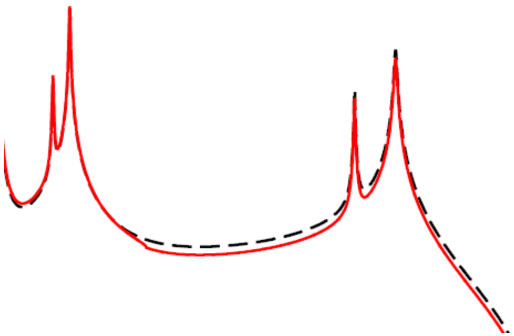
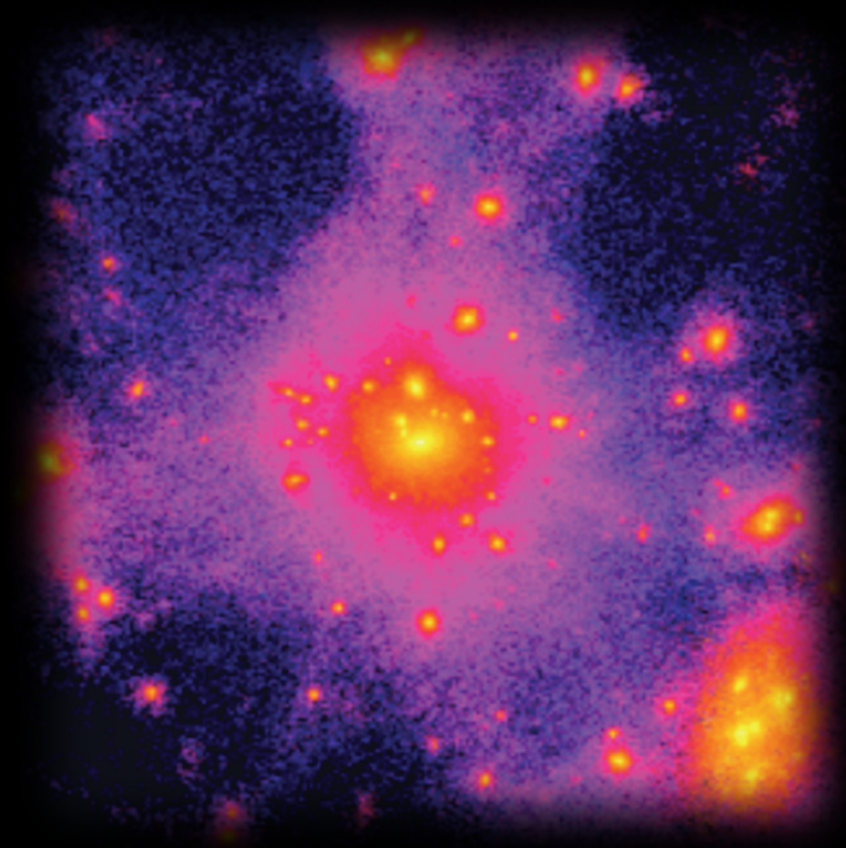
Neutrino dark matter from an experimental perspective



Loredana Gastaldo
Kirchhoff Institute for Physics, Heidelberg University

Contents

- Neutrinos as Dark Matter candidates
- Astrophysical and cosmological evidences
- Signature of keV sterile neutrinos in direct neutrino mass measurements
  - ECHo
  - KATRIN
- Conclusions and outlook



Evidence of Dark Matter

- The dynamics of galaxies and galaxy clusters cannot be explained by the Newtonian potential created by visible matter
- Cosmic large scale structures started to develop much before the decoupling of photons → much before ordinary matter could start clustering

➢ Dark Matter represents ~25% of the total energy density of the Universe

➢ Most plausible hypothesis: Dark Matter is composed by new particle(s)

Dark Matter models

Cold Dark Matter Model

→ DM particles decouple non-relativistically

→ Structure formation: small scale objects form first and then merge into larger ones

→ CDM models fit cosmological data well!

Hot Dark Matter Model

→ DM particles are produced relativistically and remain relativistic into the matter dominated epoch

→ structure formation: the first structure to collapse have size comparable to the Hubble size

→ HDM models contradict large-scale structures

Warm Dark Matter Model

→ DM particles are produced relativistically and become non-relativistic in the radiation dominated epoch

→ Structure formation: similar to CDM above the free streaming length, below this scale density fluctuations are suppressed

SM Neutrinos (1)

The only electrically neutral and long leaving Standard Model partcles are **neutrinos**

Neutrinos are **massive** particles

interacts **weakly**

→ in the early universe neutrinos are in thermal equilibrium down to temperature of a few MeV

→ background of relic neutrinos was created before primordial nucleosynthesis

SM Neutrinos (2)

- To describe the whole Dark Matter, the mass of neutrinos should be **~10 eV**
- Tremain-Gunn bound gives a lower limit for fermion DM particles $m(\nu) > 10\text{-}100$ eV

→ Contradiction with present limits

$\Sigma m_i < 1$ eV	Cosmology
$m(\nu_e) < 2$ eV	Direct measurement (^3H)

- Neutrino mass much smaller than decoupling temperature → neutrinos decouple relativistically and become non-relativistic only deeply in matter dominated epoch
  → hot Dark Matter excluded by structure formation

Standard model elementary particles cannot describe Dark Matter

Fermionic Dark Matter

- Lower limit for the mass is given by Tremain-Gunn bound
- Not necessarlily stable, but half-life significantly longer than the age of the Universe
- DM particles should have become non-relativistic sufficiently early in the radiation dominated epoch (- sub-dominat fraction)

Candidates

Weakly Interacting Massive Particles

Cold Dark Matter

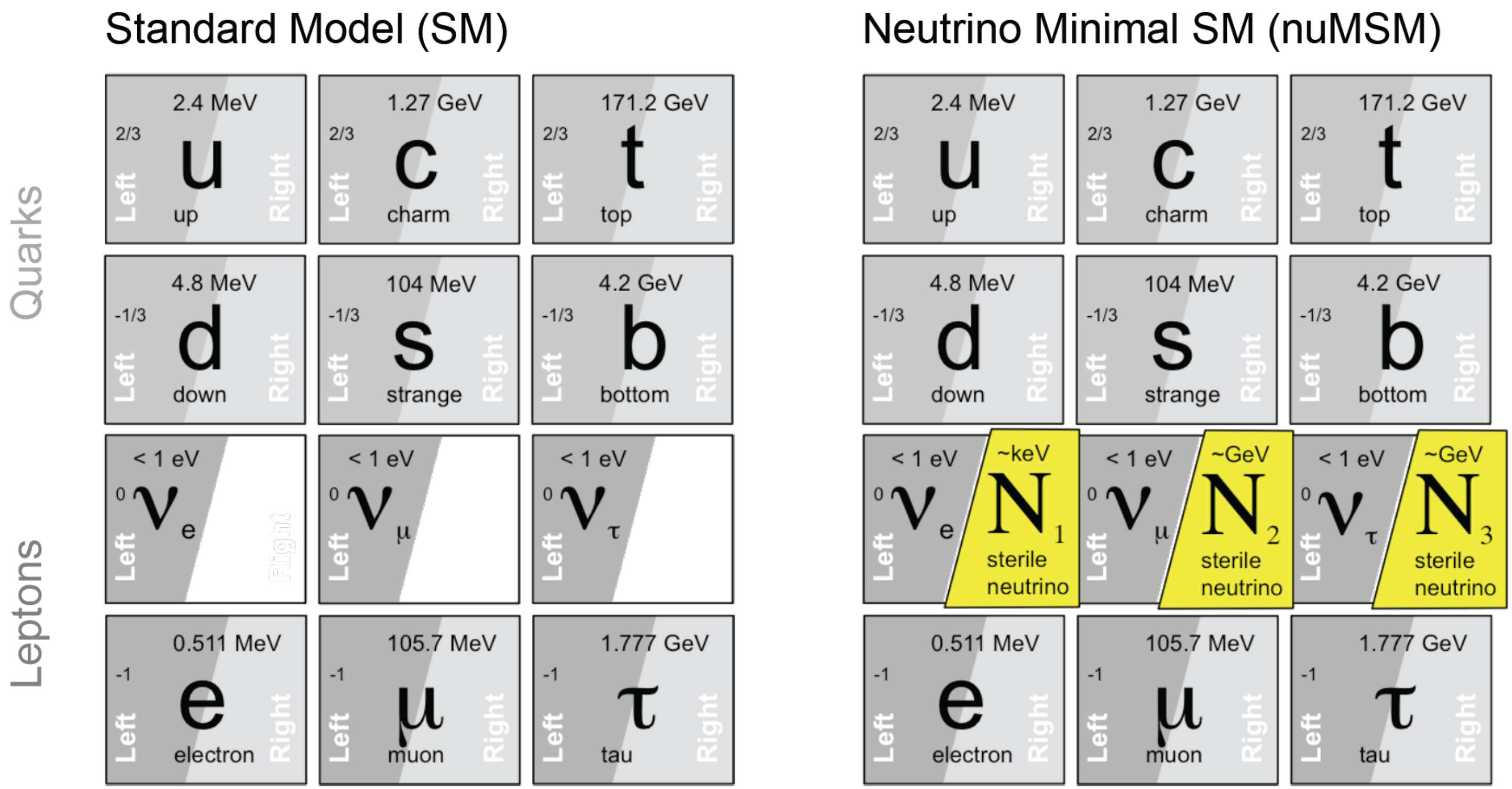
Foreseen in the Supersymmetric extension of the Standard Model

Good agreement with observations

Sterile neutrinos

Warm Dark Matter

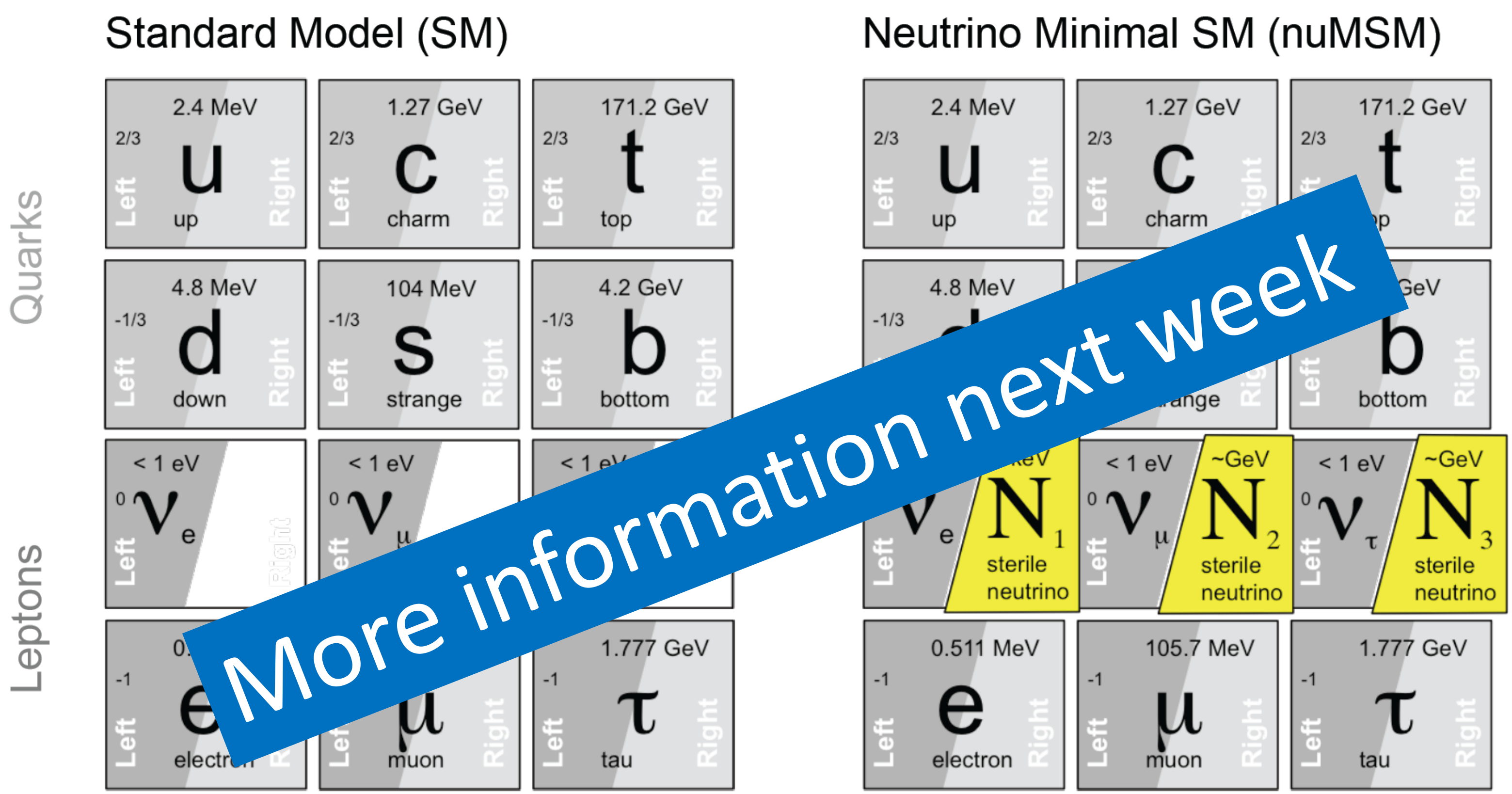
Sterile neutrinos



In order to explain dark matter and active neutrino masses, the minimal model contains three right-handed neutrinos

L. Canetti, M. Drewes, and M. Shaposhnikov, PRL **110** 061801 (2013)

Sterile neutrinos



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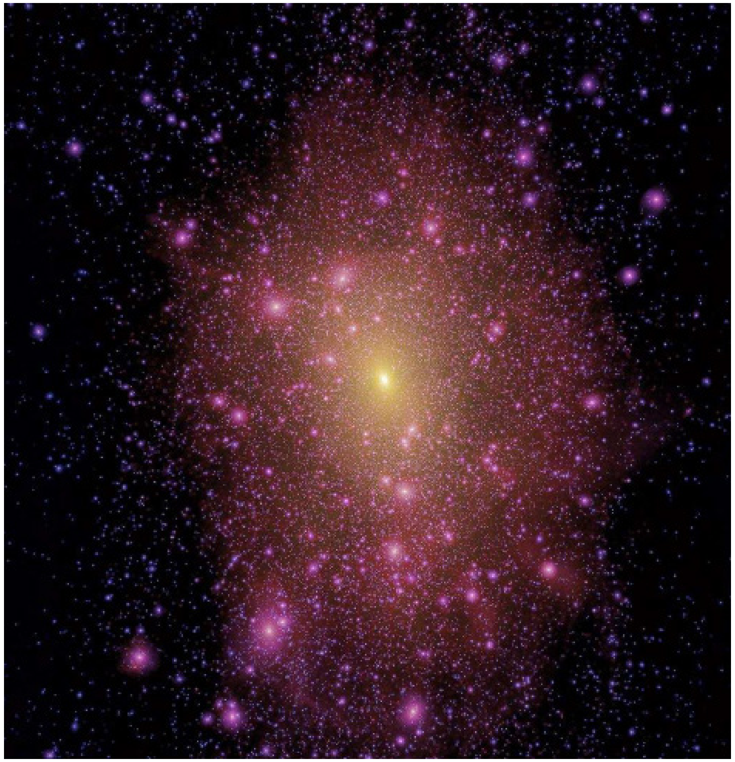
Sterile neutrinos as warm Dark Matter

COLD DM models predict millions of sub-structures within a galaxy like Milky Way



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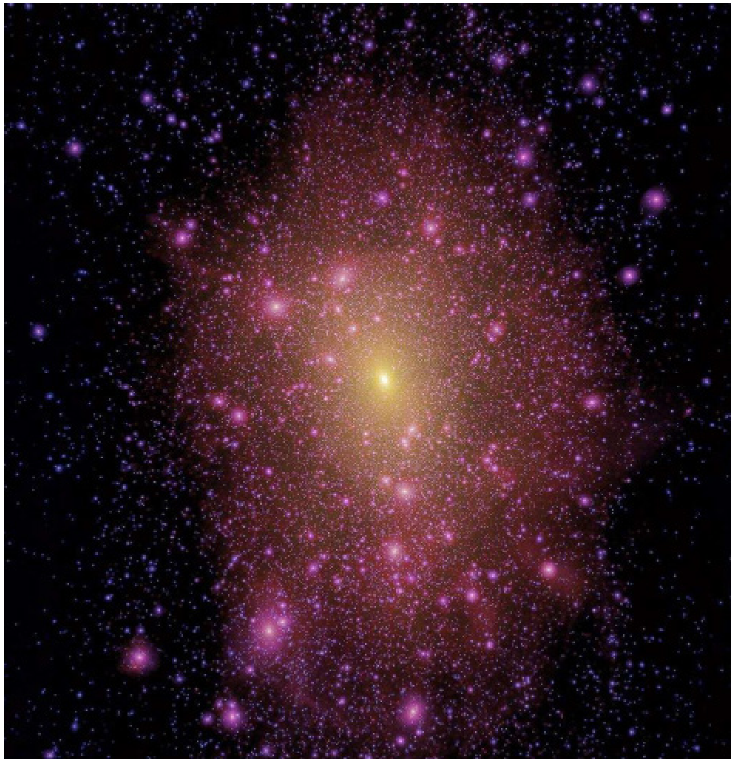
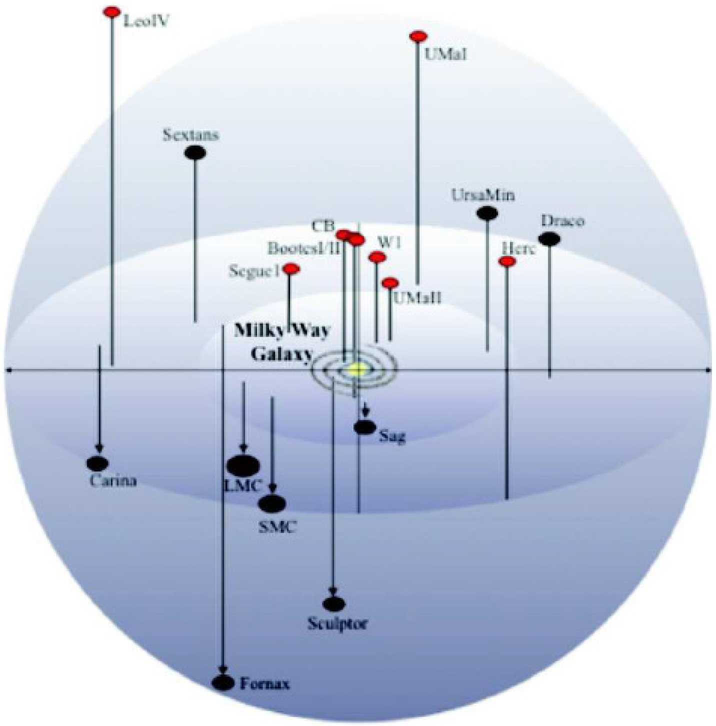
Only 30 are observed within our Galaxy. M. Geha 2010





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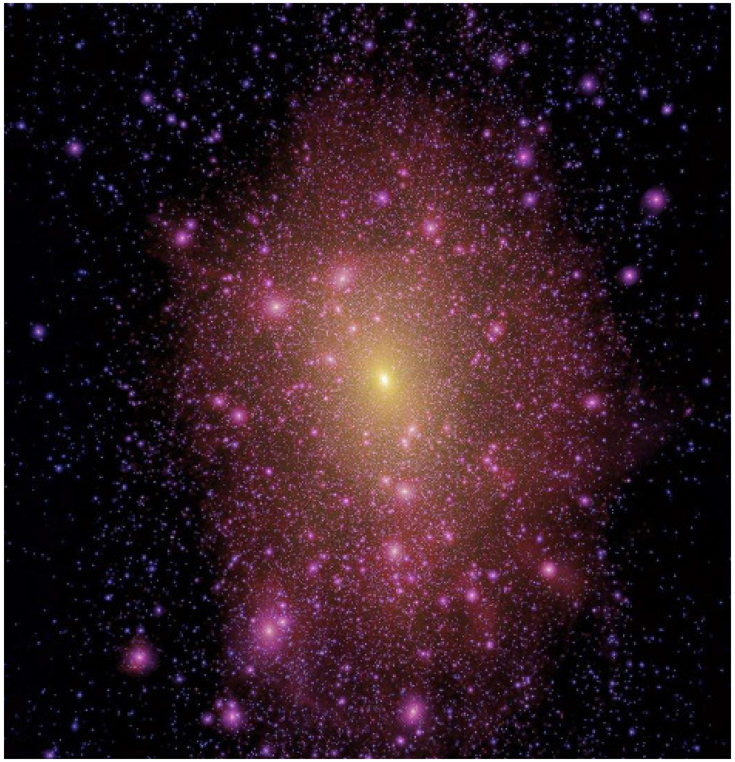
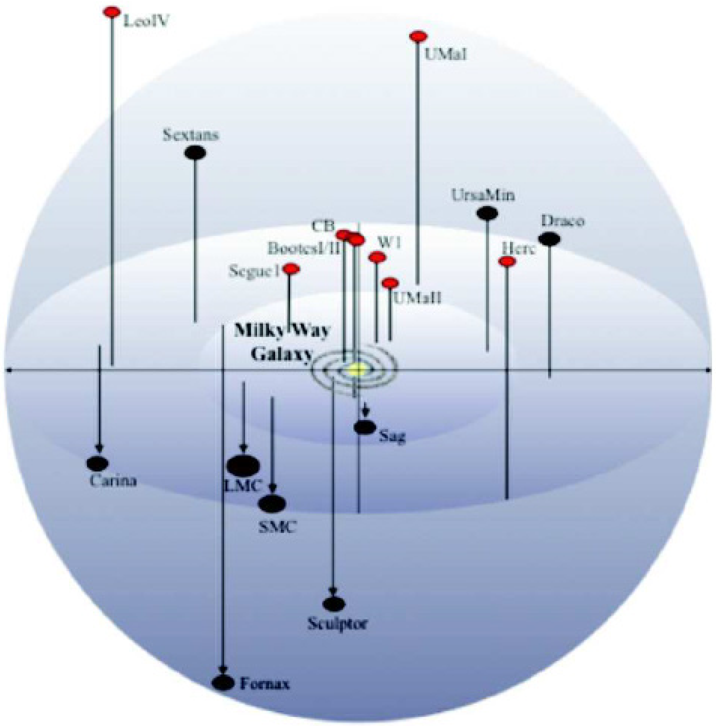
Is small number of observed substructures due to dark matter free-streaming?
Moore et al. (1999), Klypin et al. (1999)





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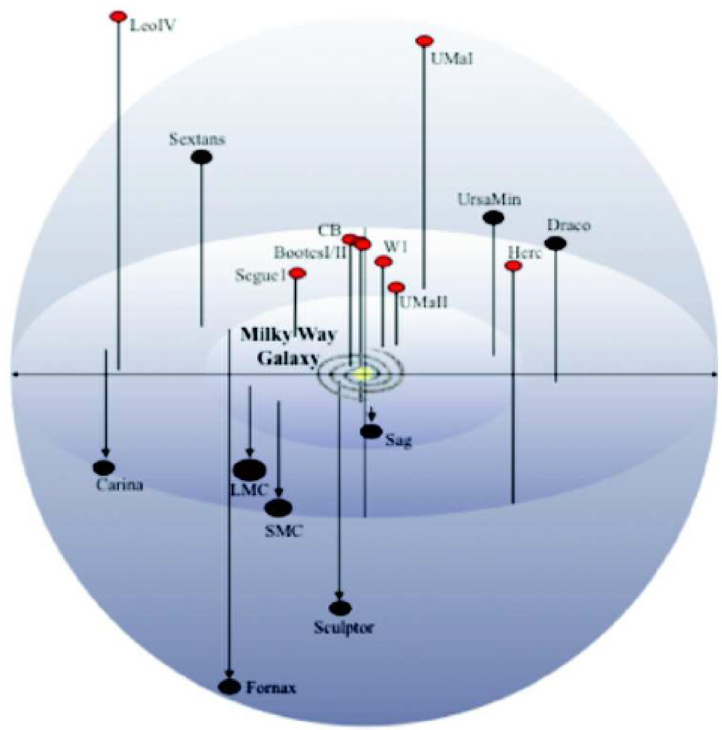

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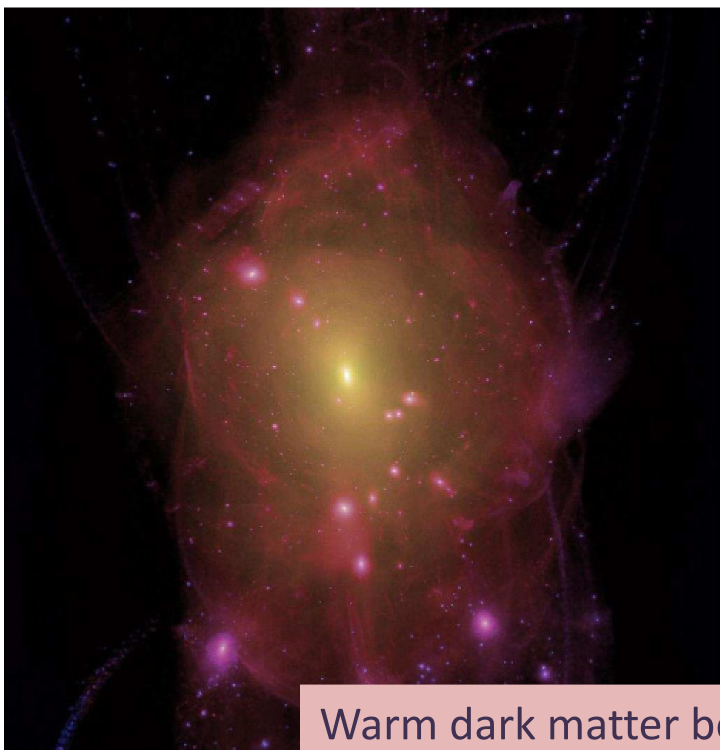
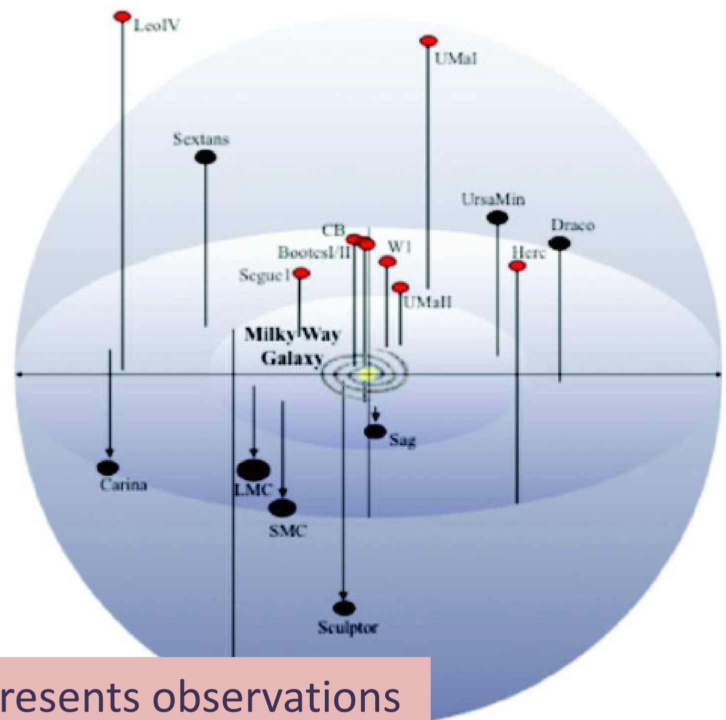


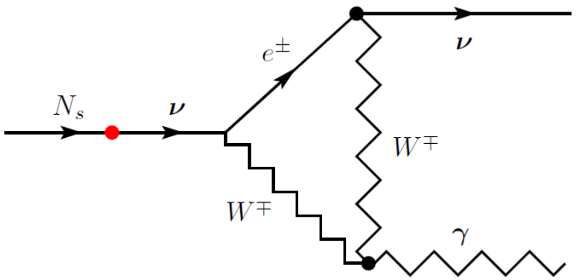


Warm dark matter better represents observations

Sterile neutrinos decay

Main decay mode: $N_S \rightarrow \nu\nu\bar{\nu}$

Subdominant process: $N_1 \rightarrow \nu + \gamma$



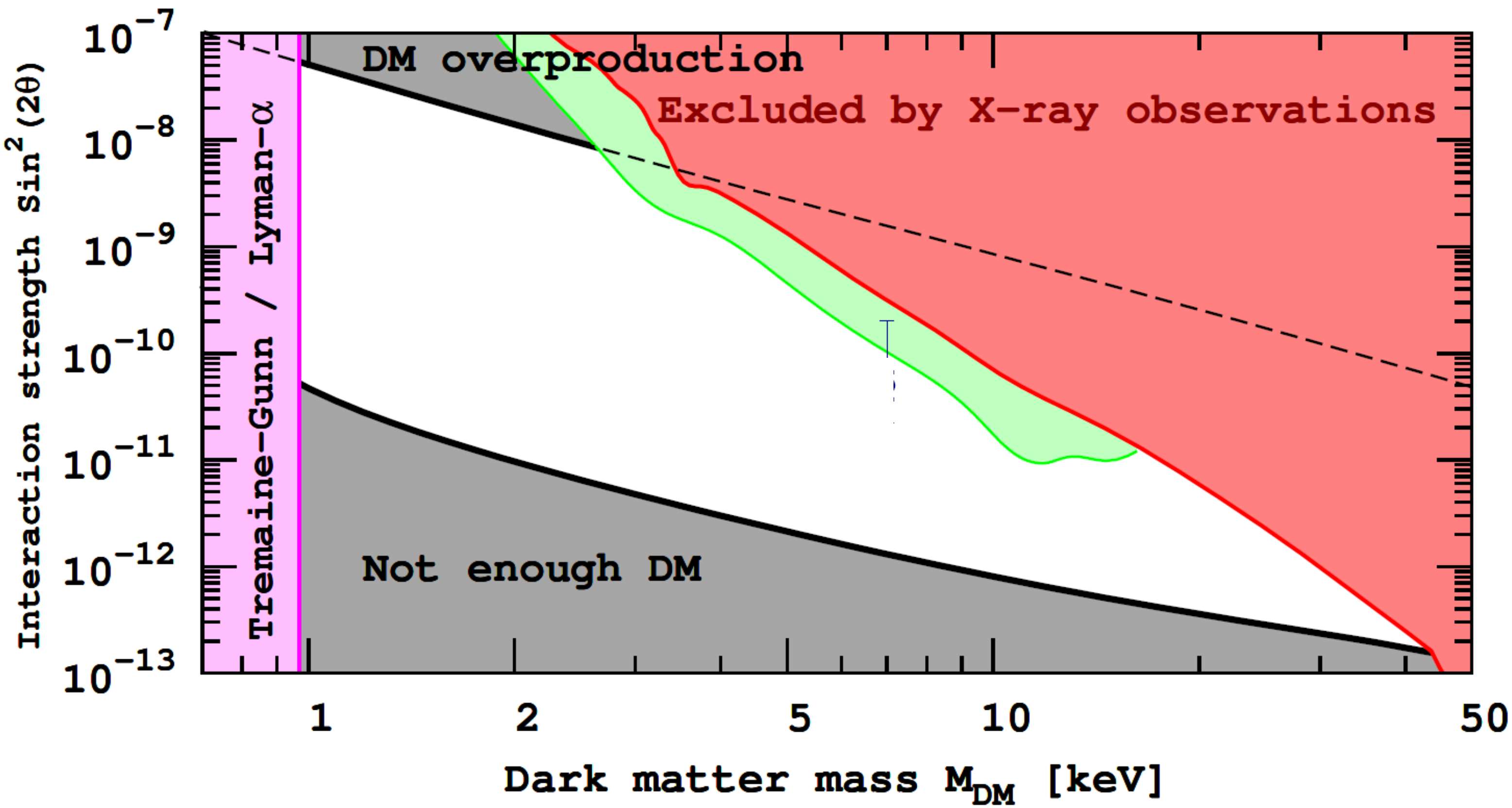
$E_\gamma = 1/2\ M_N$

Expect a signal from any large concentration of dark matter
(galaxy, galaxy group, galaxy cluster)

The width of the decay line is determined by Doppler broadening
→ narrow line in all DM-dominated objects

$$\frac{\Delta E}{E_\gamma} \approx 10^{-4} \div 10^{-2}$$

keV-scale sterile neurinos



Sterile neutrinos decay - detection

XMM Newton telescope

Chandra telescope

Sterile neutrinos decay – 3.5 keV line

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

PRL (2014) [1402.4119]

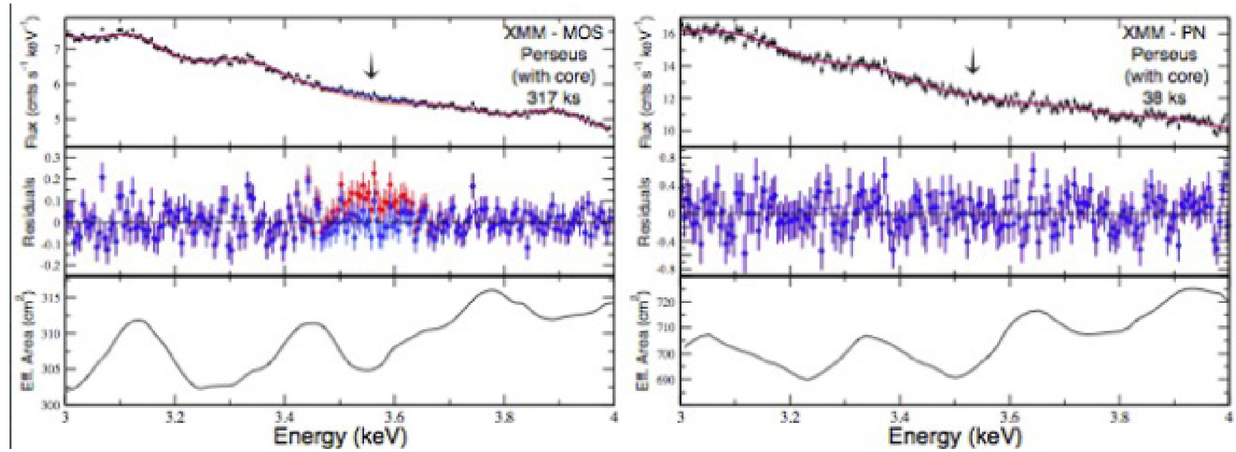
Sterile neutrinos decay – 3.5 keV line

Energy:
3.5 keV
Statistical error for
line position ~30 - 50 eV

Lifetime:
~ 10^{28} sec
(uncertainty: factor ~3)

