Direct limits on neutrino masses

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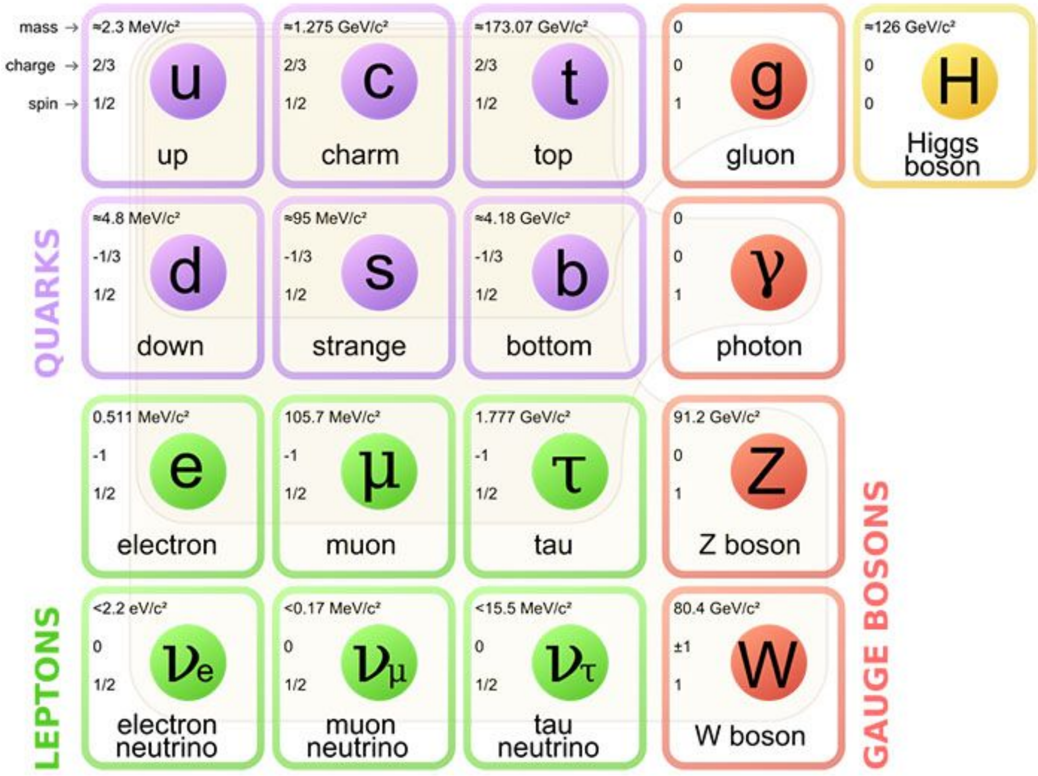
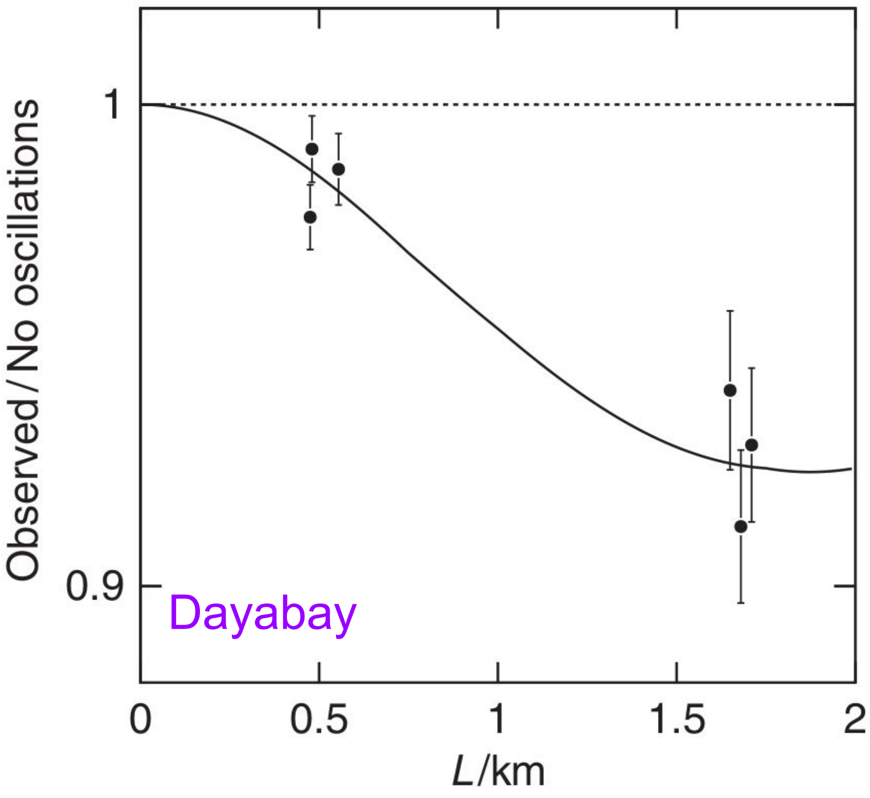
Standard model of particle physics

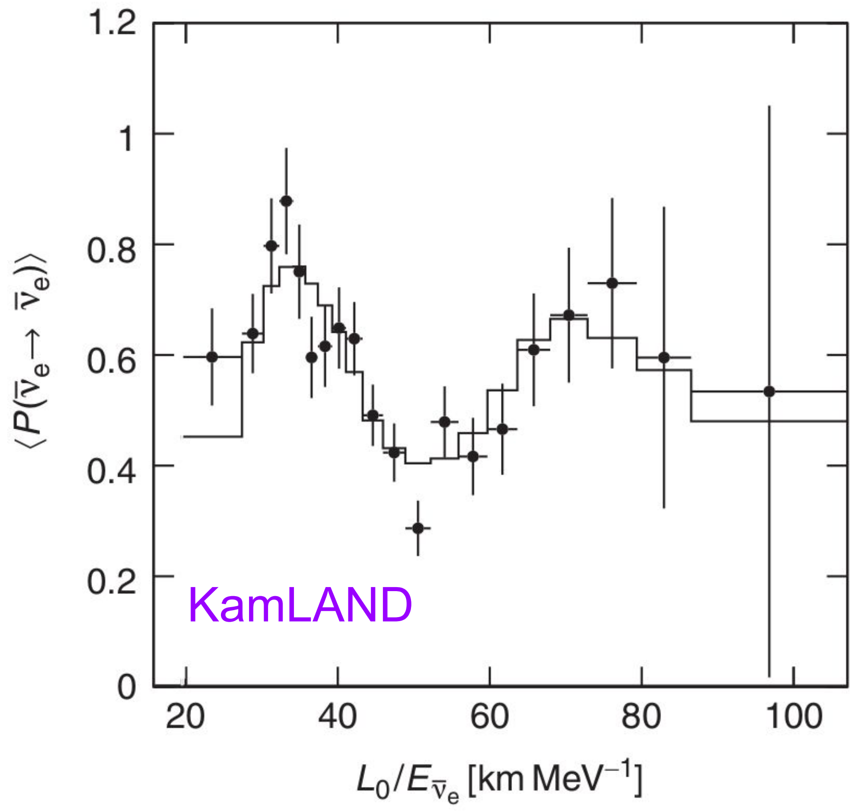
- Standard model of particle physics has been tremendously successful in explaining most of the experimental phenomena
- Unexplained phenomena:
  - Existence of dark matter
  - **Neutrino oscillations**
  - Matter/Anti-matter asymmetry
  - Hierarchy problem
  - Why only 3 generations of matter?
- SM neutrinos do not oscillate and are massless
  - Experimental evidence says otherwise!



