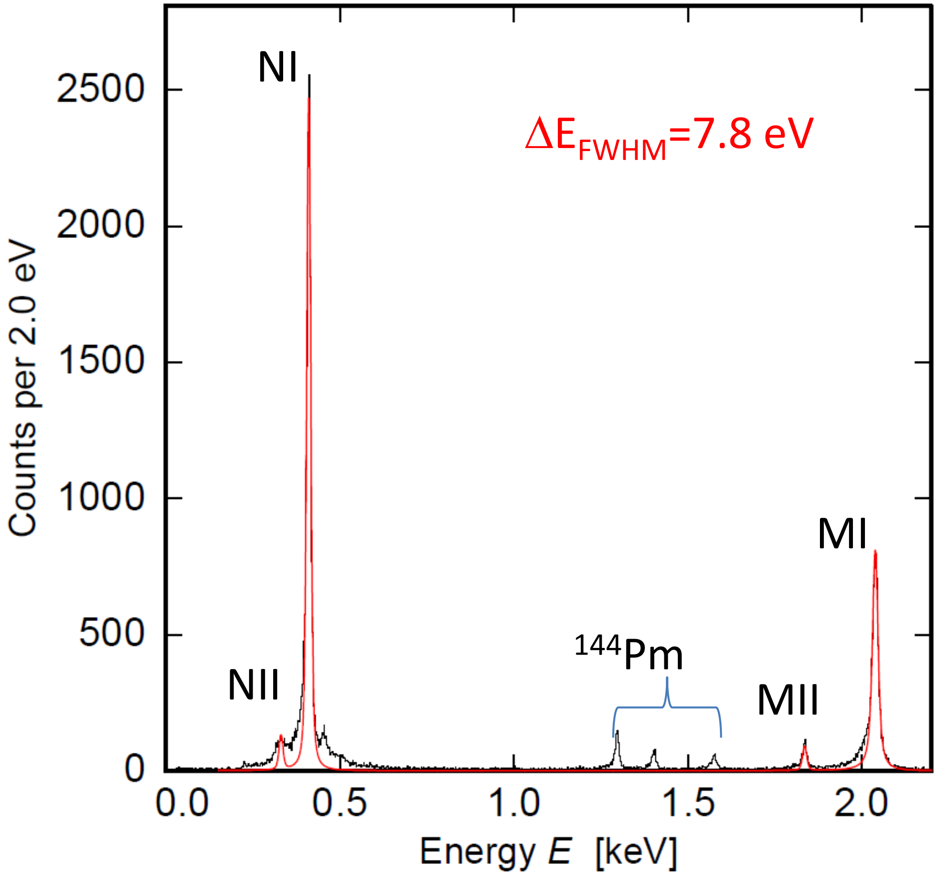
2010: 1 pixel 3 data sets



ECHo: Calorimetric spectrum

2010: 1 pixel 3 data sets

2012: 2 pixels ~40 data sets

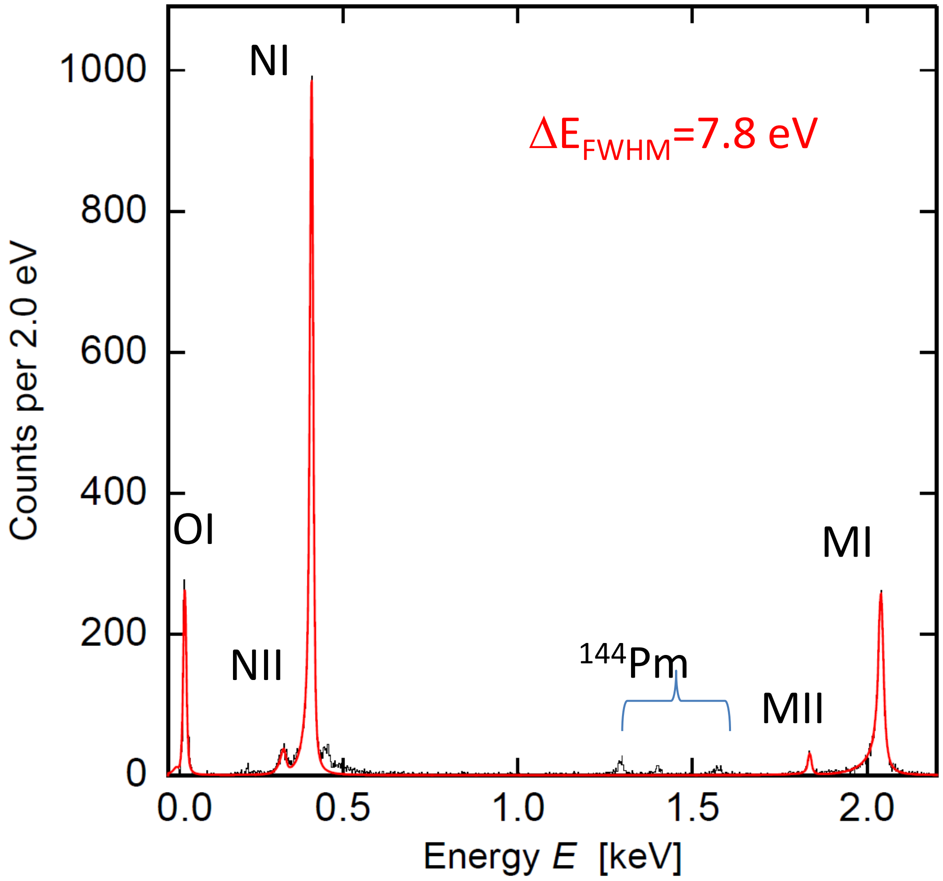


ECHo: Calorimetric spectrum

2010: 1 pixel 3 data sets

2012: 2 pixels ~40 data sets

