Perspectives for measuring the effective electron neutrino mass

Loredana Gastaldo

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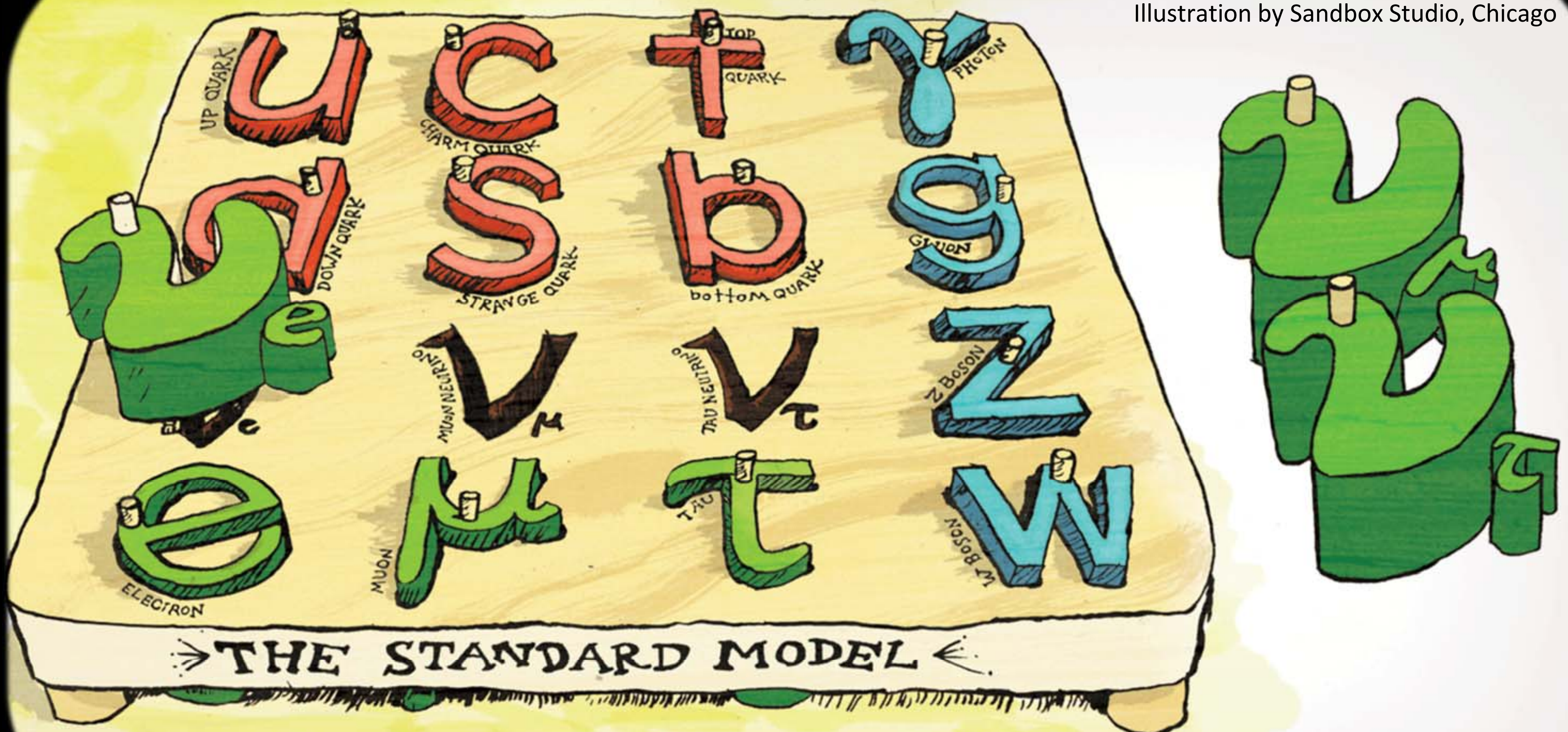
Symmetry Magazine, 02/12/13
Illustration by Sandbox Studio, Chicago



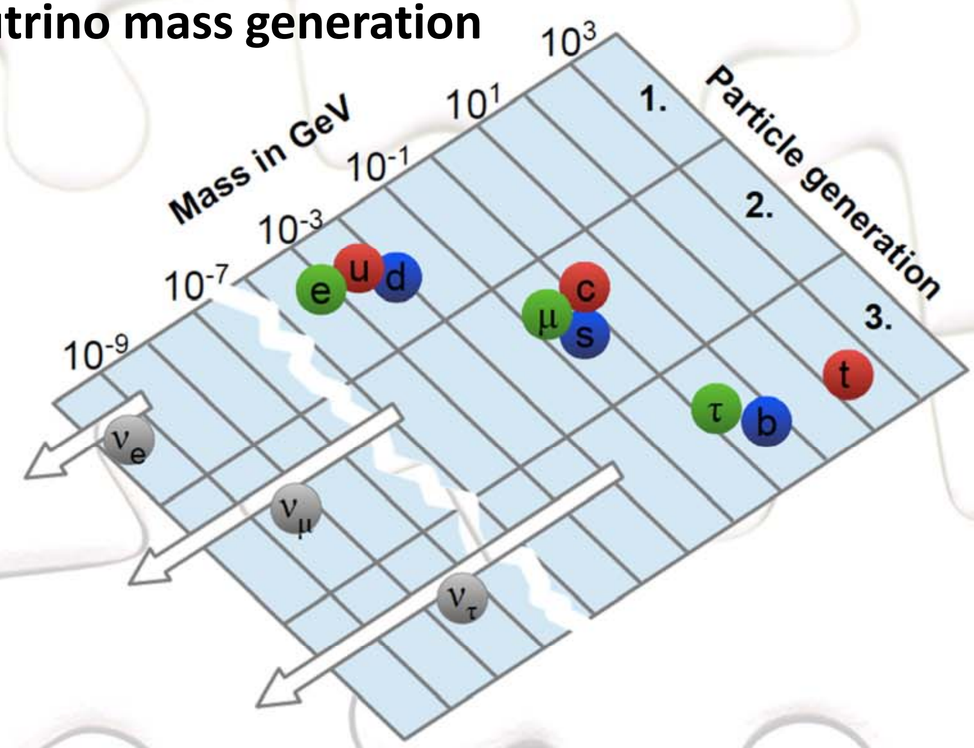
Knowing neutrino mass scale....

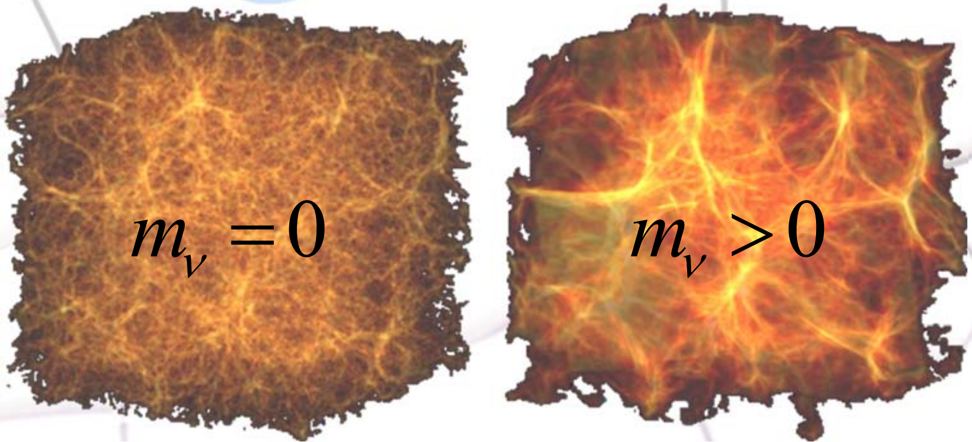
Astrophysics

Supernova neutrinos

Particle Physics

Neutrino mass generation





Cosmology

Matter distribution in the Universe

Outline

- Massive neutrinos
  - Observables and mass limits
  - Kinematics of **EC and β decay**
- Experimental approaches
  - ^{3}H & ^{163}Ho
- Beyond the 3-neutrino scenario
- Conclusions

3-neutrino scenario

3 neutrino mass eigenstates

$\nu_i = (\nu_1 , \nu_2 , \nu_3)$

Important for Cosmology

3 neutrino flavour eigenstates

$\nu_\alpha = (\nu_e , \nu_\mu , \nu_\tau)$

Important for Particle Physics

Pontecorvo–Maki–Nakagawa–Sakata matrix $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{bmatrix}$$

2-3 rotation

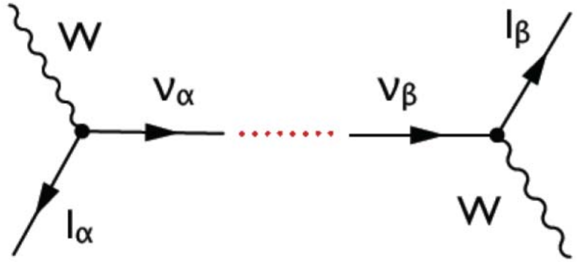
1-3 rotation
+ CP Dirac phase

1-2 rotation

extra Majorana
phases

3-neutrino scenario

Experiments studying neutrino flavor oscillations provides information on PMNS matrix parameters and difference in neutrino mass squared



Current knowledge *

$\sin^2\Theta_{12} \approx 0.303$

$\sin^2\Theta_{23} \approx 0.545$

$\sin^2\Theta_{13} \approx 0.0225$

$\Delta m^2_{12} \approx 7.34\times10^{-5}\ \text{eV}^2$

$\left|\Delta m^2_{13}\right| \approx 2.48\times10^{-3}\ \text{eV}^2$

Open questions:

- Mass ordering (>3σ NO)
- CP violation (1.6σ CPV)
- Majorana/Dirac
- Octant Θ_{23}
- Absolute scale of the neutrino masses

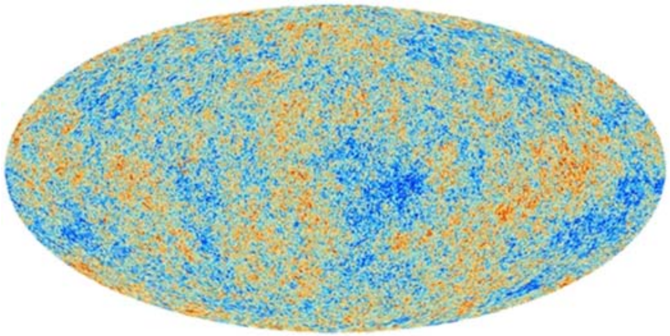
$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{bmatrix}$$

2-3 rotation | 1-3 rotation + CP Dirac phase | 1-2 rotation | extra Majorana phases

*E. Lisi, TAUP 2019

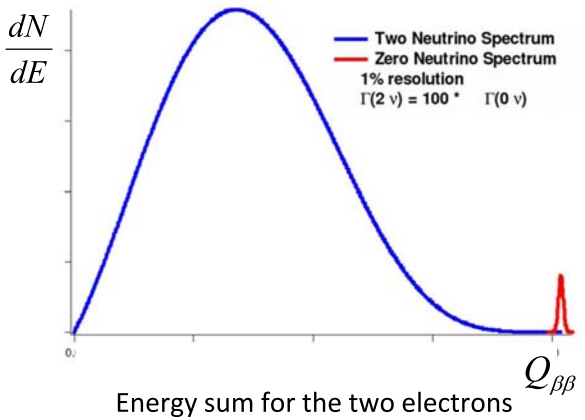
Massive neutrinos…

… affect the distribution of mass in the Universe

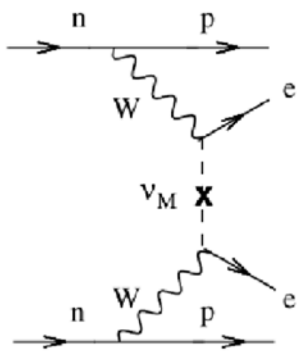


Present limit $M = \sum_i m_i \; < \; 0.12 \;\text{eV}$ (95% C.L.)
Planck 2018

… could lead to neutrinoless double beta decay



+



$$\left(\tau_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

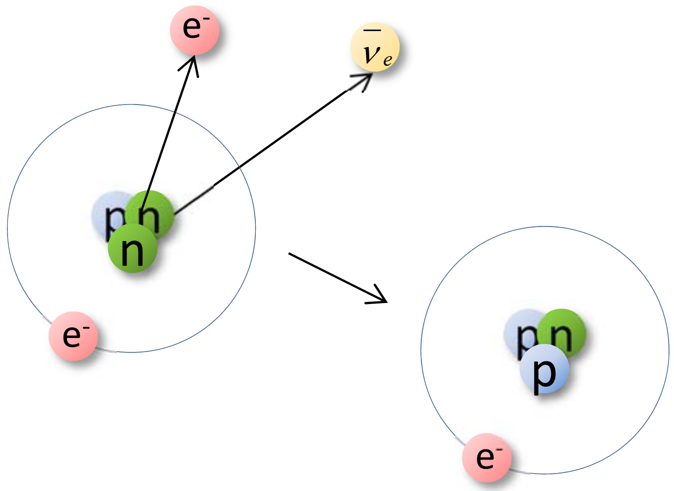
$$m_{\beta\beta}^2 = \left|\sum U_{ei}^2 m(\nu_i)\right|^2$$

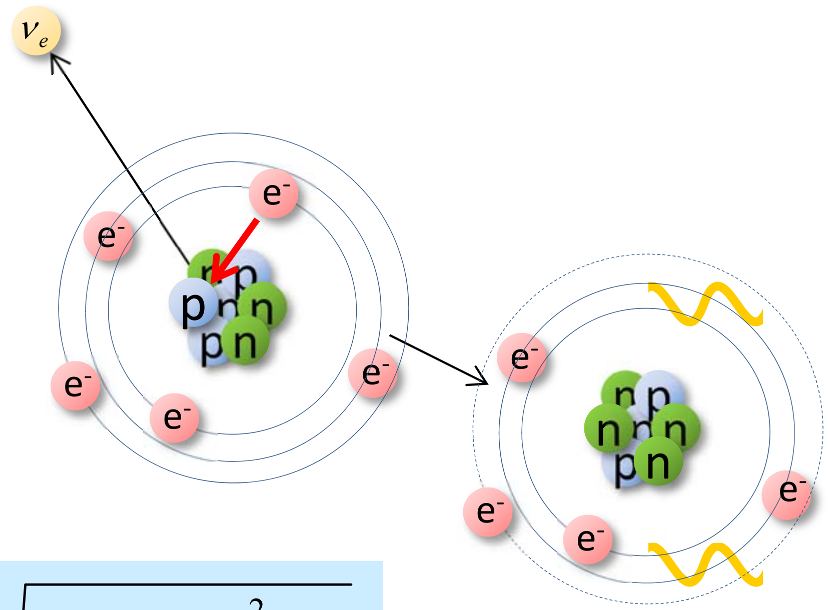
Present limit $m_{\beta\beta} < \; 0.31 \;\text{eV}$

Future $m_{\beta\beta} < \; 20-50 \;\text{meV}$

… affect the energy spectrum of low energy EC and β-decay

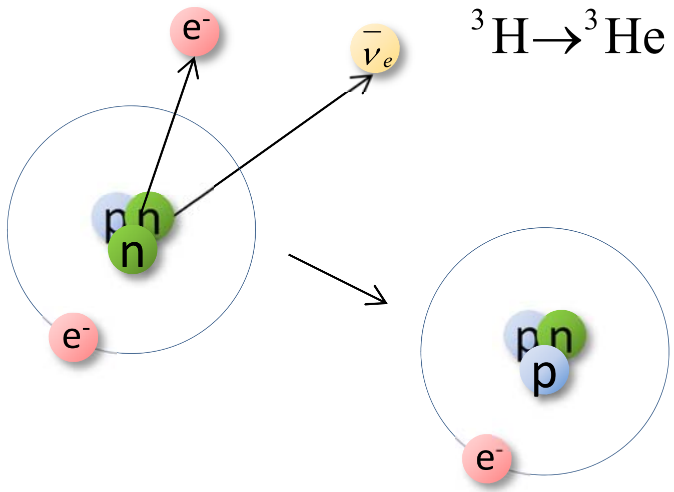
Beta decay and electron capture



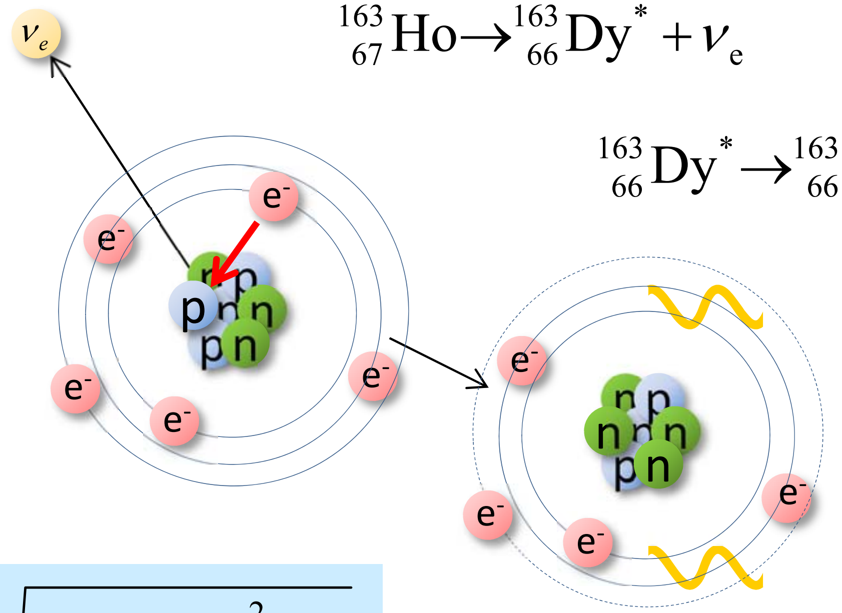


$$\frac{dW}{dE} \propto (Q - E)^2 \sqrt{1 - \frac{m_\beta^{\ 2}}{(Q - E)^2}}$$

Beta decay and electron capture



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



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

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

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

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

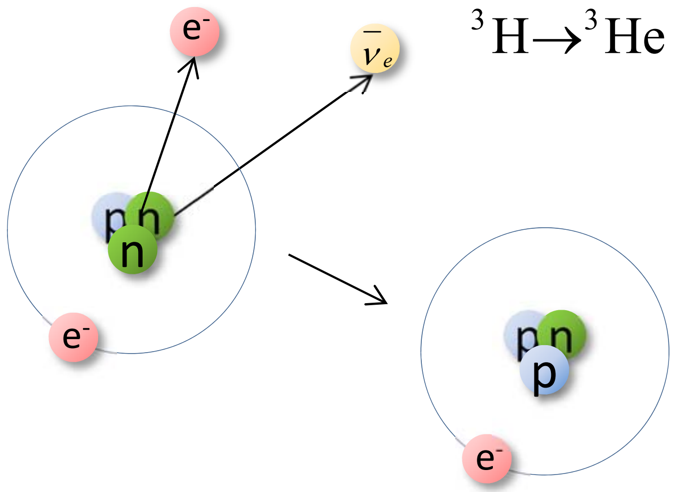
E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

