Recent results from the KATRIN experiment

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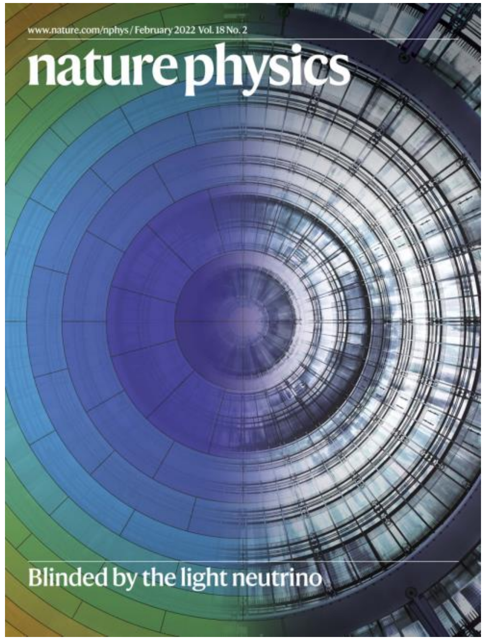
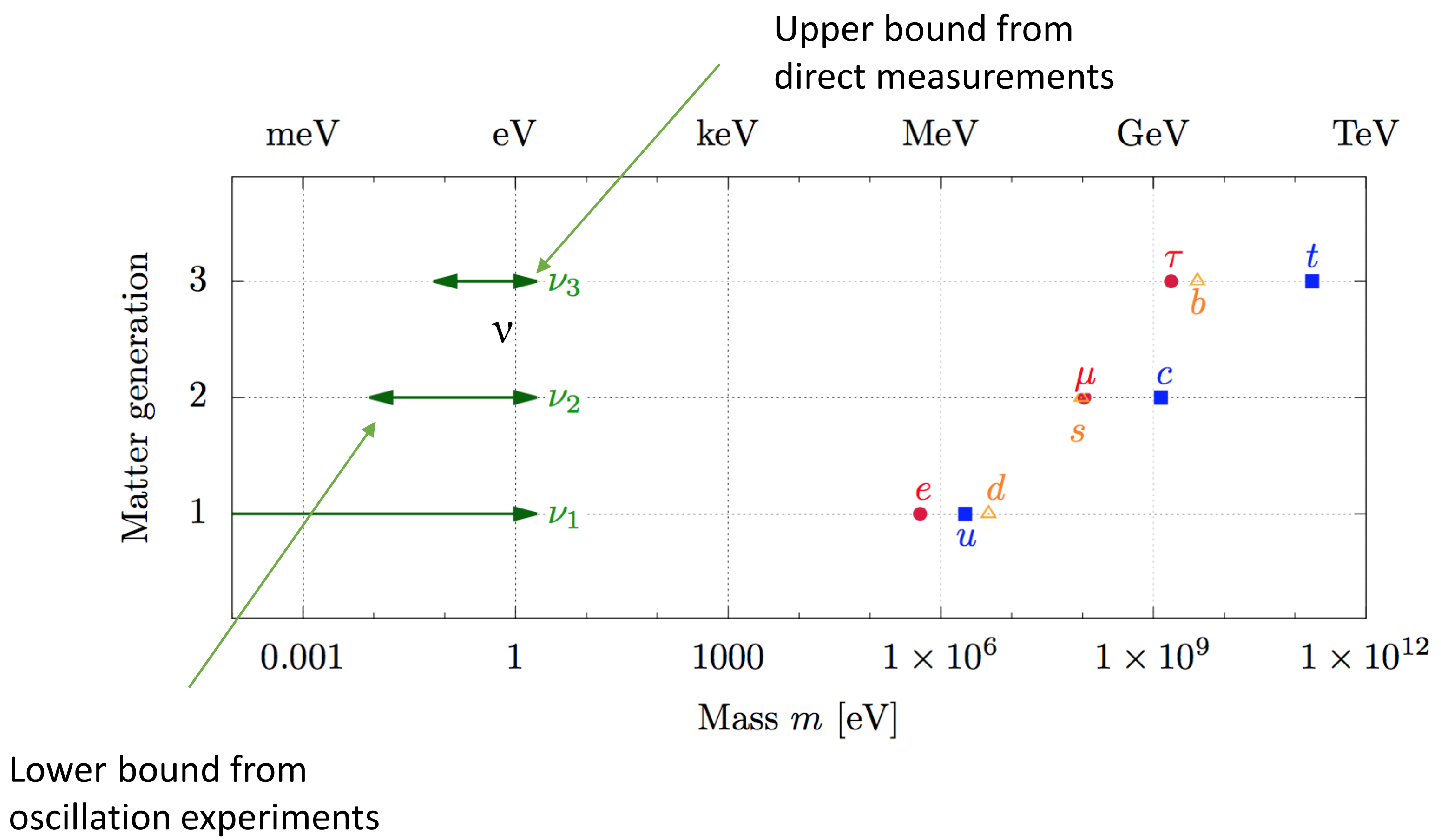
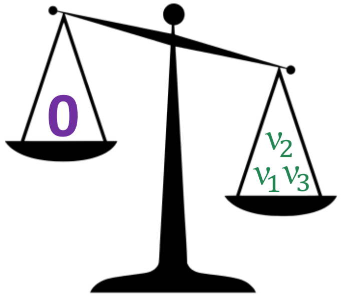
59th International Winter Meeting on Nuclear Physics



Neutrino mass





- Neutrino oscillations → Non-zero mass
- Smallness and origin of mass?

Determination methods

Cosmology

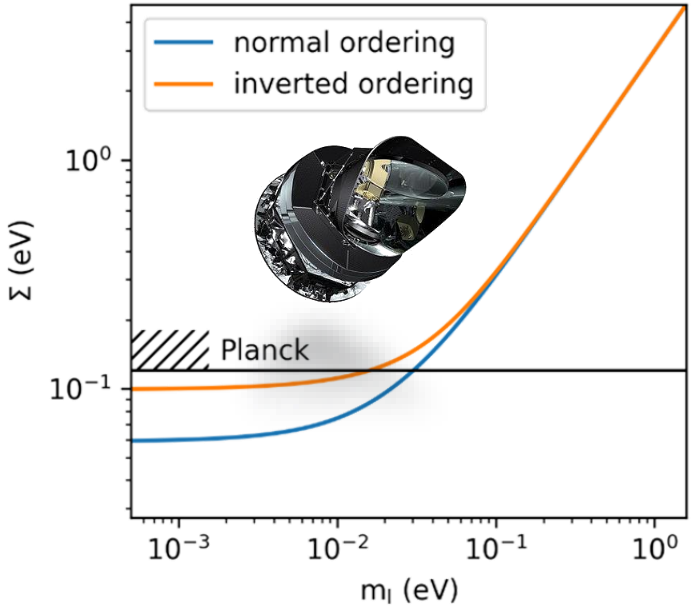
$$\Sigma = \sum_i m_i$$

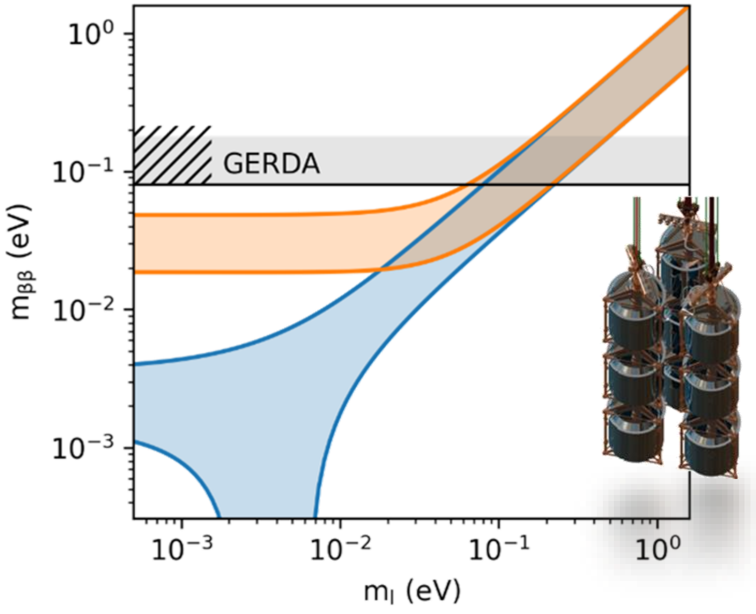
Neutrinoless ββ-decay

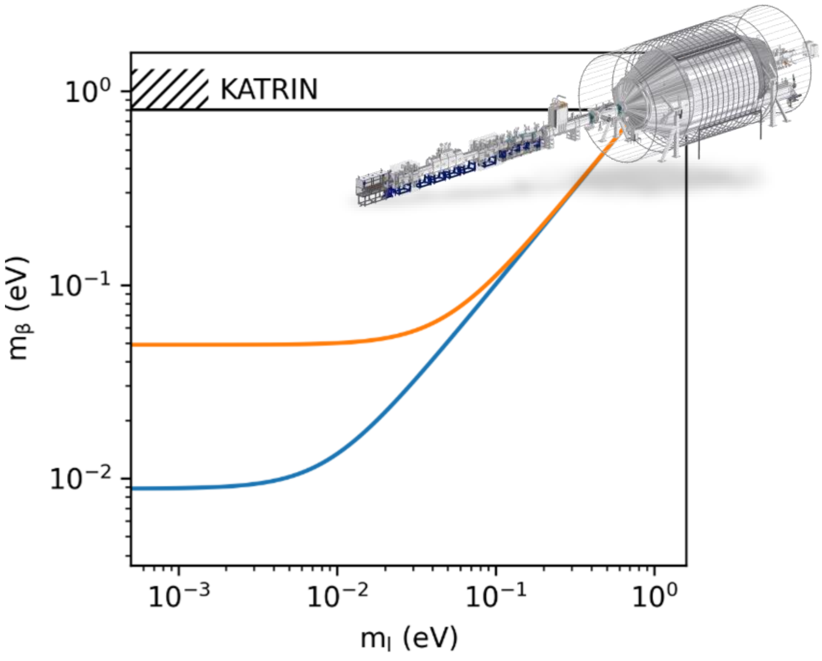
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

