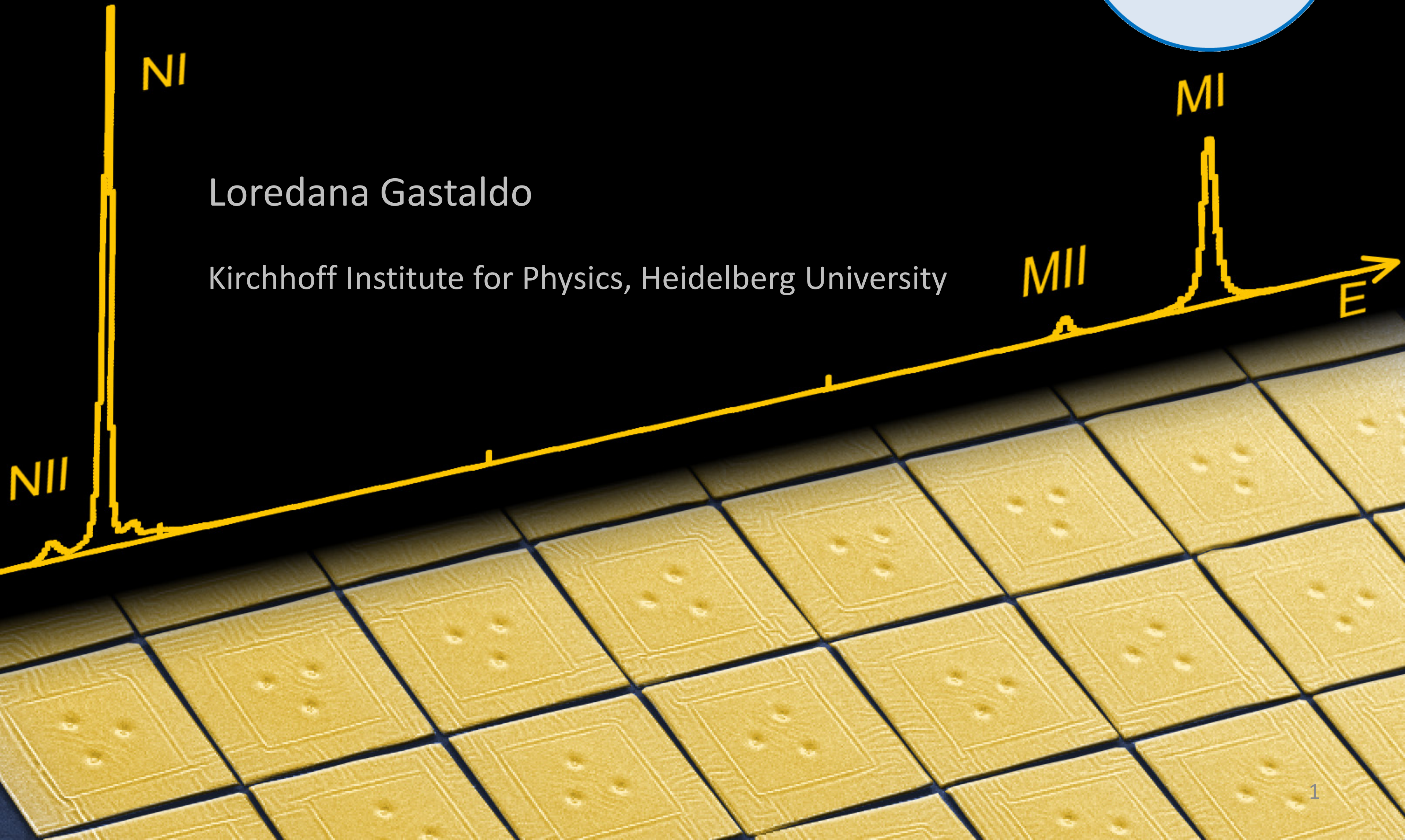
Electron Capture in ^{163}Ho experiment - ECHo



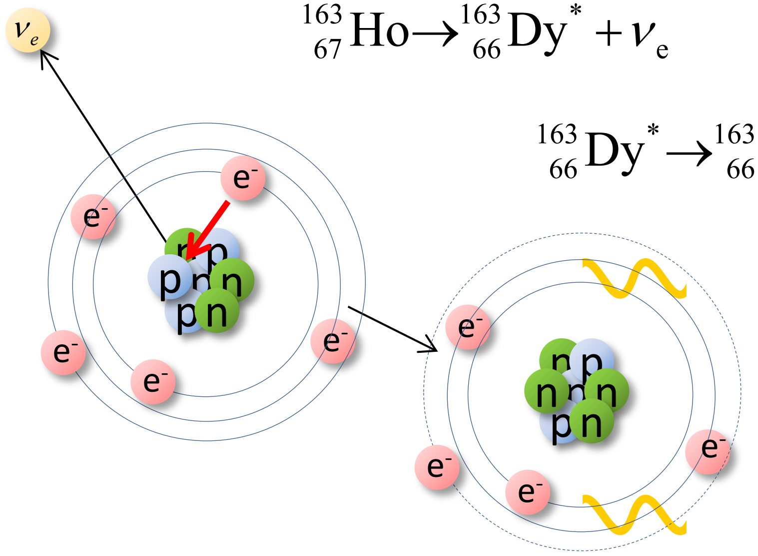
Loredana Gastaldo

Kirchhoff Institute for Physics, Heidelberg University

Outline

- Electron capture in ^{163}Ho and neutrino mass
- Requirements to achieve sub-eV sensitivity on the electron neutrino mass
- The Electron Capture in ^{163}Ho experiment - ECHo
- Conclusions and outlook

Electron capture in ^{163}Ho



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

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

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

- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)

- $Q_{\mathrm{EC}} = (2.833 \pm 0.030^{\mathrm{stat}} \pm 0.015^{\mathrm{syst}})$ keV S. Eliseev et al., *Phys. Rev. Lett.*, 115, 062501 (2015)
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- Low Q_{EC}-value allows capture only for:
  3s, $3p_{1/2}$, 4s, $p_{1/2}$, 5s, $5p_{1/2}$, 6s electrons

Electron capture in ^{163}Ho

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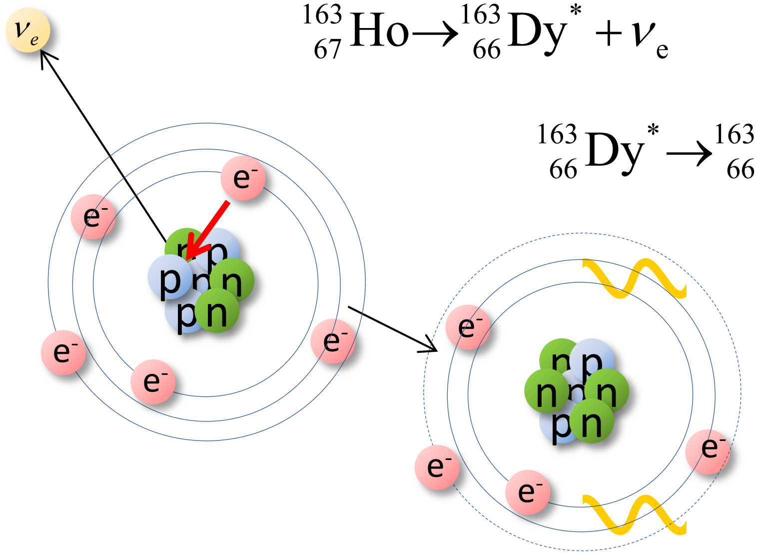

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Talk by Klaus Blaum on Wednesday

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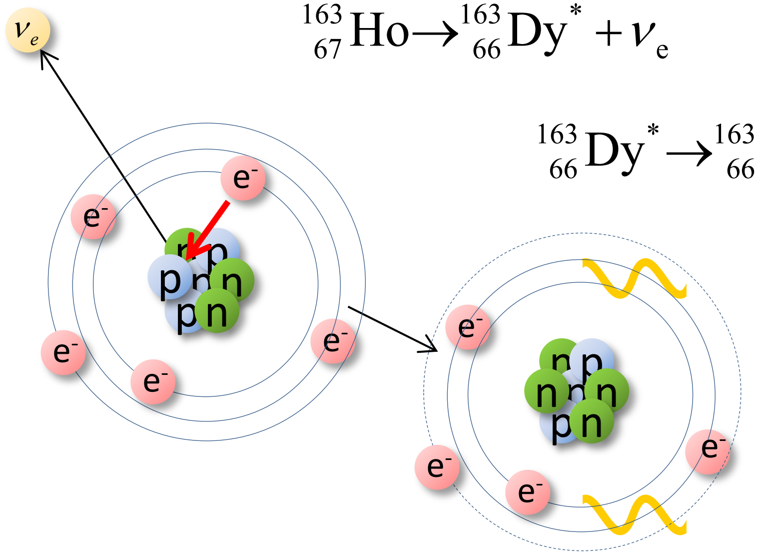

Atomic de-excitation:

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

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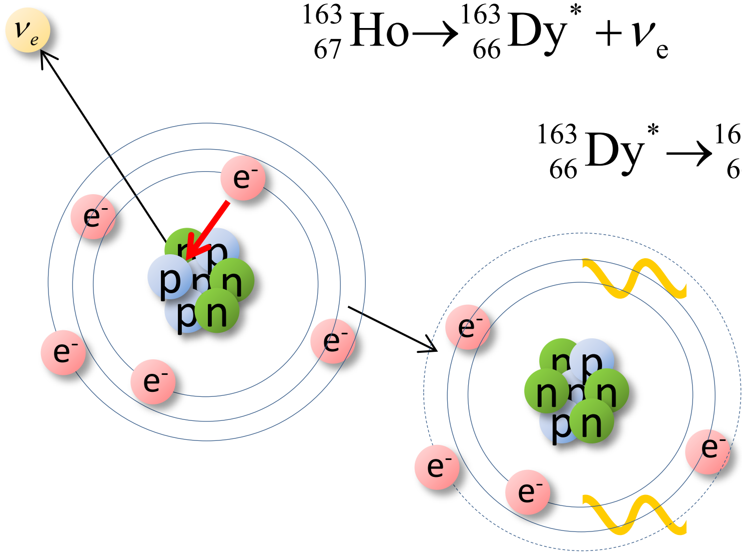
Electron capture in ^{163}Ho



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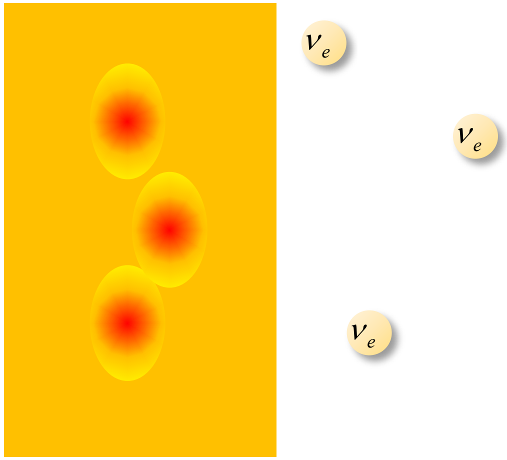
Atomic de-excitation:

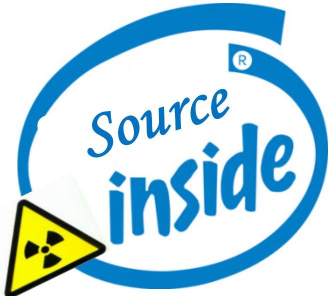
- **X-ray emission**
- **Auger electrons**
- **Coster-Kronig transitions**

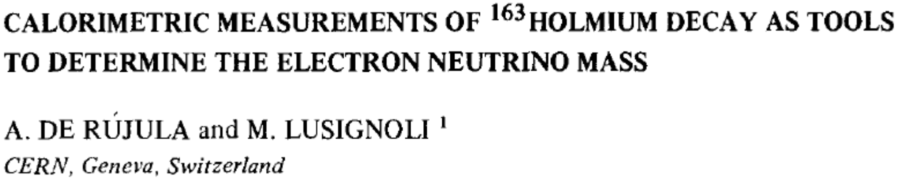
Calorimetric measurement

All the energy released in the electron capture process minus the one of the electron neutrino is measured by the detector



Source = Detector



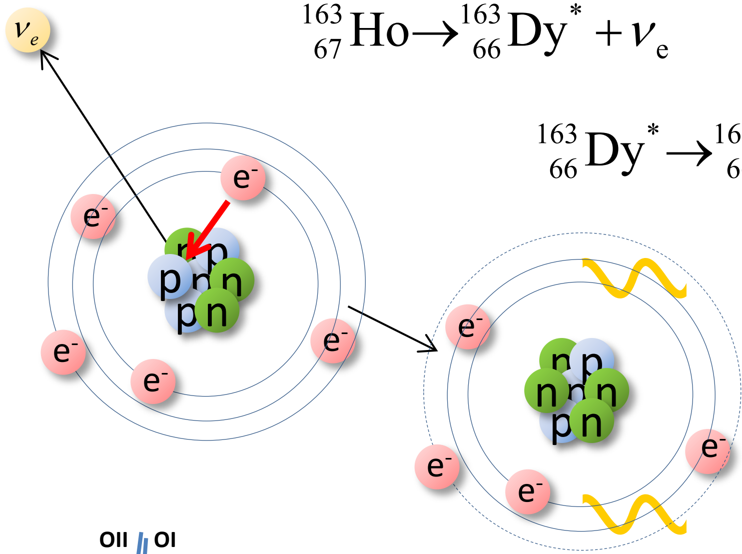

CALORIMETRIC MEASUREMENTS OF ^{163}HOLMIUM DECAY AS TOOLS TO DETERMINE THE ELECTRON NEUTRINO MASS

A. DE RÚJULA and M. LUSIGNOLI [1]

CERN, Geneva, Switzerland

Phys. Lett. 118 B (1982) 118

Electron capture in ^{163}Ho



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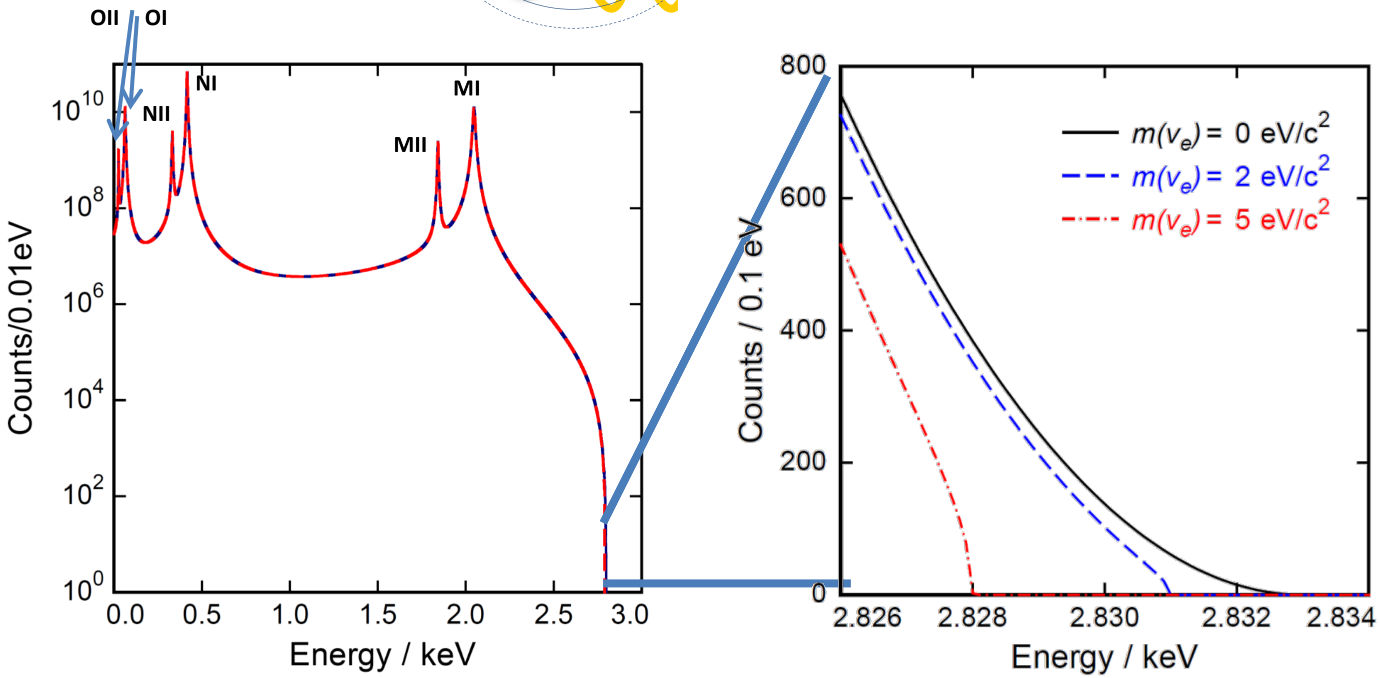


Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

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

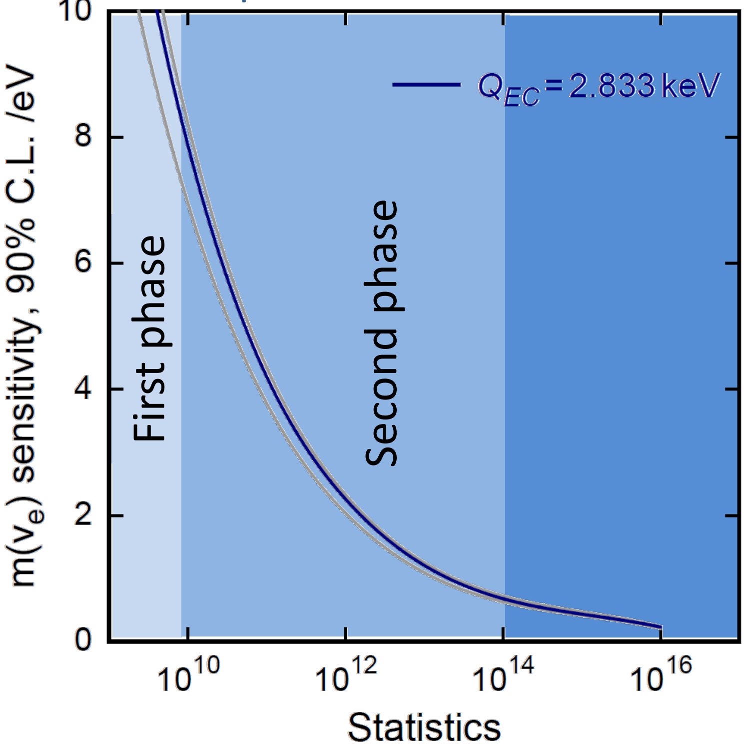
Precision characterization of the endpoint region

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

Background level

- **< 10^{-5} events/eV/det/day**

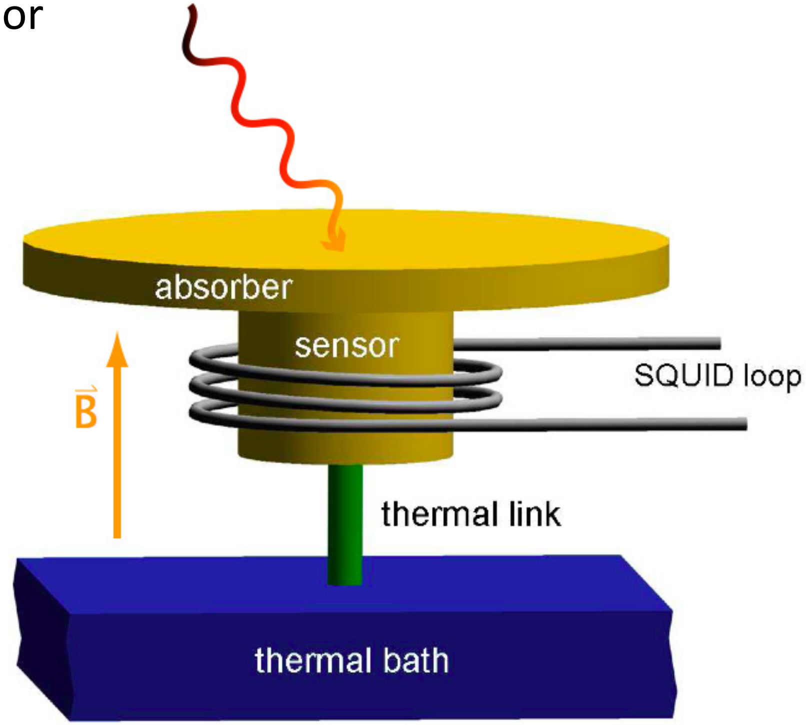
$f_{pu} = 10^{-6}$ $\Delta E_{FWHM} = 2$ eV



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

Metallic magnetic calorimeters (MMCs)

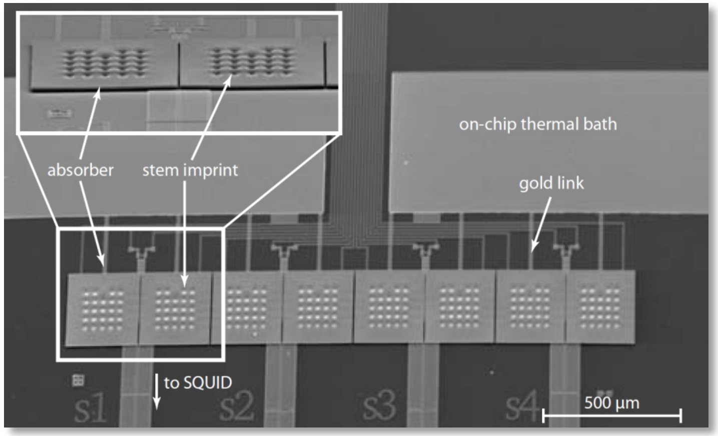
- Paramagnetic Ag:Er sensor

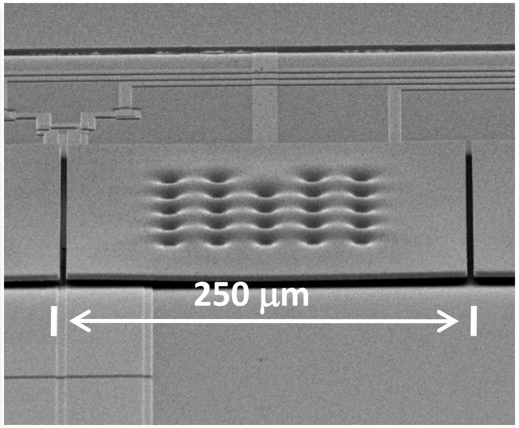


$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\,\frac{E}{C_{\mathrm{sens}}+C_{\mathrm{abs}}}$$

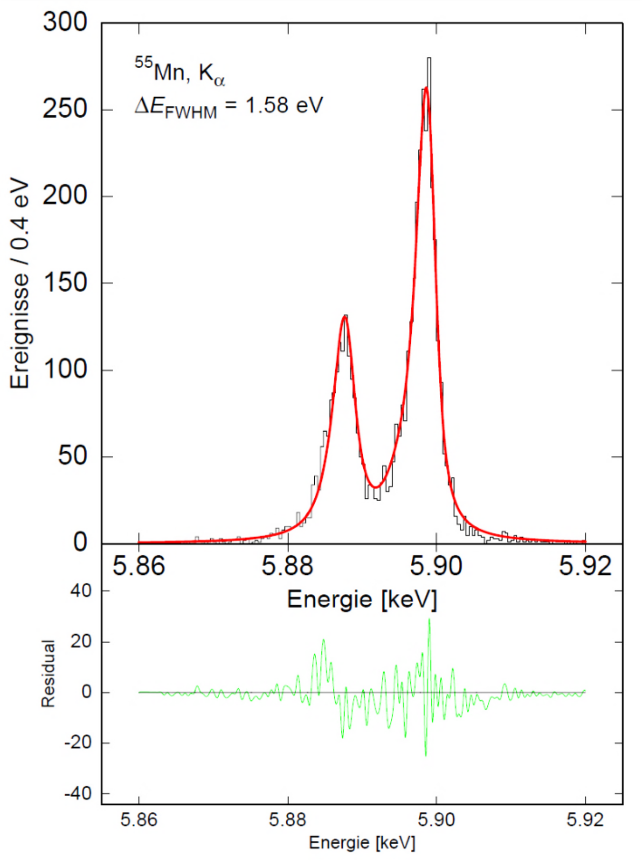
A. Fleischmann et al., *AIP Conf. Proc.* **1185**, 571, (2009)

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

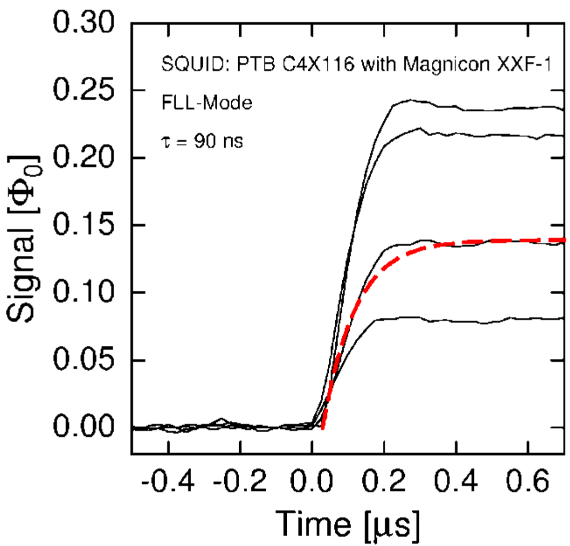




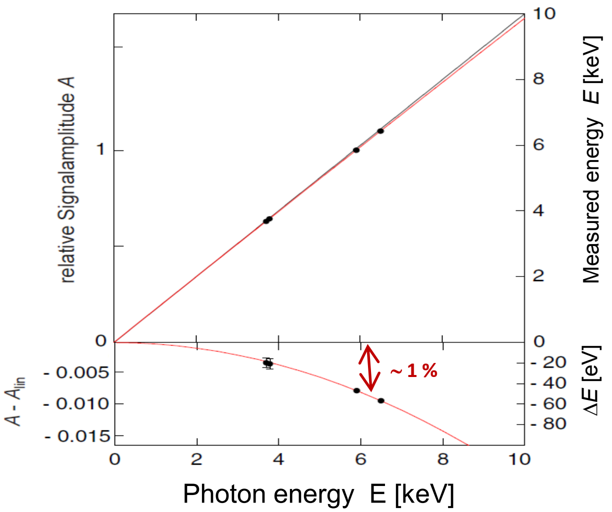
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



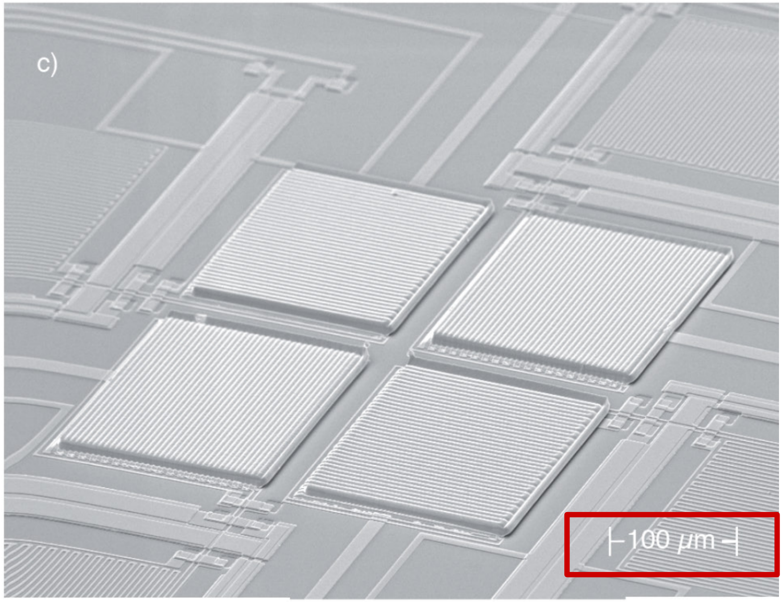
Reduction
un-resolved pile-up

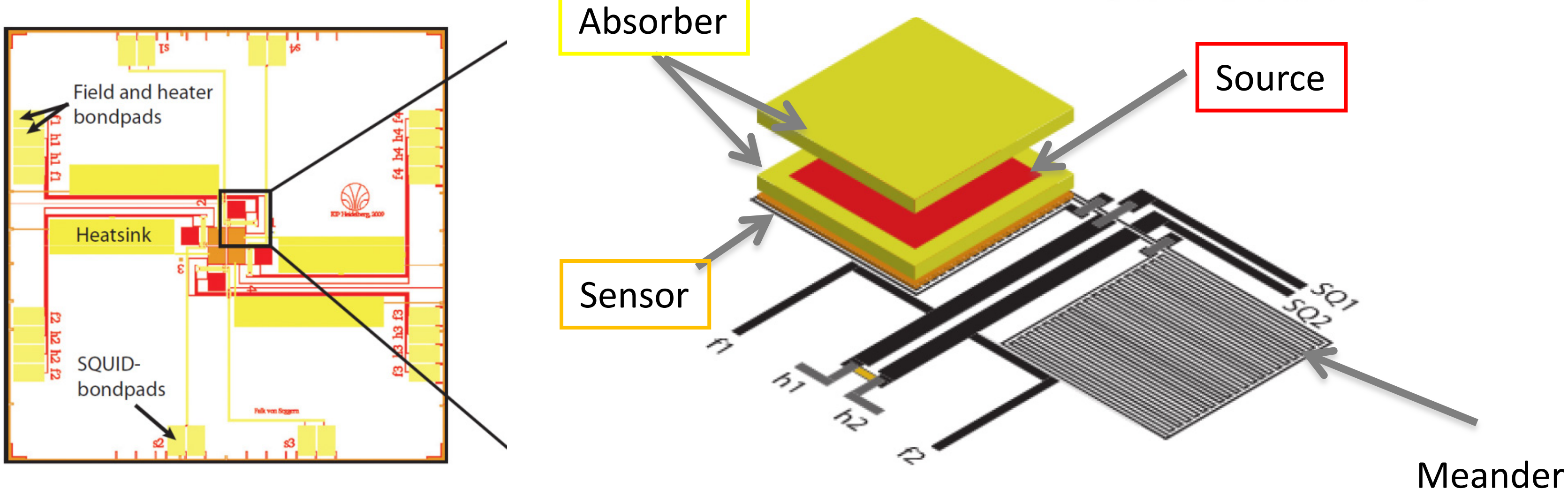
Definition
of the energy scale

Reduced smearing
in the end point region

First prototype of ^{163}Ho loaded MMC

- Absorber for metallic magnetic calorimeters
  → ion implantation @ ISOLDE-CERN in 2009
  on-line process
- About 0.01 Bq per pixel
- Operated over more than 4 years





Absorber

Source

Sensor

Meander

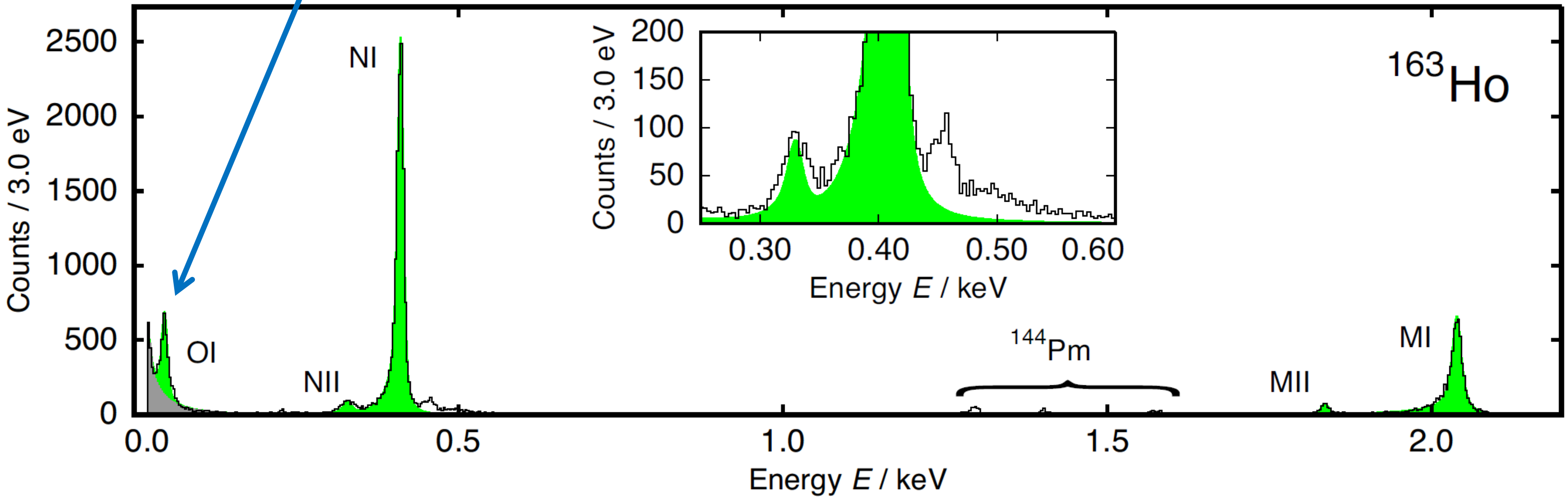
L. Gastaldo et al., Nucl. Inst. Meth. A, 711 (2013) 150