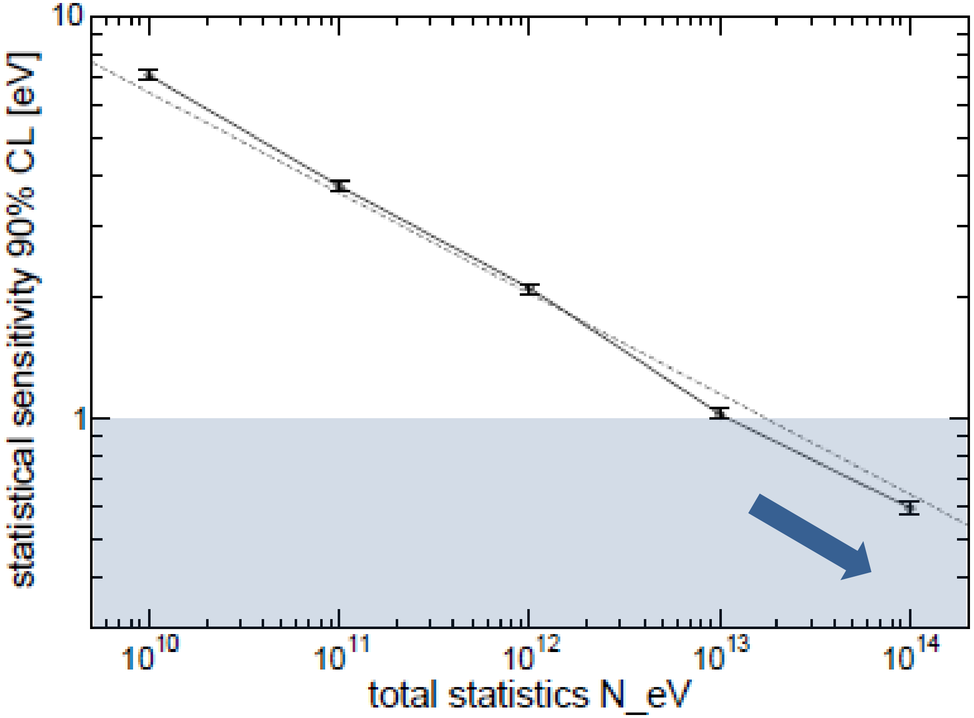
2013: 2 pixels ~30 data sets



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

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

Statistics



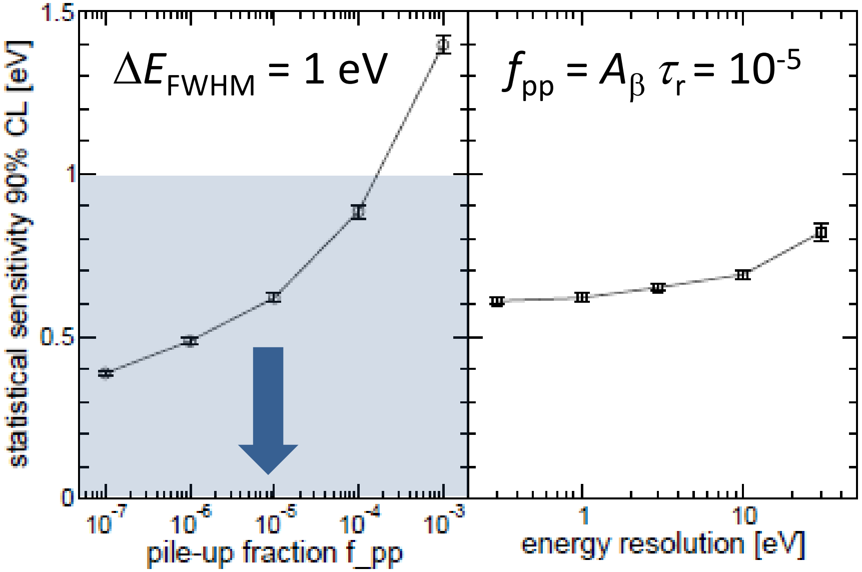
$\Delta E_{FWHM} = 1$ eV, $f_{pp} = 10^{-5}$, $Q_{EC} = 2600$ eV

