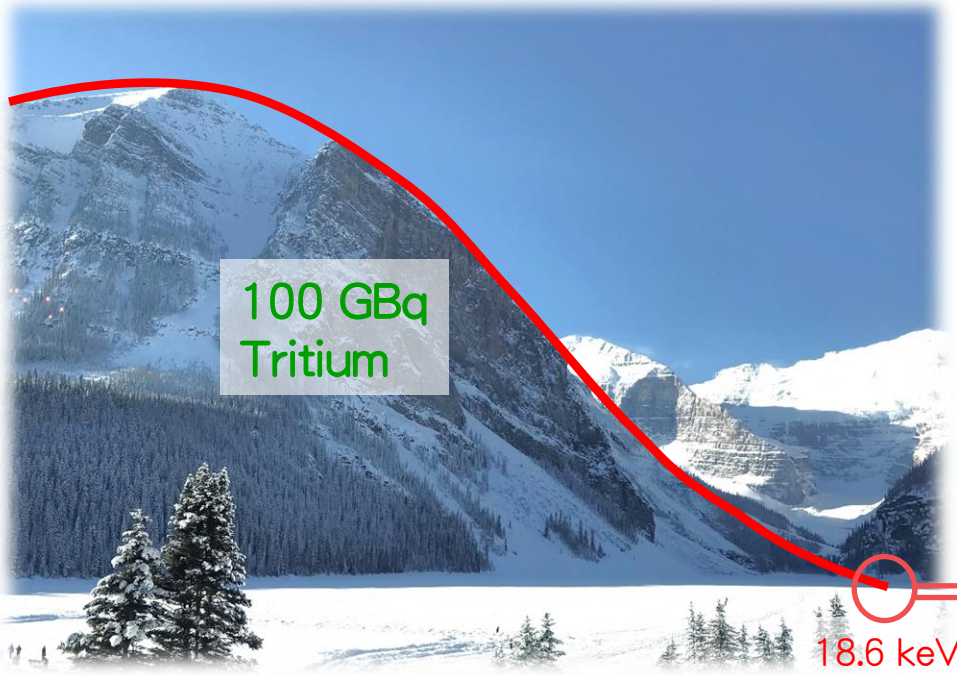
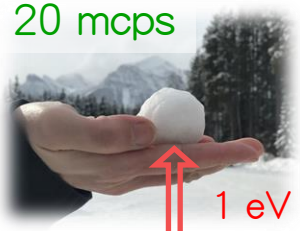
KATRIN

Direct Measurement of Neutrino Mass

Look outside for tritium beta decay spectrum



And try to see
the neutrino mass



Sanshiro Enomoto
University of Washington

KATRIN

Direct Measurement of Neutrino Mass

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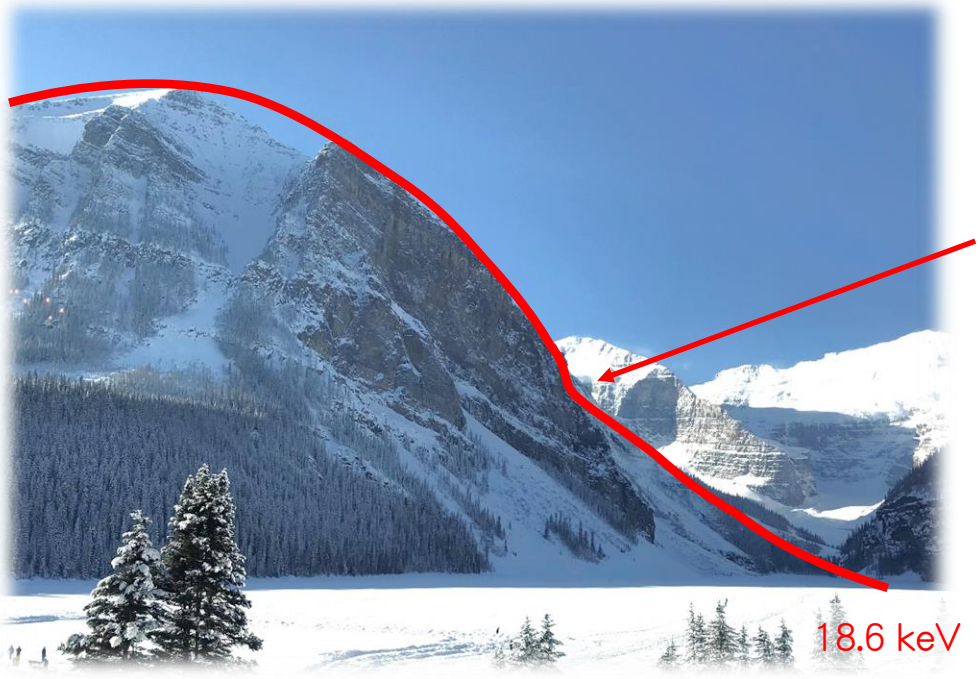


Kink from
sterile neutrinos

Sanshiro Enomoto
University of Washington

KATRIN

Direct Measurement of Neutrino Mass

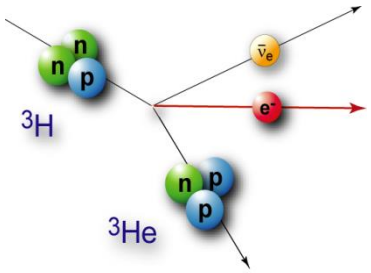
Look outside for tritium beta decay spectrum

Peak from capturing
cosmic background neutrinos

Sanshiro Enomoto
University of Washington

Neutrino Mass Measurement with Single Beta Decay

Use Kinematics only, look at the end-point shape

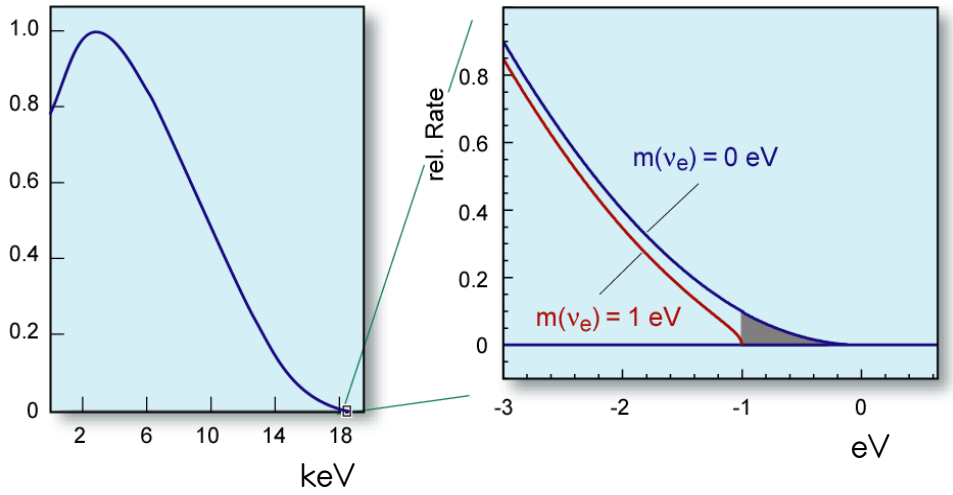


$$\frac{dN}{dE_e} = C \cdot F(E,Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e)\sqrt{(E_o - E_e)^2 - m_{\nu_e}{}^2}$$

$$\sum_i |U_{ei}|^2 \cdot m_i{}^2 \sim m_i{}^2$$

in degenerated region

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



Neutrino Mass Measurement with Single Beta Decay

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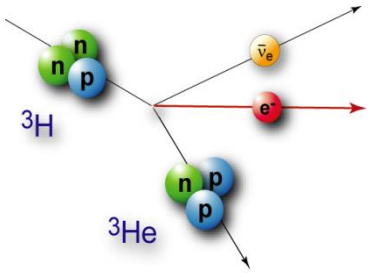