Possible origin:
DM → $\nu + \gamma$ (fermion)
DM → $\gamma+\gamma$ (boson)

Atomic Physics origin is
questionable



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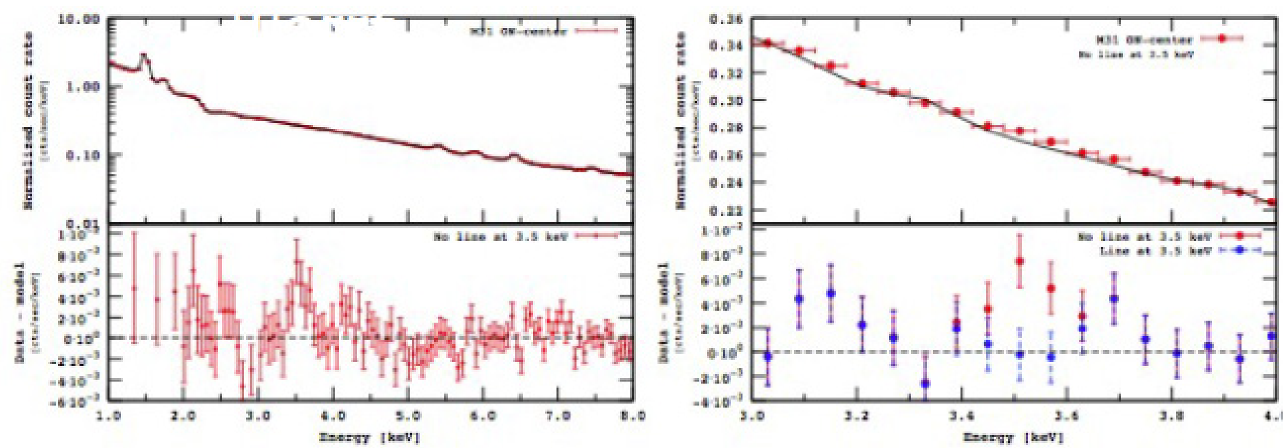

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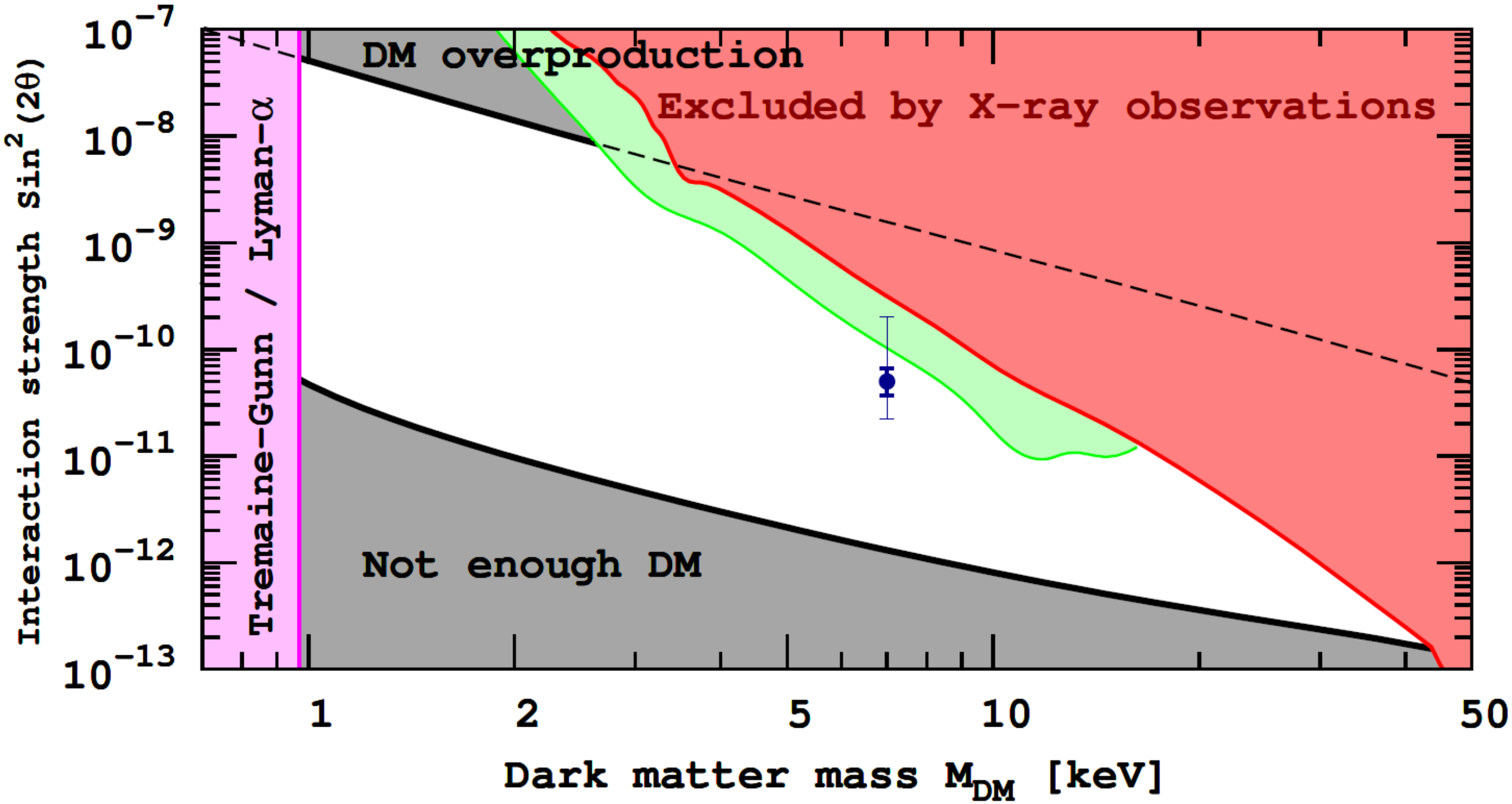
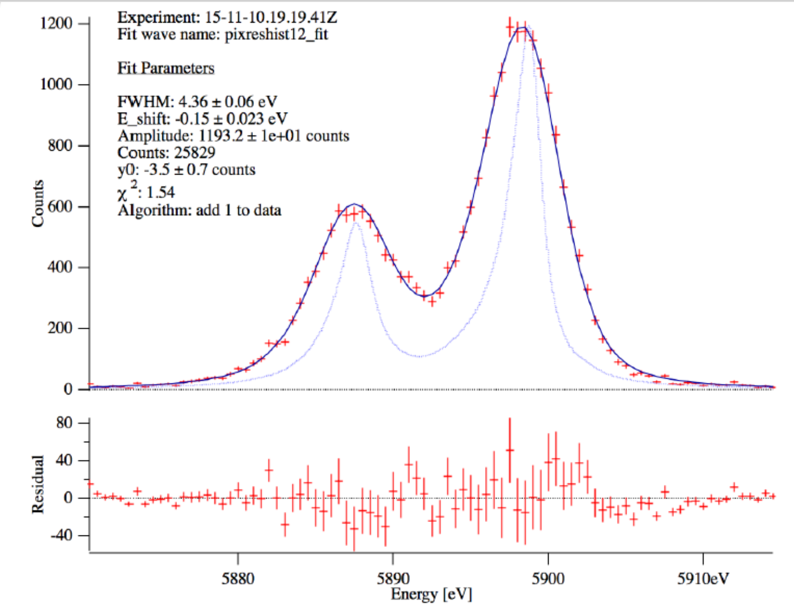
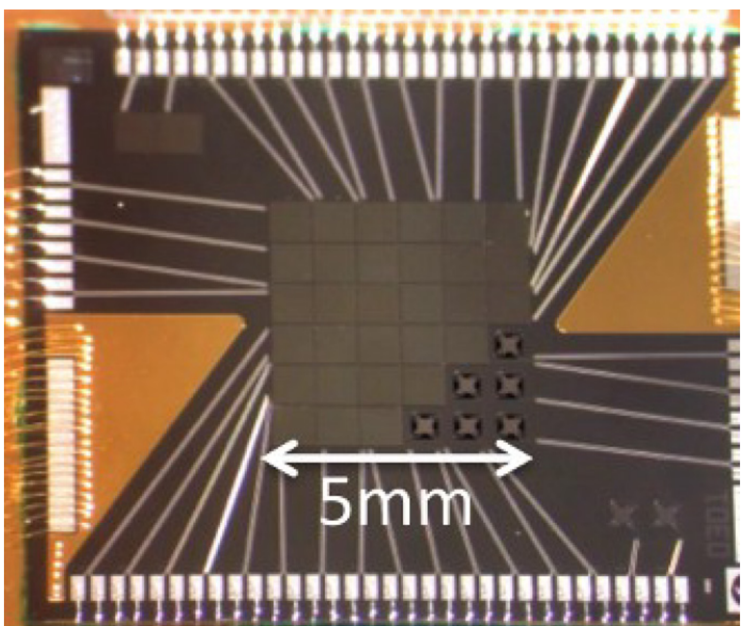
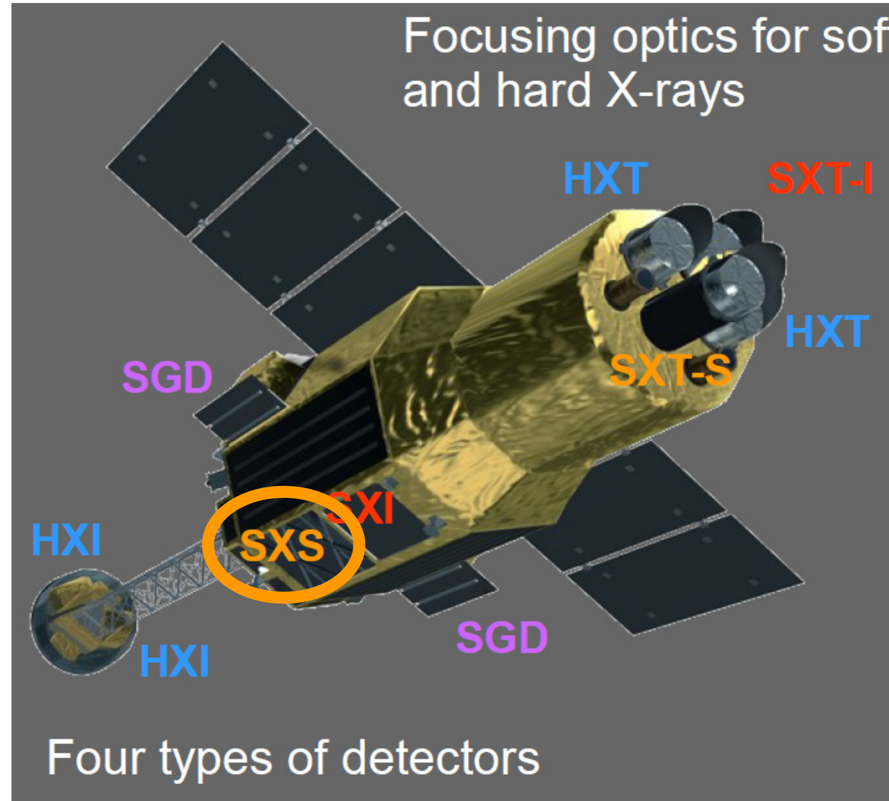


ASTRO-H HITOMI mission



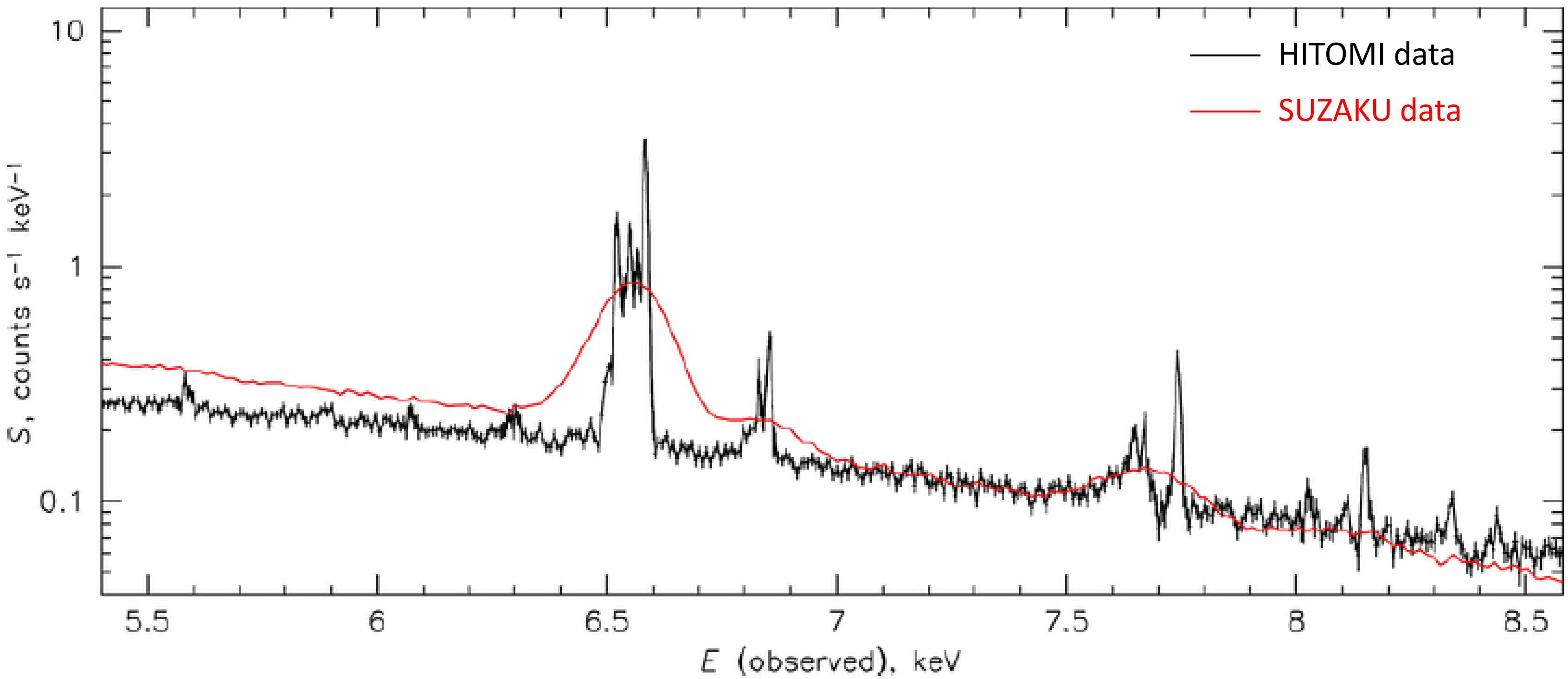




ASTRO-H - HITOMI

ASTRO-H HITOMI mission

There are observations of the center of Perseus galaxy cluster before the instrument was lost



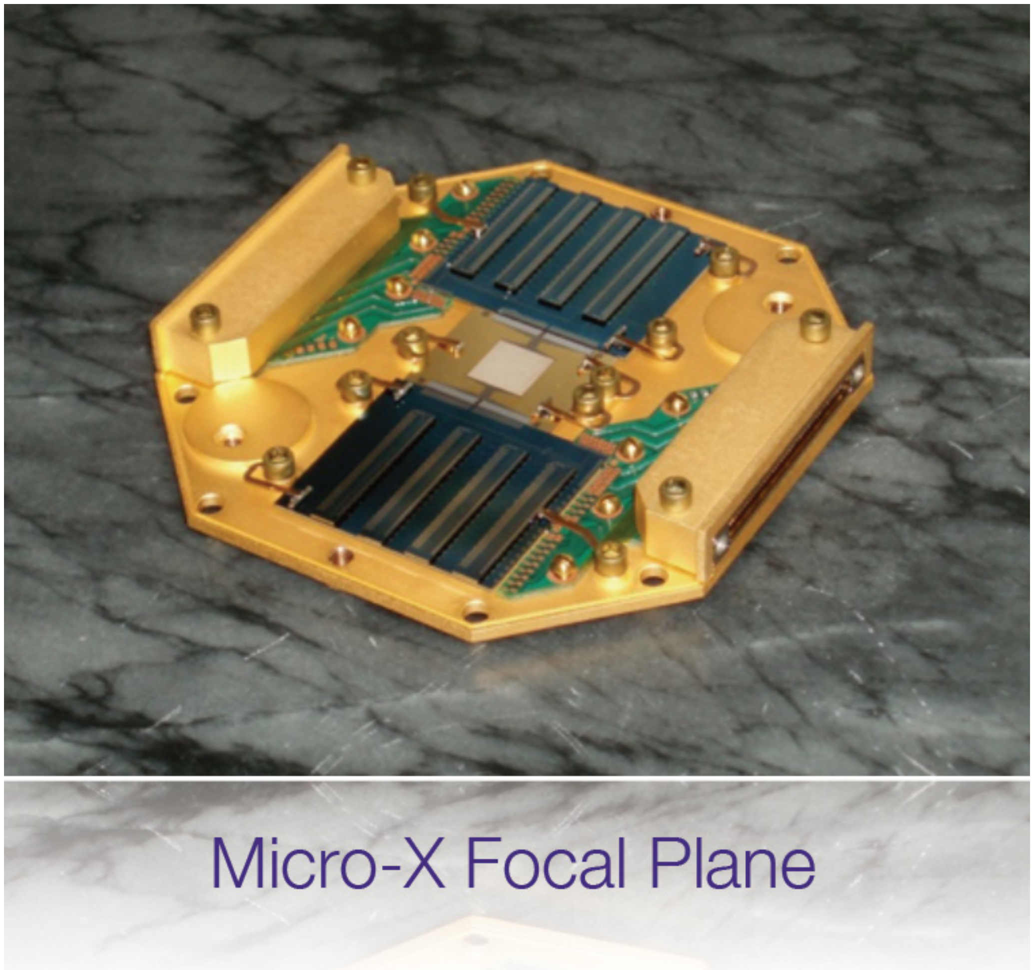
HITOMI Coll. Nature 2016

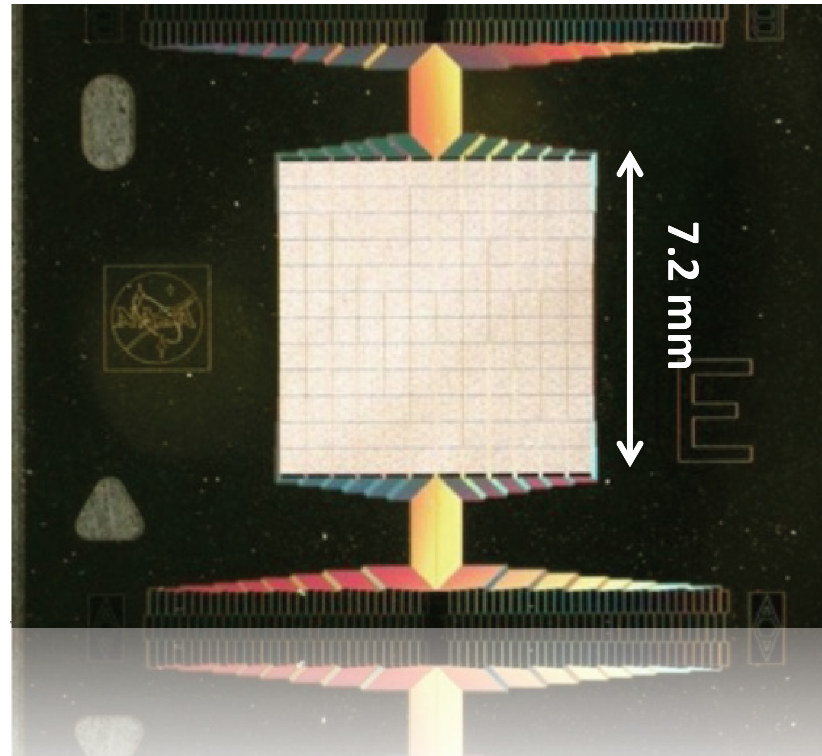
Sounding Rocket Payloads – Micro-X

- 300 seconds of on-target data above 169 km
- High resolution X-ray microcalorimeter with ~1cm^2 area and large ~steradian FOV
- Flights from White Sands Missile Range in New Mexico and Woomera Range in Australia

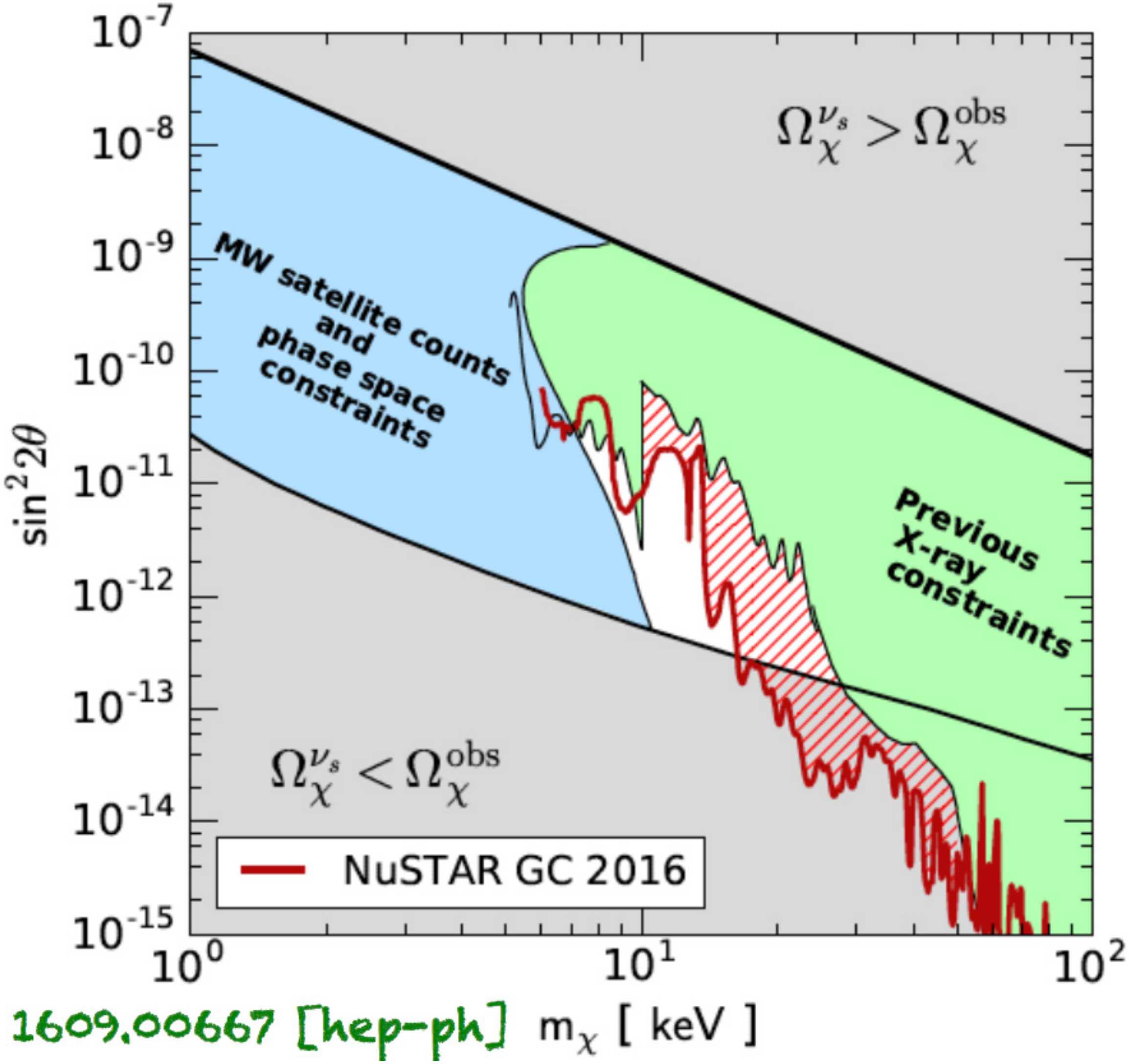
Sounding Rocket Payloads – Micro-X

12 × 12 TES pixels array





NuSTAR limit



1609.00667 [hep-ph]

Can we find direct evidence of sterile neutrinos in laboratory based experiments?

Neutrino mass determination

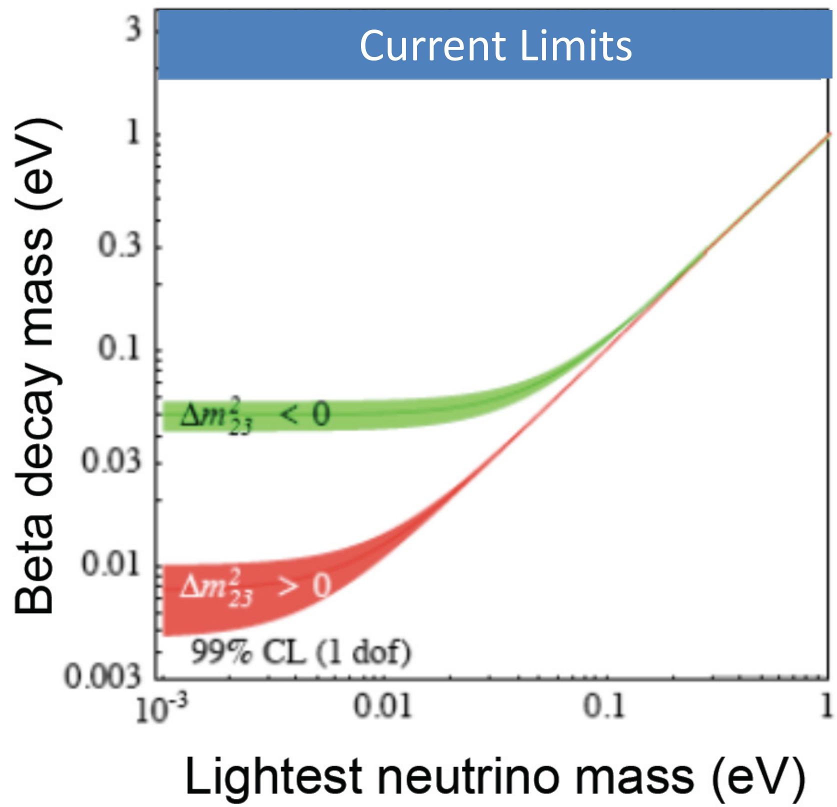
Kinematics of beta decay

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

- Model independent
- Laboratory experiments

$$m(\overline{\nu}_e) < 2.2\ eV$$ ^{3}H (1)

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



(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447
Ch. Weinheimer, Prog. Part. Nucl. Phys. **57** (2006) 22
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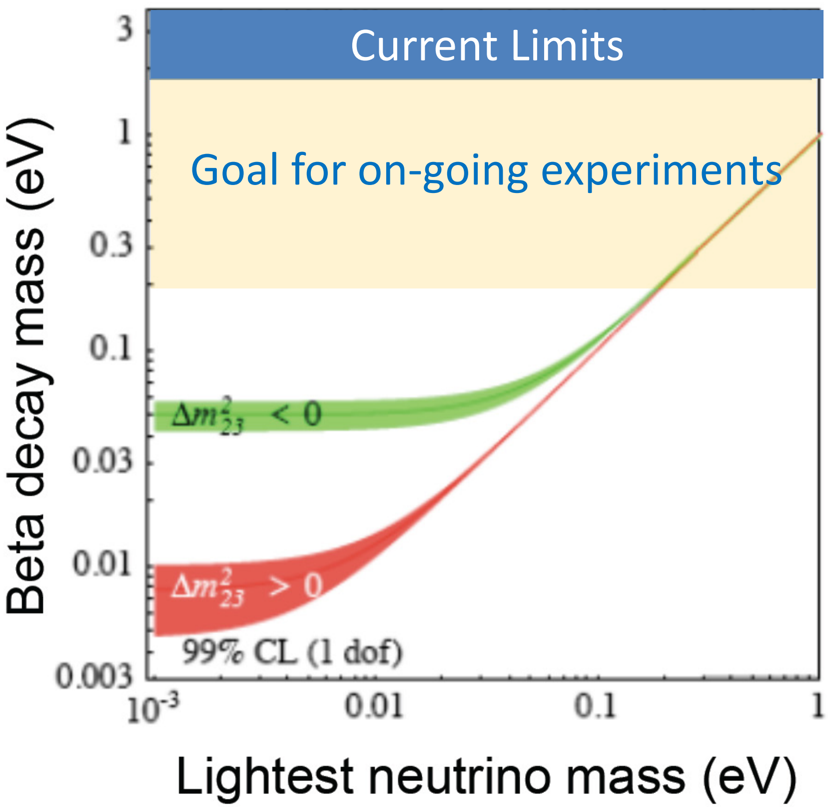
- **Next future 200 meV**



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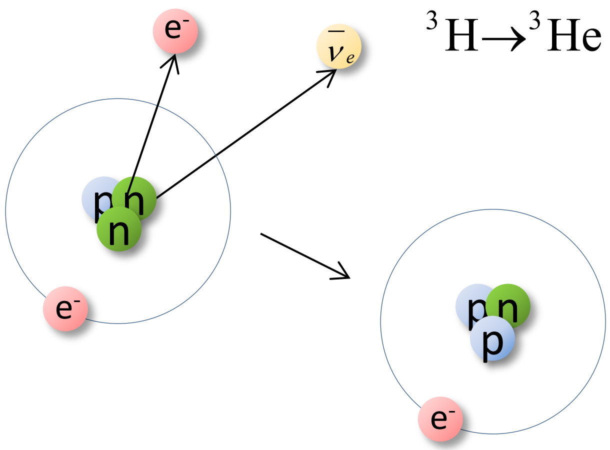
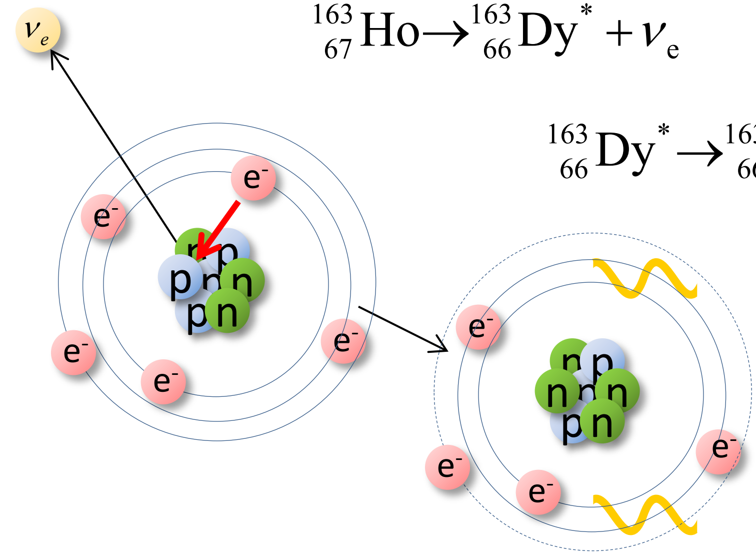
Beta decay and electron capture



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



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

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

- $\tau_{1/2} \cong 12.3$ years (4*10⁸ atoms for 1 Bq)
- Q_β = 18 592.01(7) eV

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

- $\tau_{1/2} \cong 4570$ years (2*10¹¹ atoms for 1 Bq)
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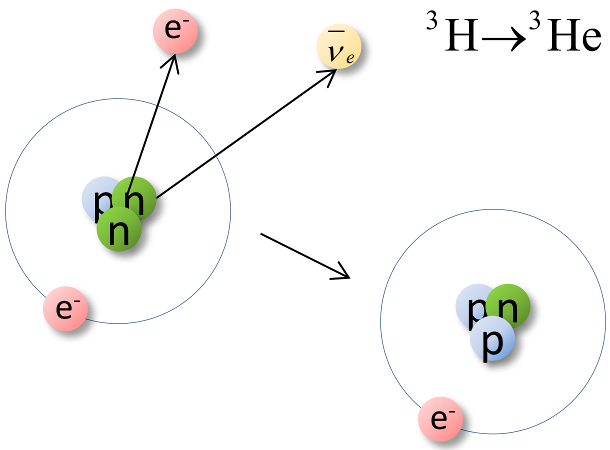

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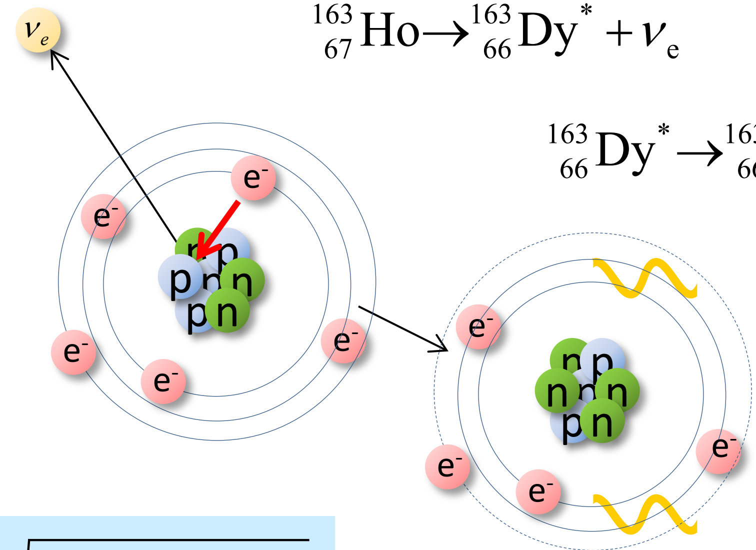

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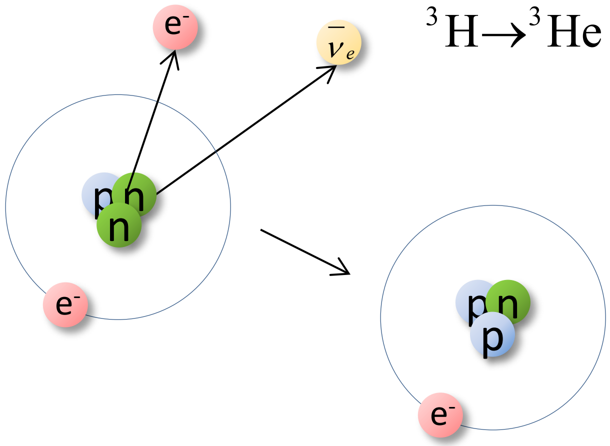

