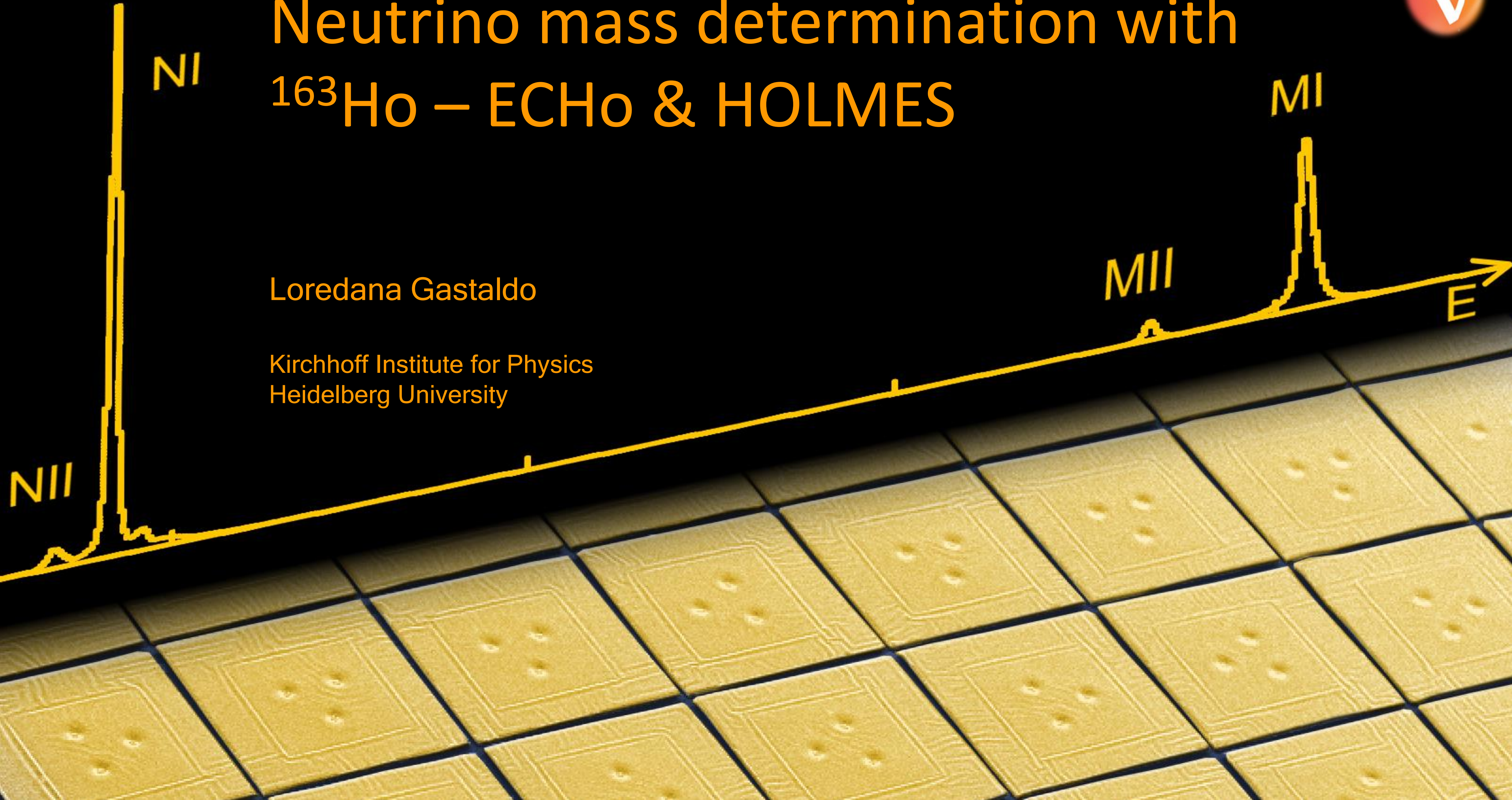
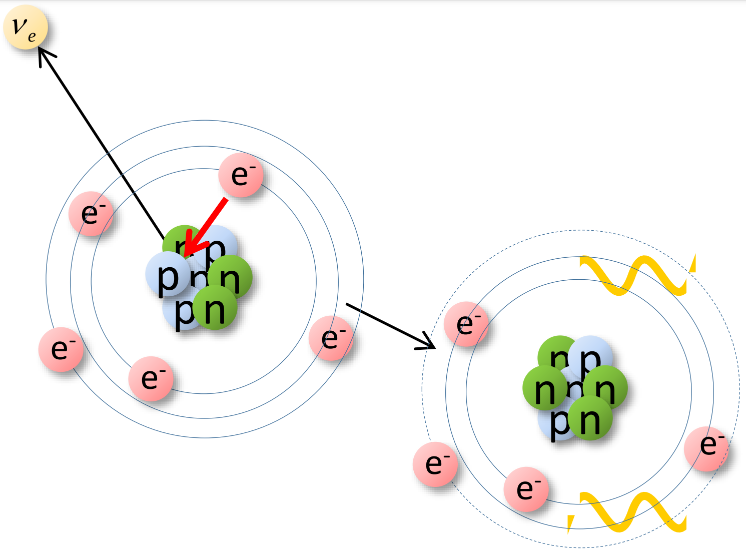
Neutrino mass determination with ^{163}Ho – ECHo & HOLMES

Loredana Gastaldo

Kirchhoff Institute for Physics
Heidelberg University



Electron Capture in ^{163}Ho

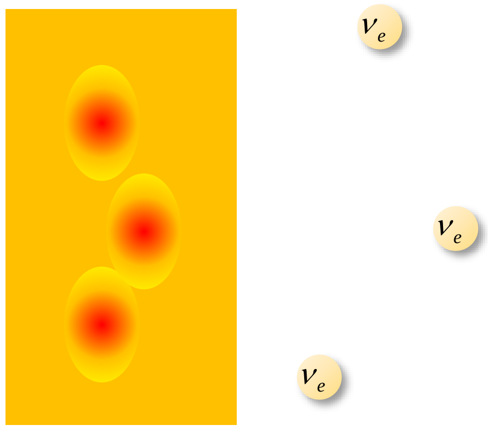


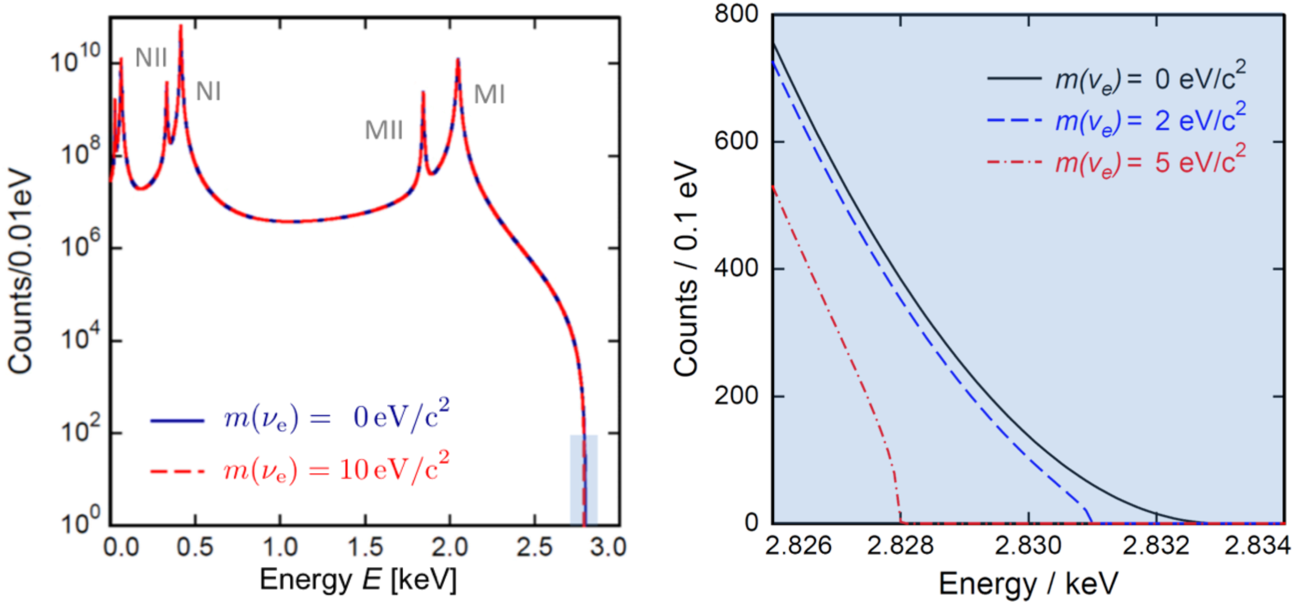
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

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

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

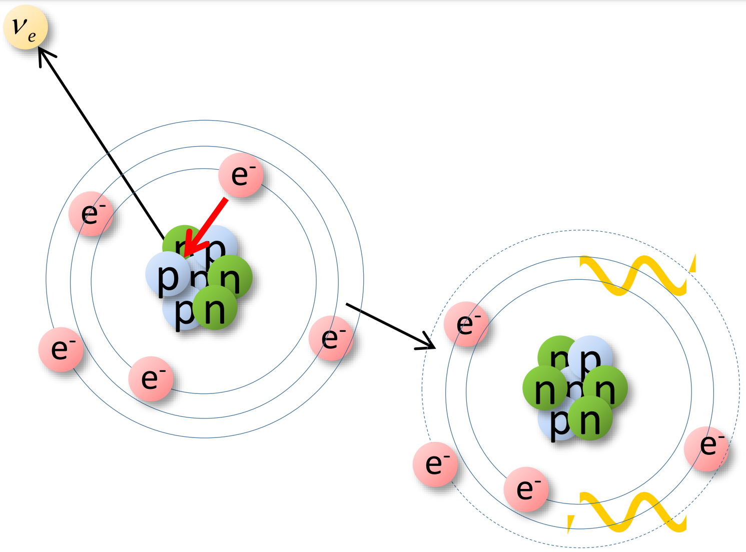
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

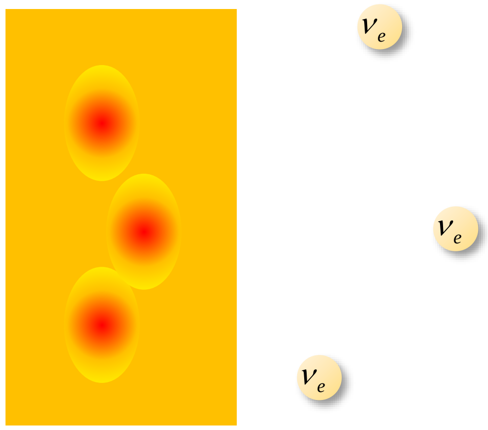




* A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

Electron Capture in ^{163}Ho





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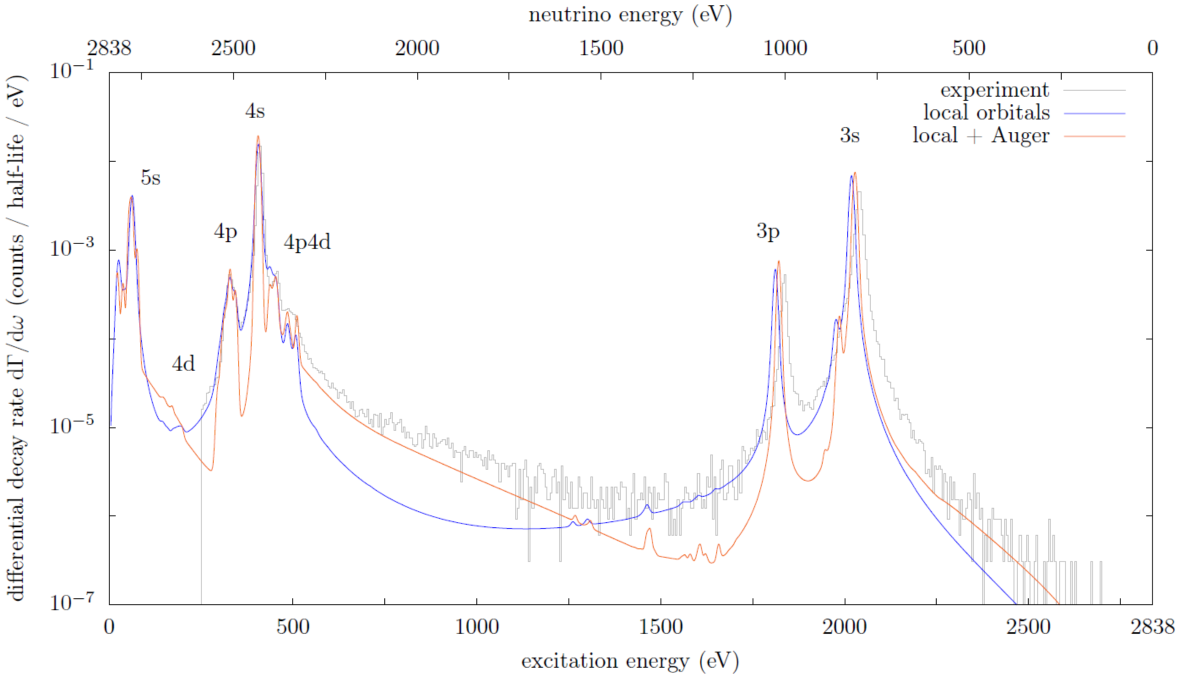

