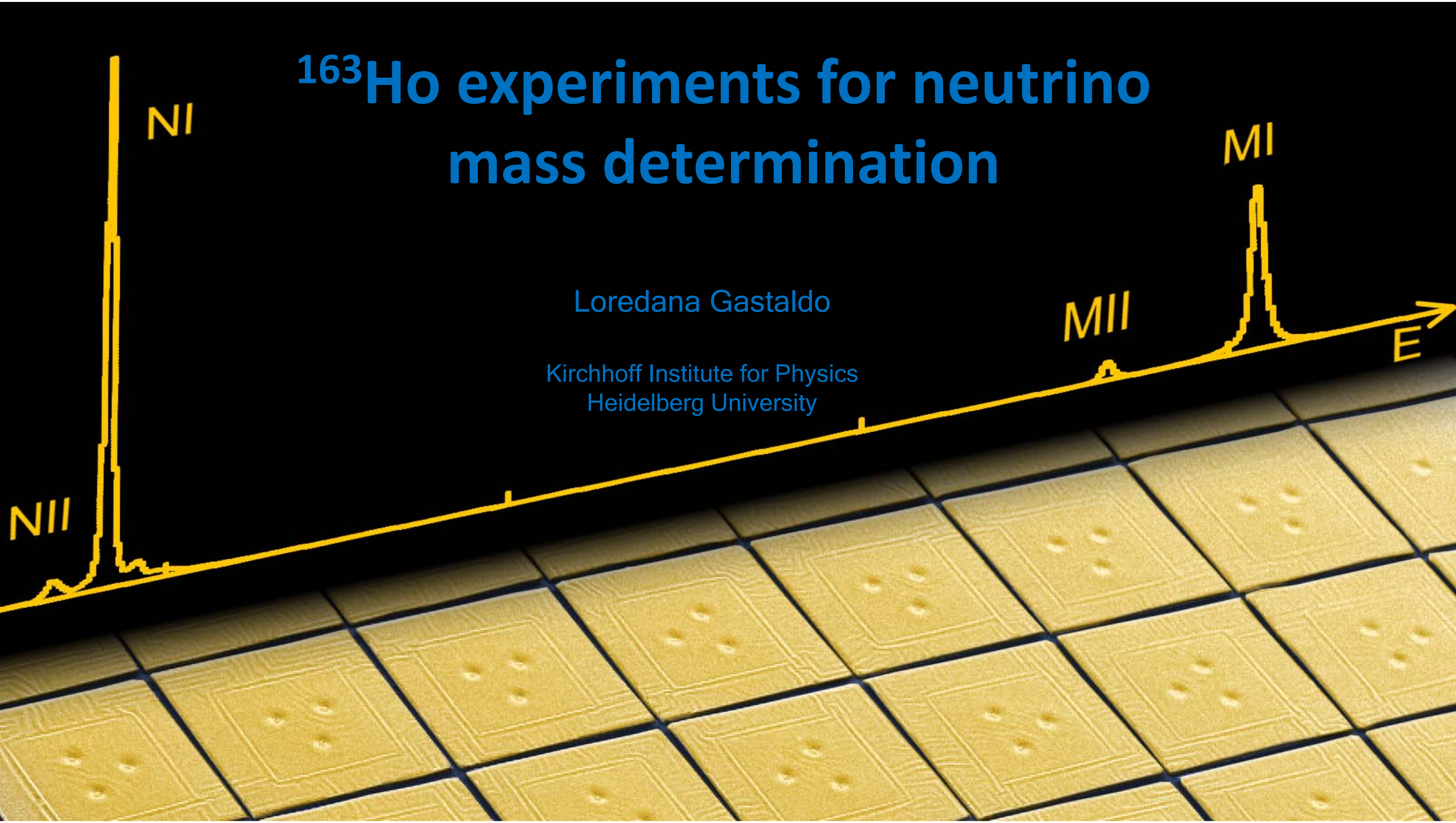
^{163}Ho experiments for neutrino mass determination

Loredana Gastaldo

Kirchhoff Institute for Physics
Heidelberg University



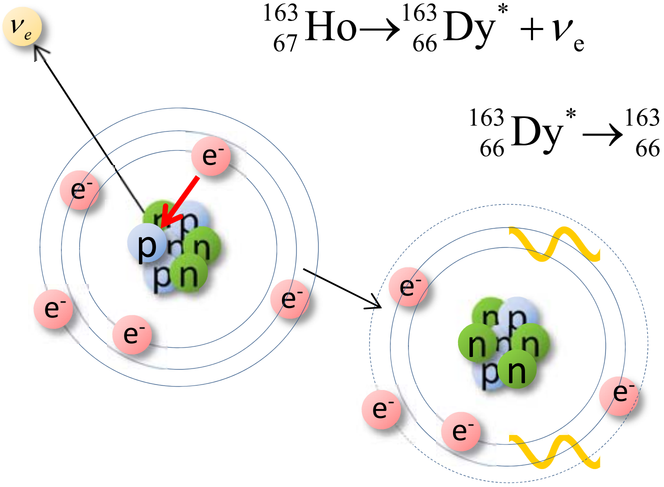
Outline

- Electron capture in ^{163}Ho and neutrino mass
  - ECHo & HOLMES
- Experimental challenges
  - ^{163}Ho Source
  - Detectors
  - readout
- From R&D to large scale experiments
- Conclusions

Electron capture in ^{163}Ho

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

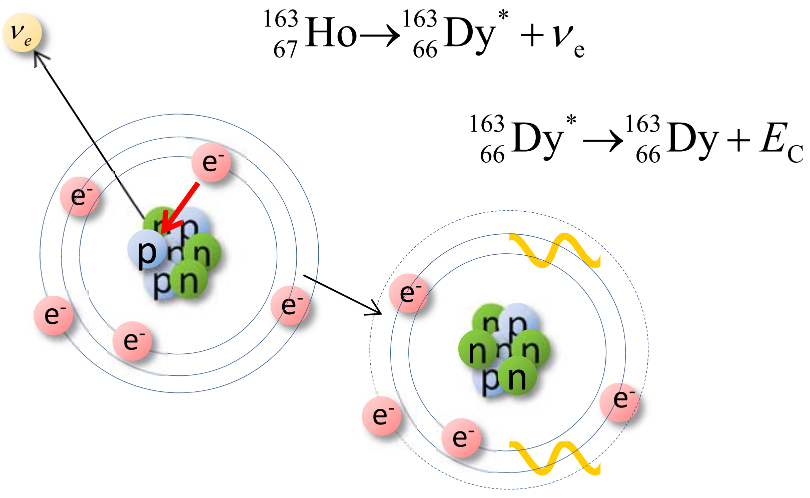
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$



- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)
- $Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

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

Electron capture in ^{163}Ho – Q_{EC}-value



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

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

Penning Trap Mass Spectroscopy

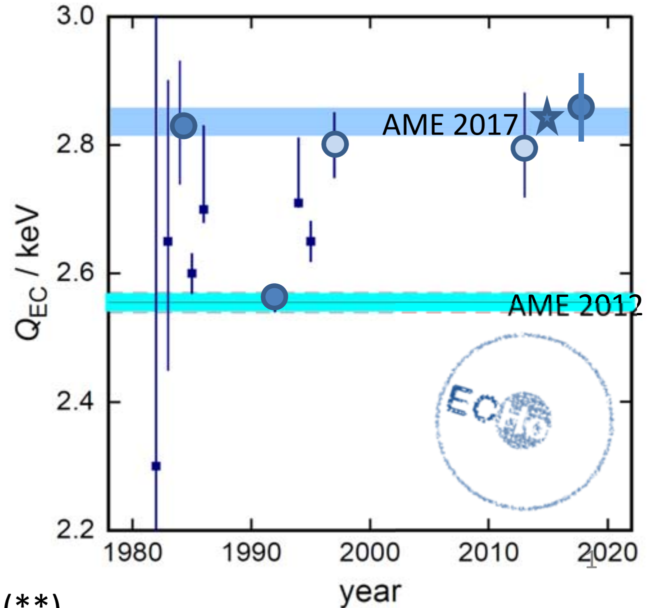
@TRIGA TRAP (Uni-Mainz) (♦)