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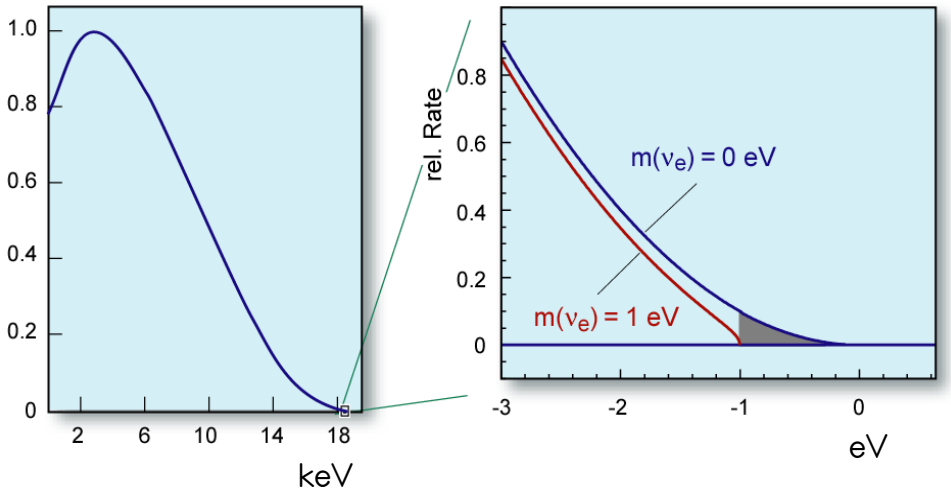
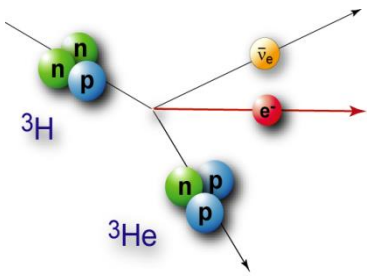


Tritium as beta-source

- low end-point (18.6 keV)
  - → relatively large deformation
  - → electro-statically reachable
- short life (12.3 y):
  - → small source amount
  - → less scattering in source
- super-allowed transition
  - → matrix element reliably calculable
- simplest molecular:
  - → molecular states calculable

Neutrino Mass Measurement with Single Beta Decay

Use Kinematics only, look at the end-point shape



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$$\sum_i |U_{ei}|^2 \cdot m_i{}^2 \sim m_i{}^2$$

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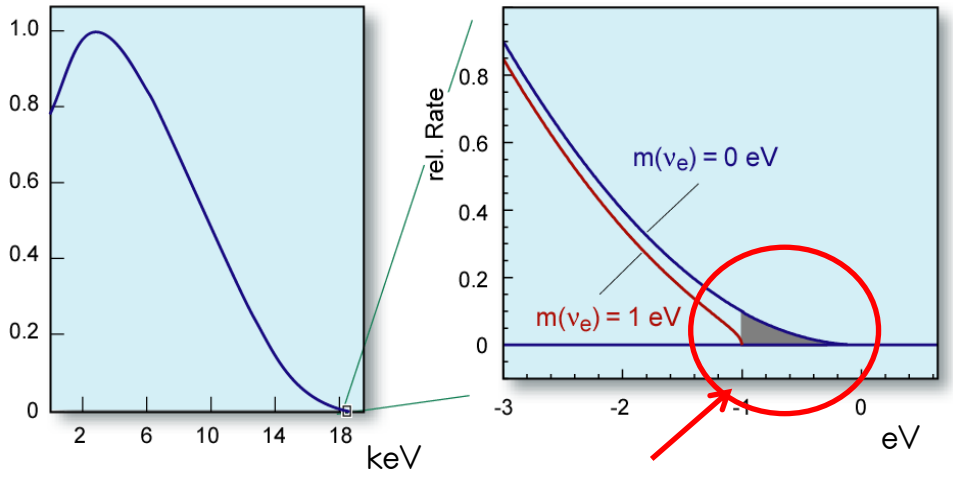


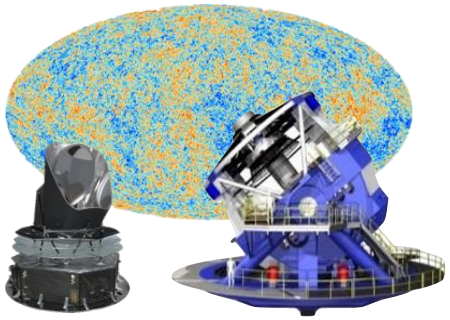
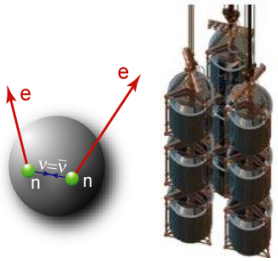
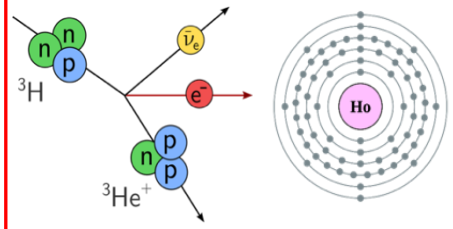
only 2×10^{-13} of all beta in last 1 eV

Needs:

- strong stable source
- high precision spectroscopy

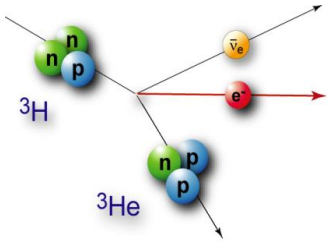
Direct Measurement Using Kinematics Only

Methods to measure Neutrino Mass

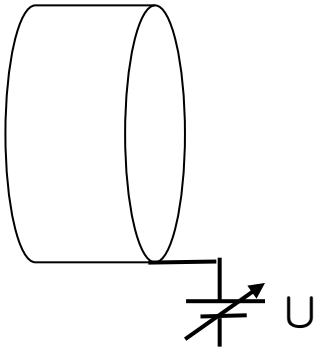
	Cosmology	0νββ	β decay / EC
			
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\lvert \sum_i U_{ei}^2 \, m_i \right\rvert^2$	$m_\beta^2 = \sum_i \lvert U_{ei} \rvert^2 \, m_i^2$
Relies on	ΛCDM	Majorana	Kinematics

