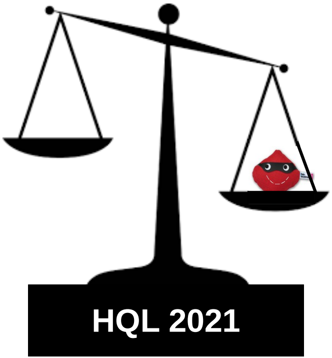
KIT
Karlsruhe Institute of Technology

Absolute neutrino mass measurements

Heavy Quarks and Leptons, Warwick 2021

Stephanie Hickford | Monday 13th September 2021

Outline



Neutrino mass determination

1896 H. Becquerel observes radioactive decay

$\Longrightarrow$ E. Rutherford and F. Soddy distinguish three types

α-decay, β-decay, γ-decay

$\Longrightarrow$ Thought to be two-body decay with discrete energy

1908 H. Geiger develops the Geiger counter

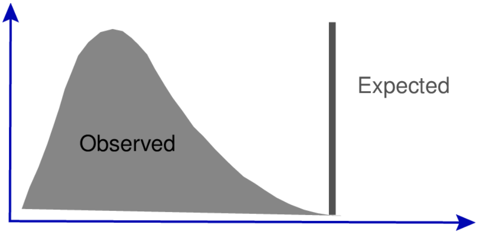
1914 J. Chadwick measures a continuous β-decay spectrum which *violates energy conservation*

1930 Wolfgang Pauli predicts a particle which is

- extremely light
- no electric charge
- inactive

resulting in a continuous β-decay energy spectrum

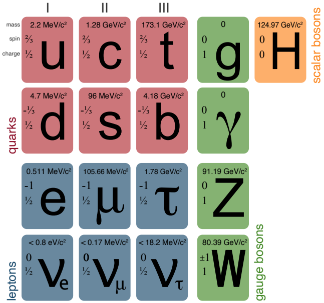
$\Longrightarrow$ E. Fermi names the "neutrino" and formulates a mechanism for three-body β-decay: $n \longrightarrow p + e^- + \bar{\nu}_e$



Measurement methods

- Cosmology
- Neutrinoless double β-decay
- Single β-decay

Neutrino mass determination

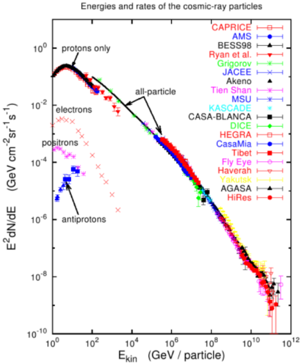


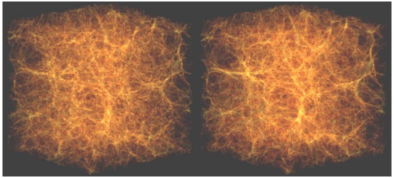
Standard Model

- Mass generation
- Weak interactions
- Oscillation

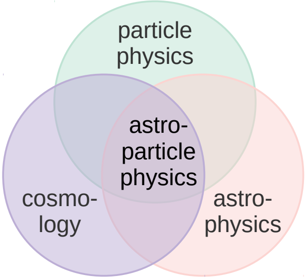
Understanding astro-physical processes

- Nuclear reactions in stars
- ν as probes for cosmic rays





$m_\nu = 0$ $m_\nu > 0$



Massive neutrinos as "cosmic architects"

- $336\,\nu/\text{cm}^3$ in the Universe

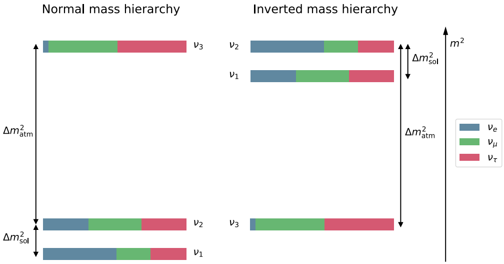
Neutrino flavour oscillation

Neutrino flavour oscillation data is fit remarkably well

$\Longrightarrow$ Determination of square mass splittings

- Solar mass splitting: $\Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\mathrm{eV}^2$
- Atmospheric mass splitting: $|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$

