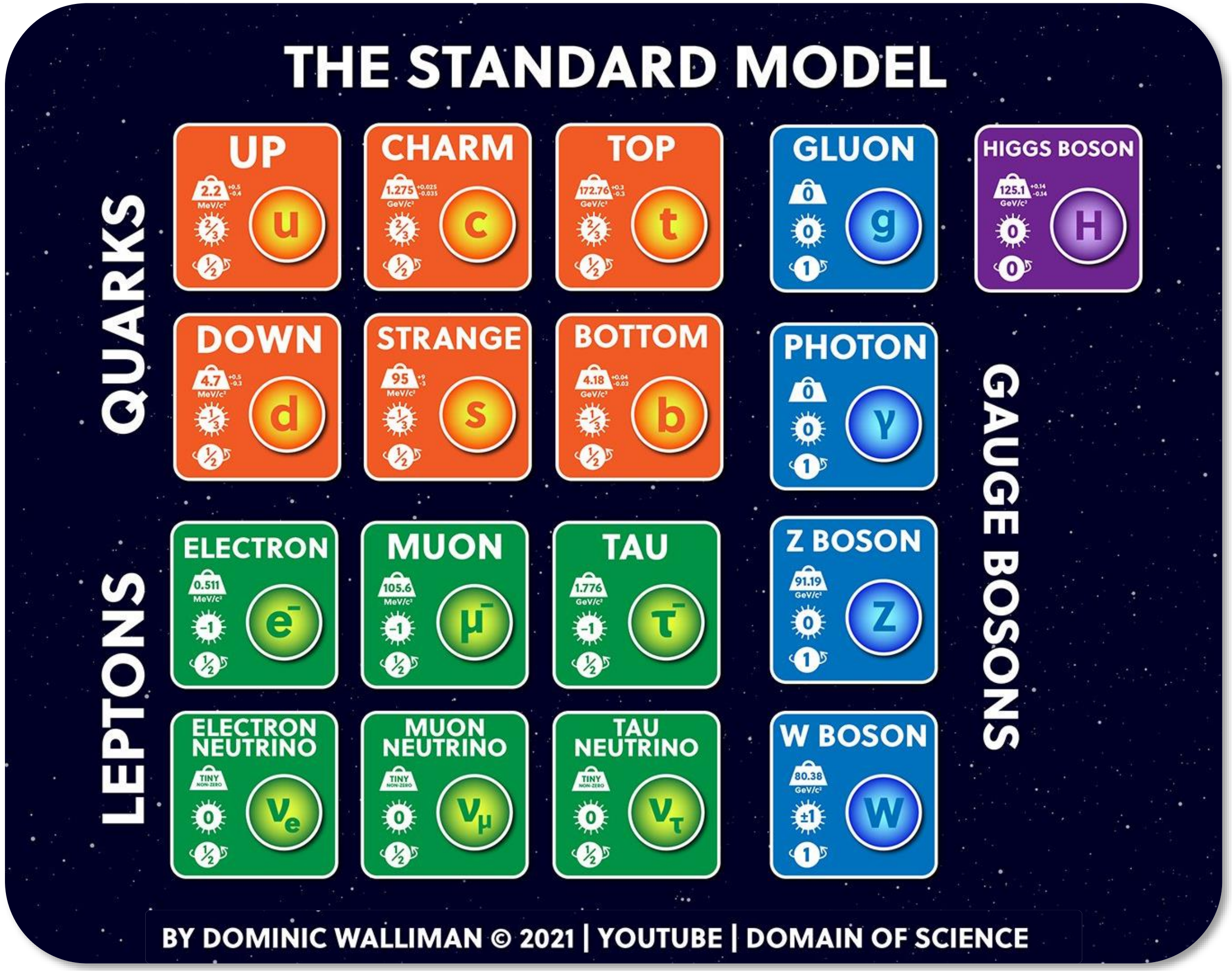
Neutrino research with KATRIN

Dr. Dominic Hinz on behalf of the KATRIN collaboration

19th Conference on Plasma Surface Engineering September 2-5, 2024, Erfurt

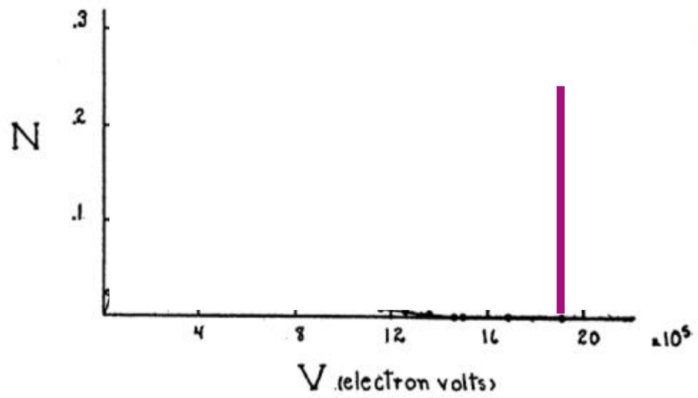
Introduction to neutrino physics: Standard Model

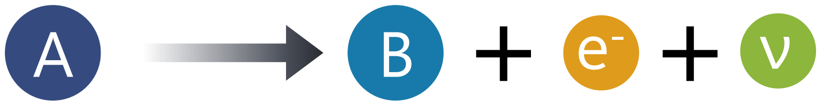


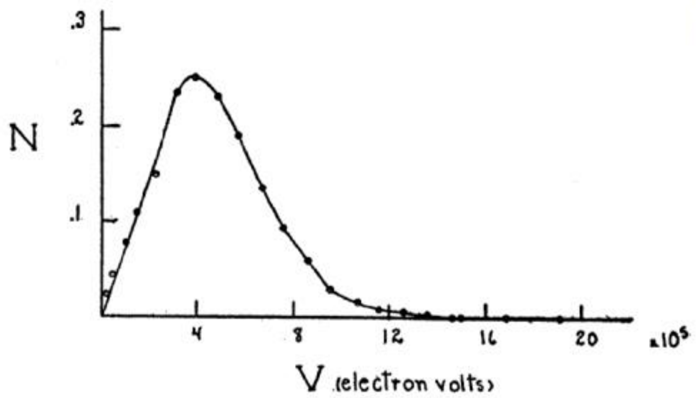
- Elementary particle
- Postulation by W. Pauli 1930
- First experimental discovery 1950s
- Only weak interaction
- Tiny but non-zero mass
  - Proven by neutrino oscillation
  - Coupling to Higgs boson unresolved
- How much do neutrinos weigh?

Introduction to neutrino physics: Postulation

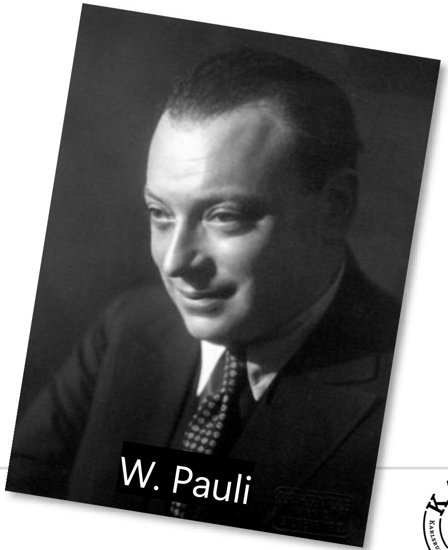
- Investigations of radioactive elements which emit electrons 1920s (beta decay)
- Expectation
  - monoenergetic line due to energy and momentum conservation
  - Electron energy given by mass difference of the elements



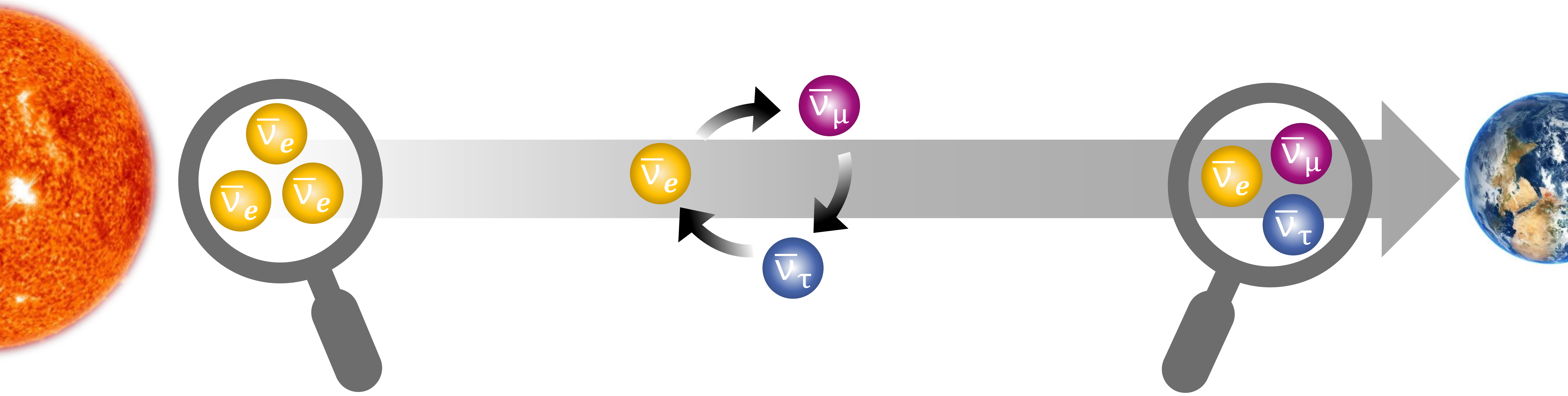




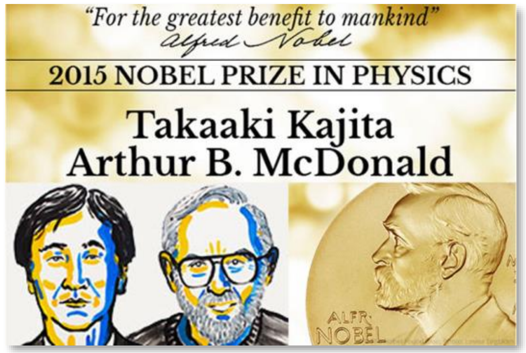
- Observation
  - Continuous energy spectrum
  - → Postulation of another decay product to conserve energy
  - Electron and neutrino share decay energy
- Beta decay theory by E. Fermi



