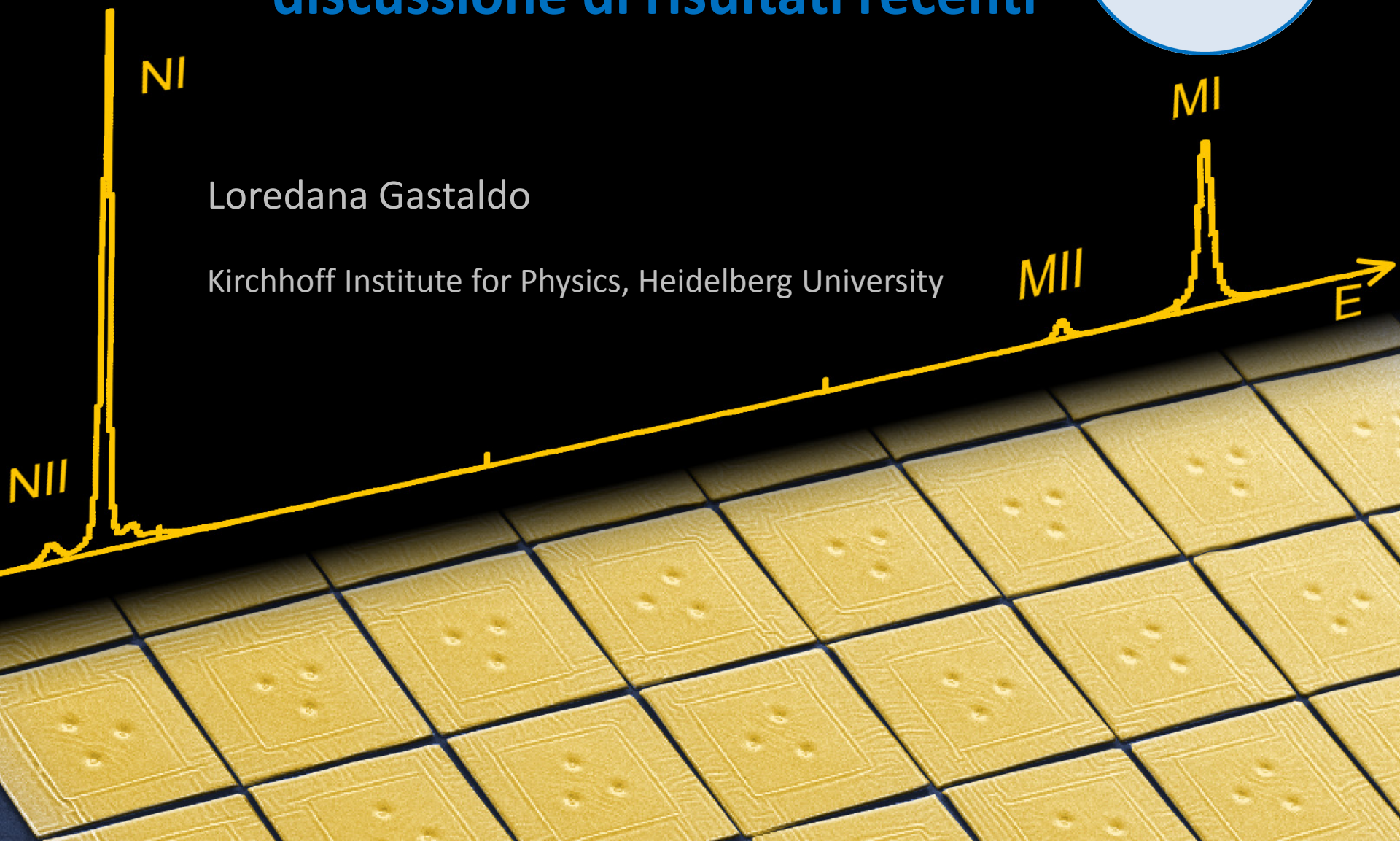


Electron Capture in ^{163}Ho experiment – ECHo



Loredana Gastaldo

Kirchhoff Institute for Physics, Heidelberg University

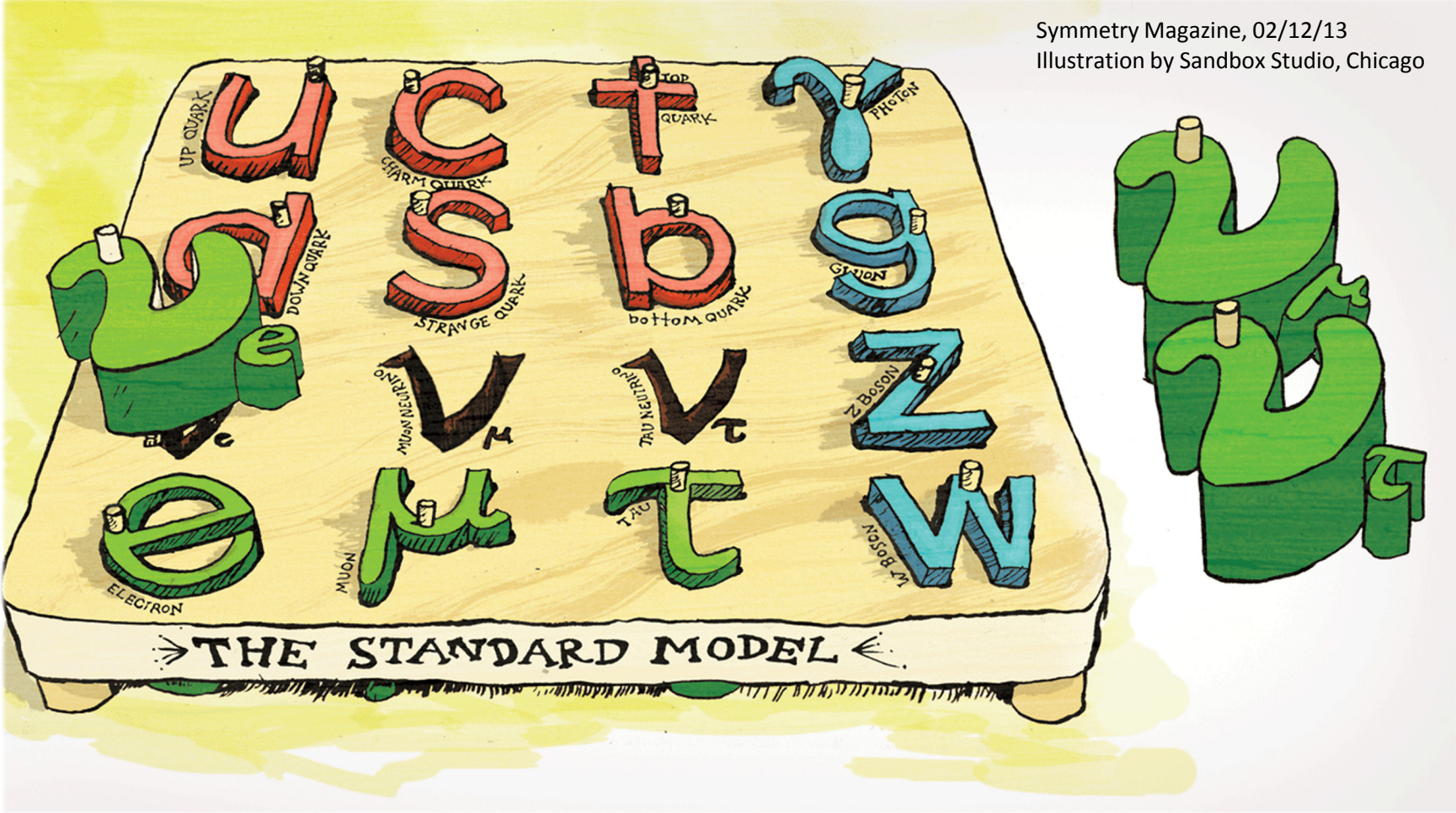


Sommario

- Introduzione: determinazione della massa dei neutrini
- Cattura elettronica in ^{163}Ho e la massa del neutrino elettronico
- Come identificare effetti dovuti a neutrini con masse sotto 1 eV
- L'esperimento ECHO
- Spettro di cattura elettronica del ^{163}Ho
- Conclusioni



Neutrini massivi

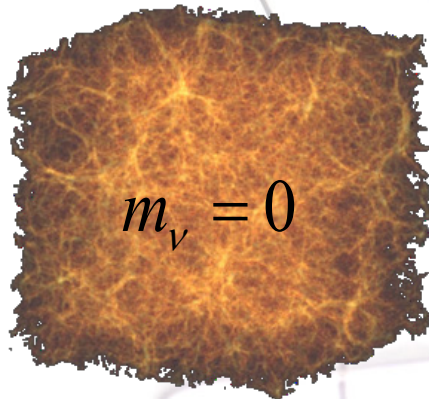


Conoscenza delle masse dei neutrini....

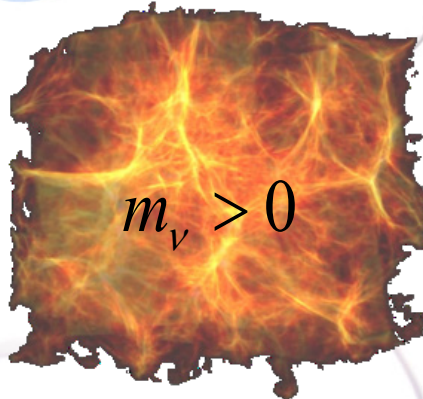


Astrofisica

Neutrini da Supernova



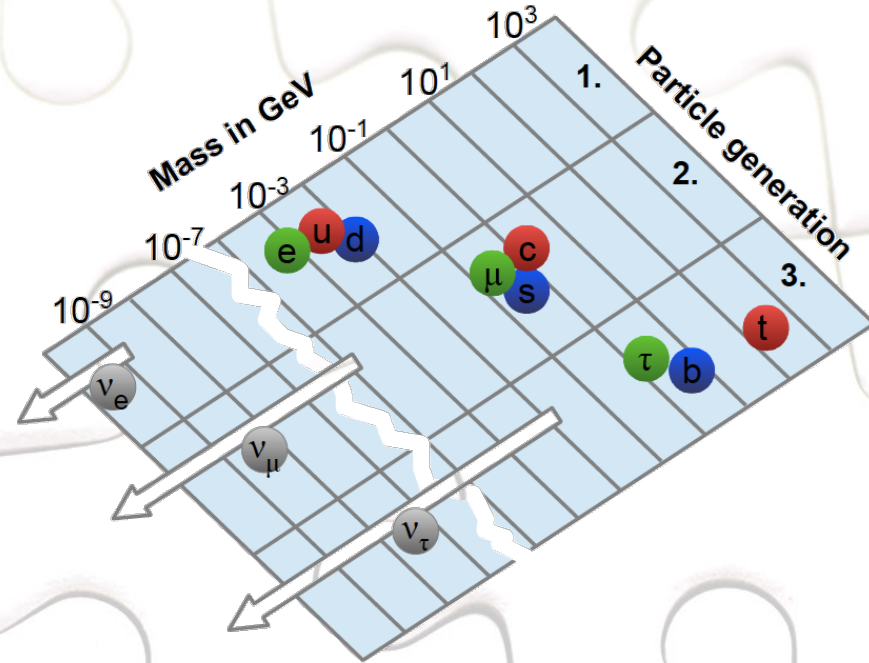
$$m_\nu = 0$$



$$m_\nu > 0$$

Fisica delle particelle

Generazione delle masse dei neutrini



Cosmologia

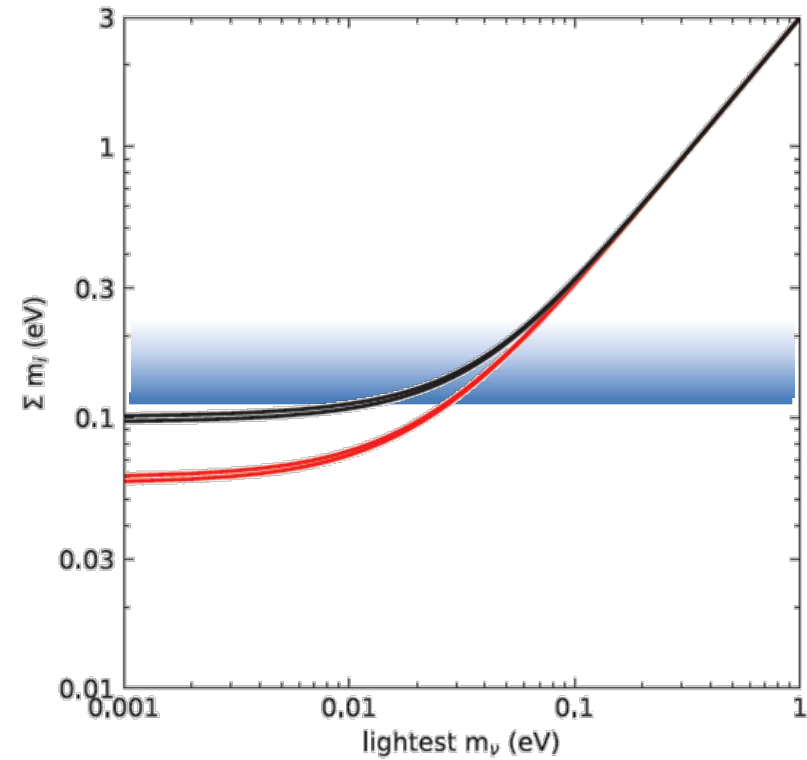
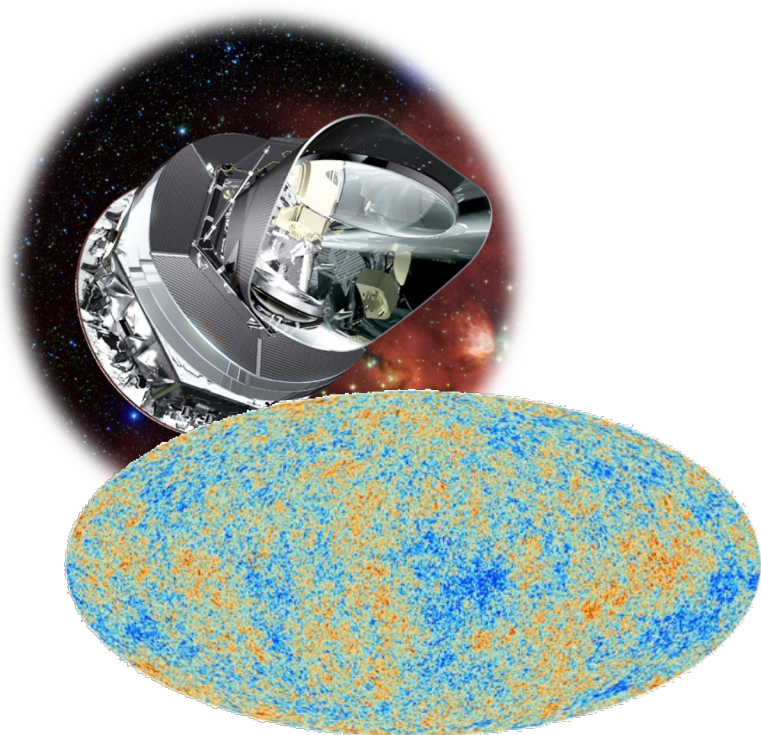
Distribuzione della materia nell'Universo

Determinazione della massa dei neutrini

Cosmologia

$$M_\nu = \sum m_i$$

- Dipendente da modelli
- Limite attuale 0.12 – 1 eV
- In futuro 15-50 meV



Determinazione della massa dei neutrini

Cosmologia

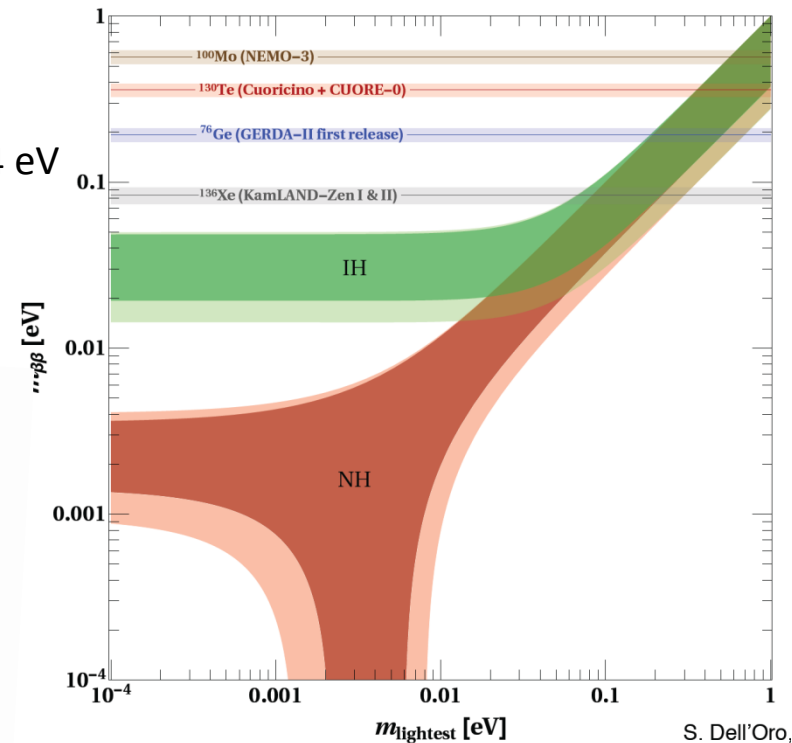
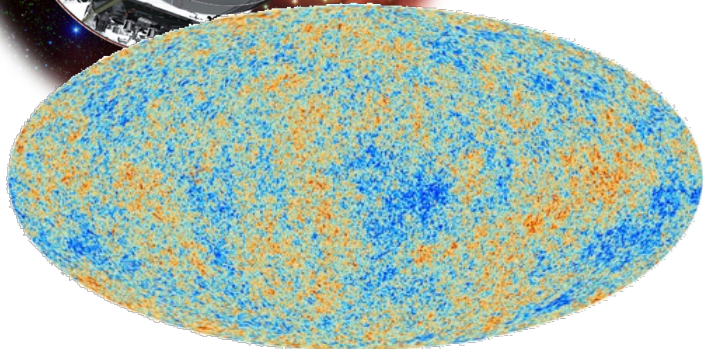
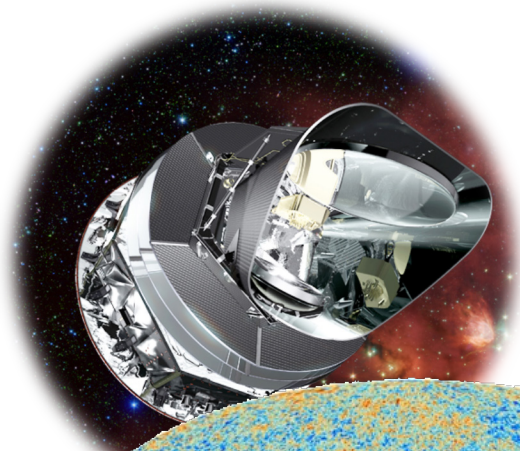
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- Dipendente da modelli
- Limite attuale 0.12 – 1 eV
- In futuro 15-50 meV

Doppio decadimento beta

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

- Dipendente da modelli
- Limite Attuale 0.1 – 0.4 eV
- In futuro 15-50 meV



Determinazione della massa dei neutrini

Cosmologia

$$M_\nu = \sum m_i$$

- Dipendente da modelli
- Limite attuale 0.12 – 1 eV
- In futuro 15-50 meV

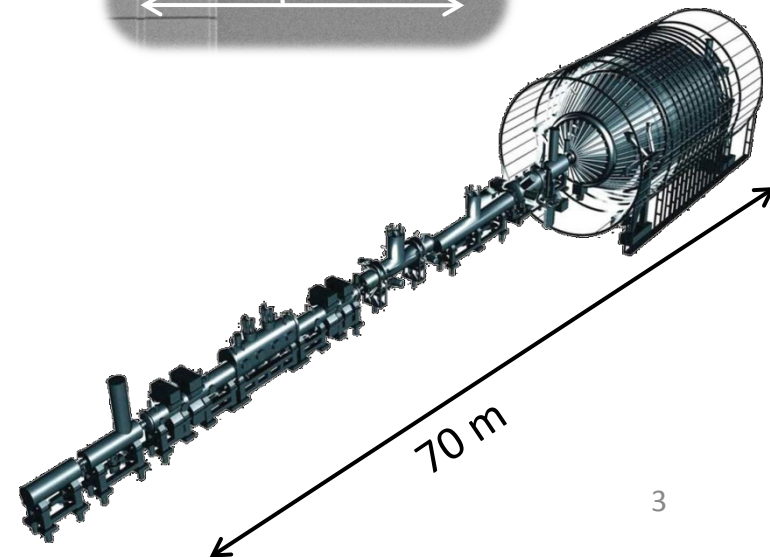
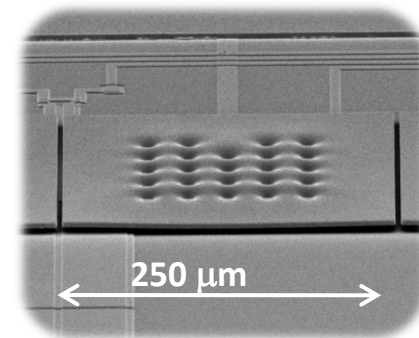
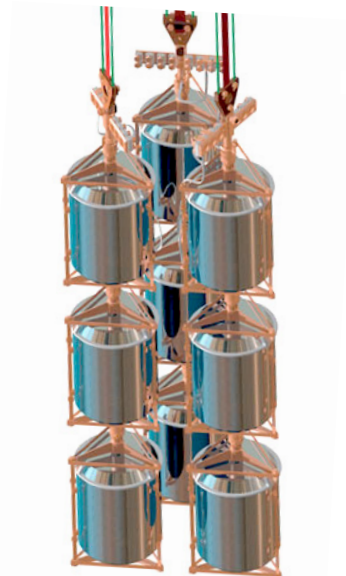
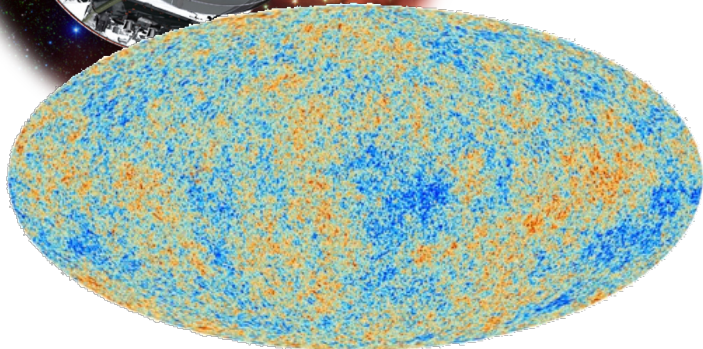
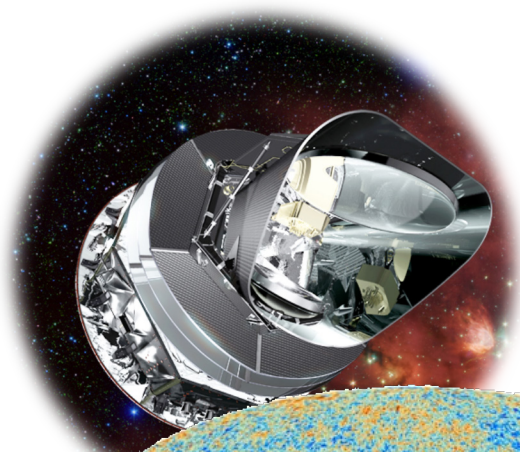
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- Dipendente da modelli
- Limite Attuale 0.1 – 0.4 eV
- In futuro 15-50 meV

Analisi cinematica: decadimento β e cattura elettronica

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

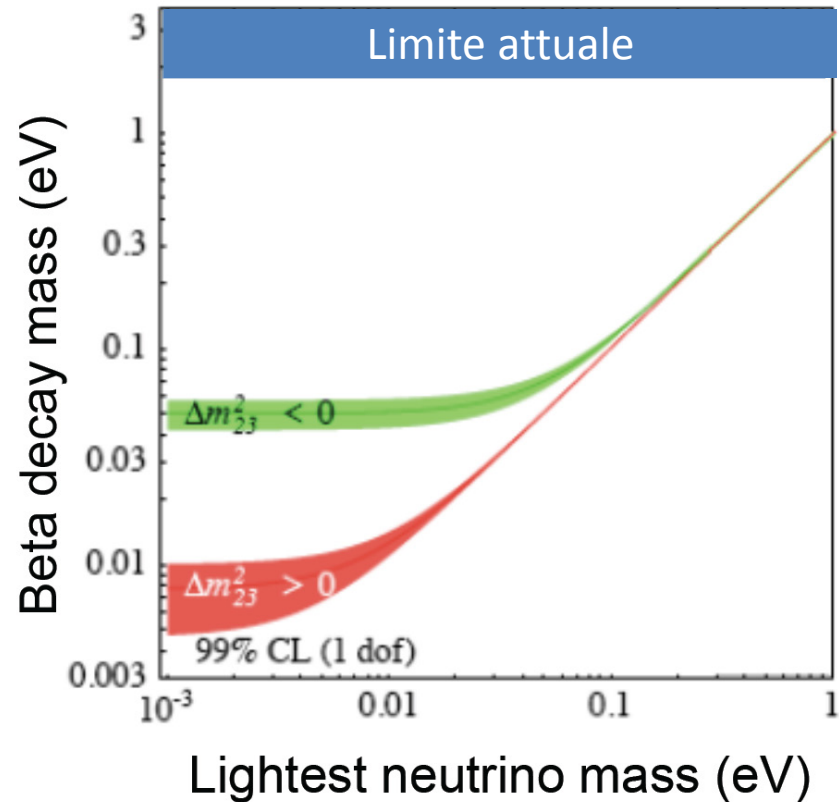


Misura diretta della massa del neutrino

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

- Indipendente da modelli
- Esperimenti da laboratorio

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



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

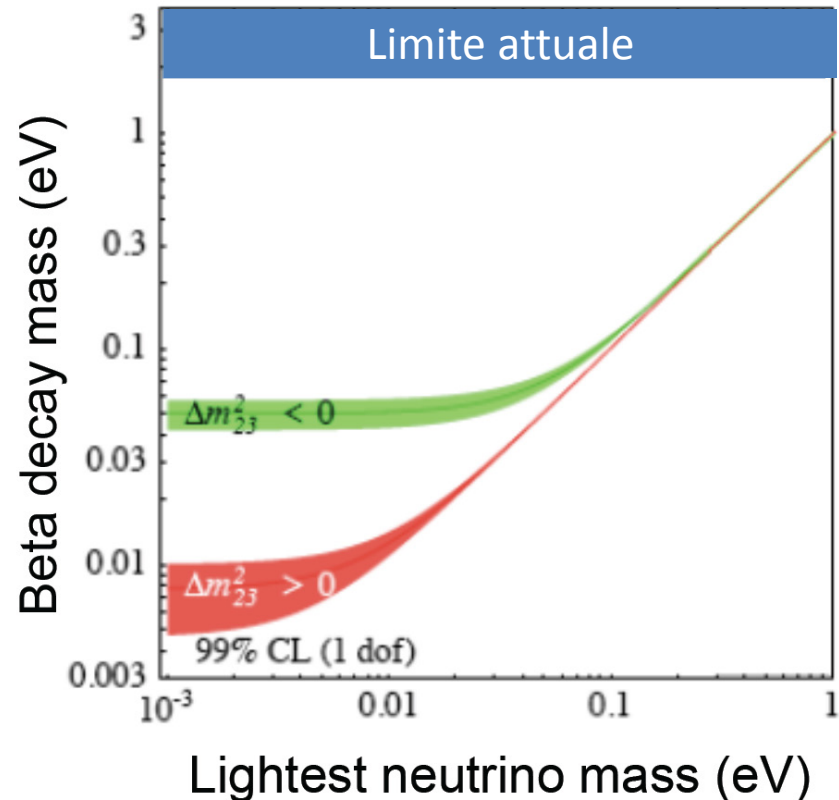
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$$m(\bar{\nu}_e) < 2 \text{ eV} \quad {}^3\text{H} \quad (1)$$

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



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

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

Misura diretta della massa del neutrino

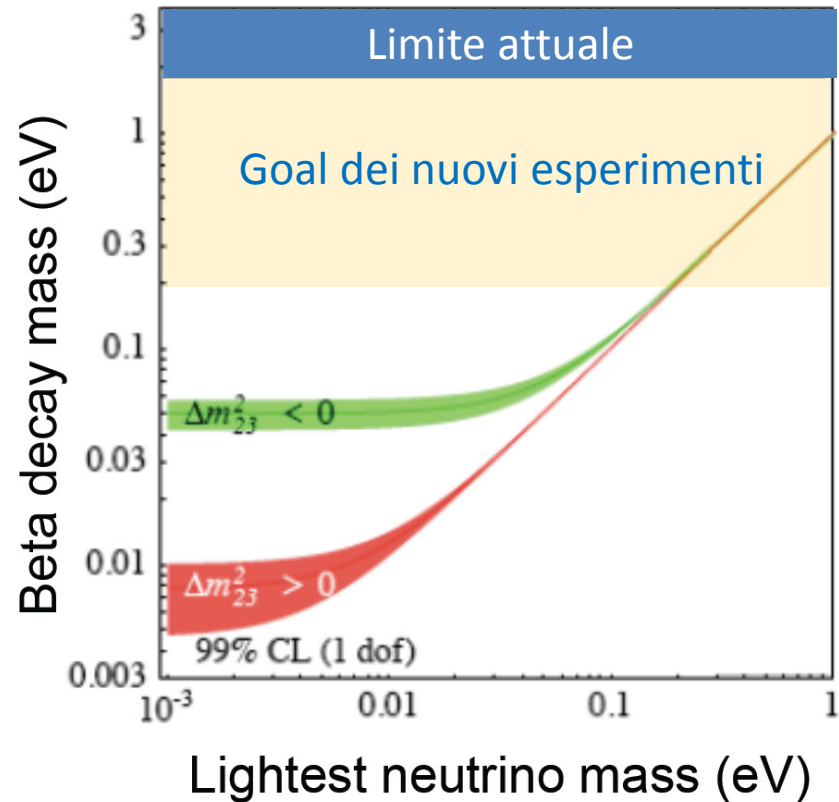
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- Indipendente da modelli
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$$m(\bar{\nu}_e) < 2 \text{ eV} \quad {}^3\text{H} \quad (1)$$

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

- Next future 200 meV

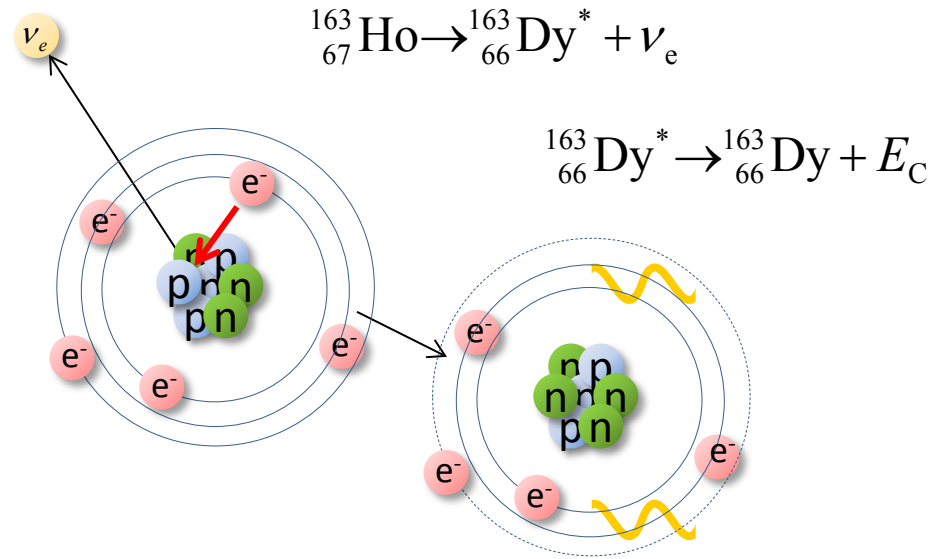
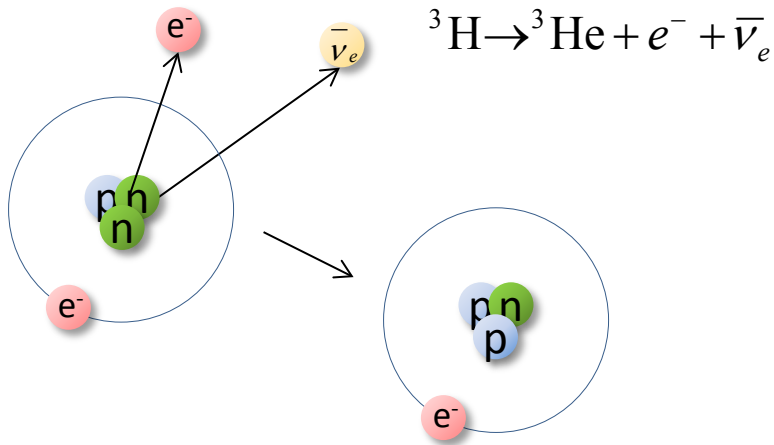


(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447

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Decadimento beta e cattura elettronica



- $\tau_{1/2} \cong 12.3 \text{ anni}$ ($4 \cdot 10^8$ atomi per 1 Bq)