Neutrinos oscillate

- From numerous experiments, we know today that neutrinos do oscillate
- The oscillations occur for all the weak flavors of neutrinos
- This implies that at least two neutrinos are massive





Neutrino oscillations ⇒ massive neutrinos?

- Neutrino weak eigenstates, ν_e, ν_μ and ν_τ, differ from the neutrino mass eigenstates
- For example, in the W^+ boson decay, ν_e is produced in association with a e^+ but it can be any mass eigenstate -> ν_e is in fact superposition of the three mass eigenstate
  - The wavefunction for ν_e at the interaction vertex can be written as

$$|\psi\rangle = U_{e1}^*|\nu_1\rangle + U_{e2}^*|\nu_2\rangle + U_{e3}^*|\nu_3\rangle.$$

- Similarly, the following PMNS matrix related the three weak eigenstates to mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillation theory

- An electron neutrino produced at the interaction point:

$$|\psi(0)\rangle = |\nu_e\rangle \equiv U_{e1}^{*}|\nu_1\rangle + U_{e2}^{*}|\nu_2\rangle + U_{e3}^{*}|\nu_3\rangle$$

- Its propagation is described by

$$\begin{aligned}|\psi(\mathbf{x},t)\rangle = {} & U_{e1}^{*}(U_{e1}|\nu_e\rangle + U_{\mu1}|\nu_\mu\rangle + U_{\tau1}|\nu_\tau\rangle)e^{-i\phi_1}\\ & + U_{e2}^{*}(U_{e2}|\nu_e\rangle + U_{\mu2}|\nu_\mu\rangle + U_{\tau2}|\nu_\tau\rangle)e^{-i\phi_2}\\ & + U_{e3}^{*}(U_{e3}|\nu_e\rangle + U_{\mu3}|\nu_\mu\rangle + U_{\tau3}|\nu_\tau\rangle)e^{-i\phi_3}\end{aligned}$$

- Probability of electron survival at length L is described by

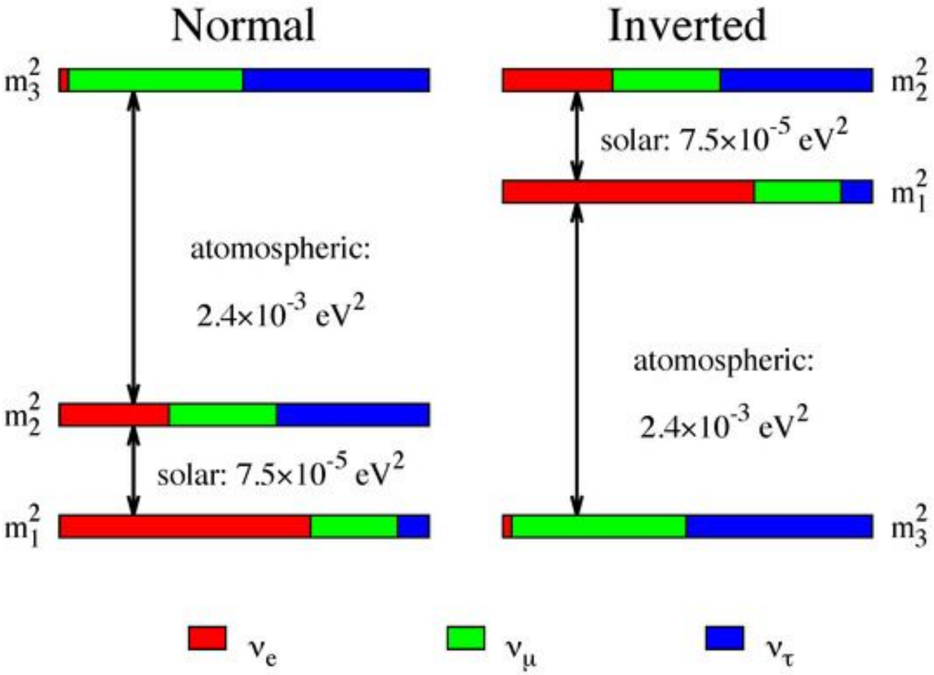
$$\begin{aligned}P(\nu_e \to \nu_e) = 1 & - 4|U_{e1}|^2|U_{e2}|^2 \sin^2\Delta_{21}\\ & - 4|U_{e1}|^2|U_{e3}|^2 \sin^2\Delta_{31} - 4|U_{e2}|^2|U_{e3}|^2 \sin^2\Delta_{32}.\end{aligned}$$

where

$$\Delta_{ji} = \frac{\phi_j - \phi_i}{2} = \frac{(m_j^2 - m_i^2)L}{4E_\nu}.$$

Probability of electron survival depends on neutrino mass difference

- If neutrinos were massless, $\Delta m^2_{31} = \Delta m^2_{21} = \Delta m^2_{32} = 0$ which implies $P(\nu_e \rightarrow \nu_e) = 1$ and there would be no oscillations
- From the neutrino oscillation experimental results, it is clear that
  - Δm^2_{31} , Δm^2_{21} and Δm^2_{32} are non-zero
  - Only two of these differences are independent and $\Delta_{31} = \Delta_{32} + \Delta_{21}$
  - From neutrino oscillations measurements, we get mass differences
- How do we measure the masses of the neutrinos?



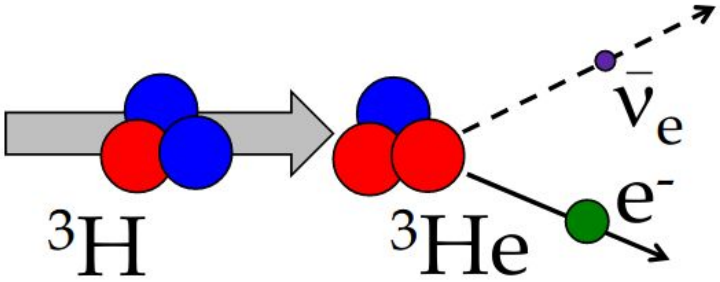
Model dependent limits

- Cosmological limits:
  - Comparing the Planck satellite data with the simulations of early universe development, yields an upper limit on sum of all neutrino masses
  - Sum of masses < 0.12 eV at 95% CL after including BAO and other data
  - Caveats:
    - Such limits depend on which data is included in the study
    - Assumes neutrinos are stable on cosmological timescales
    - Valid only in ΛCDM model
- Neutrino-less double beta decay:
  - Provides an estimate for neutrino mass assuming it is a Majorana fermion

Model independent limits

- Electron-capture decay of 163Holmium
    - Best limits from this study are mass<150 eV in 2019
- Tritium decay provides a direct measurement on neutrino mass
    - This measurement is model independent
    - End-point energy is 18.57 keV
    - Half life of Tritium is 12.32 years