Model Independent
Direct Measurement

Electron Spectroscopy with Electro-Static Filter

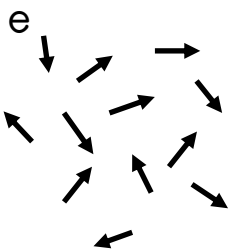


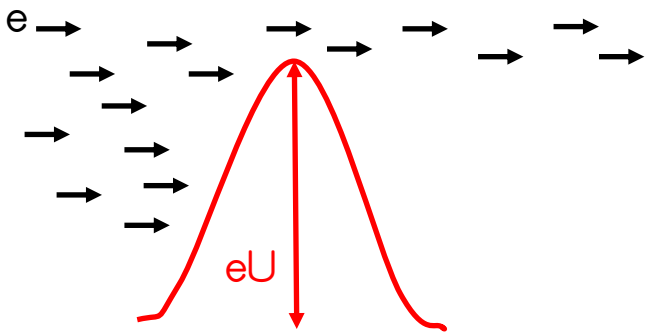
tritium
source



electro-static
retarding potential

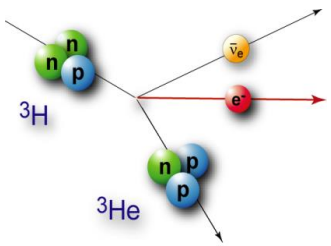
electron
counter



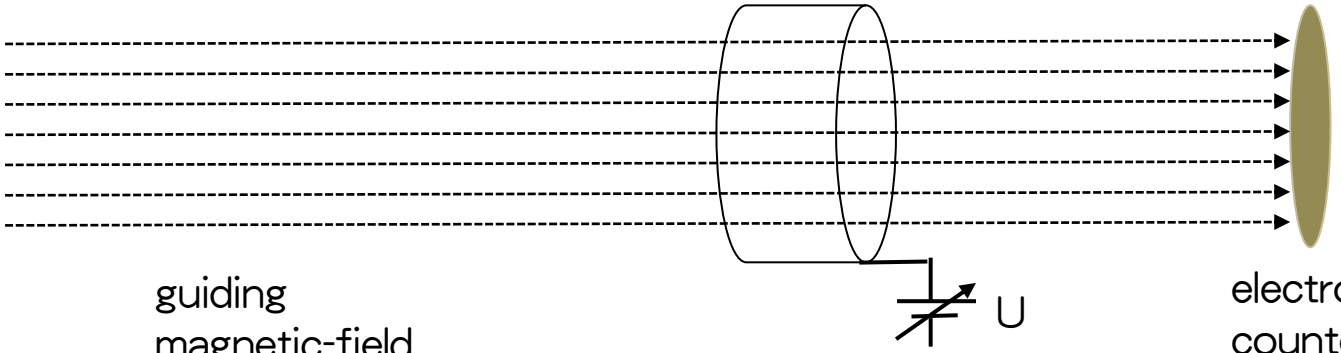


Problem: only small fraction of electrons reach this
→ guiding magnetic field

Electron Spectroscopy with Electro-Static Filter



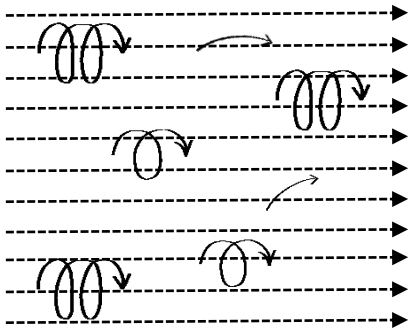
tritium source



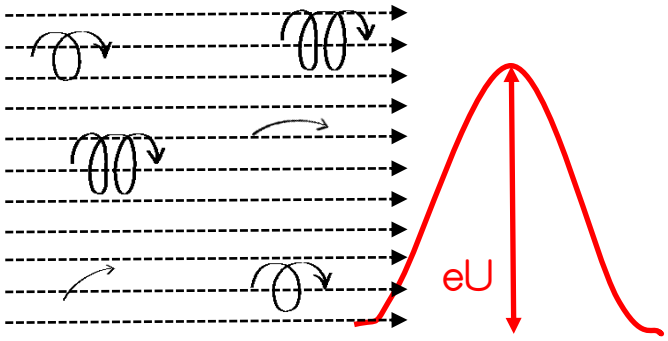
guiding magnetic-field

electro-static retarding potential

electron counter

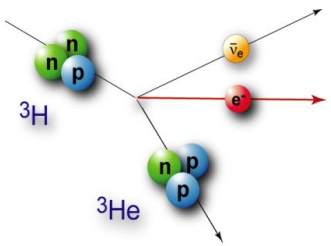


$E_{parallel}$ / $E_{transversal}$ depends on initial emission angle

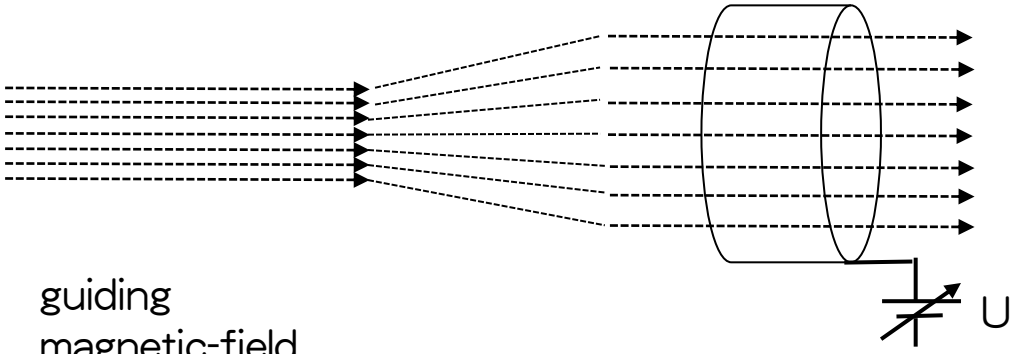


Problem: only $E_{parallel}$ is measured
→ adiabatic collimation

Electron Spectroscopy with Electro-Static Filter



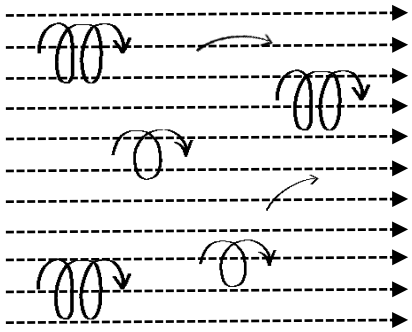
tritium source

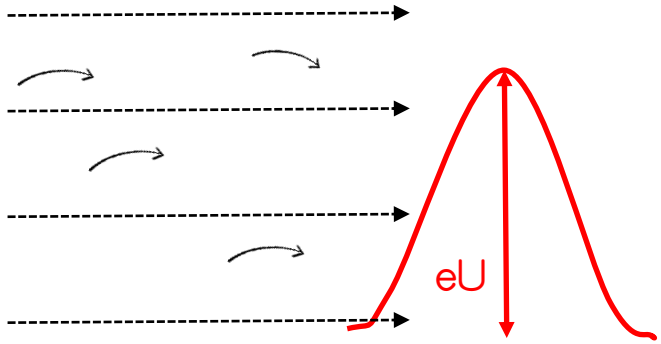


guiding magnetic-field

electro-static retarding potential

electron counter

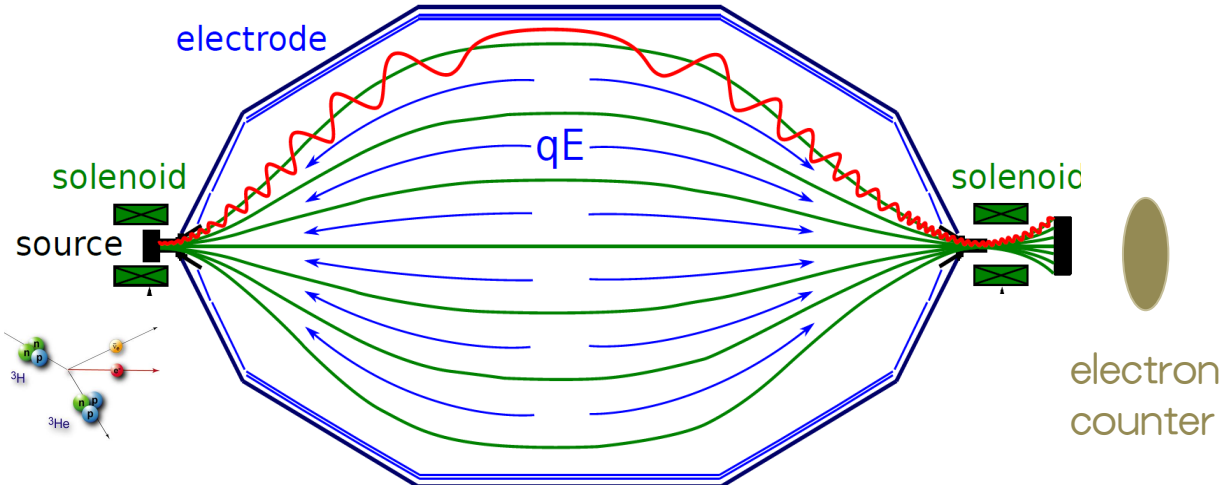


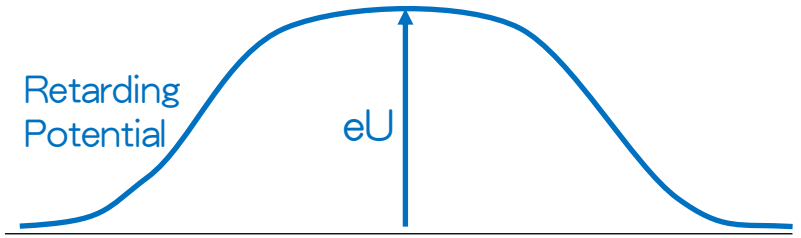


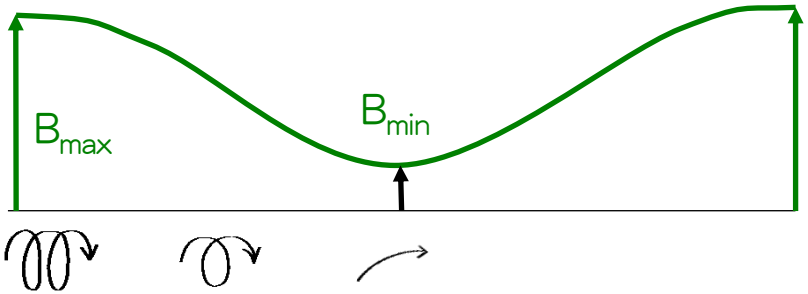
reduce magnetic field adiabatically

⇒ magnetic moment conserves: $\mu = \frac{E_\perp}{B} = \text{const}$ ⇒ collimation