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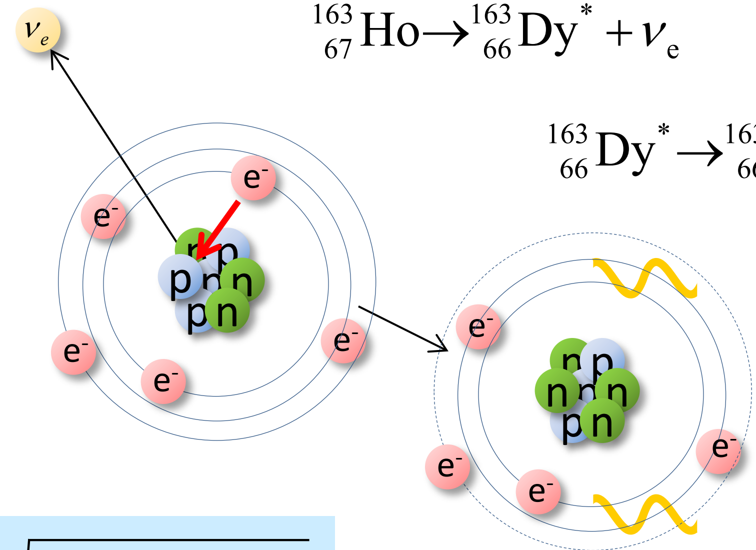

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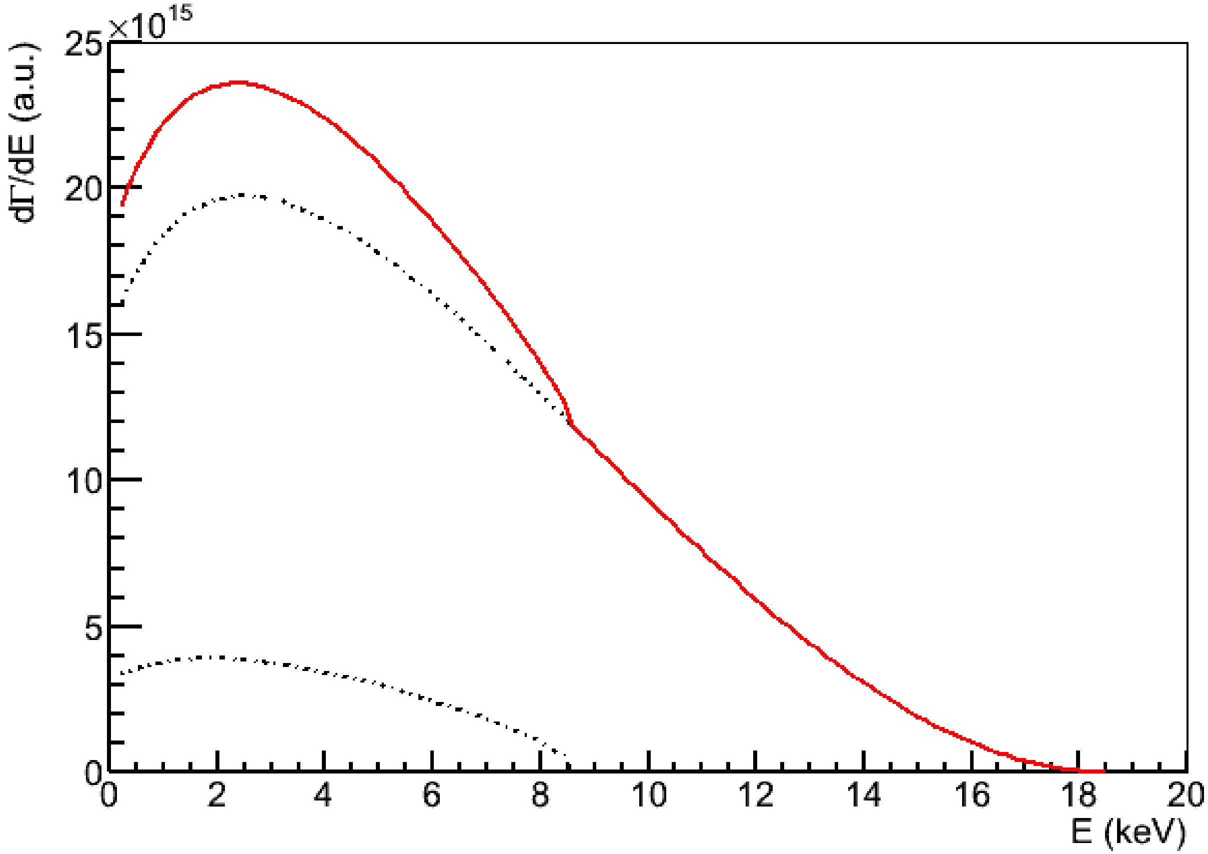

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Electron capture in ^{163}Ho

Atomic de-excitation:

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

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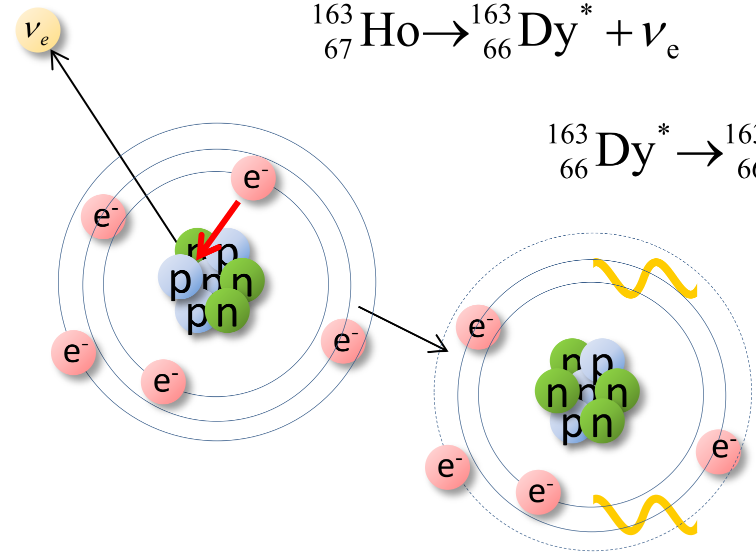

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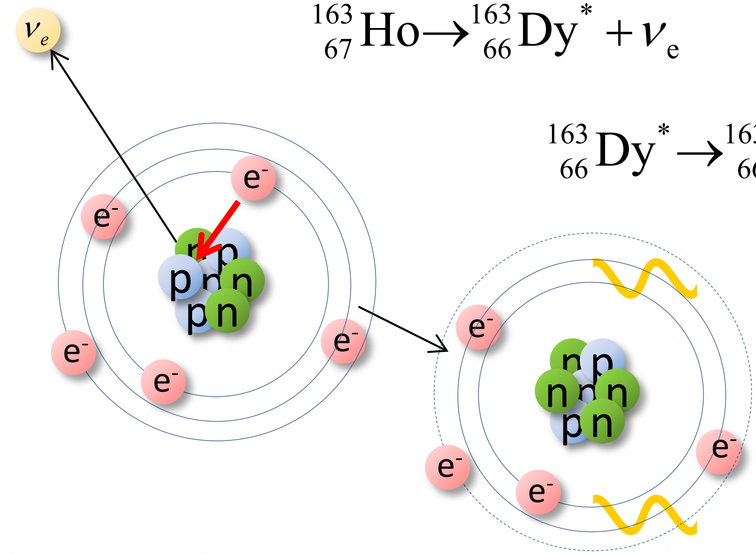

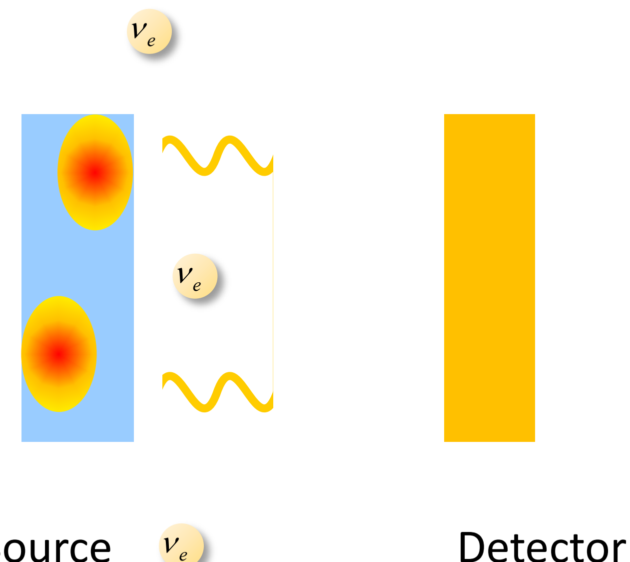

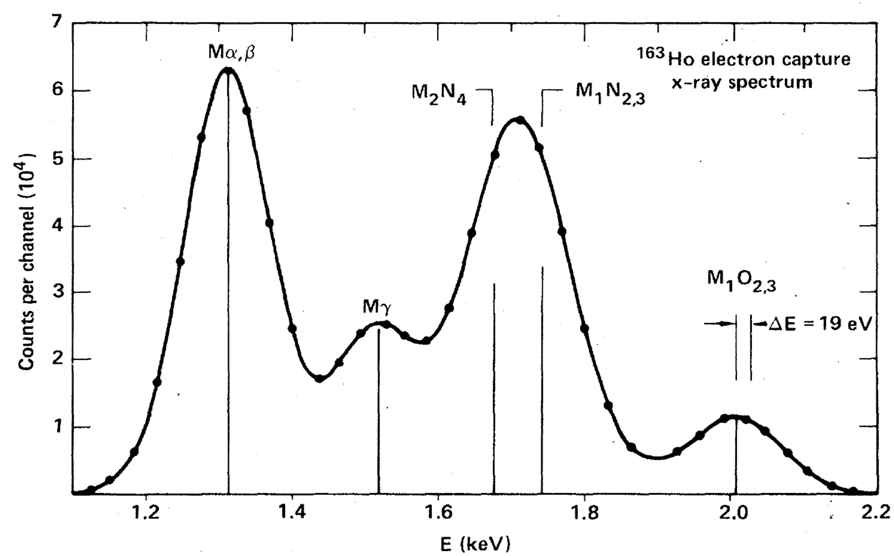

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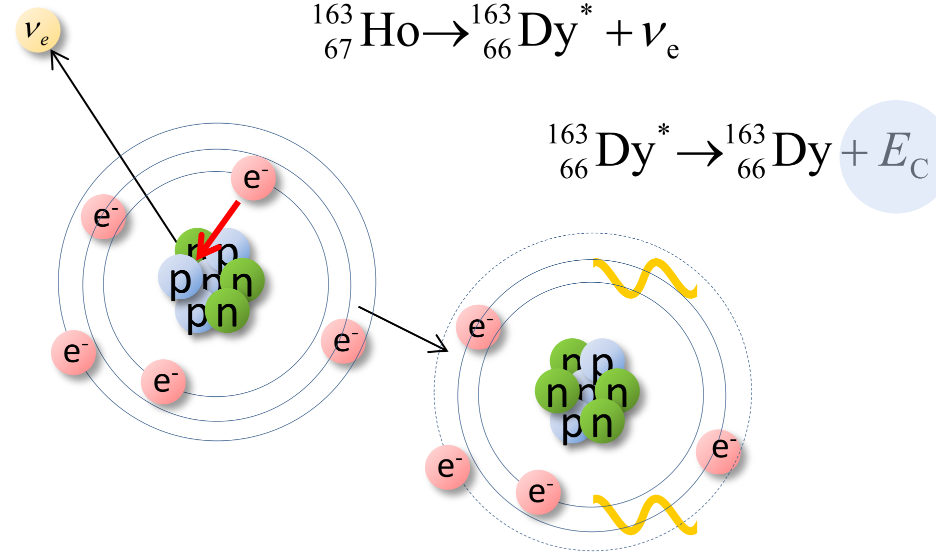
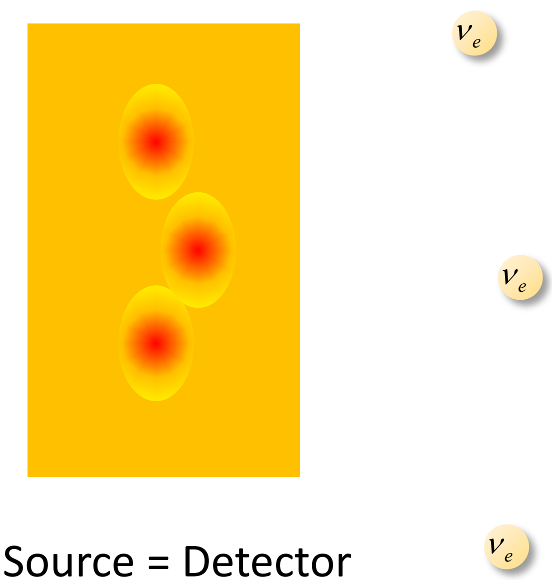


Calorimetric measurement



Source = Detector

Electron capture in ^{163}Ho

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Calorimetric measurement

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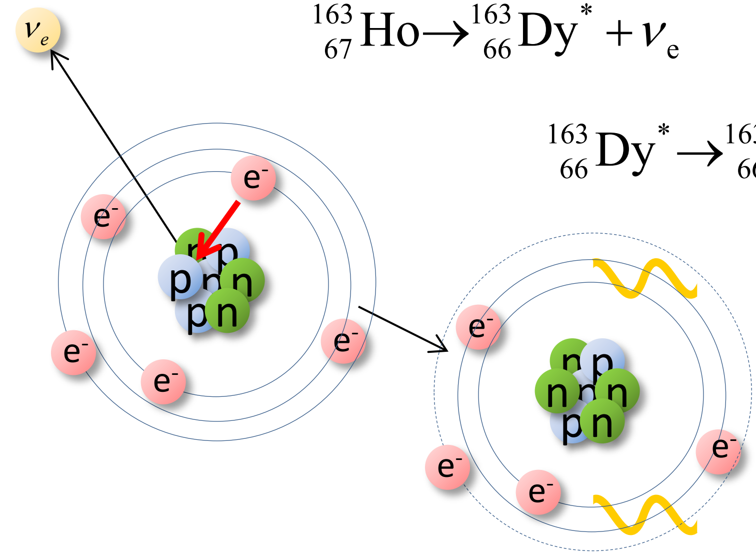


Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

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

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

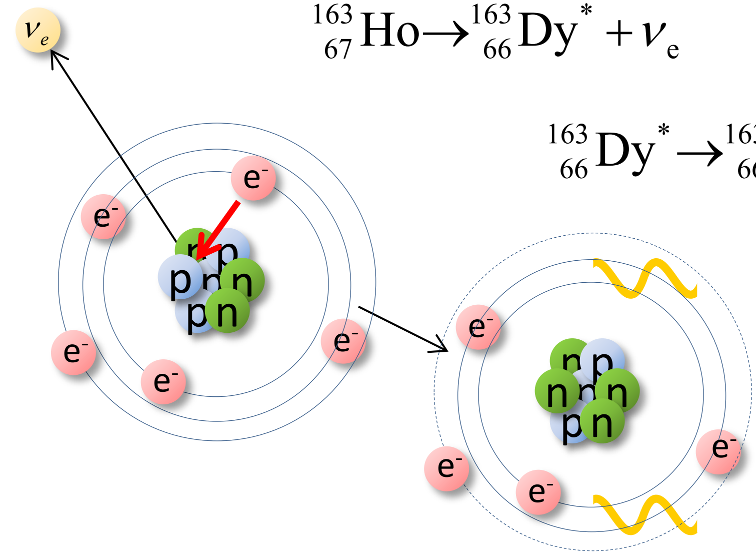
Electron capture in ^{163}Ho

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

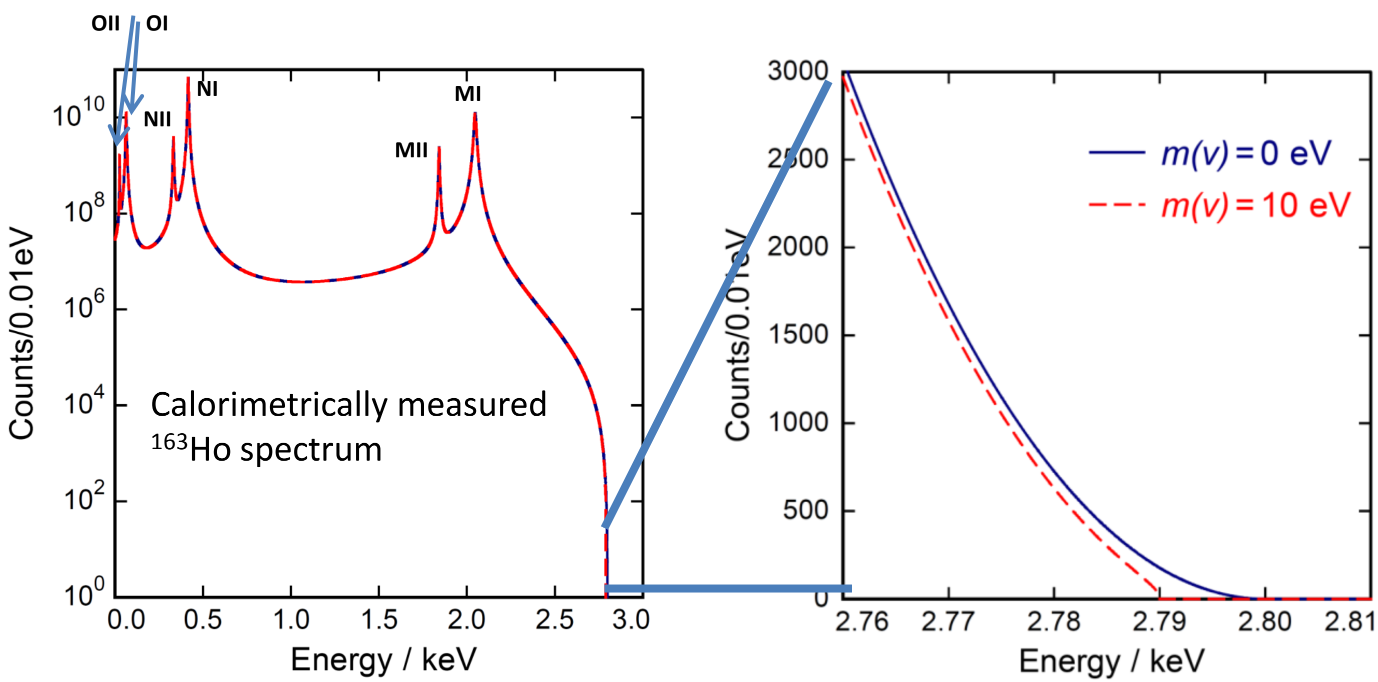
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

Atomic de-excitation:

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



Calorimetric measurement



Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

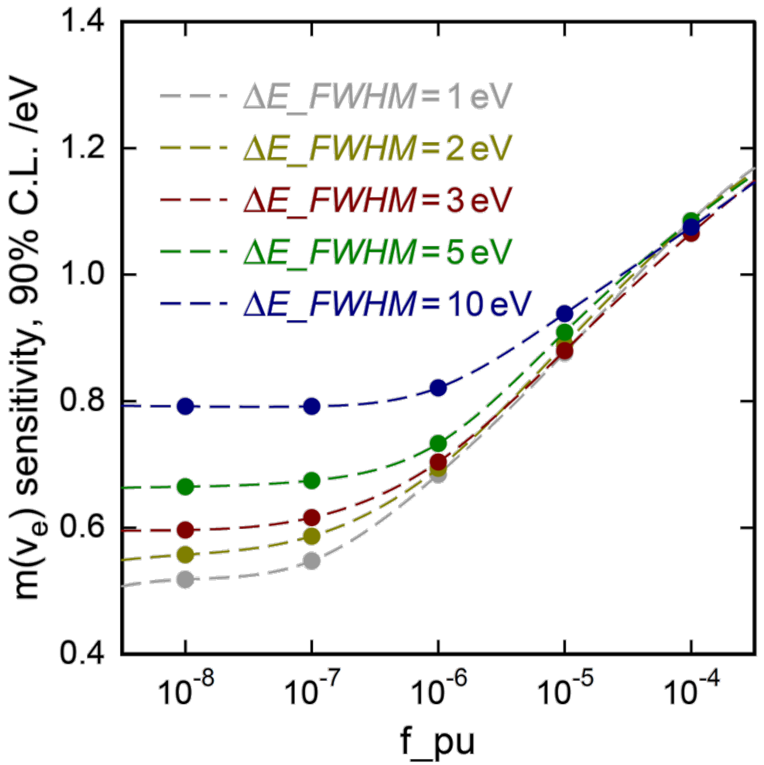
- **$f_{pu} < 10^{-5}$**
- $\tau_r < 1$ µs → a ~ 10 Bq
- 10^5 pixels → **multiplexing**

Precision characterization of the endpoint region

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

Background level

- **$< 5*10^{-5}$ events/eV/det/day**



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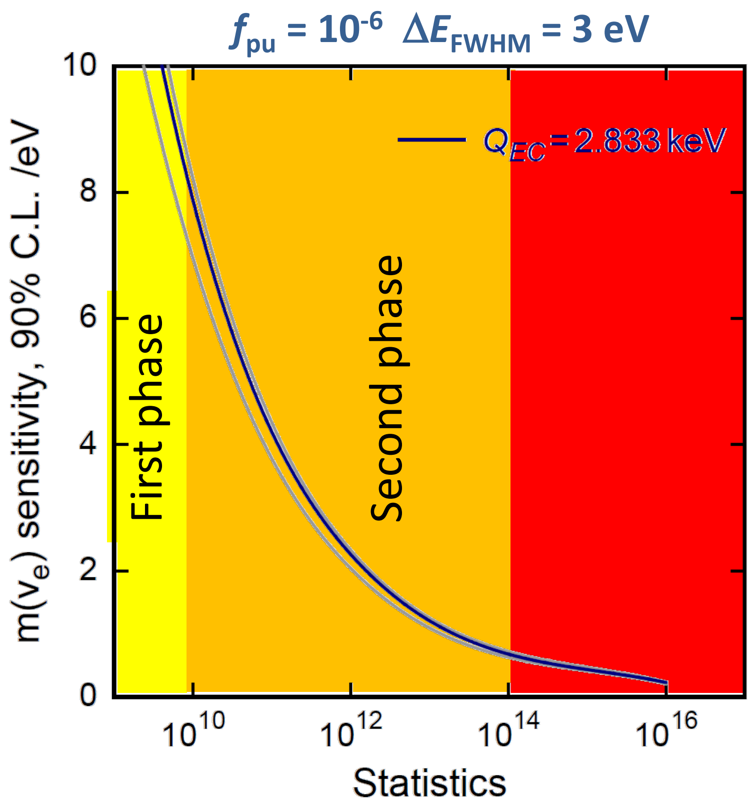
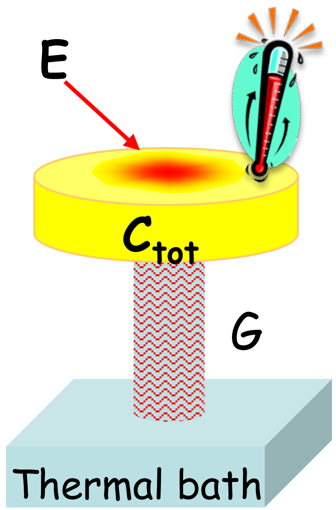
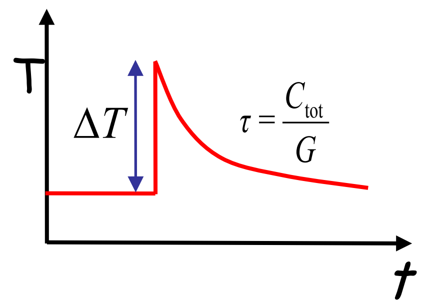


Low temperature micro-calorimeters



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



***E* = 10 keV**

C_{tot} = 1 pJ/K

→ ~ 1 mK

- Very small volume

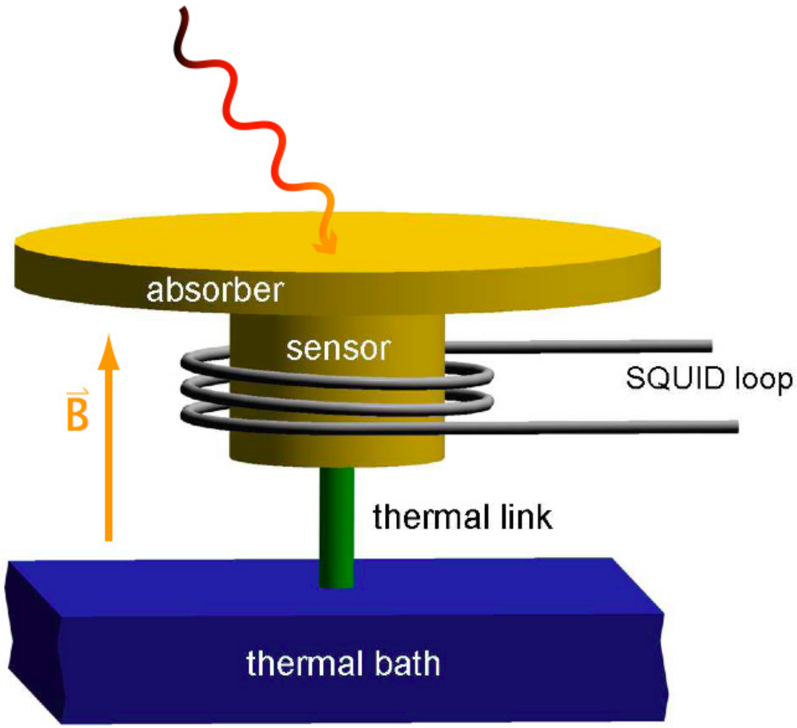
- Working temperature below 100 mK
  small specific heat
  small thermal noise

- **Very sensitive temperature sensor**

Metallic magnetic calorimeters (MMCs)

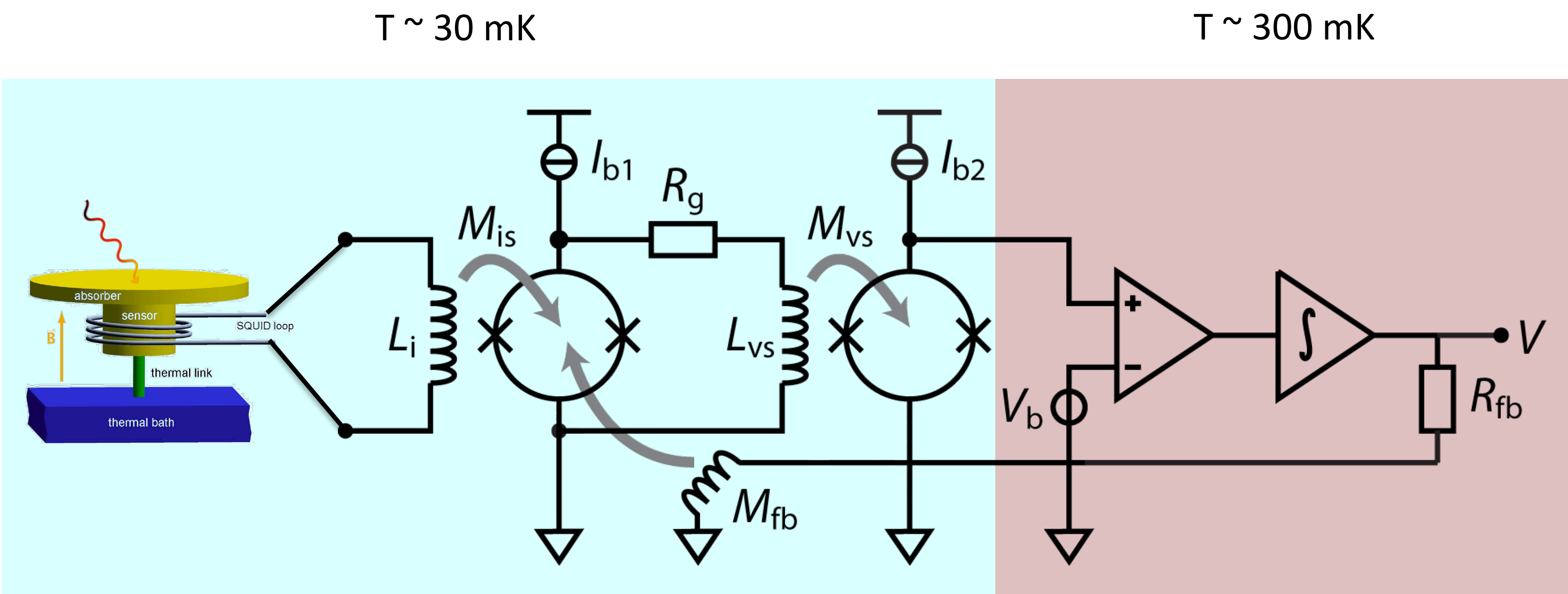
A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

- Paramagnetic Au:Er sensor
  Ag:Er



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

MMCs: Readout

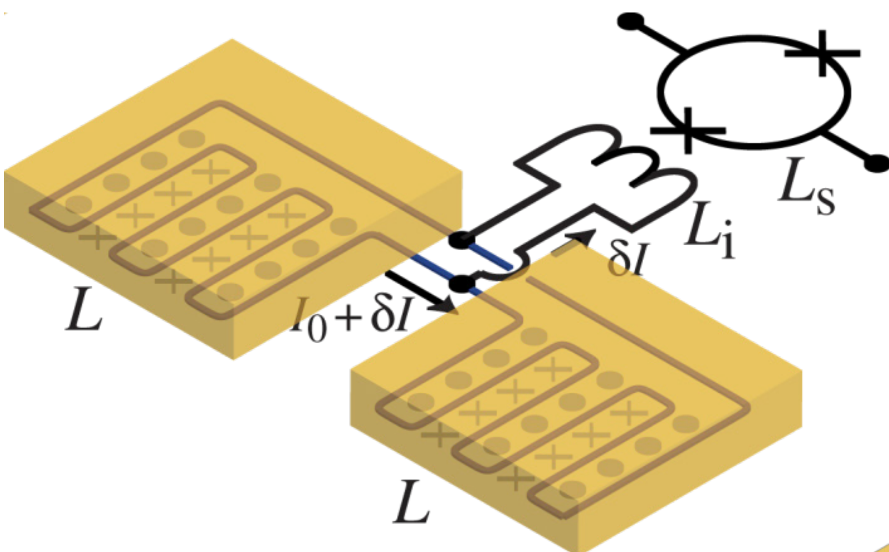


Two-stage SQUID setup with flux locked loop allows for:

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

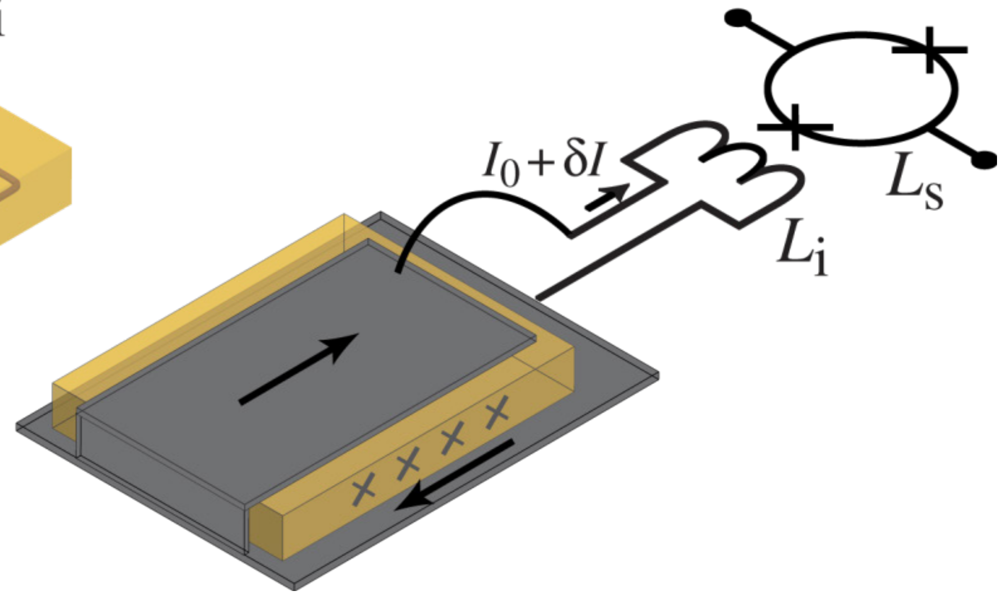
MMCs: Planar geometries

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

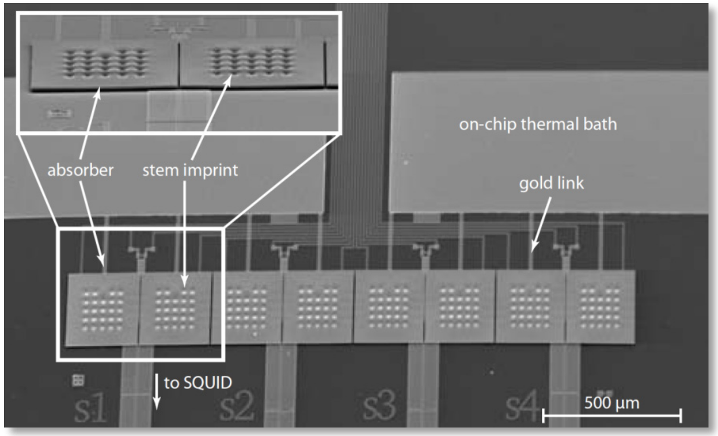


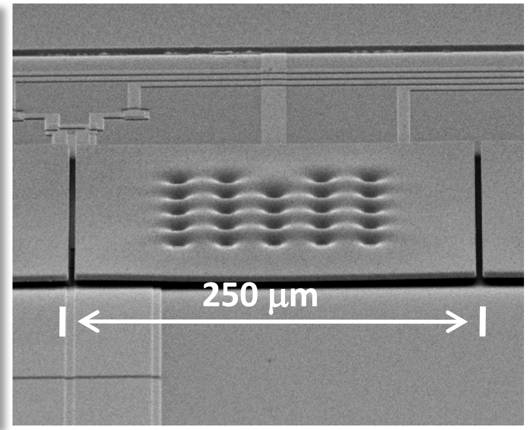
Meander-shaped pick-up coil

Sandwich design



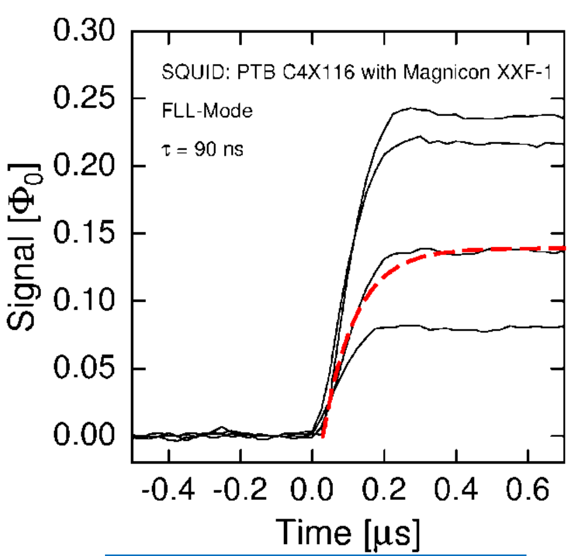
MMCs: 1d-array for soft x-rays (T=20 mK)