  $\Delta m^2_{31} > 0 \longrightarrow$ Normal mass hierarchy (NH)
  $\Delta m^2_{31} < 0 \longrightarrow$ Inverted mass hierarchy (IH)
  Bayesian global analysis has a $3.2\,\sigma$ preference for NH



$\Longrightarrow$ Leads to a ***lower limit*** on sum of neutrino masses: $\sum_\nu m_\nu \gtrsim 0.06\,\mathrm{eV}$ (NH) $\sum_\nu m_\nu \gtrsim 0.10\,\mathrm{eV}$ (IH)

Frontiers in Astronomy and Space Sciences – FSPAS 5 (2018) 36

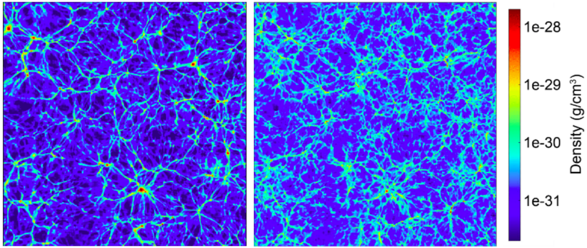
Cosmology

Neutrinos significantly effect late-times large structure formation of the Universe

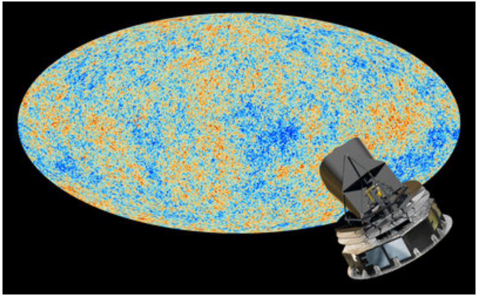
$\Longrightarrow$ Indirect determination of neutrino mass

Many (unknown) parameters in ΛCDM $+ \sum_\nu m_\nu$

$\Longrightarrow$ Model-dependent



No neutrinos | $\sum_\nu m_\nu = 1.9\,\text{eV}$



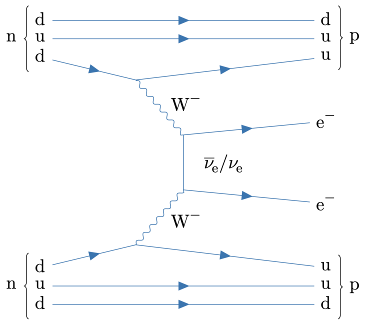
Planck CMB map

$\Longrightarrow$ ***Upper limit range*** on sum of neutrino masses:

$$\sum_\nu m_\nu < 0.11 - 0.54\,\text{eV (95\,\% CL)}$$

Particle Data Group 2020 (based on the Planck 2018 dataset)

Neutrinoless double β-decay

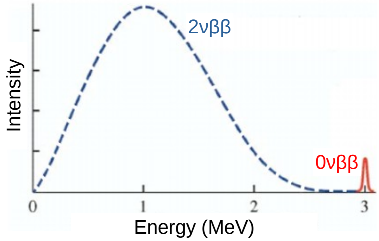


Hypothetical nuclear transition (A, Z) $\longrightarrow$ (A, Z+2) + $2e^-$

- Two neutrons convert into two protons and two electrons
- Candidate isotopes: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe, ...
  - $\Longrightarrow$ Neutrinos must be Majorana (own anti-particle)

Electrons share the entire energy released in the process

- Signature is a peak in the energy spectrum at the *Q*-value
  - $\Longrightarrow$ Half life measurement



Many experiments with different technology:

- Scintillation
- Semi-conductor
- Gaseous tracking detectors

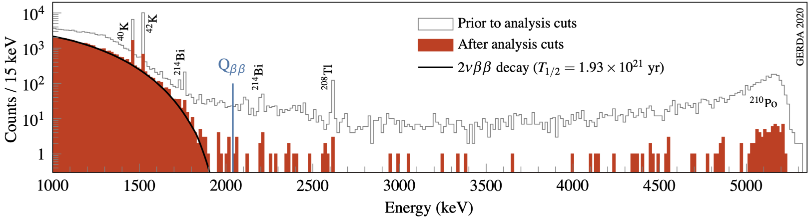
EXO, nEXO, CUORE, SNO+, KamLAND-Zen, CANDLES, LUCIFER, AMoRE, CORBRA, GERDA, MAJORANA, LEGEND, SuperNEMO

Neutrinoless double β-decay

Phase	Exposure (kgyr)
I	23.5
II	103.7
I+II	127.2

Recent results: GERDA

- $0\nu\beta\beta$-decay of high-purity Germanium ($Q = 2039.06\,\text{keV}$)
- Excellent detection efficiency because source and detector coincide
- Minimal background at Q-value



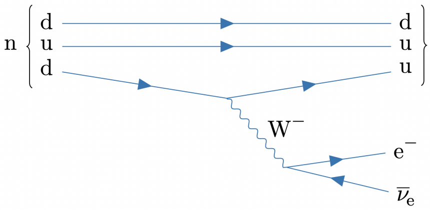
Phase I and II combined results:

- 90 % CL half life limit $T_{\frac{1}{2}} > 1.8 \times 10^{26}$ yr
- Converted to upper limit on neutrino mass from calculation with nuclear matrix elements

$\Longrightarrow$ Leading ***upper limit on Majorana*** neutrino mass: $m_{\beta\beta} < 0.079 – 0.180\,\text{eV}$ (90 % CL)

GERDA final results – Phys.Rev.Lett. 125 (2020) 252502

Single β-decay



Fermi-theory of three-body β-decay:

$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p(E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

- Fermi function, $F(E,Z)$, gives electromagnetic interactions of the electron with the daughter nucleus
- Electron neutrino flavour state emitted (flavour eigenstates are a superposition of the mass eigenstates)
- Spectrum is superposition of three spectra (weighted sum of three spectra)
- Neutrino mass is the incoherent sum of the neutrino mass square values:

$$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 \, m_{\nu_i}^2$$

Neutrino mass influences the energy spectrum of the β-decay electrons

⟹ Direct measurement

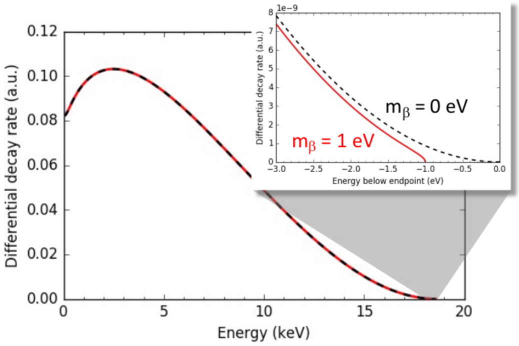
⟹ Model-independent

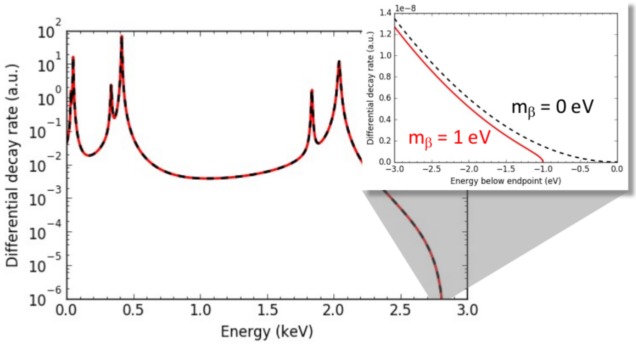
Single β-decay

Candidate isotopes			Half life, $T_{\frac{1}{2}}$	Endpoint, E_0
^{3}H	Tritium	super-allowed β-decay	12.32 yr	18.575 keV
^{163}Ho	Holmium	electron-capture decay	4570 yr	2.8 keV

