

The quest for neutrino mass and sterile neutrinos: latest results from KATRIN

Andrea Nava

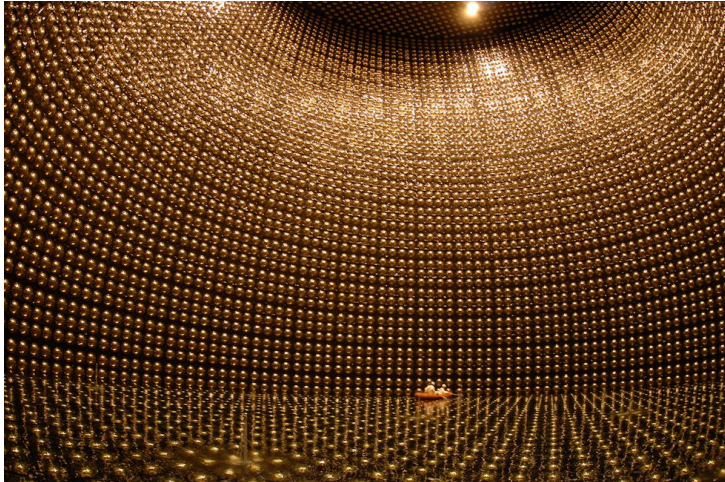
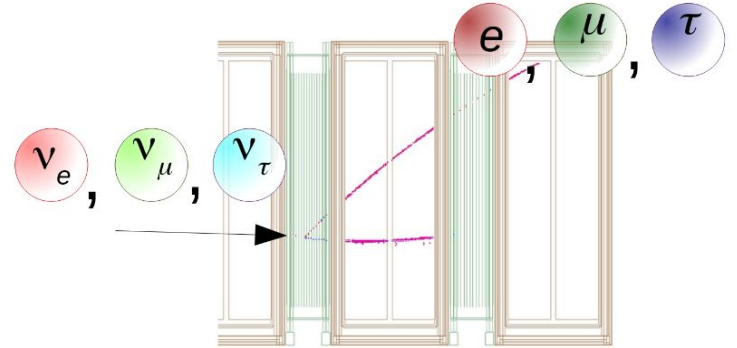
Roma - 4/05/2026

Standard Model of Particle Physics

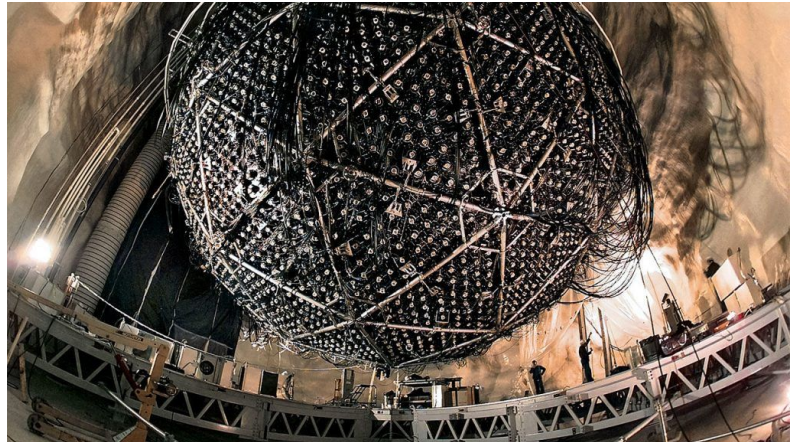
Quarks	$2/3$ Left u Right up 2.4 MeV	$2/3$ Left c Right charm 1.27 GeV	$2/3$ Left t Right top 171.2 GeV	0 0 1 g gluon	≈ 125 GeV 0 0 0 H Higgs
	$-1/3$ Left d Right down 4.8 MeV	$-1/3$ Left s Right strange 104 MeV	$-1/3$ Left b Right bottom 4.2 GeV	0 0 1 γ photon	GAUGE BOSONS VECTOR BOSONS SCALAR BOSONS
	0 Left ν_e electron neutrino < 1 eV	0 Left ν_μ muon neutrino < 1 eV	0 Left ν_τ tau neutrino < 1 eV	≈ 80.4 GeV ± 1 0 1 W W boson	
-1 Left e Right electron 0.511 MeV	-1 Left μ Right muon 105.7 MeV	-1 Left τ Right tau 1.777 GeV	≈ 91.2 GeV 0 1 Z Z boson		

- describes almost all the observables in the universe
- “matter” particles and **interaction** mediators
- assumes massless left-handed neutrinos

Anomalies in neutrino experiments

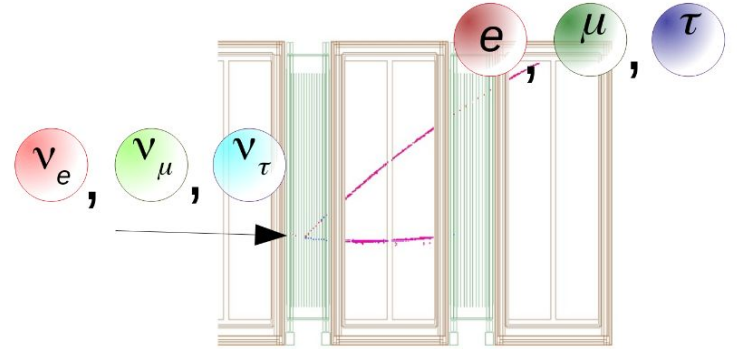
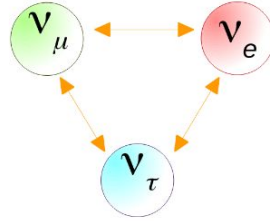


Super-Kamiokande

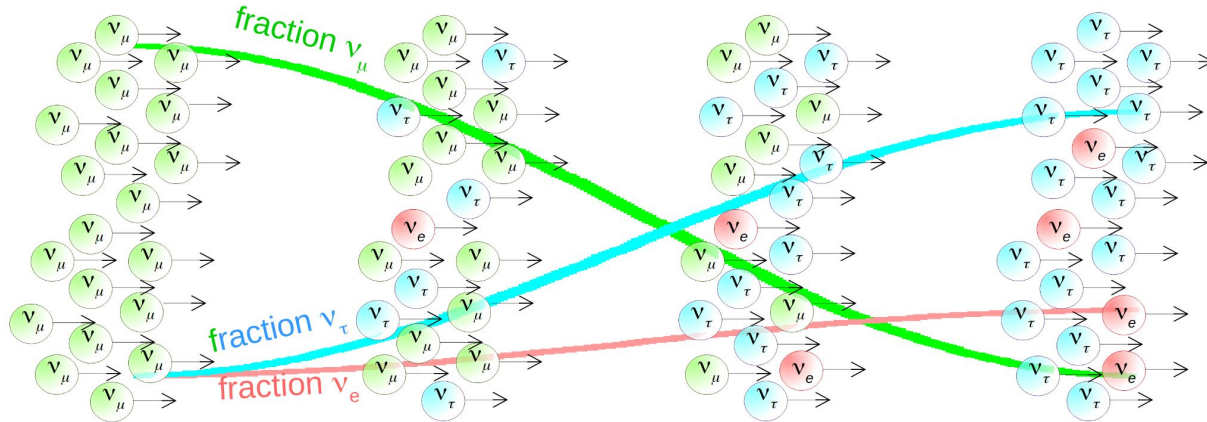
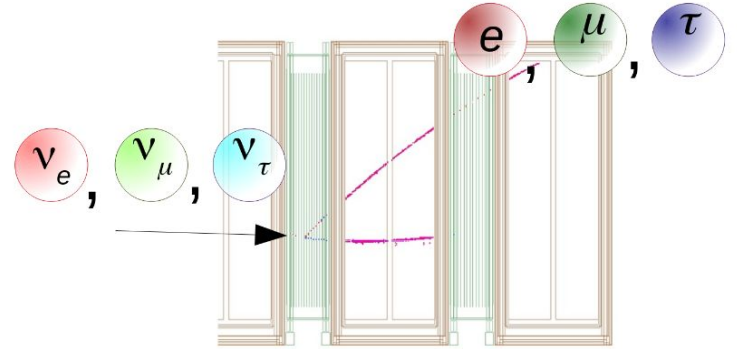
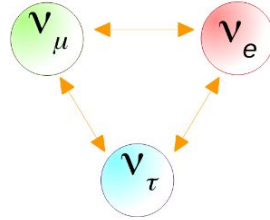


SNO

Neutrino oscillations!



Neutrino oscillations!



Mathematical parenthesis

$$\begin{array}{ccc} \text{Mass} & & \text{Flavour} \\ \text{eigenstates} & \leftarrow & \text{eigenstates} \\ & |\nu_i\rangle = \sum_{\alpha} U_{\alpha i}^* |\nu_{\alpha}\rangle & \end{array}$$

Mathematical parenthesis

Mass eigenstates $\left| \nu_i \right\rangle = \sum_{\alpha} U_{\alpha i}^* \left| \nu_{\alpha} \right\rangle$ Flavour eigenstates

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

PMNS mixing matrix

Mathematical parenthesis

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PMNS mixing matrix

$$\left| \nu_j(L) \right\rangle = e^{-im_j^2 L/(2E)} \left| \nu_j(0) \right\rangle.$$

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PMNS mixing matrix

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$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{j>k} \mathcal{R}_e \left\{ U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \right\} \sin^2 \left(\frac{\Delta_{jk} m^2 L}{4E} \right) + 2 \sum_{j>k} \mathcal{I}_m \left\{ U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \right\} \sin \left(\frac{\Delta_{jk} m^2 L}{2E} \right),$$

Oscillation probability

Neutrinos have mass!

- neutrino oscillations imply that **neutrinos have a non-zero mass**
 - oscillations can only provide a lower bound

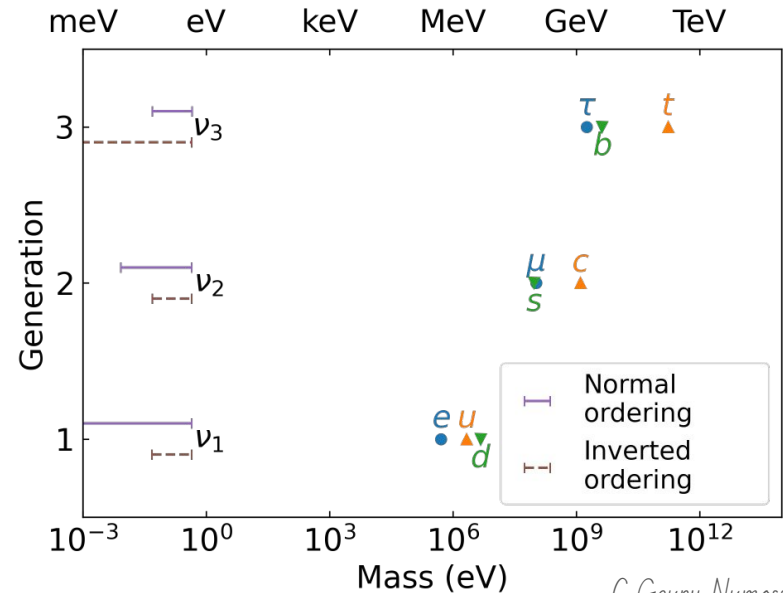


Neutrinos have mass!

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 - oscillations can only provide a lower bound



- what is the absolute scale (and ordering)?
- what is the mechanism generating the neutrino mass?
- what is the neutrino nature?



