Kirchhoff-Institut für Physik

Status of Holmium-based Neutrino Mass Measurements

Loredana Gastaldo

Heidelberg University

Contents

- Electron Capture and electron neutrino mass
- The ^{163}Ho case
- ^{163}Ho-based experiments → sub-eV sensitivity :
- Conclusions

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

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

Contents

- Electron Capture and electron neutrino mass
- The ^{163}Ho case
- ^{163}Ho-based experiments → sub-eV sensitivity:

ECHo HOLMES Efforts at **LANL, NIST, Uni-Winsconsin**

- Conclusions

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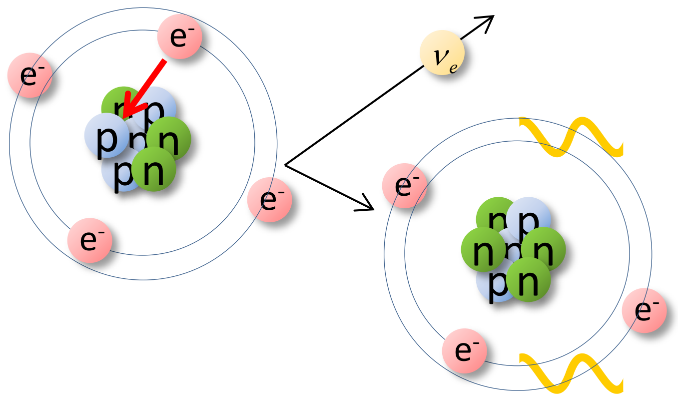
P.T. Springer et al., *Phys. Rev. A* **35**, 679 (1987)

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

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\,2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\,2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\,2}}{4}}$$

The case of ^{163}Ho

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

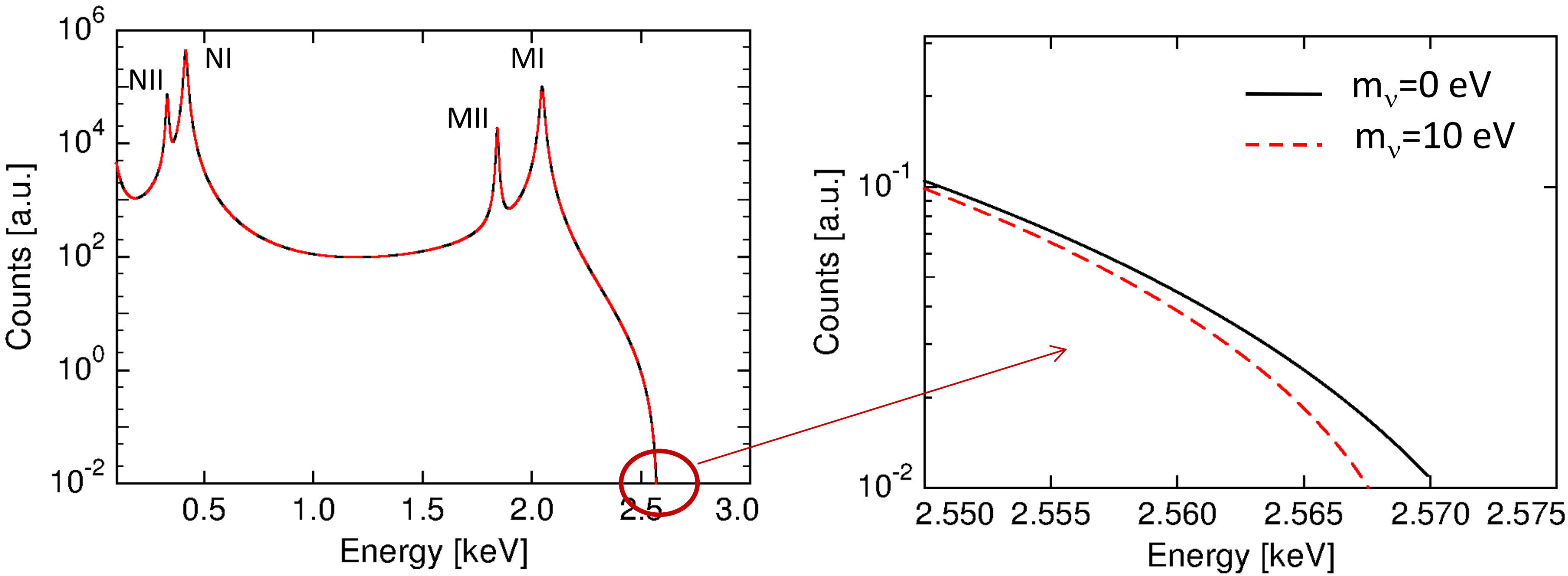
$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

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

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

- Q_{EC} = (2.555 $\pm$ 0.016) keV

  recomended value!?



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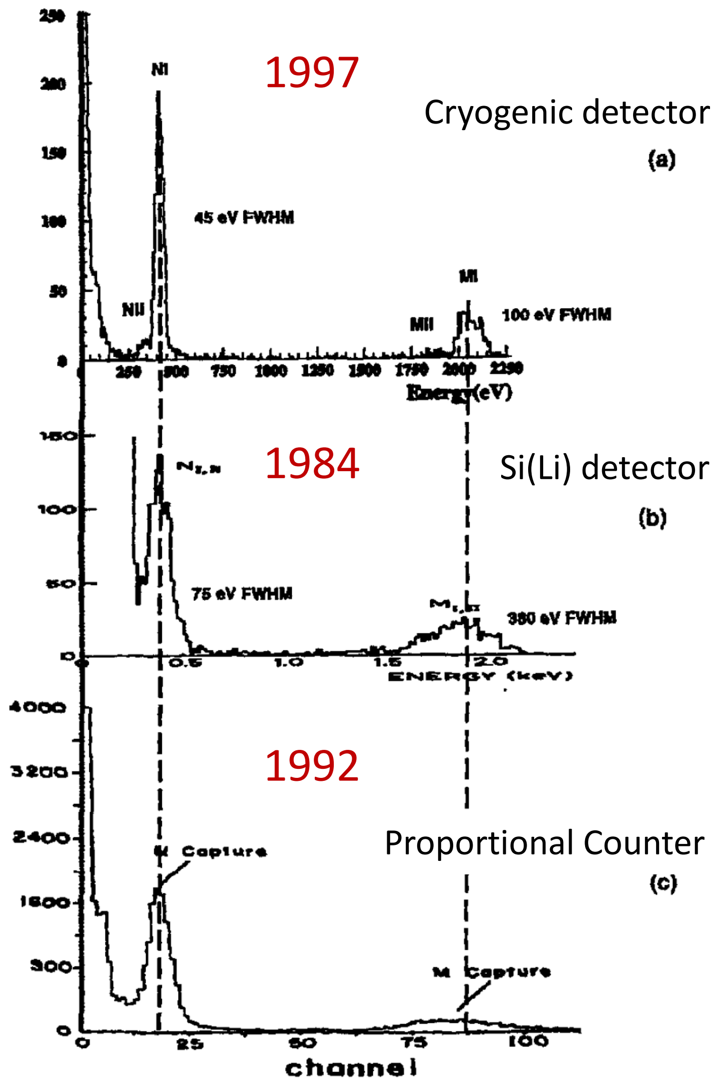
Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

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

A. DE RÚJULA and M. LUSIGNOLI [1]

CERN, Geneva, Switzerland

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).
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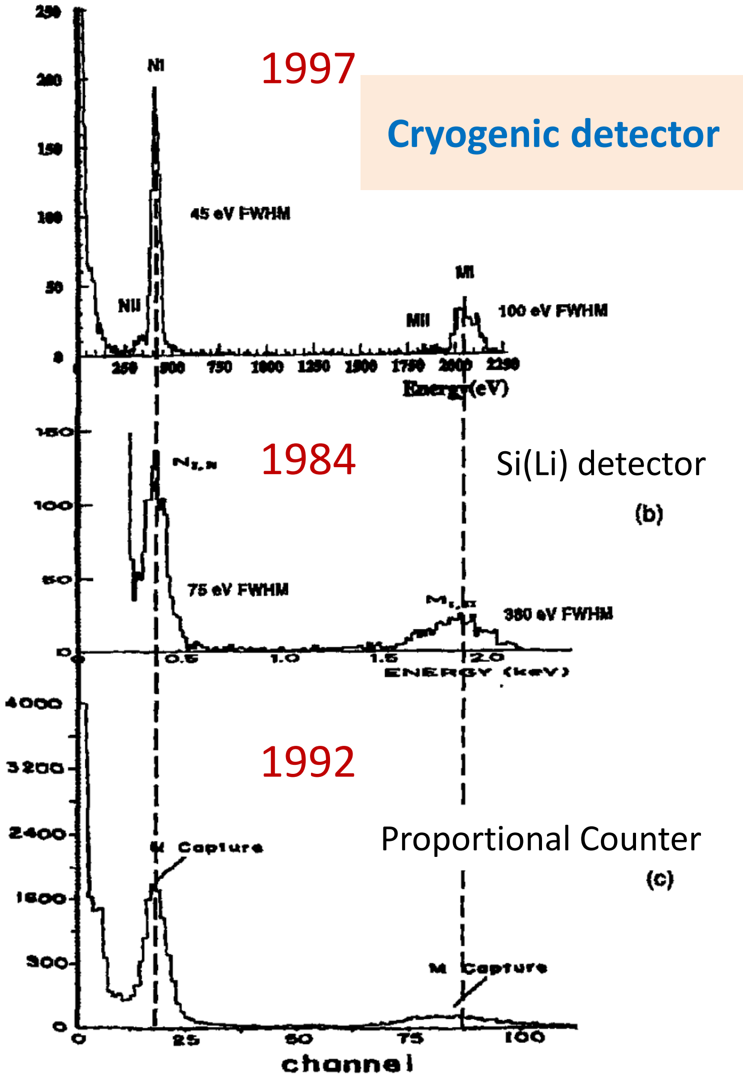
The case of ^{163}Ho



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The right way to go

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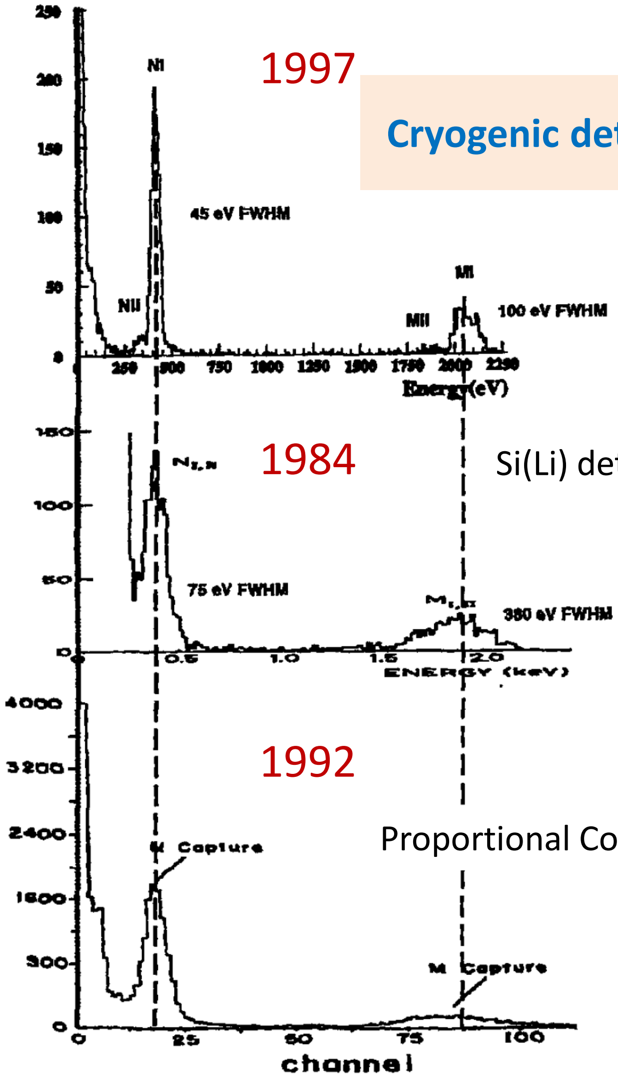
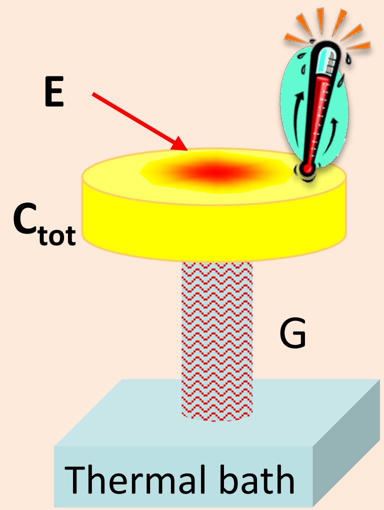


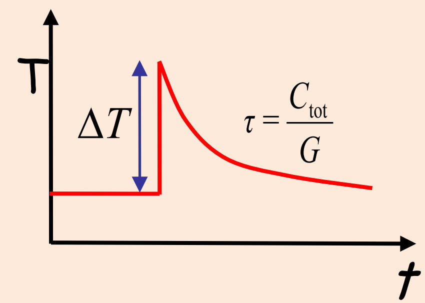
F. Gatti et al., Physics Letters B 398 (1997) 415-419

Cryogenic detector



The right way to go

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



Working temperature < 100 mK

(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).
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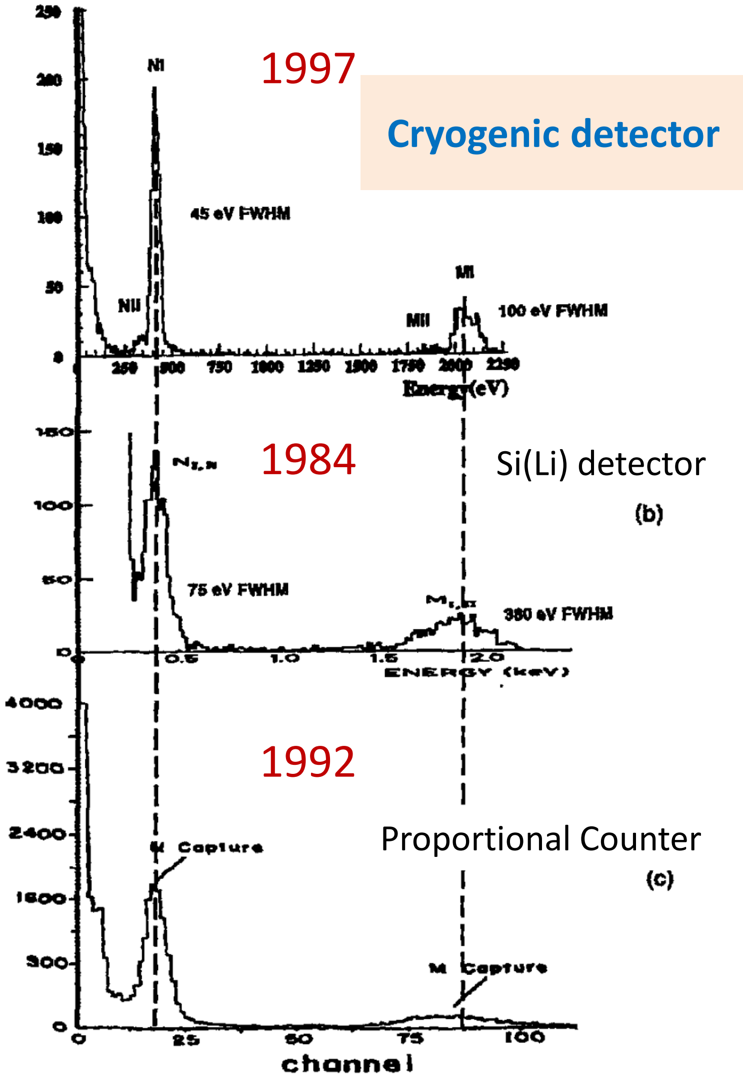
The case of ^{163}Ho



