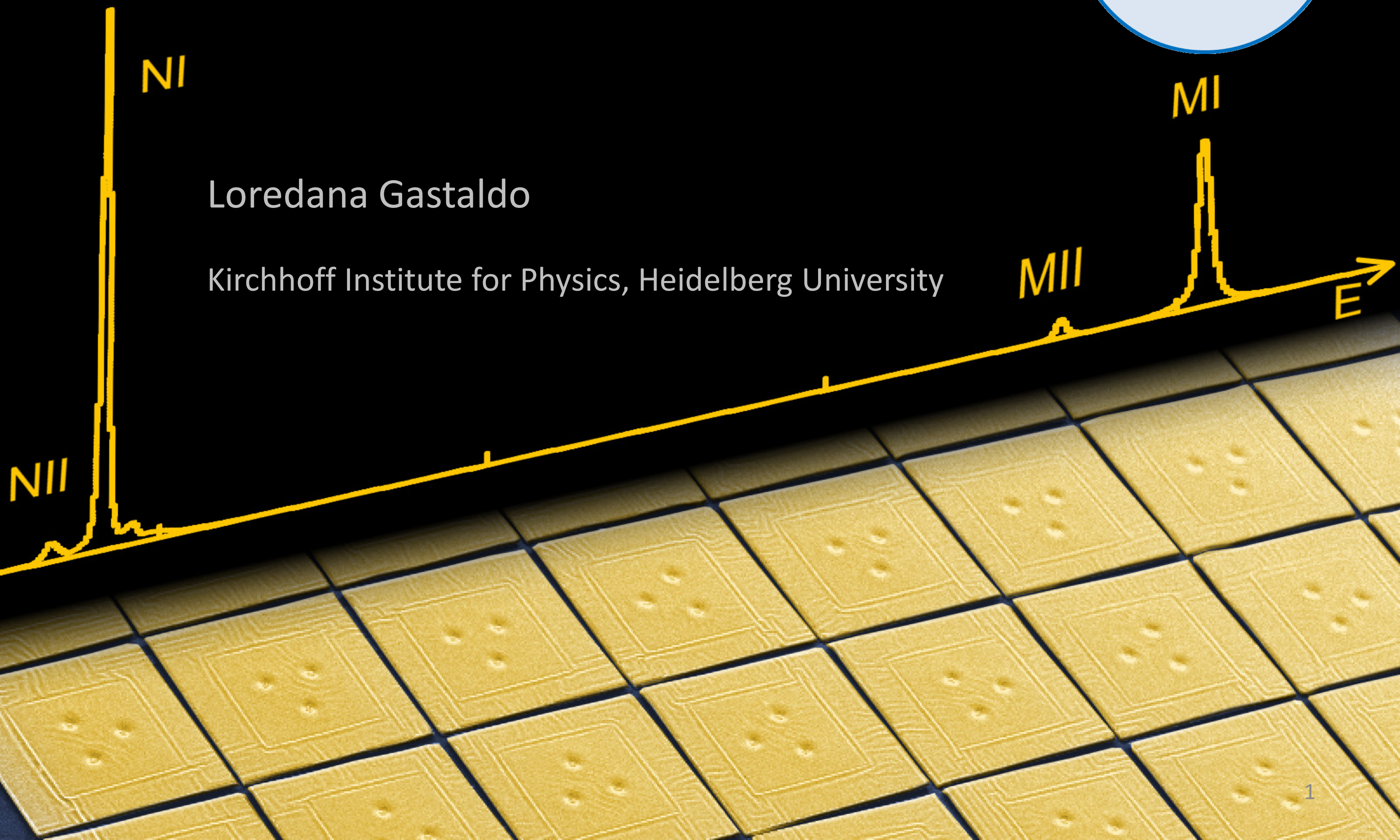
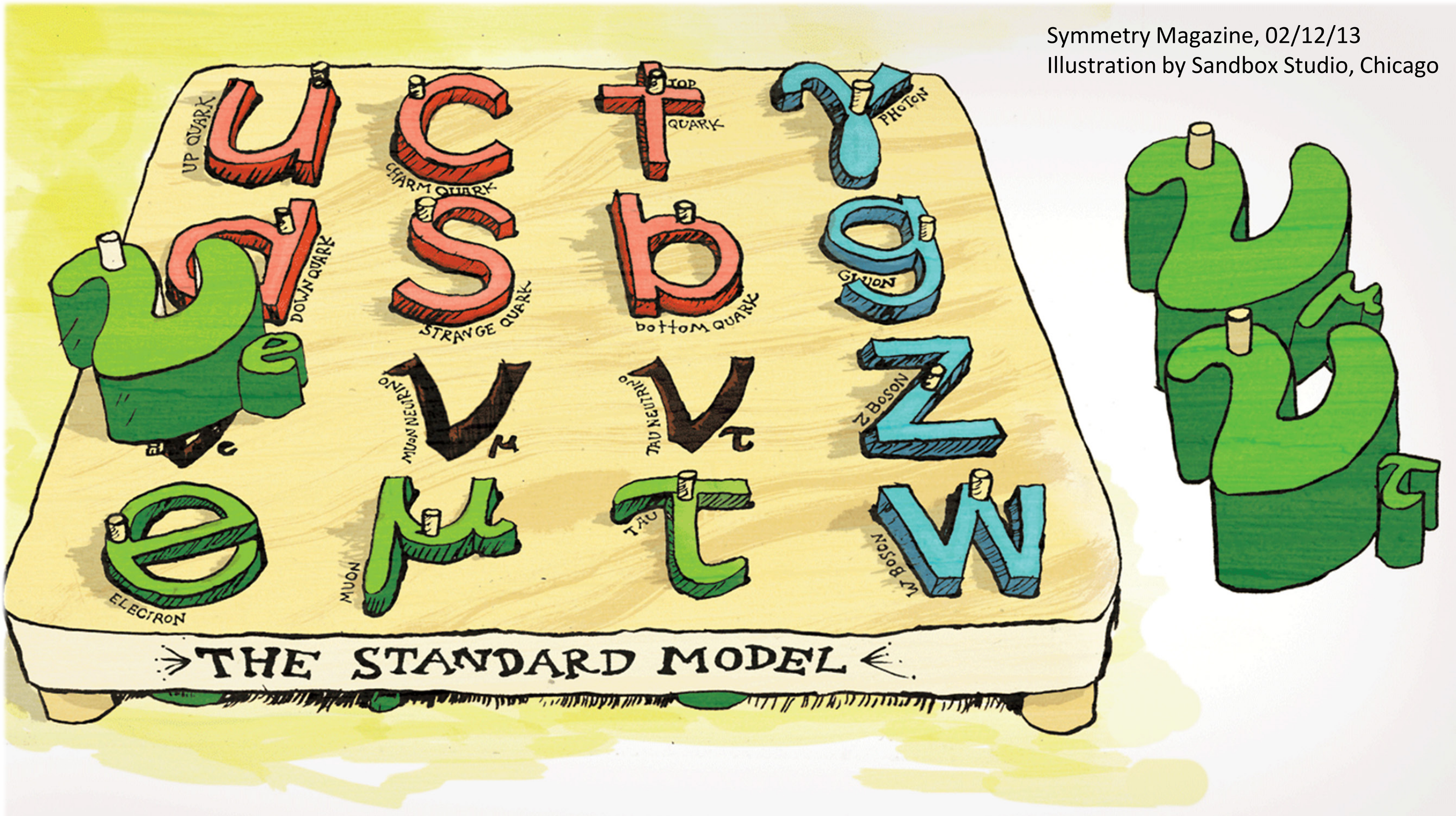
Electron Capture in ^{163}Ho experiment - ECHo

Loredana Gastaldo

Kirchhoff Institute for Physics, Heidelberg University

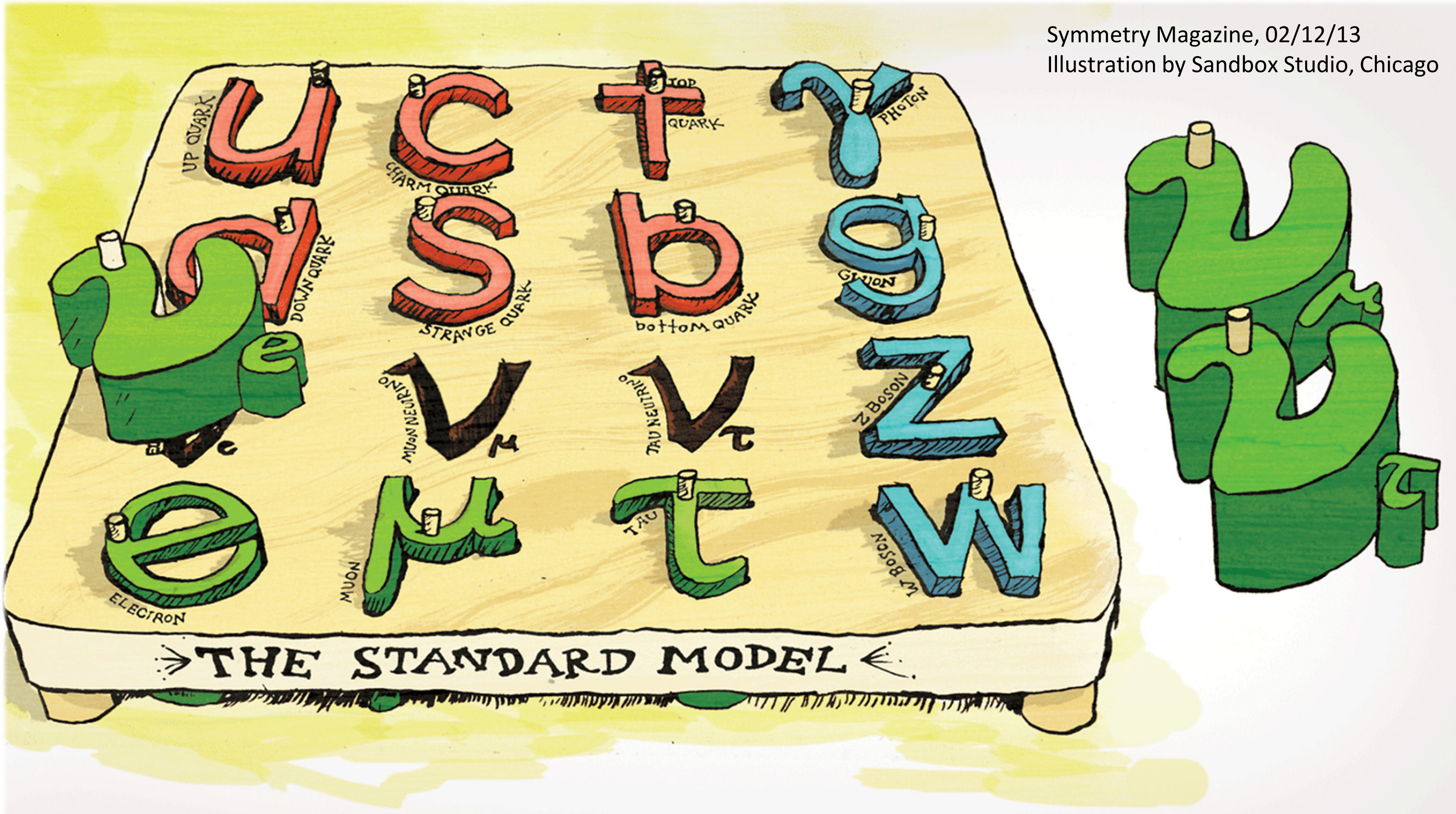


Massive Neutrinos



Symmetry Magazine, 02/12/13
Illustration by Sandbox Studio, Chicago

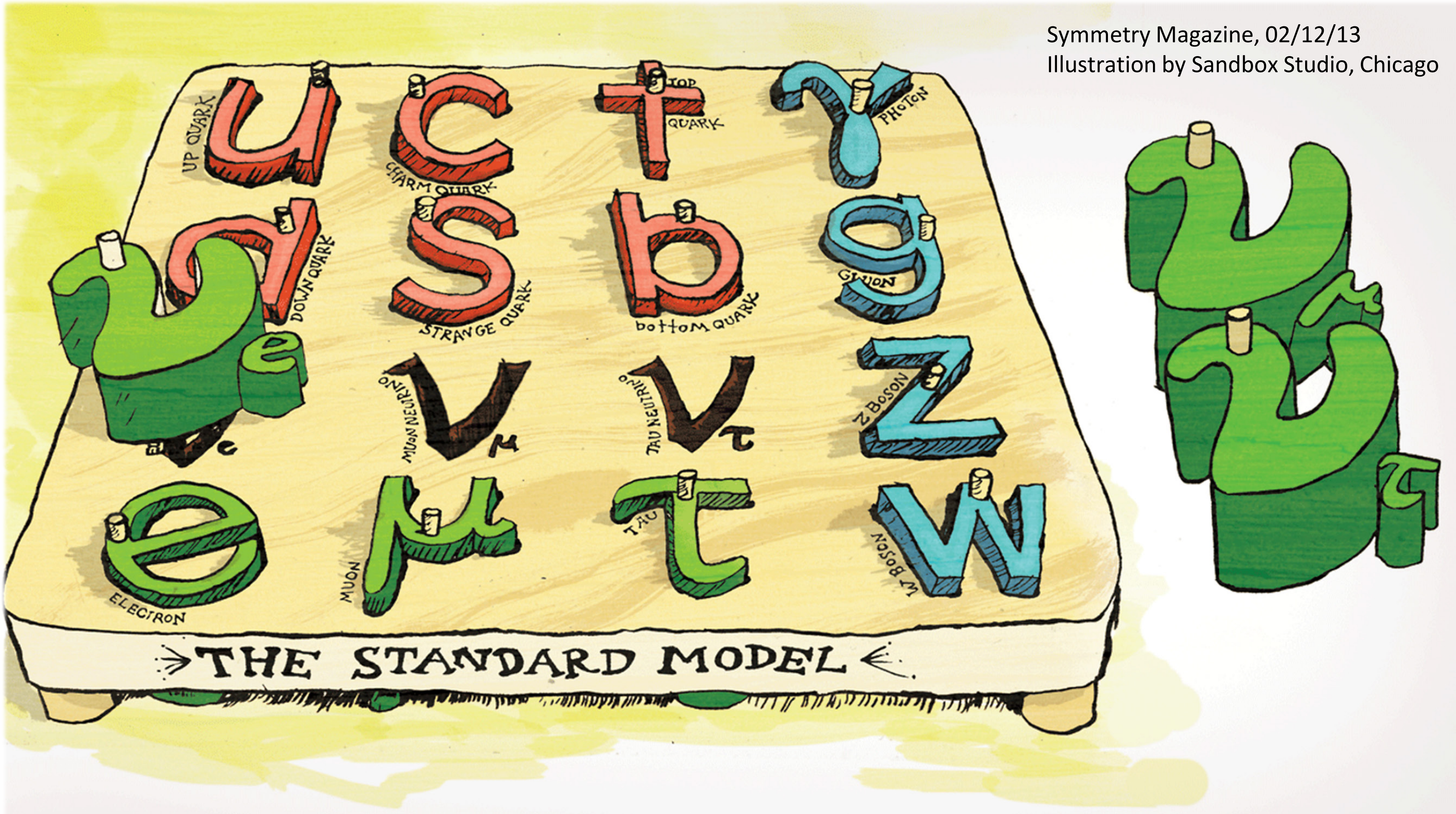
Massive Neutrinos



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

(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

Massive Neutrinos



Symmetry Magazine, 02/12/13
Illustration by Sandbox Studio, Chicago

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

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

(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

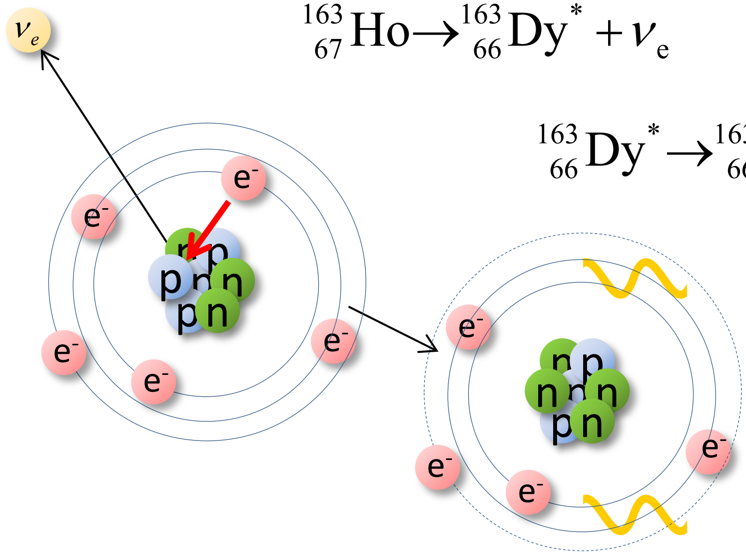
Outline

- 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

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

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



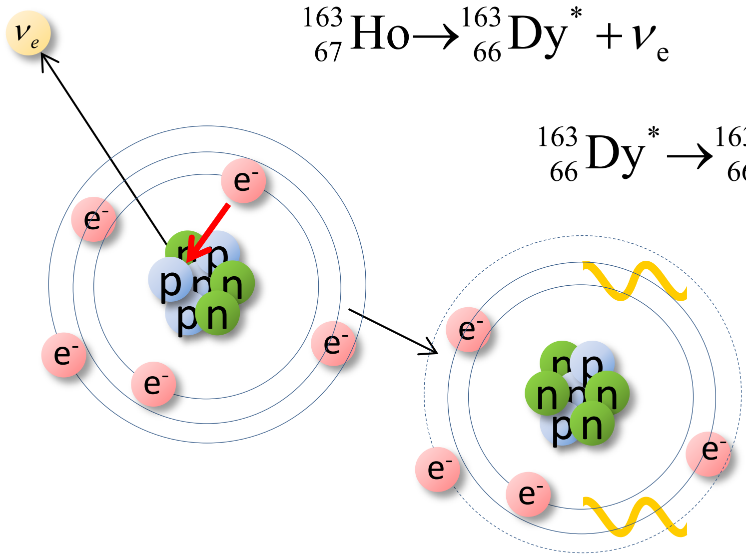
- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)

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

- Low Q_{EC}-value allows capture only for:
  3s, 3p1/2, 4s, p1/2, 5s, 5p1/2, 6s electrons

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

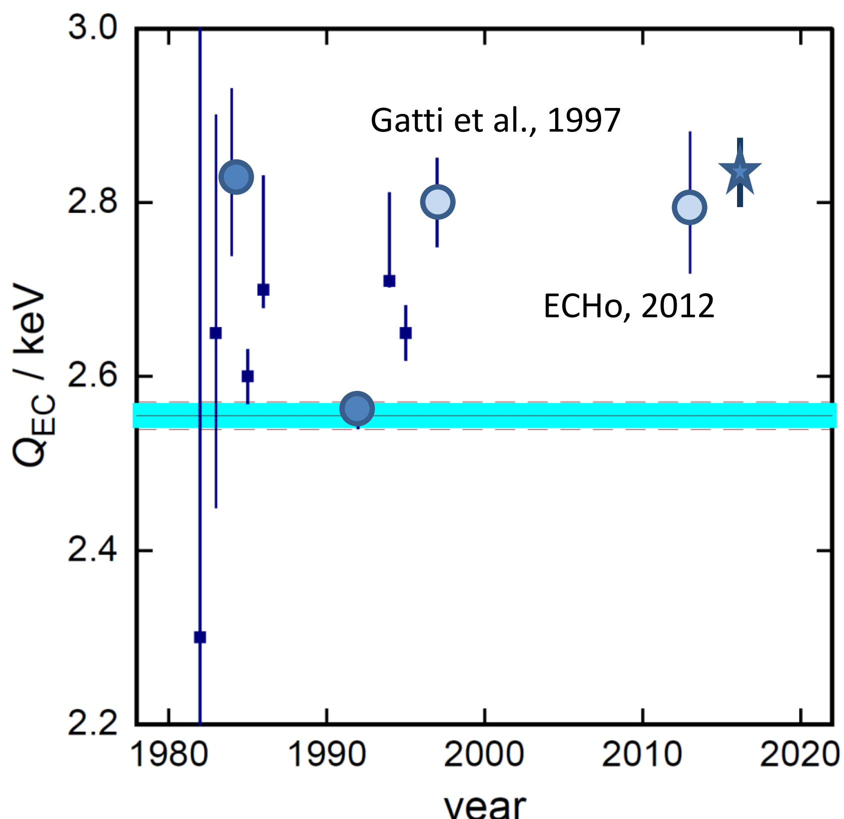
Electron capture in ^{163}Ho



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

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

Independent measurement by Penning Trap Mass Spectrometry



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

- **Q_{EC} = (2.833 ± 0.030^{stat} ± 0.015^{syst}) keV ***

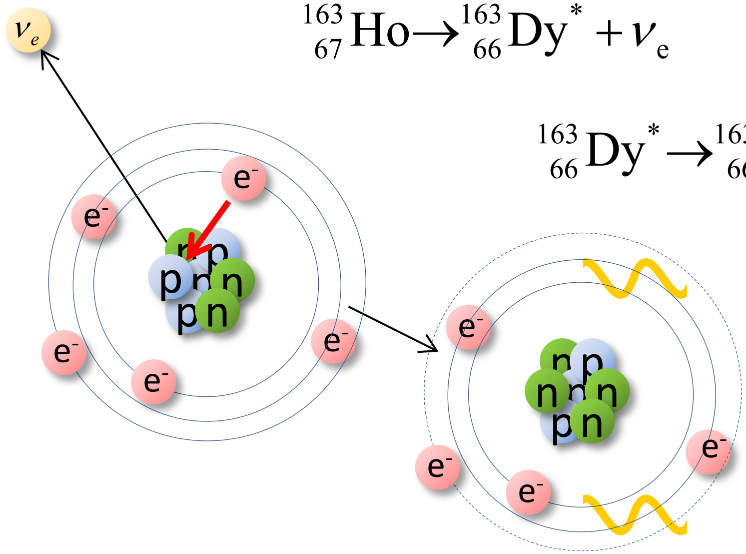
- Low Q_{EC}-value allows capture only for: 3s, 3p1/2, 4s, p1/2, 5s, 5p1/2, 6s electrons

