Universität Münster

Search for the absolute neutrino mass scale

International Symposium on Neutrino Physics and Beyond 2024

The Hong Kong University of Science and Technology, February 19-21, 2024

- Direct search for absolute neutrino mass
- The tritium experiments KATRIN and Project 8
- The holmium experiments ECHo and HOLMES
- Conclusions

living.knowledge

Christian Weinheimer – University of Münster

erc

Direct neutrino mass search:

complementary to cosmology analyses and $0\nu\beta\beta$ searches

$$m^2(\nu_e) := m_\beta^2 := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$$

no further assumptions needed

a) Time-of-flight measurements

only eV sensitivity for very far away, very strong sources, e.g. core-collapse supernova, e.g. SN1987a

$\rightarrow m_\nu < 5.7$ **eV**

b) Kinematics of weak decays,

e.g. tritium (β^-), ^{163}Ho (EC)

measure charged decay products, use E-, $\vec{p}$-conservation

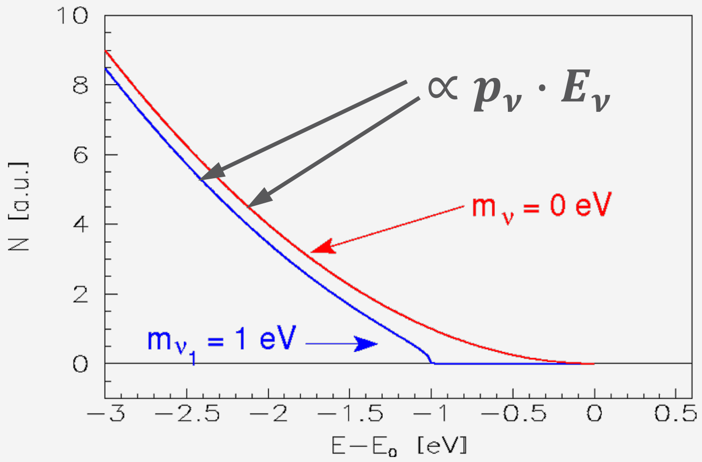
Kinematics: no further assumptions are needed,

use $E_\nu^2 = p_\nu^2 + m_\nu^2 \rightarrow m_\nu^2$

Determine m_ν^2 from beta electron spectrum

$$\beta^-: \frac{dN}{dE} = K \cdot F(E,Z) \cdot \underbrace{p}_{p_e} \cdot \underbrace{E_{tot}}_{E_e} \cdot \underbrace{(E_0 - Ee)}_{E_\nu} \cdot \sum_i |U_{ei}|^2 \cdot \underbrace{\sqrt{(E_0 - E_e)^2 - m^2(\nu_i)}}_{p_\nu}$$

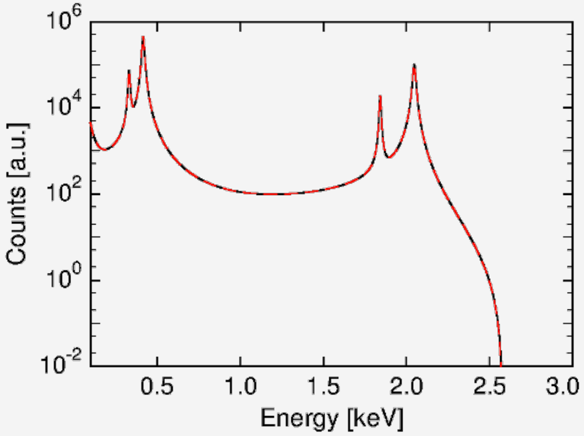
phase space: p_e E_e E_ν p_ν



EC: Also phase space near endpoint

$\propto p_\nu \cdot E_\nu$

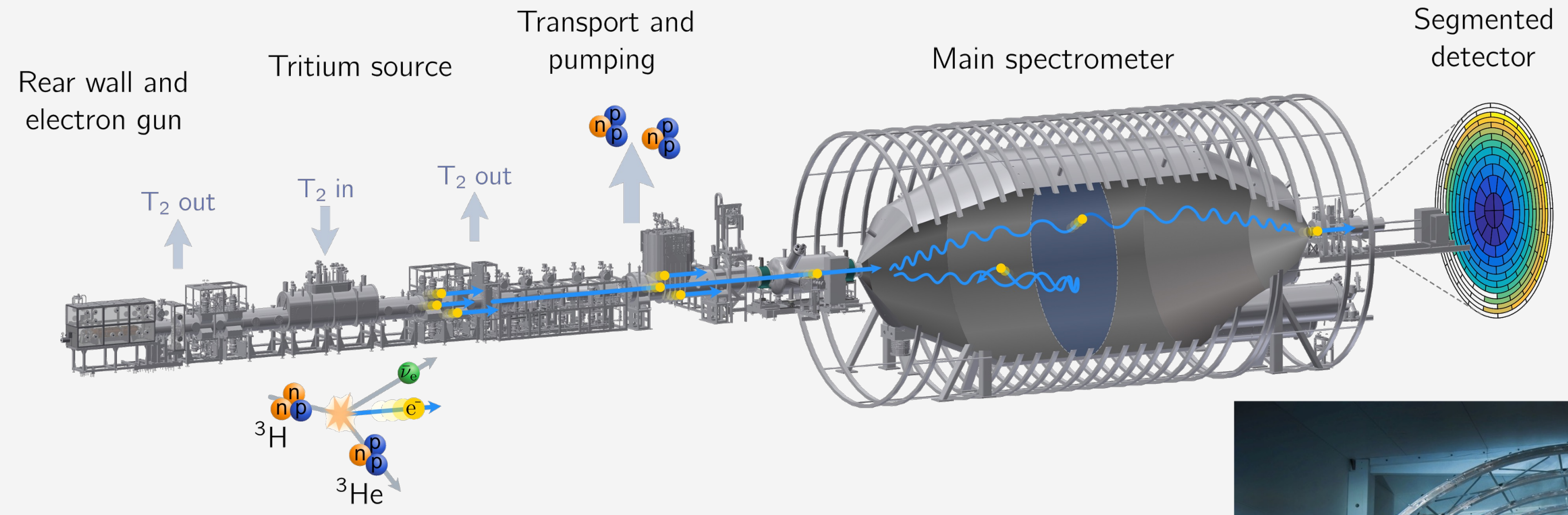
deexcitation spectrum, e.g. ^{163}Ho

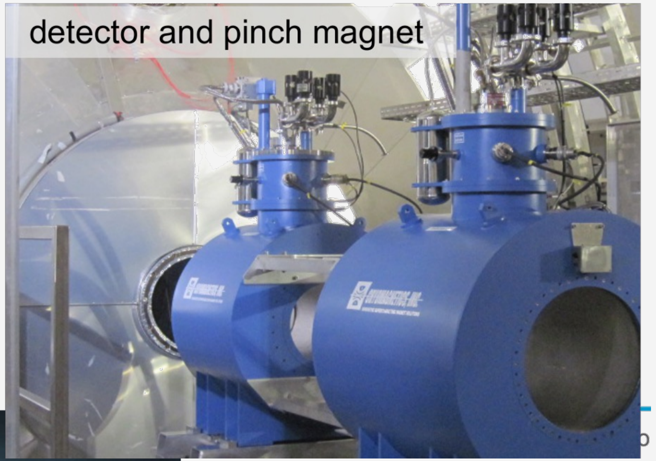


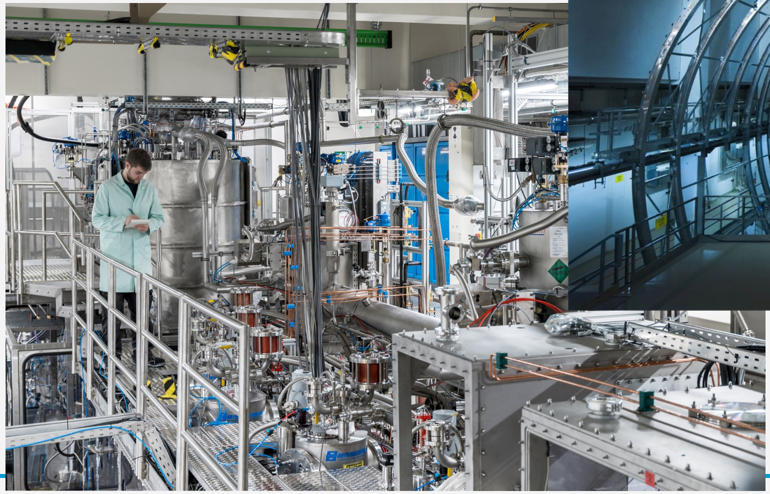
KArlsruhe TRItium Neutrino experiment KATRIN

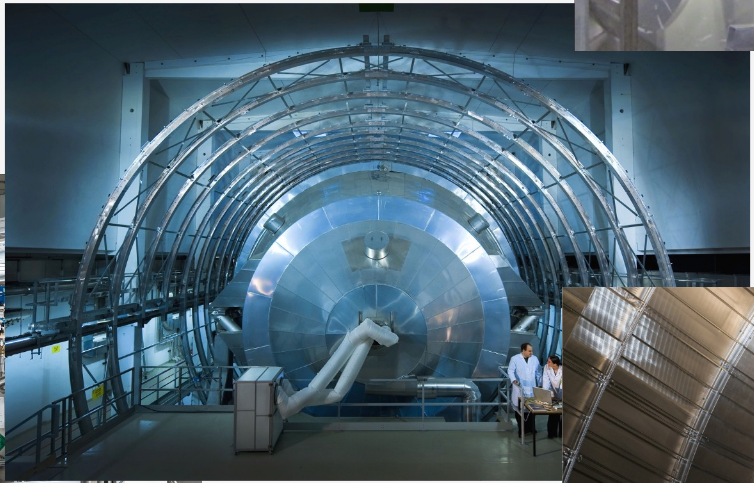
Universität Münster

A 10^{11} **Bq windowless** T_2 source with an **high acceptance & eV-resolution integrating spectrometer**









