Latest results from the KATRIN experiment and future prospects

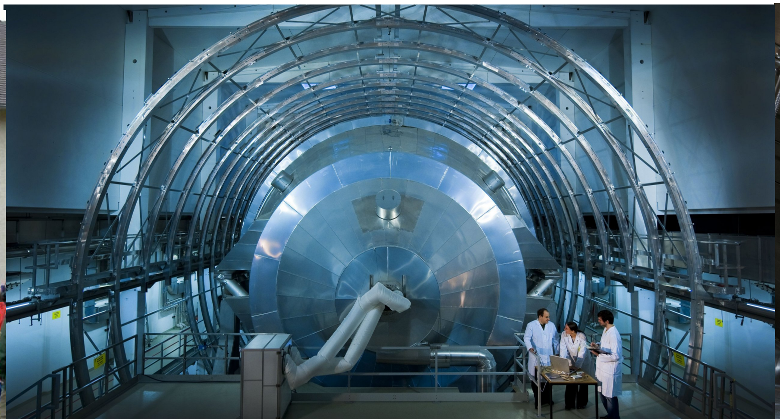
Cláudio Silva, UBI, LIP-Coimbra, for the KATRIN Collaboration, 9 de Agosto 2024

Introduction

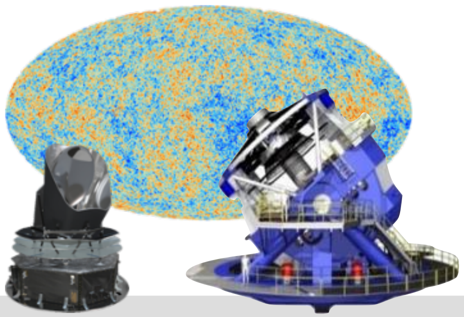
- Overview of the KATRIN experiment;
  - Observation of the **endpoint of the tritium β spectrum** - weak decay kinematics;
  - High energy resolution achieved using a Magnetic Adiabatic Collimation with an Electrostatic (**MAC-E**) filter.
- KATRIN **neutrino mass results** KNM1-KNM5 - released in 2024;
- KATRIN **eV-scale sterile** neutrino analysis (2025);
- 2026-2027: search for **keV-scale sterile** neutrinos

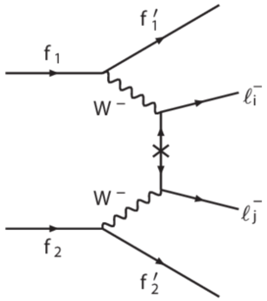
Future of the KATRIN experiment (R&D phase):

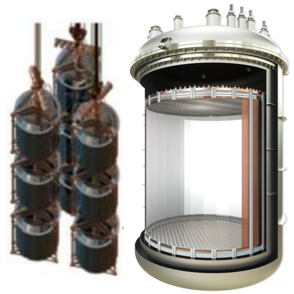
- **Improved resolution** through quantum sensors of the **MMC type** in a differential measurement approach;
- Reduced systematic uncertainties by employing an atomic tritium source instead of the current molecular source.

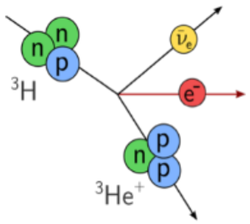



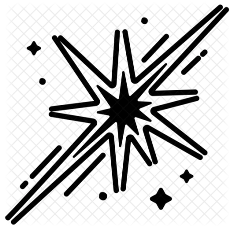

Neutrino Mass Observables





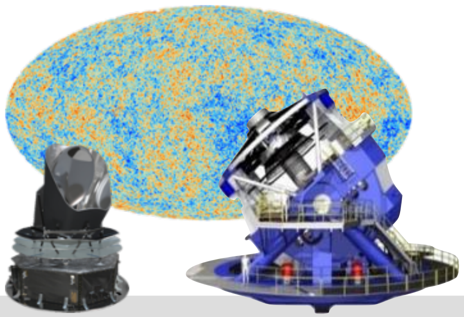


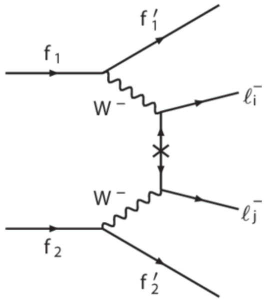


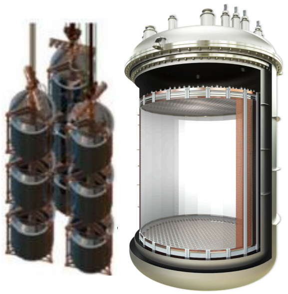


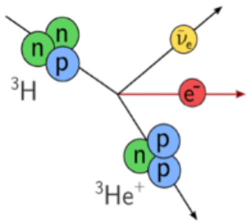
	Cosmology	Search for 0νββ	Direct Neutrino Mass Measurement
Observable	$\sum \mathbf{m_i} = \mathbf{m_1} + \mathbf{m_2} + \mathbf{m_3}$	$\mathbf{m}_{\beta\beta} = \left\lvert \sum_i \mathbf{U_{ei}}^2 \mathbf{m_i} \right\rvert$	$\mathbf{m}_{\beta}{}^2 = \sum_i \lvert \mathbf{U_{ei}} \rvert^2 \mathbf{m_i}{}^2$
Present upper limit	<0.12 eV (<0.064 eV)	< 0.156 eV	< 0.45 eV
Model dependence	Multi-parameter cosmological model	- Sensitive only to Majorana ν - contributions other than m(ν)? - Large uncertainties on the nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum: - Kinematics from the weak decay (^{3}H, ^{163}Ho) - Time-of-flight measurements (ν from super novas)

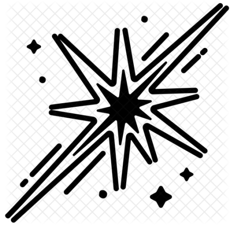
Neutrino Mass Observables











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Limits from Cosmology

DR2 data from DESI (Dark Energy Spectroscopic Instrument)

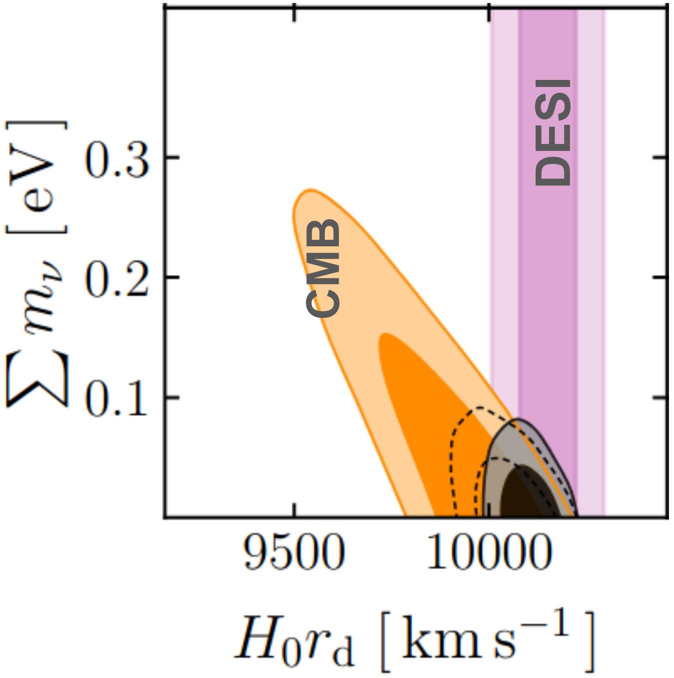
- Galaxy survey
- Measurements of the baryon acoustic oscillations (BAO) in the redshift range at z ~ 0.1-4.2
- Combined with CMB → sensitive to Σm_ν

Result (assuming ΛCDM and three degenerate neutrino states) from 2025

$$\Sigma m_\nu < 0.0642 \text{ eV}$$

From neutrino oscillations:

- **$\Sigma m_\nu > 0.0588$ eV (Normal Ordering)**
- **$\Sigma m_\nu > 0.101$ eV (Inverted Ordering)**



DESI collab., arXiv:2503.14744

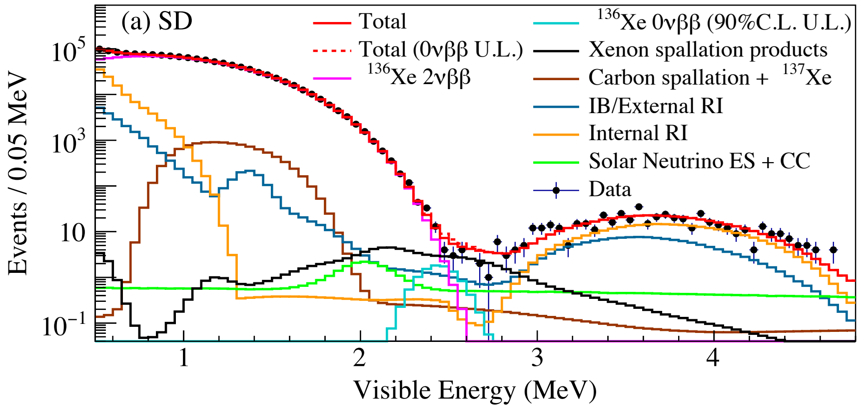
Limits from 0νββ

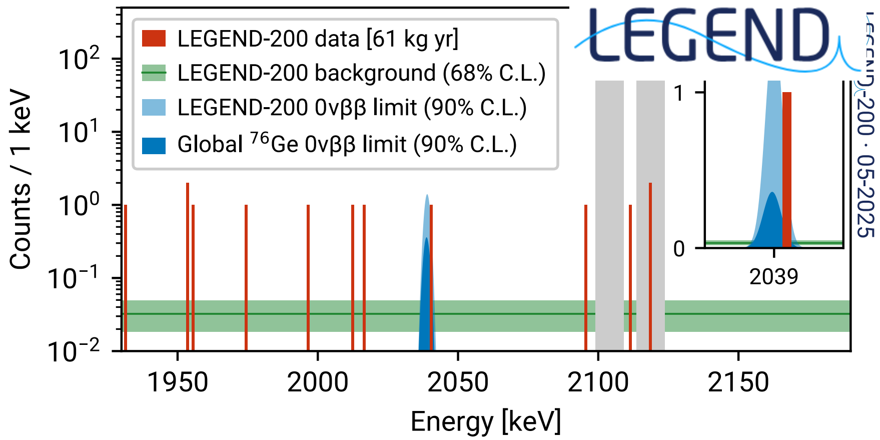
$$(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

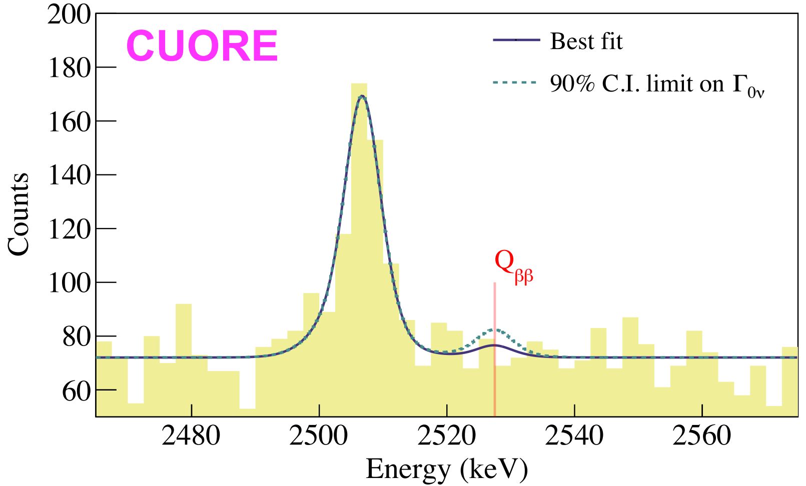
- **^{136}Xe** (Q-Value: 2.458 MeV)
  - **KamLAND-Zen 800 (complete data set)** complete dataset with 2.097 ton×yr of ^{136}Xe - **2024** [1]
  - **$T_{1/2}$ > 3.8×10^{26} years** (90% C.L.)
  - **$m_{\beta\beta}$ > 0.028–0.122 eV** (90% C.L.)
- **^{76}Ge** (Q-Value: 2.039 MeV)
  - **LEGEND-200** 61 kg×yr of ^{136}Xe - 2025 [2]
  - Limit: **$T_{1/2}$ > 1.9×10^{26} years**
  - **$m_{\beta\beta}$ > 0.075–0.200 eV** (90% C.L.)
- **^{130}Te** (Q-Value: 2.615 MeV)
  - **CUORE** 2 ton×yr of ^{136}Xe - 2025 [2]
  - Limit: **$T_{1/2}$ > 3.8×10^{25} years**
  - **$m_{\beta\beta}$ > 0.070–0.240 eV** (90% C.L.)

[1] https://arxiv.org/abs/2406.11438 (2024)
[2] https://arxiv.org/pdf/2509.21166 (2025)
[3] https://arxiv.org/abs/2404.04453 (2024)

KamLAND-Zen 800





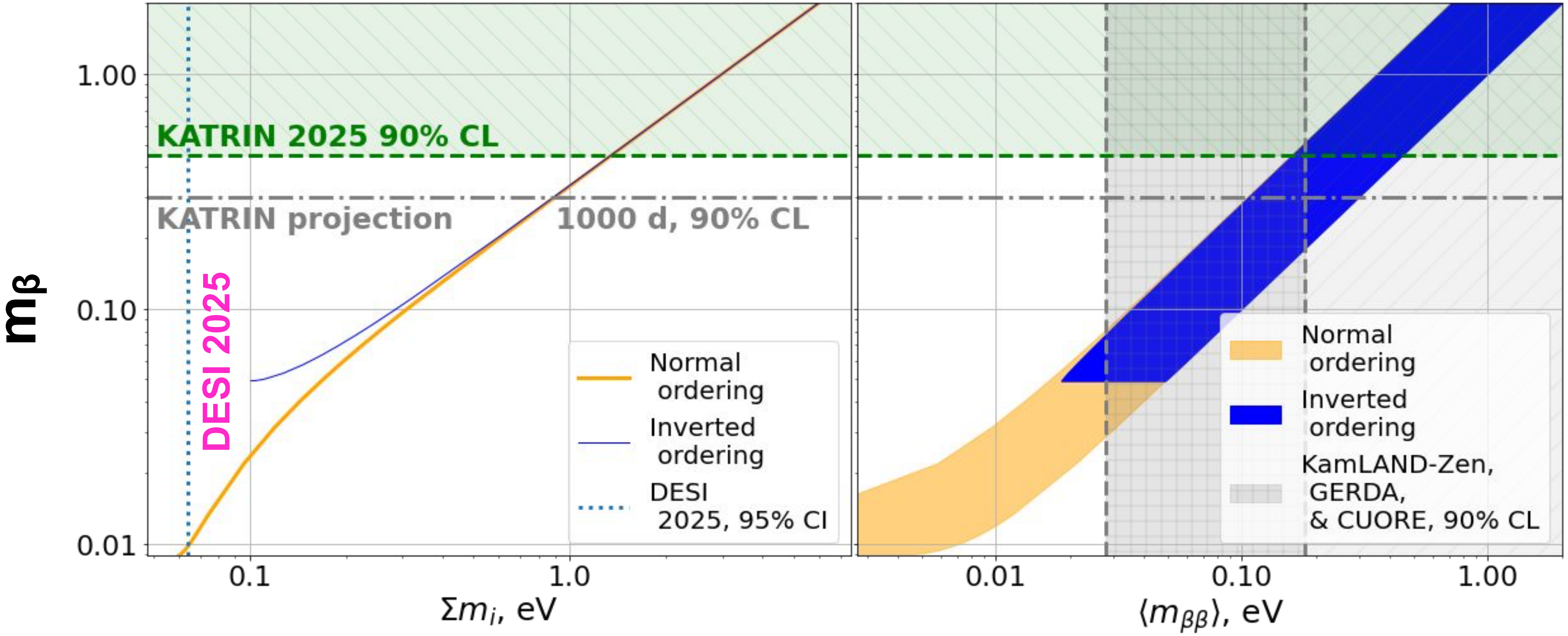


Neutrino Mass Observables

Direct Kinematic Measurements

Cosmological Observables

Neutrinoless double β-decay



Assuming mixing angles θ and $\boldsymbol{\Delta m^2}$ from oscillations

Measurement of the incoherent sum of the neutrino mass:

Ann.Rev.Nucl.Part.Sci. 72 (2022) 259-282, Updated Plot

Neutrino Mass from Tritium Decay

Why Tritium?

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

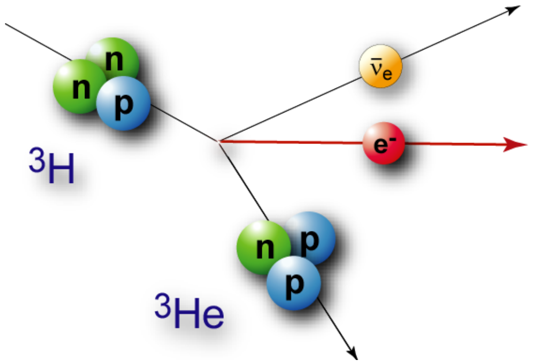
- Simple structure of atomic/nuclear shell;
- Low endpoint energy **18 592.071(22) eV** [1]
  - subtracted by 16.29 eV due to molecular disassociation);
- Super-allowed transition (**$T_{1/2}$ = 12.32 a**).

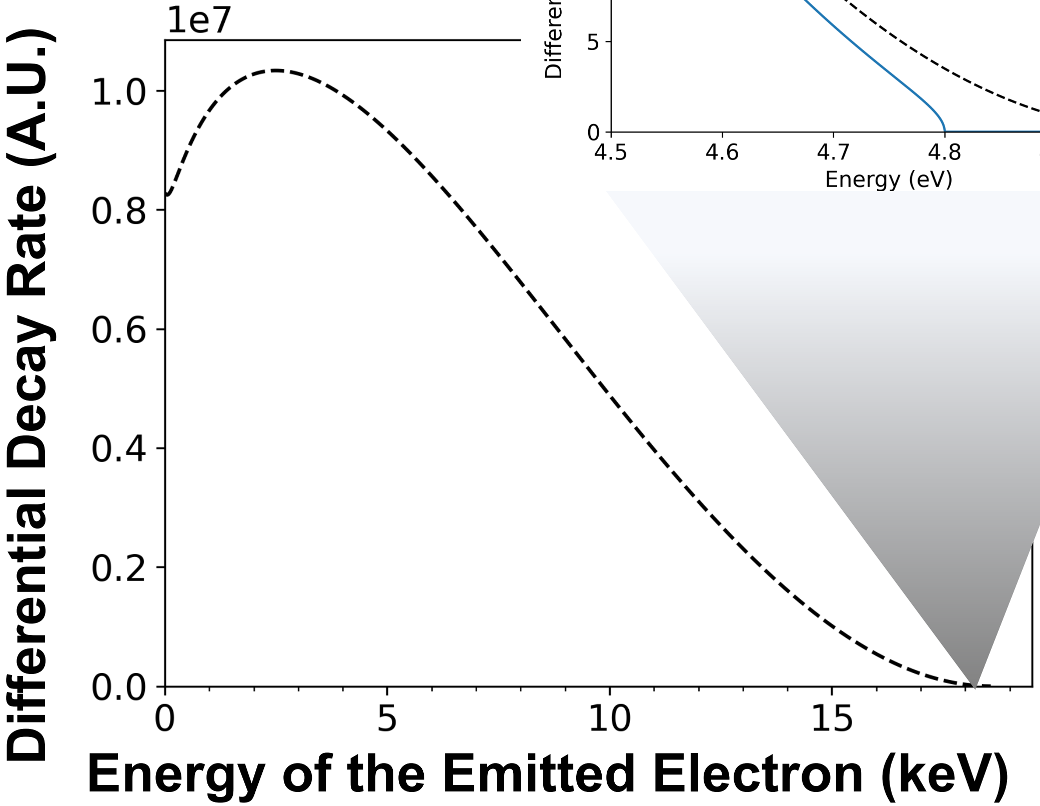
(Anti-)neutrino mass determined from spectral shape distortion near the kinematic **endpoint**:

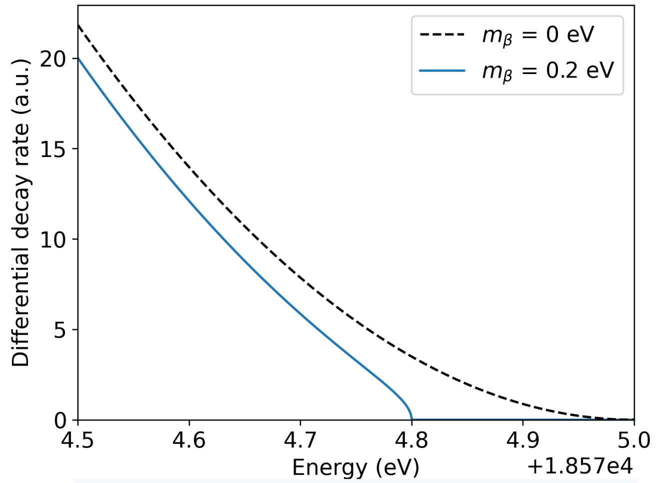
$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

with:

$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$





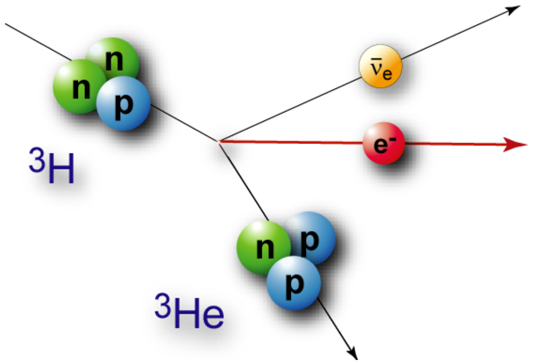


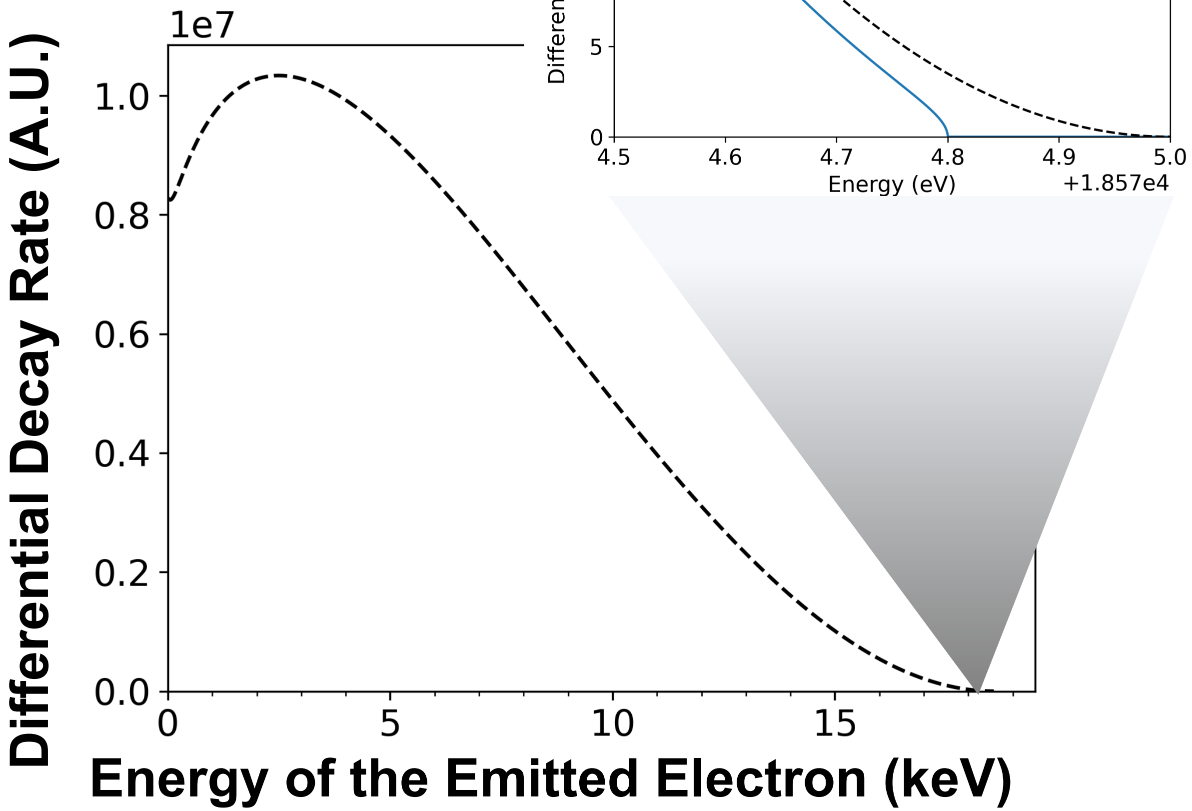
[1] Moisés Medina Restrepo and Edmund G. Myers 131, 243002 (2023)

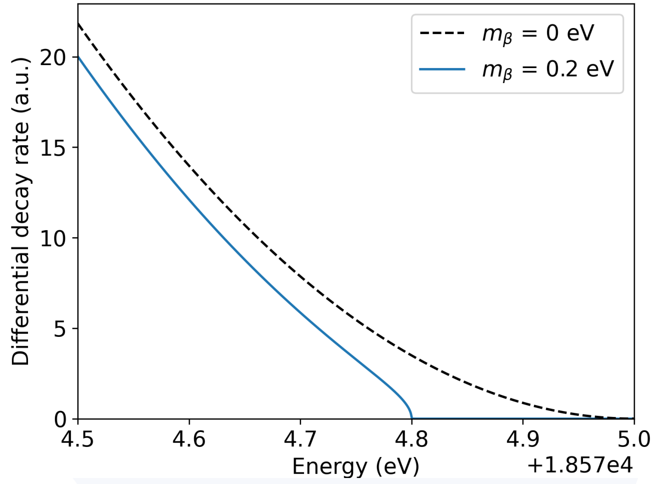
Neutrino Mass from Tritium Decay

Challenges:

- Low event rate near the endpoint → requires a **high luminosity source** and **low background**;
- Distortion is on the scale of the neutrino mass → **good energy resolution** required;
- Precise modelling of the spectral shape and hardware stability over the years.