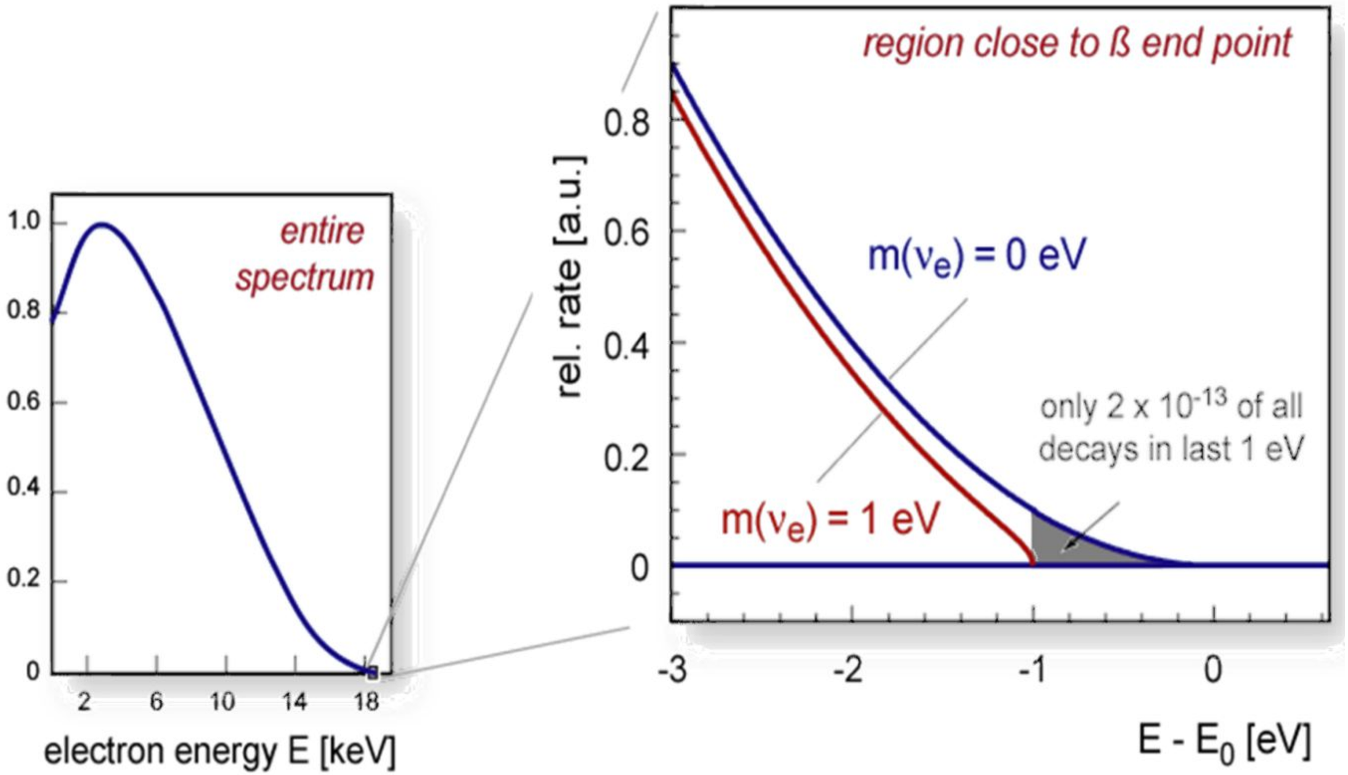
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + \mathrm{e}^{-} + \bar{\nu}_e$$



$$m^2_{\nu,\mathit{eff}} = \sum_{i}^{3} |U_{ei}|^2 m_i^2$$

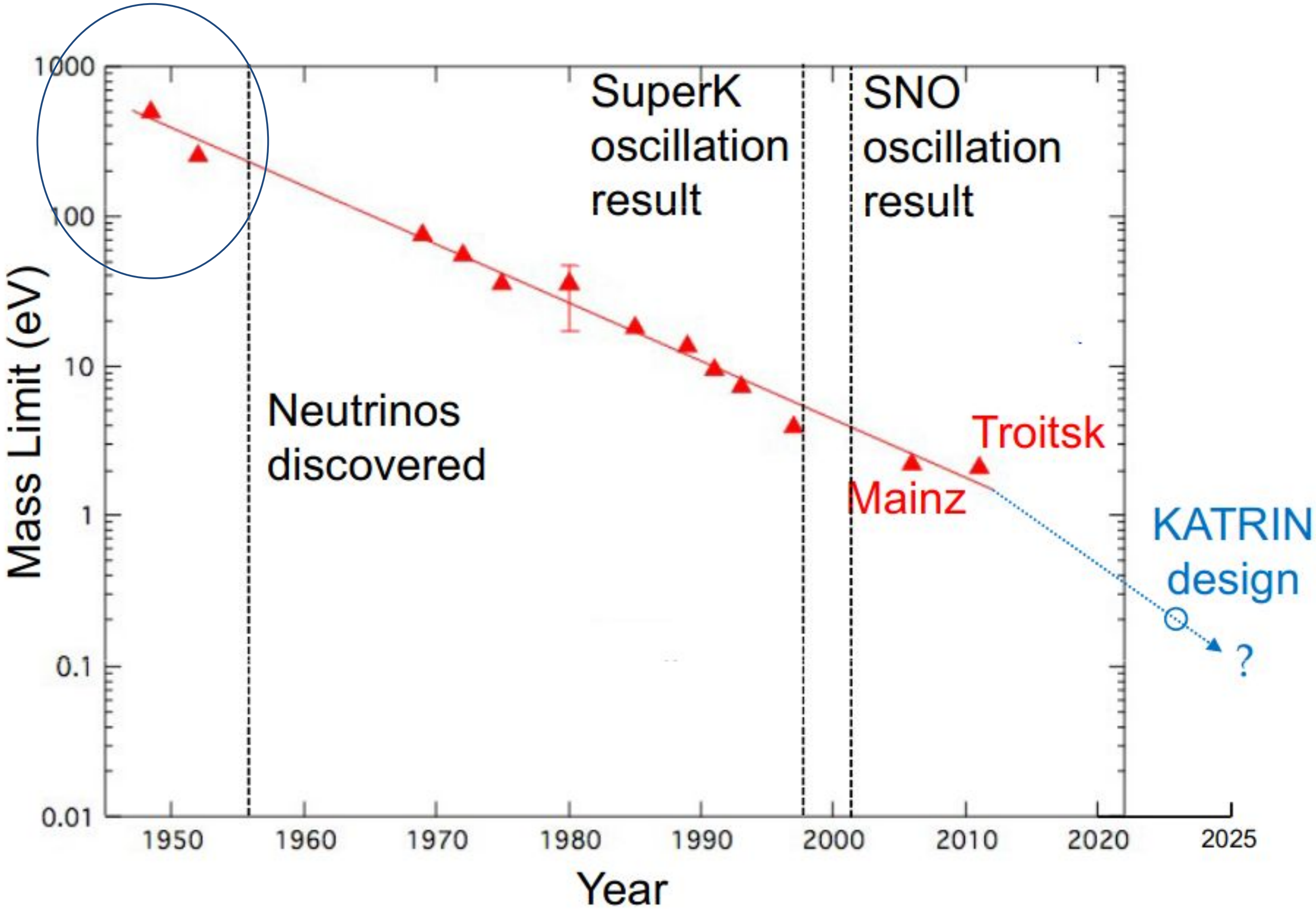
β spectrum

- Massive neutrinos distort the β spectrum of Tritium decay
- As can be seen below, the end-point in the energy spectrum looks different
- This difference can be used to measure the neutrino mass directly
- No assumptions are made in this study



