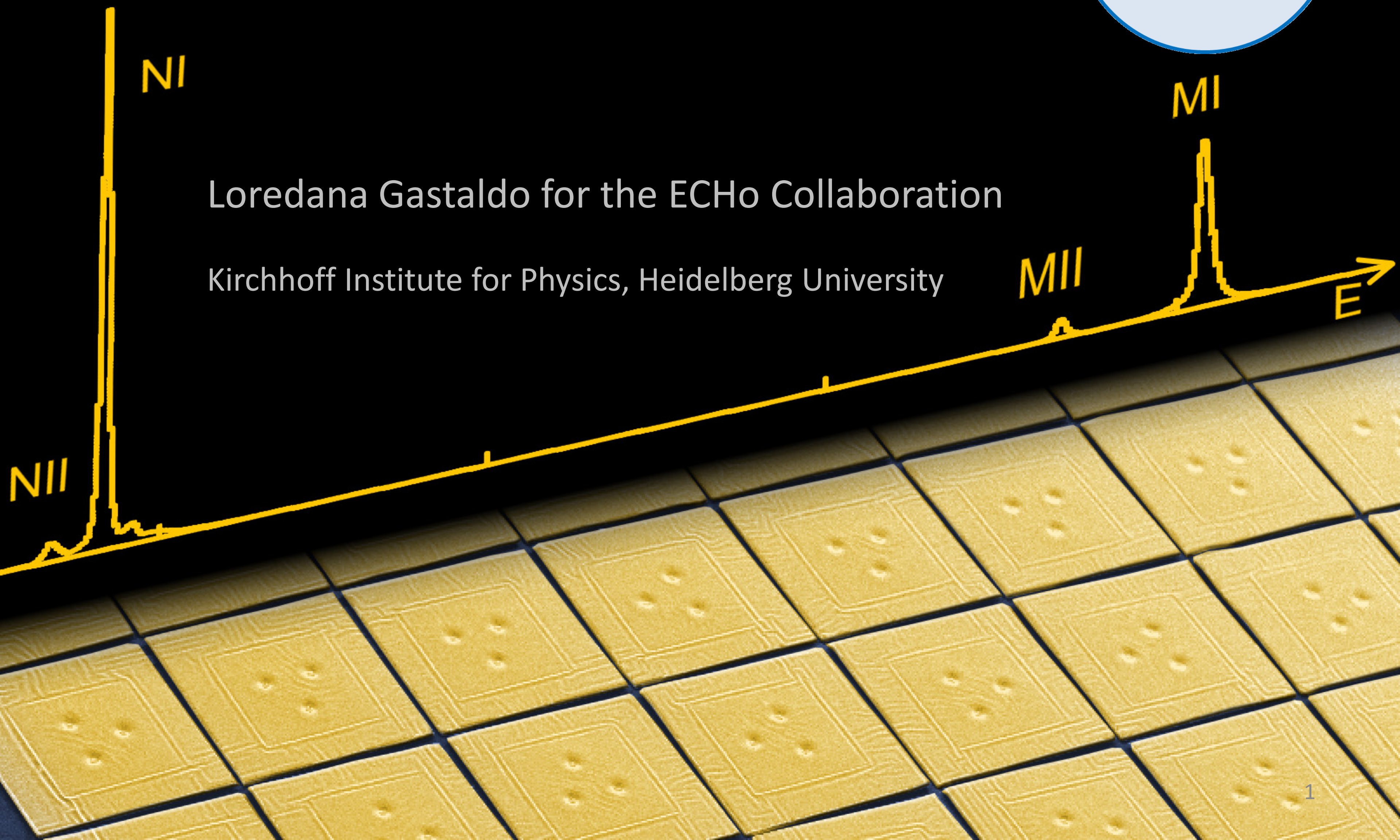
Electron Capture in ^{163}Ho experiment - ECHo

Loredana Gastaldo for the ECHo Collaboration

Kirchhoff Institute for Physics, Heidelberg University

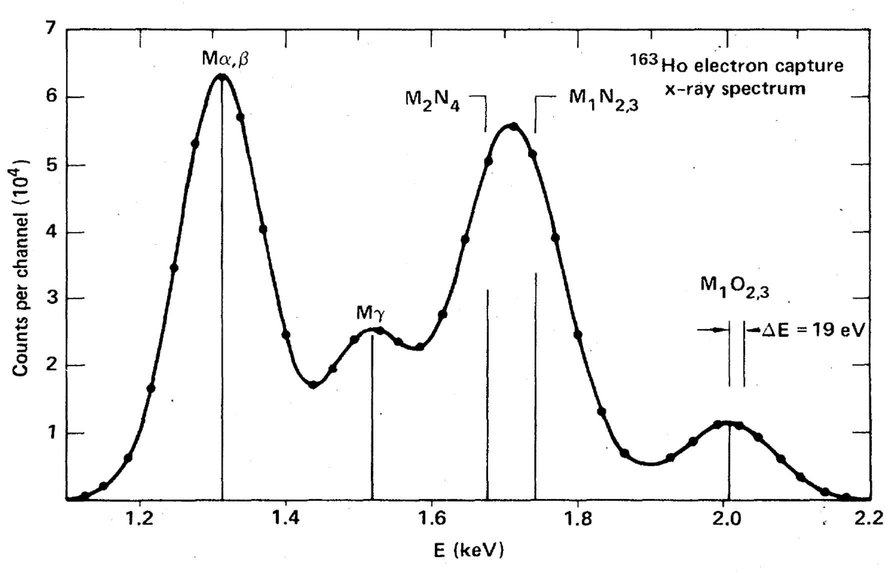


Outline

- 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 neutrino mass and ^{163}Ho

Present limit on the electron neutrino mass from ^{163}Ho x-ray spectrum



$m(\nu_e) < 225$ eV

this afternoon

Gray Ribka
Project8

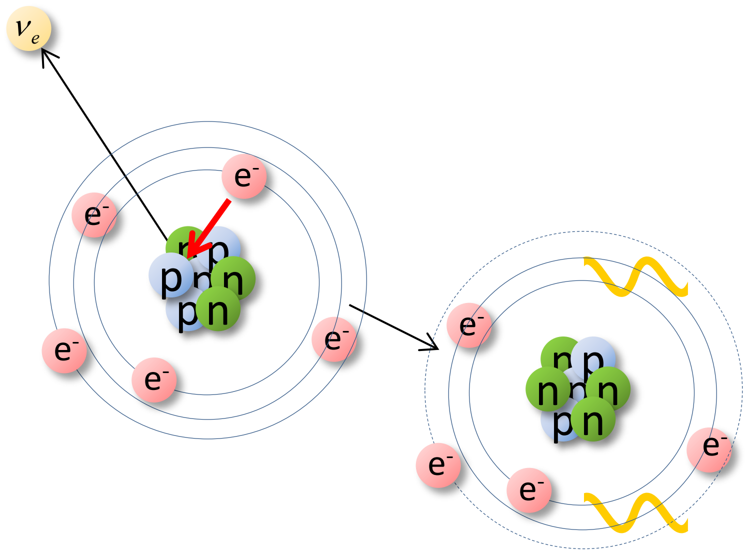
Angelo Nucciotti
HOLMES

Wonqook Choi
KATRIN

ECHo and HOLMES aim to reach sub-eV sensitivity on $m(\nu_e)$

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

^{163}Ho electron capture



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

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

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

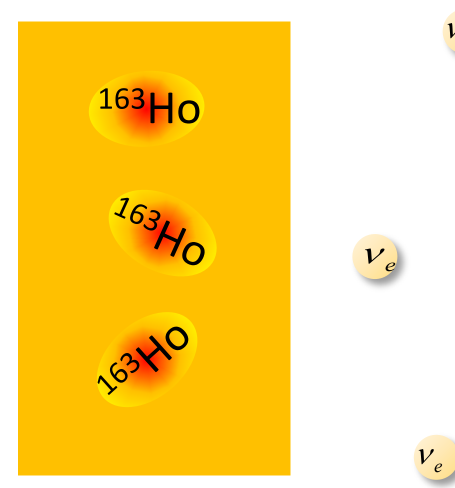
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

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

Atomic de-excitation:

