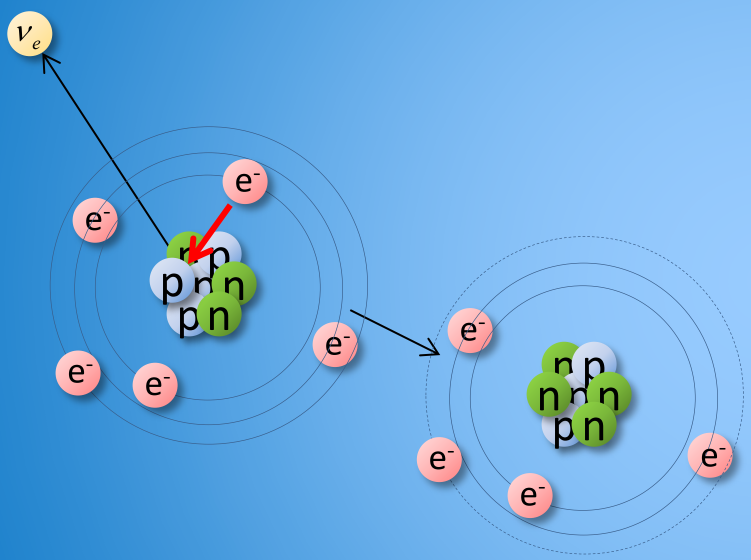
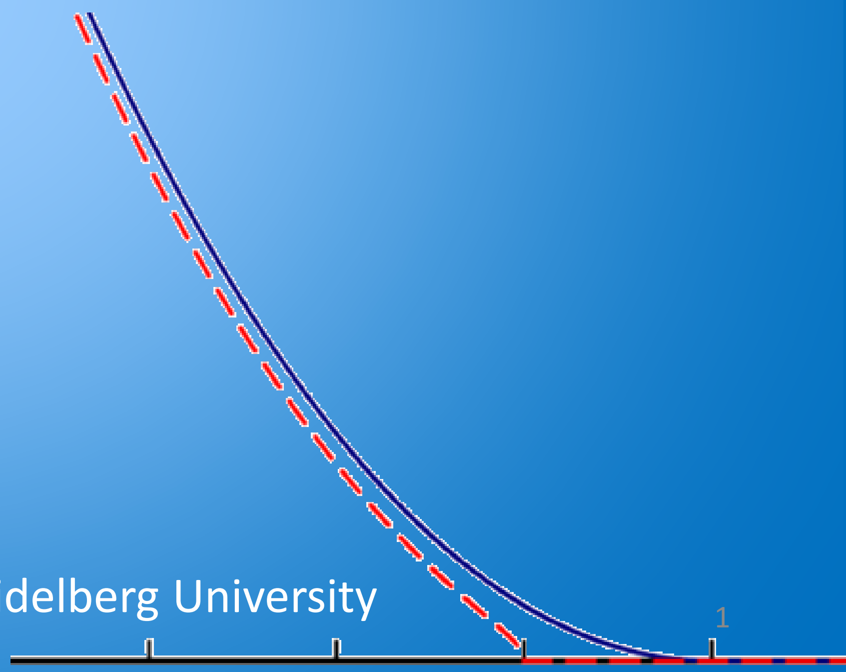
Electron neutrino mass determination using ^{163}Ho electron capture





Loredana Gastaldo

Kirchhoff Institute for Physics, Heidelberg University

Contents

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

Take-home messages

- Where a finite electron neutrino mass affects the ^{163}Ho EC spectrum
- Experimental methods (advantages and disadvantages)
- International efforts – present status of the experiments
- What else can be learned from the ^{163}Ho EC spectrum

Neutrino mass determination

Cosmology	Neutrinoless Double beta decay	Kinematics of β-decay and electron capture
$M_\nu = \sum m_i$	$m_{\beta\beta} = \left\| \sum_i U_{ei}^2 m_i \right\|$	$m^2(\nu_e) = \sum_i \|U_{ei}\|^2 m^2{}_i$

Cosmology

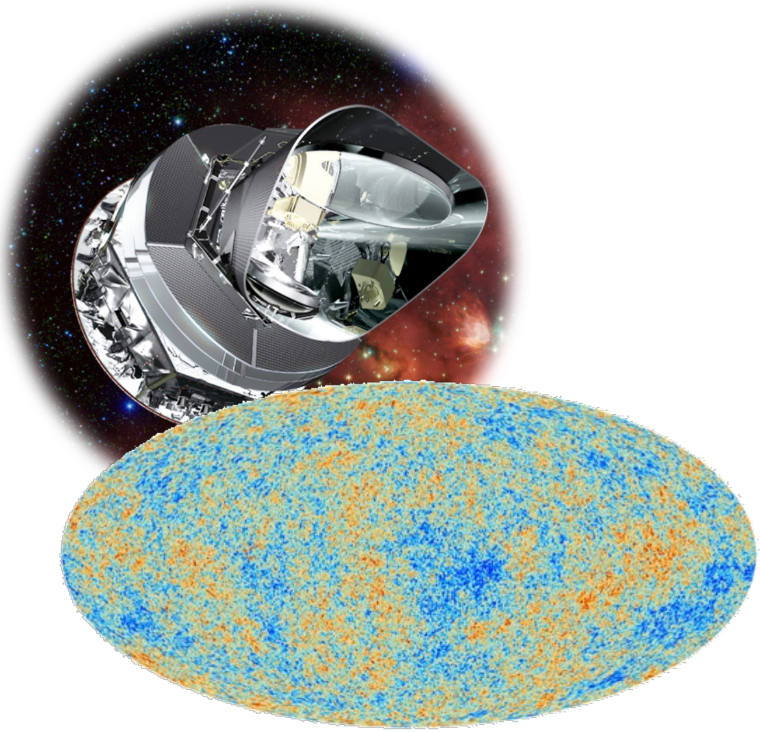
- Model dependent
- Need of satellites
- Present limit 0.12 – 1 eV
- Next future 15-50 meV

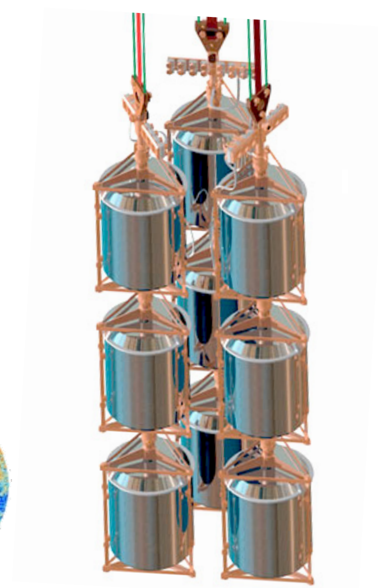
Neutrinoless Double beta decay

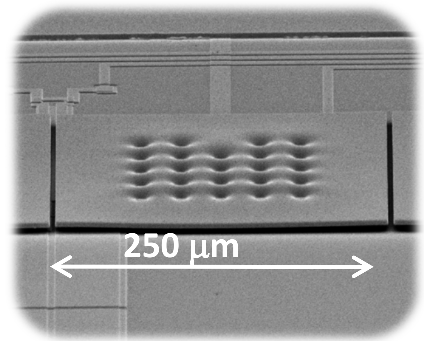
- Model dependent
- Laboratory experiments
- Present limit 0.1 – 0.4 eV
- Next future 15-50 meV

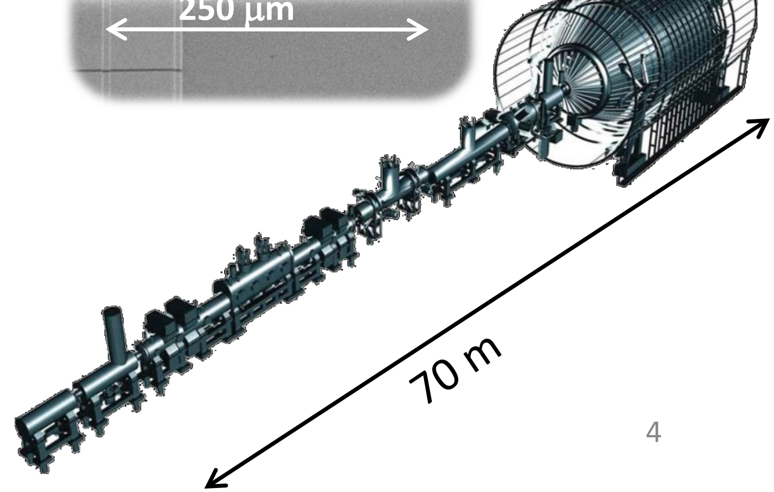
Kinematics of β-decay and electron capture

- Model independent
- Laboratory experiments
- Present limit 2 eV
- Next future 200 meV









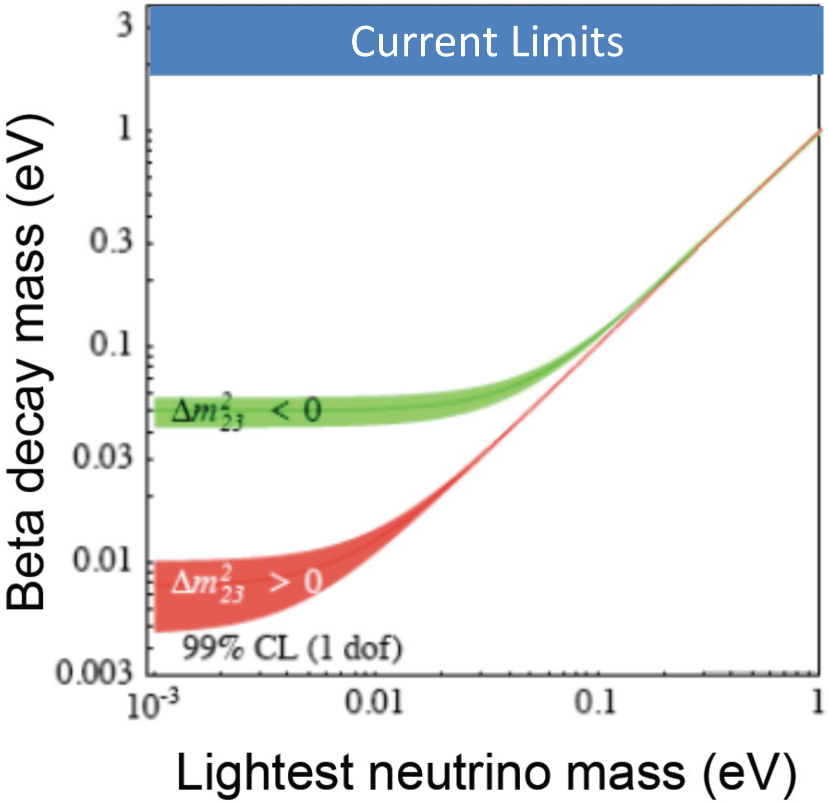
Direct neutrino mass determination

Kinematics of beta decay

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

- Model independent
- Laboratory experiments

$m(\overline{\nu}_e) < 2\ eV$ ^3H (1)



(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447
N. Aseev *et al.*, Phys. Rev D **84** (2011) 112003

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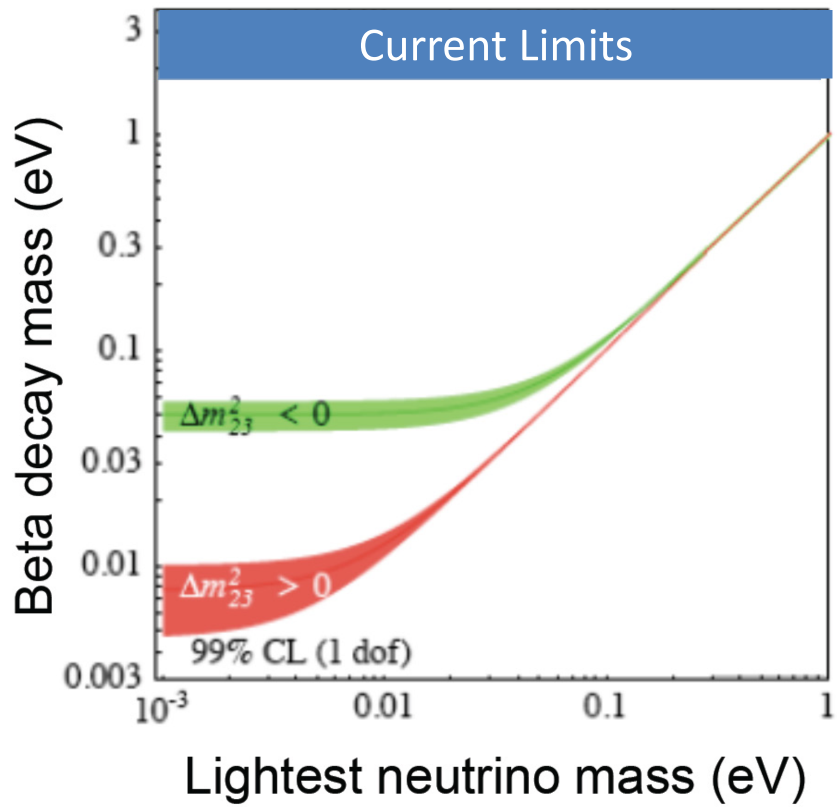
$$m(\bar{\nu}_e) < 2\ eV$$ ^3H (1)

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



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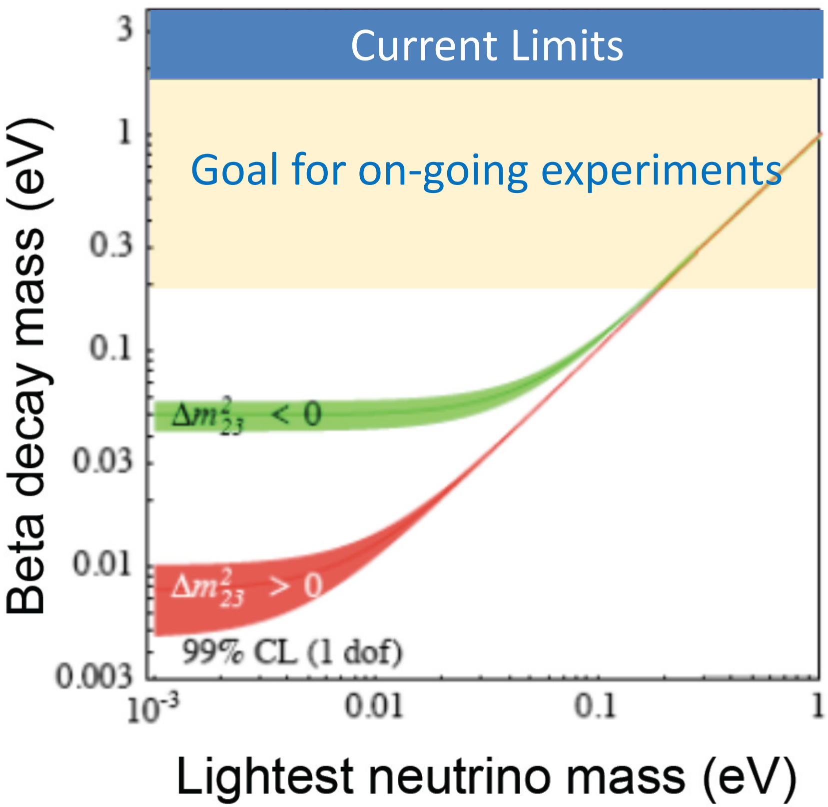
- **Next future 200 meV**



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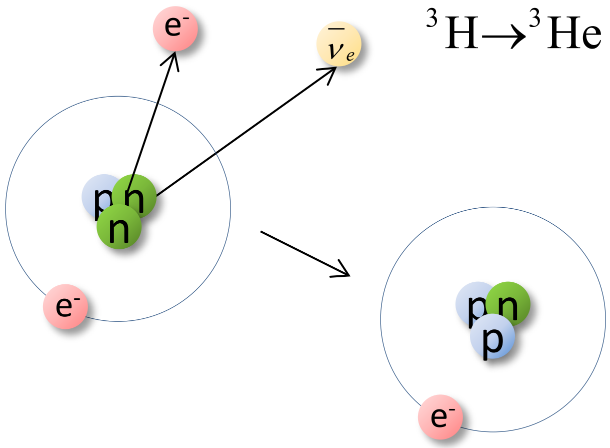
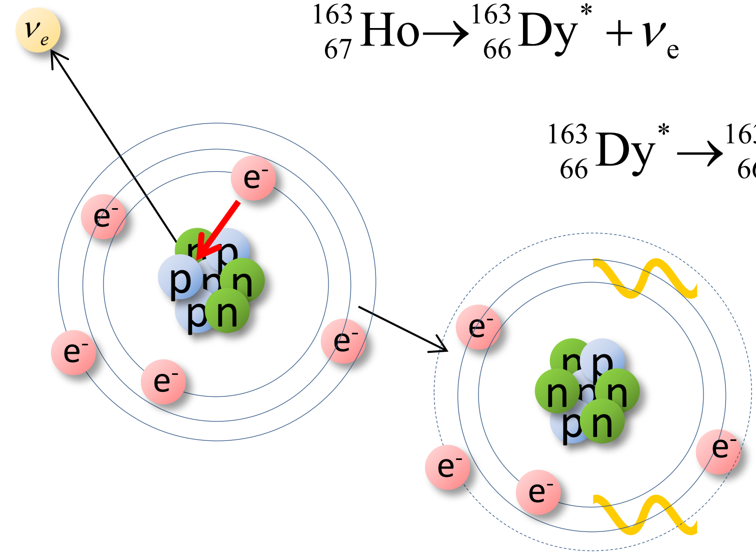
Beta decay and electron capture



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



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

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

- $\tau_{1/2} \cong 12.3$ 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)
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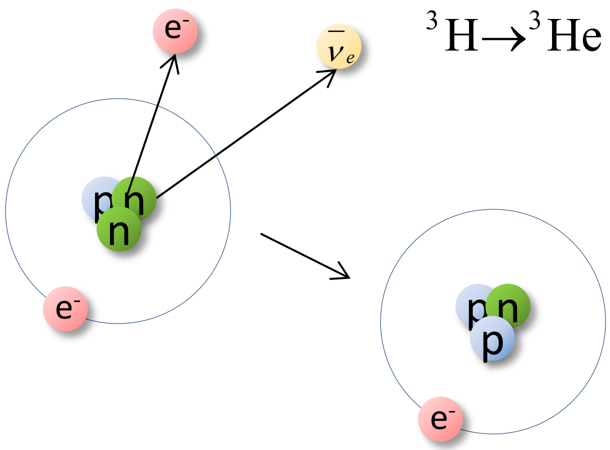
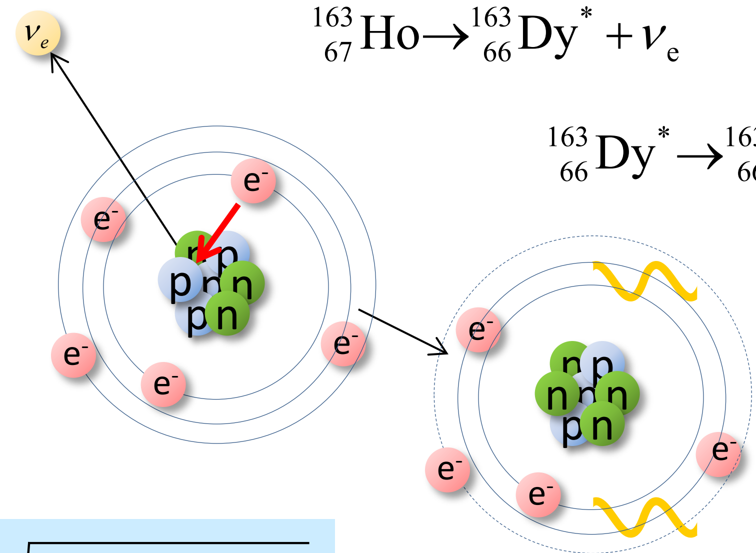
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Talk by Igor Tkachev

Beta decay and electron capture



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



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

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

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

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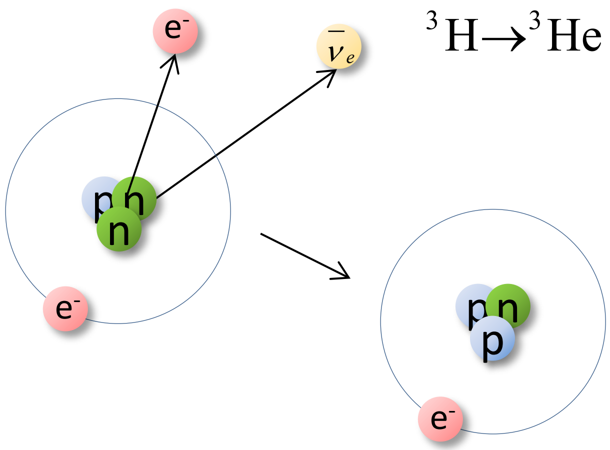
Beta decay of ^{3}H



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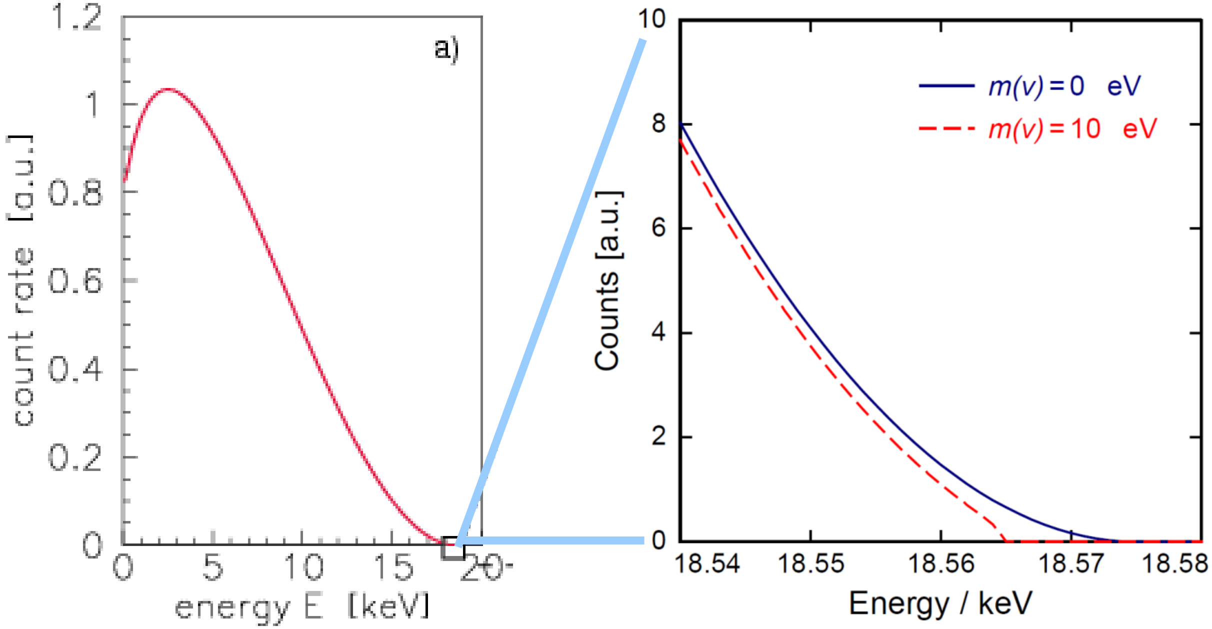

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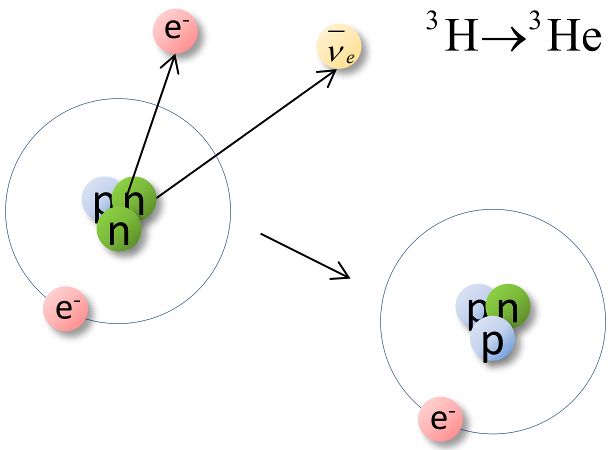

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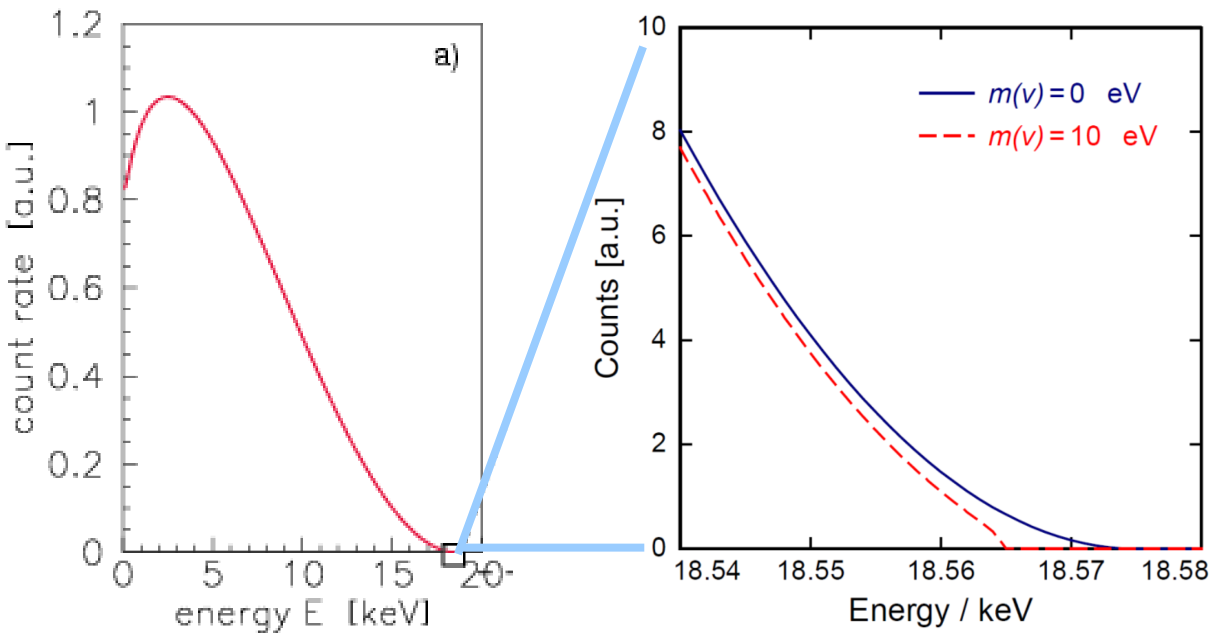
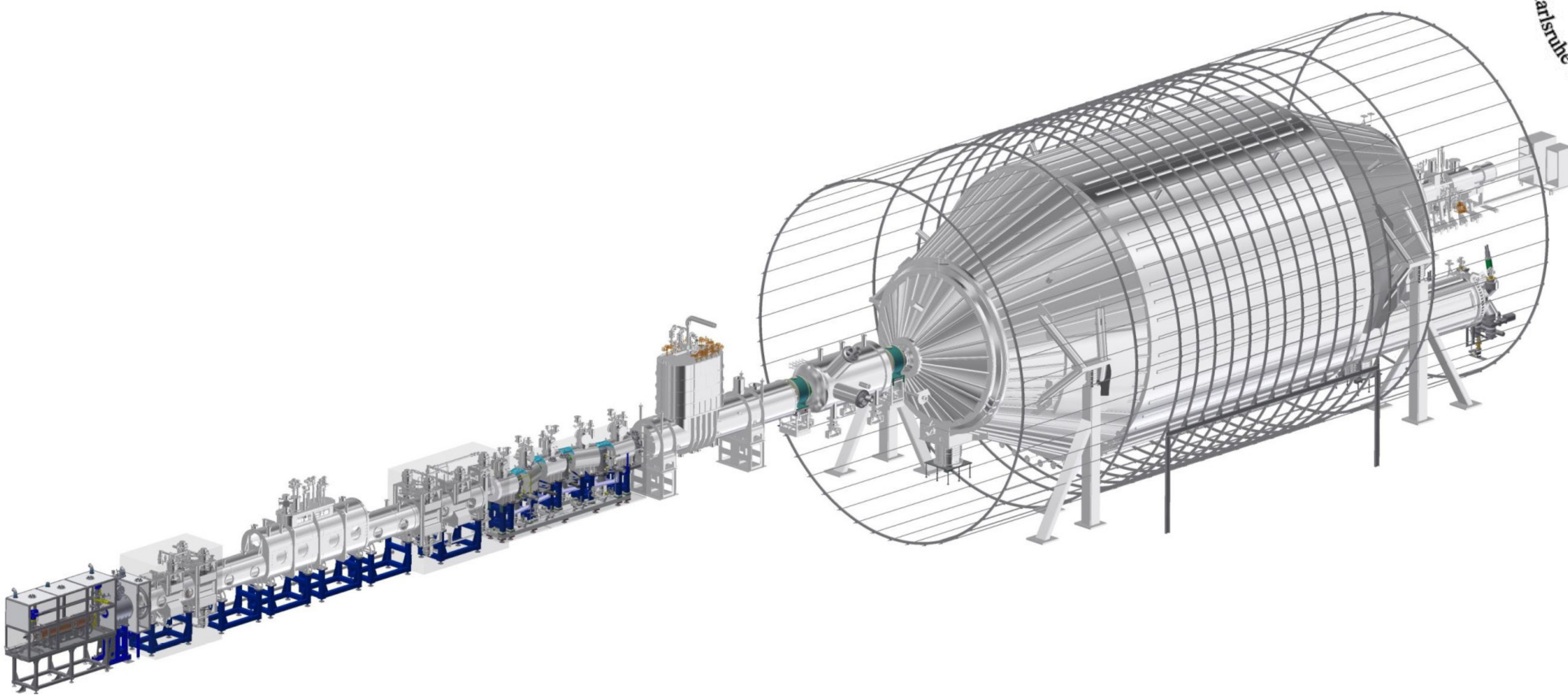


Only a small fraction of events in the last eV below the endpoint: **$2 * 10^{-13}$**

Very low background is required

The KATRIN experiment

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

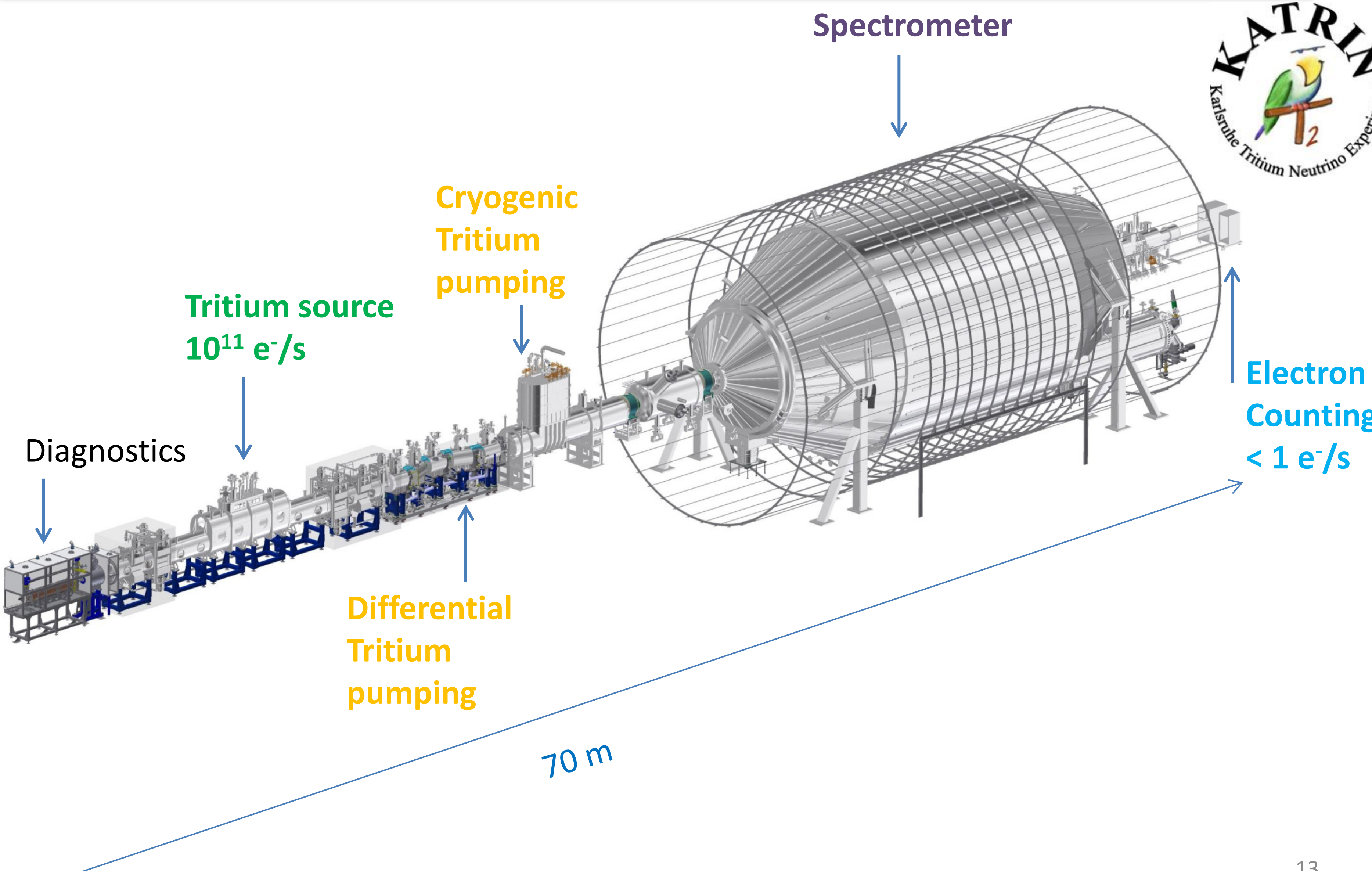


Main ideas:

- 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

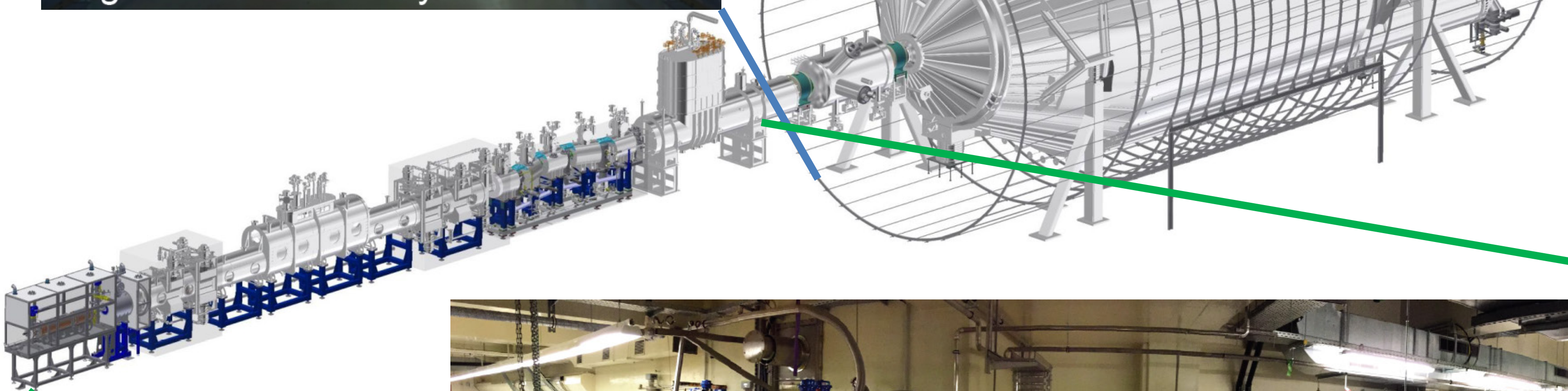


Photo K. Valerius

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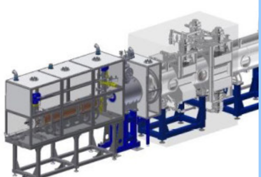
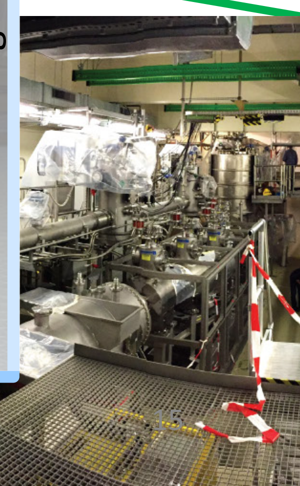




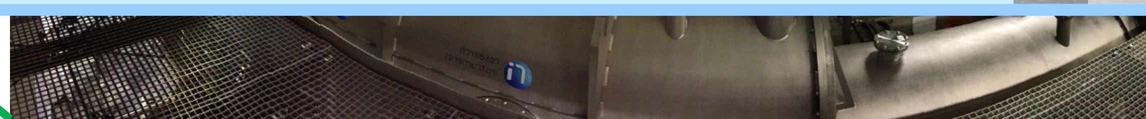


Photo K. Valerius

^{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:

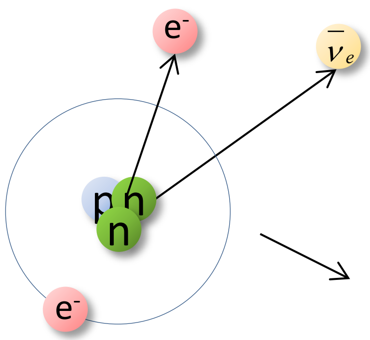
- Source = detector: $10^{11} – 10^{13}$ $^{3}H_2$ molecules /cm^{3}
- Use cyclotron frequency to extract electron energy
- Differential spectrum

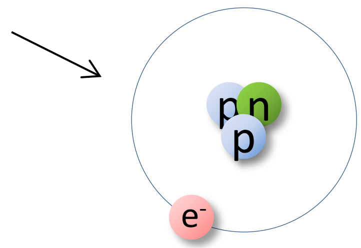
❖ PTOLEMY - Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

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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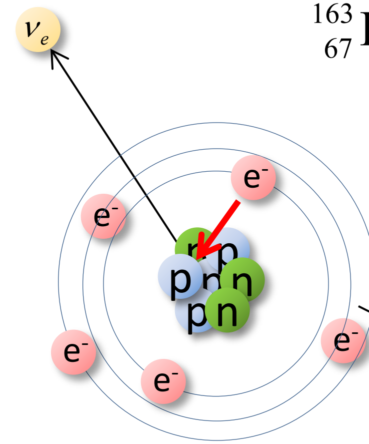

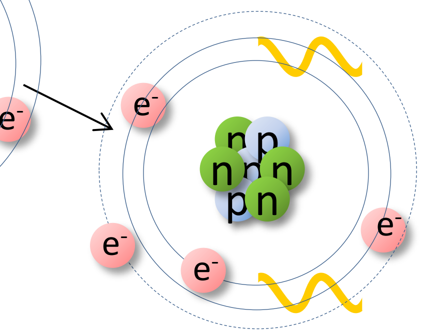

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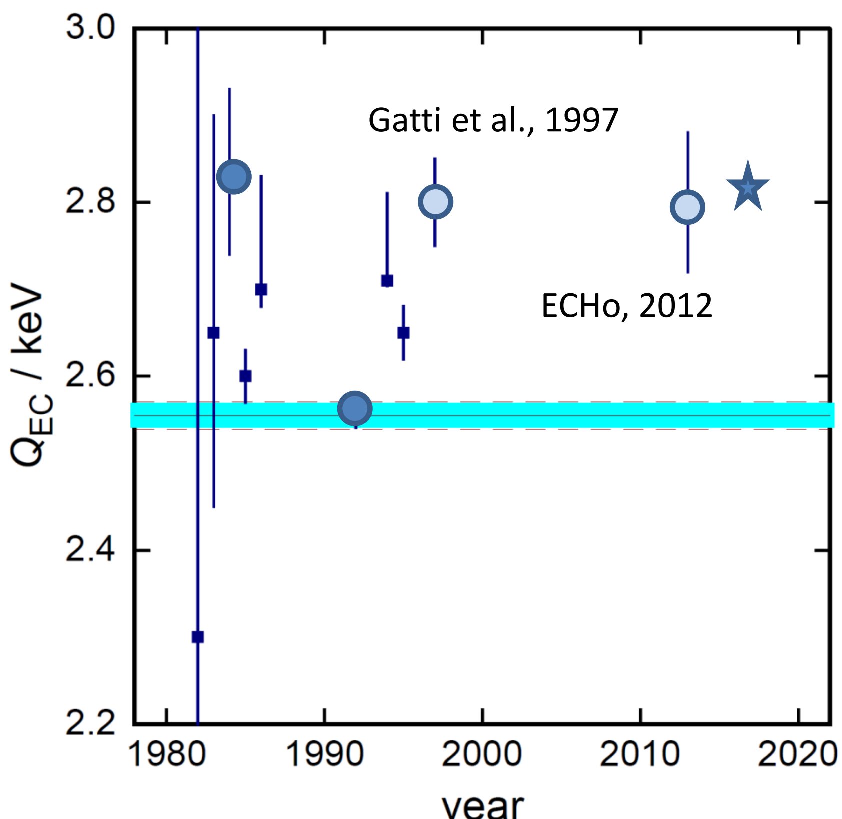
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

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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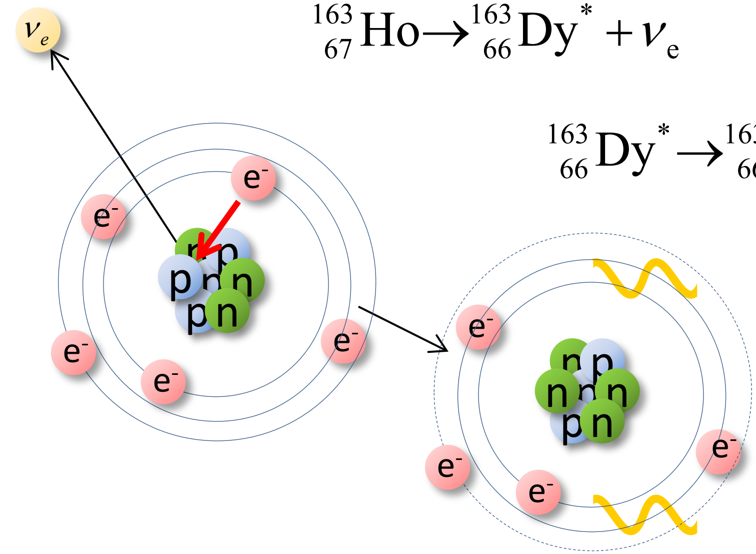

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  Penning Trap Mass Spectroscopy

  @TRIGA TRAP (Uni-Mainz) (*)

  @SHIPTRAP (GSI – Darmstadt) (**)

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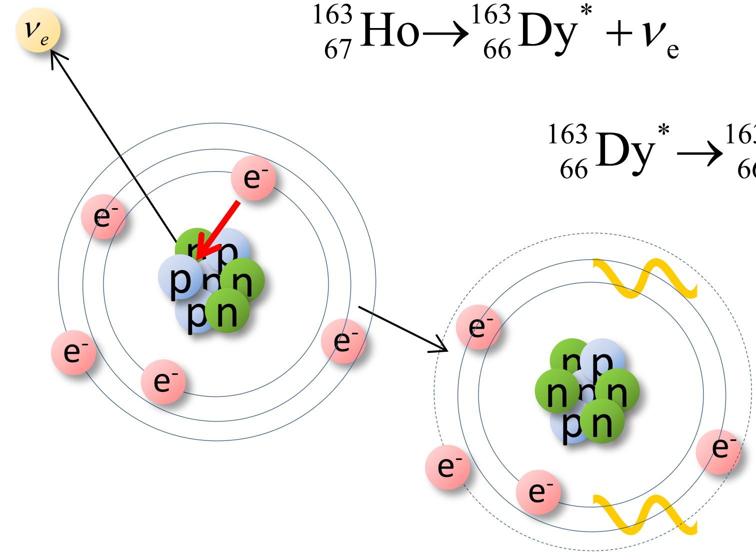
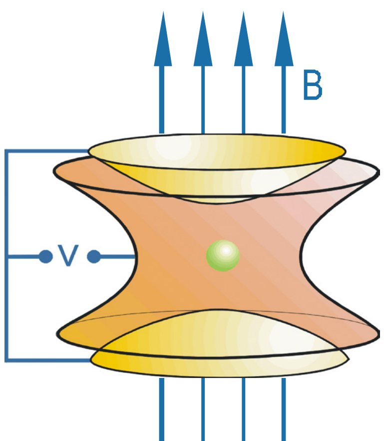
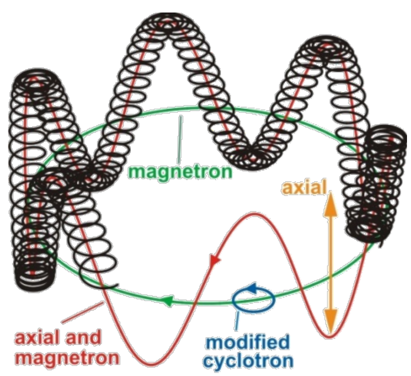


$$\nu_c = \frac{qB}{m}$$





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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: spectrum

Atomic de-excitation:

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

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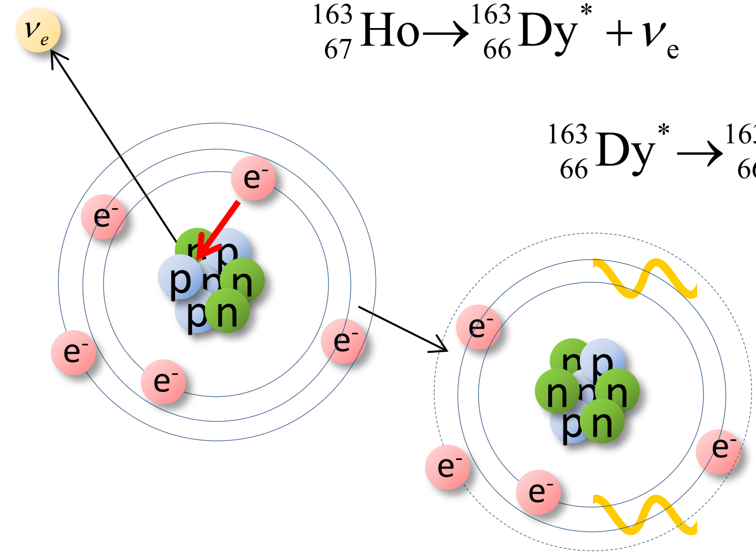

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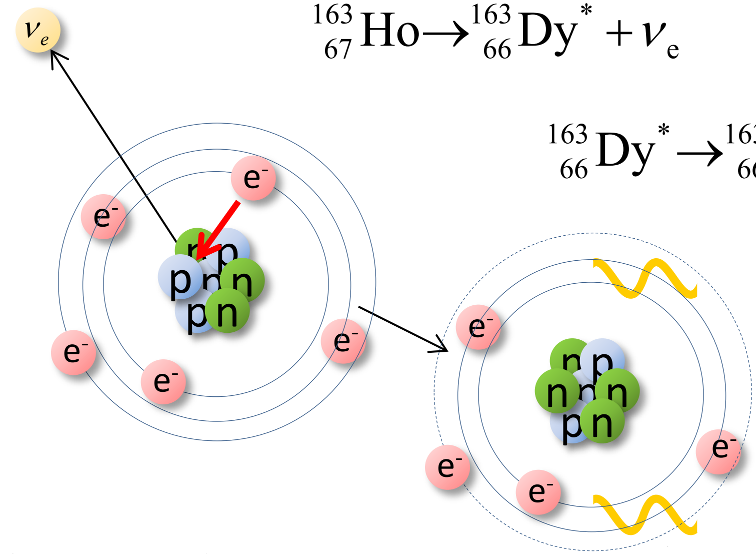

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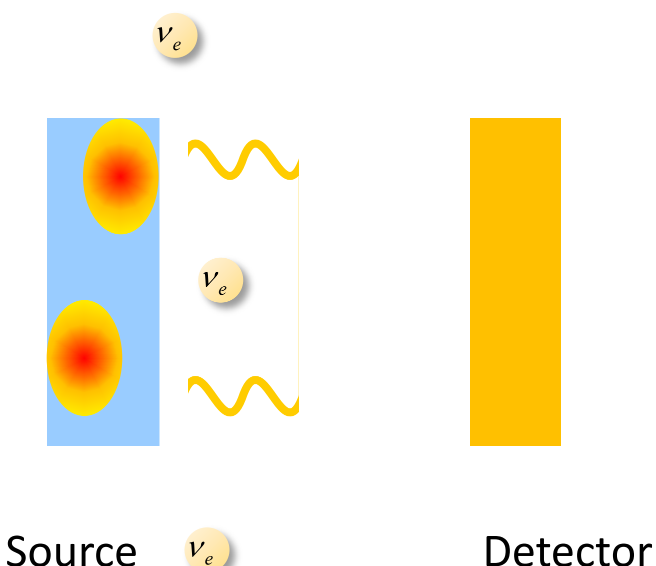

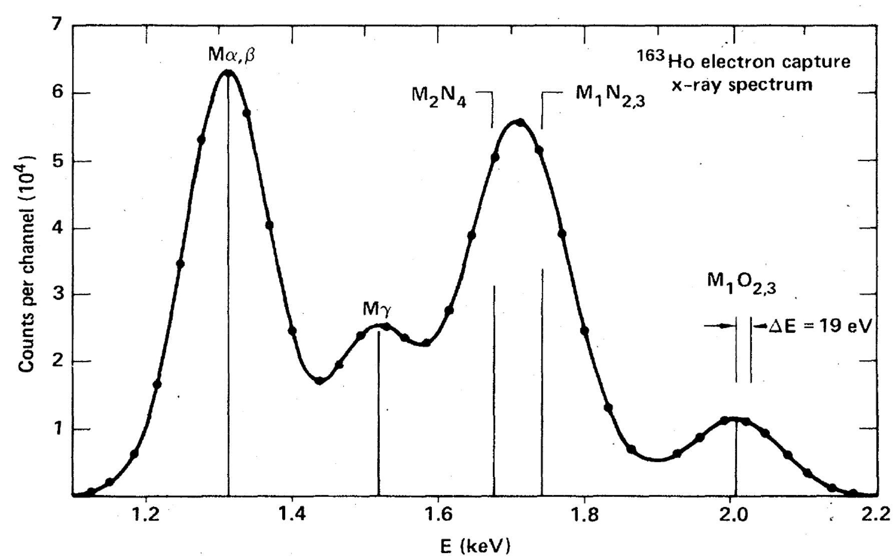

P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

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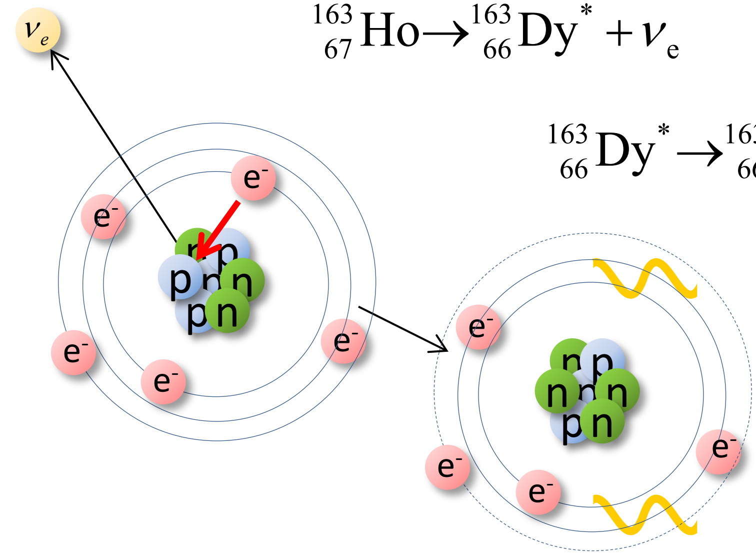
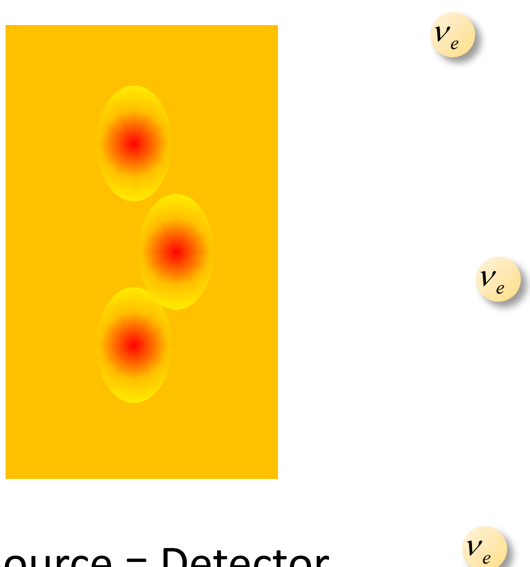


Calorimetric measurement



Source = Detector

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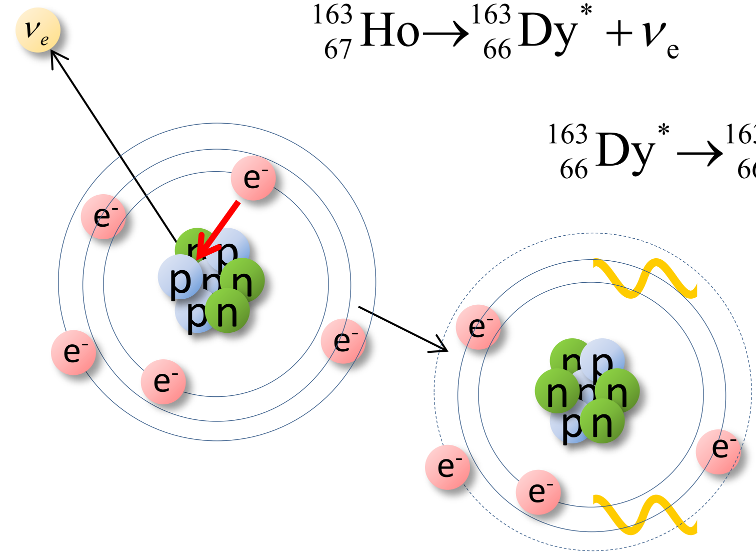

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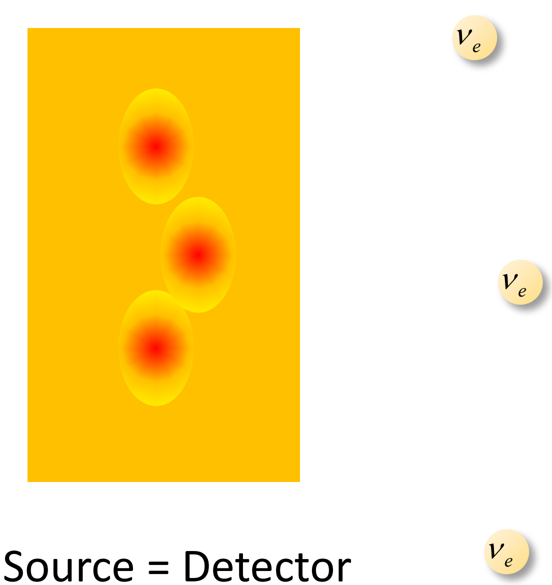

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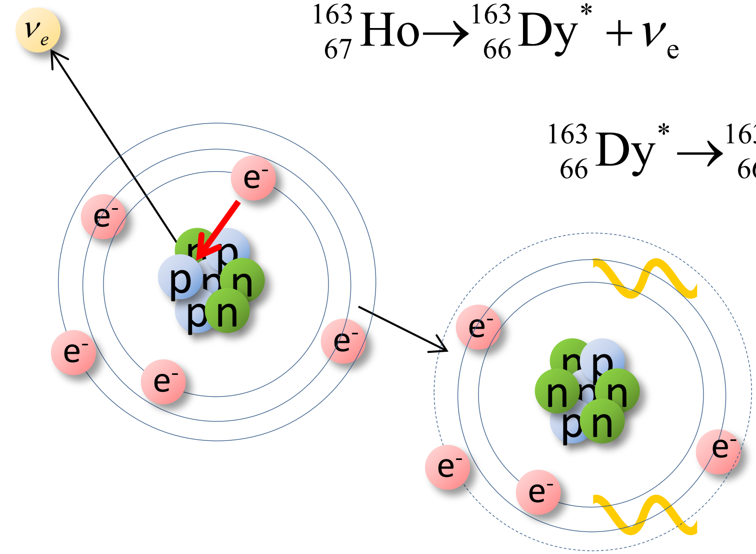

Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

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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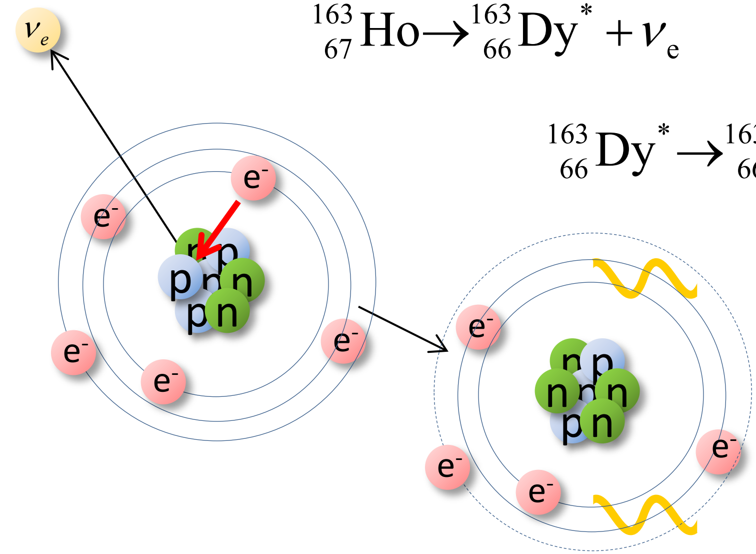
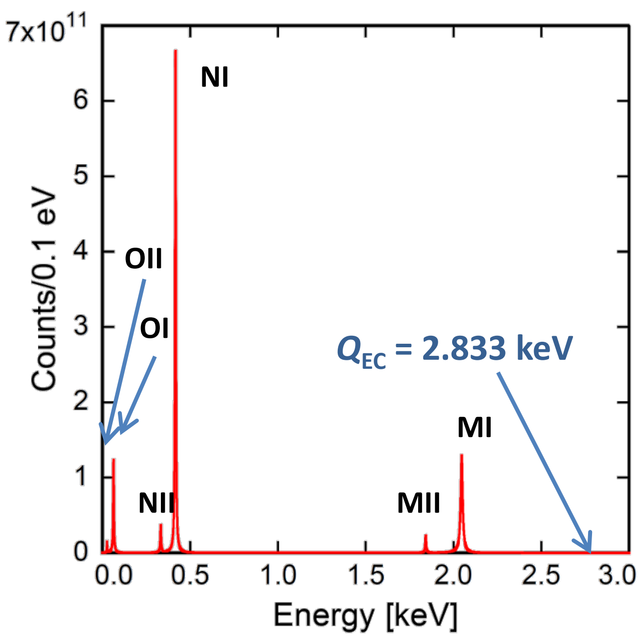


Calorimetric measurement



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

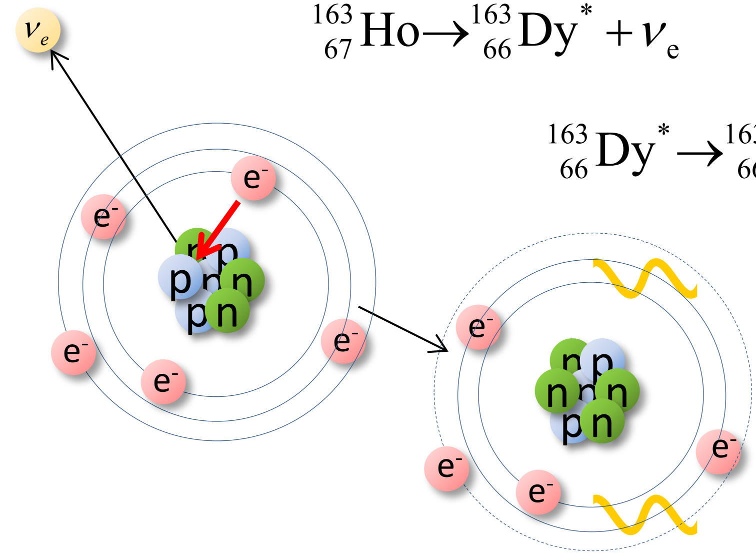
Electron capture in ^{163}Ho: spectrum

Atomic de-excitation:

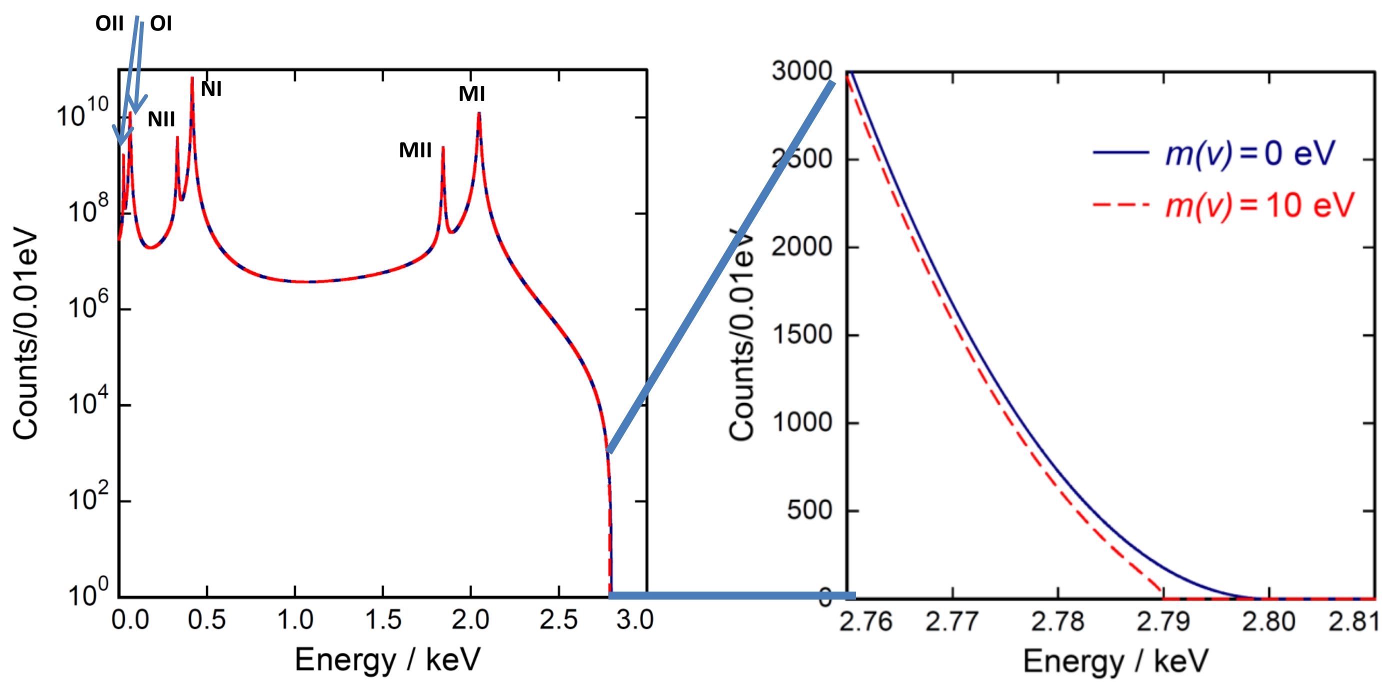
- **X-ray emission**
- **Auger electrons**
- **Coster-Kronig transitions**

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

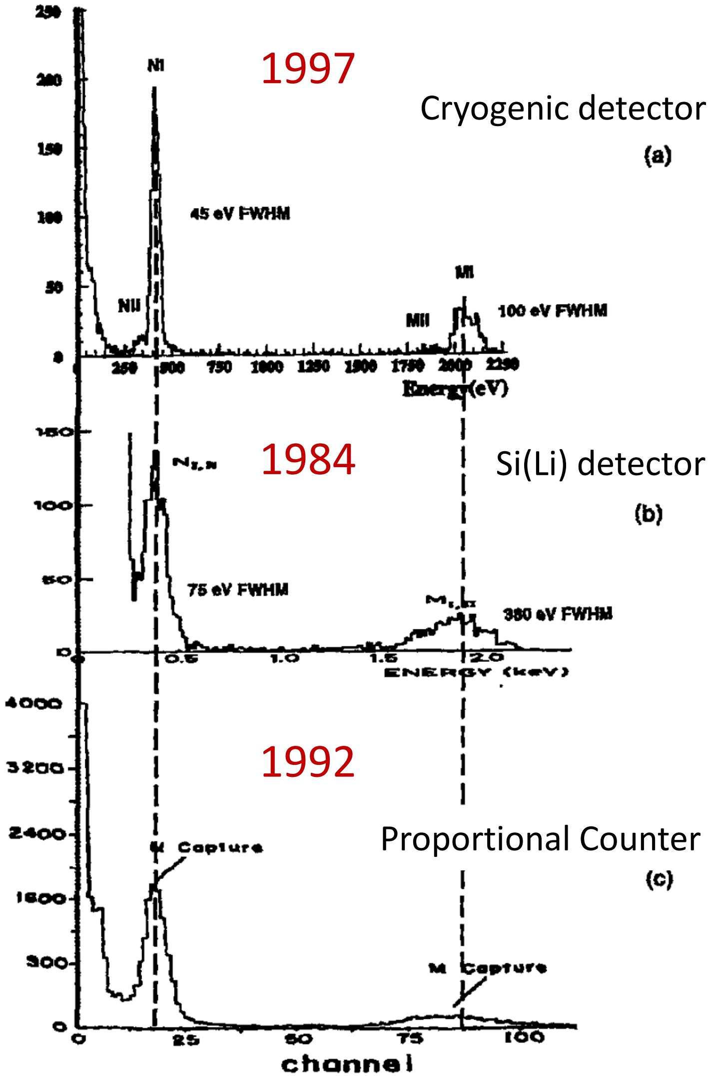
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$