β-decay kinematics

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



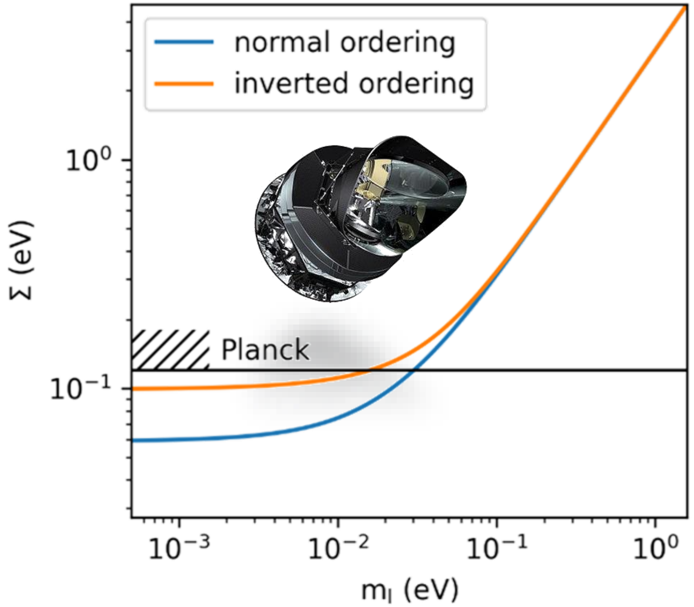




Determination methods

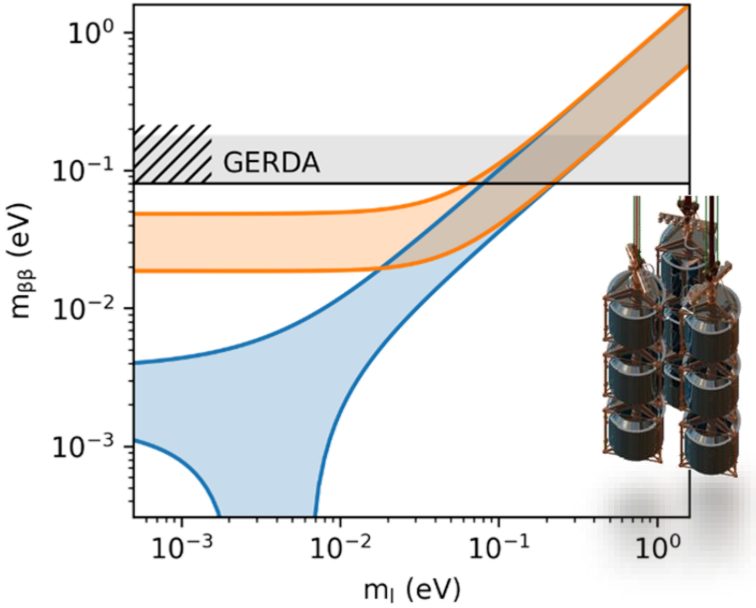
Cosmology

$$\Sigma = \sum_i m_i$$



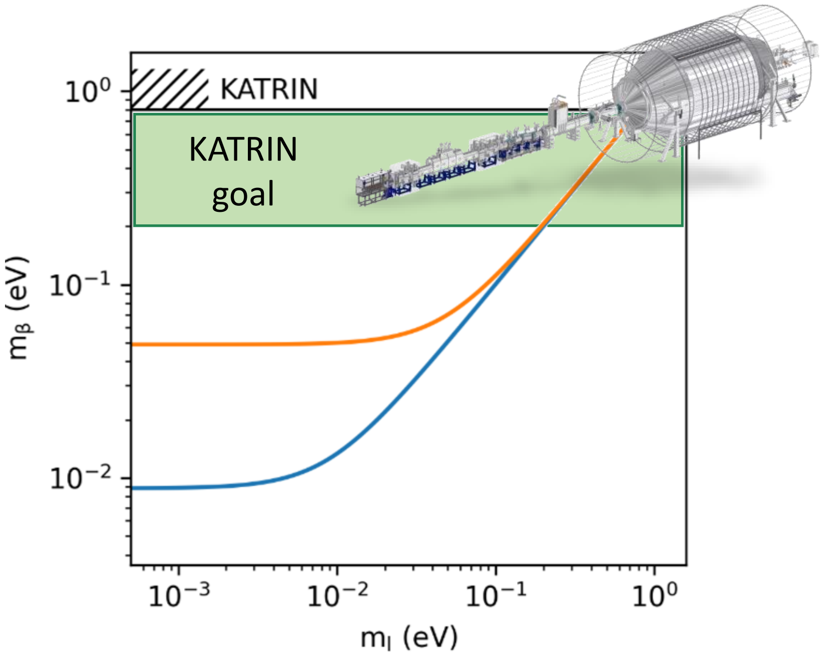
Neutrinoless ββ-decay

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



β-decay kinematics

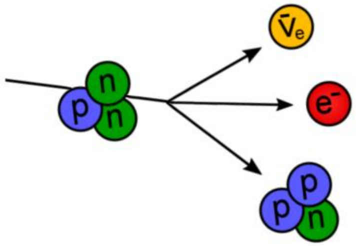
$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

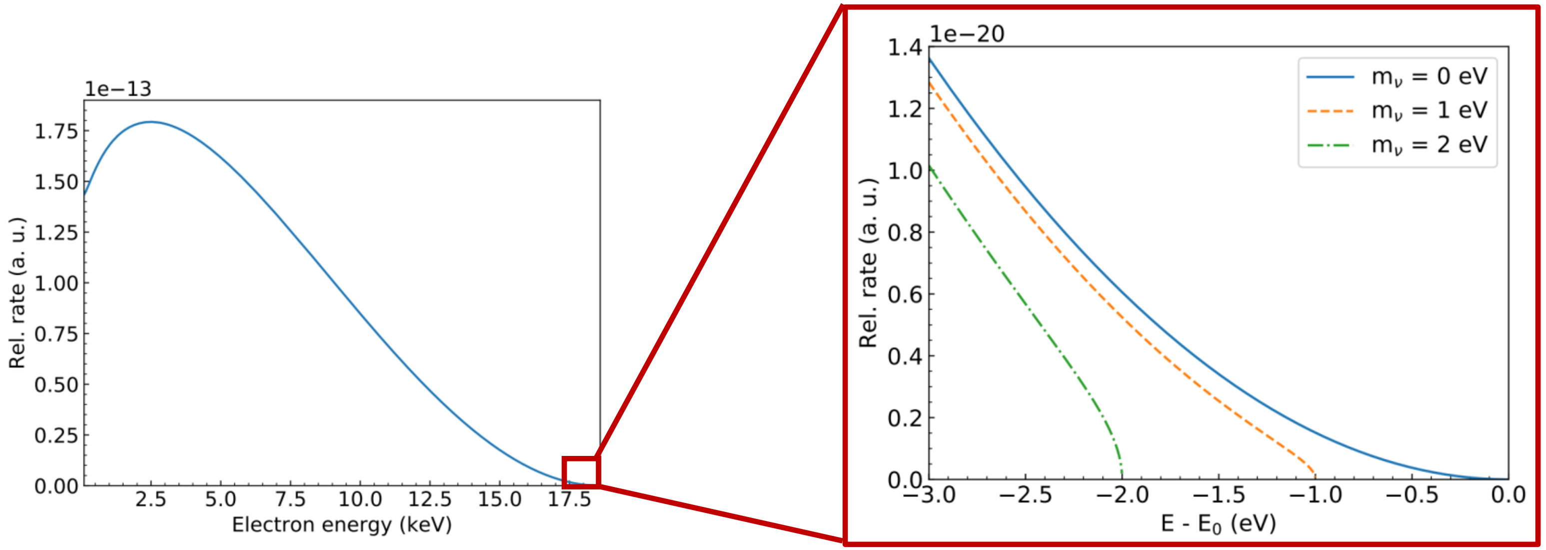


Neutrino mass signal in β-decay

- Tritium ß-decay:
  - $E_0 = 18.56\ keV$
  - $T_{1/2} = 12.3\ years$

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



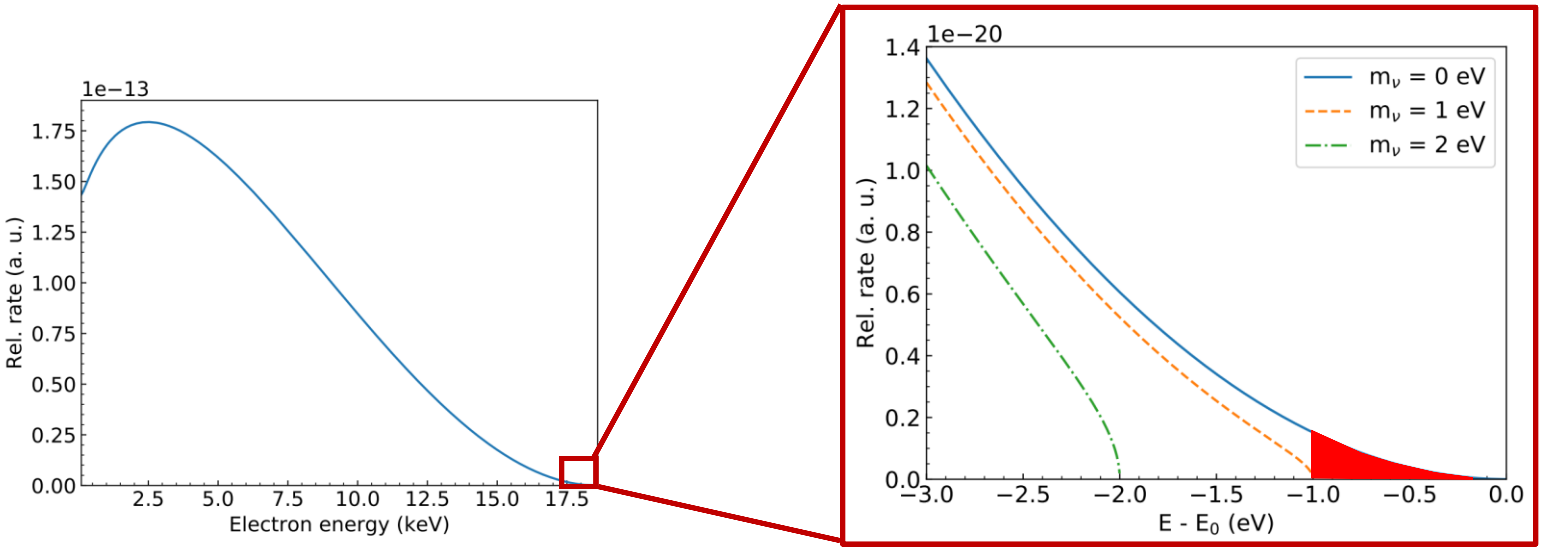


- Distortion of electron spectrum near the endpoint
- Independent of cosmology and neutrino nature

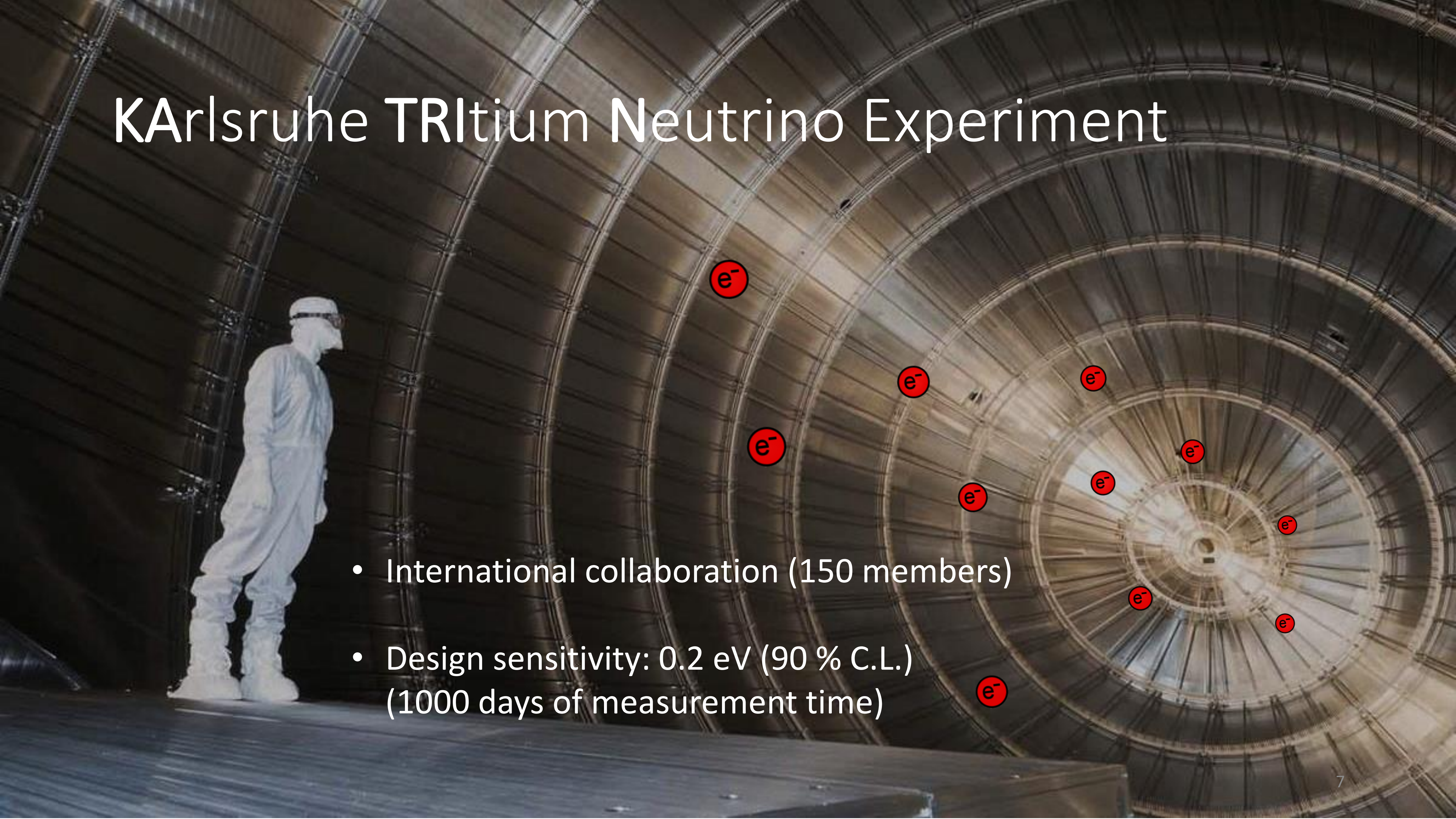
Experimental challenge

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$

- Only 10^{-13} of all decays in last 1 eV, 10^{-8} in the last 40 eV
- Strong tritium source: 10^{11} decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV
- Precise understanding of the spectrum shape