* A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

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

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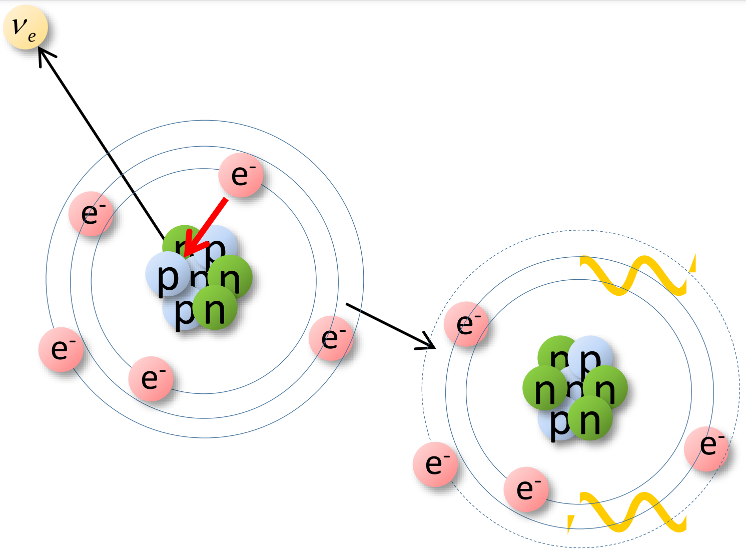

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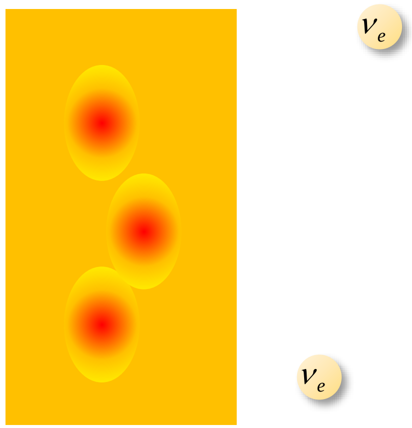

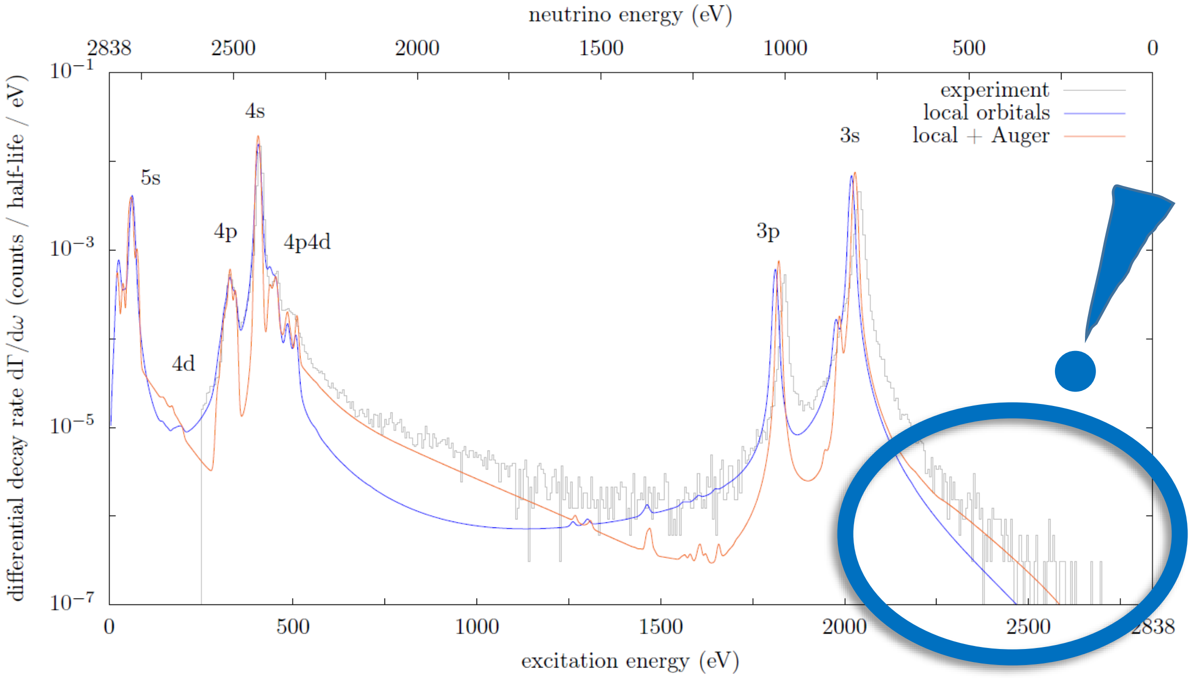

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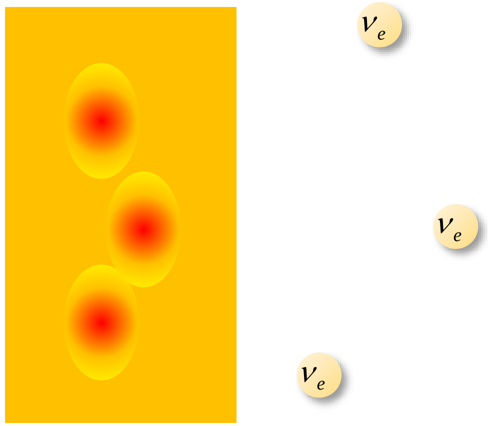
M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

Electron Capture in ^{163}Ho - Timeline

1980 1990 2000 2010 2020

* Proposal for calorimetric measurements



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Electron Capture in ^{163}Ho - Timeline

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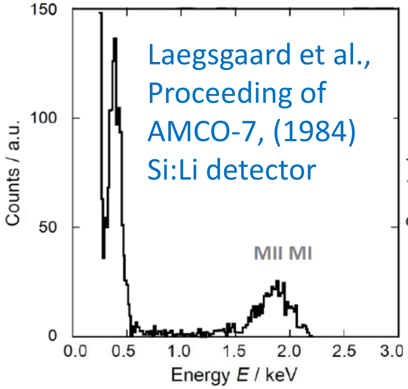
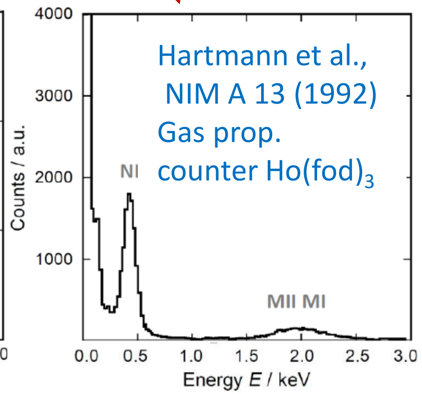
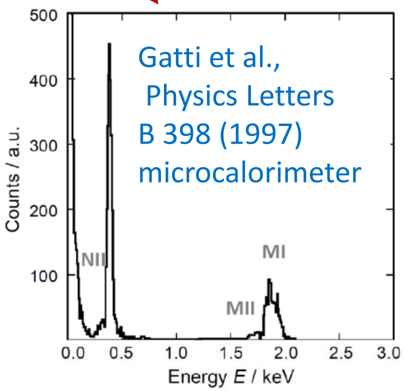
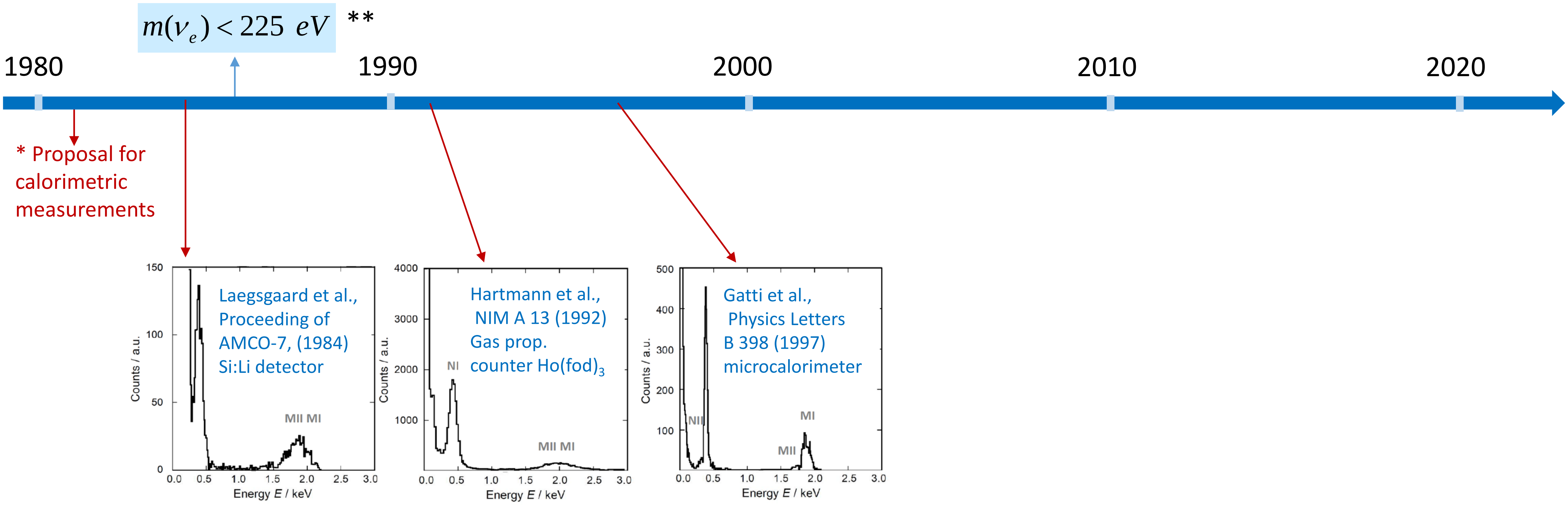






* A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

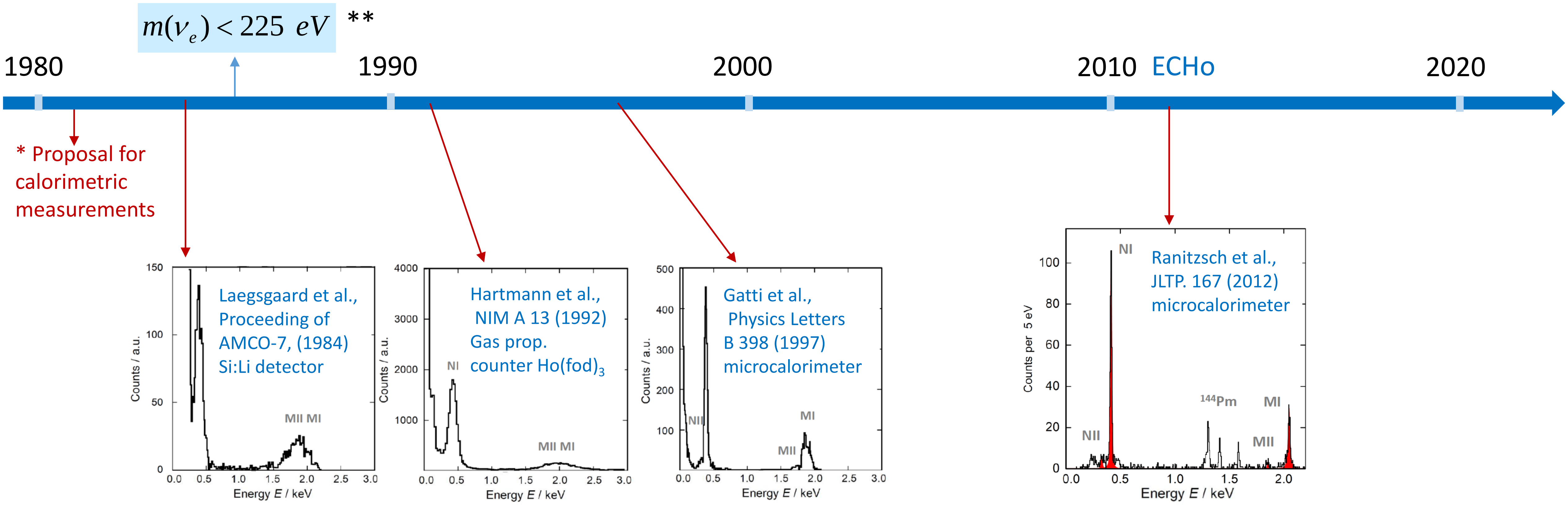
Electron Capture in ^{163}Ho - Timeline



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

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

Electron Capture in ^{163}Ho - Timeline



* A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)
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Electron Capture in ^{163}Ho - Timeline

