Holmium prospects for going beyond 0.2 eV

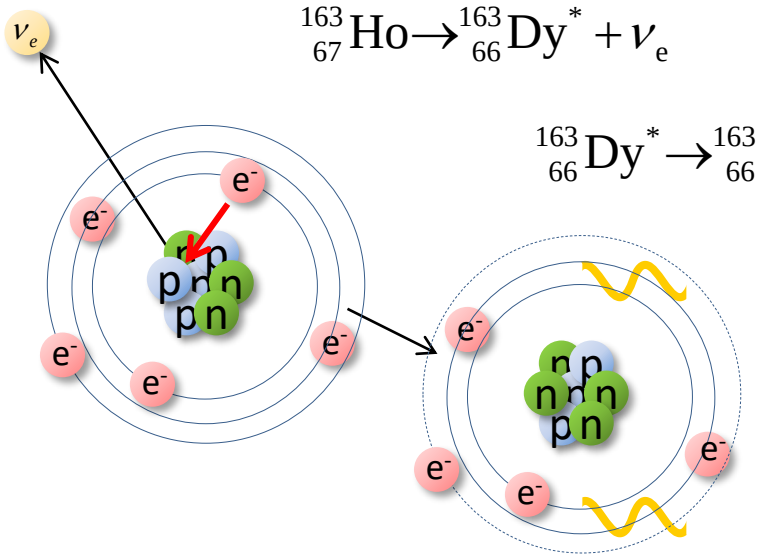
Loredana Gastaldo

Kirchhoff Institute for Physics
Heidelberg University

Outline

- Electron capture in ^{163}Ho and neutrino mass
  - Energy spectrum
  - Sensitivity to a finite neutrino mass
- Experimental challenges (for ECHo and HOLMES)
  - ^{163}Ho Source
  - Detectors
  - readout
- Status of the ^{163}Ho spectra measurements
- 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

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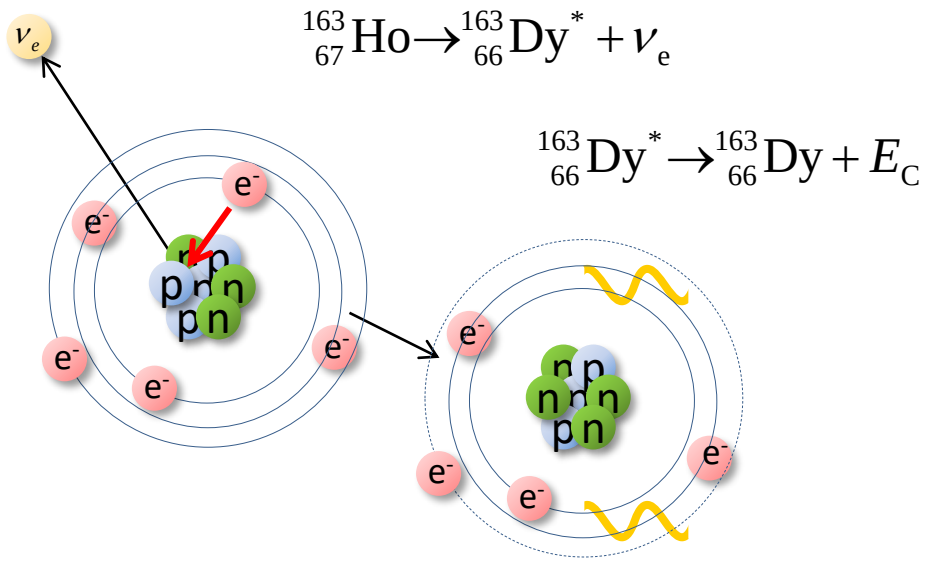

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$$Q_{\mathrm{EC}} = m(^{163}\mathrm{Ho}) - m(^{163}\mathrm{Dy})$$

Penning Trap Mass Spectroscopy

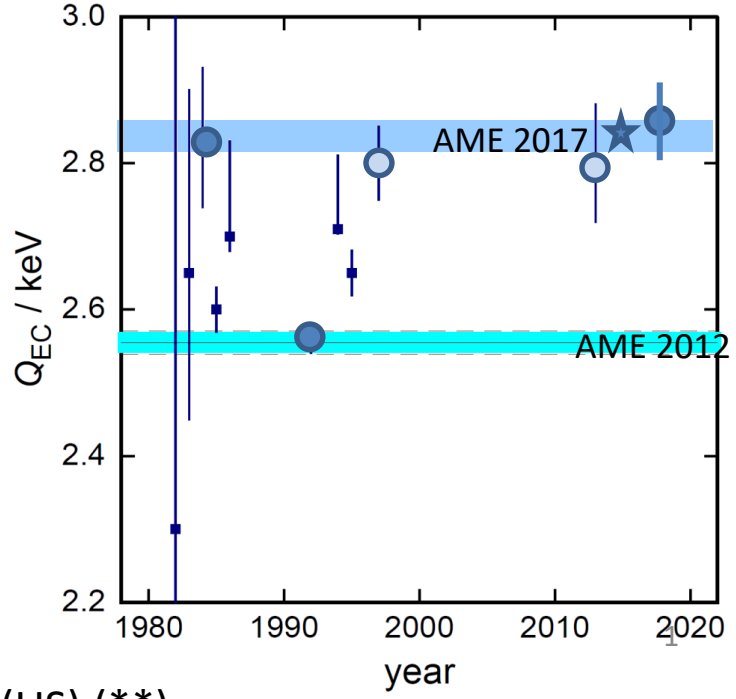
@TRIGA TRAP (Uni-Mainz) (♦)

@SHIPTRAP (GSI – Darmstadt) (♦♦)

Future goal: 1 eV precision:

PENTATRAP @MPIK, Heidelberg (*)

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



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(♦) 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

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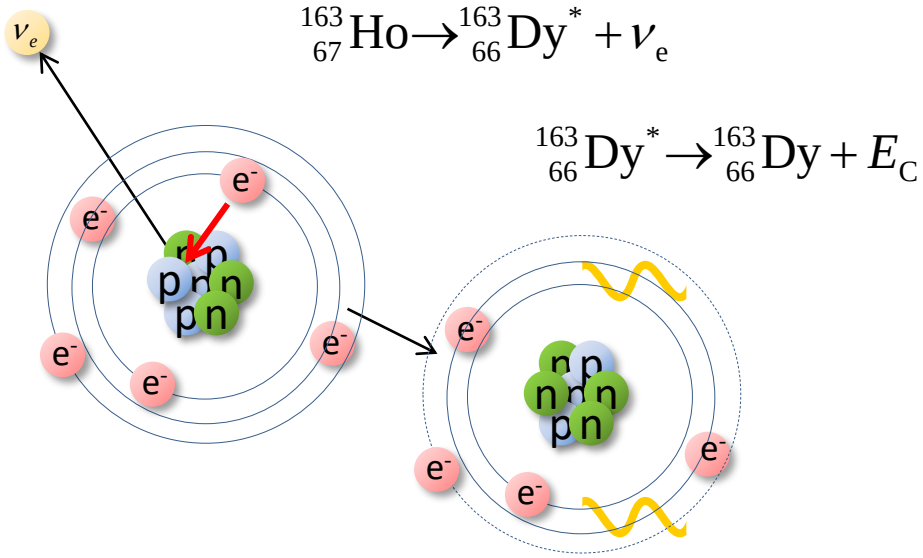

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- X-ray emission
- Auger electrons
- Coster-Kronig transitions

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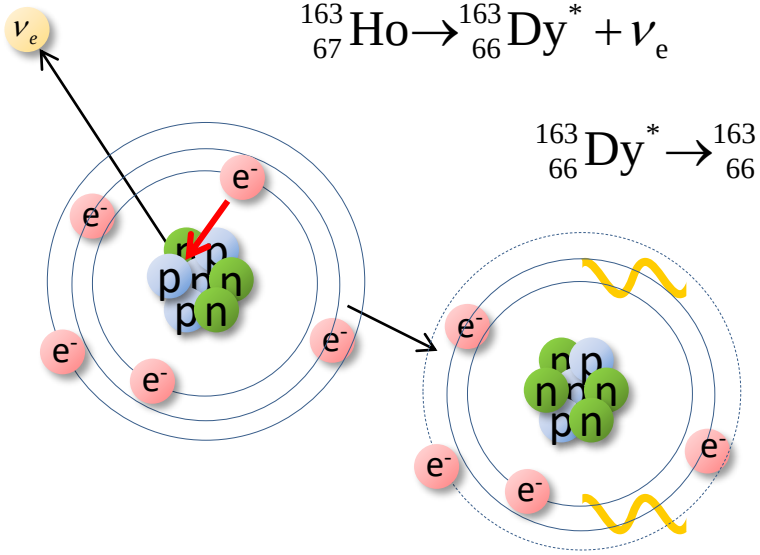

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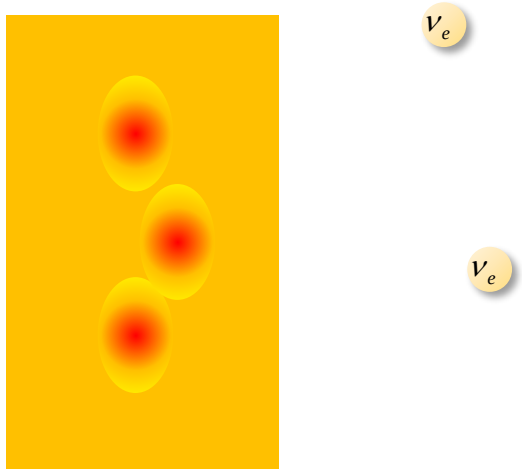

Calorimetric measurement

Source = Detector

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

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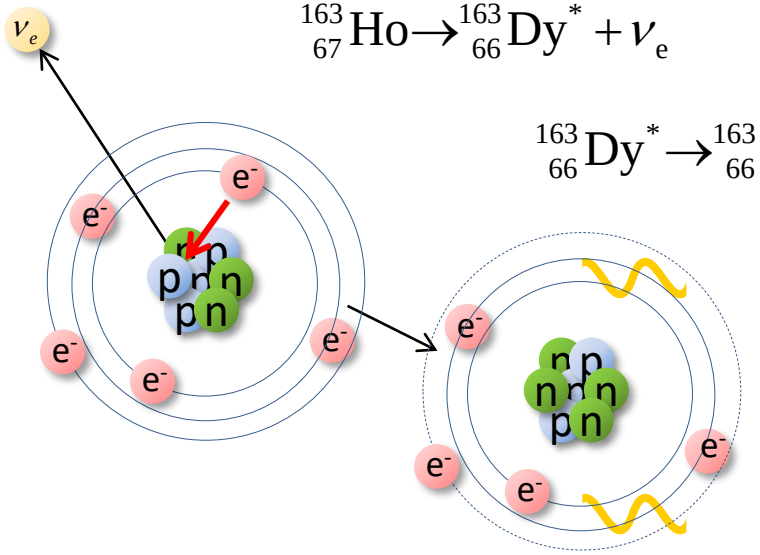

