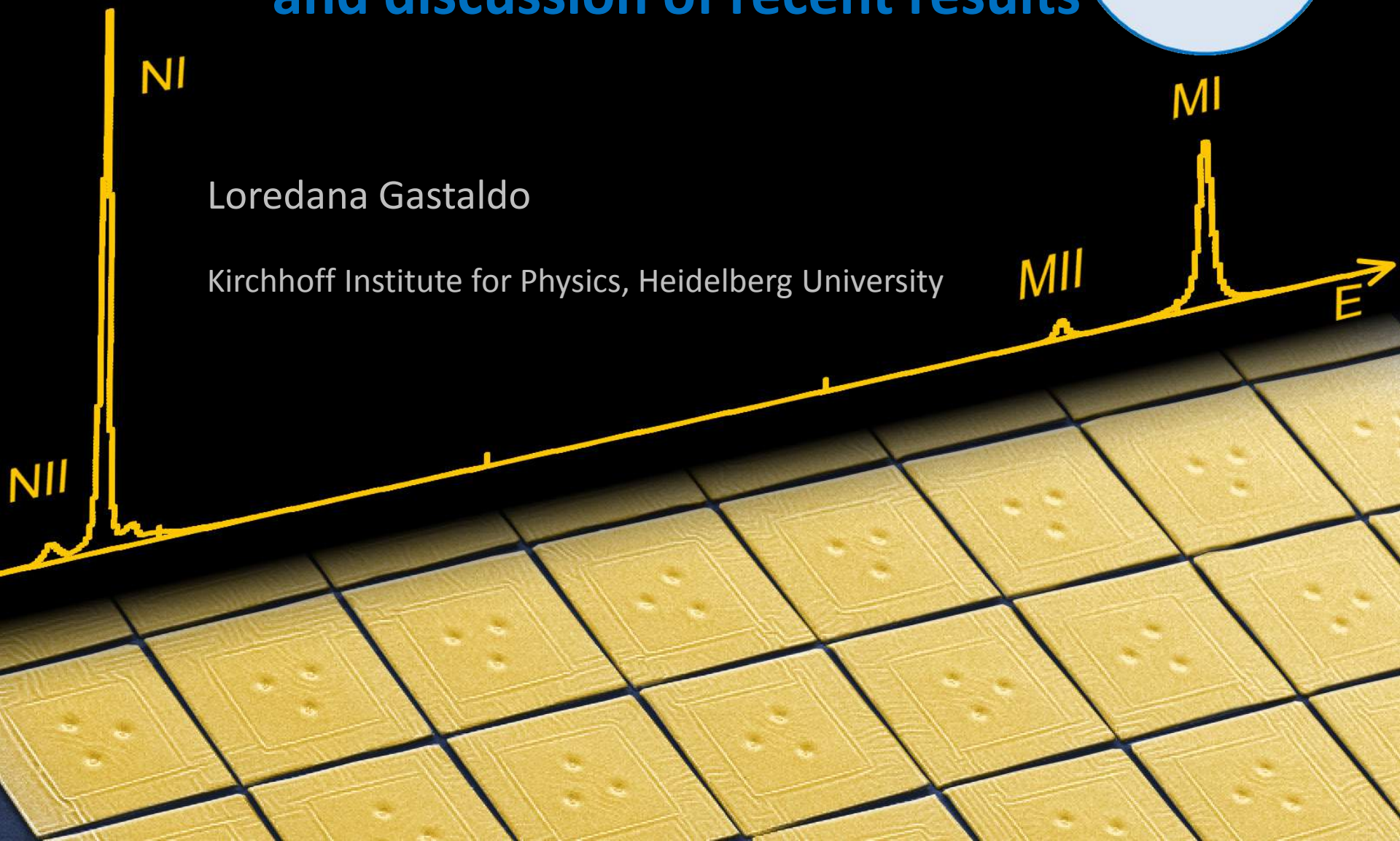
# Electron Capture in $^{163}$Ho experiment – ECHo and discussion of recent results

Loredana Gastaldo

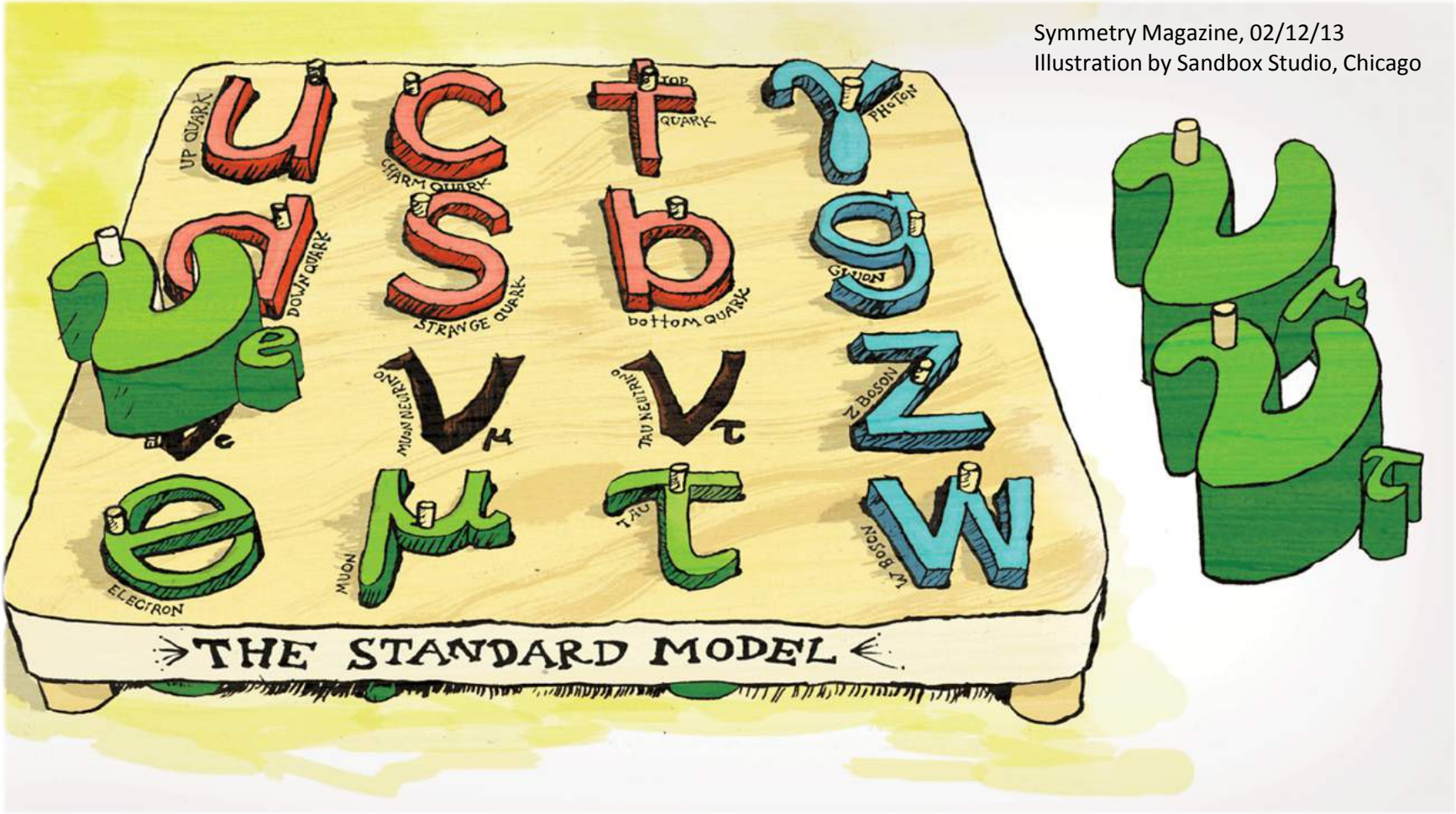
Kirchhoff Institute for Physics, Heidelberg University



# Outline

- Introduction
- Electron capture in $^{163}$Ho and neutrino mass
- Requirements to achieve sub-eV sensitivity on the electron neutrino mass
- $^{163}$Ho-based experiments
- Conclusions and outlook

# Massive Neutrinos




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

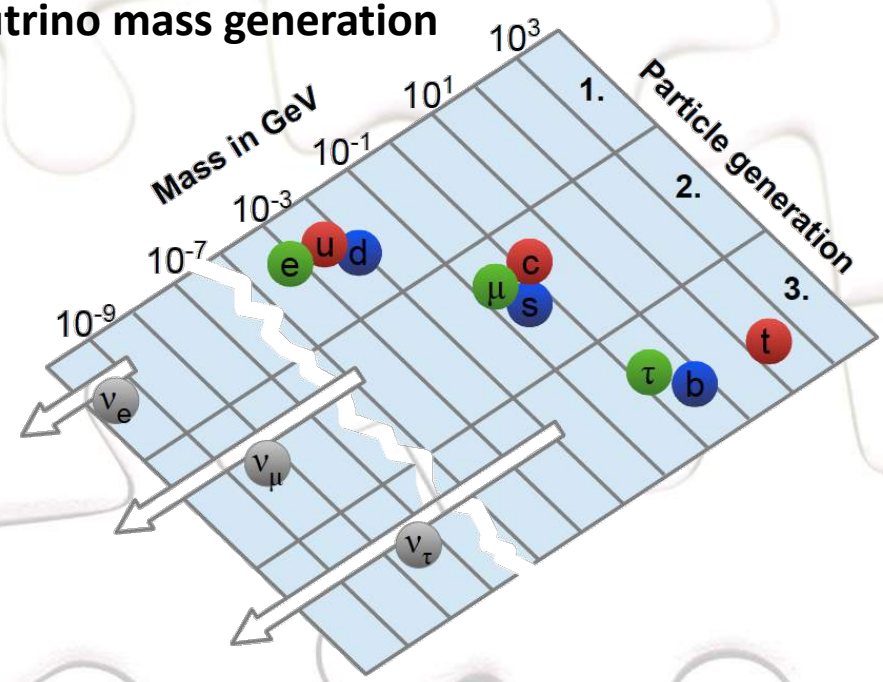
# Knowing neutrino mass scale….

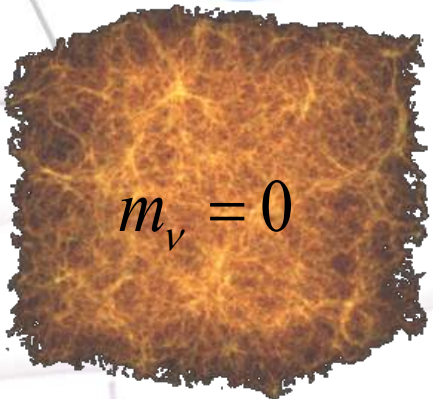
## Astrophysics

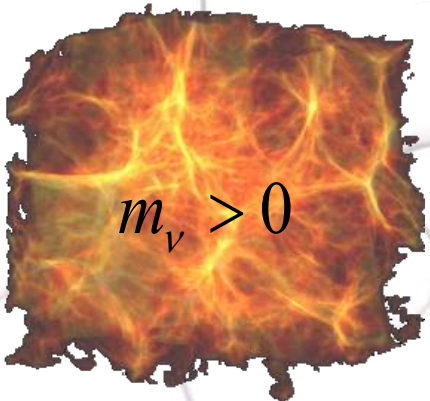
**Supernova netrinos**

## Particle Physics

**Neutrino mass generation**




## Cosmology

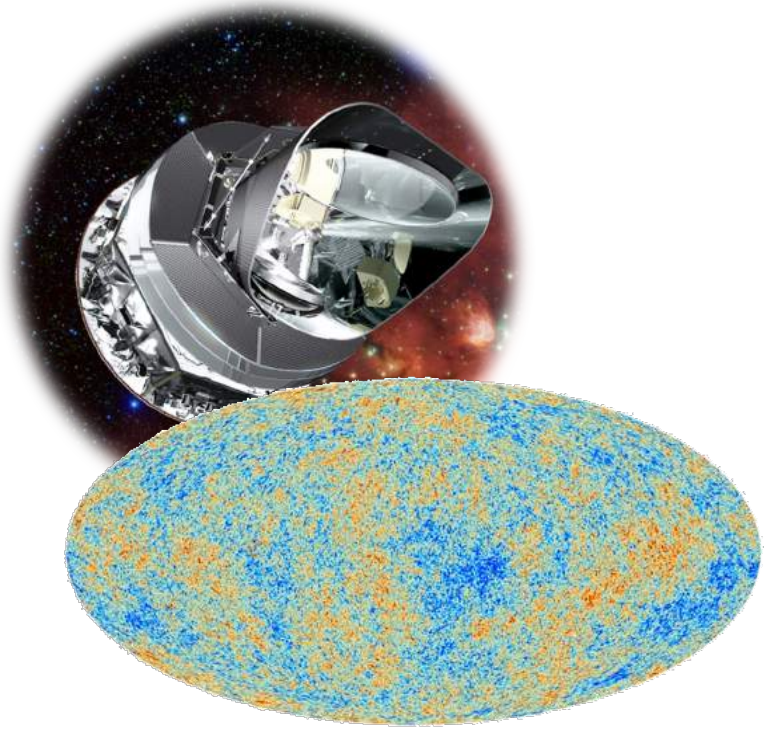
**Matter distribution in the Universe**

# Neutrino mass determination

## Cosmology

$$M_\nu = \sum m_i$$

- Model dependent
- Need of satellites
- Present limit 0.12 – 1 eV
- Next future 15-50 meV



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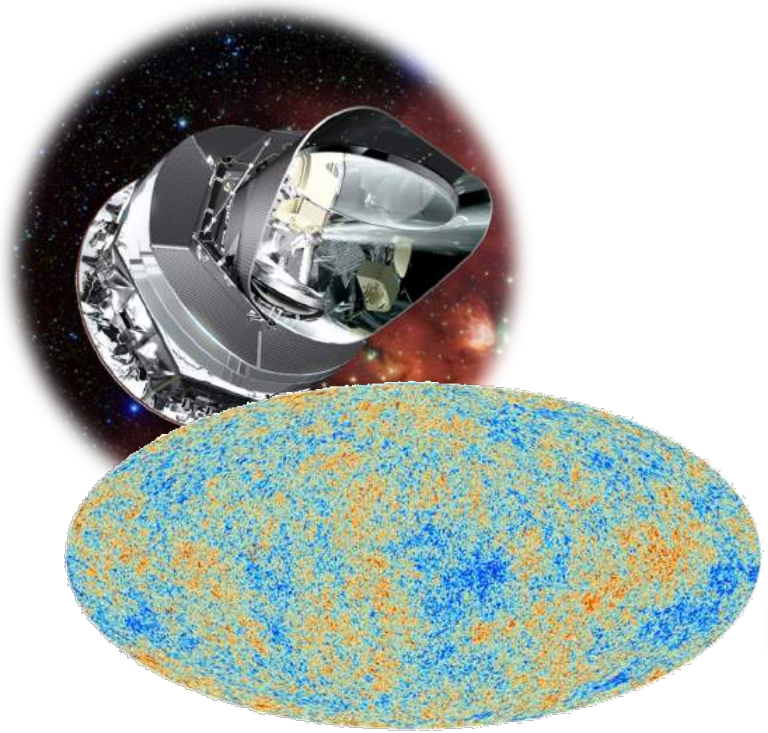
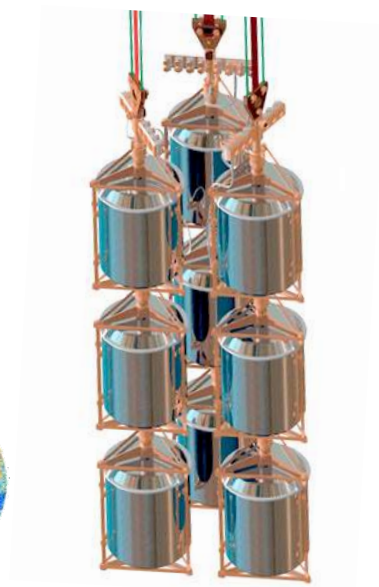
**Neutrinoless Double beta decay**

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

- Model dependent
- Laboratory experiments
- Present limit 0.1 – 0.4 eV
- Next future 15-50 meV





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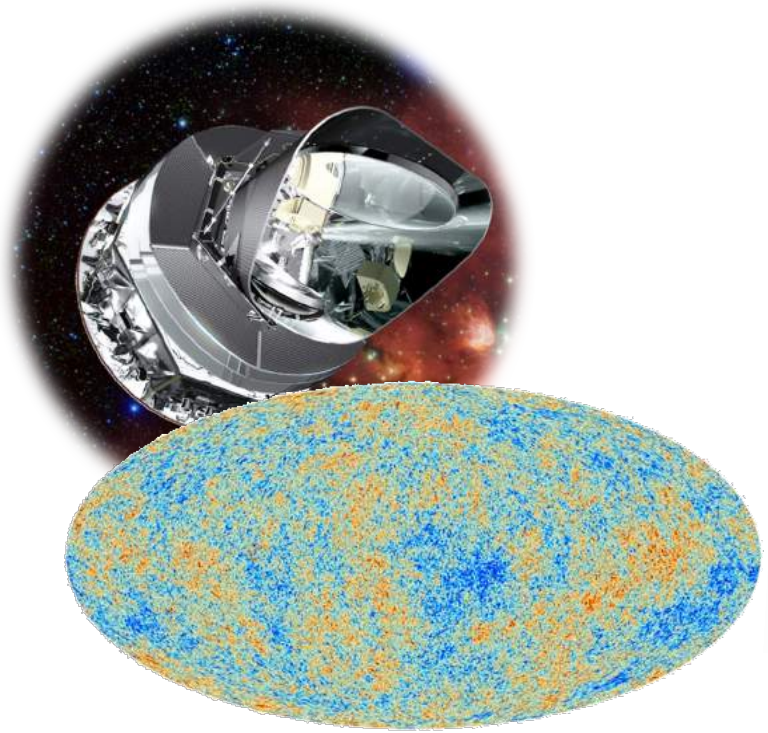
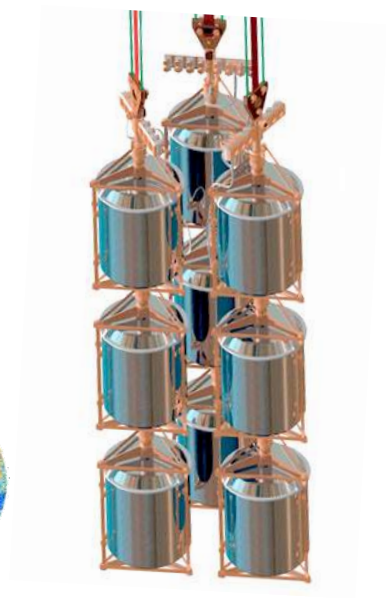
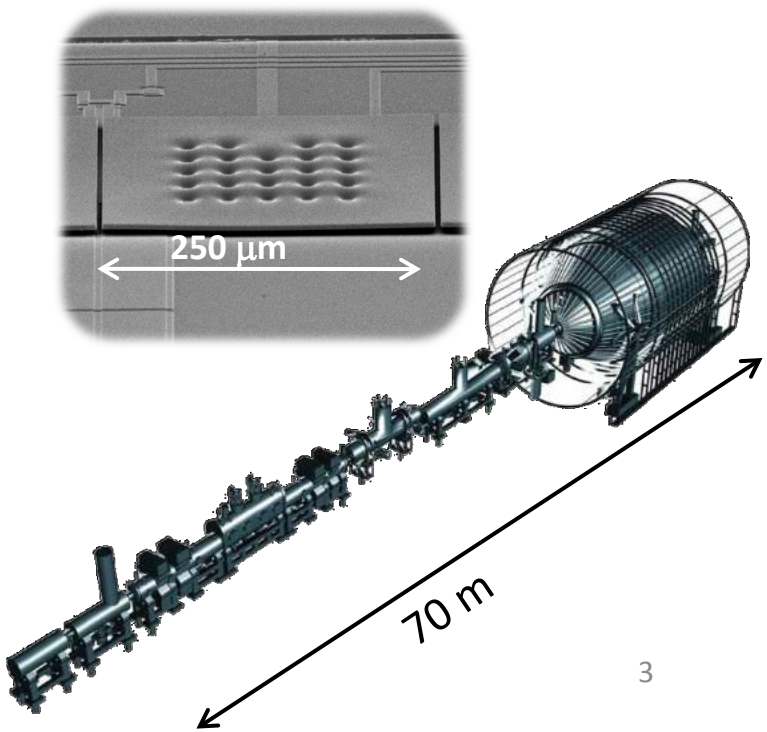
## Kinematics of β-decay and electron capture

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m^2{}_i$$

- Model independent
- Laboratory experiments
- Present limit 2 eV
- Next future 200 meV







# Direct neutrino mass determination

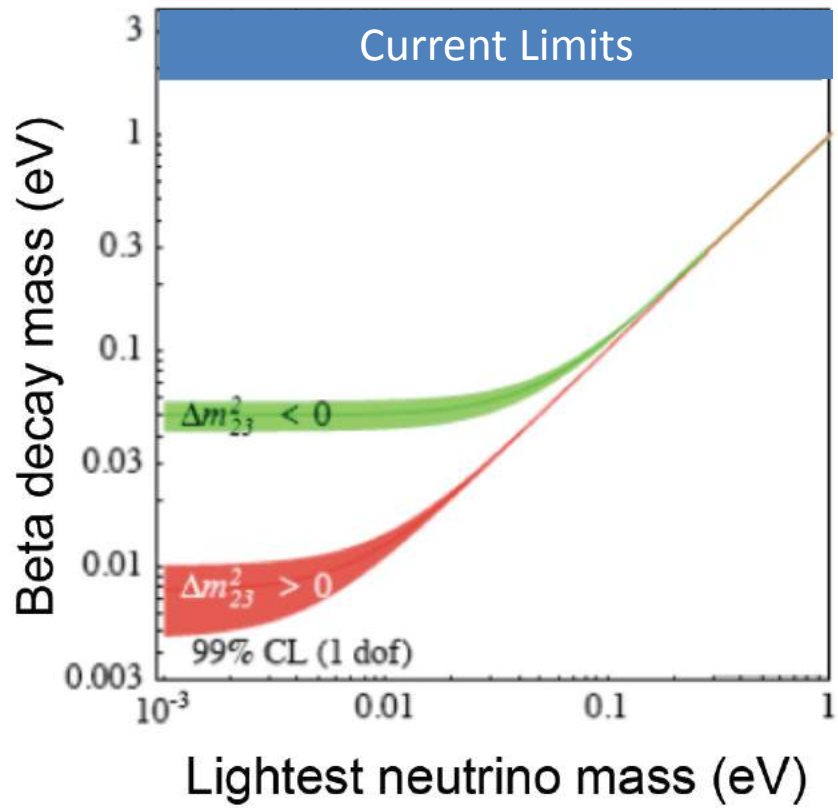
## Kinematics of beta decay

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2$$

- Model independent
- Laboratory experiments

$$m(\bar{\nu}_e) < 2\ eV$$

$^3$H (1)





(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447
N. Aseev *et al.*, Phys. Rev D **84** (2011) 112003

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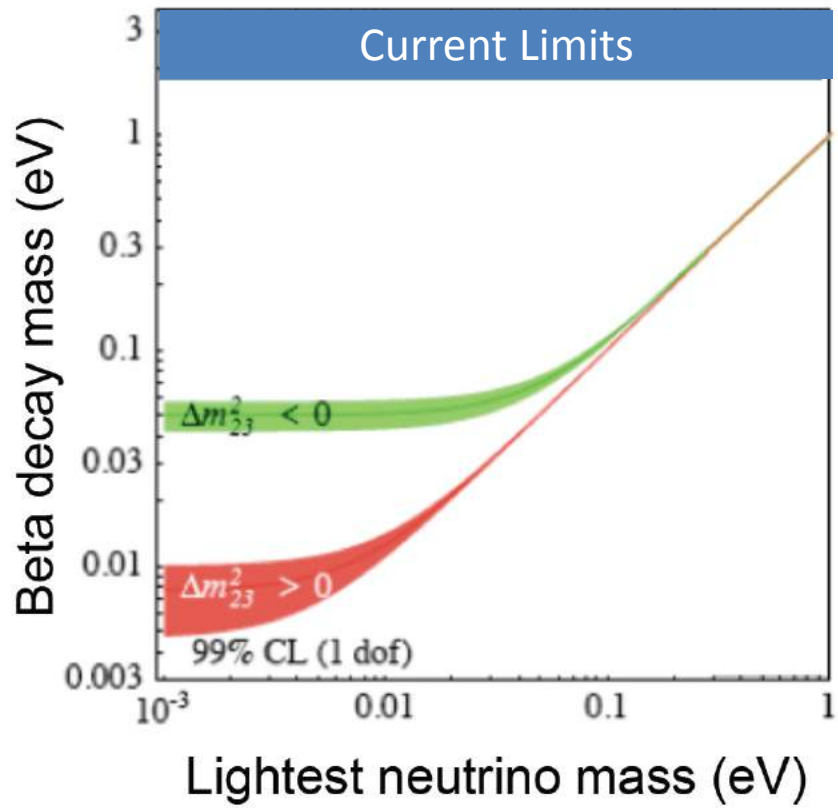
$m(\bar{\nu}_e) < 2\ eV$ $^3$H (1)

$m(\nu_e) < 225\ eV$ $^{163}$Ho (2)





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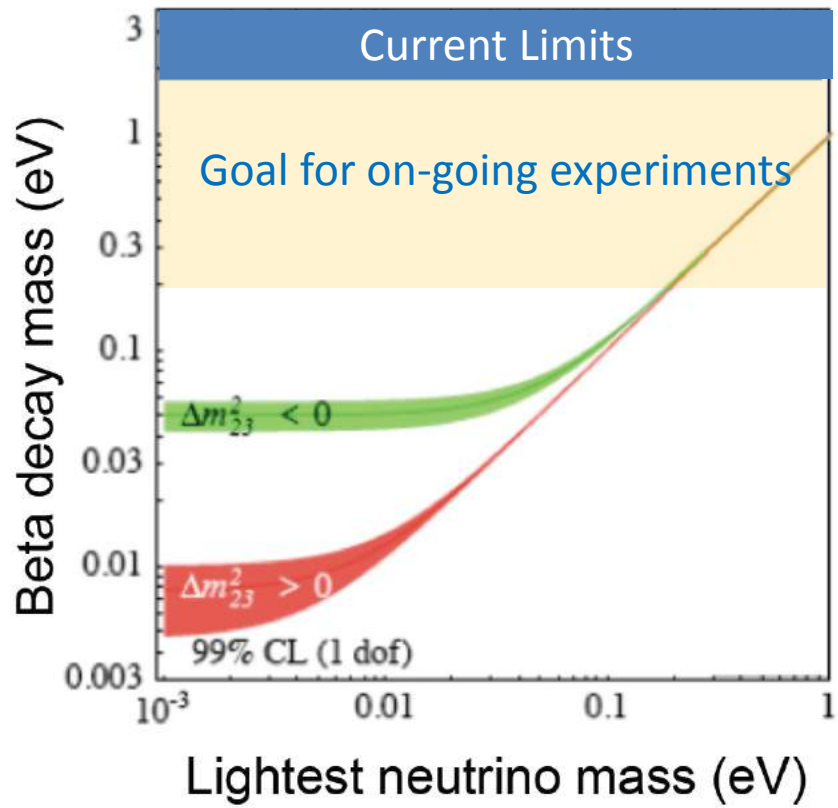
- **Next future 200 meV**





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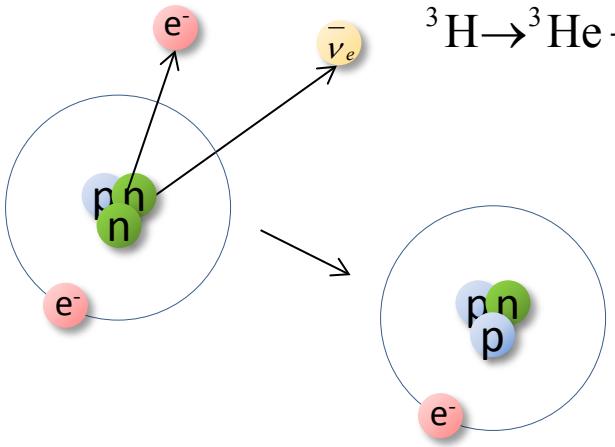
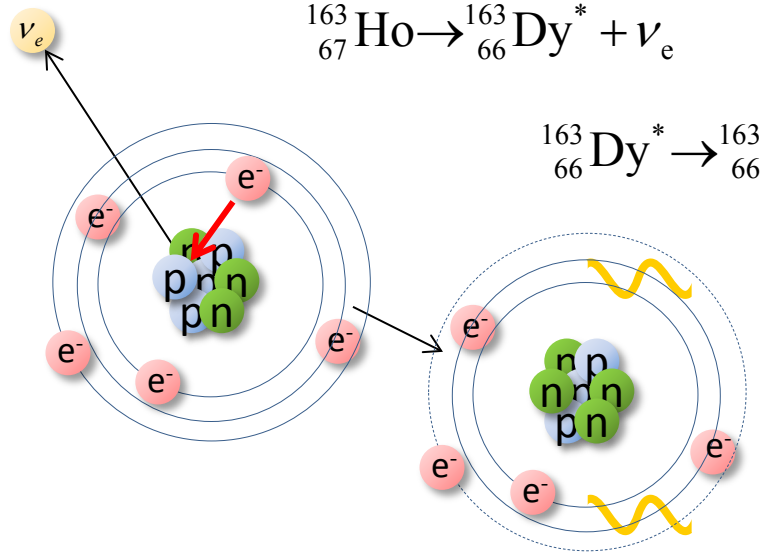
# Beta decay and electron capture




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




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

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

- $\tau_{1/2} \cong 12.3$ years (4*10$^{8}$ atoms for 1 Bq)
- $Q_\beta$ = 18 592.01(7) eV

E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

- $\tau_{1/2} \cong 4570$ years (2*10$^{11}$ atoms for 1 Bq)
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S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

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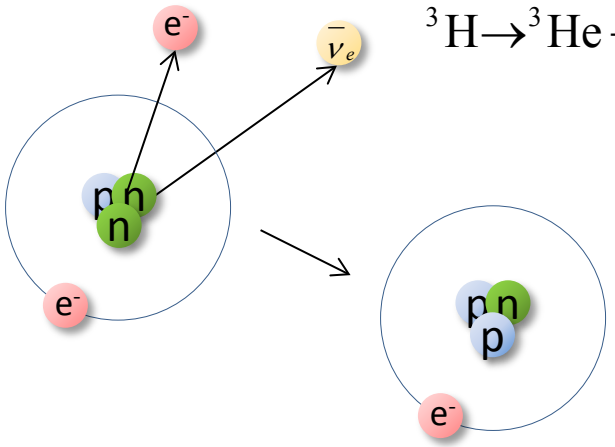


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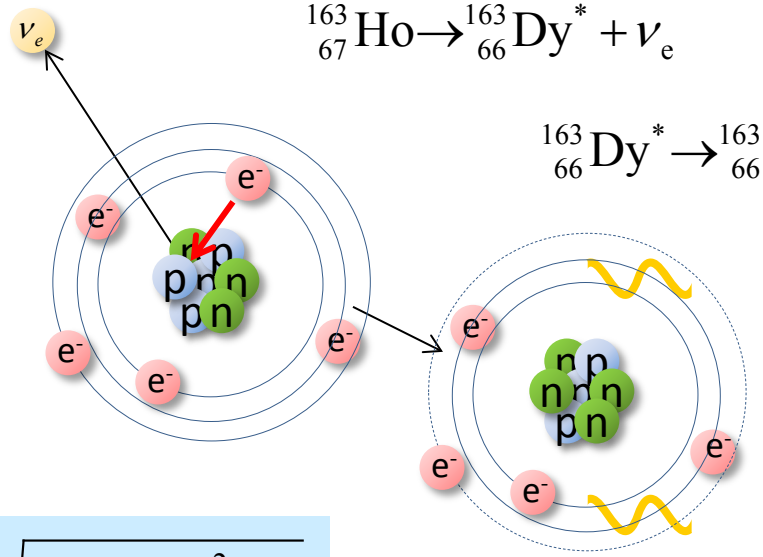


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$$\frac{dW}{dE} \propto (Q-E)^2 \sqrt{1-\frac{m_\nu^{\,2}}{(Q-E)^2}}$$

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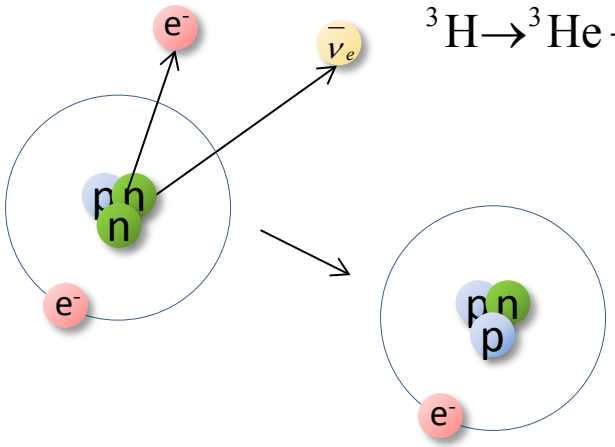
# Beta decay of $^3$H