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

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)

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

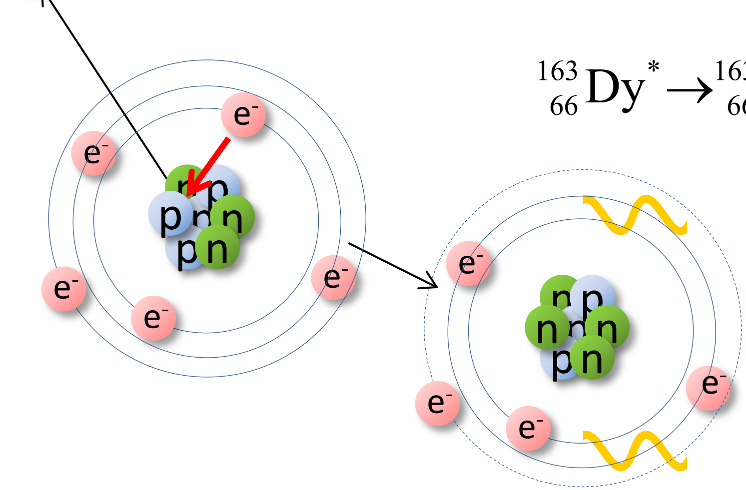
- Low Q_{EC}-value allows capture only for:
  3s, 3p1/2, 4s, p1/2, 5s, 5p1/2, 6s electrons

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

Electron capture in ^{163}Ho

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

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



Atomic de-excitation:

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

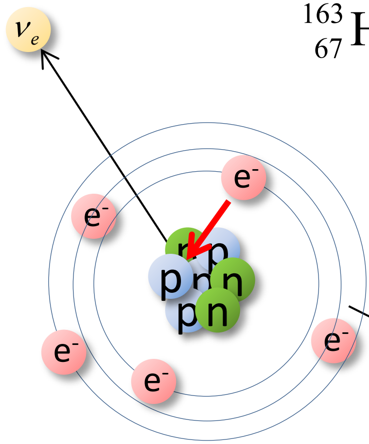
- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)

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

- Low Q_{EC}-value allows capture only for:
  3s, 3p1/2, 4s, p1/2, 5s, 5p1/2, 6s electrons

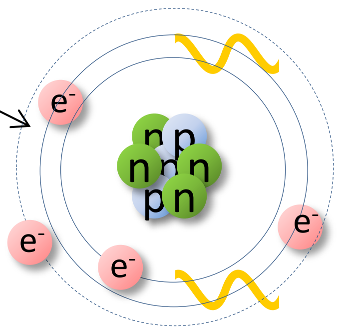
* S. Eliseev et al., *Phys. Rev. Lett.*, 115, 062501 (2015)

Electron capture in ^{163}Ho



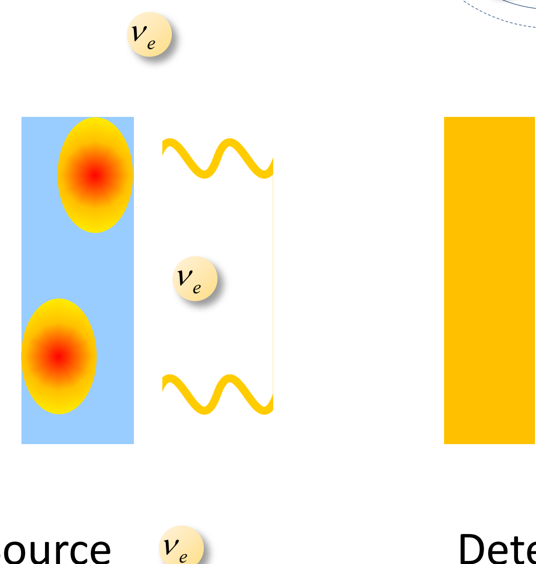
$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

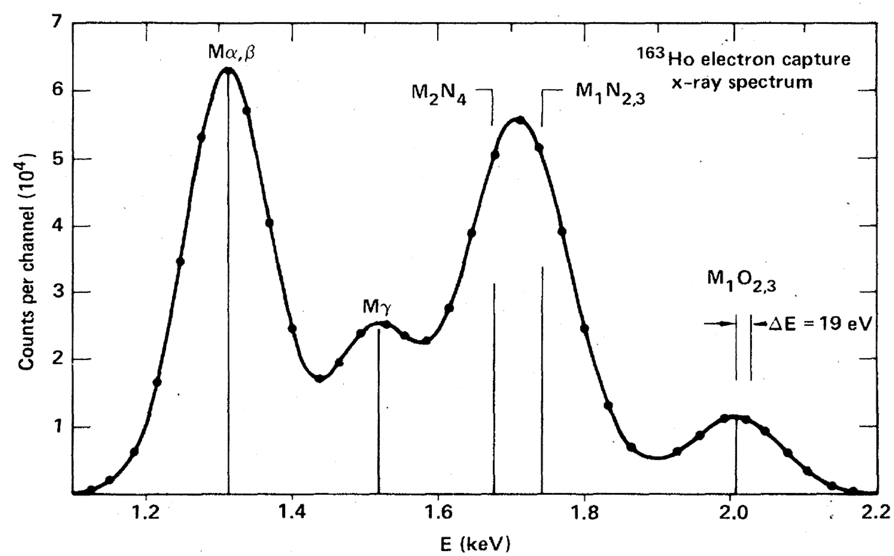
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$



Atomic de-excitation:

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



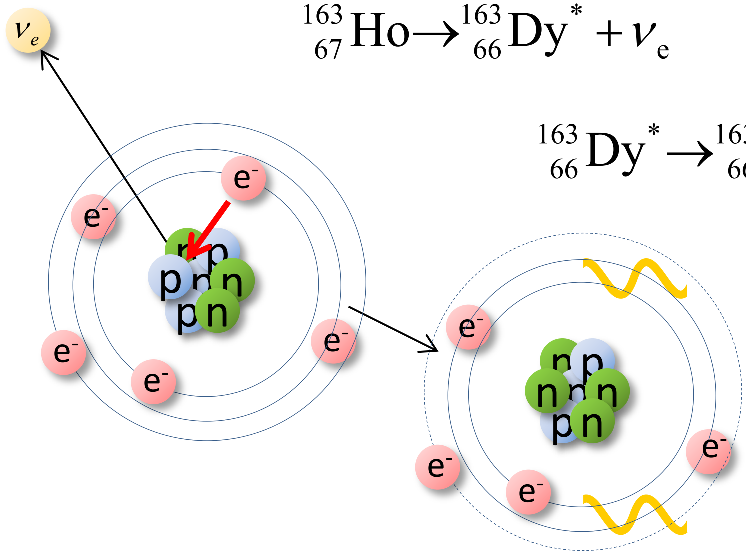


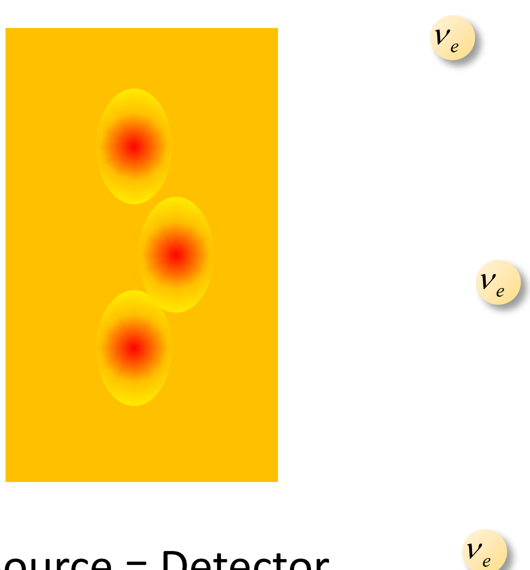
P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

Electron capture in ^{163}Ho

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

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





Source = Detector

Atomic de-excitation:

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

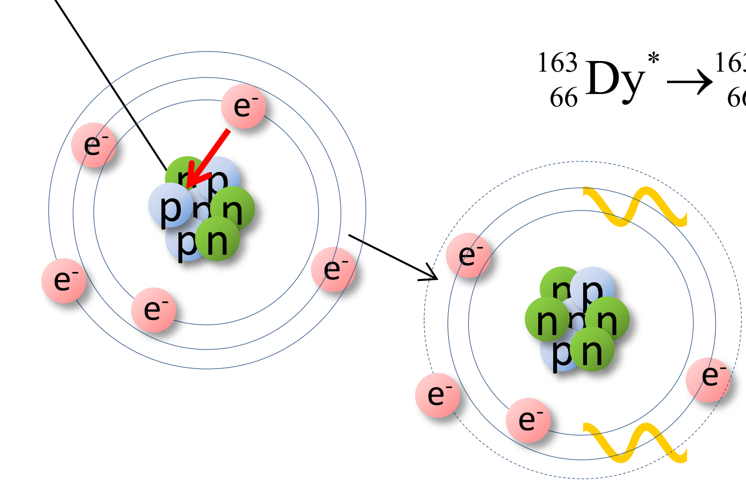
Calorimetric measurement

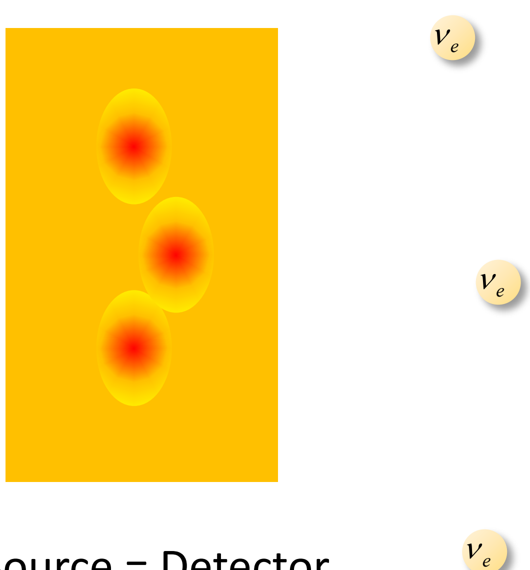
All the energy released in the electron capture process minus the one of the electron neutrino is measured by the detector

Electron capture in ^{163}Ho

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

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





Source = Detector

Atomic de-excitation:

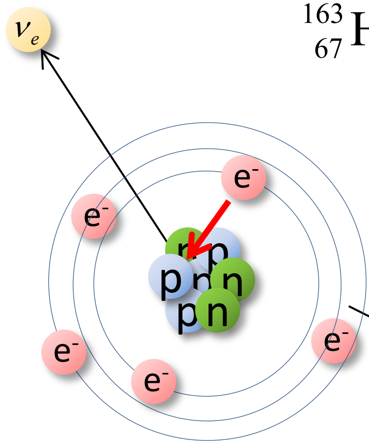
- **X-ray emission**
- **Auger electrons**
- **Coster-Kronig transitions**

Calorimetric measurement

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

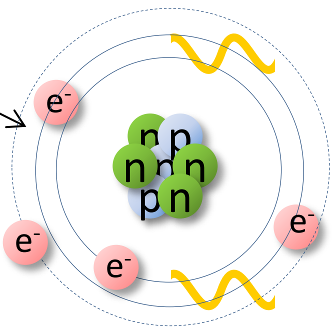
A. De Rujula and M. Lusignoli, Phys. Lett. 118 B (1982) 118

Electron capture in ^{163}Ho



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

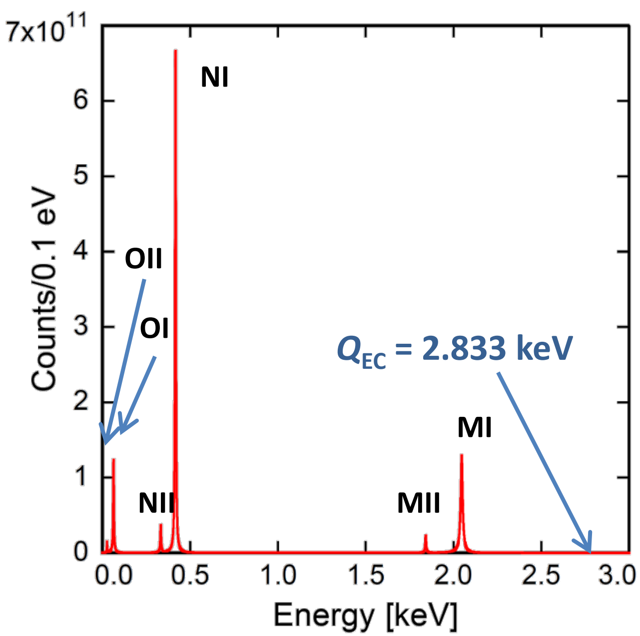
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$



Atomic de-excitation:

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

Calorimetric measurement

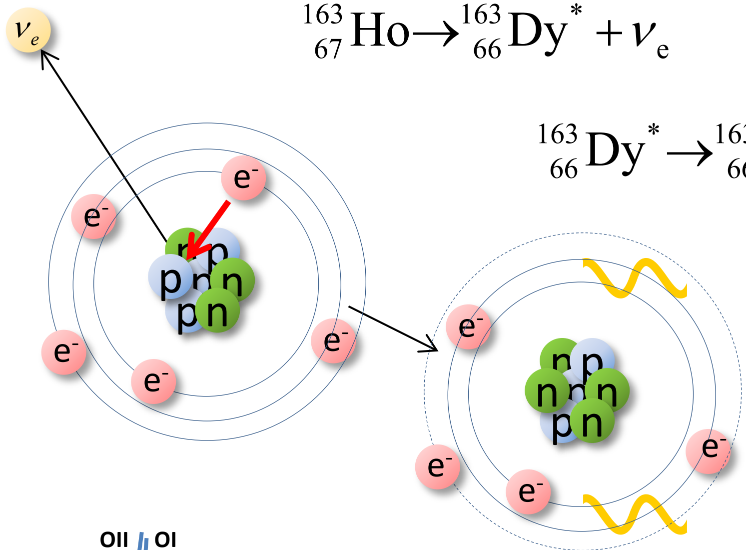


$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

Electron capture in ^{163}Ho

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

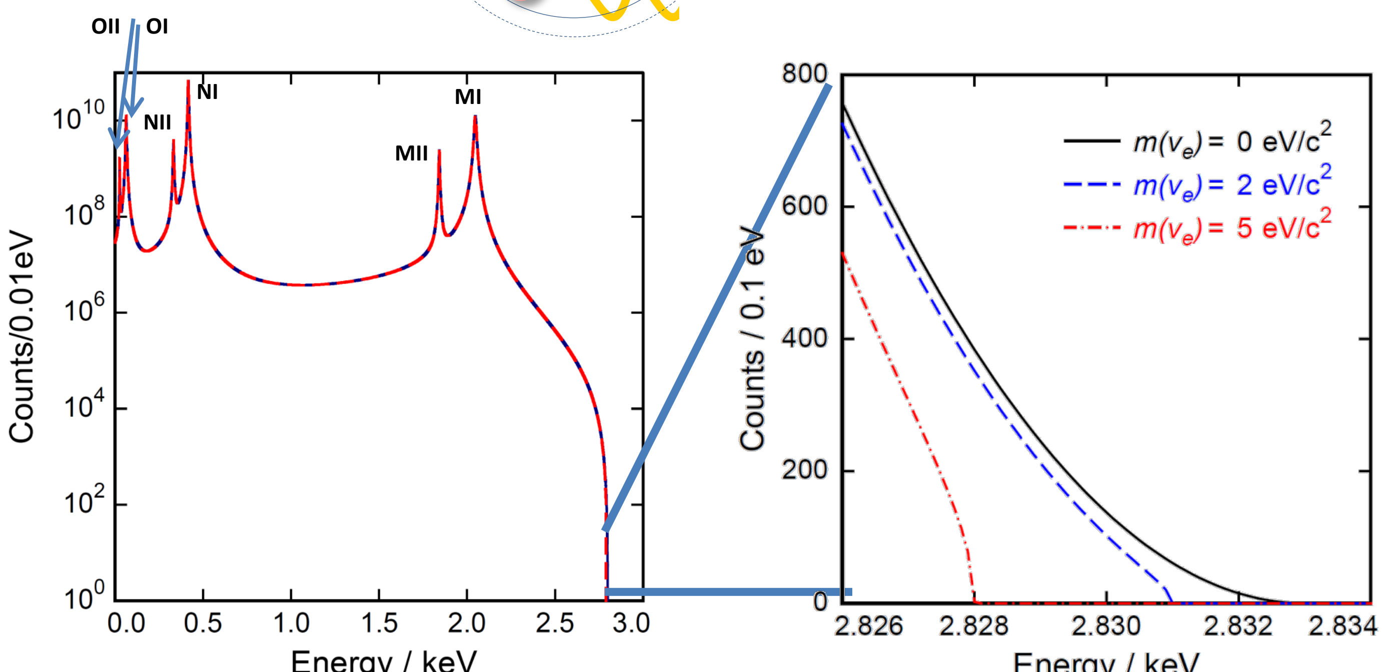
$$ {}^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C $$



Atomic de-excitation:

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

Calorimetric measurement



^{163}Ho-based experiments

ECHo (1)

- Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
- Goethe Universität Frankfurt am Main
- Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz
- Institute of Nuclear and Particle Physics, TU Dresden, Germany
- Institute for Physics, Humboldt-Universität zu Berlin, Germany
- Institute for Physics, Johannes Gutenberg-Universität
- Institute for Theoretical Physics, University of Tübingen, Germany
- Institut Laue-Langevin, Grenoble, France
- ISOLDE-CERN
- Kirchhoff-Institute for Physics, Heidelberg University, Germany
- Max-Planck Institute for Nuclear Physics Heidelberg, Germany
- Petersburg Nuclear Physics Institute, Russia
- Physics Institute, University of Tübingen, Germany

HOLMES (2)

- Milano-Bicocca University, Italy
- INFN Sez. Milano-Bicocca, Italy
- INFN Sez. Genova, LNGS, Italy
- INFN Sez. Roma, Italy
- Institut Laue-Langevin, Grenoble, France
- Lisboa University, Portugal
- Miami University, USA
- NIST, Boulder, USA
- JPL, Pasadena, USA
- PSI, Villingen, Switzerland

NuMECS (3)

- LANL, Los Alamos, USA
- NIST, Boulder, USA
- Univ. of Wisconsin, Madison, USA

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

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

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

^{163}Ho-based experiments

ECHo (1)

- Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
- Goethe Universität Frankfurt am Main
- Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz
- Institute of Nuclear and Particle Physics, TU Dresden, Germany
- Institute for Physics, Humboldt-Universität zu Berlin, Germany
- Institute for Physics, Johannes Gutenberg-Universität
- Institute for Theoretical Physics, University of Tübingen, Germany
- Institut Laue-Langevin, Grenoble, France
- ISOLDE-CERN
- Kirchhoff-Institute for Physics, Heidelberg University, Germany
- Max-Planck Institute for Nuclear Physics Heidelberg, Germany
- Petersburg Nuclear Physics Institute, Russia
- Physics Institute, University of Tübingen, Germany

