Absolute neutrino mass

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Absolute neutrino mass

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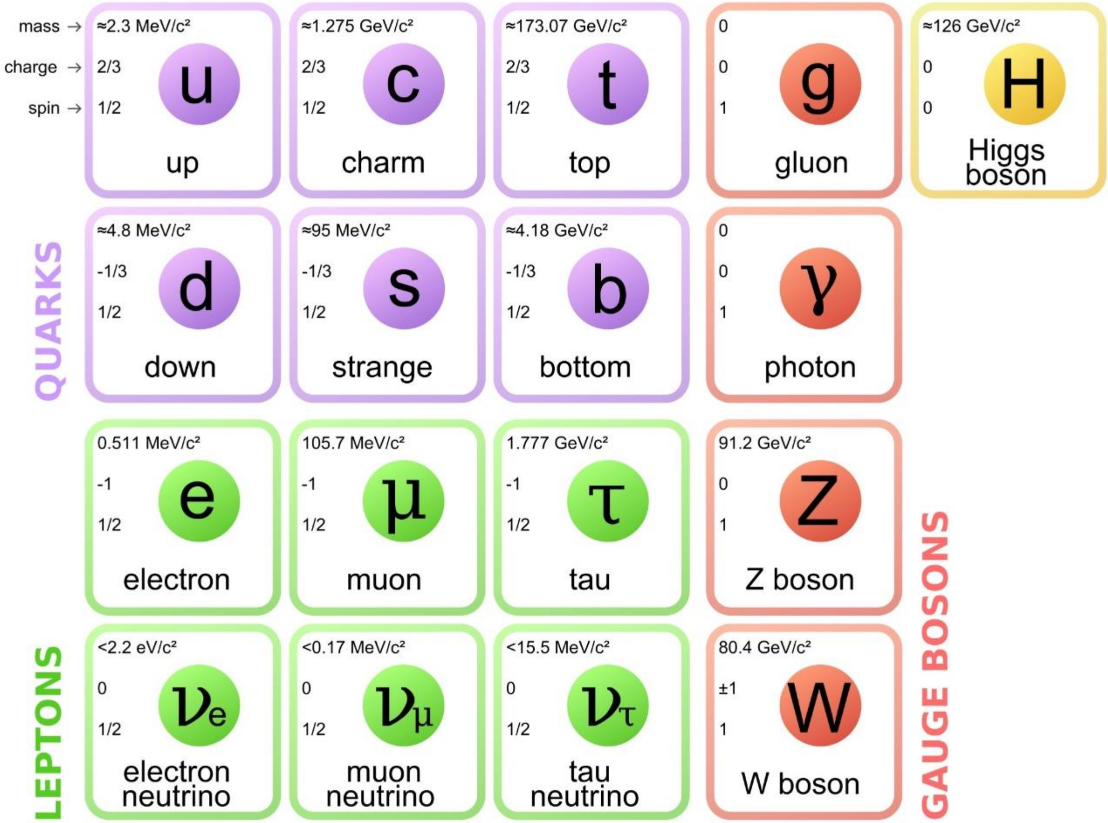
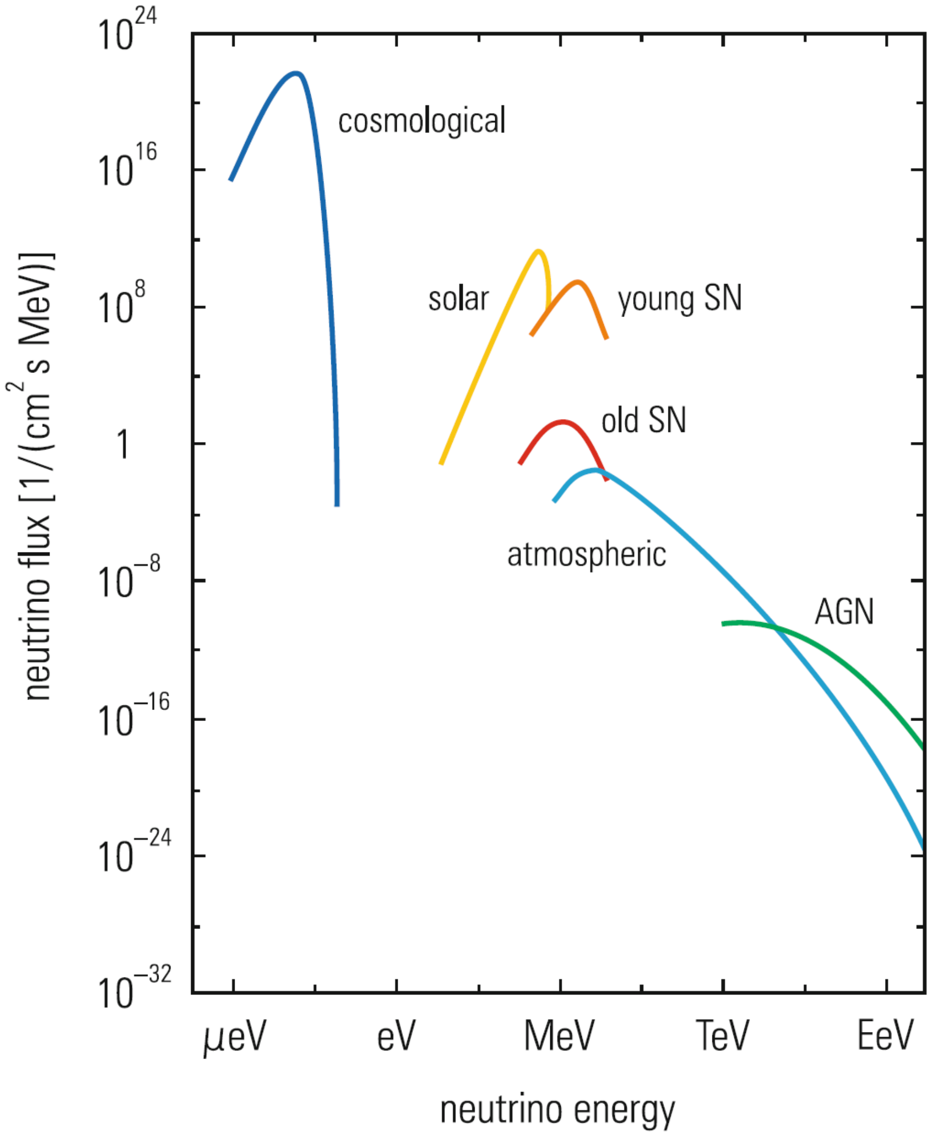
Neutrinos are massive particles

Neutrino mass scale from
- Cosmology
- Double beta decay
- Kinematic measurements

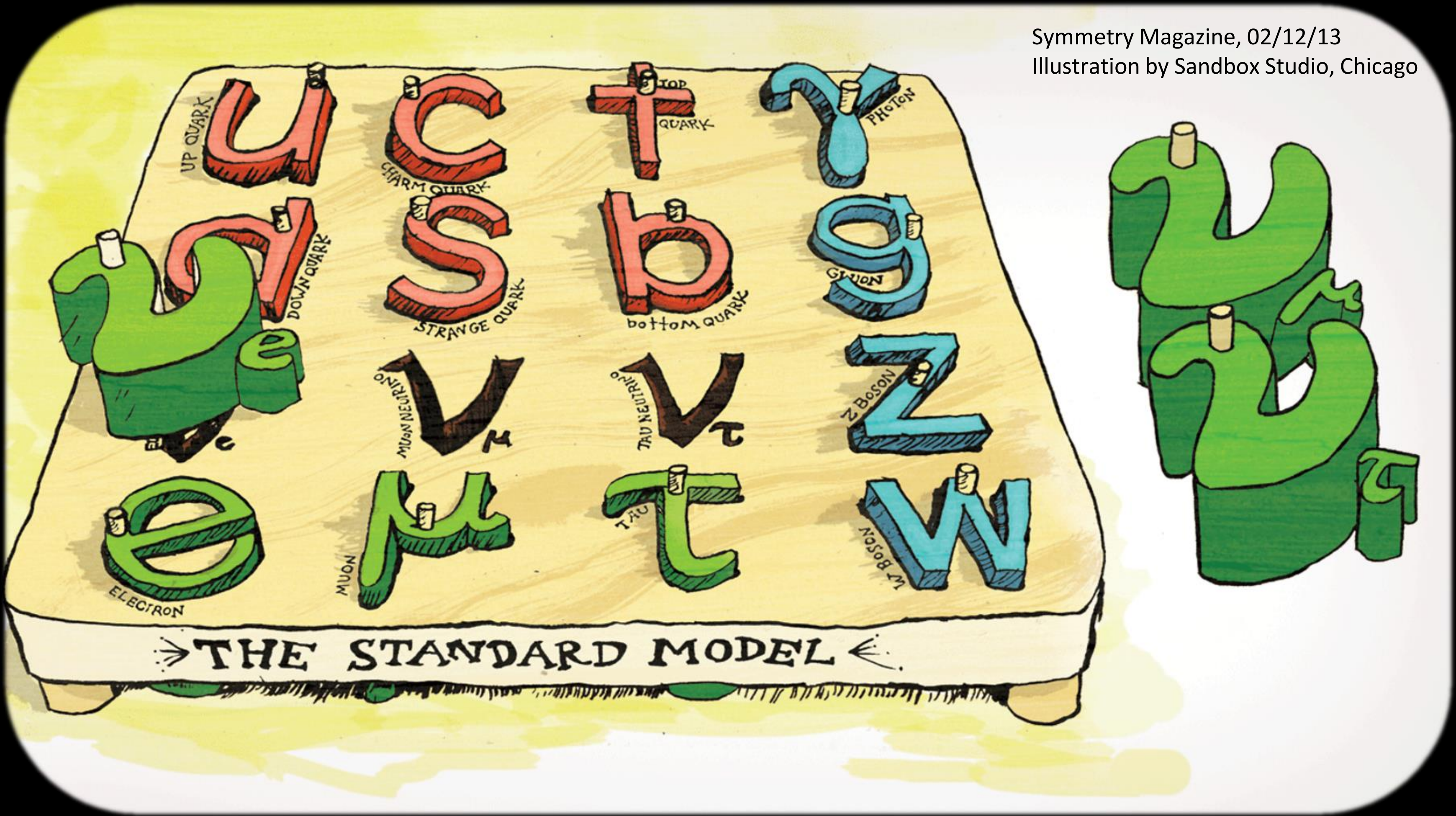
Present status and future perspectives

Neutrinos everywhere





C. Grupen, Astroparticle Physics,
Chapter 6 Second Edition, Springer (2020)



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

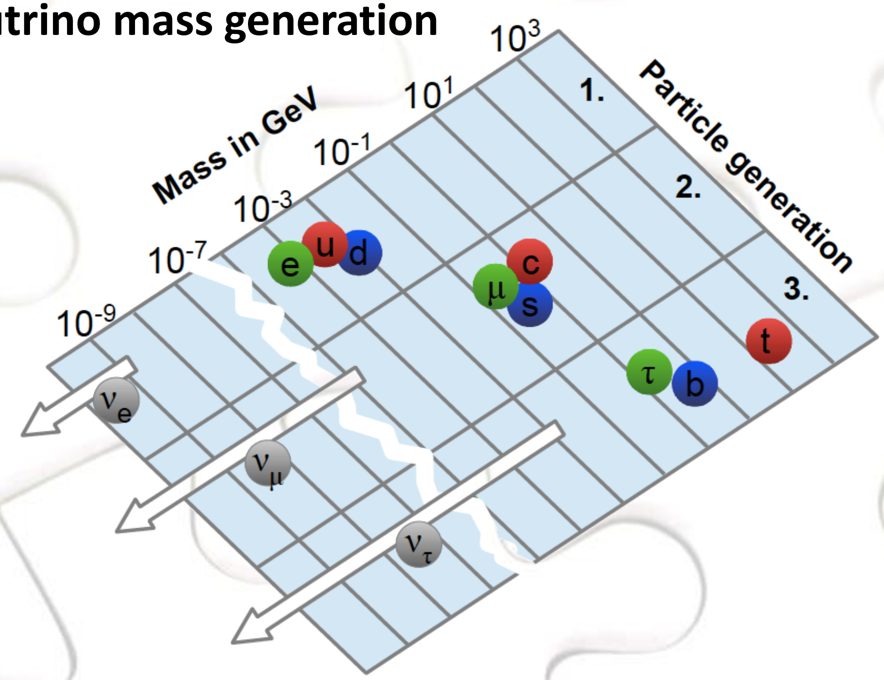
Knowing neutrino mass scale….

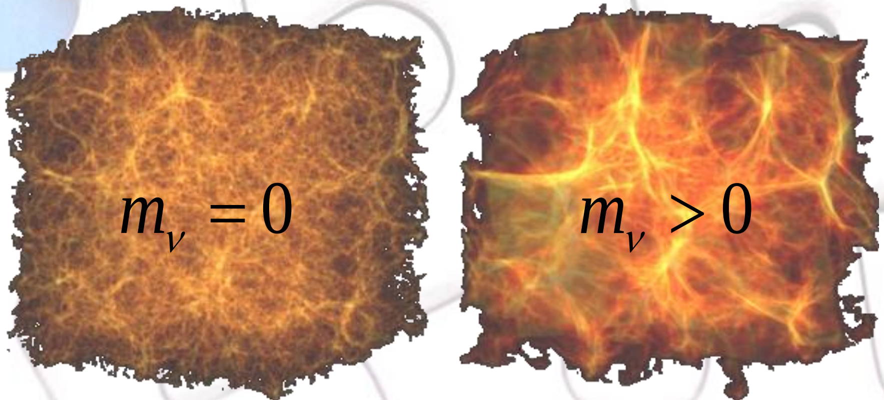
Astrophysics

Supernova neutrinos

Particle Physics

Neutrino mass generation





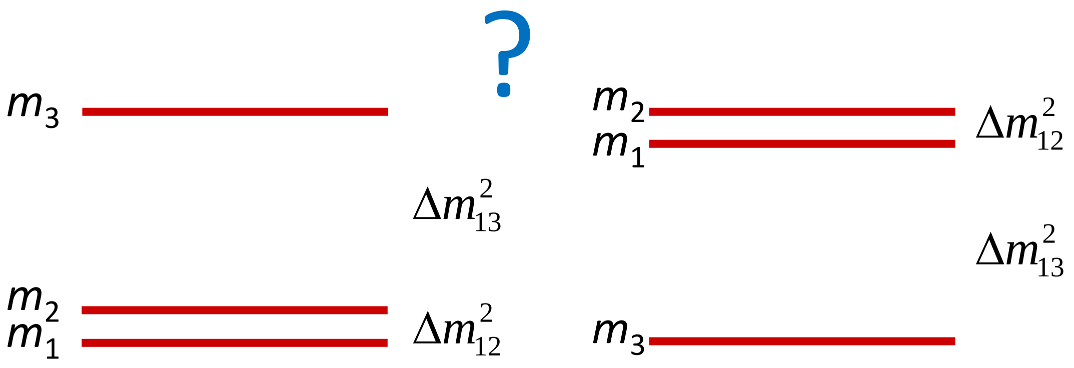
Cosmology

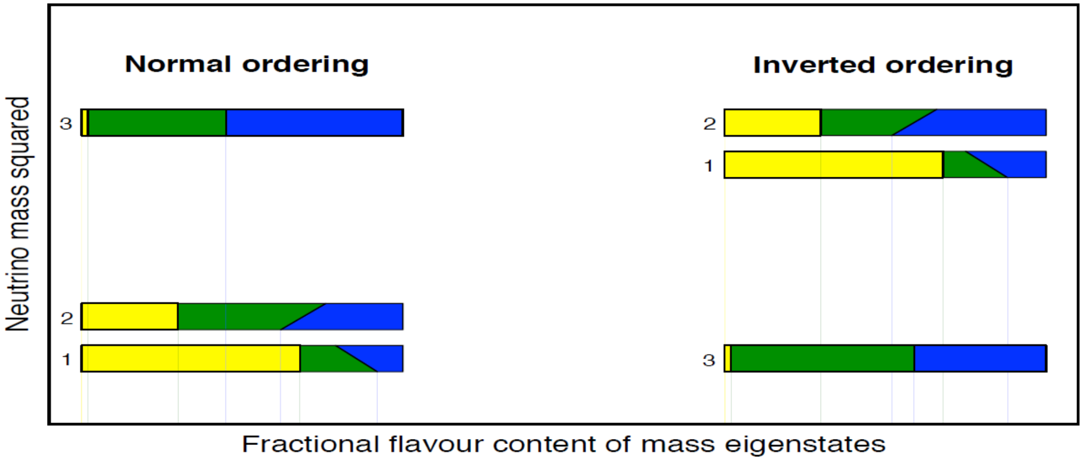
Matter distribution in the Universe

Neutrino parameters

$\Delta m^2_{21} \sim 7.49 \times 10^{-5}$ eV²

$\Delta m^2_{3l} \sim 2.5 \times 10^{-3}$ eV²





JHEP 12 (2024) 216 [arXiv:2410.05380] NuFIT 6.0 (2024)

		Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC19 without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
	$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
	$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
	$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
	$\delta_{CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
	$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

Cosmic neutrino background

Cosmic history

Neutrino has radiation

Cosmic Neutrino Background
$T \sim 1$ MeV

$$\rho_{rad} = \rho_\gamma \left[1 + N_{eff} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \right]$$

No direct detection so far

Cosmic neutrino background

Cosmic history

Neutrino has radiation

Cosmic Neutrino Background
T ~ 1 MeV

Cosmic Microwave Background
T ~ 0.2 eV

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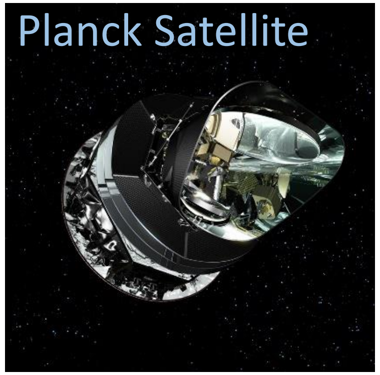
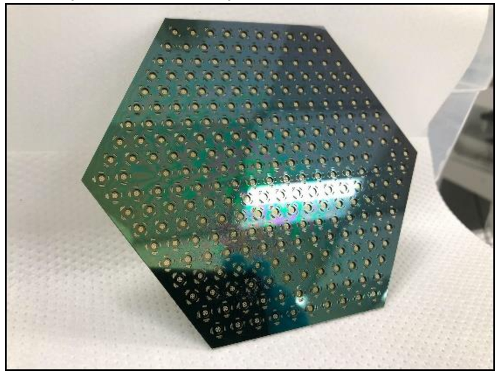
No direct detection so far



Ground-based experiments
ACT, CMB-S4, …



Cosmic neutrino background

Cosmic history

Neutrino has radiation

Neutrinos as matter (contributing to dark matter as hot dark matter)

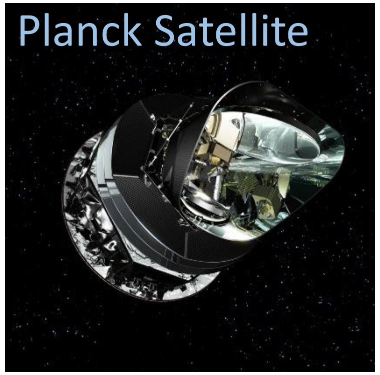
Cosmic Neutrino Background
$T \sim 1$ MeV

Cosmic Microwave Background
$T \sim 0.2$ eV

Structure Formation

$$\rho_{rad} = \rho_\gamma \left[1 + N_{eff} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3}\right]$$

No direct detection so far



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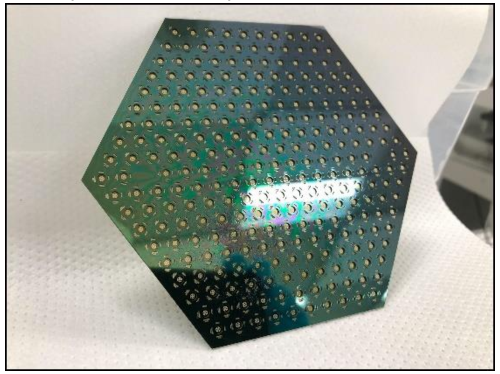

$$\Omega_\nu = \frac{\sum_i m_i}{93.12 \text{ eV}}$$

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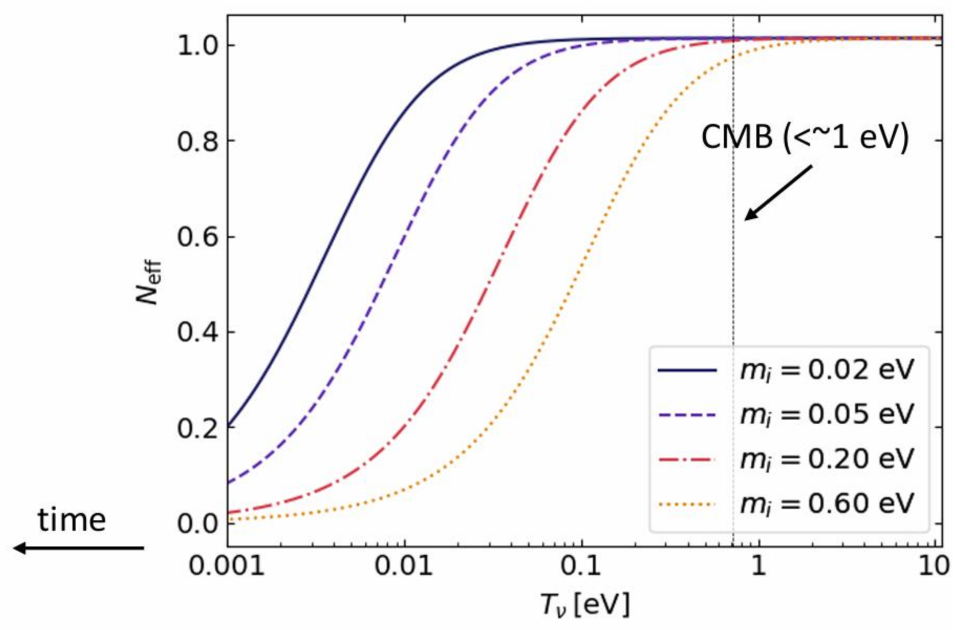

$$\sum m_i = m_1 + m_2 + m_3$$

Considering neutrino oscillation results:

Normal ordering: $\sum m_i > 0.06$ eV

Inverted ordering: $\sum m_i > 0.1$ eV

CMB + DESI BAO [DESI Collaboration: Adame et al. (2024)]

N_{eff} = 3.10 ± 0.17 (95% CL)

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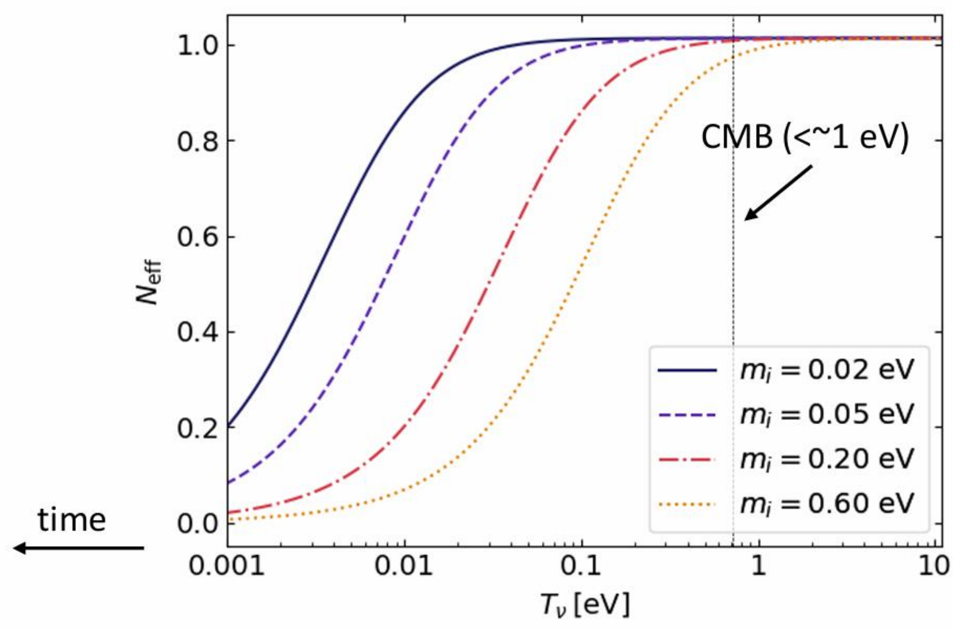

Best limit from DESI observations (arXiv:2503.14744v2)

$\sum m_i < 0.0642$ eV (95% C.L.)

Very close to the smallest value acceptable!!!