Introduction to neutrino physics: Solar neutrino problem

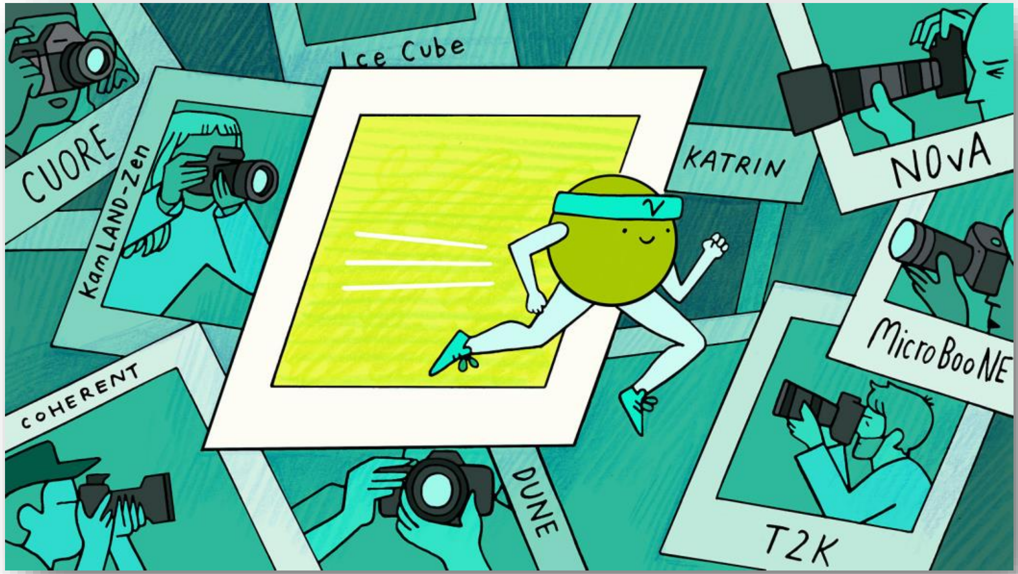


- Neutrino oscillation of three flavours:
  $\boldsymbol{\nu_e}$(Electron Neutrino), $\boldsymbol{\nu_\mu}$ (Myon Neutrino), $\boldsymbol{\nu_\tau}$ (Tau Neutrino)
- solves solar neutrino problem
- → Neutrinos must have mass



Introduction to neutrinos: Properties

- Most abundant particles in the universe
- Electrically neutral particle
- Spin ½
- Only weak interaction
  - Very large range in matter
  - Production at beta decays
- Neutrino flavour changes by oscillation
  - Not massless

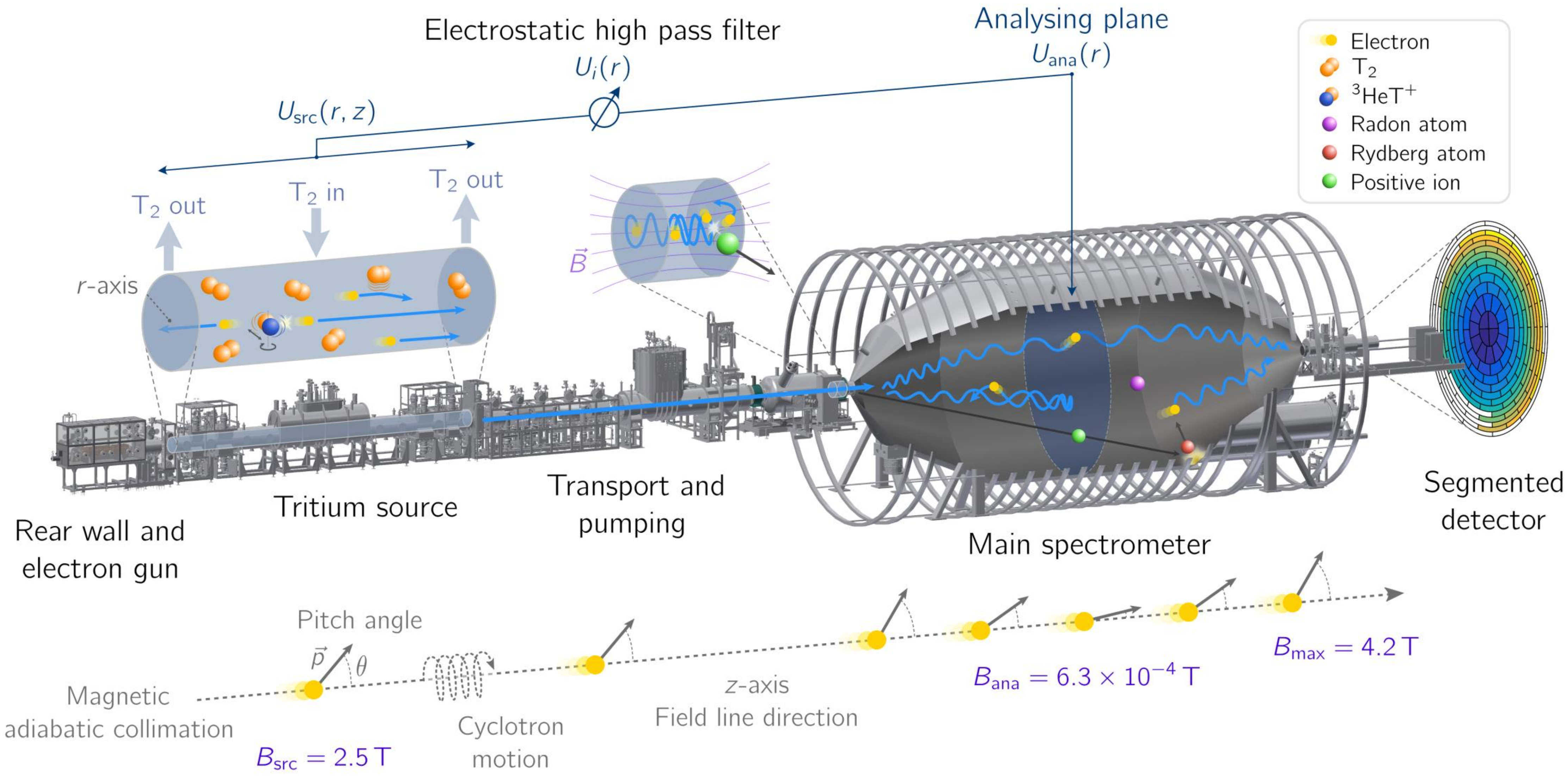


$A \rightarrow B + e^{-} + \nu$

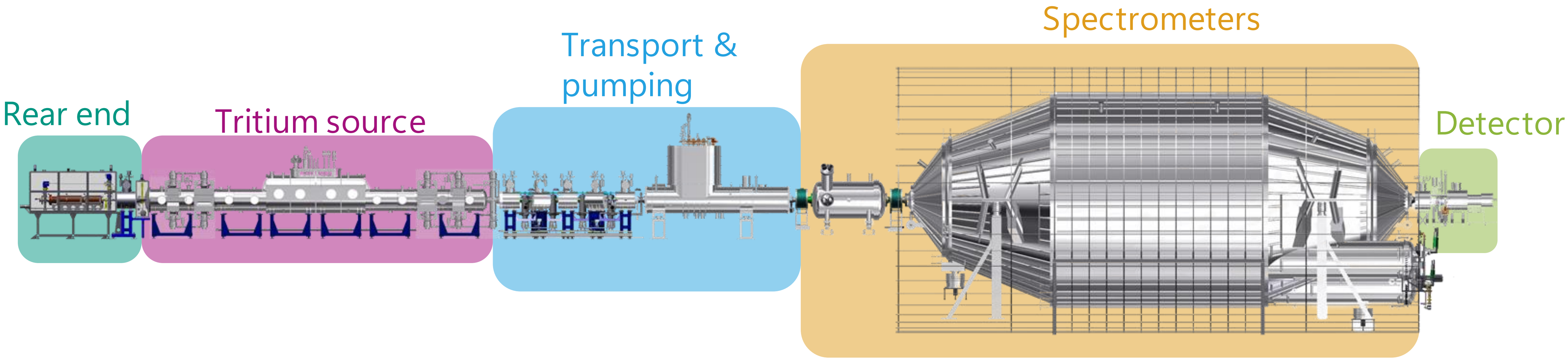
Kinematic studies of electrons provide information about the neutrino mass