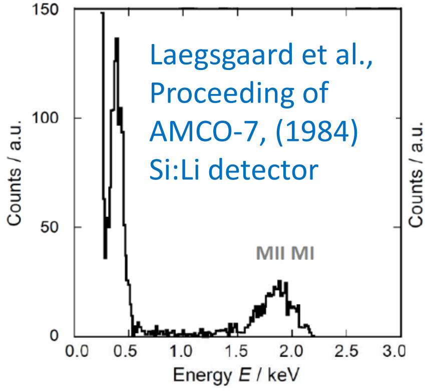
$m(\nu_e) < 225\ eV$ **

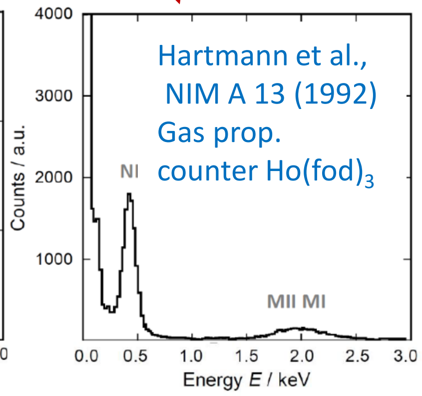
1980 1990 2000 2010 ECHo, HOLMES 2020

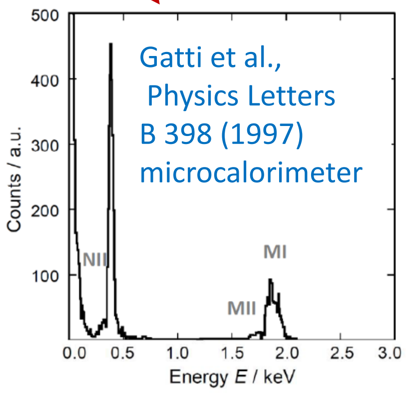
Modern ^{163}Ho experiments

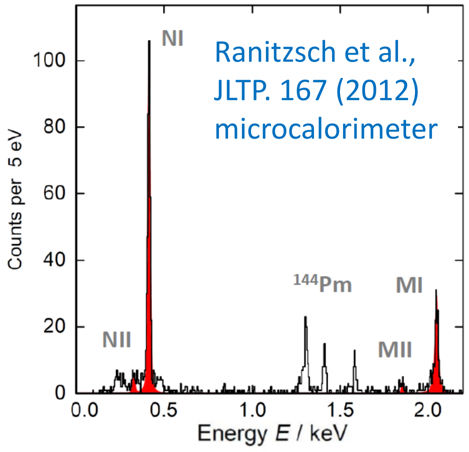
* Proposal for calorimetric measurements

$m(\nu_e) < 150\ eV$ ***









* A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)
** P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

*** C. Velte et al., (The ECHo Collaboration) *Eur. Phys. J. C* **79** (2019) 1026

Electron Capture in ^{163}Ho - Timeline

POSTERS

P0605: Mariia Fedkevych
Direct neutrino mass measurement with low-temperature microcalorimeters in HOLMES experiment

P0696: Neven Kovac
From ECHo-1k to ECHo-100k: Optimisation of High-Resolution Metallic Magnetic Calorimeters with Embedded ^{163}Ho

P0674: Markus Griedel
From Temperature pulses to the high statistic ^{163}Ho spectrum: Analysis Algorithms for the ECHo Experiment

P0700: Loredana Gastaldo
High energy resolution calorimetrically measured ^{193}Pt electron capture spectrum

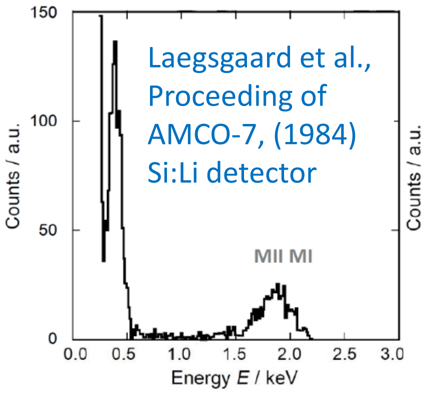
1980 — 1990 — 2010 ECHo, HOLMES — 2020

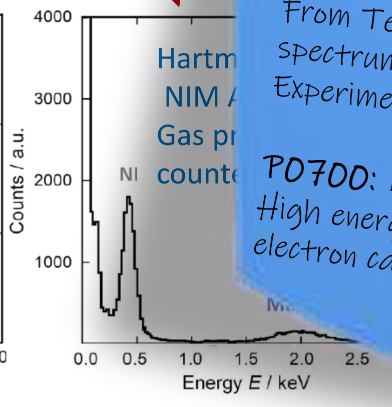
Modern ^{163}Ho experiments

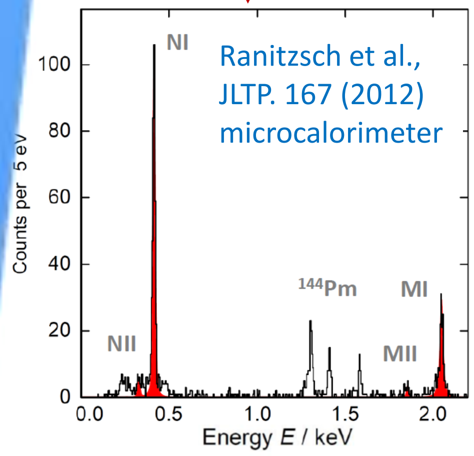
$m(\nu_e) < 225\ eV$ **

$m(\nu_e) < 150\ eV$ ***

* Proposal for calorimetric measurements







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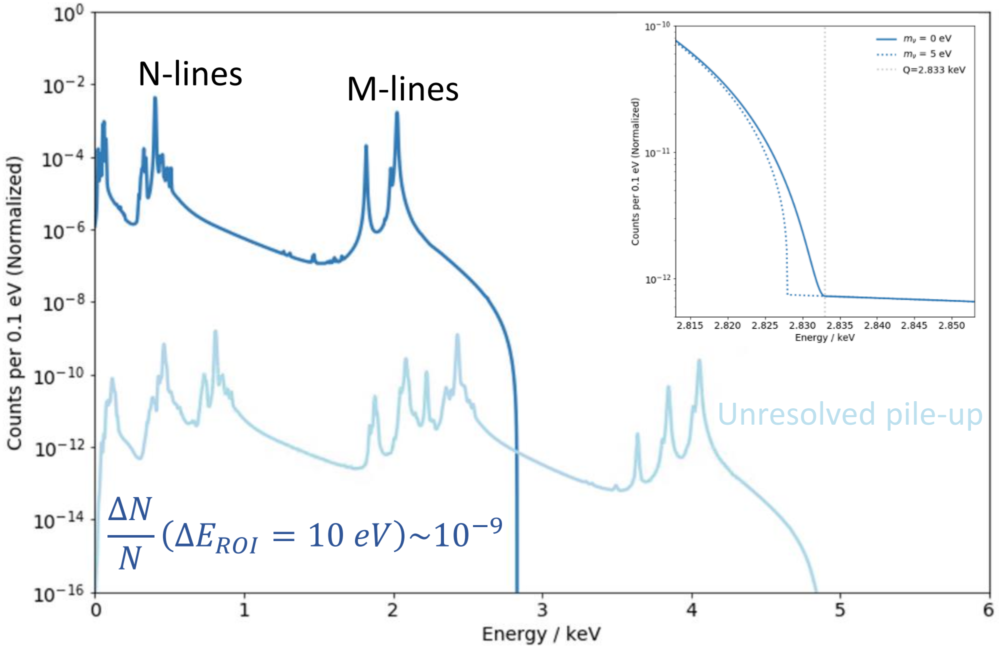
Requirements for sub-eV sensitivity



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

Statistics in the end point region $N_{ev} > 10^{14}$ → $A \approx 1$ MBq

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$) $f_{pu} < 10^{-5} - 10^{-4}$

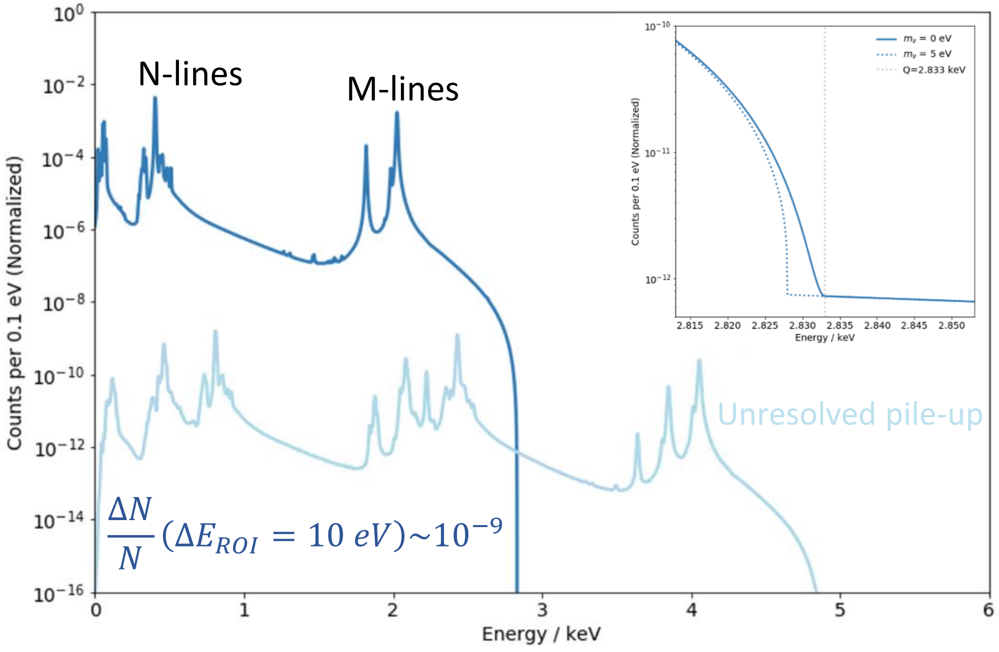
$\tau_r \sim 1\ \mu s$ → $a \sim 10 - 100$ Bq

$10^4 - 10^5$ pixels → multiplexing

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

Background level $< 10^{-6} - 10^{-4}$ events/eV/det/day

Requirements for sub-eV sensitivity



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

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

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$) $f_{pu} < 10^{-5} - 10^{-4}$

$\tau_r \sim 1$ µs → a ~ 10 - 100 Bq

$10^4 - 10^5$ pixels → multiplexing

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

Background level $< 10^{-6} - 10^{-4}$ events/eV/det/day

ECHo

Arrays of metallic magnetic calorimeters with ^{163}Ho implanted in absorber

Activity per pixel 10 Bq

- Reducing Ho-related heat capacity – no performance degradation
- Reducing systematic effects due to background

HOLMES

Array of transition edge sensors coupled to absorber with ion implanted ^{163}Ho

Activity per pixel 300 Bq

Reducing the number of readout channels

^{163}Ho source

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

Different methods to produce high purity and high intensity ^{163}Ho sources have been studied in details

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

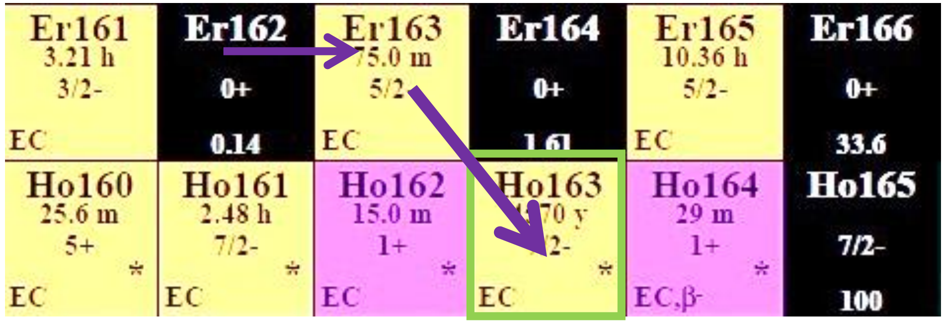
  High cross-section

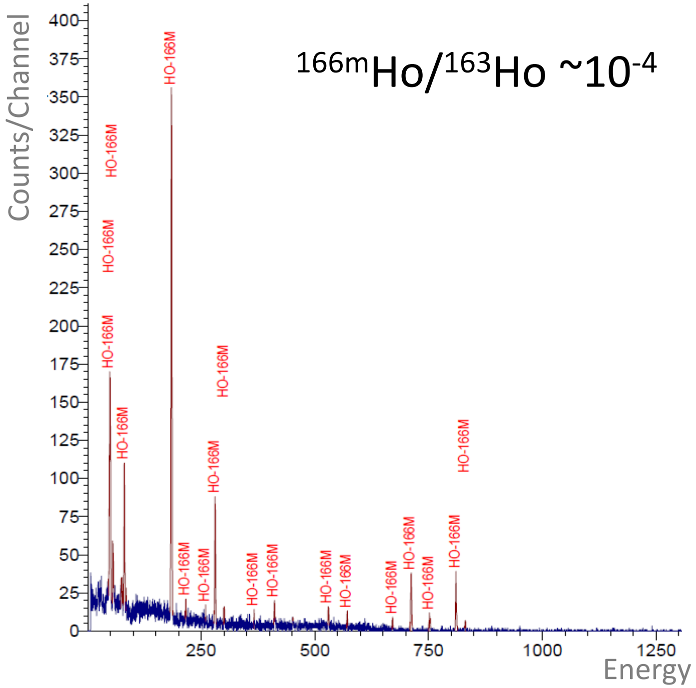
  Radioactive contaminants → Excellent chemical separation

  95% efficiency

  ECHo at Mainz University

  HOLMES at PSI Zurich





^{166m}Ho/^{163}Ho ~10^{-4}

NEUTRONS FOR SCIENCE

^{163}Ho available for each experiment

ECHo ~ 6×10^{18} atoms (30 MBq)

HOLMES ~ 2×10^{19} atoms (100 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