HOLMES (2)

- Milano-Bicocca University, Italy
- INFN Sez. Milano-Bicocca, Italy
- INFN Sez. Genova, LNGS, Italy
- INFN Sez. Roma, Italy
- Institut Laue-Langevin, Grenoble, France
- Lisboa University, Portugal
- Miami University, USA
- NIST, Boulder, USA
- JPL, Pasadena, USA
- PSI, Villingen, Switzerland

NuMECS (3)

- LANL, Los Alamos, USA
- NIST, Boulder, USA
- Univ. of Wisconsin, Madison, USA

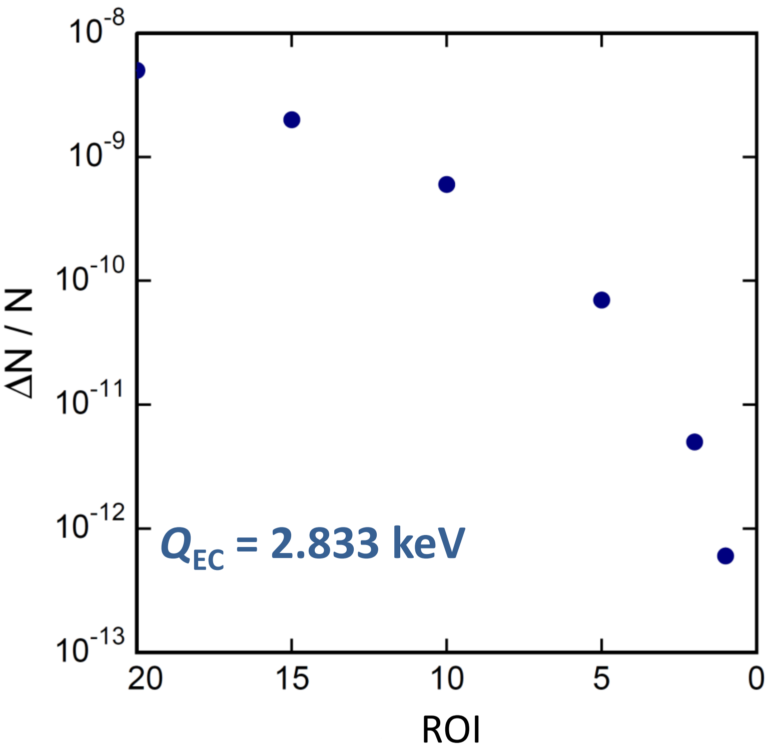
More in Gatti's talk on Thursday

(1) The ECHo Collaboration EPJ-ST 226 8 (2017) 1623
(2) B. Alpert et al, Eur. Phys. J. C 75 (2015) 112
(3) M. Croce et al., JLTP 184 3 (2016) 938

Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**



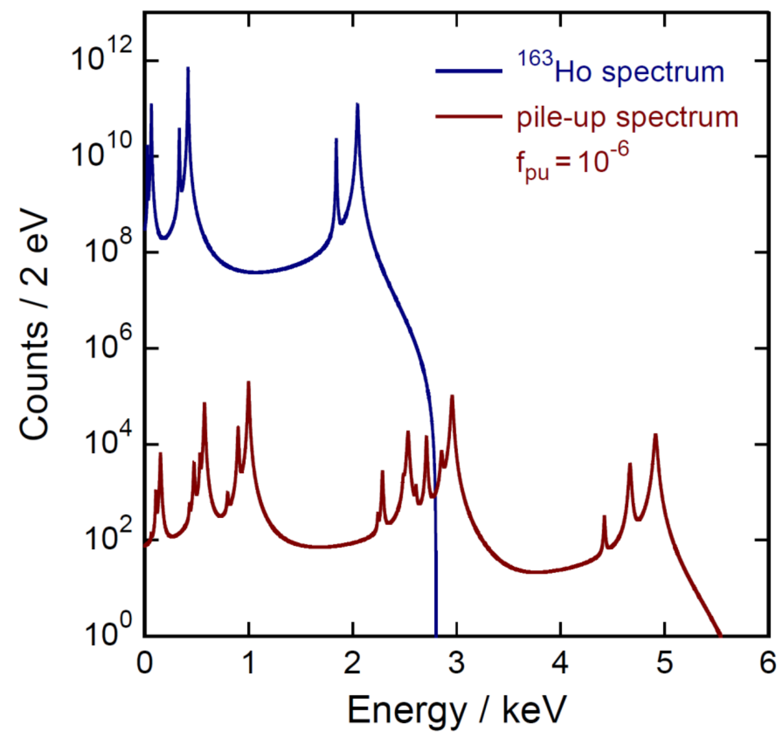
Requirements for sub-eV sensitivity in ECHo

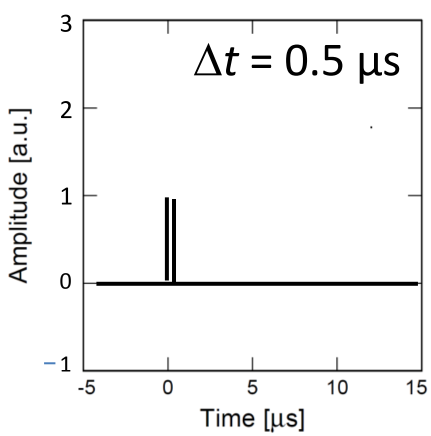
Statistics in the end point region

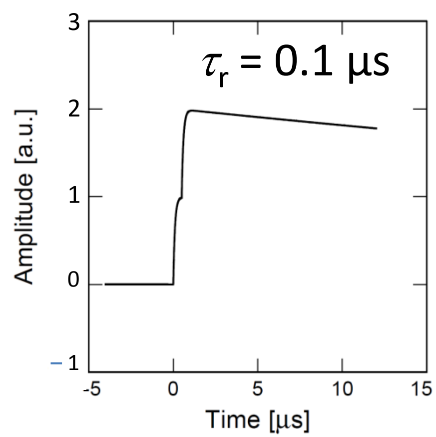
- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

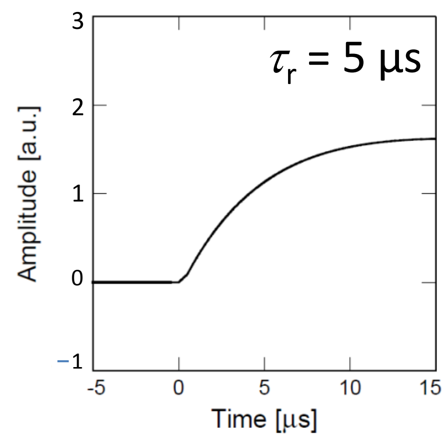
Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

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









Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

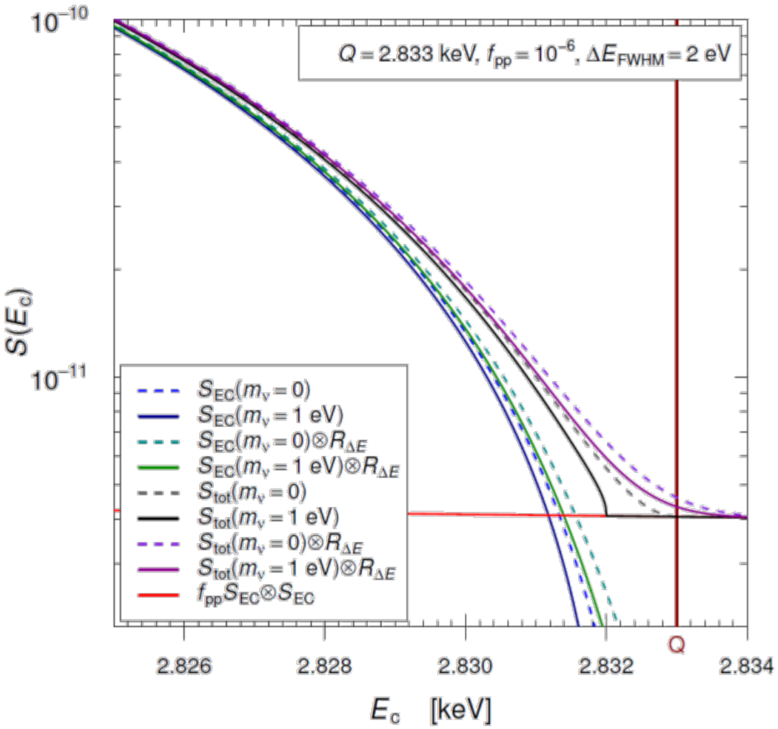
- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

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

Precision characterization of the endpoint region

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



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

Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

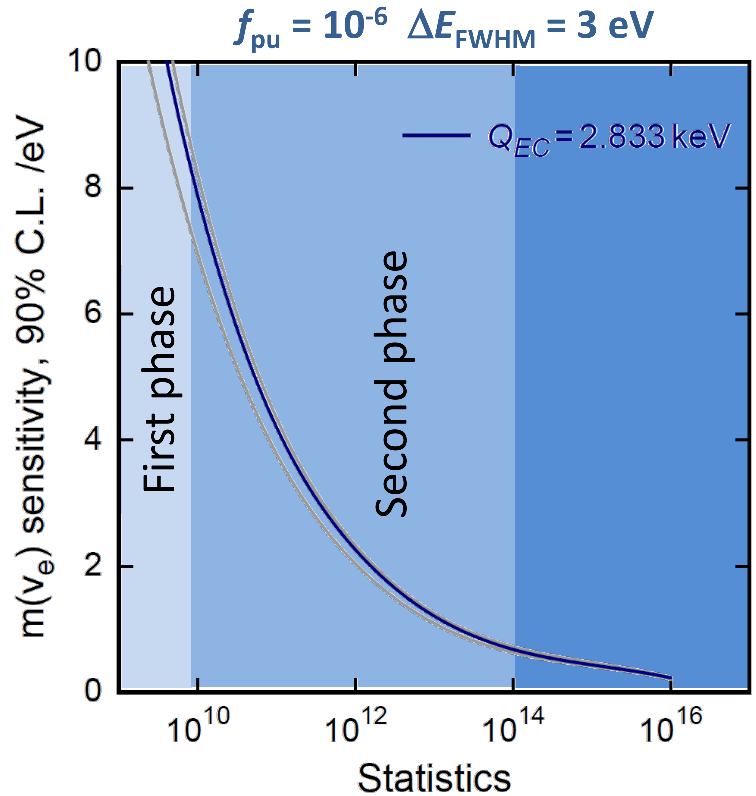
- $\boldsymbol{f_{pu} < 10^{-5}}$
- $\tau_r < 1\ \mu s$ → a ~ 10 Bq
- 10^5 pixels → **multiplexing**

Precision characterization of the endpoint region

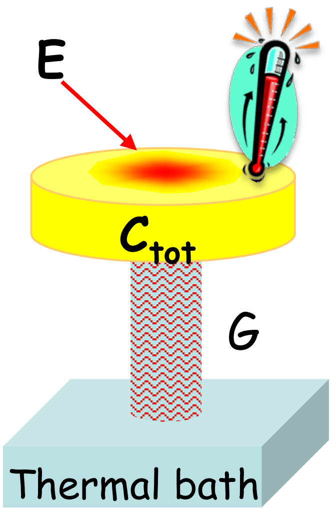
- $\boldsymbol{\Delta E_{FWHM} < 3\ eV}$

Background level

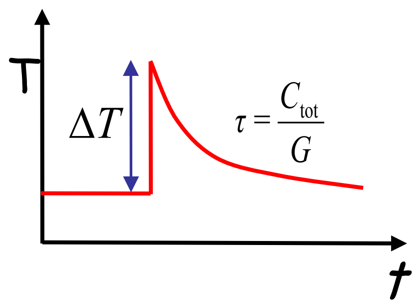
- **$< 10^{-5}$ events/eV/det/day**



Low temperature micro-calorimeters



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



***E* = 10 keV**

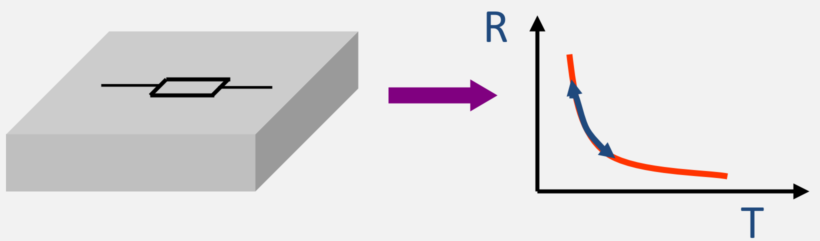
C_{tot} = 1 pJ/K

→~ 1 mK

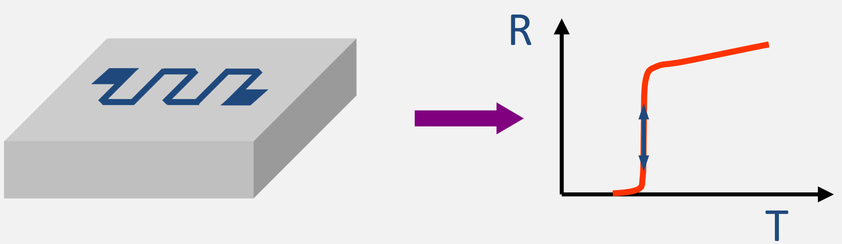
- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
- **Very sensitive temperature sensor**

Temperature sensors

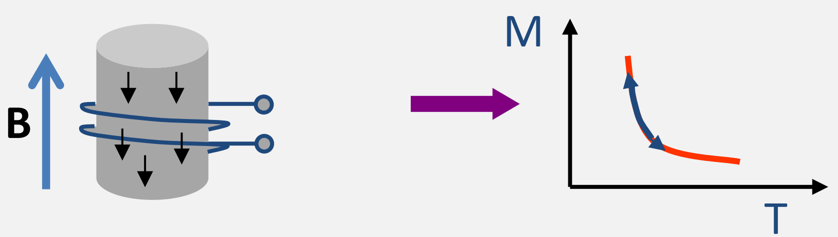
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES



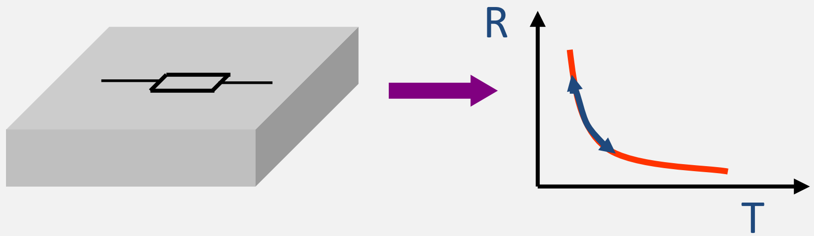
Magnetization of paramagnetic material, MMC



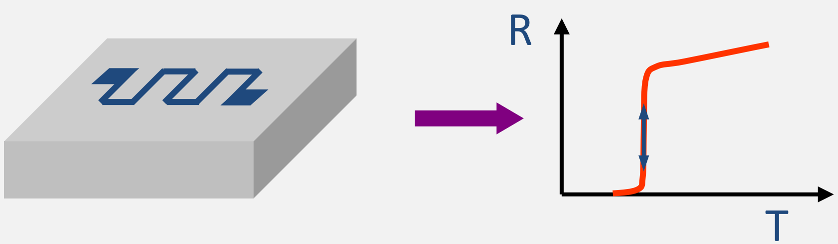
Cryogenic Particle Detection, (ed. C. Enss), Topics Appl. Phys. 99 (Springer Berlin Heidelberg 2005)

Temperature sensors

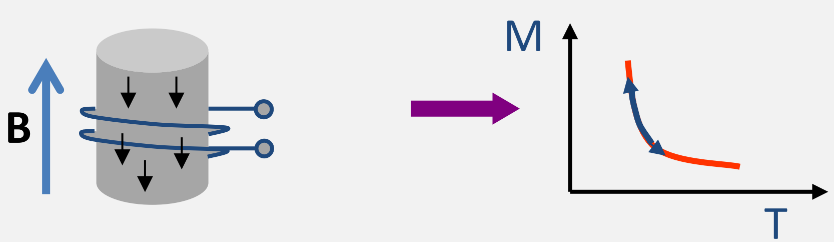
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES



Magnetization of paramagnetic material, MMC



HOLMES

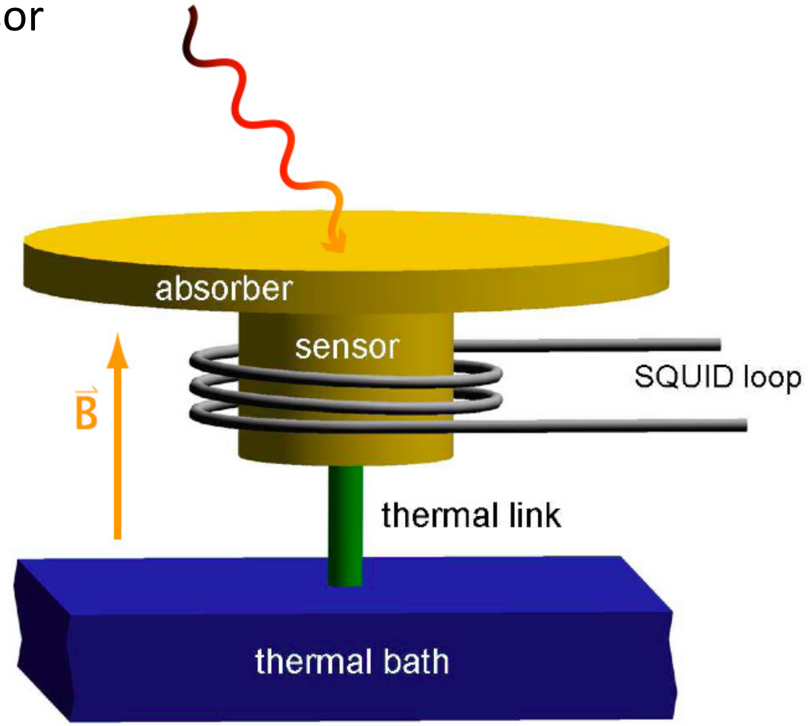
NuMECS

ECHo

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

Metallic magnetic calorimeters (MMCs)

- Paramagnetic Ag:Er sensor

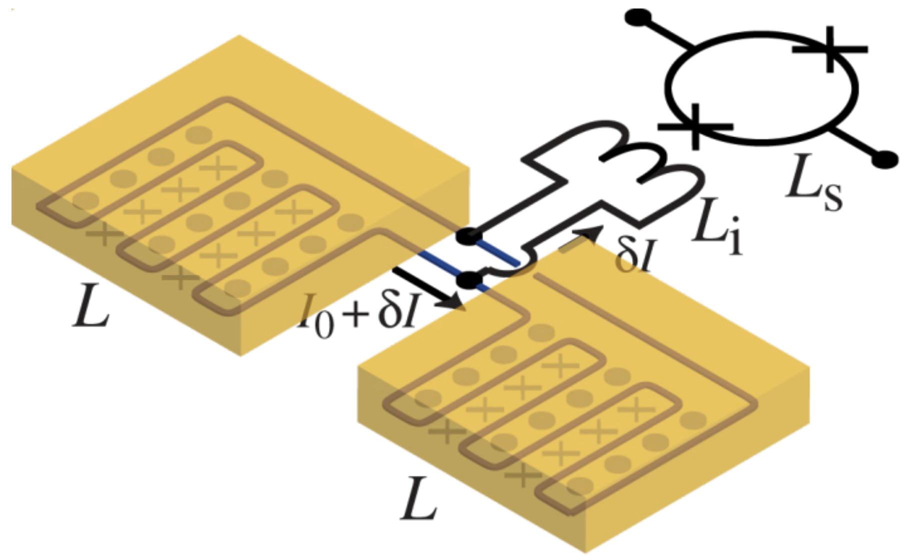


$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{\mathrm{sens}} + C_{\mathrm{abs}}}$$