KArlsruhe TRItium Neutrino Experiment



- International collaboration (150 members)
- Design sensitivity: 0.2 eV (90 % C.L.)
  (1000 days of measurement time)

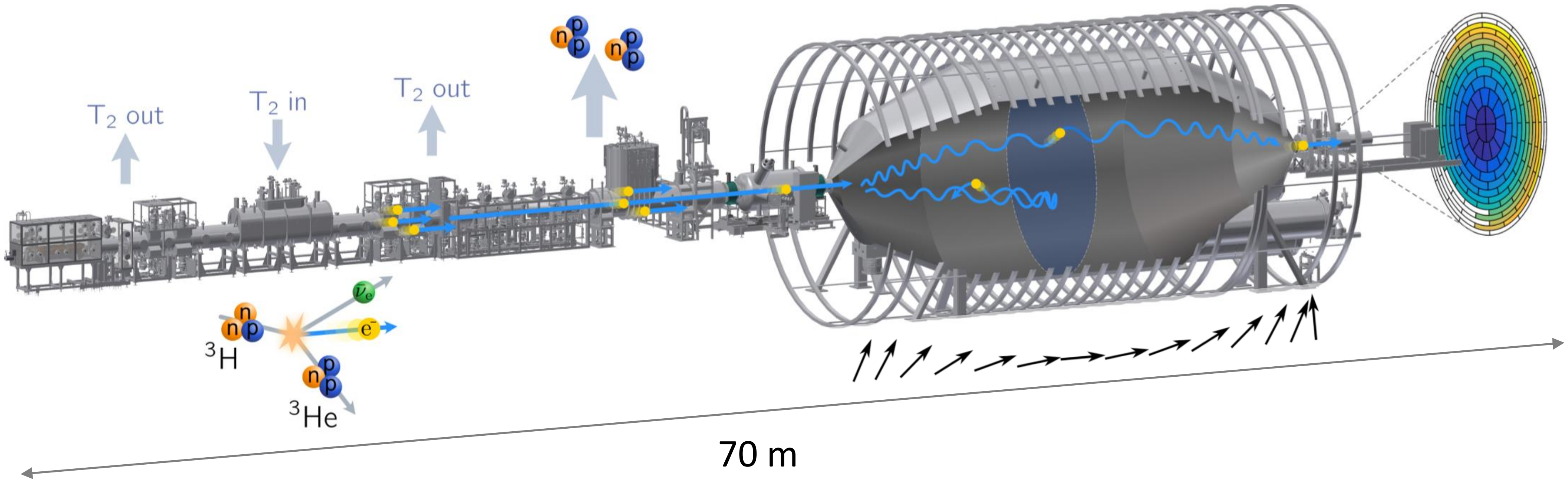
Experimental overview

Windowless gaseous tritium source
- 30 µg molecular tritium in closed loop
- **10^{11} T_2 decay/s**

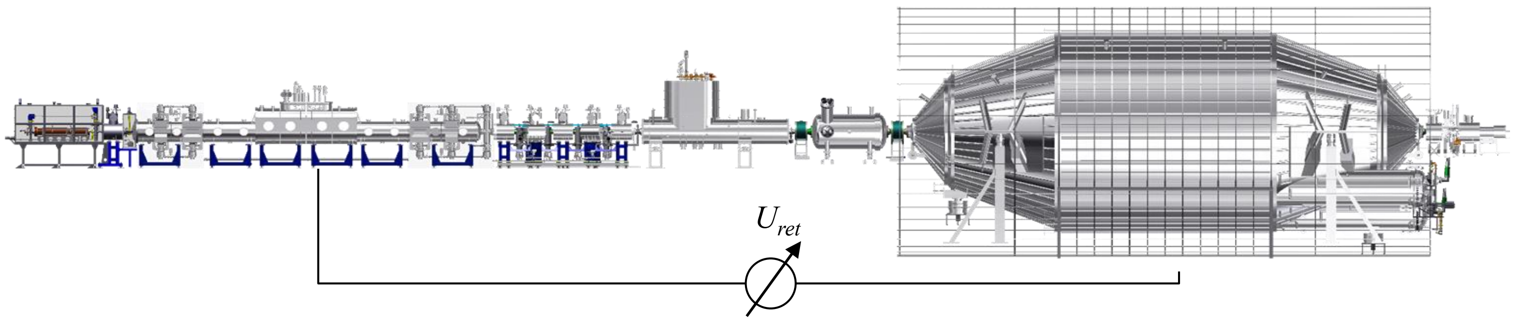
Transport section
- Tritium gas/ion removal > **10^{14}**

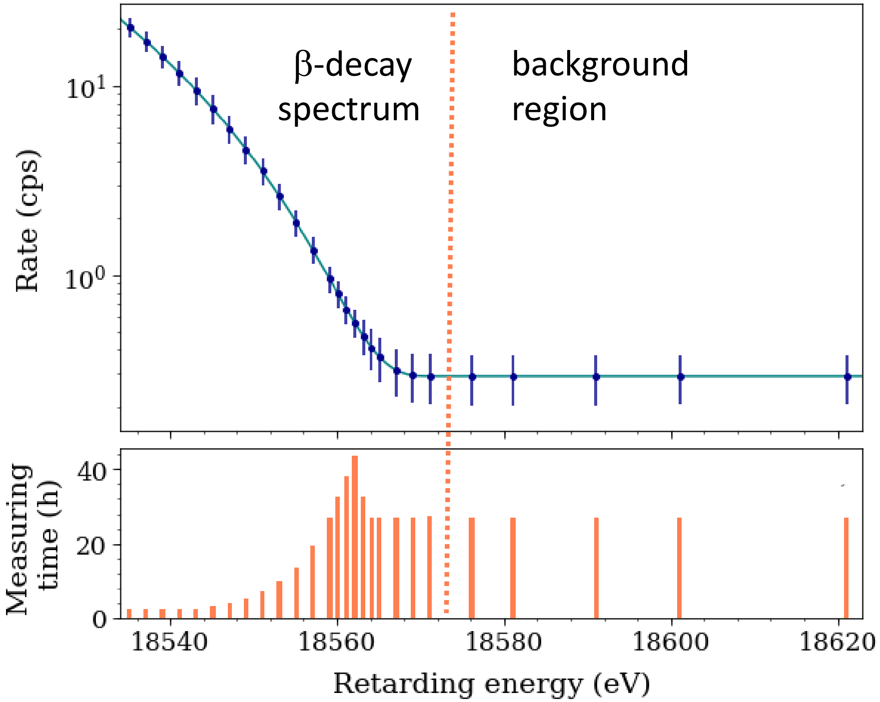
Spectrometer
- MAC-E filter principle
- High resolution: **O(1) eV**

Detector
- Focal plane detector, **148 pixel** PIN-diode
- Counts electrons



Measurement strategy

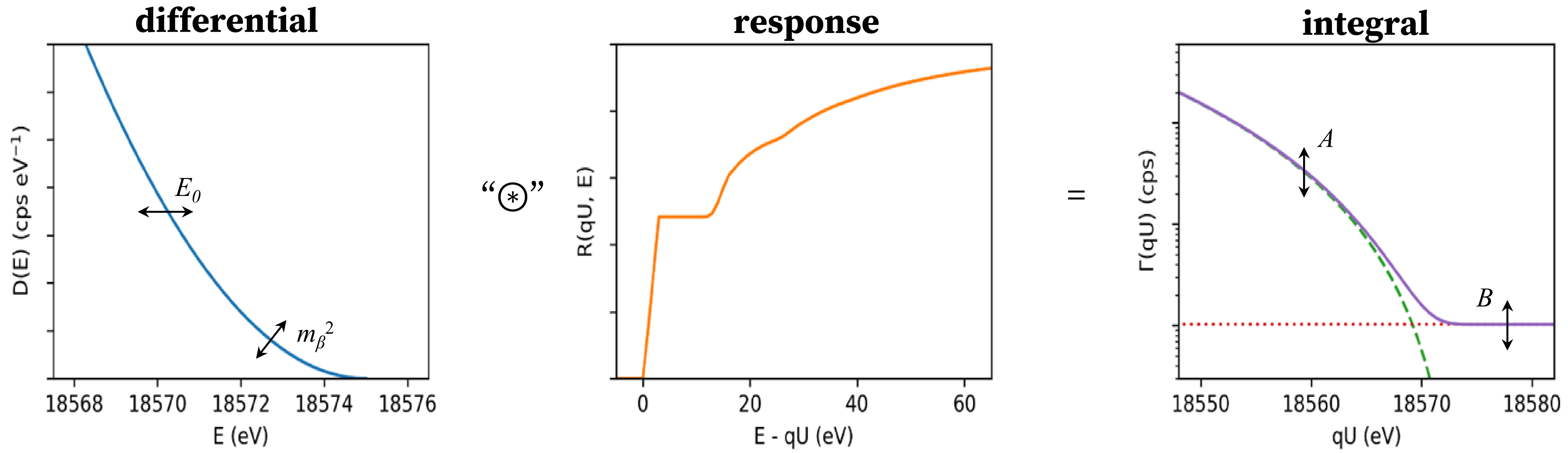




- **~30 HV set points** with varying duration
- Scan interval: $\mathbf{E_0}$ **– 40 eV ,** $\mathbf{E_0}$ **+ 130 eV**
- **~2 h scan** time
- Several **campaigns** per year O(100) scans

