

Heat Capacity, Statistics and a bit of Analysis for ECHO

HighRR 2020

Clemens Velte

status quo



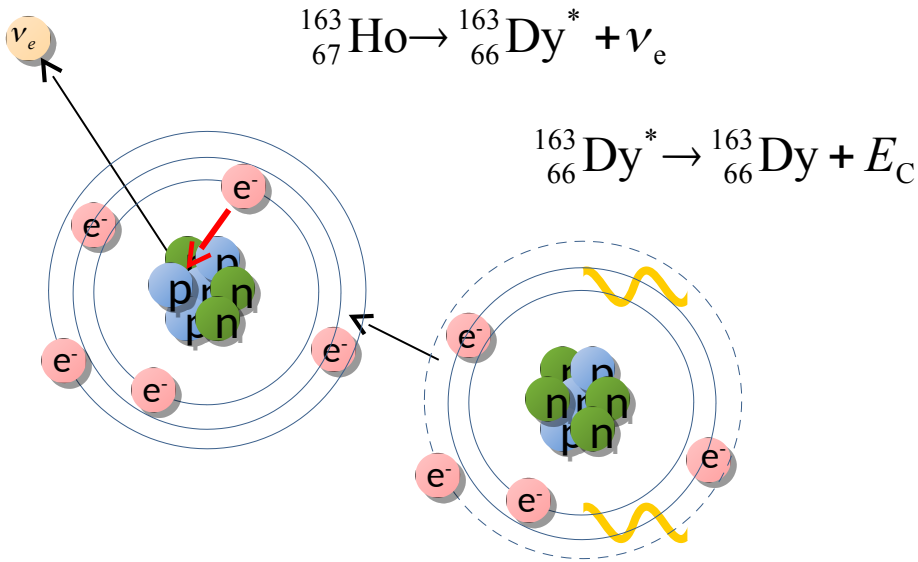
status quo



kinematic approach (model independent)

- $m(\bar{\nu}_e): < 1.1 \text{ eV } 90\% \text{ C.L.}$
G. Huang et al., Phys. Rev. D 101, 016003 (2020)
- $m(\nu_e): < 225 \text{ eV } 95\% \text{ C.L.}$
P. T. Springer et al., Phys. Rev. A 35, 679 (1987)

Electron capture in ^{163}Ho



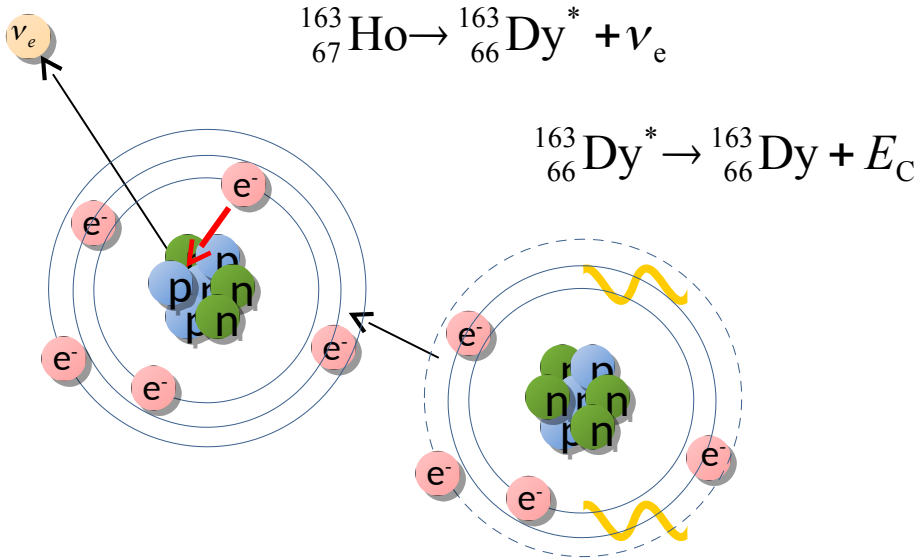
Atomic de-excitation:

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

- $T_{1/2} \approx 4570$ years
($2 \cdot 10^{11}$ atoms for 1 Bq)

- $Q_{\text{EC}} = (2.833 \mp 0.030^{\text{stat}} \mp 0.015^{\text{syst}})$ keV
S. Eliseev et al., *Phys. Rev. Lett.*, 115, 062501 (2015)

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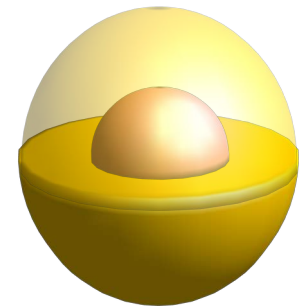
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Calorimetric measurement

A. De Rujula and M. Lusignoli
 Phys. Lett. 118 B (1982) 118

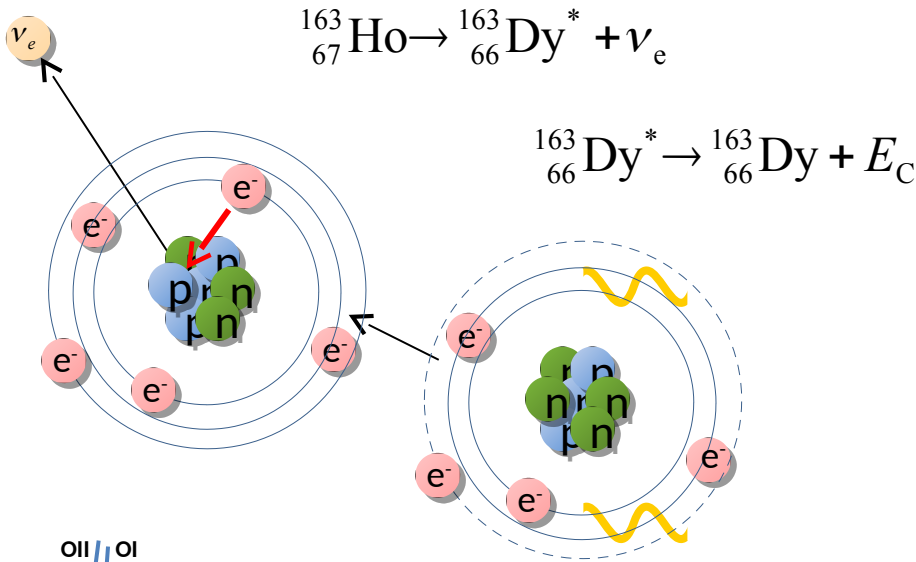
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4π encapsulation

Electron capture in ^{163}Ho

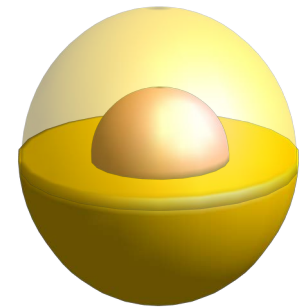
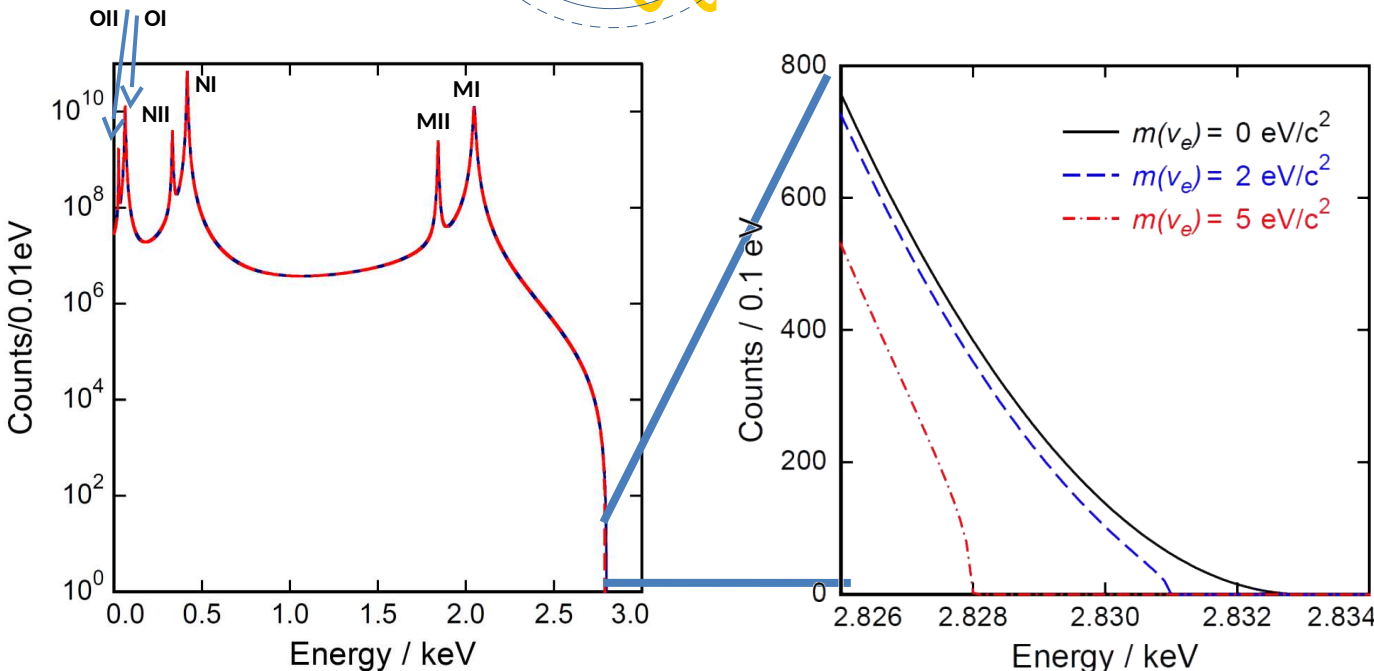
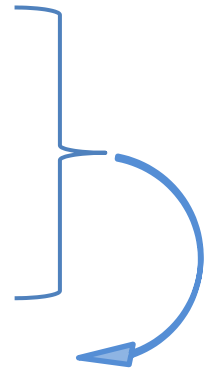


Atomic de-excitation:

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4π encapsulation

Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

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

Unresolved pile-up ($f_{\text{pu}} = a \bullet \tau_r$)