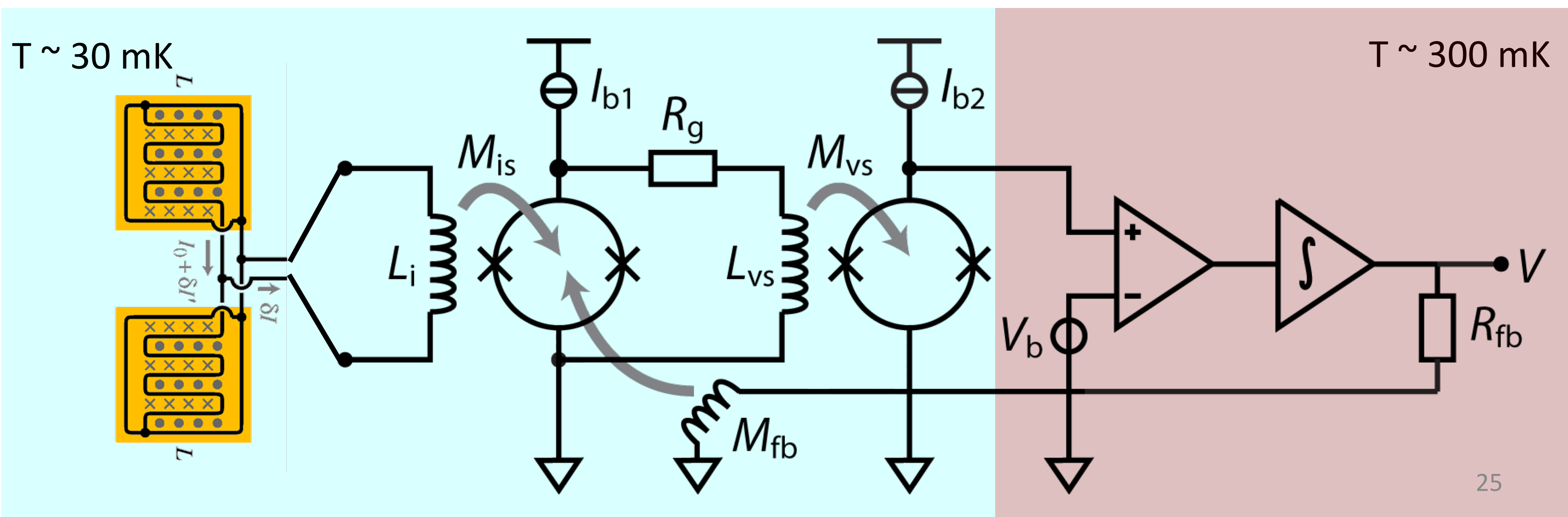
A. Fleischmann et al., *AIP Conf. Proc.* **1185**, 571, (2009)

MMC geometry and read-out

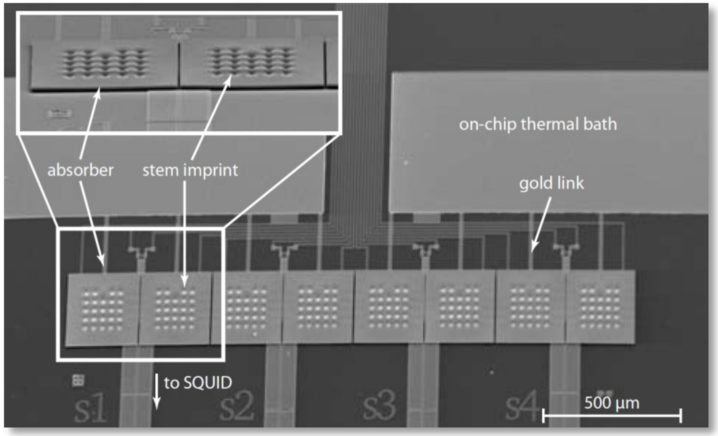
- Planar temperature sensor
- B-field generated by persistent current
- transformer coupled to SQUID

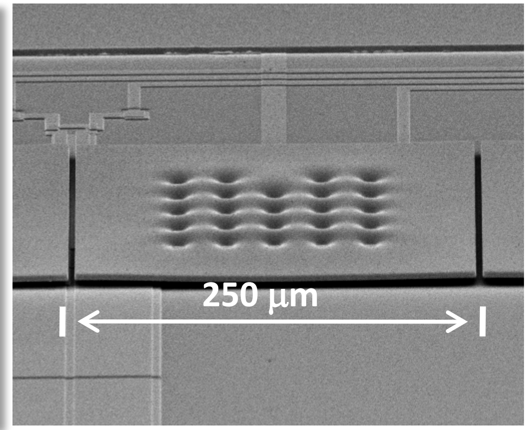


- Two-stage SQUID read-out

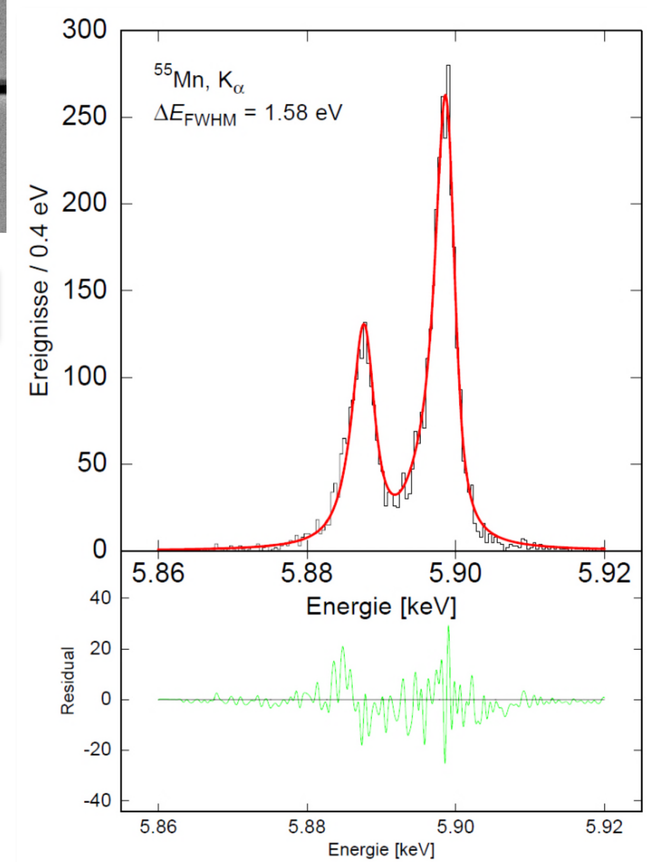


MMCs: 1d-array for soft x-rays (T=20 mK)

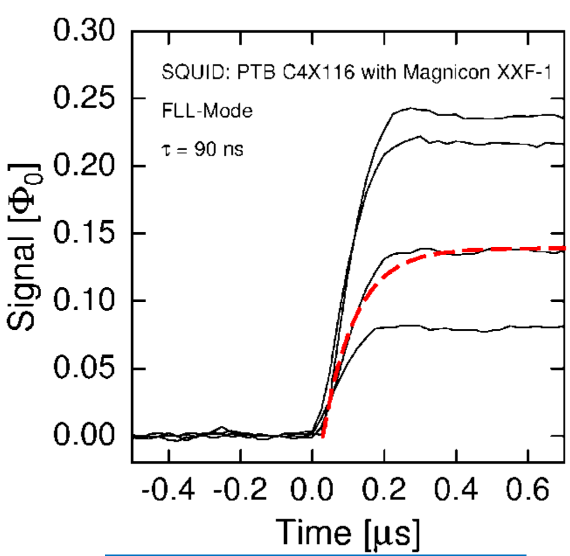




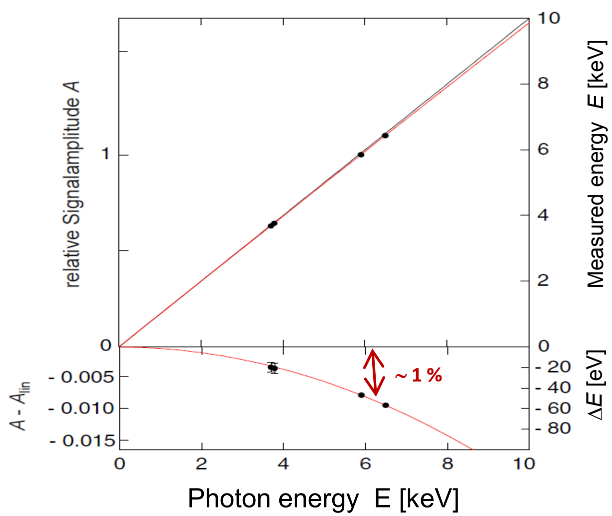
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



Non-Linearity < 1% @6keV



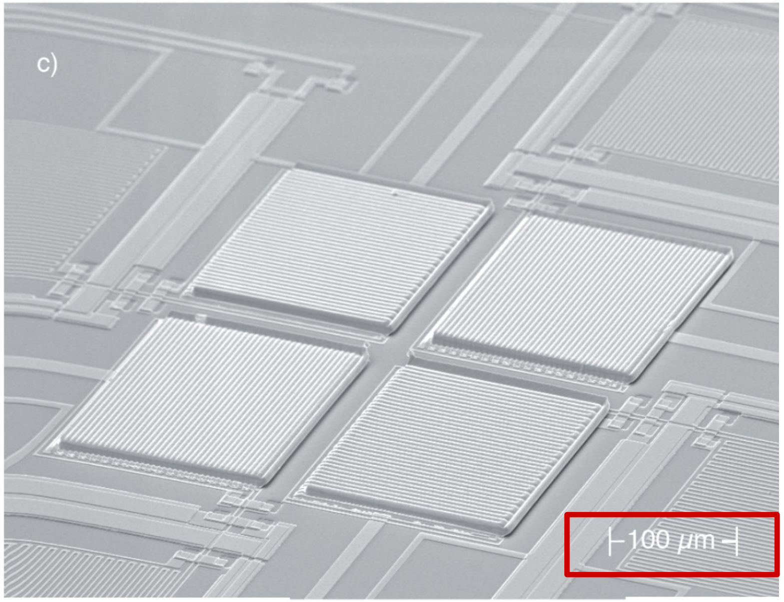
Reduction
un-resolved pile-up

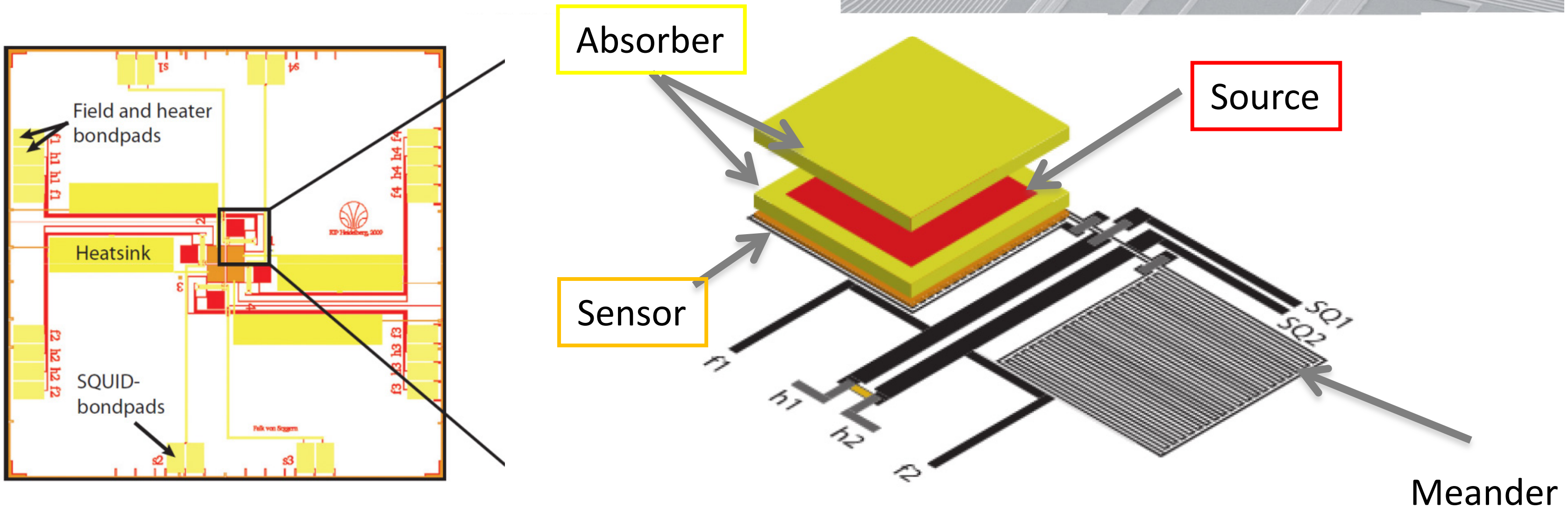
Definition
of the energy scale

Reduced smearing
in the end point region

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





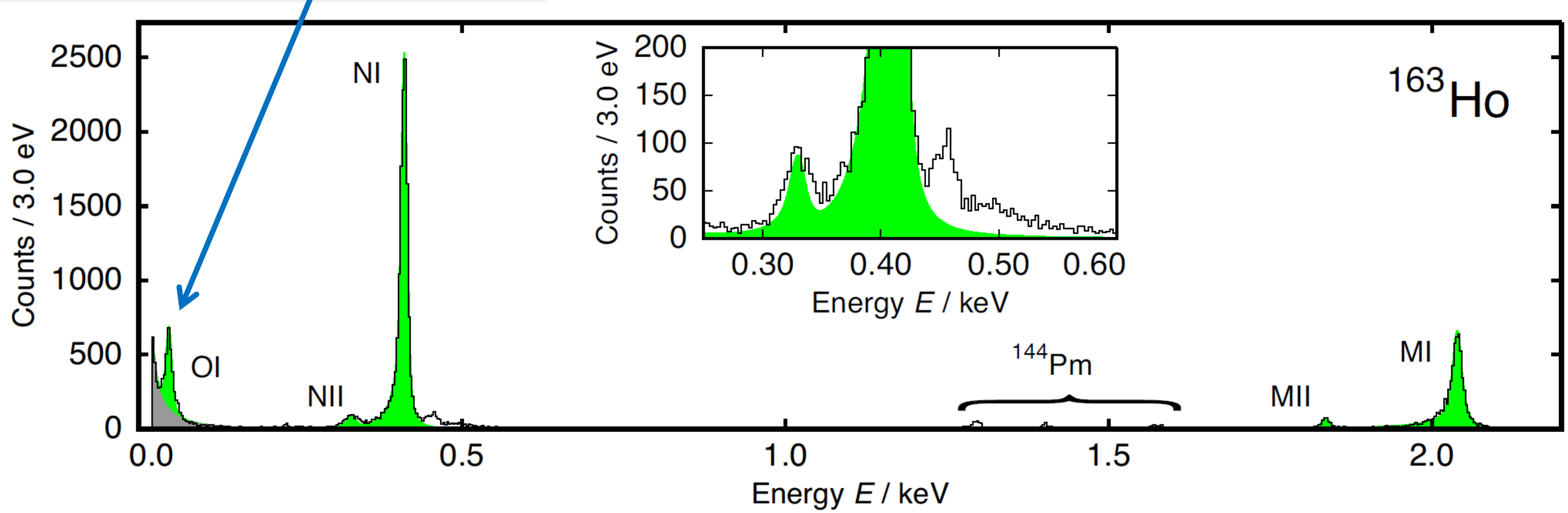
L. Gastaldo et al., Nucl. Inst. Meth. A, 711 (2013) 150

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

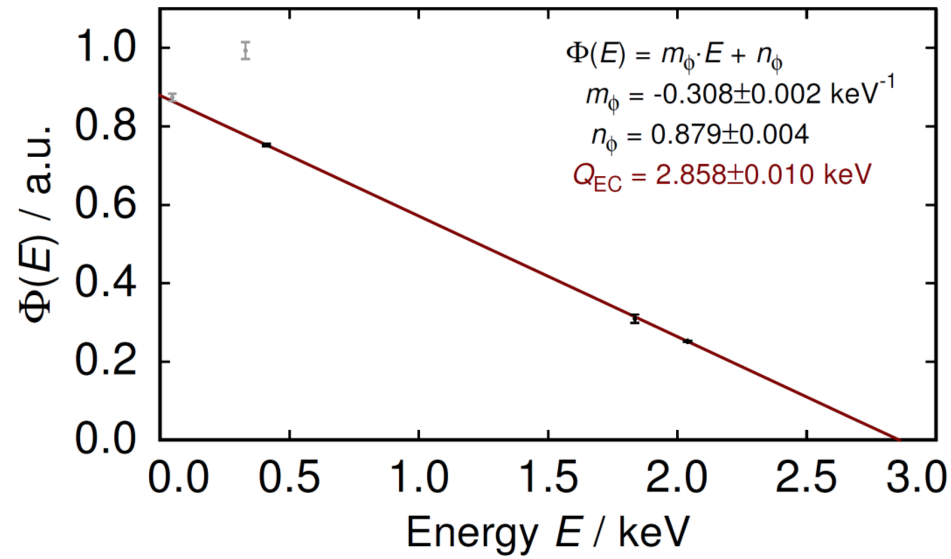


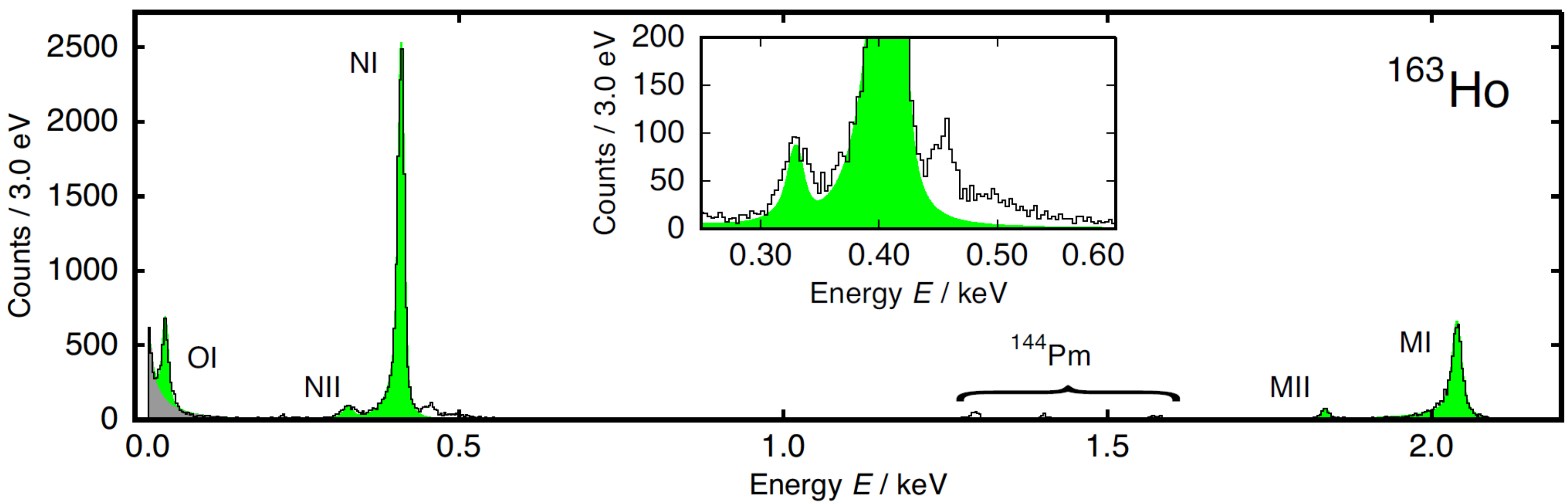
P. C.-O. Ranitzsch et al ., accepted for publication in PRL (2017)