@SHIPTRAP (GSI – Darmstadt) (♦♦)

Future goal: 1 eV precision:

PENTATRAP @MPIK, Heidelberg (*)

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



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

Electron capture in ^{163}Ho – Spectrum

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

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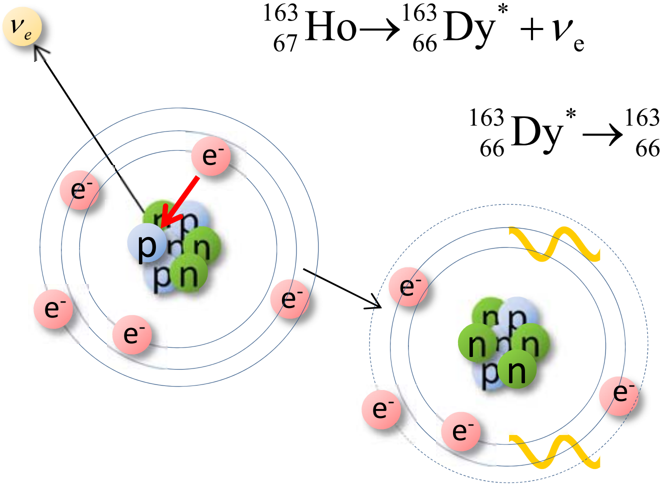

Atomic de-excitation:

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

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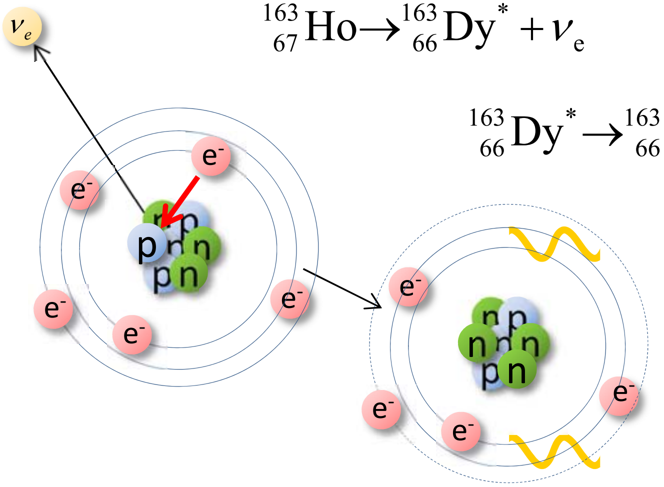

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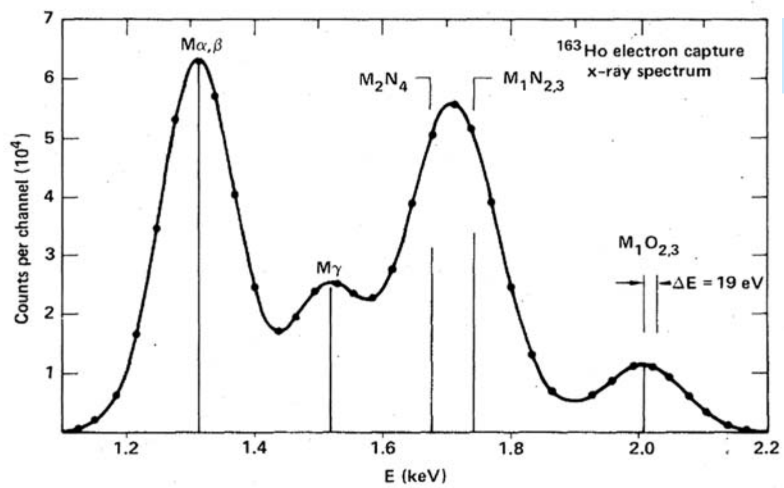

$$m(\nu_e) < 225\ eV$$

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

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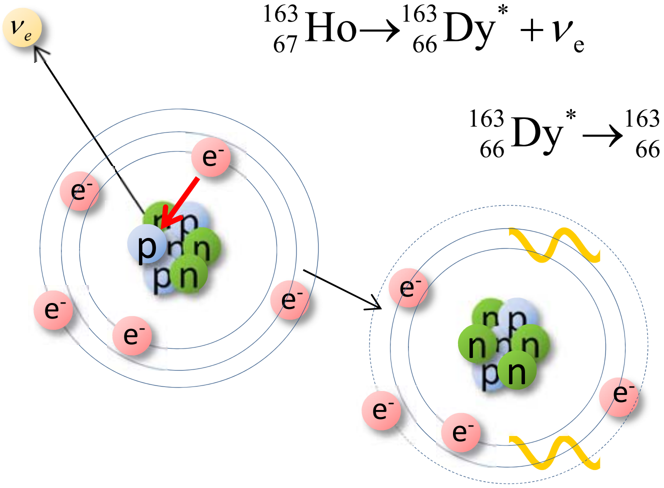

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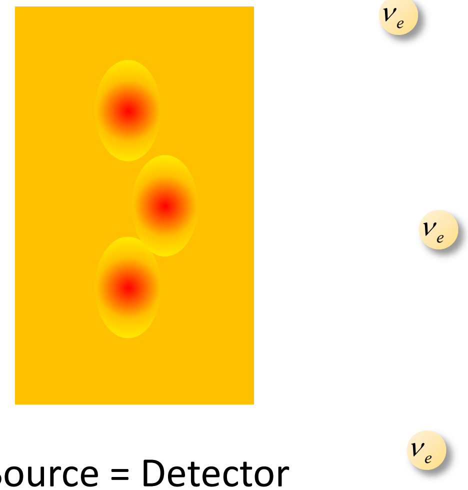
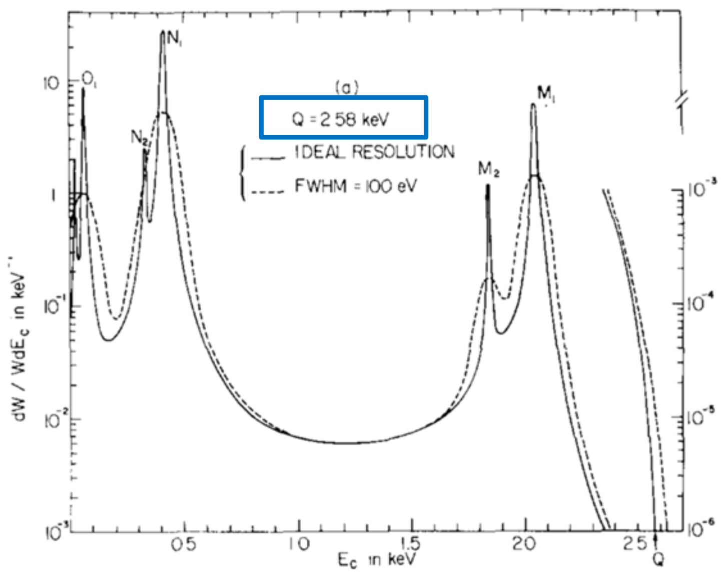


Calorimetric measurement Source = Detector

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



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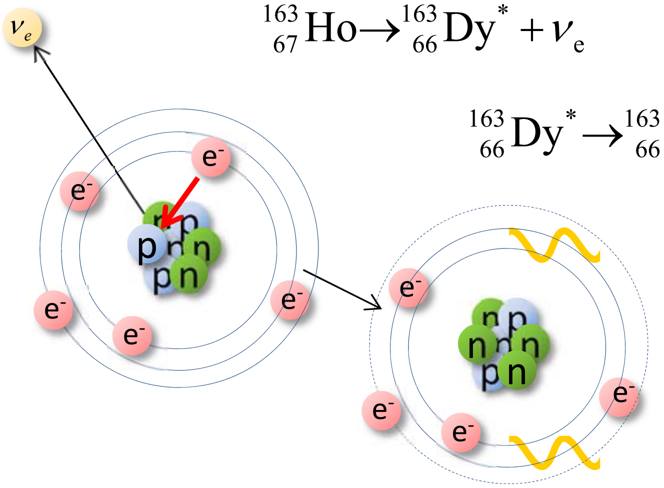