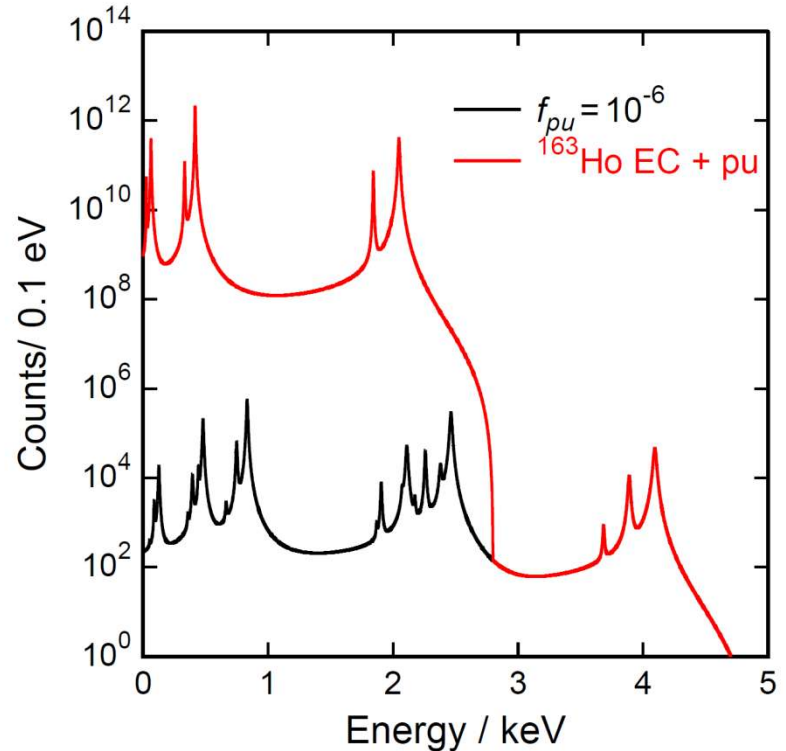
- $f_{\text{pu}} \leq 10^{-6}$
- $\tau_r < 1 \mu\text{s} \rightarrow a \sim 10 \text{ Bq}$
- $10^5 \text{ pixels} \rightarrow \text{multiplexing}$

Precision characterization of the endpoint region

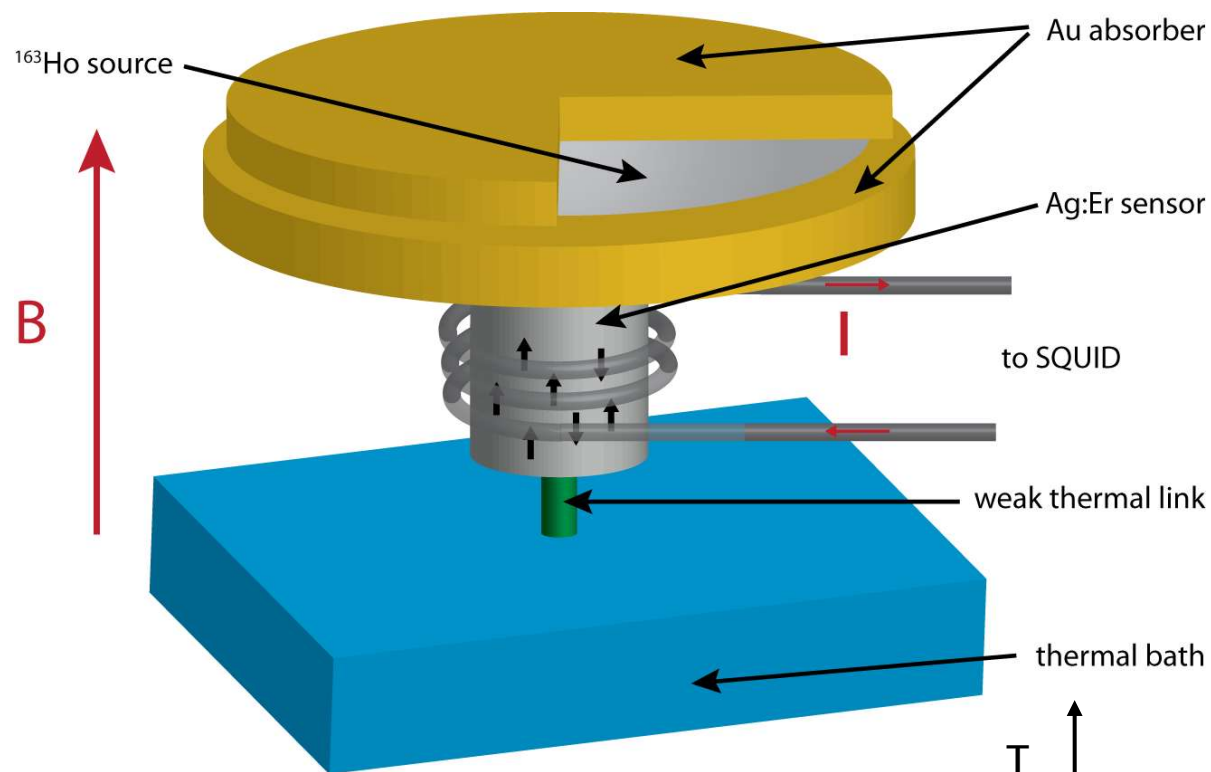
- $\Delta E_{\text{FWHM}} < 3 \text{ eV}$

Background level

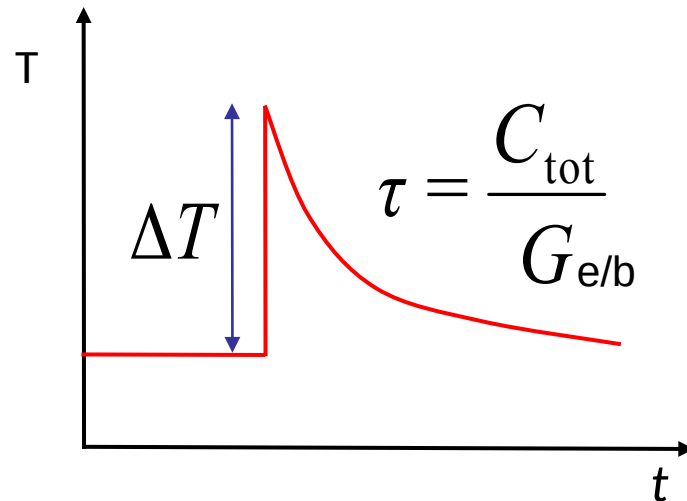
- $< 10^{-5} \text{ events/eV/det/day}$



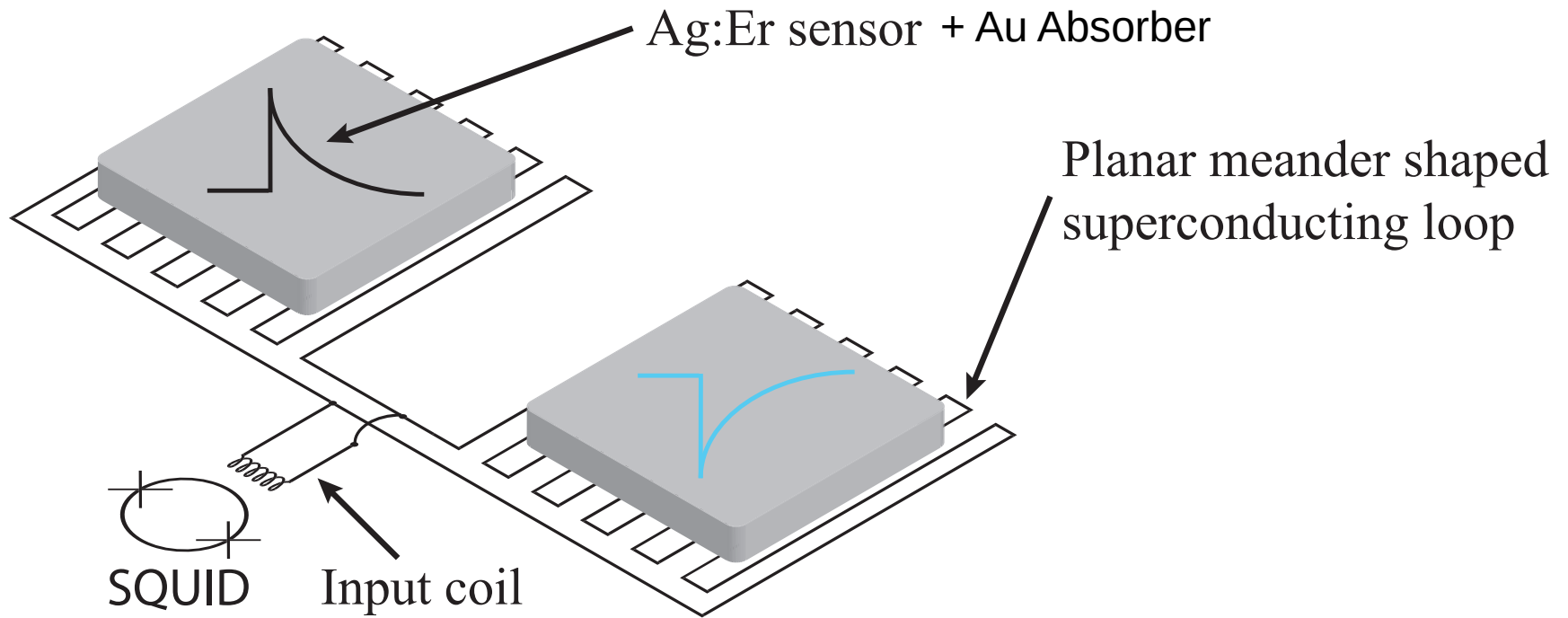
Metallic magnetic calorimeters (MMCs)