Q_{EC} determination

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

Line amplitudes are affected by the phase space factor

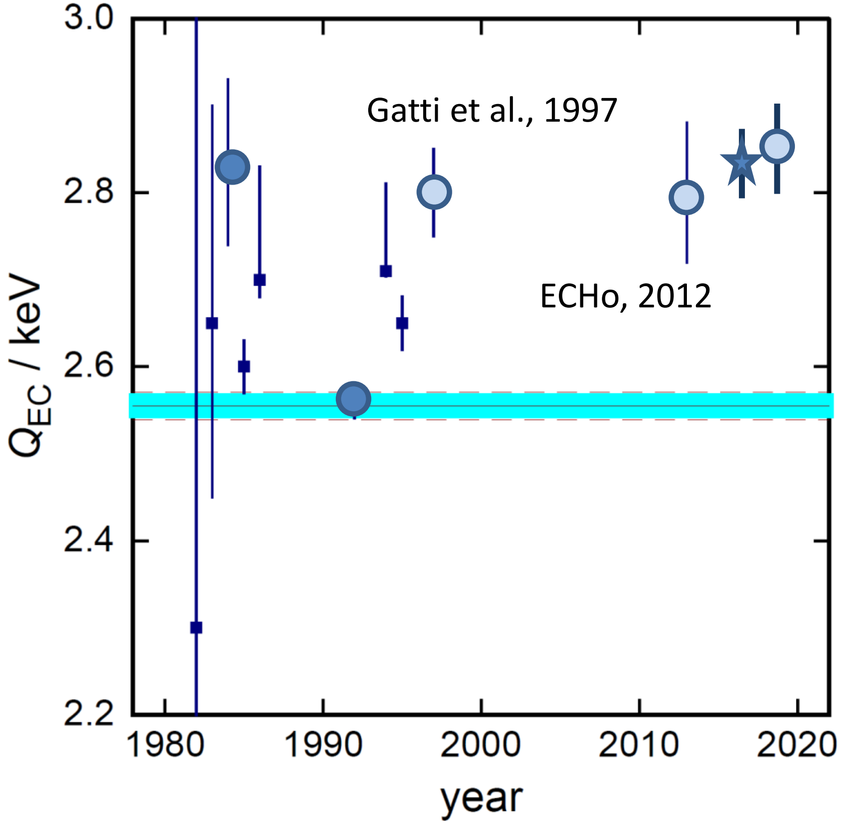


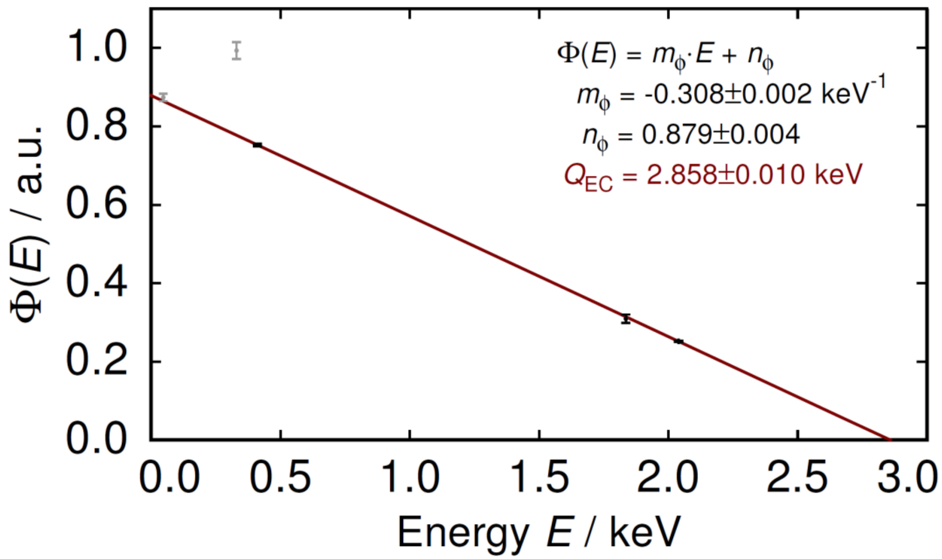


P. C.-O. Ranitzsch et al ., accepted for publication in PRL (2017)

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:

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

Penning Trap Mass Spectrometry result:

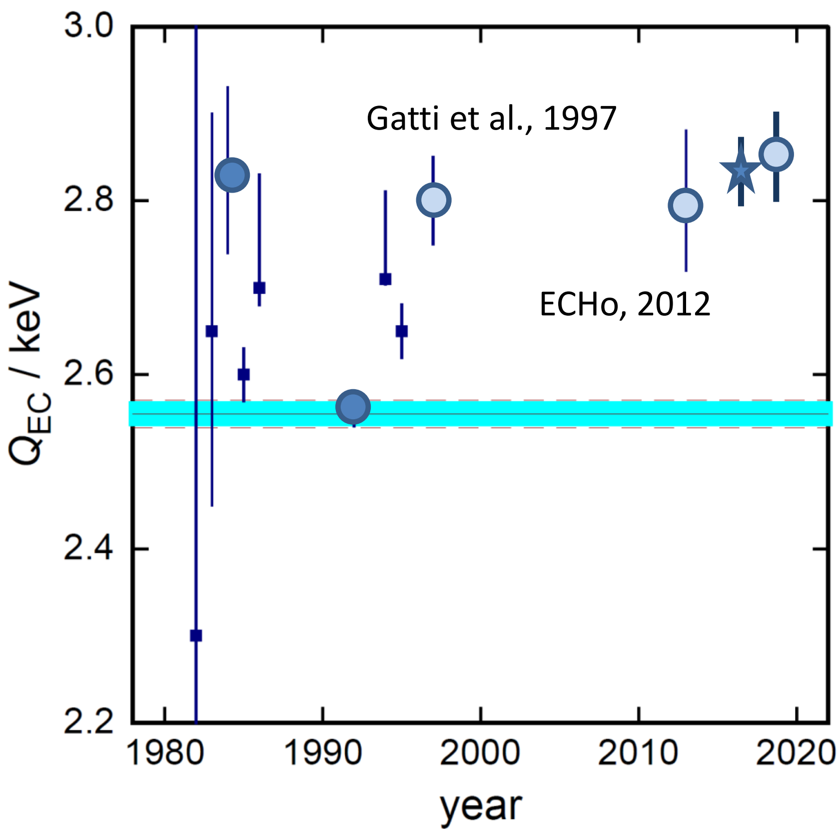
$Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

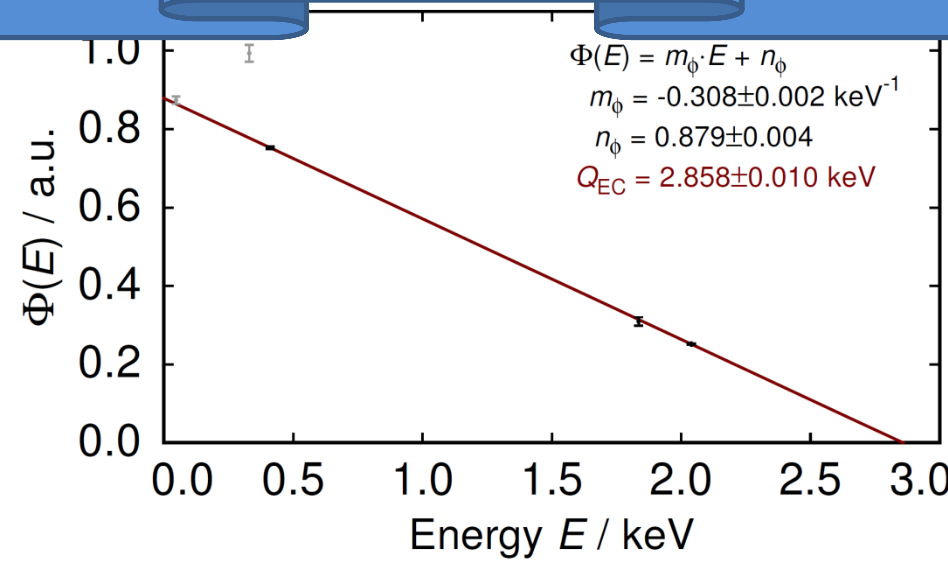
P. C.-O. Ranitzsch et al ., accepted for publication in PRL (2017)

Q_{EC} determination

Good agreement between the two measurements

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





Our result:

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

Penning Trap Mass Spectrometry result:

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

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

Scaling up

^{163}Ho high purity source

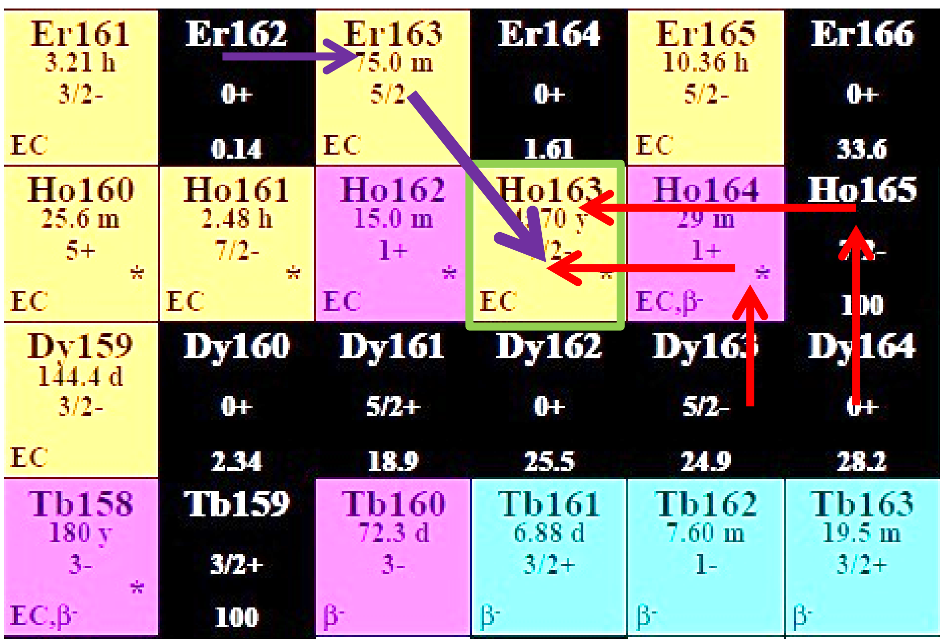
Required activity in the detectors: Final experiment → >10^6 Bq → >10^{17} atoms

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

  High cross-section

  Radioactive contaminants



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

^{163}Ho high purity source

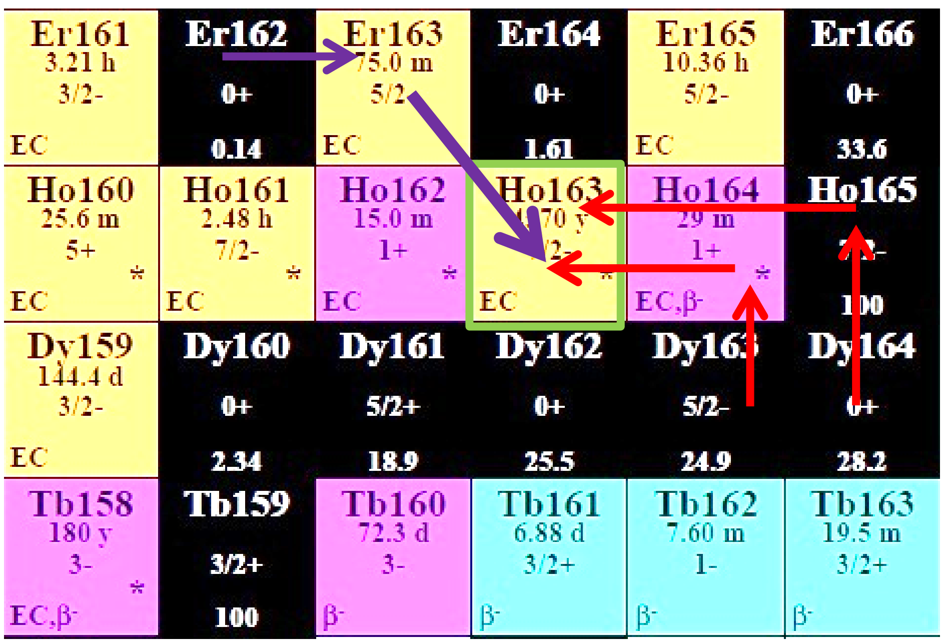
Required activity in the detectors: Final experiment → >10^6 Bq → >10^{17} atoms

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

  High cross-section

  Radioactive contaminants

ECHo HOLMES



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

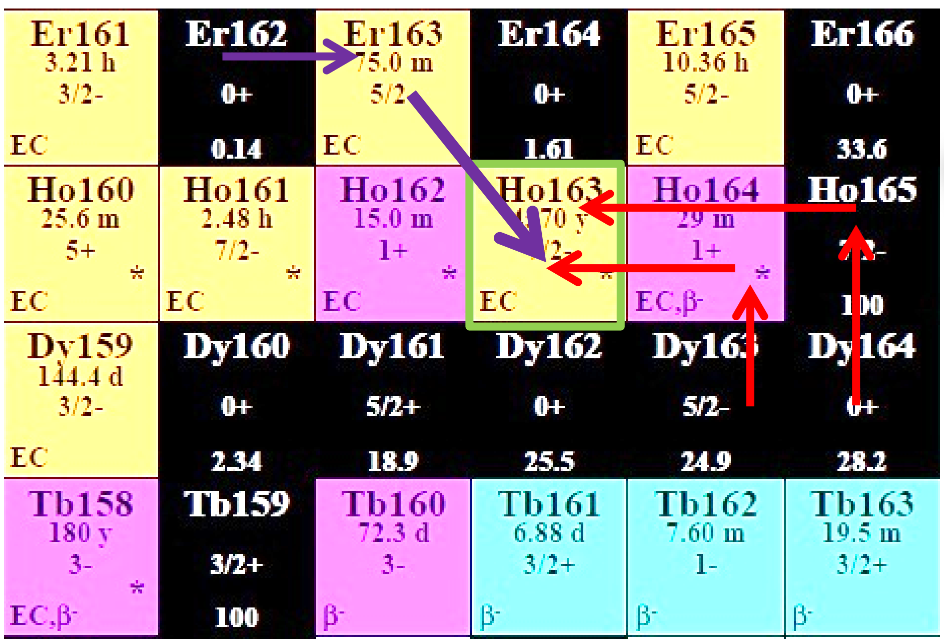
^{163}Ho high purity source

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



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

ECHo HOLMES

More in Kieck's talk today

- Ch... rticle activation

  ^{nat}Dy(p,xn) ^{163}Ho

  ^{nat}Dy(α, xn) ^{163}Er (ε) ^{163}Ho

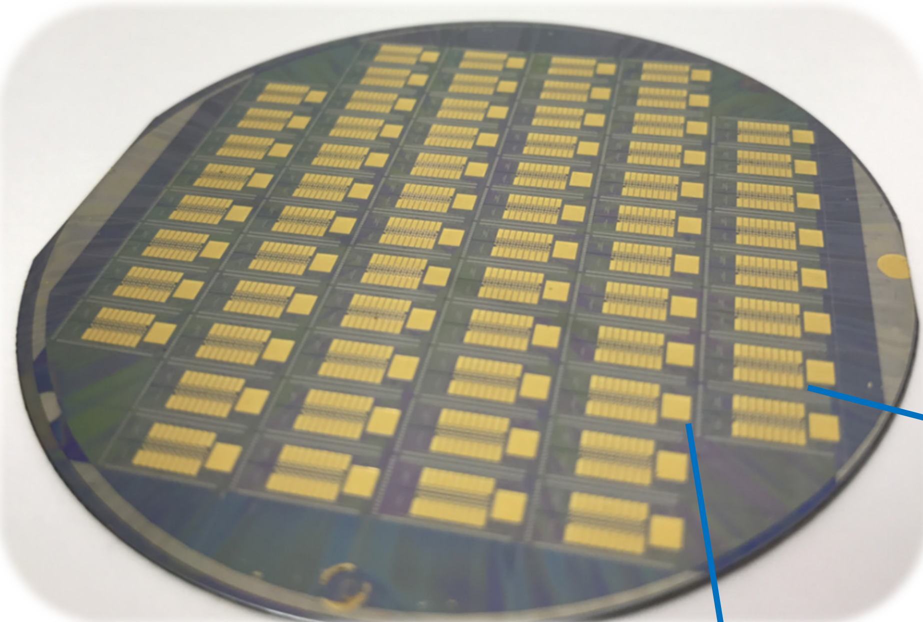
  ^{159}Tb(^{7}Li, 3n) ^{163}Er (ε) ^{163}Ho

  Small cross-section

  Few radioactive contaminants

NuMECS

ECHo-1k array

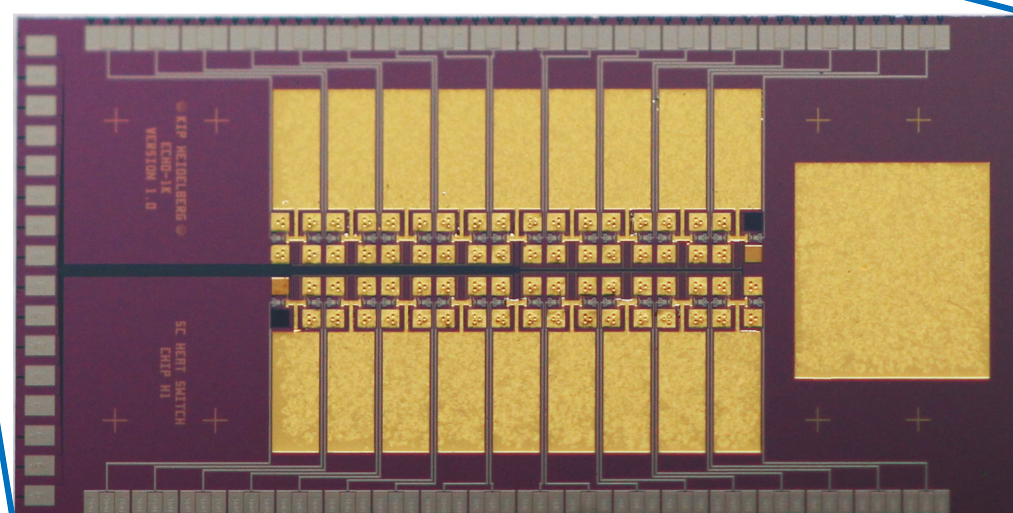


3“ wafer with 64 ECHo-1k chip

Suitable for
parallel and multiplexed readout

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

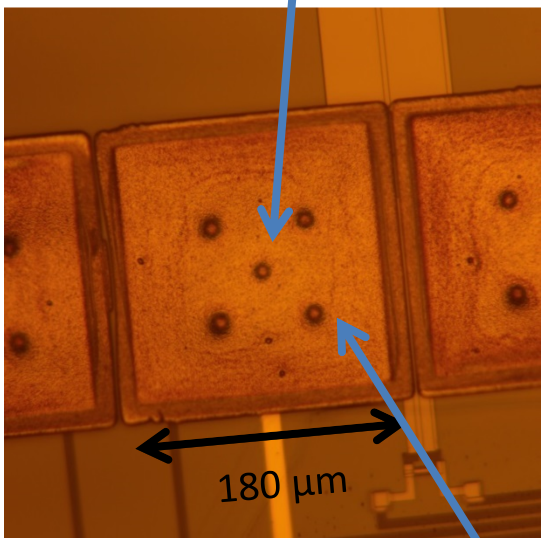
Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)
τ_r ~ 300 ns (multiplexed read-out)