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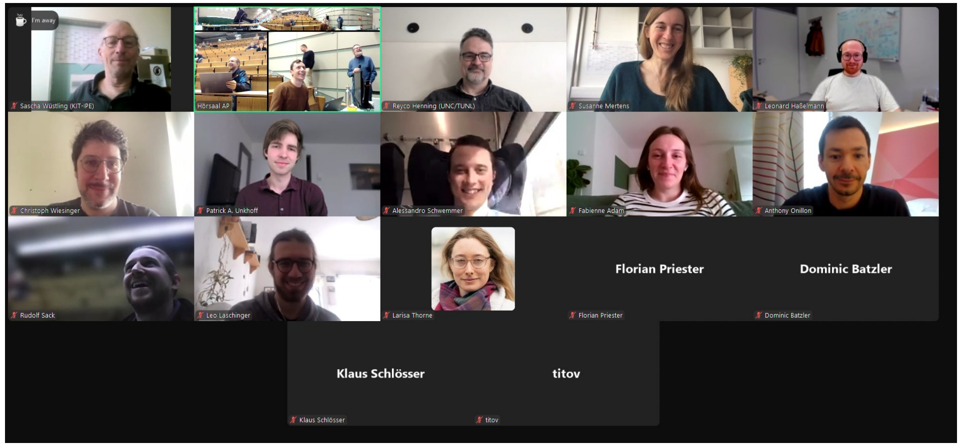
KATRIN Collaboration

49th Collaboration Meeting in Münster (2025)



KIT Karlsruher Institut für Technologie
MIT
BERKELEY LAB
Nuclear Physics Institute
cea
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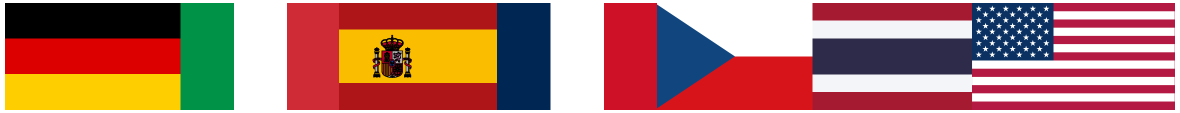
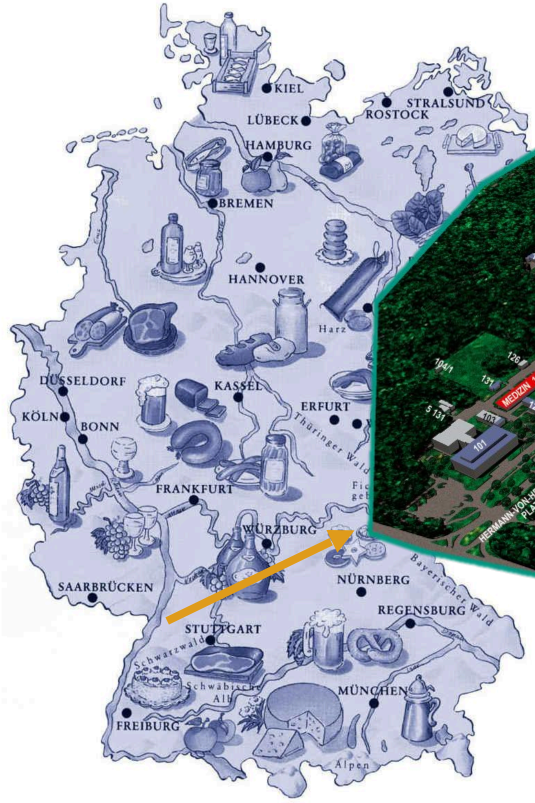
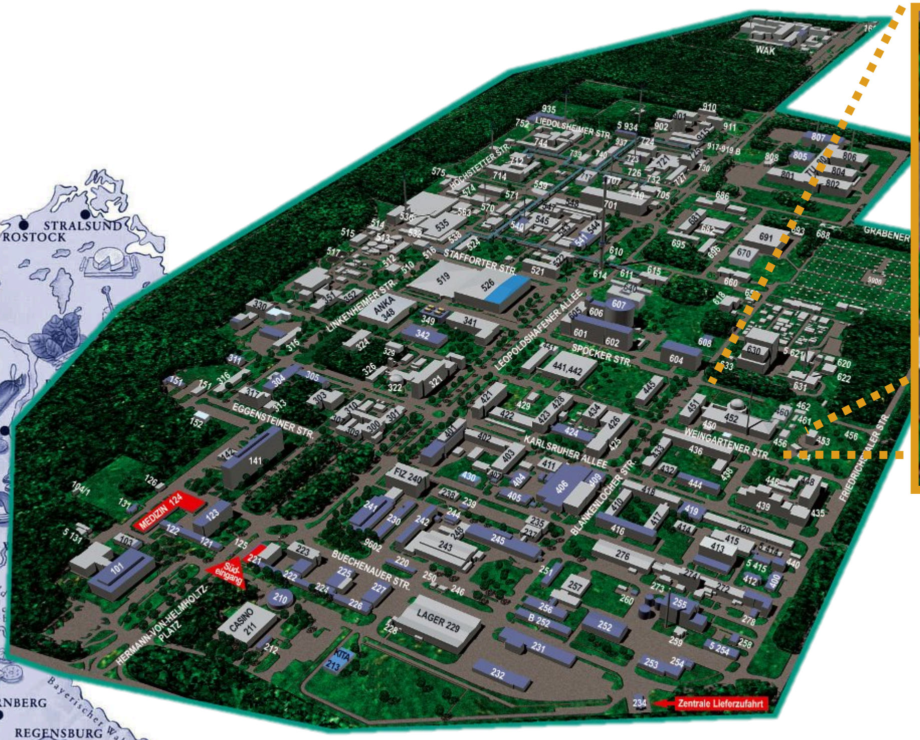
BICOCCA
INFN
POLITECNICO MILANO 1863
TUM
BERGISCHE UNIVERSITÄT WUPPERTAL
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
Max-Planck-Institut für Physik
Chula
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
Bundesministerium für Bildung und Forschung
DFG
Carnegie Mellon University
Universität Münster
UAM Universidad Autónoma de Madrid
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
Czech Republic:
INFN
U.S. DEPARTMENT OF ENERGY
Office of Science
MAX PLANCK GESELLSCHAFT
erc

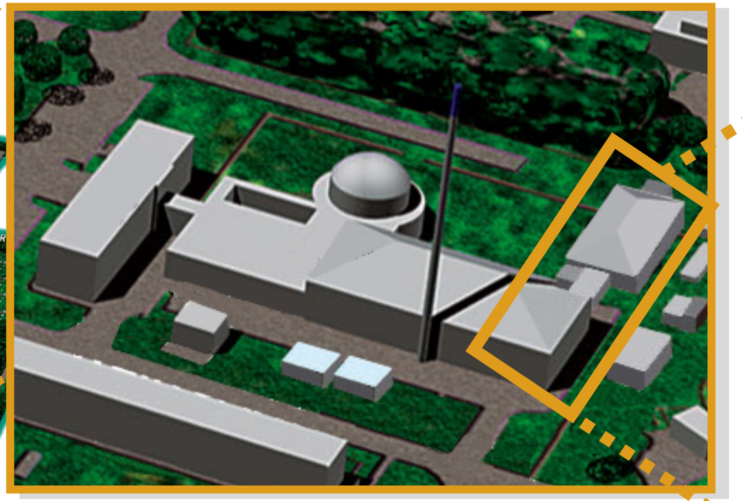
The international KATRIN collaboration:
≈150 people from 24 institutions in 7 countries
(formed in 2001)



KATRIN at Karlsruhe





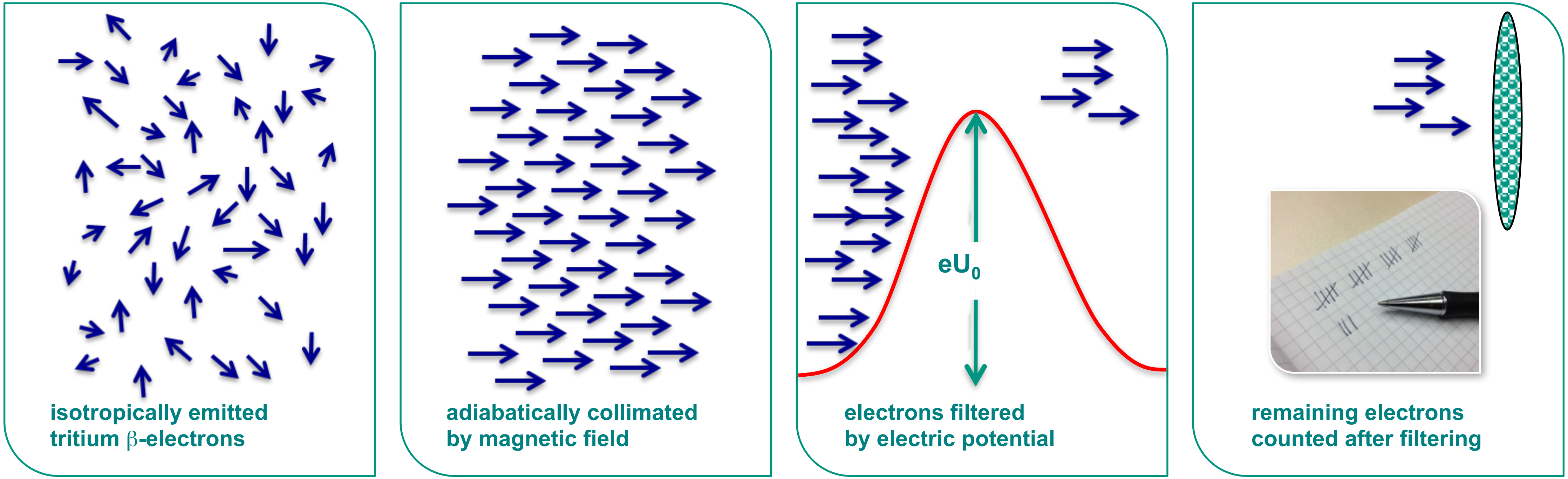


Karlsruhe Institute of Technology Campus North

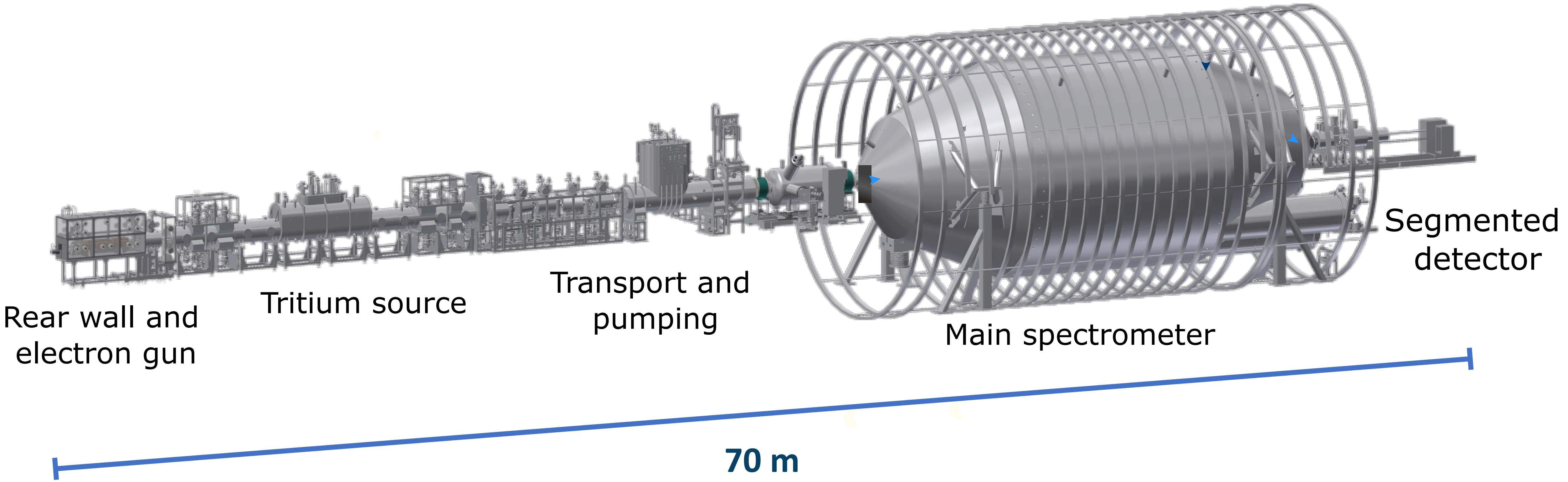
TLK Tritiumlabor Karlsruhe:

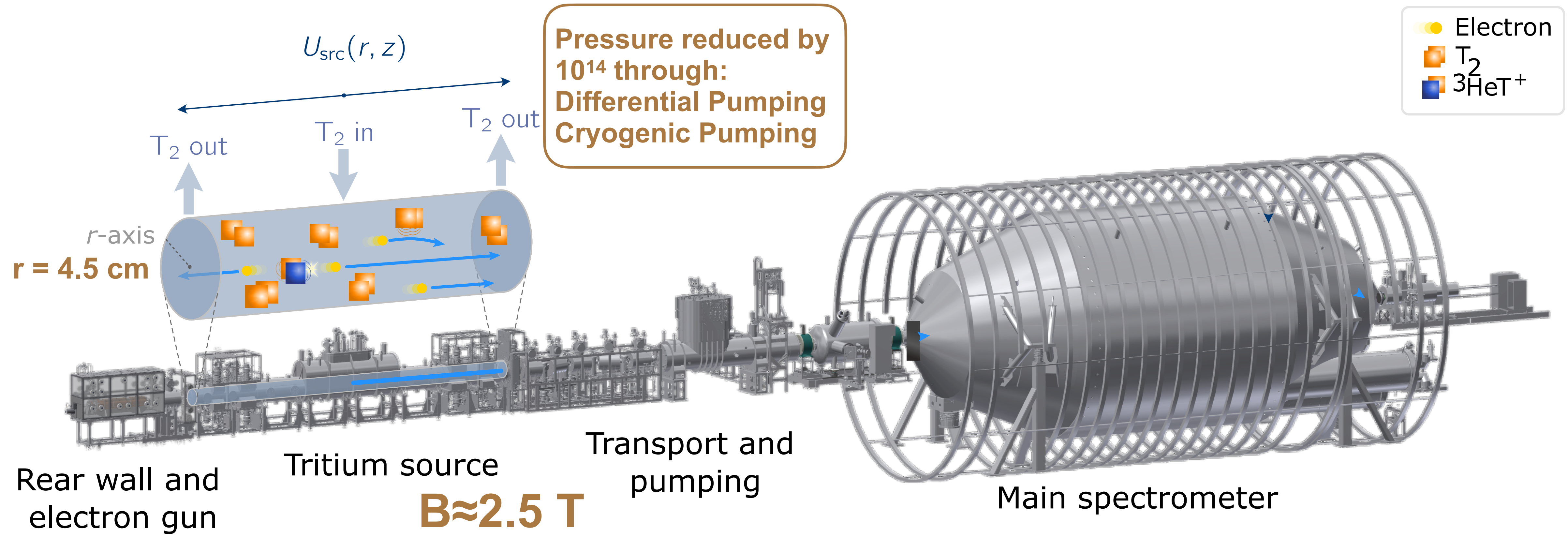
- Commissioned in 1993;
- Licensed for 40 g of Tritium
- Two missions:
    - KATRIN experiment
    - Fusion reactors

Working Principle MAC-E Filter

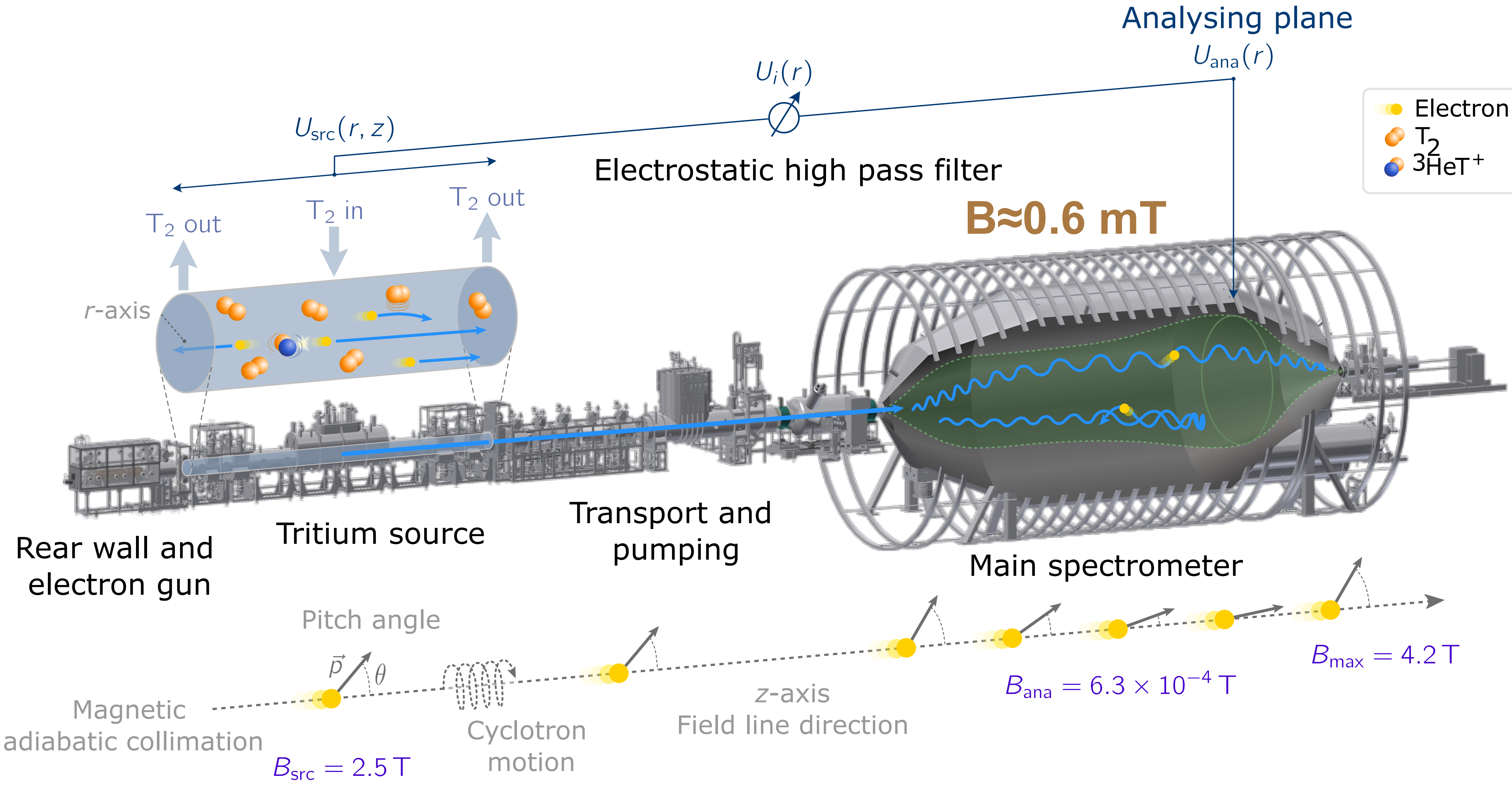


Working Principle



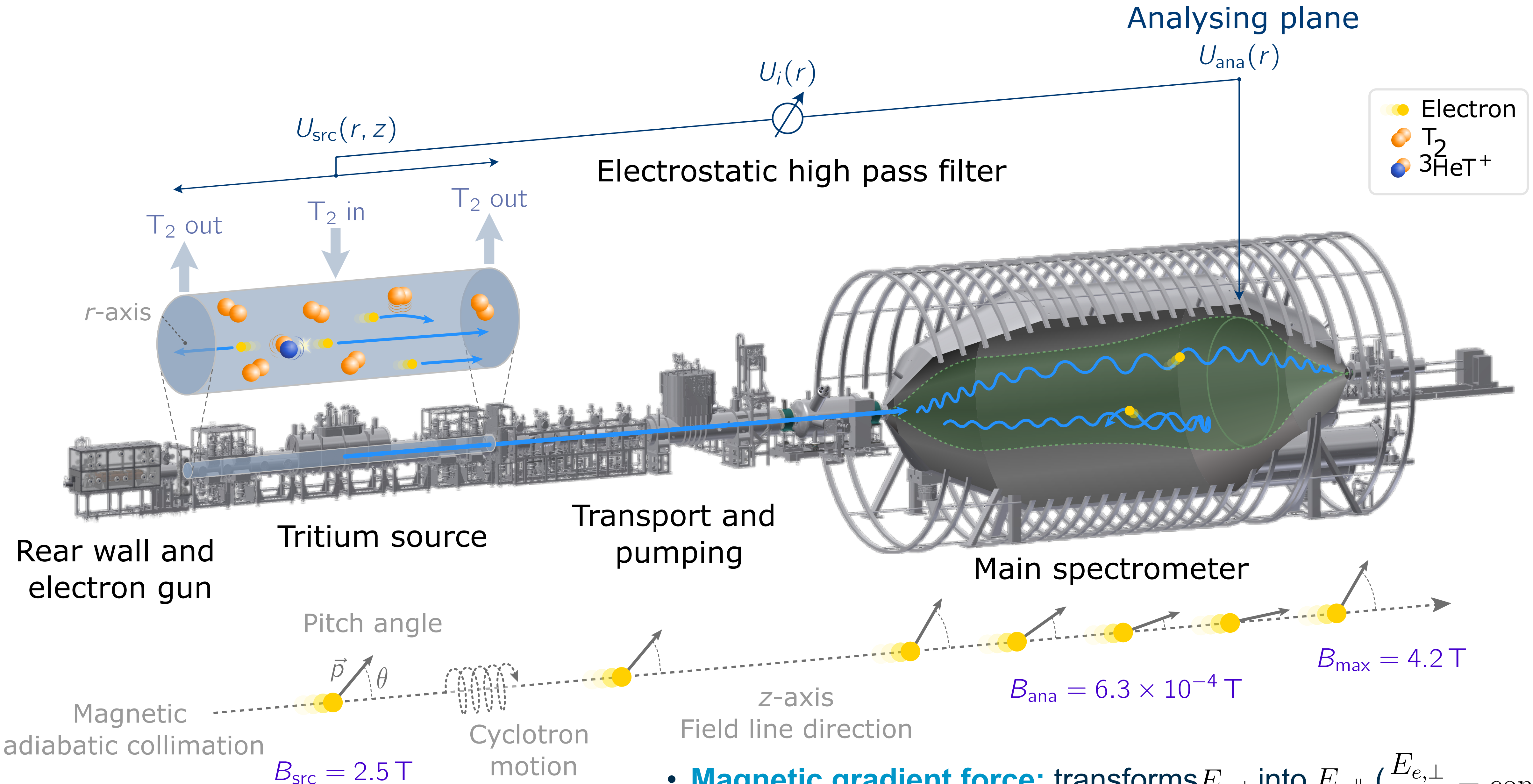


- **High-activity molecular** T_2 source (100 GBq) operated as a windowless gaseous tritium source (WGTS).
- Column density of **ρd = 4.20×10^{21} T_2/m^2** (after KNM1)
- Flow rate of 40 g T_2/day with an isotropic purity >95%.

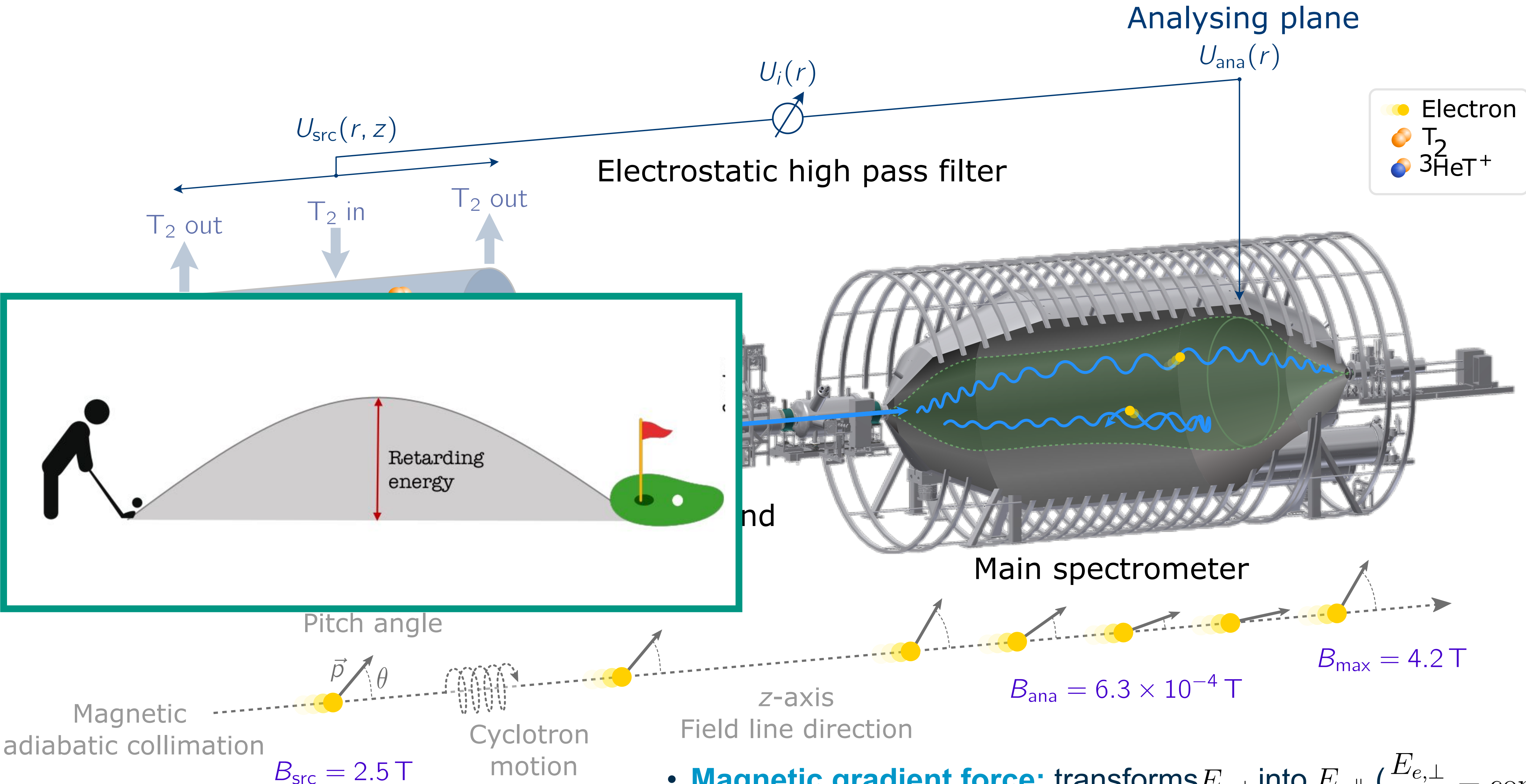


Main spectrometer: high voltage (~18 kV) and ultra-low vacuum pressure **<10^{-11} mbar**

Based on the Magnetic Adiabatic Collimation with Electrostatic (MAC-E) Filter principle.