Enclosing ^{163}Ho source – ion implantation

RISIKO @ Institute of Physics, Mainz University

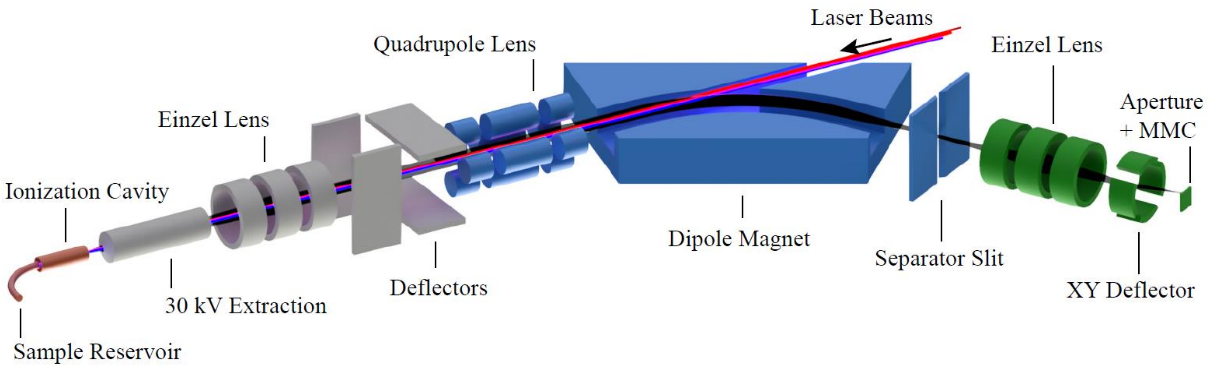
- Resonant laser ion source → efficiency:

  $(69 \pm 5^{stat} \pm 4^{syst})\%$
- Reduction of ^{166m}Ho in MMC

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

  Validation via AMS measurement @HZDR DREAMS facility
- Optimization of beam focalization

→ Coming soon: implantation on wafer scale

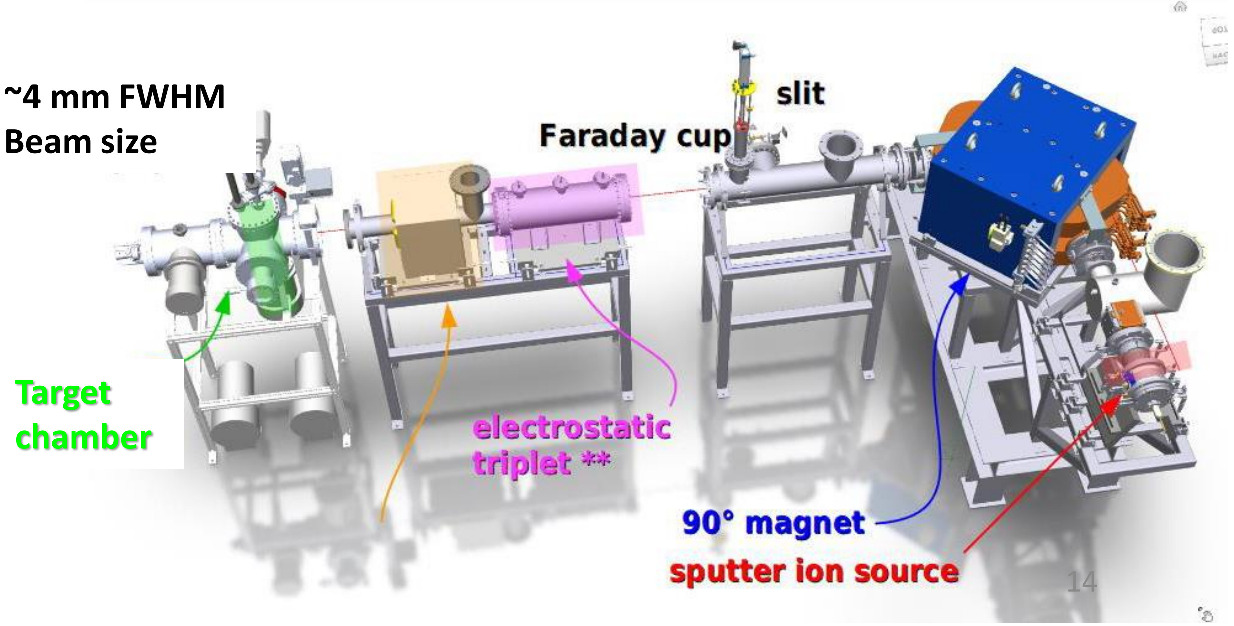


F. Schneider et al., *NIM B* **376** (2016) 388
T. Kieck et al., Rev. Sci. Inst. 90 (2019) 053304
T. Kieck et al., NIM A 945 (2019) 162602

Mass separator and implanter installed @ Physics Department, Genoa University

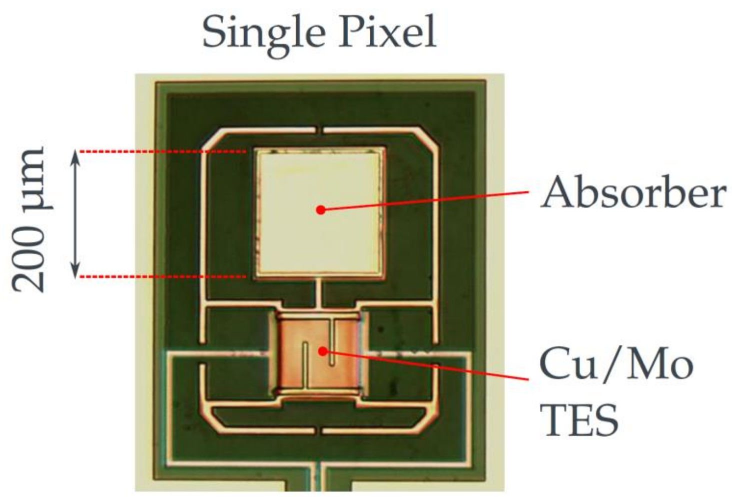
- Beam source: Argon sputter ion source
- Acceleration section → up to 50 kV
- Demonstrated current stability for ^{165}Ho beam using a sintered target

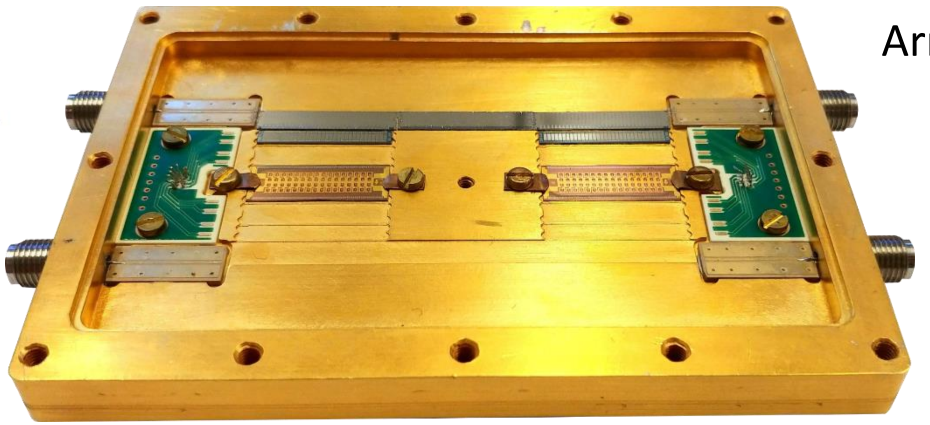
→ Coming soon: implantation of ^{163}Ho into detectors



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

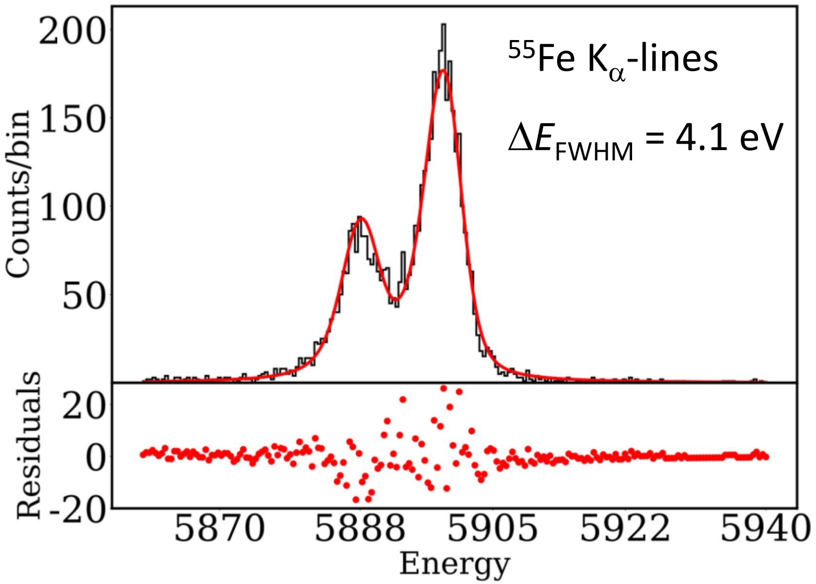
High energy resolution detectors - HOLMES

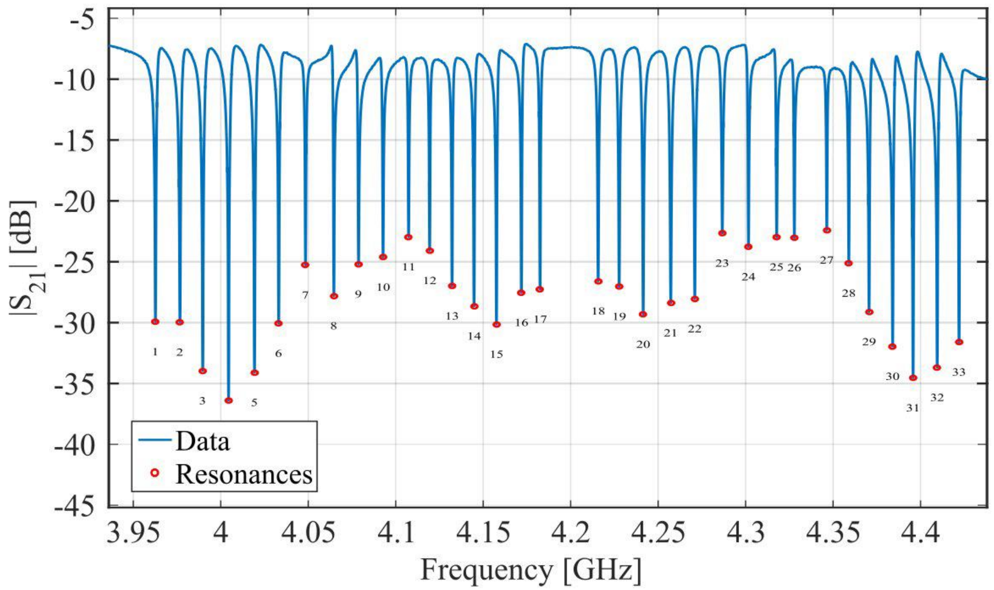




Arrays of transition edge sensors calorimeters

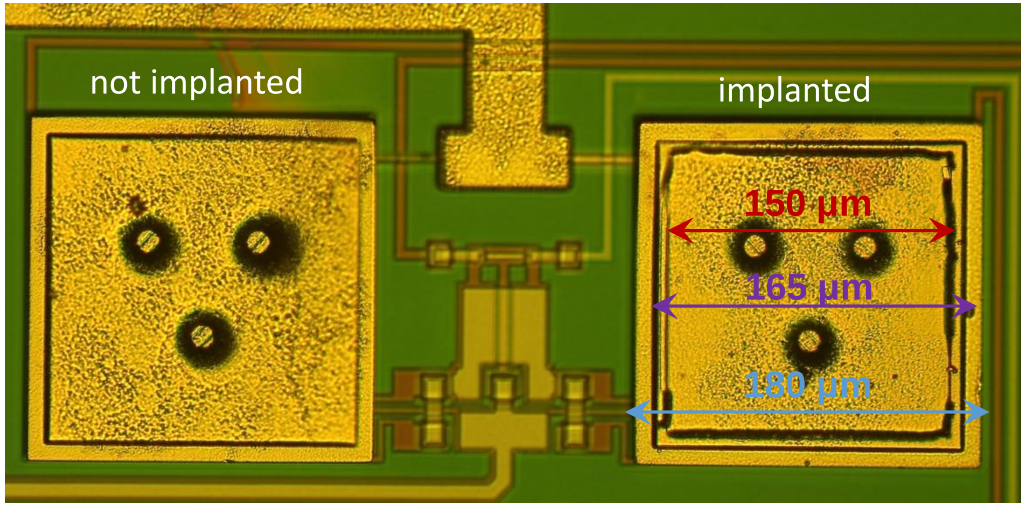
- reliable performance for pixels without ^{163}Ho
- demonstrated multiplexed readout





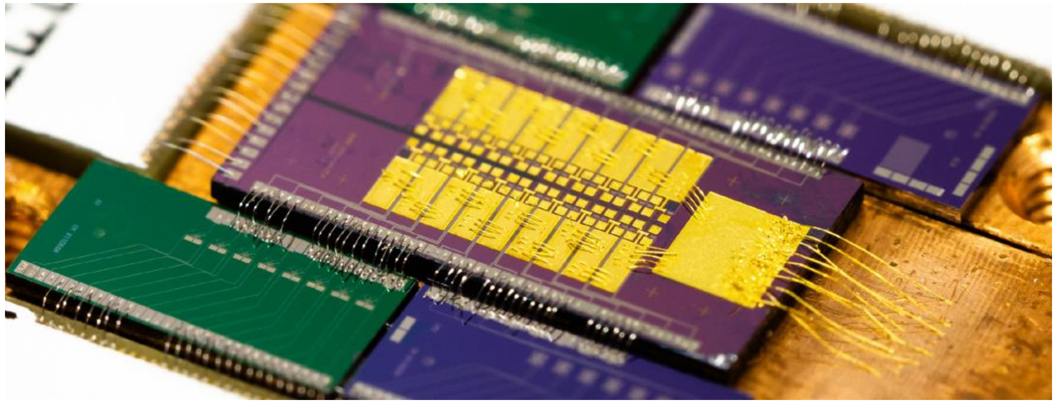
A. Giachero et al., IEEE Transactions on Applied Superconductivity 31 (2021) 2100205