Previous measurements

- History of neutrino mass from tritium decays



State of the art neutrino mass measurement

- Before 2019, state of the art measurements using Tritium decay were set by Mainz and Troitsk experiments at $m_v < 2$ eV (95 % CL)
- KATRIN experiment set the most stringent limit on neutrino mass at $m <$ 1.1 eV (90% C.L.) in 2019 with one month of data!
    - The expected sensitivity after 5 years of running is 0.2 eV, a factor of 10 improvement on the earlier measurements
    - This will be the focus of rest of my talk

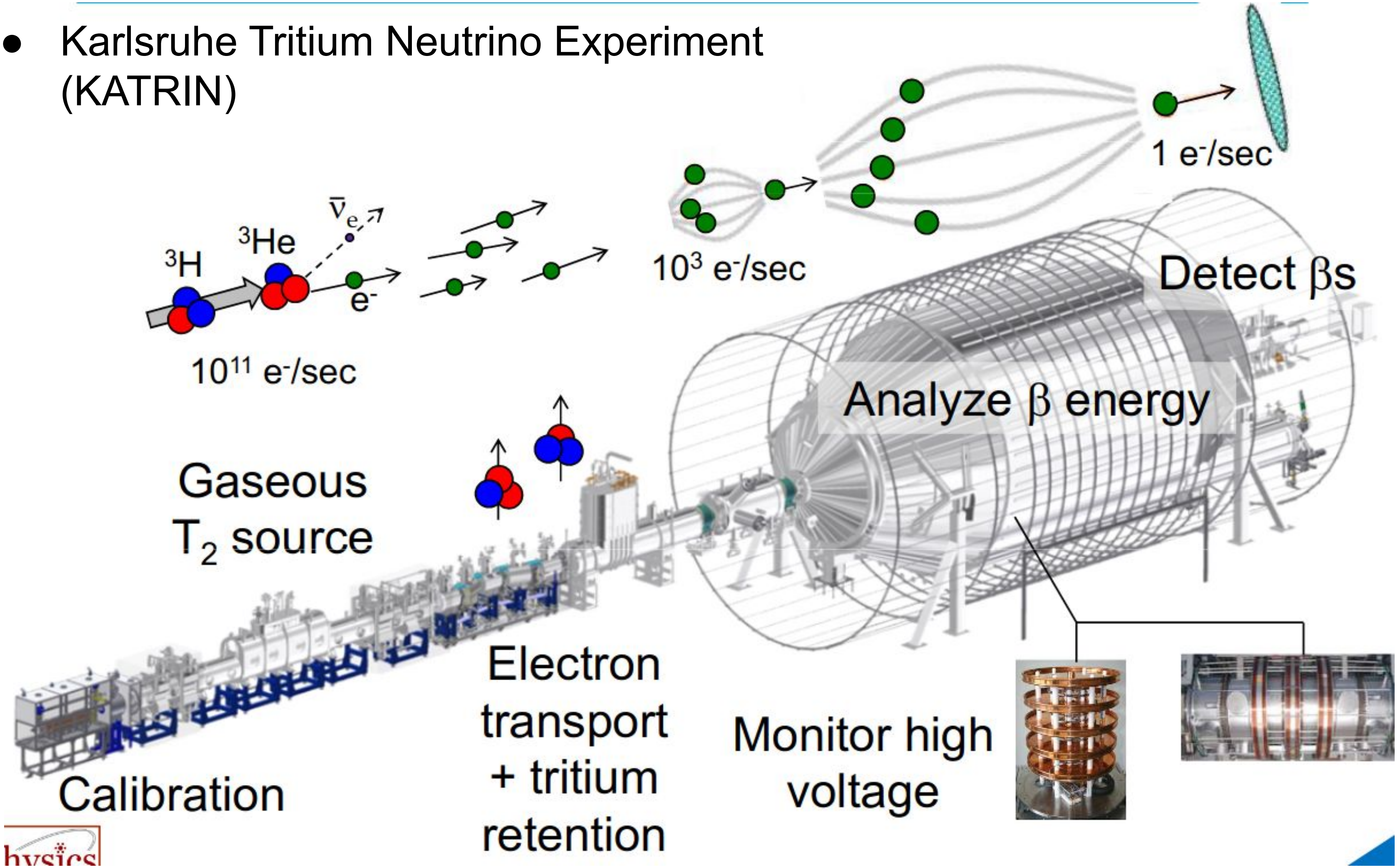
Challenges for KATRIN

- Only 10^{-13} decays end up in the last eV -> need large quantity of tritium
- Precision measurement of energy and rate at the end of β spectrum
- Observable is m_v^2 , so 100x reduced uncertainties implies 10x improvement on m_v
- Two ways to do this: Increase statistics and lower the systematics
- Improvements in KATRIN:
  - Excellent β source
  - Energy resolution better than eV
  - Low backgrounds
  - A lot of improvements in the systematics

KATRIN experiment

KATRIN experiment layout

- Karlsruhe Tritium Neutrino Experiment (KATRIN)



Tritium source

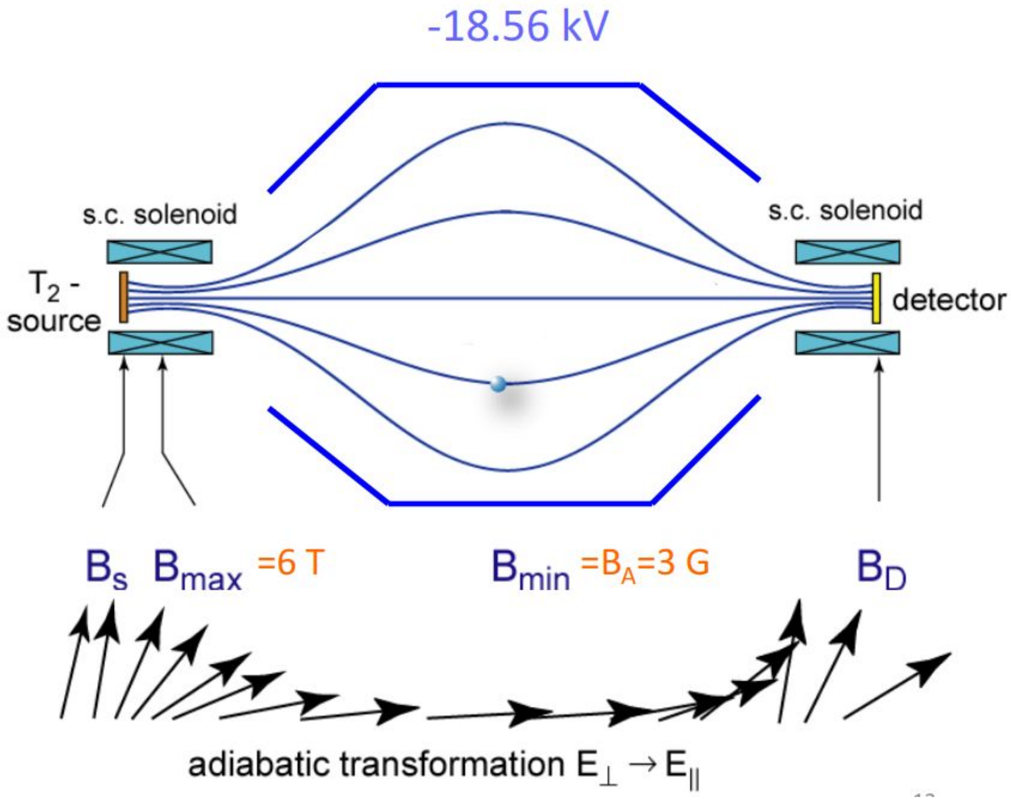
- Windowless Gaseous Tritium Source (WGTS)
- Gaseous T2 molecular source kept at 30K and pressurized
- 2.45×10^{10} decays per second
- Purified gas is passed through PdAg silver that only allows Hydrogen isotopes to pass through
- Source beam tube:
    - Tritium decays in 10m length and 90mm diameter source tube
- Given the molecular T2, the additional excitations including vibrations and rotations are carefully taken into account for the beta spectrum emission