- **Magnetic gradient force:** transforms $E_{e,\perp}$ into $E_{e,\parallel}$ ($\frac{E_{e,\perp}}{B} = \text{const.}$)
- **Electrostatic field:** only electrons with $E_e \sim E_{e,\parallel} > qU$ go through



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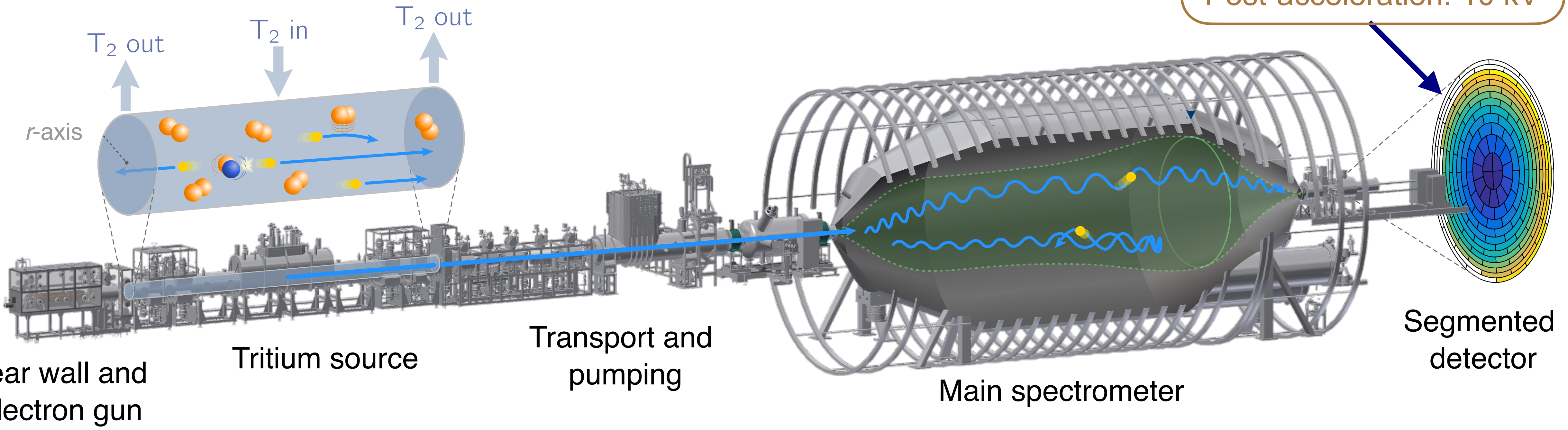
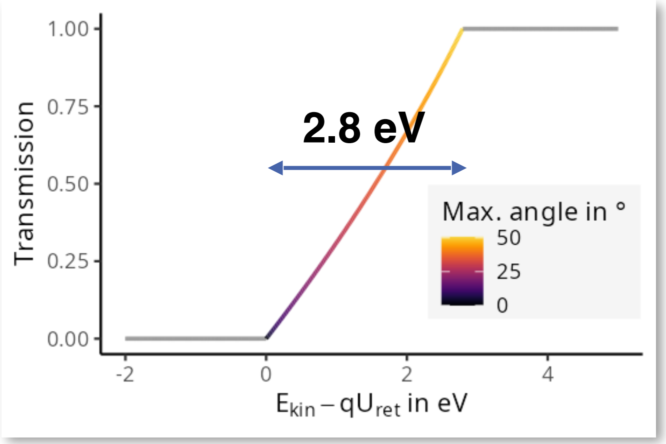
Focal Plane Detector:
148 pixels
Dartboard layout
Post-acceleration: 10 kV



Very High Energy Resolution: $\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \sim 1\text{eV}$

Very High Angular Acceptance: $\theta_{\text{max}} = 50^\circ$




St. Hildegard
Müller

RIGA MAINZ
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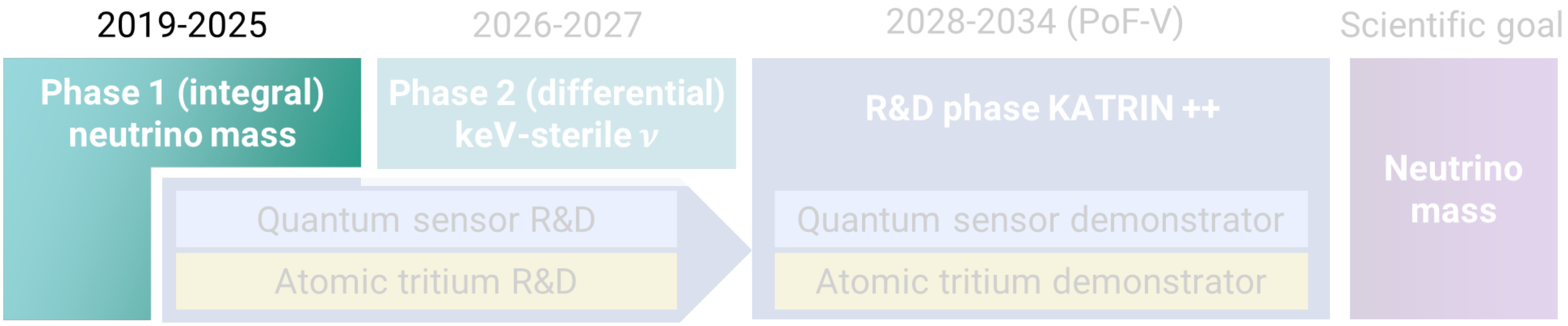
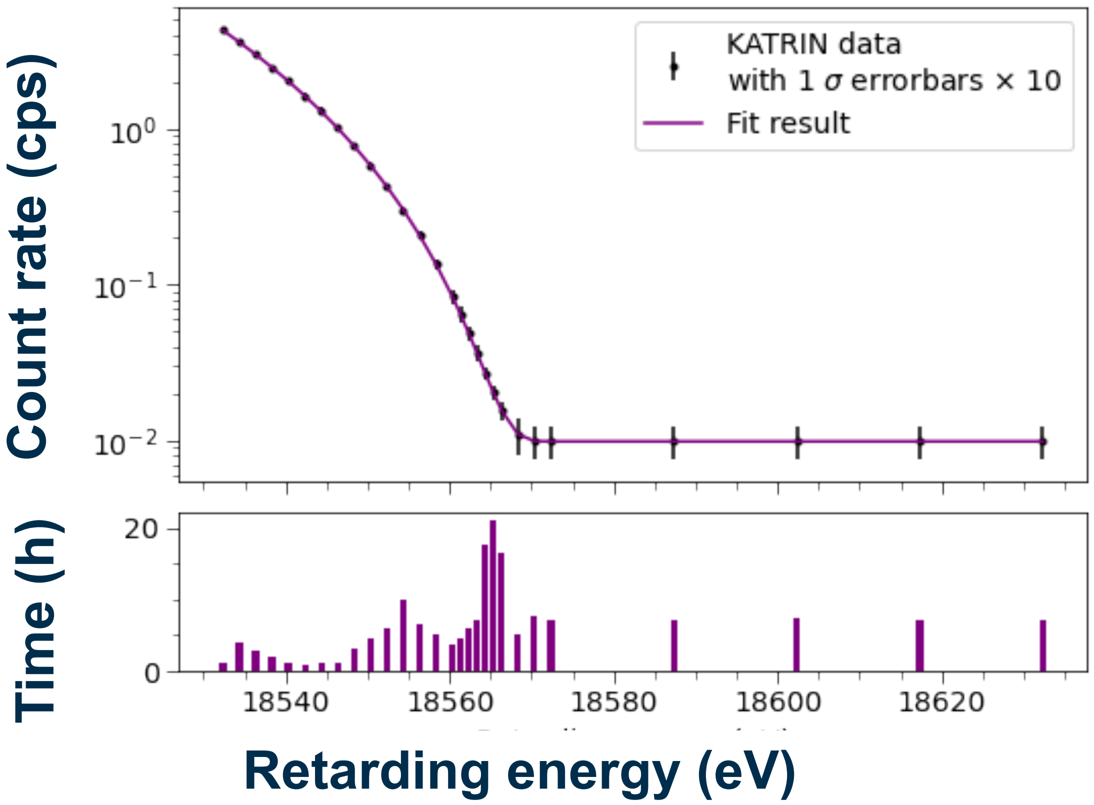
KATRIN Timeline



Modeling

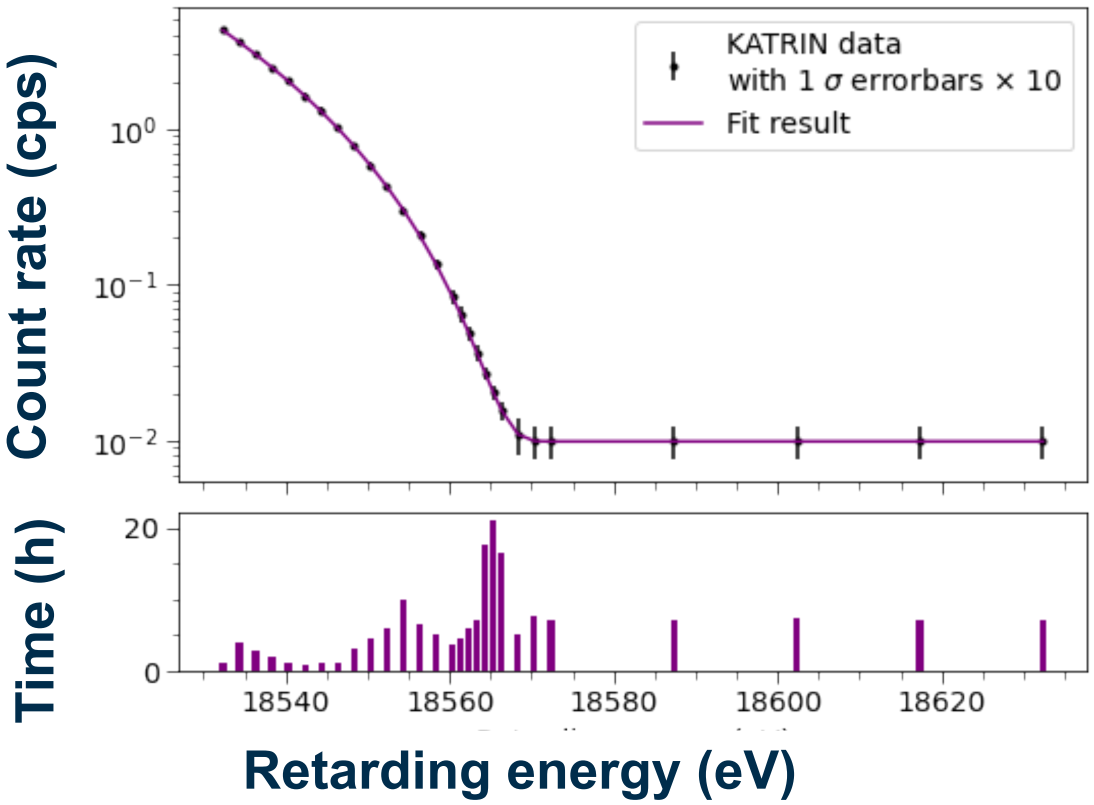
Measured individual β-spectrum



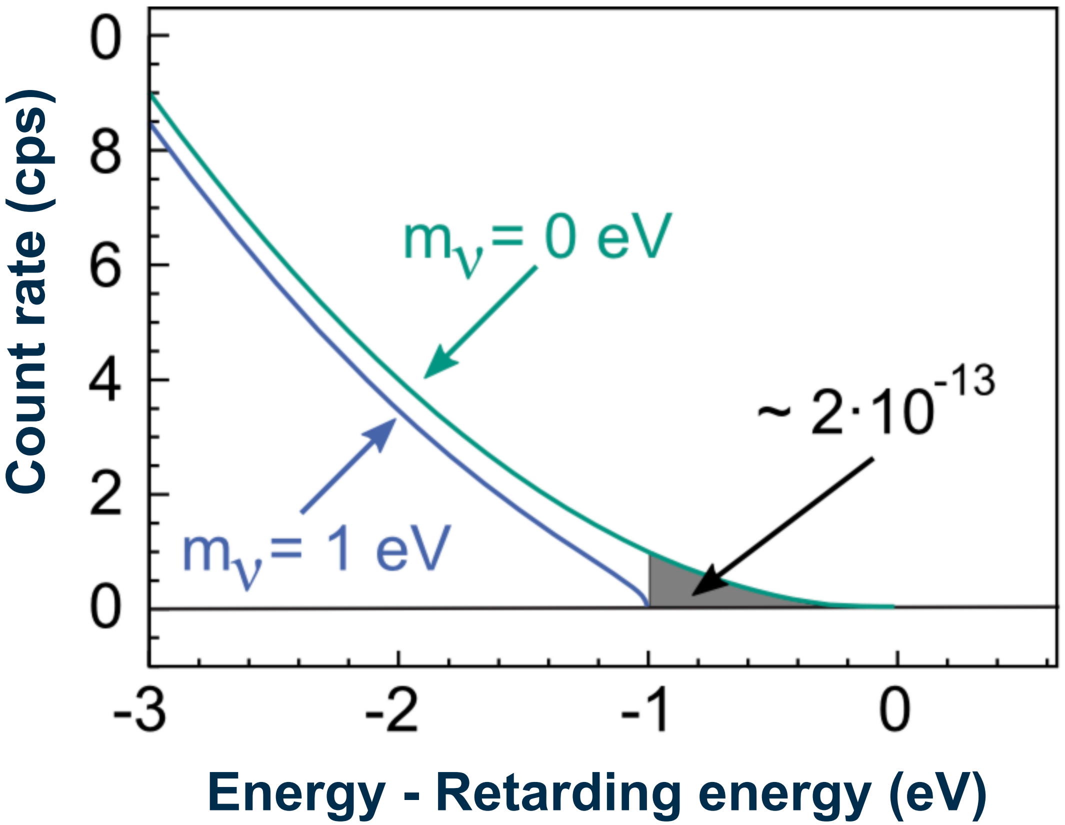
- 2-3 hour scans, about 100 scans per campaign
- Stack data points with **identical** measurement conditions.
- Analysis window: **[E_0 - 40 eV, E_0 + 135 eV]**.
  - We have data down to **E_0 - 350 eV**

Modeling

Measured individual β-spectrum



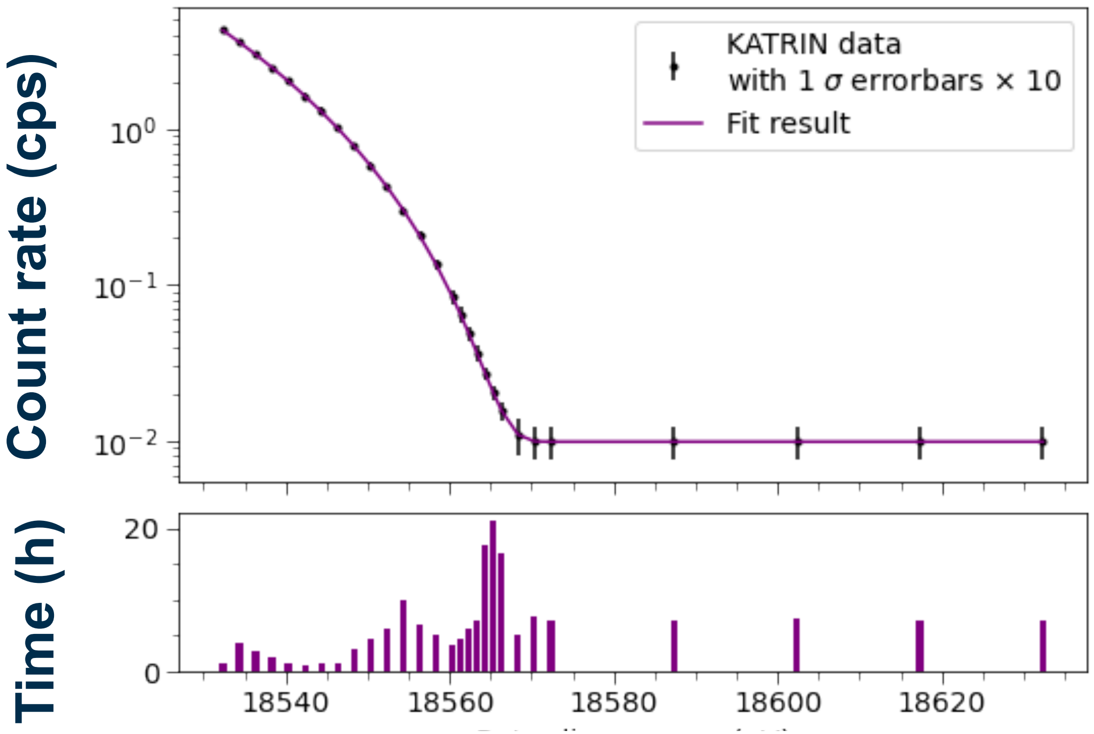
Theoretical β-spectrum



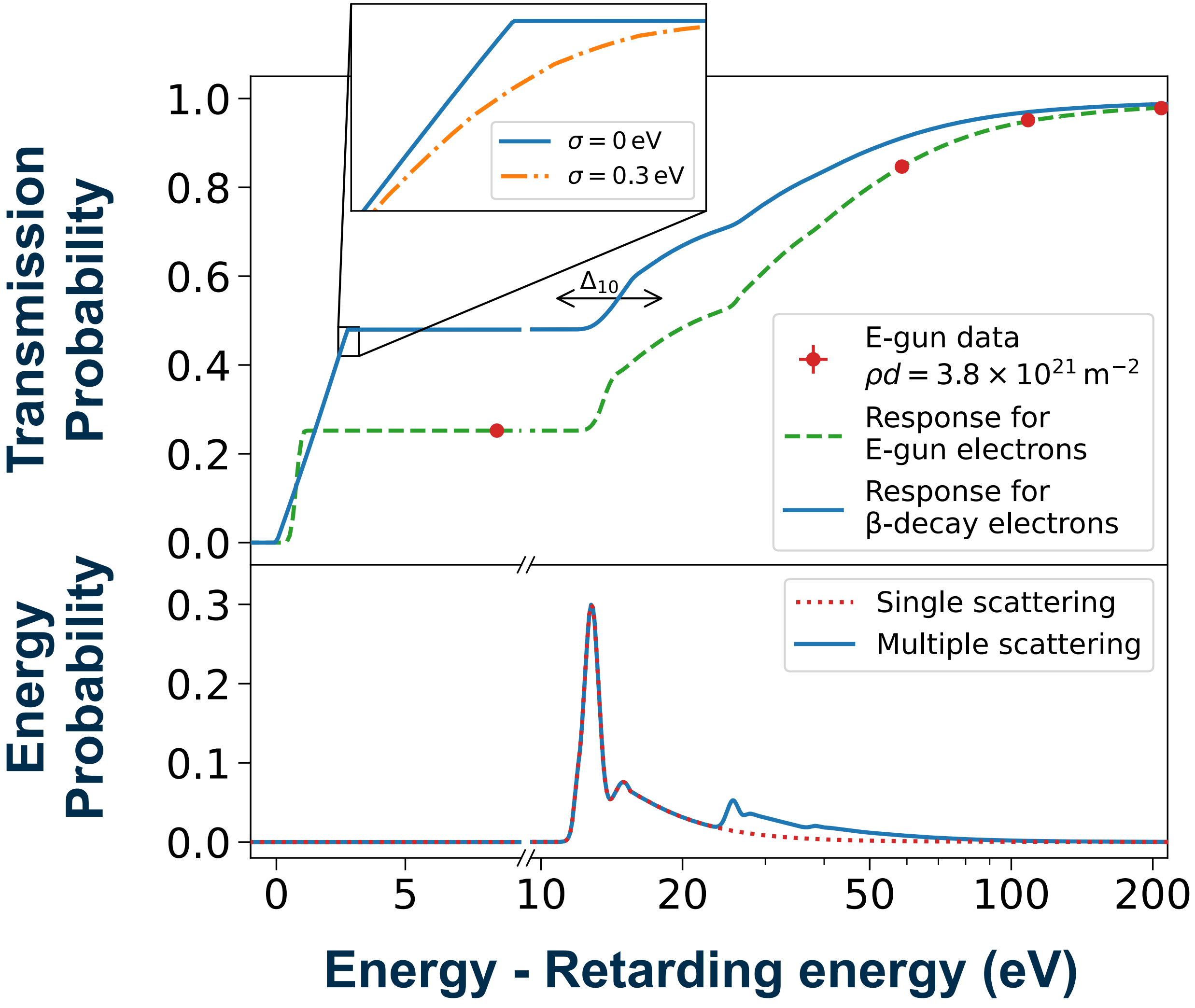
Fermi theory with radiative corrections and molecular excitations

Modeling

Measured individual β-spectrum

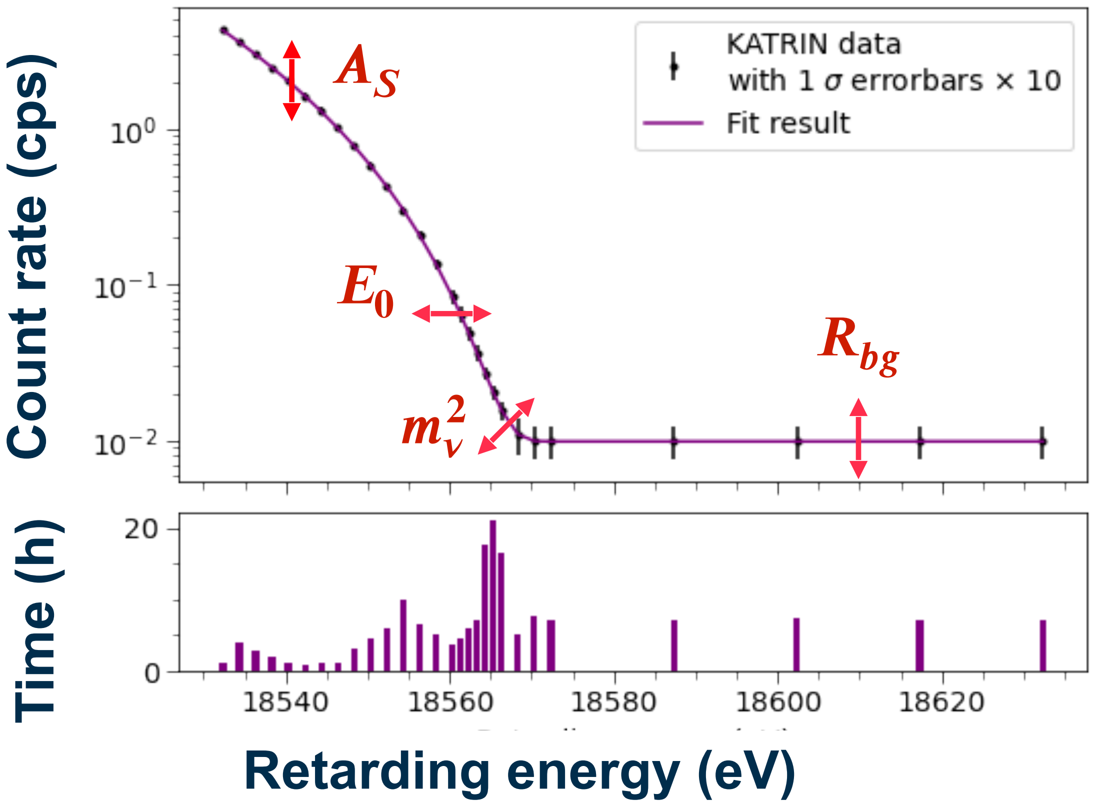


Experimental input



Spectrometer transmission and energy losses in the source
Obtained with electron gun and ^{83m}Kr calibrations

Modeling



$$R(U) = A_s \cdot N_T \int_{qU}^{E_0} \frac{d\Gamma}{dE}(E, m_\nu^2) \cdot f(E, U)\mathrm{d}E + R_{bg}$$

4 free fit parameters: A_S, E_0, m_ν^2, R_{bg}

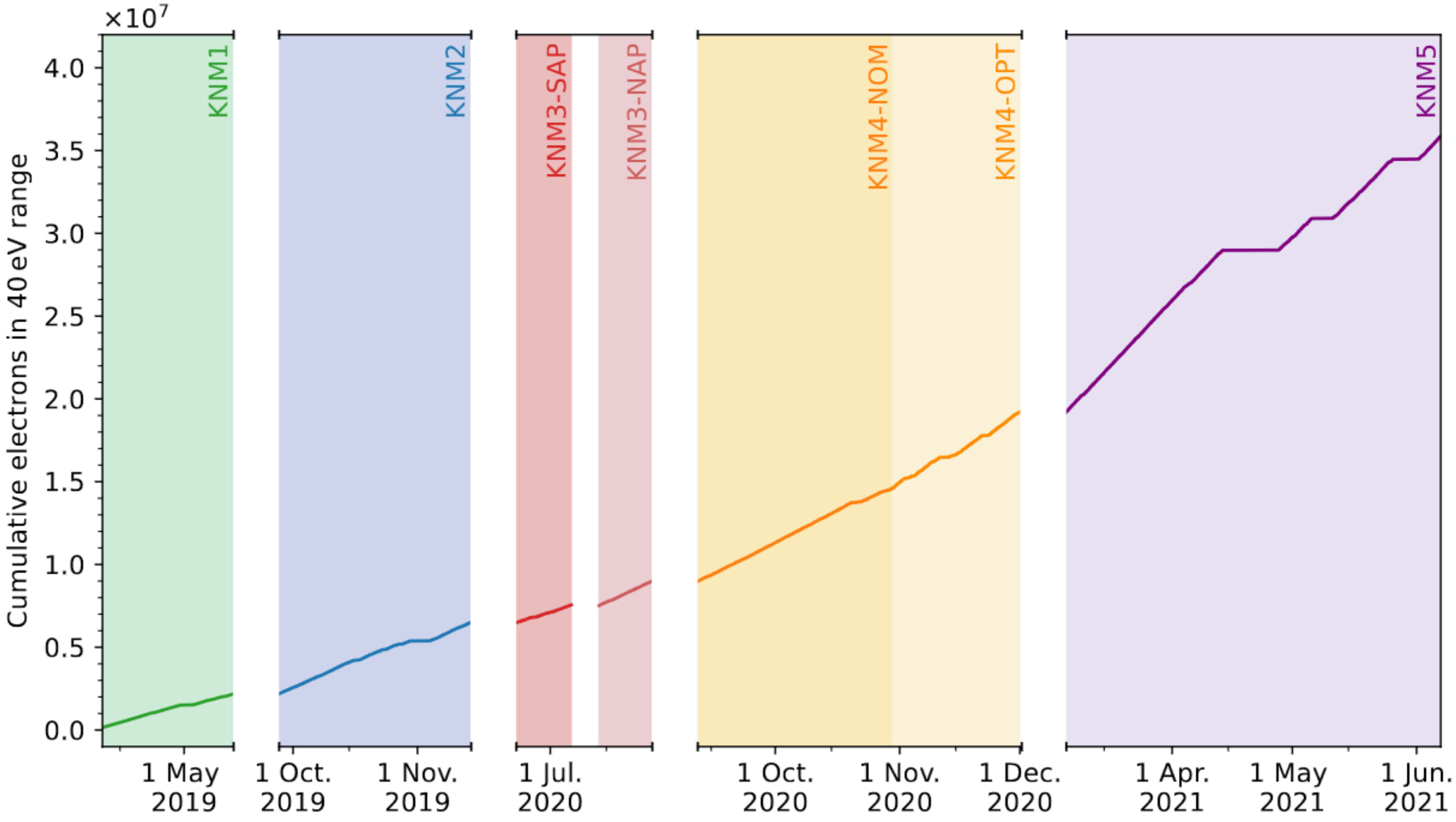
KATRIN Data Acquisition for the 2024 Result

Data Analysed: KNM1-KNM5

- **259** measurement days
- **1757** β-scans
- ~36 million counts

Previous Results (90% C.L):

- **2019: m_ν < 1.1 eV** (KNM1)
- **2022: m_ν < 0.8 eV** (KNM1-2)



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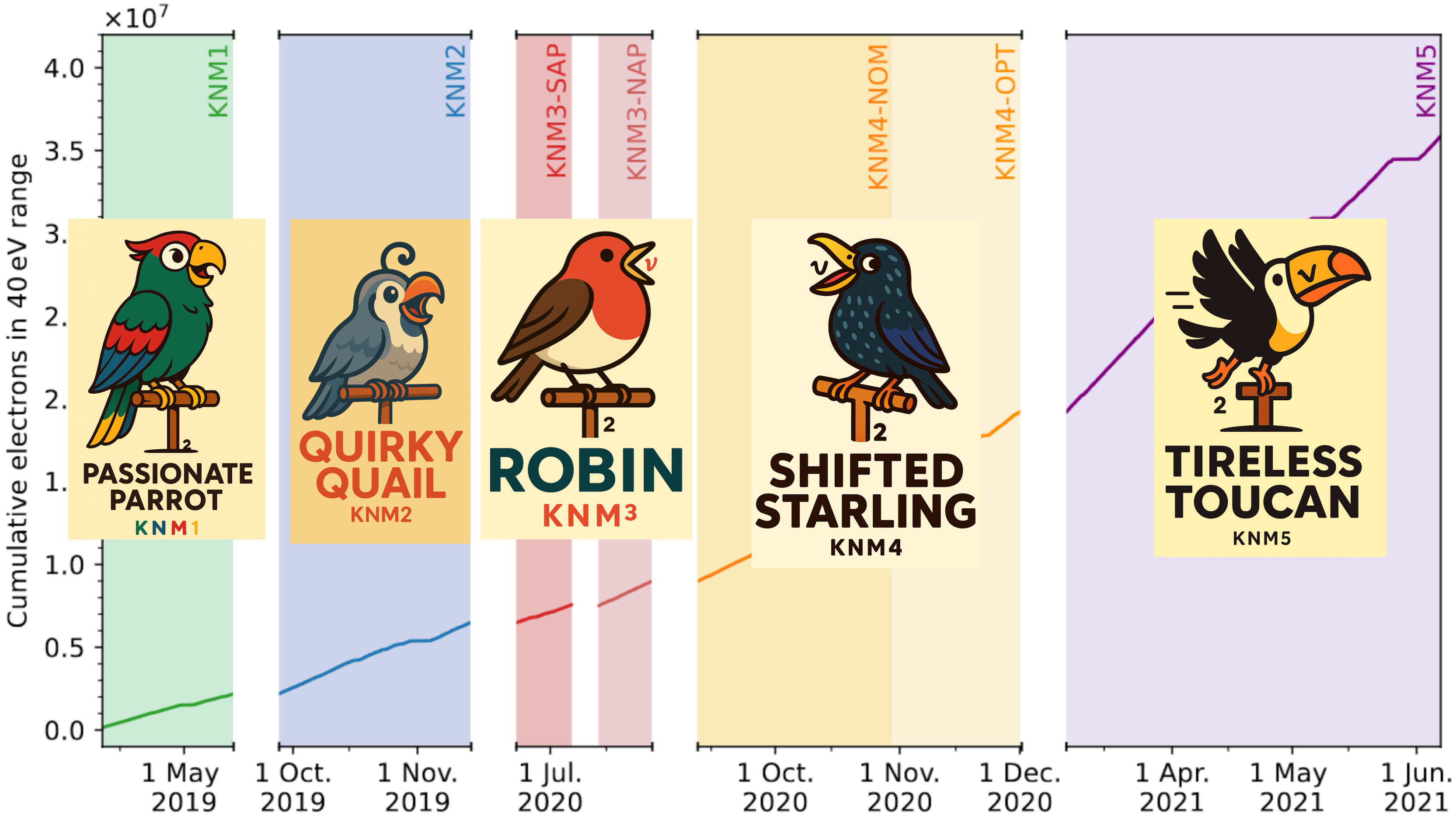
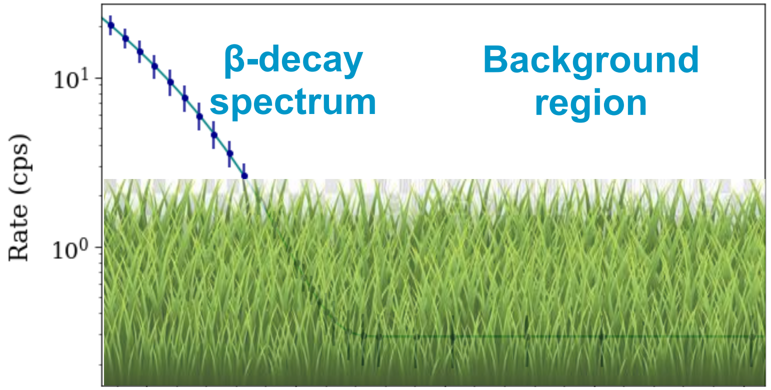