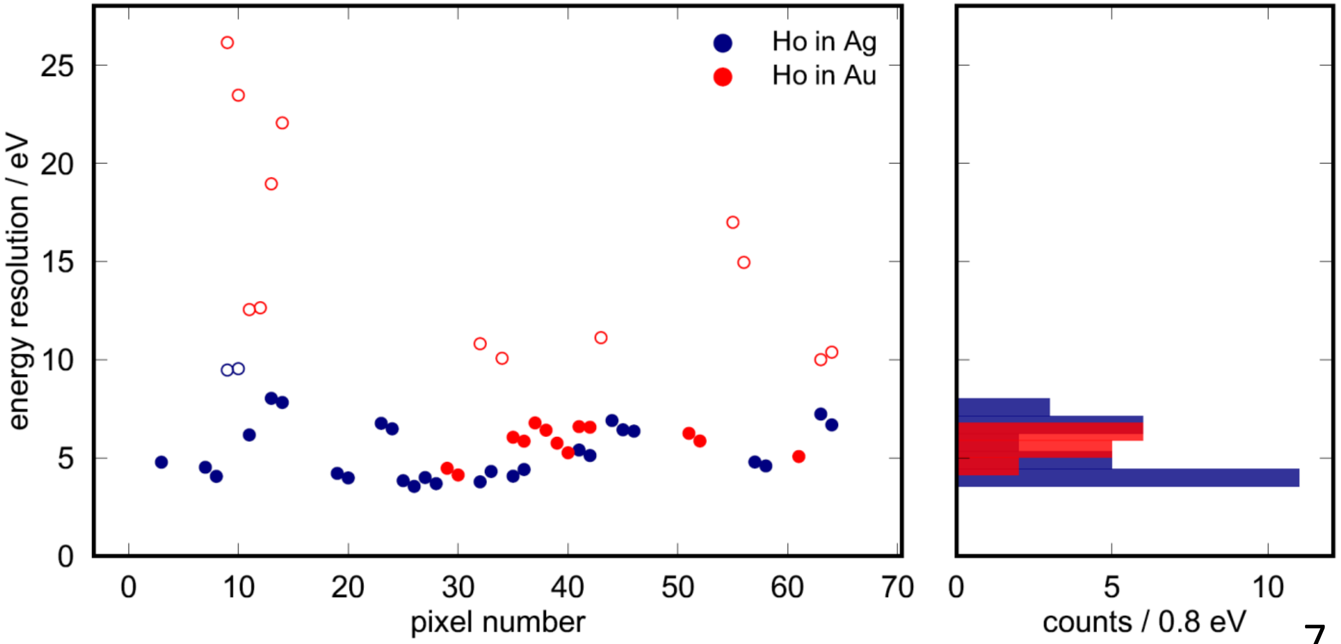
High energy resolution detectors - ECHo



Arrays of metallic magnetic calorimeters

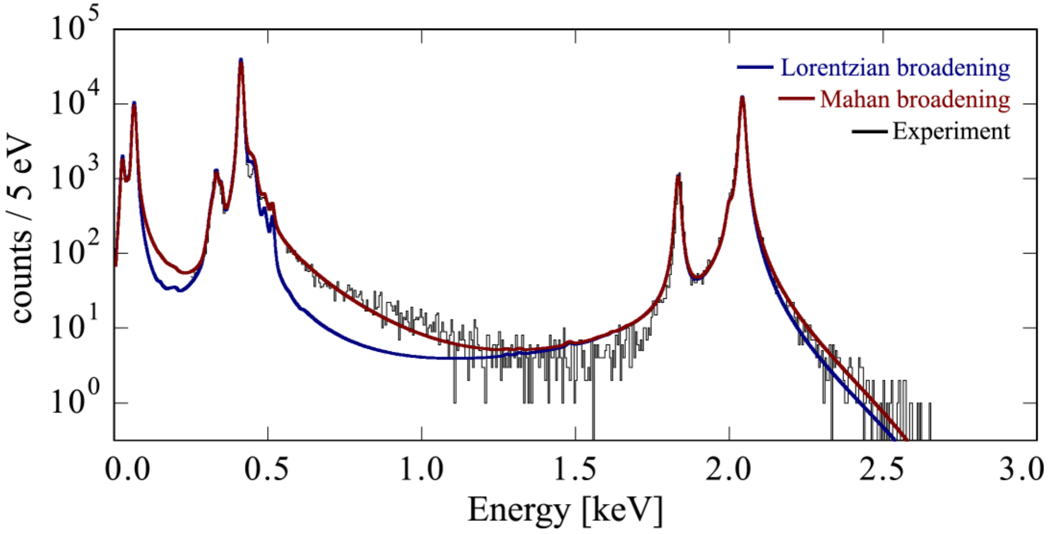
- reliable enclosing of ^{163}Ho in absorbes
- reliable performance for pixels with ^{163}Ho
- first experiments with parallel readout





F. Mantegazzini et al., *Nucl. Instrum. Meth. A* **1030** (2022) 166406

ECHo recent results



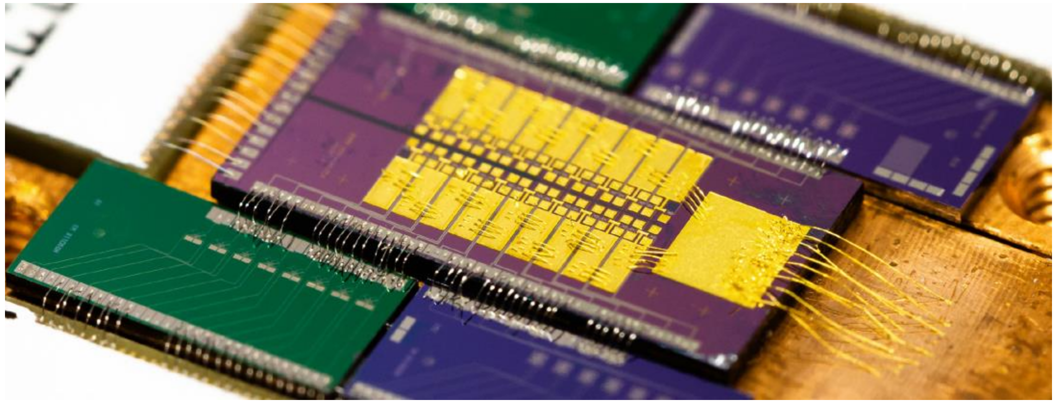
C. Velte et al., EPJC **79** (2019) 1026

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

Energy resolution ΔE_{FWHM} = 9.2 eV

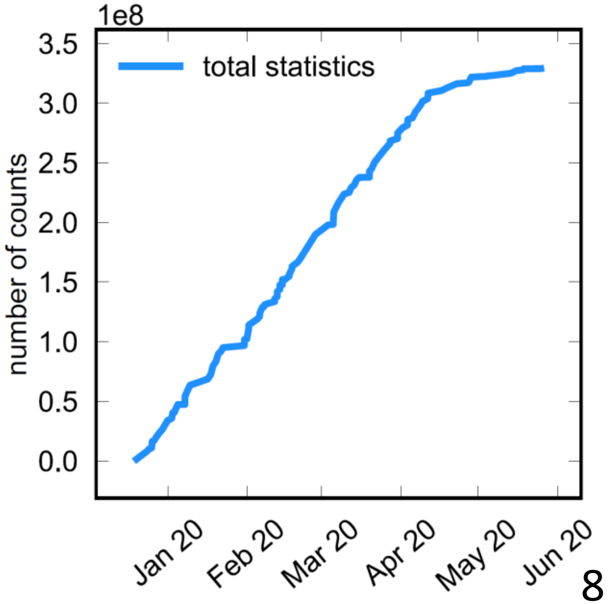
Background level $b < 1.6 \times 10^{-4}$ events/eV/pixel/day

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



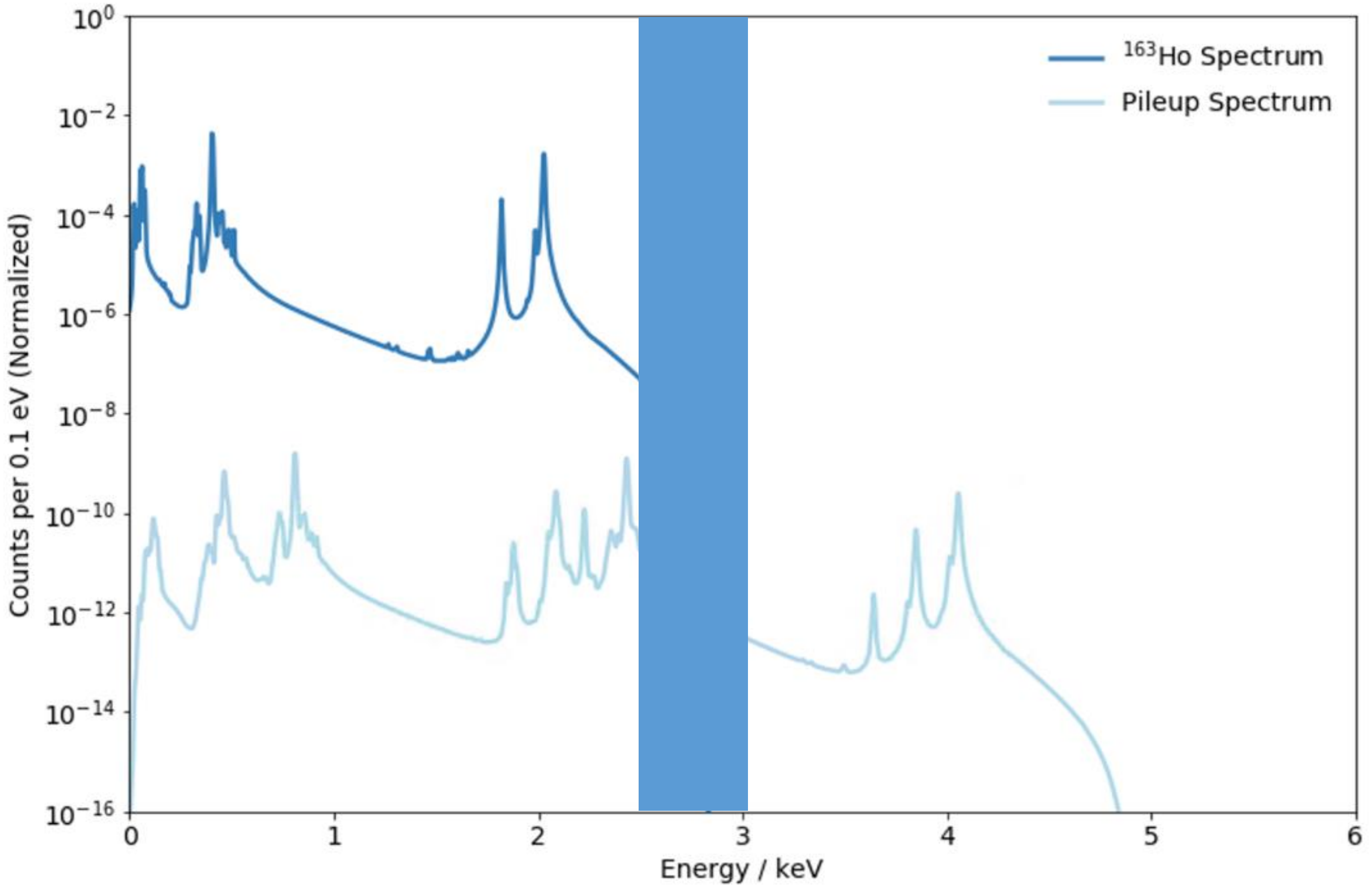
60 MMC pixels with about 1 Bq ^{163}Ho
parallel 2-stage SQUID readout
more that 10^8 ^{163}Ho events

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



F. Mantegazzini et al., *Nucl. Instrum. Meth. A* **1030** (2022) 166406

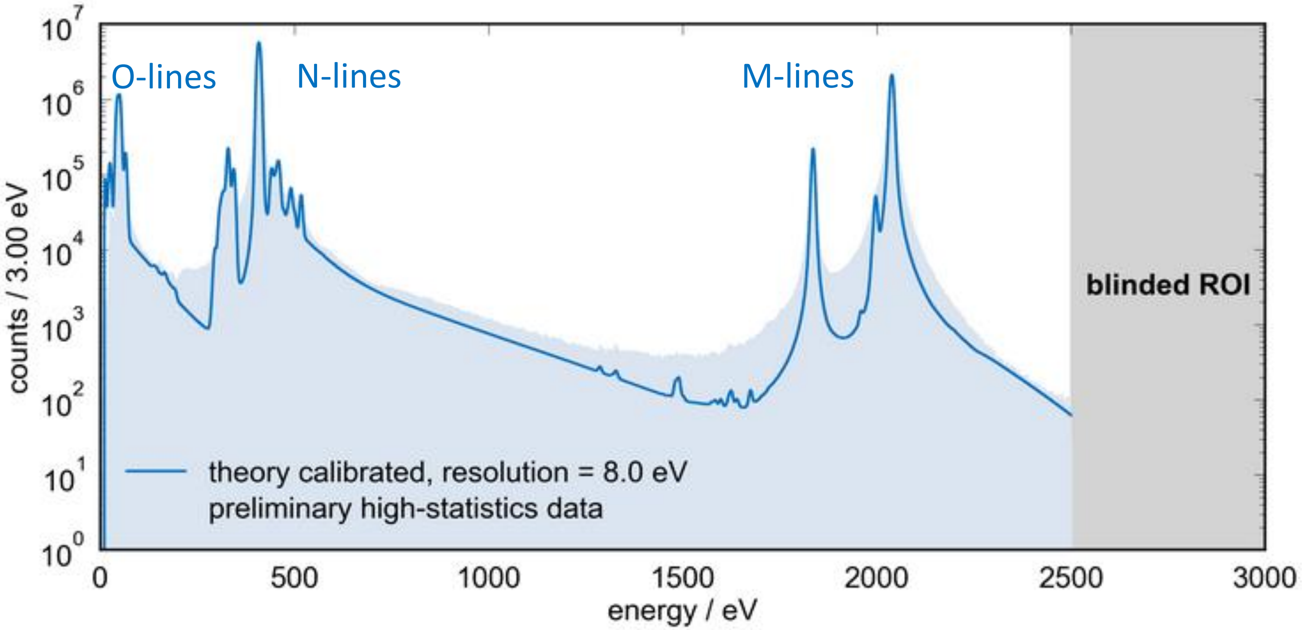
Analysis of the ^{163}Ho electron capture spectrum