- $Q_\beta = 18\,592.01(7) \text{ eV}$

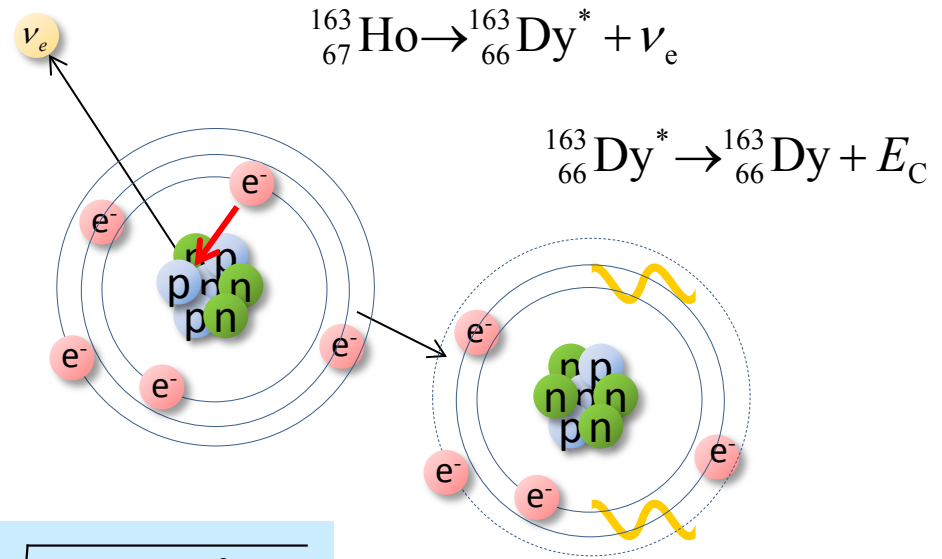
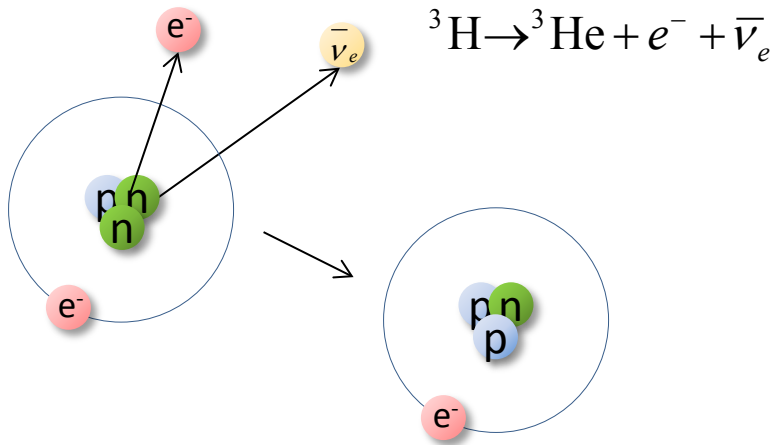
E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

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

Decadimento beta e cattura elettronica



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

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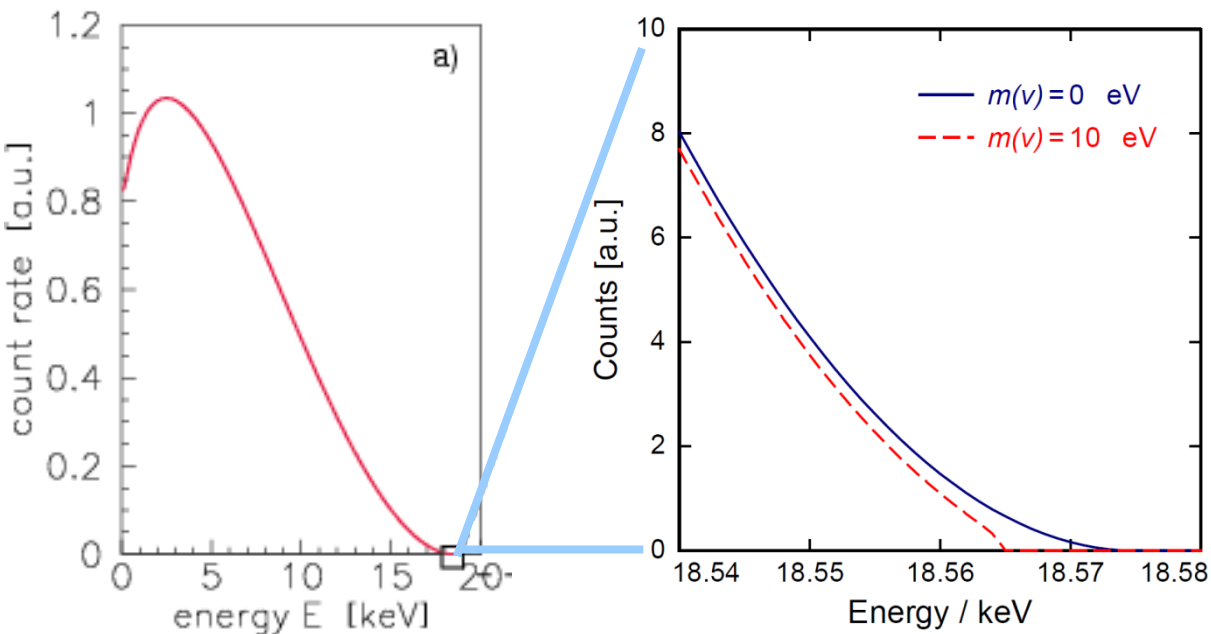
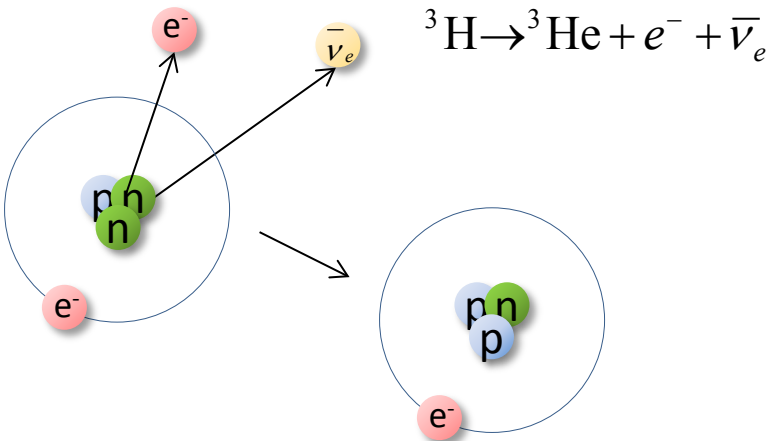
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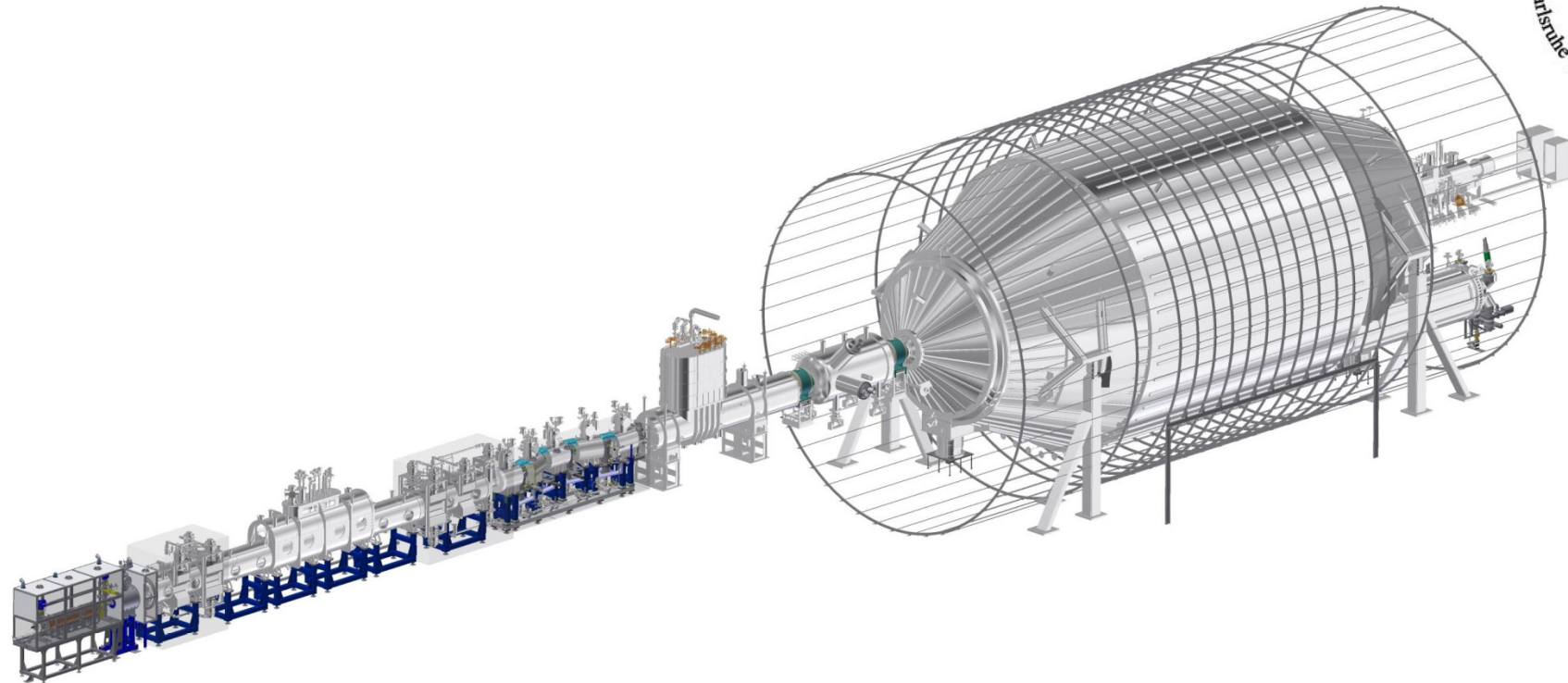
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Decadimento beta del ^3H



L'esperimento KATRIN

❖ KATRIN - Karlsruhe Tritium Neutrino Experiment



Idee principali:

- sorgente di alta attività 10^{11} e⁻/s
- MAC-E* filtro ad alta risoluzione per selezionare elettroni
- conteggio di elettroni in funzione del potenziale ritardante
→ spettro integrale

*MAC-E: Magnetic Adiabatic Collimation with Electrostatic Filter

L'esperimento KATRIN: stato attuale



Large Helmholtz coil system

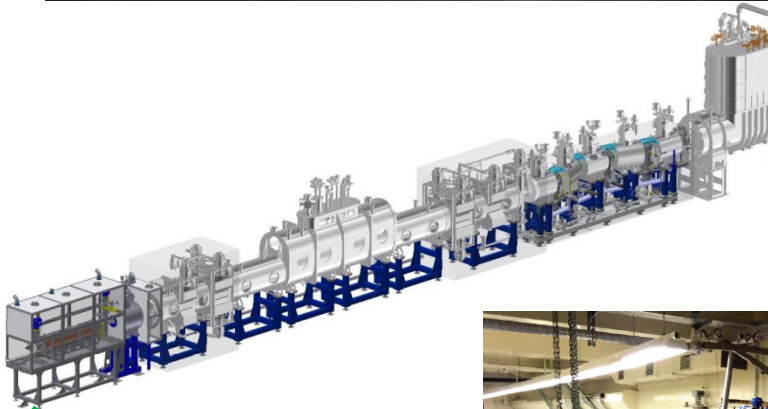
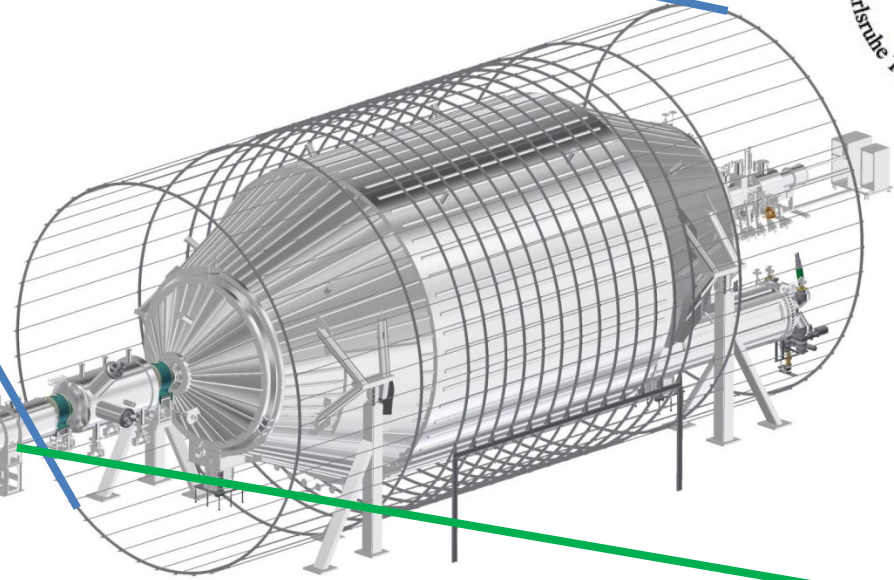


Photo K. Valerius

L'esperimento KATRIN: stato attuale



First light 14 Ottobre 2016

Photo Patrick Langer

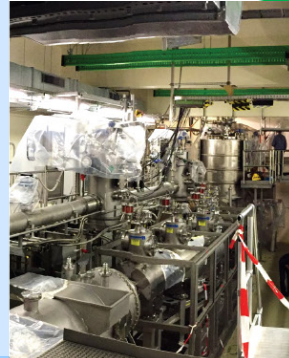


Photo K. Valerius

^3H based experiments

❖ KATRIN - Karlsruhe Tritium Neutrino Experiment

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- sorgente di alta attività 10^{11} e⁻/s
 - filtro MAC-E ad alta risoluzione per selezionare elettroni
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❖ Project8

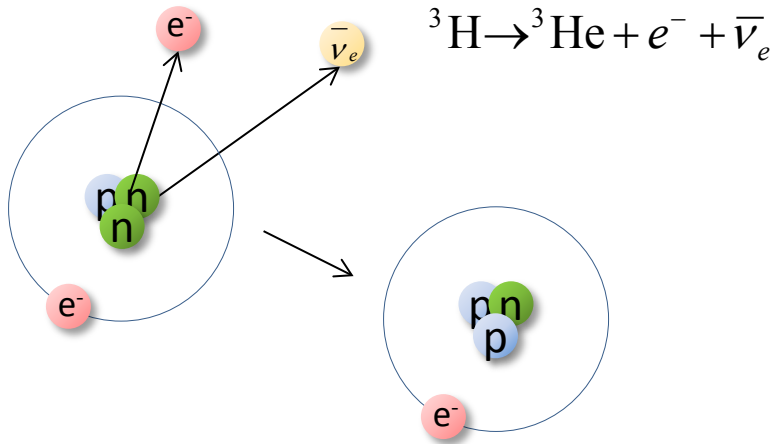
- Idee principali:
- Sorgente = rivelatore $10^{11} - 10^{13}$ $^3\text{H}_2$ molecole /cm³
 - Uso della frequenza di ciclotrone per determinare l'energia degli elettroni
→ spettro differenziale

❖ PTOLEMY - Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

- Idee principali:
- sorgente di ^3H con grossa superficie: 100 g ^3H atomico
 - filtro MAC-E per selezionare elettroni
 - Tracciamento RF e sistema per determinare tempo di volo
 - Calorimetria criogenica → spettro differenziale



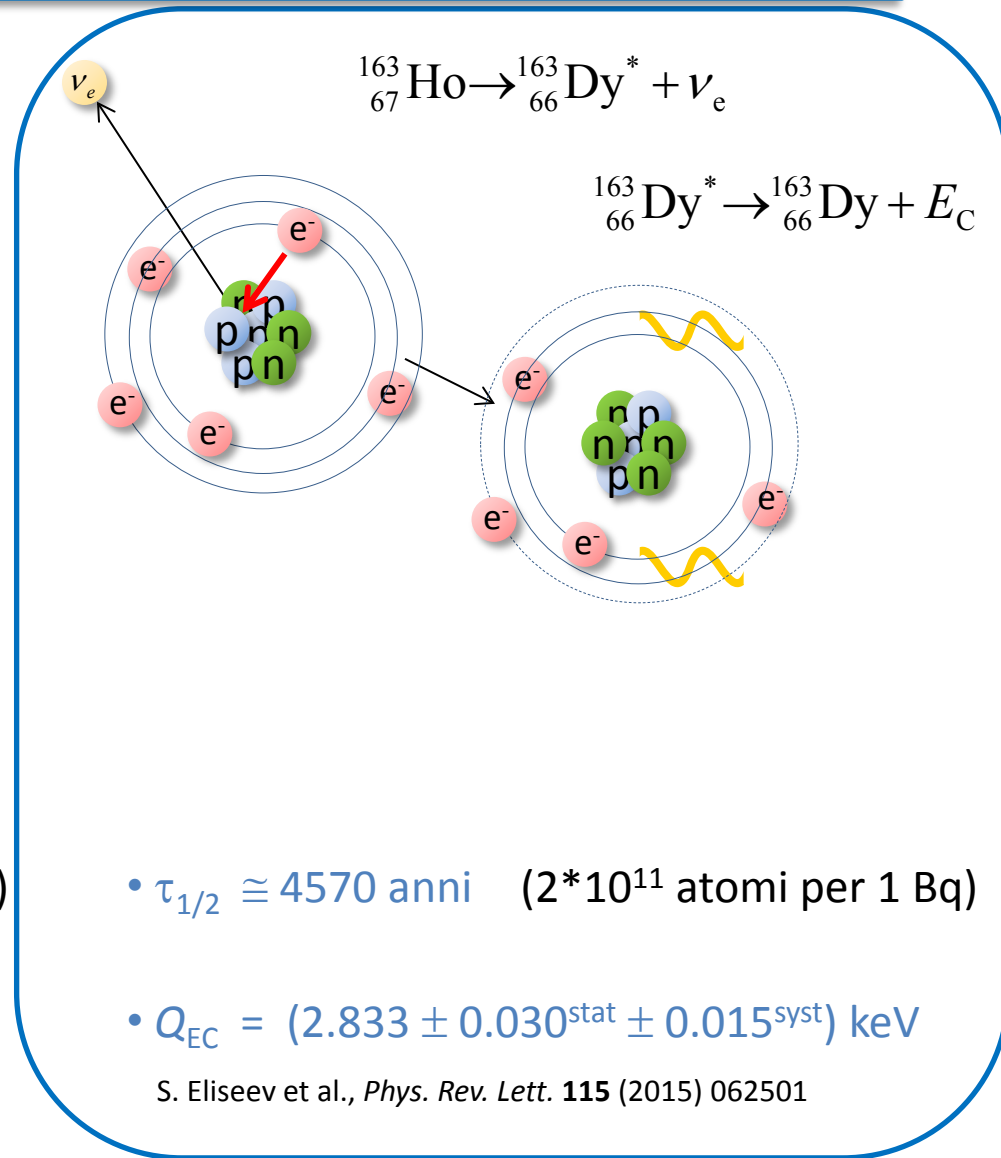
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E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003



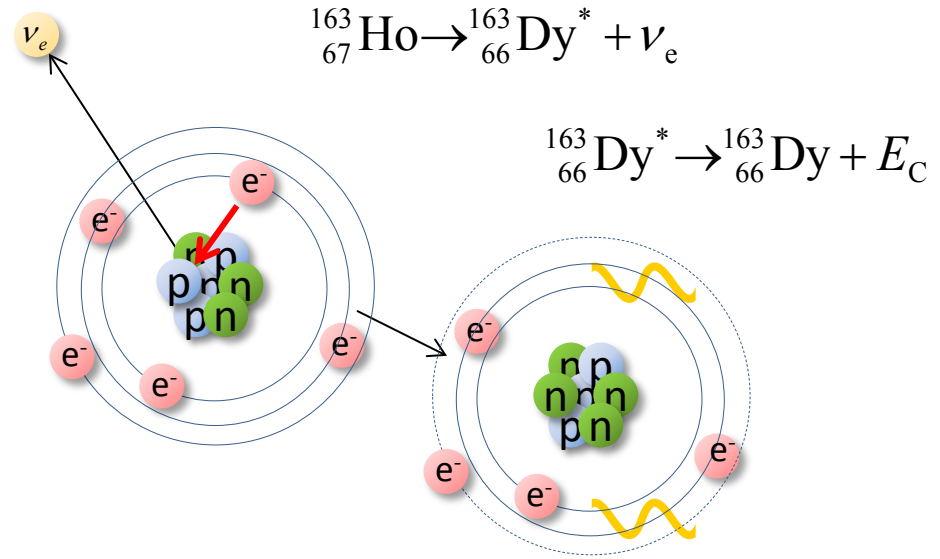
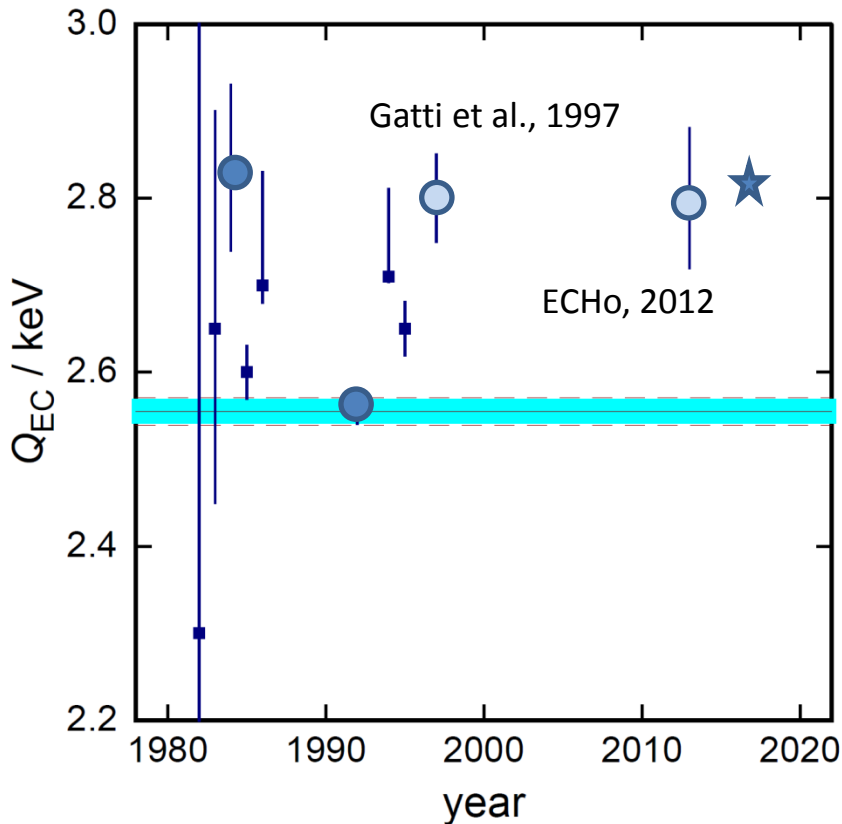
- $\tau_{1/2} \cong 4570$ anni ($2 \cdot 10^{11}$ atomi per 1 Bq)

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

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

Cattura elettronica in ^{163}Ho : valore di Q_{EC}

- Misure calorimetriche
- Misure di raggi X
- ★ $Q_{\text{EC}} = m(^{163}\text{Ho}) - m(^{163}\text{Dy})$



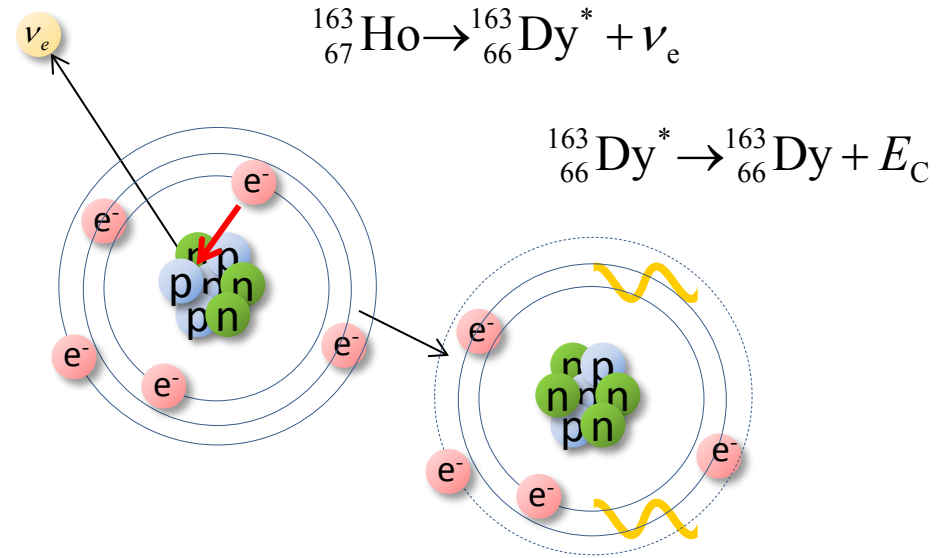
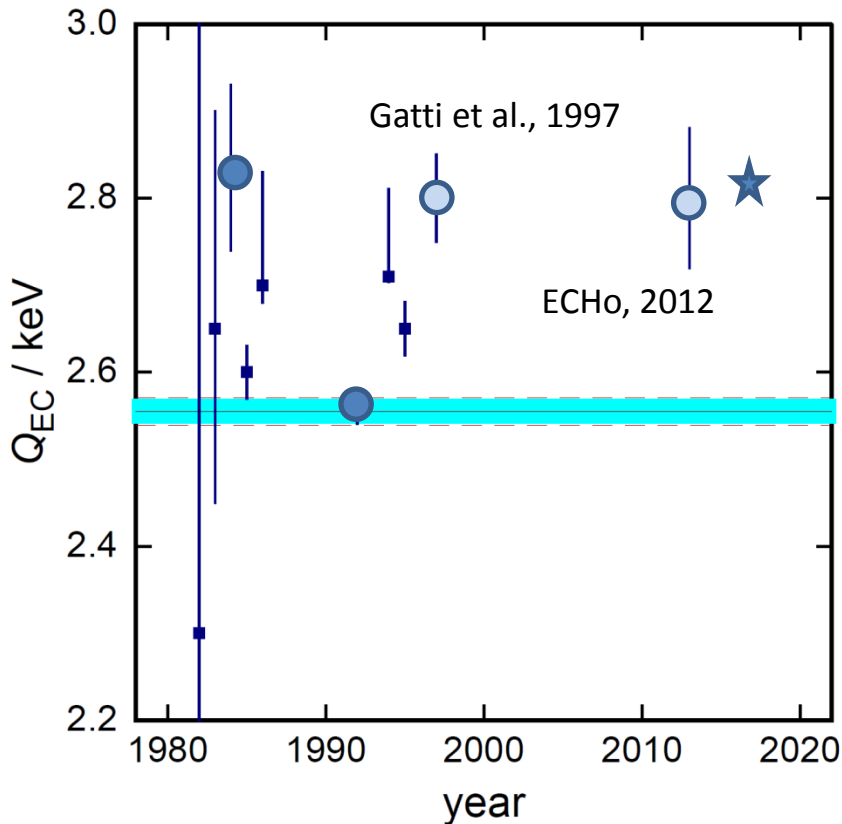
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S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

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Precisione a 1 eV
 PENTATRAP

• $\tau_{1/2} \cong 4570$ anni ($2 \cdot 10^{11}$ atomi per 1 Bq)

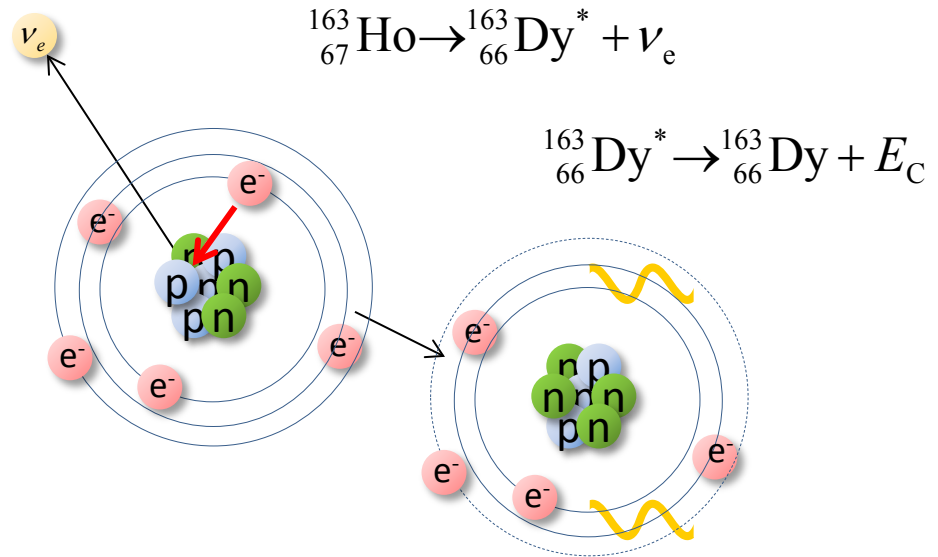
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S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Cattura elettronica in ^{163}Ho : osservabili

De-eccitazioni atomiche:

- emissione di raggi X
- elettroni Auger
- Transizioni di Coster-Kronig



• $\tau_{1/2} \cong 4570$ anni ($2 \cdot 10^{11}$ atomi per 1 Bq)

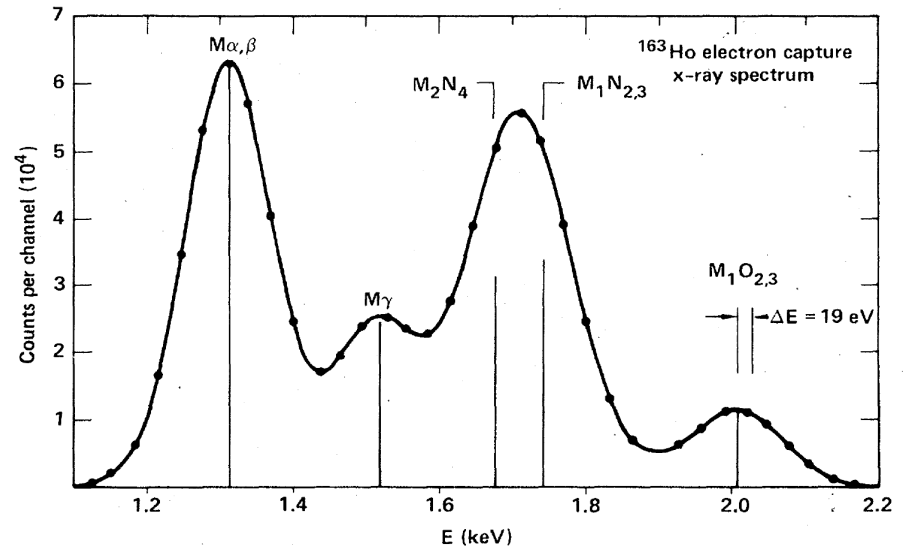
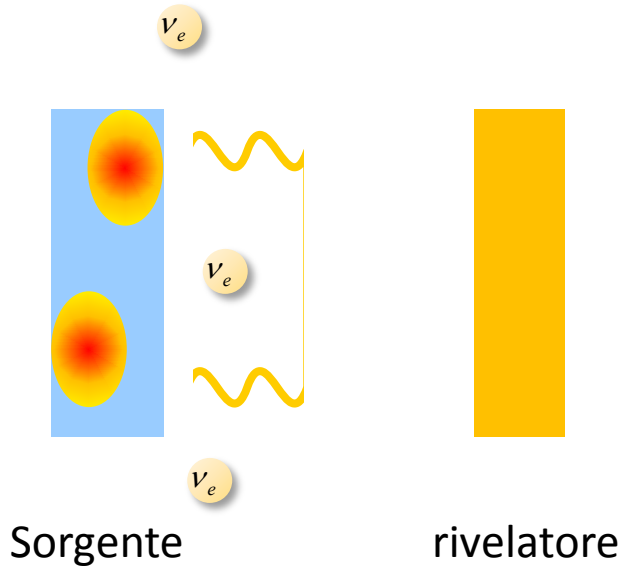
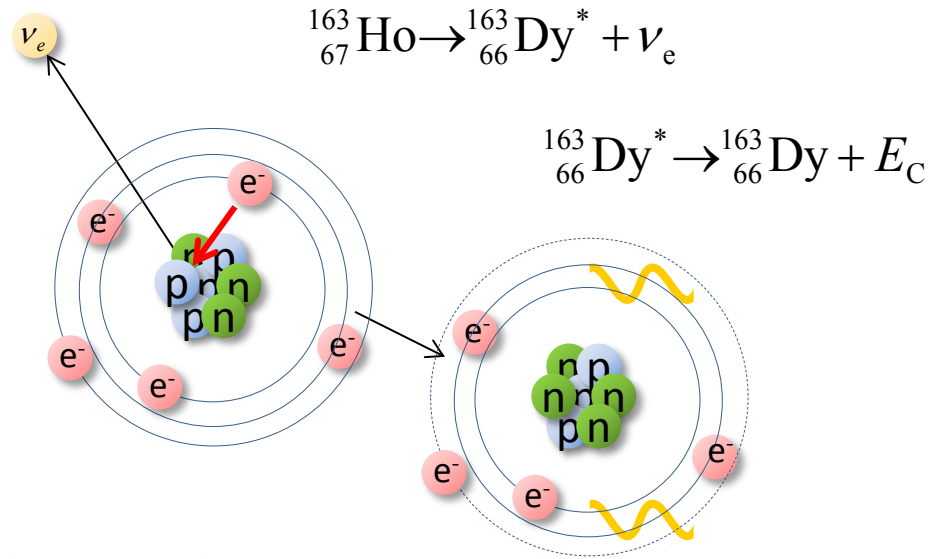
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S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Cattura elettronica in ^{163}Ho : osservabili

