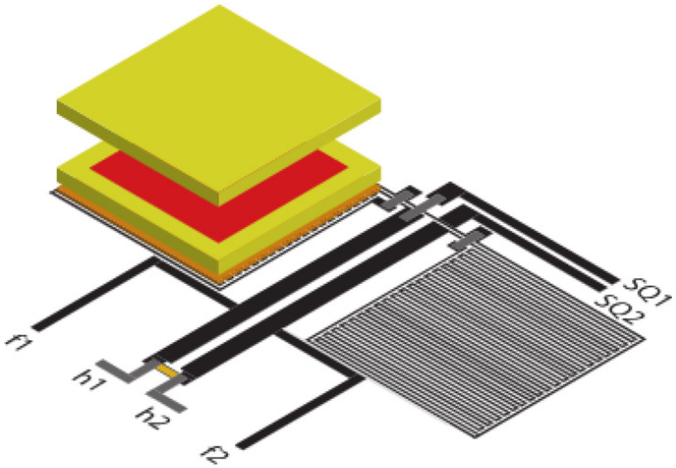
The Electron Capture in ^{163}Ho experiment

Loredana Gastaldo
for the ECHo Collaboration

Kirchhoff Institute for Physics, Heidelberg University



Contents

- ^{163}Ho and neutrino mass
- Low temperature metallic magnetic calorimeters
- Recent results
- Conclusions and outlook

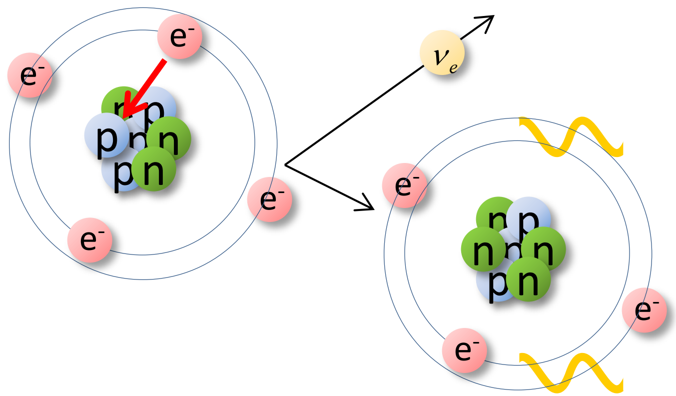
Contents

- ^{163}Ho and neutrino mass
- Low temperature metallic magnetic calorimeters
- Recent results
- Conclusions and outlook

Present limit:
$m(\nu_e) < 225$ eV (95% C.L.)

P.T. Springer et al., *Phys. Rev. A* **35**, 679 (1987)

Electron Capture



A non- zero neutrino mass affects the de-excitation energy spectrum

Atomic de-excitation:

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

} Calorimetric measurement

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

The case of ^{163}Ho

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

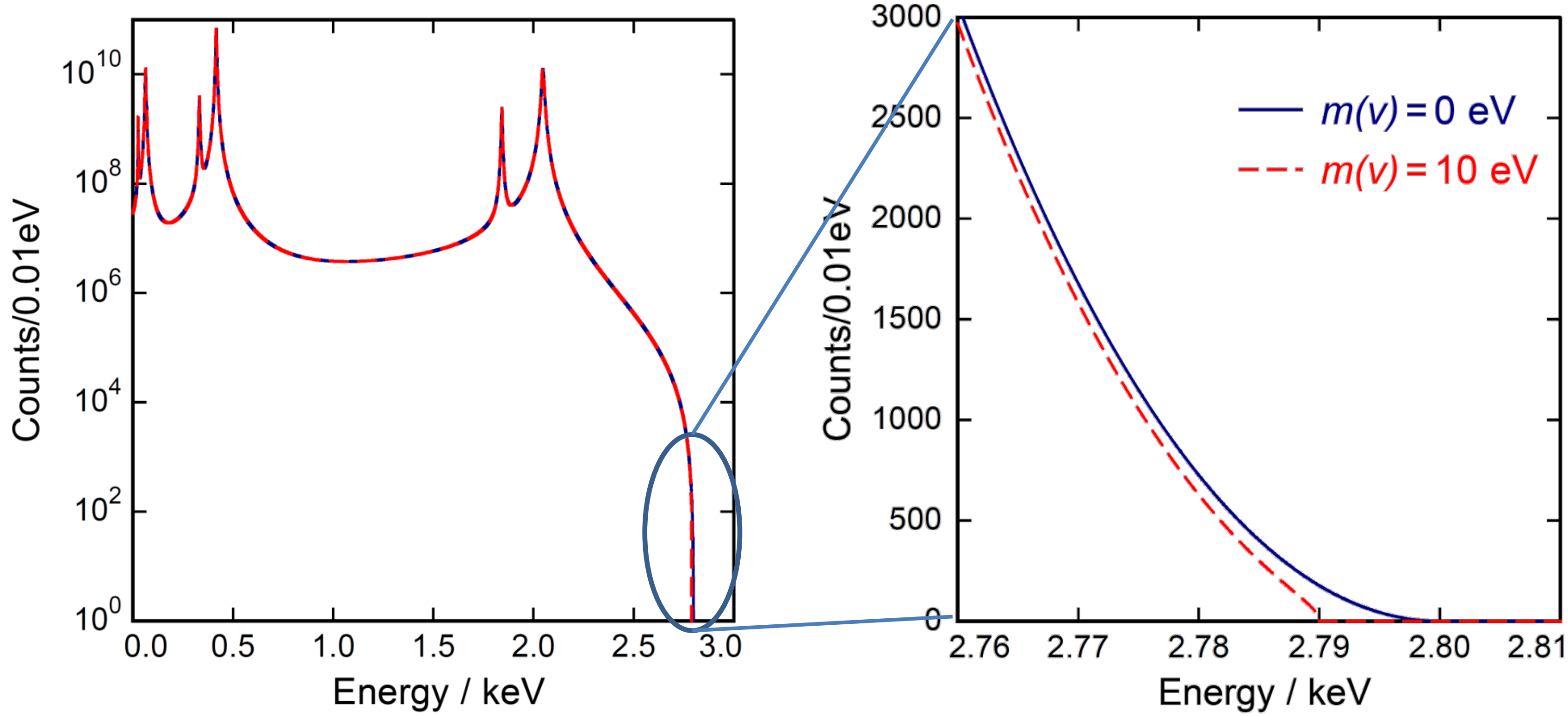
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

- $\tau_{1/2} \cong$ 4570 years

  (2*10^{11} atoms for 1 Bq)

- Q_{EC} = (2.555 ± 0.016) keV *

  recomended value!?



*M. Wang, G. Audi et al., *Chinese Phys. C* **36**, 1603, (2012)

The case of ^{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)

- $Q_{EC} = (2.555 \pm 0.016)$ keV *
  recomended value!?

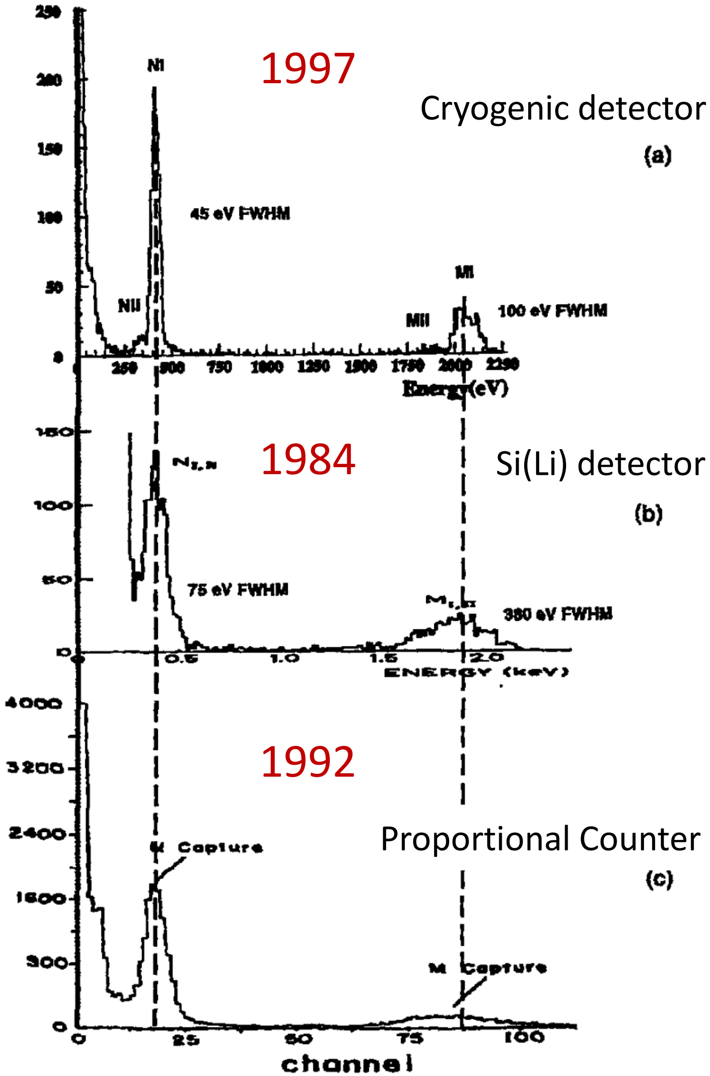
Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

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

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

*M. Wang, G. Audi et al., *Chinese Phys. C* **36**, 1603, (2012)

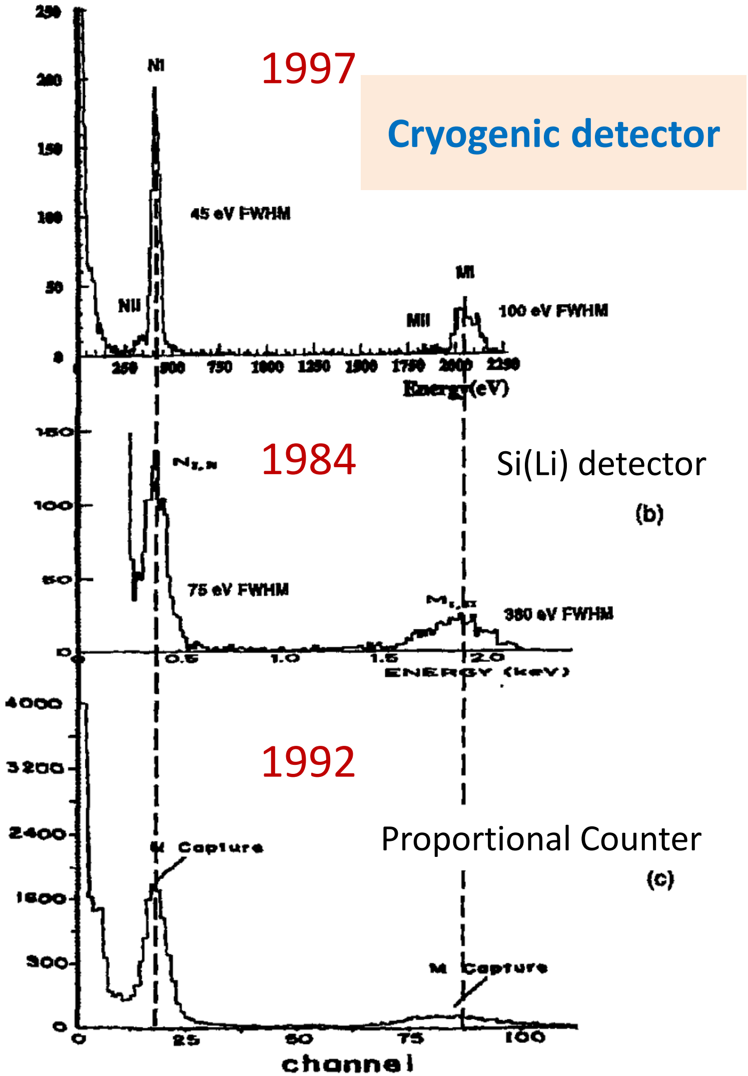
The case of ^{163}Ho



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.

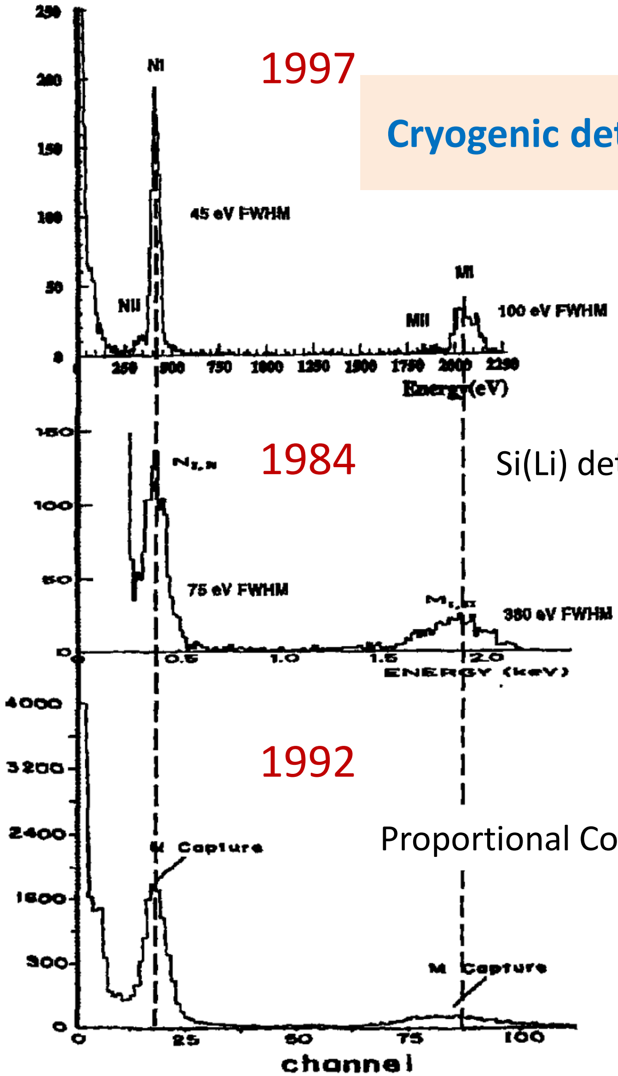
The case of ^{163}Ho



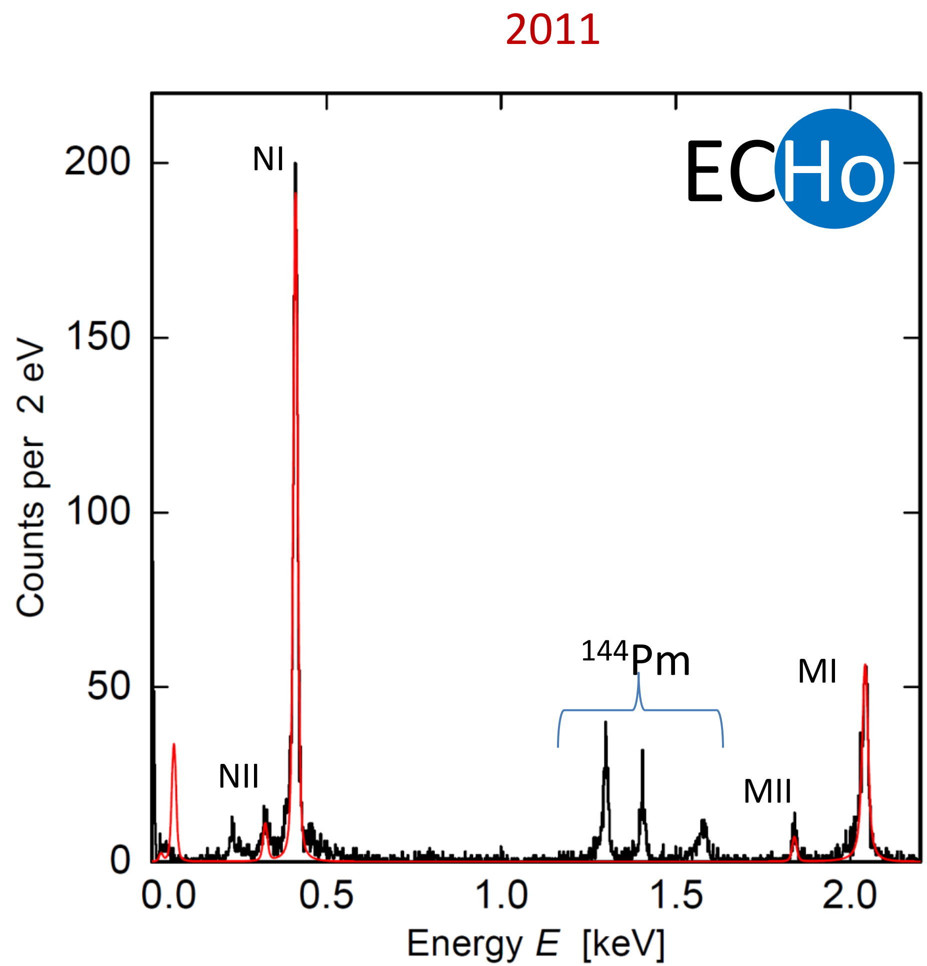
F. Gatti et al., Physics Letters B 398 (1997) 415-419

(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.

The case of ^{163}Ho



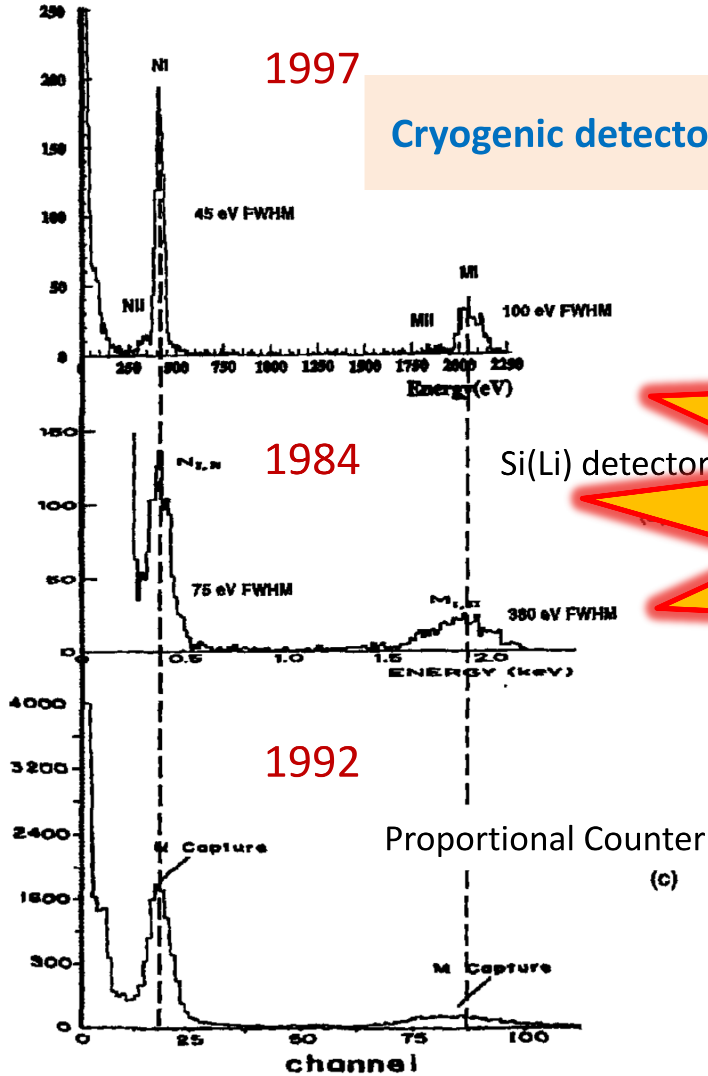
F. Gatti et al., Physics Letters B 398 (1997) 415-419



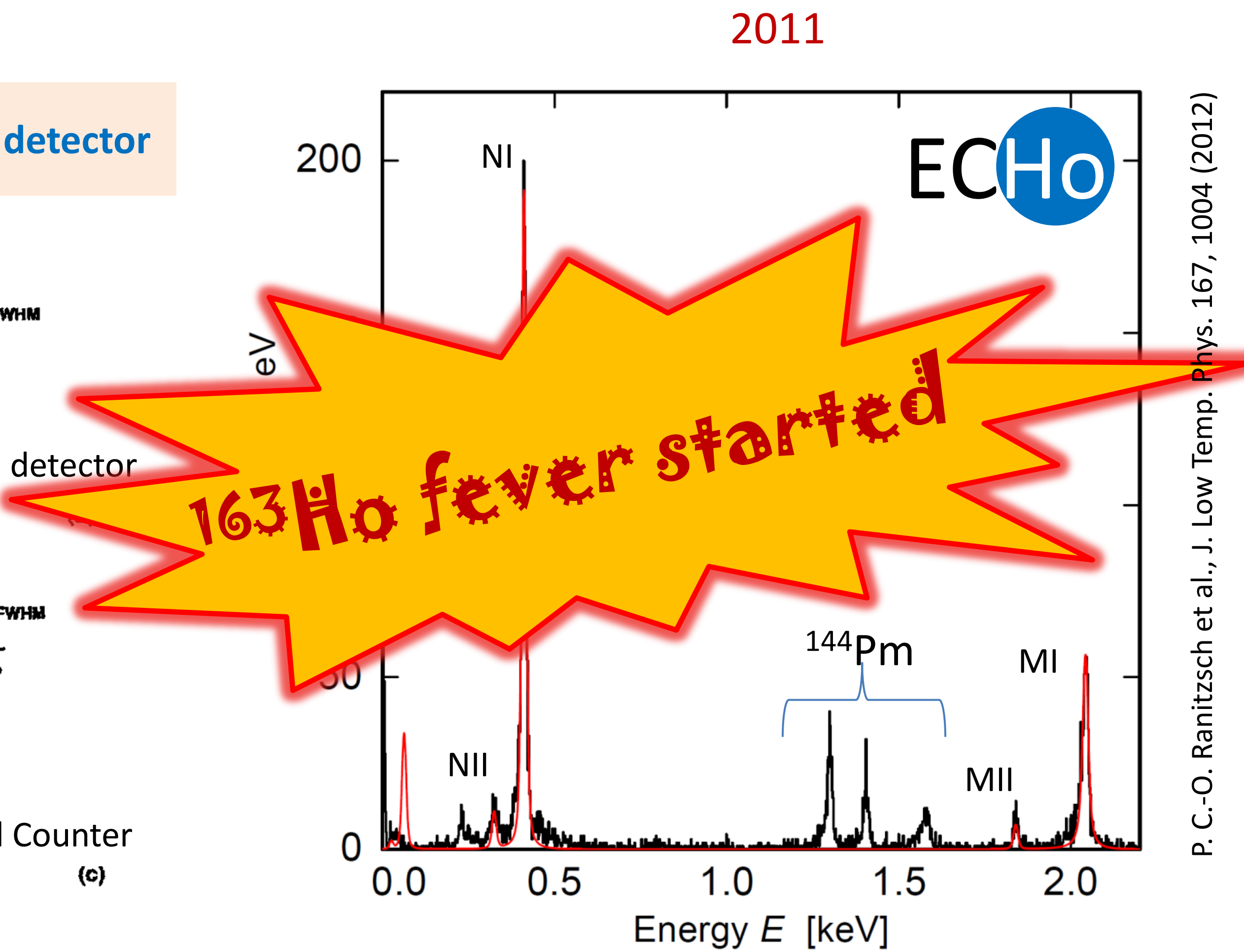
P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)

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

The case of ^{163}Ho



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



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
(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.