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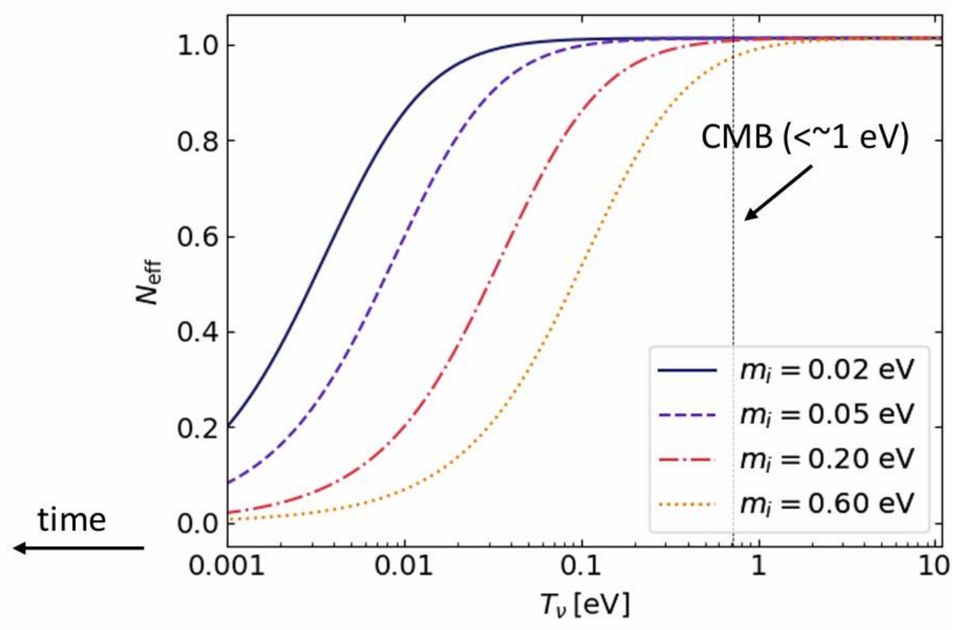

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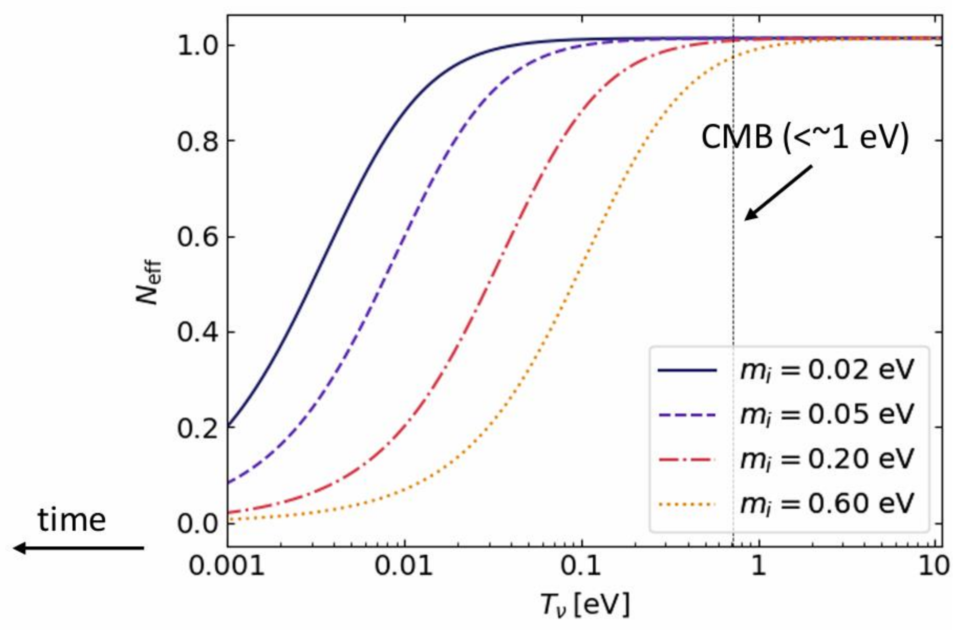

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Wrong interpretation of the data?
Cosmological model ΛCDM does not work?

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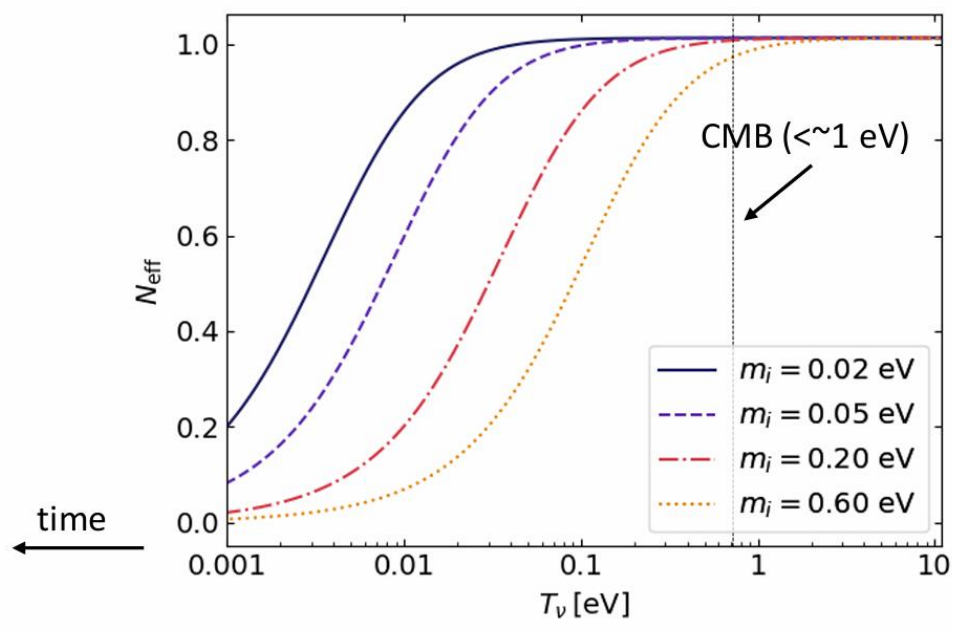

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Cosmological model ΛCDM does not work?

Modification to the ΛCDM as evolving dark energy could allow for combining early "vanishing" neutrino mass with the present final value

Cosmic neutrino background

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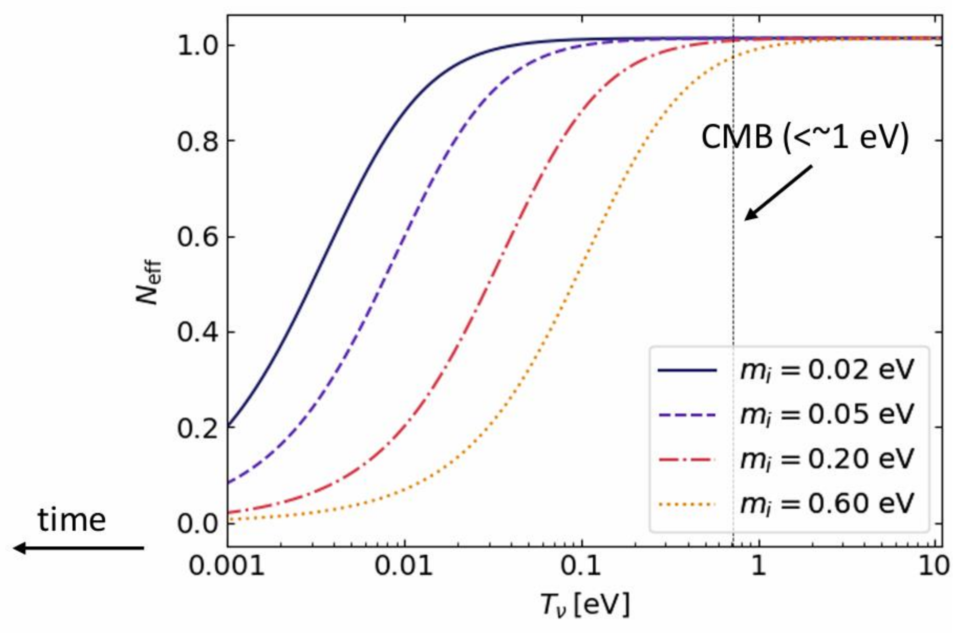

CMB + DESI BAO [DESI Collaboration: Adame et al. (2024)]

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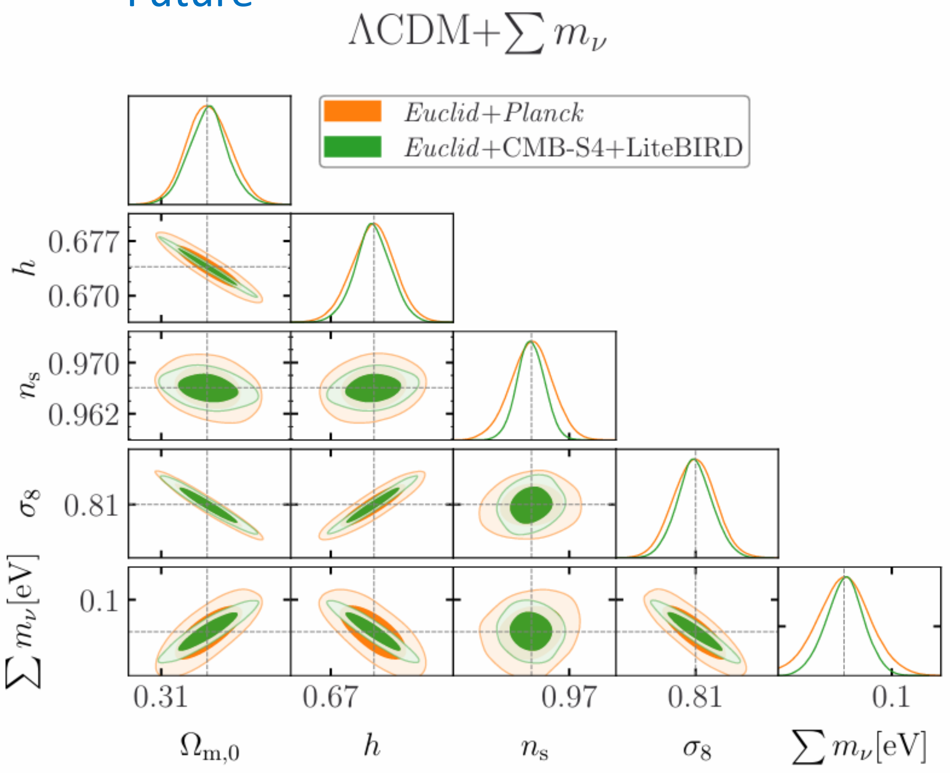
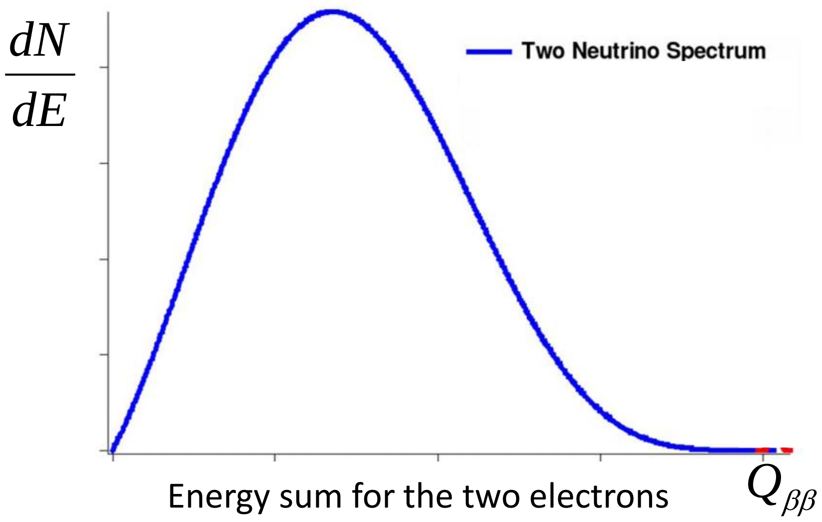
Future



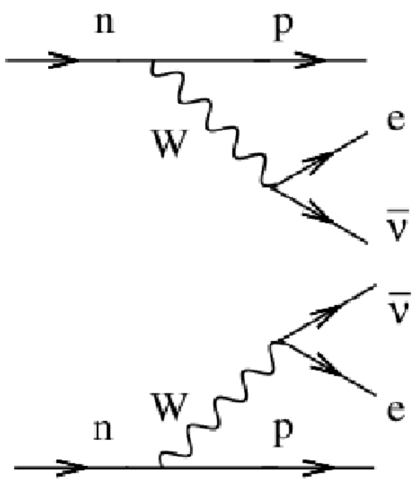
Euclid Collaboration: Archidiacono et al. (2024)

Double Beta Decay



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

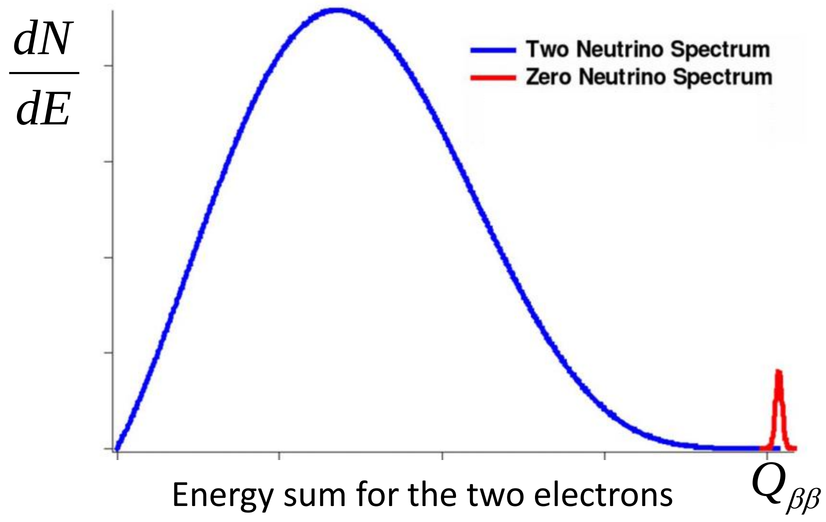
$\tau_{1/2} \approx 10^{20}$ years



Just to put the number under perspectives

^{14}C ~ 10^4 years
^{40}K ~ 10^9 years
^{232}Th ~ 10^{10} years
The Universe ~ 10^{10} years
Proton Decay >10^{30} years

Double Beta Decay



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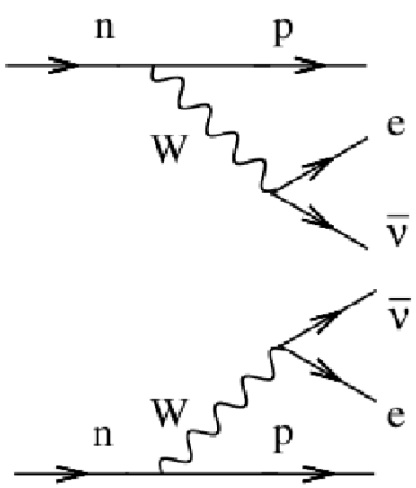
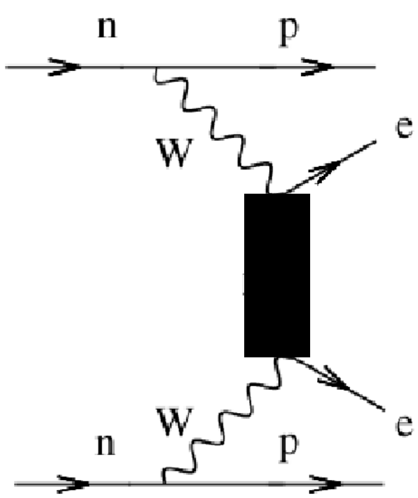
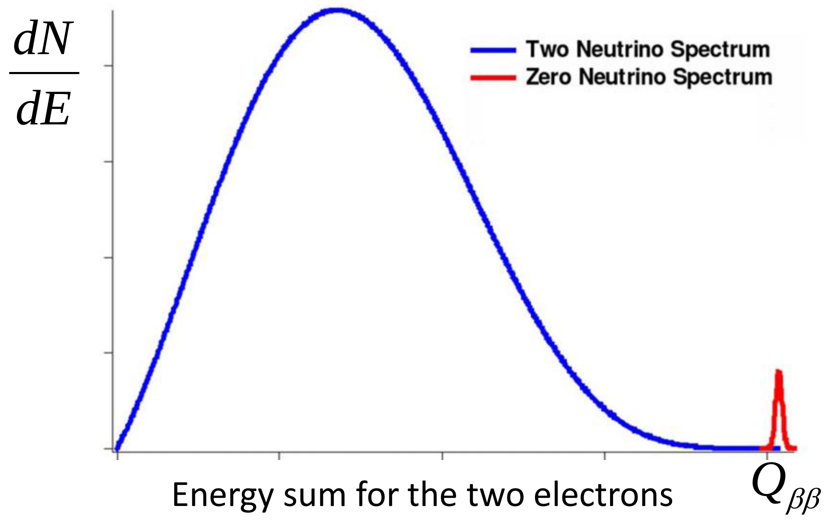


$0\nu\beta\beta$: (A,Z) → (A, Z+2) + $2e^-$

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



Double Beta Decay



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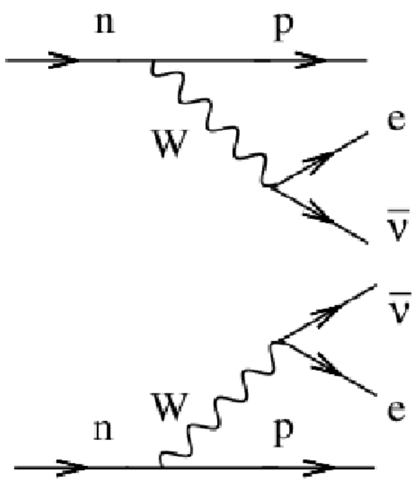

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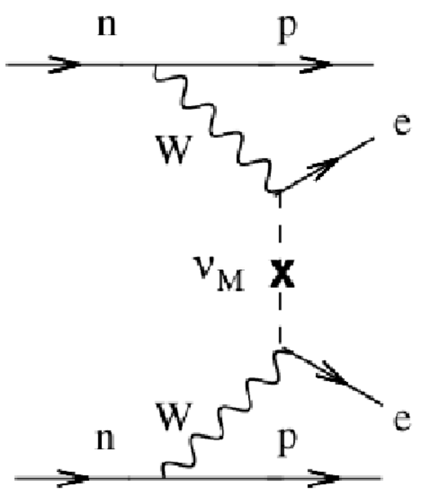
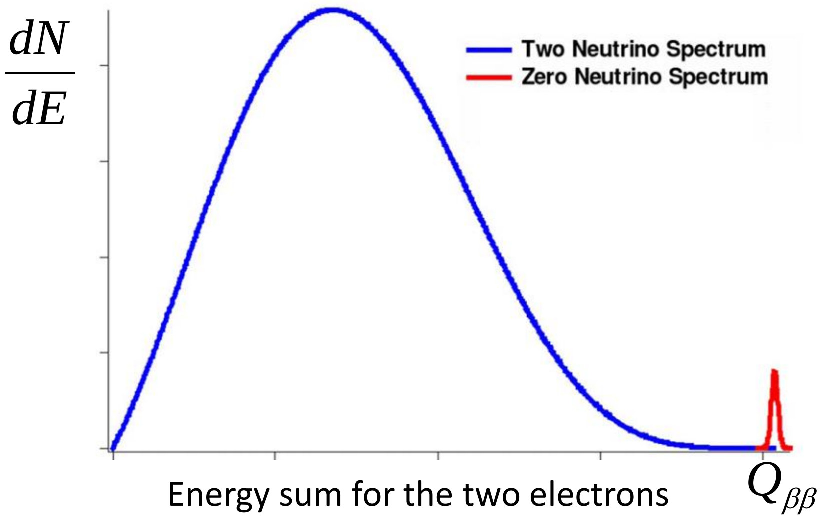
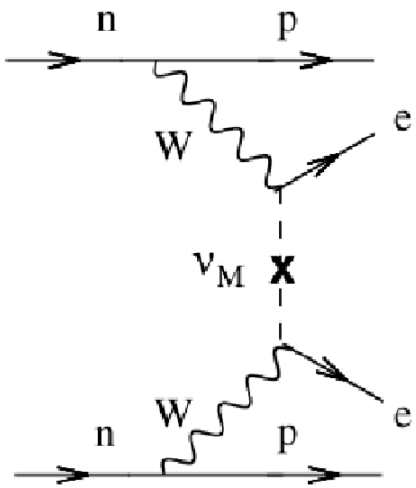