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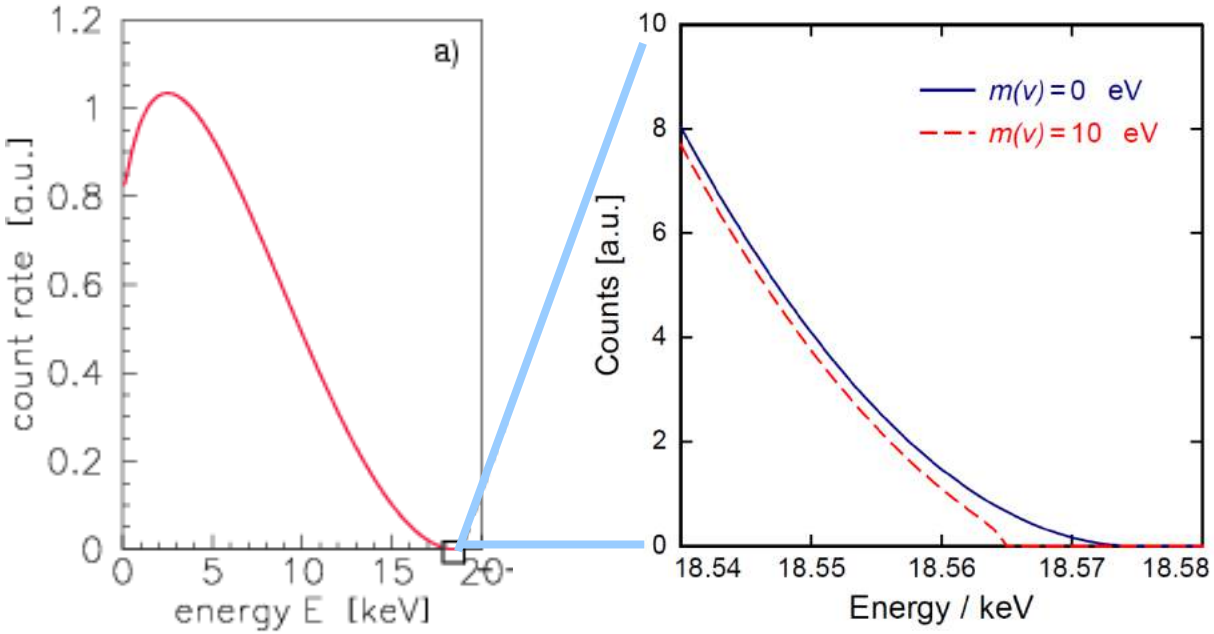
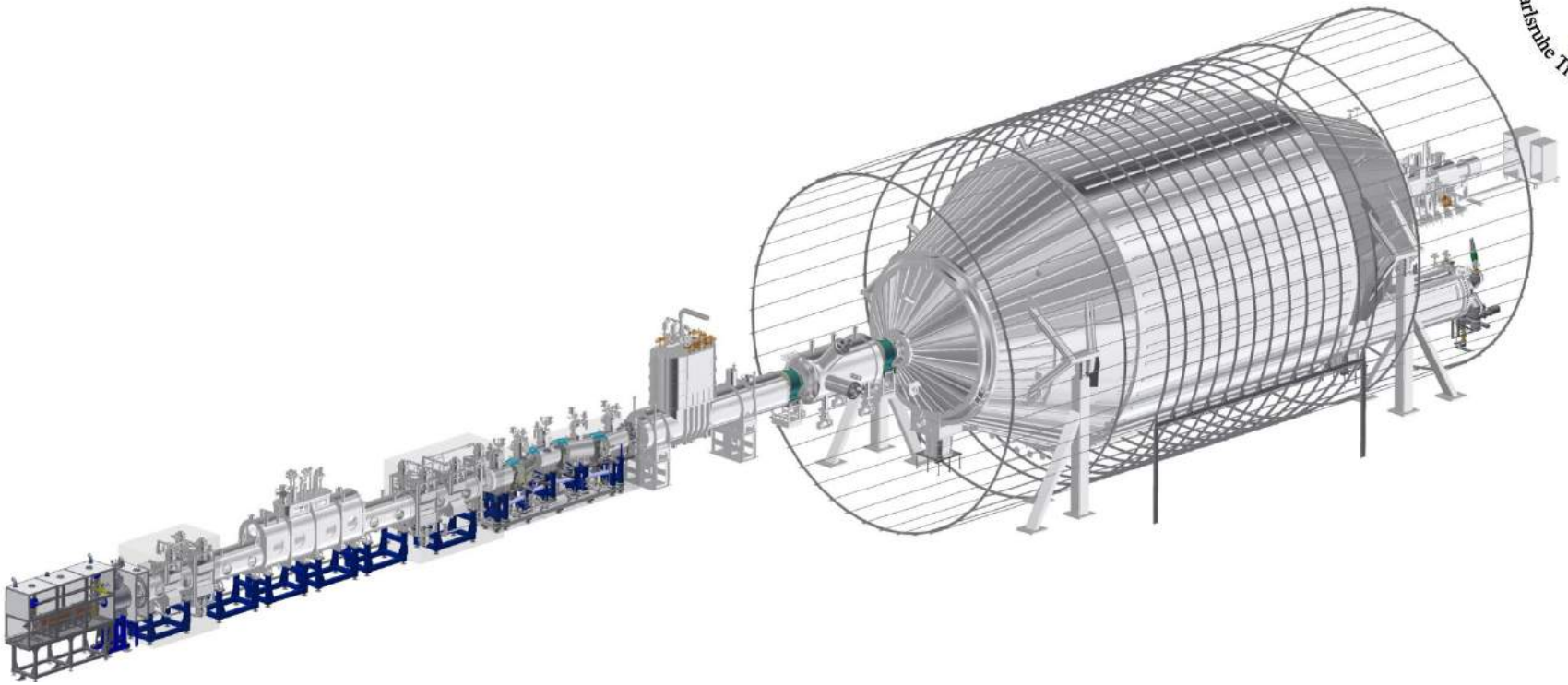


# The KATRIN experiment

❖ **KATRIN** - **Ka**rlsruhe **Tri**tium **N**eutrino Experiment



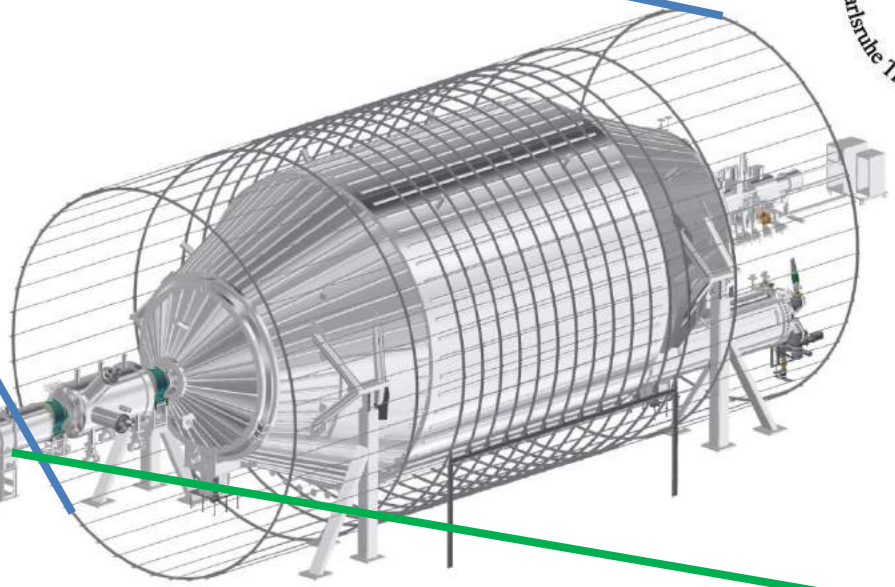
Main ideas:

- high activity source $10^{11}$ $e^-$/s
- high resolution MAC-E* filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum



*MAC-E: Magnetic Adiabatic Collimation with Electrostatic Filter

# The KATRIN experiment: present status

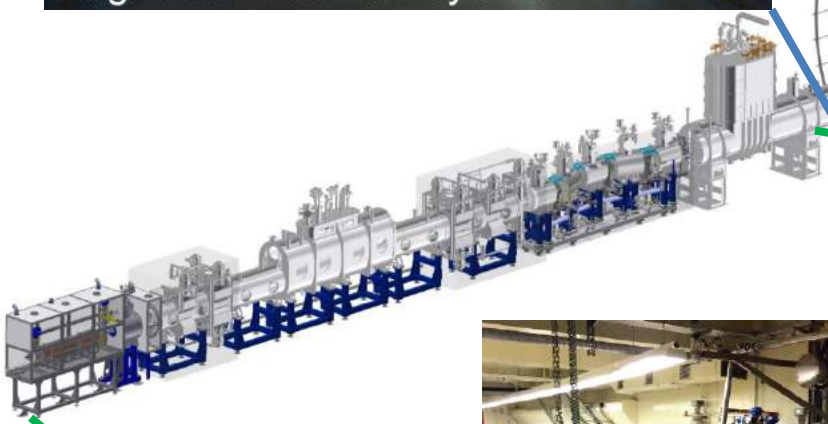


Photo K. Valerius

# The KATRIN experiment: present status



**First light 14th October 2016**

Photo Patrick Langer

Photo K. Valerius

# $^3$H based experiments

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Main ideas:

- high activity source: $10^{11}$ $e^-$/s
- high resolution MAC-E filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum

❖ **Project8**

Main ideas:

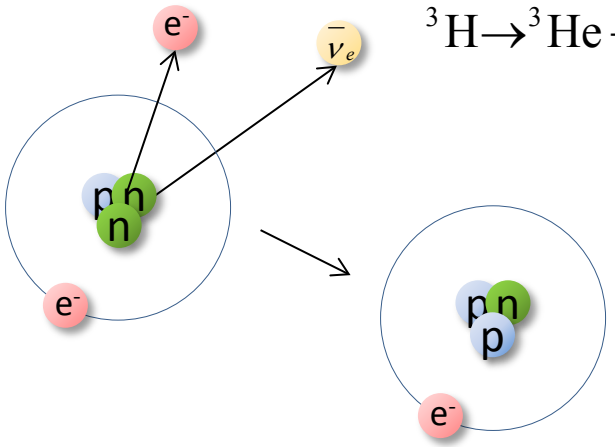
- Source = detector: $10^{11} – 10^{13}$ $^3H_2$ molecules /cm$^3$
- Use cyclotron frequency to extract electron energy
- Differential spectrum

❖ **PTOLEMY** - **P**rinceton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield

Main ideas:

- large area tritium source: 100 g atomic $^3$H
- MAC-E lter to select electrons close to the end point
- RF tracking and time-of-flight systems
- cryogenic calorimetry → differential spectrum

# Beta decay and electron capture

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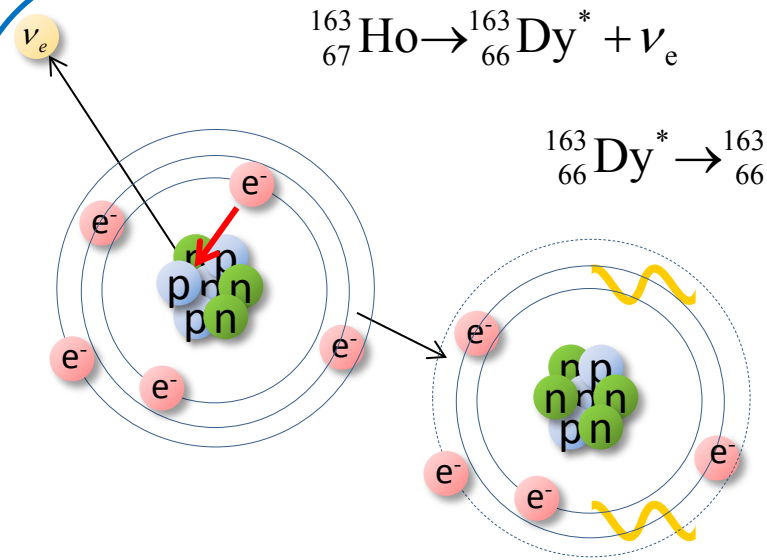


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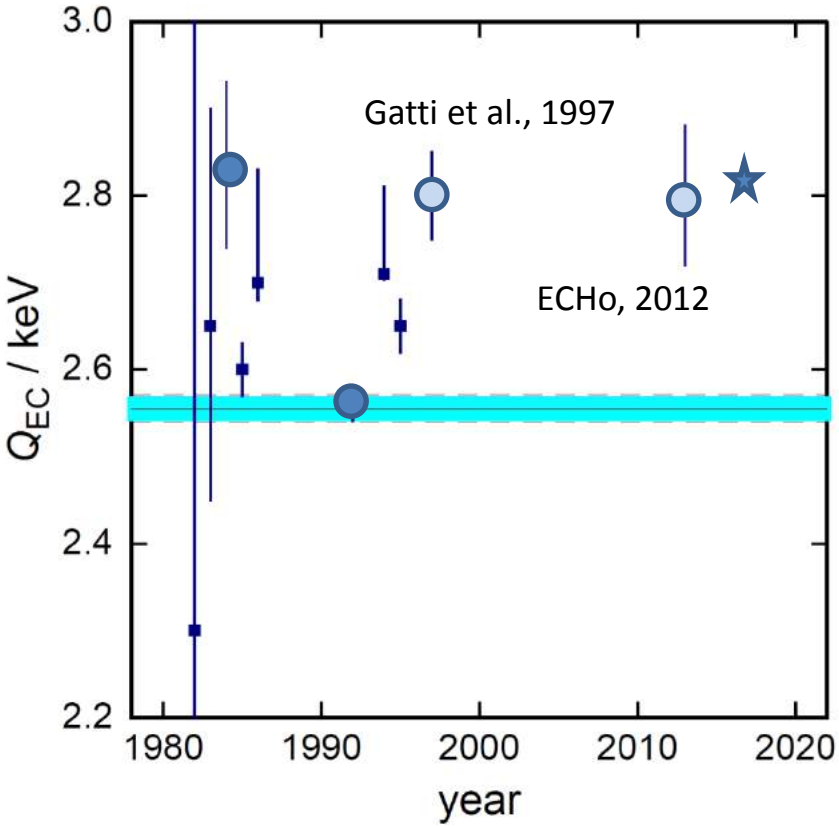
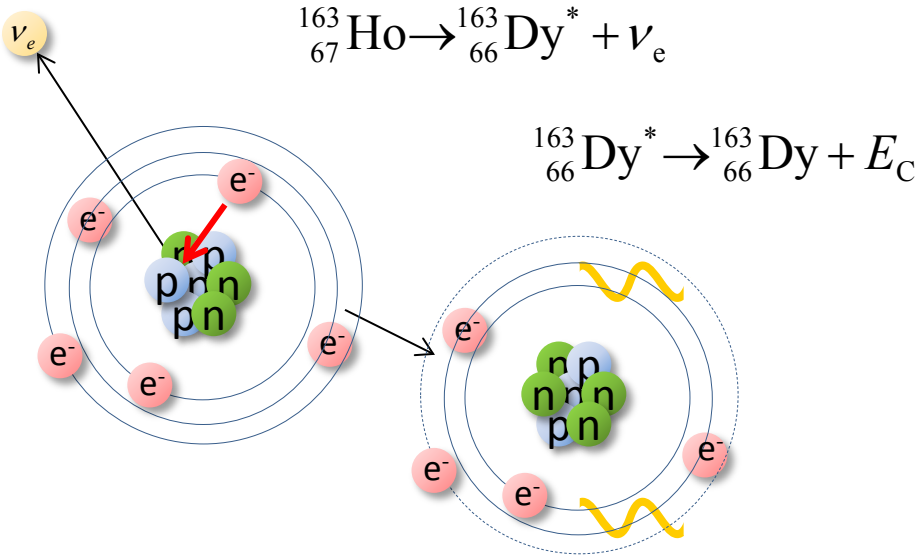
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

# Electron capture in $^{163}$Ho: $Q_{EC}$ determination

- Calorimetric measurements
- Measurements of x-rays
- ★ $Q_{EC} = m(^{163}\mathrm{Ho}) - m(^{163}\mathrm{Dy})$

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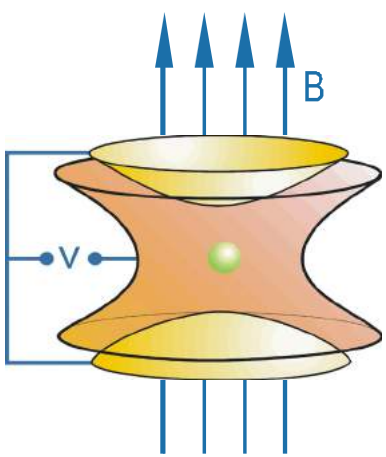
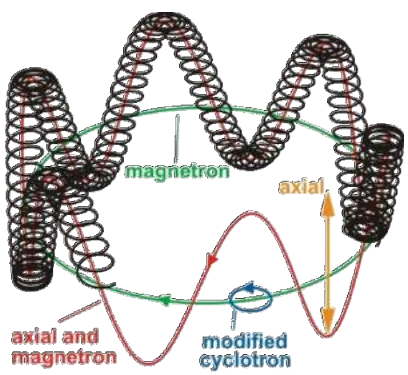
**Penning Trap Mass Spectroscopy**

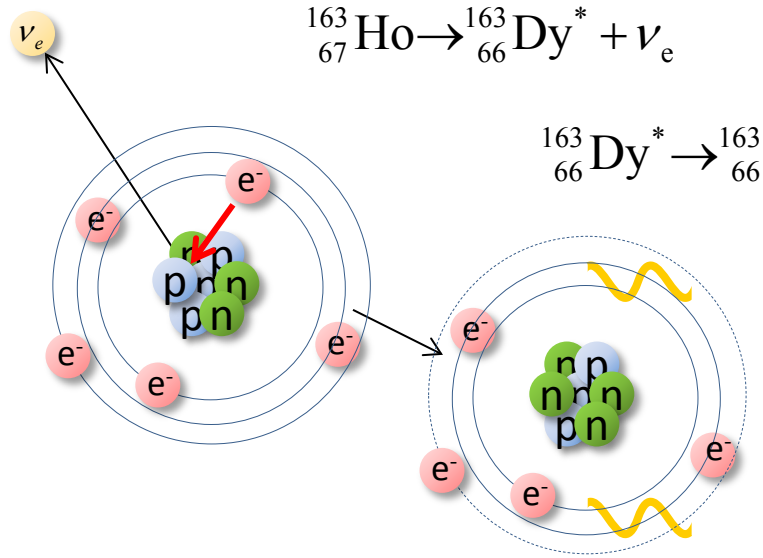
@TRIGA TRAP (Uni-Mainz) (*)

@SHIPTRAP (GSI – Darmstadt) (**)

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

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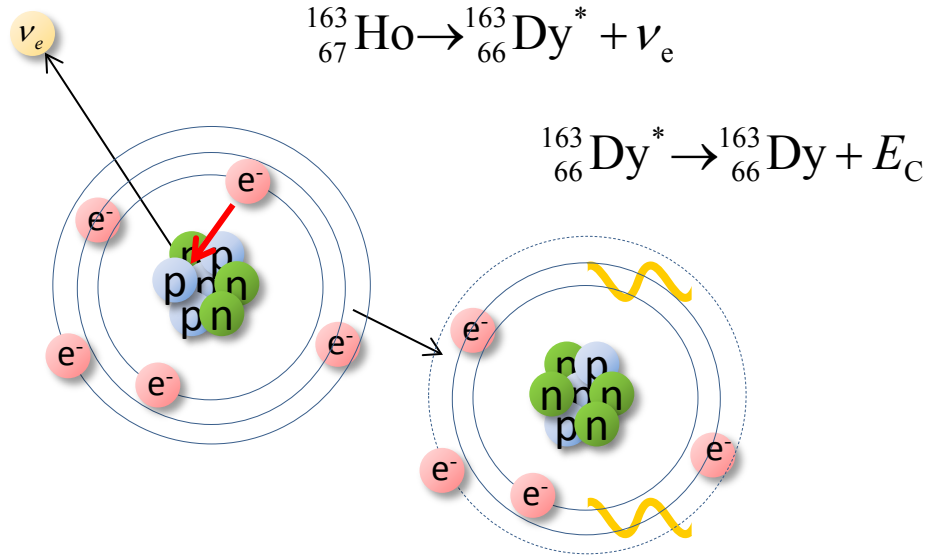
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501 (**)
F. Schneider et al., Eur. Phys. J. A **51** (2015) 89 (*)

# Electron capture in $^{163}$Ho: spectrum

Atomic de-excitation:

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

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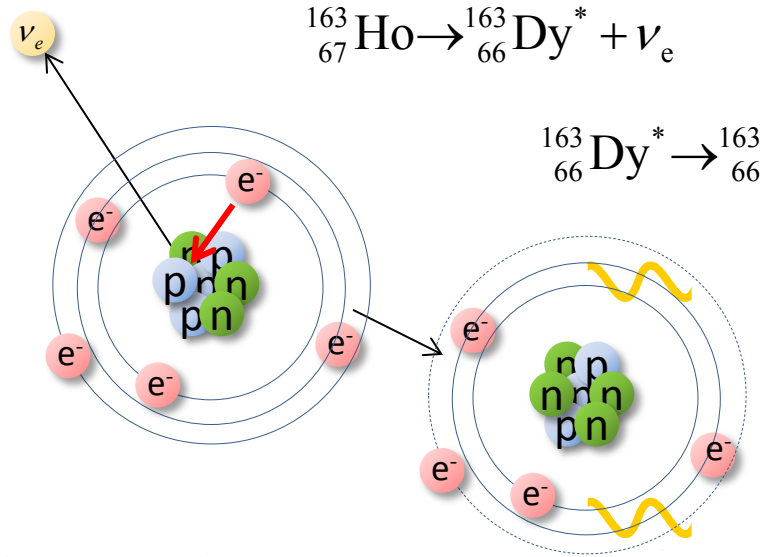


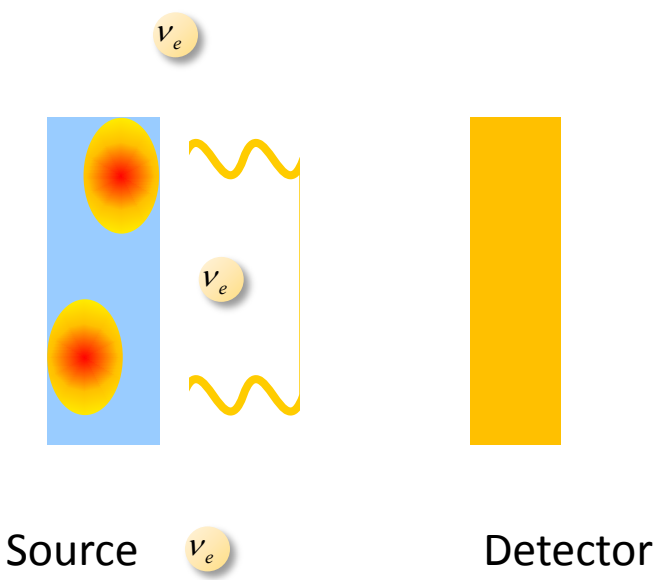


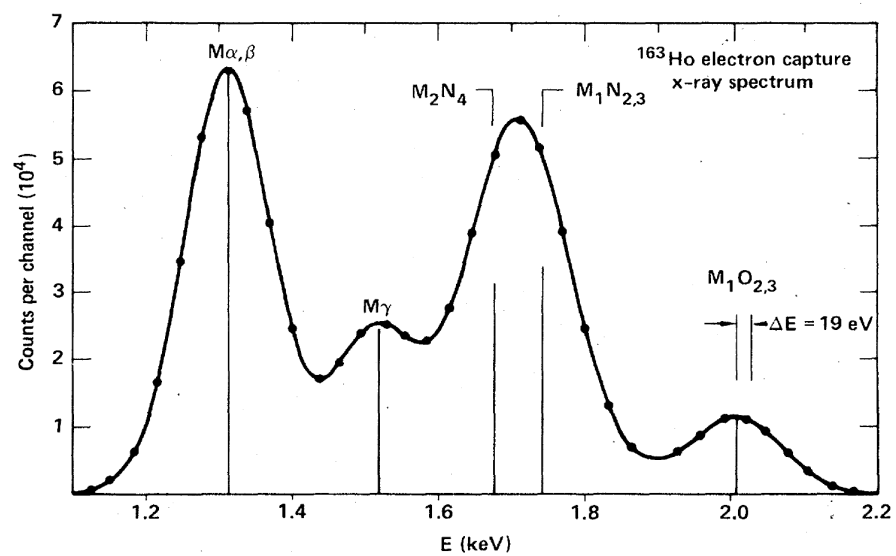


P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

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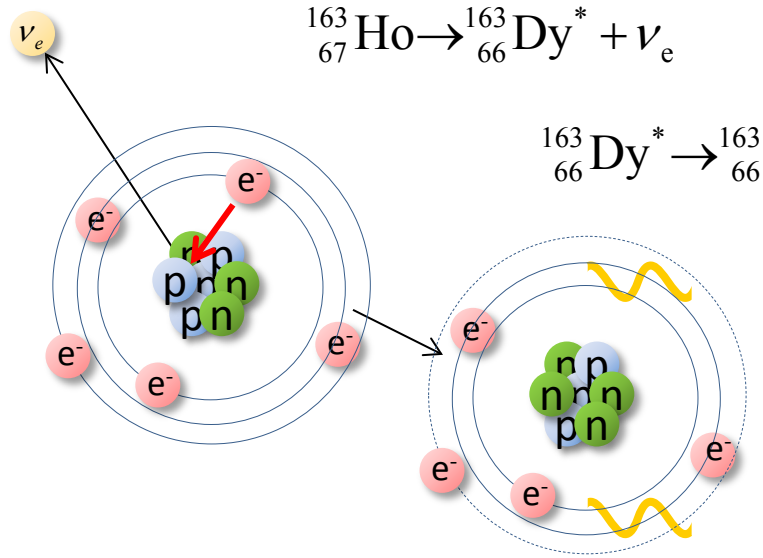
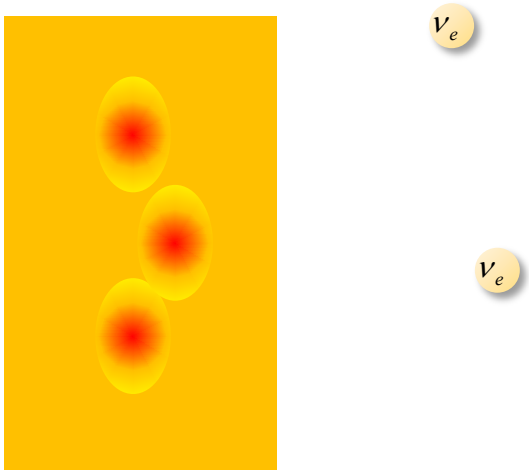



**Calorimetric measurement**




Source = Detector

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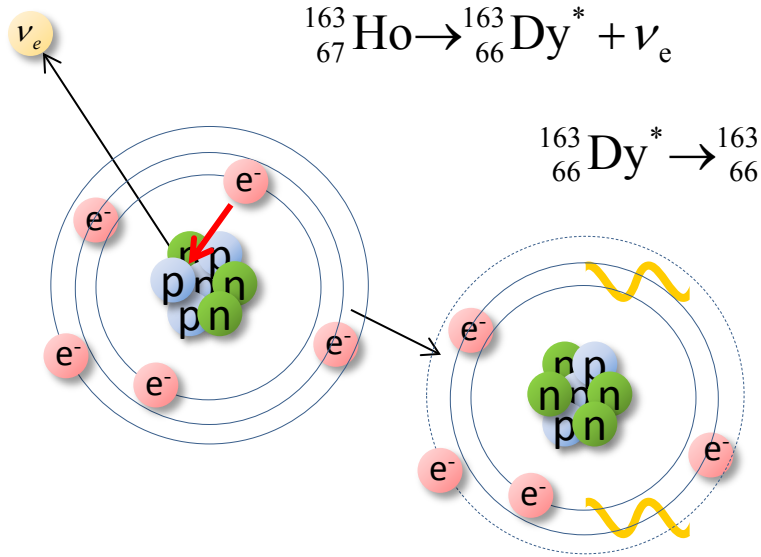


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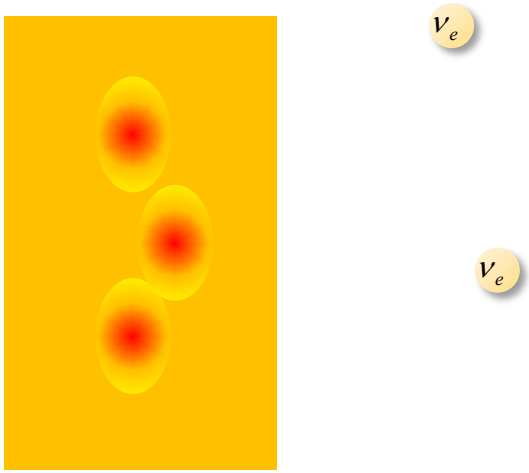


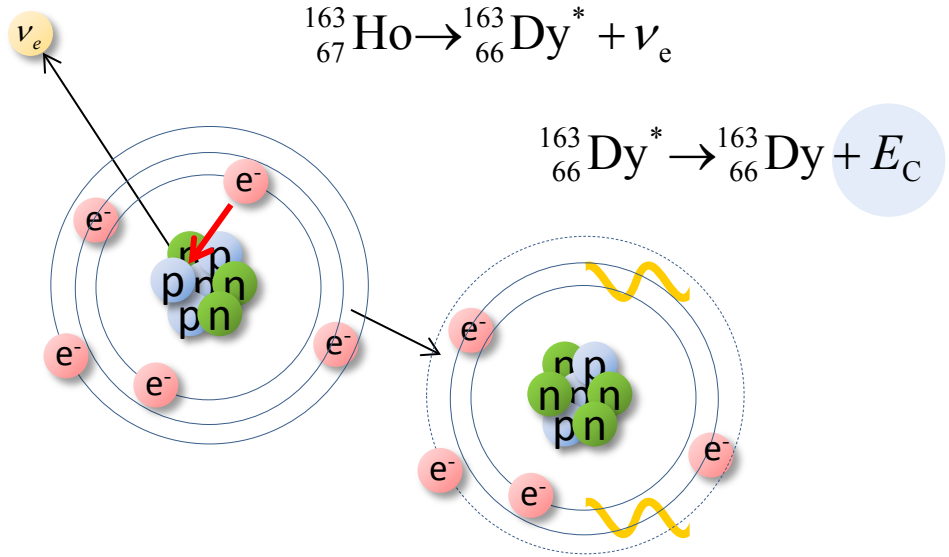

Source = Detector

# Electron capture in $^{163}$Ho: spectrum

Atomic de-excitation:

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

**Calorimetric measurement**




Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

**CALORIMETRIC MEASUREMENTS OF $^{163}$HOLMIUM DECAY AS TOOLS TO DETERMINE THE ELECTRON NEUTRINO MASS**

A. DE RÚJULA and M. LUSIGNOLI [1]
*CERN, Geneva, Switzerland*

# Electron capture in $^{163}$Ho: spectrum

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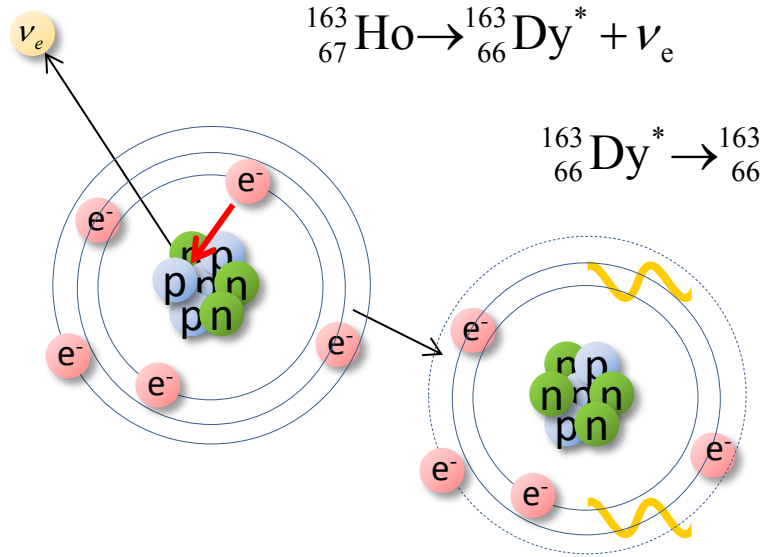
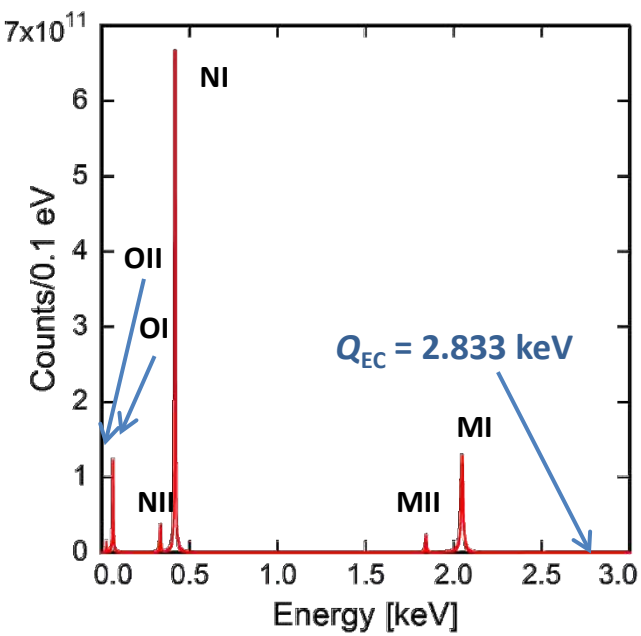
- **Auger electrons**
- **Coster-Kronig transitions**