Electron beam

- Electrons from the source beam tube are guided using magnetic field
- Specially designed electrodes prevent the transmission of tritium atoms
- Uses two Magnetic Adiabatic Collimation + Electrostatic (MAC-E) filters
    - First MAC-E filter has a fixed energy threshold at 10keV to remove bulk of the low-energy electrons
    - Second MAC-E filter is the main spectrometer that analyzes the integral beta spectrum

MAC-E filters

- Isotropic electron motion at the source is converted to longitudinal motion
- High magnetic field is applied at the both ends with low field in the analyzing plane in the center
- Resulting magnetic moment is held constant in the adiabatic transport of electrons
- Only very high energy electrons at the end-point of beta spectrum can be selected by tuning the magnetic fields -> MAC-E acts as a high pass filter

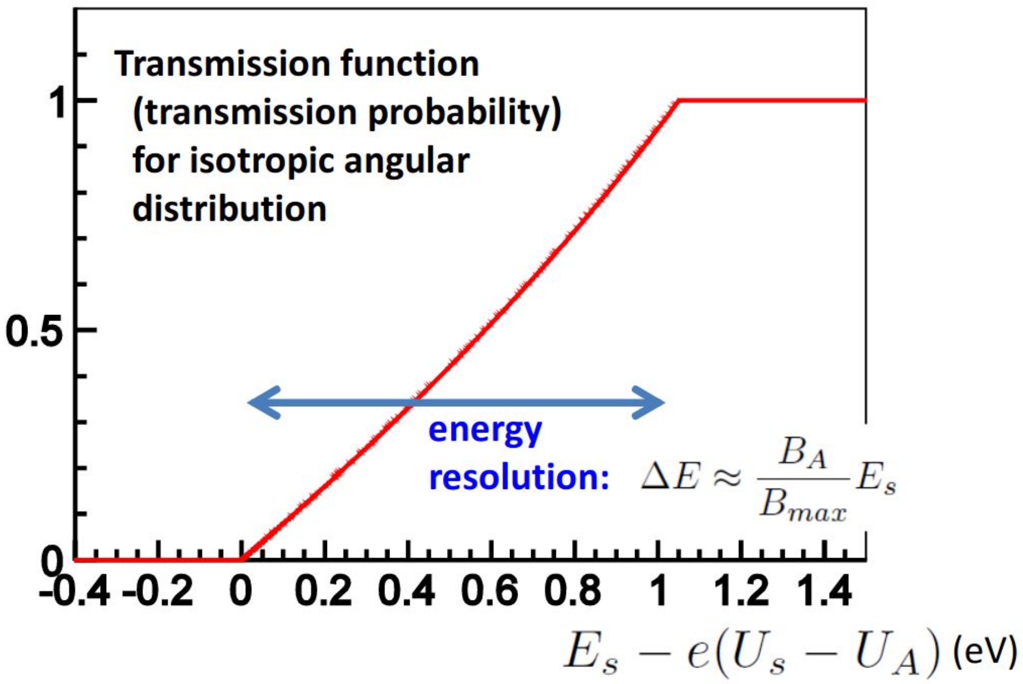


$$\mu = \frac{E_\perp}{B} = \mathrm{const}$$

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

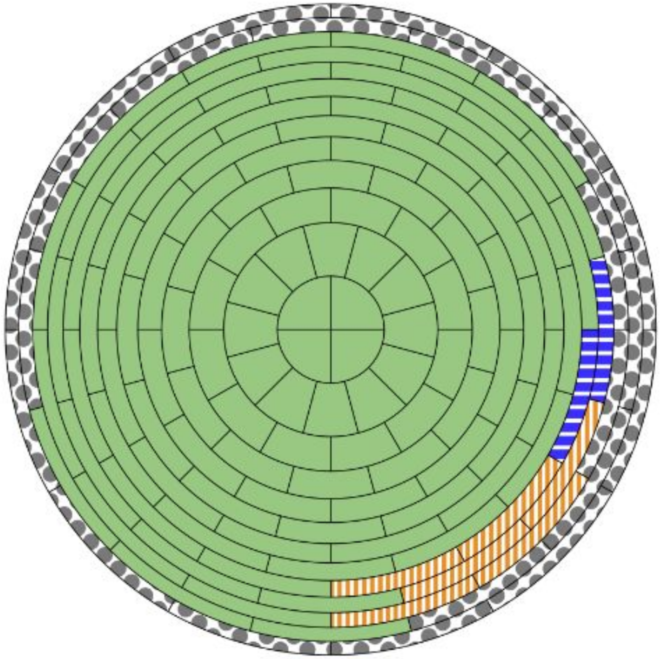
Energy resolution

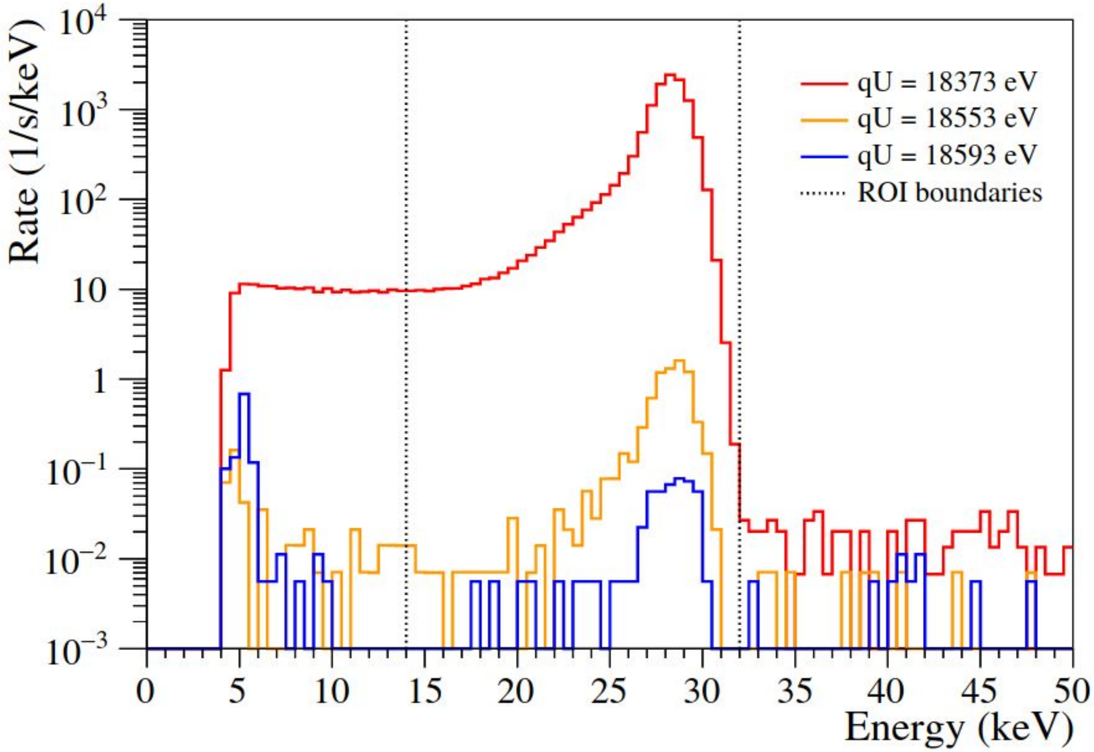
- The MAC-E acts as a high pass filter to allow only electrons near the tail of beta spectrum
- The transmission probability spectrum below shows an energy resolution of 0.93 eV
- KATRIN runs scans at different MAC-E filter potentials and performs an integral analysis on the final spectrum