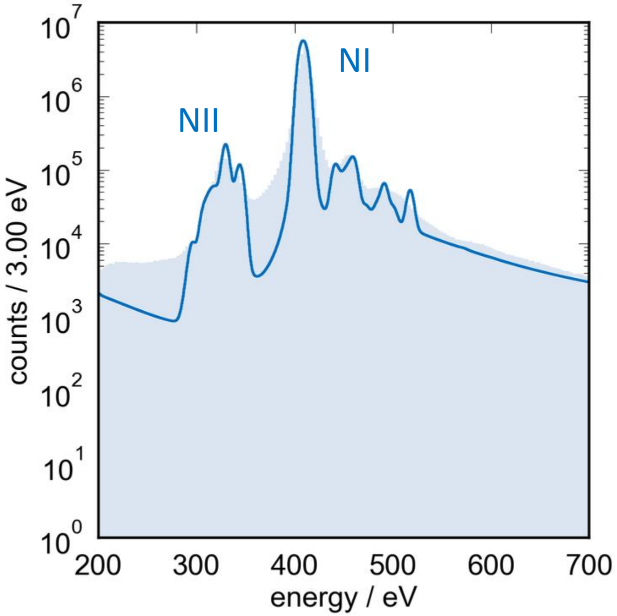


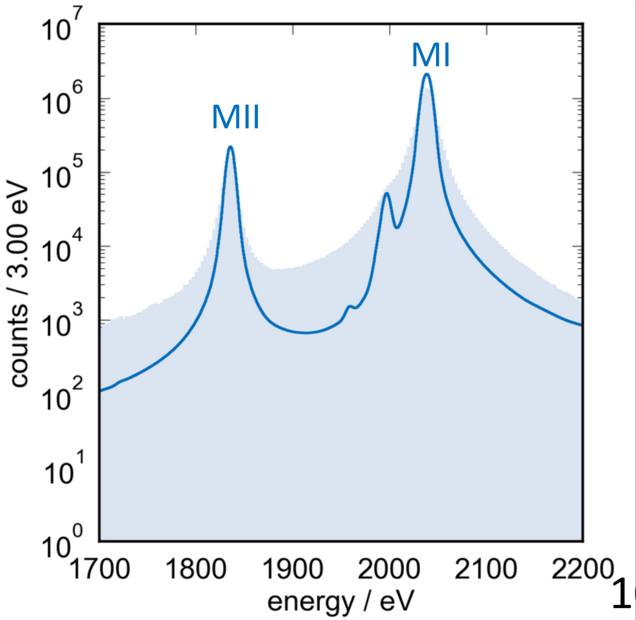
$E \leq 2.5$ keV
determination spectrum parameters
(intensity, peak energies, widths, Q-value)

$E \geq 3$ keV
determination unresolved pile-up spectrum
and natural background

E < 2.5 keV







Fraction of data corresponding to 6×10^7 events acquired with detectors having ^{163}Ho in Ag

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

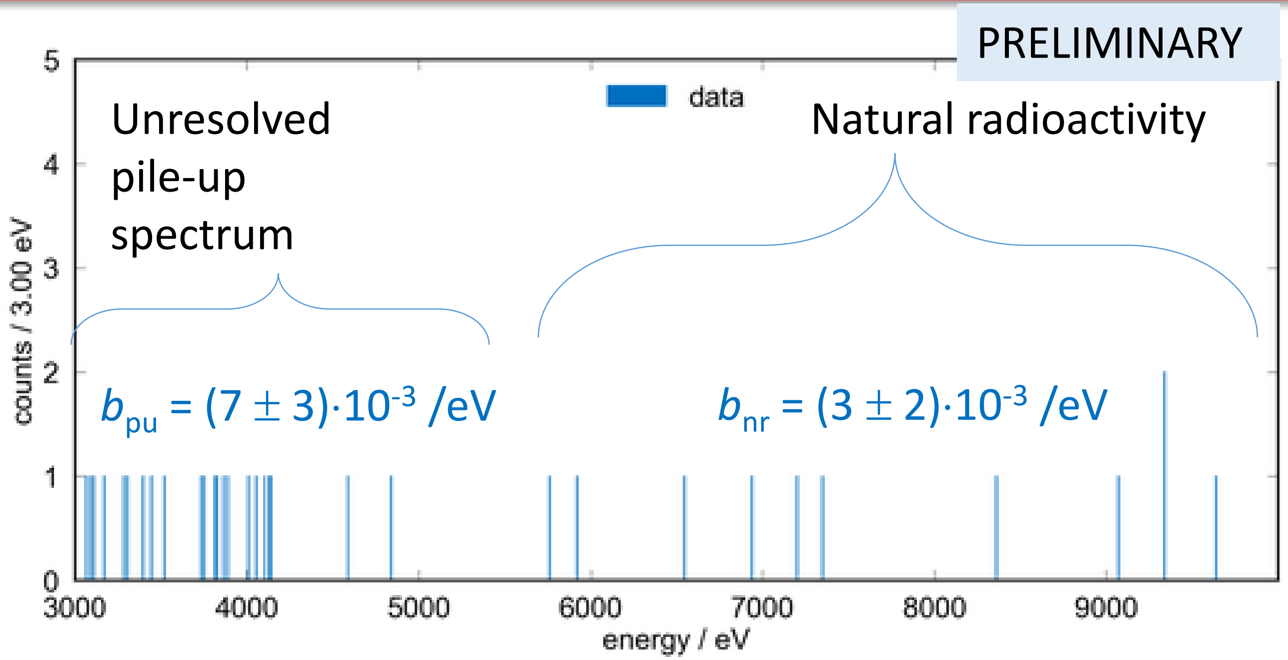
- bound-states, i.e. the spectrum is given by a finite number of resonances
- states with multiple correlated holes in local atomic orbitals interacting with unbound Auger-Meitner electrons

Missing

- Linewidth due to truncated sum
- Fluorescence

M. Braß et al., *Phys. Rev. C* **97** (2018) 054620, M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

E > 3 keV

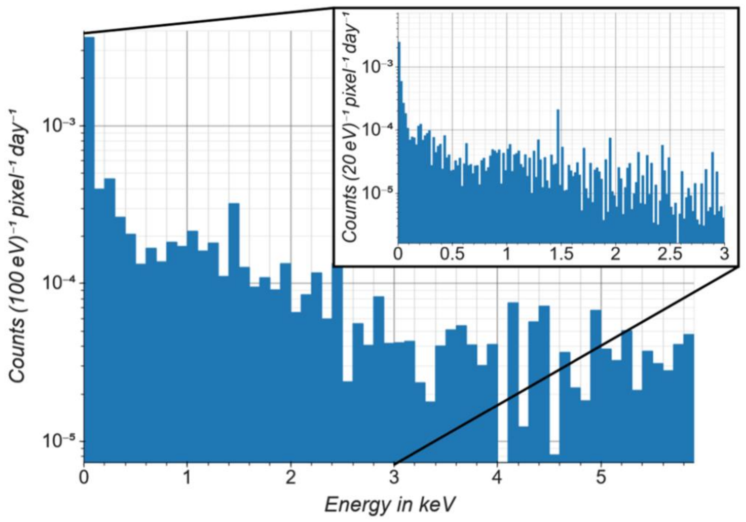


Two major contributions

- unresolved pile-up for $E < 5.7$ keV
- natural radioactivity + muon related events for $E > 5.7$ keV