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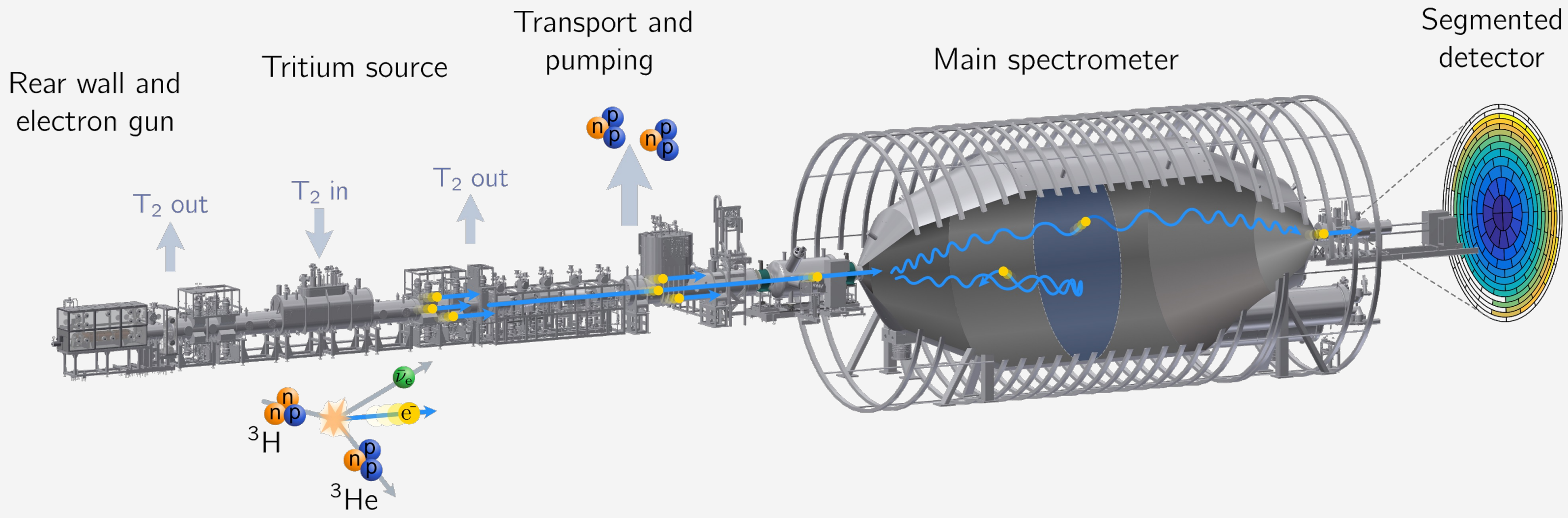
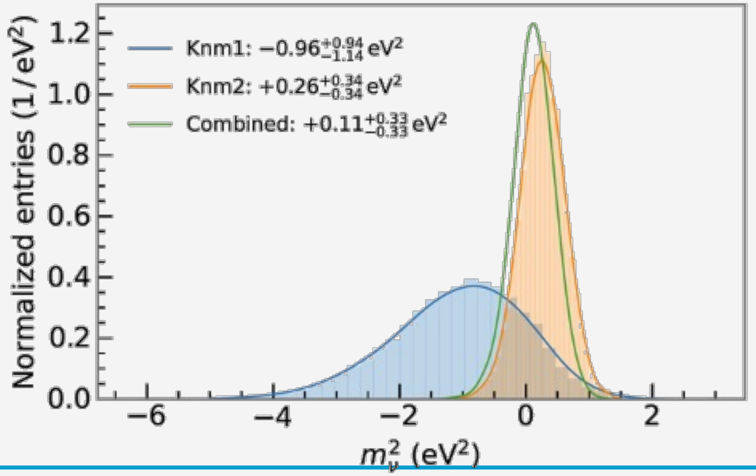
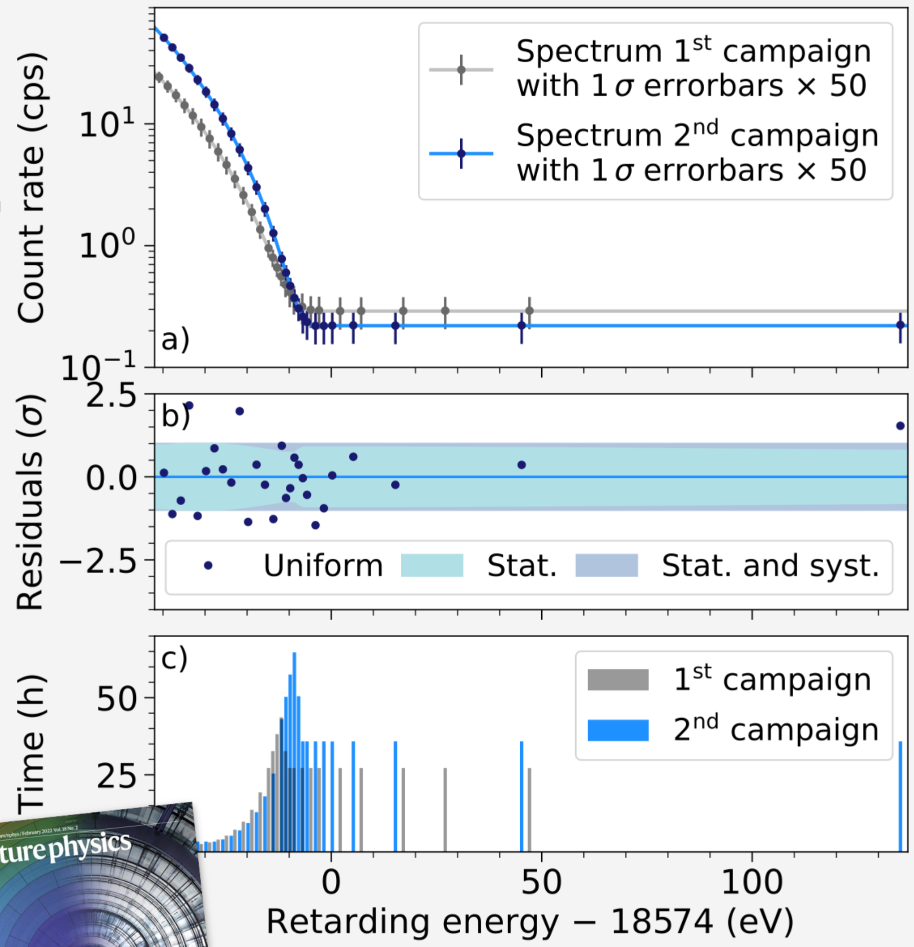






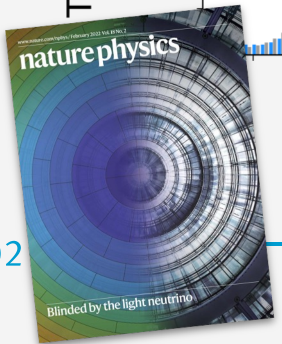
KNM1 and KNM2 campaigns:

$m^2(\nu) = (0.11 \pm 0.33)$ **eV²**

→ compatible with zero

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

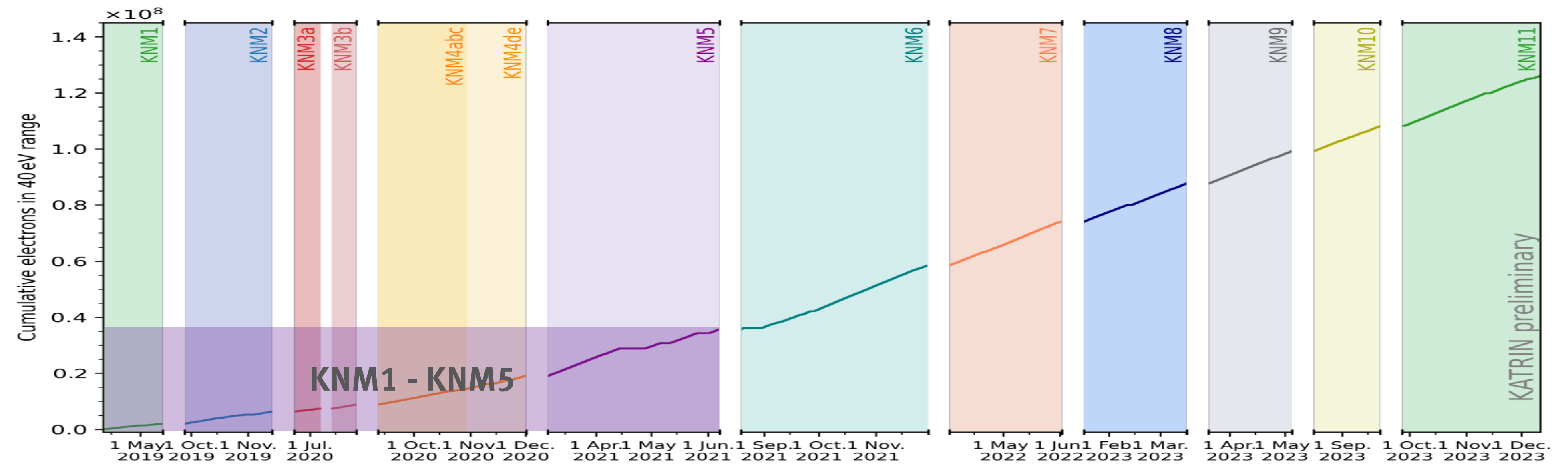
Bayes: $m_\nu < 0.7$ **eV (90% CL)**



Phys. Rev. Lett. 123 (2019) 221802

Nature Physics 18 (2022) 160

KATRIN data taking and data analysis



courtesy M. Schlösser

February 2024: Science run KNM12 started and is running smoothly

Data analysis KNM1-5 is being finished, release planned for summer 2024

Statistical (systematical) uncertainty will be about a factor 3 (2.5) better than that of KNM1+KNM2

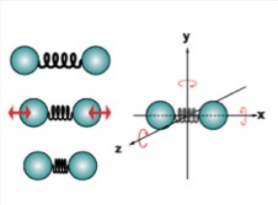
→ sensitivity of KNM1-KNM5 better than $m_\nu < 0.5$ eV

KATRIN final data set up to end of 2025: $m_\nu < 0.3$ eV

Systematic effects and uncertainties

Molecular final states
- quantum-chemical computations

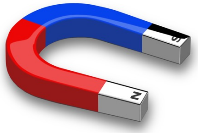
arXiv:2310.12634

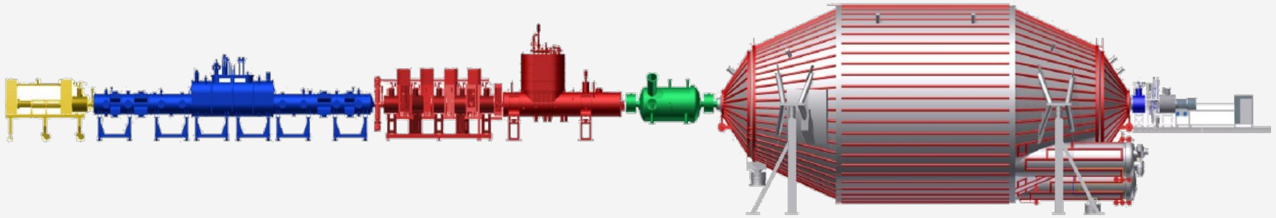


Source electric potential
- plasma properties
- surface conditions

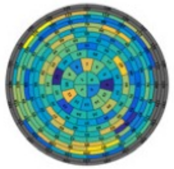
JINST **17** P06029

Magnetic fields
- source
- spectrometer
- detector



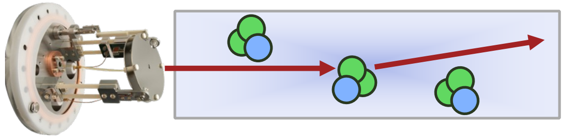


Detection efficiency



Nucl. Inst. Meth. A 778 (2015) 40-60

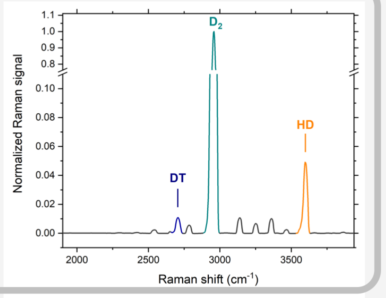
Energy loss by scattering



EPJ C 79 (2019) 204
EPJ C 81 (2021) 579

Activity fluctuations
- column density
- tritium (T_2, DT, HT)
- concentration

Sensors 20 (2020) 4827



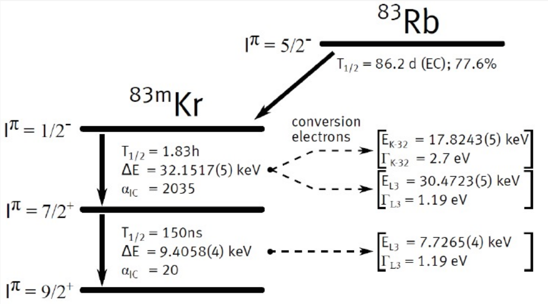
Background
- dependence on retarding potential
- time structure due to trapped electrons