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

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




**Calorimetric measurement**




$$\frac{dW}{dE_{\mathrm{C}}} = \mathrm{A}\left(Q_{\mathrm{EC}} - E_{\mathrm{C}}\right)^{2} \sqrt{1 - \frac{m_{\nu}^{2}}{\left(Q_{\mathrm{EC}} - E_{\mathrm{C}}\right)^{2}}} \sum_{\mathrm{H}} B_{H} \varphi_{\mathrm{H}}^{2}(0) \frac{\frac{\Gamma_{\mathrm{H}}}{2\pi}}{\left(E_{\mathrm{C}} - E_{\mathrm{H}}\right)^{2} + \frac{\Gamma_{\mathrm{H}}^{2}}{4}}$$

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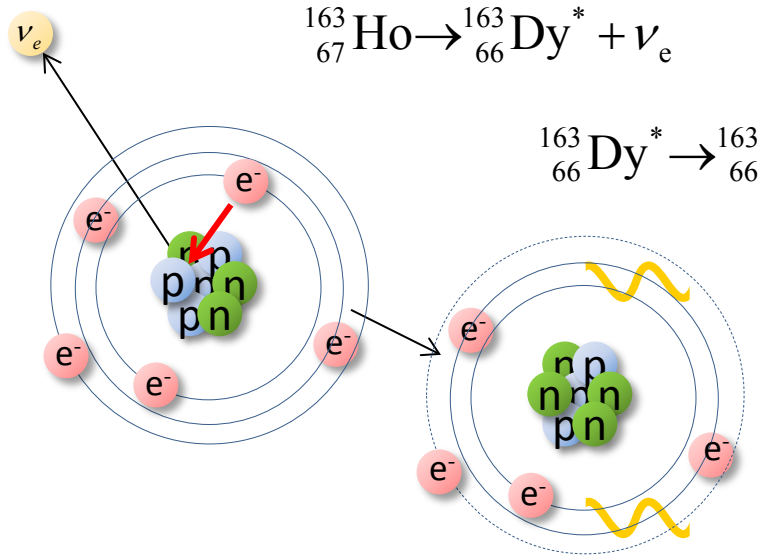


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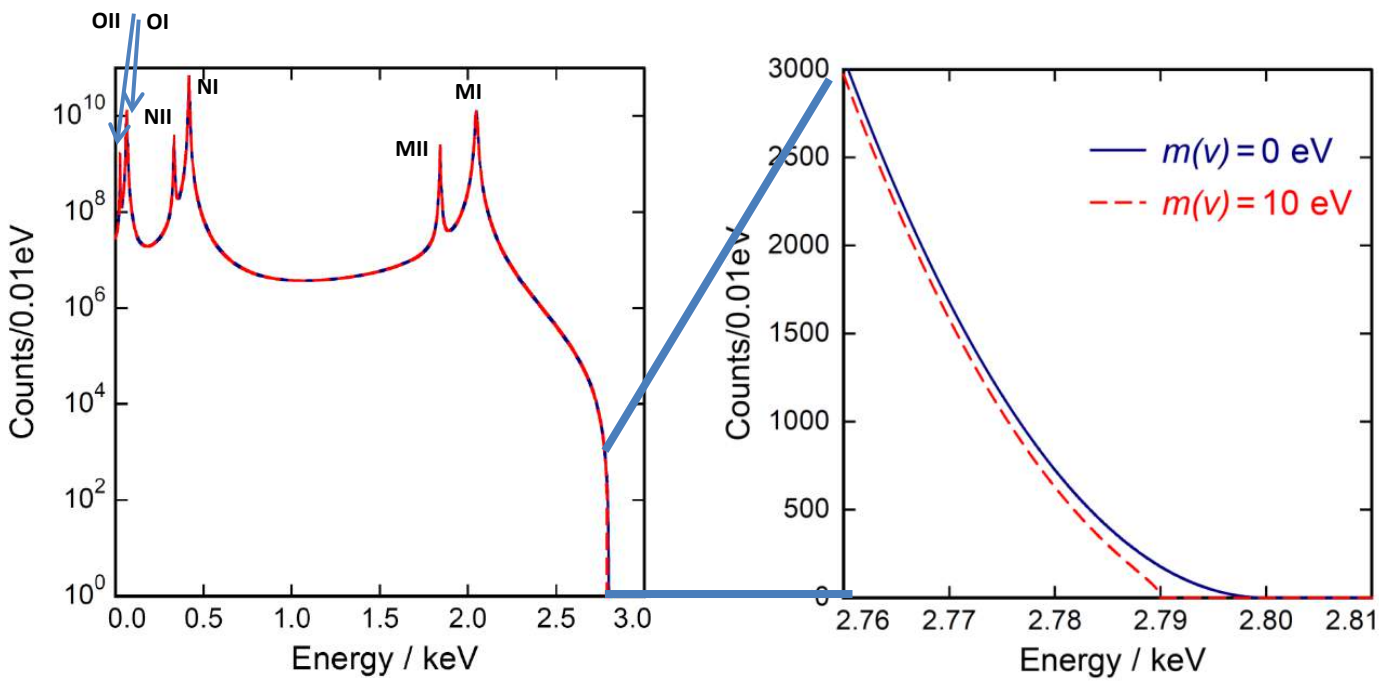
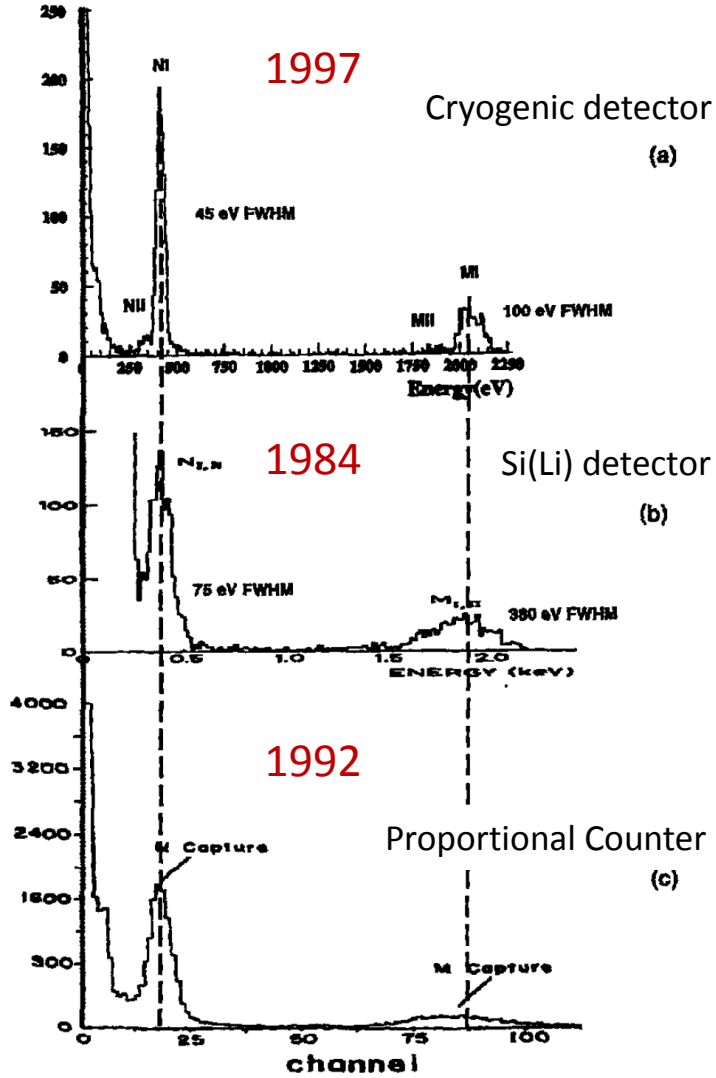


# Electron capture in $^{163}$Ho: history




F. Gatti et al., Physics Letters B 398 (1997) 415-419


(a) F. Gatti et al., Physics Letters B 398 (1997) 415-419
(b) E. Laesgaard et al., Proceeding of 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), (1984).
(c) F.X. Hartmann and R.A. Naumann, Nucl. Instr. Meth. A 3 13 (1992) 237.

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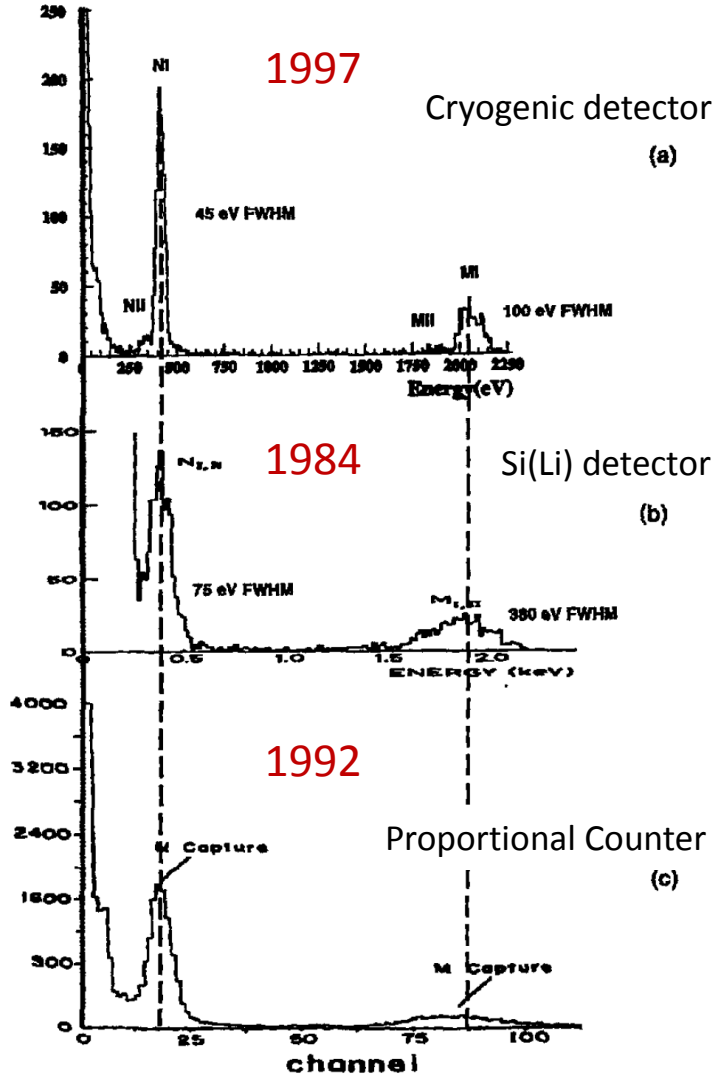


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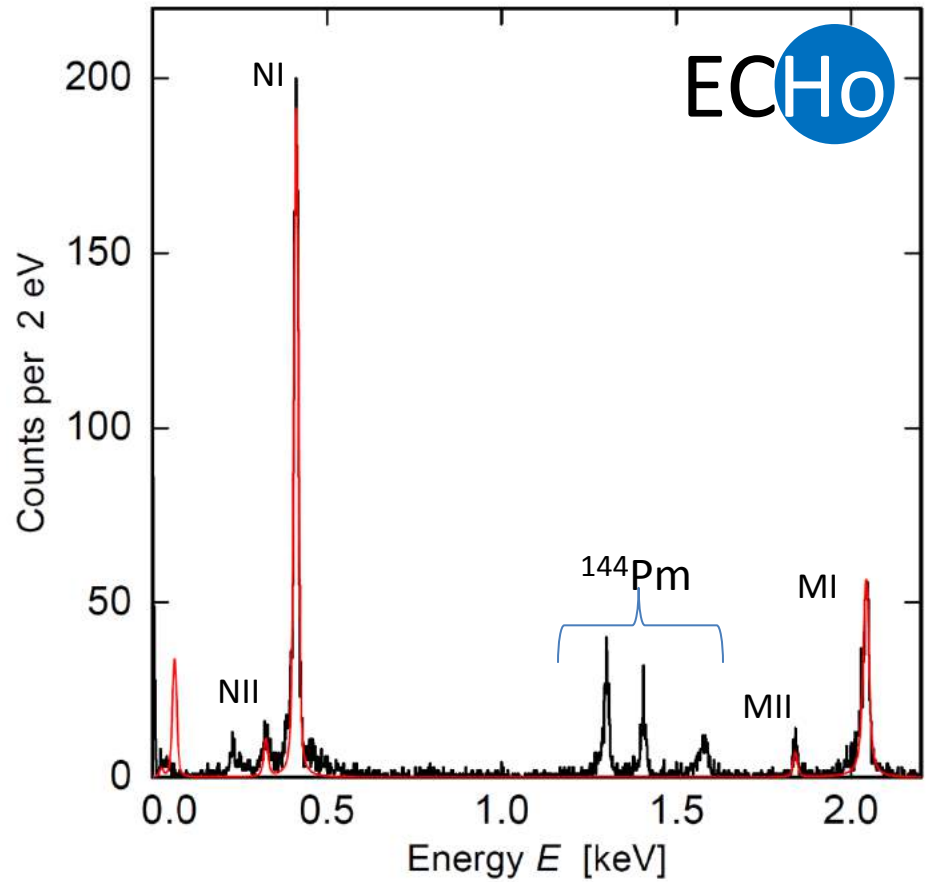
2011




P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)

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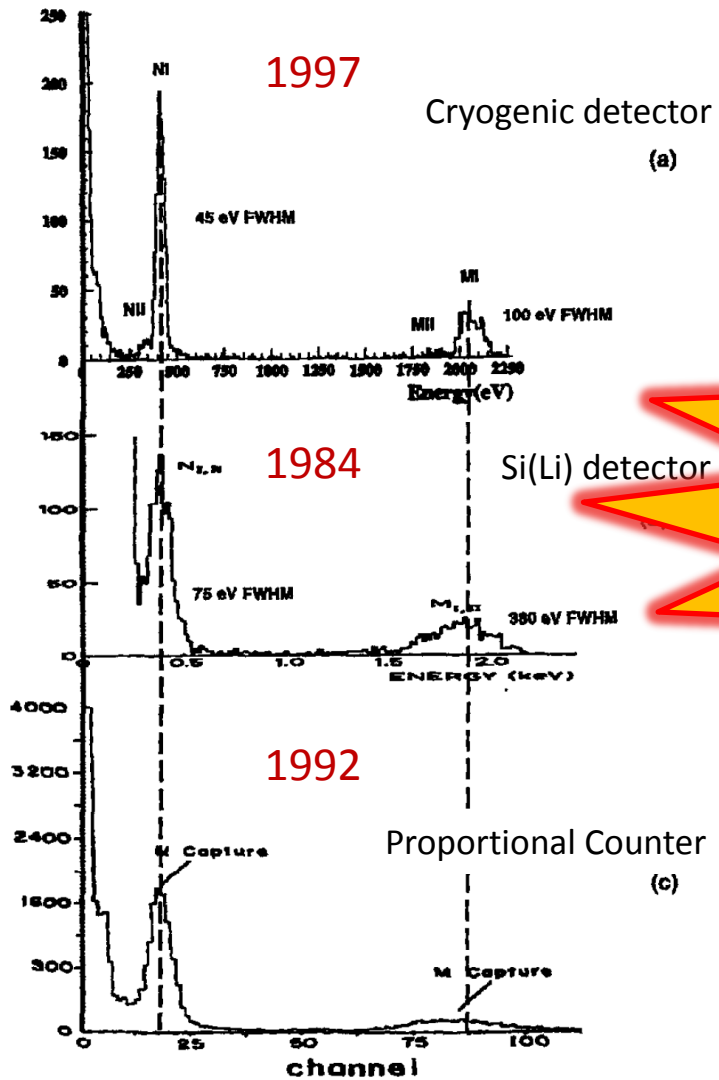


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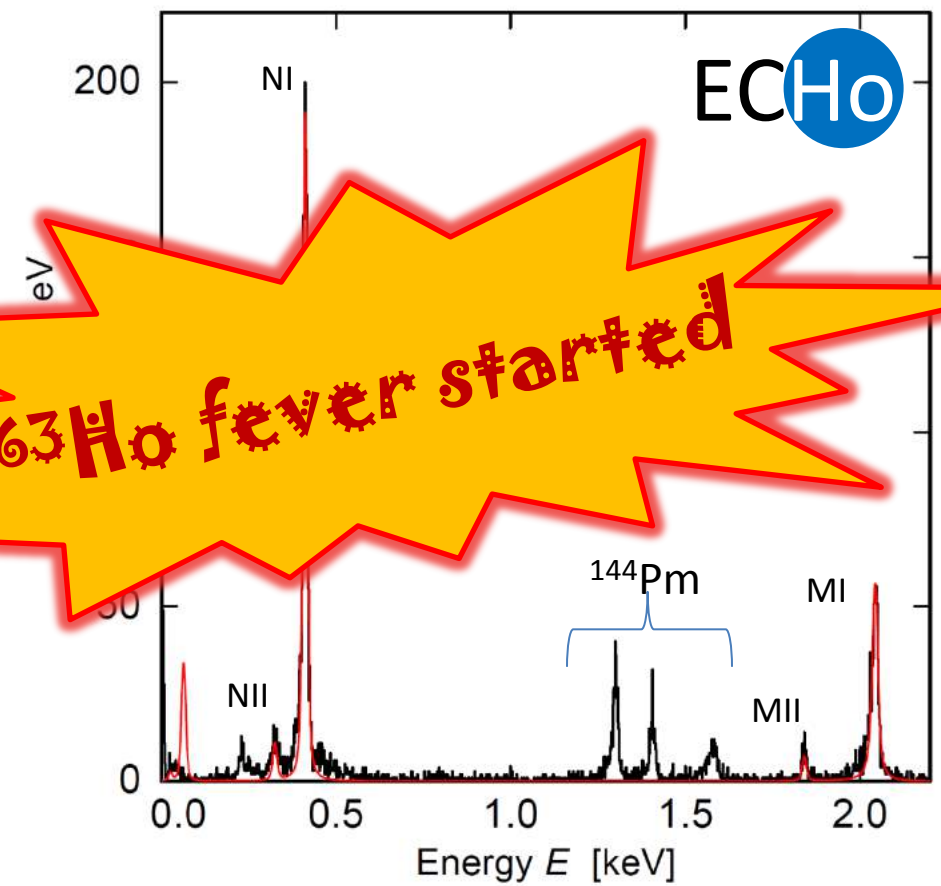


$^{163}$Ho fever started

P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)

(a) F. Gatti et al., Physics Letters B 398 (1997) 415-419
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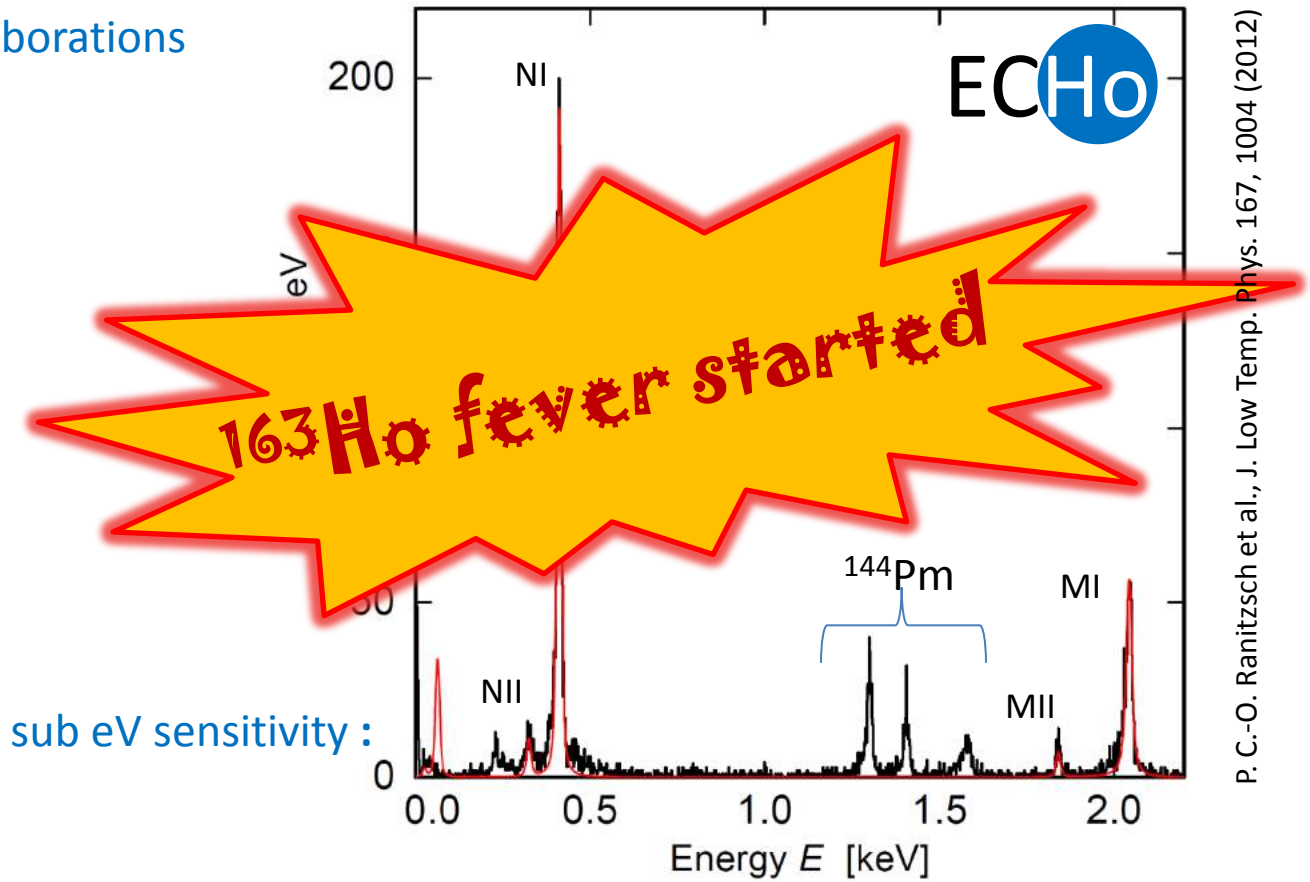
# Electron capture in $^{163}$Ho: present

- Calorimetric measurement of the $^{163}$Ho spectrum 2011
- Three internaltional collaborations

ECHo (1)

HOLMES (2)

NuMECS (3)




P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)

Common challenges to reach sub eV sensitivity :

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


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

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

(3) M. Croce et al., arXiv:1510.03874

# Requirements for sub-eV sensitivity in ECHo

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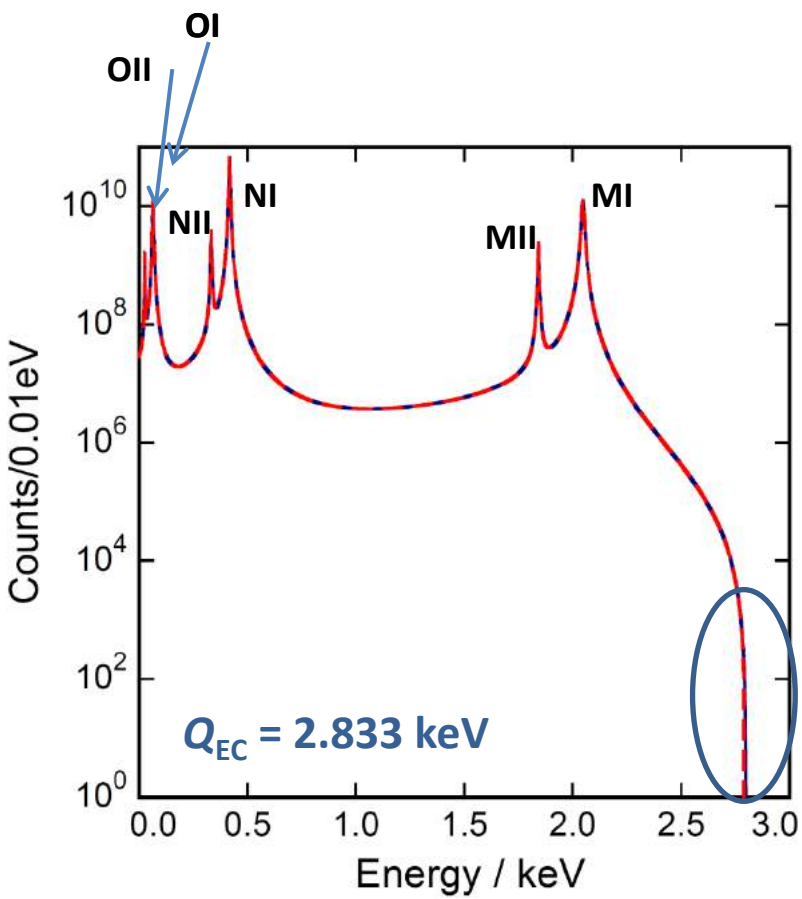
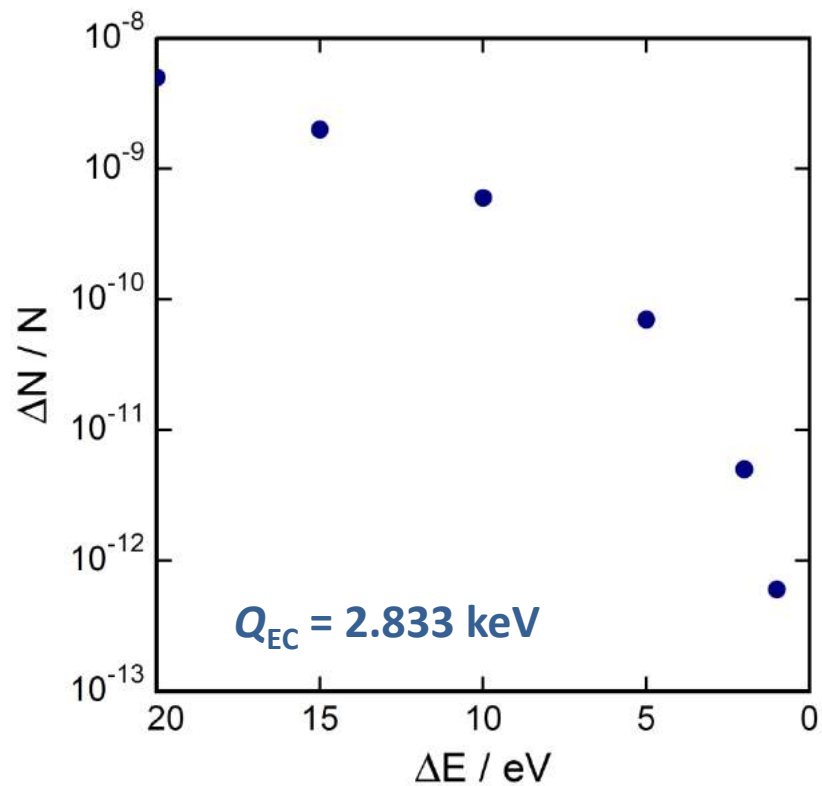
Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Fraction of events at endpoint regions

➢ In the interval 2.832 -2.833 keV only $6\times10^{-13}$



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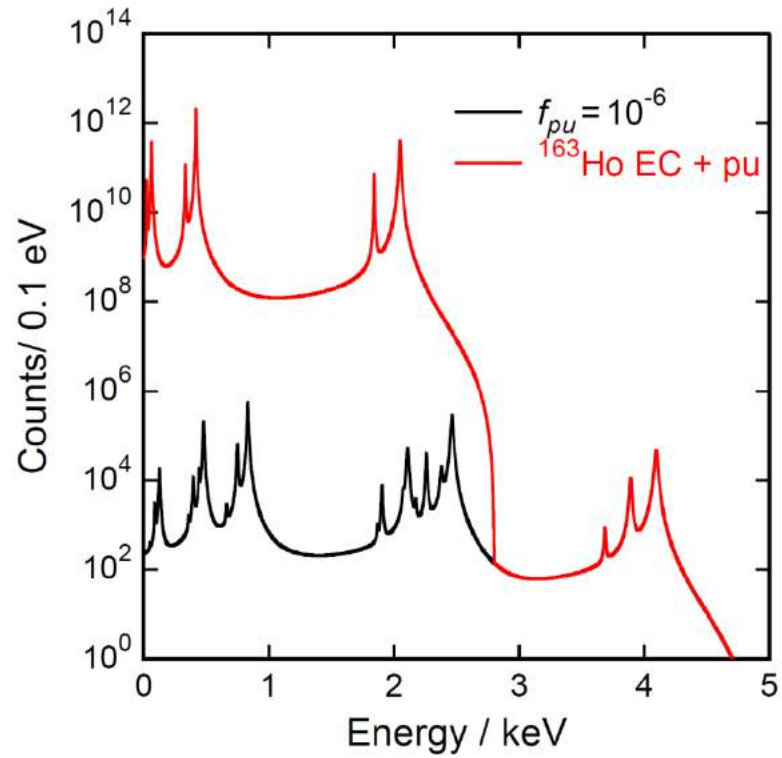
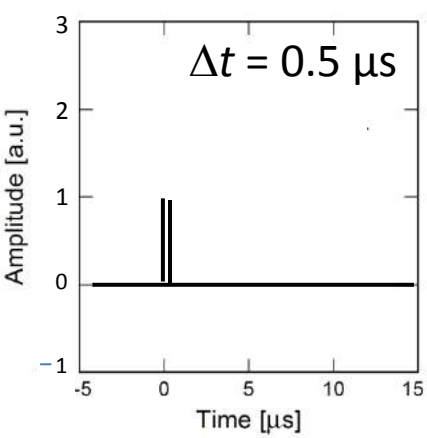
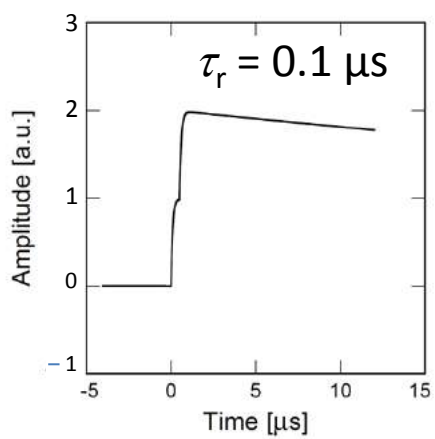
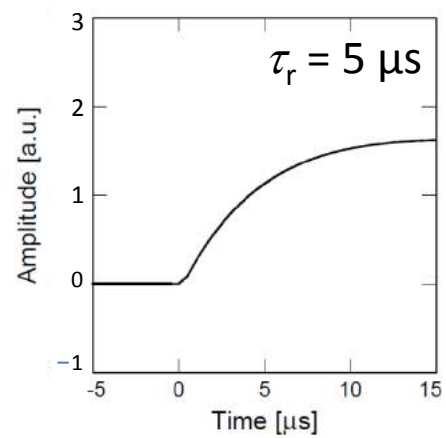
Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

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



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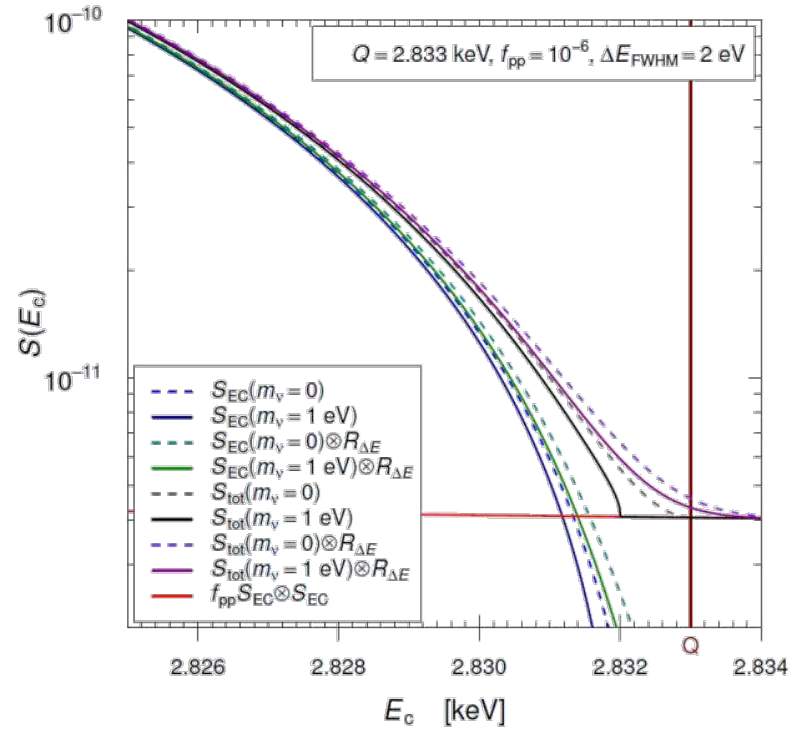
Precision characterization of the endpoint region

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



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Precision characterization of the endpoint region