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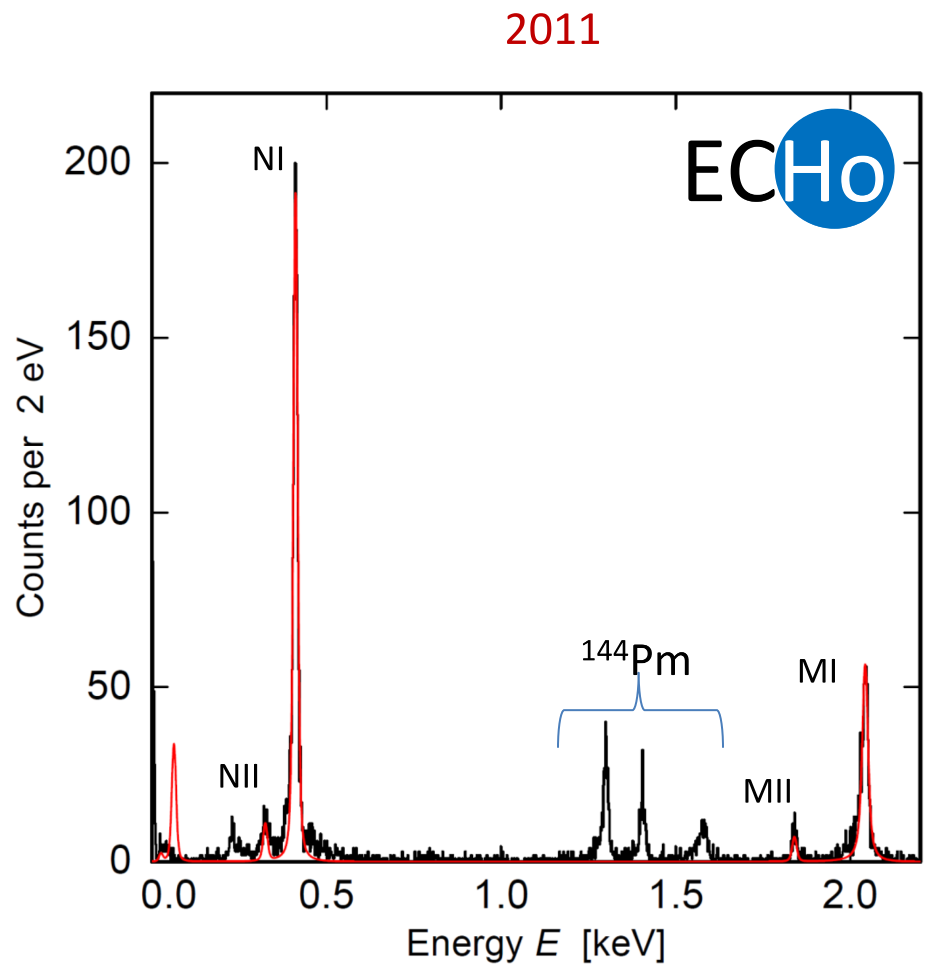

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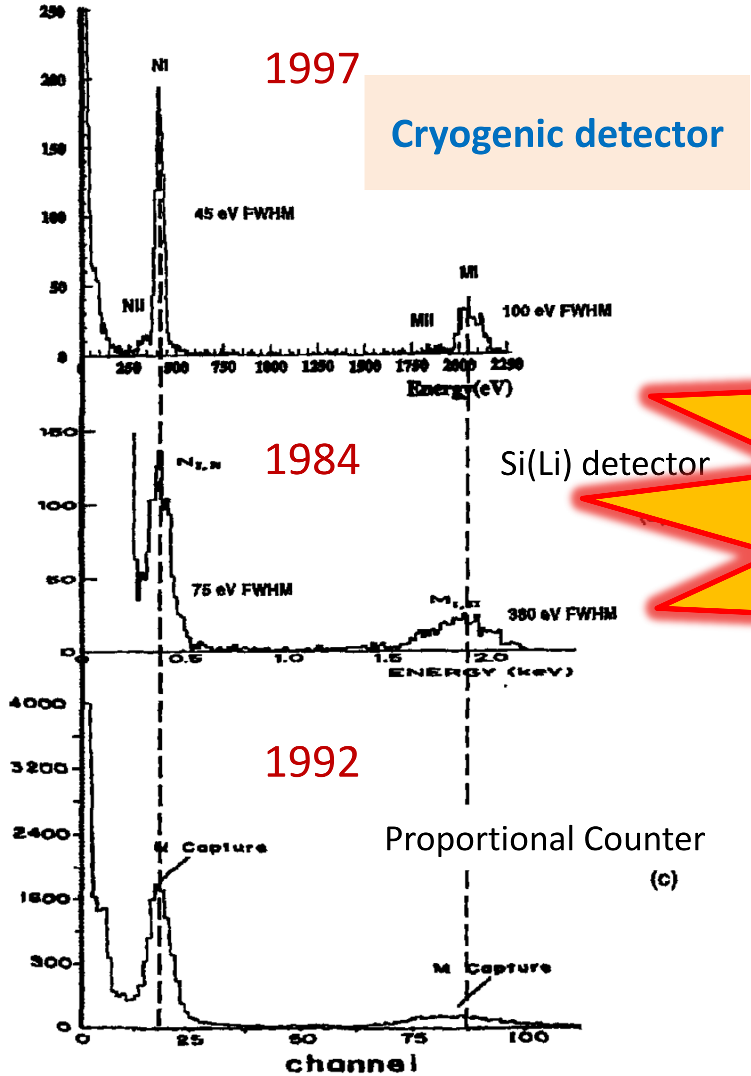

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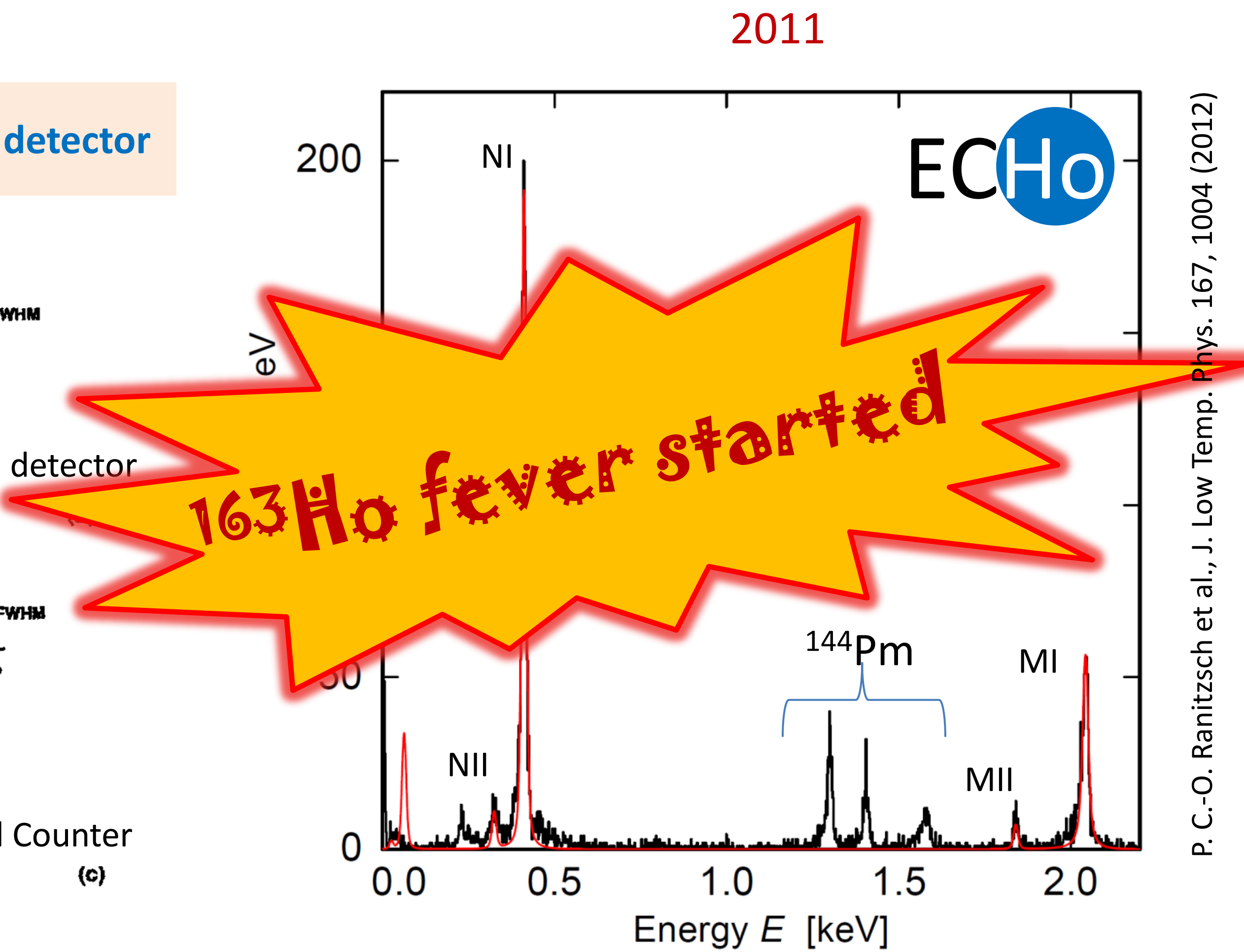

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^{163}Ho-based experiments

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

LANL

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

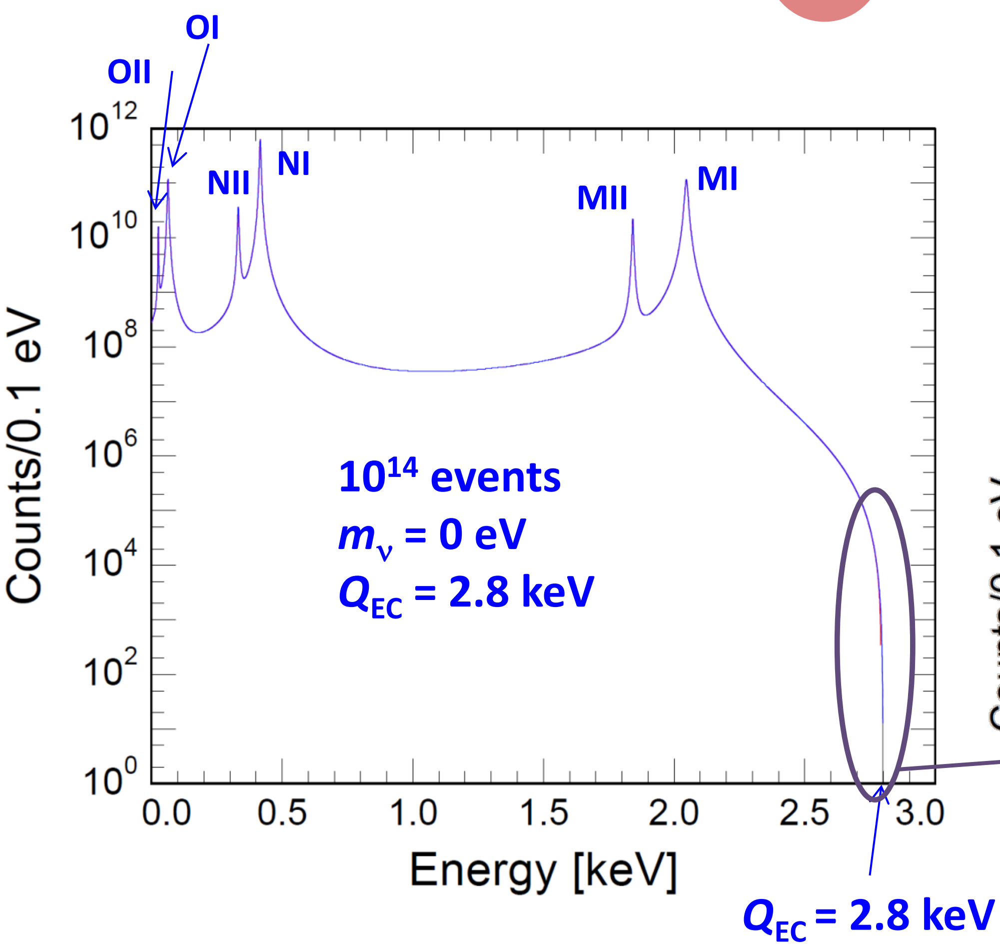
Common challenges to reach sub eV sensitivity **:**

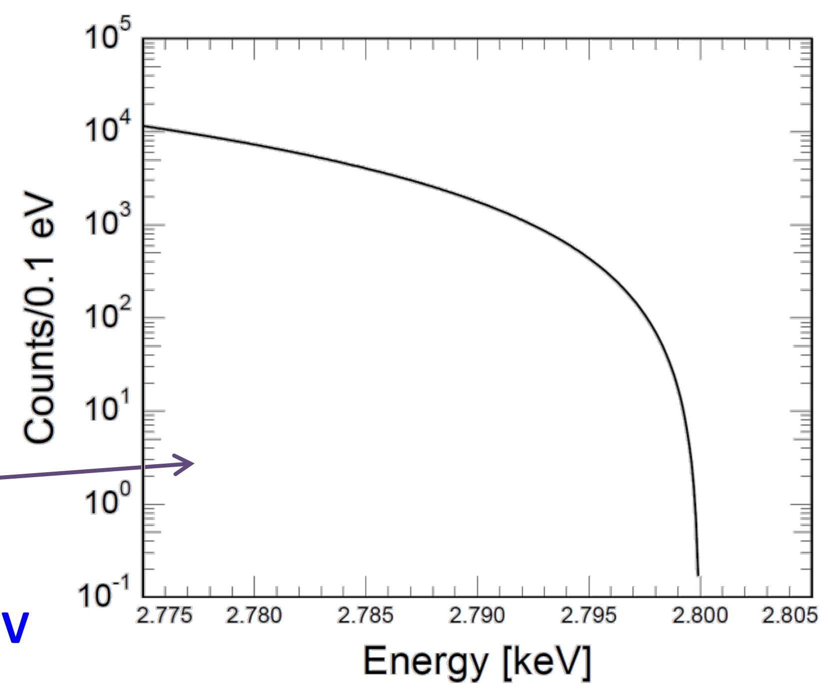
- **Detector performance**
- **High purity ^{163}Ho source**
- Background reduction
- Description of the ^{163}Ho EC spectrum