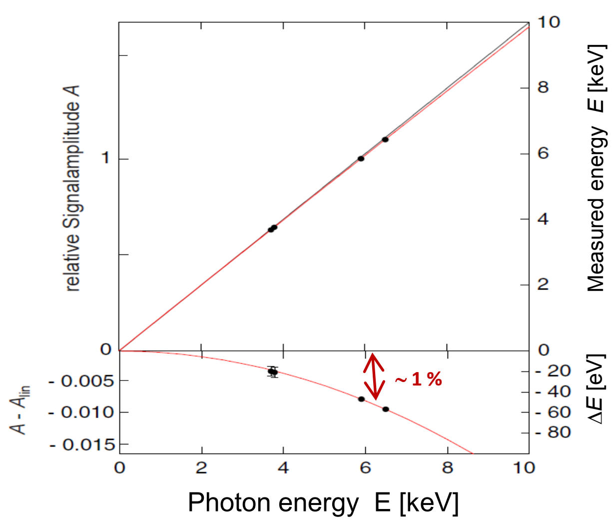


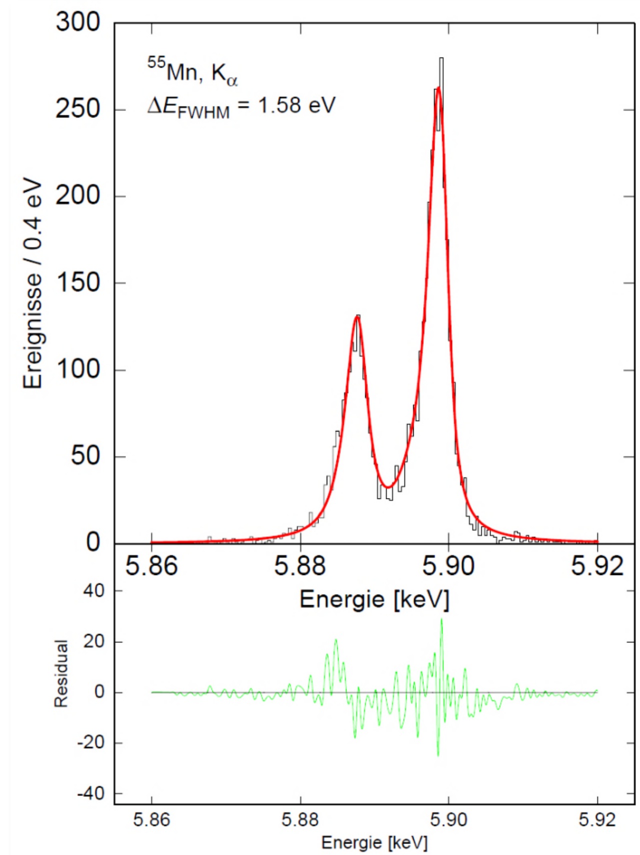
ΔE_{FWHM} = 1.6 eV @ 6 keV

Rise Time: 90 ns



Non-Linearity < 1% @6keV





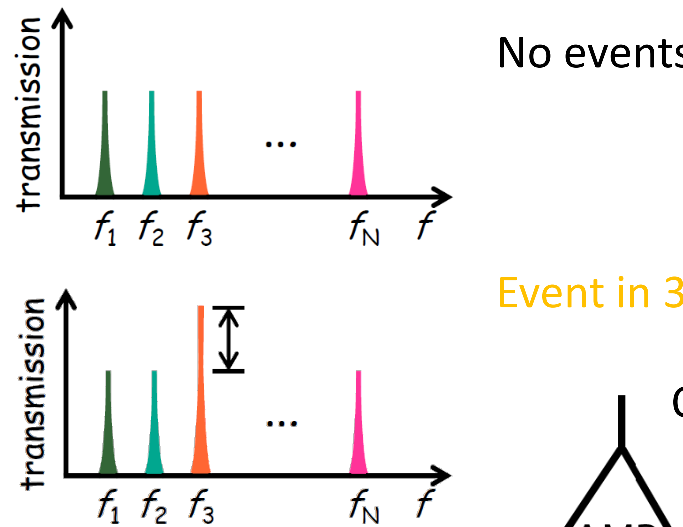
Reduction
un-resolved pile-up

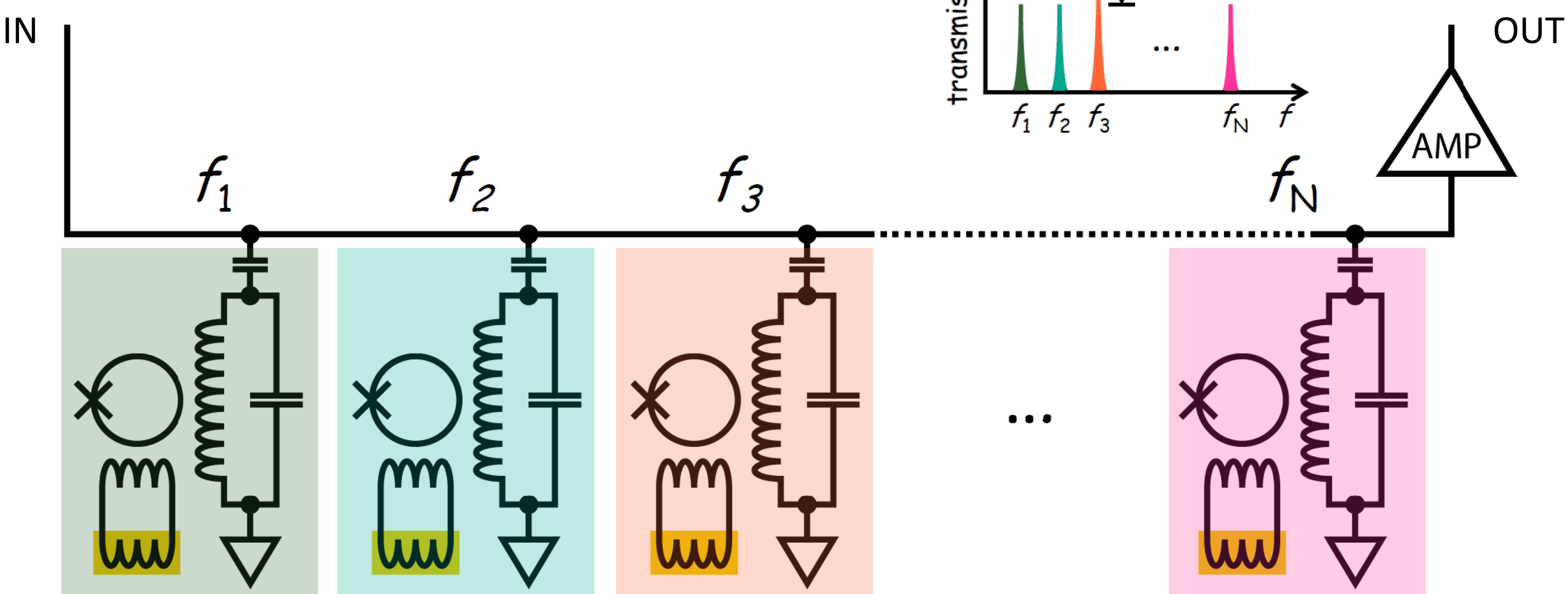
Definition
of the energy scale

Reduced smearing
in the end point region

MMCs: Microwave SQUID multiplexing

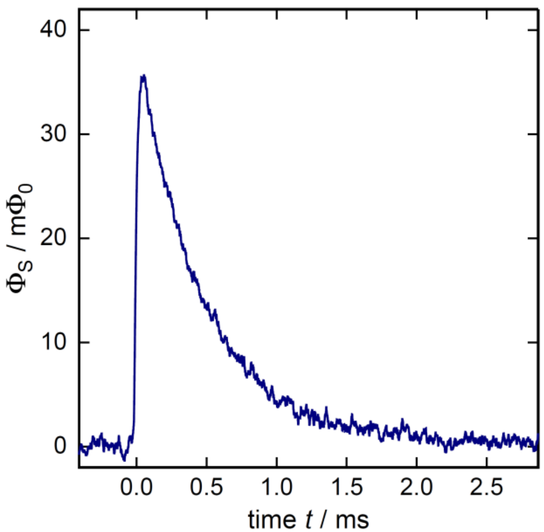
- Single HEMT amplifier and 2 coaxes to read out **100 - 1000** detectors



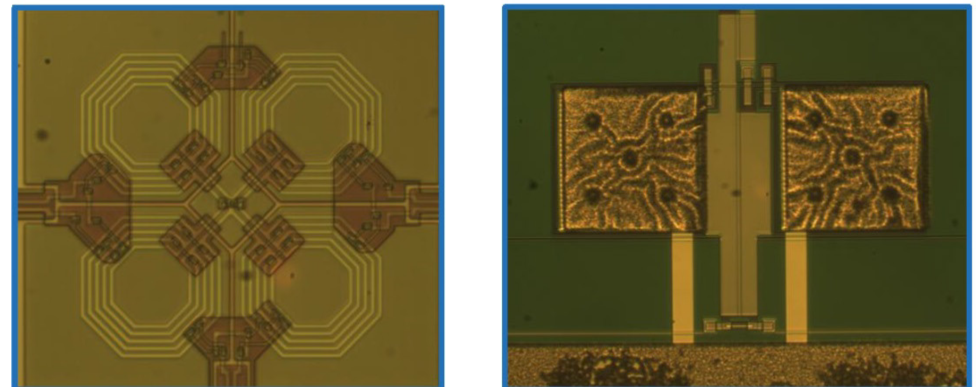


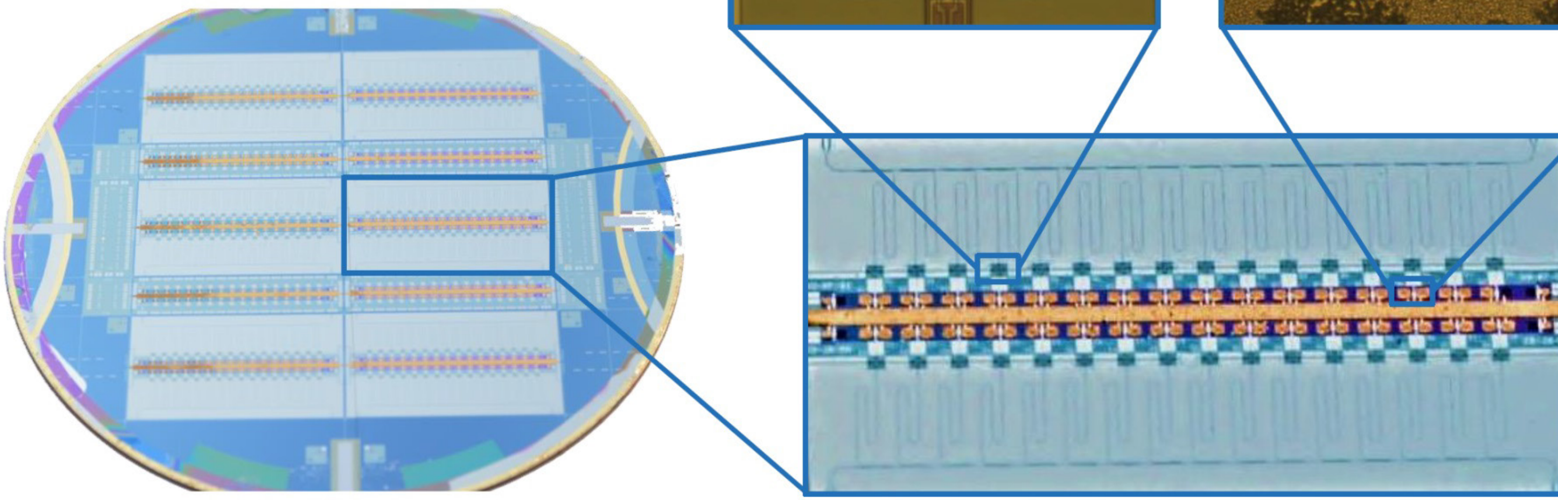
Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

MMCs: Microwave SQUID multiplexing



Successful production and test of the first prototype

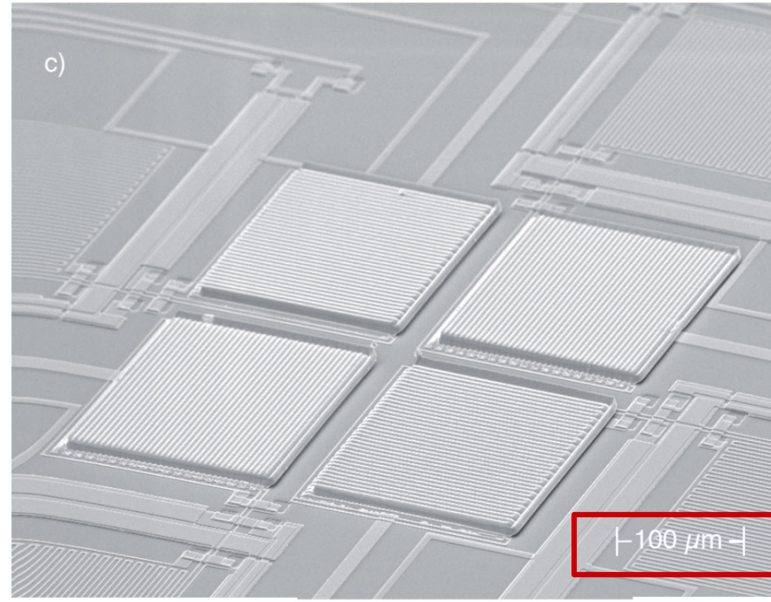


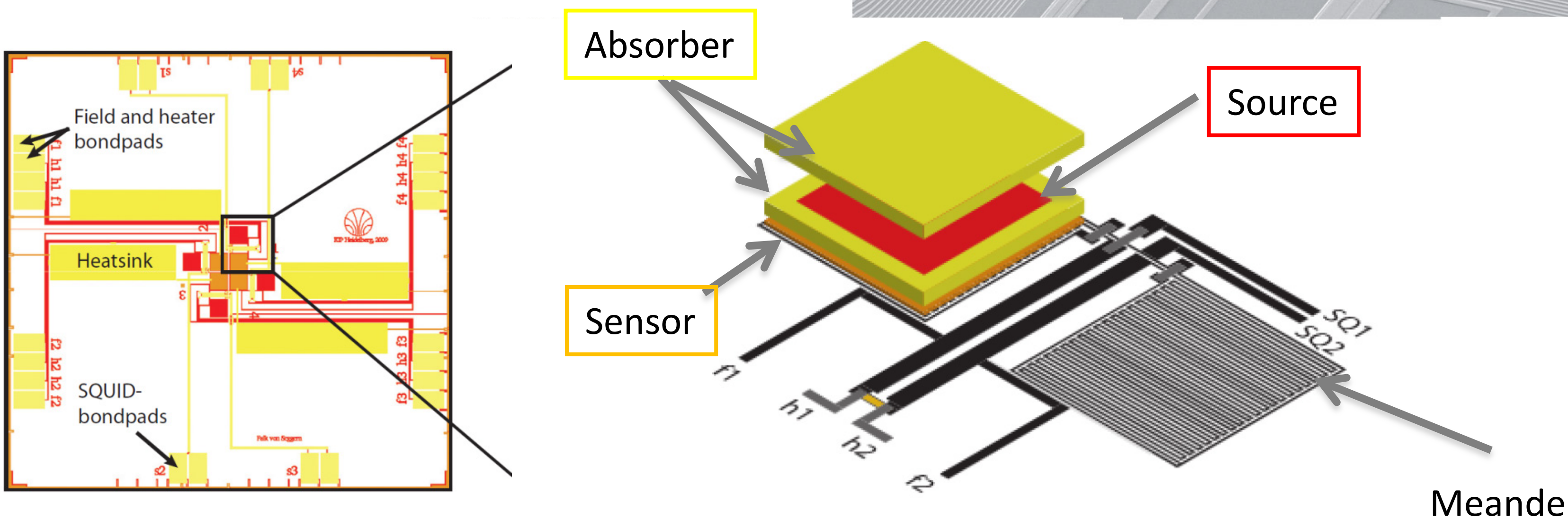


Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

ECHo First detector prototype

- Absorber for metallic magnetic calorimeters
  → ion implantation @ ISOLDE-CERN in 2009
  on-line process
- About 0.01 Bq per pixel
- Operated over more than 4 years



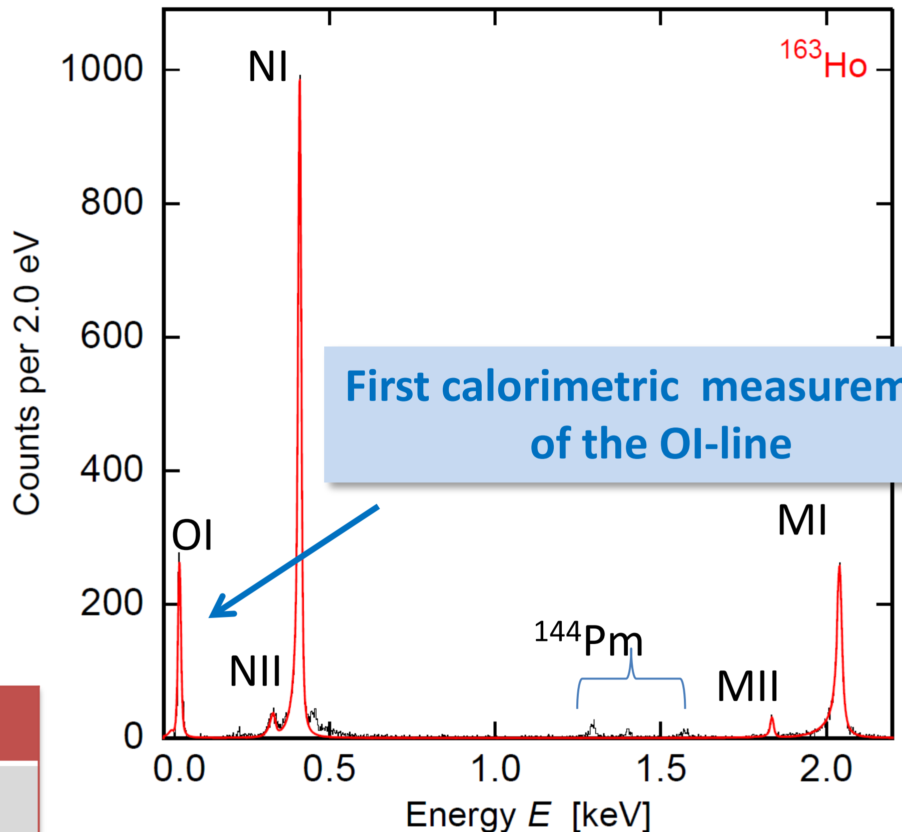


L. Gastaldo et al.,
Nucl. Inst. Meth. A, 711 (2013) 150

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

ECHo Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{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

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

Where to improve

High purity ^{163}Ho source:

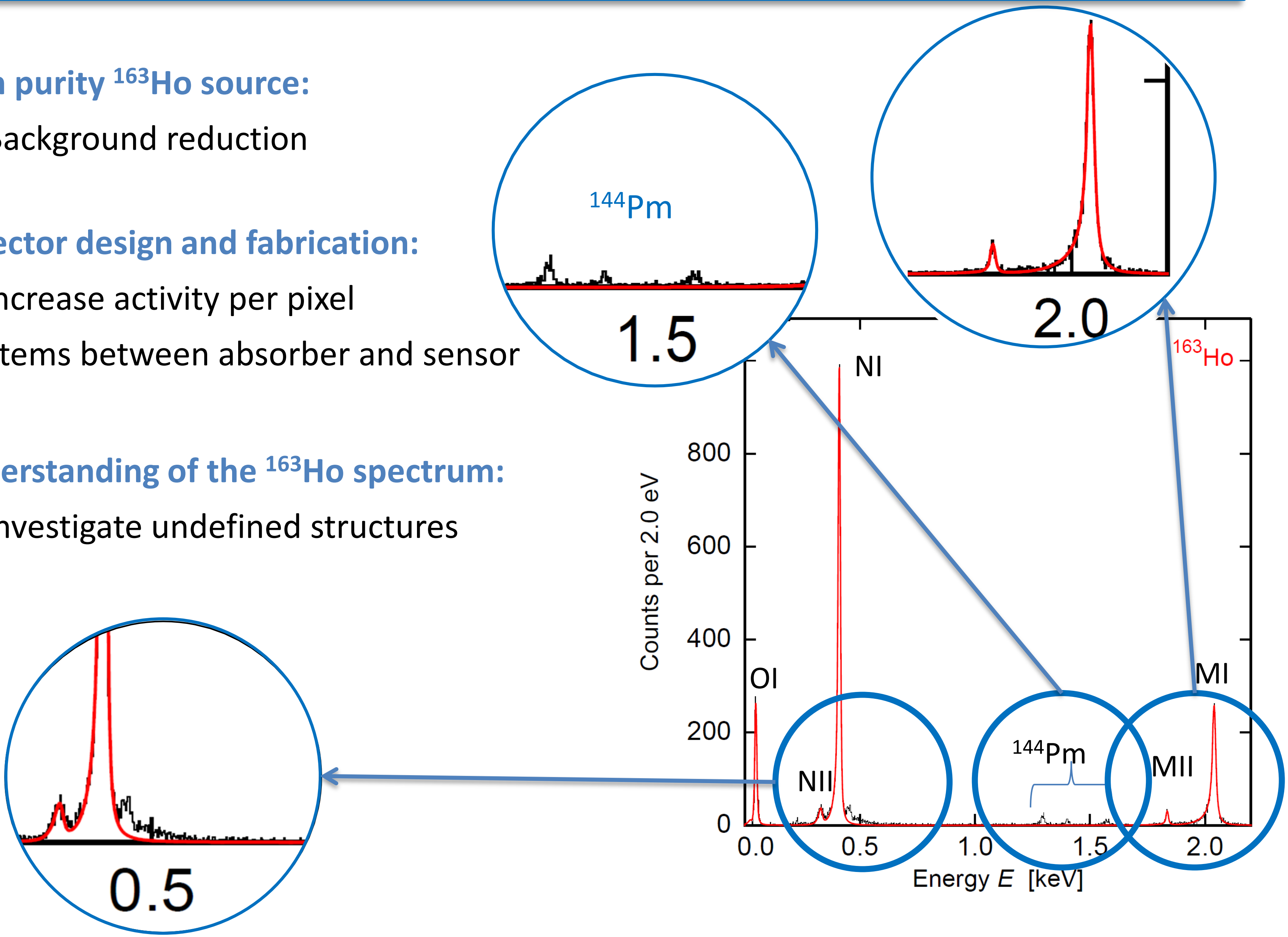
- Background reduction

Detector design and fabrication:

- Increase activity per pixel
- Stems between absorber and sensor

Understanding of the ^{163}Ho spectrum:

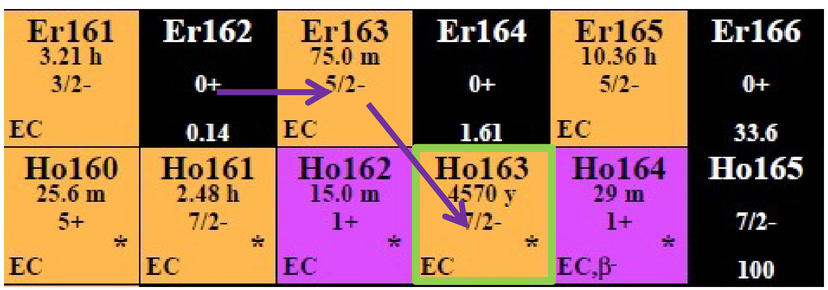
- Investigate undefined structures



High purity ^{163}Ho source: Chemical purification

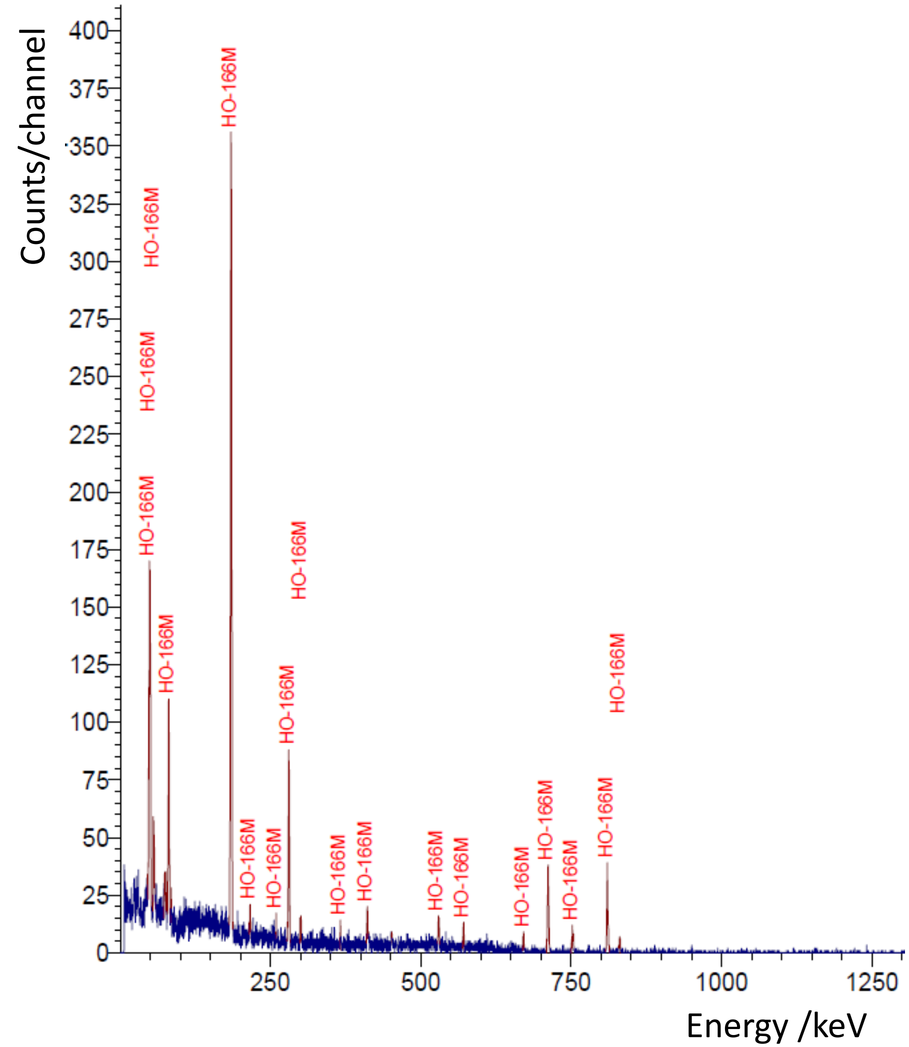
Requirement : >10^6 Bq → >10^{17} atoms

- (n,γ)-reaction on ^{162}Er
  - High cross-section 
  - Radioactive contaminants 



- Excellent chemical separation
  Only ^{166m}Ho

- Available ^{163}Ho source:
  ~ 10^{18} atoms



H. Dorrer, A. Türler et al., to be submitted

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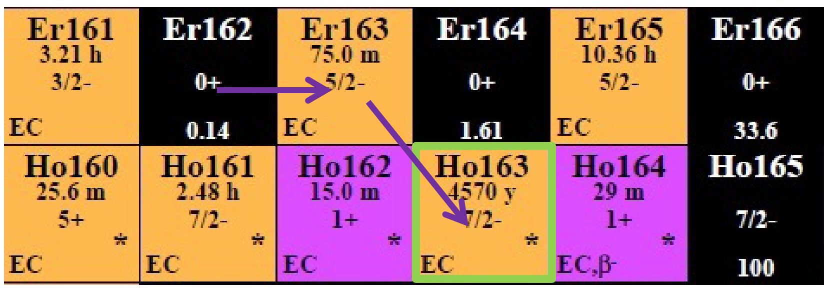

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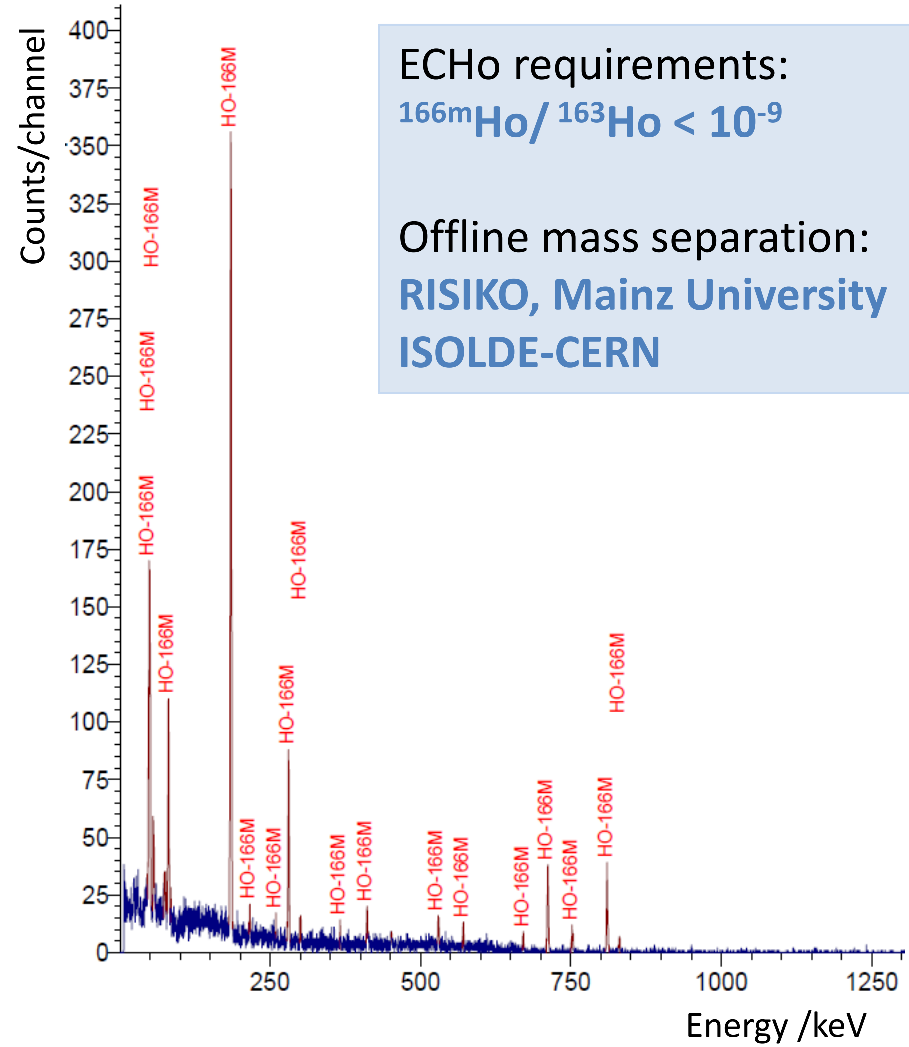


ECHo requirements:

^{166m}Ho/ ^{163}Ho < 10^{-9}

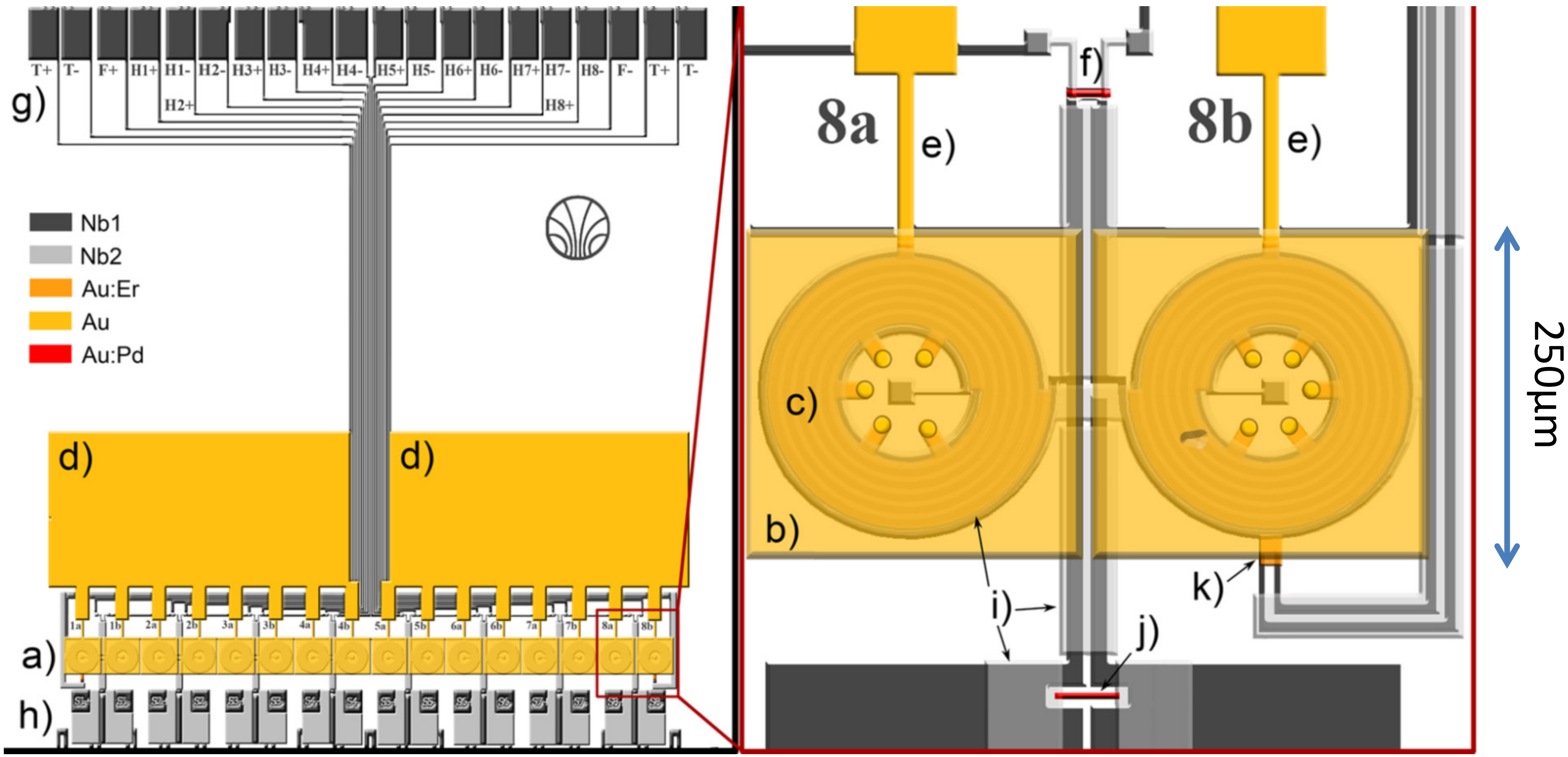
Offline mass separation:

RISIKO, Mainz University

ISOLDE-CERN

H. Dorrer, A. Türler et al., to be submitted

ECHo Second ^{163}Ho implantation

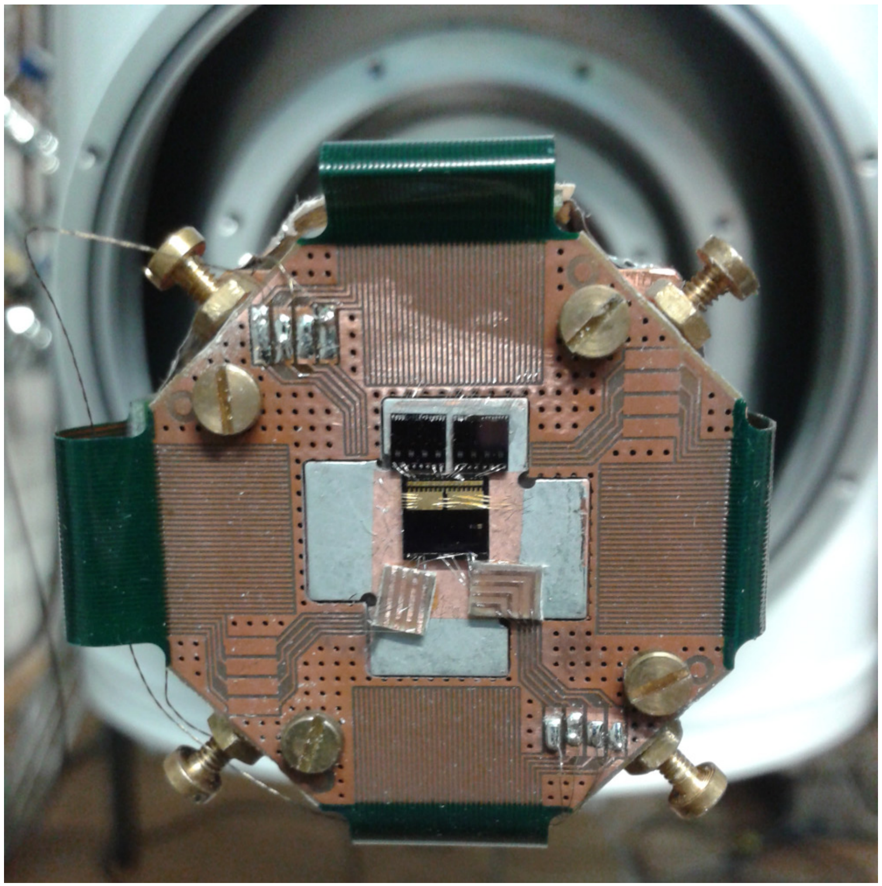


- Chemically purified ^{163}Ho source
- Offline implantation @ISOLDE-CERN using GPS and RILIS (December 2014)

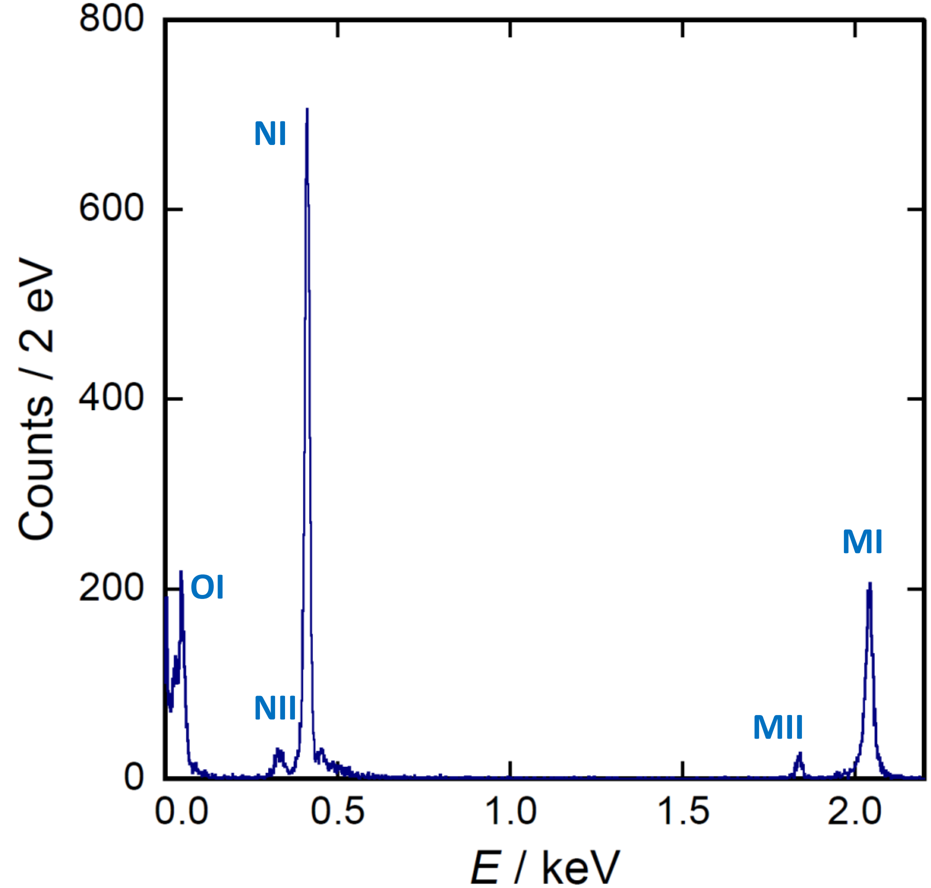
C. Hassel et al.,JLTP (2016)

ECHo New detectors

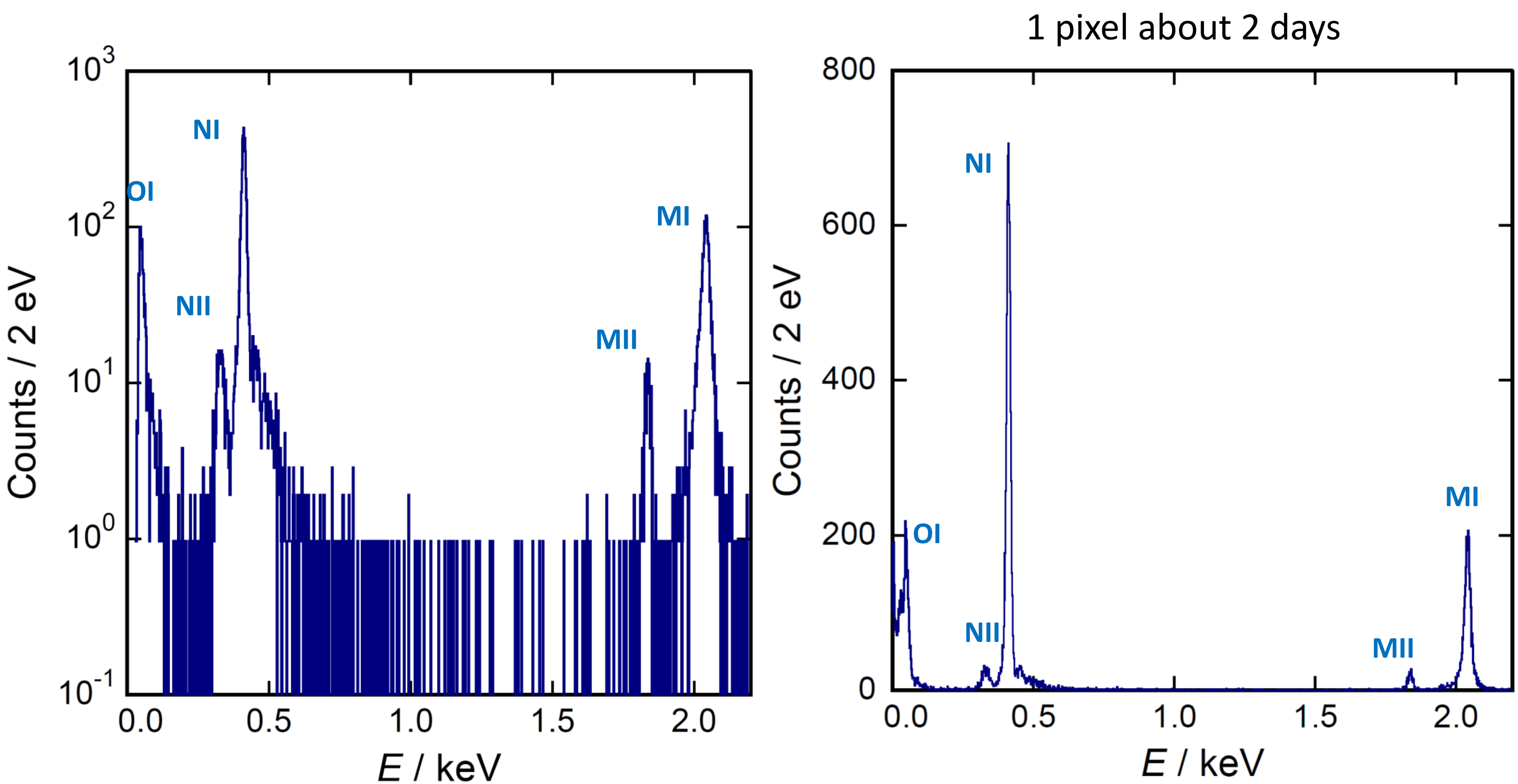
Mounted on a cold arm of a dry cryostat



1 pixel about 2 days

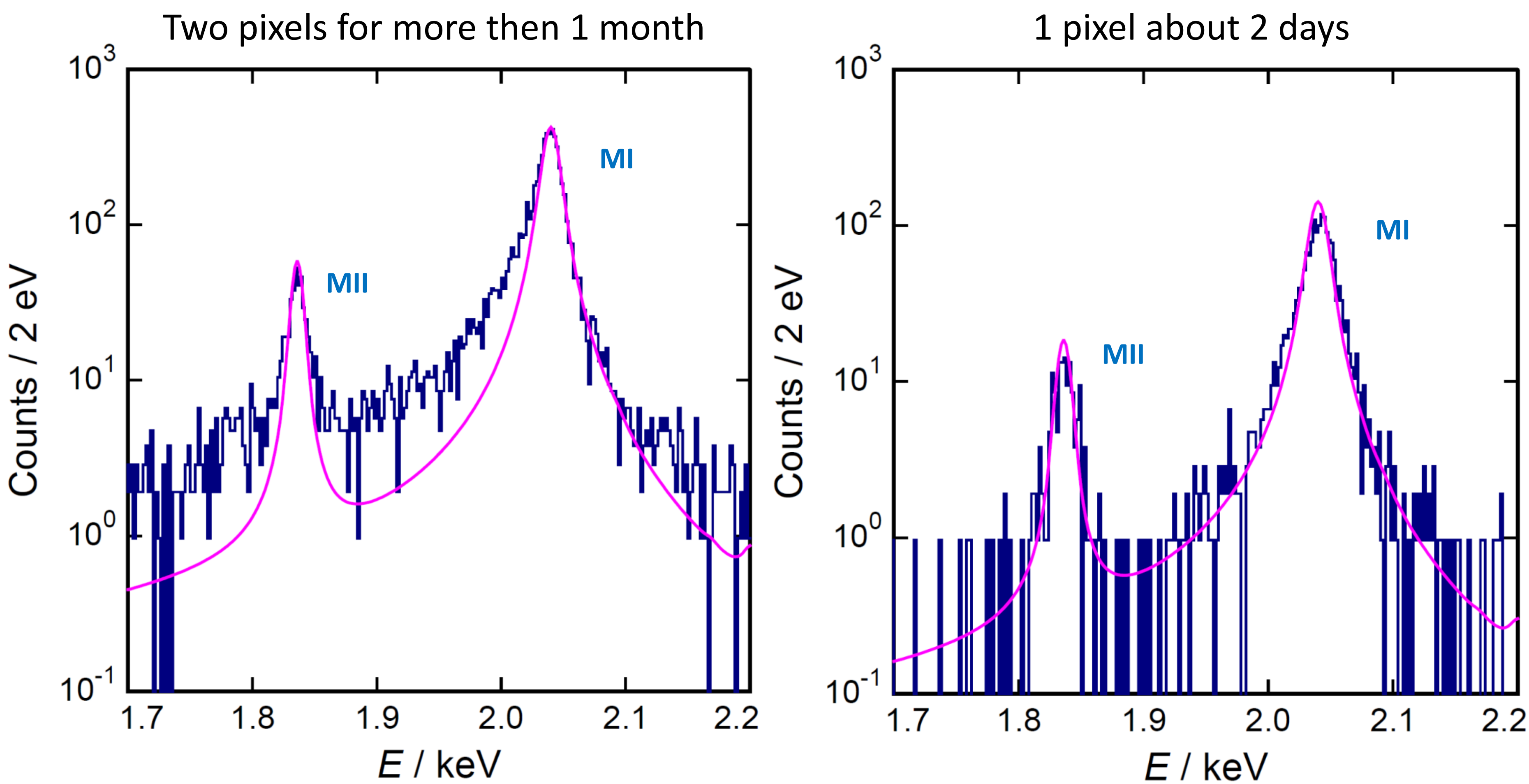


... first results



- Activity per pixel $A \sim 0.2$ Bq
- Baseline resolution $\Delta E_{FWHM} \sim 5$ eV
- No strong evidence of radioactive contamination in the source

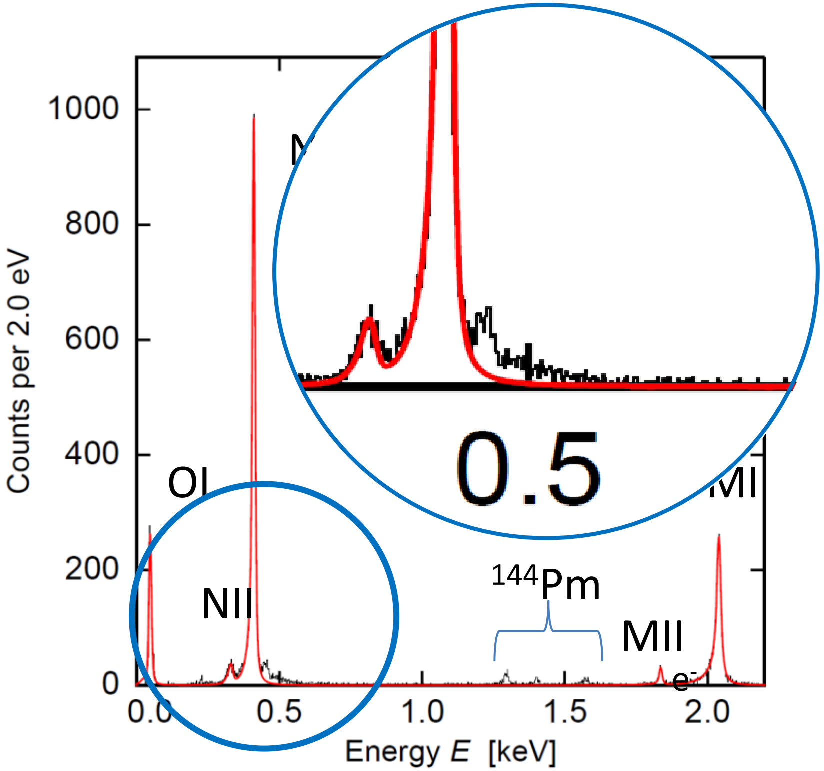
… first results



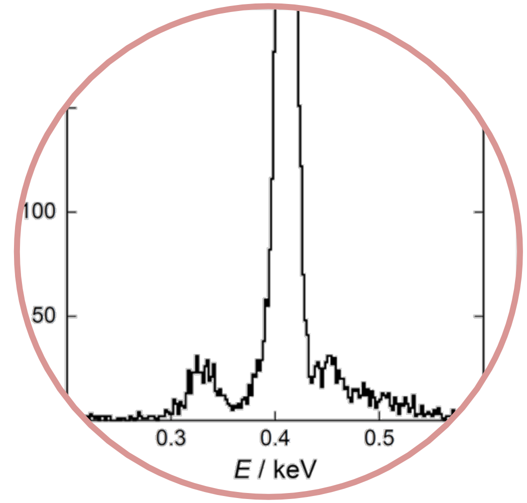
- Activity per pixel $A \sim 0.1$ Bq
- Baseline resolution $\Delta E_{FWHM} \sim 5$ eV
- No strong evidence of radioactive contamination in the source
- Symmetric detector response

C. Hassel et al.,JLTP (2015)

Characterisation of spectral shape



Structures present also in new data



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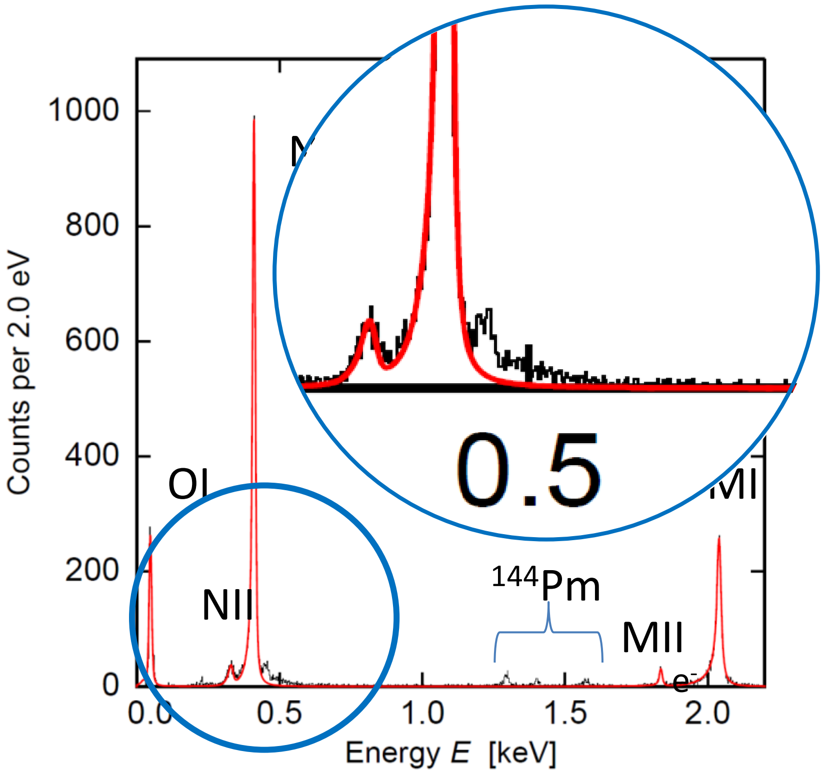
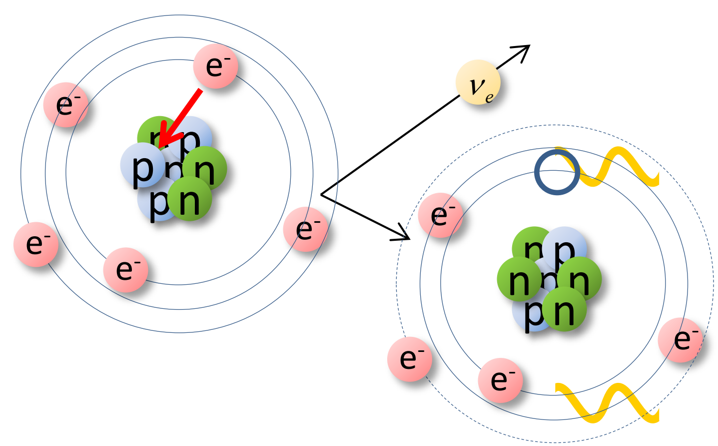


Estimate the effect of

- **Higher order excitation in ^{163}Ho**

- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler and F. Simkovic
  Phys. Rev. C **91**, 045505 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. De Rujula and M. Lusignoli
  arXiv:1601.04990v1 [hep-ph] 19 Jan 2016



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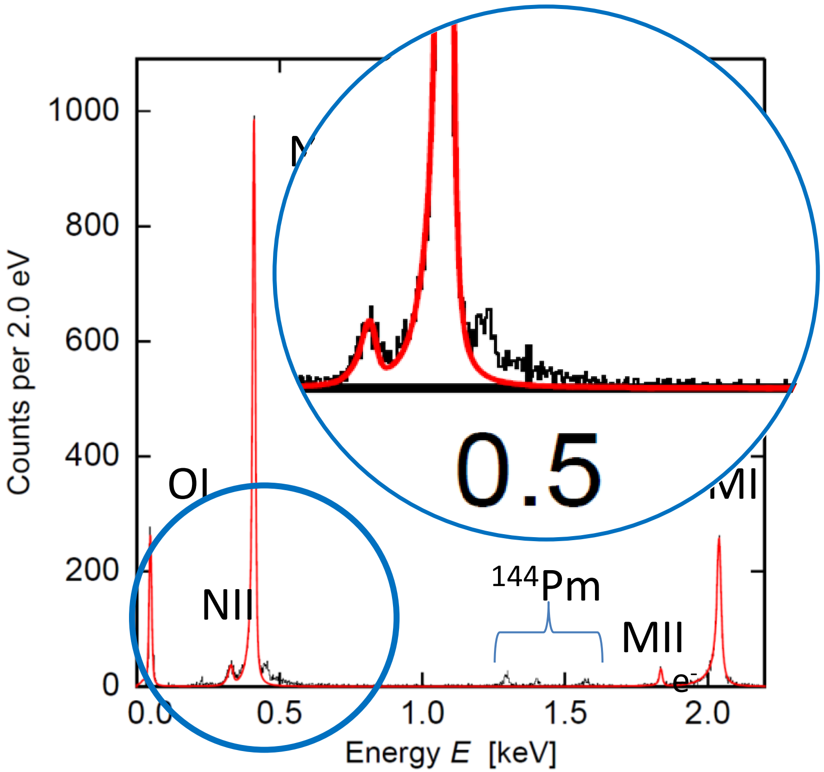

Two-holes excited states: shake-up

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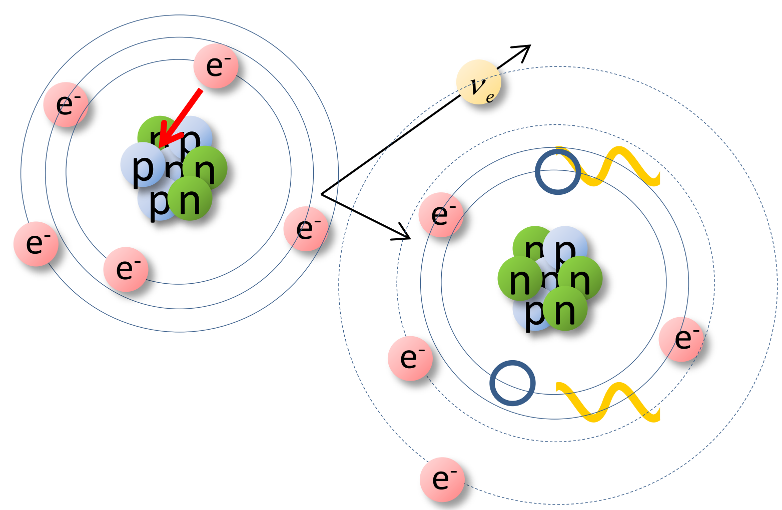
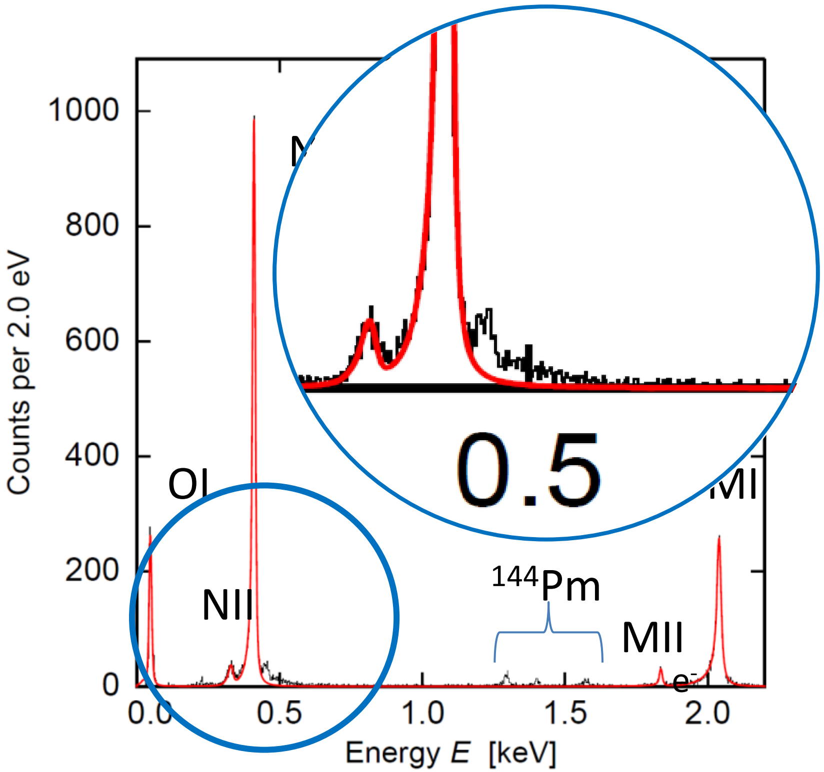


Characterisation of spectral shape



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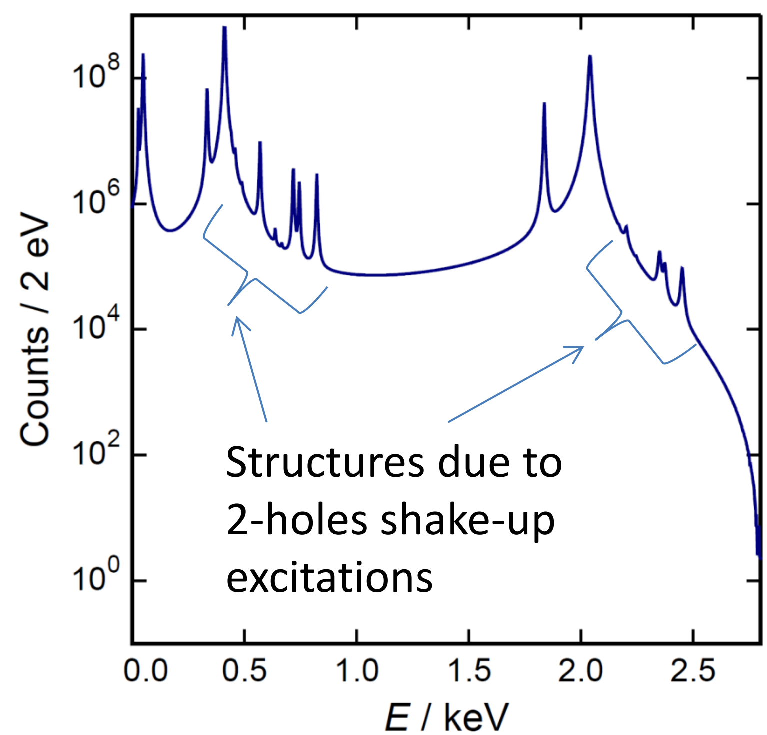

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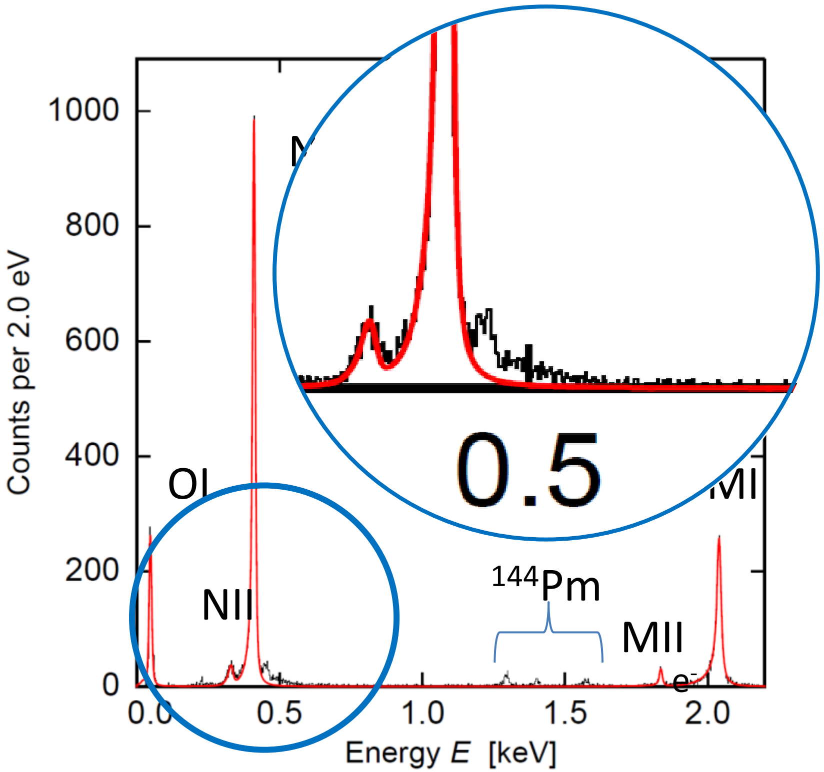

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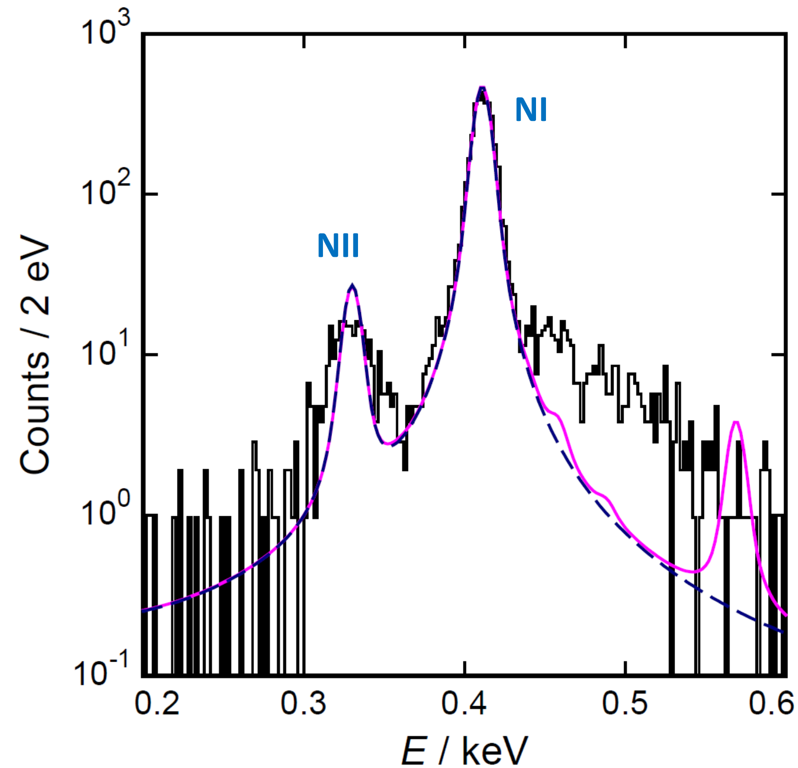
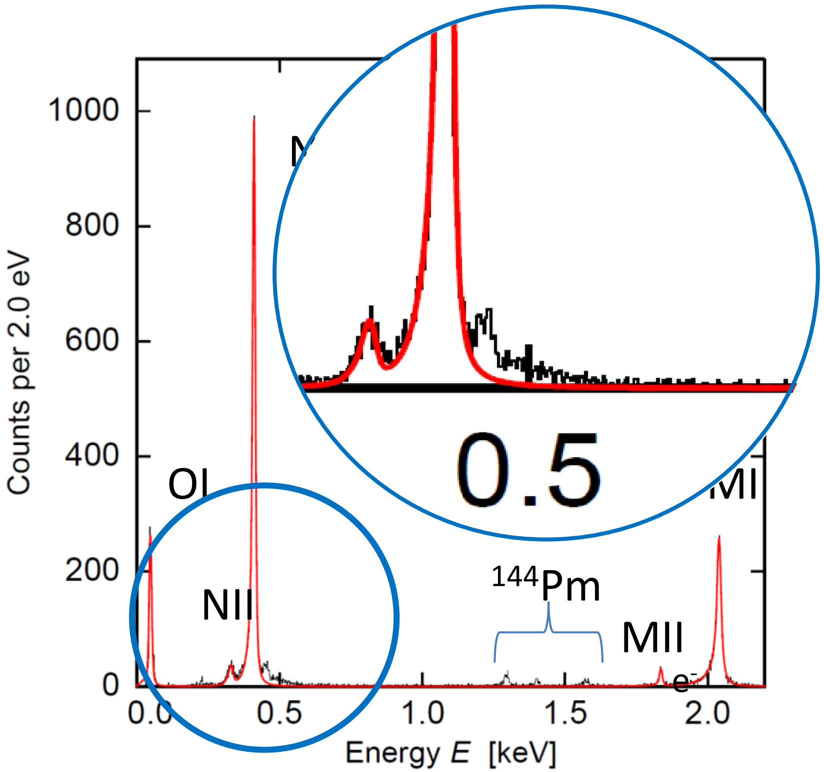