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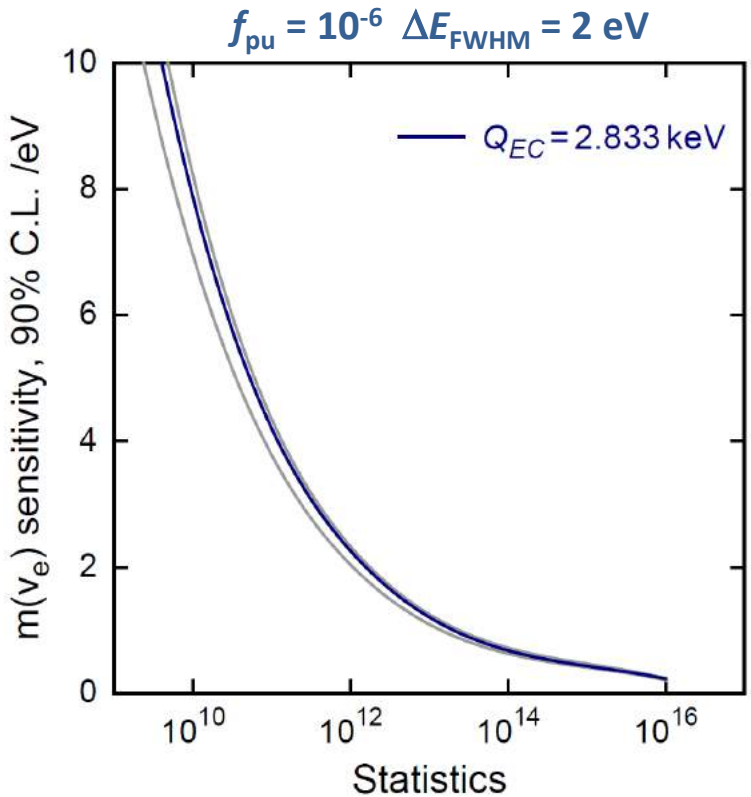
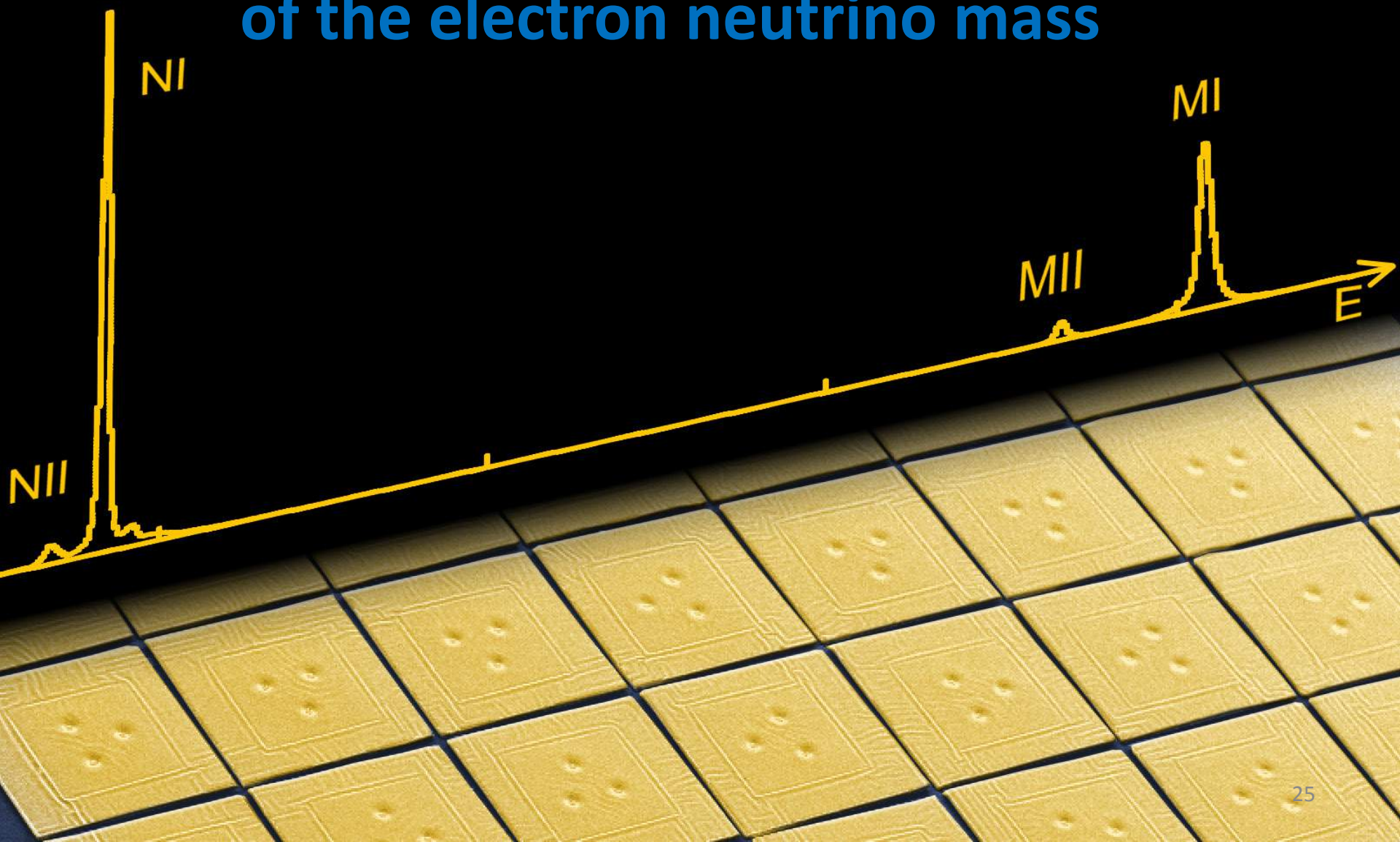
Background level

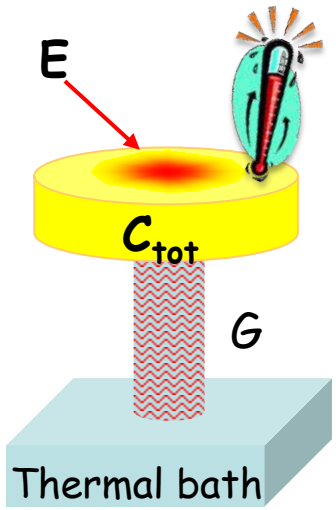
- **< $10^{-6}$ events/eV/det/day**



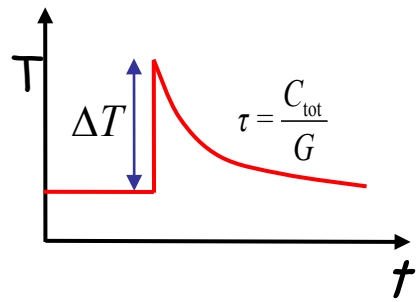
# Low temperature detectors for direct determination of the electron neutrino mass



# Low temperature micro-calorimeters




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




$E$ = 10 keV

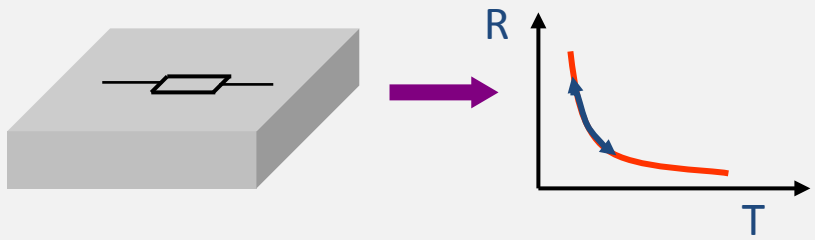
$C_{tot}$ = 1 pJ/K

→ ~ 1 mK

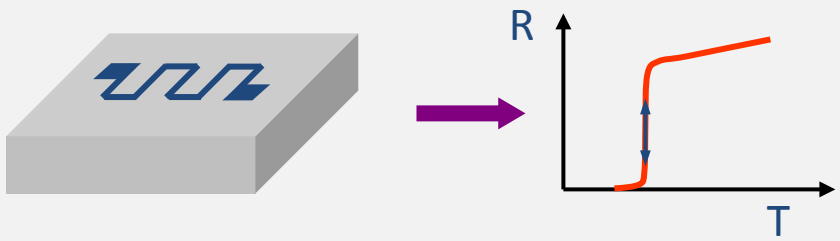
- Very small volume
- Working temperature below 100 mK
  small specific heat
  small thermal noise
- **Very sensitive temperature sensor**

# Temperature sensors

Resistance of highly doped semiconductors



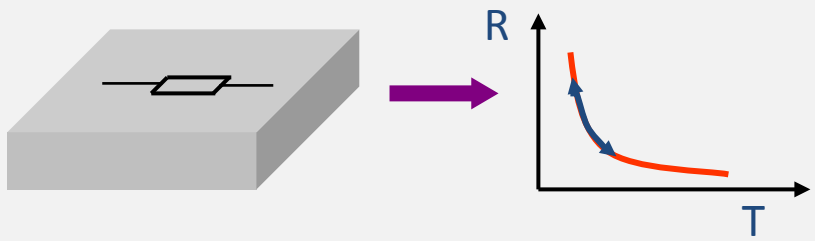

Resistance at superconducting transition,TES




Magnetization of paramagnetic material, MMC

# Temperature sensors

Resistance of highly doped semiconductors

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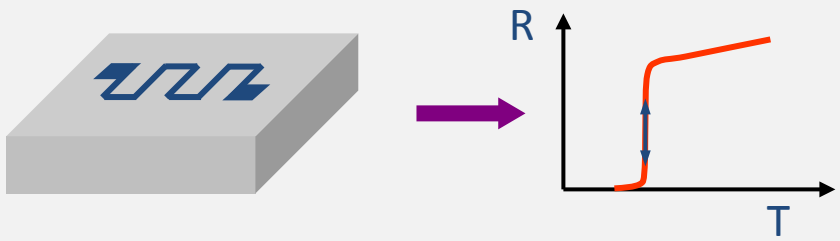


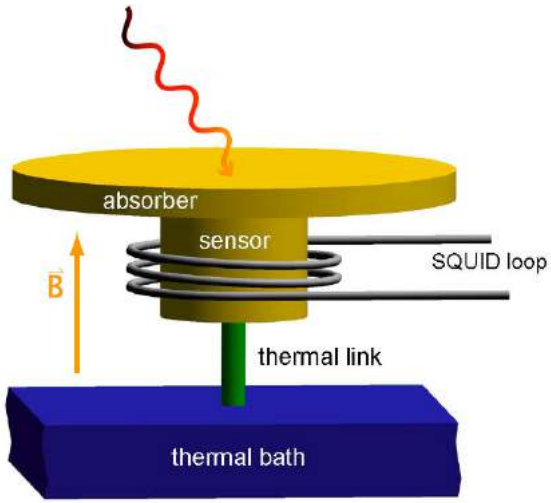

Magnetization of paramagnetic material, MMC


HOLMES

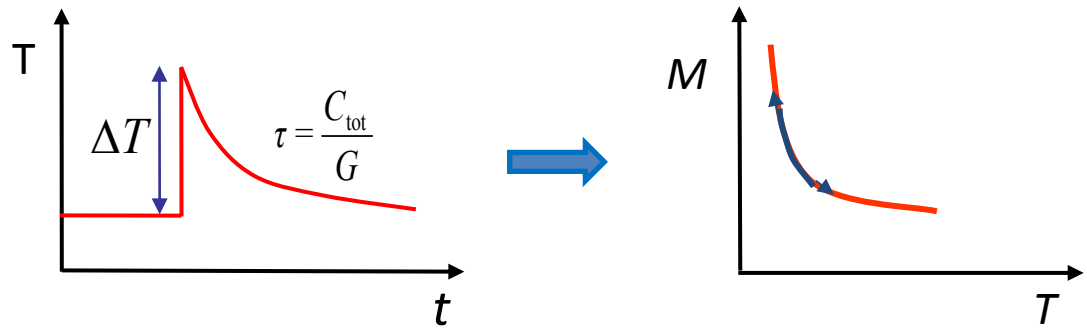
NuMECS

ECHo

# Metallic magnetic calorimeters (MMCs)



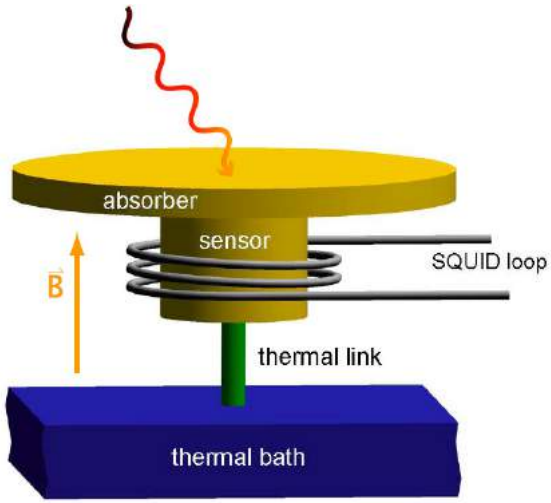

A. Fleischmann et al.,
*AIP Conf. Proc.* **1185**, 571, (2009)

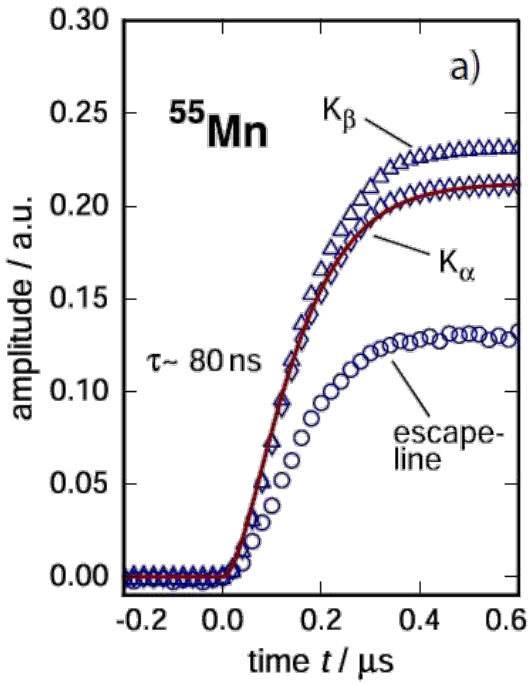



- Paramagnetic Au:Er sensor
  Ag:Er

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

# Metallic magnetic calorimeters (MMCs)




Fast risetime

→ Reduction un-resolved pile-up

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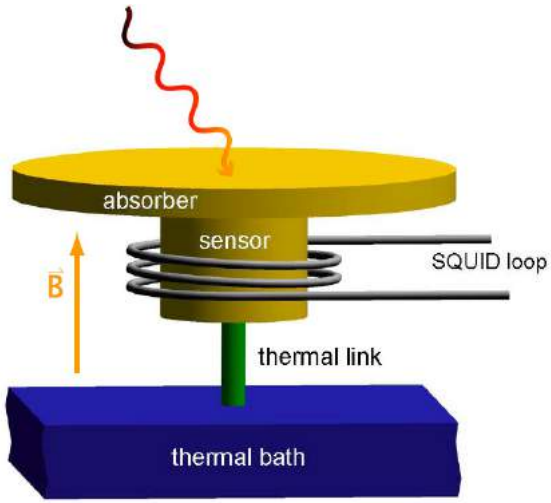
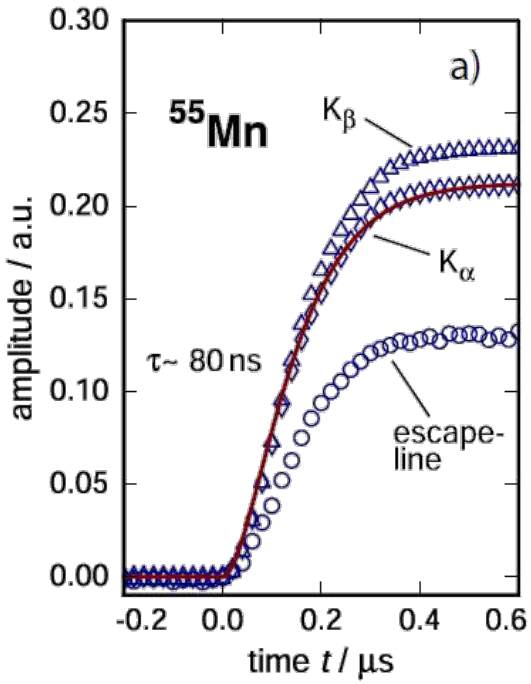
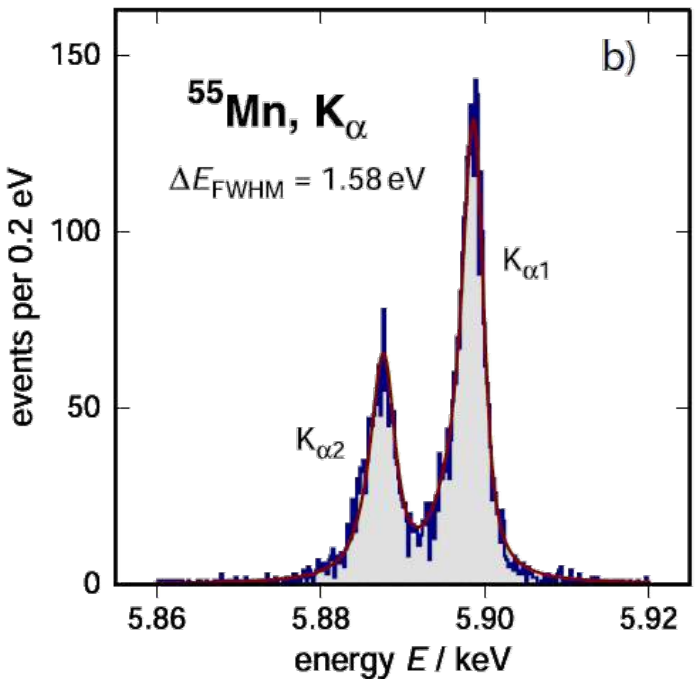



Fast risetime
→ Reduction un-resolved pile-up

Extremely good energy resolution
→Reduced smearing in the end point region



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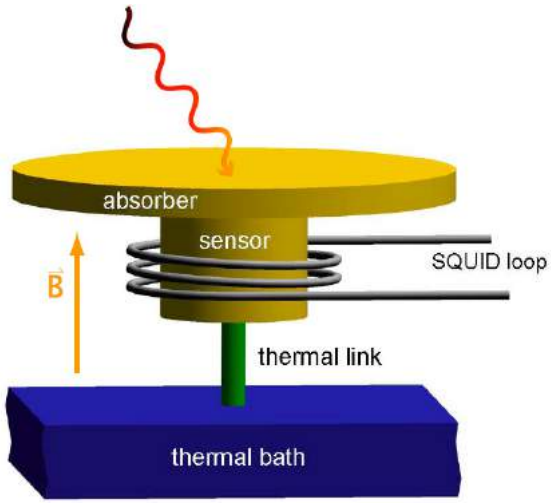
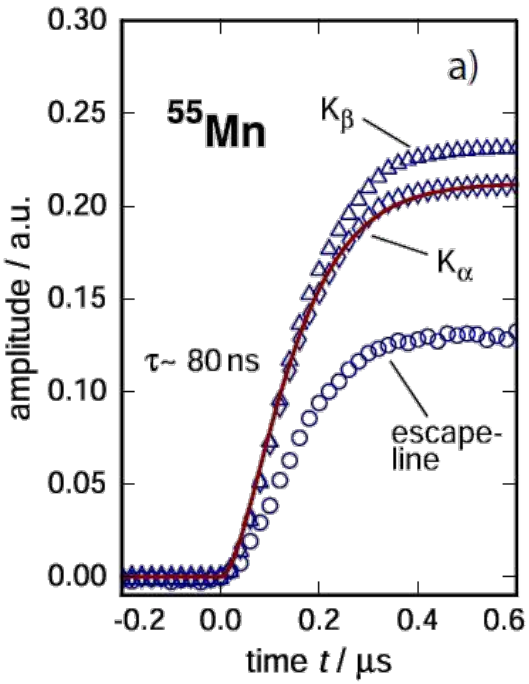
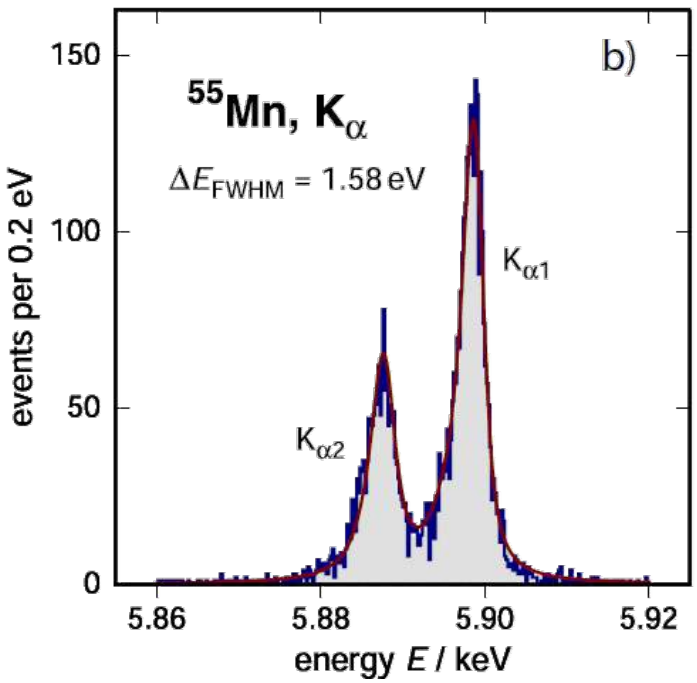


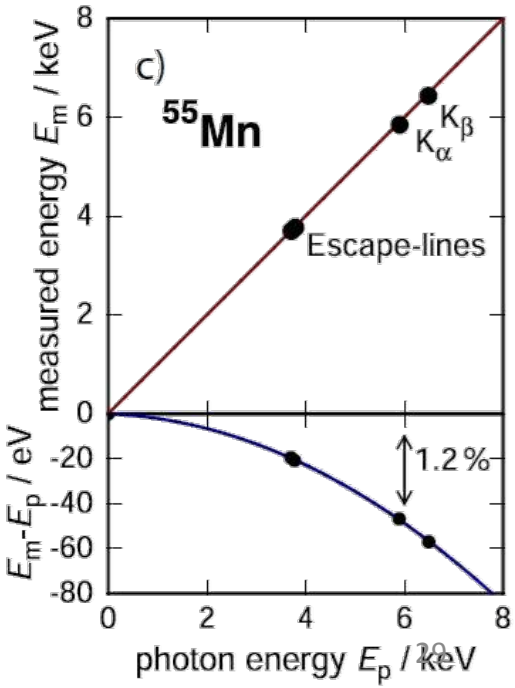

Fast risetime
→ Reduction un-resolved pile-up

Extremely good energy resolution
→Reduced smearing in the end point region

Excellent linearity
→ precise definition of the energy scale

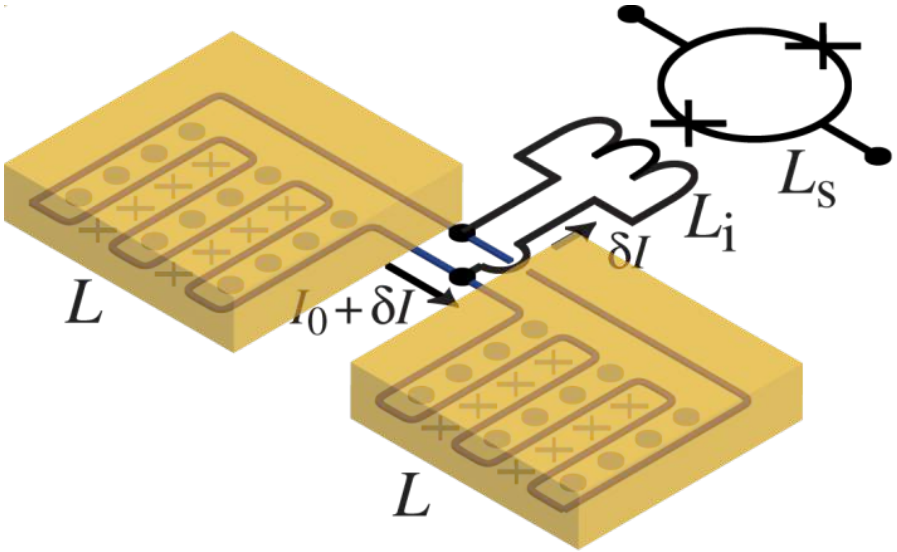


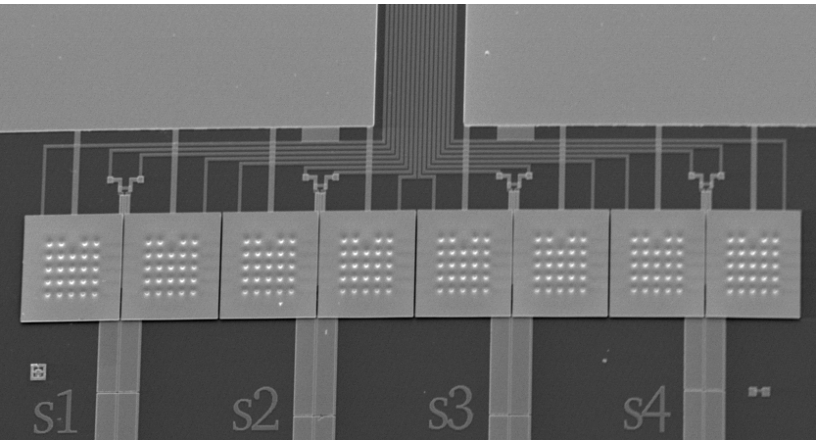



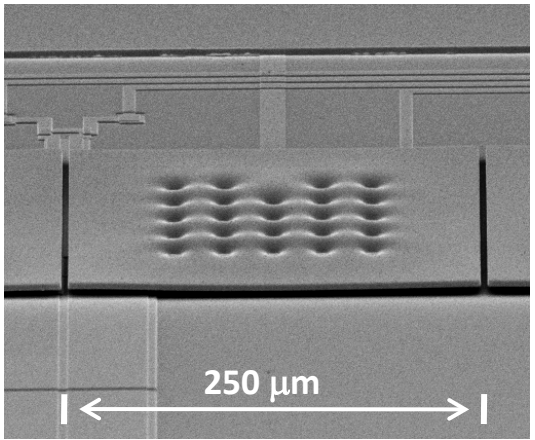



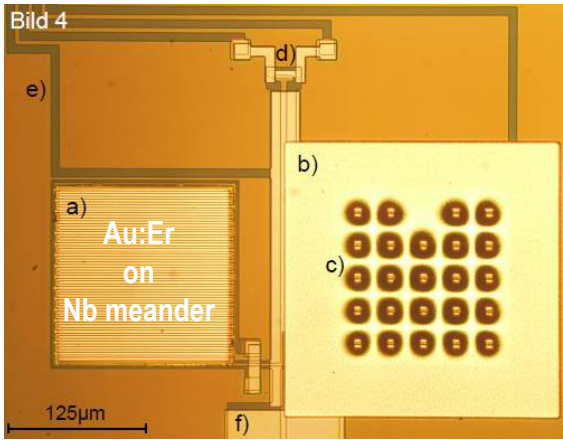
# MMC geometry and read-out

- Planar temperature sensor
- B-field generated by persistent current



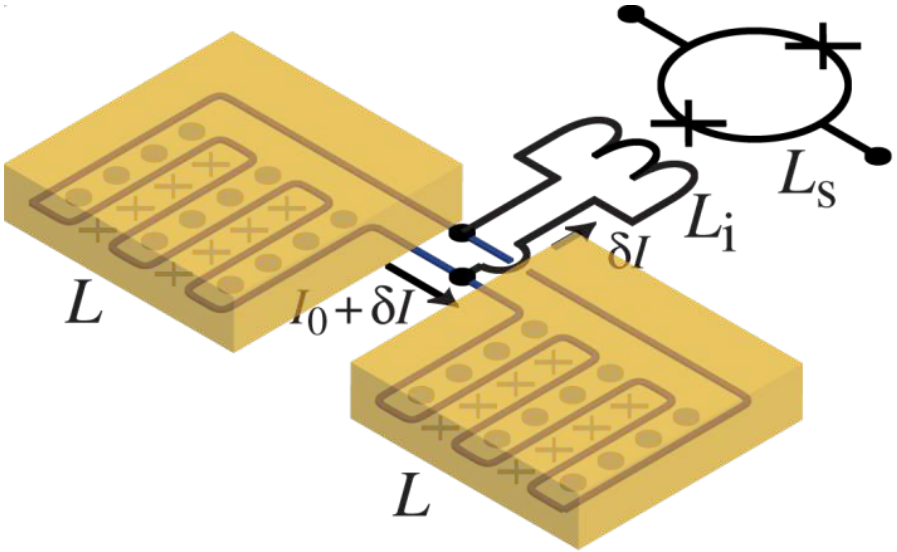



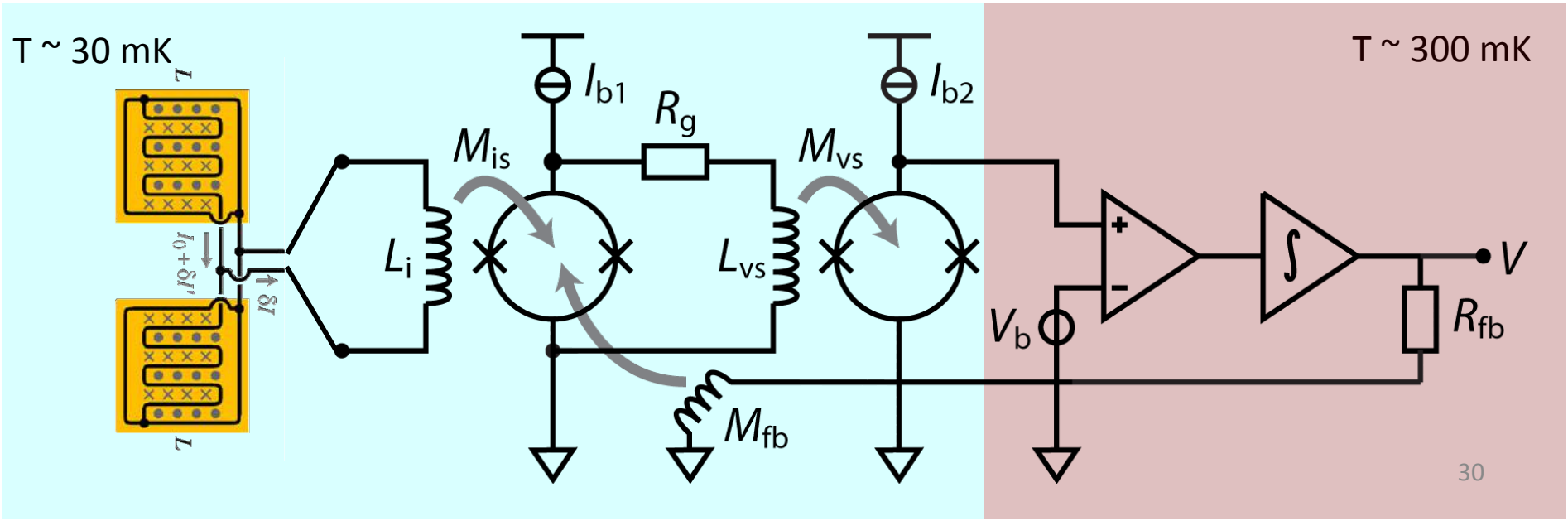



# MMC geometry and read-out

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



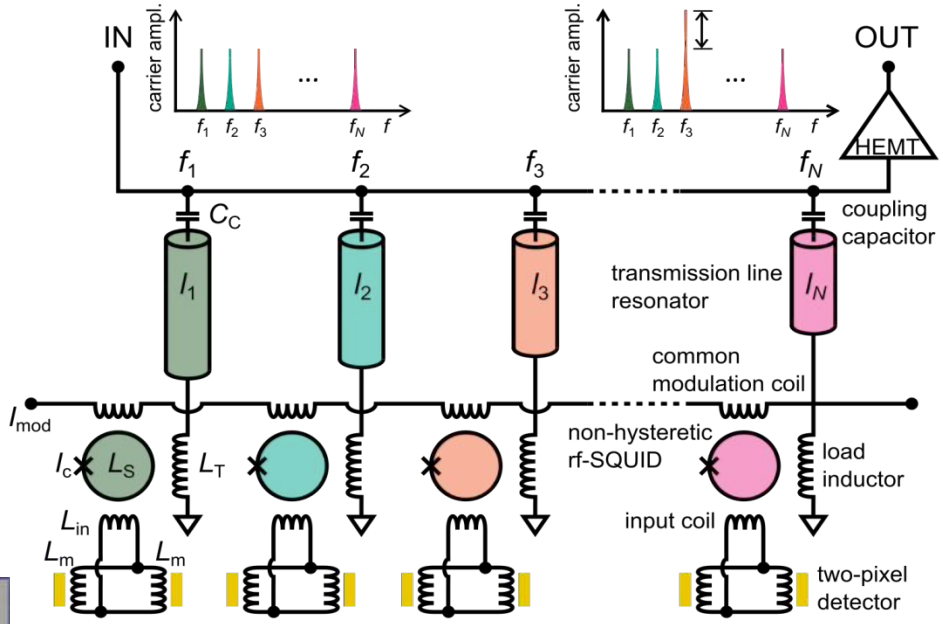

- Two-stage SQUID read-out

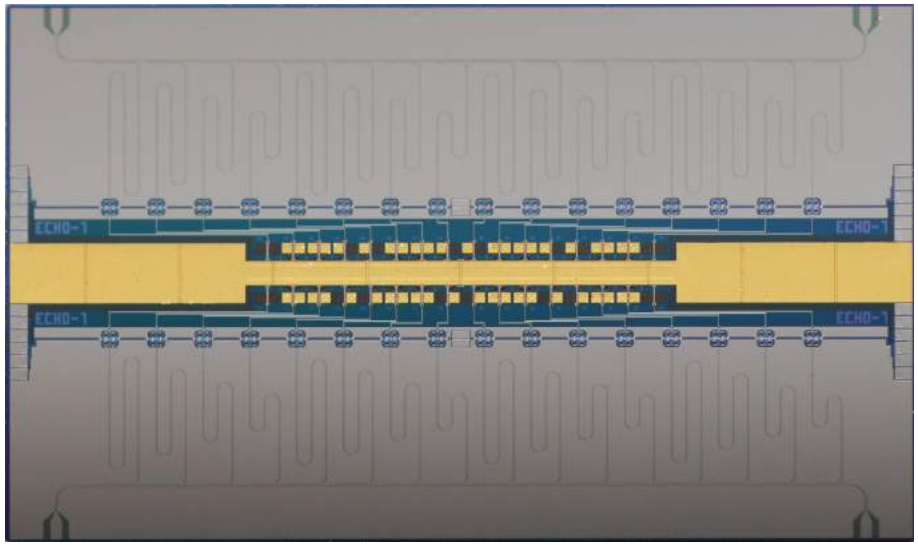


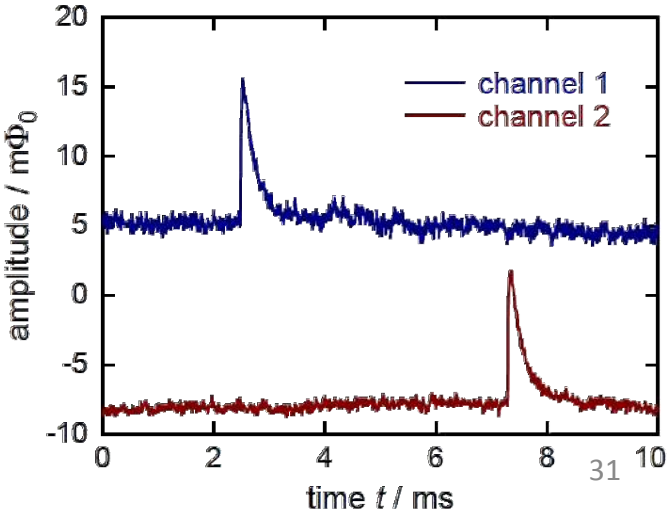
# Multiplexing readout

**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





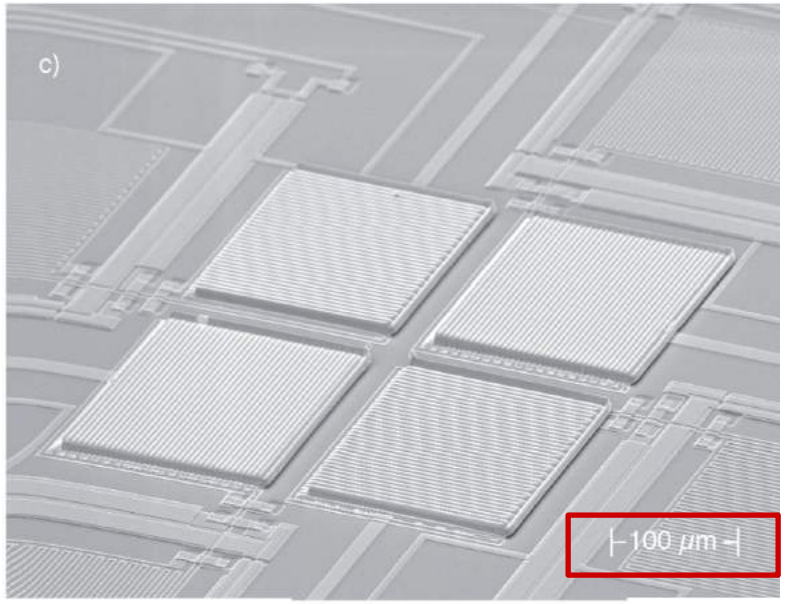

Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

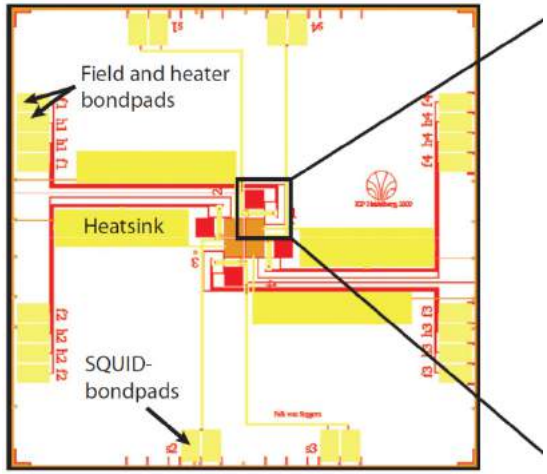
# First detector prototype for $^{163}$Ho – ECHo-0