Effective Majorana mass





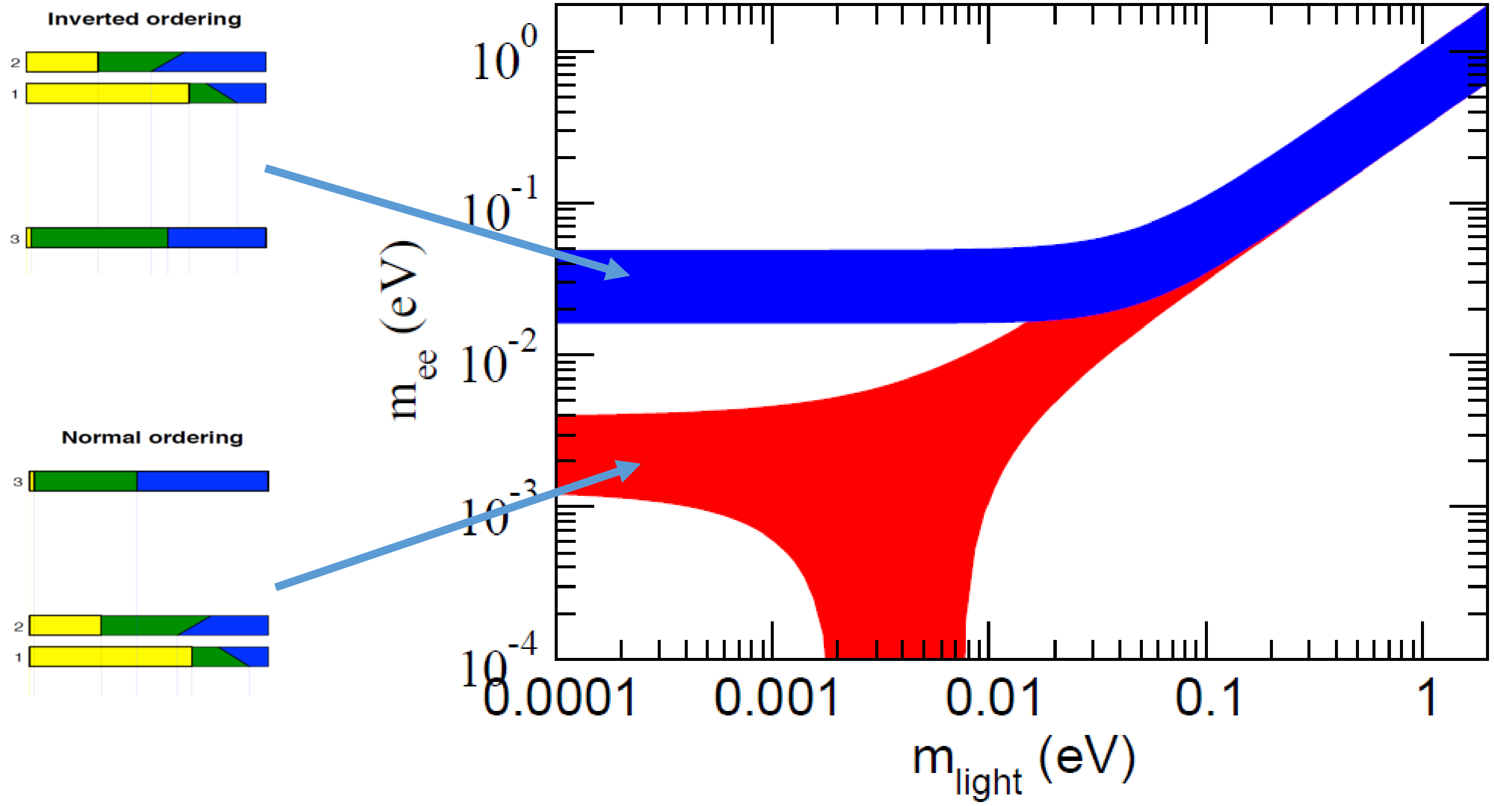
Exchange of a light Majorana neutrino

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

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

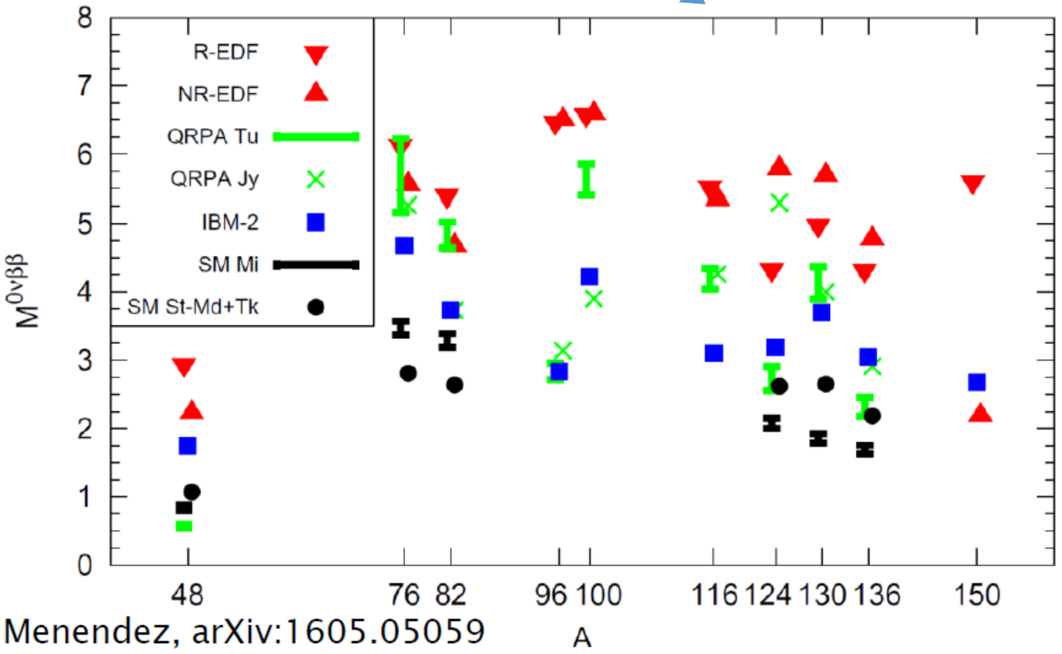
Effective Majorana mass

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

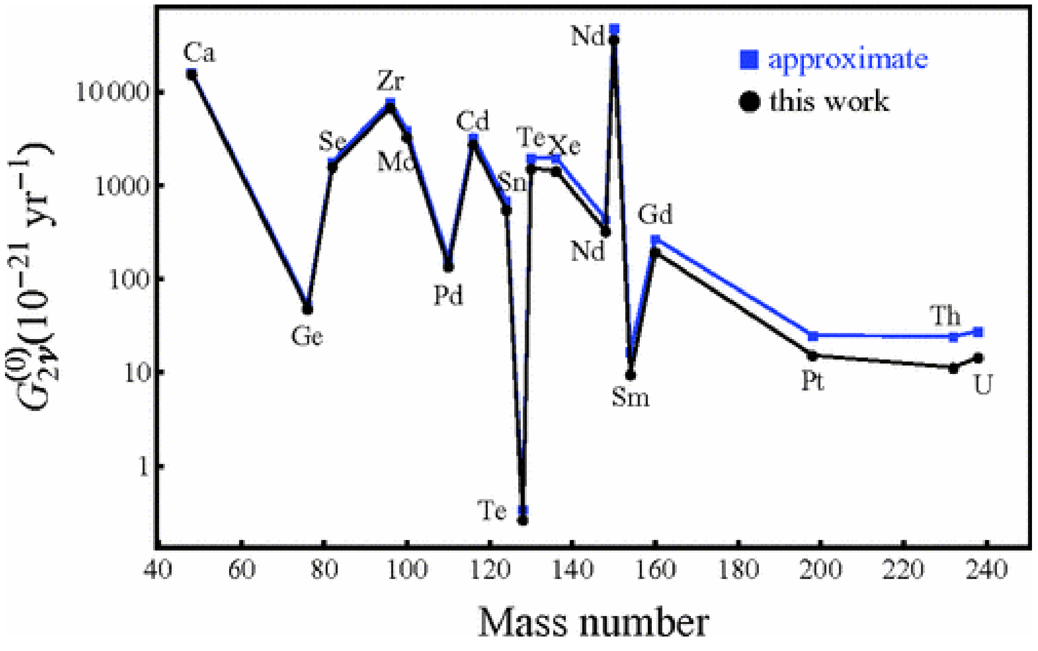


Deriving $m_{\beta\beta}$ - Theory

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



Menendez, arXiv:1605.05059



Kotila Iachello, PRC 85 (2012)

Deriving $m_{\beta\beta}$ - experimental evidence

A limit on the halflife for 0ν2e 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***	[$keV^{-1}ton^{-1}year^{-1}$]	
Detector efficiency	***ε***		
Natural abundance	***a***		

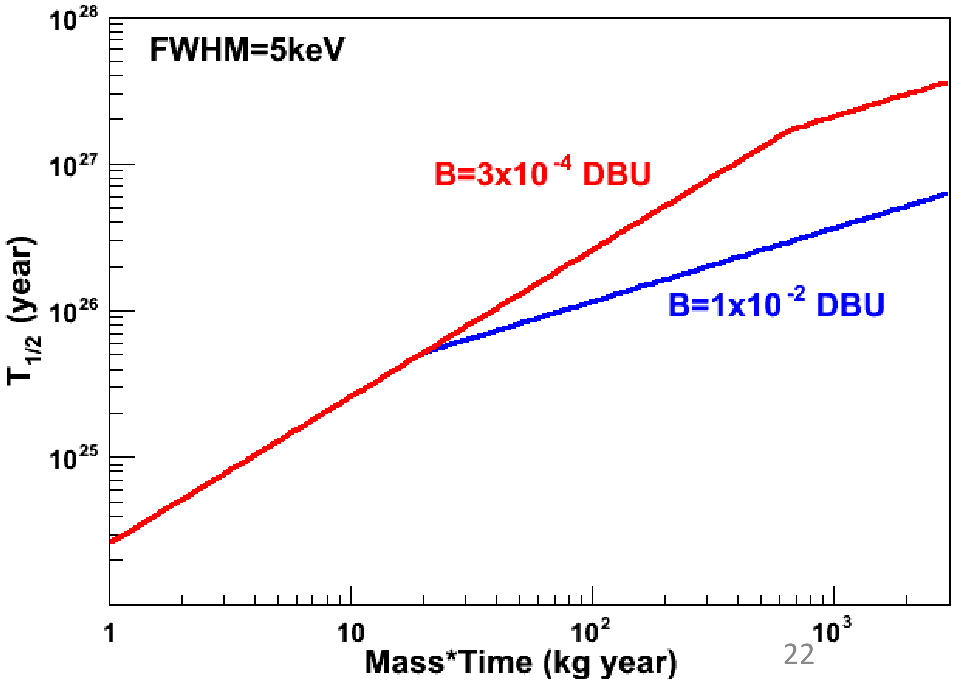
Two limits defined by the background index

< 1 background events in ROI

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

>1 background events in ROI

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

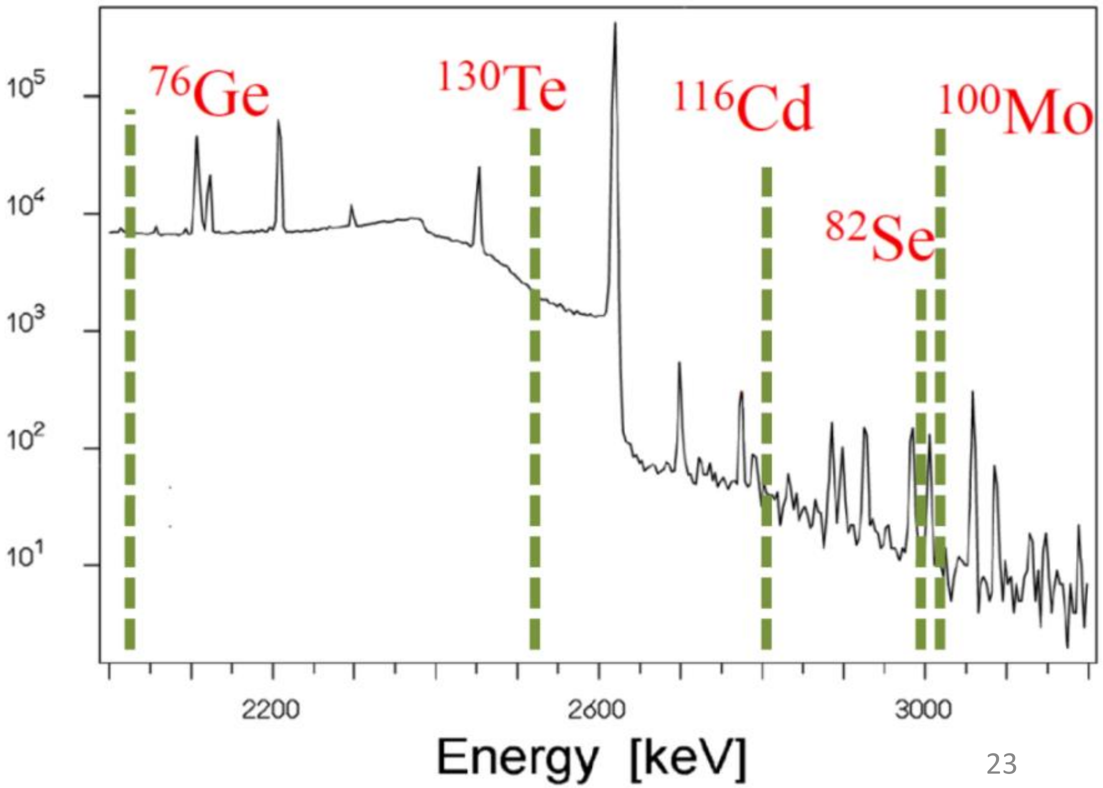


Deriving $m_{\beta\beta}$ - experimental evidence

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

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

transition	$G^{01}(E_0, Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)
$^{150}Nd \rightarrow {}^{150}Sm$	26.9	3.667	6
$^{48}Ca \rightarrow {}^{48}Ti$	8.04	4.271	0.2
$^{96}Zr \rightarrow {}^{96}Mo$	7.37	3.350	3
$^{116}Cd \rightarrow {}^{116}Sn$	6.24	2.802	7
$^{136}Xe \rightarrow {}^{136}Ba$	5.92	2.479	9
$^{100}Mo \rightarrow {}^{100}Ru$	5.74	3.034	10
$^{130}Te \rightarrow {}^{130}Xe$	5.55	2.533	34
$^{82}Se \rightarrow {}^{82}Kr$	3.53	2.995	9
$^{76}Ge \rightarrow {}^{76}Se$	0.79	2.040	8



Some experiments

GERDA

- High purity Ge detectors: 86% ^{76}Ge
- ΔE 0.2% at $Q_{\beta\beta}$
- 32 (27) kg Ge (F.V.)

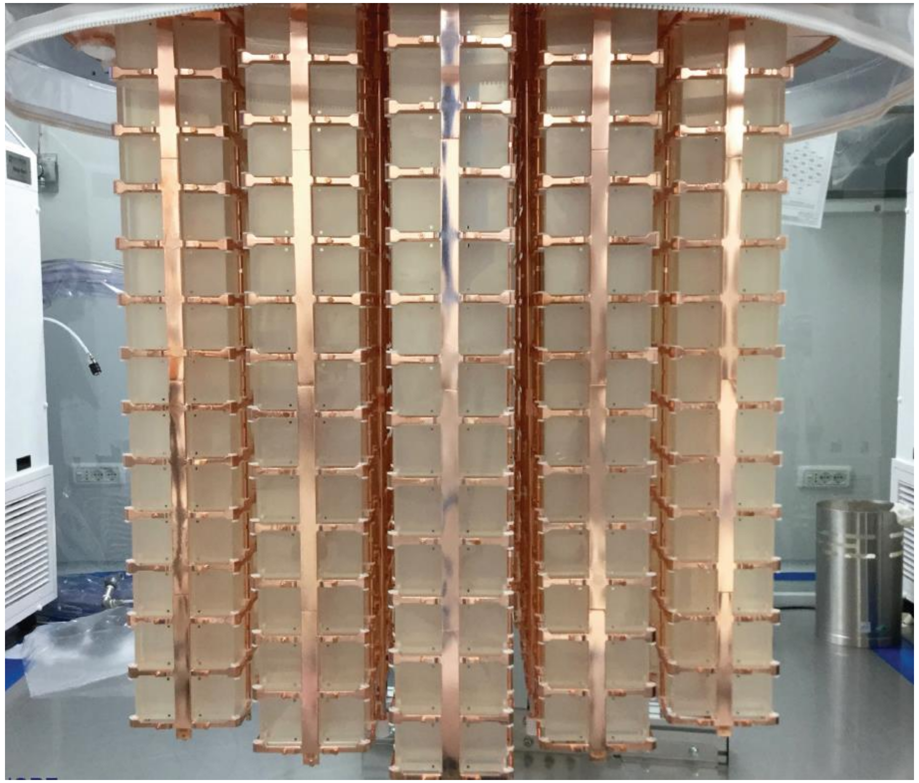
CUORE

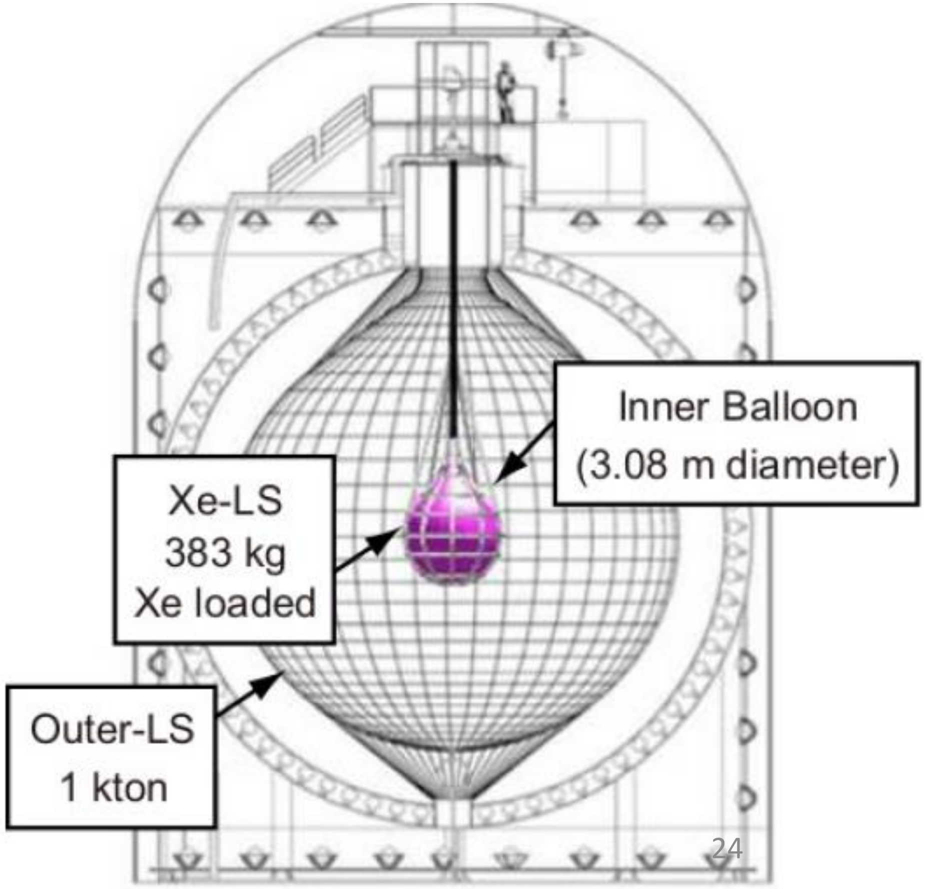
- 988 $^{nat}TeO_2$ thermal detectors
- 19 towers 13 floors each
- total mass: 206 kg of ^{130}Te
- operated at 10 mK

KamLAND-Zen

Xe-loaded LS

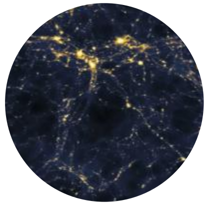
- Active target: ~350 kg
- σE/E: ~11% @ Q value





Status of the art

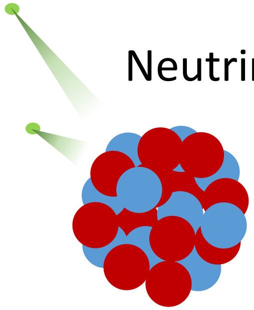
Cosmology



$$\sum m_i < 0.0642\ \text{eV at } 95\%\ \text{C.L.}$$

DESI Coll., arXiv:2503.14744v2

Neutrinoless double beta decay

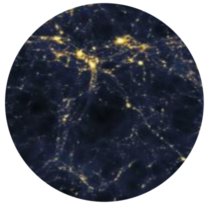


$$\left|\sum_{1=1}^{3} U_{ei}^2 m_i\right| < \begin{cases} 0.079 - 0.180\ \text{eV}\ 90\%\ \text{C.L.}\ {}^{76}\text{Ge} \\ 0.070 - 0.240\ \text{eV}\ 90\%\ \text{C.L.}\ {}^{130}\text{Te} \\ 0.036 - 0.156\ \text{eV}\ 90\%\ \text{C.L.}\ {}^{136}\text{Xe} \end{cases}$$

M. Agostini et al., Phys. Rev. Lett. 125, 252502 (2020)
D. Q. Adams et al., arXiv:2404.04453 [nucl-ex] (2024)
S. Abe et al., Phys. Rev. Lett. 130, 051801 (2023)

Status of the art

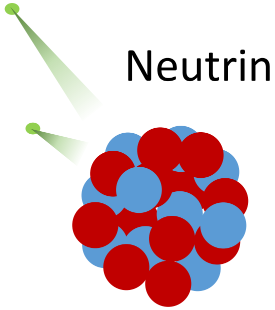
Cosmology



$$\sum m_i < 0.0642\ \text{eV at } 95\%\ \text{C. L.}$$

DESI Coll., arXiv:2503.14744v2

Neutrinoless double beta decay



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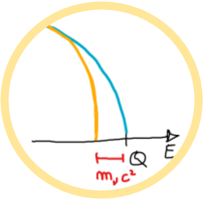
Kinematic approach

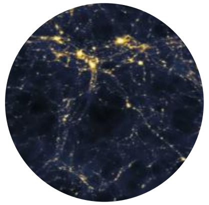


$$\sqrt{\sum_{i=1}^{3} |U_{ei}|^2\, m_i^2} < \begin{cases} 0.45\ \text{eV}\ 90\%\ \text{C. L.}\ ^{3}\text{H} - m(\bar{\nu}_e) \\ 27\ \text{eV}\ 90\%\ \text{C. L.}\ ^{163}\text{Ho} - m(\nu_e) \end{cases}$$

KATRIN Coll., Science 338 (2025)
BK. Alpert et al., arXiv:2503.19920v2 [hep-ex]

Status of the art

Cosmology



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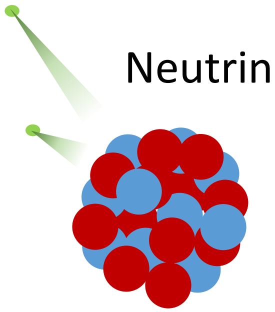
Neutrinoless double beta decay



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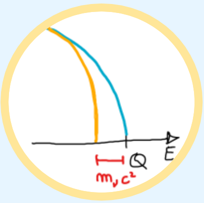
Model independent

Kinematic approach



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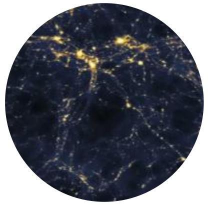
Status of the art

Cosmology



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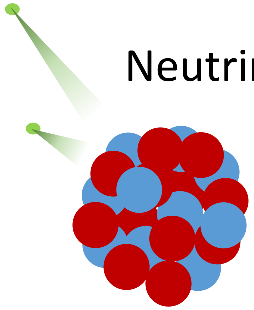

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Model independent

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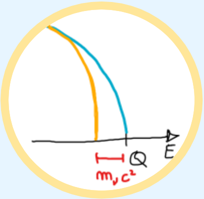

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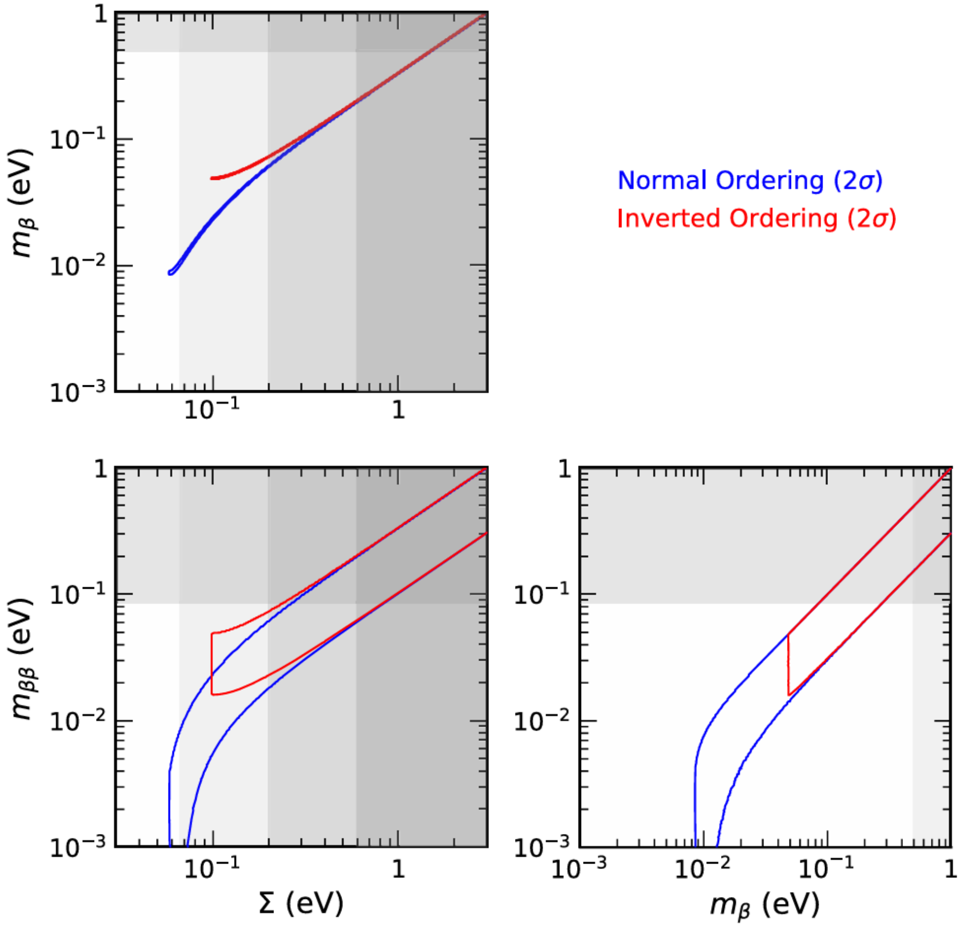
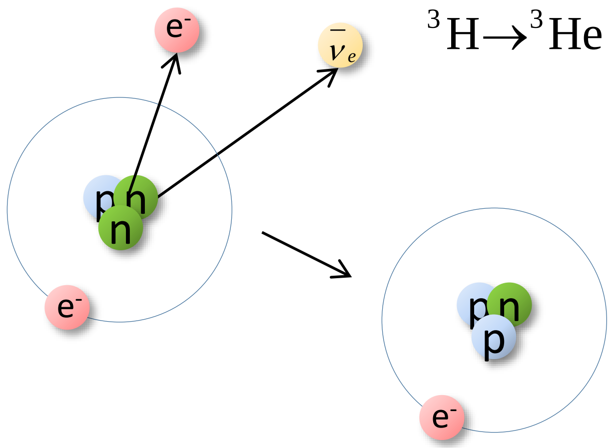


Neutrino mass determination via kinematic approach

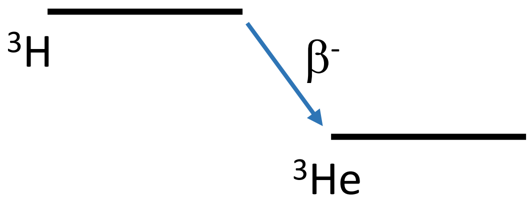
- will play major role in understanding the evolution of the Universe
- will guide the design of future DBD experiments

F. Capozzi et al. *Phys. Rev. D* **111** (2025) 093006

Beta decay and electron capture



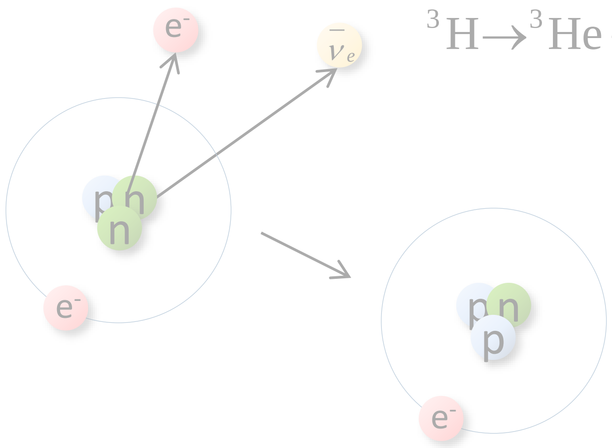
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_e$$