C. Goupy, Numass 2026

β spectrum and neutrino mass

$$\frac{dN}{dE} \cong C \cdot F(E, Z) P_e(E_e + m_e c^2) (E_0 - E_e) \sqrt{(E_0 - E_e)^2 - m_\beta^2}$$

$$m_\beta = \sqrt{\sum_{i=1}^3 |U_{ei}|^2 m_i^2}$$



Neutrino mass induces a distortion close to the β spectrum **endpoint**

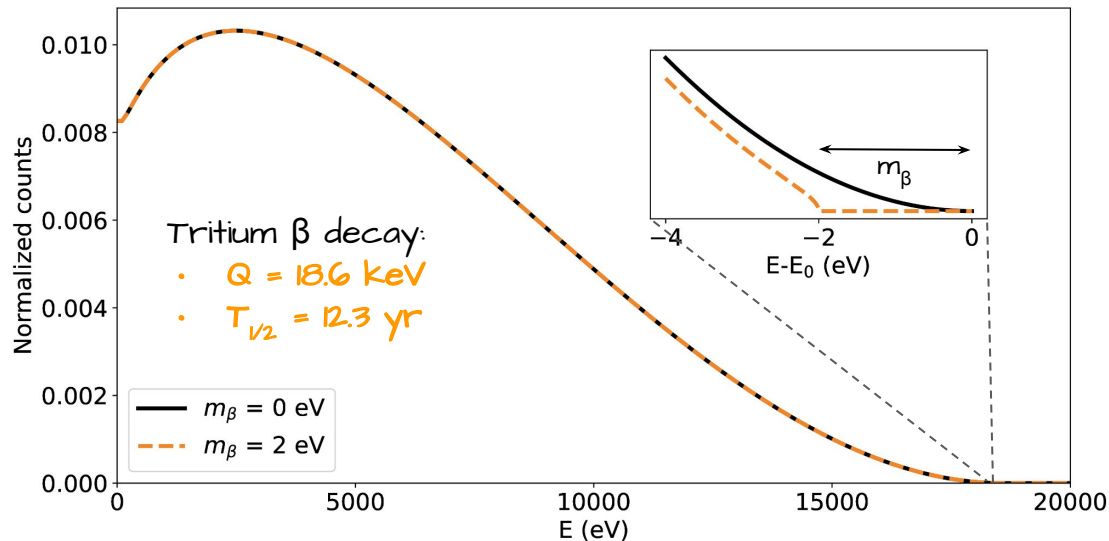
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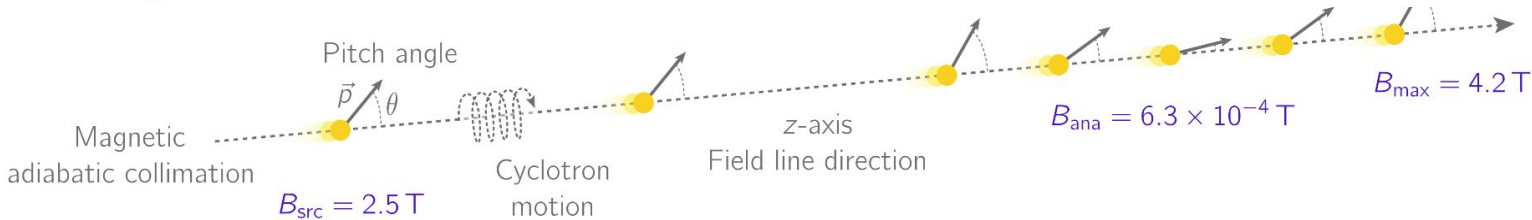
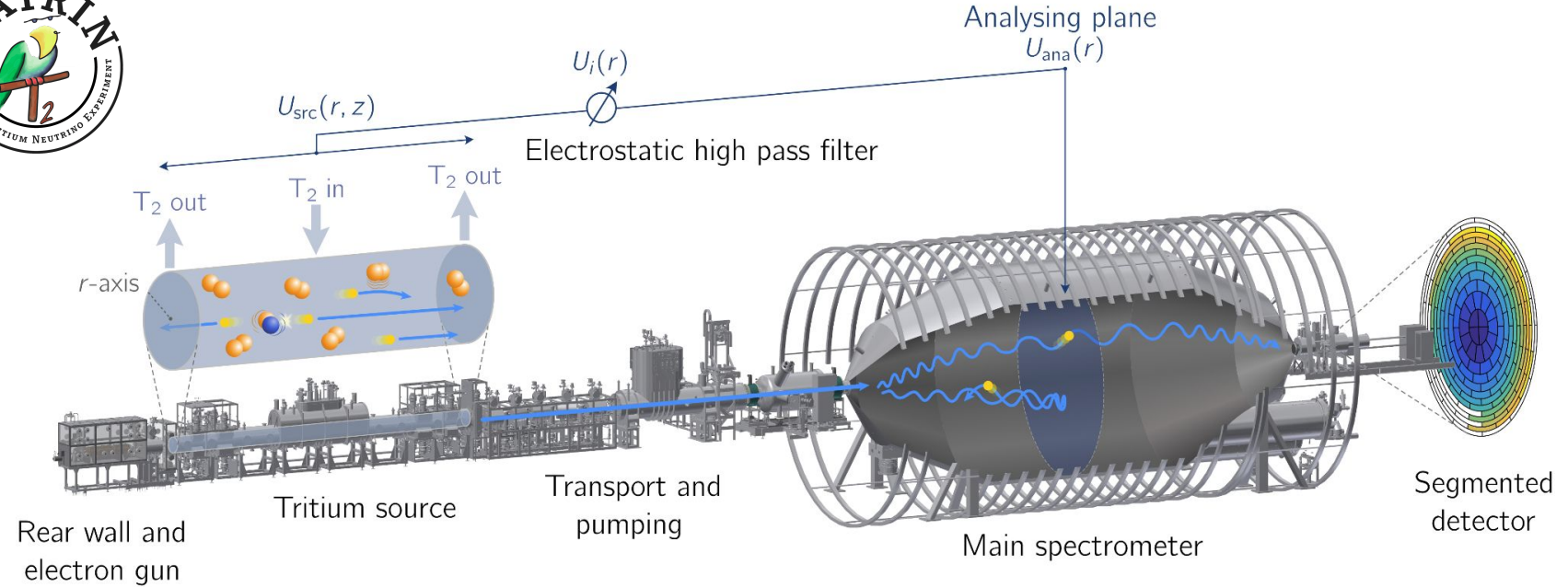
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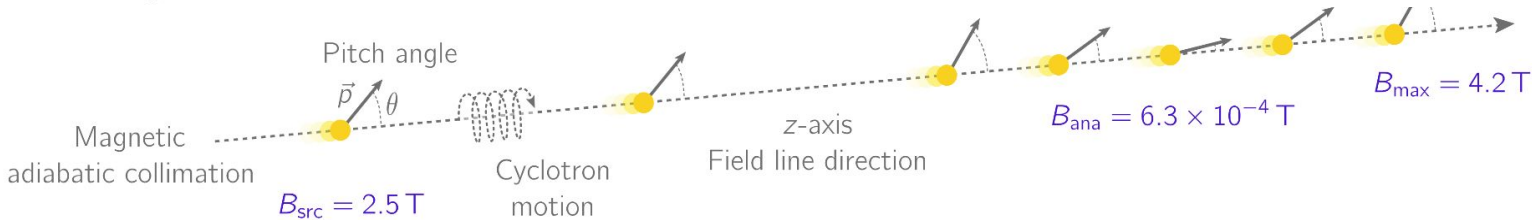
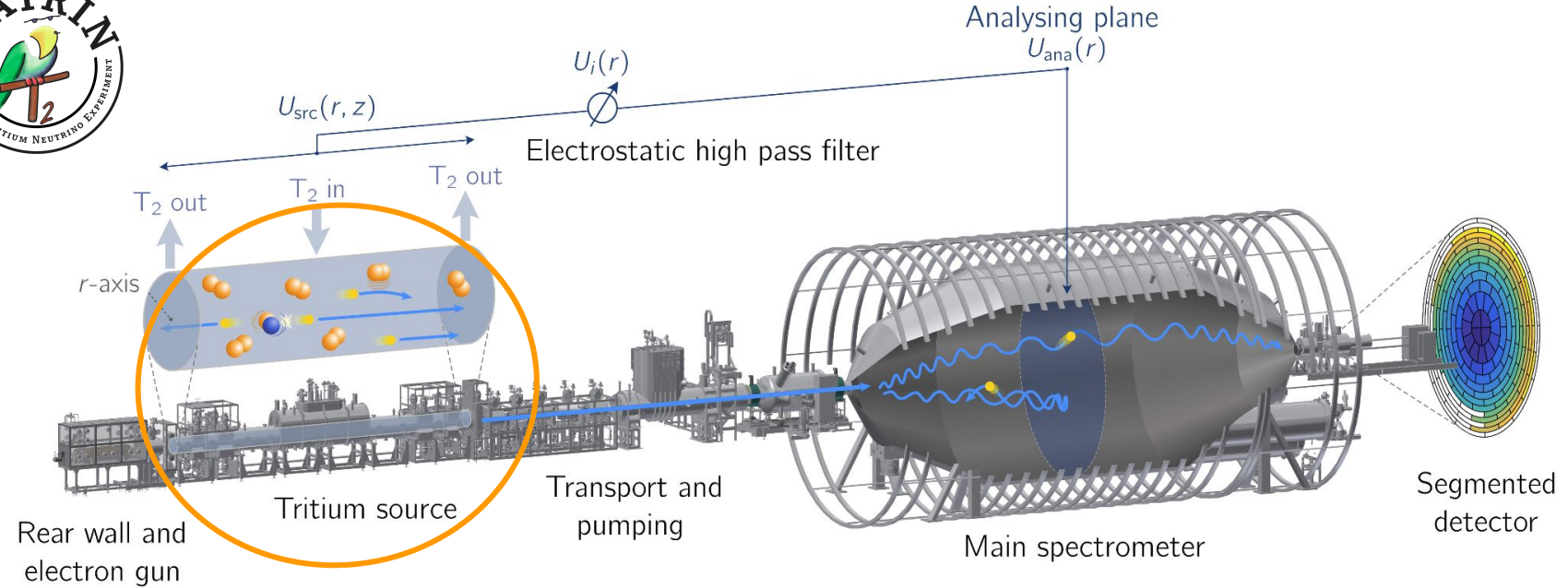
Requirements

- source with ultra-high activity and low Q-value
- excellent energy resolution ($\sim 1 \text{ eV}$ @ endpoint)
- low background ($< 1 \text{ cps}$)

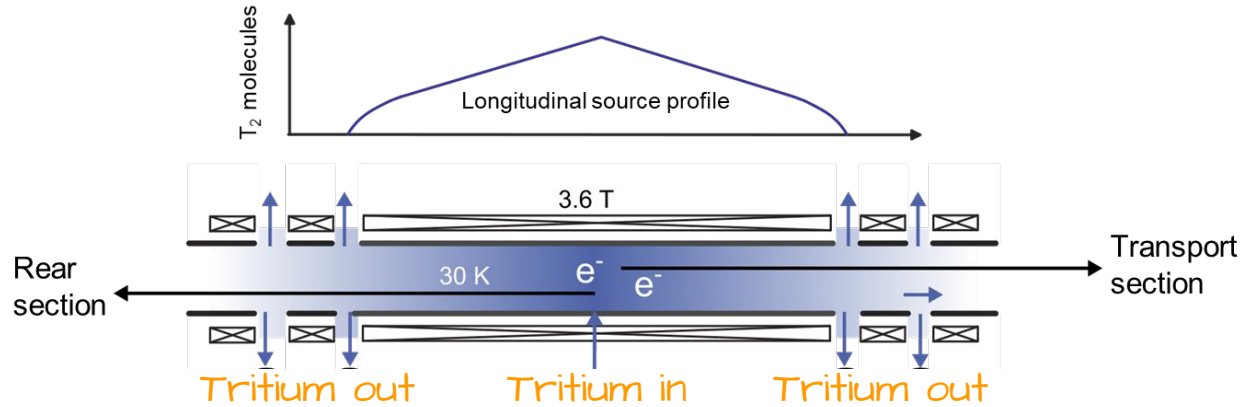
The KATRIN experiment



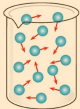
How to get the activity



How to get the activity



WGTS



continuous gas circulation $\rightarrow \sim 5 \cdot 10^{17} T_2 / \text{cm}^2 (>95\% T_2)$

