Constraints from KATRIN

Cláudio Silva, KIT ETP, for the KATRIN Collaboration

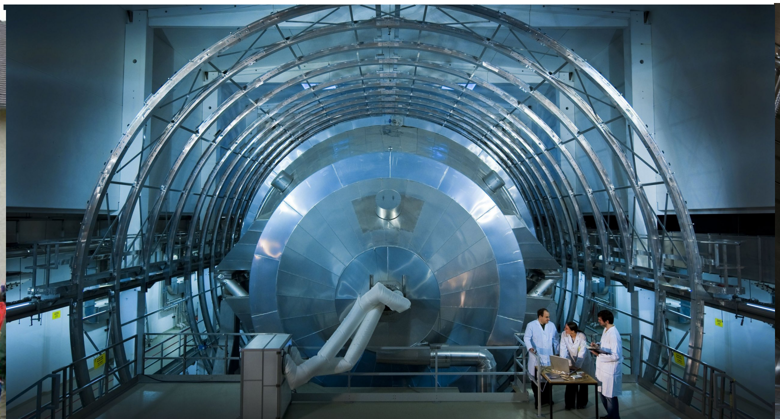
Workshop: New-ν Physics: From Colliders to Cosmology, Durham Univesity 2025

Introduction

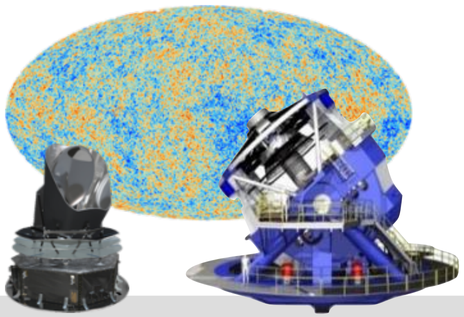
- Overview of the KATRIN experiment;
  - Observation of the **endpoint of the tritium β spectrum** - weak decay kinematics;
  - High energy resolution achieved using a Magnetic Adiabatic Collimation with an Electrostatic (**MAC-E**) filter.
- KATRIN **neutrino mass results** KNM1-KNM5 - released in 2024;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

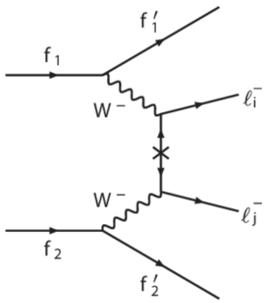
Future of the KATRIN experiment (R&D phase):

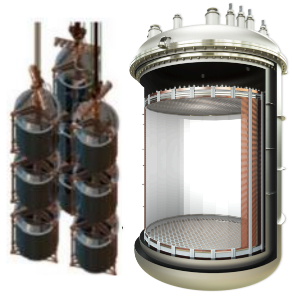
- **Improved resolution** through quantum sensors of the **MMC type** in a differential measurement approach;
- Reduced systematic uncertainties by employing an atomic tritium source instead of the current molecular source.

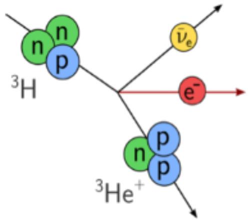



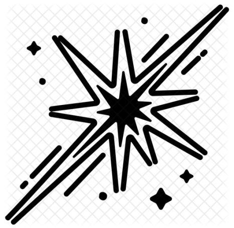

Neutrino Mass Observables





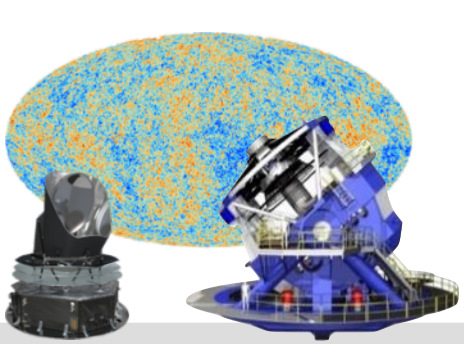
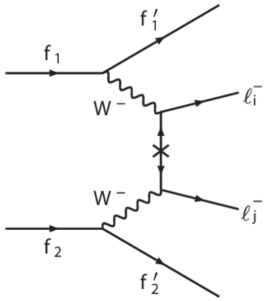


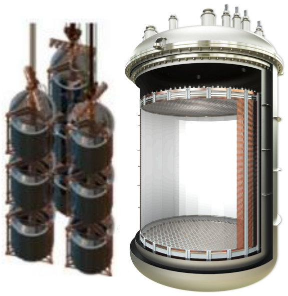
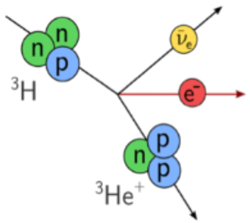


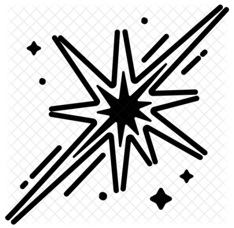


	Cosmology	Search for 0νββ	Direct Neutrino Mass Measurement
Observable	$\sum m_i = m_1 + m_2 + m_3$	$m_{\beta\beta} = \left\lvert \sum_i U_{ei}{}^2 m_i \right\rvert$	$m_\beta{}^2 = \sum_i \lvert U_{ei}\rvert^2 m_i{}^2$
Present upper limit	<0.12 eV (<0.064 eV)	< 0.156 eV	< 0.45 eV
Model dependence	Multi-parameter 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 (^3H, ^{163}Ho) - Time-of-flight measurements (ν from super novas)

Neutrino Mass Observables



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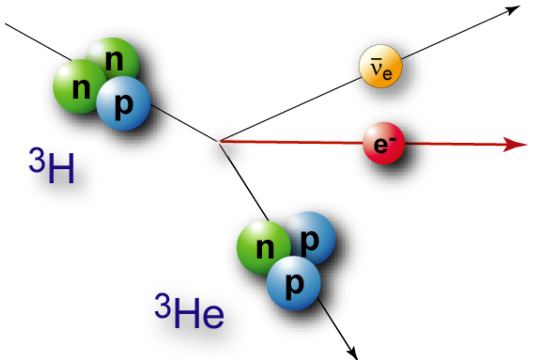
Neutrino Mass from Tritium Decay

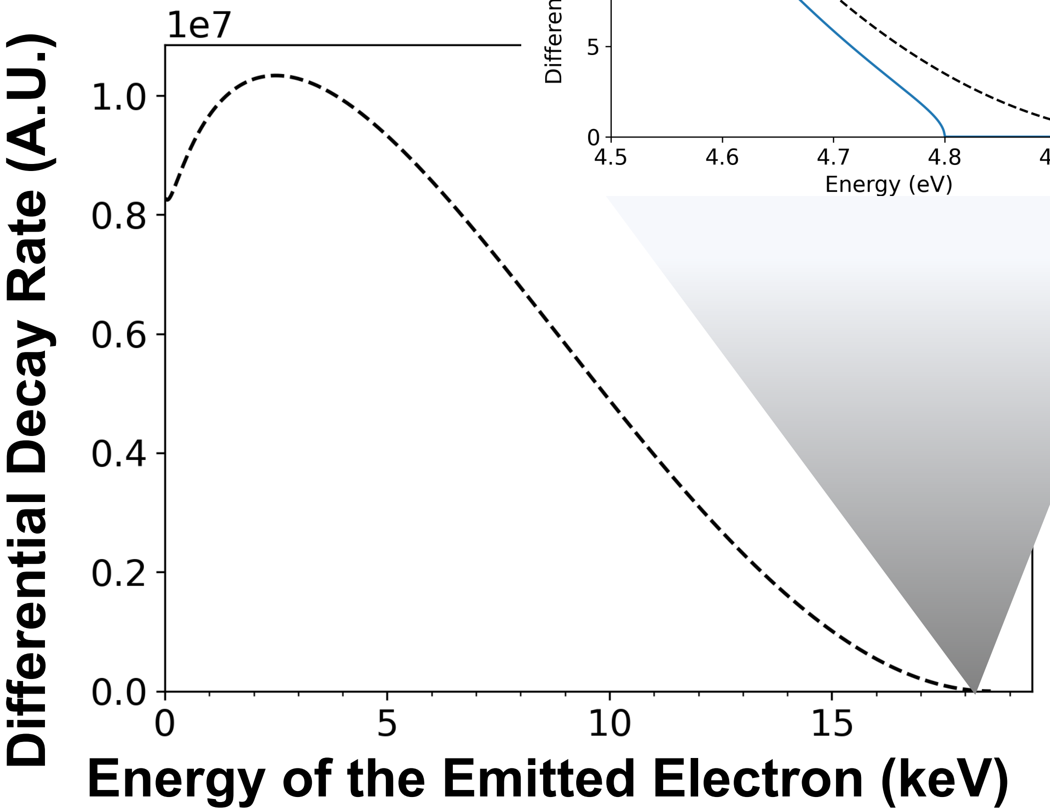
Why Tritium?

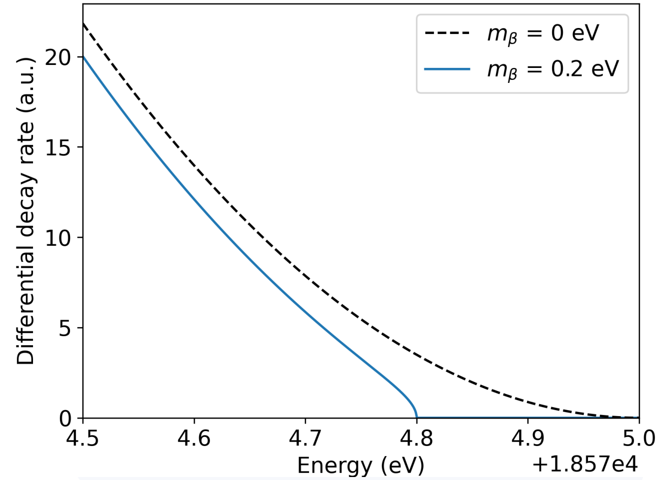
$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$

- 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**.





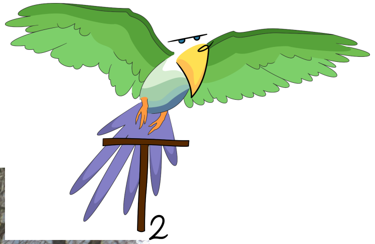


Challenges:

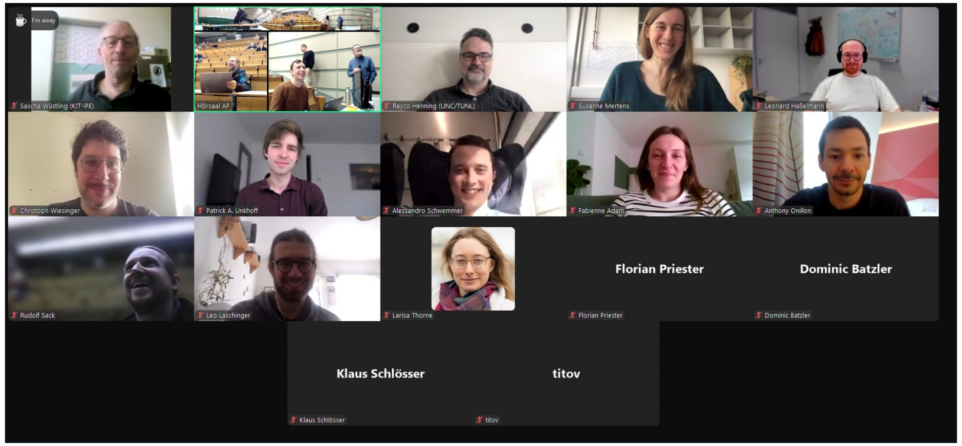
- Low event rate near the endpoint → requires a **high luminosity source** and **low background**;
- Distortion is on the scale of the neutrino mass → **good energy resolution** required;
- Precise modelling of the spectral shape and hardware stability over the years.

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

KATRIN Collaboration



49th Collaboration Meeting in Münster (2025)



**The international KATRIN collaboration:
≈150 people from 24 institutions in 7 countries**

KIT Karlsruher Institut für Technologie · MIT · Berkeley Lab · Humboldt-Universität zu Berlin · Nuclear Physics Institute · cea · Universität Bonn · Università degli Studi di Milano Bicocca · INFN · Politecnico Milano 1863

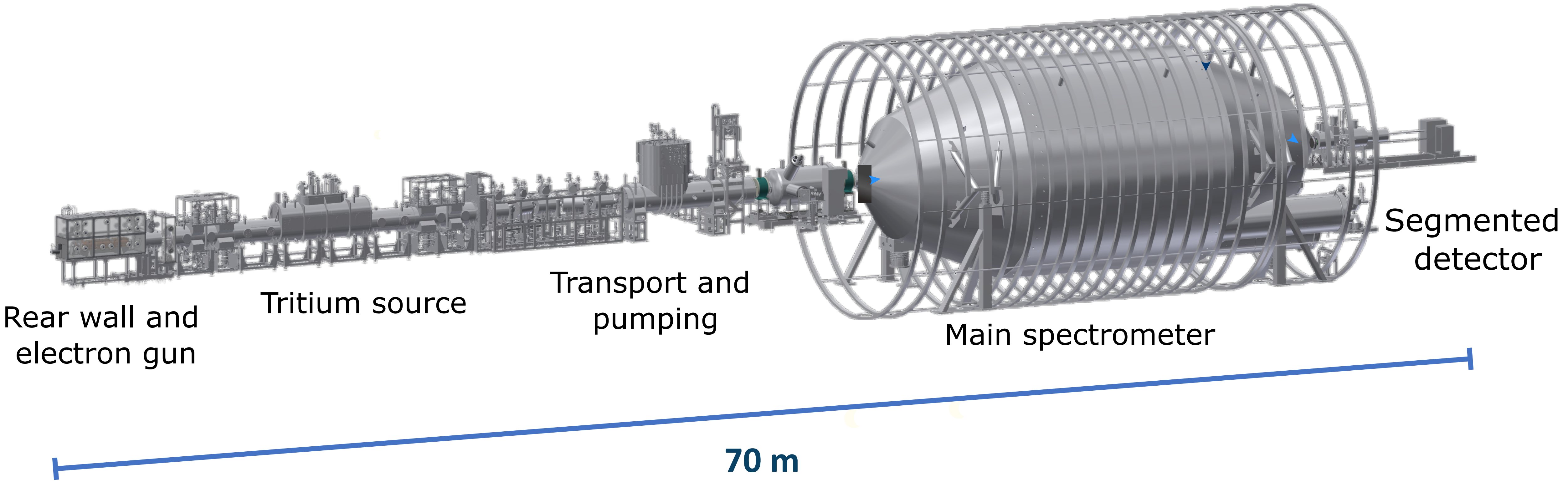
TUM · Bergische Universität Wuppertal · Universität Heidelberg Zukunft seit 1386 · Max-Planck-Institut für Physik · Chula Chulalongkorn University