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

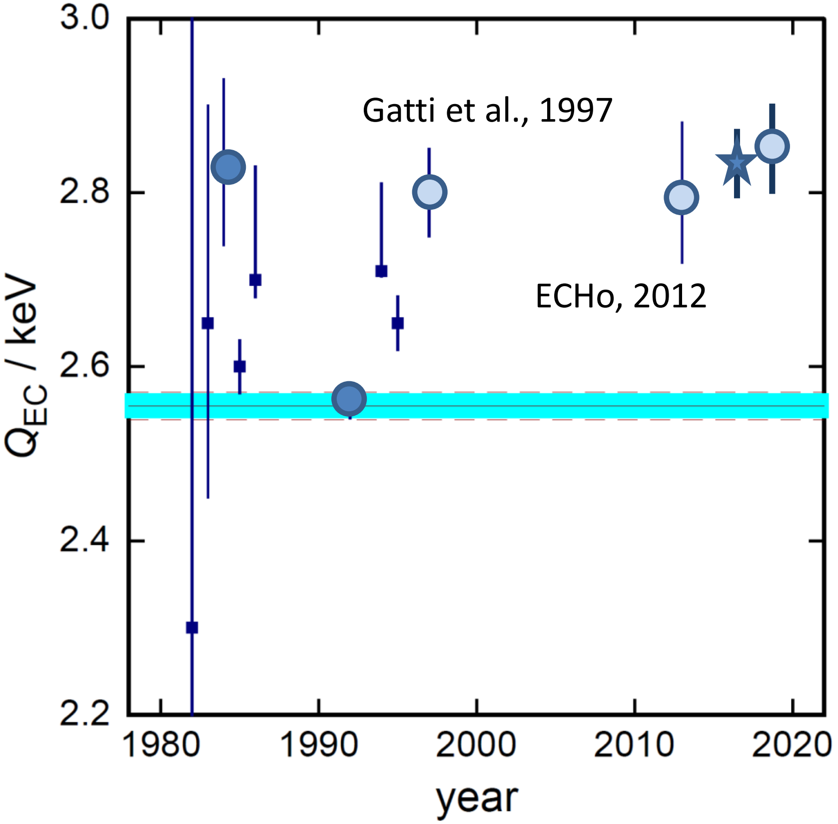
First calorimetric measurement of the OI-line

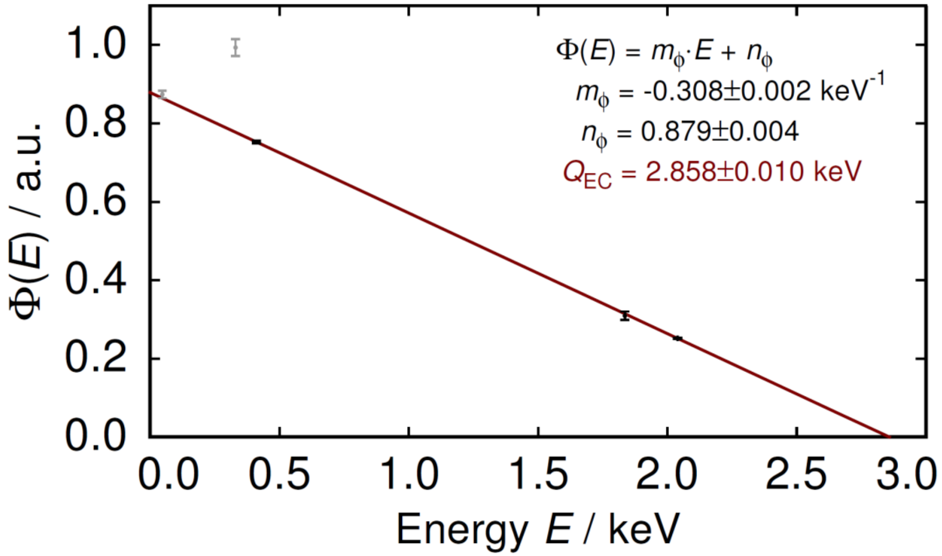


P. C.-O. Ranitzsch et al., *Phys. Rev. Lett.*, 119, 122501 (2017)

Q_{EC} determination

$$\Phi_H(E) = \sqrt{\frac{n_H}{\varphi_H^2(0) B_H}} \propto \sqrt{C}(Q_{EC} - E_H)$$





Our result:

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

P. C.-O. Ranitzsch et al., *Phys. Rev. Lett.*, 119, 122501 (2017)

Penning Trap Mass Spectrometry result:

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

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

Scaling up

^{163}Ho high purity source

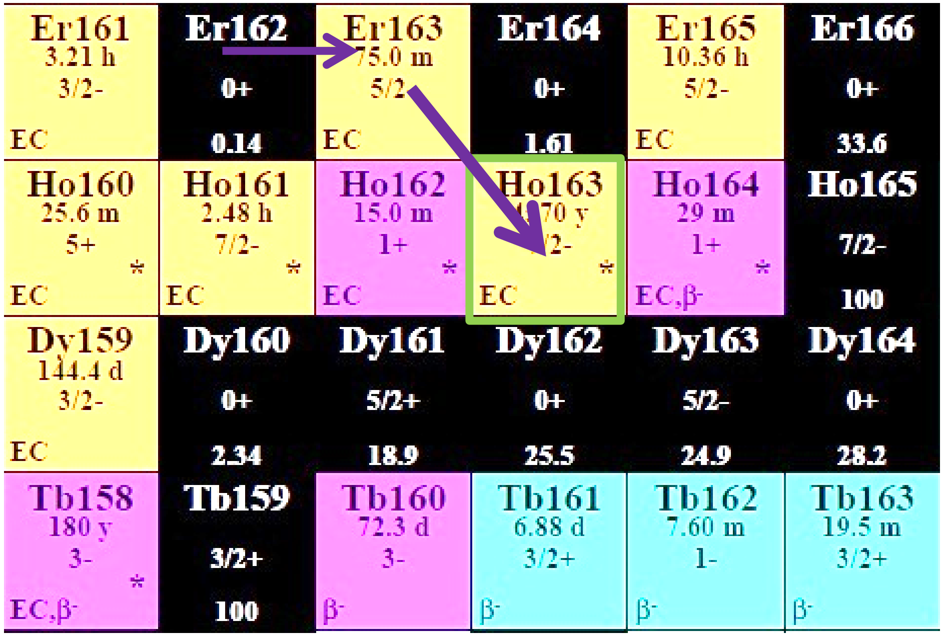
Required activity in the detectors: Final experiment → >10^6 Bq → >10^{17} atoms

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

  High cross-section ☺

  Radioactive contaminants 🚫



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 [illegible]70 y [illegible]/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100
Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb158 180 y 3- * EC,β-	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-

H. Dorrer et al, submitted to Radiochim. Acta (2017)

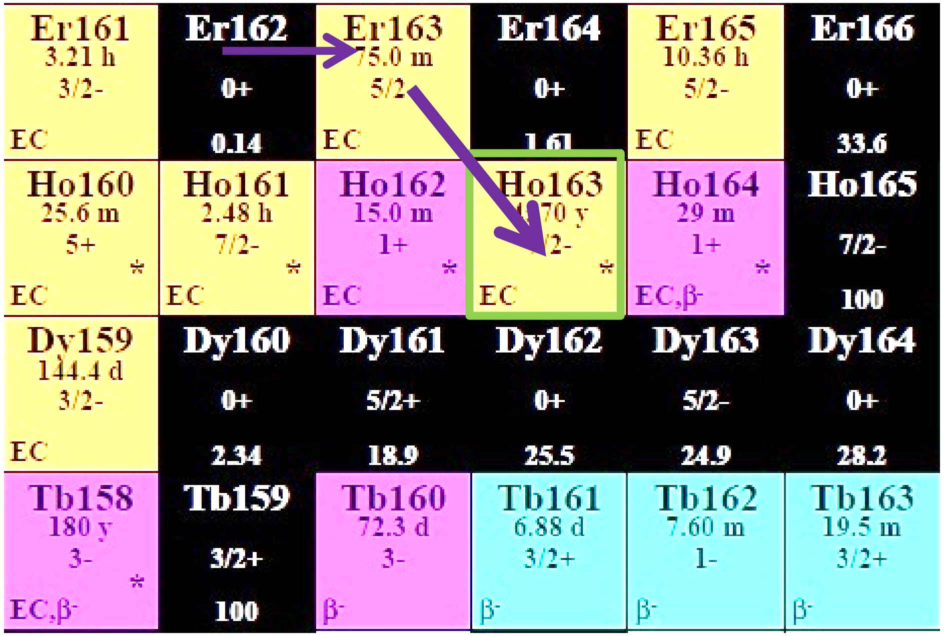
^{163}Ho high purity source

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 → Excellent 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 70 y /2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100
Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb158 180 y 3- * EC,β-	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-

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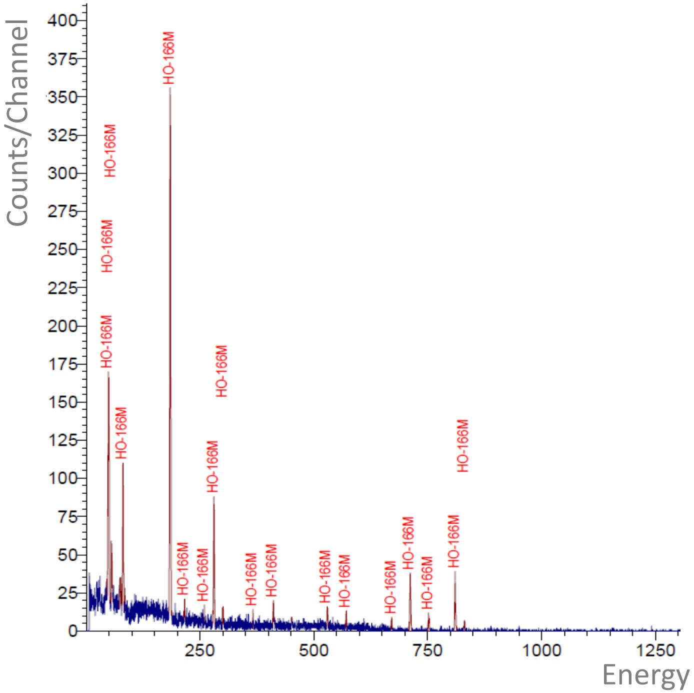
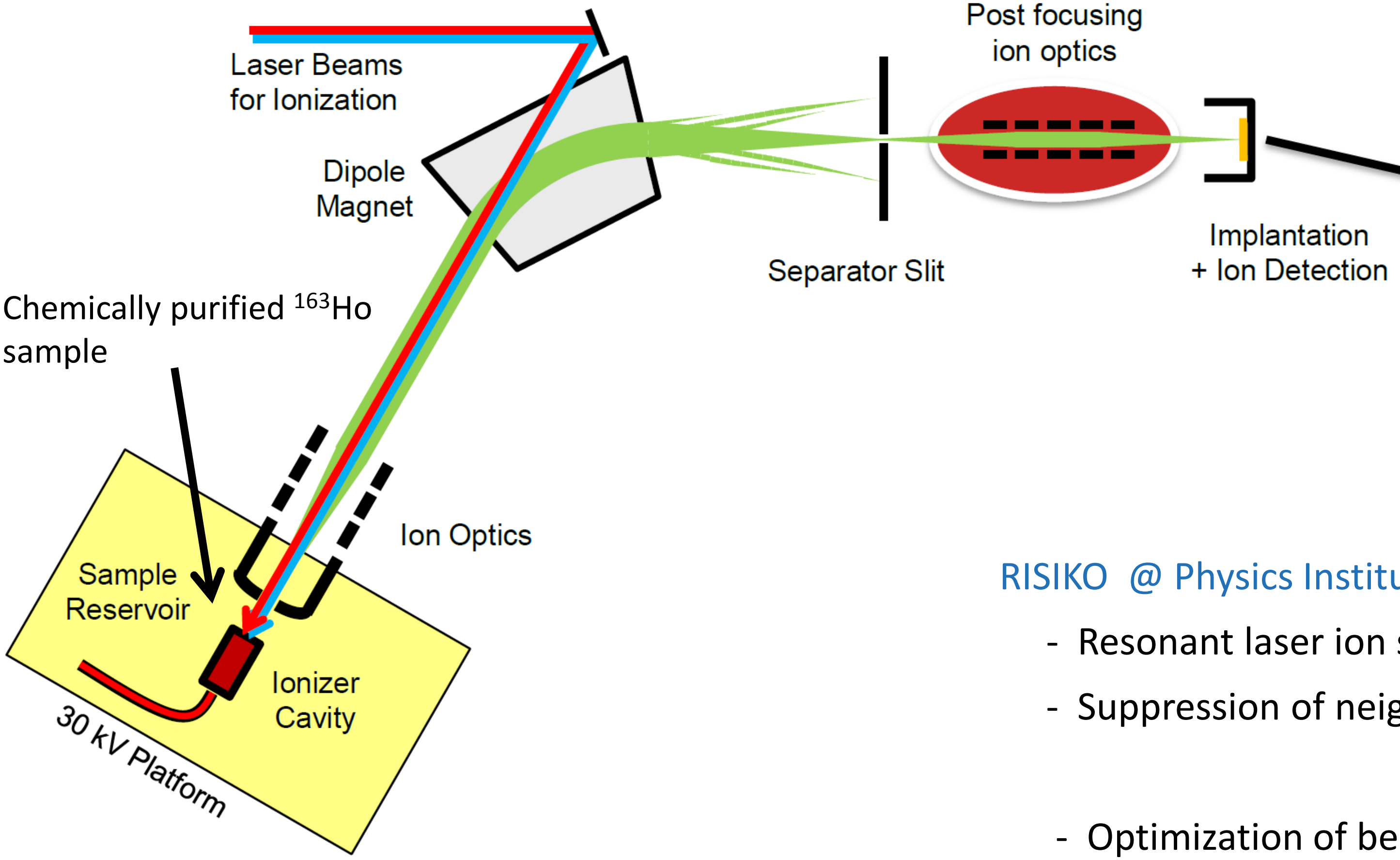
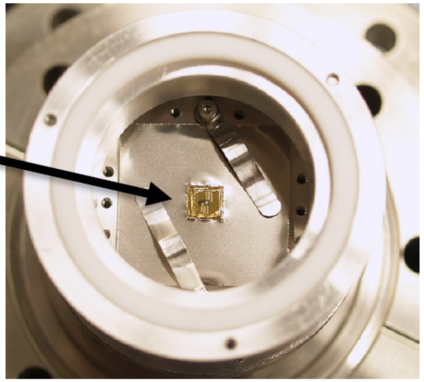


Mass separation and ^{163}Ho ion-implantation





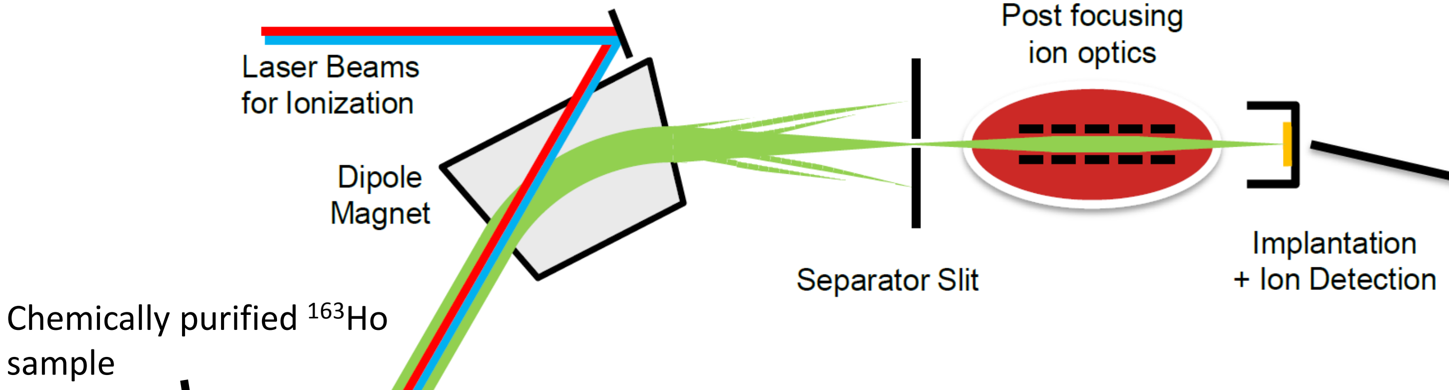
RISIKO @ Physics Institute, Mainz University