KATRIN Backgrounds

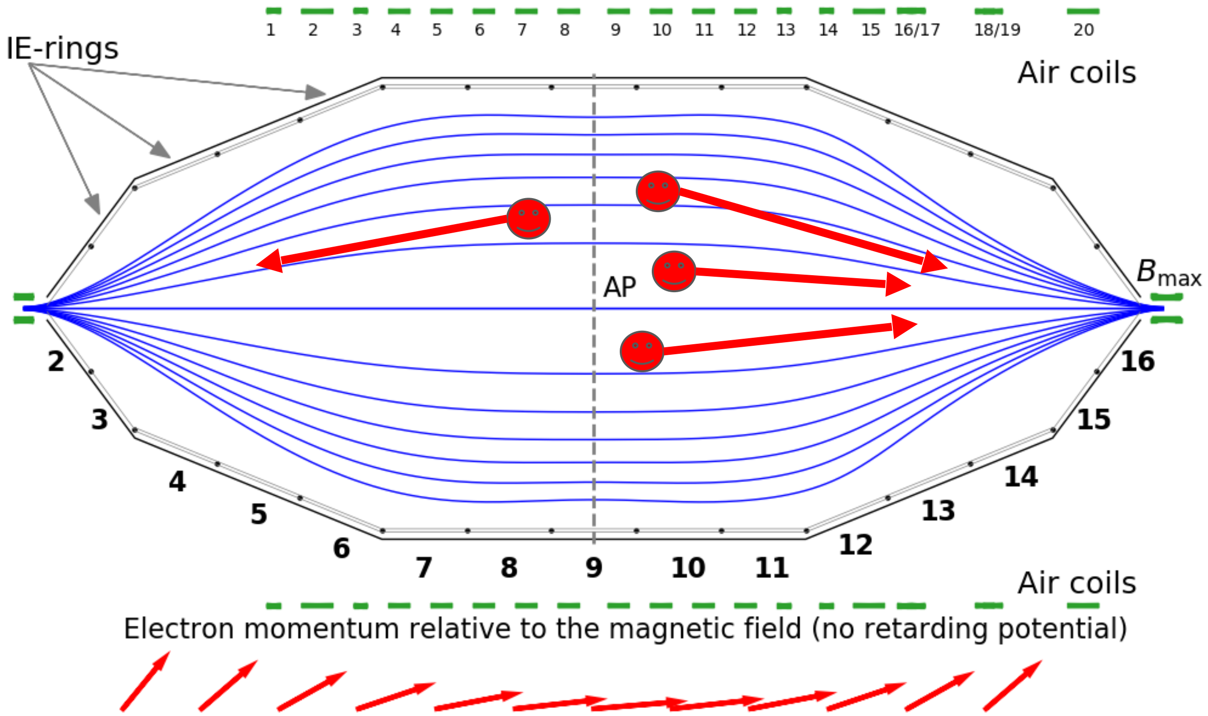
- Most sensitive region to the neutrino mass with signal/background ~ 1
- High background hides the shape distortion of spectrum by m_ν



Katrin Technical Design: **10 mcps**

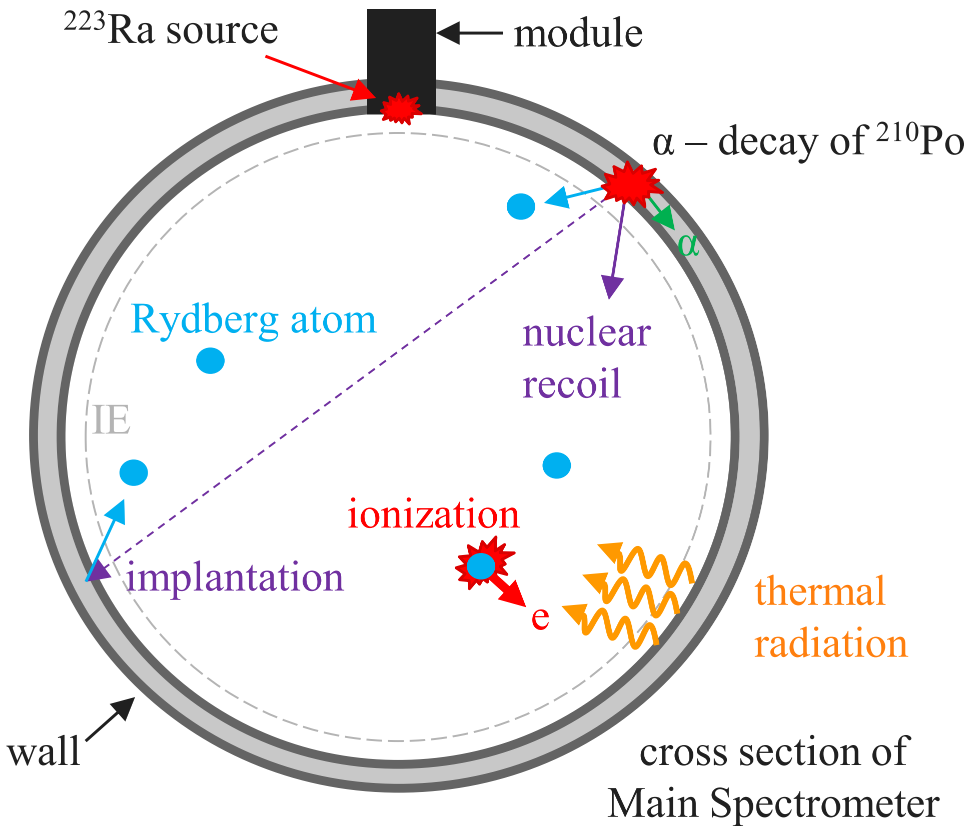
KNM 1: **293 mcps**

No significant background from **μ^+/μ^-**, external **γ**'s, radon, penning discharges.



Backgrounds originate from low-energy electrons generated beyond the analyzing plane (plane where the potential is highest).

KATRIN Backgrounds



- Spectrometer was exposed to air during the installation of the inner electrodes - platting of ^{210}Pb ($t_{1/2}$ = 22.23 a) in the walls
- Decay of ^{210}Pb ($t_{1/2}$ = 22.23 a) in the vessel wall
- Sputtering of atoms excited in Rydberg states (n>20) from the wall due to α-decay of ^{210}Po
    - Ionized in the volume by the blackbody radiation or autoionisation → very low energy electrons of sub-eV range
- Electron Background **distributed uniformly** in the volume

F.M. Fränkle, et al., Astropart. Phys. 138 (2022) 102686

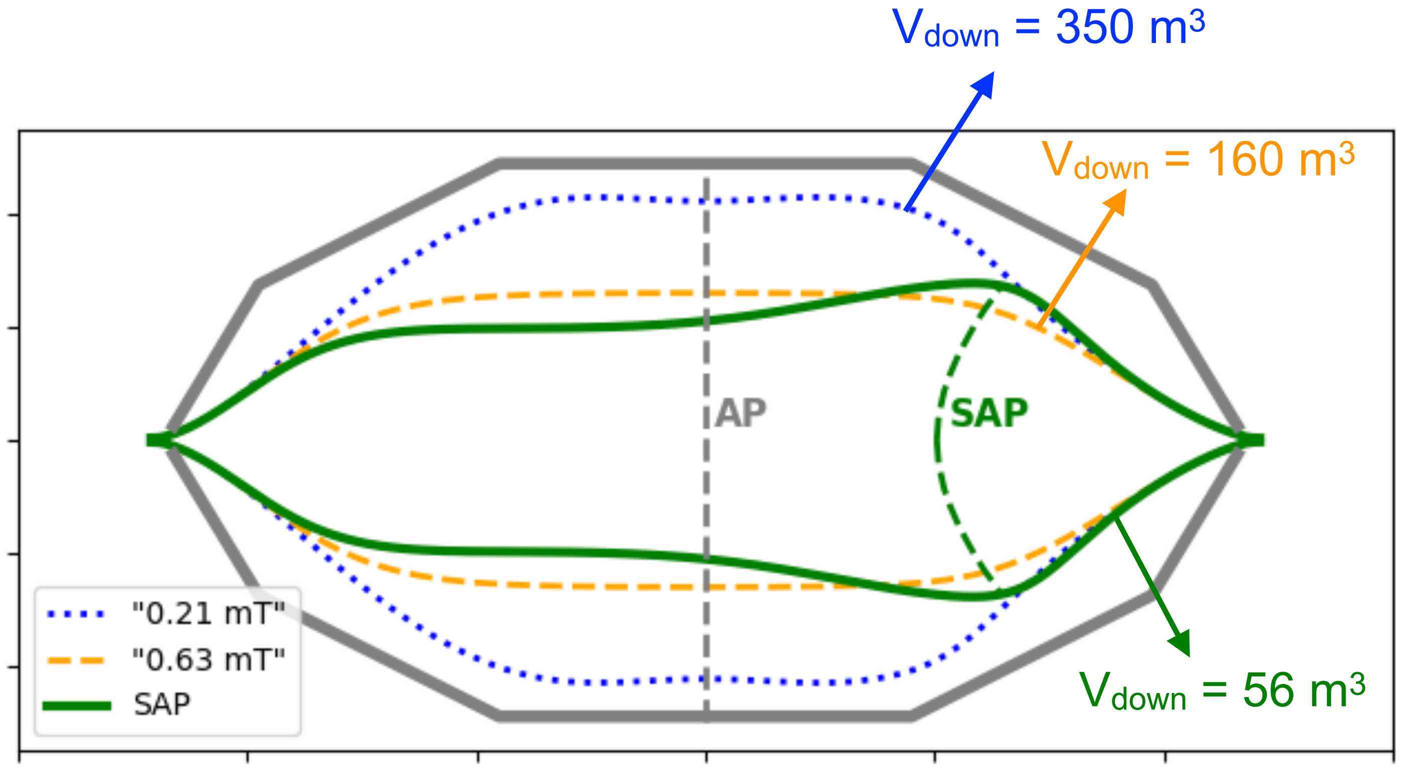
Shifted Analysis Configuration

Shifted analysis configuration (from KNM3, 2020 onwards, [1]):

- Idea: **minimizing the volume** between the AP and detector
- **Same or better** energy resolution.
- **Reduced background by a factor of 2**

But, with trade-offs:

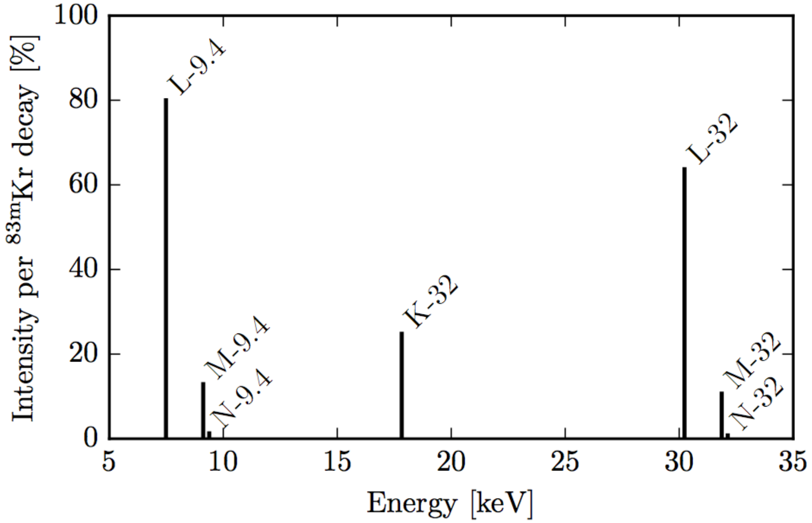
- Smaller source volume mapped onto detector;
- Inhomogeneous EM-fields:
  - Data segmented is 14 bins;
  - Simulations not reliable - field Calibration required.

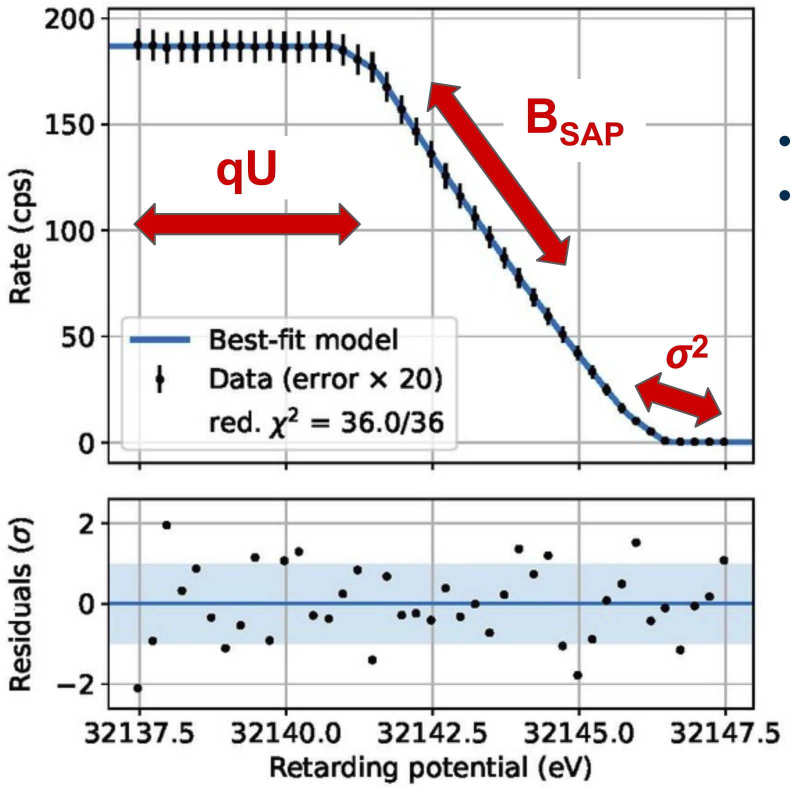


[1] A.Lokhov et al. Eur. Phys. J. C 82:258 (2022)
[2] A. Marsteller et al. JINST 17 P12010 (2022)

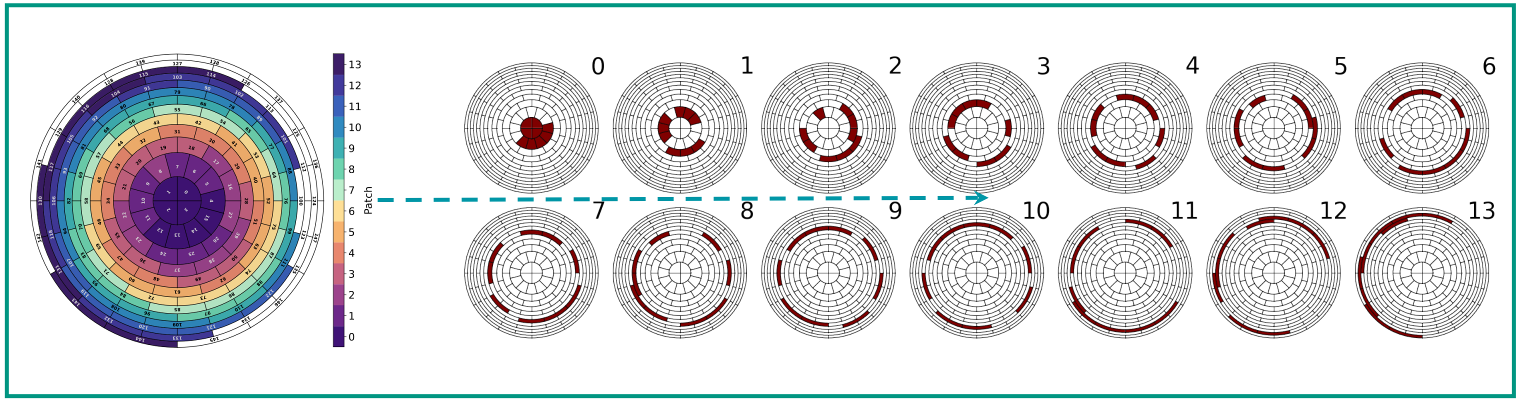
Calibration of the EM Fields

- In situ calibration using ^{83m}Kr
  - $N_{2,3}$-32 lines (E = 32.1 keV, Γ – negligible) - **mono-energetic source**.

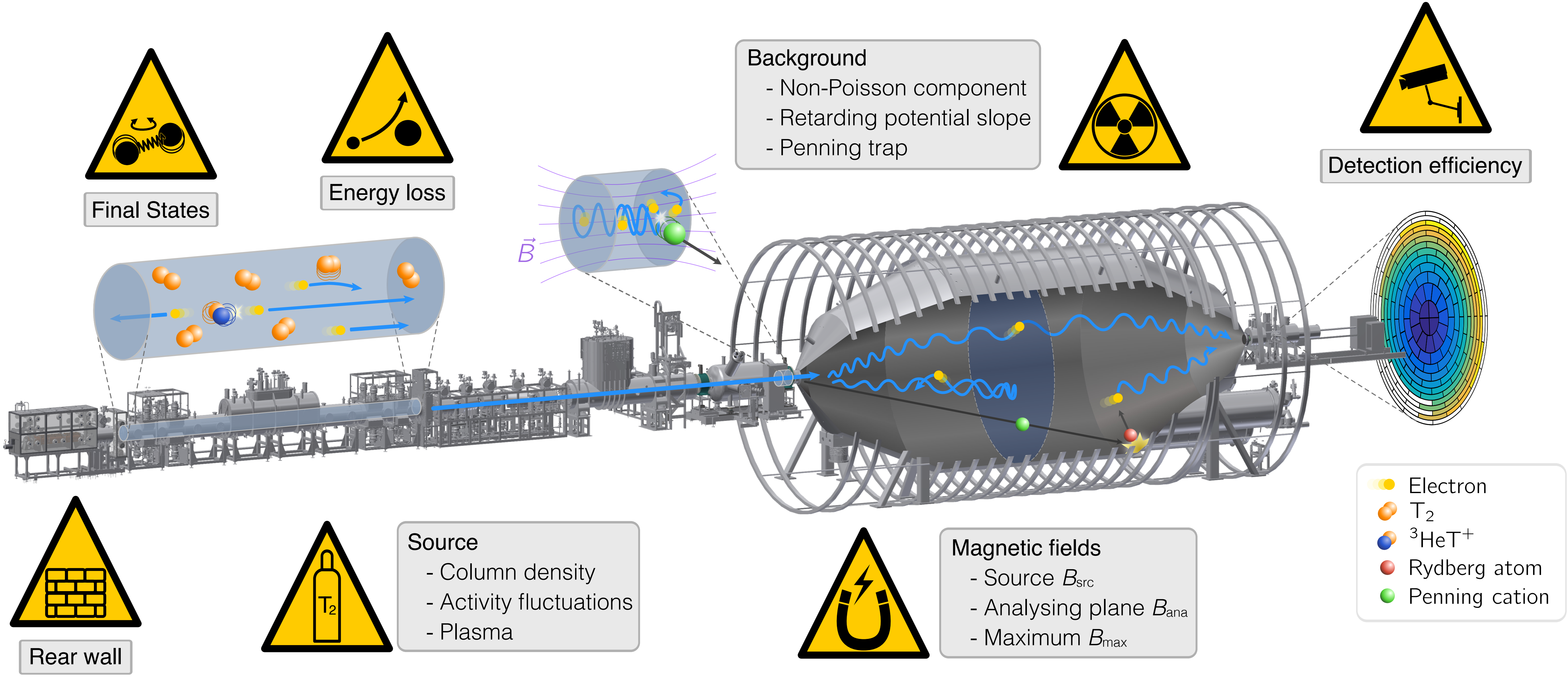




- Transmission parameters for each detector pixel
- Combine pixels with similar parameters into **"patches"**
  - More segmented data, x 14 to nominal configuration → challenge for the analysis



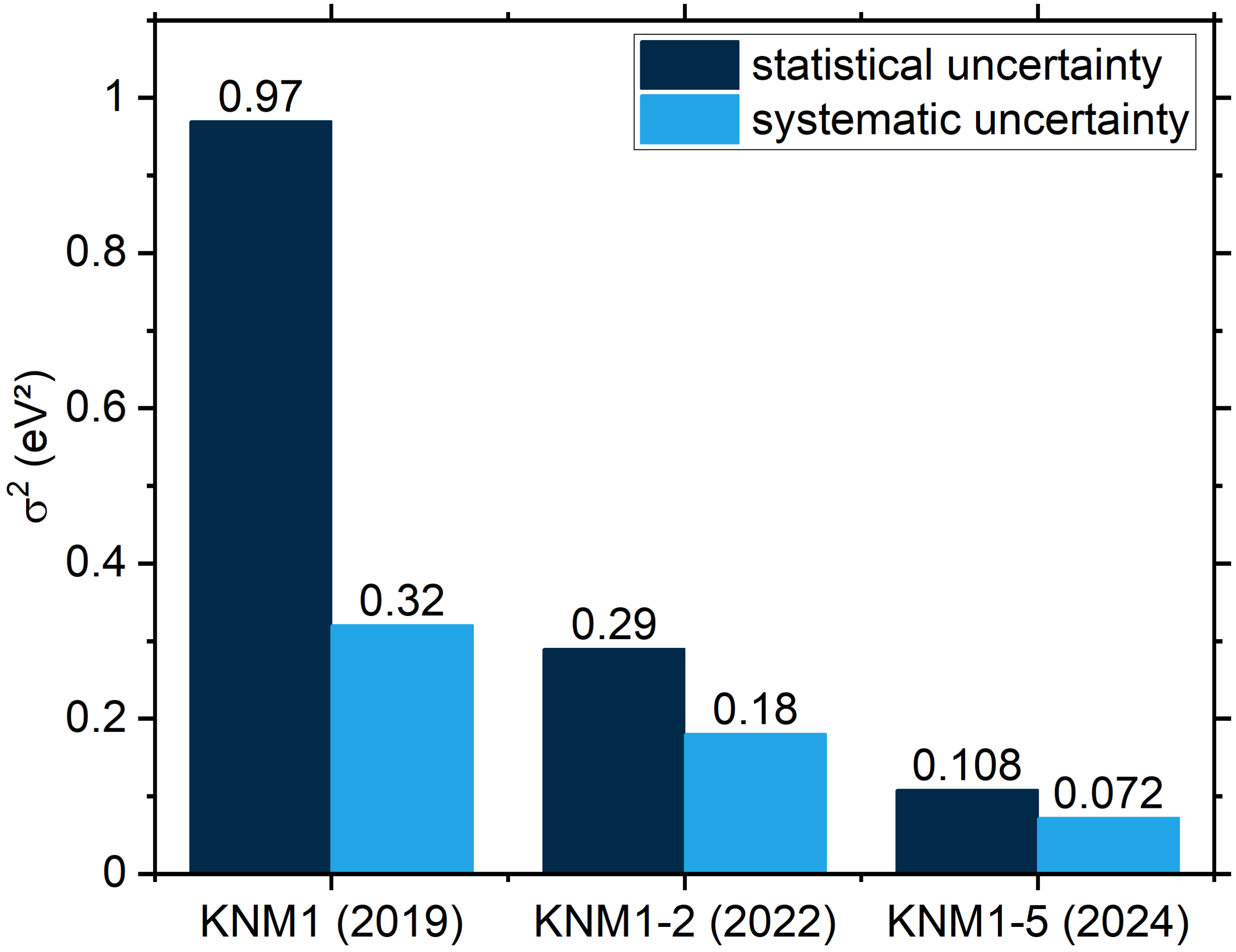
Systematic Uncertainties



Systematic Uncertainties

- **Statistical uncertainties** dominate;
- Significant reduction of background-related systematics in KNM1-5
  - Better control over source scattering
  - Removal of the penning trap [1]
  - **Reduction** of the molecular final states uncertainties [2]
    - Reassessment of theoretical uncertainty estimation: *S. Schneidewind et al. Our. Phys. J. C 84, 494 (2024)*

Improvement of statistics and systematics



[1] M. Aker et al. Eur. Phys. J. C 80: 821 (2020)

[2] Reassessment of theoretical uncertainty estimation: *S. Schneidewind et al. Our. Phys. J. C 84, 494 (2024)*

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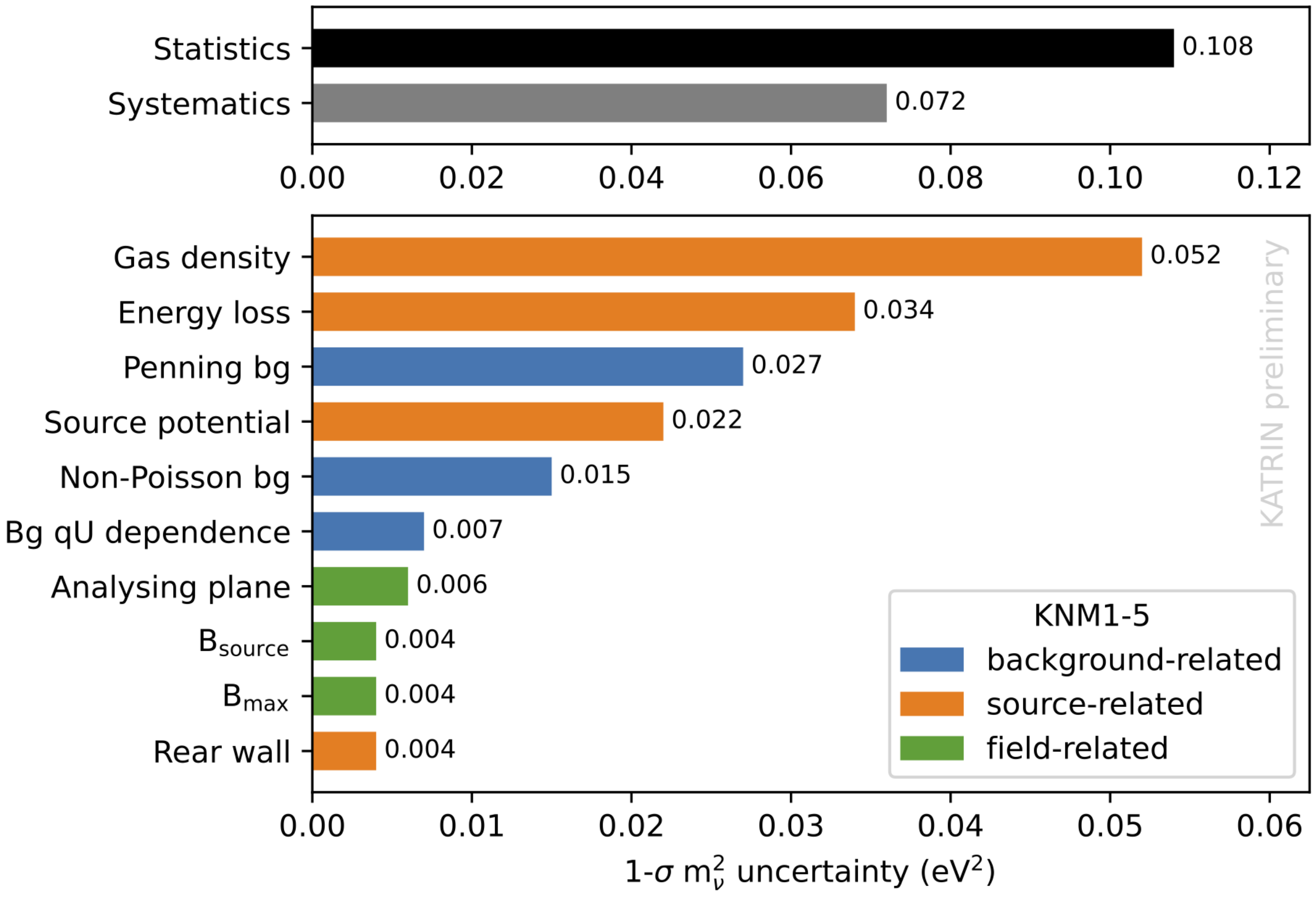