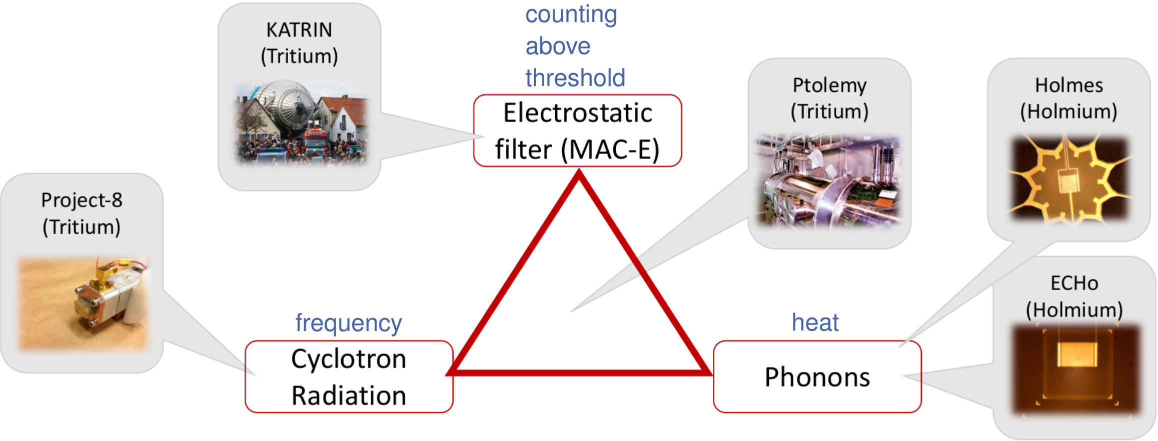
Tiny signal near endpoint

- Strong source
- Low background
- Excellent energy resolution





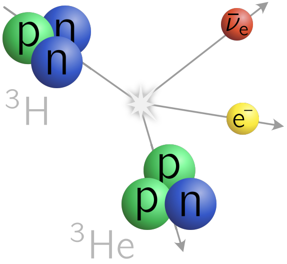
Single β-decay



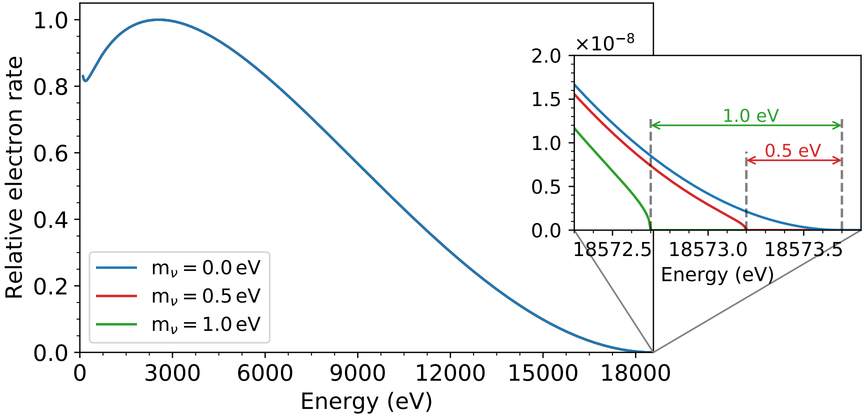
Currently taking competitive neutrino mass data: KATRIN

Demonstrator and R&D: ECHo, Holmes, Project-8 Possible future prospects: Ptolemy, ...