$$\Delta T = \frac{\Delta E}{C_{\text{tot}}}$$



Gradiometric MMCs



Heat Capacity

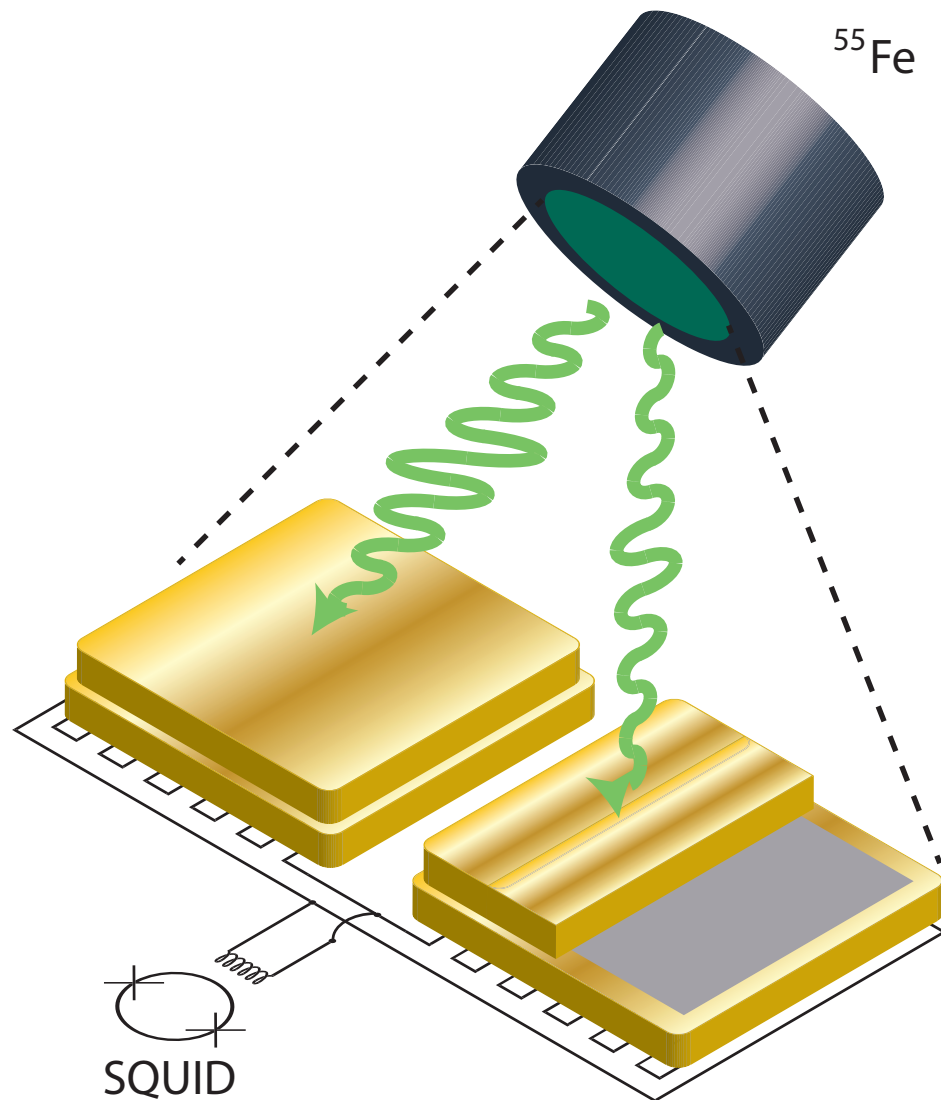
$$\Delta E_{FWHM} < 3 \text{ eV} \quad a \sim 10 \text{ Bq}$$

$$\Delta E_{FWHM} \propto \sqrt{C_{tot}}$$

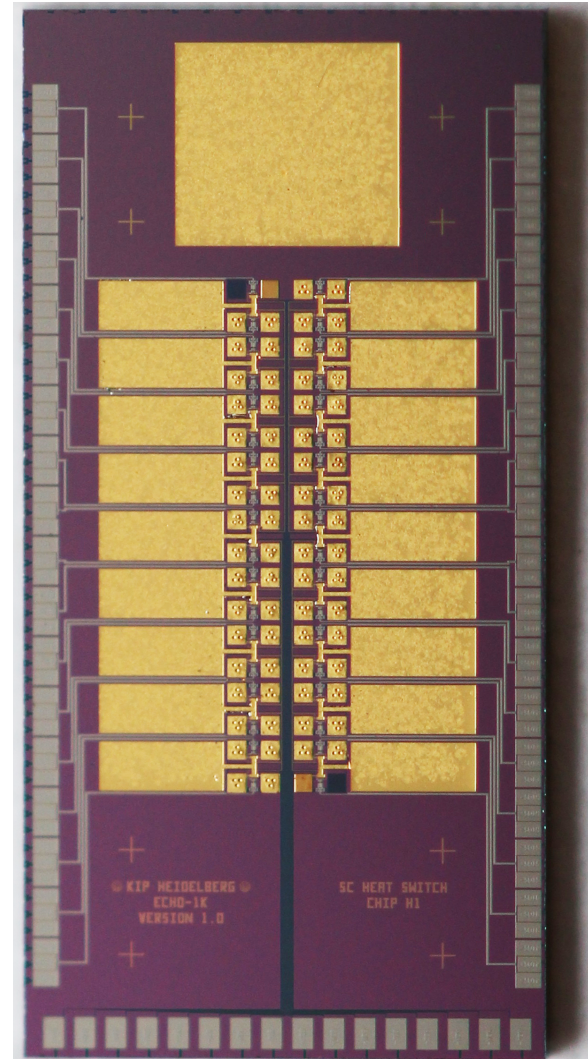
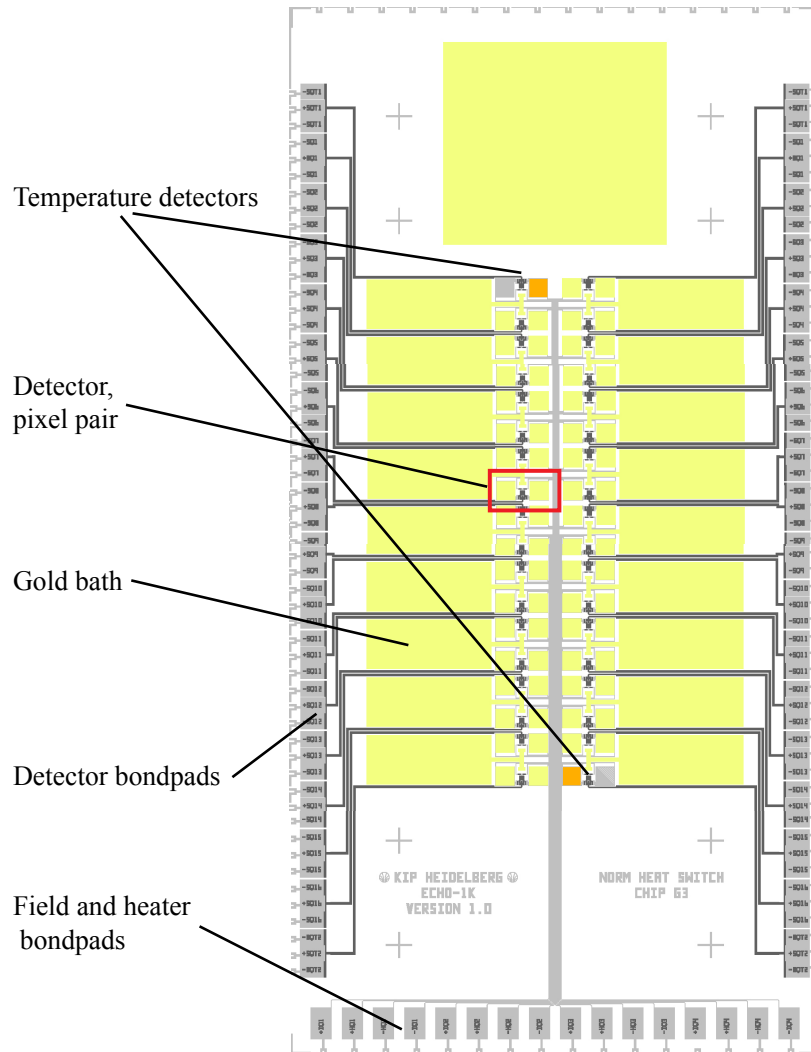
$$C_{Ho}(1\text{Bq}) = ?$$