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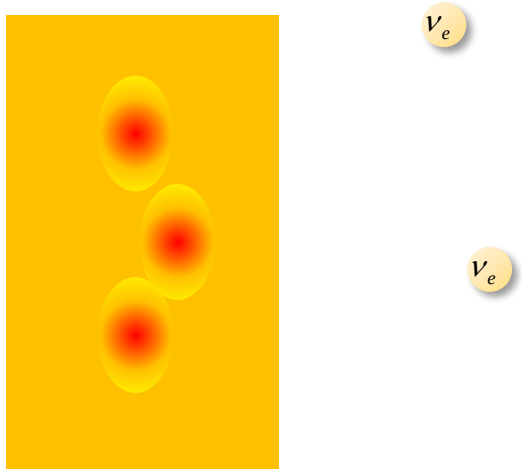

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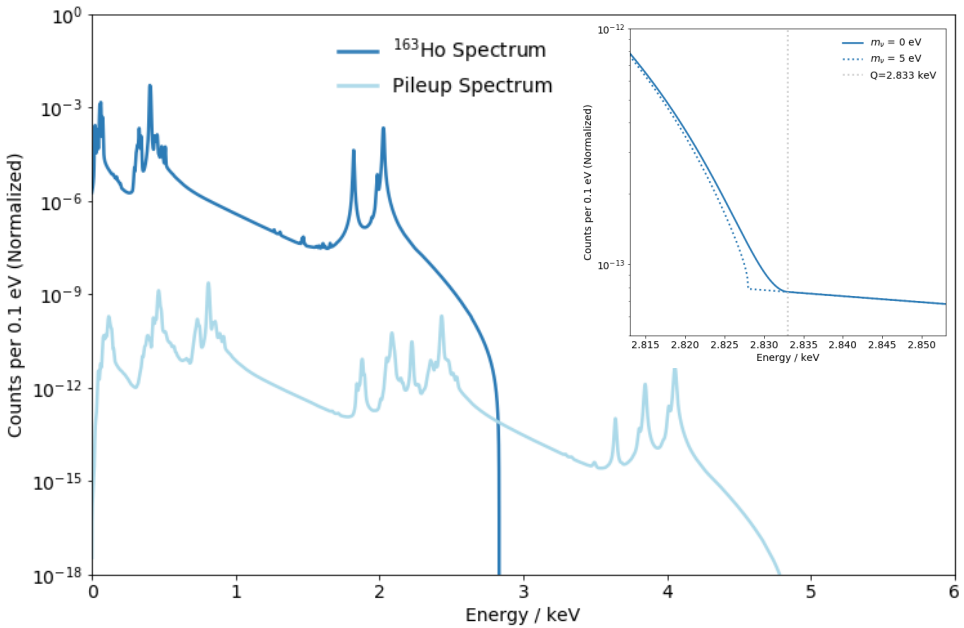

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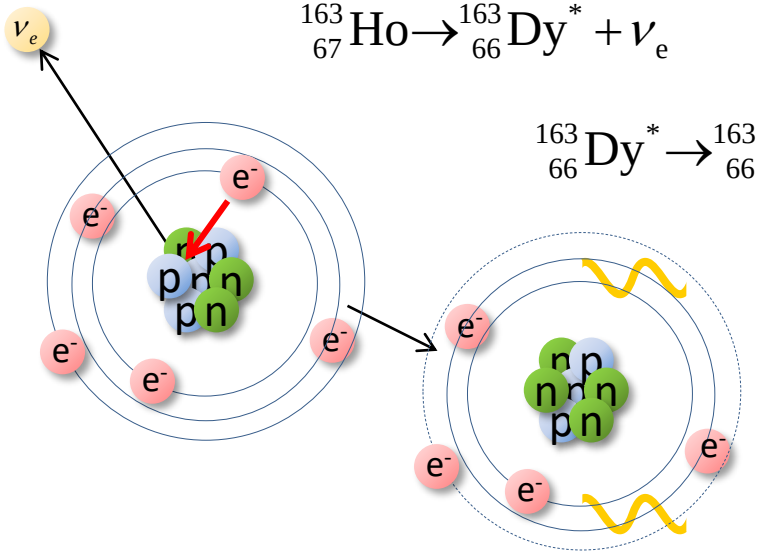

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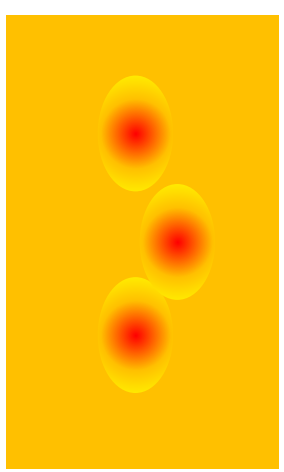

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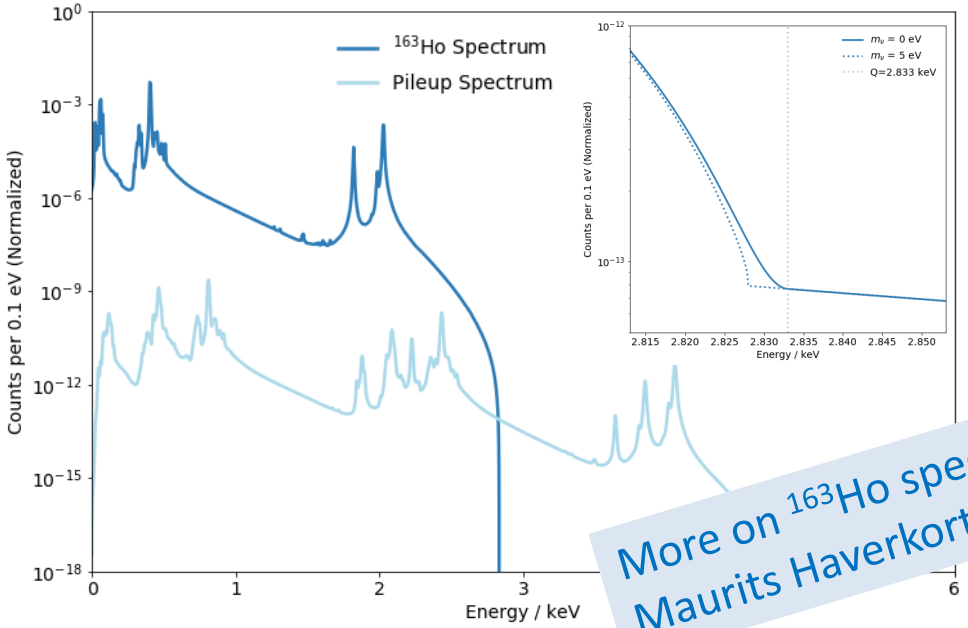

More on ^{163}Ho spectrum in Maurits Haverkort's talk

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Parameters for ν mass sub-eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

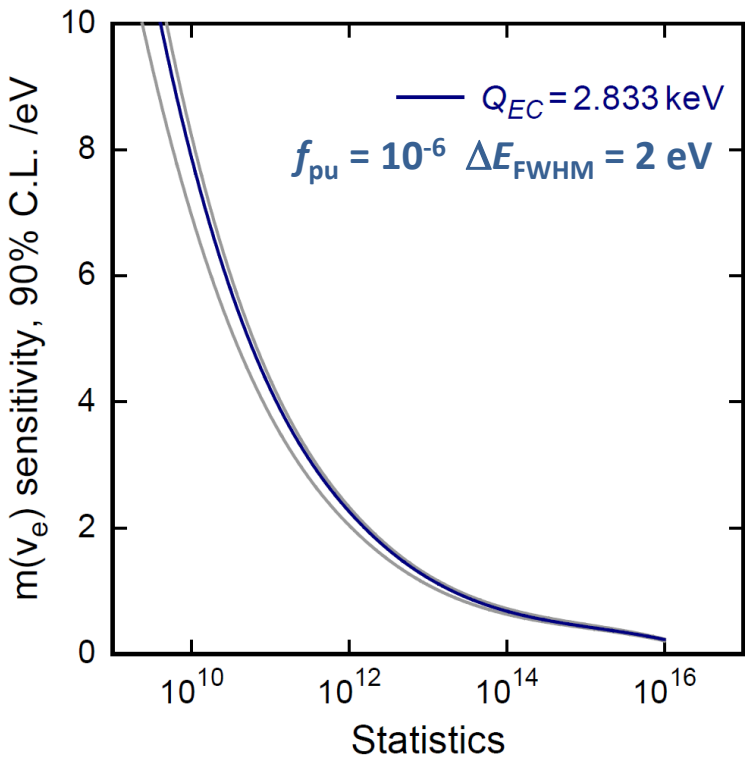
- f_{pu} **< 10^{-5}**
- τ_r < 1 µs → a ~ 10 Bq
- 10^5 pixels

Precision characterization of the endpoint region

- **ΔE_{FWHM} < 3 eV**

Background level

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



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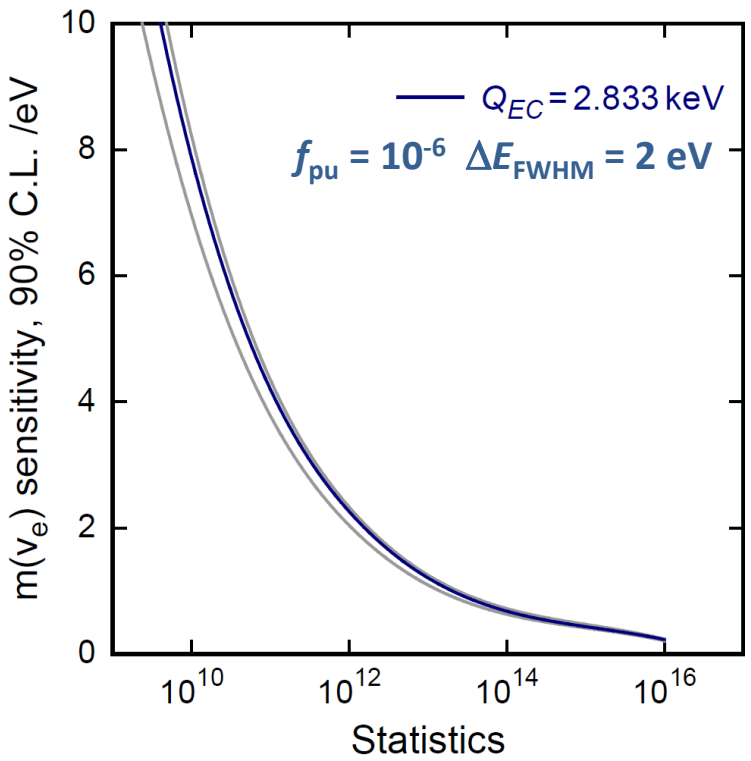