Forward Pixel Detector

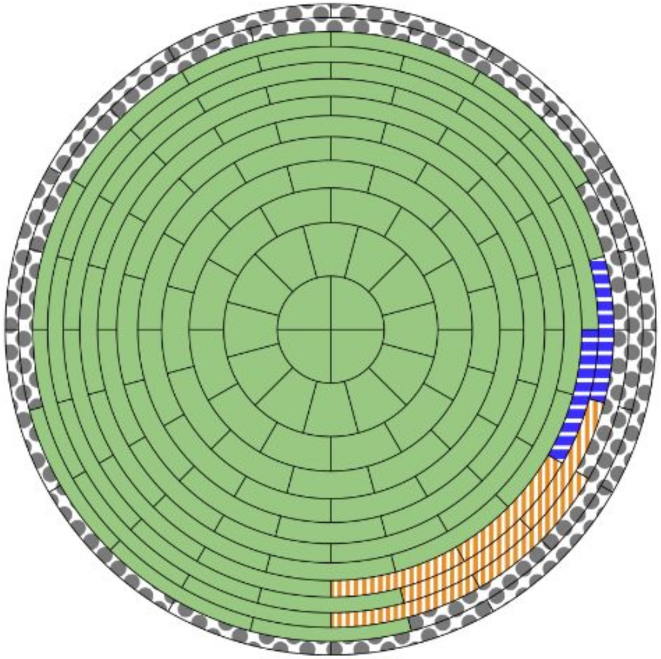
- Electrons passing the MAC-E filters are accelerated further using an electrode
- The rate and spectrum of these electrons is recorded using a silicon pixel detector
- FPD acts as a low resolution electron counter

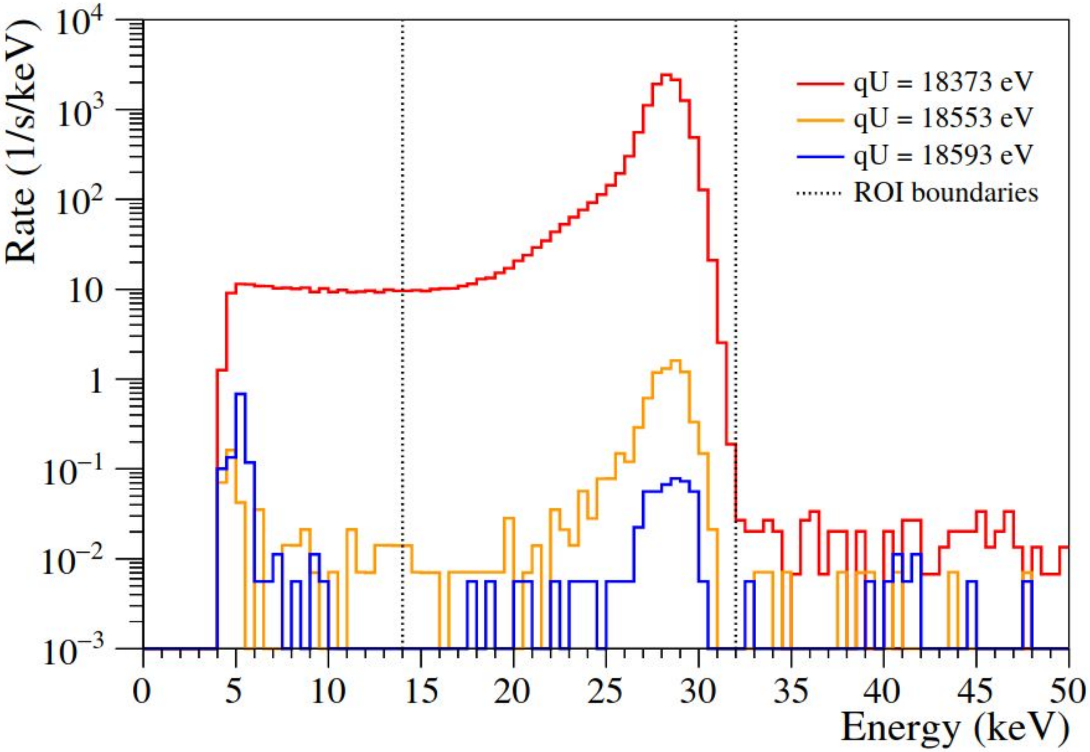




Forward Pixel Detector

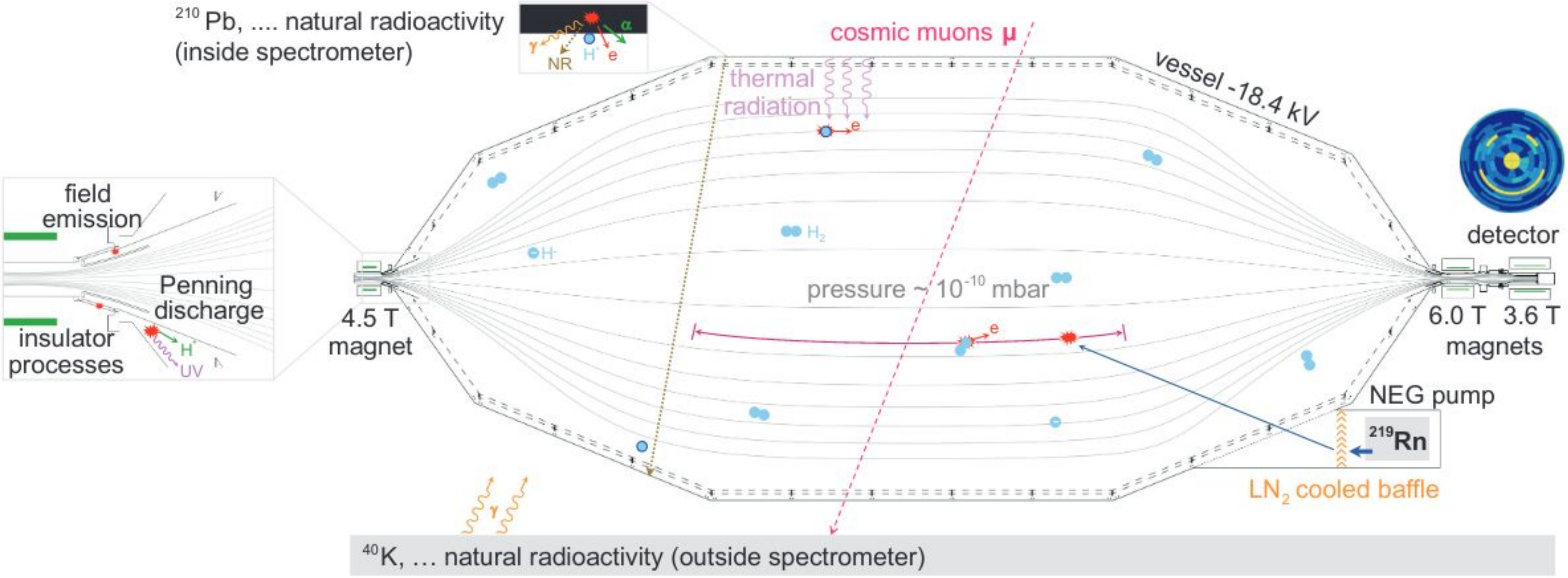
- Retarding potential of 18 keV and additional acceleration of 10keV results in a signal broad peak in FPD at ~28 keV
- Detector noise peaks can be seen at ~7 keV