- Resonant laser ion source efficiency **41%**
- Suppression of neighboring masses > **700**

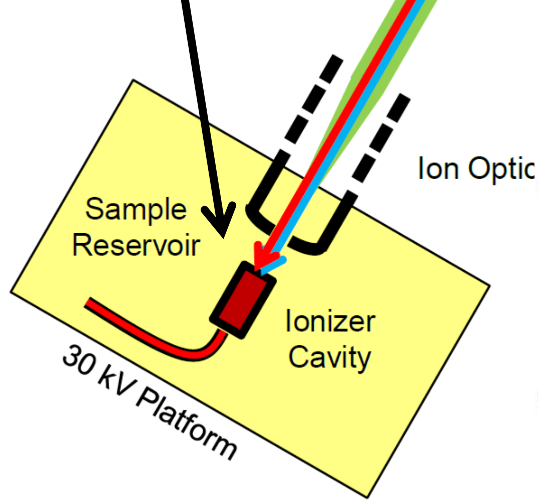
  → **^{166m}Ho/^{163}Ho < 10^{-8}**
- Optimization of beam focalization

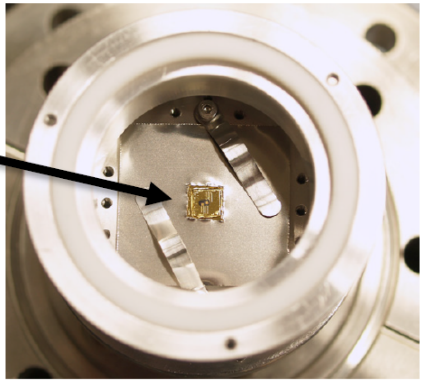
F. Schneider et al ., *NIM B* **376** (2016) 388

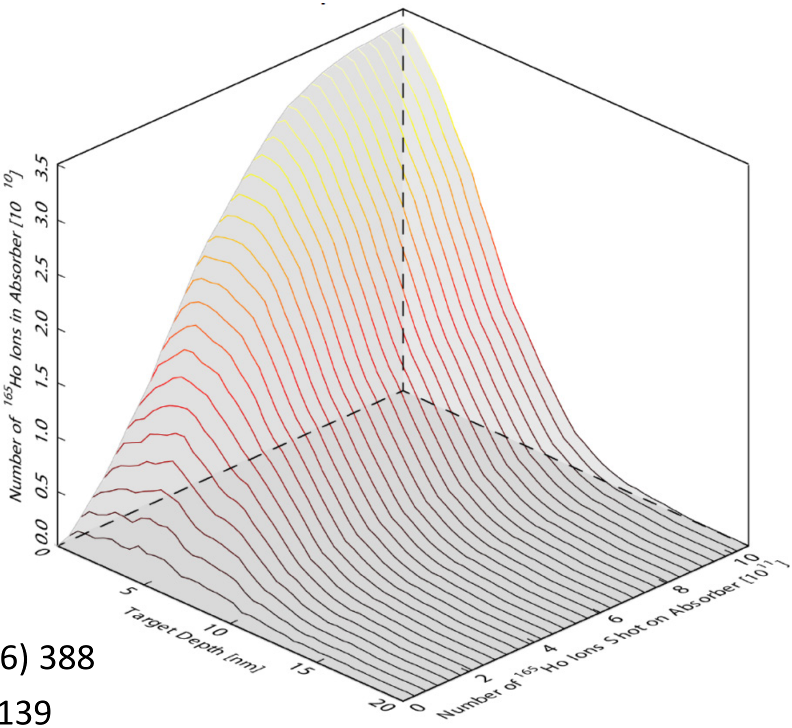
Mass separation and ^{163}Ho ion-implantation



Chemically purified ^{163}Ho sample





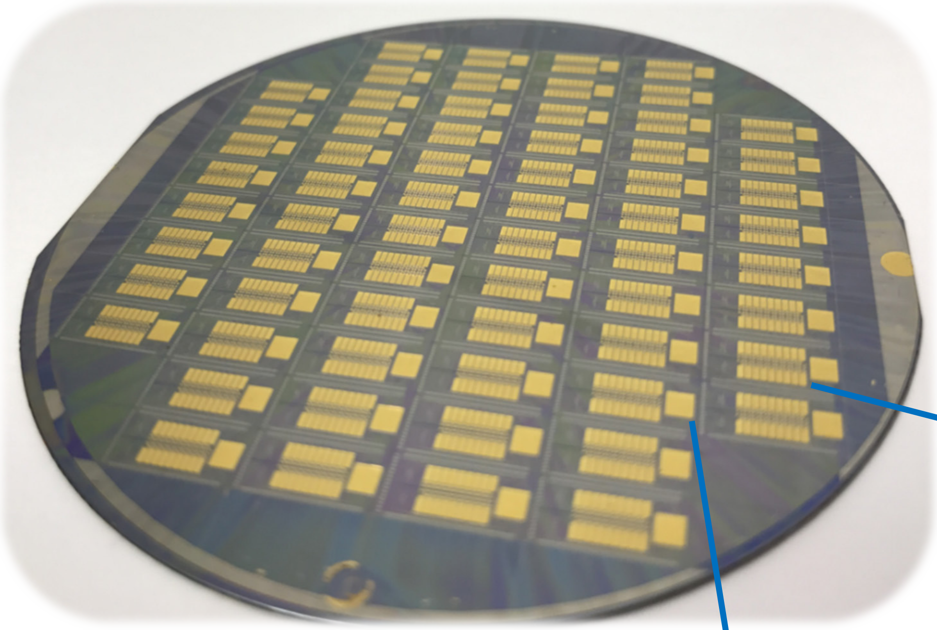


Backscattering and sputtering of absorber atoms affect implantation process:
Implanted activity ≠ beam current × irradiation time

Solution:
in situ deposition of gold

F. Schneider et al ., *NIM B* **376** (2016) 388
L. Gamer et al., *NIM A* **854** (2017) 139

ECHo-1k array

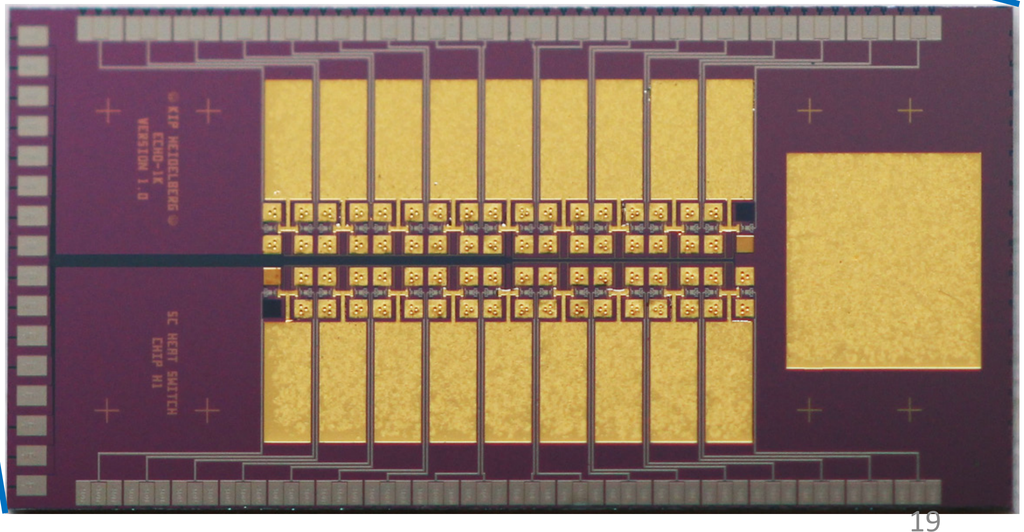


3“ wafer with 64 ECHo-1k chip

Suitable for
parallel and multiplexed readout

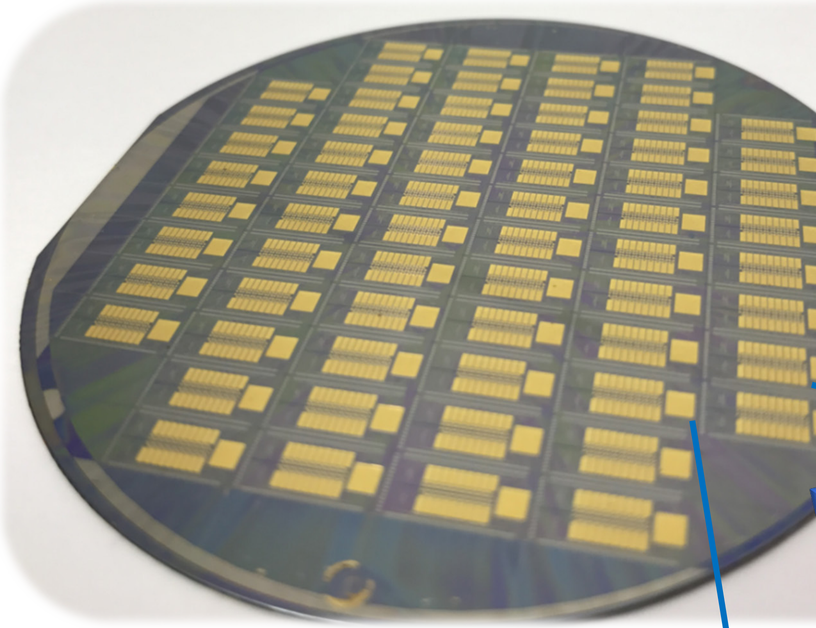
64 pixels which can be loaded with ^{163}Ho
+ 4 detectors for diagnostics

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



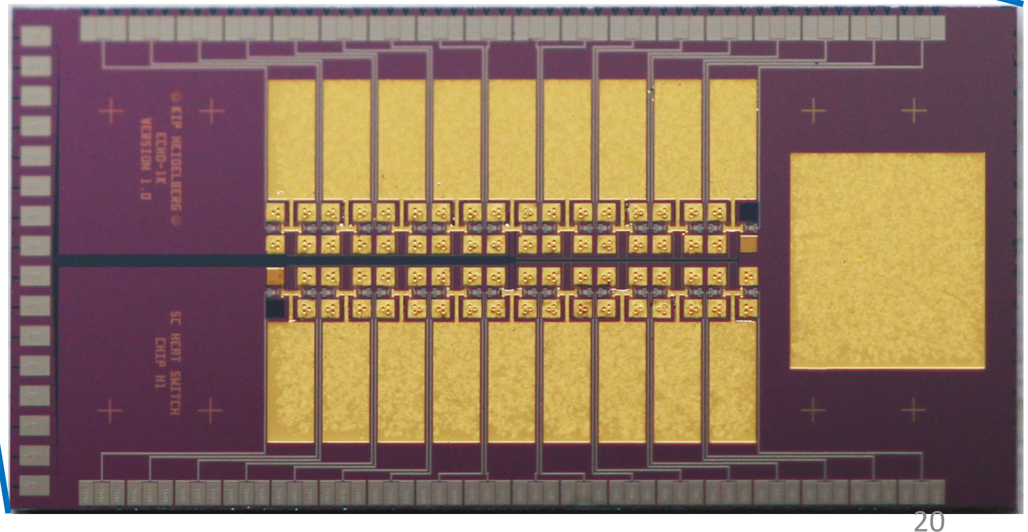
3“ wafer with 64 ECHo-1k chip

Suitable for
parallel and multiplexed readout

4 chips implanted:
Expected activity between 1 Bq and 3 Bq

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)



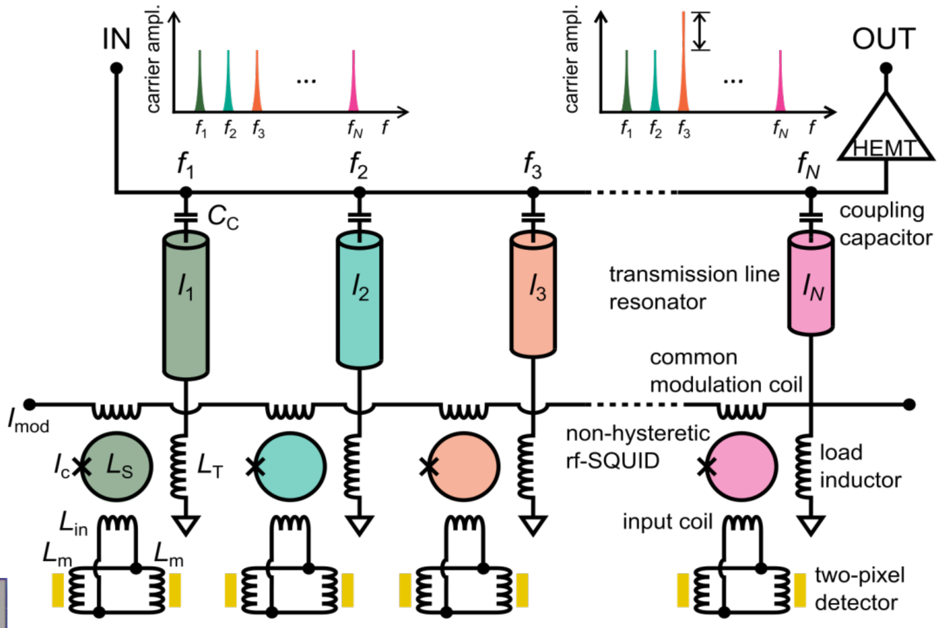
S.Kempf *et al., J. Low. Temp. Phys*. **176** (2014) 426