ECHo

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

NuMECS

US collaboration
First R&D funds, now stopped

M. Croce et al., JLTP 184 (2016) 938
K.E. Köhler et al., JLTP 193 (2018) 1151

Experimental challenges 1: ^{163}Ho source

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

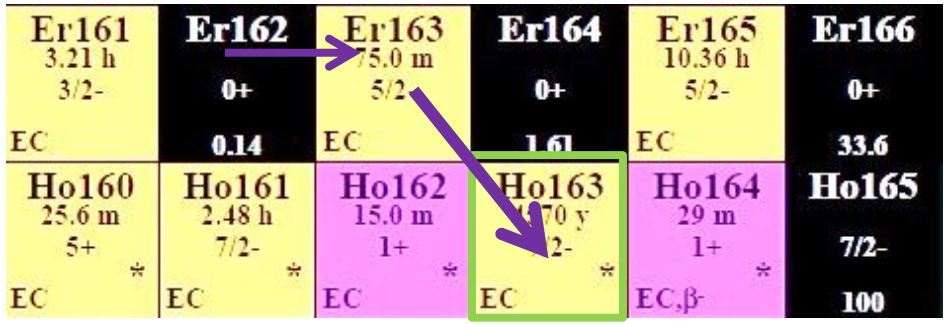
Different methods to produce high purity and high intensity ^{163}Ho sources have been studied in details

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

  High cross-section

  Radioactive contaminants

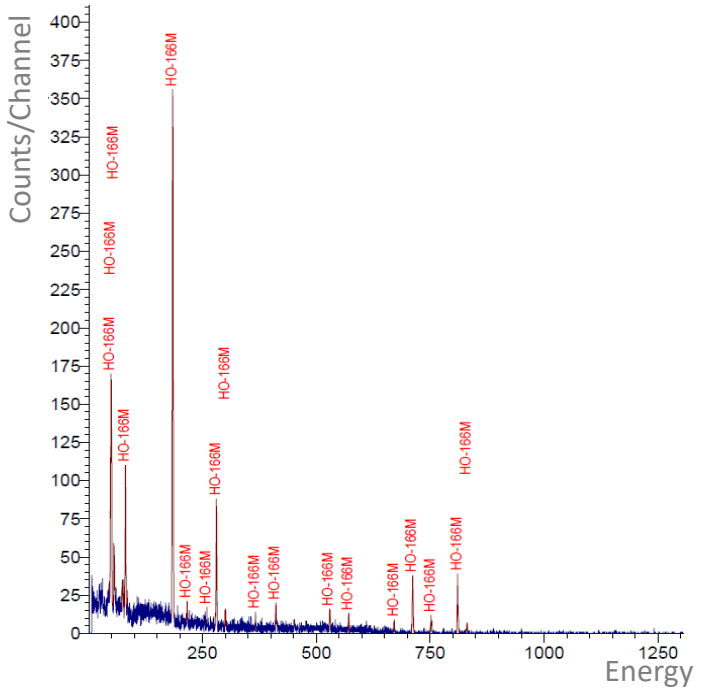


→ Excellent chemical separation

95% efficiency

ECHo at Mainz University

HOLMES at PSI Zurich



^{163}Ho available for each experiment

ECHo $\sim 2 \times 10^{18}$ atoms (10 MBq)

HOLMES $\sim 2 \times 10^{19}$ atoms (110 MBq)

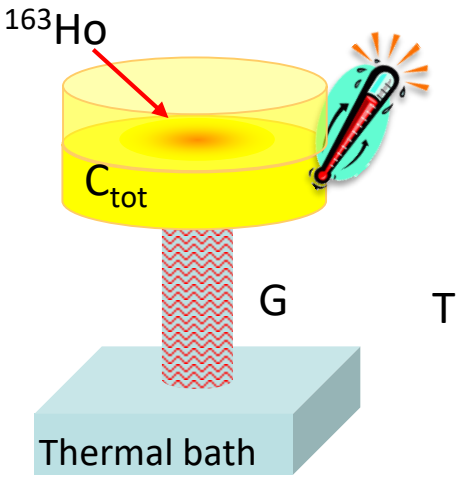
S. Heinitz et al., PLoS ONE 13(8): e0200910

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

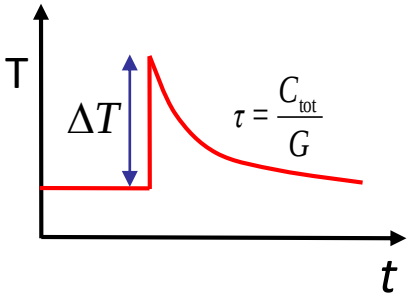
J.W. Engle et al., Nucl. Instrum. Meth. B 311 (2013) 131

Experimental challenges 2: high resolution detectors

Low temperature microcalorimeters for the calorimetric 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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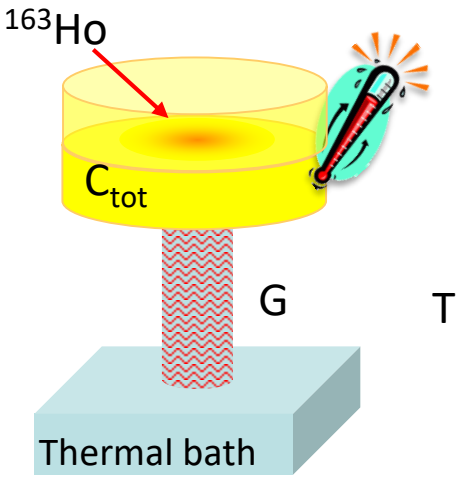

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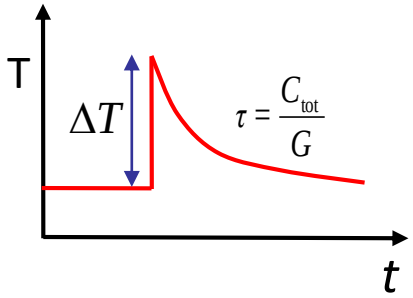

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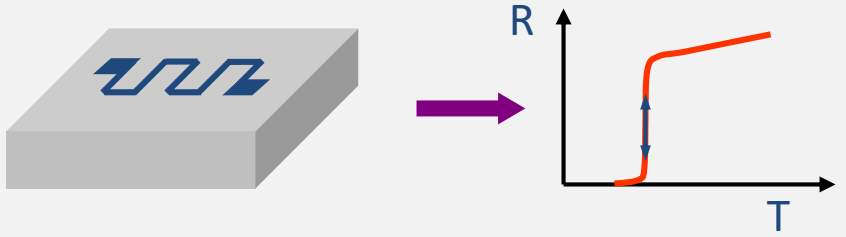
Resistance at superconducting transition,TES



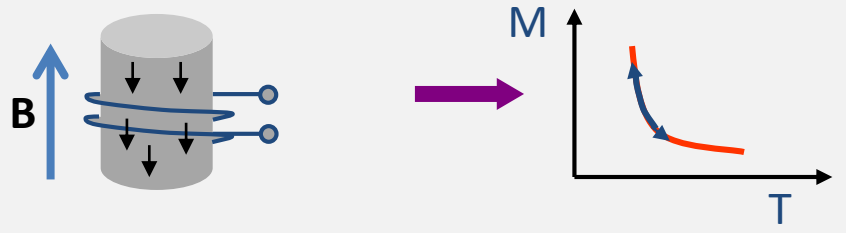
K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63

HOLMES

NuMECS

Detector arrays produced at NIST (Boulder US)

Magnetization of paramagnetic material, MMC



A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

T.R. Stevenson et al., J. of Astronomical Telescopes, Instruments, and Systems, 5(2) (2019) 021009 – Group at NASA Goddard also leader in MMC development

ECHo

Detector arrays produced at KIP, Heidelberg University

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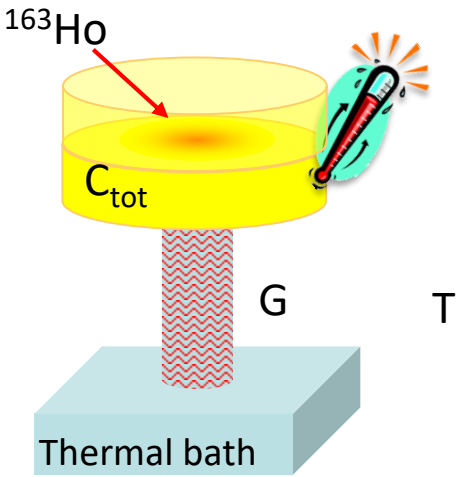

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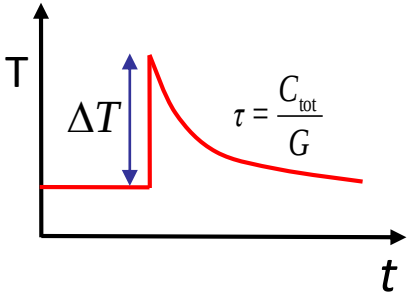