Two-holes excited states: shake-up

Characterisation of spectral shape



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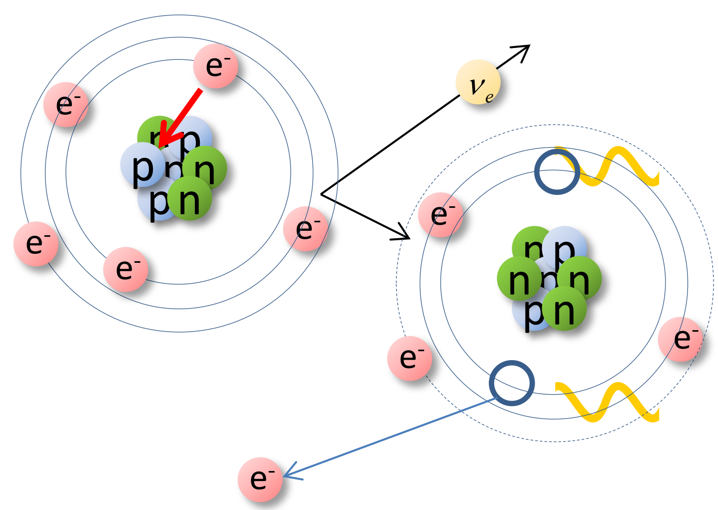
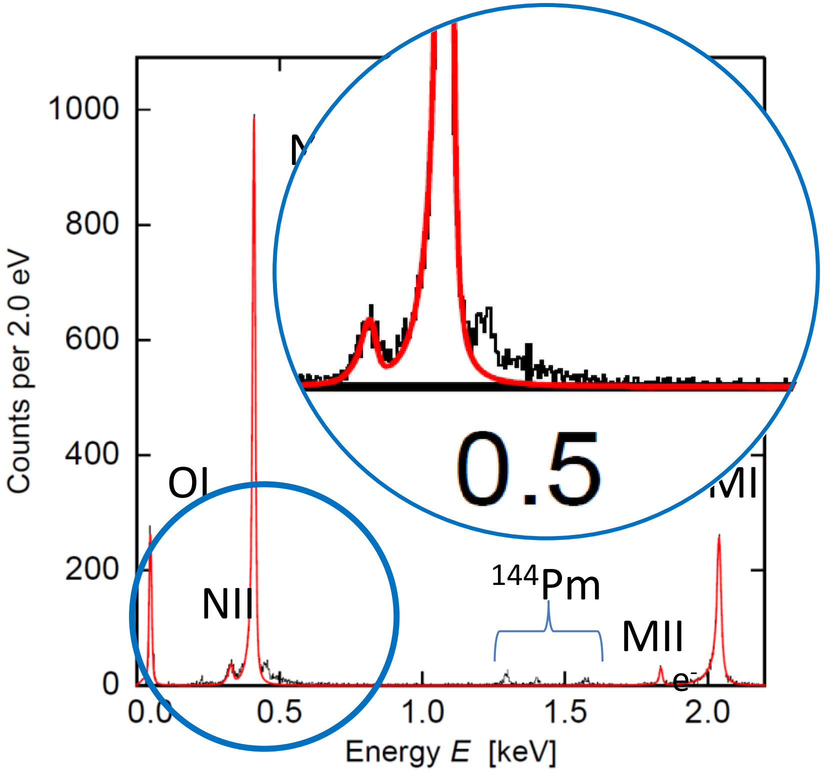


Two-holes excited states: shake-up
shake-off

Characterisation of spectral shape



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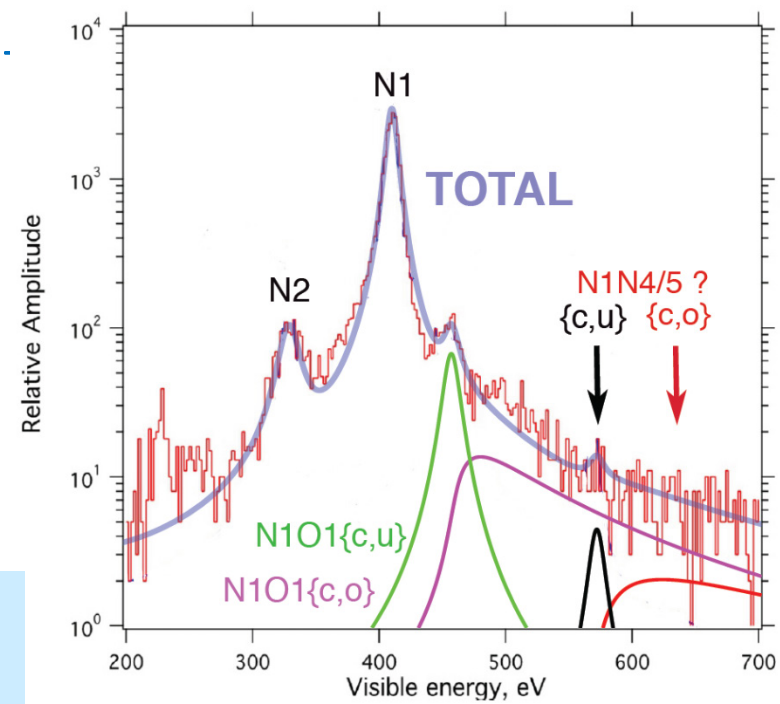


Two-holes excited states: shake-up
shake-off

High statistics and high energy resolution spectra will provide information on the spectral shape

ECHo timeline

- Prove scalability with medium large experiment **ECHo-1K** (2015 - 2018)

  - A ~ 1000 Bq — High purity ^{163}Ho source (produced at ILL)
  - $\Delta E_{FWHM} < 5$ eV
  - $\tau_r < 1$ μs
  - **multiplexed arrays → microwave SQUID multiplexing**

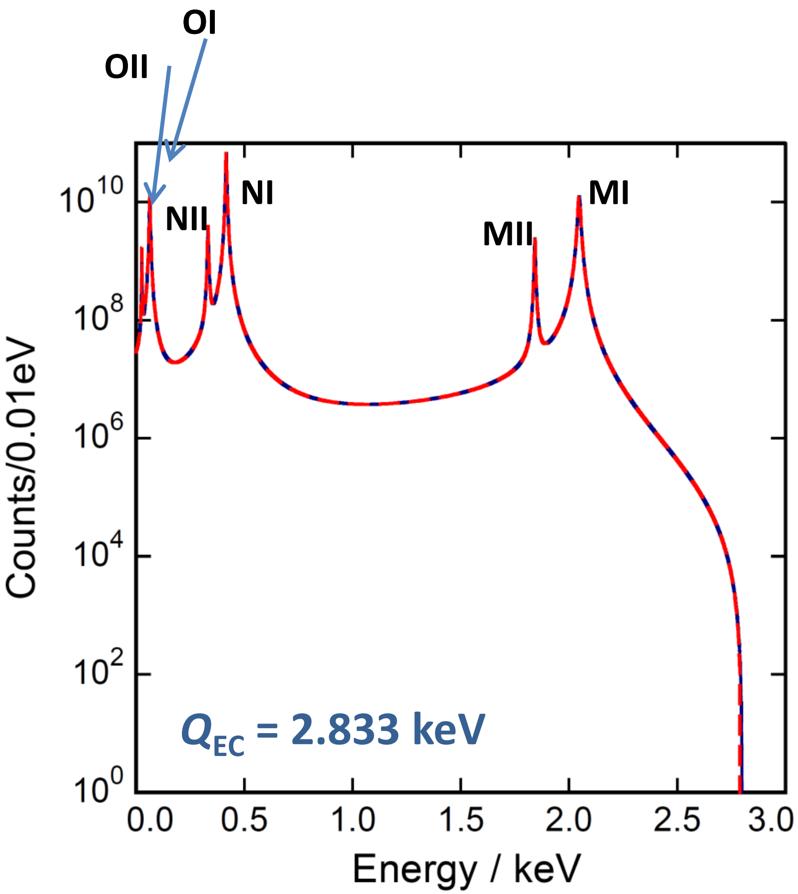
  - 1 year measuring time → 10^{10} counts = Neutrino mass sensitivity $m_\nu < 10$ eV

  Supported by **DFG** through **Research Unit FOR 2202/1**

- **ECHo-1M** towards sub-eV sensitivity (2017 - 2021)

Sterile Neutrino and ^{163}Ho

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



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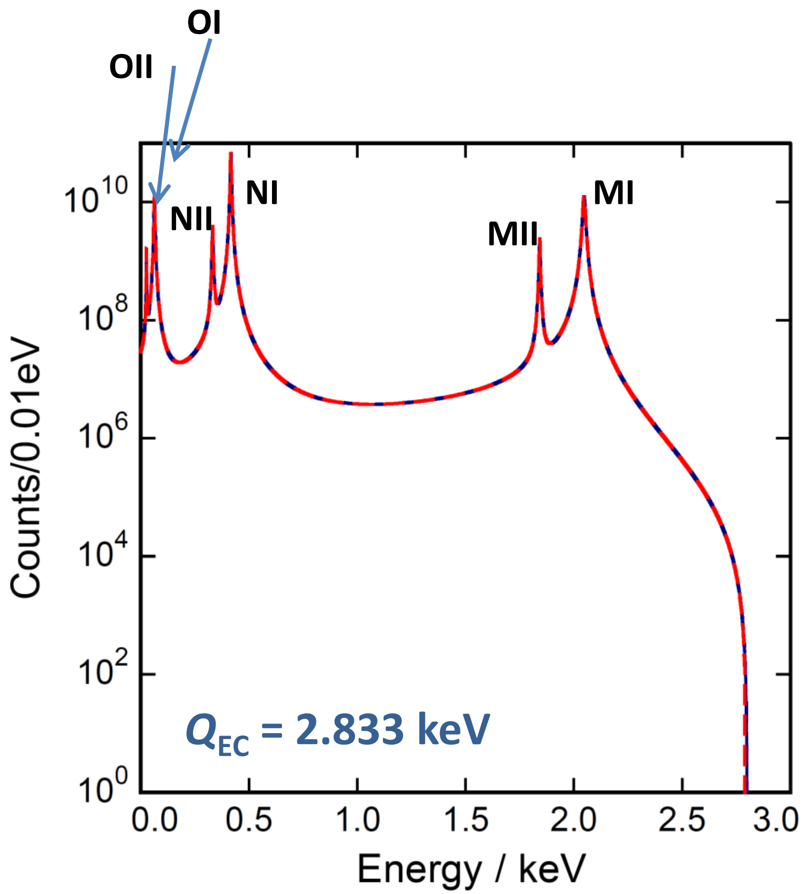
$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$



Sterile Neutrino and ^{163}Ho

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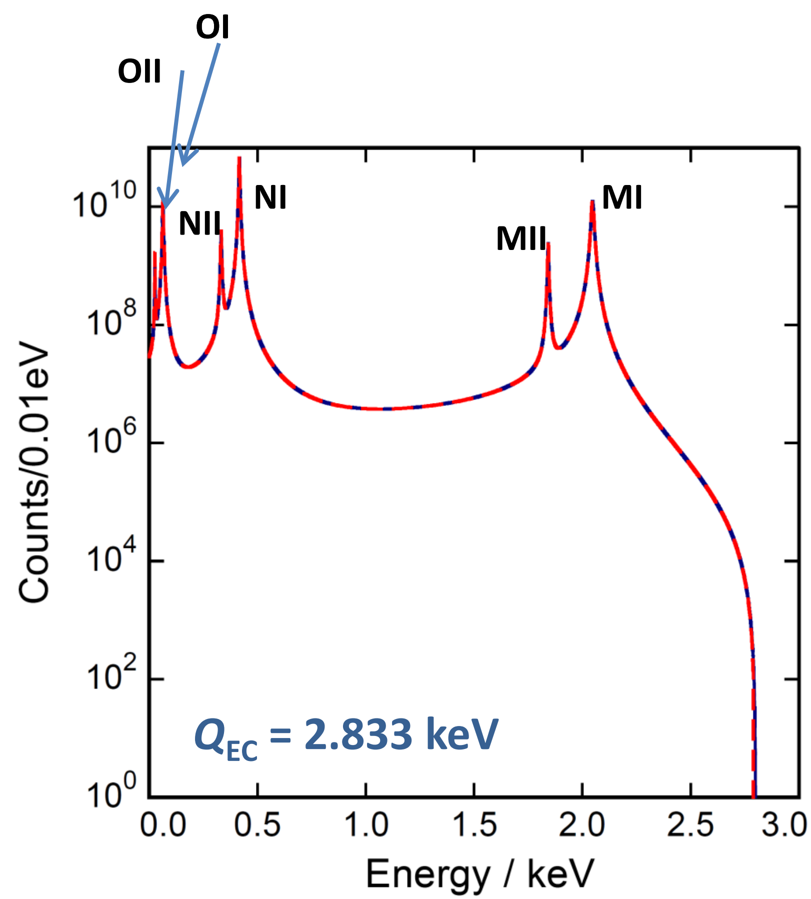


Sterile Neutrino and ^{163}Ho

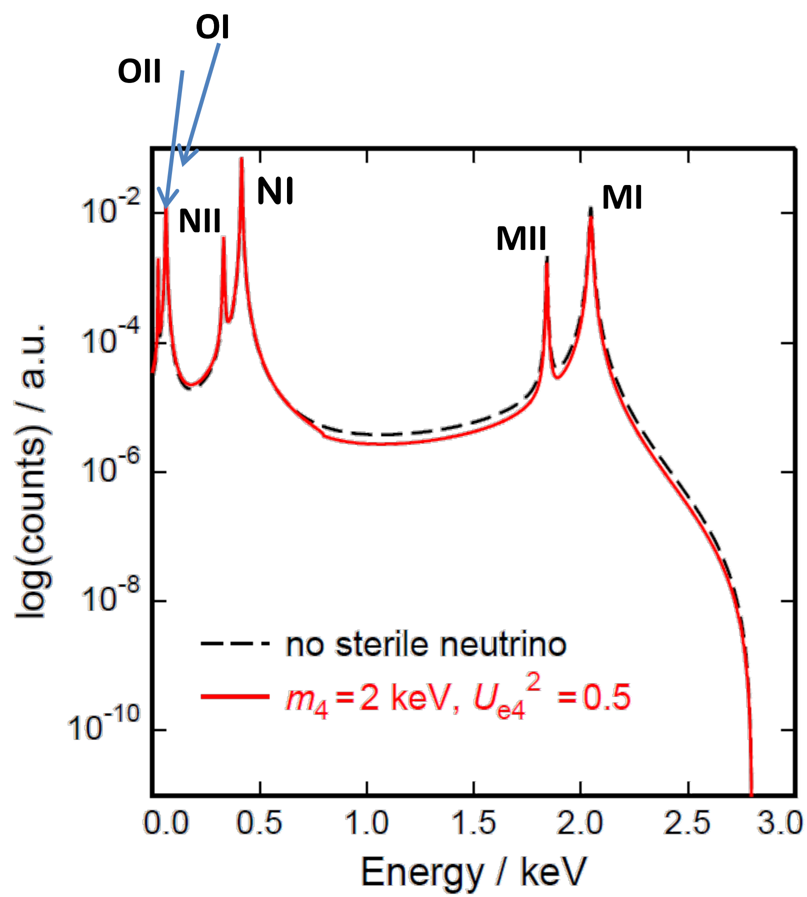
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \left[\left(1 - |U_{e4}|^2\right) + |U_{e4}|^2 \sqrt{1 - \frac{m_4^{\,2}}{(Q_{EC} - E_C)^2}} H(Q_{EC} - E_c - m_4) \right] \sum_H B_H \varphi_H^{\,2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\,2}}{4}}$$

$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$

$$m_{1,2,3} = 0$$

$$m_4 \neq 0$$

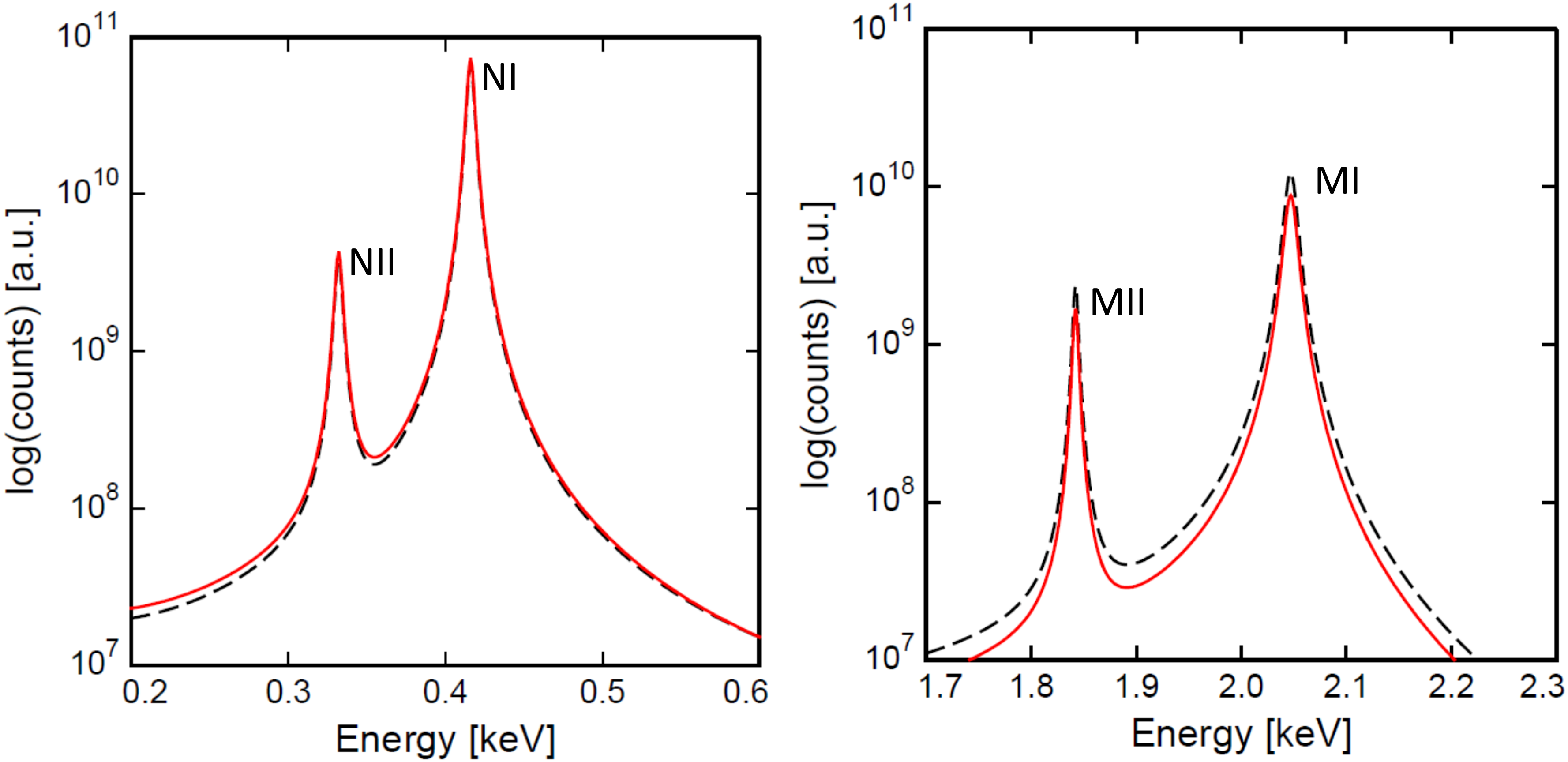
$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} |\nu_i\rangle + U_{e4} |\nu_4\rangle$$



Sterile Neutrino and ^{163}Ho

m_4=2 keV, U_{e4}^2=0.5

no sterile neutrino



Sterile Neutrino and ^{163}Ho

- Amplitude of the line H for only active neutrinos

$$W_{Ha} = \mathrm{A}\left(Q_{\mathrm{EC}} - E_{\mathrm{H}}\right)^2 B_H \varphi_{\mathrm{H}}{}^2(0)$$

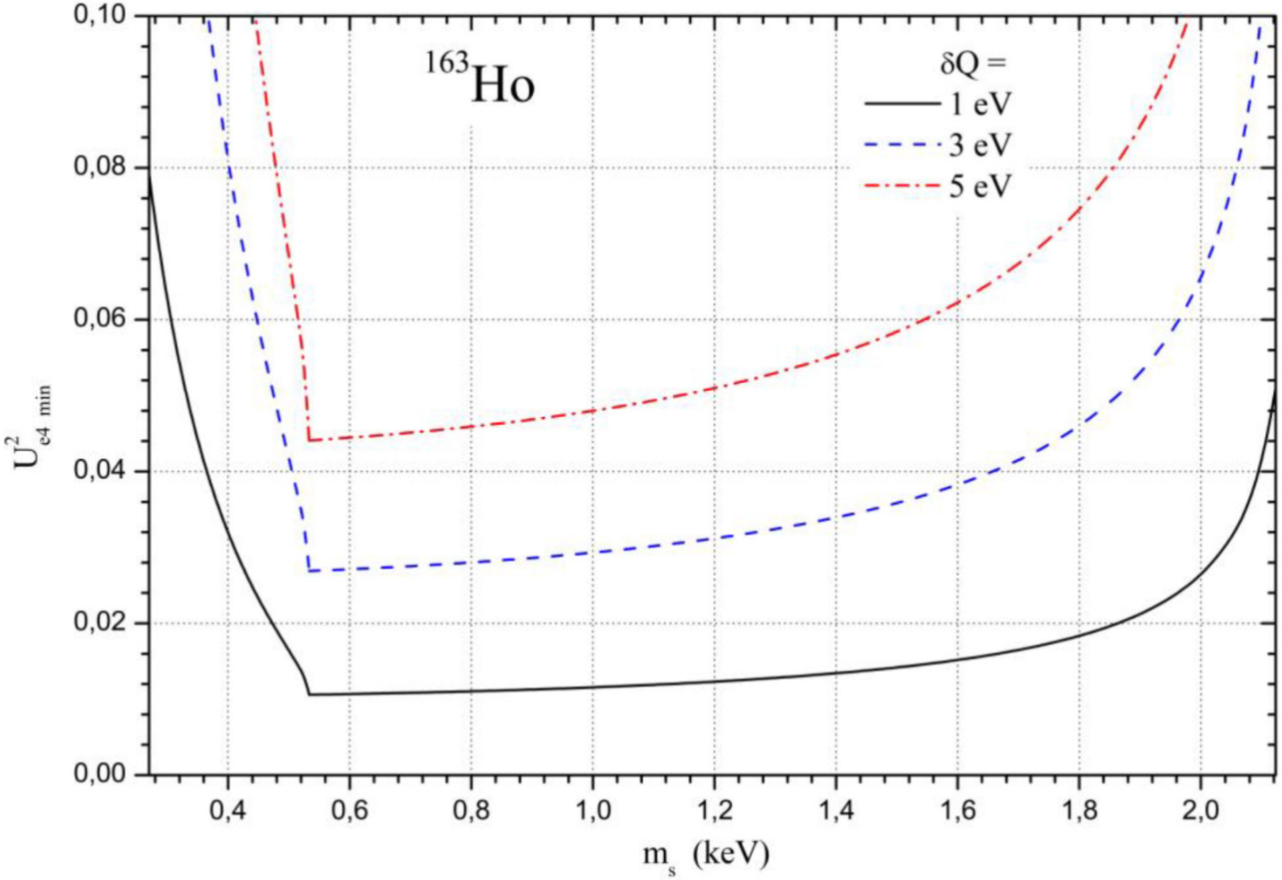
- Amplitude of the line H for 3+1 model in case of m_a = 0 eV

$$W_{Hs} = \mathrm{A}\left(Q_{\mathrm{EC}} - E_{\mathrm{H}}\right)^2 \left[\left(1 - \left|U_{e4}\right|^2\right) + \left|U_{e4}\right|^2 \sqrt{1 - \frac{m_4{}^2}{\left(Q_{\mathrm{EC}} - E_{\mathrm{C}}\right)^2}} H\left(Q_{EC} - E_c - m_4\right) \right] B_H \varphi_{\mathrm{H}}{}^2(0)$$

- Ratio between amplitudes of two lines in the spectrum for 3+1 model in case of m_a = 0 eV

$$\left(\frac{W_{H1}}{W_{H2}}\right)_s = \left(\frac{W_{H1}}{W_{H2}}\right)_a \frac{\left|U_{e4}\right|^2 \left[H\left(Q_{EC} - E_1 - m_4\right) \sqrt{1 - \frac{m_4{}^2}{\left(Q_{\mathrm{EC}} - E_1\right)^2}} - 1 \right] + 1}{\left|U_{e4}\right|^2 \left[H\left(Q_{EC} - E_2 - m_4\right) \sqrt{1 - \frac{m_4{}^2}{\left(Q_{\mathrm{EC}} - E_2\right)^2}} - 1 \right] + 1}$$

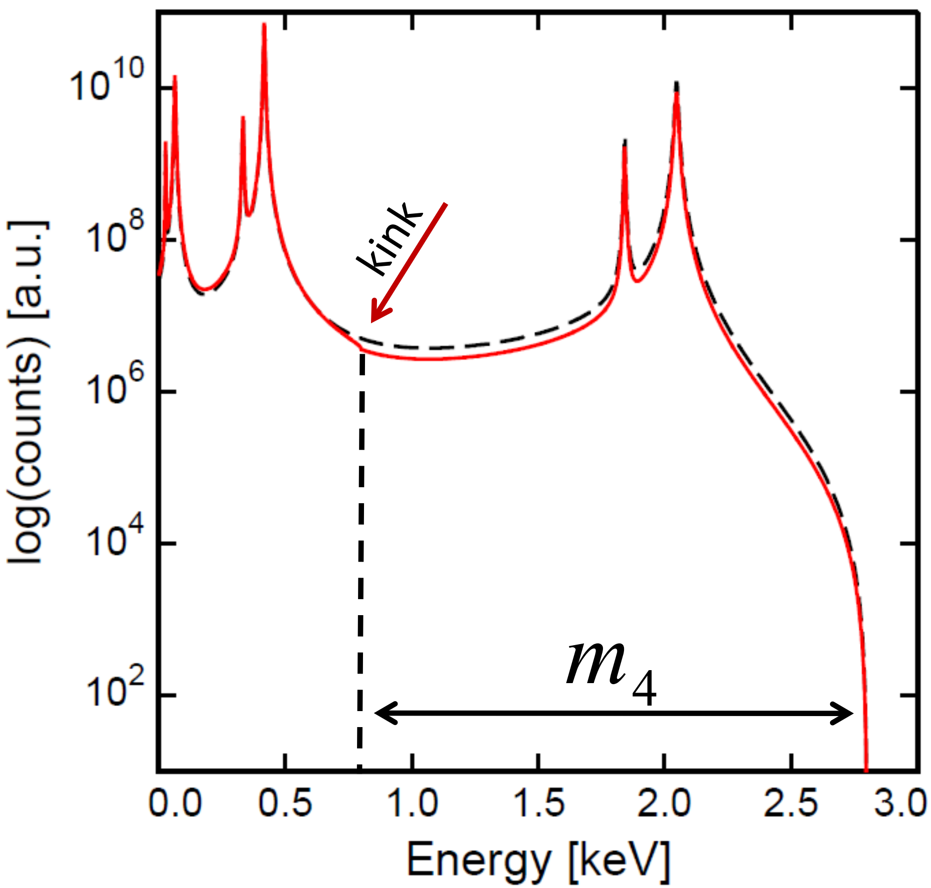
Sterile Neutrino and ^{163}Ho



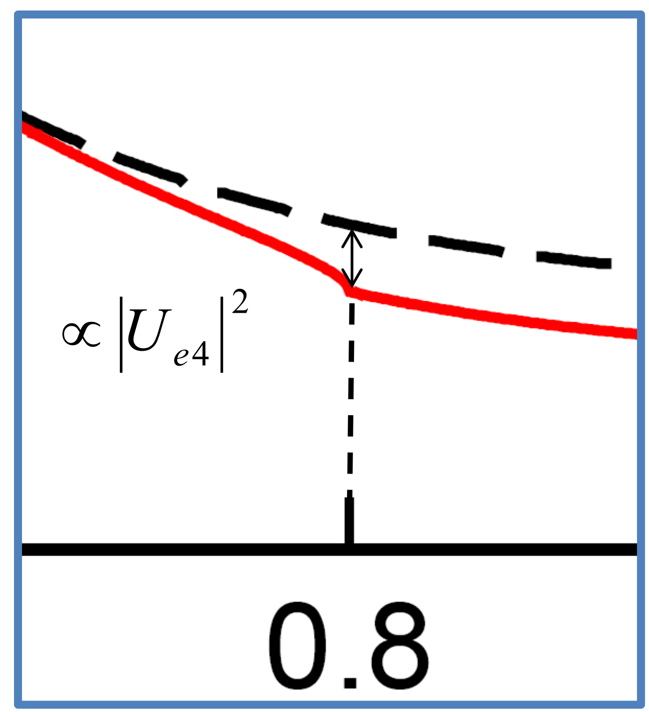
Sensitivity to the mixing matrix element at 90% CL as a function of the sterile neutrino mass achievable with about 10^{10} events in the full EC spectrum.

P. Filianin et al. arXiv: 1402.4400

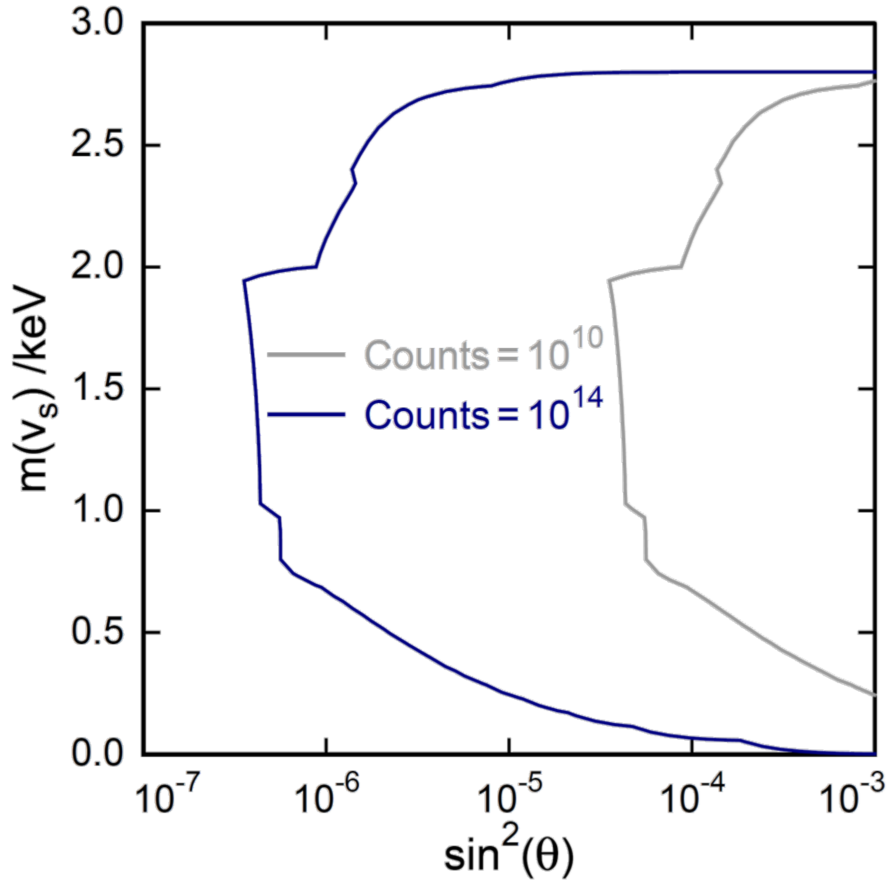
Sterile Neutrino and ^{163}Ho



- postion of kink => m_4
- depth of kink => $|U_{e4}|^2$



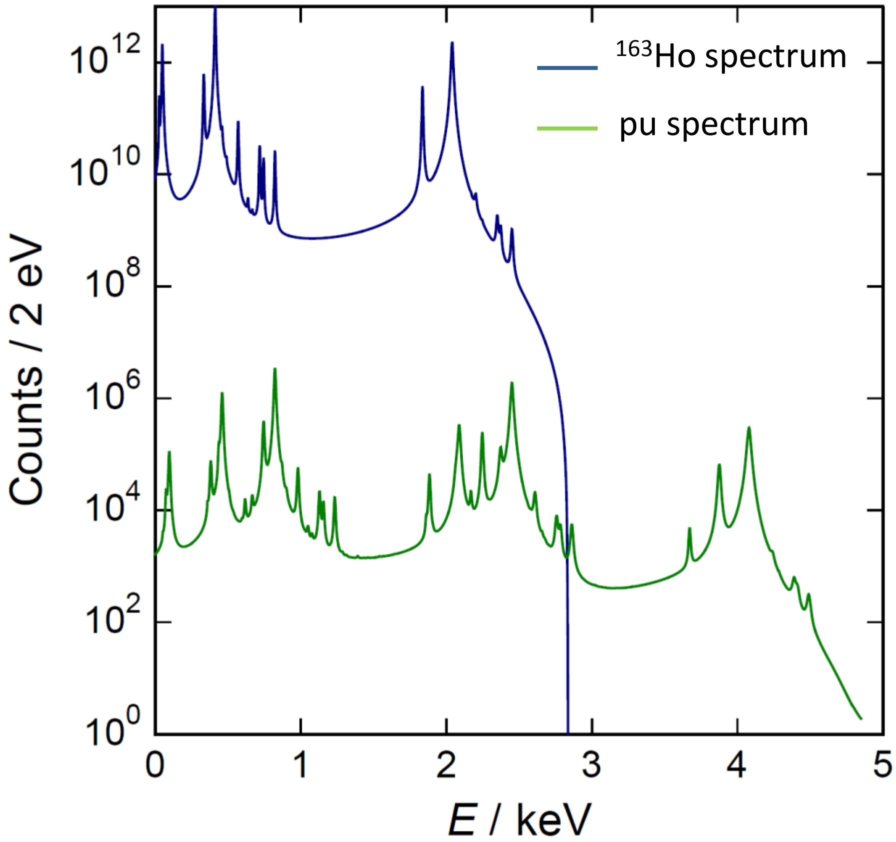
Sterile Neutrino in ECHo



- **Statistical Fluctuation**
- **No Pile Up**
- **Theoretical Spectrum supposed to be perfectly known**

A White Paper on keV Sterile Neutrino Dark Matter arXiv:1602.04816v1

Other small structures on the ^{163}Ho spectrum



Many peaks due to higher order excited states in ^{163}Dy and the corresponding structures in the pile up spectrum

Identification of sterile neutrinos signatures could be limited by the complex structure of the ^{163}Ho spectrum

^{163}Ho-based experiments

ECHo HOLMES NuMECS

Calorimetric measurement of the ^{163}Ho spectrum

Common challenges to reach sub eV sensitivity :

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

For sterile neutrino signature

- The complete spectrum should be analysed

Sterile Neutrino (keV) and Electron Capture

Other condidates in the EC branch:

- Q_{EC} < 100 keV
- Reasonable halflife

Nuclide	$T_{1/2}$	EC-transition	Q (keV) [22]	B_i (keV) [23]	B_j (keV) [23]	$\lvert\psi_i\rvert^2/\lvert\psi_j\rvert^2$	$Q-B_i$ (keV)
^{123}Te	$>2\cdot10^{15}$ y	?	52.7(16)	K: 30.4912(3)	L_I: 4.9392(3)	7.833	22.2
^{157}Tb	71 y	$3/2^+\rightarrow3/2^-$	60.04(30)	K: 50.2391(5)	L_I: 8.3756(5)	7.124	9.76
^{163}Ho	4570 y	$7/2^-\rightarrow5/2^-$	2.555(16)	M_I: 2.0468(5)	N_I: 0.4163(5)	4.151	0.51
^{179}Ta	1.82 y	$7/2^+\rightarrow9/2^+$	105.6(4)	K: 65.3508(6)	L_I: 11.2707(4)	6.711	40.2
^{193}Pt	50 y	$1/2^-\rightarrow3/2^+$	56.63(30)	L_I: 13.4185(3)	M_I: 3.1737(17)	4.077	43.2
^{202}Pb	52 ky	$0^+\rightarrow2^-$	46(14)	L_I: 15.3467(4)	M_I: 3.7041(4)	4.036	30.7
^{205}Pb	13 My	$5/2^-\rightarrow1/2^+$	50.6(5)	L_I: 15.3467(4)	M_I: 3.7041(4)	4.036	35.3
^{235}Np	396 d	$5/2^+\rightarrow7/2^-$	124.2(9)	K: 115.6061(16)	L_I: 21.7574(3)	5.587	8.6