Calorimetric measurement



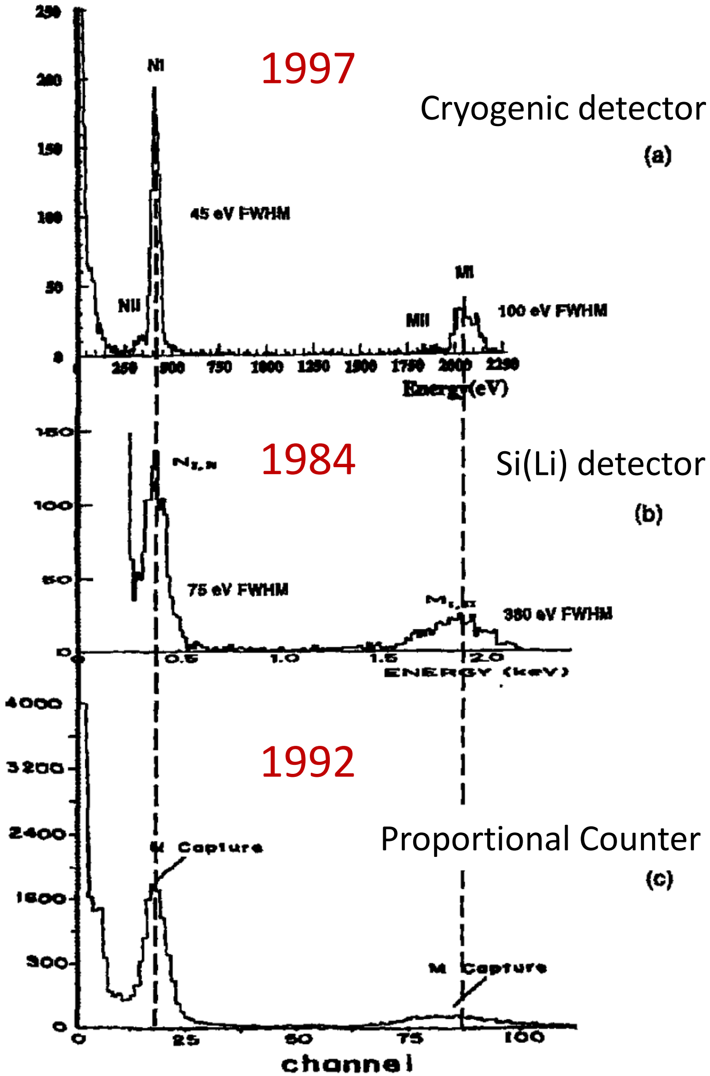
Electron capture in ^{163}Ho: history



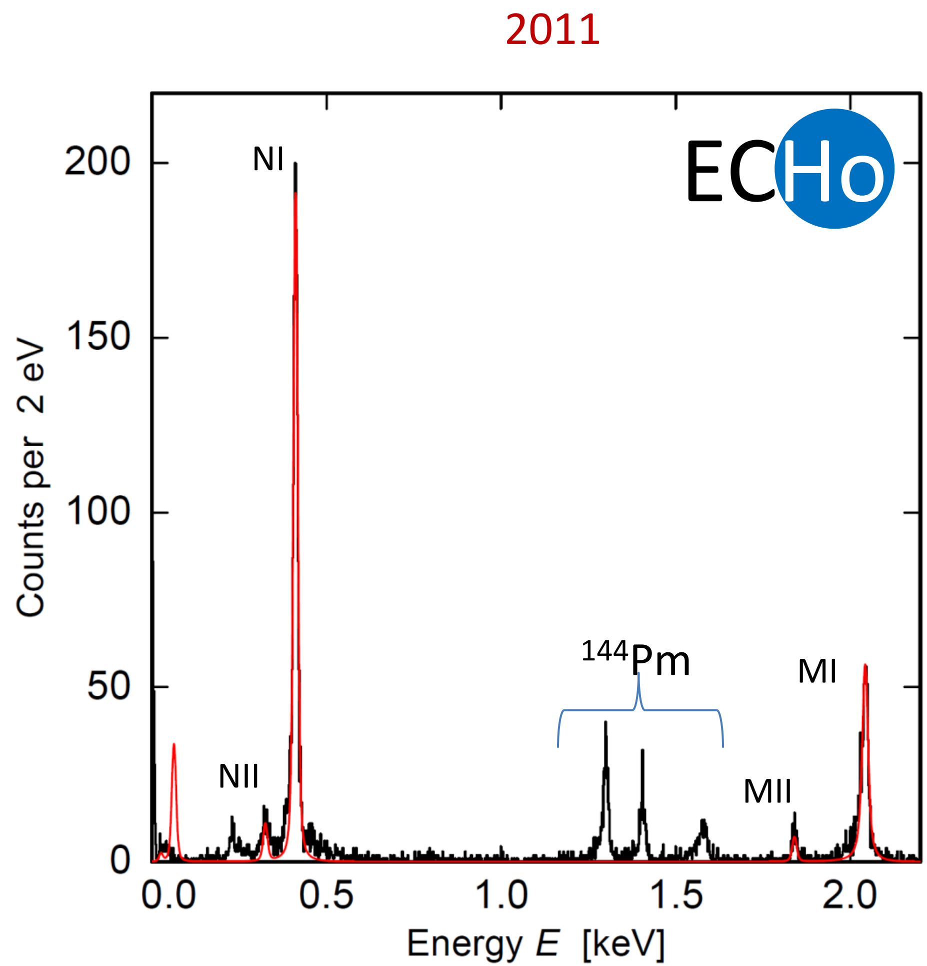
F. Gatti et al., Physics Letters B 398 (1997) 415-419

(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: history



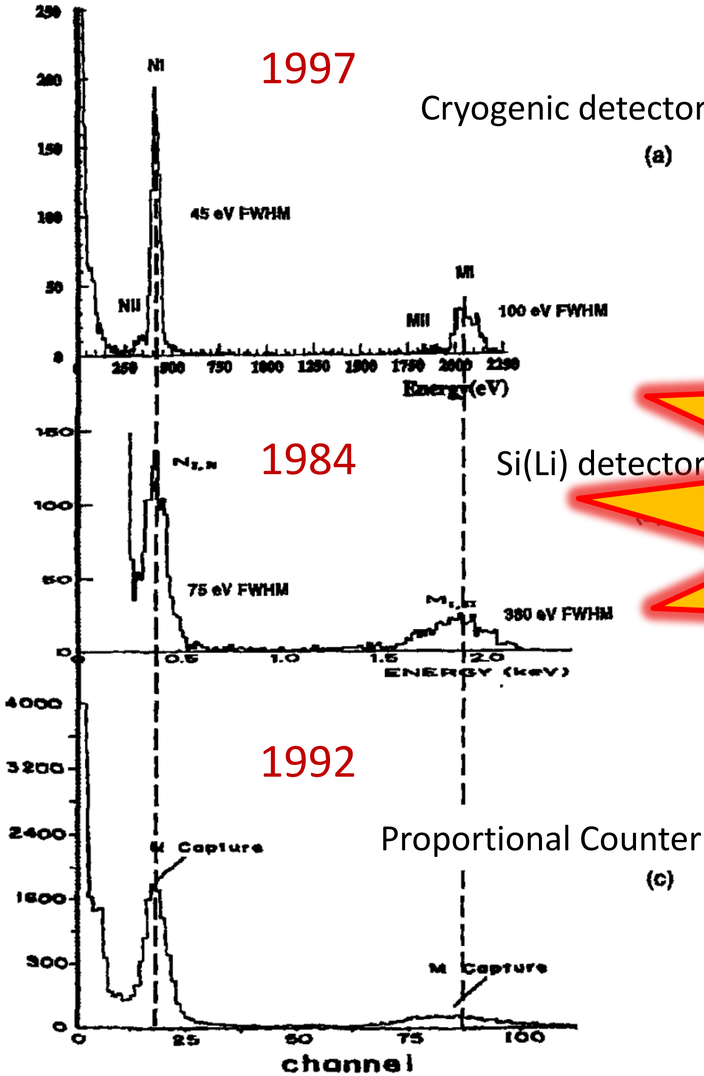
F. Gatti et al., Physics Letters B 398 (1997) 415-419



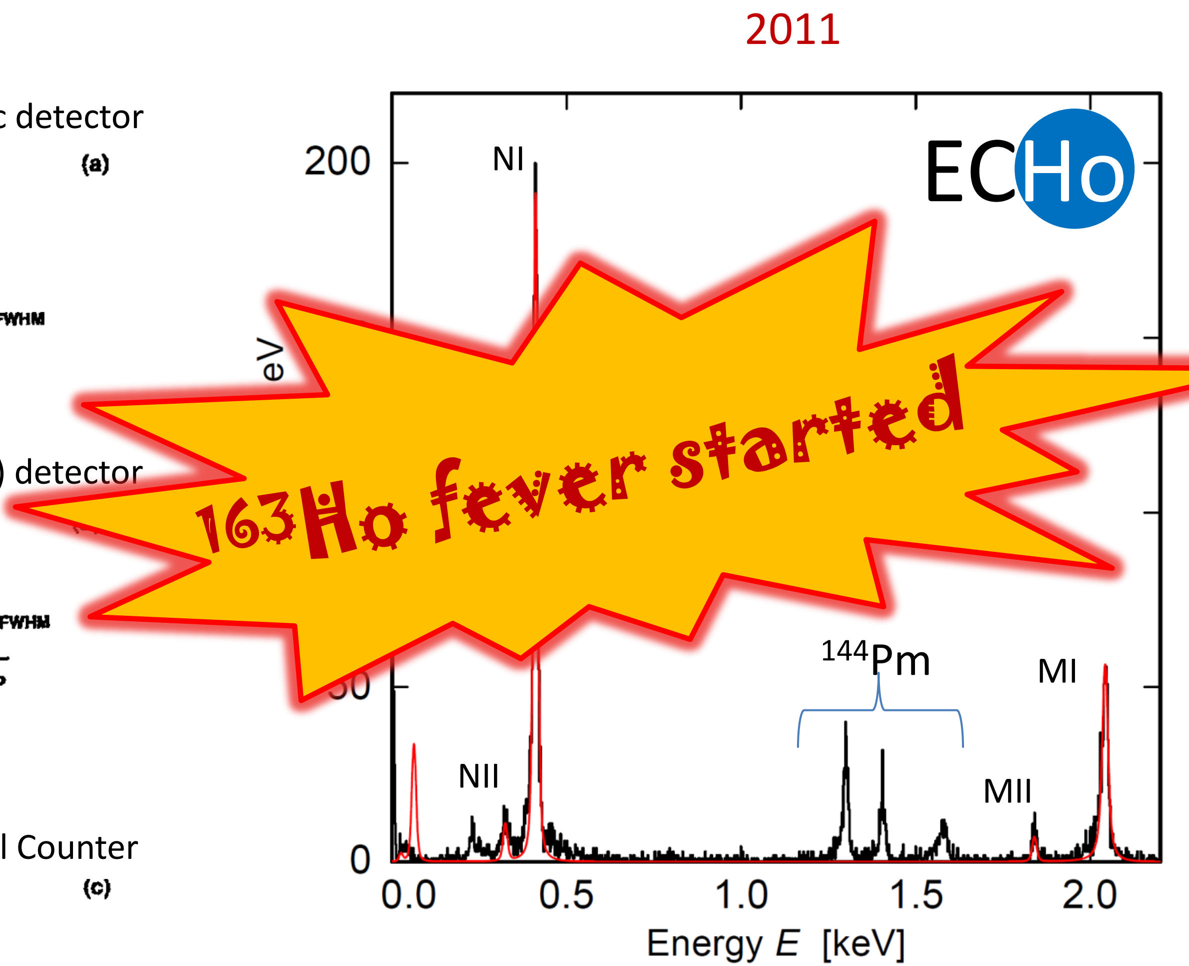
P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)

(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: history



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



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

(a) F. Gatti et al., Physics Letters B 398 (1997) 415-419
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(c) F.X. Hartmann and R.A. Naumann, Nucl. Instr. Meth. A 3 13 (1992) 237.

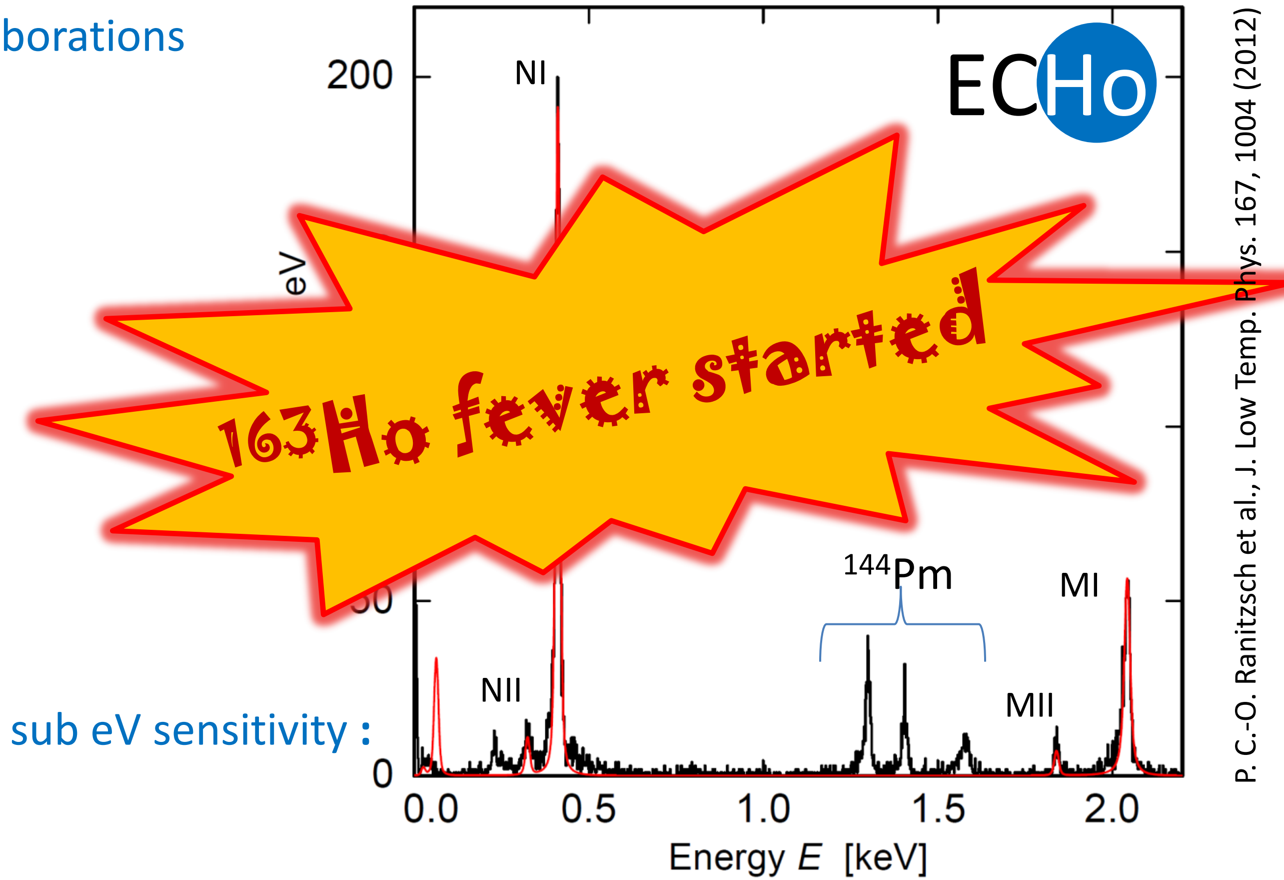
Electron capture in ^{163}Ho: present

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

ECHo (1)

HOLMES (2)

NuMECS (3)



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

Common challenges to reach sub eV sensitivity :

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

(1) The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

(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

Requirements for sub-eV sensitivity in ECHo

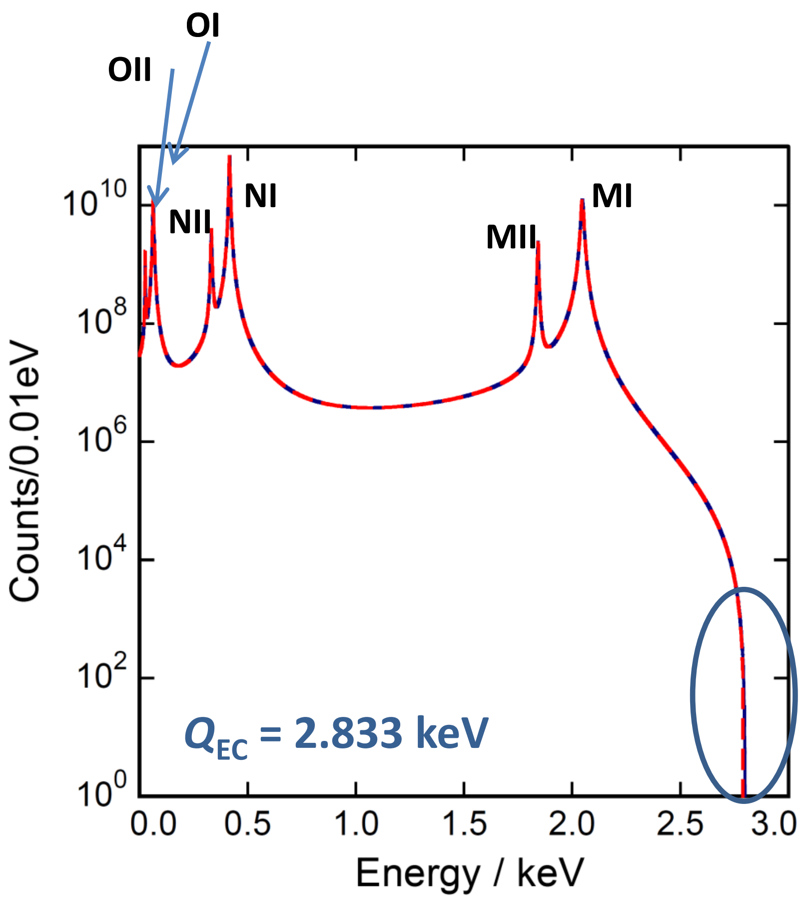
Requirements for sub-eV sensitivity in ECHo

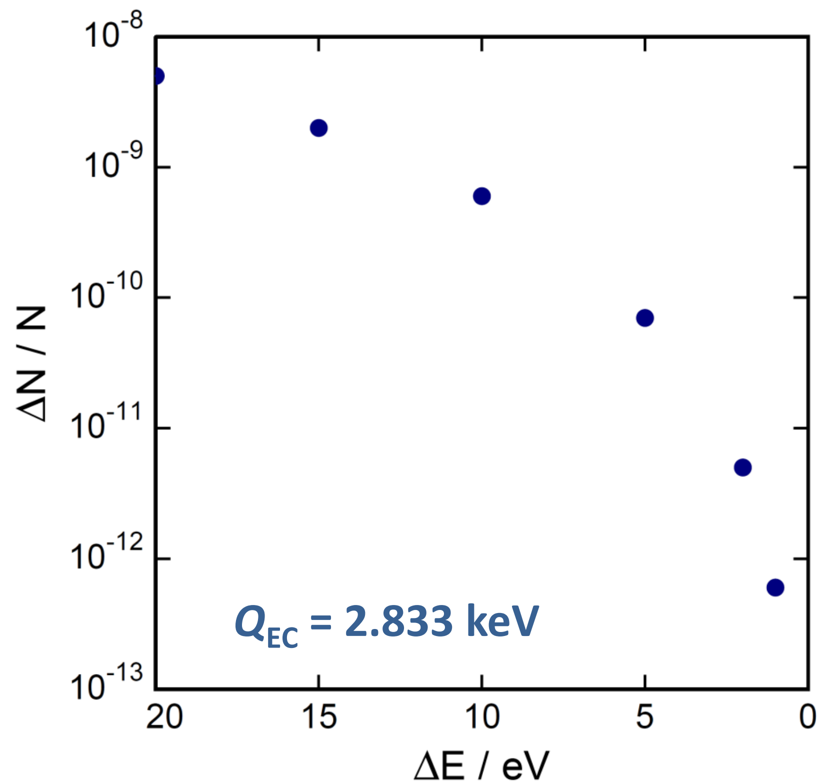
Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Fraction of events at endpoint regions

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





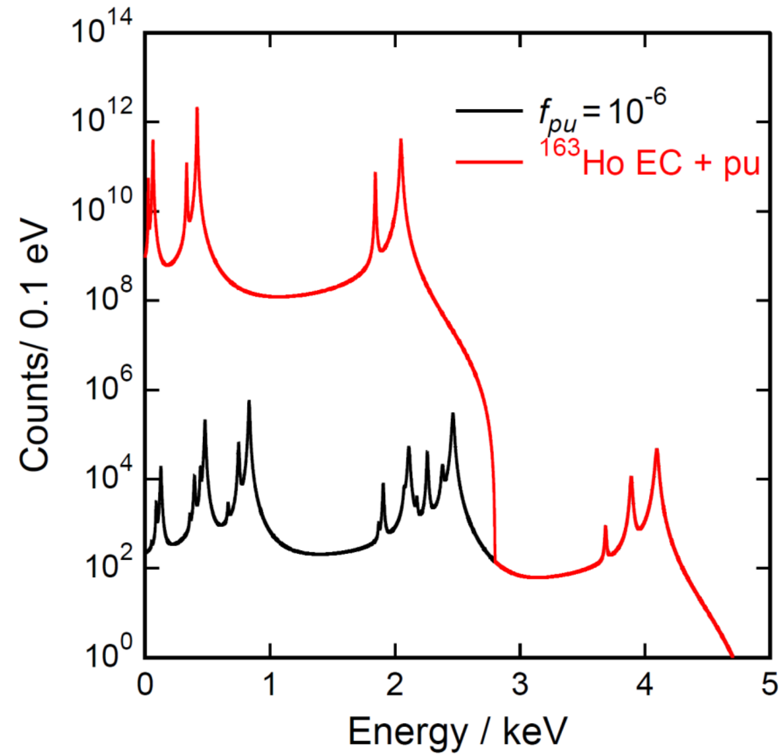
Requirements for sub-eV sensitivity in ECHo

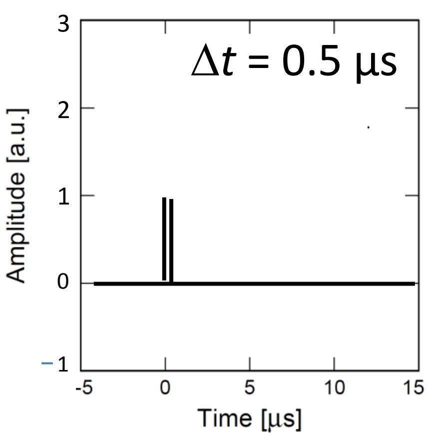
Statistics in the end point region

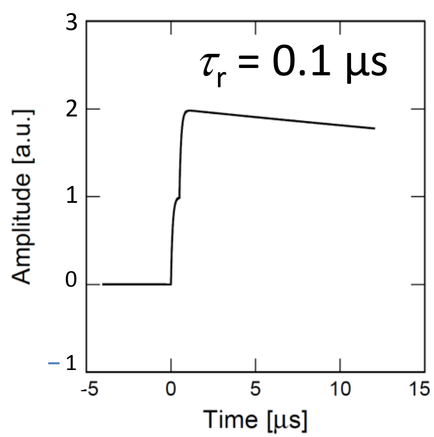
- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

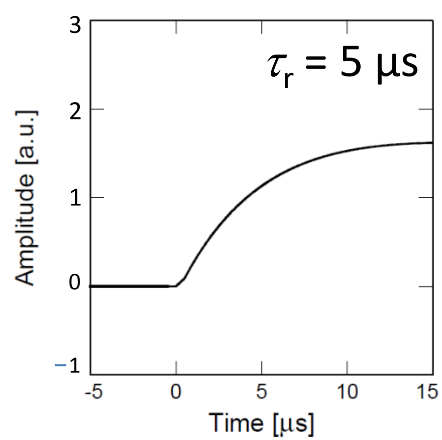
Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

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









Requirements for sub-eV sensitivity in ECHo

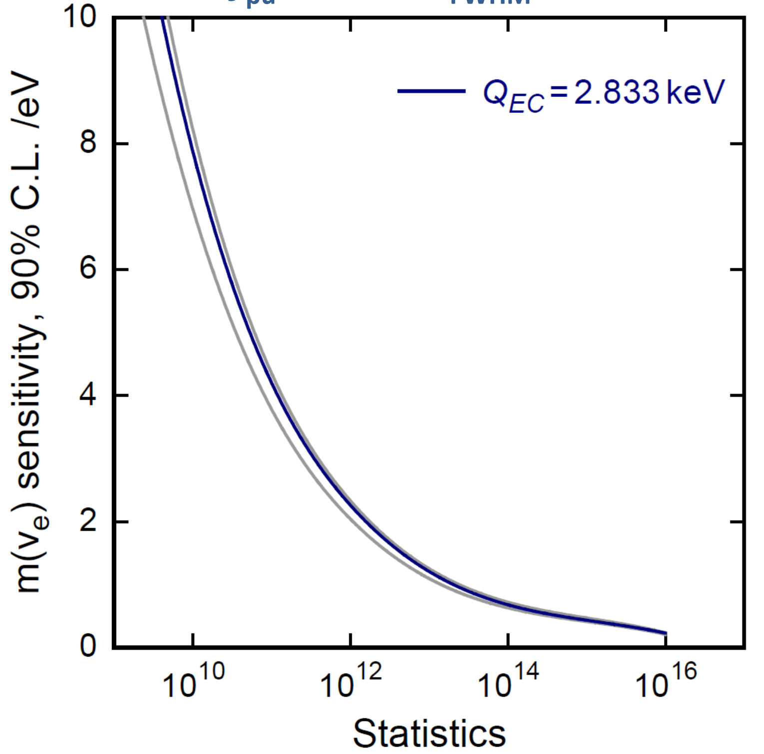
Statistics in the end point region
- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)
- **$f_{pu} < 10^{-5}$**
- $\tau_r < 1$ µs → a ~ 10 Bq
- 10^5 pixels

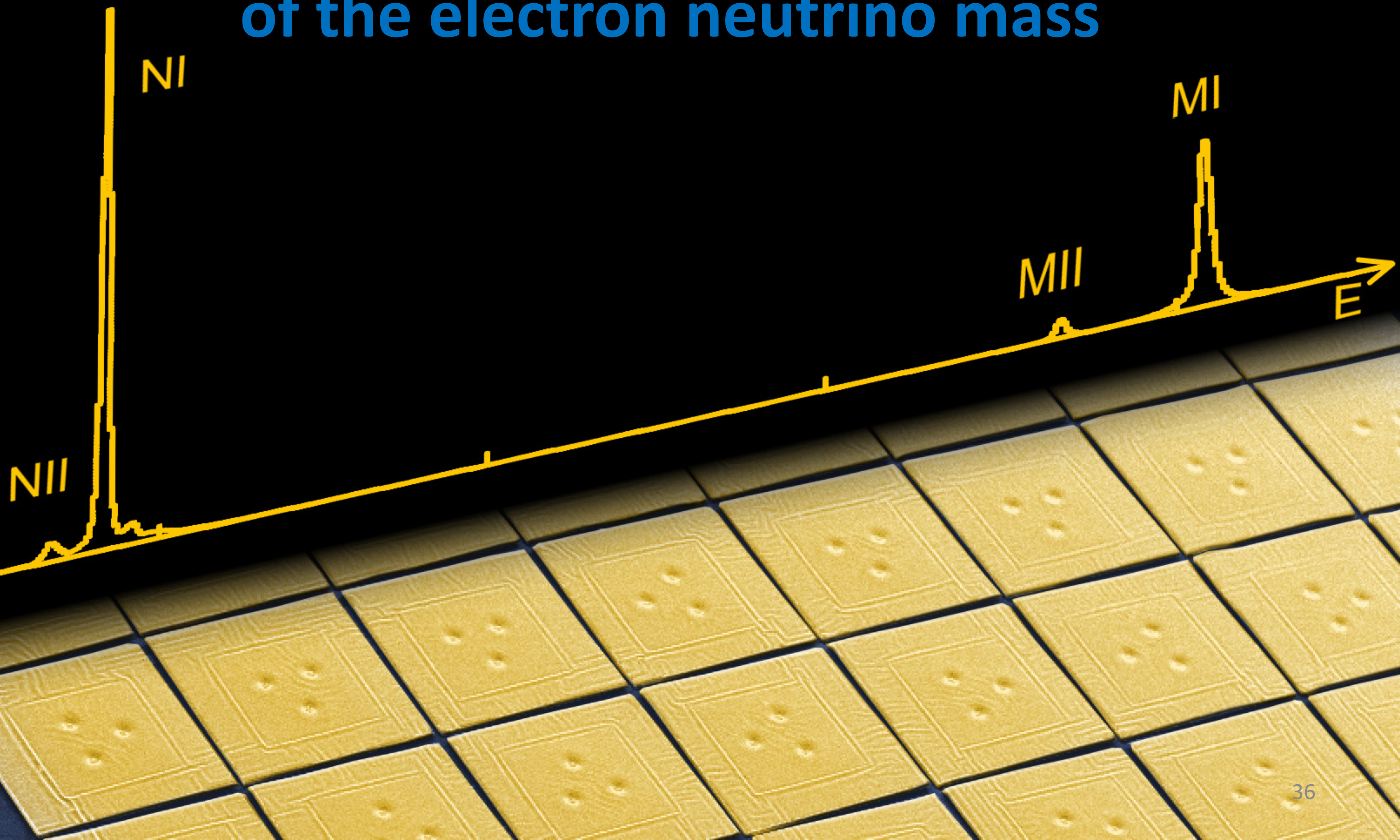
Precision characterization of the endpoint region
- **$\Delta E_{FWHM} < 3$ eV**

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

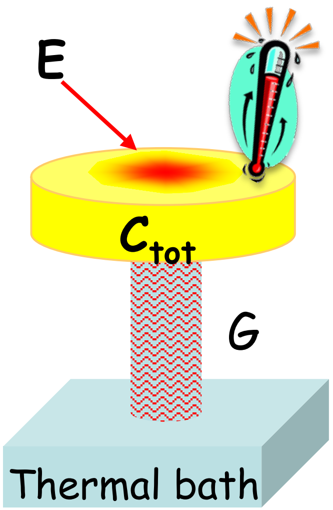
$f_{pu} = 10^{-6}$ $\Delta E_{FWHM} = 2$ eV



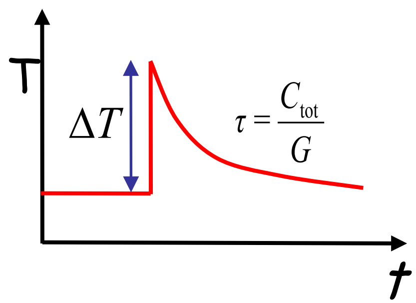
Low temperature detectors for direct determination of the electron neutrino mass