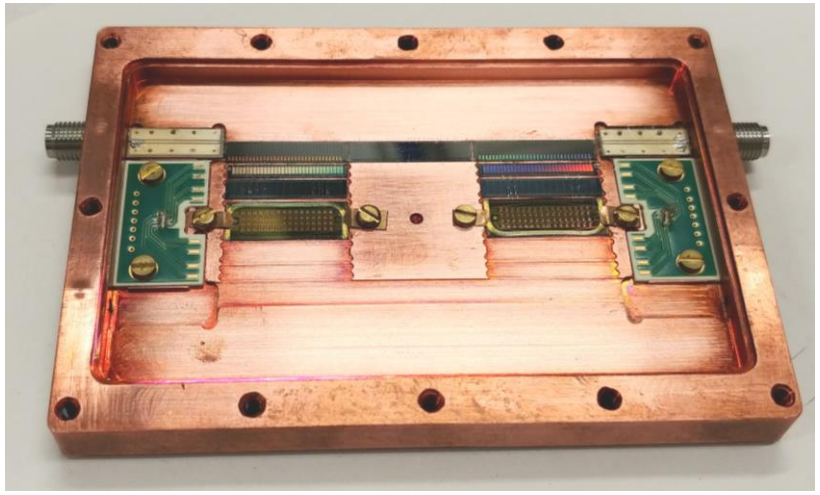

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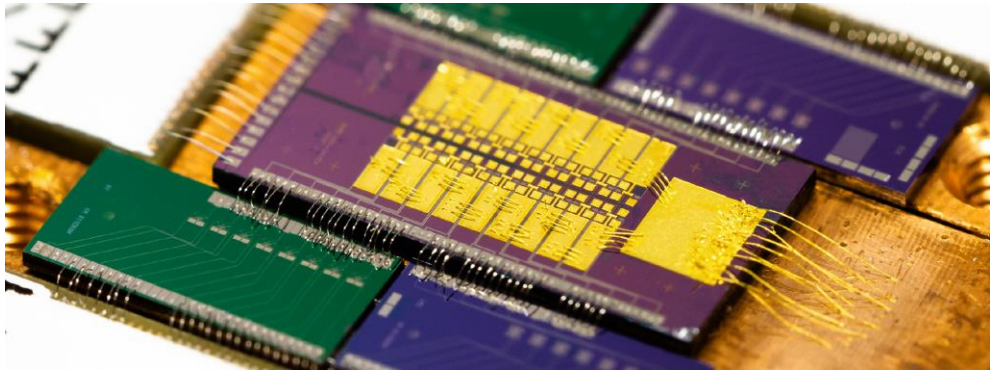

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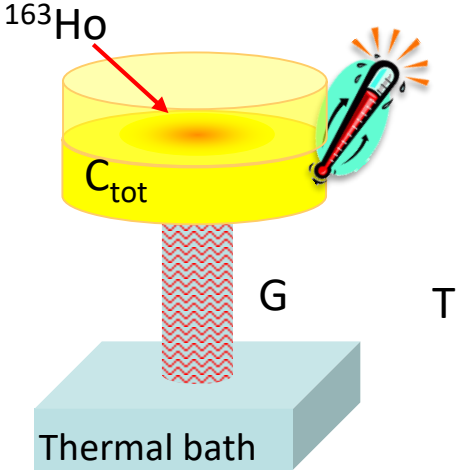

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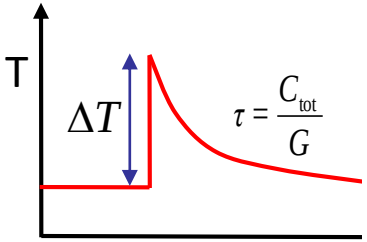

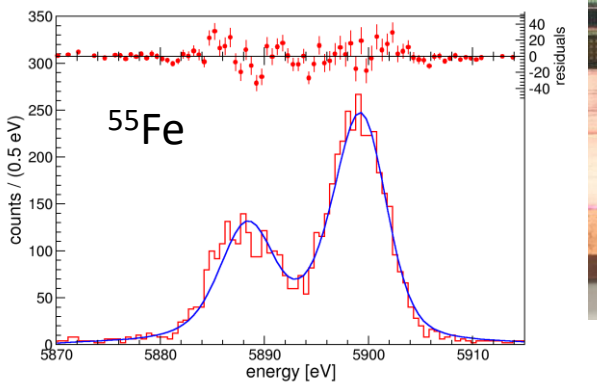

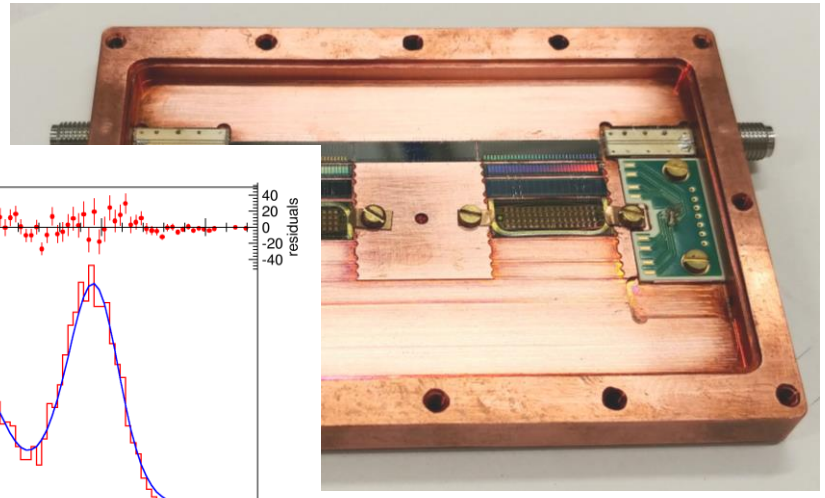

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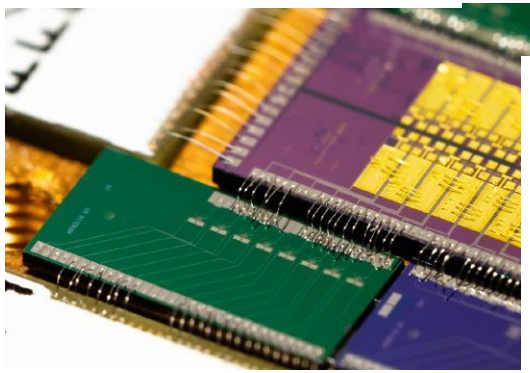

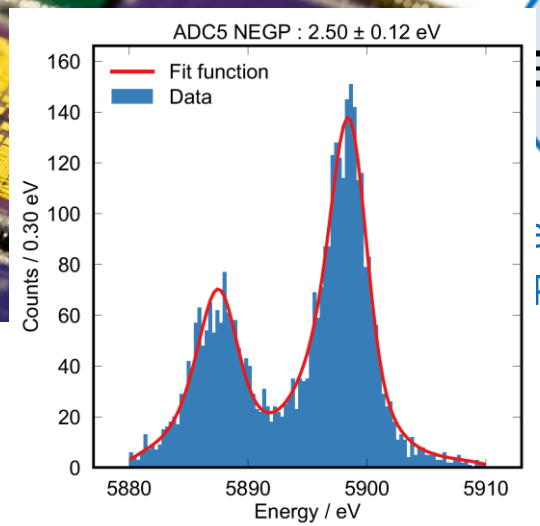

ECHo

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P, Heidelberg University

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

Experimental challenges 3: enclosing ^{163}Ho

The most reliable approach to enclose ^{163}Ho in absorbers of microcalorimeters is ^{163}Ho ion-implantation
This approach is used both by ECHo and HOLMES:

<u>Mass separation and ion implantation in MMC pixels</u>

RISIKO @ Institute of Physics, Mainz University

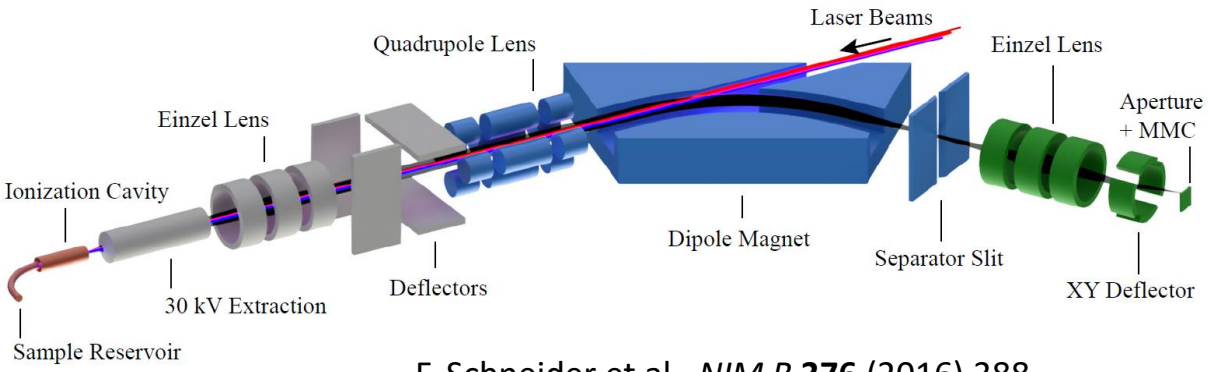
- Resonant laser ion source efficiency

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

- Reduction of ^{166m}Ho in MMC

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

- Optimization of beam focalization



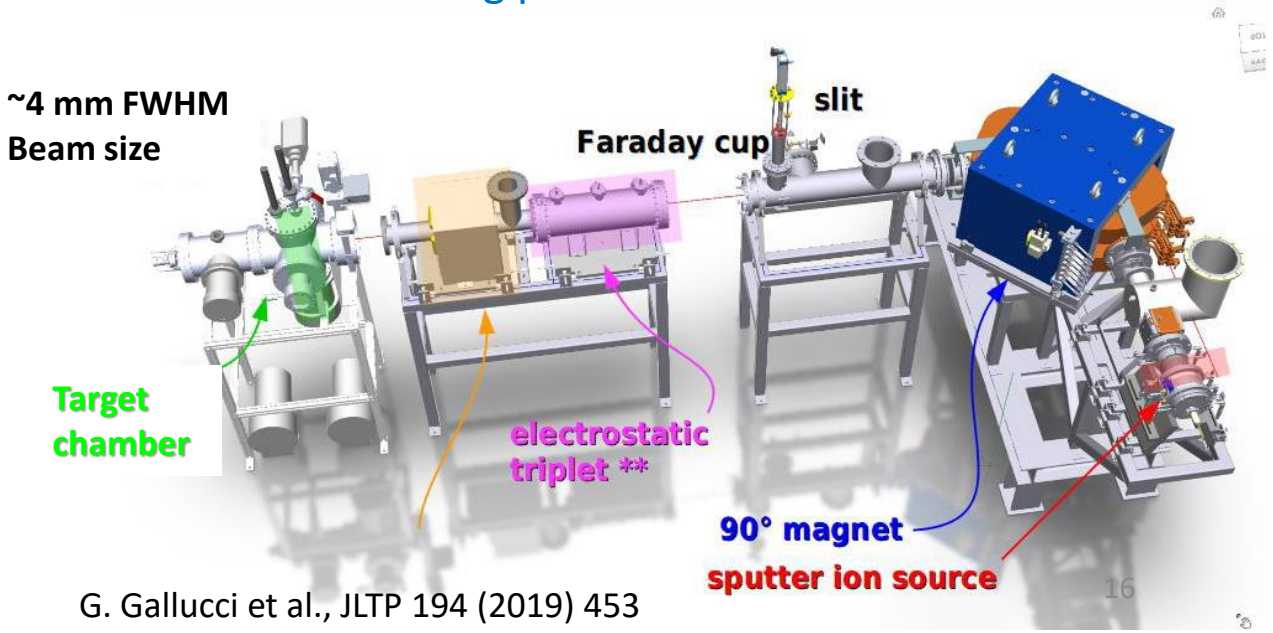
F. Schneider et al., *NIM B* **376** (2016) 388
T. Kieck et al., Rev. Sci. Inst. 90 (2019) 053304
T. Kieck et al., NIM A 945 (2019) 162602