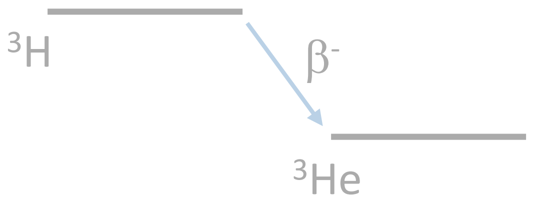
- $\tau_{1/2} \cong 12.3$ years (4*10^8 atoms for 1 Bq)
- Q_β = 18 592.01(7) eV

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

Beta decay and electron capture

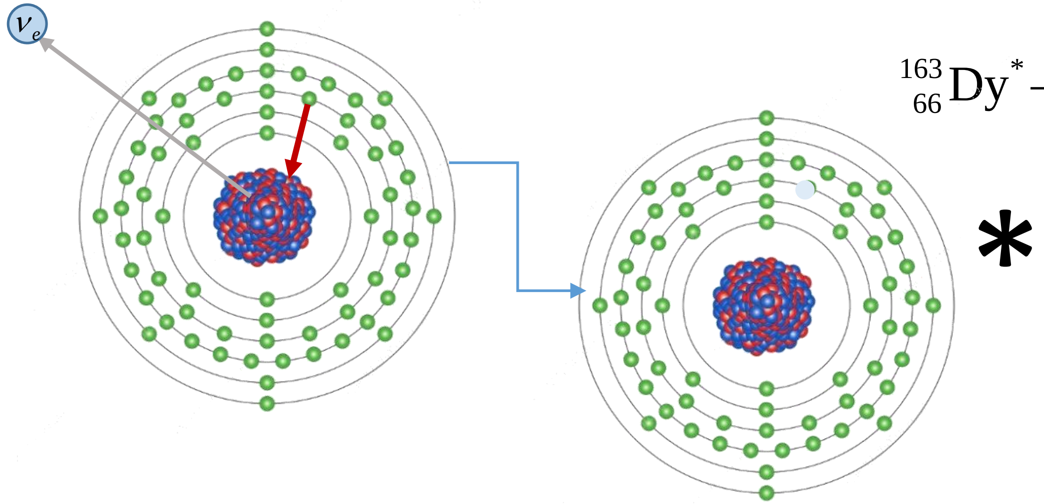


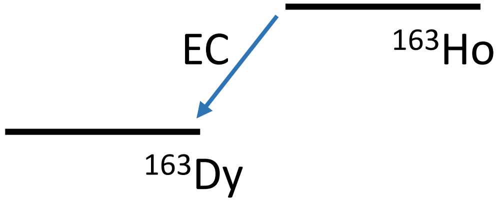
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_{e}$$



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

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





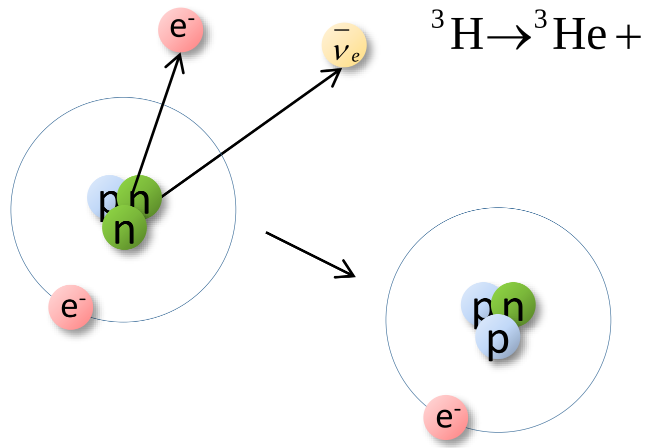
- $\tau_{1/2} \cong$ 12.3 years (4*10^{8} atoms for 1 Bq)
- Q_{β} = 18 592.01(7) eV

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

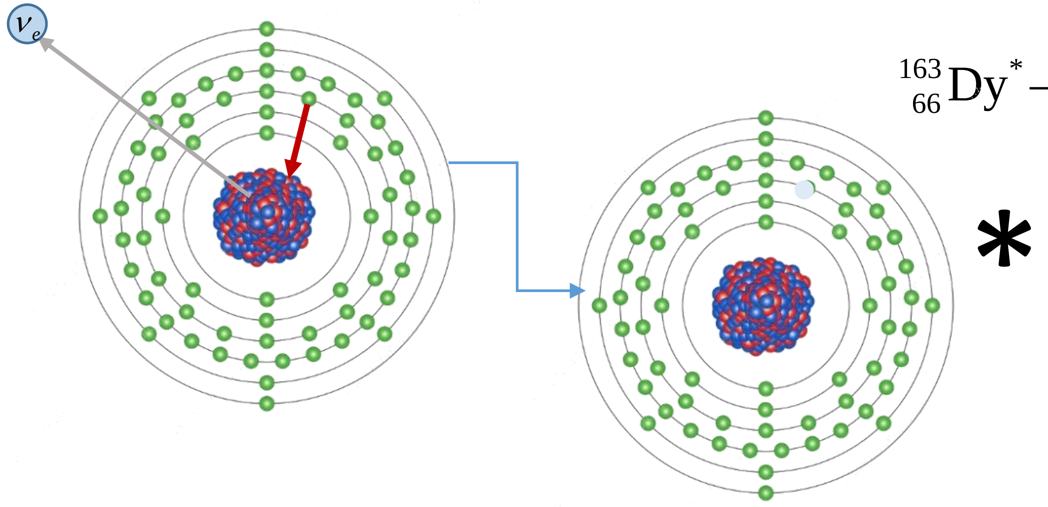
- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = (2863.2 ± 0.6) eV

Ch. Schweiger et al.,
Nat. Phys. **20**, 921–927 (2024)

Beta decay and electron capture



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

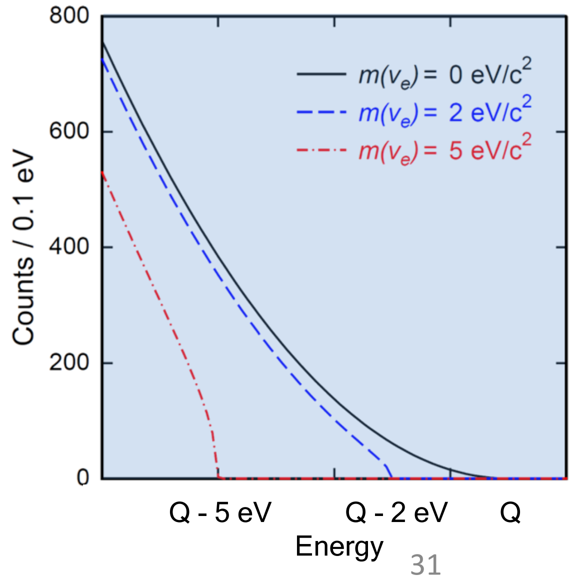


$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

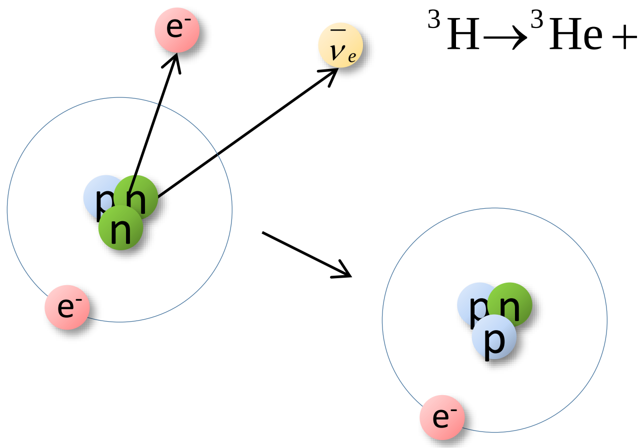
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

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

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



^{3}H-based experiments



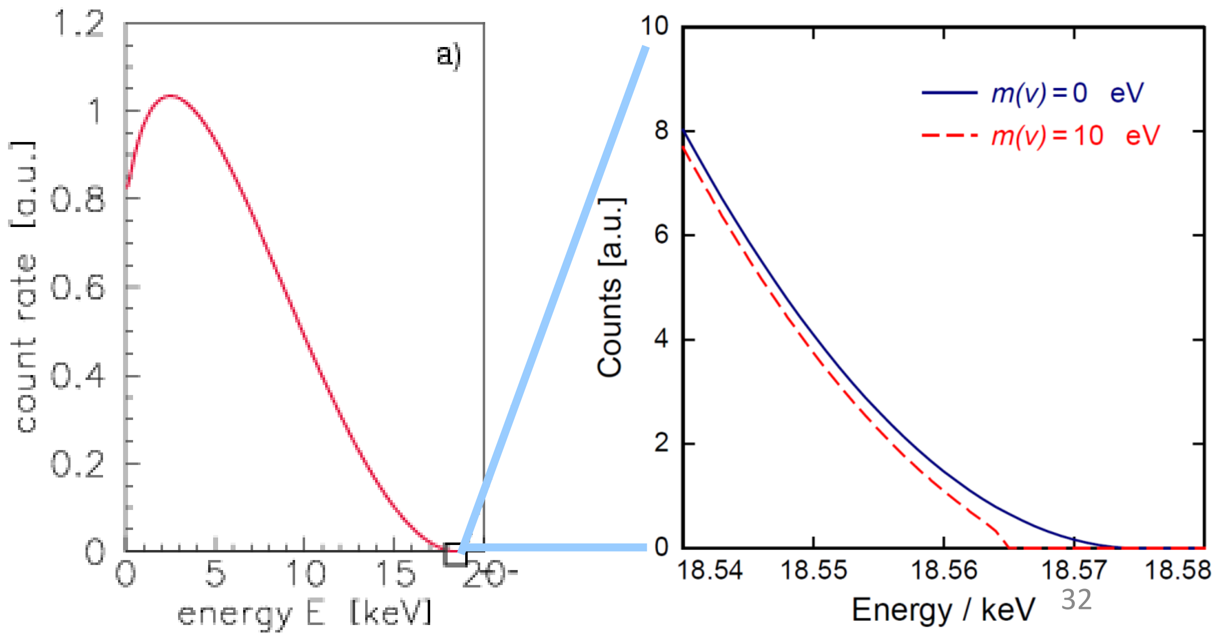
$$^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$$

- electrons can be adiabatically extracted from the source and detected
- cyclotron radiation for electron in B~1T can be precisely measured

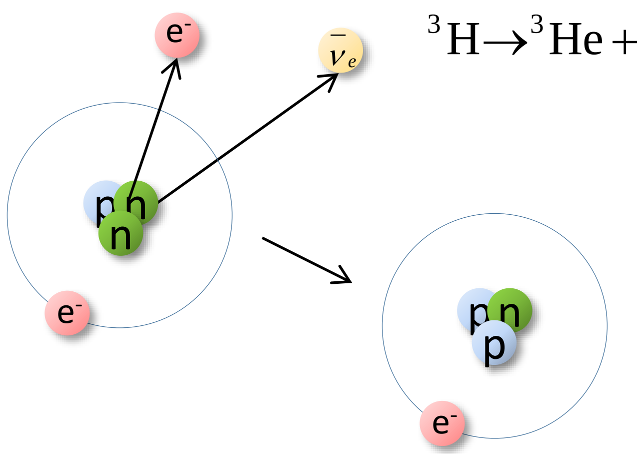
- $\tau_{1/2} \cong 12.3$ years (4*10^8 atoms for 1 Bq)

- Q_β = 18 592.01(7) eV

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



^{3}H-based experiments



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

- electrons can be adiabatically extracted from the source and detected
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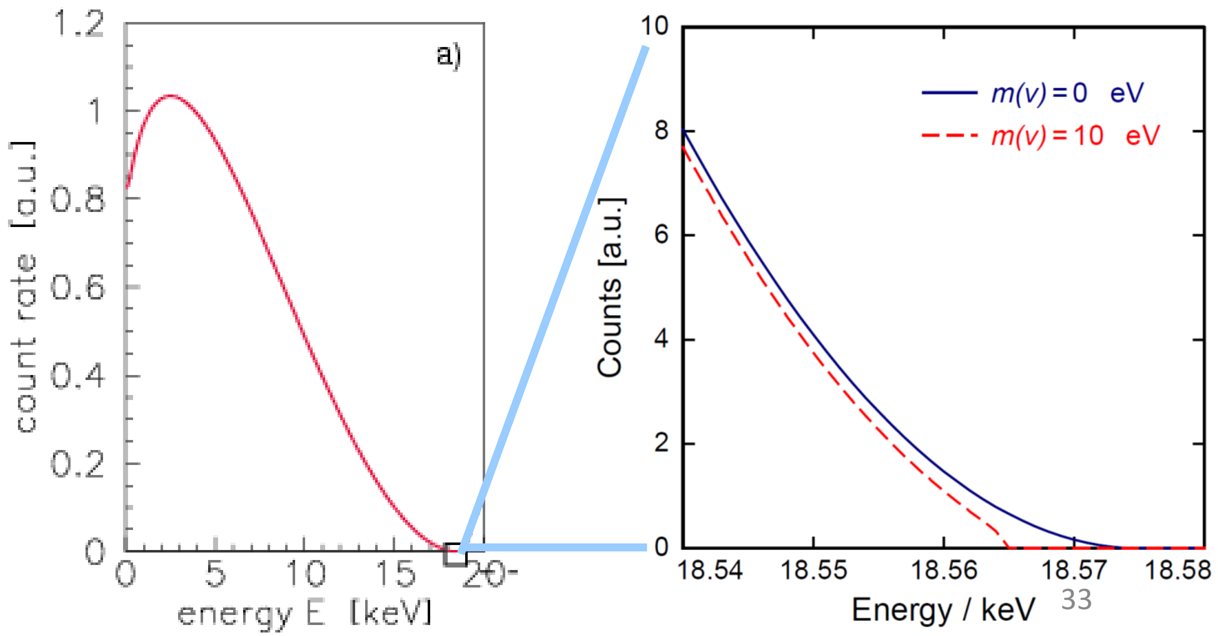
KATRIN

PROJECT 8

CRESDA QTNM

PTOLEMY



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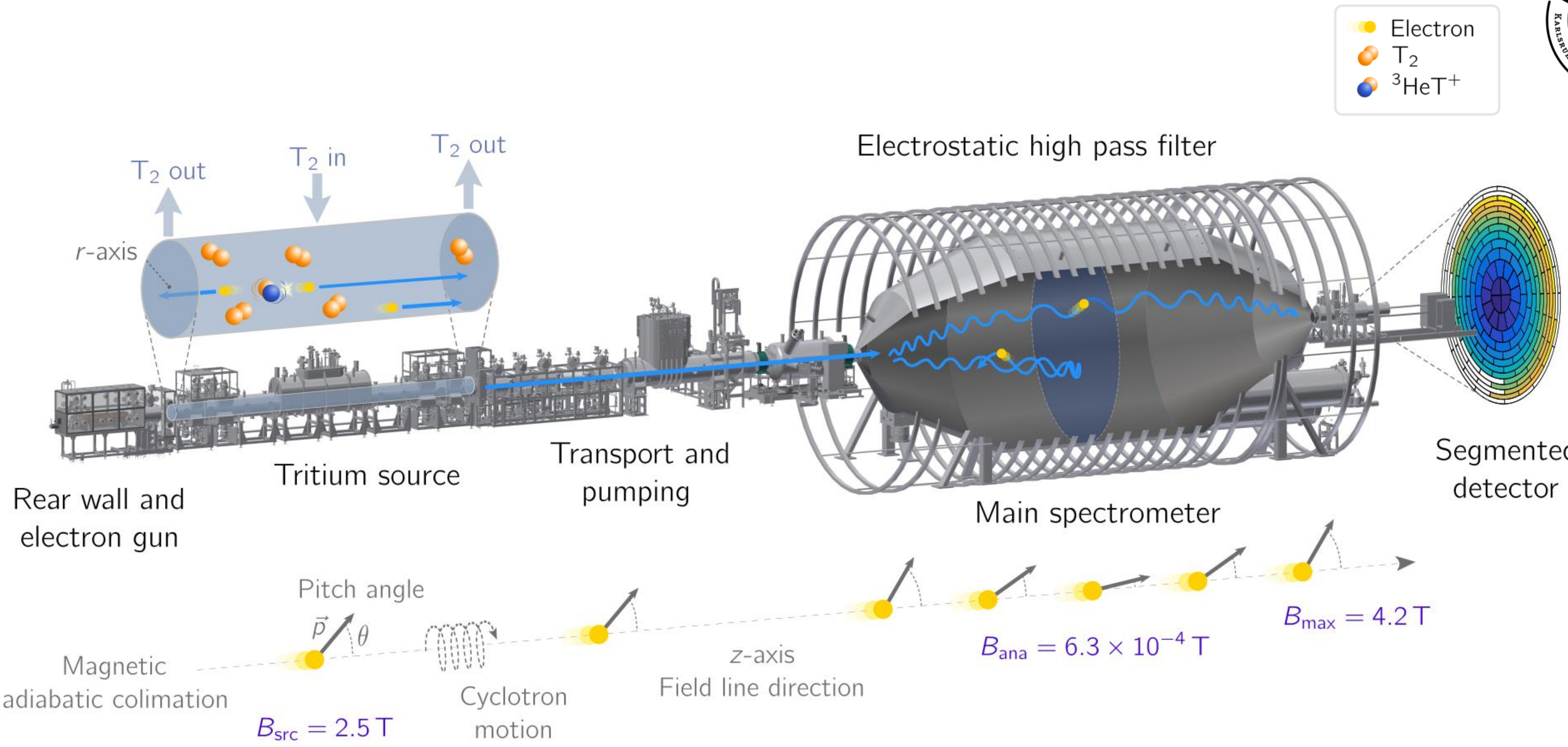
E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

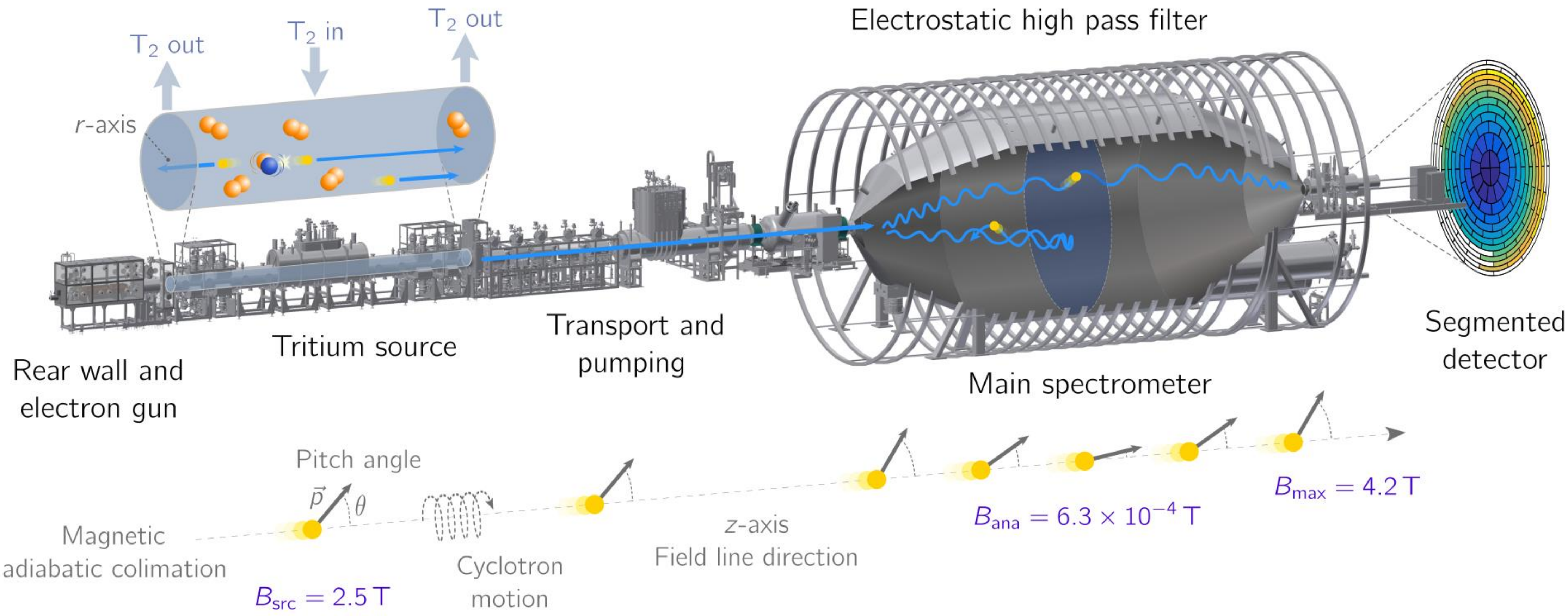
Working principles of KATRIN



Artwork L. Köllenberger

Working principles of KATRIN

INTEGRAL SPECTRUM



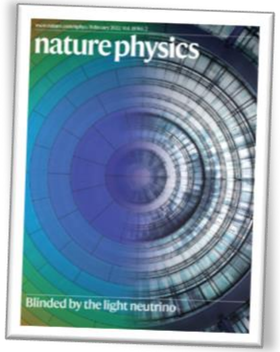
Artwork L. Köllenberger

KATRIN – recent results

- First campaign (“KNM1”, spring 2019)
  - total stat.: 2 million events
  - best fit: $m^2(\nu_e) = -1.0^{+0.9}_{-1.1} \text{eV}^2$
  - limit: $m(\nu_e) < 1.1$ eV (90% C.L.)

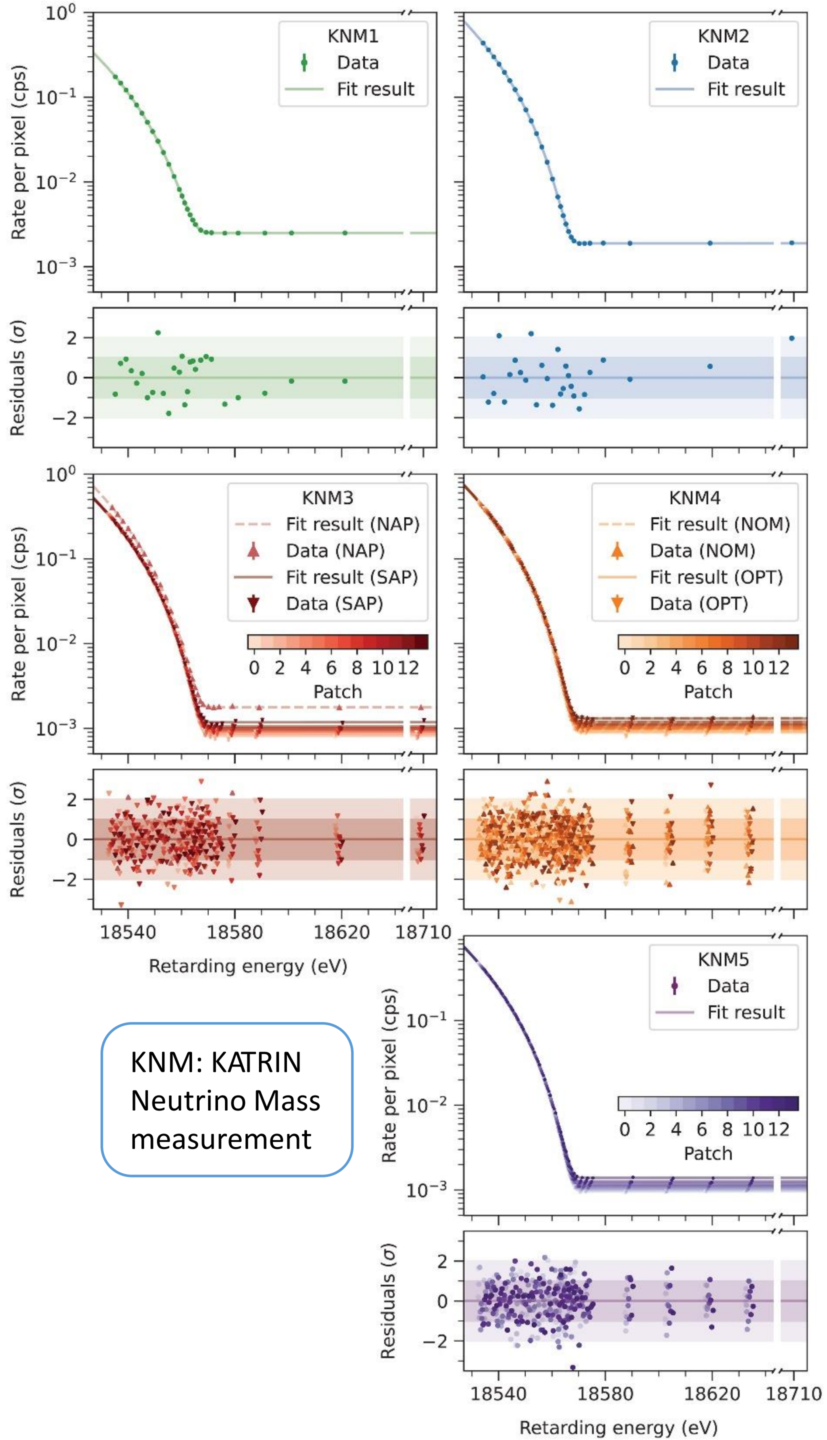
Phys. Rev. Lett. 123, 221802 (2019)
Phys. Rev. D. 104 (1), 012005 (2021)

- Second campaign (“KNM2”, autumn 2019)
  - total stat.: 4.3 million events
  - best fit: $m^2(\nu_e) = 0.26^{+0.34}_{-0.34} \text{eV}^2$
  - limit: $m(\nu_e) < 0.9$ eV (90% C.L.)
- Combined result: $m(\nu_e) < 0.8$ eV (90% C.L.)