MAC-E (Magnetic-Adiabatic-Collimation Electro-static) Filter







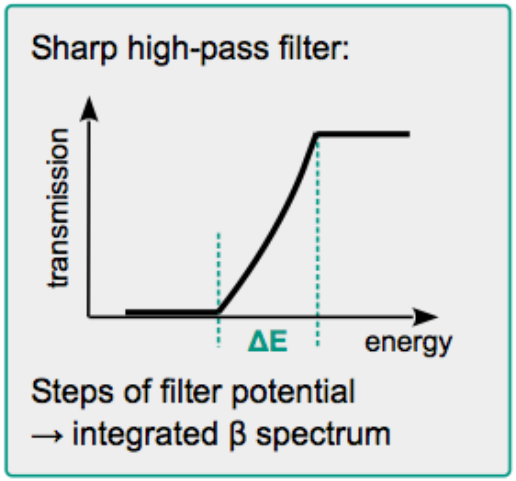
Adiabatic Transmission (or blocking)

Adiabatic Transmission
(constant magnetic moment)

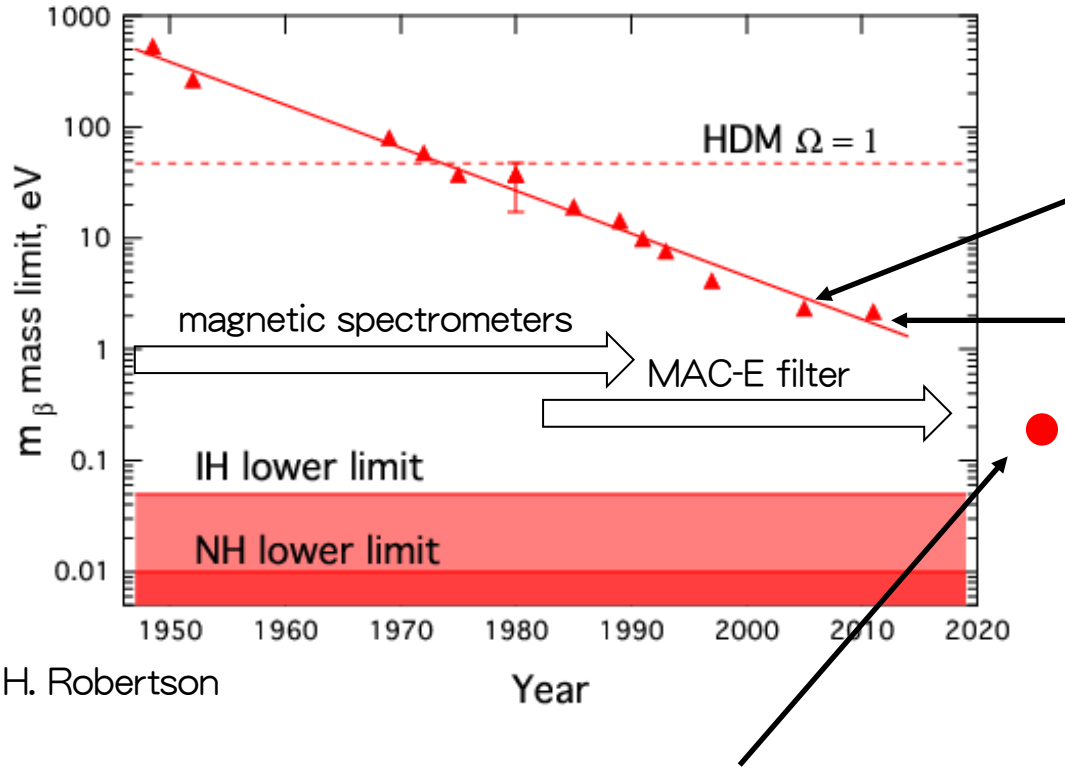
$$\mu = \frac{E_\perp}{B} = \text{const}$$

Energy resolution is determined by B-Ratio

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

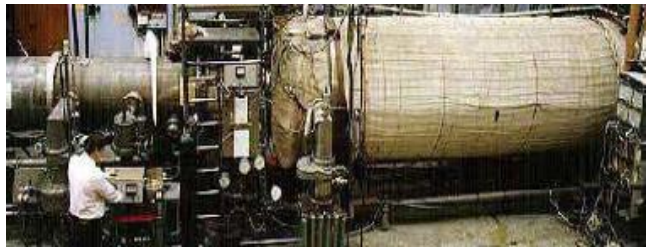


Present Mass Limit and KATRIN Experiment



H. Robertson

Mainz (2005, final result)
$m(\nu_e) < 2.3$ eV (95%CL)



Troitsk (2011, re-analysis)
$m(\nu_e) < 2.05$ eV (95%CL)

KATRIN

design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL)

sensitivity 1/10 on m_ν

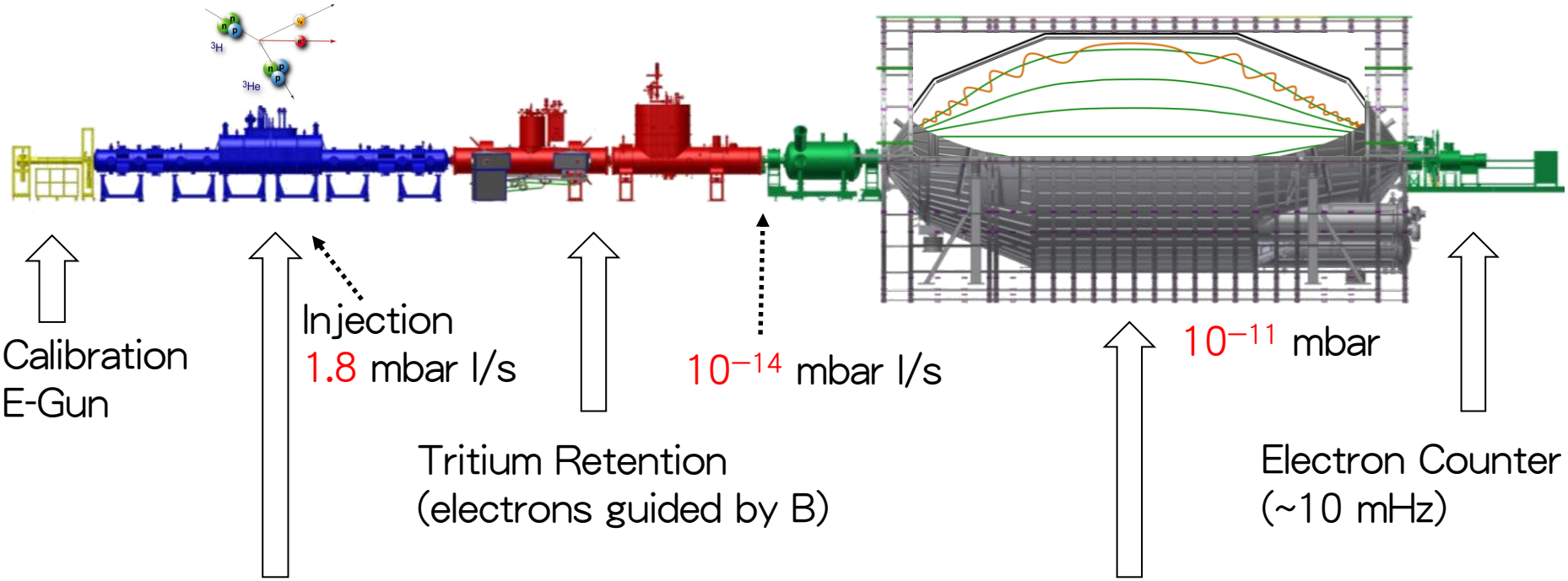
⇒ sensitivity 1/100 on m_ν^2

⇒ x100 statistics, 1/100 systematics

KATRIN Experiment

KArlsruhe TRItium Neutrino Experiment

- located at Karlsruhe Institute of Technology, Karlsruhe, Germany
- design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL, 3 years)