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

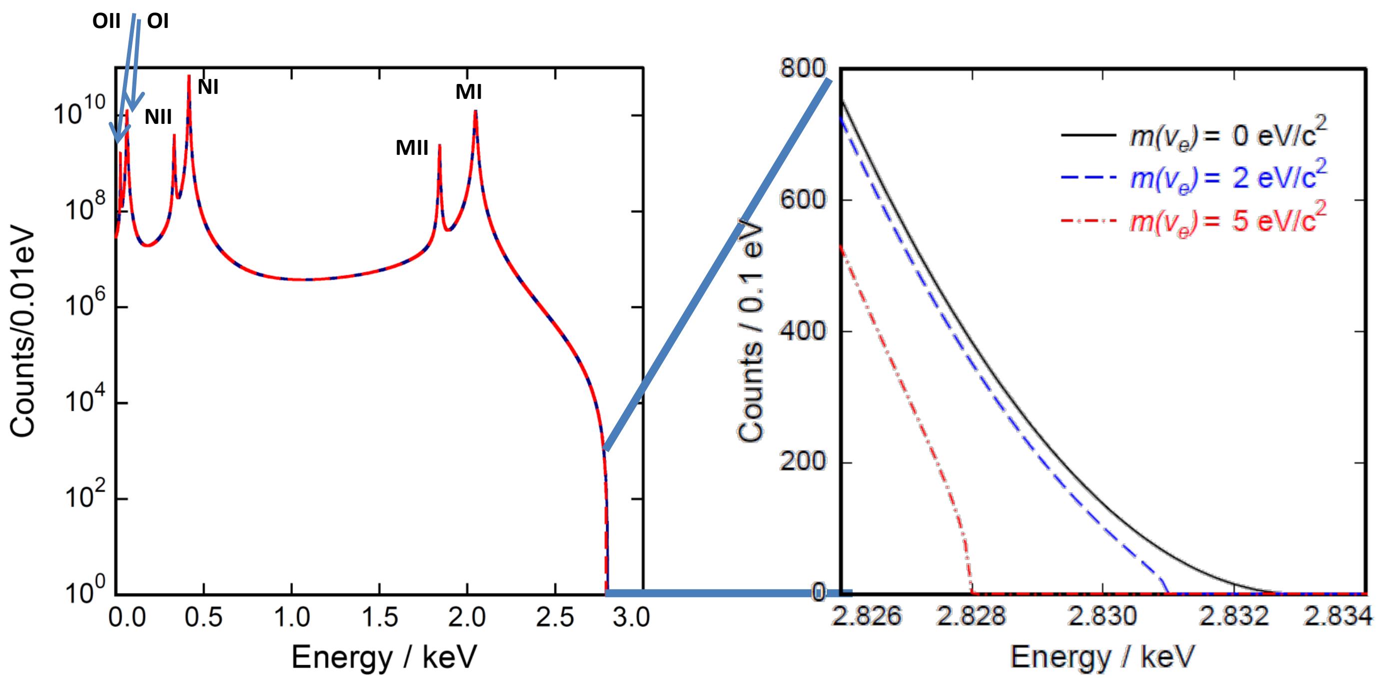
Calorimetric measurement



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

^{163}Ho calorimetrically measured spectrum

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



Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

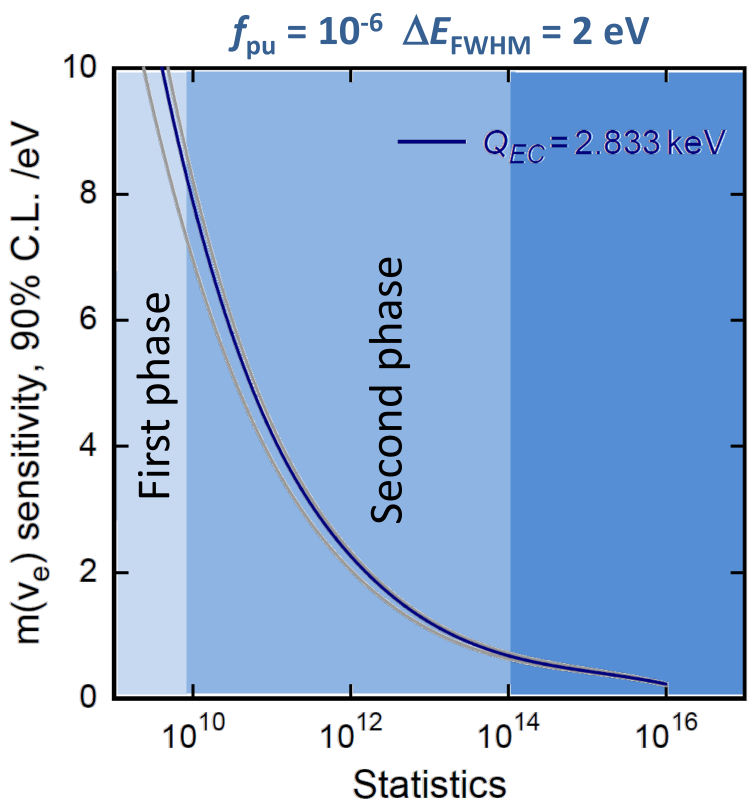
- $\boldsymbol{f_{pu} < 10^{-5}}$
- $\tau_r < 1\ \mu s$ → a ~ 10 Bq
- 10^5 pixels → **multiplexing**

Precision characterization of the endpoint region

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

Background level

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



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

^{163}Ho high purity source

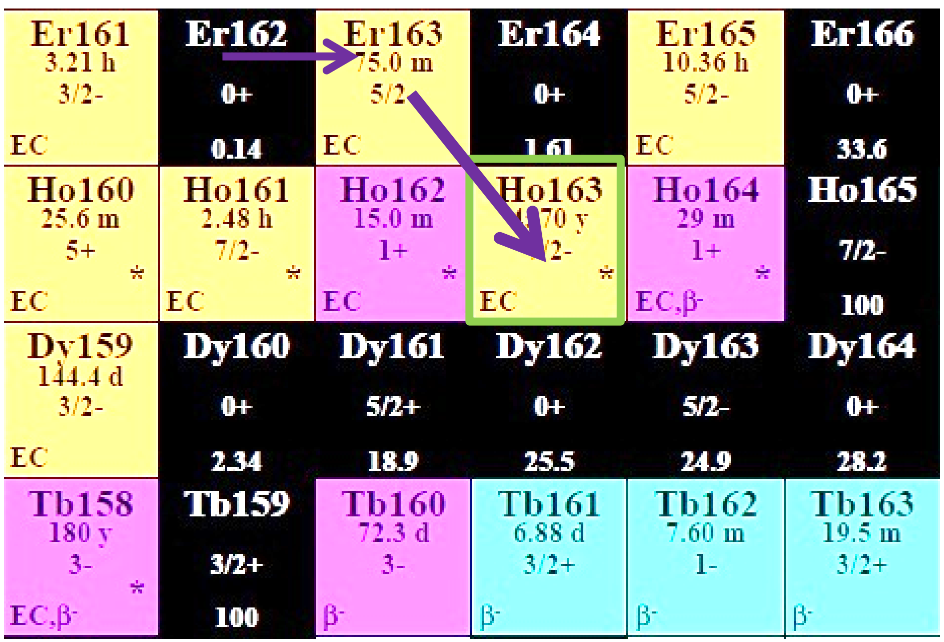
Required activity in the detectors: Final experiment → $>10^6$ Bq → $>10^{17}$ atoms

- Neutron irradiation

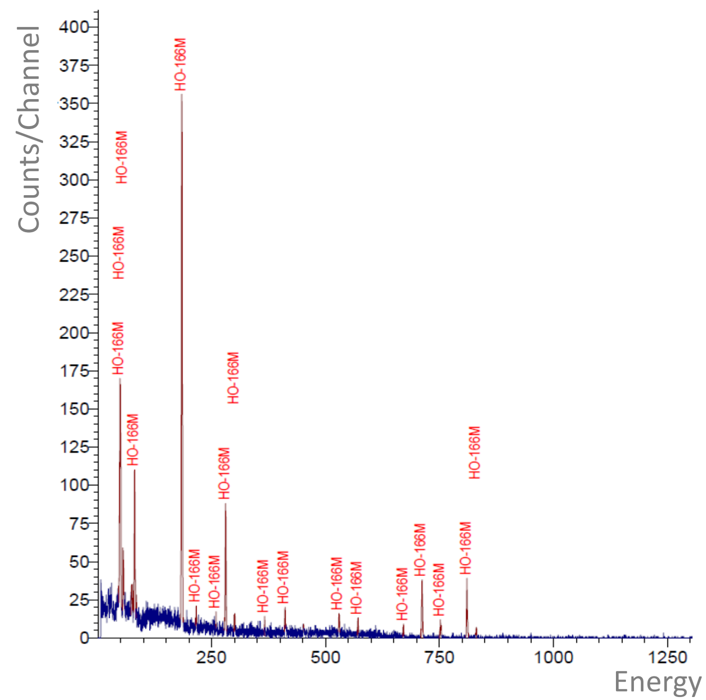
  (n,γ)-reaction on ^{162}Er

  High cross-section

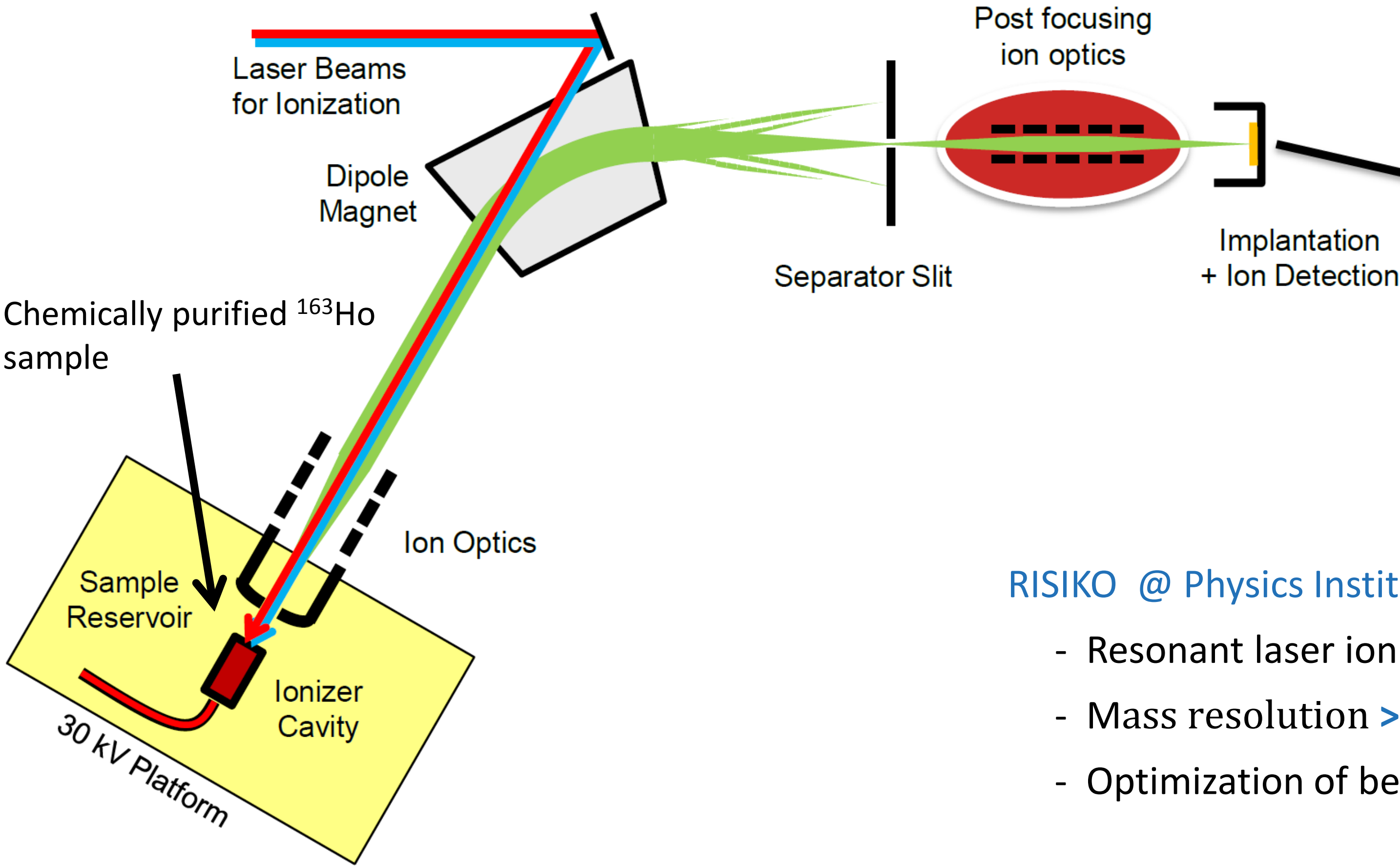
  Radioactive contaminants → Excellent chemical separation

