The Electron Capture in ^{163}Ho experiment ECHo: towards sub-eV sensitivity on the electron neutrino mass

Loredana Gastaldo (for the ECHo Collaboration)

Kirchhoff Institute for Physics, Heidelberg University

Contents

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

Direct neutrino mass determination

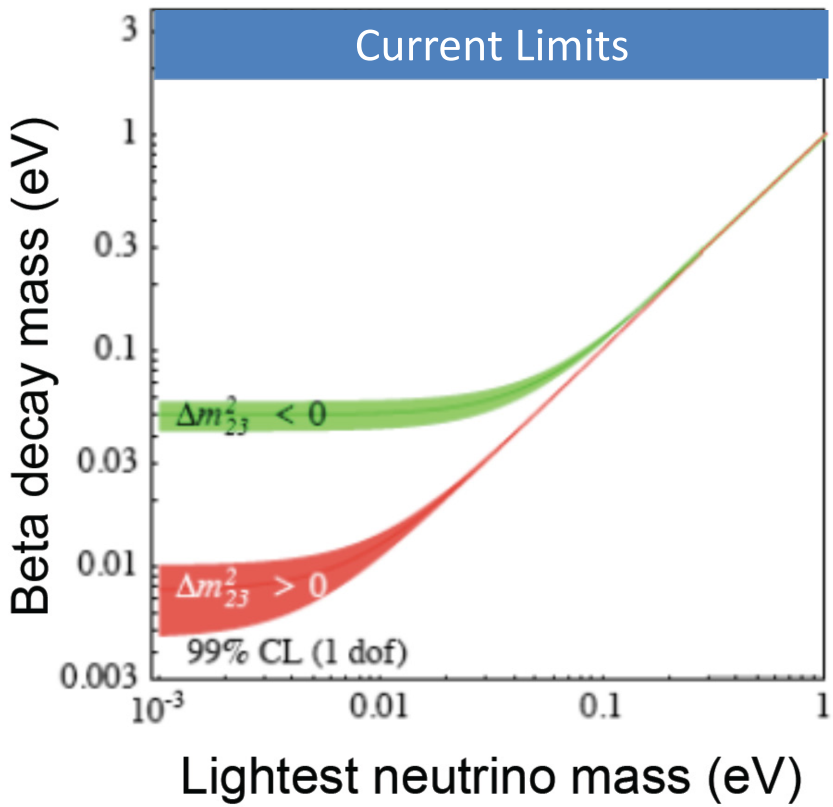
Kinematics of beta decay

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2$$

- Model independent
- Laboratory experiments

$$m(\bar{\nu}_e) < 2.2 \ eV$$ ^3H (1)

$$m(\nu_e) < 225 \ eV$$ ^{163}Ho (2)



(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447
Ch. Weinheimer, Prog. Part. Nucl. Phys. **57** (2006) 22
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(2) P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

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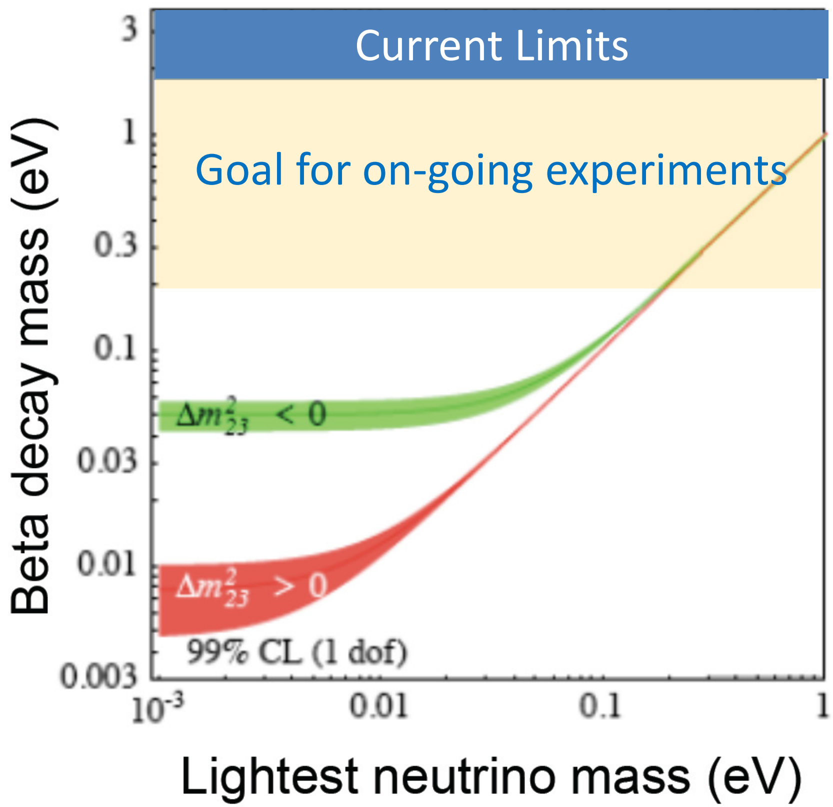
- **Next future 200 meV**



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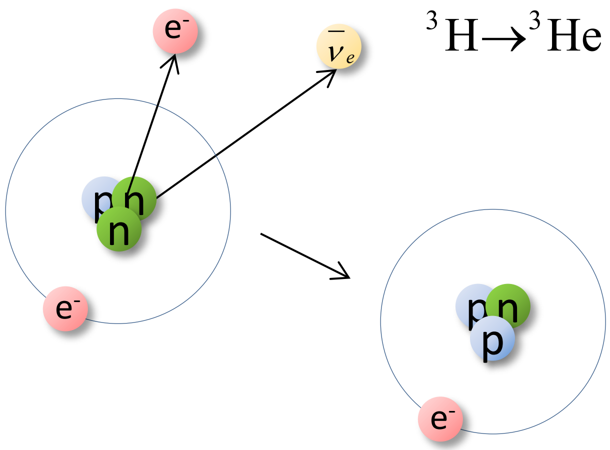
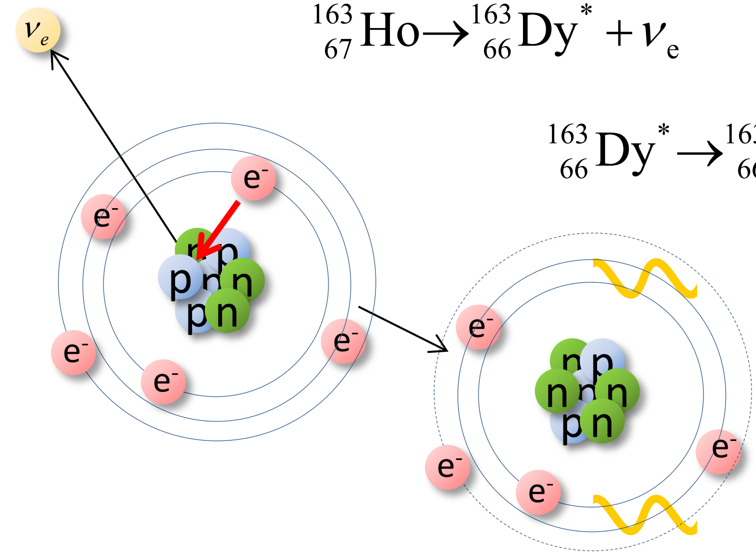
Beta decay and electron capture



$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e}$$



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

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

- $\tau_{1/2} \cong$ 12.3 years (4*10^8 atoms for 1 Bq)
- Q_{β} = 18 592.01(7) eV

E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

- $\tau_{1/2} \cong$ 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** (2015) 062501

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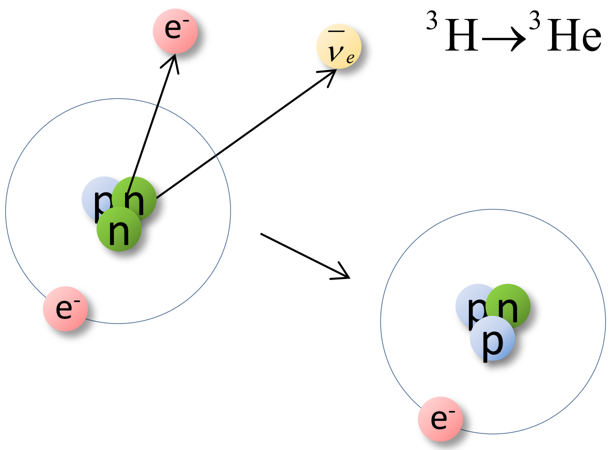

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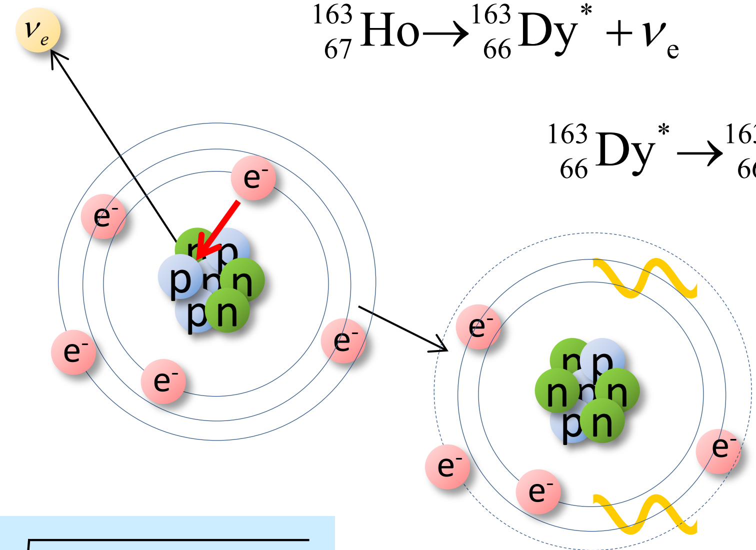

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$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

$$\frac{dW}{dE} \propto (Q - E)^2 \sqrt{1 - \frac{m_\nu^2}{(Q - E)^2}}$$

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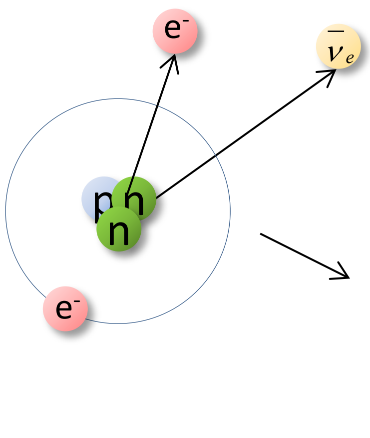

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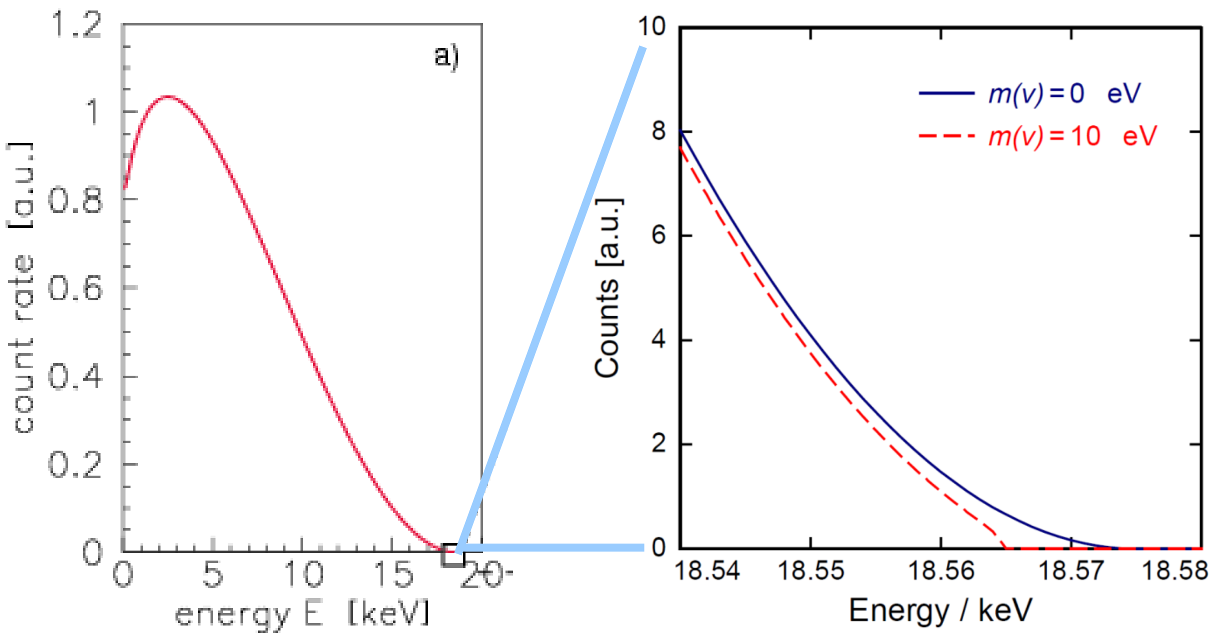

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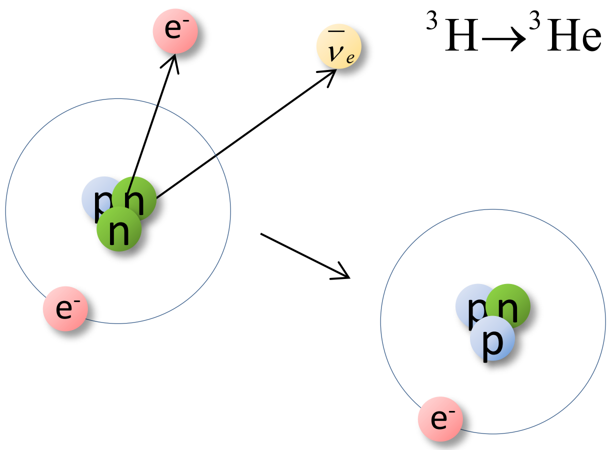

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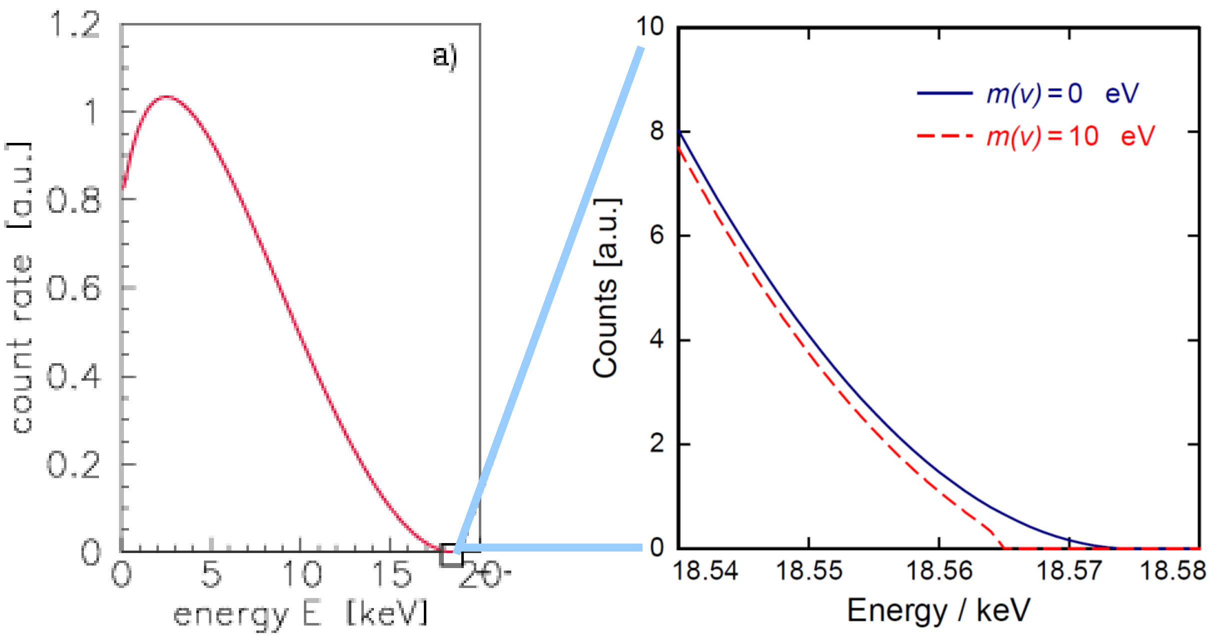
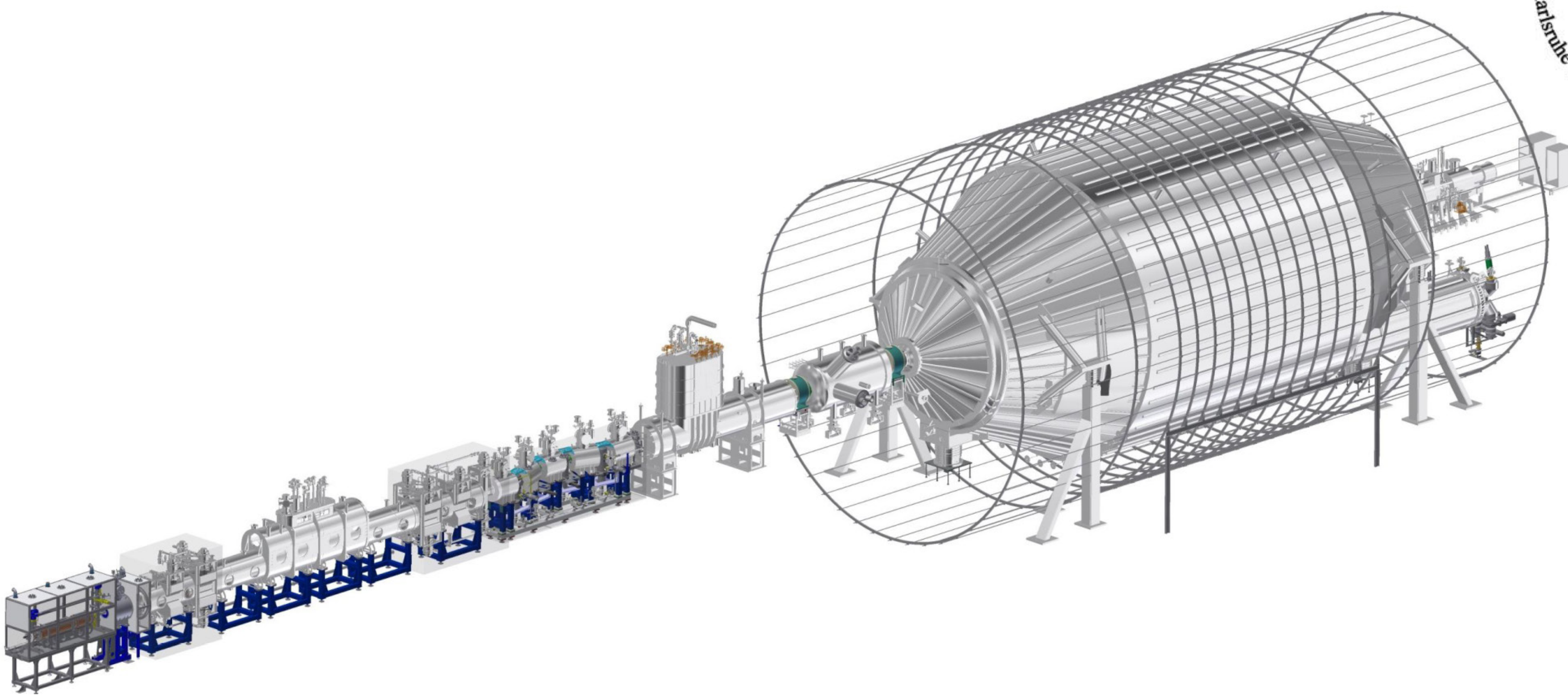


Only a small fraction of events in the last eV below the endpoint: **$2 * 10^{-13}$**

Very low background is required

The KATRIN experiment

❖ **KATRIN** - **Ka**rlsruhe **Tri**tium **N**eutrino Experiment

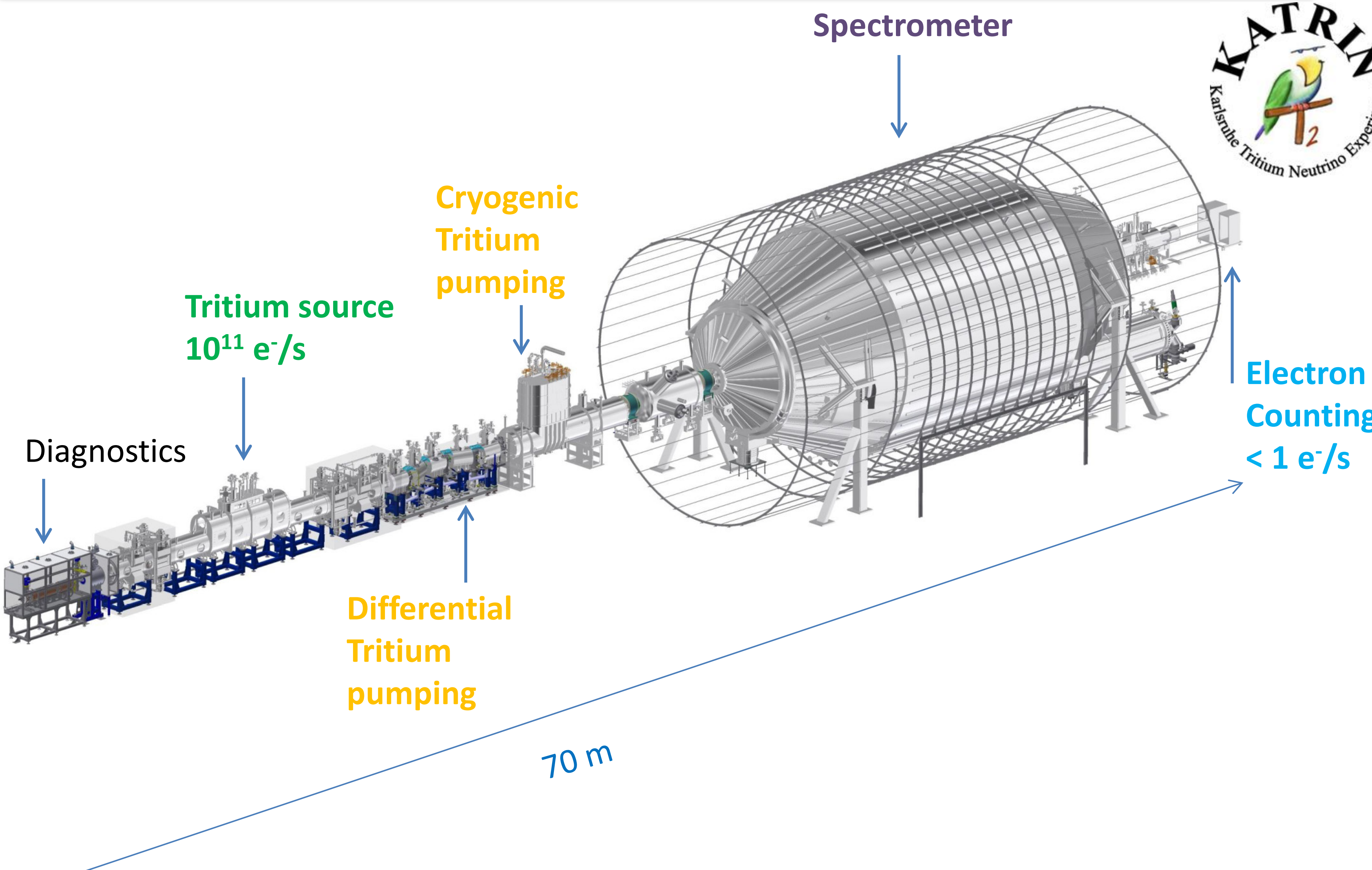


Main ideas:

- high activity source 10^{11} e^-/s
- high resolution MAC-E* filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum

*MAC-E: Magnetic Adiabatic Collimation with Electrostatic Filter

The KATRIN experiment



J. Angrik et al (KATRIN Collaboration) 2004 Wissenschaftliche Berichte FZ Karlsruhe 7090

The KATRIN experiment: present status

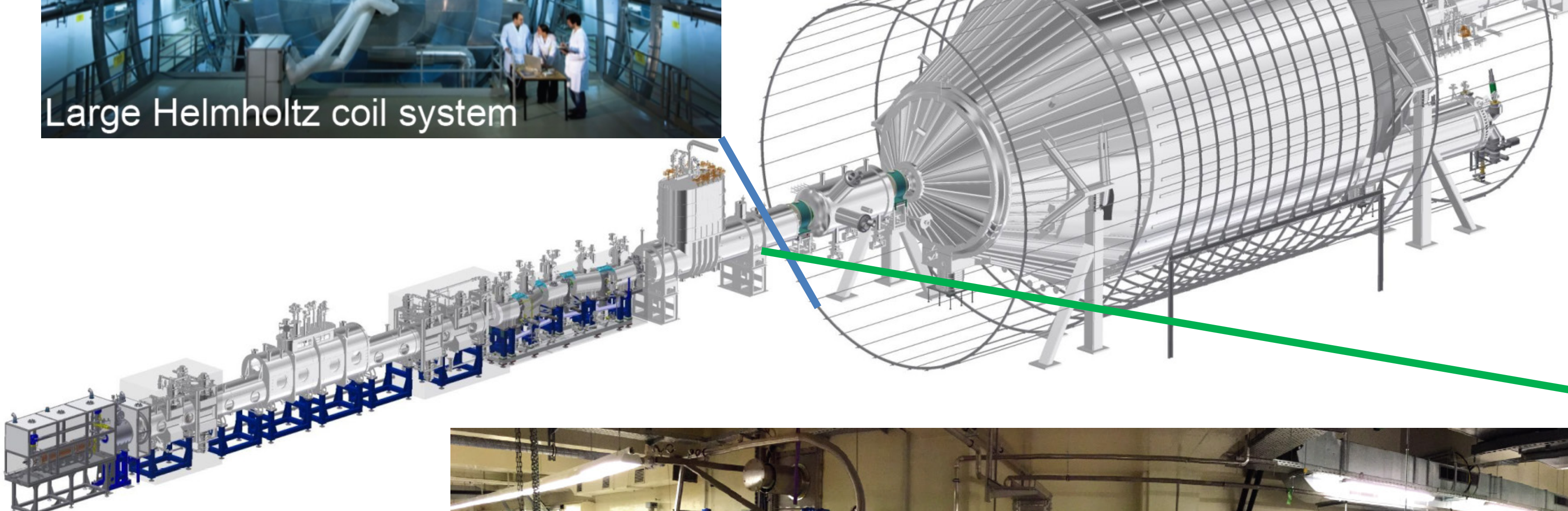


Photo K. Valerius

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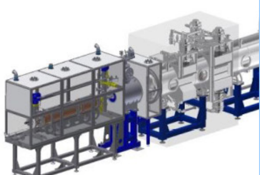


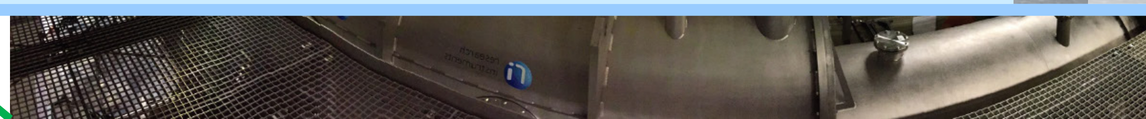


Photo K. Valerius

^{3}H based experiments

❖ KATRIN - Karlsruhe Tritium Neutrino Experiment

Main ideas:
- high activity source: 10^{11} e^-/s
- high resolution MAC-E filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum

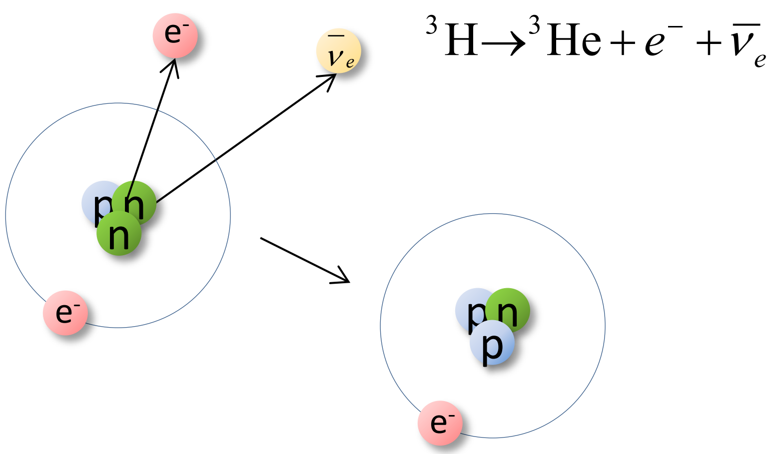
❖ Project8

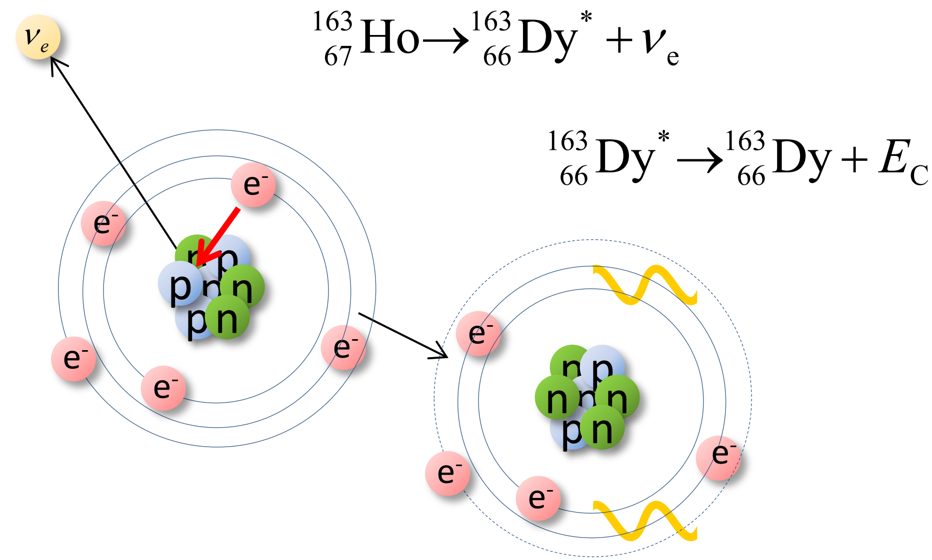
Main ideas:
- Source = detector: $10^{11} – 10^{13}$ $^3H_2$ molecules /cm^3
- Use cyclotron frequency to extract electron energy
- Differential spectrum