KATRIN:
KArlsruhe TRItium Neutrino Experiment

The KATRIN Experiment



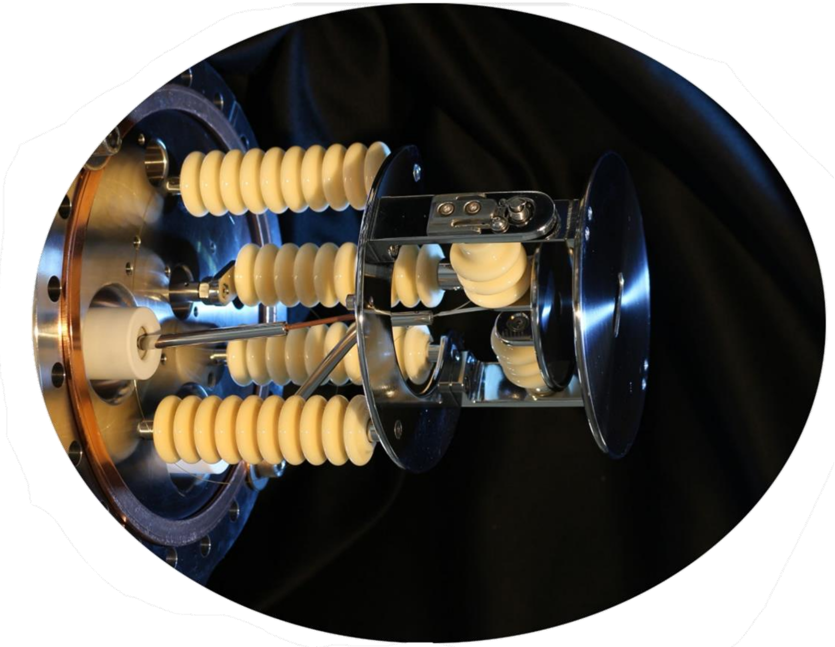
KATRIN: experimental overview

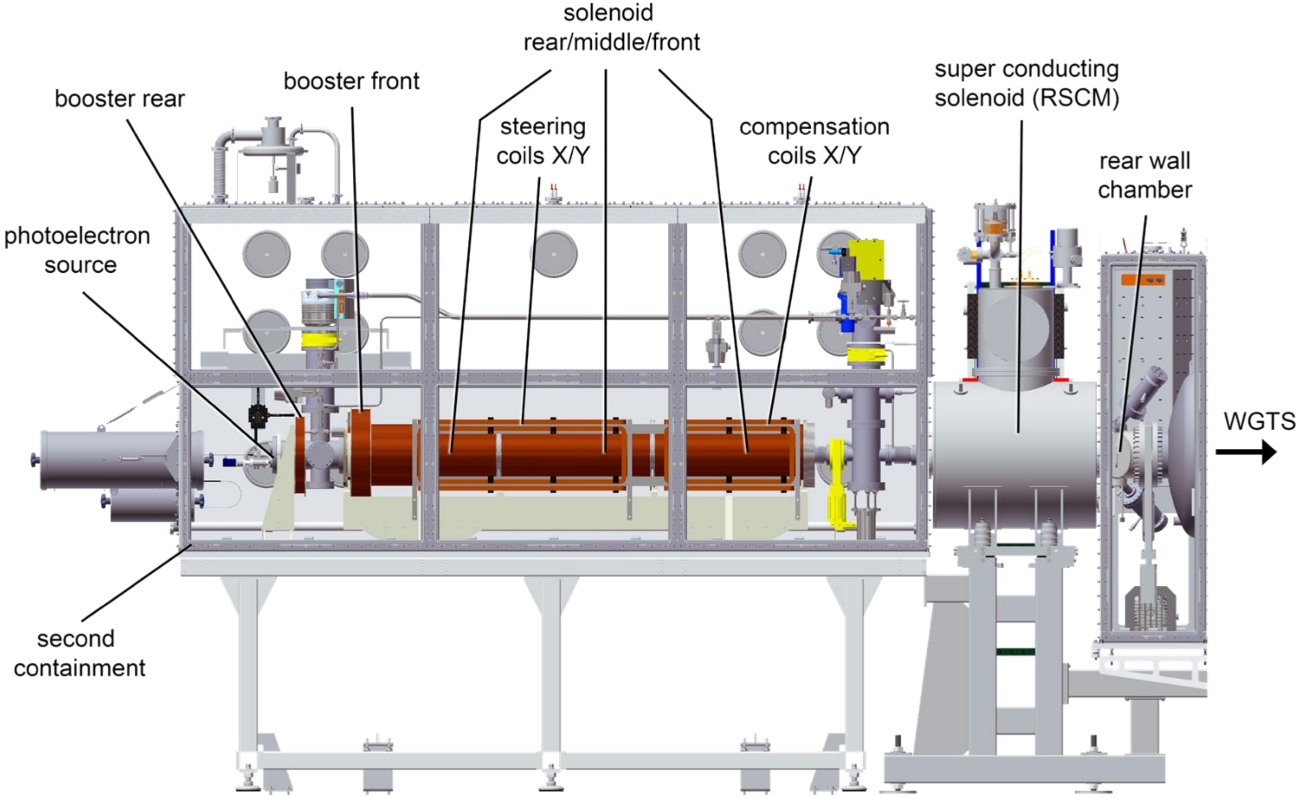


Rear section

- Rear end of experiment
- Golden platet titanium rear wall
  - Plasma potential coupling

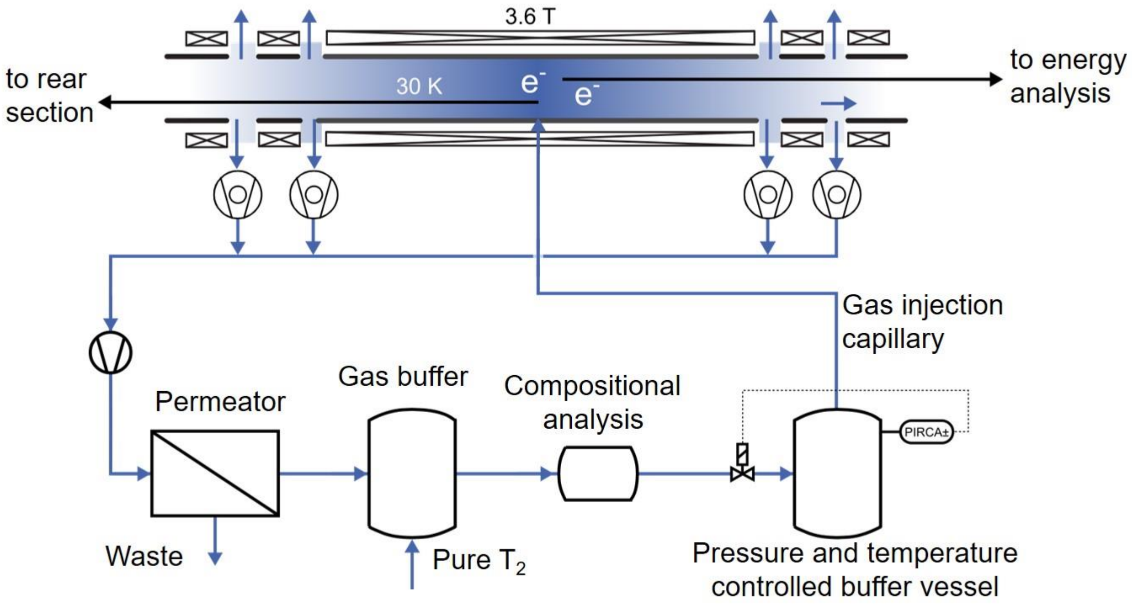
- Calibration technique: electron source
  - Narrow energy and angle width





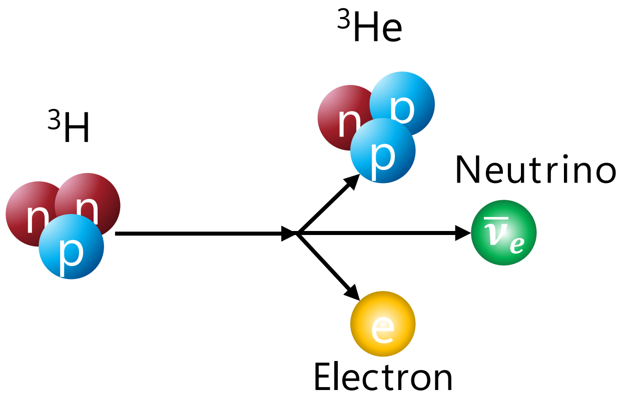
Tritium source

- 10m long Windowless Gaseous Tritium Source (WGTS)
- Stable density of tritium (σ ~ 0.1%/h)
- Gas composition with high tritium purity (>95%)
- Activity ~100 GBq
- Stable cryostat temperature (mK scale)

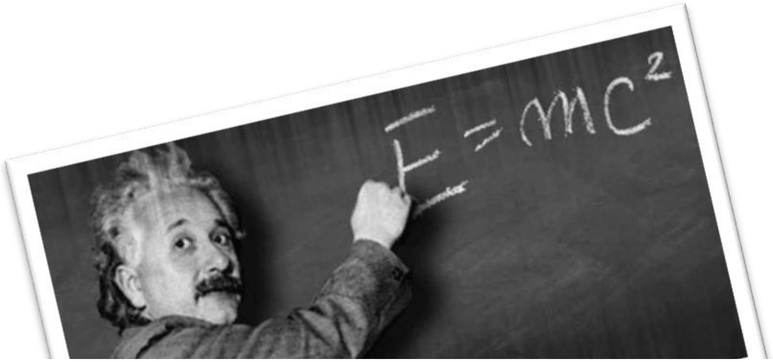


Why do we use tritium?