^{163}Ho-based experiments

ECHo

- Comenius University, Bratislava, Slovakia
- Department of Physics, IIT Roorkee, India
- Johannes Gutenberg University Mainz
- Institute of Nuclear Research of the Hungarian Academy of Sciences
- ITEP, Moscow, Russia
- University of Tübingen, Germany
- KIP, Heidelberg University, Germany
- MPI-K, Heidelberg, Germany
- PNPI, Petersburg, Russia
- Saha Institute of Nuclear Physics, Kolkata, India

HOLMES

- Milano-Bicocca University, Italy
- INFN Sez. Milano-Bicocca, Italy
- INFN Sez. Genova, LNGS, Italy
- INFN Sez. Roma, Italy
- Lisboa University, Portugal
- Miami University, USA
- NIST, Boulder, USA
- JPL, Pasadena, USA

NuMECS

- LANL, Los Alamos, USA
- NIST, Boulder, USA
- Univ. of Wisconsin, Madison, USA

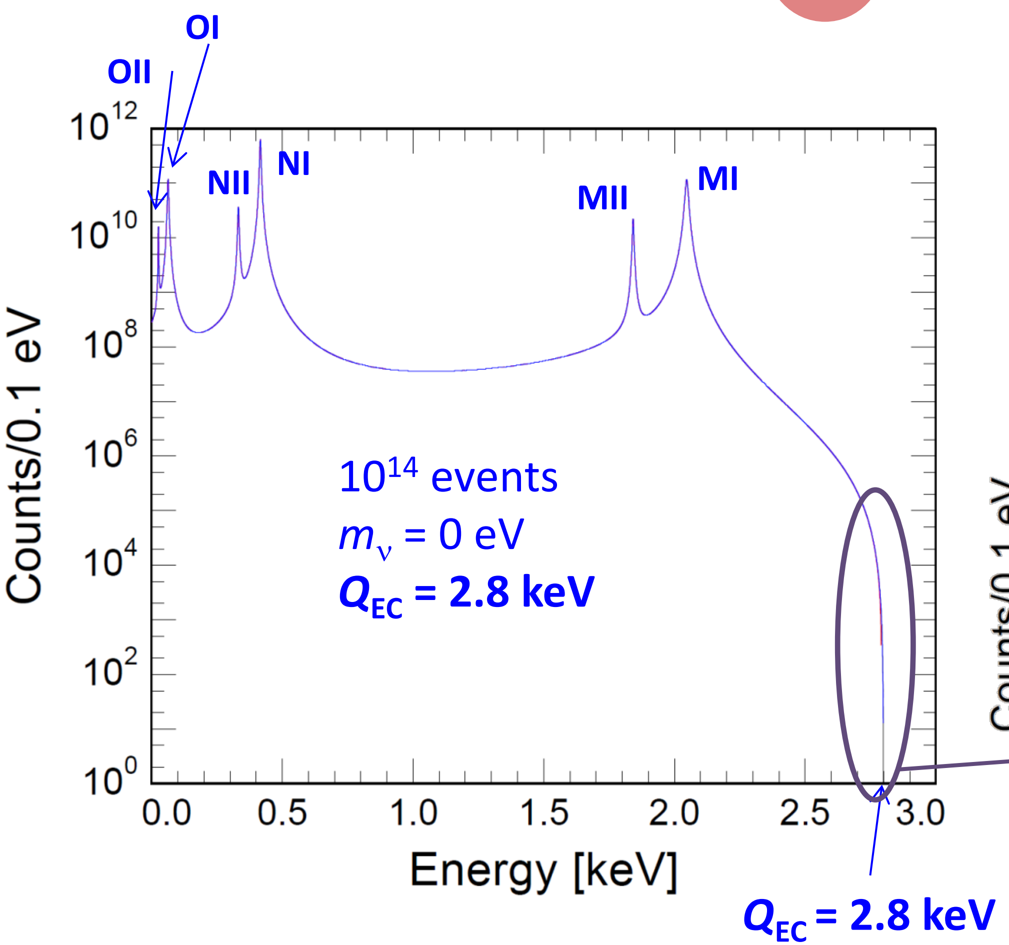
Common challenges to reach sub eV sensitivity :

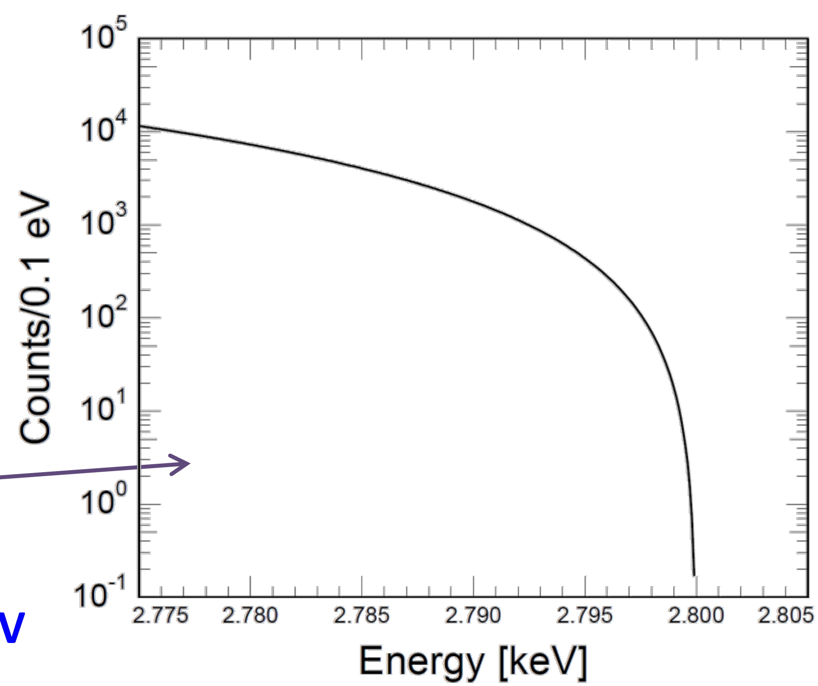
- **Detector performance**
- High purity ^{163}Ho source
- Background reduction
- Description of the ^{163}Ho EC spectrum

The case of ^{163}Ho: Statistics

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

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

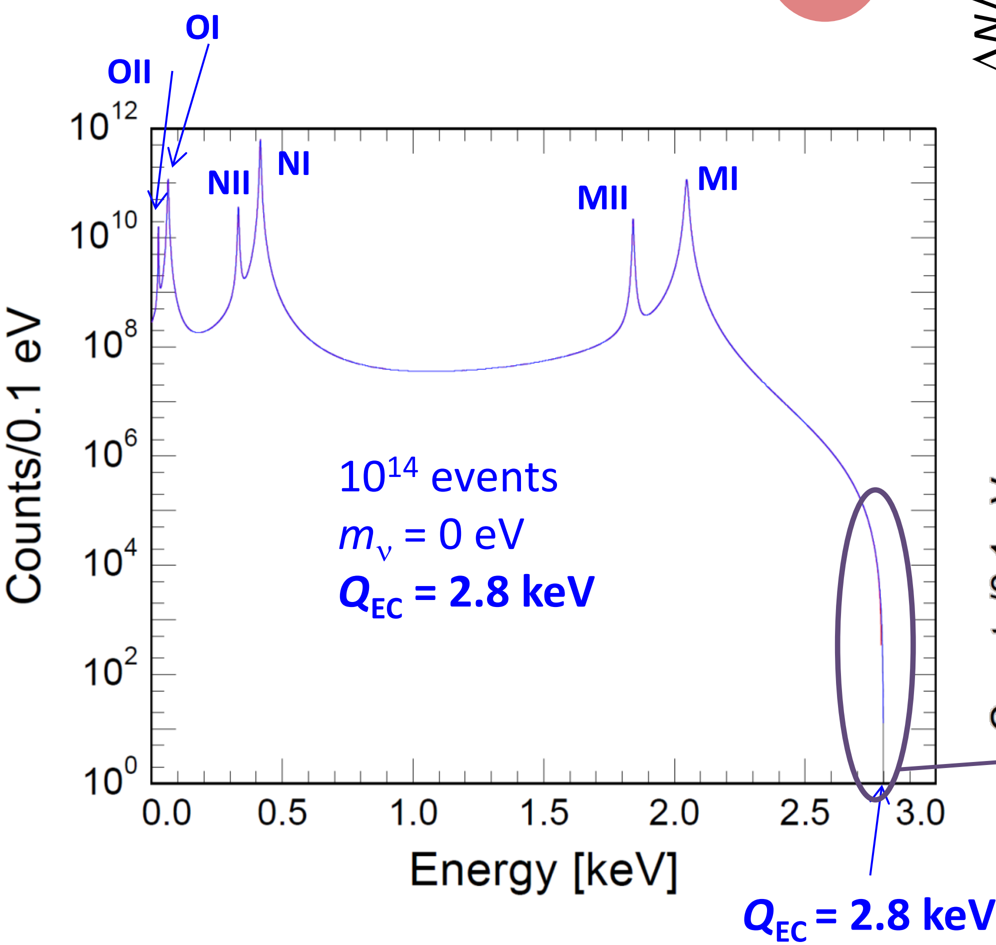


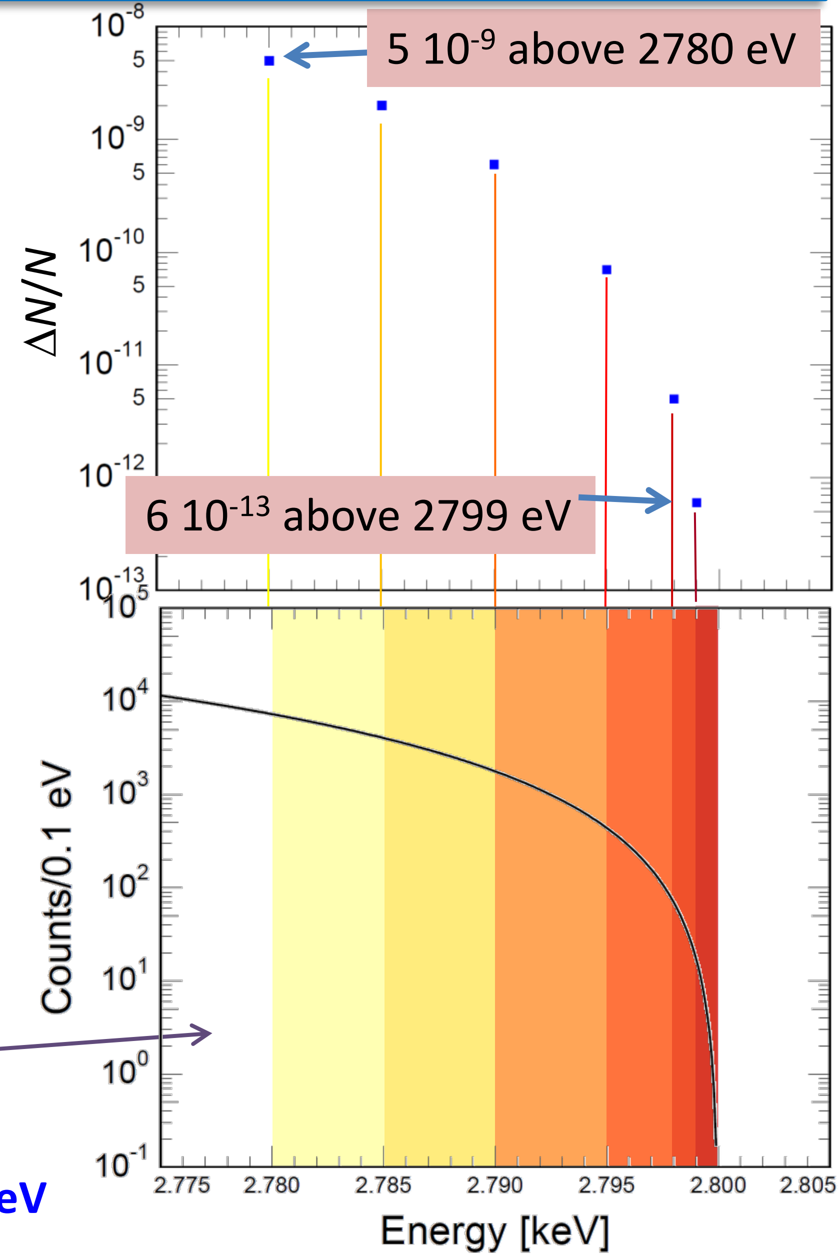


The case of ^{163}Ho: Statistics

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

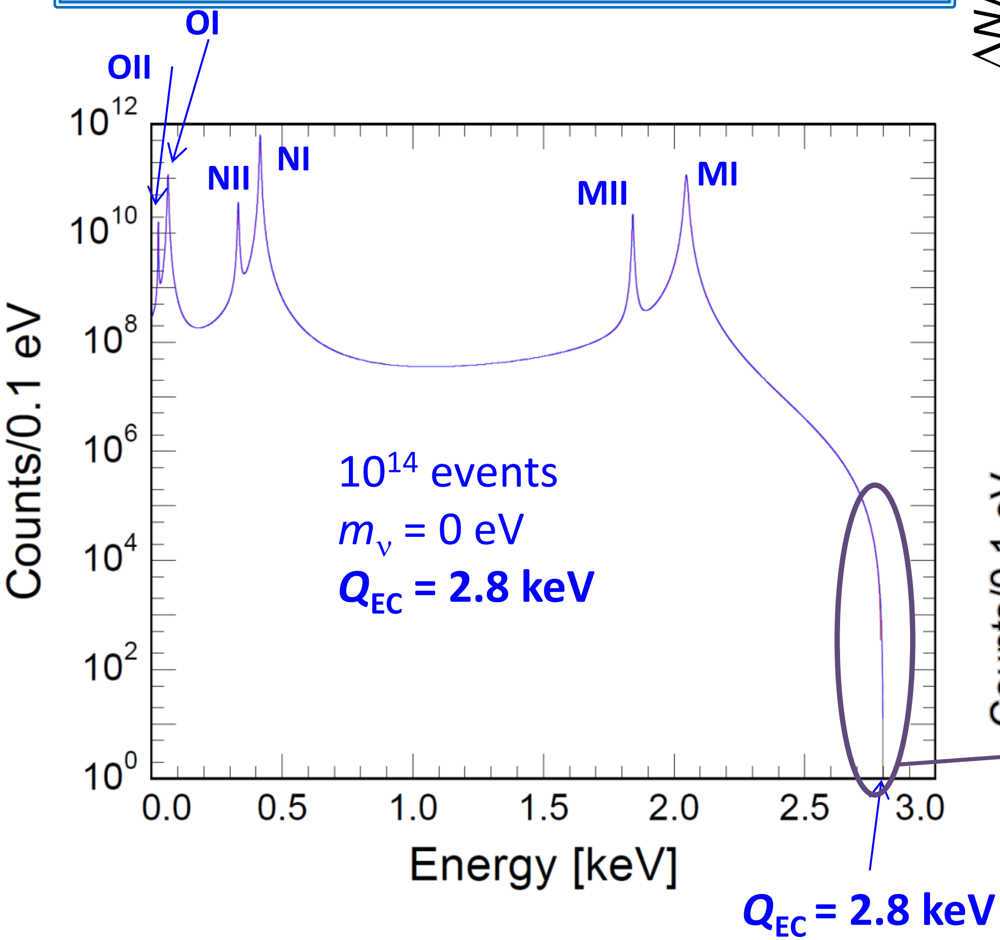
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

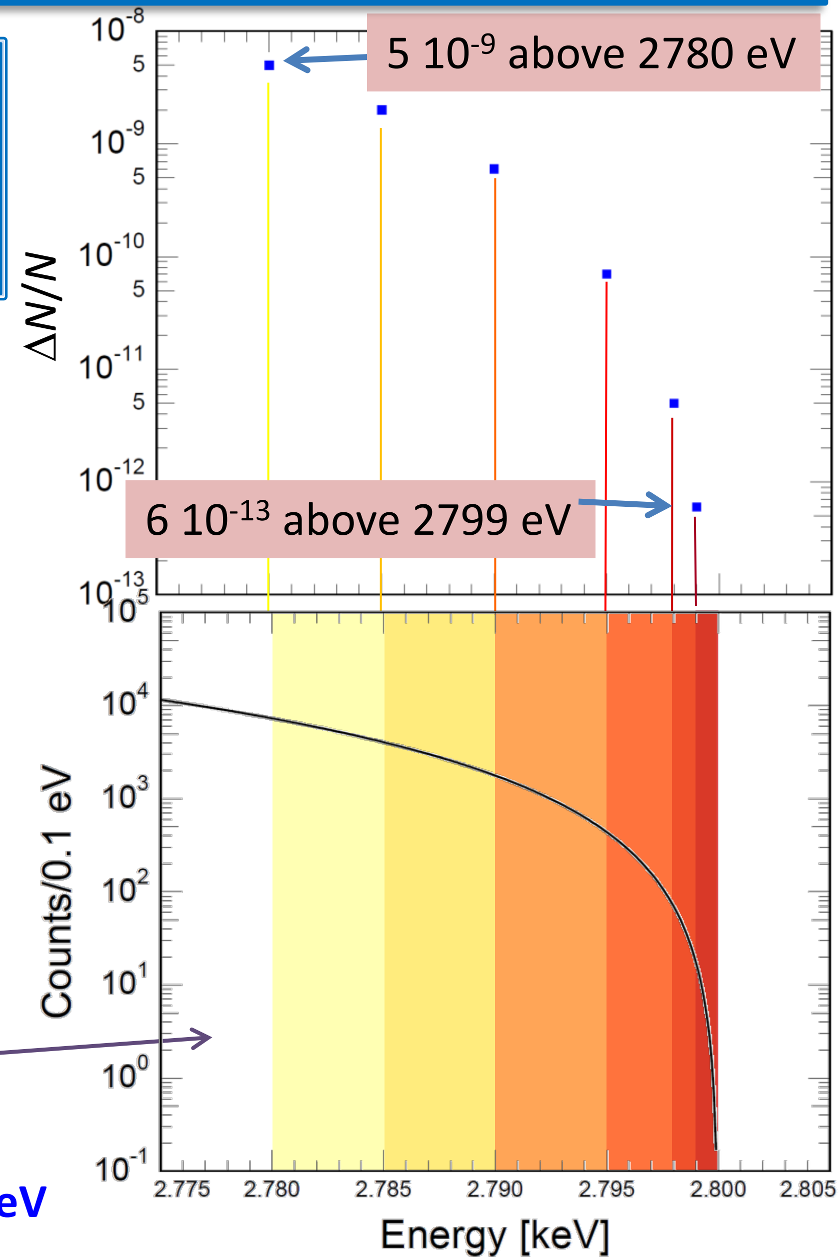




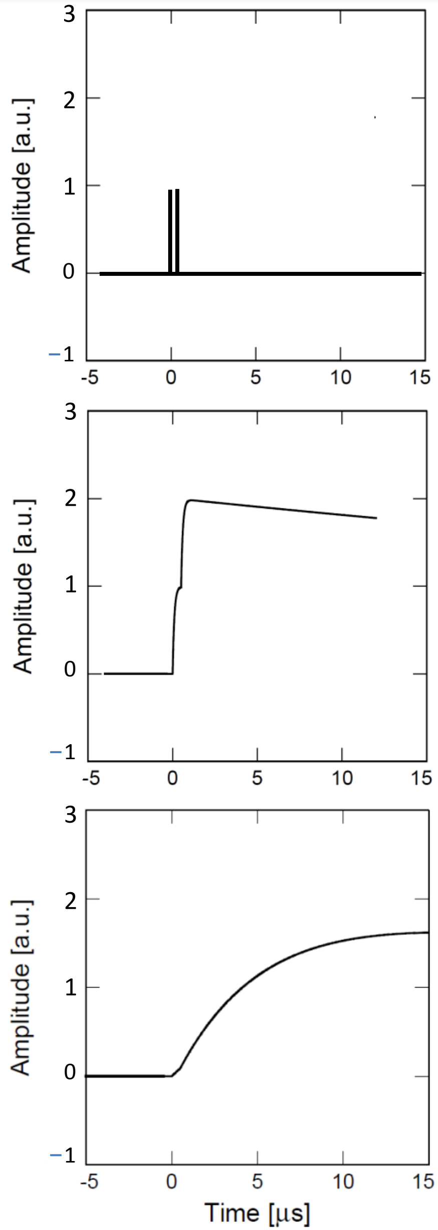
The case of ^{163}Ho: Statistics

More than 10^{14} events
→ A ~ MBq





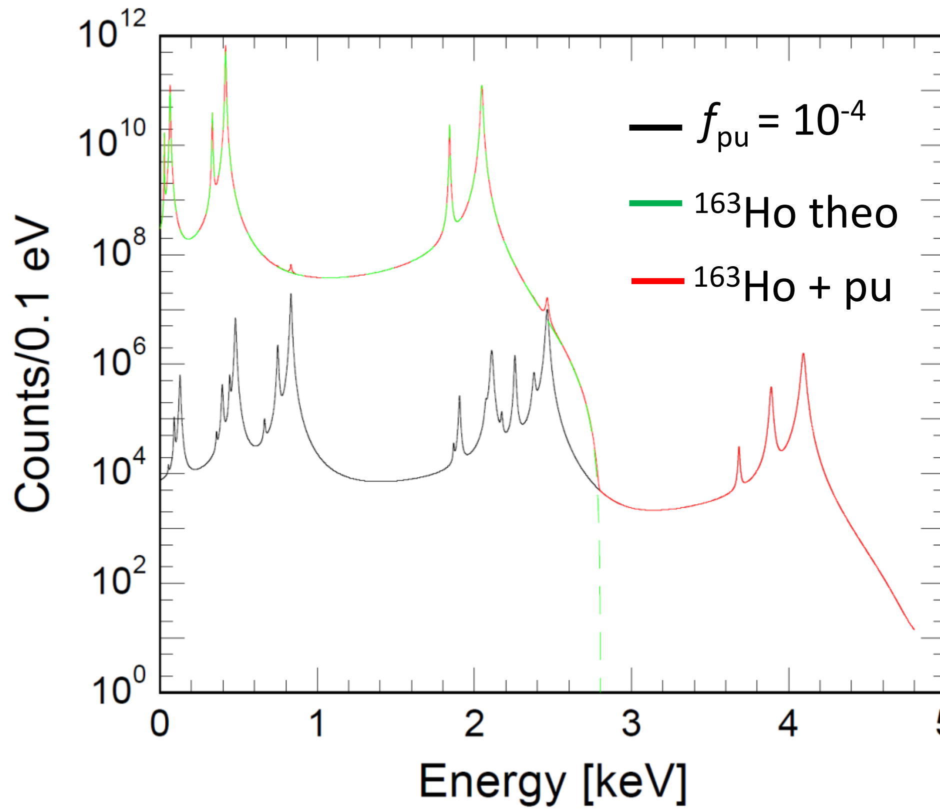
The case of ^{163}Ho: Unresolved pile-up