HC setup

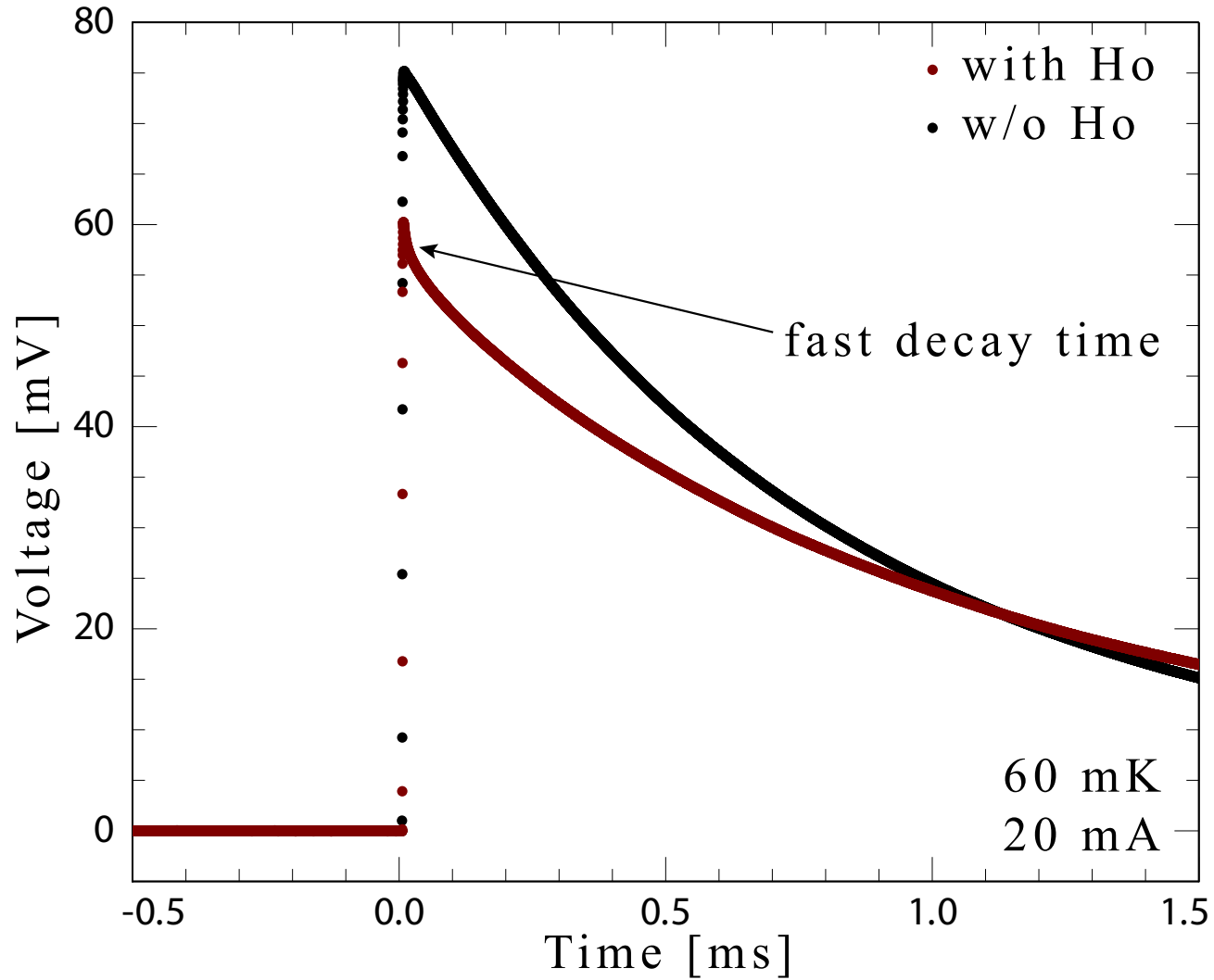
$$\Delta T = \frac{\Delta E}{C_{tot}}$$



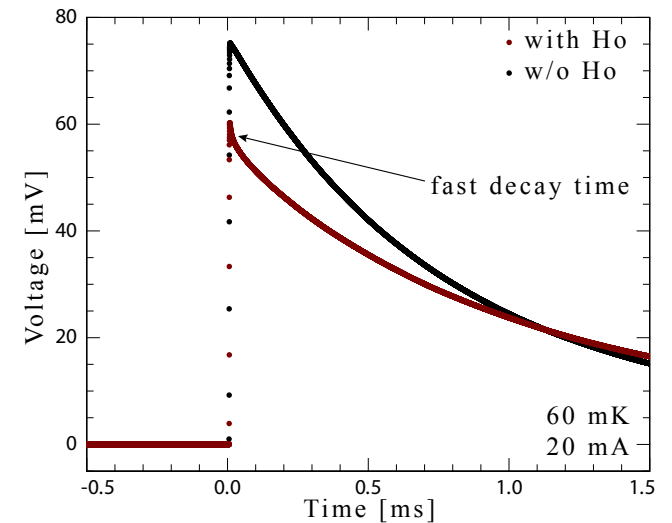
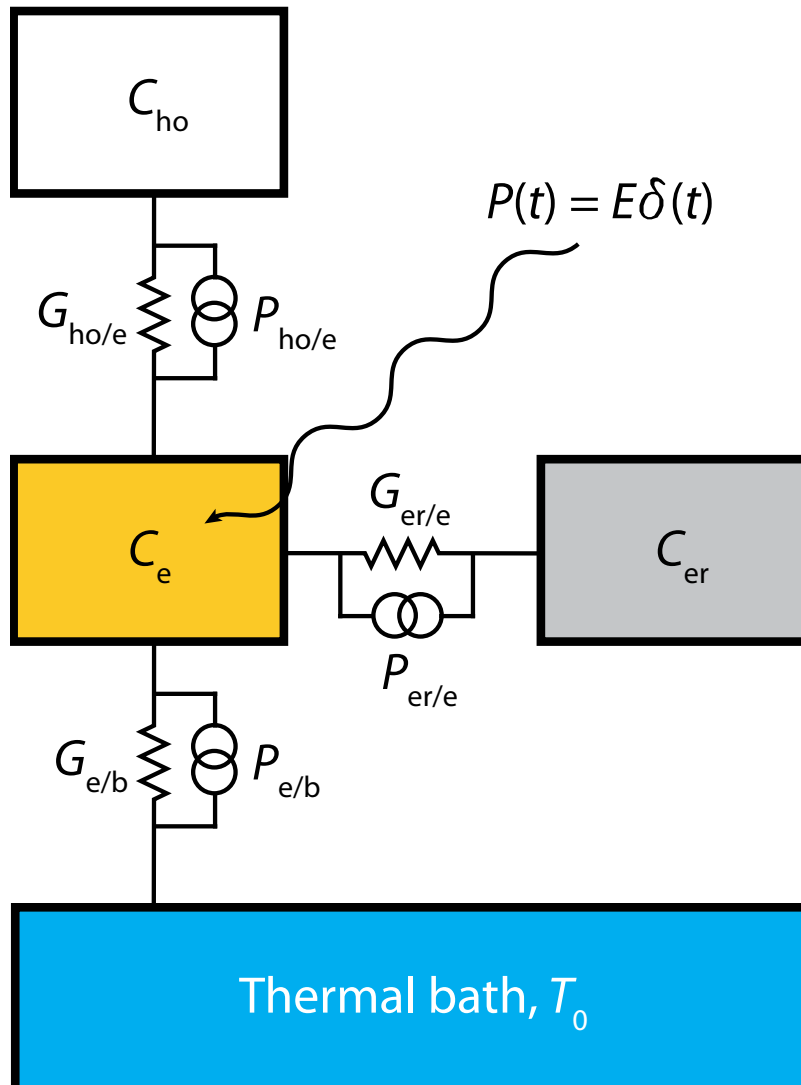
ECHO-1k detector chip



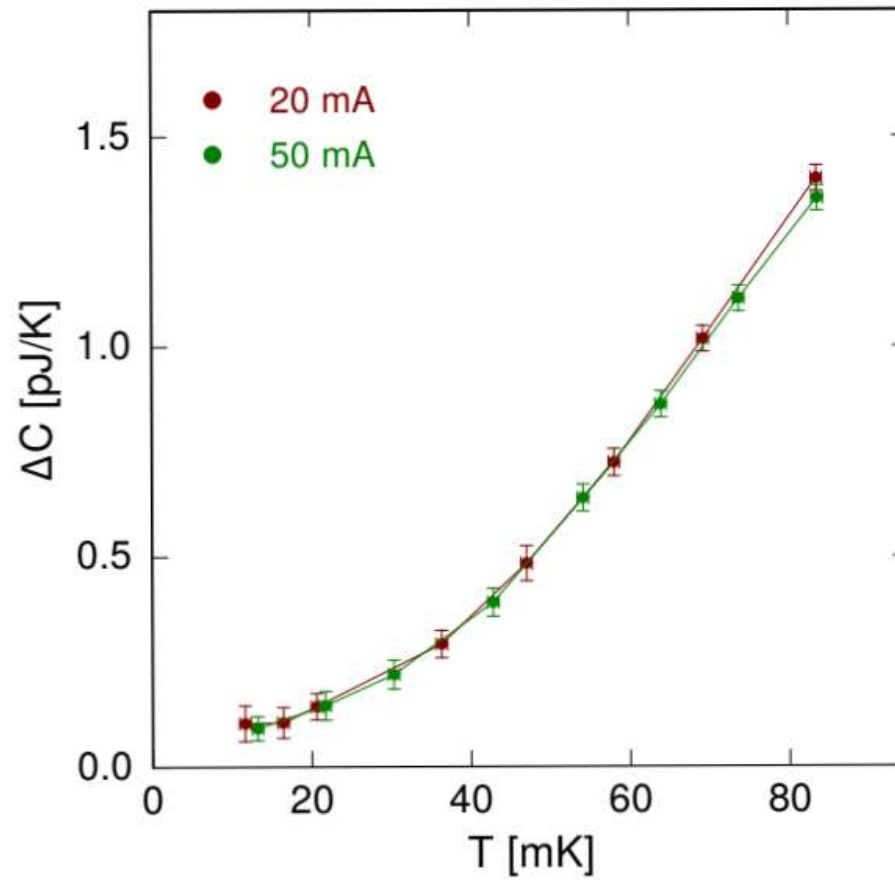
Pulse height for ^{55}Fe



HC due to ^{163}Ho



Heat capacity of ^{163}Ho



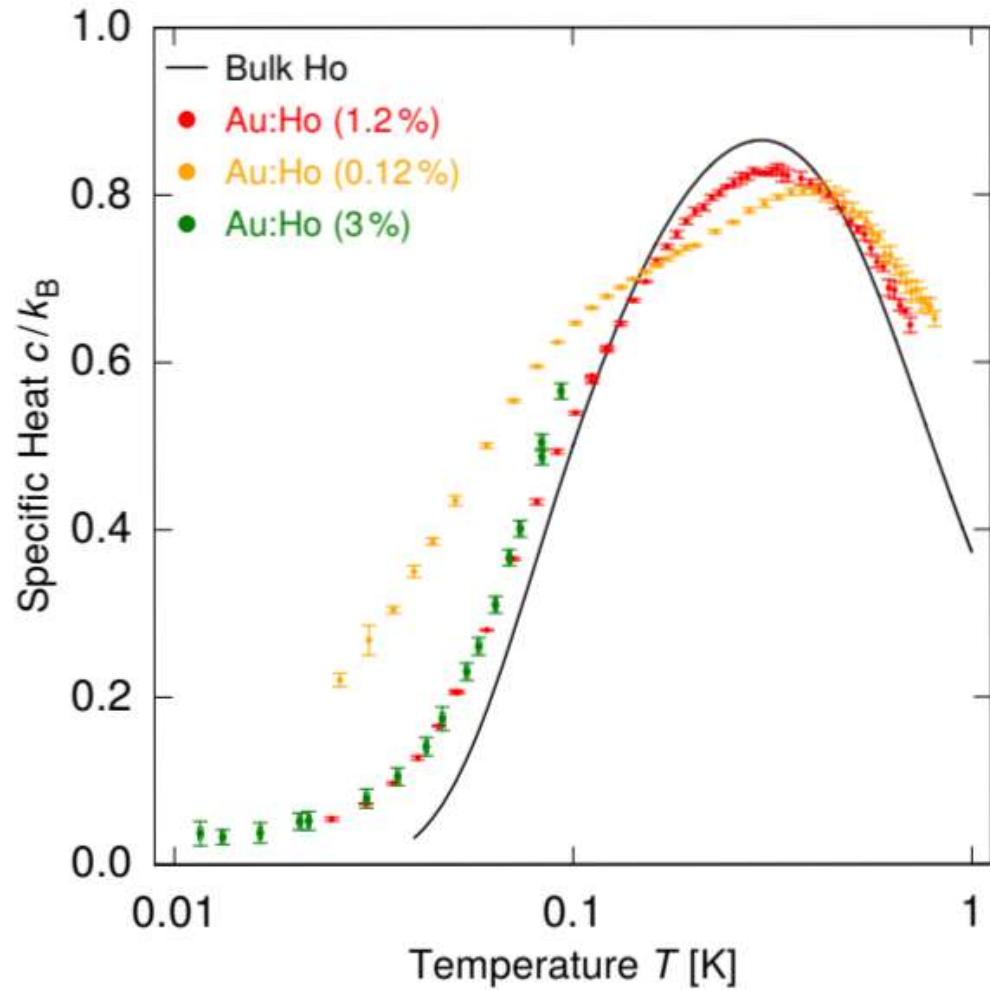
Heat capacity of ^{163}Ho

0.9 Bq @ 20 mK
4% higher C_{tot}

→ 10 Bq @ 20 mK
40% higher C_{tot}

$$\Delta E_{FWHM} \propto \sqrt{C_{\text{tot}}}$$

→ 10 Bq are no problem



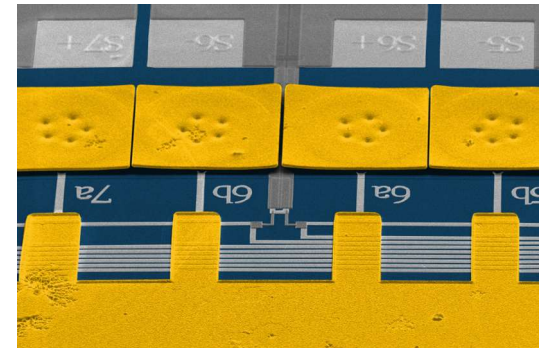
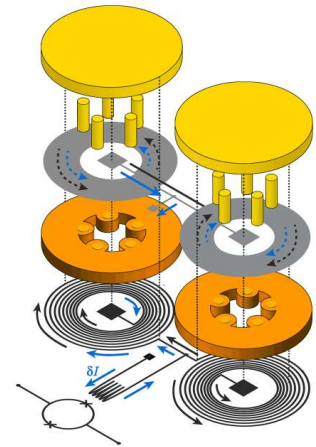
Statistics & Analysis