JINST 13 (2018) T10004
Eur. Phys. J. A 44 (2010) 499
Astropart. Phys. 138 (2022) 102686

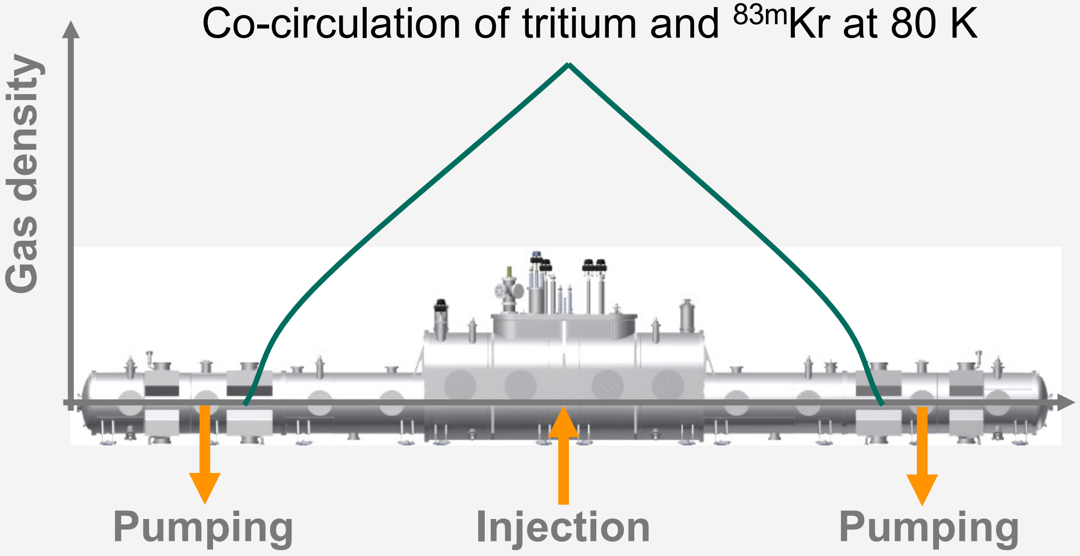
Three complementary strategies to include systematics in the fit:
(a) covariance matrix, (b) Monte-Carlo propagation, (c) pull-term method

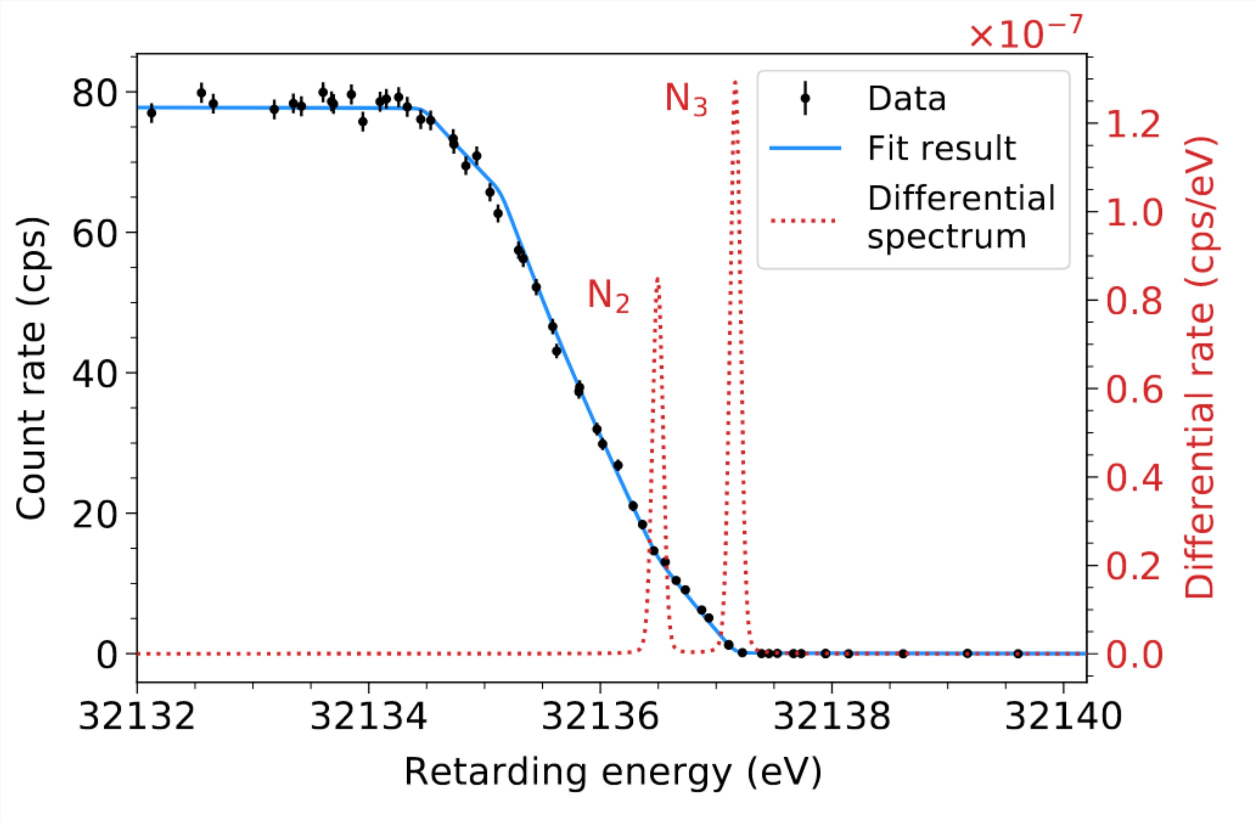
see PRL 123 (2019) 221802 + detailed analysis PRD 104 (2021) 012005 + Nature Physics 18 (2022) 160

Improving source-related systematics



Co-circulation of tritium and ^{83m}Kr at 80 K





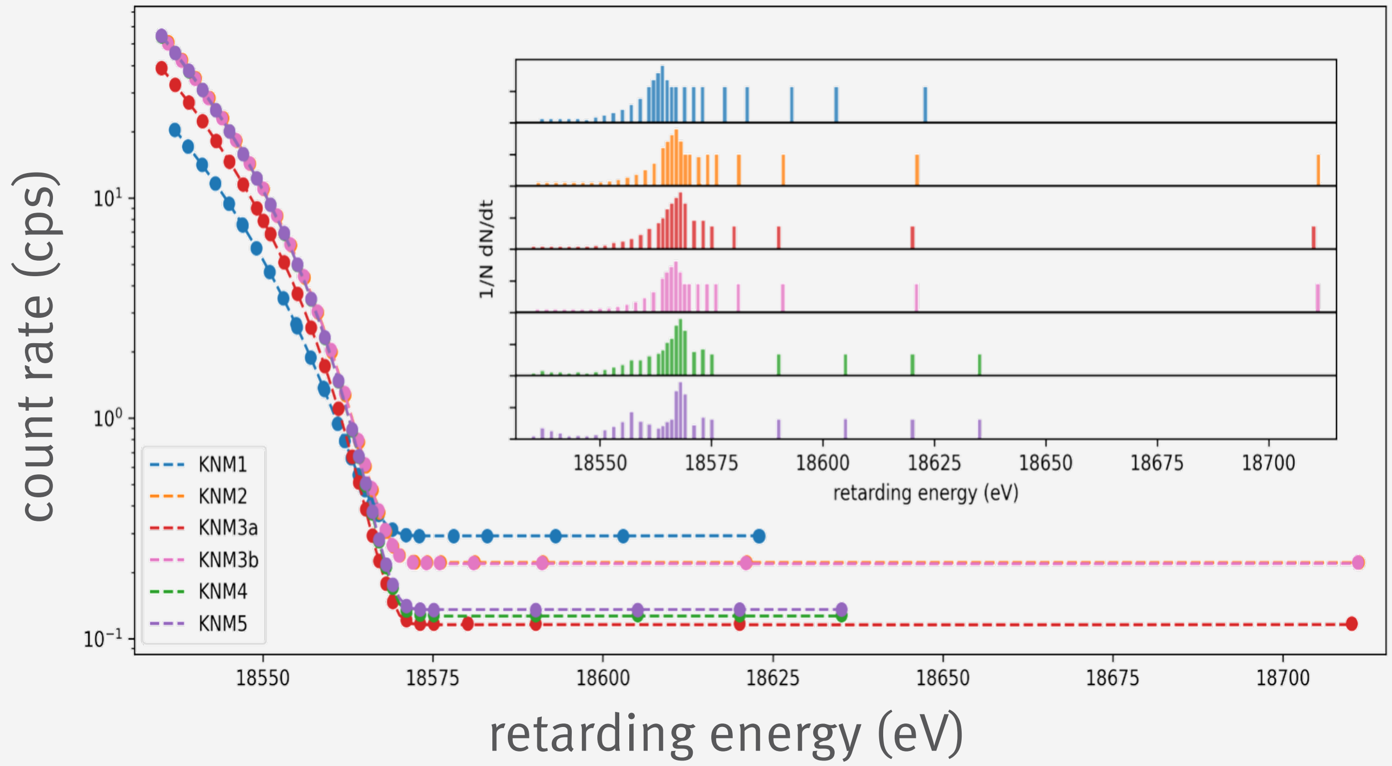
Data of 2020 krypton run at 40% tritium column density used to constrain systematics in 2nd campaign *Nature Phys. 18 (2022) 160*