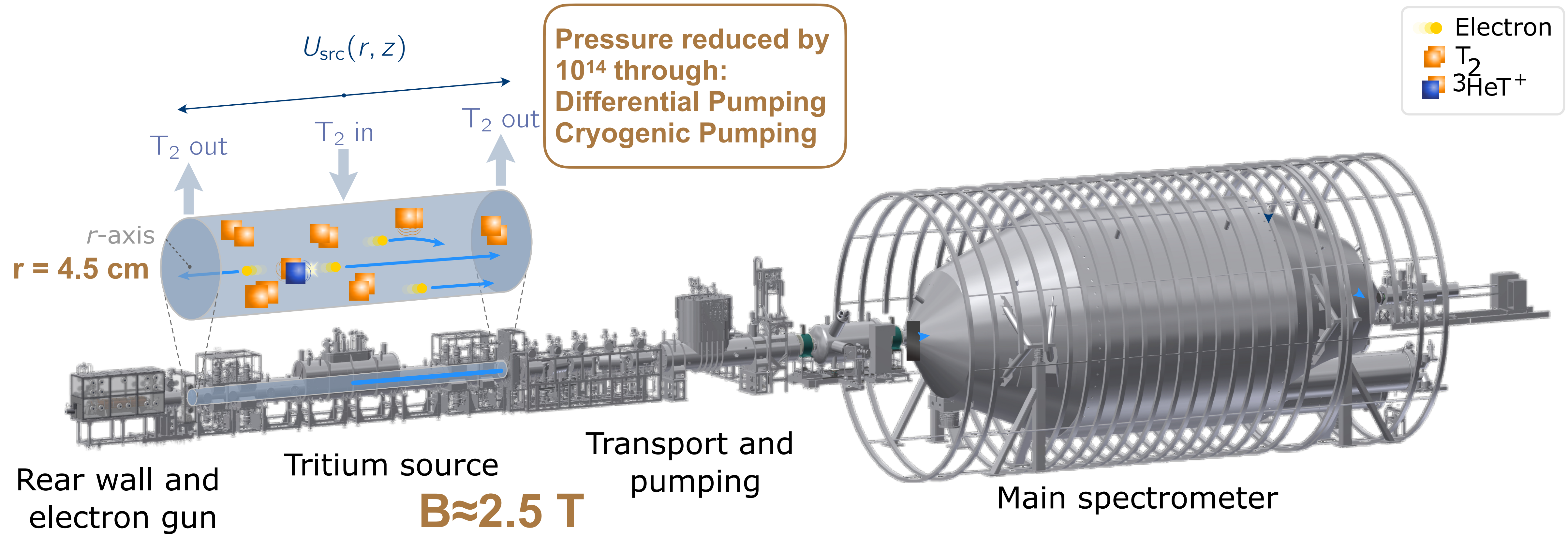
The University of North Carolina at Chapel Hill · University of Washington · Johannes Gutenberg Universität Mainz · Bundesministerium für Bildung und Forschung · DFG

Carnegie Mellon University · Universität Münster · UAM Universidad Autónoma de Madrid · HELMHOLTZ Research for Grand Challenges · Czech Republic:

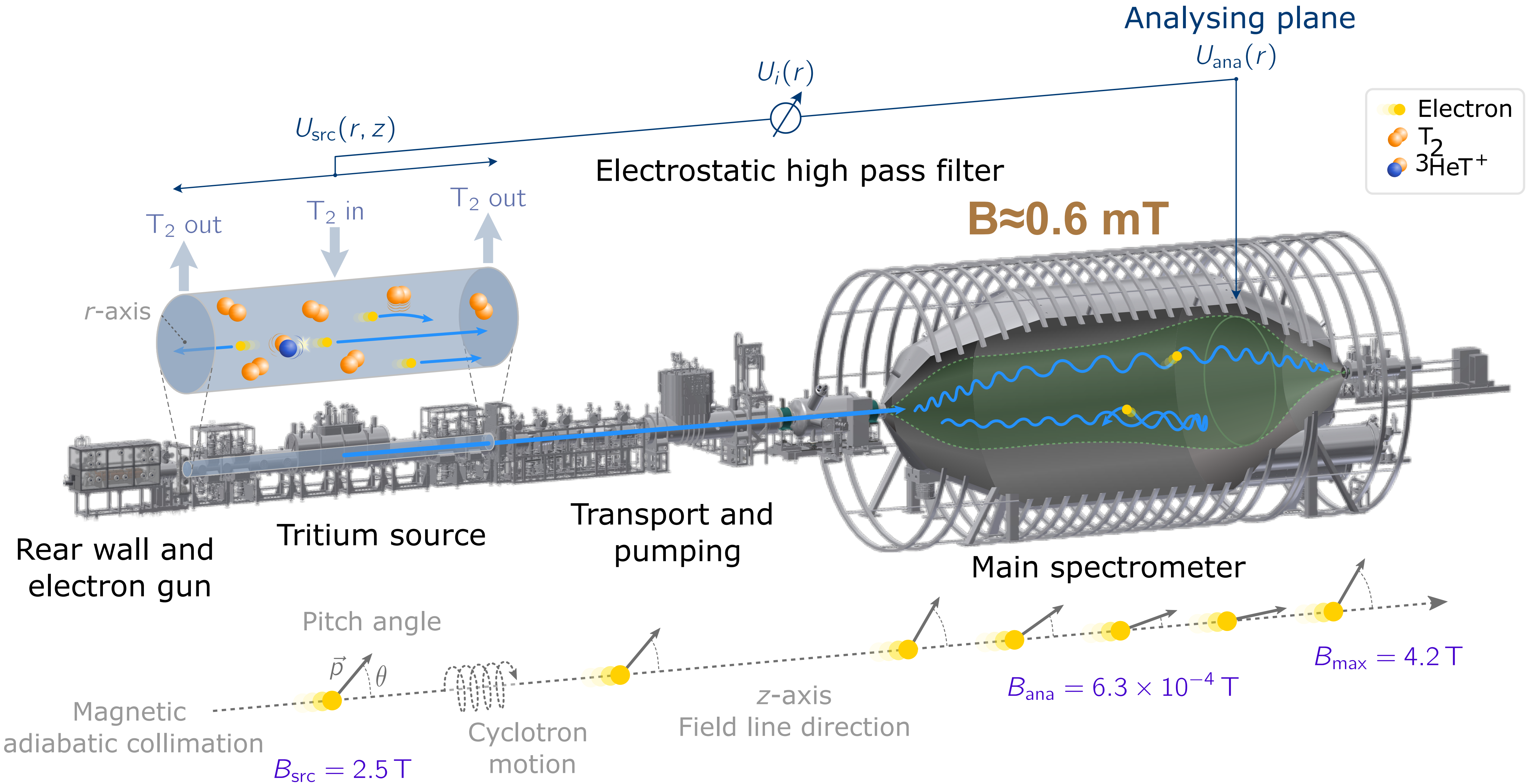
INFN · U.S. Department of Energy · Office of Science · Max Planck Gesellschaft · erc

Working Principle



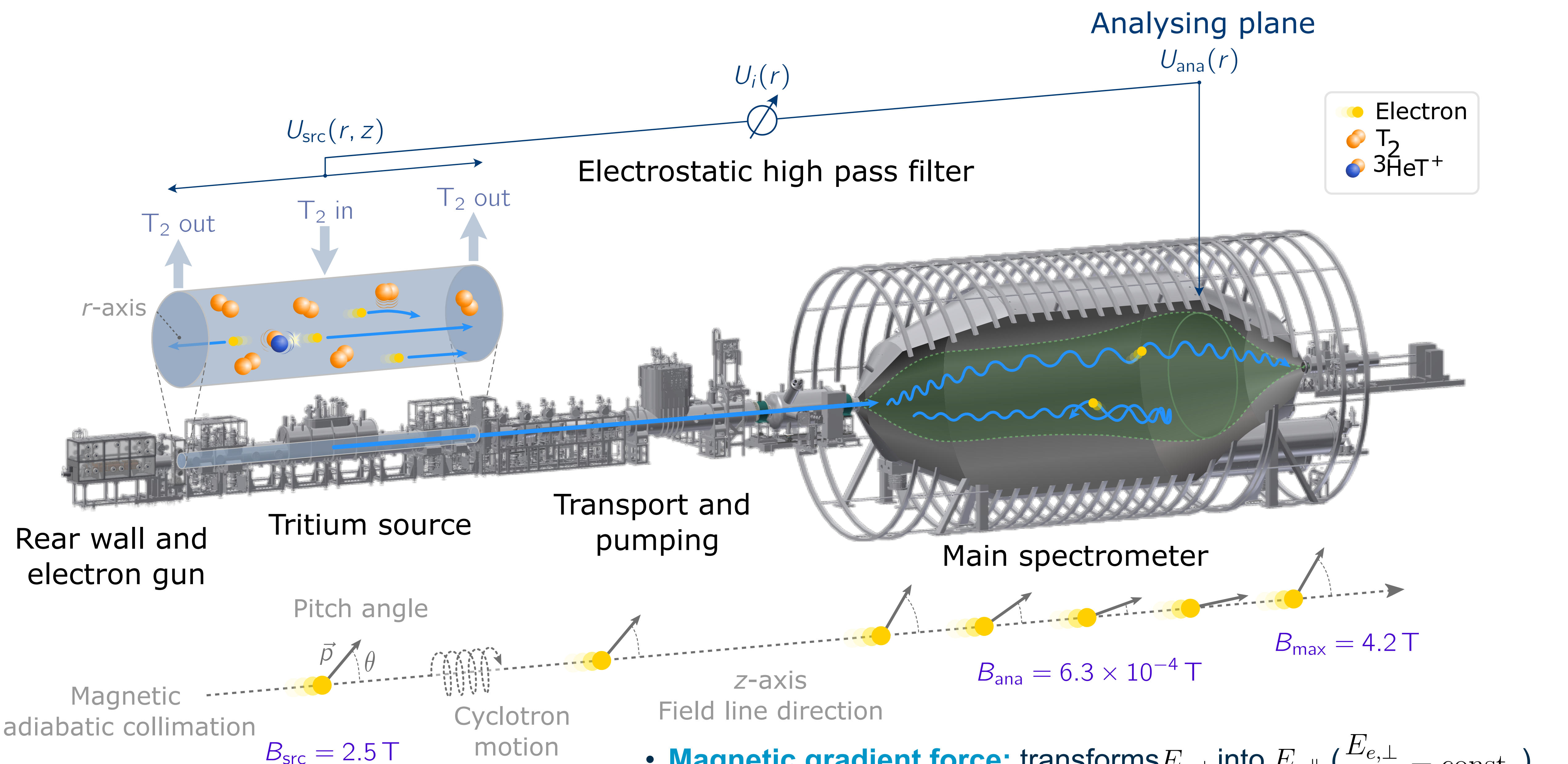


- **High-activity molecular** T_2 source (100 GBq) operated as a windowless gaseous tritium source (WGTS).
- Column density of **$\rho d = 4.20\times10^{21}$ T_2/m^2** (after KNM1)
- Flow rate of 40 g T_2/day with an isotropic purity >95%.



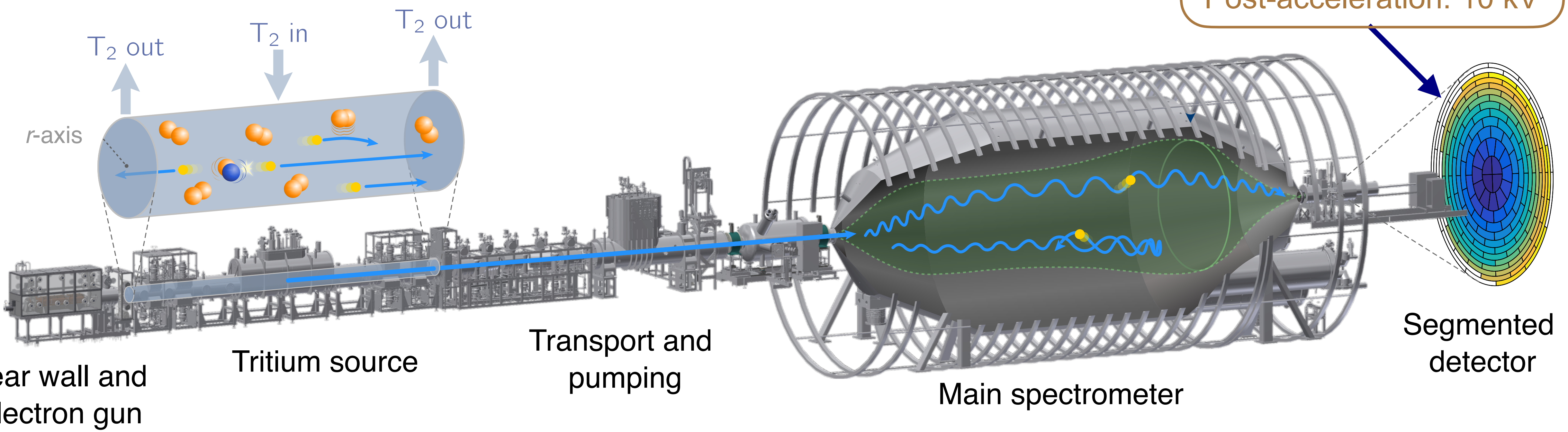
Main spectrometer: high voltage (~18 kV) and ultra-low vacuum pressure **<10^{-11} mbar**

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



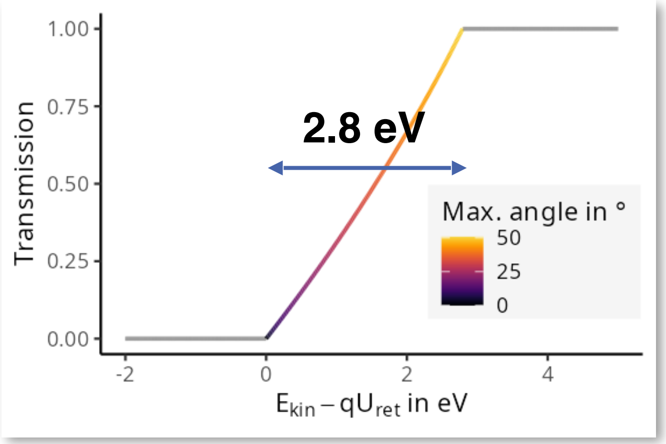
- **Magnetic gradient force:** transforms $E_{e,\perp}$ into $E_{e,\parallel}$ ($\frac{E_{e,\perp}}{B} = \mathrm{const.}$)
- **Electrostatic field:** only electrons with $E_e \sim E_{e,\parallel} > qU$ go through

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

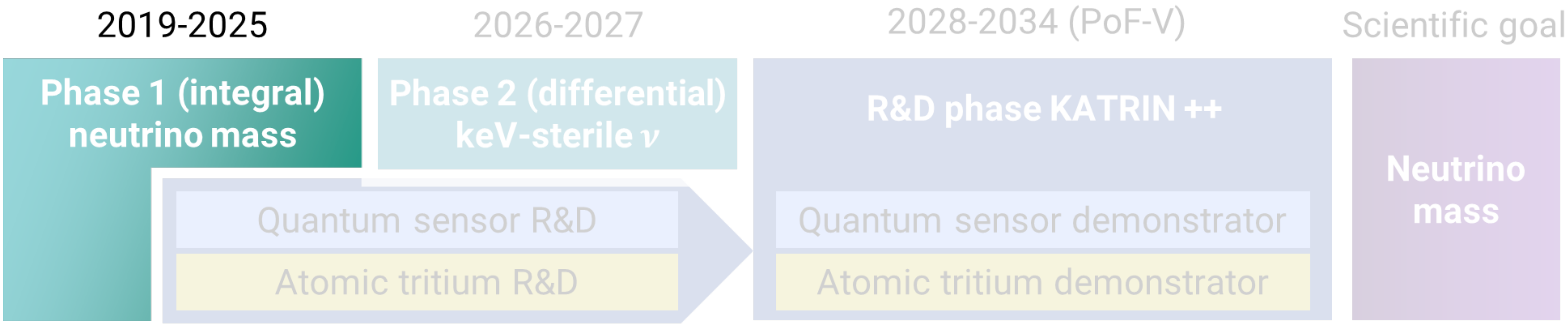


Very High Energy Resolution: $\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \sim 1\text{eV}$