Modane

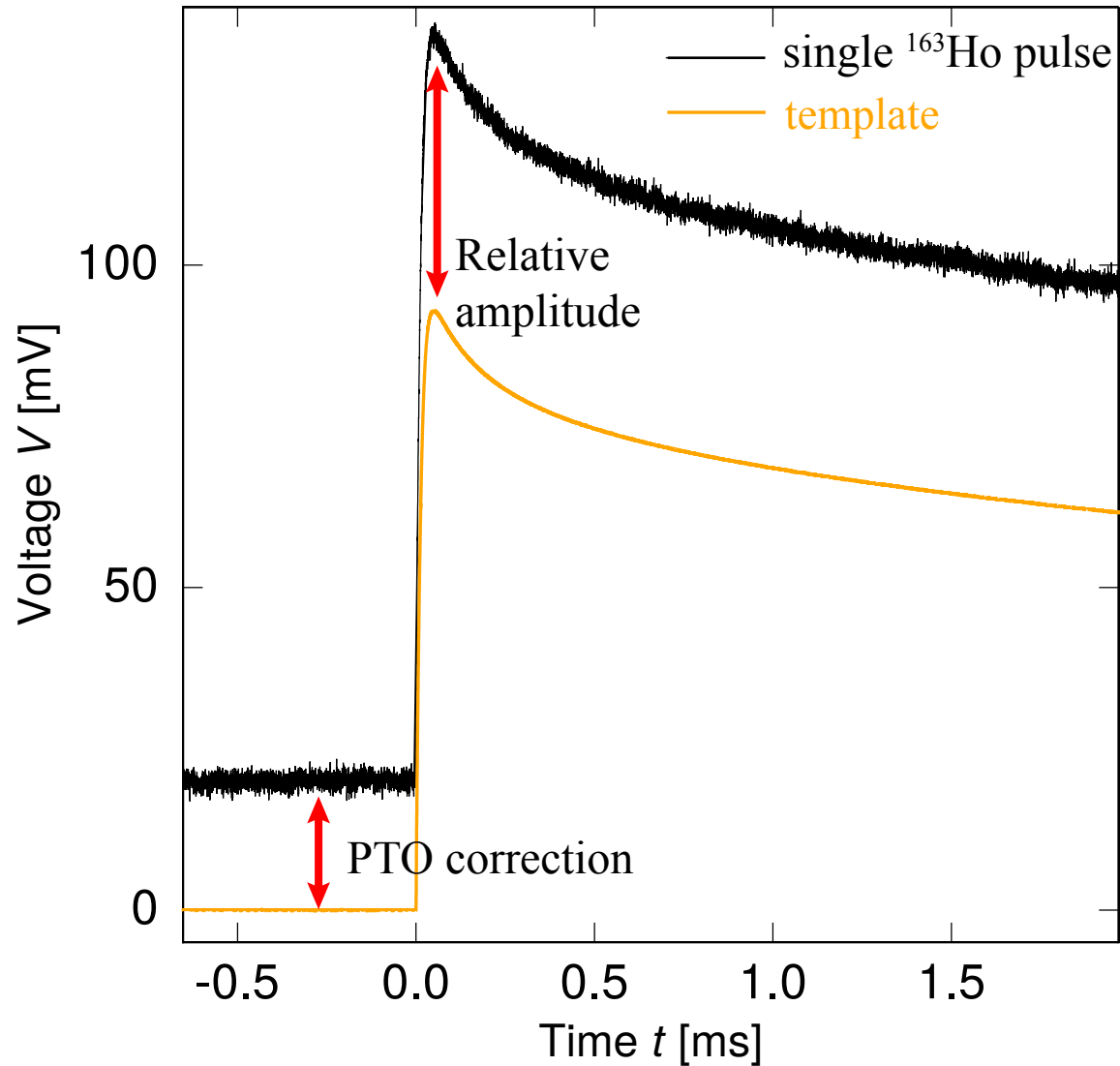
4 pixels, 4 days

275 000 events

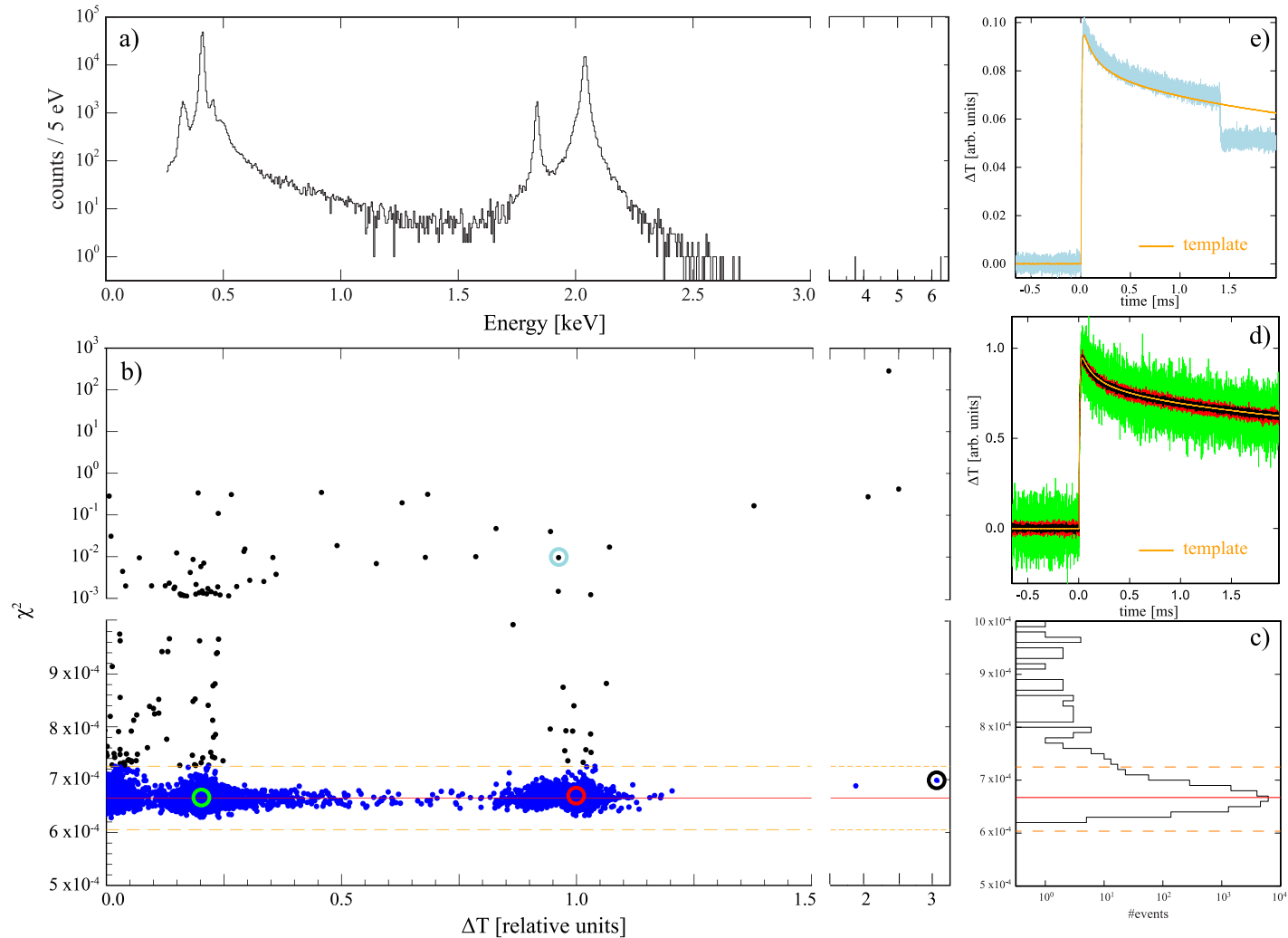
clean ^{163}Ho source



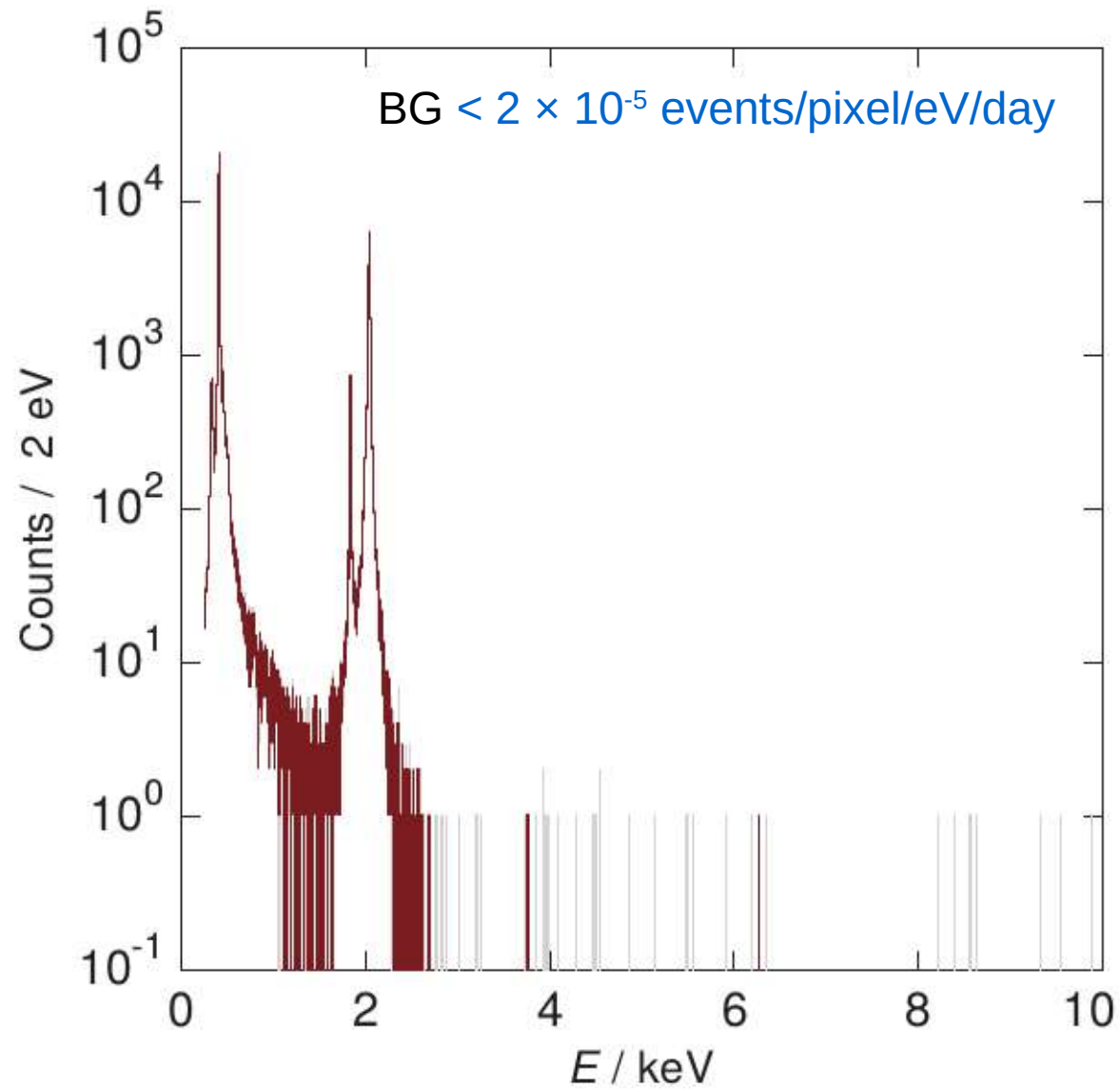
Fitting pulses



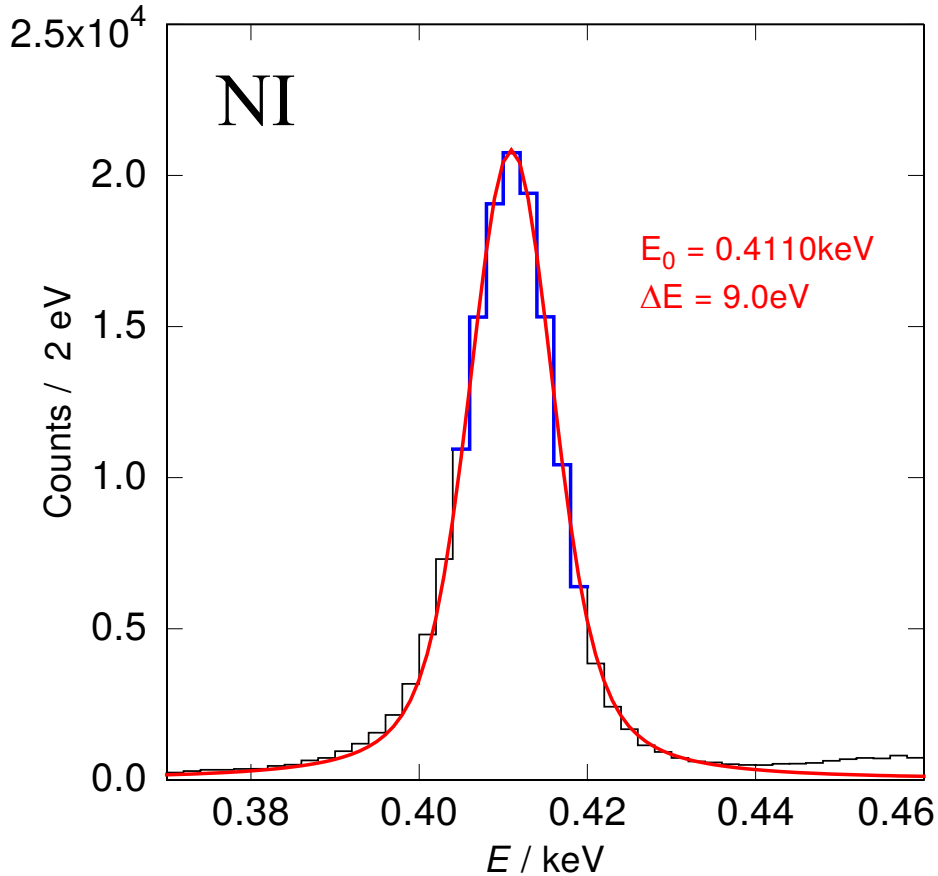
A nice and clean ^{163}Ho spectrum



Background



Spectrum



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

$$N_{\text{ev}} = 275\,000$$