The case of ^{163}Ho: Statistics

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

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





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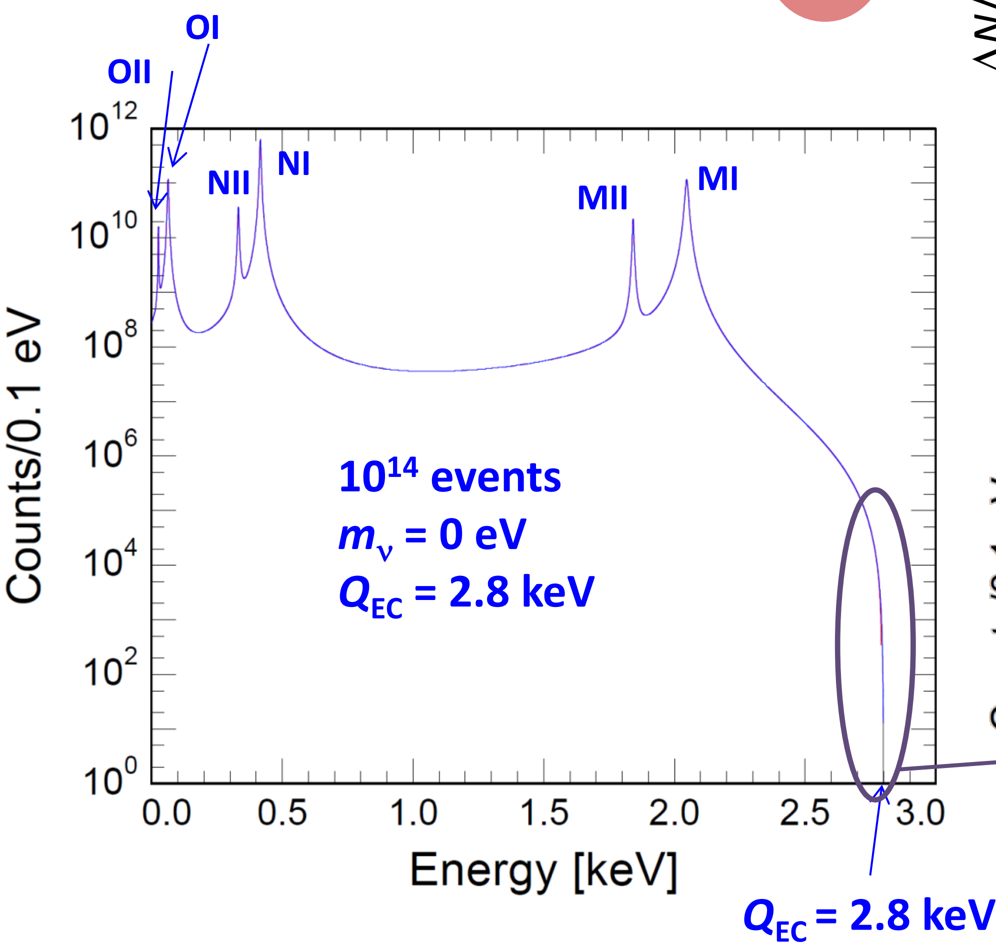
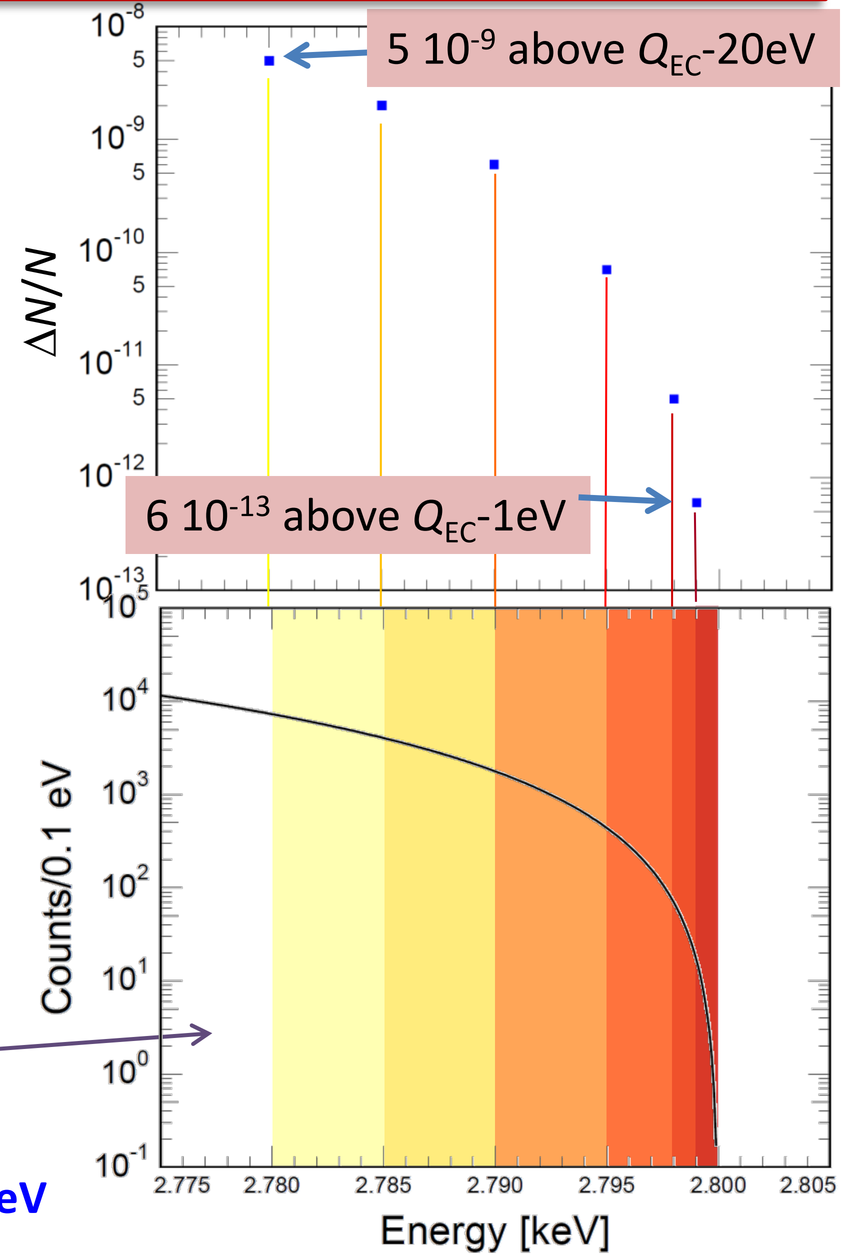
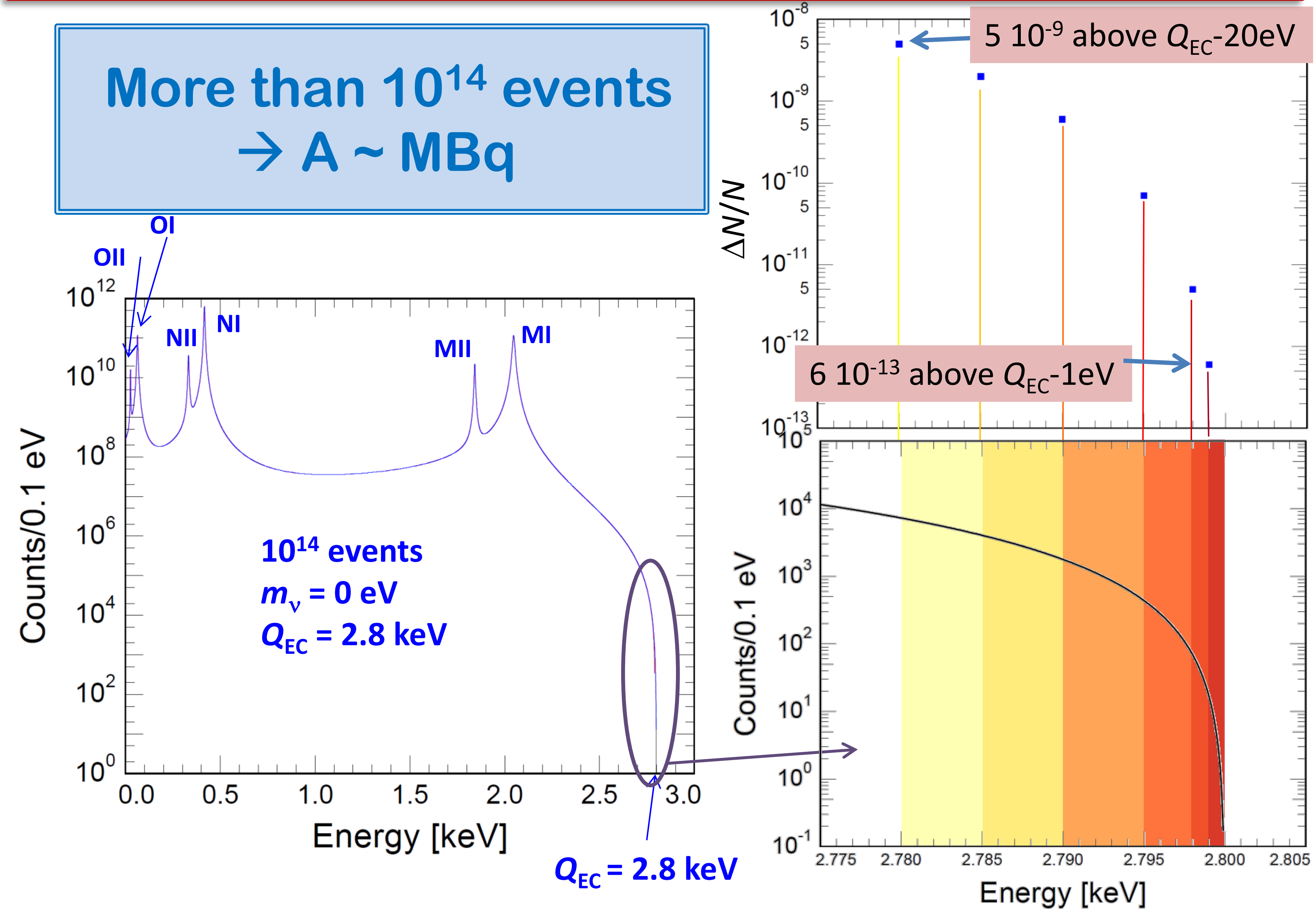


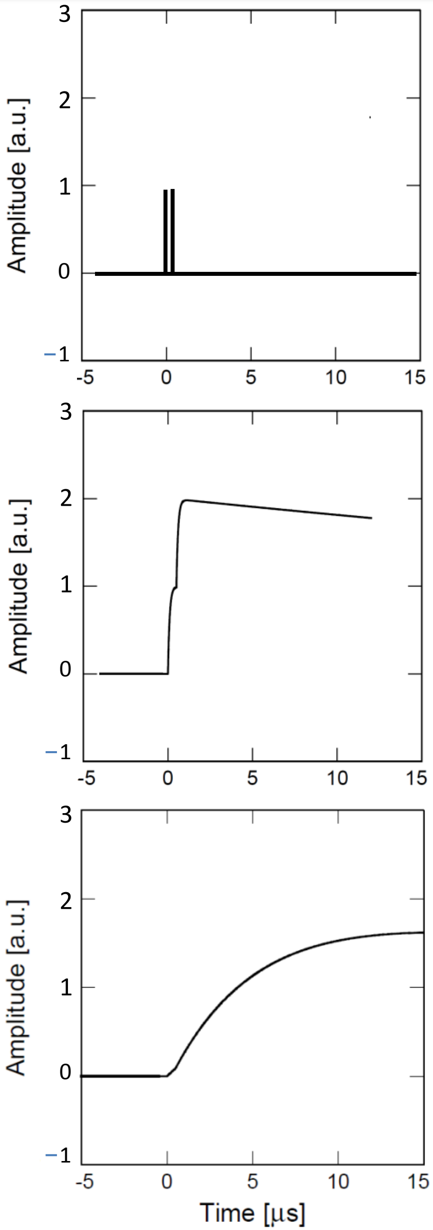


The case of ^{163}Ho: Statistics

More than 10^{14} events
→ A ~ MBq



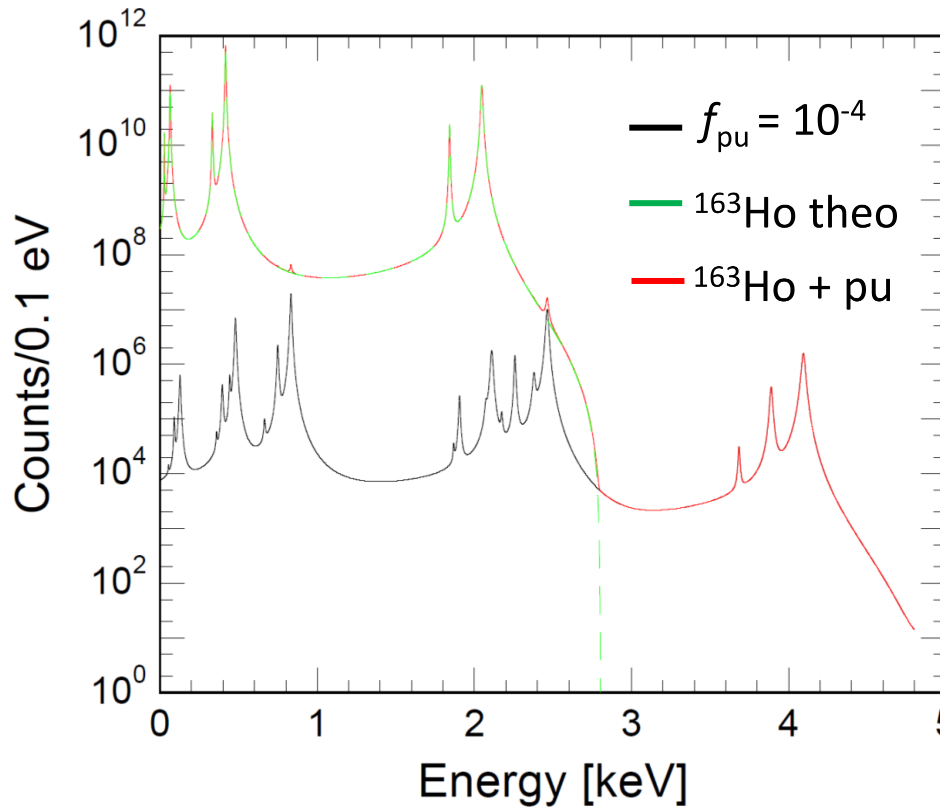
The case of ^{163}Ho: Unresolved pile-up



Δt = 0.5 µs

τ_r = 0.1 µs

τ_r = 5 µs



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

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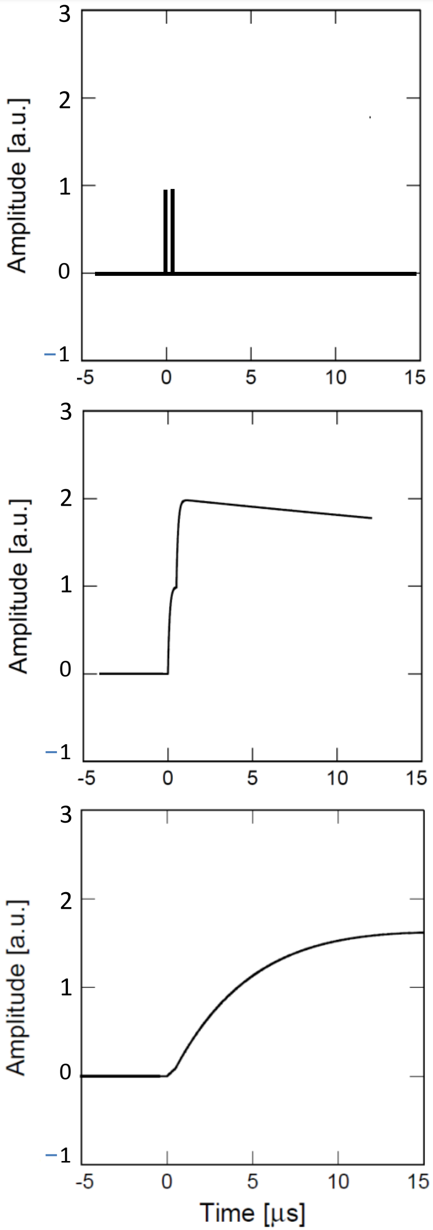

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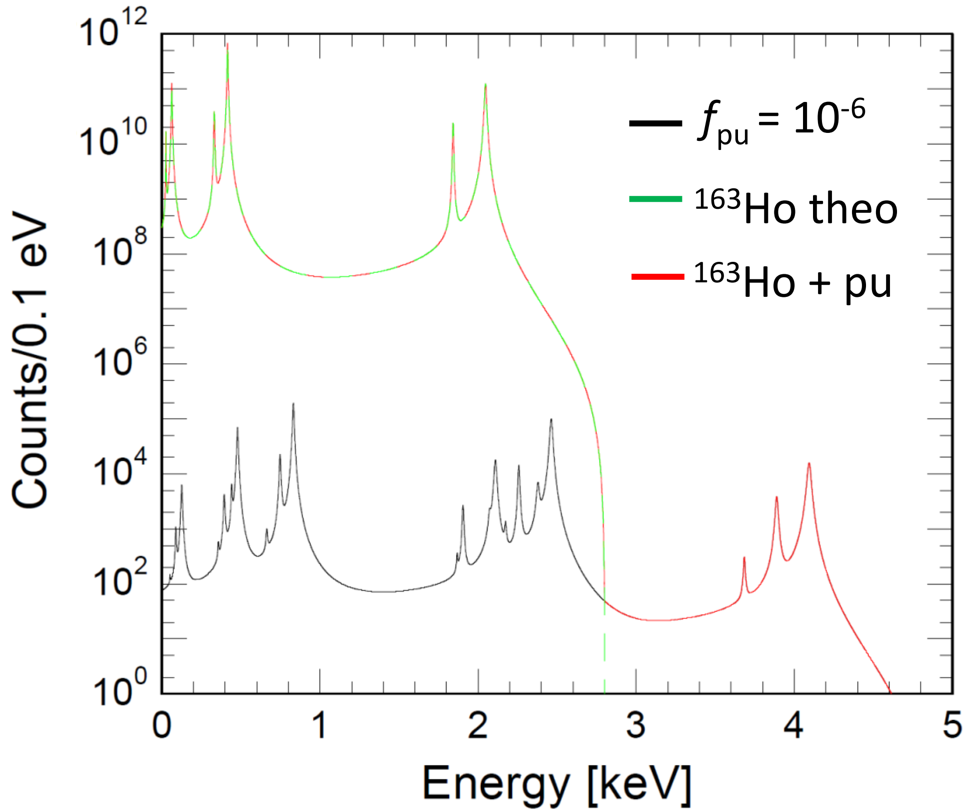
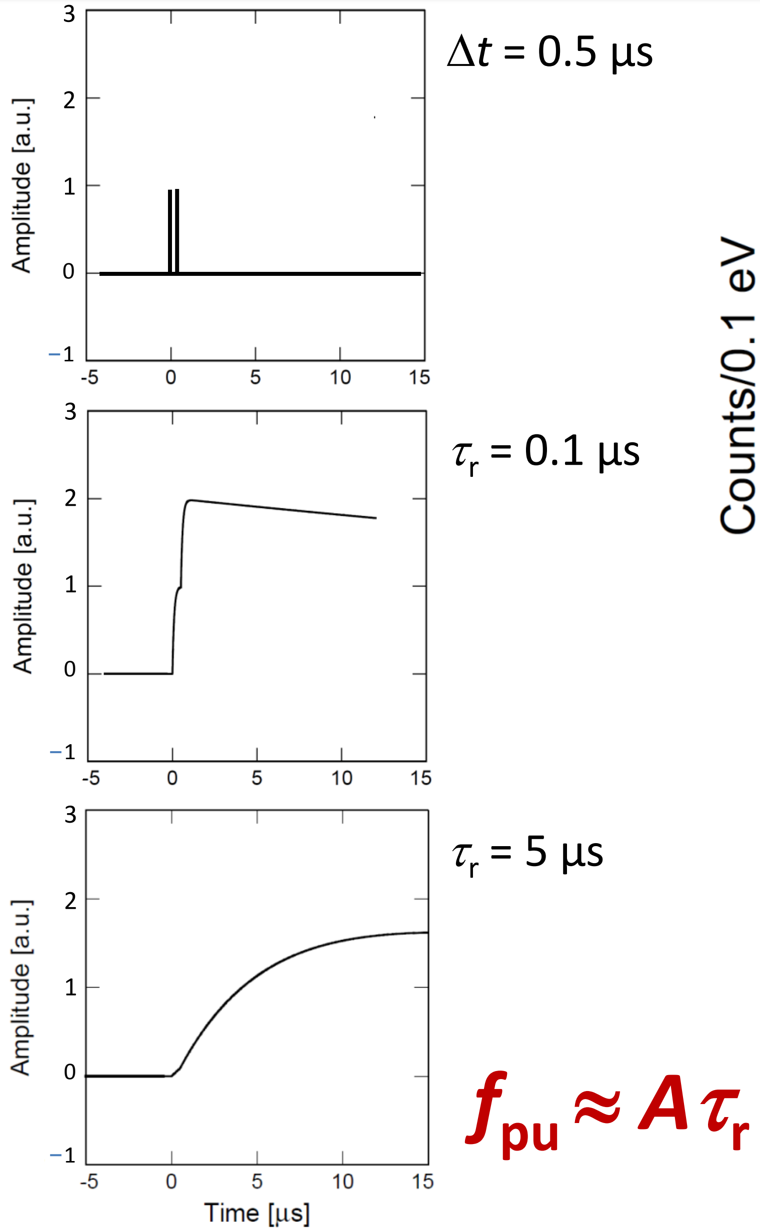