Nat. Phys. 18, 160–166 (2022)

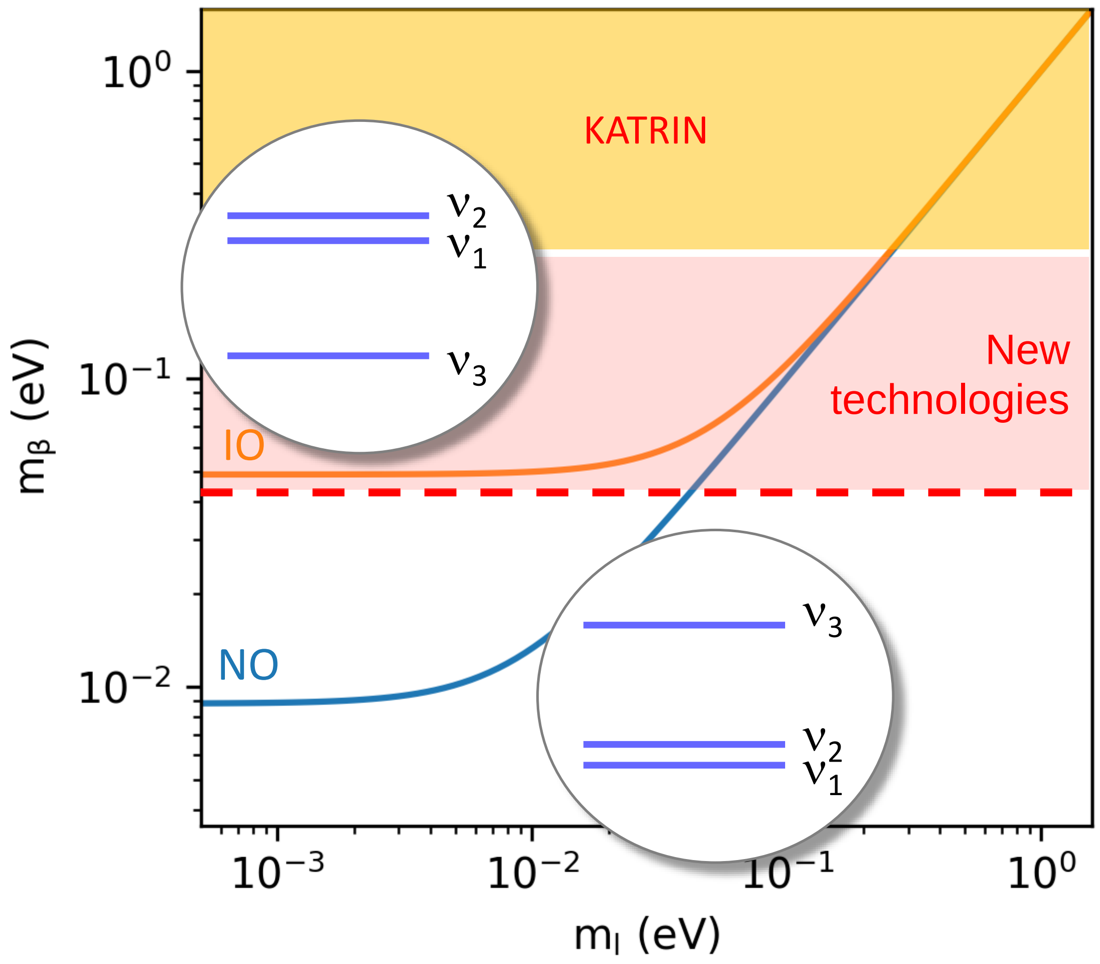
- 2025
- 259 measurement days
- ~36 x 10^6 counts
- Most stringent limit: $m(\nu_e) < 0.45$ eV (90% C.L.)



KNM: KATRIN Neutrino Mass measurement

KATRIN Coll., Science 338 (2025)

KATRIN beyond KATRIN

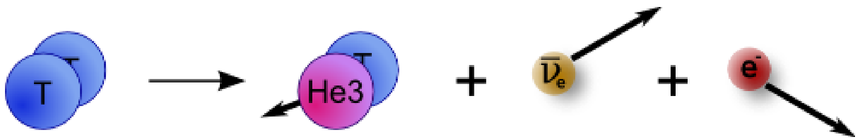


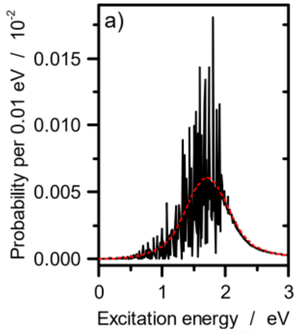
- KATRIN final: < **0.3 eV** (90% CL)
  Distinguish between **degenerate** and **hierarchical** scenario

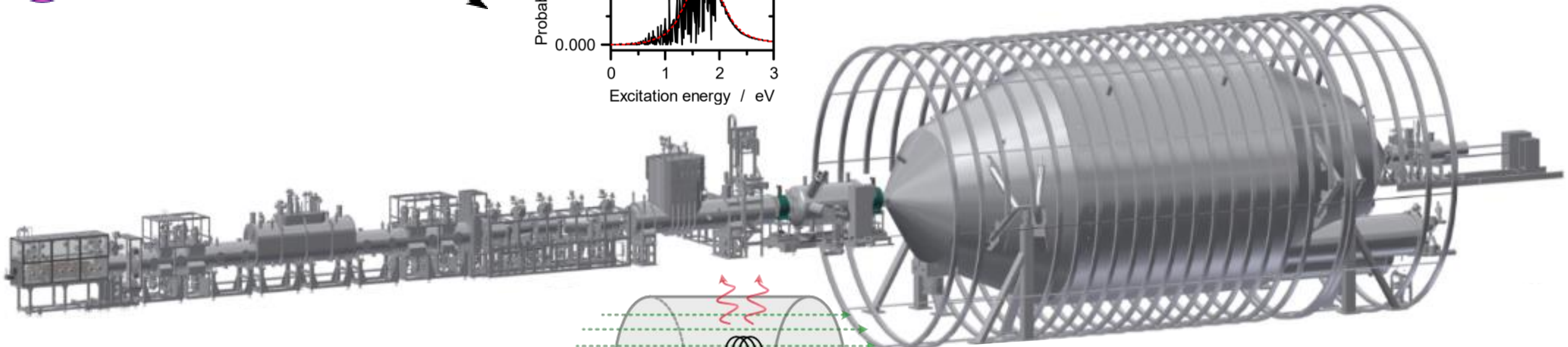
- New technologies: < **0.05 eV**
  Cover **inverted** ordering

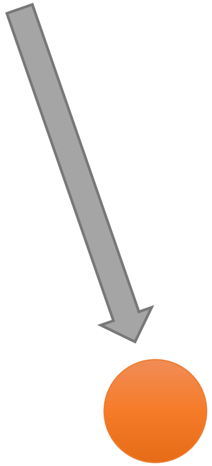
KATRIN beyond KATRIN

- Molecular effects → spectral broadening

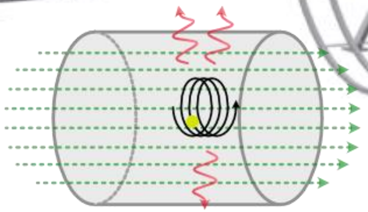






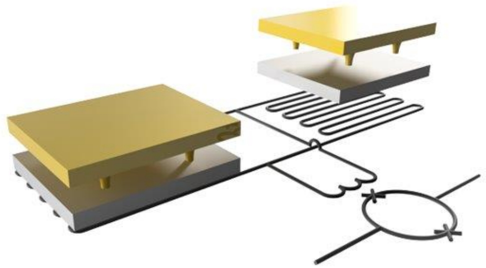


Atomic source technology



Option 2
Time-of-flight via electron tagging

Quantum detector technology

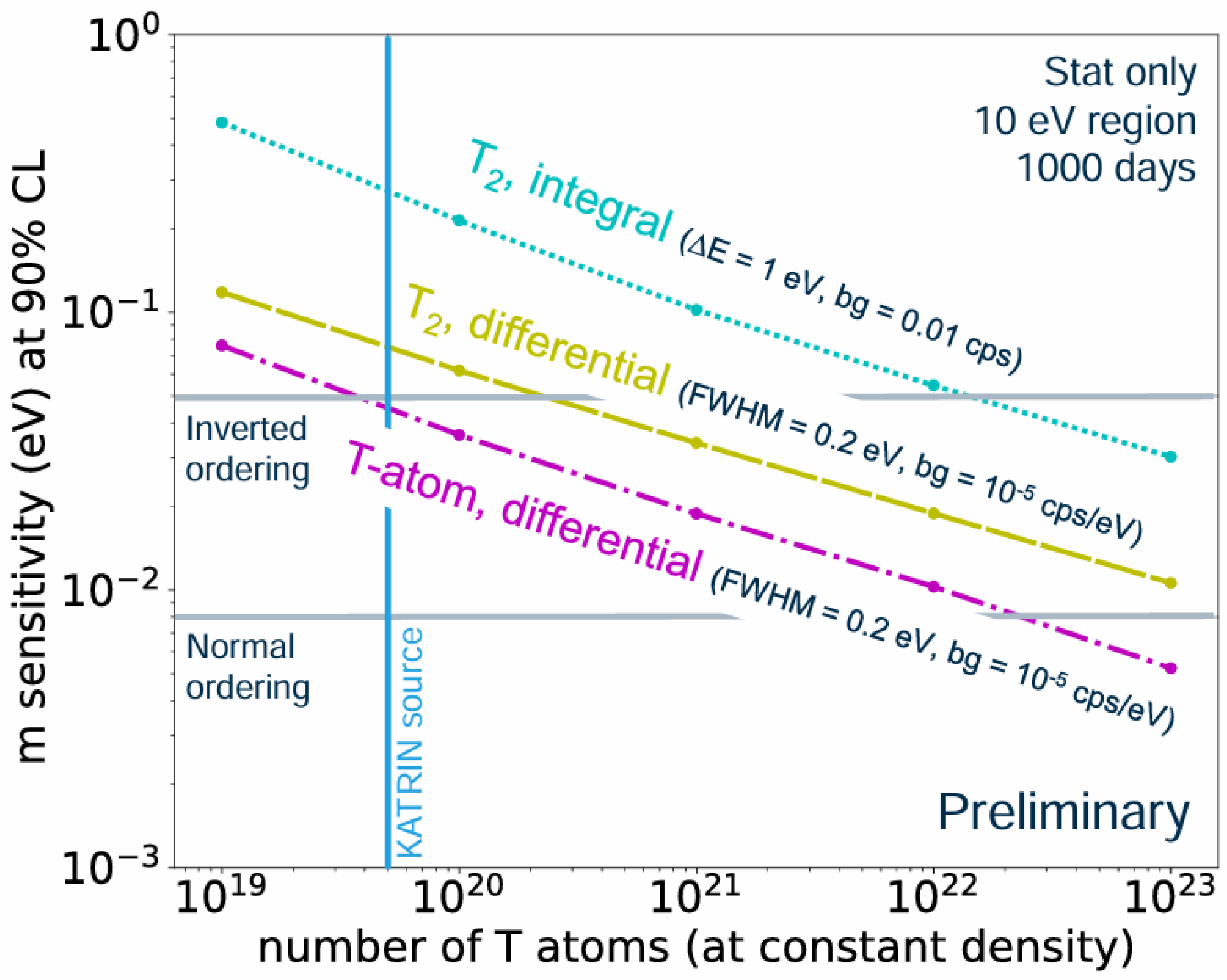


Option 1
µm-size calorimeters

eV resolution for differential detection

More in Magnus' Lecture!

KATRIN ++



MMCs represent a very good opportunity

Challenges:

- Operation in magnetic field (~20 mT)
- Coupling of mK cryo-platform with RT spectrometer

M. Schlösser, Private Communication

Project 8

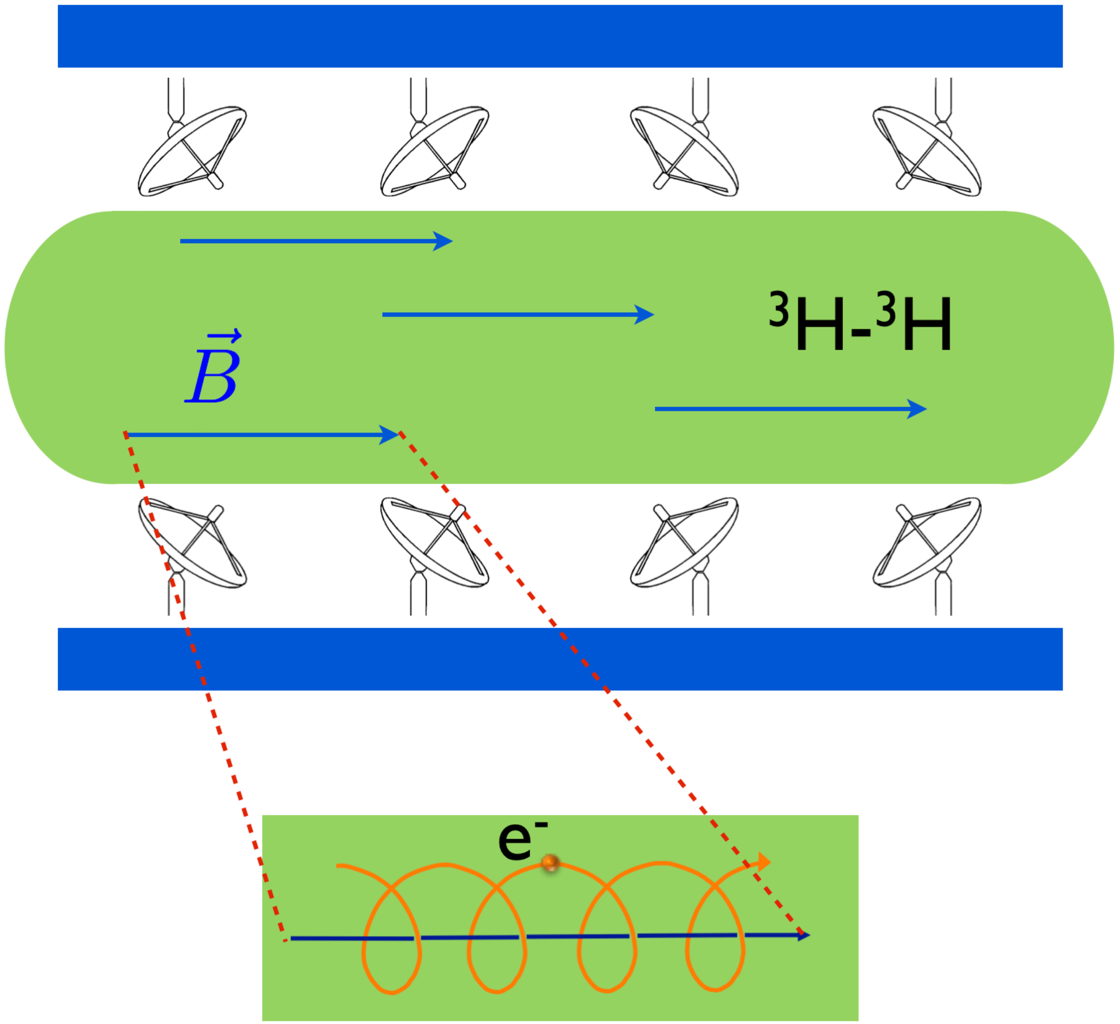
Cyclotron Radiation Emission Spectroscopy – CRES

Tritium in a magnetic field
→ Decay electrons emit cyclotron radiation
→ Frequency of the radiation determines electron kinetic energy

- Non-destructive measurement of 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 and J. Formaggio, Phys. Rev. D80 051301 (2009)

Project 8 – Phase 1

PROJECT 8

Cyclotron Radiation Emission Spectroscopy – CRES

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→ Decay electrons emit cyclotron radiation
→ Frequency of the radiation determines
electron kinetic energy

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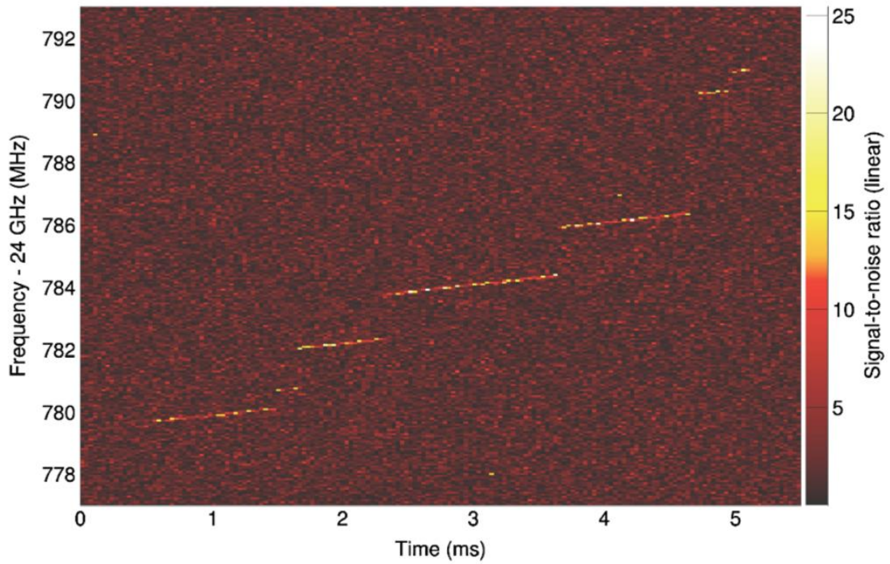
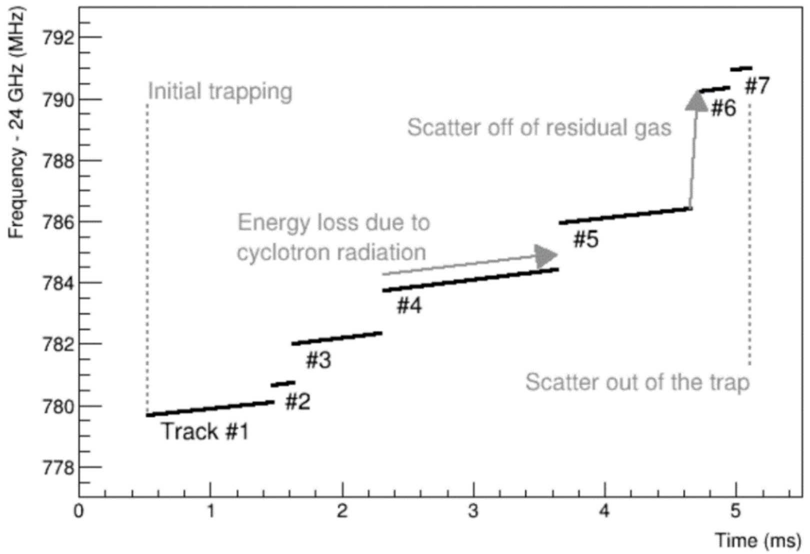
$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

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

- Phase 1: CRES demonstration with ^{83m}Kr

First CRES observation from single electrons June 2014

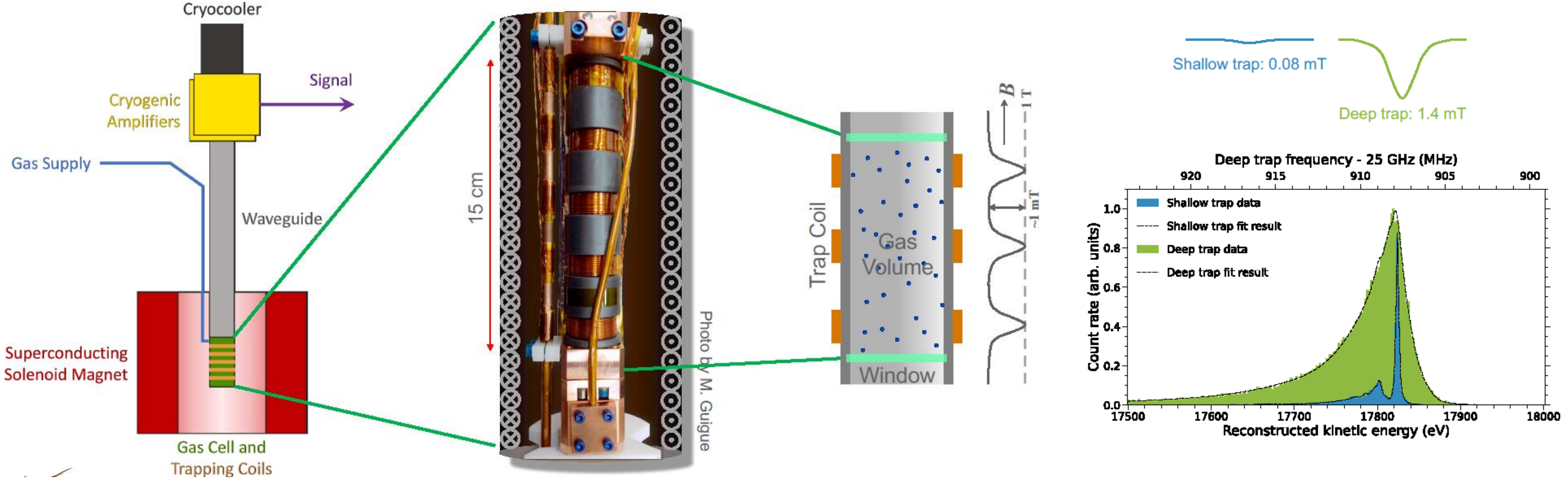




Asner et al., PRL 114 (2015) 162501

Project 8 – Phase 2

First time CRES with molecular tritium



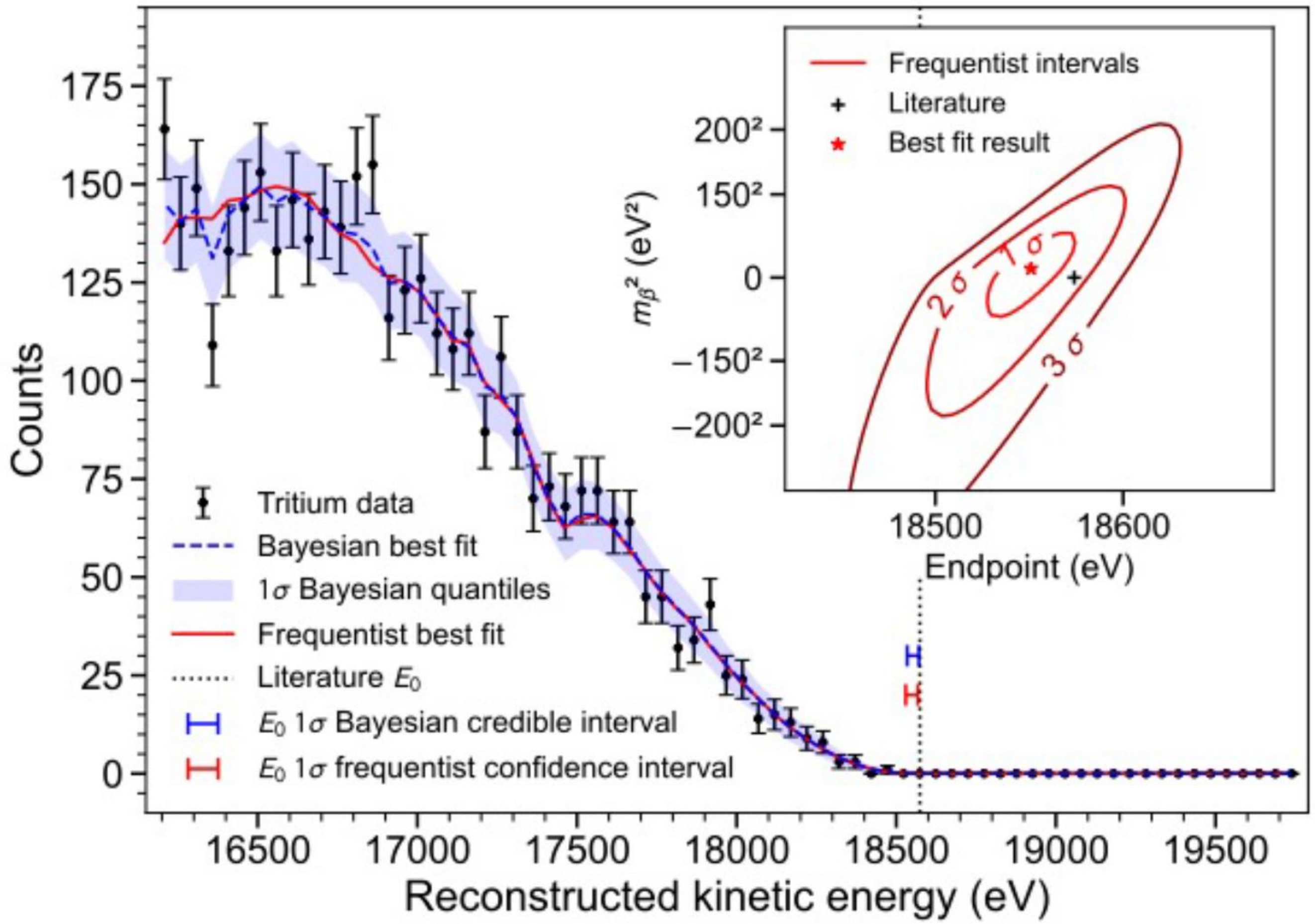
Selection of the trap depth as compromise between energy resolution and achievable statistics