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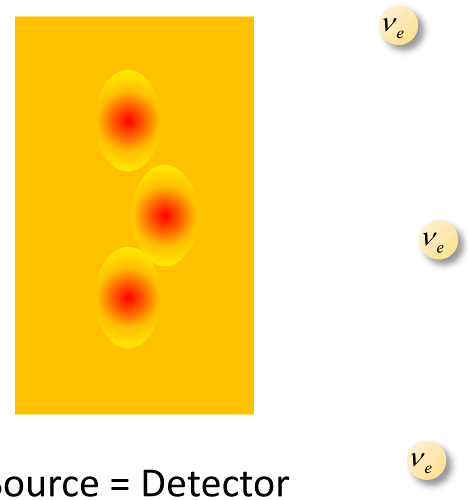

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P. C.-O. Ranitzsch et al., Phys. Rev. Lett. **119** (2017) 122501

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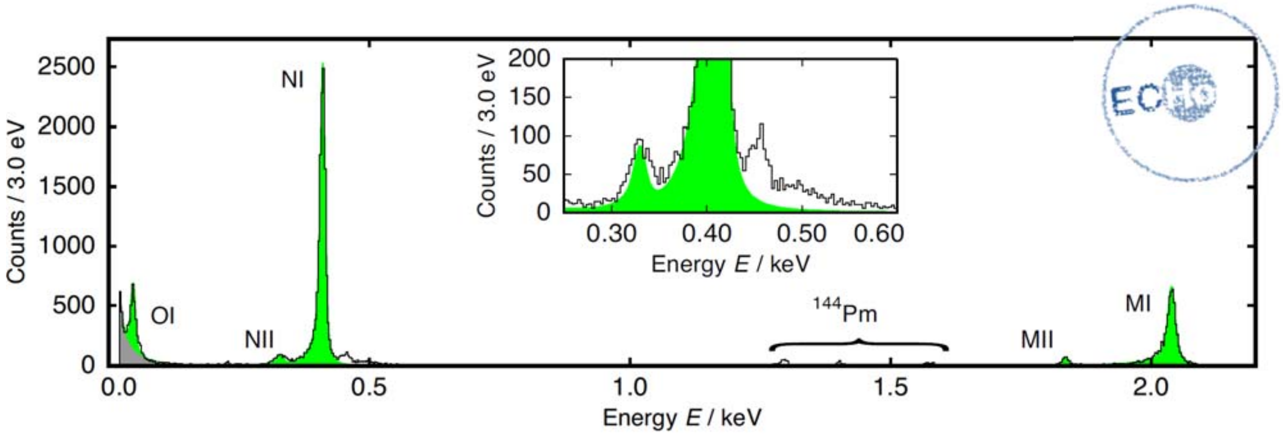

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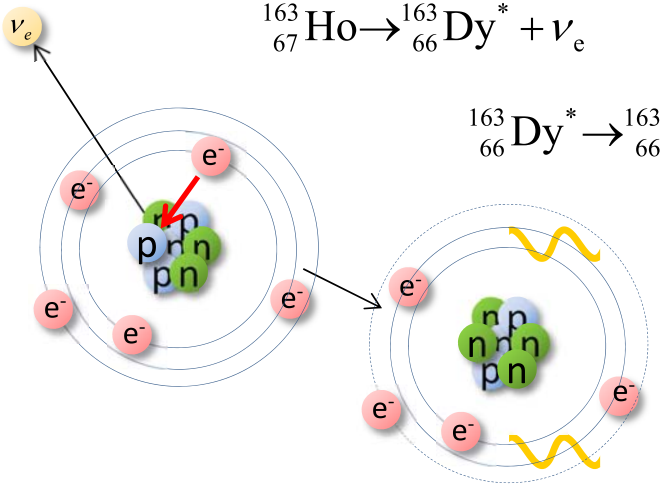

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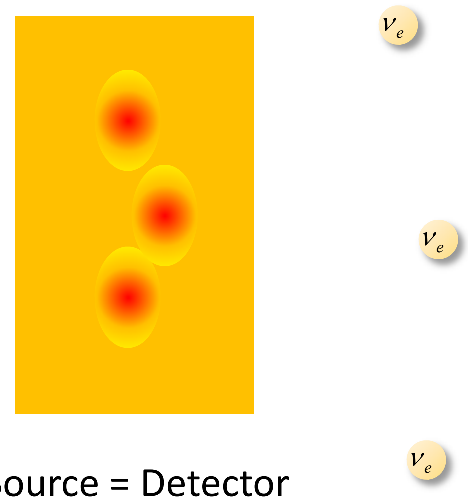

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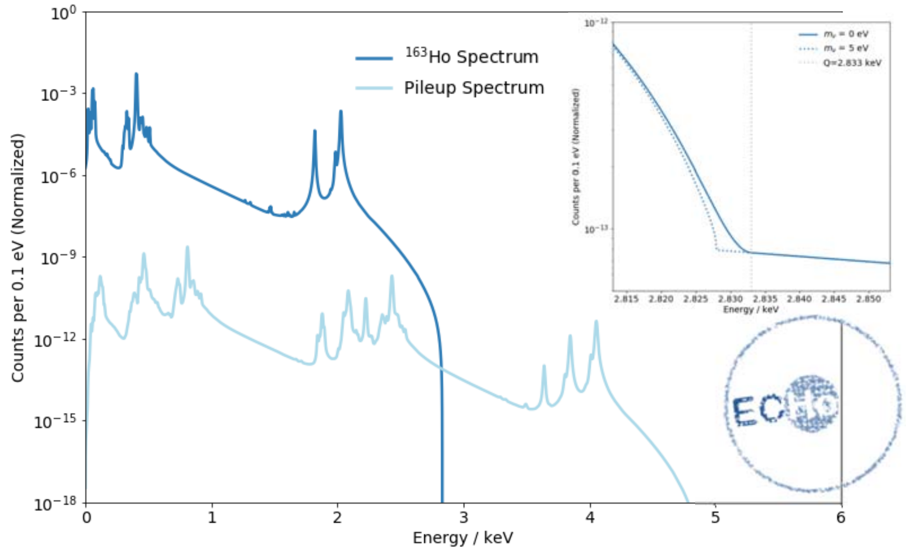
M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018



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

Ab-initio calculations foresee a smooth shape at the endpoint region

!

Parameters for ν mass sub-eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

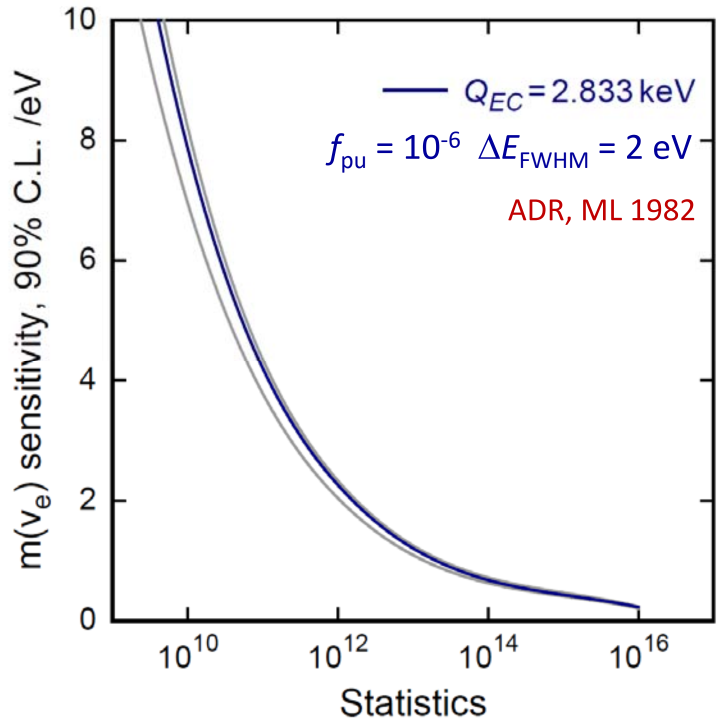
- $\boldsymbol{f_{pu} < 10^{-5}}$
- $\tau_r < 1$ µs → a ~ 10 Bq
- 10^5 pixels