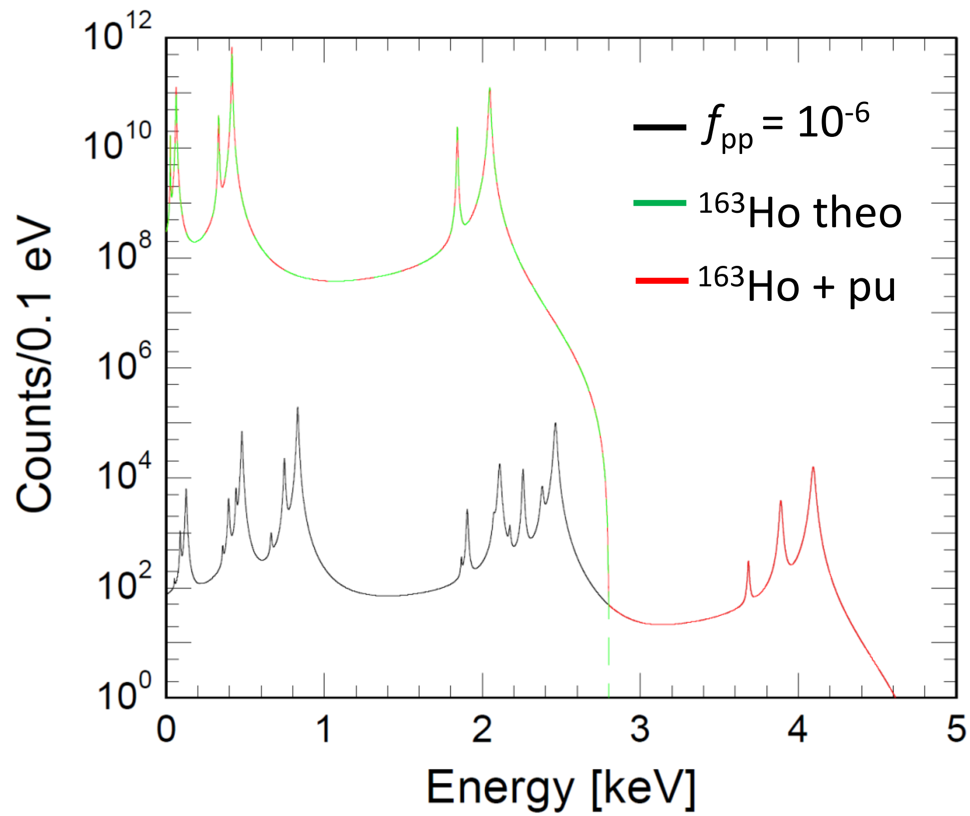
$f_{pu} = 10^{-6}$

$\tau_r = 10^{-6}$ 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: high purity source

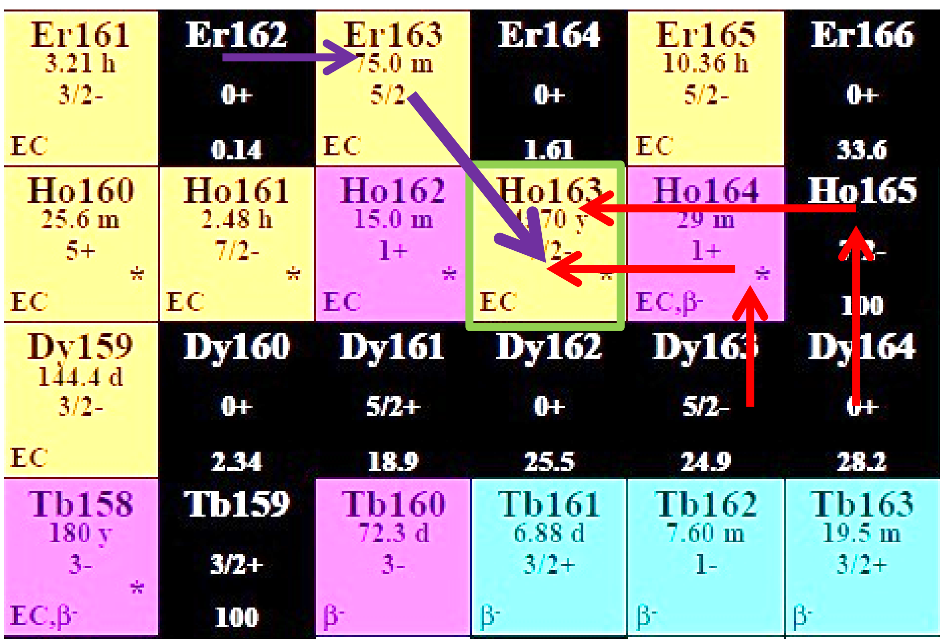
Required activity in the detectors: Final experiment → $>10^6$ Bq → $>10^{17}$ atoms

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

  High cross-section

  Radioactive contaminants



- Charged particle activation

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

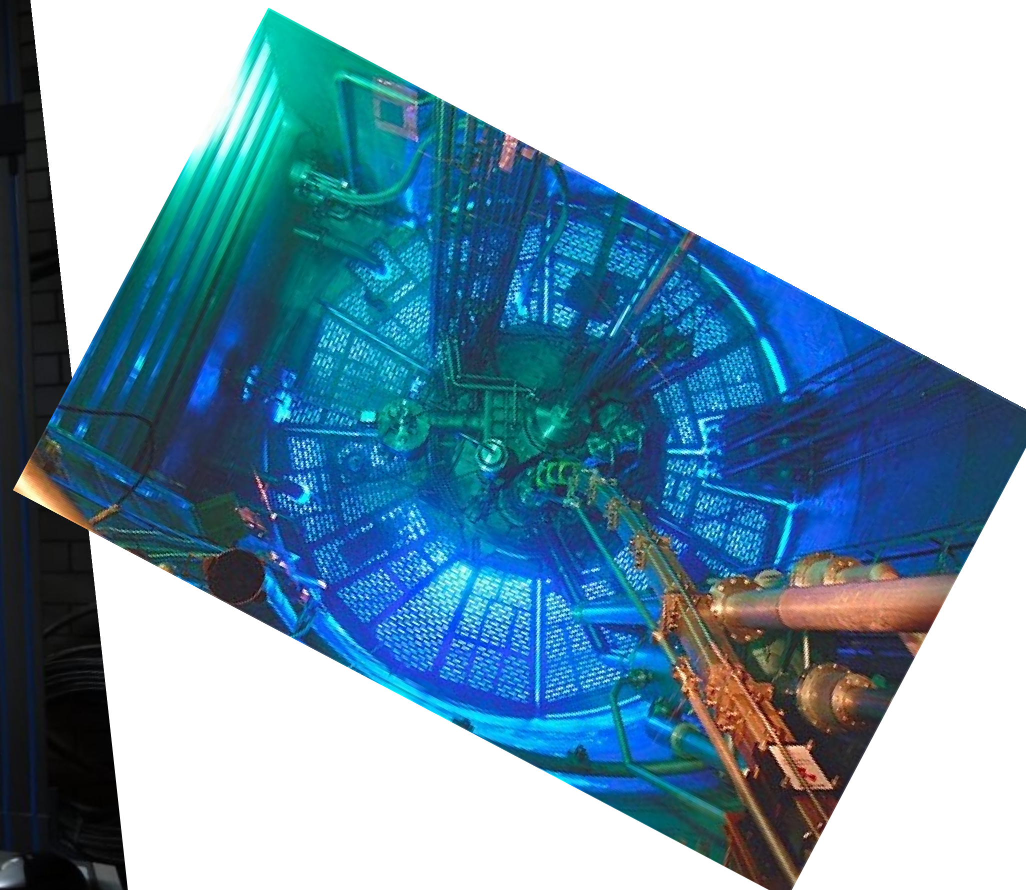
  ^{nat}Dy(α, xn) ^{163}Er (ε) ^{163}Ho

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

  Small cross-section

  Few radioactive contaminants

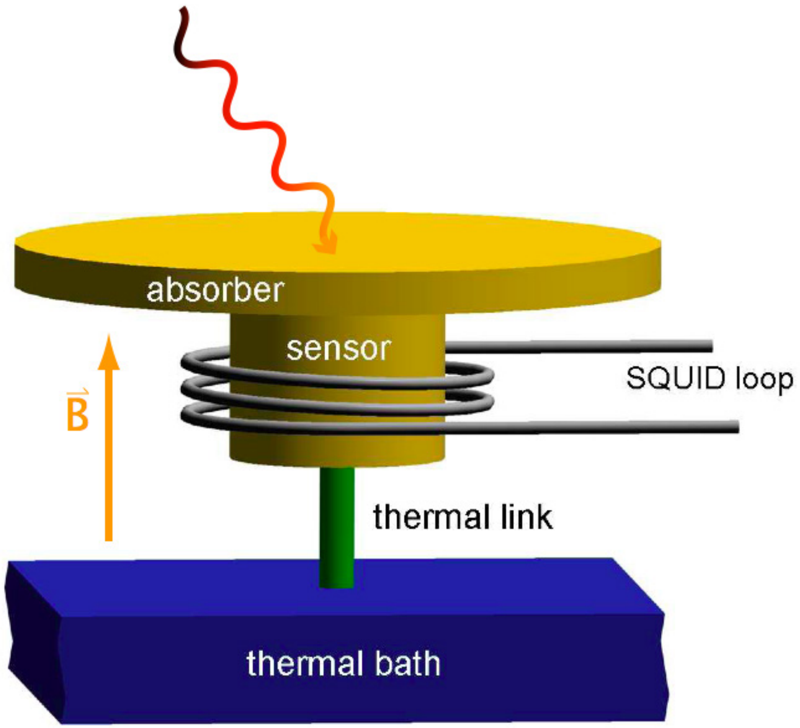
Current status



ECHo :Metallic Magnetic Calorimeters

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

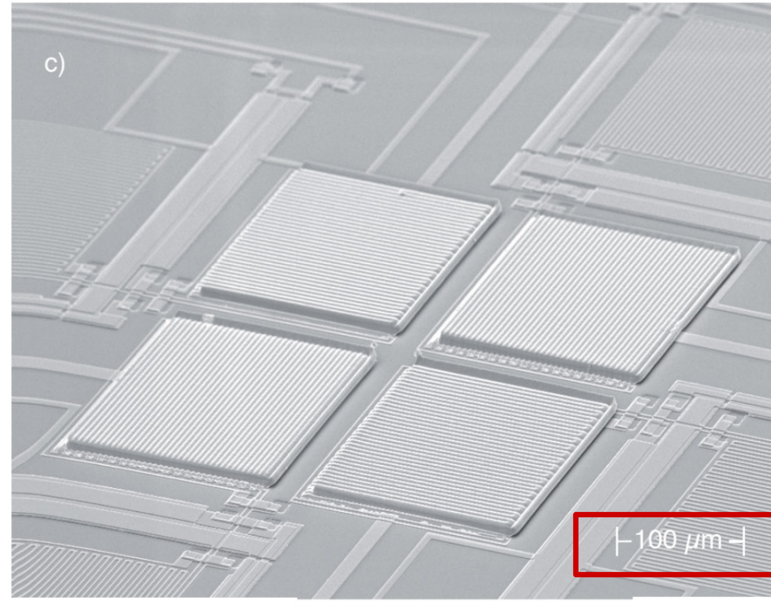
- Paramagnetic Au:Er sensor

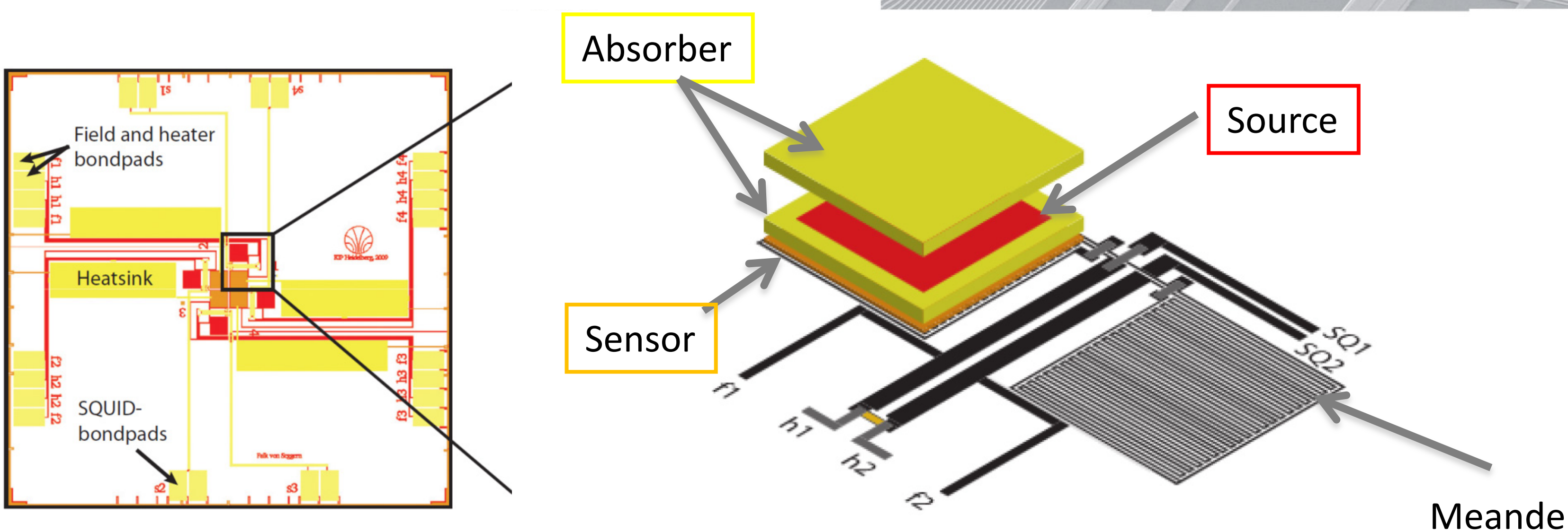


$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

ECHo : first detector prototype

- Low temperature metallic magnetic calorimeters
- Embedding of ^{163}Ho source:
  → ion implantation @ ISOLDE-CERN
- About 0.01 Bq per pixel
- Two pixels have been simultaneusly measured





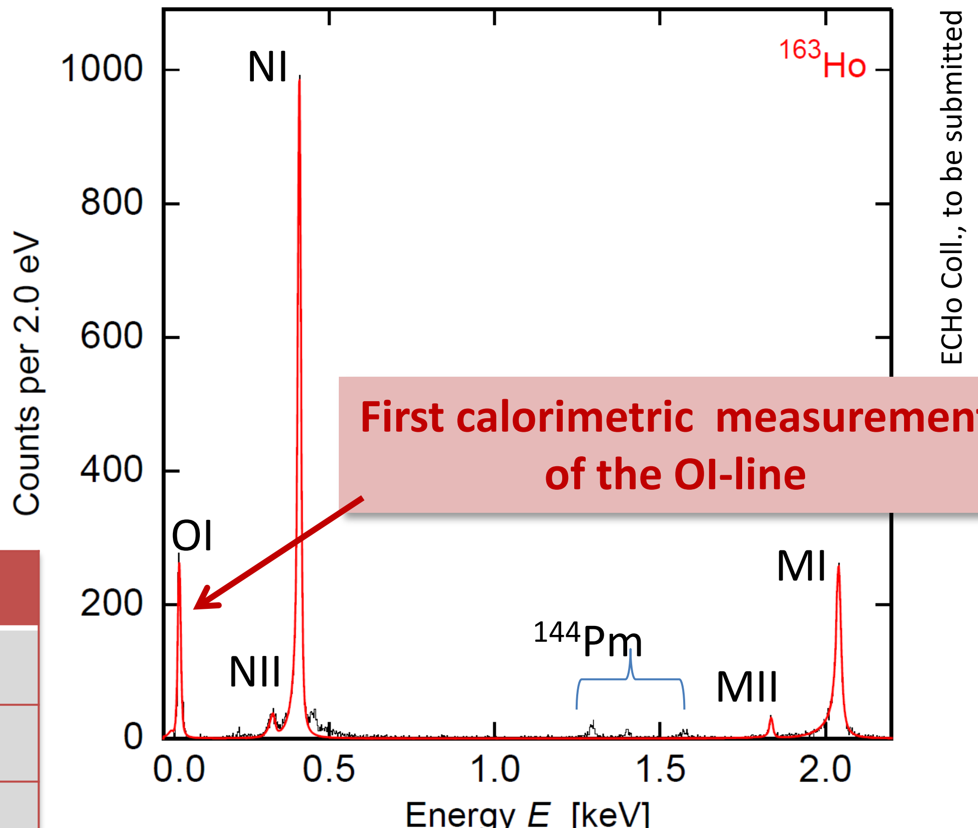
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