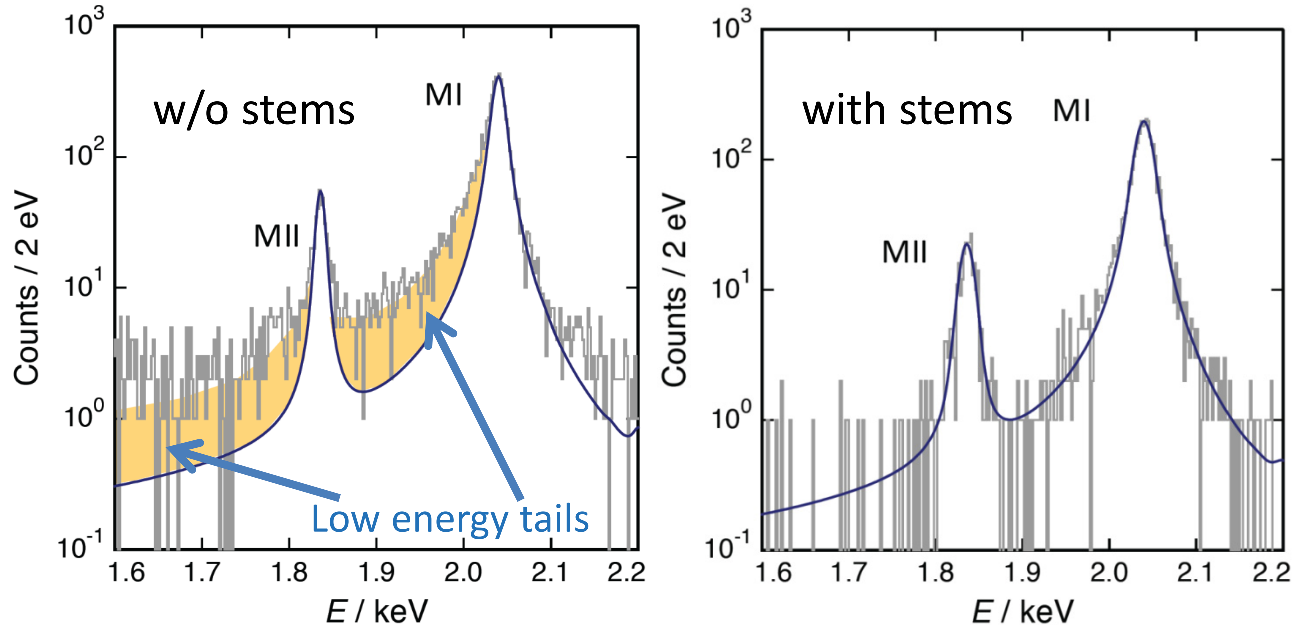


F. Mantegazzini, to be submitted

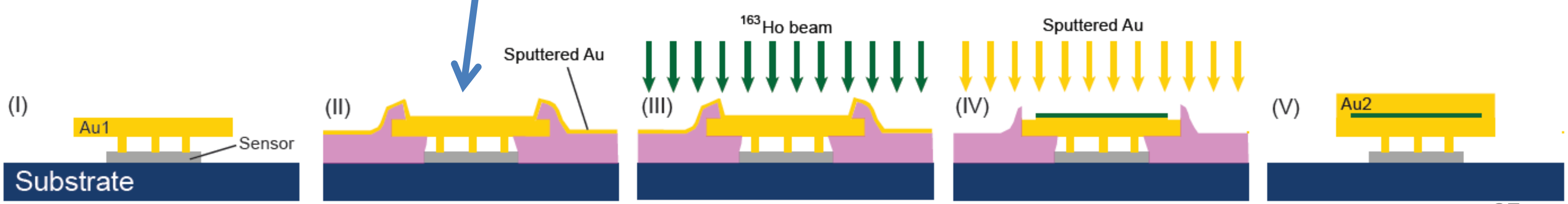
Fabrication 4π absorber

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



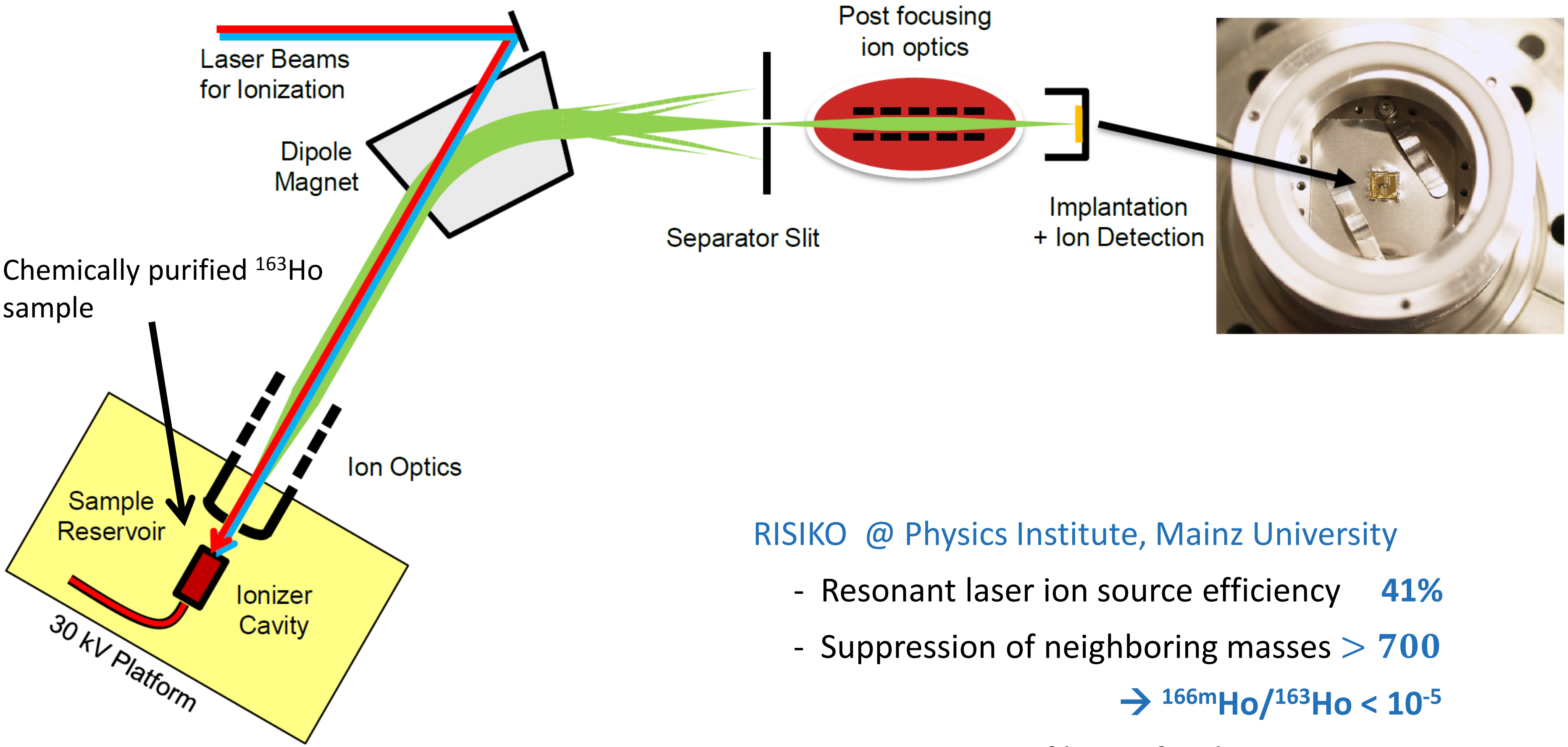


Definition of the implantation area by microstructuring a photoresist layer



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

Mass separation and ^{163}Ho ion-implantation



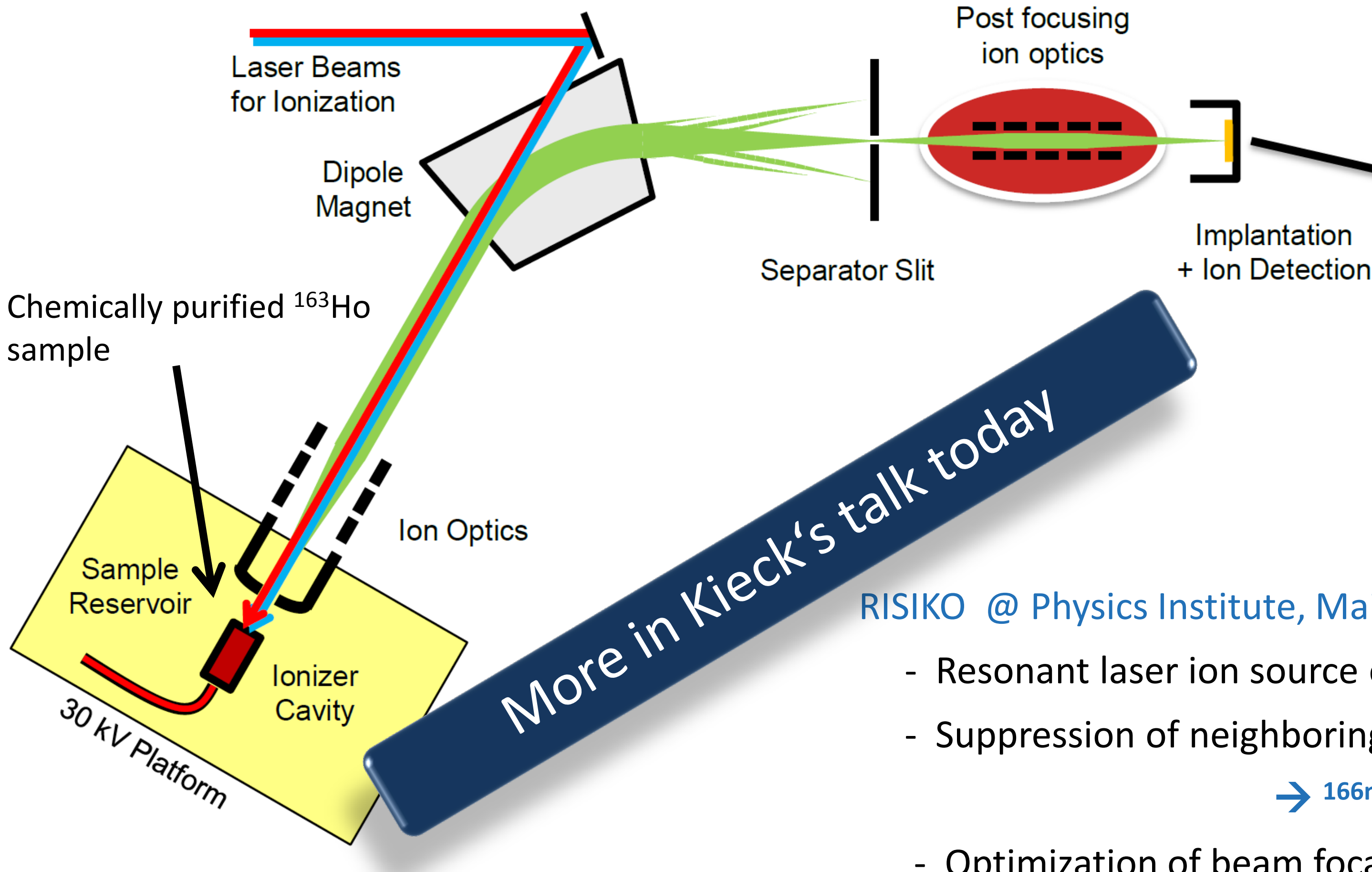
RISIKO @ Physics Institute, Mainz University

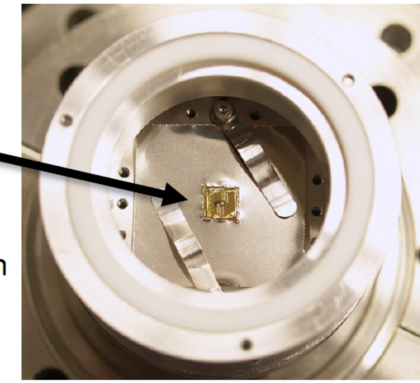
- Resonant laser ion source efficiency **41%**
- Suppression of neighboring masses > 700

  → **^{166m}Ho/^{163}Ho < 10^{-5}**
- Optimization of beam focalization

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

Mass separation and ^{163}Ho ion-implantation





RISIKO @ Physics Institute, Mainz University

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

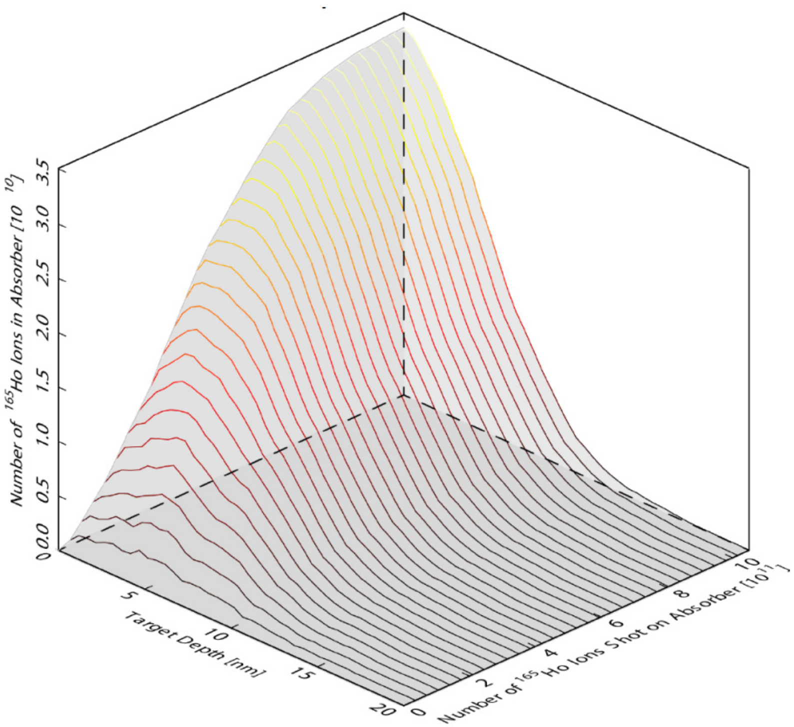
  → **^{166m}Ho/^{163}Ho < 10^{-5}**

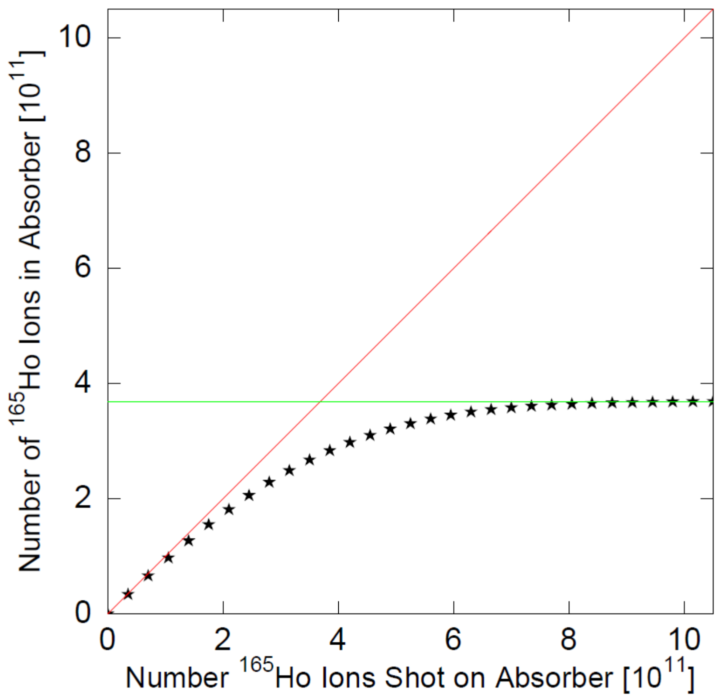
- Optimization of beam focalization

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

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

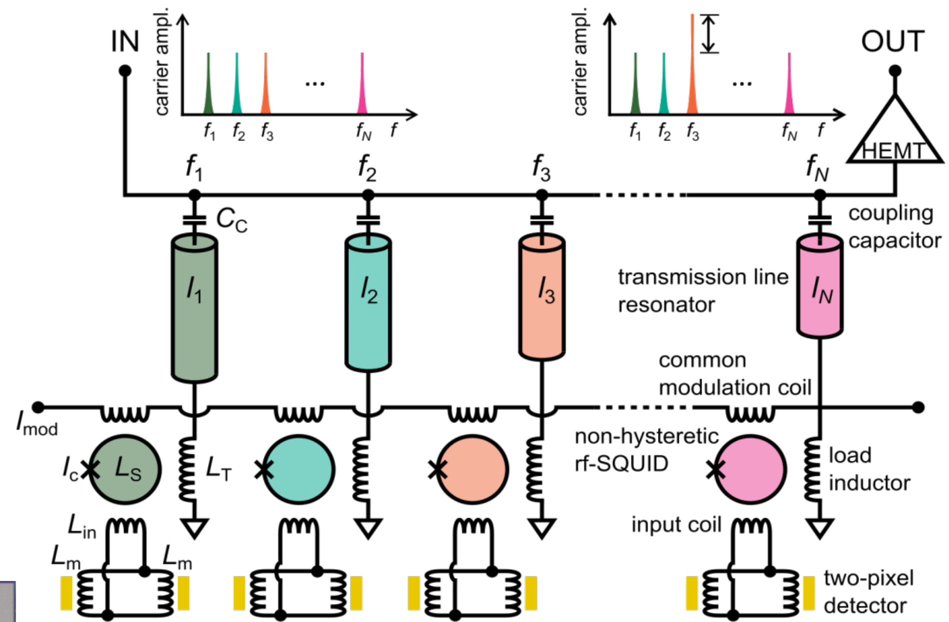
Solution: in situ deposition of gold

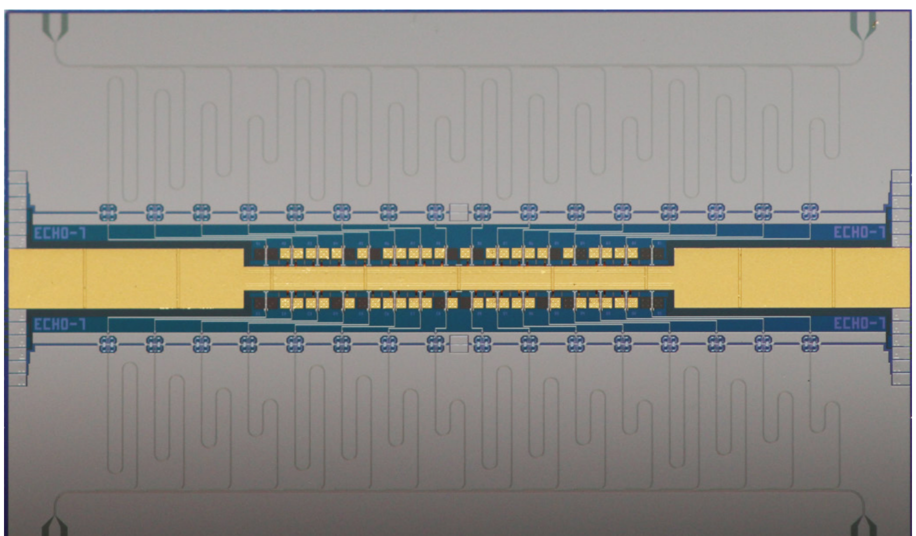
L. Gamer et al., *NIM A* **854** (2017) 139