- Halflife of 12.3 years
- Low endpoint of 18.57 keV

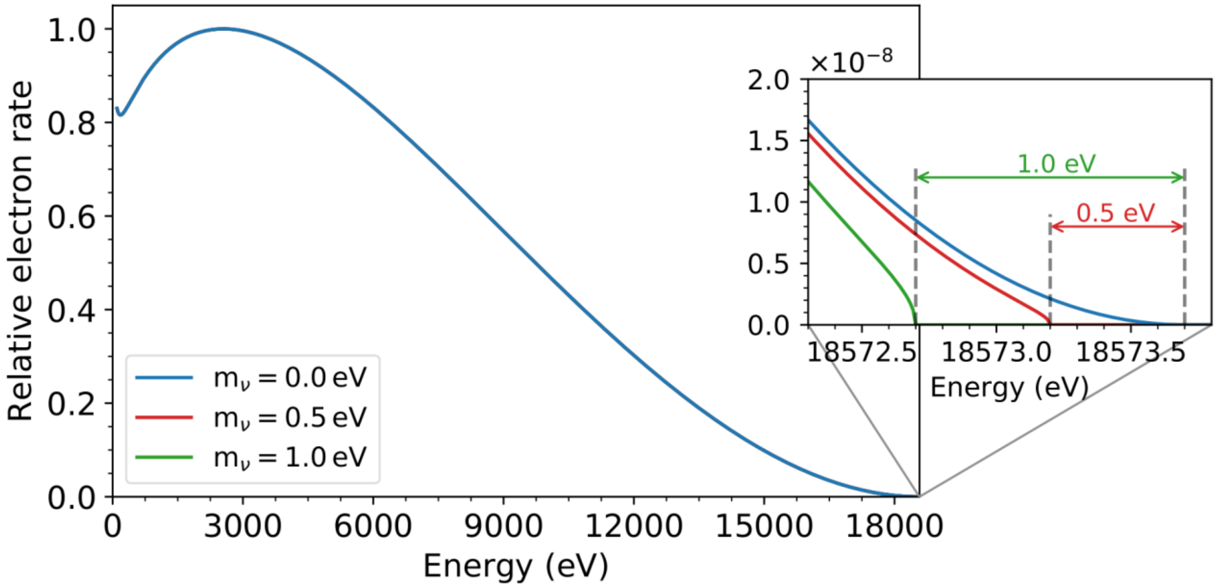


- Endpoint shifts with neutrino mass

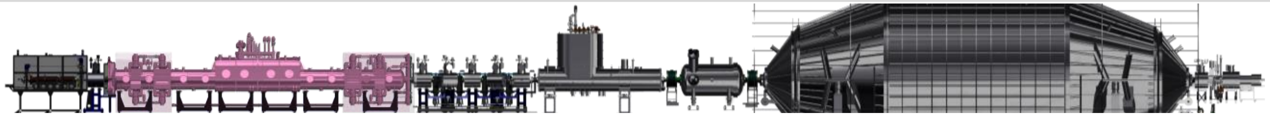


- Precise measurement of spectrum tail
- → Neutrino mass m_ν as missing energy at Beta decay

$$E = (m_M - m_T) \cdot c^2 = m_e c^2 + T_e + m_\nu c^2 + T_\nu$$

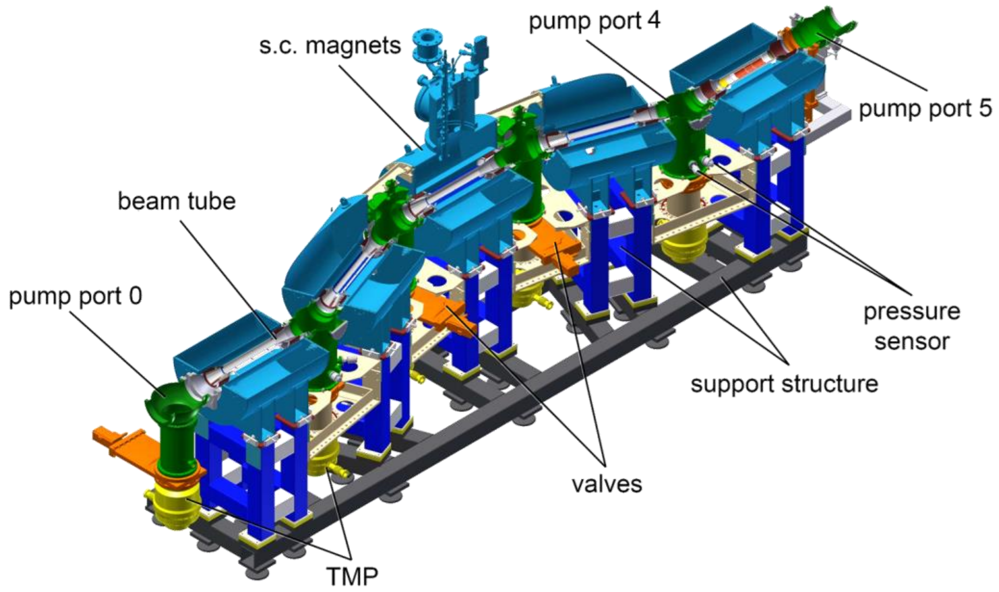


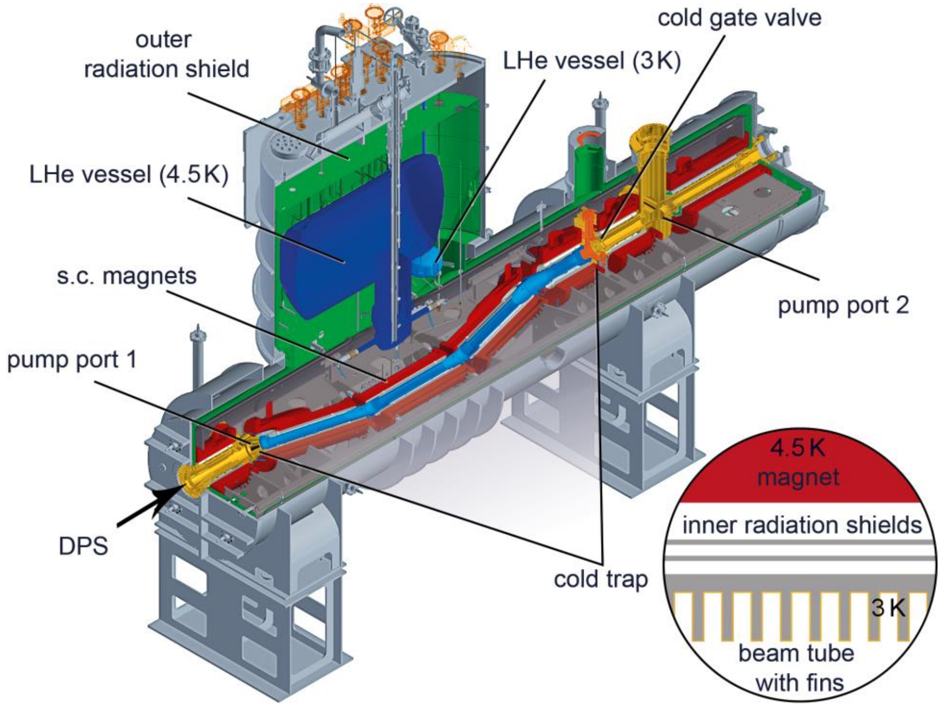
- Best limit before KATRIN: $m_\nu < 2$ eV/c^2



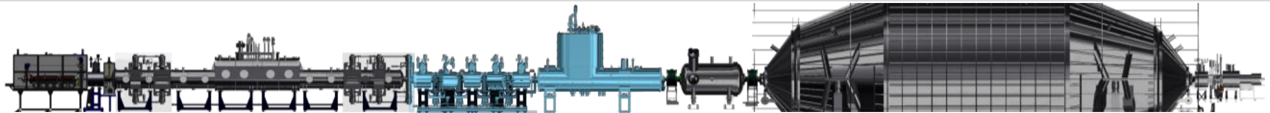
Transport and pumping section

- Differential Pumping Section (DPS)
- Magnetic chicane
  - Efficient pumping of neutral molecules
  - Charged electrons guided magnetically
- Tritium reduction by $4 \cdot 10^3$

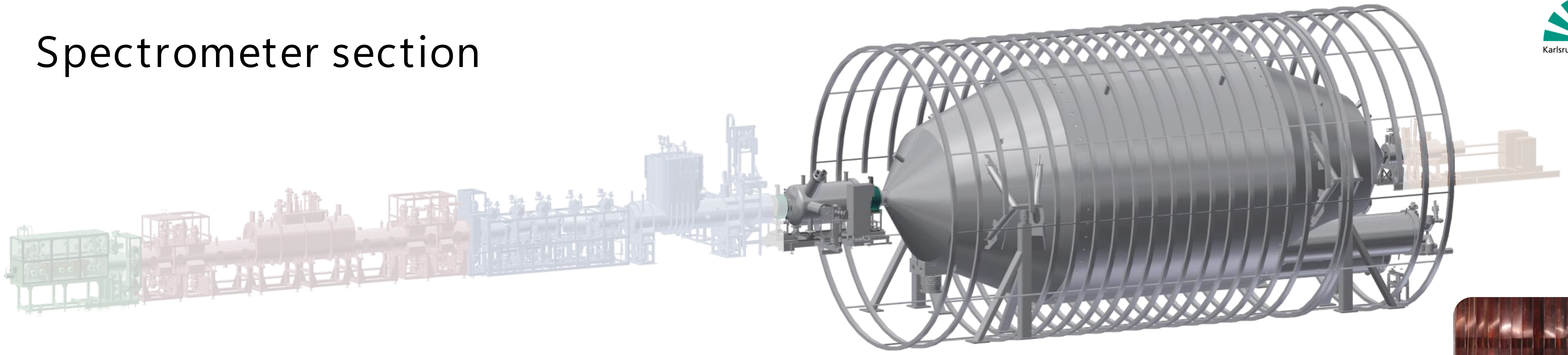


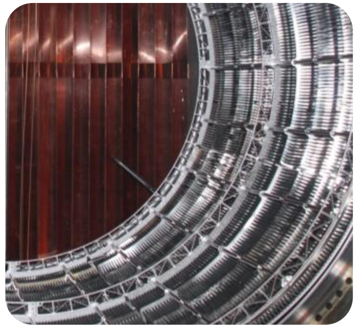


- Cryogenic Pumping Section (CPS)
- Magnetic chicane
- Cryo-cooled golden beam tube fins
  - Condensed Argon frost layer
  - Large surface with tritium capture capability
- Tritium reduction by $\geq 10^8$