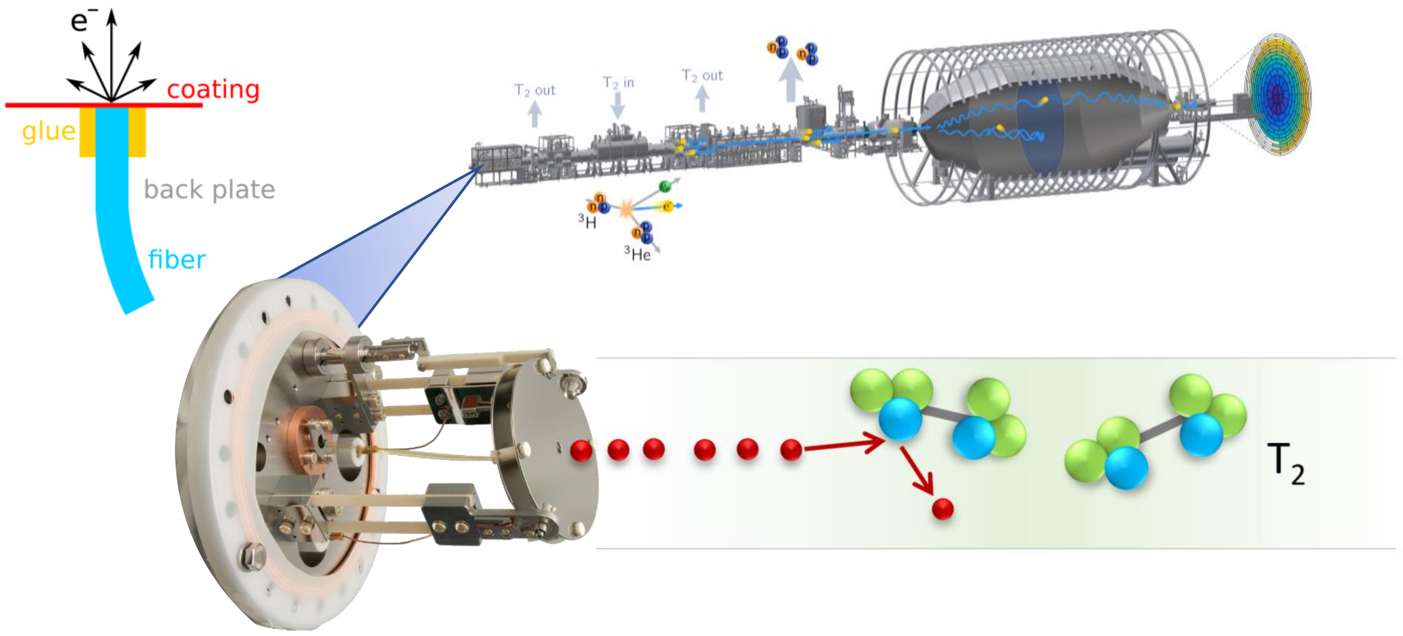
Analysis strategy

- Maximum likelihood fit of **model** $$\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$$



- Free parameters: Amplitude **A**, squared neutrino mass $\boldsymbol{m_\beta^2}$, endpoint $\boldsymbol{E_0}$ and background **B**
- **Theoretical** (Fermi theory, molecular excitations) and **experimental inputs** (calibration measurements)

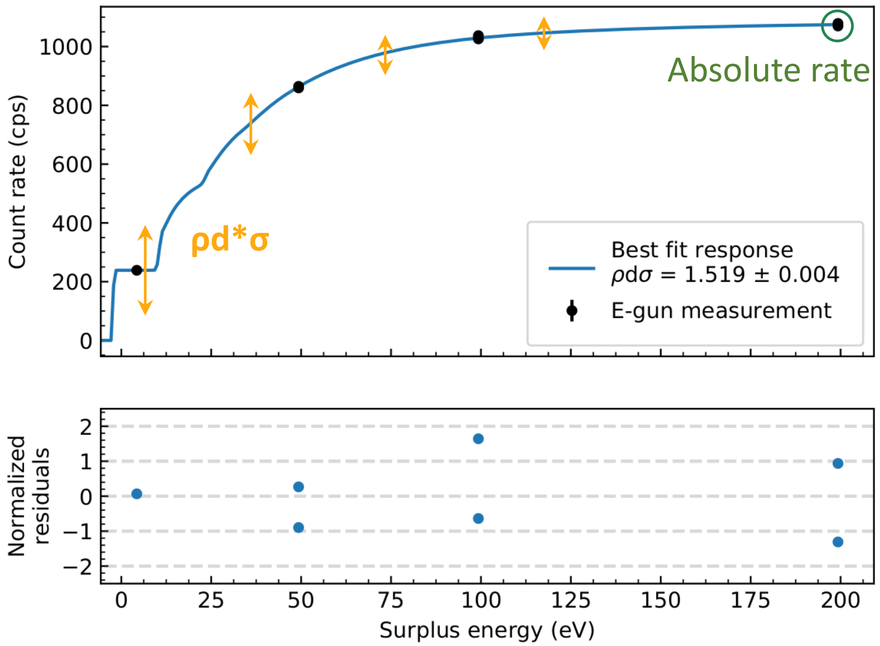
Column density determination



Electron-gun

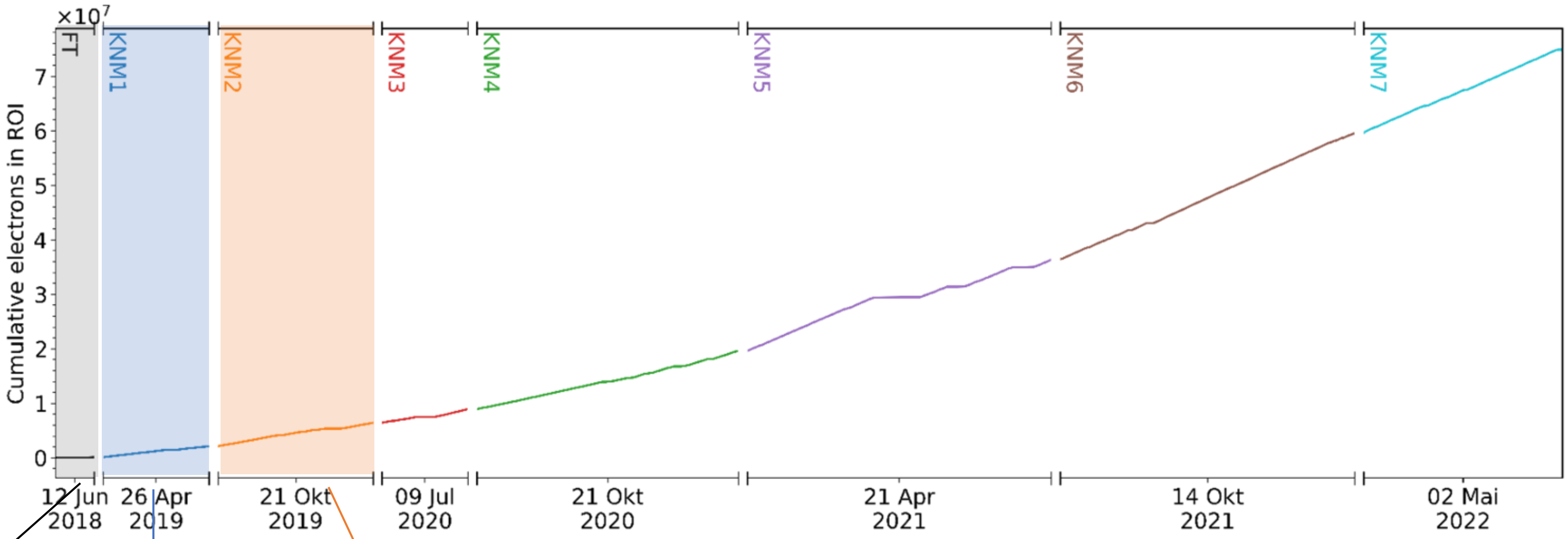
- Source scattering depending on:
  - Electron path
  - **Column density**
  - Cross section

→ Input for **response function**



- Electron rate measured at different retarding potentials: ~30 min
- Fit with model response function:
  - Absolute **electron rate**
  - **ρd*σ** (column density * cross section)

Data taking overview

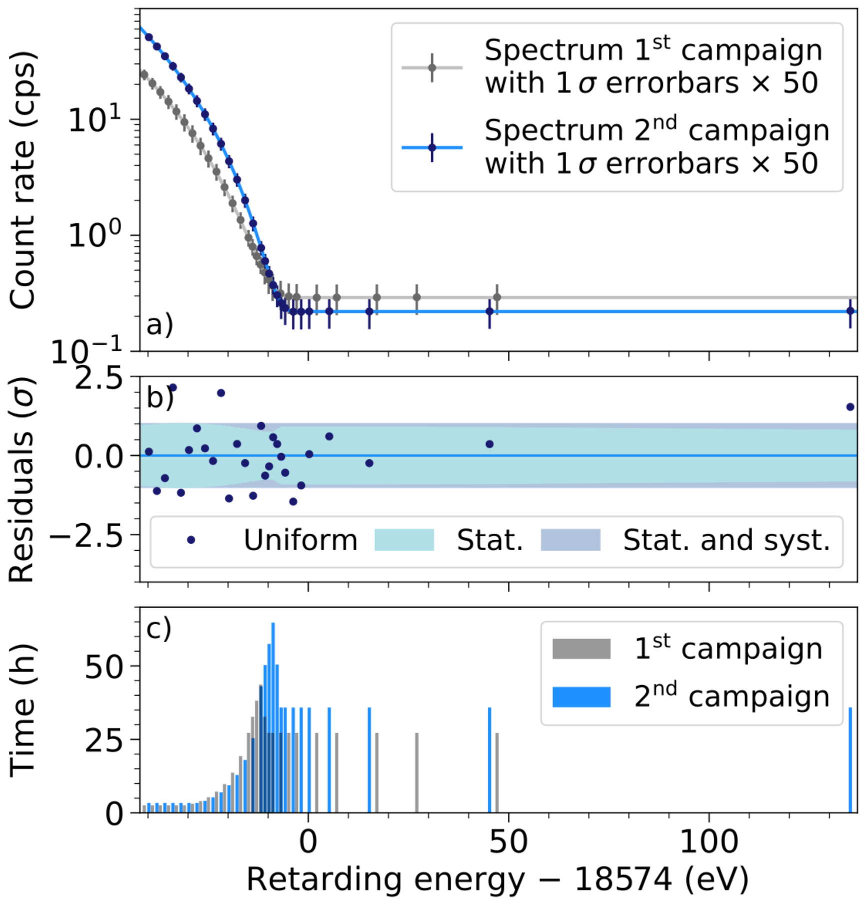


Comissioning
[EPJ C 80, 264 (2020)]

< 1.1 eV (90% CL)
[Aker et al., PRL 123 (2019) 22, 221802]