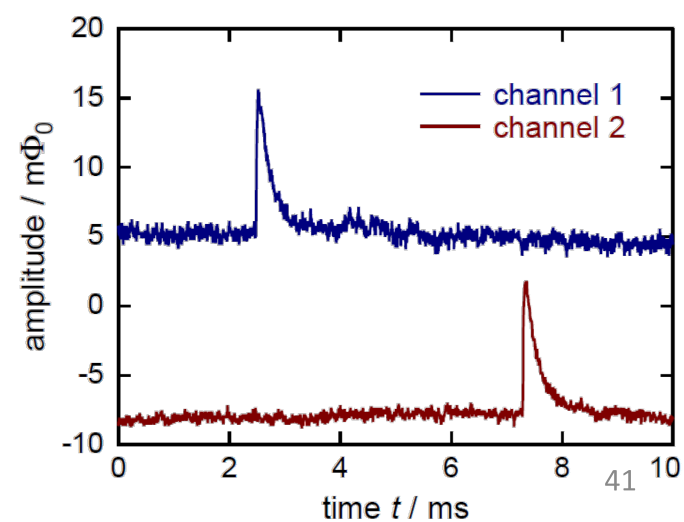
Multiplexing readout

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

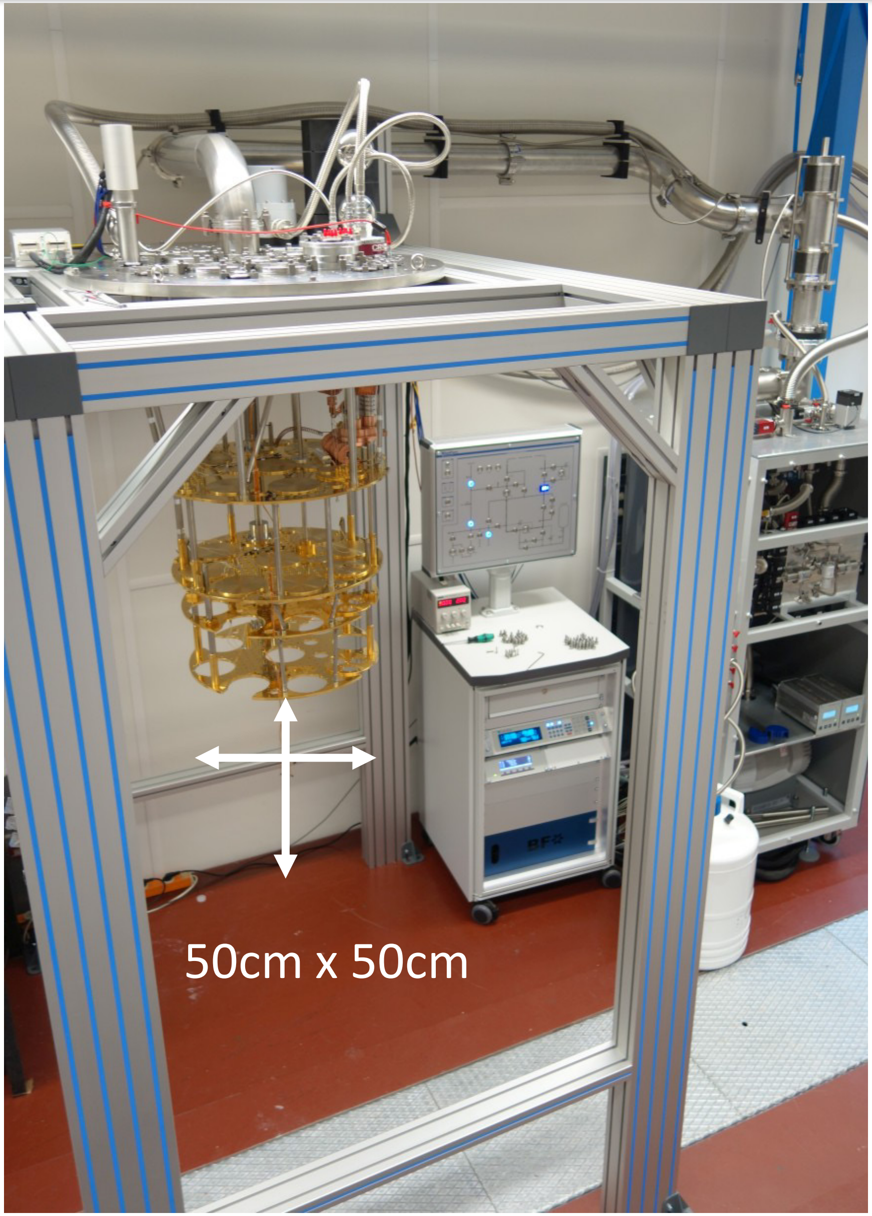




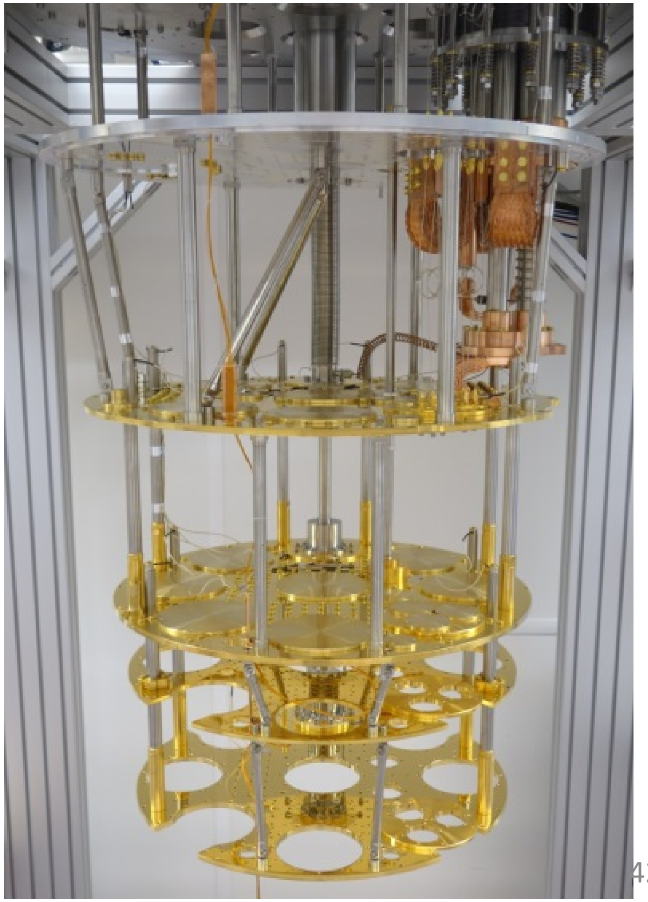


S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

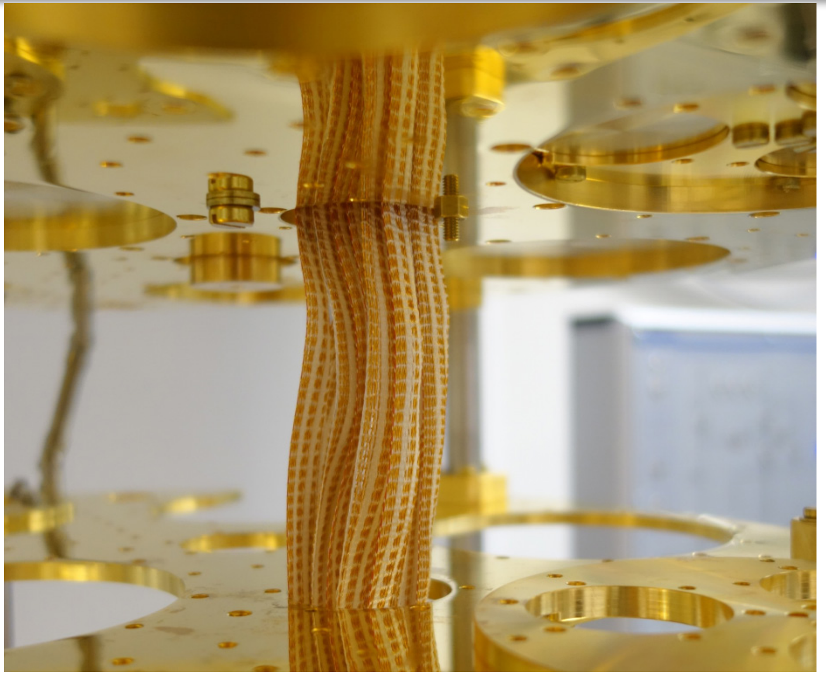
ECHo cryogenic platform

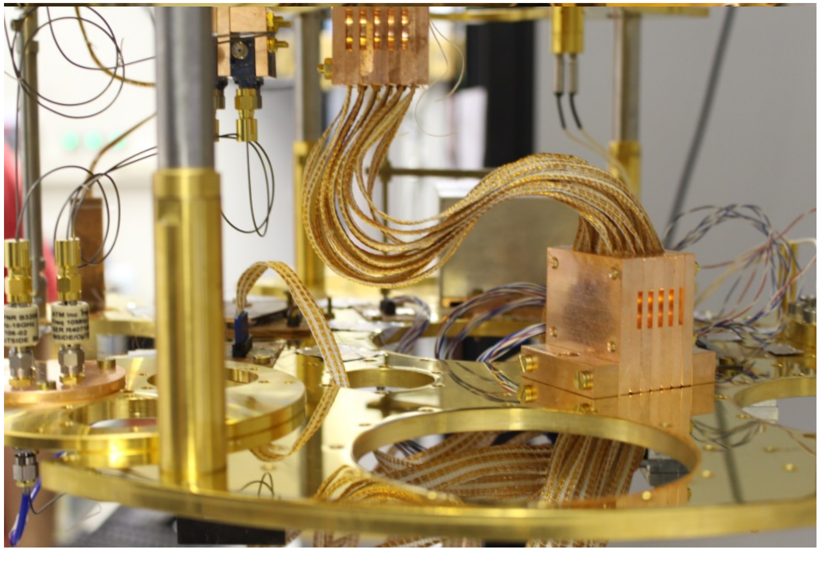


- Large space at MXC enough for several ECHo phases
- cooling power: 15μW @ 20 mK
- Possibility to load 200kg for passive shielding



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

Low background spectrum

NEW (4 pixel, about 4 days in Modane)

- A. Faessler and F. Simkovic
  Phys. Rev. C **91**, 045505 (2015)
- A. De Rujula and M. Lusignoli
  JHEP 05 (2016) 015, arXiv:1601.04990v1

- 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**, 064302 (2015)
- A. Faessler et al.
  Phys. Rev. C **95**, (2017) 045502

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**

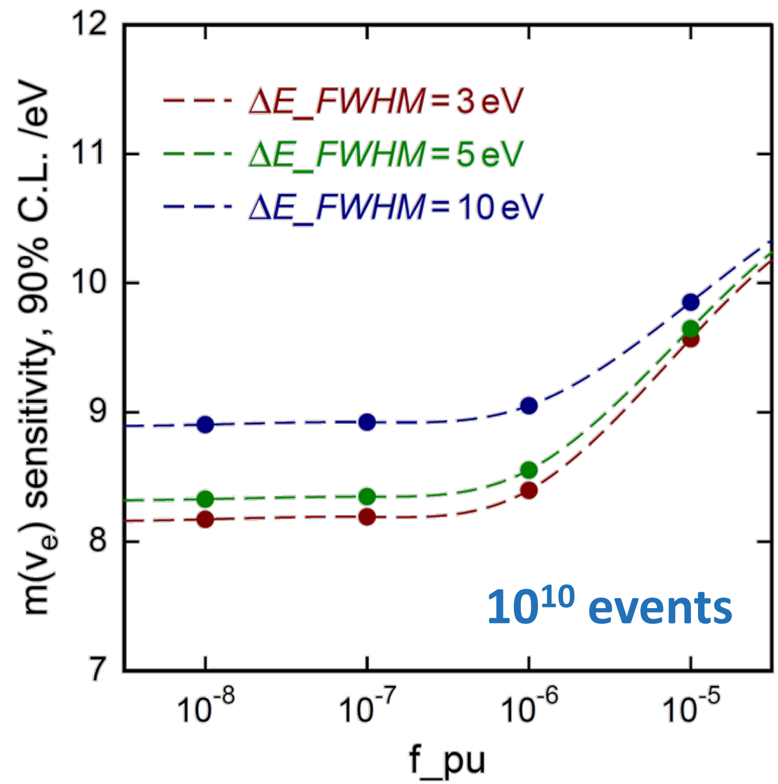
→number of detectors **N = 100**

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: $\mathbf{A_t = 1\ MBq}$

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

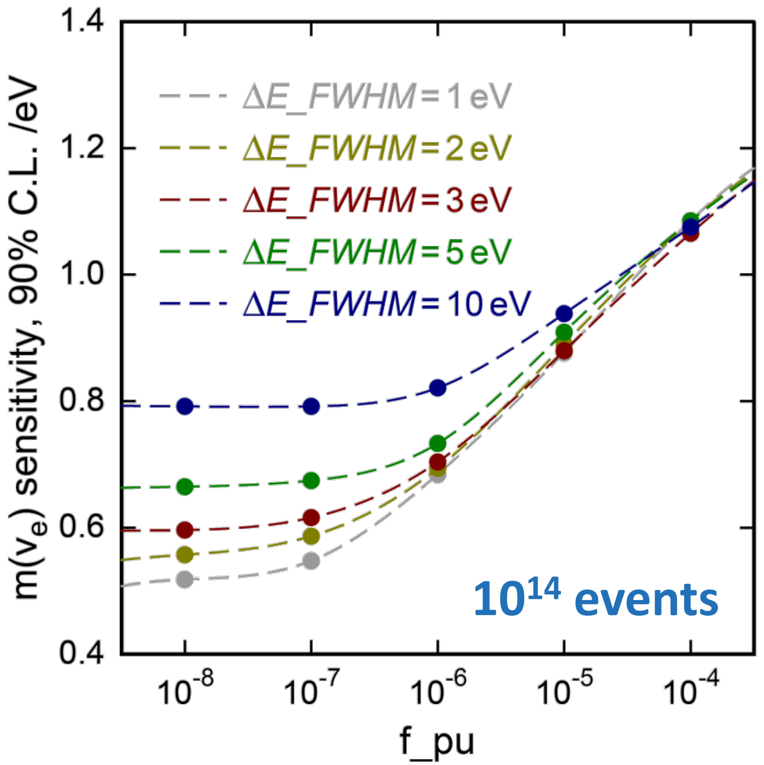
→number of detectors $N = 10^5$

Read-out : Microwave SQUID Multiplexing

→ 100 arrays with ~1000 single pixels

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

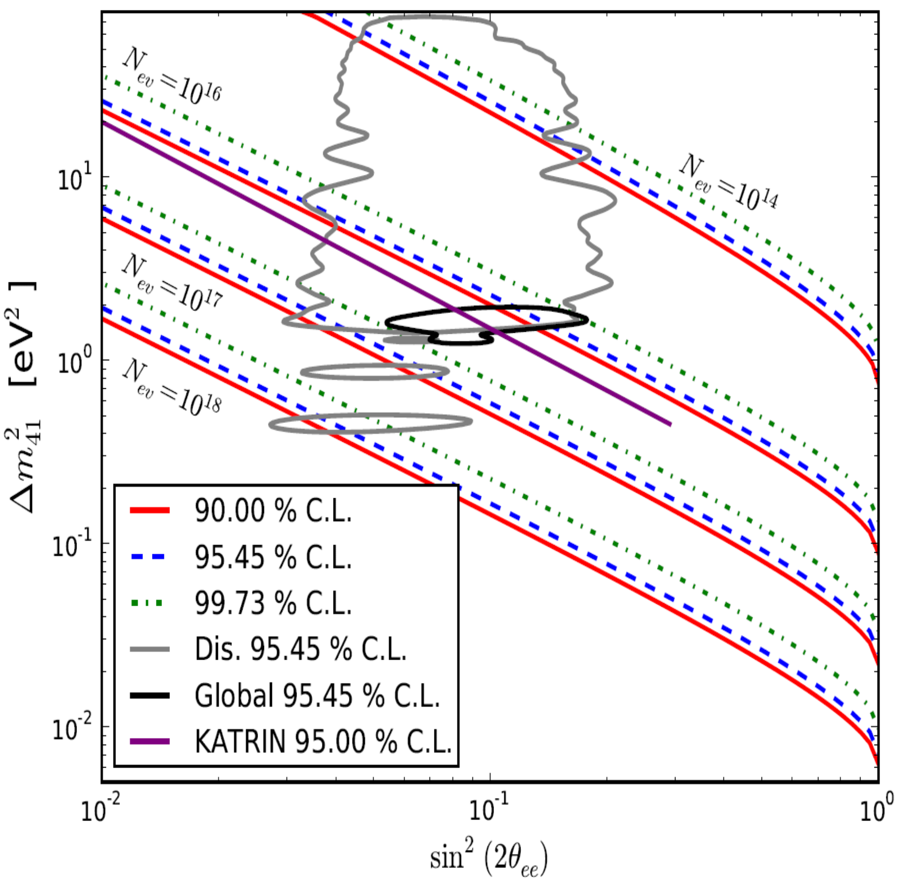
Measuring time $t = 1 – 3$ year



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

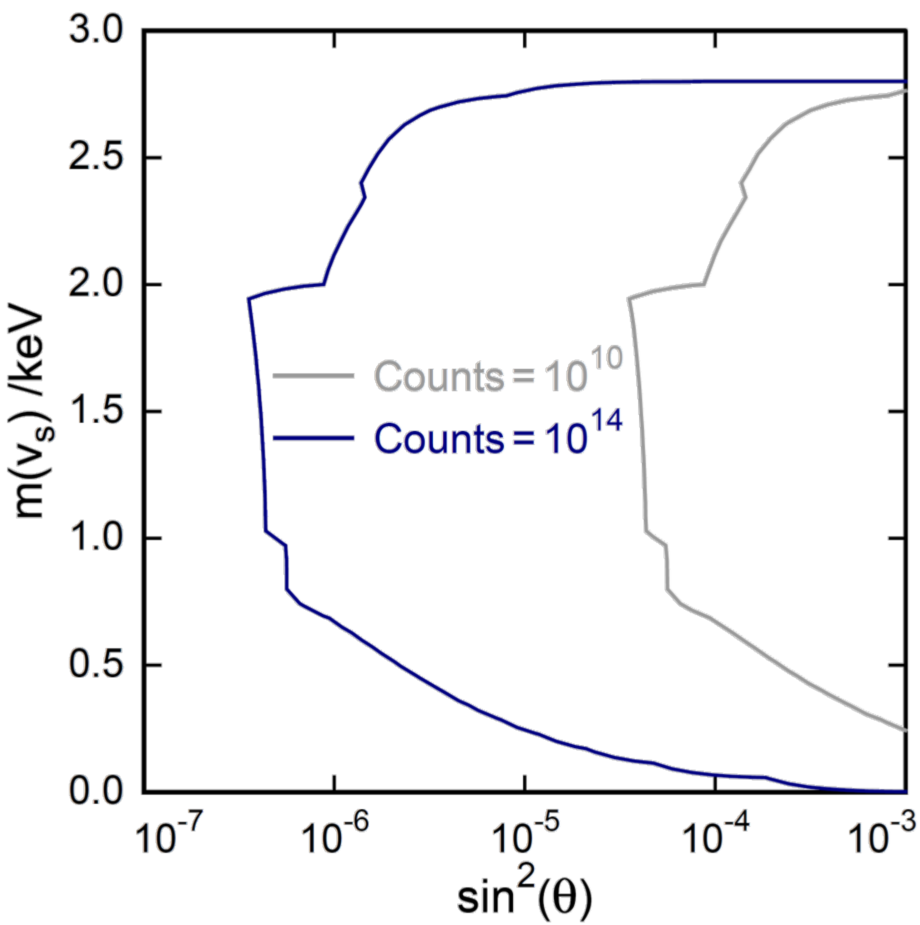
Sterile neutrinos

eV-scale sterile neutrinos



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

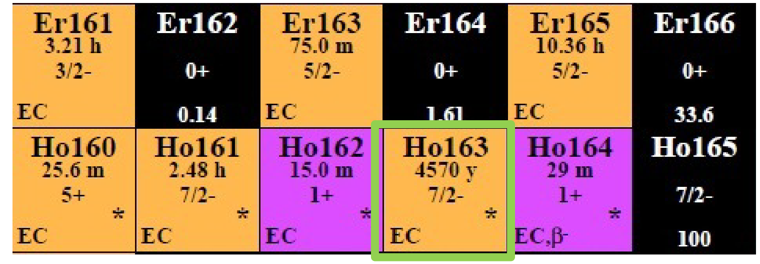
keV-scale serile neutrinos



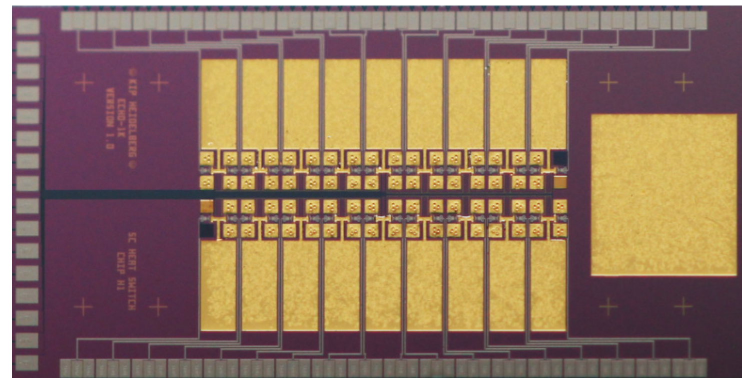
A White Paper on keV Sterile
Neutrino Dark Matter, JCAP01(2017)025

Conclusions and outlook

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

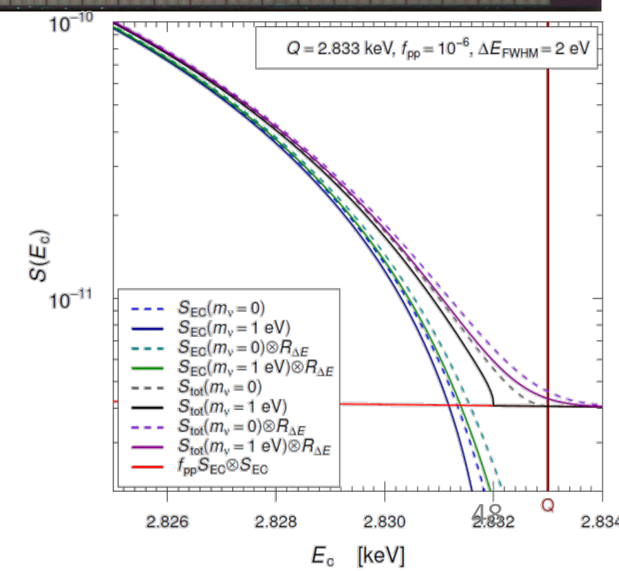


- High purity ^{163}Ho sources have been produced



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

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



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

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, 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, Loredana Gastaldo, Andreas Fleischmann,
Clemens Hassel, 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

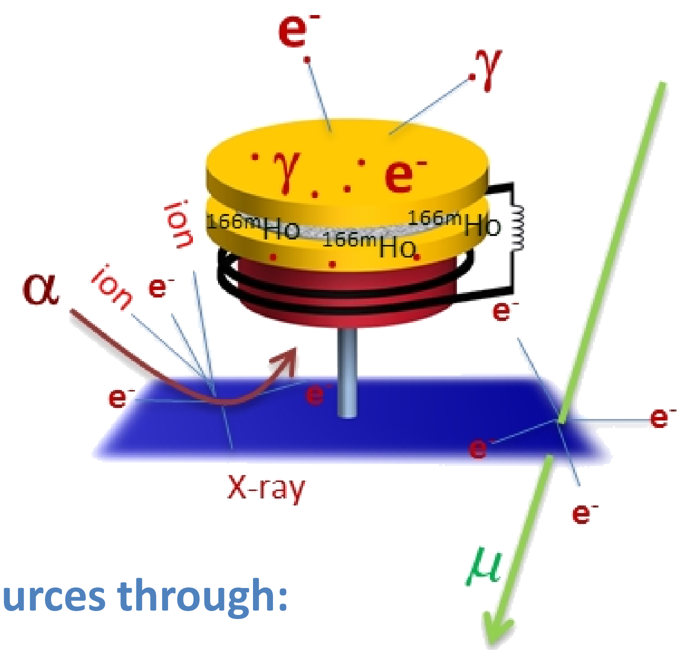
ECHo

Thank you !