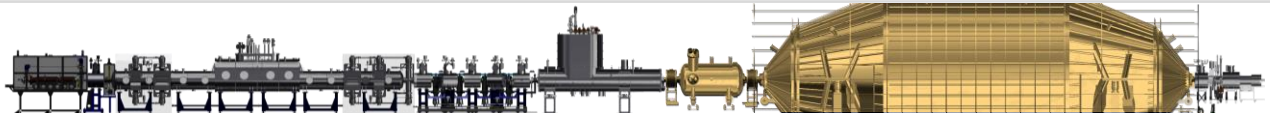
Spectrometer section



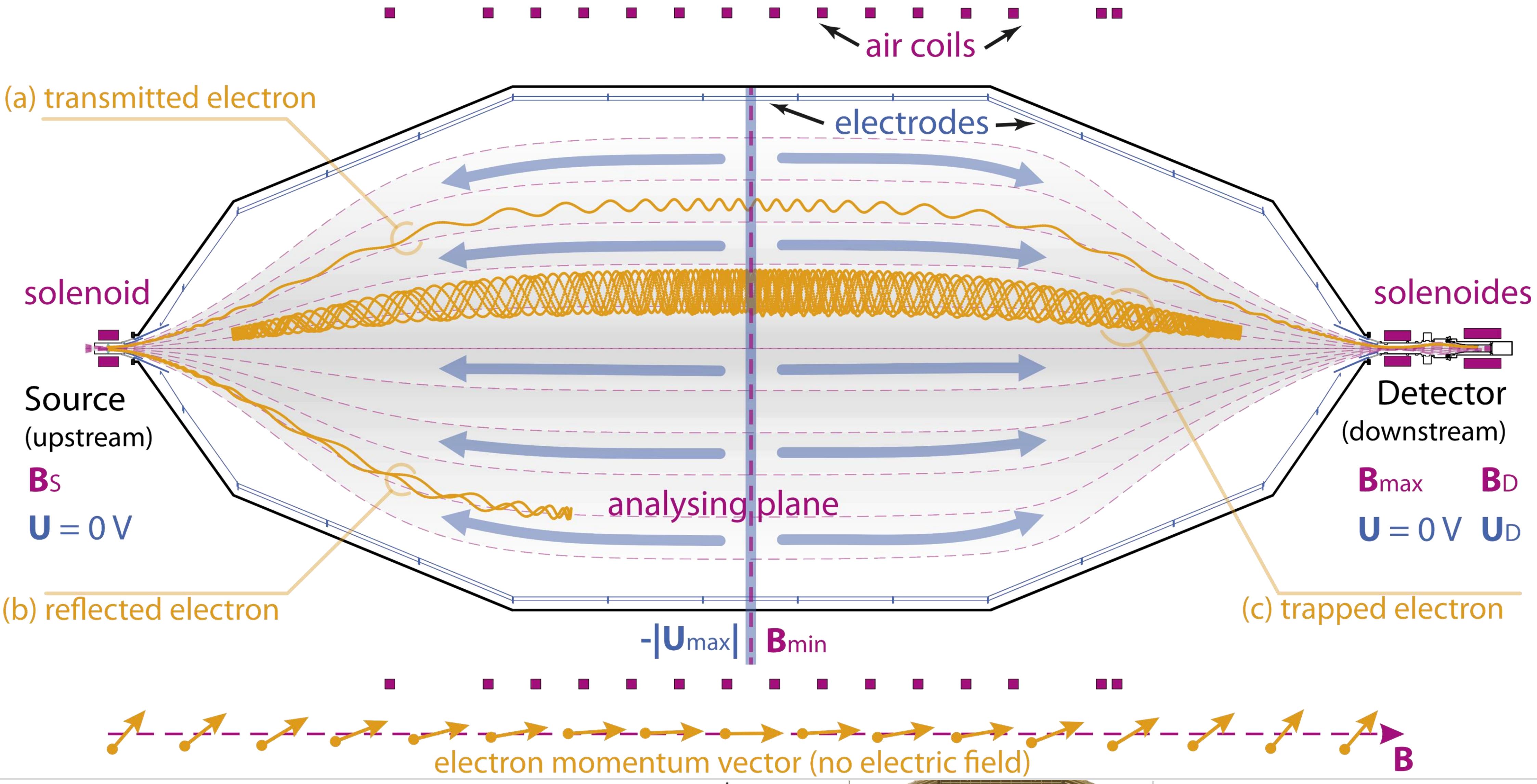


NEG material

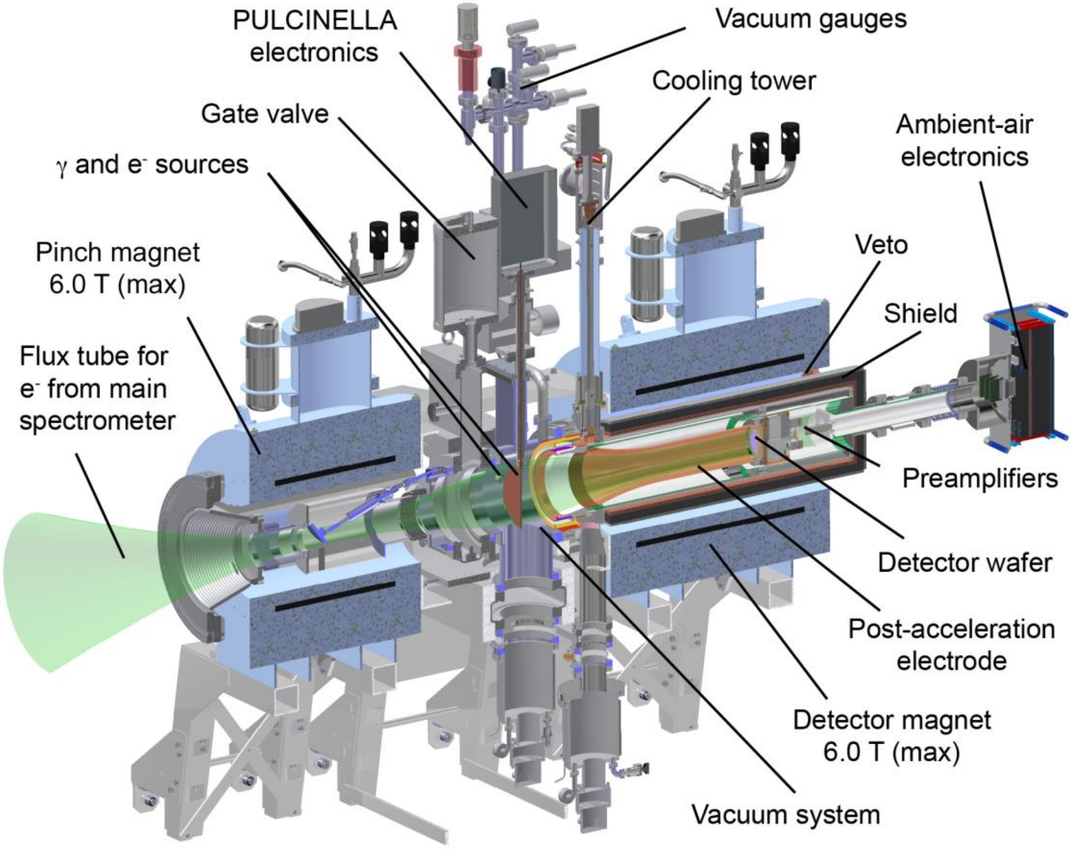
- Pre spectrometer
  - Inner vessel surface: 25.6 m^2, volume: 7.6 m^3
  - Superconducting magnets up to 4.5 T
  - 90m non-evaporable-getter (NEG)
- Retention of low-energy electrons by high voltage
- Main spectrometer
  - Inner vessel surface: 640 m^2, volume: 1240 m^3
  - 1.4429 stainless steel
  - Pinch magnet up to 6 T
  - 3 km (60.000 m^2) of Zr-V-Fe NEG material
  - → p ~ 1 e-11 mbar
- Spectroscopy of β-decay electrons with high resolution (~1 eV)
  - High voltage with inner wire electrode system
  - → MAC-E-filter principle