Project 8 – Phase 2 results

First time CRES with molecular tritium

- ✓ Endpoint agrees with literature
- ✓ No background events above the endpoint

T_2 endpoint	Bayesian: $Q = (18553^{+18}_{-19})$ eV
	Frequentist: $Q = (18548^{+19}_{-19})$ eV
Neutrino Mass	Bayesian: m_β < 155 eV
	Frequentist: m_β < 152 eV
Background rate	$< 3 \times 10^{-10}$ eV^{-1} s^{-1}



A. Ashtari Esfahani, *et al.*, *Phys. Rev. Lett*. **131** (2023) 102502
arXiv 2212.05048

Project 8 - Future

Phase III:
Neutrino mass sensitivity $m_\beta \geq 100$ meV

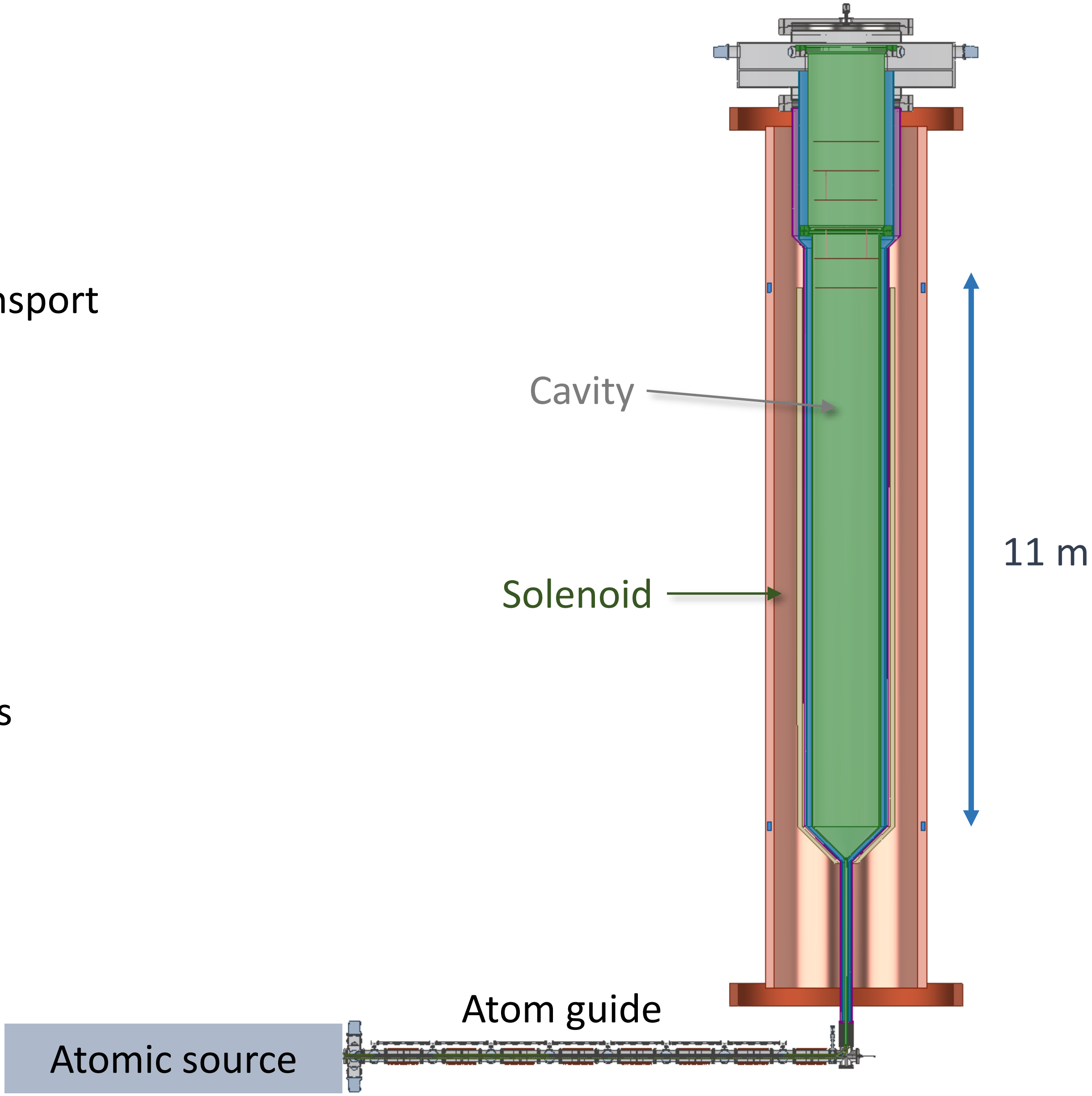
- Atomic source development

→ T_2 molecules need to be broken
→ System with a particular magnetic field configuration for transport and to avoid molecular recombination

- Large-volume CRES

Cavity-Based CRES Experiment
→ Cavity at 26 GHz: using *TE*01 mode in 1 T MRI magnet
Same frequency as Phase II: same RF setup,
waveguide L = 14 cm, R = 0.7 cm, $V \sim 20$ cm^3
→ Low frequency apparatus: feasibility of CRES in large volumes
low fields , and frequencies
$B \approx 0.035$ T, $f_c \approx 1$ GHz, $V \sim 0.3$m^3

Phase IV:
Neutrino mass measurement if $m_\beta \geq 40$ meV



Quantum Technologies for Neutrino Mass - QTNM

Based on CRES concept

Production and confinement of tritium atoms
$\geq 10^{12}$ cm^{-3} → scalable to 10^{20} atom × yr

B-field mapping with < 1 µT precision and ~ 1 mm spatial resolution

CRES of O(10keV) electrons scalable to ~m^3 detection volumes with
- sub-eV energy resolution
- high detection efficiency

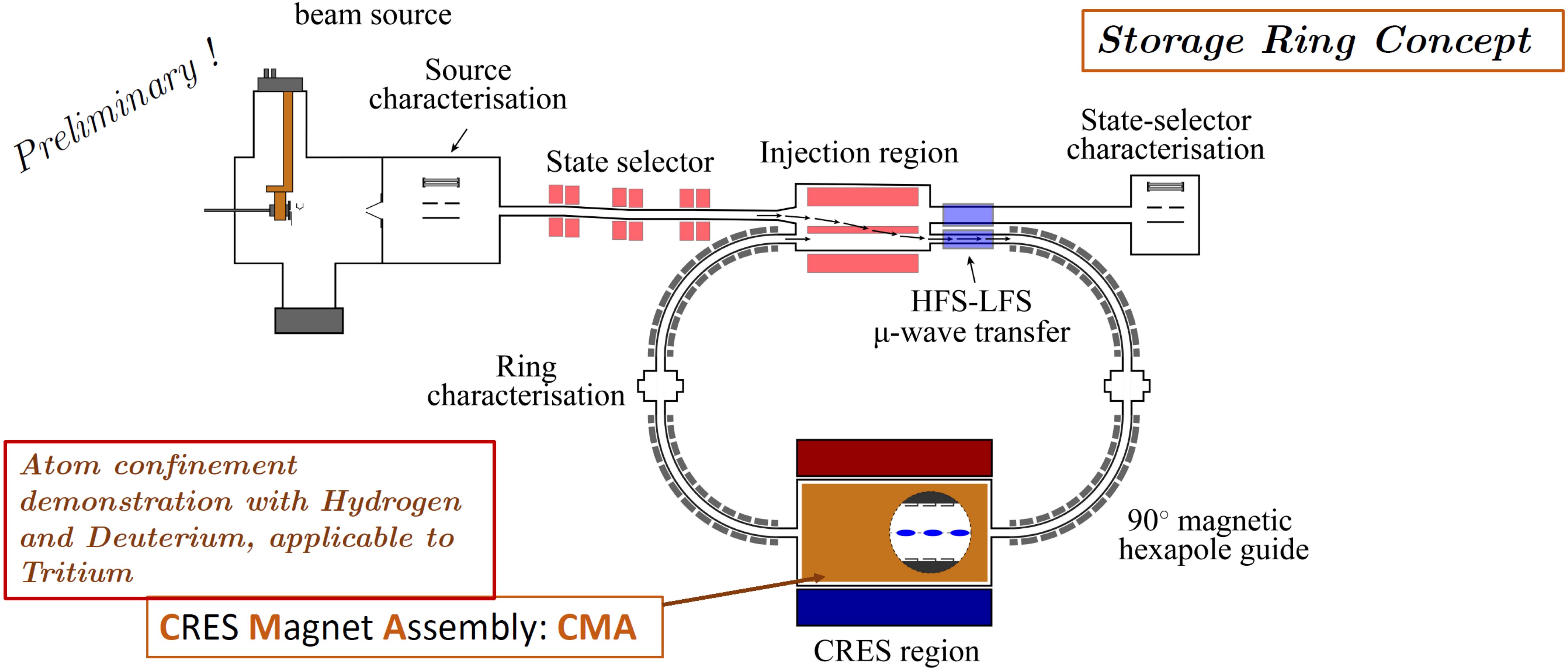
New concepts
tritium atoms in a storage ring
quantum technology (parametric amplifiers) for signal readout

CRESDA – CRES Demonstrator Apparatus

https://www.hep.ucl.ac.uk/qtnm/

Quantum Technologies for Neutrino Mass - QTNM

CRESDA Schematics



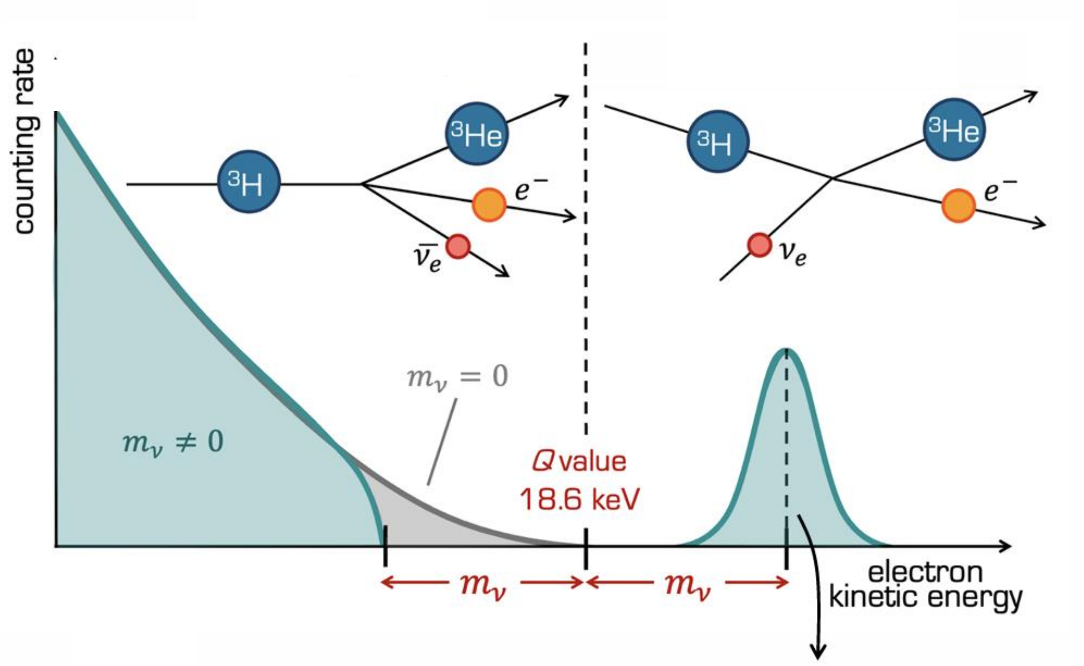
Atom confinement demonstration with Hydrogen and Deuterium, applicable to Tritium

CRES **M**agnet **A**ssembly: **CMA**

Slide by Ruben Saakyan

PTOLEMY

PonTecorvo / PrinceTon Observatory for Light Early-universe Massive-neutrino Yield
Aim: detection of relic neutrinos via capture on intense atomic ^3H source



Evidence for relic neutrino capture:
events at a distance 2 mv from the 3H beta spectrum endpoint

Effective electron neutrino mass determination as by-product of the experiment

M.G. Betti et al JCAP07(2019)047

PTOLEMY

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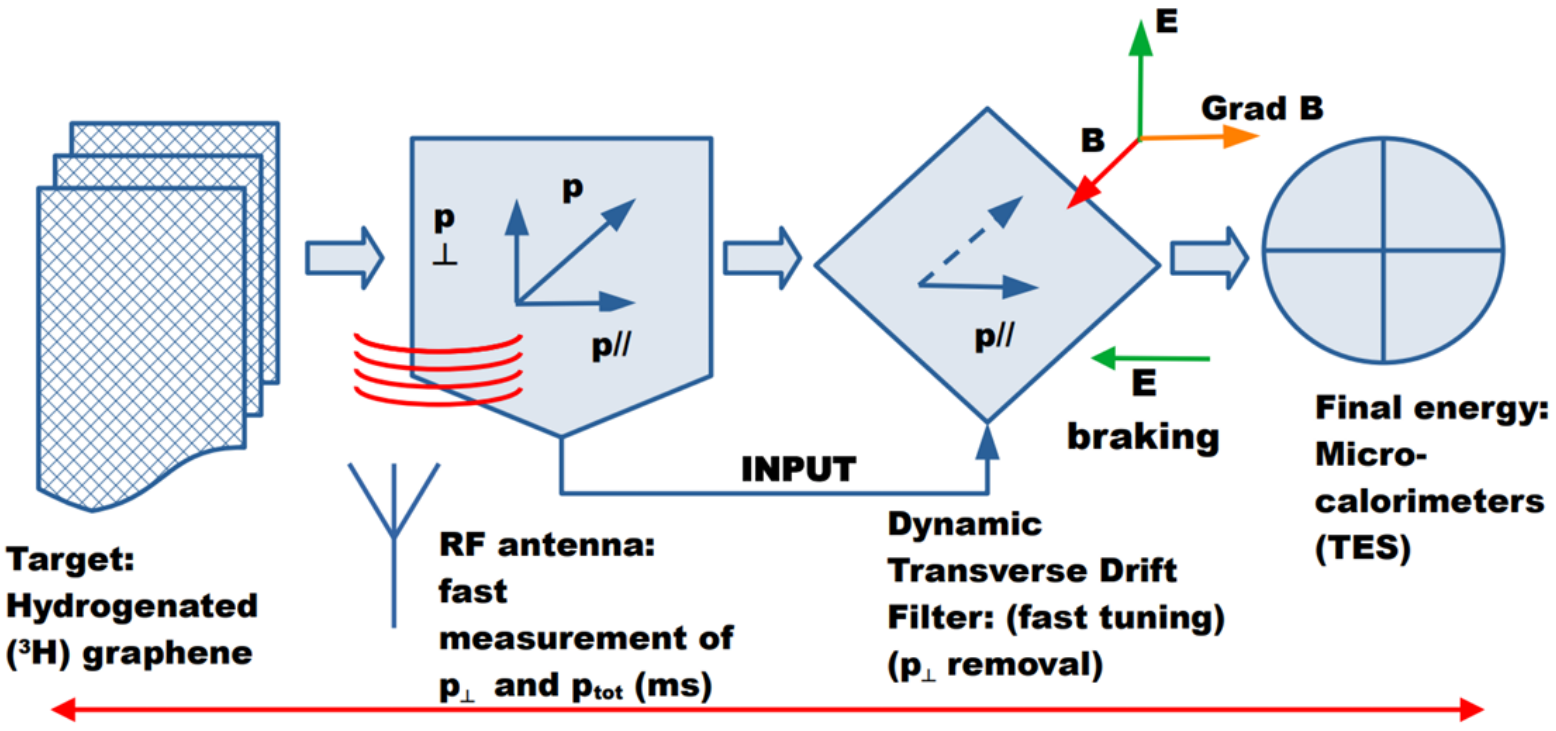


electrons near endpoint are slowed down by EM filter to an energy range of ~ 0−10 eV

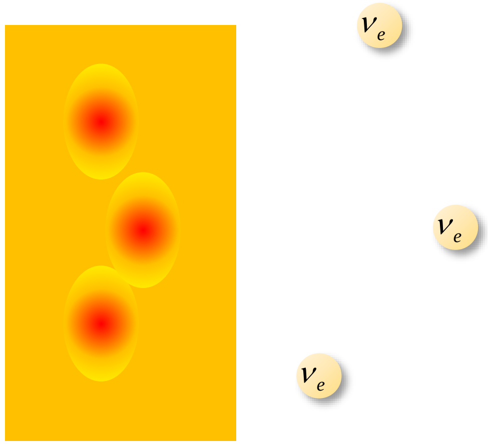
PTOLEMY goal:
σ_E =50 meV for E = 10 eV

M.G. Betti et al JCAP07(2019)047

^{163}Ho-based experiments

Atomic de-excitation via Auger electrons and as subdominant component photons

High resolution measurement only with source enclosed in detectors
→ Low temperature micro-calorimeters



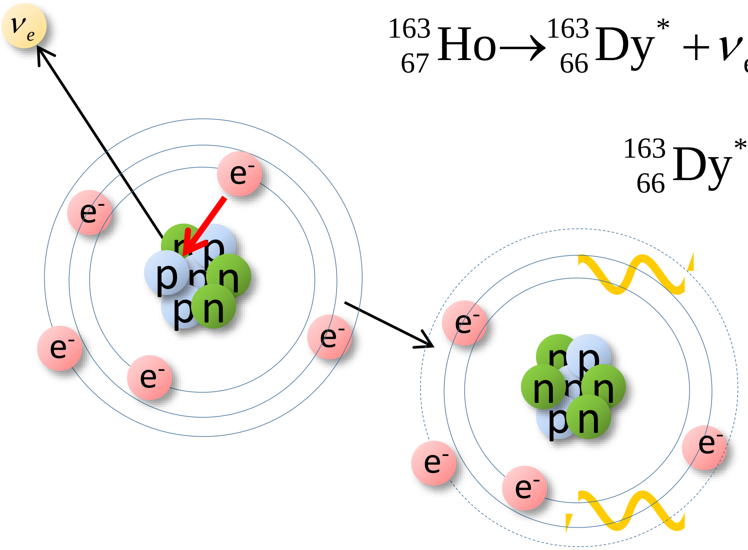
Source = Detector

Calorimetric measurement

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

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

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



- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)

- Q_{EC} = (2863.2 ± 0.6) eV

Ch. Schweiger et al., *Nat. Phys.* **20**, 921–927 (2024)

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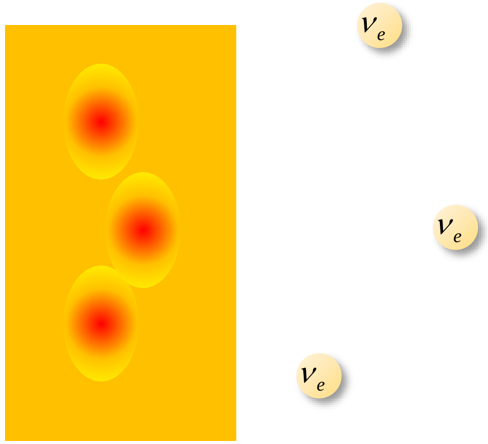

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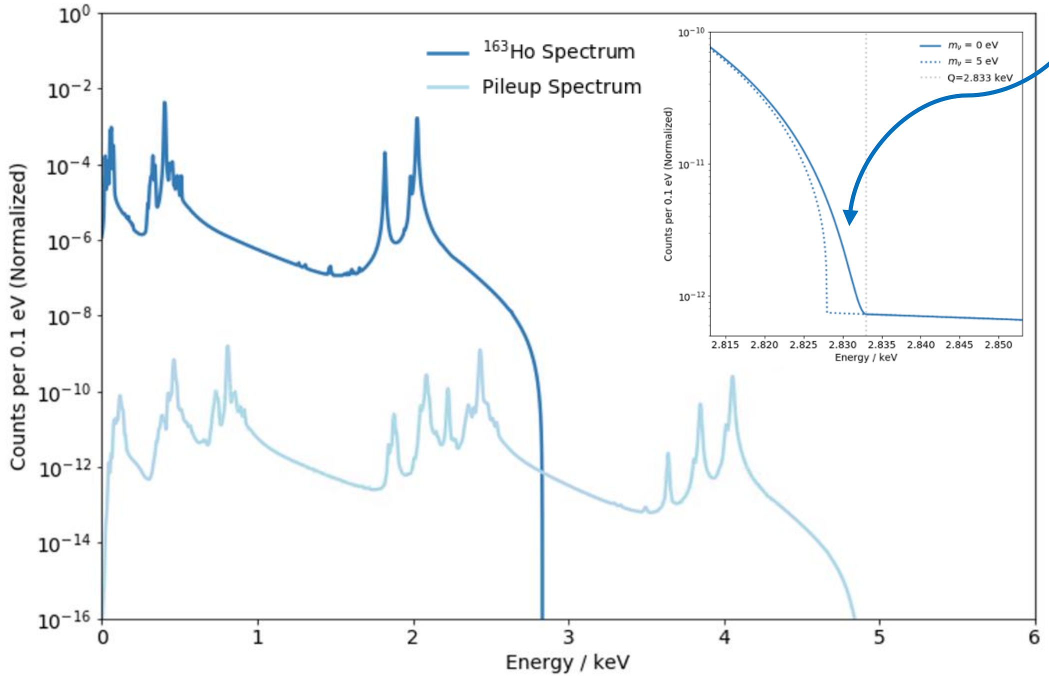
Fraction of events in the last eV ~10^{-12}



M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

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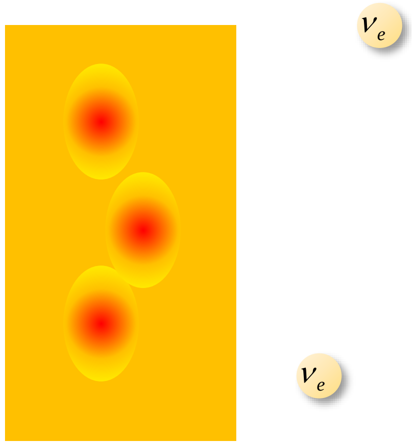