ECHo : Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV
- Non-Linearity < 1% @ 6keV
- Presently most precise ^{163}Ho spectrum

	E_H lit.	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

2013



First calorimetric measurement of the OI-line

Q_{EC} =(2.80±0.08) keV

P. C.-O. Ranitzsch et al., J. Low Temp. Phys. 167, 1004 (2012)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

ECHo : Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV
- Non-Linearity < 1% @ 6keV
- Presently most precise ^{163}Ho spectrum
- ΔE_{FWHM} = 4.7 eV @ 6 keV (2014) *

	E_H lit.	E_H exp.	Γ_H lit.	Γ_H exp
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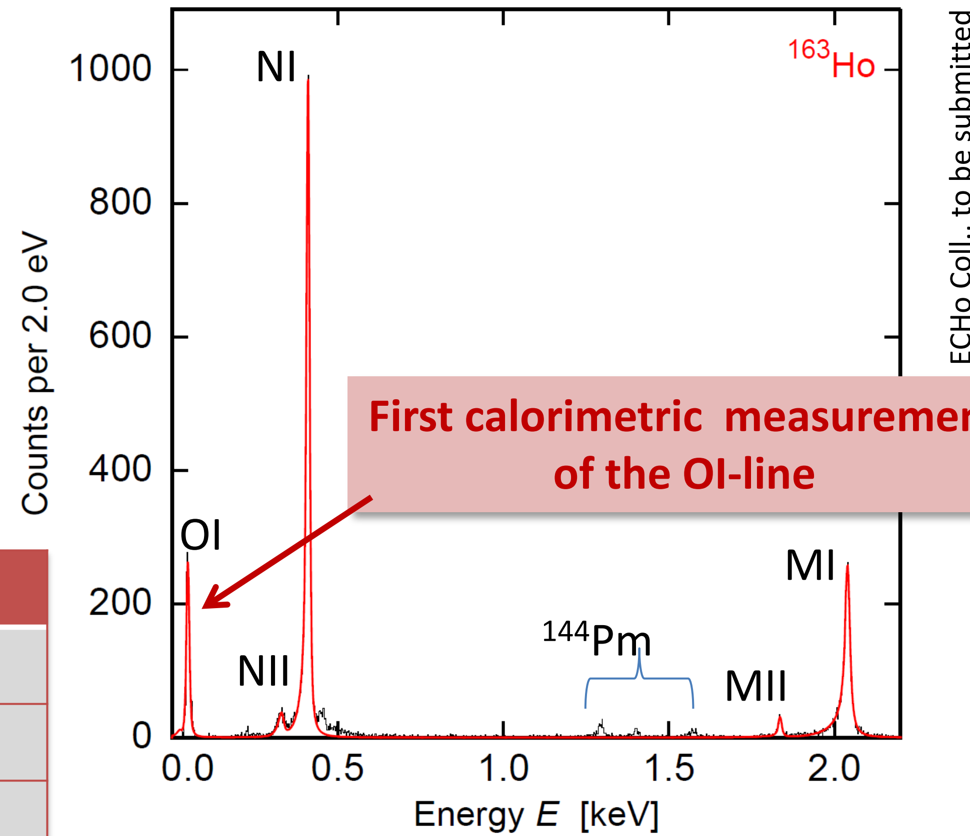
2013



First calorimetric measurement of the OI-line

Q_{EC} =(2.80±0.08) keV

*Gastaldo et al., Poster ID 28 Tuesday

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•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

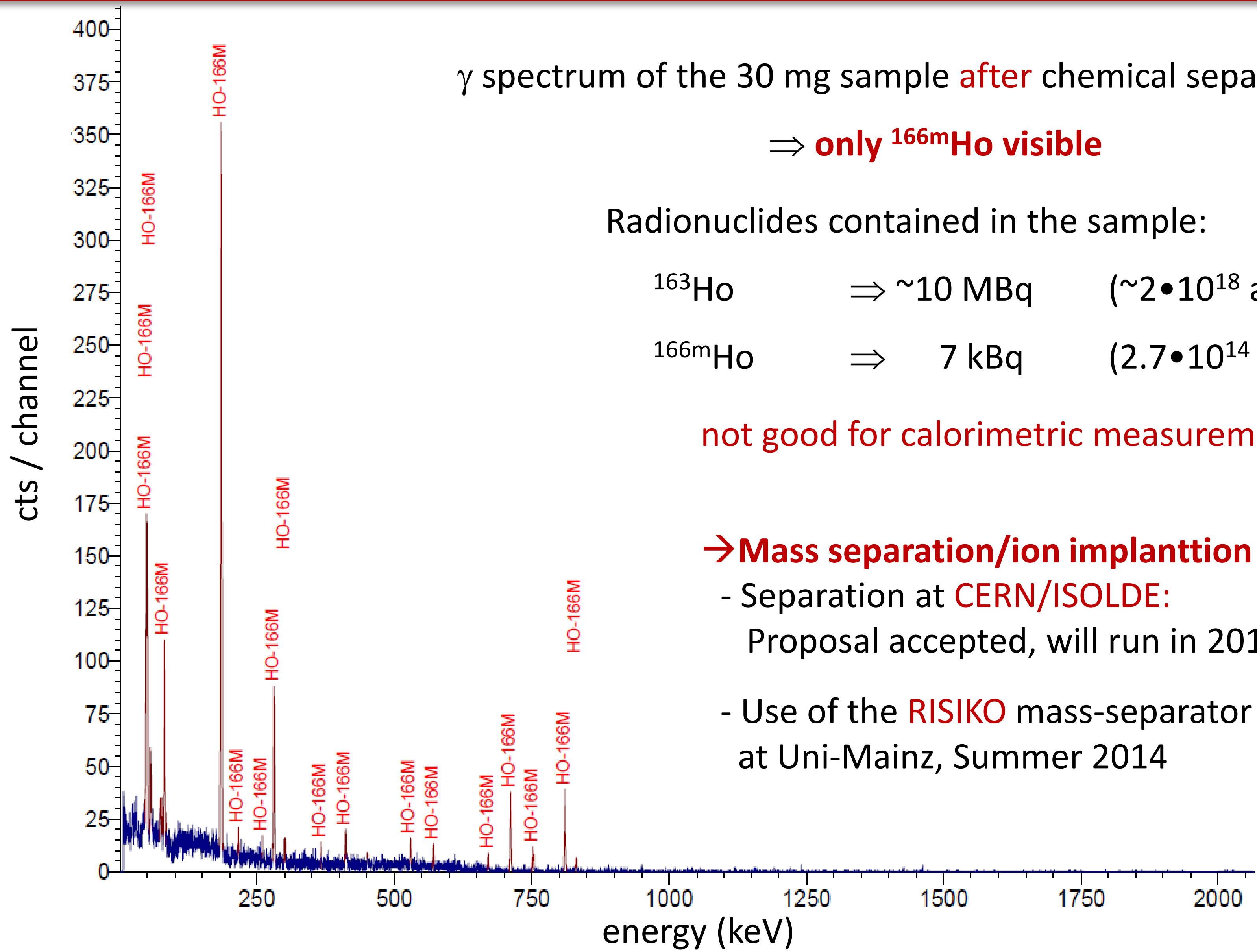
- 30 mg for 55 days $\Rightarrow$ 1.6•10^{18} atoms ^{163}Ho
- 7 mg for 7 days $\Rightarrow$ 1.4•10^{16} atoms ^{163}Ho

Thermal neutron flux (Φ): 1.3x10^{15} cm^{-2}s^{-1}

NEUTRONS FOR SCIENCE

Gastaldo et al.,
Poster ID 28 Tuesday

ECHo : ^{163}Ho source - Purification of ^{163}Ho at PSI



γ spectrum of the 30 mg sample after chemical separation:

$\Rightarrow$ **only ^{166m}Ho visible**

Radionuclides contained in the sample:

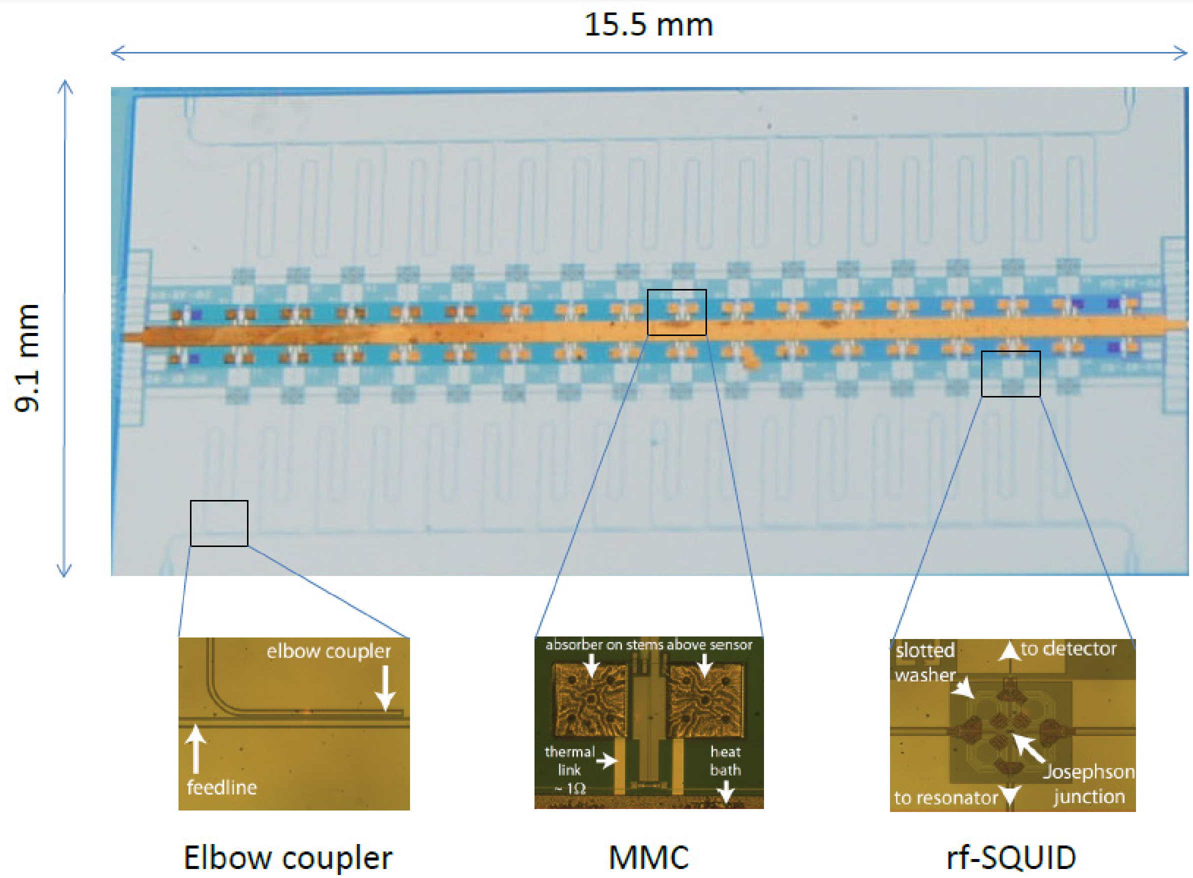
^{163}Ho	$\Rightarrow$ ~10 MBq	(~2•10^{18} atoms)
^{166m}Ho	$\Rightarrow$ 7 kBq	(2.7•10^{14} atoms)

not good for calorimetric measurement

→Mass separation/ion implanttion

- Separation at CERN/ISOLDE:
  Proposal accepted, will run in 2014
- Use of the RISIKO mass-separator
  at Uni-Mainz, Summer 2014

ECHo : next step



Gastaldo
Poster ID 28 Tuesday

Ranitzsch
Poster ID 35 Tuesday

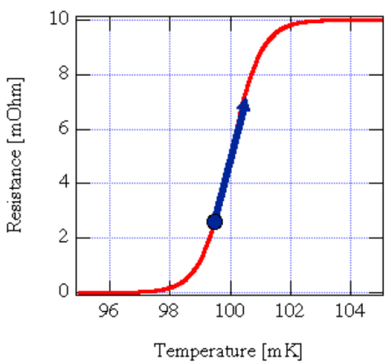
S. Kempf et al, JLTP online first
doi *10.1007/s10909-013-1041-0*

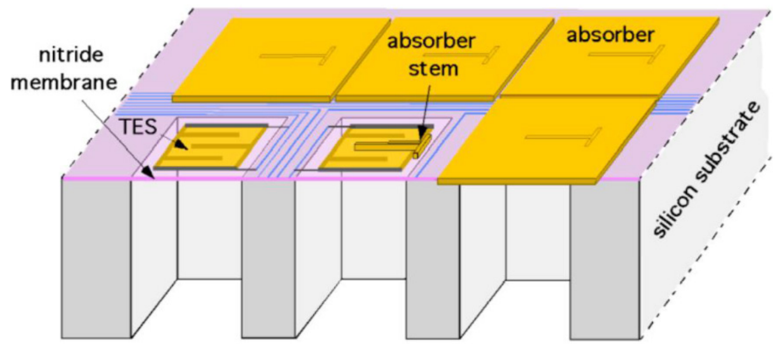
- Microwave multiplexing technique
- 64 pixels, ΔE_{FWHM} = 5 eV, 10 Bq/pixel
- 2 chips

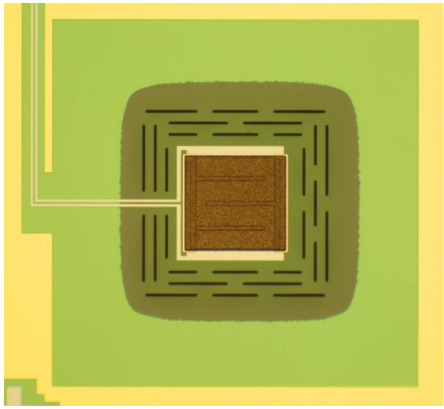
<10 eV m_ν sensitivity
Prove scalability

HOLMES: Detectors

Transition Edge Sensor: MoCu or MoAu superconducting films





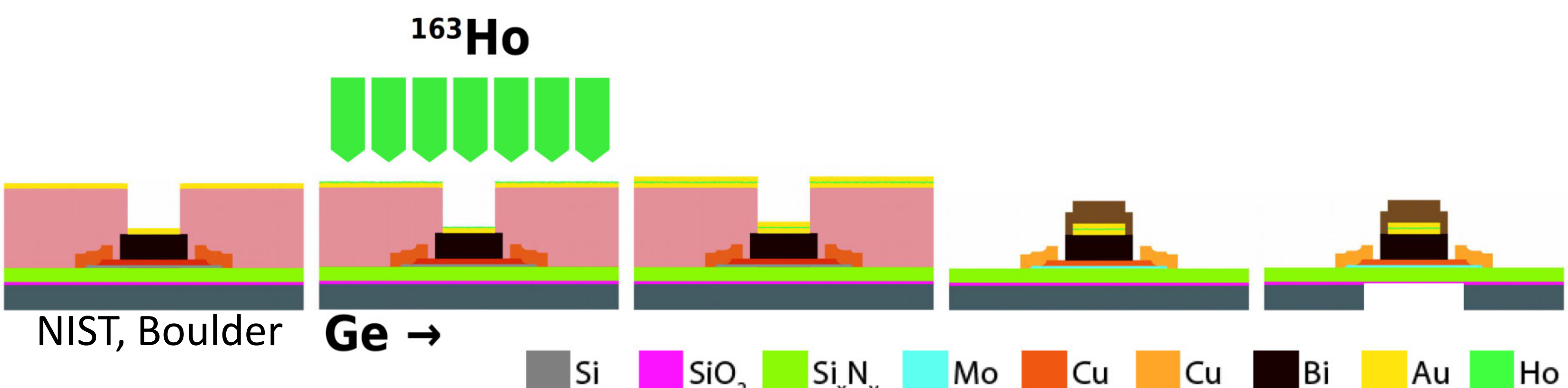


NIST, Boulder

Absorber: Bi-Au or Au + 6.5x10[13] ^{163}Ho per detector → 300 dec/sec

Microwave multiplexing → 1000 channel arrays

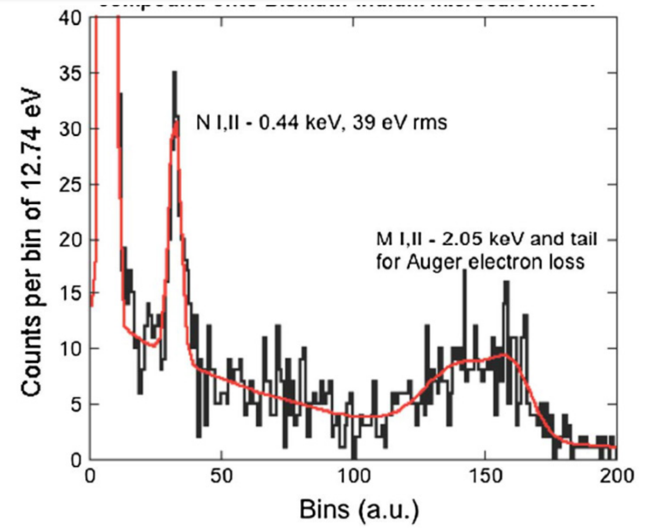
$\Delta E \approx 1$eV and $\tau_R \approx 1\mu s$