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

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

$N_{ev} > 10^{14}$
$f_{pp} < 10^{-5}$

Detector performance



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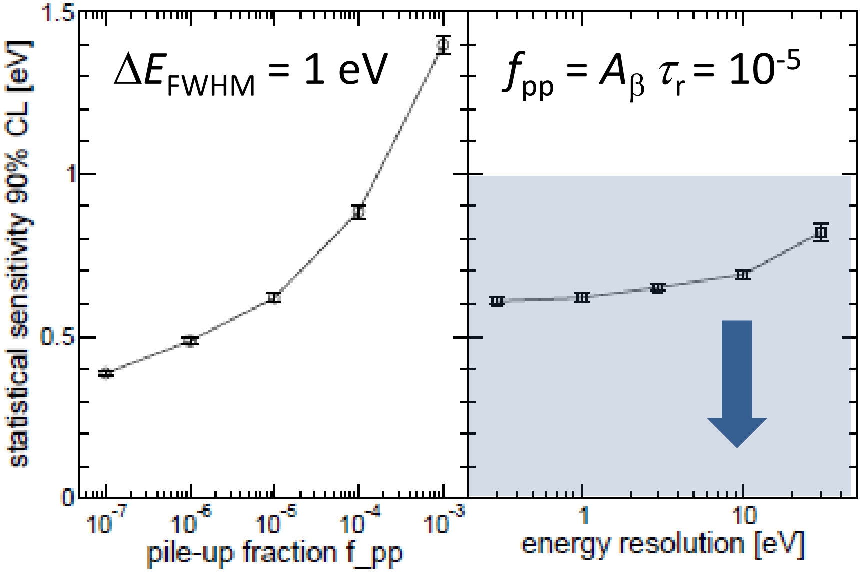
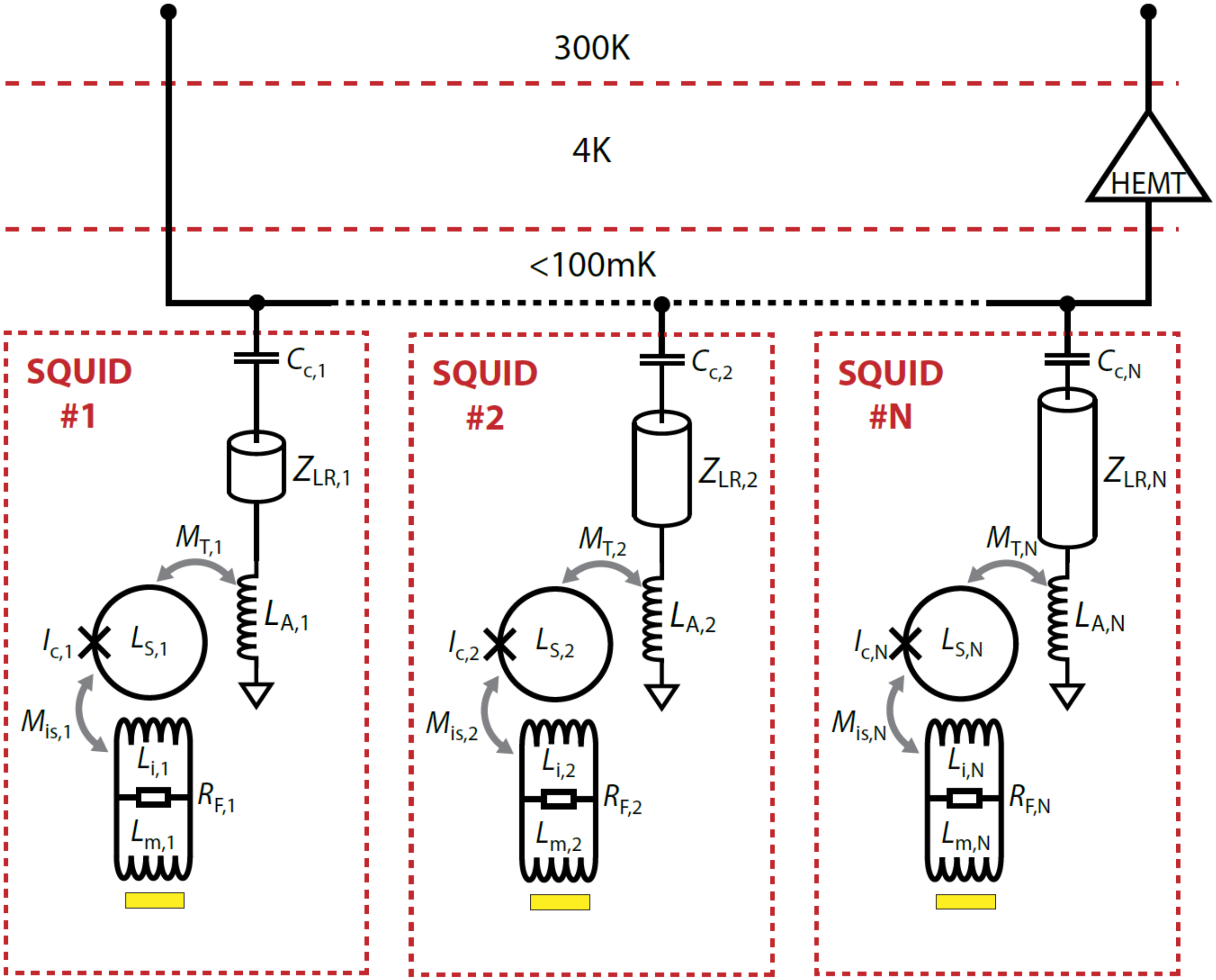