Δt = 0.5 µs

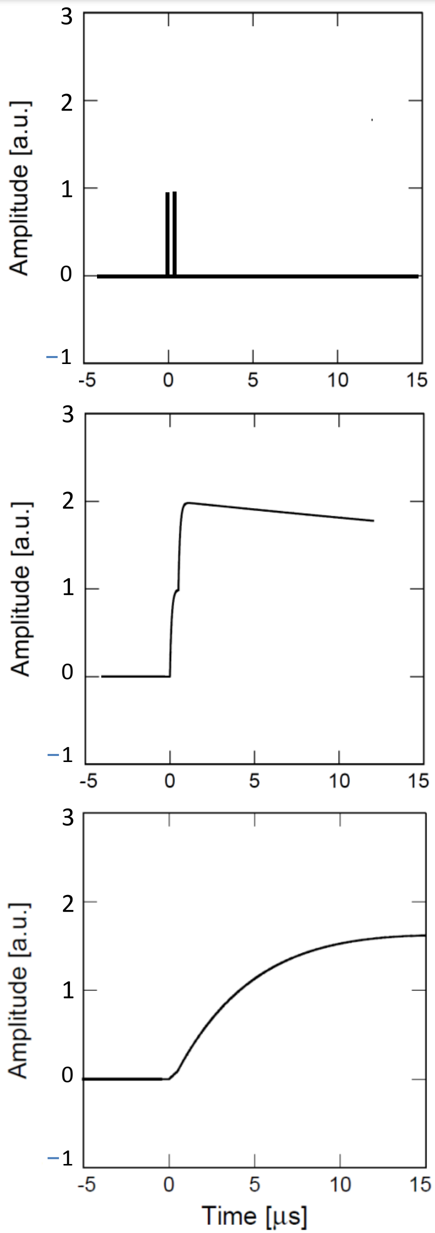
τ_r = 0.1 µs

τ_r = 5 µs



$$f_{pu} \approx A\tau_r$$

The case of ^{163}Ho: Unresolved pile-up

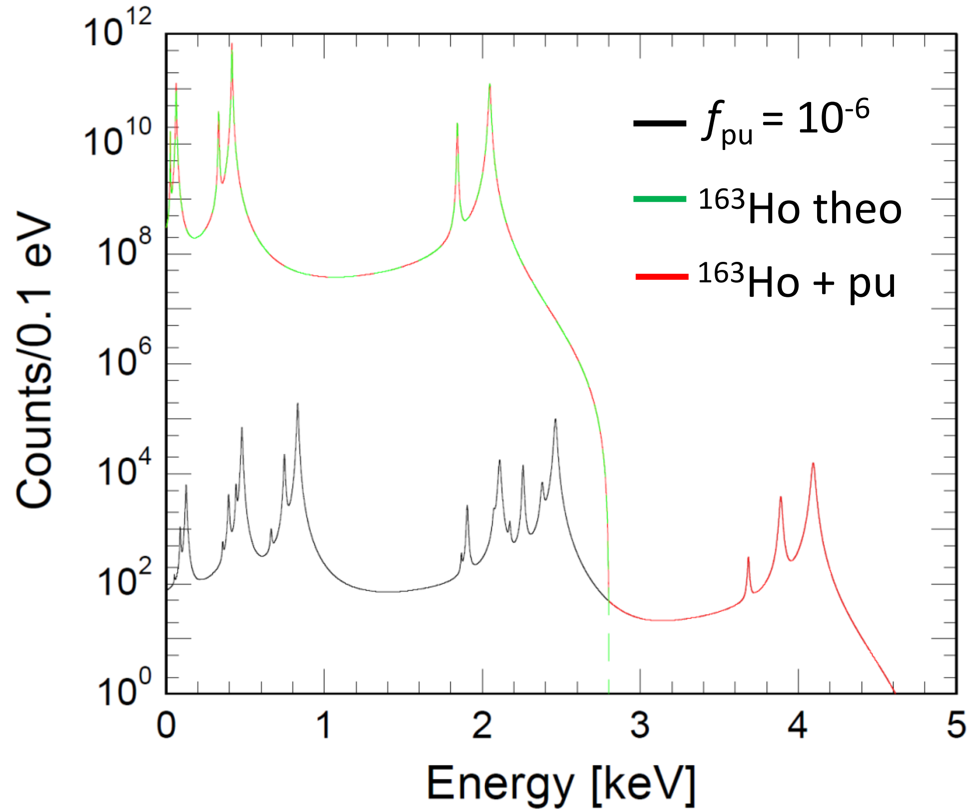


Δt = 0.5 µs

τ_r = 0.1 µs

τ_r = 5 µs

$$f_{pu} \approx A\tau_r$$

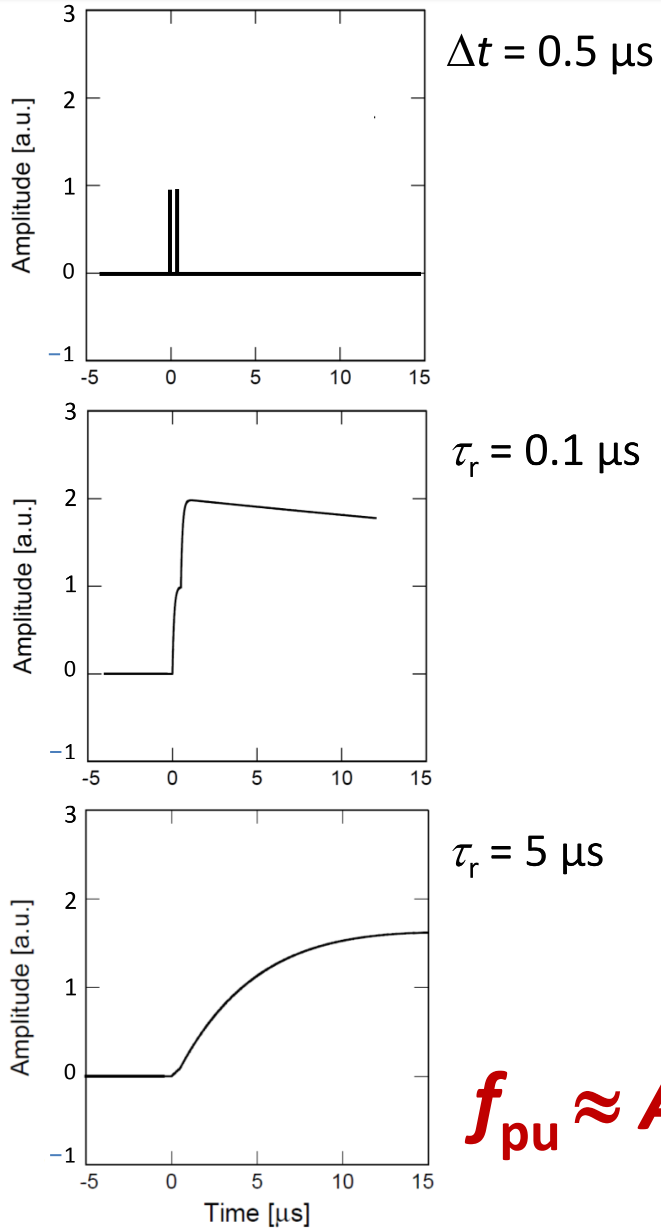


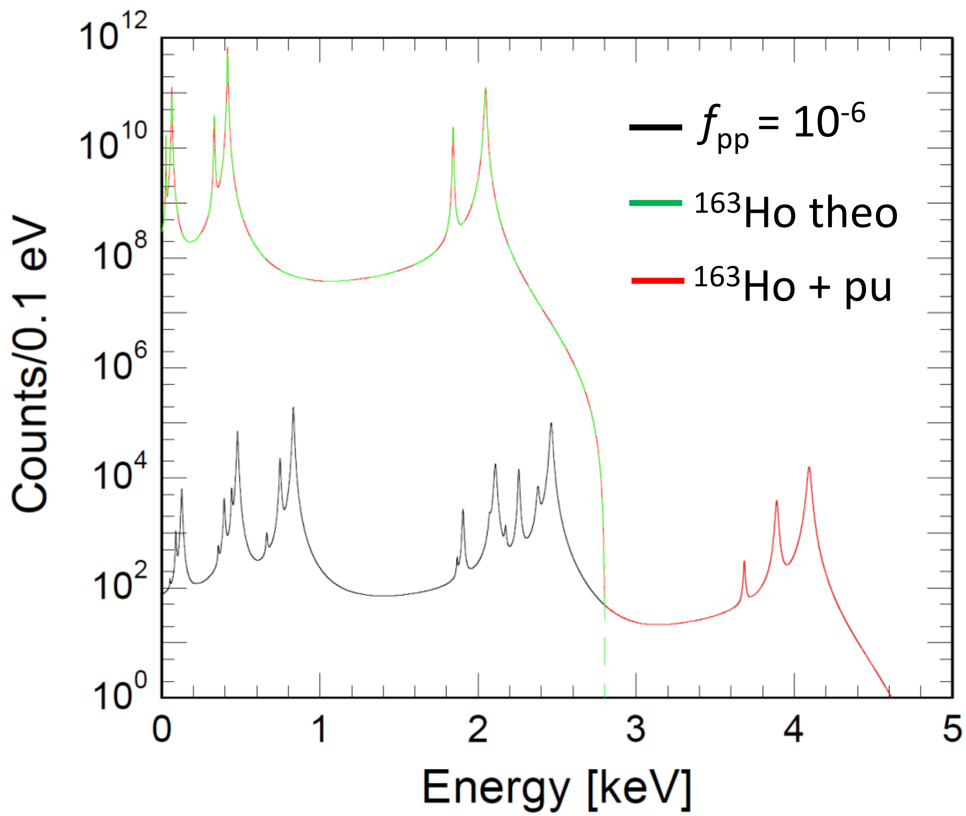
$f_{pu} = 10^{-6}$

$\tau_r = 10^{-6}$ s → A = 1 Bq

10^6 Bq → **10^6 detectors**

The case of ^{163}Ho: Unresolved pile-up





$$f_{pu} \approx A\tau_r$$

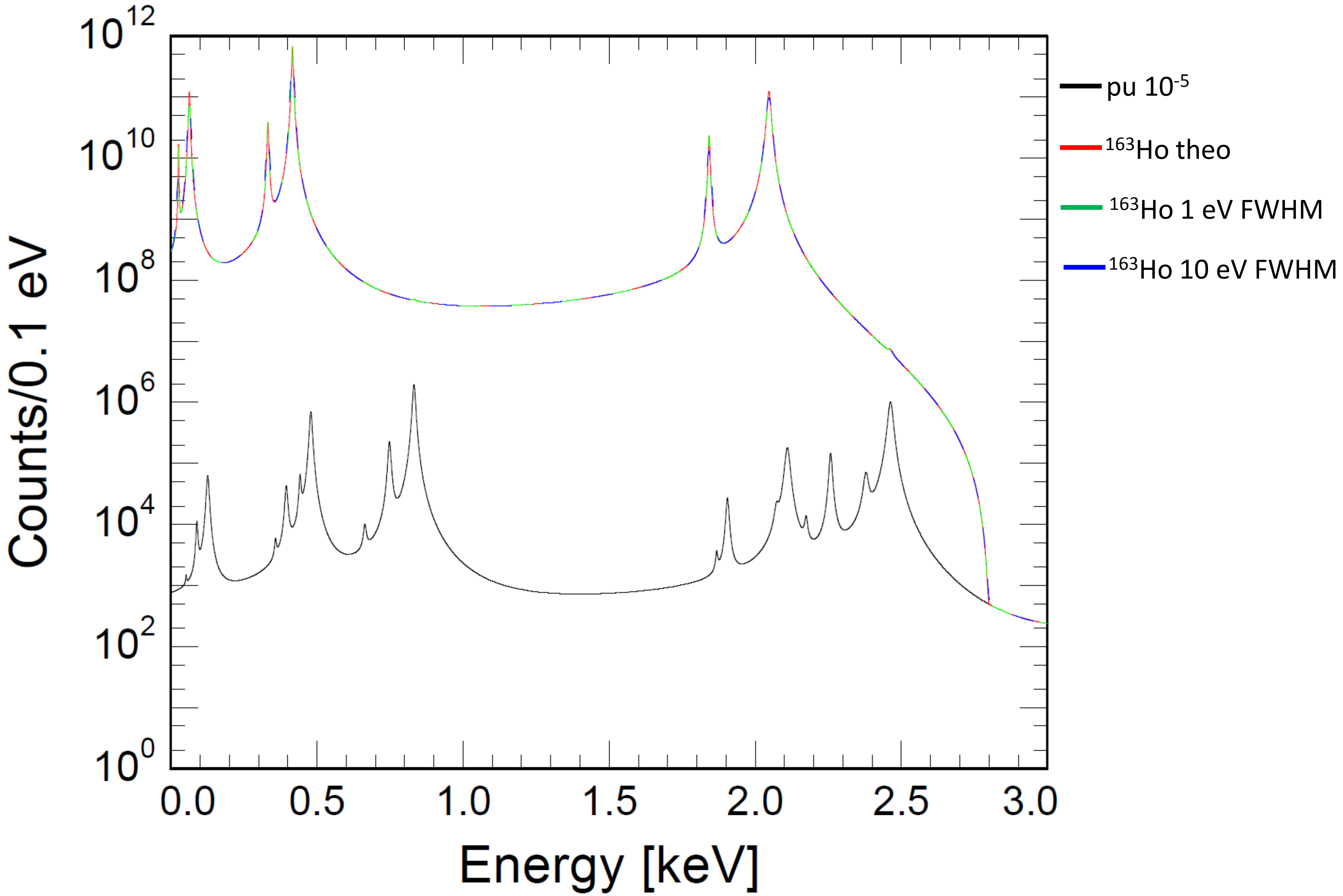
f_{pu} = 10^{-6}

$\tau_r = 10^{-6}$ s → A = 1 Bq

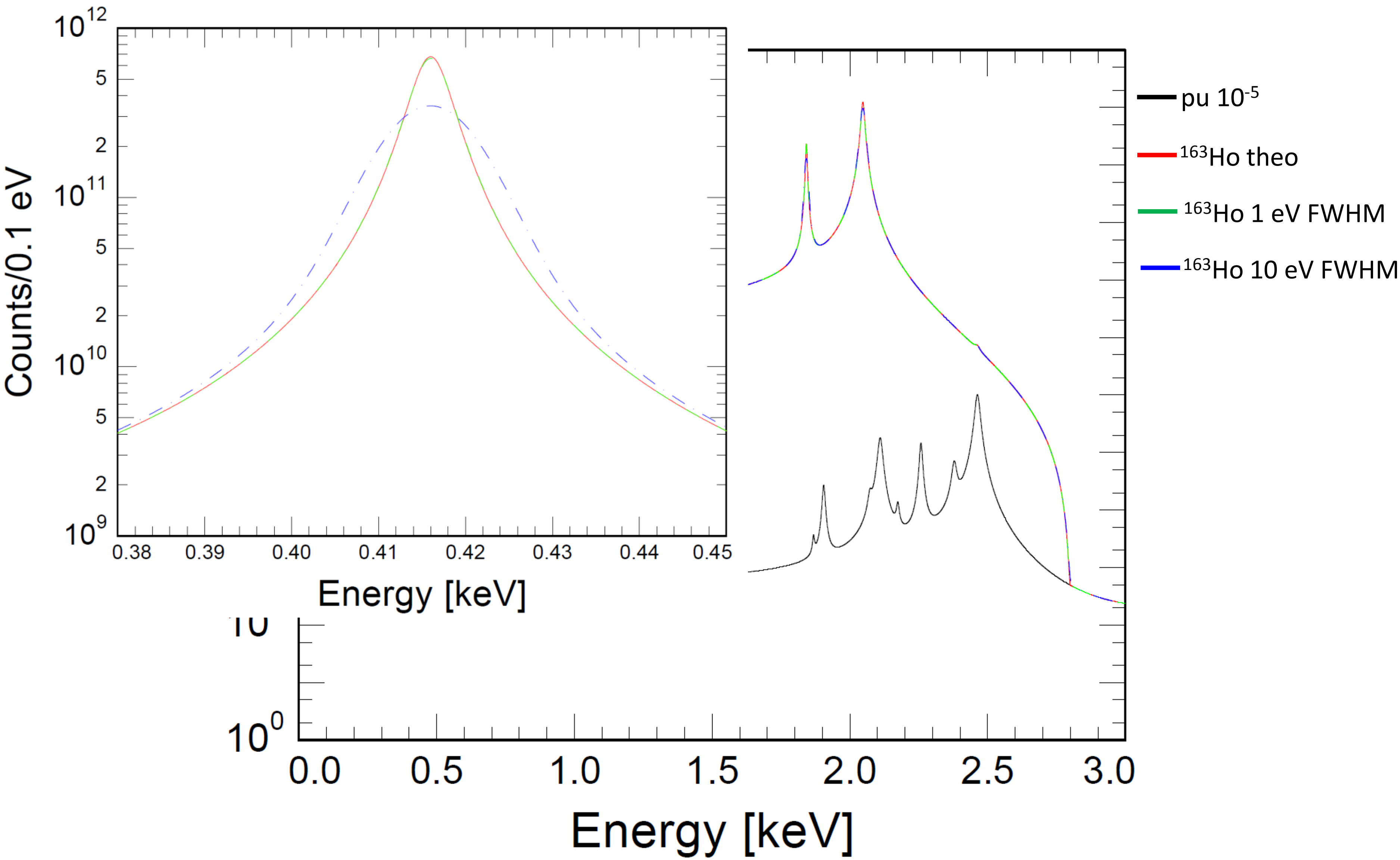
10^6 Bq → **10^6 detectors**

Fast detectors

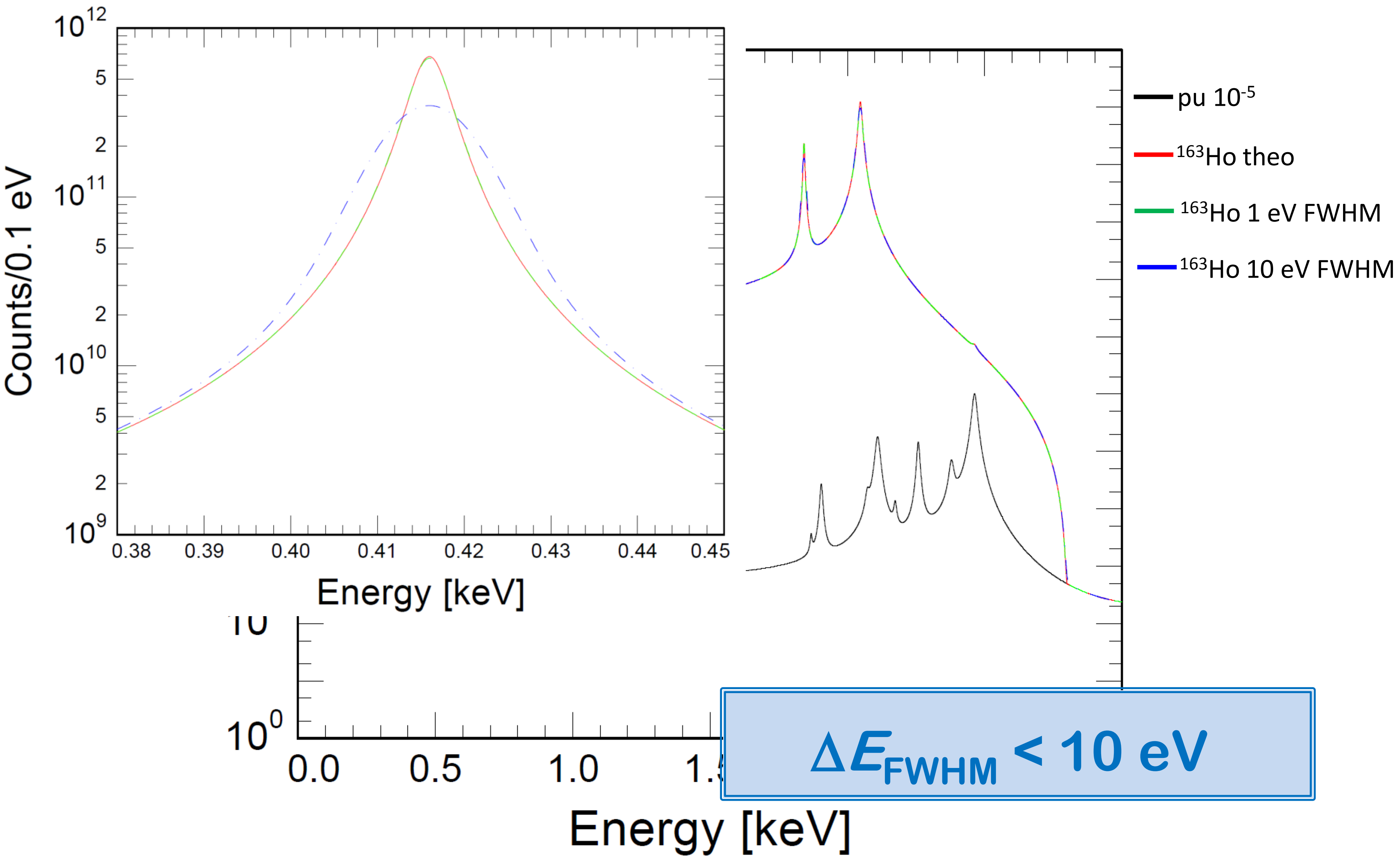
The case of ^{163}Ho: Energy resolution



The case of ^{163}Ho: Energy resolution

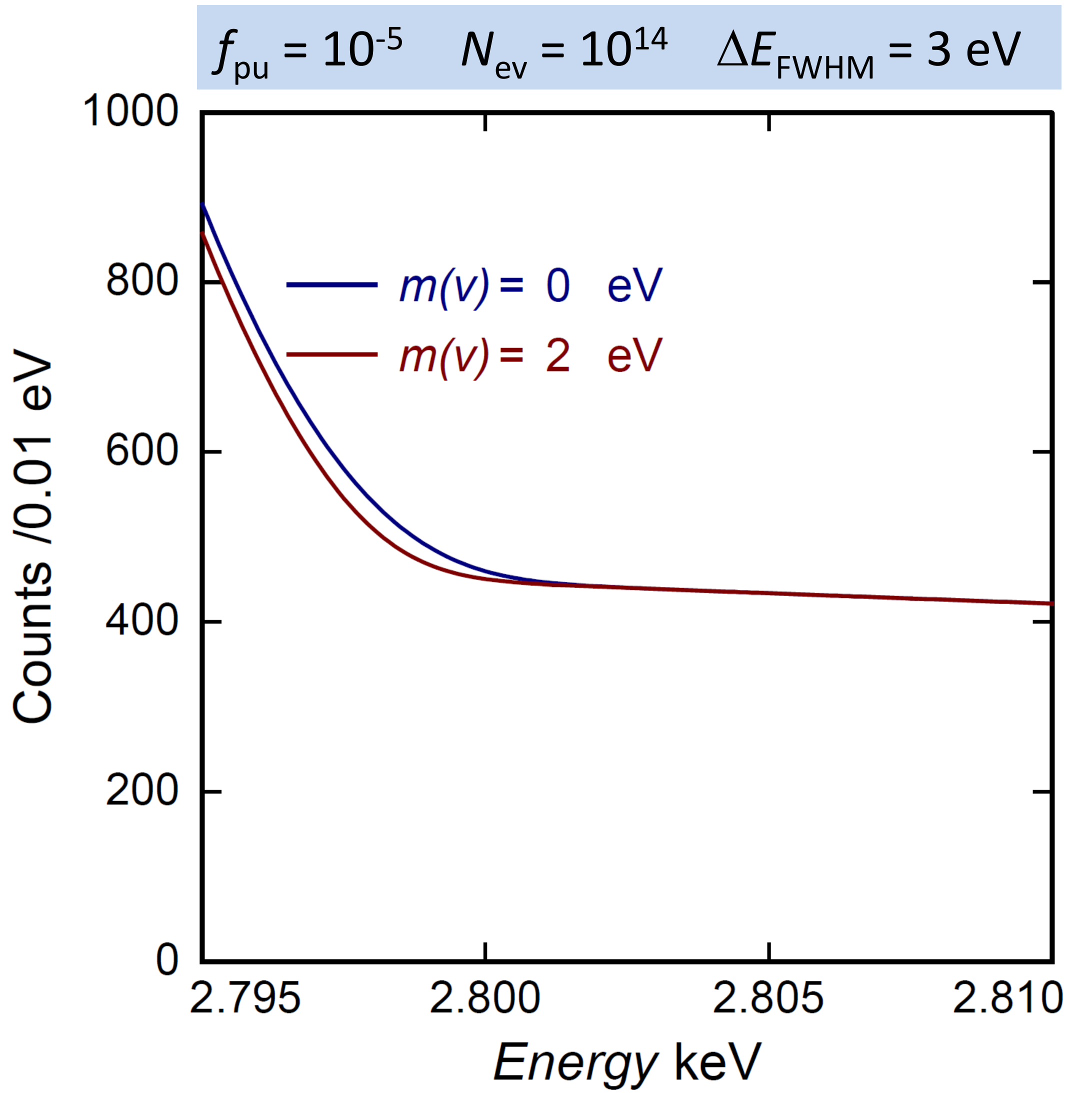


The case of ^{163}Ho: Energy resolution



$\Delta E_{FWHM} < 10$ eV

The case of ^{163}Ho: Energy resolution



Sub-eV sensitivity

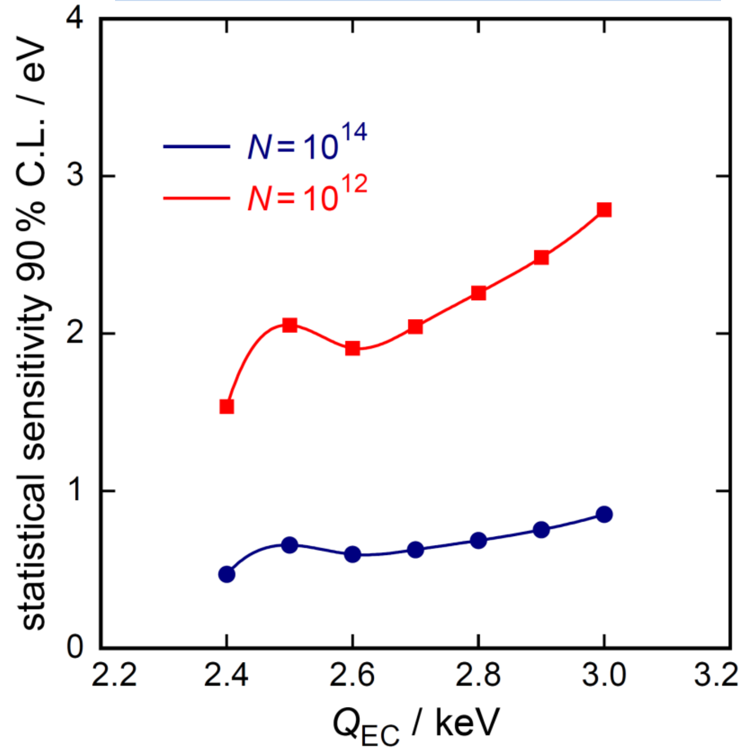
- $N_{ev} > 10^{14}$
- $f_{pu} < 10^{-5}$
- $\Delta E_{FWHM} < 10$ eV

- Strongly affected by Q_{EC}

➢ Independent measurement of Q_{EC} to design the final experiment

Penning trap mass spectroscopy

$f_{pu} = 10^{-6}$ $\Delta E_{FWHM} = 3$ eV



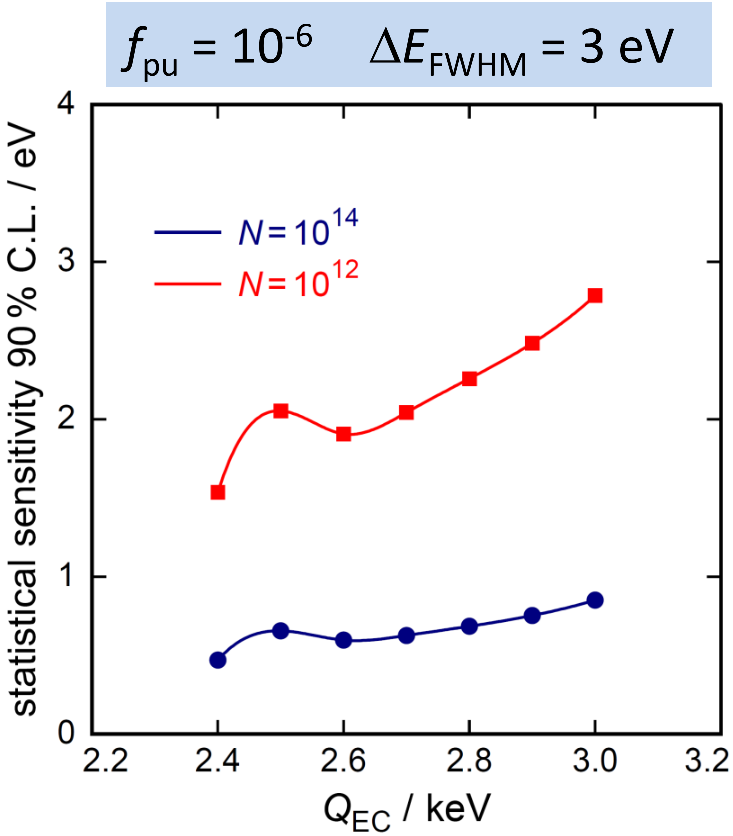
Sub-eV sensitivity

- $N_{ev} > 10^{14}$
- $f_{pu} < 10^{-5}$
- $\Delta E_{FWHM} < 10$ eV

- Strongly affected by Q_{EC}

➢ Independent measurement of Q_{EC} to design the final experiment

Penning trap mass spectroscopy



ECHo

PENTATRAP @MPI-K HD → 1 eV precision !

Sub-eV sensitivity

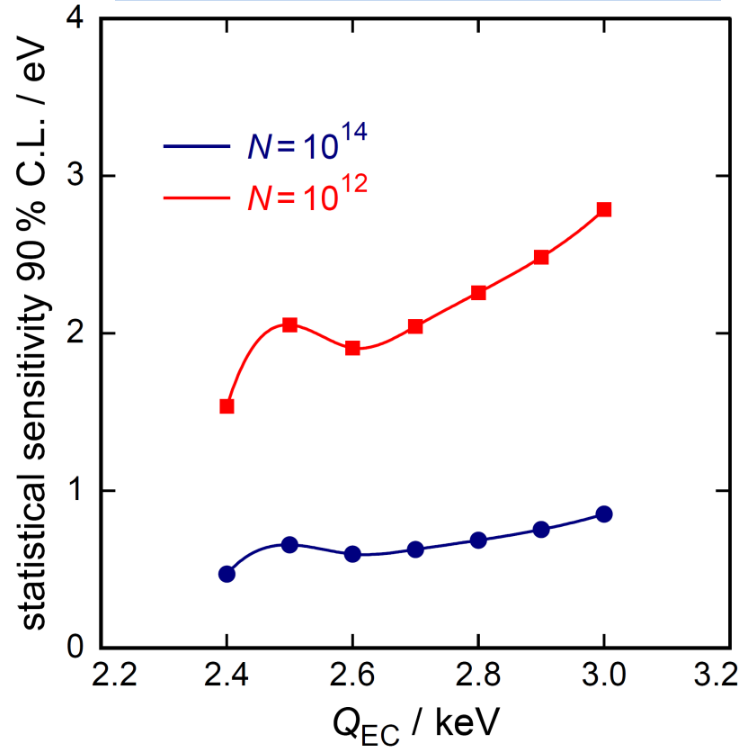
- $N_{ev} > 10^{14}$
- $f_{pu} < 10^{-5}$
- $\Delta E_{FWHM} < 10$ eV

- Strongly affected by Q_{EC}

➢ Independent measurement of Q_{EC} to design the final experiment