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

Beta decay and electron capture

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



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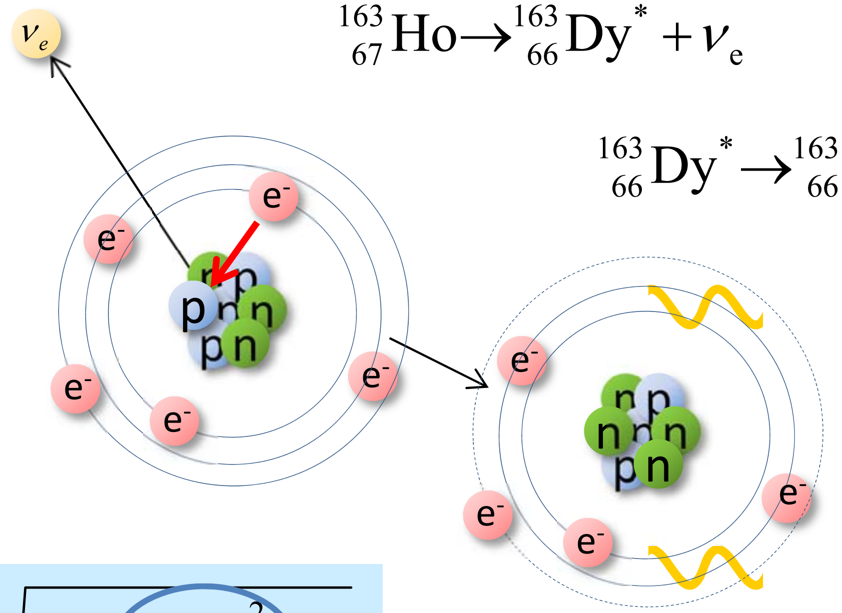


$$\frac{dW}{dE} \propto (Q - E)^2 \sqrt{1 - \frac{m_\beta^{\,2}}{(Q - E)^2}}$$

$$\frac{dW}{dE_\mathrm{C}} \propto (Q - E)^2 \sum_i |U_{ei}|^2 \sqrt{1 - \frac{m_i^{\,2}}{(Q - E)^2}}$$

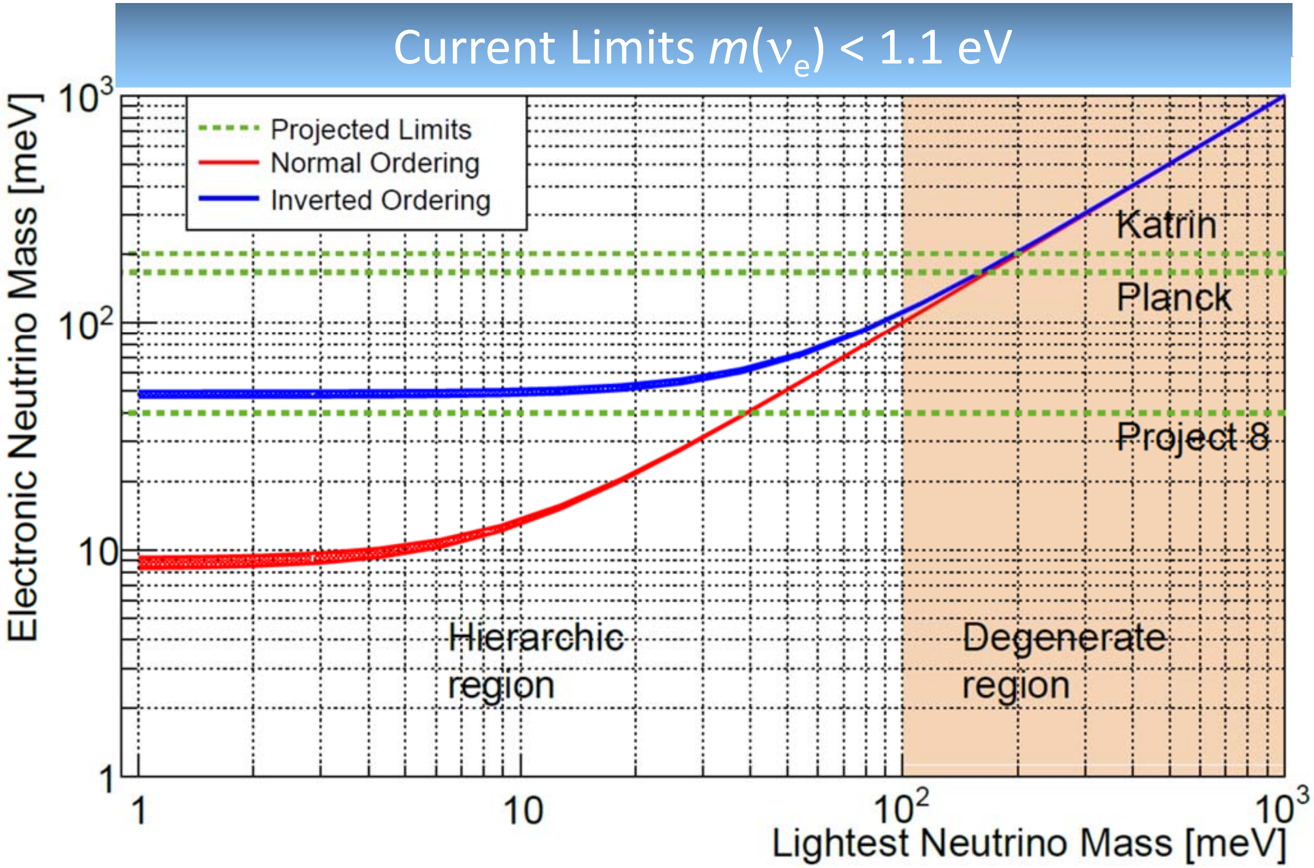
finite energy resolution →

$$m_\beta^{\,2}(\nu_e) = \sum_i |U_{ei}|^2 m_i^2$$

G.-Y. Huang et al., *Phys. Rev. D* **101** (2020) 016003 → test of different effective masses according to energy resolution

Beta decay and electron capture

Ahtari et al., *JPhysG* **44** (2017) 5

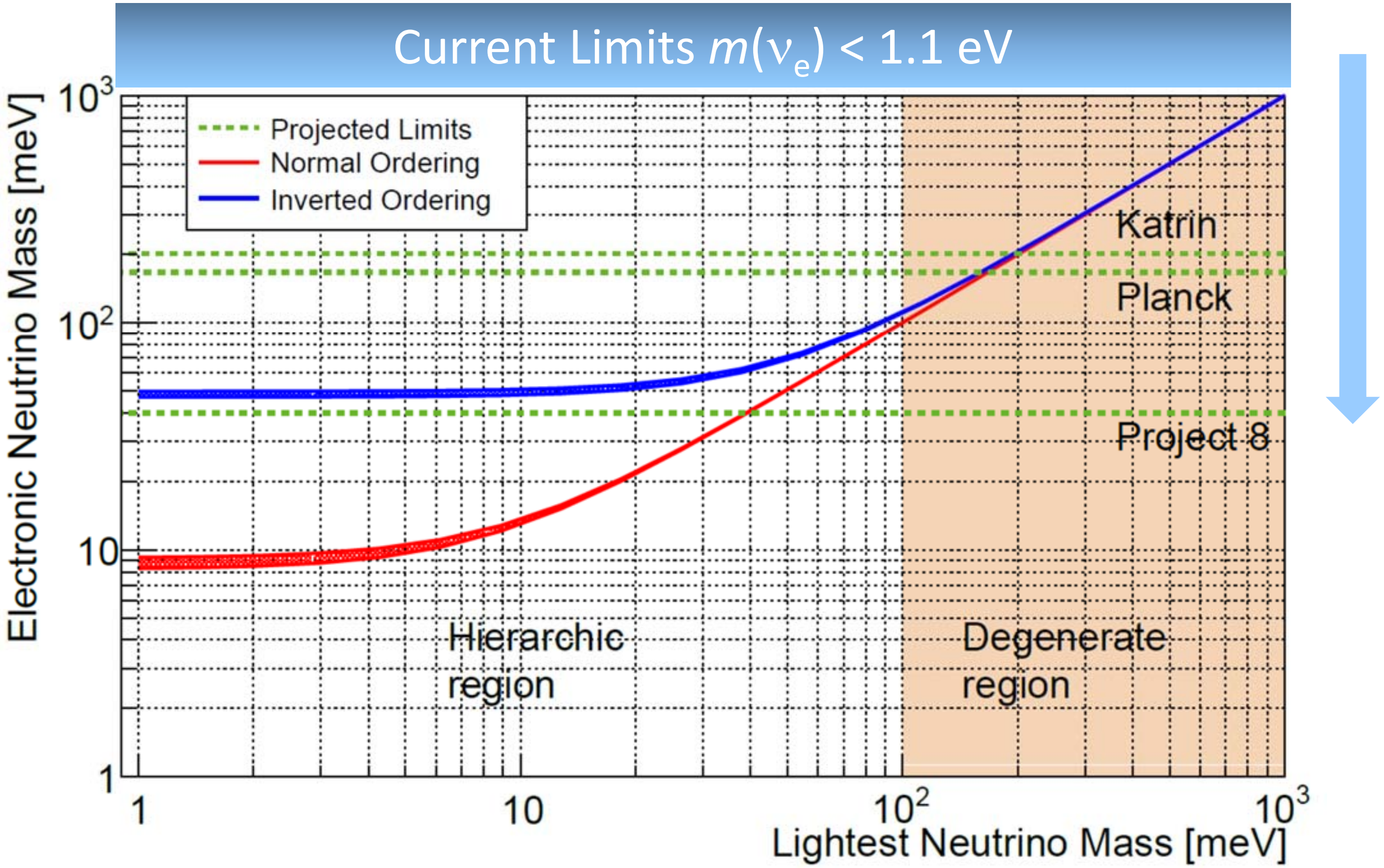


$m(\bar{\nu}_e) < 1.1\ eV$ $\quad$ ^3H $\quad$ Aker et al., (The KATRIN Collaboration)
Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN, *Phys. Rev. Lett.* **123** (2019) 221802

$m(\nu_e) < 150\ eV$ $\quad$ ^{163}Ho $\quad$ C. Velte et al., (The ECHo Collaboration)
High-resolution and low-background Ho spectrum: interpretation of the resonance tails, *Eur. Phys. J. C* **79** (2019) 1026

Beta decay and electron capture

Ahtari et al., *JPhysG* **44** (2017) 5



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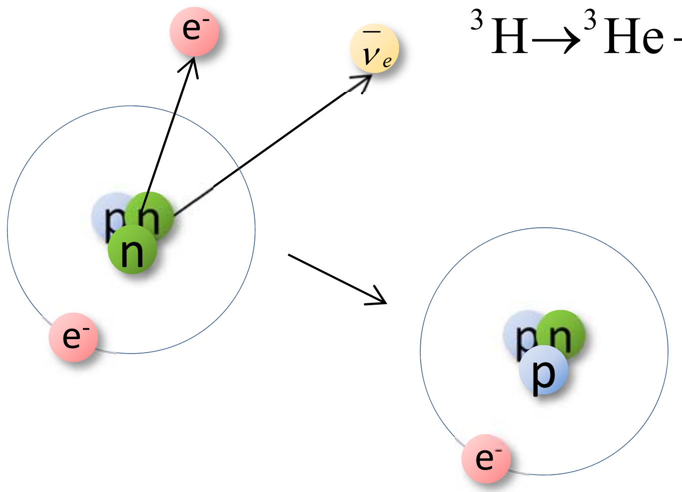
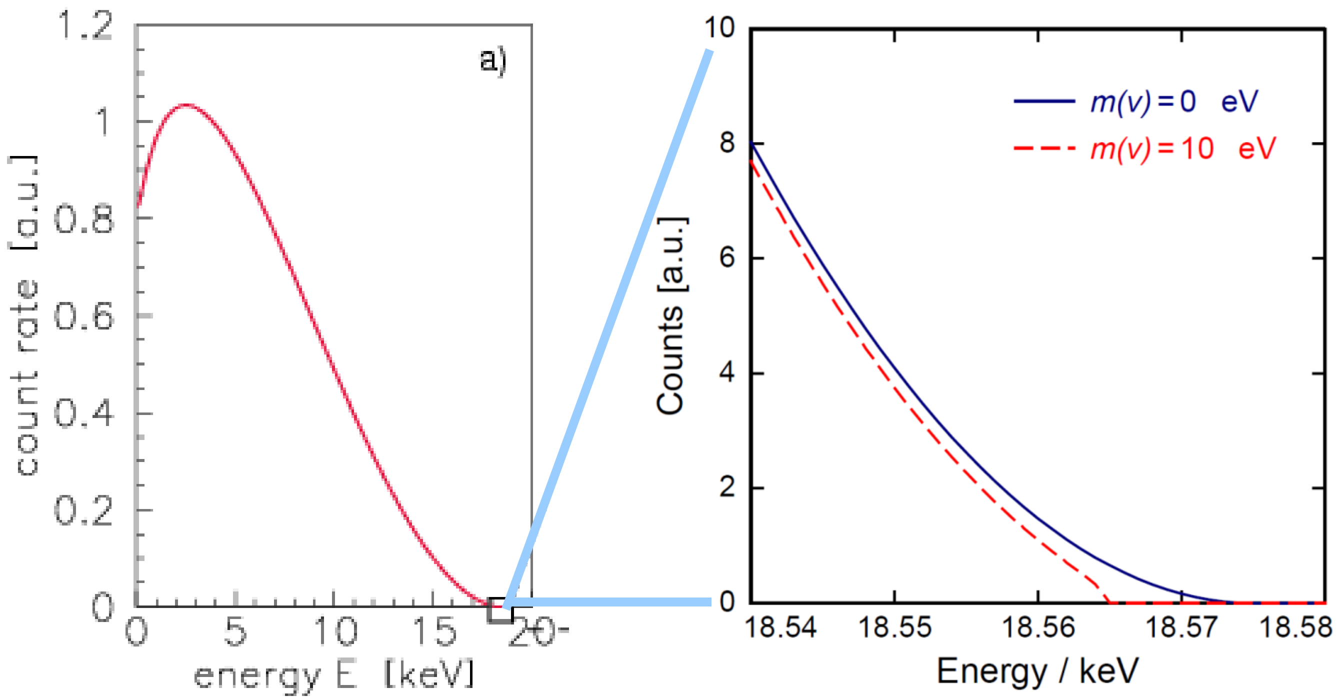
Experimental approaches

Beta decay of ^3H



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



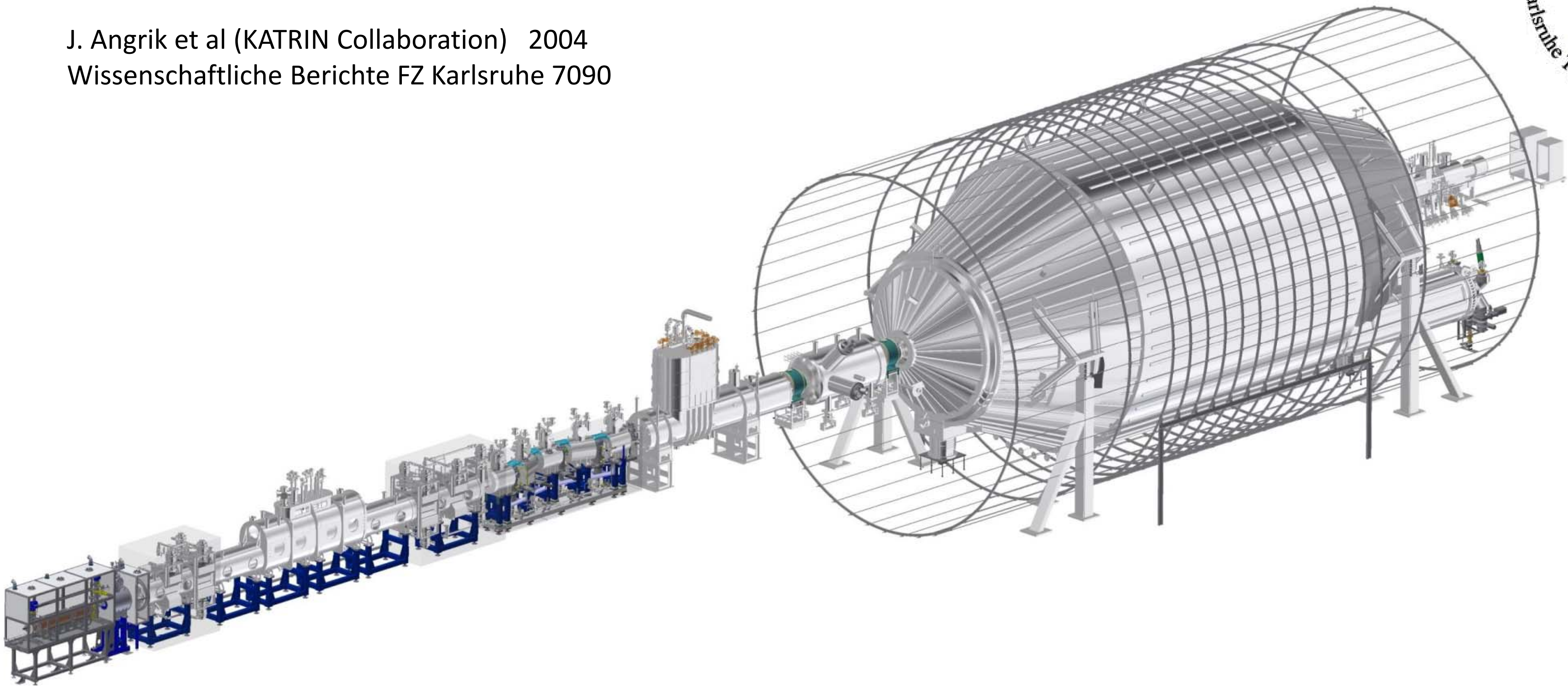
Only a small fraction of events in the last eV below the endpoint: **$2 * 10^{-13}$**

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

^3H based experiments

The Karlsruhe Tritium Neutrino Experiment – **KATRIN**

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



Main ideas:

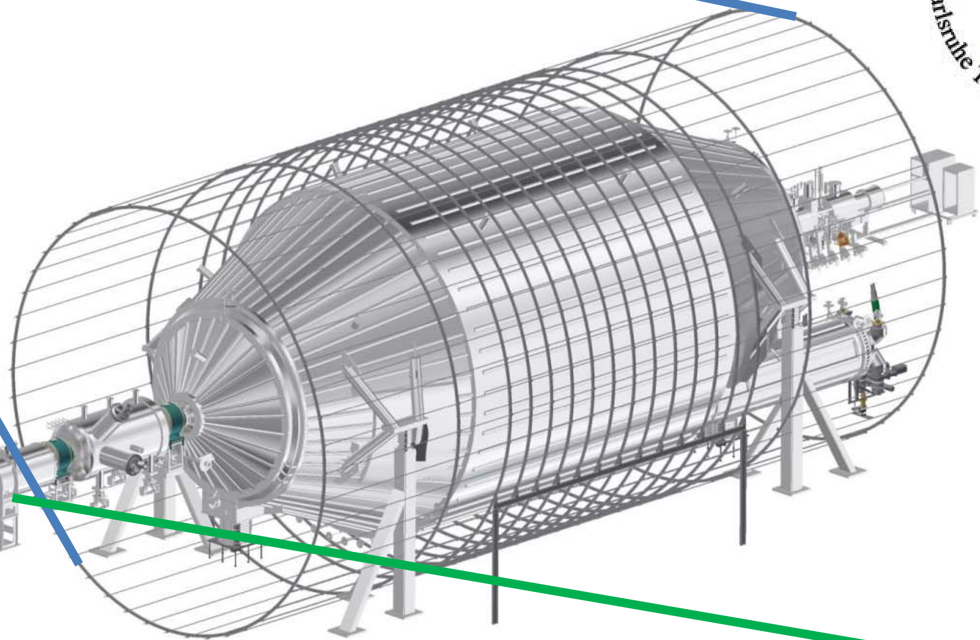
- high activity source 10^{11} e^-/s
- high resolution MAC-E* filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum

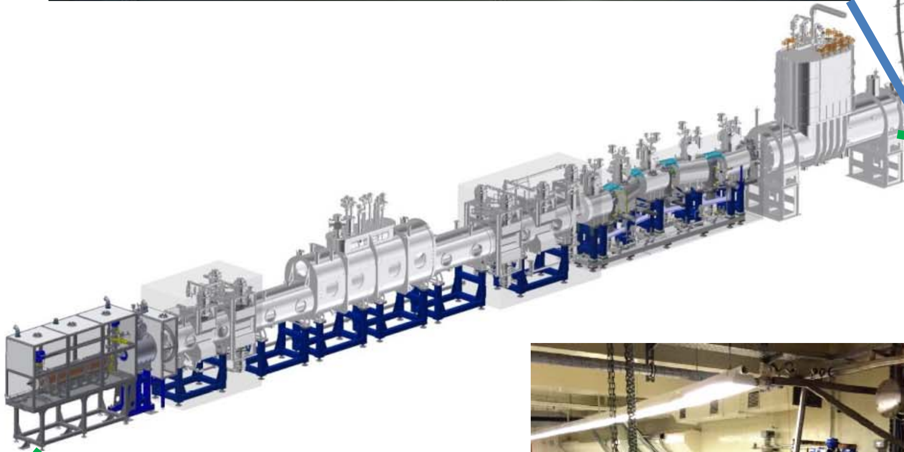
*MAC-E: Magnetic Adiabatic Collimation with Electrostatic Filter

The KATRIN experiment: present status

KATRIN

Karlsruhe Tritium Neutrino Experiment





The KATRIN experiment: recent results

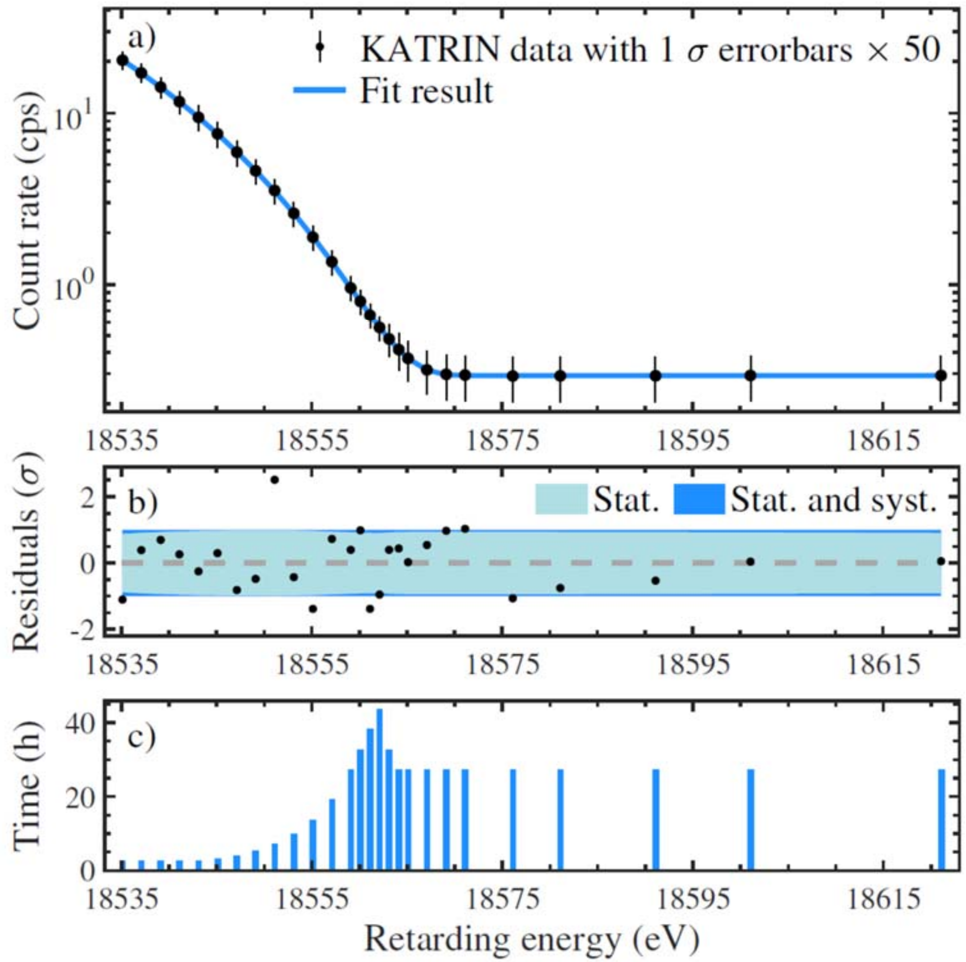
Neutrino Mass campaign #1

- April 10 – May 13 2019 → 780 h
- 22% nominal activity → 2.45 10^{10} Bq

- Integral spectrum in the energy range [Q - 40 eV; Q + 50 eV]
  → 2 10^6 events in in 90-eV-wide interval

Fit of the integral spectrum

- excellent goodness-of-fit χ^2 = 21.4 for 23 d.o.f. (p-value = 0.56)



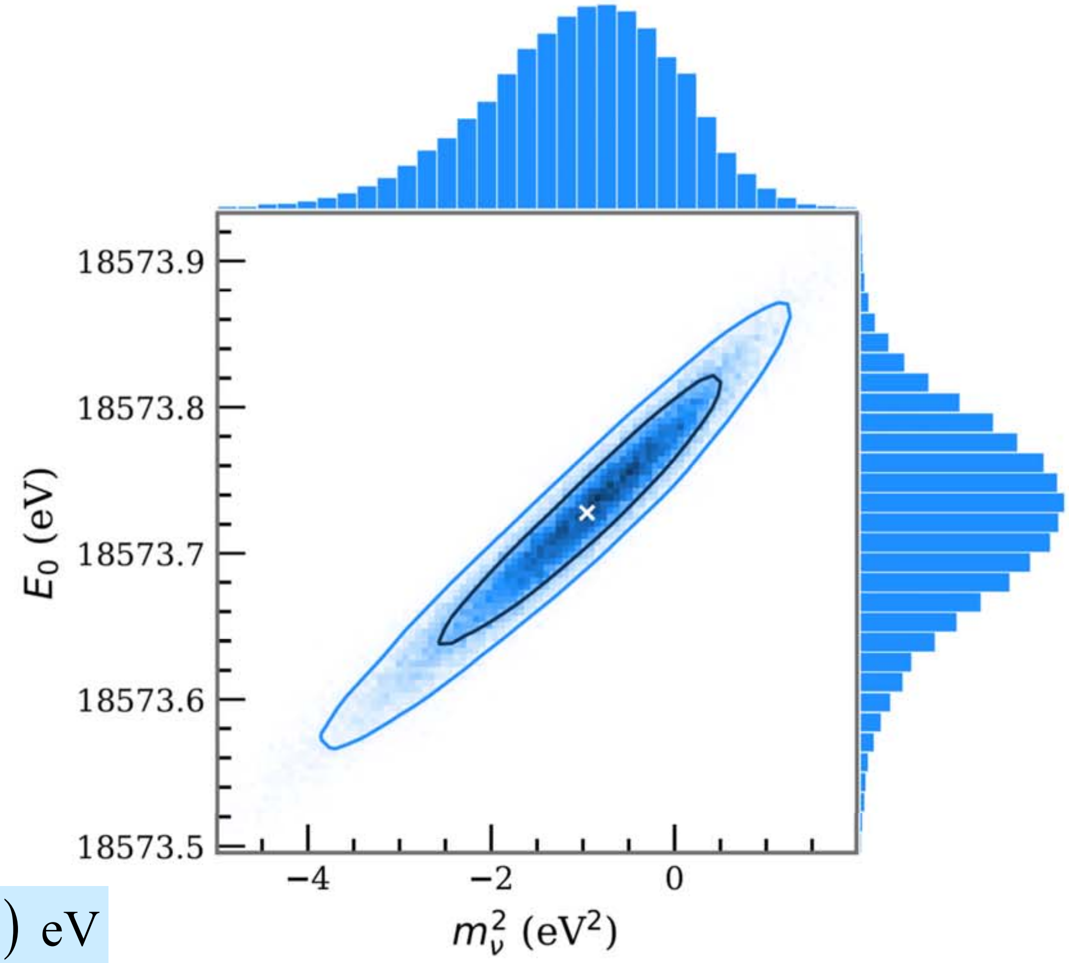
Aker et al., (The KATRIN Collaboration) *Phys. Rev. Lett.* **123** (2019) 221802

The KATRIN experiment: recent results

Two independent analysis methods

- covariance matrix
- MC propagation

→ both methods agree to a few percent



Best fit results - ν-mass and E_0

$$m^2(\nu_e) = \left(-1.0^{+0.9}_{-1.1}\right)\ \text{eV}^2 \quad (90\%\ \text{CL})$$

$$E_0 = (18573.7 \pm 0.1)\ \text{eV} \Rightarrow \quad Q = (18575.2 \pm 0.5)\ \text{eV}$$

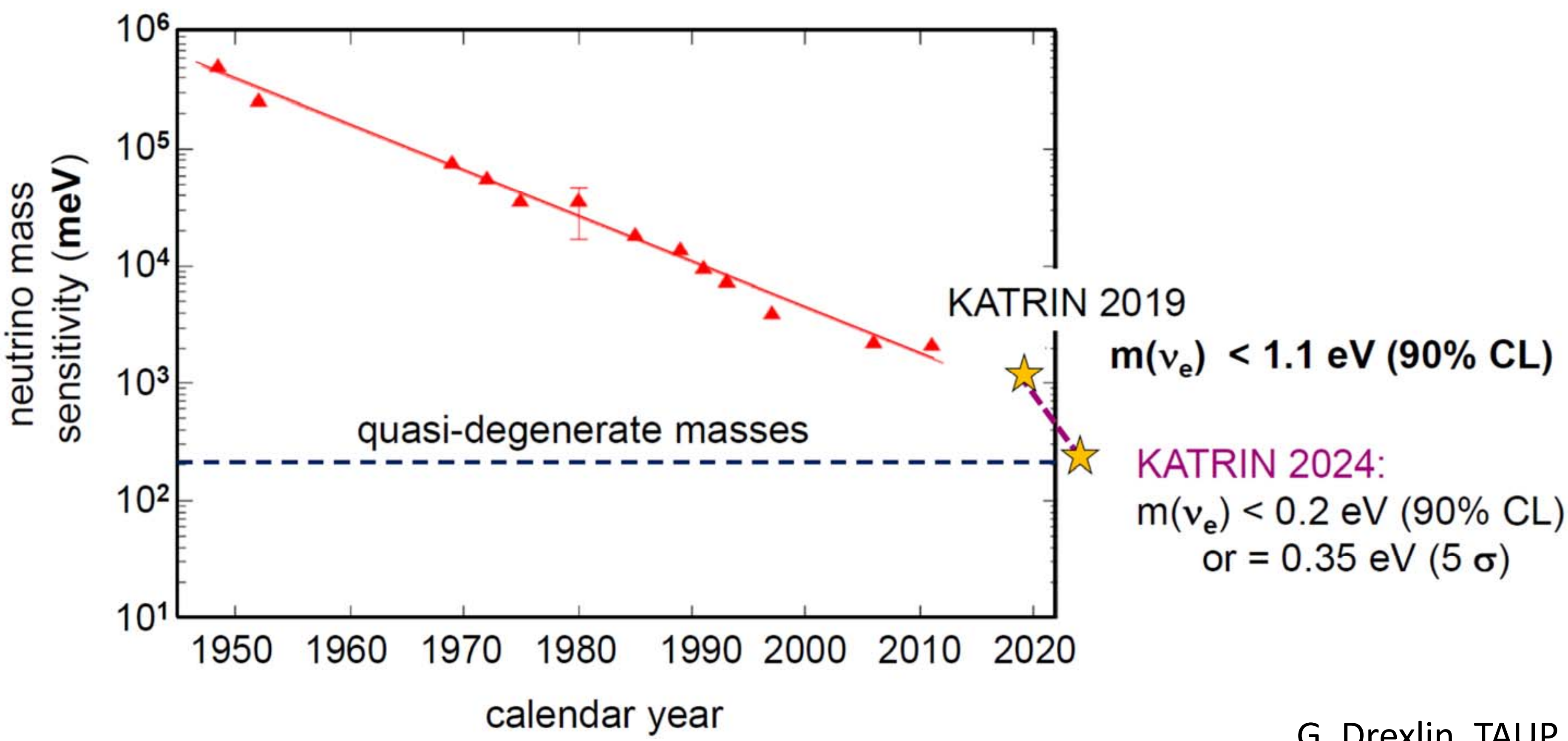
To be compared to $Q\left[\Delta M\left({}^3H, {}^3He\right)\right] = (18575.72 \pm 0.07)\ \text{eV}$

Upper limit on the effective electron neutrino mass: $m(\nu_e) < 1.1\ \text{eV} \quad (90\%\ \text{CL})$

Aker et al., (The KATRIN Collaboration) *Phys. Rev. Lett.* **123** (2019) 221802

The KATRIN experiment: future plans

- Reduction of background and systematics
- 1000 days of measurements at nominal ρd ($5 \cdot 10^{17}$ molecules cm^{-2}) corresponding to 3 tritium campaigns (65 days each) per calendar year over the next 5 years



G. Drexlin, TAUP 2019

^3H based experiments

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

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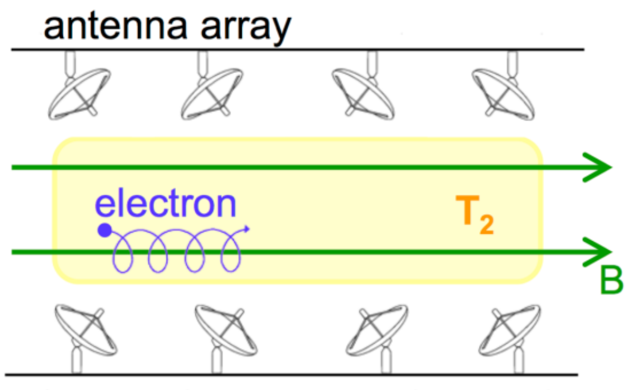
❖ **Project8**

Main ideas:
- Source = detector: $10^{11} – 10^{13}$ $^3T_2$ molecules /cm^3
- Use cyclotron frequency to extract electron energy
- Differential spectrum



$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

@ 1 Tesla ω(18 keV) ~ 26 GHz
P(18 keV) = 1.2 fW

B. Monreal & J. Formaggio PRD 80 (2009) 051301

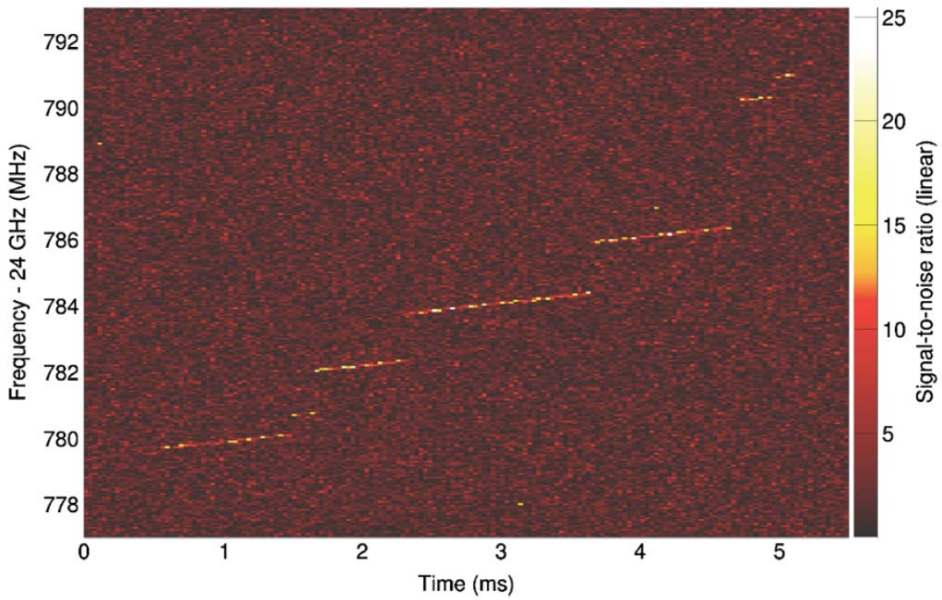
Project 8

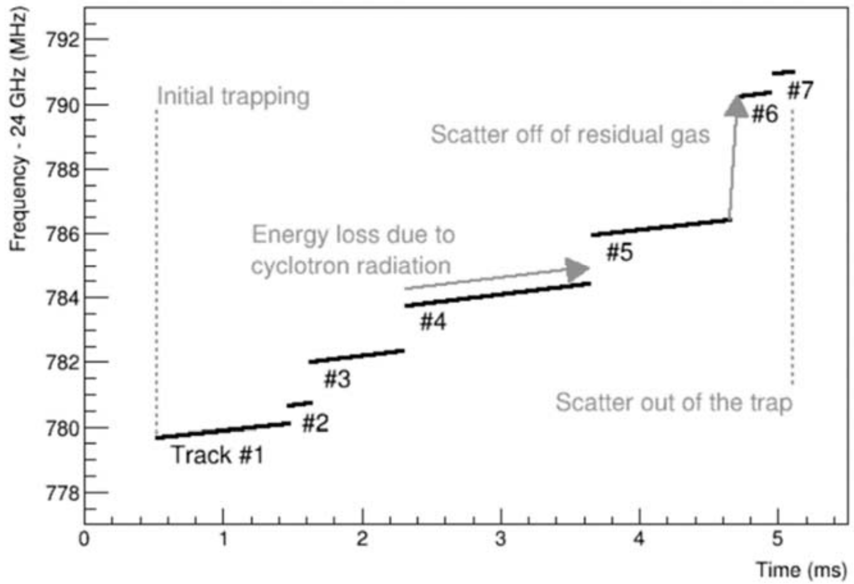
Phase I (2010 - 2016)
Demonstration of the CRES method
Conversion electron lines from ^{83m}Kr source

Phase II (2015 - 2019)
Spectroscopy of continuous T_2 spectrum
Study of systematics
improvement of the energy resolution

Phase III (2016 - 2023)
200 cm^3 effective source volume (1 year)
Phased array antenna
Sensitivity goal: $m(\nu_e) < 2$ eV 90% C.L.

Phase IV (2022 +)
Large scale exp. with atomic ^{3}H source for
Sensitivity goal: $m(\nu_e) < 40$ meV 90% C.L.