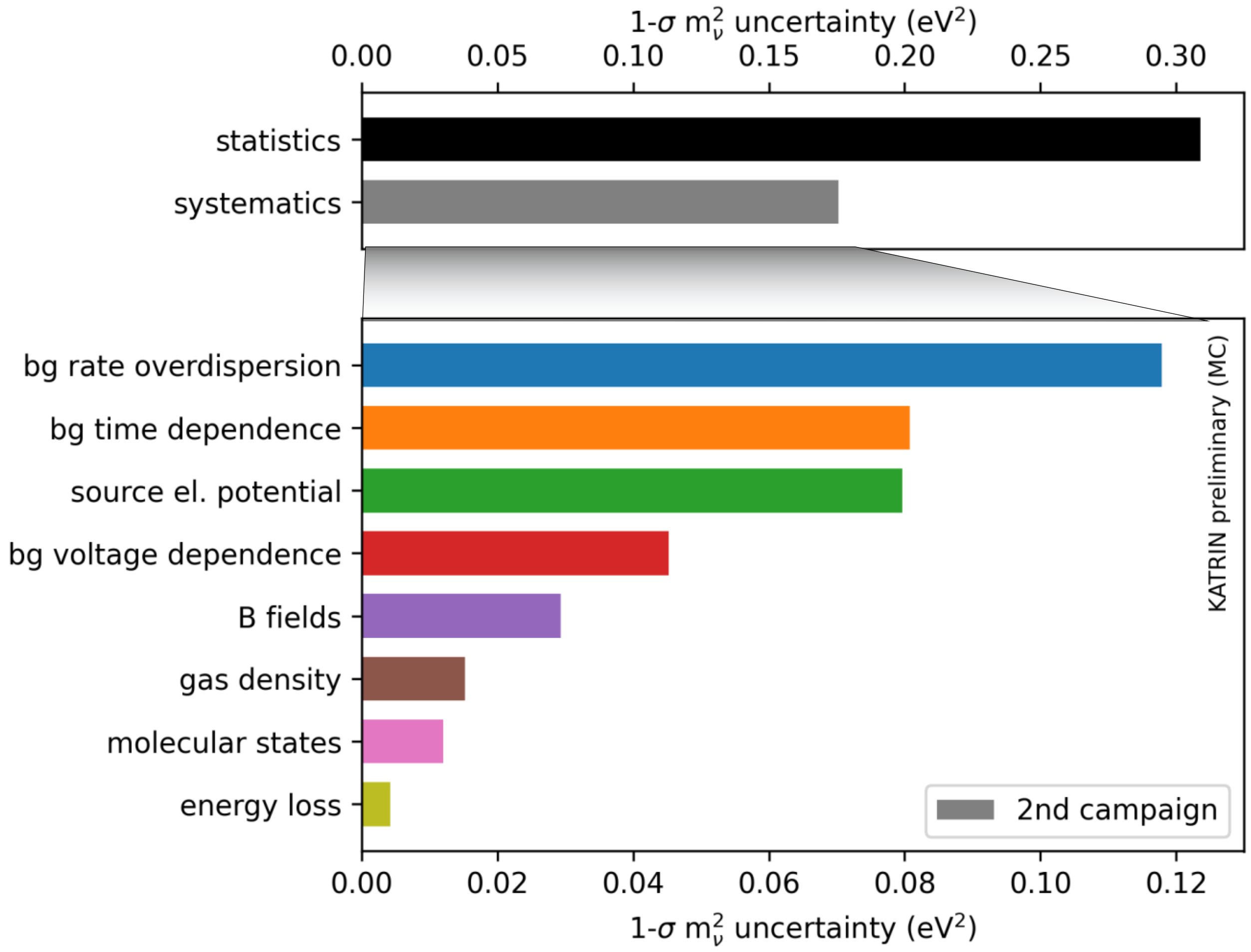
< 0.8 eV (90% CL)
[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

Latest neutrino mass result

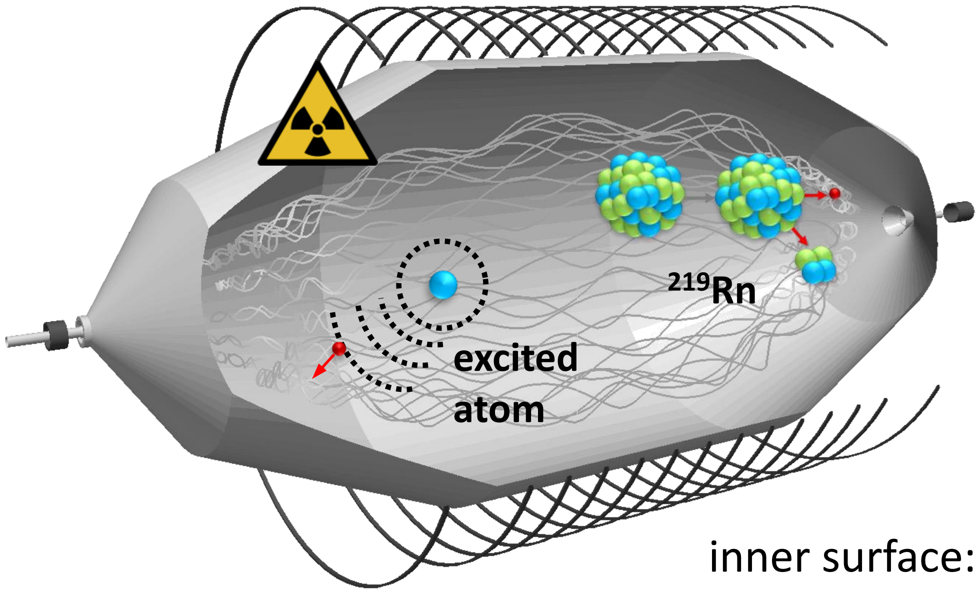


- KNM1:
  - Best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV²
  - Limit: $m_\nu < 1.1$ eV (90% CL)
- KNM2:
  - Best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$eV²
  - Limit: $m_\nu < 0.9$ eV (90% CL)
- Combined result: $m_\nu < 0.8$ eV (90% CL)

Uncertainty breakdown: 2^{nd} campaign

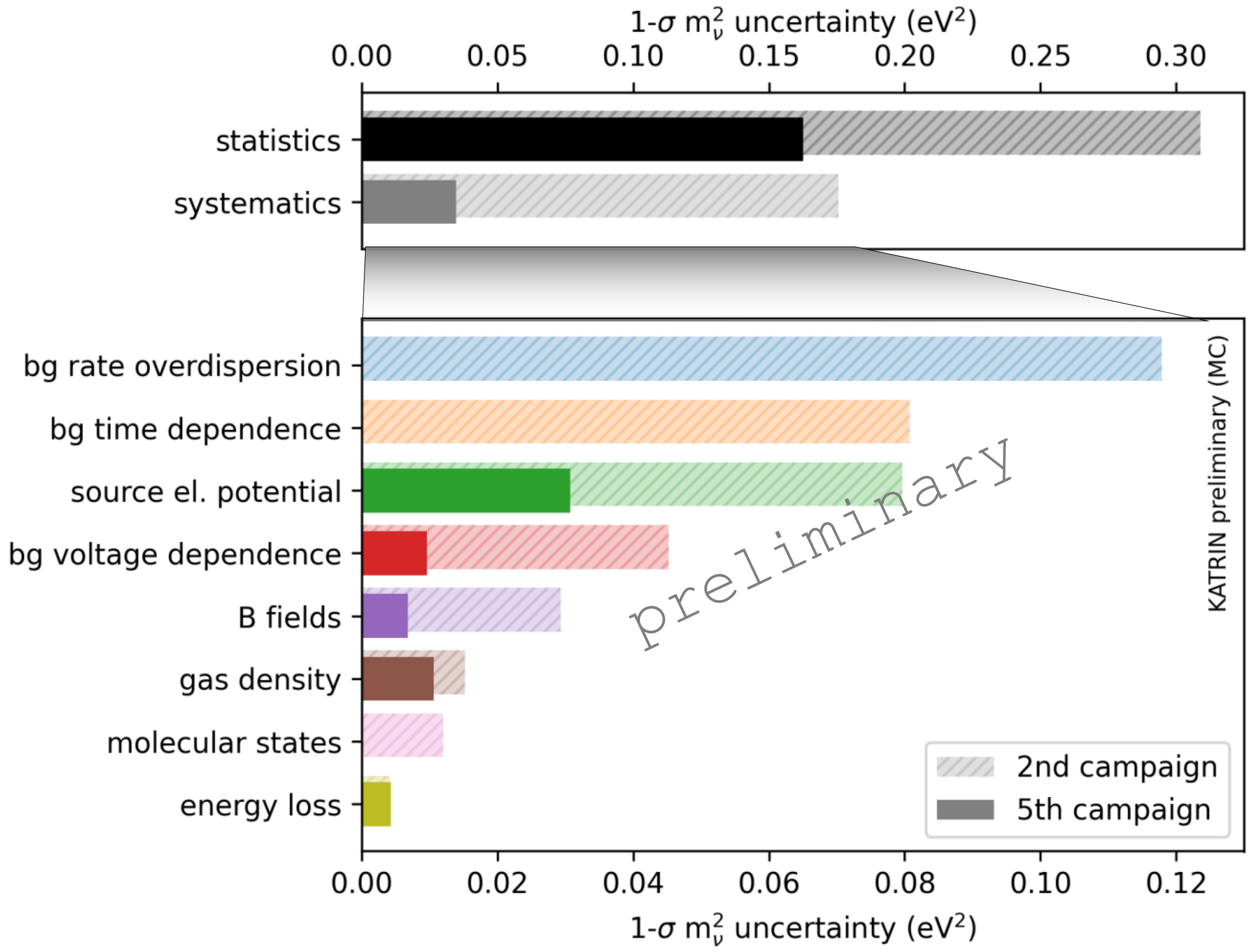


- **Statistical uncertainty dominates**, systematics non-negligible
- **Background**-related uncertainties dominate systematics budget