<u>Mass seperation and ion implantation in TES pixels</u>

Mass separator and implanter installed @ Physics Department, Genoa University

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

→ Commissioning phase

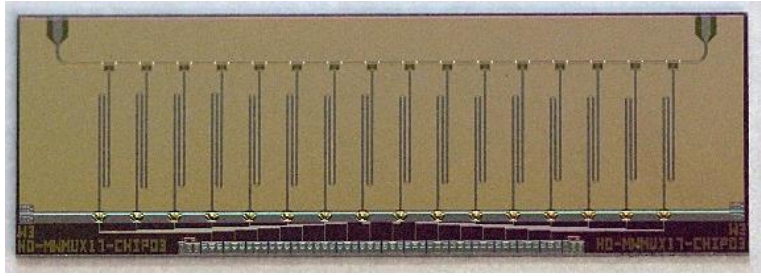


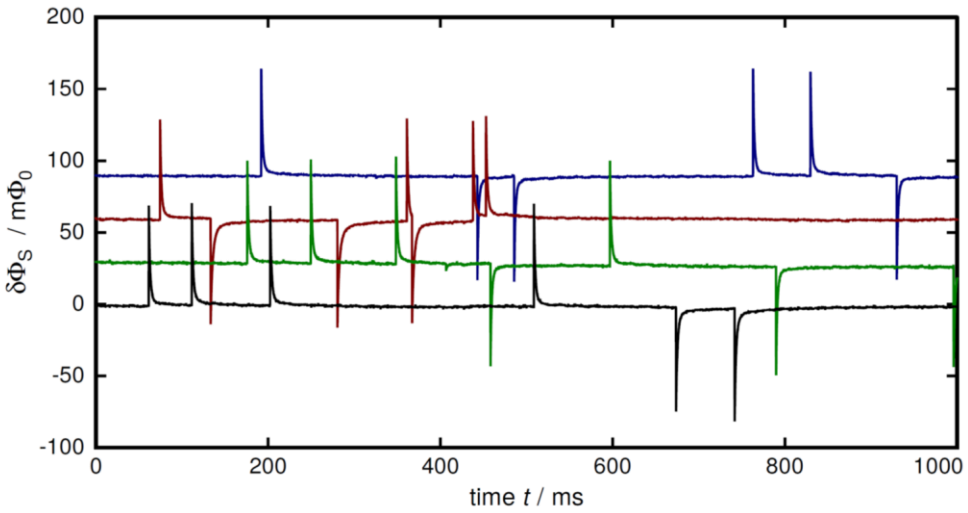
G. Gallucci et al., JLTP 194 (2019) 453

Experimental challenges 4: multiplexing

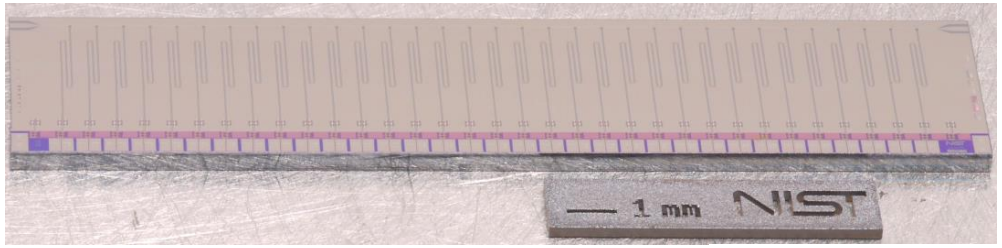
Microwave SQUID multiplexing offers the possibility to readout a large number of channels maintaining a large bandwidth
Both ECHo and HOLMES use such approach, but differently optimized

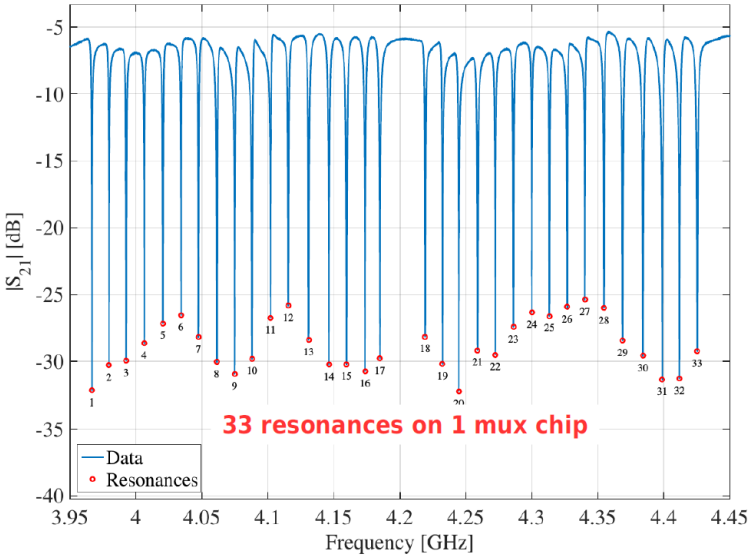
ECHo multiplexer developed at KIP, Heidelberg University
Software Defined Radio developed at Karlsruhe Institute for Technology

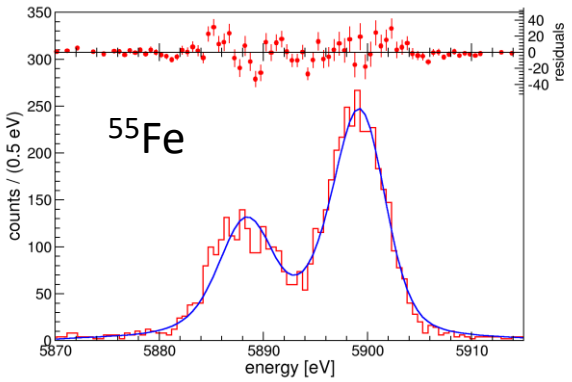




Multiplexer optimized for HOLMES at NIST
Software Defined Radion: ROACH2/ADC 32 channel



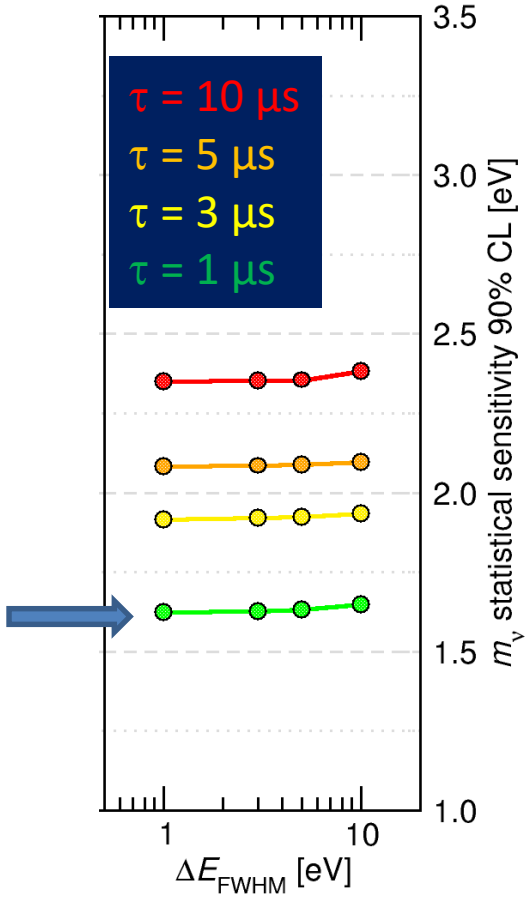




S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

D.T. Becker et al, JINST 14 (2019) P10035

^{163}Ho based experiments - HOLMES



HOLMES baseline: large arrays of Transition Edge Sensors

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

Present status:

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

Ion implantation system:
- commissioning in 2020

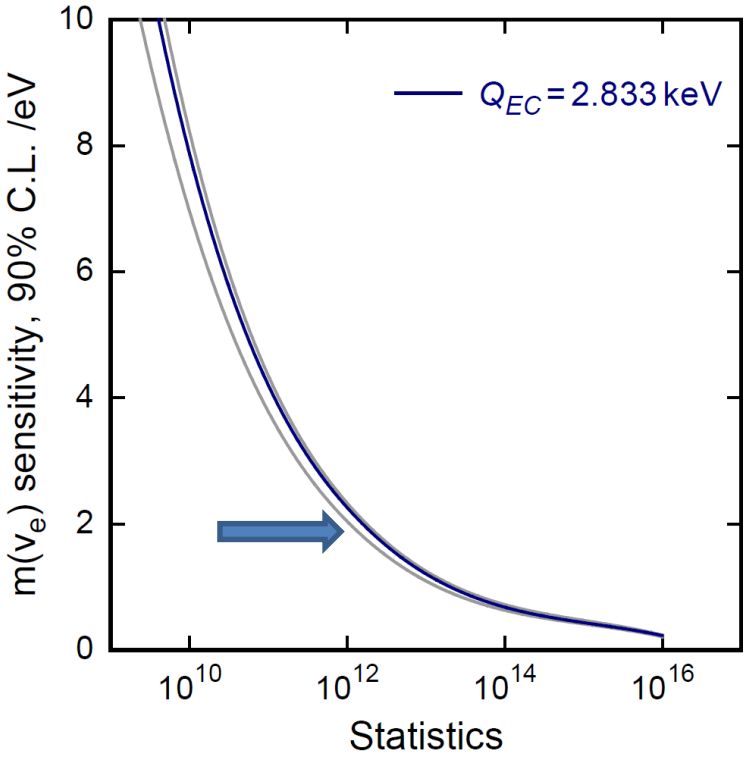
Transition Edge Sensor arrays
- reliable fabrication of large TES array
- succesfull characterization of empty arrays
- still to demonstrate performance with 300 Bq