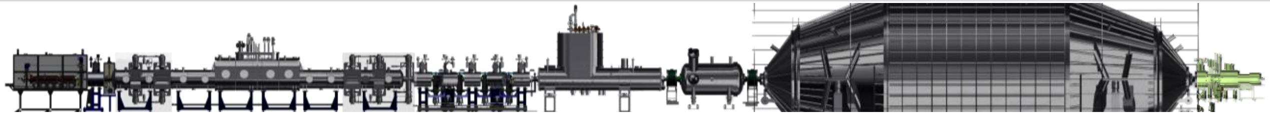
The MAC-E filter principle



Detector section

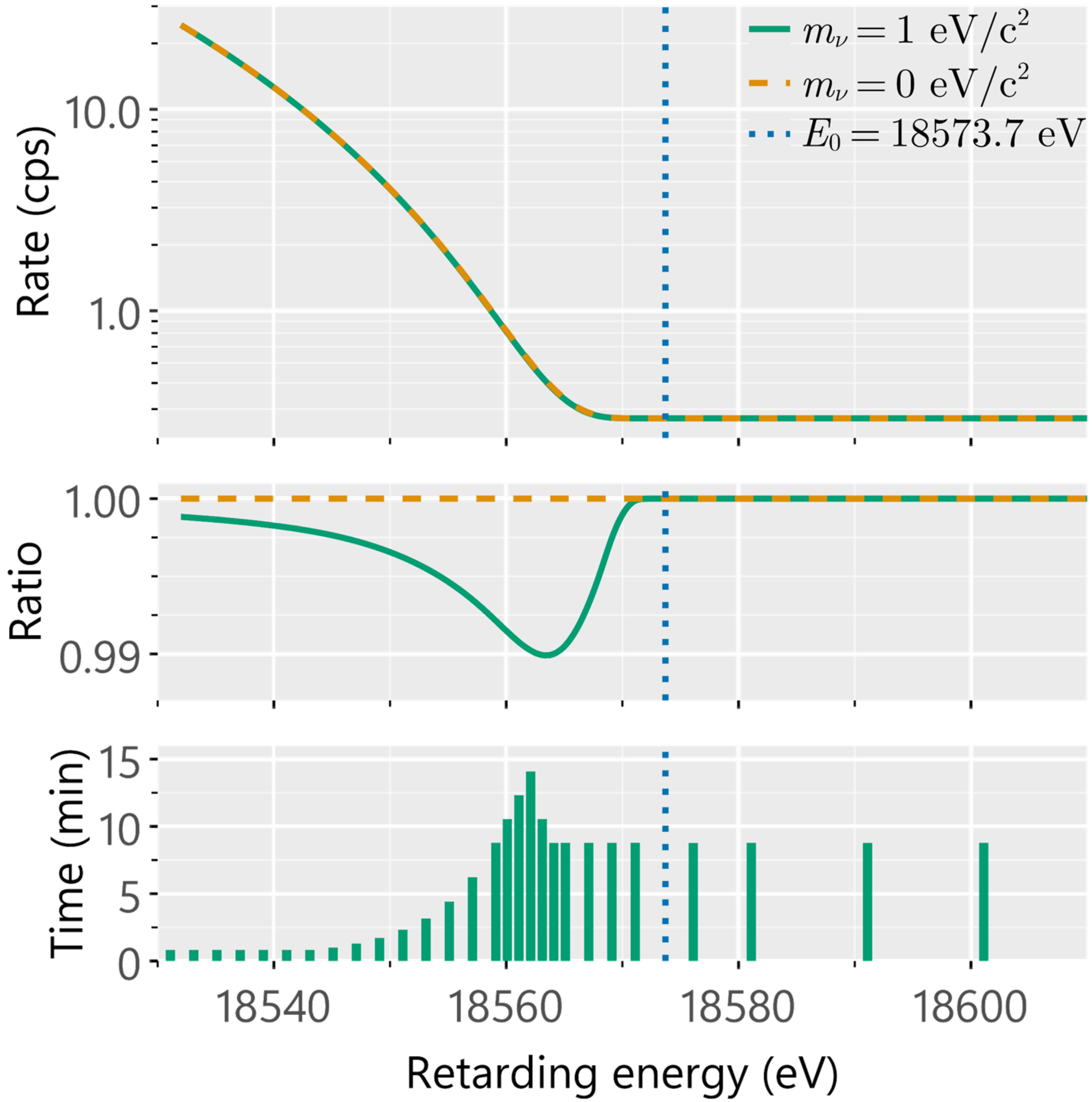


- Calibration tools and detector
  - γ and e^- sources
- Post-acceleration electrode (PAE)
  - Increase electron energy
  - → better sensitivity
- Focal plane dector (FPD)
  - Segmented Silicon pin detector
  - 148 pixels of same size
  - Up to 10^5 e^-/s
  - In high magnetic field up to 6 T

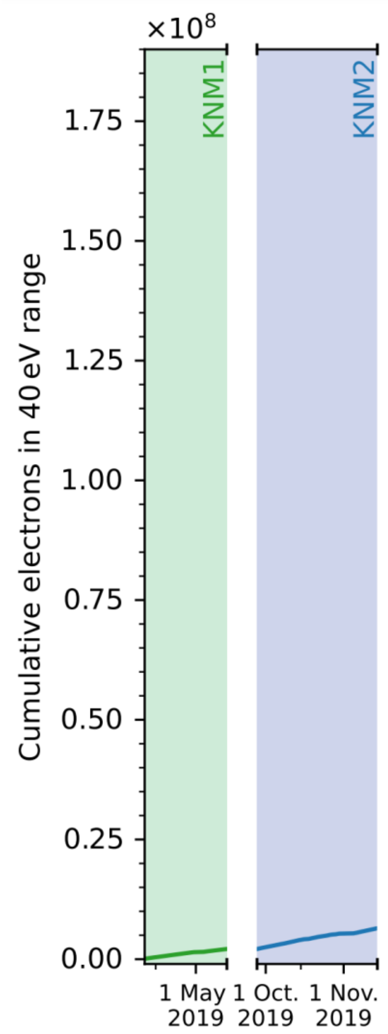


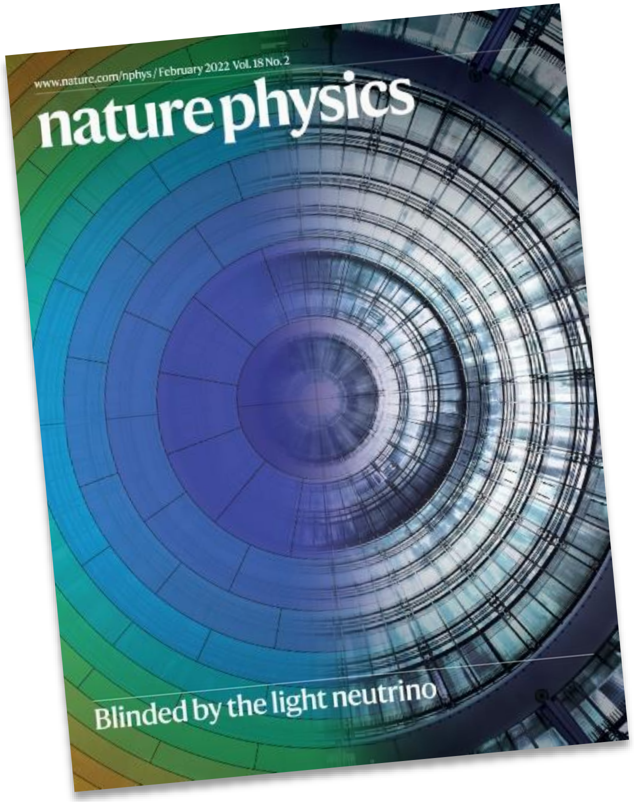
Taking data with KATRIN

- Integral measurement of β-spectrum
- Neutrino mass signature largest at E_0
- Optimised Measurement Time Distribution (MTD)
  - 2-3 hour scans
  - O(100) scans per campaign
- Background rate beyond E_0
- Stack data points with same conditions
- Analysis window: [E_0 – 40 eV, E_0 + 135 eV]



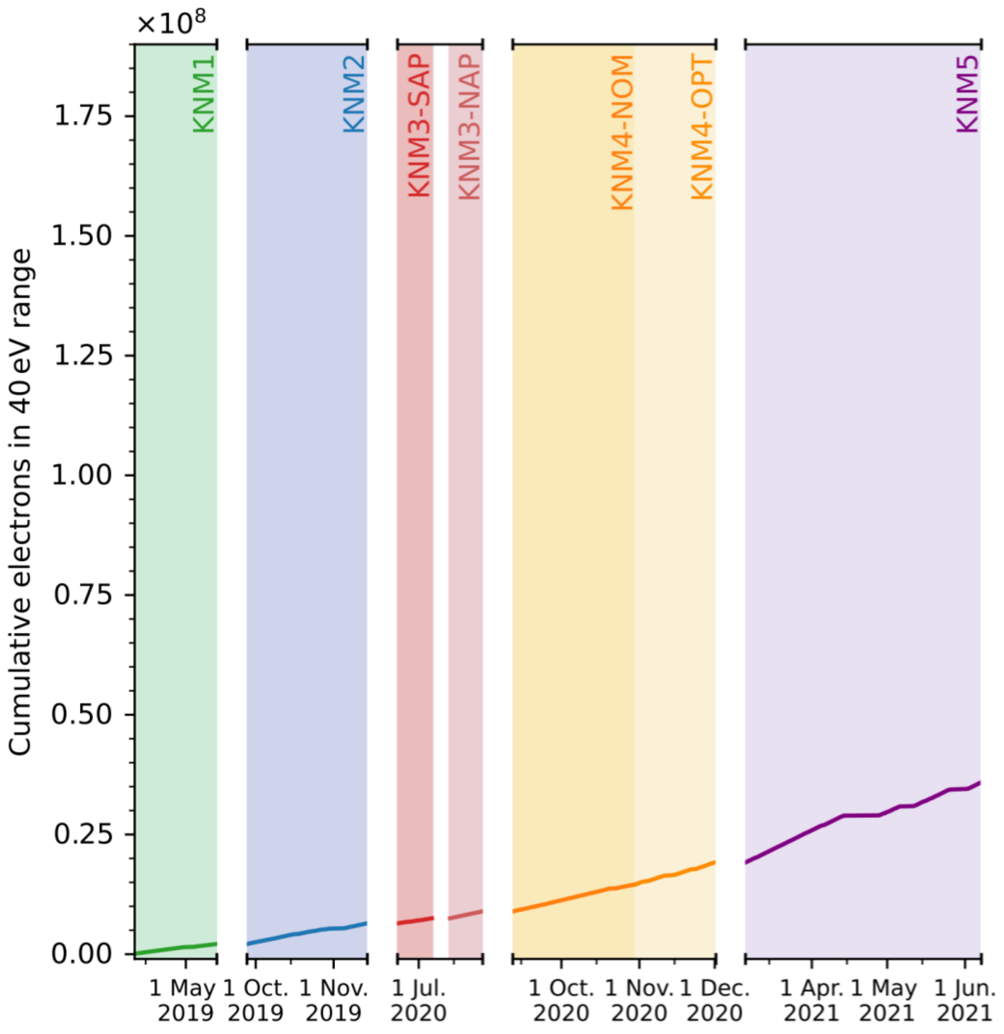
Data aquisition





First KATRIN limit
with ~6 million electrons in analysing window
$m_\nu < 0.8$ eV (90% C.L.)