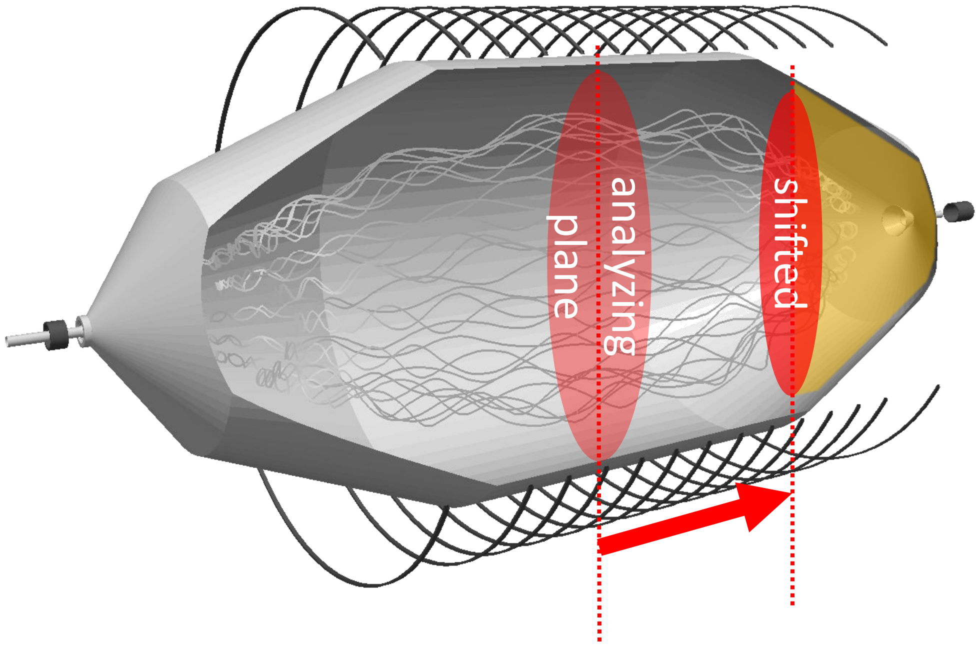


inner surface: $650m^2$
volume: $1400m^3$

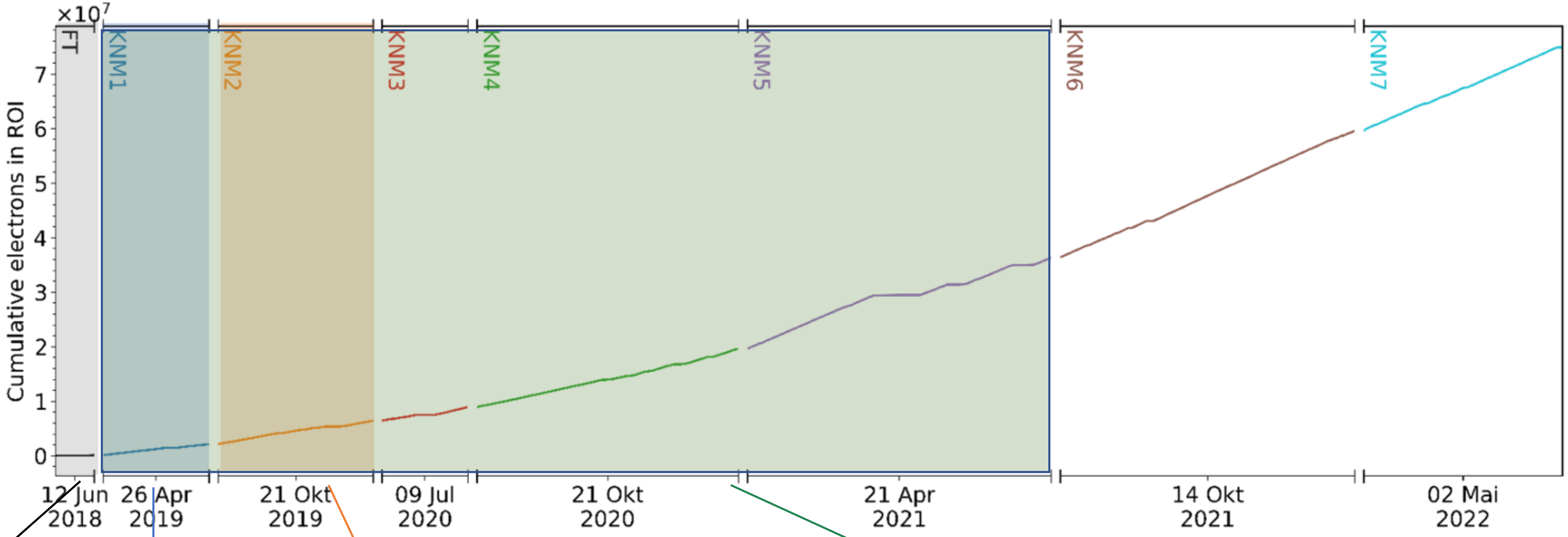
Preview: 5th campaign



- Still statistics dominated, **systematics largely improved**
- **Major improvement:** Background reduction (÷2) via new EM field layout
  Lokhov et al arXiv:2201.11743 (2022)



Outlook



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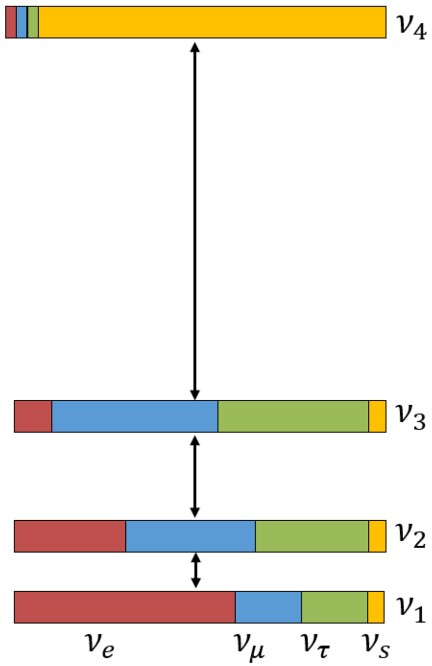
- **Combined** analysis of first 5 campaigns
- Model evaluation **computationally challenging**

→ Fast **neural network** interpolation [Karl et al., EPJ C 82 (2022) 5, 439]

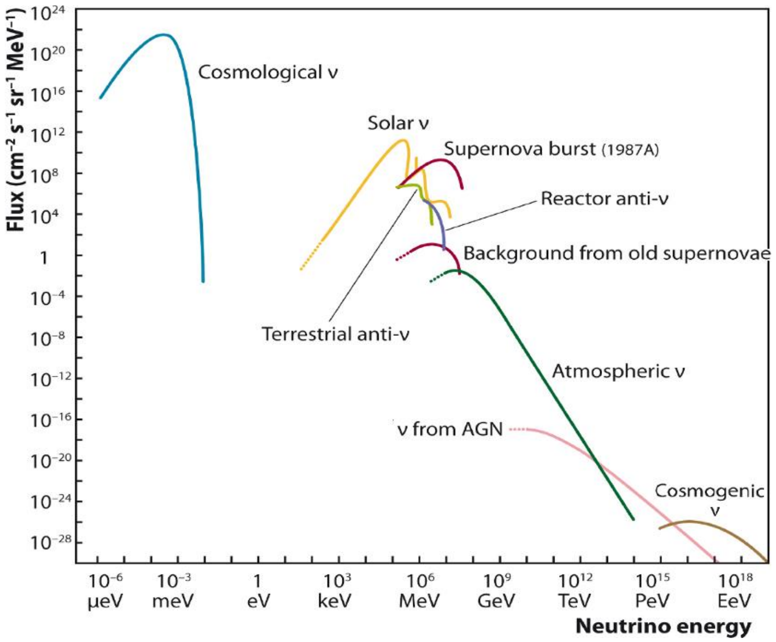
- Next data release in summer
- Sensitivity projection: $\boldsymbol{m_\beta}$ **< 0.5 eV** (90% CL)

Physics beyond neutrino mass

Search for light sterile neutrinos



Search for Big Bang neutrinos

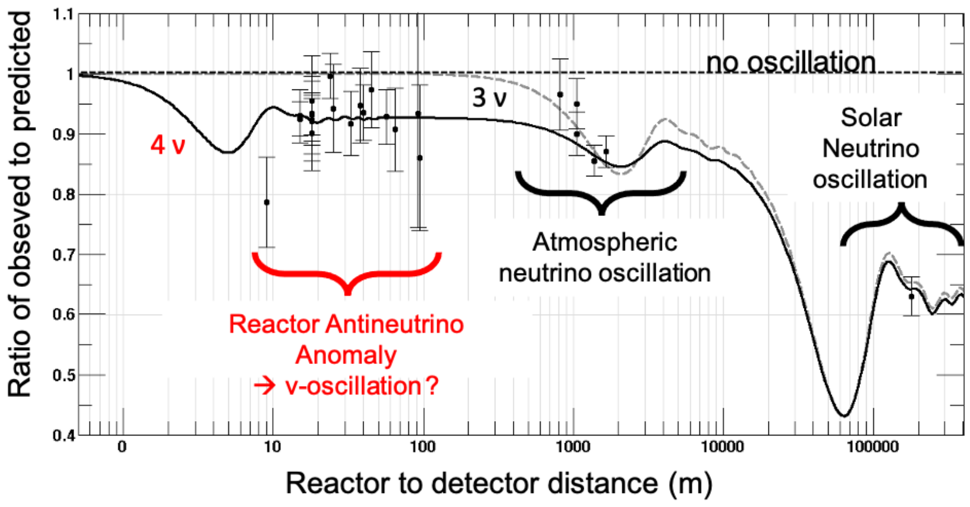


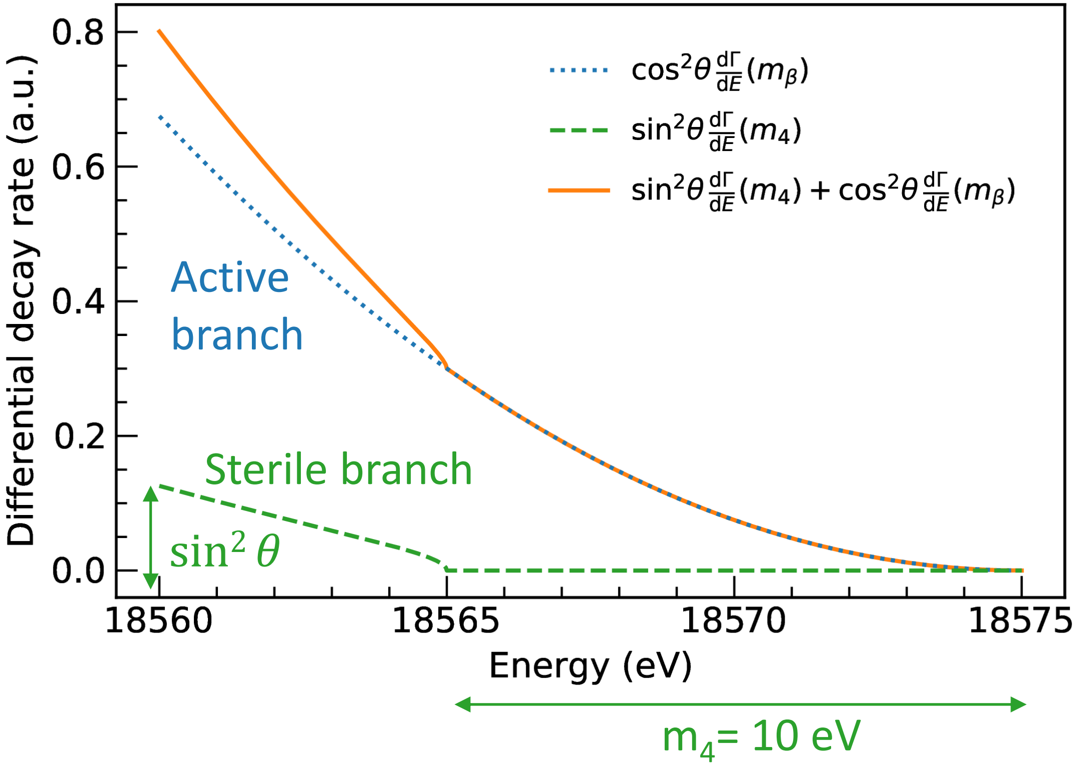
and more …
(not in this talk)

Light sterile neutrinos

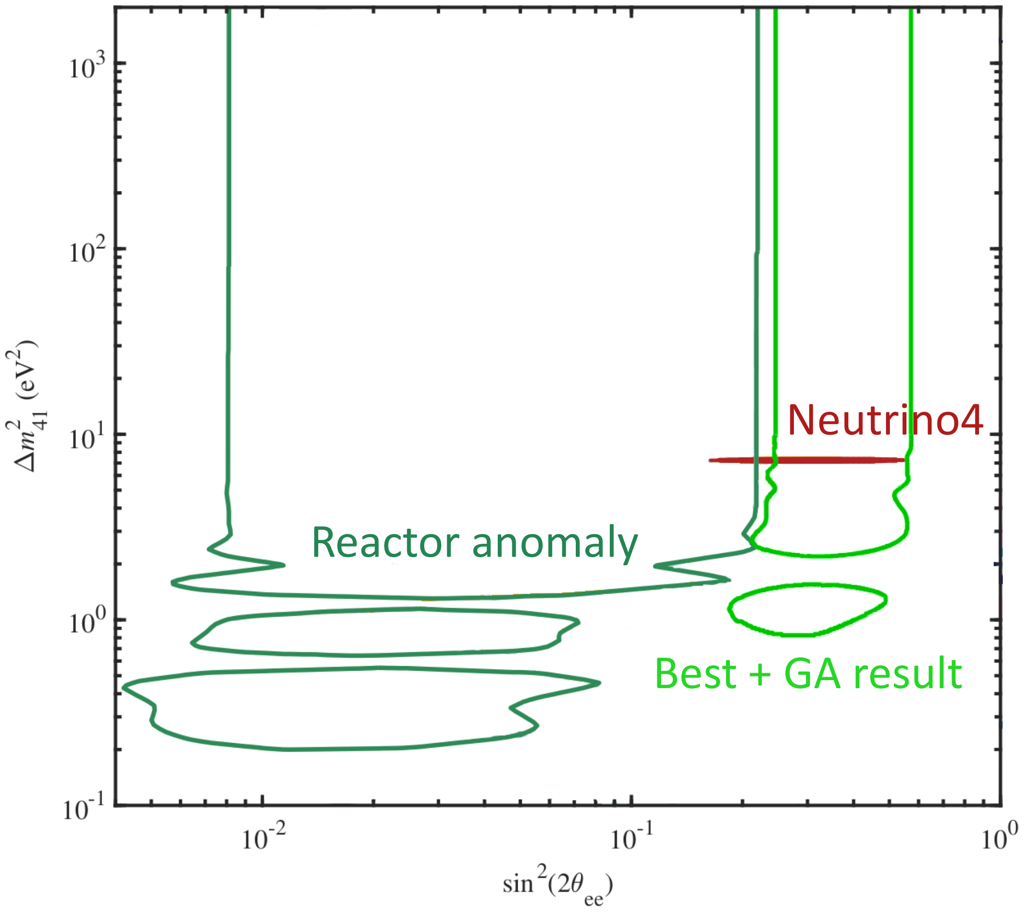
- Motivated by anomalies in ν-oscillation experiments → **eV-scale**