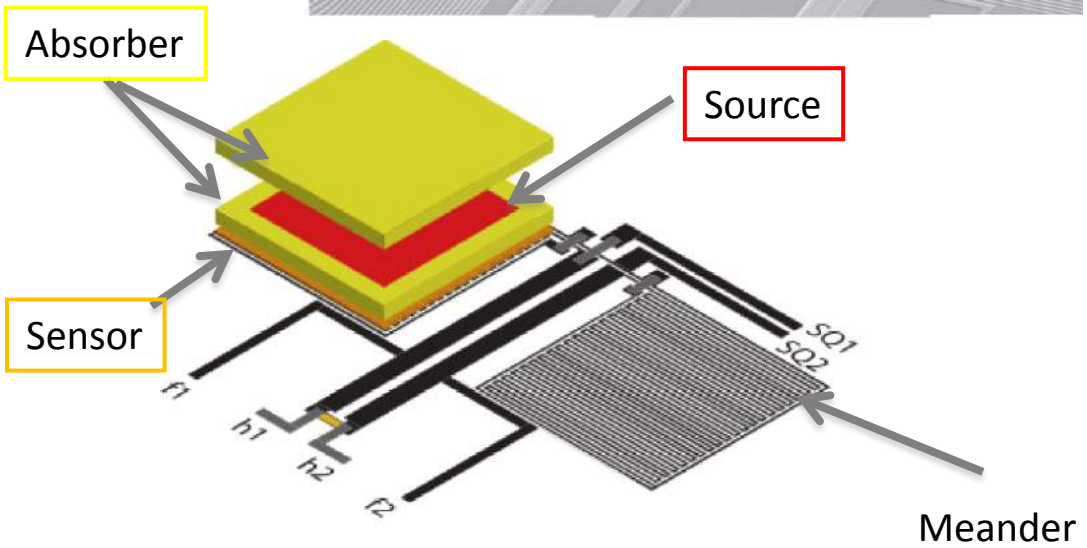
- Absorber for calorimetric measurement
  → ion implantation @ ISOLDE-CERN in 2009
  on-line process

- About 0.01 Bq per pixel

- Operated over more than 4 years




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

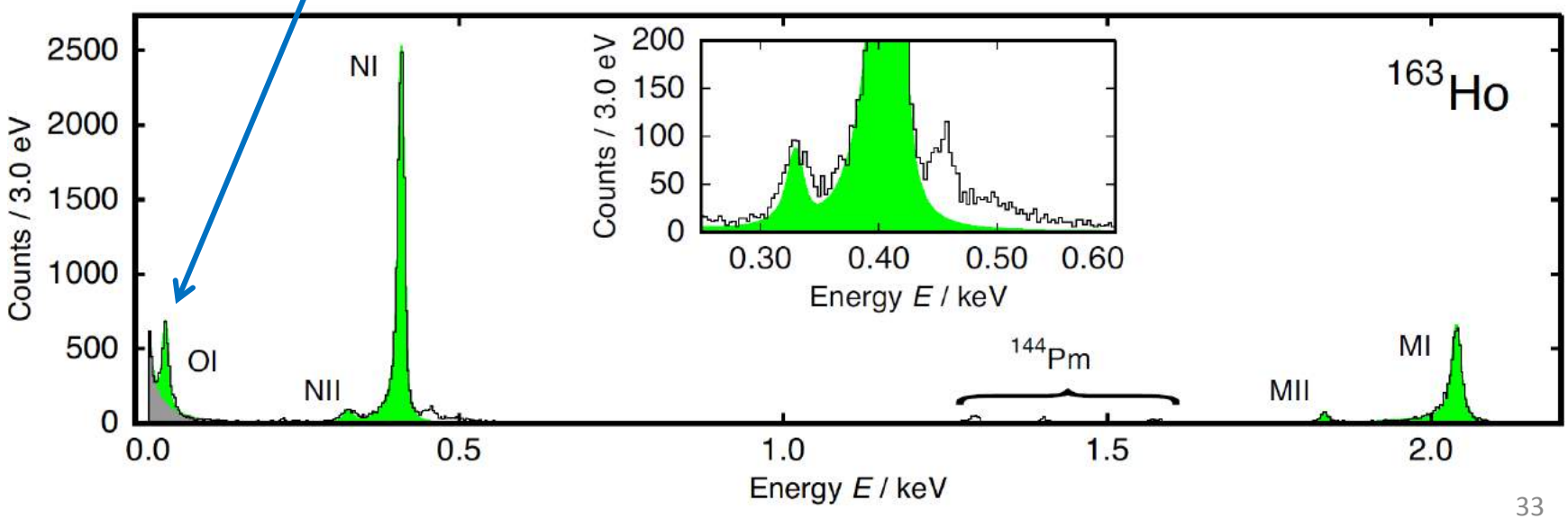
P. C.-O. Ranitzsch et al.,
http://arxiv.org/abs/1409.0071v1

# Calorimetric spectrum

- Rise Time ~ 130 ns
- $\Delta E_{FWHM}$ = 7.6 eV @ 6 keV (2013)
- Non-Linearity < 1% @ 6keV

| | $E_H$ bind. | $E_H$ exp. | $\Gamma_H$ lit. | $\Gamma_H$ 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**

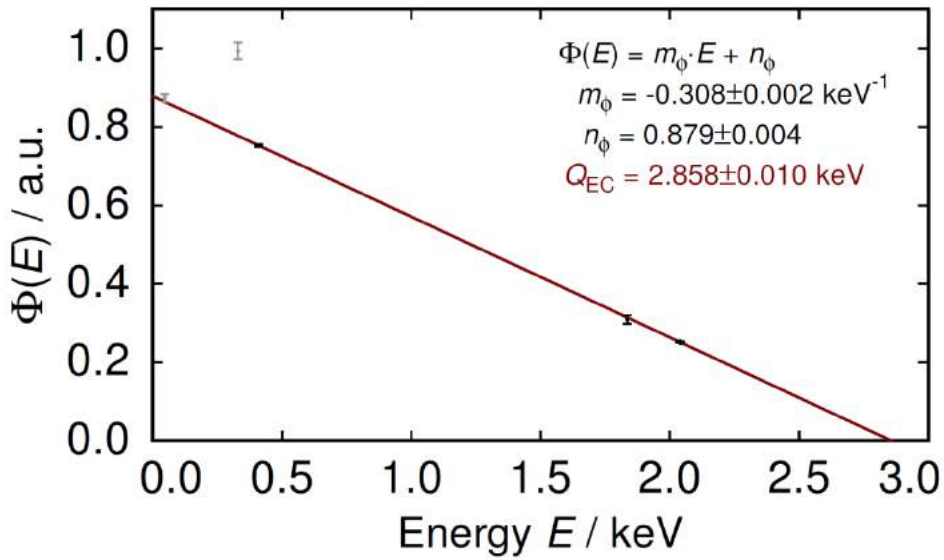


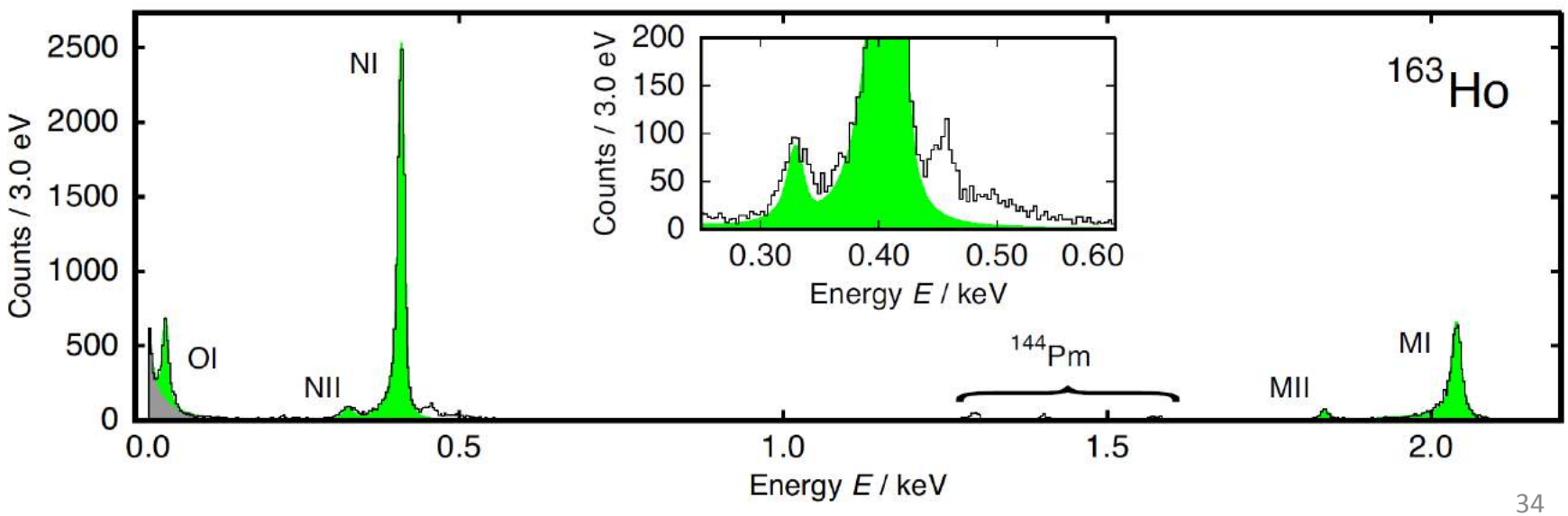

P. C.-O. Ranitzsch et al ., accepted for publication in PRL (2017)

# $Q_{EC}$ 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)

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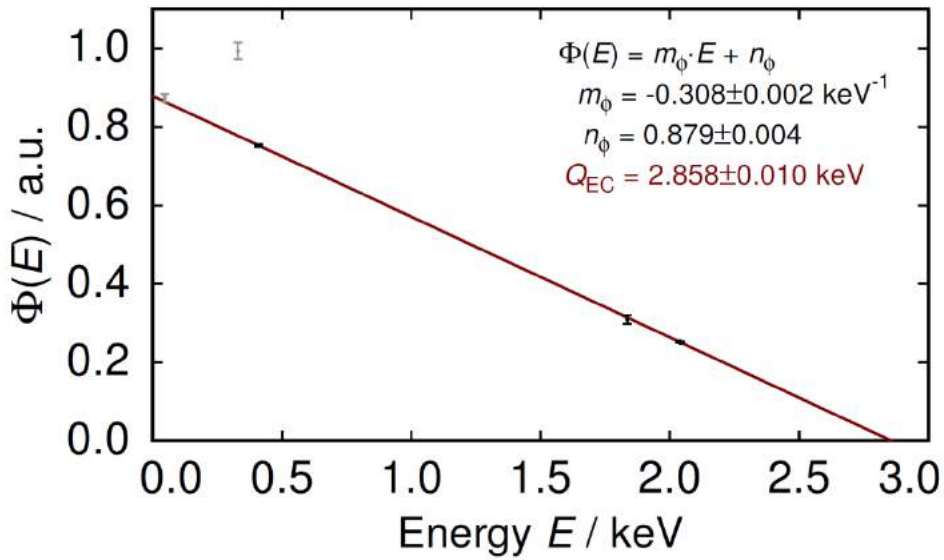
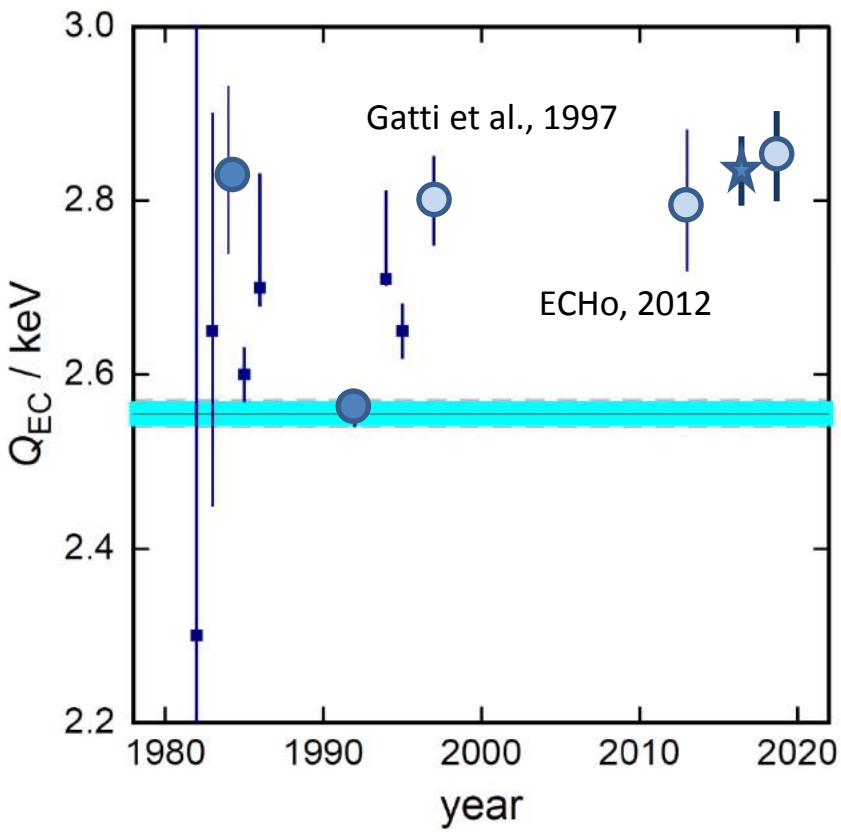



Our result:

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

Penning Trap Mass Spectrometry result:

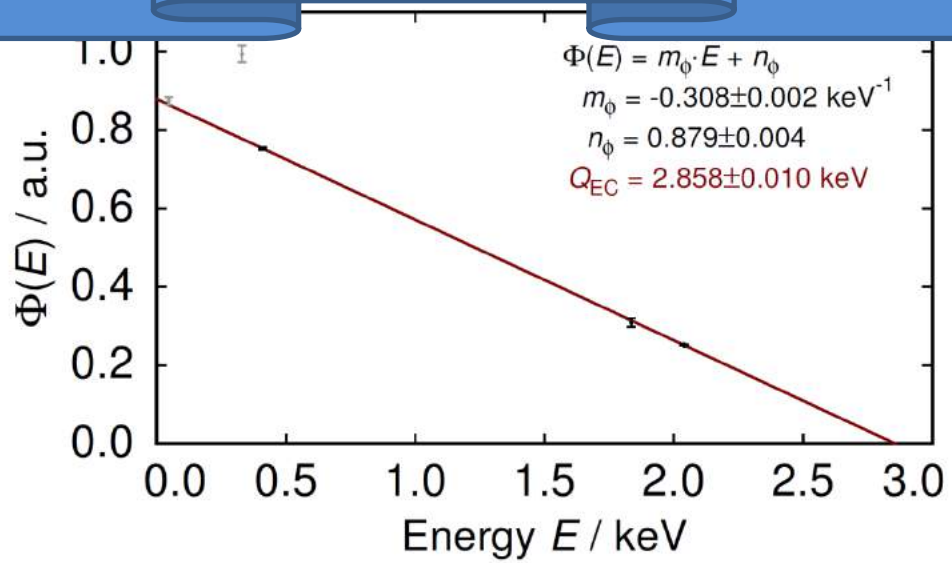
$$Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})\ \text{keV}$$

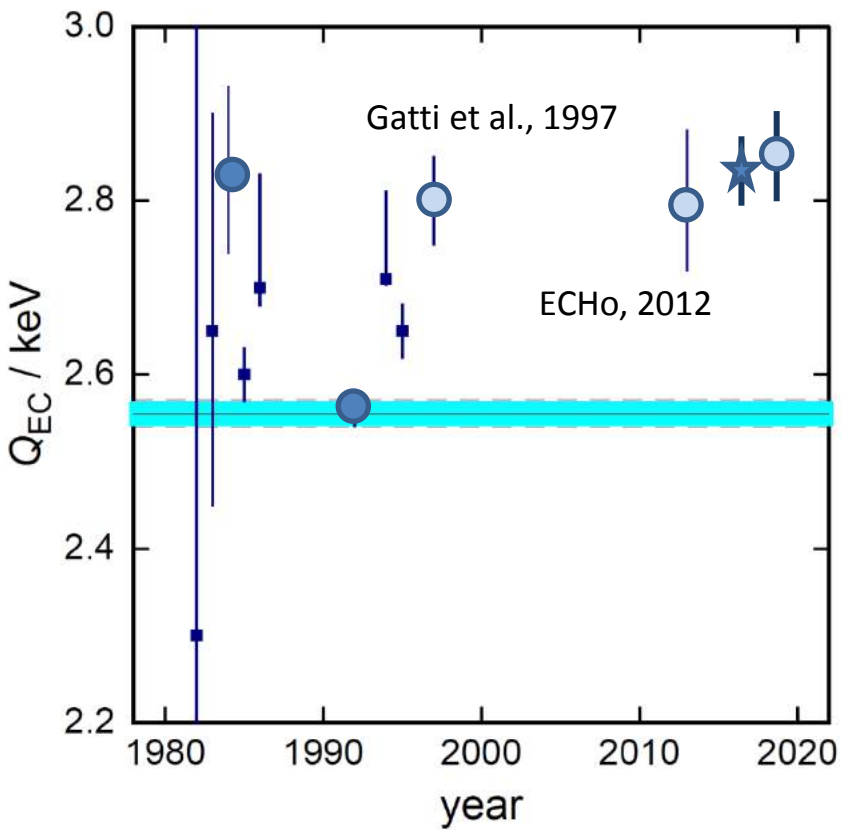
P. C.-O. Ranitzsch et al ., accepted for publication in PRL (2017)

# $Q_{EC}$ determination

**Good agreement between the two measurements**

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

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

# Scaling up

# 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

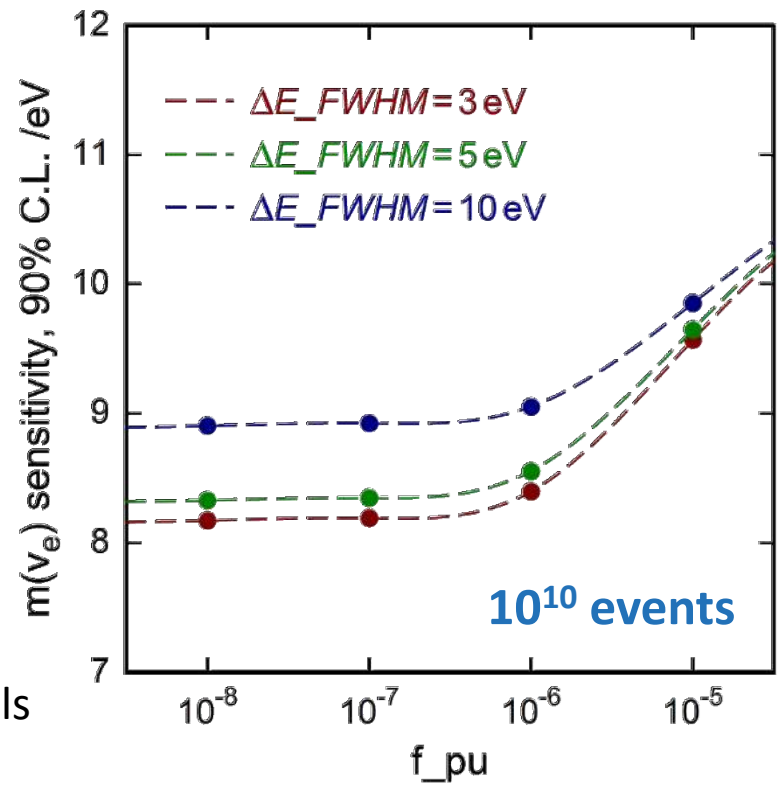
→number of detectors $N$ = 100

Read-out : Parallel read-out: 1 array ~50 single pixels

→ Demonstrate Microwave SQUID Multiplexing

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: $A_t$ = 1 MBq

Detectors: Metallic Magnetic Calorimeters

→ Energy resolution $\Delta E_{FWHM} \leq 3$ eV

→ Time resolution $\tau \leq 0.1$ µs

Unresolved pile-up fraction $f_{pu} \leq 10^{-6}$

→activity per pixel: $A$ = 10 Bq

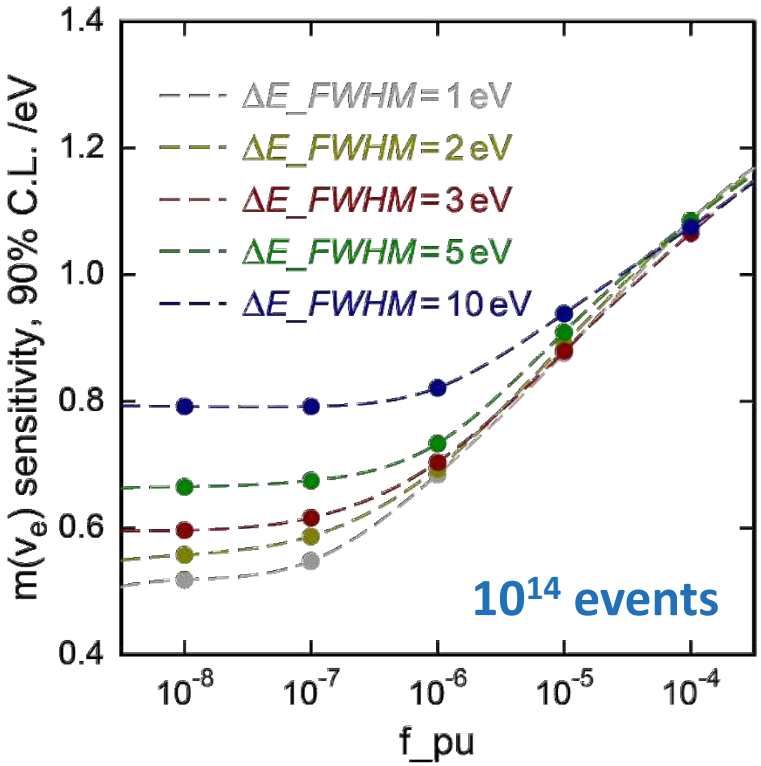
→number of detectors $N = 10^5$

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.

# $^{163}$Ho high purity source

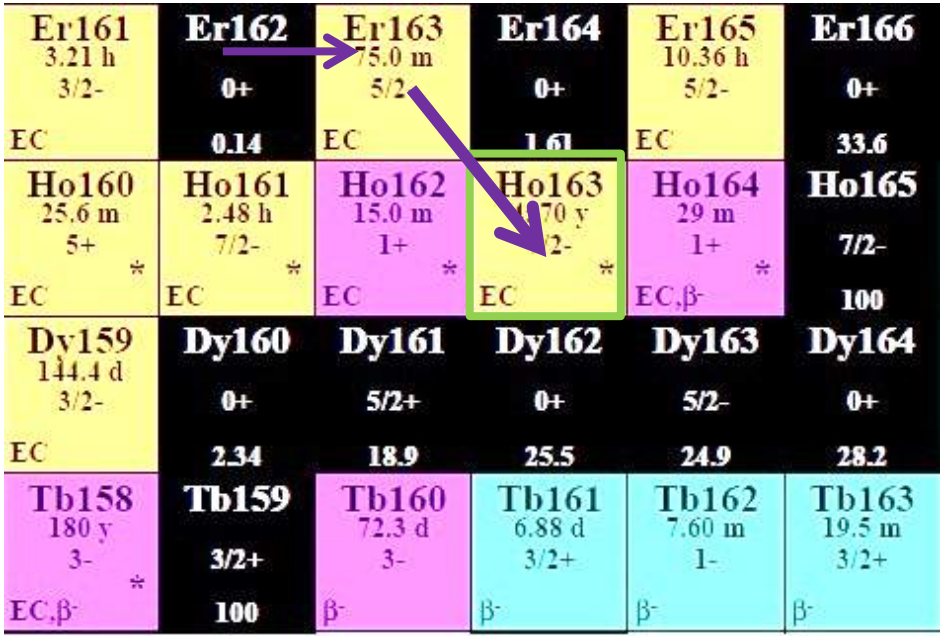
Required activity in the detectors: Final experiment → >$10^6$ Bq → >$10^{17}$ atoms

- Neutron irradiation

  **(n,γ)-reaction on $^{162}$Er**

  **High cross-section**

  **Radioactive contaminants**




H. Dorrer et al, accepted for publication in Radiochim. Acta (2018)

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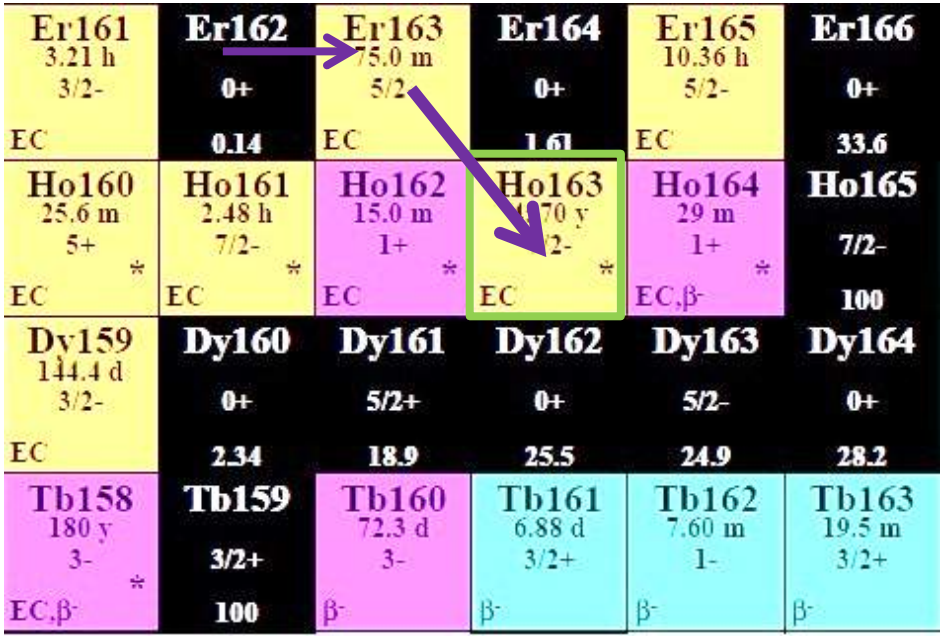
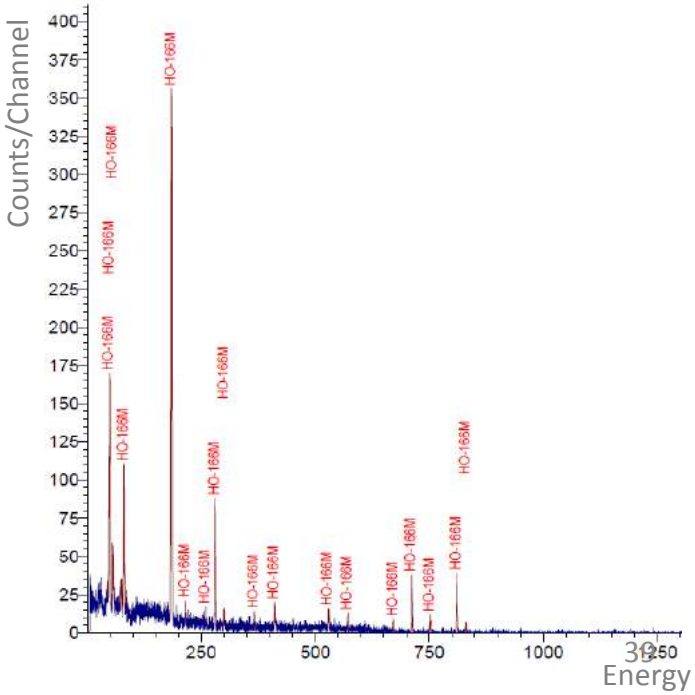
Required activity in the detectors: Final experiment → >$10^6$ Bq → >$10^{17}$ atoms