$$\text{BG} < 10^{-5} \text{ events/pixel/eV/day}$$

$$\text{BG} < 2 \times 10^{-5} \text{ events/pixel/eV/day}$$

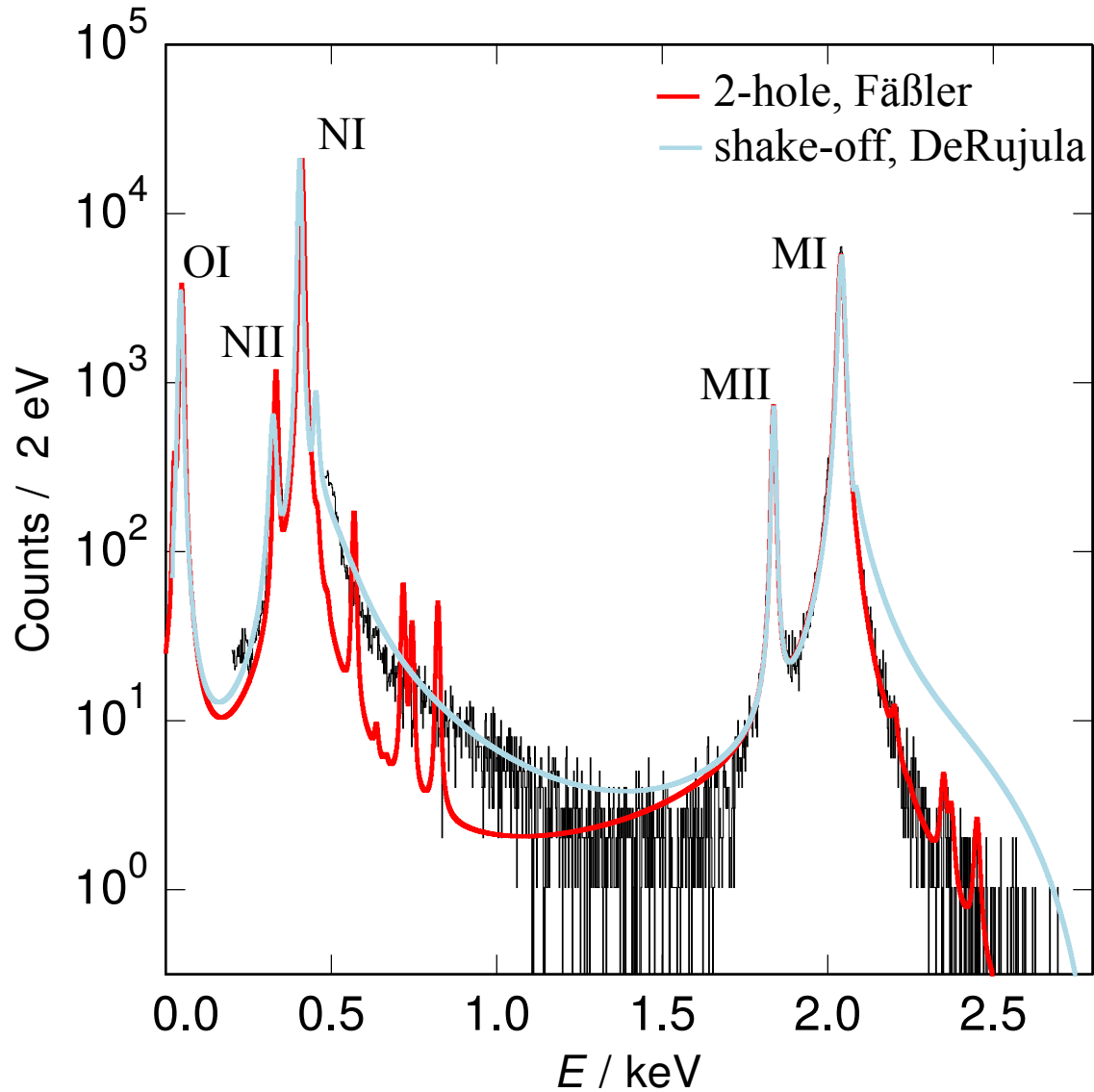
$$\Delta E_{\text{FWHM}} < 3 \text{ eV}$$

$$\Delta E_{\text{FWHM}} = 9 \text{ eV}$$

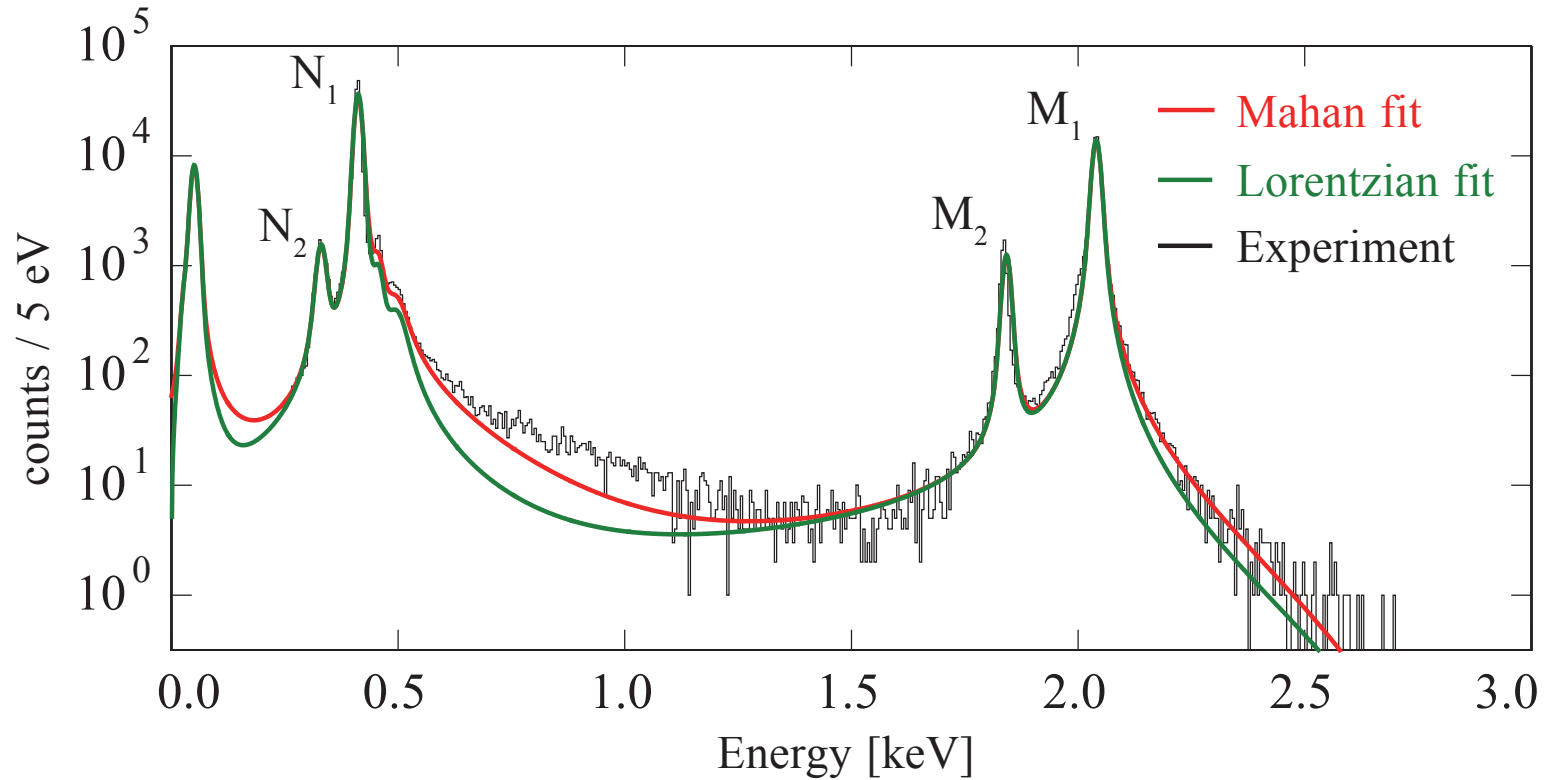
$$Q_{\text{EC}} = (2.833 \mp 0.030^{\text{stat}} \mp 0.015^{\text{syst}}) \text{ keV}$$