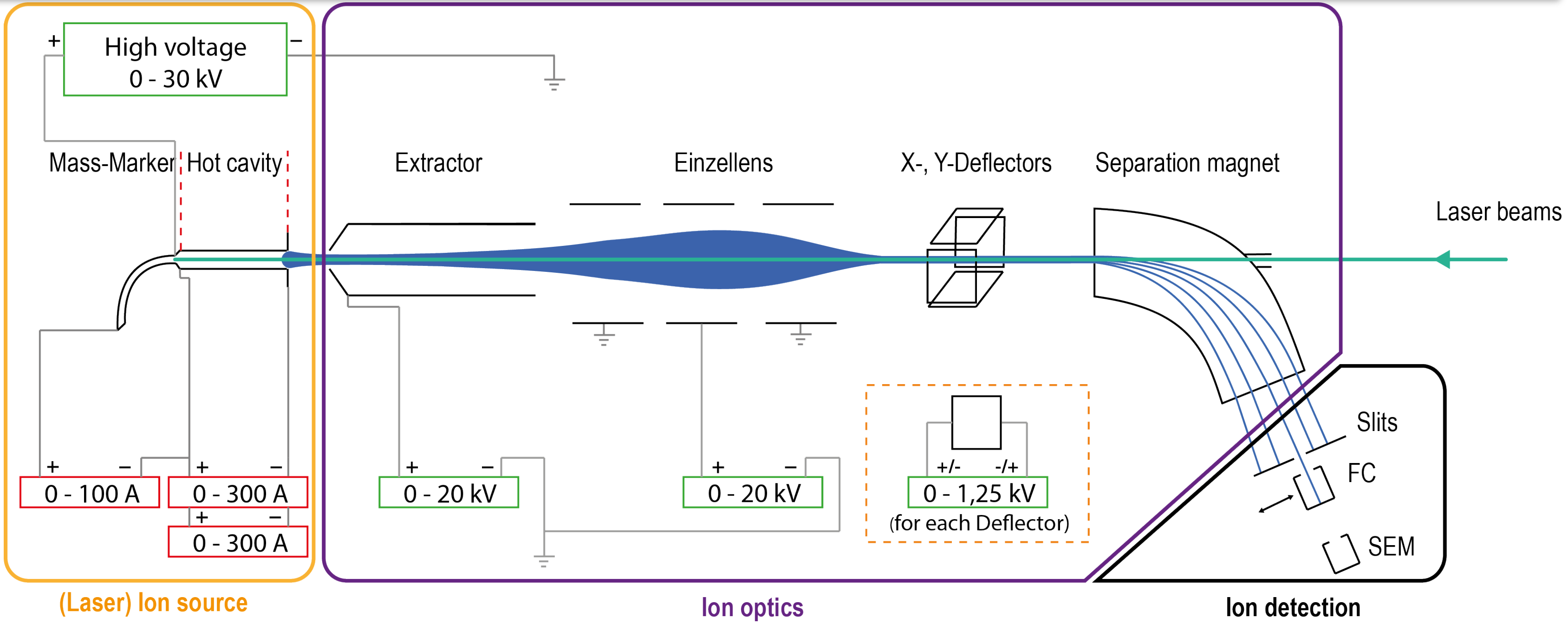
$N_{ev} = 10^{14}$, $Q_{EC} = 2600$ eV

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

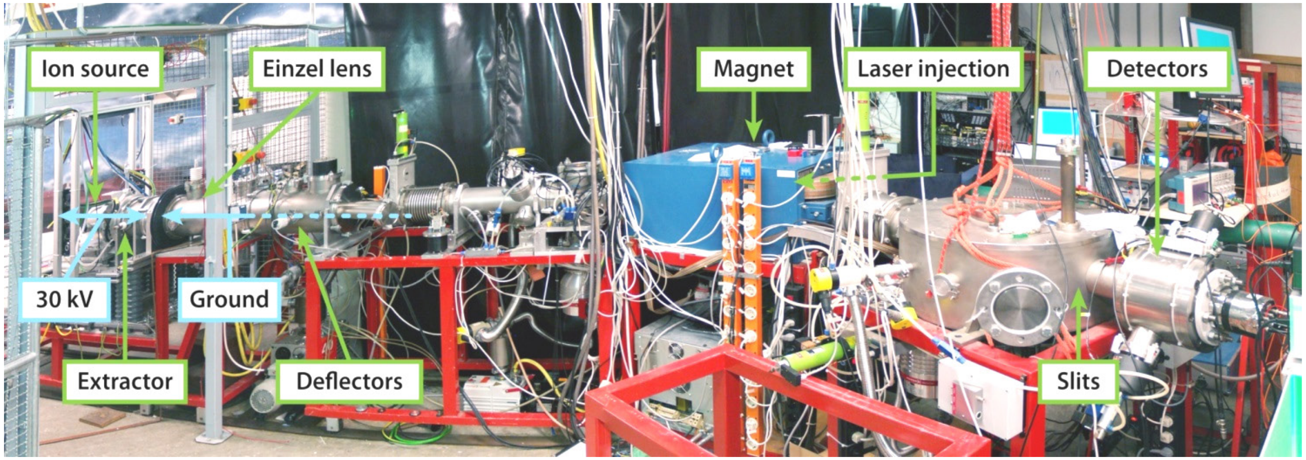
ECHo experiment: µwave SQUID multiplexing



The RISIKO mass separator at JGU Mainz



- 10 – 30 % overall efficiency for lanthanides
- separation magnet: mass resolution ~ 500



ECHo : ^{163}Ho source

Methods for production of high intensity and high purity ^{163}Ho source

- ^{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 ^{163}Ho

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

Two sources already produced