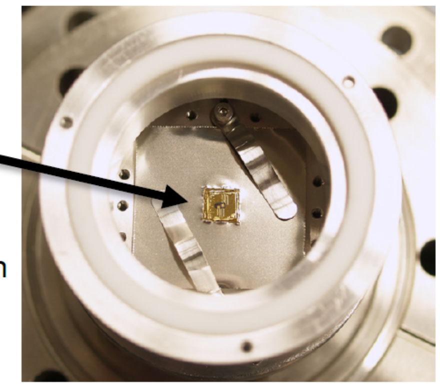


H. Dorrer et al, Radiochim. Acta (2018)



Mass separation and ^{163}Ho ion-implantation





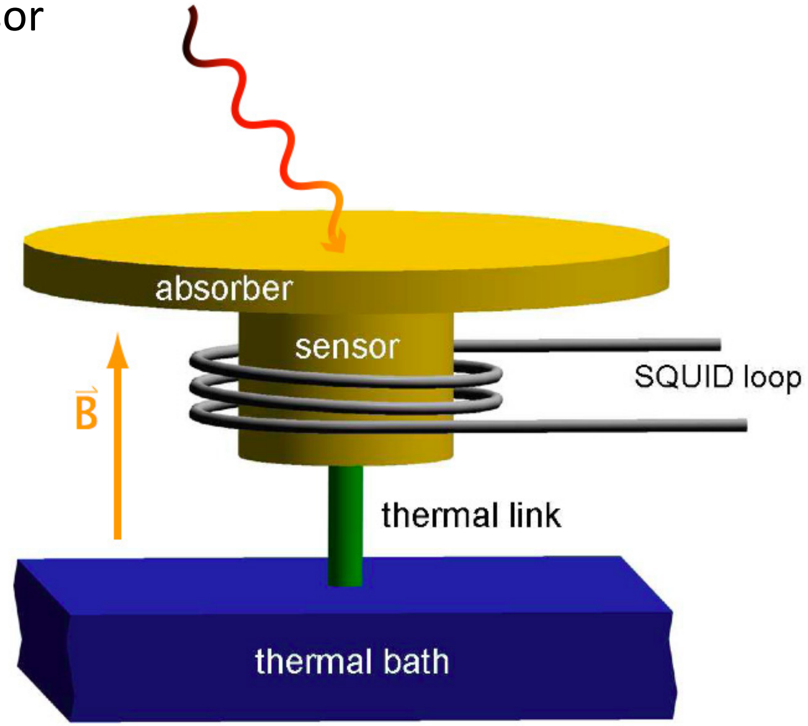
RISIKO @ Physics Institute, Mainz University

- Resonant laser ion source efficiency **41%**
- Mass resolution **> 700**
- Optimization of beam focalization

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

Metallic magnetic calorimeters (MMCs)

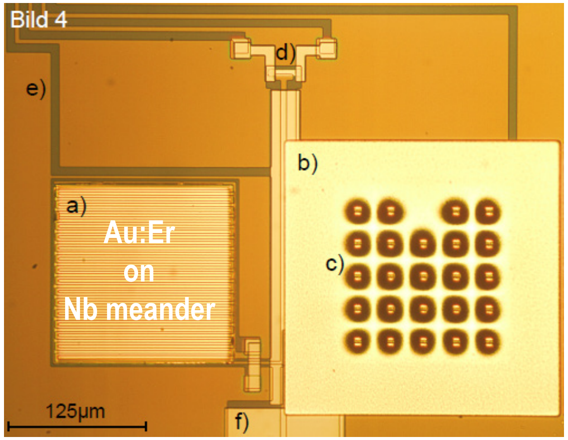
- Paramagnetic Ag:Er sensor



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

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

Metallic magnetic calorimeters (MMCs)



Fast risetime

→ Reduction un-resolved pile-up

Extremely good energy resolution

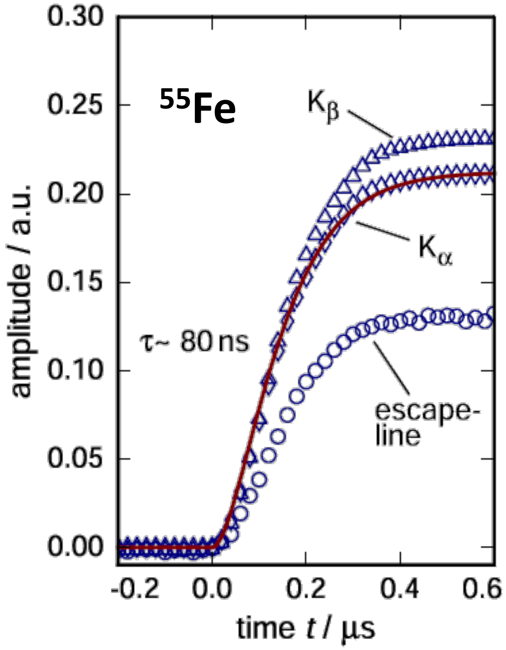
→Reduced smearing in the end point region

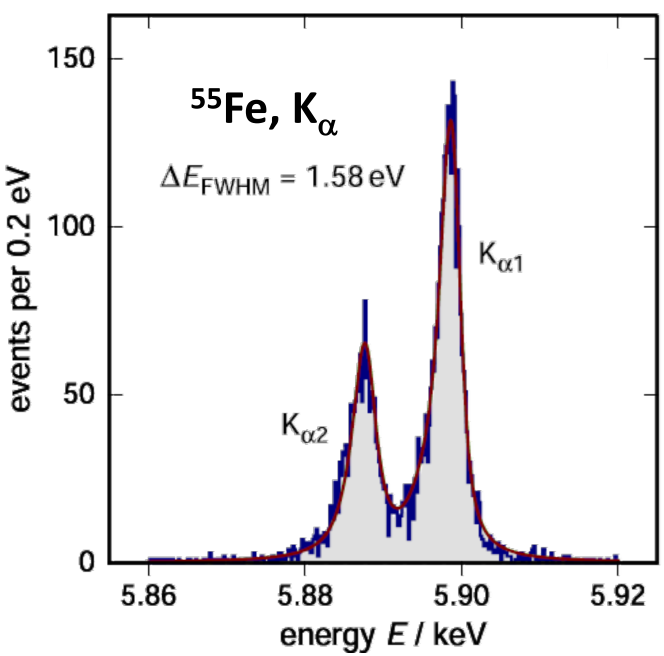
Excellent linearity

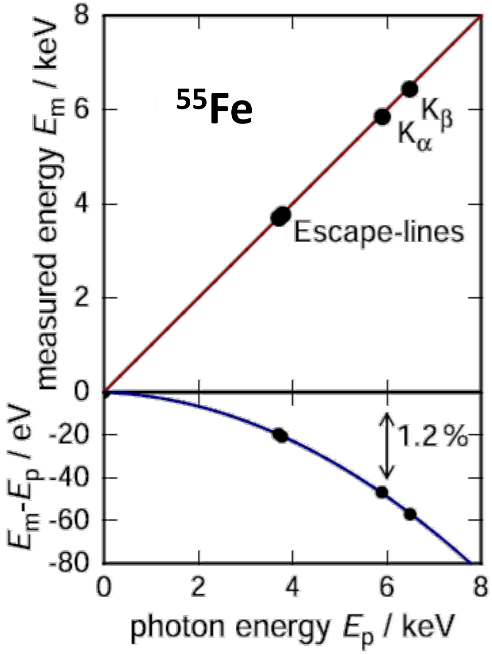
→ precise definition of the energy scale