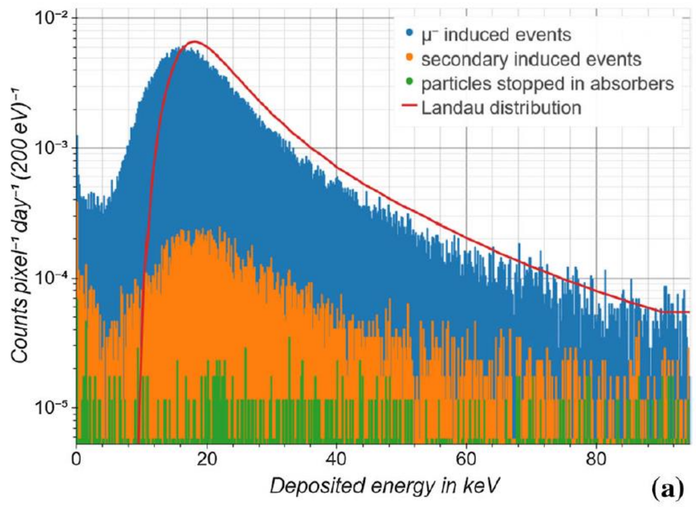
Comparison with simulation on-going

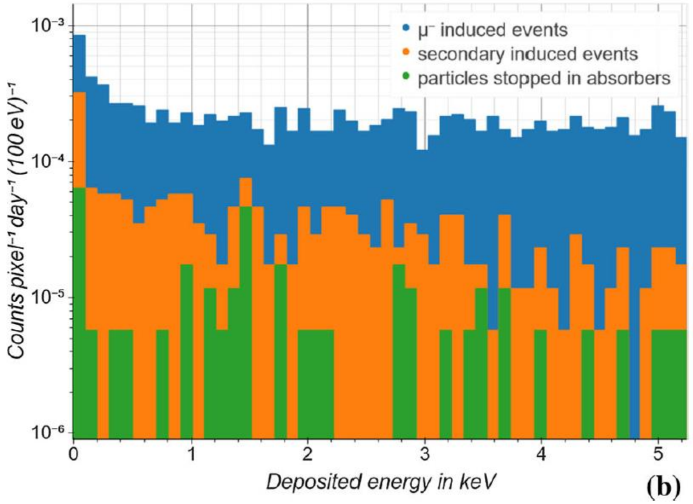
Natural radioactivity



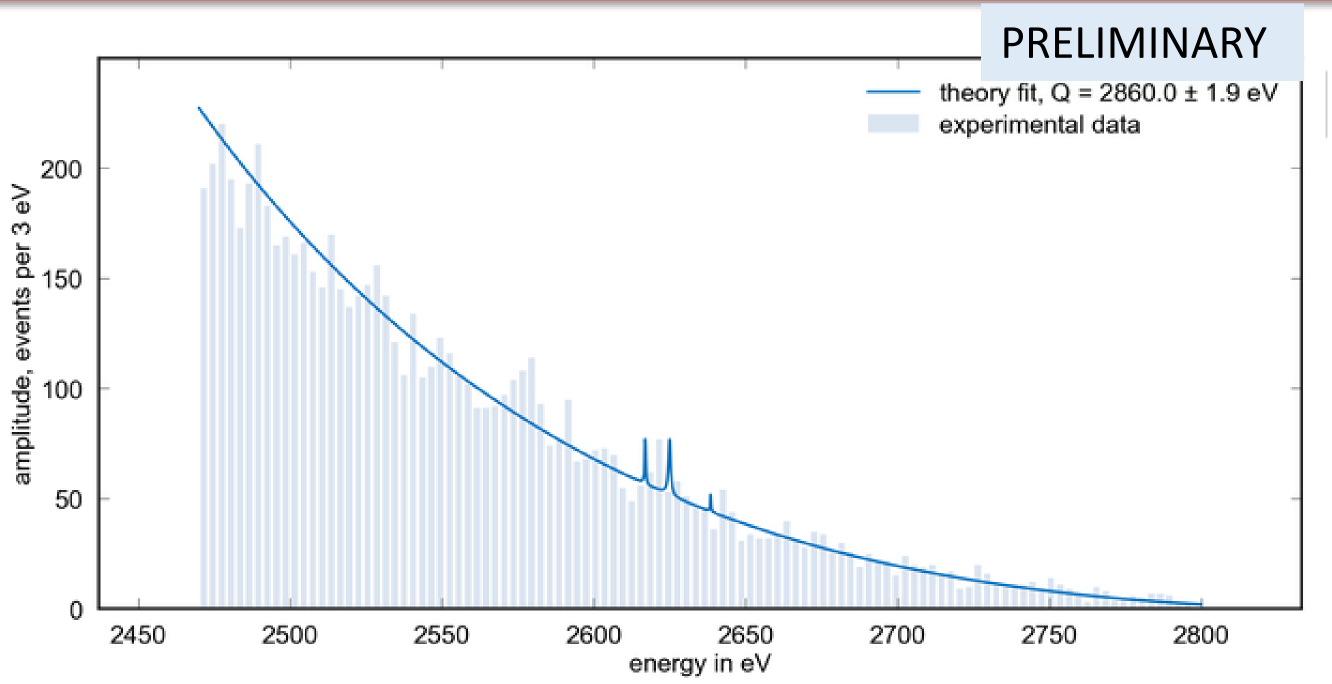
Muon related background

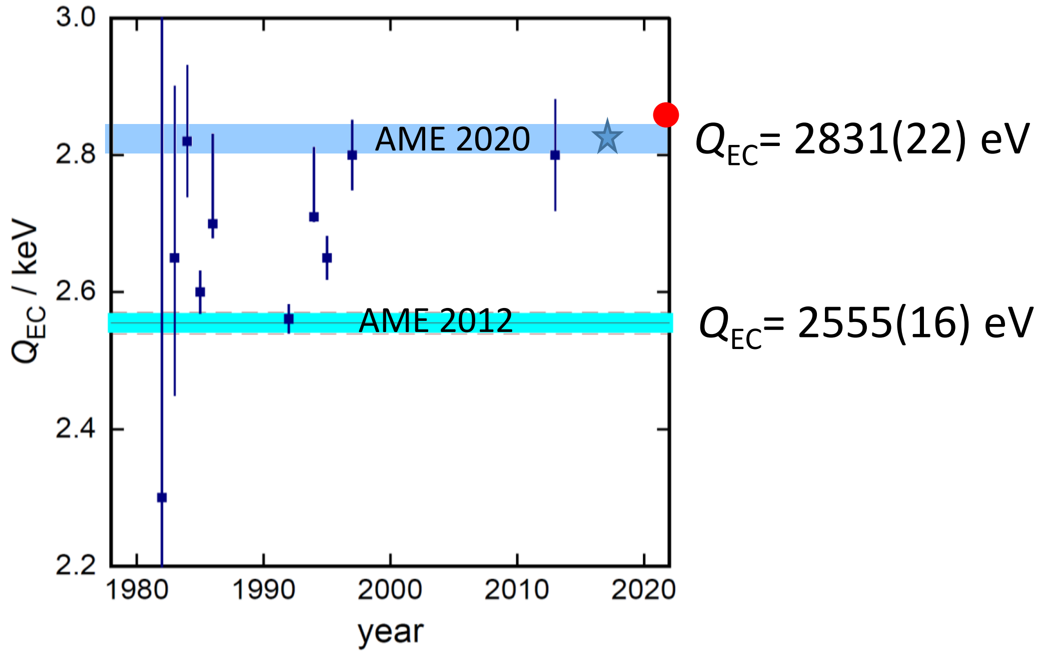
A. Goeggelmann et al., *Eur.Phys.J.C* **81** (2021) 363
A. Goeggelmann et al., *Eur.Phys.J.C* **82** (2022) 139





2.5 keV < E < 2.8 keV





Determination of Q_{EC} by fitting the spectrum using:

- Brass & Haverkort theory
- Flat background

$Q_{EC} = (2860 \pm 2_{stat} \pm 5_{syst})$ eV

Systematic uncertainties related to theoretical spectral shape
...still too large for analysis of smaller endpoint region

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

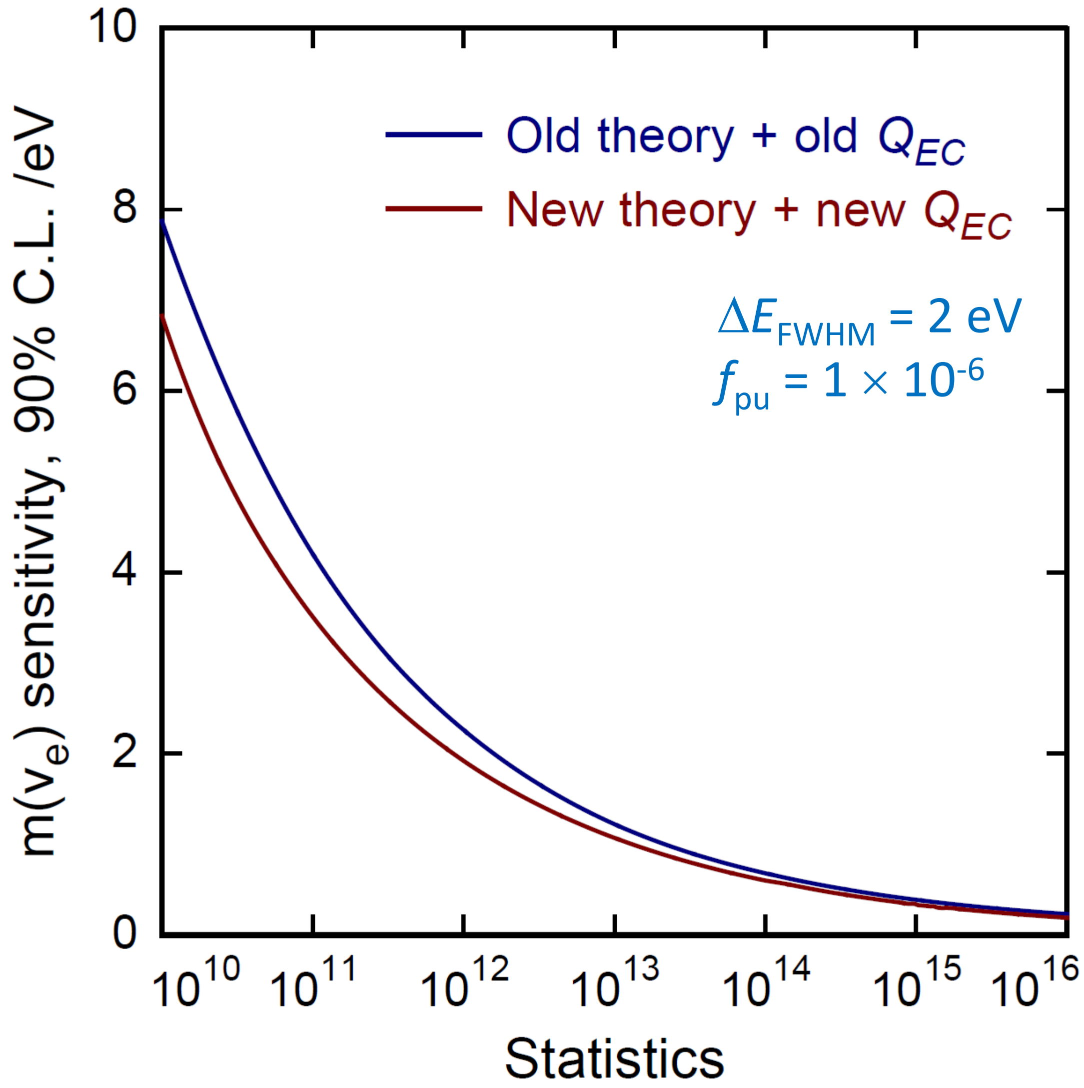
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Waiting for new PENTATRAP* results

(*) J. Repp et al., Appl. Phys. B **107** (2012) 983
C. Roux et al., Appl. Phys. B **107** (2012) 997

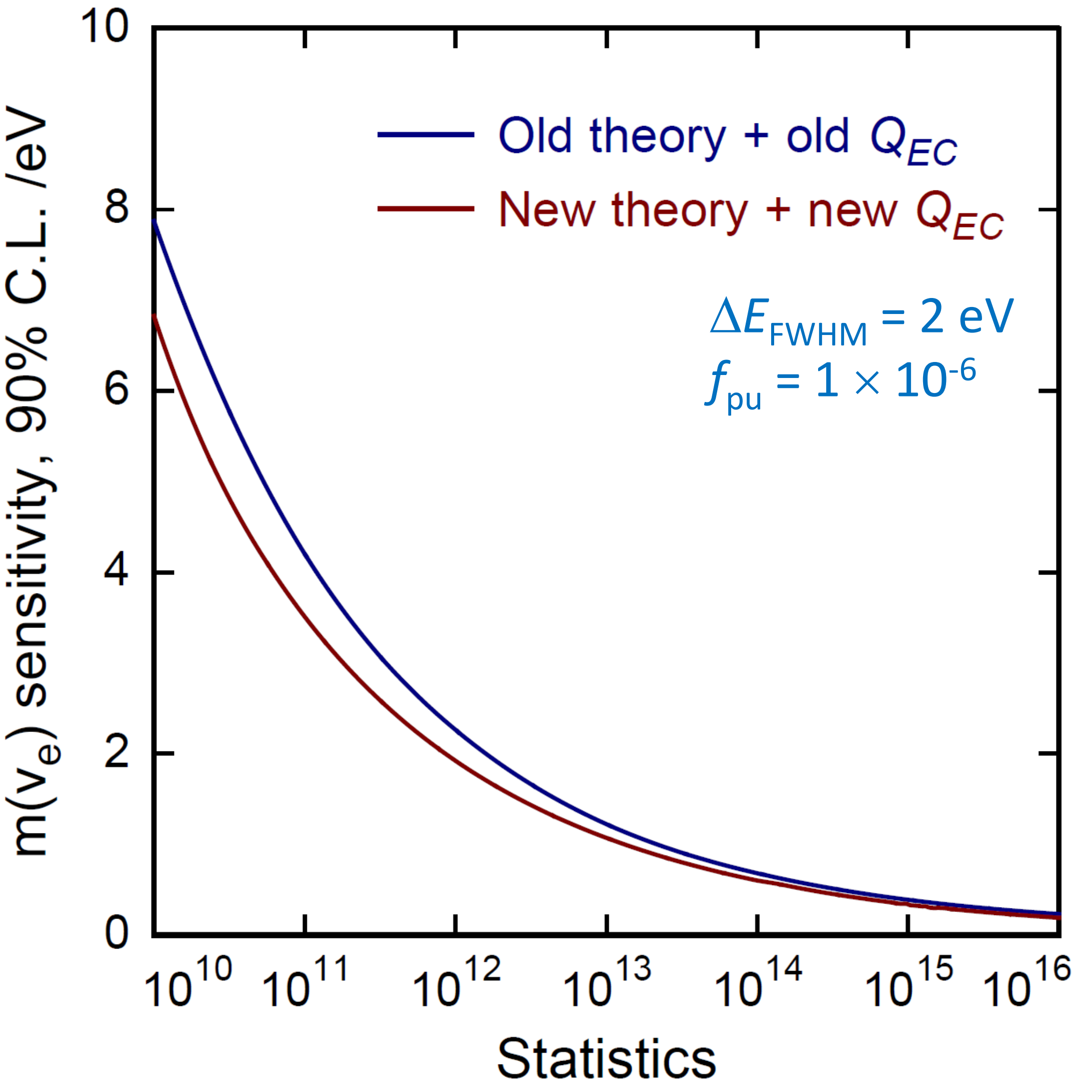
Updated sensitivity

Brass & Haverkort theoretical model + new Q_{EC}-value

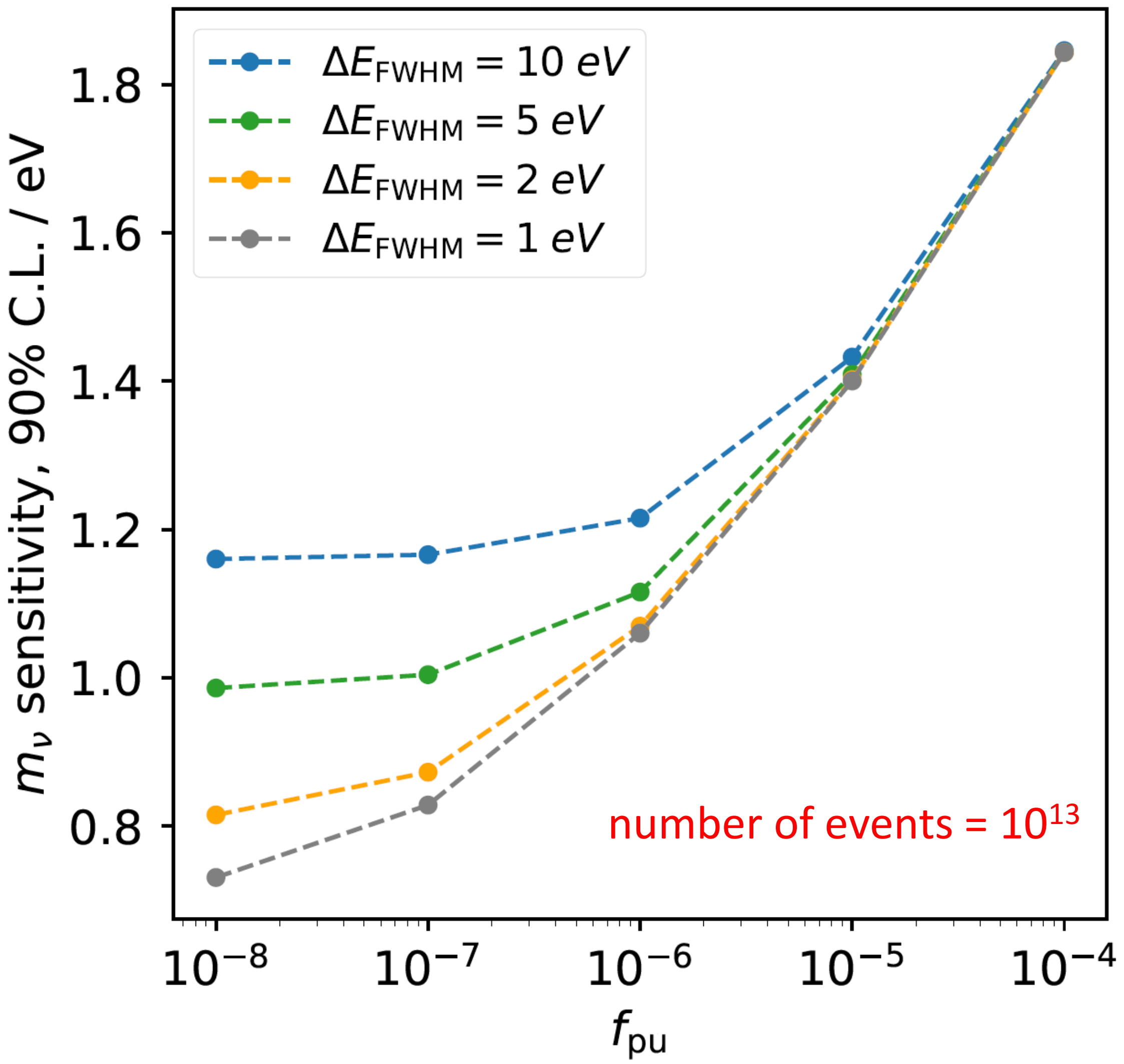


Updated sensitivity

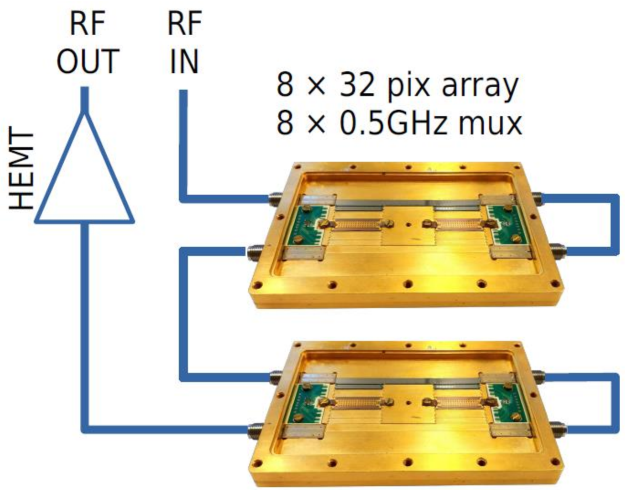
Brass & Haverkort theoretical model + new Q_{EC}-value