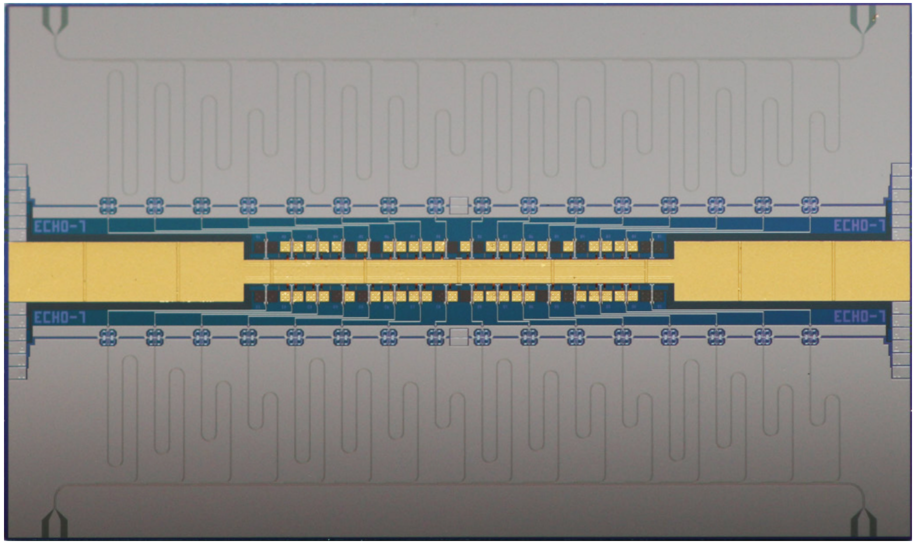
Multiplexing readout

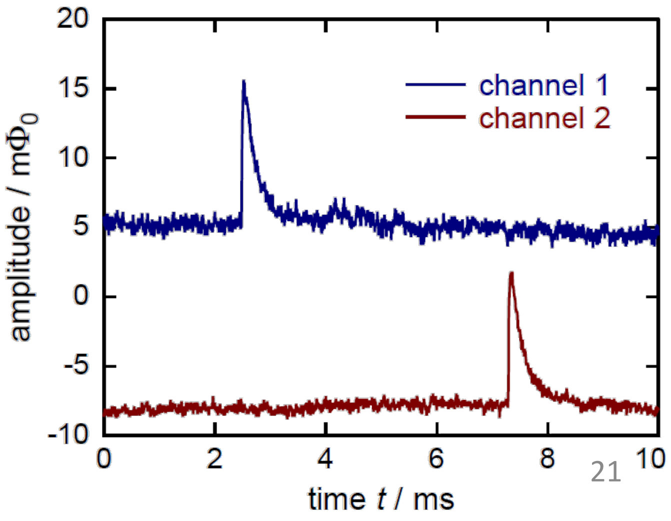
Microwave SQUID multiplexing

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

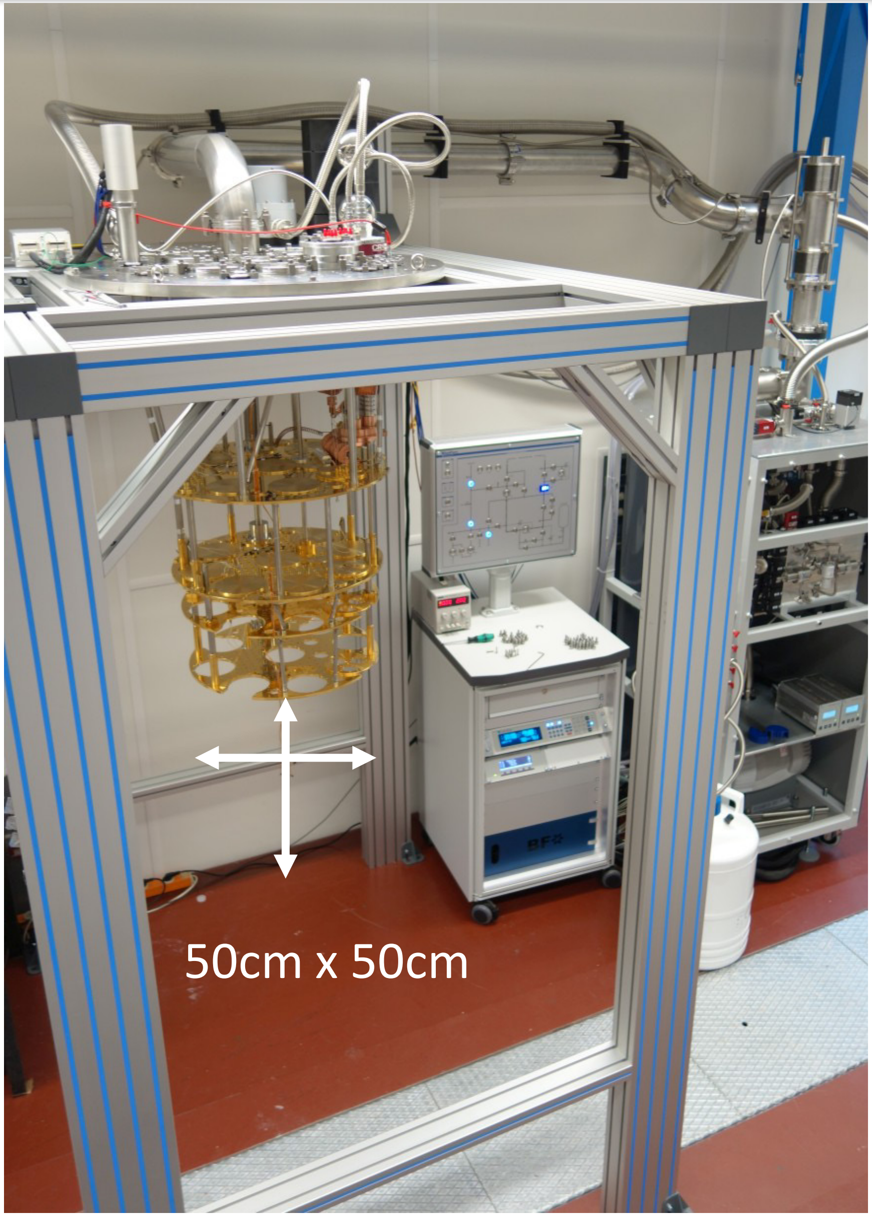




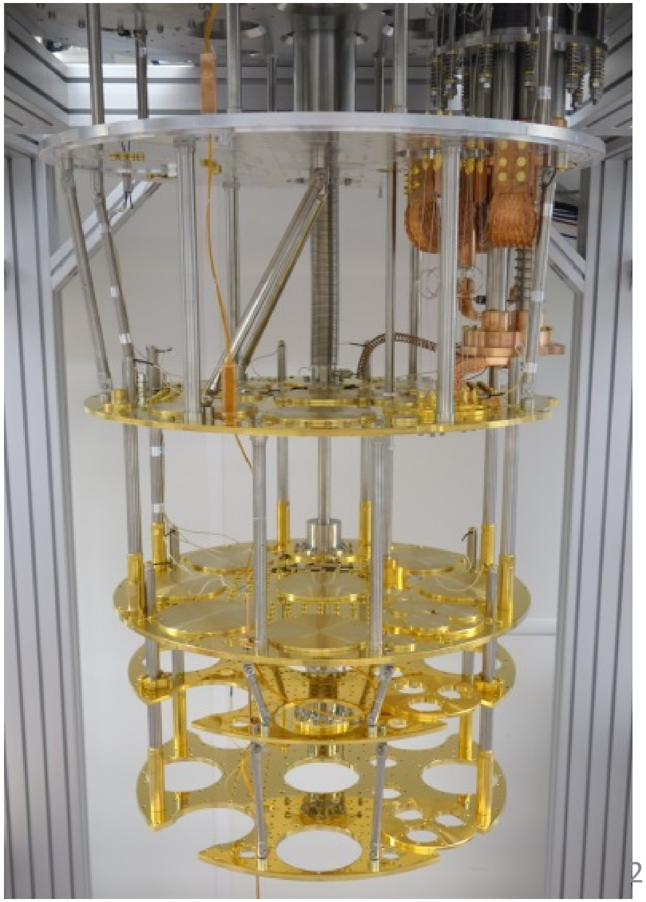


S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

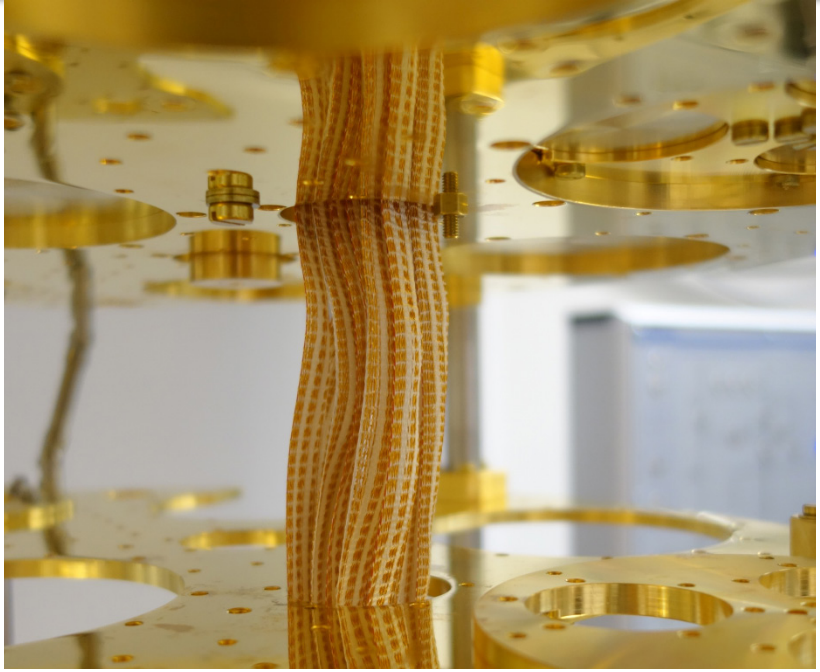
ECHo cryogenic platform

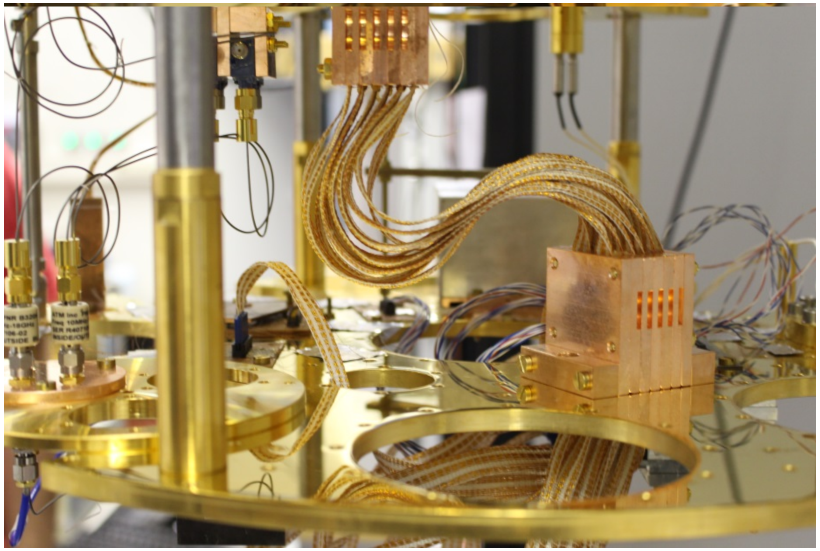


- Large space at MXC enough for several ECHo phases
- cooling power: 15µW @ 20 mK
- Possibility to load 200kg for passive shielding



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**

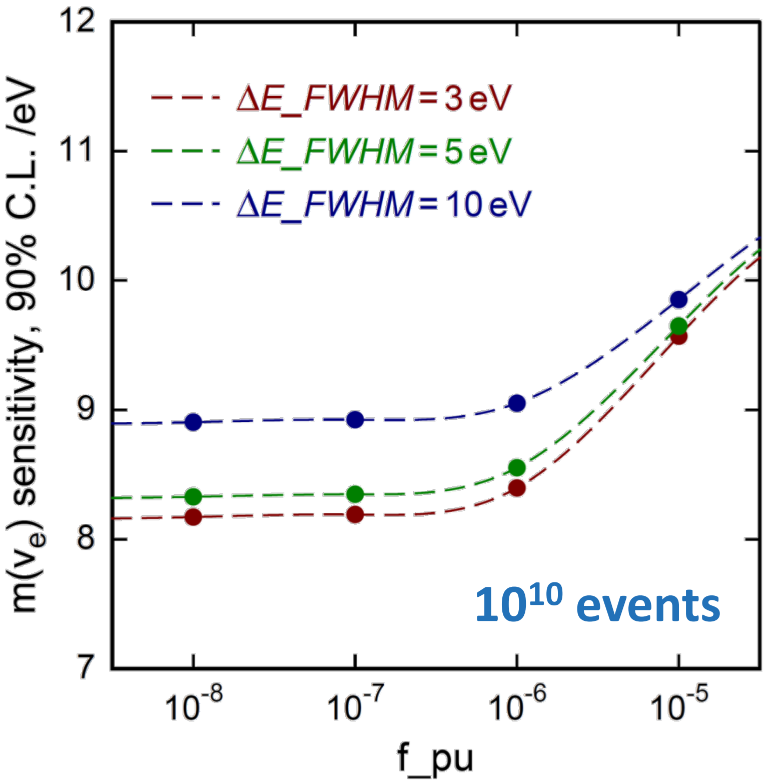
→number of detectors **N = 100**

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.

Supported by **DFG** through **Research Unit FOR 2202/1**

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 **$\tau \leq 0.1\ \mu s$**

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

→activity per pixel: **A = 10 Bq**

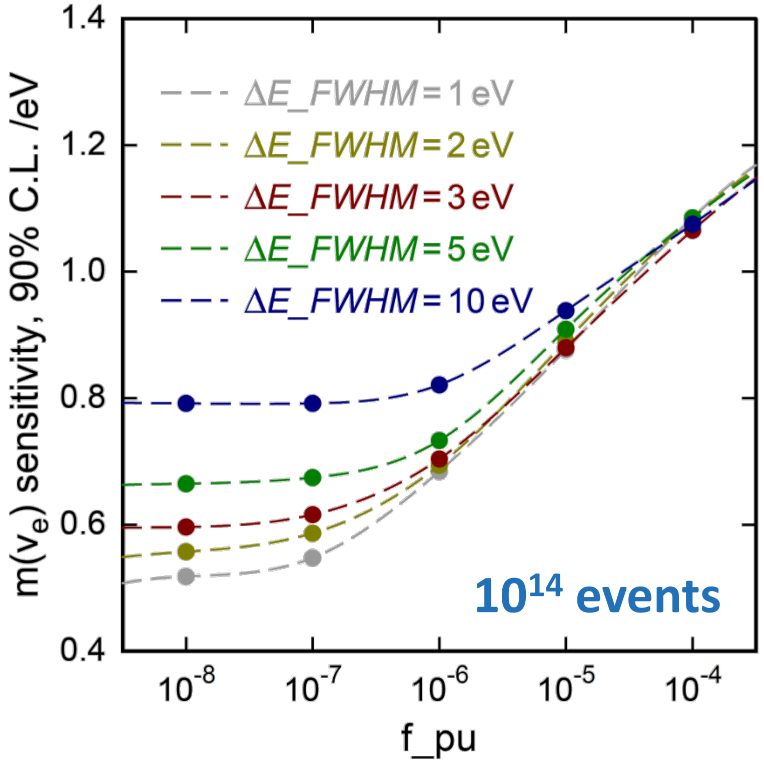
→number of detectors **$N = 10^5$**

Read-out : Microwave SQUID Multiplexing

→ 100 arrays with ~1000 single pixels

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

Measuring time **t = 1 – 3 year**

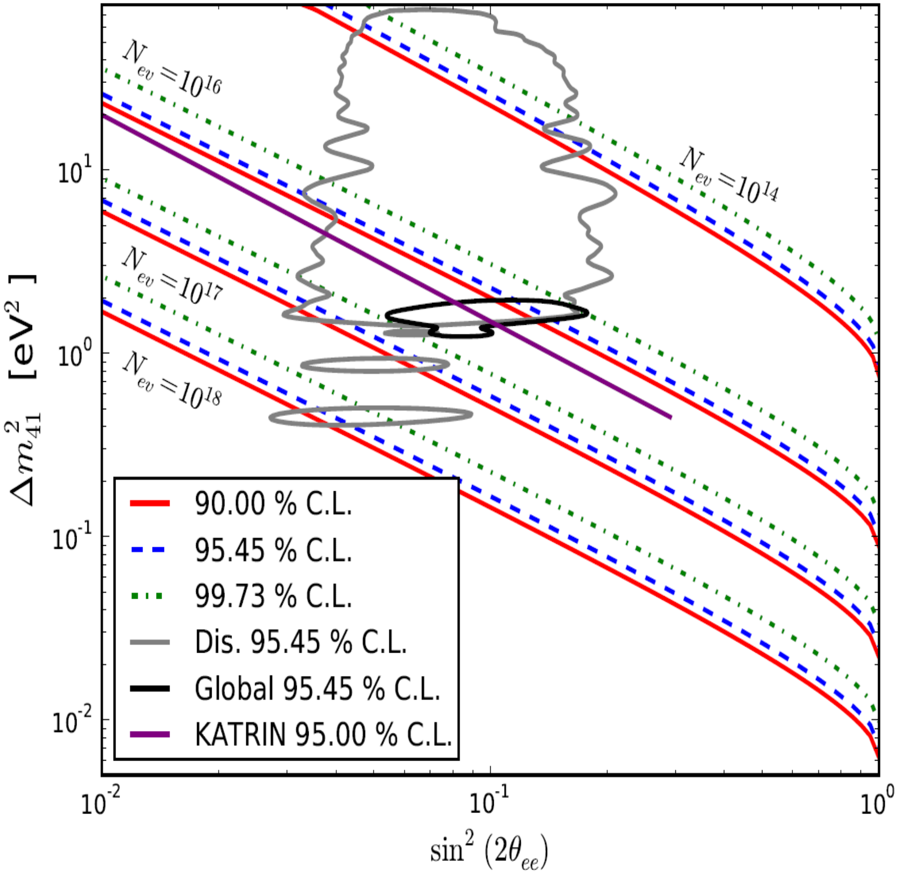


$m(\nu_e) < 1$ eV 90% C.L.