10^{11} Bq Gaseous Tritium Source
(largest ever tritium throughput, as of 2018)

0.9 eV Resolution MAC-E Filter
(largest ever UHV vessel, as of 2013)

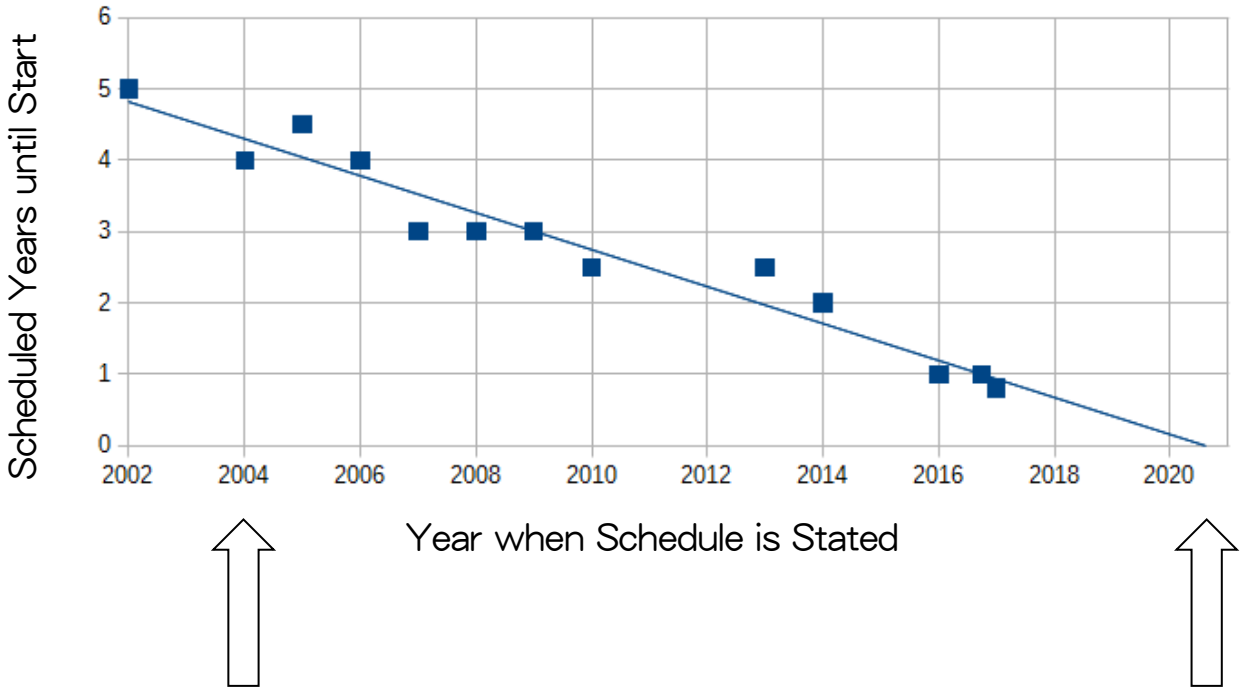
All numbers are from KATRIN Design Report (2004)

KATRIN Collaboration

- ~150 Collaborators
- 20 Institutions
- 6 Countries
  DE, US, RU, CZ, FR, ES

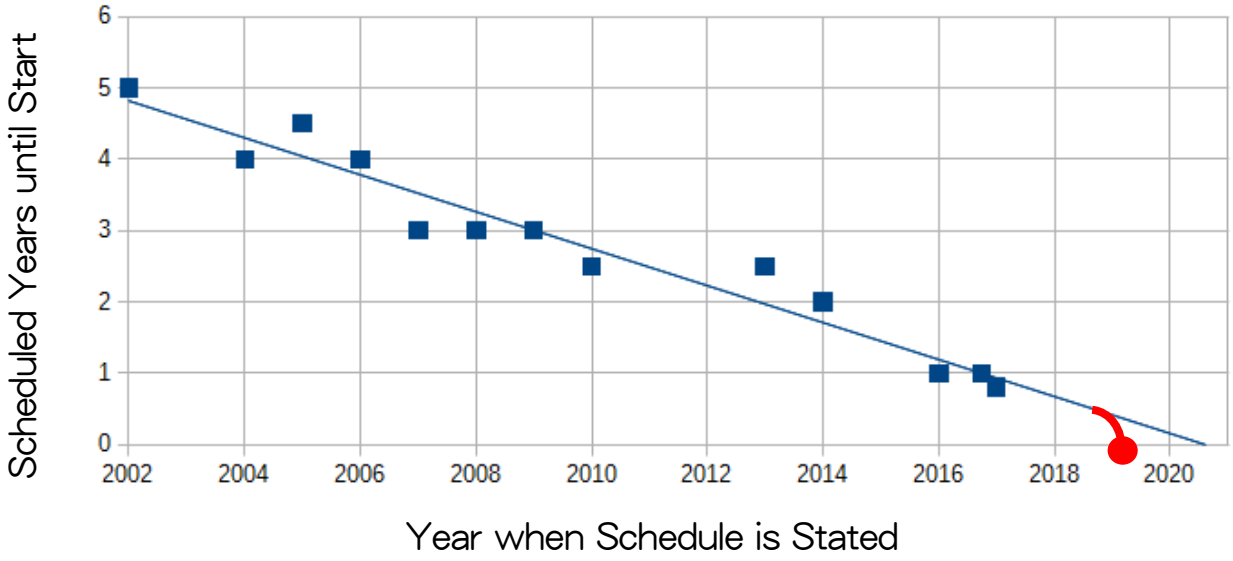
KATRIN History

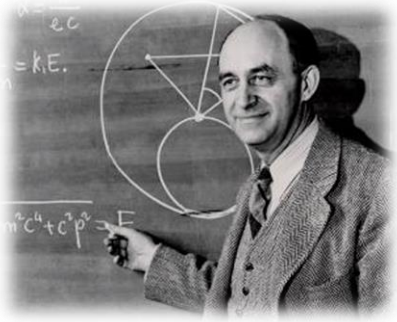
- Design Report in 2004, planned to start in 4 years



KATRIN History

- Design Report in 2004, planned to start in 4 years
- Started data taking in 2019





Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

KATRIN has demonstrated end-points are deformed!!

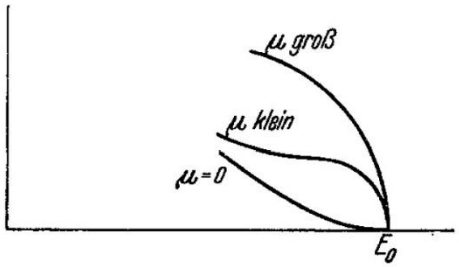


Fig. 1.