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

^{163}Ho based experiments - ECHo



Deutsche Forschungsgemeinschaft

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

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

Present status:

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

Ion implantation system:
- demostrated and continuously optimized

Metallic magnetic calorimeters
- reliable fabrication of large MMC array
- successfull characterization of arrays with ^{163}Ho

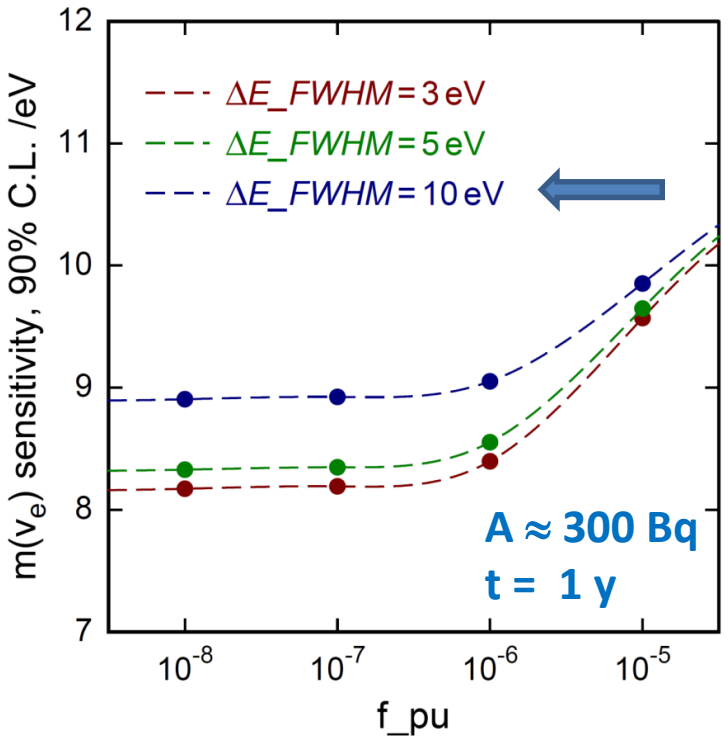
Multiplexing and data acquisition:
- demostrated for 4 channels
- still to show scaling of the system

Data reduction
- optimized energy independedt algorithm to identify spurious traces

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

First two ECHo phases

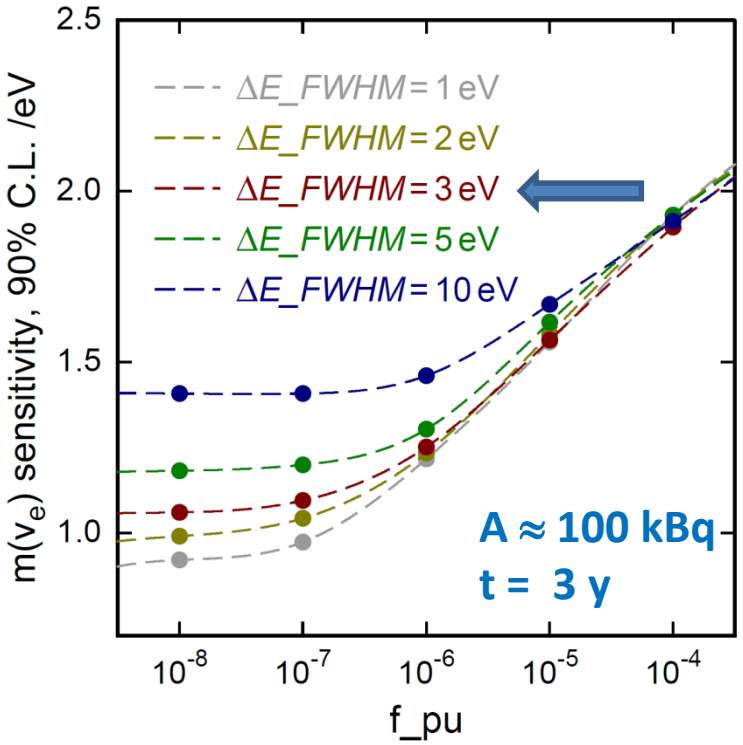
ECHo-1k – revised (2015 – 2018+)



$m(\nu_e) < 20$ eV 90% C.L.

Activity per pixel: 1 - 5 Bq
Number of detectors: 60 - 100
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

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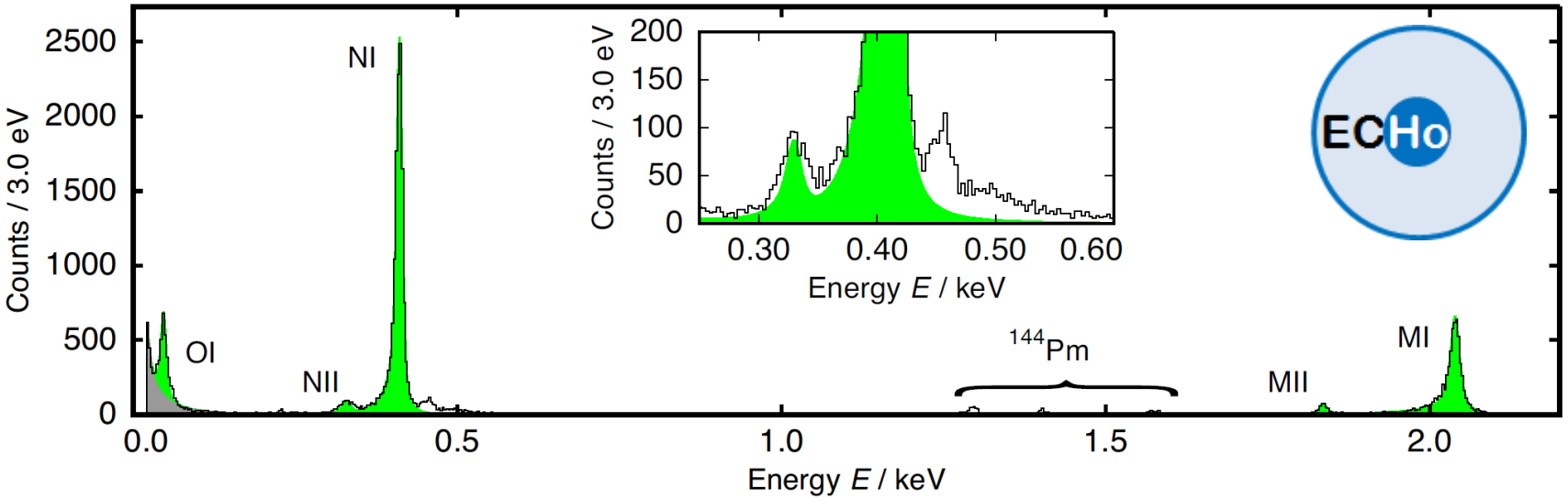
Supported by DFG Research Unit FOR 2022/1

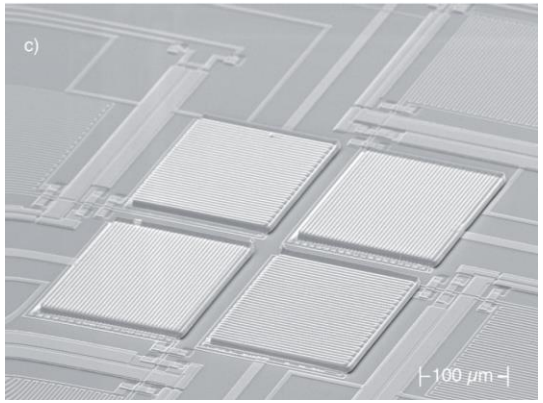
Supported by DFG Research Unit FOR 2022/2

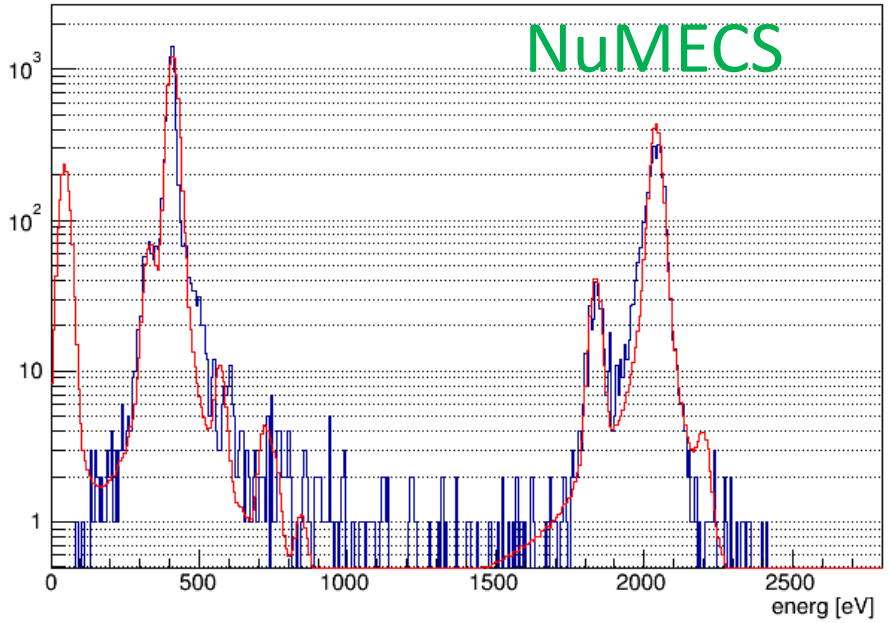
^{163}Ho spectrum measurements



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

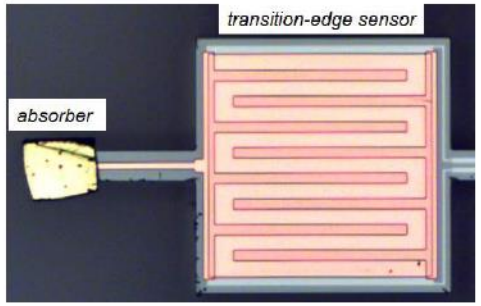
Identification of non-expected structures in the spectrum