✓ Helmoltz Zentrum Berlin

✓ Institut Laue-Langevin in Grenoble →

Ion-implantation @ISOLDE:
Off-line process
with ^{163}Ho target prepared in Mainz

3-step purification procedures

1. Chemical pre-purification of ^{162}Er material for the target
2. Chemical post-purification of the separated ^{163}Ho source
3. Phyical separation to select only the mass 163 amu → no ^{166m}Ho

ECHo: Sub-eV sensitivity

$N_{ev} > 10^{14}$
$f_{pp} < 10^{-5}$
$\Delta E_{FWHM} < 10$ eV

→

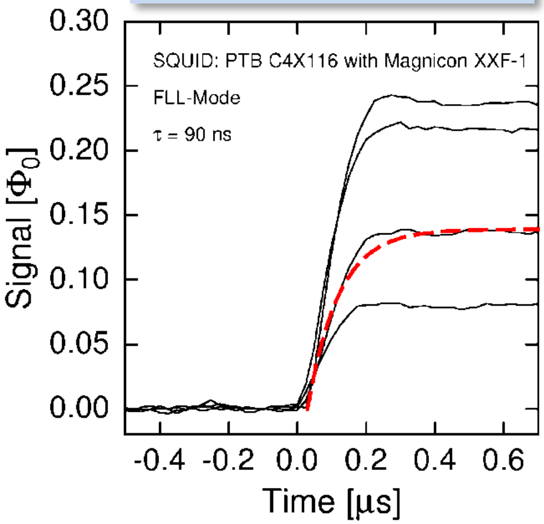
$\tau_r \sim 0.1$ µs
$\Delta E_{FWHM} = 2$ eV
$A_\beta \approx 10$ s^{-1}