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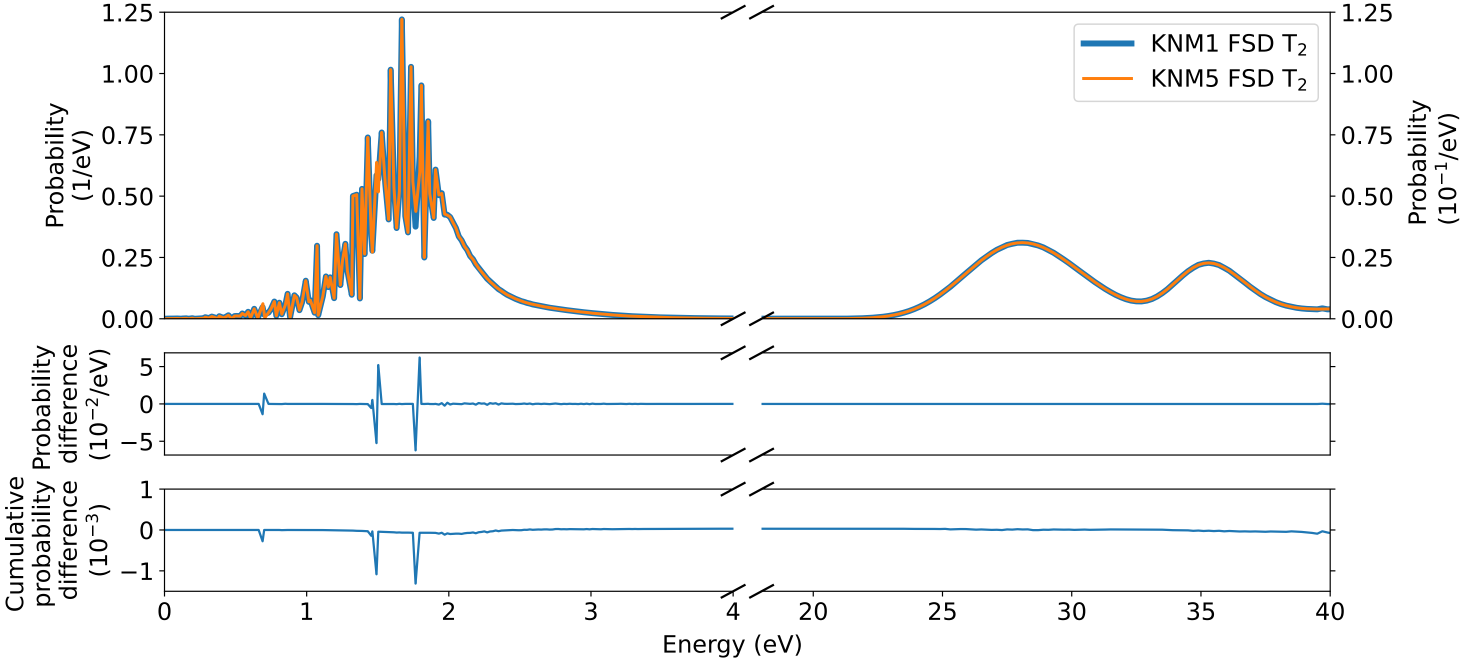

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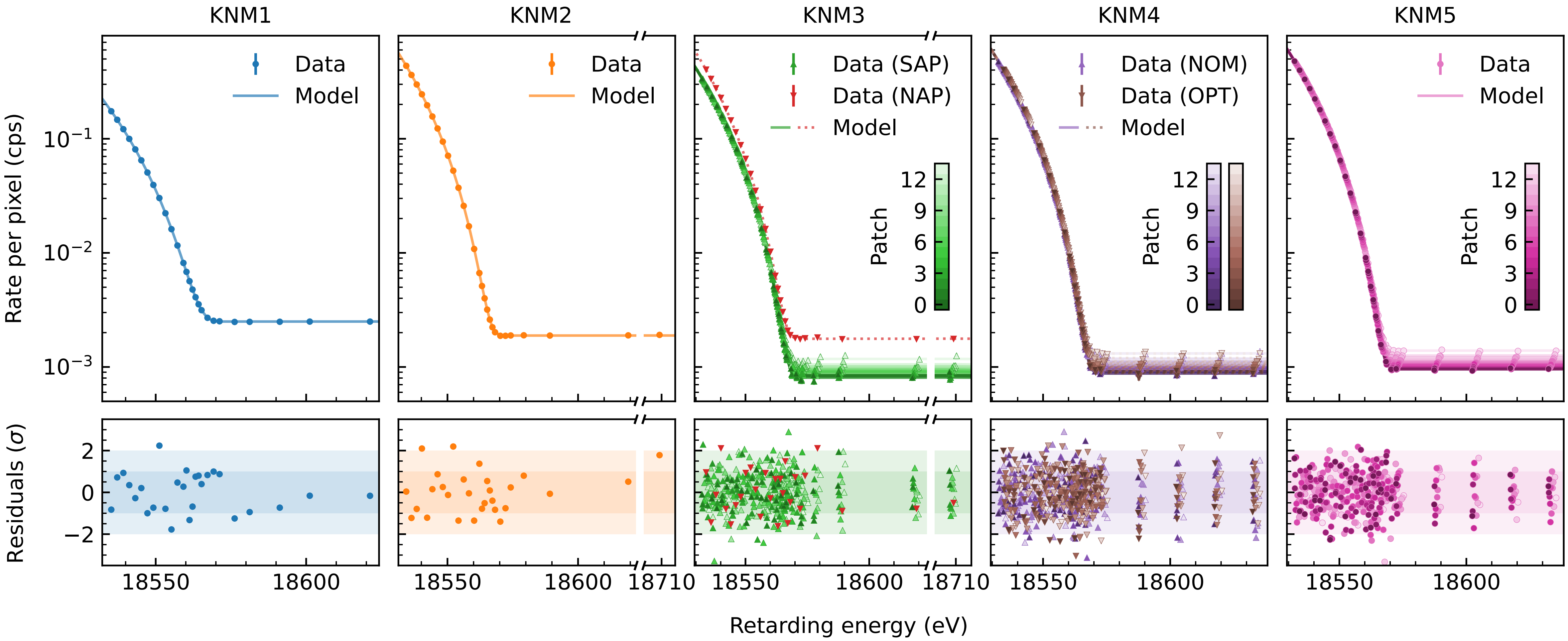
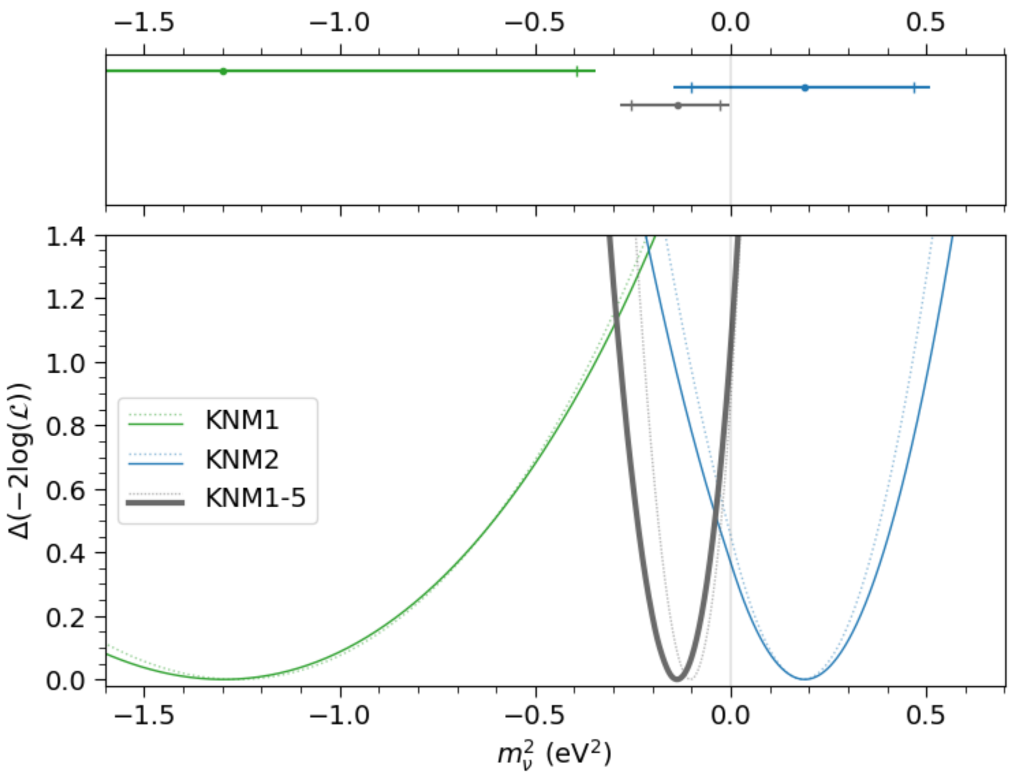


Simultaneous maximum likelihood fit with common m_ν^2 parameter - **p-value=0.84**.

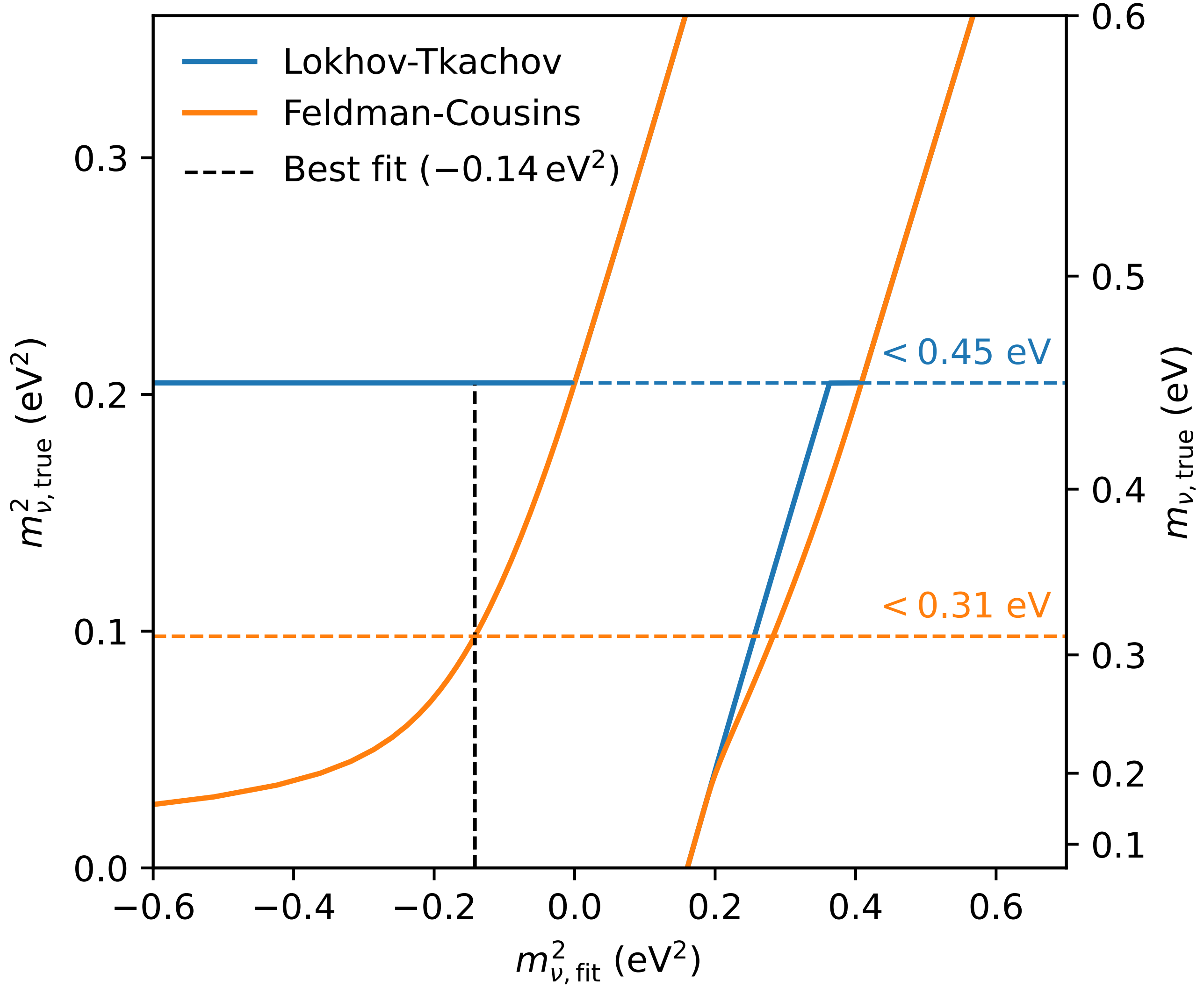
- Highly segmented data (**1609 data points**).

Fit Result



$$m_\nu^2 = \left(-0.14^{+0.13}_{-0.15}\right)\,\mathrm{eV}^2$$

Q-value: (18 575.0 ± 0.3) eV

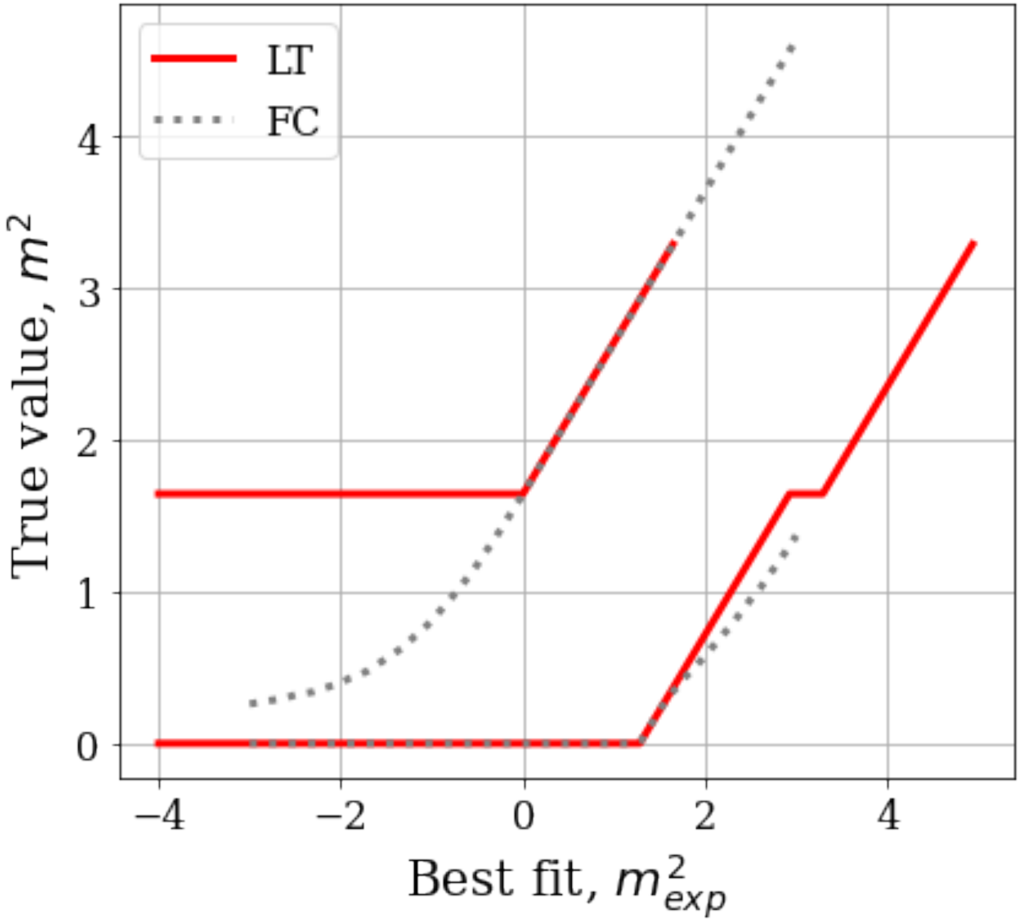


$$m_\nu < 0.45\,\mathrm{eV}\ (90\,\%\ \mathrm{CL})$$

Lokhov, Tkachov, Phys. Part. Nucl. 46 (2015) 3, 347-365

Neutrino mass limit

- **Frequentist** confidence interval with a priori information: $m^2 \geq 0$
- **Feldman-Cousins** → a special way of accumulating probability
  - Shrinking upper limit for negative $(m_\nu)^2$
- **Lokhov-Tkachov** → constant upper limit below $m^2 = 0$
  - Sensitivity of the experiment for $m^2 < 0$
  - No "improvement" of upper limit for negative $(m_\nu)^2$



PARTICLE PHYSICS

Closing the gap in the neutrino mass

New measurements make an important step toward demystifying the fundamental particle

By **Loredana Gastaldo**

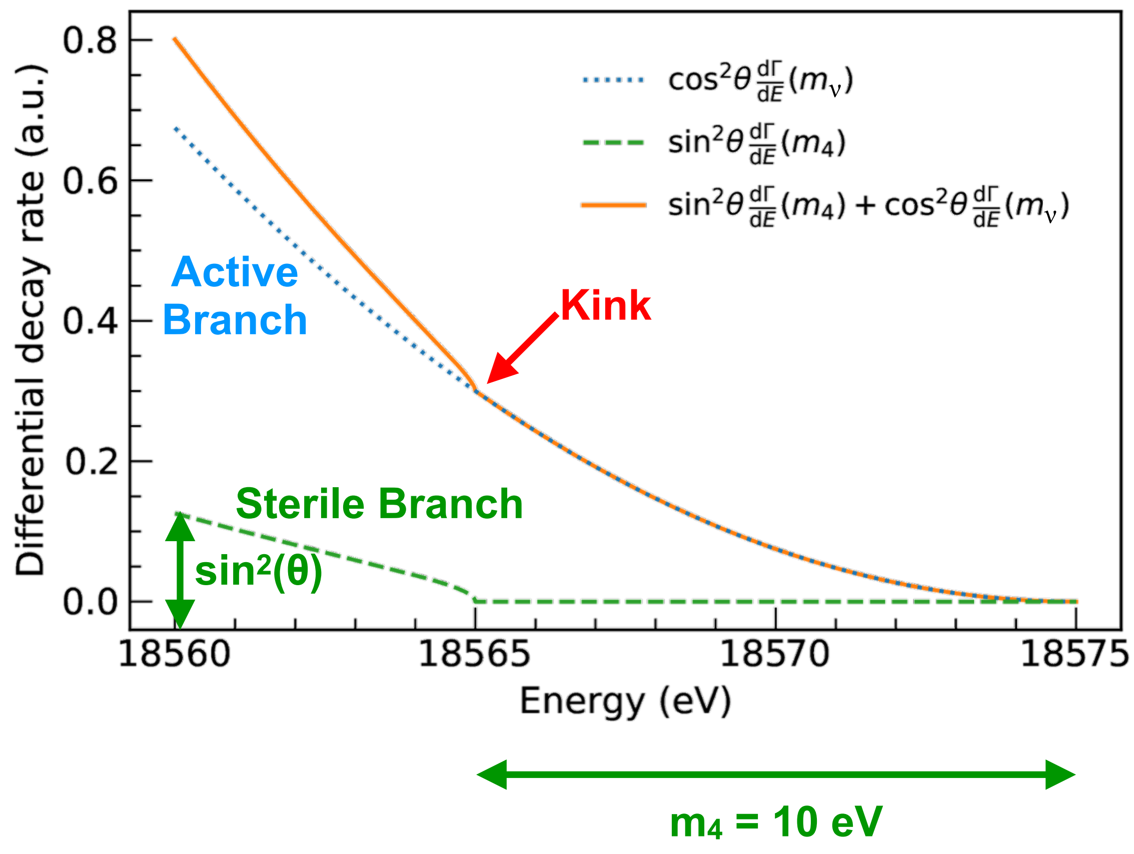
Each second, more than 100 billion neutrinos—electrically neutral elementary particles of the Standard Model of particle physics—that originate from the Sun's core pass through a human body. Neutrinos are described by "flavor," each with distinct properties: electron, muon, and tau neutrino. Oscillations between these flavor states as the particle travels through space indicates that neutrinos have a distinct mass. However, neutrinos are the only fundamental particle whose mass is still unknown. On page 180 of this issue, the KATRIN Collaboration (*1*) report the new results obtained with the Karlsruhe Tritium Neutrino (KATRIN) experiment that narrows down the allowed range of the neutrino mass. This latest upper limit of 0.45 eV at 90% confidence level implies that the mass of a neutrino is less than 1 millionth the mass of an electron. Determining this fundamental

PHOTO: MICHAEL ZACHER/KATRIN COLLABORATION

SCIENCE VOL. 388, NO. 6743

eV Sterile Neutrinos

Expected signature in KATRIN



Several experimental anomalies:

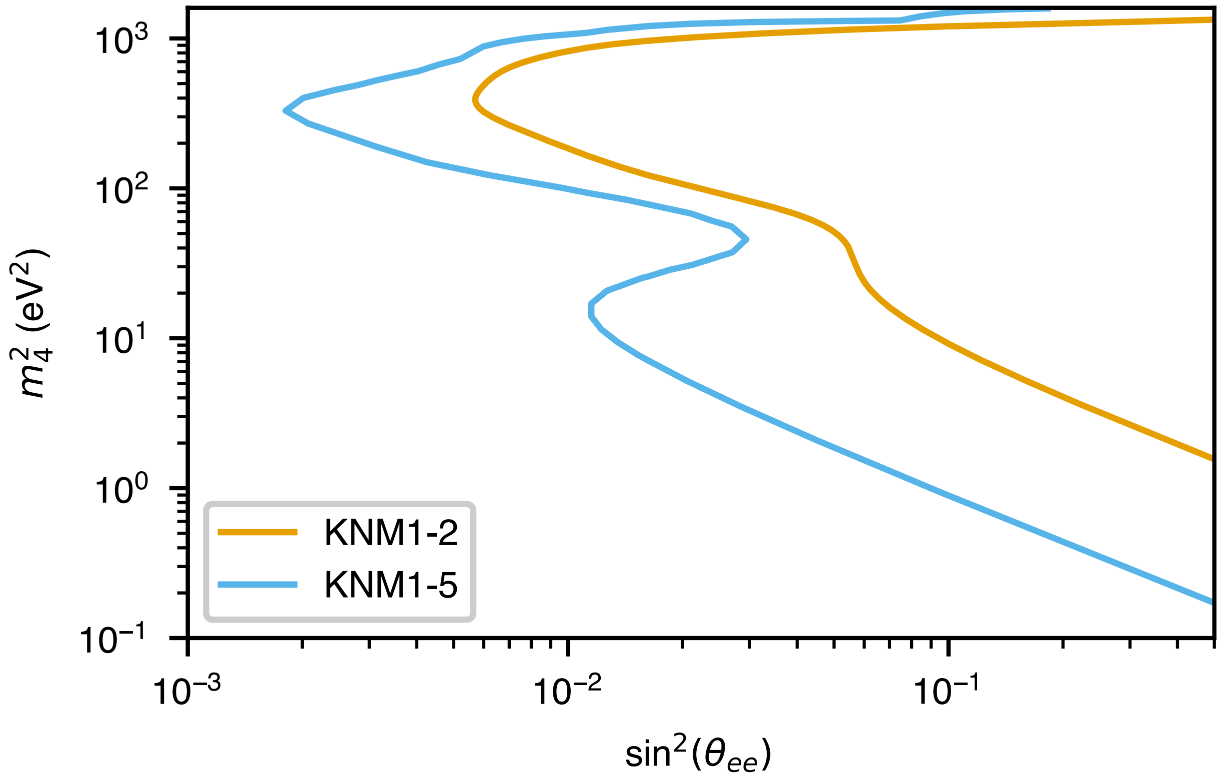
- Reactor Antineutrino Anomaly (RAA, ~3σ)
- Gallium flux (~4σ)

$$\frac{d\Gamma}{dE} = \underbrace{(1-\sin^2\theta)\frac{d\Gamma}{dE}(m_\nu^2)}_{\text{SM light (anti-)neutrino}} + \underbrace{\sin^2\theta\frac{d\Gamma}{dE}(m_4^2)}_{\text{eV Sterile (anti-)neutrino}}$$

Maximum likelihood fit of model for 3ν + 1 includes two additional parameters in the fit:

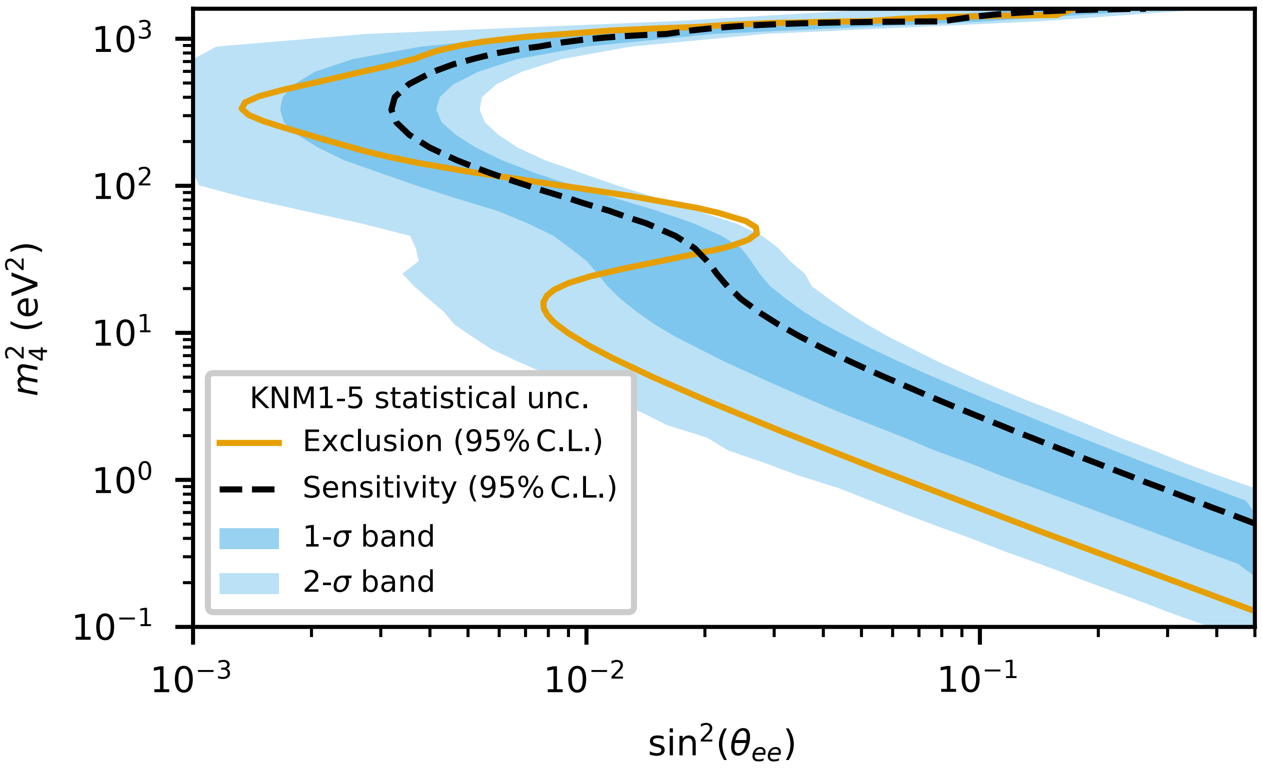
- **m_4**: mass of the eV-sterile neutrino;
- **$\sin^2\theta$**: the mixing angle of the fourth neutrino.
- **m_ν:** constrained to 0 or free

Results - m_ν=0



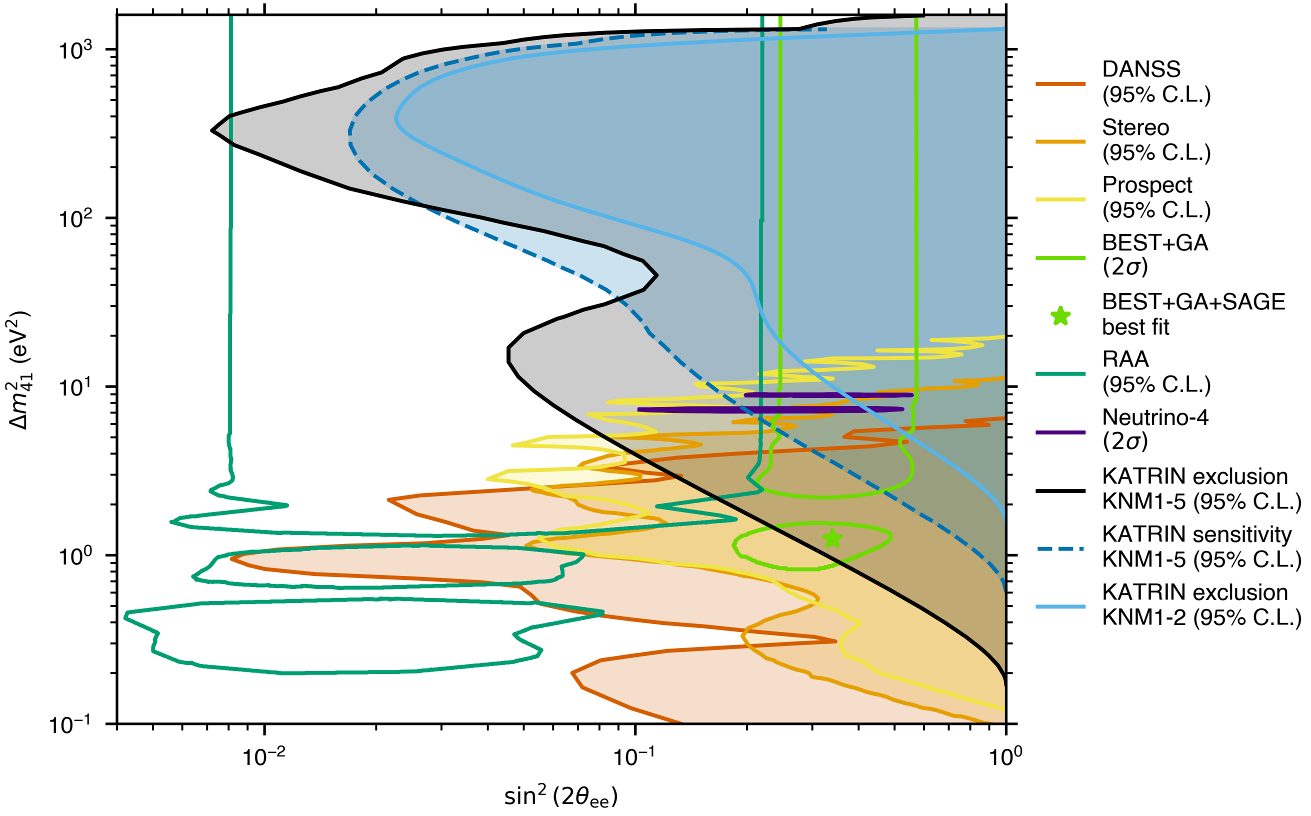
- Using the same data for the sterile neutrino searches - with a different signal model.
- No evidence found for an eV-sterile neutrino. Limits on 90% C.L presented.
- Statistical uncertainties dominate for all masses.