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

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

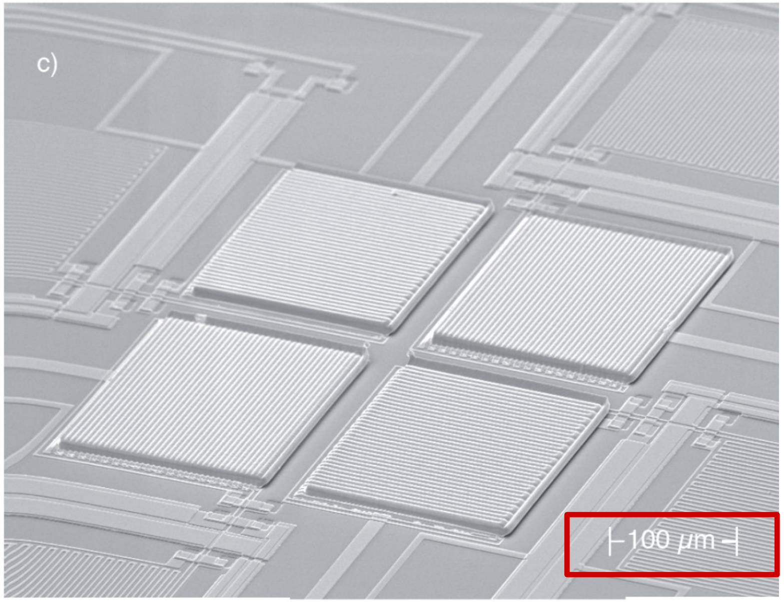


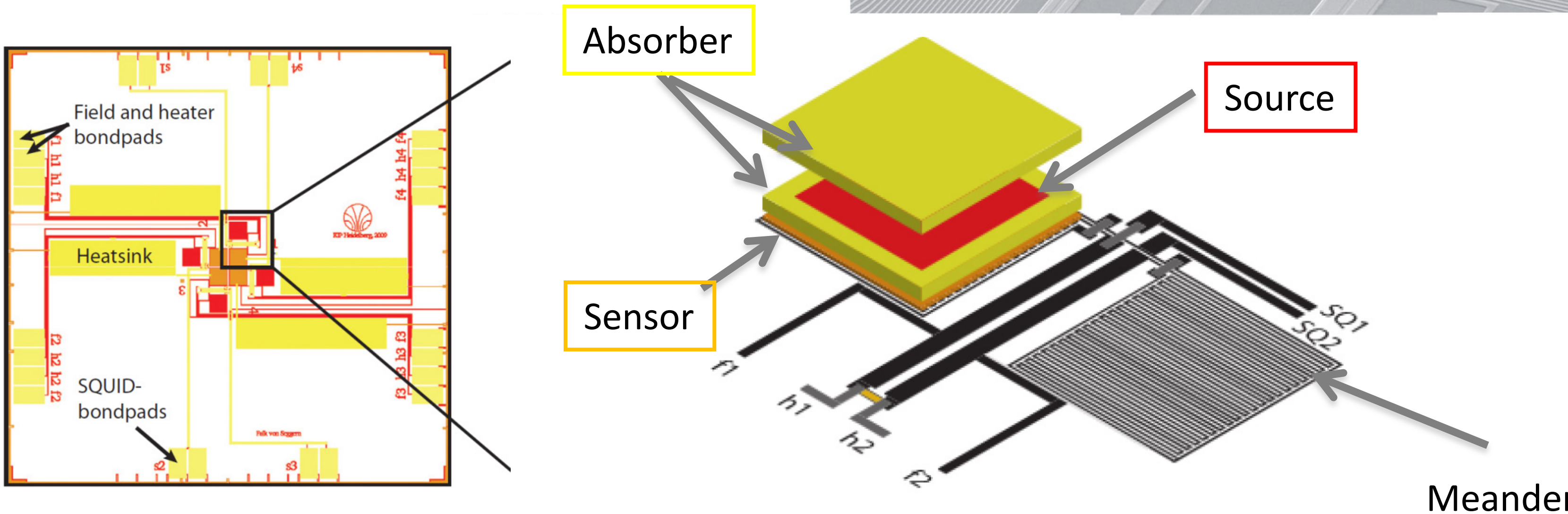




First prototype of ^{163}Ho loaded MMC

- 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





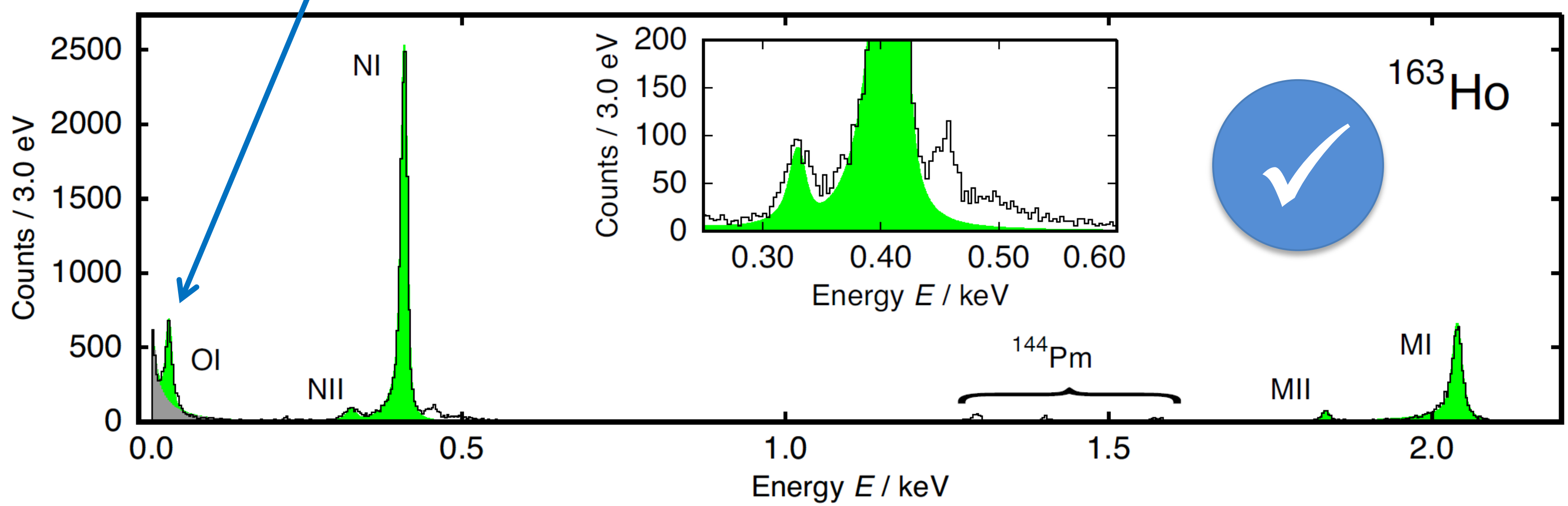
L. Gastaldo et al., Nucl. Inst. Meth. A, 711 (2013) 150

Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV
- Non-Linearity < 1% @ 6keV

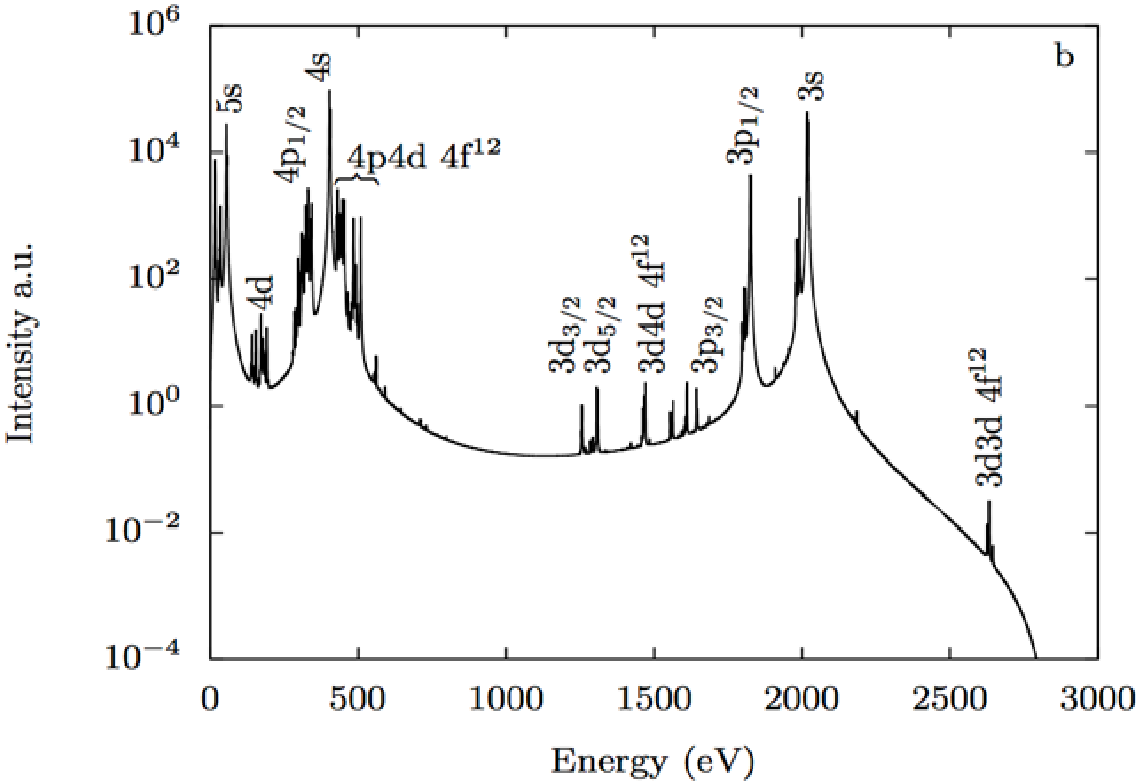
	E_H bind.	E_H exp.	Γ_H lit.	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

First calorimetric measurement of the OI-line



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

Calorimetric spectrum - theory



New approach

Ab inito calculation of the ^{163}Ho electron capture spectrum

Experimental support:

High statistics ^{163}Ho spectra

^{193}Pt EC spectrum (*)

(*) *K. Koehler*, *et al.* accepted *JLTP. arXiv:1803.06370*

Restricted to bound-states only, i.e. the spectrum is given by a finite number of resonances