→

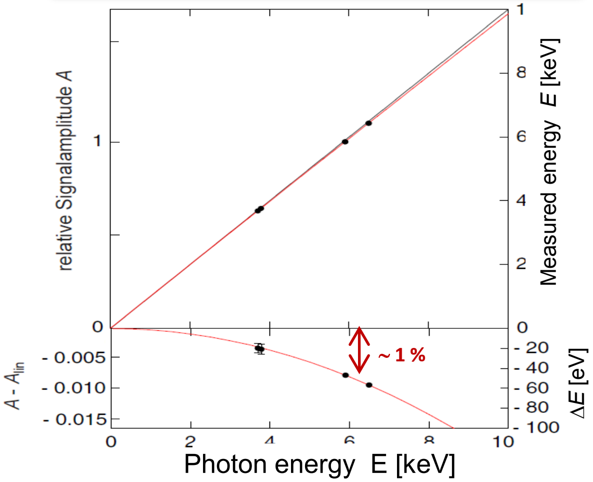
≥10^5 detectors

Low temperature
Metallic Magnetic Calorimeter

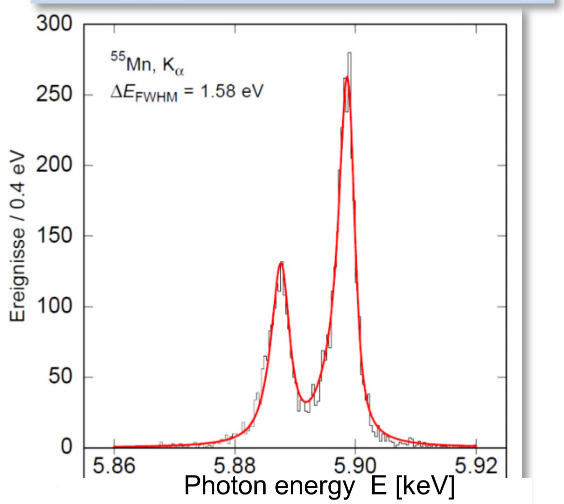
Rise Time: 90 ns



Non-Linearity < 1% @6keV



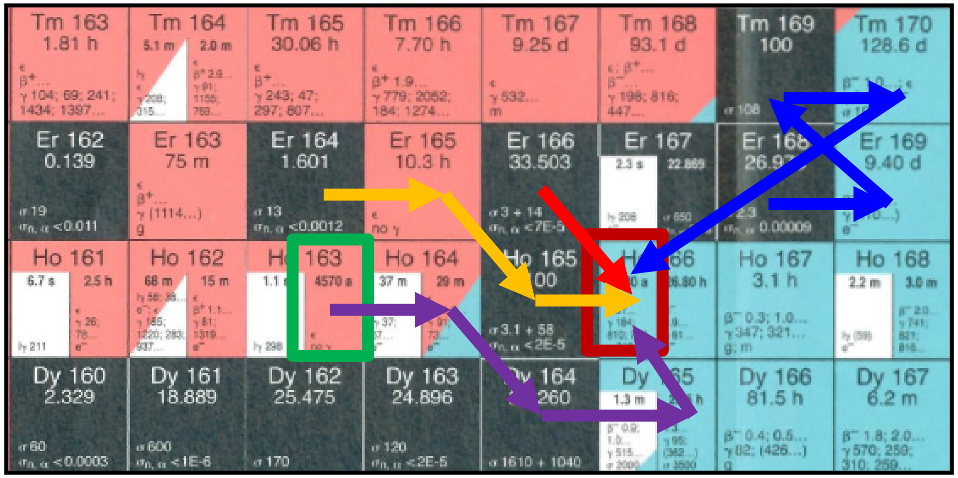
ΔE_{FWHM} = 1.6 eV @ 6 keV



ECHo : ^{163}Ho source

1) Develop higher quality chemical separation procedure
2) Separate Er from all LIGHTER Ln before irradiation.
3) Perform neutron irradiation
4) Separate Ho from all HEAVIER Ln after irradiaton (incl. Er)

Remaining question: what about ^{166m}Ho?



Pathways leading to ^{166m}Ho:

🟦 ^{168}Er(n,γ)^{169}Er –ß$^{-}$→ ^{169}Tm(n,α)^{166m}Ho

🟥 ^{166}Er(n,p)^{166m}Ho

🟨 ^{163}Ho(n,γ)^{164}Ho –EC→ ^{164}Dy(n,γ)^{165}Dy–ß$^{-}$→ ^{165}Ho(n,γ)^{166m}Ho

🟪 ^{164}Er(n,γ)^{165}Er –EC→ ^{165}Ho(n,γ)^{166m}Ho

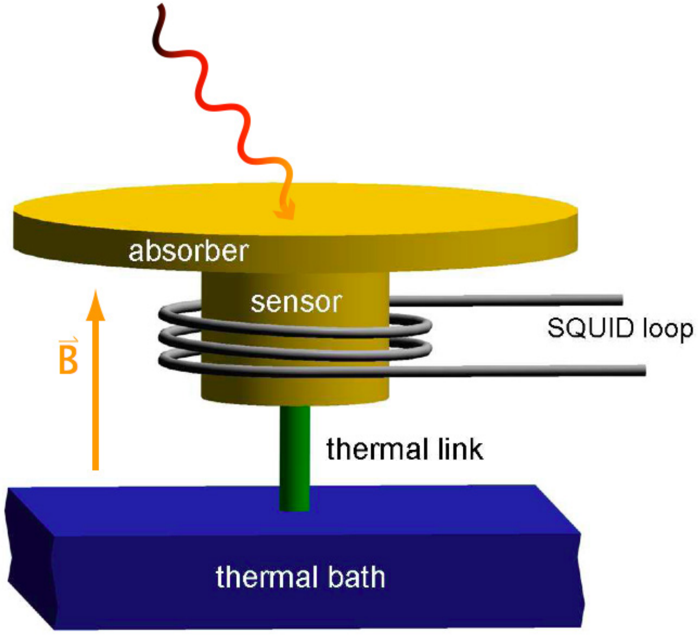
Removal of ^{166m}Ho possible by mass-separation