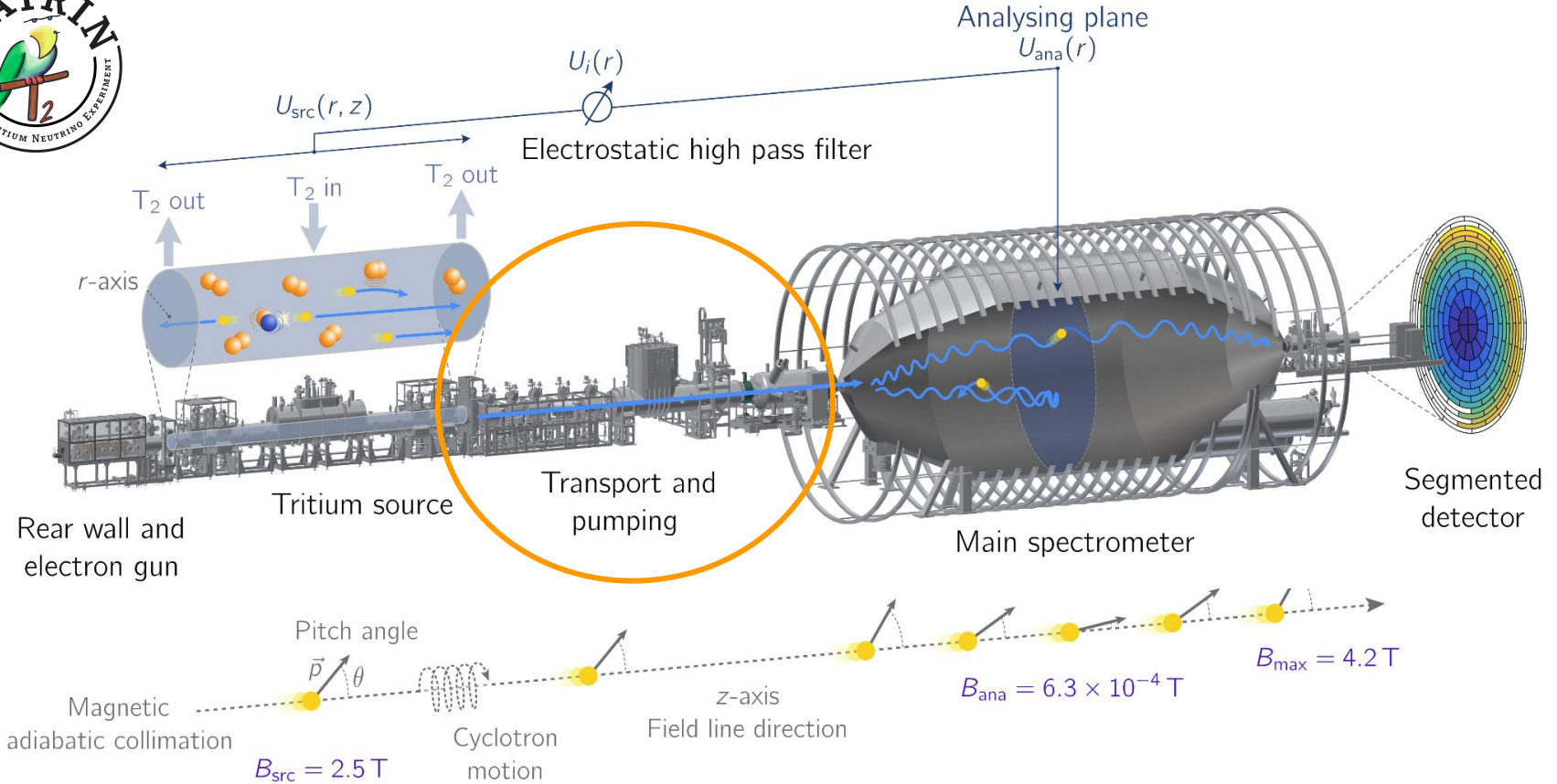


$T = 80\text{K}$



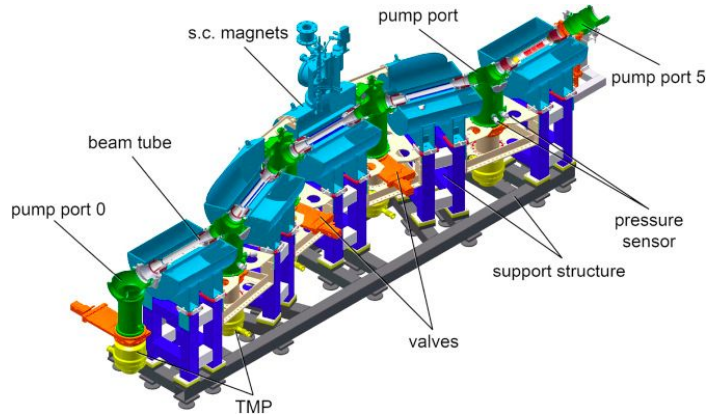
$B = 2.5\text{ T} \rightarrow$ electrons confined in flux tube

Tritium removal

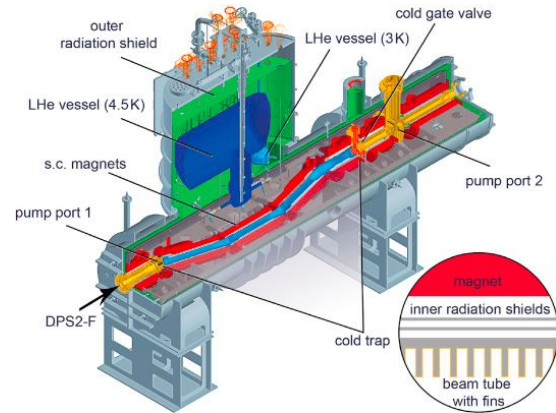


Tritium removal

Differential pumping section



Cryogenic pumping section



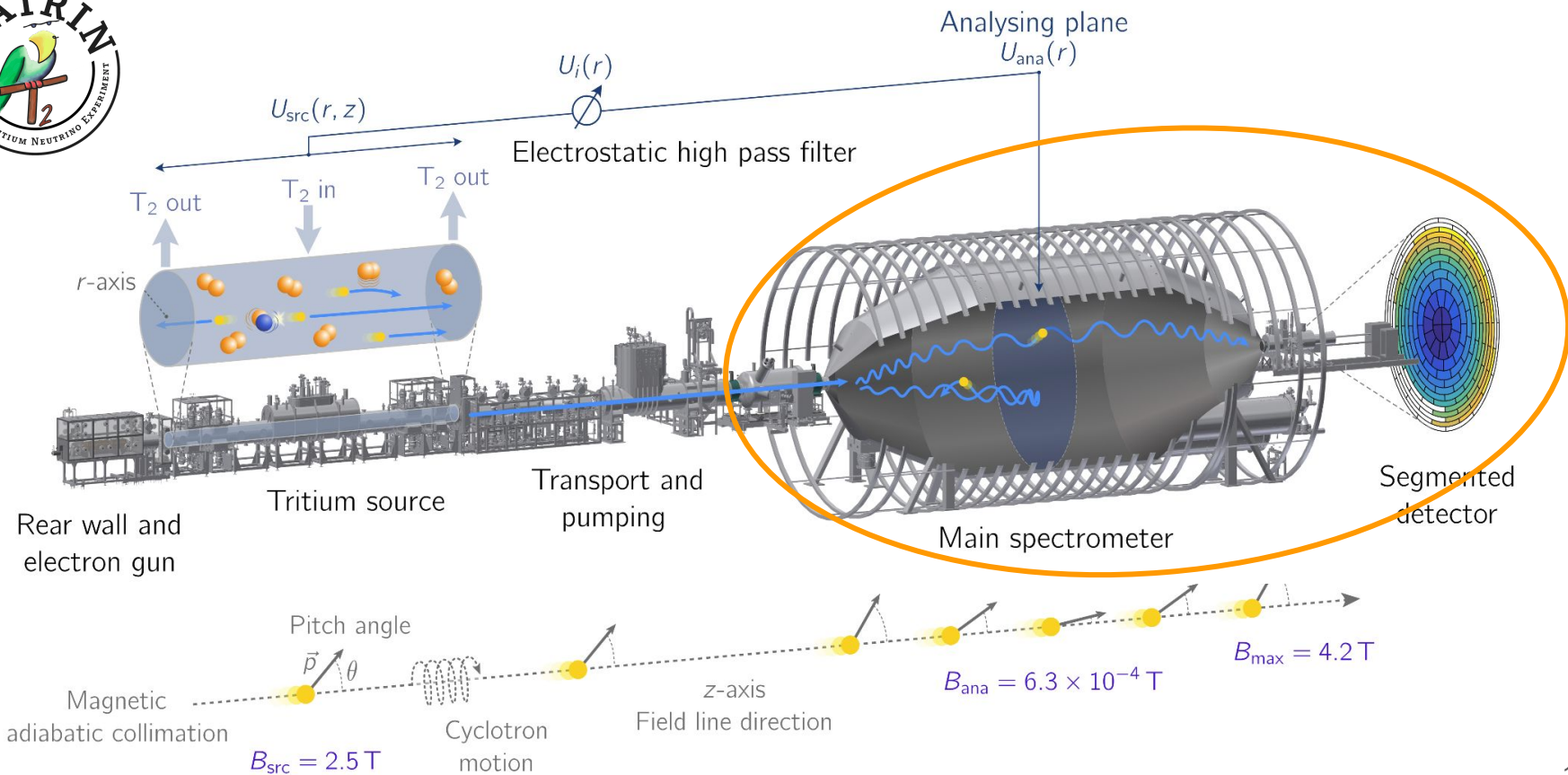
chicane to remove positive ions



neutral atoms stick on frozen argon layer

→ tritium amount decreased by a factor 10^{14}

How to get the resolution



How to get the resolution

MAC-E filter → align electron angles magnetically and filter them electrostatically

$$\frac{E \cdot \sin^2\theta}{B} = \text{const}$$

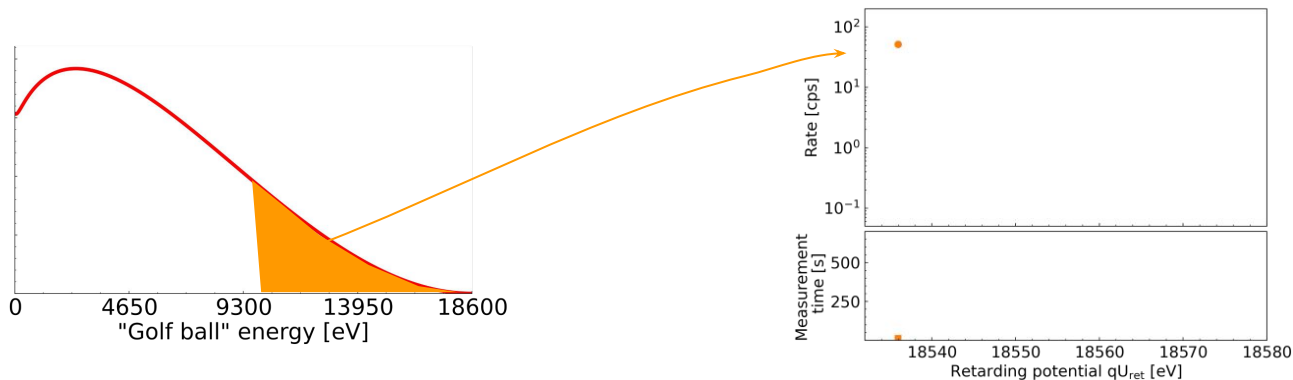
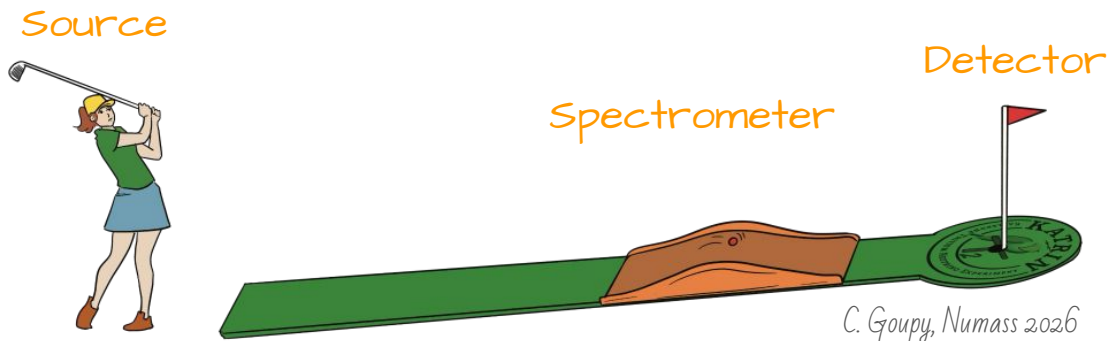
Adiabatic principle



decrease B → decrease θ → collimation ($<1^\circ$)

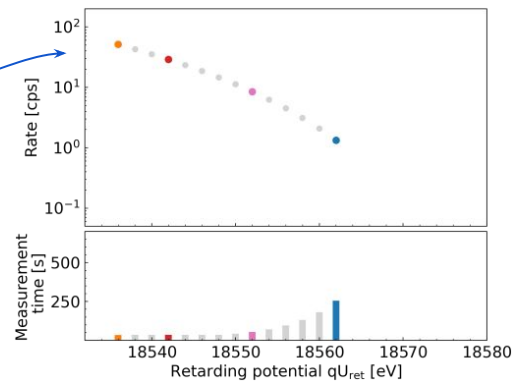
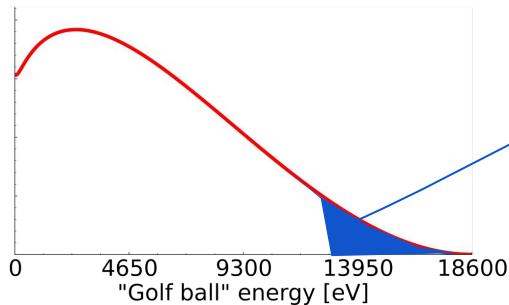
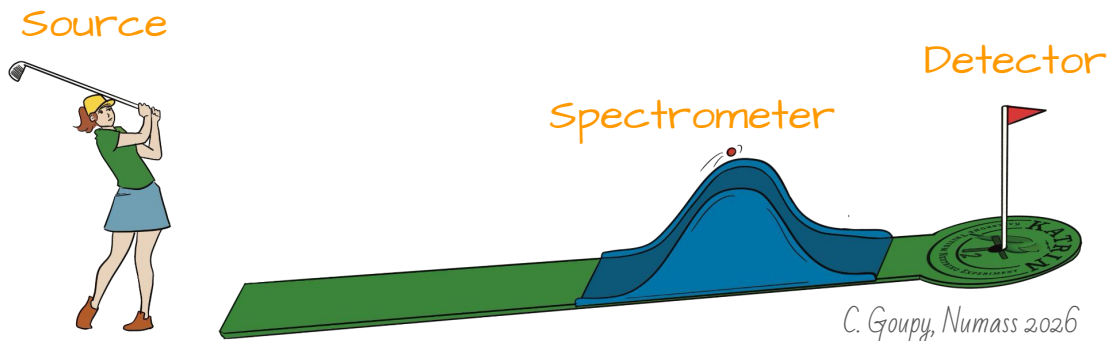
How to get the resolution