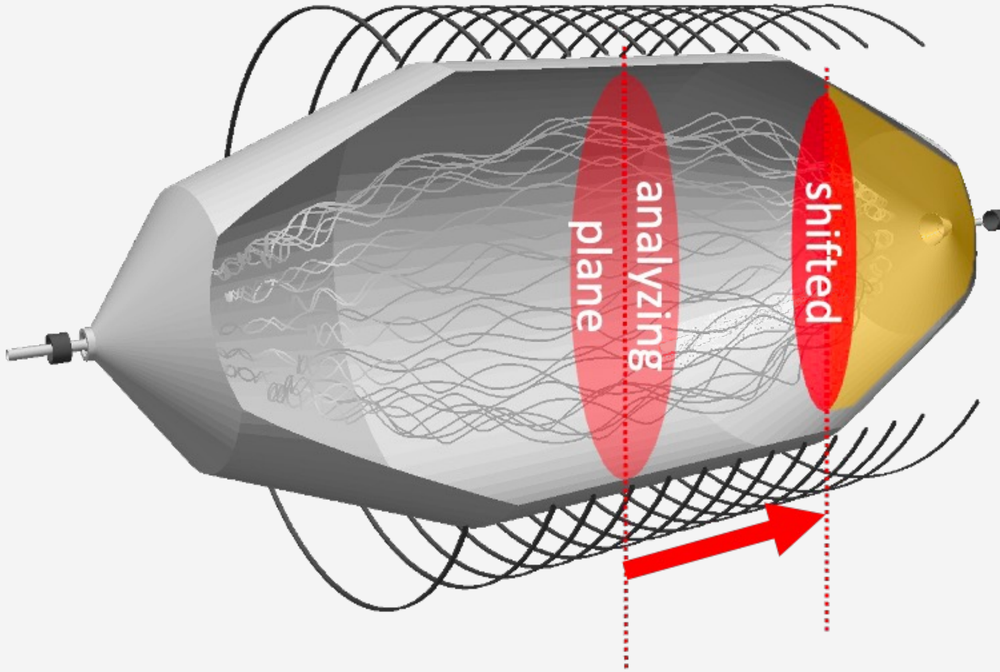
Since then: New operation mode with stable co-circulation of both T_2 and ^{83m}Kr at high column density at 80 K

From summer 2021 on: **10 GBq Krypton generator (activity x6) ➜ further reduction of plasma systematics**

KATRIN signal & background impovements

- continuous improvement of signal-to-background ratio

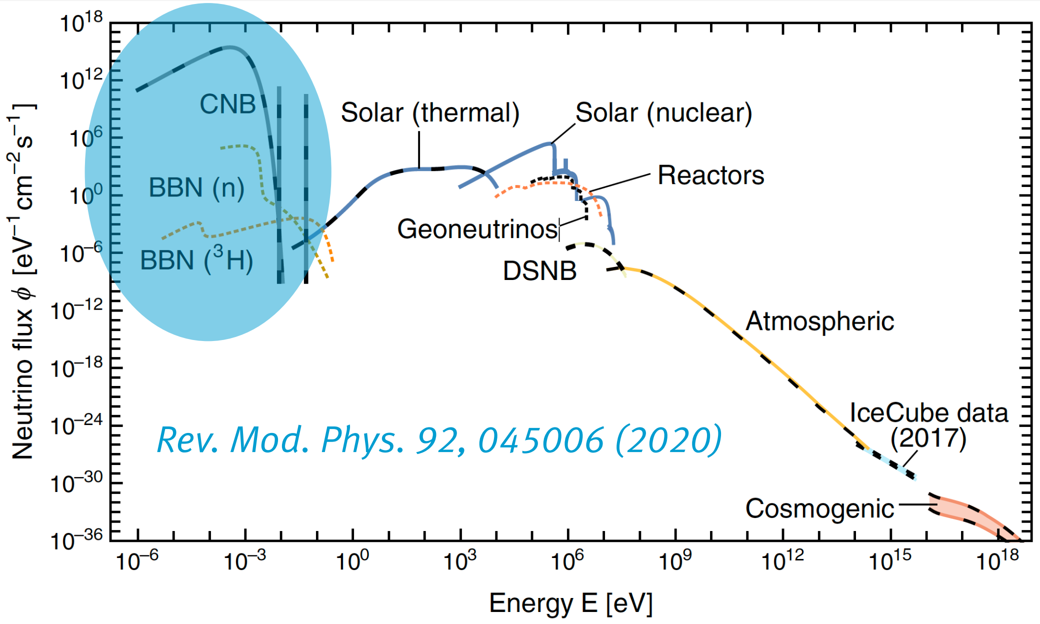




Shifting the analysis plane towards the detector reduced background by factor of 2 since KNM4 standard mode

Eur. Phys. J. C 82 (2022) 258

Other physics channels of KATRIN: Search for overdensity of cosmic relic neutrinos



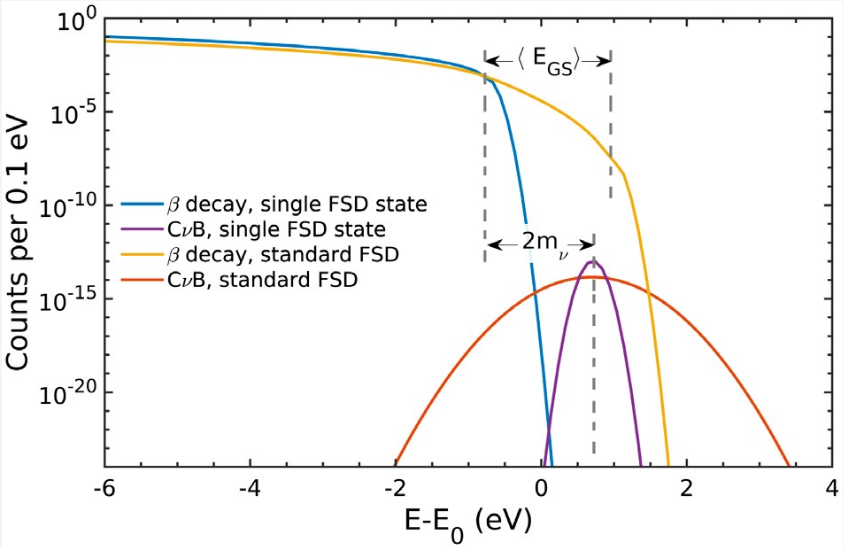
Rev. Mod. Phys. 92, 045006 (2020)

Detection via inverse β-decay on tritium:

$$\nu_e + \mathrm{T} \rightarrow {}^3\mathrm{He}^+ + \mathrm{e}^-$$

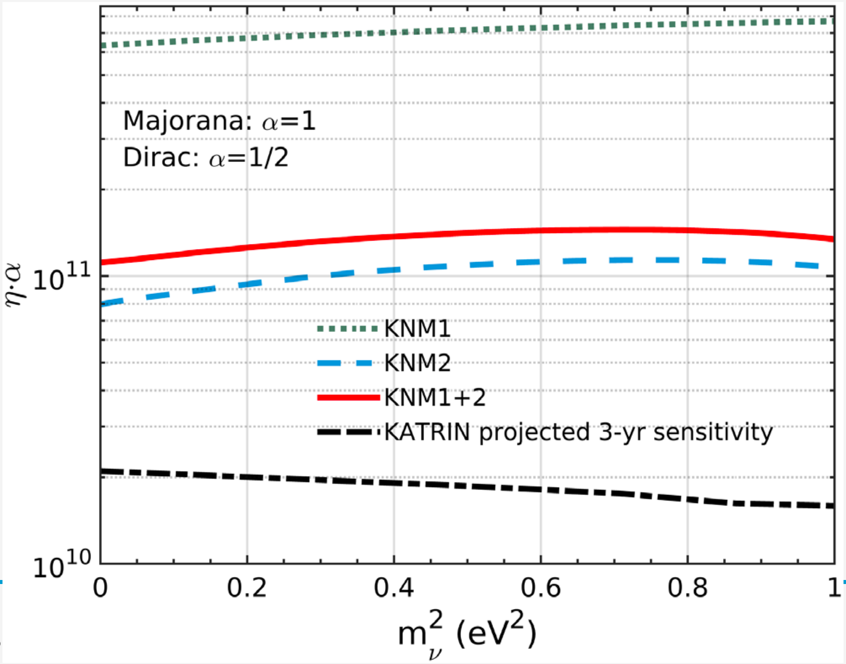
→ monoenergetic electron

Signature at KATRIN



Results by KATRIN

Phys. Rev. Lett. 129 (2022) 011806

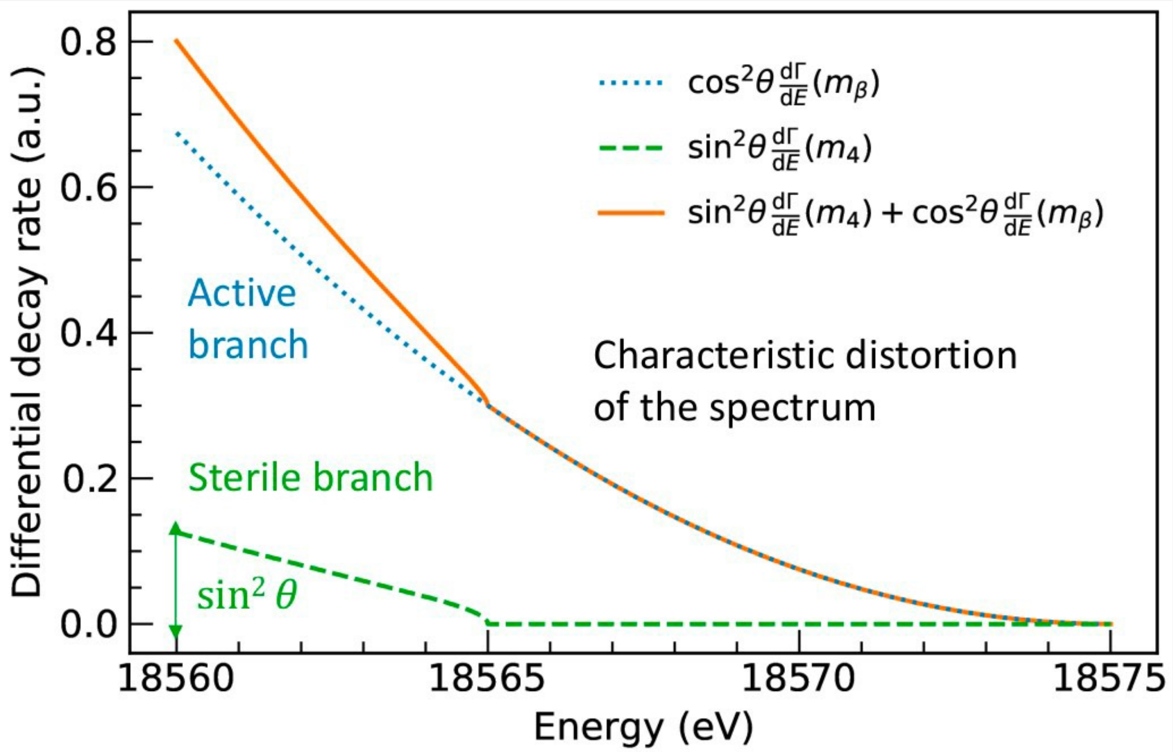


Constraints on light sterile neutrinos

Sterile neutrinos at eV-scale: a 4th state? $\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = U'_{PMNS}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$