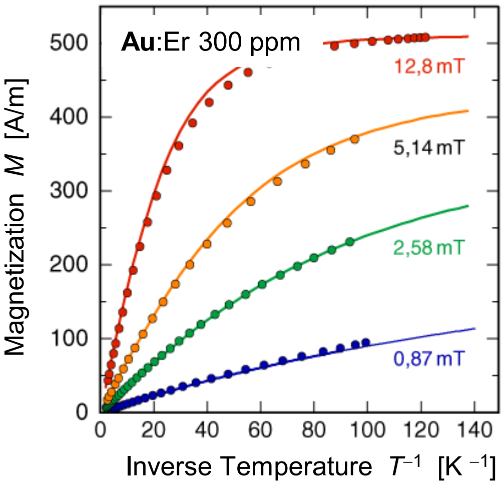
ECHo option 1: Separation at CERN/ISOLDE: Proposal accepted, will run in 2014
ECHo option 2: Use of the RISIKO mass-separator at Uni-Mainz, Summer 2014

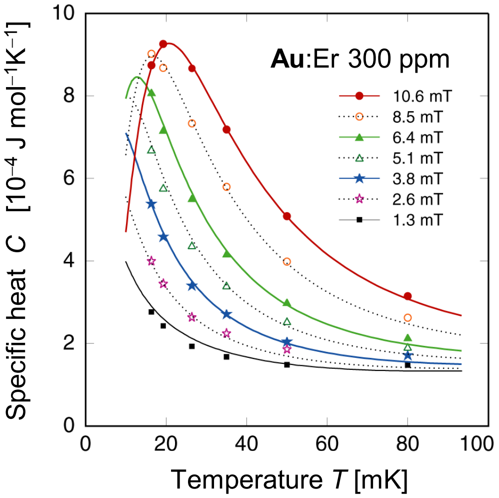
MMCs: Concept

- Paramagnetic Au:Er sensor

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







Main differences to calorimeters with resistive thermometers

no dissipation in the sensor

no galvanic contact to the sensor

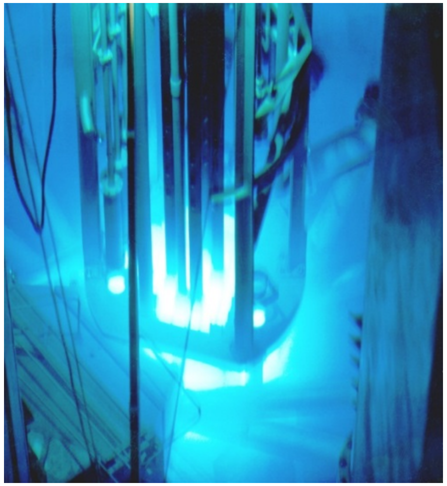
ECHo : ^{163}Ho source - (n,γ)-reaction on ^{162}Er

June 2012 : one irradiation at BER II Research Rector Berlin :