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

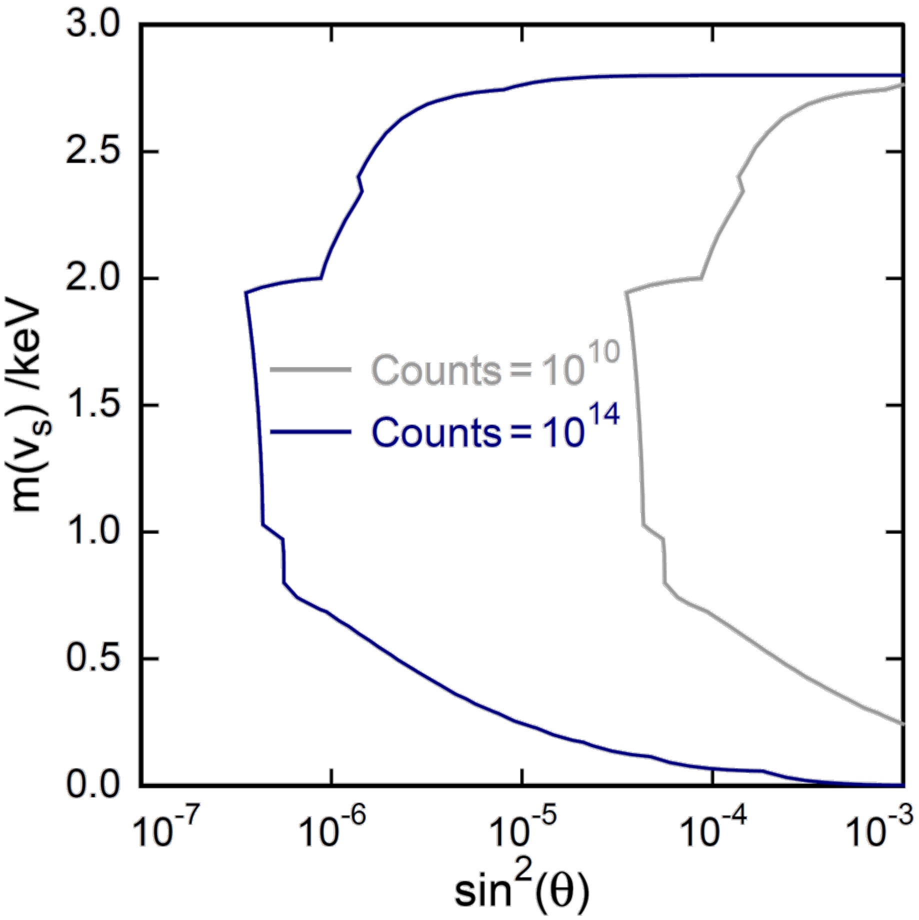
Sterile neutrinos

eV-scale sterile neutrinos



L. Gastaldo, C. Giunti, E. Zavanin.,
High Energ. Phys. **06** (2016) 61.

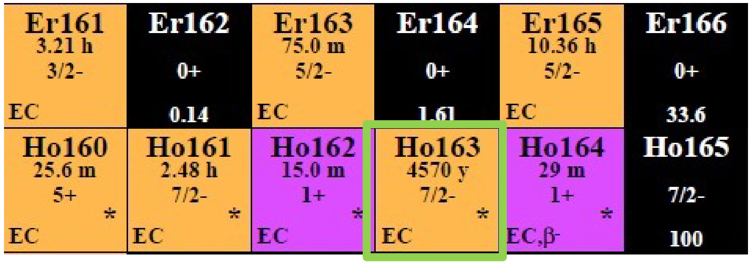
keV-scale serile neutrinos



A White Paper on keV Sterile
Neutrino Dark Matter, JCAP01(2017)025

Conclusions and outlook

The ECHo collaboration aims to reach sub-eV sensitivity on the electron neutrino mass analysing high statistics and high resolution ^{163}Ho spectra

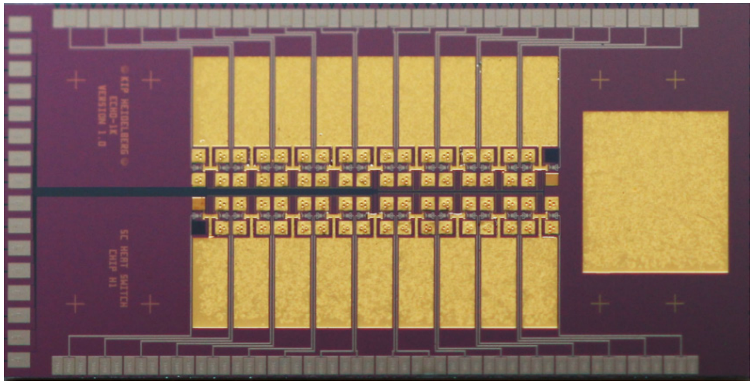


Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ * EC	Ho161 2.48 h 7/2- * EC	Ho162 15.0 m 1+ * EC	Ho163 4570 y 7/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100

- Independent ^{163}Ho Q_{EC} measurement

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

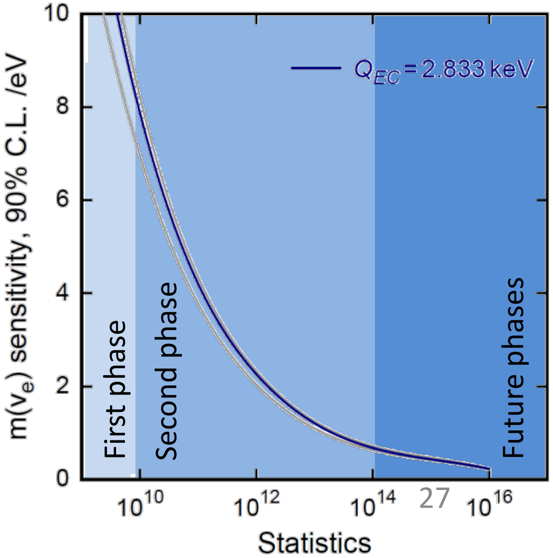
  $Q_{EC} = (2.858 \pm 0.010^{stat} \pm 0.05^{syst})$ keV



- 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



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

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

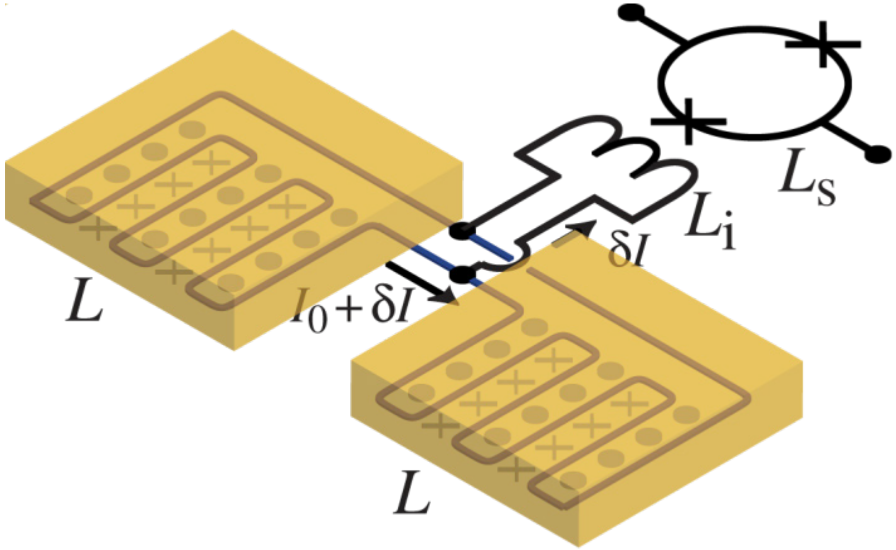
Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
Fedor Simkovic
Department of Physics, Indian Institute of Technology Roorkee, India
Moumita Maiti
Goethe Universität Frankfurt am Main
Udo Kebschull, Panagiotis Neroutsos
Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz
Christoph E. Düllmann, Klaus Eberhardt, Holger Dorrer, Fabian Schneider
Institute of Nuclear Research of the Hungarian Academy of Sciences
Zoltán Szúcs
Institute of Nuclear and Particle Physics, TU Dresden, Germany
Kai Zuber
Institute for Physics, Humboldt-Universität zu Berlin
Alejandro Saenz
Institute for Physics, Johannes Gutenberg-Universität
Klaus Wendt, Sven Junck, Tom Kieck
Institute for Theoretical Physics, Heidelberg University
Maurits Haverkort, Martin Brass
Institute for Theoretical Physics, University of Tübingen, Germany
Amand Fäßler
Institut Laue-Langevin, Grenoble, France
Ulli Köster
ISOLDE-CERN
Marsh Bruce, Day Goodacre Tom, Johnston Karl, Rothe Sebastian,
Stora Thierry, Veinhard Matthieu
Kirchhoff-Institute for Physics, Heidelberg University, Germany
Christian Enss, Dorothea Fonnesu, Loredana Gastaldo, Andreas Fleischmann,
Clemens Hassel, Federica Mantegazini, Sebastian Kempf, Mathias Wegner
Max-Planck Institute for Nuclear Physics Heidelberg, Germany
Klaus Blaum, Andreas Dörr, Sergey Eliseev, Mikhail Goncharov,
Yuri N. Novikov, Alexander Rischka, Rima Schüssler
Petersburg Nuclear Physics Institute, Russia
Yuri Novikov, Pavel Filianin
Physics Institute, University of Tübingen, Germany
Josef Jochum, Stephan Scholl
Saha Institute of Nuclear Physics, Kolkata, India
Susanta Lahiri

ECHo

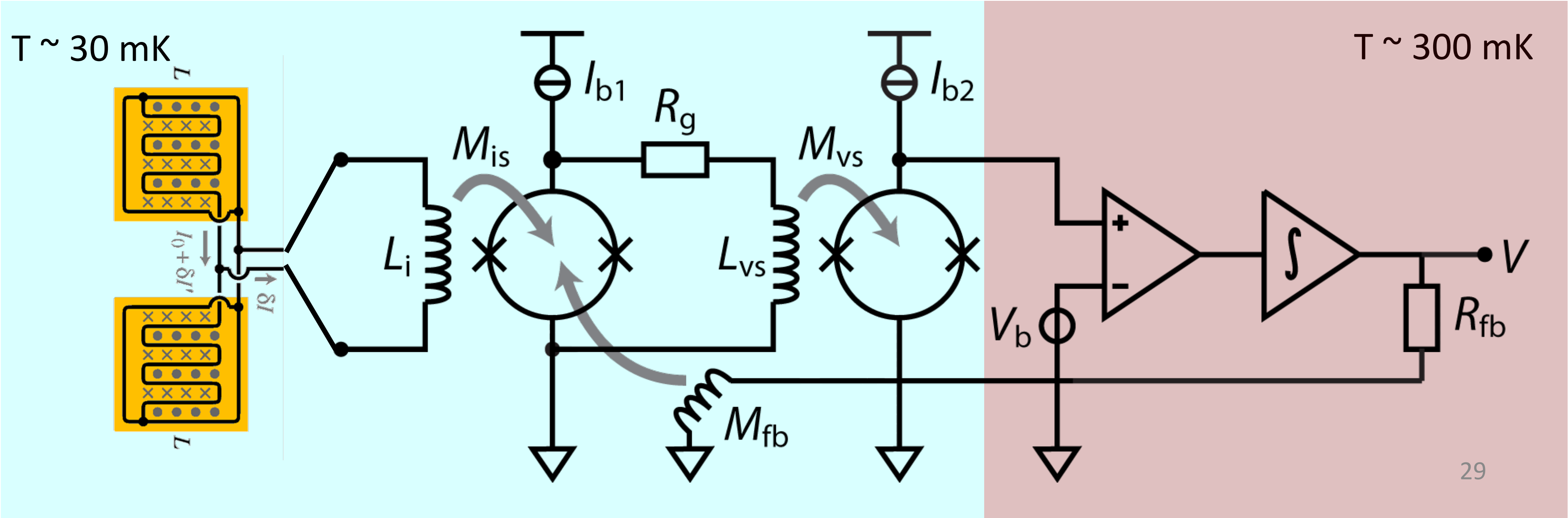
Thank you !

MMC geometry and read-out

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



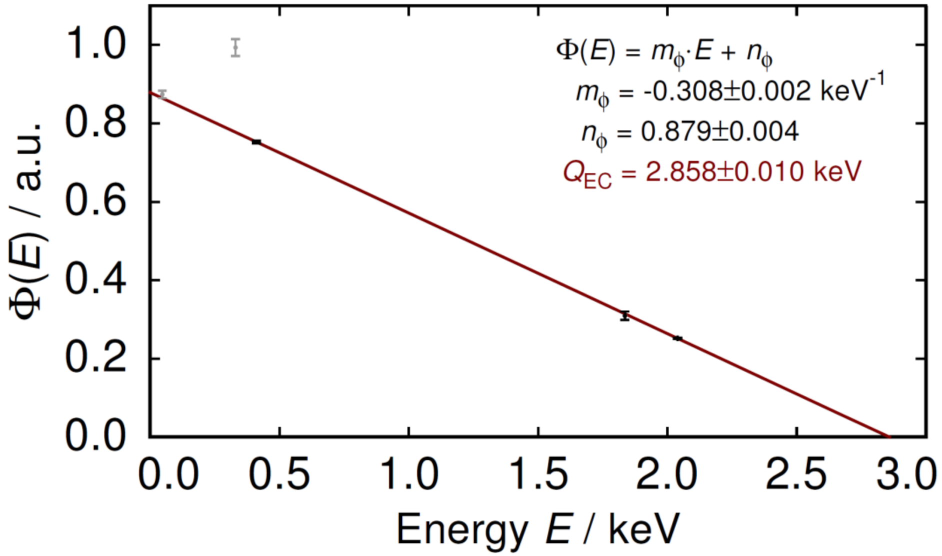
- Two-stage SQUID read-out

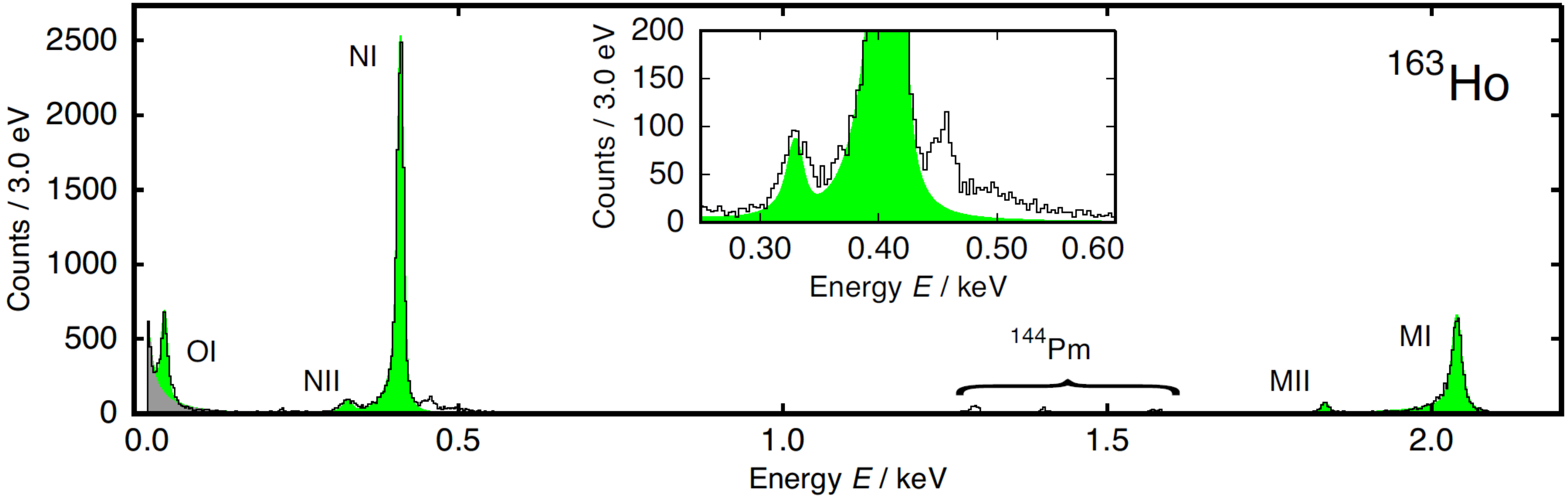


Q_{EC} determination

$$\Phi_H(E) = \sqrt{\frac{n_H}{\varphi_H^2(0) B_H}} \propto \sqrt{C}\left(Q_{EC} - E_H\right)$$