MAC-E filter → align electron angles magnetically and filter them electrostatically




How to get the resolution

MAC-E filter → align electron angles magnetically and filter them electrostatically



The price to pay for the resolution

energy resolution limited by residual angular distribution → in KATRIN ~1eV @18.6 keV

but... $B \cdot A = \text{const}$  decrease B → increase A → spectrometer must be large
Fluxtube conservation

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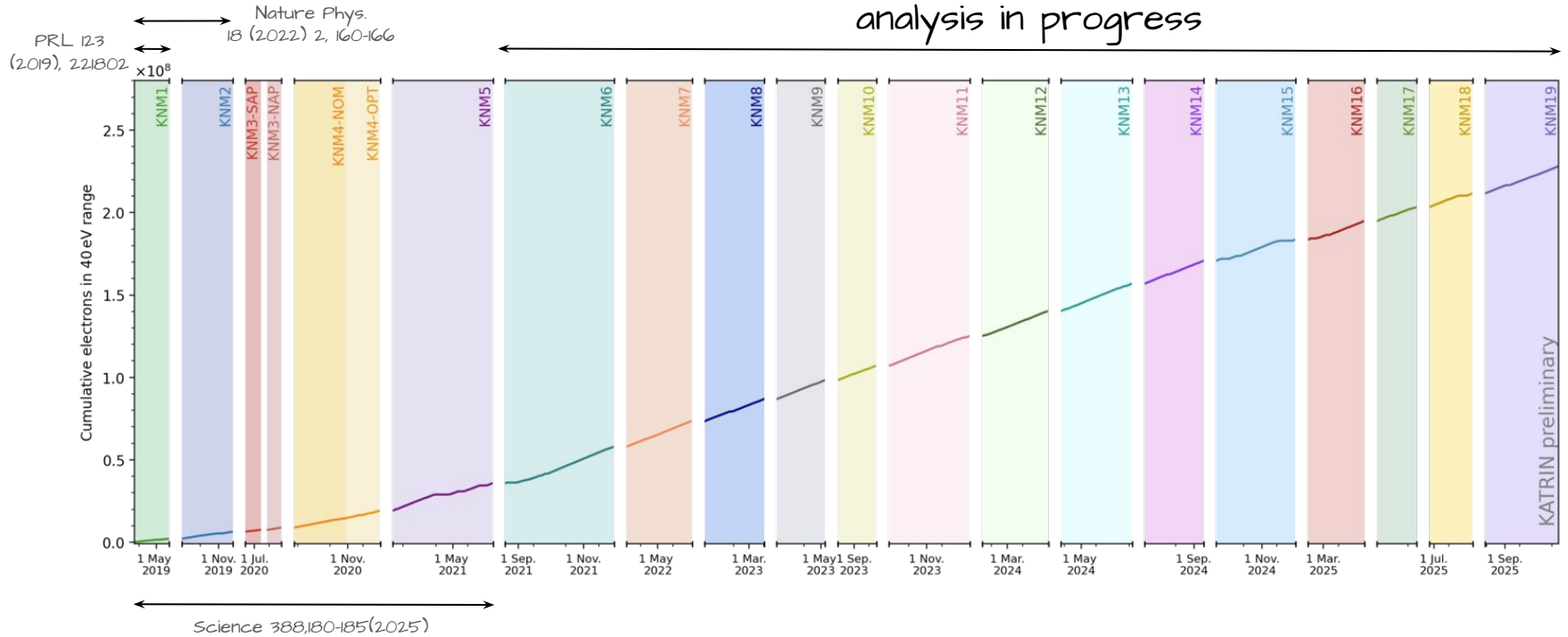
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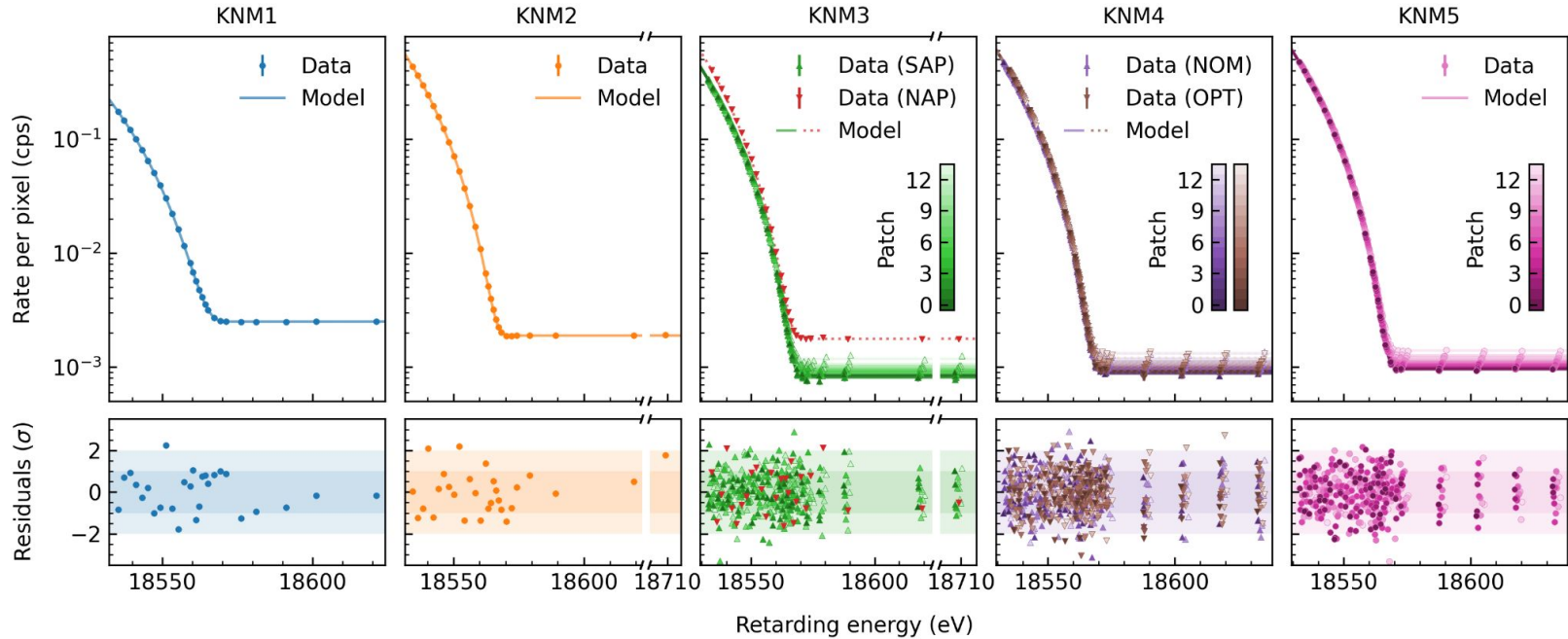


*Spectrometer arrival in Karlsruhe,
November 2006*

Data collection



Latest neutrino mass result



Combined analysis of $\sim 1/6$ of the total statistics \Rightarrow world-leading limit of $m_{\beta} < 0.45$ eV (90% C.L.)

Other anomalies in neutrino experiments

Observed in $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillations

- Reactor Antineutrino Anomaly (RAA)
 - deficit in neutrino rate from reactors measured by short-baseline experiments
 - also spectral shape mismatch (“5 MeV bump”)
- Gallium Anomaly (GA)
 - deficit in neutrino captures in Gallium experiments (GALLEX, SAGE)
 - observed for neutrino sources “inside” the detector

Common point is the short source-detector distance

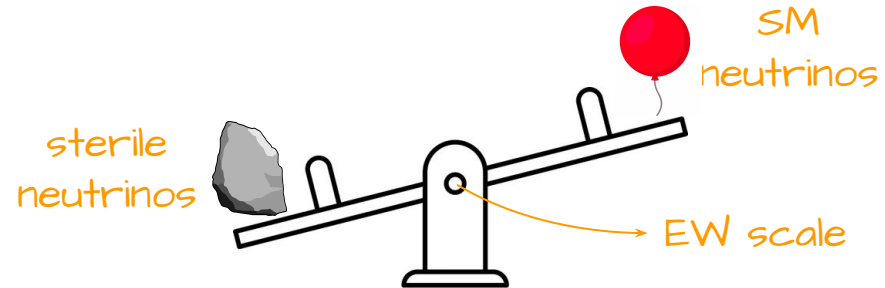
→ a **fast oscillation into a sterile state** can explain both the discrepancies

→ $\Delta m^2 > 1\text{eV}^2$ required

Sterile neutrinos

$\frac{2}{3}$ Left u Right up 2.4 MeV	$\frac{2}{3}$ Left c Right charm 1.27 GeV	$\frac{2}{3}$ Left t Right top 171.2 GeV
$-\frac{1}{3}$ Left d Right down 4.8 MeV	$-\frac{1}{3}$ Left s Right strange 104 MeV	$-\frac{1}{3}$ Left b Right bottom 4.2 GeV
0 Left ν_e Right sterile neutrino N_1 ~keV < 1 eV	0 Left ν_μ Right sterile neutrino N_2 ~GeV < 1 eV	0 Left ν_τ Right sterile neutrino N_3 ~GeV < 1 eV
-1 Left e Right electron 0.511 MeV	-1 Left μ Right muon 105.7 MeV	-1 Left τ Right tau 1.777 GeV

- hypothetical particles predicted by many **BSM theories**
- right-handed counterparts of SM active neutrinos → **no SM interactions**, only gravity
- often invoked to explain the smallness of the neutrino mass → seesaw mechanism

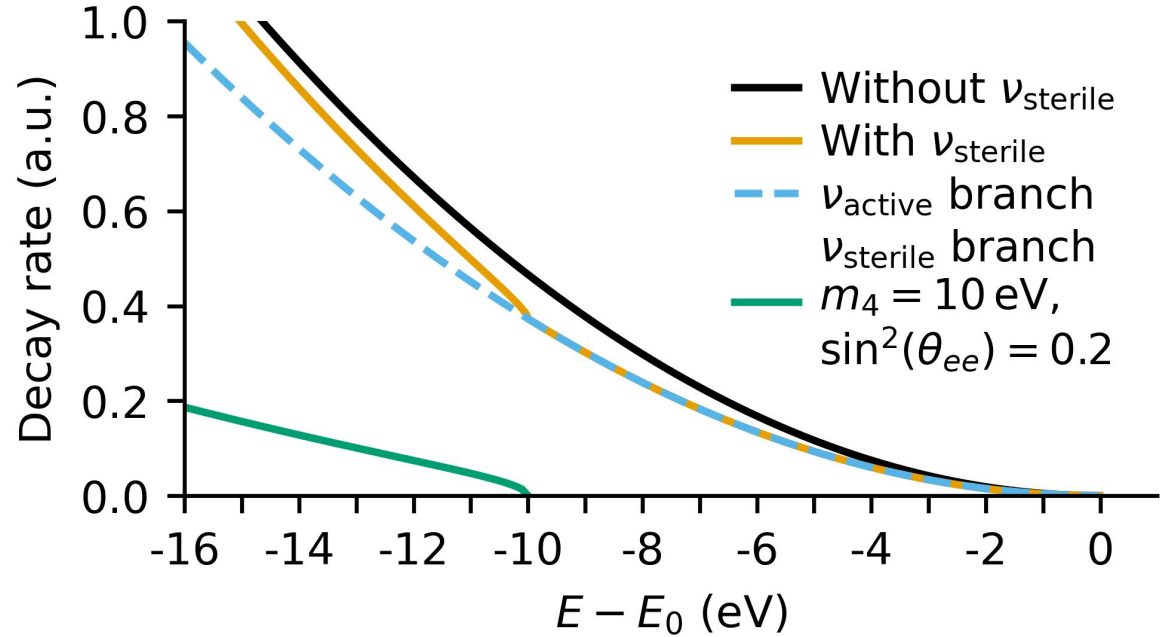
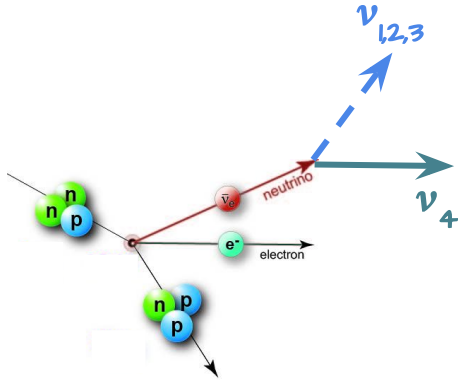


The quest for sterile neutrinos

- **RAA** has been tested with dedicated experiments (STEREO, PROSPECT, DANSS), but no evidence of sterile neutrino oscillation
 - refined nuclear calculations point towards a systematic effect in the reactor flux prediction → anomaly **seems to be solved**
 - However, **Neutrino-4** claimed a measurements of an oscillation compatible with the sterile neutrino existence!
- The **GA** has instead been tested by BEST
 - anomaly is **still there**
 - it might be due to an overestimation of the neutrino cross-section calculation