Data aqusition



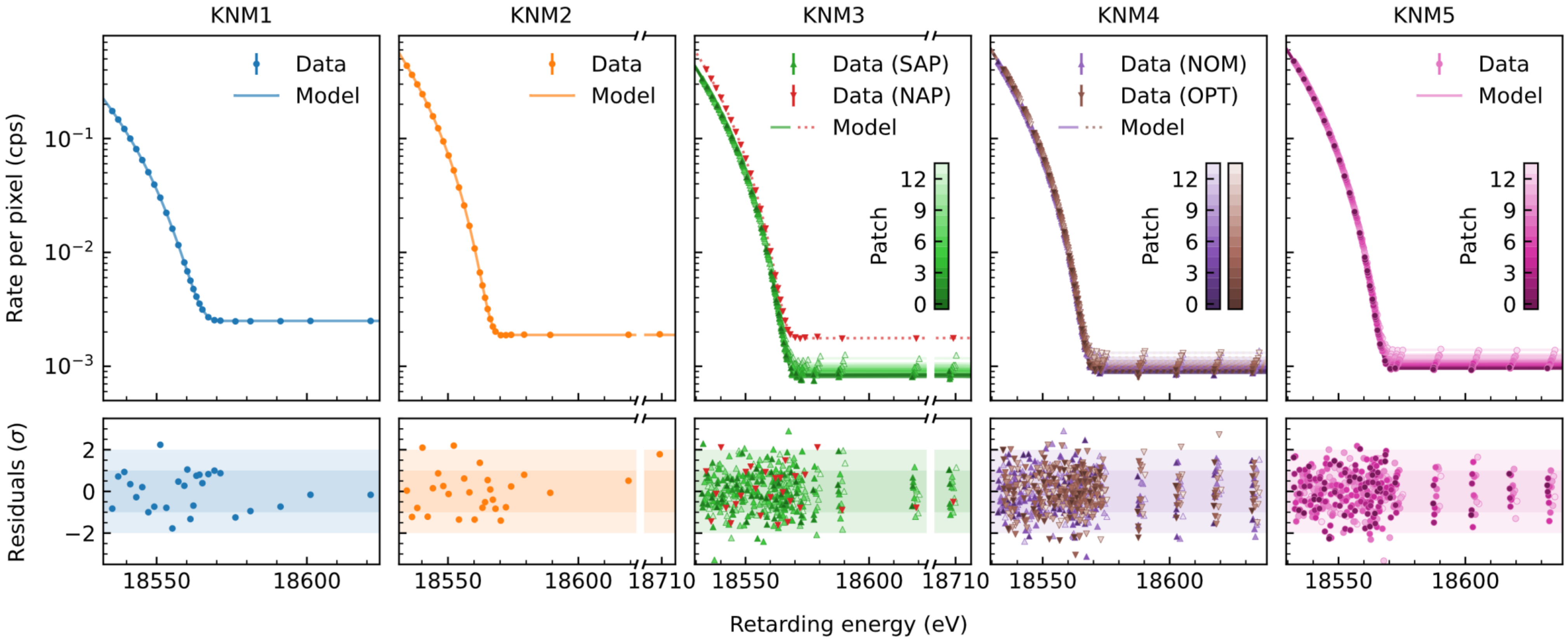
Direct neutrino-mass measurement based on 259 days of KATRIN data

New limit with first 5 campaigns (6 times more statistics)

$m_\nu < 0.45$ eV (90% C.L.)

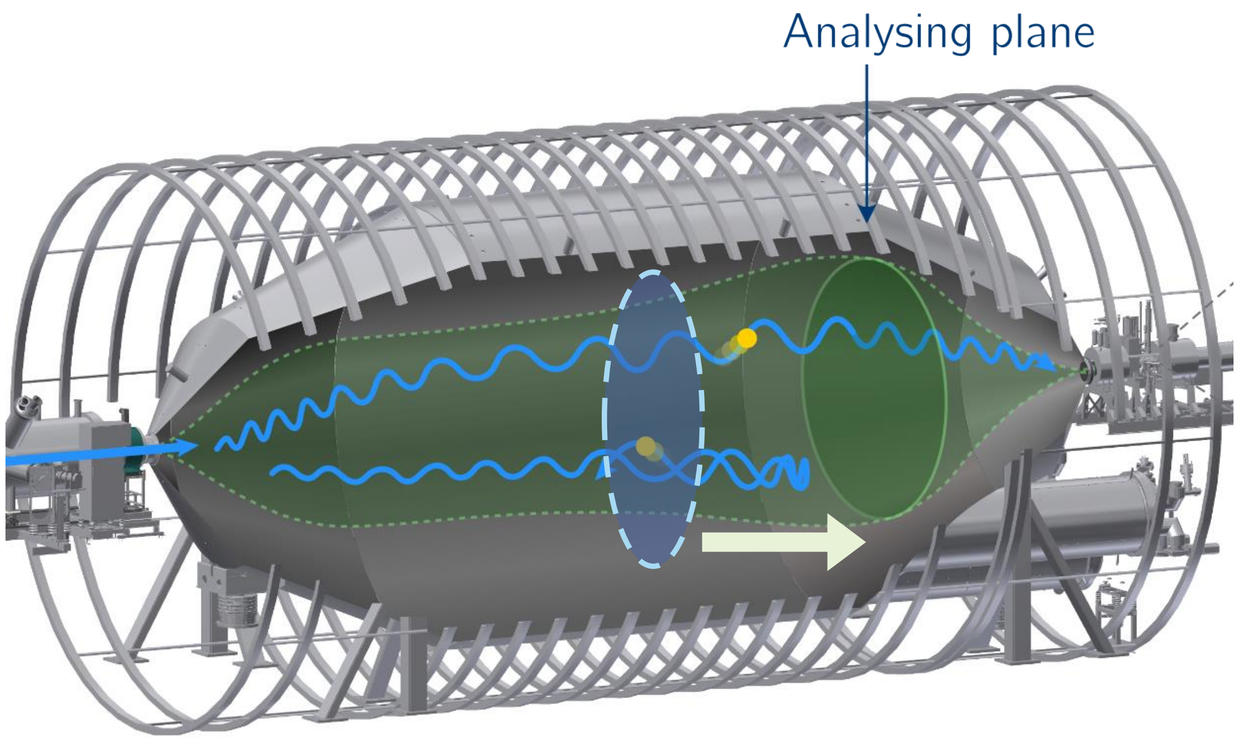
Submitted to arXiv:2406.13516

Data combination



- 59 stacked spectra with a total of 1609 data points
- Computationally expensive model evaluations with 144 correlated systematic parameters
- Experimental improvements regarding background suppression and other systematic effects

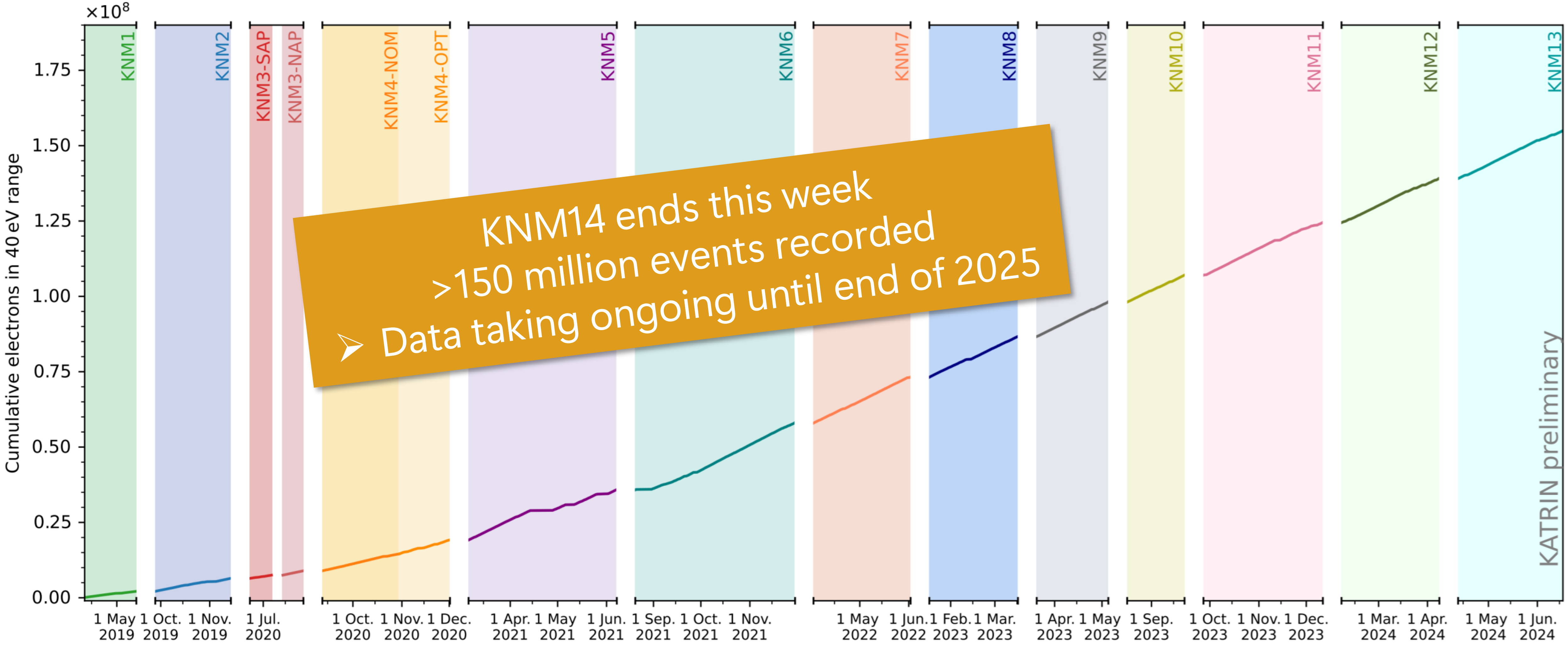
Background suppression: Shifted analysing plane (SAP)