$$Q_{\text{EC}} = (2.838 \pm 0.014) \text{ keV}$$

Comparison with theory



Comparison with theory

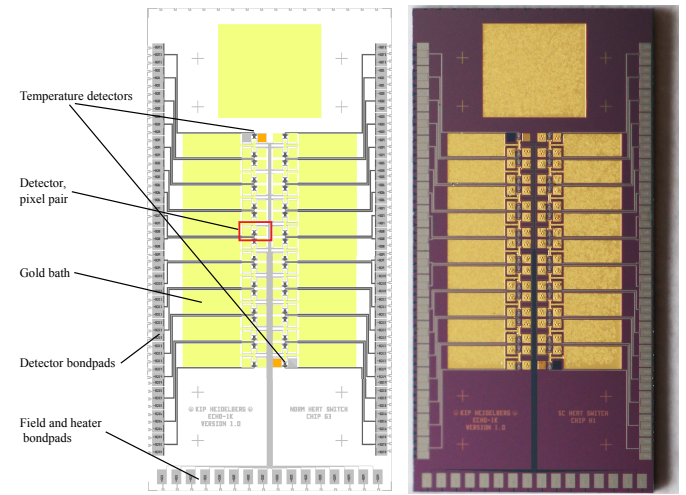
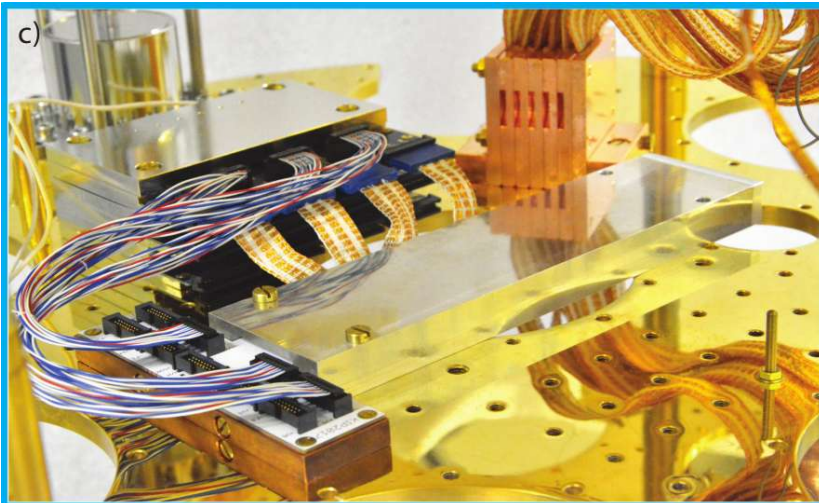


Statistics & Analysis

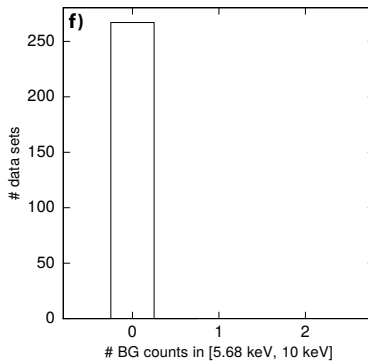
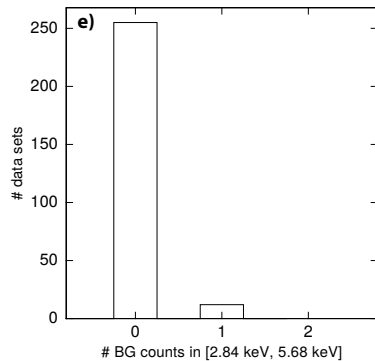
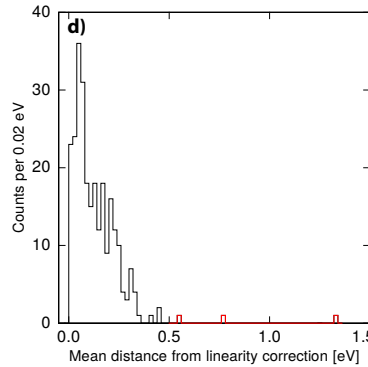
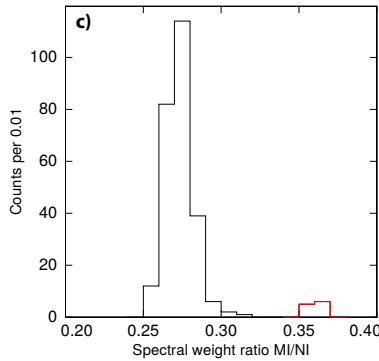
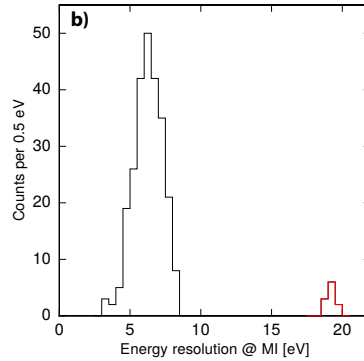
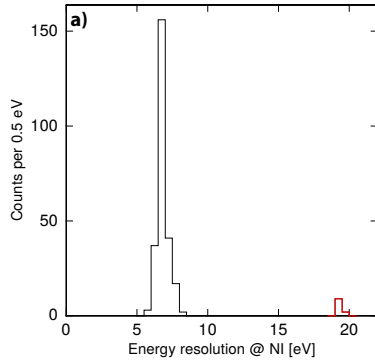
ECHo-1k chip

23 pixels, 22 days

3×10^7 events



High statistic ^{163}Ho spectrum



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

$$N_{\text{ev}} = 3 \times 10^7$$

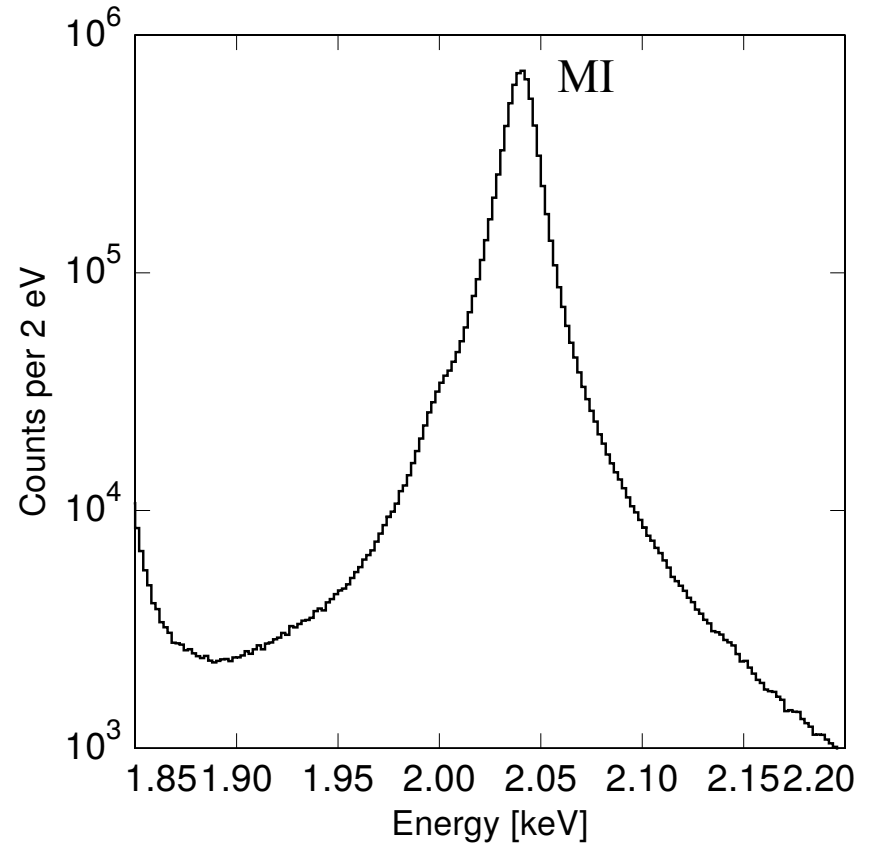
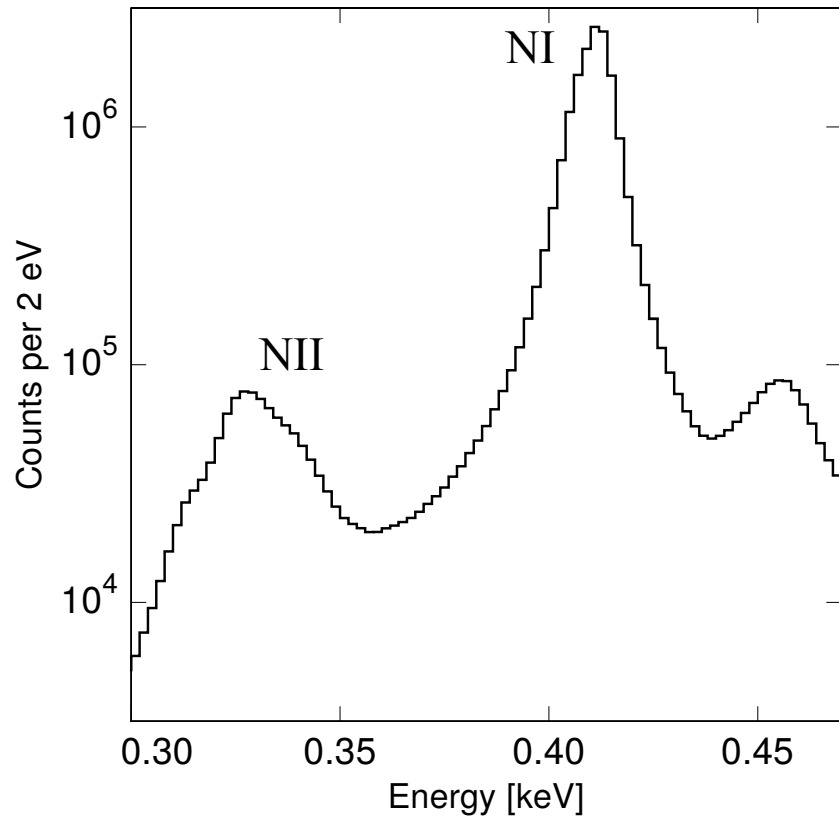
$$\text{BG} < 10^{-5} \text{ events/pixel/eV/day}$$