De-eccitazioni atomiche:

- **emissione di raggi X**
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- Transizioni di Coster-Kronig

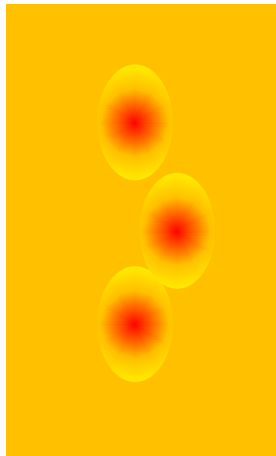


Cattura elettronica in ^{163}Ho : osservabili

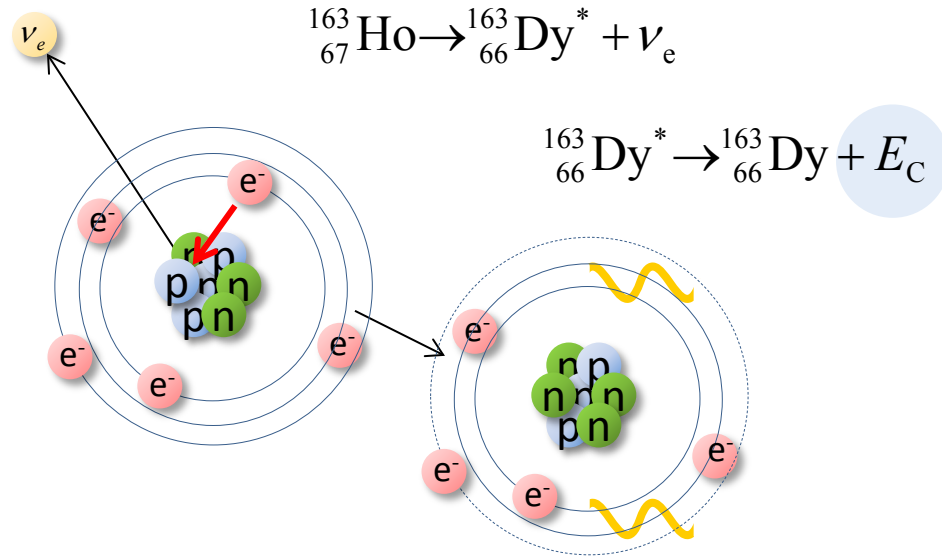
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- Transizioni di Coster-Kronig

Misure calorimetriche



Sorgente = Rivelatore



ν_e

ν_e

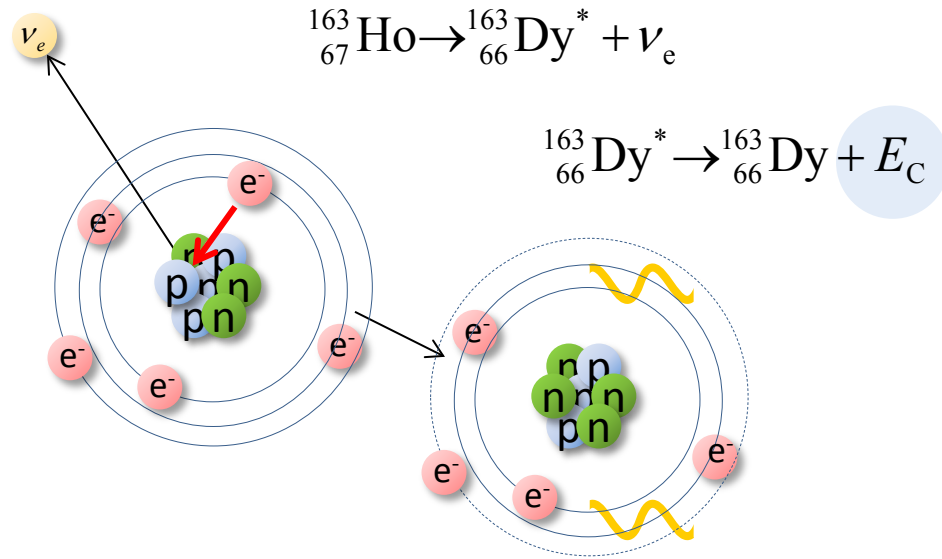
ν_e

Cattura elettronica in ^{163}Ho : osservabili

De-eccitazioni atomiche:

- emissione di raggi X
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Misure calorimetriche



Volume 118B, number 4, 5, 6

PHYSICS LETTERS

9 December 1982

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

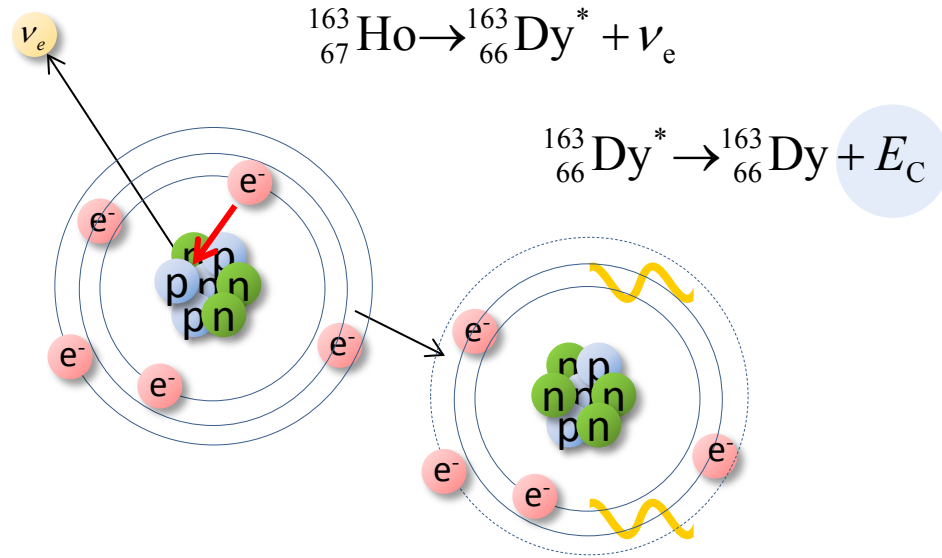
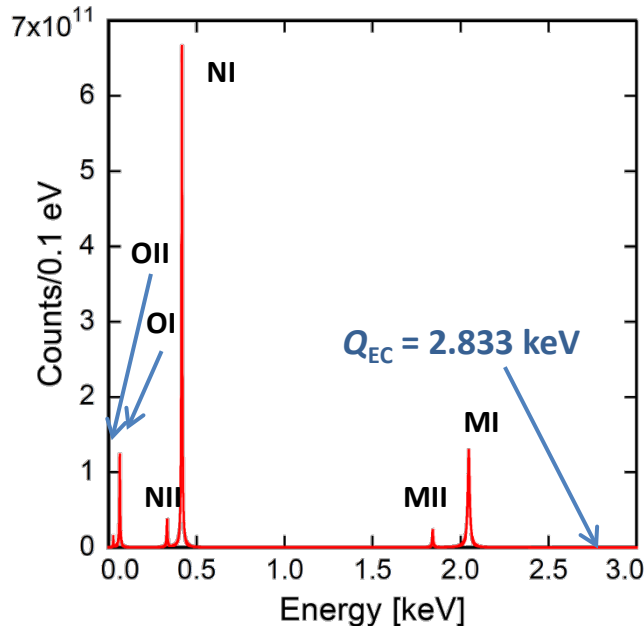
A. DE RÚJULA and M. LUSIGNOLI ¹
CERN, Geneva, Switzerland

Cattura elettronica in ^{163}Ho : spettro

De-eccitazioni atomiche:

- emissione di raggi X
- elettroni Auger
- Transizioni di Coster-Kronig

Misure calorimetriche

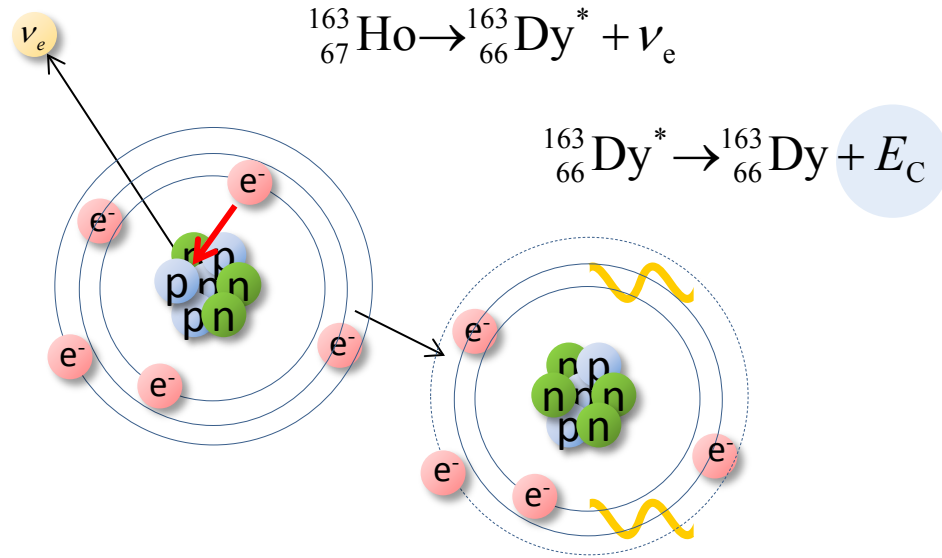


$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \phi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

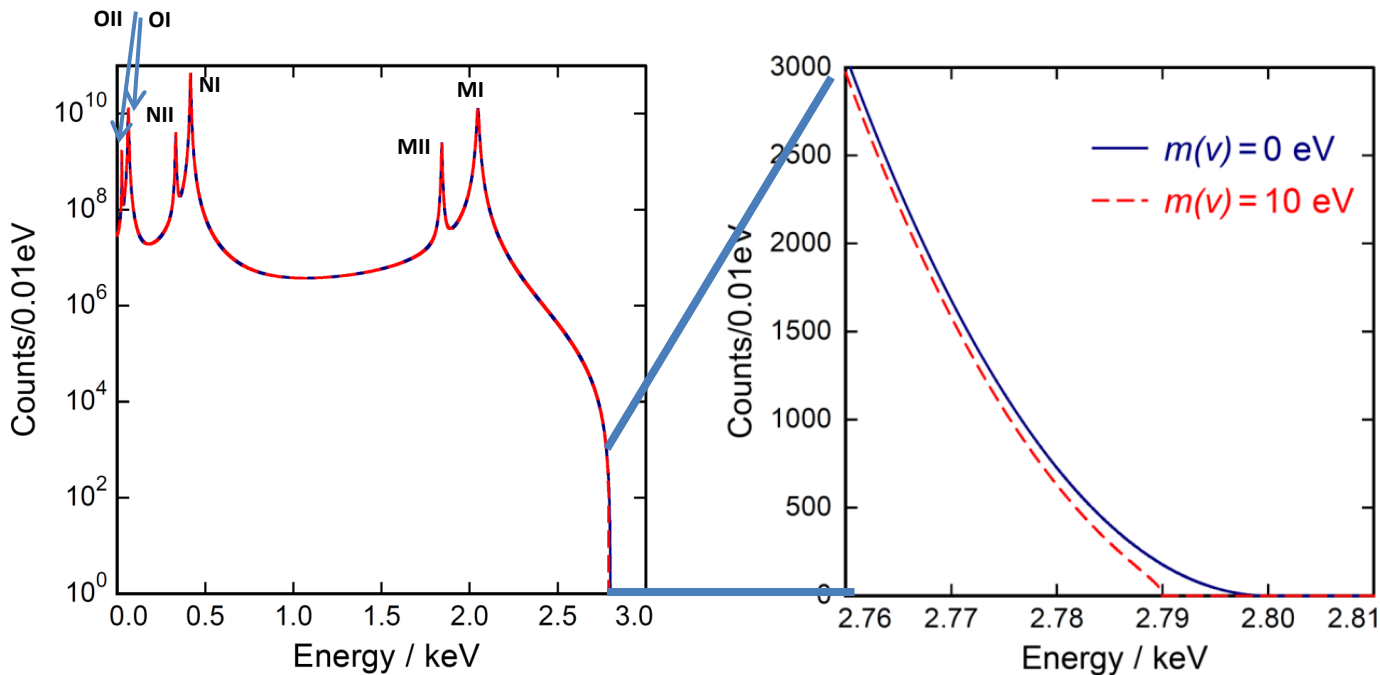
Cattura elettronica in ^{163}Ho : spettro

De-eccitazioni atomiche:

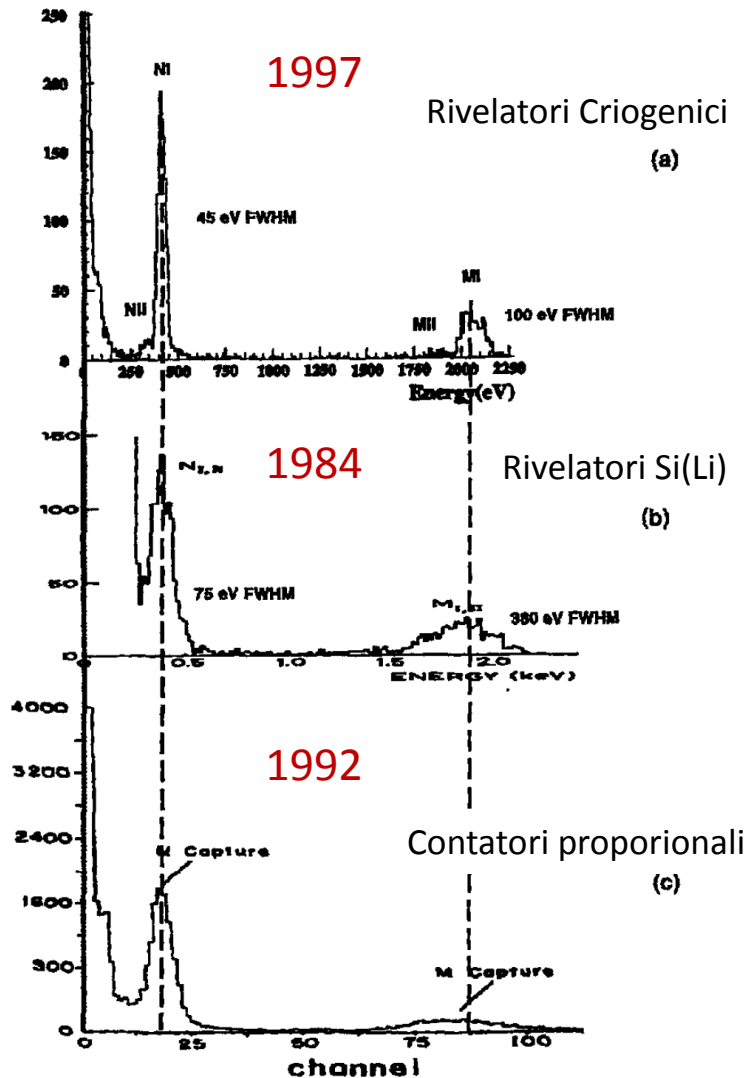
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Misure calorimetriche



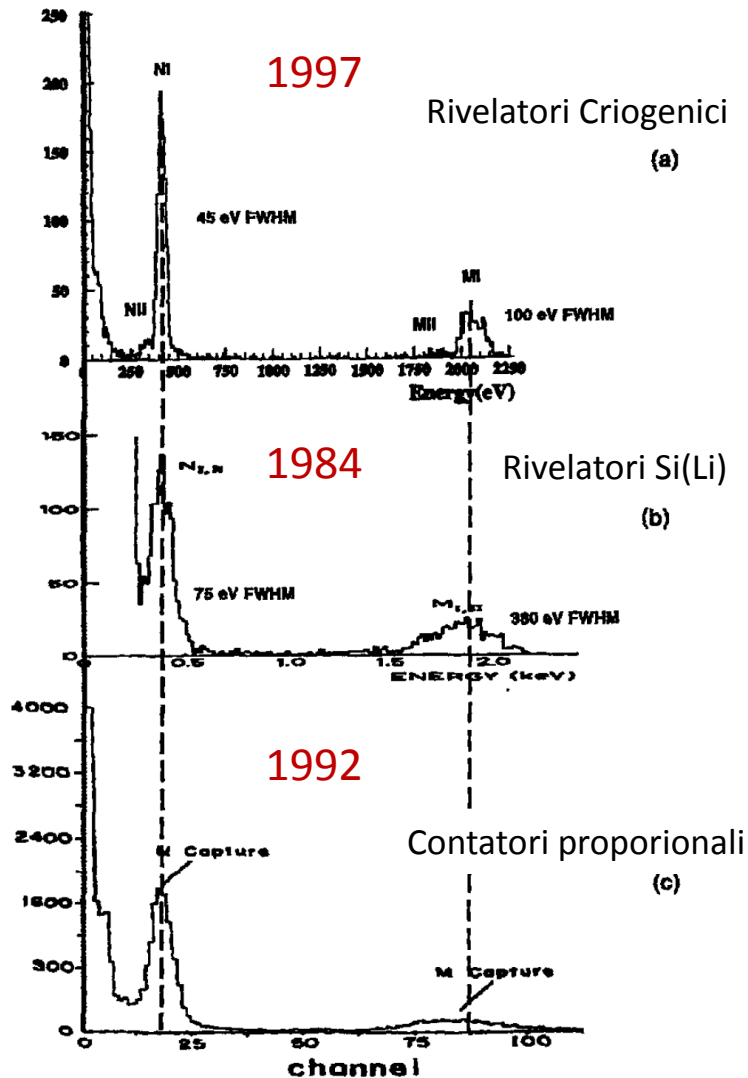
Cattura elettronica in ^{163}Ho : storia



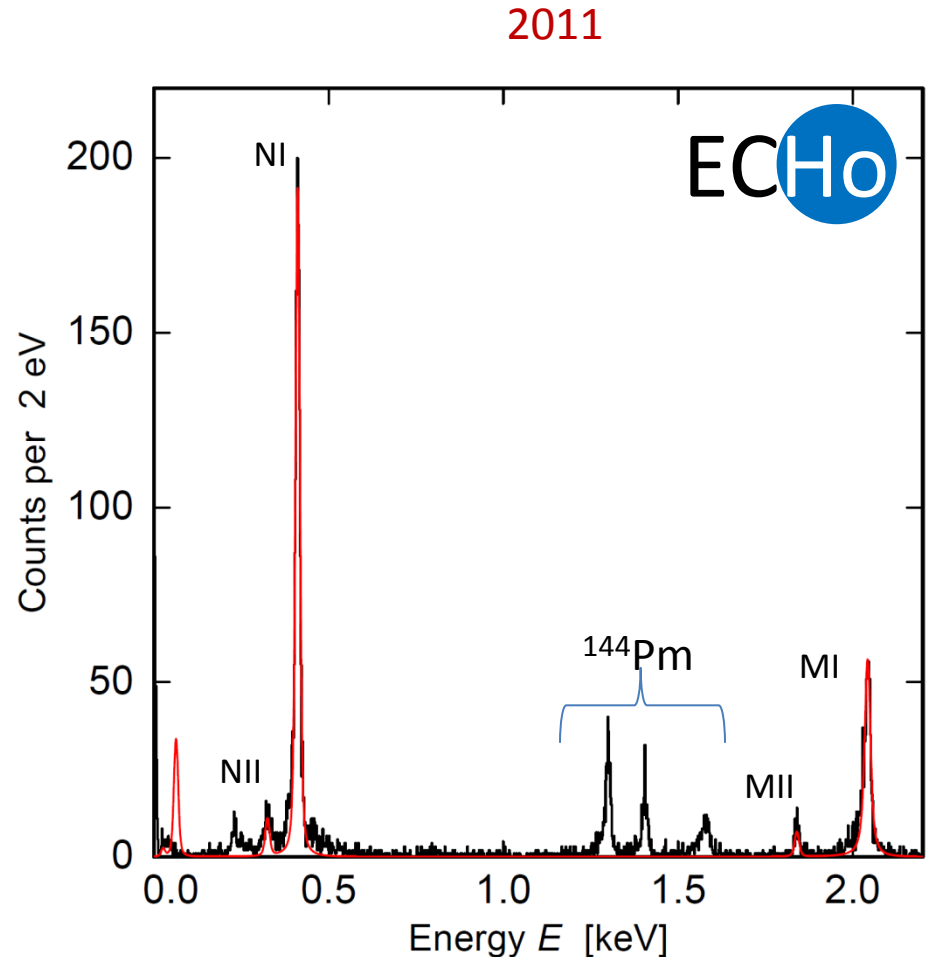
F. Gatti et al., Physics Letters B 398 (1997) 415-419

- (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.

Cattura elettronica in ^{163}Ho : storia



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



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Cattura elettronica in ^{163}Ho : presente

- Tre collaborazioni internazionali
- Misura calorimetrica dello spettro del ^{163}Ho

ECHo (1)

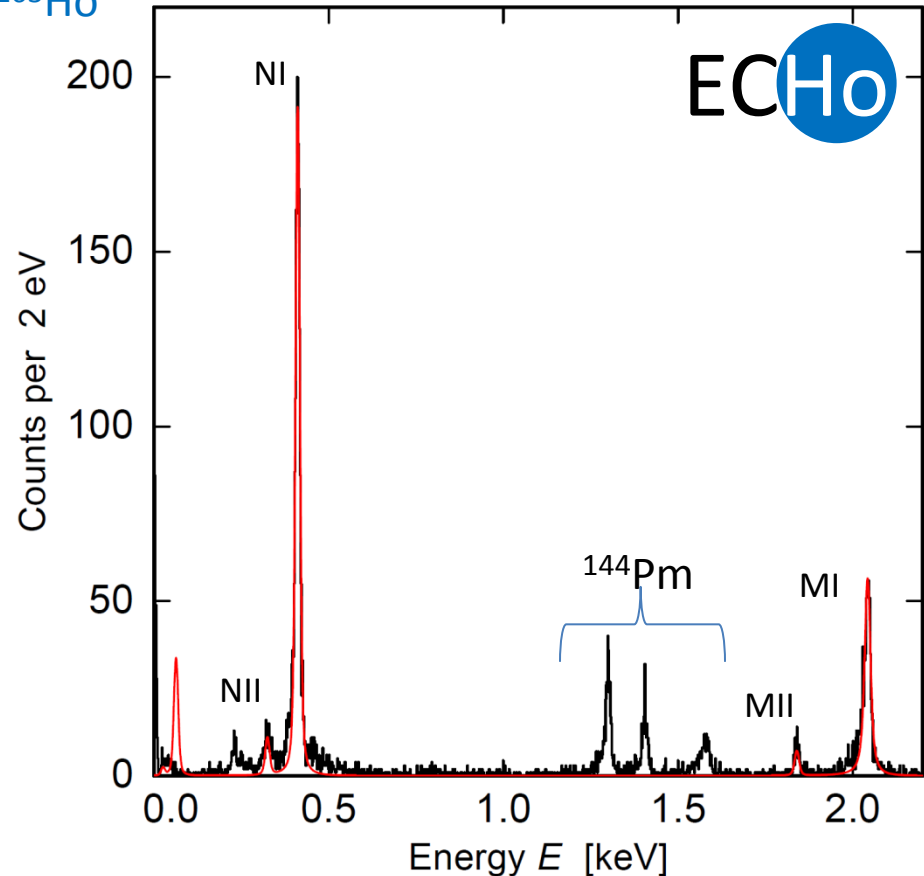
HOLMES (2)

NuMECS (3)

Comune approccio per la strutturazione dell'esperimento :

- Performance dei rivelatori
- Sorgente di ^{163}Ho di grande purezza
- Riduzione del background
- Descrizione dello spettro di cattura elettronica del ^{163}Ho

2011



(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

Requisiti sperimentali in ECHO

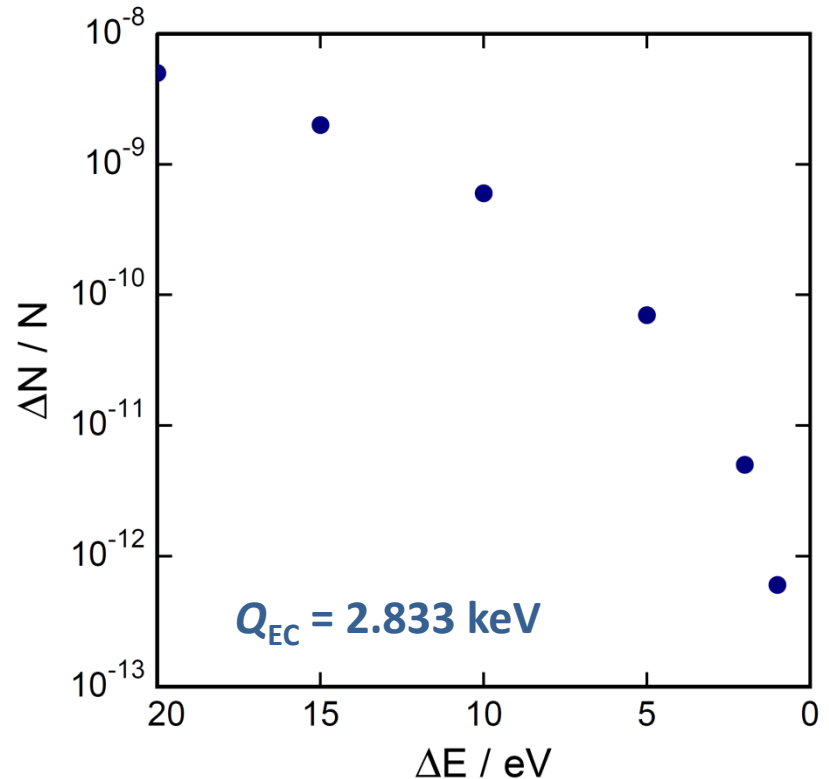
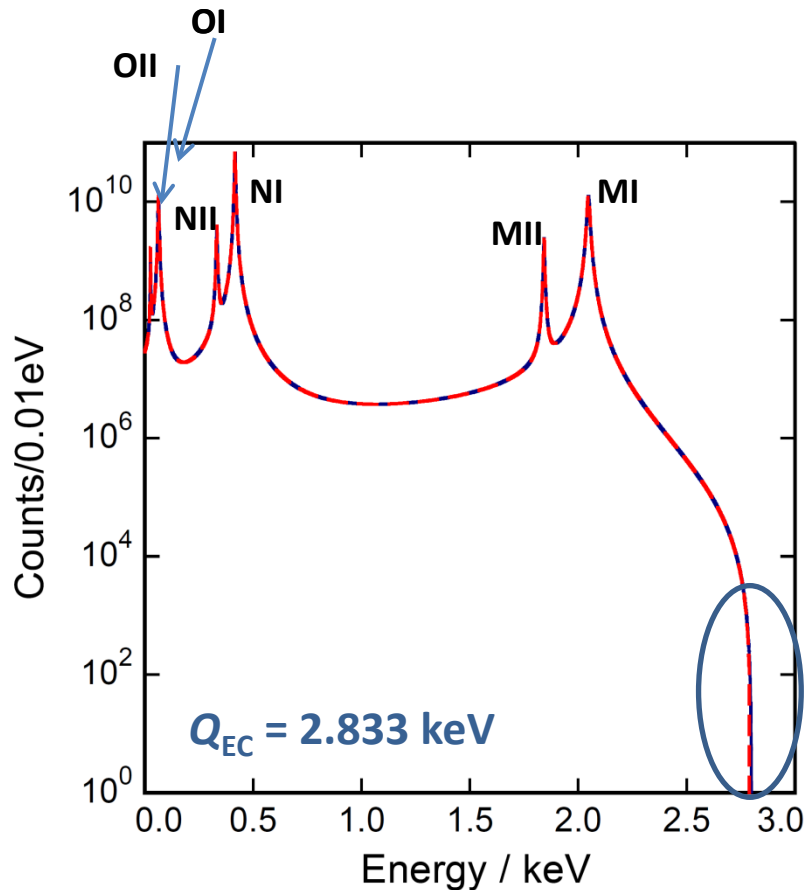
Requisiti sperimentali in ECHO

Numero di conteggi nella regione di interesse

- $N_{ev} > 10^{14} \rightarrow A \approx 1 \text{ MBq}$

Frazione di conteggi in $\Delta E_{ROI} = 1 \text{ eV}$

$\sim 6 \times 10^{-13}$



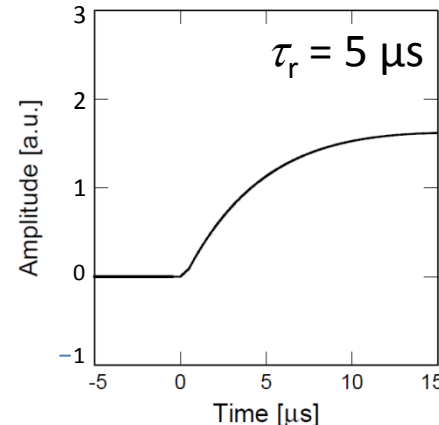
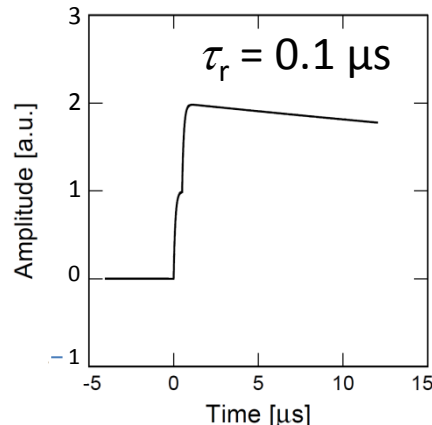
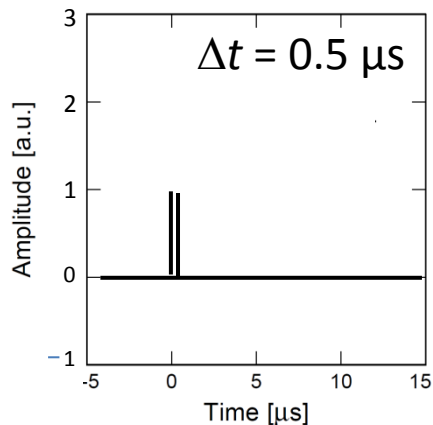
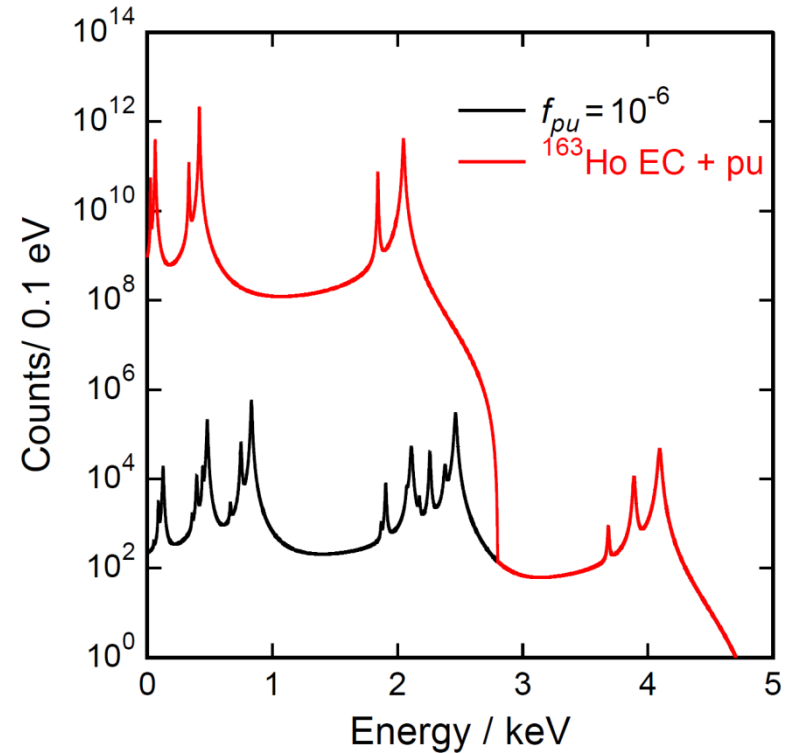
Requisiti sperimentali in ECHO

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

- $f_{pu} < 10^{-5}$
- $\tau_r < 1 \mu\text{s} \rightarrow a \sim 10 \text{ Bq}$
- 10^5 pixels