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

**High cross-section**

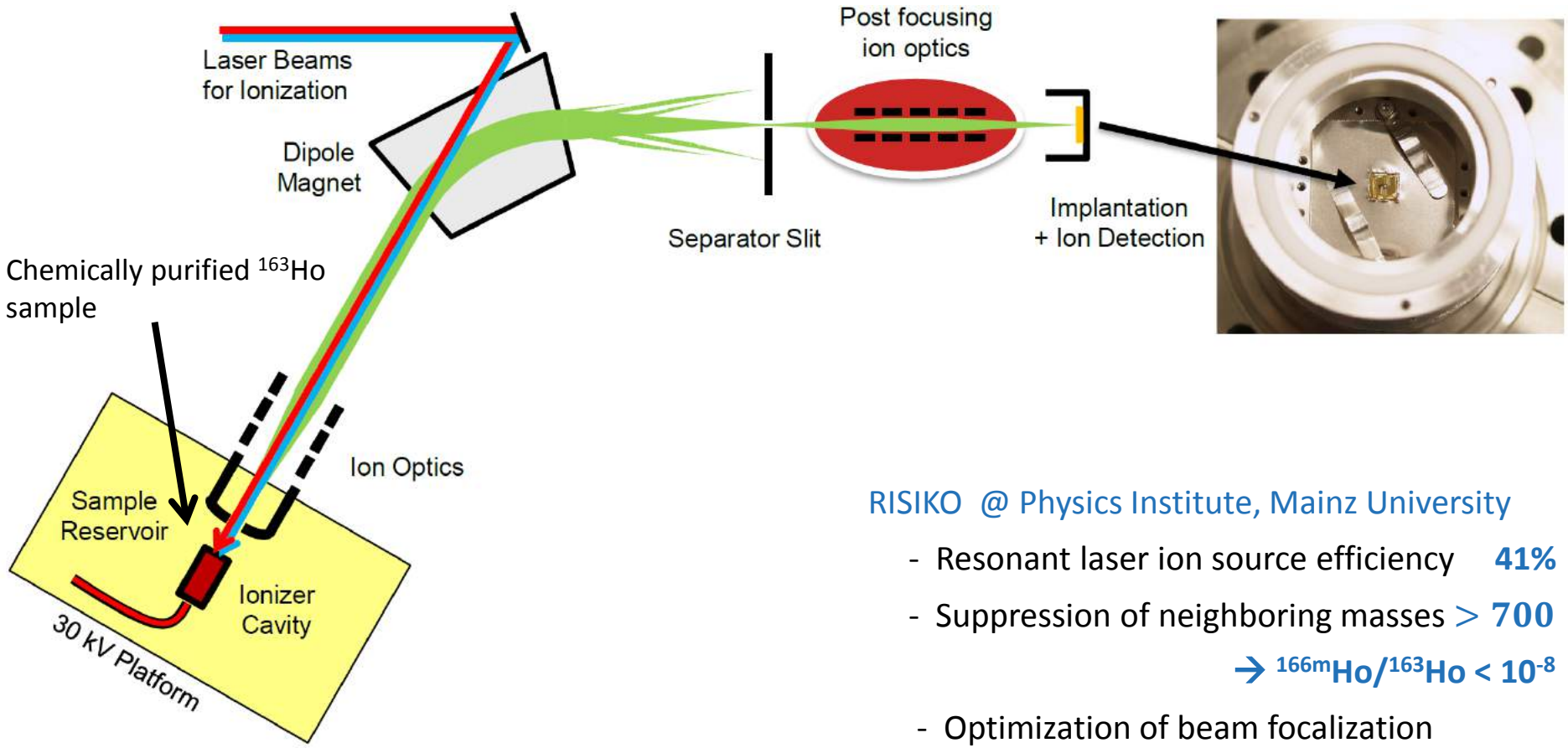
**Radioactive contaminants** → Excellent chemical separation




H. Dorrer et al, accepted for publication in Radiochim. Acta (2018)

# Mass separation and $^{163}$Ho ion-implantation



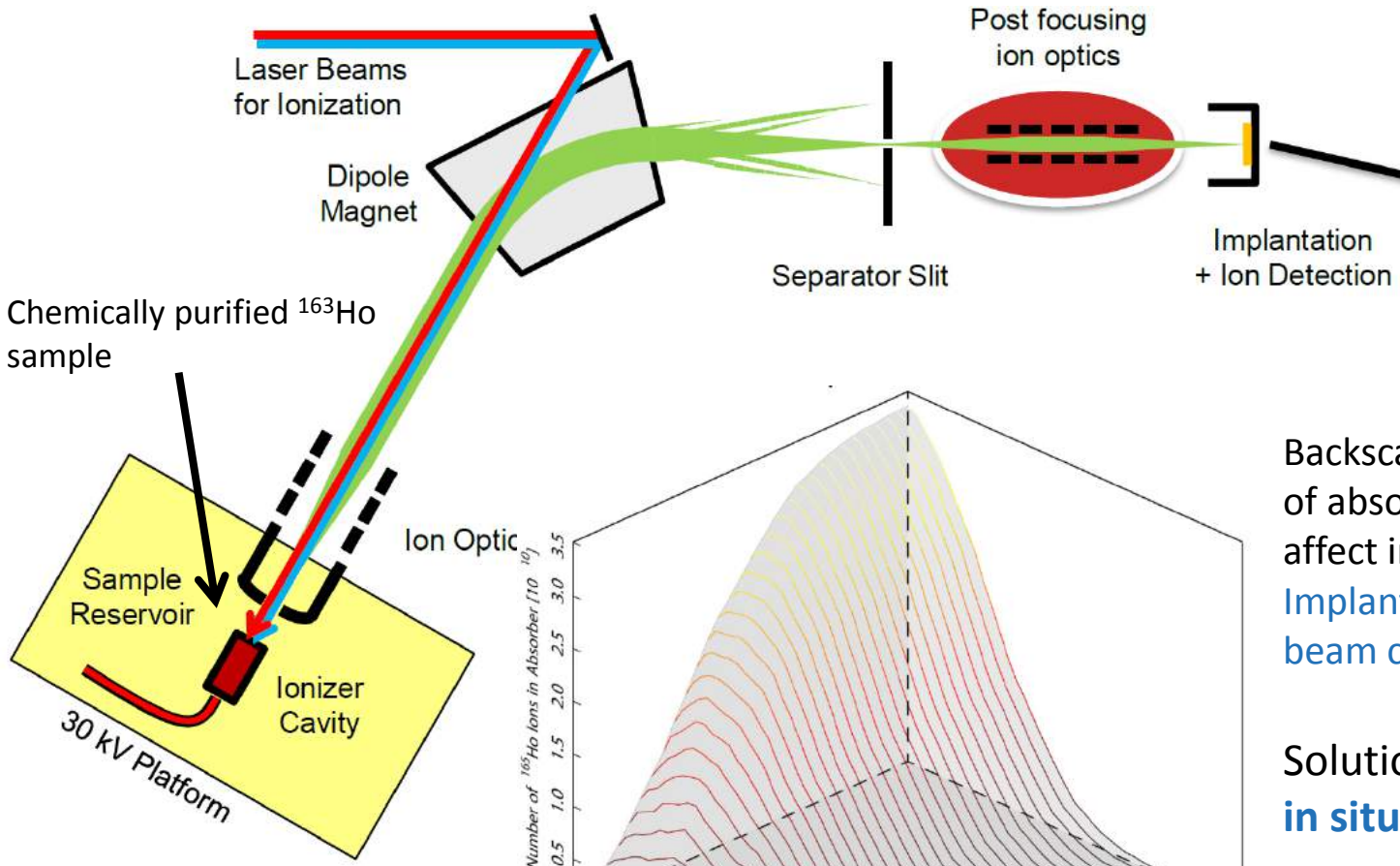

RISIKO @ Physics Institute, Mainz University

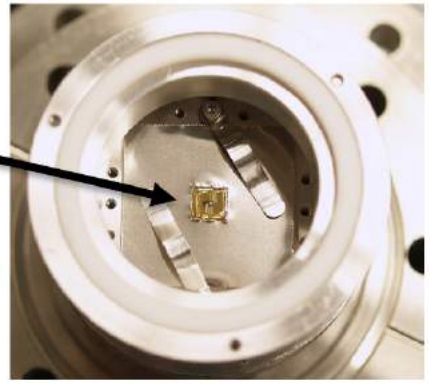
- Resonant laser ion source efficiency **41%**
- Suppression of neighboring masses $>$ **700**

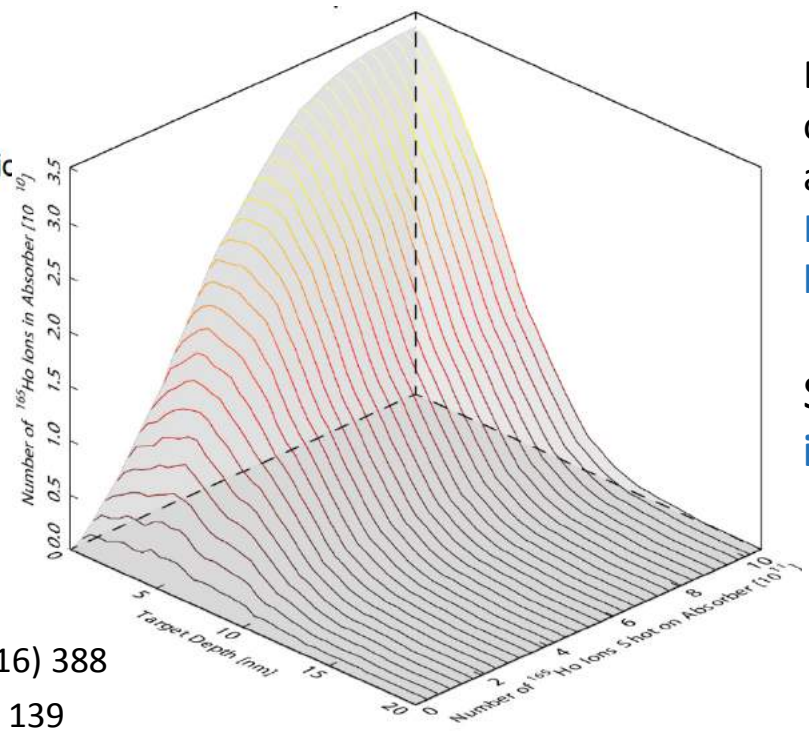
  → $^{166m}$Ho/$^{163}$Ho $< 10^{-8}$
- Optimization of beam focalization

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

# Mass separation and $^{163}$Ho ion-implantation



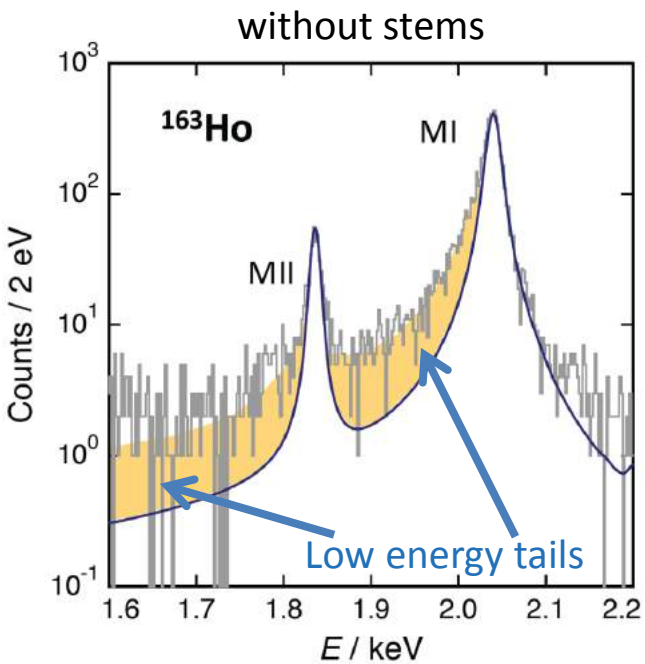



Backscattering and sputtering of absorber atoms affect implantation process:
Implanted activity ≠
beam current × irradiation time

Solution:
**in situ deposition of gold**

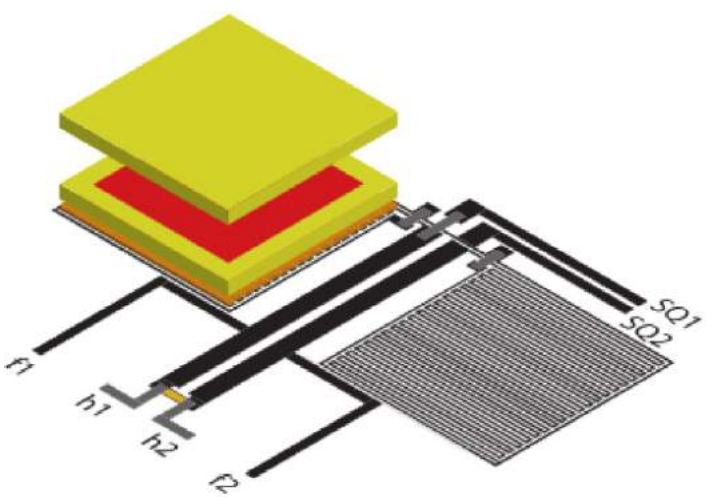
F. Schneider et al ., *NIM B* **376** (2016) 388
L. Gamer et al., *NIM A* **854** (2017) 139

# Enclosing $^{163}$Ho in MMC absorbers




ECHo-0 detector showed asymmetric detector response

- Loss of high energy phonons to the substrate
- full contact between sensor and absorber



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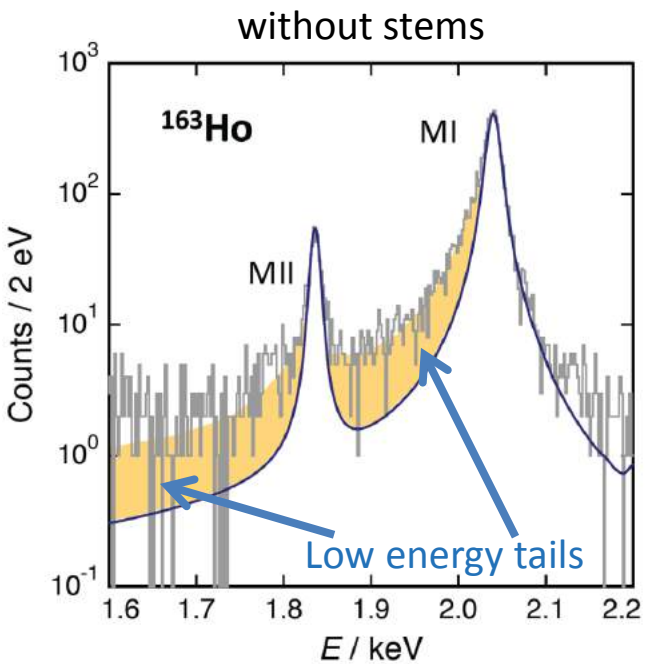
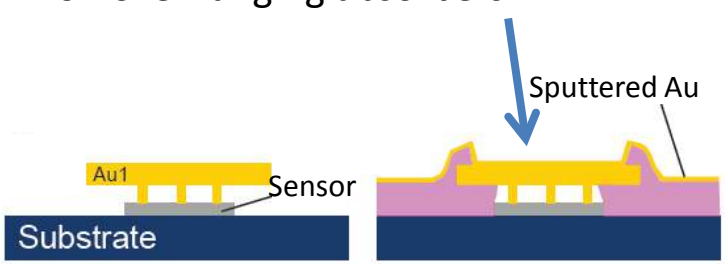



ECHo-0 detector showed asymmetric detector response

- Loss of high energy phonons to the substrate
- full contact between sensor and absorber

→ New detector fabrication process
reduced contact area between absorber and sensor

Definition of the implantation area by microstructuring a photoresist layer on overhanging absorbers



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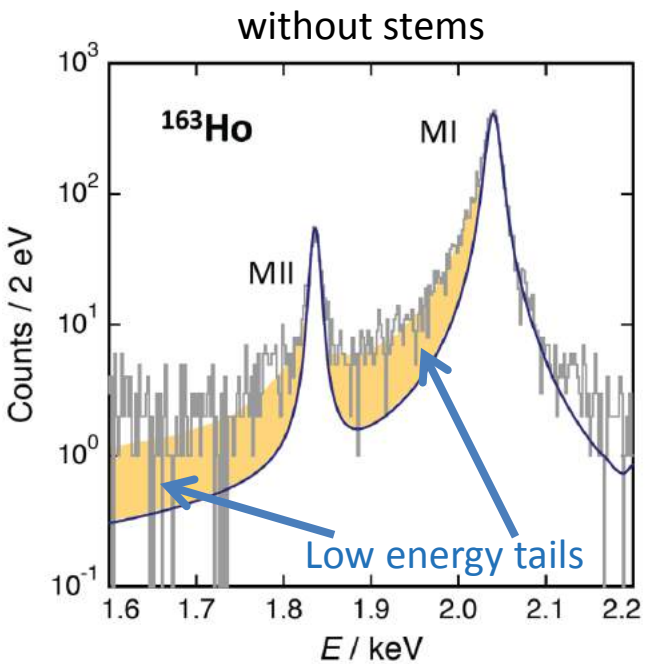


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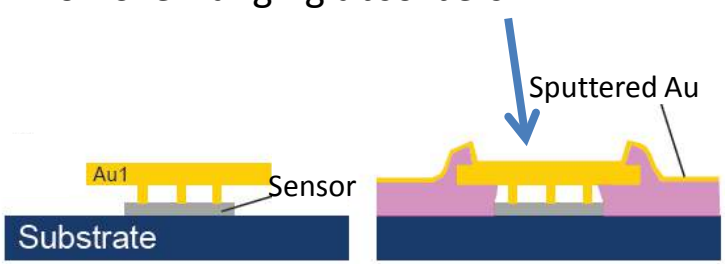


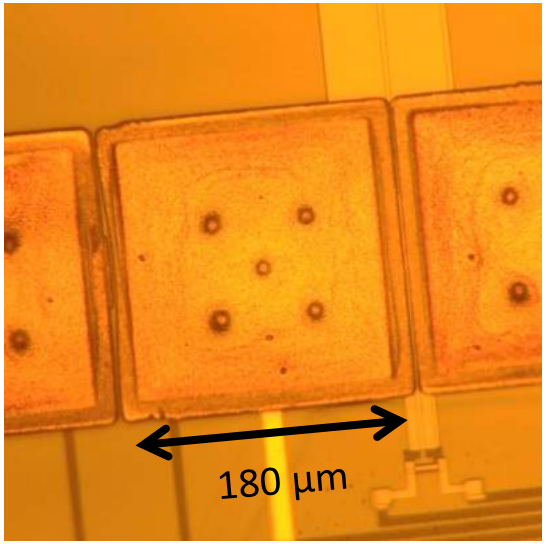

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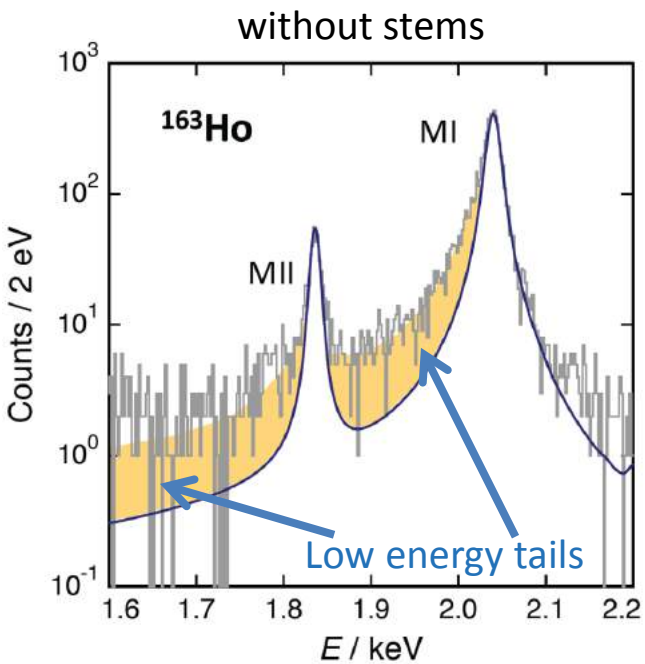


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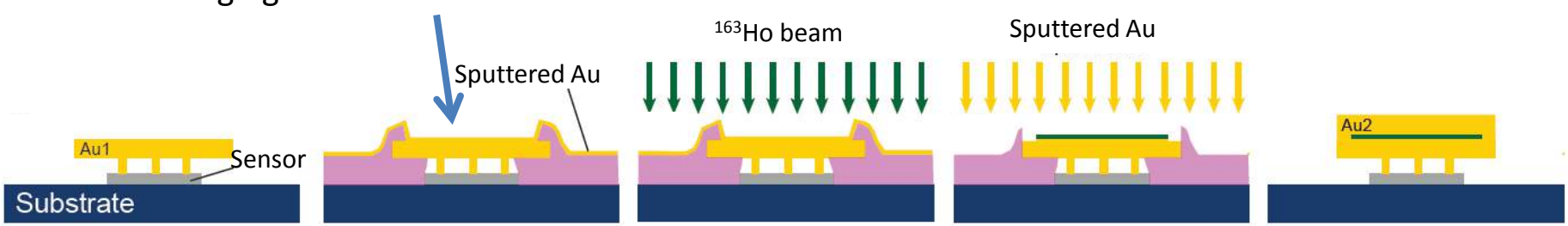
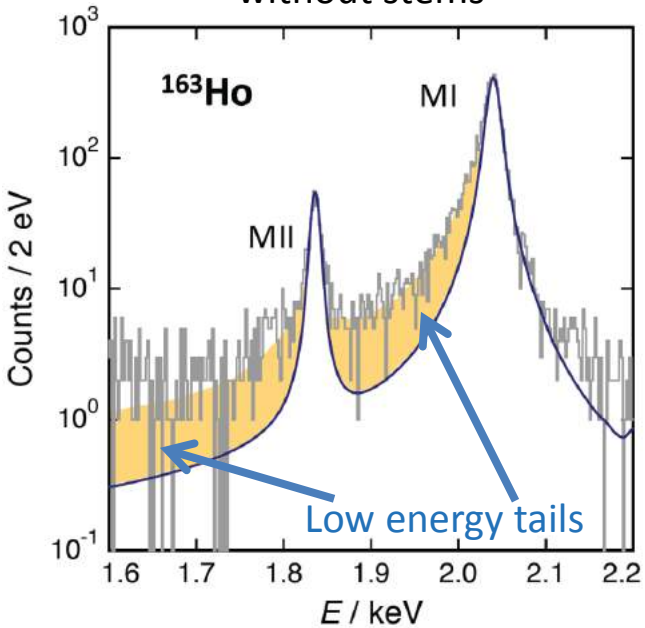
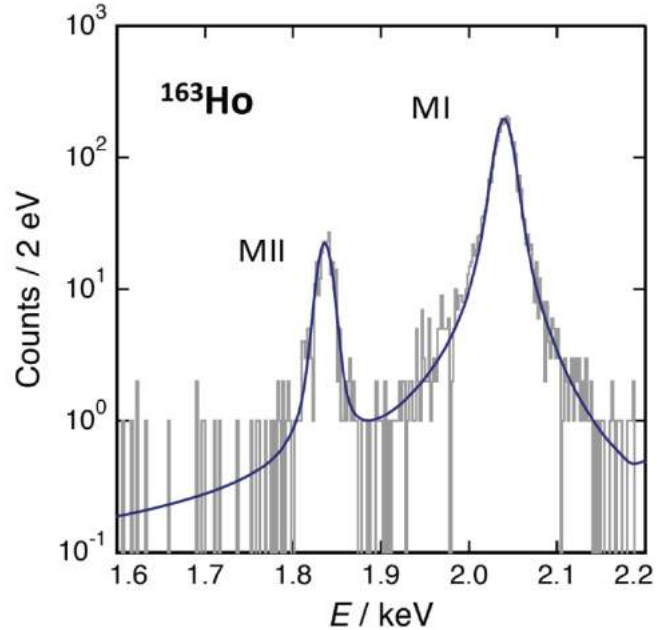


# Enclosing $^{163}$Ho in MMC absorbers

without stems

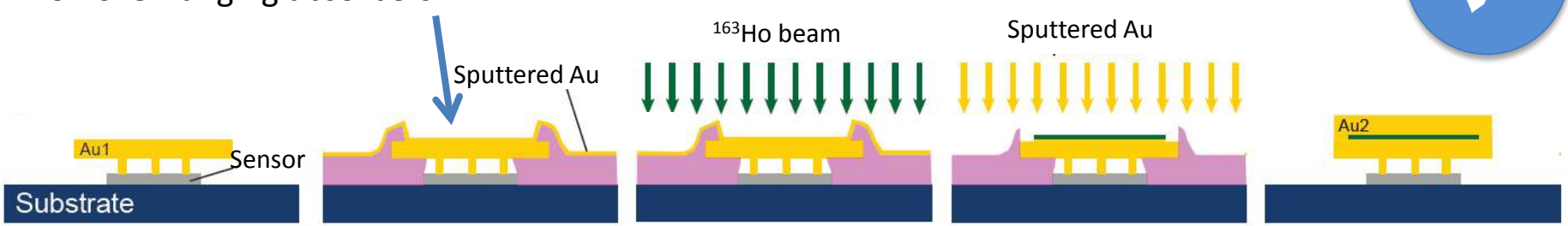



with stems




Definition of the implantation area by microstructuring a photoresist layer on overhanging absorbers

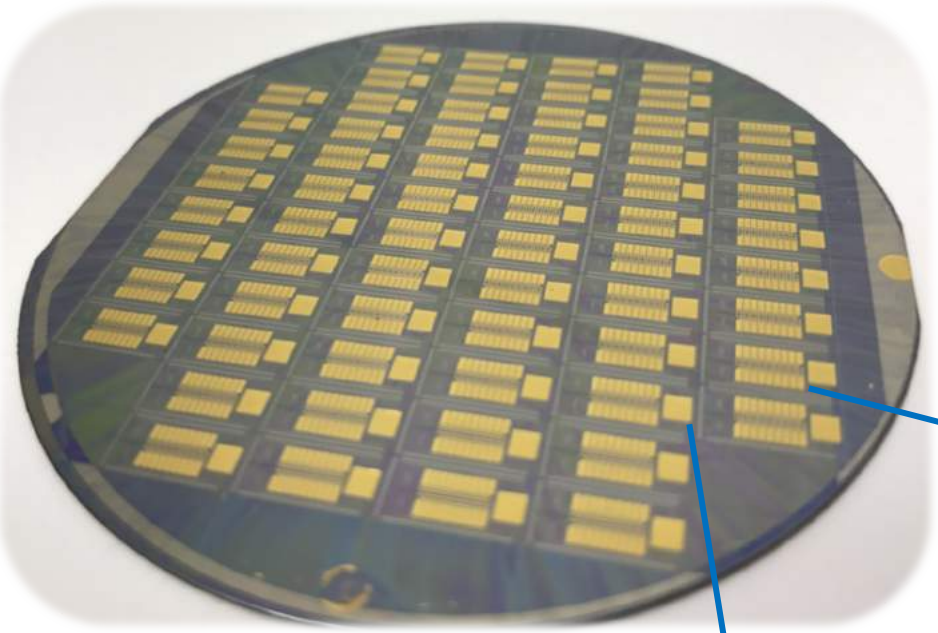
**Symmetric detector response**





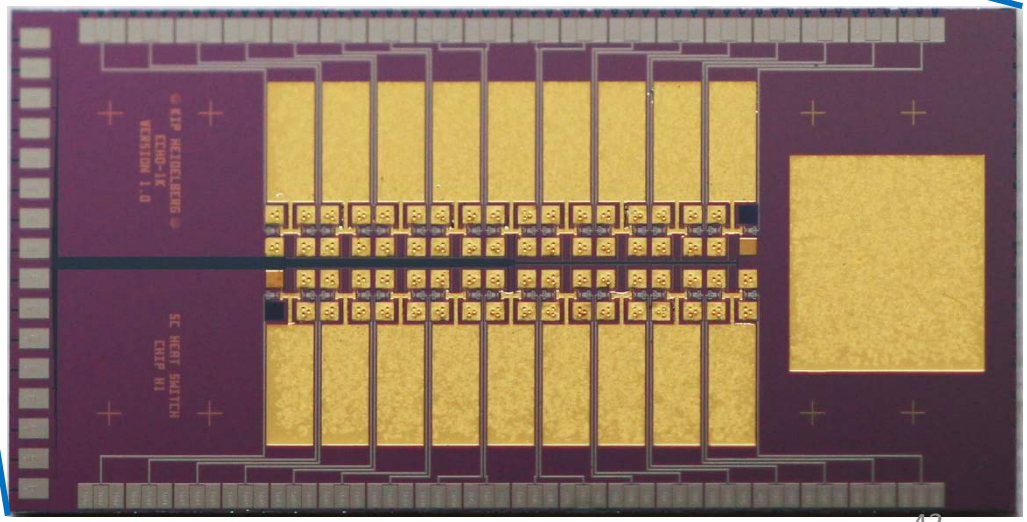

C. Hassel et al ., *JLTP* **184** (2016) 910

# 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

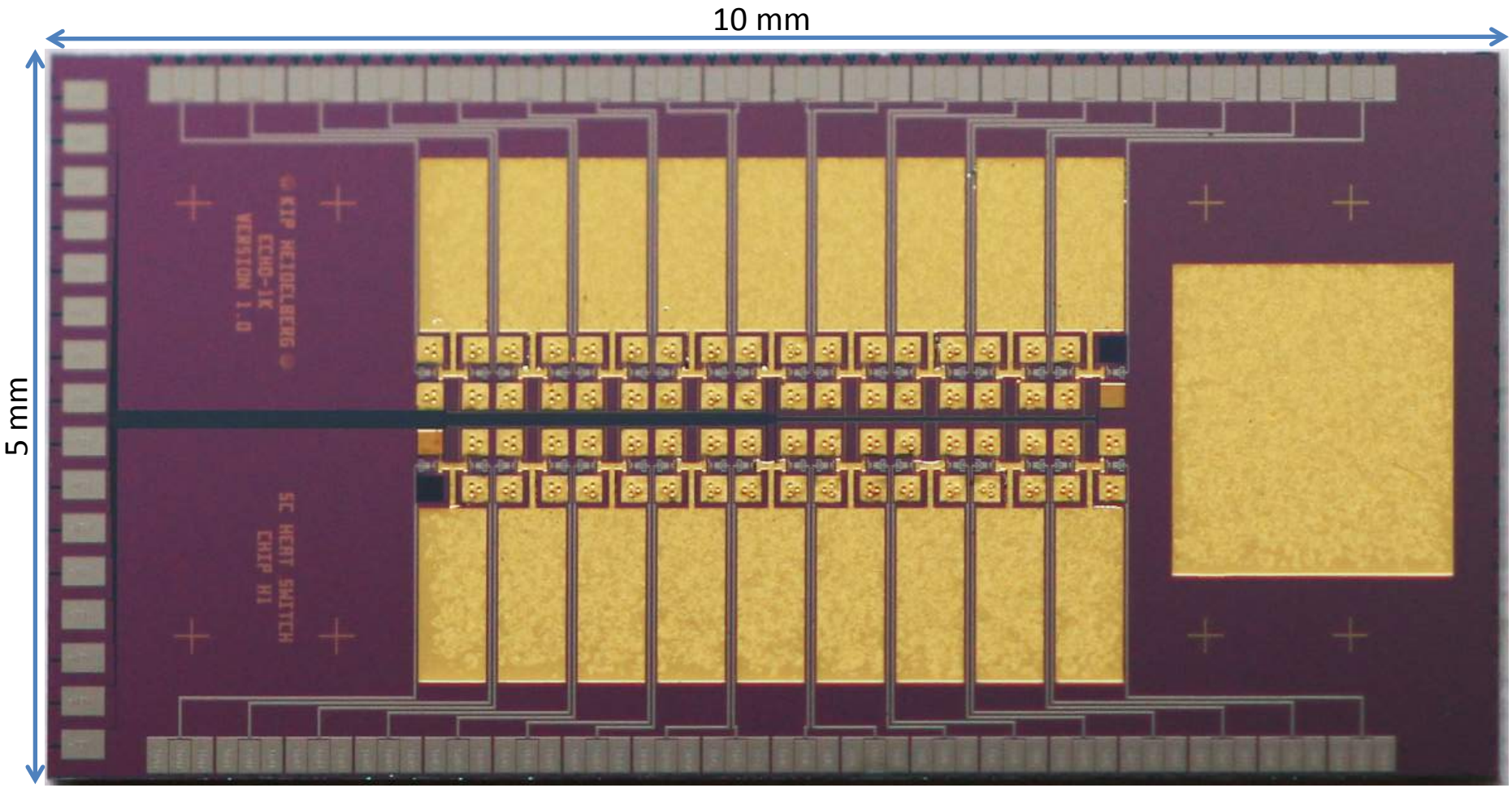
Design performance:
$\Delta E_{FWHM}$ ~ 5 eV
$\tau_r$ ~ 90 ns (single channel readout)
$\tau_r$ ~ 300 ns (multiplexed read-out)