$$\text{BG} < 1 \times 10^{-6} \text{ events/pixel/eV/day}$$

$$\Delta E_{\text{FWHM}} < 3 \text{ eV}$$

$$\Delta E_{\text{FWHM}} = 6.6 \text{ eV}$$

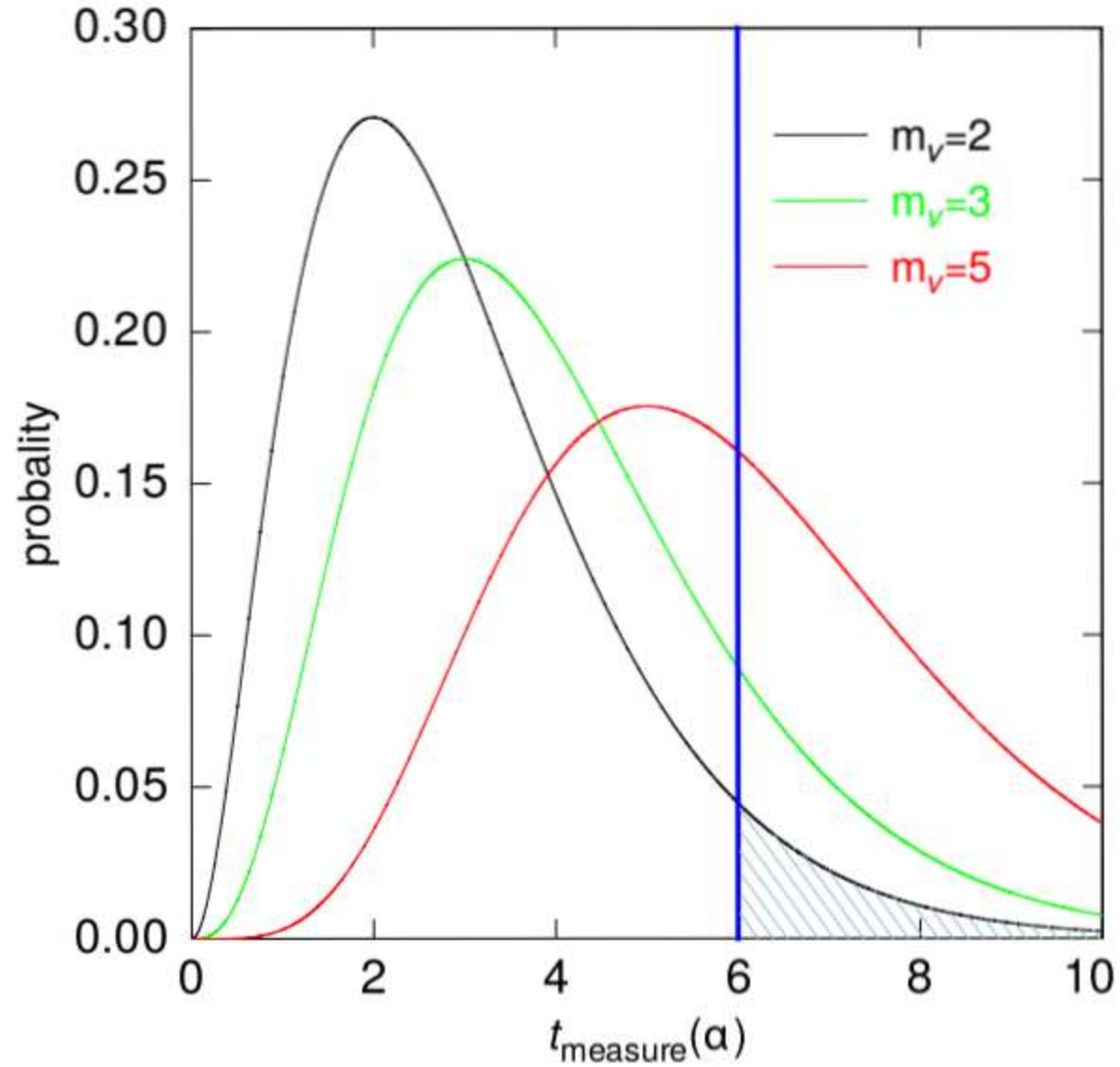
^{163}Ho spectrum



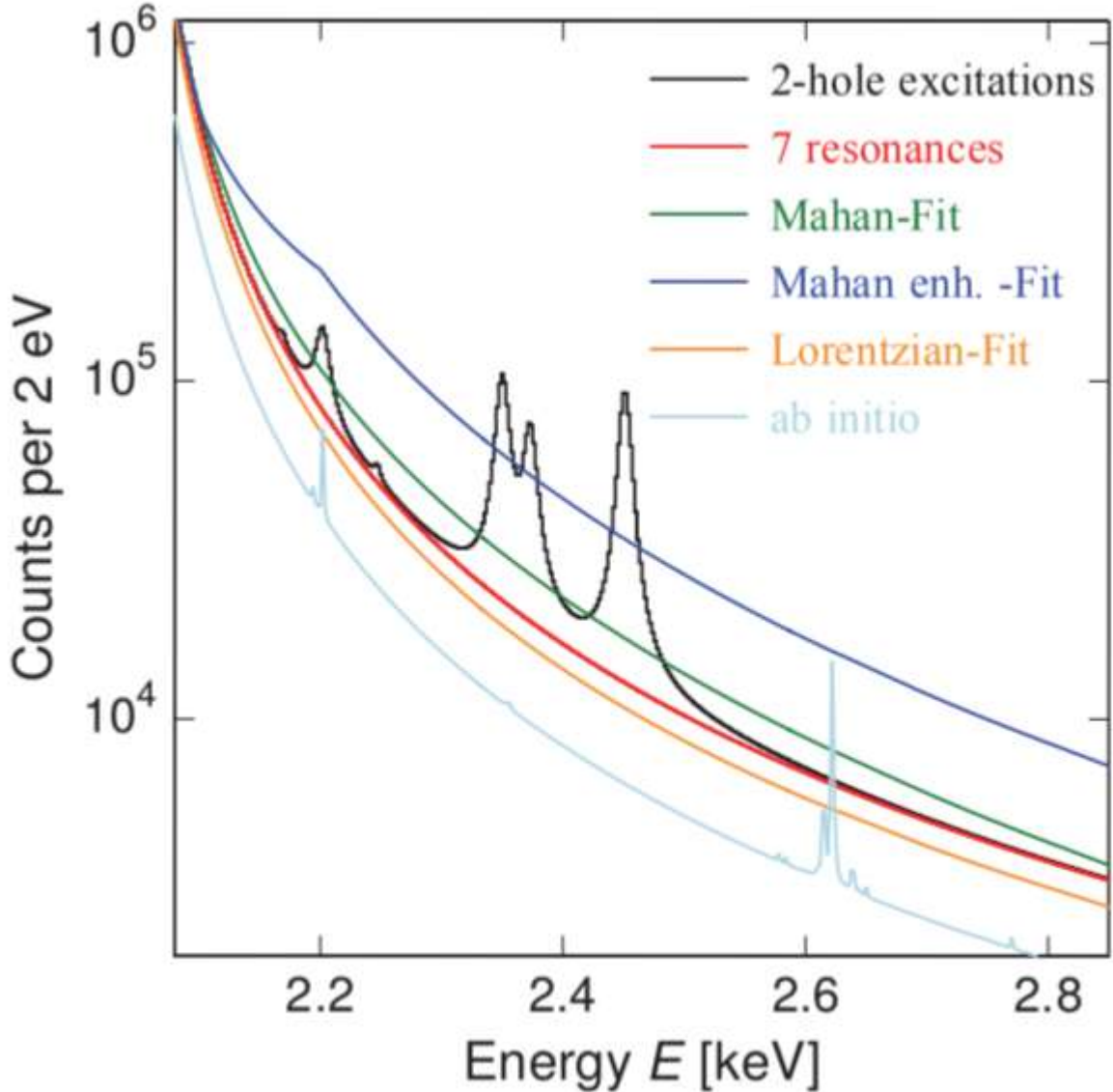
Comparison with theory

- $Q_{\text{EC}} = (2.833 \mp 0.030^{\text{stat}} \mp 0.015^{\text{syst}}) \text{ keV}$

p-value



theories



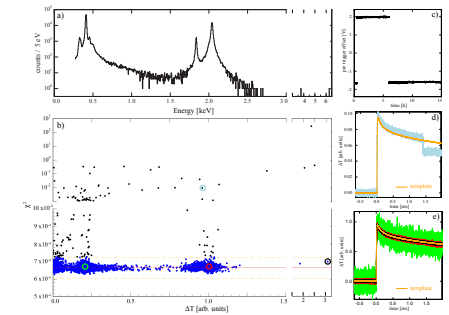
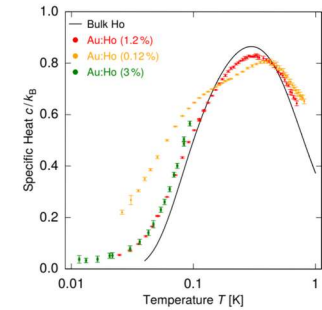
Neutrino mass

Conclusion

HC: specific heat per ^{163}Ho -ion = $0.05 k_B$ at $T = 20 \text{ mK}$
→ $a = 10\text{Bq}$ is allowed

Modane: clean ^{163}Ho implantation is possible
new features need advanced theories
 Q matches with PENNING TRAP measurement

ECHo-1k Chip: more statistics give new input to theory
best achieved energy resolution with
 ^{163}Ho at that time



and much more ...