Low temperature micro-calorimeters



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

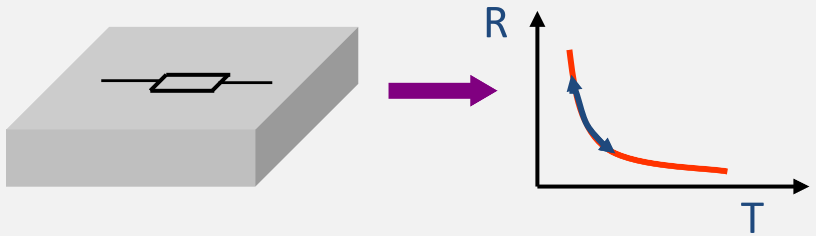


E = 10 keV
C_{tot} = 1 pJ/K
→ ~ 1 mK

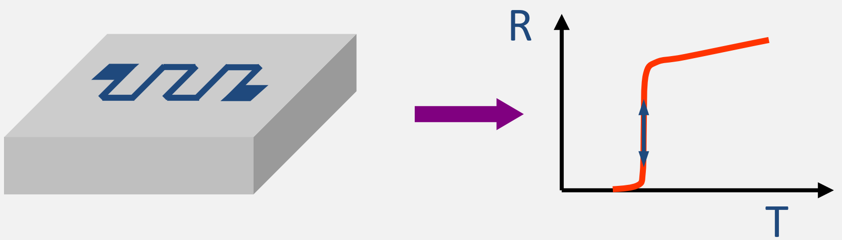
- Very small volume
- Working temperature below 100 mK
  small specific heat
  small thermal noise
- **Very sensitive temperature sensor**

Temperature sensors

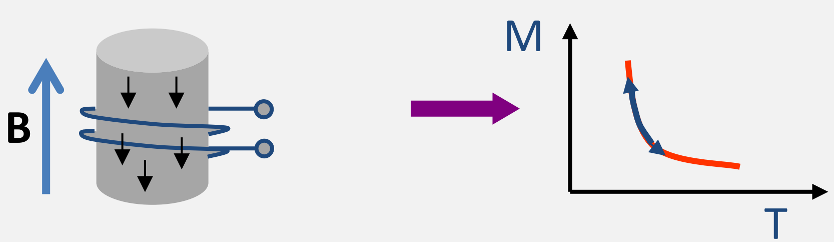
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES

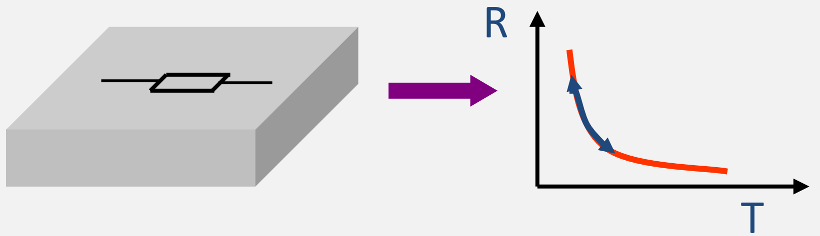


Magnetization of paramagnetic material, MMC



Temperature sensors

Resistance of highly doped semiconductors



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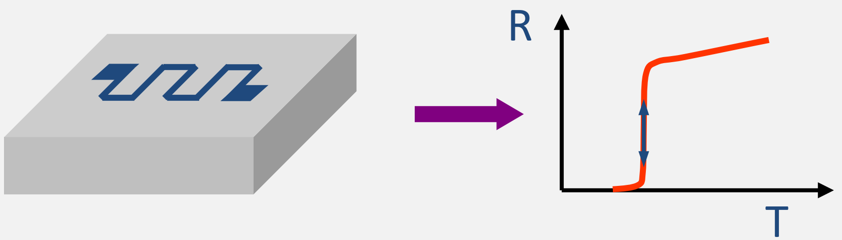
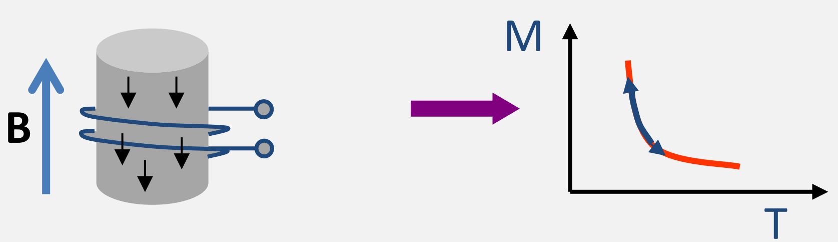


Magnetization of paramagnetic material, MMC



HOLMES

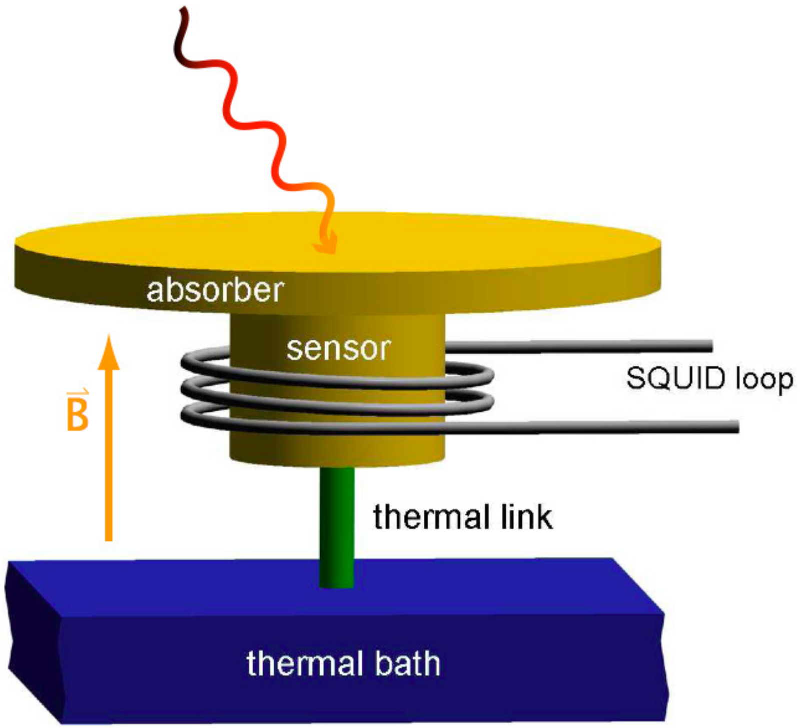
NuMECS

ECHo

Metallic magnetic calorimeters (MMCs)

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

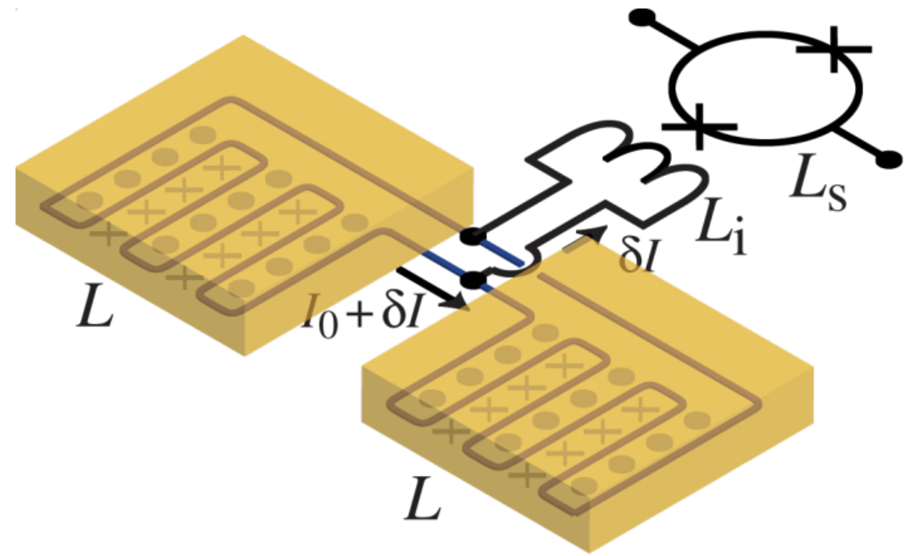
- Paramagnetic Au:Er sensor
  Ag:Er



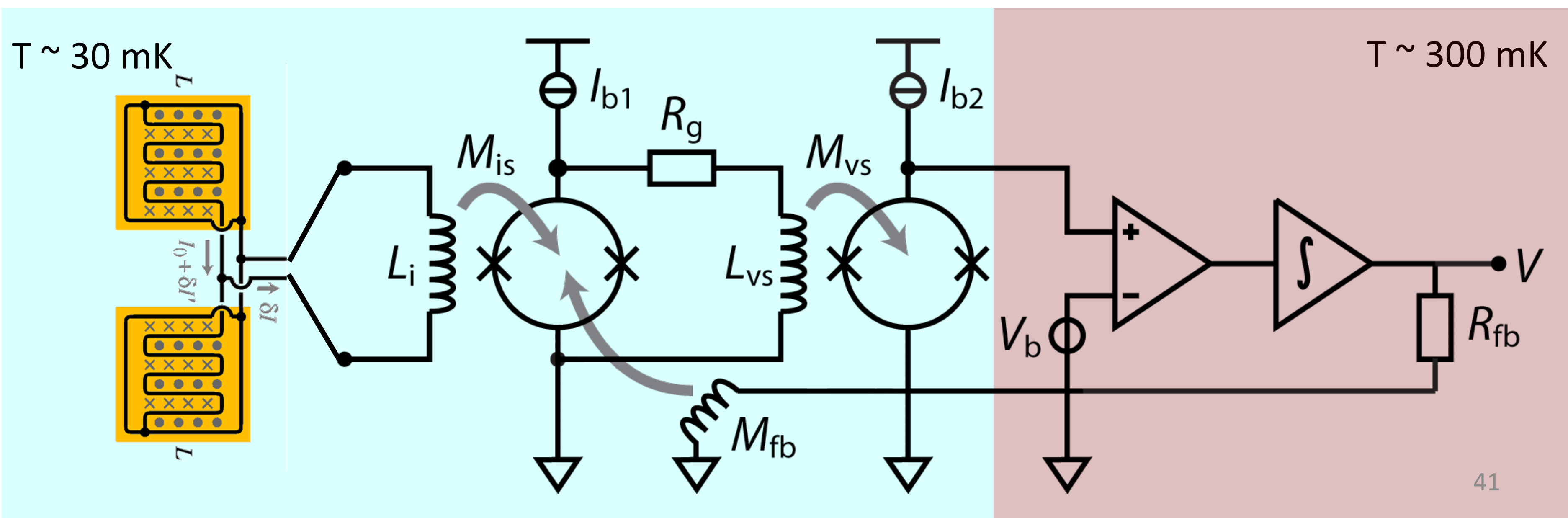
$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\,\frac{E}{C_{sens}+C_{abs}}$$

MMC geometry and read-out

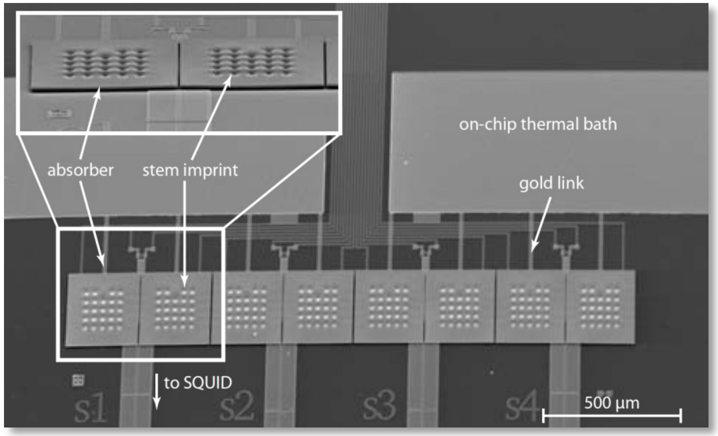
- Planar temperature sensor
- B-field generated by persistent current
- transformer coupled to SQUID

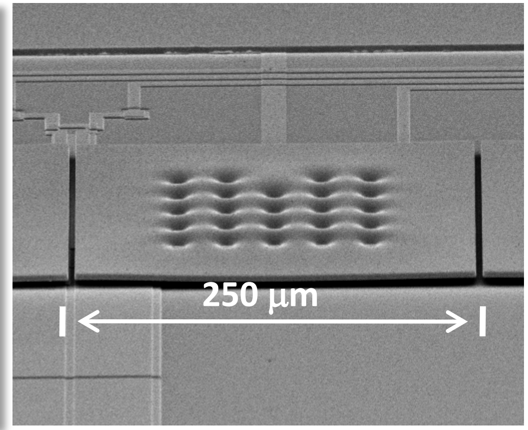


- Two-stage SQUID read-out

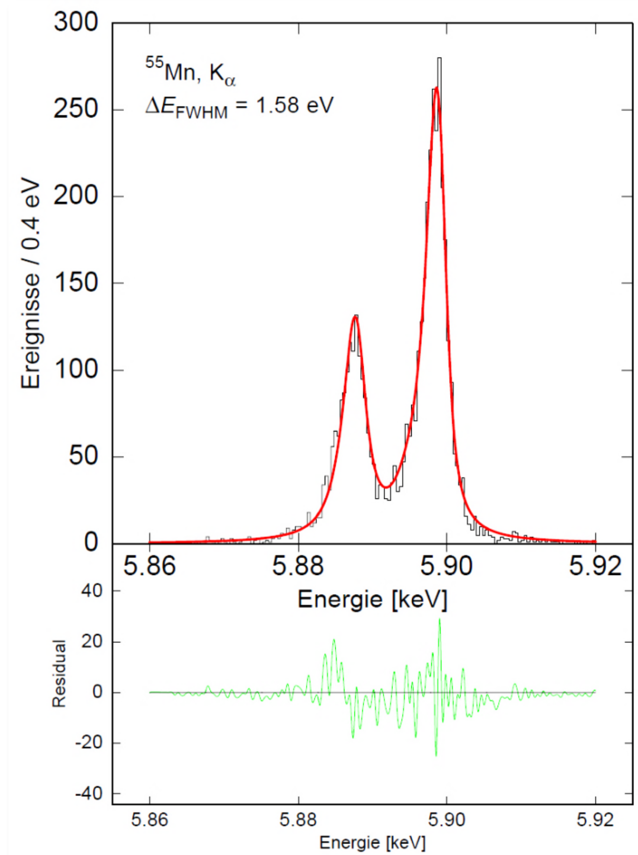


MMCs: 1d-array for soft x-rays (T=20 mK)

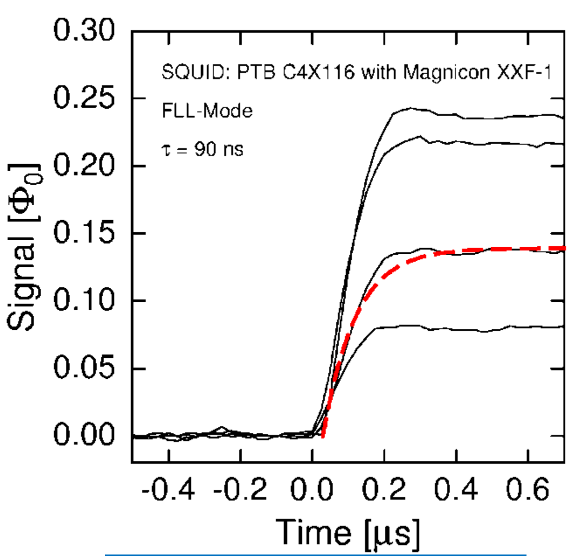




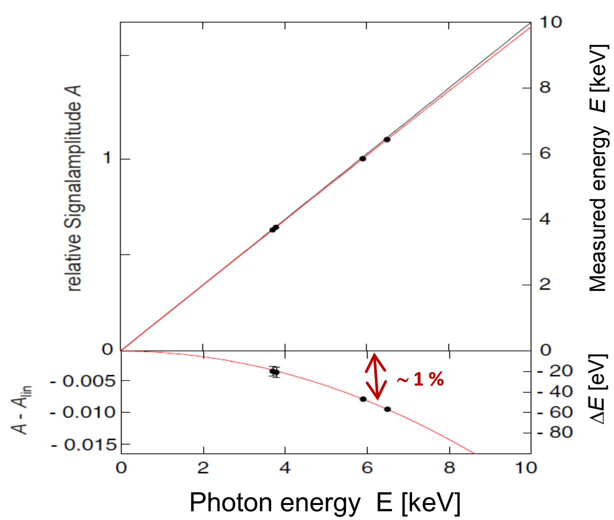
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



Reduction un-resolved pile-up

Definition of the energy scale

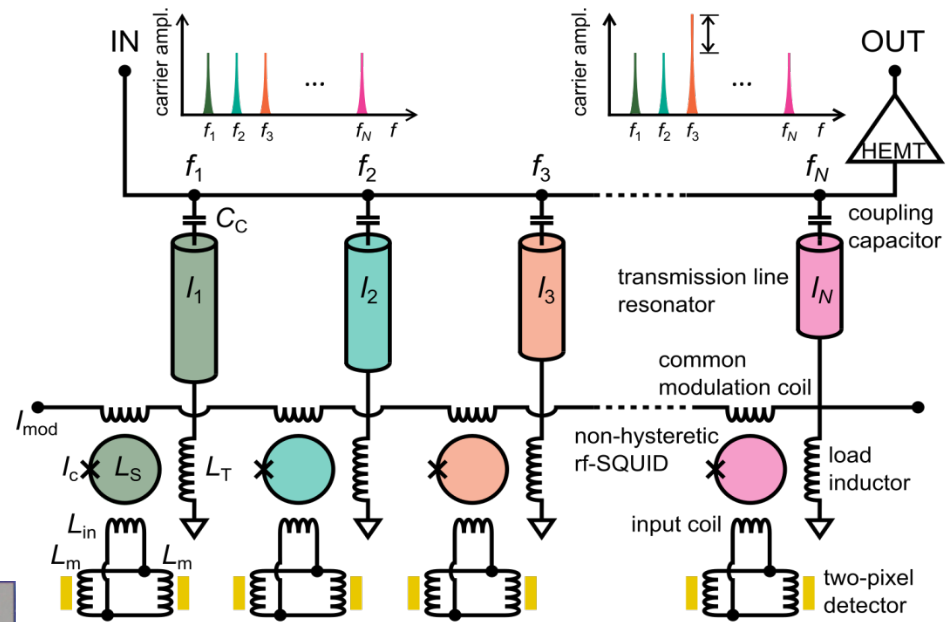
Reduced smearing in the end point region

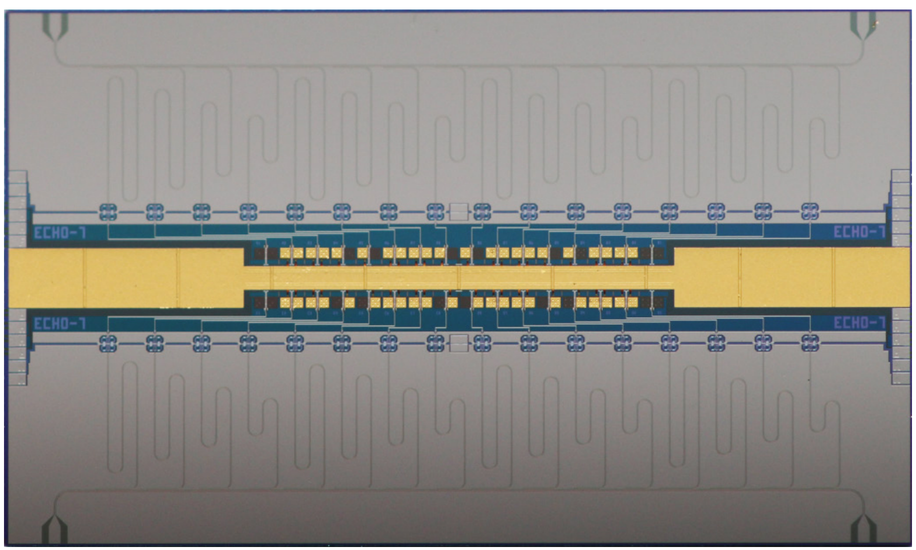
Multiplexing readout

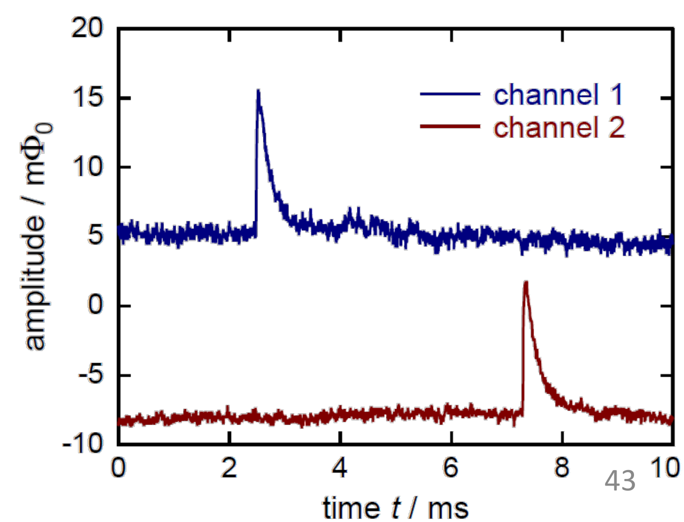
Microwave SQUID multiplexing

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

- Reliable fabrication of 64-pixel array
- Successful characterization of first prototypes
  → optimization of design parameters



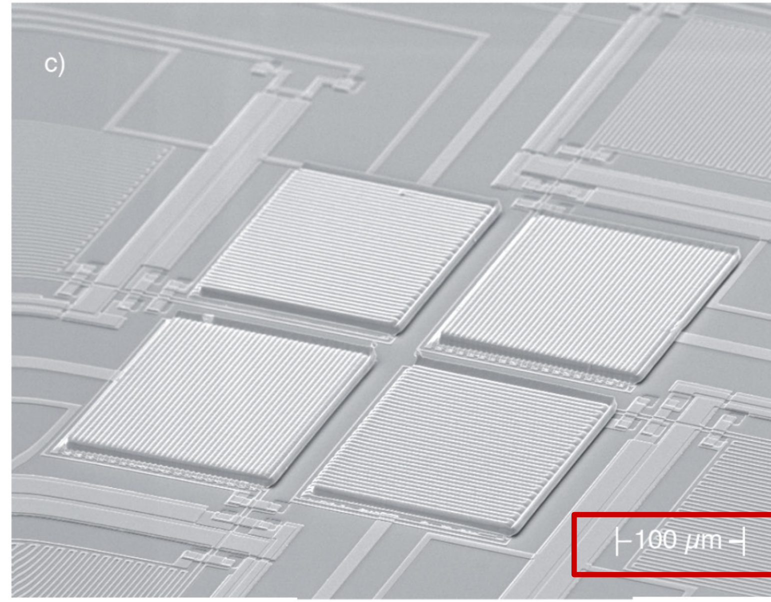


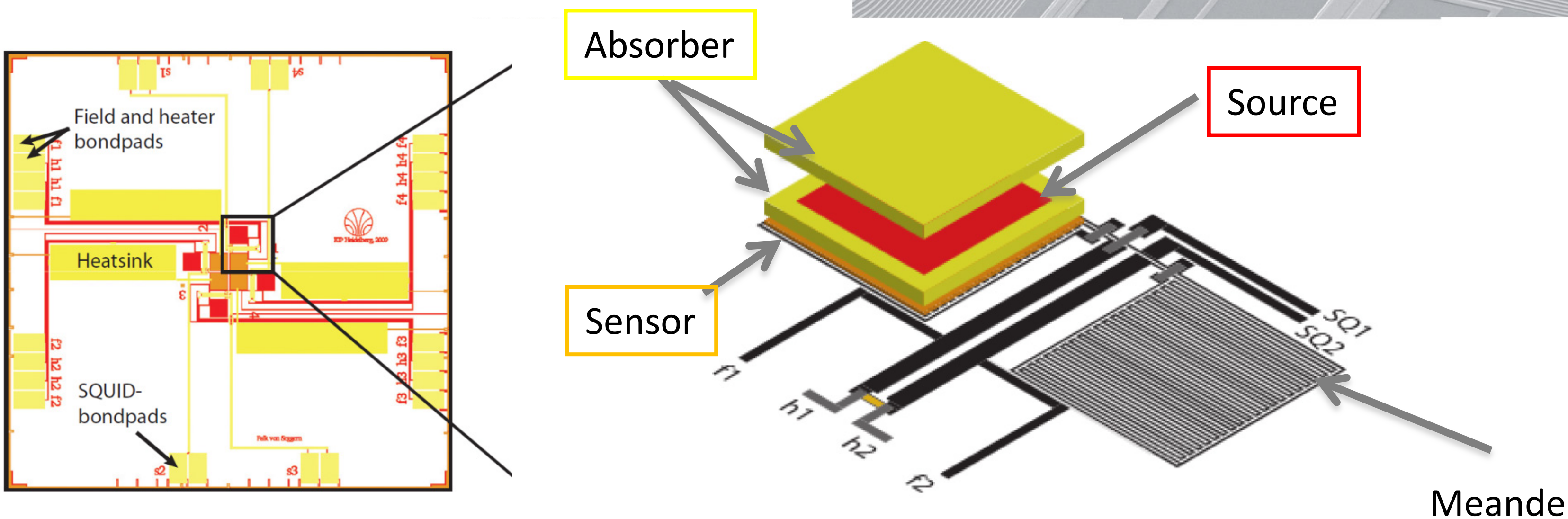


Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

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



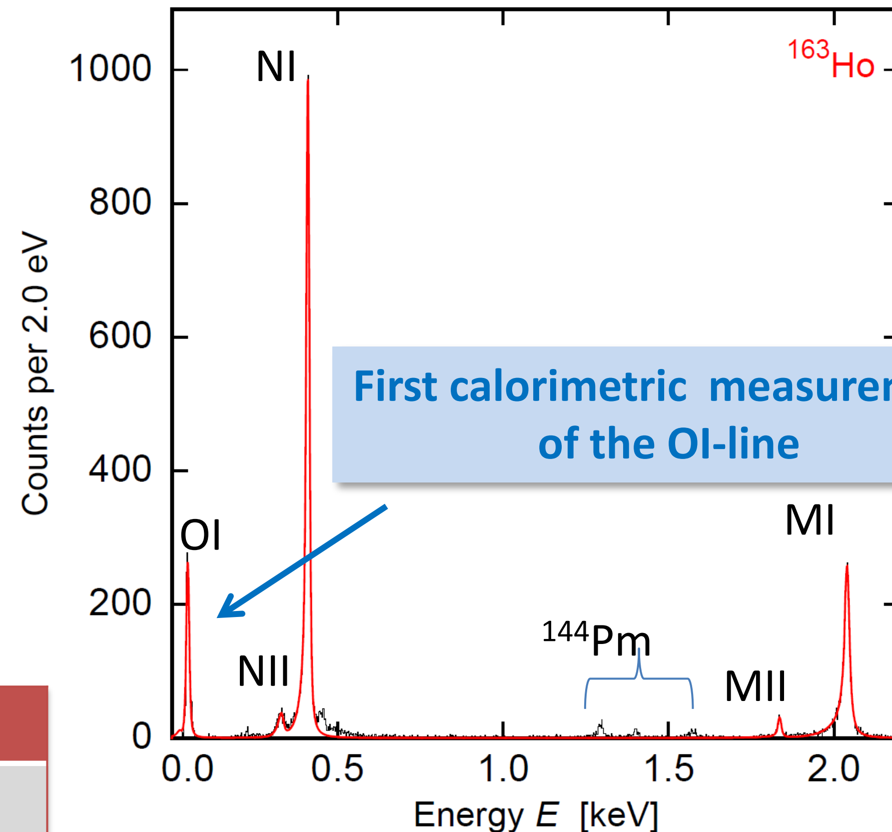


L. Gastaldo et al.,
Nucl. Inst. Meth. A, 711 (2013) 150

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



First calorimetric measurement of the OI-line

	E_H bind.	E_H exp.	Γ_H lit.	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

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

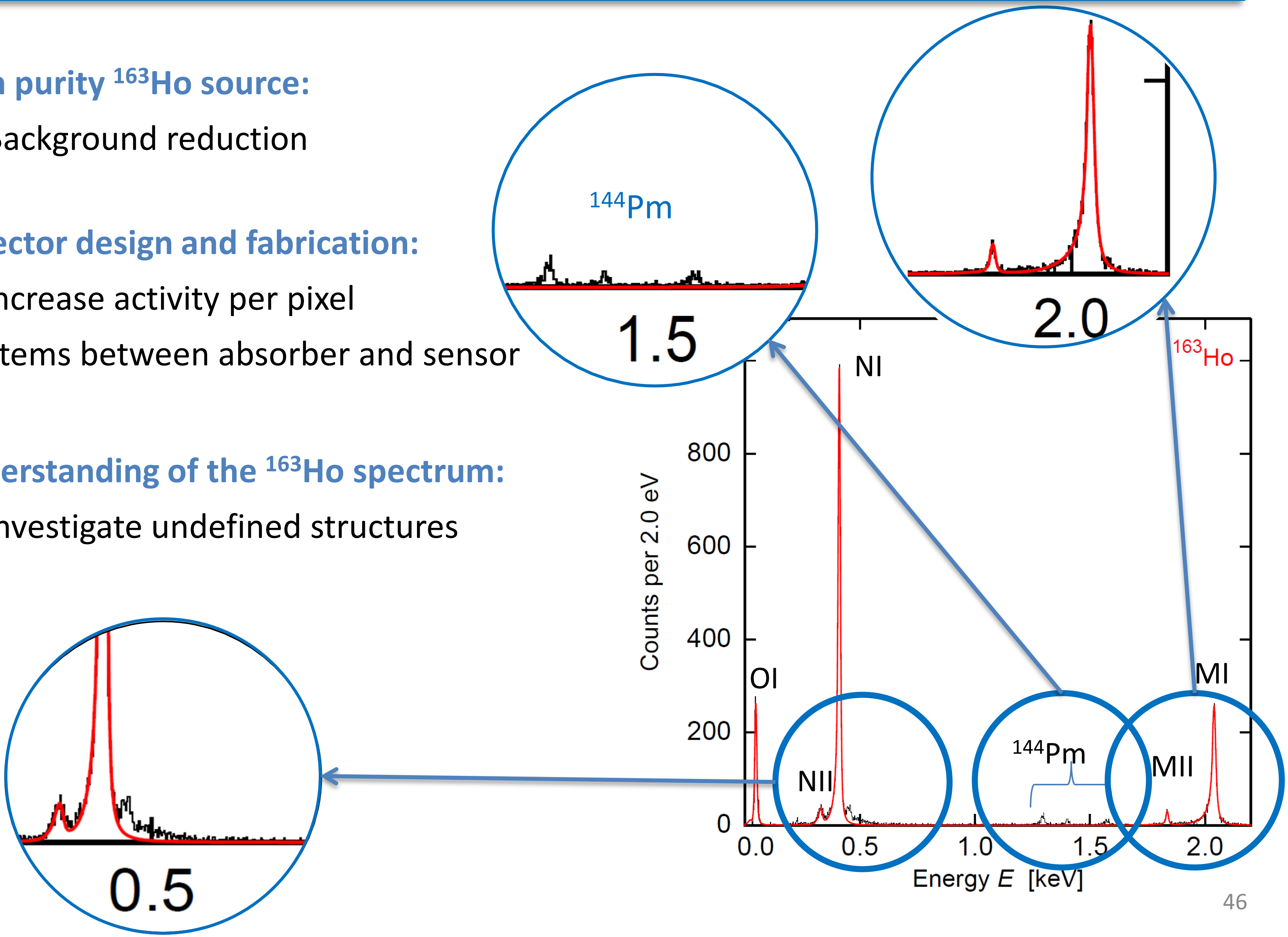
- Background reduction

Detector design and fabrication:

- Increase activity per pixel
- Stems between absorber and sensor

Understanding of the ^{163}Ho spectrum:

- Investigate undefined structures



^{163}Ho high purity source

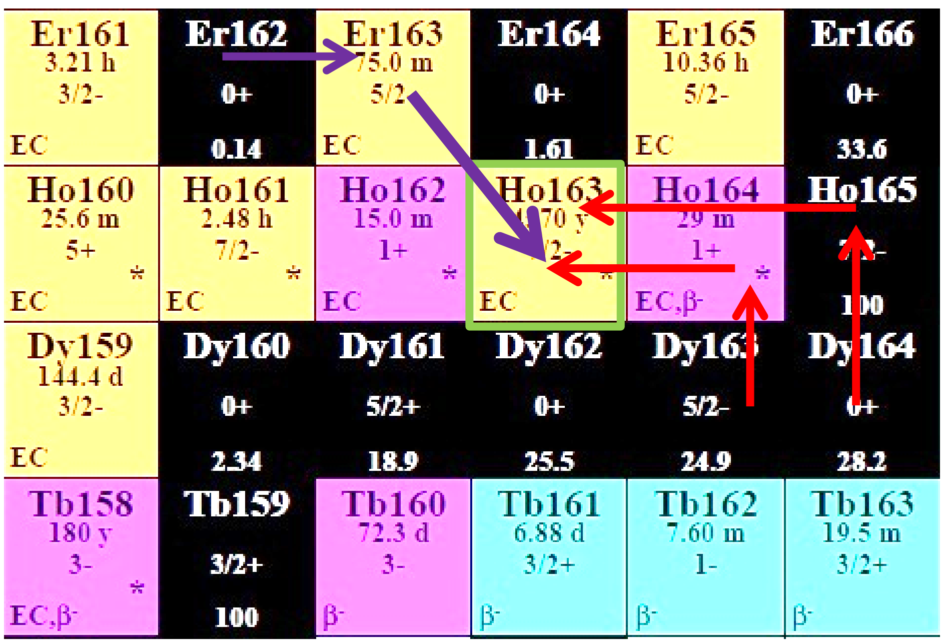
Required activity in the detectors: Final experiment → $>10^6$ Bq → $>10^{17}$ atoms