The KATRIN experiment



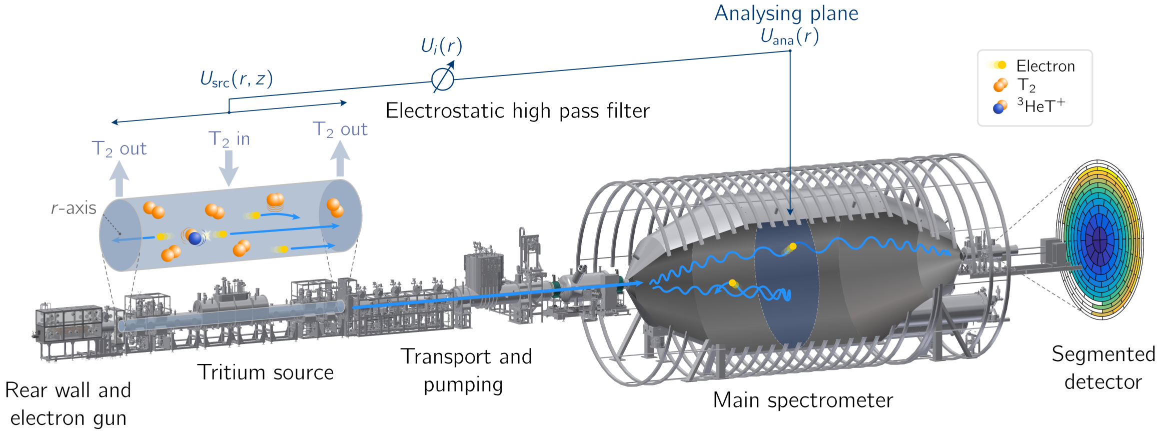
$$T_2 \longrightarrow He^+ + e^- + \bar{\nu}_e$$



m_ν^2 is determined with a precise measurement of the β-electron spectrum near the endpoint

- KATRIN measures the ***integrated*** β-electron spectrum
- Influence of m_ν^2 is seen a few eV below E_0

The KATRIN experiment



Spectrometer and detector section

Magnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic filter (MAC-E filter)

Beamson et al. (1980), Lobashev, Spivak (1985), Picard et al. (1992)

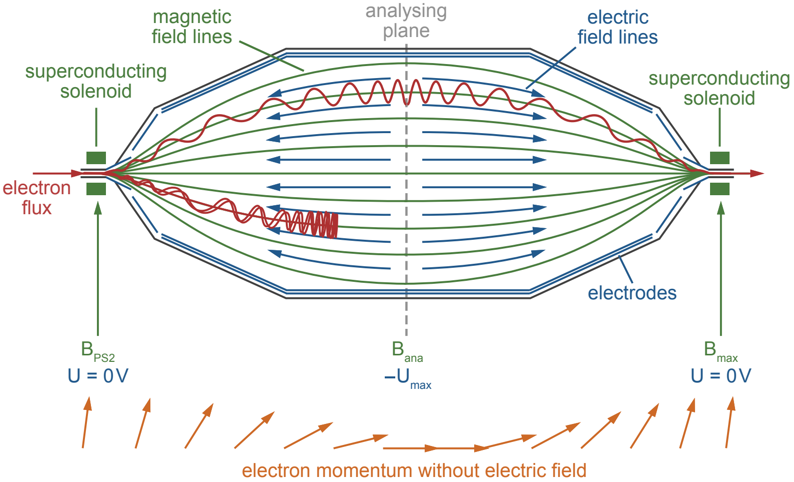
Electrons are guided and filtered according to their kinetic energy