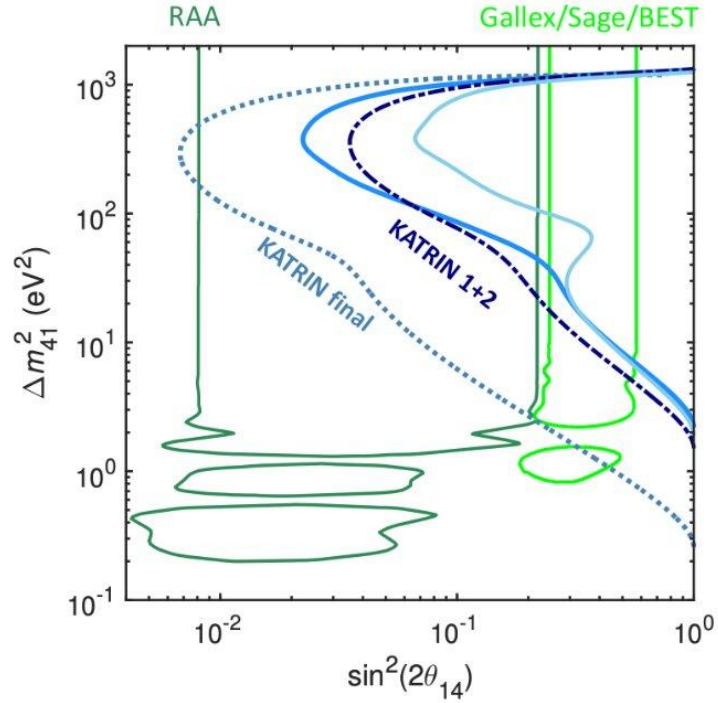
A model-independent search for sterile neutrinos has to be carried out to probe the GA and the Neutrino-4 claim

β spectrum and sterile neutrinos



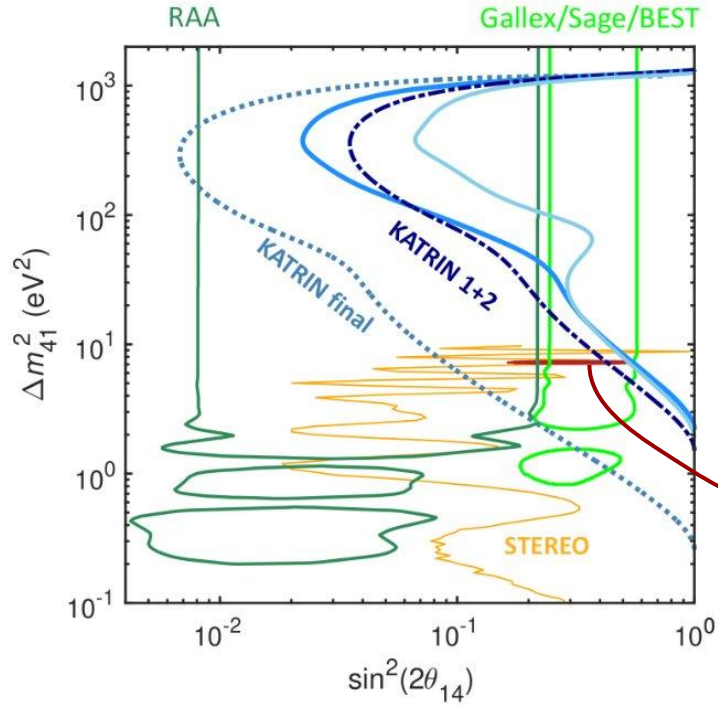
- kink m_4 eV before the endpoint + global spectrum distortion (proportional to mixing $\sin^2\theta$)
- **KATRIN can probe sterile neutrinos** with Δm^2 up to 10^3 eV²

Existing limits



- KATRIN already probed a part of the GA parameter space

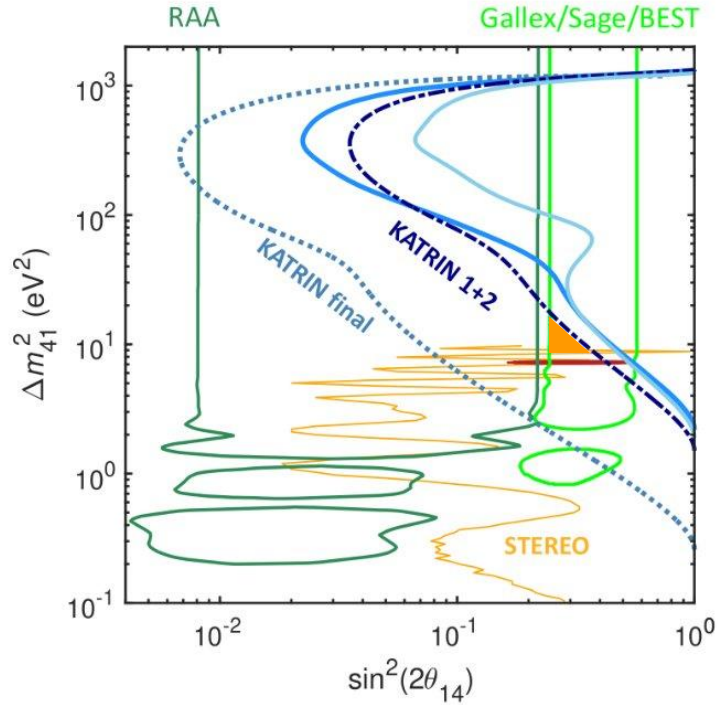
Existing limits



- KATRIN already probed a part of the GA parameter space
- strong complementarity with reactor-based experiments

Neutrino-4

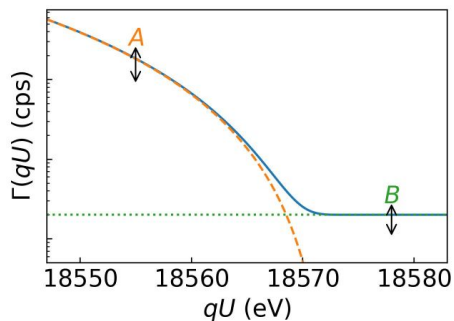
Existing limits



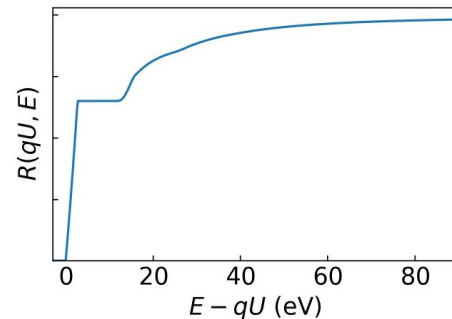
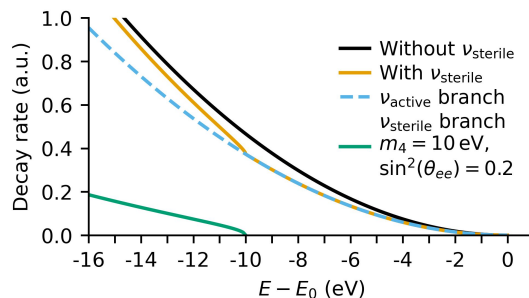
- KATRIN already probed a part of the GA parameter space
- strong complementarity with reactor-based experiments
- **a part of the parameter space** has still to be probed, as well as the Neutrino-4 region

New dataset: campaigns 1-5

- 259 measurement days \rightarrow 1757 β scans
- \sim 36 million electrons in ROI
- 180 unconstrained parameters in the fit



The model

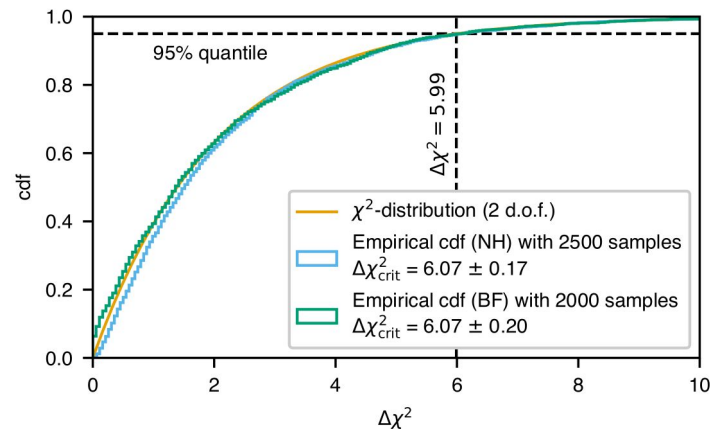


- **theory:** Fermi β spectrum, corrections, molecular final states
- **experiment:** fields, gas density, energy loss in scattering

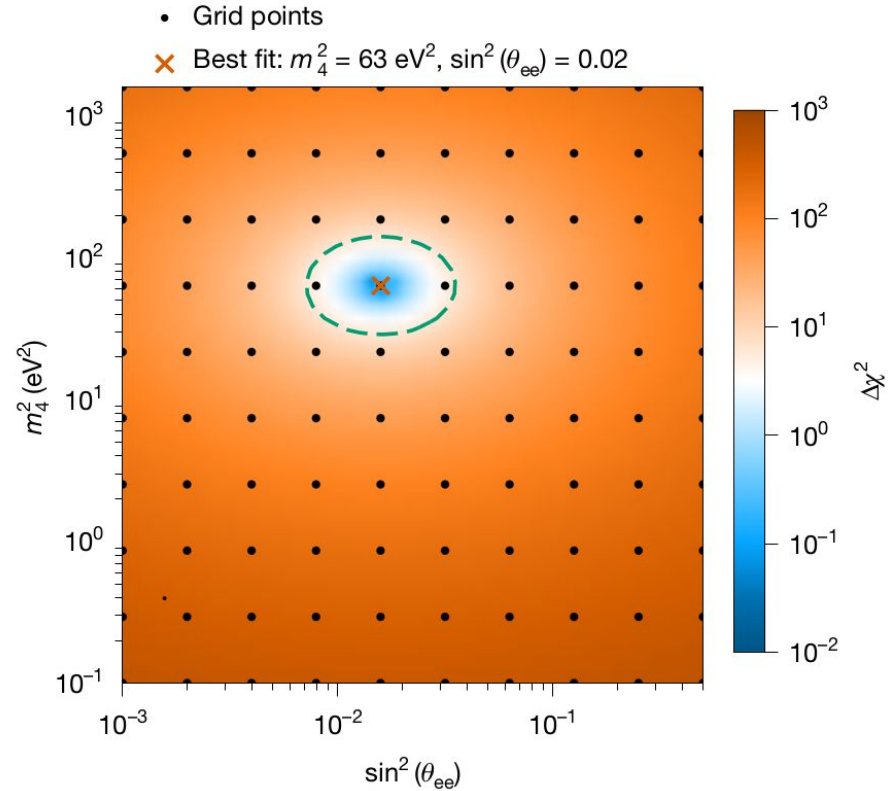
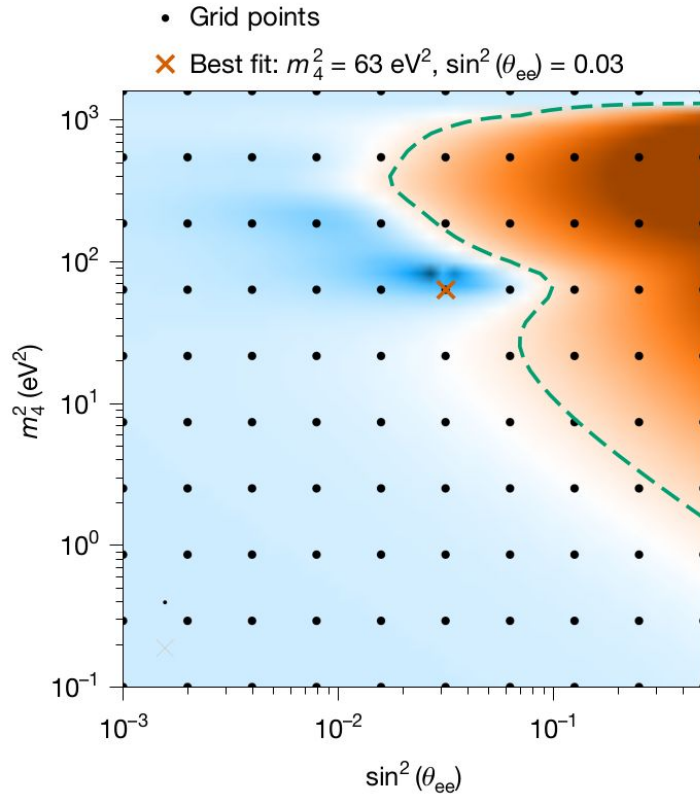
Analysis methods

1. fix sterile mass
2. fix sterile-to-active mixing
3. frequentist minimization of neg log likelihood, systematics encoded in covariance matrices
4. change the mixing, and re-do the minimization
5. find the $\chi^2 = \chi^2_{\text{crit}}$, for a given confidence level