G. Mention et al Phys. Rev. D **83**, 073006 (2011)





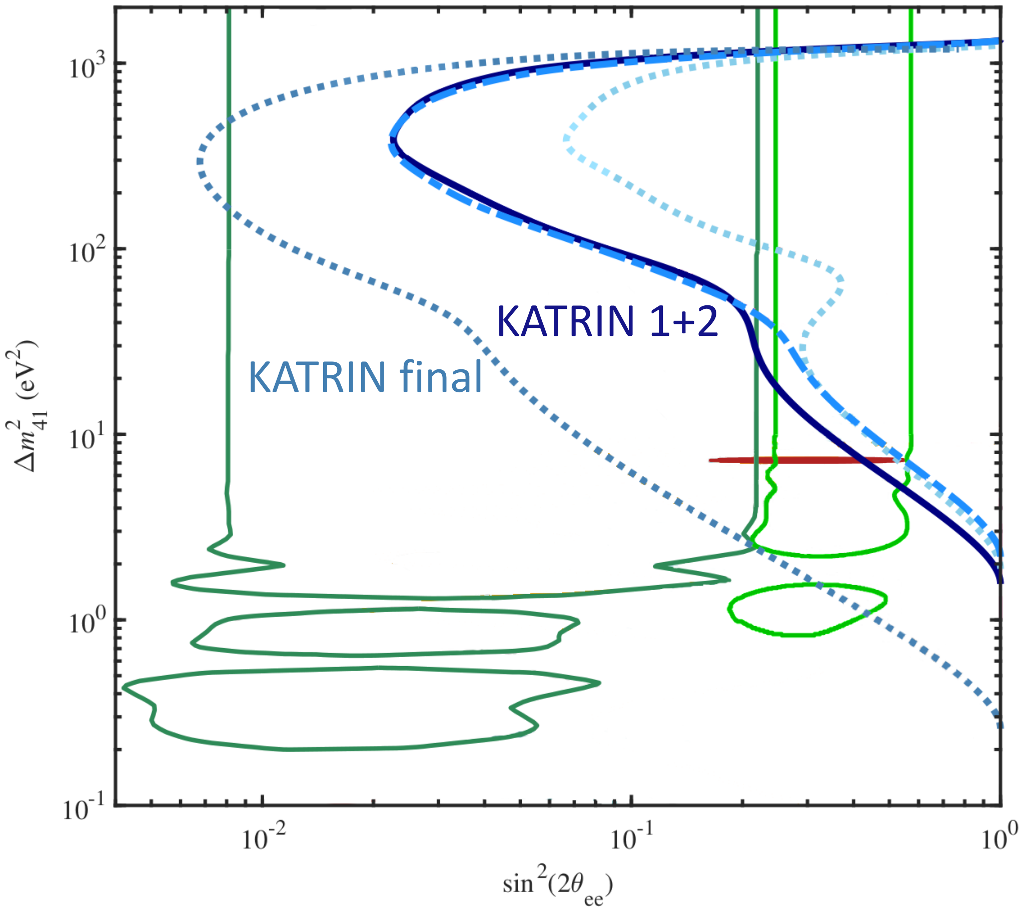
Sterile neutrino parameter space



- Neutrino4 result → disputed
- Reactor anomaly → resolved?
- Gallium anomaly → strengthened with BEST result

G. Mention et al Phys. Rev. D **83**, 073006 (2011)
A. P. Serebrov et al., Pisma Zh. Eksp. Teor. Fiz. 109, 209 (2019)
V. V. Barinov et al. (BEST), arXiv:2109.11482 (2021)

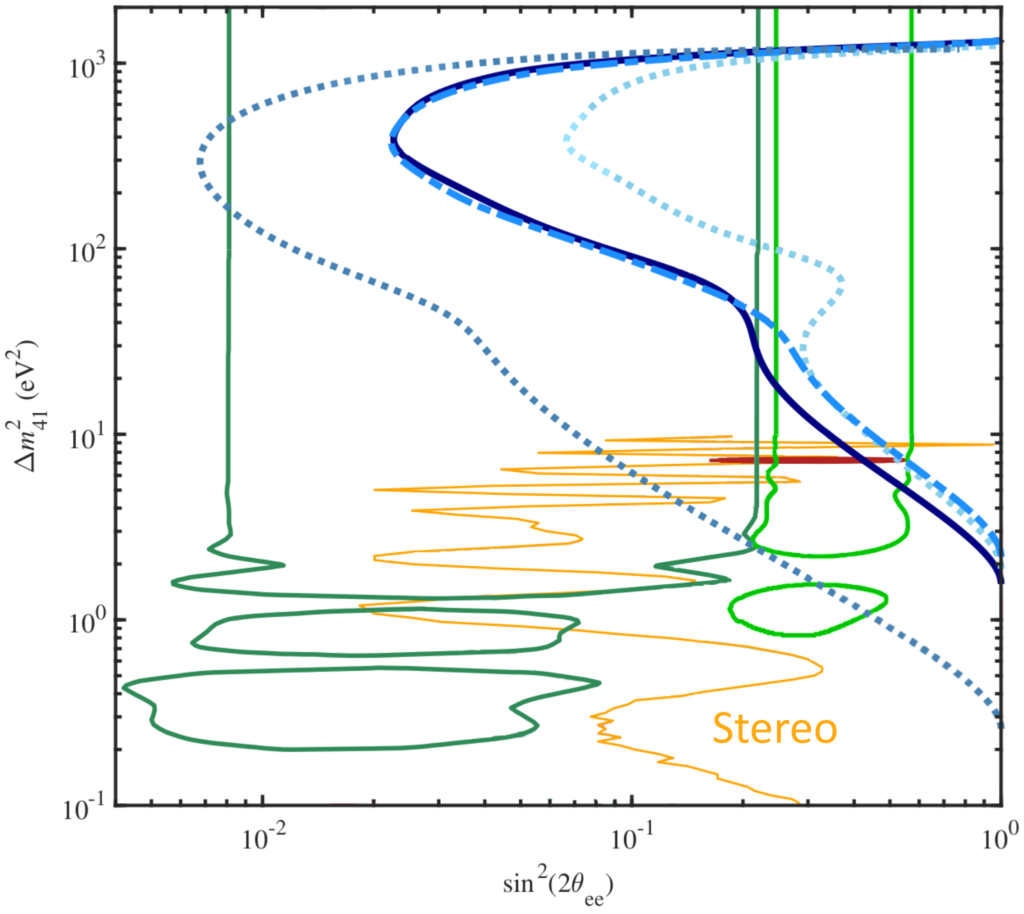
Sterile neutrino parameter space



- **Partly exclusion** of Neutrino4 and GA with recent KATRIN result
- Potential to probe Neutrino4 and GA to **great extend**

KATRIN Collab., PRL. 126, 091803 (2021)
KATRIN Collab. arXiv:2201.11593 (2022)

Sterile neutrino parameter space



- Complementary probe to oscillation-based experiments

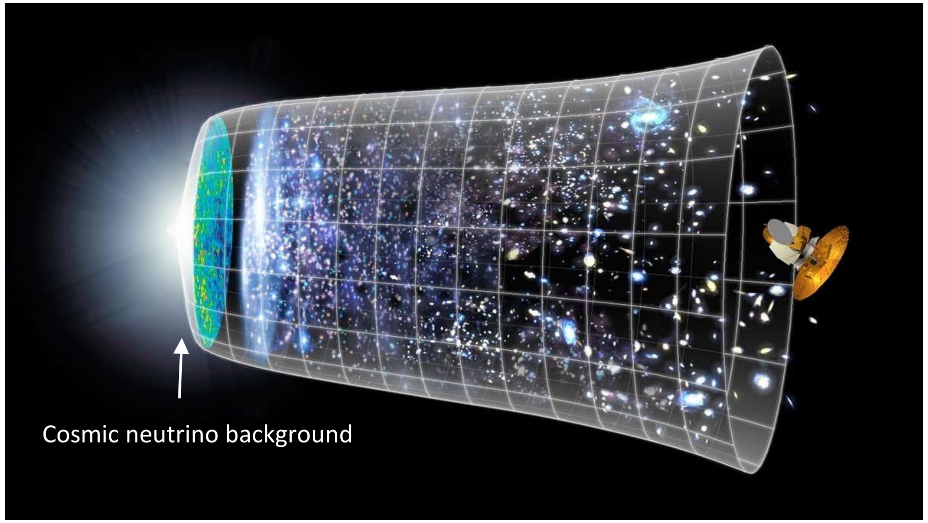
DANSS, arXiv:1911.10140 (2019)
STEREO, Phys. Rev. D 102, 052002 (2020)
PROSPECT, Phys. Rev. D 103, 032001 (2021)

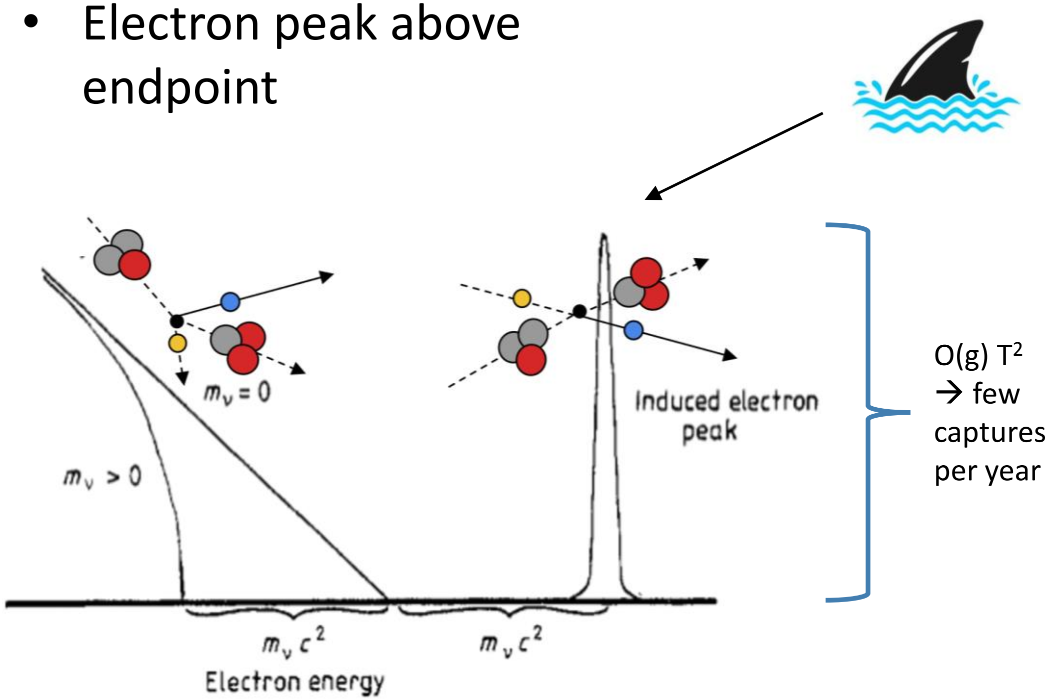
Relic neutrino signature

- Cosmic neutrino background (**CνB**)
  - Neutrino decoupling 1 s after Big Bang
  - High abundance: 400 ν/cm^3 today
  - Challenge: Tiny cross-section