Requisiti sperimentali in ECHO

Numero di conteggi nella regione di interesse

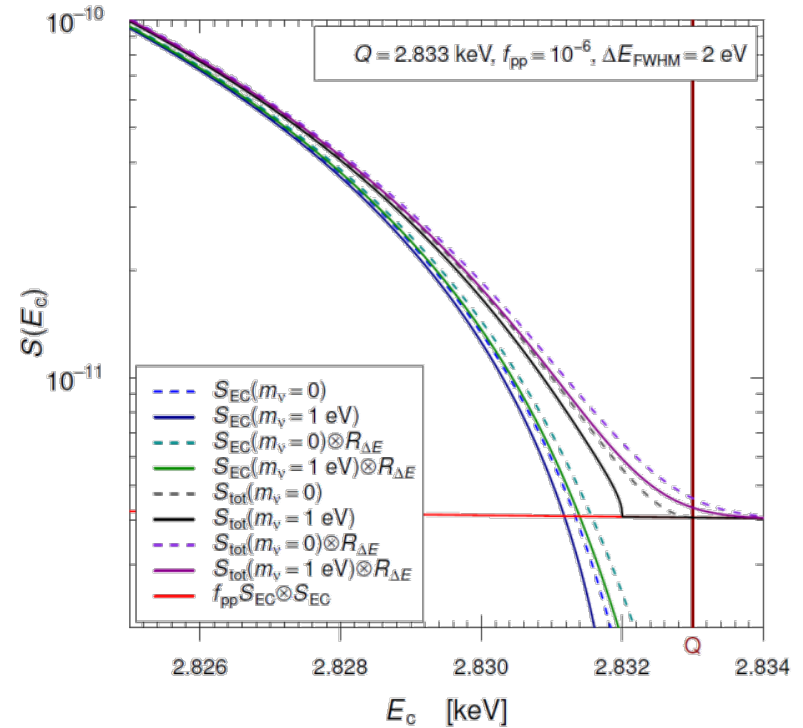
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- 10^5 pixels

Caratterizzazione precisa dello spettro

- $\Delta E_{FWHM} < 3 \text{ eV}$



Requisiti sperimentali in ECHO

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

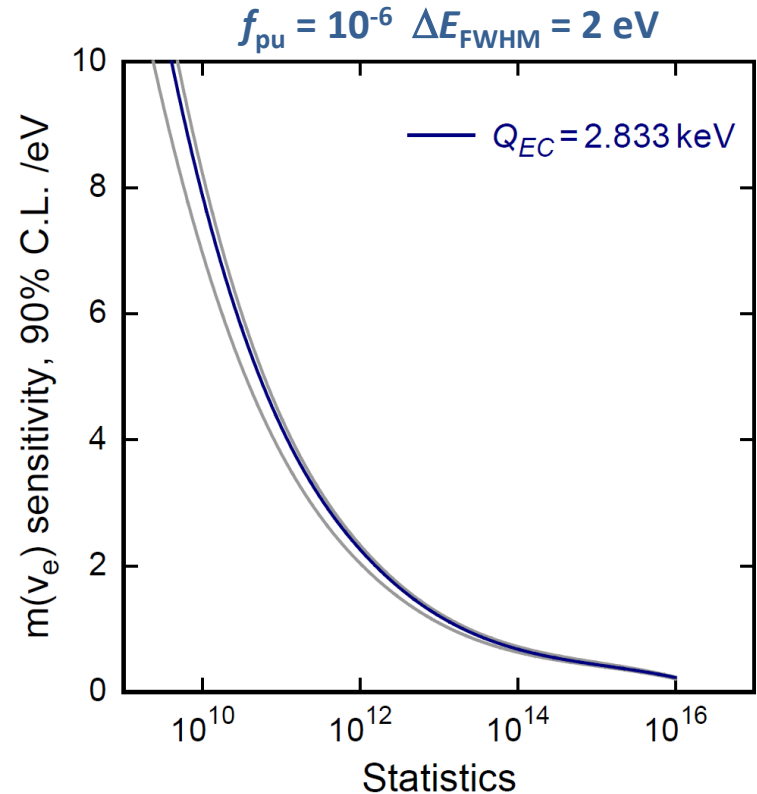
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Caratterizzazione precisa dello spettro

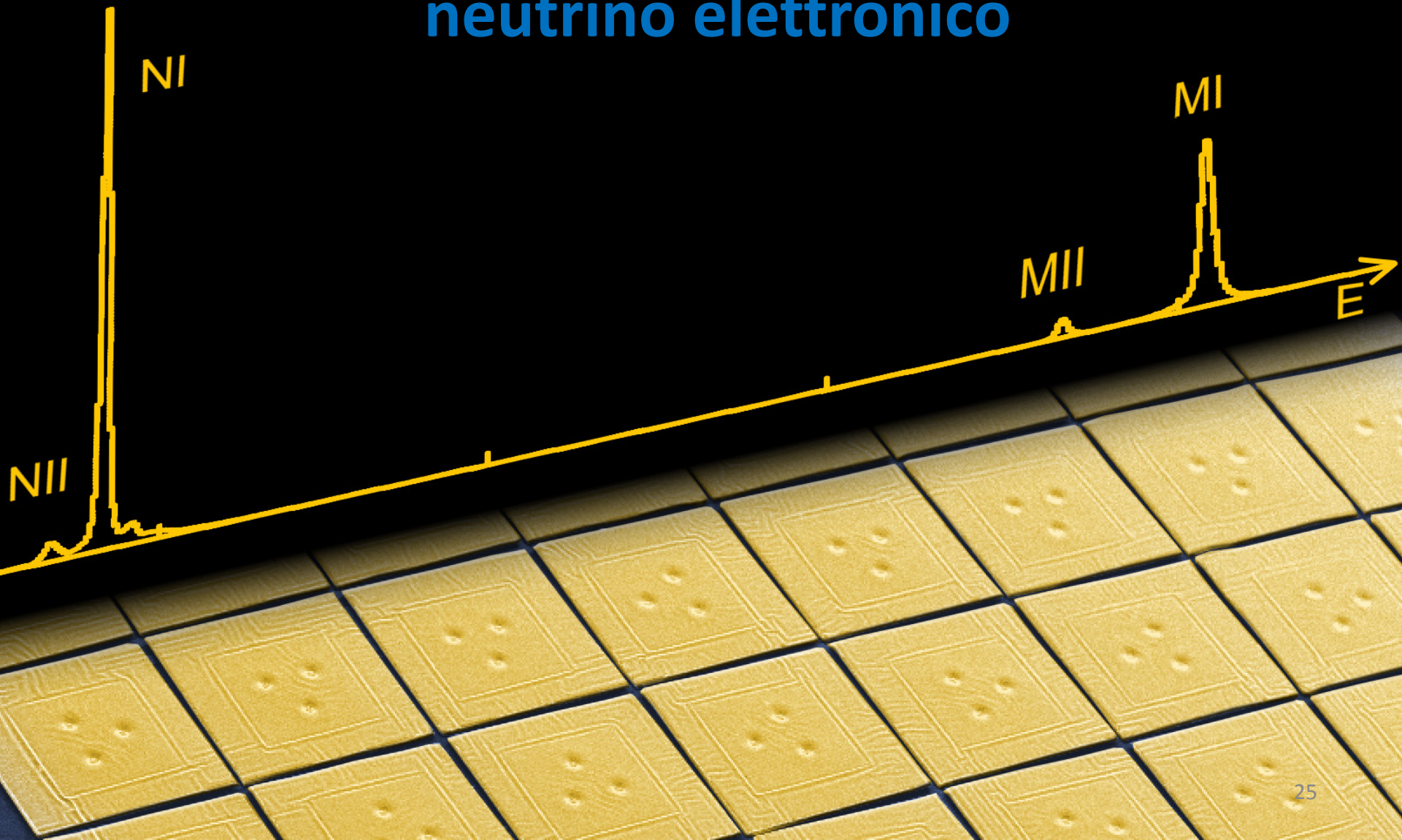
- $\Delta E_{\text{FWHM}} < 3 \text{ eV}$

Basso livello di background

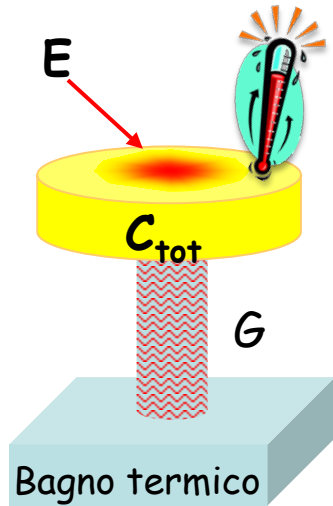
- $< 10^{-6} \text{ events/eV/det/day}$



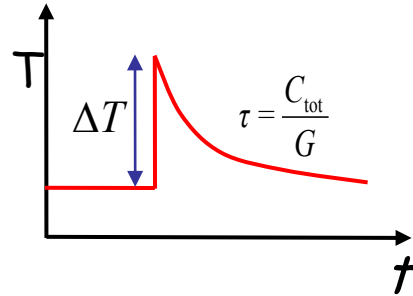
Rivelatori calorimetrici per la determinazione della massa del neutrino elettronico



Micro-calorimetri a basse temperature



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

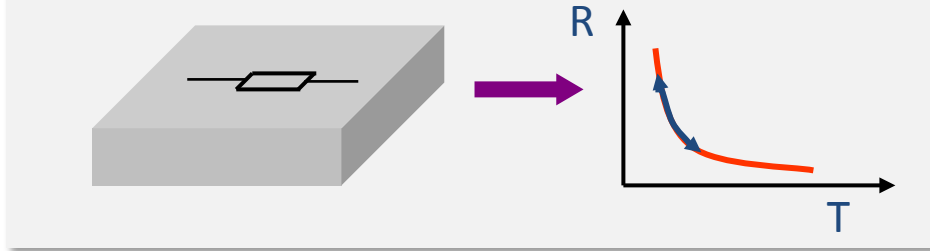


$$\left. \begin{array}{l} E = 10 \text{ keV} \\ C_{\text{tot}} = 1 \text{ pJ/K} \end{array} \right\} \rightarrow \sim 1 \text{ mK}$$

- Volumi molto piccoli
- temperature di lavoro sotto i 100 mK
calori specifici piccoli
basso rumore termico
- **Sensori di temperatura molto precisi**

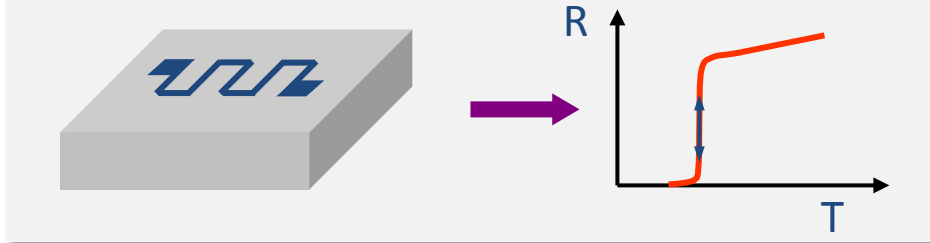
Sensori di temperatura

Resistenza di semiconduttori altamente dopati



Ge-NTD
Termistori di Si

Resistenza di film superconduttivi



TES

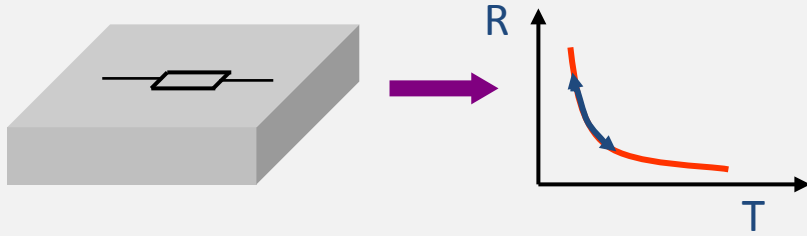
Magnetizzazione di materiali paramagnetici



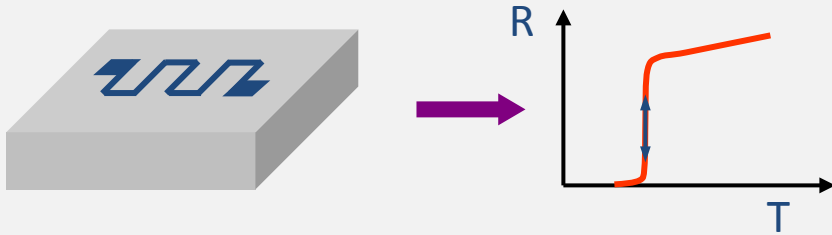
MMC

Sensori di temperatura

Resistenza di semiconduttori altamente dopati



Resistenza di film superconduttivi



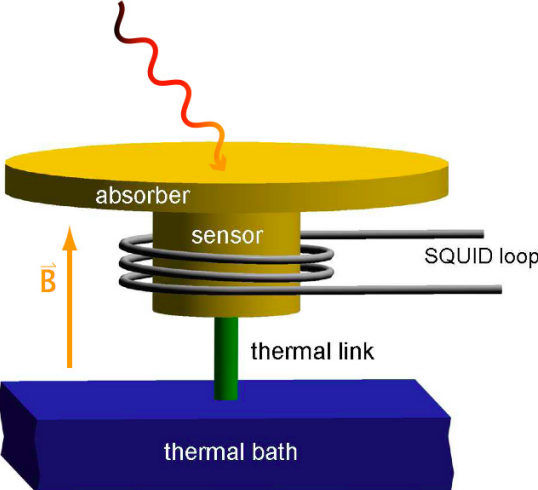
Magnetizzazione di materiali paramagnetici



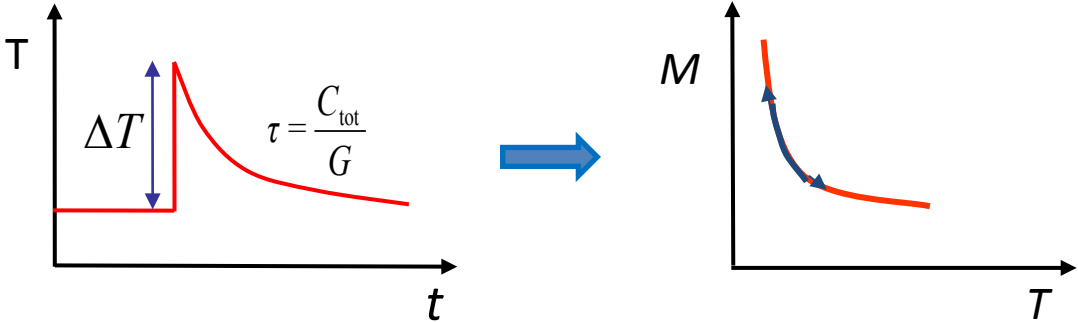
HOLMES
NuMECS

EC**Ho**

Metallic magnetic calorimeters (MMCs)



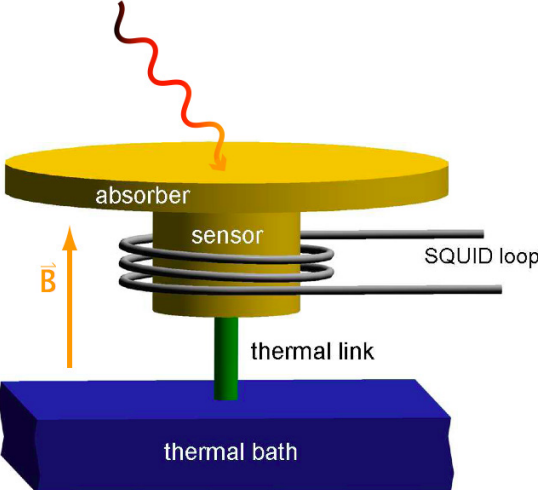
A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)



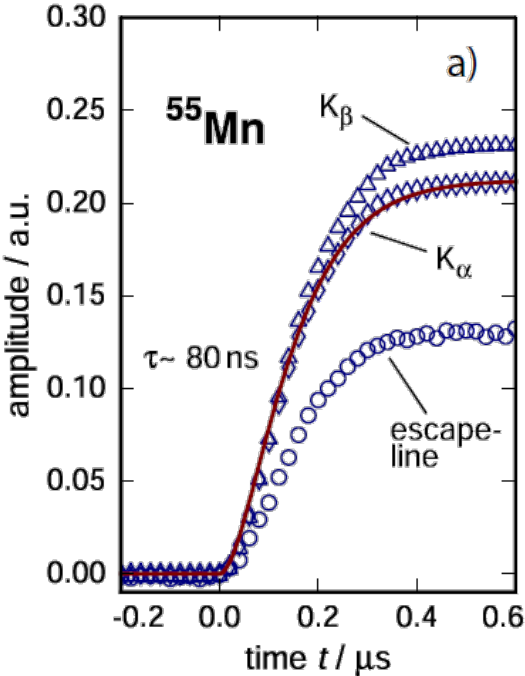
- Sensore paramagnetico
Au:Er
Ag:Er

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

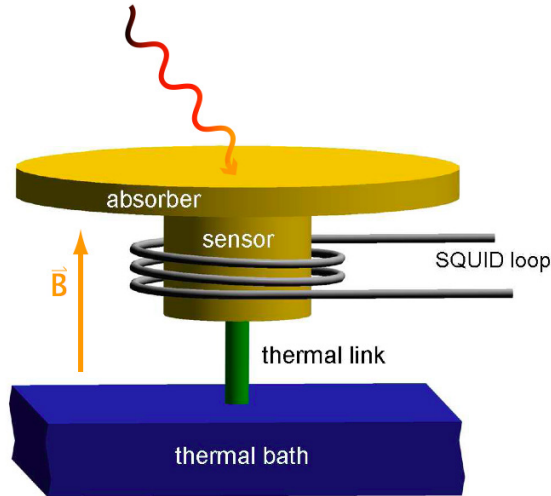
Metallic magnetic calorimeters (MMCs)



Tempo di salita veloce
→ Riduzione del un-resolved pile-up



Metallic magnetic calorimeters (MMCs)

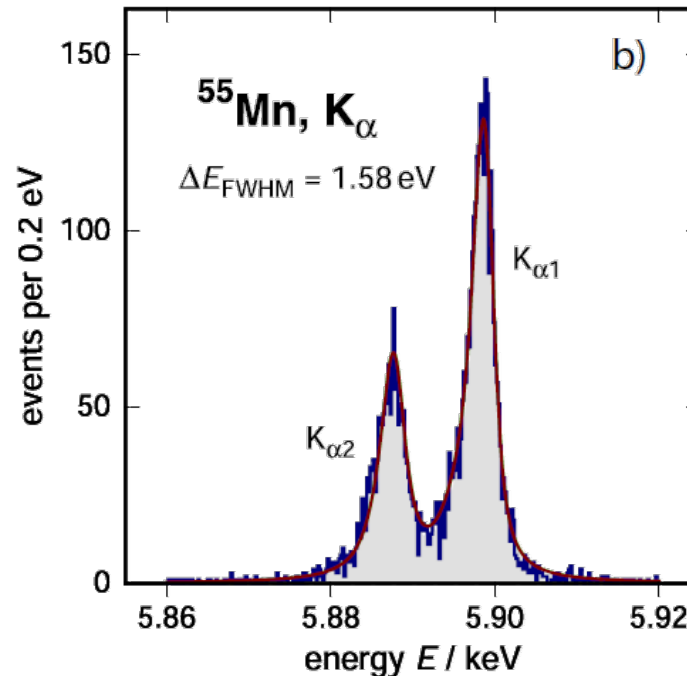
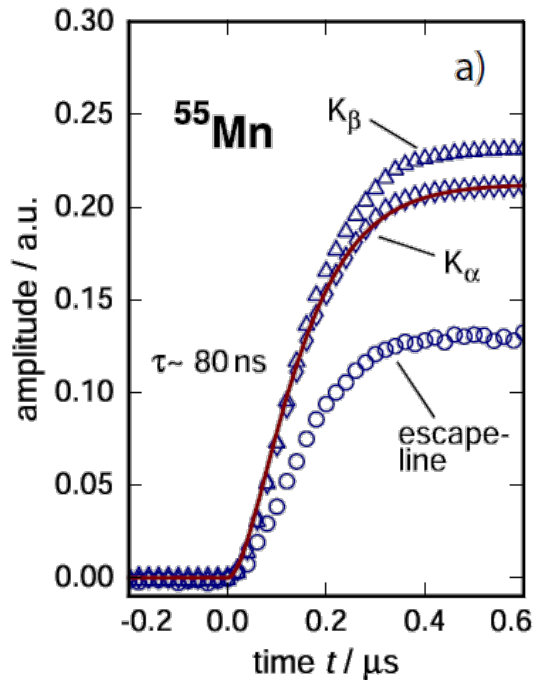


Tempo di salita veloce

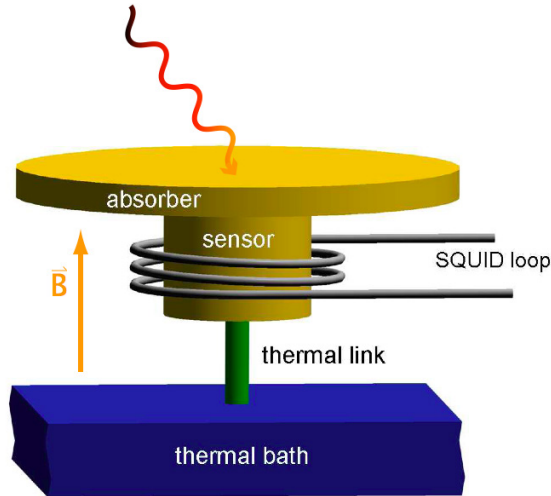
→ Riduzione del un-resolved pile-up

Ottima risoluzione energetica

→ Determinazione della forma dello spettro



Metallic magnetic calorimeters (MMCs)



Tempo di salita veloce

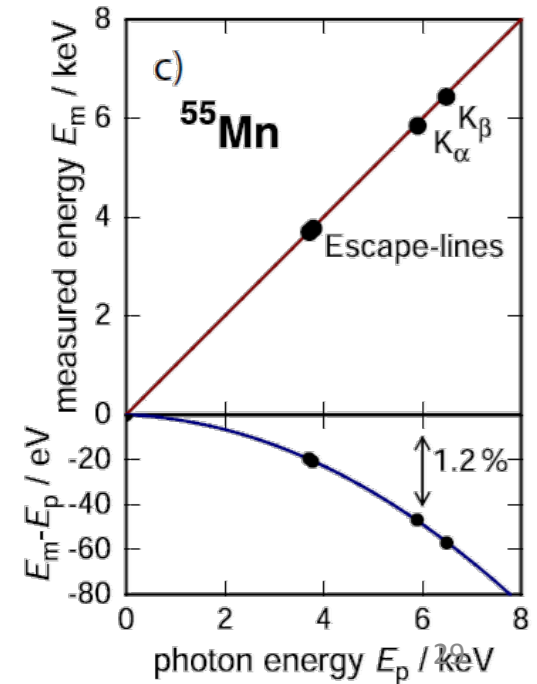
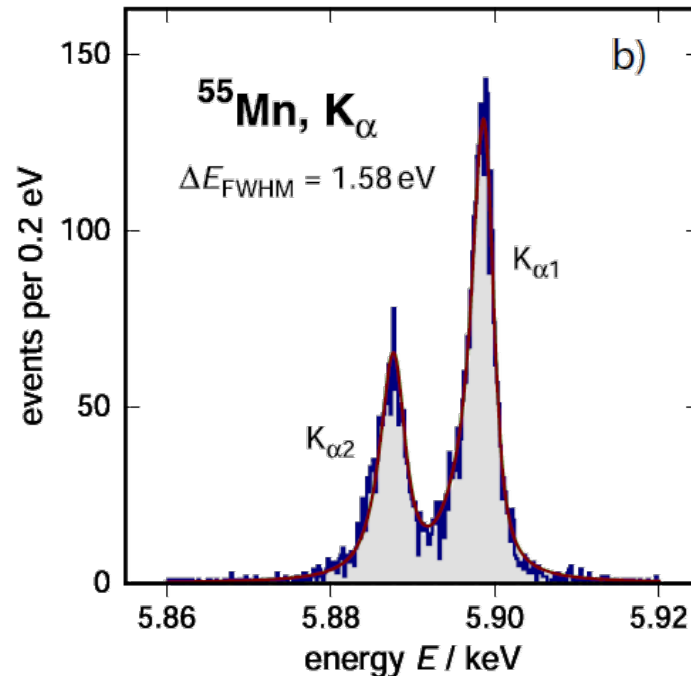
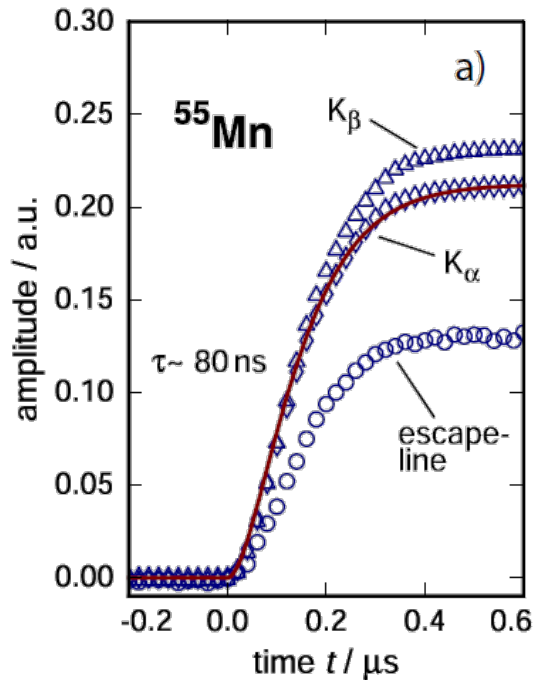
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Ottima risoluzione energetica

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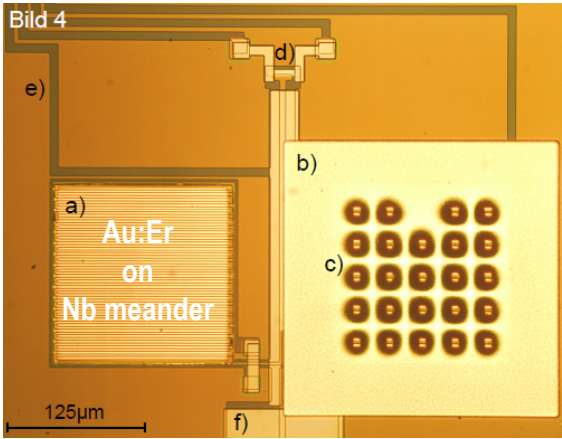
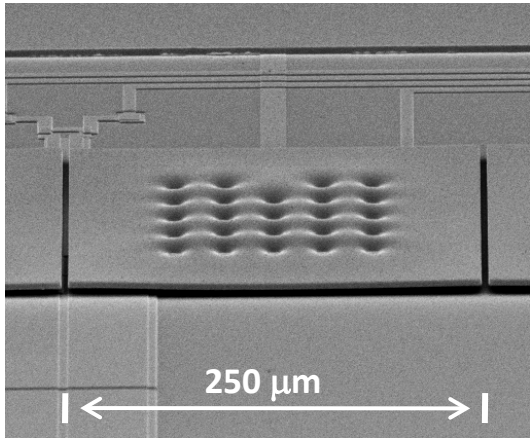
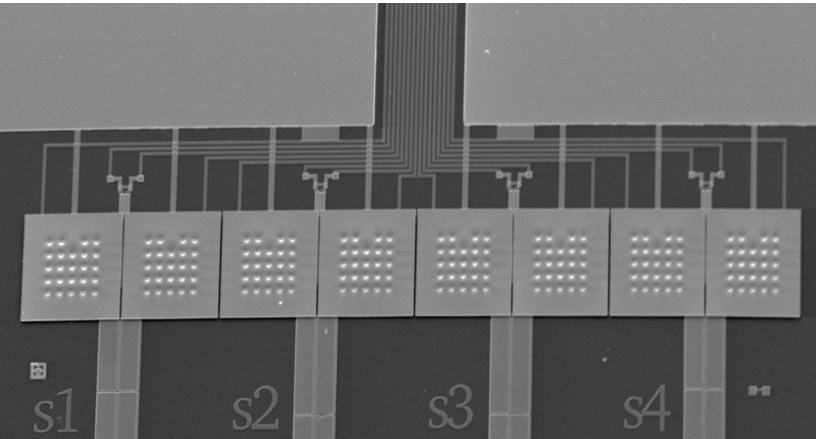
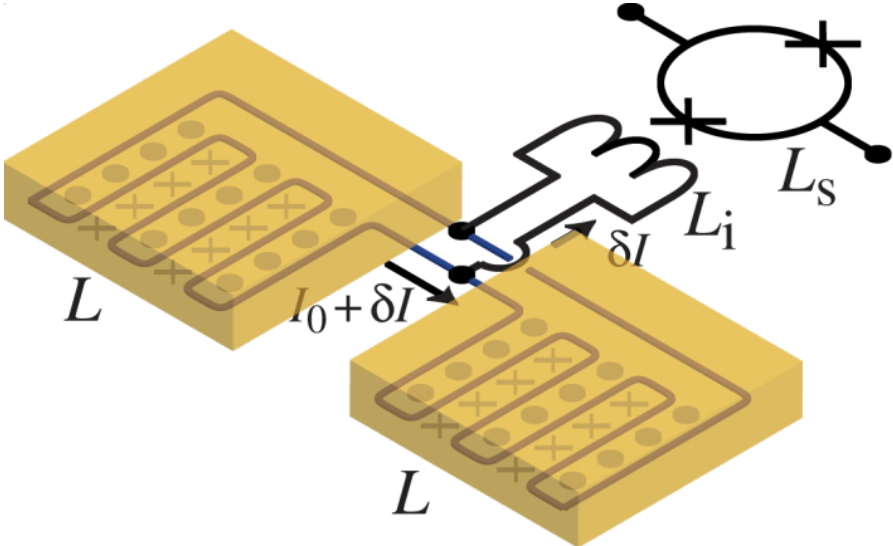
Linearità della funzione di calibrazione

→ Definizione precisa della scala di energia



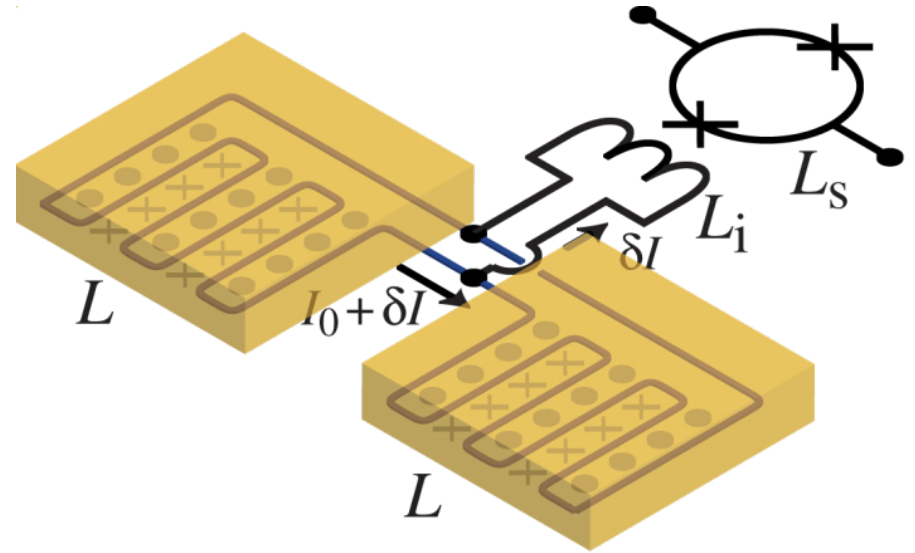
MMC: geometria e lettura

- Sensore di temperatura planare
- Campo B generato da correnti persistenti



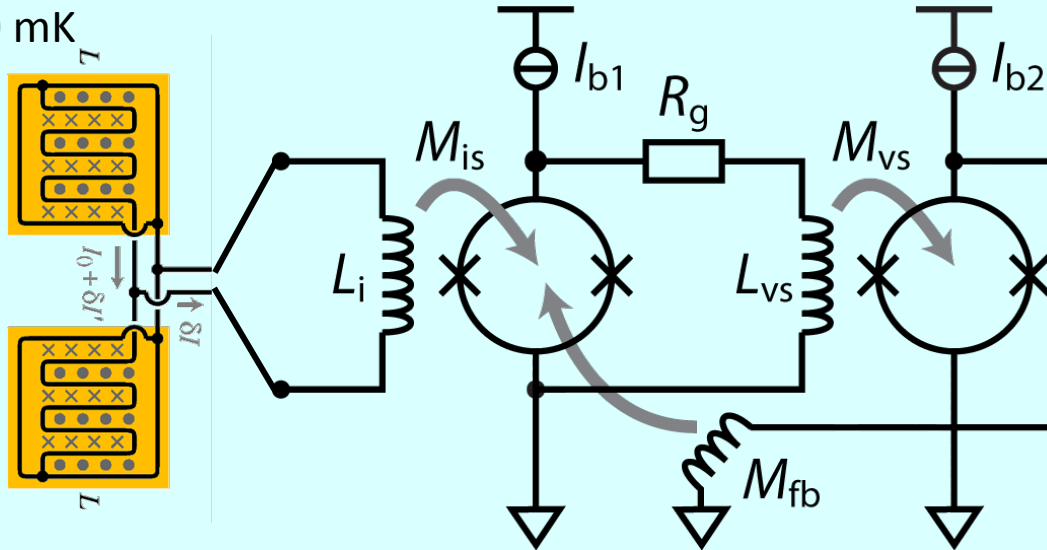
MMC: geometria e lettura

- Sensore di temperatura planare
- Campo B generato da correnti persistenti
- Accoppiato a SQUID