The 4th neutrino mass state ν_4
would manifest in a kink in the beta spectrum

$$\frac{d\Gamma}{dE} = \underbrace{\left(1-|U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2\frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$



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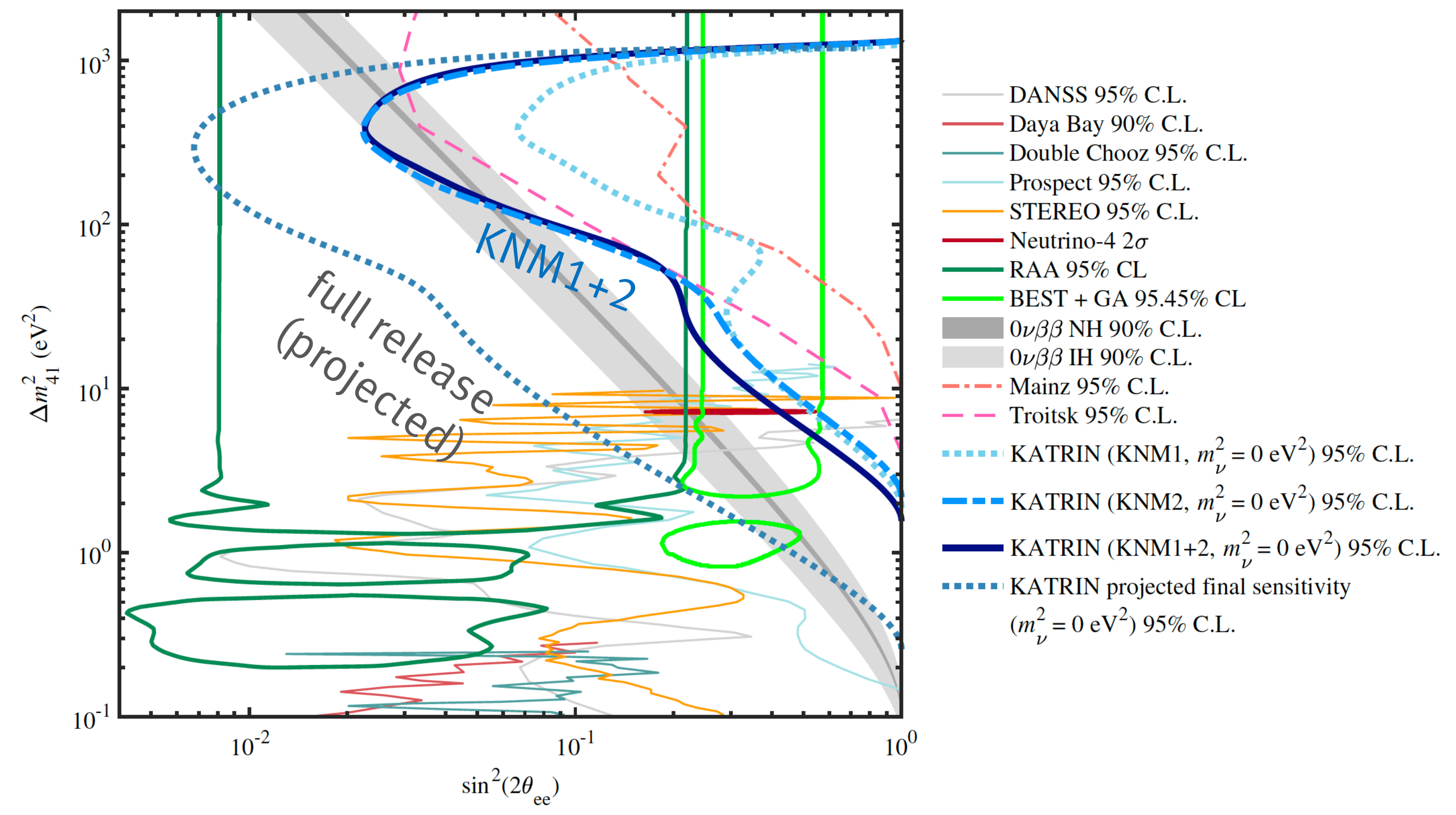
The motivation comes from anomalies in short baseline oscillation accelerator, solar and reactor neutrino experiments

KATRIN starts to probe very interesting parameter space, complementary to oscillation searches



Phys. Rev Lett. 126, 091803 (2021)
Phys. Rev. D 105 (2022) 7, 072004

Expected sensitivities on light sterile neutrinos

Sterile neutrinos at eV-scale: a 4th state? $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U'_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boldsymbol{\nu_4} \end{pmatrix}$

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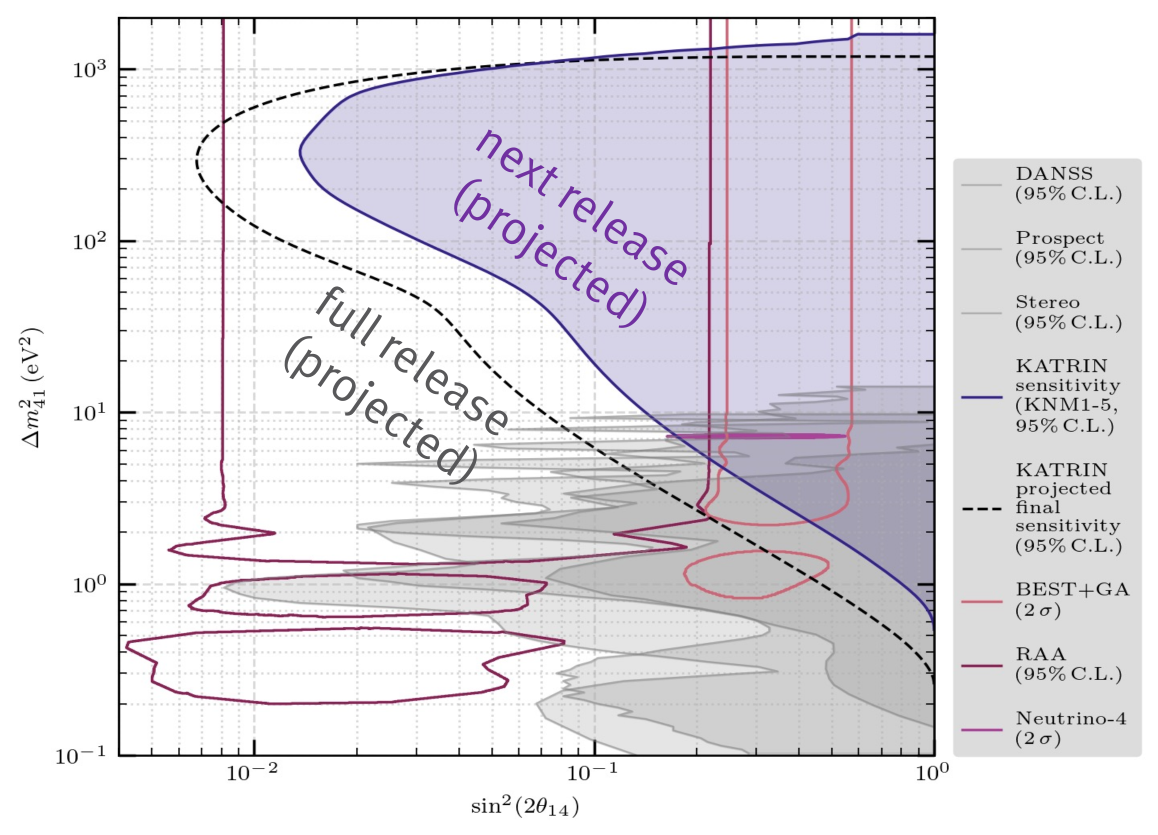
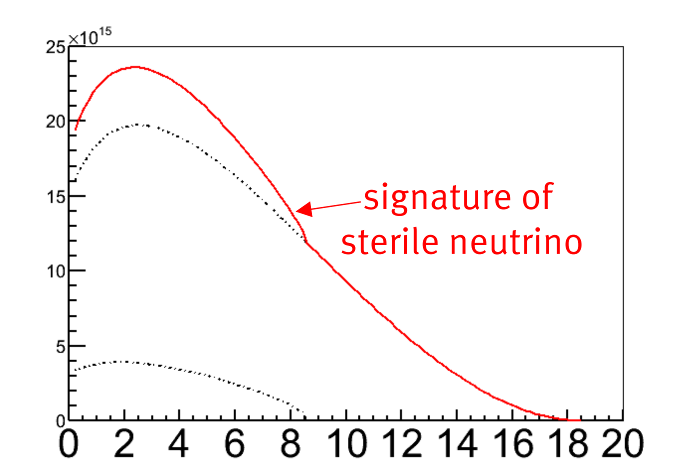
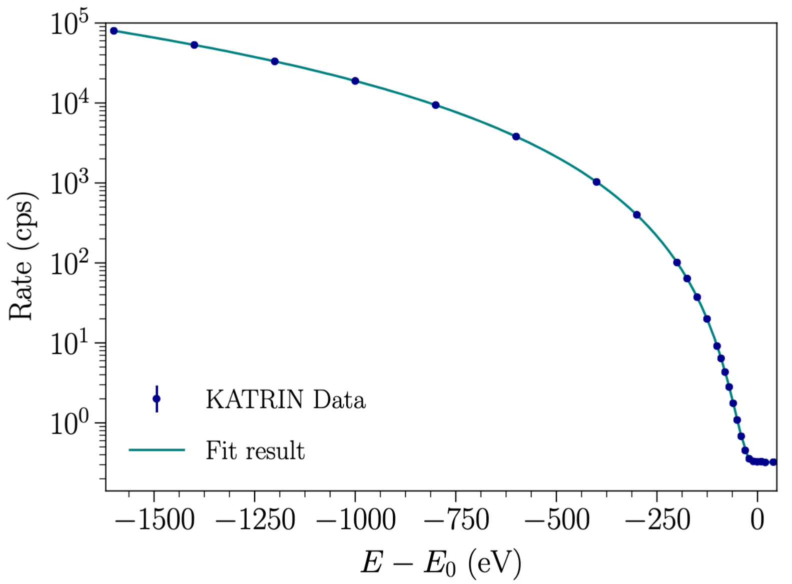
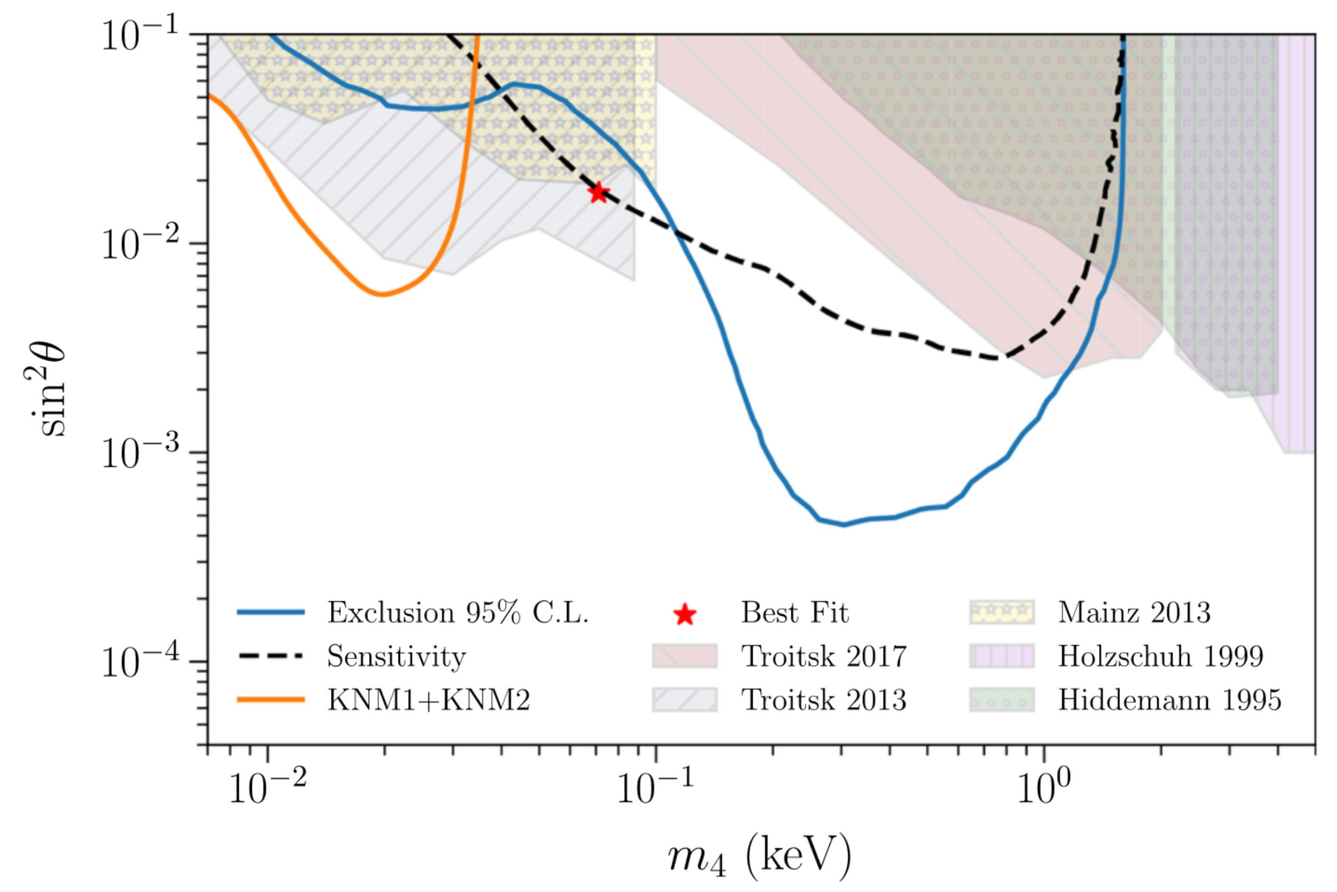