Source = Detector

Calorimetric measurement

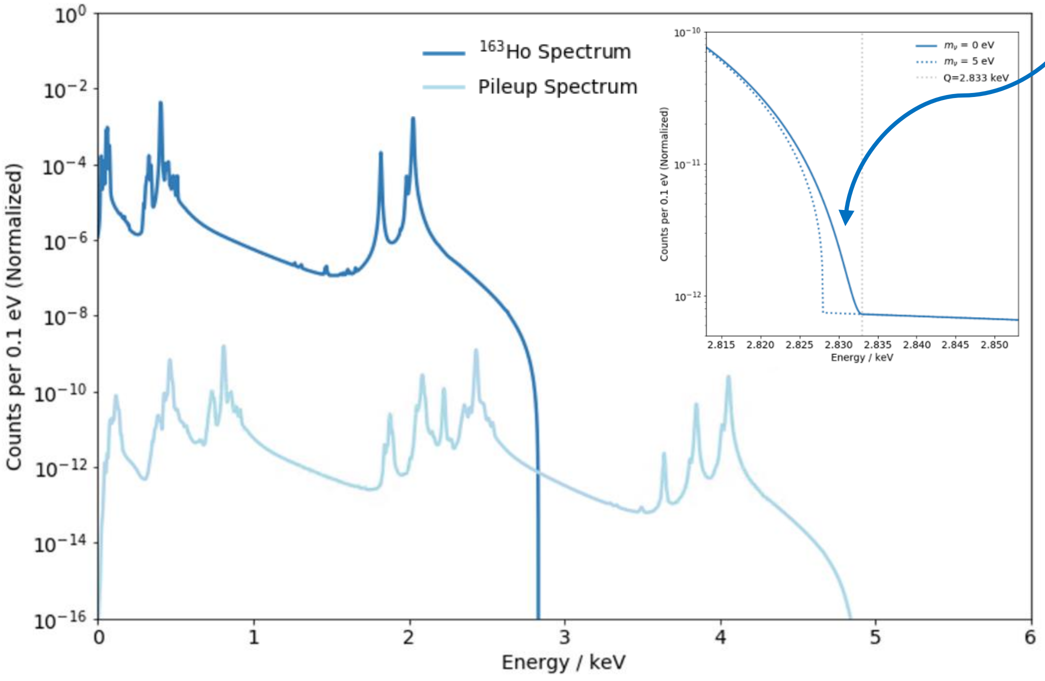
A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

Advantages: Measured neutrino complementary spectrum

No final state problems

Disadvantages: Unresolved pile-up

Fraction of events in the last eV ~10^{-12}



M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

^{163}Ho-based experiments – sub-eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

→ Large amount of high purity ^{163}Ho source

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

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

→ Fast and multiplexable detectors

Background level below unresolved pile-up

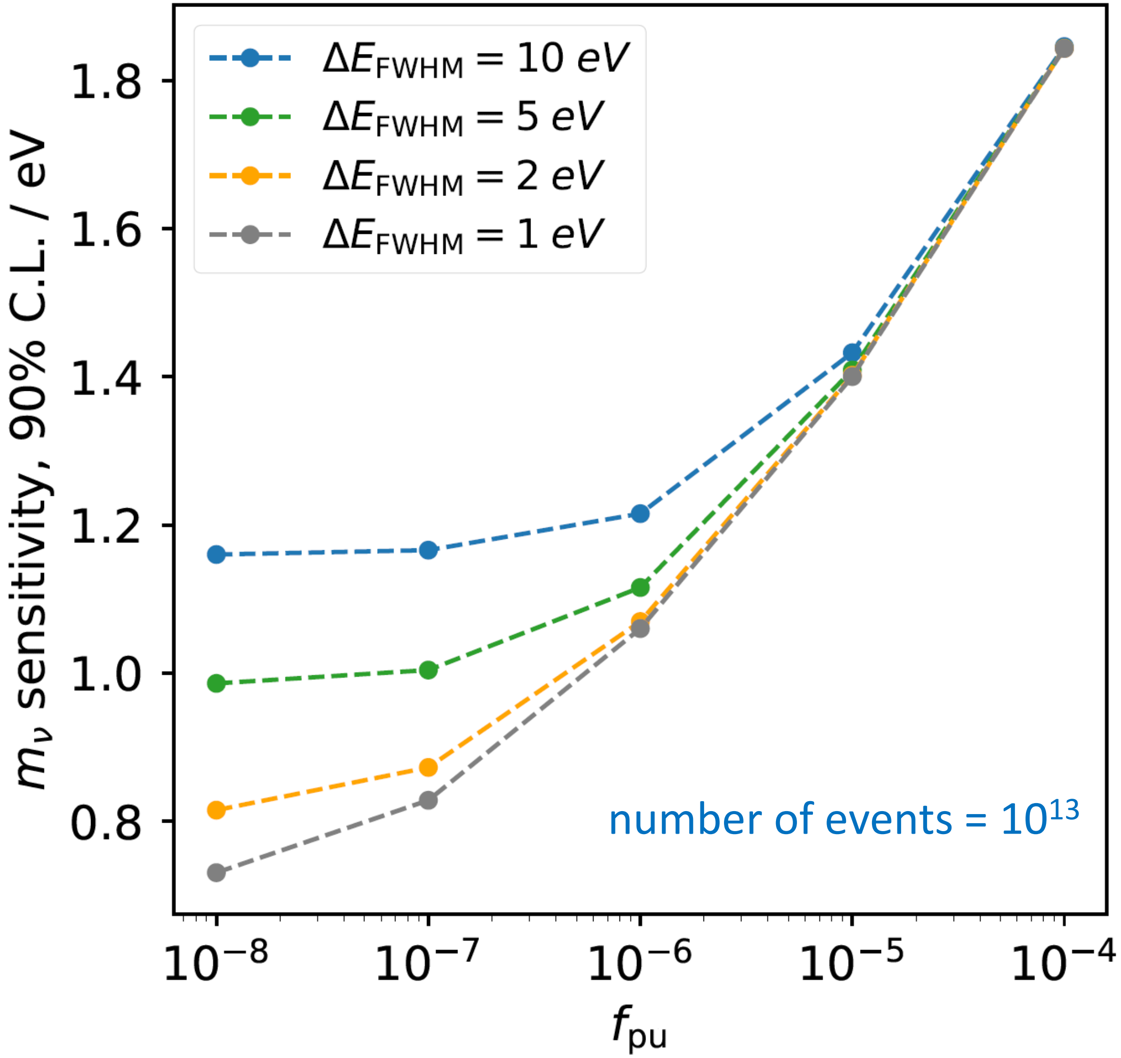
- **< 10^{-6} events/eV/det/day**

→ Identification and suppression of background sources

Precise characterization of the endpoint region

- **ΔE_{FWHM} < 3 eV**

→ High energy resolution low temperature microcalorimeters with enclosed ^{163}Ho

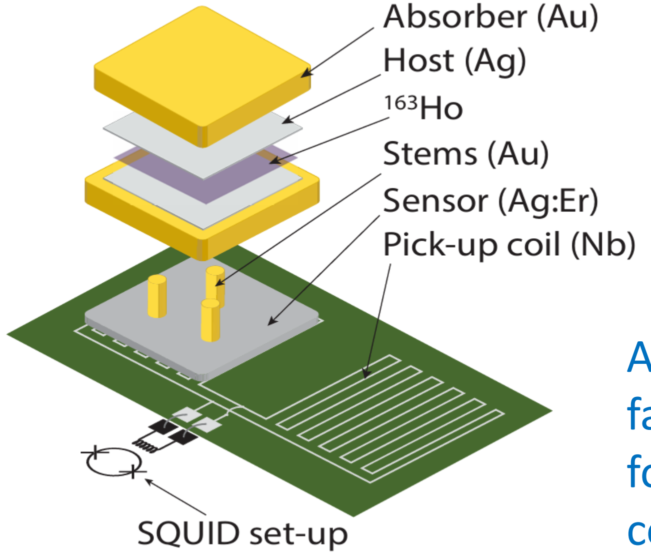


Neutrino mass with ^{163}Ho: ECHo and HOLMES

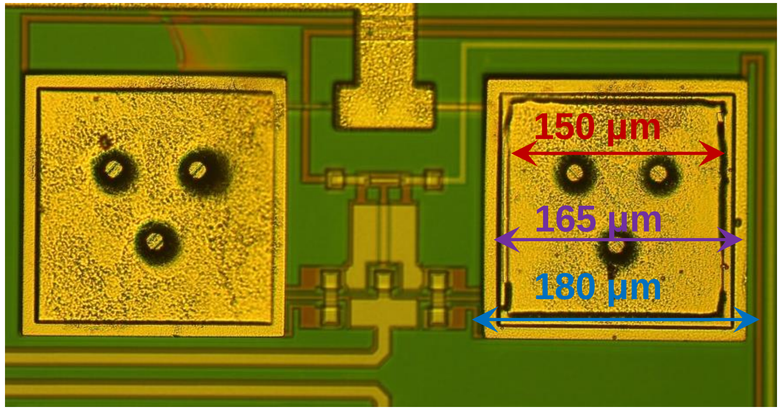
ECHo

Detector concept

MMC with ion-implanted ^{163}Ho



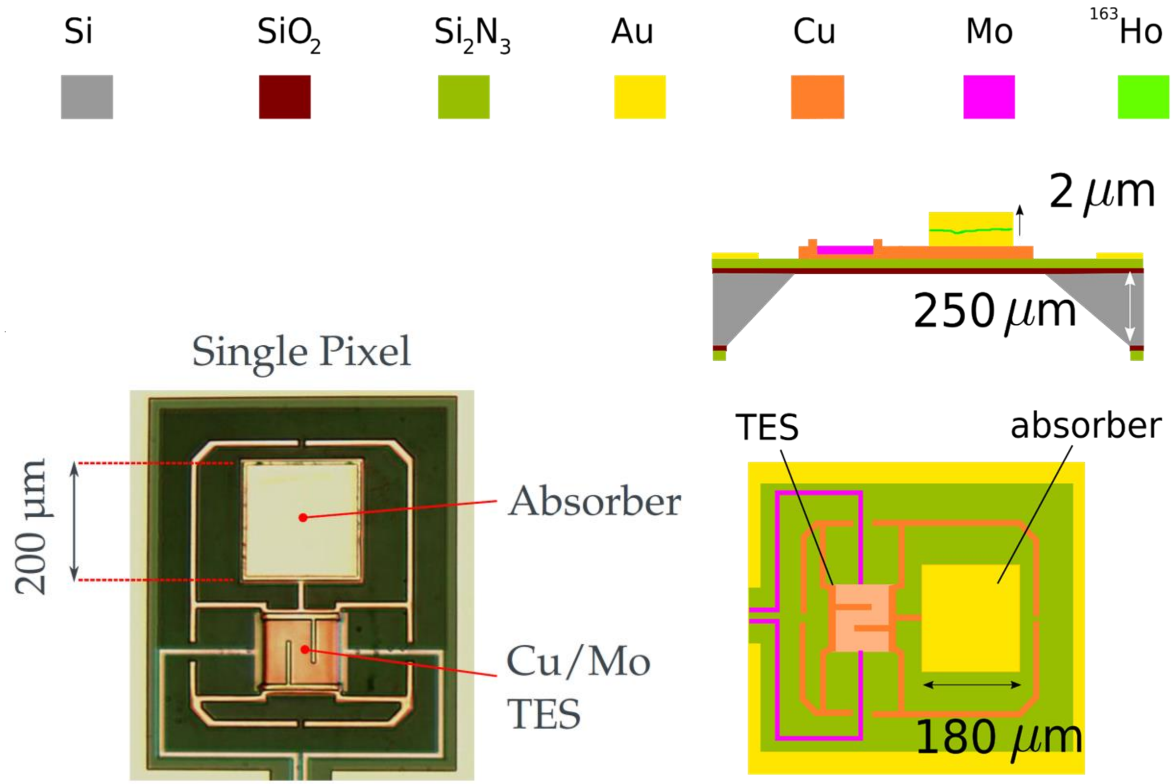
Absorber design and fabrication optimized for full energy containment



F. Mantegazzini et al., *Nucl. Instrum. Meth. A* **1030** (2022) 166406

HOLMES

TES with ion-implanted ^{163}Ho



Possible energy loss at the side-walls

A. Giachero et al., IEEE Transactions on Applied Superconductivity 31 (2021) 2100205

Neutrino mass with ^{163}Ho: ECHo and HOLMES

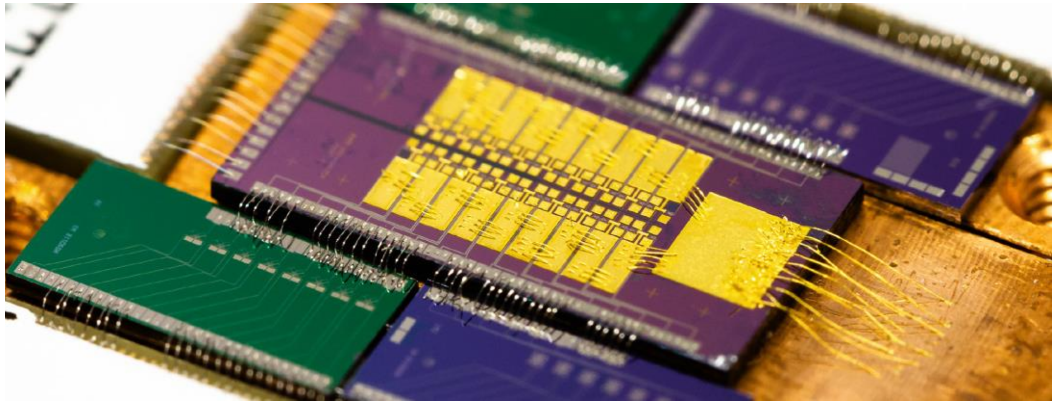
Proof of concept experiment

ECHo-1k 2-stage SQUID readout

ECHo-1k chip-Au 13 channels + 2 temperature channels
23 pixel with implanted ^{163}Ho
3 background pixels
average activity = 0.94 Bq total activity of 22 Bq

ECHo-1k chip-Ag 20 channels + 2 temperature channels
34 pixel with implanted ^{163}Ho
6 background pixels
average activity = 0.71 Bq total activity of 24 Bq

Experiment duration: 6 months

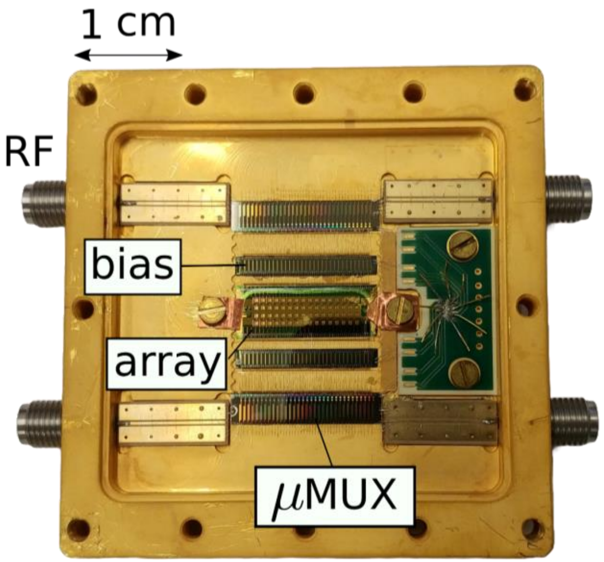


HOLMES Multiplexed readout

48 detectors

15 Bq total activity

Experiment duration: 2 months



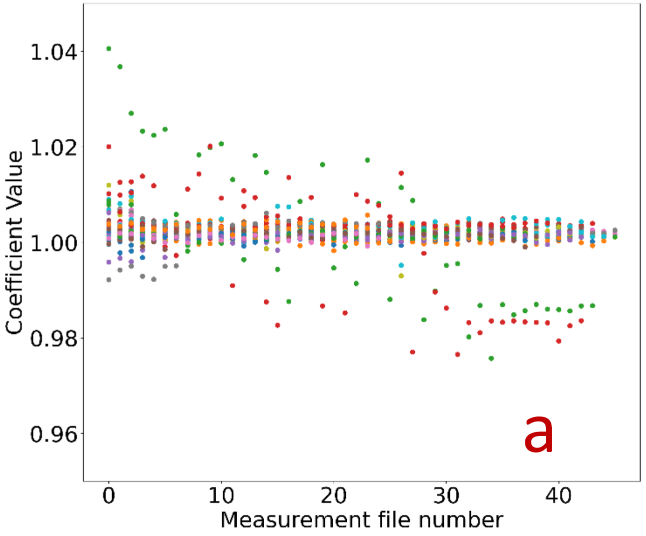
Neutrino mass with ^{163}Ho: ECHo and HOLMES

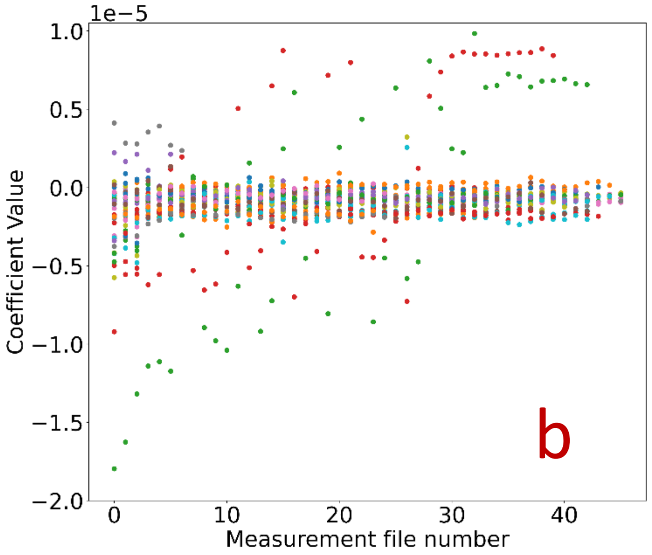
Proof of concept experiment

ECHo-1k

HOLMES

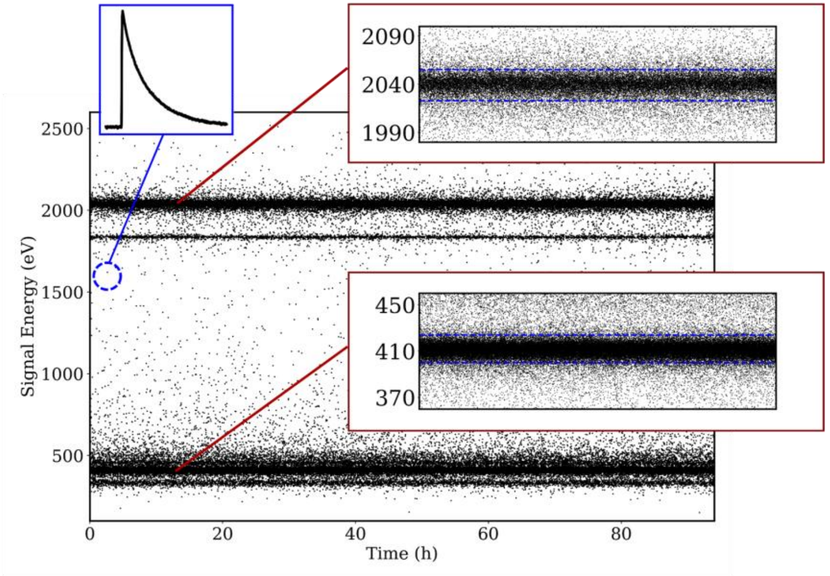
Stability of calibration parameters for different pixels





$$E_{exp} = aE_{theo} + bE_{theo}^2$$

Example of stability of energy after data processing



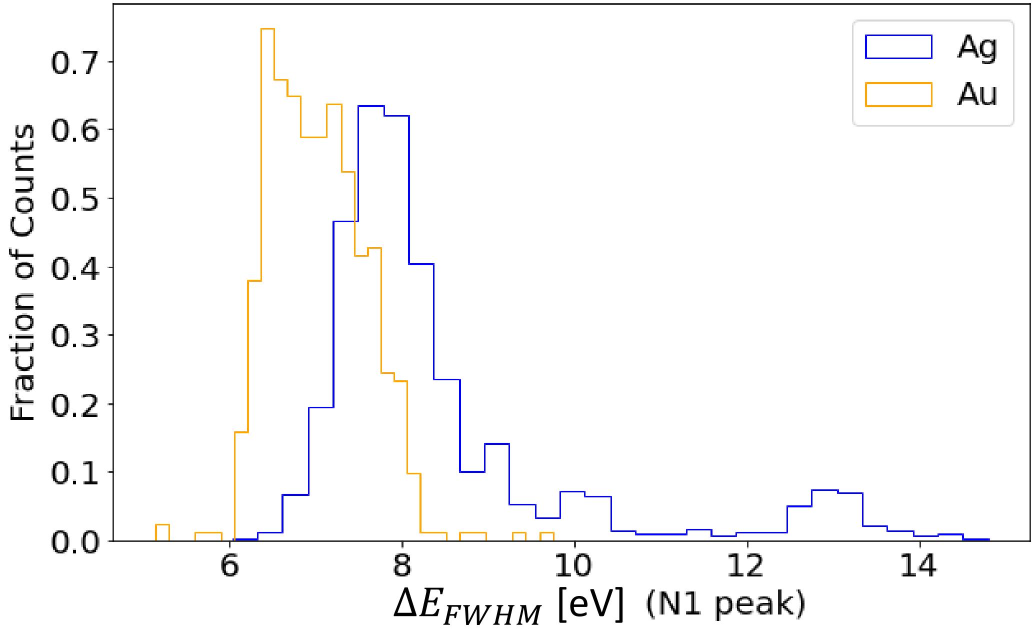
Neutrino mass with ^{163}Ho: ECHo and HOLMES