KATRIN Results

Nov 2019: First Result

PRL 123, 221802 (2019)

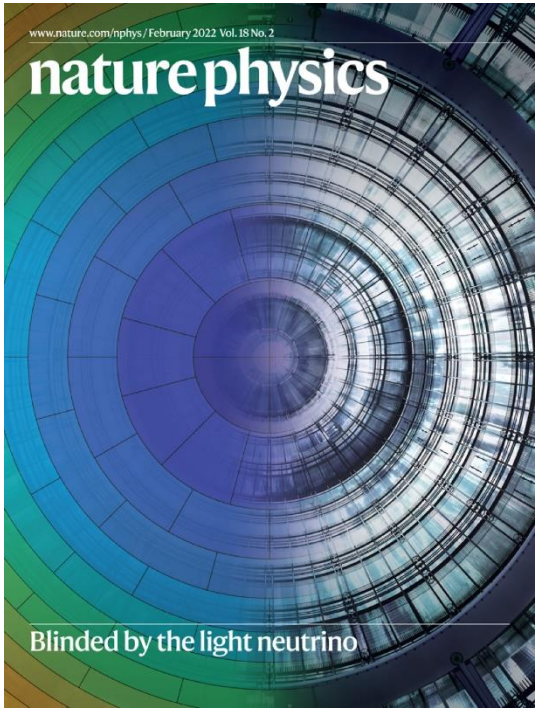
- 3 weeks live-time
- Limited tritium activity

$m_\nu^2 = -1.0^{+0.9}_{-1.1}\ \mathrm{eV}^2$

$m_\nu < 1.1\ \mathrm{eV}$ (90%CL) (Previous limit 2.0 eV)

Last Week!!

Feb 2022: Second Result



Nature Physics 18, 160-166 (2022)

- Additional 4 weeks live-time
- Full tritium activity
- Reduced backgrounds

Towards 2022 Result

Run 1 (2019 Apr-May)

- 22 days live-time
- 290 mcps BG
- 25 GBq source

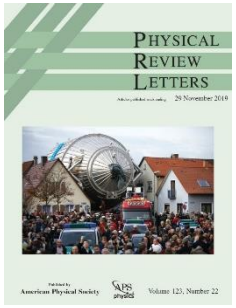
Run 2 (2019 Sep-Nov)

- 31 days live-time
- 220 mcps BG (-25%)
- 95 GBq source (×4 (to nominal))
  ⇒ instability by plasma

Run 3 (2020-)

- Further BG reduction tested
- Intensive plasma investigation

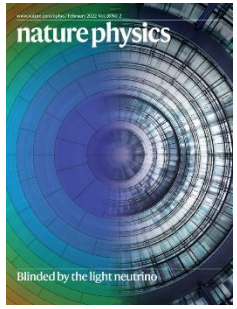
PRL 2019



Run 1

$m_\nu < 1.1$ eV (90%CL)

Nature Physics 2022



Run 2 Only

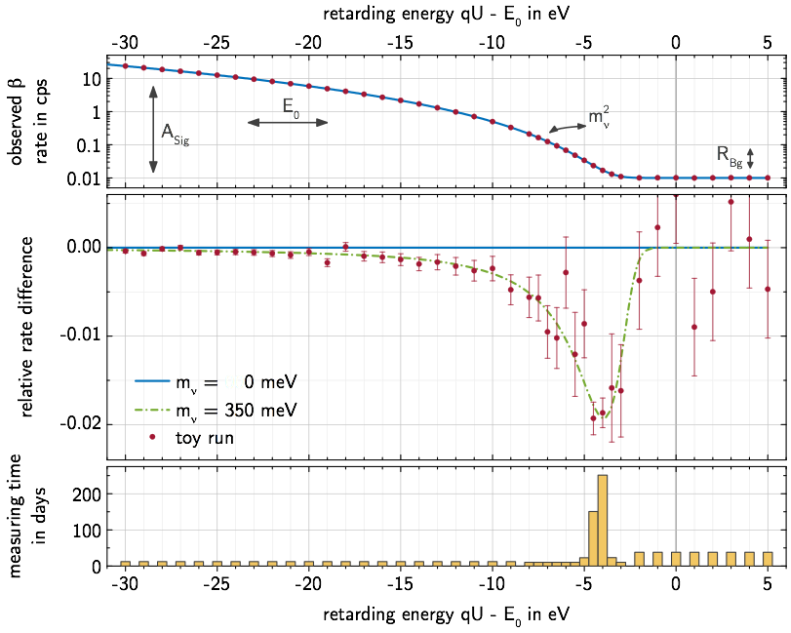
$m_\nu < 0.9$ eV (90%CL)

Run 1 & 2 Combined

$m_\nu < 0.8$ eV (90%CL)

Neutrino Mass Analysis and Results

Spectrum Model and Measurement Strategy

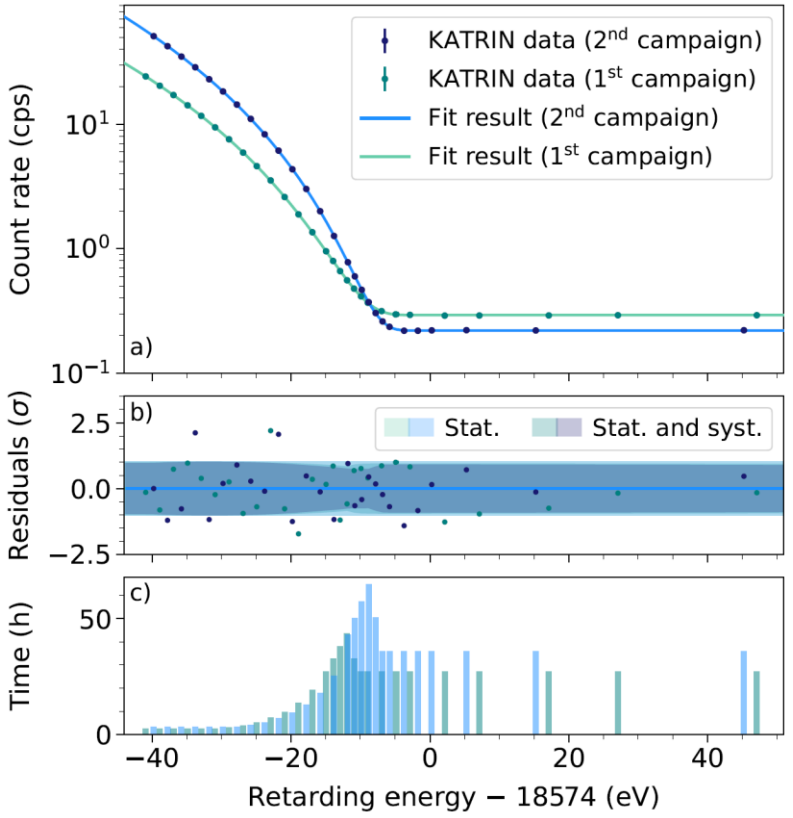


$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_{\beta}(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

activity — beta decay spectrum — apparatus response — backgrounds

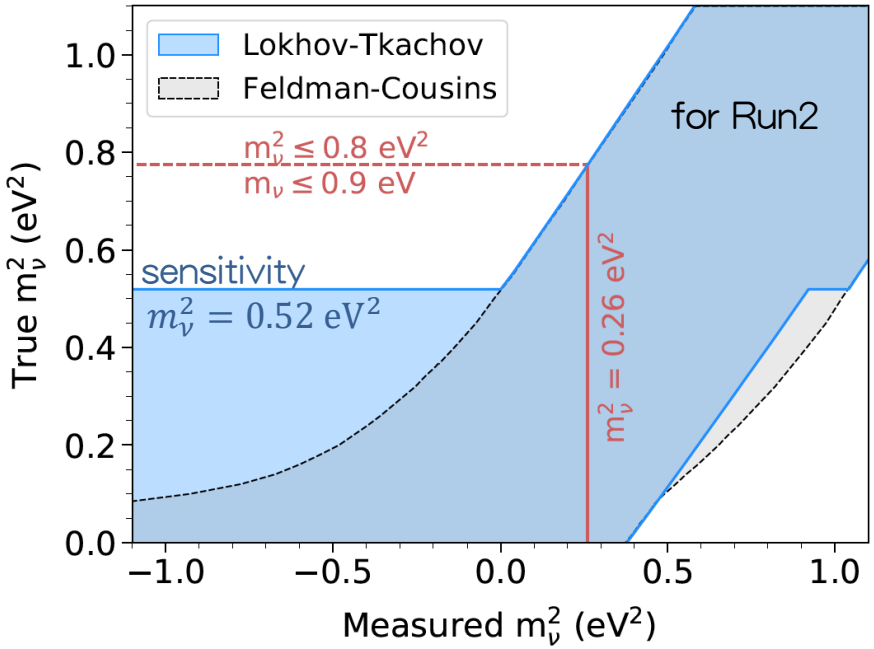
plus a number of nuisance parameters

Measured Spectra and Fitting Results



$$m_\nu^2 = 0.26 \pm 0.34 \ \text{eV}^2$$

Mass Limit Setting



Feldman-Cousins (FC)