Phys. Rev Lett. 126, 091803 (2021)
Phys. Rev. D 105 (2022) 7, 072004

KATRIN: search for sterile neutrinos at keV-scale







Eur. Phys. J. C **83, 763 (2023)**

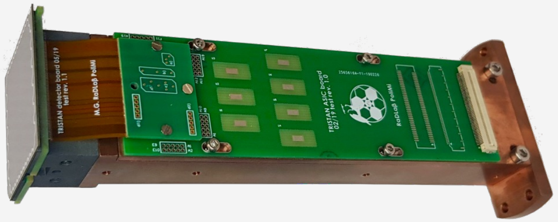
Next measurement phase of KATRIN:
dedicated search for sterile keV neutrinos

4th mass eigenstate of neutrino mixed with flavour eigenstates
→ BSM particle, dark matter candidate

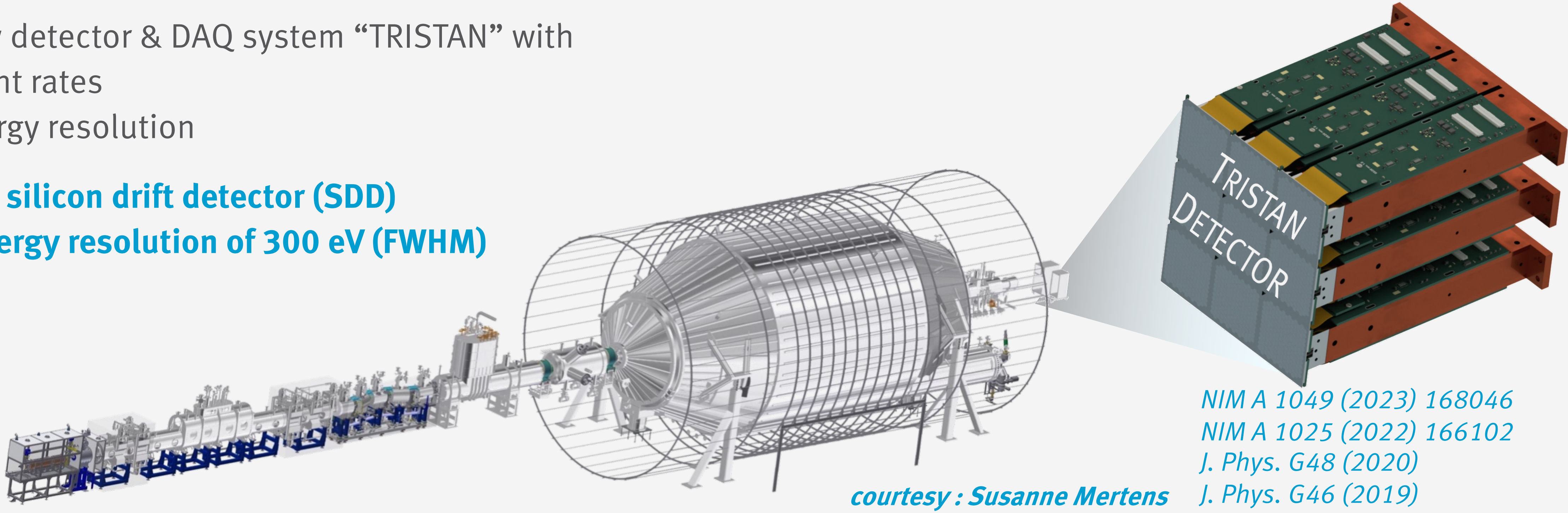
Look for the kink in the β-spectrum
Target sensitivity of $sin^2\,\theta < 10^{-6}$
→ dedicated search for sterile keV neutrinos in 2026/27

requires a new detector & DAQ system "TRISTAN" with
- large count rates
- good energy resolution

→ **1000 pixel silicon drift detector (SDD) with an energy resolution of 300 eV (FWHM)**



Successfully tested first prototype module at KATRIN's monitor spectrometer

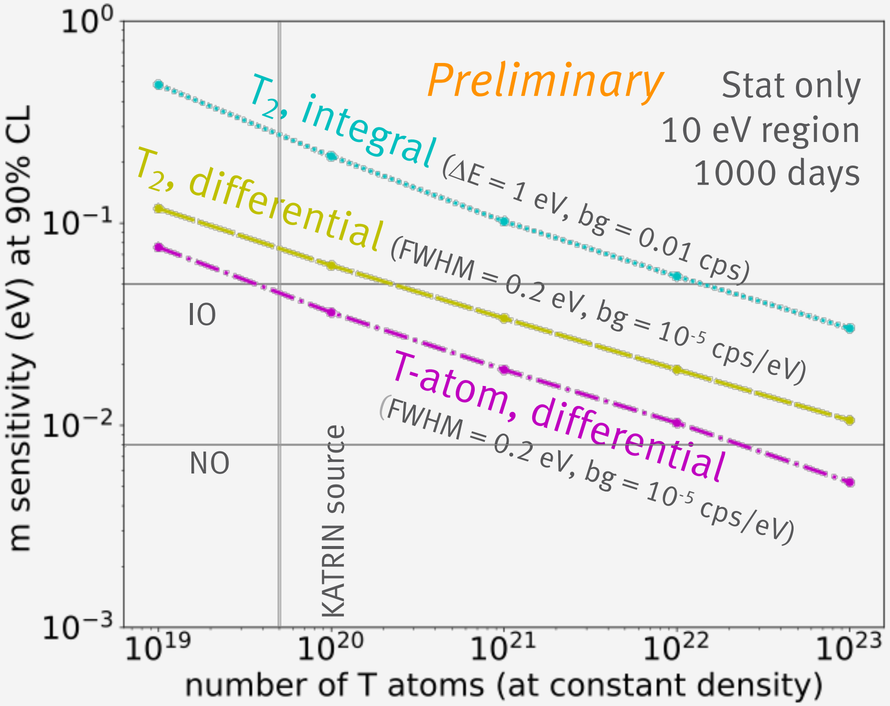


courtesy : Susanne Mertens

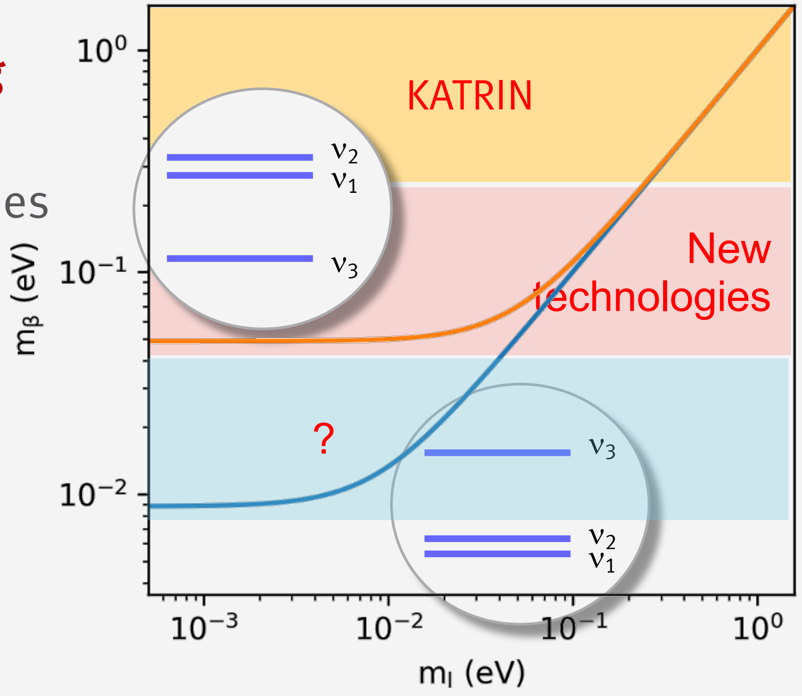
NIM A 1049 (2023) 168046
NIM A 1025 (2022) 166102
J. Phys. G48 (2020)
J. Phys. G46 (2019)