Background processes

- Cosmic rays
- Radon induced background
- Natural radioactivity
- Due to upstream source

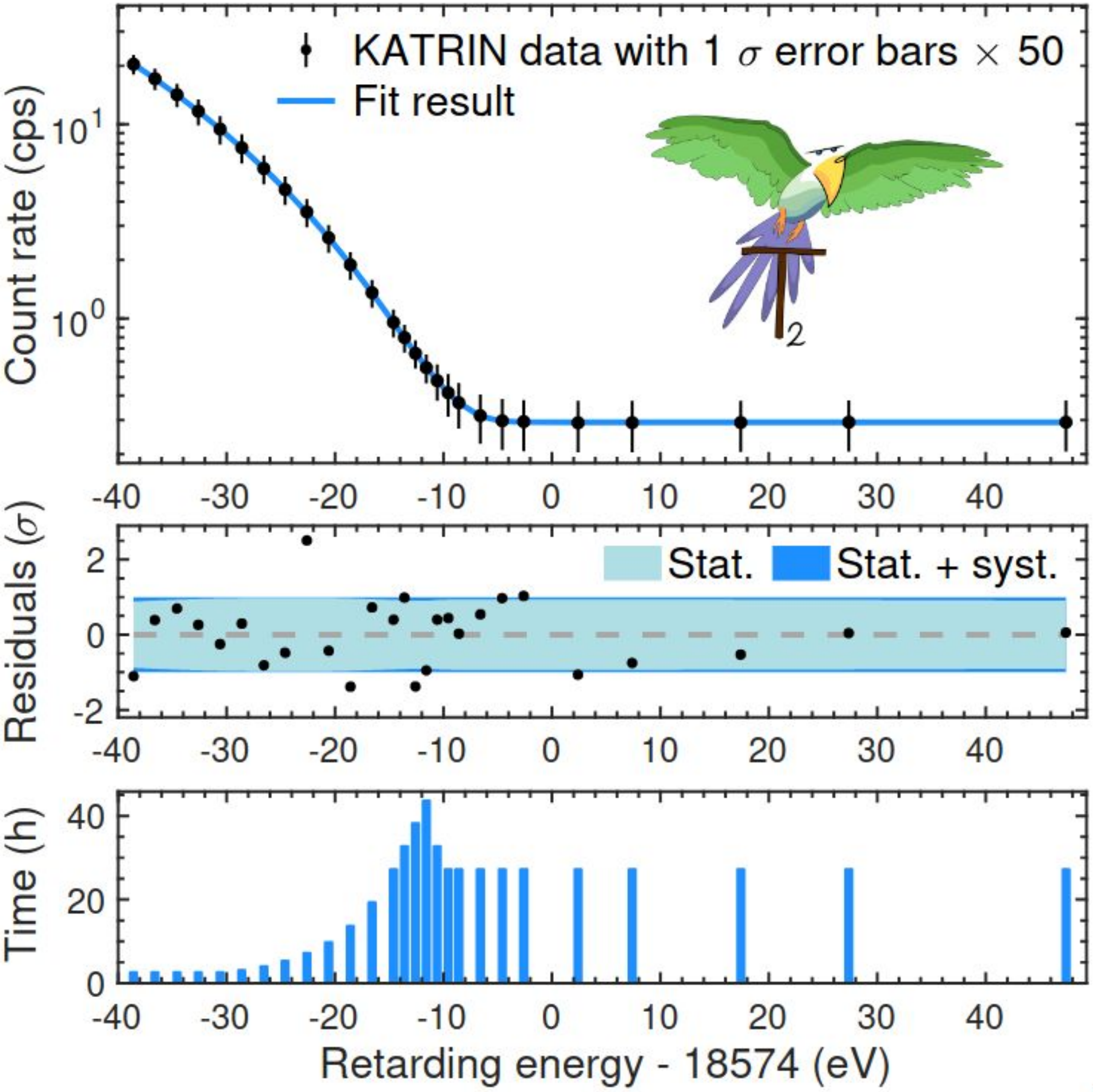


Main background due to lead

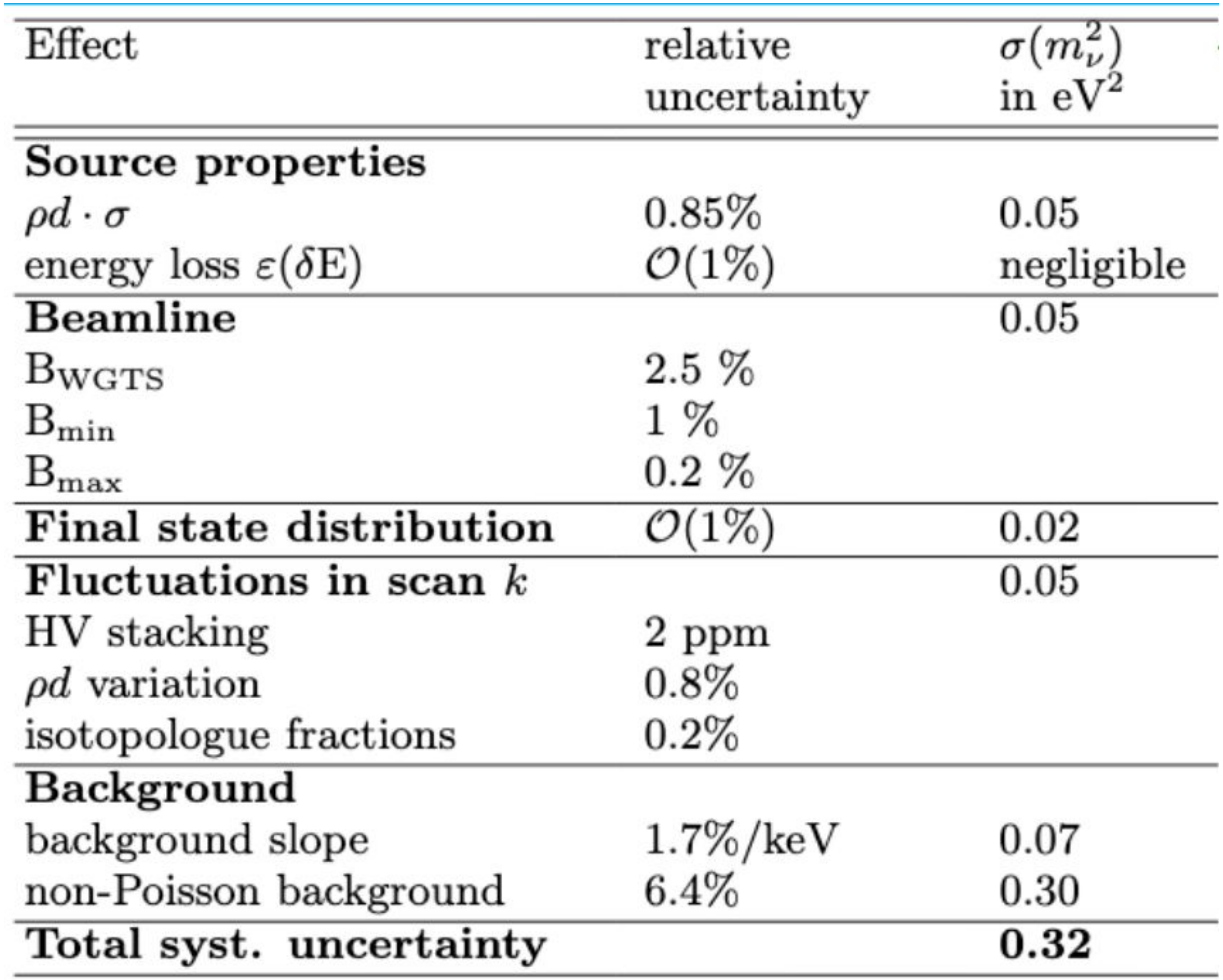
- 210 Pb decays produce electrons and Rydberg atoms
  - atoms where the electrons are far away from nucleus but the atoms are not ionized
- Rydberg atoms are ionized from thermal radiation inside the spectrometer and lead to the largest background in the spectrometer
- This process is well measured and can be accounted for with great precision