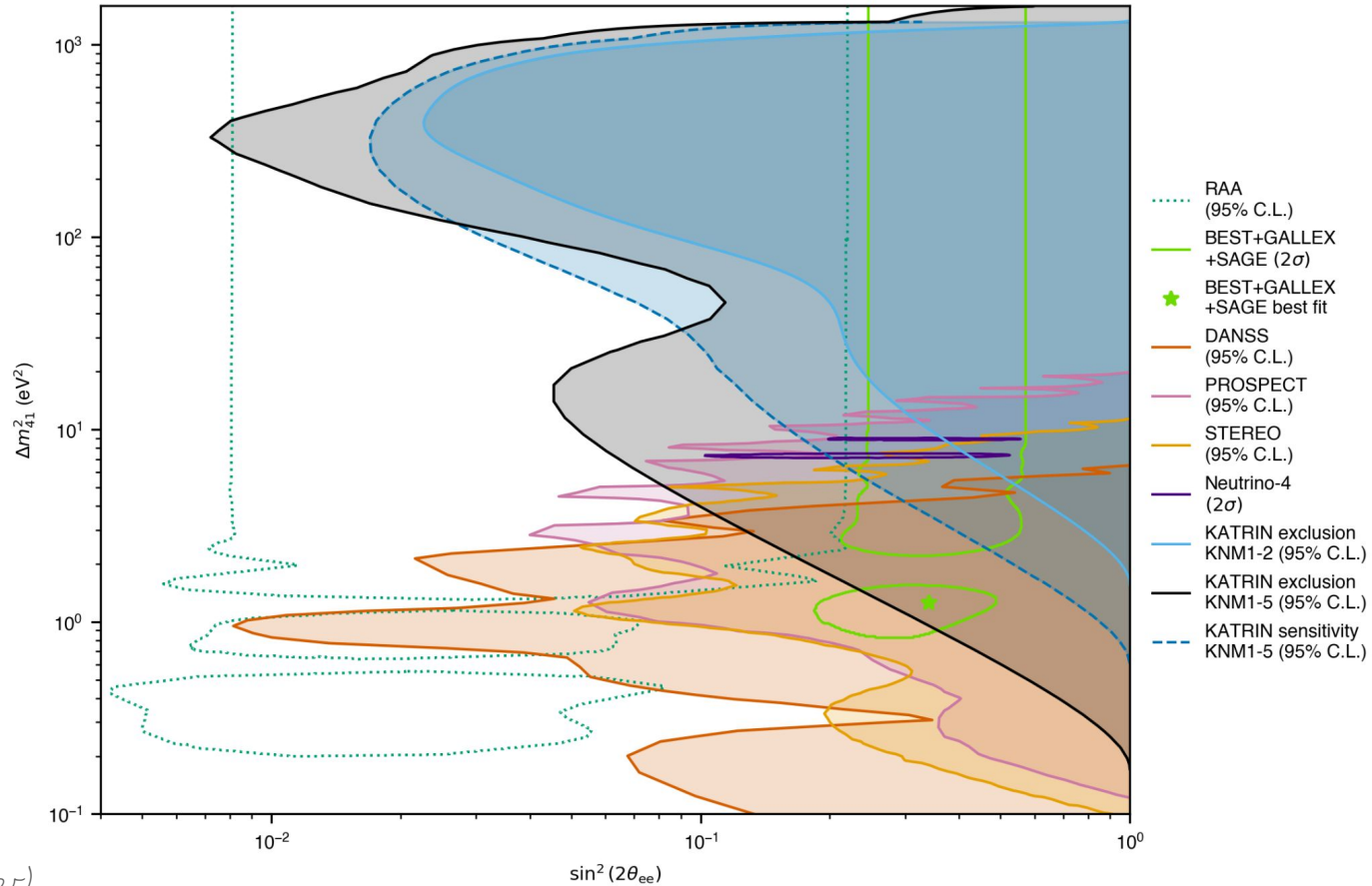
$$\begin{aligned}\chi_{\text{comb}}^2(\boldsymbol{\theta}) &= \sum_{k \in \mathcal{I}_G} \chi_{G,k}^2 \left(m_\nu^2, m_4^2, \sin^2 \theta_{ee}, \right. \\ &\quad \left. E_{0k}, \text{Sig}_k, \text{Bg}_k, \xi \right) \\ &+ \sum_{l \in \mathcal{I}_p} \sum_{p=0}^{13} \chi_{P,lp}^2 \left(m_\nu^2, m_4^2, \sin^2 \theta_{ee}, \right. \\ &\quad \left. E_{0lp}, \text{Sig}_{lp}, \text{Bg}_{lp}, \xi \right) \\ &+ (\hat{\xi} - \xi)^T \Sigma^{-1} (\hat{\xi} - \xi).\end{aligned}$$



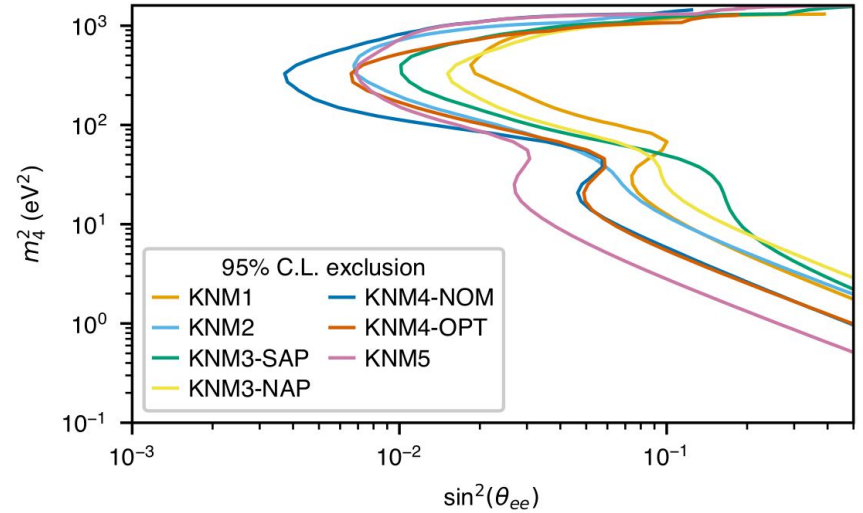
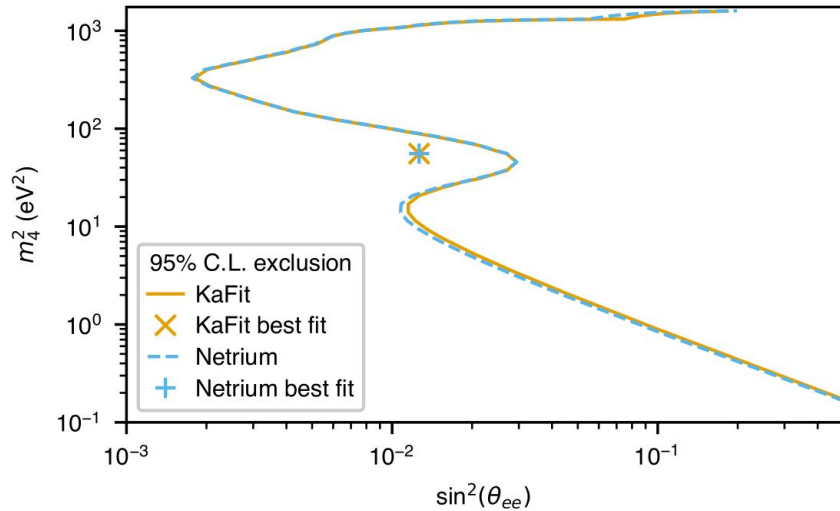
Simulated results



Final result

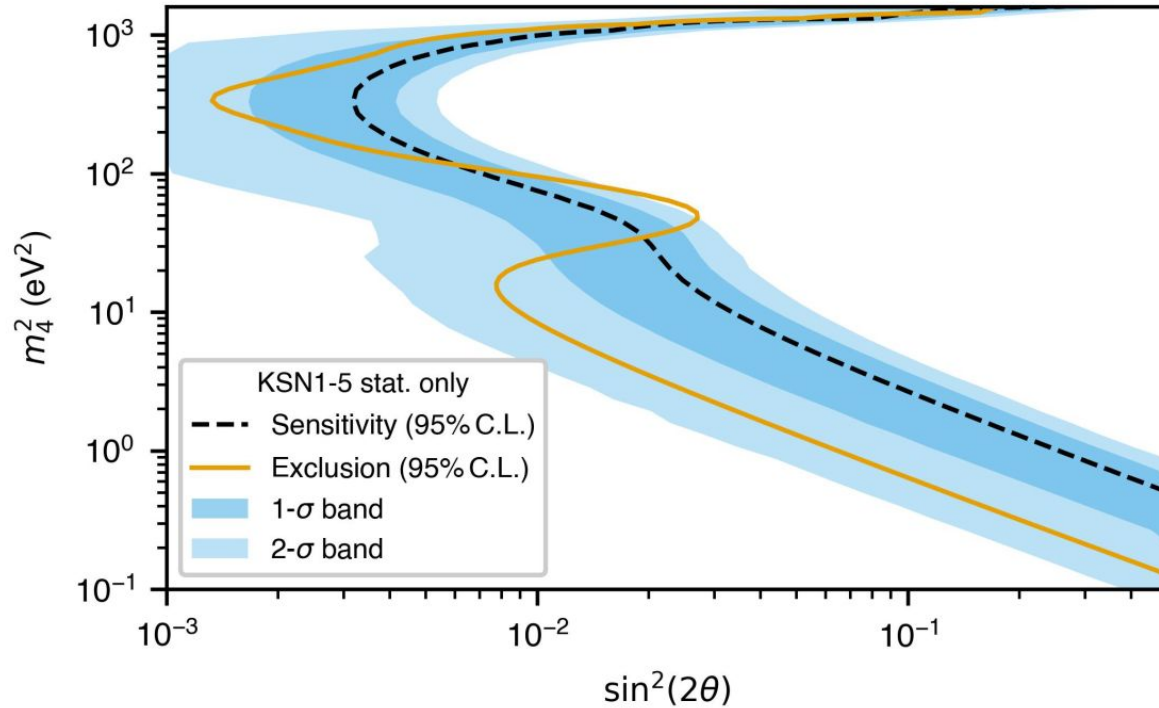


A couple of crosschecks



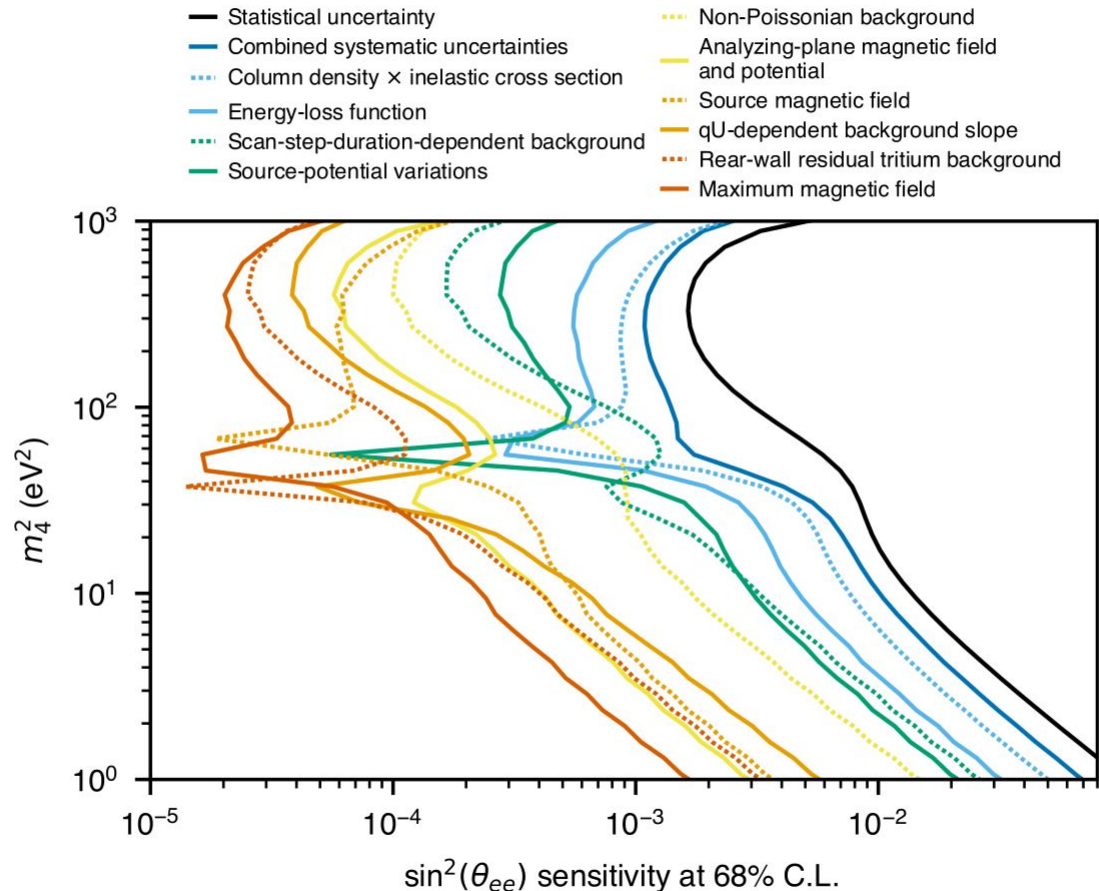
- excellent agreement between two independent analysis
- reasonable exclusion contours campaignwise