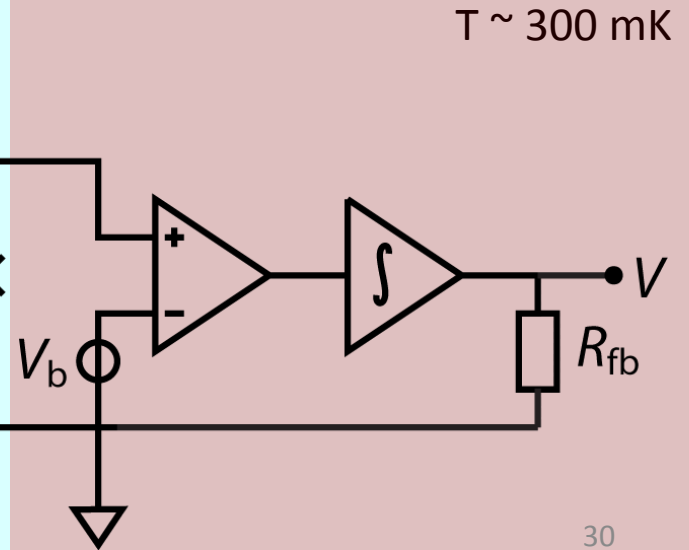


- Two-stage SQUID read-out

$T \sim 30 \text{ mK}$



$T \sim 300 \text{ mK}$

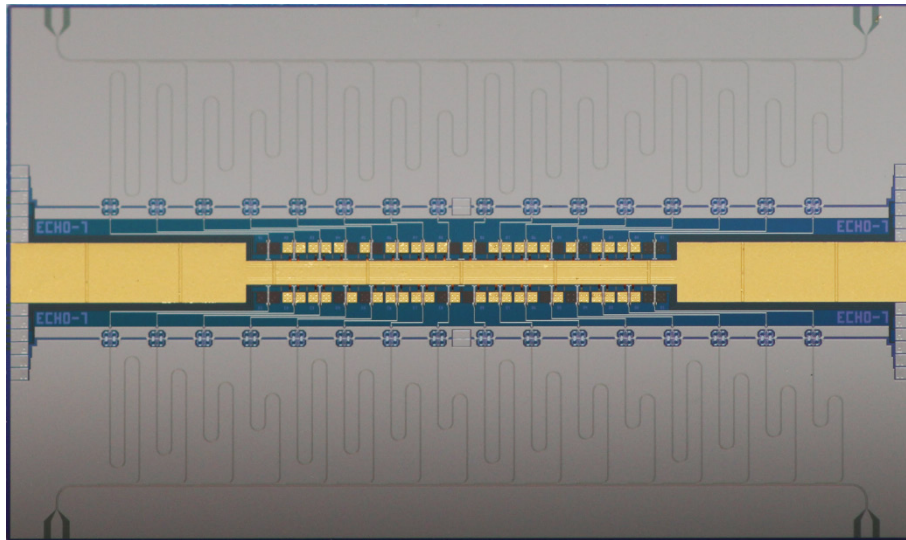
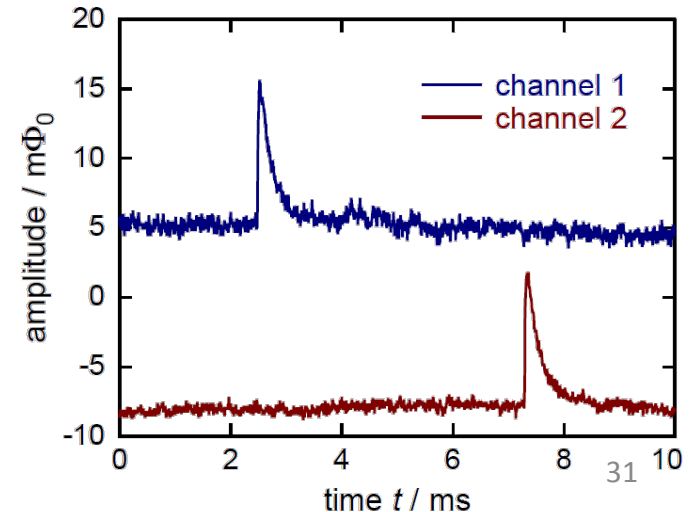
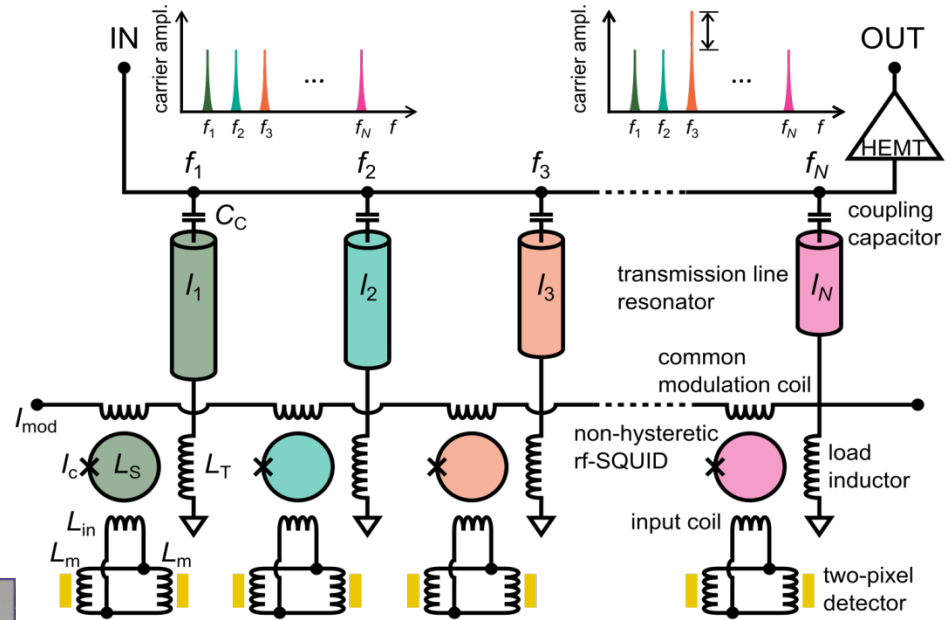


Multiplexing readout

Microwave SQUID multiplexing

Un singolo amplificatore HEMT e 2 cavi coassiali per leggere **100 - 1000** rivelatori

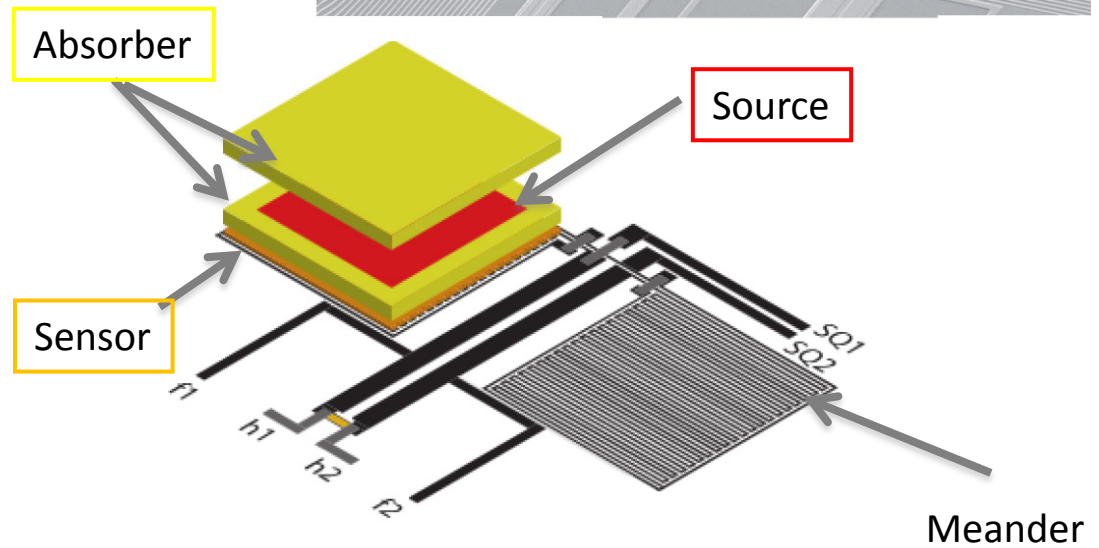
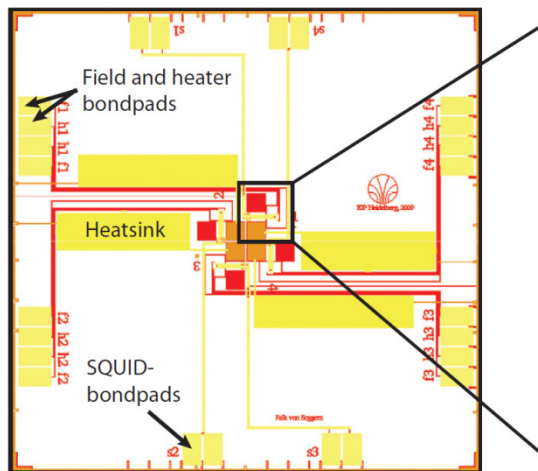
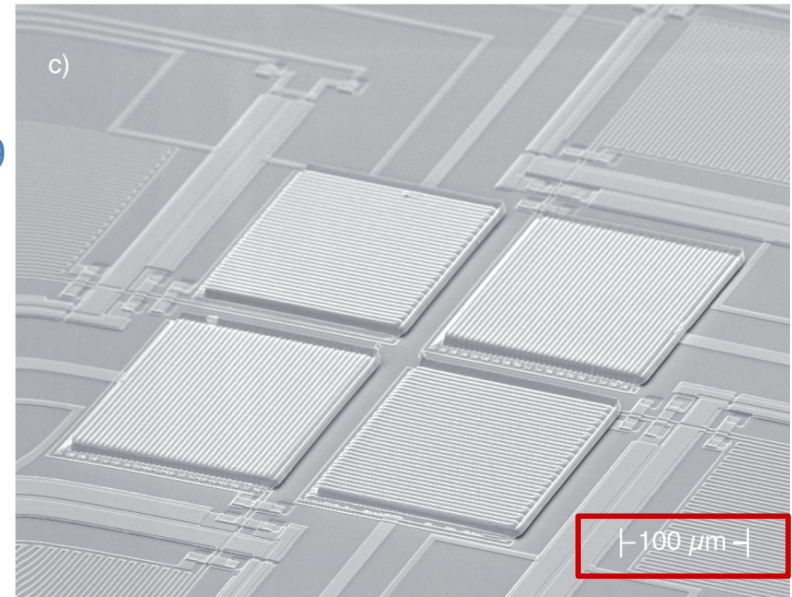
- Fabbricazione affidabile di array con **64 pixel**
- Caratterizzazione dei primi prototipi
→ **ottimizzazione dei parametri dell'array**



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

Primo prototipo per ^{163}Ho – ECHo-0

- Assorbitore per misure calorimetriche
→ impiantazione ionica @ ISOLDE-CERN in 2009
processo on-line
- Circa 0.01 Bq per pixel
- In funzione per piú di 4 anni

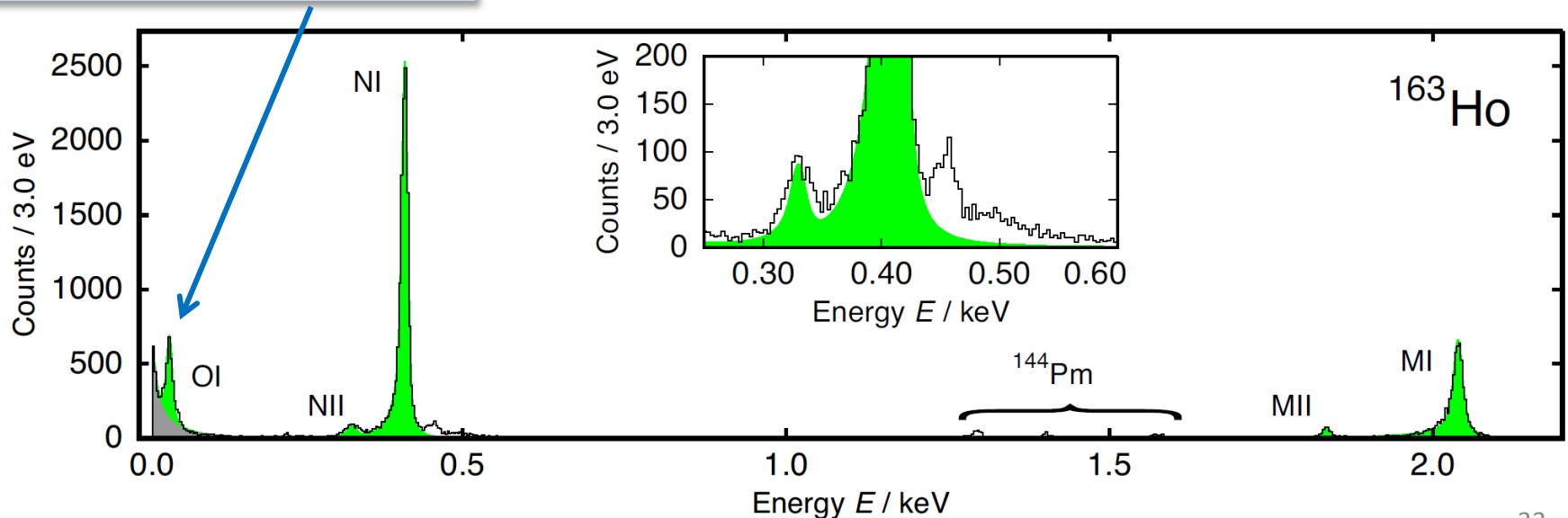


Spettro calorimetrico

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

	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

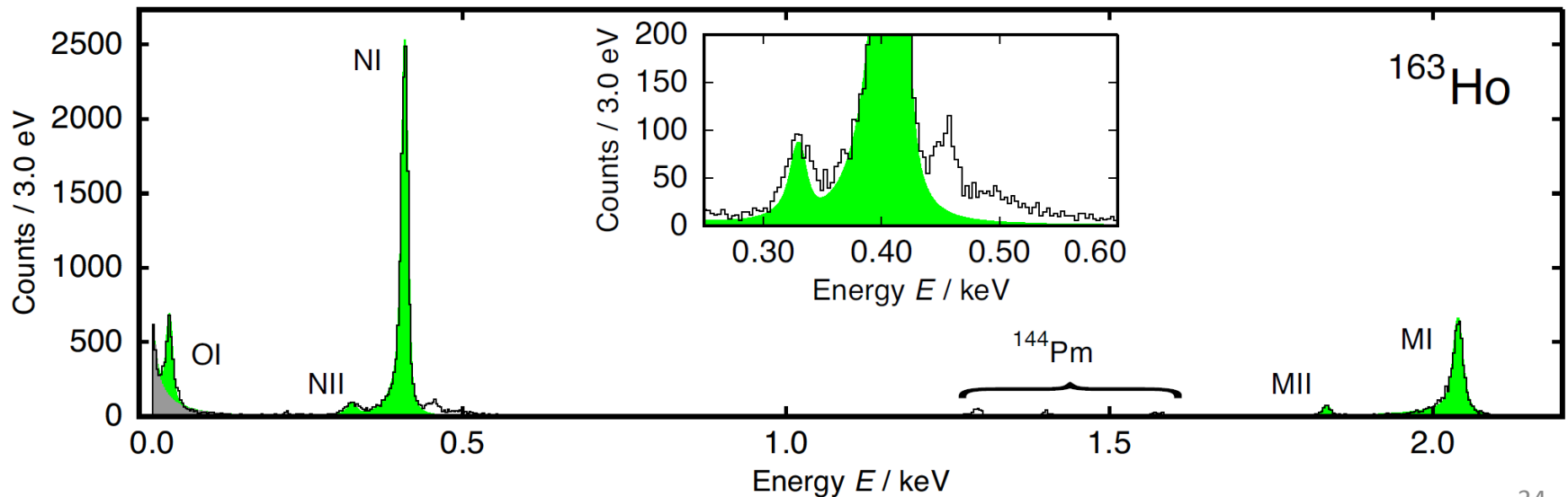
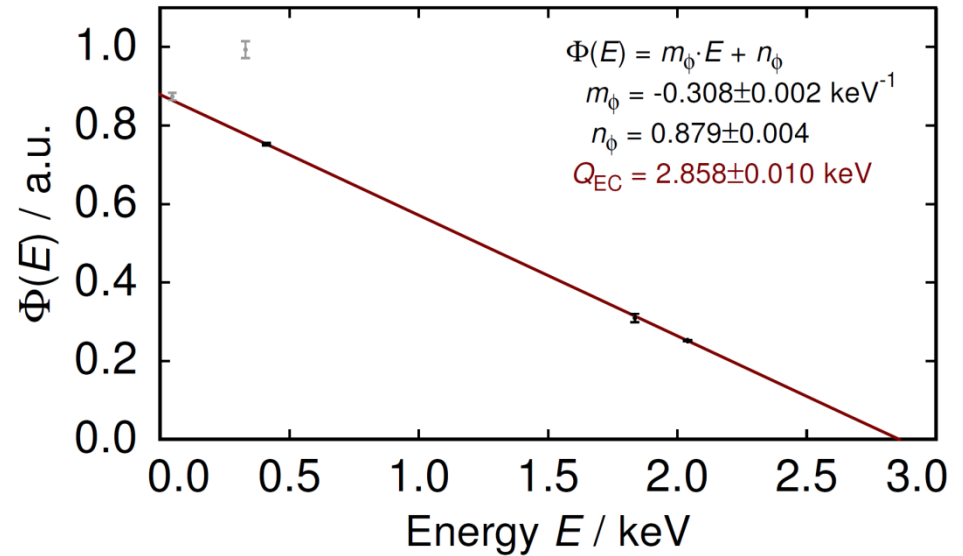
Prima misura calorimetrica della linea OI



Determinazione di Q_{EC}

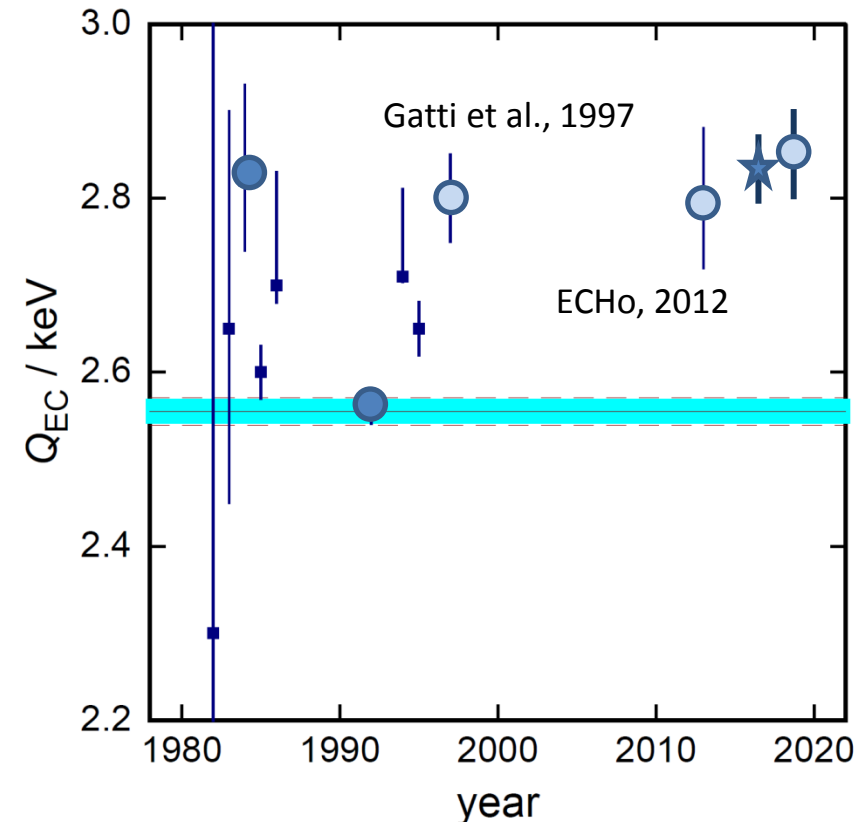
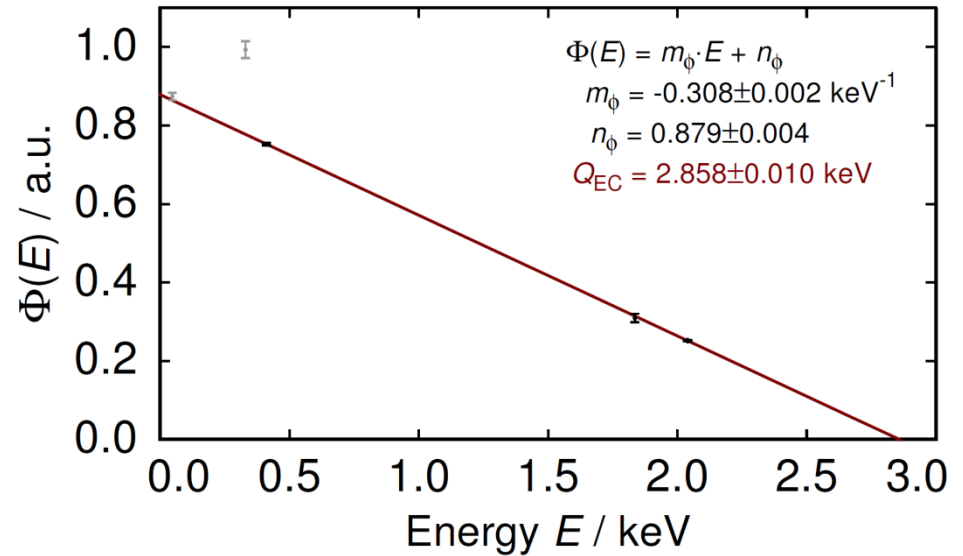
$$\Phi_H(E) = \sqrt{\frac{n_H}{\varphi_H^2(0)B_H}} \propto \sqrt{C}(Q_{EC} - E_H)$$

L'ampiezza delle linee é modellata dallo spazio delle fasi



Determinazione di Q_{EC}

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



Risultato dallo spettro del ^{163}Ho :

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

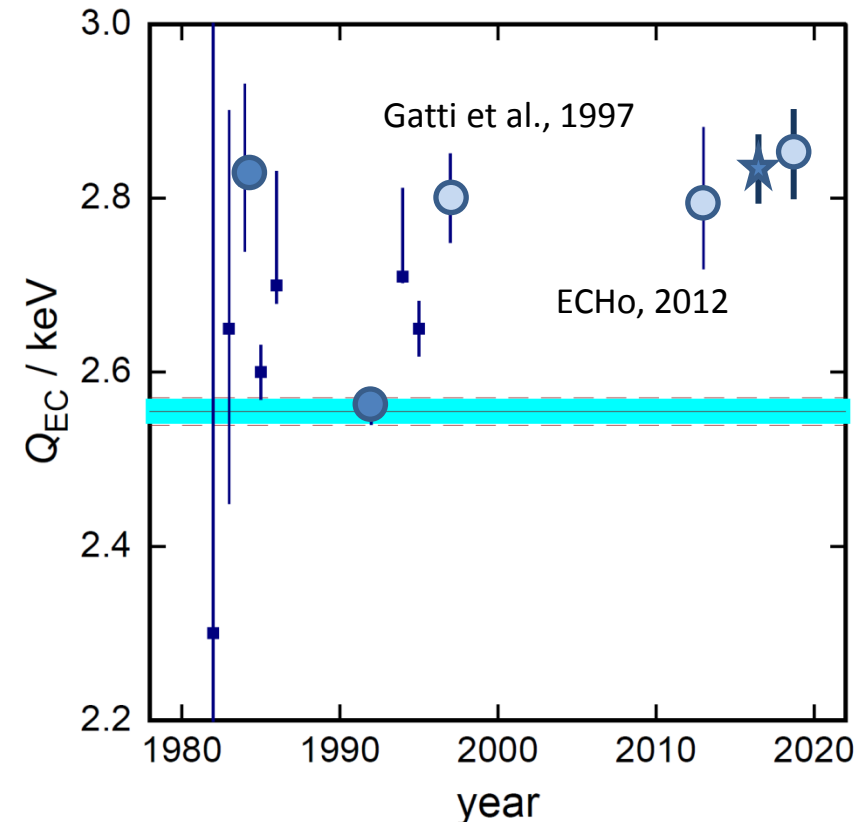
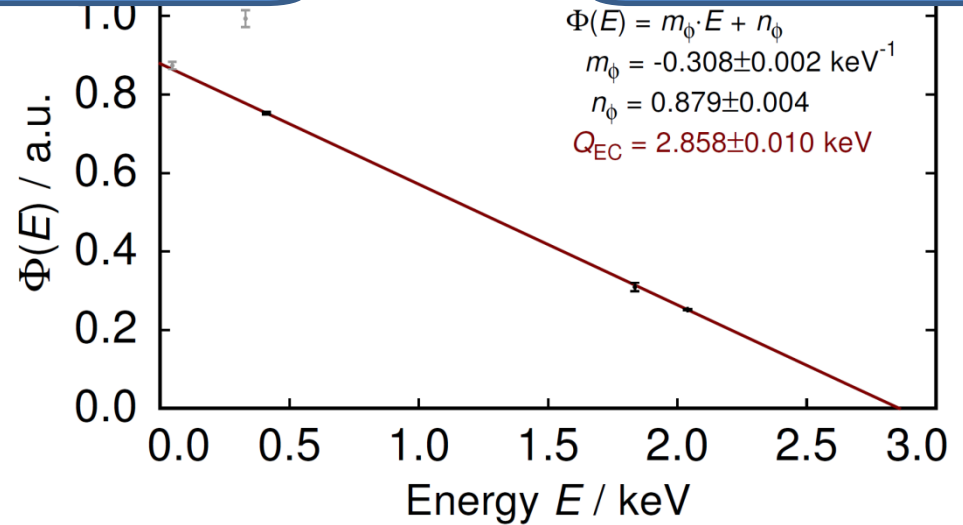
Risultato da misure di massa in Penning Trap:

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

Determinazione di Q_{EC}

Ottimo accordo tra
le due misure

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



Risultato dallo spettro del ^{163}Ho :

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

Risultato da misure di massa in Penning Trap:

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



Scaling up

ECHo-1k (2015 - 2018)

^{163}Ho attività: $A_t = 1 \text{ kBq}$

Rivelatori: **Metallic Magnetic Calorimeters**

→ Risoluzione energetica $\Delta E_{\text{FWHM}} \leq 5 \text{ eV}$

→ Risoluzione temporale $\tau \leq 1 \mu\text{s}$

Frazione unresolved pile-up $f_{\text{pu}} \leq 10^{-5}$

→ attività per pixel: $A = 10 \text{ Bq}$

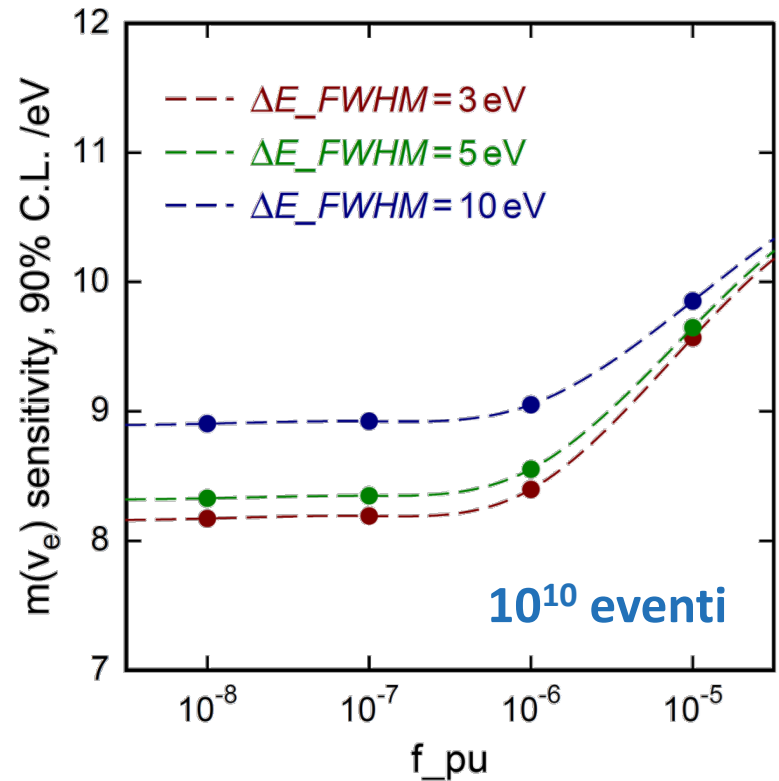
→ numero di rivelatori $N = 100$

Parallel read-out: 1 array ~ 50 pixels

Dimostrazione di **Microwave SQUID Multiplexing**

Background $b < 10^{-5} \text{ /eV/det/day}$

Tempo di misura $t = 1 \text{ year}$



$m(\nu_e) < 10 \text{ eV}$ 90% C.L.

ECHo-1M (Futuro)

^{163}Ho attività: $A_t = 1 \text{ MBq}$

Rivelatori: **Metallic Magnetic Calorimeters**

→ Risoluzione energetica $\Delta E_{FWHM} \leq 3 \text{ eV}$

→ Risoluzione temporale $\tau \leq 0.1 \mu\text{s}$

Frazione unresolved pile-up $f_{pu} \leq 10^{-6}$

→ attività per pixel: $A = 10 \text{ Bq}$

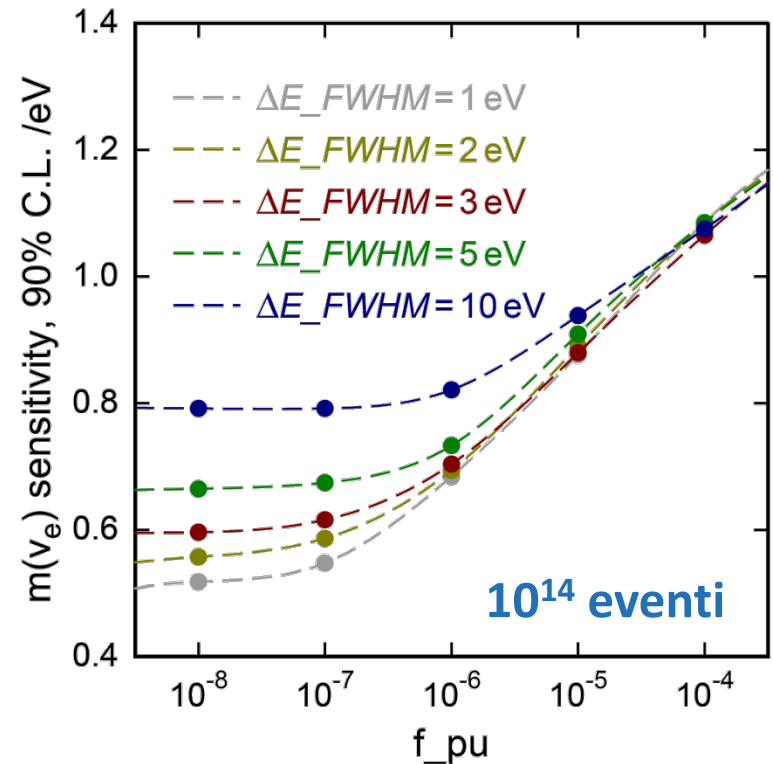
→ numero di rivelatori $N = 10^5$

Read-out : **Microwave SQUID Multiplexing**

→ 100 arrays con ~ 1000 pixels

Background $b < 10^{-6} \text{ /eV/det/day}$

Tempo di misura $t = 1 - 3 \text{ year}$



$m(\nu_e) < 1 \text{ eV } 90\% \text{ C.L.}$

Sorgente di ^{163}Ho ad alta purezza

Attività richiesta nei rivelatori: sub-eV sensitivity $\rightarrow >10^6 \text{ Bq} \rightarrow >10^{17}$ atomi

- Irradiazione neutronica
reazione (n,γ) su ^{162}Er

Alta cross-section 

Contaminazioni radioattive 

Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ EC *	Ho161 2.48 h 7/2- EC *	Ho162 15.0 m 1+ EC *	Ho163 4.70 y 2- EC *	Ho164 29 m 1+ EC,β-	Ho165 7/2- 100
Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb158 180 y 3- EC,β- *	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-

Sorgente di ^{163}Ho ad alta purezza

Attività richiesta nei rivelatori: sub-eV sensitivity $\rightarrow >10^6 \text{ Bq} \rightarrow >10^{17}$ atomi

- Irradiazione neutronica
reazione (n,γ) su ^{162}Er

Alta cross-section



Contaminazioni radioattive



Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2 EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ EC *	Ho161 2.48 h 7/2- EC *	Ho162 15.0 m 1+ EC *	Ho163 4.70 y 2- EC *	Ho164 29 m 1+ EC,β-	Ho165 7/2- 100
Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb158 180 y 3- EC,β- *	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-

Nuclide	(atoms)	Share ^a (%)	Analytical technique(s)
Ho fraction of the 6.7 mg target			
^{23}Na	$(1.1 \pm 0.1) \cdot 10^{18}$	–	NAA
^{160}Dy	$(1.6 \pm 0.2) \cdot 10^{12}$	0.004	RIMS, NAA
^{161}Dy	$(1.3 \pm 0.2) \cdot 10^{13}$	0.032	RIMS, NAA
^{162}Dy	$(3.0 \pm 0.3) \cdot 10^{13}$	0.074	RIMS, NAA
^{163}Dy	$(3.0 \pm 0.3) \cdot 10^{13}$	0.074	RIMS, NAA
^{164}Dy	$(2.5 \pm 0.2) \cdot 10^{13}$	0.062	NAA
^{163}Ho	$(3.6 \pm 0.2) \cdot 10^{16}$	89	ICP-MS, RIMS, NAA
^{165}Ho	$(4.5 \pm 0.1) \cdot 10^{15}$	11	ICP-MS
$^{166\text{m}}\text{Ho}$	$(8.7 \pm 0.7) \cdot 10^{11}$	0.002	γ-ray spectrometry
Ho fraction of the 30 mg target			
^{23}Na	$(3.5 \pm 0.2) \cdot 10^{18}$	–	NAA
^{160}Dy	$(4.3 \pm 1.8) \cdot 10^{13}$	0.002	RIMS, NAA
^{161}Dy	$(3.6 \pm 0.8) \cdot 10^{14}$	0.018	RIMS, NAA
^{162}Dy	$(6.9 \pm 0.8) \cdot 10^{14}$	0.034	RIMS, NAA
^{163}Dy	$(1.2 \pm 0.1) \cdot 10^{15}$	0.059	RIMS, NAA
^{164}Dy	$(6.3 \pm 0.3) \cdot 10^{15}$	0.31	NAA
^{163}Ho	$(1.2 \pm 0.2) \cdot 10^{18}$	59	ICP-MS, RIMS, NAA
^{165}Ho	$(6.3 \pm 0.8) \cdot 10^{17}$	31	ICP-MS
$^{166\text{m}}\text{Ho}$	$(3.8 \pm 0.3) \cdot 10^{14}$	0.019	γ-ray spectrometry
^{162}Er	$(3.4 \pm 0.7) \cdot 10^{16}$	1.7	NAA, ICP-MS
^{164}Er	$(8.7 \pm 1.7) \cdot 10^{15}$	0.43	NAA, ICP-MS
^{166}Er	$(6.2 \pm 1.2) \cdot 10^{16}$	3.0	NAA, ICP-MS
^{167}Er	$(4.2 \pm 0.8) \cdot 10^{15}$	0.21	NAA, ICP-MS
^{168}Er	$(7.5 \pm 1.5) \cdot 10^{16}$	3.7	NAA, ICP-MS
^{170}Er	$(1.5 \pm 0.3) \cdot 10^{16}$	0.74	NAA

^aNormalized to the total content in the mass region around A=163, i.e. without considering ^{23}Na , which is easily quantitatively removed in the mass separation step.