KATRIN data analysis

- KATRIN beta spectrum is modeled by 4 main parameters
  - Intensity
  - End-point energy
  - Background
  - Neutrino mass
- The fitted spectrum matches the data quite well
- Statistics limited result from 2019
  - With more data, the result would be much better



Uncertainties and impact on m^2_ν



Effect	relative uncertainty	$\sigma(m_\nu^2)$ in eV^2
Source properties		
$\rho d \cdot \sigma$	0.85%	0.05
energy loss $\varepsilon(\delta E)$	$\mathcal{O}(1\%)$	negligible
Beamline		0.05
B_{WGTS}	2.5 %	
B_{min}	1 %	
B_{max}	0.2 %	
Final state distribution	$\mathcal{O}(1\%)$	0.02
Fluctuations in scan *k*		0.05
HV stacking	2 ppm	
ρd variation	0.8%	
isotopologue fractions	0.2%	
Background		
background slope	1.7%/keV	0.07
non-Poisson background	6.4%	0.30
Total syst. uncertainty		**0.32**

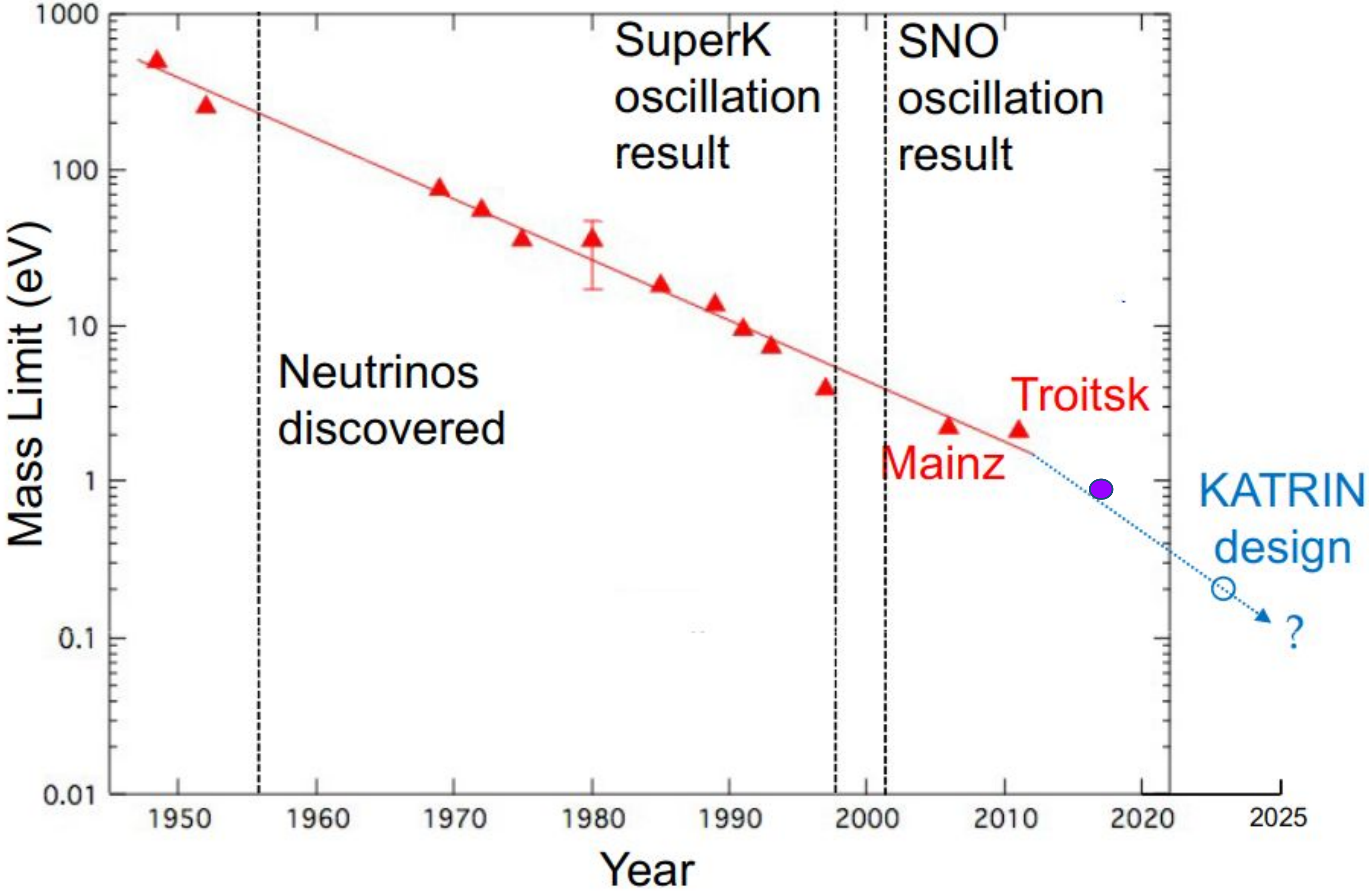
Statistical uncertainty **0.97**

Result

- Limit on neutrino mass from 1 month of KATRIN run:

$$\boxed{\begin{gathered} m_\nu^2 = (-1.0^{+0.9}_{-1.1})\ \mathrm{eV}^2 \\ m_\nu < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{C.L.}) \end{gathered}}$$

Comparing against other experiments



Outlook

- Since 2019, KATRIN experiment has recorded a lot more data and expect future results with reduced systematics and more statistics
    - 5 year projection aims to set a limit of 0.2 eV
- Multiple experiments studying electron-capture decay of Holmium underway
    - HOLMES, ECHo, and NuMECS
    - ECHo targets sub-eV neutrino mass range
- A lot of interesting results from this will be showing up over the next decade to address the question of nominal hierarchy vs inverted hierarchy of neutrino masses

References

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