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



KATRIN Timeline



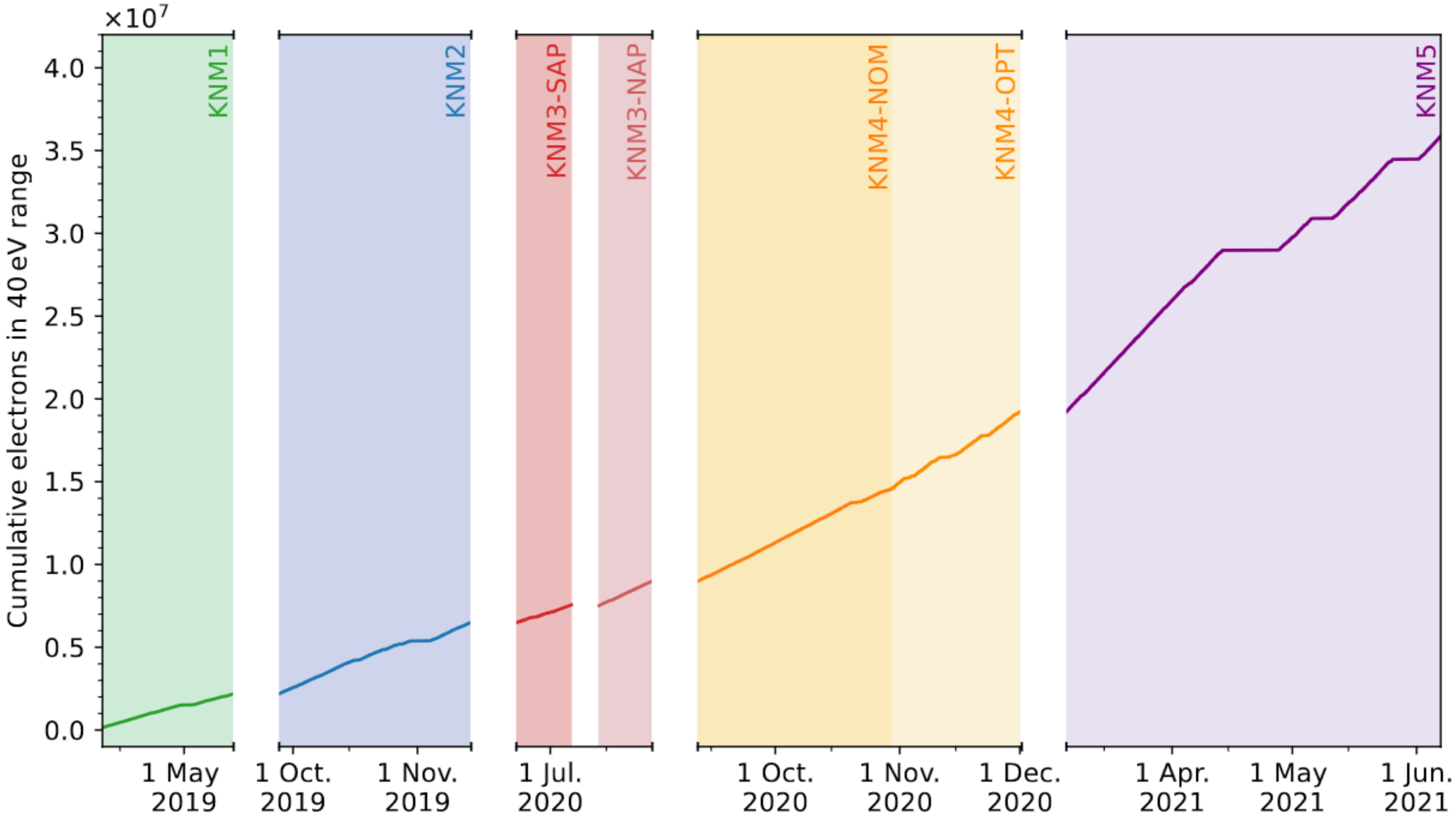
KATRIN Data Acquisition for the 2024 Result

Data Analysed: KNM1-KNM5

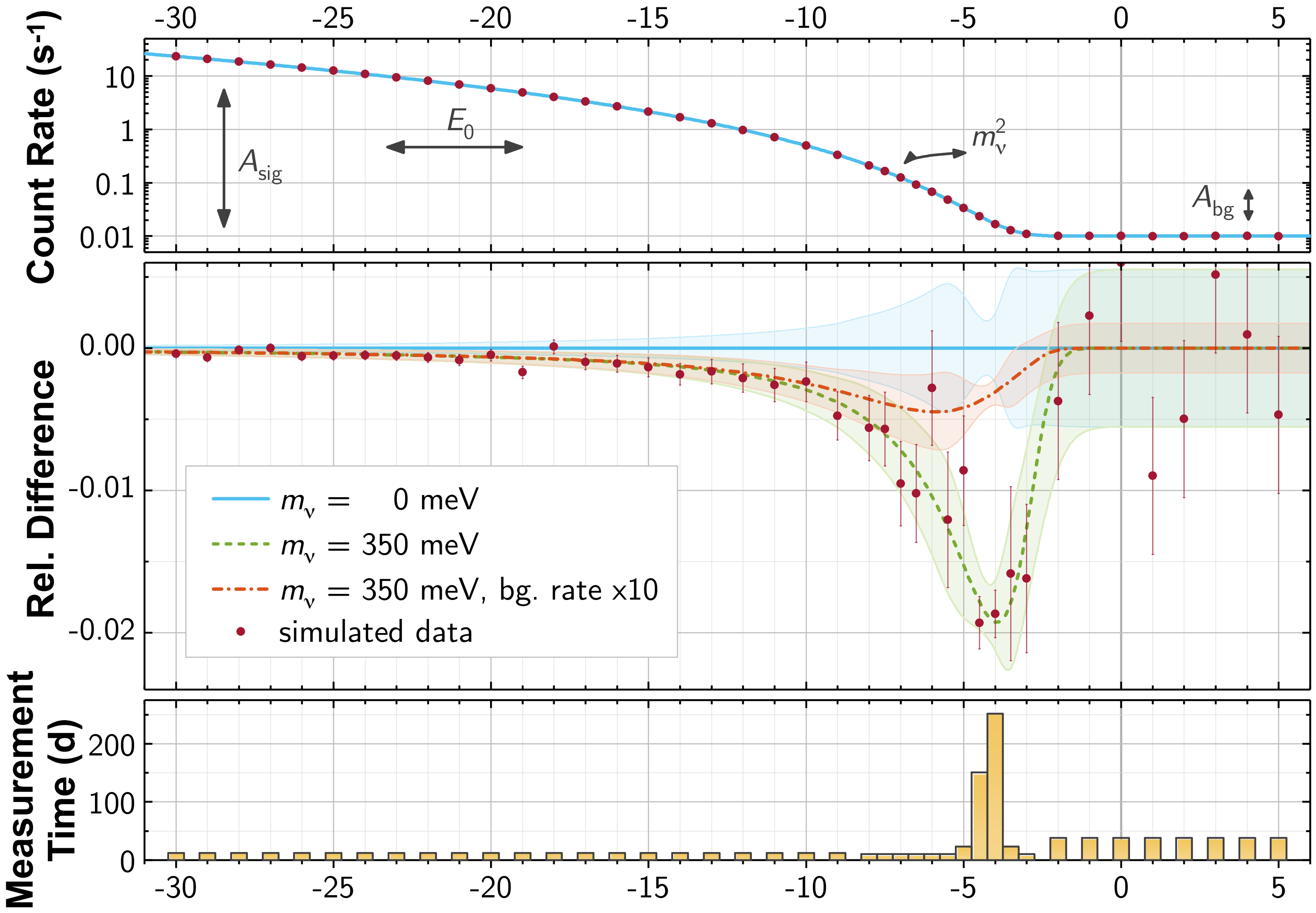
- **259** measurement days
- **1757** β-scans
- ~36 million counts

Previous Results (90% C.L):

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



Measurement Principle



Direct shape measurements of integral β-spectrum for various energies qU around the endpoint.

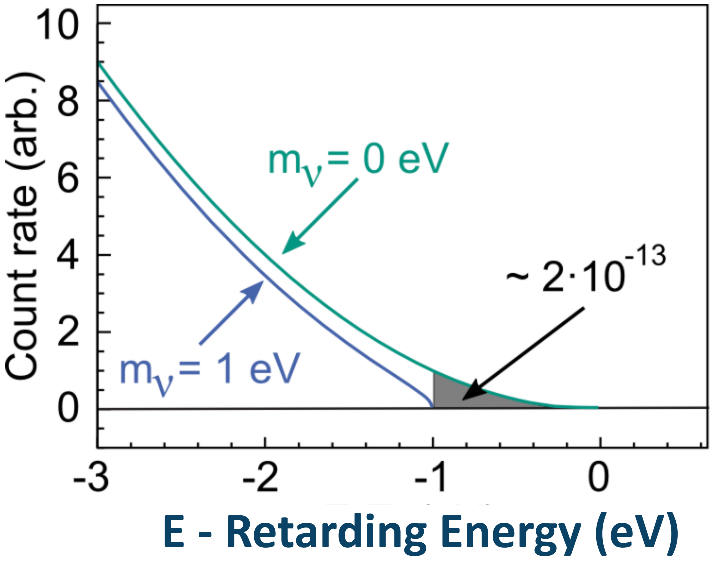
- ~40 keV below the endpoint

4 fitting parameters:

- **A_{sig}**: amplitude of the signal
- **E_0**: spectrum endpoint
- A_{bg}: background rate
- **m_ν^2**: mass of the neutrino squared

Modelling the Tritium Spectrum

Tritium Spectrum Rβ



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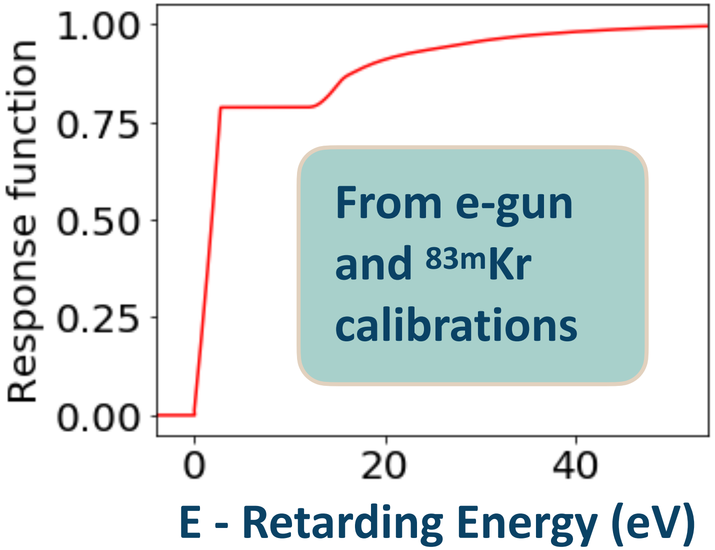
Experimental Response f



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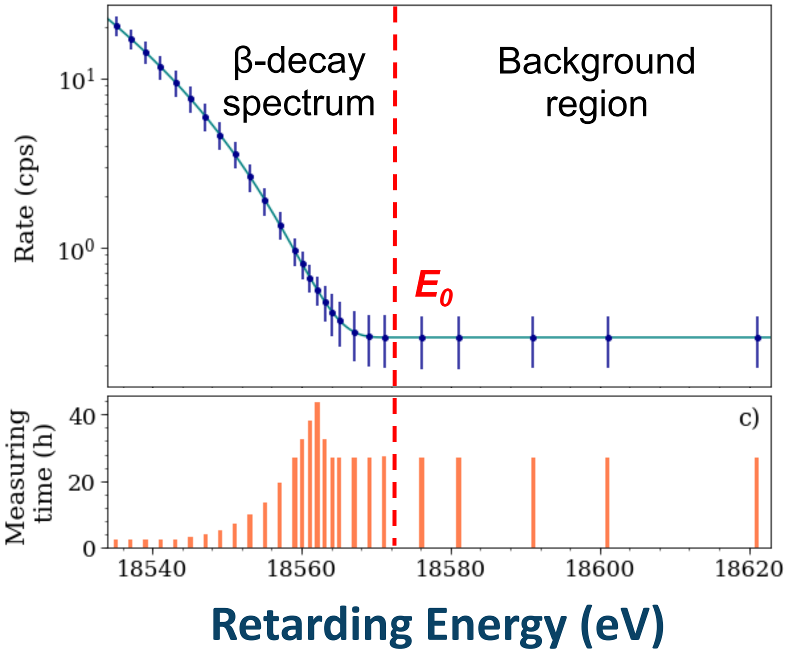
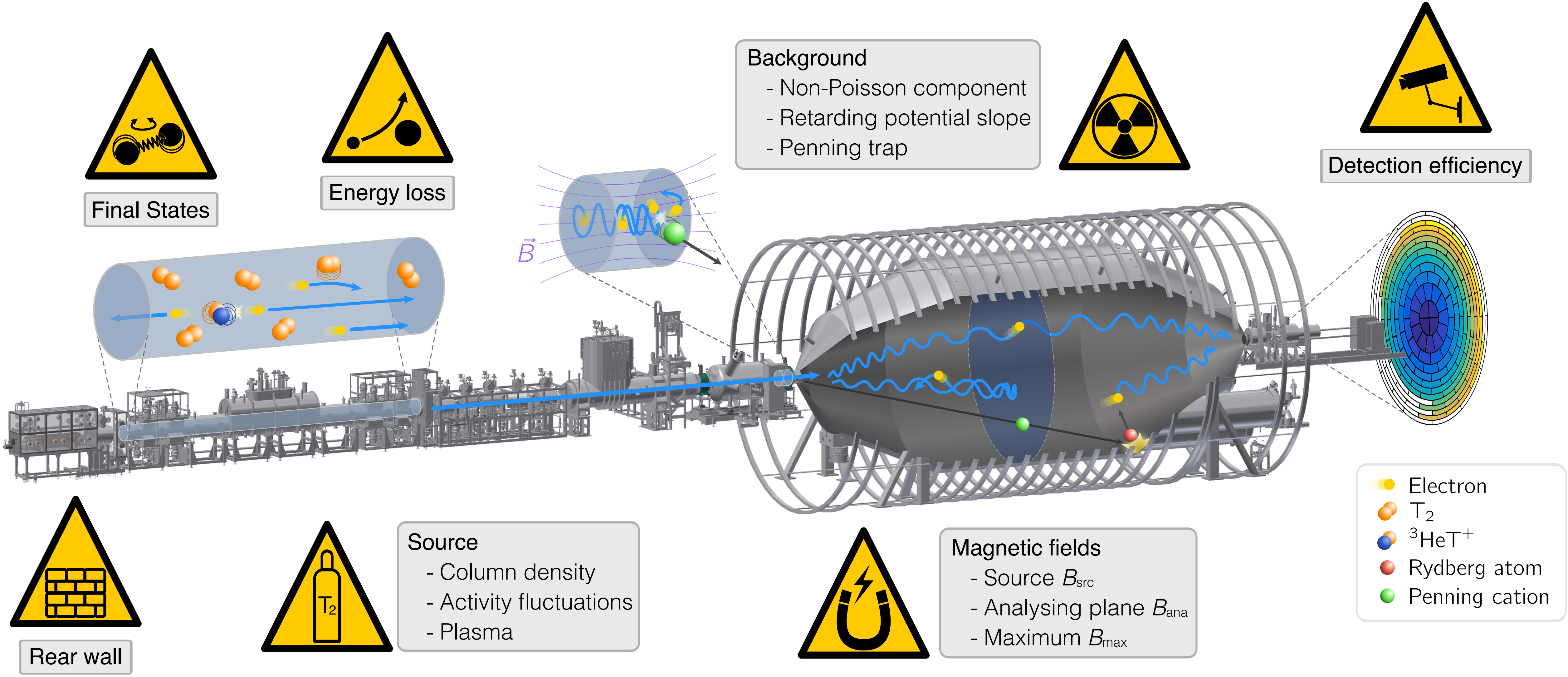


$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E)dE + R_{bg}$$

- Stack data points with **identical** measurement conditions.
- Analysis window: **[E_0 - 40 eV, E_0 + 135 eV]**.
- Fit model informed by **theoretical** and **experimental** inputs (electron gun, ^{83m}Kr calibrations, monitoring systems, …)