✓ **Penning trap mass spectroscopy**

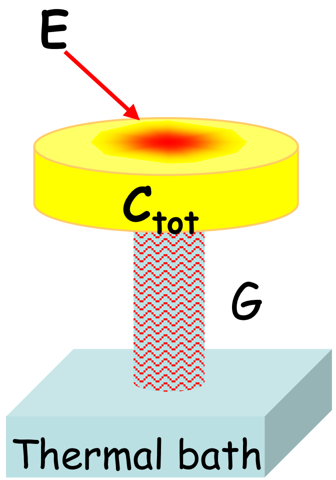
$f_{pu} = 10^{-6}$ $\Delta E_{FWHM} = 3$ eV



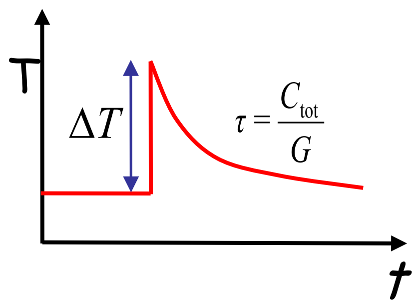
Low temperature

Metallic Magnetic Calorimeter

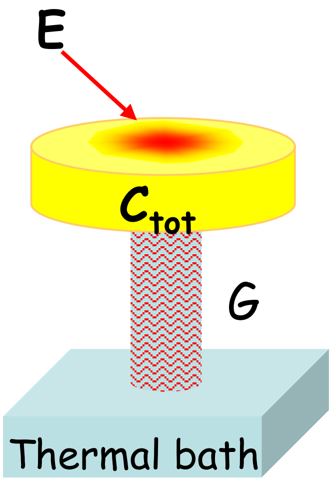
Low temperature micro-calorimeters



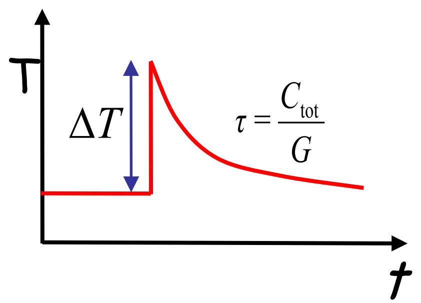
$$\Delta T \cong \frac{E}{C_{\mathrm{tot}}}$$



Low temperature micro-calorimeters

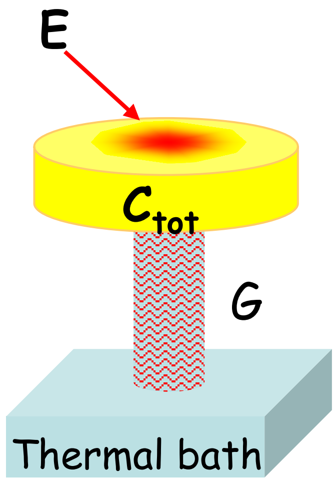


$$\Delta T \cong \frac{E}{C_{tot}}$$

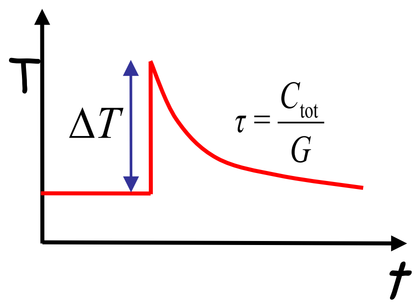


E = 10 keV
C_{tot} = 1 pJ/K
→ ~ 1 mK

Low temperature micro-calorimeters



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



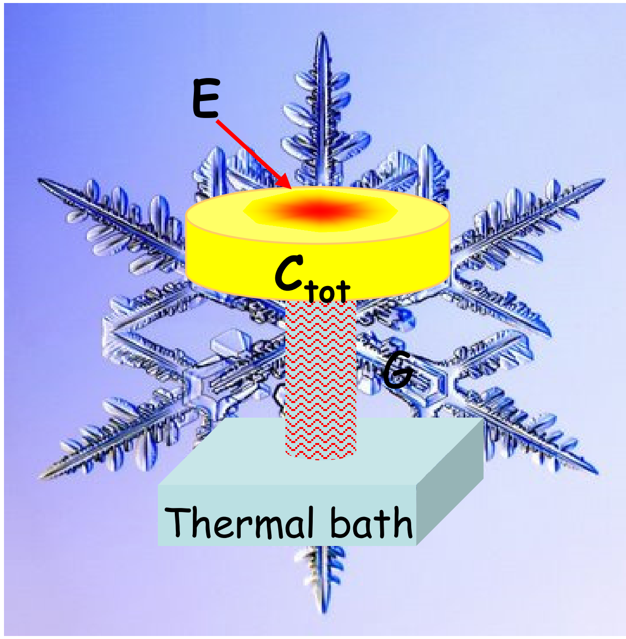
E = 10 keV

C_{tot} = 1 pJ/K

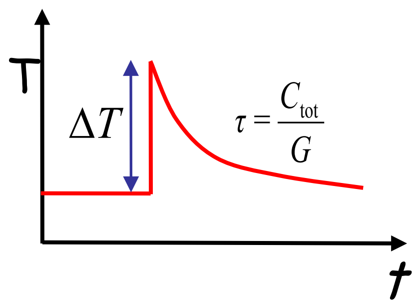
→ ~ 1 mK

- Very small volume

Low temperature micro-calorimeters



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



***E* = 10 keV**

C_{tot} = 1 pJ/K

→ ~ 1 mK

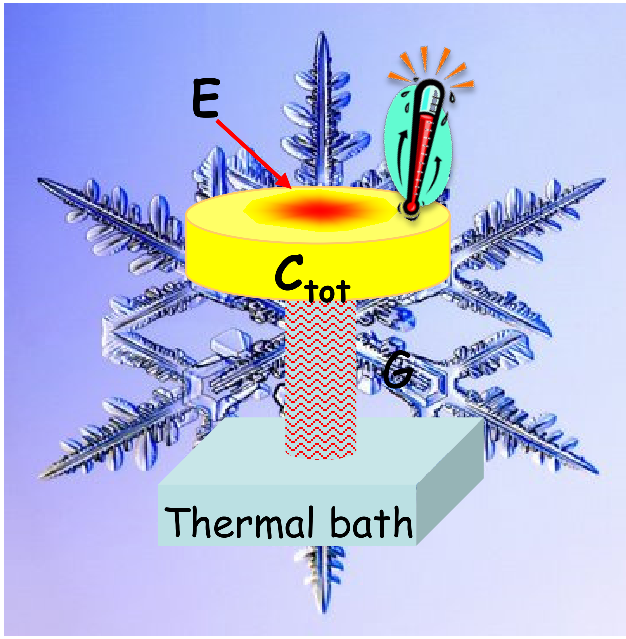
- Very small volume

- Working temperature below 100 mK

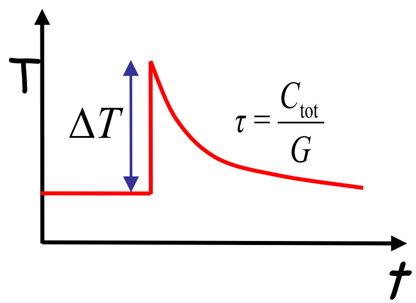
  small specific heat

  small thermal noise

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

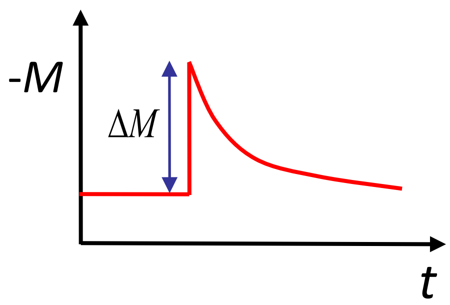
  small thermal noise
- **Very sensitive temperature sensor**

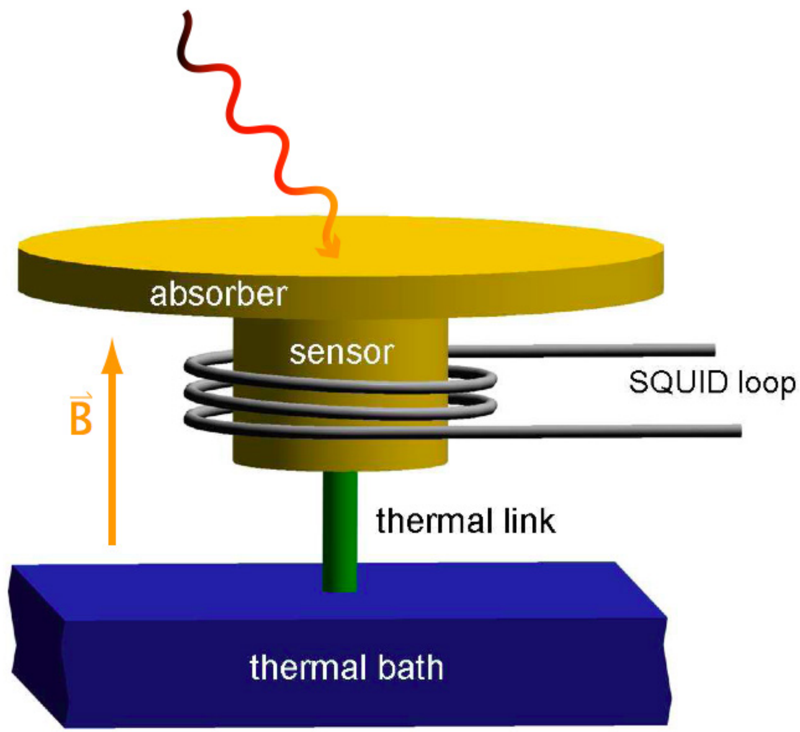
Metallic Magnetic Calorimeters

- Paramagnetic Au:Er sensor

S. Bandler et al,
J. Low Temp. Phys. **93** (1993)

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



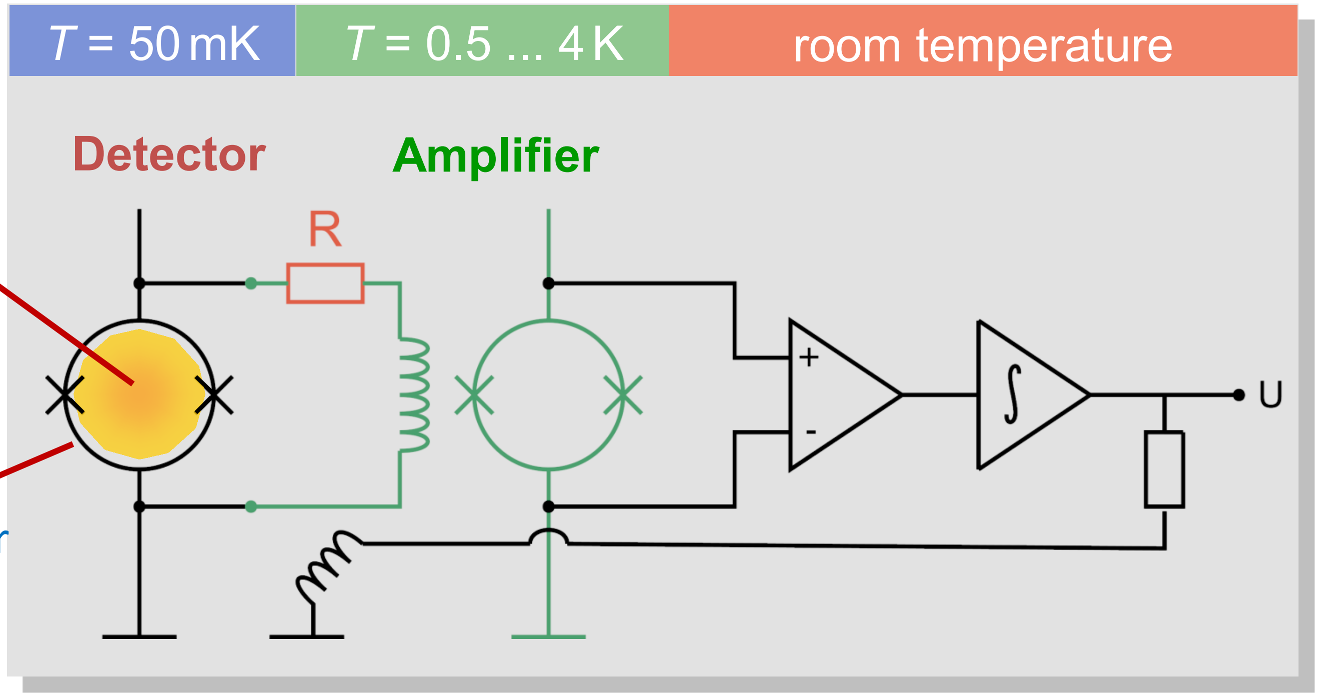


$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

MMCs: Readout

paramagnetic sensor

SQUID magnetometer



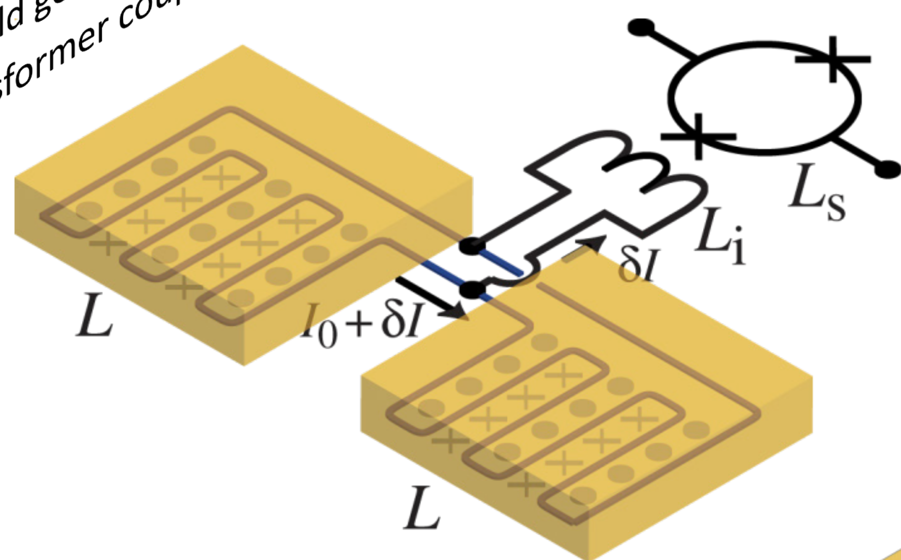
Two-stage SQUID setup with flux locked loop to linearize the first stage SQUID allows for:

- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)

MMCs: Geometries

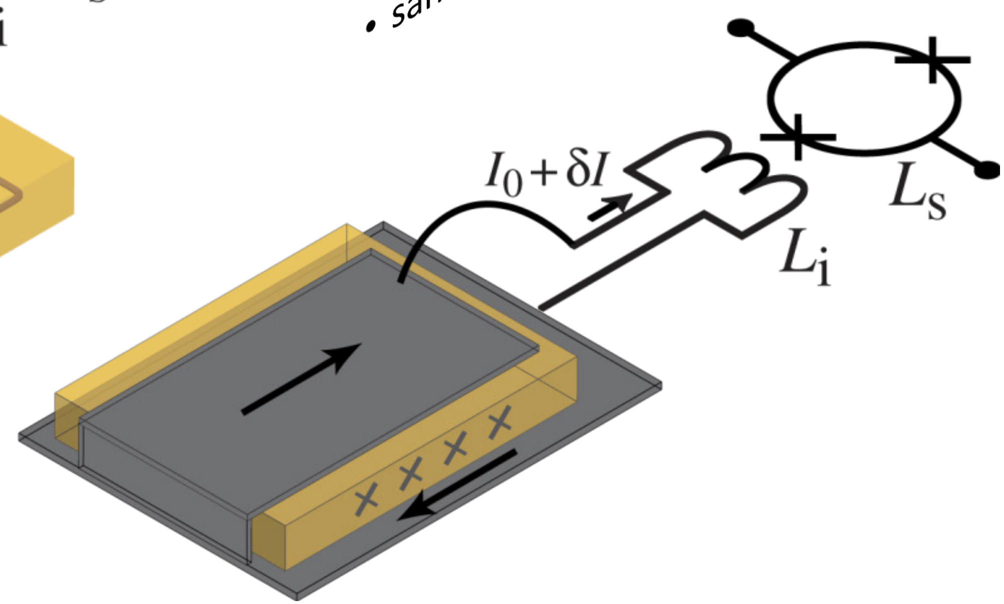
Well established:

- *planar T-sensor*
- *superconducting meander shaped pickup loop*
- *B-field generated by persistent current*
- *transformer coupled to SQUID*

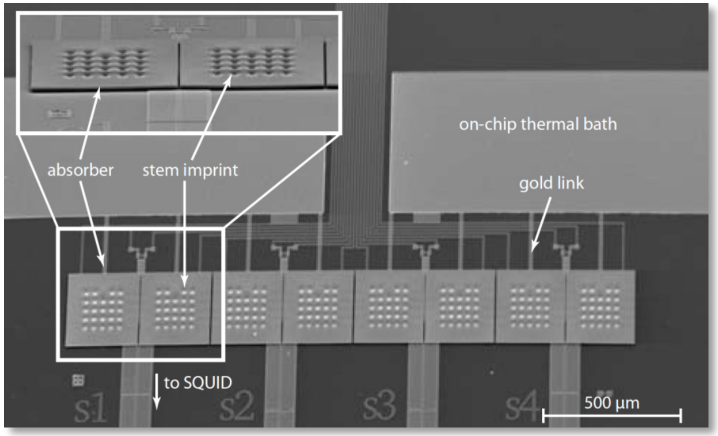


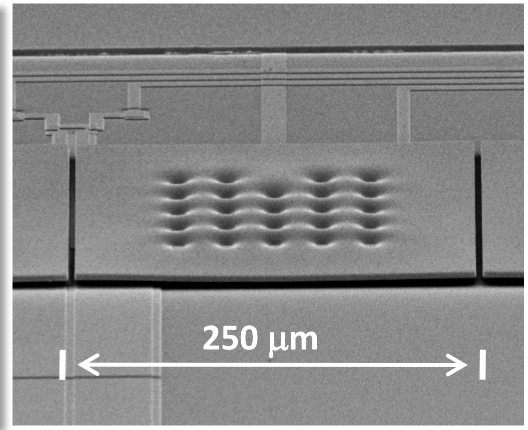
New sandwich geometry:

- *best magn. flux coupling,*
- *planar sensor*
- *sandwiched between stripline*

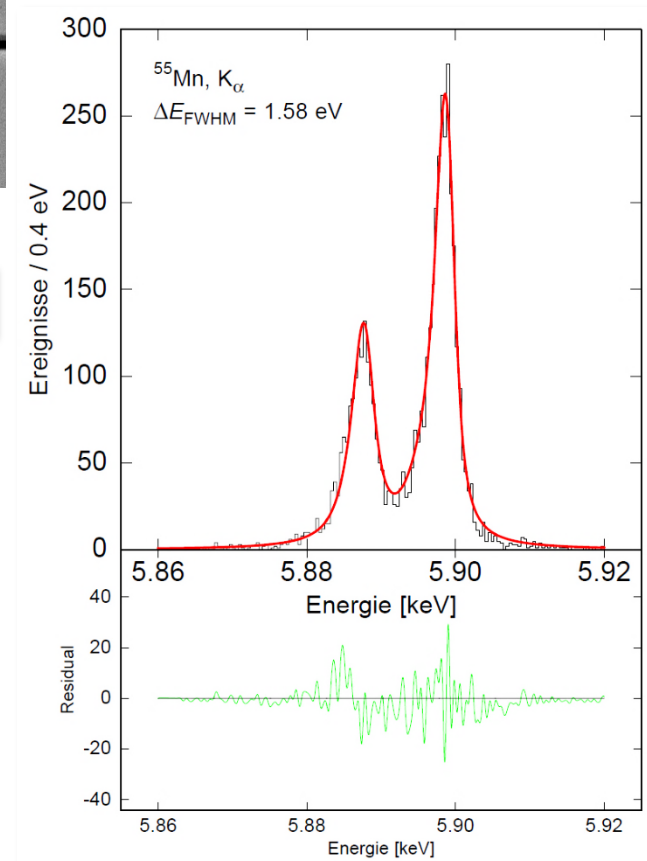


MMCs: 1d-array for soft x-rays (*T*=20 mK)

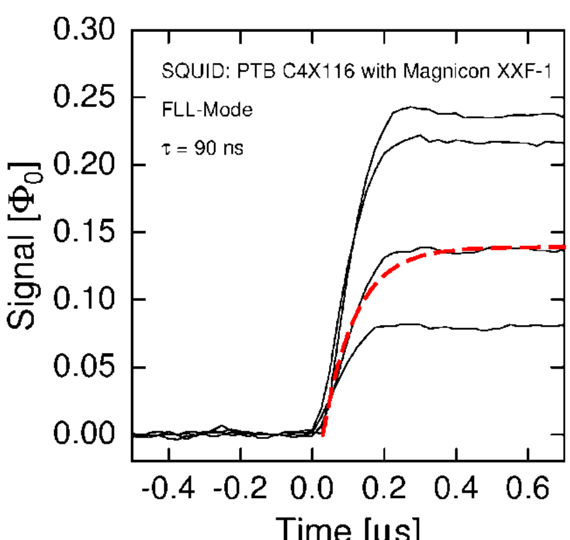




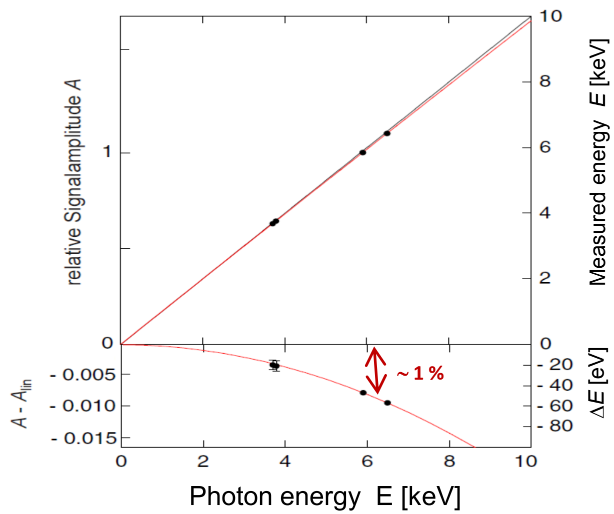
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns

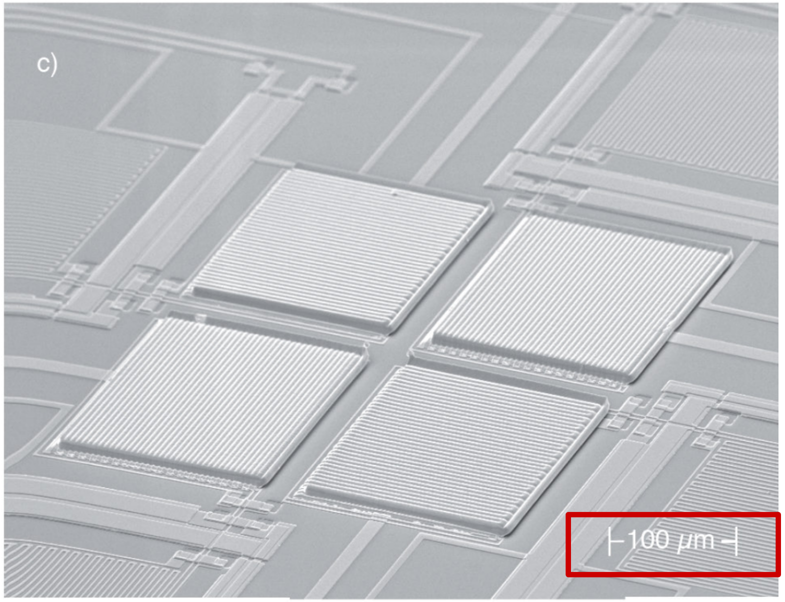


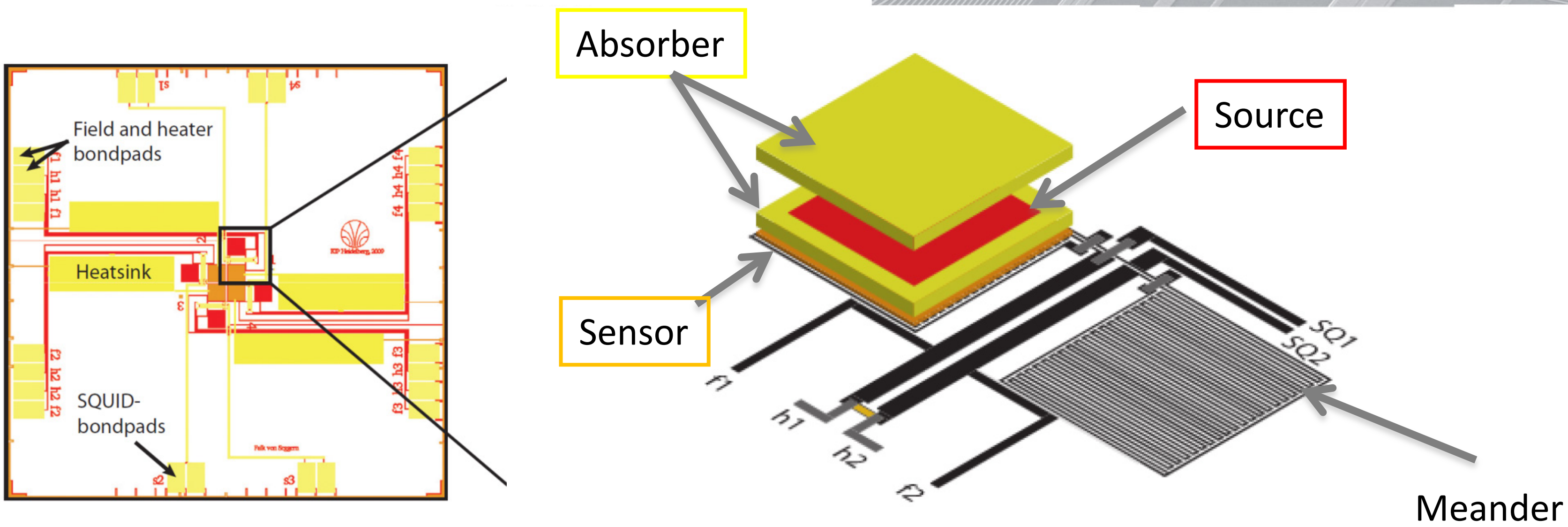
Non-Linearity < 1% @6keV



ECHo : first detector prototype

- Embedding of ^{163}Ho source:
  → ion implantation @ ISOLDE-CERN
- About 0.01 Bq per pixel
- 100 % quantum efficiency

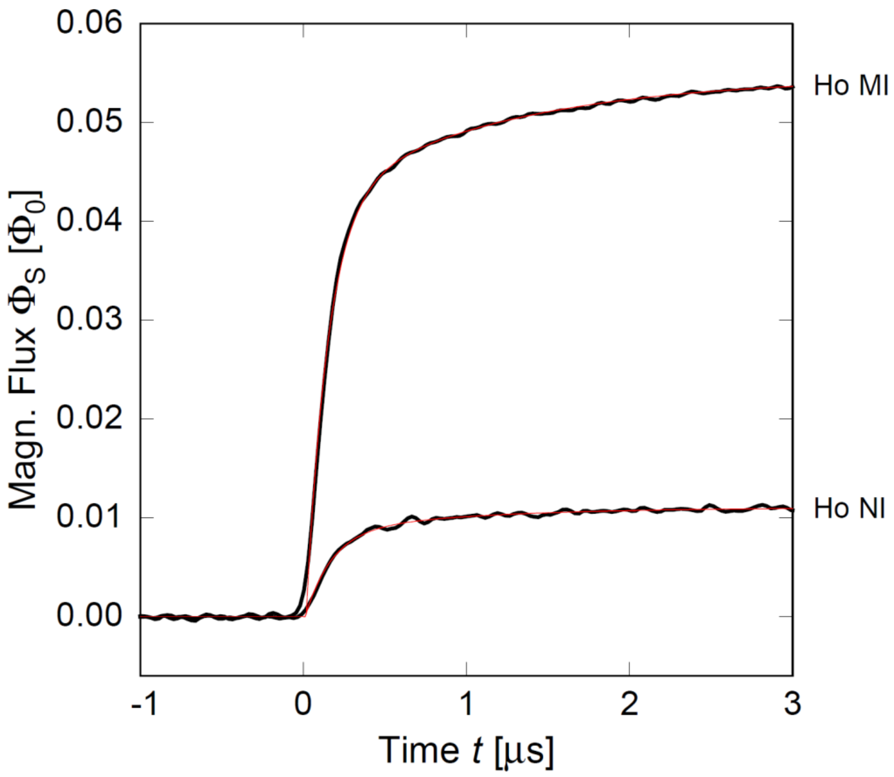




L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

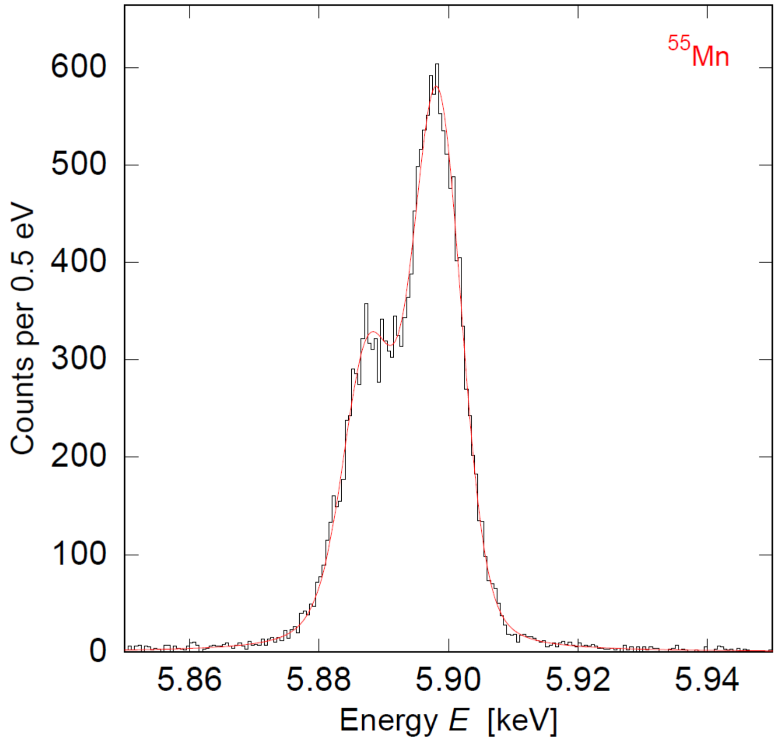
ECHo: Recent results

- Rise Time ~ 130 ns



ECHo: Recent results

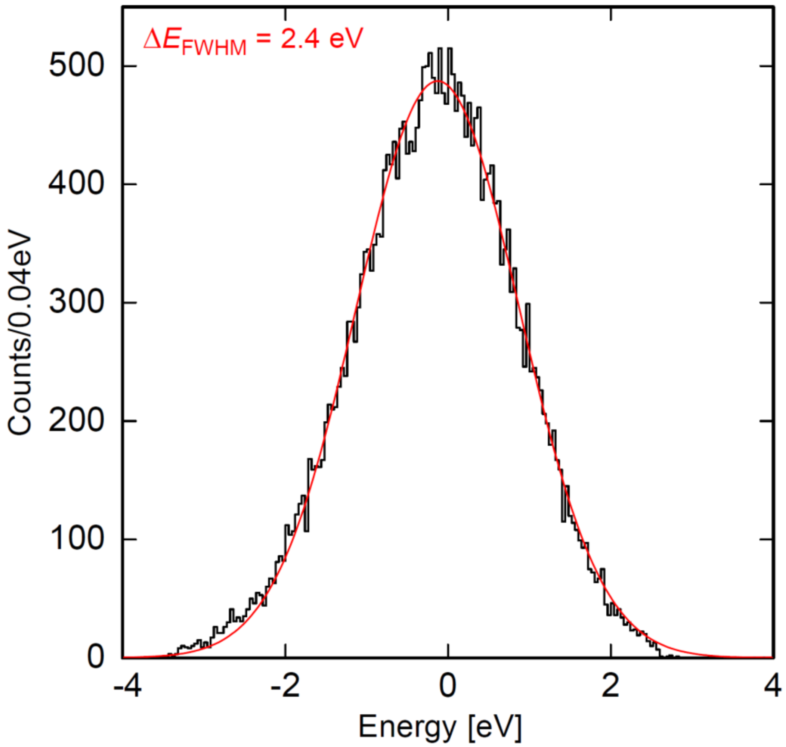
- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)



ECHo: Recent results

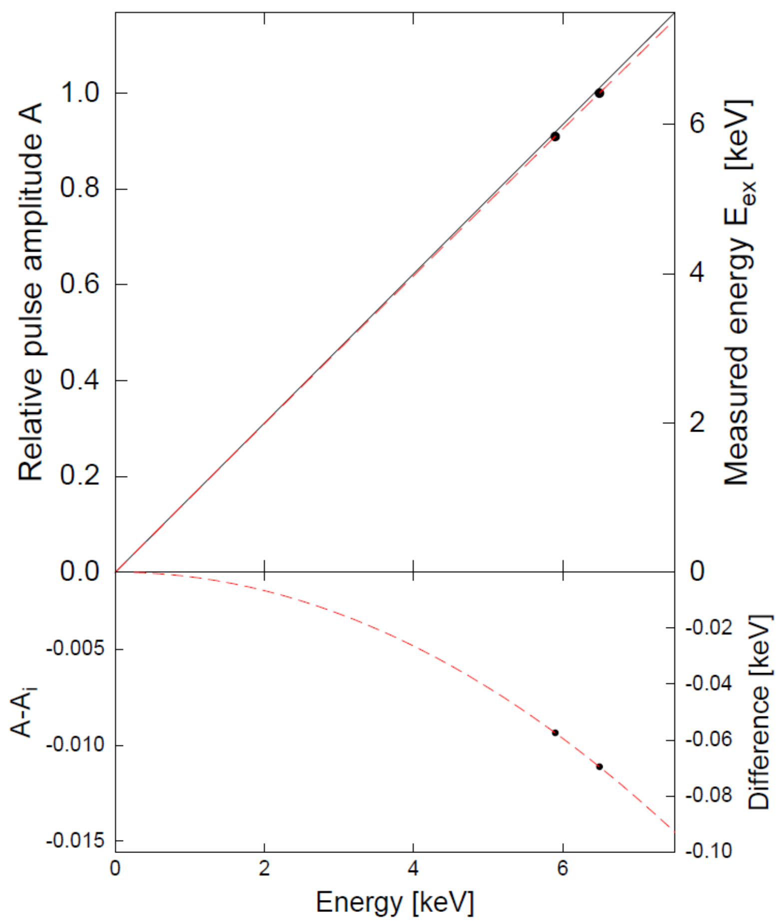
- Rise Time ~ 130 ns

- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)