❖ PTOLEMY - Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

Main ideas:
- large area tritium source: 100 g atomic ^{3}H
- MAC-E lter to select electrons close to the end point
- RF tracking and time-of-flight systems
- cryogenic calorimetry → differential spectrum

Beta decay and electron capture





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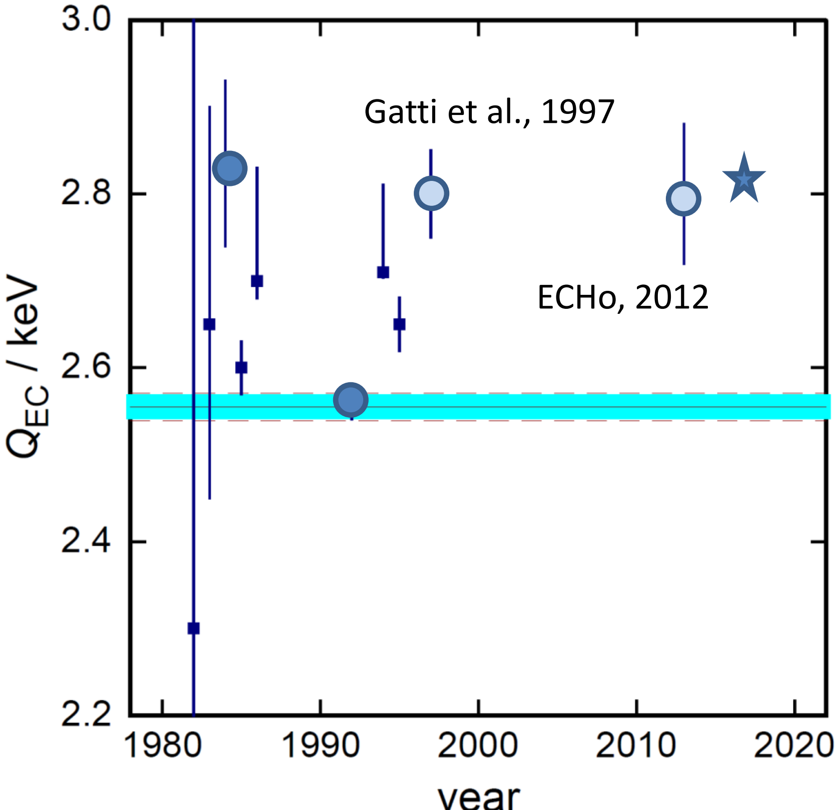
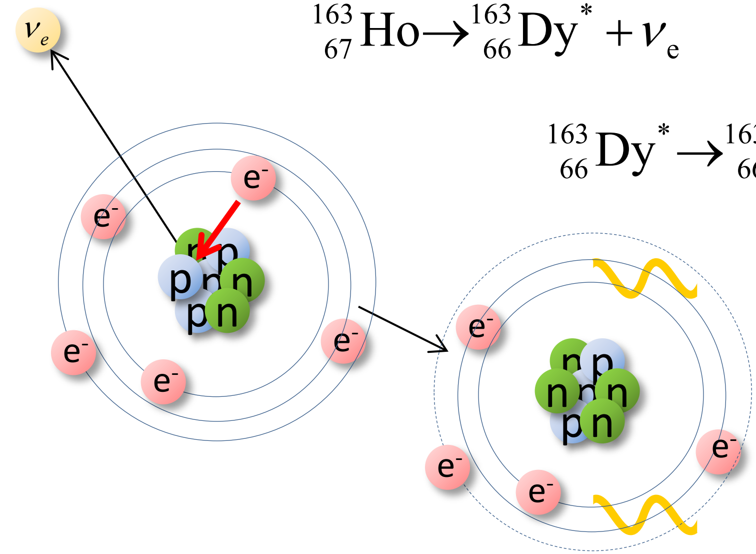
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Electron capture in ^{163}Ho: Q_{EC} determination

- ● Calorimetric measurements
- ■ Measurements of x-rays
- ★ $Q_{EC} = m(^{163}\mathrm{Ho}) - m(^{163}\mathrm{Dy})$





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Penning Trap Mass Spectroscopy

@TRIGA TRAP (Uni-Mainz) (*)

@SHIPTRAP (GSI – Darmstadt) (**)

$$\nu_c = \frac{qB}{m}$$

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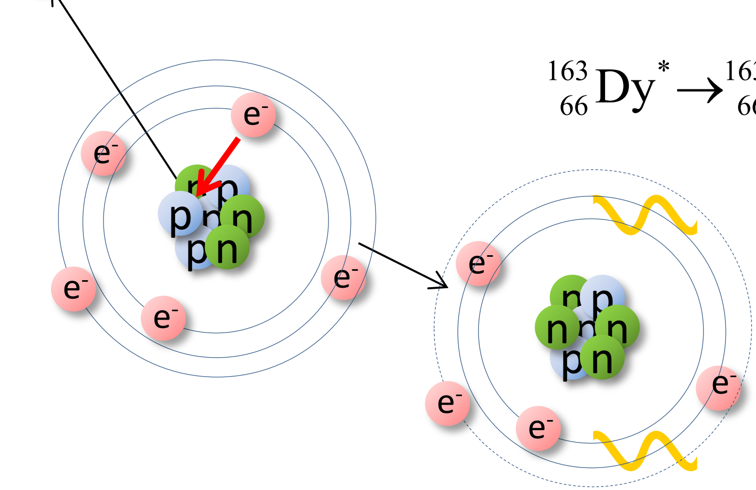

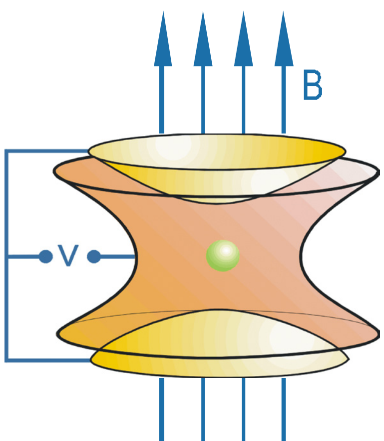

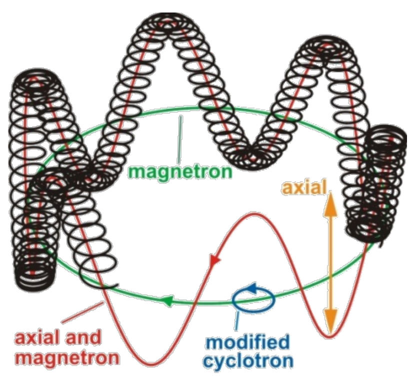

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S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501 (**)
F. Schneider et al., Eur. Phys. J. A **51** (2015) 89 (*)

Electron capture in ^{163}Ho

Atomic de-excitation:

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

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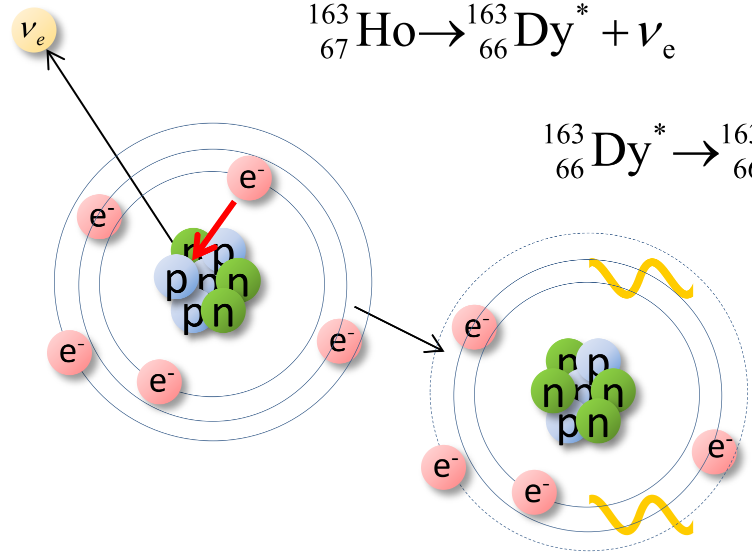

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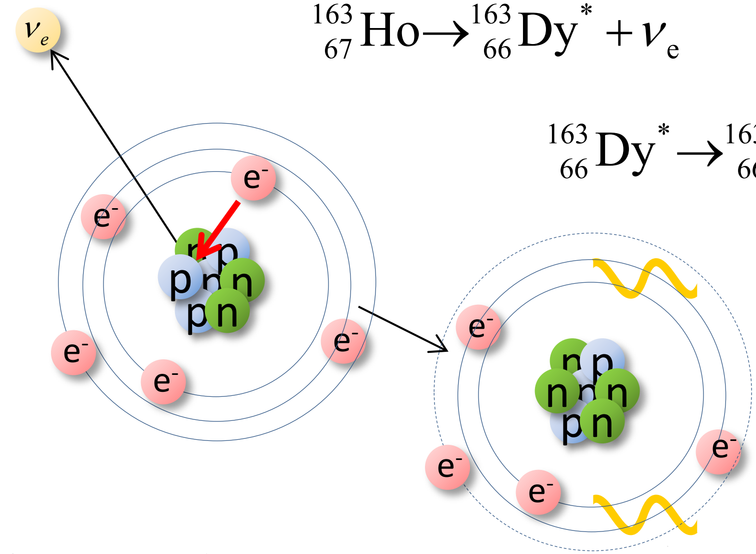

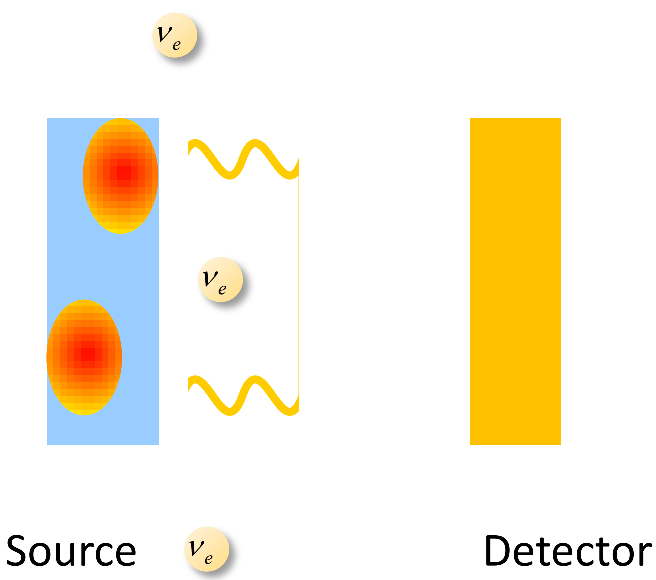

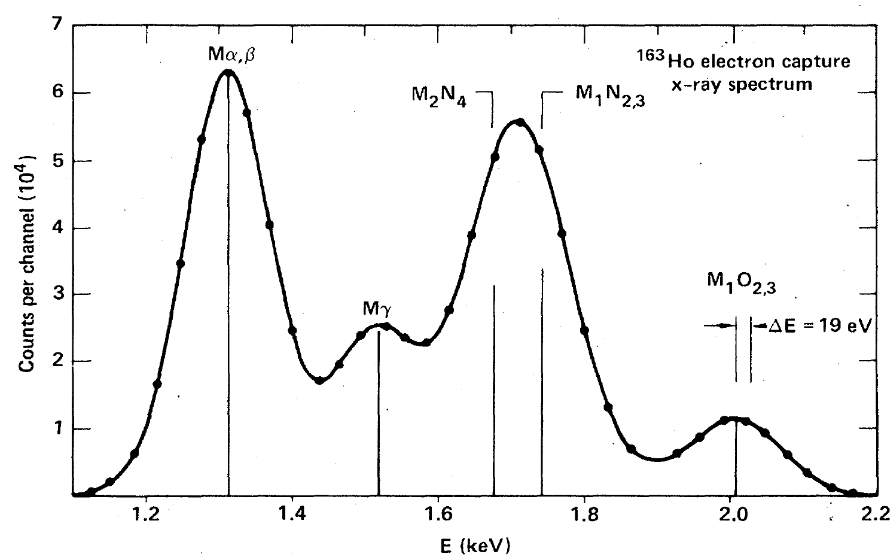

P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

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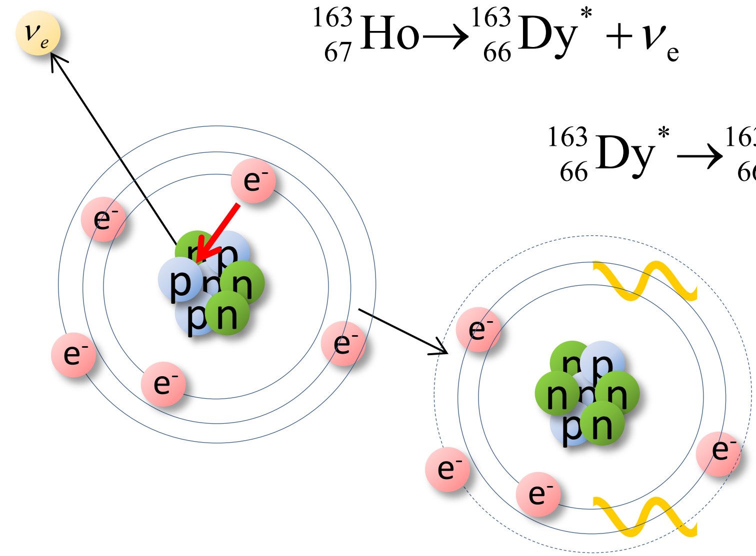
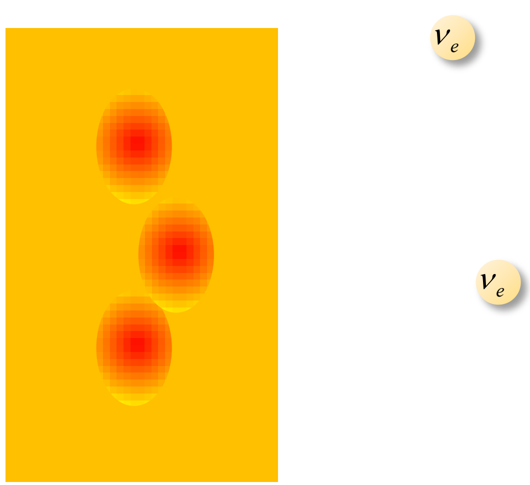


Calorimetric measurement



Source = Detector

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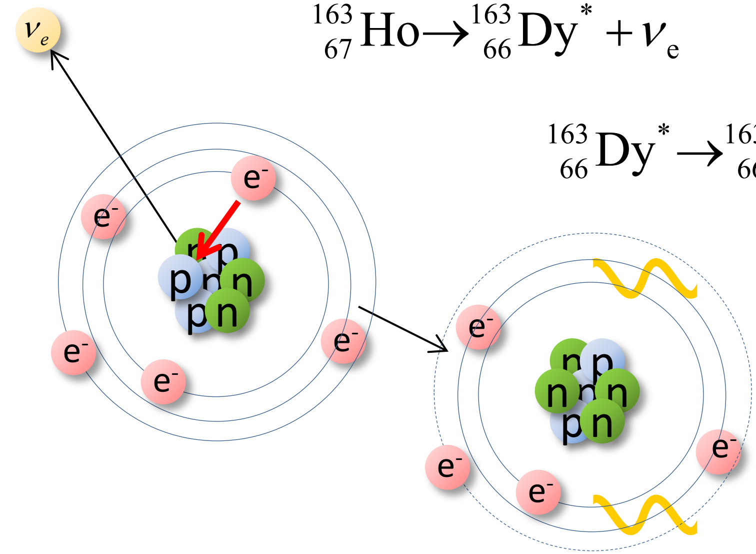

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Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

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

A. DE RÚJULA and M. LUSIGNOLI [1]

CERN, Geneva, Switzerland

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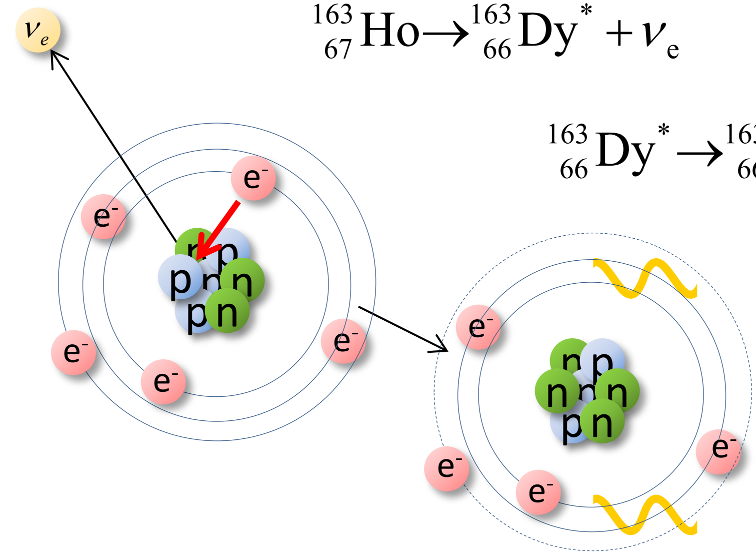

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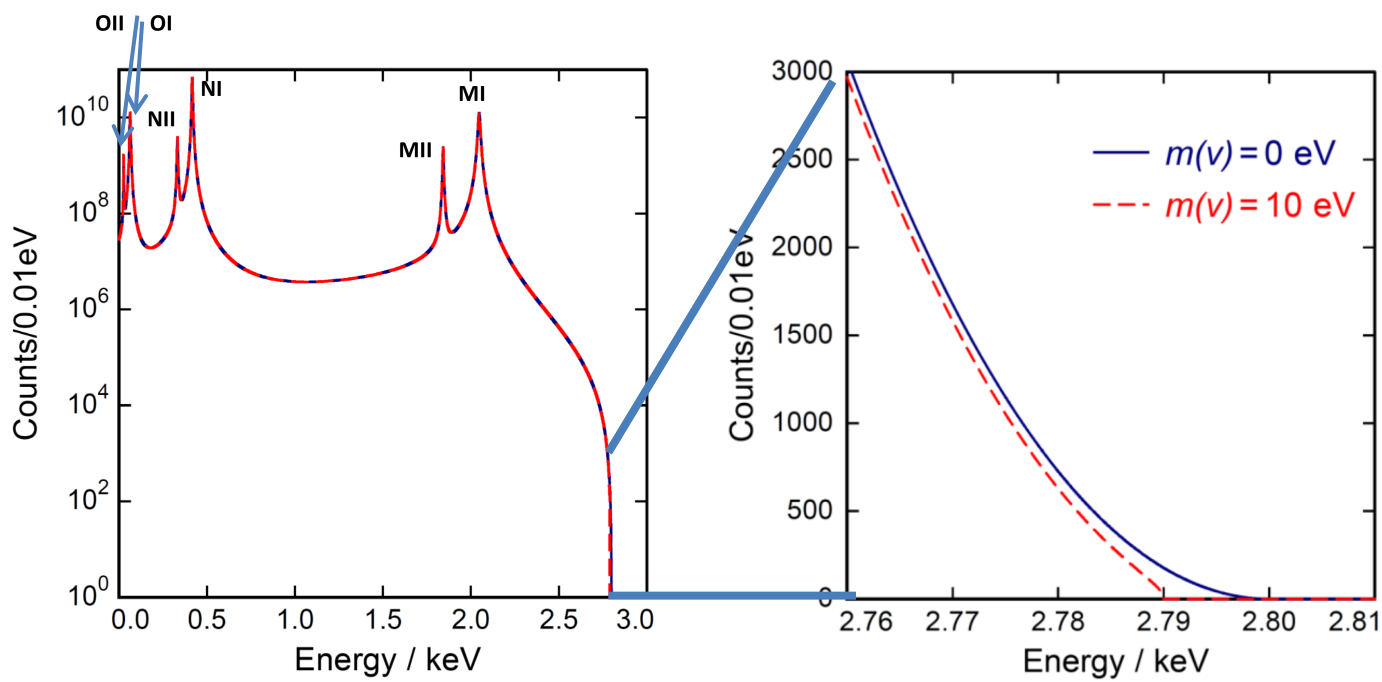

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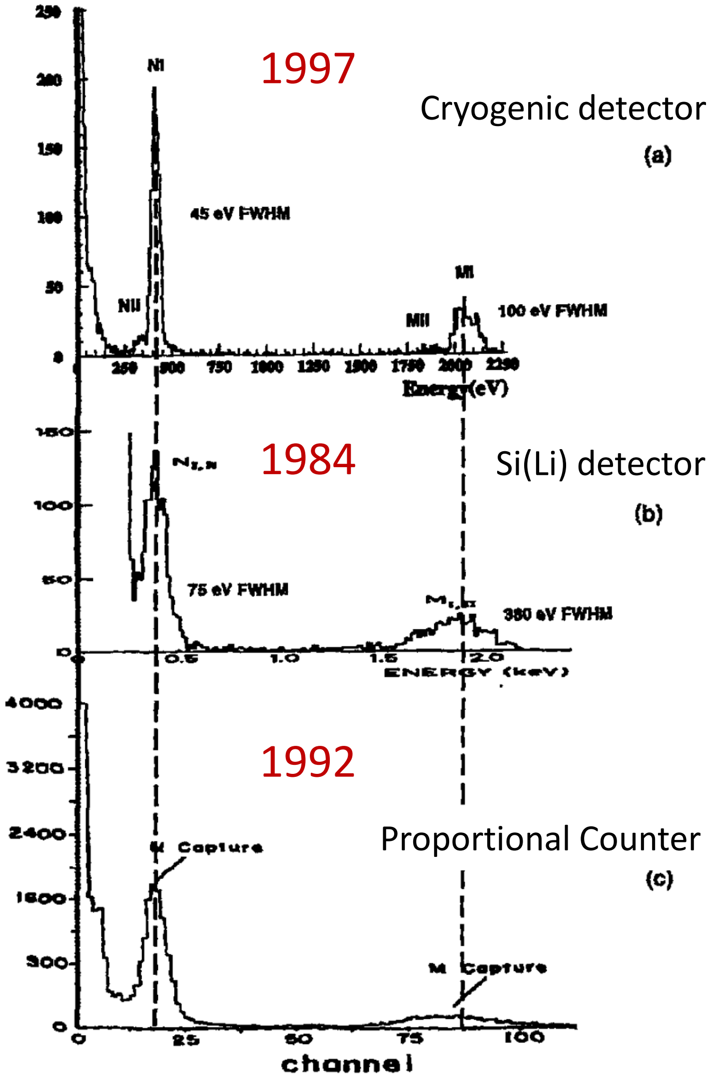
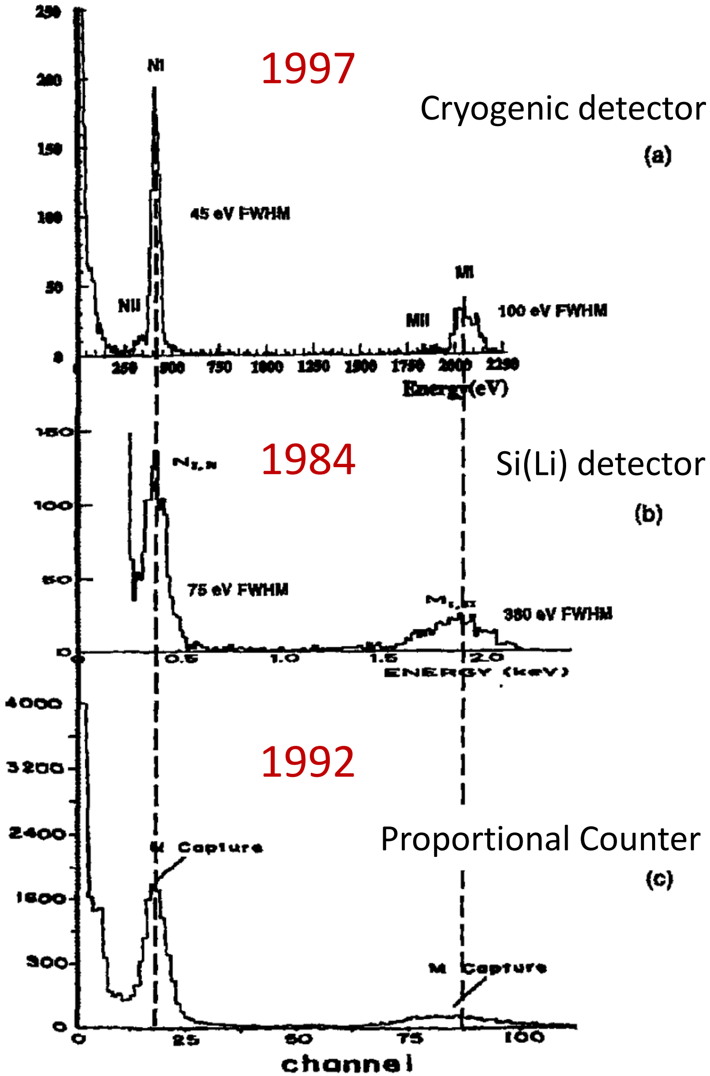


F. Gatti et al., Physics Letters B 398 (1997) 415-419

(a) F. Gatti et al., Physics Letters B 398 (1997) 415-419
(b) E. Laesgaard et al., Proceeding of 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), (1984).
(c) F.X. Hartmann and R.A. Naumann, Nucl. Instr. Meth. A 3 13 (1992) 237.