Line amplitudes are affected by the phase space factor

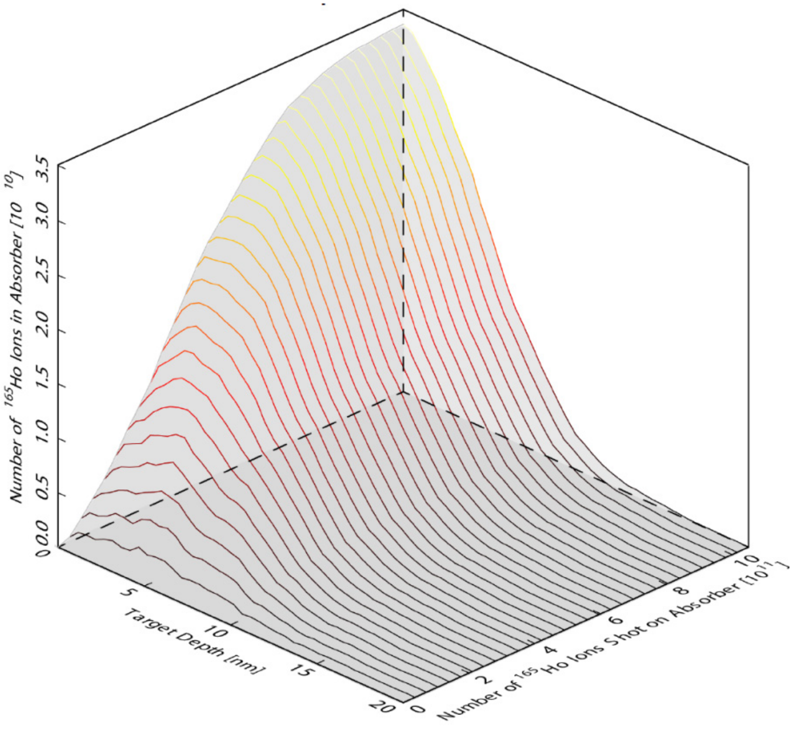


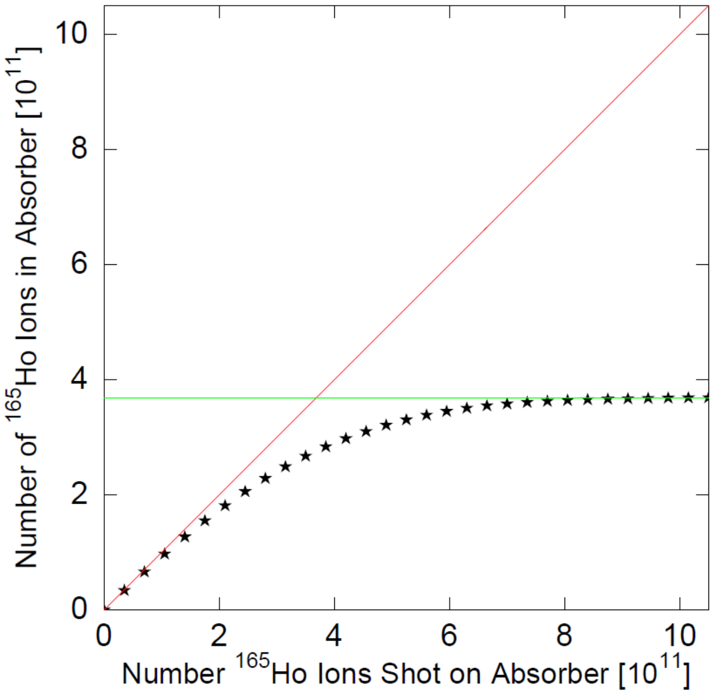


P. C.-O. Ranitzsch et al ., accepted for publication in PRL (2017)

Mass separation and ^{163}Ho ion-implantation

Implantation with 30 keV at RISIKO in Mainz in an area of 150 µm × 150 µm





Backscattering and sputtering of absorber atoms affect implantation process:
Implanted activity ≠ beam current × irradiation time

→

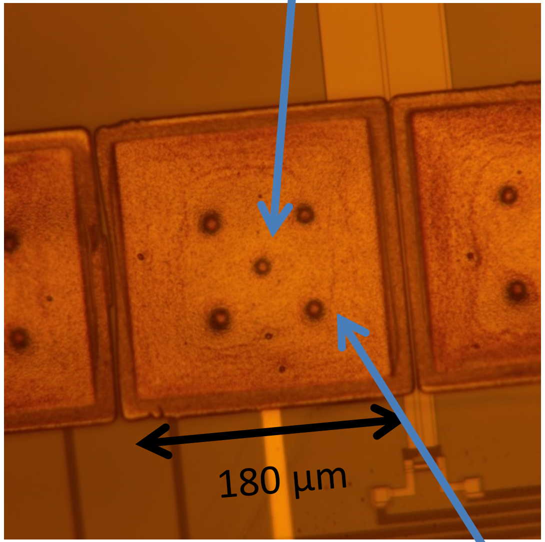
Implantation of Ho in gold with E = 30 keV:
maximum number of Ho ions ~ 3.6×10^{11}
corresponding to only ~ 2 Bq

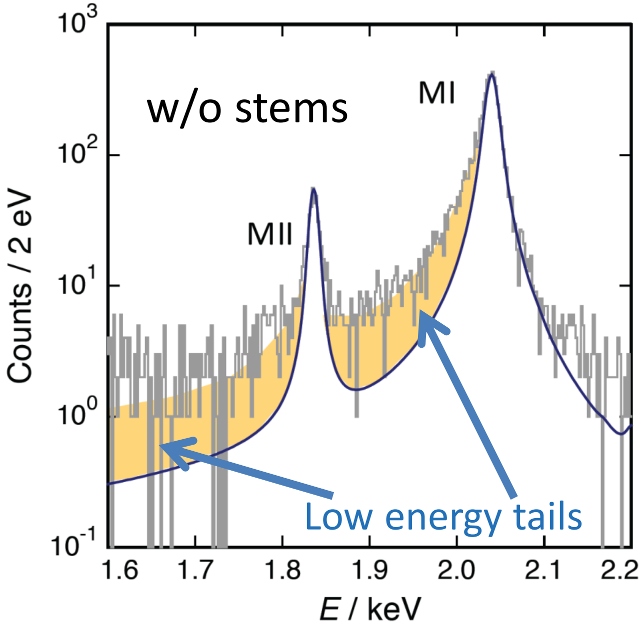
Solution: in situ deposition of gold

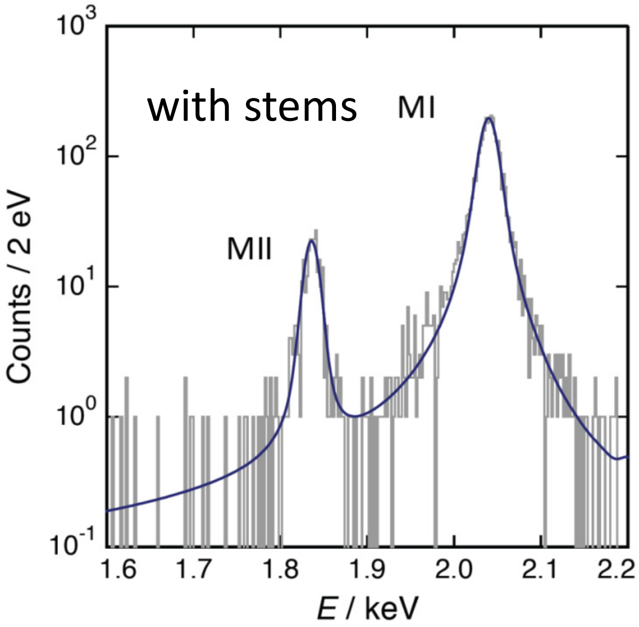
L. Gamer et al., *NIM A* **854** (2017) 139

Fabrication 4π absorber

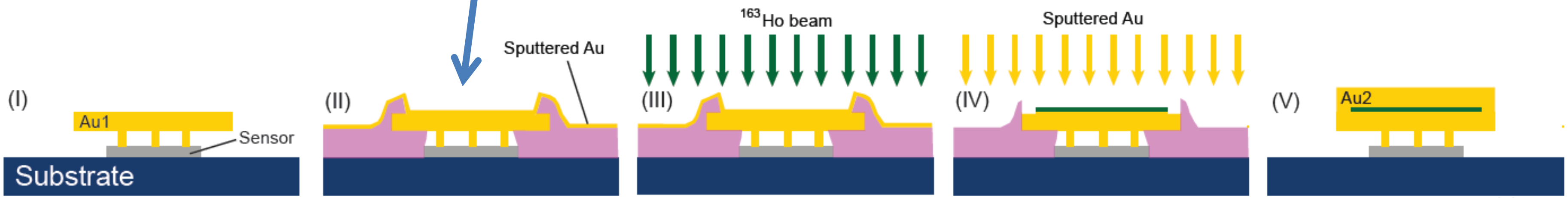
Stems between absorber and sensor prevent athermal phonon loss to the substrate







Definition of the implantation area by microstructuring a photoresist layer



C. Hassel et al ., *JLTP* **184** (2016) 910

^{163}Ho high purity source

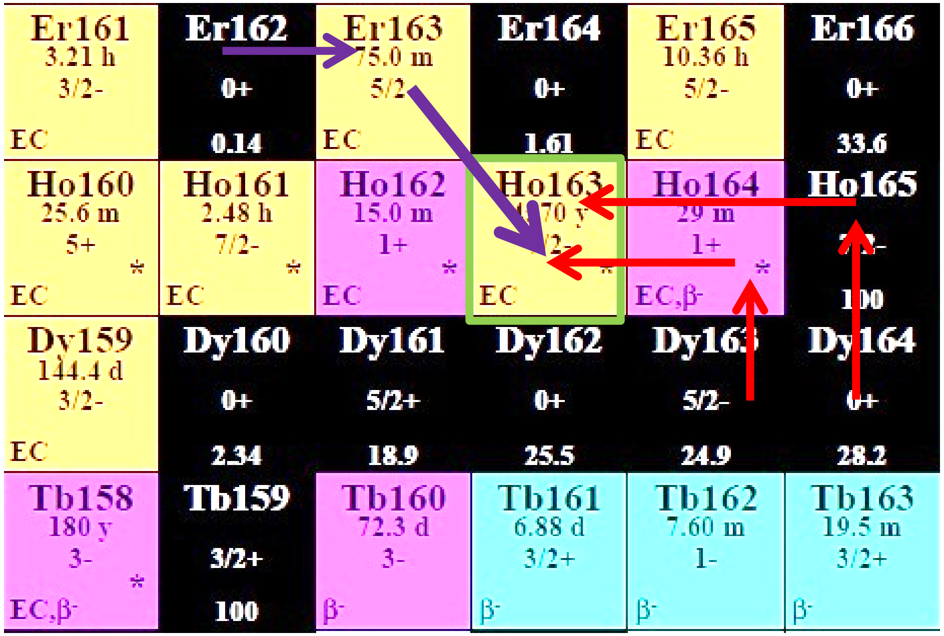
Required activity in the detectors: Final experiment → $>10^6$ Bq → $>10^{17}$ atoms

- Neutron irradiation
  (n,γ)-reaction on ^{162}Er

  High cross-section ☺

  Radioactive contaminants 🛇

ECHo HOLMES



Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ * EC	Ho161 2.48 h 7/2- * EC	Ho162 15.0 m 1+ * EC	Ho163 4570 y 7/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100
Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb158 180 y 3- * EC,β-	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-

H. Dorrer et al, submitted to Radiochim. Acta (2017)

- 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

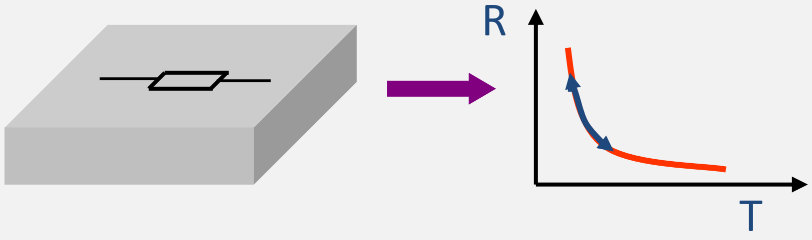
  Small cross-section 🛇

  Few radioactive contaminants ☺

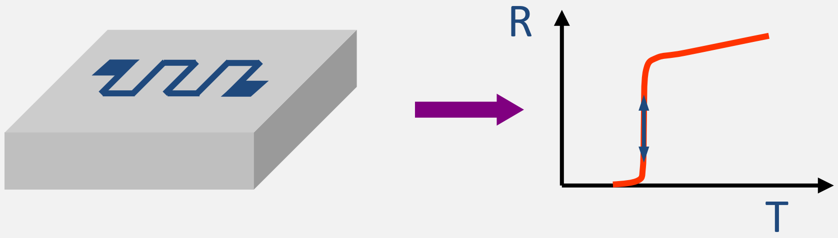
NuMECS

Temperature sensors

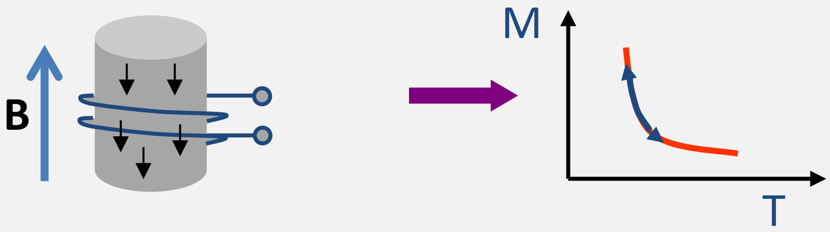
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES



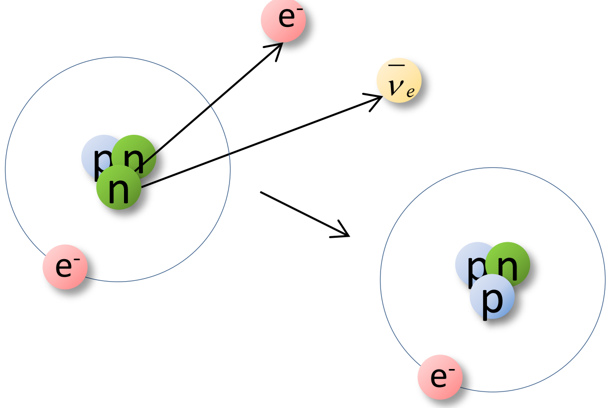
Magnetization of paramagnetic material, MMC



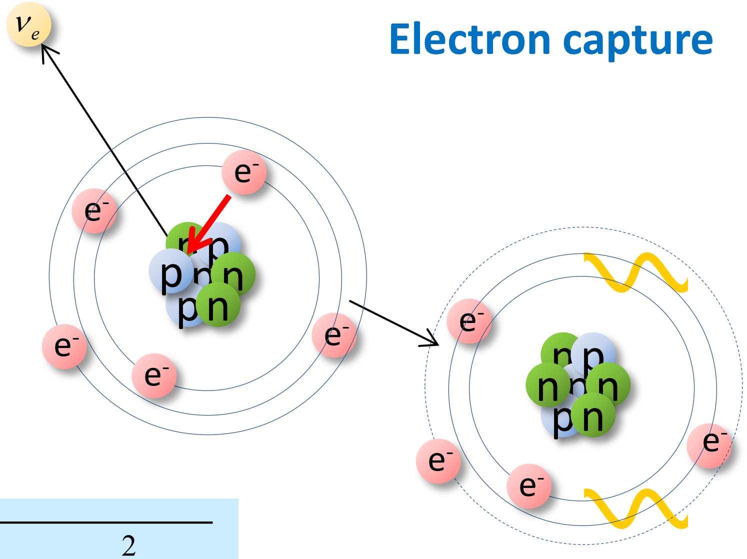
Cryogenic Particle Detection, (ed. C. Enss), Topics Appl. Phys. 99 (Springer Berlin Heidelberg 2005)

Kinematic approach

Beta decay



Electron capture

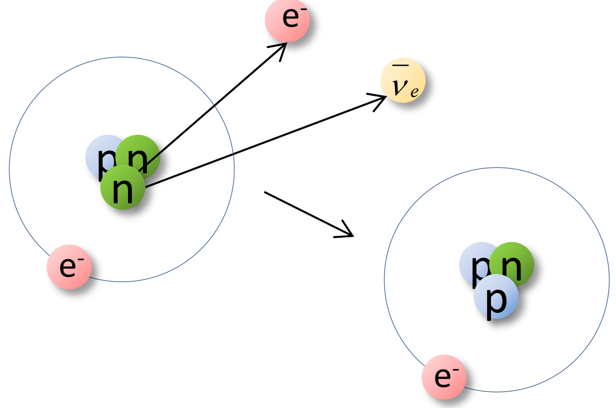


$$\frac{dW}{dE} \propto (Q-E)^2 \sqrt{1-\frac{m_\nu^2}{(Q-E)^2}}$$

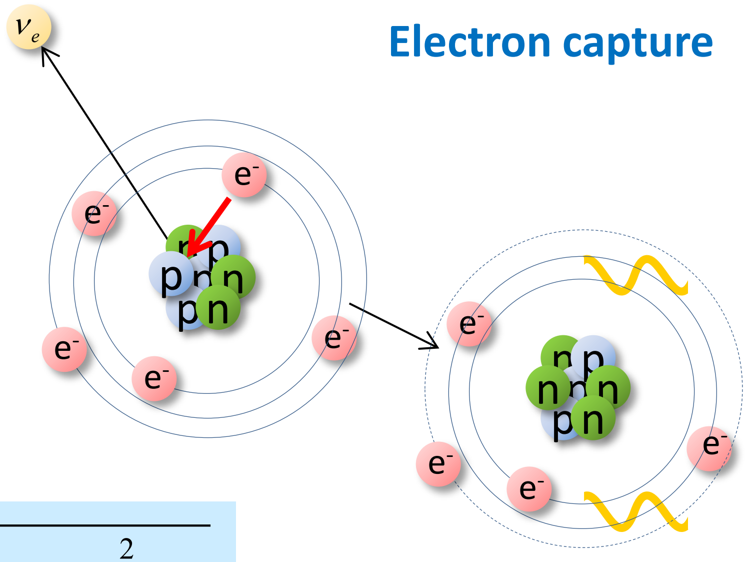
- A finite neutrino mass modify the spectrum in a small region close to the end-point
- Low Q-values enhance the fraction of events in the region of interest