Sorgente di ^{163}Ho ad alta purezza

Attività richiesta nei rivelatori: sub-eV sensitivity $\rightarrow >10^6 \text{ Bq} \rightarrow >10^{17}$ atomi

- Irradiazione neutronica
reazione (n,γ) su ^{162}Er

Alta cross-section

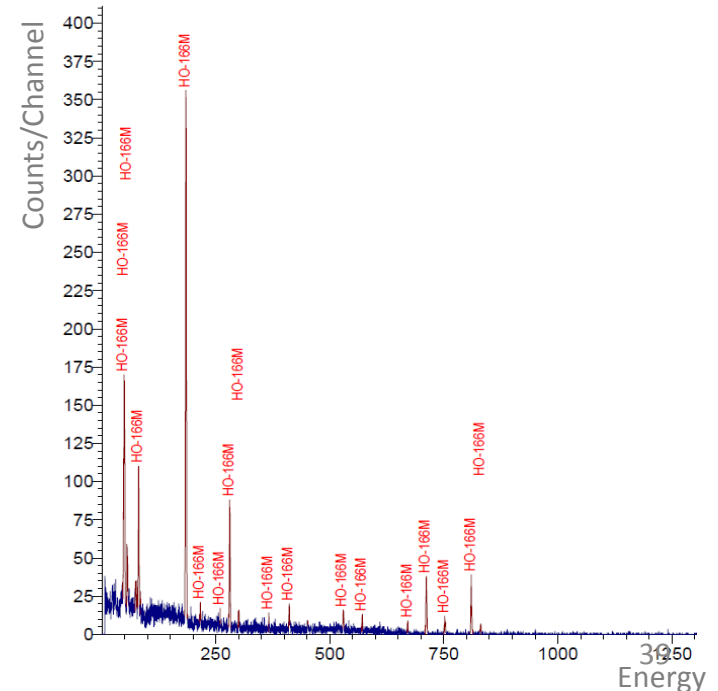


Contaminazioni radioattive

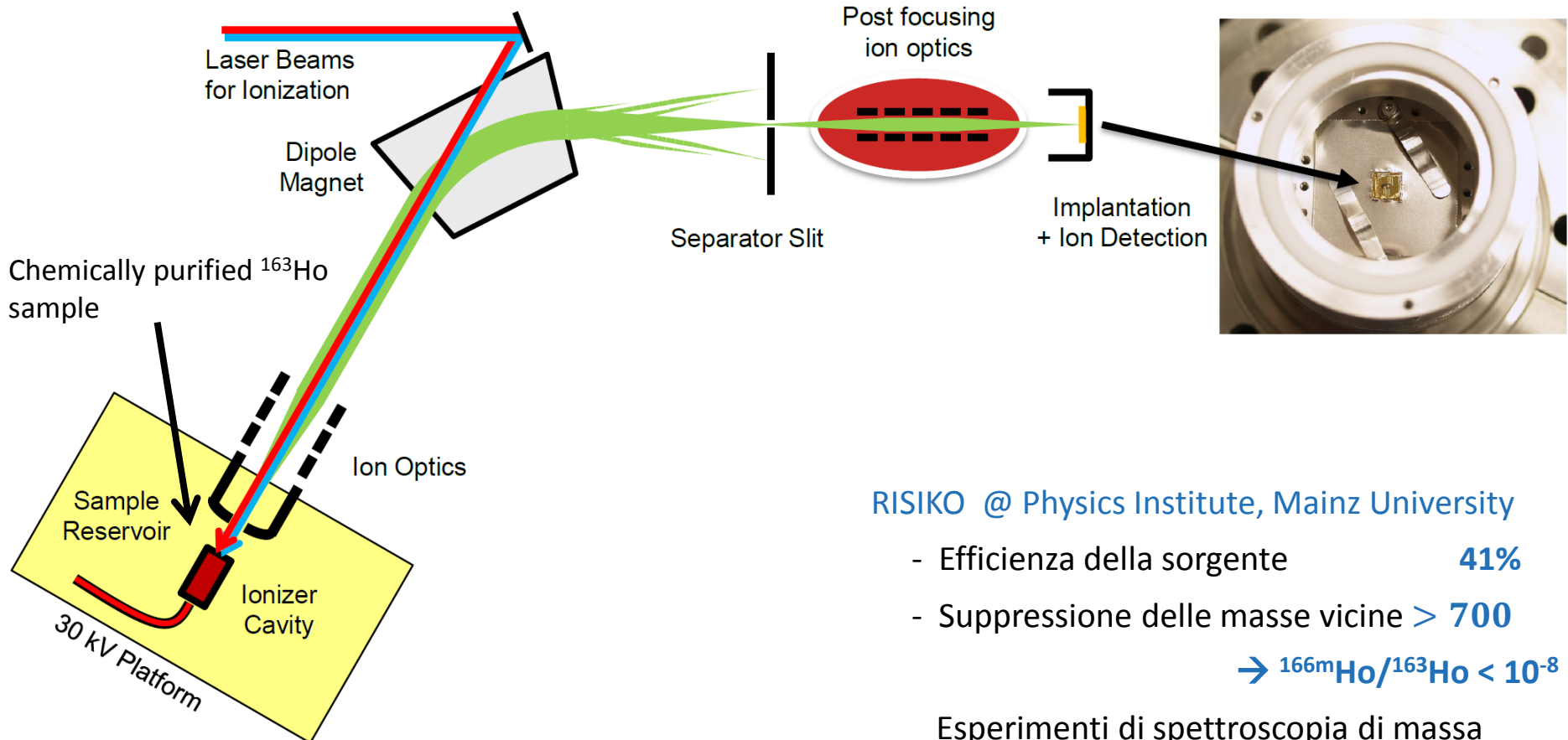


Eccellente separazione chimica

Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ EC *	Ho161 2.48 h 7/2- EC *	Ho162 15.0 m 1+ EC *	Ho163 1.70 y 2- EC *	Ho164 29 m 1+ EC,β-	Ho165 7/2- 100
Dy159 144.4 d 3/2- EC	Dy160 0+ 2.34	Dy161 5/2+ 18.9	Dy162 0+ 25.5	Dy163 5/2- 24.9	Dy164 0+ 28.2
Tb158 180 y 3- EC,β- *	Tb159 3/2+ 100	Tb160 72.3 d 3- β-	Tb161 6.88 d 3/2+ β-	Tb162 7.60 m 1- β-	Tb163 19.5 m 3/2+ β-



Separazione di massa e impiantazione di ^{163}Ho



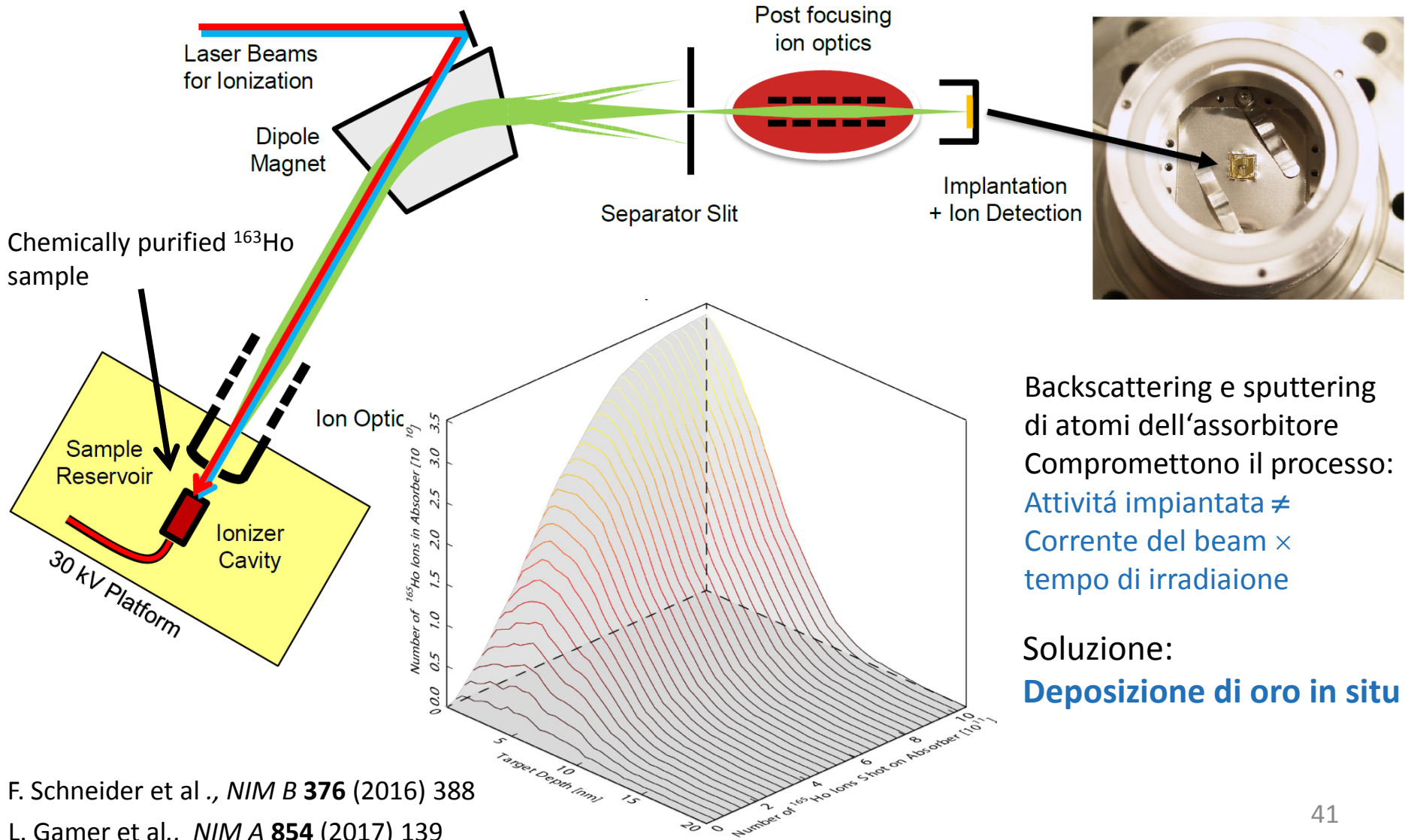
RISIKO @ Physics Institute, Mainz University

- Efficienza della sorgente **41%**
- Suppressione delle masse vicine **> 700**
→ $^{166\text{m}}\text{Ho}/^{163}\text{Ho} < 10^{-8}$

Esperimenti di spettroscopia di massa
con acceleratori a DREAMS Dresden

- Ottimizzazione della focalizzazione del beam

Separazione di massa e impiantazione di ^{163}Ho



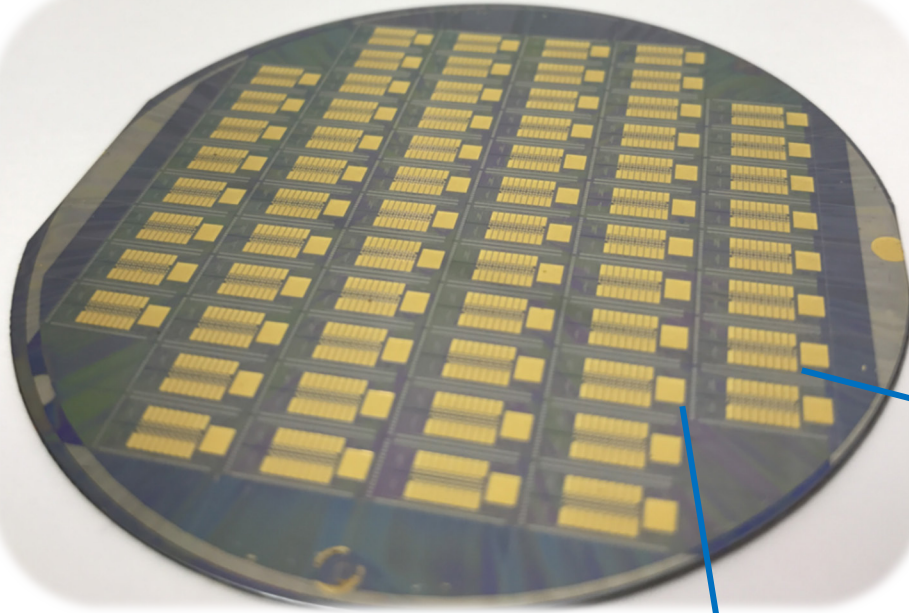
Backscattering e sputtering di atomi dell'assorbitore Compromettono il processo:

Attività impiantata \neq Corrente del beam \times tempo di irradiazione

Soluzione:

Deposizione di oro in situ

Array ECHo-1k



3" wafer con 64 ECHo-1k chip

Adatto per lettura
parallela e a multiplexing

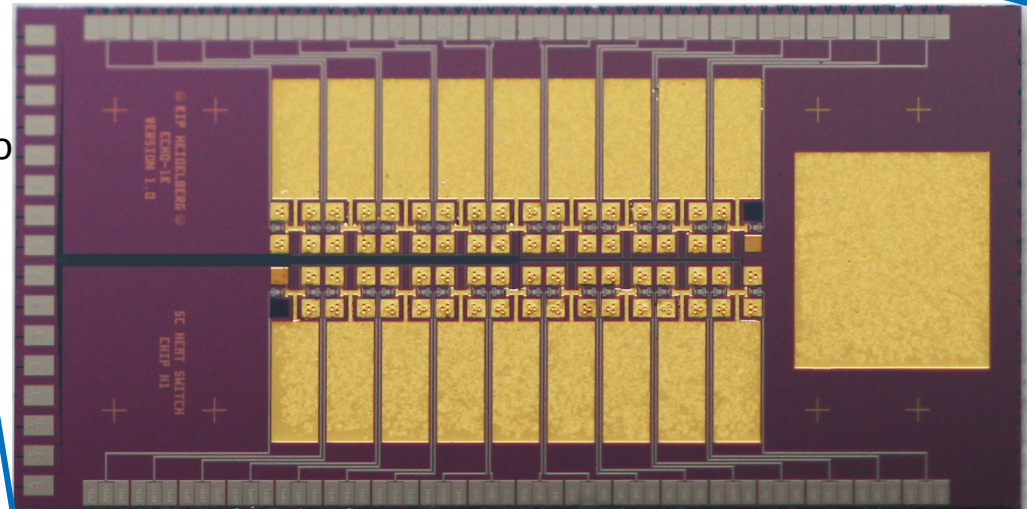
64 pixels che possono essere caricati con ^{163}Ho
+ 4 rivelatori per diagnostica

Design performance:

$$\Delta E_{\text{FWHM}} \sim 5 \text{ eV}$$

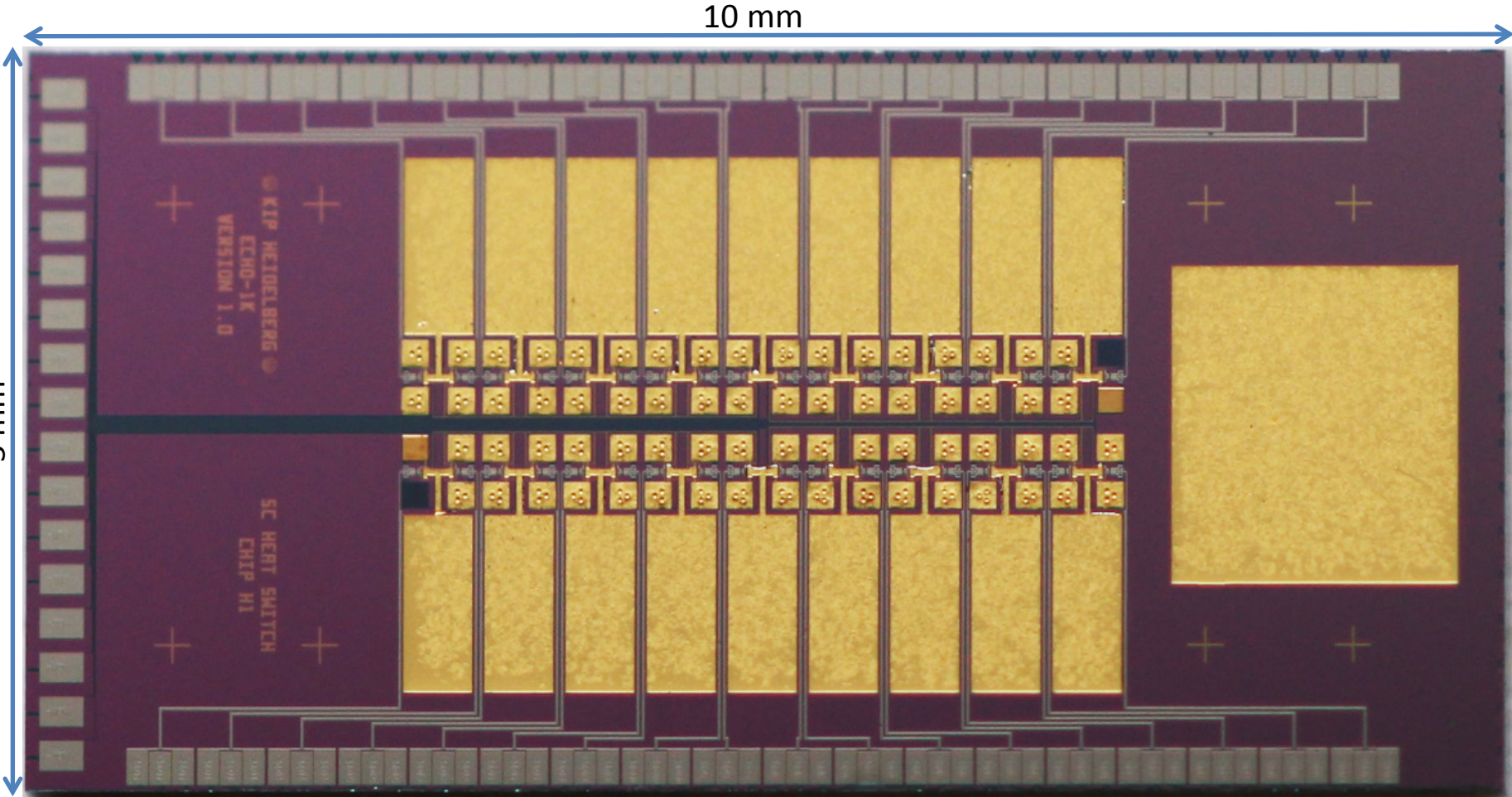
$$\tau_r \sim 90 \text{ ns (single channel read-out)}$$

$$\tau_r \sim 300 \text{ ns (multiplexed read-out)}$$

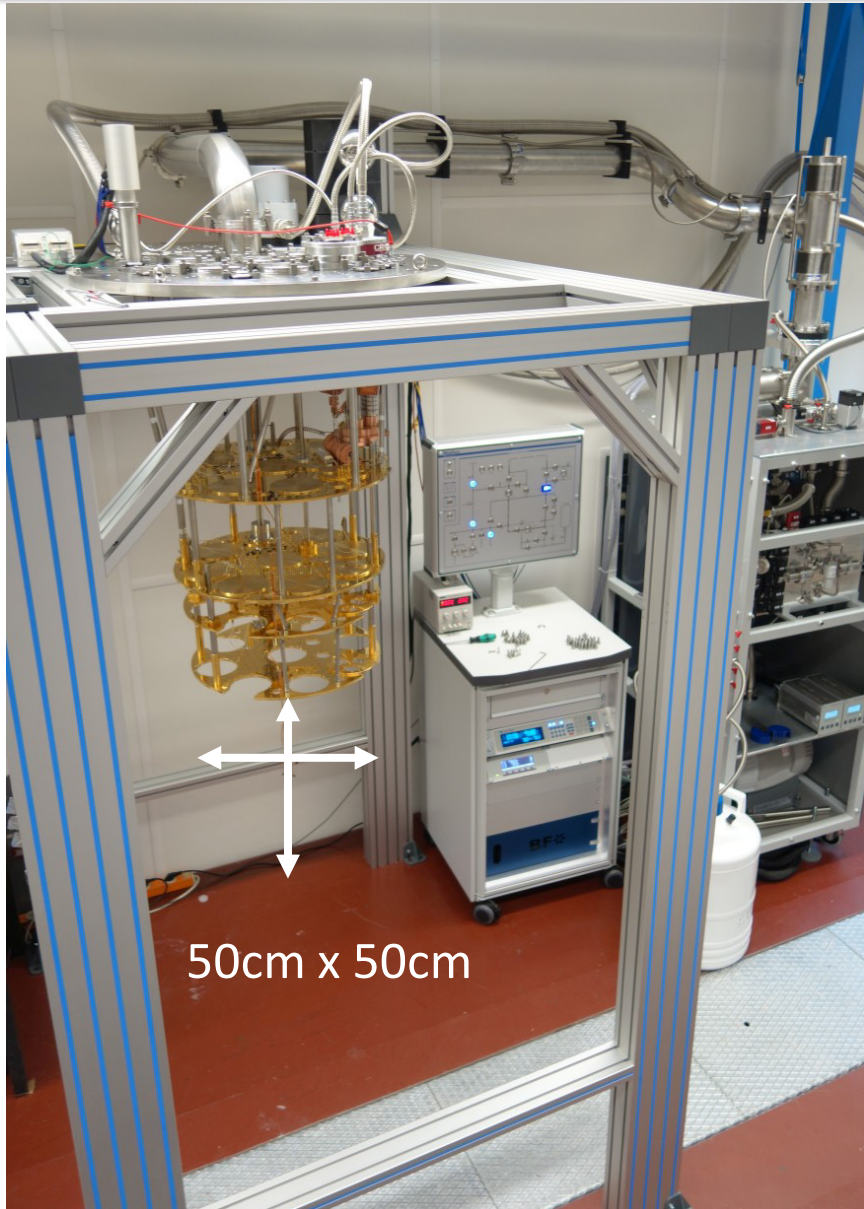


ECHo-1k array

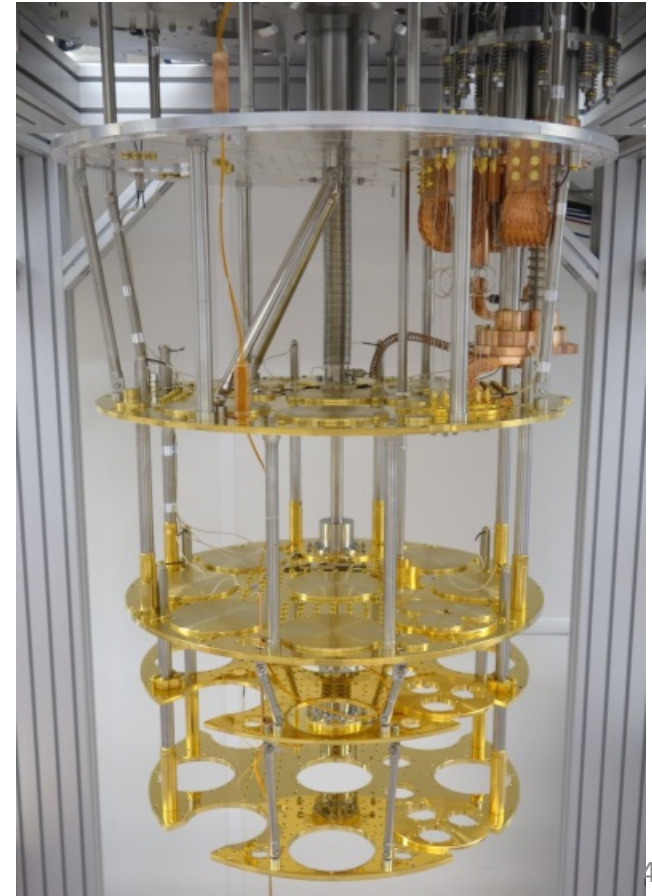
100% dei chips selezionati a temperatura ambiente hanno buone performance a basse temperature



Piattaforma criogenica per ECHO

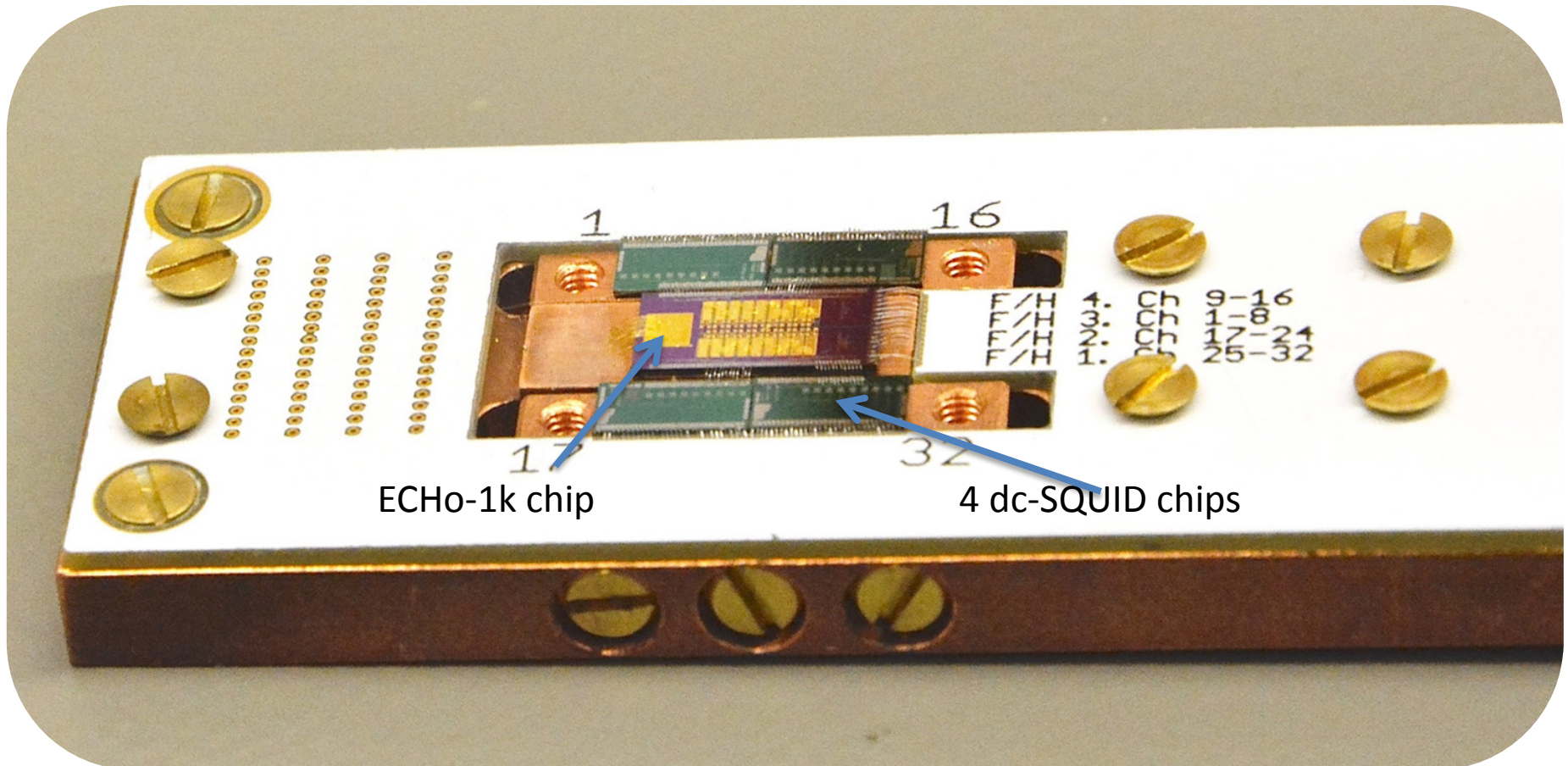


- Spazio alla MXC sufficiente per diverse fasi di ECHO
- cooling power: $15\mu\text{W}$ @ 20 mK
- Possibilità di caricare 200kg per schermatura attiva/passiva



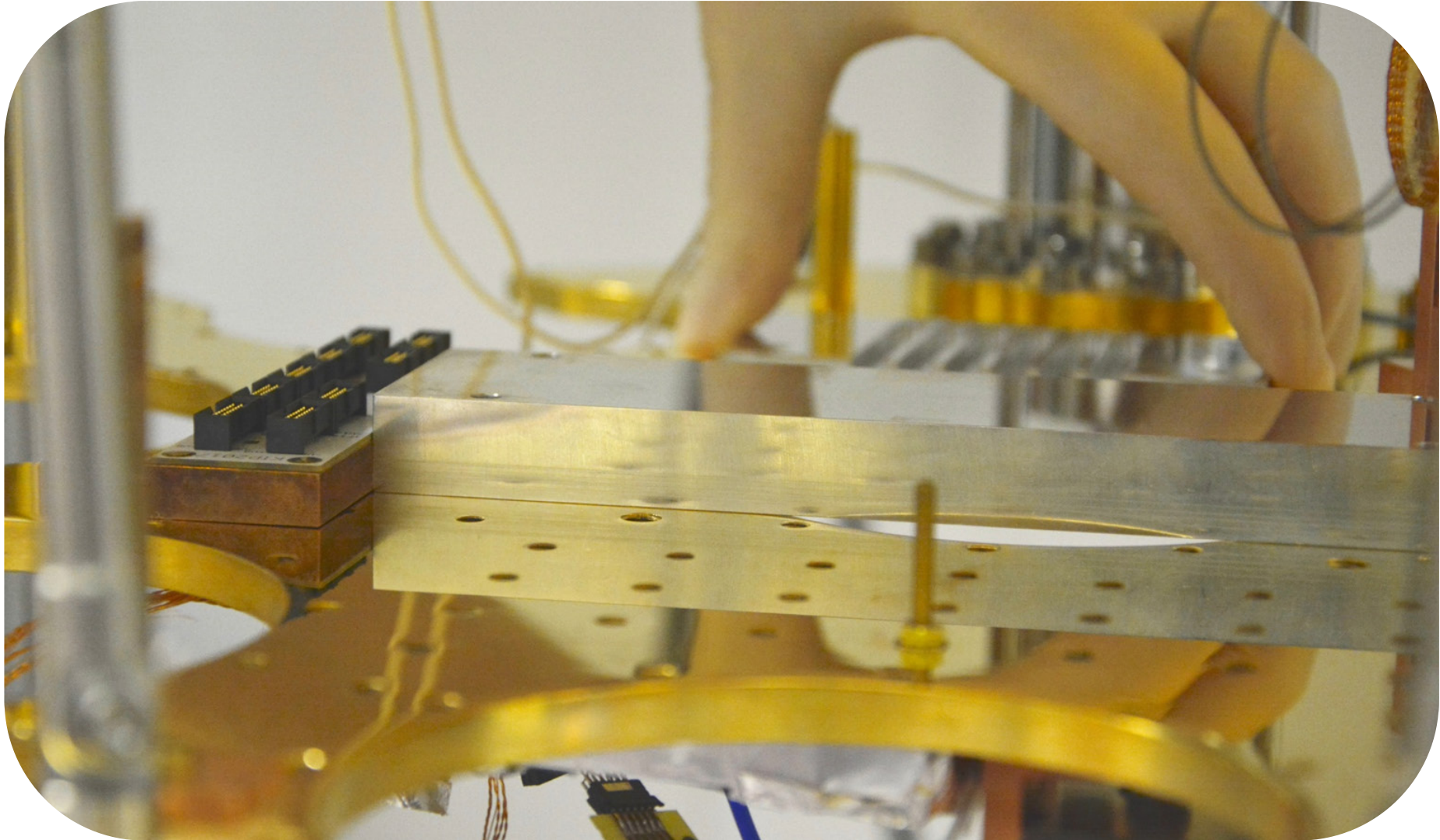
Set-up per ECHo-1k

- ECHo-1k chip impiantato a RISIKO Uni-Mainz
→ ^{163}Ho attività: $A = 2 \text{ Bq}$
- 4 Front-end chips ognuno con 8 dc-SQUIDs