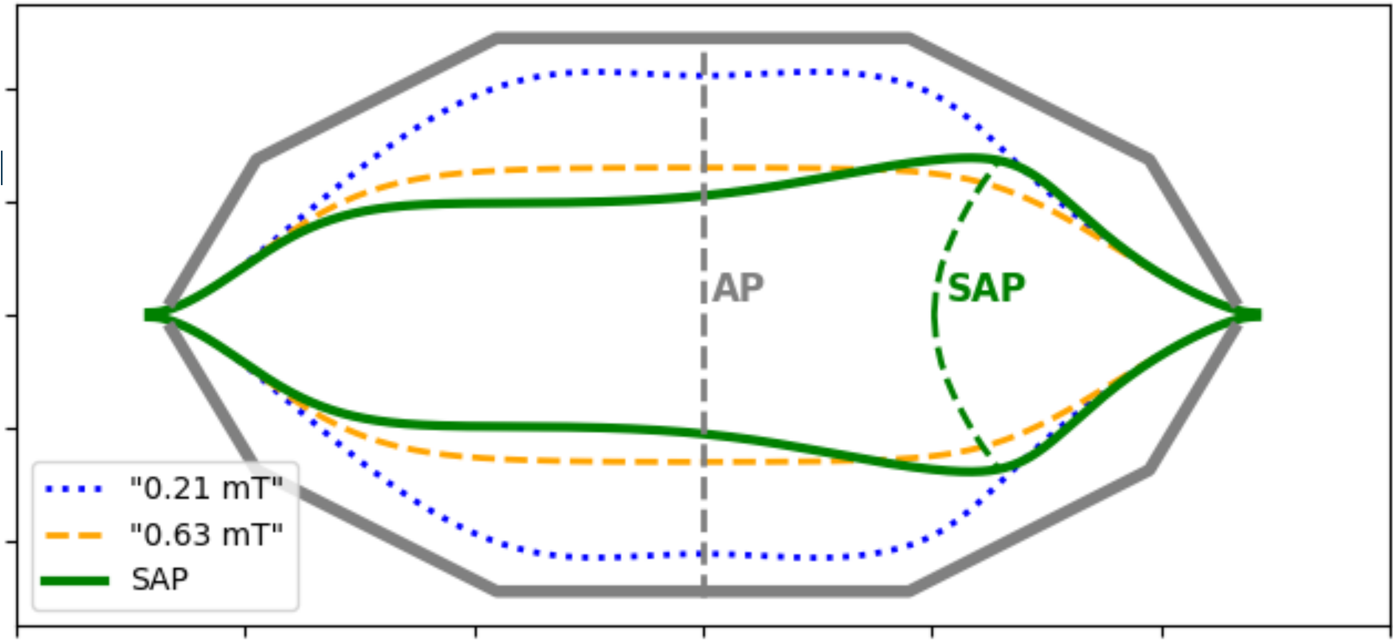
Systematic Uncertainties

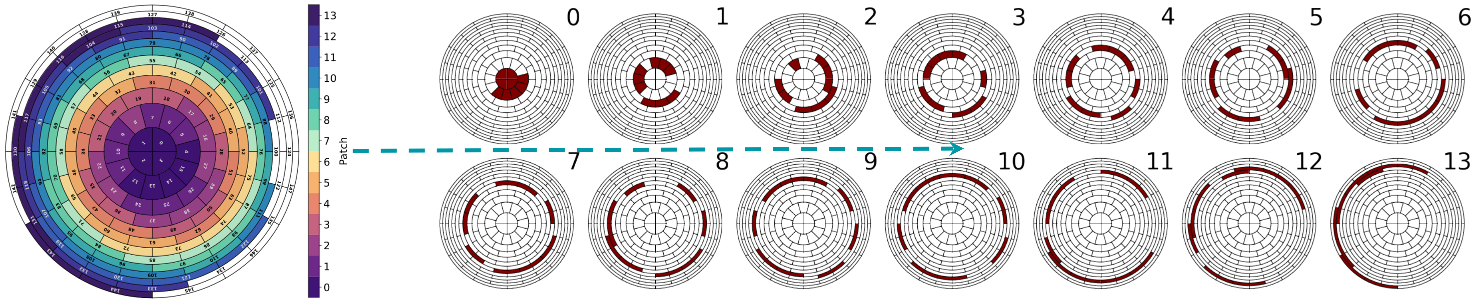


Data Analysis Improvements

- **Shifted analysis configuration** (from KNM3, 2020 onwards, [1]):
  - Reduced background by a **factor of 2** (mainl from platted ^{210}Pb)

  But, this comes with trade-offs:
  - Smaller source volume mapped onto detector;
  - Inhomogeneous EM-fields:
    - Data segmented is 14 bins;
    - Field Calibration required.
- Improved Calibrations:
  - **^{83m}Kr co-circulation:** Probe of electric potential variation in the source and field mapping in the spectrometer;
  - **Electron gun:** energy loss through scat in the source and tritium gas density.

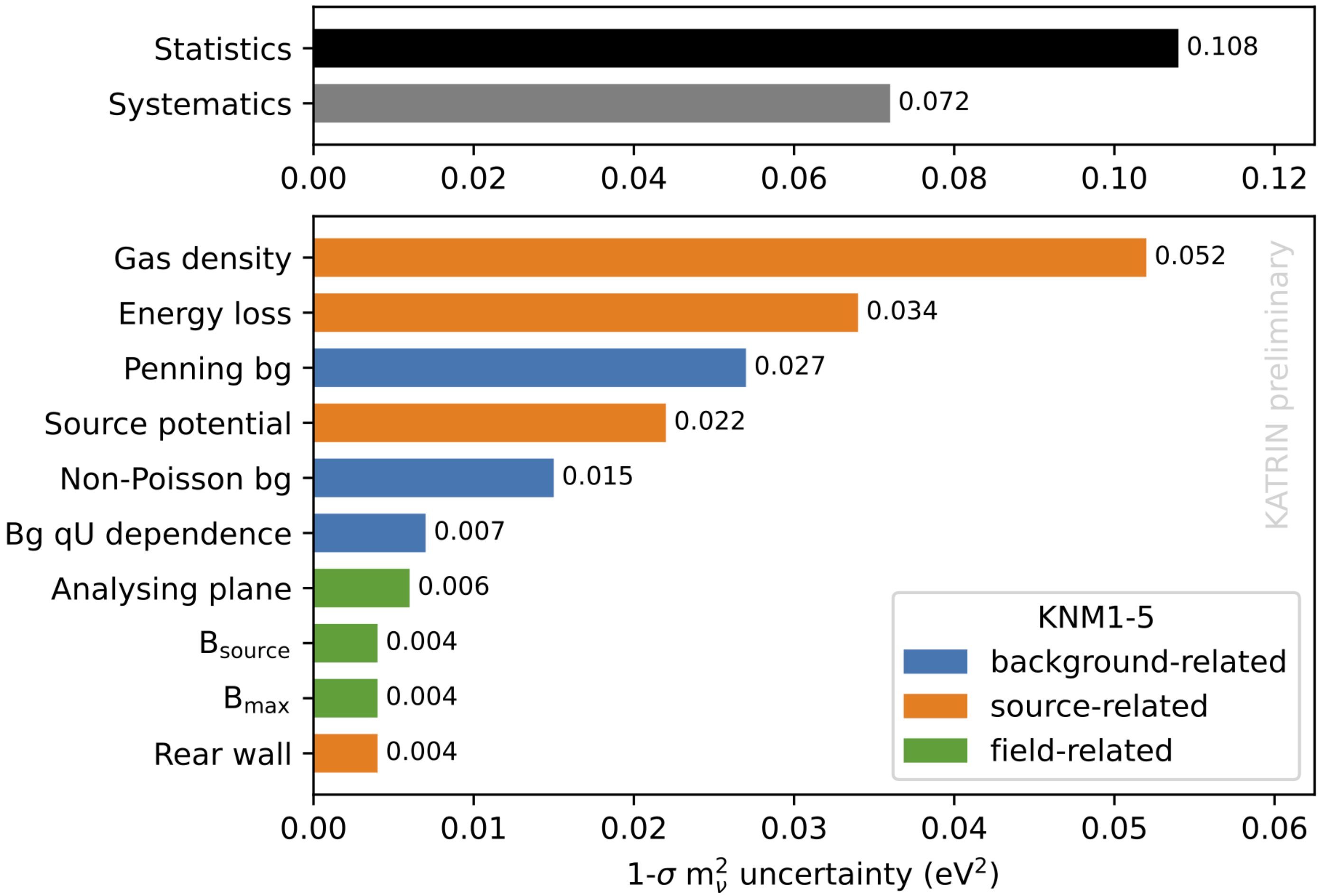




[1] A.Lokhov et al. Eur. Phys. J. C 82:258 (2022)
[2] A. Marsteller et al. JINST 17 P12010 (2022)

KATRIN Uncertainties

- Results dominated by **statistical uncertainties**;
- 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)*



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

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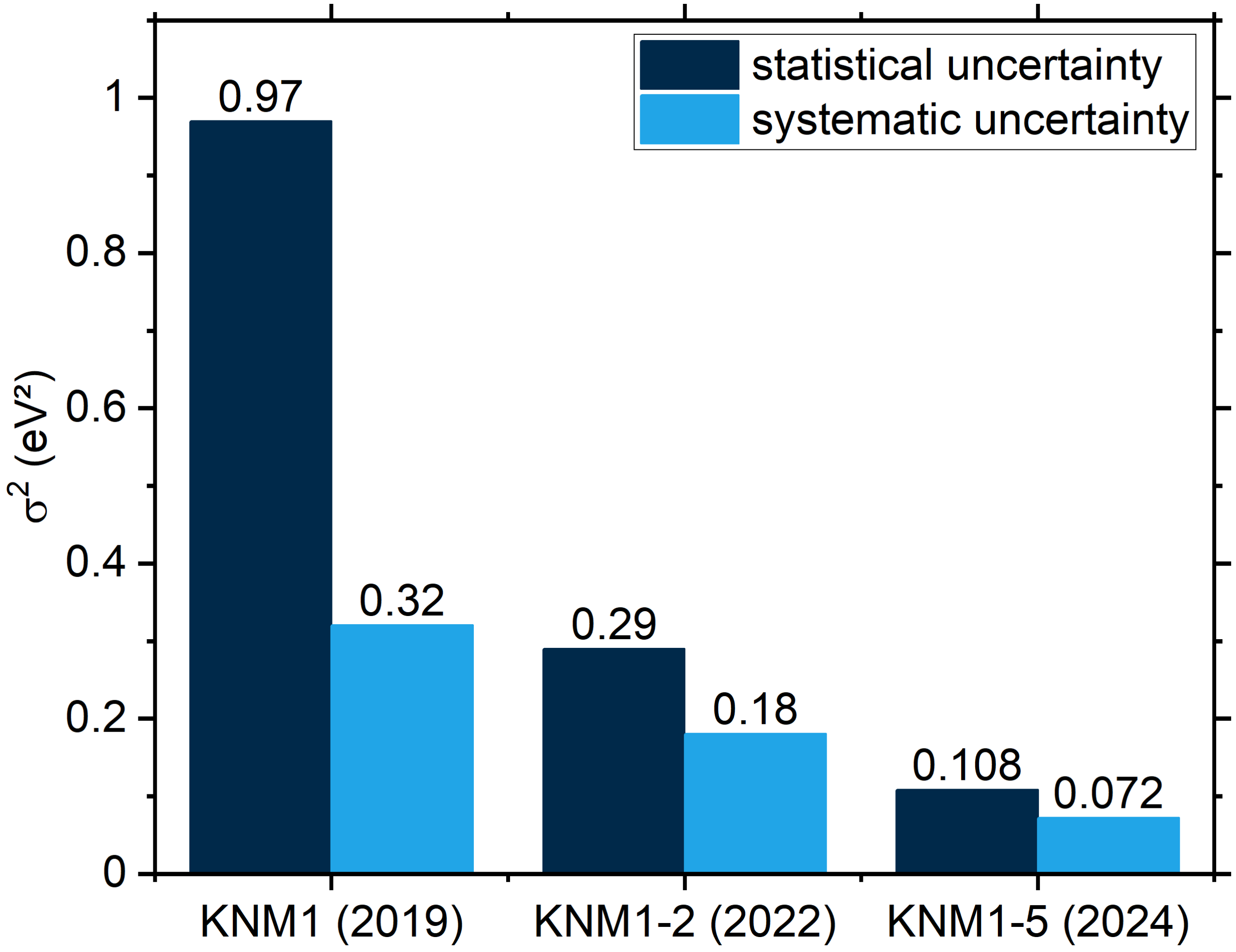
Improvement of statistics and systematics



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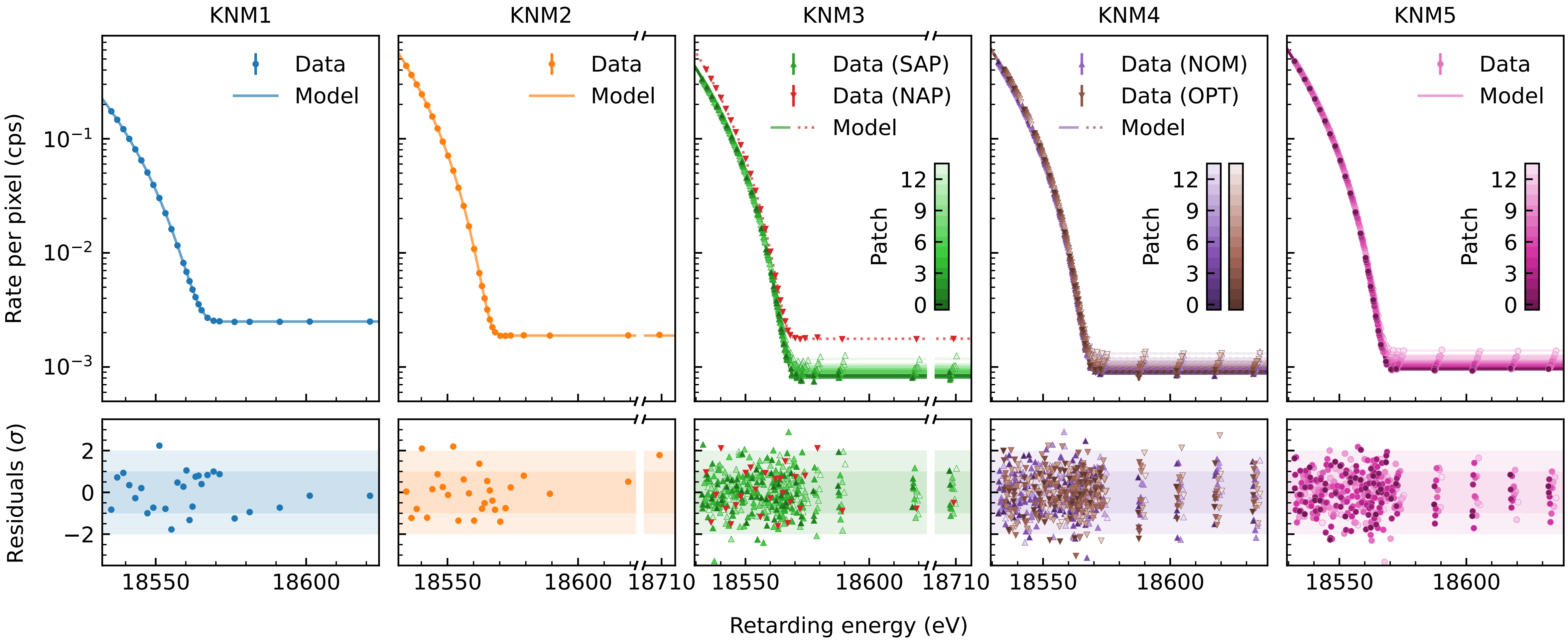
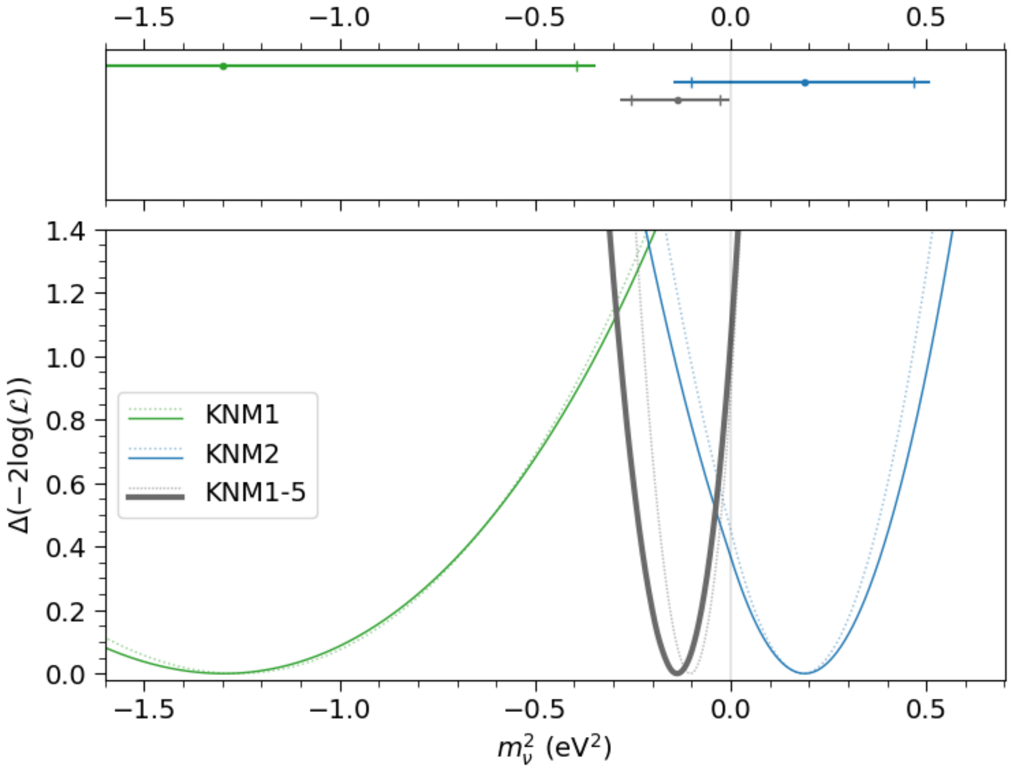