Precision characterization of the endpoint region

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

Background level

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



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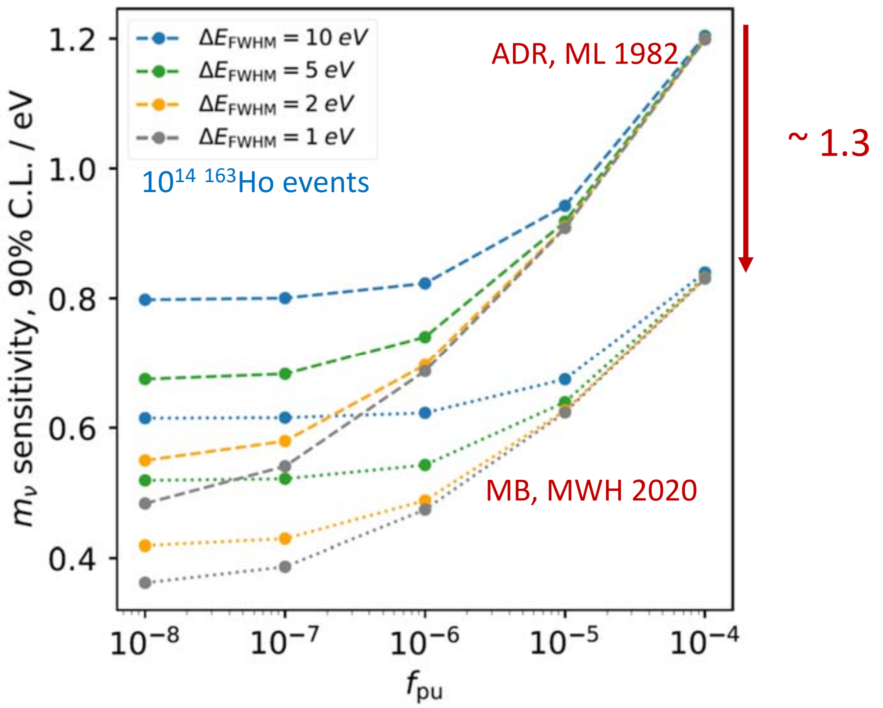

Improved sensitivity for a given number of ^{163}Ho events due to larger count-rate in the endpoint region

!

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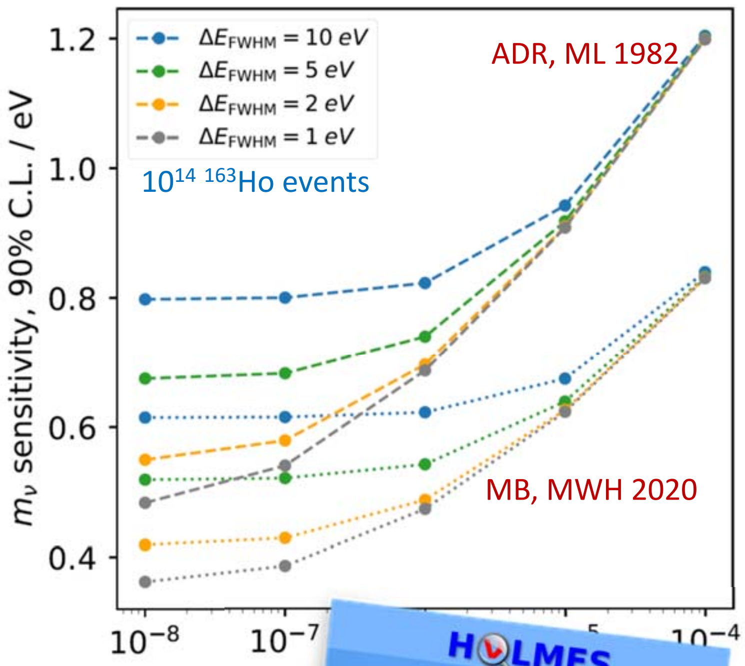


HOLMES

Monday 23.08 at 14:00

M. De Gerone
"A direct neutrino mass measurement with ^{163}Ho: The HOLMES experiment"

ECHo

European (strong German group) collaboration
Funded to ~eV sensitivity

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

HOLMES

European/US collaboration
Funded to ~eV sensitivity

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

Experimental challenges

Experimental challenges 1: ^{163}Ho source

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

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

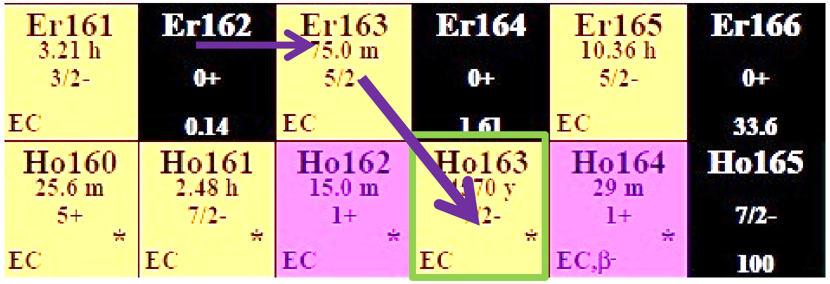
  High cross-section

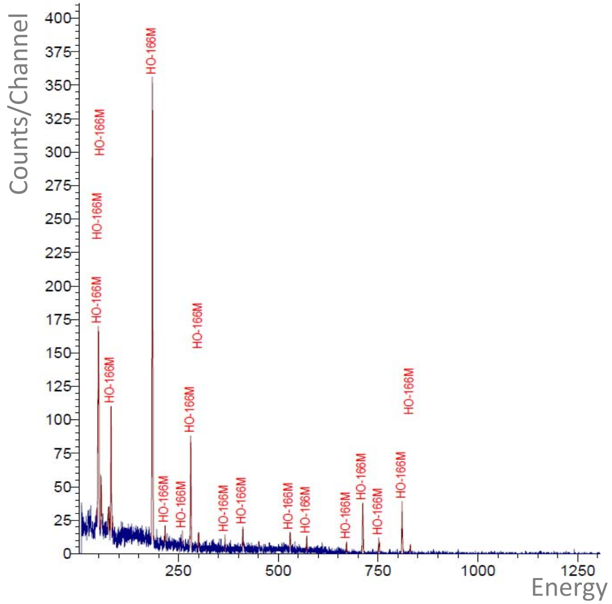
  Radioactive contaminants → Excellent chemical separation

  95% efficiency

  ECHo at Mainz University

  HOLMES at PSI Zurich





^{163}Ho available for each experiment

ECHo ~ 2×10^{18} atoms (10 MBq)

HOLMES ~ 2×10^{19} atoms (110 MBq)

!