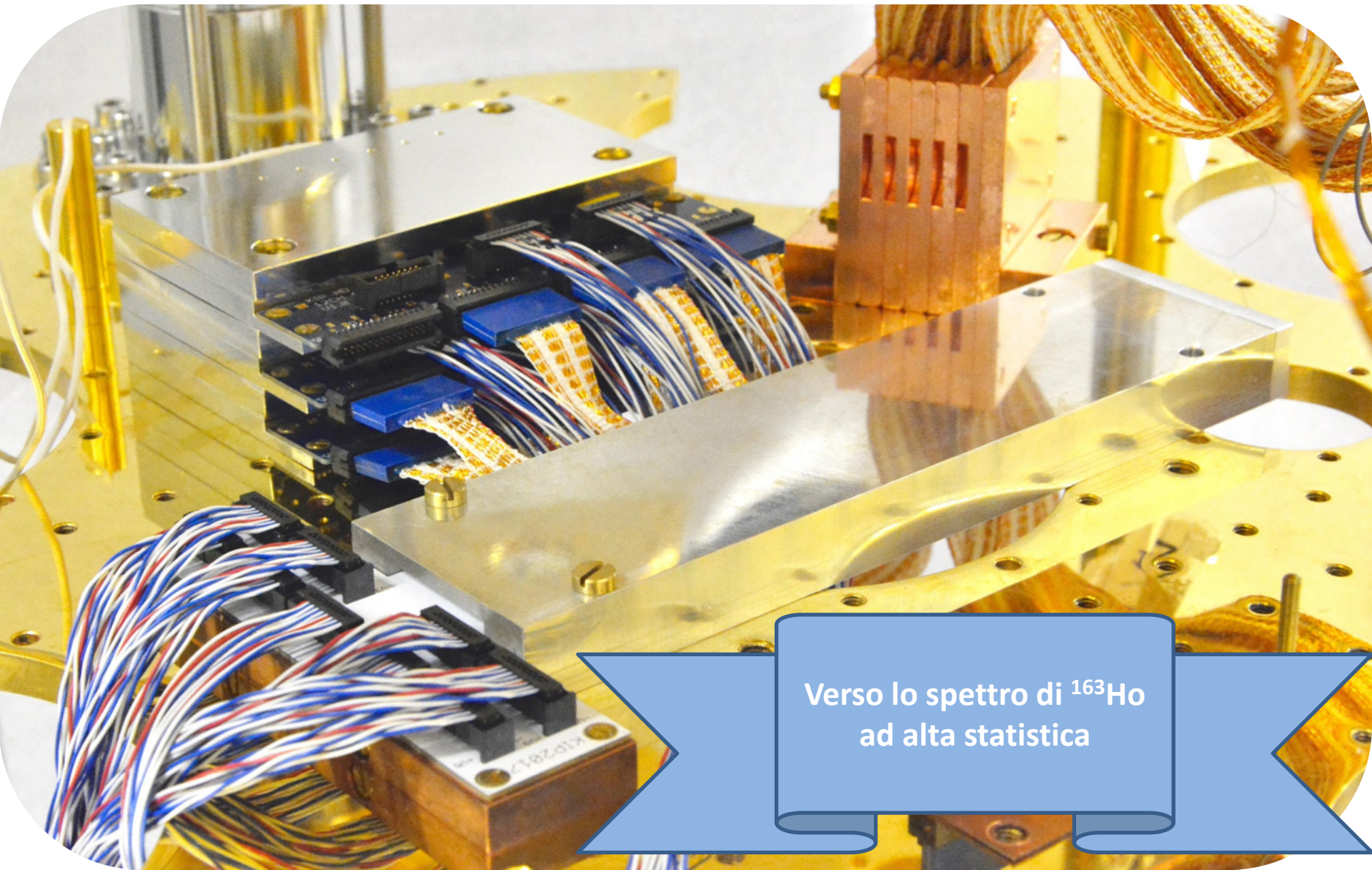


Set-up per ECHO-1k

Schermatura superconduttiva di alluminio



Set-up per ECHo-1k

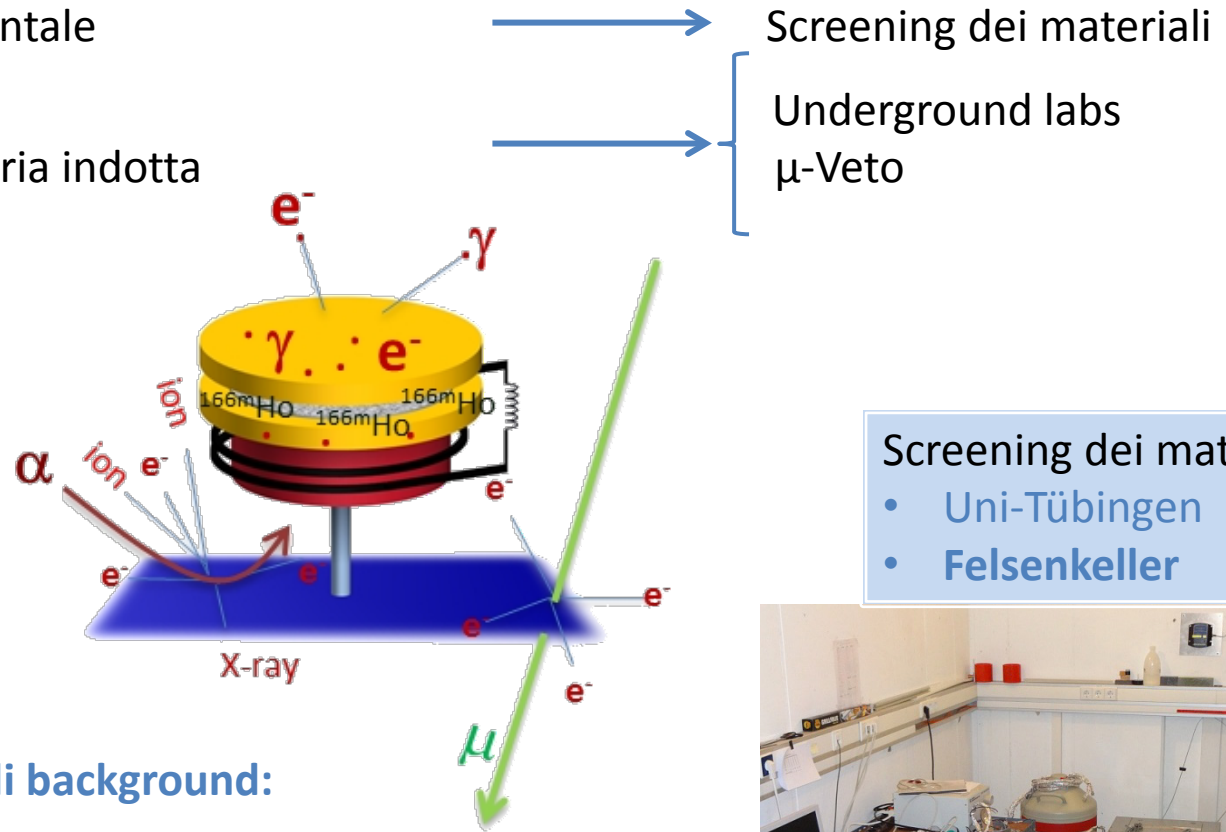


Verso lo spettro di ^{163}Ho
ad alta statistica

Background in ECHO

Sorgenti di background:

- Radioattività nel rivelatore
- Radioattività ambientale
- Raggi cosmici
- Radiazione secondaria indotta

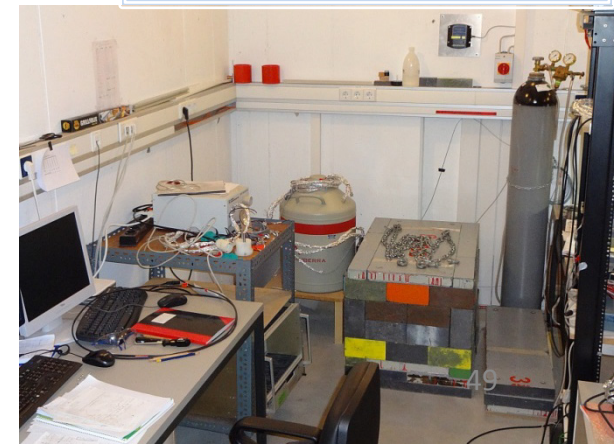


Screening dei materiali

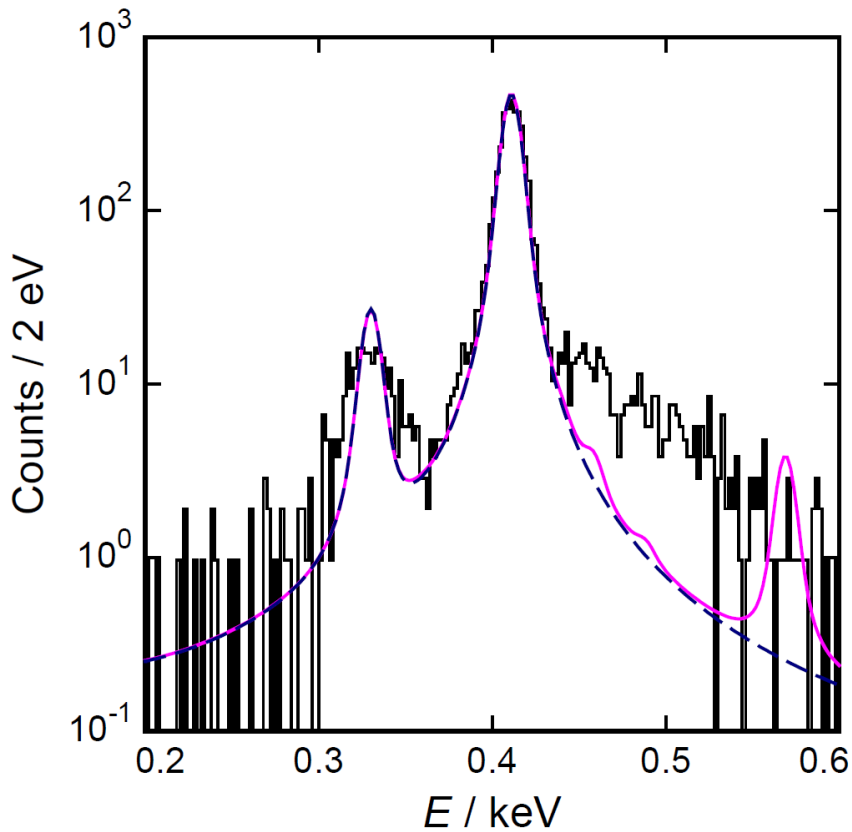
- Uni-Tübingen
- Felsenkeller

Studio delle sorgenti di background:

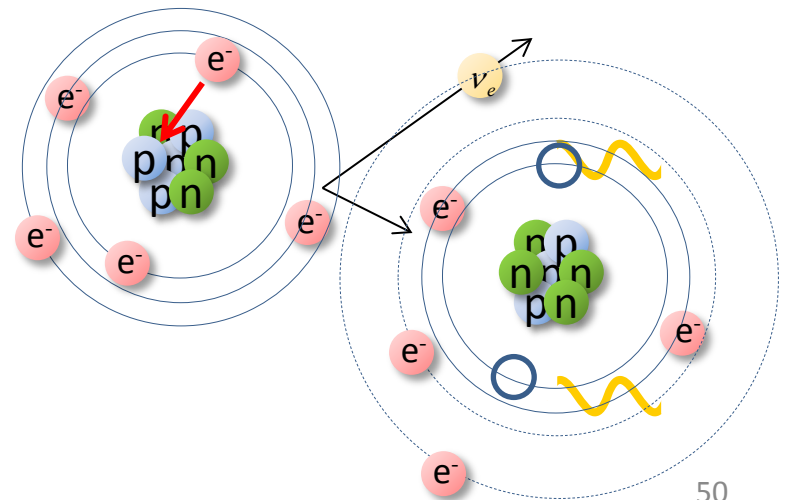
- Simulazioni Monte Carlo
- Esperimenti mirati



Forma dello spettro del ^{163}Ho

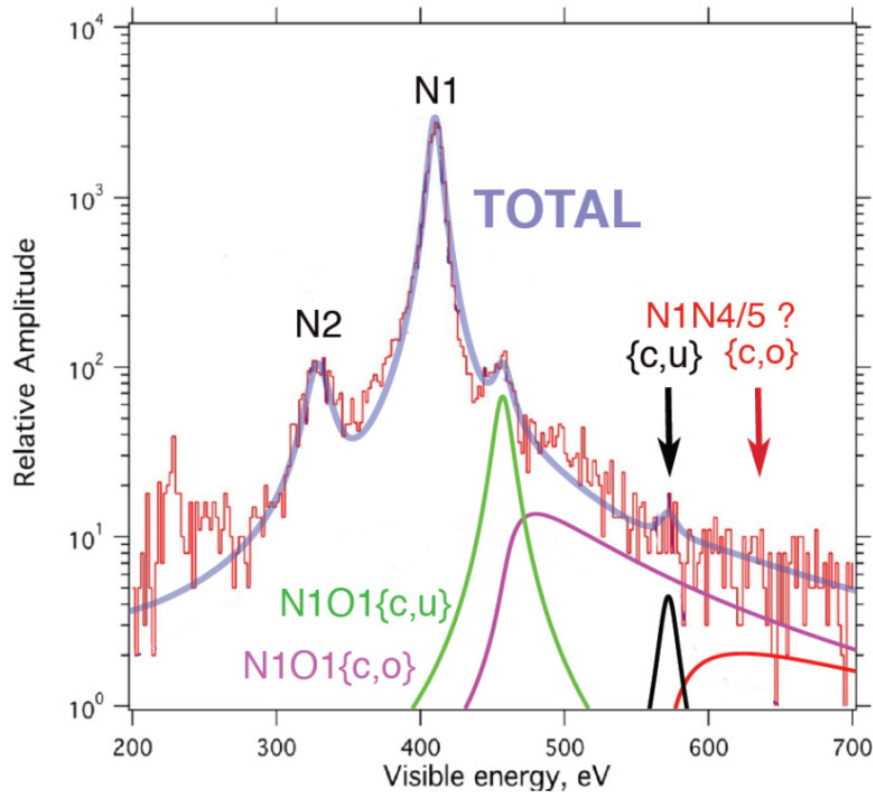


- R. G. H. Robertson
Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
J. Phys. G **42** (2015) 015108
- **A. Faessler and F. Simkovic**
Phys. Rev. C **91**, 045505 (2015)
- A. Faessler et al.
Phys. Rev. C **91**, 064302 (2015)

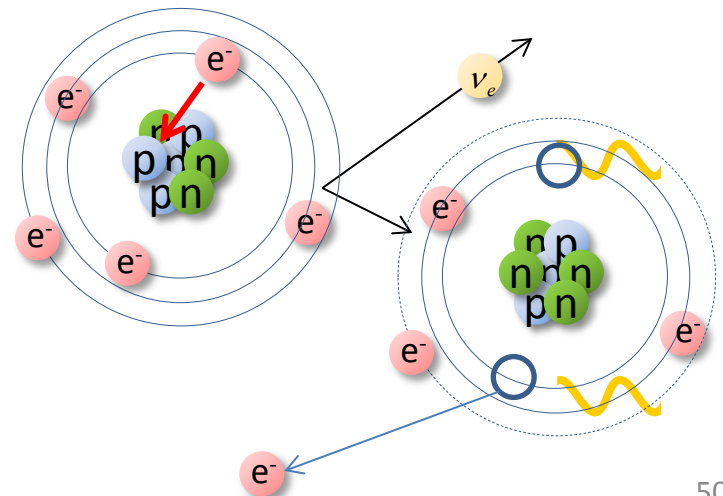


Eccitazioni di shake-up

Forma dello spettro del ^{163}Ho

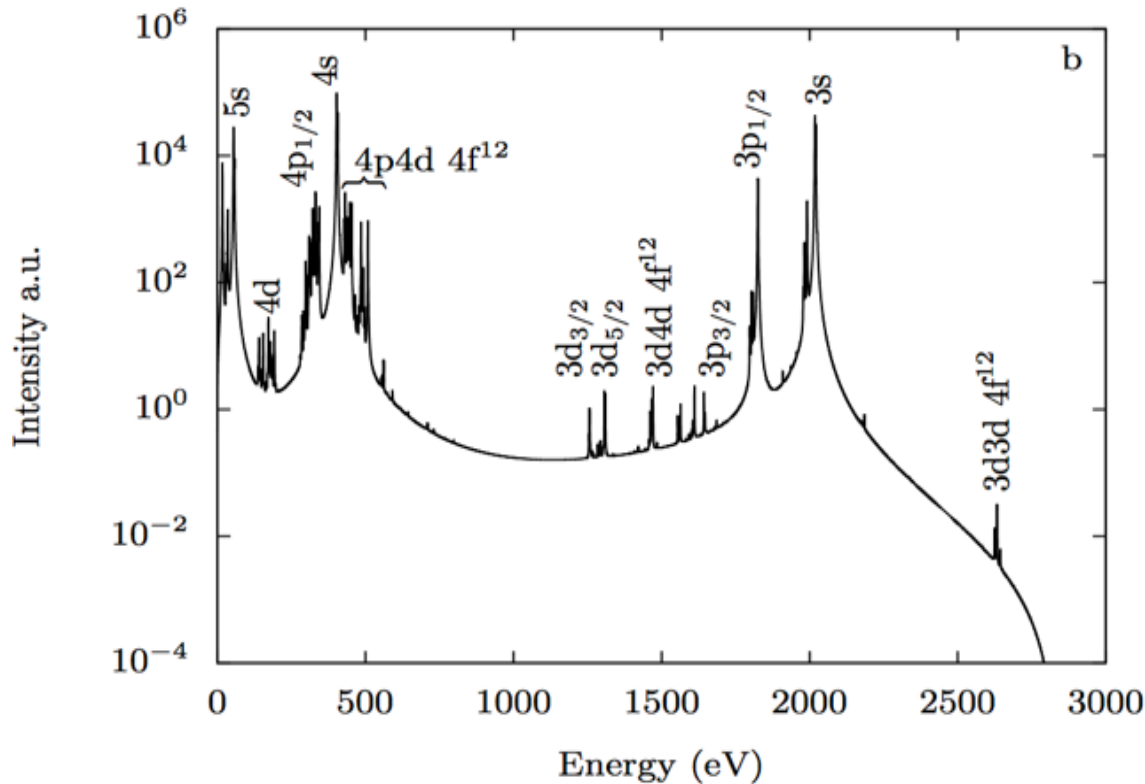


- R. G. H. Robertson
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- A. Faessler et al.
Phys. Rev. C **91**, 064302 (2015)
- **A. De Rujula and M. Lusignoli**
JHEP **05** (2016) 015, arXiv:1601.04990v1
- A. Faessler et al.
Phys. Rev. C **95**, (2017) 045502



Eccitazioni di shake-up
Eccitazioni di shake-off

Forma dello spettro del ^{163}Ho



Nuovo metodo

Calcolo *ab initio* dello spettro di cattura elettronica del ^{163}Ho

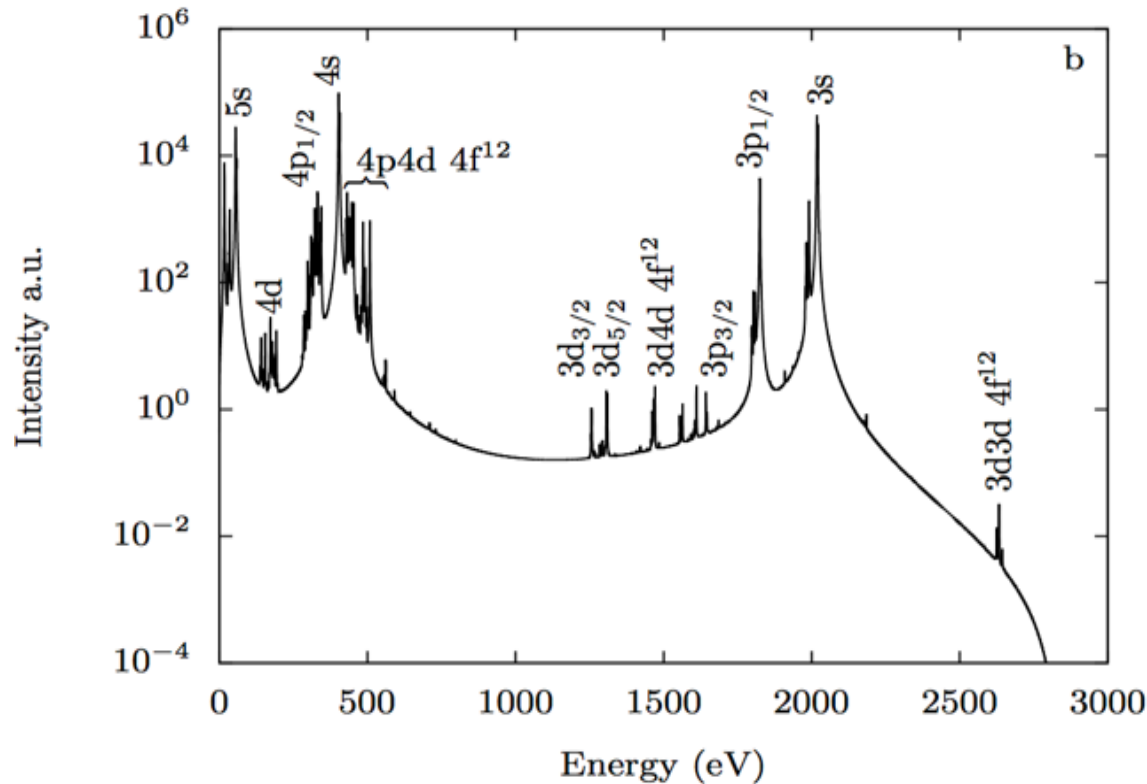
Brass et al., <https://arxiv.org/abs/1711.10309>

$$\frac{dN}{dE} \propto \left| \sum_{\Psi_{\text{Dy}^*+\nu}} \langle \Psi_{\text{Dy}^*+\nu} | T | \Psi_{\text{Ho}} \rangle \right|^2 \delta(E_{\text{Ho}}, E_{\text{Dy}^*} + E_{\nu})$$

Ψ_{Ho} many body ground state dell'atomo ^{163}Ho $\Psi_{\text{Ho}} = \Phi_{z=67} \times \psi_{\text{Ho}}^{e^-}$

$\Psi_{\text{Dy}^*+\nu}$ uno dei tanti stati eccitati dell'atomo Dy e il neutrino emesso $\Psi_{\text{Dy}^*+\nu} = \Phi_{Z=66} \times \psi_{\text{Dy}^*}^{e^-} \times \varphi_{\nu}$

Forma dello spettro del ^{163}Ho



Nuovo metodo

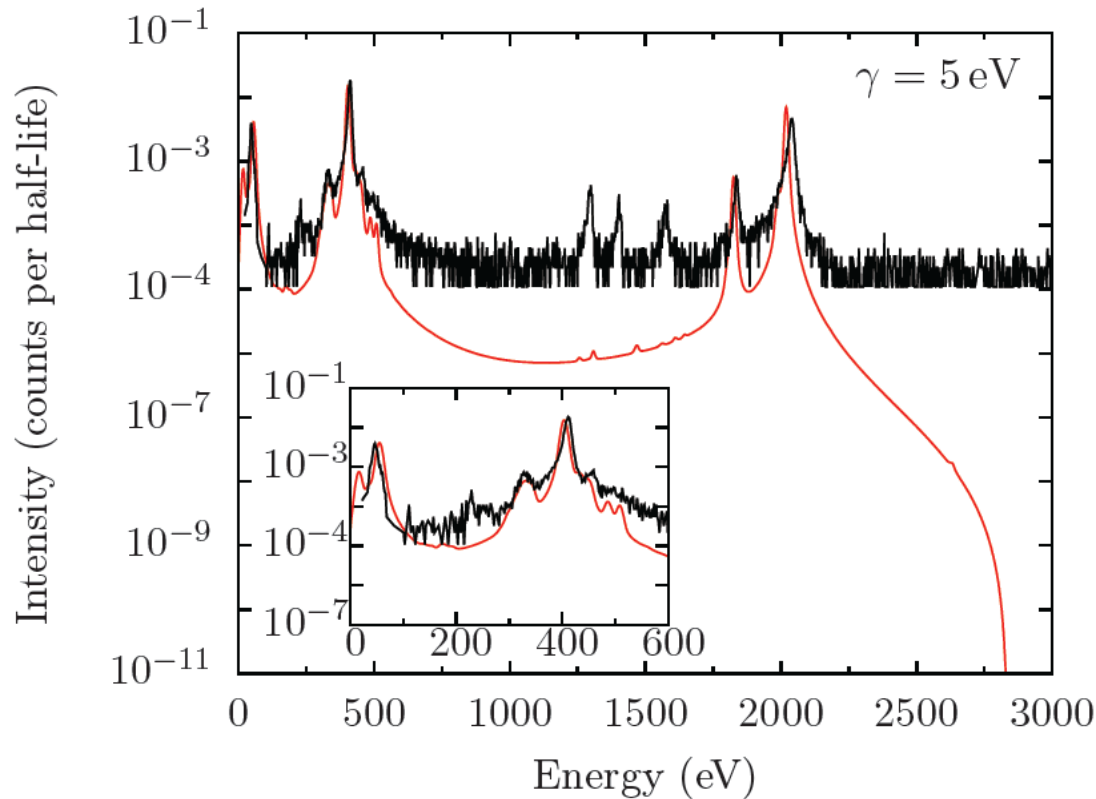
Calcolo *ab initio* dello spettro di cattura elettronica del ^{163}Ho

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

$$\frac{dN}{dE} \propto \left| \sum_{\Psi_{Dy^{*+v}}} \langle \Psi_{Dy^{*+v}} | T | \Psi_{Ho} \rangle \right|^2 \delta(E_{Ho}, E_{Dy^*} + E_v)$$

$$\frac{dN}{dE} \propto \left| \sum_{\Psi_{Dy^*}} \langle \Psi_{Dy^*}^{e^-} | T | \Psi_{Ho}^{e^-} \rangle \right|^2 \times \delta(\omega - E_{Dy^*} + E_{Dy}) (Q - \omega) \sqrt{(Q - \omega)^2 - m_v^2}$$

Forma dello spettro del ^{163}Ho



Nuovo metodo

Calcolo *ab initio* dello spettro di cattura elettronica del ^{163}Ho

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

Solo stati legati sono inclusi nel calcolo →
lo spettro consiste di un numero finito di risonanze

- Includere decadimenti nel continuo
- Studiare l'effetto del host metallico

Conclusioni e prospettive

La collaborazione ECHo ha lo scopo di investigare la massa del neutrino elettronico sotto 1 eV

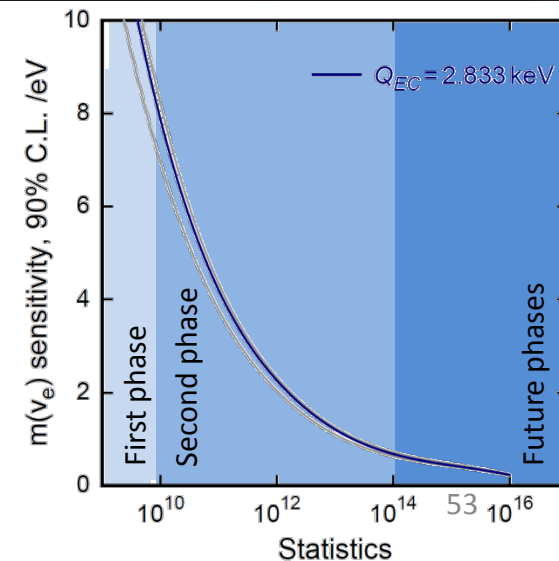
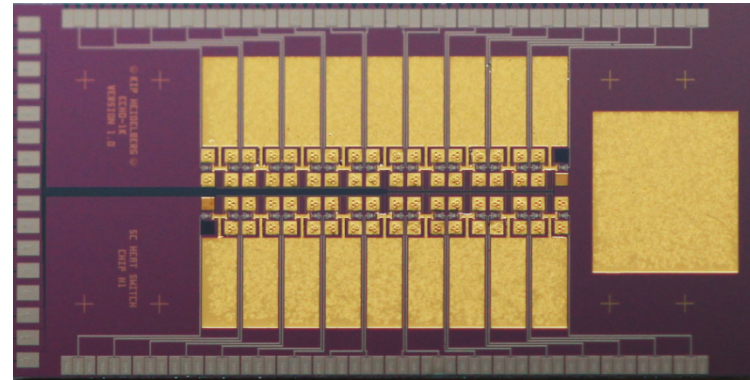
- Il valore Q_{EC} del ^{163}Ho è stato precisamente misurato

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

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

- Sorgenti di ^{163}Ho ad alta purezza sono state prodotte
- Ioni di ^{163}Ho possono efficacemente essere impiantati in assorbitori si microcalorimetri
- Array sono stati sviluppati e testati e **microwave SQUID multiplexing** è stato dimostrato
- **Migliore** accordo tra modelli teorici dello spettro e dati ma non ancora perfetto
- **Presto nuovo limite sulla massa del neutrino elettronico**

Er161 3.21 h 3/2-	Er162 0+	Er163 75.0 m 5/2-	Er164 0+	Er165 10.36 h 5/2-	Er166 0+
EC	0.14	EC	1.61	EC	33.6
Ho160 25.6 m 5+	Ho161 2.48 h 7/2- *	Ho162 15.0 m 1+ *	Ho163 4570 y 7/2- *	Ho164 29 m 1+ *	Ho165 7/2-
EC	EC	EC	EC	EC,β	100



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Goethe Universität Frankfurt am Main

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Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz

Christoph E. Düllmann, Klaus Eberhardt, Holger Dorrer, Fabian Schneider

Institute of Nuclear Research of the Hungarian Academy of Sciences

Zoltán Szúcs

Institute of Nuclear and Particle Physics, TU Dresden, Germany

Alexander Domula, Kai Zuber

Institute for Physics, Humboldt-Universität zu Berlin

Alejandro Saenz

Institute for Physics, Johannes Gutenberg-Universität

Klaus Wendt, Sven Junck, Tom Kieck

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Martin Brass, Maurits Haverkort

Institute for Theoretical Physics, University of Tübingen, Germany

Amand Fäßler

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ISOLDE-CERN

Marsh Bruce, Day Goodacre Tom, Johnston Karl, Rothe Sebastian,

Stora Thierry, Veinhard Matthieu

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Clemens Hassel, Sebastian Kempf, Federica Mantegazzini, Mathias Wegner

Max-Planck Institute for Nuclear Physics Heidelberg, Germany

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

Yuri N. Novikov, Alexander Rischka, Rima Schüssler

Petersburg Nuclear Physics Institute, Russia

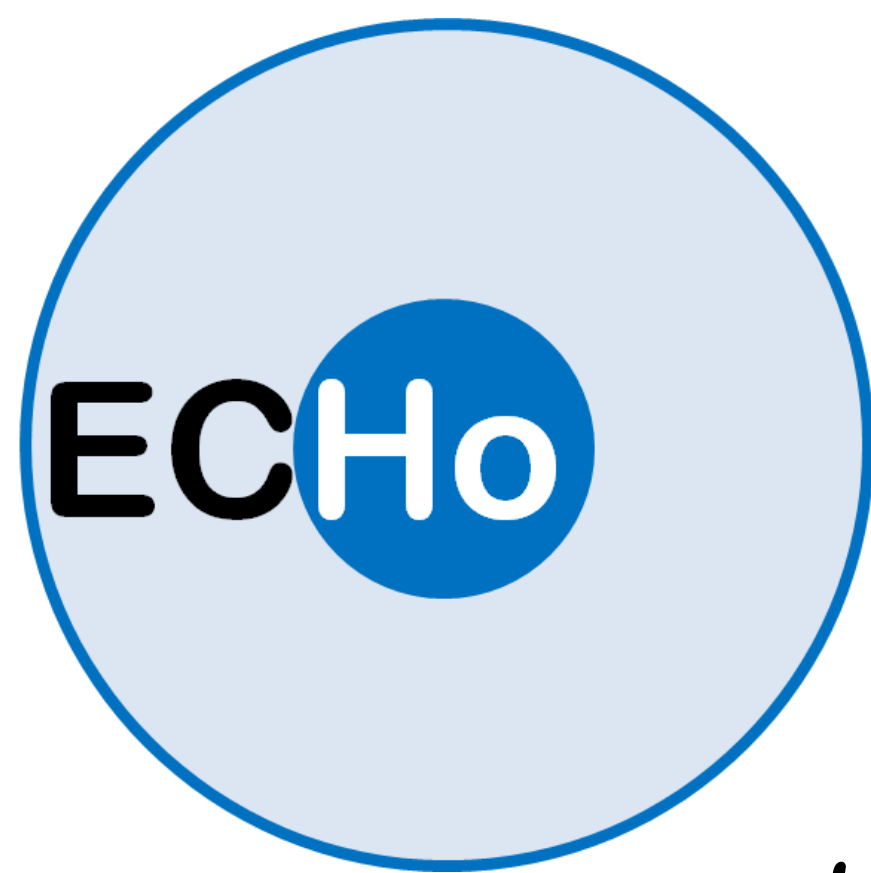
Yuri Novikov, Pavel Filianin

Physics Institute, University of Tübingen, Germany

Josef Jochum, Stephan Scholl

Saha Institute of Nuclear Physics, Kolkata, India

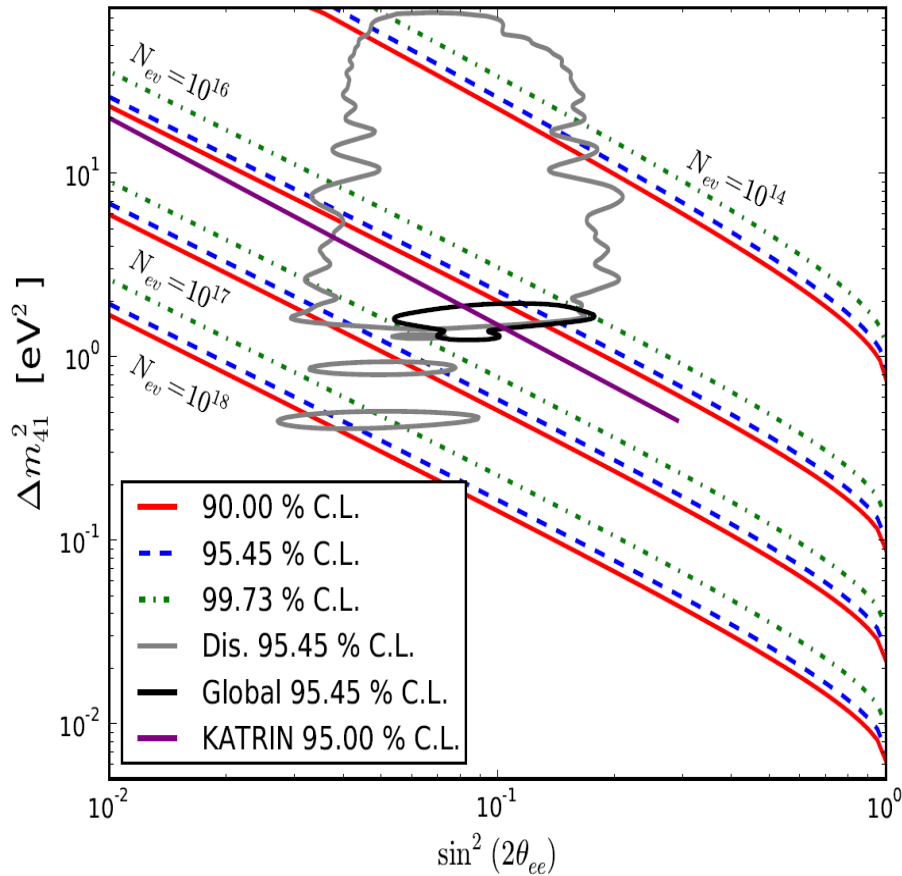
Susanta Lahiri



Grazie per l'attenzione!