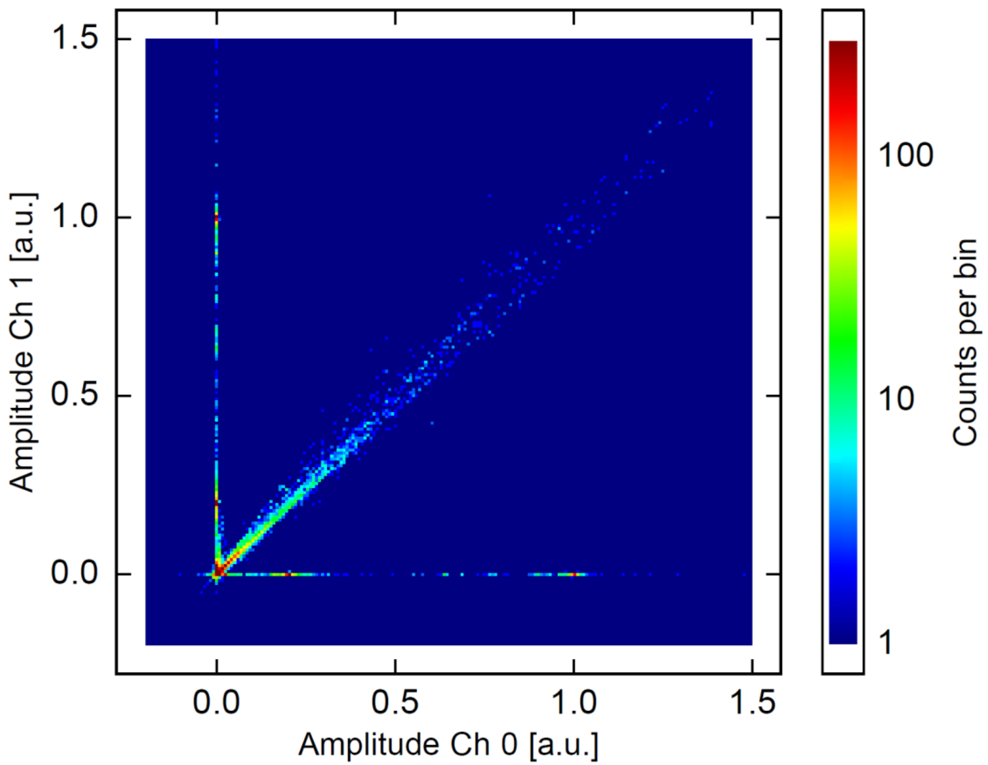
ECHo: Recent results

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV



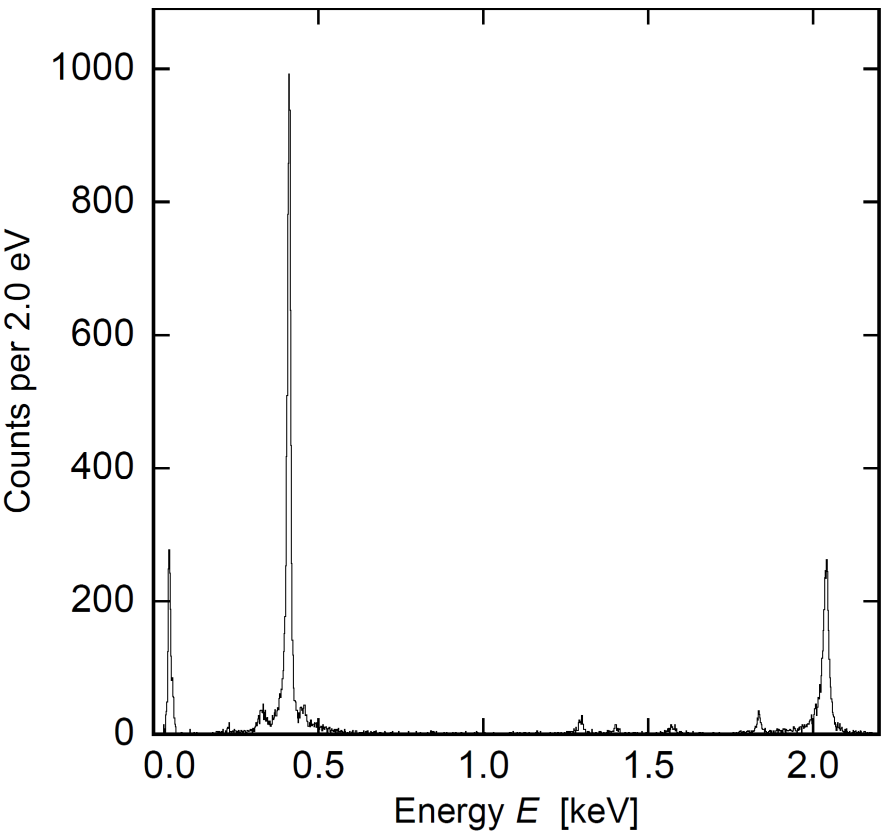
ECHo: Recent results

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels



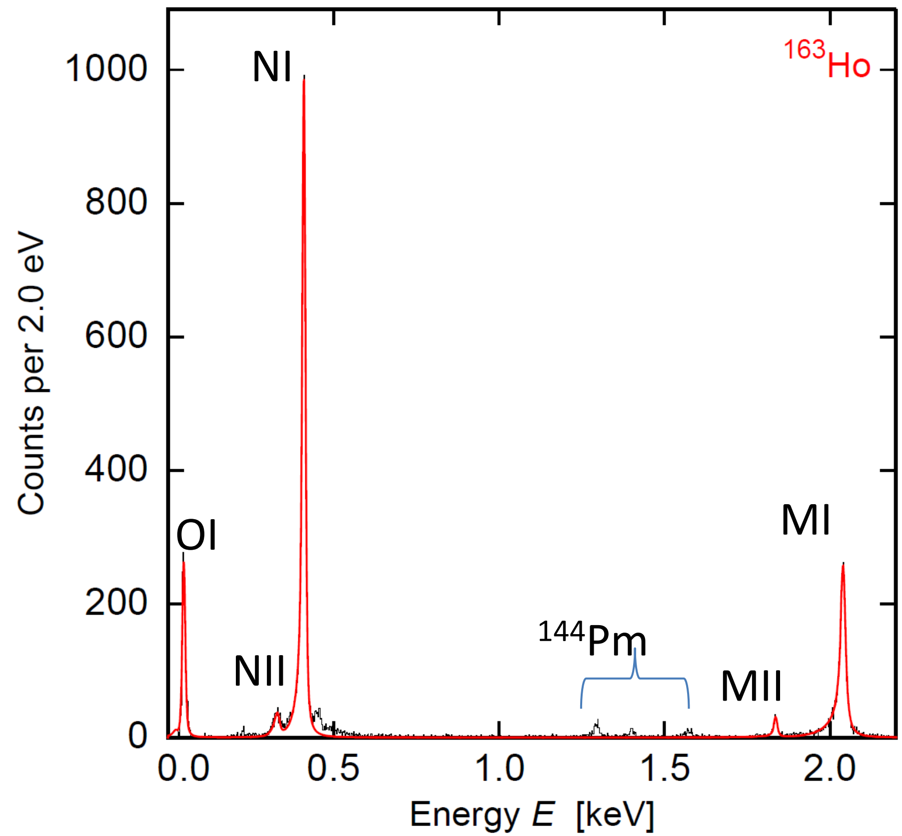
ECHo: Recent results

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels



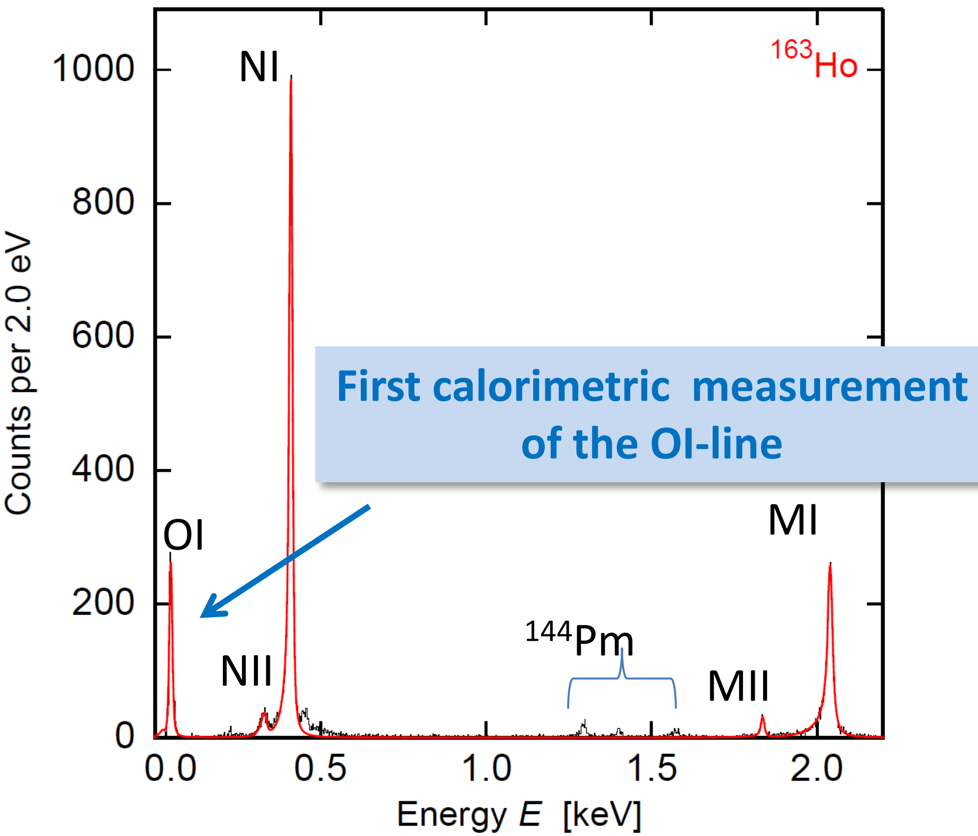
ECHo: Recent results

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels
- Presently most precise ^{163}Ho spectrum



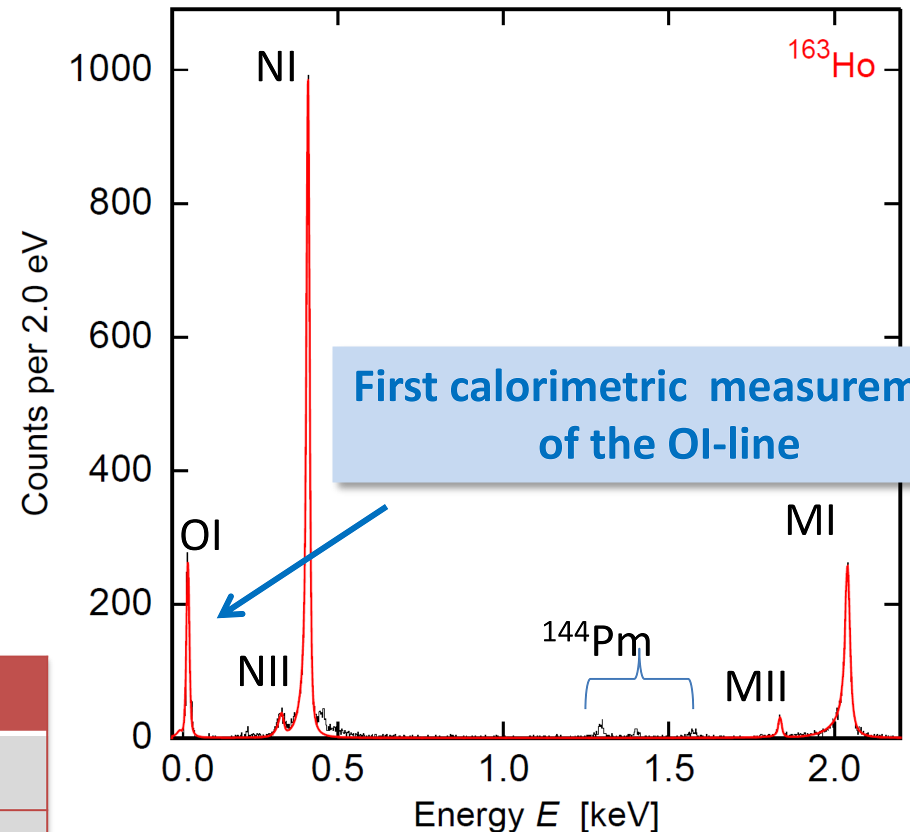
ECHo: Recent results

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels
- Presently most precise ^{163}Ho spectrum



ECHo: Recent results

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels
- Presently most precise ^{163}Ho spectrum



First calorimetric measurement of the OI-line

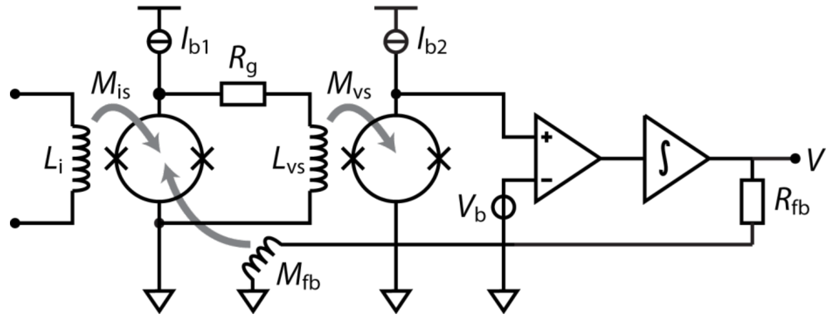
	E_H bind.	E_H exp.	Γ_H lit.	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

$Q_{EC} = (2.843 \pm 0.009^{stat} - 0.06^{syst})$ keV

P. C.-O. Ranitzsch et al ., http://arxiv.org/abs/1409.0071v1)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

ECHo: Multiplexing

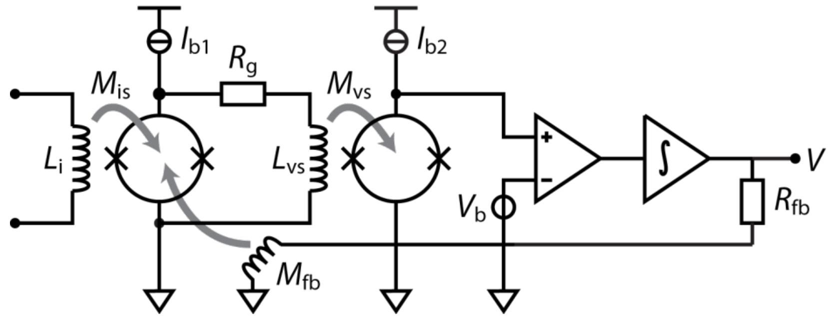
single channel detector:



10 wires
2 SQUIDs,
1 electronics

ECHo: Multiplexing

single channel detector:

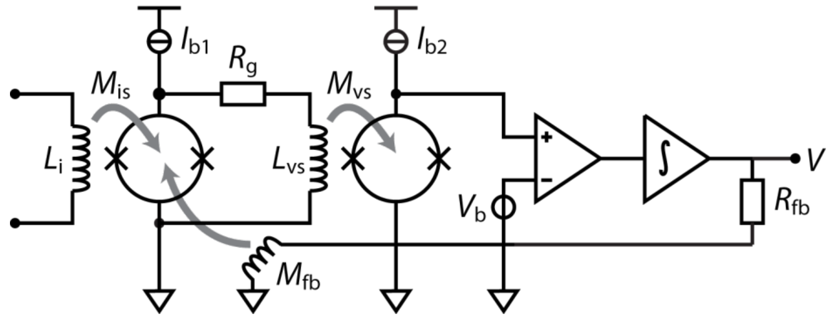


10 wires
2 SQUIDs,
1 electronics

how to read a large number of detectors?

ECHo: Multiplexing

single channel detector:



10 wires
2 SQUIDs,
1 electronics

how to read a large number of detectors?

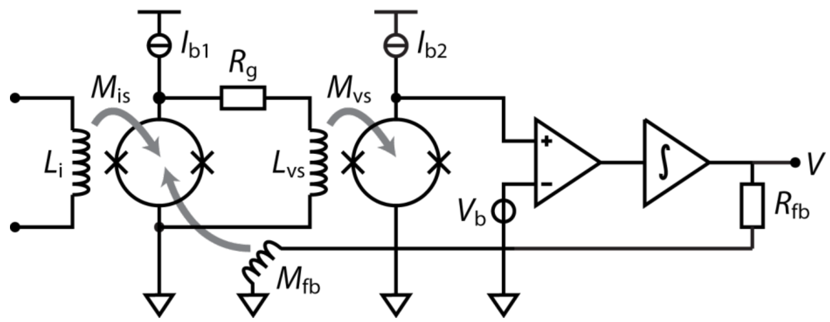
simplest idea: duplicate single channel detector readout

- number of wires
- parasitic heat load
- costs
- complexity

} $\sim N$

ECHo: Multiplexing

single channel detector:



10 wires
2 SQUIDs,
1 electronics

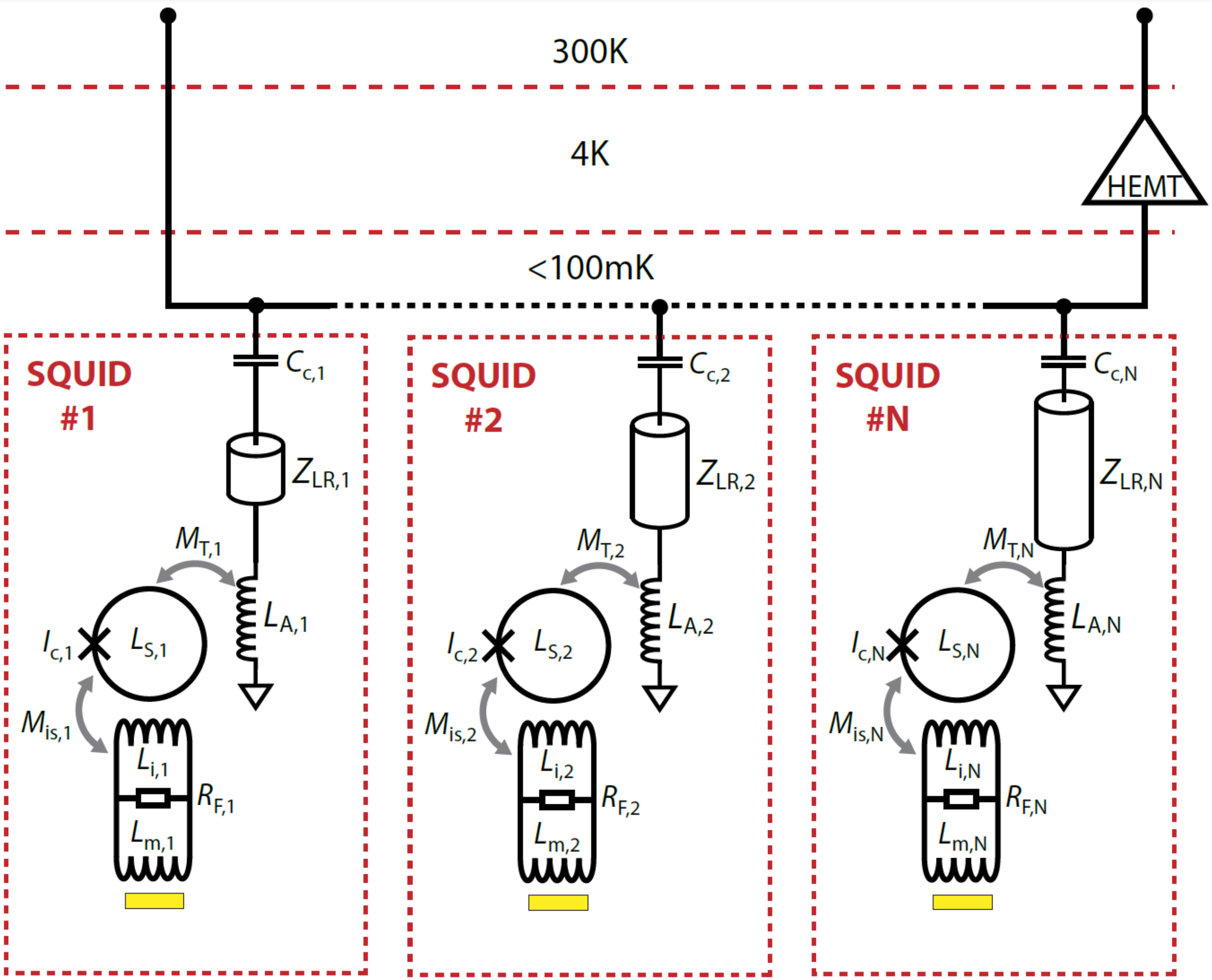
how to read a large number of detectors?