P. Filianin et al. *J. Phys. G: Nucl. Part. Phys.* **41** (2014) 095004

Sterile Neutrino (keV) and Electron Capture

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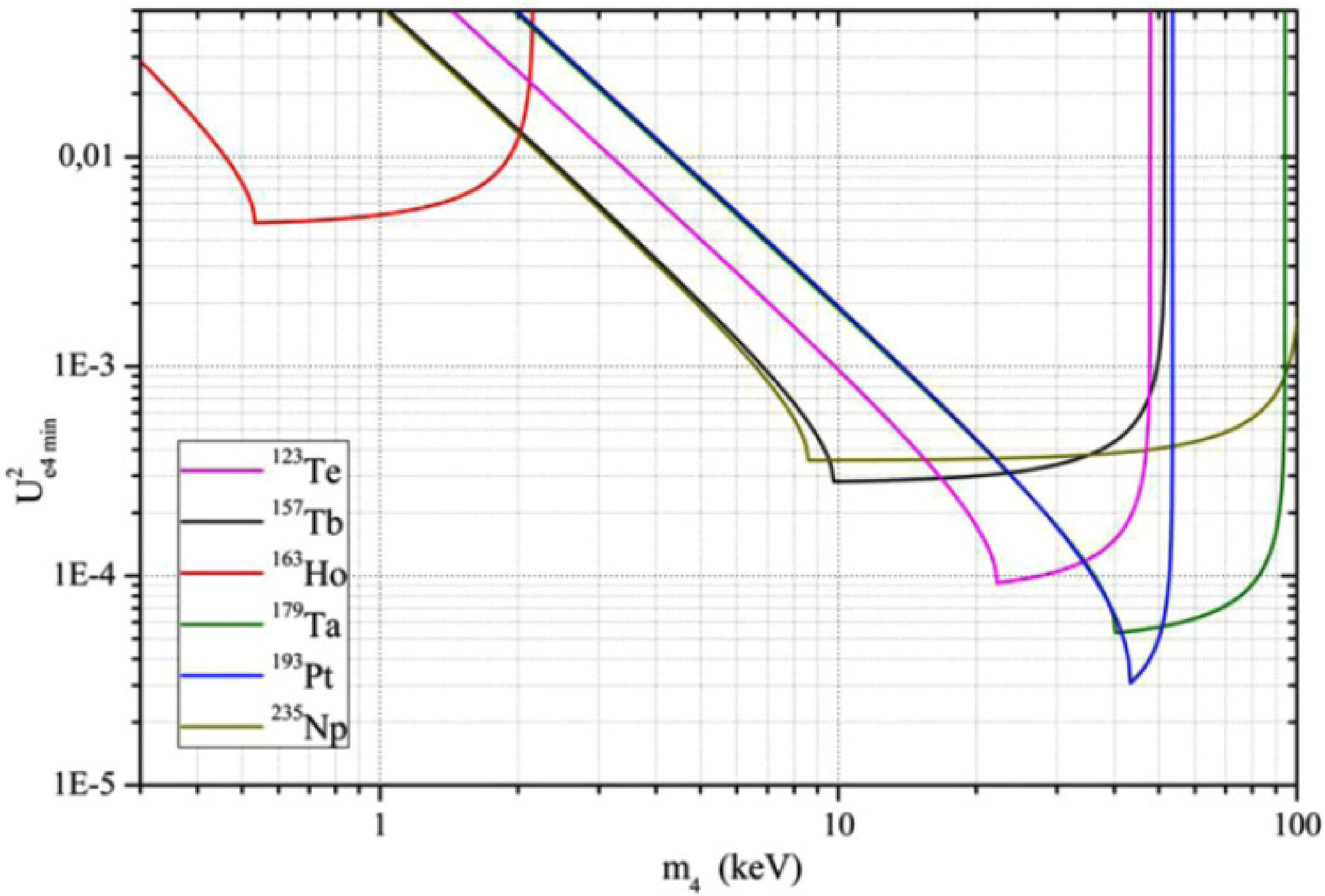
P. Filianin et al. *J. Phys. G: Nucl. Part. Phys.* **41** (2014) 095004

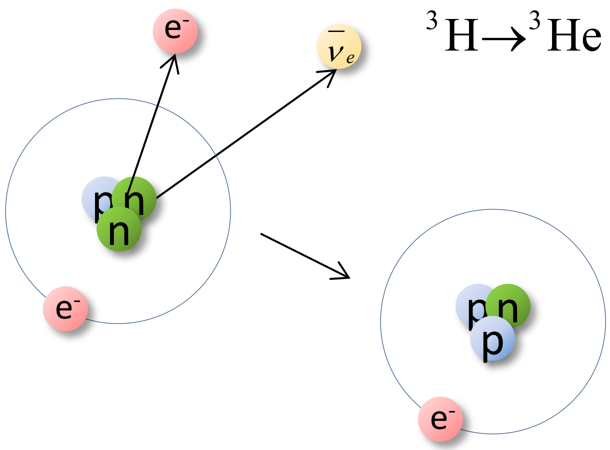
Sterile Neutrino (keV) and Electron Capture



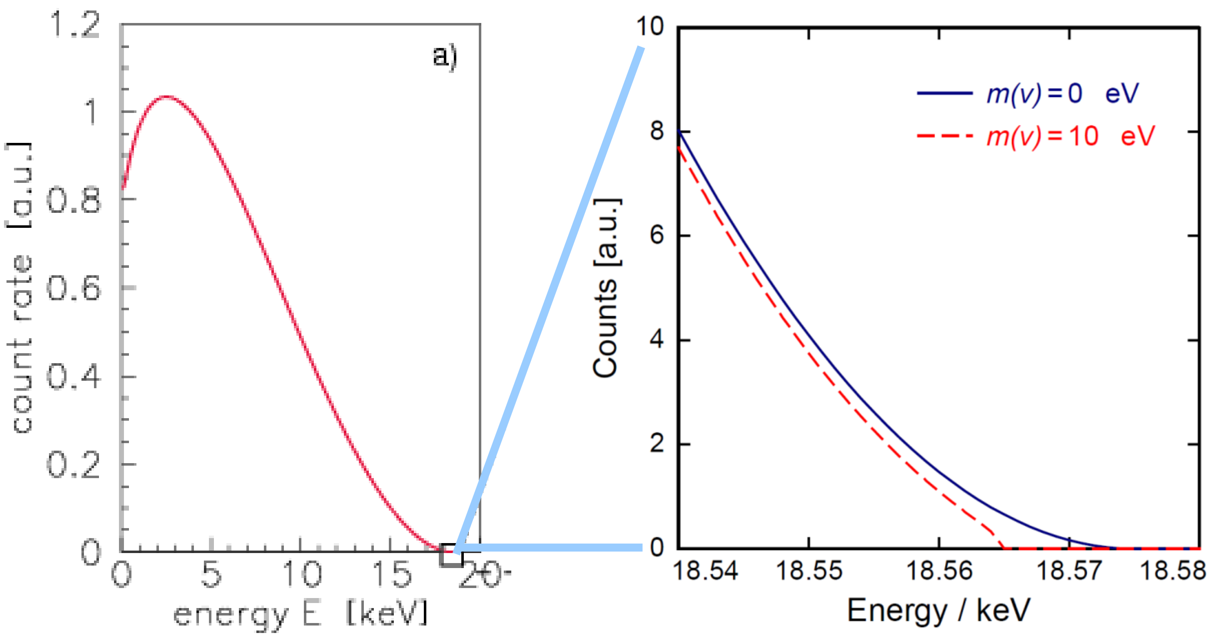
Same statistics + including errors : ($\delta\, \psi_{i,j} = 0$) δQ_{EC} = 1 eV $\delta E_{i,j}$ = 0.1 eV.

P. Filianin et al. *J. Phys. G: Nucl. Part. Phys.* **41** (2014) 095004

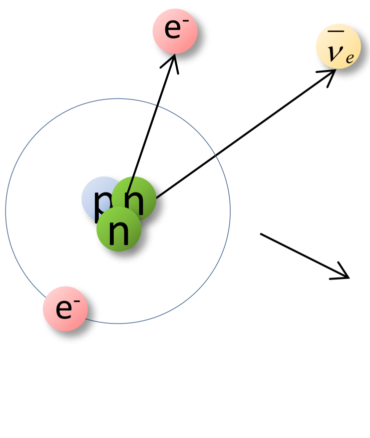
Beta decay of ^{3}H



$$^3\text{H} \rightarrow {}^3\text{He} + e^- + \overline{\nu}_e$$



Beta decay of ^3H



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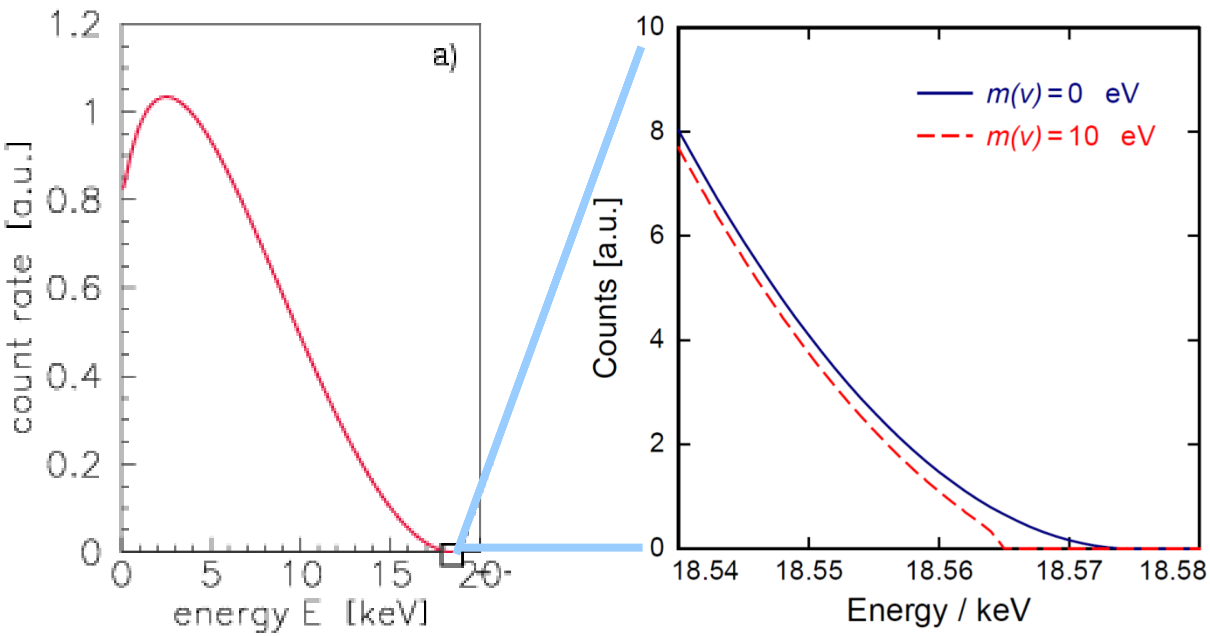
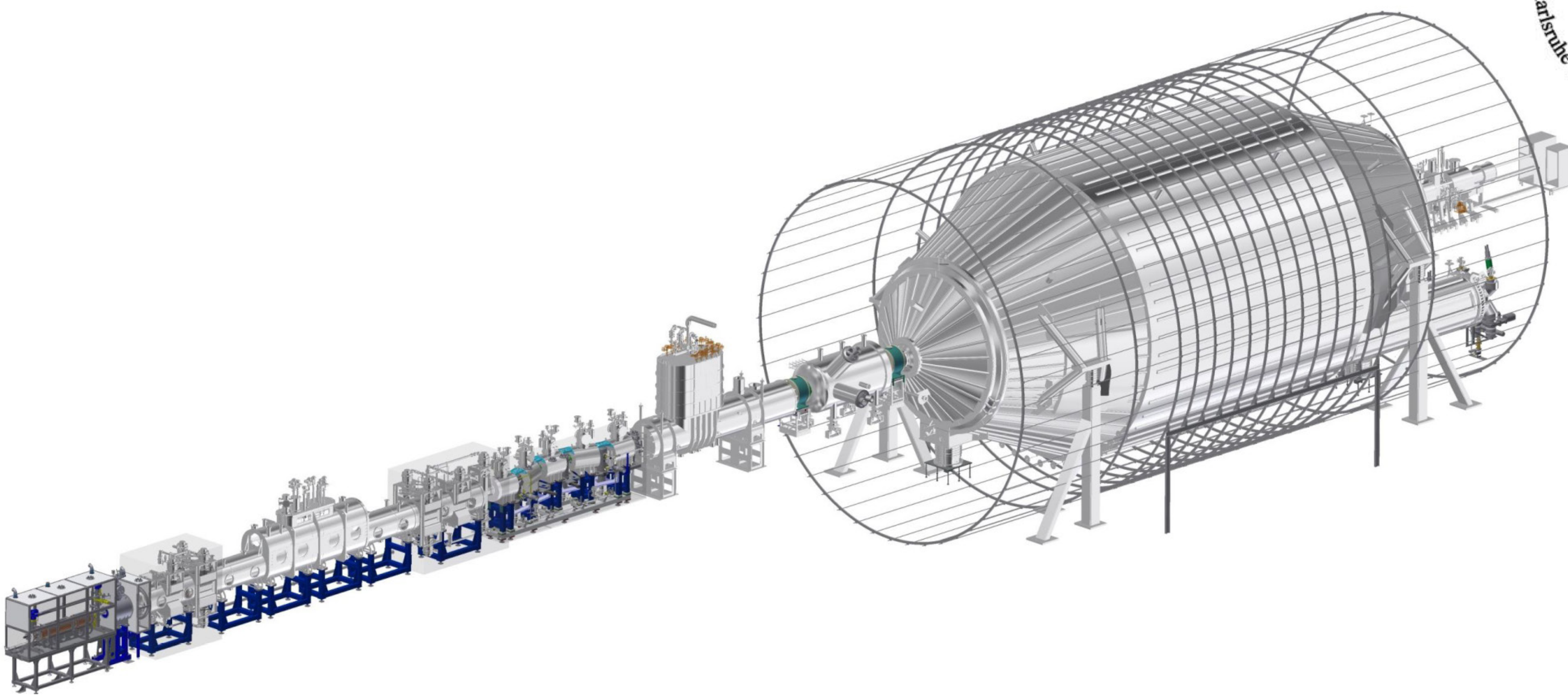


Only a small fraction of events in the last eV below the endpoint: **$2 * 10^{-13}$**

Triutium is present as **bi-atomic molecules**

^{3}H based experiments

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

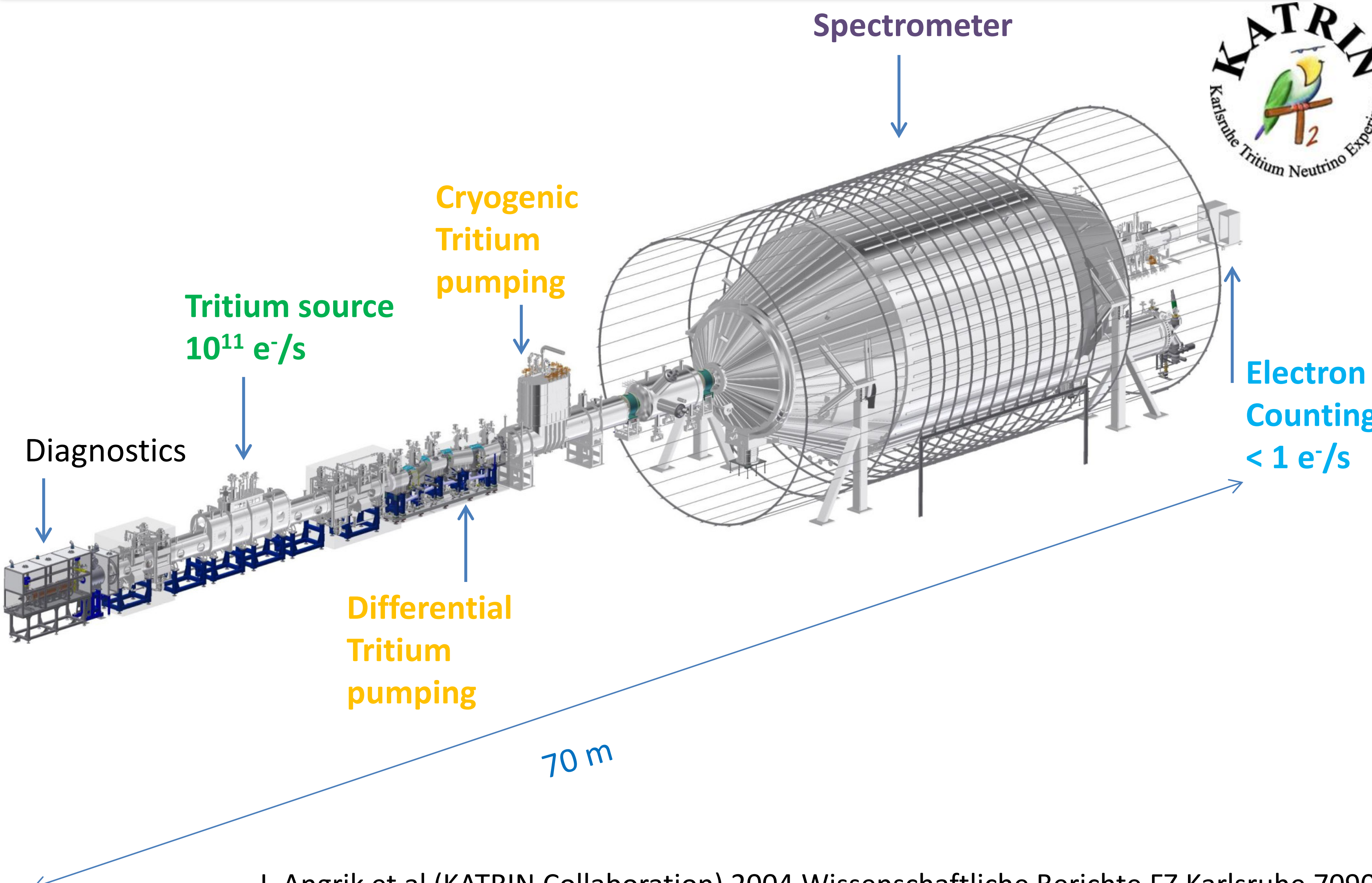


Main ideas:

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

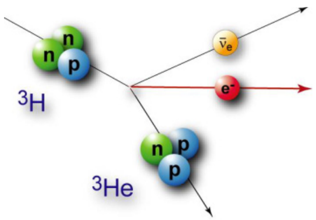
*MAC-E: Magnetic Adiabatic Collimation with Electrostatic Filter

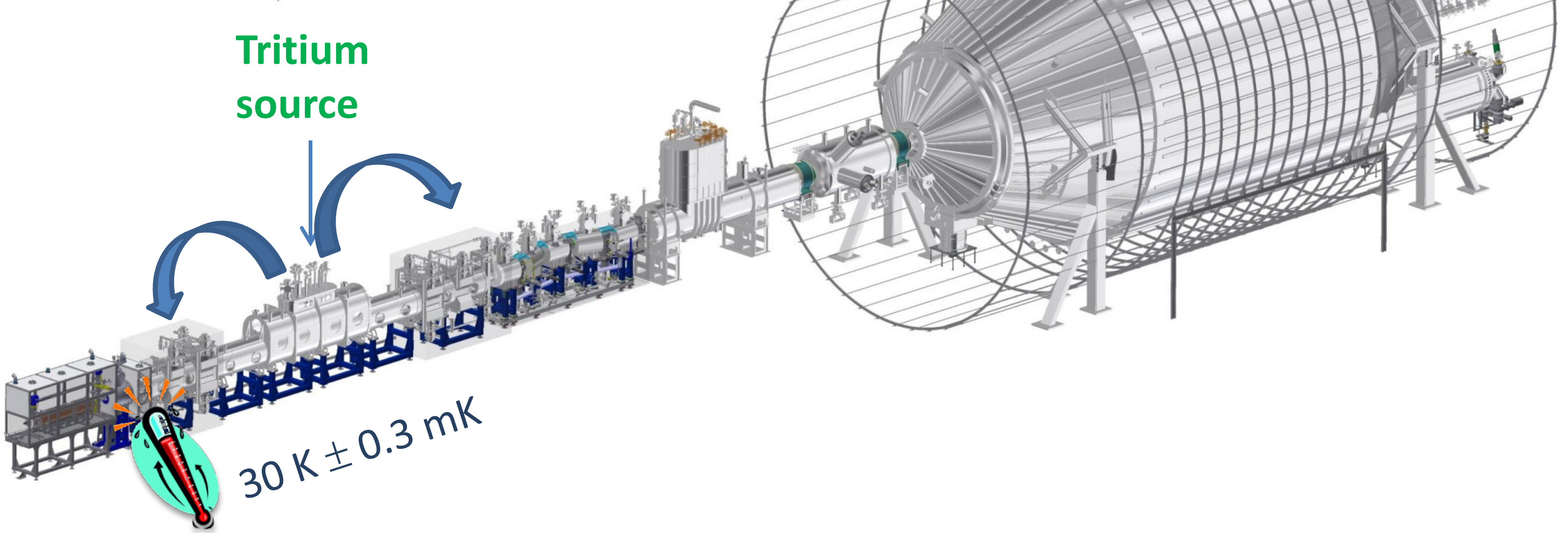
The KATRIN experiment



J. Angrik et al (KATRIN Collaboration) 2004 Wissenschaftliche Berichte FZ Karlsruhe 7090

The KATRIN experiment





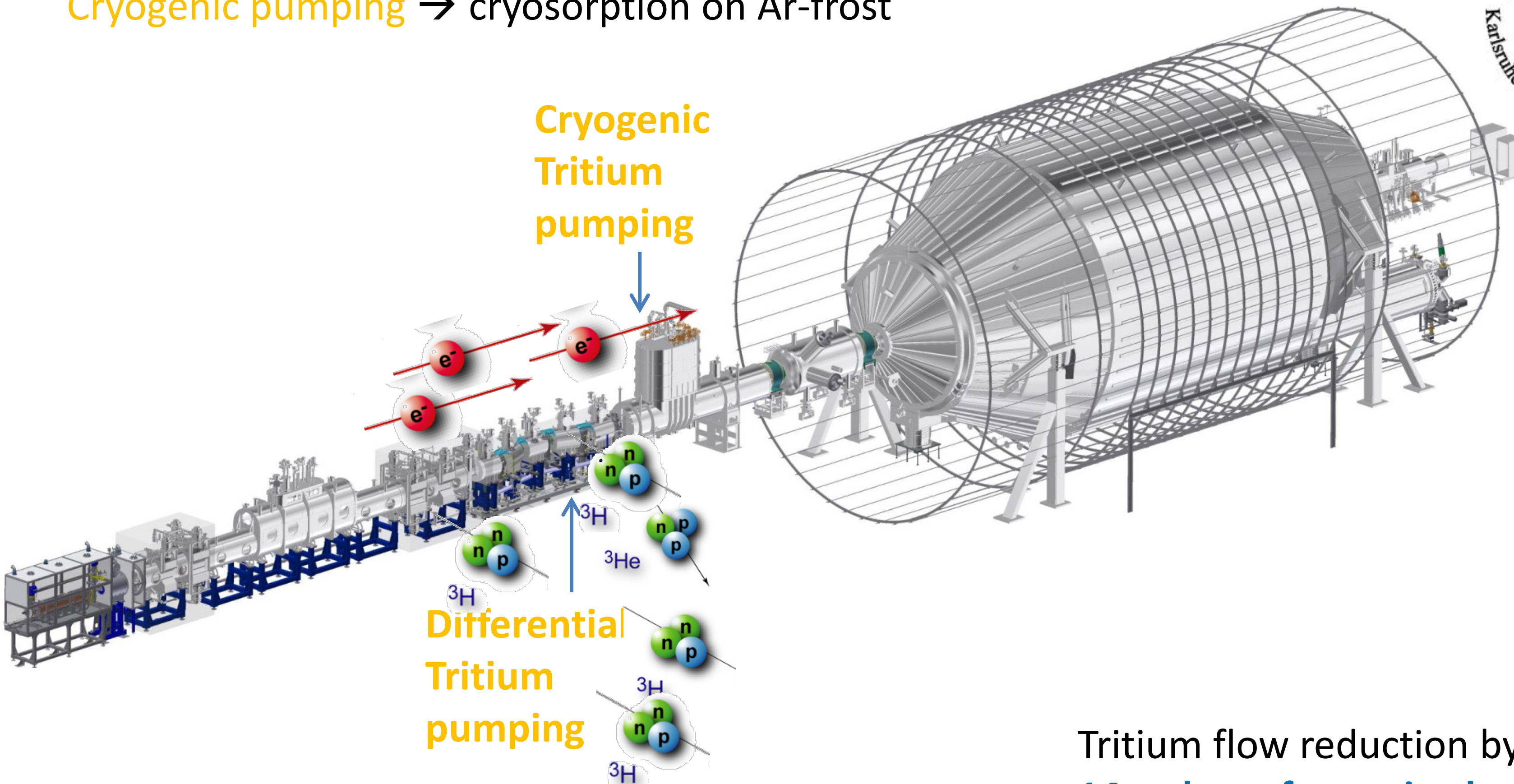
Windowless Gaseous Molecular Tritium Source

High luminosity: **10^{11} β-decay /s**

High stability : **10^{-3} level**

The KATRIN experiment

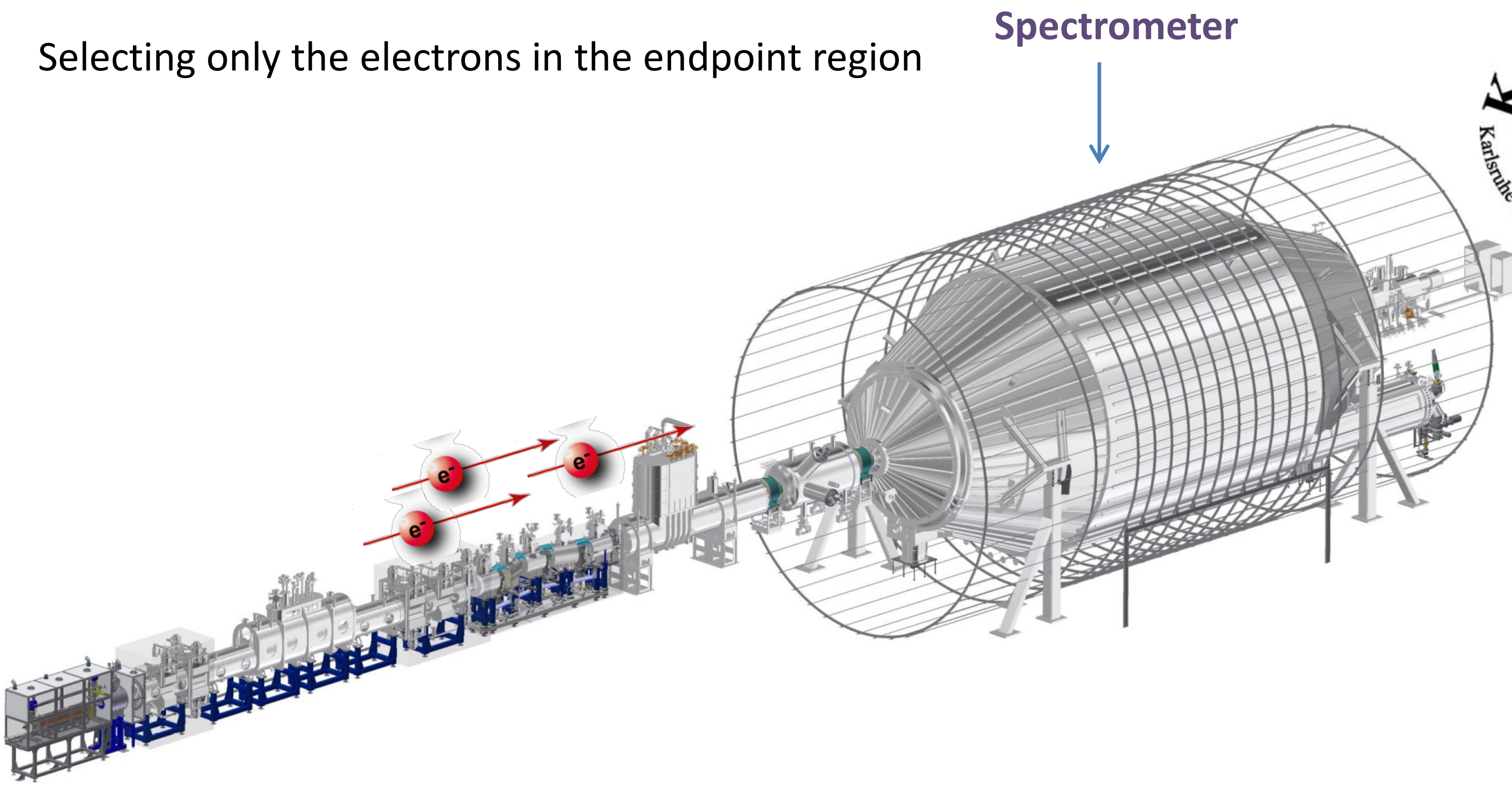
Differential pumping → active pumping by Turbo Molecular Pumps
Cryogenic pumping → cryosorption on Ar-frost



Tritium flow reduction by
14 orders of magnitudes

The KATRIN experiment

Selecting only the electrons in the endpoint region

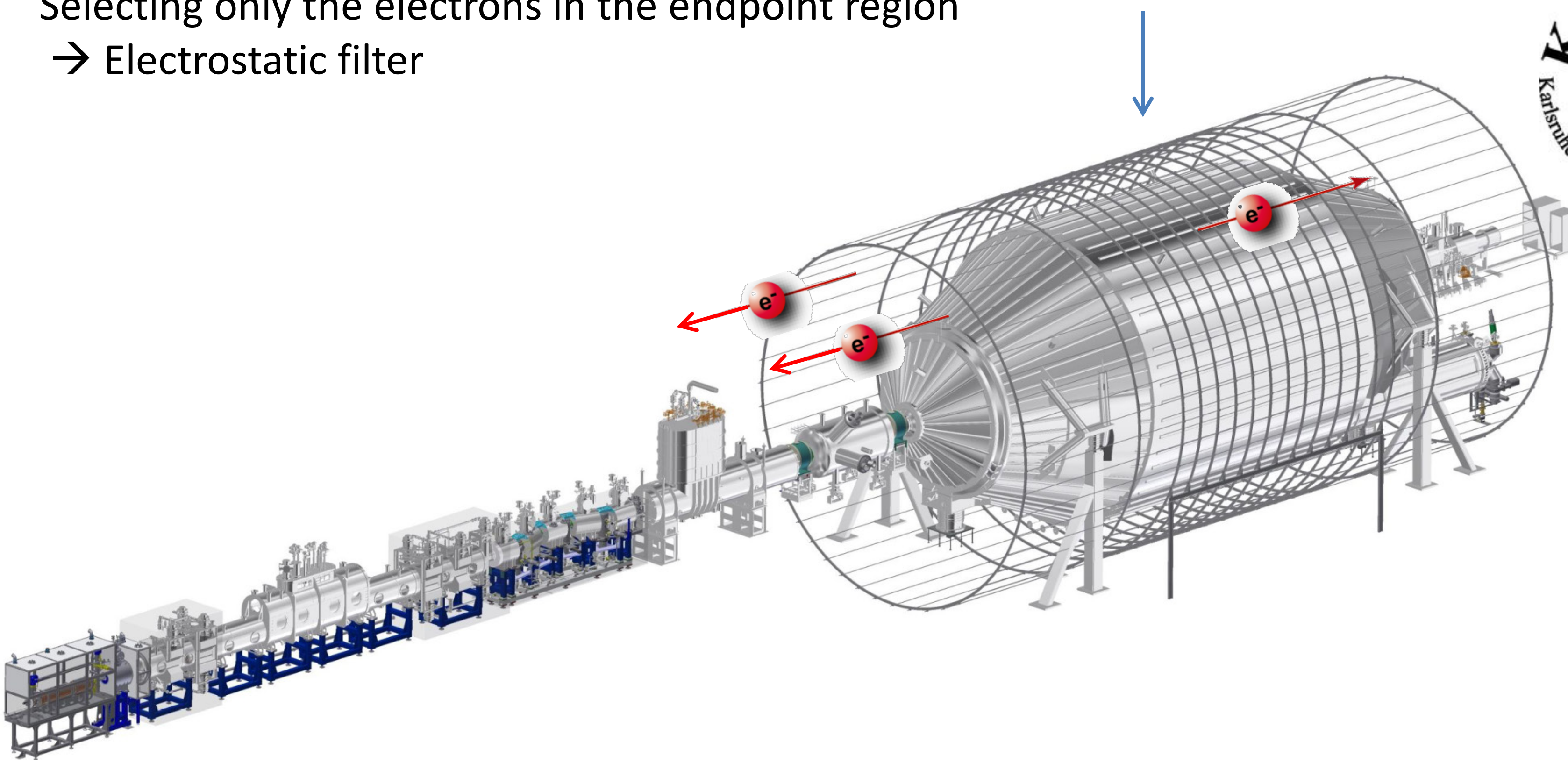


The KATRIN experiment

Selecting only the electrons in the endpoint region

→ Electrostatic filter

Spectrometer

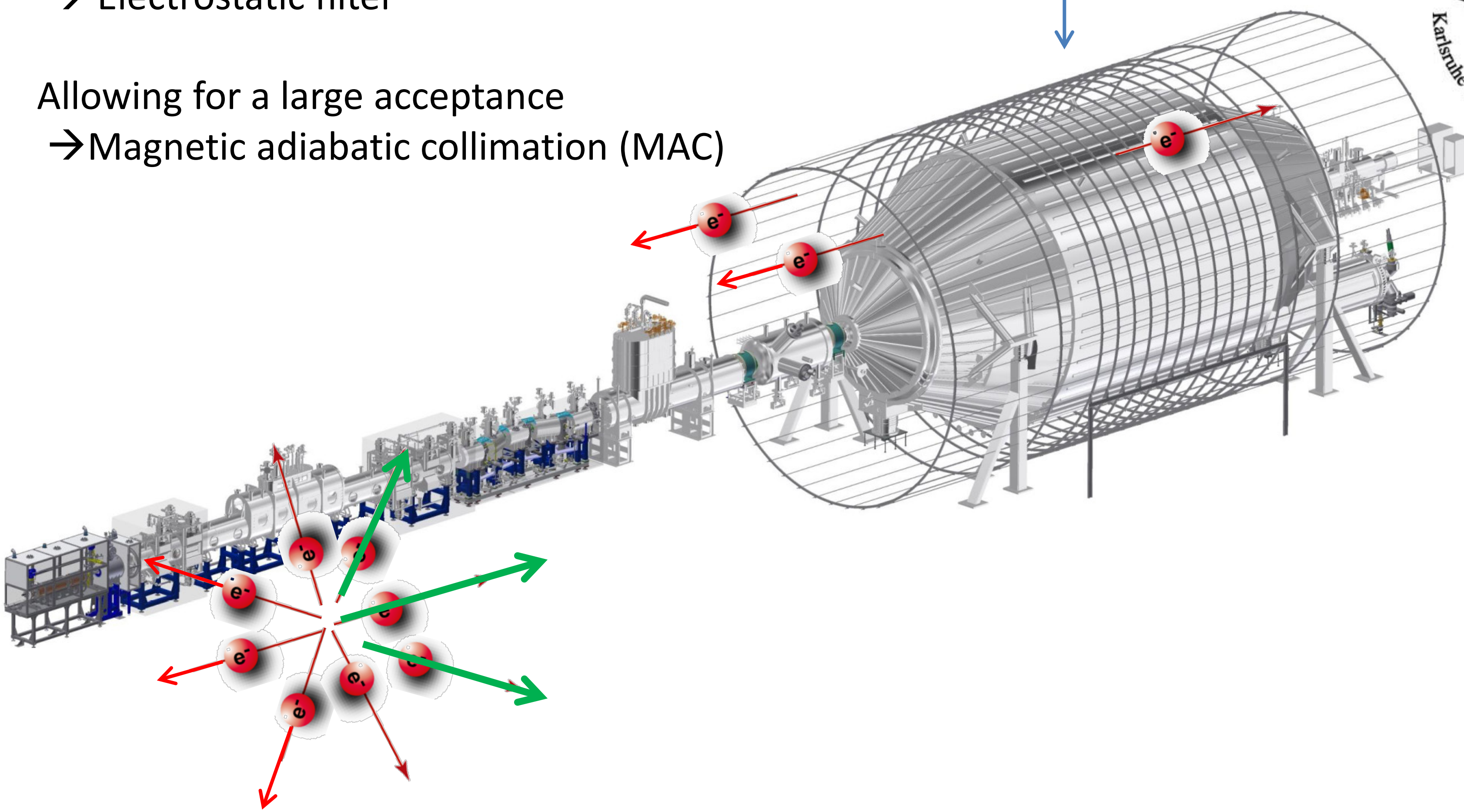


The KATRIN experiment

Selecting only the electrons in the endpoint region
→ Electrostatic filter

Allowing for a large acceptance
→Magnetic adiabatic collimation (MAC)