Sensitivity for the coming phases of ECHo and HOLMES



HOLMES – sub-2eV sensitivity



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

M. Borghesi et al., *Eur. Phys. J. C* (2021) 81:385
M. Borghesi et al., *Eur. Phys. J. C* (2022) 82:421

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 100 MBq

Ion implantation system:

- commissioning to be concluded in 2022

Transition Edge Sensor arrays

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

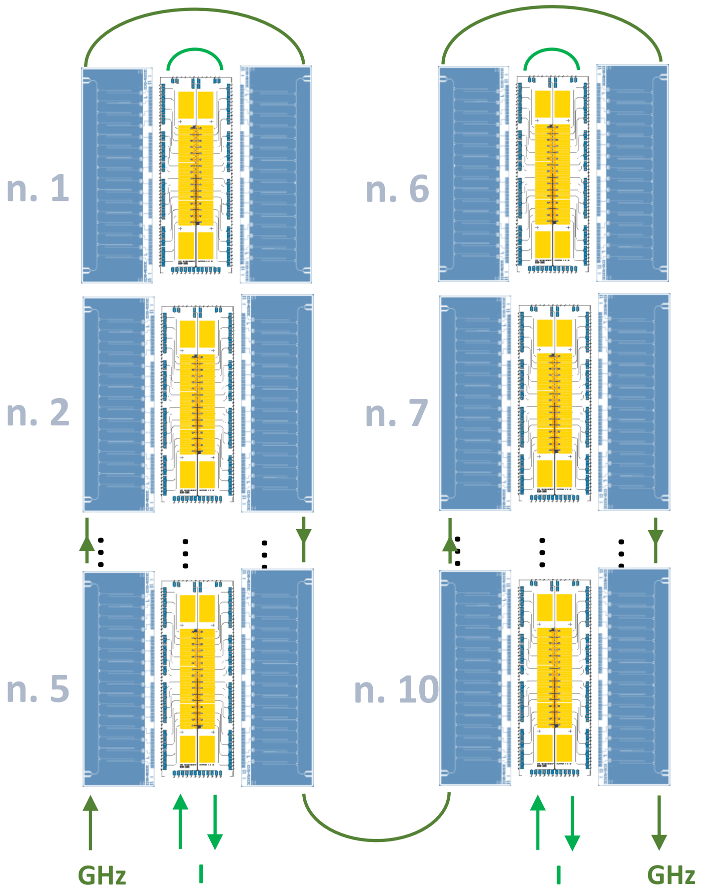
Multiplexing and data acquisition:

- completed and demonstrated for 32 channels

Data reduction

- optimized algorithms to reduce unresolved pile-up background

ECHo-100k – sub-2eV sensitivity



Deutsche Forschungsgemeinschaft

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

R. Hammann et al., *Eur. Phys. J. C* (2021) 81:963

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 30 MBq

Ion implantation system:

- demostrated and continuously optimized

Metallic magnetic calorimeters

- reliable fabrication of large MMC array
- succesfull characterization of arrays with ^{163}Ho

Multiplexing and data acquisition:

- demostrated for 8 channels
- still to show scaling of the system
- development of the SDR electronics

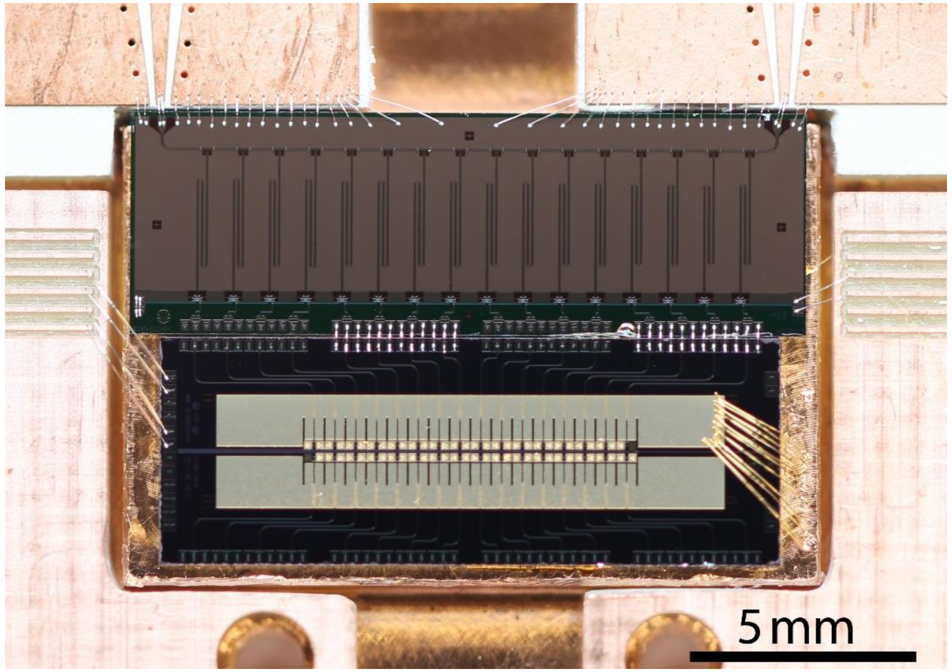
Data reduction

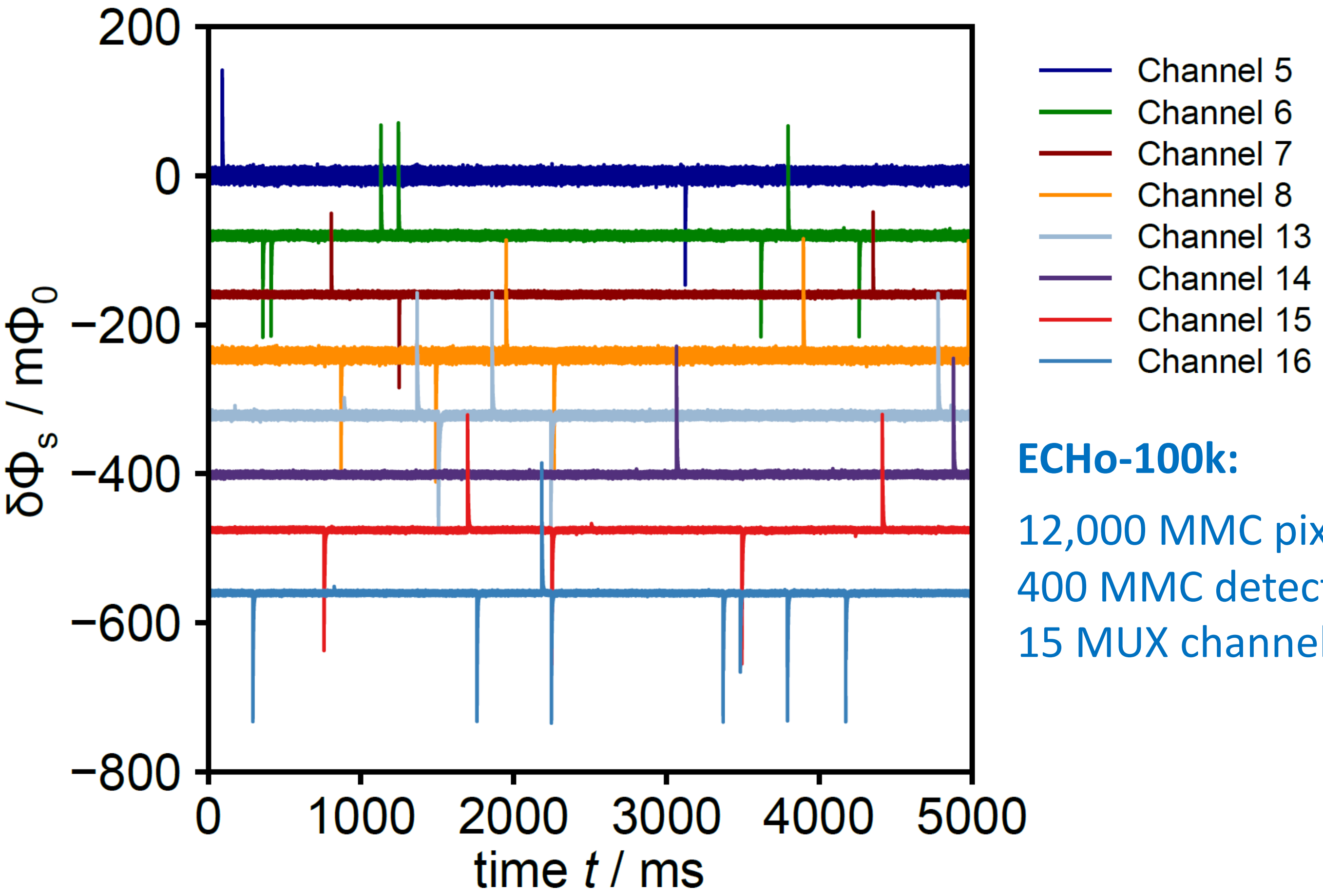
- optimized energy independent algorithm to identify spurious traces

ECHo-100k - multiplexing

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

- Successful characterization of first prototypes with external ^{55}Fe
  → Very promising results:
  8 channels (16 pixels)





ECHo-100k:

12,000 MMC pixels =
400 MMC detectors ×
15 MUX channels

Soon tests with ^{163}Ho loaded MMC arrays

S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860
M. Wegner et al., J. Low Temp. Phys. **193**, 462 (2018)

Conclusions and outlook

- The determination of the $m(\nu_e)$ with ^{163}Ho is complementary to the determination of $m(\bar{\nu}_e)$ with ^{3}H
- ECHo and HOLMES are moving forwards to reach eV sensitivity on $m(\nu_e)$
  - ^{163}Ho source available in suitable amount and purity
  - Reliable operation of detector enclosing ^{163}Ho in ECHo
  - Multiplexed readout demonstrated for „small arrays“ → on going R&D for 10^3 – 10^4 pixels
- Theoretical description of ^{163}Ho spectrum still to be improved + validation of new Q_{EC}

Snowmass Process
many groups are interested in contributing to a large ^{163}Ho-based experiment

arXiv > nucl-ex > arXiv:2203.07572

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Nuclear Experiment

[Submitted on 15 Mar 2022]

Measuring the electron neutrino mass using the electron capture decay of 163Ho

Joel Ullom, Daniel Schmidt, Simon Bandler, Thomas Stevenson, Mark Croce, Katrina Koehler, Matteo De Gerone, Loredana Gastaldo, Christian Enss, Geonbo Kim, Angelo Nucciotti, Stefano Ragazzi, Kyle Leach, Diana Parno, Brian Mong, Josef Frisch, Christopher Kenney

While the mass differences between neutrino mass states are known, their absolute masses and mass hierarchy have not yet been determined. Determining the mass of neutrinos provides access to physics beyond the Standard Model and the resulting value has implications for the growth of large-scale structure in the universe over cosmic history. Because of the importance of the topic, a number of efforts are already underway to determine the mass of neutrinos including direct kinematic measurements and indirect measurements of astrophysical phenomena that constrain the sum of the mass eigenstates through models of cosmic evolution. Here, we advocate for a collaborative international effort to perform a kinematic determination of the effective electron neutrino mass using calorimetric measurements of the decay of 163Ho. This effort is justified by the success of current experiments using the technique, its high benefit-to-cost ratio, the value of approaches with different systematic errors, and the value of measuring the electron neutrino mass rather than the electron anti-neutrino mass.

Comments: contribution to Snowmass 2021
Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Phenomenology (hep-ph); Instrumentation and Detectors (physics.ins-det)
Cite as: arXiv:2203.07572 **[nucl-ex]**
(or arXiv:2203.07572v1 **[nucl-ex]** for this version)
https://doi.org/10.48550/arXiv.2203.07572

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Special thanks to the members of the ECHo and HOLMES collaborations

Thank you for the attention!