Asner et al., PRL 114 (2015) 16501

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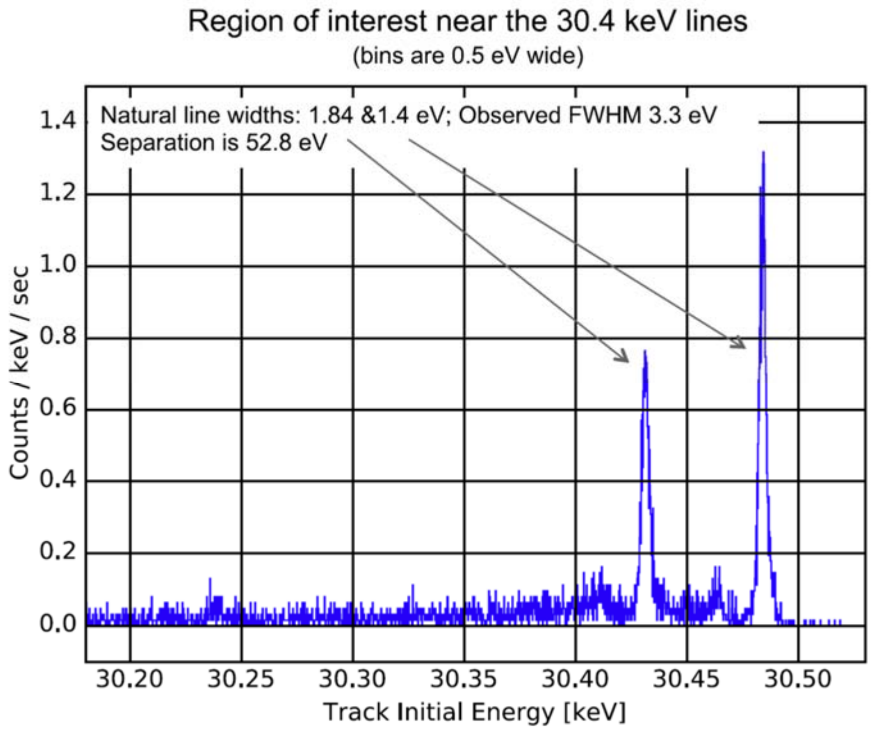

Esfahani et al., *J. Phys. G: Nucl. Part. Phys.* **44** (2017) 054004

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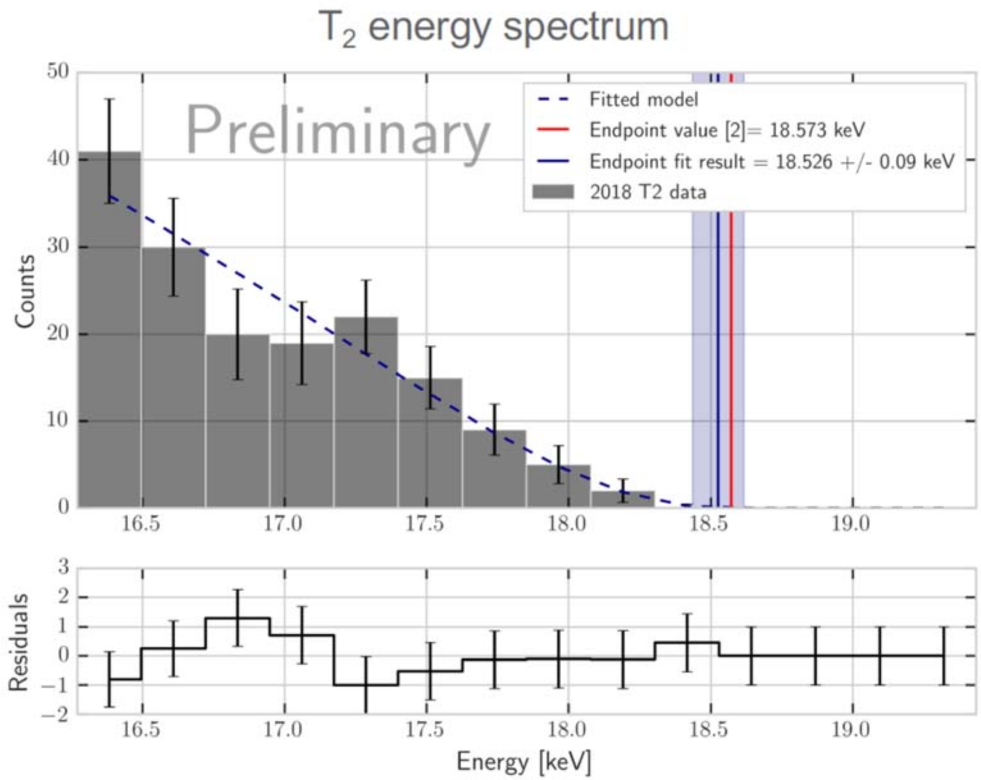

N. Oblath TAUP 2019

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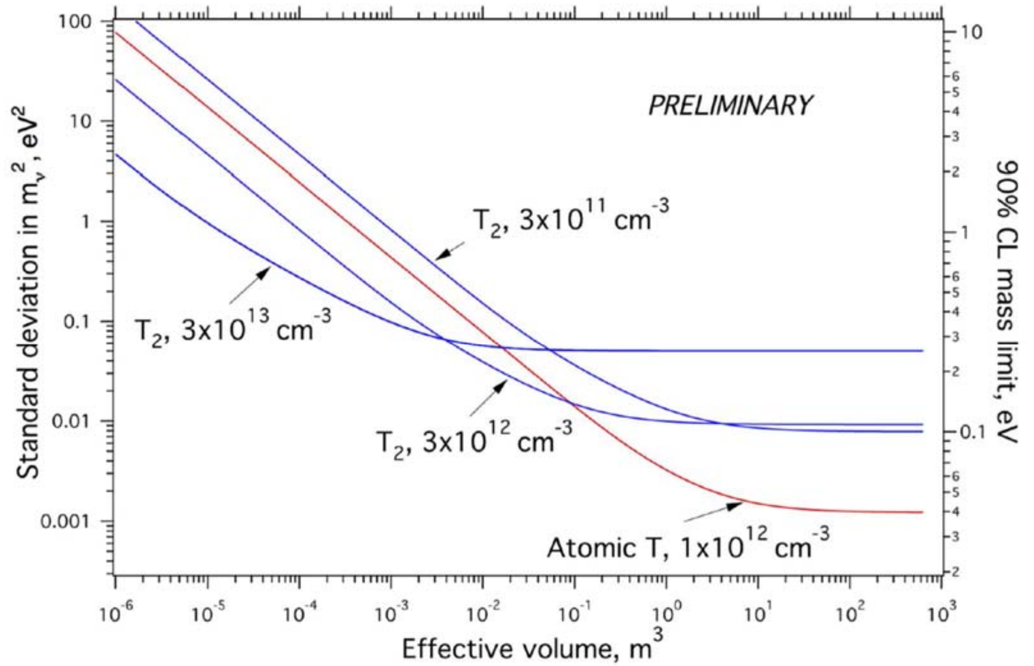

Esfahani et al., *J. Phys. G: Nucl. Part. Phys.* **44** (2017) 054004

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

Main ideas:

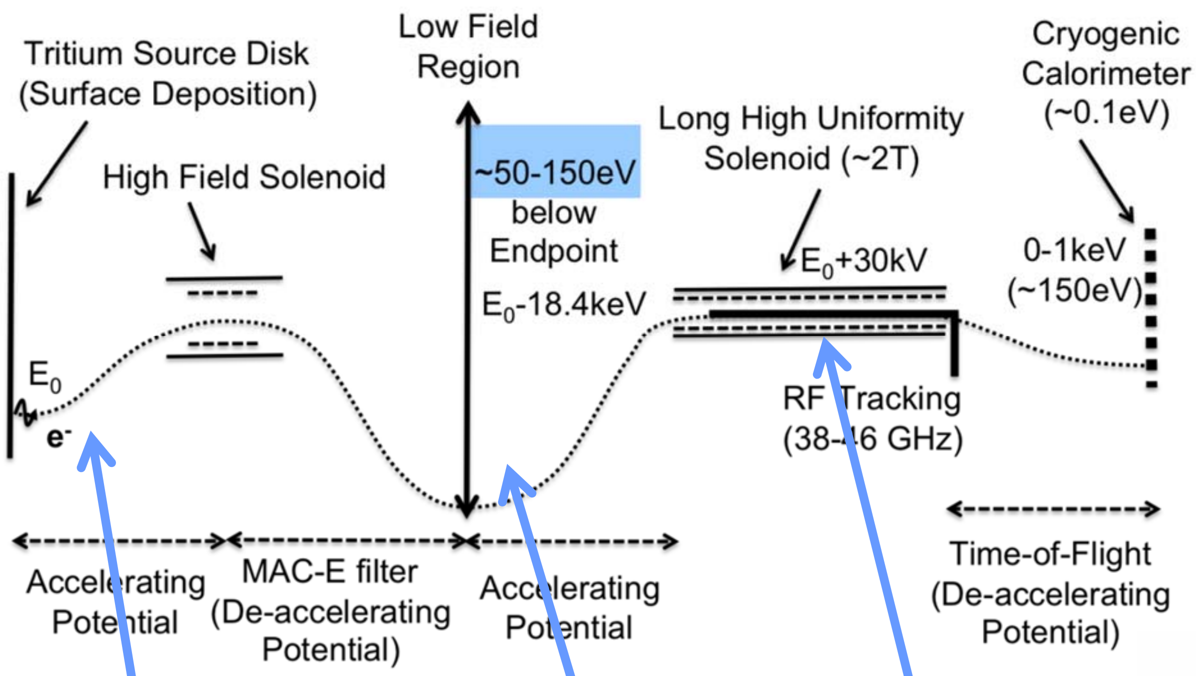
large area tritium source: 100 g atomic ^{3}H

MAC-E lter methods

RF tracking and time-of-flight systems

cryogenic calorimetry → differential spectrum

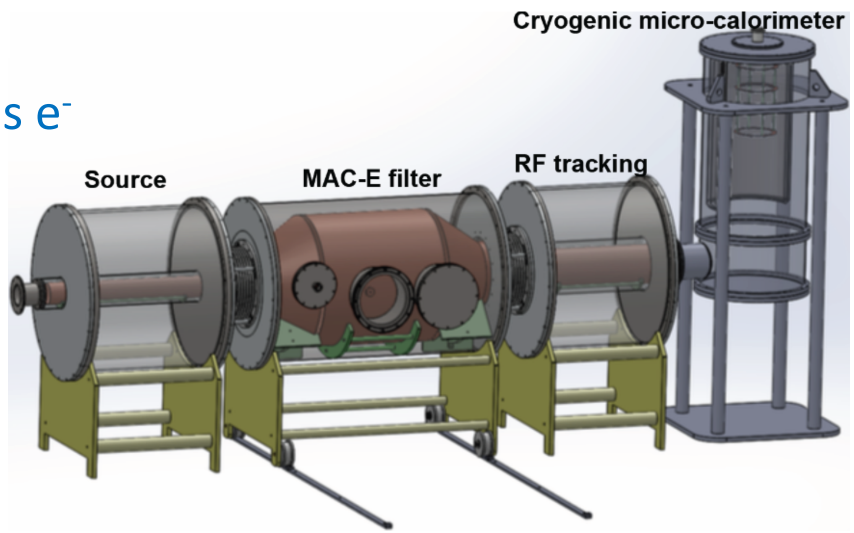
PTOLEMY



Tracker identifies e$^-$

e$^-$ from Tritium start here

Filter removes most low energy e$^-$



S. Betts et al., [astro-ph.IM] arXiv:1307.4738v2

Ptolemy Collaboration *JCAP* **07** (2019) 047

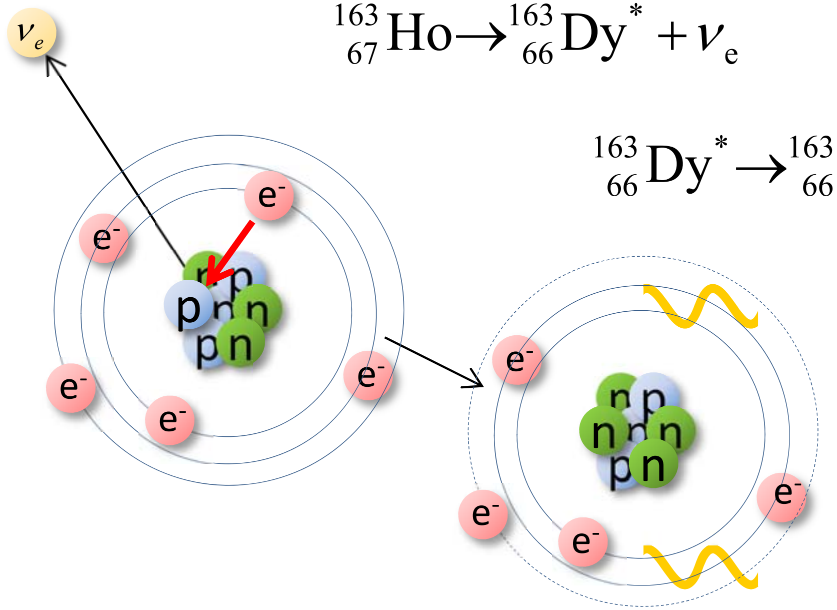
Electron capture in ^{163}Ho

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

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

Atomic de-excitation:

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



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

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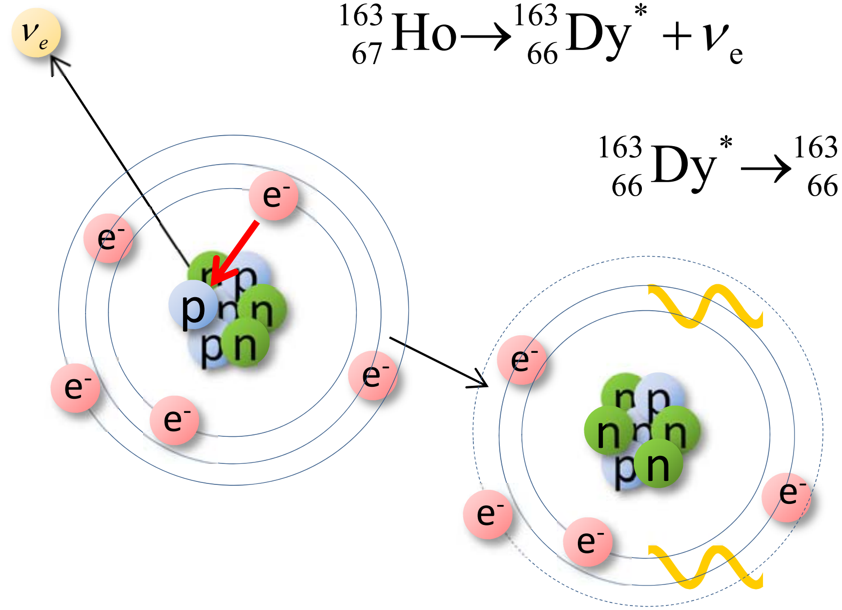
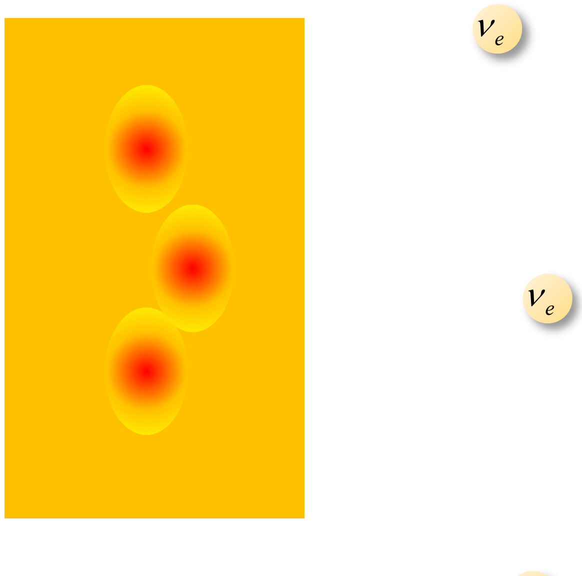


Calorimetric measurement

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)



Source = Detector

ECHo

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

HOLMES

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

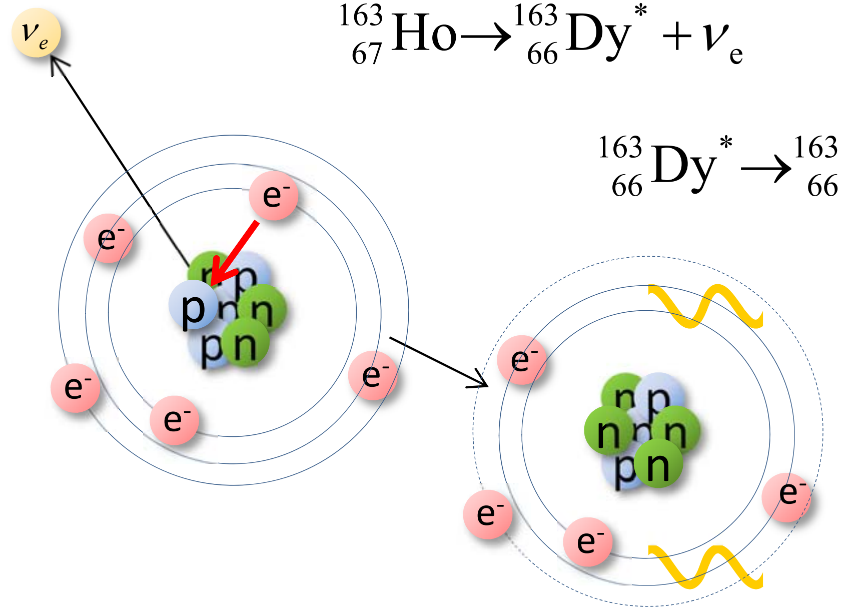
Electron capture in ^{163}Ho: spectrum

Atomic de-excitation:

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

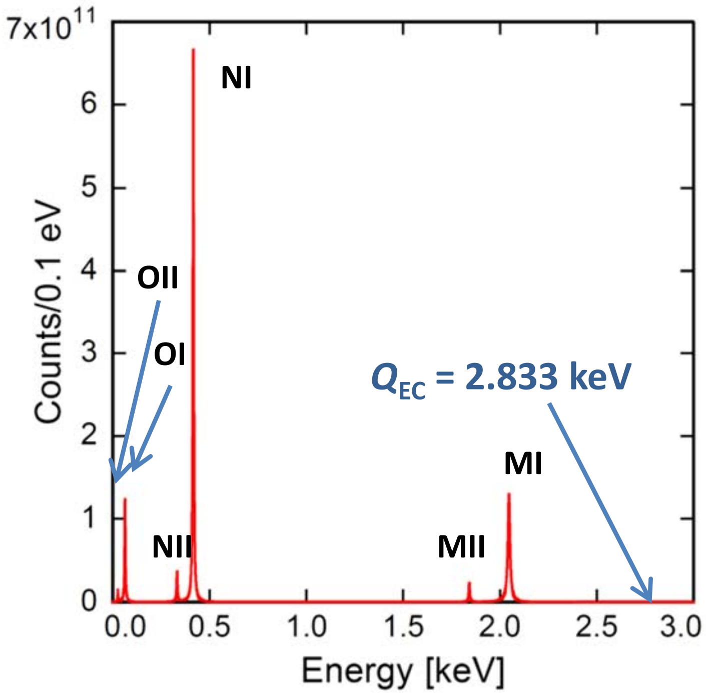
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

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



Calorimetric measurement

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)



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

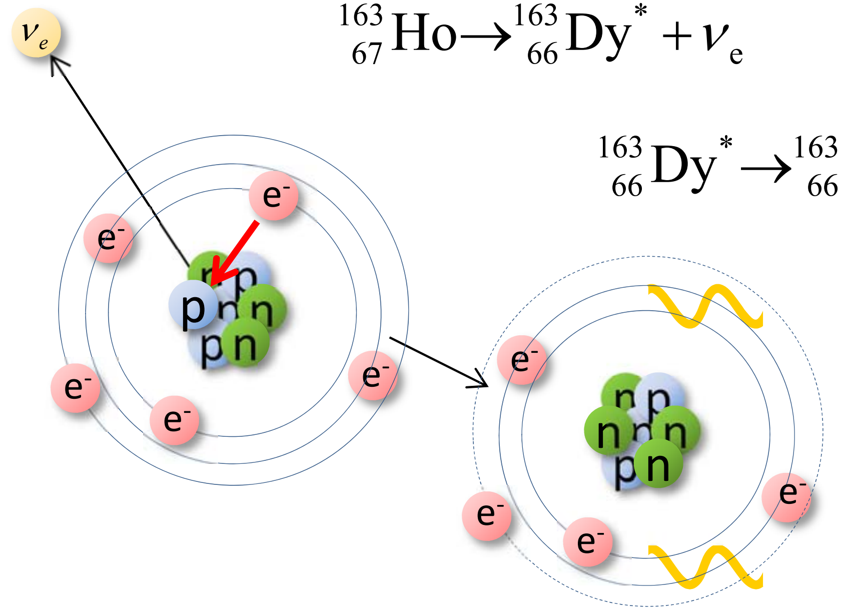
Electron capture in ^{163}Ho: spectrum

Atomic de-excitation:

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

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

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



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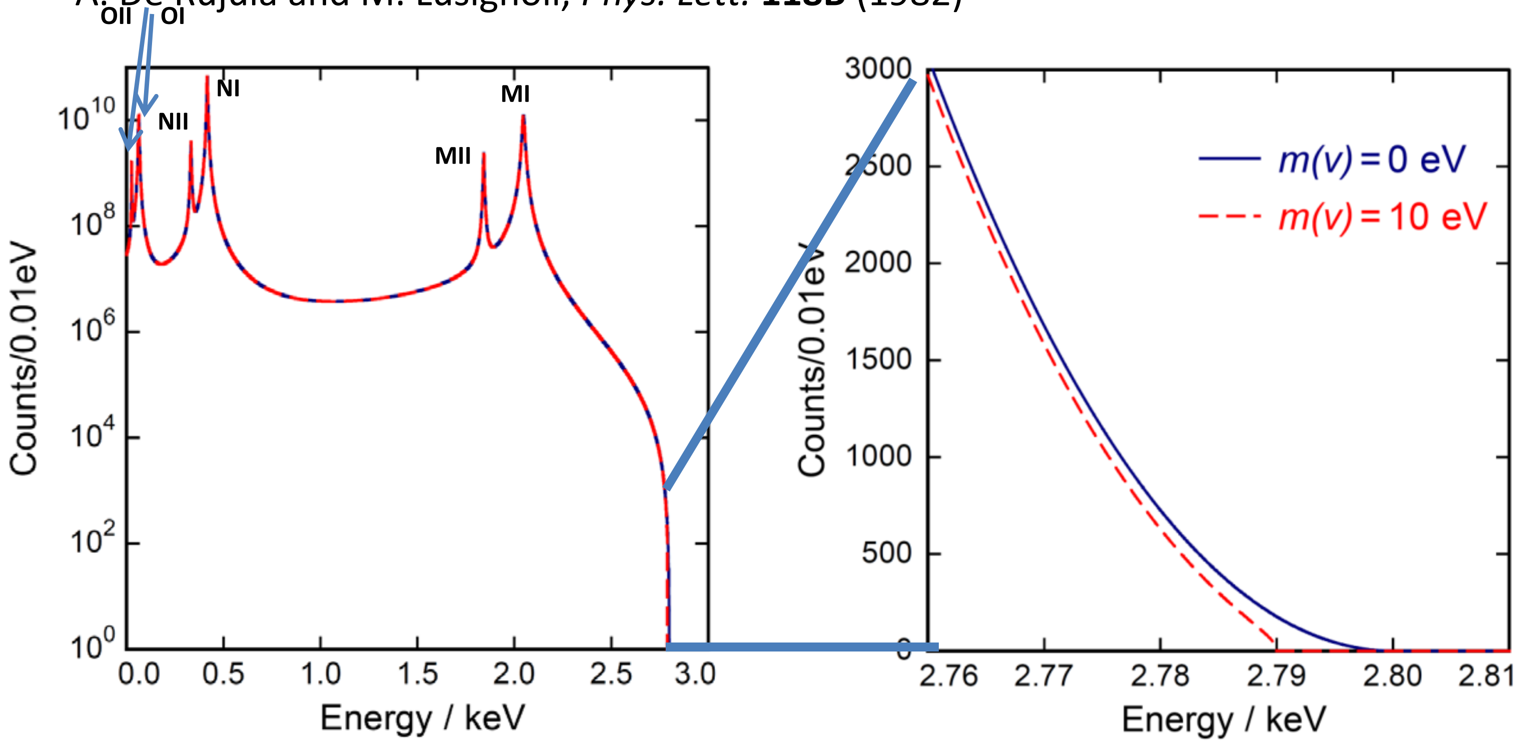


Requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

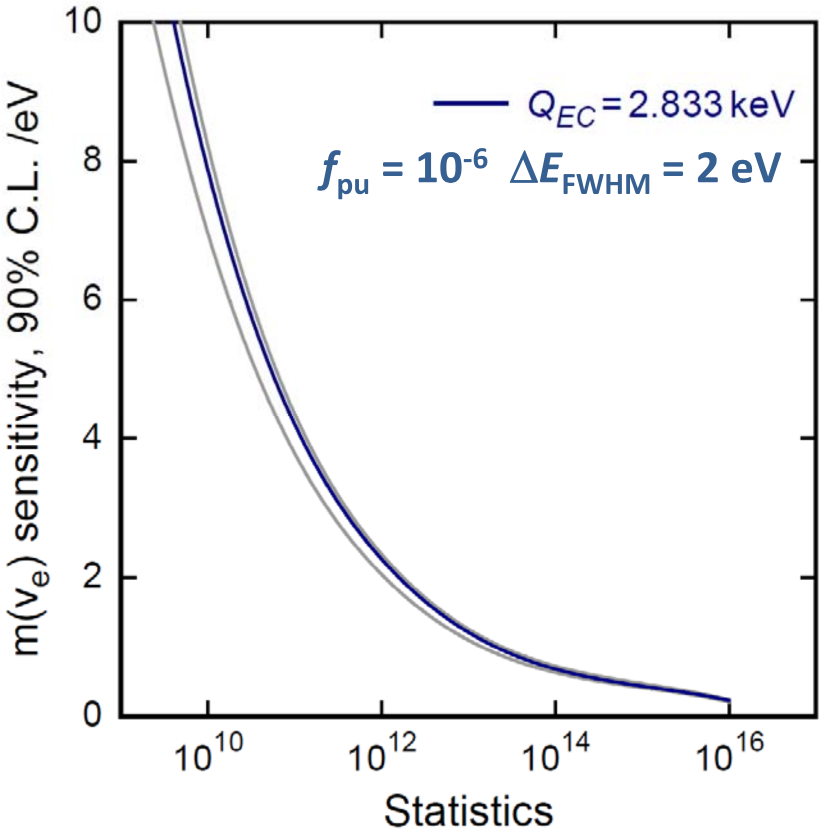
- $\boldsymbol{f_{pu} < 10^{-5}}$
- $\tau_r < 1\ \mu s$ → a ~ 10 Bq
- 10^5 pixels

Precision characterization of the endpoint region

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

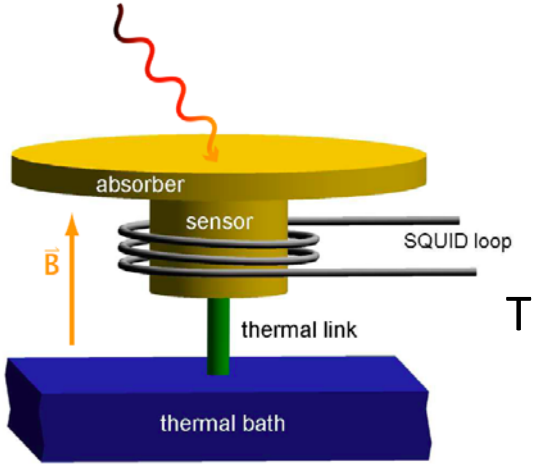
Background level

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

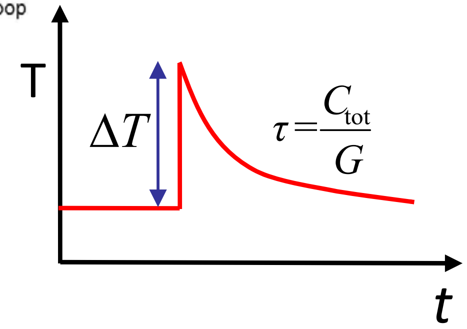


ECHo detectors

ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho



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



A.Fleischmann, C. Enss and G. M. Seidel,
Topics in Applied Physics **99** (2005) 63

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

L. Gastaldo et al.,
Nucl. *Inst. Meth. A*, **711** (2013) 1

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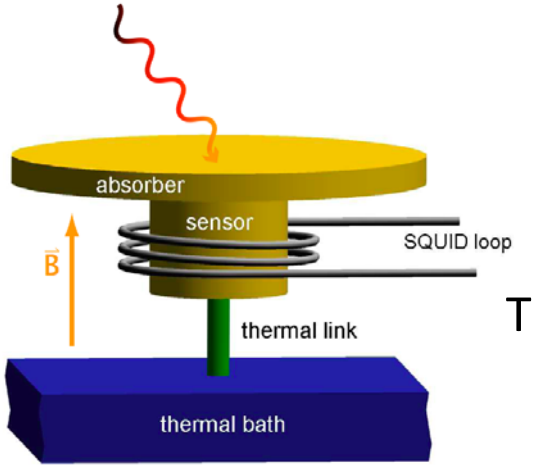

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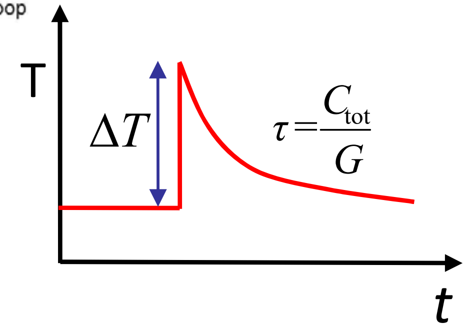

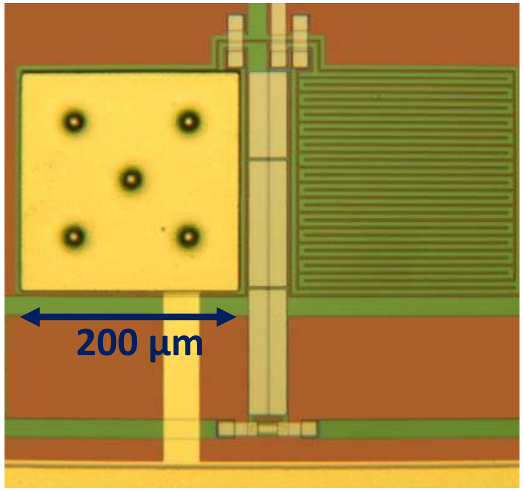

A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics **99** (2005) 63

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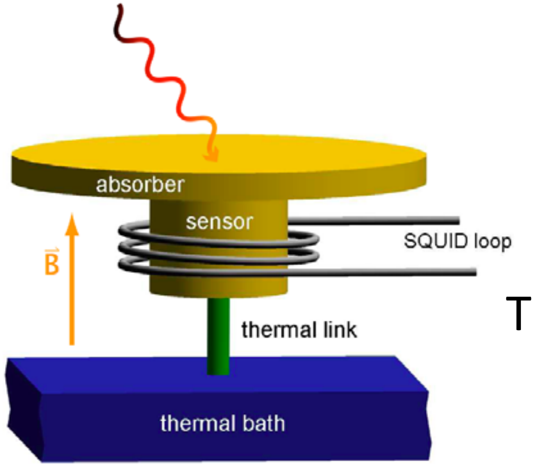
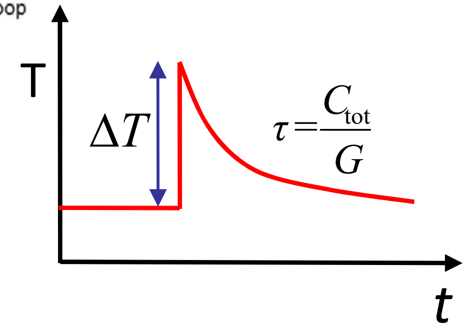
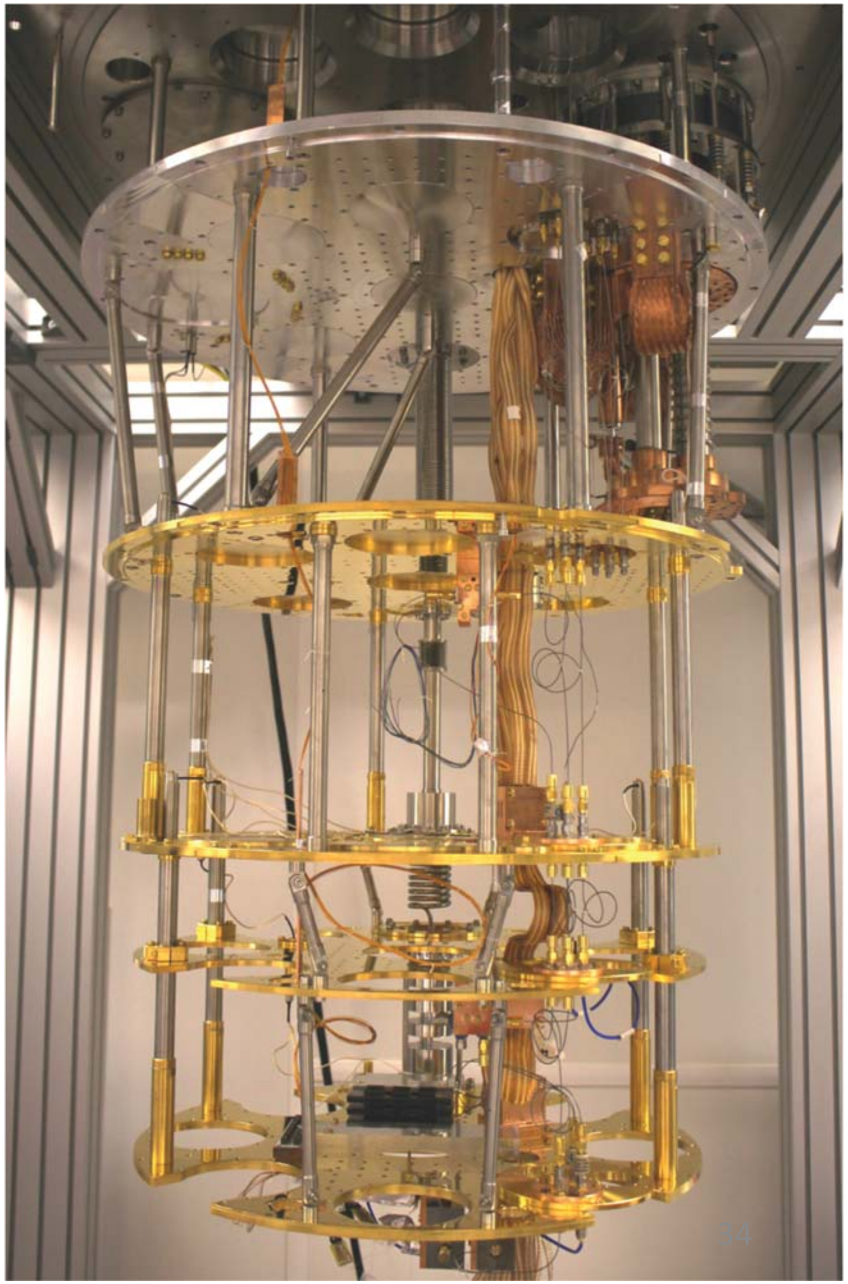


$$\Delta T \cong \frac{E}{C_{tot}}$$

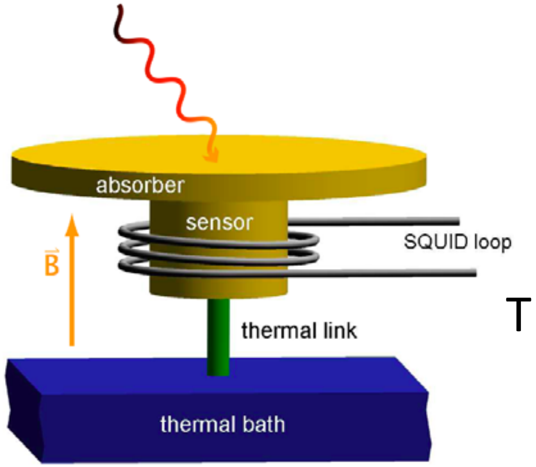




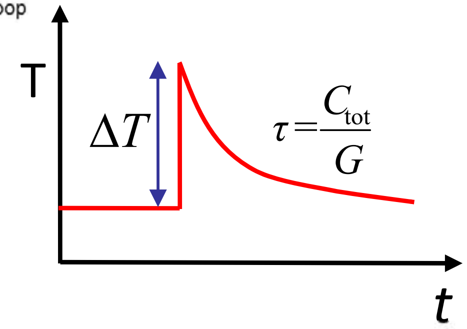
Operated at T ≅ 20 mK

ECHo detectors

ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho



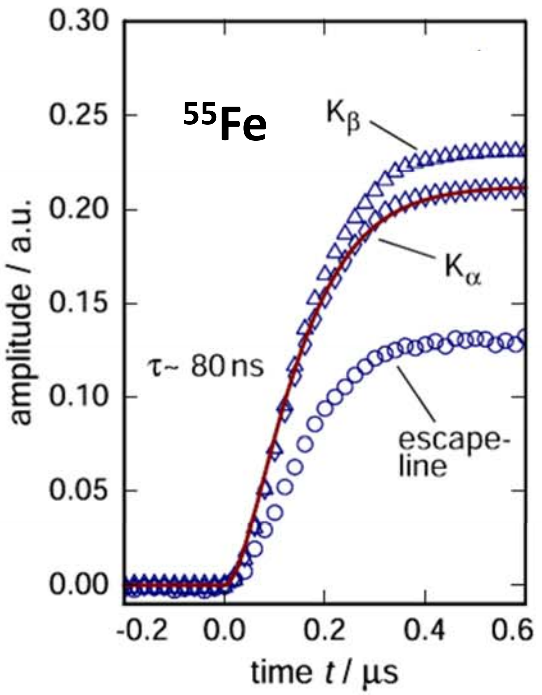
$$\Delta T \cong \frac{E}{C_{\mathrm{tot}}}$$

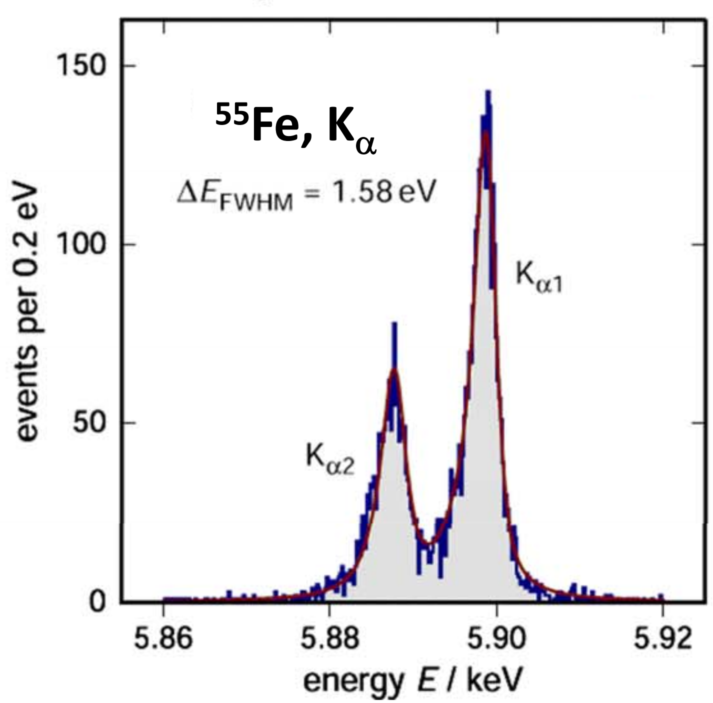


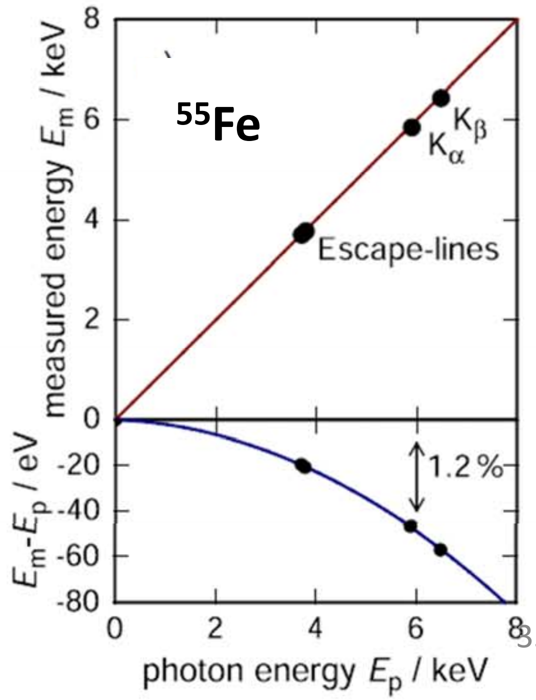
Fast risetime
→ Reduction un-resolved pile-up