Results - m_ν=0

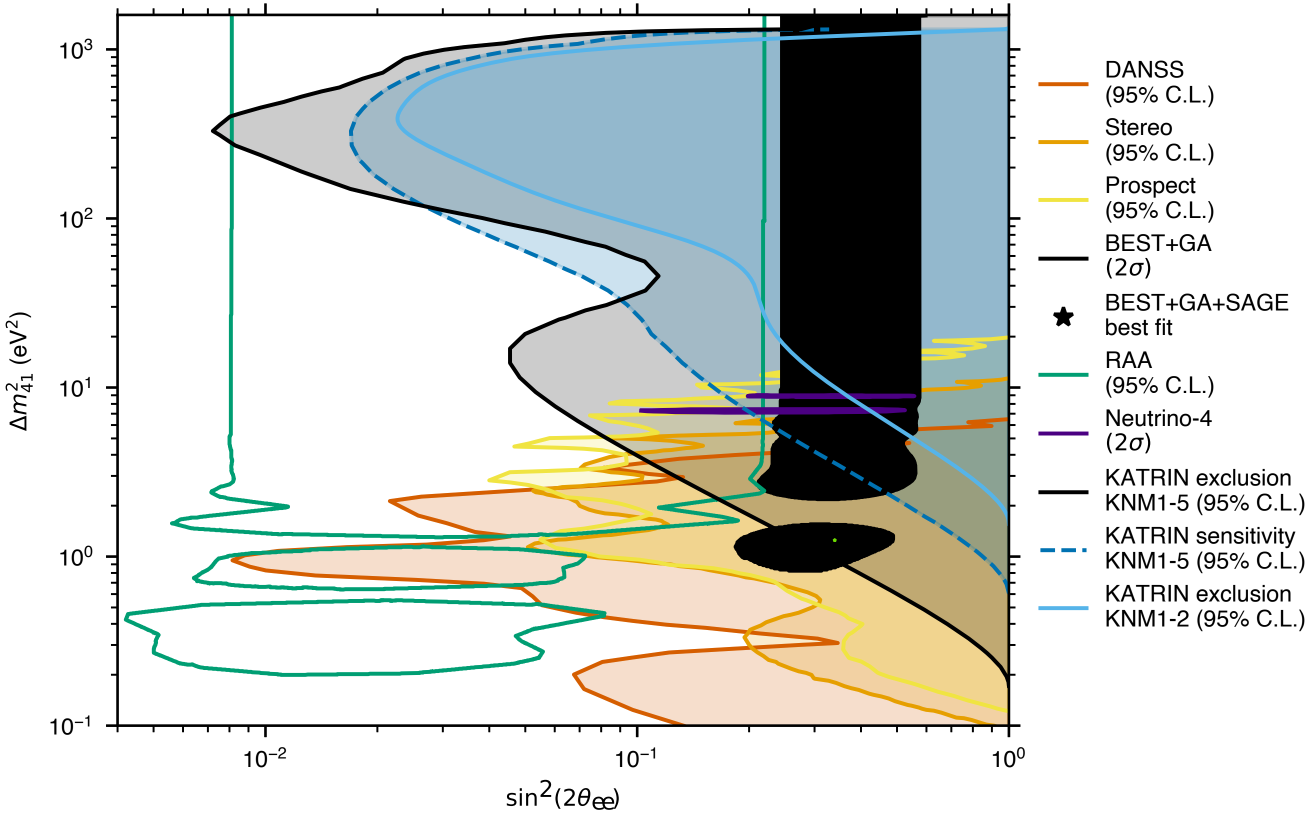


- Using the same data for the sterile neutrino searches - with a different signal model.
- No evidence found for an eV-sterile neutrino.
- Statistical uncertainties dominate for all masses.
- 1σ and 2σ statistical sensitivity bands reconstructed from simulations.
- New exclusion contour aligns with expected statistical fluctuations within 95%

Results - m_ν=0

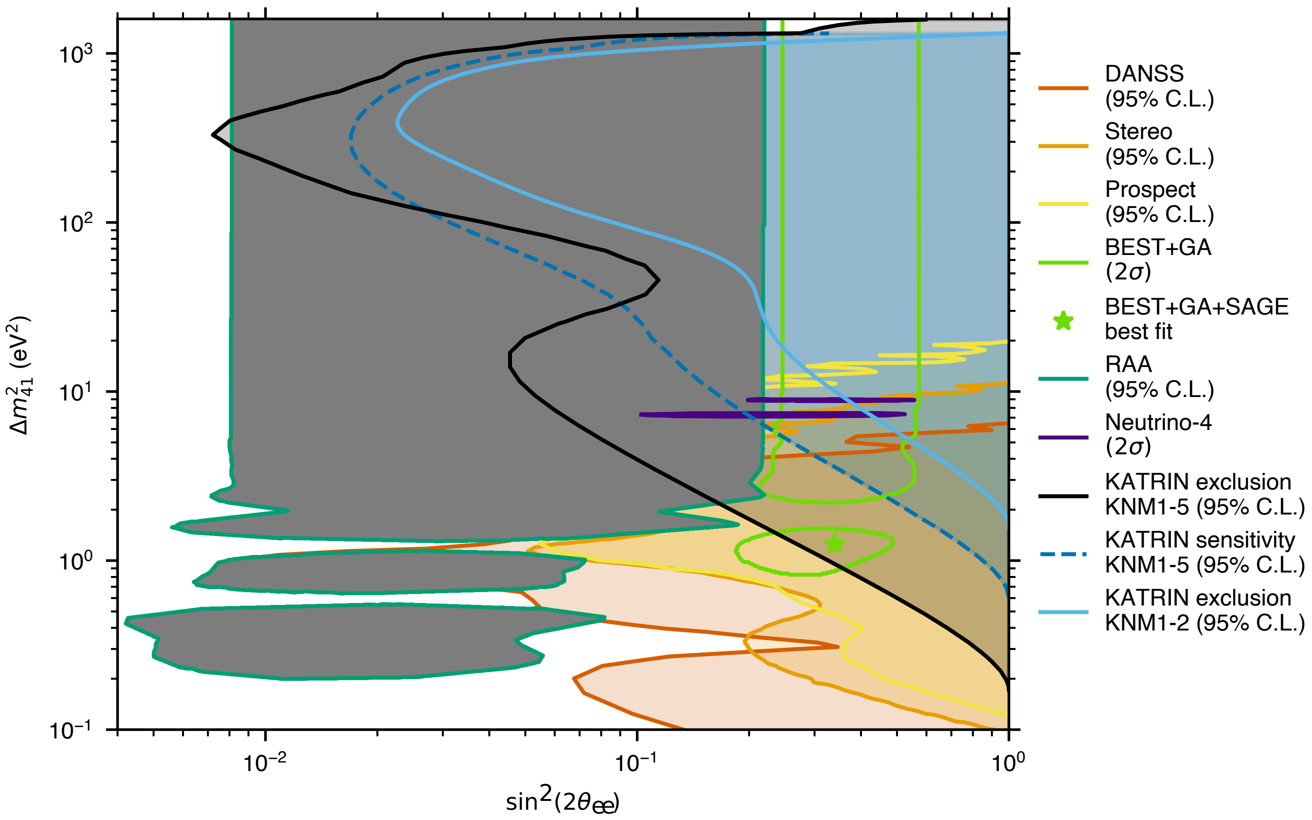


Results - m_ν=0



- Almost excluded the allowed region with the Gallium anomaly except a small region.

Results - m_ν=0



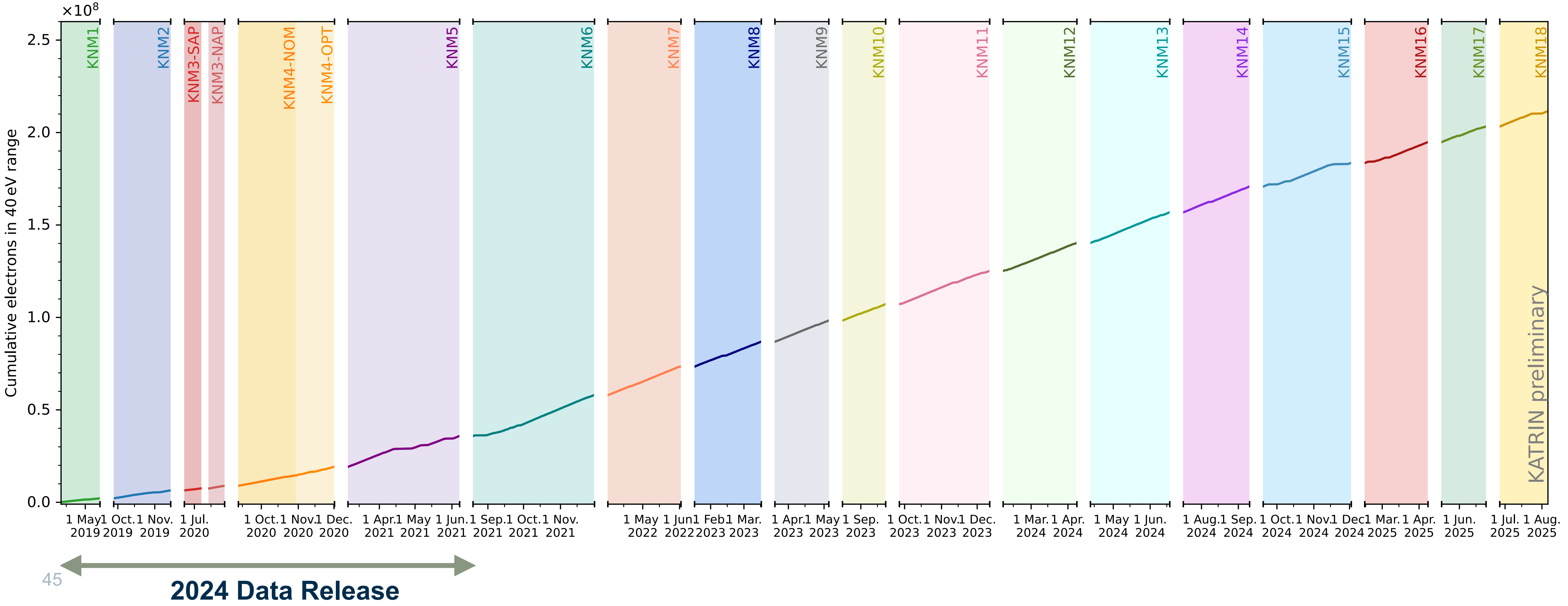
- Almost excluded the allowed region with the Gallium anomaly except a small region.
- A large section of the Reactor Antineutrino Anomaly was also excluded as exemplified.

Pre-print available **"Sterile-neutrino search based on 259 days of KATRIN data", https://arxiv.org/abs/2503.18667**

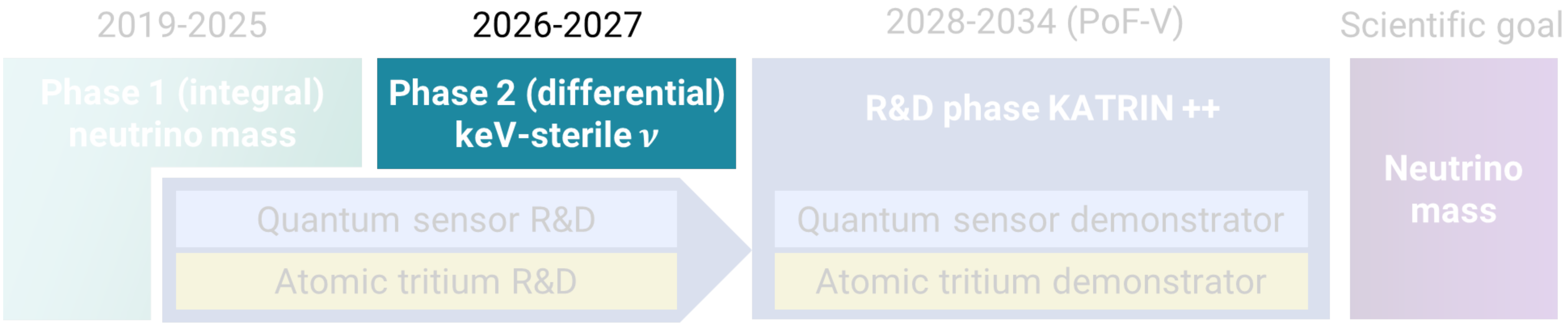
KATRIN Data Taking until 2025

18 measurement campaigns completed until now - 2 Campaigns Remain until we reach 1000 days

- More than 210 million counts recorded – **x5.8 of this release**!
- plus calibrations and improvement in the systematics uncertainties (e.g. https://arxiv.org/pdf/2503.13221) .

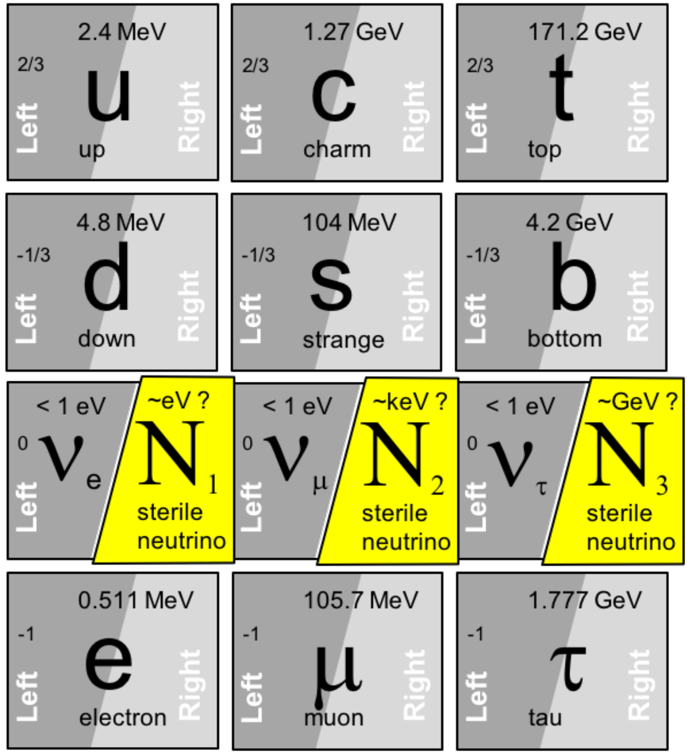


KATRIN Timeline - The TRISTAN Phase

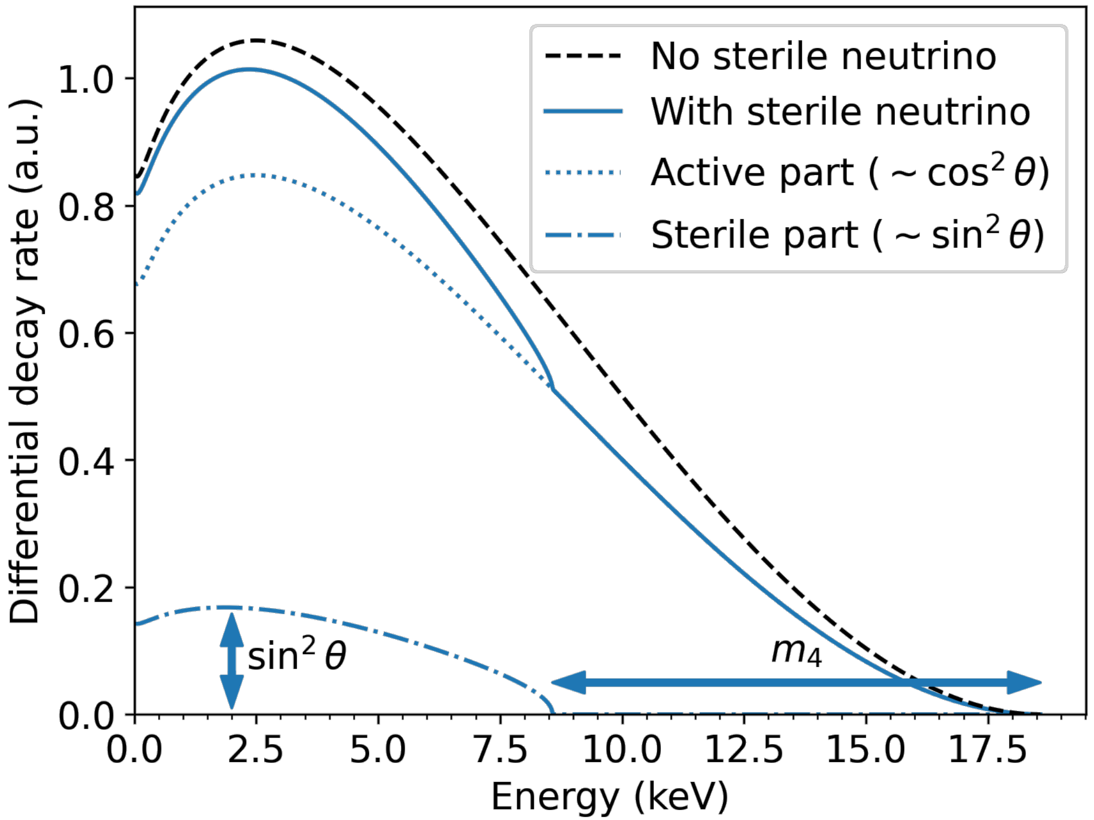


keV Sterile Neutrinos

Standard Model (SM)

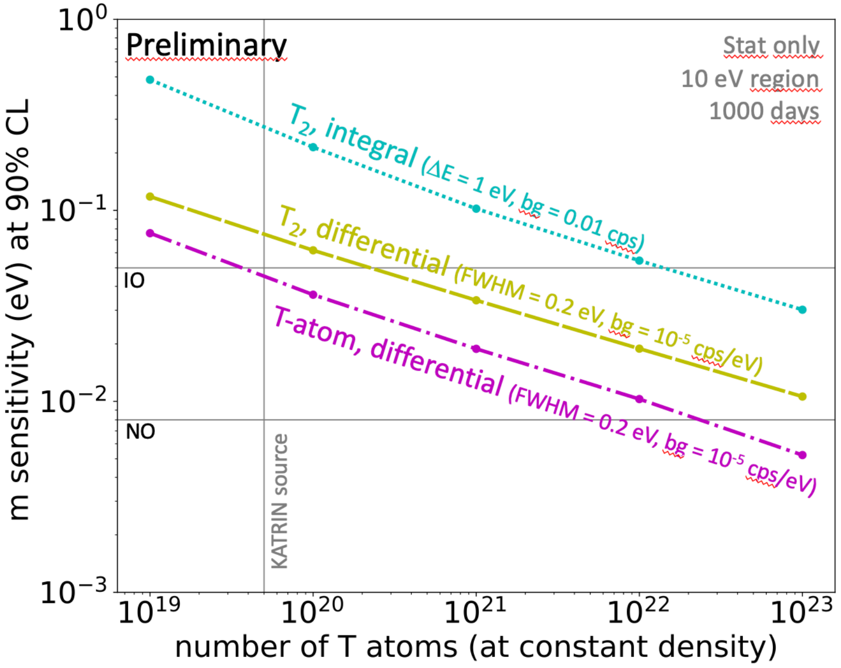


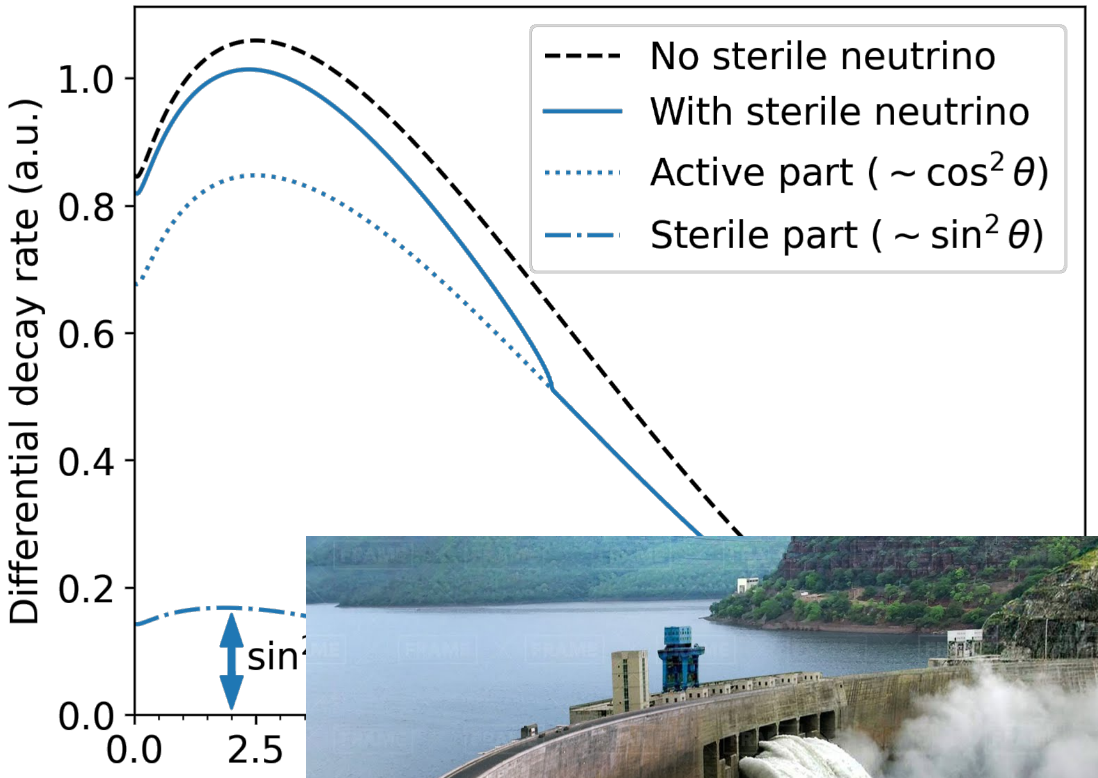
PRL 110 061801 (2013)



- **Kink-like distortion** in the differential β-spectrum
  - Position governed by the mass of the neutrino;
  - Amplitude governed by mixing angle $\sin^2\theta$;

Integral versus Differential Measurement



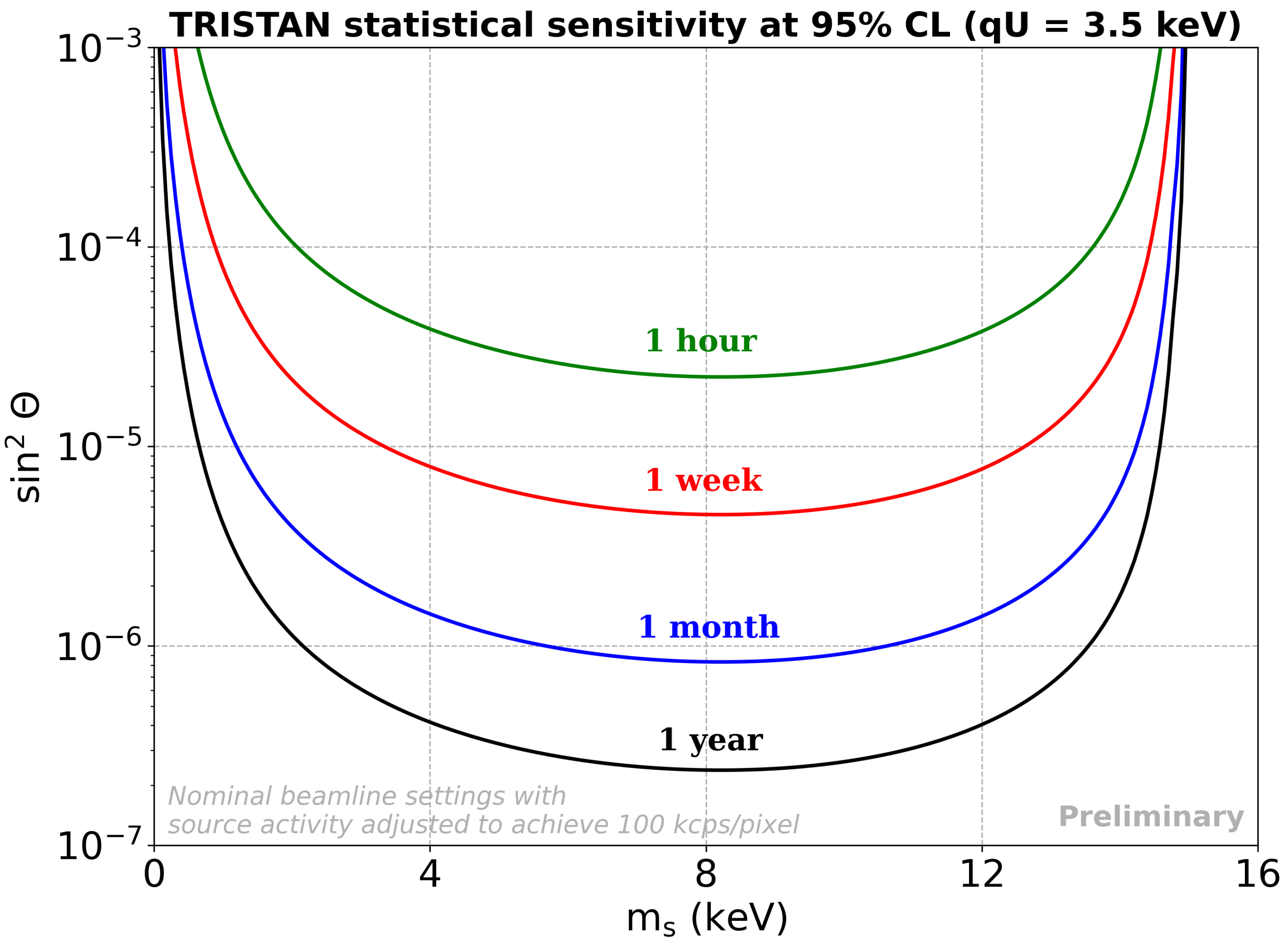


- A **differential measurement** makes more effective use of statistics;
- Requires upgrading the KATRIN at multiple levels.