→

- **Capture on tritium**, no energy threshold
- Electron peak above endpoint



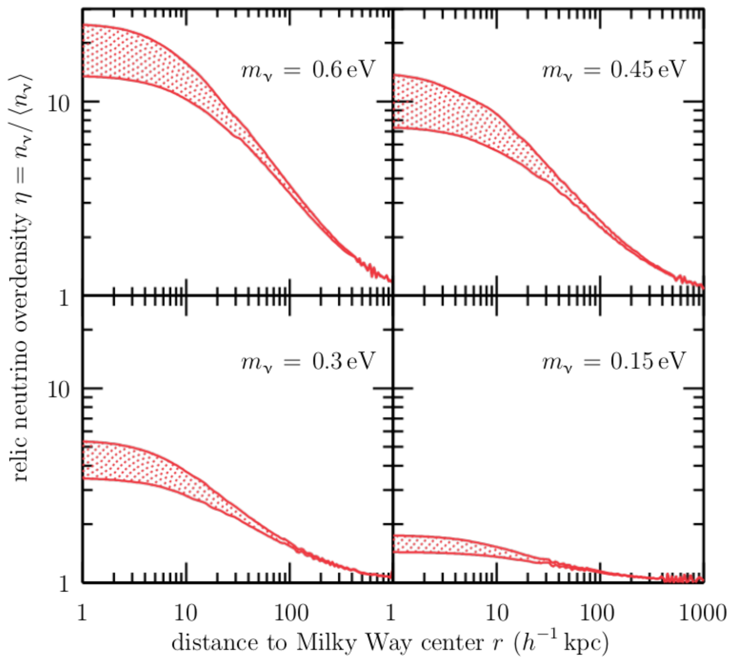


O(g) T^2
→ few captures per year

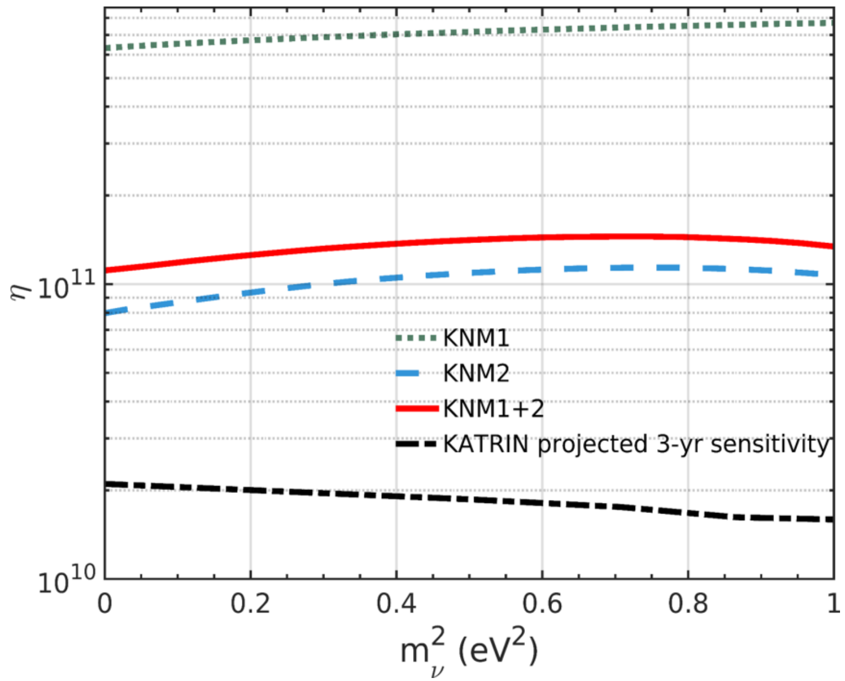
Relic neutrino overdensity

- KATRIN data:
  - constraint on **local overdensity** η < 1.1·10^{11} (95% CL)
  - ➔ **x100 improvement** over previous laboratory bounds

Ringwald, Wong JCAP 0412 (2004) 005



[Phys.Rev.Lett. 129 (2022) 1, 011806]

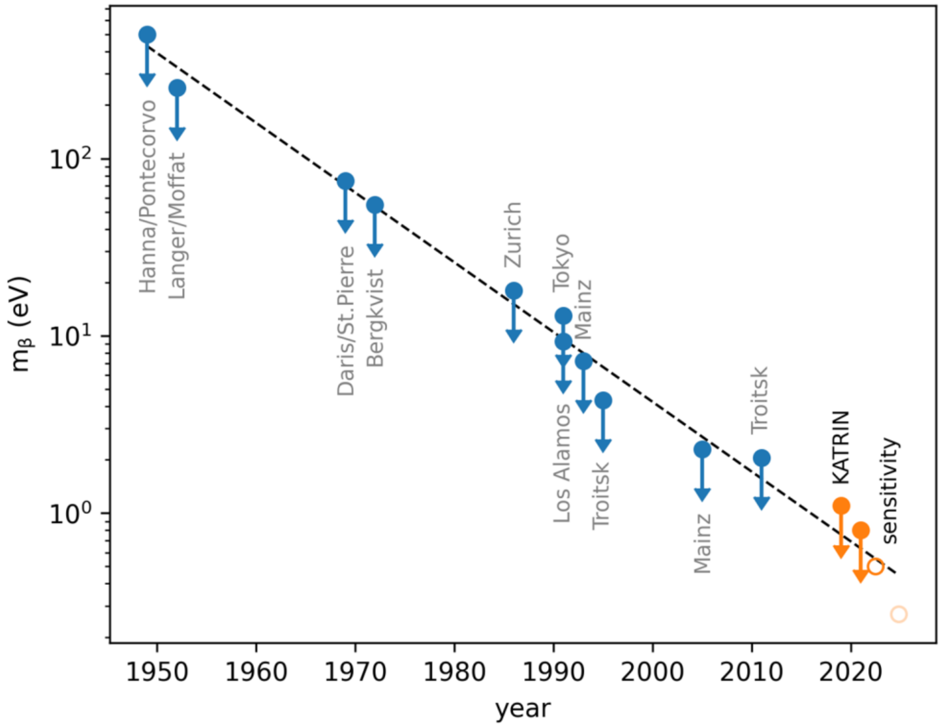


Summary

- First **sub-eV neutrino mass limit** from a direct experiment: $m_\beta < 0.8$ eV

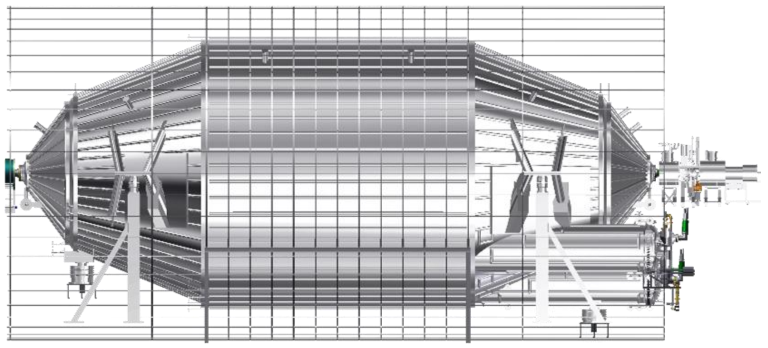
- Projected sensitivity for next data release: $m_\beta < 0.5$ eV

- Beyond the neutrino mass:
  - Complementary search for eV-scale neutrinos
  - New limit on relic neutrino overdensity

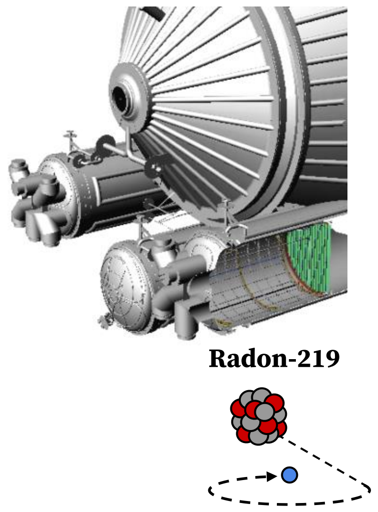


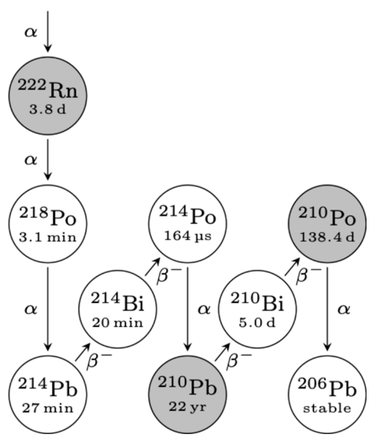
Backup

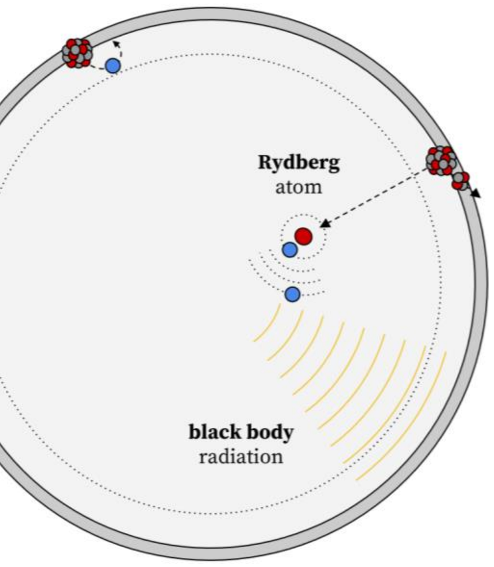
Spectrometer background

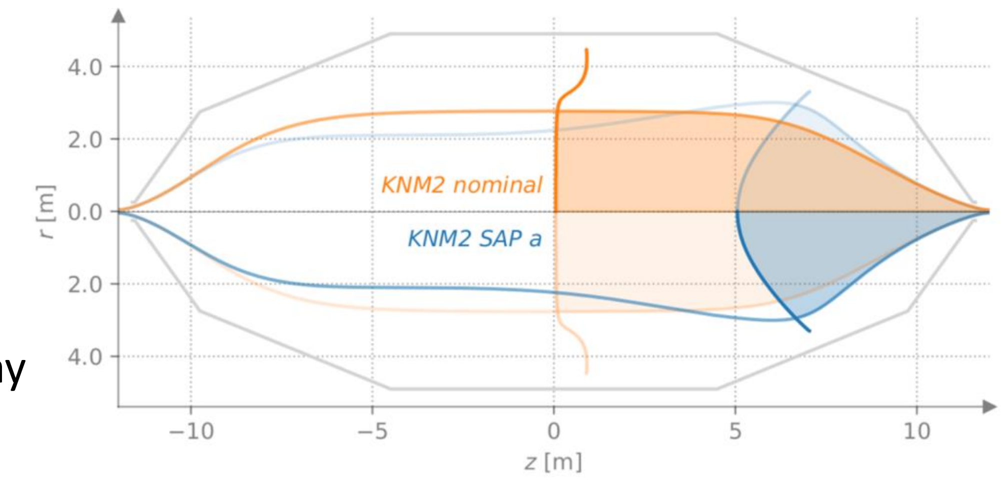


- ^{219}Rn decays in spectrometer → trapped electrons, non-Poisson rate









- ^{222}Rn on spectrometer walls (650 m^2)
- Sputtering of Rydberg atoms in ^{210}Po decay
- Ionization by black body radiation

→ Shifted-analyzing plane (SAP)