Simultaneous maximum likelihood fit with common m_ν^2 parameter - **p-value=0.84.**

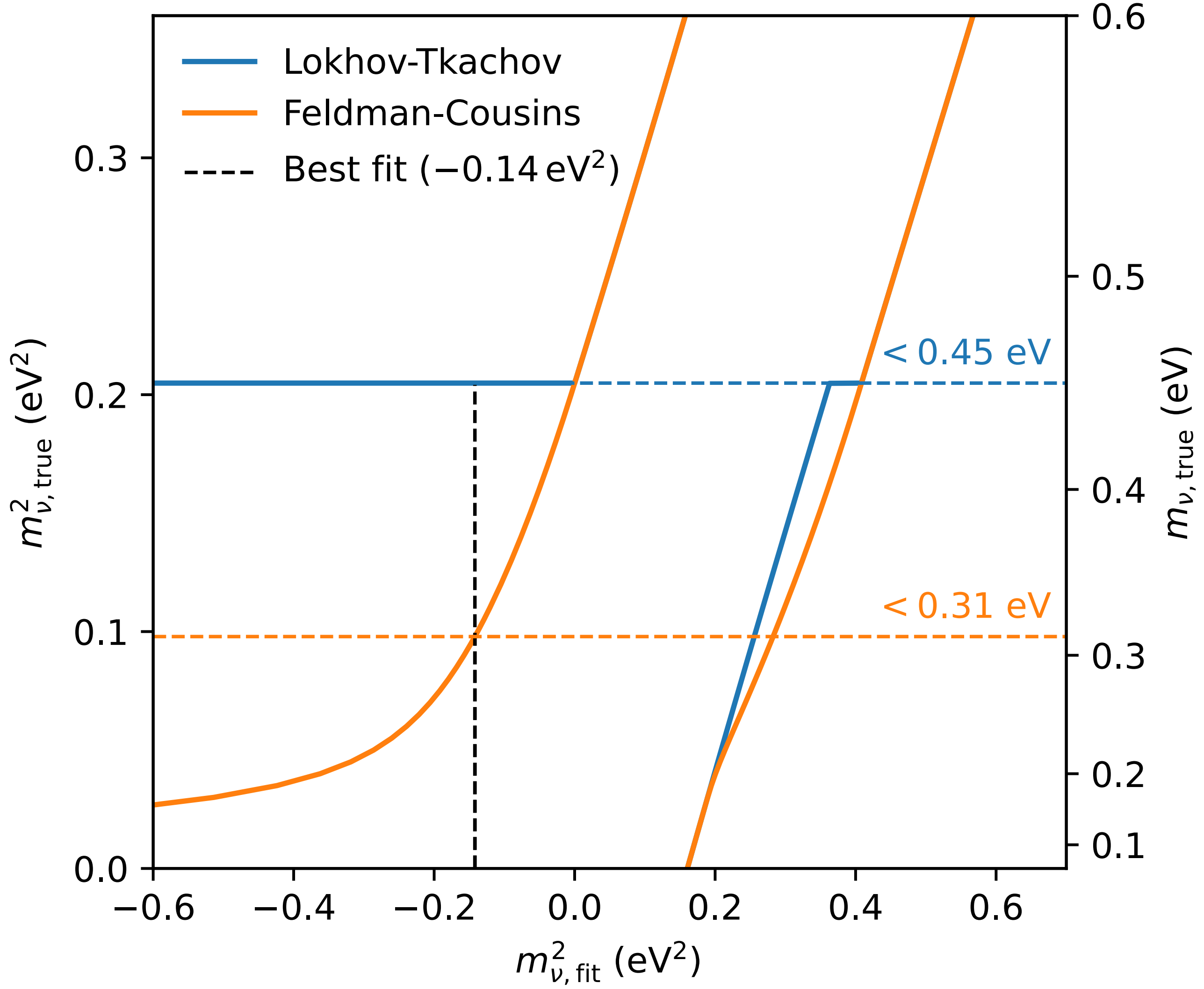
- Highly segmented data (**1609 data points**).

Fit Result



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

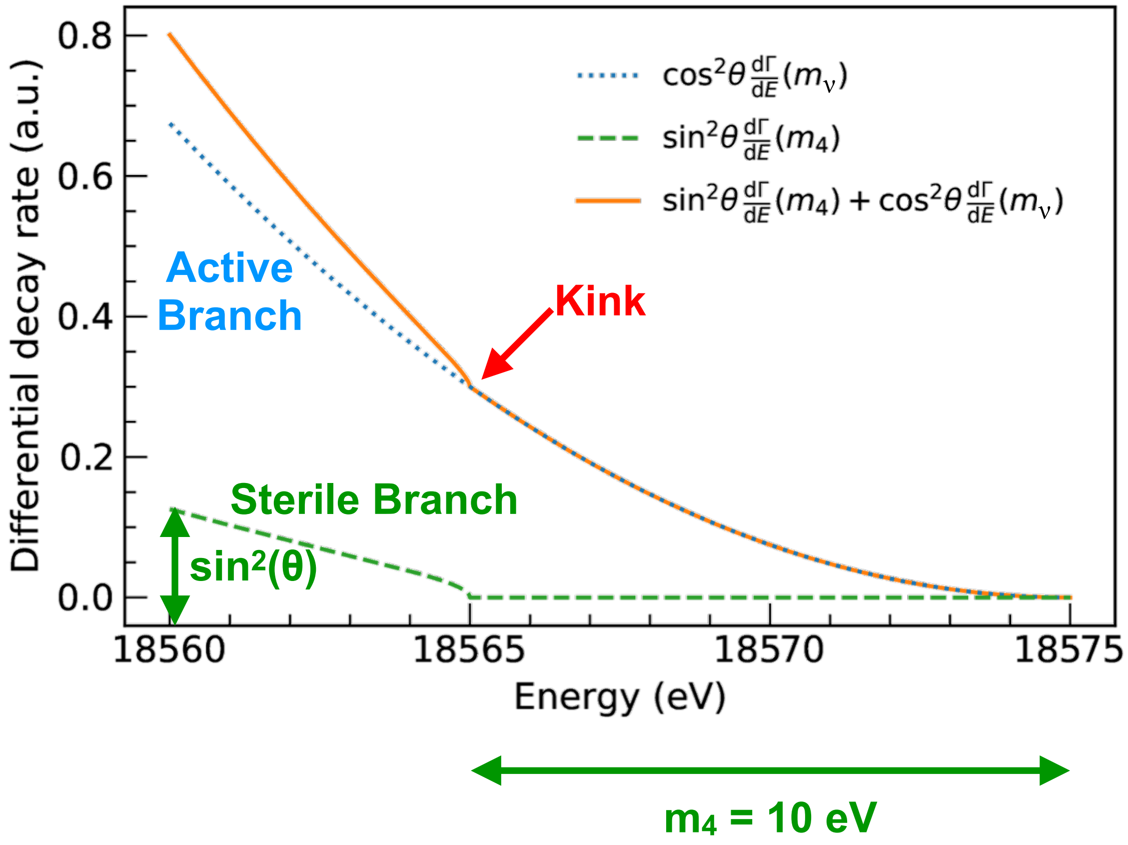
Q-value: (18 575.0 ± 0.3) eV



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

eV Sterile Neutrinos

Expected signature in KATRIN

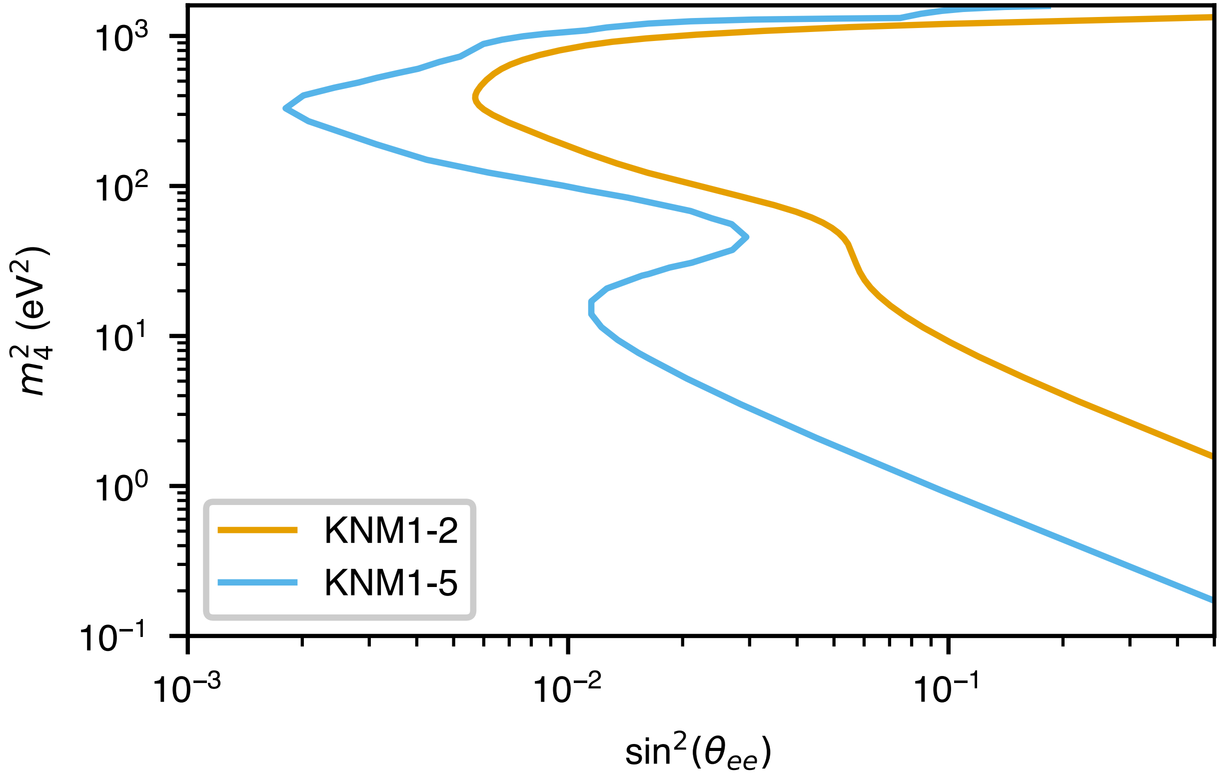


Several experimental anomalies:
- Reactor Antineutrino Anomaly (RAA, ~3σ)
- Gallium flux (~4σ)

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

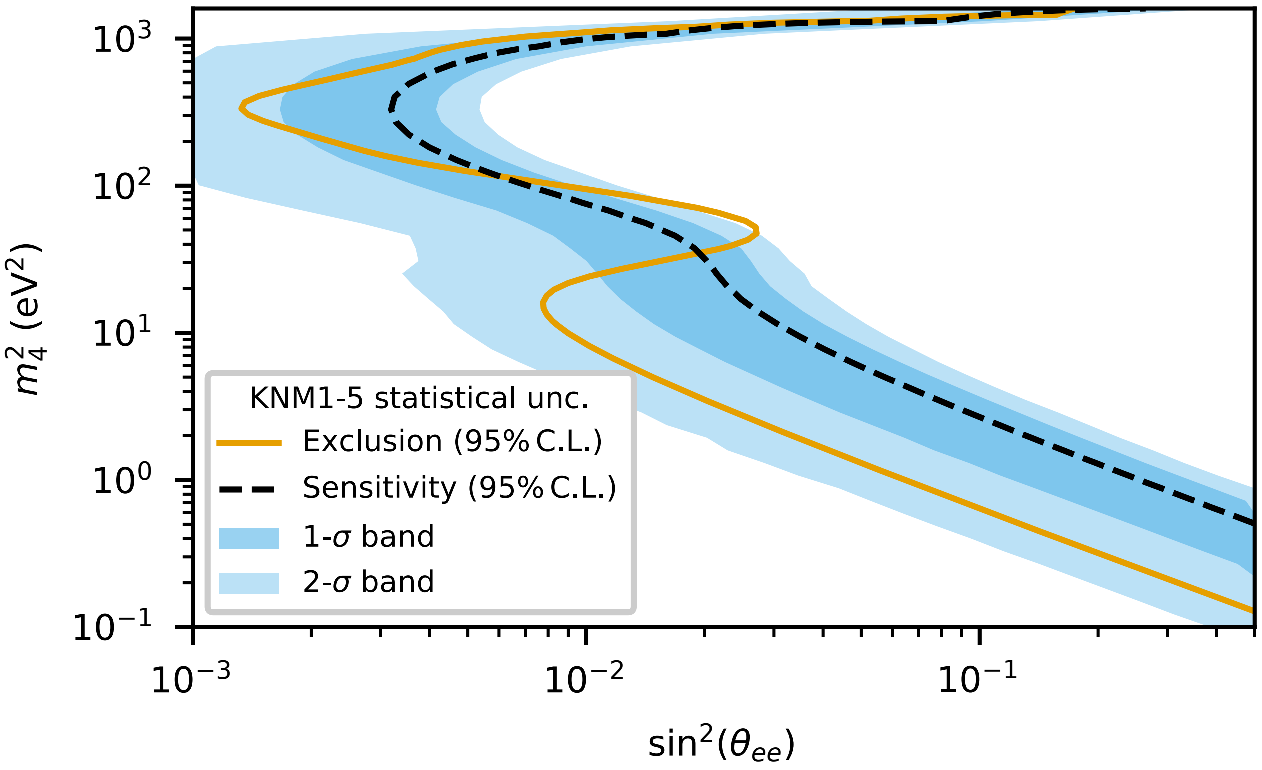
Maximum likelihood fit of model for 3ν + 1 includes two additional parameters in the fit:
- **m_4**: mass of the eV-sterile neutrino;
- **$\sin^2\theta$**: the mixing angle of the fourth neutrino.
- **m_ν:** constrained to 0 or free