Electron capture in ^{163}Ho



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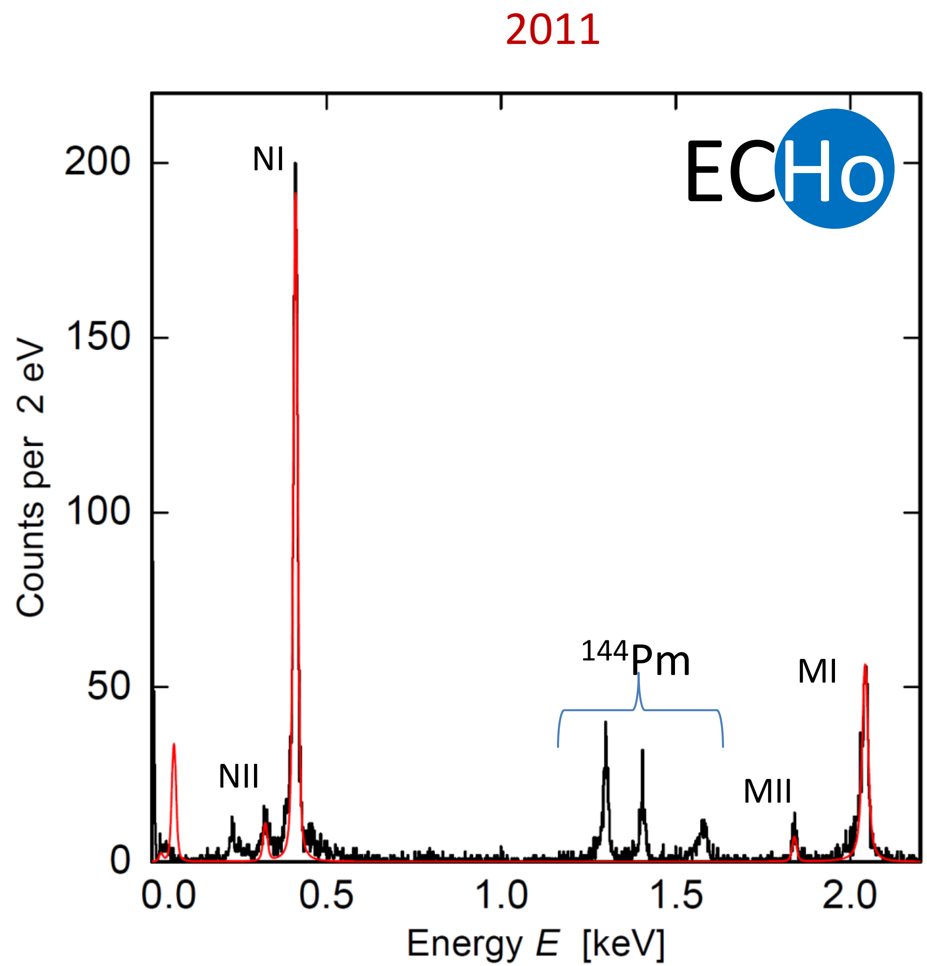

P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)

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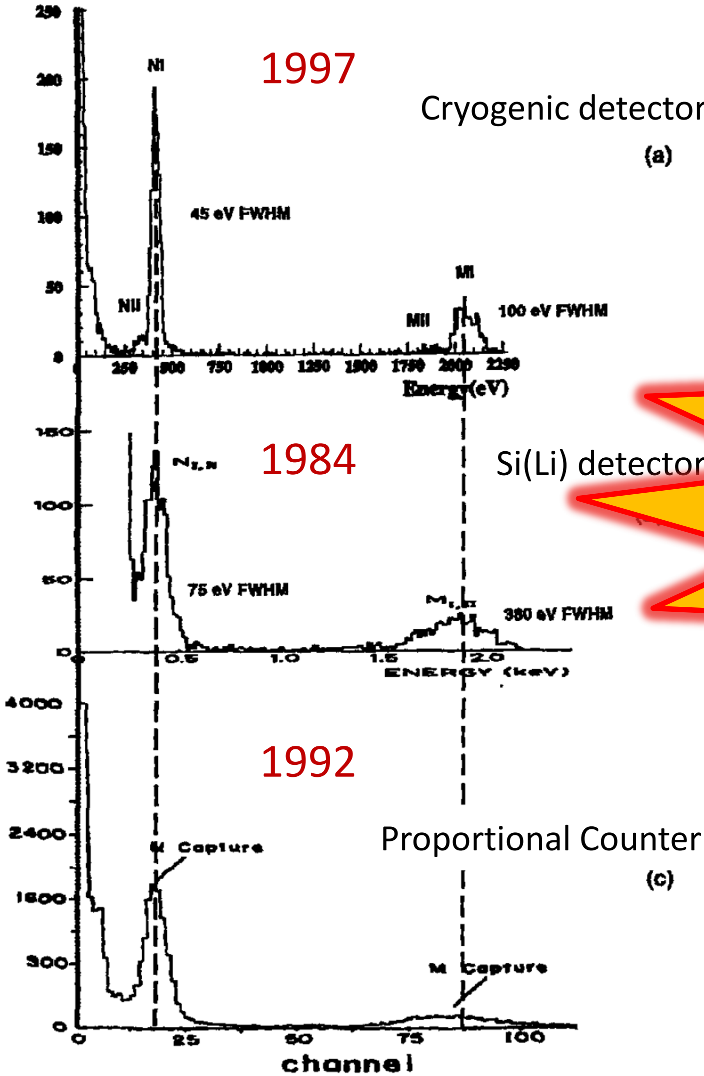

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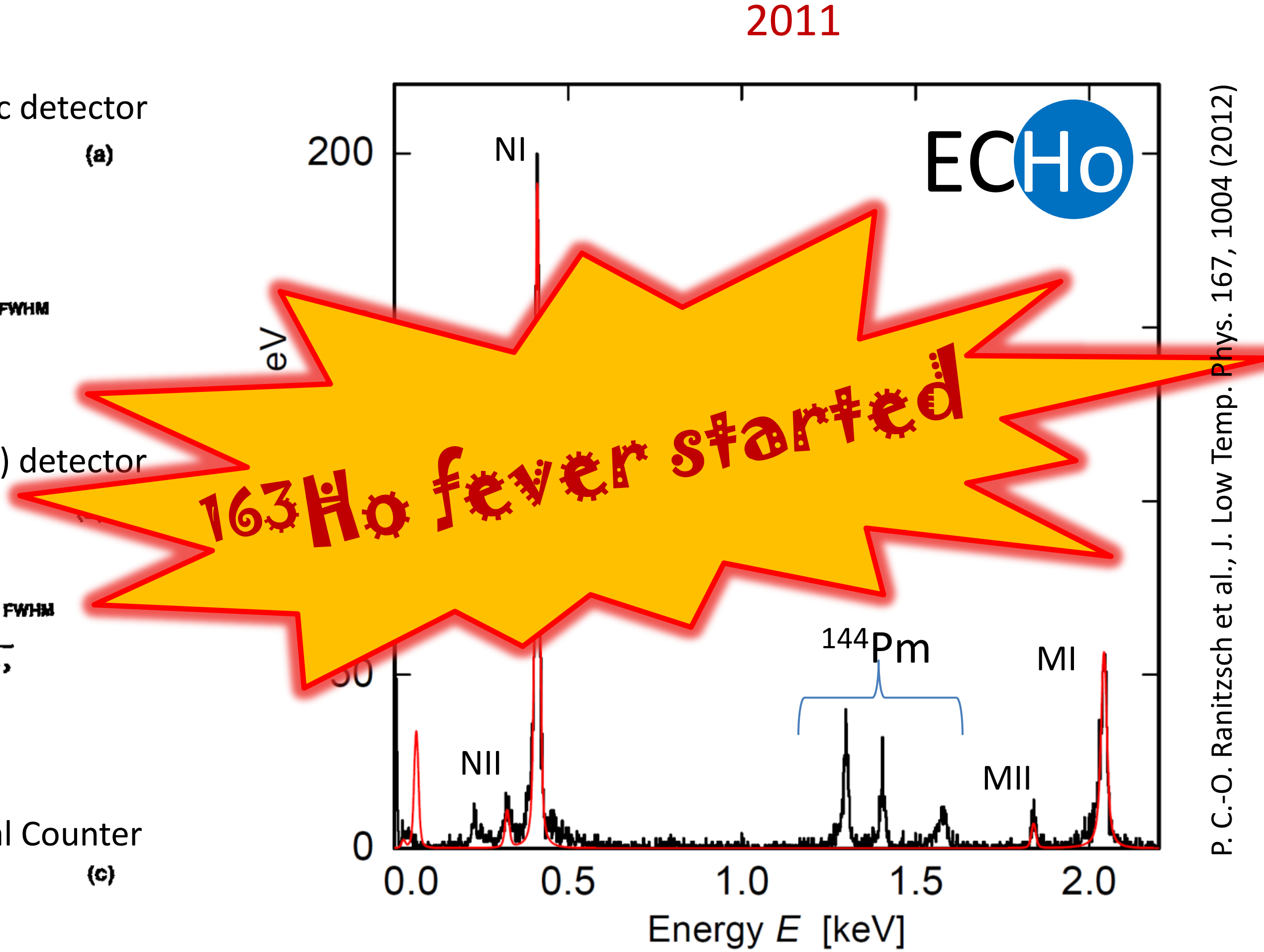

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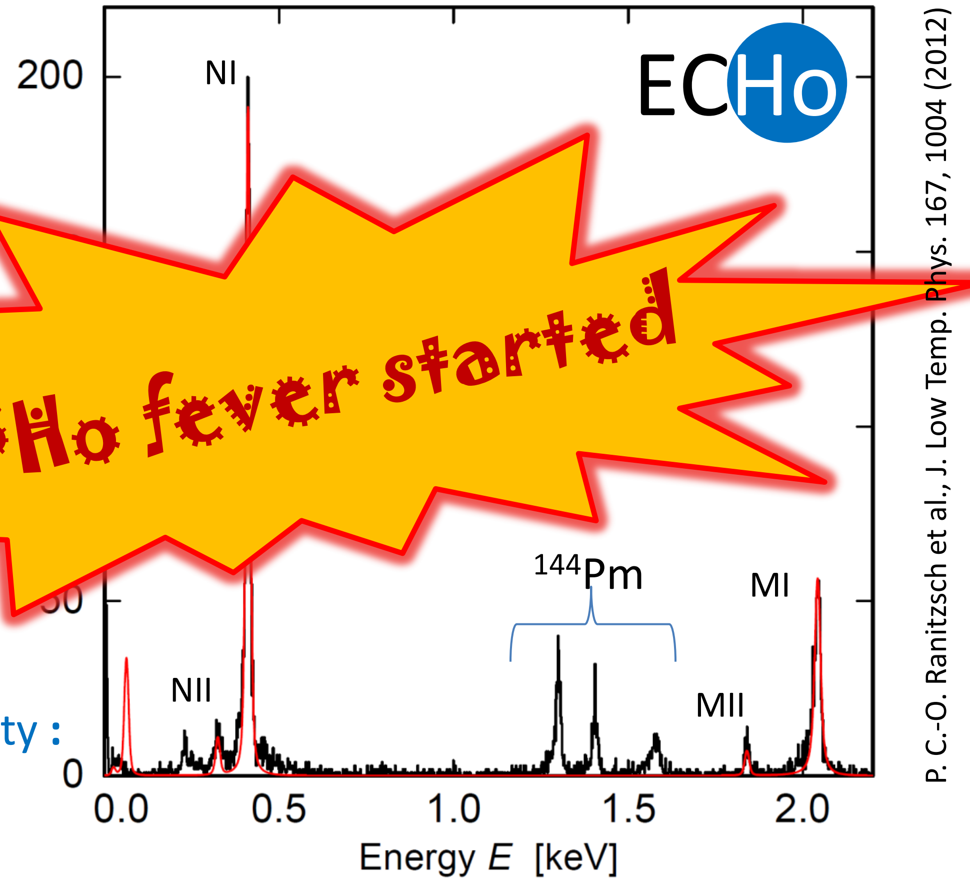
Electron capture in ^{163}Ho

- Calorimetric measurement of the ^{163}Ho spectrum — 2011
- Three internaltional collaborations

ECHo (1)

HOLMES (2)

NuMECS (3)



Common challenges to reach sub eV sensitivity :

- Detector performance
- High purity ^{163}Ho source
- Background reduction
- Description of the ^{163}Ho EC spectrum

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

(2) B. Alpert et al, Eur. Phys. J. C (2015) 75:112

(3) M. Croce et al., arXiv:1510.03874

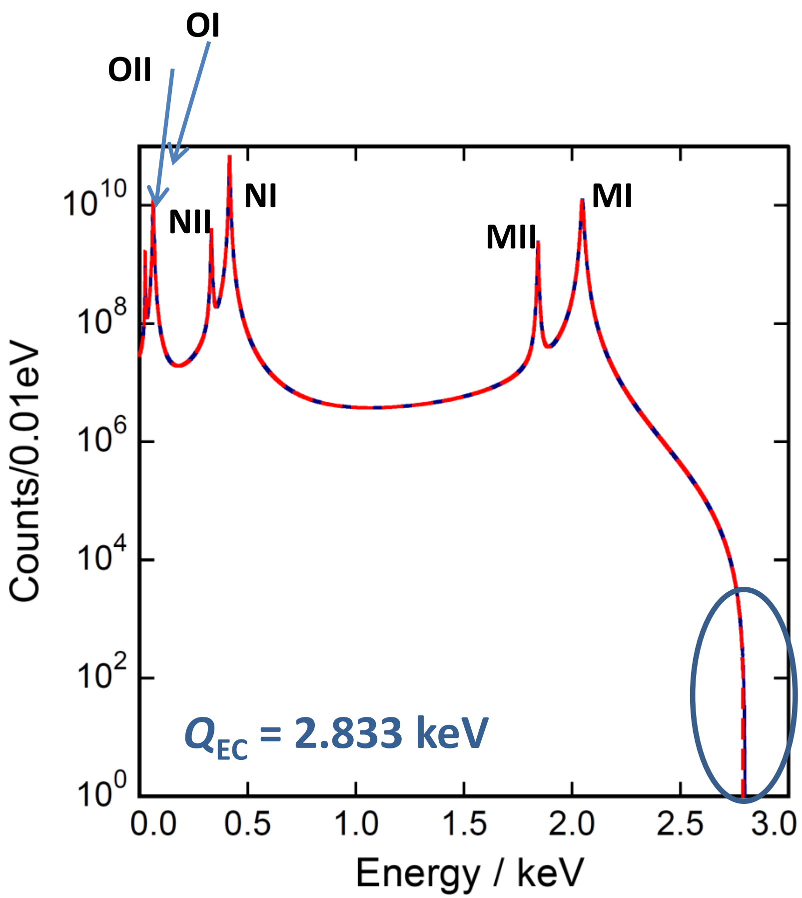
Requirements for sub-eV sensitivity in ECHo

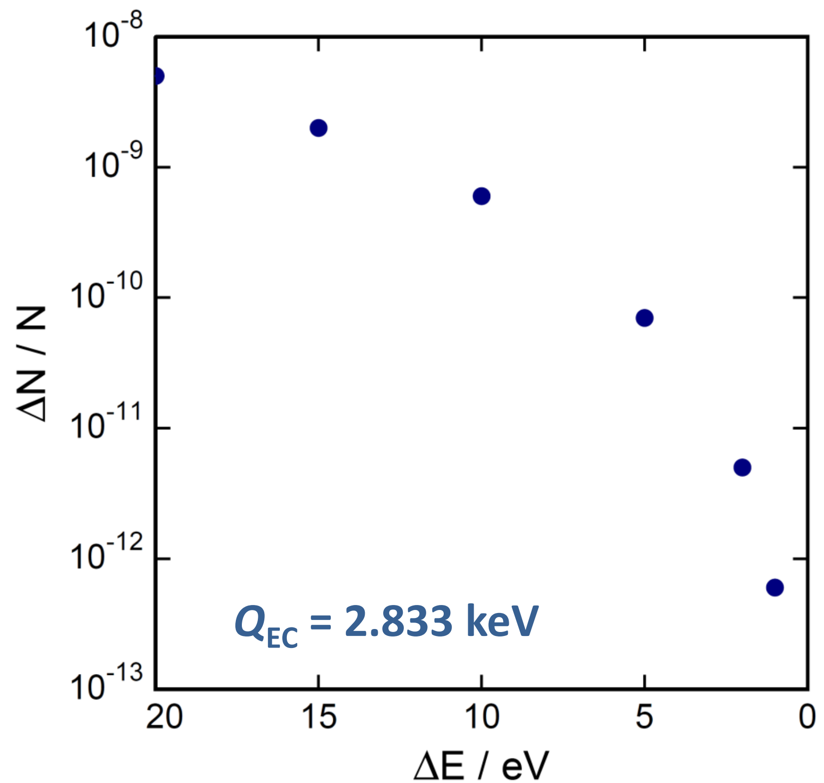
Statistics in the end point region

- $N_{ev} > 10^{14}$ → **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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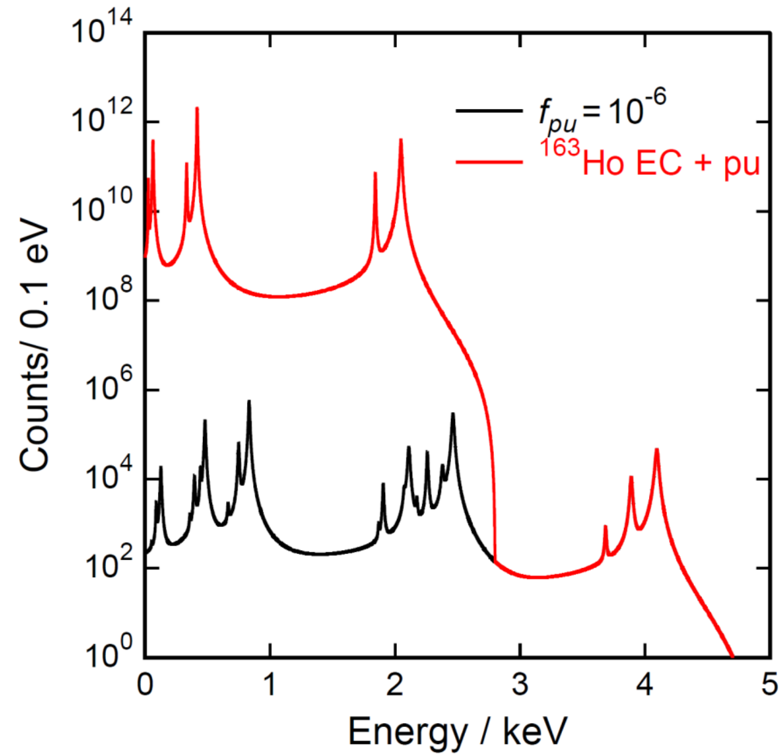
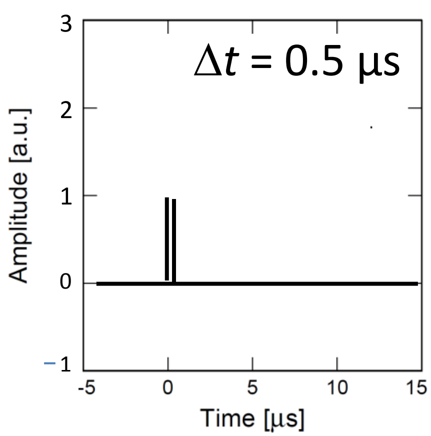
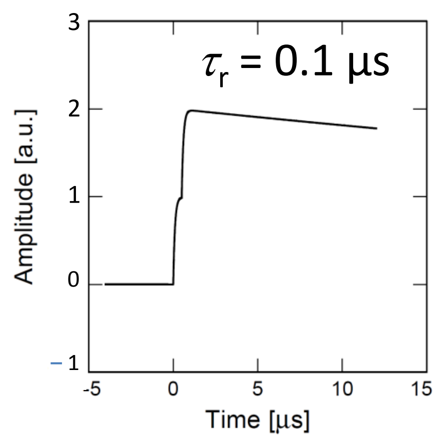
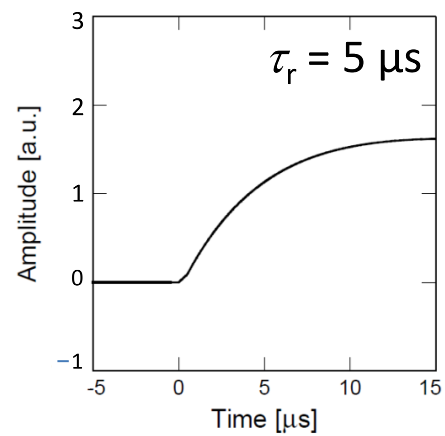
Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

- $\boldsymbol{f_{pu} < 10^{-5}}$
- $\tau_r < 1$ µs → a ~ 10 Bq
- 10^5 pixels









Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

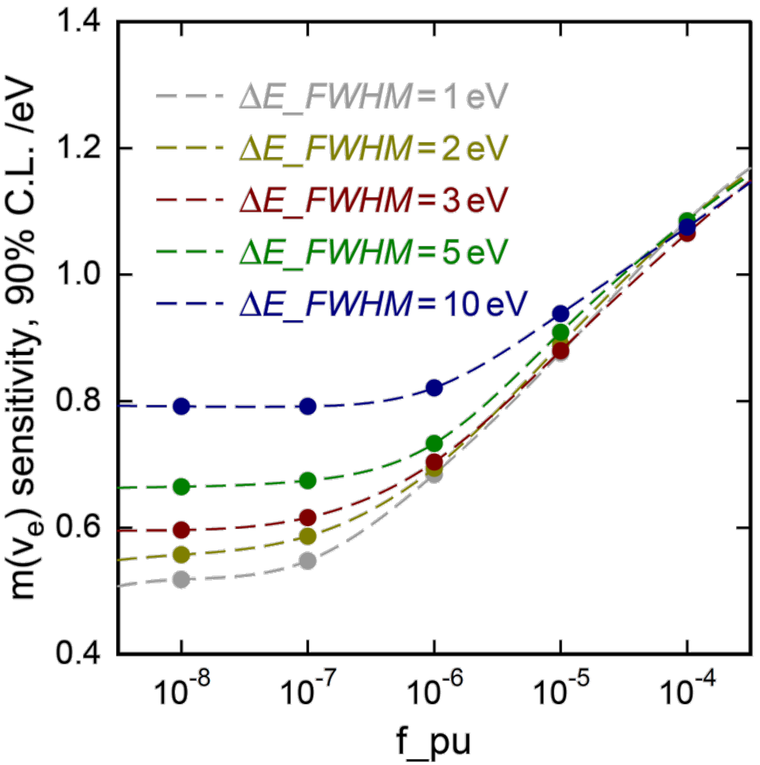
- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

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

Precision characterization of the endpoint region

- **ΔE_{FWHM} < 3 eV**



Requirements for sub-eV sensitivity in ECHo

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- $\tau_r < 1$ µs → a ~ 10 Bq
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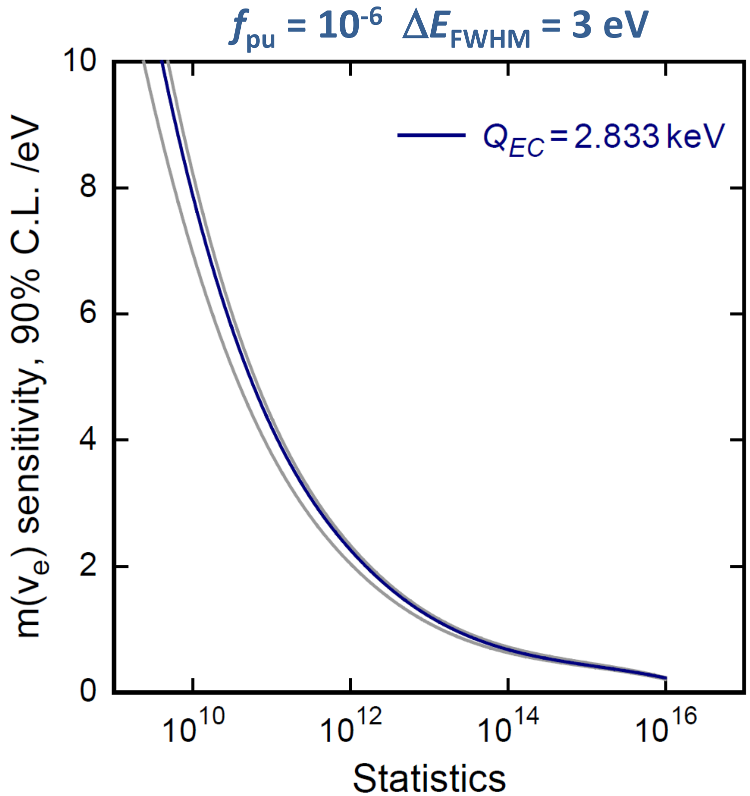
Precision characterization of the endpoint region

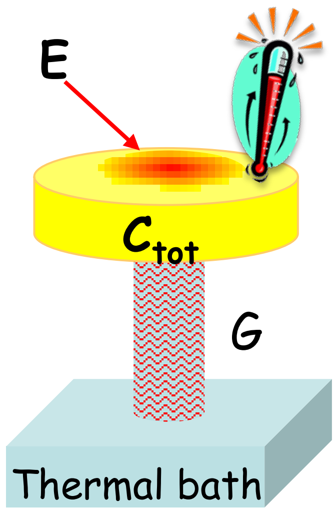
- $\boldsymbol{\Delta E_{FWHM} < 3}$ **eV**

Background level

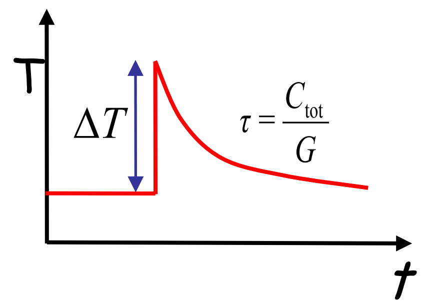
- **< 10^{-6} events/eV/det/day**



Low temperature micro-calorimeters



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



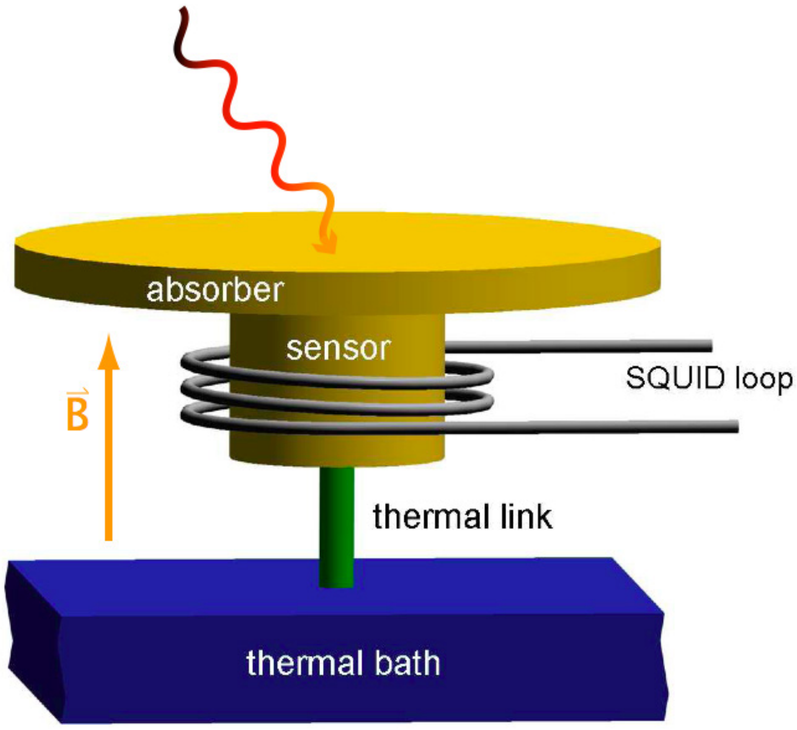
E = 10 keV
C_{tot} = 1 pJ/K
→ ~ 1 mK

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

Metallic magnetic calorimeters (MMCs)

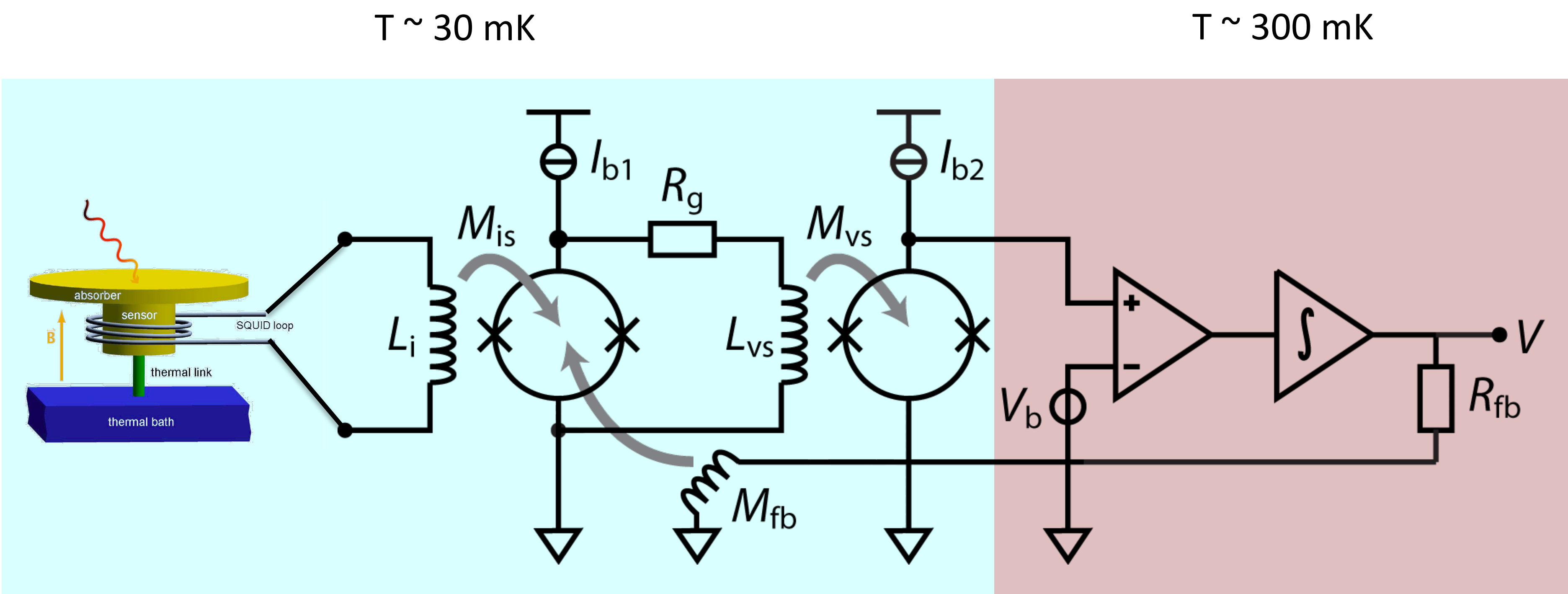
A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

- Paramagnetic Au:Er sensor
  Ag:Er



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

MMCs: Readout



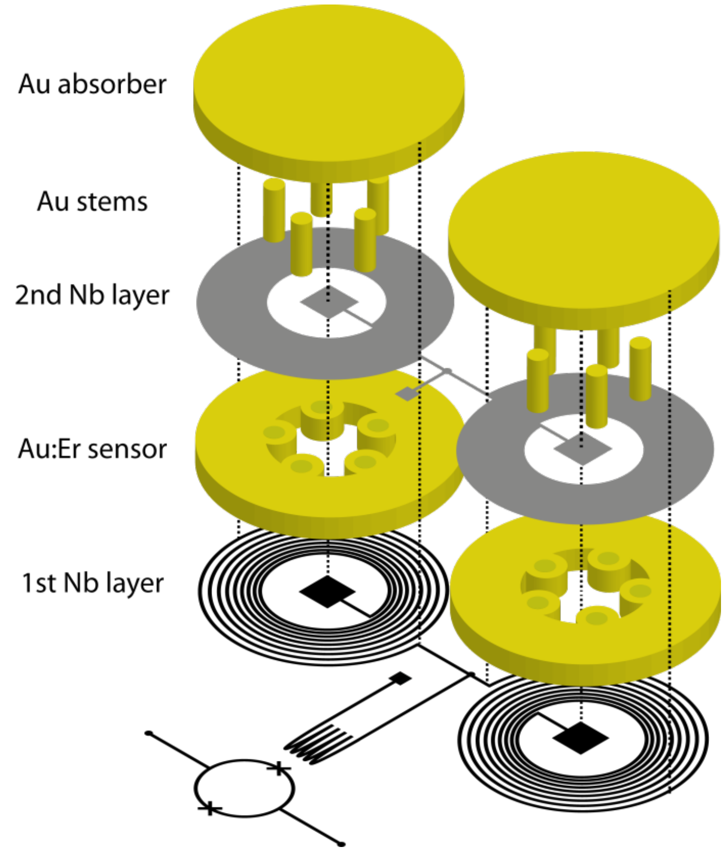
Two-stage SQUID setup with flux locked loop allows for:

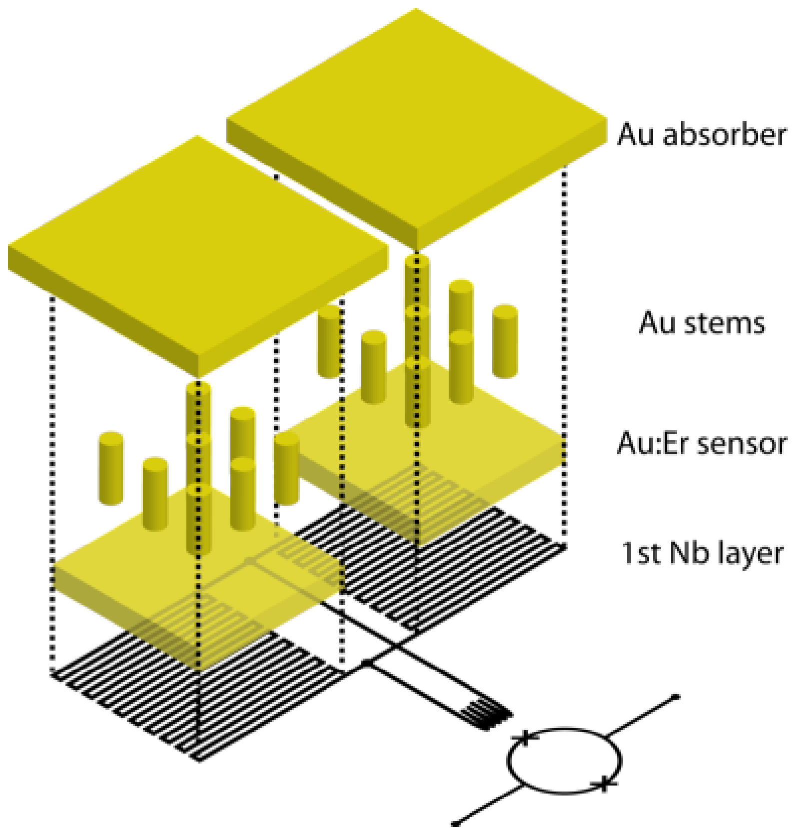
- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)

MMCs: Planar geometries

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

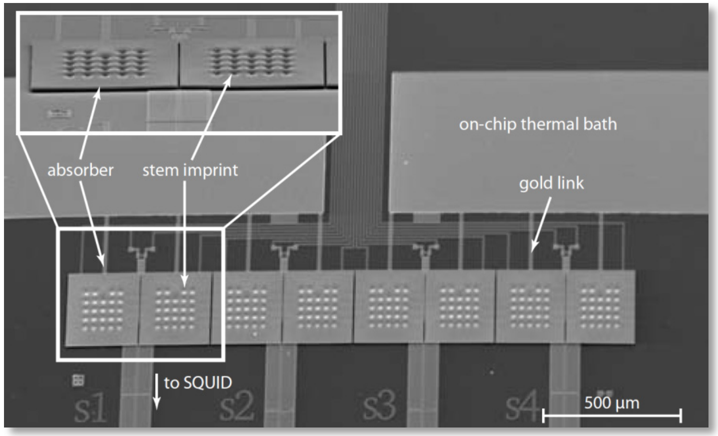
Sandwich geometry

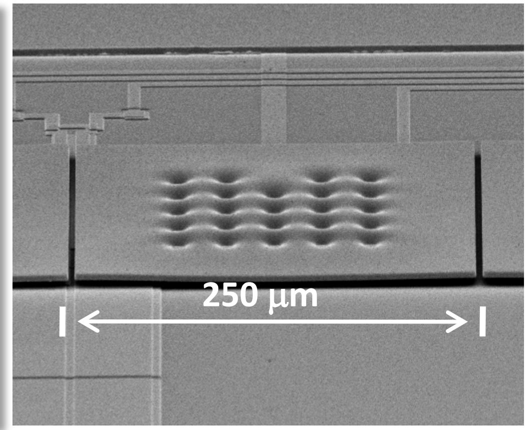




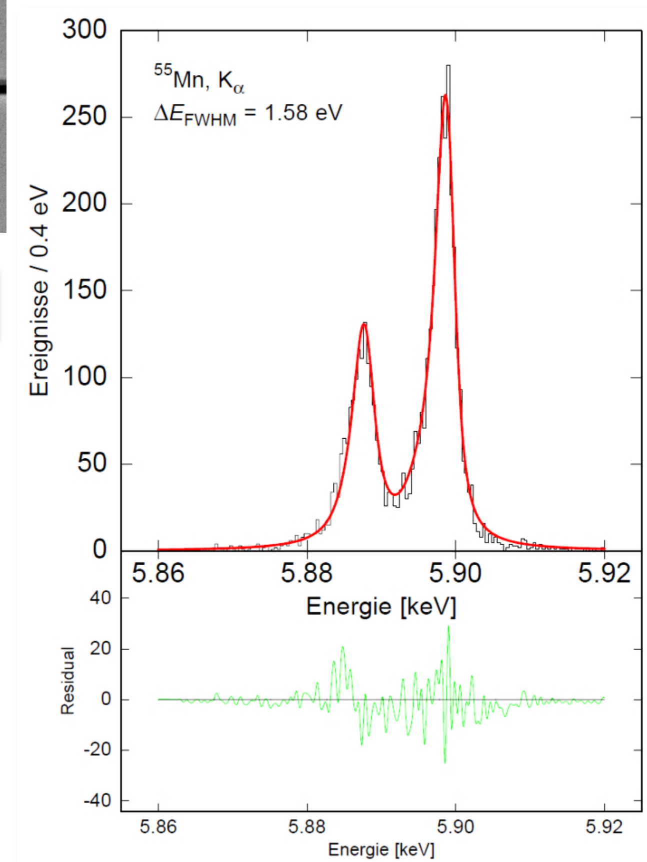
Double meander geometry

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

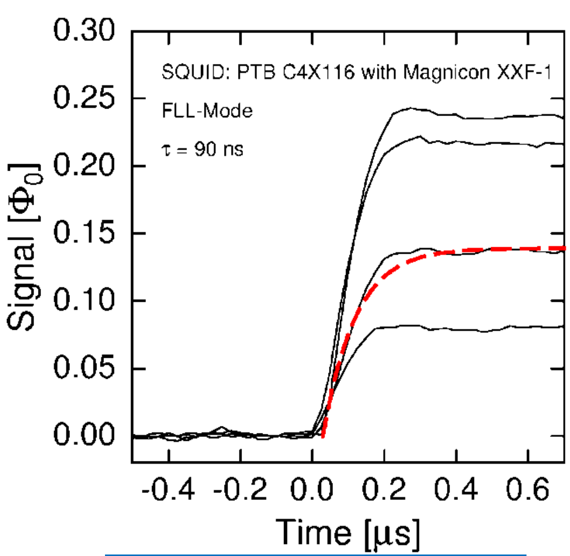




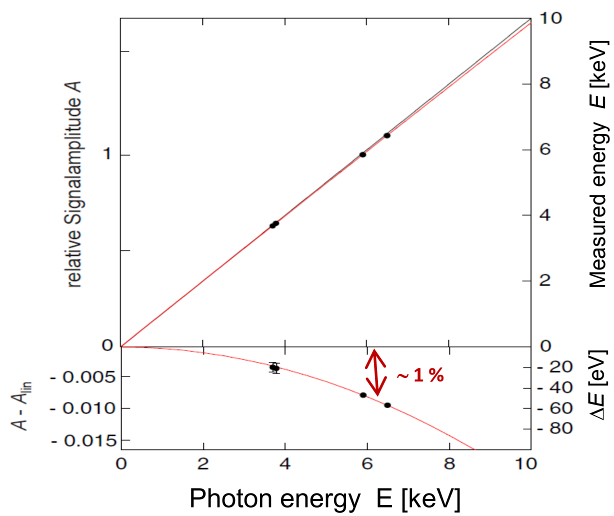
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



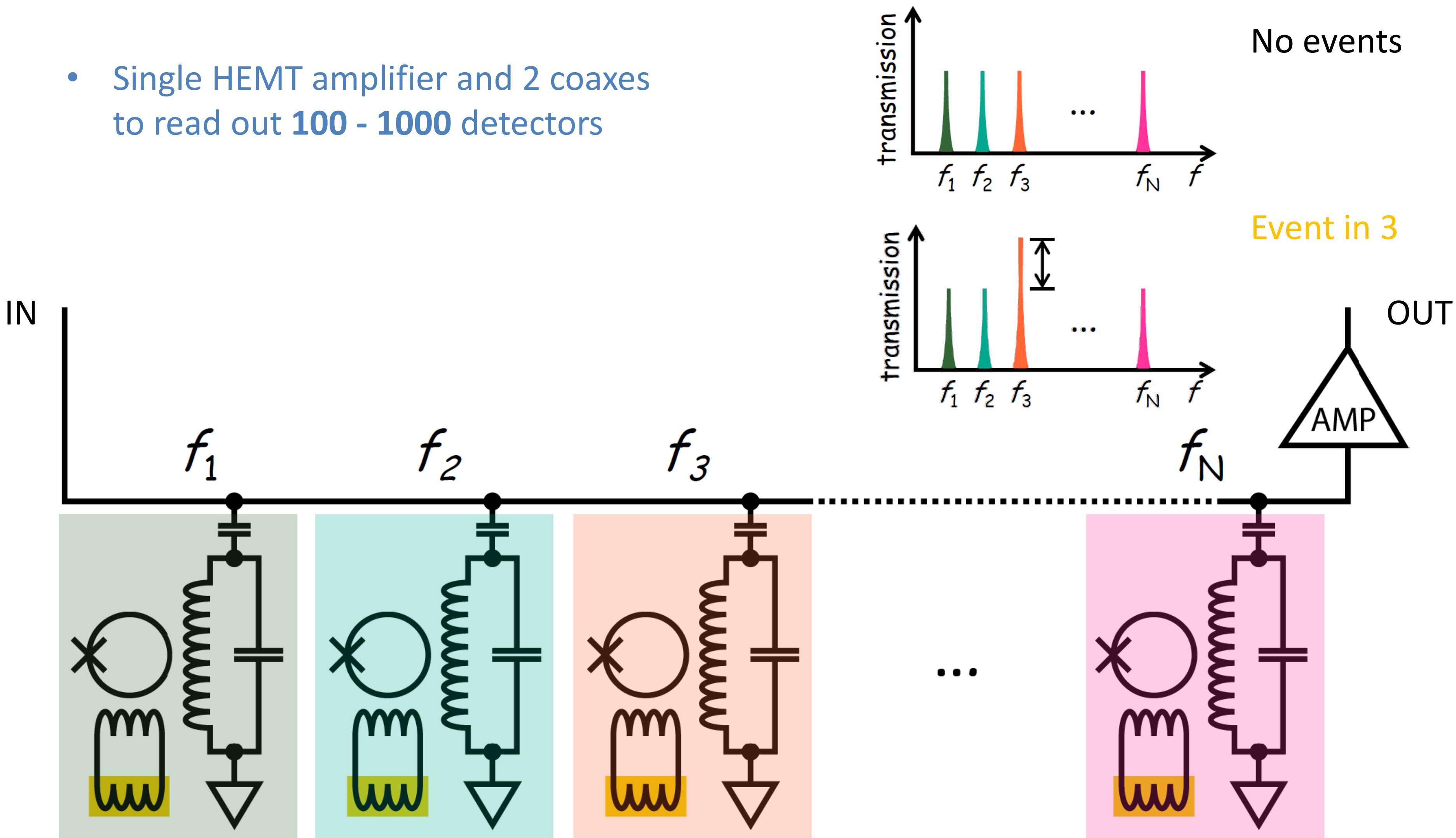
Reduction
un-resolved pile-up

Definition
of the energy scale

Reduced smearing
in the end point region

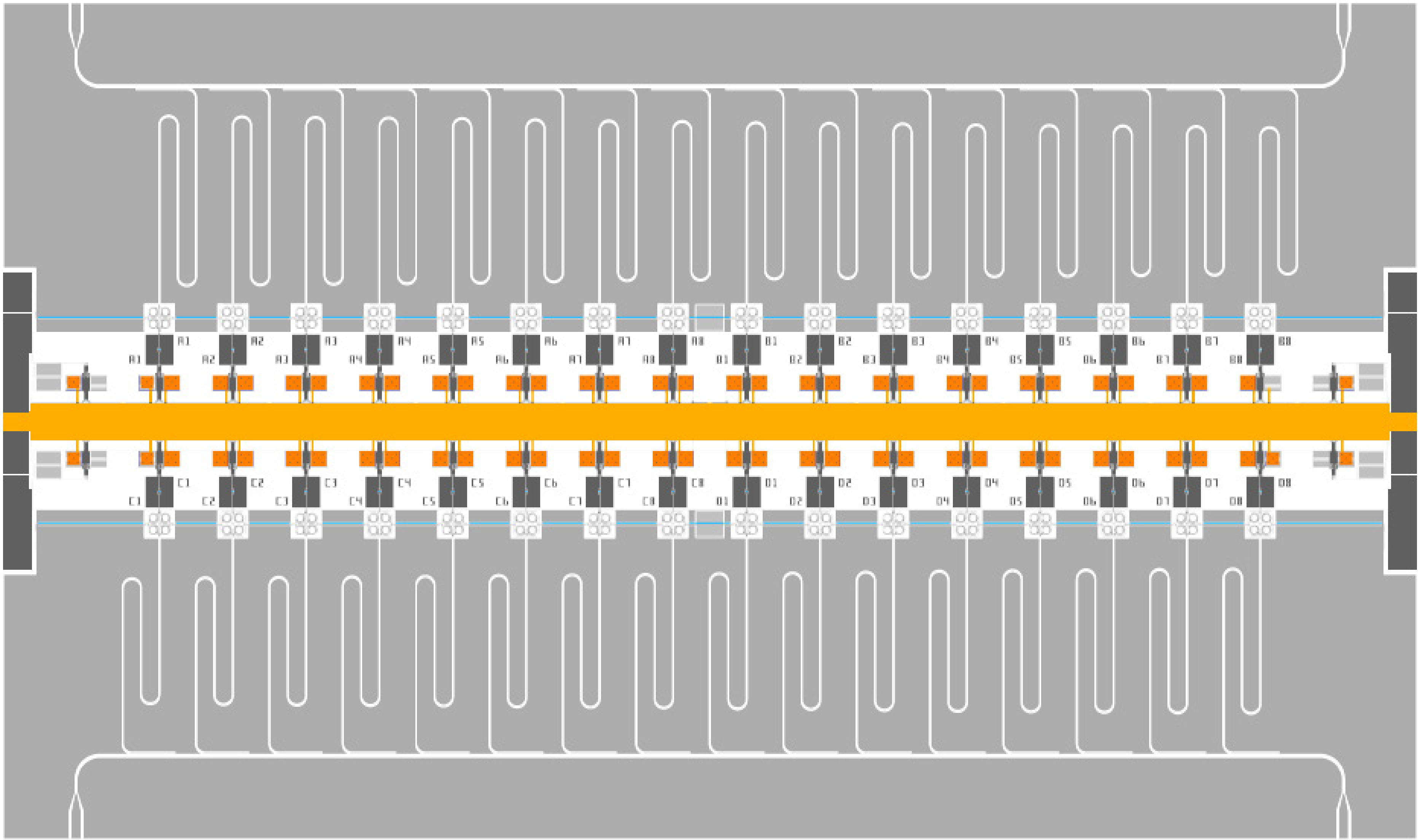
MMCs: Microwave SQUID multiplexing

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



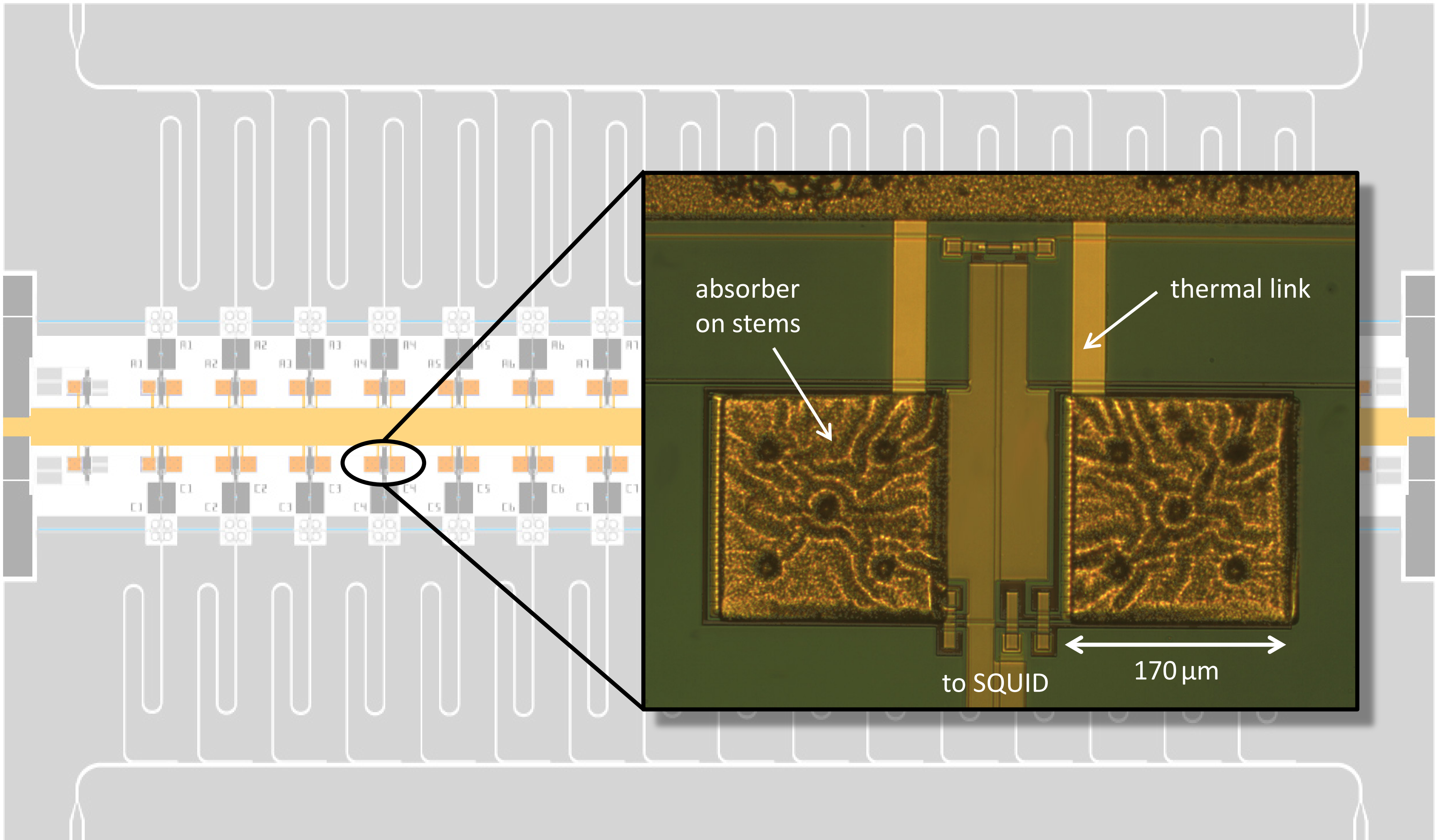
Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