→ Include decay to the continuum states

→ Study the effect of metallic host

Brass et al., *Phys. Rev. C* **97** (2018) 054620

^{163}Ho Q_{EC} determination

$$Q_{\mathrm{EC}} = m(^{163}\mathrm{Ho}) - m(^{163}\mathrm{Dy})$$

Penning Trap Mass Spectroscopy

@TRIGA TRAP (Uni-Mainz)

@SHIPTRAP (GSI – Darmstadt)

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

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

Perfect agreement with Q_{EC} from ^{163}Ho spectrum

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

Sergey Eliseev

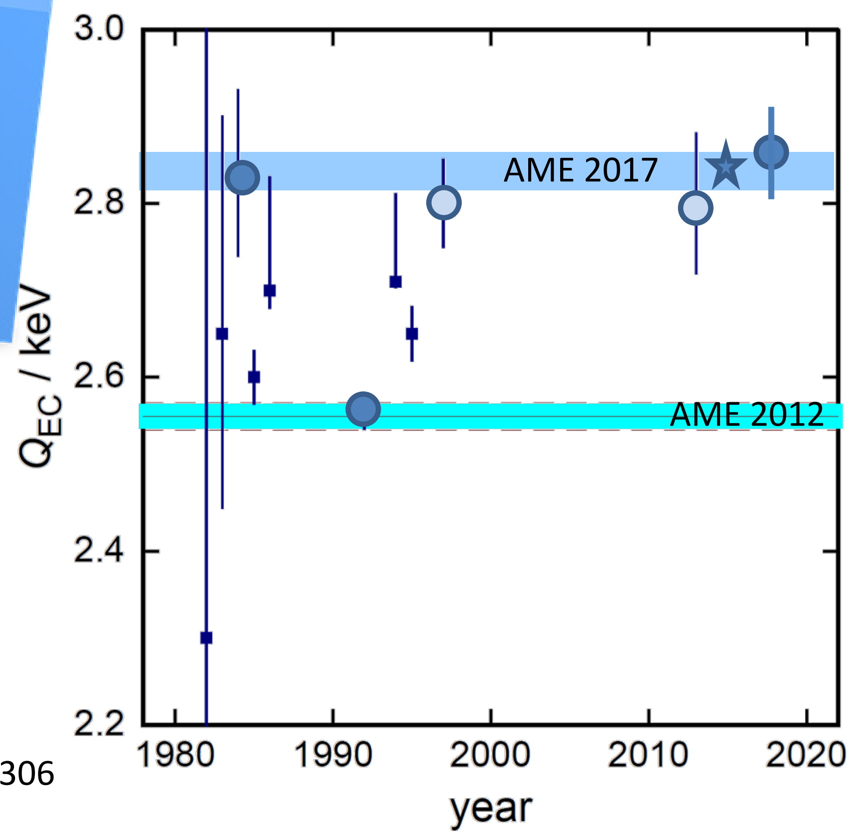
PTMS with PENTATRAP

Yesterday 16:30

Future goal: 1 eV precision

PENTATRAP @MPIK, Heidelberg (D) (*)

CHIP-TRAP @CMU Mount Pleasant (US) (**)



(*) J. Repp et al., Appl. Phys. B 107 (2012) 983

(*) C. Roux et al., Appl. Phys. B 107 (2012) 997

(**) M. Redshaw et al Nucl.Instrum.Meth. B376 (2016) 302-306

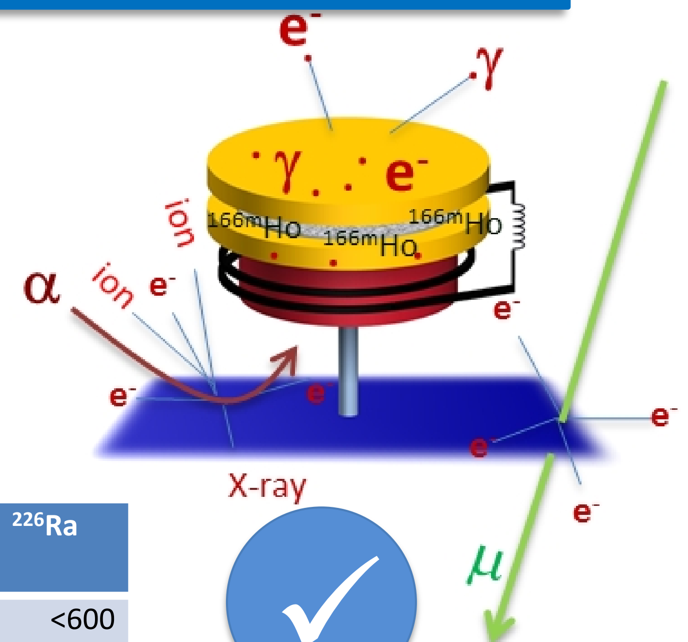
Background in ECHo

Background sources:

- Radioactivity in the detector
- Environmental radioactivity
- Cosmic rays
  Induced secondary radiation

Material screening

Muon veto



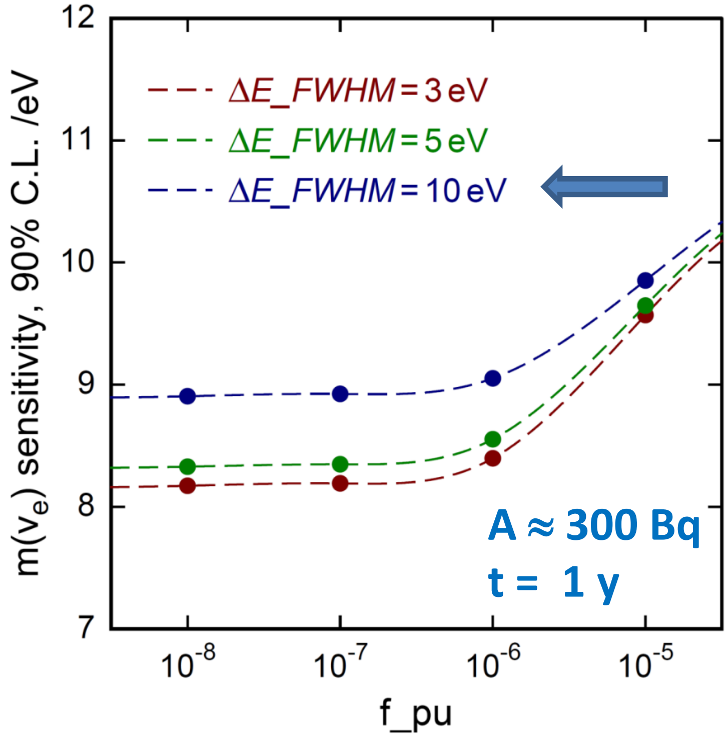
Sample	^{40}K	^{208}Tl	^{212}Pb	^{214}Bi	^{214}Pb	^{226}Ra
Cryostat copper [mBq/kg]	<480	<80	<190		<96	<600
Cryoperm [mBq/kg]	<335	<25	<45	<170	<40	<200
Connectors [mBq/kg]	5600	1600	10800	10800	10800	8000
Connectors [mBq] p.p.	3	1	6	6	6	4
Circuit board [mBq/kg]	625	4800	16300	8700	8000	5300
Circuit board[mBq/cm²]	0.45	1.39	4.75	2.53	2.33	1.54
Cables [mBq/cm²]	0.49					

After comparison with MC simulations
No background above the unresolved pile-up

On-going: validation by in-situ measurements

Planned phases of ECHo

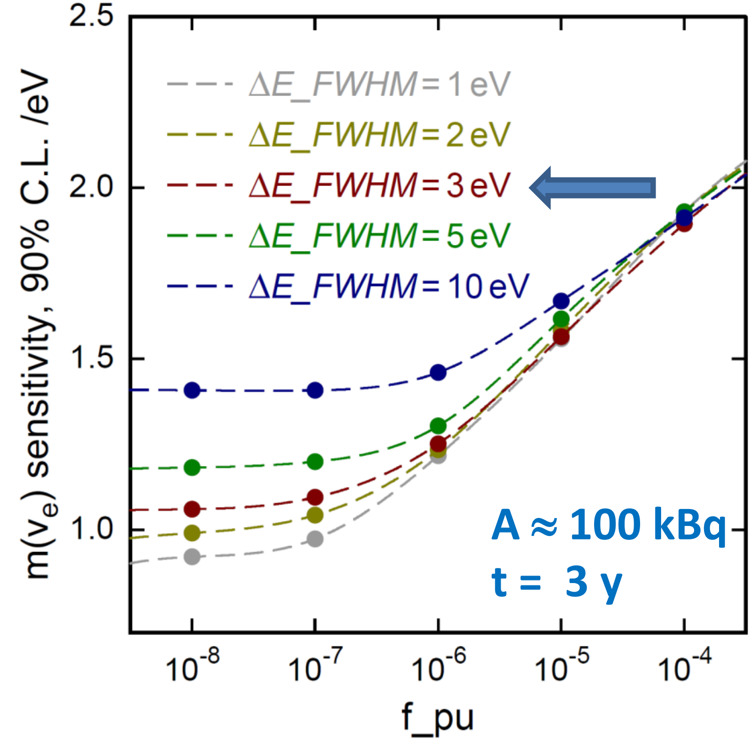
ECHo-1k – revised (2015 – 2018)



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

Activity per pixel 5 Bq
Number of detectors 60
Readout: parallel two stage SQUID

ECHo-100k (2018 – 2021)