HOLMES: ^{163}Ho source

^{163}Ho production via (n,γ)-reaction on ^{162}Er (20% enriched target):

- 3 irradiatons at Lisboa research reactor (ITN)
- 1 irradiation at Grenoble reactor (ILL) → >10MBq of ^{163}Ho
- To be tested p irradiation of natural dysprosium at PSI



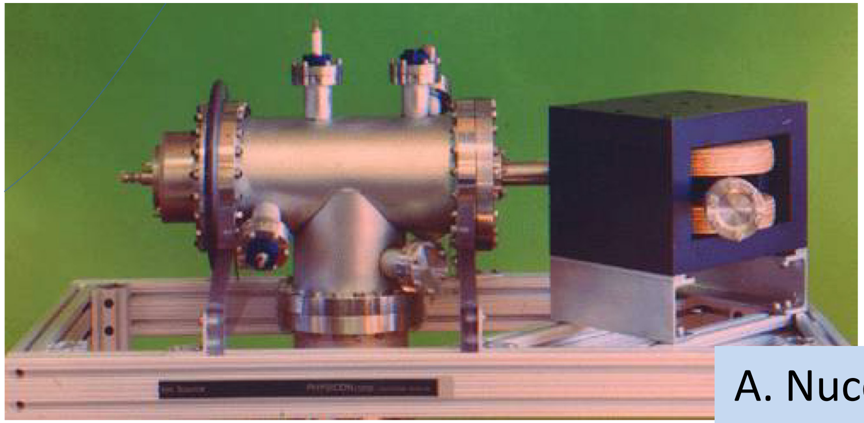
M. Ribeiro Gomes et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

Er_2O_3/Ho_2O_3 thermoreduction→ metallic target

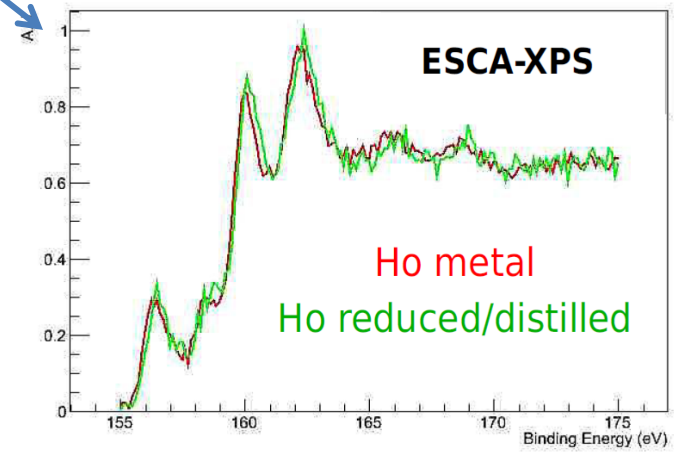
- $Y_5Si_3+Ho_2O_3$ → $Y_{5-x}Ho_xSi_3$ a 600-800°C
- $Ho_2O_3+2Y(met)$ → $2Ho(met)+Y_2O_3$ at 2000°C

Implantation in Au absorbers

- custom ion implanter design



A. Nucciotti
Poster ID 56 Tuesday

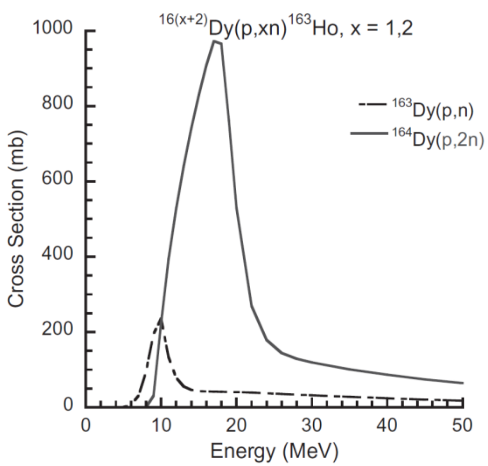


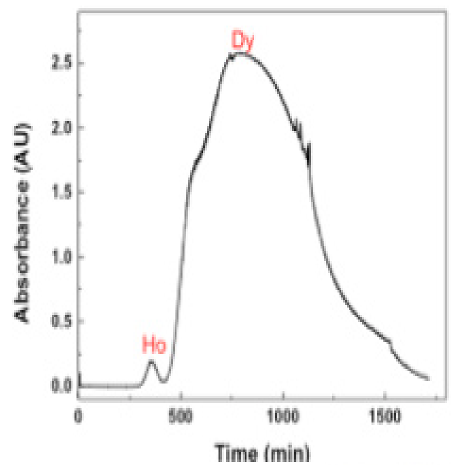
LANL: ^{163}Ho source

Proton irradiation of natural Dy at high-current LANL proton accelerator

Factor of 10^4-10^7 lower co-production rate of interfering isotope (^{166m}Ho)

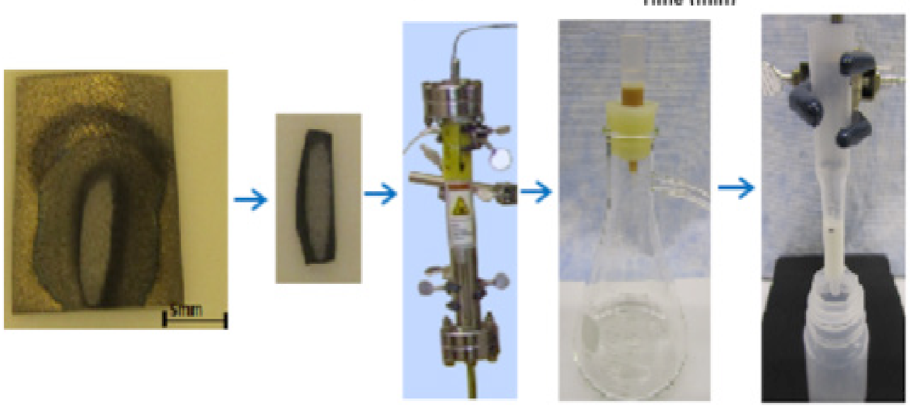
J.W. Engle et al. NIM B 311 (2013) 131–138





separation of ~500 µg of Ho from 110 mg Dy

	24.75 ±1.32 ng
^{163}Ho product	**~440 Bq**
	~9 × 10^{13} atoms
^{165}Ho/^{163}Ho atom ratio	397 due to natural Ho (^{165}Ho) present in Dy target and brief (~10 hour) beam exposure
Purification factor	99.9997% Dy removed
Mass scale for HPLC separation	55 mg Dy with ~400 ng Ho
Yield (Ho-out/Ho-in ratio)	**67 %**



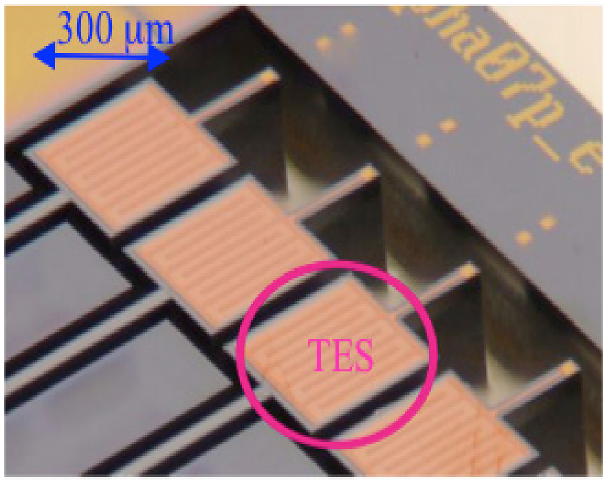
Dy target

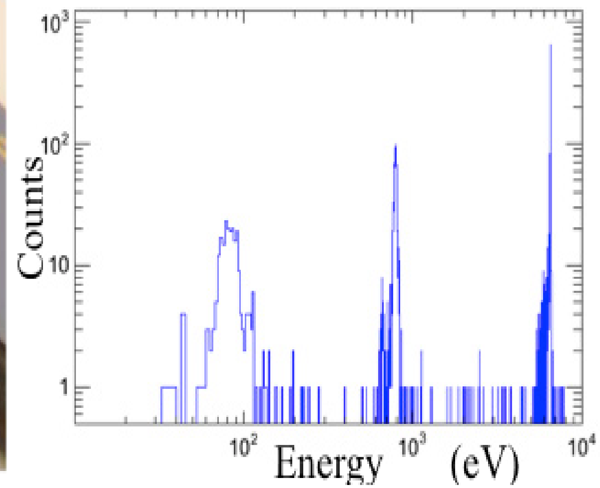
Ion chromatography

LANL: Detectors

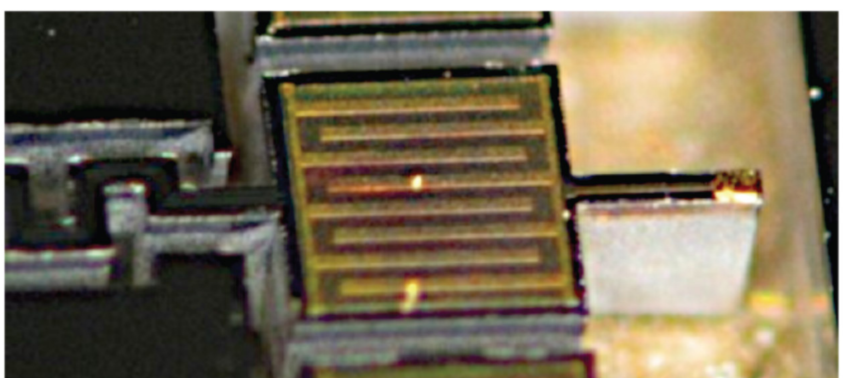
Transition Edge Sensor: MoCu superconducting films on solid silicon

- Completed the high-yield microfabrication our first microcalorimeter sensors
- Microwave multiplexing technique





- ✓ Feasibility demonstrated with embedding ^{55}Fe source
- ✓ Recent experiment shows ΔE ~ 7.5 eV FWHM