⟹ Electron momentum perpendicular component is transferred to parallel component

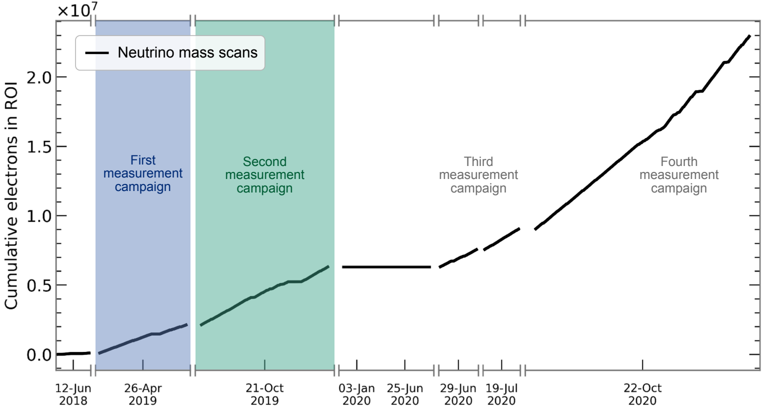
$$\mu = \frac{E}{B} = \text{constant}$$

⟹ Electrons filtered by electric field in analysing plane

$$\Delta E = \frac{B_{\text{ana}}}{B_{\text{max}}} E$$



Measurement campaigns



Published results: 1st and 2nd measurement campaigns

1st	Apr 2019	–	May 2019
2nd	Sep 2019	–	Nov 2019
3rd	Jun 2020	–	Jul 2020
4th	Sep 2020	–	Dec 2020
5th	Mar 2021	–	May 2021
6th	Sep 2021	–	......

Analyses are ongoing in parallel as data is continuously being measured

- m_ν^2 analysis
- BSM analyses
  - eV-sterile
    PRL 126 (2021) 2011.05087
  - keV-sterile
  - Cosmic relic neutrinos
  - Right-handed currents
  - Lorentz invariance violation

The KATRIN experiment

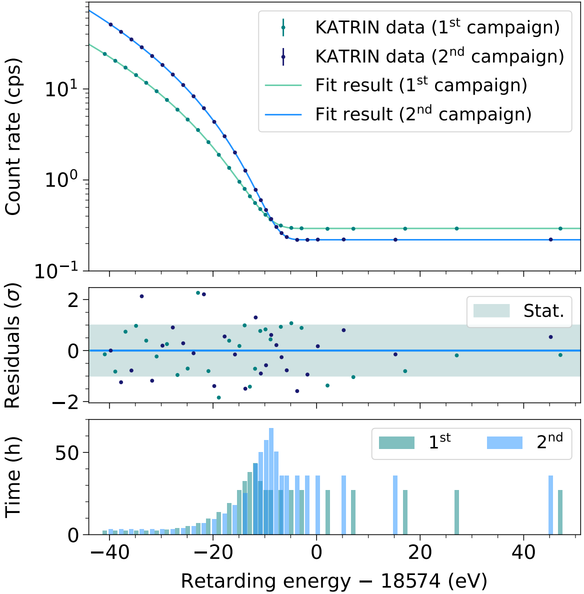
Simultaneous fit of 1st and 2nd measurement campaigns with one likelihood:

$$-\log \mathcal{L} = \sum_i -\log \mathcal{L}_i \left(m_\nu^2, E_{0\,i}, \mathrm{Sig}_i, \mathrm{Bg}_i \right)$$

- Statistics dominated fit result
- Central value $m_\nu^2 = 0.07 \pm 0.32\,\mathrm{eV}^2$

$\Longrightarrow$ Leading ***upper limit*** on neutrino mass:

$m_\nu < 0.75\,\mathrm{eV}$ (90 % CL)



PRL 123 (2019) 22-221802, Nature in preparation (2021)

Summary

Neutrino flavour oscillation

⟹ Determination of mass splittings

⟹ Lower limit

$$\sum_\nu m_\nu \gtrsim 0.06\,\text{eV (NH)},\ 0.10\,\text{eV (IH)}$$

Cosmology

⟹ Indirect determination from Universe structure

⟹ Model-dependent, upper limit range

$$\sum_\nu m_\nu < 0.11 - 0.54\,\text{eV (95 \% CL)}$$

Neutrinoless double β-decay

⟹ Half life measurement

⟹ Neutrinos must be Majorana (own anti-particle)

- World's leading upper limit: GERDA

$$m_{\beta\beta} < 0.079 - 0.180\,\text{eV (90 \% CL)}$$

Single β-decay

⟹ Direct measurement

⟹ Model-independent

- World's leading upper limit: KATRIN

$$m_\nu < 0.75\,\text{eV (90 \% CL)}$$