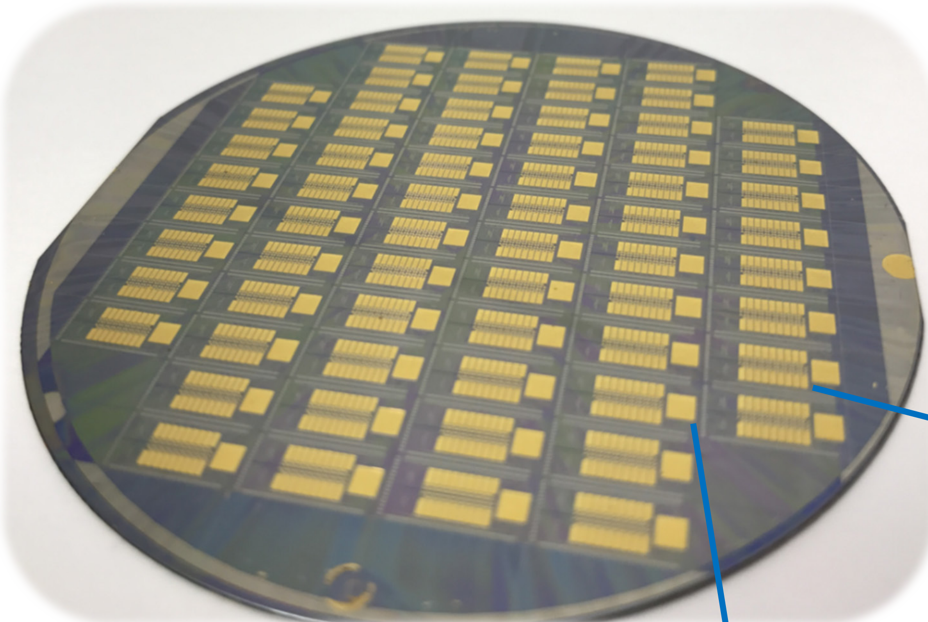
$m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel 10 Bq
Number of detectors 12000
Readout: microwave SQUID multiplexing

Supported by DFG Research Unit FOR 2022/1

Supported by DFG Research Unit FOR 2022/2

ECHo-1k array

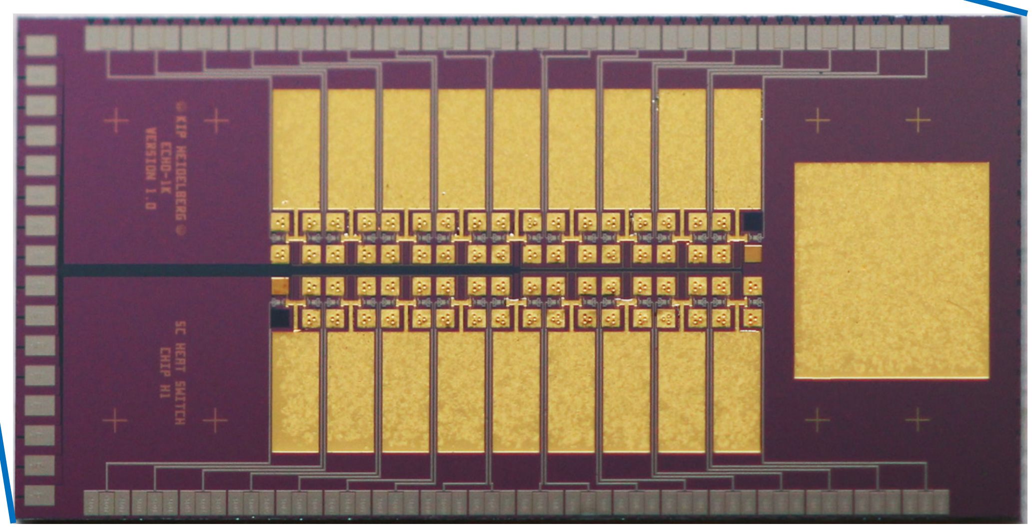


3“ wafer with 64 ECHo-1k chip

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)