- De facto standard
- Provided only for supplementary

Lokhov-Tkachov (LT)

- No "tighter limit" from negative m^2
- For negative m^2, stop at the sensitivity
- Coverage is still correct (no flip-flopping)

Run 1

$m_\nu^2 = -1.0^{+0.9}_{-1.1}$ eV^2

$m_\nu < 1.1$ eV (LT 90%CL)

($m_\nu < 0.8$ eV (FC 90%CL))

Run 2

$m_\nu^2 = 0.26 \pm 0.34$ eV^2

$m_\nu < 0.9$ eV (90%CL)

Run 1 & 2 combined

$m_\nu^2 = 0.1 \pm 0.3$ eV^2

$m_\nu < 0.8$ eV (90%CL)

Independent Consistency Check: Beta-decay Q-value

KATRIN: 18575.20 ± 0.60 eV

Δm (^{3}He - ^{3}H): 18575.72 ± 0.07 eV (this information is not used for spectrum fitting)

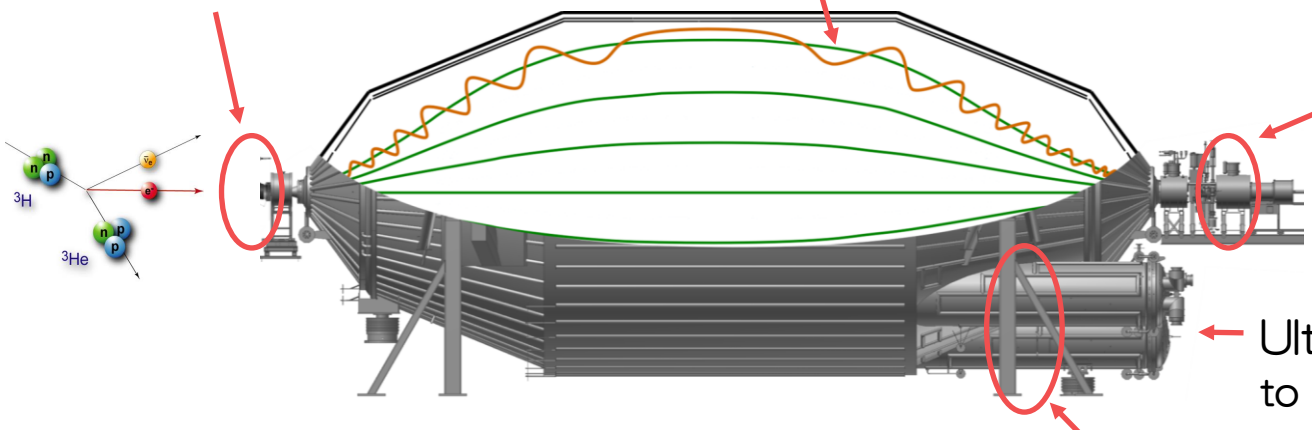
KATRIN Backgrounds and Suppression

Backgrounds: electrons not from tritium, reaching the detector

Prevention / Suppression Methods

E and B fields
to prevent charged particles from entering

Beamline Wiper
to remove trapped particles



Active Muon Veto &
Passive Gamma Shields
surrounding the detector

Ultra High Vacuum Pumping
to reduce residual gas ionization

Cooled Baffle
to trap Radon

Everything worked out beautifully

Unexpected Backgrounds: Rydberg Atoms (excited Hydrogen atoms)

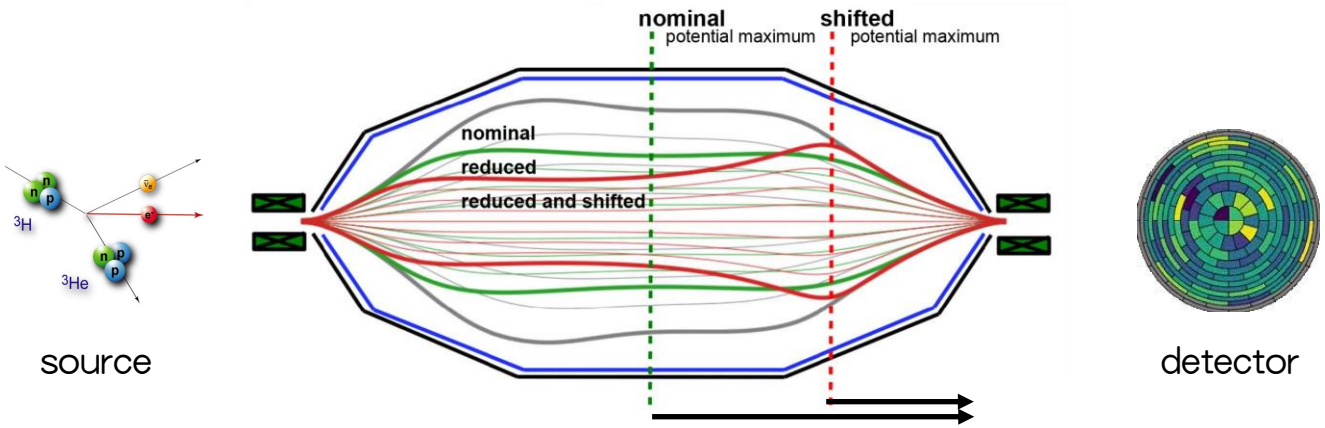
- Hydrogen on the wall is excited by ^{210}Po α-decays and released to volume
- Then de-excites in vacuum with emitting an electron

Background rates: 10 mcps (design report) → 290 mcps (Run 1)

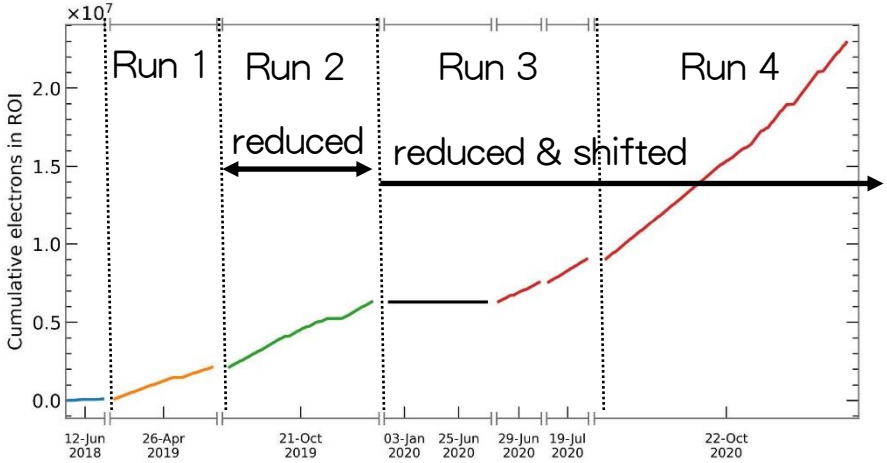
cps:
counts-per-sec

Rydberg Background Reduction

Rydberg BG electrons originate all the volume in the spectrometer
⇒ reduce the flux volume
⇒ shift the retarding potential peak (analyzing plane) towards detector