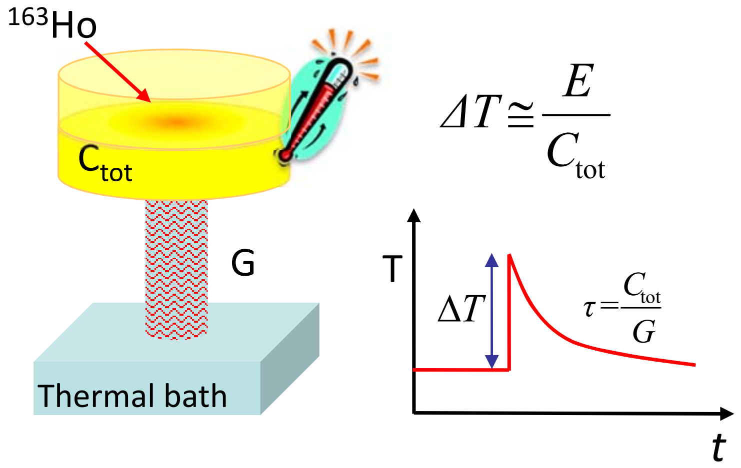
S. Heinitz et al., PLoS ONE 13(8): e0200910

H. Dorrer et al, Radiochim. Acta 106(7) (2018) 535–48

J.W. Engle et al., Nucl. Instrum. Meth. B 311 (2013) 131

Experimental challenges 2: high resolution detectors

Low temperature microcalorimeters for the measurement of the ^{163}Ho spectrum



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

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

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

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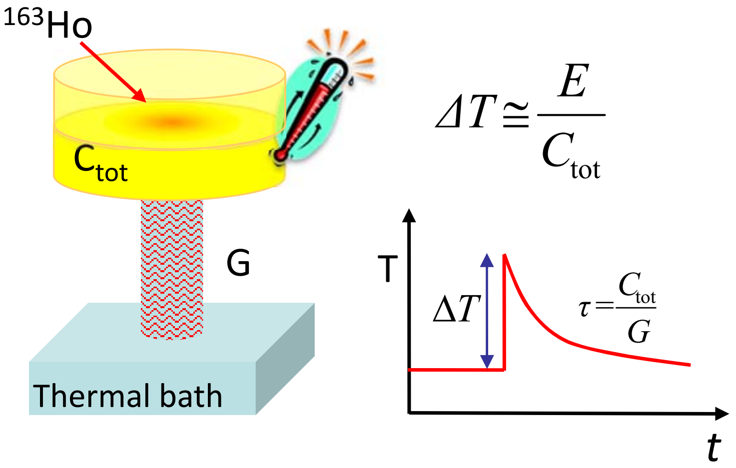
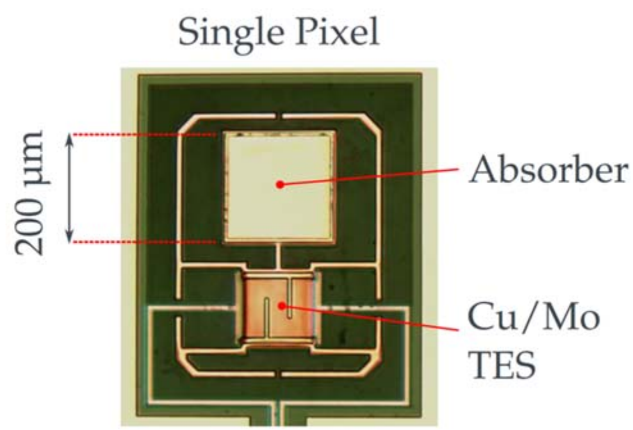


$$\Delta T \cong \frac{E}{C_{tot}}$$

$$\tau = \frac{C_{tot}}{G}$$



A. Giachero et al., IEEE Transactions on Applied Superconductivity 31 (2021) 2100205

HOLMES

Detector arrays produced at NIST (Boulder US)

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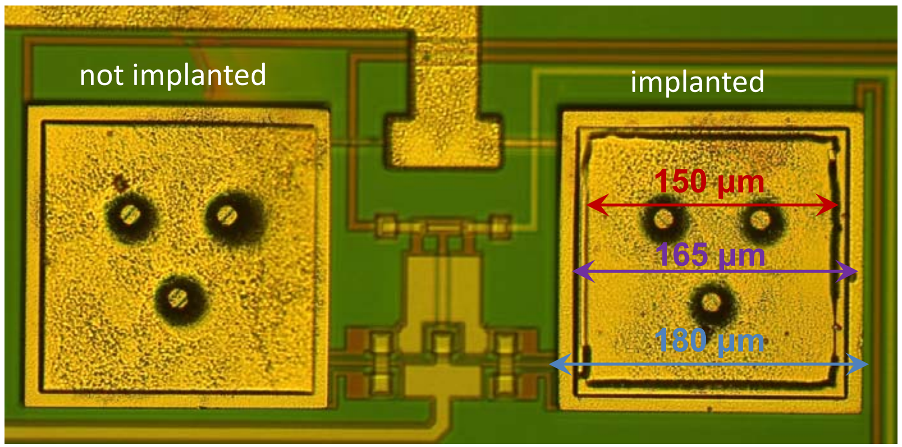

ECHo

Detector arrays produced at KIP, Heidelberg University

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

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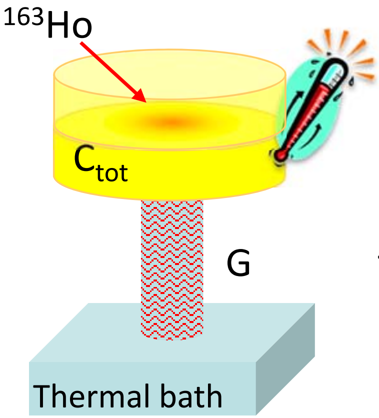

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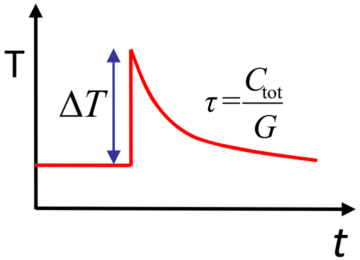

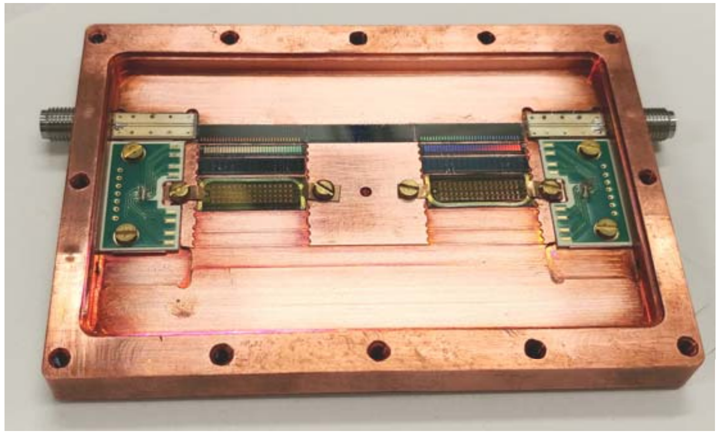

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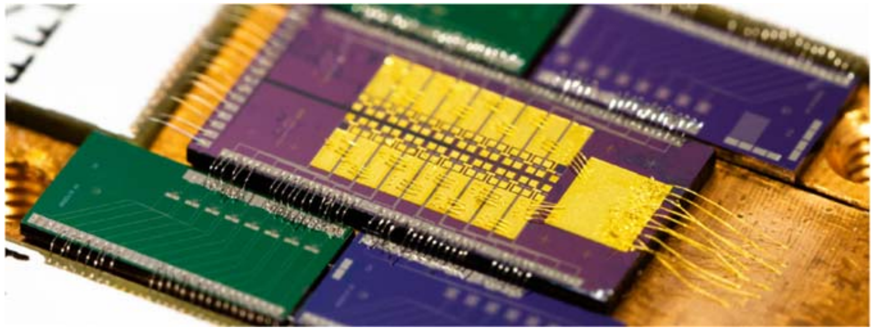

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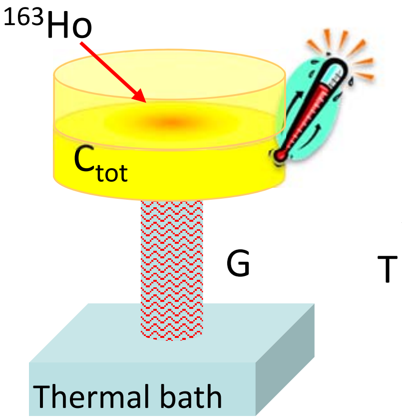