- ➢ Testing several methods of incorporating Ho into absorbers

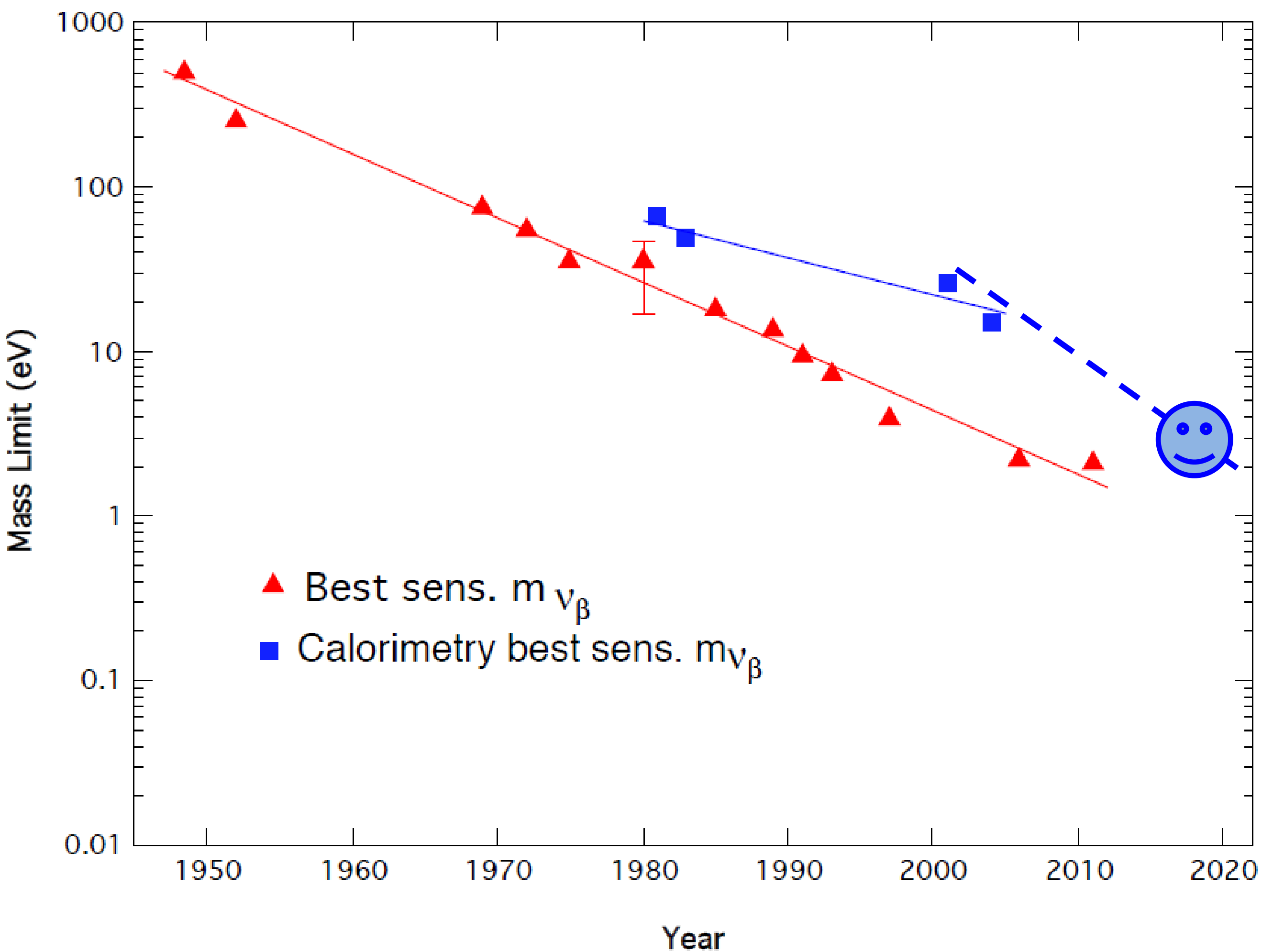
Conclusions

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

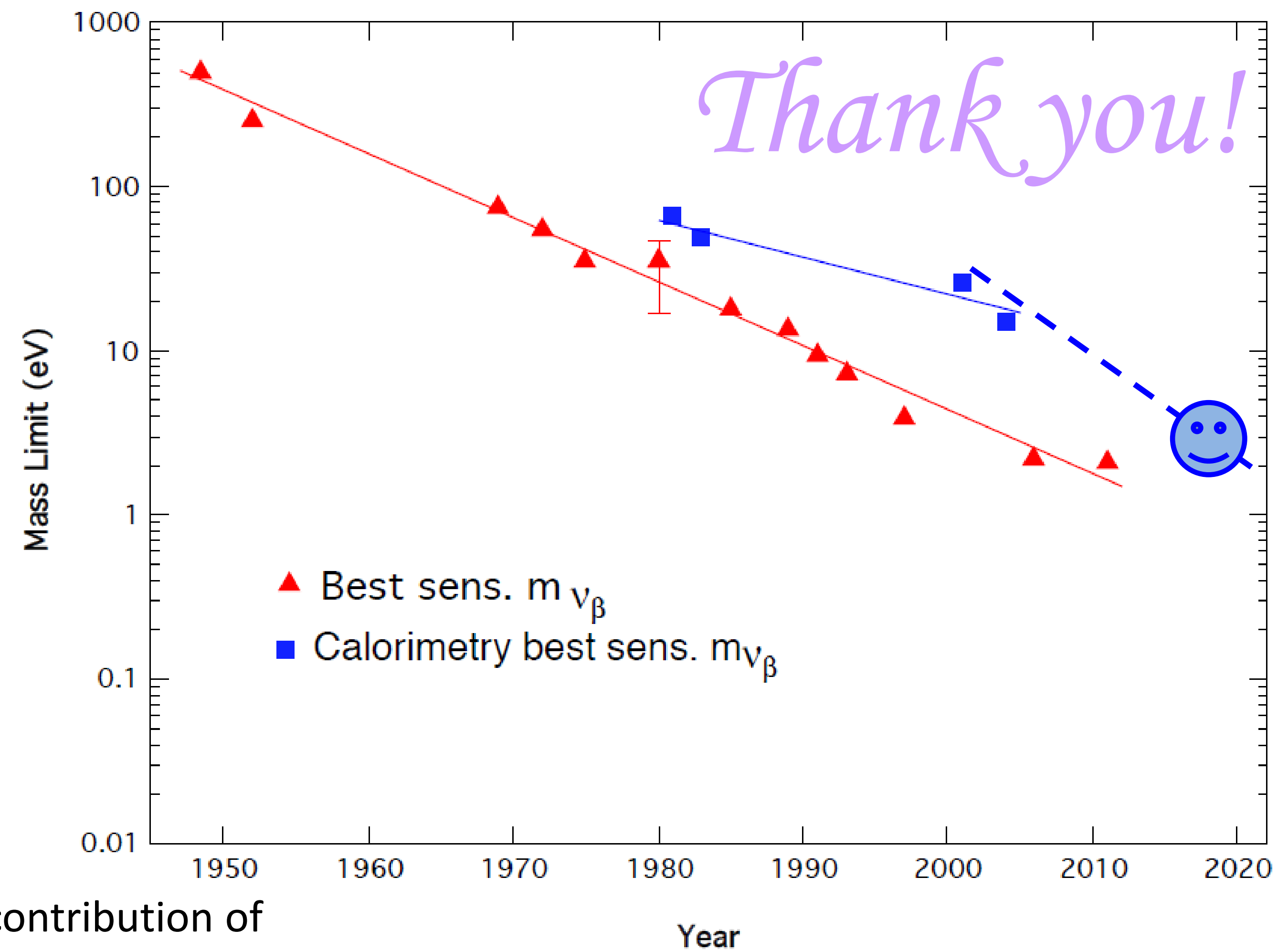
→ $m(\nu_e) < 10$ eV

Conclusions



J.F. Wilkerson

Conclusions



Thank the contribution of

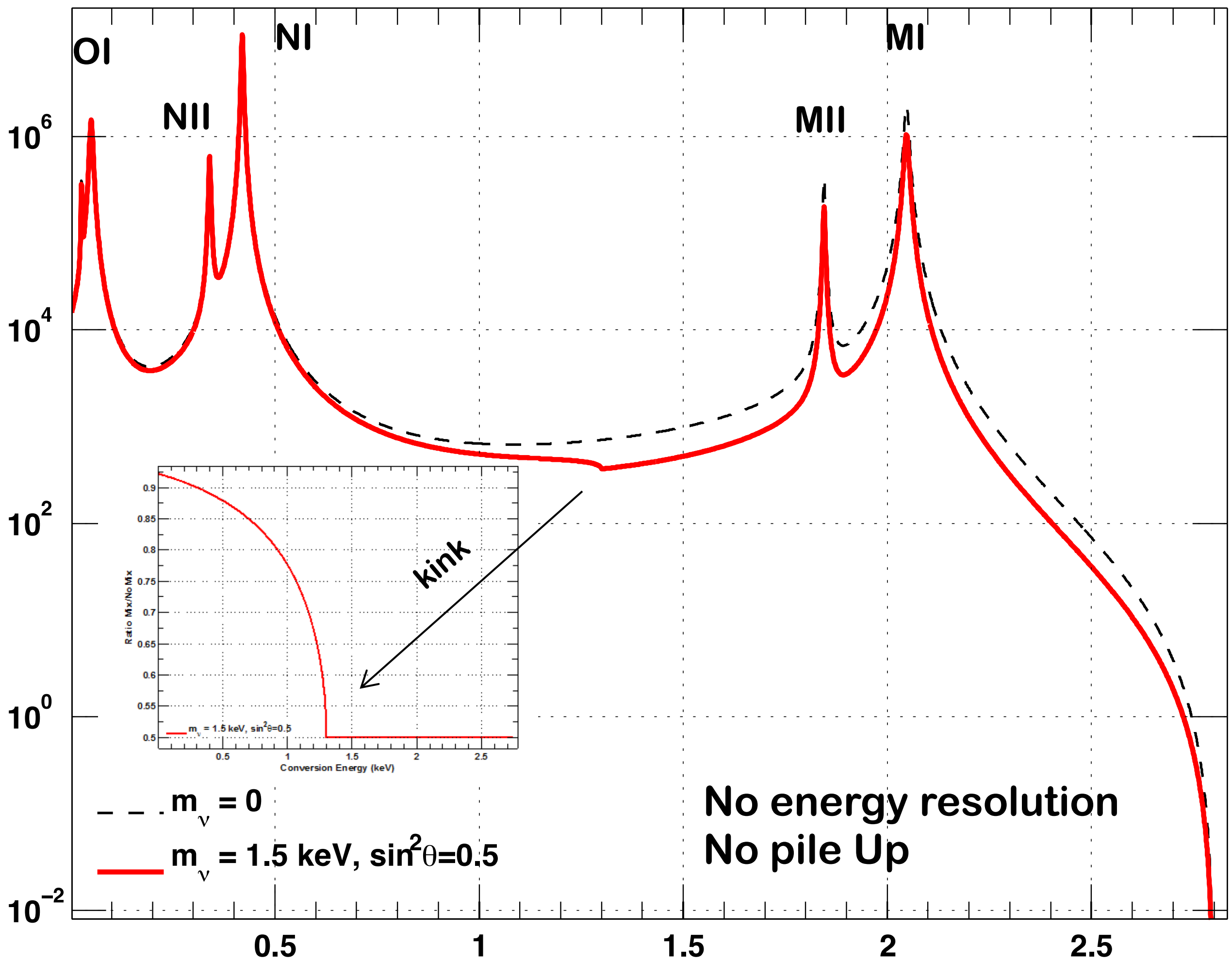
Flavio Gatti

Angelo Nucciotti

Michael Rabin

J.F. Wilkerson

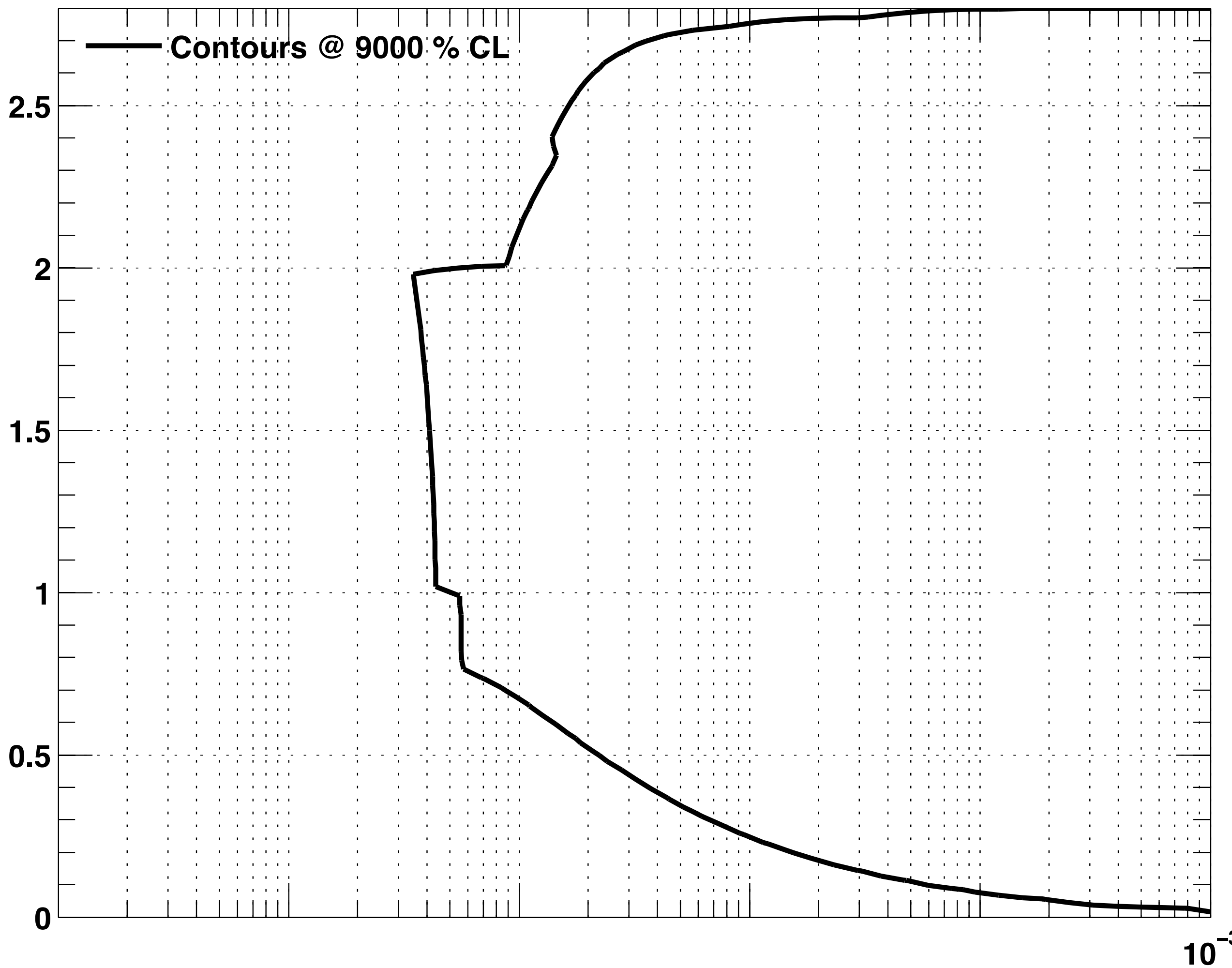
keV Sterile Neutrino



Thierry Lassere, LG Work in progress

keV Sterile Neutrino

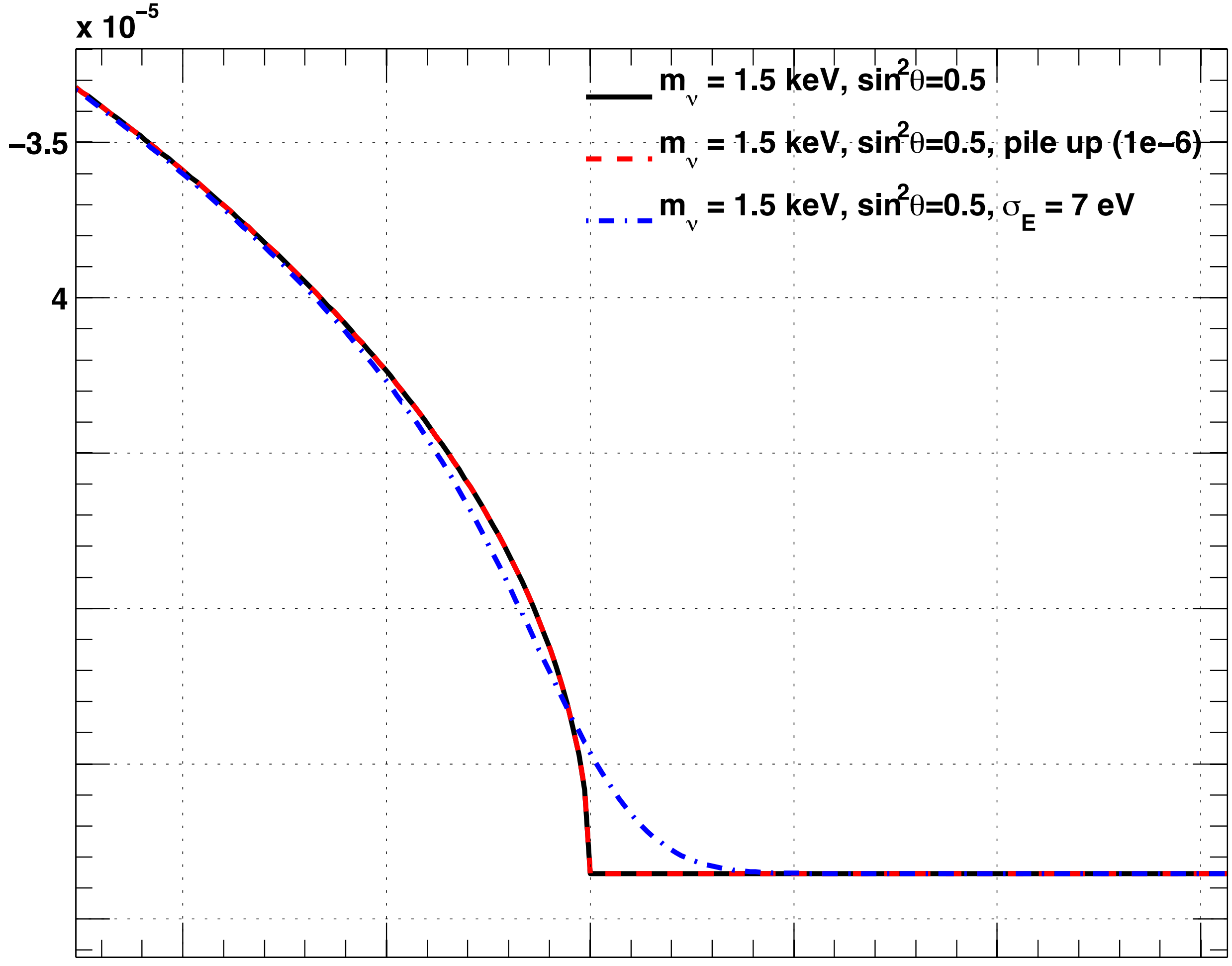
Statistical Fluctuation – No Pile Up – Counts = 1e14
Theoretical Spectrum Supposed to be perfectly known



Thierry Lassere, LG Work in progress

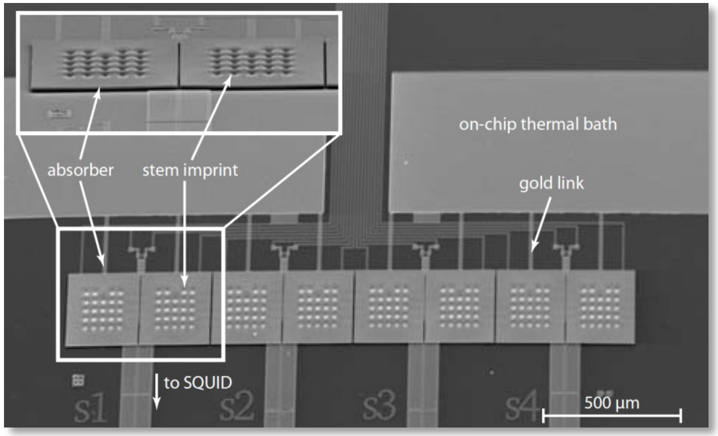
keV Sterile Neutrino

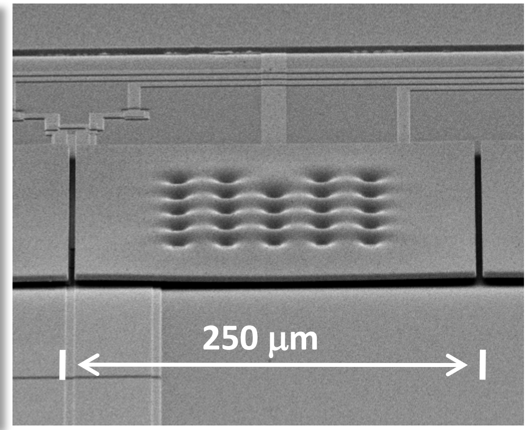
No impact of the pile up, if exactly known
Weak impact on the energy resolution for keV neutrino kink search