simplest idea: duplicate single channel detector readout

- number of wires
- parasitic heat load
- costs
- complexity

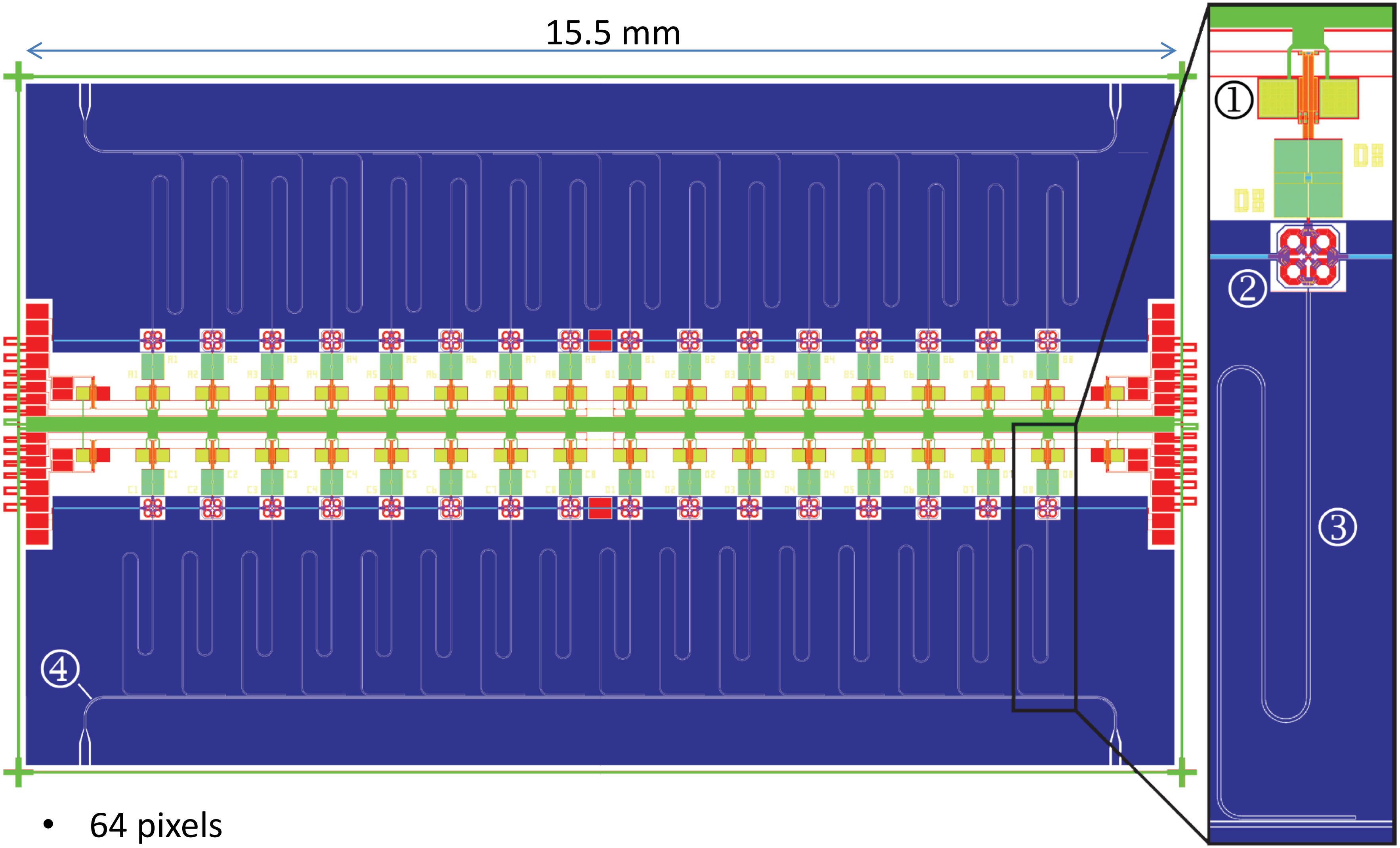
} ~ *N* ⇒ **multiplexing scheme**
Microwave SQUID multiplexing

ECHo : µ-wave SQUID multiplexing



single HEMT amplifier and 2 coaxes to read out 100 - 1000 detectors

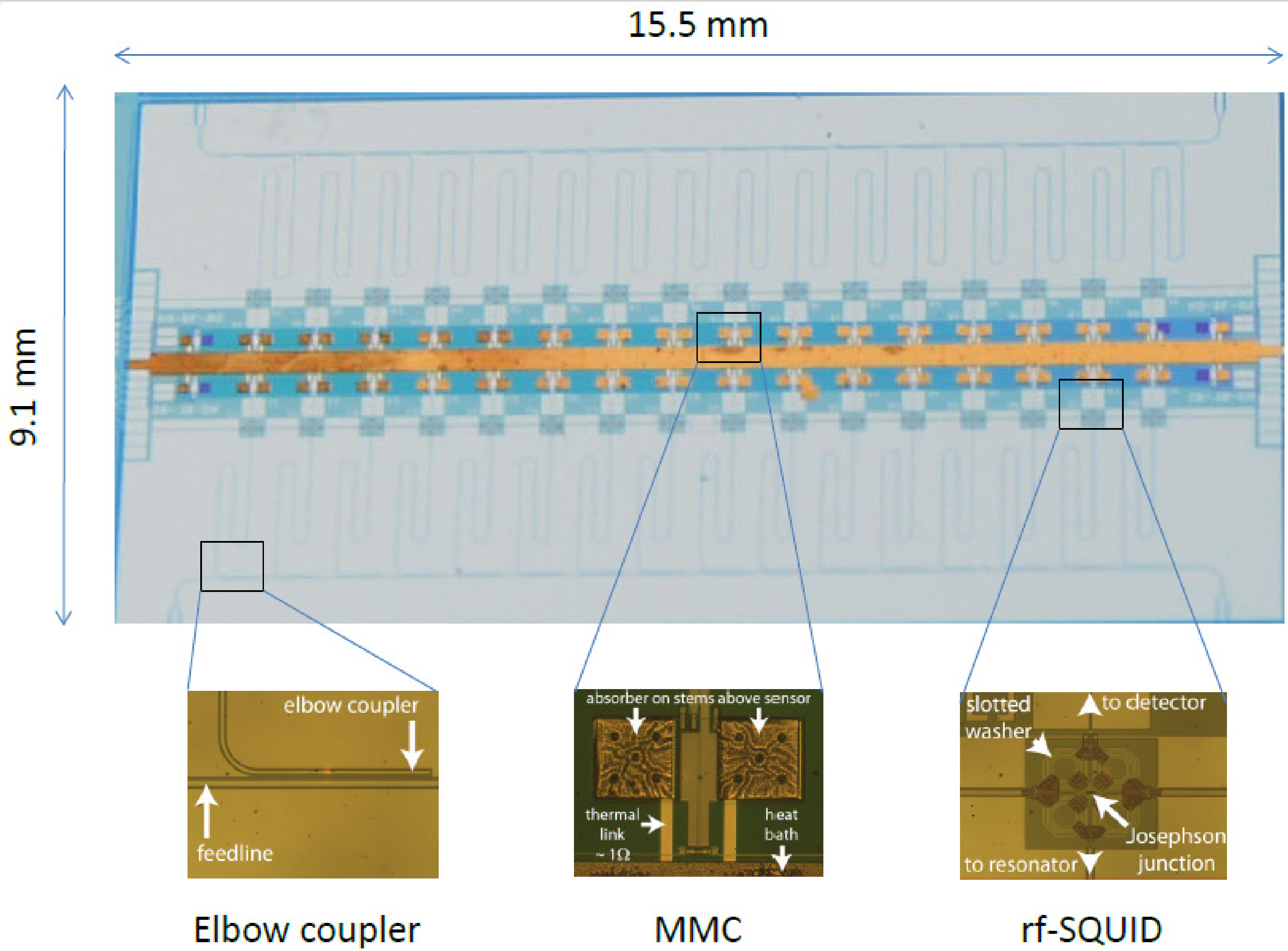
ECHo : µ-wave SQUID multiplexing



- 64 pixels
- ΔE_{FWHM} = 5 eV

S. Kempf et al, JLTP 176 (2014) 426-432

ECHo : µ-wave SQUID multiplexing



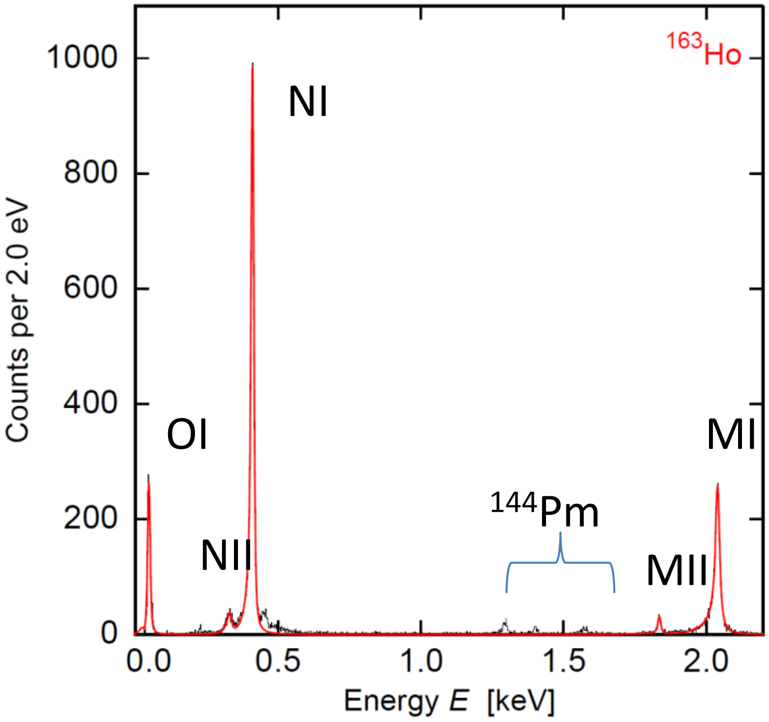
Successfully tested!

S. Kempf et al, JLTP 176 (2014) 426-432

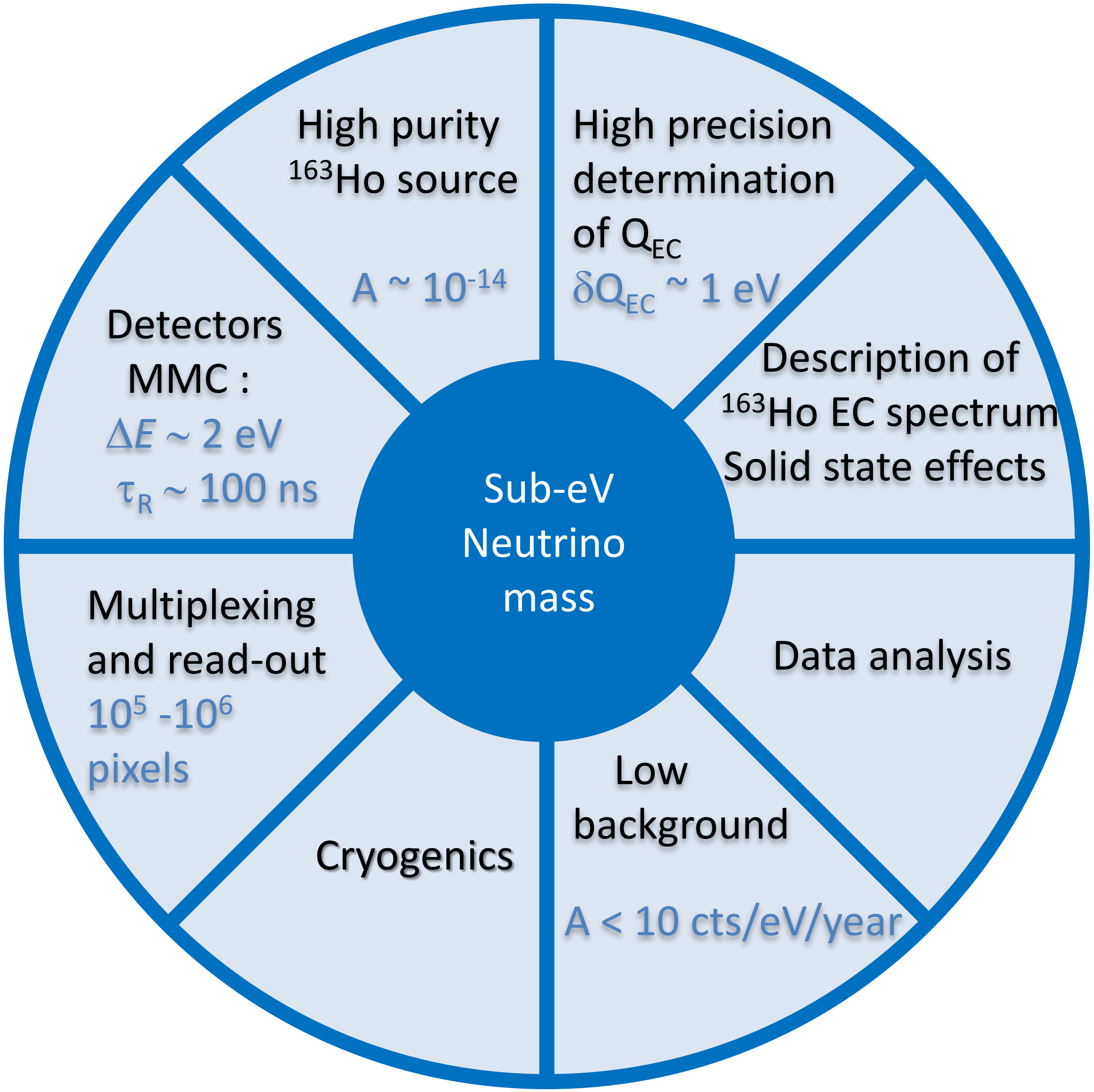
Conclusions

- MMCs fullfil the requirements to reach sub-eV sensitivity
  - $\Delta E_{\mathrm{FWHM}} < 10$ eV
  - $\tau_{\mathrm{r}} < 1$ µs
  - reliable energy calibration

- Large MMC arrays can be read out using µ-wave multiplexing



ECHo : sub-eV sensitivity



Outlook

- Prove scalability with medium large experiment **ECHo-1K**

  - A ~ 1000 Bq — High purity ^{163}Ho source
  - $\Delta E_{FWHM} < 5$ eV
  - $\tau_r < 1$ µs
  - multiplexed arrays

  - 1 year measuring time → 10^{10} counts

  \+ theoretical investigation
  \+ Q_{EC} measurement with Penning trap mass spectrometry → Spectral shape determination

  \+ background characterization and reduction

  = Neutrino mass sensitivity $m_\nu < 10$ eV

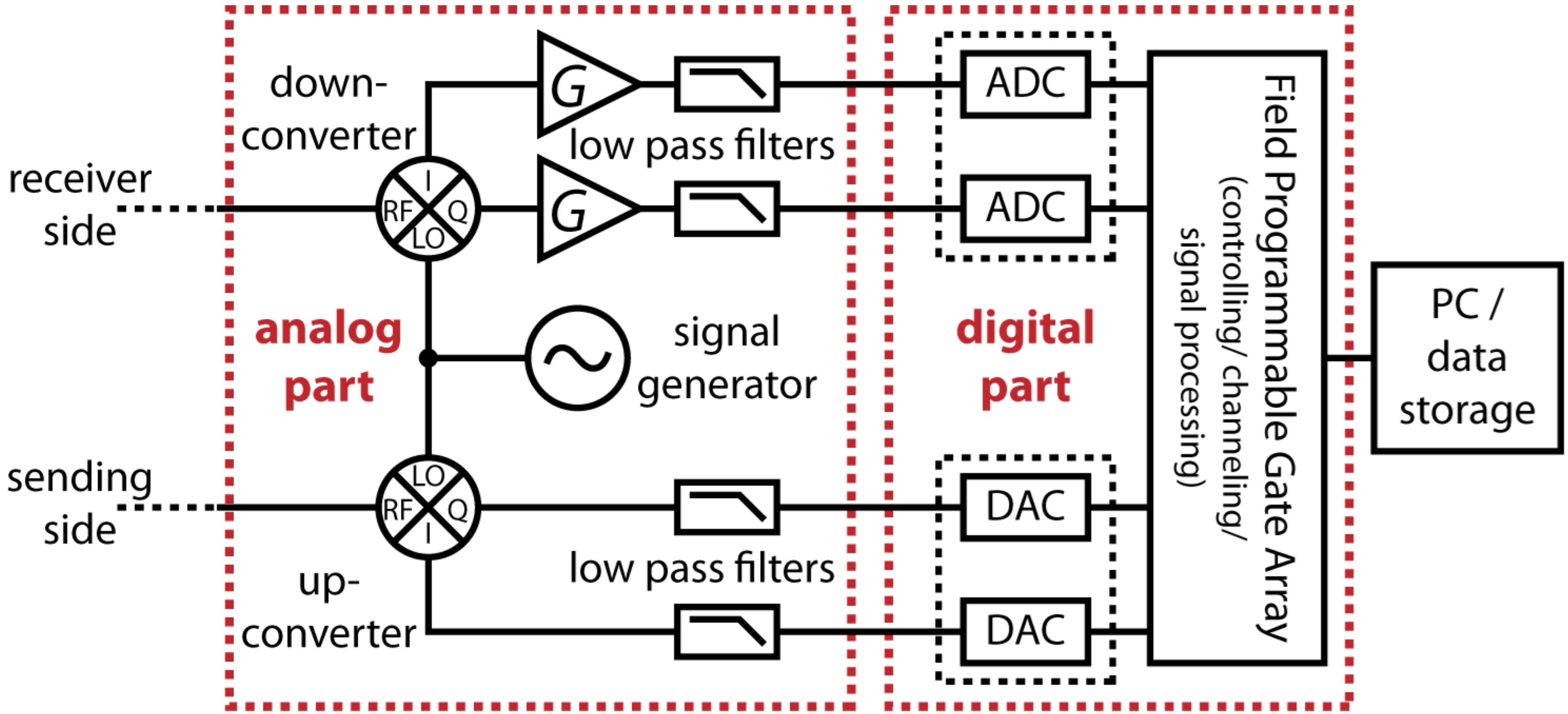
- **ECHo-1M** for sub-eV sensitivity

Thank you!

Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
Fedor Simkovic
Department of Physics, Indian Institute of Technology Roorkee, India
Moumita Maiti
Institut für Kern- und Teilchenphysik
Kai Zuber
Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz
Christoph E. Düllmann, Holger Dorrer, Klaus Eberhardt, Sven Junck,
Tom Kieck, Fabian Schneider, Klaus Wendt
Institute of Nuclear Research of the Hungarian Academy of Sciences
Zoltán Szúcs
Institute for Theoretical and Experimental Physics Moscow, Russia
Mikhail Krivoruchenko
Institute for Theoretical Physics, University of Tübingen, Germany
Amand Fäßler
Kepler Center for Astro and Particle Physics, University of Tübingen
Josef Jochum, Stephan Scholl
Kirchhoff-Institut for Physics, Heidelberg University, Germany
Christian Enss, Andreas Fleischmann, Loredana Gastaldo,
Clemens Hassel, Sebastian Kempf, Mathias Wegner
Max-Planck Institut for Nuclear Physics Heidelberg, Germany
Klaus Blaum, Andreas Dörr, Sergey Eliseev, Mikhail Goncharov,
Yuri Novikov, Alexander Rischka, Rima Schüssler
Petersburg Nuclear Physics Institute, Russia
Yuri Novikov, Pavel Filianin
Saha Institute of Nuclear Physics, Kolkata, India
Susanta Lahiri

Software Defined Radio

hardware-based resonator readout and signal processing

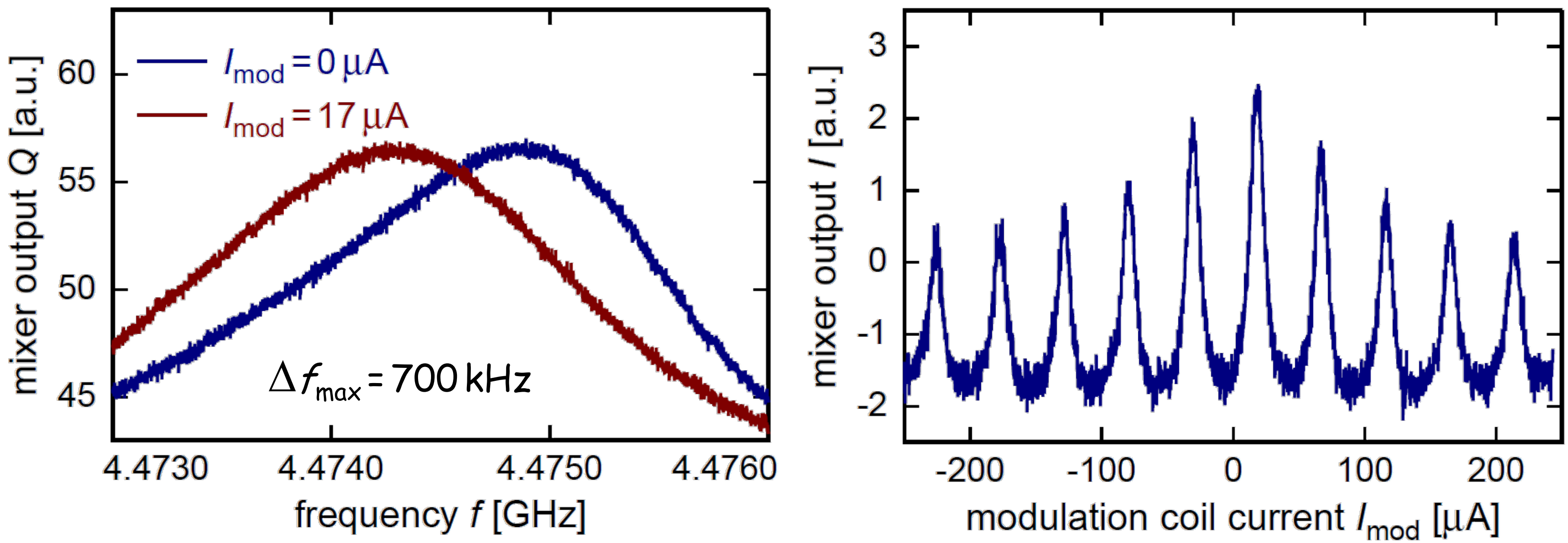


simultaneous readout of 10^1-10^2 detectors

μMUX Prototype

prototype device with 14 photolithographic layers

(homodyne detection, non-muxed operation)

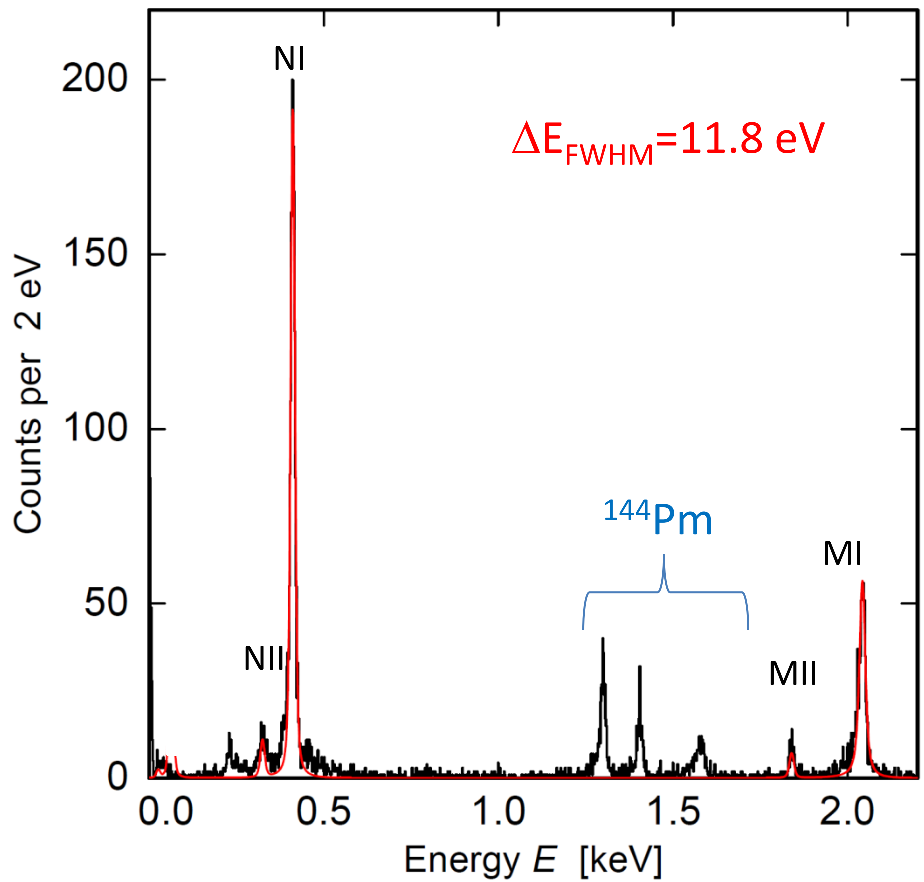


μMUX prototype working!