KATRIN^{++} - R&D for the next generation m_ν search

Goal: **Develop technologies and methods to fully cover inverted mass ordering based on the KATRIN setup and know-how**
and which in principle can go down to the lowest possible neutrino masses



courtesy : Susanne Mertens



→ **more tritium atoms will help**
but need **"differential mode"**
with **"sub-eV energy resolution"**,
and ultimately an **"atomic tritium source"**

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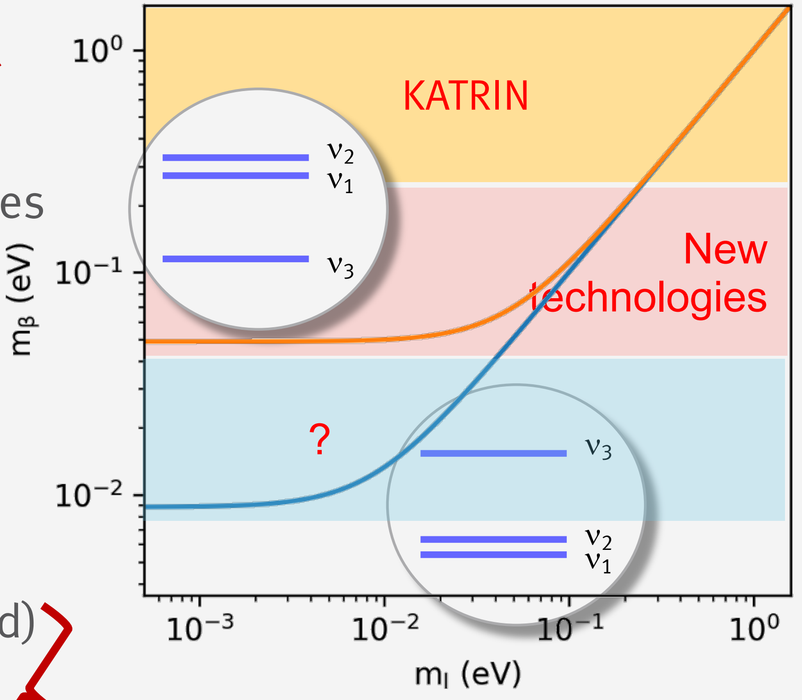
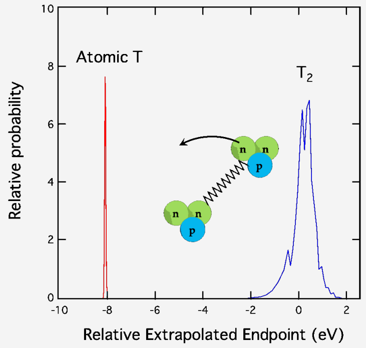


Three major improvements required:

1. **Differential measurements**, to avoid ≈ 30 steps to measure β-spectrum
   → gain of factor ≈ 30 in signal statistics
   & and get rid of the main background component ("Rydberg" electrons)
   by a **cryobolometer detector array** (challenges: large area, strong magnetic field)
   or by **time-of-flight** (challenge: high efficiency electron tagger)

new quantum detectors required

2. **Improve energy resolution to sub-eV level**
   in principle possible with cryobolometers (but it is the 3rd big challenge)
   or by the new idea of a "transverse energy compensator" for MAC-E-Filters
3. **Atomic tritium source** to avoid intrinsic limitation of energy resolution
   due to ro-vibrational final states $\sigma \approx 0.4$ eV ↔ $\Delta E \approx 1$ eV
   (atomic tritium source R&D in cooperation with partners)

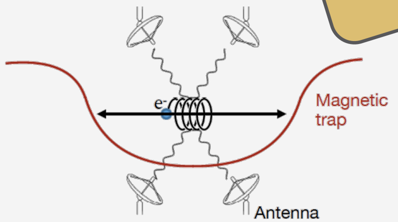


see talk by Magnus Schlösser at NuMass 2024 next week at Genoa

Project 8: tritium β spectroscopy with CRES

Universität Münster

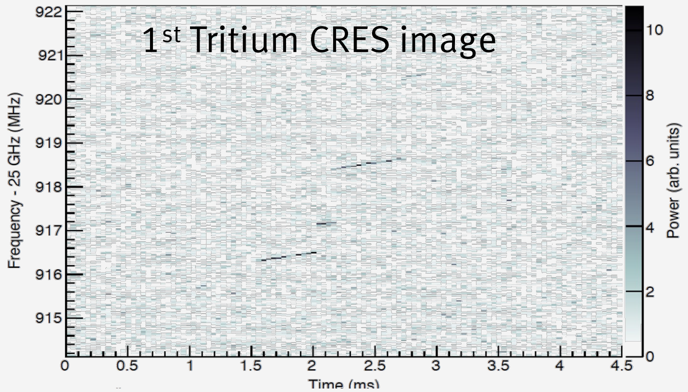
see talk by Carsten Heeger NPB 2024



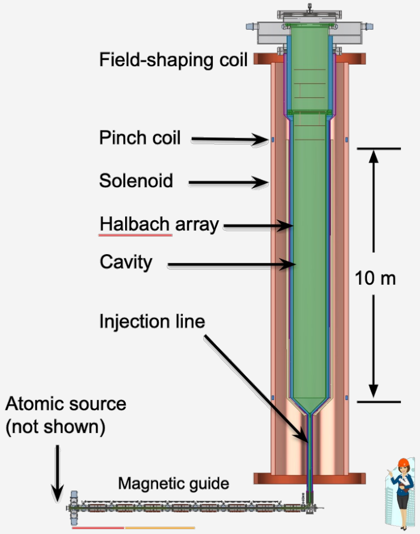
Cyclotron radiation:

$$\boldsymbol{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boldsymbol{E_{kin}}}$$

Cyclotron Radiation Emission Spectroscopy (CRES)

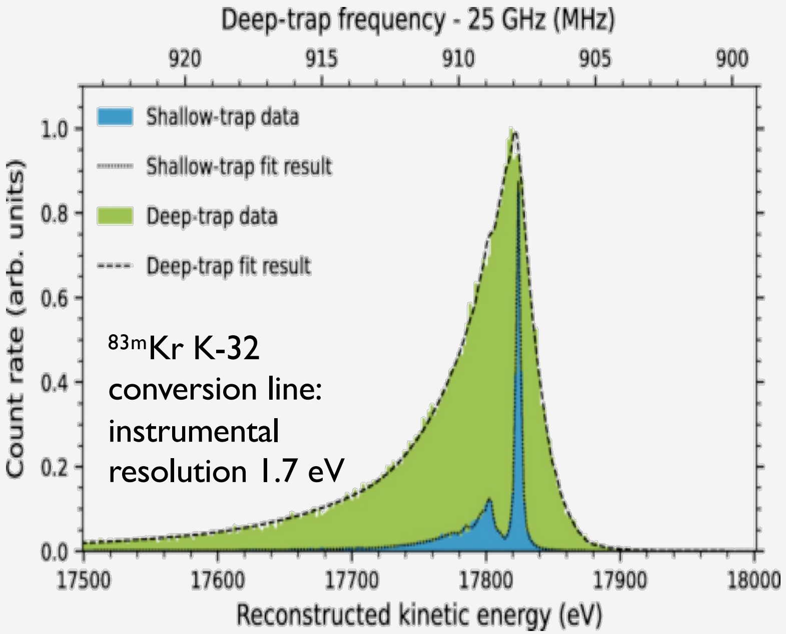


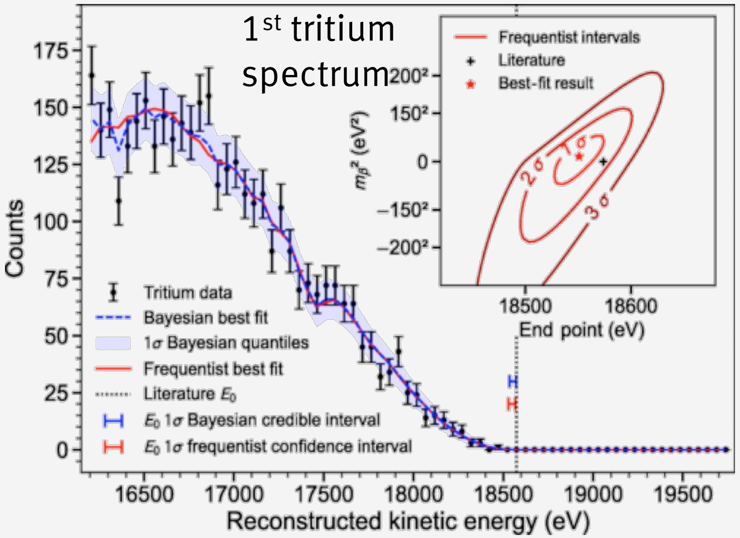
Phase III:
A future CRES experiment will require large volumes and an **atomic tritium source**



arXiv:2203.07349

Phase I & II





In first tritium run using CES, no background observed:

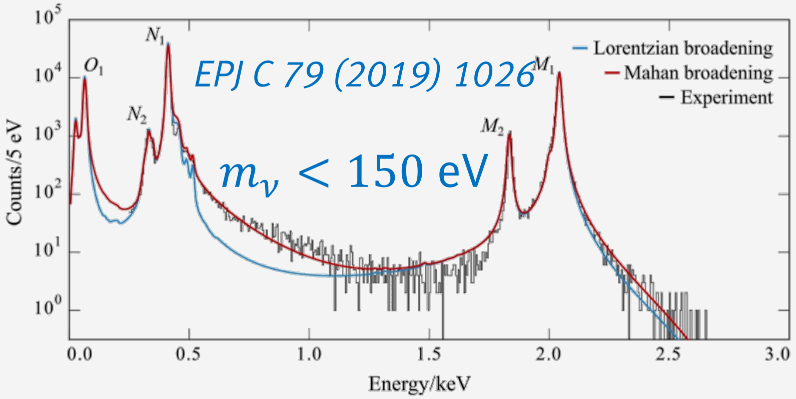
$m_\nu < 155\ (152)$ **eV**

PRL 131, 102502 (2023)
Courtesy: M. Fertl

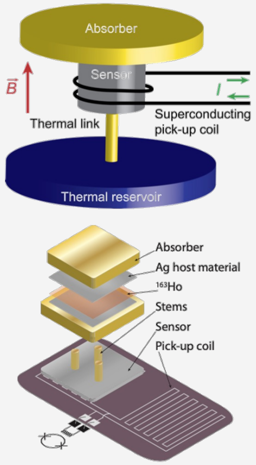
Phase IV:
Eventually, Project 8 wants to build an experiment with sensitivity O(40 meV)