MMCs: Microwave SQUID multiplexing

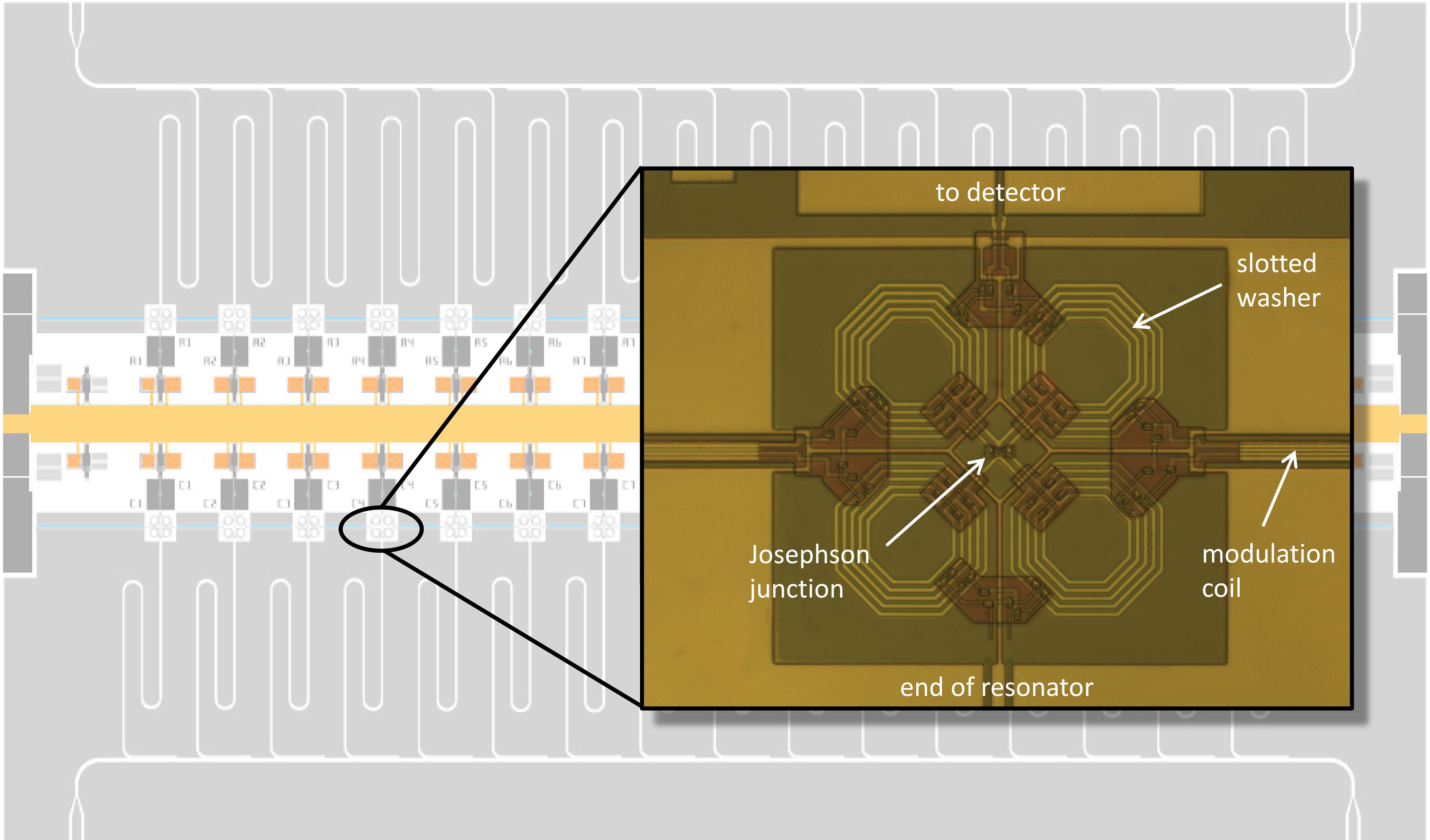


S.Kempf *et al.*, J. Low. Temp. Phys. **176** (2014) 426

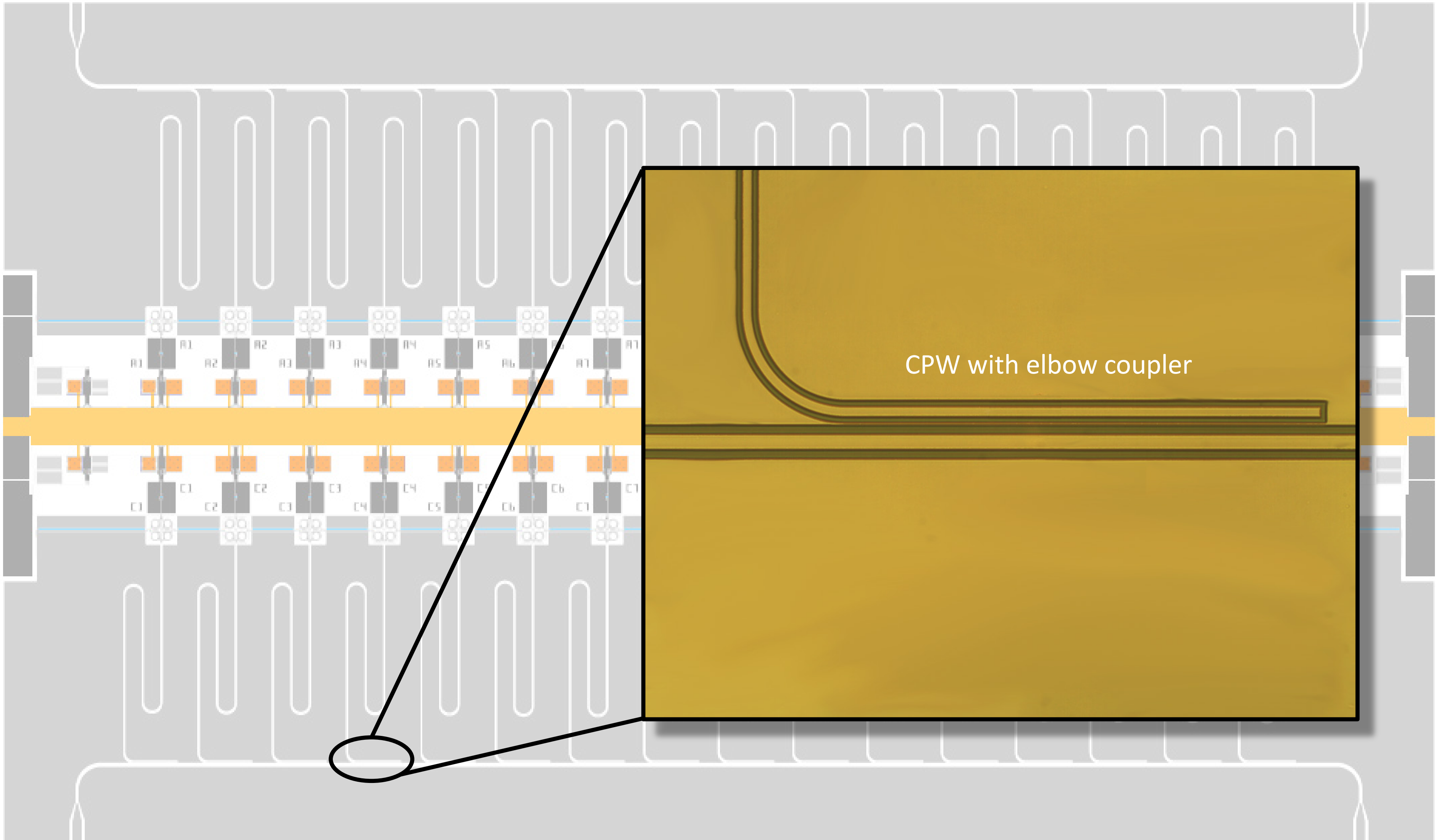
MMCs: Microwave SQUID multiplexing



MMCs: Microwave SQUID multiplexing

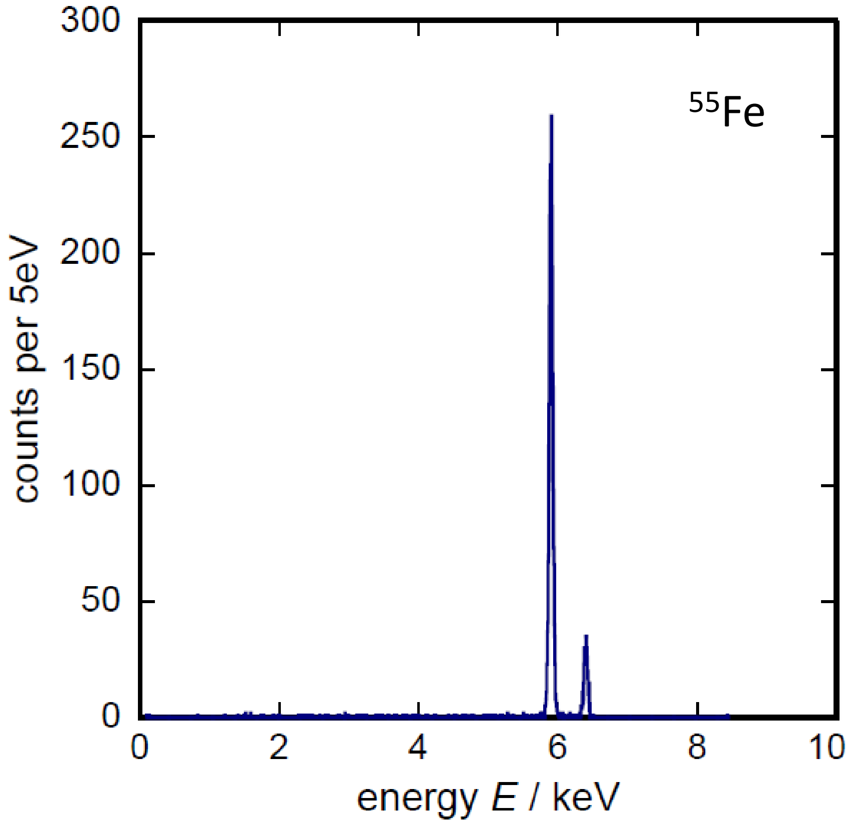


MMCs: Microwave SQUID multiplexing



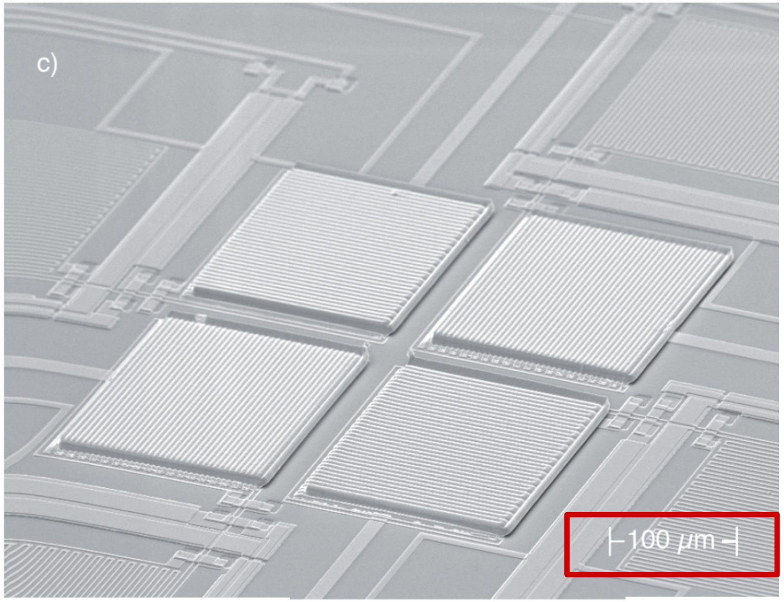
MMCs: Microwave SQUID multiplexing

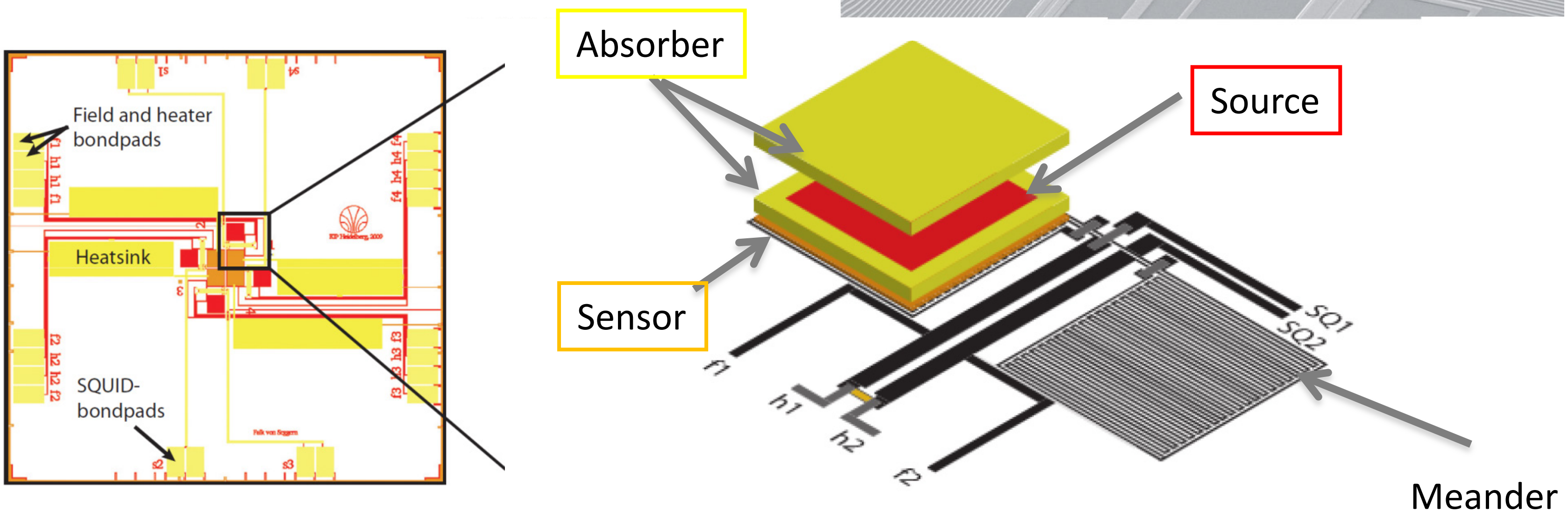
measurement of the spectrum of ^{55}Fe to determine the energy resolution



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



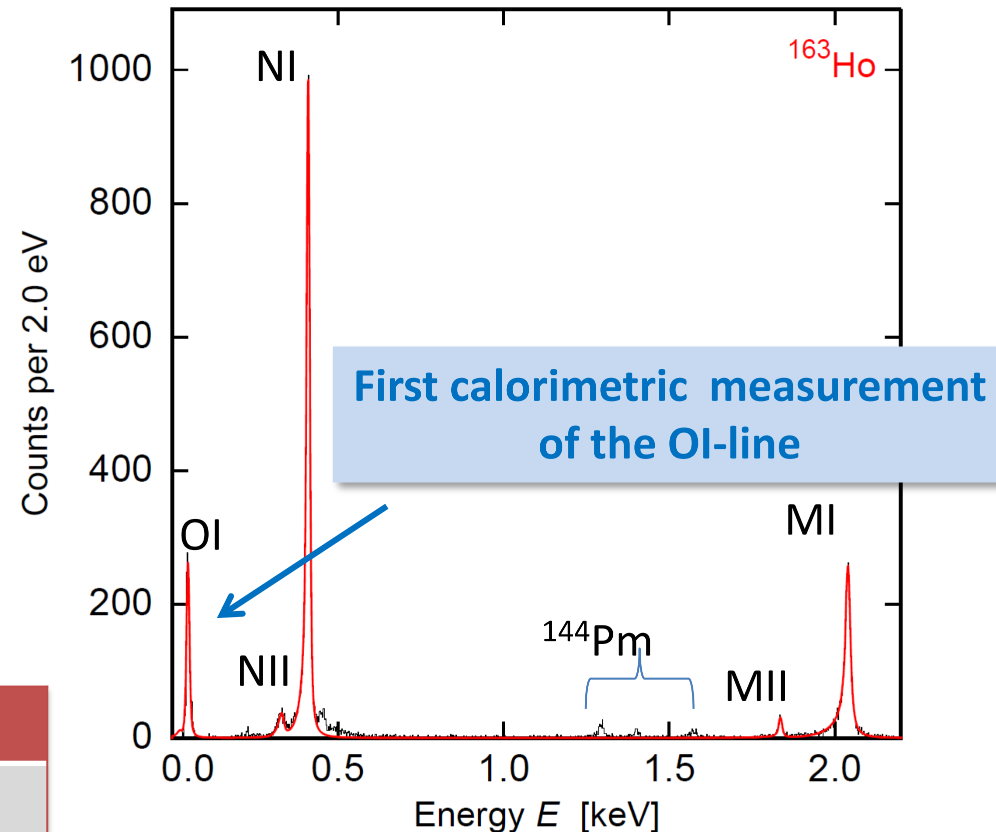


L. Gastaldo et al.,
Nucl. Inst. Meth. A, 711 (2013) 150

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



	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

$Q_{EC} = (2.858 \pm 0.010^{stat} \pm 0.05^{syst})$ keV

P. C.-O. Ranitzsch et al ., to be submitted
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

Where to improve

High purity ^{163}Ho source:

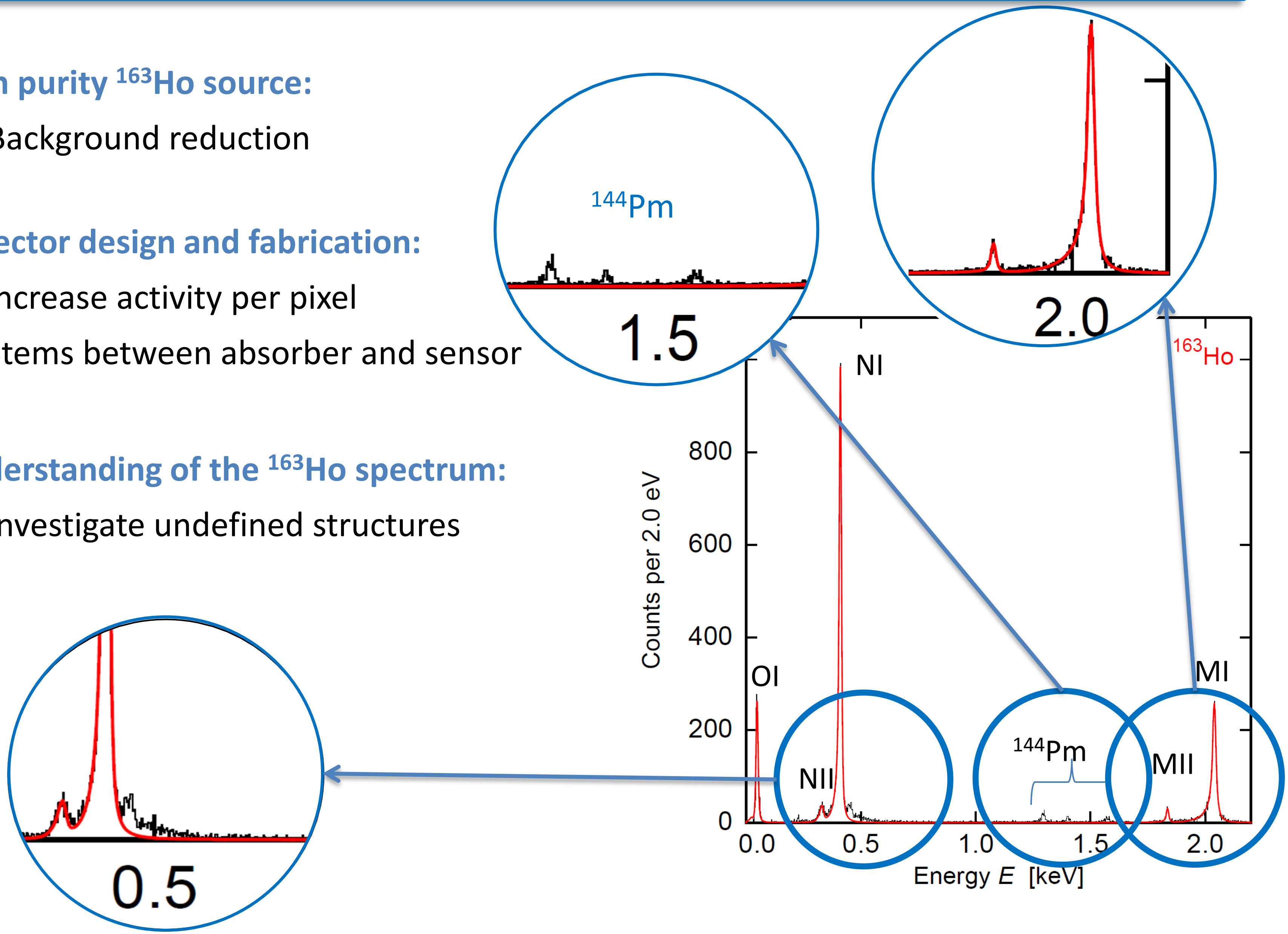
- Background reduction

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

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

- (n,γ)-reaction on ^{162}Er
  - High cross-section
  - Radioactive contaminants → **need of chemical separation**

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

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

NEUTRONS FOR SCIENCE

Summer 2013: Two irradiations at ILL

- Treatment of Er prior to irradiation:
- Treatment of Er after irradiation:

- 30 mg for 55 days ⇒ ~10^{18} atoms ^{163}Ho
- 7 mg for 7 days ⇒ ~10^{16} atoms ^{163}Ho

High purity ^{163}Ho source: Mass separation

RISIKO off-line mass separator

- Optimized resonant laser ionization for Ho
  → efficiency larger than 32%
- Focalization of the beam for implantation onto sub-mm detector absorber
- 1×8 array with 1 Bq / pixels has been successfully implanted

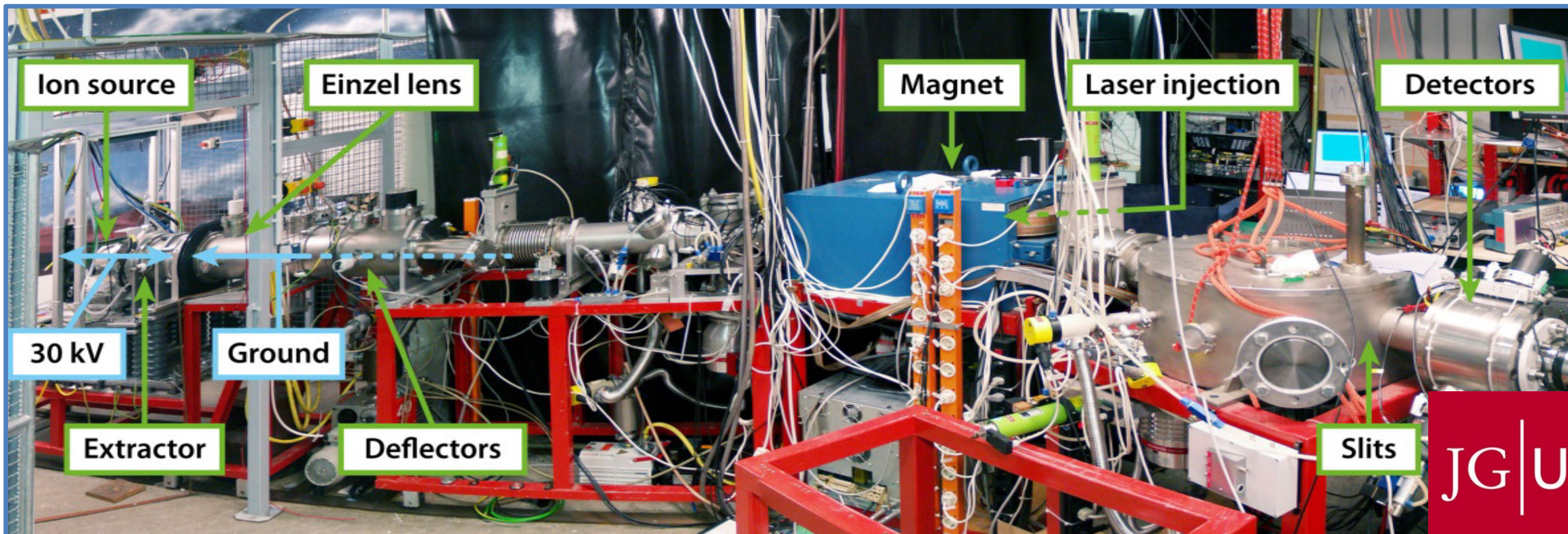
Magnetic sector-field Mass Spect.

30 kV two stage acceleration

60° double focussing separator magnet

Mass resolution: $\frac{m}{\Delta m} = 500 - 1000$

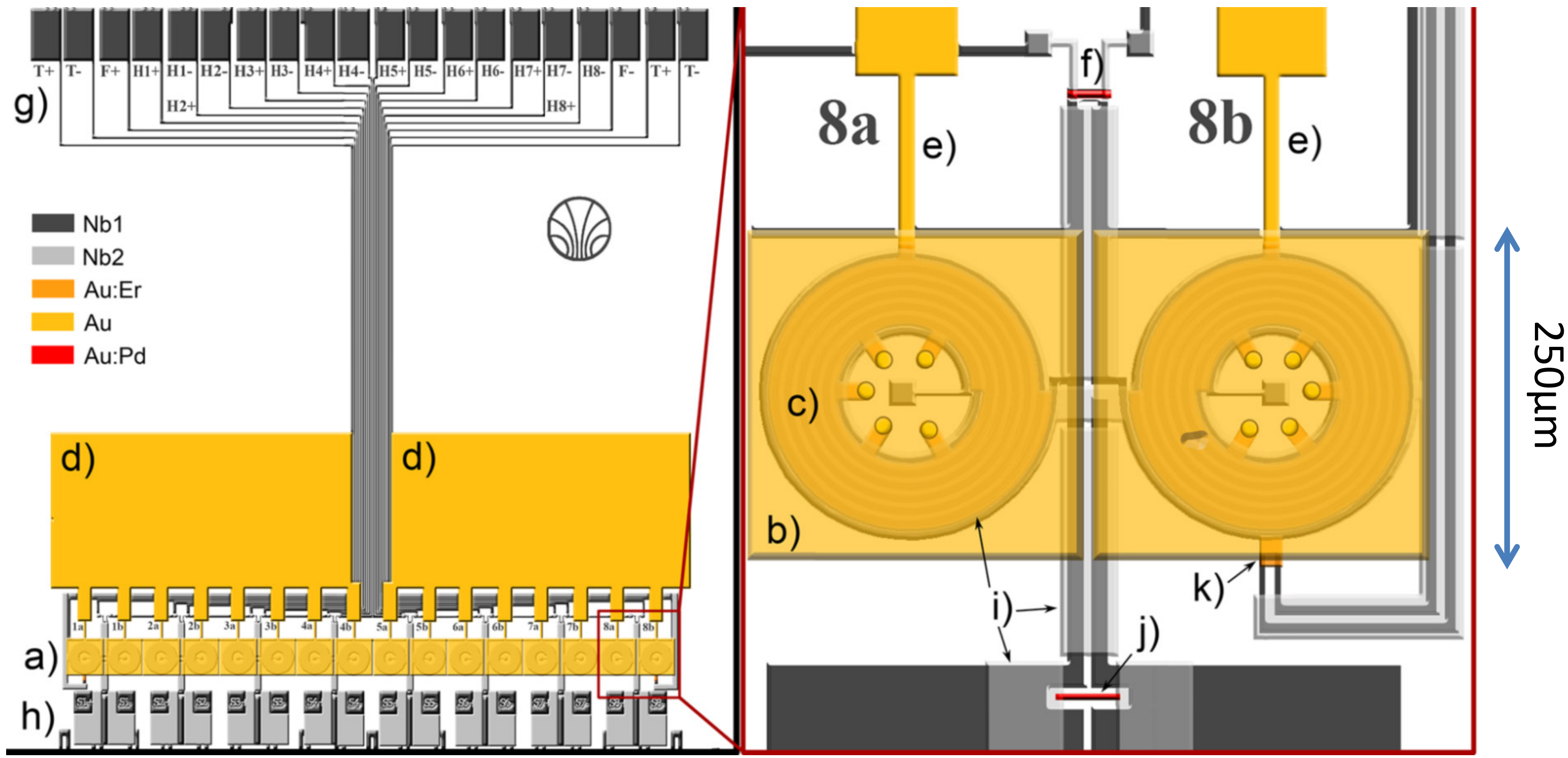
Suppression of neighboring masses > 10^3



F. Schneider et al., *NIM B* **376** (2016) 388

Second ^{163}Ho implantation

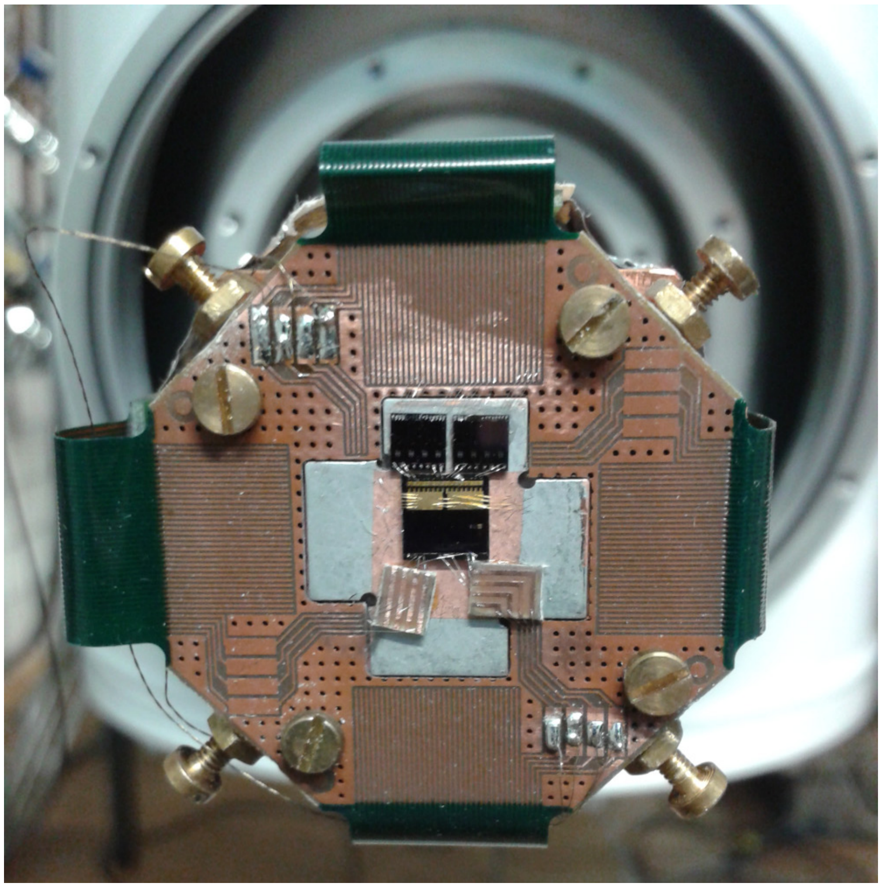
- Chemically purified ^{163}Ho source
- Offline implantation @ISOLDE-CERN using GPS and RILIS (December 2014)



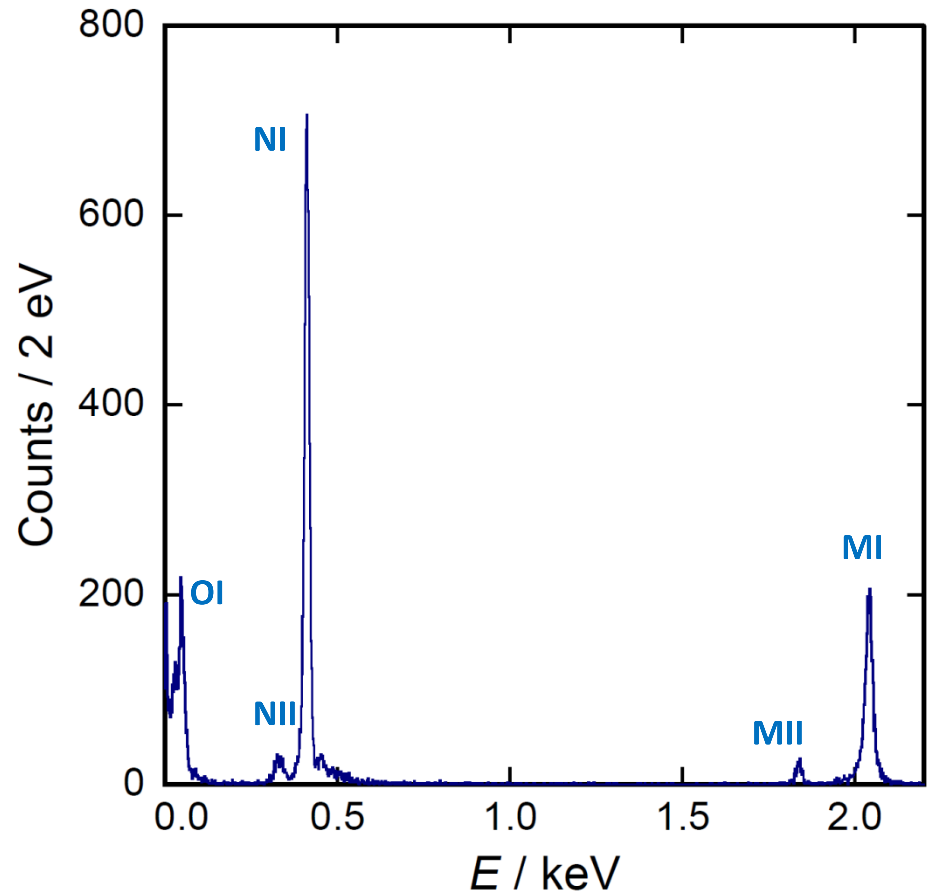
C. Hassel et al.,JLTP (2015)

Second ^{163}Ho implantation: first results

Mounted on a cold arm of a dry cryostat



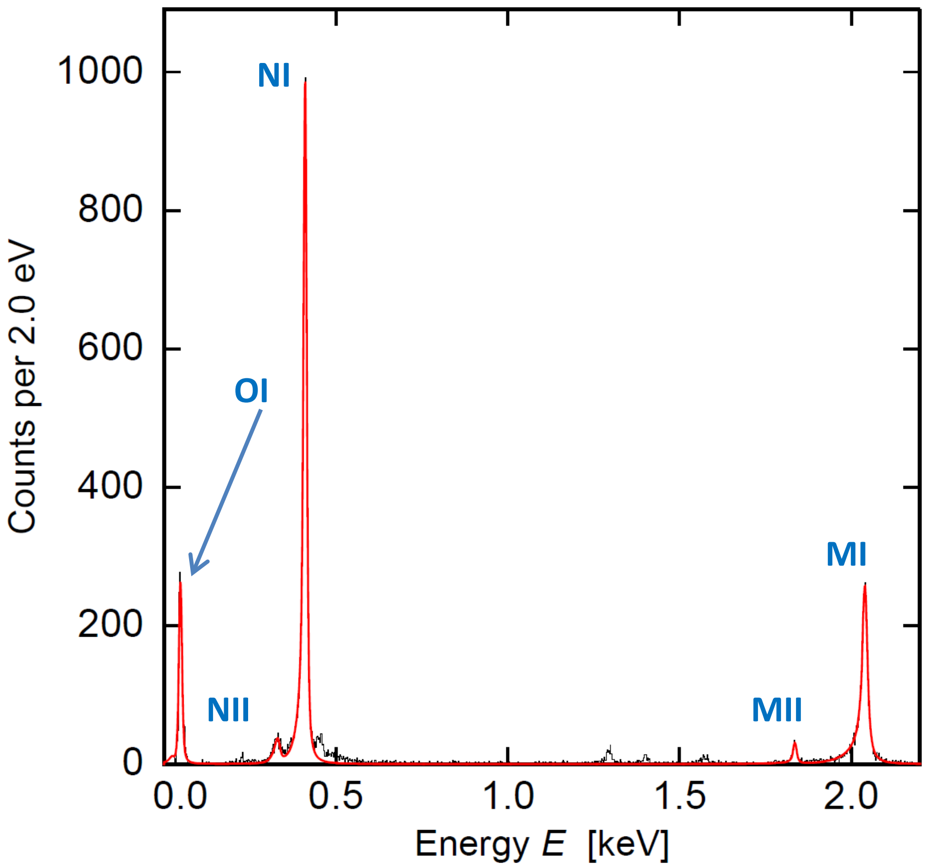
1 pixel about 2 days



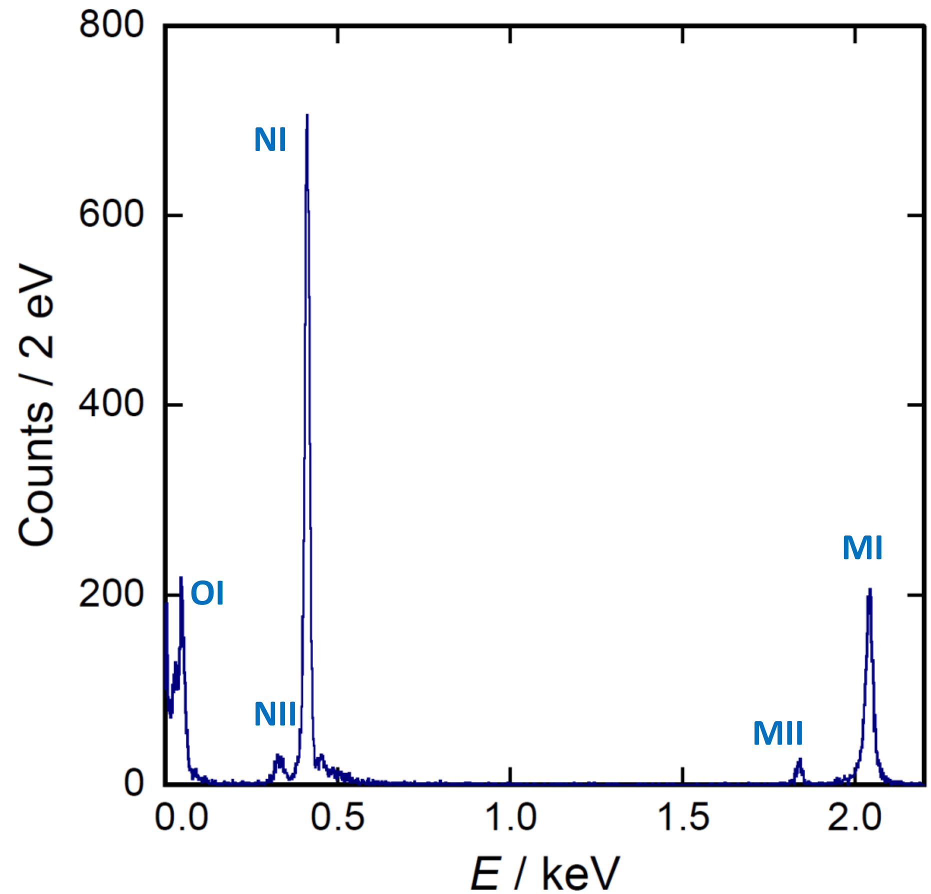
C. Hassel et al.,JLTP (2015)