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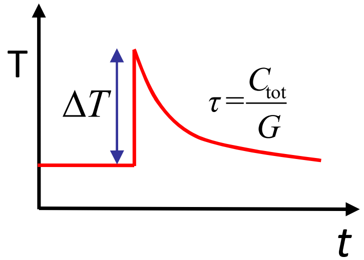

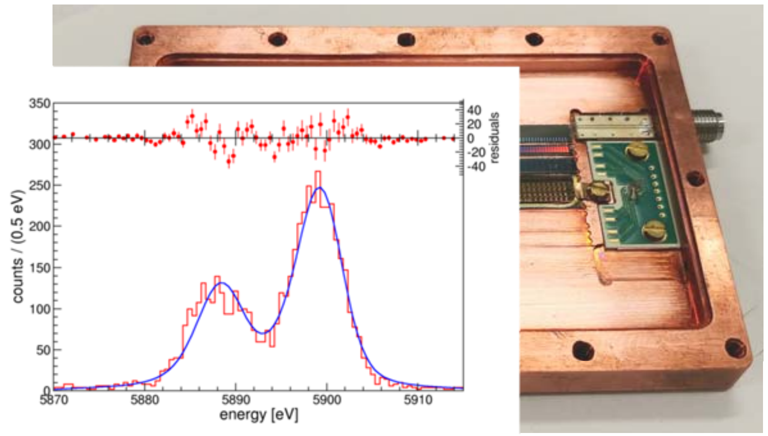

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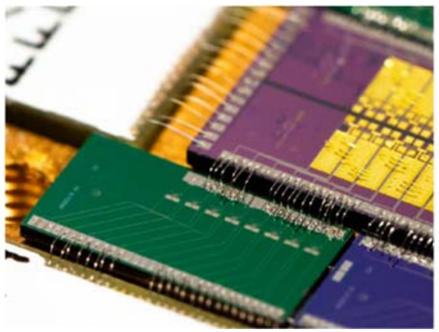
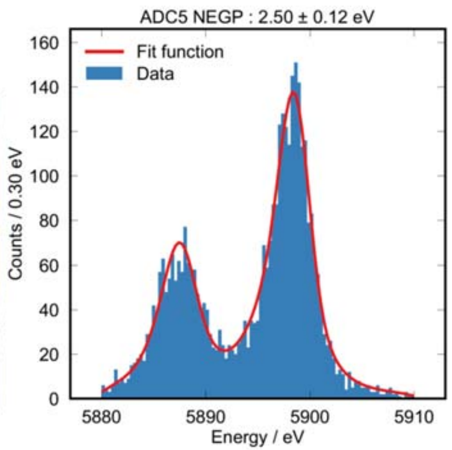




Detector arrays produced at KIP, Heidelberg University

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

eV-scale energy resolution achieved !

Experimental challenges 3: enclosing ^{163}Ho

^{163}Ho ion-implantation is used both by ECHo and HOLMES:

Mass separation and ion implantation in MMC pixels

RISIKO @ Institute of Physics, Mainz University

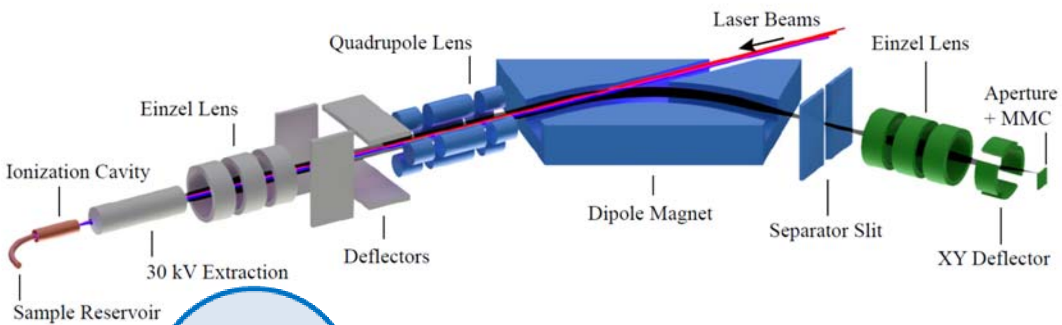
- Resonant laser ion source efficiency

  $(69 \pm 5^{stat} \pm 4^{syst})\%$

- Reduction of ^{166m}Ho in MMC

  $^{166m}Ho/^{163}Ho < 4(2)10^{-9}$!

- Optimization of beam focalization



ECHo

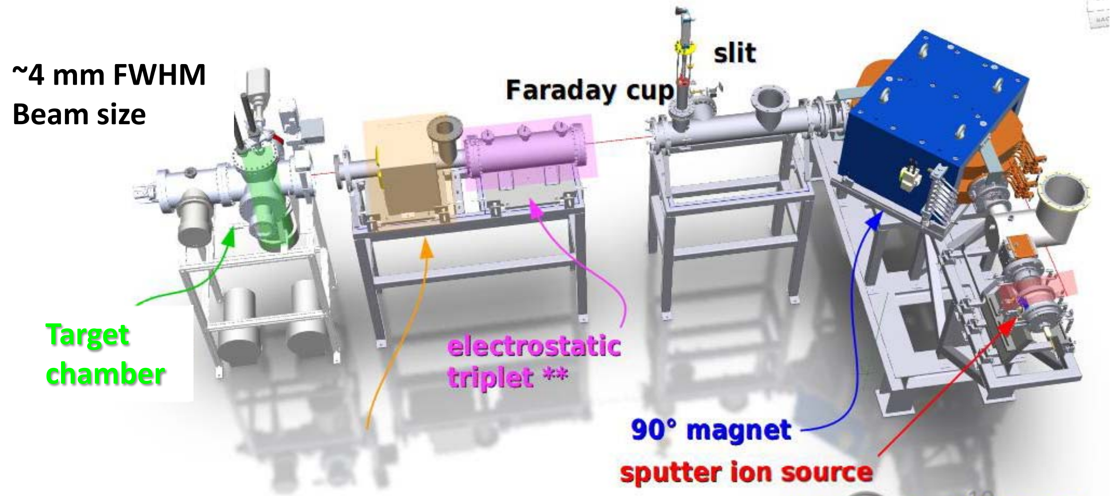
F. Schneider et al., *NIM B* **376** (2016) 388
T. Kieck et al., Rev. Sci. Inst. 90 (2019) 053304
T. Kieck et al., NIM A 945 (2019) 162602