Background

Background sources:

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



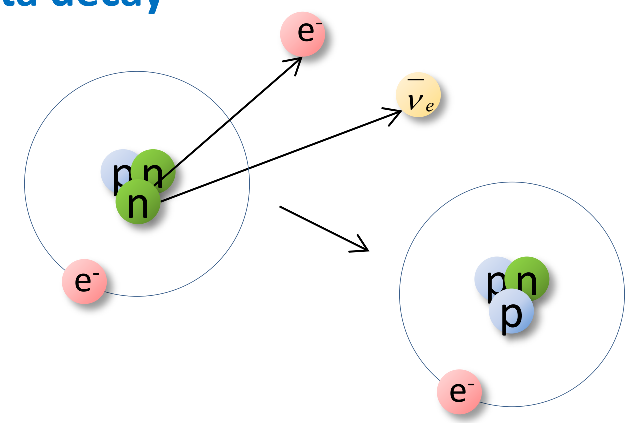
Study of background sources through:

- Monte Carlo simulations
- Dedicated experiments

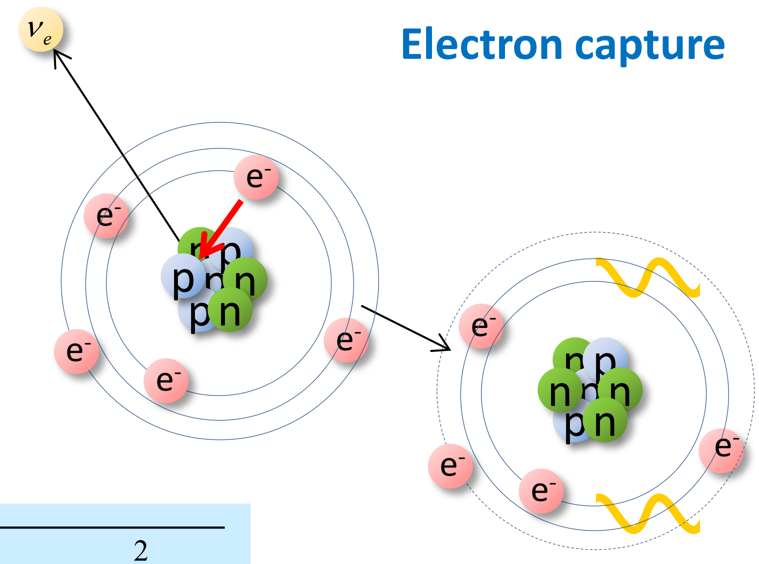
Screening facilities
- **Uni-Tübingen**
- **Felsenkeller**

Kinematic approach

Beta decay



Electron capture

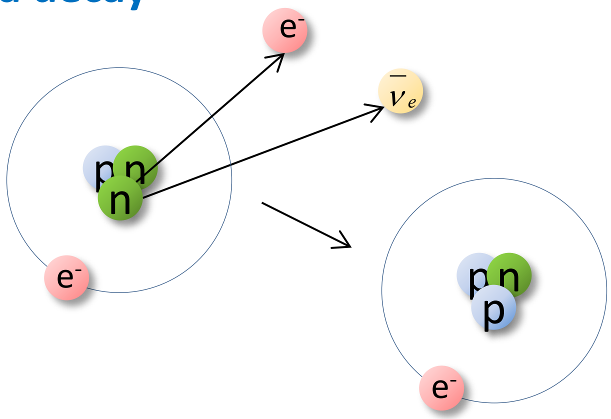


$$\frac{dW}{dE} \propto (Q-E)^2 \sqrt{1-\frac{m_\nu^2}{(Q-E)^2}}$$

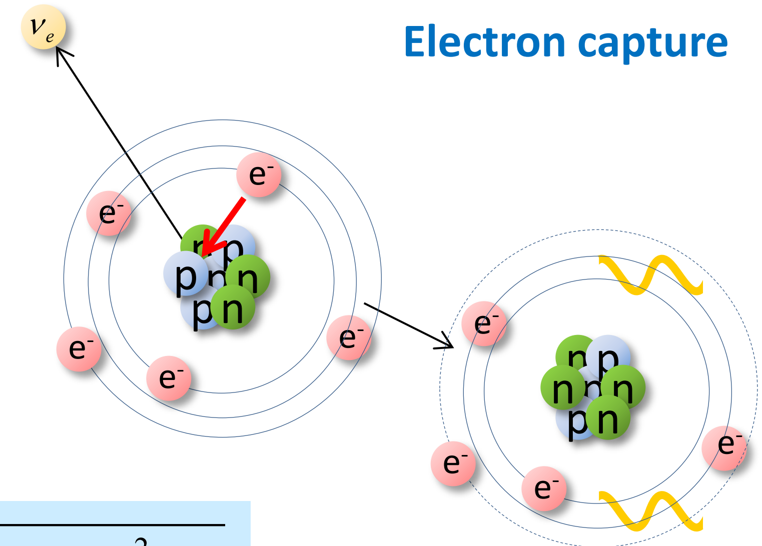
- A finite neutrino mass modify the spectrum in a small region close to the end-point
- Low Q-values enhance the fraction of events in the region of interest

Kinematic approach

Beta decay



Electron capture



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

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

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

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

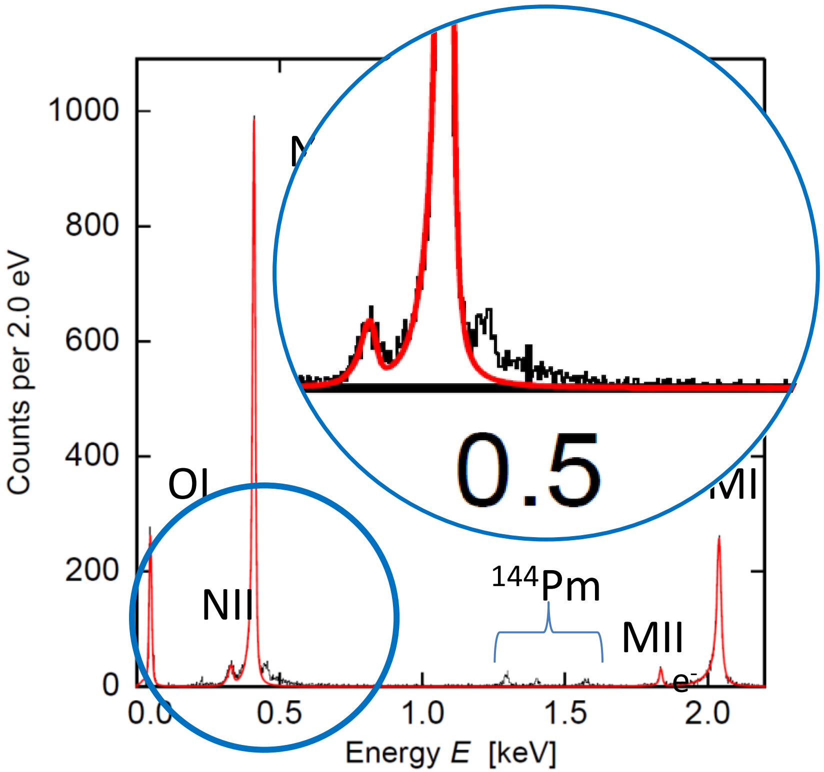
$$ m(\bar{\nu}_e) < 2.2\ eV \quad (1) $$

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

(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

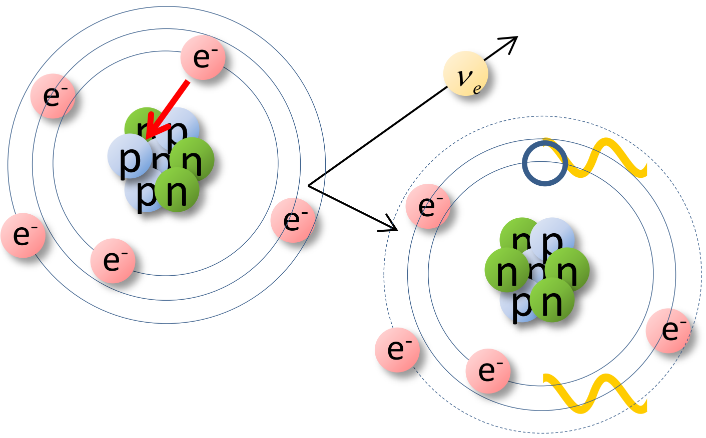
Characterisation of spectral shape



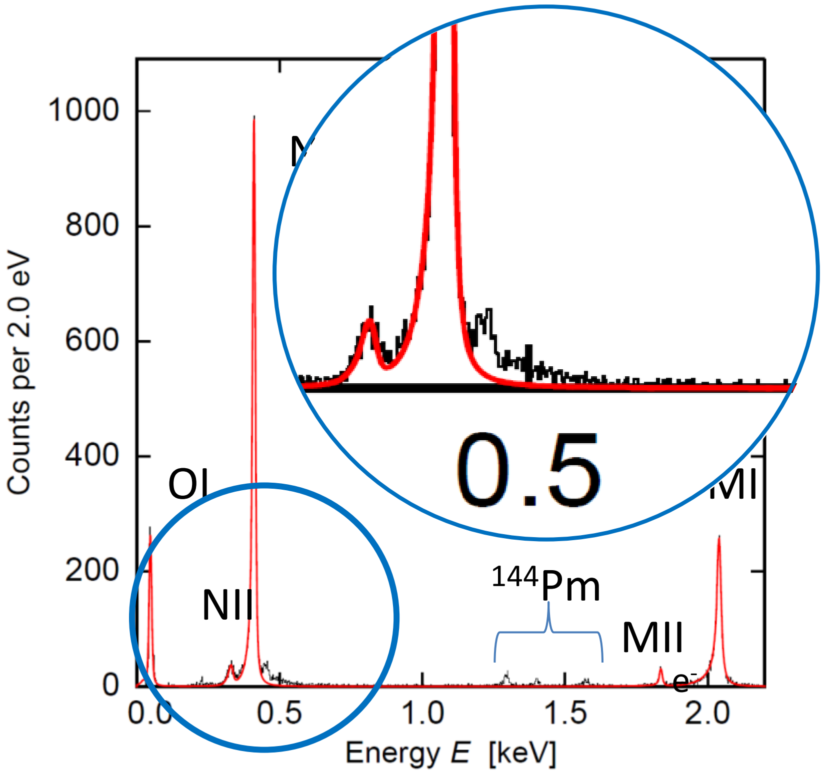
Estimate the effect of

- **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 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

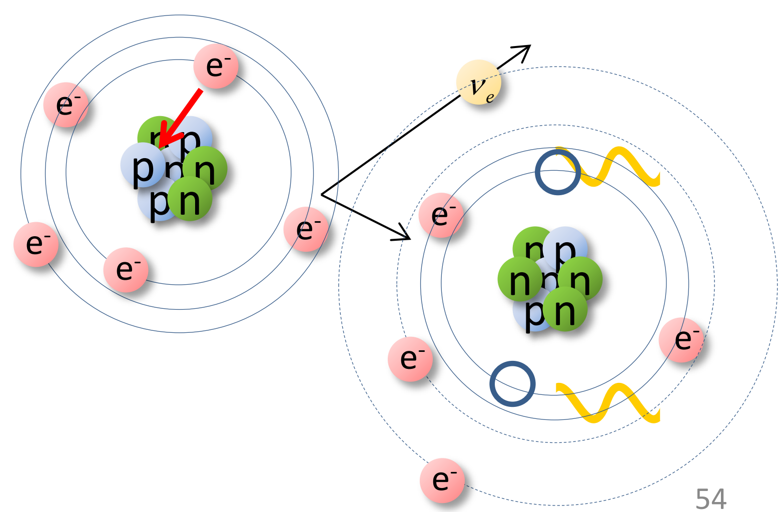


Characterisation of spectral shape

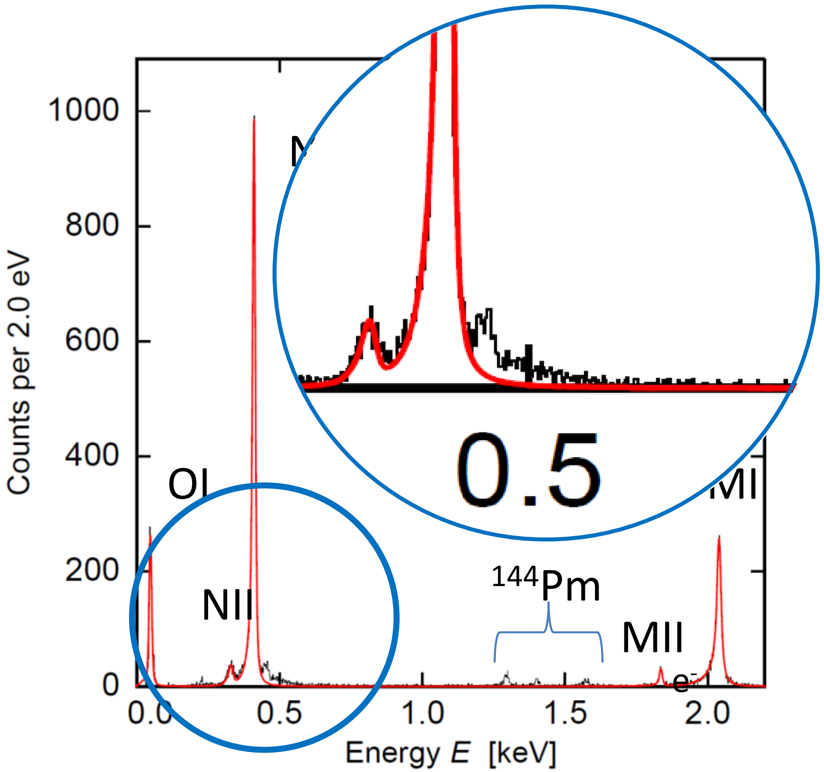


- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 045505 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula et al.
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016

Two-holes excited states: shake-up

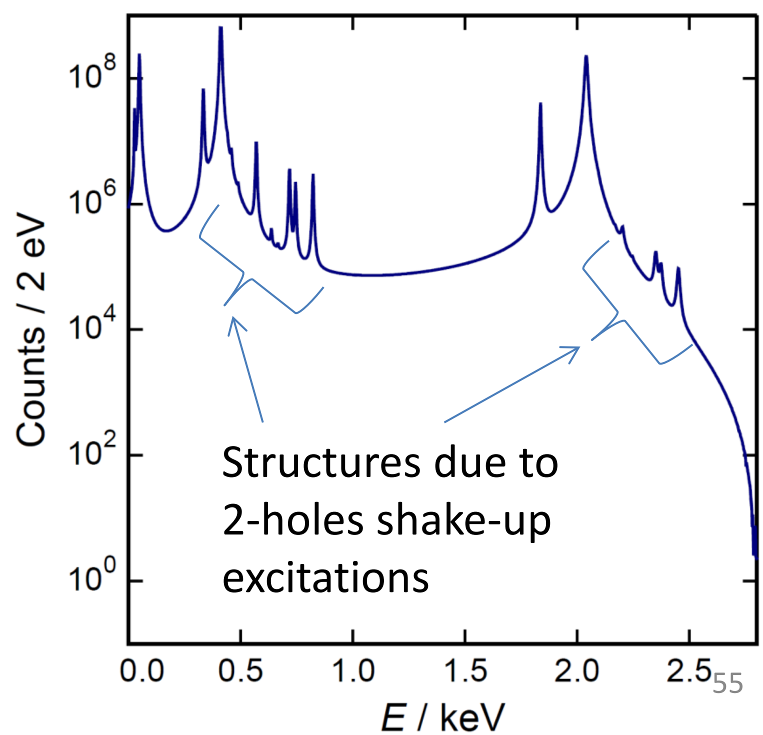


Characterisation of spectral shape

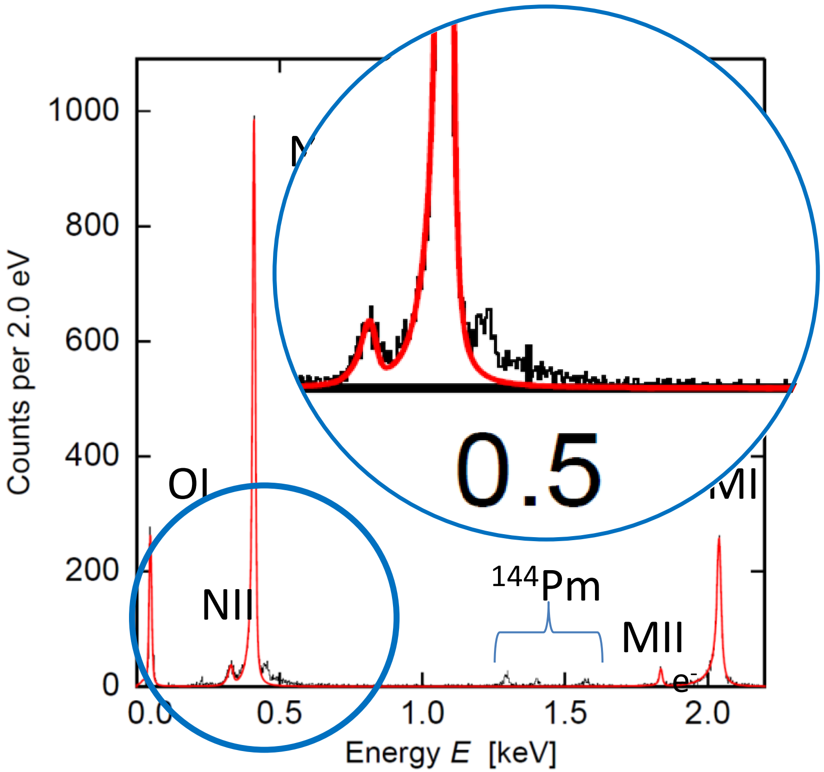


Two-holes excited states: shake-up

- 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

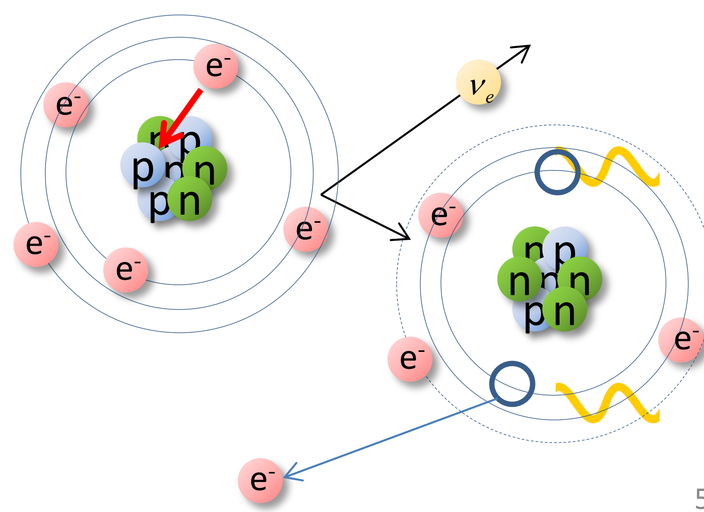


Characterisation of spectral shape



- 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

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



^{163}Ho-based experiments

ECHo HOLMES NuMECS

Calorimetric measurement of the ^{163}Ho spectrum

Common challenges to reach sub eV sensitivity :

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