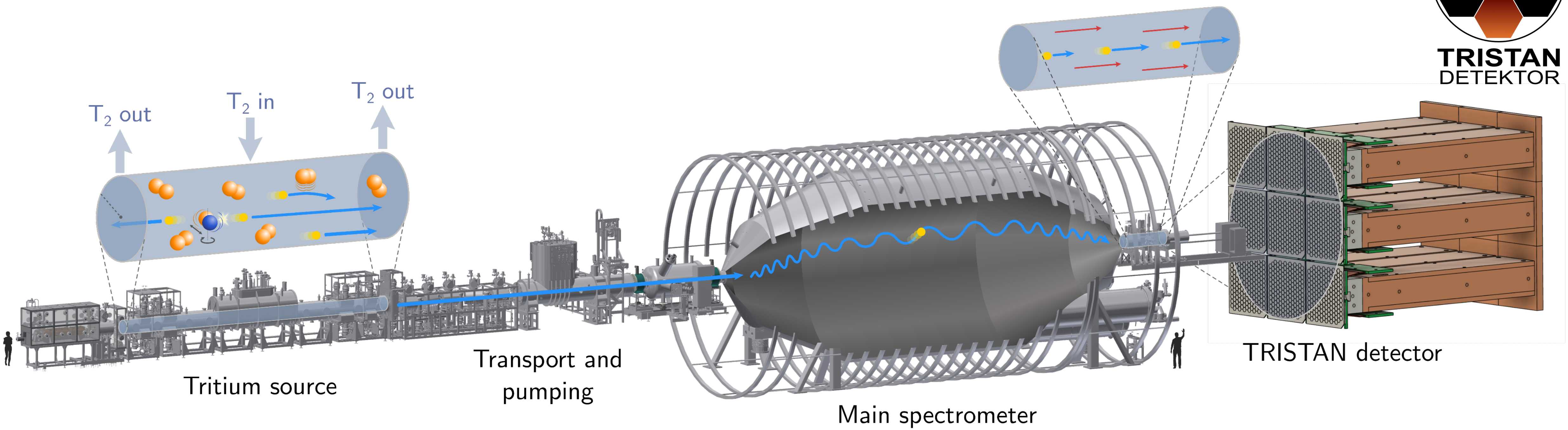
Differential Measurement

HIGH STATISTICS!

Systematic uncertainties must be carefully controlled!



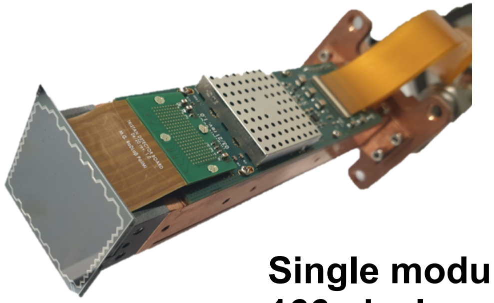
Differential Measurement



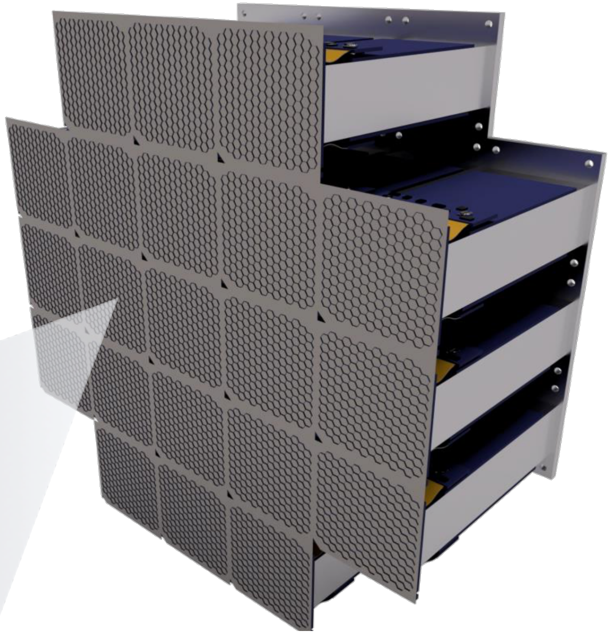
- New detector system capable of handling high rates with an excellent energy resolution and low noise, etc…
  - **SDD - Silicon Drift Detector**;
- Source Activity to be reduced to **0.1–1% of the current values**;
- The rear wall has to be reconfigured to reduce the amount of backscattering;
- New field configuration to **ensure adiabatic transport** and a new post-acceleration electrode.

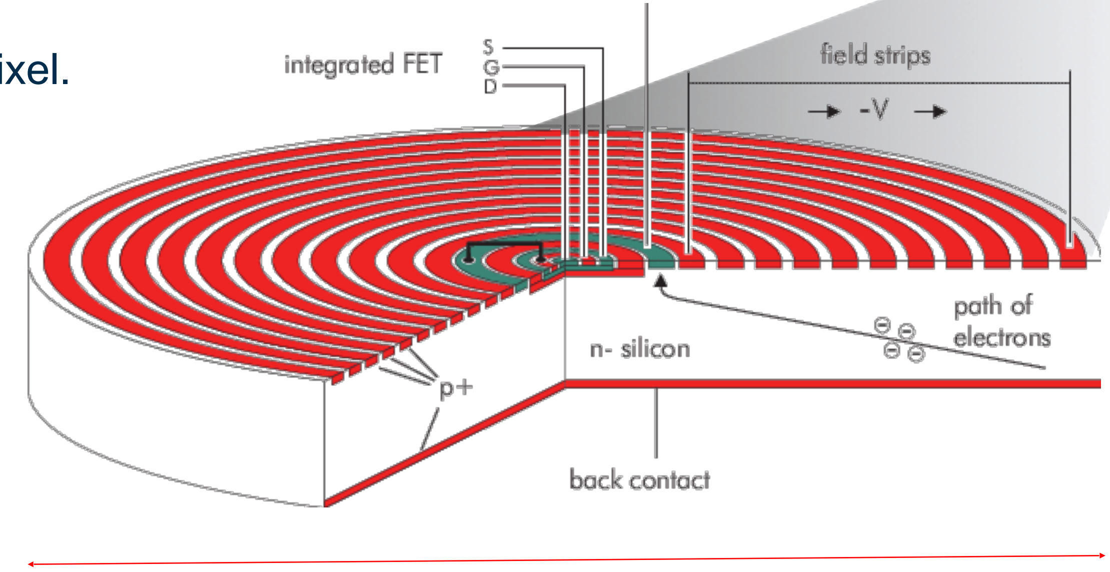
TRISTAN - The Novel Detector System

- The detector needs to handle high rates
  - **Small readout contact:** Small detector capacitance
    Low noise (good resolution) for high rates
- Needs an excellent energy resolution and be linear, to resolve the kink
  - **Integrated amplification (nJFET):** energy resolution better than 360 eV;
- Needs to cover the full electron beam, minimizing dead area
  - **Large detector area** for each pixel.

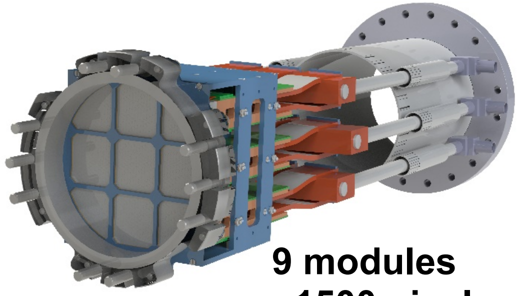


Single module
166 pixels





3 mm, 220 fF



9 modules
~1500 pixels

Further Reading:

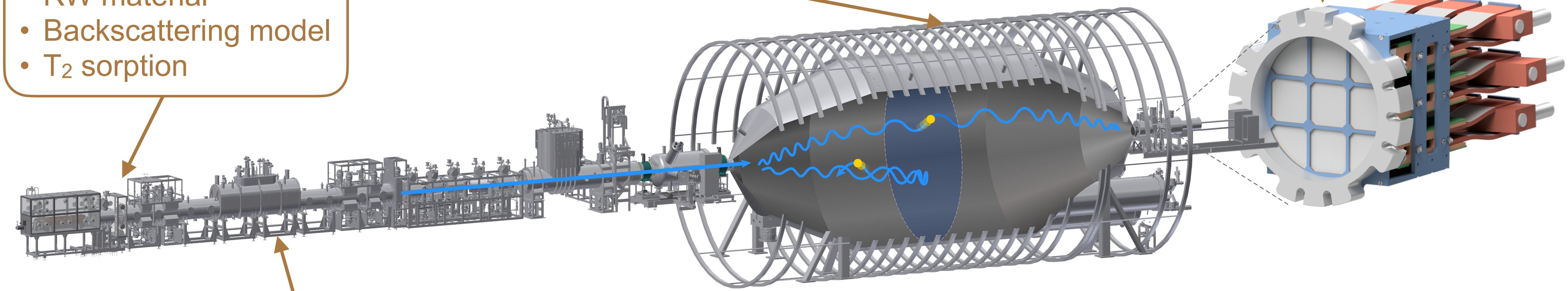
D. Siegmann: J. Phys. G: Nucl. Part. Phys. 51 (2024) 085202 (25pp)

Differential Measurement - Systematics

Detector:
Energy loss in a passive layer
Electron backscattering
Charge sharing between pixels
Fano factor of the silicon

EM Transport:
- Non-Adiabaticity
- Magnetic reflection

Rear Wall section:
- RW material
- Backscattering model
- T_2 sorption



Source:
- Source scattering
- Tritium density
- Tritium spectrum
- Magnetic Traps
- Plasma Potential

Data Acquisition:
Electronic noise
Deadtime, threshold
Nonlinearity
Pileup

Rear Wall section:
- RW material
- Backscattering model
- T_2 sorption

EM Transport:
- Non-Adiabaticity
- Magnetic reflection
- Backgrounds

Detector:
- Energy loss in a passive layer
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- Charge sharing between pixels
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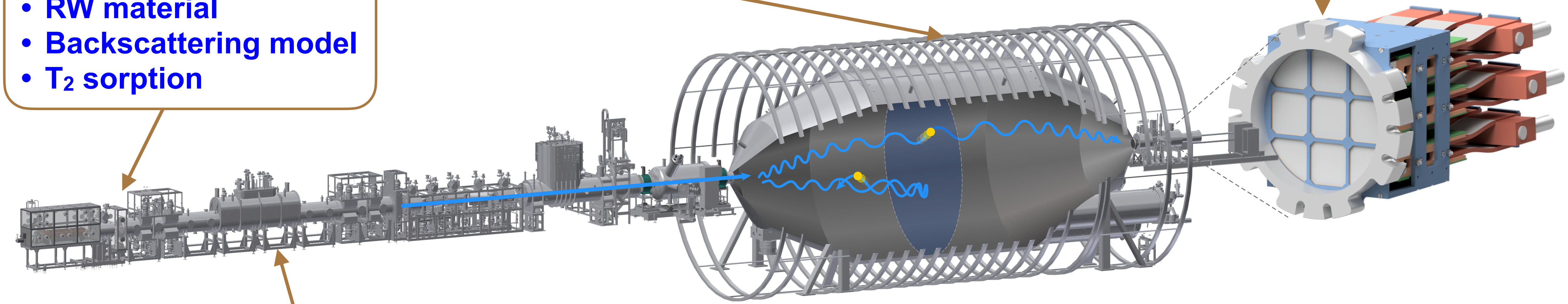

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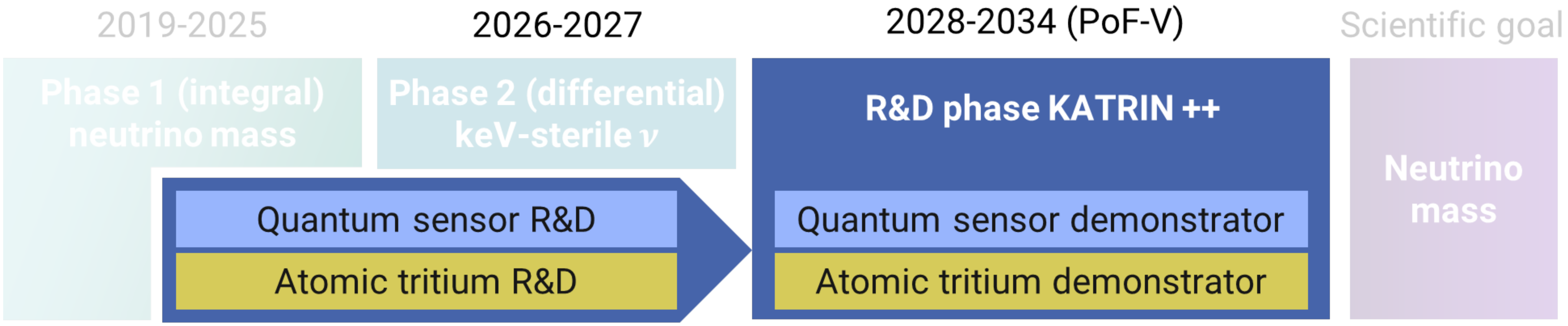
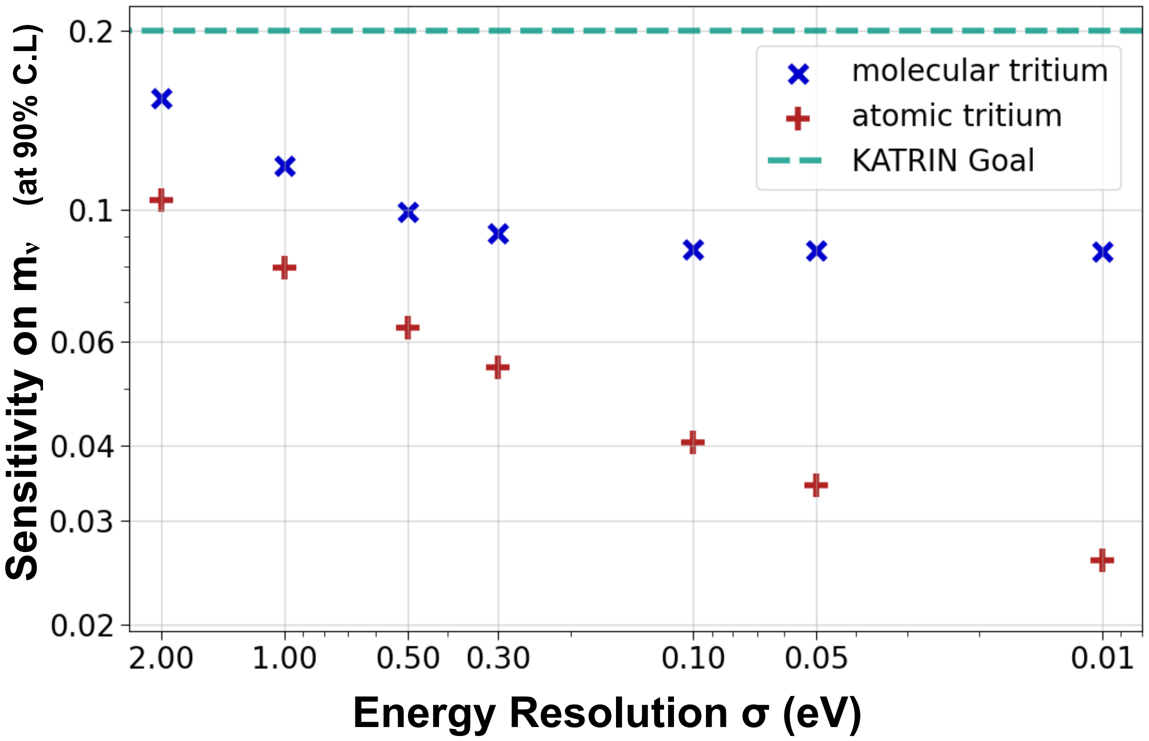
KATRIN Timeline

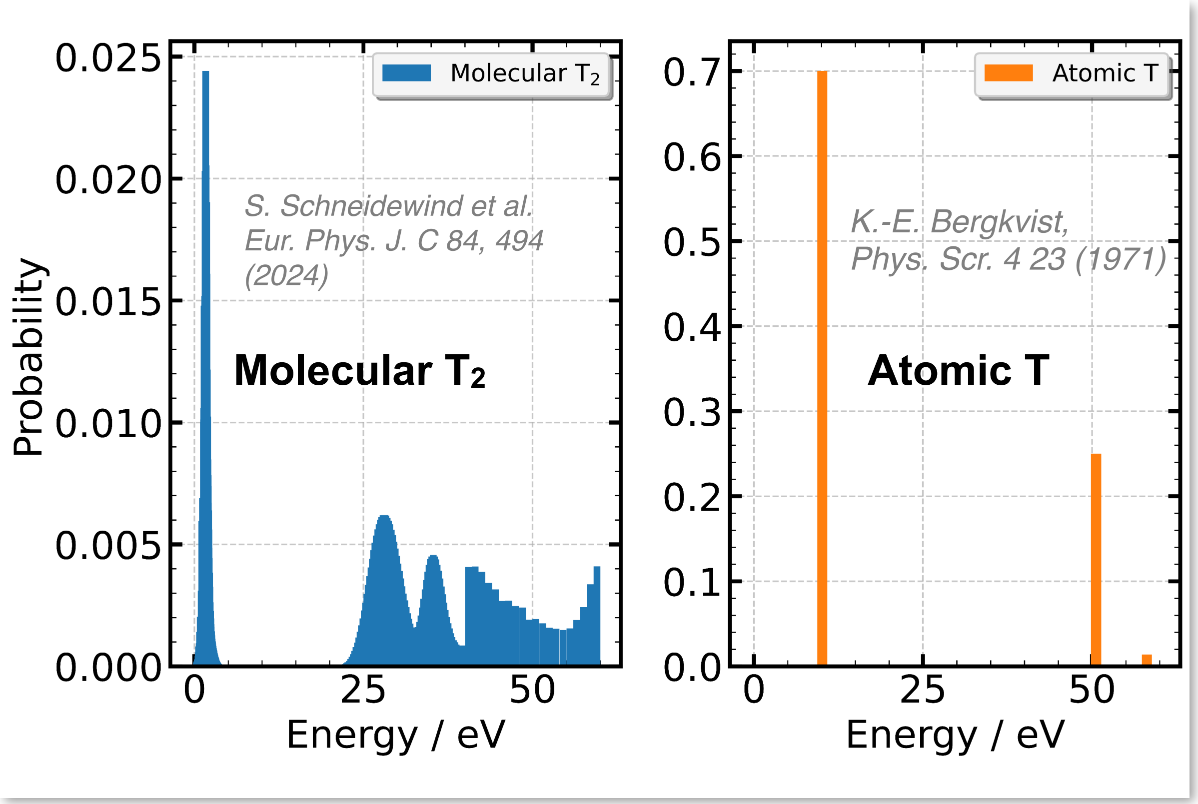


- Reduction on the **systematic uncertainties**:
  - Reduction of the final state uncertainties → **atomic source tritium**
- Improvement of energy resolution:
  - **MAC-E:** implementation of a high-pass filter → **Transverse Energy Compensator;**
  - **Calorimetry:** measuring the deposited energy by temperature change → **Quantum sensors**;
  - **Cyclotron Radiation Emission Spectroscopy:** measuring E via cyclotron ν **(Project 8 Collaboration)**

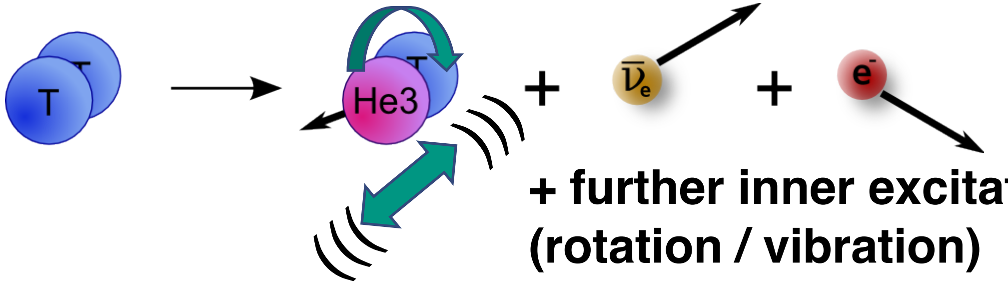
KATRIN++



Final-state distribution

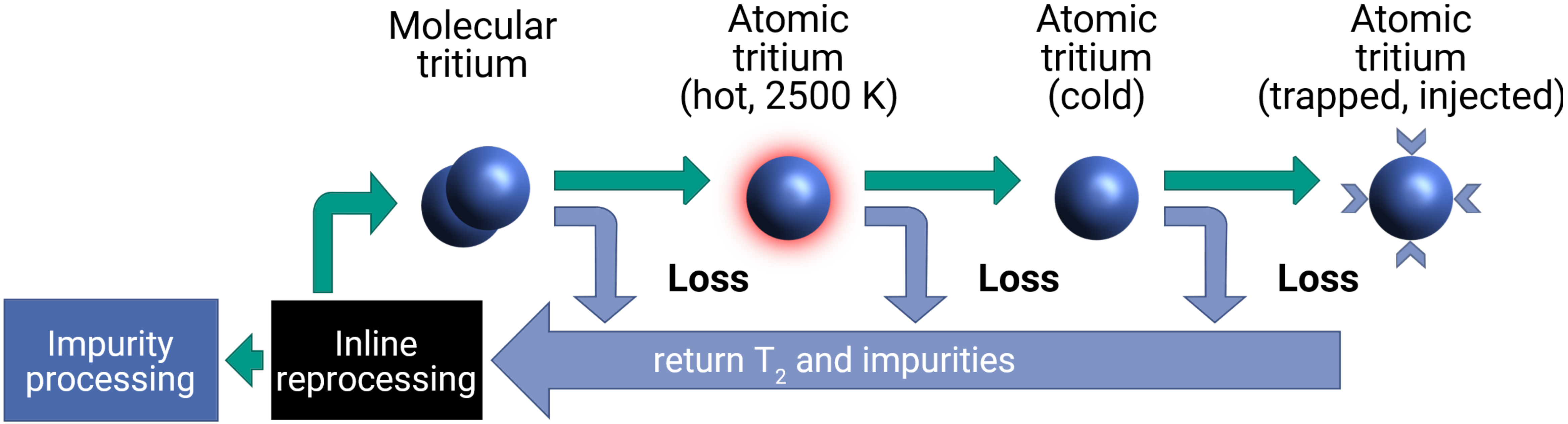


- Daughter molecule $^3HeT^+$ exhibits inner excitations (rotations and vibrations) after tritium beta decay.
- Intrinsic broadening of ground state (std. dev. of about 0.4 eV).



+ further inner excitations (rotation / vibration)

Development of an Atomic Tritium Source



Development of an Atomic Tritium Source

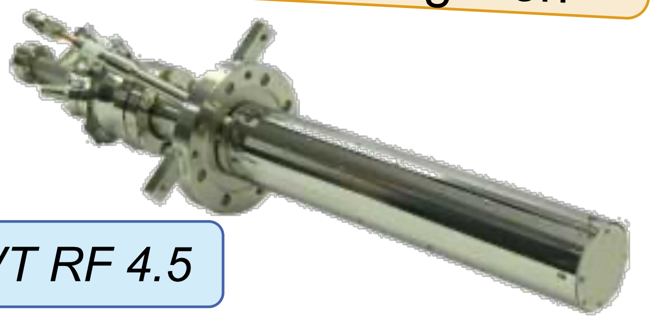
Installation of first ever atomic **tritium** source at KIT ongoing

Atomic Tritium Demonstrator at KIT:

- Development at Tritiumlabor Karlsruhe (TLK) for future m_ν-experiments;
- Simple setup to demonstrate tritium operation and investigate tritium compatibility, recovery and isotopic effects.

Thermal Dissociation:

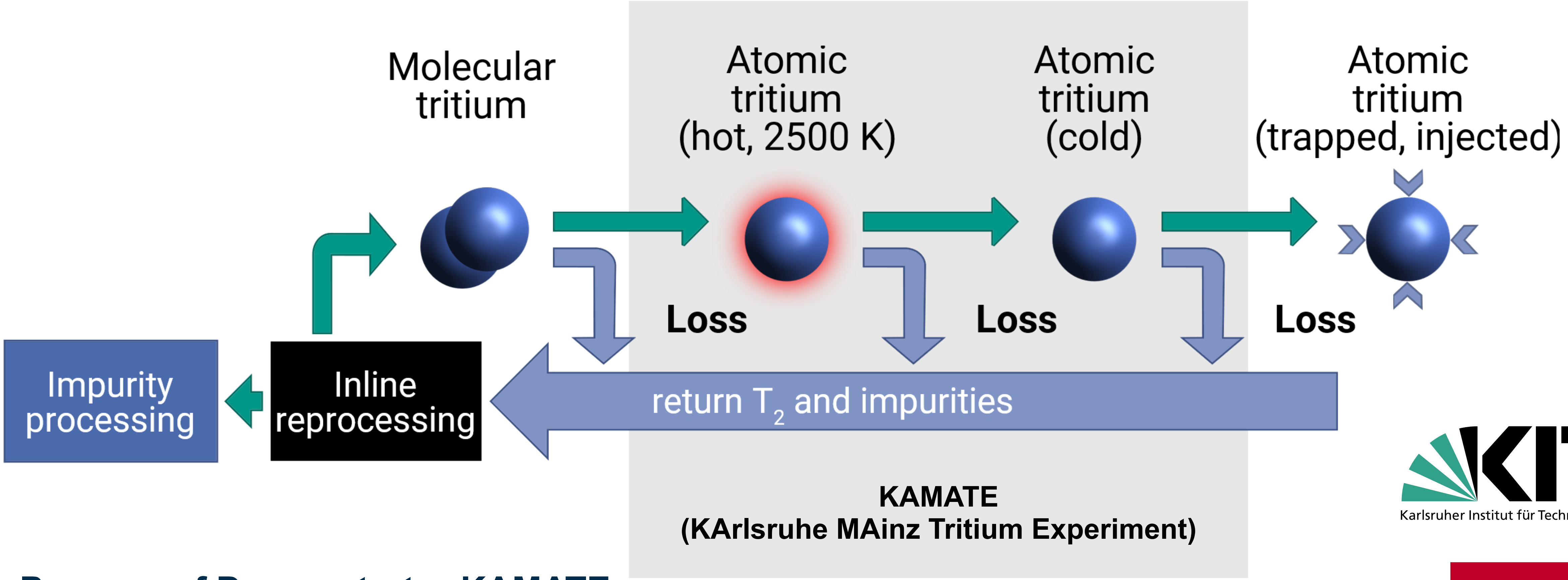
- Fine tungsten capillarity heated by electron bombardment
- **Atoms with > 2000 K**



RF-discharge:

- A Radio frequency field is applied to the gas creating a plasma of ions, electrons, and excited atoms.
- **Atoms are colder compared to Tetra h-flux**

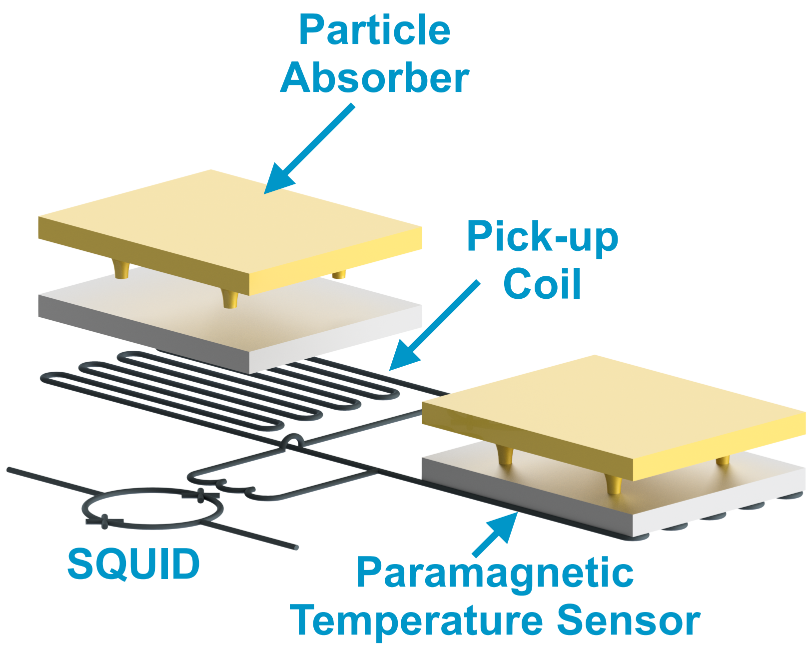
Development of an Atomic Tritium Source

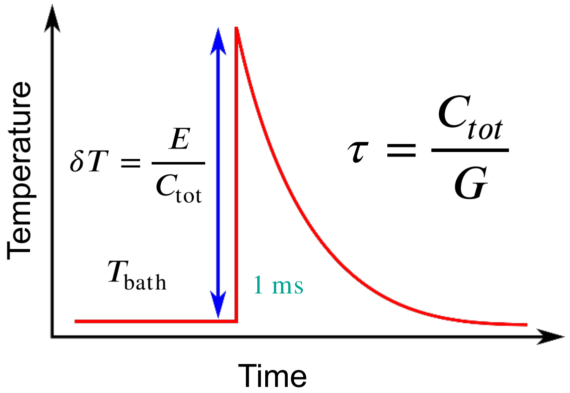


- **Propose of Demonstrator KAMATE:**
  - Develop a cooling mechanism for atoms (**≈10 mK**);
  - Generate an atom throughput on the order of **10 g day** (c.f. KATRIN: 40 g/day);
  - Investigate trapping times and maximal atom densities.