Kinematic approach

Beta decay



Electron capture



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

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

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

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

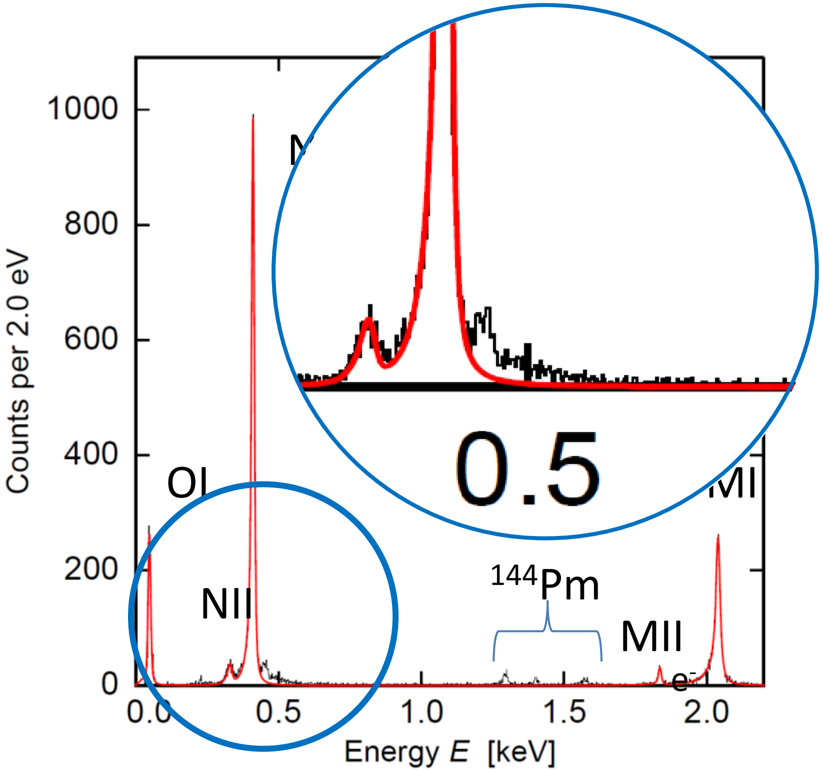
$m(\bar{\nu}_e) < 2.2\ eV$ (1)

$m(\nu_e) < 225\ eV$ (2)

(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447
Ch. Weinheimer, Prog. Part. Nucl. Phys. **57** (2006) 22
N. Aseev *et al.*, Phys. Rev D **84** (2011) 112003

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

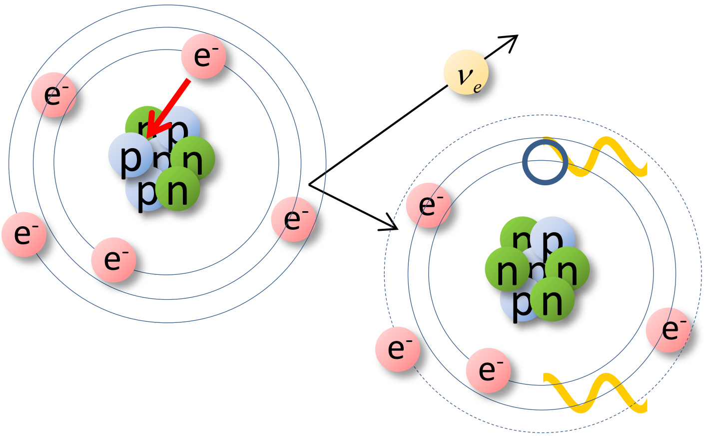
Characterisation of spectral shape



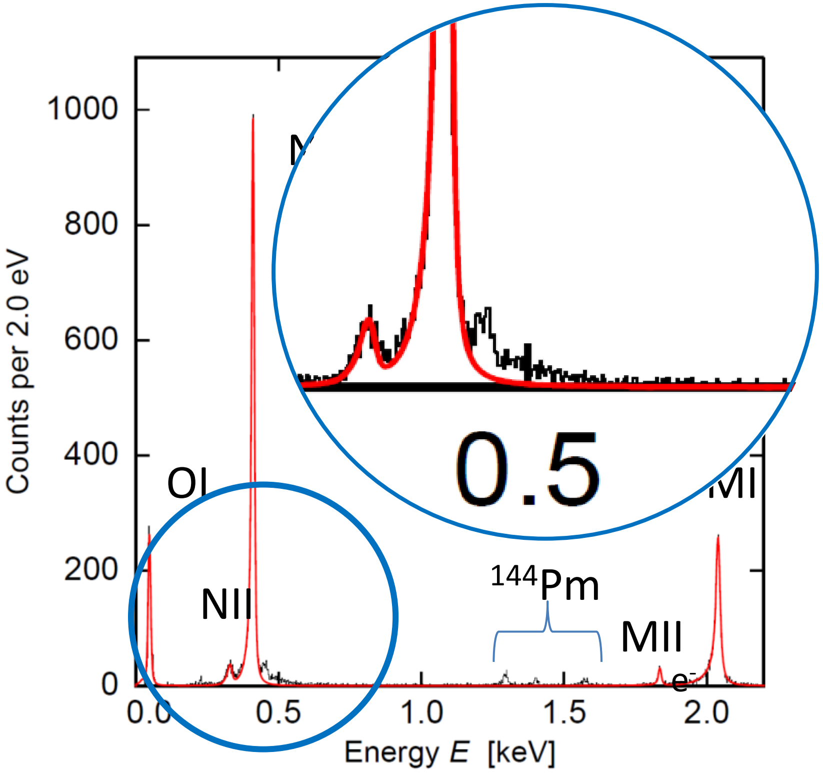
- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 045505 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula et al.
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016

Estimate the effect of

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



Characterisation of spectral shape



- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
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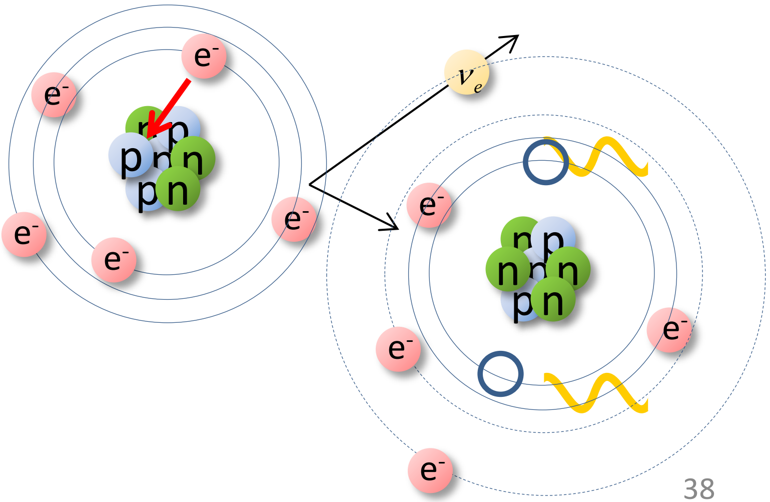

Two-holes excited states: shake-up

Characterisation of spectral shape

- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
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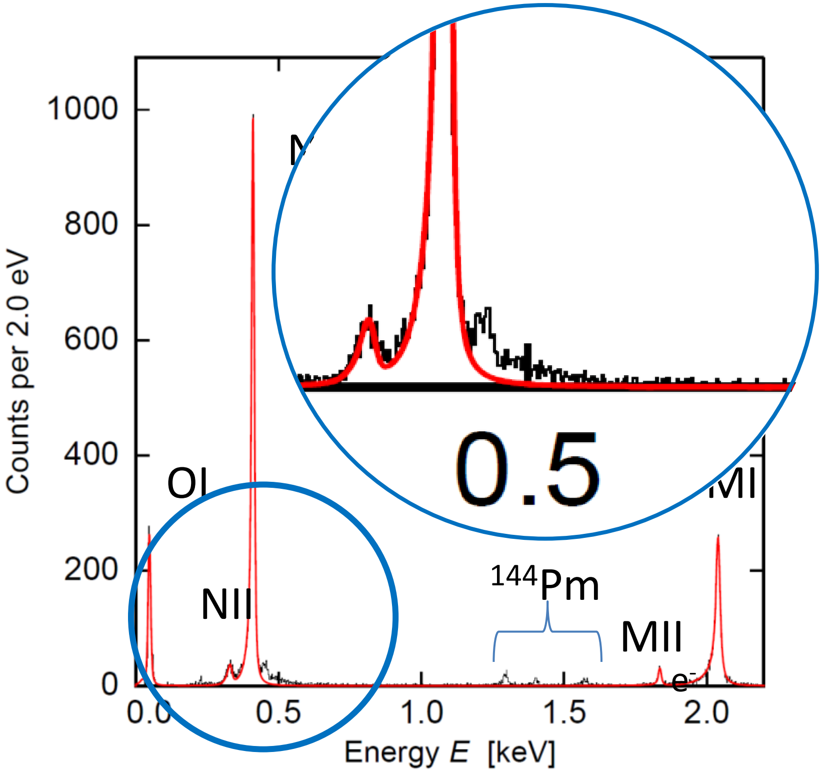
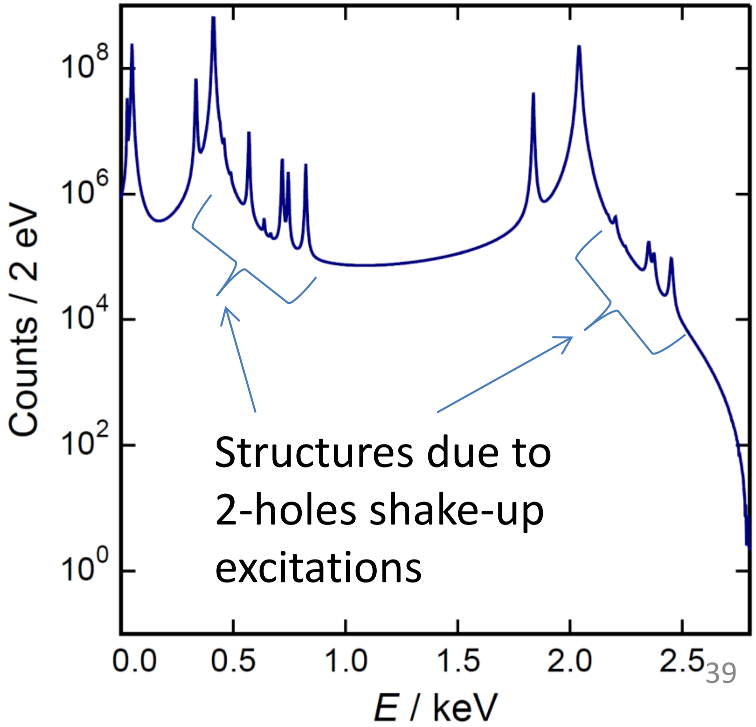
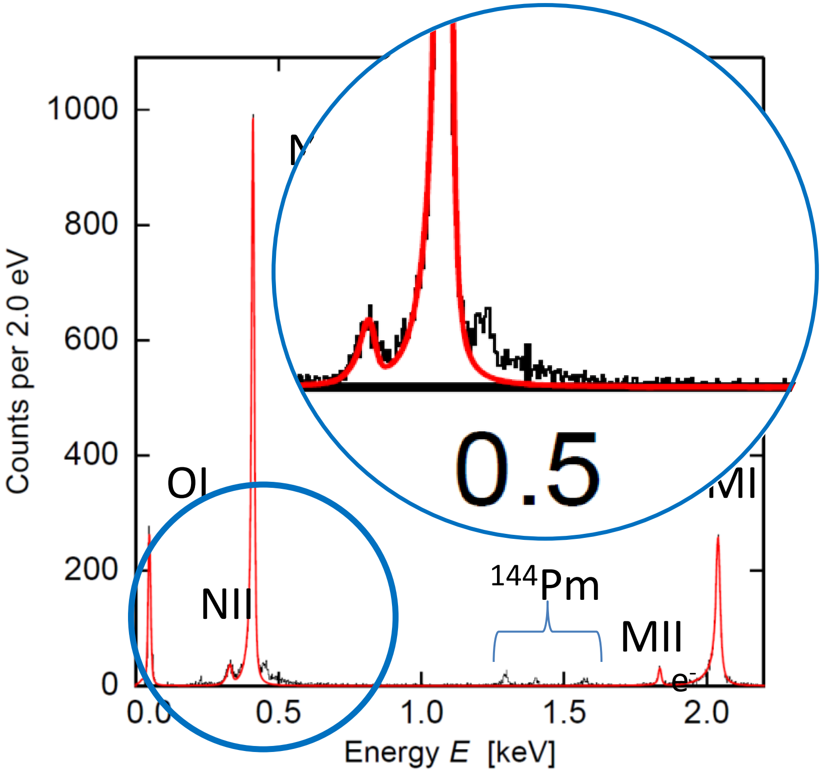


Two-holes excited states: shake-up



Structures due to 2-holes shake-up excitations

Characterisation of spectral shape



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- R. G. H. Robertson
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- A. Faessler et al.
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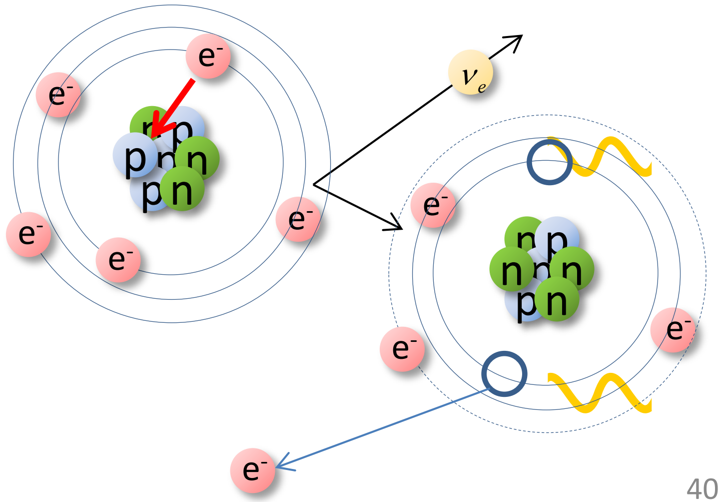
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula et al.
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016

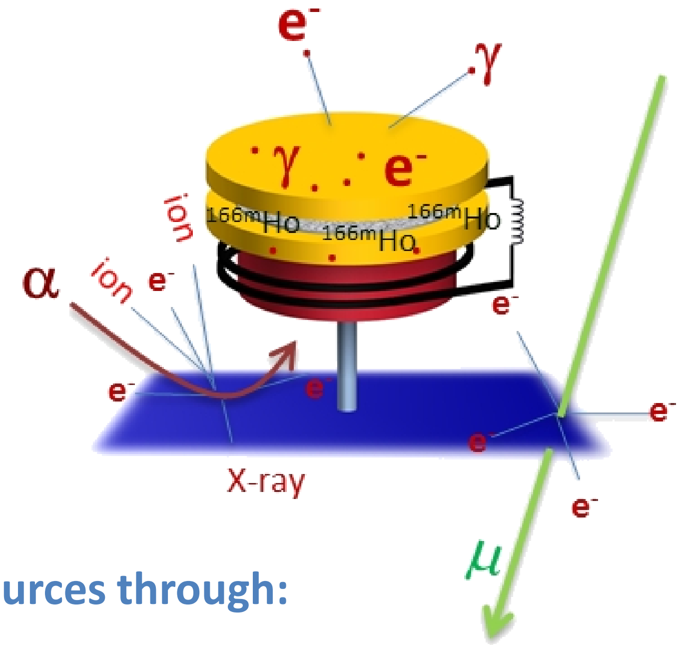
Two-holes excited states: shake-up
shake-off



Background

Background sources:

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



Study of background sources through:

- Monte Carlo simulations
- Dedicated experiments

Screening facilities
- **Uni-Tübingen**
- **Felsenkeller**