Exclusion vs sensitivity



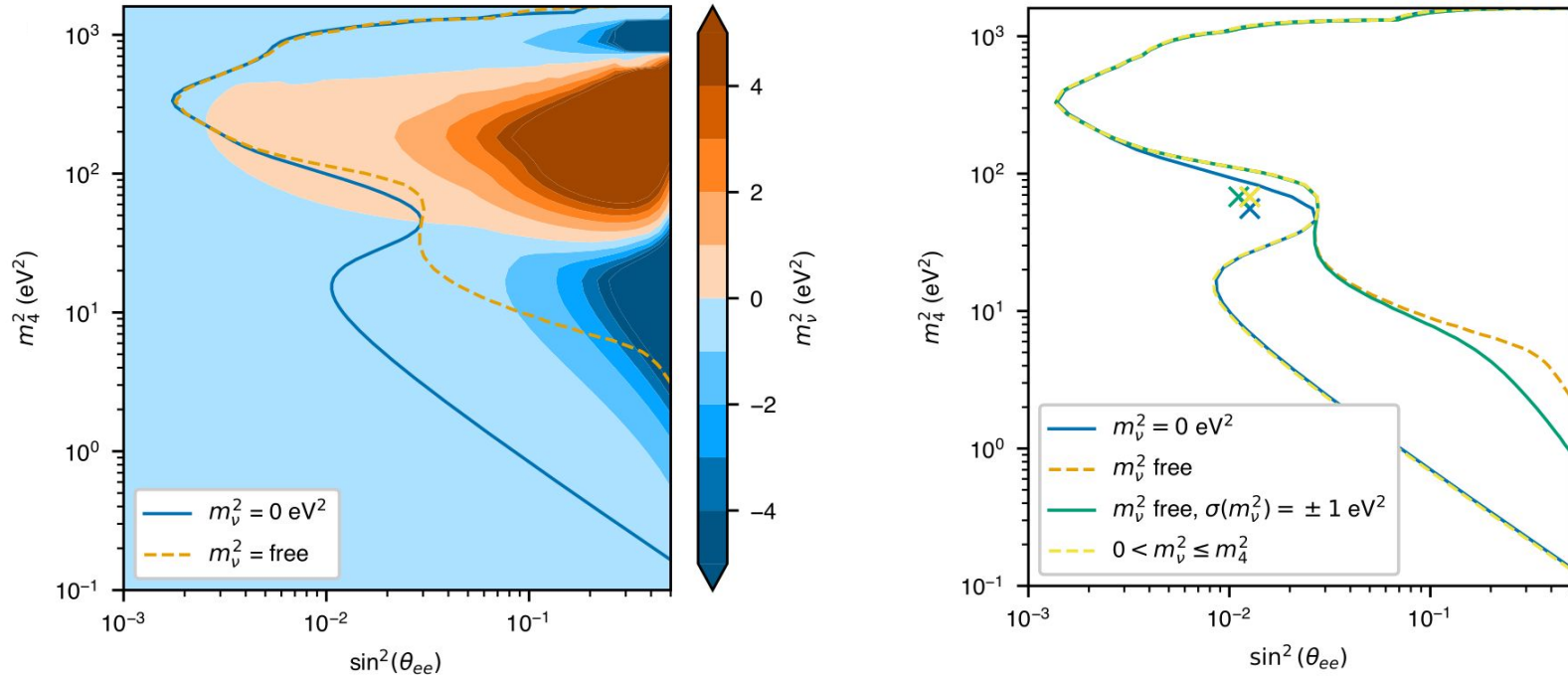
- sensitivity computed for many stat fluctuated MC spectra
- our result is statistically compatible with the expected sensitivity

A look at the systematics



- results are statistically dominated
- source-related systematics are the dominant ones
 - gas density
 - energy loss in a scattering
 - plasma effects

The interplay with the neutrino mass



- leaving the neutrino mass free in the analysis modifies the contours
- for physical motivated priors on the neutrino mass the GA and Neutrino-4 regions are still excluded

Summary

- the search of **neutrino mass** and **sterile neutrinos** are among the most interesting challenges in modern particle physics
- **KATRIN** is a unique experiment with high sensitivity to both these searches
- from a combined analysis of its first 5 campaigns, KATRIN placed the current best limit on the neutrino mass of 0.45 eV and excluded the region of the sterile neutrino parameter space related to GA and Neutrino-4
- stay tuned for KATRIN's final analysis!

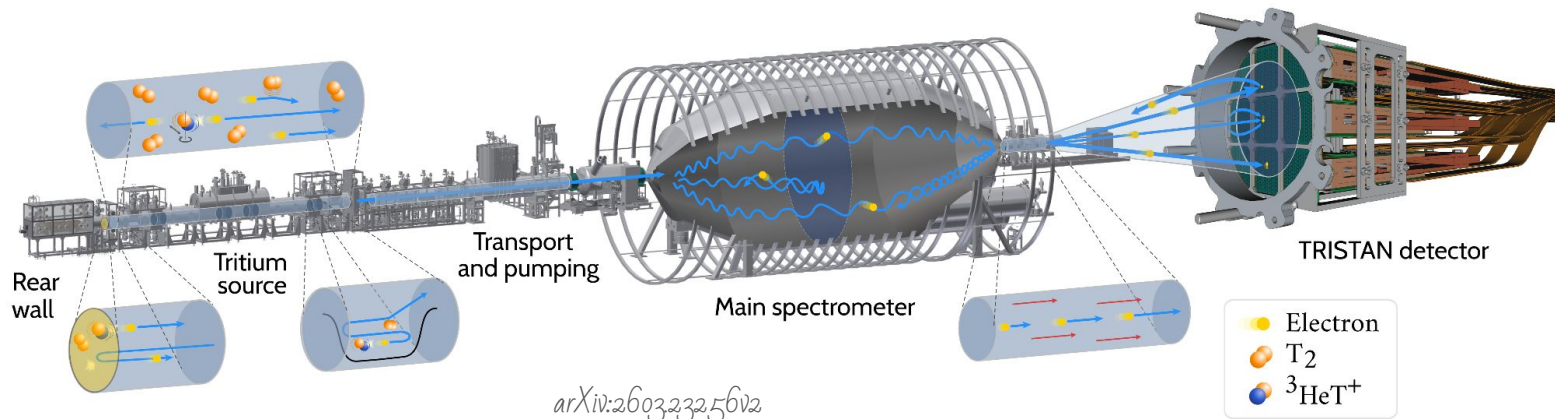


Outlook

- extended analysis range ($\rightarrow 90$ eV) → planned for final analysis
 \rightarrow huge gain for eV sterile neutrinos search
- differential measurement of the whole spectrum with a fast detector (TRISTAN)
 \rightarrow search for keV sterile neutrinos (Dark Matter candidates)

→

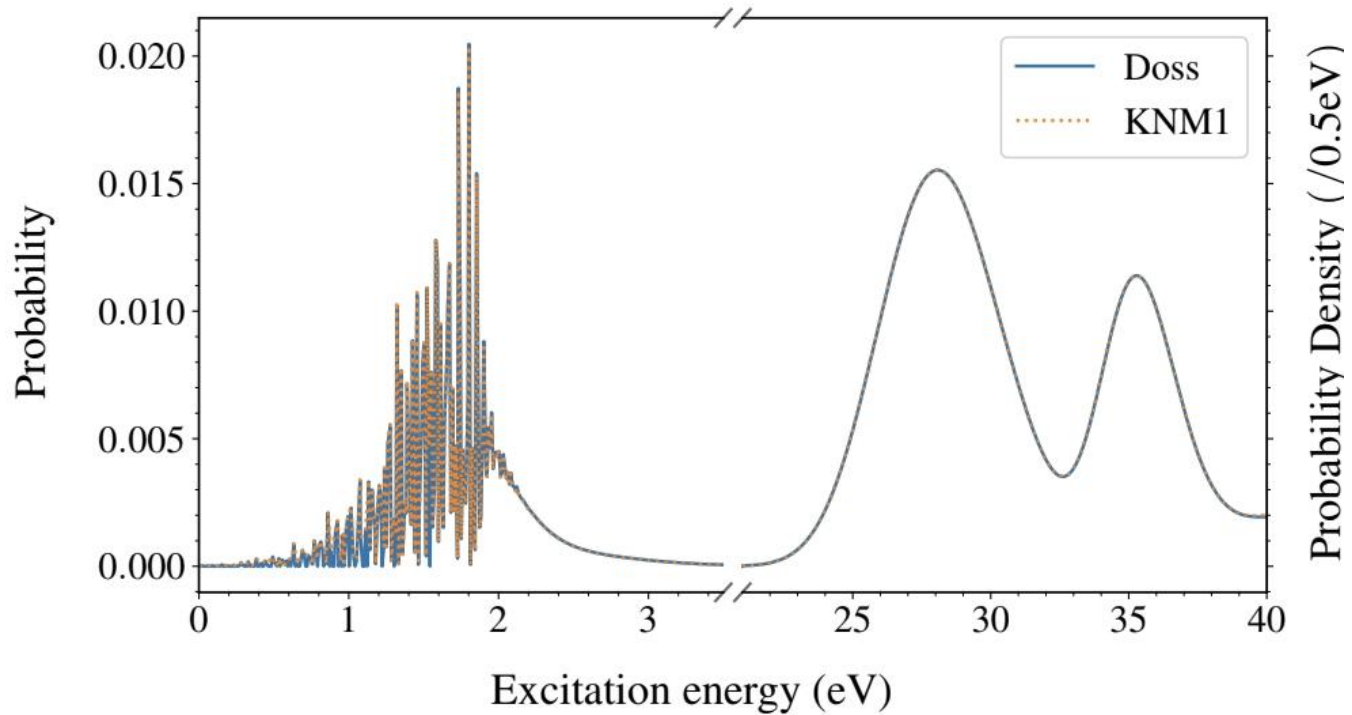
next KATRIN phase!