More on atomic cooling: https://arxiv.org/pdf/2502.00188 (2025)

Quantum Sensors as High Resolution Detectors





Principle of Working:

- **Metallic Magnetic Calorimeters:** temperature-dependence in sensor magnetisation [1, 2];

Advantages:

- Energy Resolution of **< 1 eV** (not tested with external electrons)
- Fast rise time (~100 ns) and near 100% quantum efficiency
- No dead layer.

Challenges:

- Operation in magnetic field;
- Coupling of mK-cold sensors with room temperature spectrometer;
- Large number of channels required (about $10^5 - 10^6$ channels)

We have a clear strategy to solve each of these challenges.

[1] NIMA 1030 (2022) 166406 (2021)
[2] https://arxiv.org/abs/2502.05975

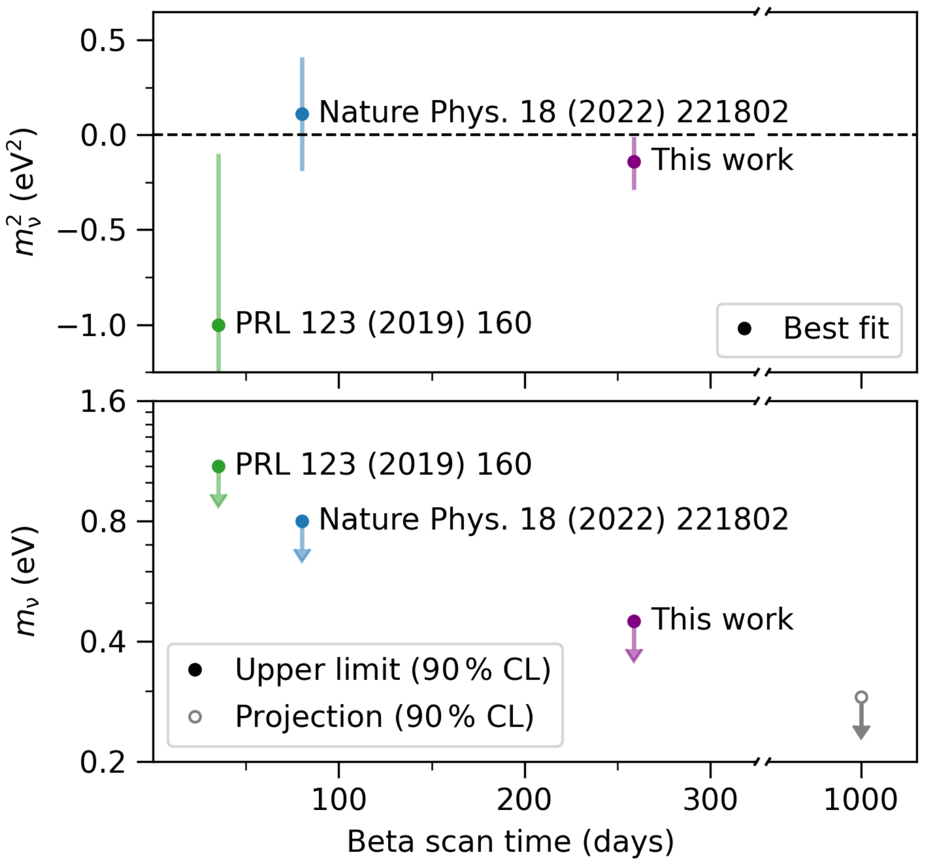
Conclusion and Outlook

- The current KATRIN data release sets an **upper bound** on the neutrino mass of:

$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

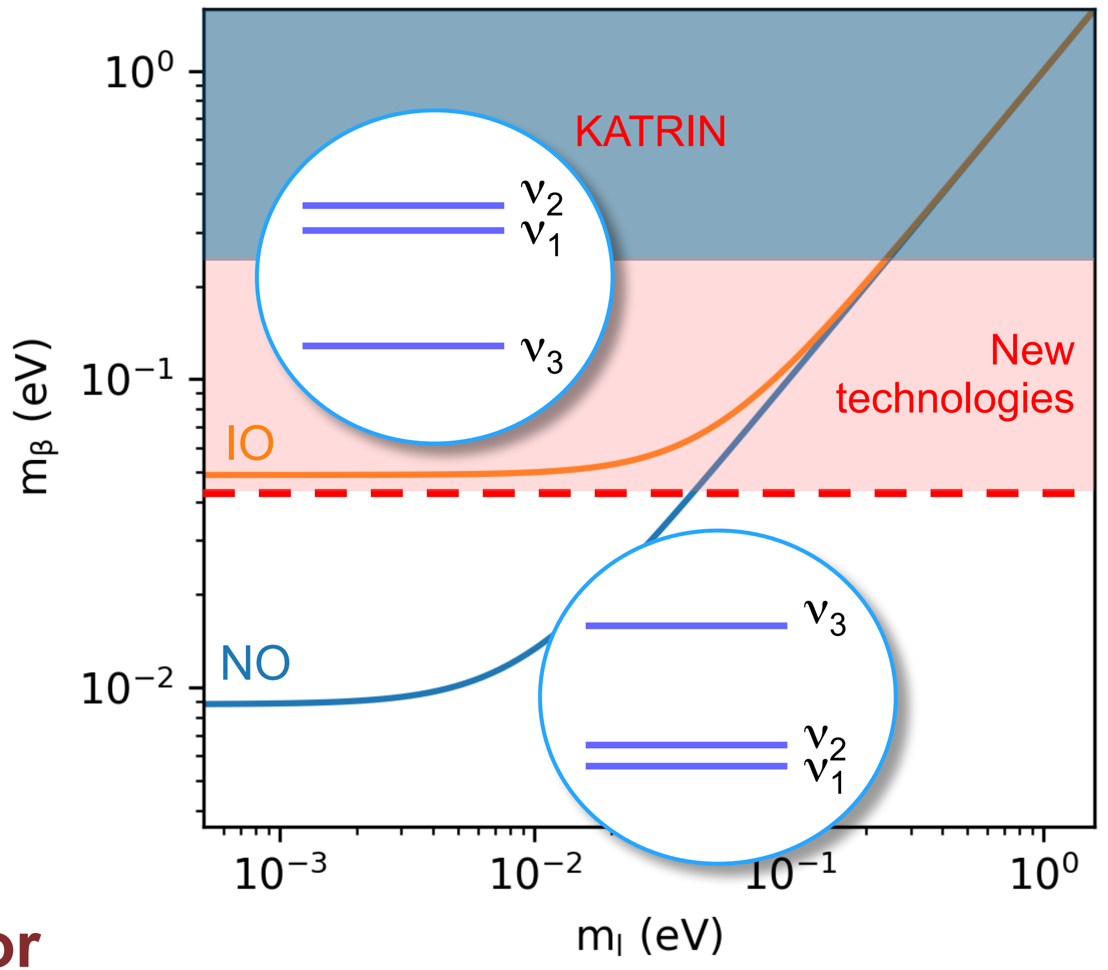
- keV sterile search ruled-out most of the parameter space allowed by the gallium anomaly and a large section of the **RAA allowed region**.
- Ongoing data taking through 2025 → **1000 days**
  - Targeting a sensitivity below 0.3 eV.

$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$



Conclusion and Outlook

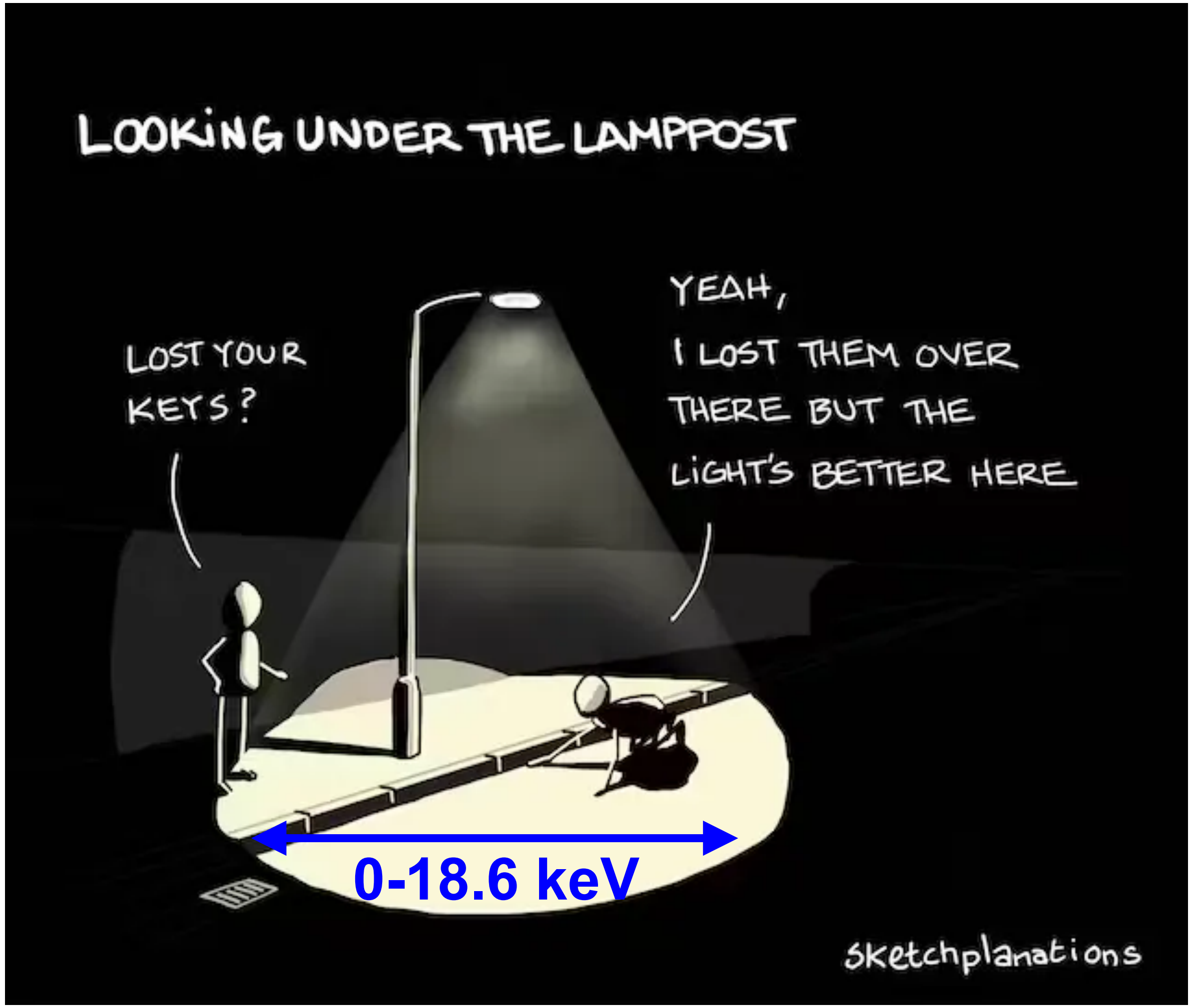
- **Neutrino Sterile Search**:
  - **2026:** we will modify the detector from an integral measurement to a differential measurement in order to detect sterile neutrinos with masses up to 18 keV.
- **Katrin++:** R&D program to develop an experiment with sensitivity on $m_\beta < 0.05$ eV. It would cover the inverted order. It requires:
  - A high resolution detection: MAC-E with compensator or/and a differential method with quantum sensors;
  - A tritium atomic source cooled down to mK to reduce the systematics.
  - New opportunities to look for new-ν with lower mixing angles.



Thank you for your attention!

Conclusion and Outlook

- **Neutrino Sterile Search**:
  - **2026:** we will modify the detector from an integral measurement to a differential measurement in order to detect sterile neutrinos with masses up to 18 keV.
- **Katrin++:** R&D program to develop an experiment with sensitivity on $m_\beta < 0.05$ eV. It would cover the inverted order. It requires:
  - A high resolution detection: MAC-E with compensator or/and a differential method with quantum sensors;
  - A tritium atomic source cooled down to mK to reduce the systematics.
  - New opportunities to look for new-ν with lower mixing angles.



Thank you for your attention!

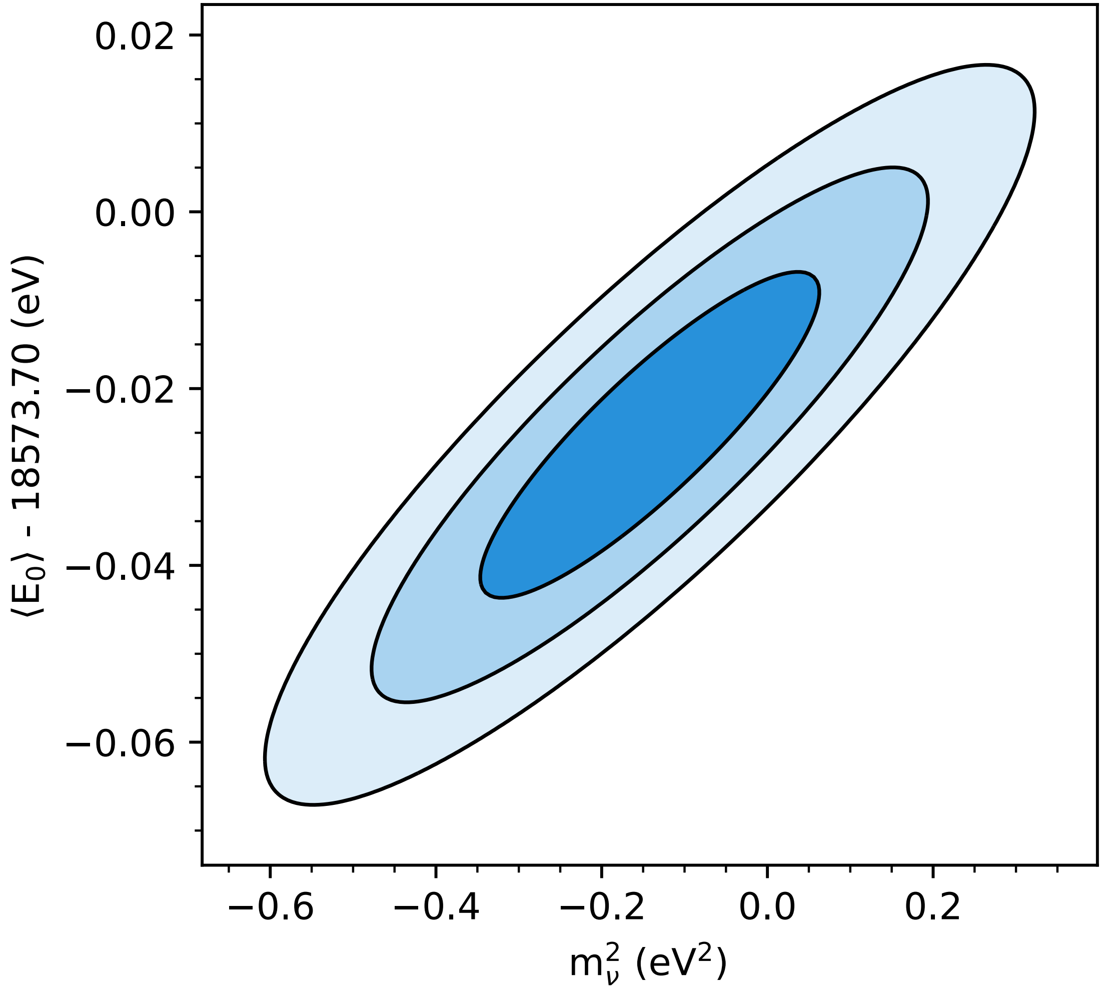
Backup Slides

Overview of the KATRIN Runs

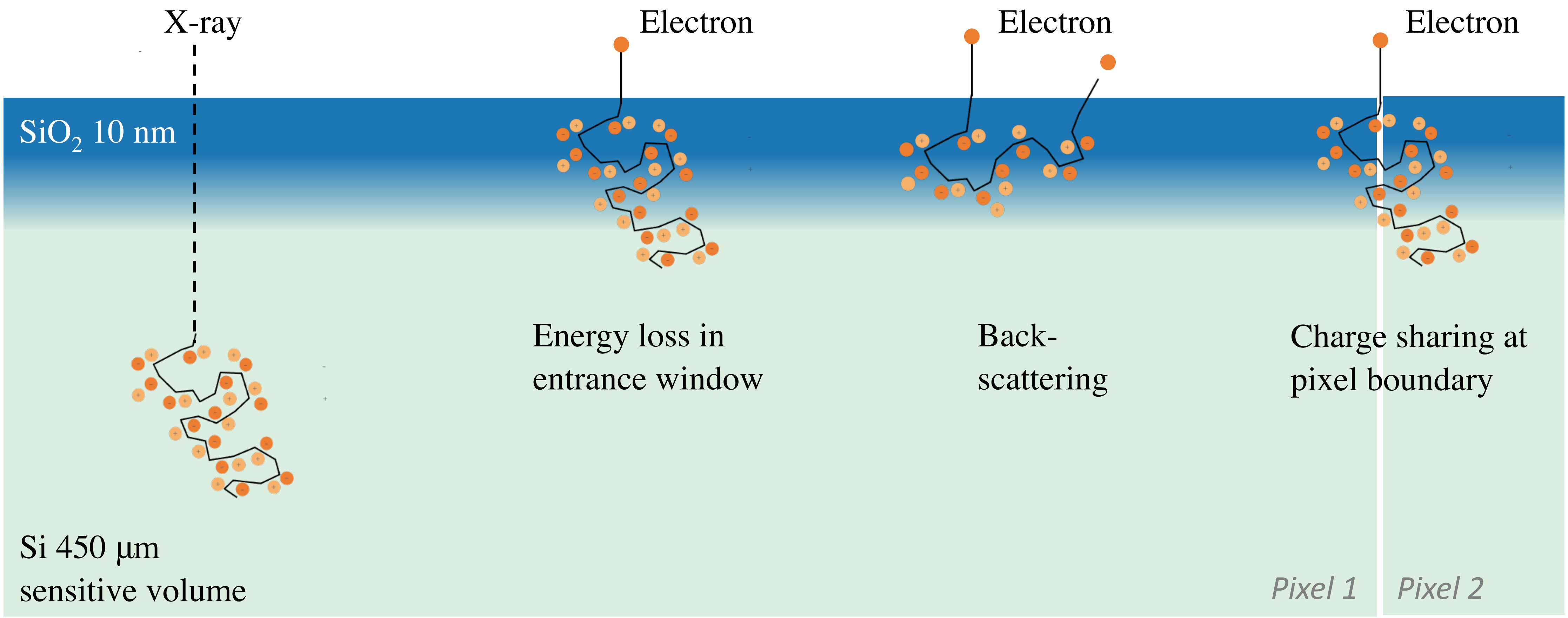
Table 1: Key features of the measurement campaigns. The live time corresponds to the data used for analysis. The values are quoted for the number of active pixels in each measurement campaign and all the scan-steps above $E_0 - 40\,\mathrm{eV}$.

	KNM1	**KNM2**	**KNM3-SAP**	**KNM3-NAP**	**KNM4-NOM**	**KNM4-OPT**	**KNM5**
Year	2019	2019	2020	2020	2020	2020	2021
Month	04 – 05	10 – 12	06 – 07	07	09 – 10	10 – 12	04 – 06
Measurement days	35	45	14	14	49	30	72
Analyzing plane	nominal	nominal	shifted	nominal	shifted	shifted	shifted
Pre-spectrometer voltage (kV)	-10.5	-10.5	-10.5	-10.5	-10.5	$-10.5/-0.1$	-0.1
Scan-step duration	nominal	nominal	nominal	nominal	nominal	optimized	optimized
Rear-wall	-	-	-	-	-	-	cleaned
Source temperature (K)	30	30	80	80	80	80	80
Background rate (cps)	0.29	0.22	0.12	0.22	0.13	0.13	0.14
Number of scans	274	361	114	116	320	150	422
Live time (hrs)	522	694	220	224	835	432	1226
Active pixels	117	117	126	126	126	126	126
Column density ($\times 10^{21}\,\mathrm{m}^{-2}$)	1.08	4.20	2.05	3.70	3.76	3.76	3.77
Source activity (GBq)	24	94	46	83	84	84	84
Number of counts ($\times 10^6$)	2.03	4.31	1.07	1.43	5.64	4.58	16.65

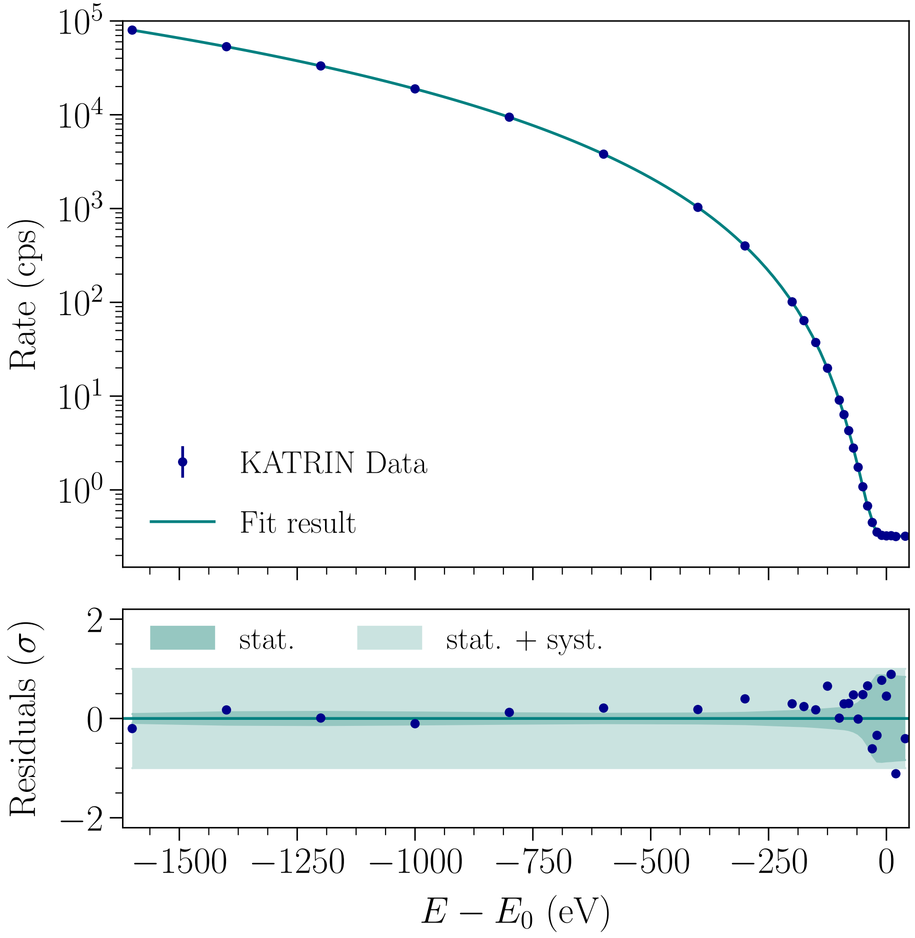
Correlation Between Mass and Endpoint

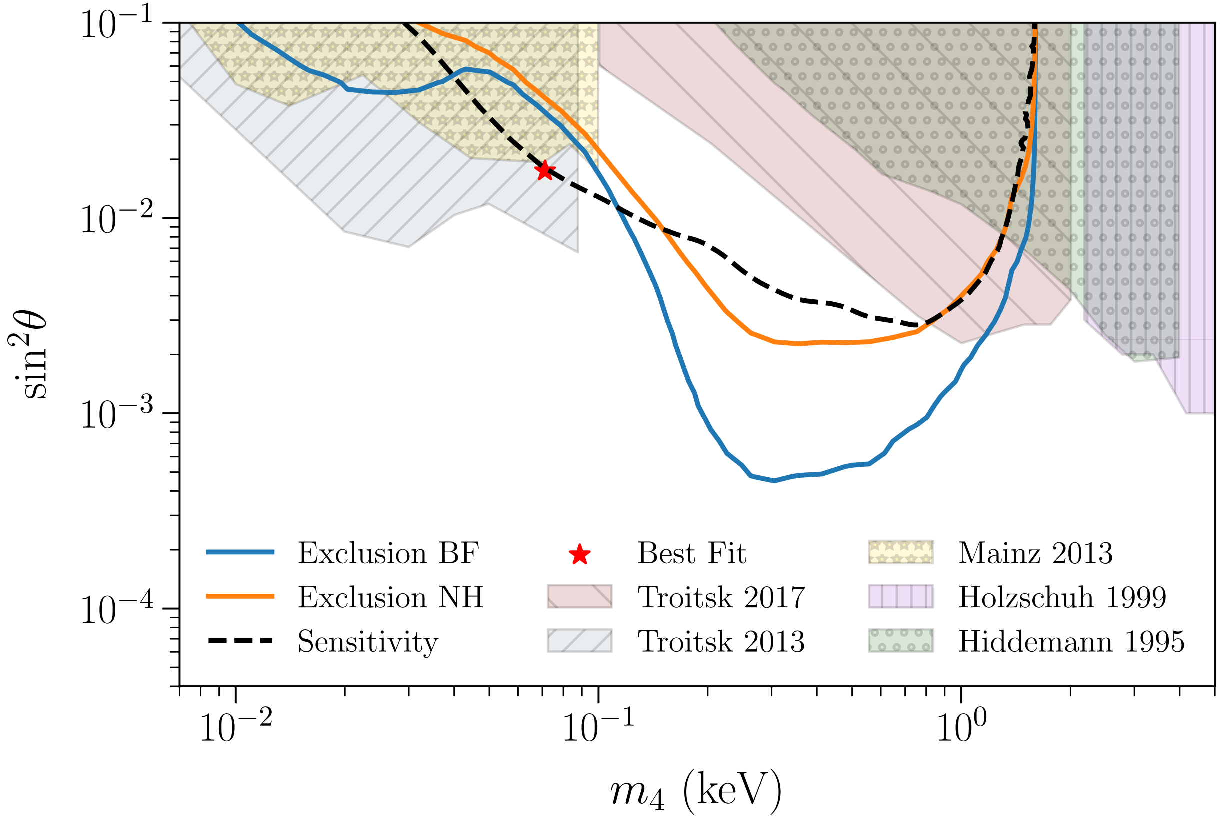


Interaction in the SDD Detector



Search for Sterile Neutrinos in the First Campaign





12 day measurement taken during KATRIN commissioning up to 1.6 keV below the endpoint Improves on laboratory limits for m_4 from 0.1-1.0 keV.

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