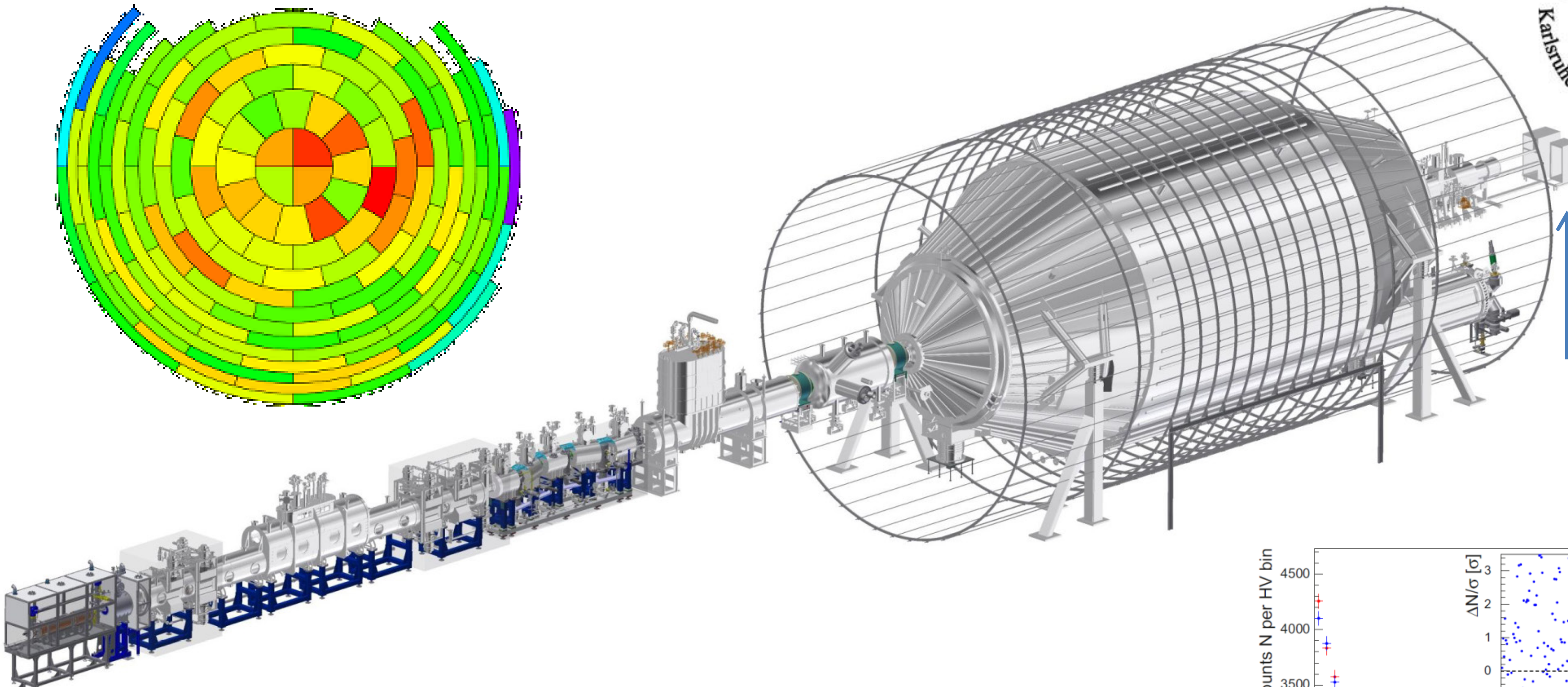
Spectrometer



MAC-E filter principle allows for < 1 eV energy cut off

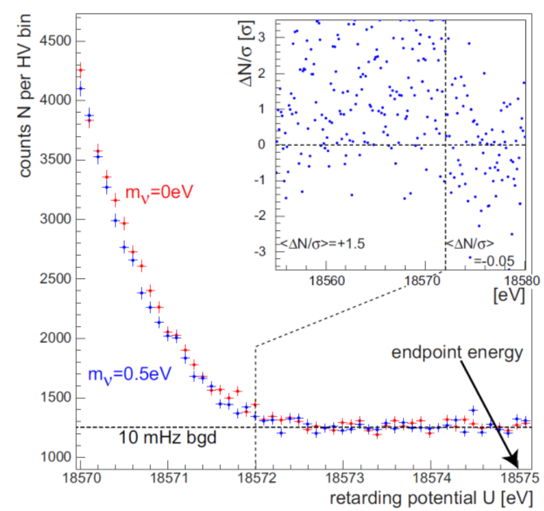
The KATRIN experiment

148 Pixel Si-pin diode detector system

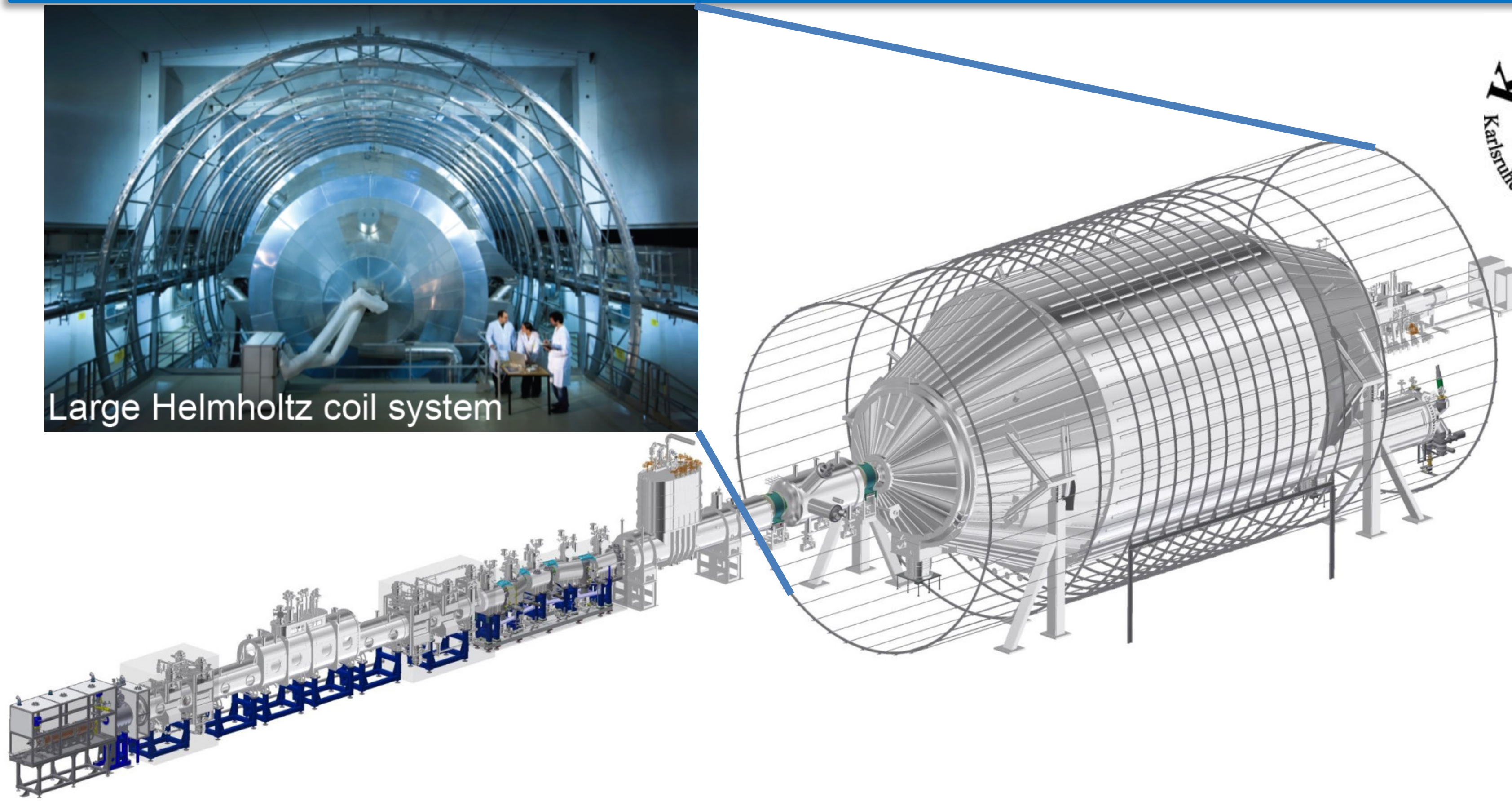


Electron counting

Integral measurement down to 30 eV below the endpoint



The KATRIN experiment: present status



The KATRIN experiment: present status

KATRIN
Karlsruhe Tritium Neutrino Experiment

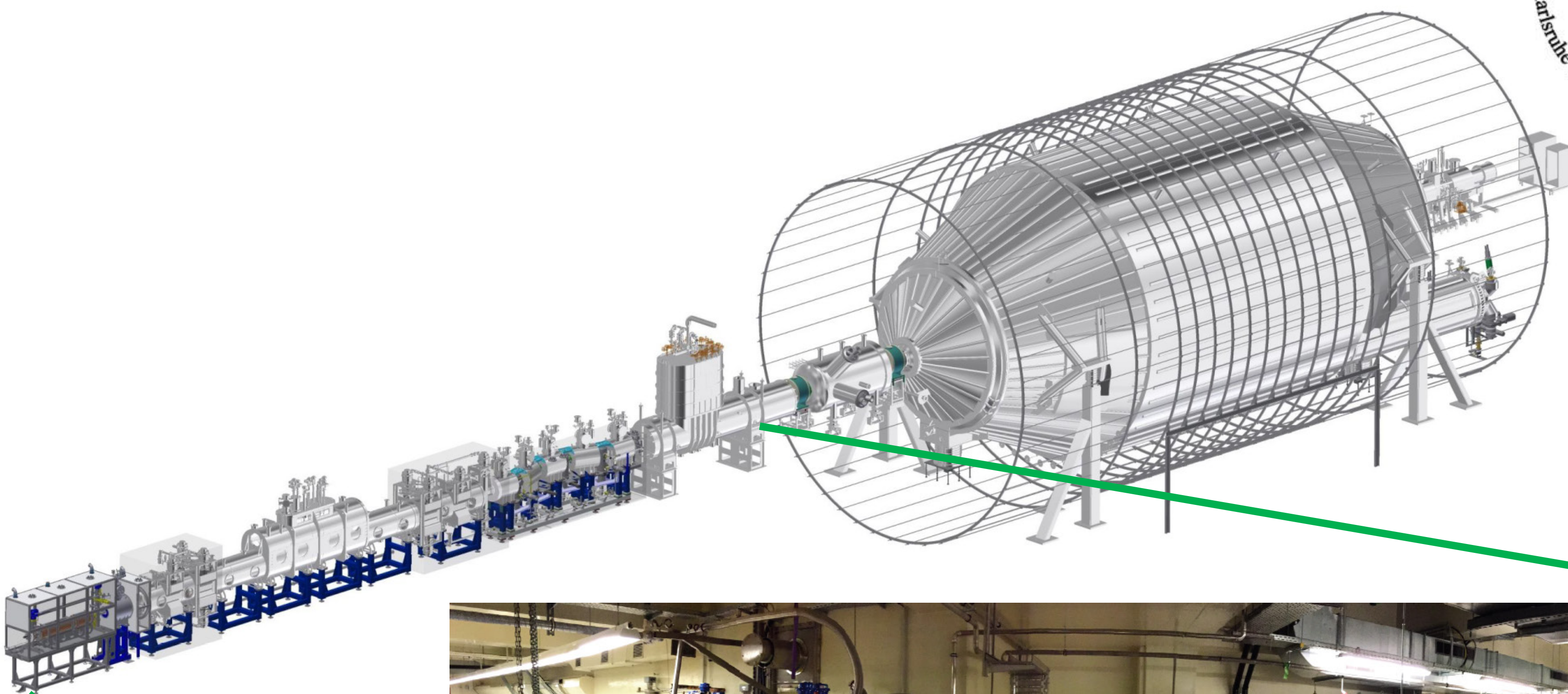
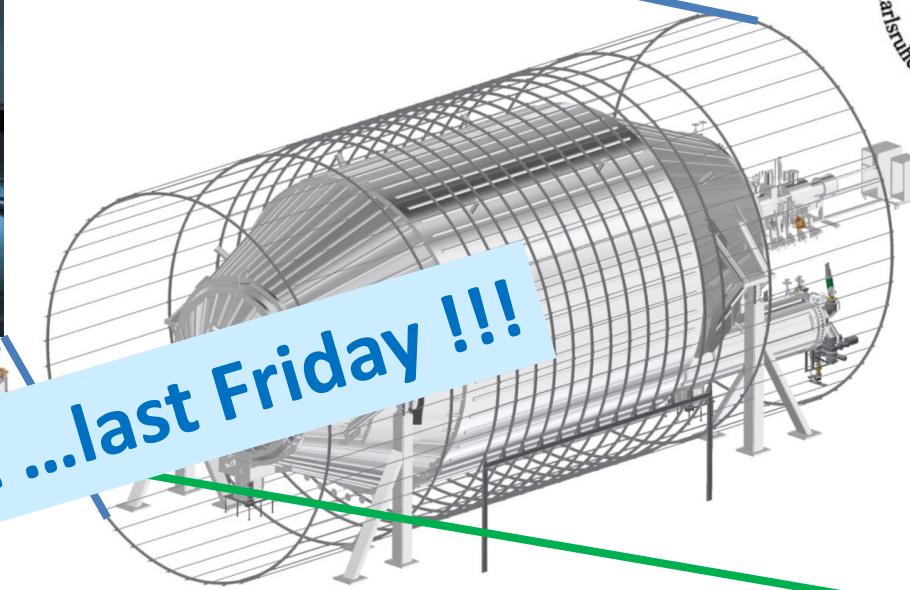


Photo K. Valerius

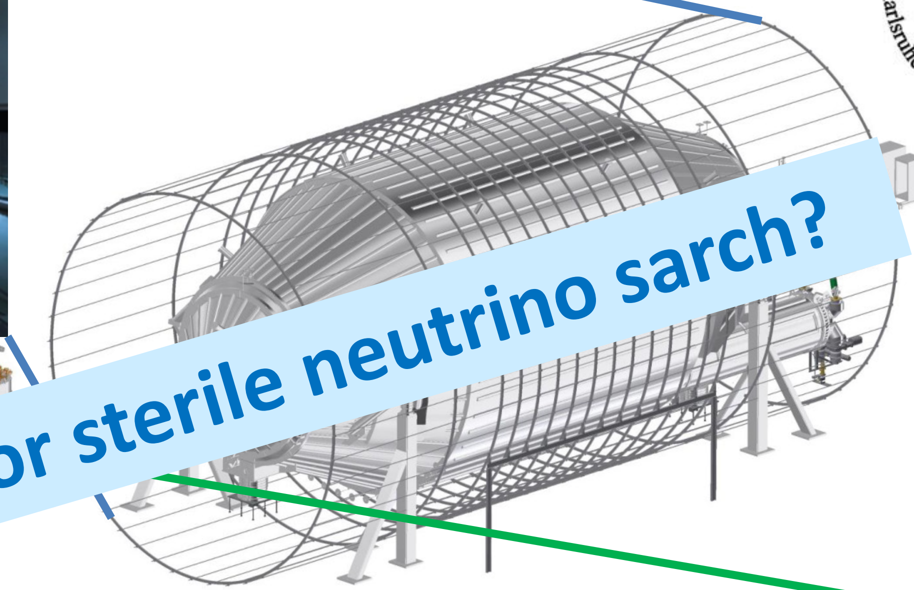
The KATRIN experiment: present status



First light …last Friday !!!

Photo K. Valerius

The KATRIN experiment: present status

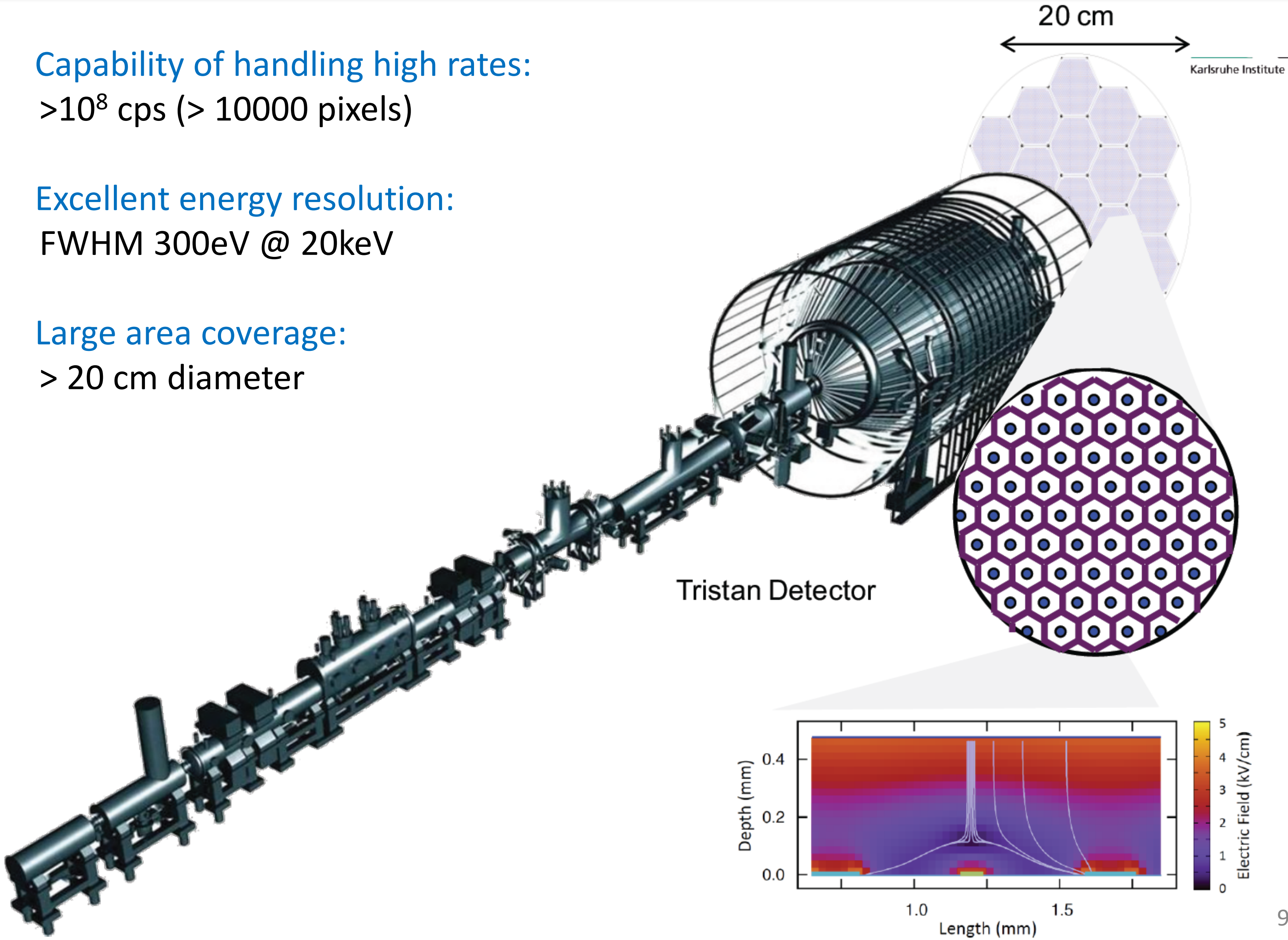


Is this enough for sterile neutrino sarch?

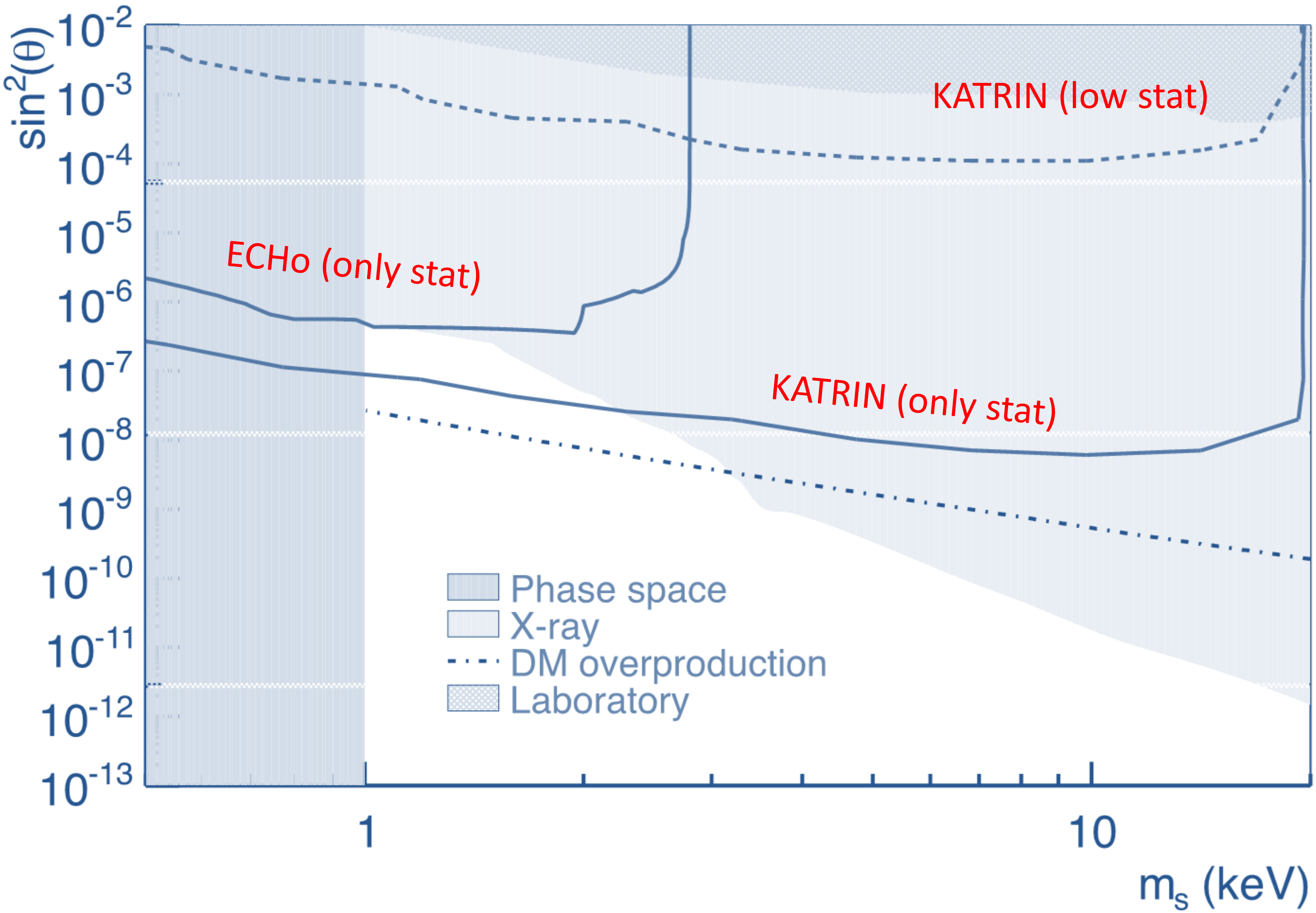
Photo K. Valerius

The KATRIN experiment: differential spectrum

- Capability of handling high rates:
  >10^8 cps (> 10000 pixels)
- Excellent energy resolution:
  FWHM 300eV @ 20keV
- Large area coverage:
  > 20 cm diameter



keV-scale sterile neurinos



S. Mertens

^{3}H based experiments

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

Main ideas:

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

❖ **Project8**

Main ideas:

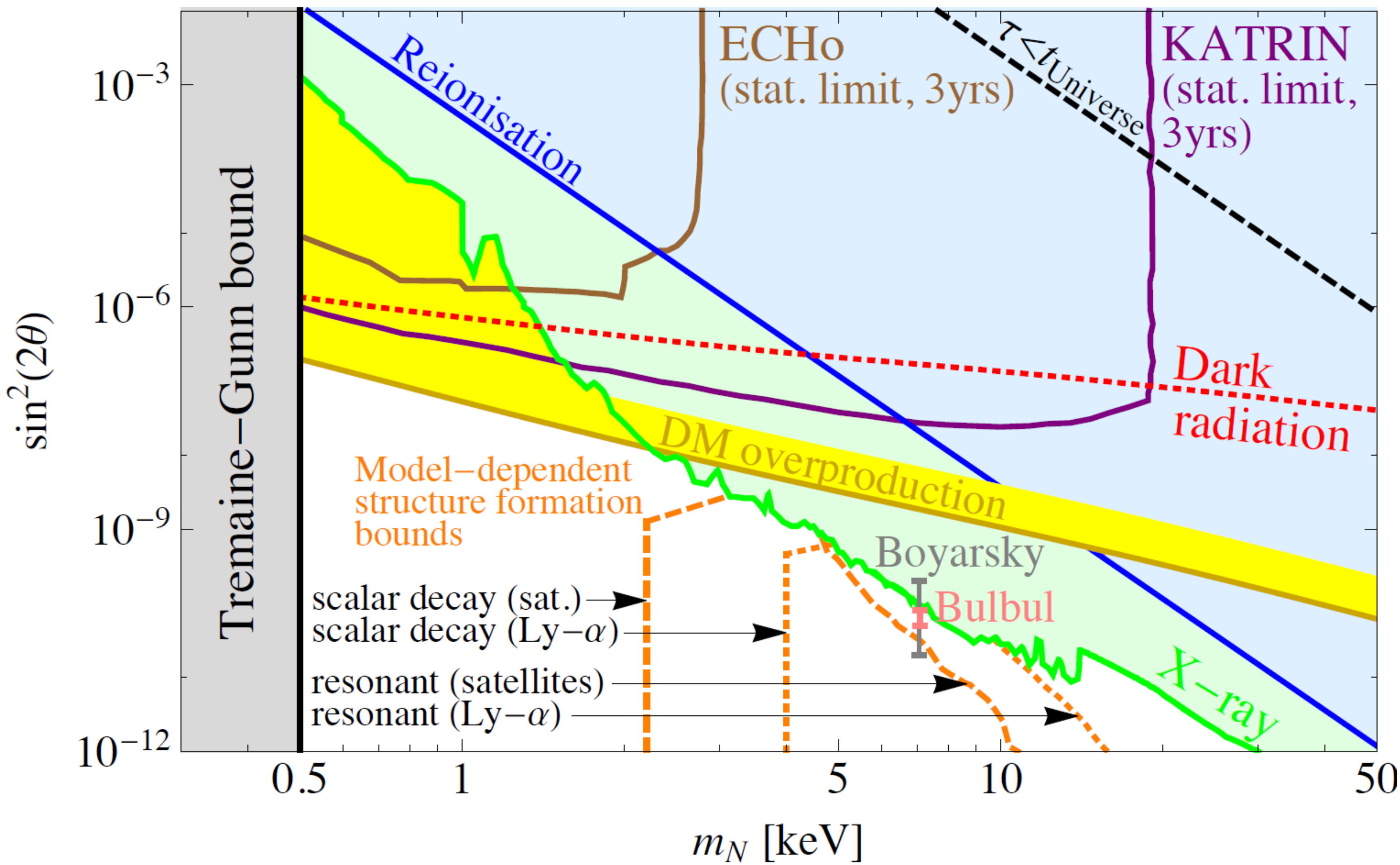
- Source = detector: $10^{11} – 10^{13}$ $^3H_2$ molecules /cm^3
- Use cyclotron frequency to extract electron energy
- **Differential spectrum**

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

Main ideas:

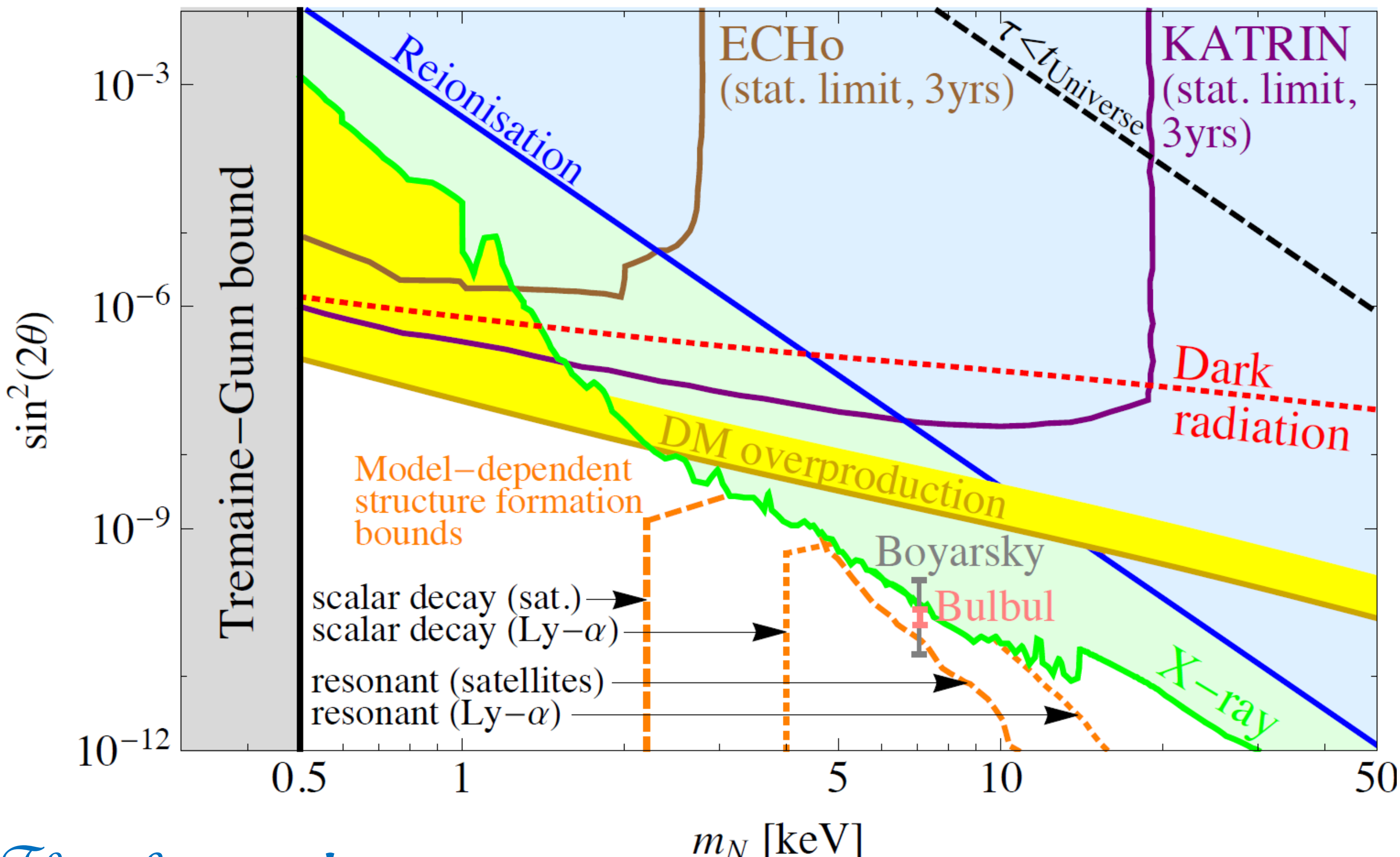
- large area tritium source: 100 g atomic ^{3}H
- MAC-E lter to select electrons close to the end point
- RF tracking and time-of-flight systems
- cryogenic calorimetry → **differential spectrum**

Conclusions and outlook



A. Merle

Conclusions and outlook



Thank you !

A. Merle