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

Excellent linearity
→ precise definition of the energy scale



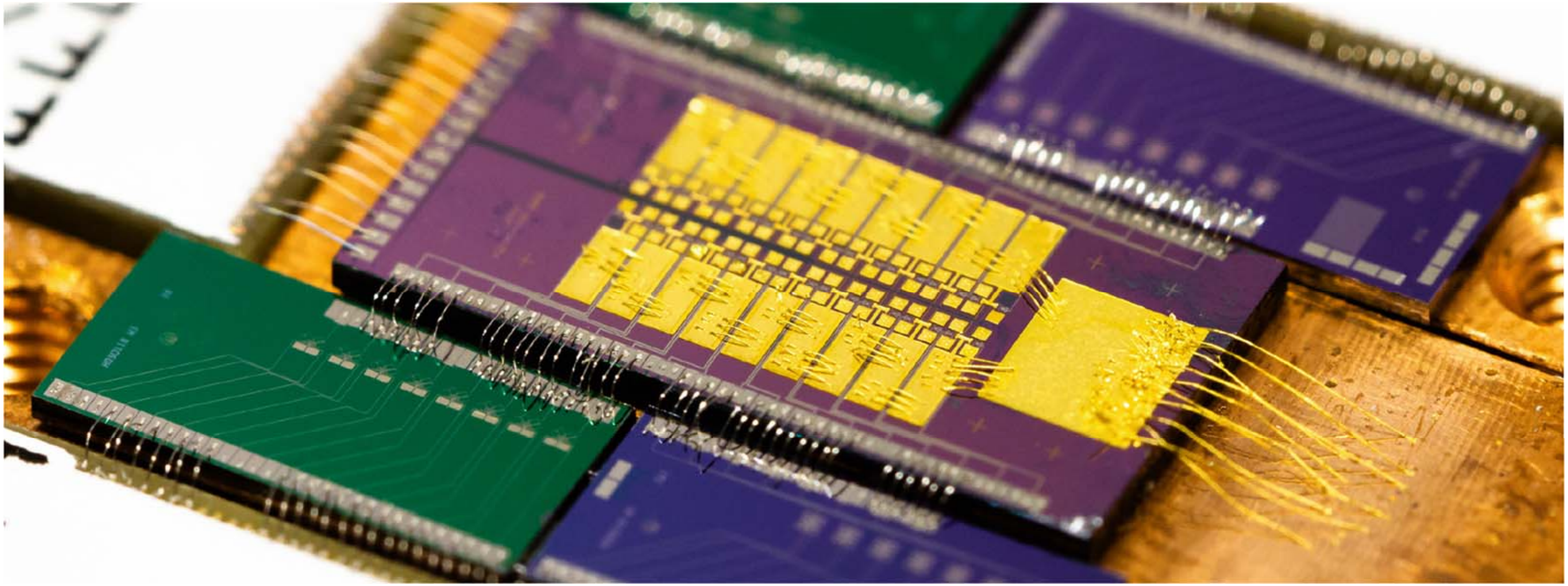




ECHo detectors

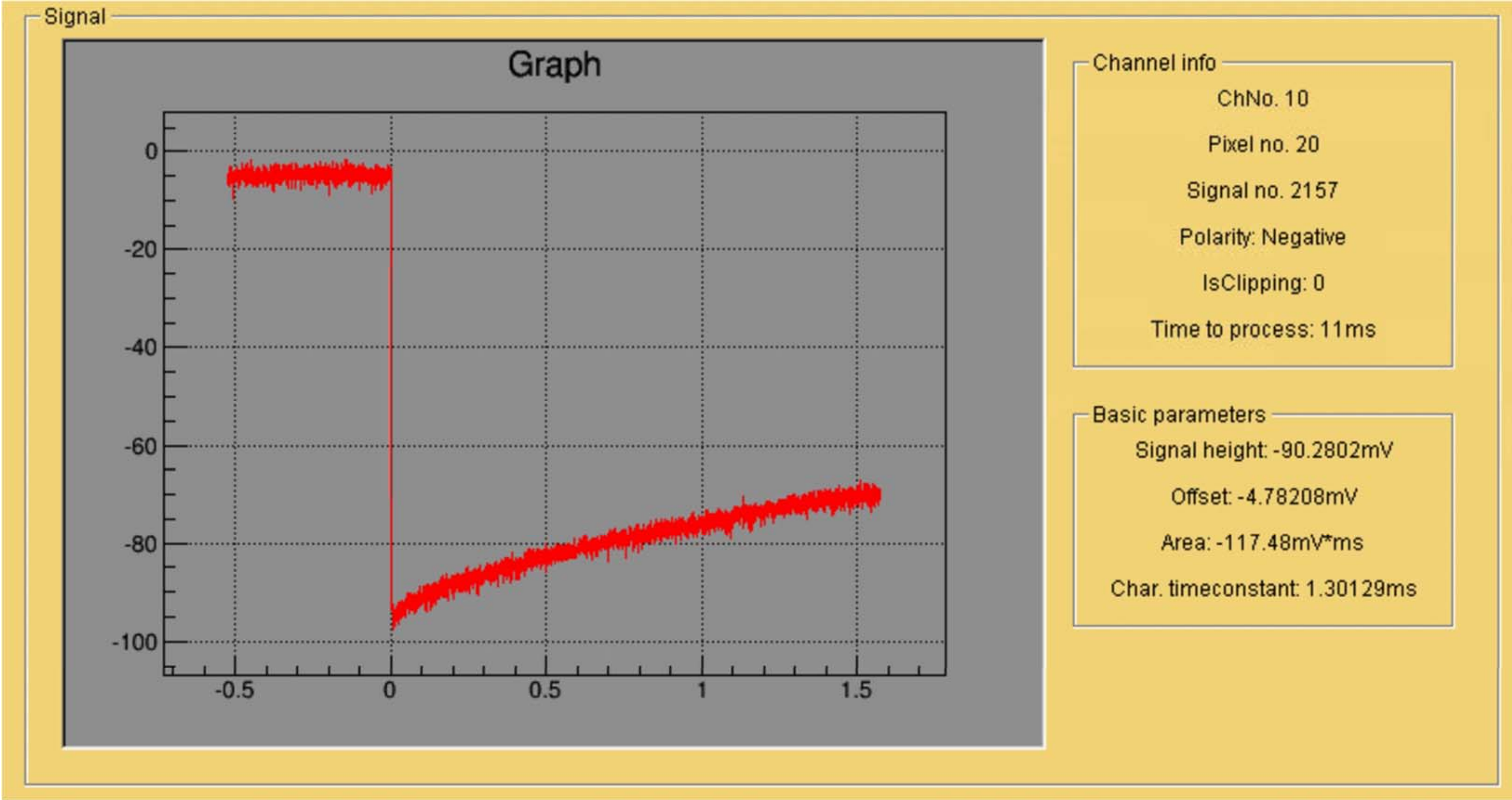
ECHo-1k chip-Au

- High purity ^{163}Ho source * → activity per pixel $a \approx 1$ Bq
- 4 Front-end chips each with 8 dc-SQUIDs for parallel readout



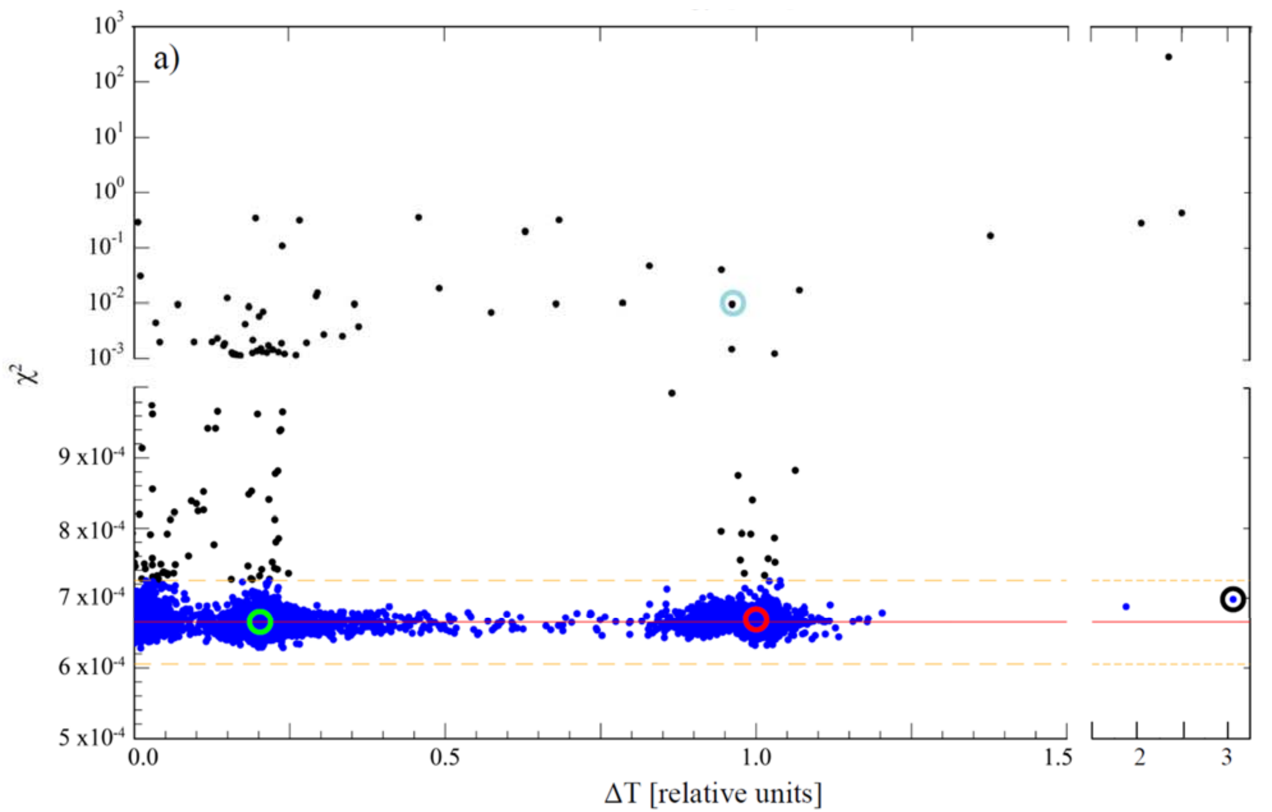
* H. Dorrer et al, Radiochim. Acta (2018)
F. Schneider et al ., *NIM B* **376** (2016) 388
T. Kieck et al., Rev. Sci. Instrum. 90 (2019) 053304

ECHo signals



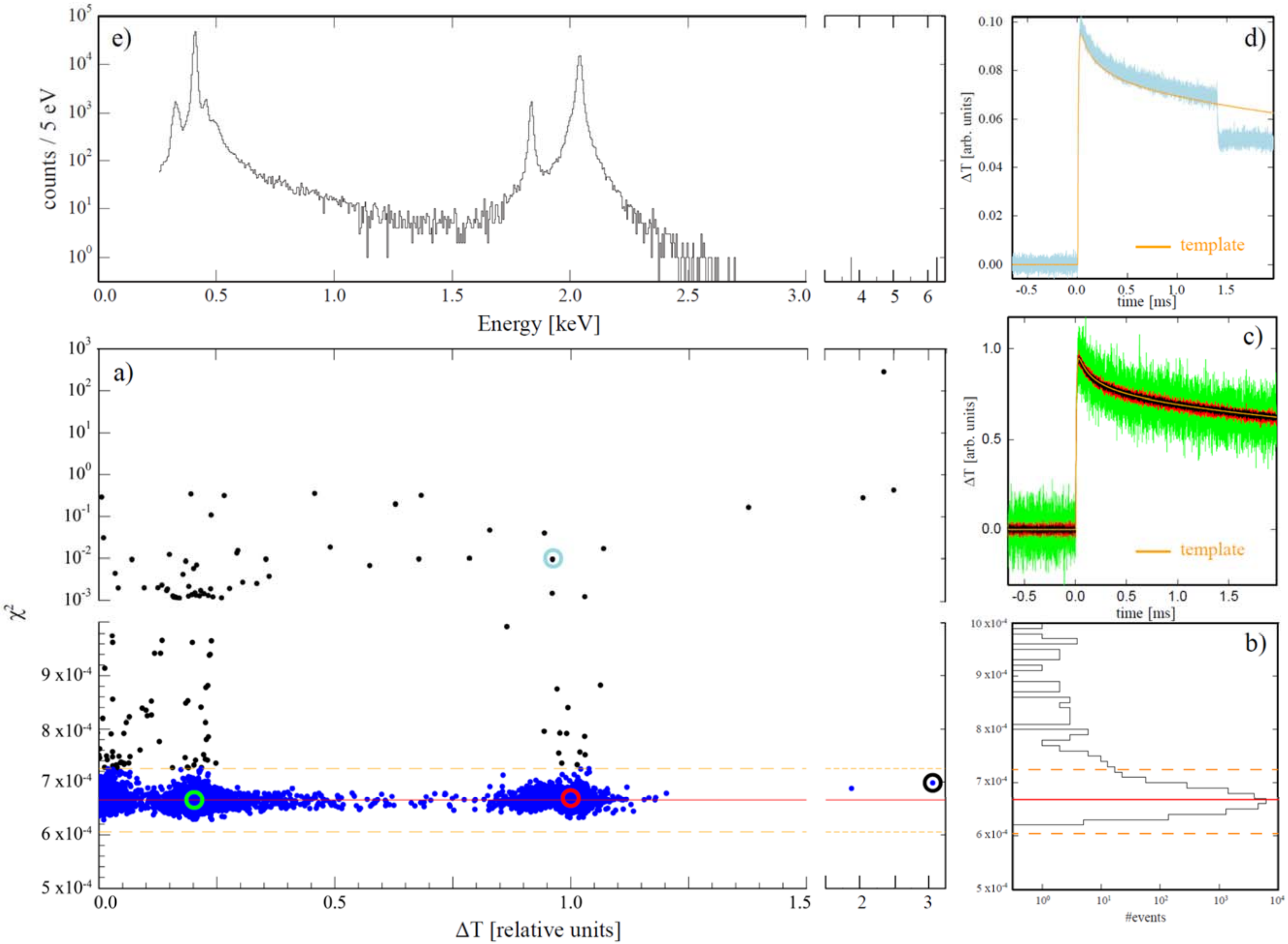
From signals to spectrum

Fit all pulses with time template
key parameters are extracted to perform cuts



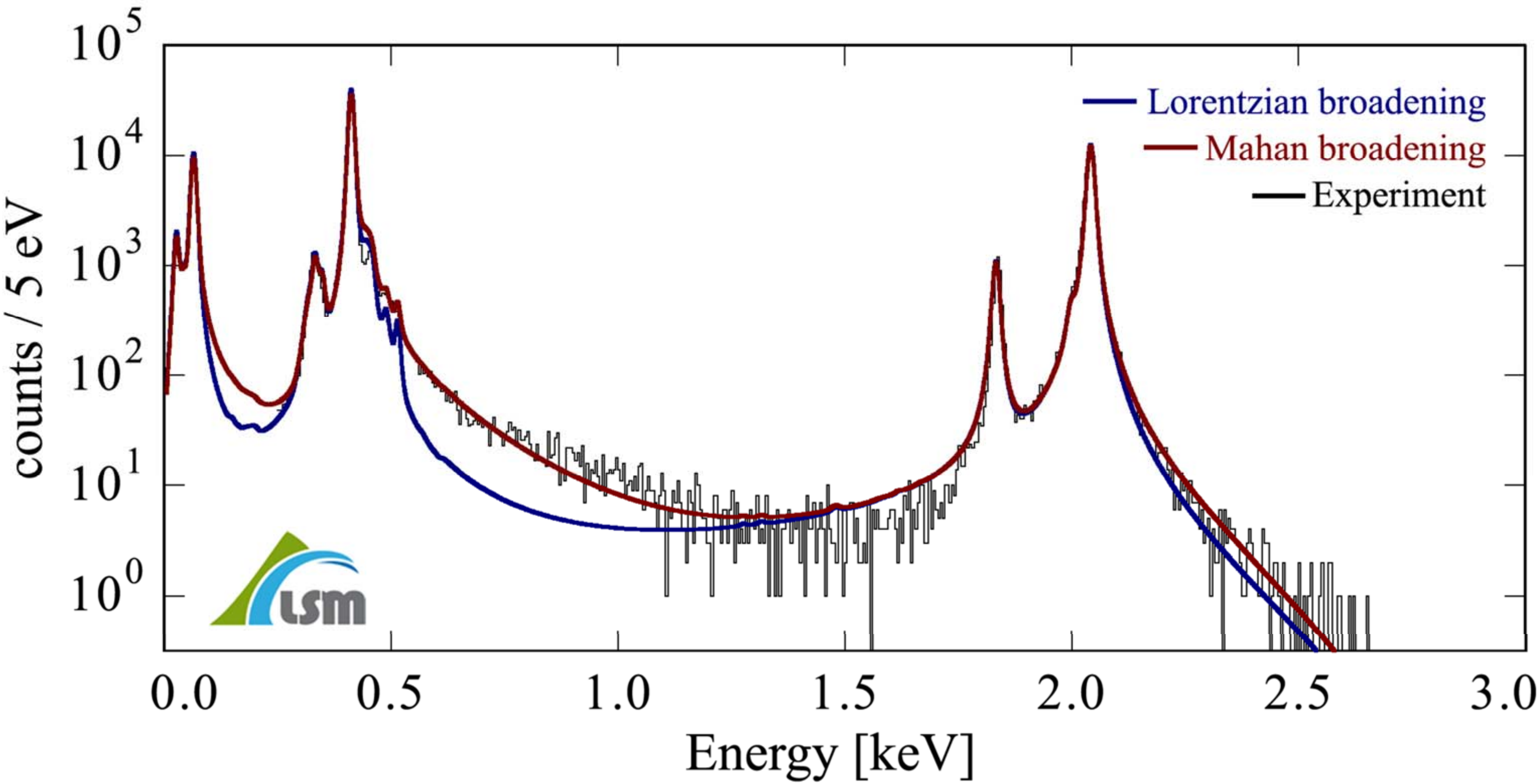
C. Velte et al., Eur. Phys. J. C (2019) **79**: 1026