Results - m_ν=0



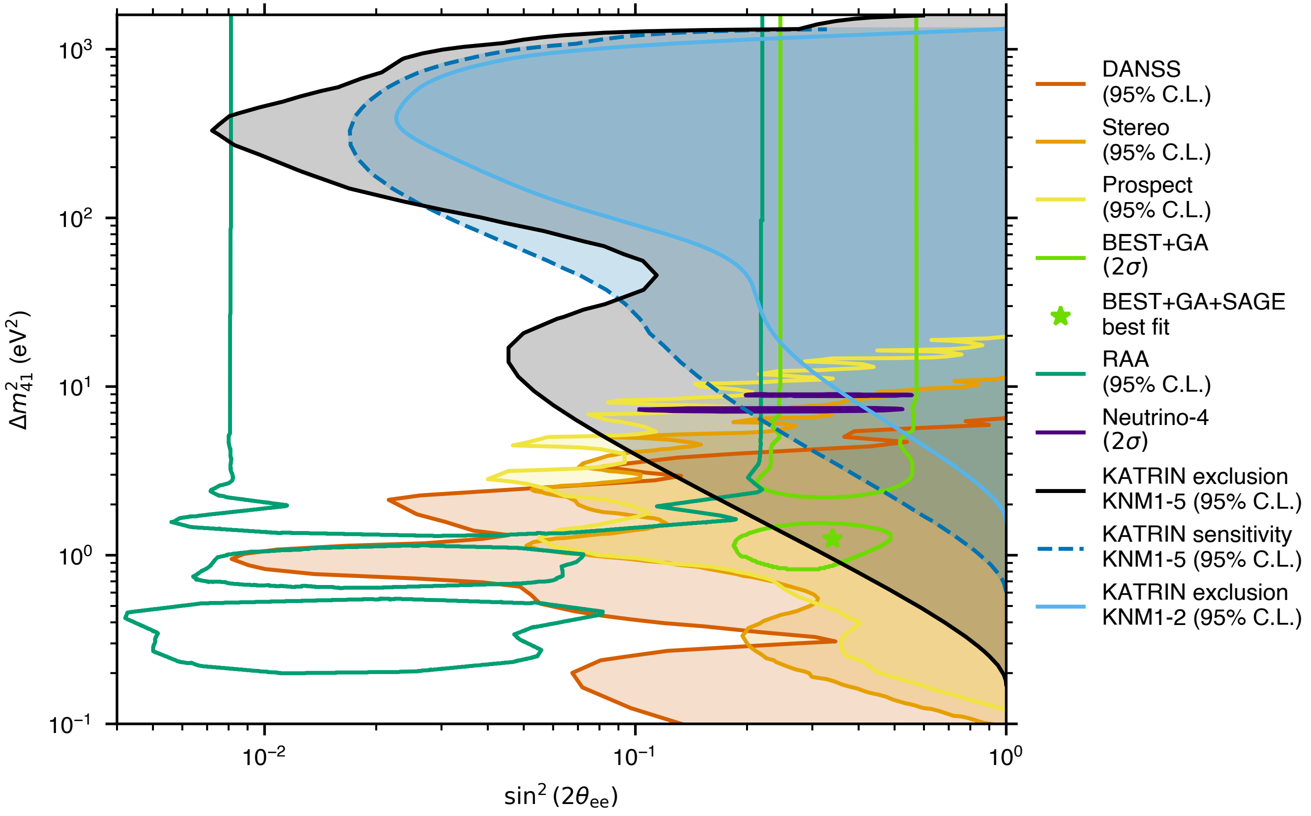
- Using the same data for the sterile neutrino searches - with a different signal model.
- No evidence found for an eV-sterile neutrino. Limits on 90% C.L presented.
- Statistical uncertainties dominate for all masses.

Results - m_ν=0

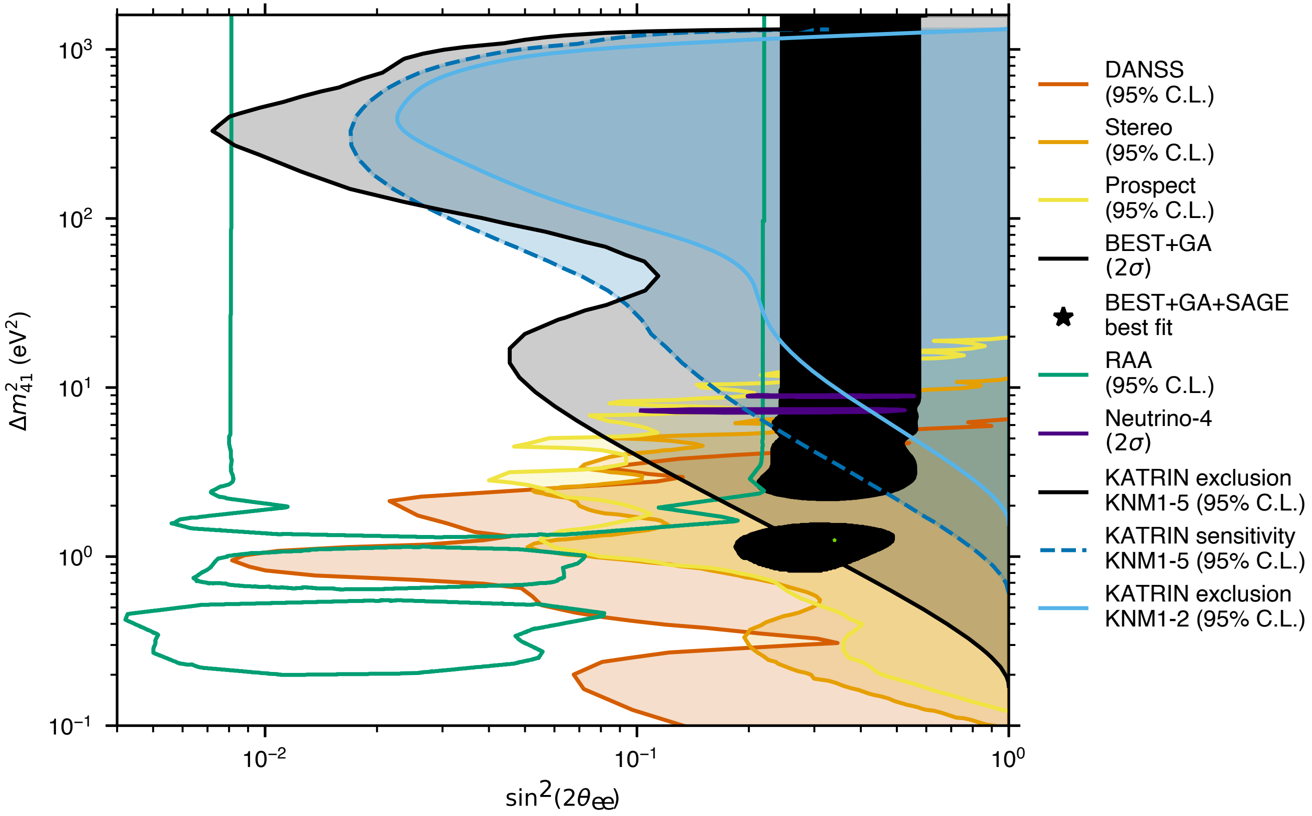


- Using the same data for the sterile neutrino searches - with a different signal model.
- No evidence found for an eV-sterile neutrino.
- Statistical uncertainties dominate for all masses.
- 1σ and 2σ statistical sensitivity bands reconstructed from simulations.
- New exclusion contour aligns with expected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

Results - m_ν=0

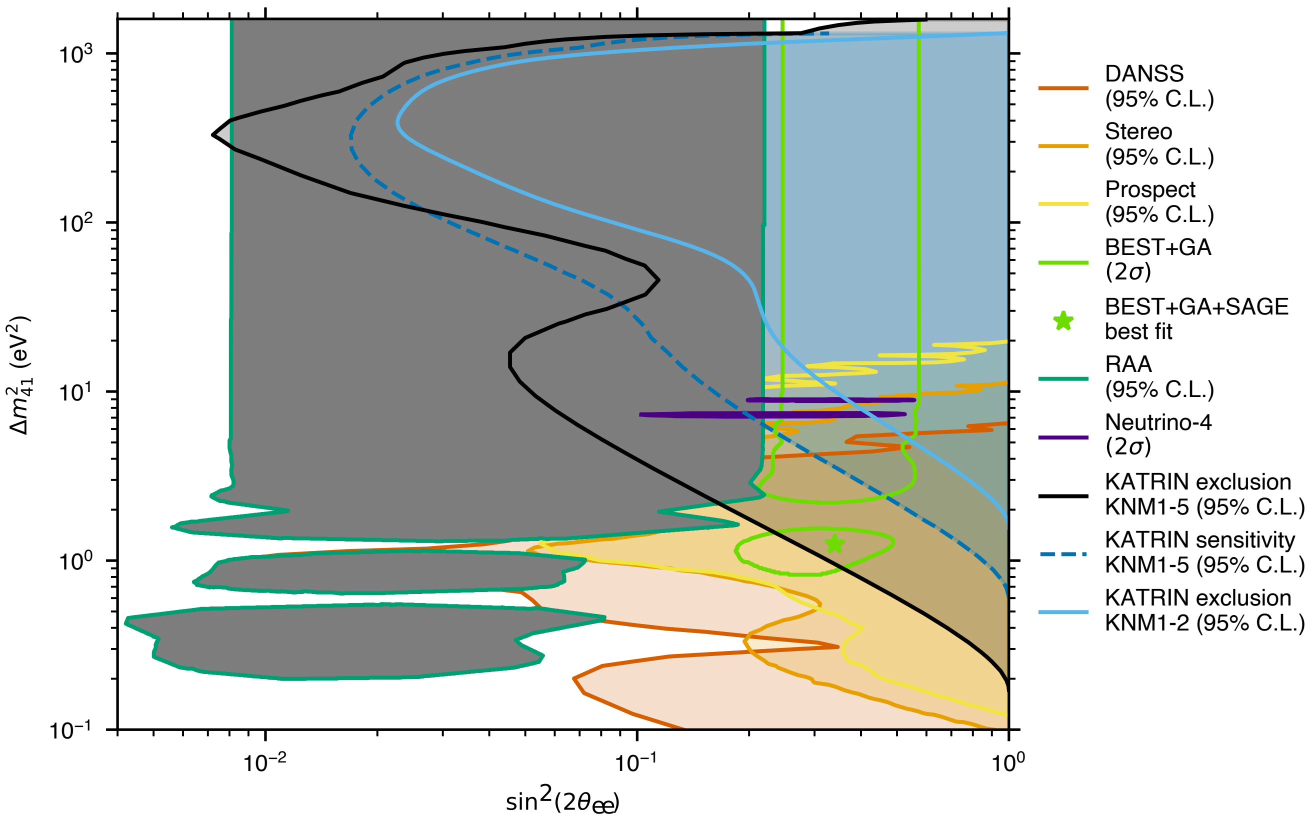


Results - m_ν=0



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

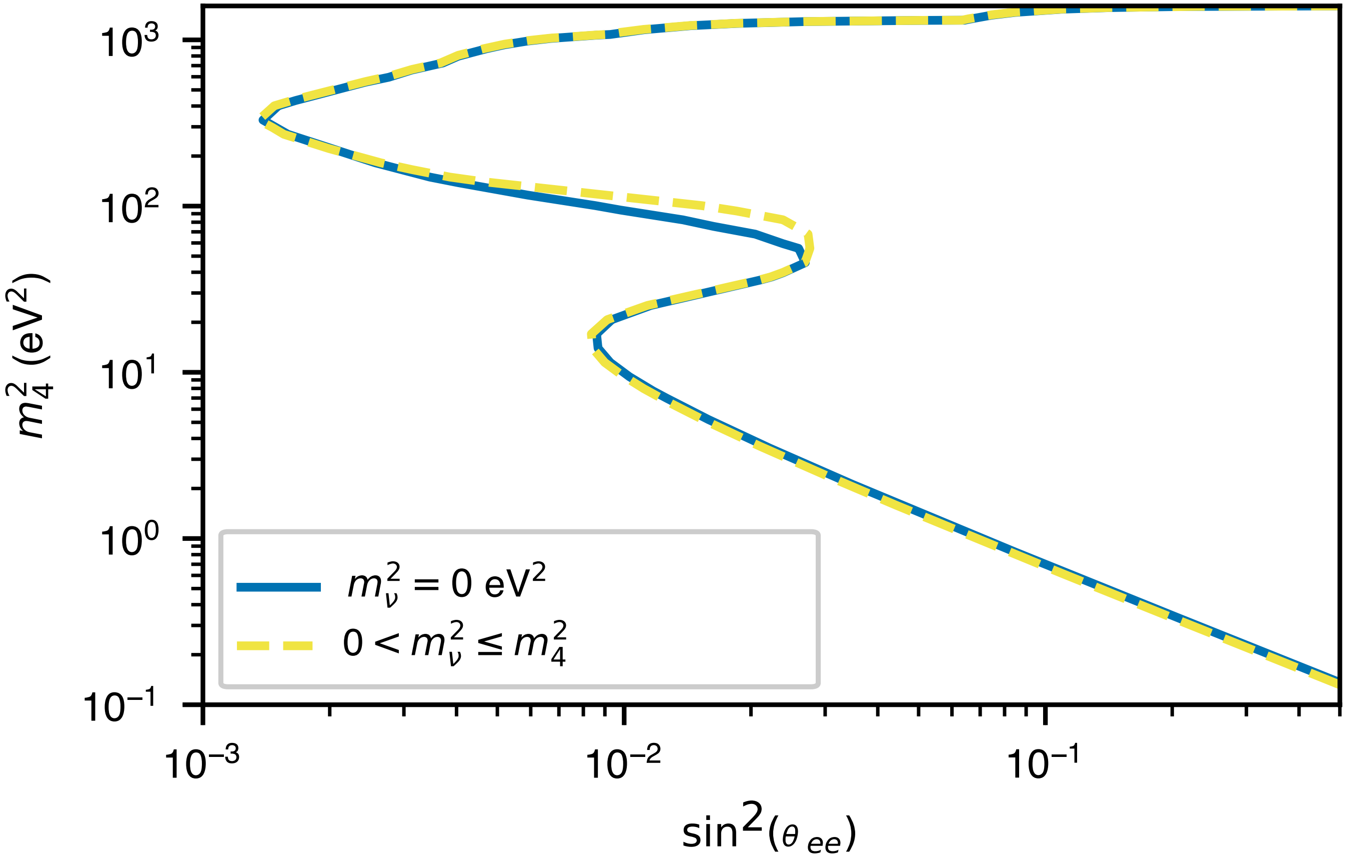
Results - m_ν=0



- 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**

Results - Free Neutrino Mass



Free active neutrino mass (m_ν) analysis leads to a m_ν–m_4 degeneracy with sensitivity loss at m_4<30 eV^2.

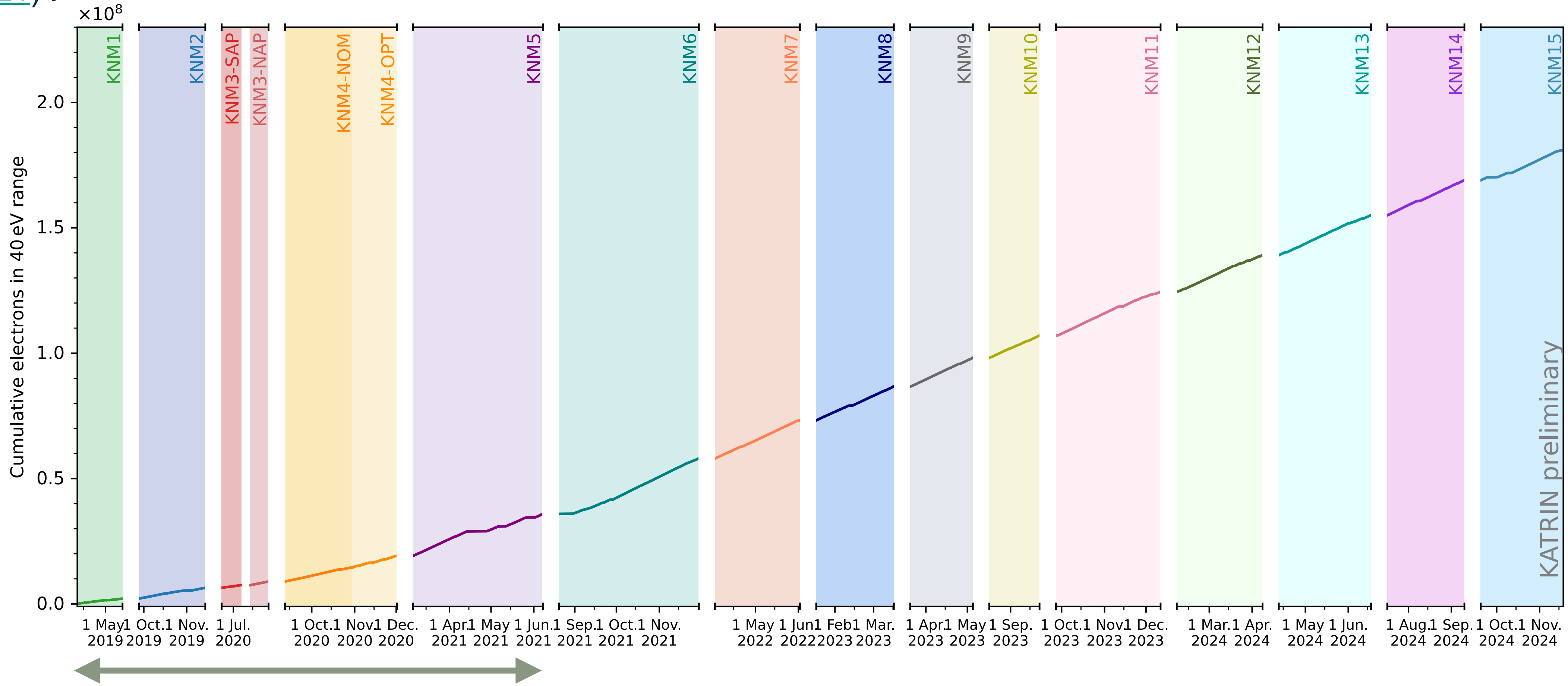
Full sensitivity at low m_4 is recovered if we assumed **0< m_ν<m_4**.