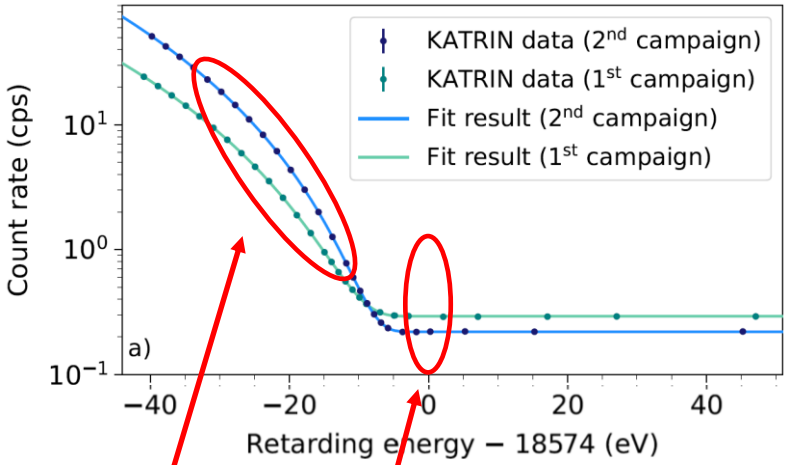


Data Being Taken in New Configuration



Also other ideas are being developed
ex) filtering by pitch-angles

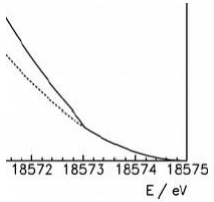
Other Physics from KATRIN



Cosmic neutrino backgrounds make a peak here through capture of them

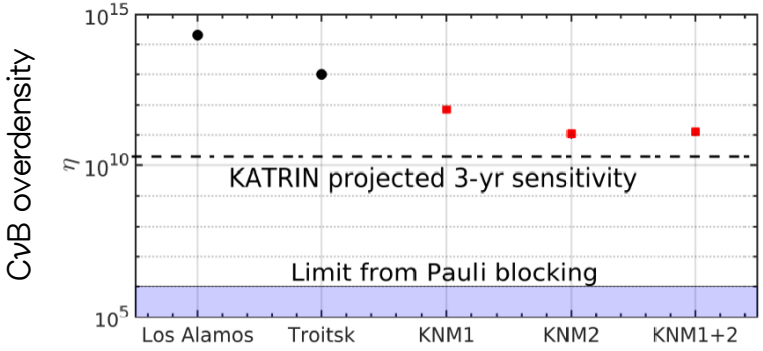
Sterile neutrinos make a kink here through state mixing

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



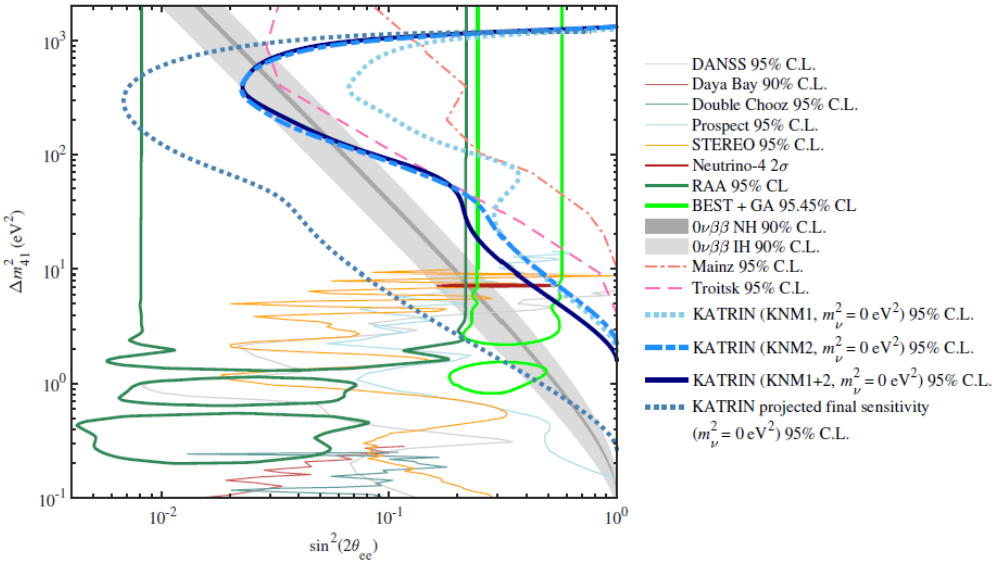
Cosmic Neutrino Background

arXiv: 2201.04587 (9 Feb 2022) Fresh!



Sterile Neutrinos

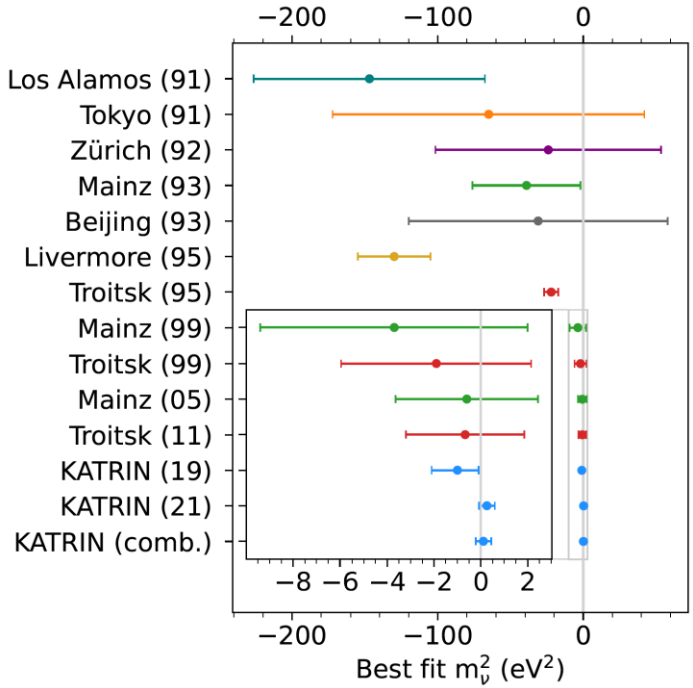
arXiv: 2201.11593 (27 Jan 2022) Fresh!

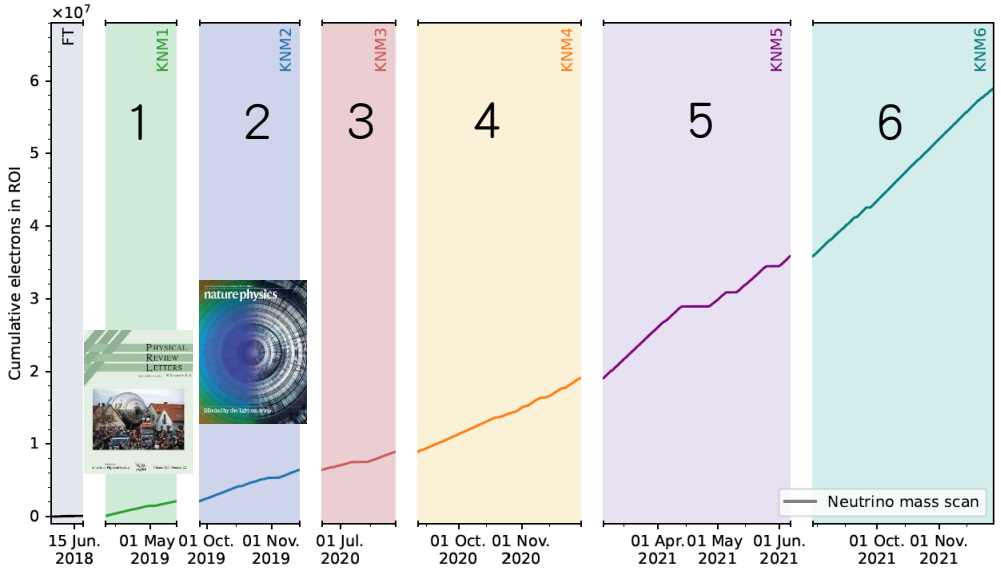


Conclusions and Outlook

- First sub-eV result: $m_\nu < 0.8$ eV (90%CL)
- Final design sensitivity 0.2 eV (90%CL) in 5 years

- Limits on sterile neutrinos, cosmic relic neutrinos, and more to come
  (Lorentz violation, right-handed current, additional light bosons, keV-scale sterile neutrinos)





Run 7 is about to start

- Much more data already in hand, being analyzed (still blinded)
- Further background reduction on going