Second ^{163}Ho implantation: first results

Two pixels for more then 1 month



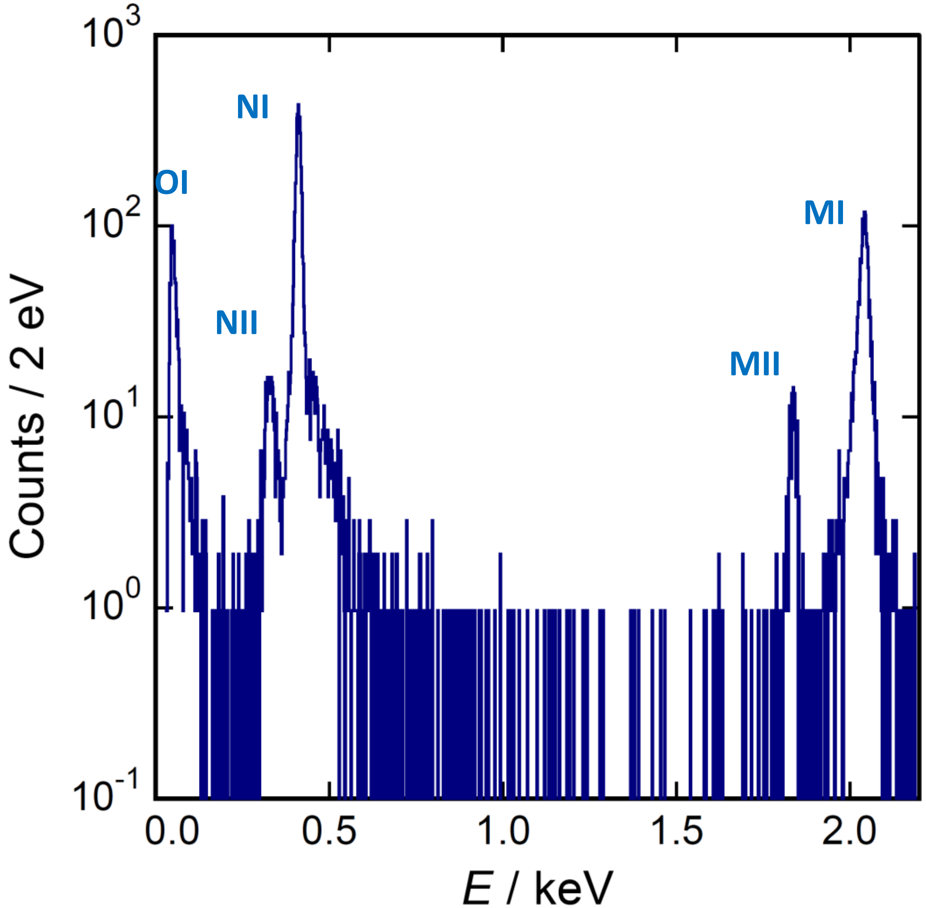
1 pixel about 2 days



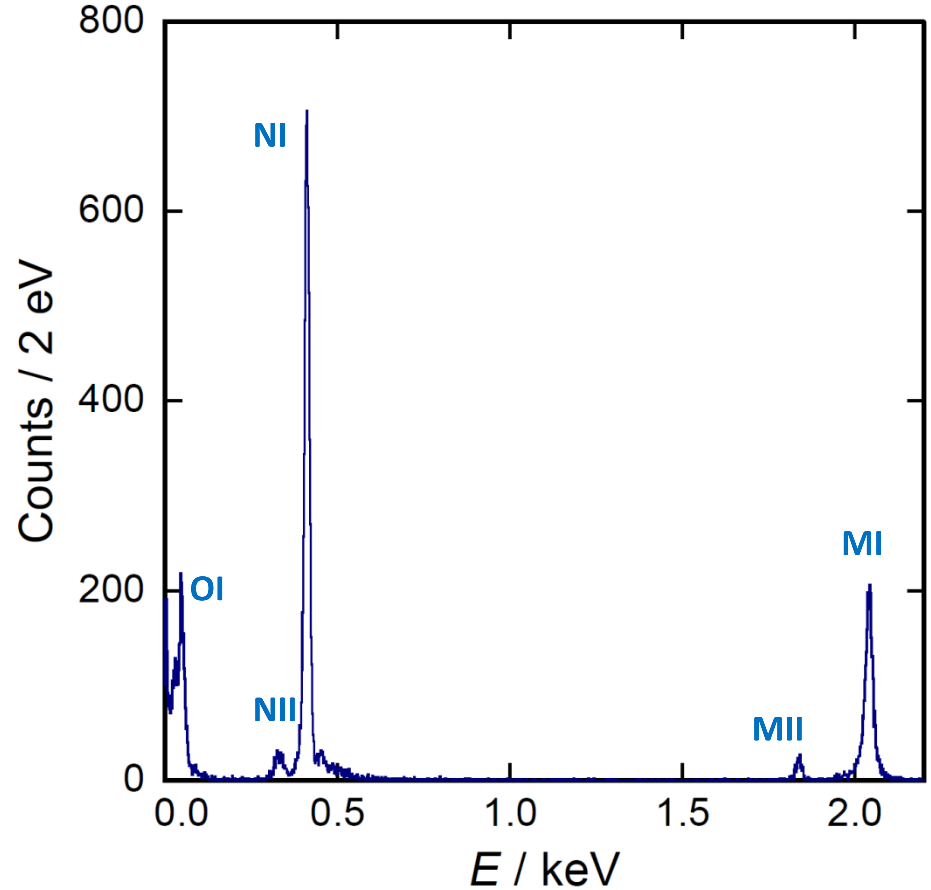
- Activity per pixel A ~ 0.2 Bq
- Baseline resolution ΔE_{FWHM} ~ 5 eV

C. Hassel et al.,JLTP (2015)

Second ^{163}Ho implantation: first results



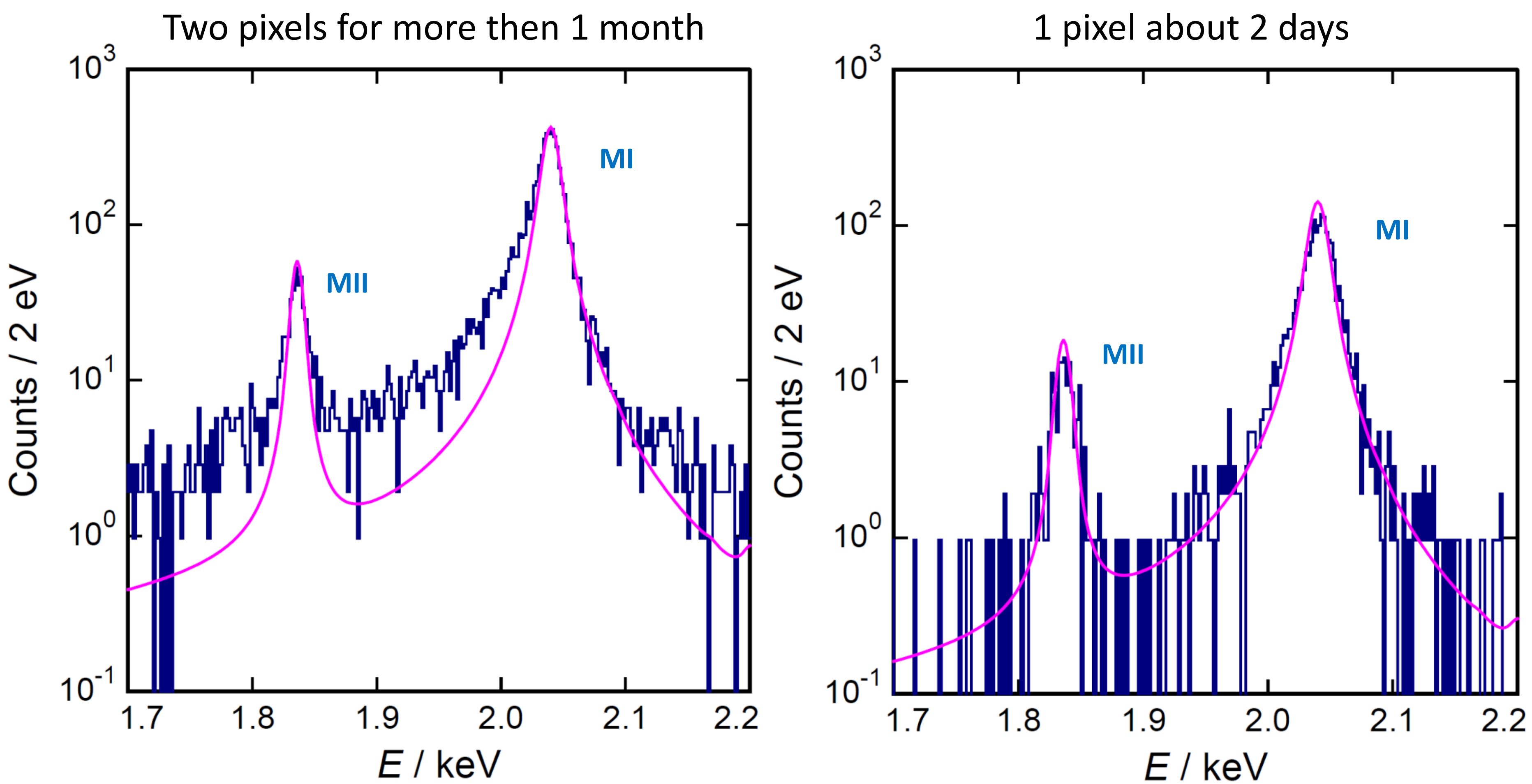
1 pixel about 2 days



- Activity per pixel A ~ 0.2 Bq
- Baseline resolution ΔE_{FWHM} ~ 5 eV
- No strong evidence of radioactive contamination in the source

C. Hassel et al.,JLTP (2015)

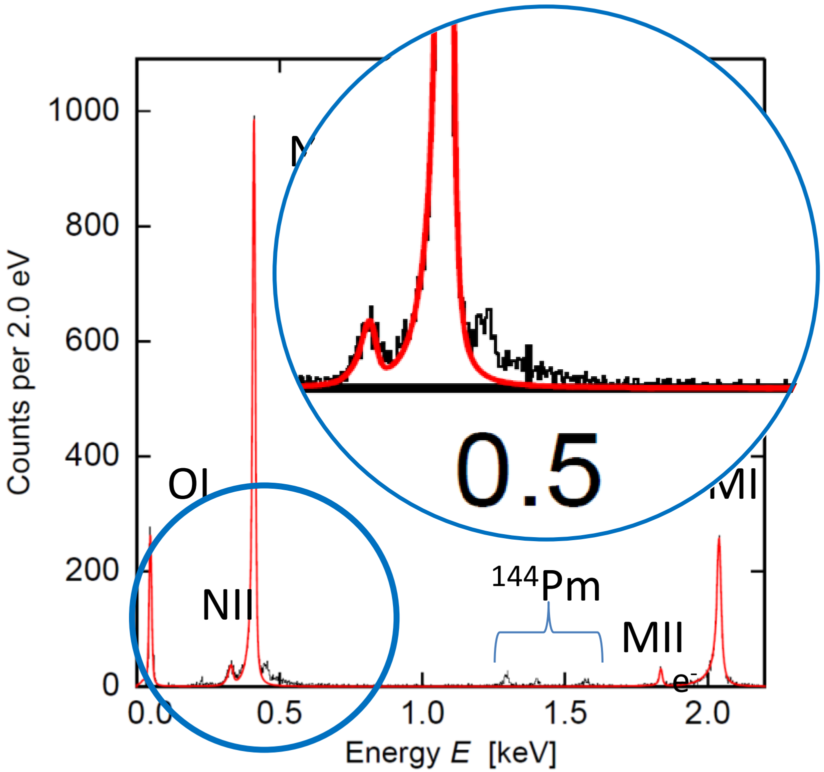
Second ^{163}Ho implantation: first results



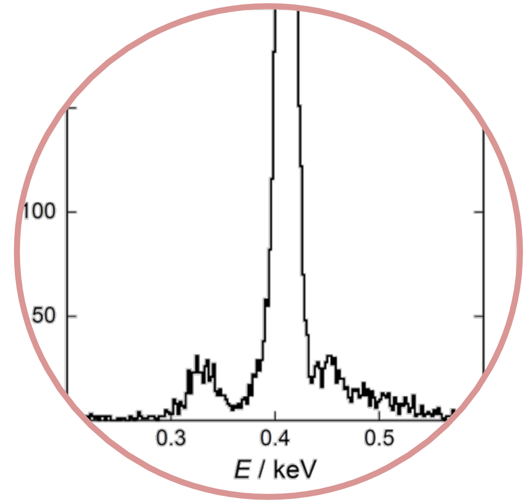
- Activity per pixel A ~ 0.1 Bq
- Baseline resolution ΔE_{FWHM} ~ 5 eV
- No strong evidence of radioactive contamination in the source
- Symmetric detector response

C. Hassel et al.,JLTP (2015)

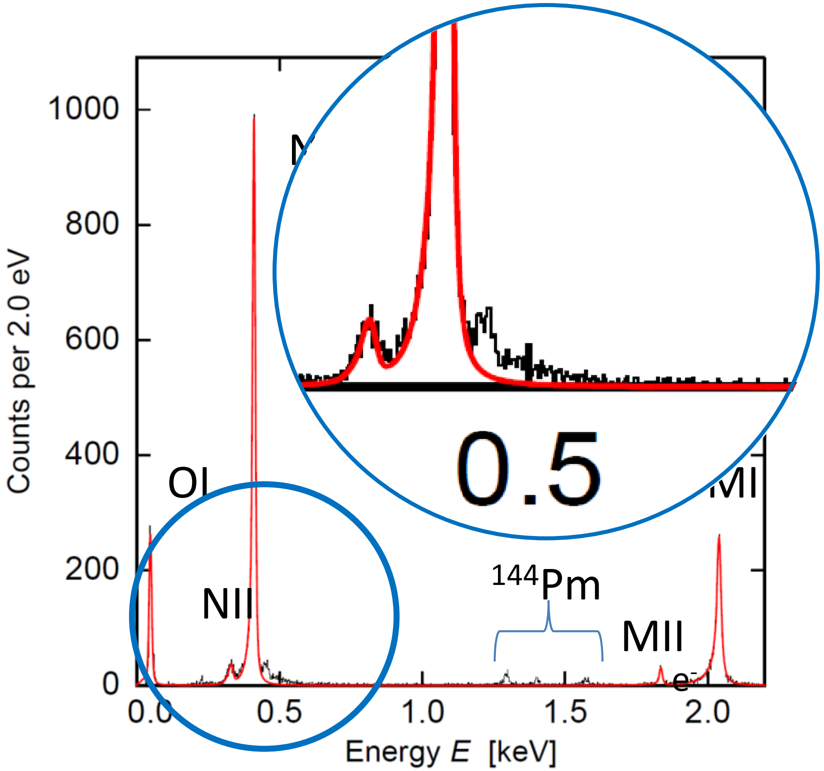
Characterisation of spectral shape



Structures present also in new data



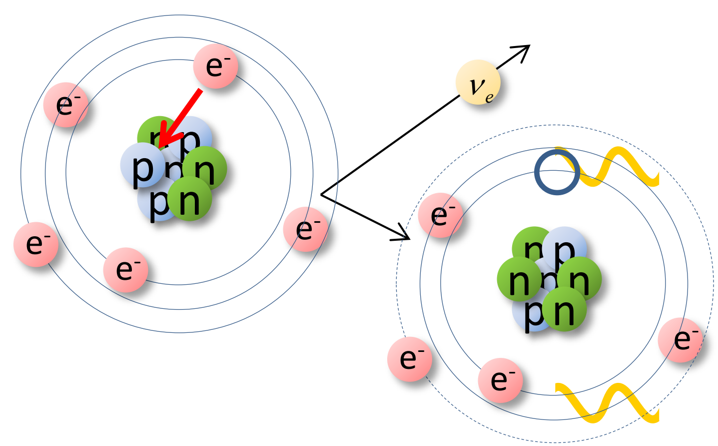
Characterisation of spectral shape



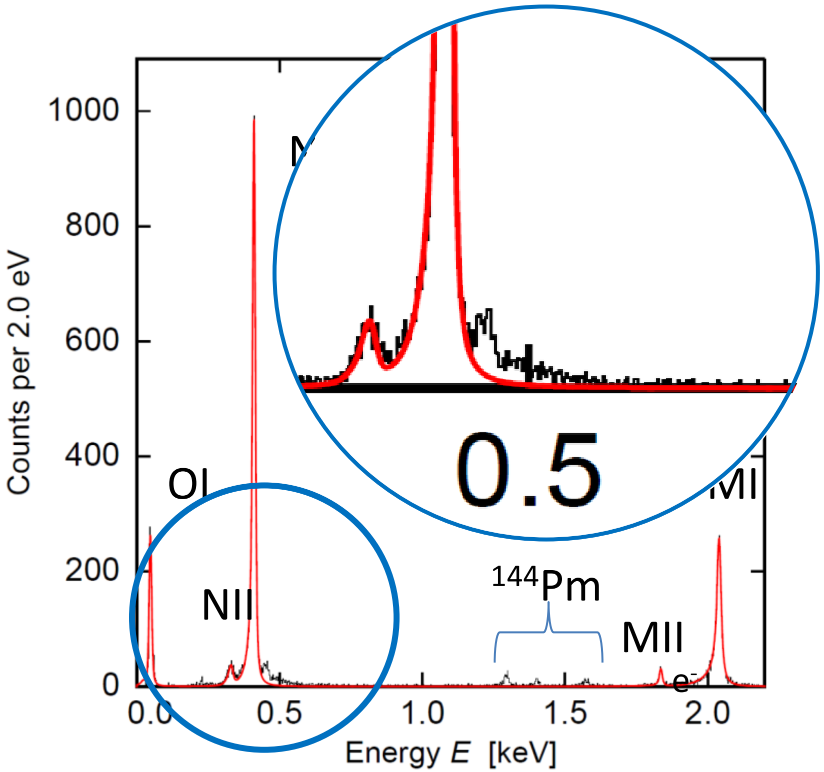
Estimate the effect of

- **Higher order excitation in ^{163}Ho**

- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler and F. Simkovic
  Phys. Rev. C **91**, 045505 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula and M. Lusignoli
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016



Characterisation of spectral shape



- A. Faessler et al. *J. Phys. G* **42** (2015) 015108
- R. G. H. Robertson Phys. Rev. C **91**, 035504 (2015)
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- A. Faessler et al. Phys. Rev. C **91**, 064302 (2015)
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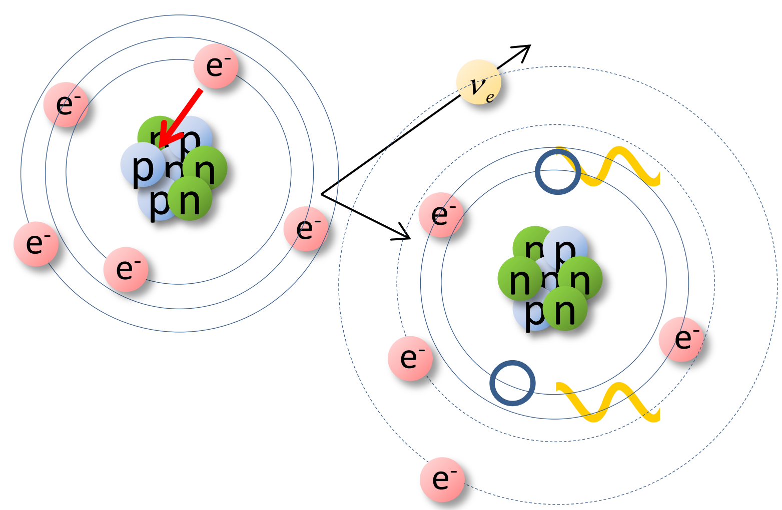
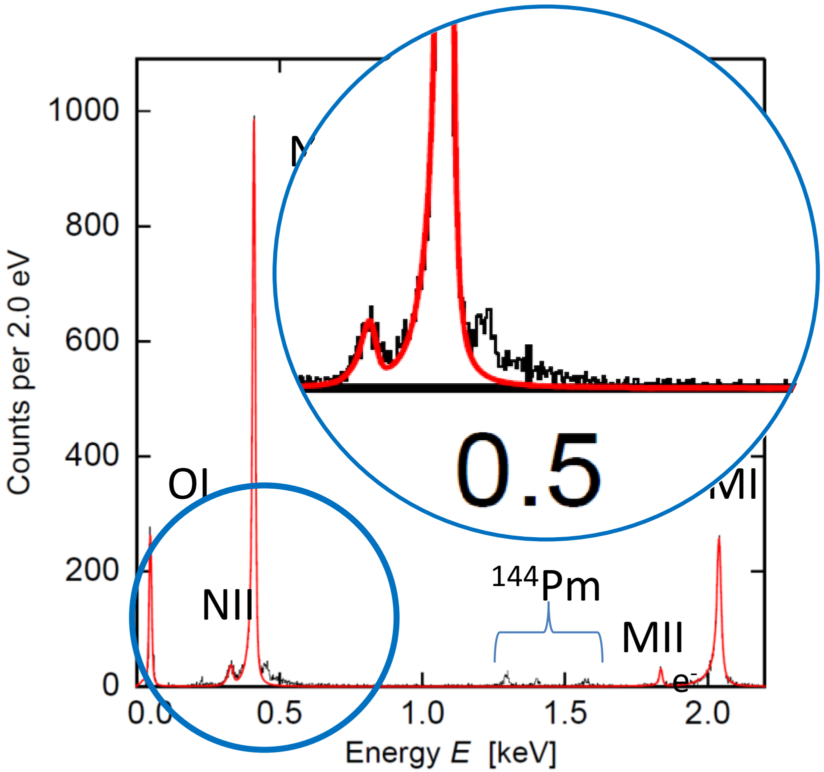
Two-holes excited states: shake-up



Characterisation of spectral shape



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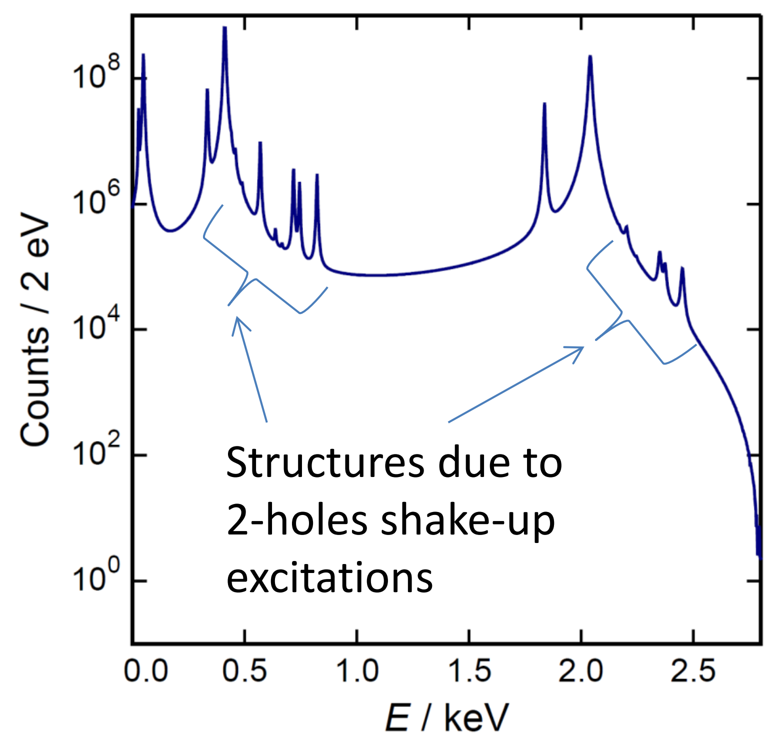
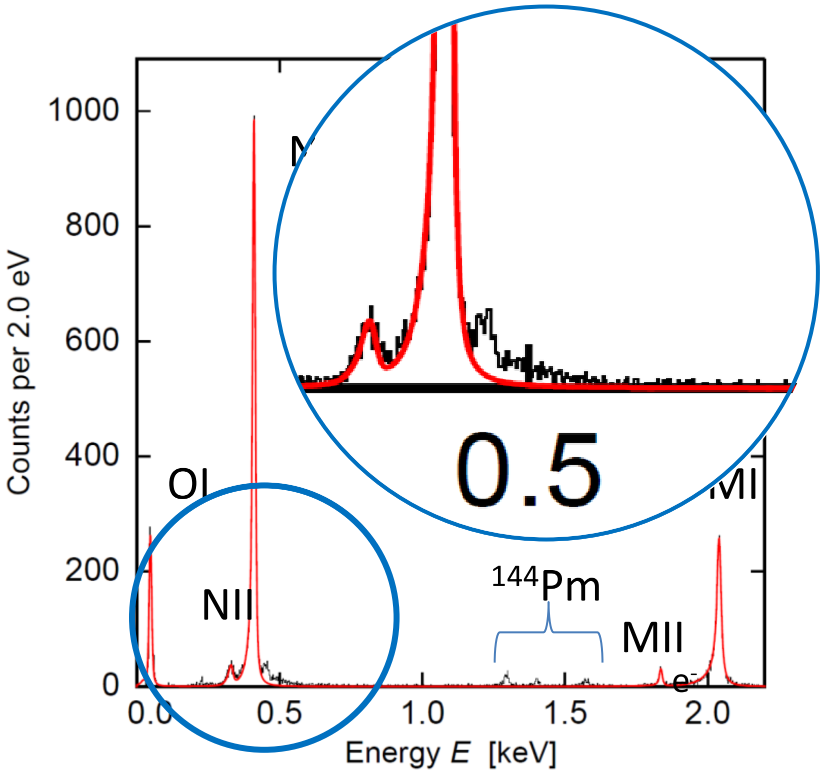


Two-holes excited states: shake-up

Characterisation of spectral shape



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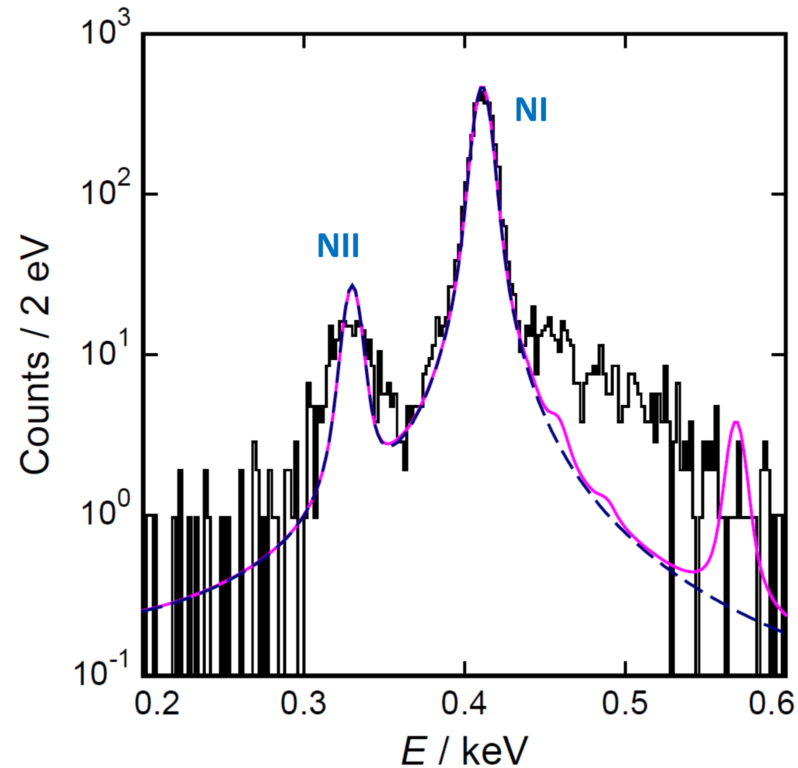
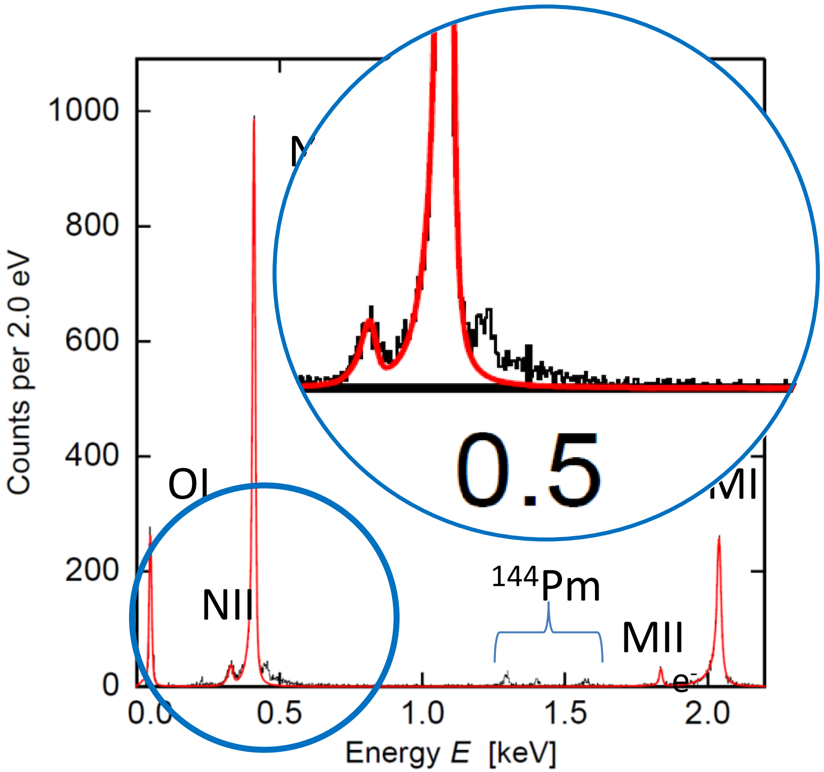