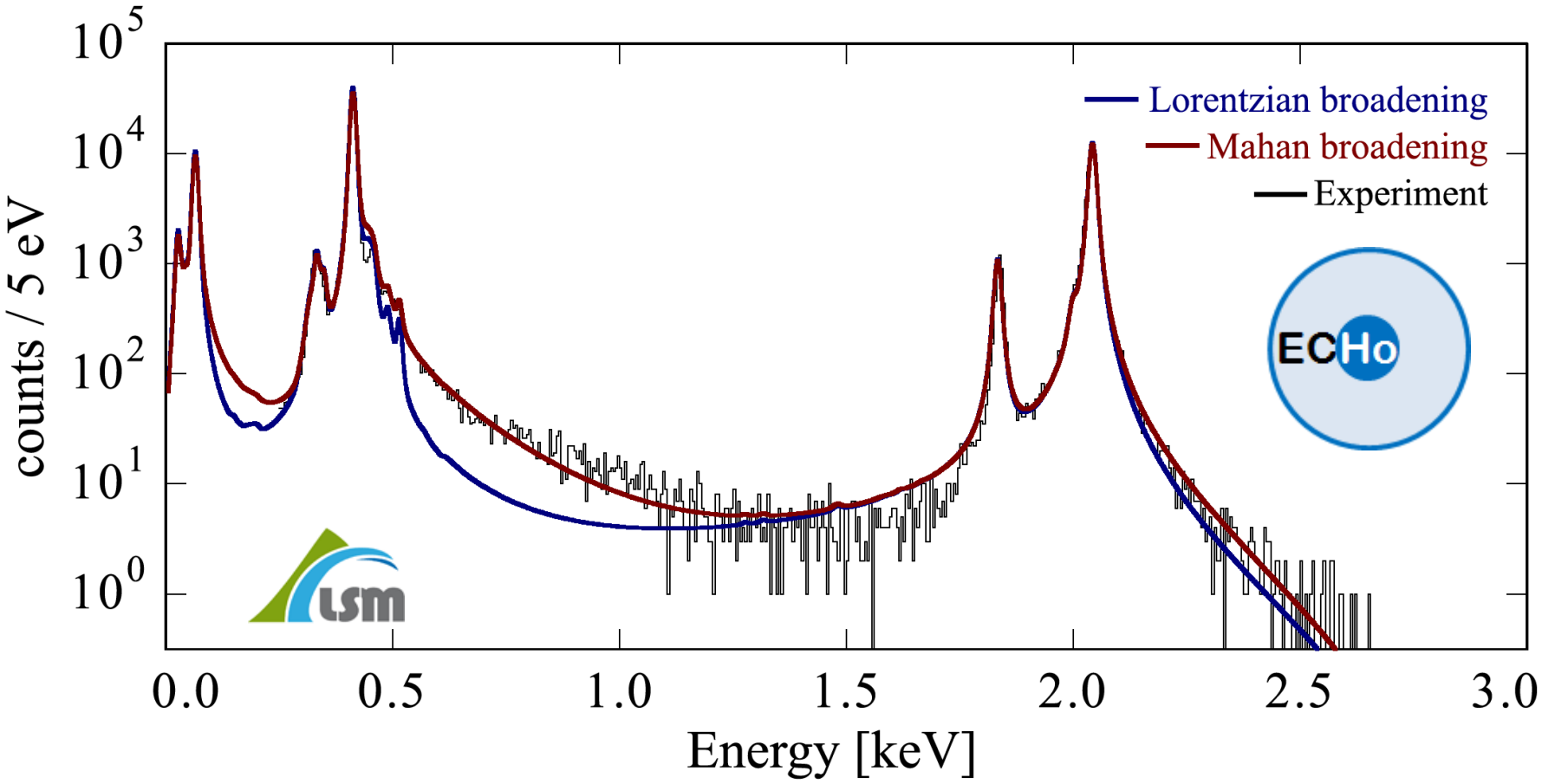


M. Croce et al., J. Low Temp. Phys. 184 (2016) 938 arXiv:1510.03874

Confirmation of additional structures above the NI-line



^{163}Ho spectrum measurements



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

Energy resolution
ΔE_{FWHM} = 9.2 eV

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

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

- measurement performed underground
- test for data reduction and spectral shape analysis

Test of analysis routines:

- Q_{EC} = (2838 ± 14) eV
- $m(\nu_e)$ < 150 eV (95% C.L.) profile log-likelihood ratio hypothesis test

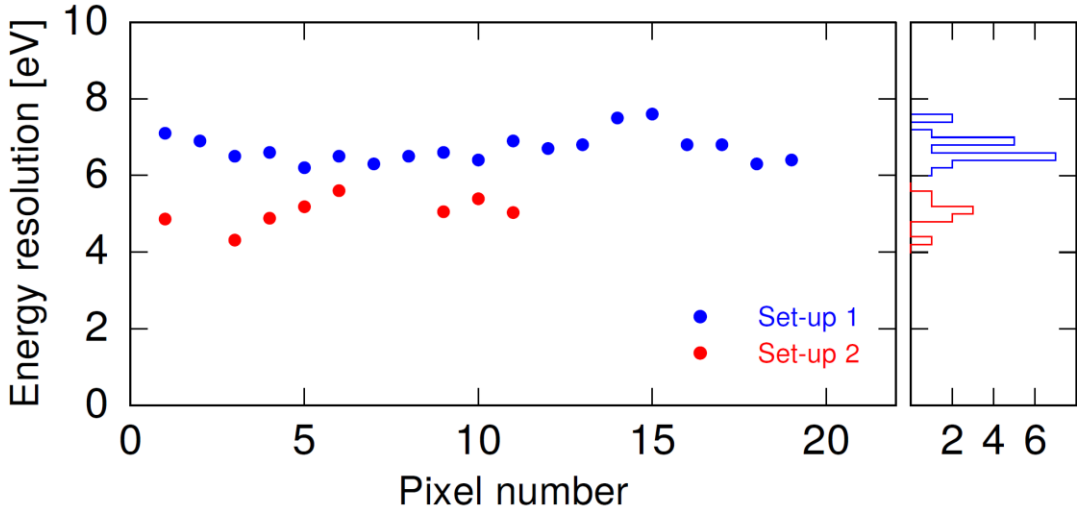
^{163}Ho spectrum measurements

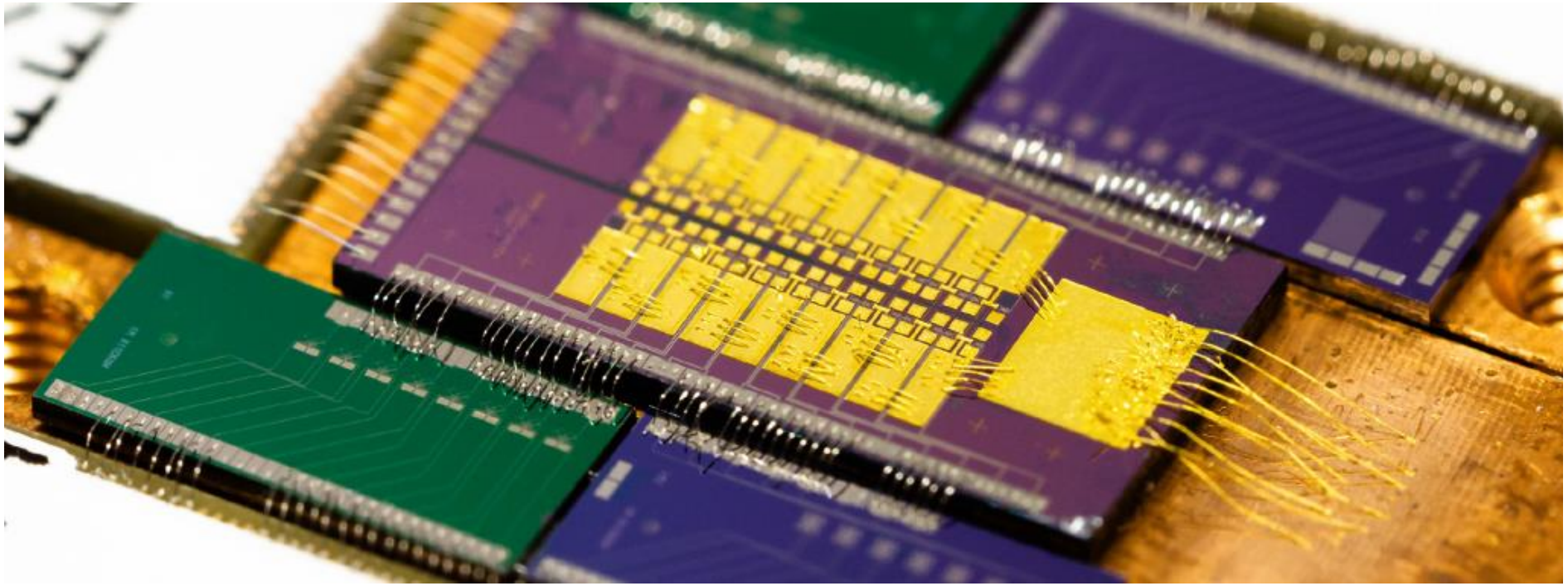
ECHo-1k chip-Au

- ^{163}Ho activity per pixel $a \approx 1$ Bq average activity
- 4 Front-end chips each with 8 dc-SQUIDs for parallel readout

ECHo-1k chip-Ag

- ^{163}Ho activity per pixel $a \approx 0.7$ Bq average activity
- 4 Front-end chips each with 8 dc-SQUIDs for parallel readout