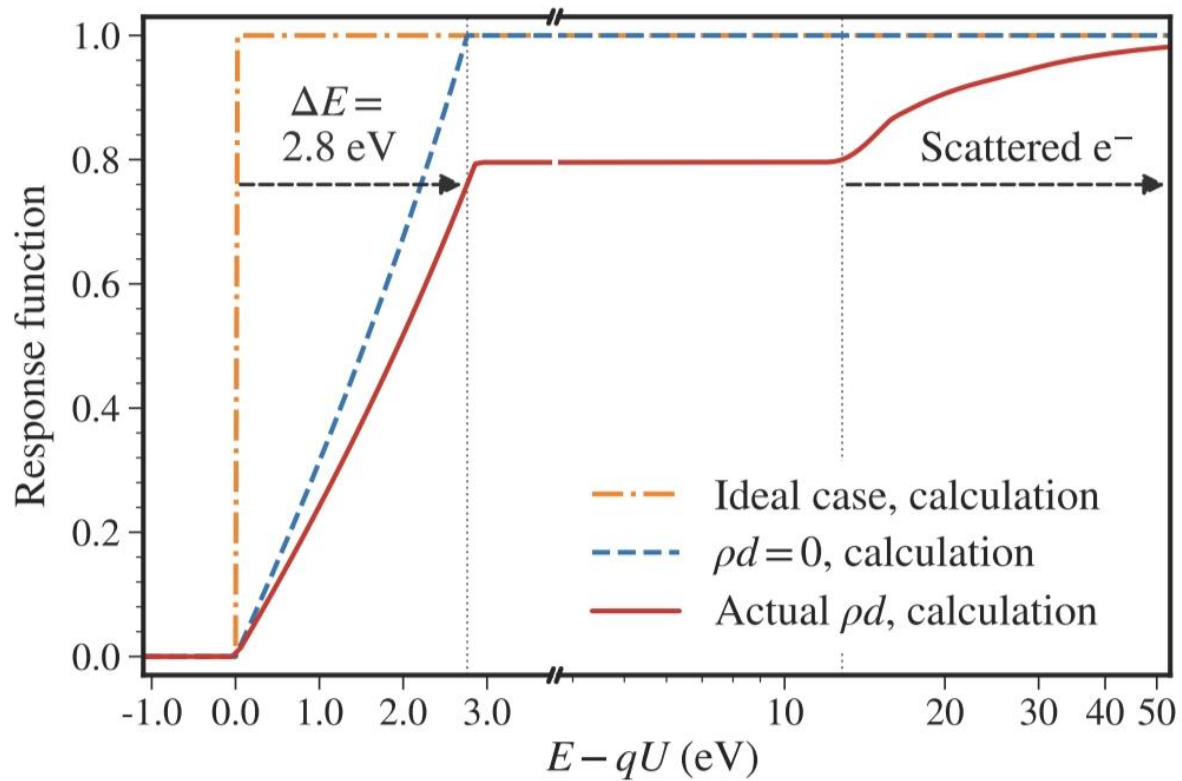


Backup

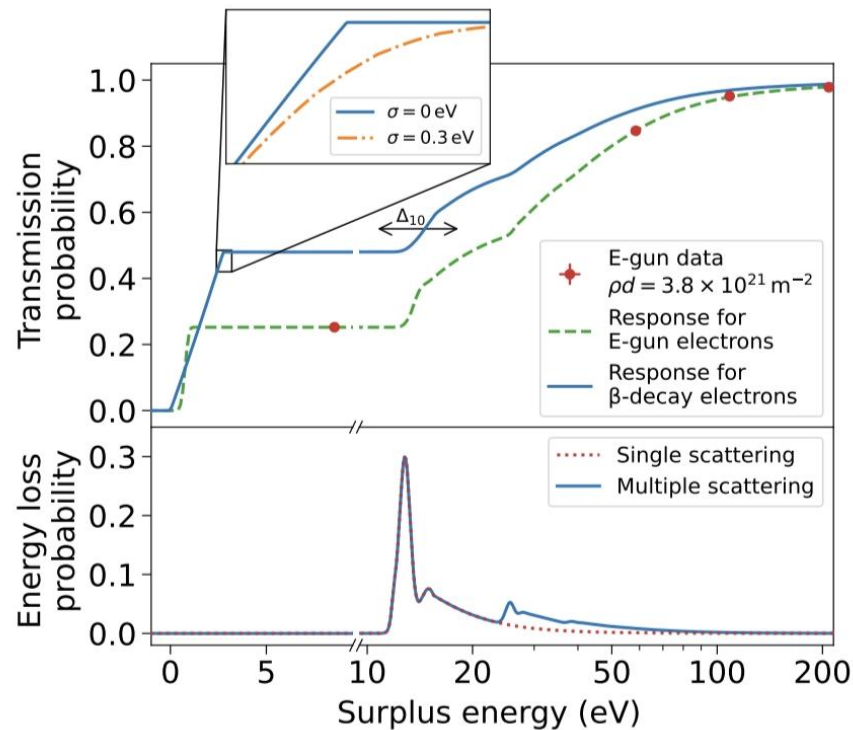
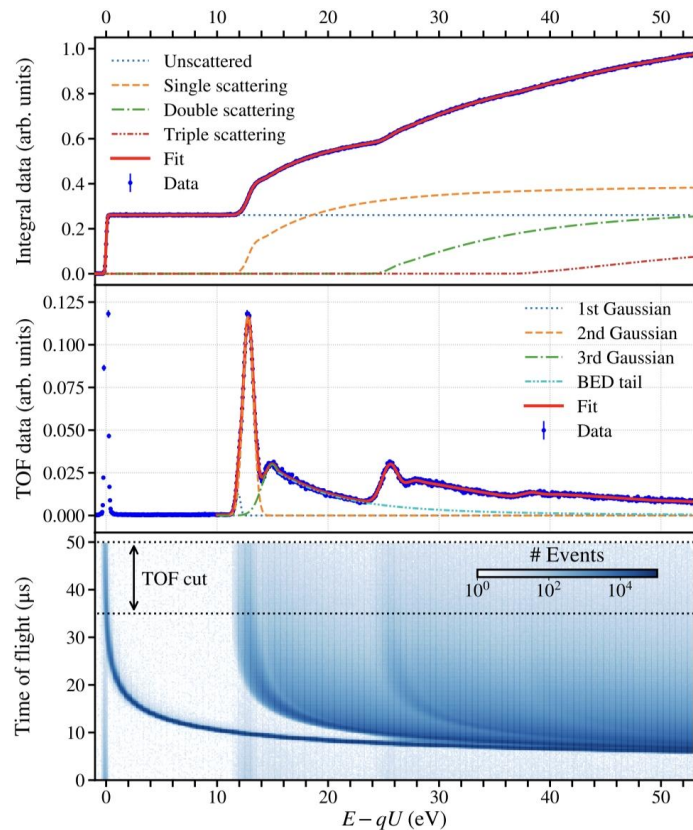
KATRIN's systematics



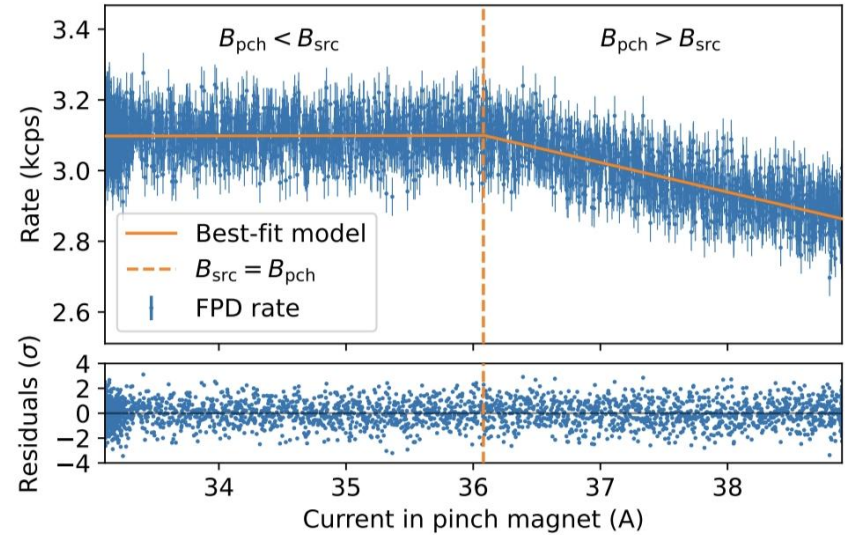
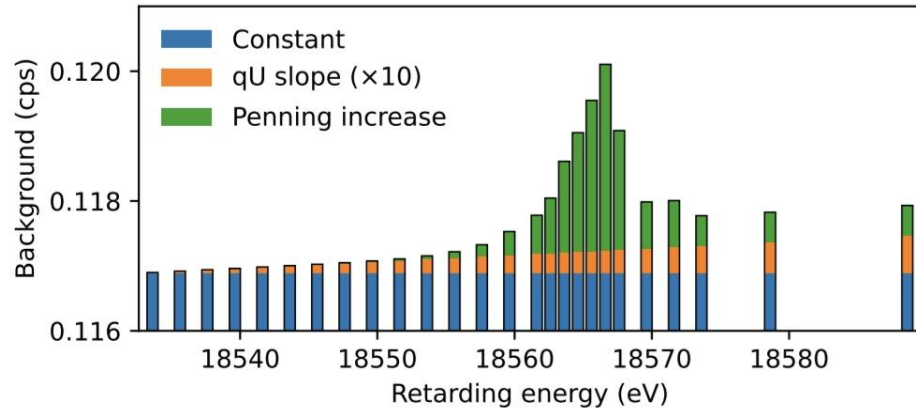
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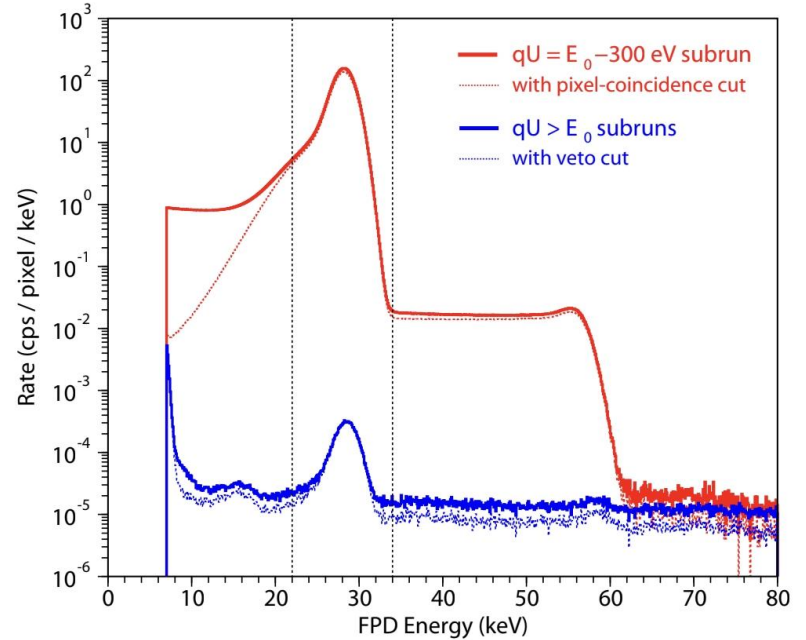
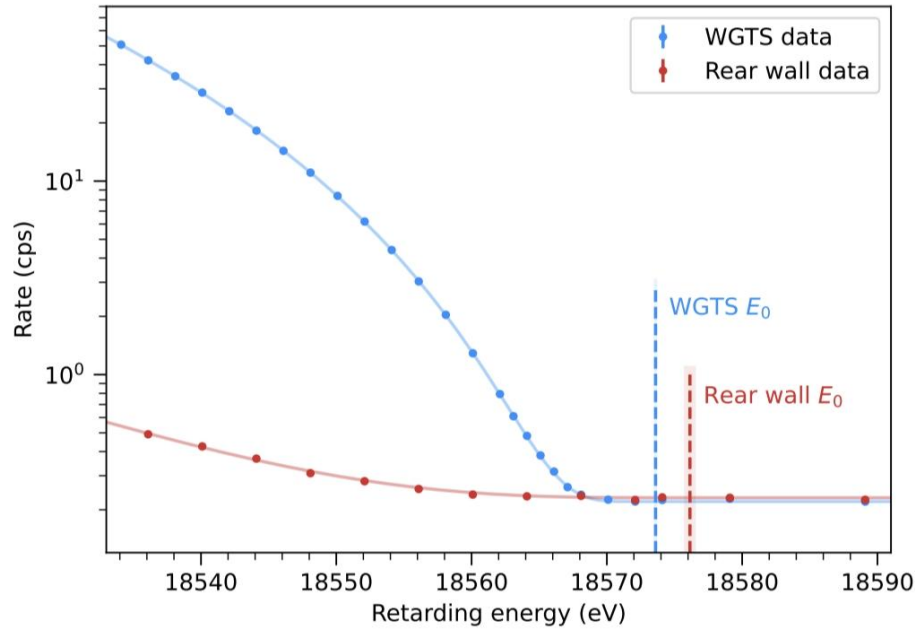
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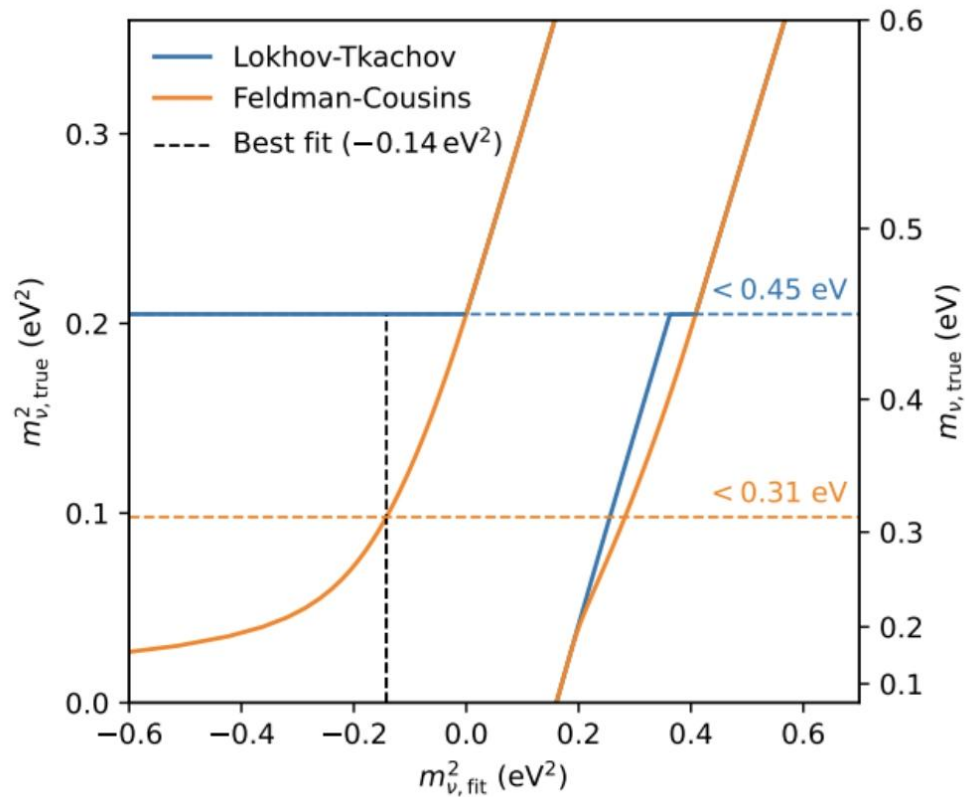
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KATRIN's systematics



KATRIN's systematics



KATRIN's systematics