Two-holes excited states: shake-up

Characterisation of spectral shape



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- A. Faessler and F. Simkovic
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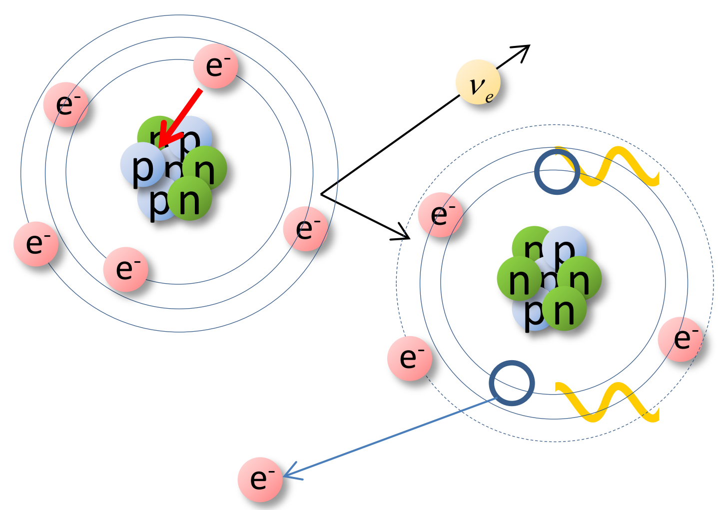
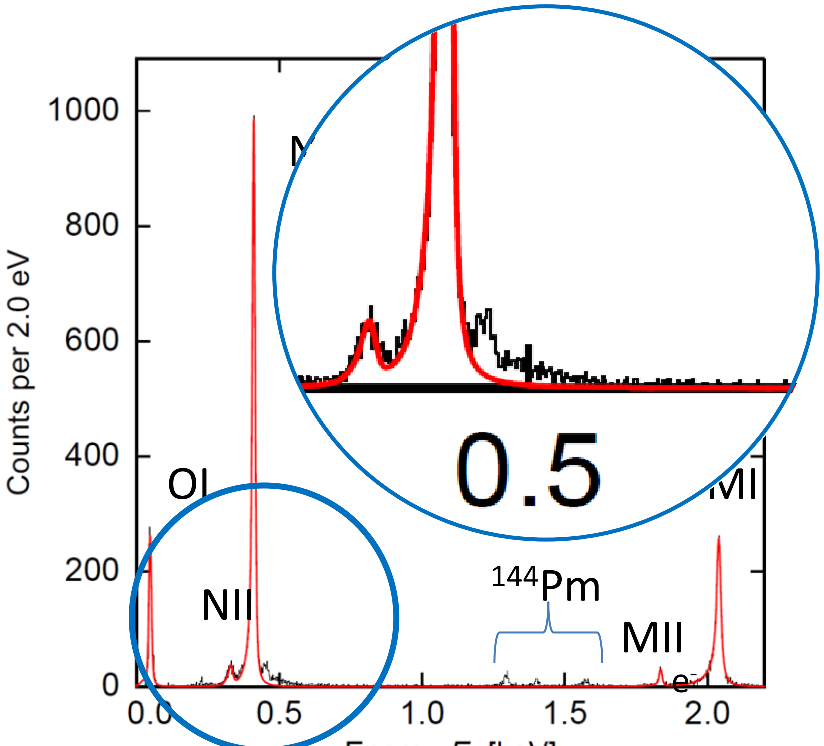
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula and M. Lusignoli
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016

Two-holes excited states: shake-up
shake-off



Characterisation of spectral shape



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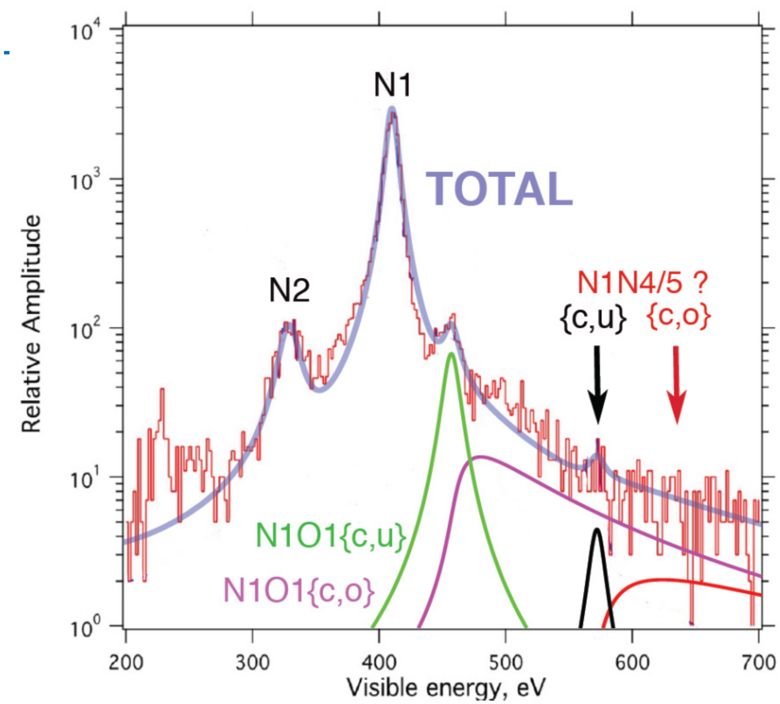
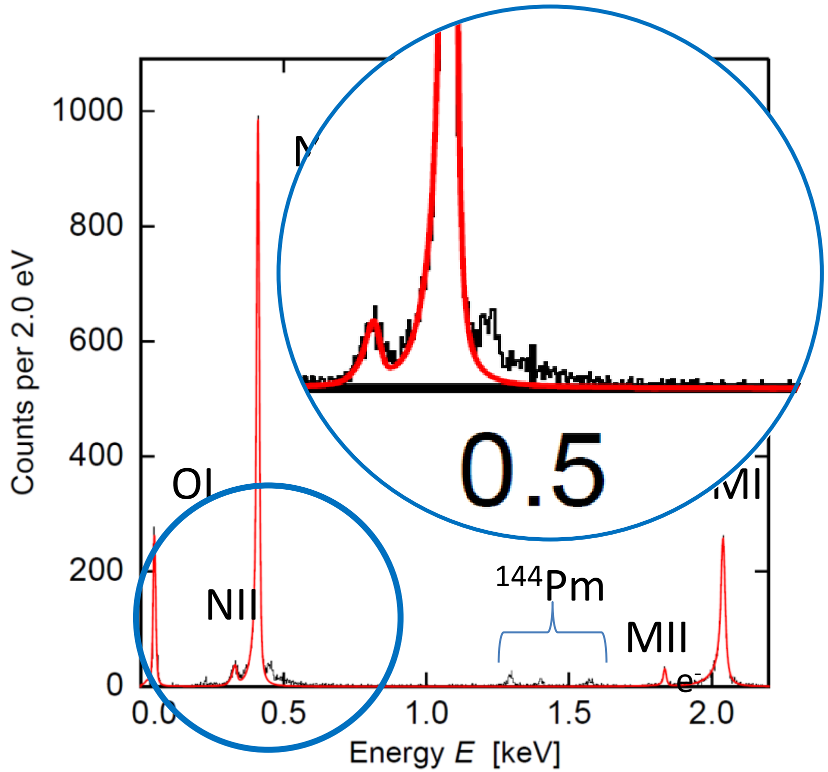
- A. De Rujula and M. Lusignoli
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016



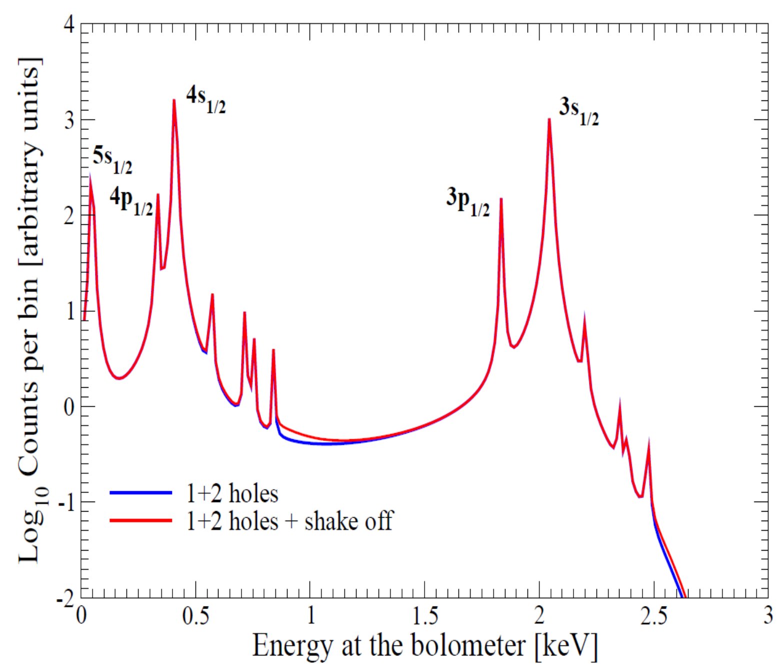
Two-holes excited states: shake-up
shake-off

Characterisation of spectral shape



Two-holes excited states: shake-up
shake-off

- A. Faessler et al. *J. Phys. G* **42** (2015) 015108
- R. G. H. Robertson Phys. Rev. C **91**, 035504 (2015)
- A. Faessler and F. Simkovic Phys. Rev. C **91**, 045505 (2015)
- A. Faessler et al. Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula and M. Lusignoli arXiv:1601.04990v1 [hep-ph] 19 Jan 2016
- A. Faessler et al., https://arxiv.org/abs/1611.00325

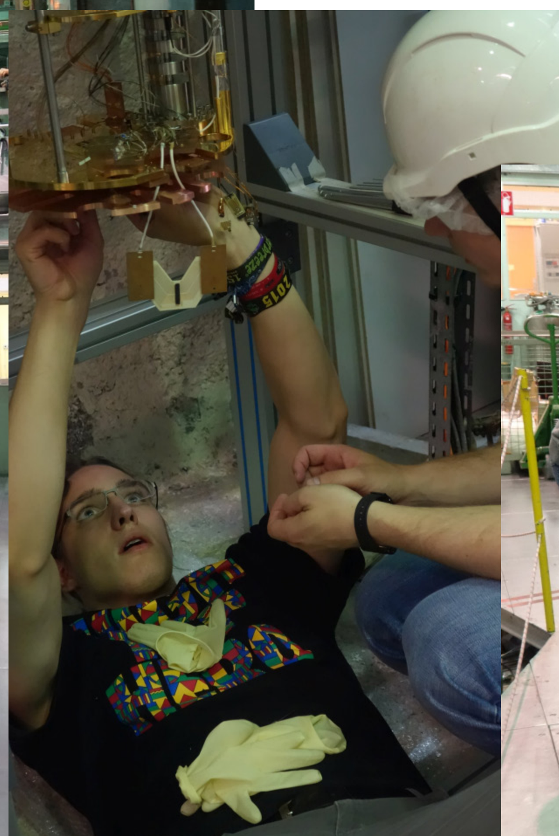


MMCs move to the mountains

Modane, France - 15th of September 2015

….or better under the mountains

- Study intrinsic background of MMCs
- Low background ^{163}Ho spectrum

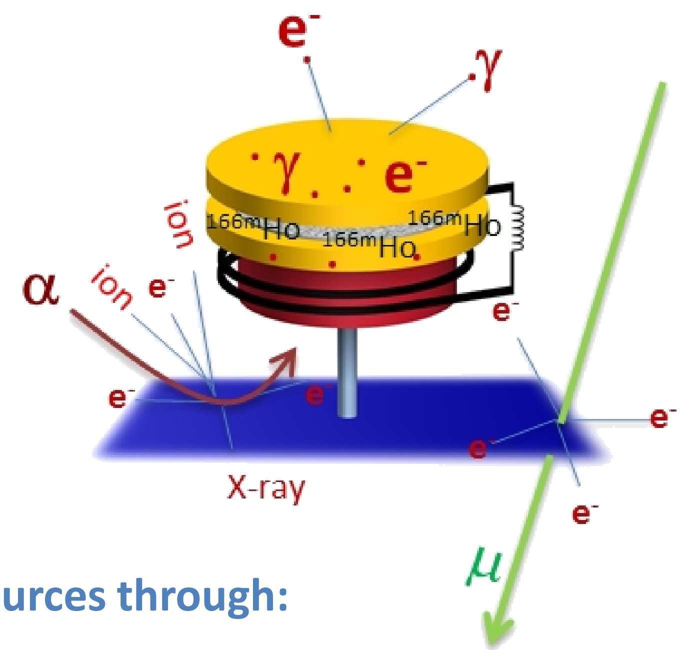


Background

Background sources:

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

Underground measurements in **Modane**



Study of background sources through:

- Monte Carlo simulations
- Dedicated experiments

Screening facilities

- **Uni-Tübingen**
- **Felsenkeller**

ECHo-1k (2015 - 2018)

^{163}Ho activity: **A_t = 1 kBq**

Detectors: Metallic Magnetic Calorimeters

→ Energy resolution **$\Delta E_{FWHM} \leq 5$ eV**

→ Time resolution **$\tau \leq 1$ µs**

Unresolved pile-up fraction $f_{pu} \leq 10^{-5}$

→activity per pixel: **A = 10 Bq**

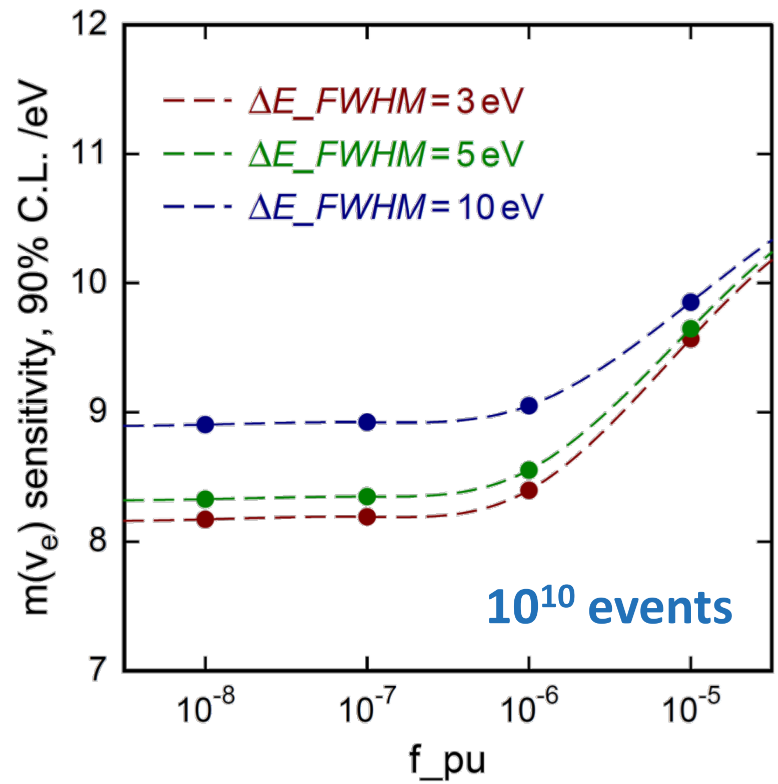
→number of detectors **N = 100**

Read-out : Microwave SQUID Multiplexing

→ 2 arrays with ~50 single pixels

Background **$b < 10^{-5}$ /eV/det/day**

Measuring time **t = 1 year**



$m(\nu_e) < 10$ eV 90% C.L.

ECHo-1M (2019 - 2022)

^{163}Ho activity: A_t = **1 MBq**

Detectors: Metallic Magnetic Calorimeters

→ Energy resolution $\Delta E_{FWHM} \leq$ **3 eV**

→ Time resolution $\tau \leq$ **0.1 μs**

Unresolved pile-up fraction $f_{pu} \leq 10^{-6}$

→activity per pixel: A = **10 Bq**

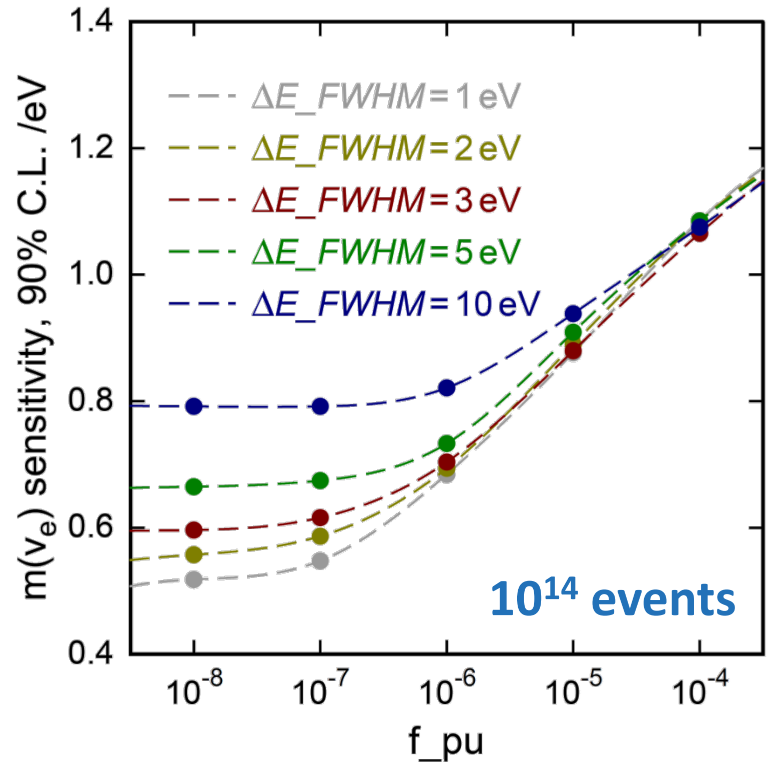
→number of detectors $N = 10^5$

Read-out : Microwave SQUID Multiplexing

→ 100 arrays with ~1000 single pixels

Background $b < 10^{-6}$ **/eV/det/day**

Measuring time t = **1 – 3 year**



$m(\nu_e) < 1$ eV 90% C.L.

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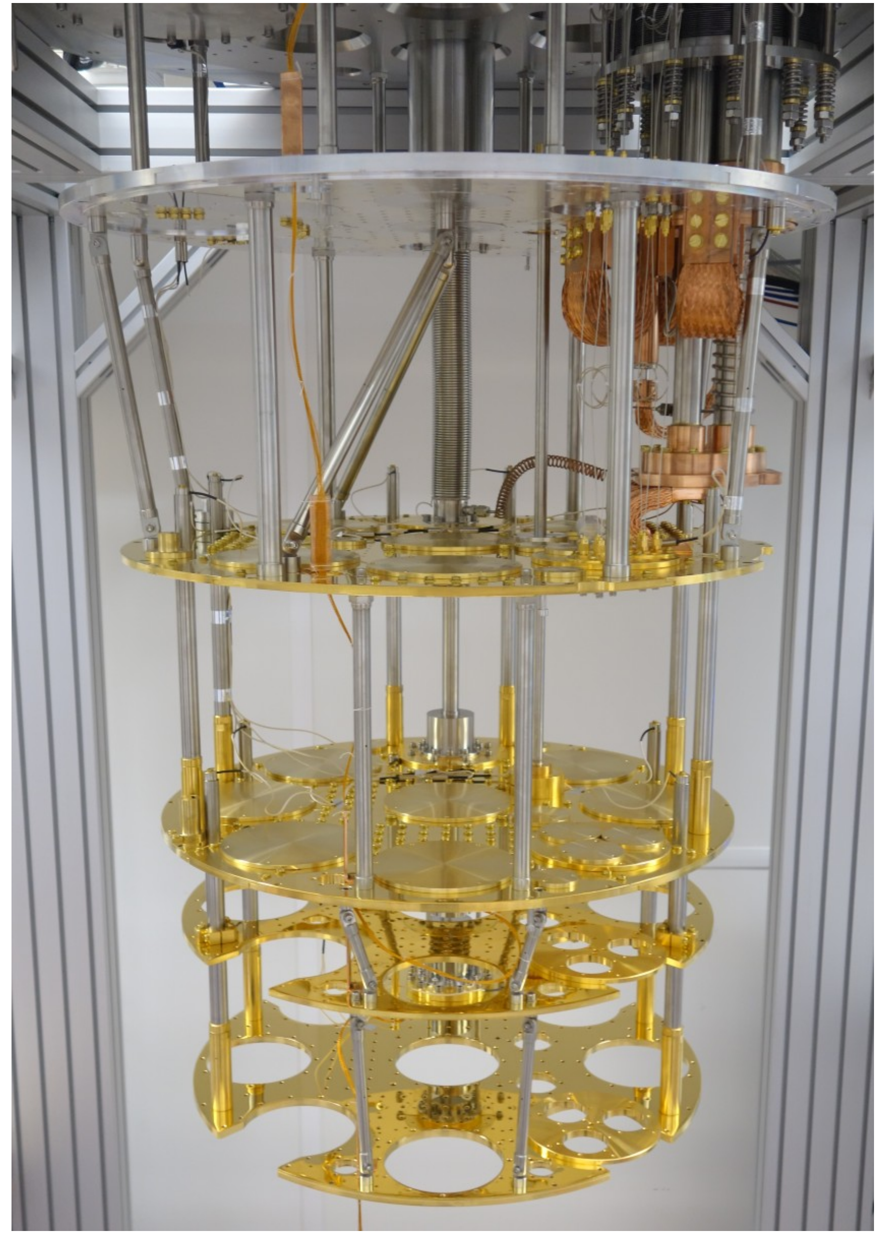
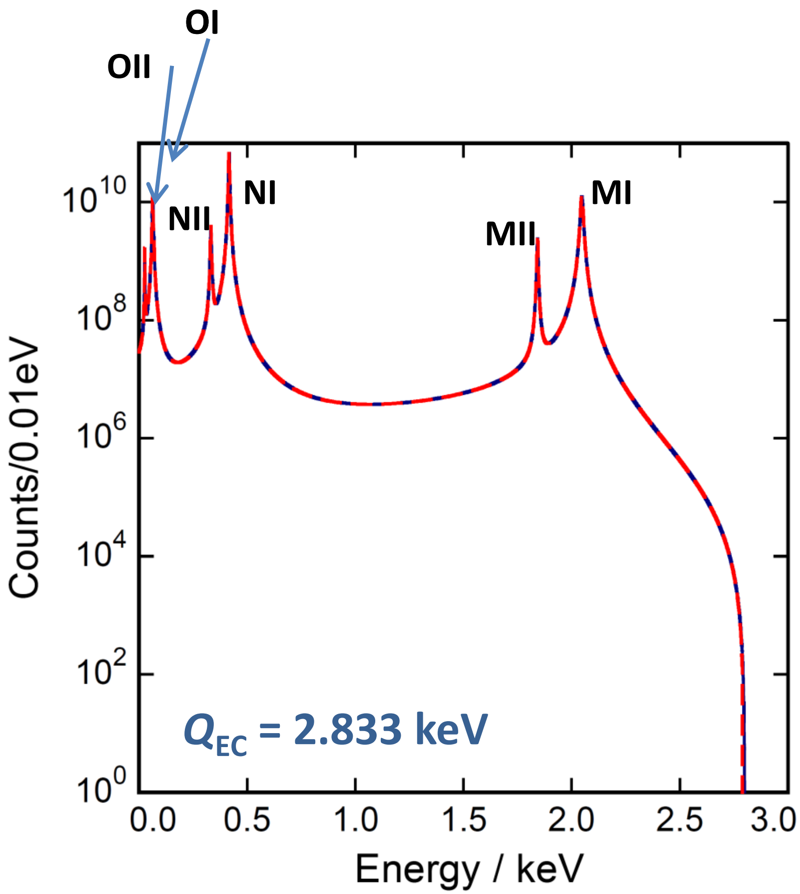


How does
the existence of sterile neutrino
affect the EC spectrum?