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

  High cross-section

  Radioactive contaminants



- 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

^{163}Ho high purity source

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

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  (n,γ)-reaction on ^{162}Er

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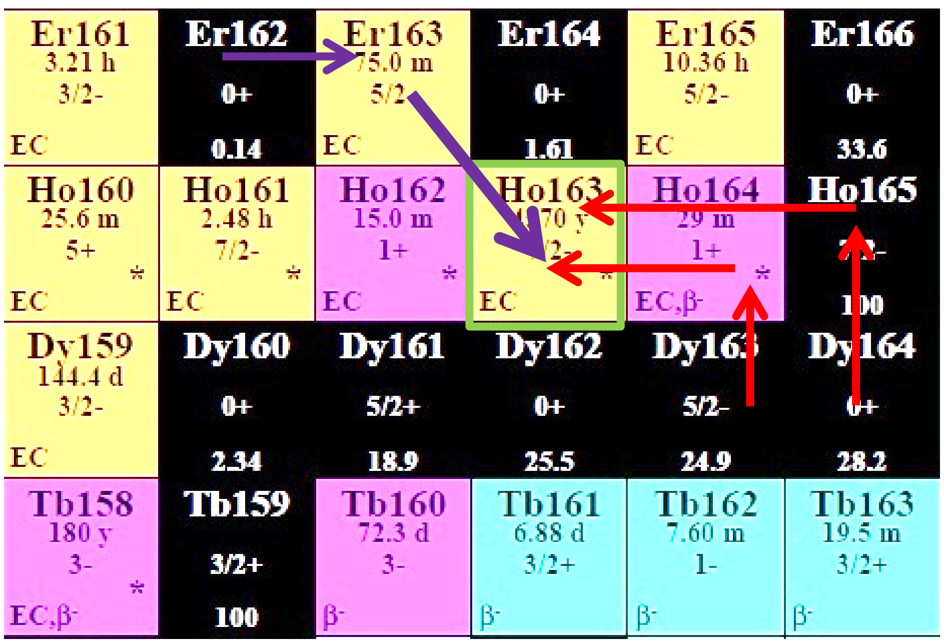
ECHo HOLMES



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  Small cross-section

  Few radioactive contaminants

NuMECS

High purity ^{163}Ho source in ECHo

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

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

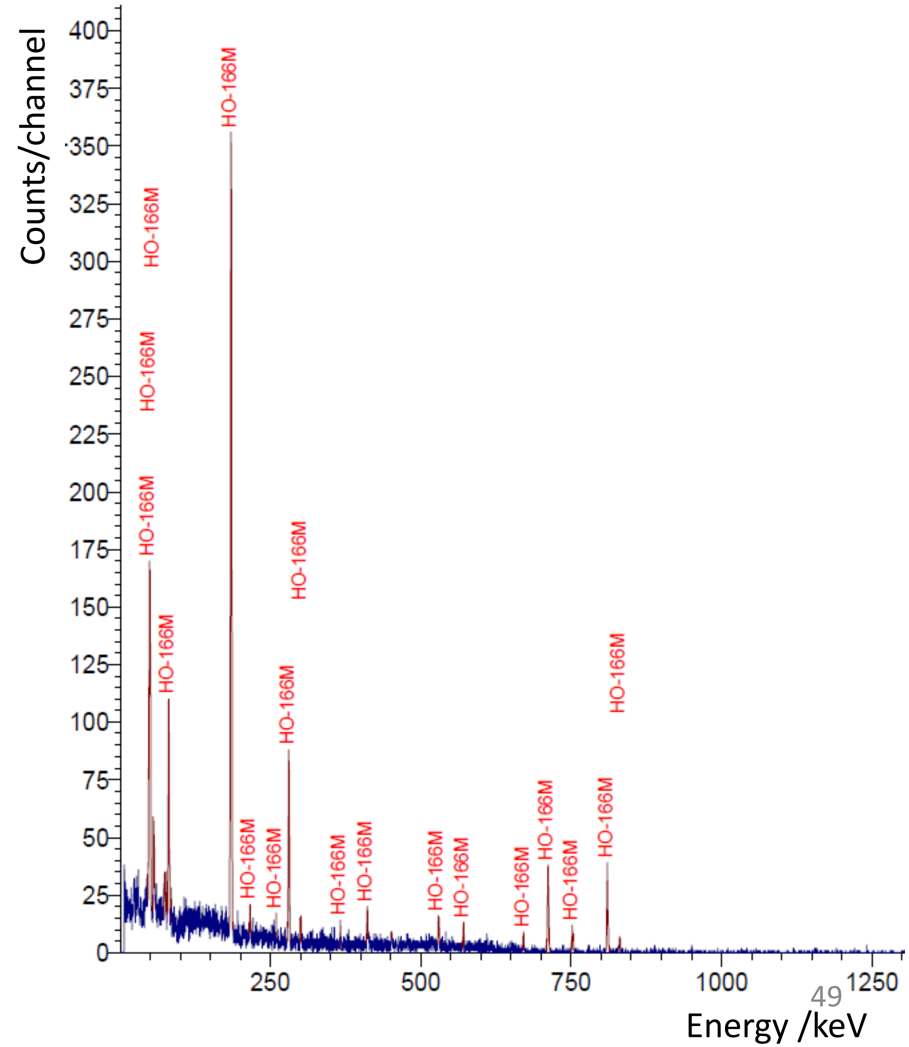
Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ * EC	Ho161 2.48 h 7/2- * EC	Ho162 15.0 m 1+ * EC	Ho163 4570 y 7/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100

- Excellent chemical separation

  Only ^{166m}Ho

- Available ^{163}Ho source:

  ~ 10^{18} atoms



The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

High purity ^{163}Ho source in ECHo

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

- (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

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  Only ^{166m}Ho

- Available ^{163}Ho source:

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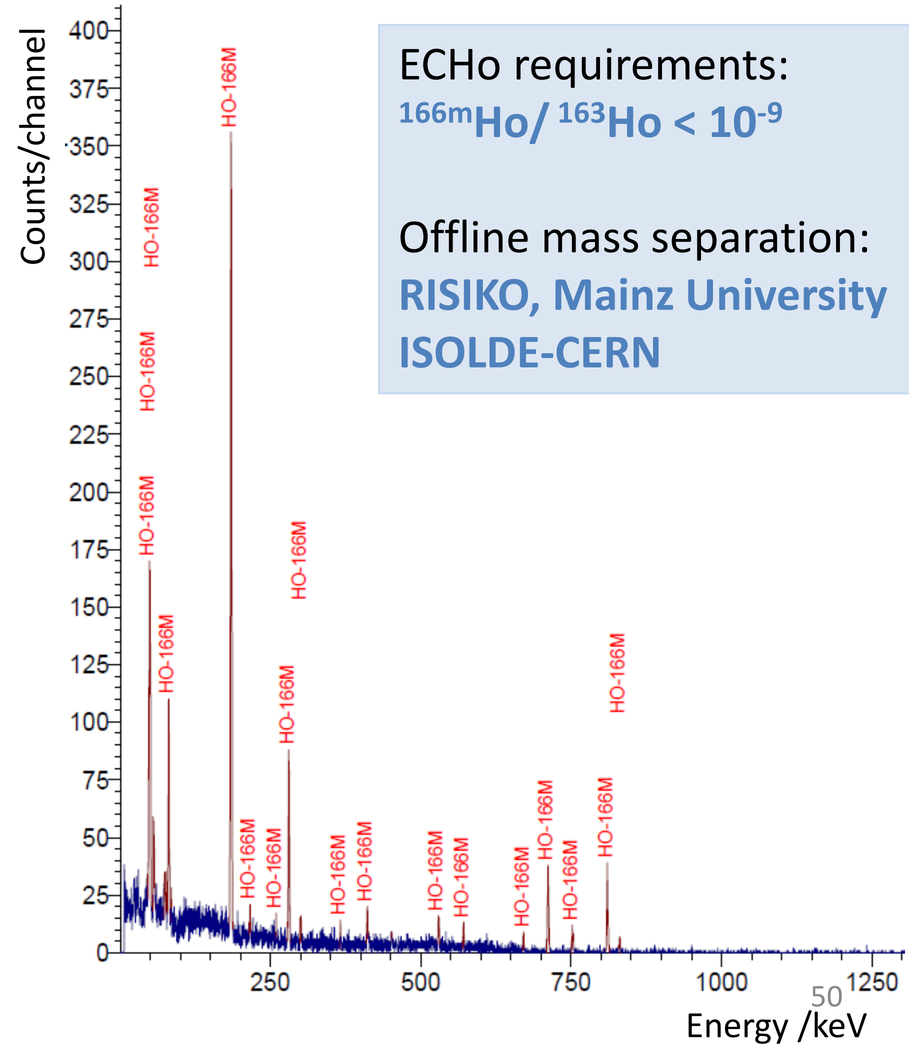
The ECHo Collaboration EPJ-ST 226 8 (2017) 1623



ECHo requirements:

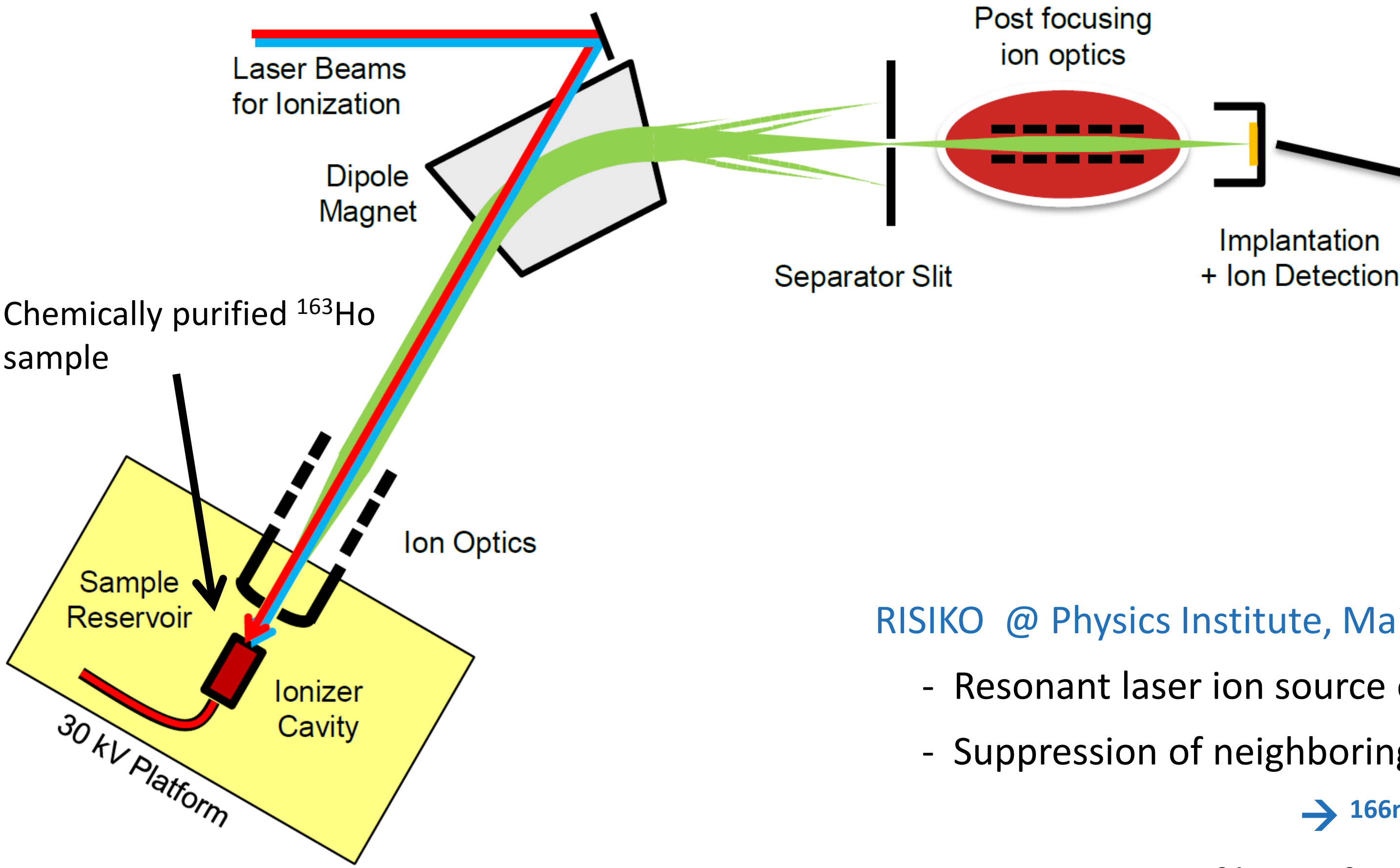
^{166m}Ho/ ^{163}Ho < 10^{-9}

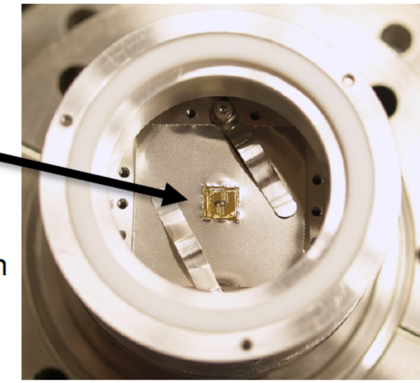
Offline mass separation:

RISIKO, Mainz University

ISOLDE-CERN

Mass separation and ^{163}Ho ion-implantation





RISIKO @ Physics Institute, Mainz University

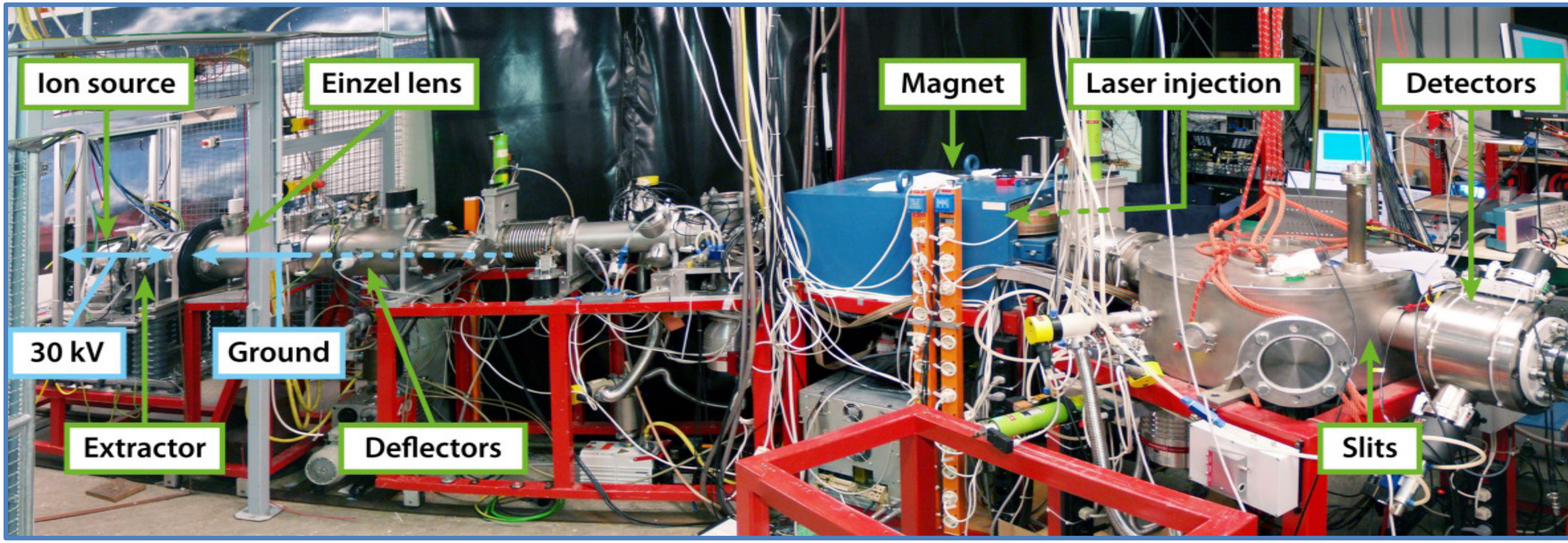
- Resonant laser ion source efficiency **42%**
- Suppression of neighboring masses > 700

  → **^{166m}Ho/^{163}Ho < 10^{-5}**

- Optimization of beam focalization

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

Mass separation and ^{163}Ho ion-implantation



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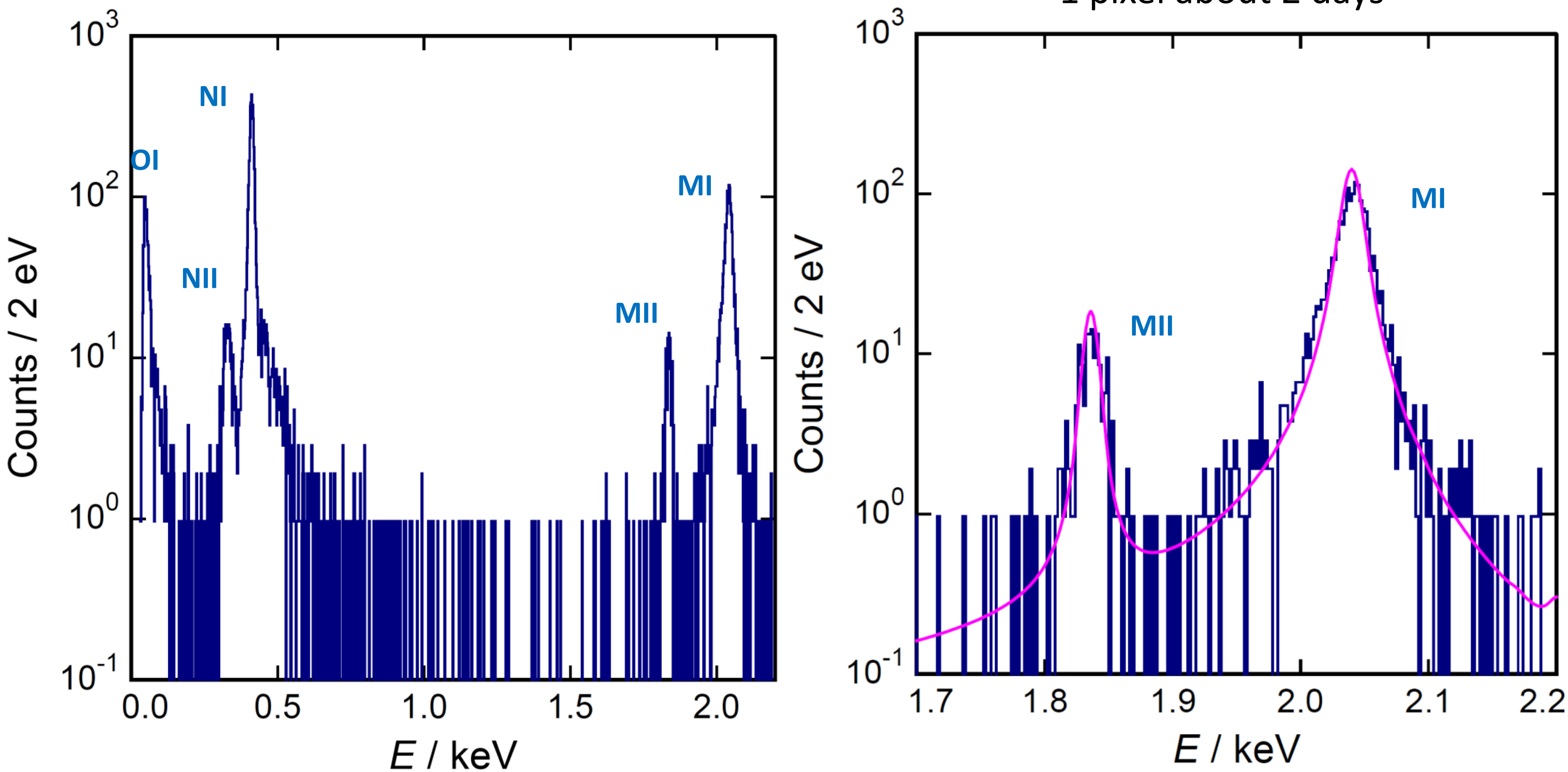
F. Schneider et al ., *NIM B* **376** (2016) 388

163Ho off-line implantation: results

1 pixel about 2 days

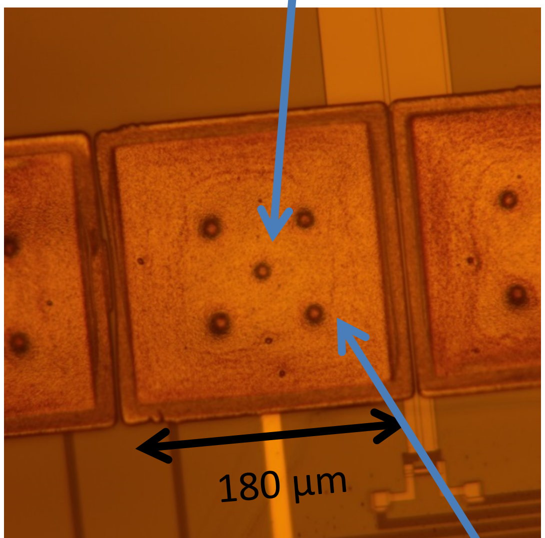


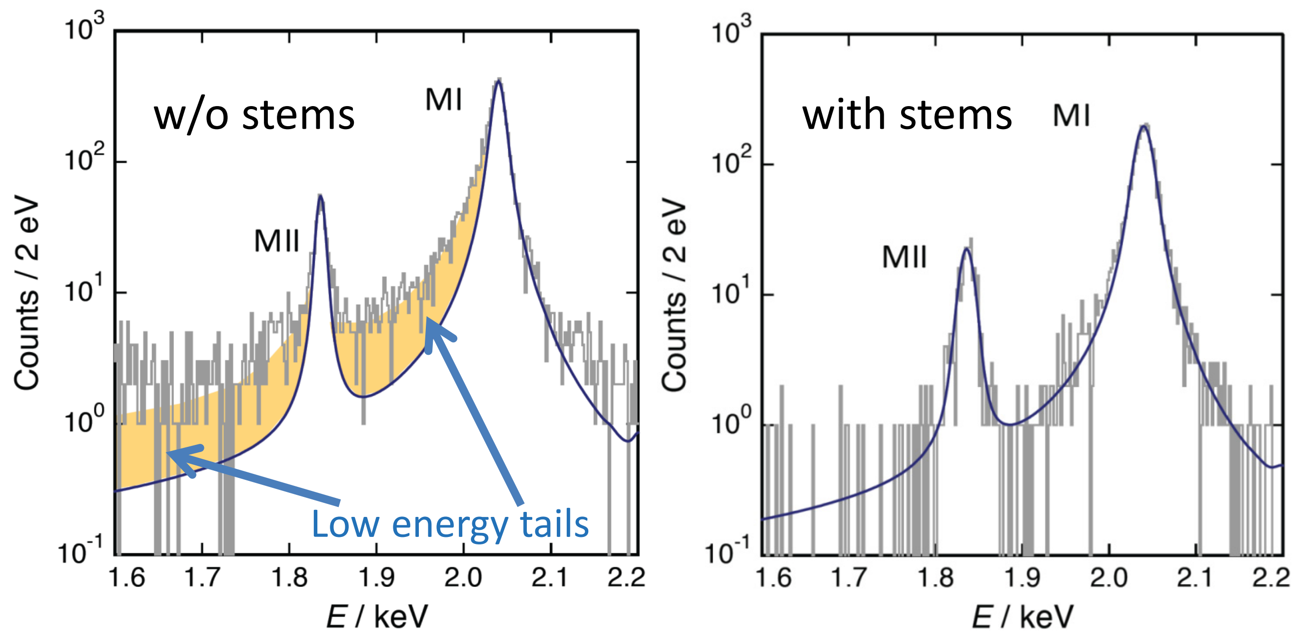
- Activity per pixel $A \sim 0.1$ Bq
- Energy resolution $\Delta E_{FWHM} \sim 10$ eV
- No strong evidence of radioactive contamination in the source
- Symmetric detector response

C. Hassel et al.,JLTP (2015)

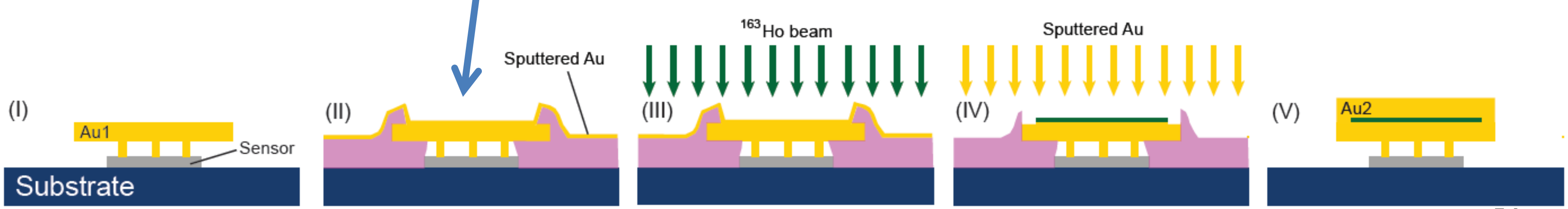
Fabrication 4π absorber

Stems between absorber and sensor prevent athermal phonon loss to the substrate





Definition of the implantation area by microstructuring a photoresist layer



Where to improve

High purity ^{163}Ho source:

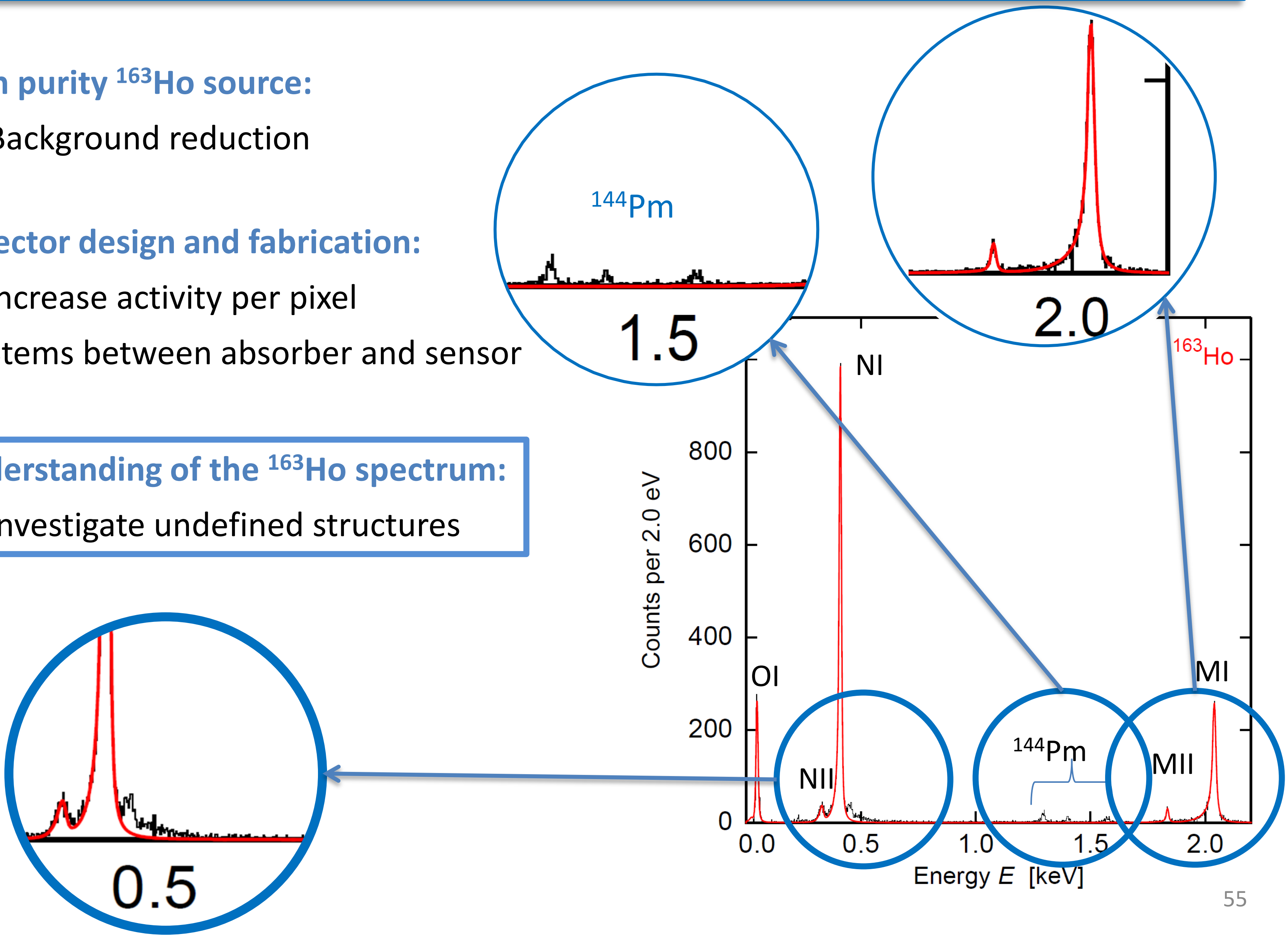
- Background reduction

Detector design and fabrication:

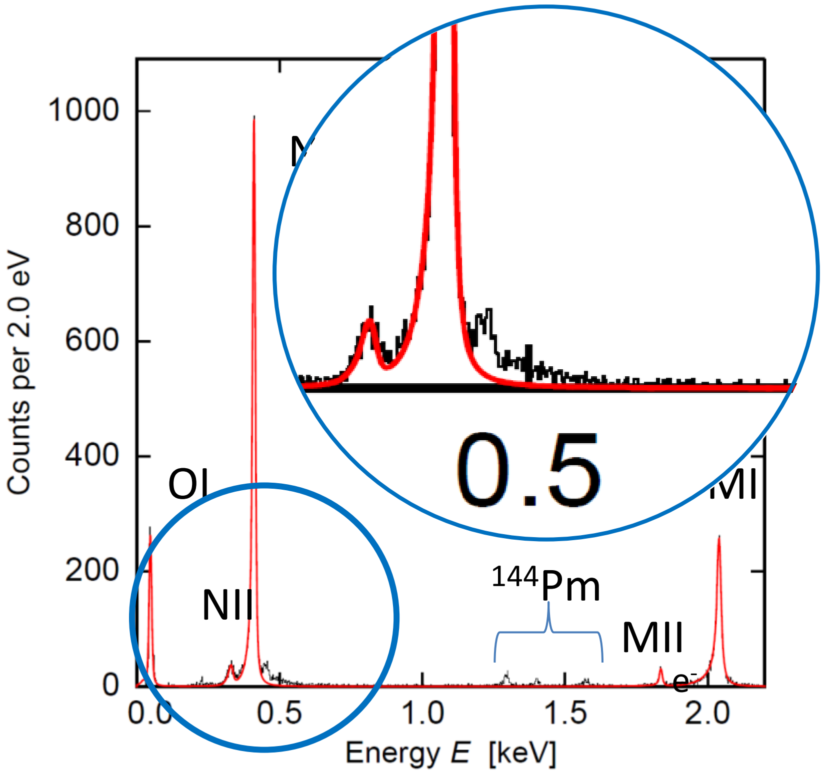
- Increase activity per pixel
- Stems between absorber and sensor

Understanding of the ^{163}Ho spectrum:

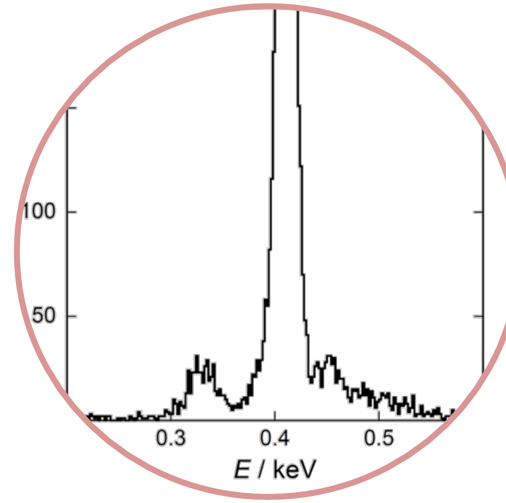
- Investigate undefined structures

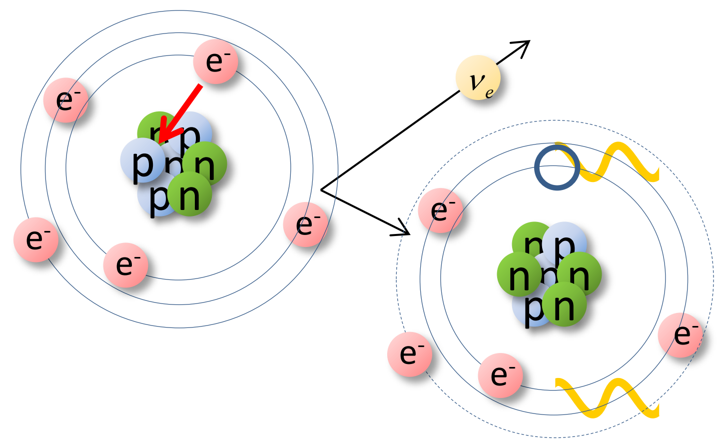


Characterisation of spectral shape



Structures present also in new data





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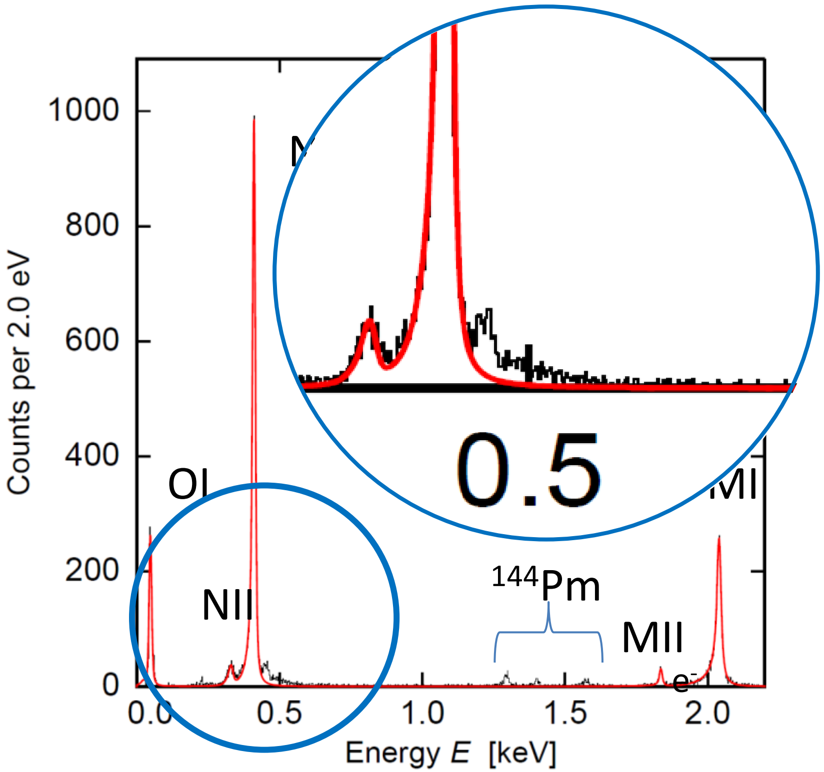

- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler and F. Simkovic
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- A. Faessler et al.
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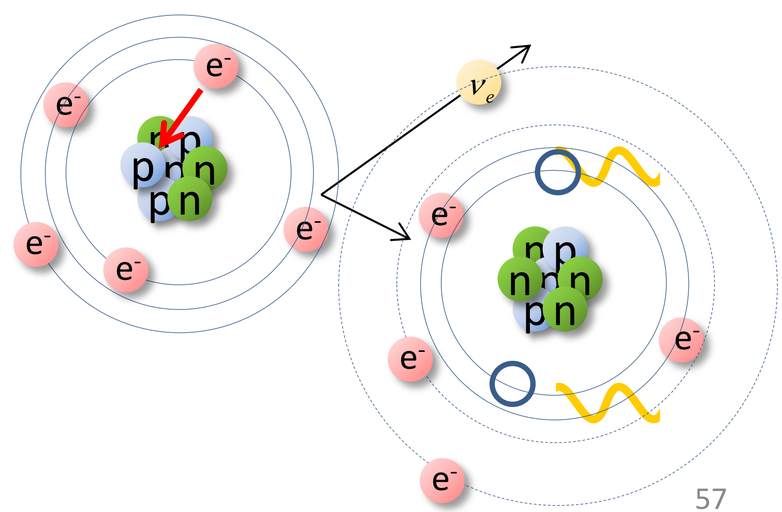
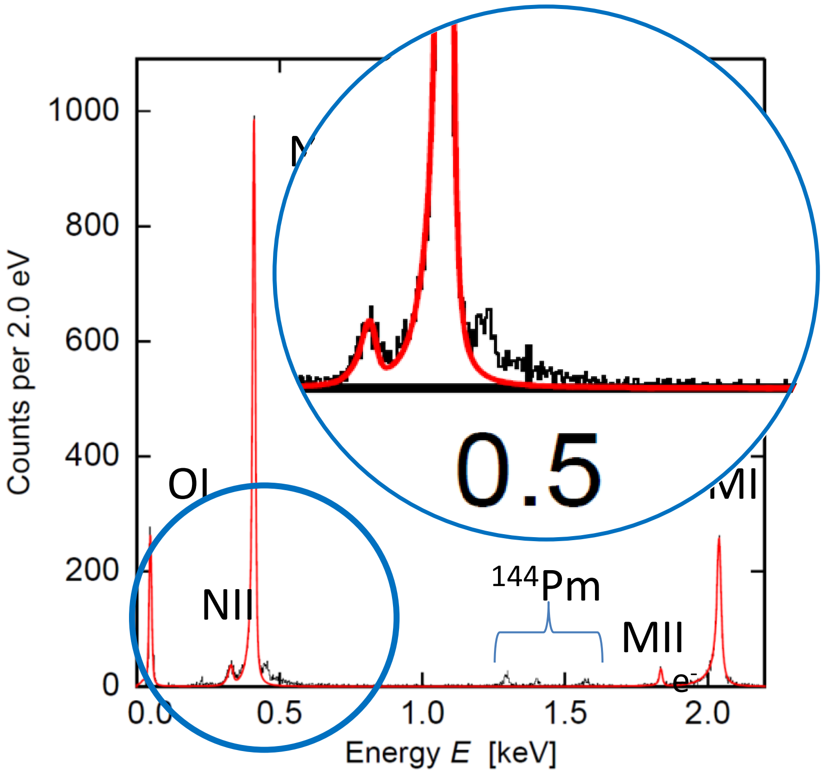
- A. De Rujula and M. Lusignoli
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016
- A. Faessler et al.
  Phys. Rev. C **95**, (2017) 045502



Two-holes excited states: shake-up

Characterisation of spectral shape



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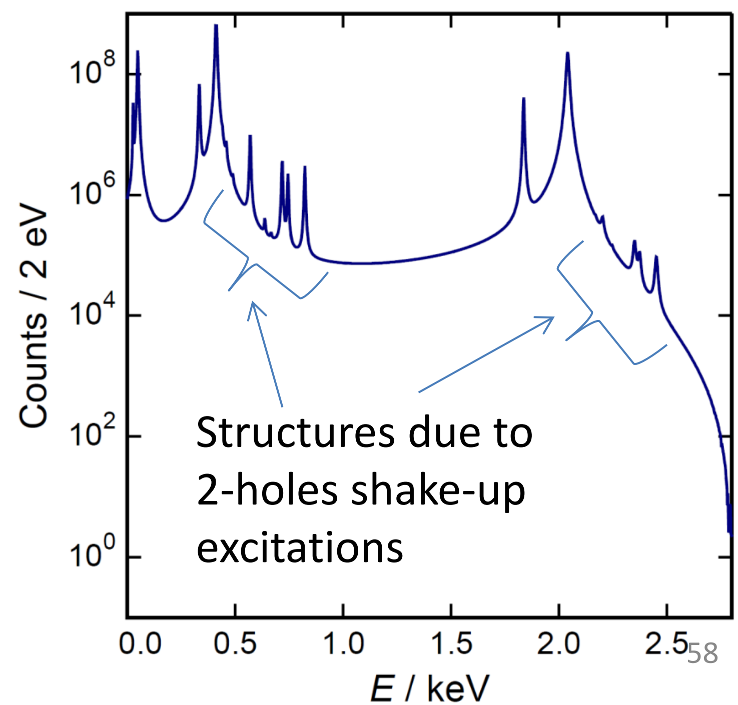
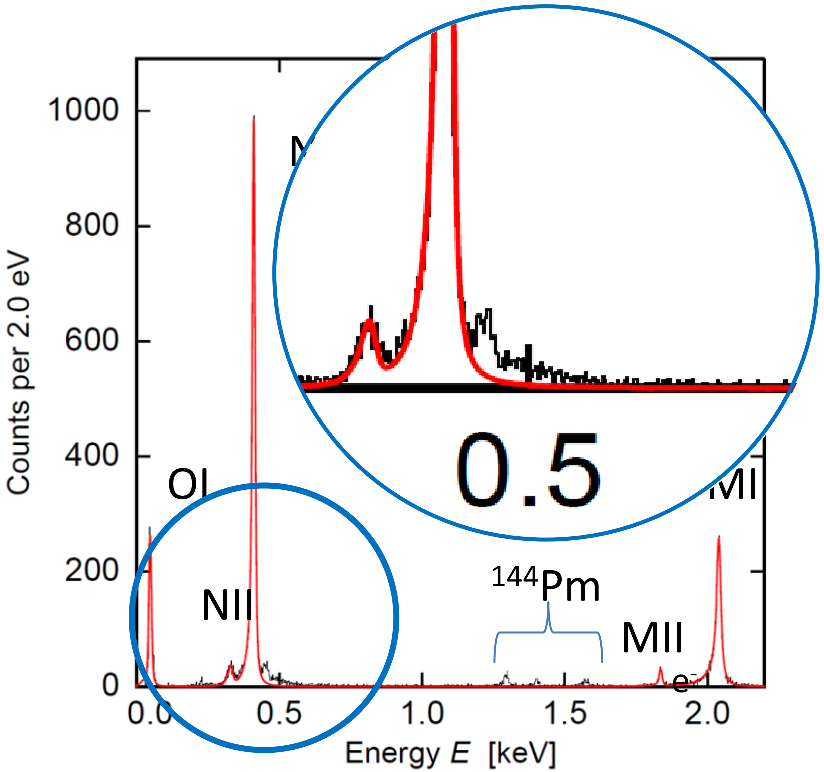
T

Two-holes excited states: shake-up



Characterisation of spectral shape



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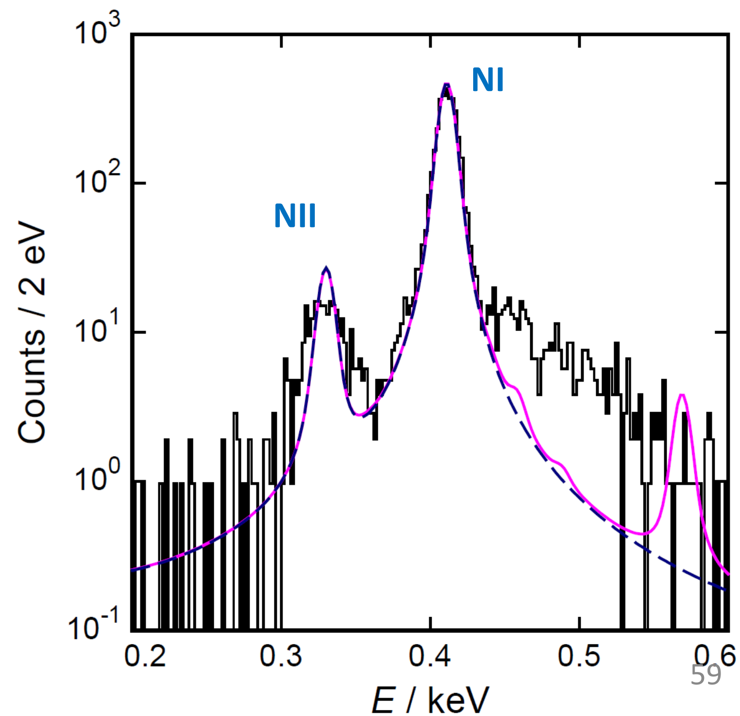
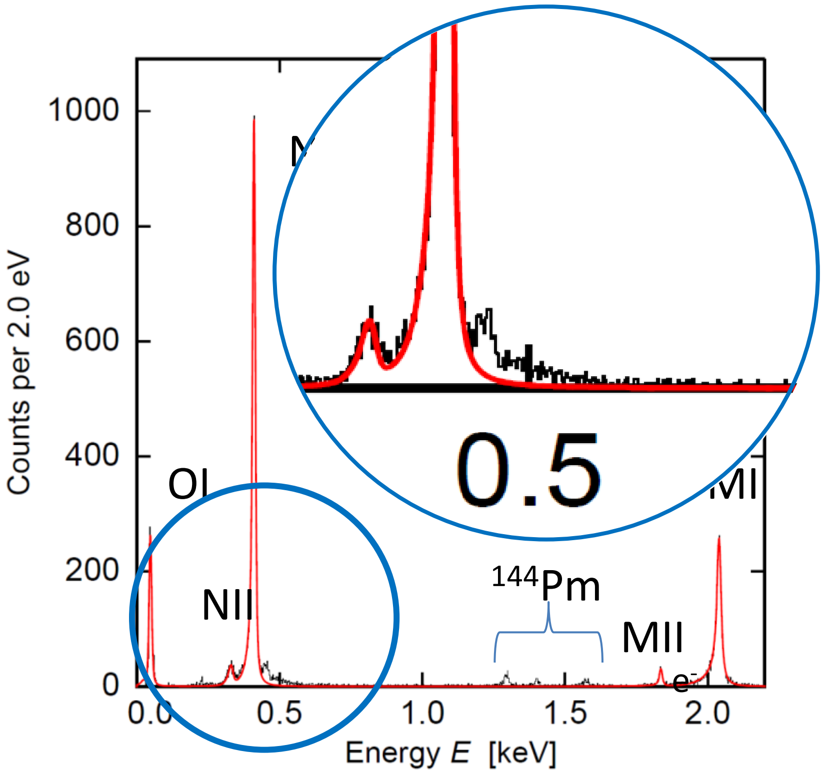


Characterisation of spectral shape



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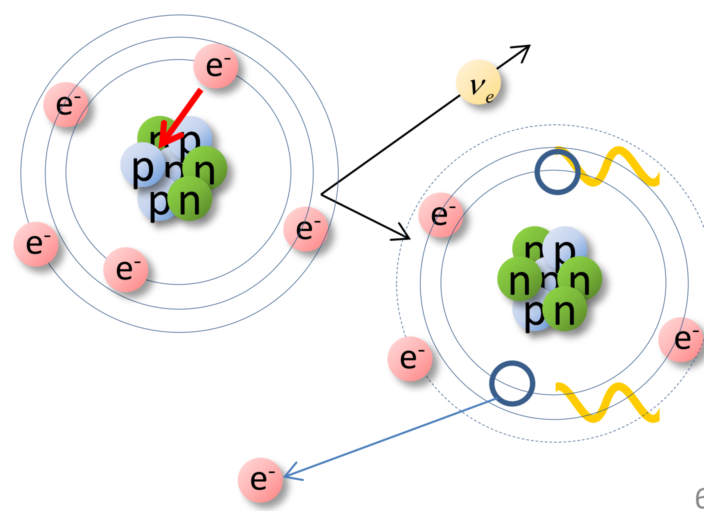
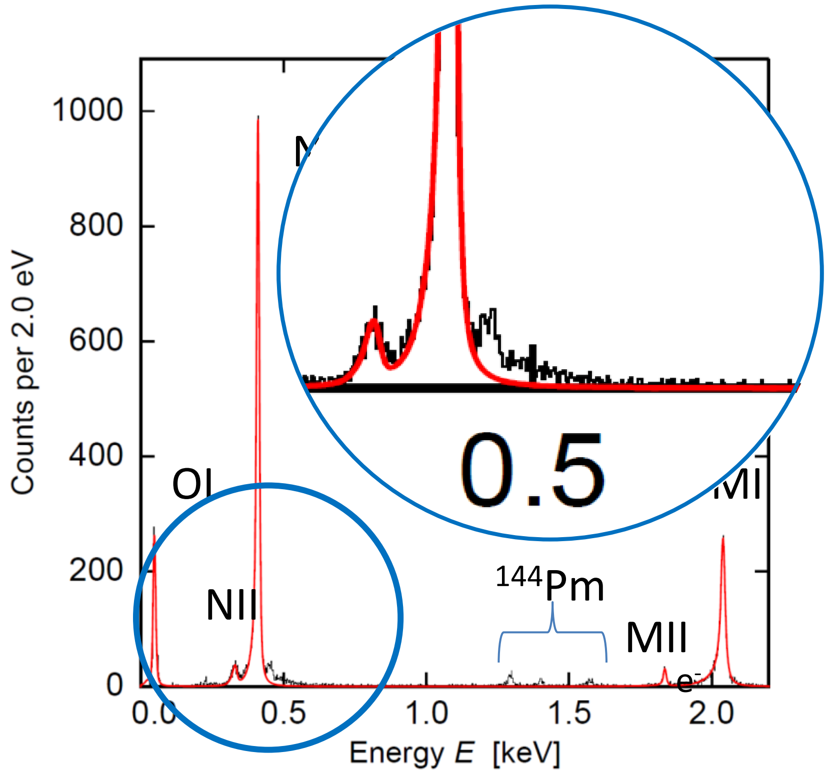
Two-holes excited states: shake-up
shake-off



Characterisation of spectral shape



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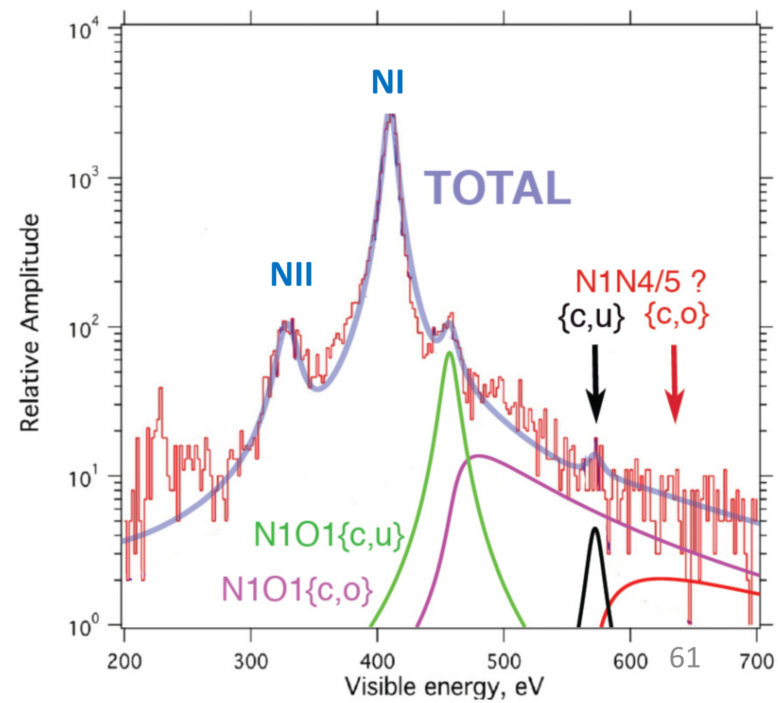
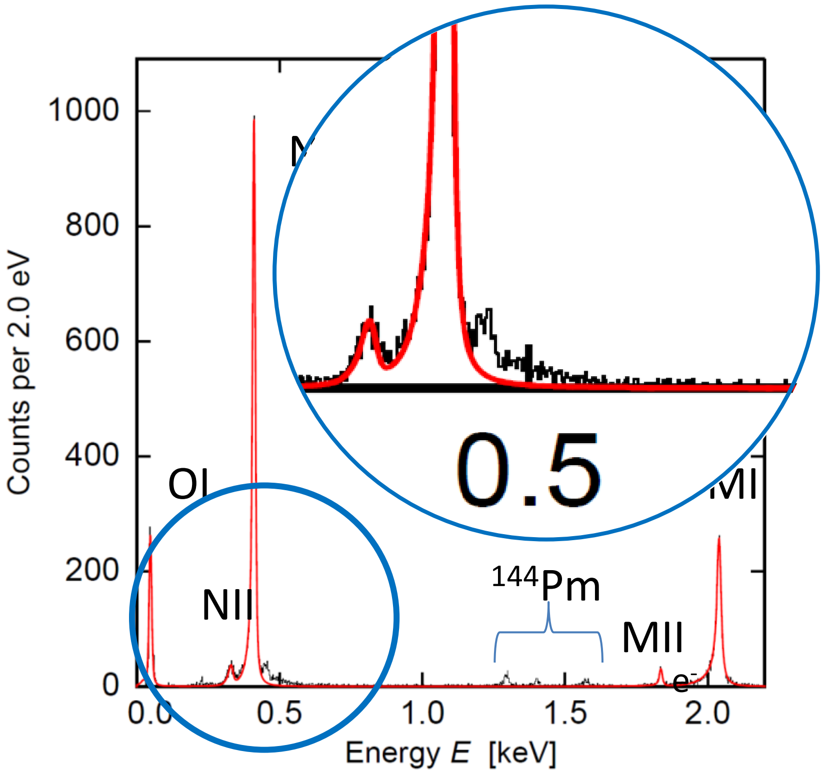


Two-holes excited states: shake-up
shake-off

High statistics and high energy resolution spectra will provide information on the spectral shape

Characterisation of spectral shape



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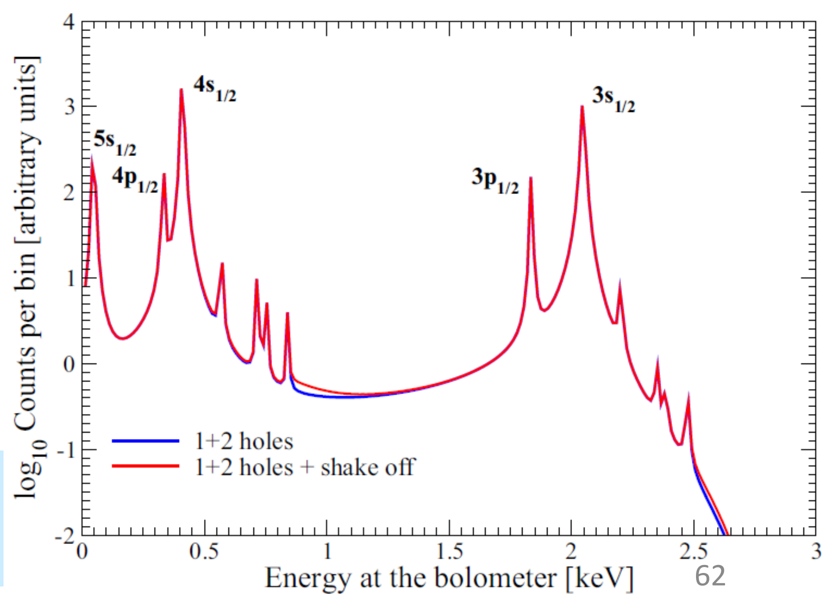
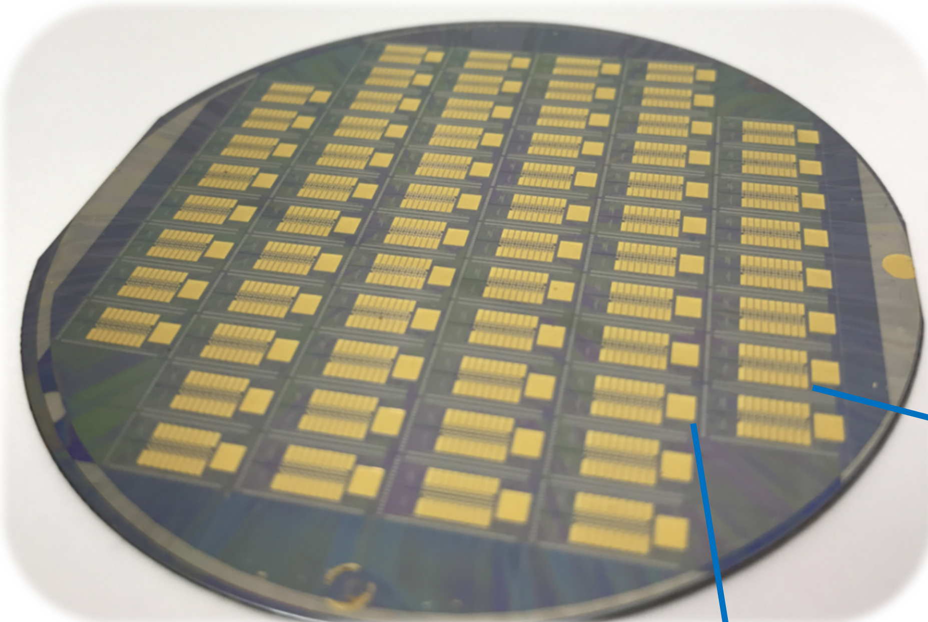
Two-holes excited states: shake-up
shake-off



High statistics and high energy resolution spectra will provide information on the spectral shape

Present status

ECHo-1k array

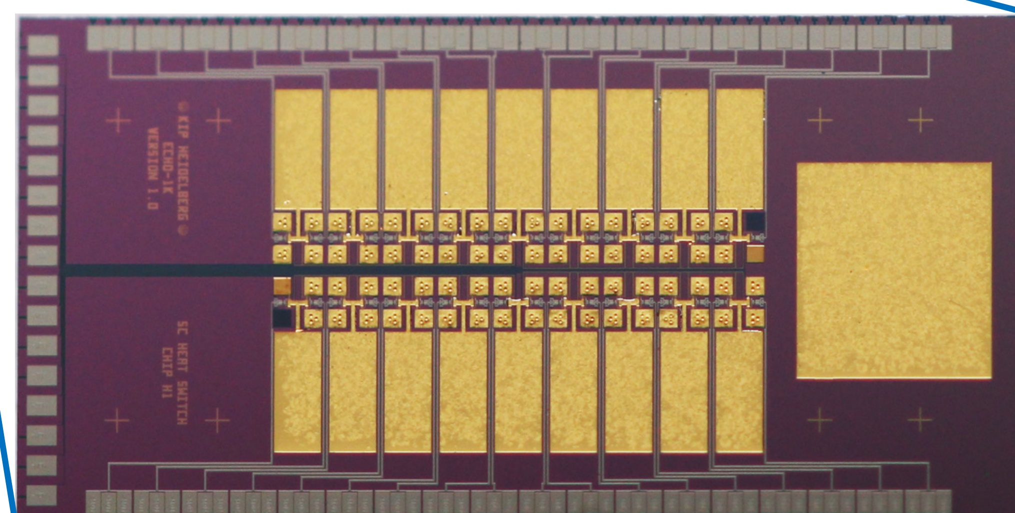


3“ wafer with 64 ECHo-1k chip

Suitable for
parallel and multiplexed readout

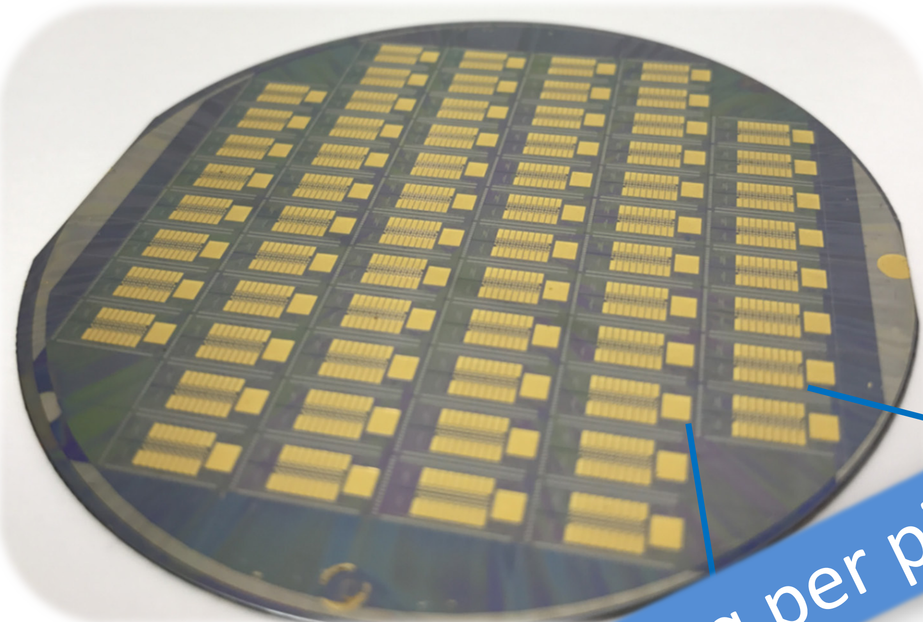
64 pixels which can be loaded with ^{163}Ho
+ 4 detectors for diagnostics

Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)
τ_r ~ 300 ns (multiplexed read-out)



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

ECHo-1k array



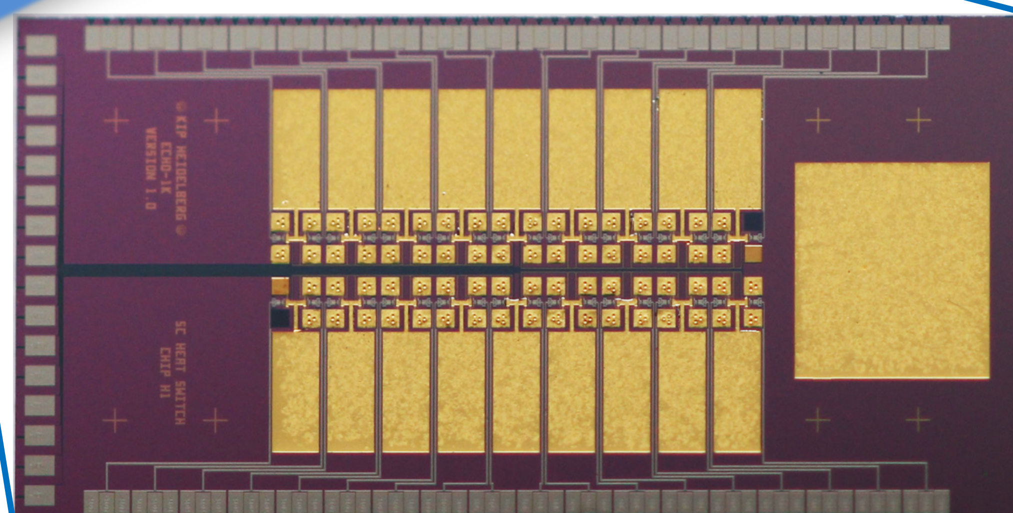
3" wafer with 64 ECHo-1k chip

Suitable for
parallel and mu... ...dout

4 chips with a few Bq per pixel ready to be measured

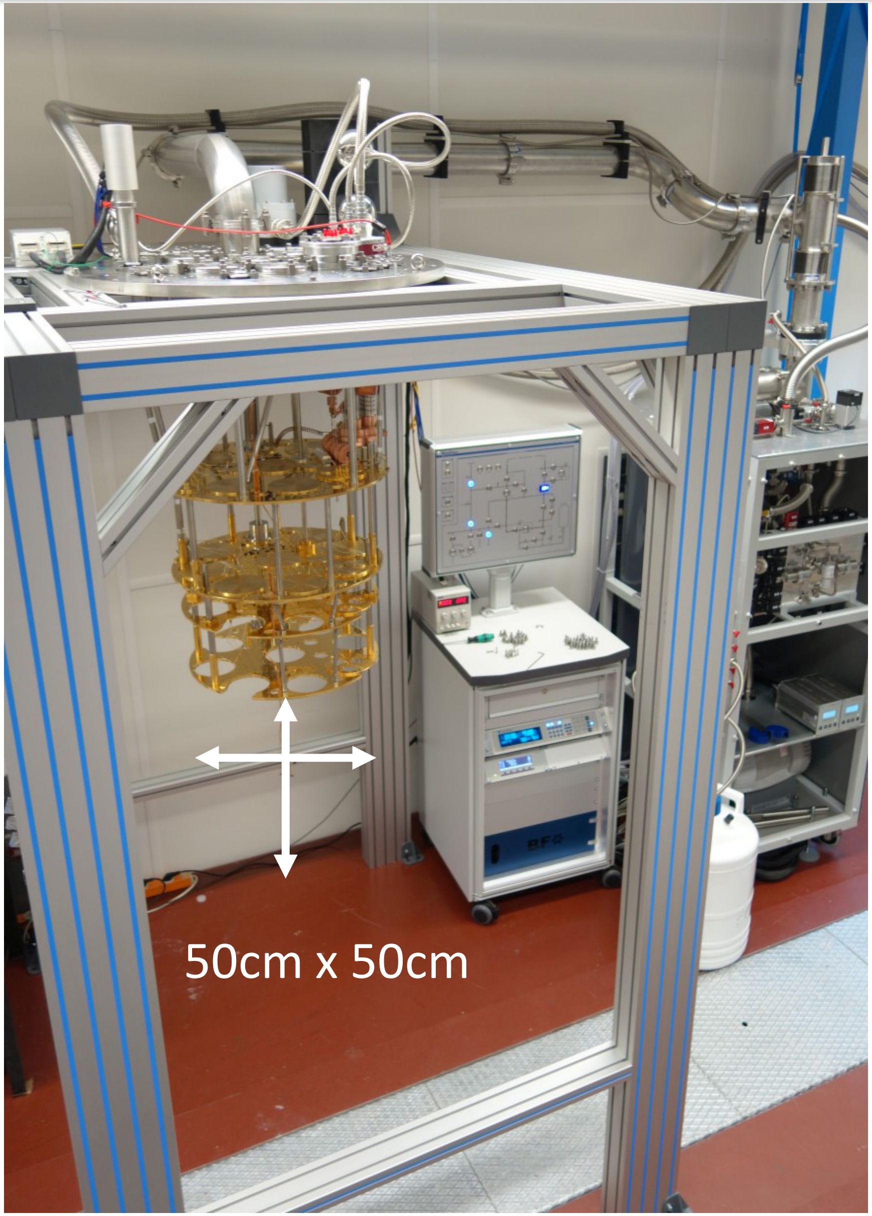
64 pixels which ... ...d with ^{163}Ho
+ 4 detect... ...ostics