Mass seperation and ion implantation in TES pixels

Mass separator and implanter installed @ Physics Department, Genoa University

- Argon sputter ion source
- Acceleration section → up to 50 kV

→ Commissioning phase

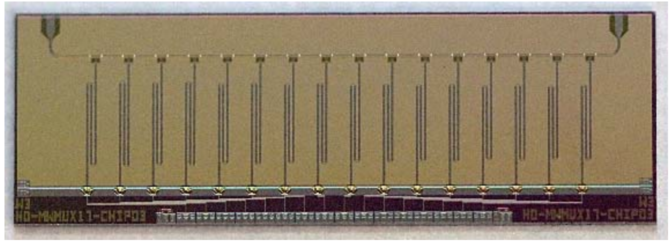


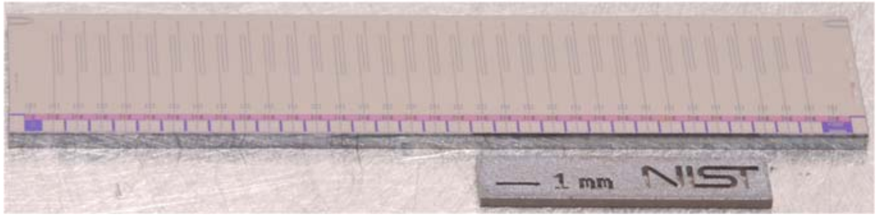
G. Gallucci et al., JLTP 194 (2019) 453

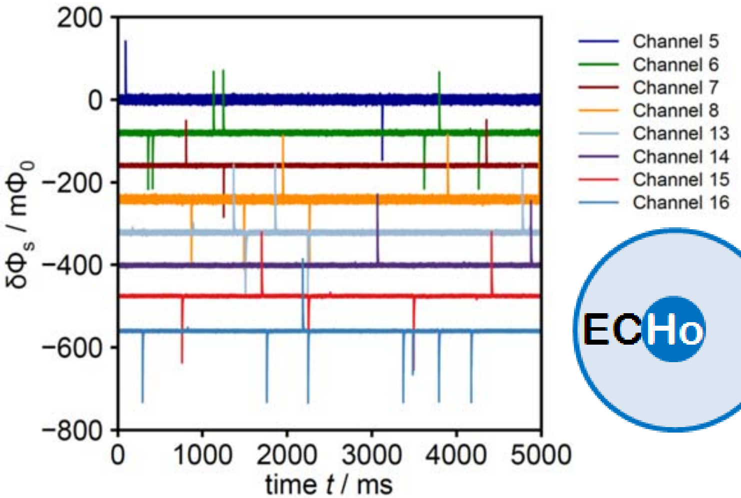
HOLMES

Experimental challenges 4: multiplexing

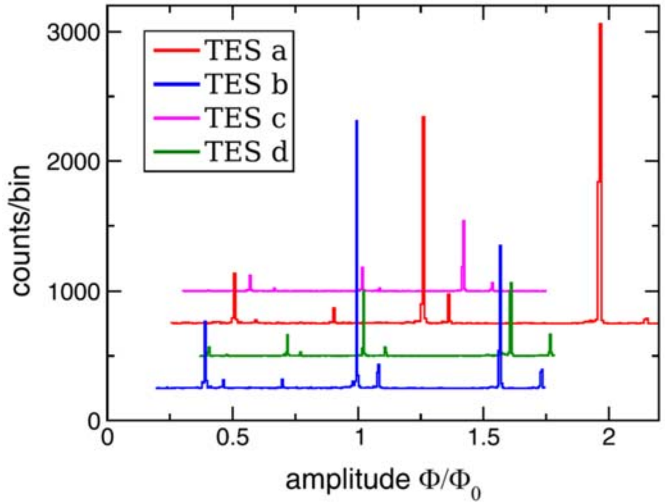
Microwave SQUID multiplexing offers the possibility to readout a large number of channels maintaining a large bandwidth
Both ECHo and HOLMES use such approach, but differently optimized







ECHo



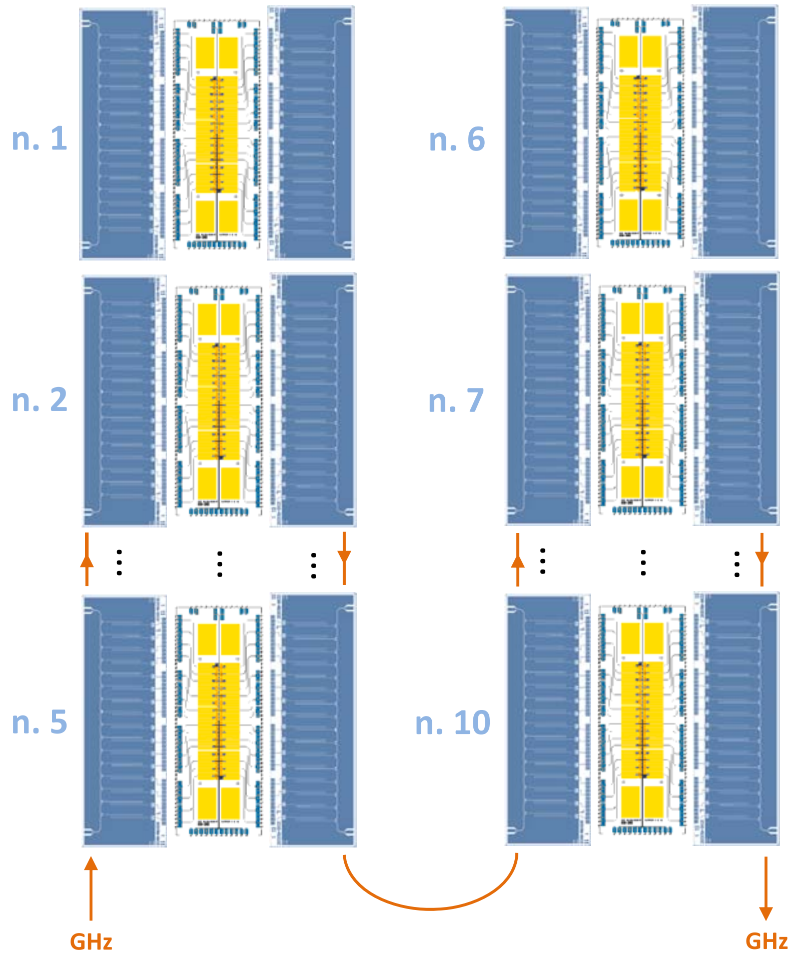
HOLMES

S.Kempf et al., *AIP Advances* **7** (2017) 015007
M. Wegner et al., J. Low Temp. Phys. **193**, 462 (2018)

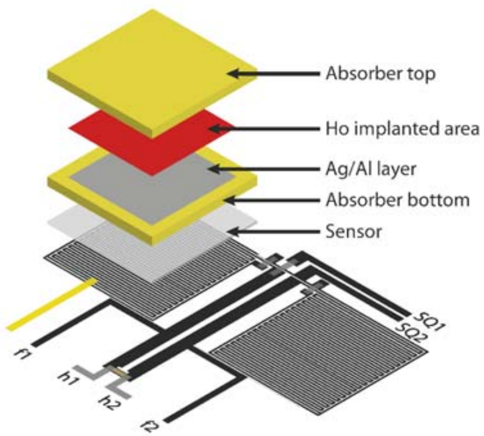
B. Alpert et al., *EPJ C* ***79*** *(2019) 304*

From R&D to large experiments

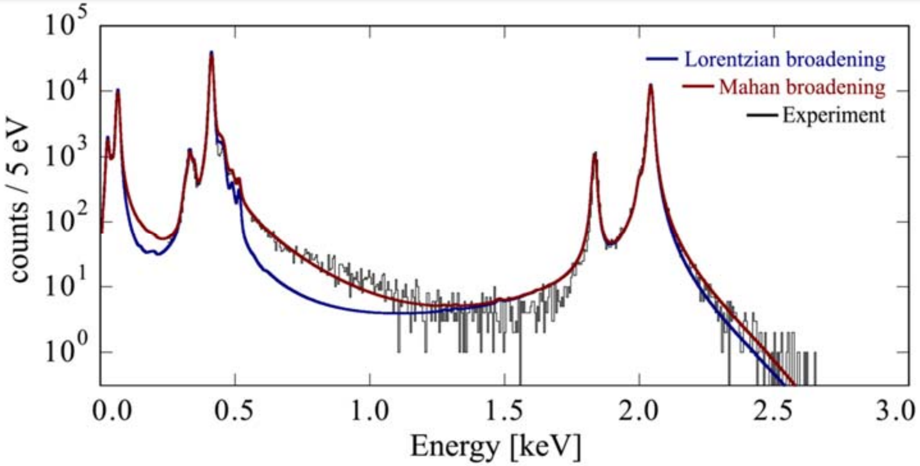
1 readout channel → ~100 detectors



1 readout channel → 1 detector



ECHo-1k



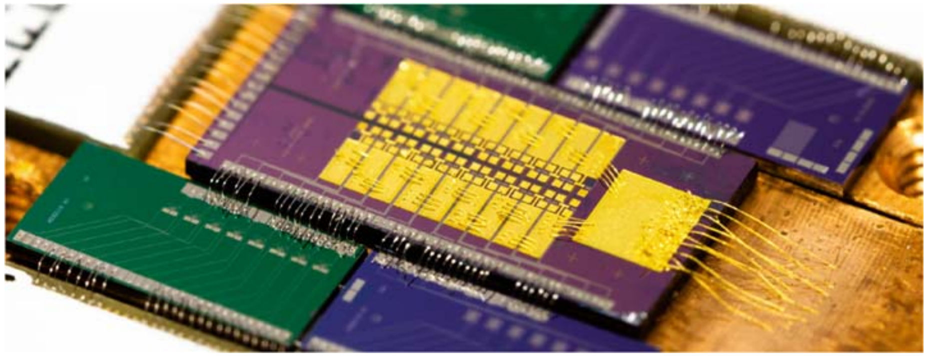
C. Velte et al., EPJC **79** (2019) 1026