Sterile Neutrino and ^{163}Ho

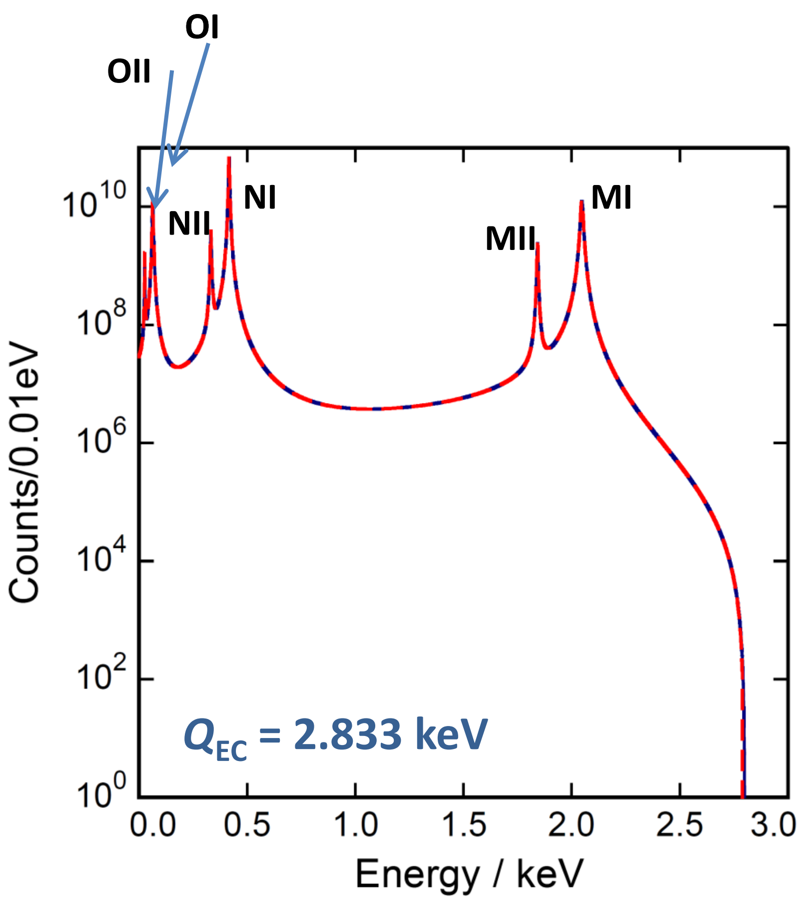
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\,2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\,2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\,2}}{4}}$$



Sterile Neutrino and ^{163}Ho

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

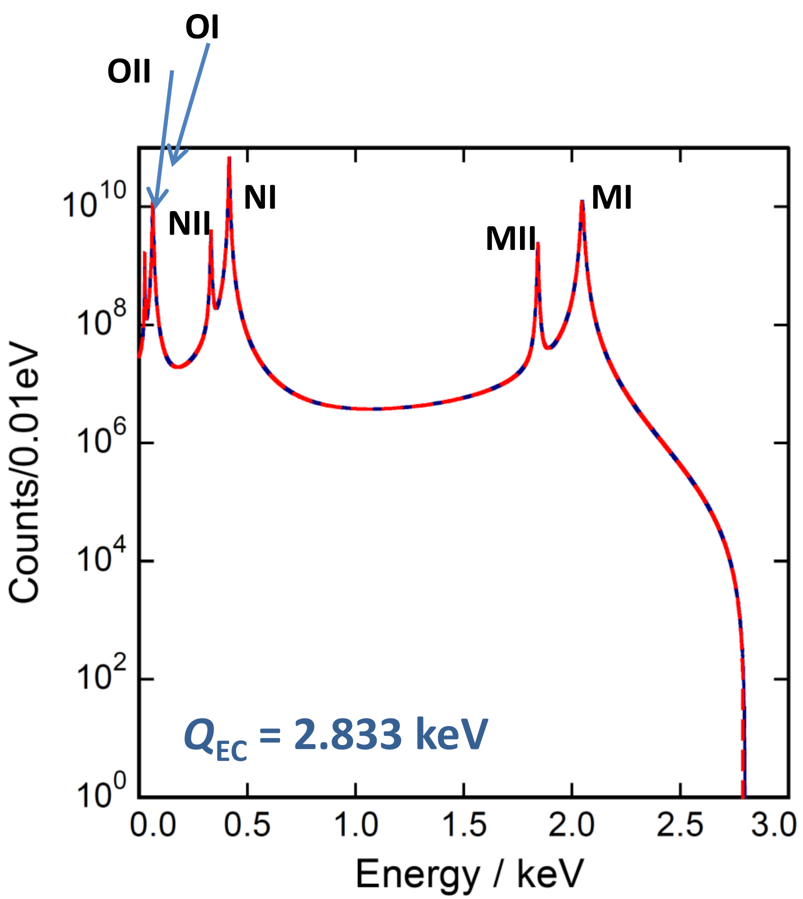
$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$



- Electron neutrino mass as superposition of mass eigenstates

Sterile Neutrino and ^{163}Ho

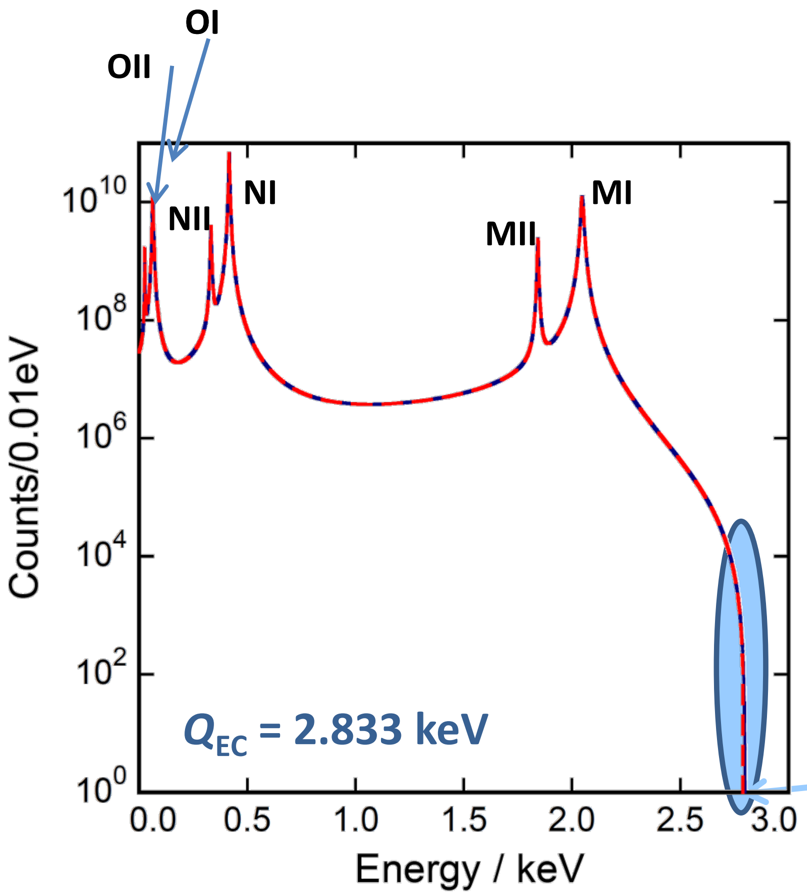
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \left[\left(1 - |U_{e4}|^2\right) + |U_{e4}|^2 \sqrt{1 - \frac{m_4^{\,2}}{(Q_{EC} - E_C)^2}} H(Q_{EC} - E_c - m_4) \right] \sum_H B_H \varphi_H^{\,2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\,2}}{4}}$$



- Electron neutrino mass as superposition of mass eigenstates
- $m_{i=1,2,3} << m_4$
- $m_{i=1,2,3} \sim 0$ eV

Sterile Neutrino and ^{163}Ho

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



- Electron neutrino mass as superposition of mass eigenstates
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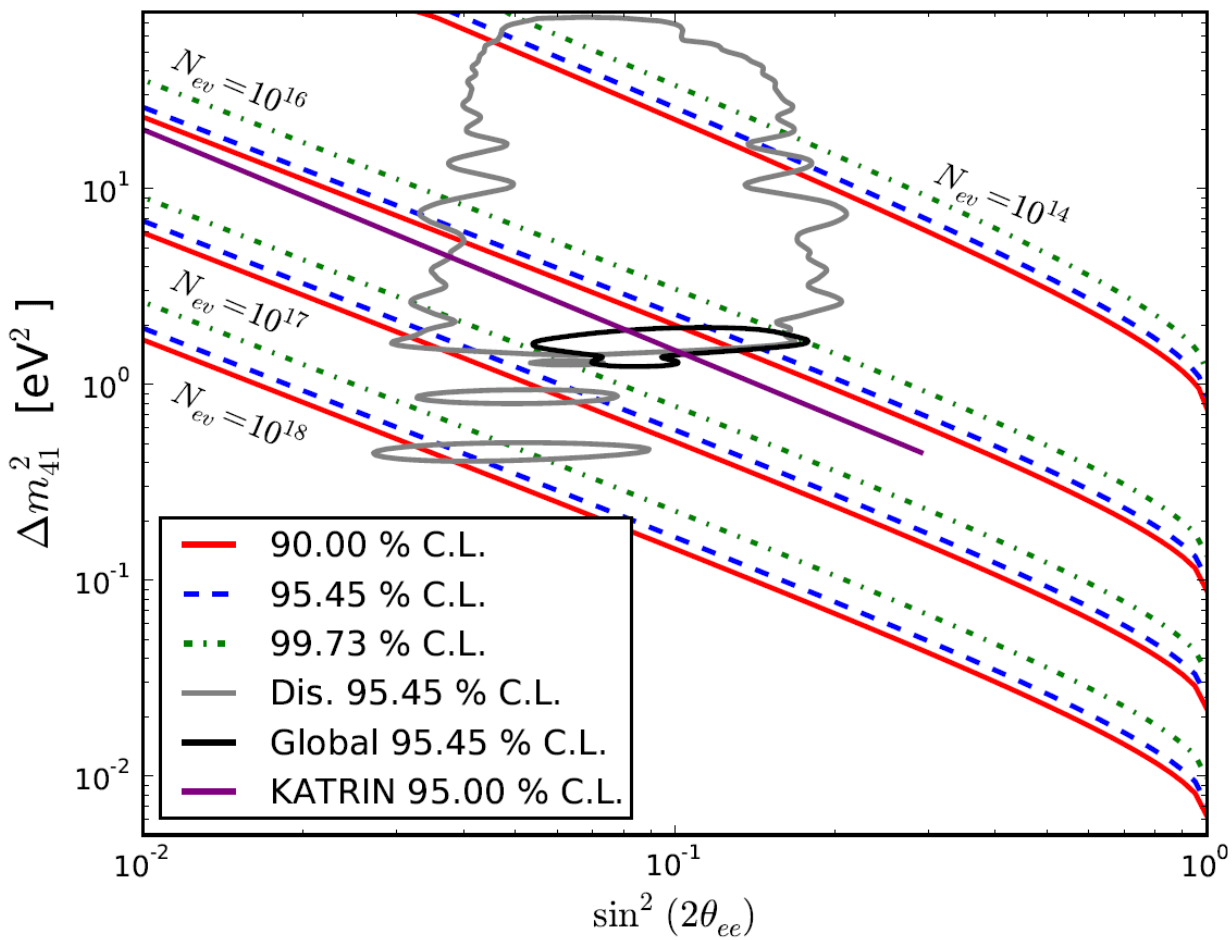
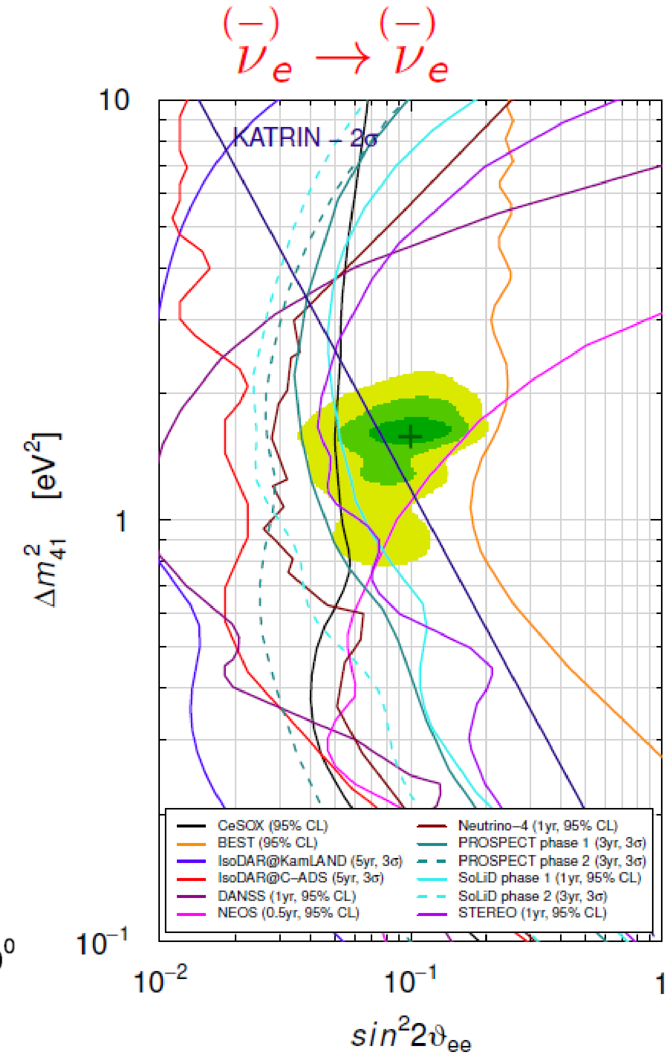
eV-scale sterile neutrinos

eV-scale sterile neutrino



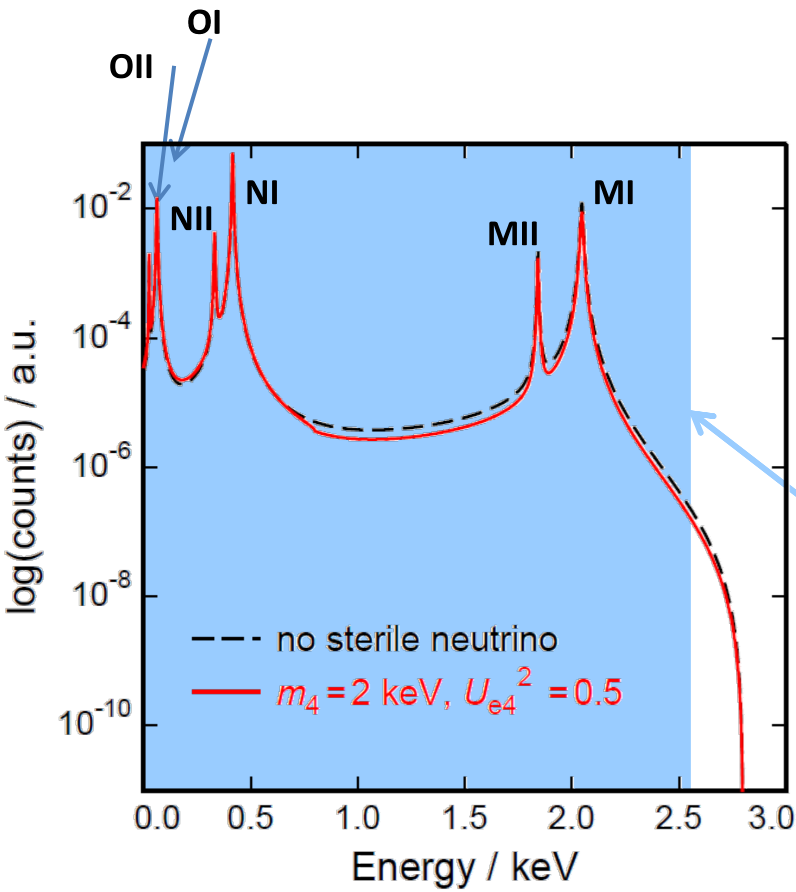


L. Gastaldo, C. Giunti, E. Zavanin., 2016

C. Giunti NOW 2016

keV-scale sterile neutrino

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



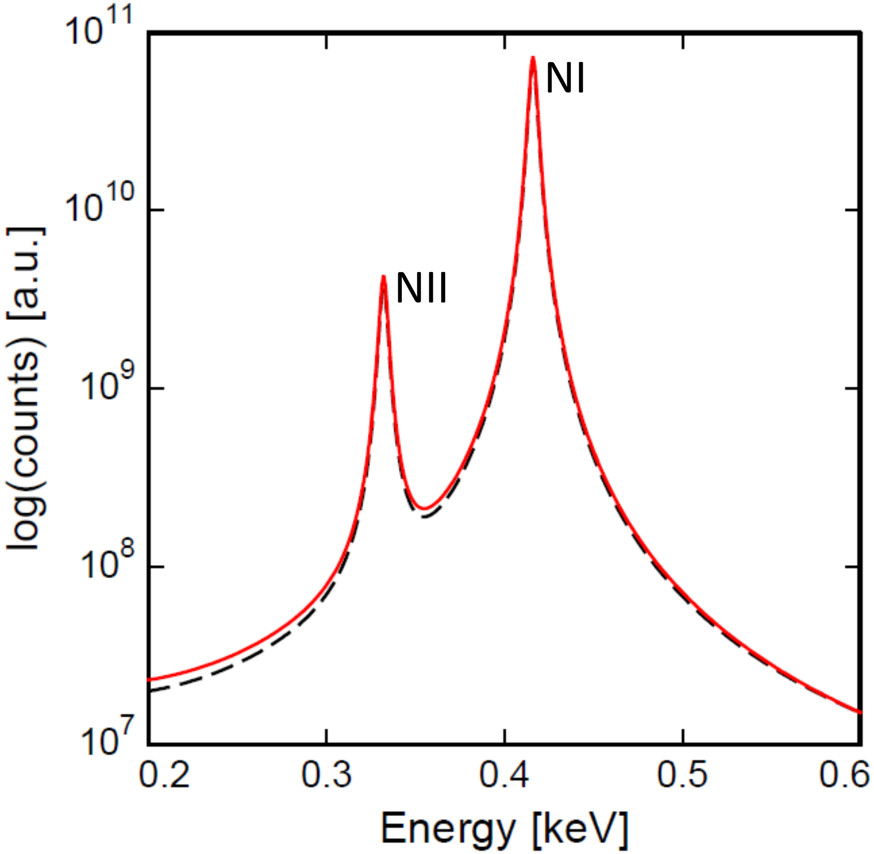
- Electron neutrino mass as superposition of mass eigenstates
- $m_{i=1,2,3} << m_4$
- $m_{i=1,2,3} \sim 0$ eV

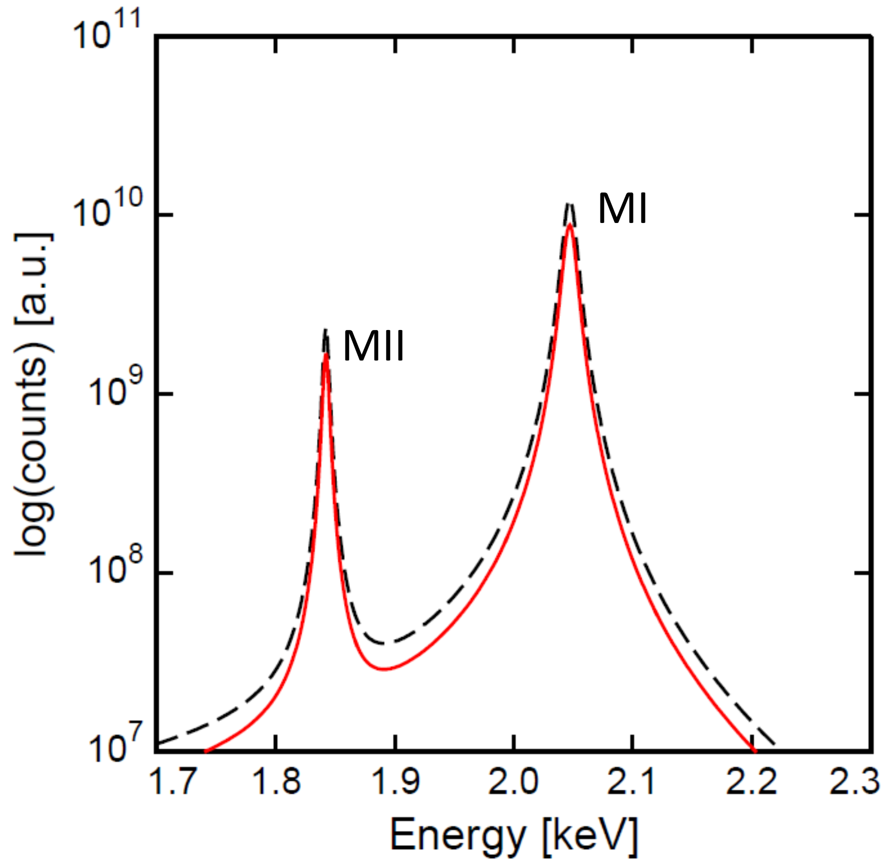
keV-scale sterile neutrinos

keV-scale sterile neutrino

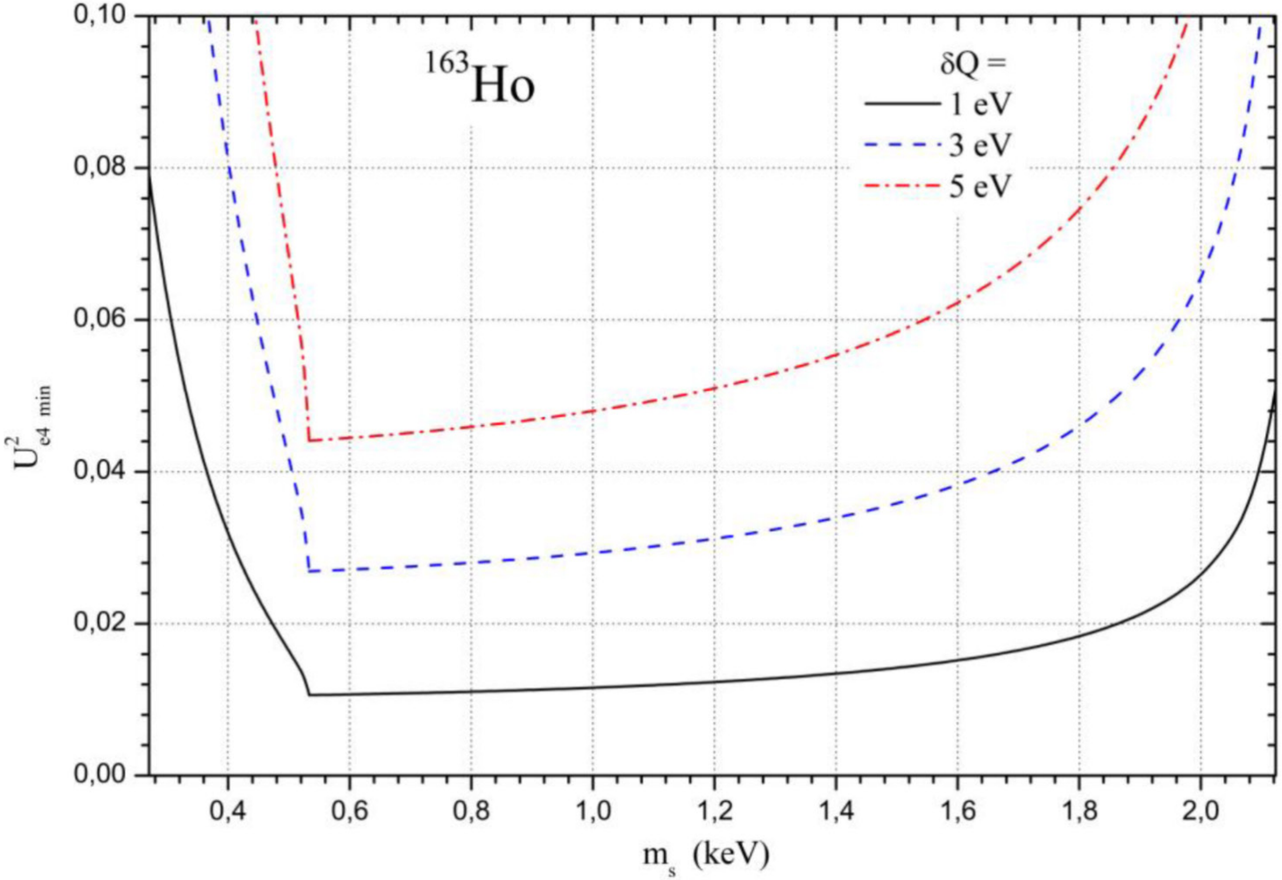
m_4=2 keV, U_{e4}^2=0.5

no sterile neutrino





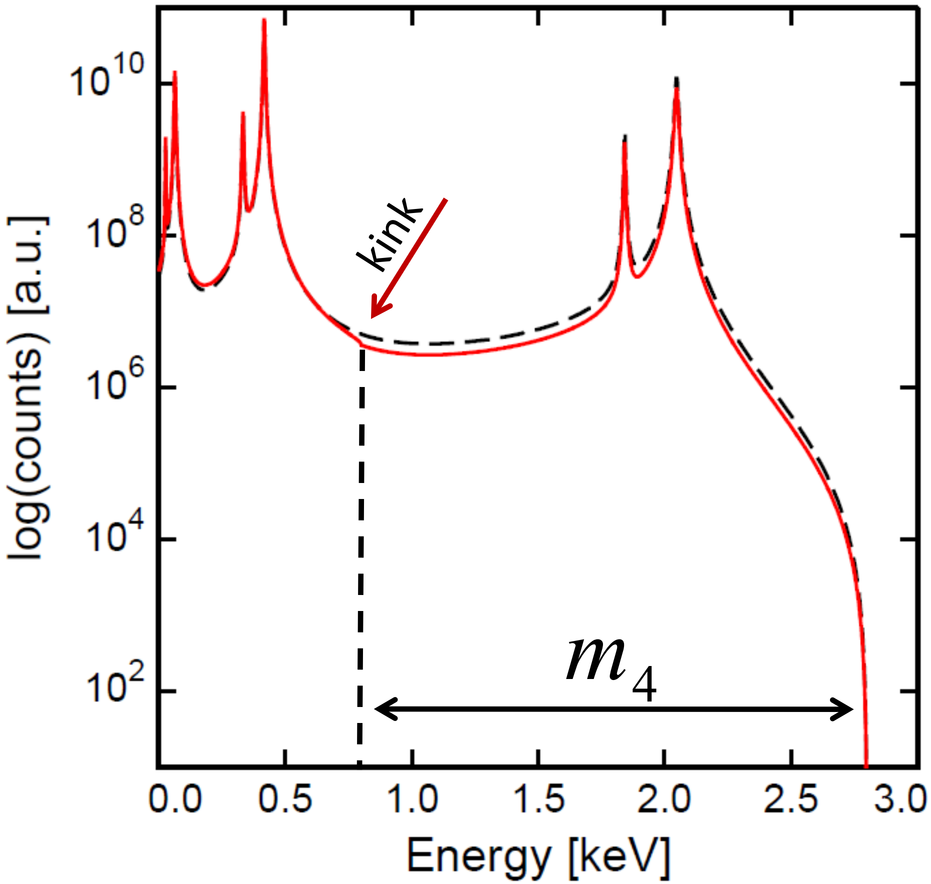
keV-scale sterile neutrino



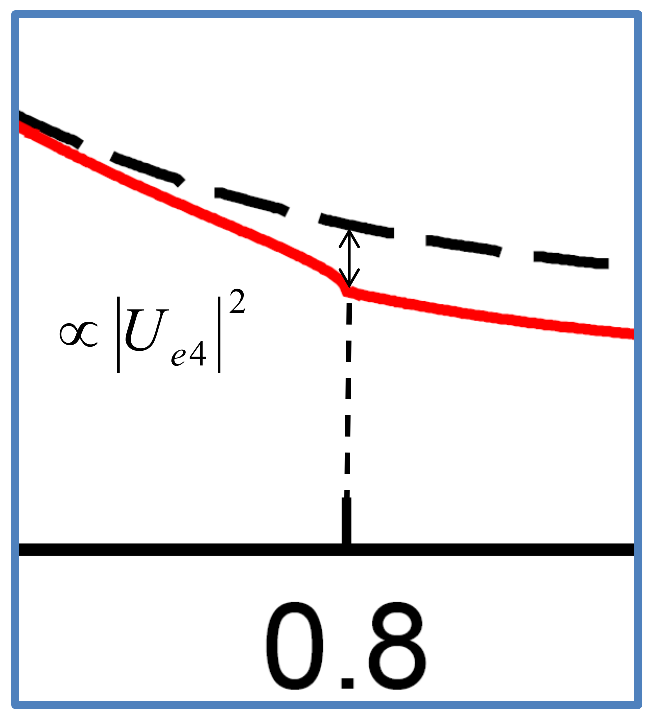
Sensitivity to the mixing matrix element at 90% CL as a function of the sterile neutrino mass achievable with about 10^{10} events in the full EC spectrum.

P. Filianin et al. arXiv: 1402.4400

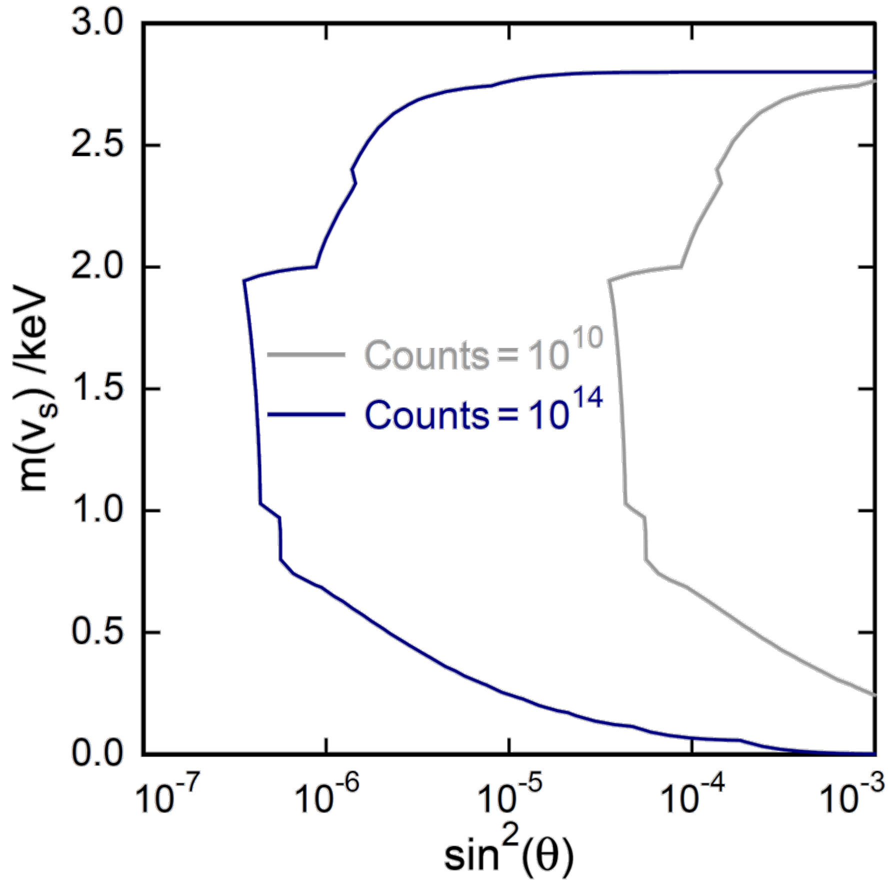
keV-scale sterile neutrino



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



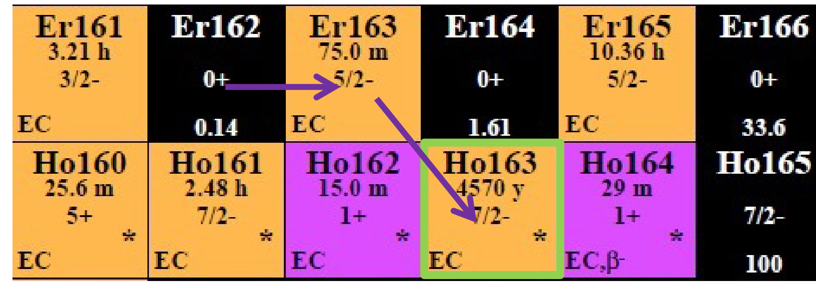
keV-scale sterile neutrino



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

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

Conclusions...



- Independent ^{163}Ho Q_{EC} measurement
  $Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

- High purity ^{163}Ho source has been produced

- ^{163}Ho ions have been successfully implanted
  in offline process @ISOLDE-CERN in 32 pixels
  @RISIKO in 8 pixels

- Possibility to investigate spectral shape
  with new implanted detectors

Conclusions and outlook

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

  - A ~ 1000 Bq — High purity ^{163}Ho source (produced at reactor)
  - $\Delta E_{\mathrm{FWHM}} < 5$ eV
  - $\tau_r < 1$ µs
  - multiplexed arrays → microwave SQUID multiplexing

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

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

- High energy resolution and high statistics ^{163}Ho spectra allow to investigate the existence of **sterile neutrinos** in the eV-scale and keV-scale

DFG Deutsche Forschungsgemeinschaft

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

Thank you!

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ECHo