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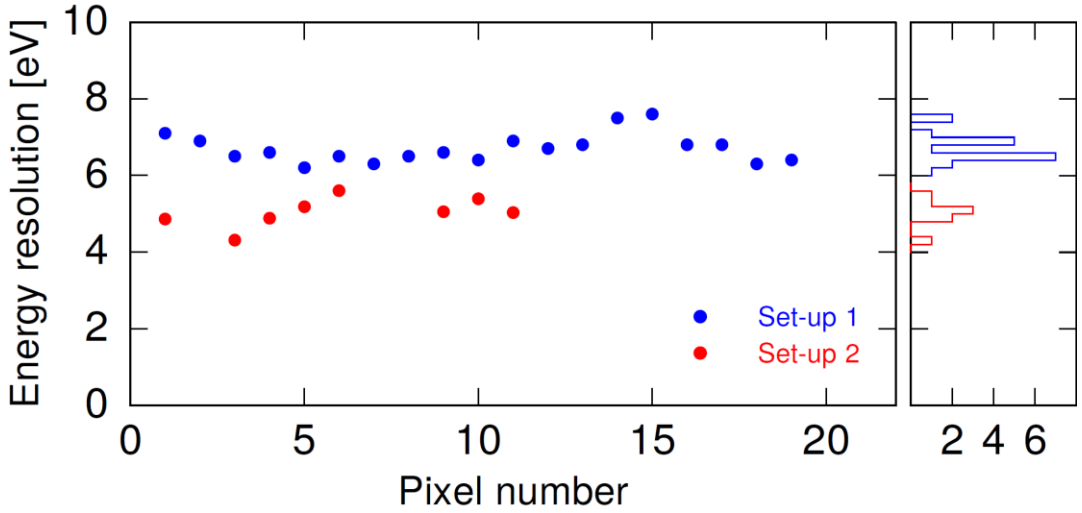
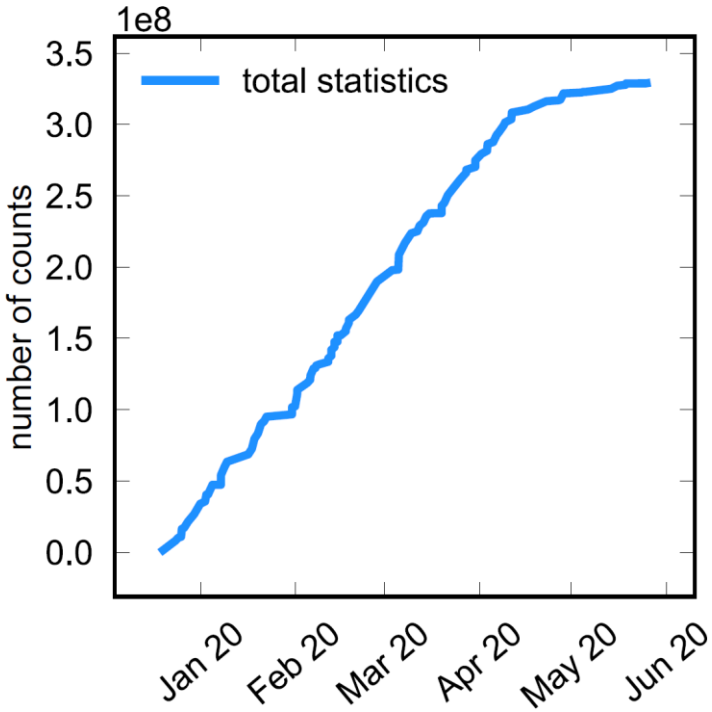




A number of ^{163}Ho events larger than 10^8 has been acquired in the first months of 2020

This statistics allow for investigating the value of the electron neutrino effective mass down to 20 eV

Data analysis is on going

New limit on the electron neutrino effective mass before end 2020

Parameters for ν mass sub-0.2 eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{16}$ → **A ≈ 10 -100 MBq** ✓

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

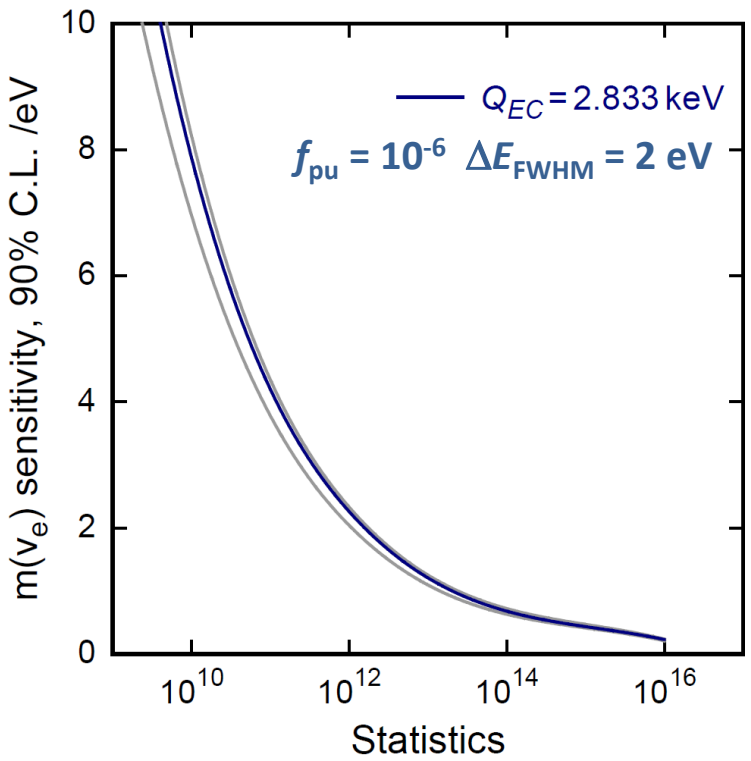
- f_{pu} **< 10^{-5}**
- τ_r < 1 µs → a ~ 10 Bq
- $10^6 – 10^7$ pixels

Precision characterization of the endpoint region

- **ΔE_{FWHM} < 2 eV** ✓

Background level

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



The two basic requirements have been proved:

- availability of high purity ^{163}Ho source for both experiment in 10 -100 MBq
- Single pixel performance fulfill the requirements (ECHo with ^{163}Ho, HOLMES w/o ^{163}Ho)

Theory suggest that the spectrum in the endpoint region is smooth → shape dominated by phase space factor

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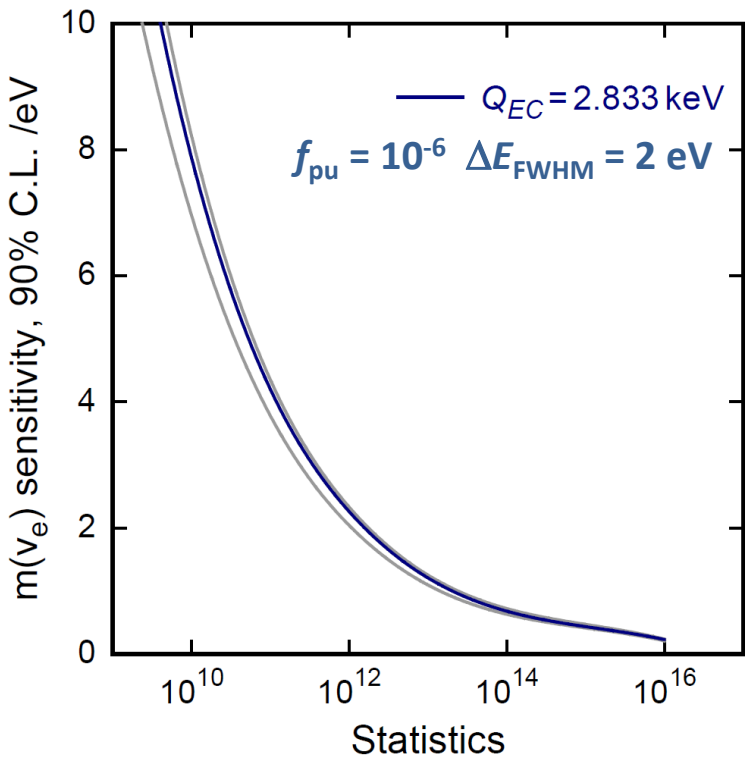

Multiplexing has been proven both for TES and MMC → next step demonstrate that the performance of multiplexed pixel are not degraded

How many pixel can one readout?

ECHo is presently funded for 12000 multiplexed pixel (< 50 EUR/pixel)
HOLMES has 1000 pixels as goal (~100 EUR/pixel)
→ R&D for lowering the cost/pixel

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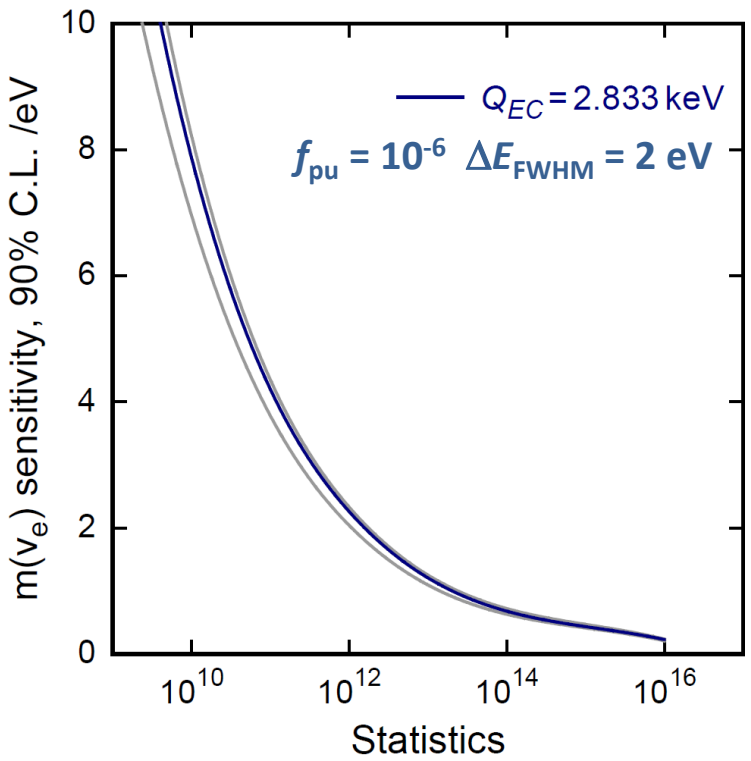

The background model for both experiment is still not ready (longer measurements are necessary to validate MC)

Nevertheless first investigations point out

- material can be selected with low contamination
- muon veto could be used to reduce muon related BG
  pulse-shape analysis is an important tool to detect BG
  → requires fast on-line analysis (full traces can't be acquired at Mcps)

Conclusions

- The determination of the electron neutrino mass with ^{163}Ho is complementary to the determination of the electron antineutrino mass with ^{3}H

- Determination of the ^{163}Ho spectral shape is indicates that the spectral shape at the endpoint region is smooth

- 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 detector

- HOLMES detector modules will be soon tested for ^{163}Ho enclosure

- 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

- No indications for systematic effects which could prevent studying the neutrino mass with ^{163}Ho

- Upcoming background model should indicate if the limit of the unresolved pile-up (10^{-6}) can be achieved

- First multiplexed ^{163}Ho spectra will tell us if reaching sub-eV sensitivity is just a matter of scaling up

Conclusions

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Direct determination of the effective electron neutrino mass via the analysis of electron capture and beta spectra allows for obtaining results which are model independent

Neutrino oscillations results tell us that a finite value for neutrino masses exists
→ direct determination of the neutrino masses has a clear goal which can be achieved if technology and investments allow for

8 institutions
About 50 scientists

6 institutions
About 40 scientists

NuMECS

Stopped

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

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

M. Croce et al., J. Low Temp. Phys. 184 (2016) 938 arXiv:1510.03874