4-day measurement with 4 pixels loaded with ~0.2 Bq ^{163}Ho

Energy resolution $\Delta E_{FWHM} = 9.2$ eV
Background level $b < 1.6 \times 10^{-4}$ events/eV/pixel/day

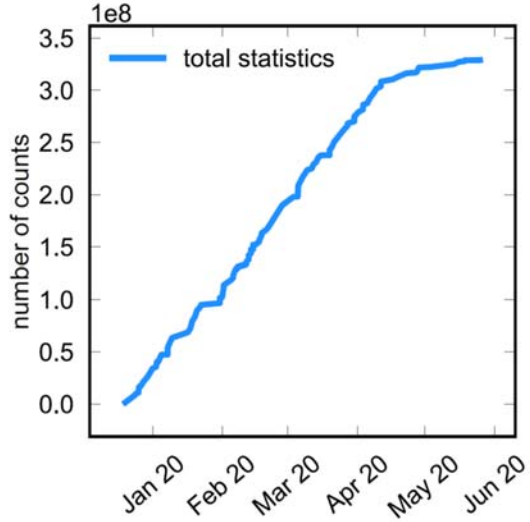
- $Q_{EC} = (2838 \pm 14)$ eV
- $m(\nu_e) < 150$ eV (95% C.L.)

!

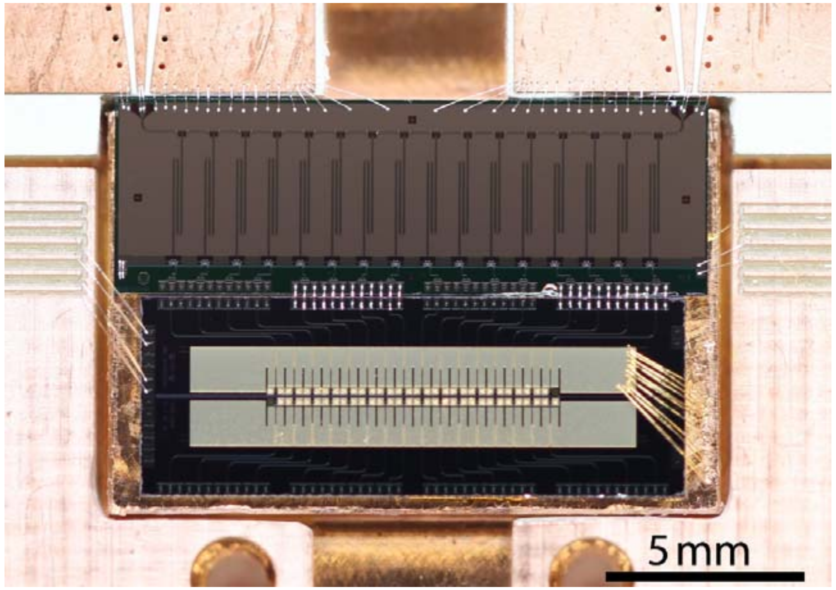


60 MMC pixels with about 1 Bq ^{163}Ho
parallel 2-stage SQUID readout
more that 10^8 ^{163}Ho events

Achievable sensitivity
$m(\nu_e) < 20$ eV (95% C.L.)



ECHo-100k: sub-2eV sensitivity



ECHo-100k baseline: large arrays of metallic magnetic calorimeters

Number of detectors: 12000
Activity per pixel: 10 Bq (2 × 10^{12} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source:
- available about 18 MBq

Ion implantation system:
- demostrated on single chip
  → next stage: wafer scale implantation

Metallic magnetic calorimeters
- reliable fabrication of large MMC array
  → next stage: ECHo-100k wafers in production
- successfull characterization of arrays with ^{163}Ho

Multiplexing and data acquisition:
- demostrated for 8 channels
  → next stage: ^{163}Ho spectrum and test on larger arrays

Data reduction
- optimized energy independent algorithm to identify spurious traces

DFG Deutsche Forschungsgemeinschaft

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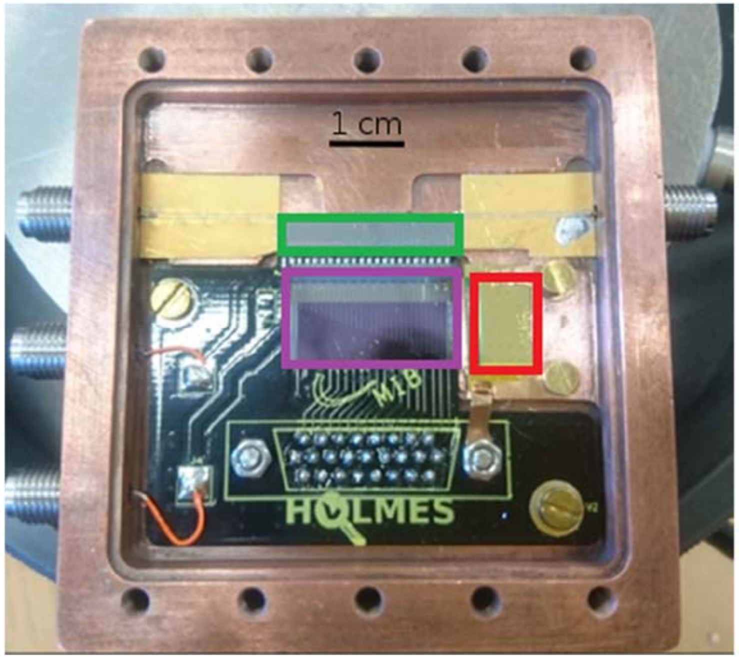
HOLMES: sub-2eV sensitivity



HOLMES baseline: large arrays of Transition Edge Sensors

Number of detectors: 1000
Activity per pixel: 300 Bq (6×10^{13} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source:
- available about 110 MBq

Ion implantation system:
- commissioning in 2021

Transition Edge Sensor arrays
- reliable fabrication of large TES array
- succesfull characterization of empty arrays
- still to demonstrate performance with 300 Bq

Multiplexing and data acquisition:
- completed and demonstrated for 32 channels

Data reduction
- optimized algorithms to reduce unresolved pile-up background

B. Alpert et al, Eur. Phys. J. C (2015) 75:112
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

Conclusions and outlook

- ν The determination of the electron neutrino mass with ^{163}Ho is complementary to the determination of the electron antineutrino mass with ^{3}H
- ν Determination of the ^{163}Ho spectral shape is indicates that the spectral shape at the endpoint region is smooth
- ν ECHo and HOLMES have already demonstrated:
  - production and purification of large amount of ^{163}Ho sample
  - operation of large arrays of high resolution low temperature detectors
- ν Background identification and suppression to achieve the unresolved pile-up limit
- ν HOLMES detector modules will be soon tested for ^{163}Ho enclosure
- ν ECHo is now a running experiment on the way to provide a new limit on the electron neutrino mass and ready for upgrades to larger arrays
- ν First multiplexed ^{163}Ho spectra will tell us if reaching sub-eV sensitivity is just a matter of scaling up

ECHo

7 institutions
About 50 scientists

HOLMES

6 institutions
About 40 scientists

Thank you for the attention!

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