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

# ECHo-1k array

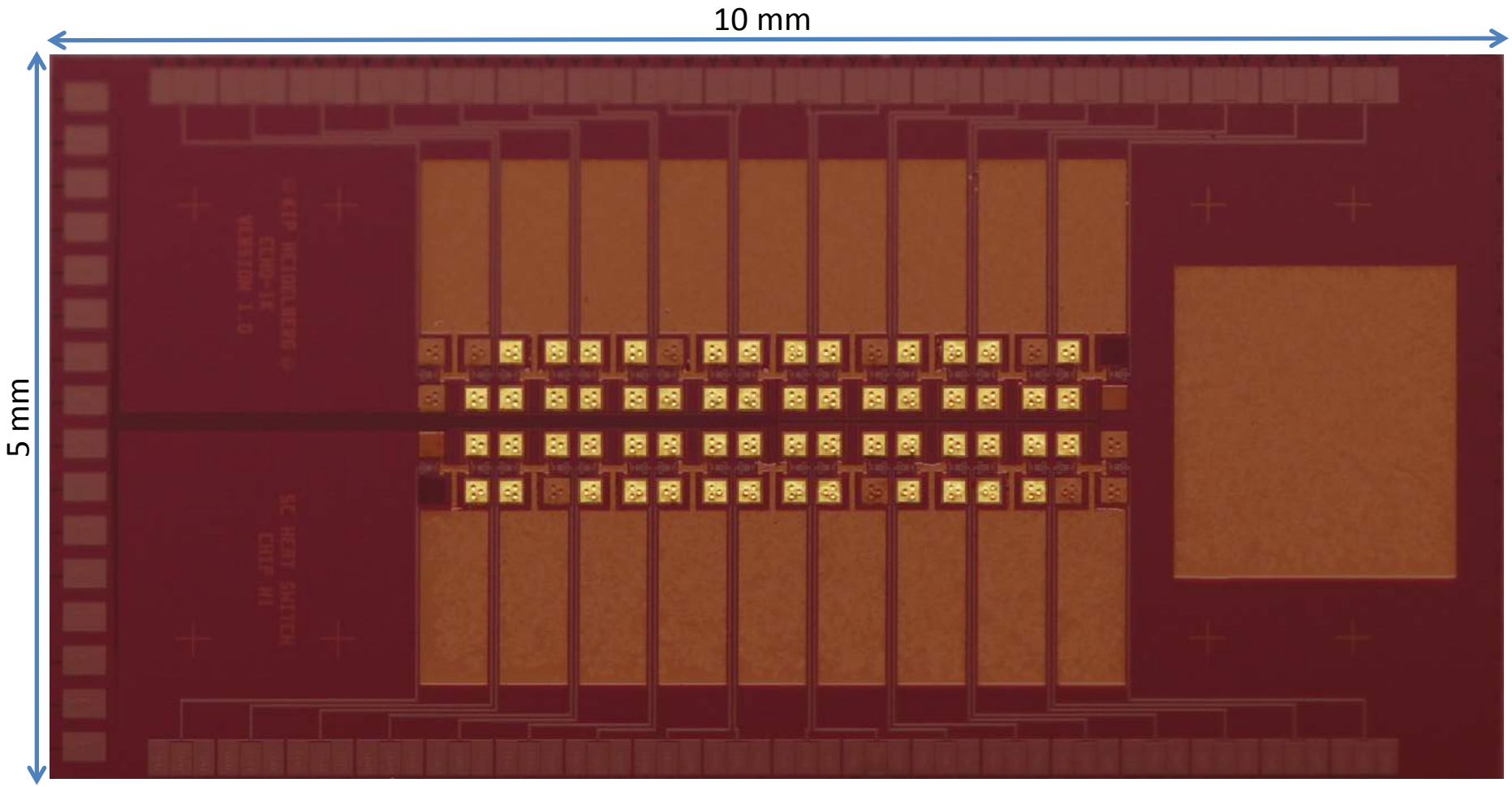
100% of the chips selected at RT have good performance at low temperature



# ECHo-1k array

high geometrical efficiency for $^{163}$Ho implantation

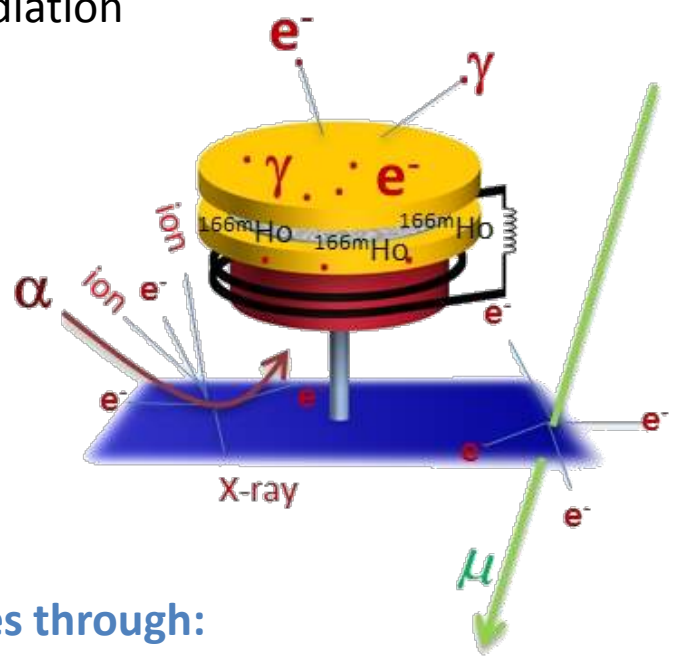
presence of non-implanted chips for in-situ background determination



# Background in ECHo

**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**

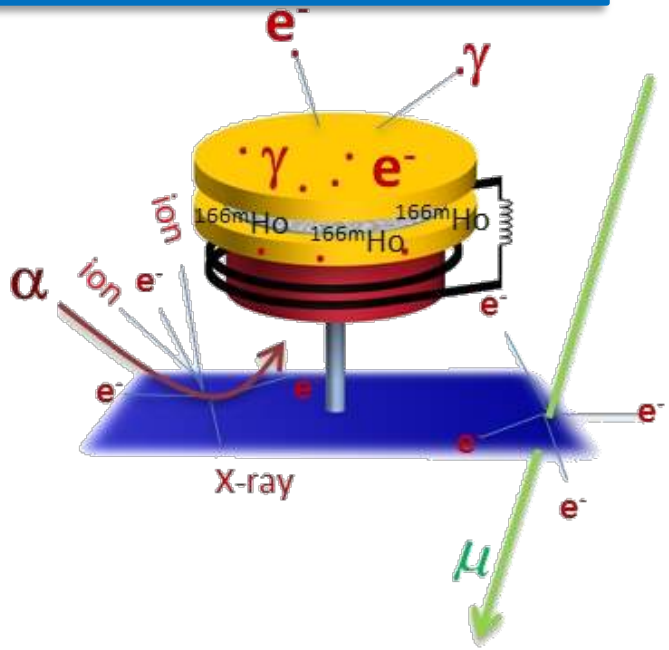
# Background in ECHo

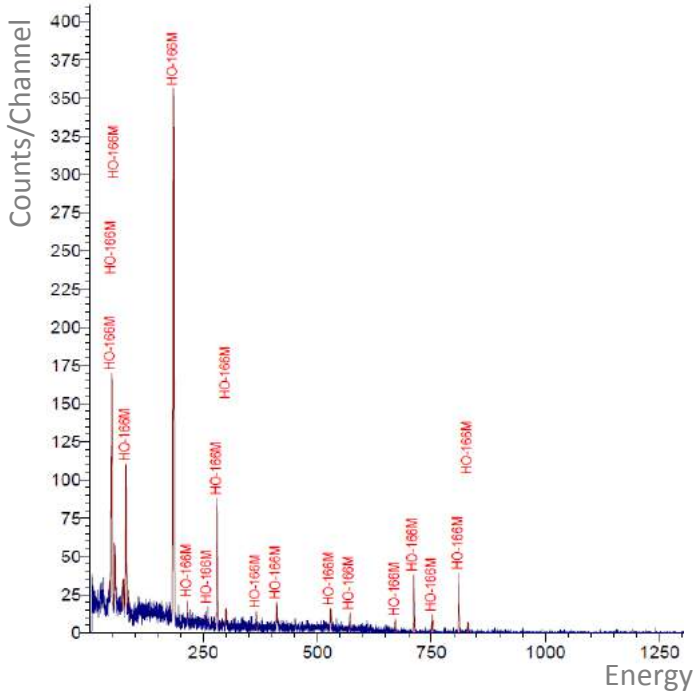
## Background sources:

- **Radioactivity in the detector**
  presence of $^{166m}$Ho in Ho samples for implantation

RISIKO @ Physics Institute, Mainz University

→ **$^{166m}$Ho/$^{163}$Ho < $10^{-8}$**



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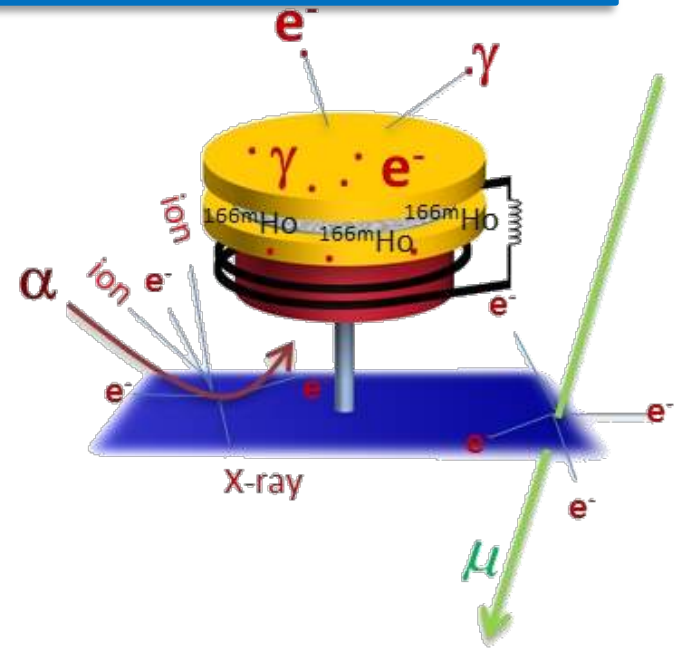
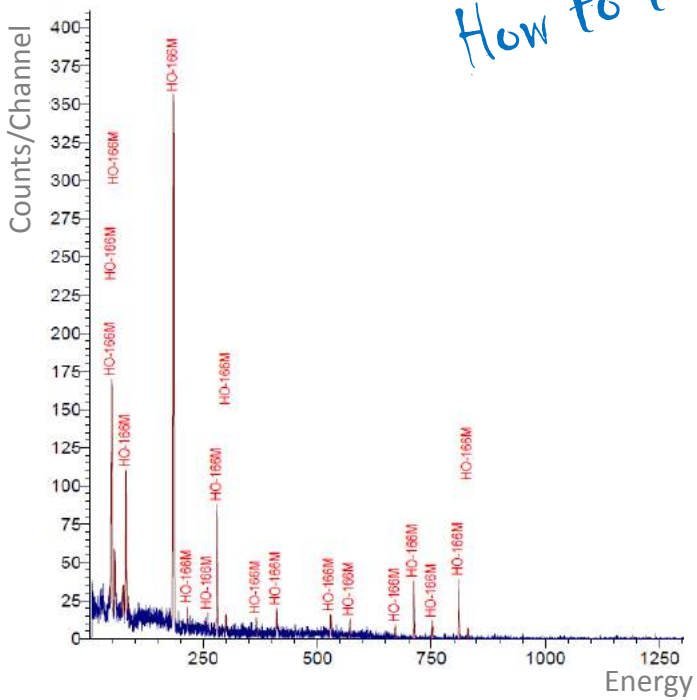



How to test??



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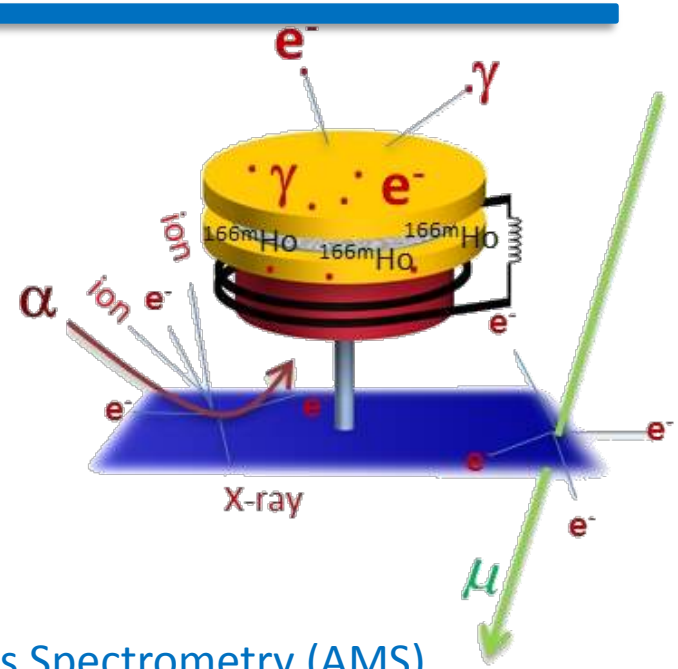
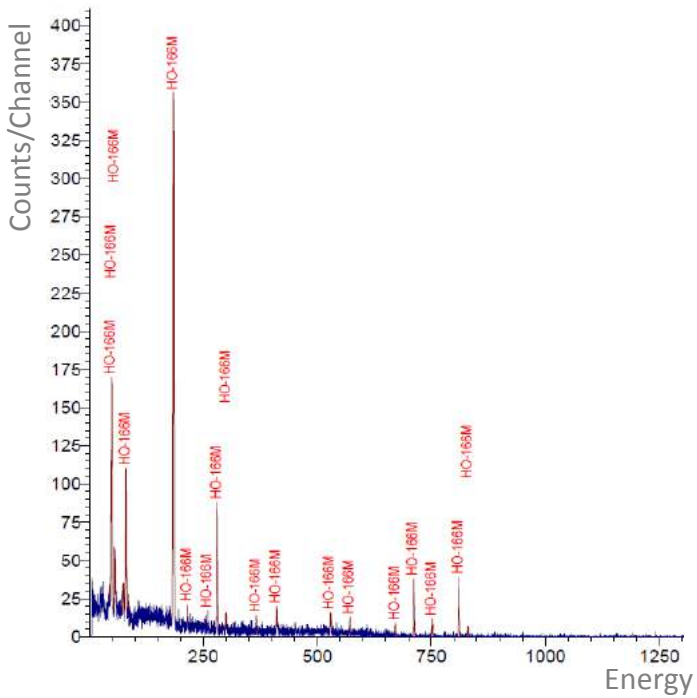
→ **$^{166m}$Ho/$^{163}$Ho < $10^{-8}$**




Accelerator Mass Spectrometry (AMS)
is a very powerful technique for measuring the corresponding very low isotopic ratio

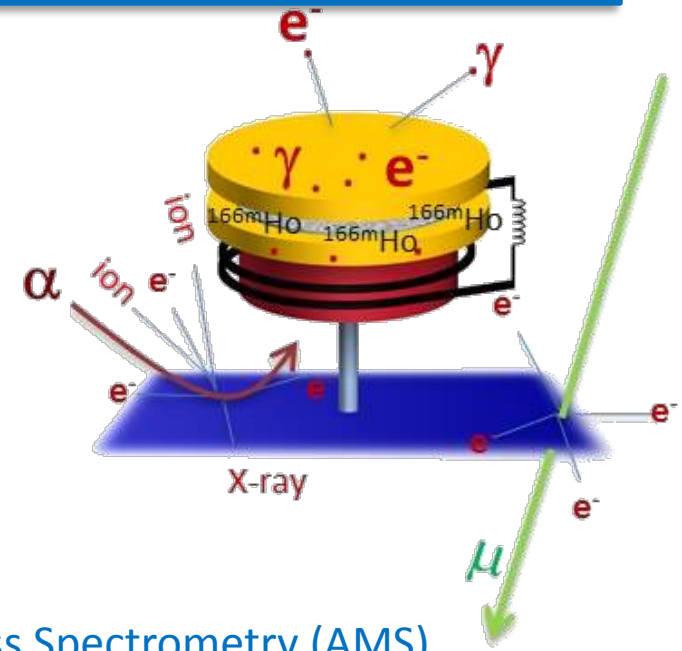
# Background in ECHo

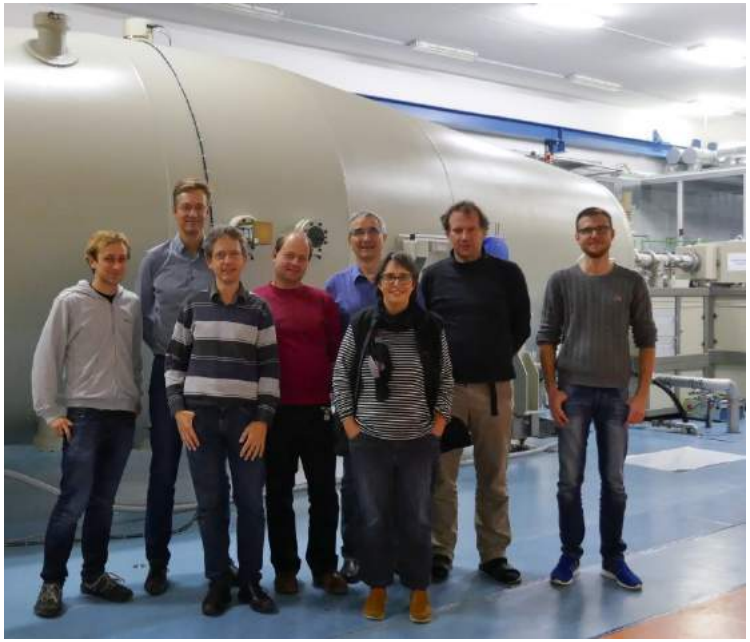
**Background sources:**

- **Radioactivity in the detector**
  presence of $^{166m}$Ho in Ho samples for implantation

RISIKO @ Physics Institute, Mainz University

→ **$^{166m}$Ho/$^{163}$Ho < $10^{-8}$**



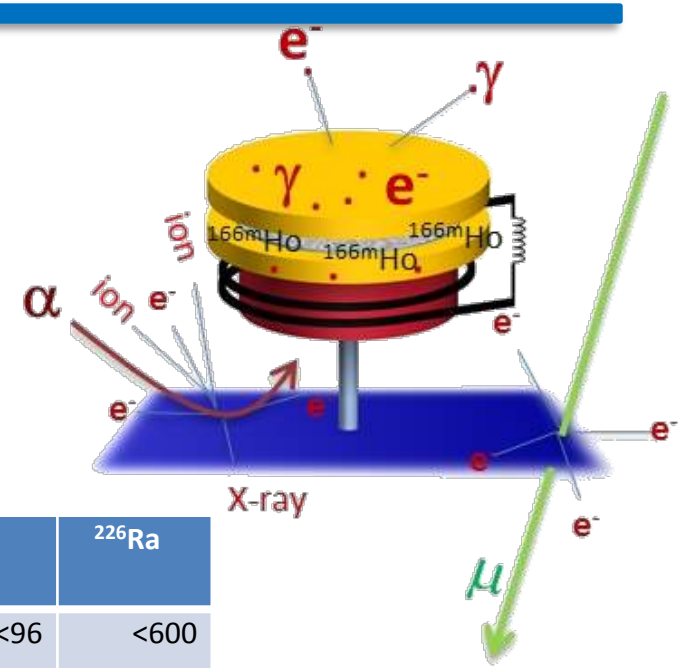
Accelerator Mass Spectrometry (AMS)
is a very powerful technique for measuring the corresponding very low isotopic ratio

First tests at the DREsden AMS facility (DREAMS) at Helmholtz-Zentrum Dresden-Rossendorf for experimental determination of the ratio $^{163}$Ho/$^{166m}$Ho in ECHo samples

# Background in ECHo

## Background sources:

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

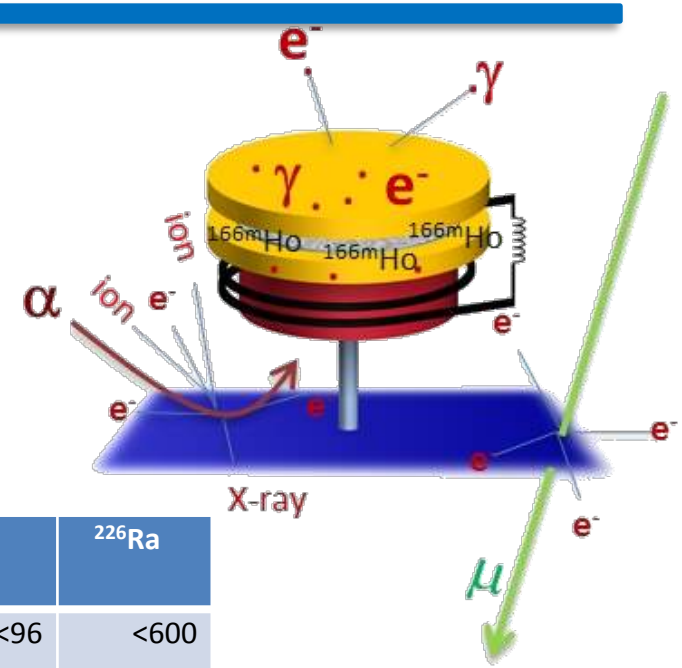



| Sample | $^{40}$K | $^{208}$Tl | $^{212}$Pb | $^{214}$Bi | $^{214}$Pb | $^{226}$Ra |
|---|---|---|---|---|---|---|
| Cryostat copper [mBq/kg] | <480 | <80 | <190 | | <96 | <600 |
| Cryoperm [mBq/kg] | <335 | <25 | <45 | <170 | <40 | <200 |
| Connectors [mBq/kg] | 5600 | 1600 | 10800 | 10800 | 10800 | 8000 |
| Connectors [mBq] p.p. | 3 | 1 | 6 | 6 | 6 | 4 |
| Circuit board [mBq/kg] | 625 | 4800 | 16300 | 8700 | 8000 | 5300 |
| Circuit board [mBq/cm$^2$] | 0.45 | 1.39 | 4.75 | 2.53 | 2.33 | 1.54 |
| Cables [mBq/cm$^2$] | 0.49 | | | | | |

# Background in ECHo

## Background sources:

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

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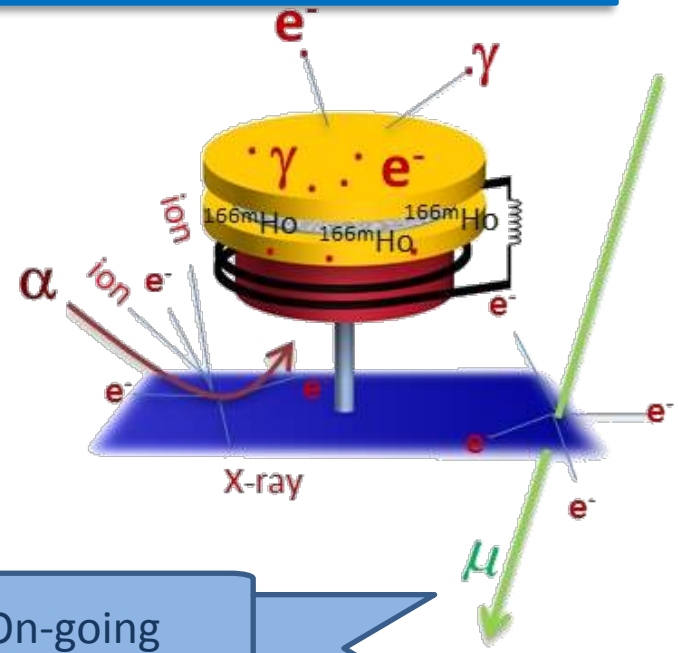
| Circuit | | | | | | |

After comparison with MC simulations none of these item would lead to background above the unresolved pile up limit

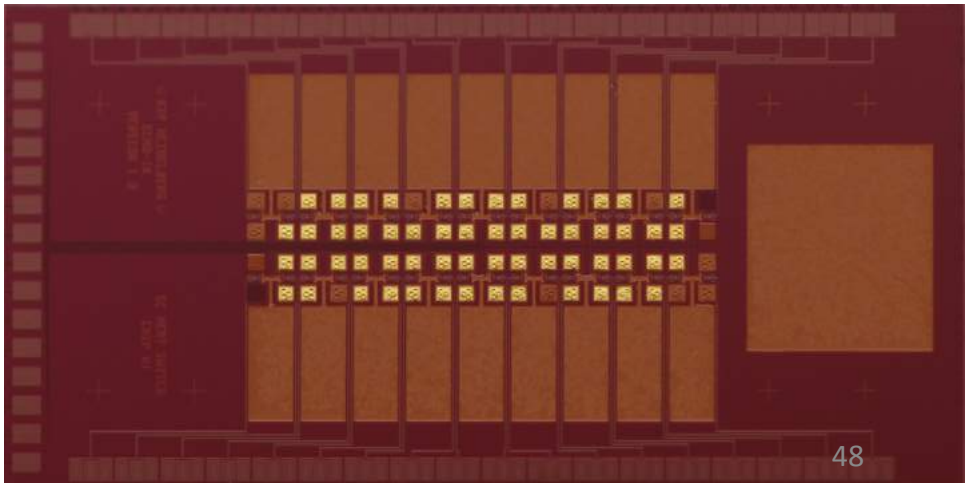
# Background in ECHo

**Background sources:**

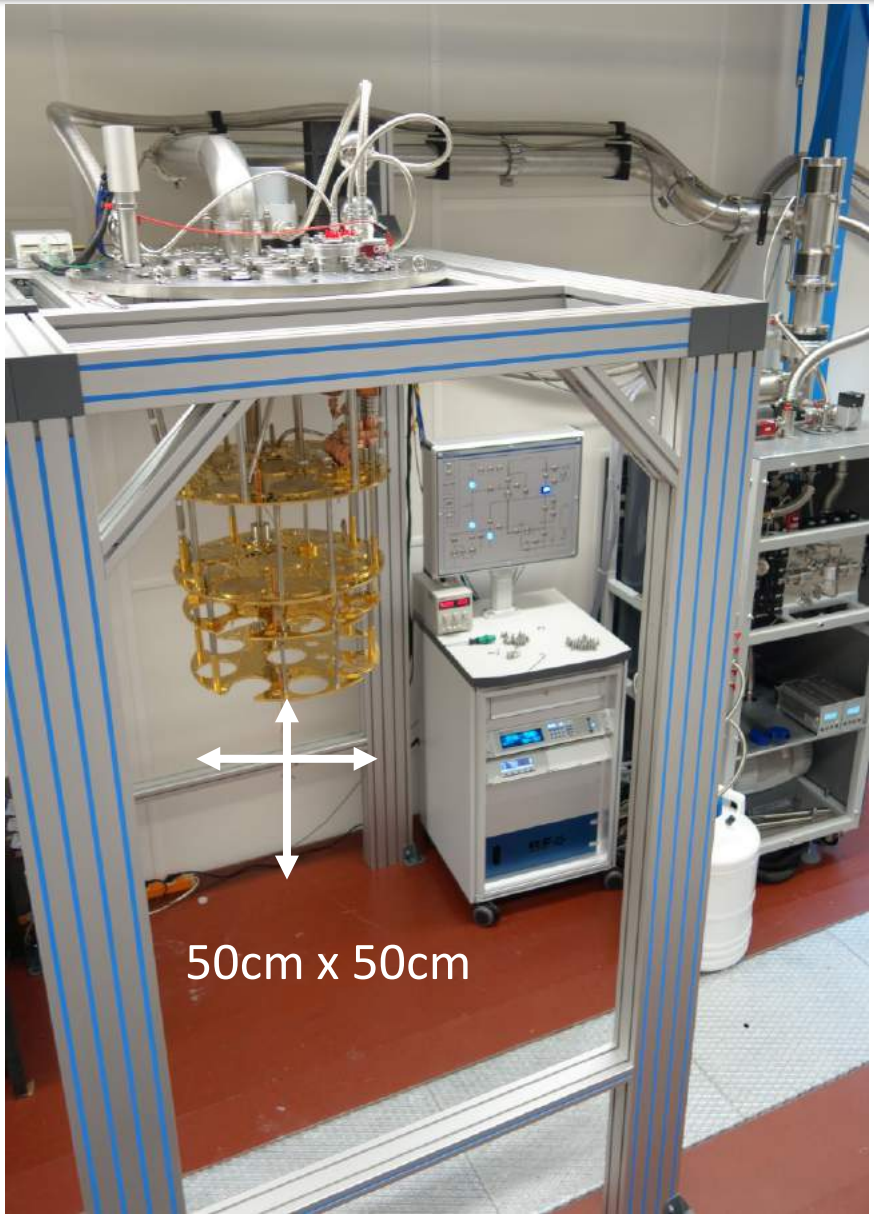
- Radioactivity in the detector
- Environmental radioactivity
- **Cosmic rays**
  **Induced secondary radiation**



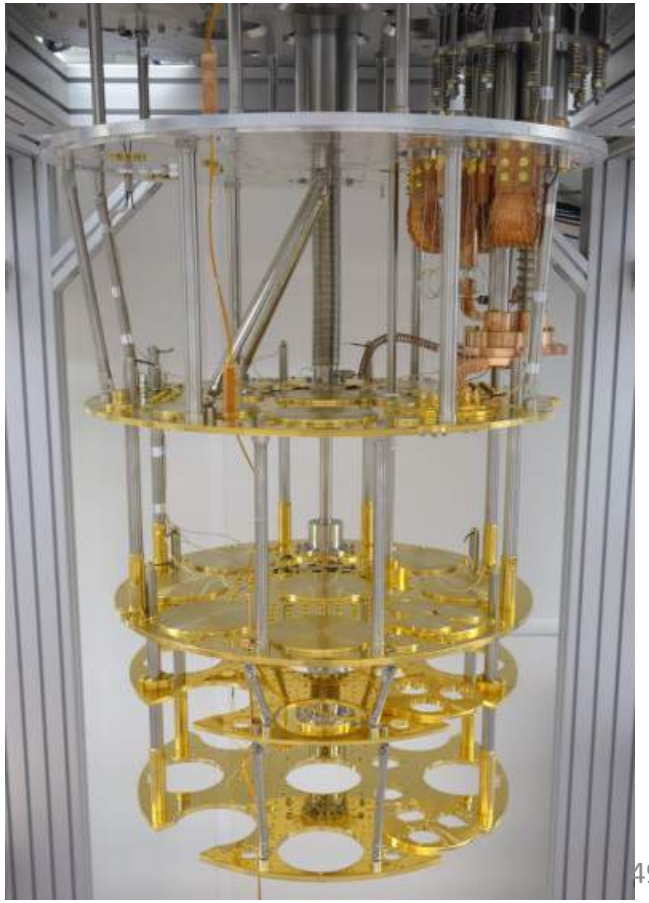

On-going



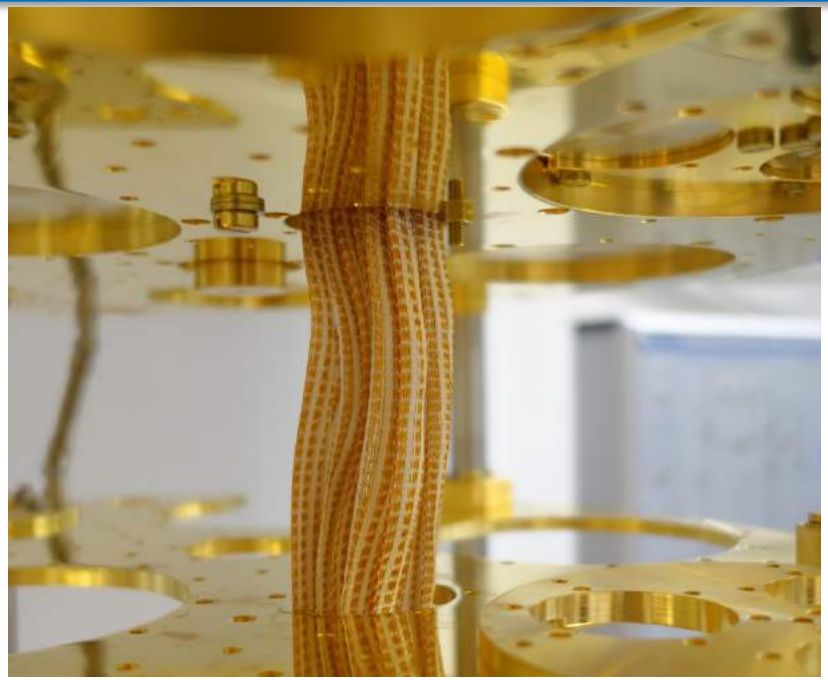
# ECHo cryogenic platform

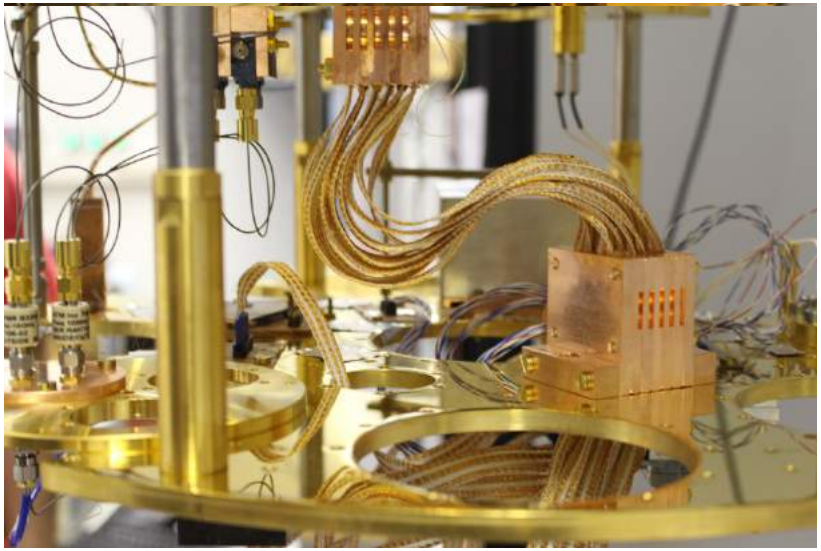



- Large space at MXC enough for several ECHo phases
- cooling power: 15µW @ 20 mK
- Possibility to load 200kg for passive shielding