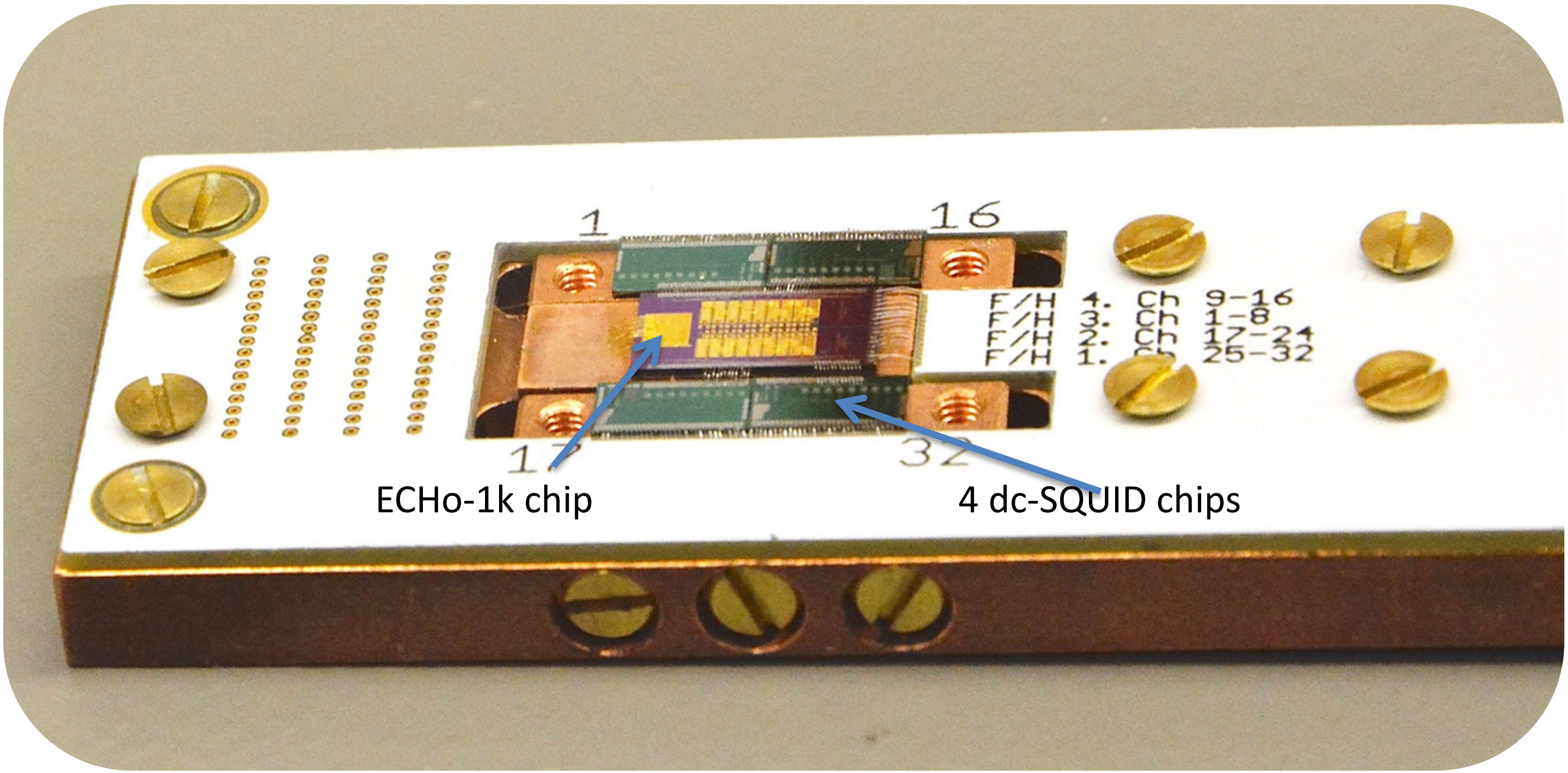


S.Kempf *et al., J. Low. Temp. Phys.* **176** (2014) 426

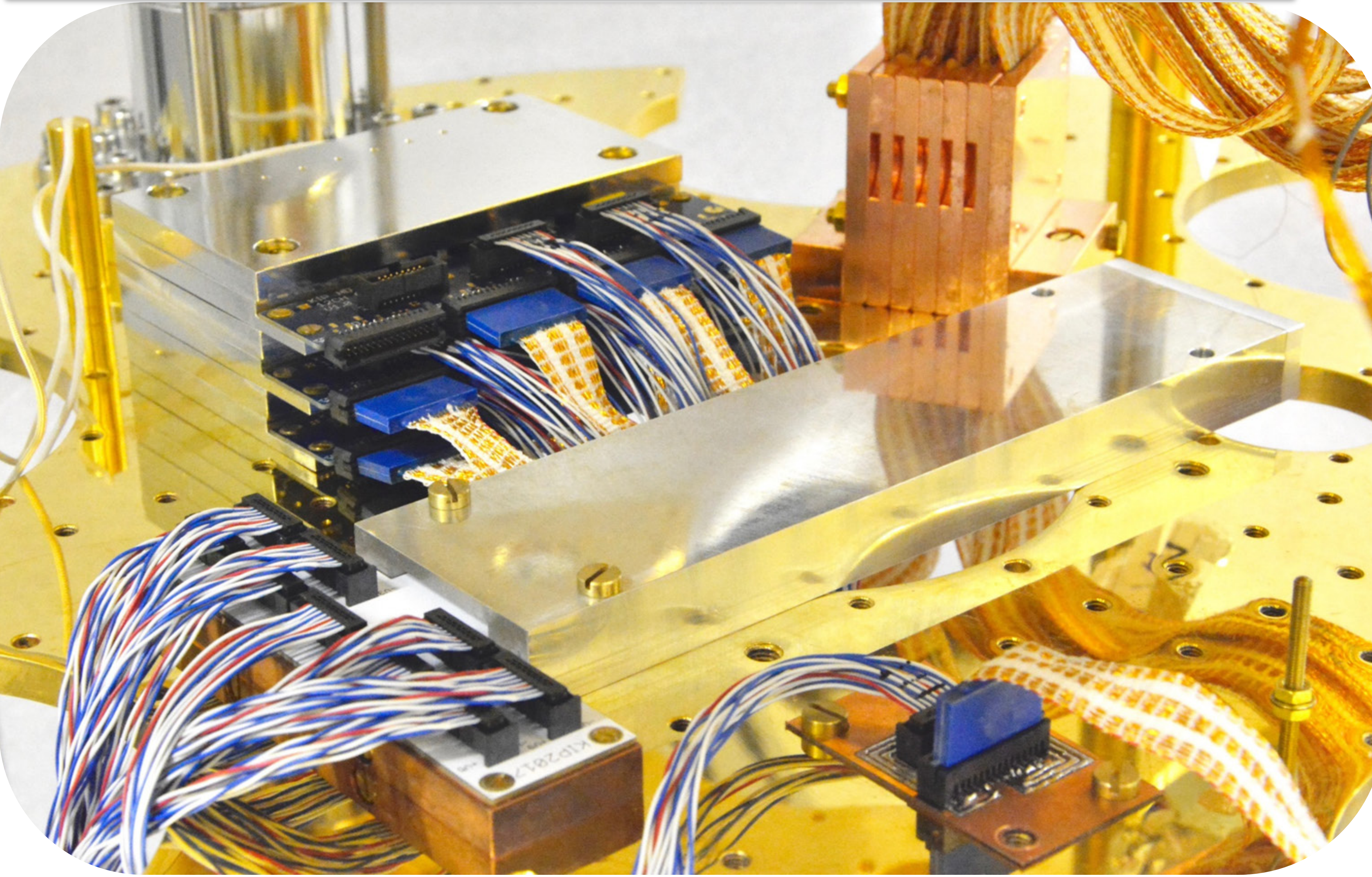
ECHo-1k array and read-out

- ECHo-1k chip implanted at RISIKO Uni-Mainz

  → ^{163}Ho activity per pixel $a \approx 1.5$ Bq (total activity $A \approx 100$ Bq)
- 4 Front-end chips each with 8 dc-SQUIDs

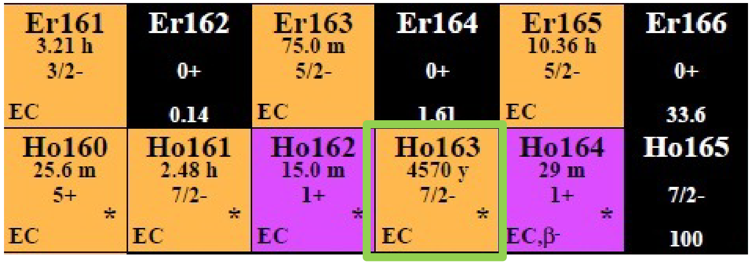


ECHo-1k experimental set-up



Conclusions and outlook

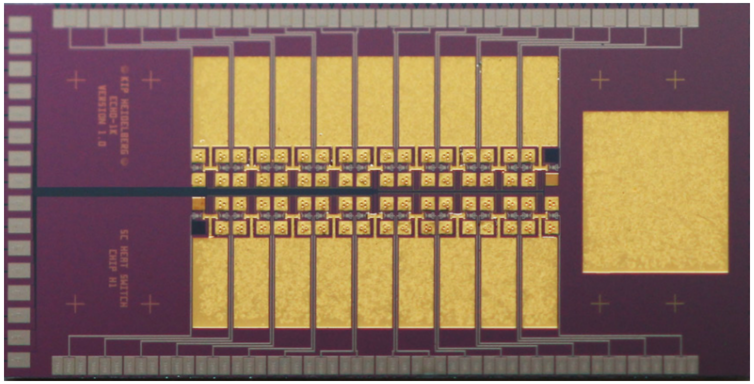
The ECHo collaboration aims to reach sub-eV sensitivity on the electron neutrino mass analysing high statistics and high resolution ^{163}Ho spectra



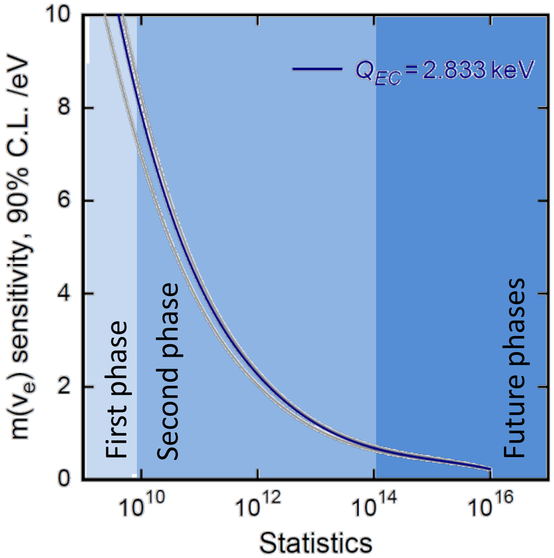
- Independent ^{163}Ho Q_{EC} measurement

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

ISOLDE

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HUMBOLDT-UNIVERSITÄT ZU BERLIN

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

DFG Deutsche Forschungsgemeinschaft

ECHo

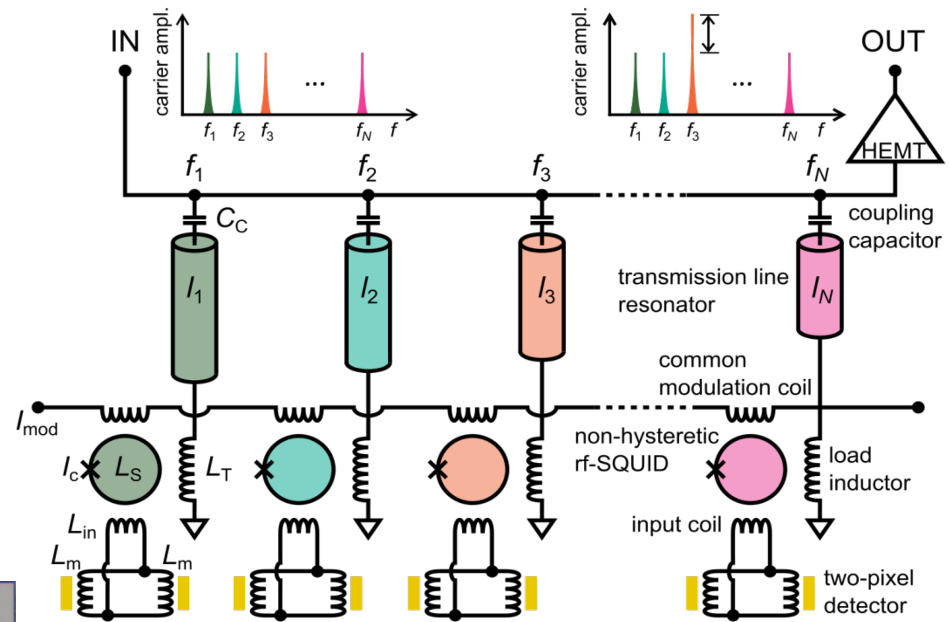
Thank you !

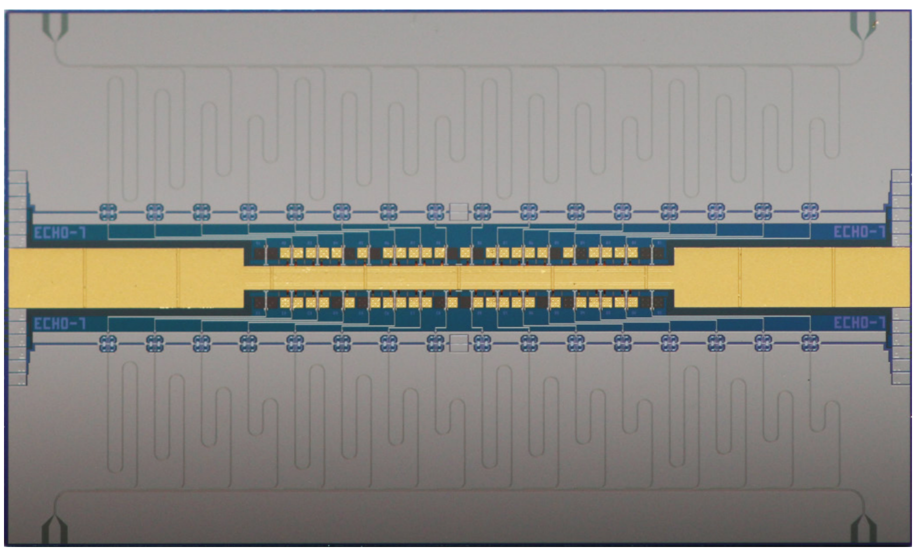
The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