now optimization for ECHo-1k

ECHo: Calorimetric spectrum

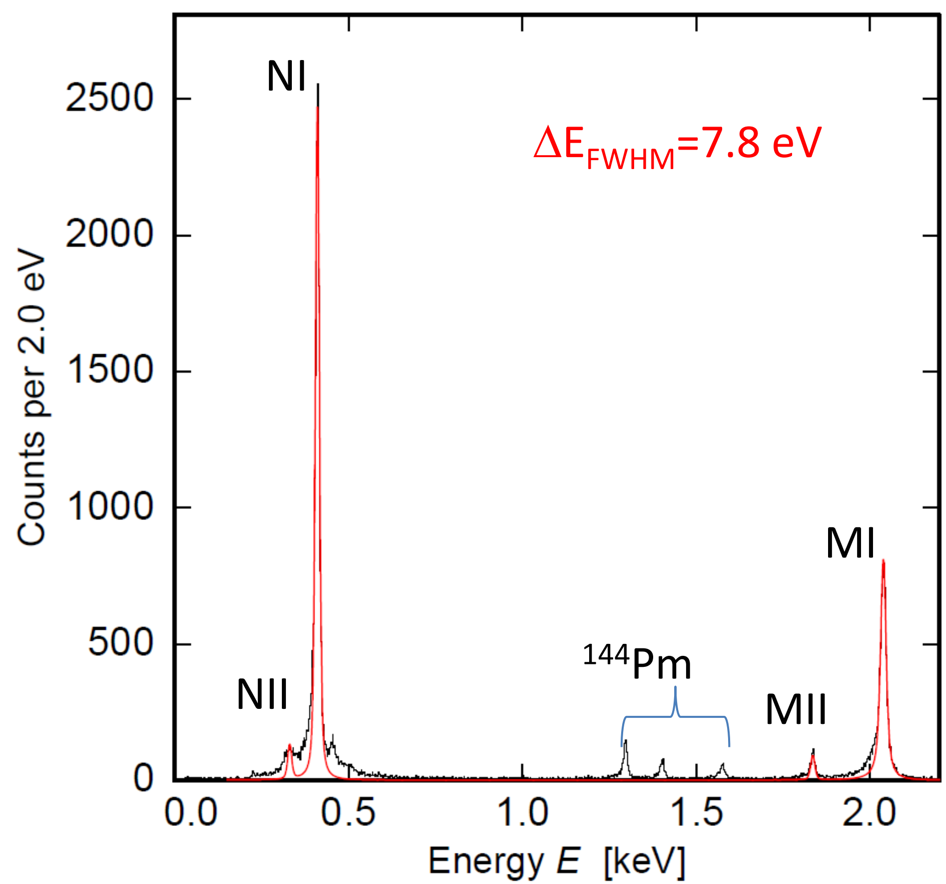
2010: 1 pixel 3 data sets



ECHo: Calorimetric spectrum

2010: 1 pixel 3 data sets

2012: 2 pixels ~40 data sets

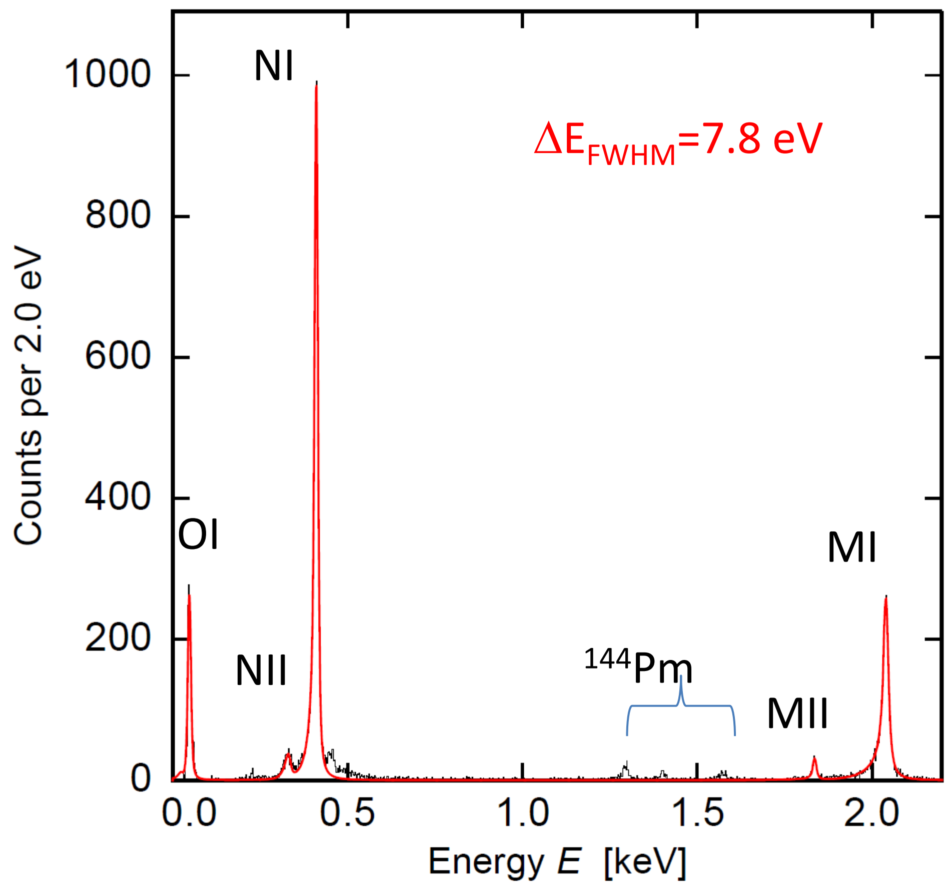


ECHo: Calorimetric spectrum

2010: 1 pixel 3 data sets

2012: 2 pixels ~40 data sets

2013: 2 pixels ~30 data sets



ECHo : ^{163}Ho source

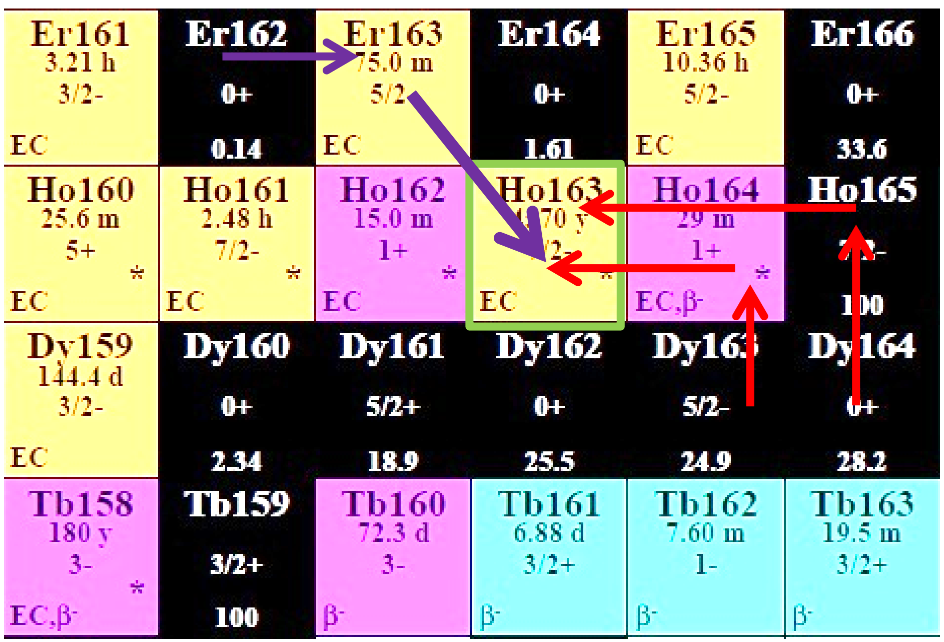
Required activity in the detectors: Final experiment → >10^{6} Bq → >10^{17} atoms

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

  High cross-section

  Radioactive contaminants



- Charged particle activation

  ^{nat}Dy(p,xn) ^{163}Ho

  ^{nat}Dy(α, xn) ^{163}Er (ε) ^{163}Ho

  ^{159}Tb(^{7}Li, 3n) ^{163}Er (ε) ^{163}Ho

  Small cross-section

  Few radioactive contaminants

ECHo : ^{163}Ho source - (n,γ)-reaction on ^{162}Er

June 2012 : one irradiation at BER II Research Rector Berlin :

-Irradiate 5 mg Er for 11 days $\Rightarrow$ $1.5 \bullet 10^{16}$ atoms ^{163}Ho

Summer 2013: Two irradiations at ILL

- Treatment of Er prior to irradiation:
  all elements lighter than Er separated

- Treatment of Er after irradiation:
  all elements heavier than Ho are separated

- 30 mg for 55 days $\Rightarrow$ $1.6 \bullet 10^{18}$ atoms ^{163}Ho
- 7 mg for 7 days $\Rightarrow$ $1.4 \bullet 10^{16}$ atoms ^{163}Ho

Thermal neutron flux
(Φ): 1.3×10^{15} cm^{-2}s^{-1}

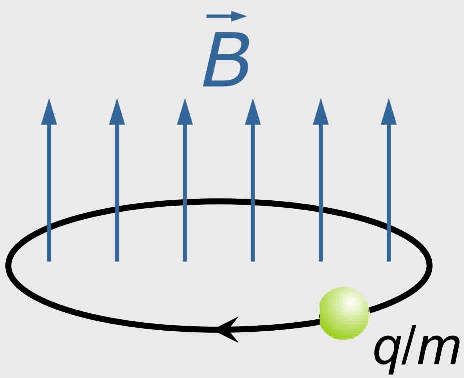
NEUTRONS
FOR SCIENCE

Slide by Ch. E. Duellmann, UNI-Mainz

ECHo : Q_{EC} determinetion

Penning Trap mass spectroscopy

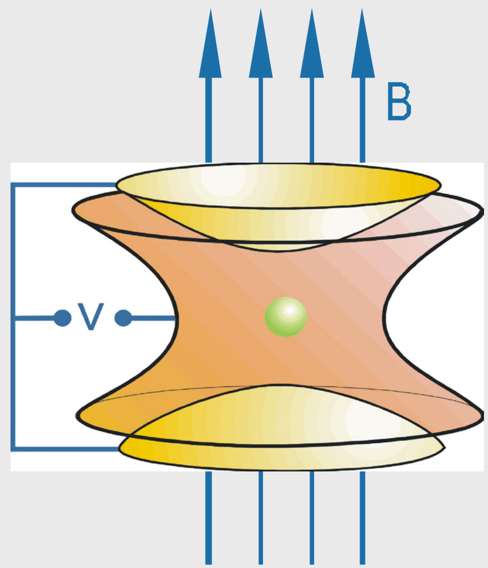
uniform B-field



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

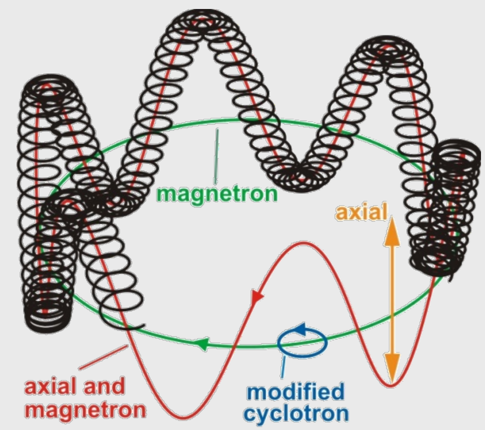
+

quadrupole E-field



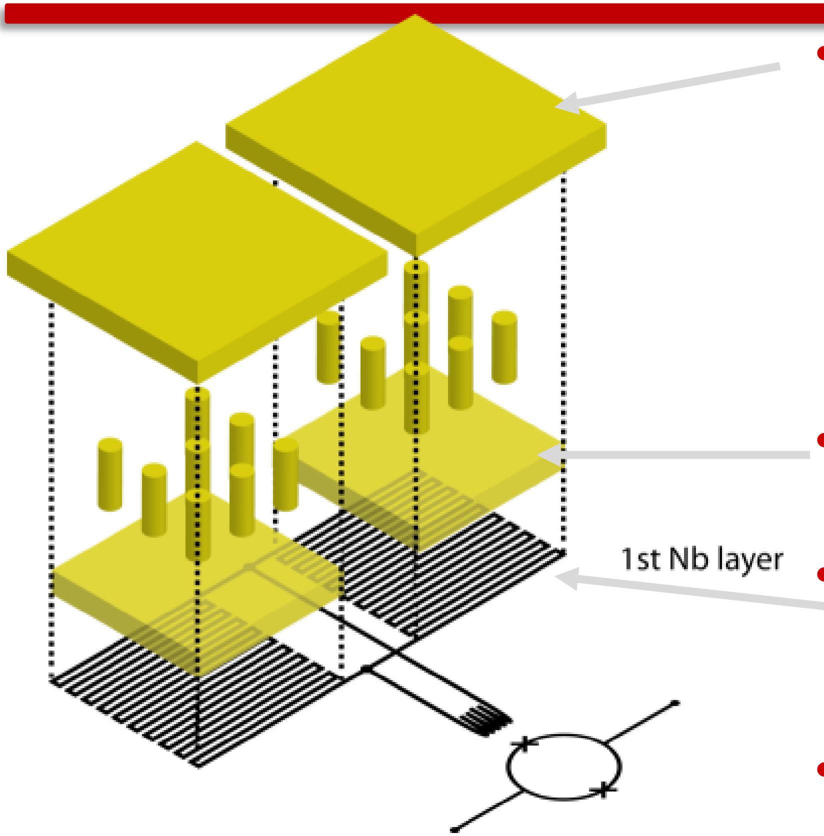
=

Penning Trap

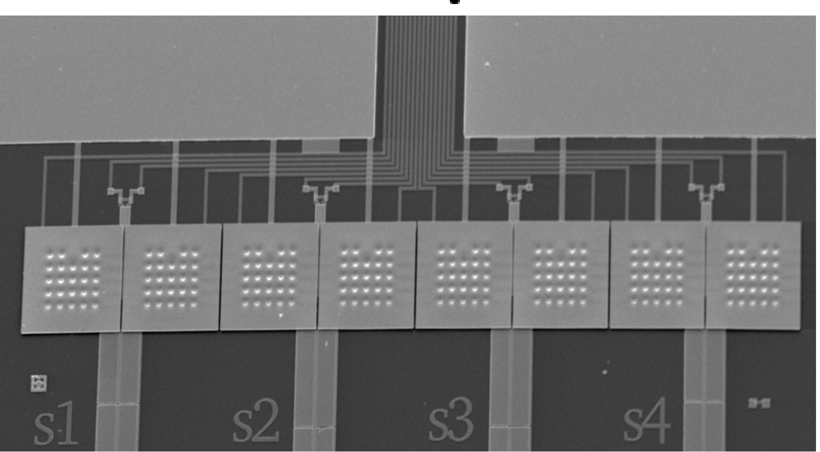


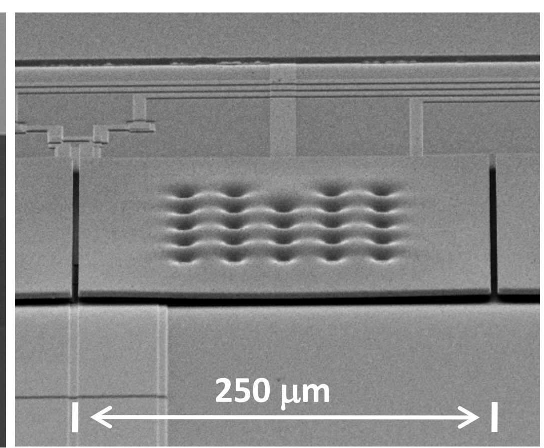
ν_+ - modified cyclotron
ν_- - magnetron
ν_z - axial

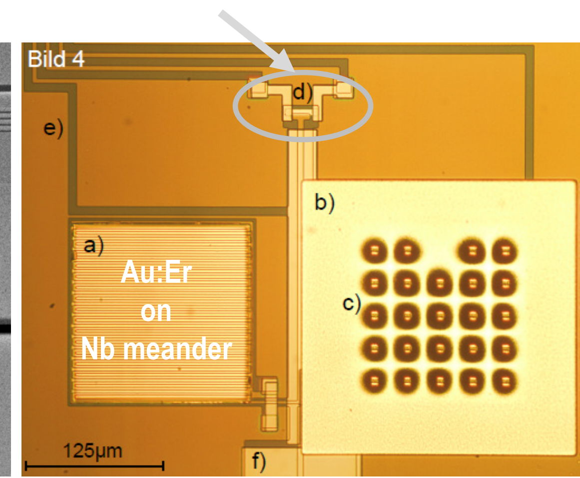
maXs20: 1d-array for soft x-rays



- **1×8 x-ray absorbers**
  - **250µm×250µm** gold**, 5µm thick**
  - **98%** Qu.-Eff. @ 6 keV
  - electroplated into photoresist mold (RRR>15)
  - **mech/therm contact to sensor by stems** to prevent loss of initially hot phonons
- **Au:^{166}Er$_{300ppm}$ temperature sensors**
  - co-sputtered from pure Au and high conc. AuEr target
- **Meander shaped pickup coils**
  - 2.5 µm wide Nb lines
  - I_c ≈ **100mA**
- **On-chip persistent current switch** (AuPd)







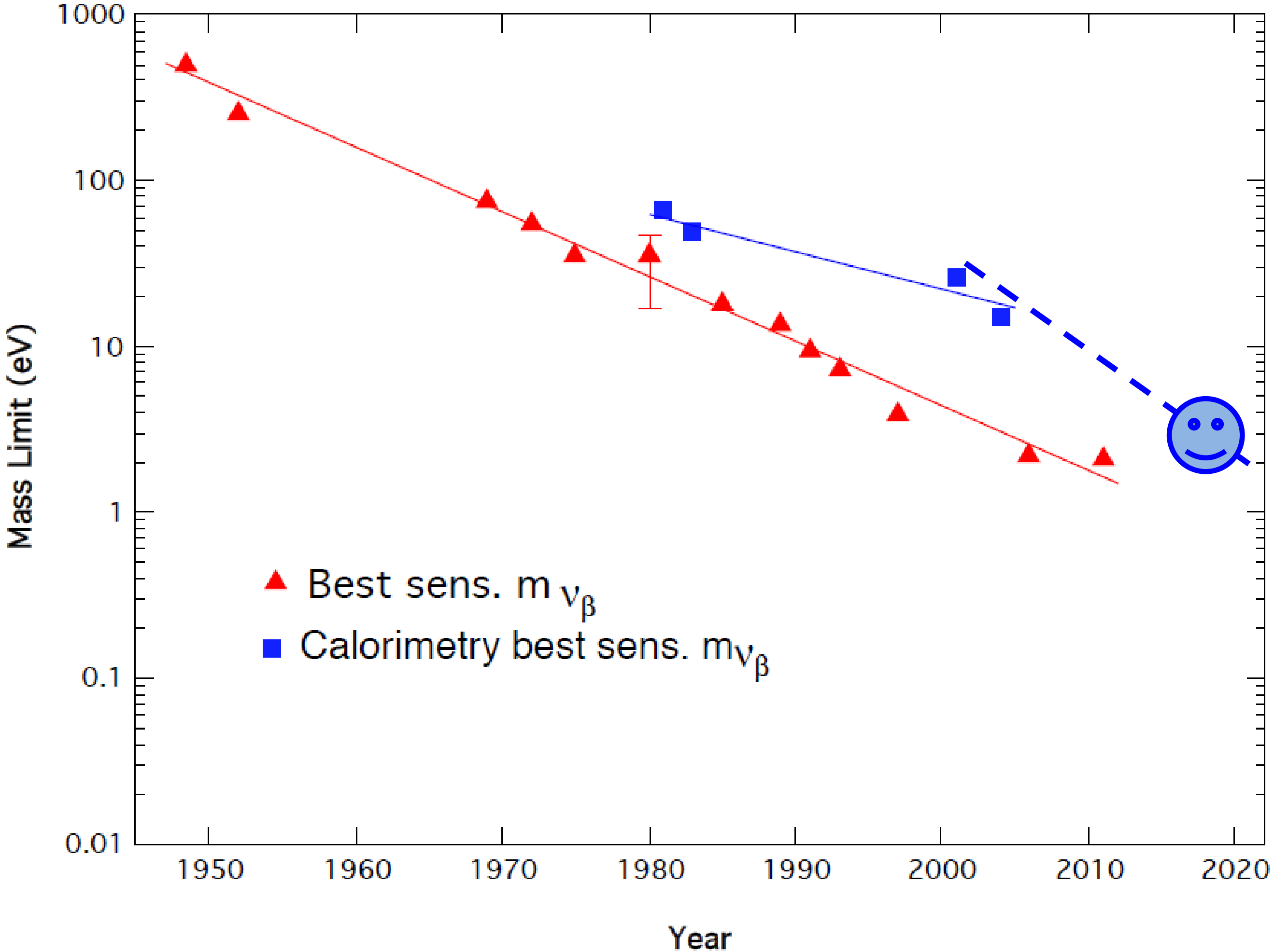
Conclusions

Techniques	ECHo (goal)	ECHo (achieved)	HOLMES (goal)	HOLMES (achieved)	LANL (goal)	LANL (achieved)
Detector	MMC		TES		TES	
ΔE_{FWHM}	2 eV	**4.7 eV**	~1 eV		~1 eV	
τ_R	0.1 μs	**0.13 μs**	~ 1 μs		~ 1 μs	
Multiplexing	Microwave		Microwave		Microwave	
Source	**^{162}Er(n,γ)** Chem. Purification Mass separation Implantation		**^{162}Er(n,γ)** Chem. Purification Mass separation Implantation		**^{nat}Dy(p,xn)** Chem. Purification	

In few years ^{163}Ho spectra with more 10^{10} counts

→ $m(\nu_e) < 10$ eV ☺

Conclusions



J.F. Wilkerson