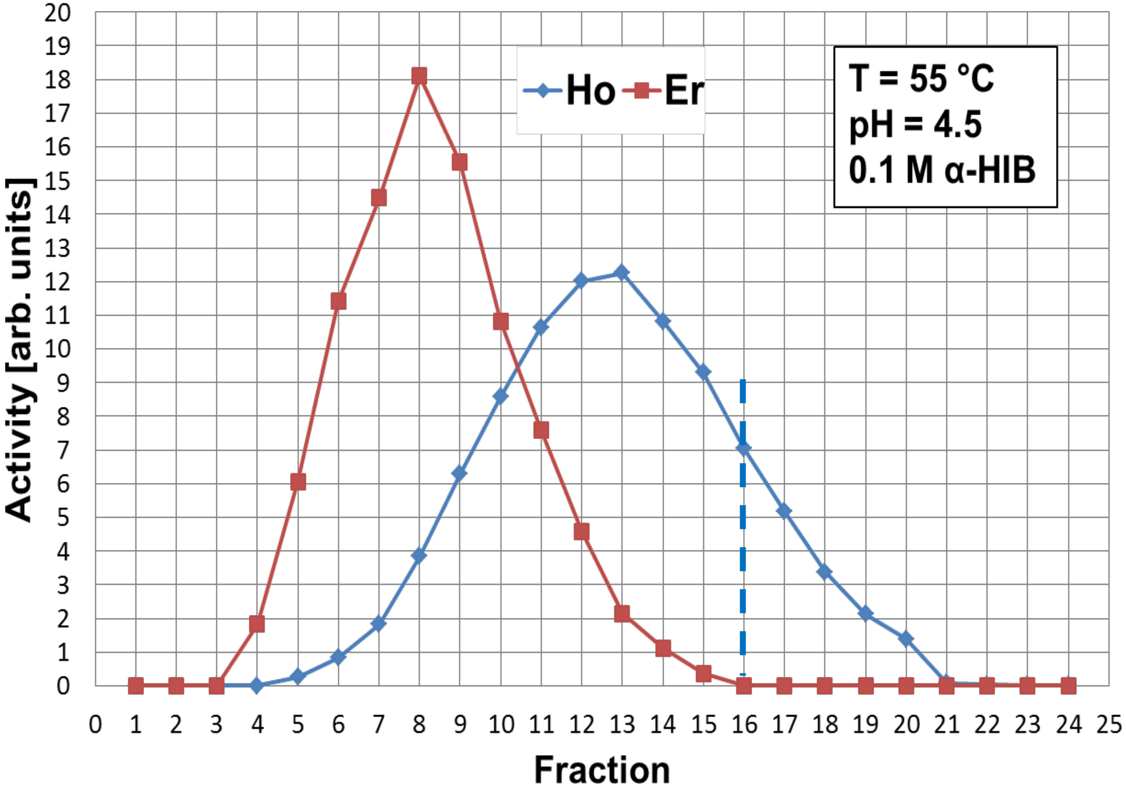
-Irradiate 5 mg Er for 11 days ⇒ $1.5 \bullet 10^{16}$ atoms ^{163}Ho

-Ho separated at Institute for Nuclear Chemistry Uni-Mainz using conventional ion-chromatographic resin

-Material still contains Er (and Dy)



Thermal neutron flux (Φ): 1.2×10^{14} $cm^{-2}s^{-1}$



Used for first measurement at TRIGA-TRAP

About $1.2 \bullet 10^{16}$ atoms ^{163}Ho still available

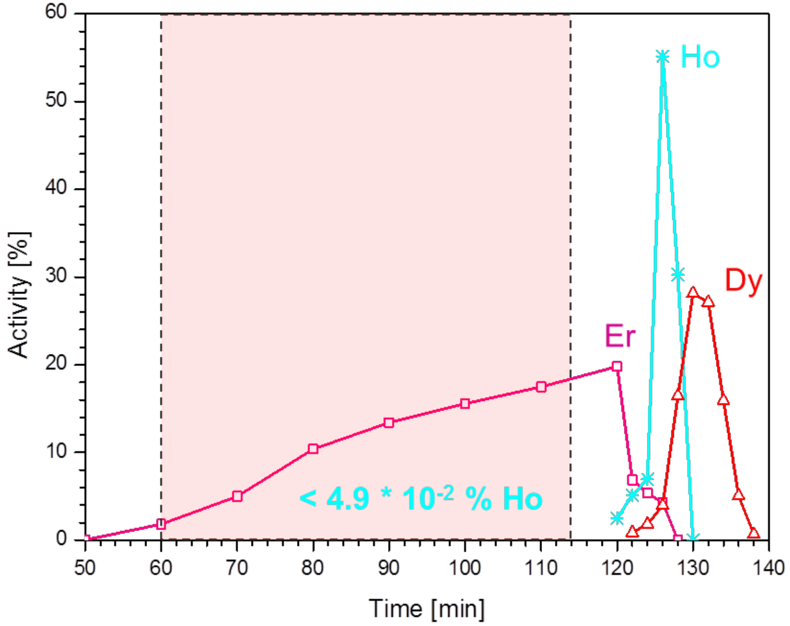
ECHo : ^{163}Ho source - (n,γ)-reaction on ^{162}Er

Summer 2013: Two irradiations at ILL

- Treatment of Er prior to irradiation:
  all elements lighter than Er separated with special ion-chromatographic resin

- 30 mg for 55 days $\Rightarrow$ $1.6 \bullet 10^{18}$ atoms ^{163}Ho
- 7 mg for 7 days $\Rightarrow$ $1.4 \bullet 10^{16}$ atoms ^{163}Ho

Thermal neutron flux
(Φ): 1.3×10^{15} cm^{-2}s^{-1}



heavy ⟷ Lanthanides ⟷ light

(developed for radiopharmaceutical applications)