# 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

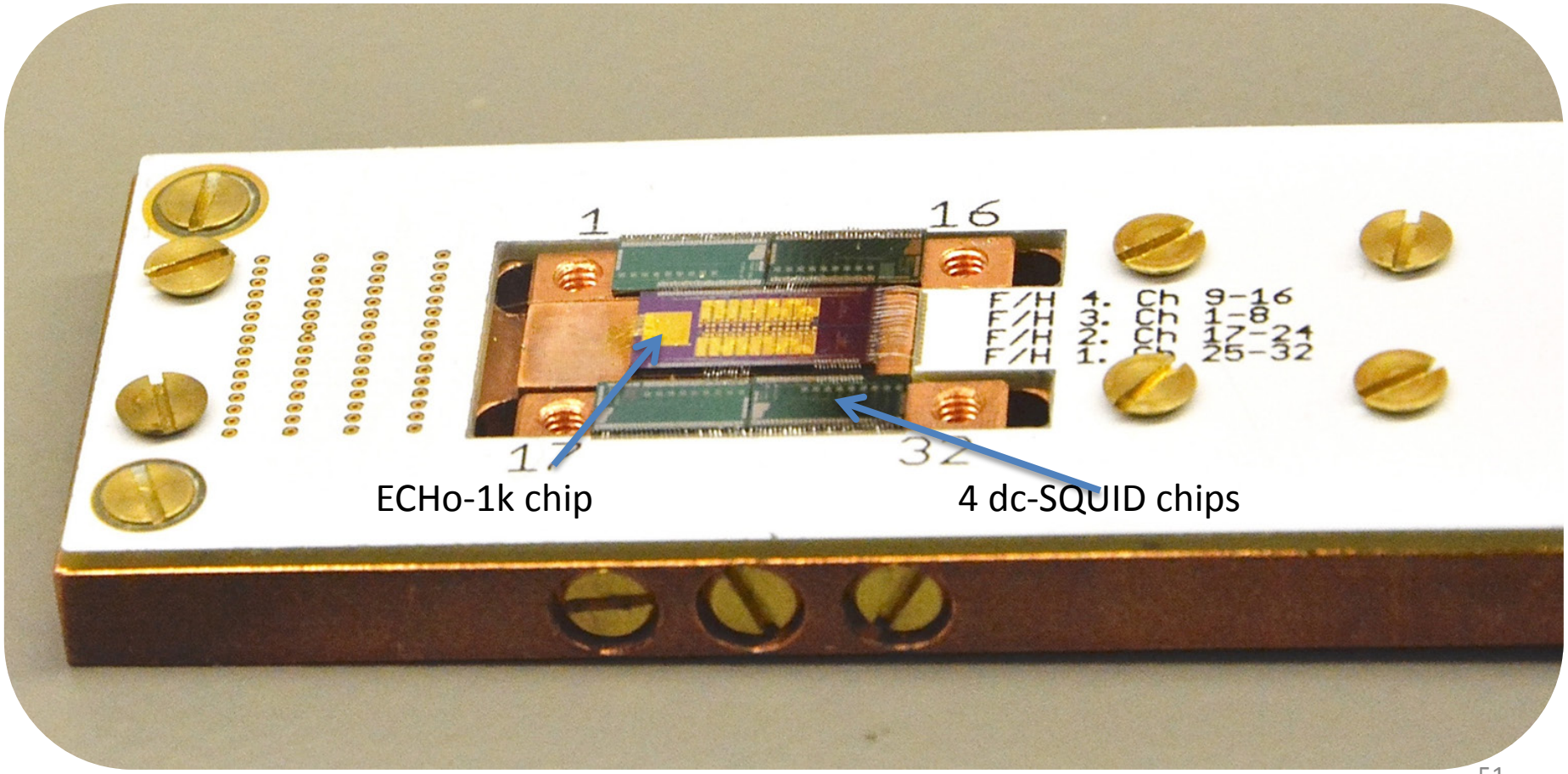
  12 ribbons each with 30 Cu98Ni2 0.2 mm, 1.56 Ohm/m, cables from RT to mK
  → allows for parallel readout of 36 two-stage SQUID set-up

# ECHo-1k set-up

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

  → $^{163}$Ho activity A = 2 Bq

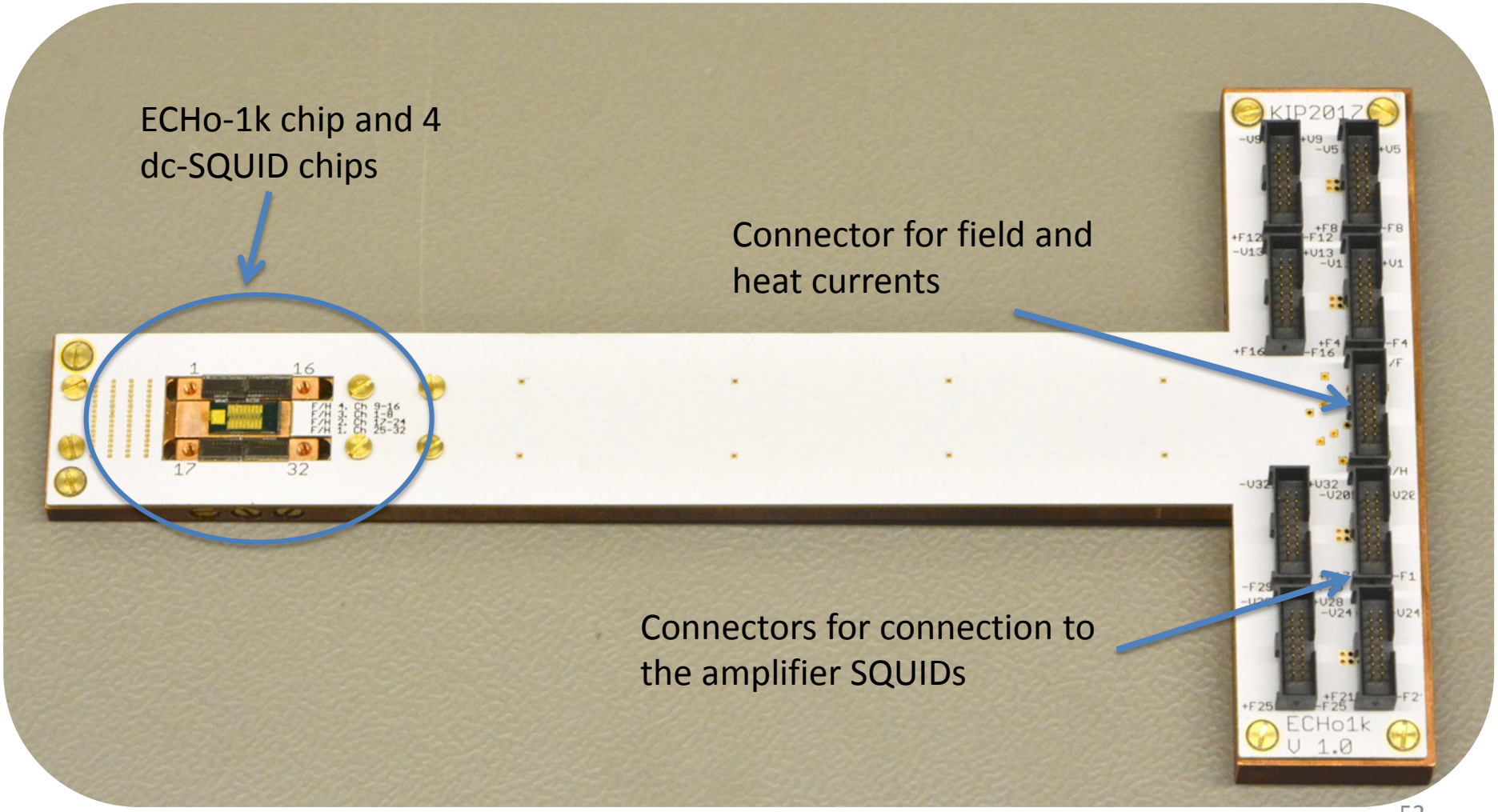
- 4 Front-end chips each with 8 dc-SQUIDs



# ECHo-1k set-up

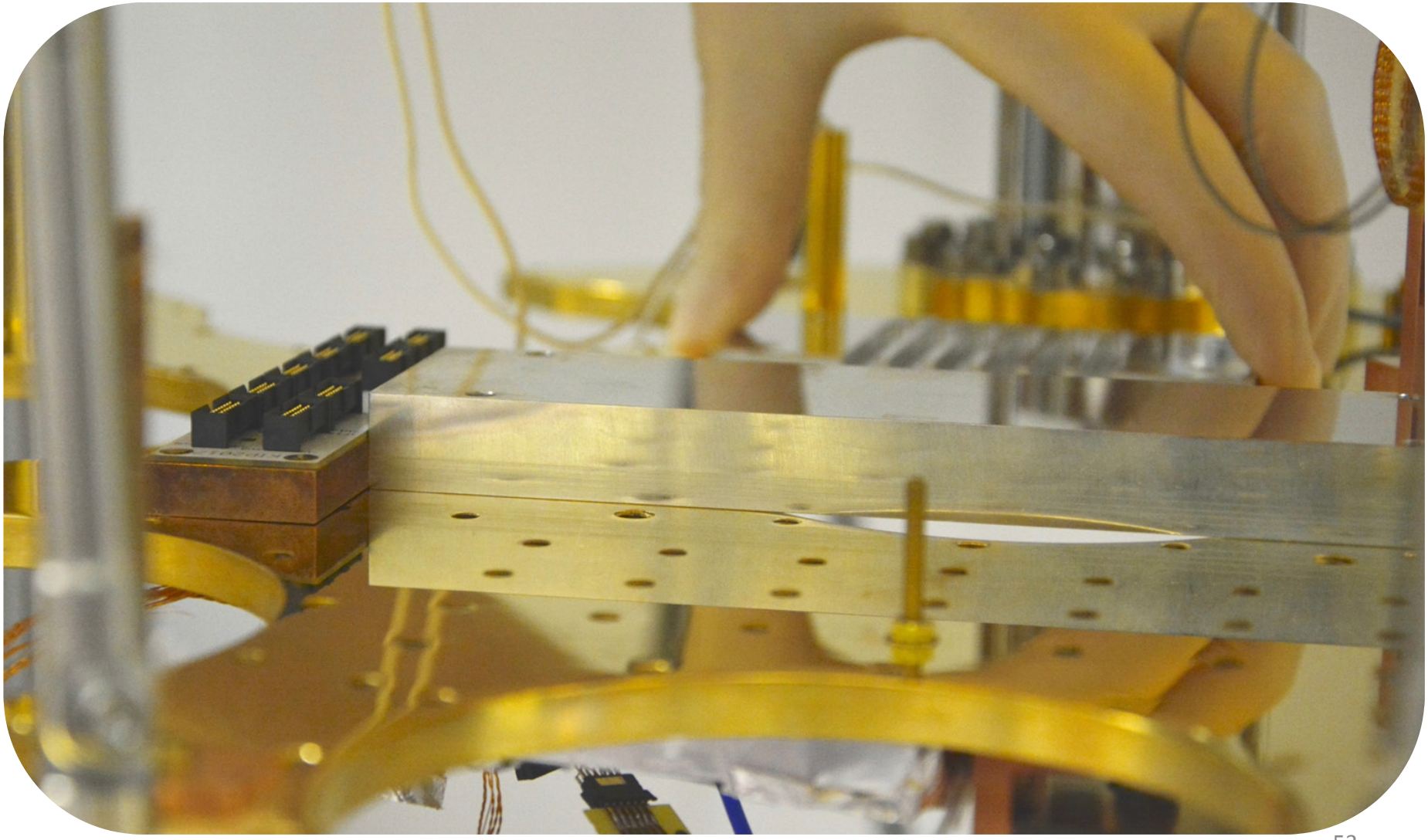
- Circuit board designed for the ECHo-1k experiment

  →Parallel read-out of 64 pixels

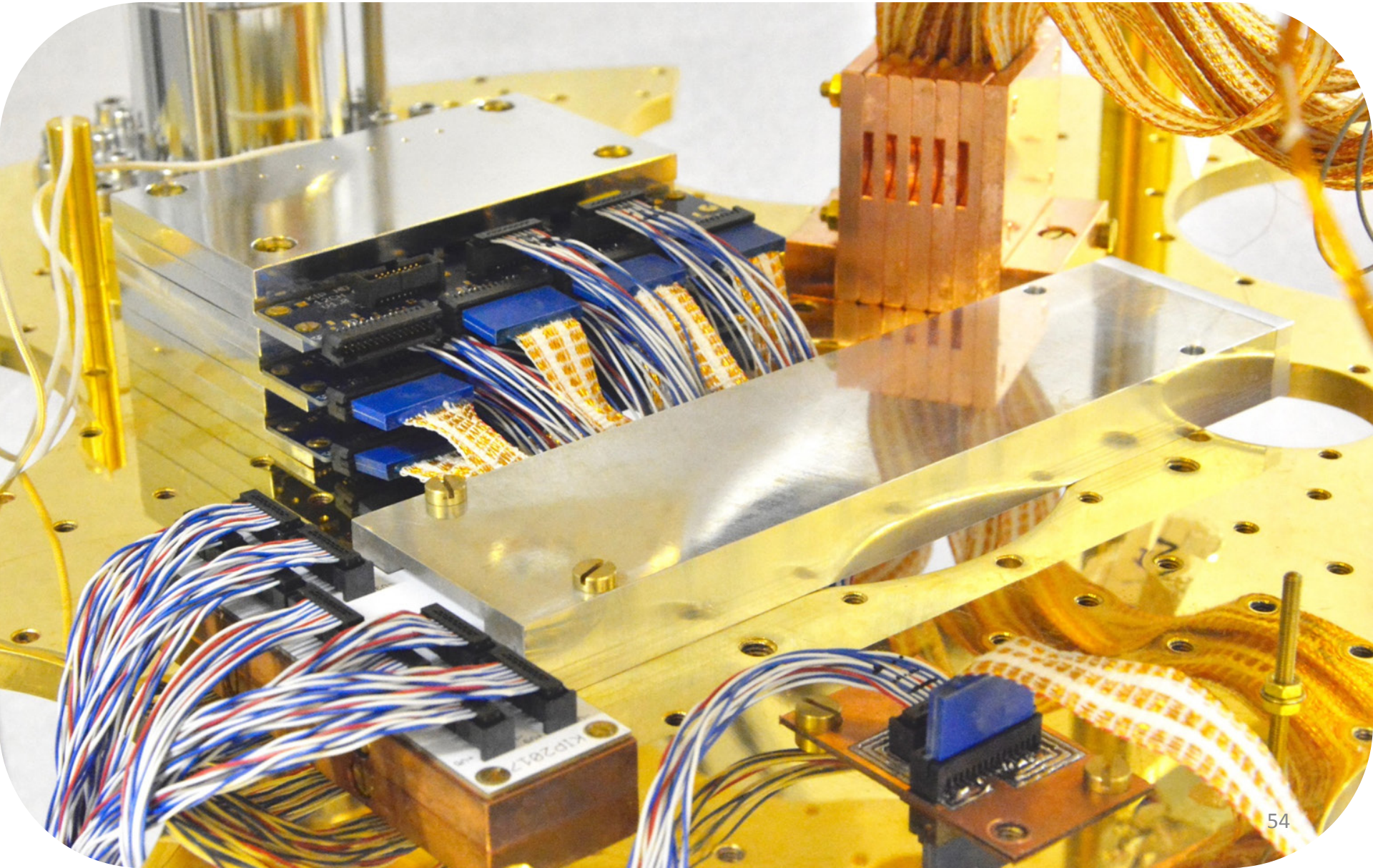


# ECHo-1k set-up

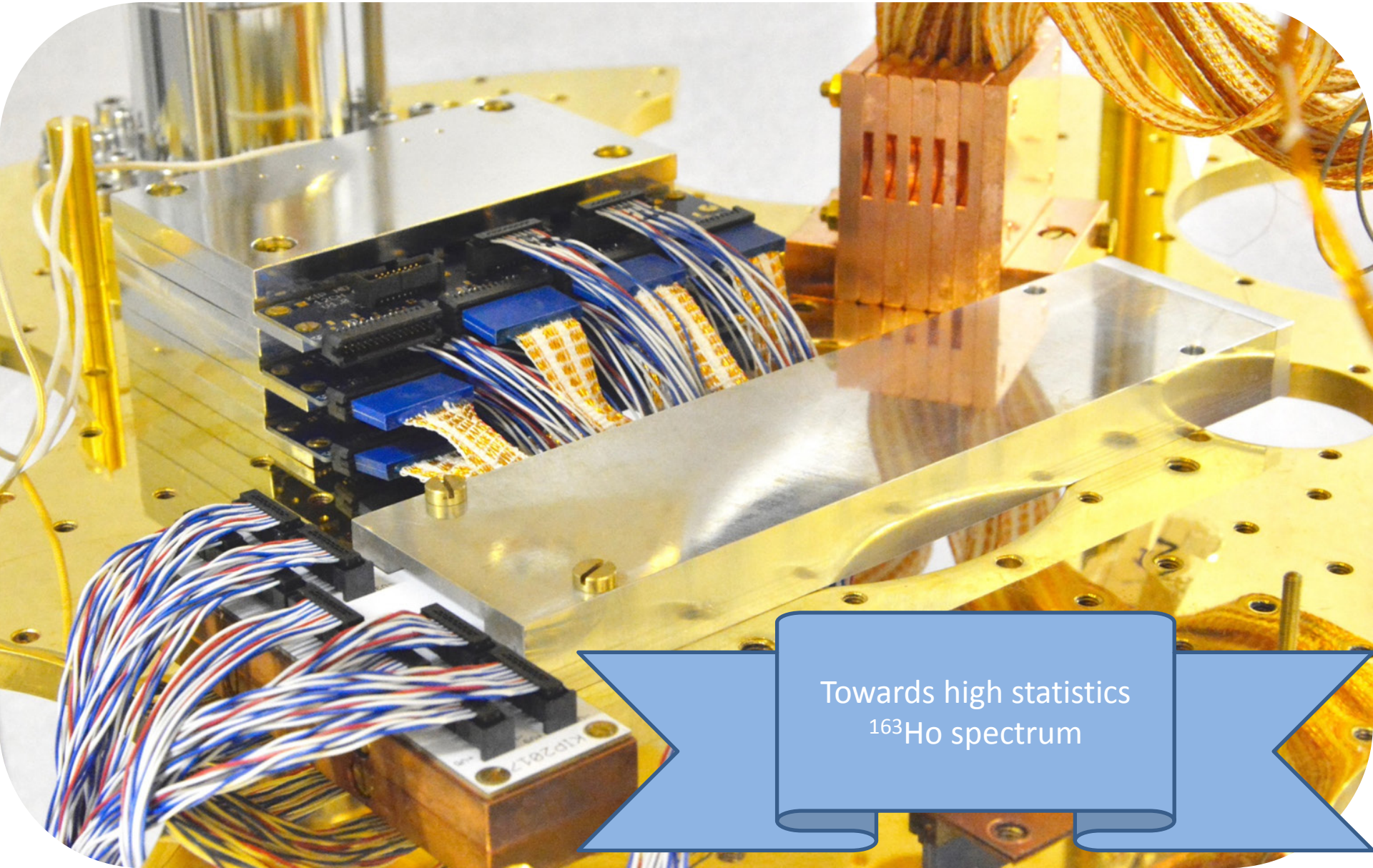
Aluminum superconducting shield



# ECHo-1k set-up

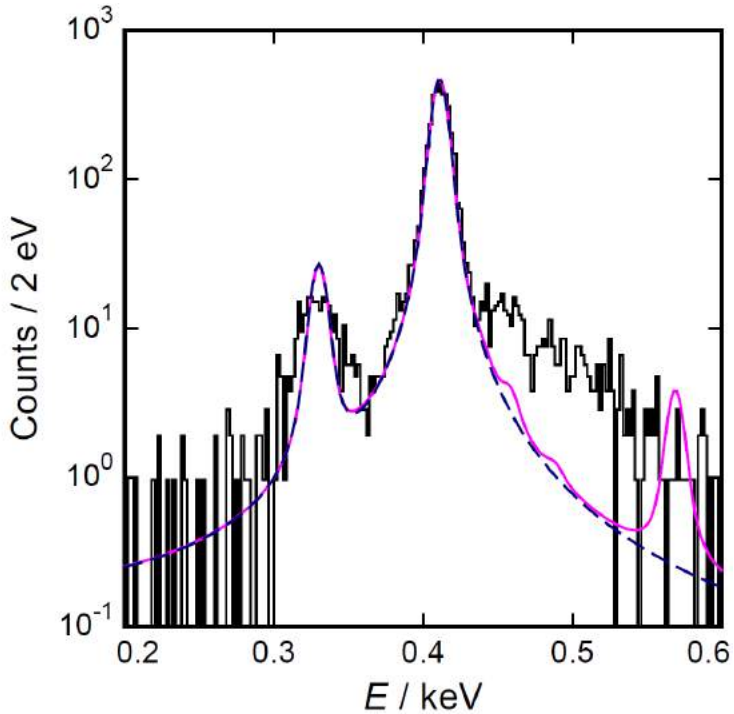


# ECHo-1k set-up



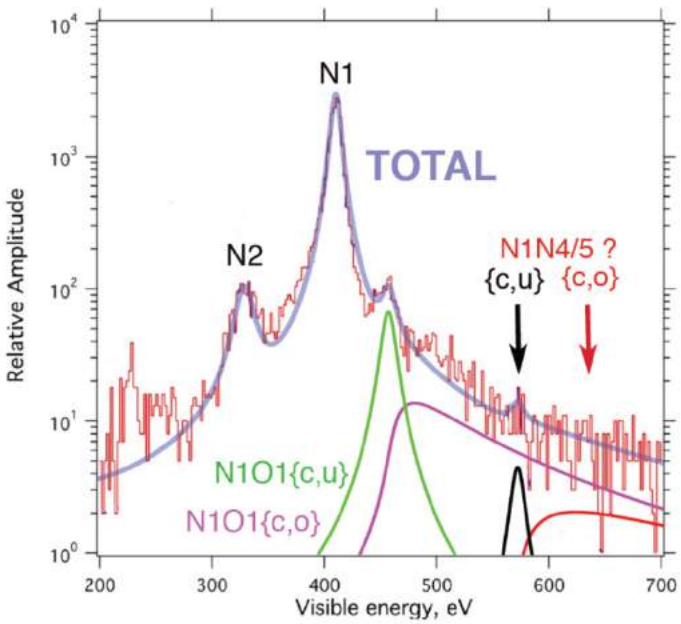
Towards high statistics
$^{163}$Ho spectrum

# $^{163}$Ho spectral shape

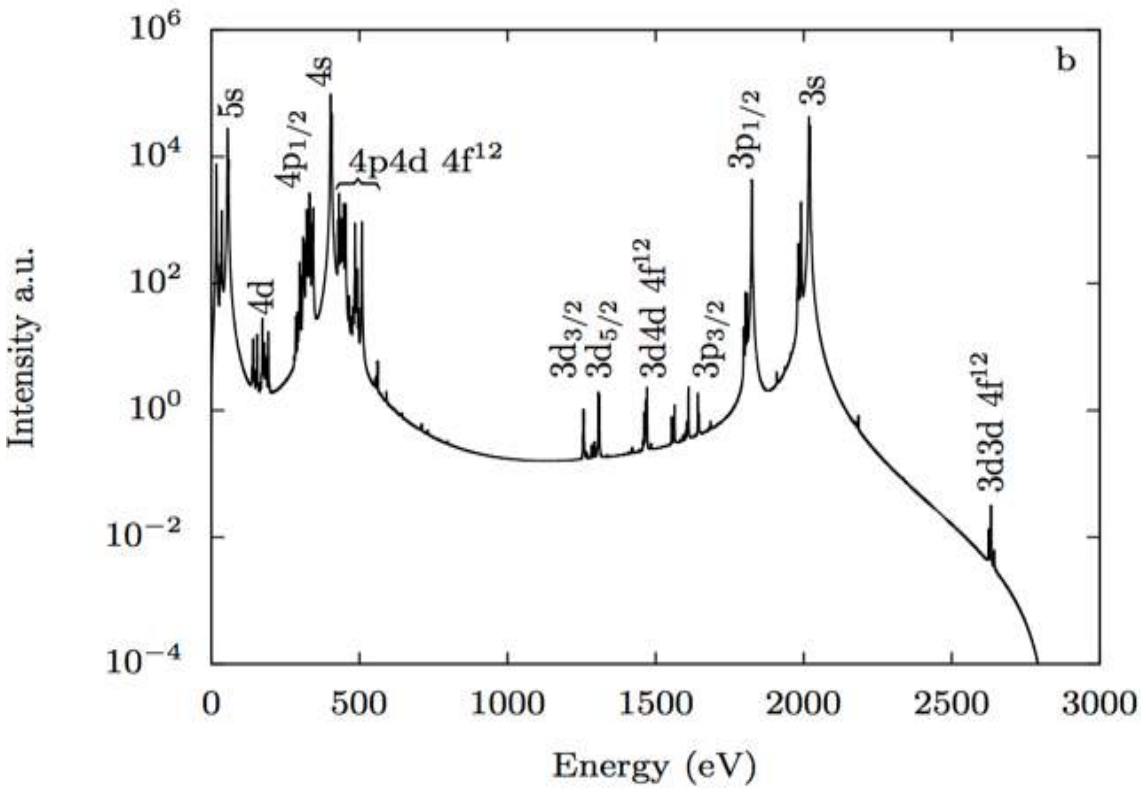



- A. Faessler and F. Simkovic
  Phys. Rev. C **91**, 045505 (2015)
- A. De Rujula and M. Lusignoli
  JHEP 05 (2016) 015, arXiv:1601.04990v1
- A. Faessler et al.
  *J. Phys. G* **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. Faessler et al.
  Phys. Rev. C **95**, (2017) 045502

No good agreement between experimental spectrum and theory



# $^{163}$Ho spectral shape




New approach

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

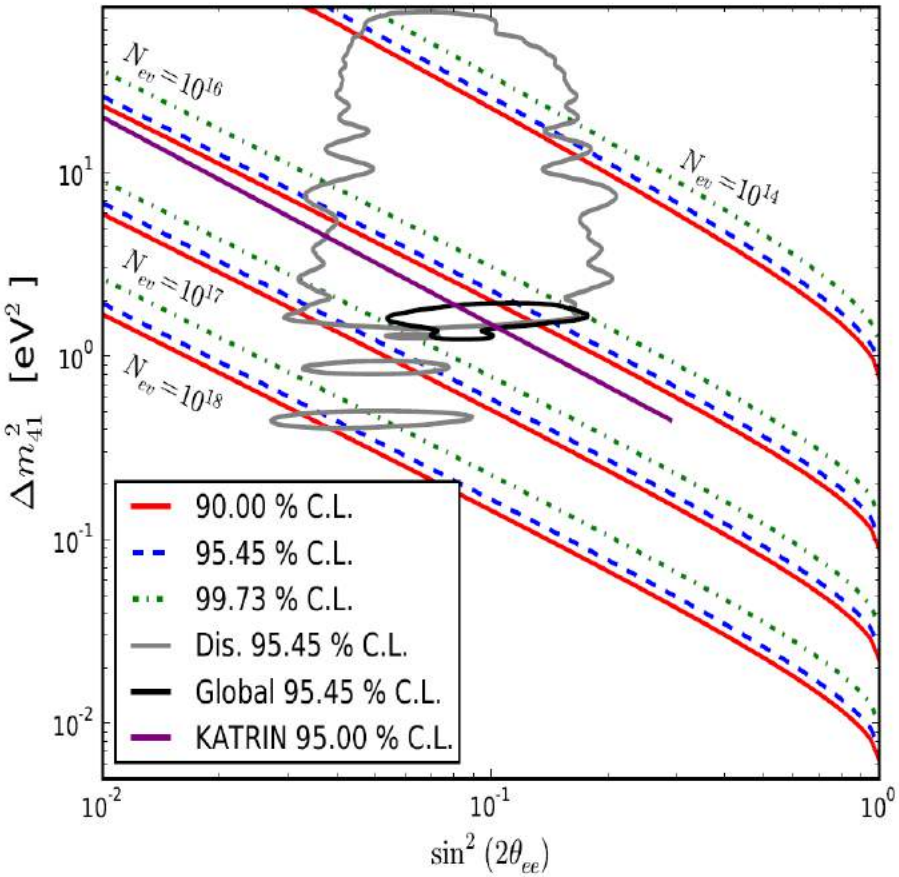
Brass et al., https://arxiv.org/abs/1711.10309

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

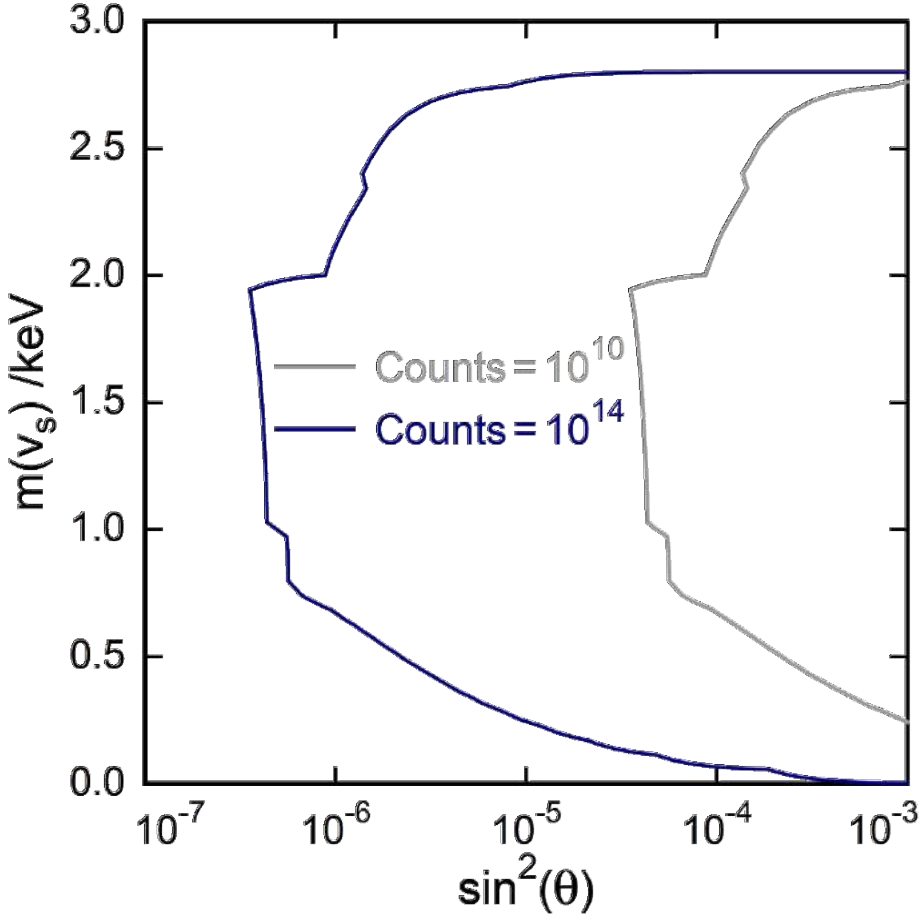
# Sterile neutrinos search in ECHo

eV-scale sterile neutrinos




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

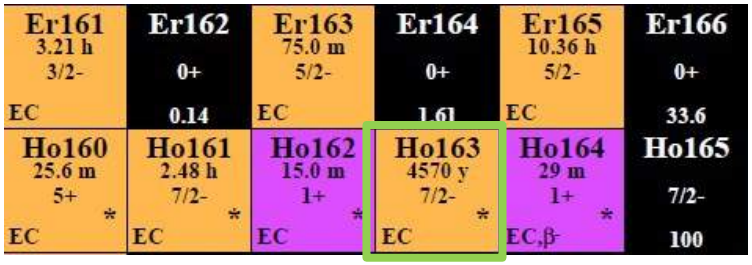
keV-scale serile neutrinos

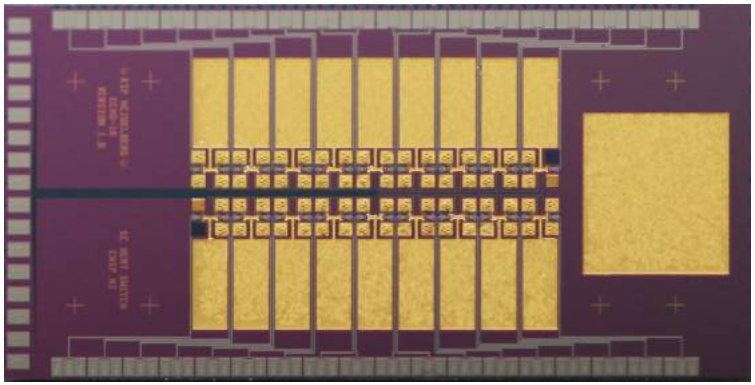



A White Paper on keV Sterile Neutrino Dark Matter, JCAP01(2017)025

# Conclusions and outlook

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

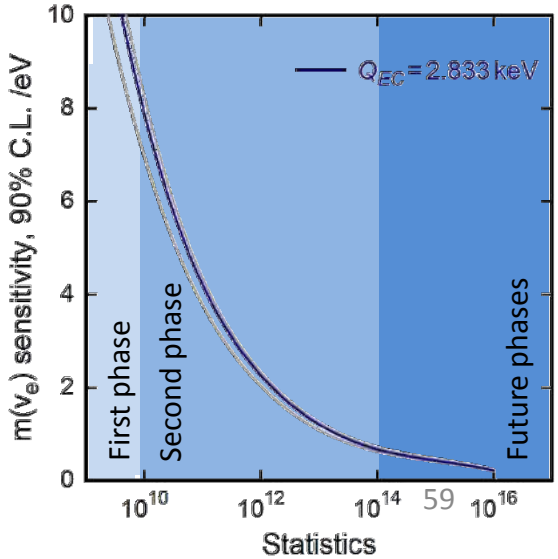
  $Q_{EC} = (2.858 \pm 0.010^{stat} \pm 0.05^{syst})$ keV

- 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

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Klaus Blaum, Andreas Dörr, Sergey Eliseev, Mikhail Goncharov,
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ECHo

*Thank you !*