Desig... ...ormance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)
τ_r ~ 300 ns (multiplexed read-out)

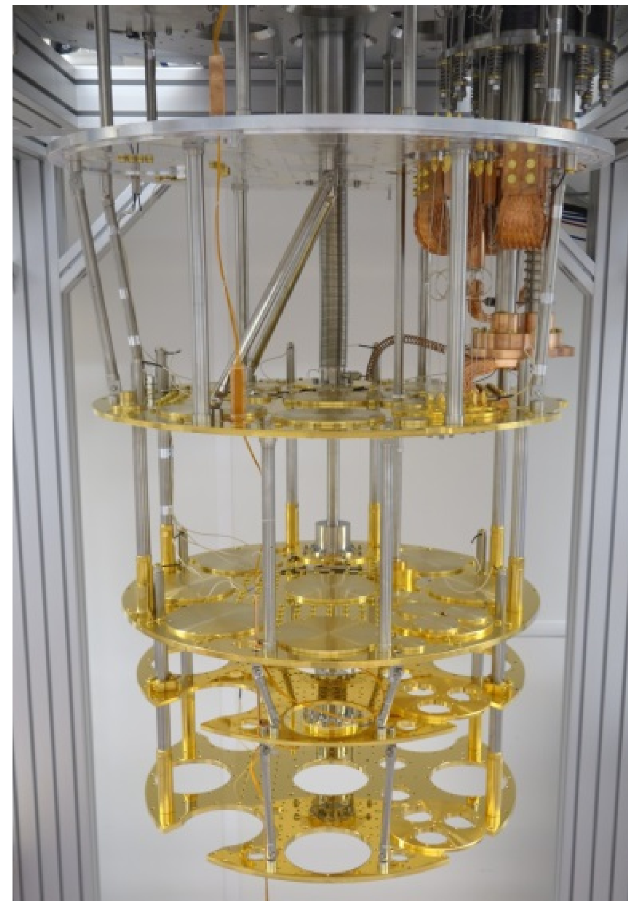


S.Kempf *et al.*, *J. Low. Temp. Phys.* **176** (2014) 426

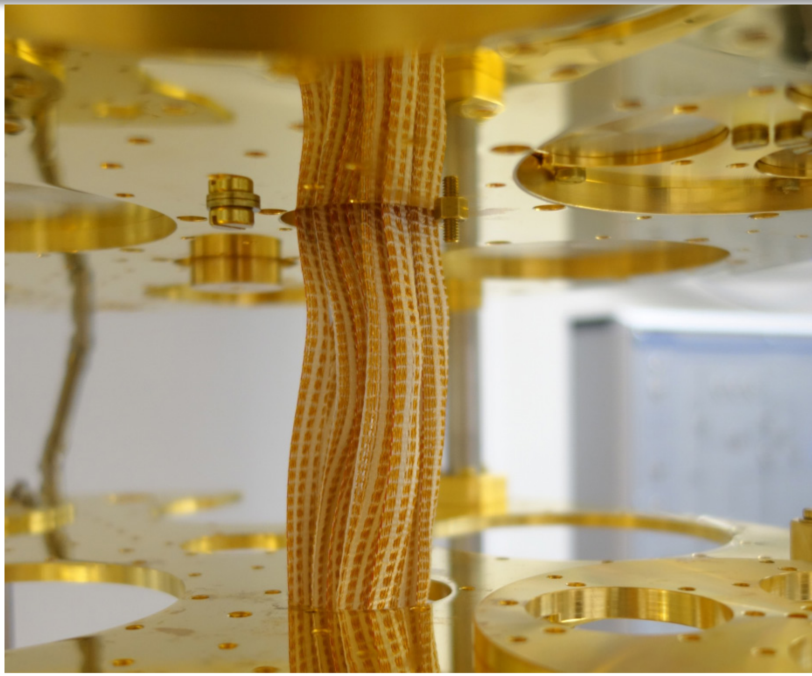
ECHo cryogenic platform

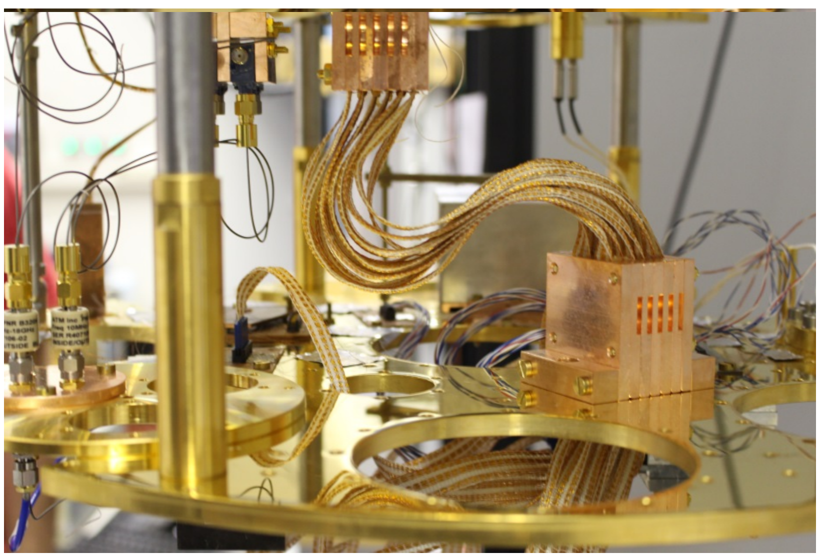


- Large space at MXC enough for several ECHo phases
- cooling power: 15µW @ 20 mK
- Possibility to load 200kg for passive shielding



ECHo cryogenic platform





- Large space at MXC enough for several ECHo phases
- cooling power: 15µW @ 20 mK
- Possibility to load 200kg for passive shielding
- Presently equipped with:

  2 RF lines for microwave
  multiplexing readour of 2 MMC arrays

  12 ribbons each with 30 Cu98Ni2 0.2 mm,
  1.56 Ohm/m, cables from RT to mK
  → allows for parallel readout of
  36 two-stage SQUID set-up

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**

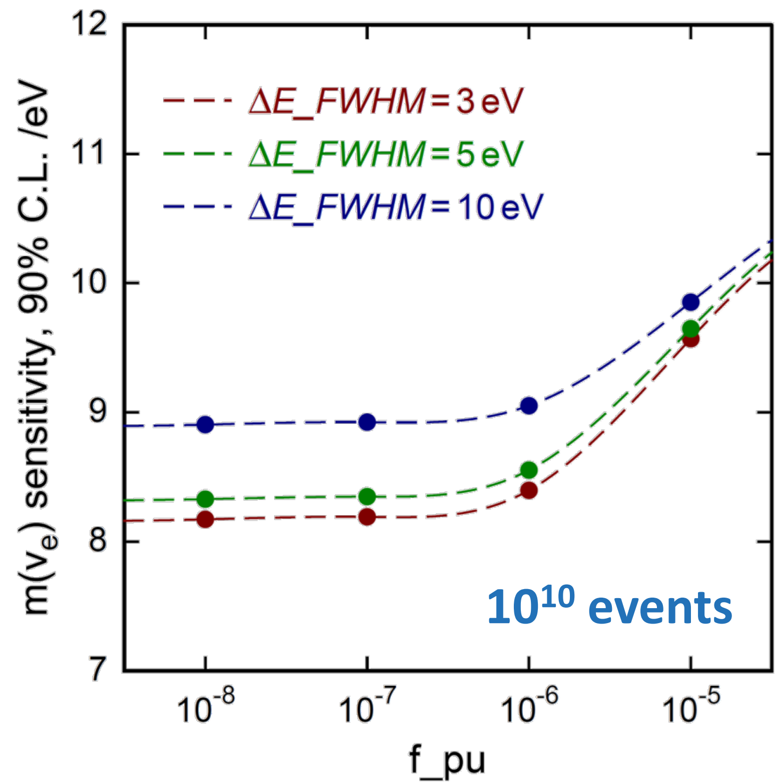
→number of detectors N = **100**

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.

The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

ECHo-1M (next future)

^{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

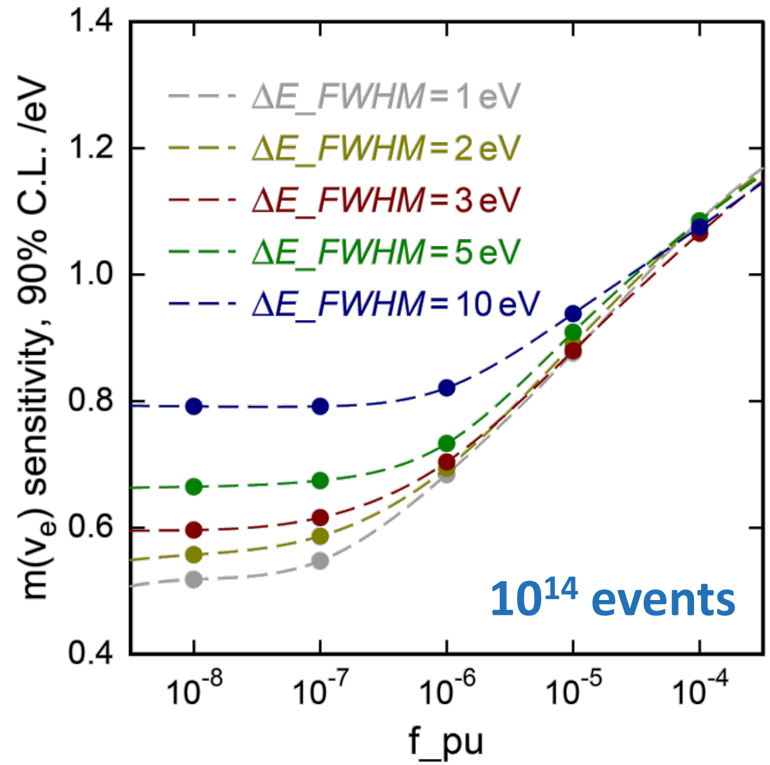
→number of detectors $N = 10^5$

Read-out : Microwave SQUID Multiplexing

→ 100 arrays with ~1000 single pixels

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

Measuring time t = 1 – 3 year



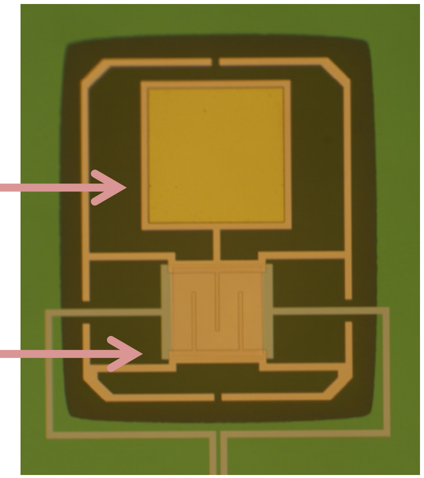
$m(\nu_e) < 1$ eV 90% C.L.

The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

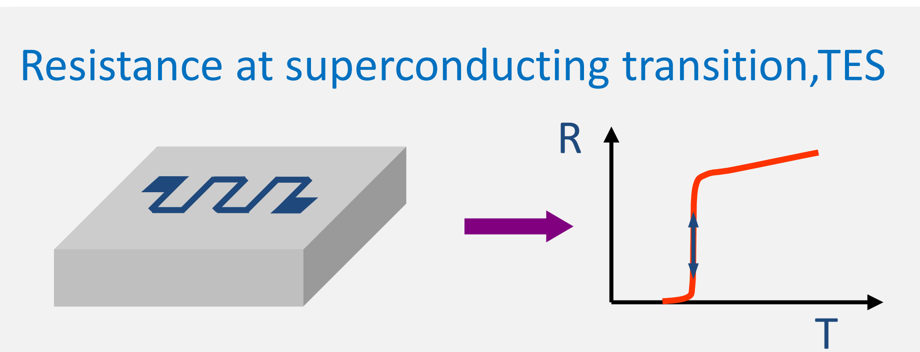
HOLMES: Detectors

Absorber: Bi-Au or Au + 6.5x10^{13} ^{163}Ho per detector → **300 dec/sec**
^{163}Ho ion implanted in absorber using dedicated facility at Genoa University

Transition Edge Sensor: MoCu or MoAu superconducting films



NIST, Boulder



Definition of the critical temperature thanks to the proximity effect: normal metal suppress superconductivity in a superconducting thin film in good electrical contact

HOLMES: Detectors

Absorber: Bi-Au or Au + 6.5x10^{13} ^{163}Ho per detector → **300 dec/sec**
^{163}Ho ion implanted in absorber using dedicated facility at Genoa University

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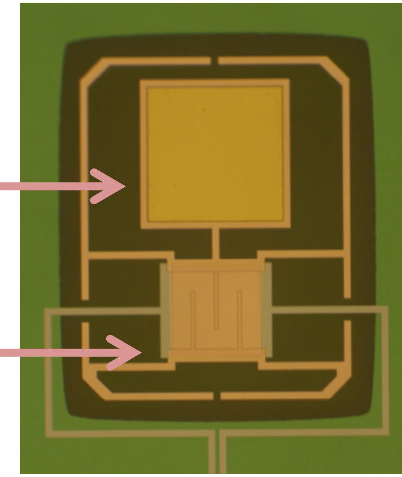
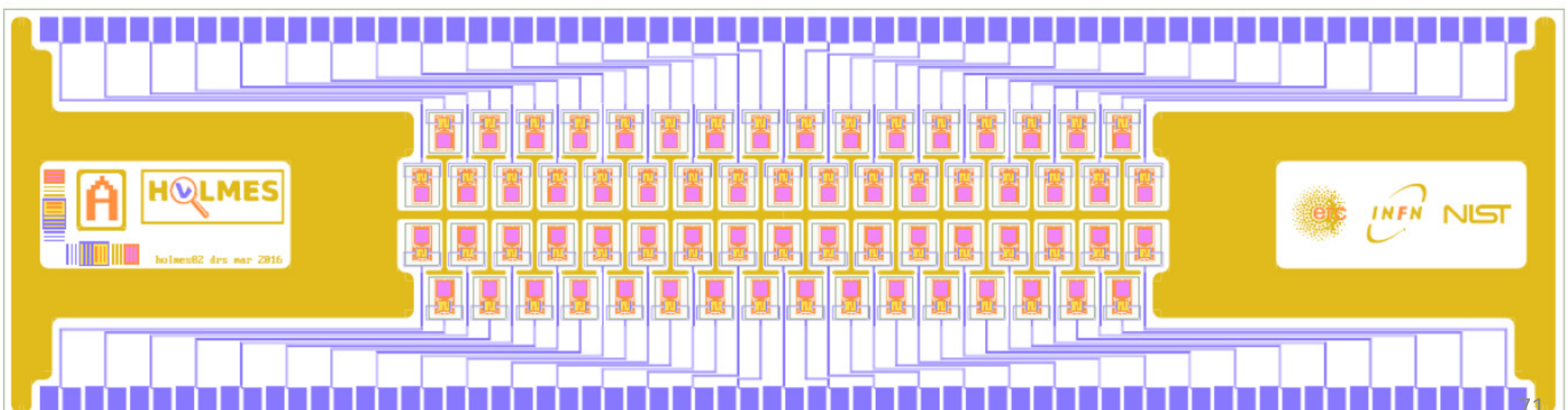
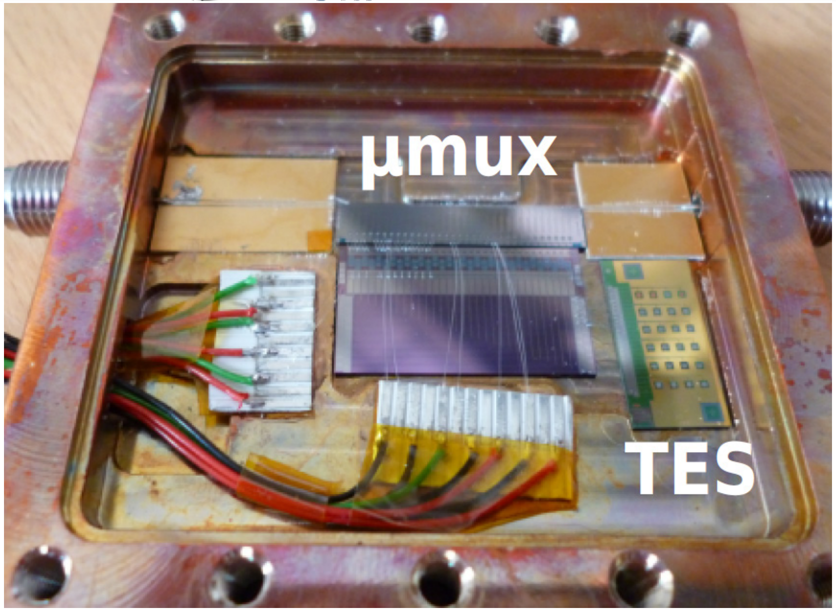


NIST, Boulder

Microwave multiplexing → HOLMES **4✕16 linear sub-array** → **ΔE≈1eV and τ_R≈1µs**
goal →**1000 pixels**

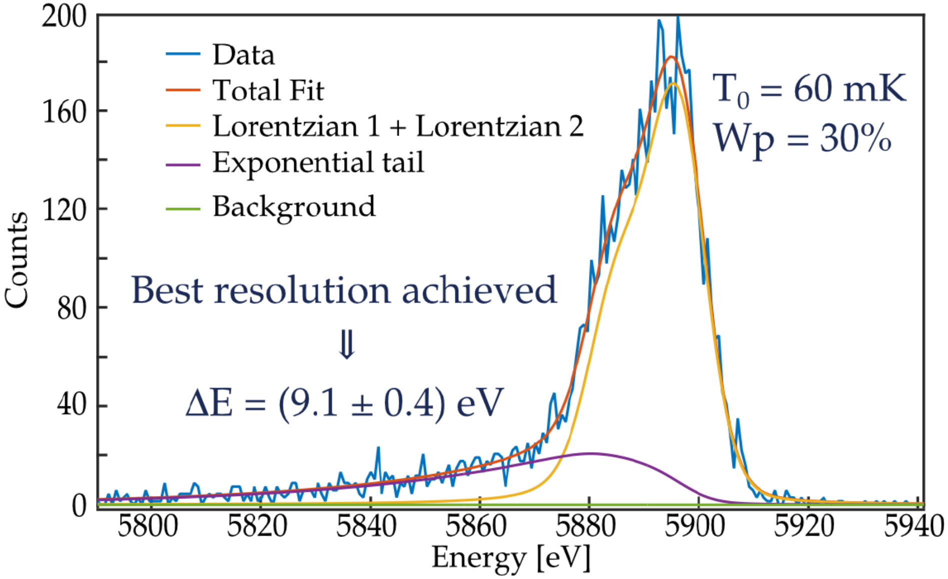


HOLMES: new results and future plans



First text of multiplexed TES detectors with no implanted ^{163}Ho

→ Very good energy resolution



HOLMES Timeline

End 2016 ^{163}Ho implantation in arrays

2017 detector characterization

2018 + measurements

3×10^{13} events in 3 years

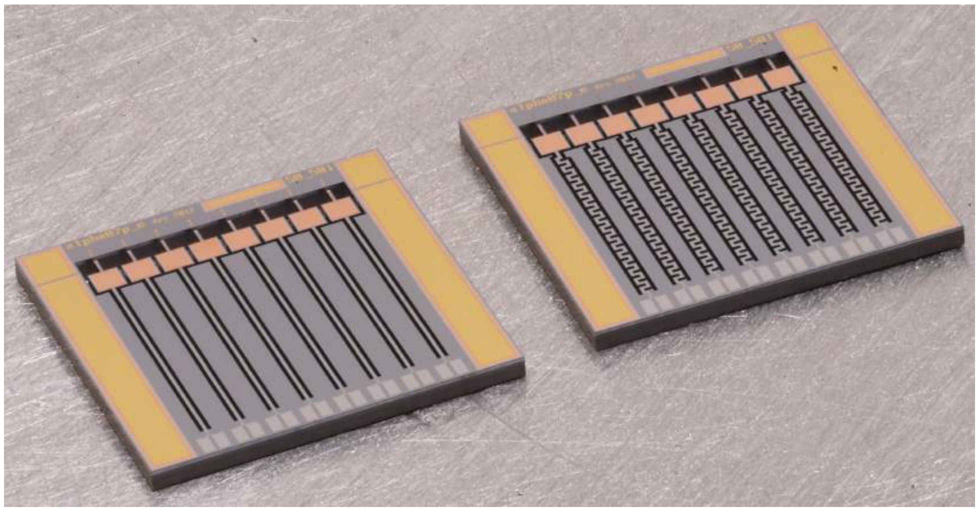
~ 1 eV sensitivity

A. Nucciotti, Trento Workshop 2016

NuMECS detectors

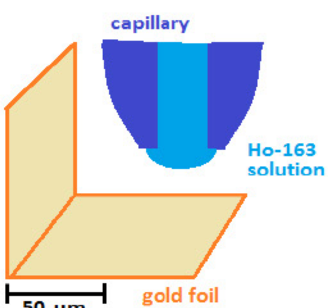
Transition Edge Sensor: MoCu superconducting films on solid silicon

- Completed the high-yield microfabrication
- Microwave multiplexing technique

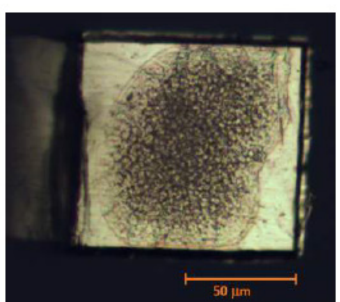


- Testing several methods of incorporating Ho into absorbers
  - * Au nanofoam

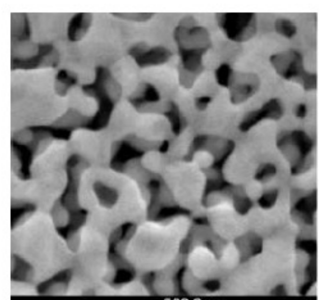
^{163}Ho depositon



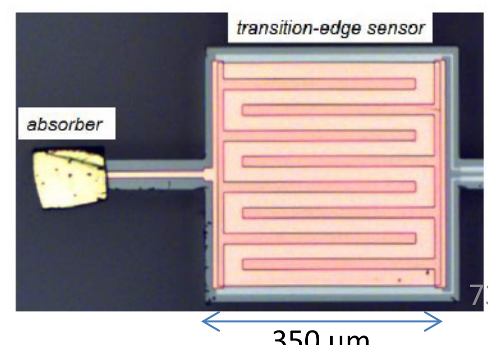
^{163}Ho salt on Au Foil



Nanoporous Au SEM

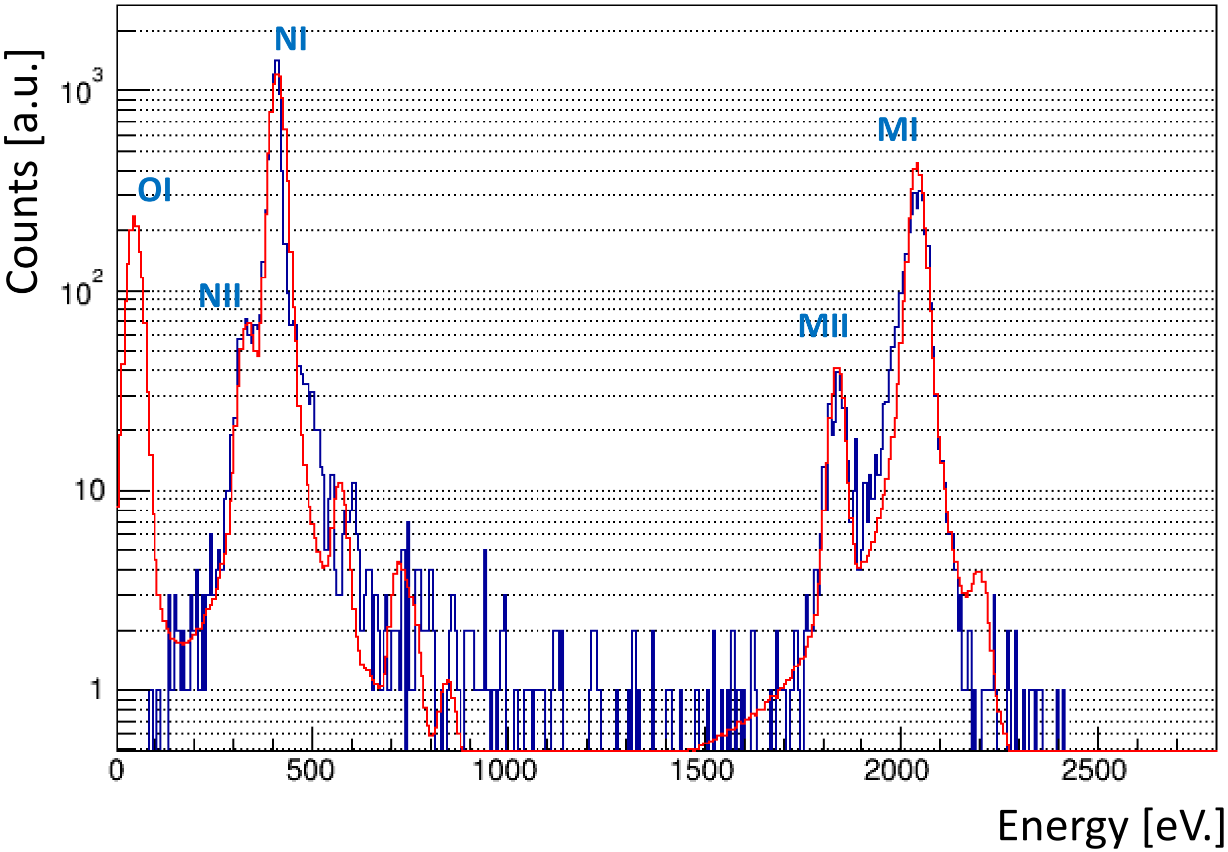


Absorber attached to TES



NuMECS: ^{163}Ho spectrum

^{163}Ho spectrum measured with detector prototypes



Very promising results!