KATRIN Data Taking until 2025

15 measurement campaigns completed until the end of 2024

- Almost 200 Mio counts recorded – **x5 of this release**!

More data to come in 2025 plus calibrations and improvement in the systematics uncertainties (e.g. https://arxiv.org/pdf/2503.13221) .



2024 Data Release

KATRIN Timeline - The TRISTAN Phase

2019-2025

Phase 1 (integral) neutrino mass

2026-2027

Phase 2 (differential) keV-sterile ν

Quantum sensor R&D

Atomic tritium R&D

2028-2034 (PoF-V)

R&D phase KATRIN ++

Quantum sensor demonstrator

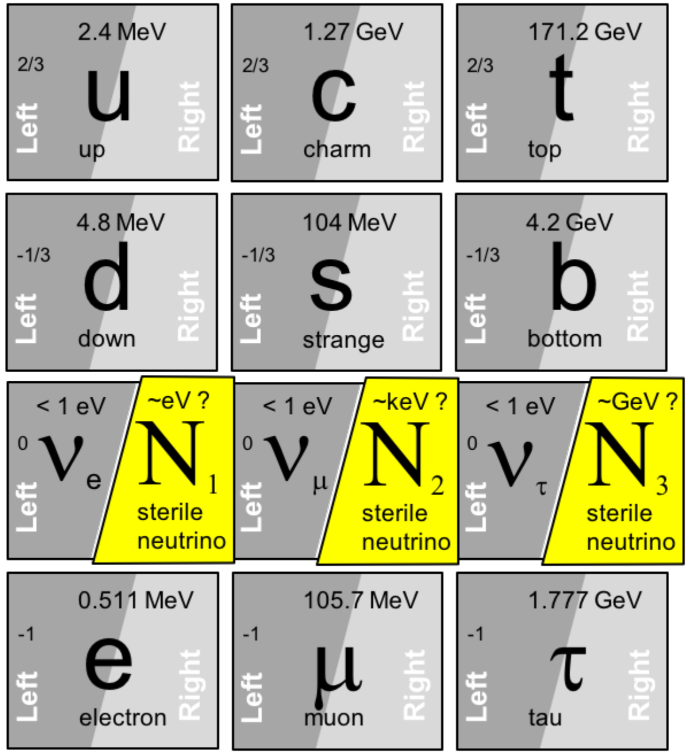
Atomic tritium demonstrator

Scientific goal

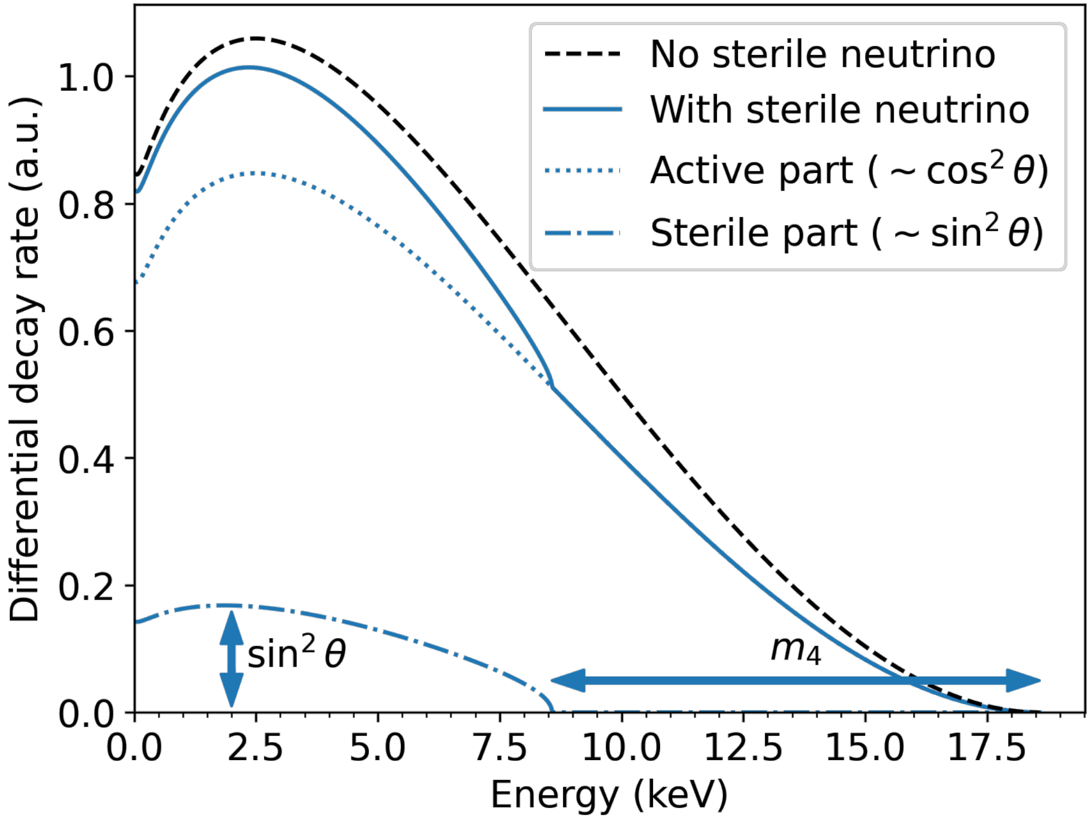
Neutrino mass

keV Sterile Neutrinos

Standard Model (SM)

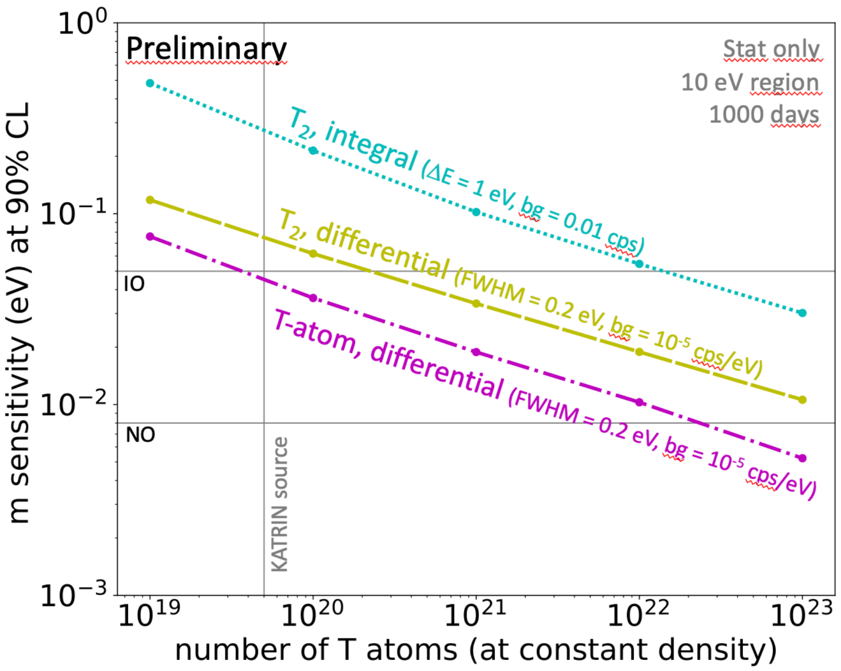


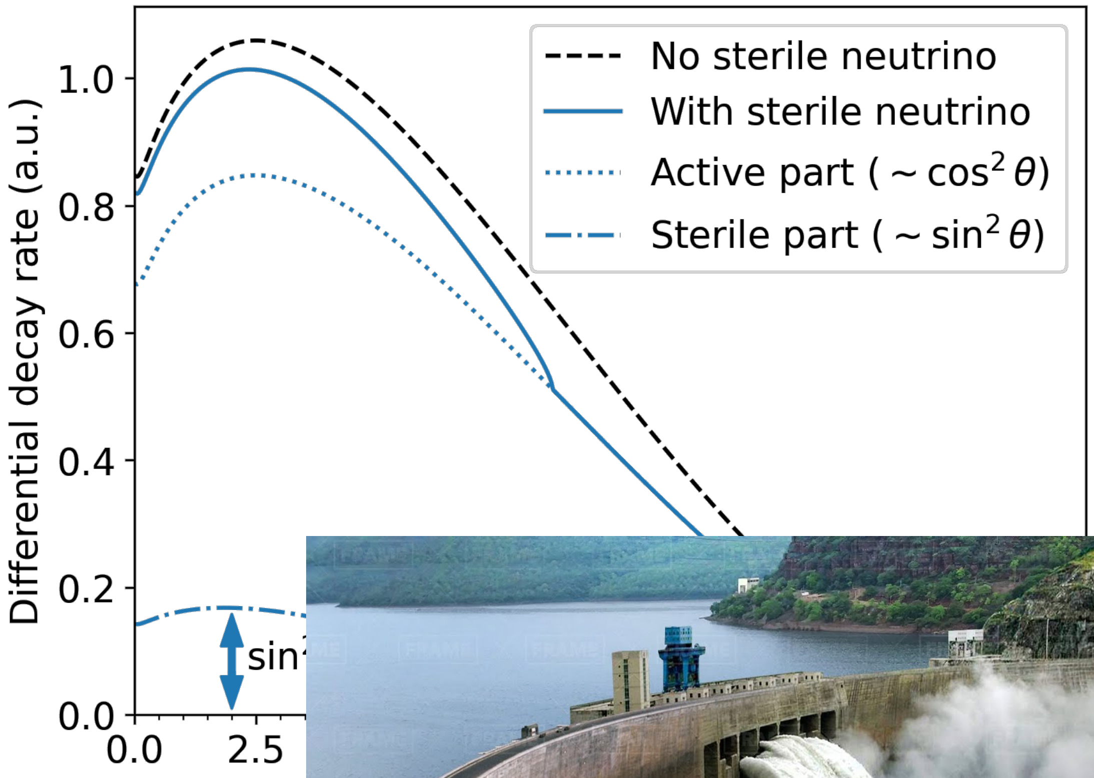
PRL 110 061801 (2013)



- **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

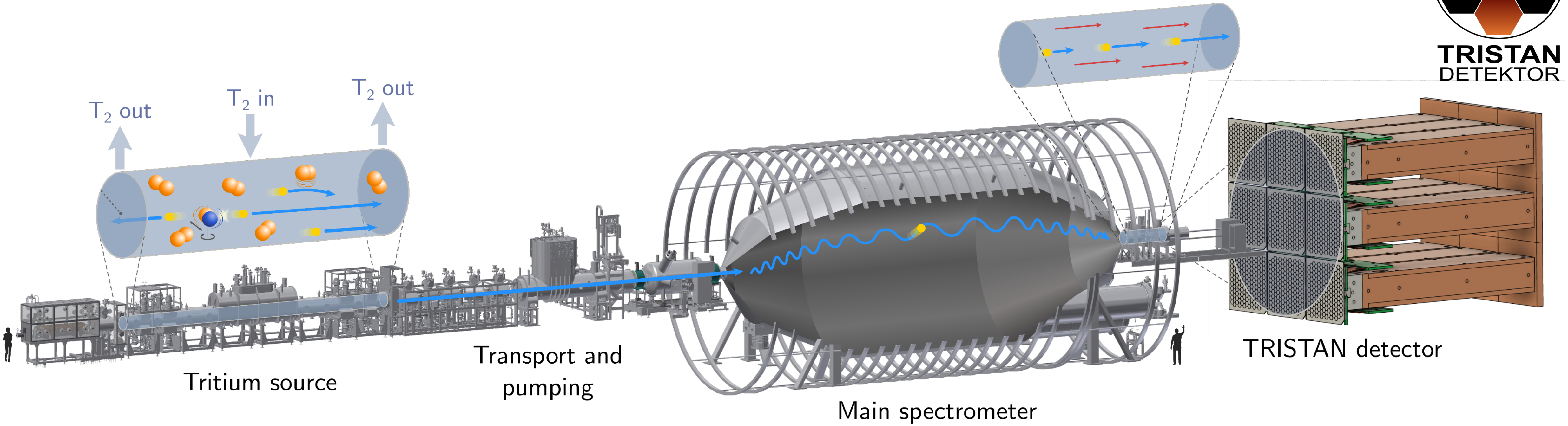




- A **differential measurement** makes more effective use of statistics;
- Requires upgrading the KATRIN at multiple levels.

Differential Measurement

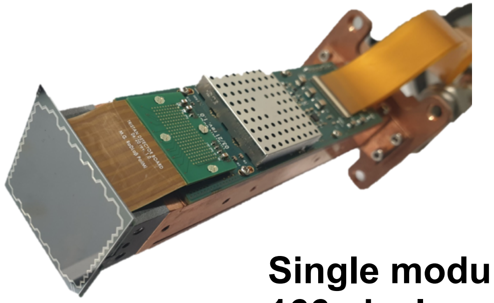
TRISTAN
DETEKTOR



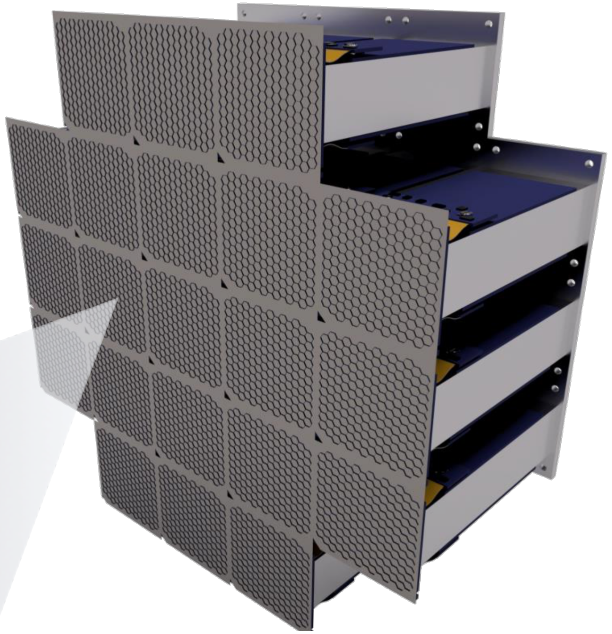
- New detector system capable of handling high rates with an excellent energy resolution and low noise, etc…
  - **SDD - Silicon Drift Detector**;
- Source Activity to be reduced to **0.1–1% of the current values**;
- The rear wall has to be reconfigured to reduce the amount of backscattering;
- New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

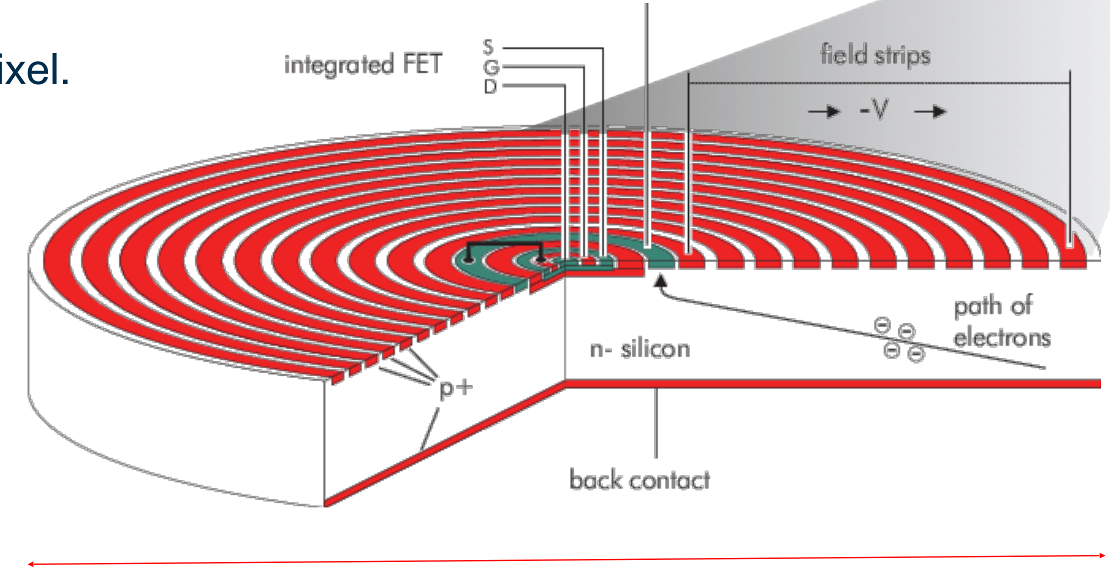
TRISTAN - The Novel Detector System

- 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.