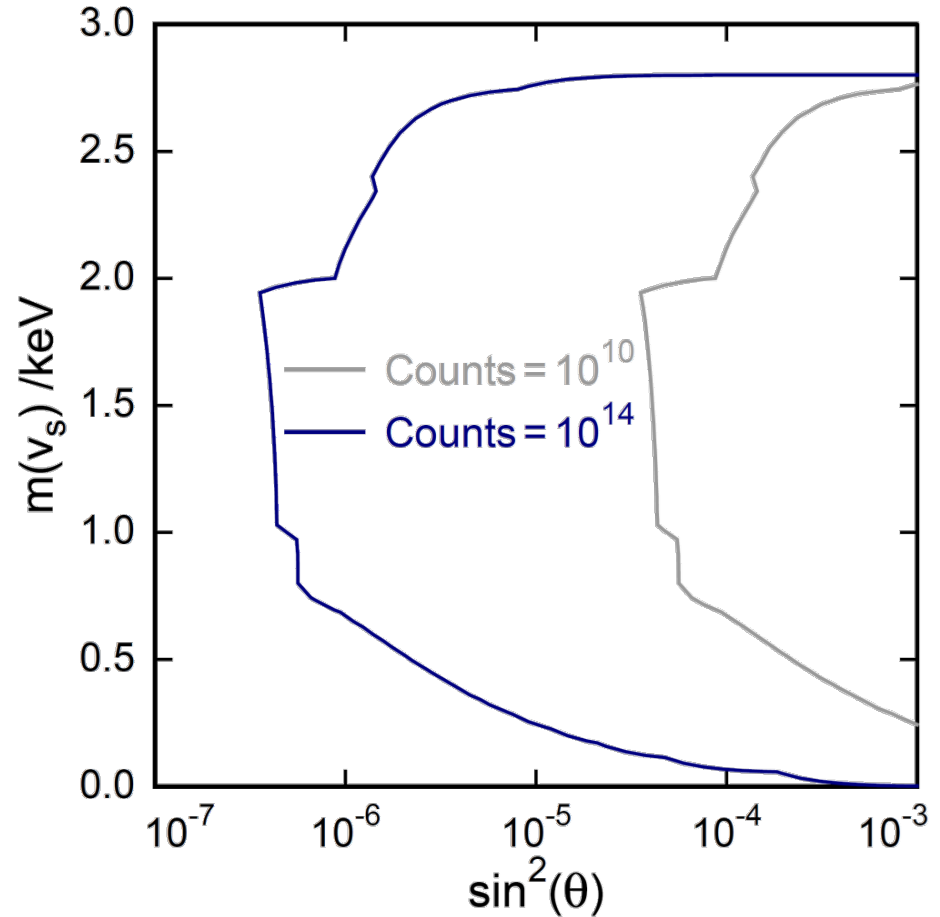
Ricerca di neutrini sterili in ECHO

Neutrini sterili con masse $\sim eV$



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

Neutrini sterili con masse $\sim keV$



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

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

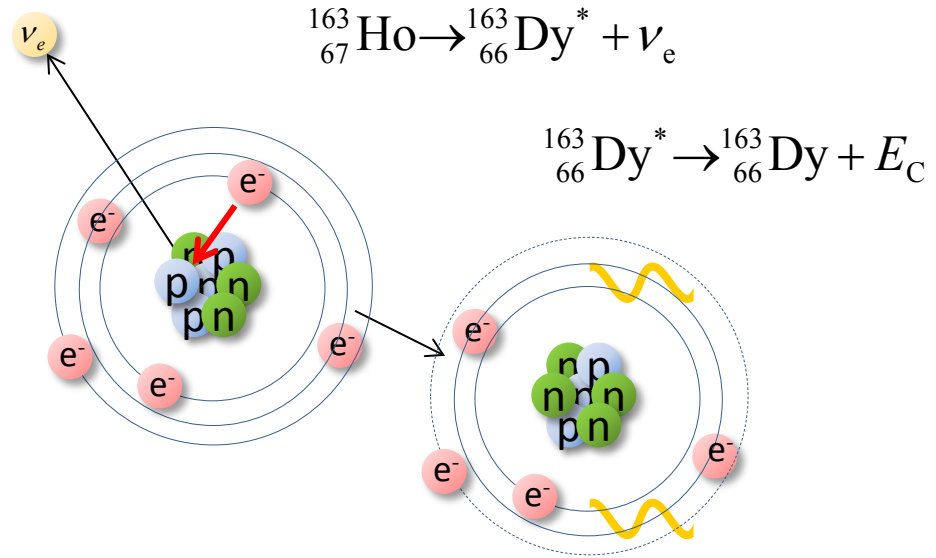
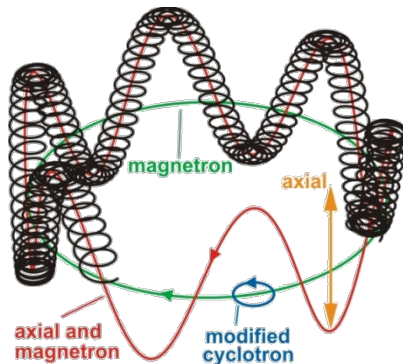
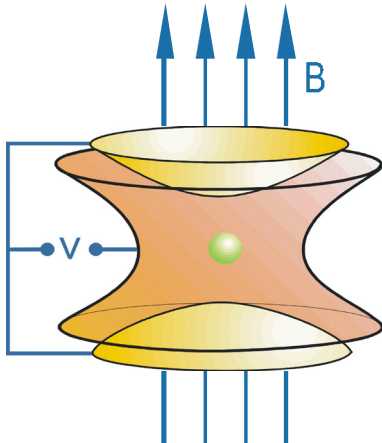
- Calorimetric measurements
- Measurements of x-rays
- ★ $Q_{\text{EC}} = m(^{163}\text{Ho}) - m(^{163}\text{Dy})$

Penning Trap Mass Spectroscopy

@TRIGA TRAP (Uni-Mainz) (*)

@SHIPTRAP (GSI – Darmstadt) (**)

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



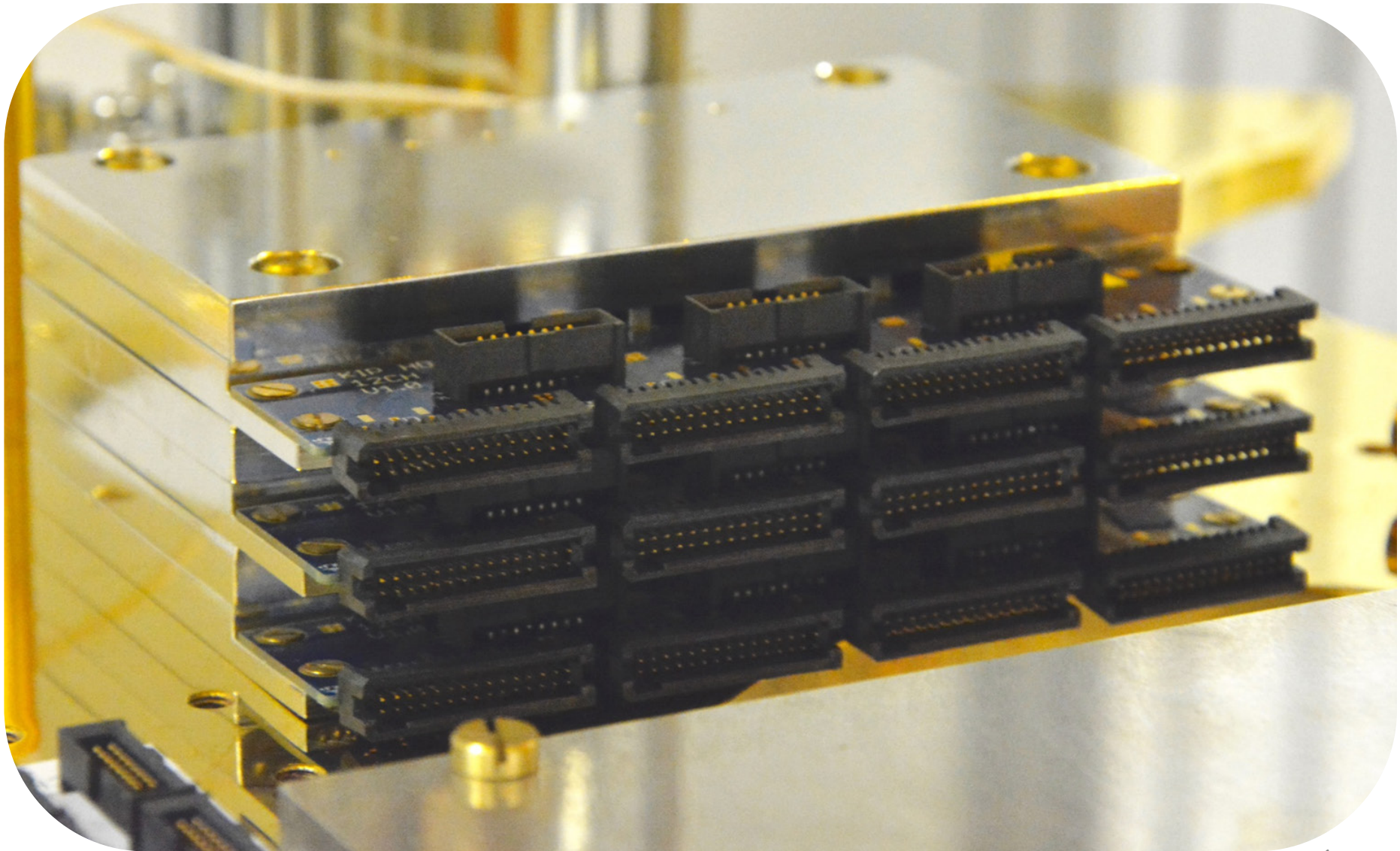
• $\tau_{1/2} \cong 4570 \text{ years}$ ($2 \cdot 10^{11}$ atoms for 1 Bq)

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

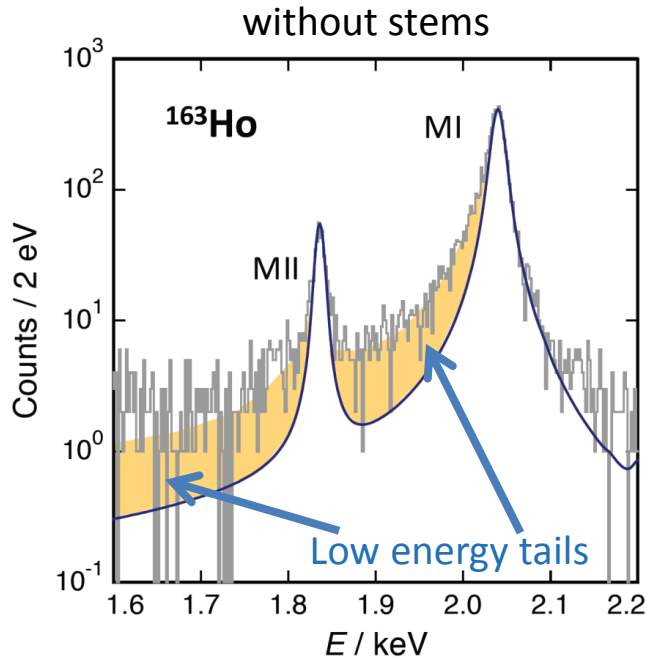
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501 (**)

F. Schneider et al., *Eur. Phys. J. A* **51** (2015) 89 (*)

EChO set-up

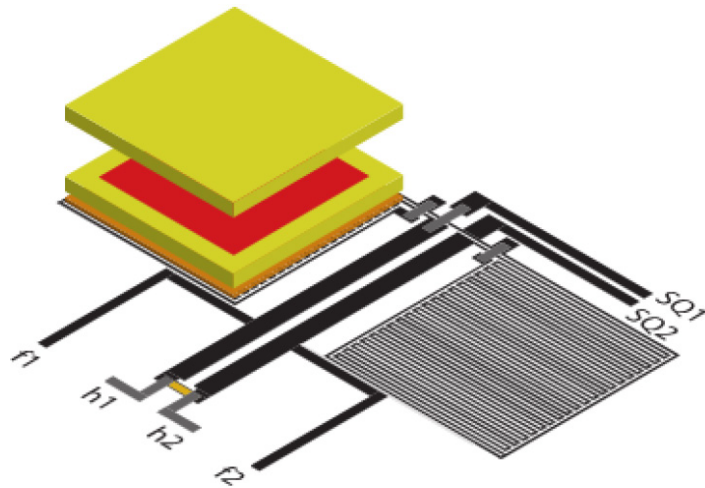


Enclosing ^{163}Ho in MMC absorbers

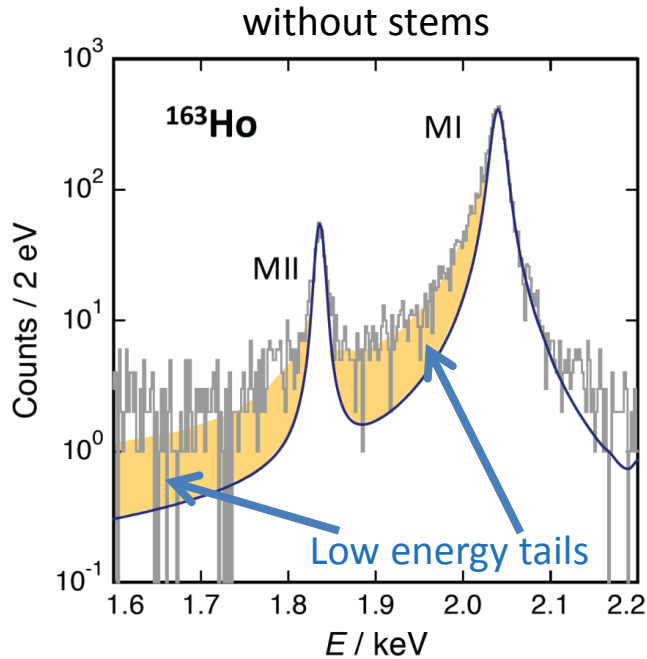


ECHo-0 detector showed **asymmetric detector response**

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



Enclosing ^{163}Ho in MMC absorbers

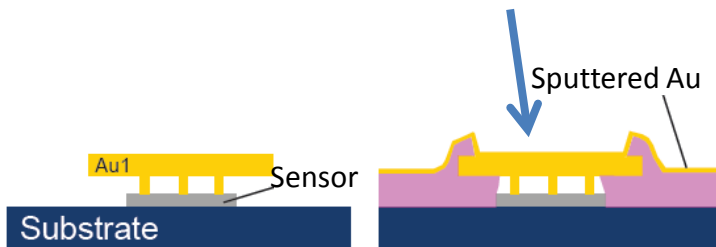


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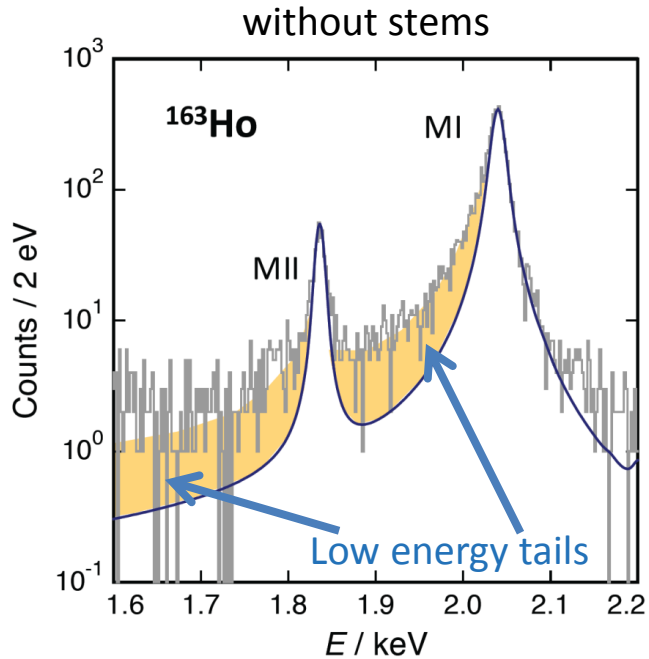
- Loss of high energy phonons to the substrate
- full contact between sensor and absorber

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

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



Enclosing ^{163}Ho in MMC absorbers

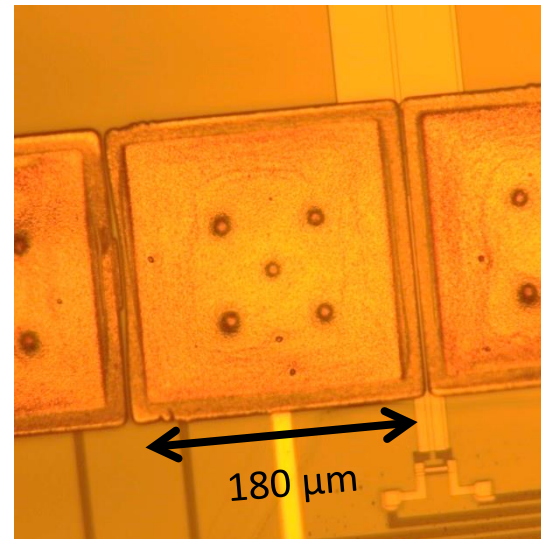
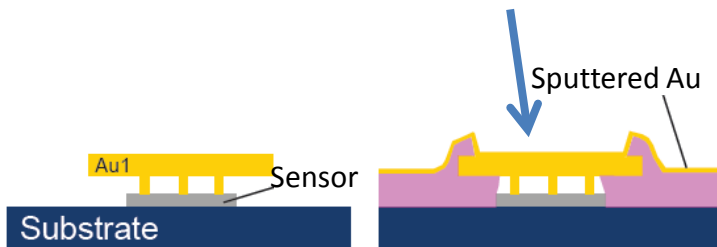


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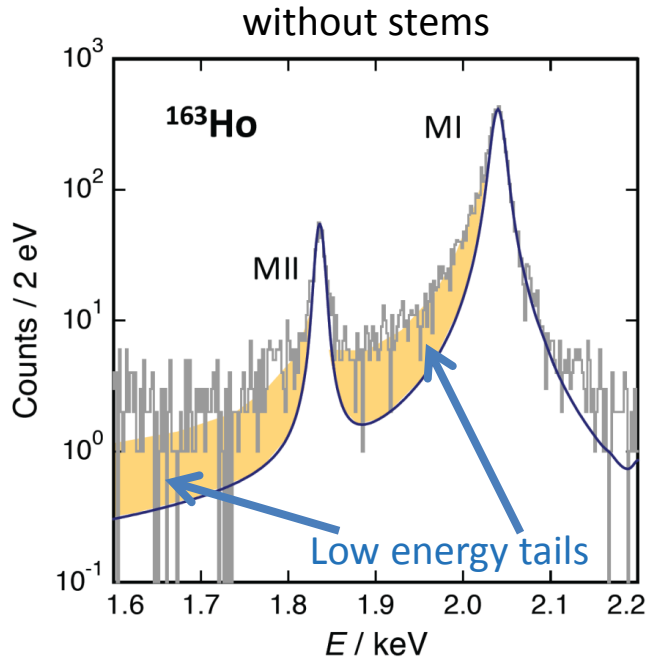
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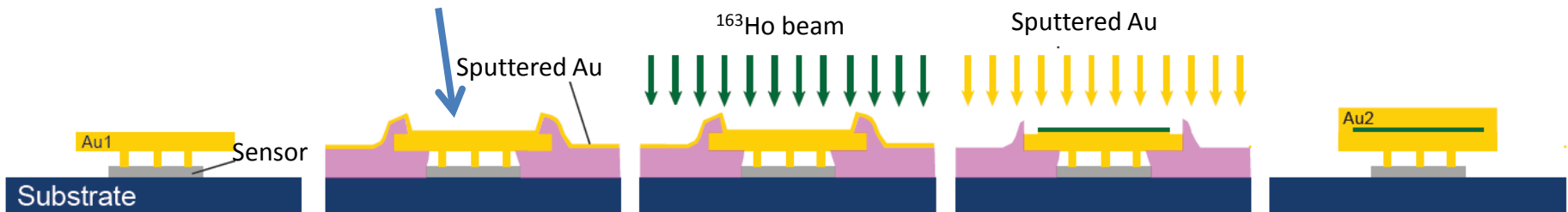


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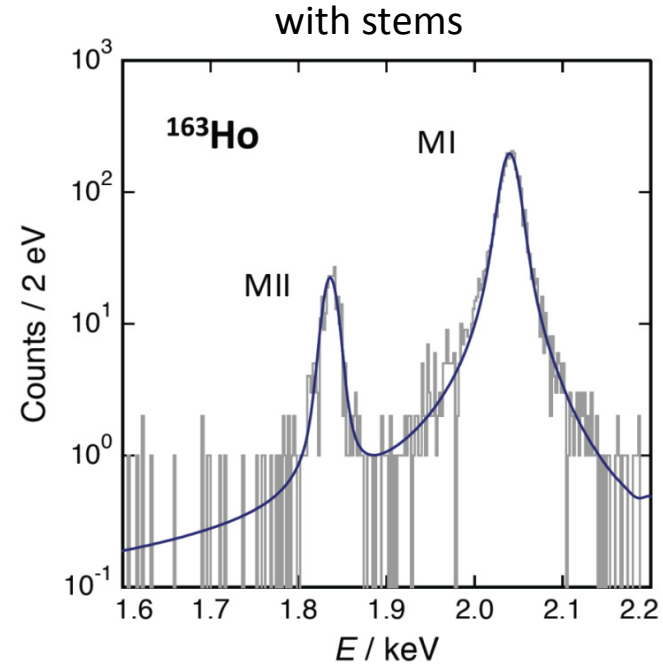
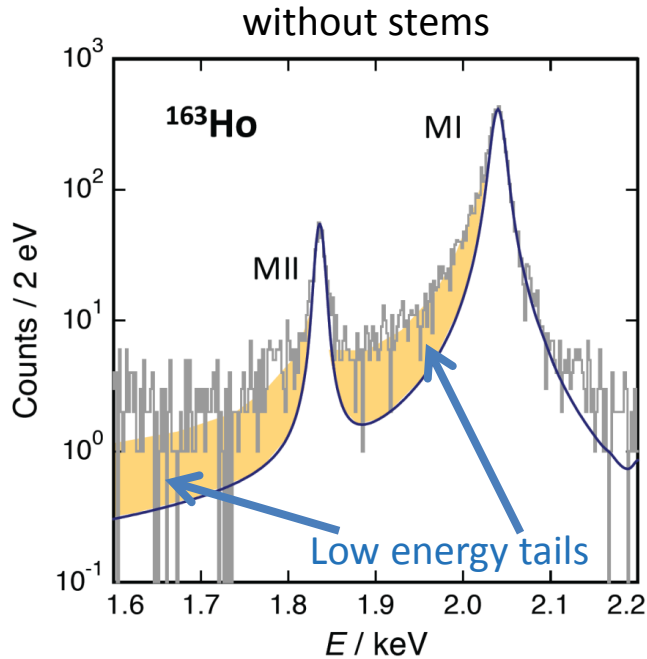
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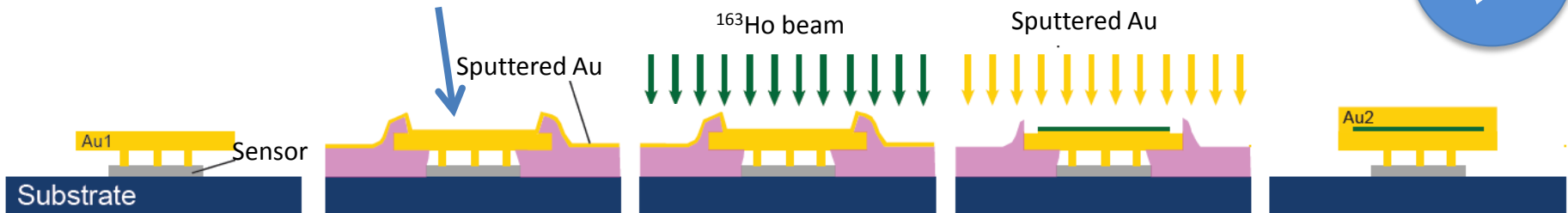
Definition of the **implantation area** by microstructuring a photoresist layer on overhanging absorbers



Enclosing ^{163}Ho in MMC absorbers



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



Symmetric detector response



Background in ECHO

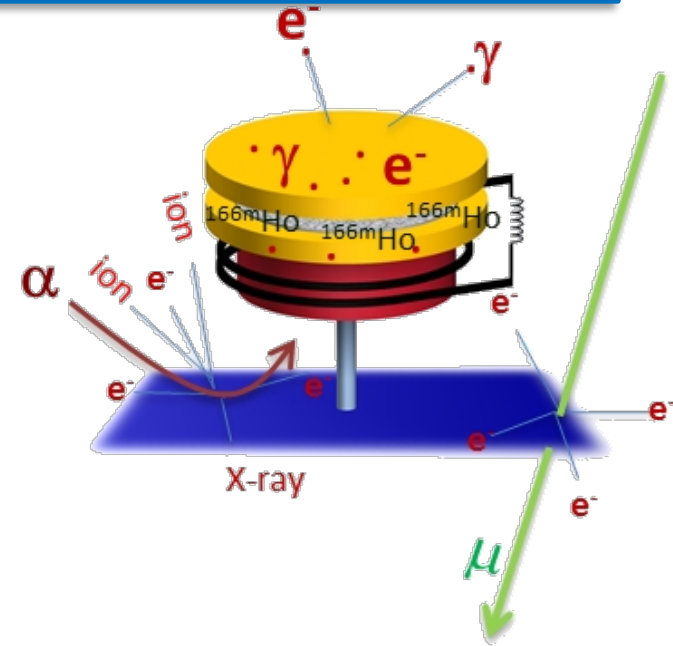
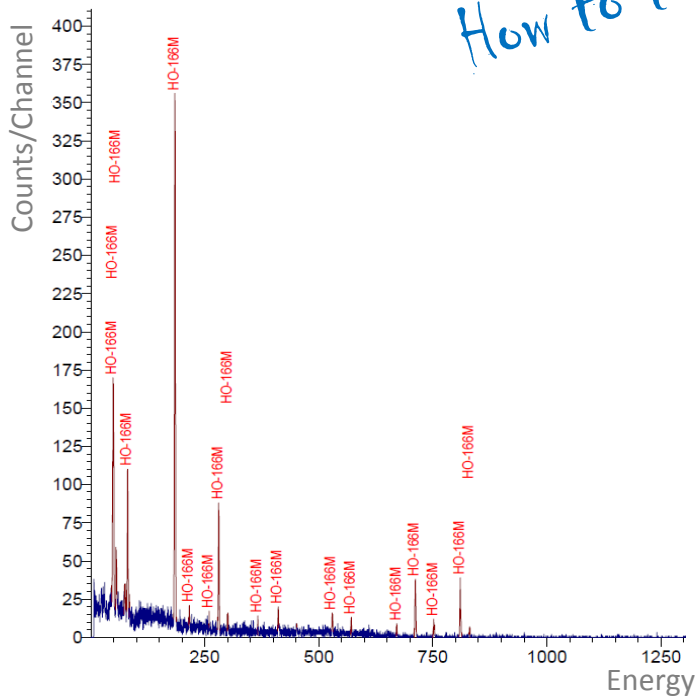
Background sources:

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

RISIKO @ Physics Institute, Mainz University

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

How to test??



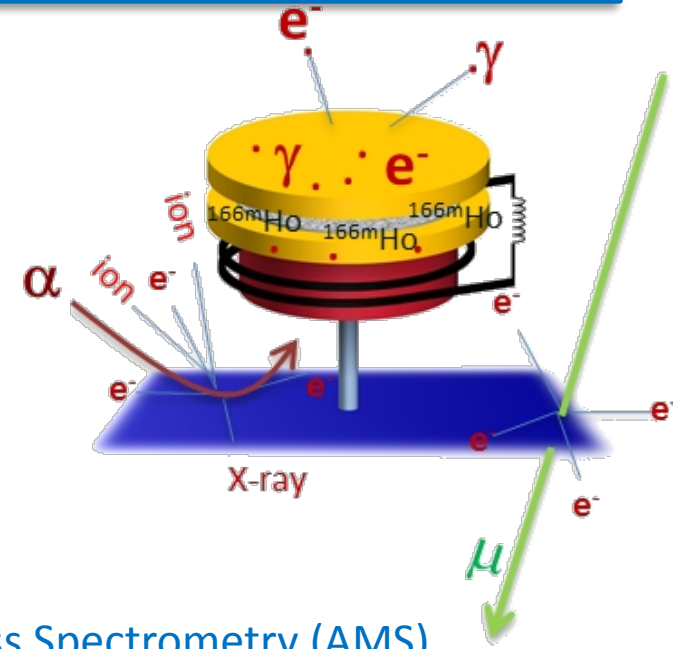
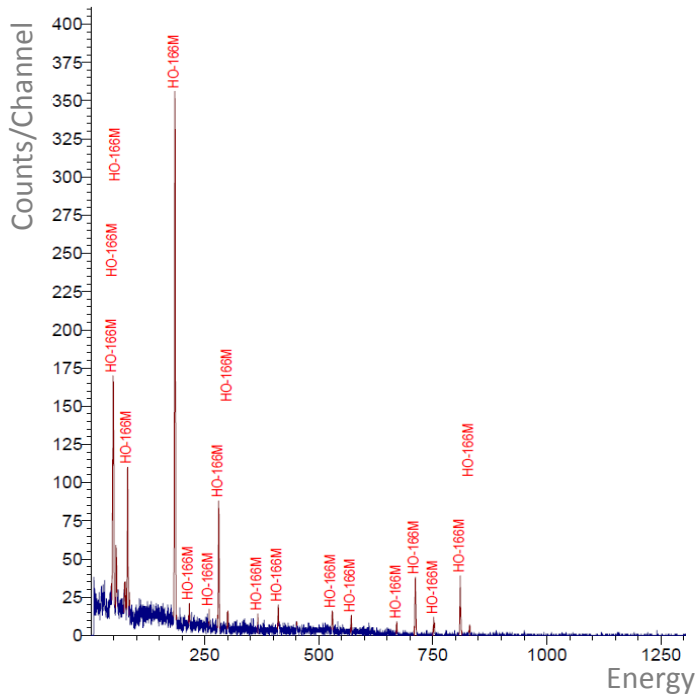
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Accelerator Mass Spectrometry (AMS)
is a very powerful technique for measuring the
corresponding very low isotopic ratio