EC with ^{163}Ho cryogenic bolometers: ECHo

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e \rightarrow {}^{163}Dy + \gamma/e^- + \nu_e$

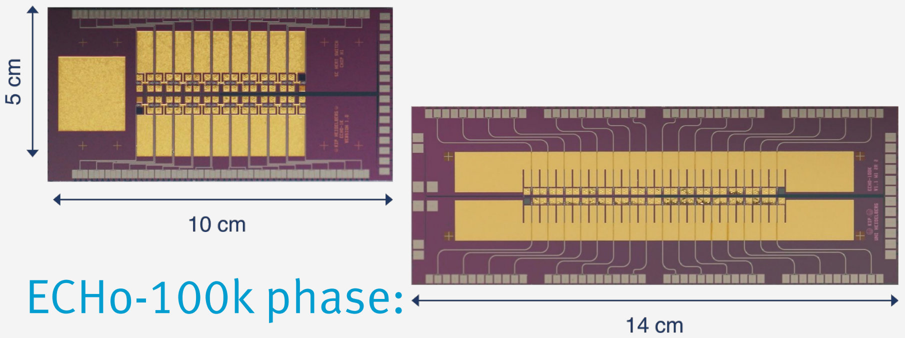


ECHo: metallic magnetic calorimeters (MMC):



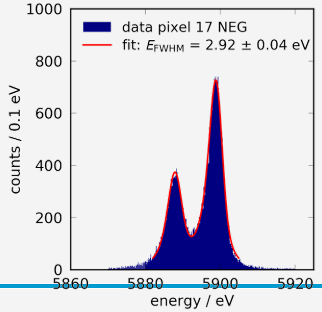
ECHo-1k phase:

sensitivity $m(\nu_e) < 20$ eV



ECHo-100k phase:

expected sensitivity: $m(\nu_e) \approx 1.5$ eV



ECHo-100k baseline: multiplexing to read-out large # MMC

number of detectors: 12000

activity per pixel: 10 Bq (2×10^{12} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source: available about 30 MBq

Ion implantation system: demonstrated, continuously optimized

Metallic magnetic calorimeters:

succesfull characterization of arrays with ^{163}Ho

More than 10^8 ^{163}Ho events have been acquired within the ECHo-1k phase:

→ a new neutrino mass limit ≈ 20 eV is on the way

Important steps towards ECHo-100k have been demonstrated:

new ECHo-100k array

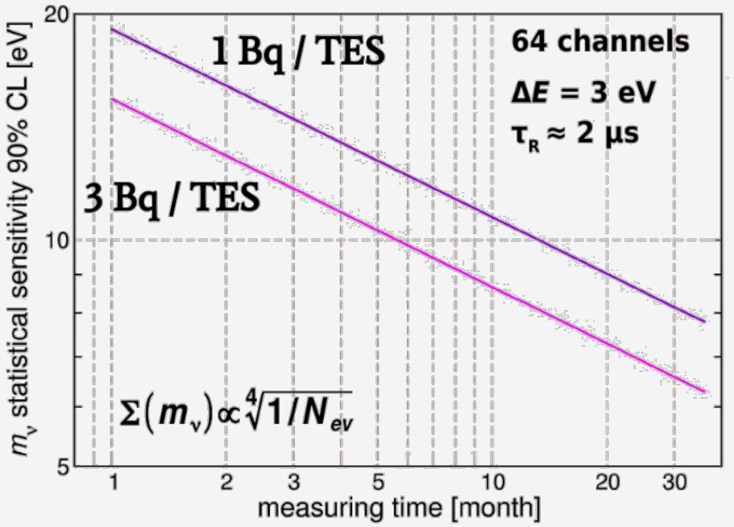
implantation of wafer scale

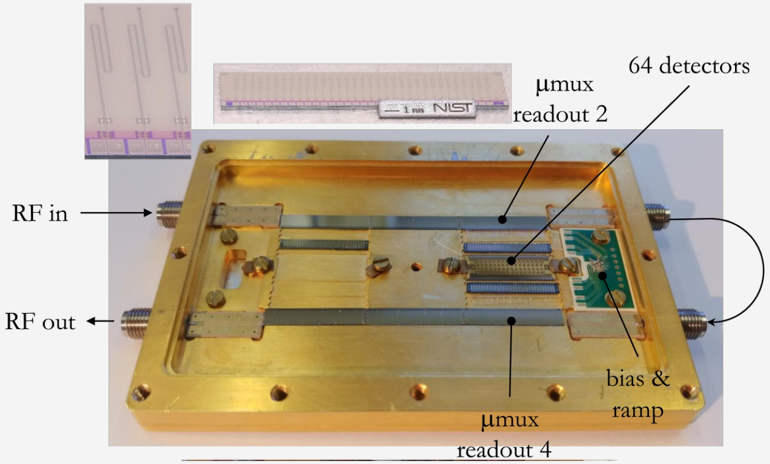
multiplexed readout

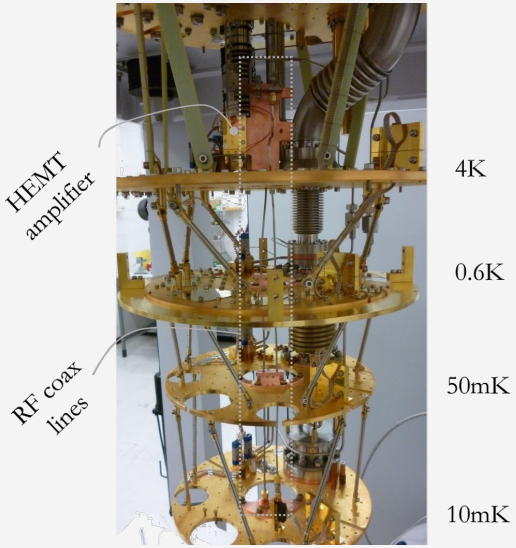
courtesy: Loredana Gastaldo

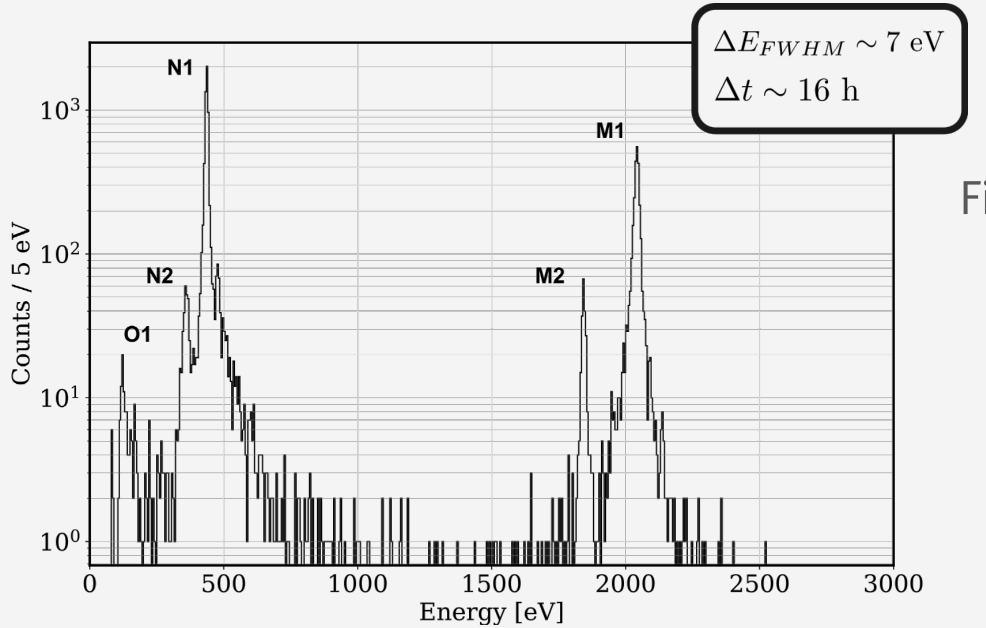
EC with ^{163}Ho cryogenic bolometers: HOLMES

HOLMES: superconducting transition edge sensors (TES)
^{163}Ho being implanted in gold absorber
read-out: frequency multiplexing

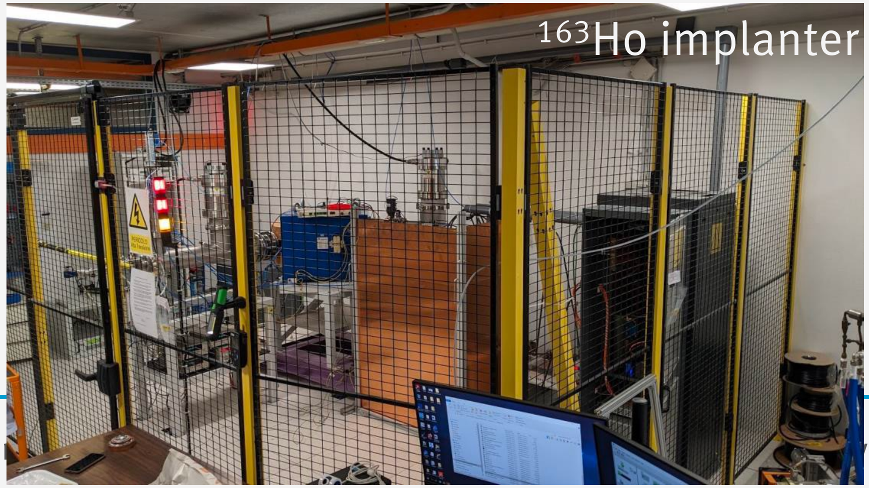








First ^{163}Ho spectrum



courtesy: A. Nucciotti

Conclusions

- KATRIN reached sub-eV sensitivity and has much more data, next data release planned for sommer,
  Up to the end of 2025, KATRIN will have collected data for a $m_\nu < 0.3$ eV sensitivity.
- From 2026 on, KATRIN will search for keV sterile neutrinos (with TRISTAN detector)
- R&D is starting for KATRIN^{++} with the goal to cover completely the inverted mass ordering
  using KATRIN as an R&D platform
  3 major steps: differential detection, better energy resolution, atomic tritium source
- Project 8 (CRES-technology, similar QTNM) is opening a new road towards sub-eV neutrino mass sensitivity with tritium
- Cryo-bolometers with ^{163}Ho (ECHo, HOLMES) are both running experiments
  Near (far) goals is to reach stepwise a (sub)eV-sensitivity with large arrays of multiplexed pixels
- Direct neutrino mass search with tritium at the extreme: towards CνB, R&D with PTOLEMY for the (very far) future