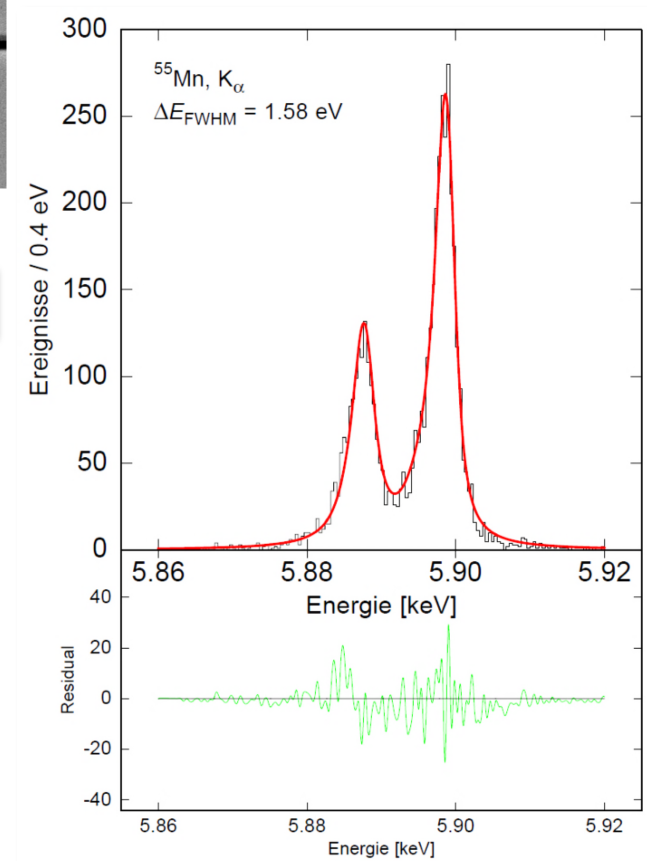
Thierry Lassere, LG Work in progress

ECHo :Metallic Magnetic Calorimeters

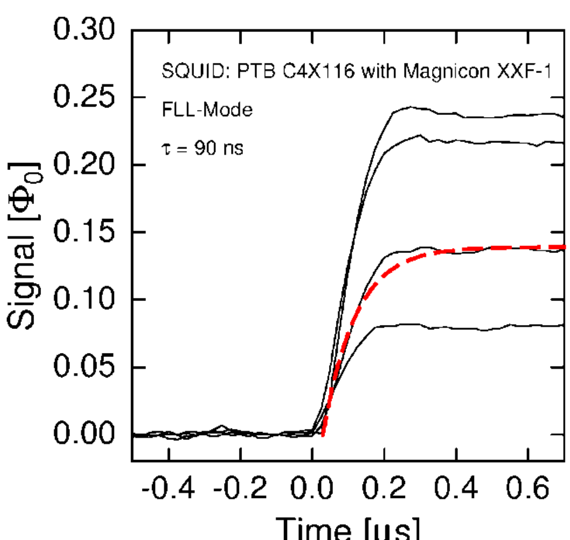




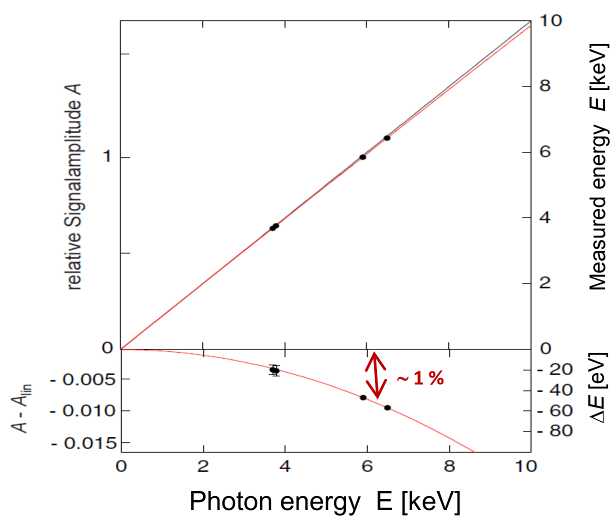
ΔE_{FWHM} = 1.6 eV @ 6 keV



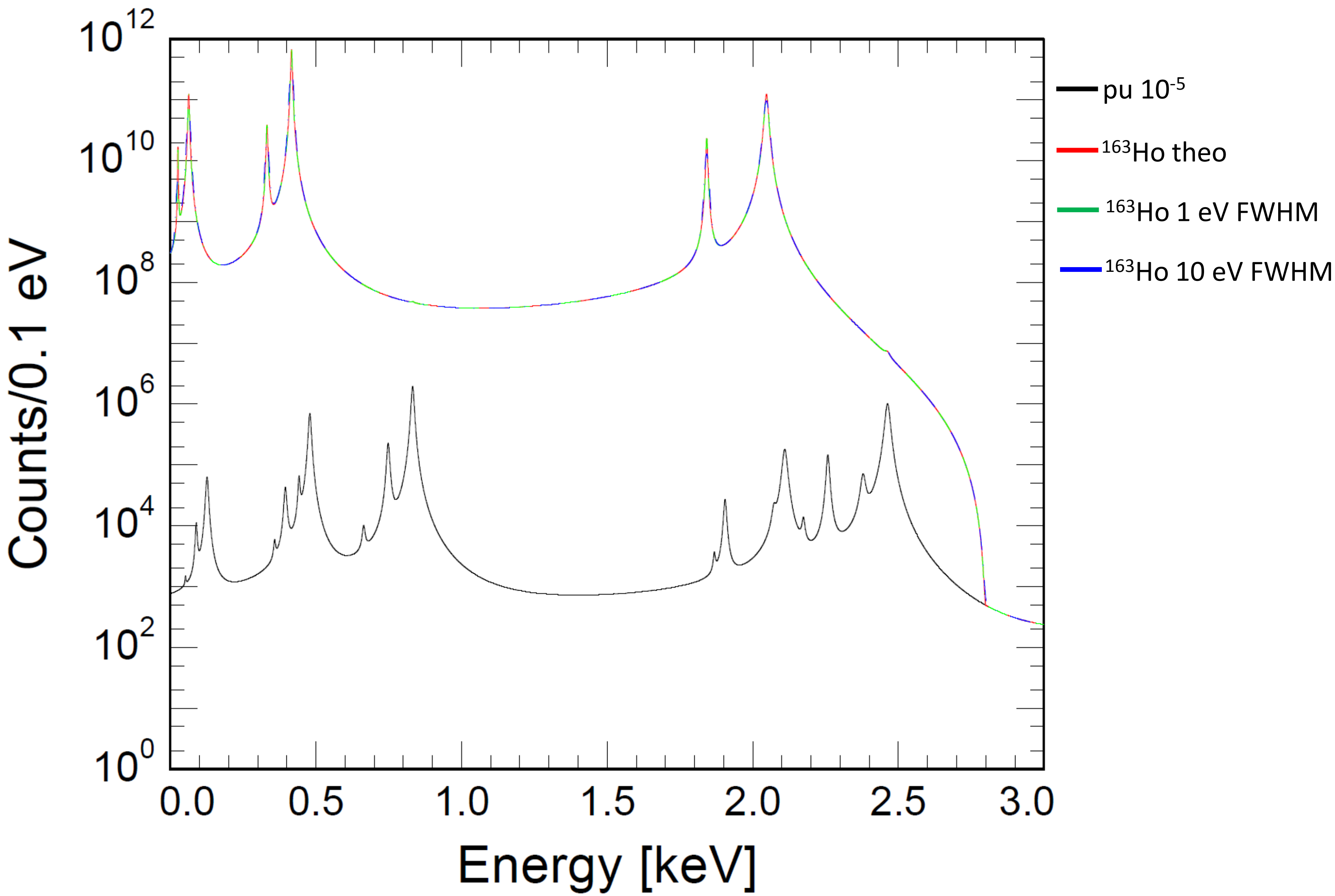
Rise Time: 90 ns



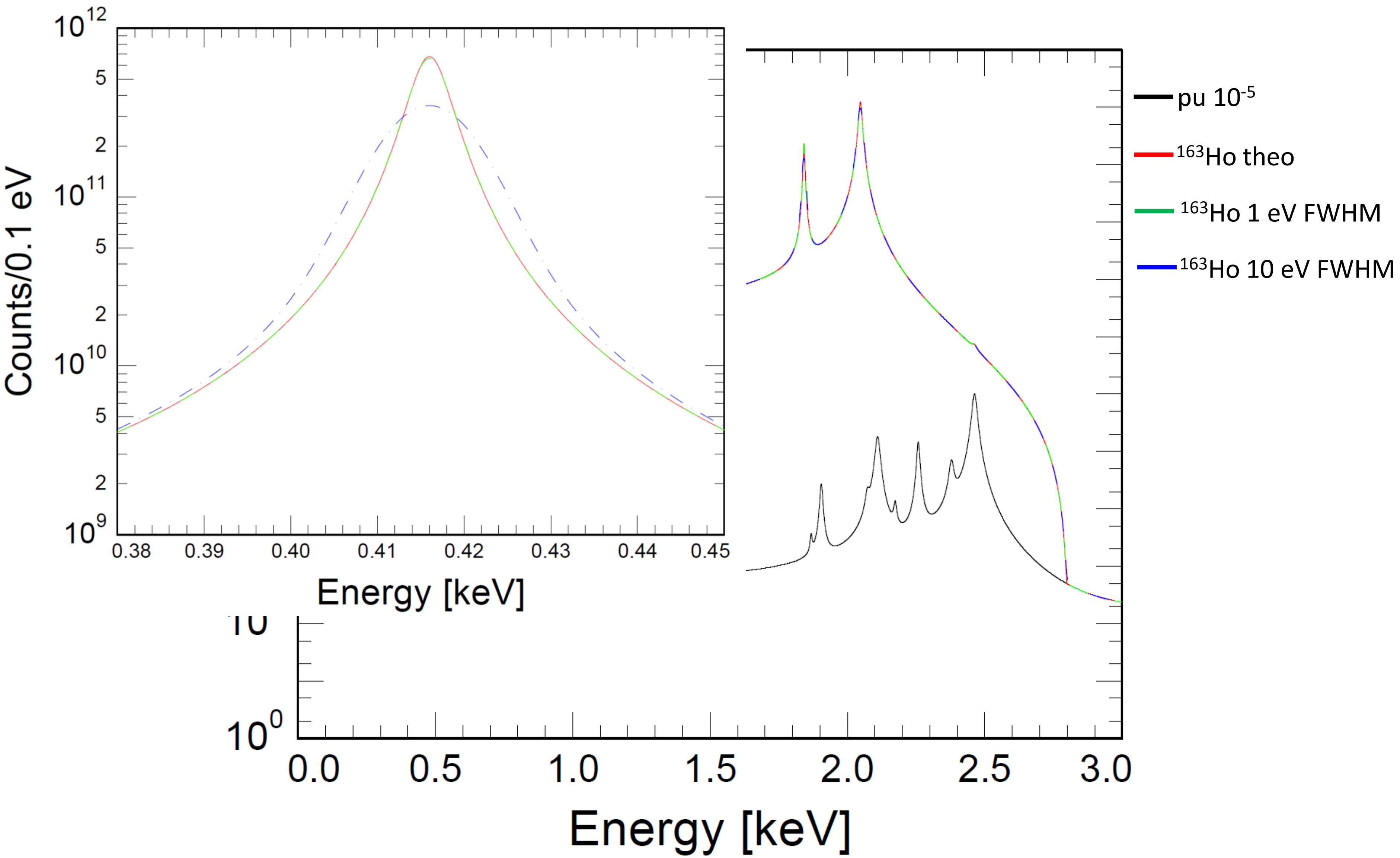
Non-Linearity < 1% @6keV



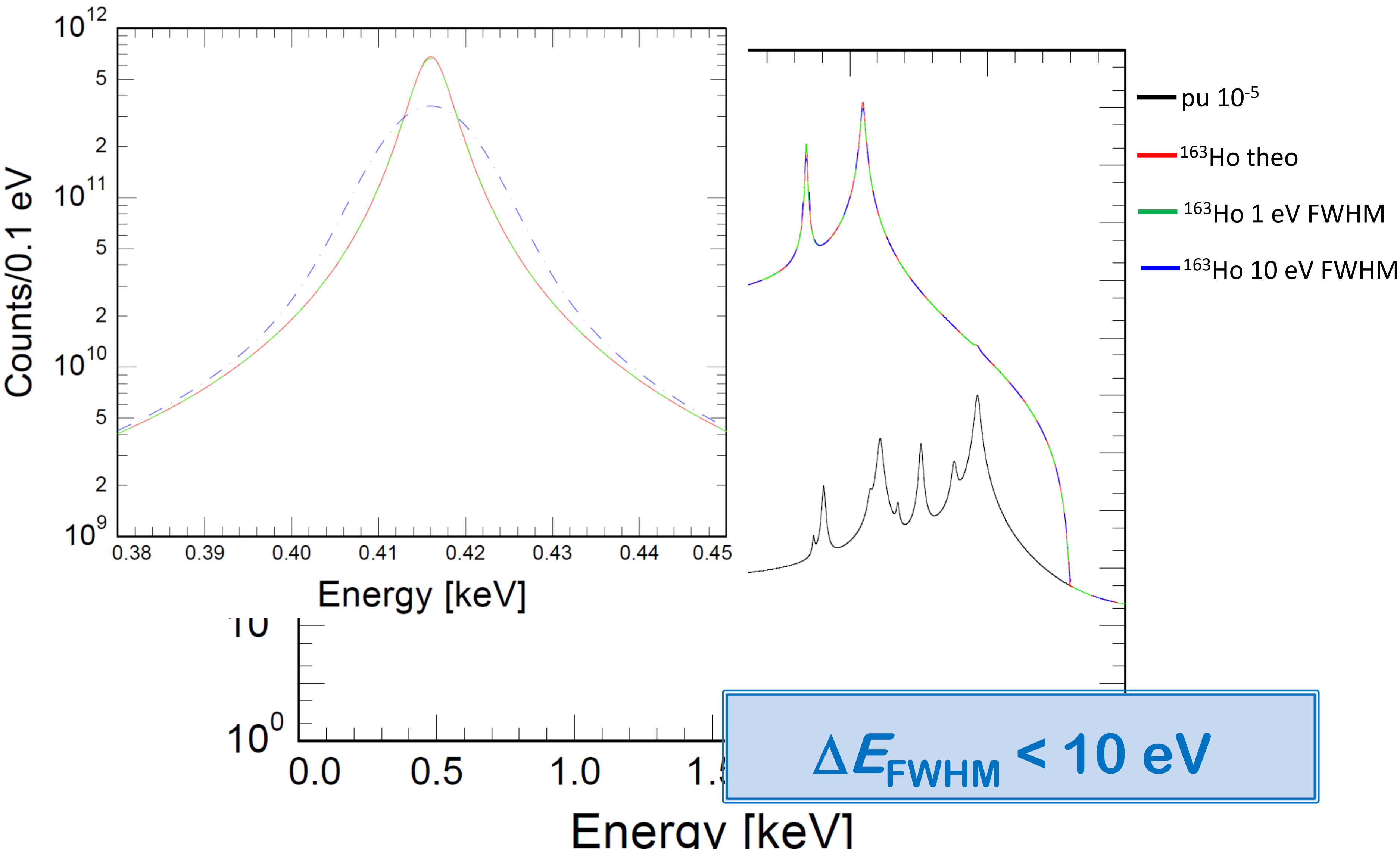
The case of ^{163}Ho: Energy resolution



The case of ^{163}Ho: Energy resolution

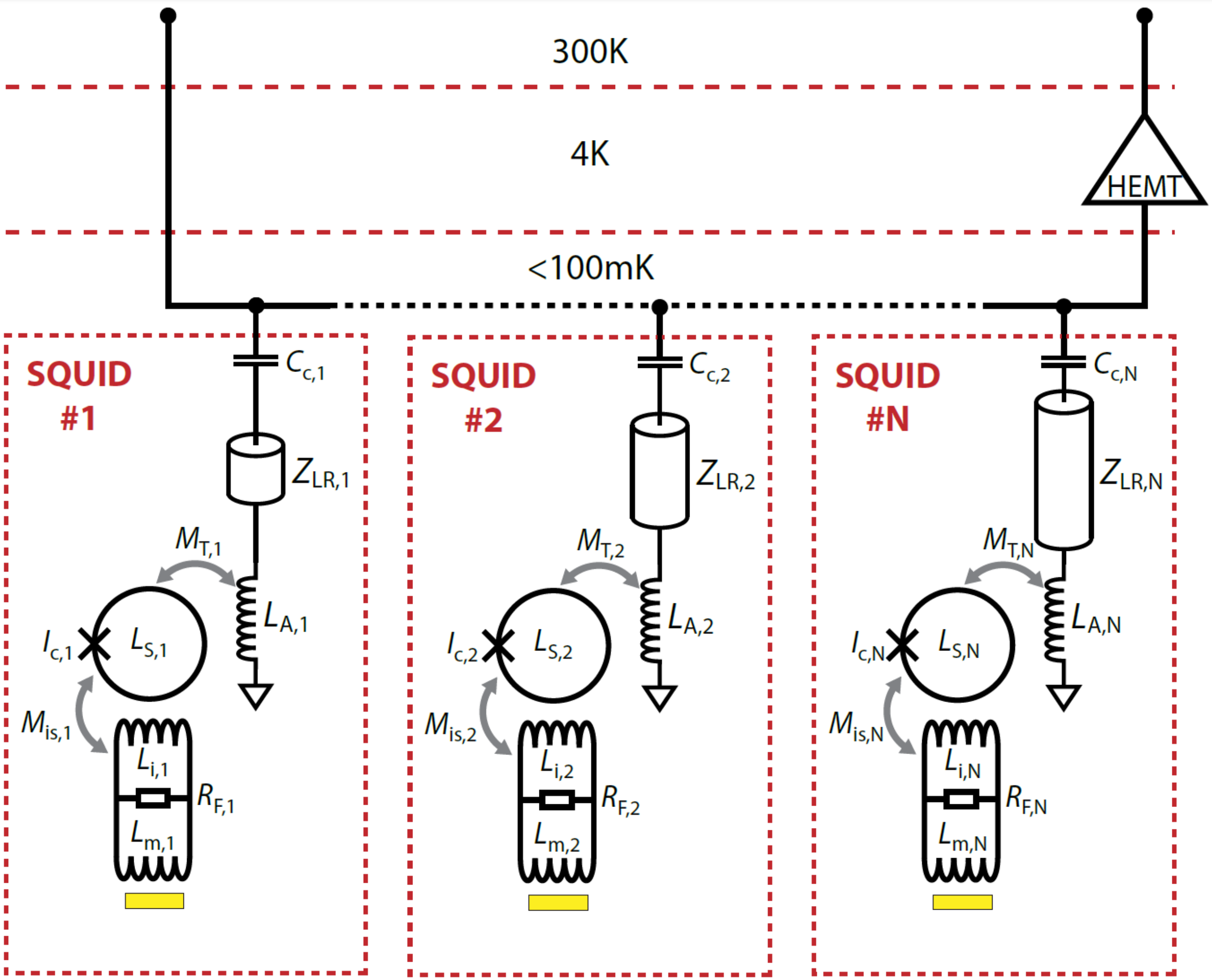


The case of ^{163}Ho: Energy resolution



$\Delta E_{FWHM} < 10$ eV

ECHo : µ-wave SQUID multiplexing



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

ECHo : Parameterization of the spectrum

How precise do we know the calorimetric spectrum of ^{163}Ho?

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{2}}{4}}$$

- Determination of the Q_{EC} at 1 eV uncertainty by means of Penning Trap mass spectroscopy
  - 2014: TRIGATRAP - SHIPTRAP → Q_{EC} determination within 30 - 100 eV
  - In few years: PENTATRAP (MPI-K HD) → Q_{EC} determination within 1 eV
- Density Functional Theory (DFT) and Quasiparticle Random Phase Approximation (QRPA)
- Solid state effects like core level binding energy shift: theoretical and experimental approaches