Proof of concept experiment

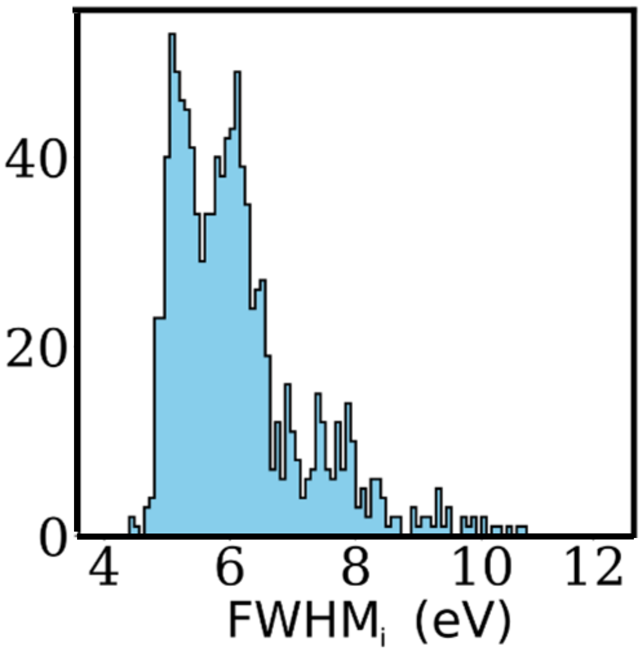
ECHo-1k

HOLMES

Histogram of pseudo energy resolution per file



Energy resolution from ^{55}Fe calibration



Neutrino mass with ^{163}Ho: ECHo and HOLMES

Proof of concept experiment

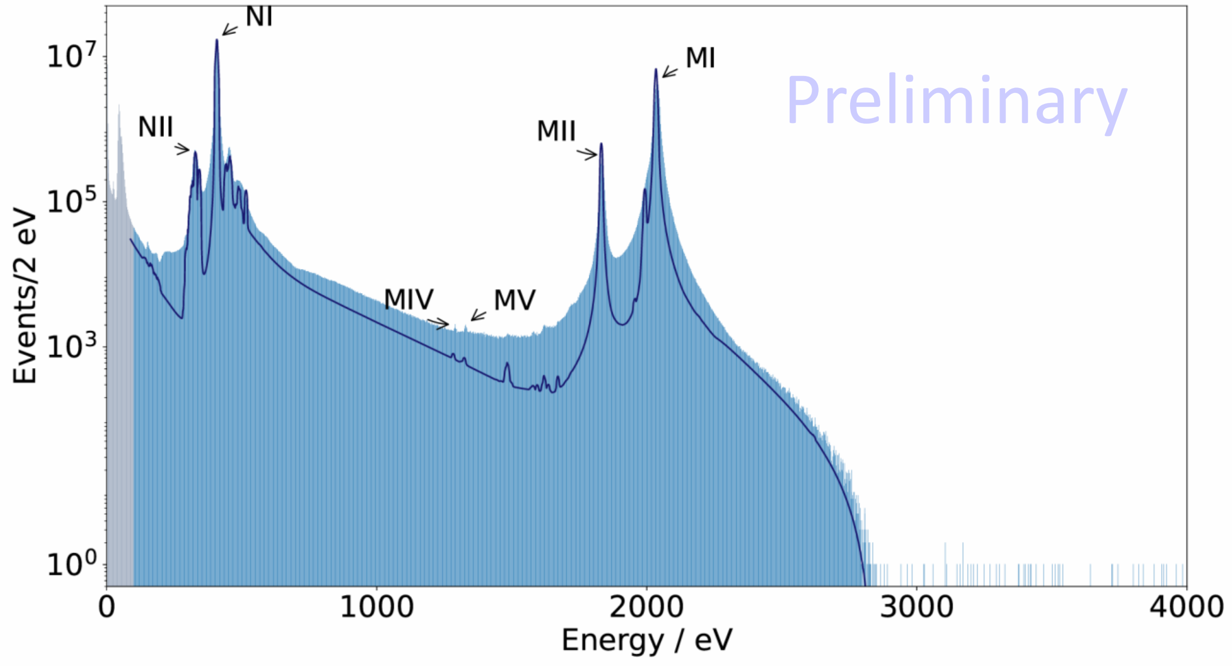
ECHo-1k

200 million events from 100 eV to 5000 eV

ΔE_{FWHM} = (6.59 ± 0.16) eV

number of events in [2900 – 5000] eV = 80

b = (9±4) × 10^{-6} /eV/pixel/day

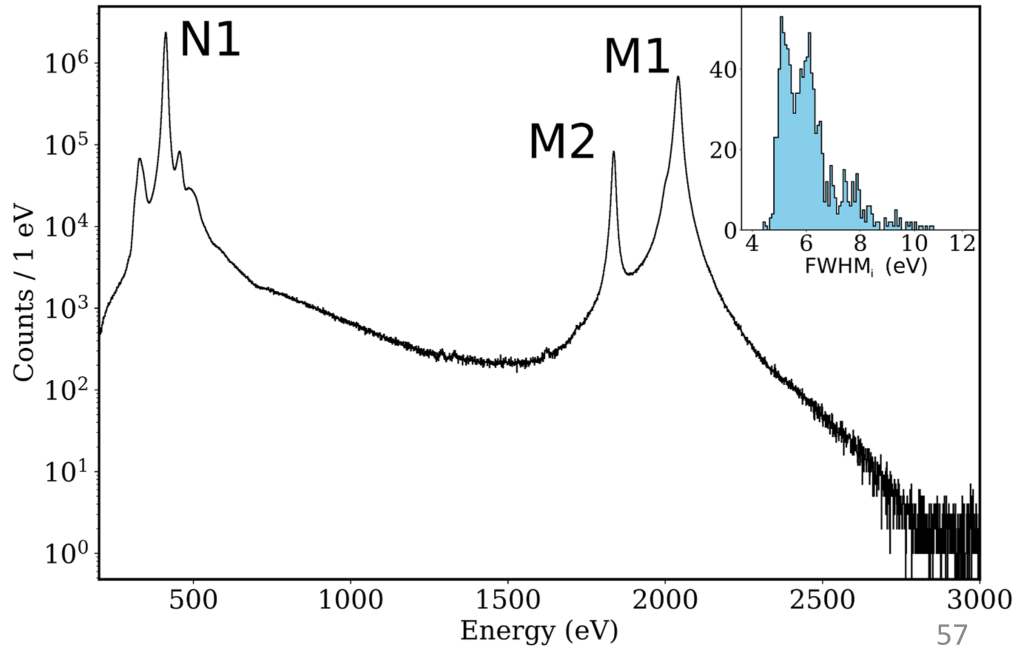


HOLMES

60 million events above 300 eV

ΔE_{FWHM} = (6 ± 1) eV

b= (1.7 ± 0.1) × 10^{-4}/eV/pixel/day



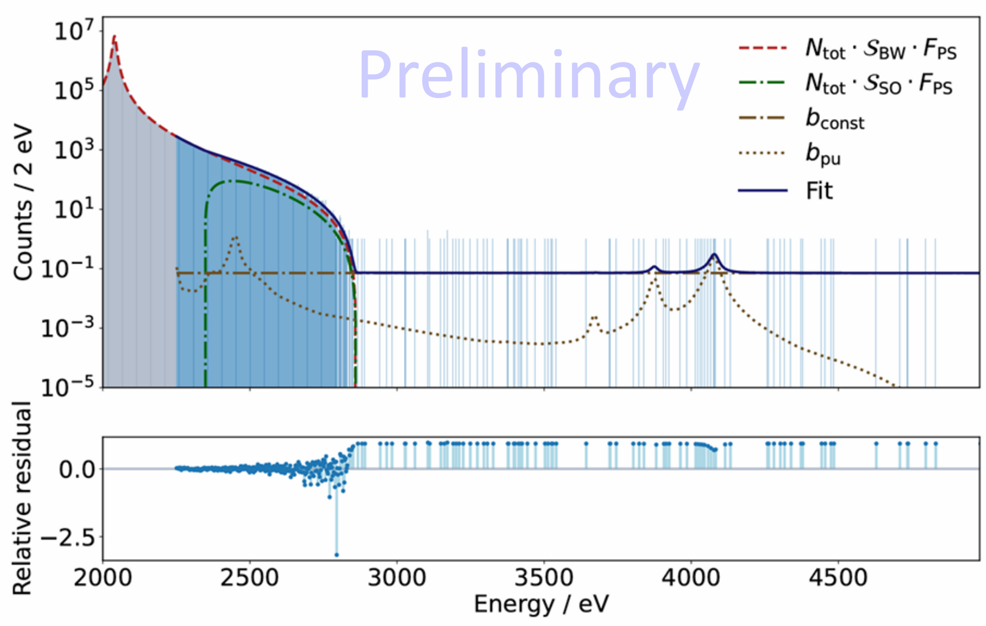
Neutrino mass with ^{163}Ho: ECHo and HOLMES

Proof of concept experiment

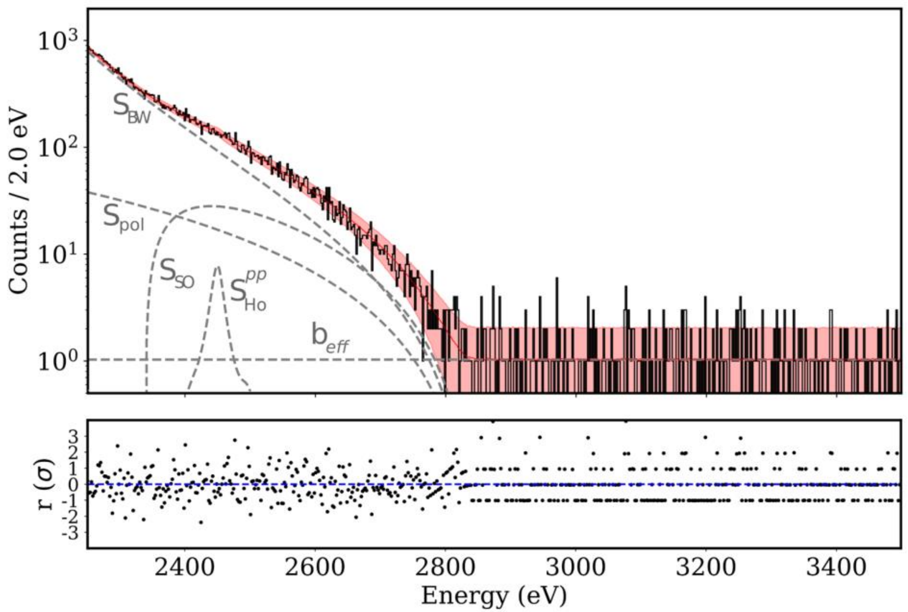
$$\frac{dN}{dE} = C \times [A(E) \times F_{PS}(Q,E)] \otimes g(E,\sigma) + b(E) \qquad F_{PS} = (Q-E)\sqrt{(Q-E)^2 - m_\beta^2}$$

- No analytical function is available to describe $A(E)$, the probability to create excited states with a given energy in the ^{163}Dy atom
- In M. Braß et al., New J. Phys. 22 (2020) 093018 it is stated that $A(E)$ is very smooth
- Test of different functions has been performed

ECHo-1k



HOLMES



BK. Alpert et al., arXiv:2503.19920v2 [hep-ex]

ECHo and HOLMES future

Aim: reach sub-eV sensitivity in next upgrade

Minimal design:

20000 pixel → Multiplexed readout

~10 Bq/pixel

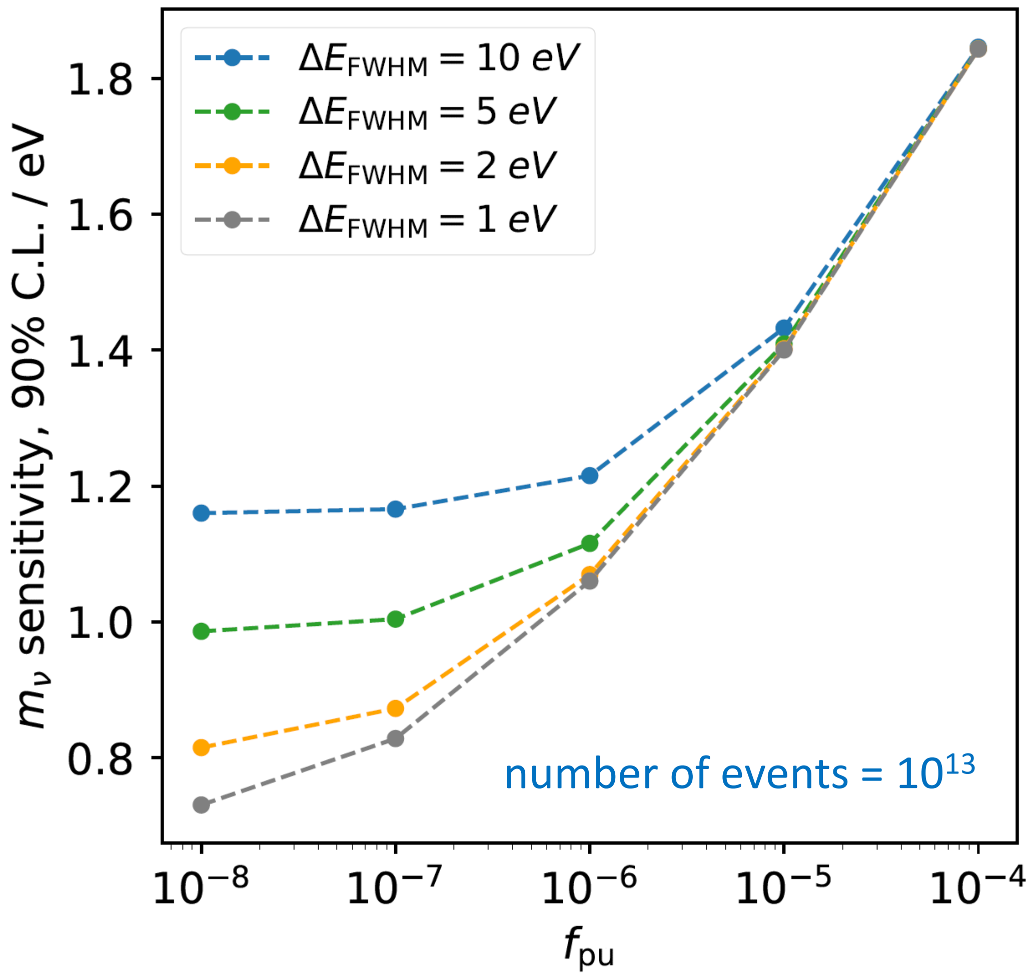
ΔE_{FWHM} < 5 eV

$f_{\mathrm{pu}} < 10^{-6}$

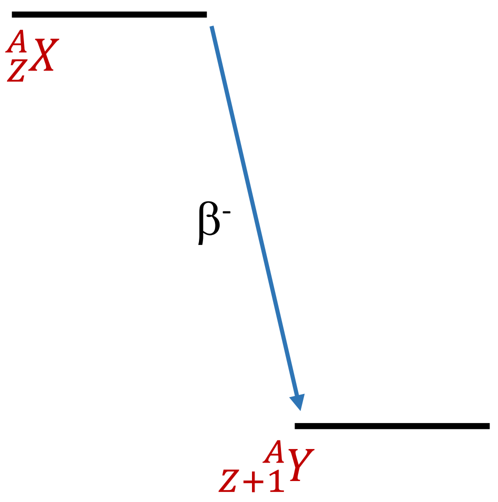
$b < 10^{-6}$ /eV/detector/day

Better model of ^{163}Ho spectrum

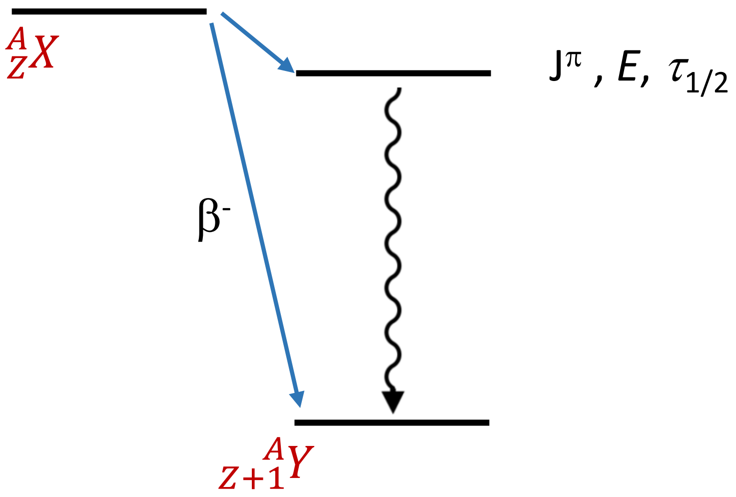
Scaling-up present concepts is not sufficient



Decay to excited nuclear states



Q-value ~ MeV



Q-value ~ MeV

Q_{EX}-value = Q - E

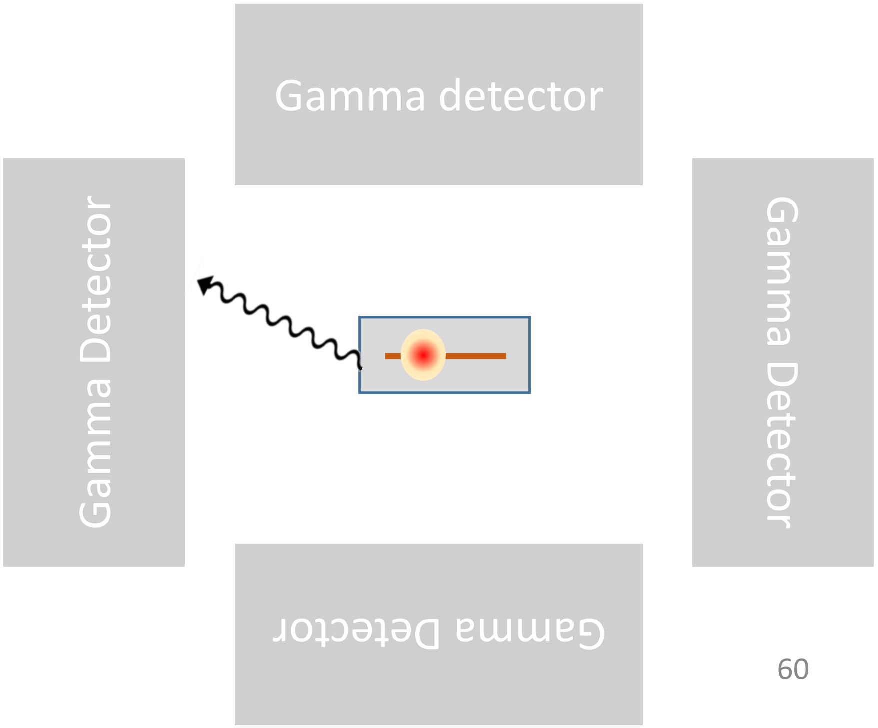
If $\tau_{1/2} <$ μs
coincidence measurement of beta electron and gamma

Experimental method

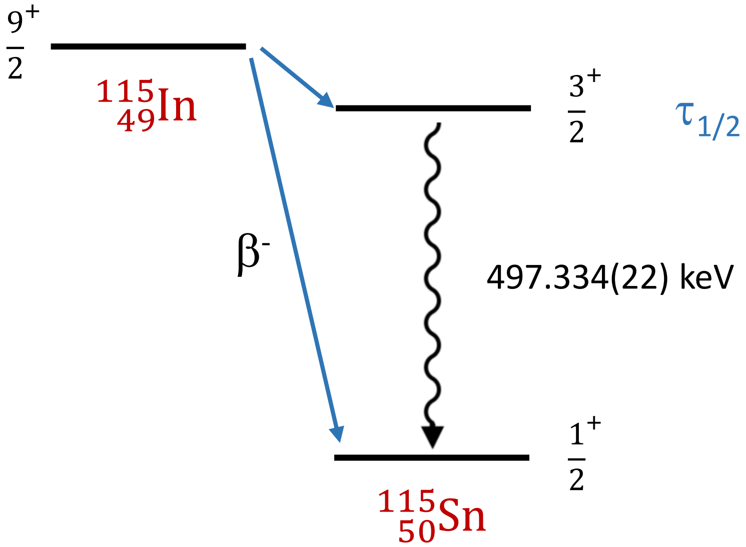
microcalorimeters enclosing the source
(as ^{163}Ho detectors)

surrounded by cryogenic gamma detectors
(as DBD or DM detectors)

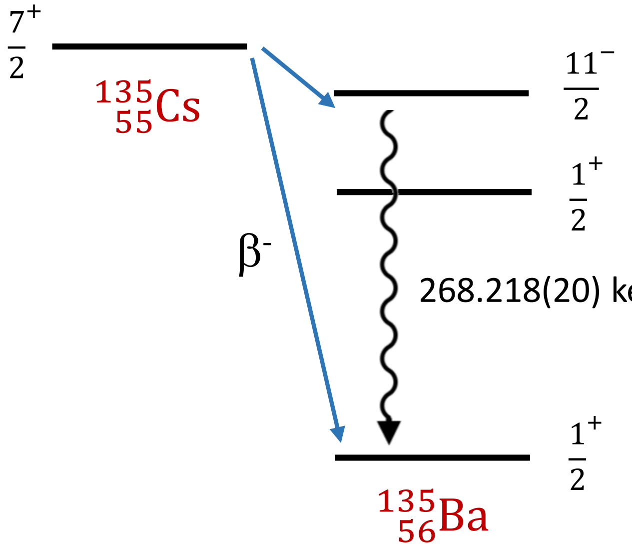
Why there is still not such an experiment?



Decay to excited nuclear states - candidates



$\tau_{1/2} \cong 11$ ps



$\tau_{1/2} \cong 28.11$ h

$\tau_{1/2} \cong 4.4 \times 10^{14}$ years

1 Bq ~ 2×10^{22} ^{115}In atoms

96% natural abundance

$Q = 497.489(10)$ keV

$Q_{Ex} = 155$ eV

B.R. ~ 1.2×10^{-4}

$\tau_{1/2} \cong 1.3 \times 10^{6}$ years

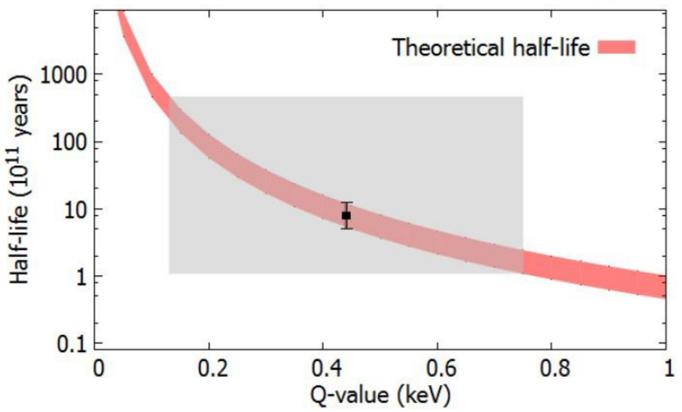
1 Bq ~ 6×10^{13} ^{135}Cs atoms

artificially produced

$Q = 268.66(30)$ keV

Q_{Ex} ~ 440 eV

B.R. ~ 1.6×10^{-6}



C.M. Cattadori et al., *Phys. of Atom. Nucl.* **70(1)** (2007) 127
B.J. Mount et al., *Phys. Rev. Lett.* **103** (2009) 122502

A. de Roubin et al. Phys. Rev. Lett. 124, 222503 (2020)

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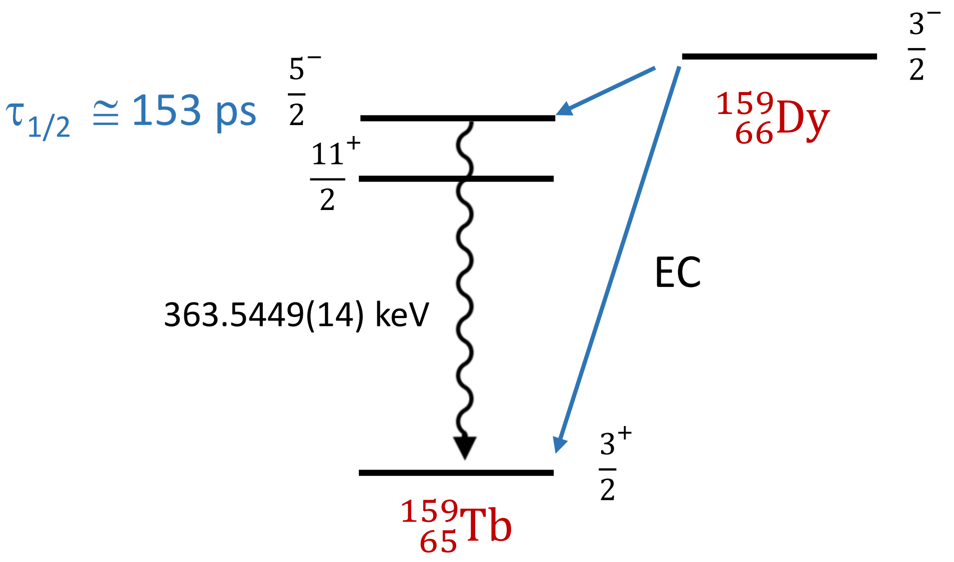

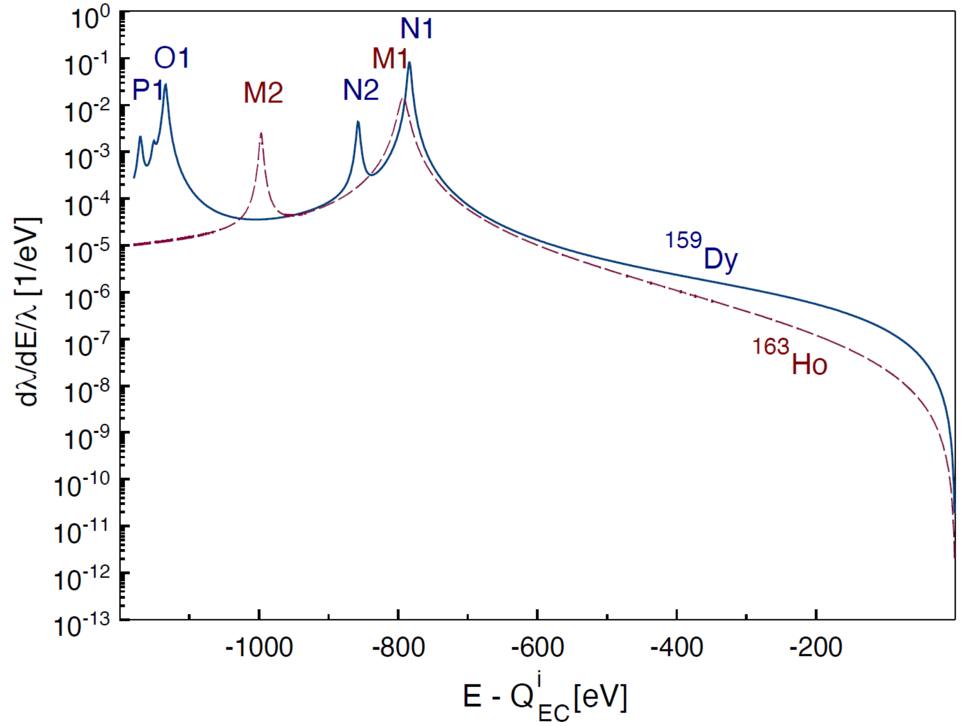

$\tau_{1/2} \cong 144.4(2)$ d

1 Bq ~ 1.8×10^7 ^{159}Dy atoms produced artificially

$Q = 364.73(19)$ keV

$Q_{5/2} = 1.18(19)$ keV

partial $\tau_{1/2} = 2.08 \times 10^5$ year 1Bq ~ 9.5×10^{12} ^{159}Dy atoms)

For normalized spectra ^{159}Dy has a higher fraction of events in the end-point region compared to ^{163}Ho

BUT to acquire the same statistics a factor 10^6 more events occur in the detectors

^{163}Ho has still the highest fraction of "useful decay"/detector

Z. Ge et al. arXiv:2106.06626 [nucl-ex]

Conclusions

- ν The determination of the neutrino mass scale will guide beyond Standard Model theories and support our understanding of the Universe

- ν The study of low energy electron capture and beta spectra provides a less model dependent approach for neutrino mass determination, even if the less sensitive s far

- ν ^{3}H is an ideal candidate for determining the neutrino mass scale – different experimental concept have been developed and continuously improved

- ν ^{163}Ho is gaining importance thanks to the successful R&D in ECHo and HOLMES

- ν Challenging but realistic plans for the determination of the neutrino mass scale are going to be implemented

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Thank you !