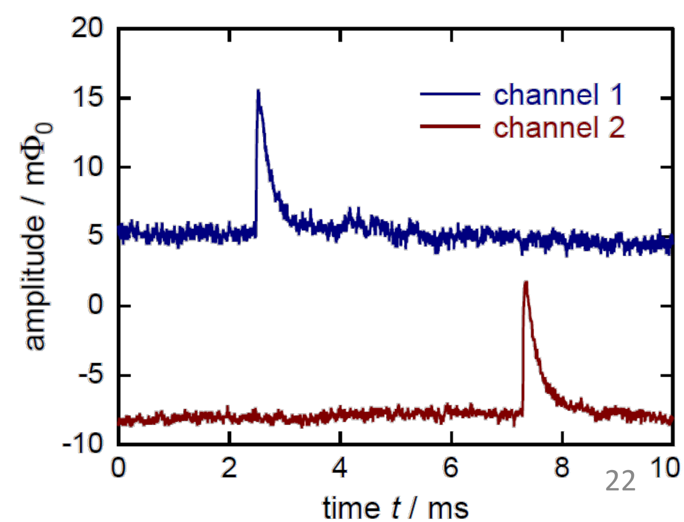
Multiplexing readout

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

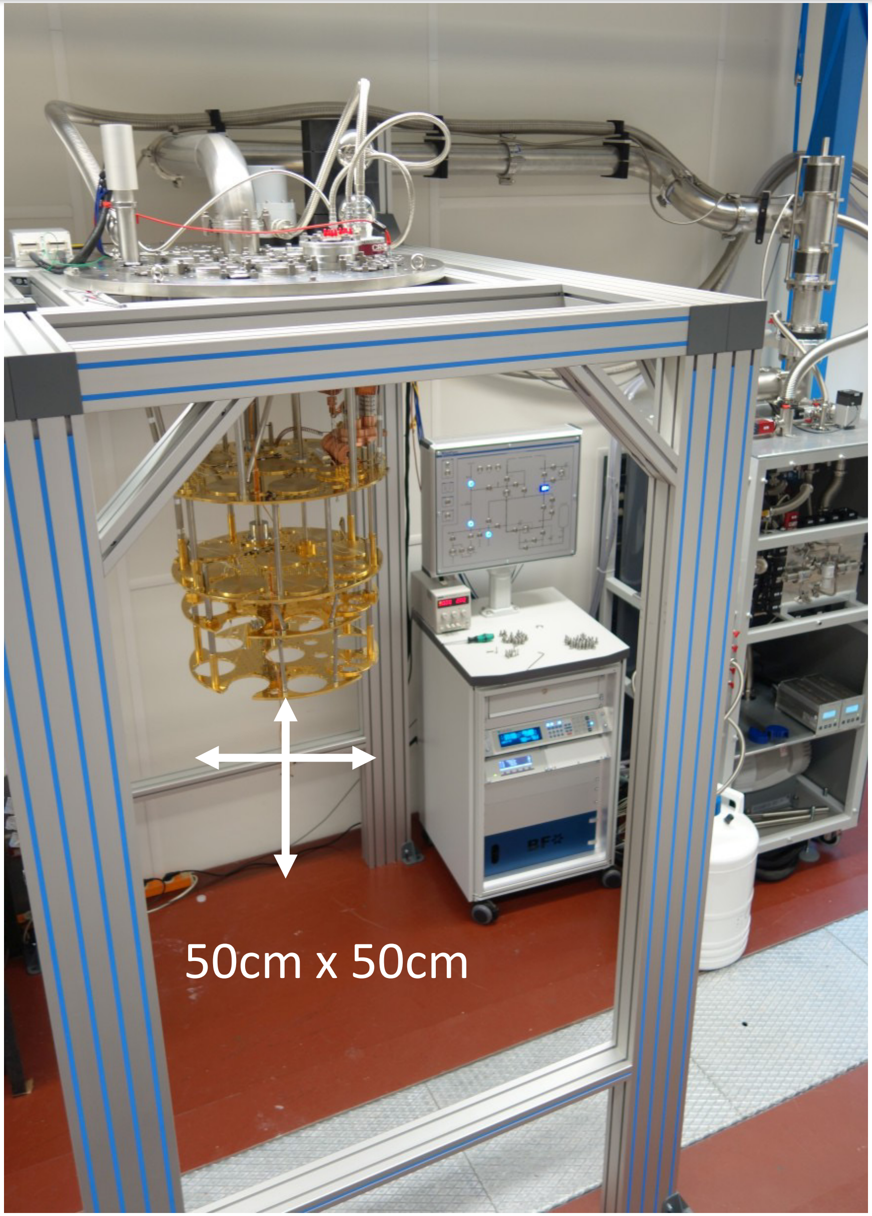




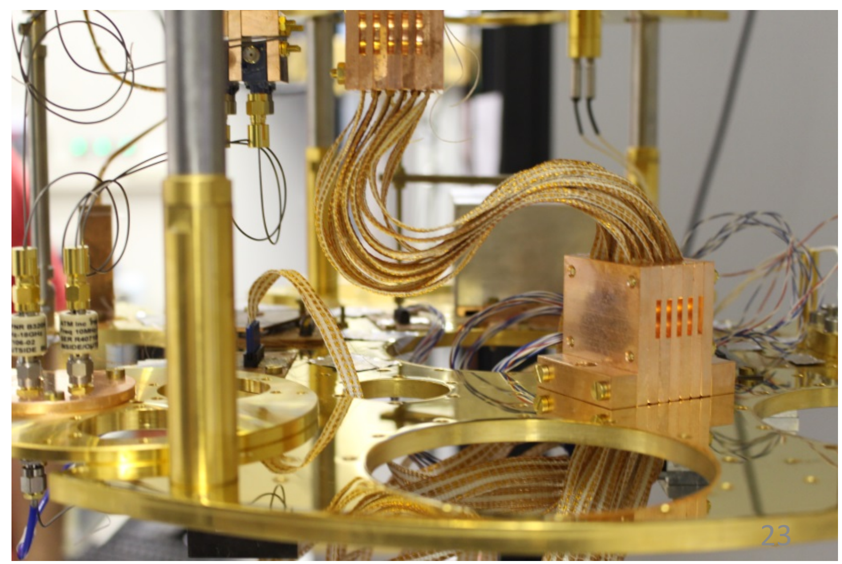


S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

ECHo cryogenic platform



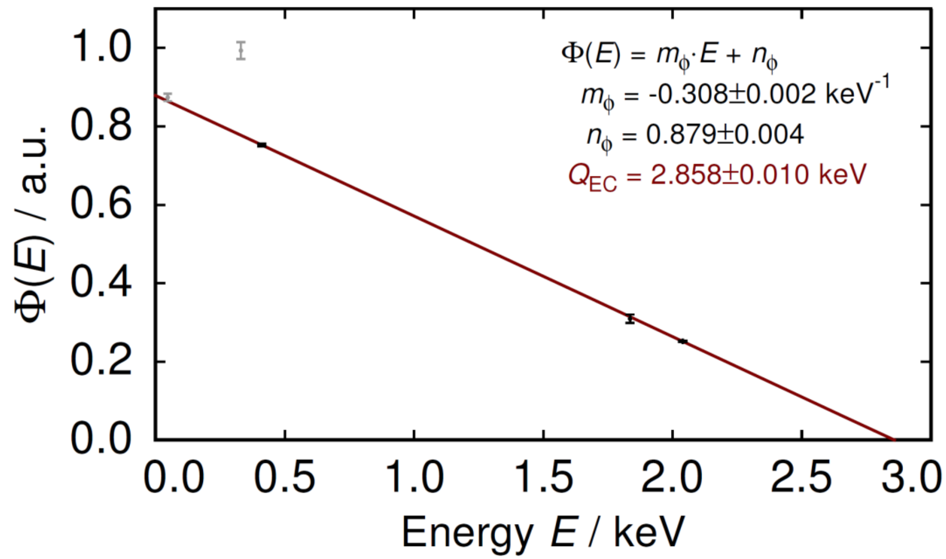
- Large space at MXC enough for several ECHo phases
- cooling power: 15µW @ 20 mK
- Possibility to load 200kg for passive shielding
- Equipped with 32 parallel read-out channel and 2 coaxial cable for multiplexing

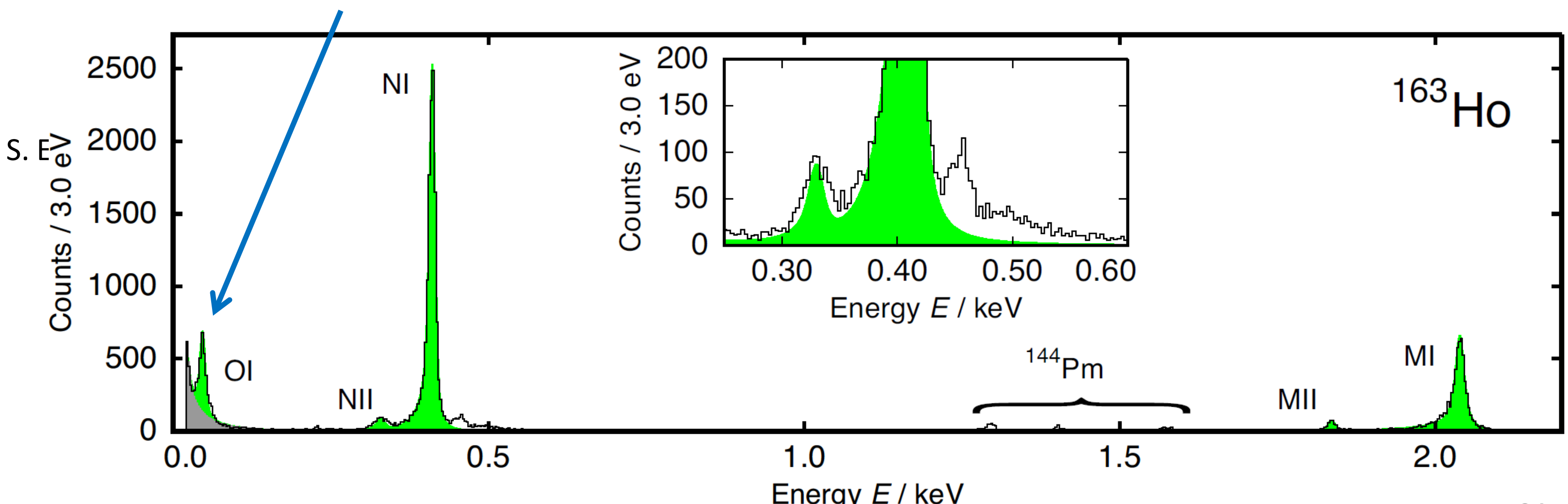


Calorimetric spectrum

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

Q_{EC} = (2.858 ± 0.010^{stat} ± 0.05^{syst}) keV





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