From signals to spectrum



C. Velte et al., Eur. Phys. J. C (2019) **79**: 1026

^{163}Ho spectral shape analysis

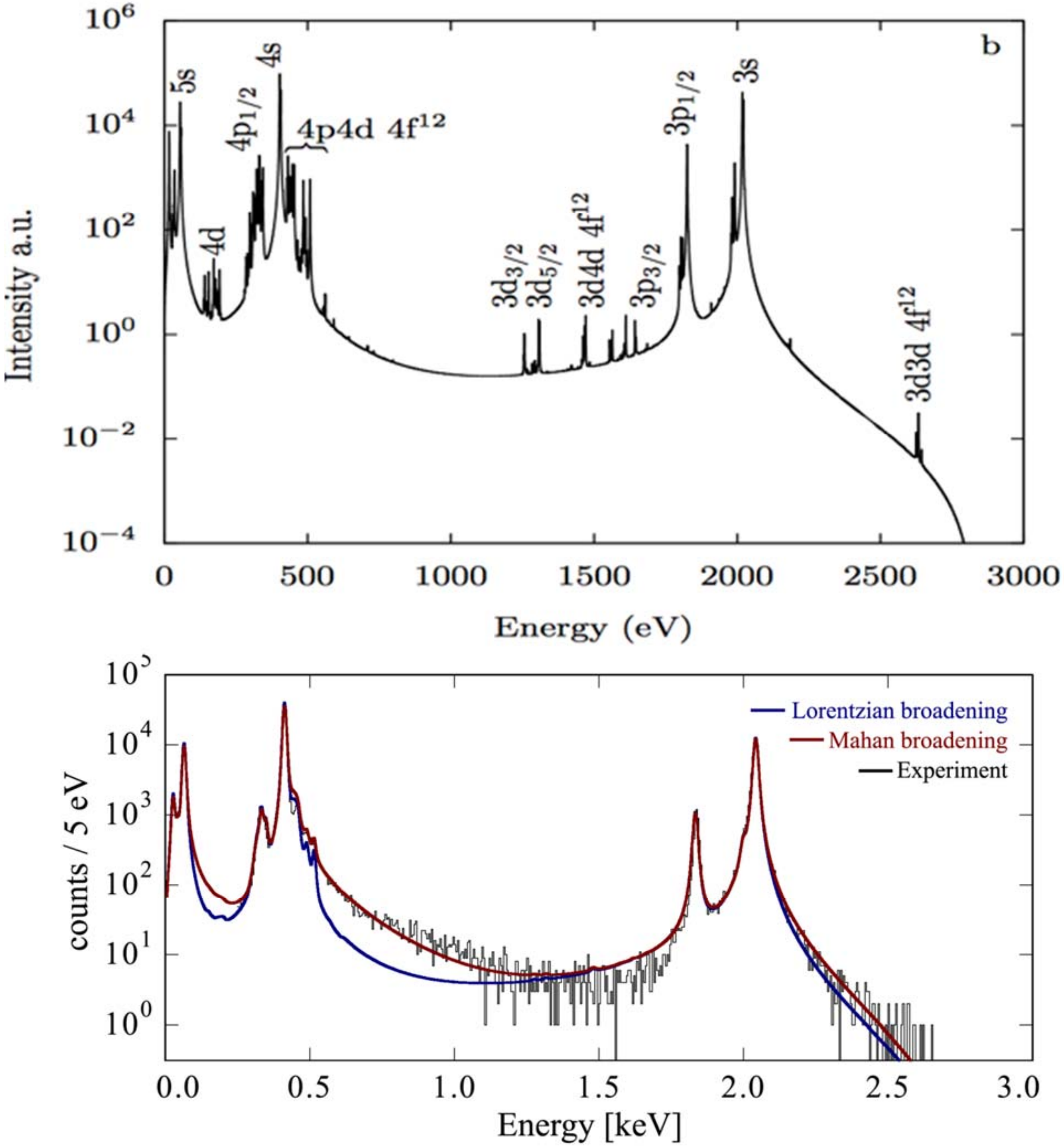


test of analysis routines: Q_{EC} = (2838 ± 14) eV

$m(\nu_e)$ < 150 eV (95% C.L.) profile log-likelihood ratio hypothesis test

C. Velte et al., Eur. Phys. J. C (2019) **79**: 1026

^{163}Ho spectral shape analysis



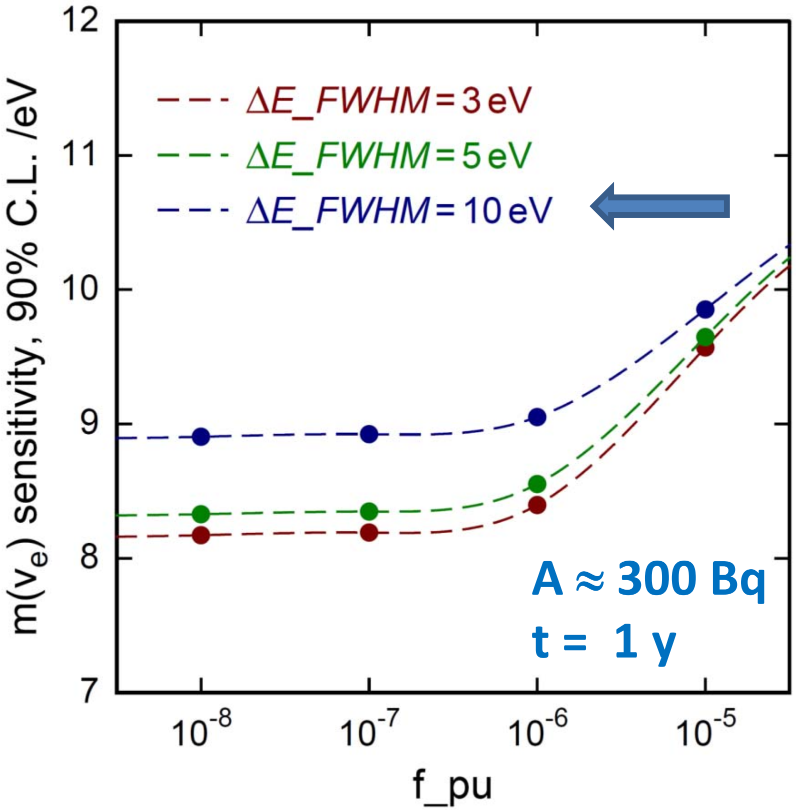
- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. Faessler et al.
  Phys. Rev. C **95**, (2017) 045502
- A. Faessler and F. Simkovic
  Phys. Rev. C **91**, 045505 (2015)
- A.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

❖ Brass et al., *Phys. Rev. C* **97** (2018) 054620
Ab-initio calculation

C. Velte et al., Eur. Phys. J. C (2019) **79**: 1026

ECHo timeplan

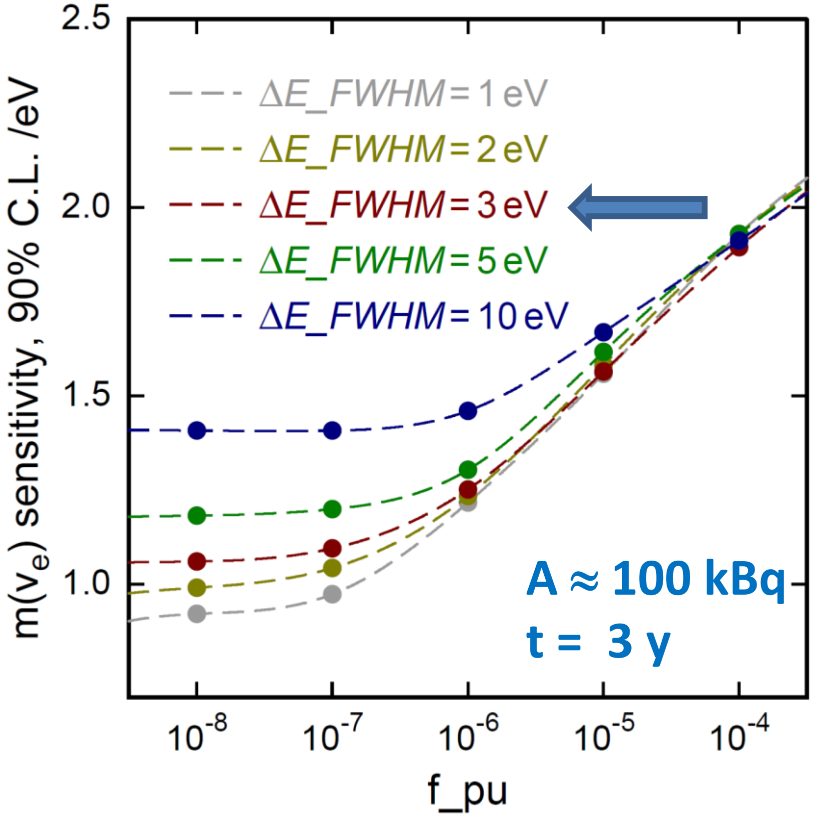
ECHo-1k – revised (2015 – 2018+)



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

Activity per pixel: 1 - 5 Bq
Number of detectors: 60 - 100
Readout: parallel two stage SQUID

ECHo-100k (2018 – 2021+)



$m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel: 10 Bq
Number of detectors: 12000
Readout: microwave SQUID multiplexing

Supported by DFG Research Unit FOR 2022/1

Supported by DFG Research Unit FOR 2022/2

Towards ECHo-100k

ECHo-100k chip in fabrication

- single pixel optimization: ^{163}Ho activity per pixel $a \approx 10$ Bq
  reduced absorber thickness → increase signal to noise ratio
- suitable for parallel and multiplexed readout

→ ^{163}Ho implantation on several chips foreseen before the end of the year

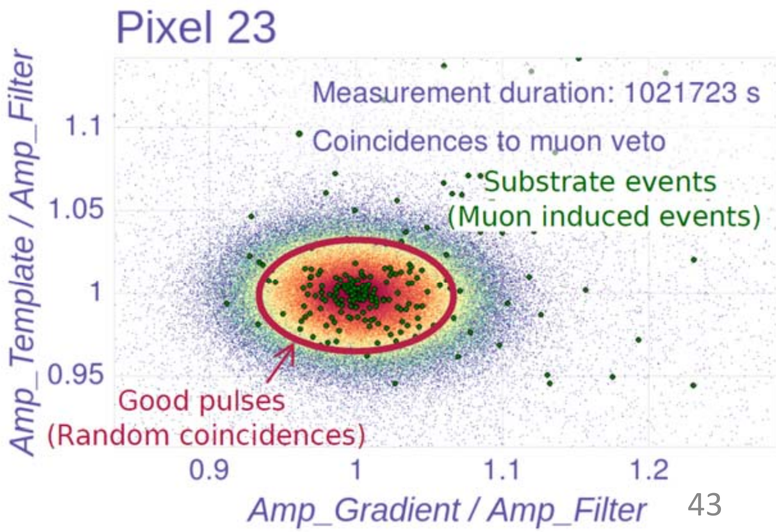
Microwave multiplexed readout of MMC demonstrated

- adapt room temperature electronics for larger number of detectors/channel (goal 400 det/ch)
- install 13 new microwave channels in ECHo cryostat

→ ^{163}Ho spectrum acquired at GHz frequency foreseen early 2020

Preparation of background model for ECHo

- Experiments with muon veto demonstrate that muon related events discriminated via pulse shape
- Effect of low energy secondary radiation is being investigated via Monte Carlo simulations



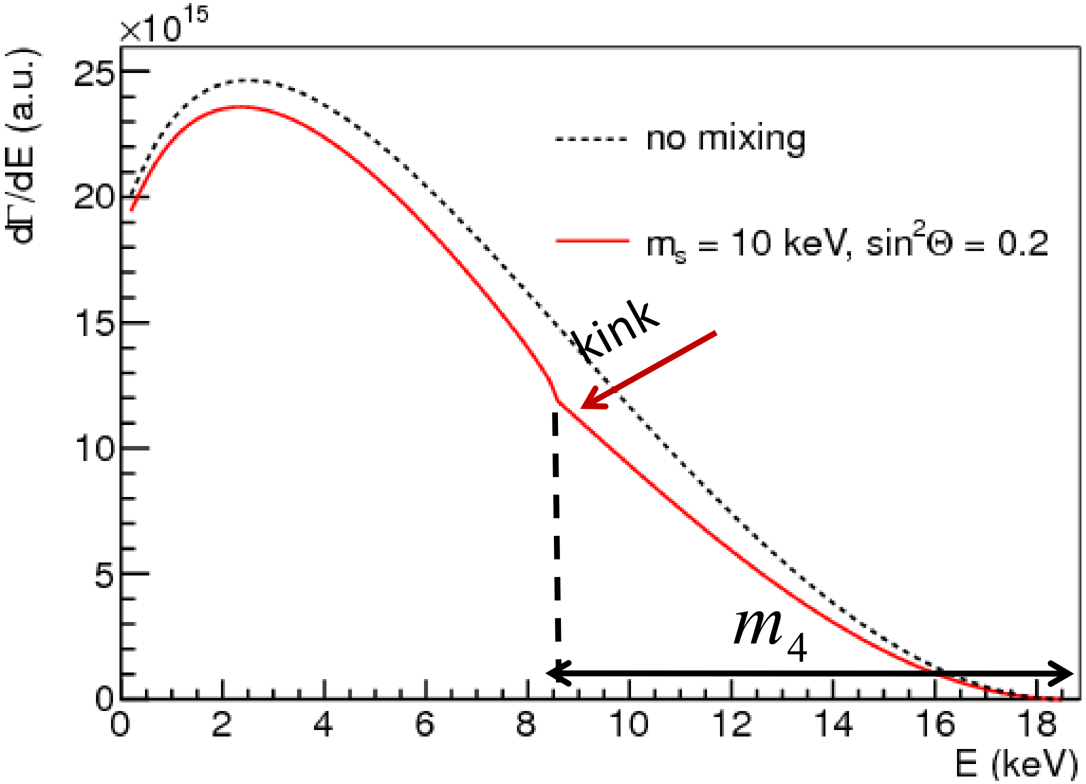
A. Göggelmann et al. Muon induced background in ECHo, in preparation

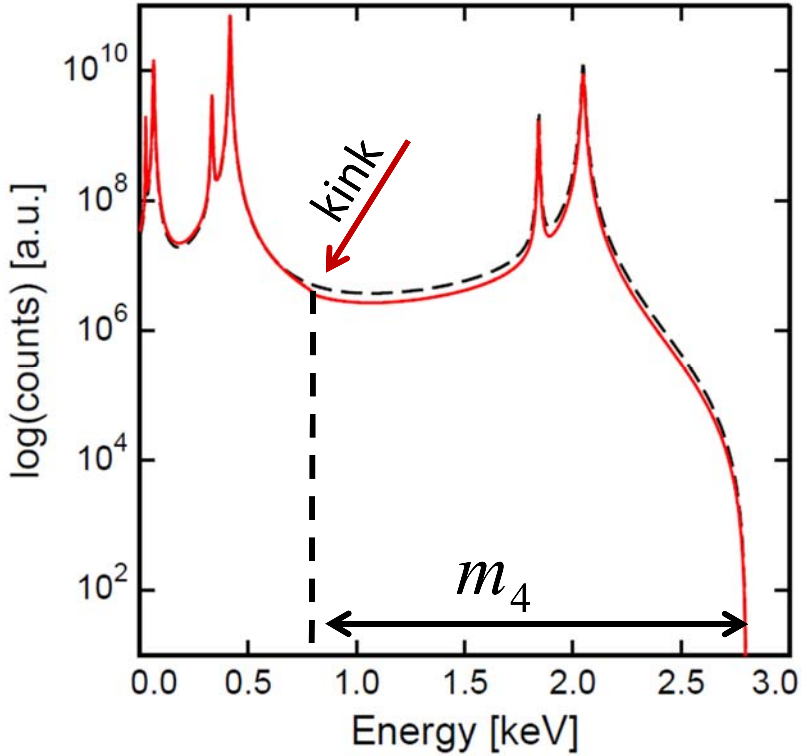
Beyond the standard 3-neutrino scenario

Sterile neutrinos in β- and EC spectra

The existence of a sterile neutrino implies the existence of a fourth mass eigenstate

$$\frac{dN}{dE} = \cos^2 \vartheta_s \frac{dN}{dE}(m_{active}) + \sin^2 \vartheta_s \frac{dN}{dE}(m_{sterile})$$



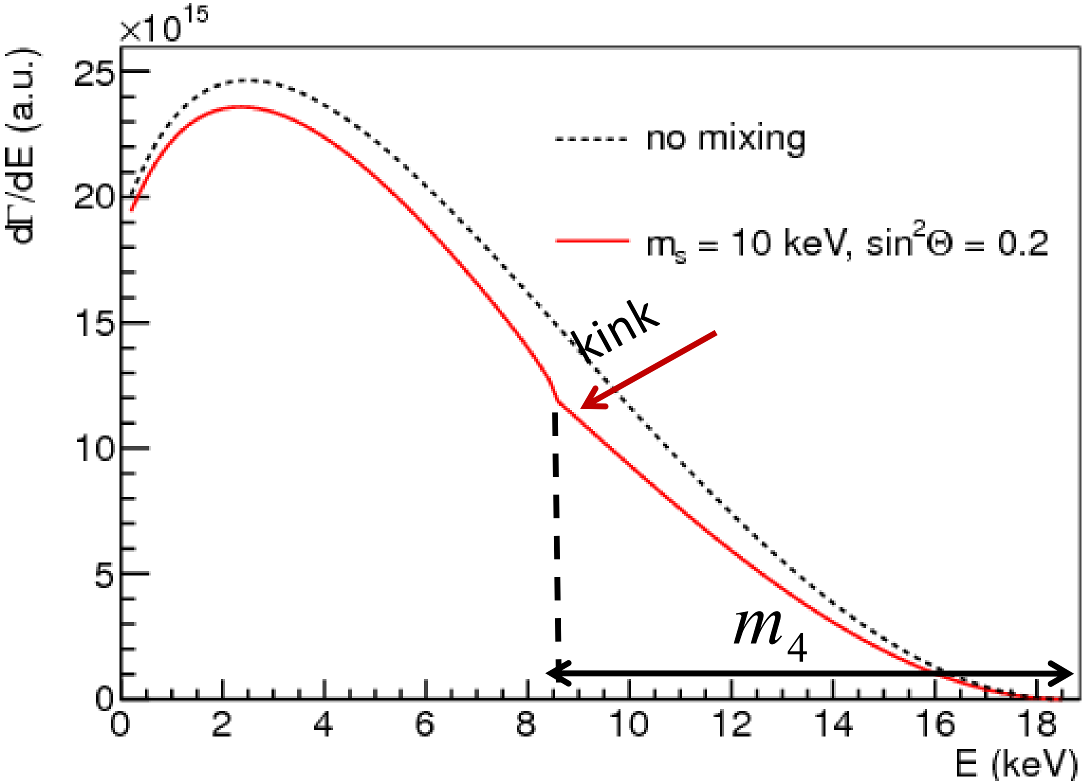


Search for sterile neutrino signature both at the eV scale as well as keV scale

Sterile neutrinos in β- and EC spectra

The existence of a sterile neutrino implies the existence of a fourth mass eigenstate

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \cos^2\vartheta_s \frac{\mathrm{d}N}{\mathrm{d}E}(m_{active}) + \sin^2\vartheta_s \frac{\mathrm{d}N}{\mathrm{d}E}(m_{sterile})$$



eV-scale

Esmaili & Peres, *Phys. Rev. D* **85** (2012) 117301

Giunti, Li, Zhang, arXiv:1912.12956

keV-scale

TRISTAN experiment

Mertens et al., *J. Phys. G: Nucl. Part. Phys.* **46** (2019) 065203

Benso et al., *Phys. Rev. D* 100 (2019) 115035

Sterile neutrinos in β- and EC spectra

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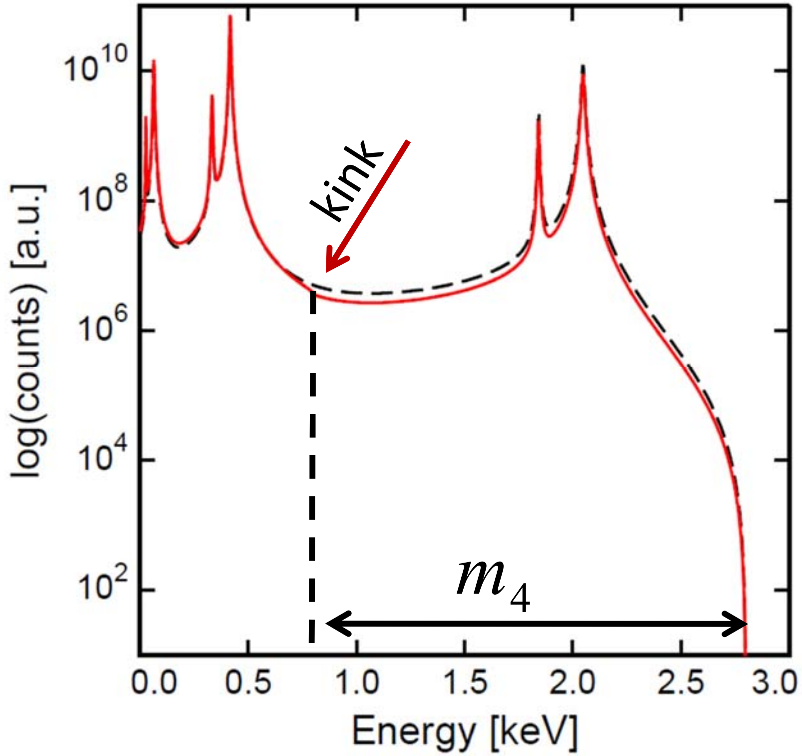
eV-scale