Main spectrometer

- Magnetic field minimum and potential maximum shifted towards detector
- Significant reduction of the sensitive fluxtube volume → factor 2 in background rate
- Inhomogeneous EM-fields → More segmented data and calibration mandatory

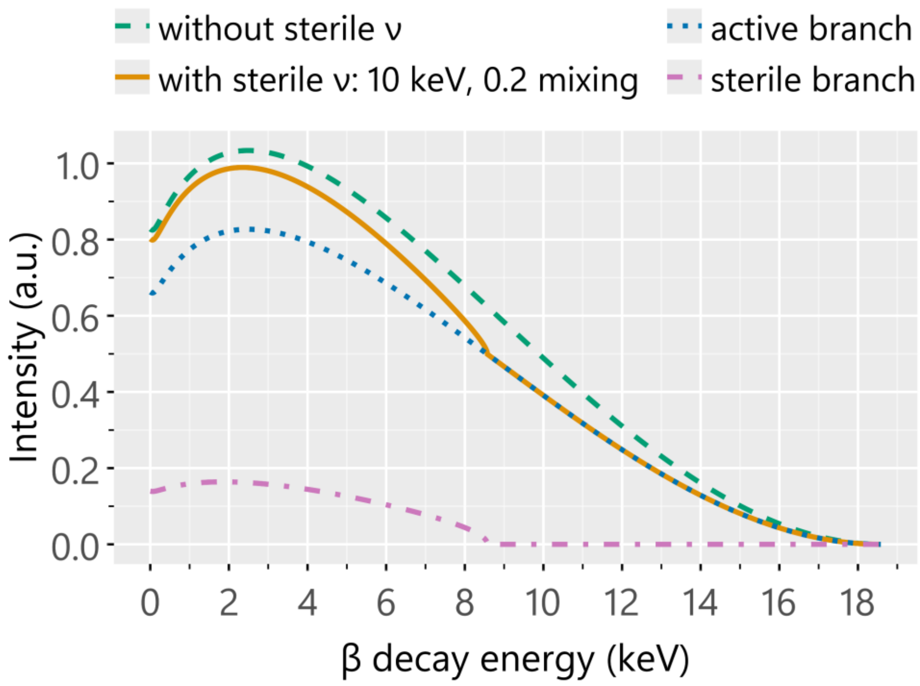
Data aqusition

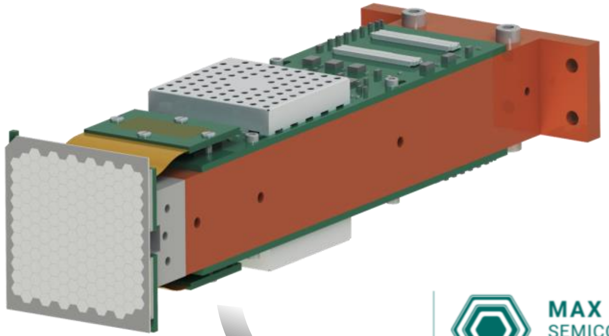


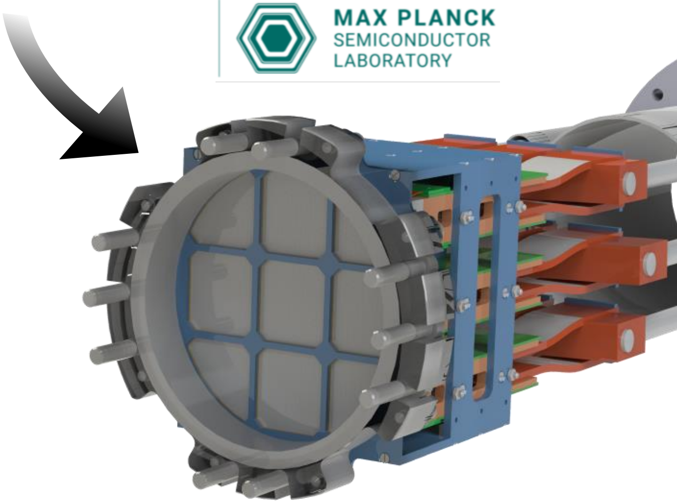
KNM14 ends this week
>150 million events recorded
➤ Data taking ongoing until end of 2025

KATRIN beyond 2025

- TRISTAN detector upgrade to search for keV sterile neutrinos starting in 2026
  - Novel SDD array
  - Different measurement mode







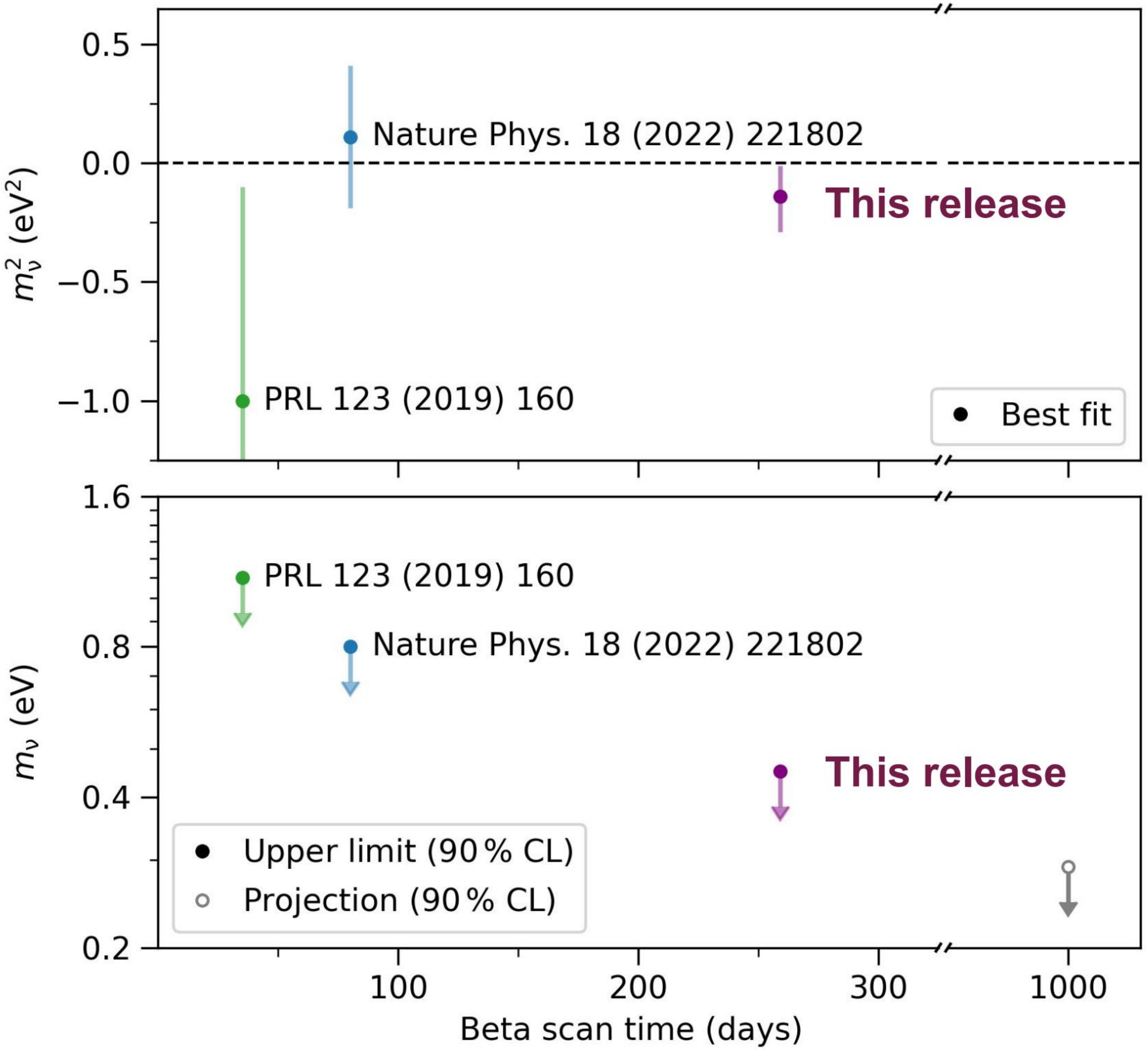
- Timeline
  - 2024: Assembling 3 modules together at detector replica
  - 2025: Full operation of 9 modules in replica for final characterisation measurements
  - 2026: Installation in the KATRIN beamline and data taking

Conclusion and Outlook

- New KATRIN release improves upper limit on the neutrino mass by a factor of 2:

$m_\nu < 0.45$ eV (90% C.L.)

- Ongoing analysis:
  - 70% of total anticipated data recorded with improvements in systematics
  - Several beyond standard model physics searches: eV-sterile, exotic interactions, light bosons, relic ν, …
- Ongoing data taking in 2025 → 1000 days of beta scanning
  - Target sensitivity $m_\nu < 0.3$ eV/c^2



KATRIN Collaboration

46th Collaboration meeting, March 2024, Munich