R&D is on-going to improve detector performance

Experiments to study spectral shape

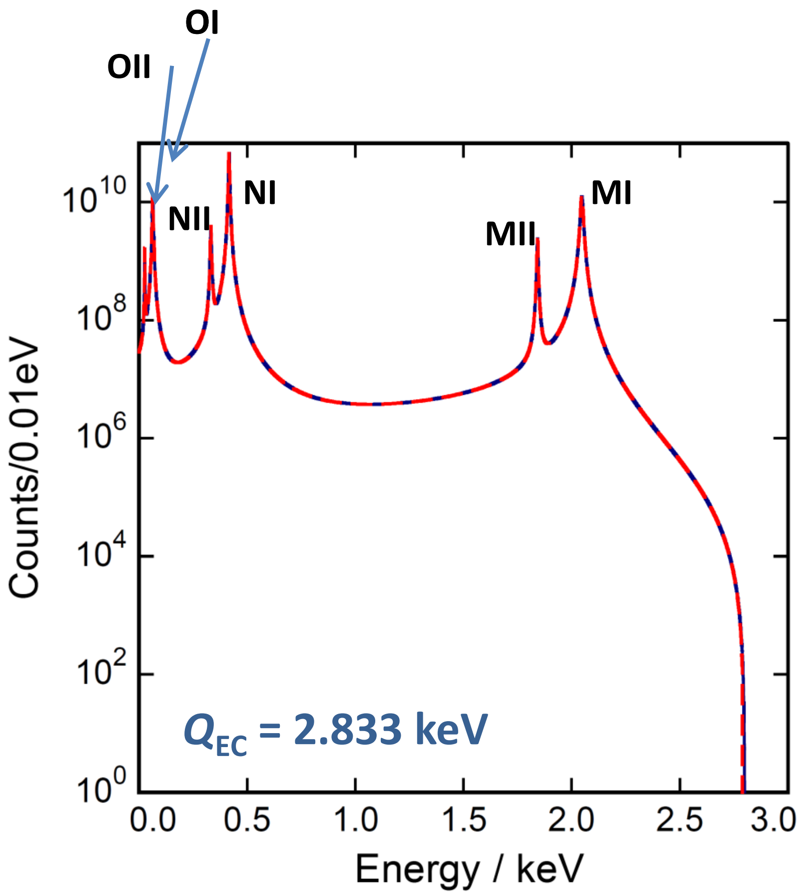
35 eV FWHM Gaussian convolved with calculation from *Faessler et al., Phys. Rev. C. 2015*

M. Croce et al., JLTP 184 3 (2016) 938

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

Sterile Neutrino and ^{163}Ho

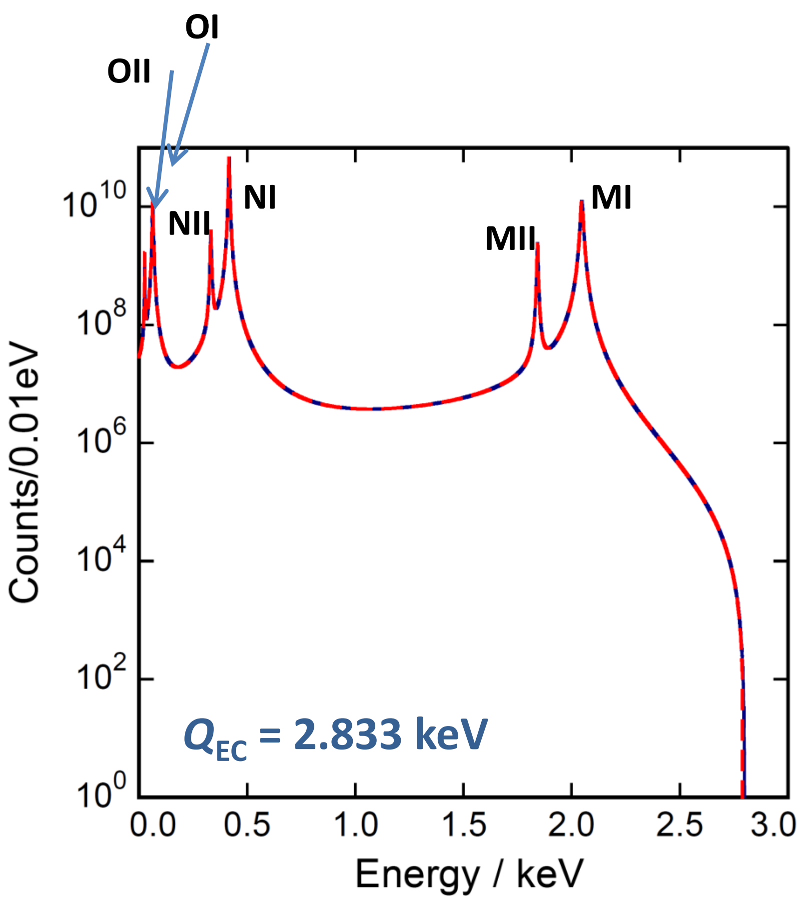
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$



Sterile Neutrino and ^{163}Ho

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

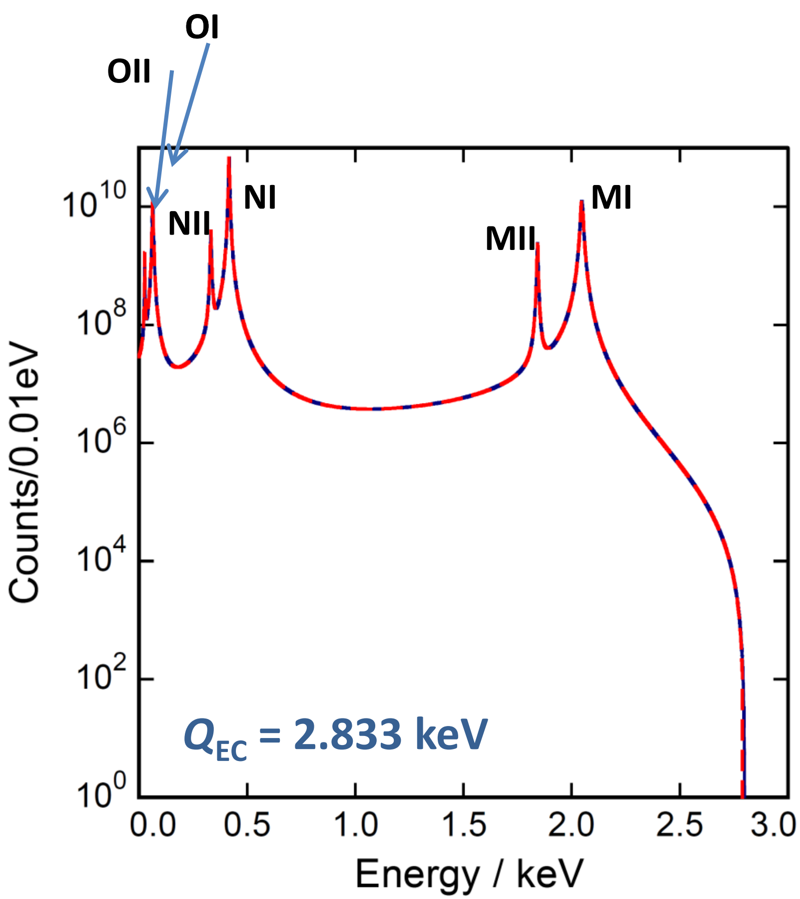
$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$



- Electron neutrino mass as superposition of mass eigenstates

Sterile Neutrino and ^{163}Ho

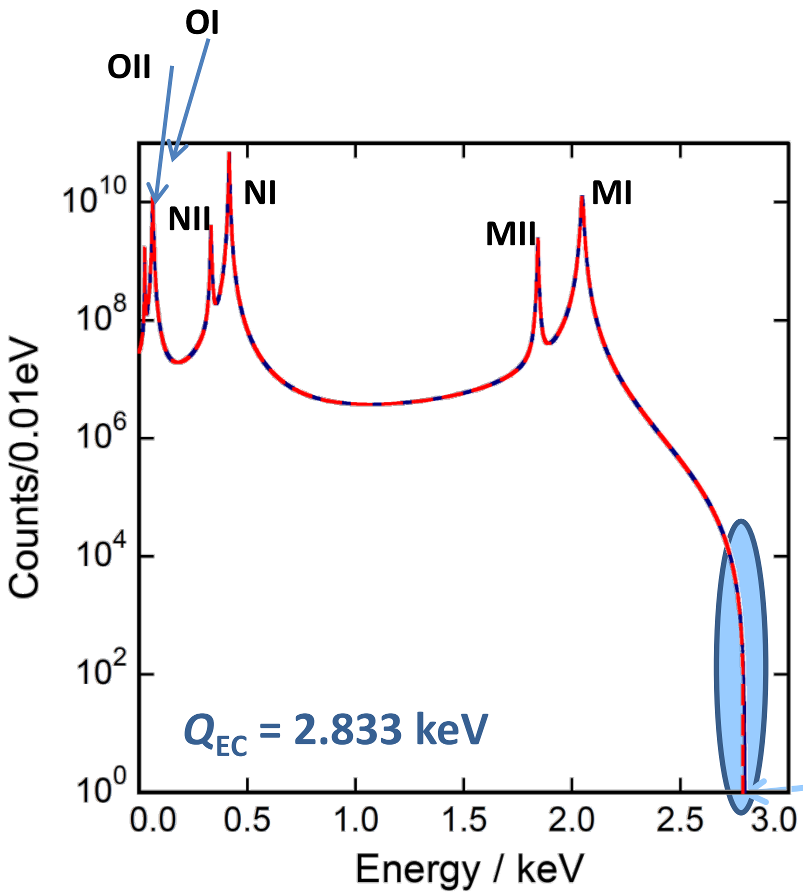
$$\frac{dW}{dE_C} = A(Q_{EC}-E_C)^2\left[\left(1-|U_{e4}|^2\right)+|U_{e4}|^2\sqrt{1-\frac{m_4^{\,2}}{(Q_{EC}-E_C)^2}}H(Q_{EC}-E_c-m_4)\right]\sum_H B_H\varphi_H^{\,2}(0)\frac{\frac{\Gamma_H}{2\pi}}{(E_C-E_H)^2+\frac{\Gamma_H^{\,2}}{4}}$$



- 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

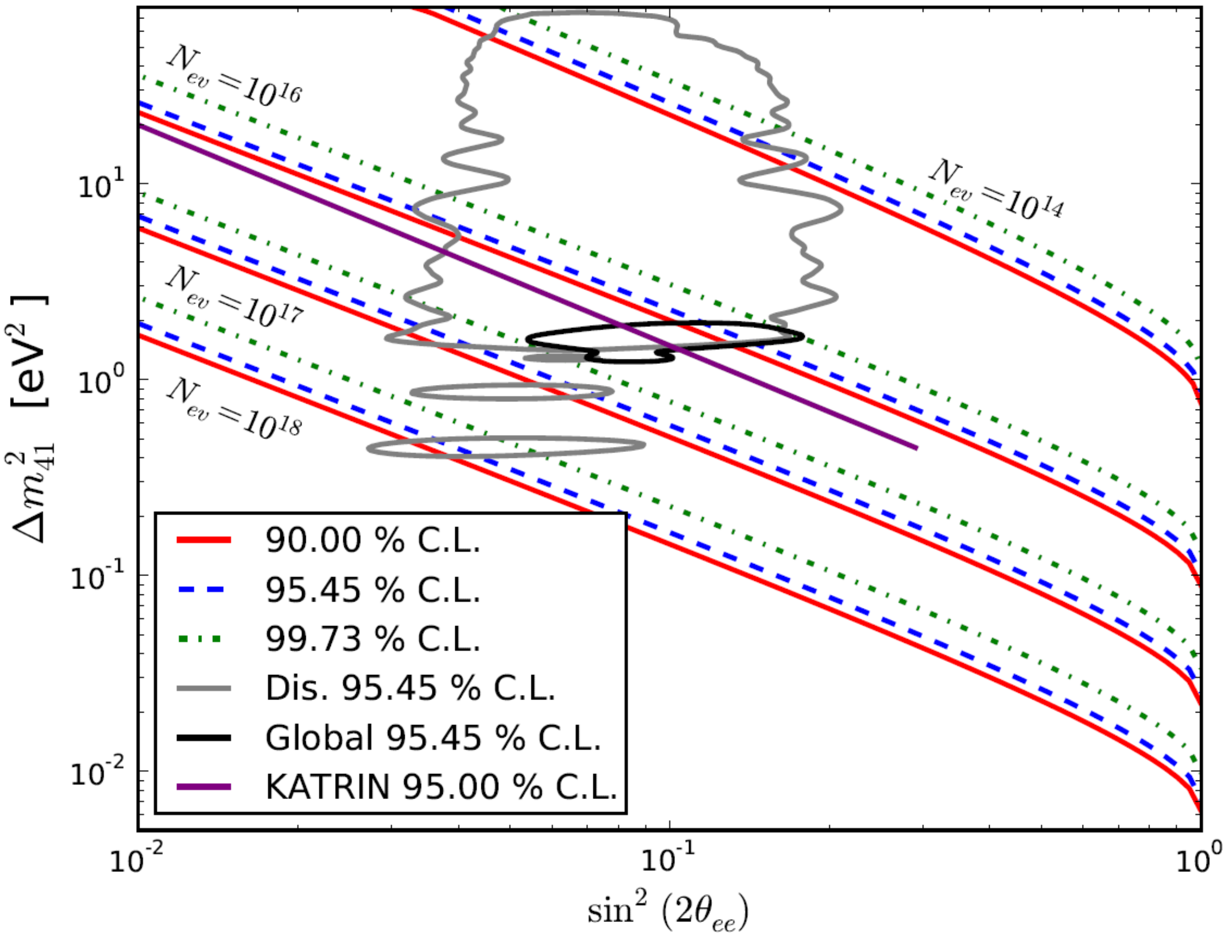
$$\frac{dW}{dE_C} = A(Q_{EC}-E_C)^2\left[\left(1-|U_{e4}|^2\right)+|U_{e4}|^2\sqrt{1-\frac{m_4{}^2}{(Q_{EC}-E_C)^2}}H(Q_{EC}-E_c-m_4)\right]\sum_H B_H\varphi_H{}^2(0)\frac{\frac{\Gamma_H}{2\pi}}{(E_C-E_H)^2+\frac{\Gamma_H{}^2}{4}}$$



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

eV-scale sterile neutrinos

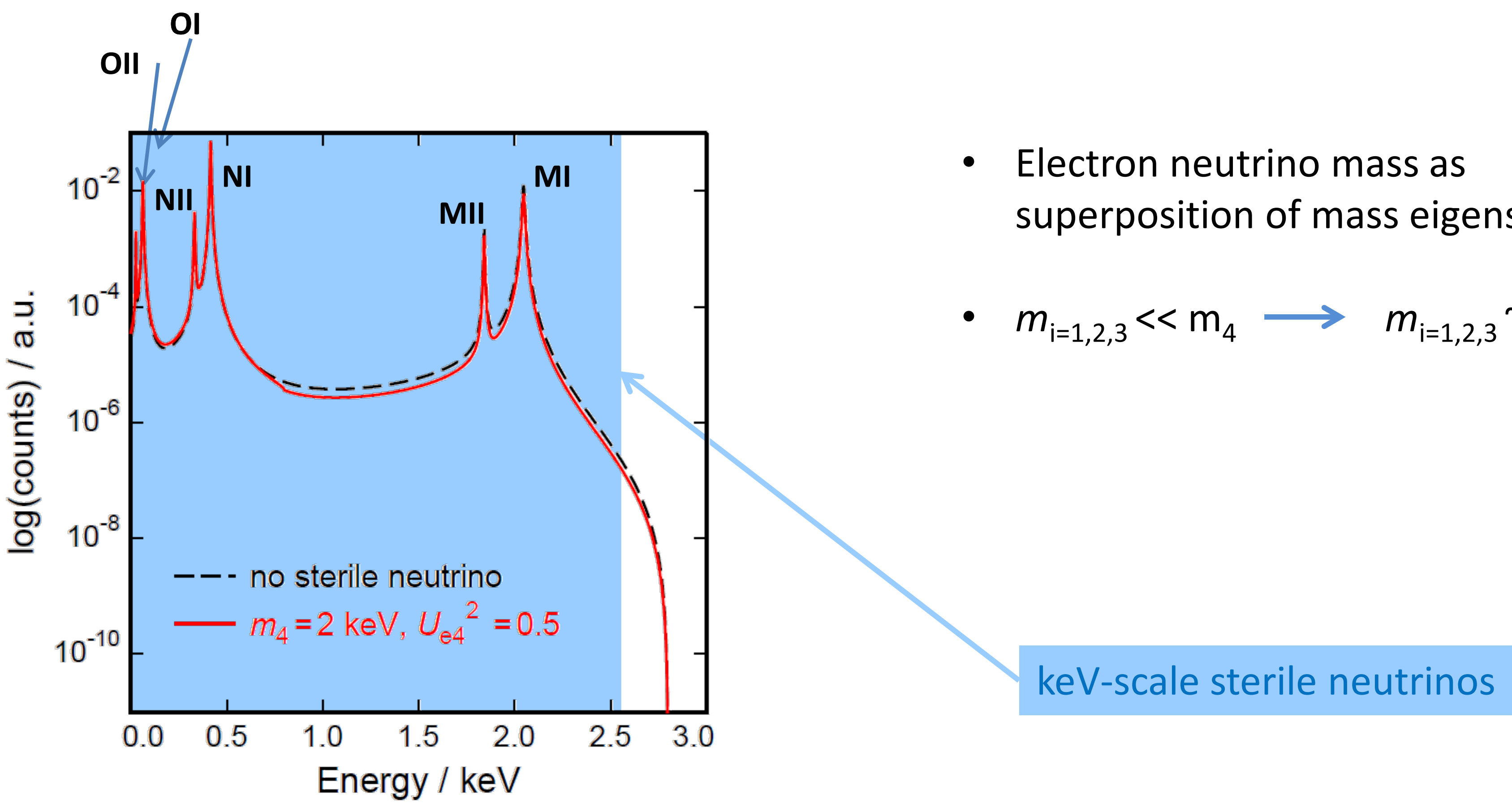
eV-scale sterile neutrino



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

keV-scale sterile neutrino

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

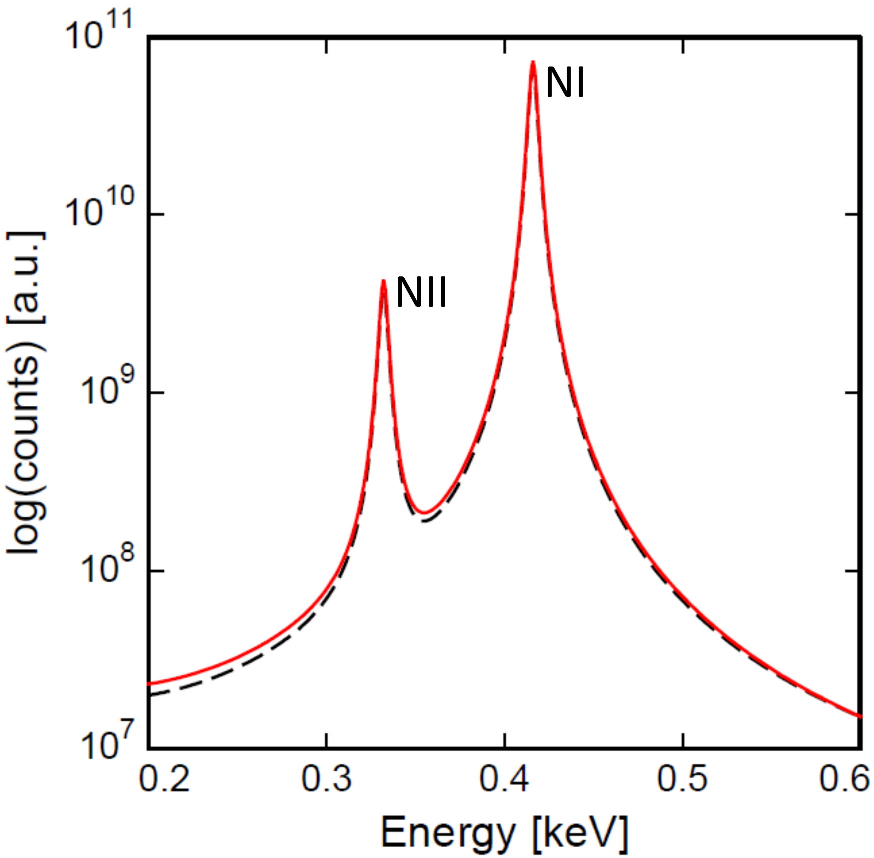


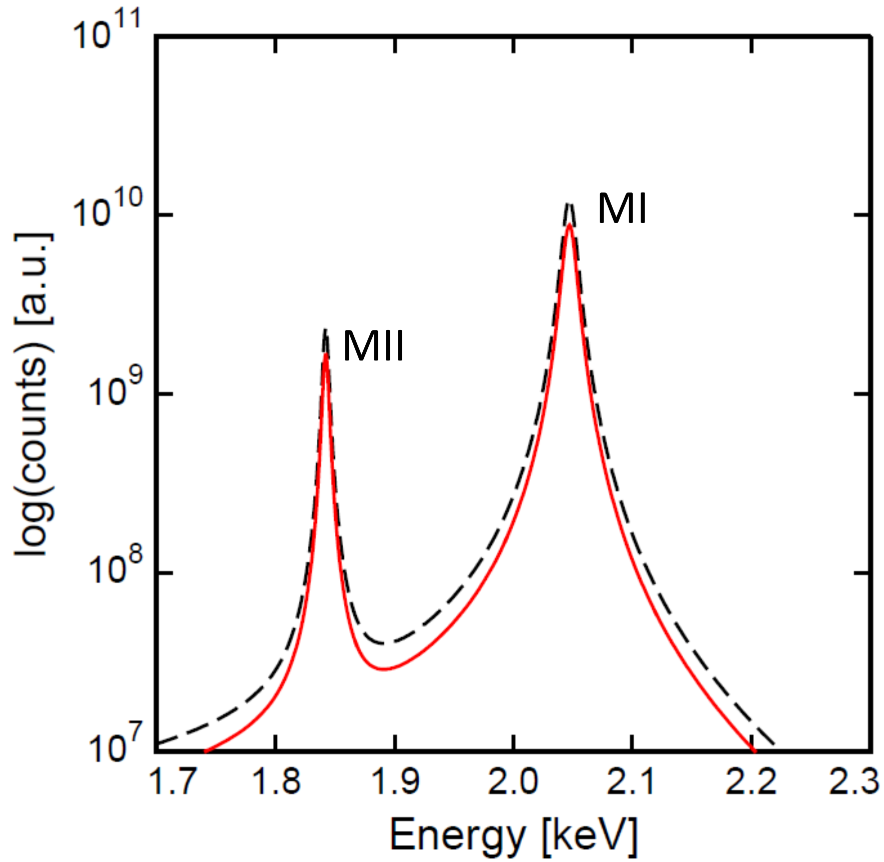
- Electron neutrino mass as superposition of mass eigenstates
- $m_{i=1,2,3} << m_4$ → $m_{i=1,2,3} \sim 0$ eV

keV-scale sterile neutrino

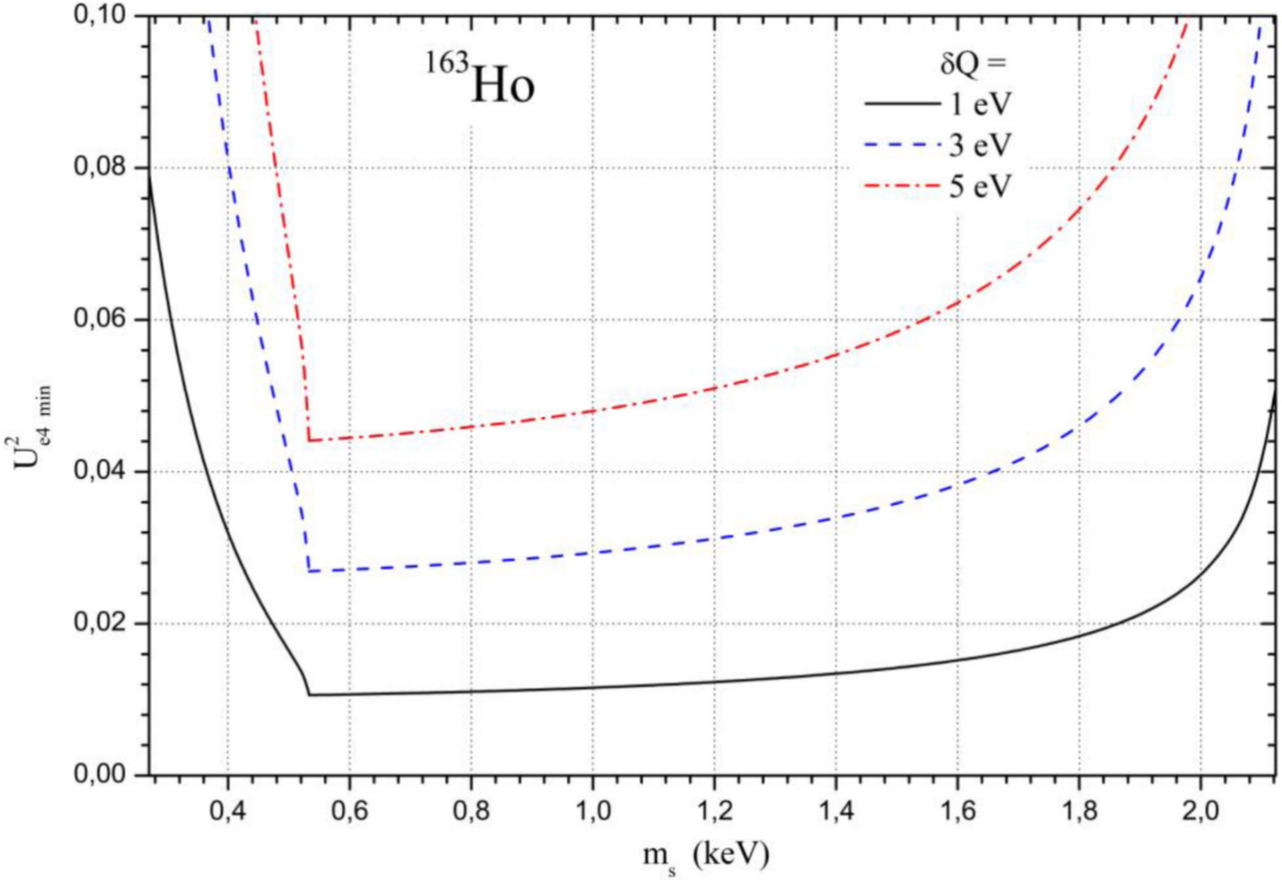
m_4=2 keV, $U_{e4}{}^2$=0.5

no sterile neutrino





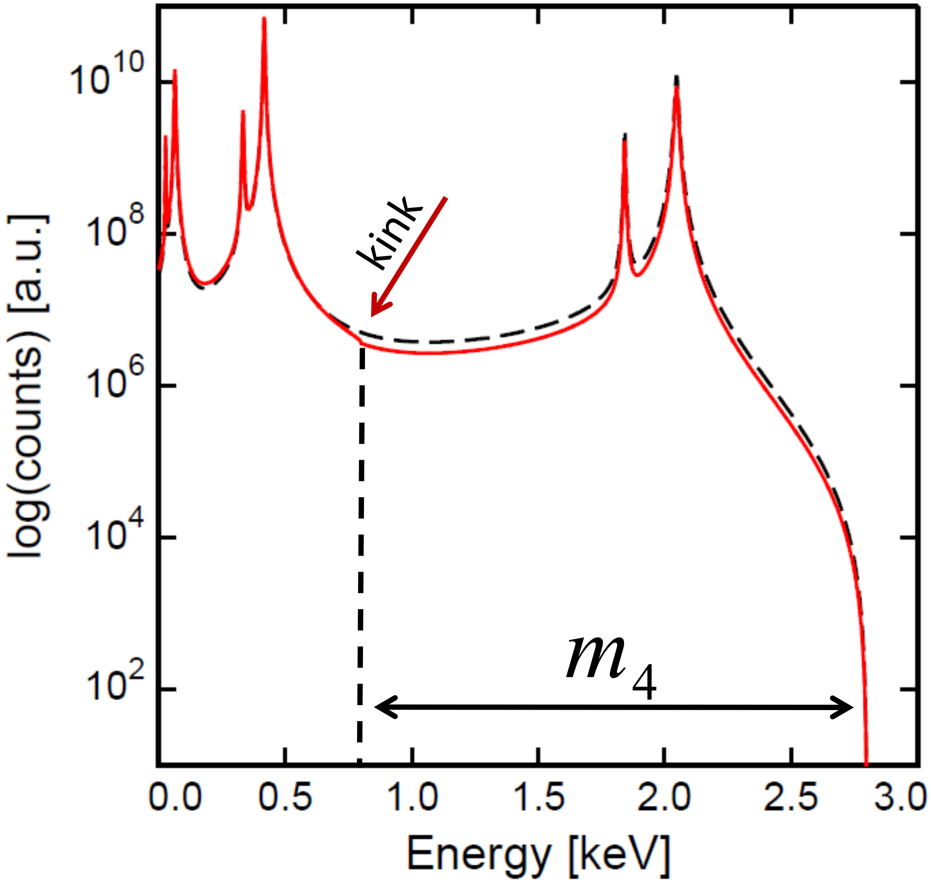
keV-scale sterile neutrino



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

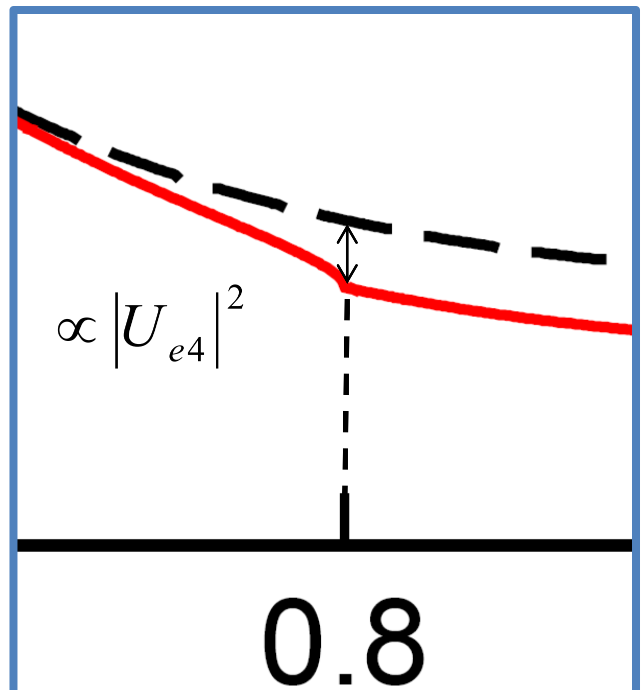
keV-scale sterile neutrino



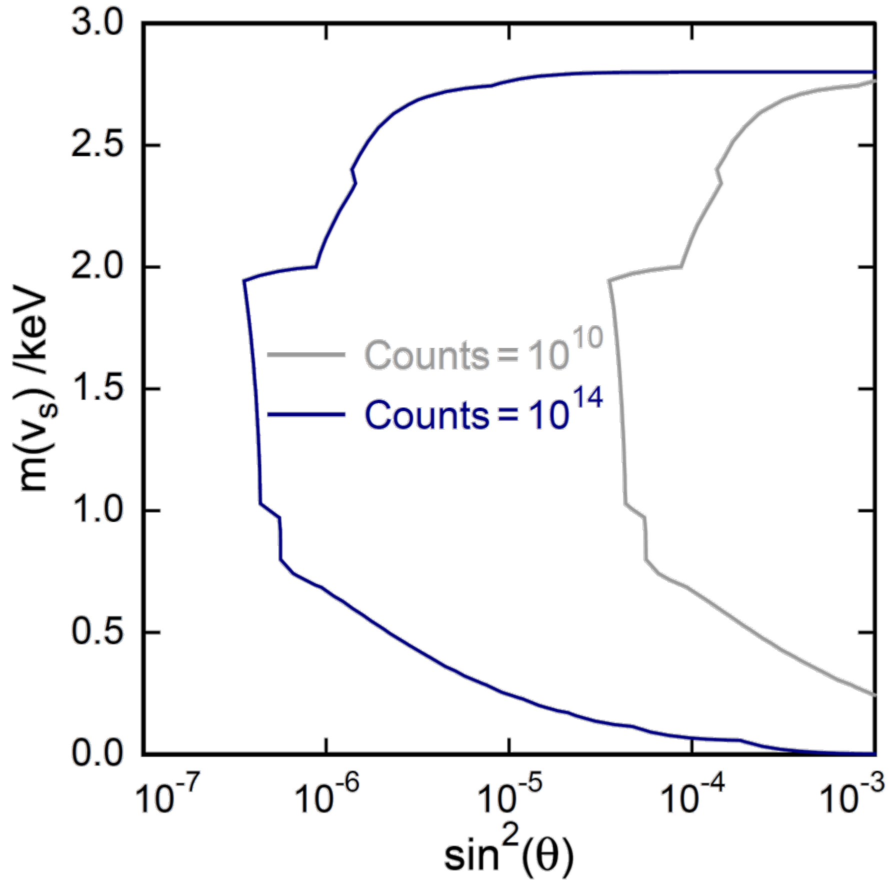
m_4=2 keV, U_{e4}^2=0.5

no sterile neutrino

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



keV-scale sterile neutrino

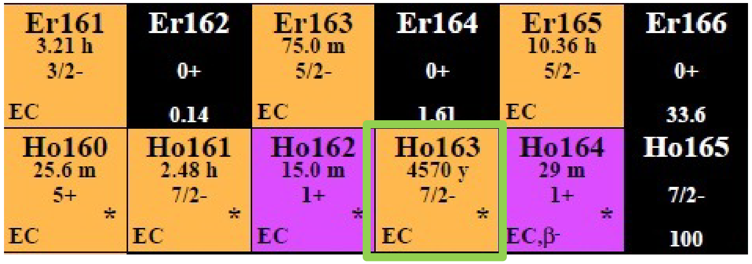


- Statistical Fluctuation
- No Pile Up
- Theoretical Spectrum supposed to be perfectly known

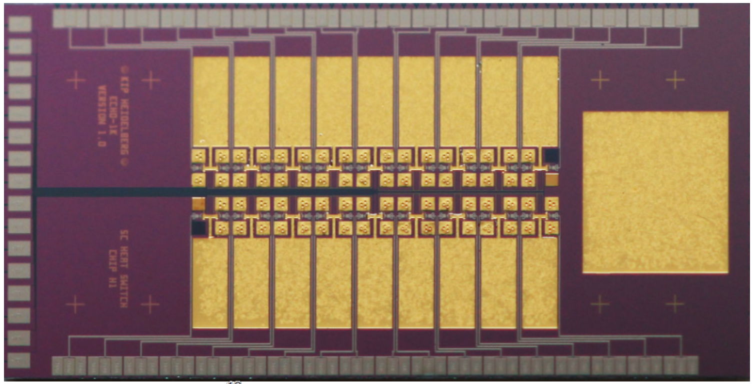
A White Paper on keV Sterile Neutrino Dark Matter arXiv:1602.04816v1

Conclusions and outlook

Three large collaboration aim to reach sub-eV sensitivity on the electron neutrino mass analysing high statistics and high resolution ^{163}Ho spectra

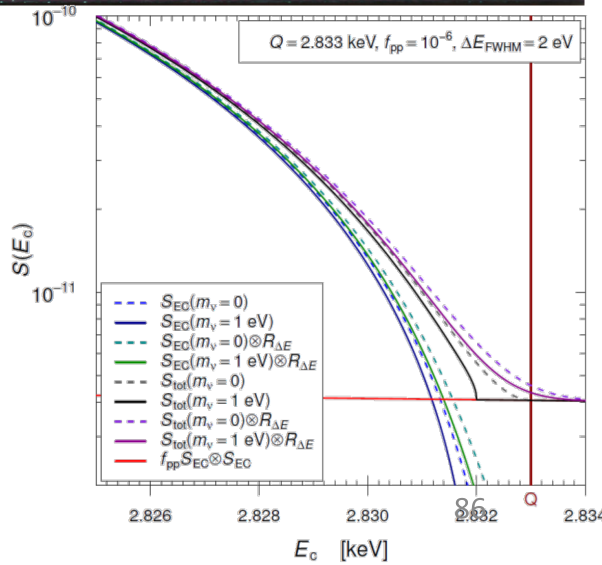


- High purity ^{163}Ho sources have been produced



- ^{163}Ho ions can be successfully enclosed in microcalorimeter absorbers

- Large arrays have been tested and microwave SQUID multiplexing has been successfully proved



- Search for signature of sterile neutrinos (eV- and keV-scale)

- **A new limit on the electron neutrino mass is approaching**


NI
MI
Thank you!
MII
E
NII

Take-home messages

- Where a finite electron neutrino mass affects the ^{163}Ho EC spectrum
- Experimental methods (advantages and disadvantages)
- International efforts – present status of the experiments
- What else can be learned from the ^{163}Ho EC spectrum