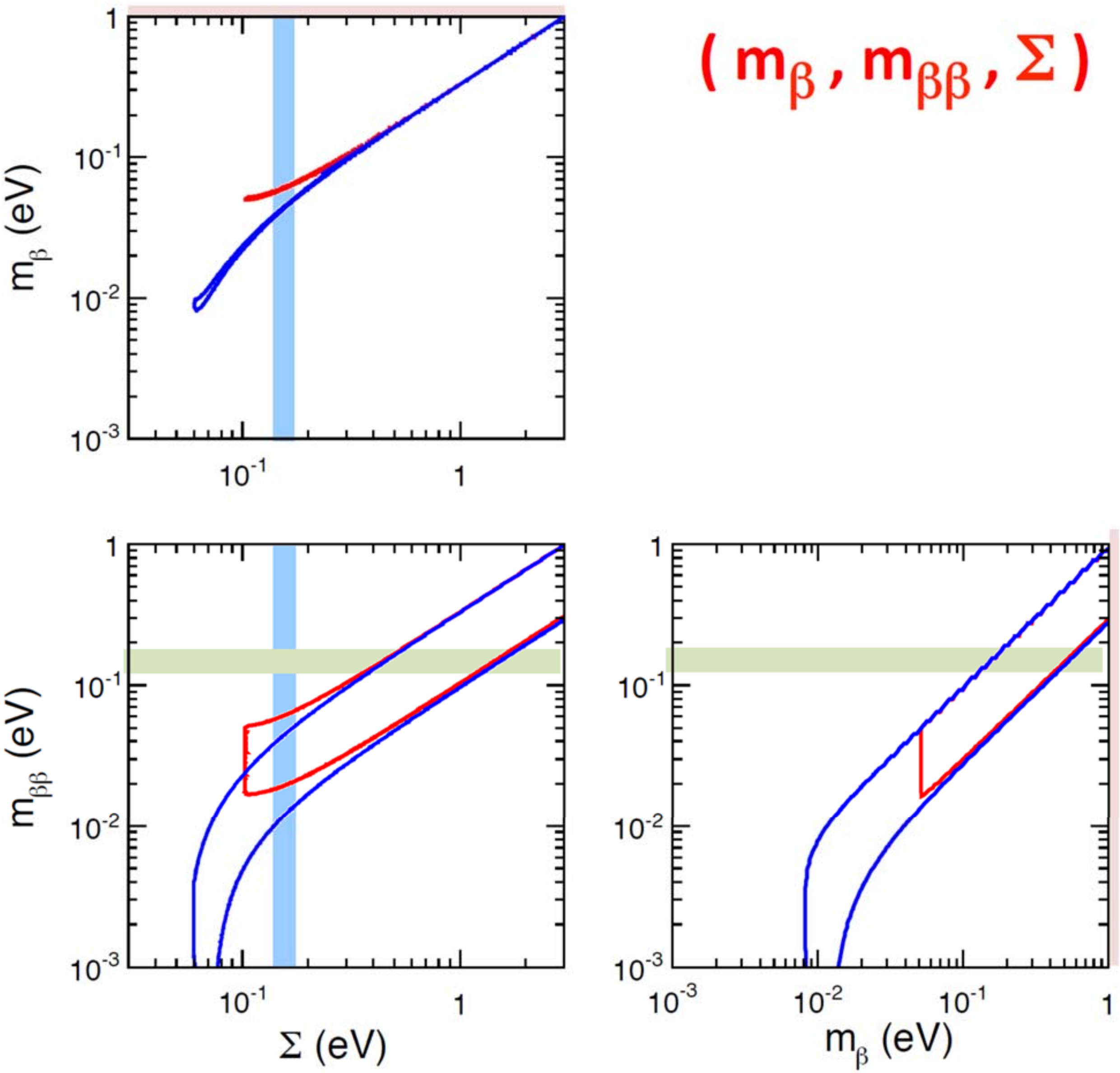
Gastaldo, Giunti, Zavanin, J. High Energy Physics **2016** (2016) 61

keV-scale

A White Paper on keV Sterile Neutrino Dark Matter
JCAP **01** (2017) 025



Conclusions



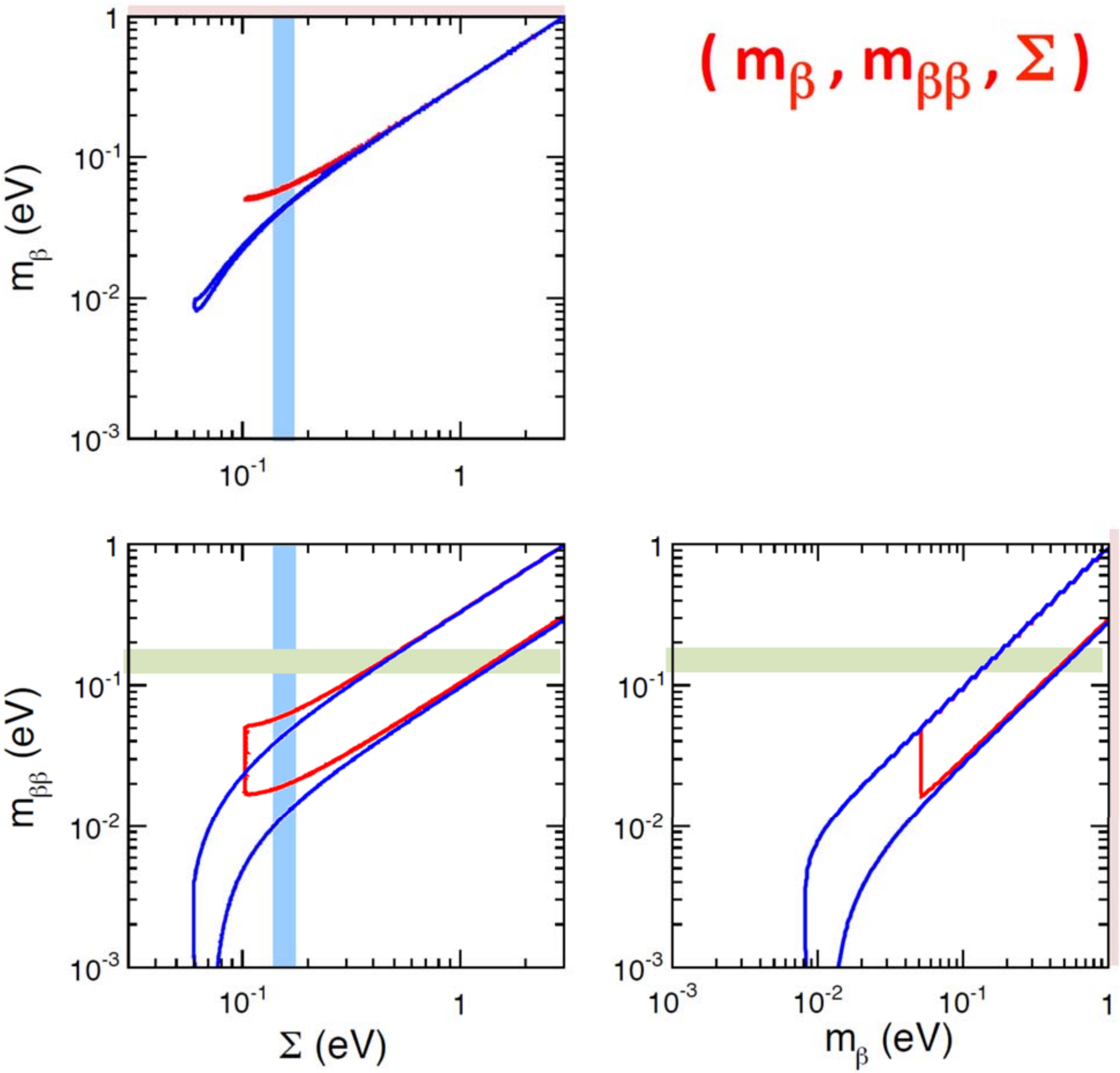
(m_β , $m_{\beta\beta}$, Σ)

$$\Omega_\nu h^2 \cong \sum \frac{m_\nu}{93\ \text{eV}}$$

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

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

Conclusions



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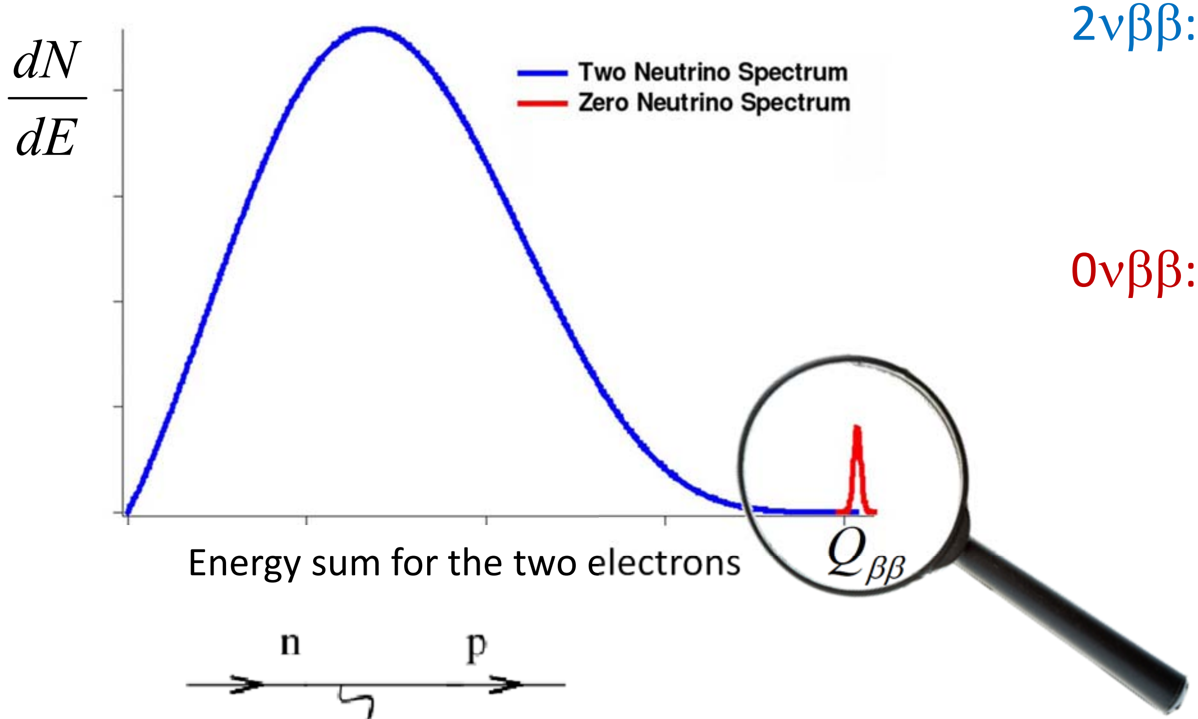
$$m_\beta{}^2(\nu_e) = \sum_i |U_{ei}|^2 m^2{}_i$$

Thank you!

Neutrinoless double beta decay - ν mass

The halflife for 0ν2β decay depends on the neutrino mass

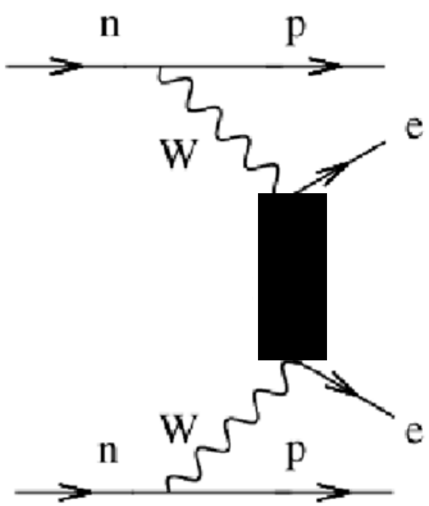


$2\nu\beta\beta$: (A,Z) → (A, Z+2) + $2e^-$ + $2\bar{\nu}_e$

$\tau_{1/2} \approx 10^{20}$ years

$0\nu\beta\beta$: (A,Z) → (A, Z+2) + $2e^-$

$\tau_{1/2} > 10^{25}$ years



Neutrinoless double beta decay - ν mass

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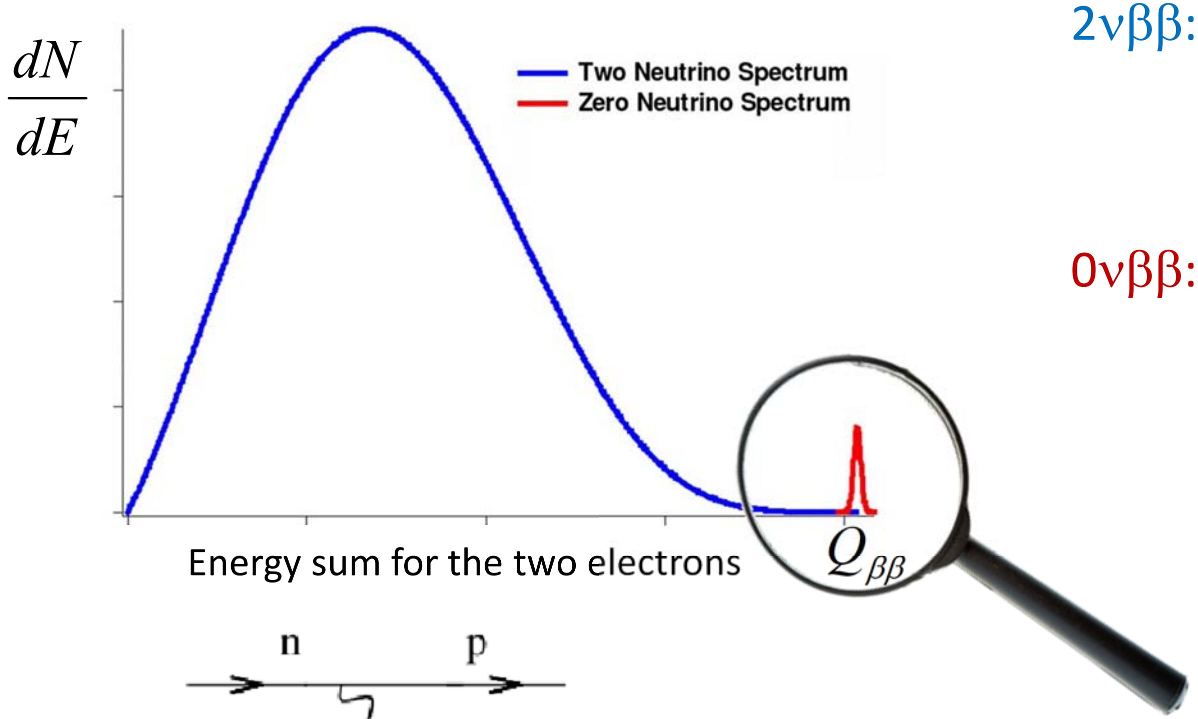

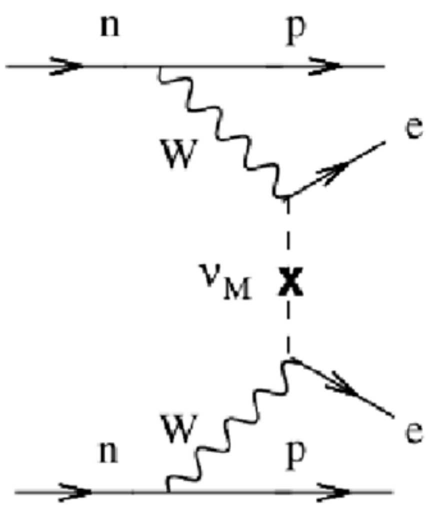

2νββ: (A,Z) → (A, Z+2) + 2e$^-$ + 2$\bar{\nu}_e$

$\tau_{1/2} \approx 10^{20}$ years

0νββ: (A,Z) → (A, Z+2) + 2e$^-$

$\tau_{1/2} > 10^{25}$ years

$$m_{\beta\beta}^2 = \left|\sum U_{ei}^2 m(\nu_i)\right|^2$$

Phase space term

Nuclear matrix element

$$\left(\tau_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

Neutrinoless double beta decay - sensitivity

Typically an excess of events is not found…

A limit on the halflife for 0v2e decay can be defined as function of:

Mass of the isotope	***M***	[kg]	Exposure $M\times T$	[kg × year]
Measuring time	***T***	[year]		
Energy resolution	***ΔE***	[keV]		
Background index	***b***	$[keV^{-1}ton^{-1}year^{-1}]$		

Two limits defined by the background index

> 1 background events in ROI

$$\left(\tau_{1/2}^{\exp}\right)^{-1} = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

<1 background events in ROI

$$\left(\tau_{1/2}^{\exp}\right)^{-1} = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$

Fight against background

Direct reduction of background activity

- Select and use ultra-pure materials
- Minimize all passive (non "source") materials
- Avoid material re-contamination (machining, manipulation, storage)
- Fabricate ultra-clean materials (underground fab if needed)
- underground labs — reduced muon flux & related induced activations

Discrimination techniques

- Energy resolution
- Active veto detector
- Tracking (topology)
- Particle ID, angular, spatial, time correlations
- Fiducial Fits
- Granularity (arrays)
- Pulse shape discrimination (PSD)
- Ion Identification

Methods	
TPCs (liquid, gas)	^{136}Xe
Doped Liquid Scintillators	^{136}Xe, ^{130}Te
Solid state detectors	^{76}Ge, ^{116}Cd
Bolometers (+ enhancements)	^{130}Te, ^{82}Se, ^{100}Mo, ^{116}Cd
Foils with tracking chambers	^{82}Se, ^{150}Nd, ^{100}Mo

Both approaches are needed

Many different experiments

Experiment	Isotope	Technique	Mass ββ(0ν) isotope
CUORICINO	130Te	TeO2 Bolometer	10 kg
NEMO3	100Mo/82Se	Foils with tracking	6.9/0.9 kg
GERDA I	76Ge	Ge diodes in LAr	15 kg
EXO200	136Xe	Xe liquid TPC	160 kg
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg
CUORE-0	130Te	TeO2 Bolometer	11 kg
GERDA II	76Ge	Point contact Ge in LAr	30+35 kg
Majorana D	76Ge	Point contact Ge	30 kg
CUORE	130Te	TeO2 Bolometer	206 kg
SNO+	130Te	0.3% natTe suspended in Scint	55 kg
NEXT-100	136Xe	High pressure Xe TPC	80 kg
SuperNEMO D	82Se	Foils with tracking	7 kg
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg
LUCIFER	82Se	ZnSe scint. bolometer	18 kg
1TGe (GERDA+MJ)	76Ge	Best technology from GERDA and MAJORANA	~ tonne
CUPID	-	Hybrid Bolometers	~ tonne
nEXO	136Xe	Xe liquid TPC	~ tonne
SuperNEMO	82Se	Foils with tracking	100 kg
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg
MOON	100Mo	Mo sheets	200 kg
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne
DCBA	150Nd	Nd foils & tracking chambers	20 kg

Best results