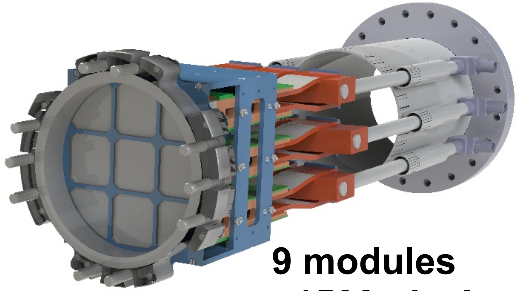


Single module
166 pixels





3 mm, 220 fF



9 modules
~1500 pixels

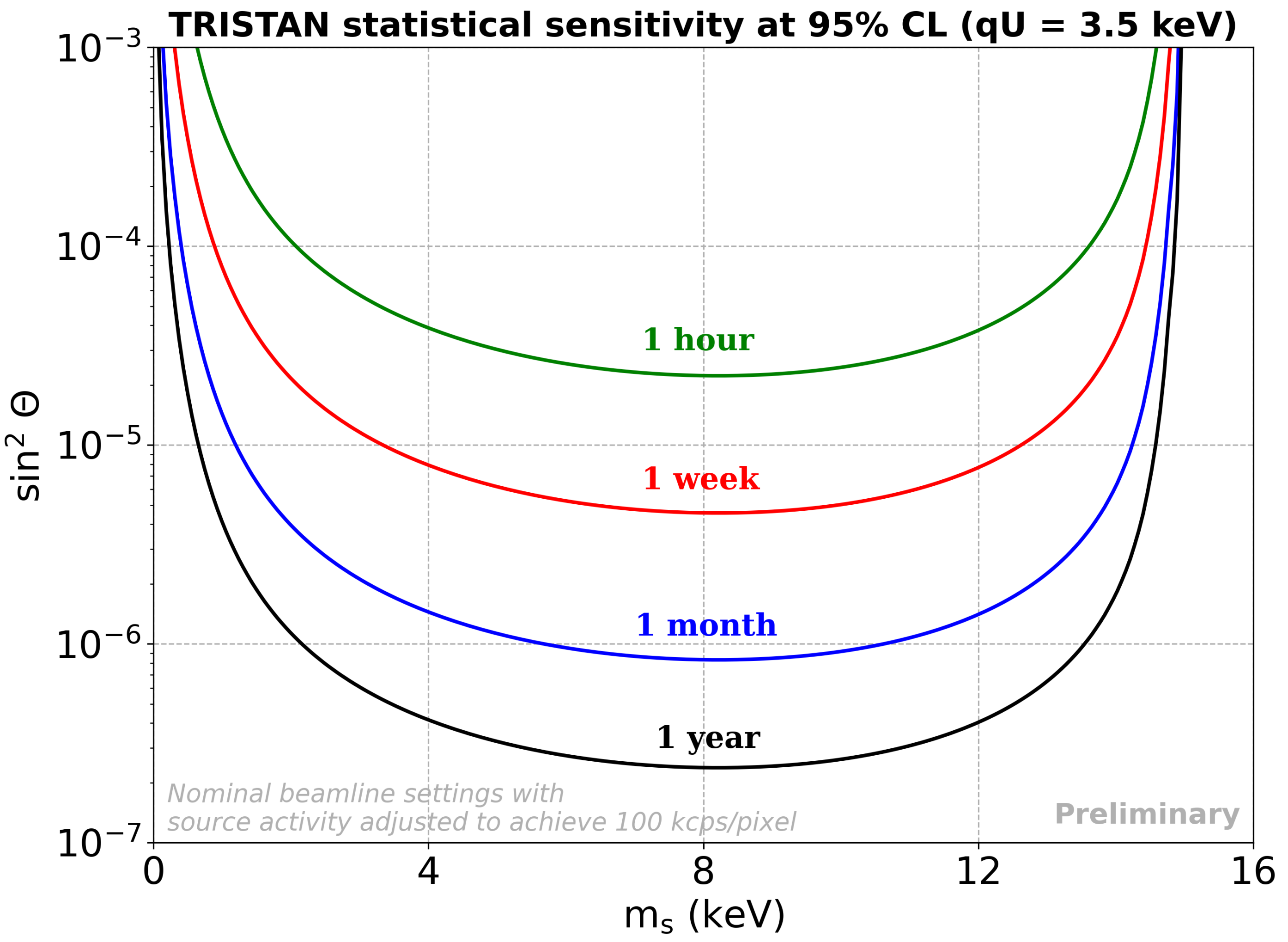
Further Reading:

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

Differential Measurement

HIGH STATISTICS!

Systematic uncertainties must be carefully controlled!

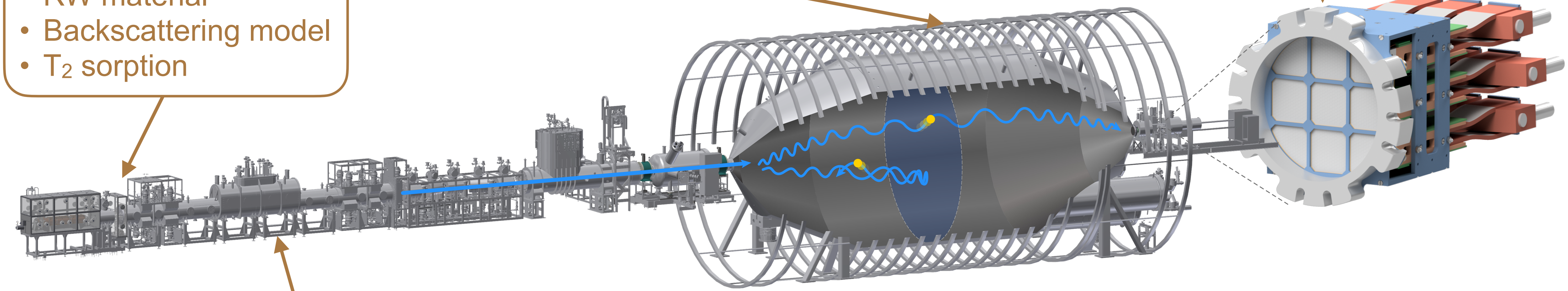


Differential Measurement - Systematics

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

EM Transport:
- Non-Adiabaticity
- Magnetic reflection

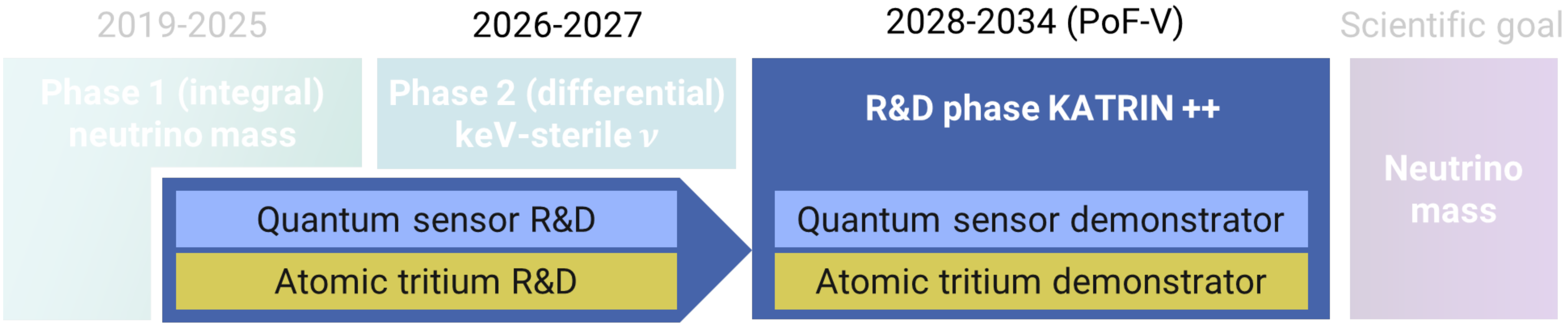
Rear Wall section:
- RW material
- Backscattering model
- T_2 sorption



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

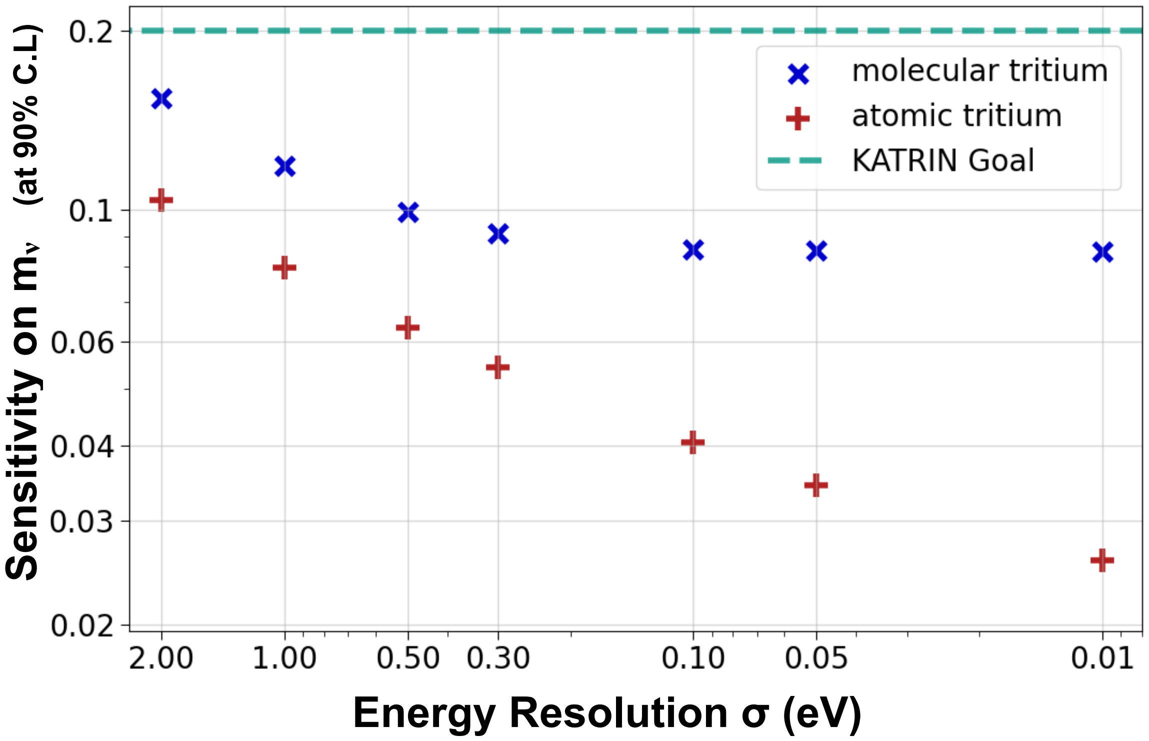
Data Acquisition:
Electronic noise
Deadtime, threshold
Nonlinearity
Pileup

KATRIN Timeline

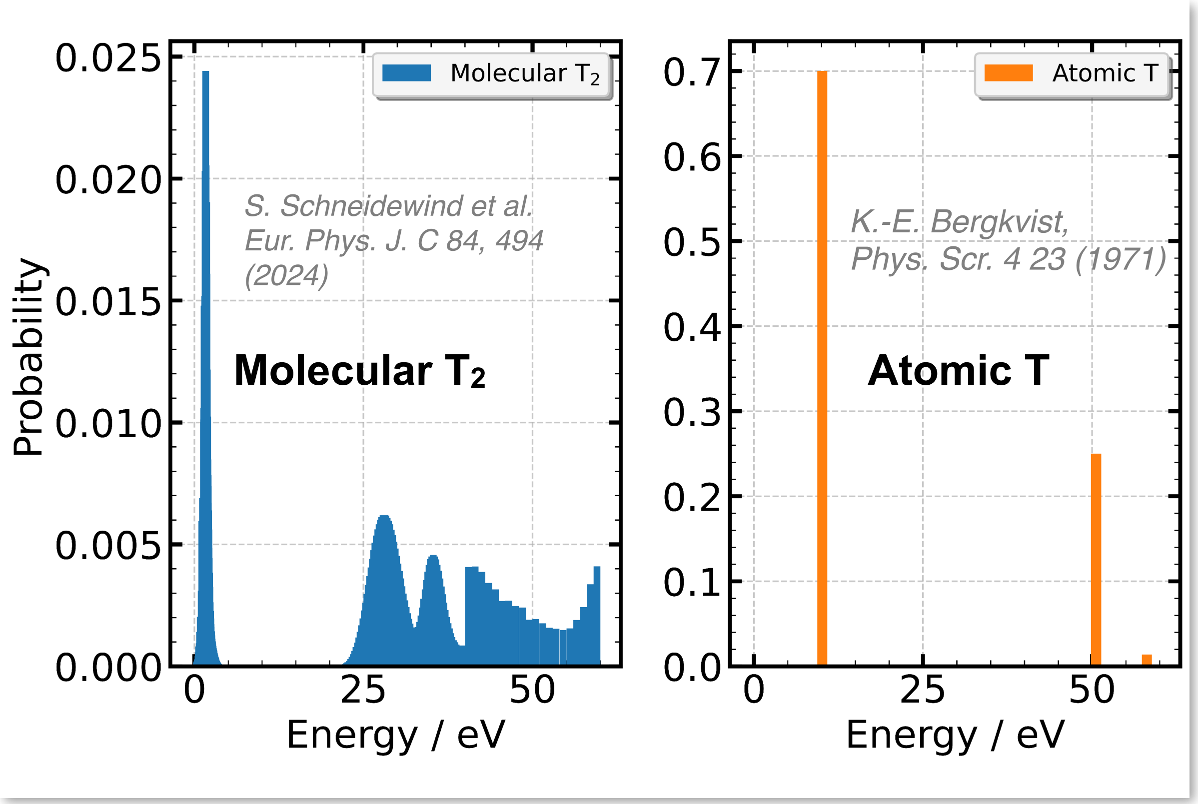


- Reduction on the **systematic uncertainties**:
  - Reduction of the final state uncertainties → **atomic source tritium**
- Improvement of energy resolution:
  - **MAC-E:** implementation of a high-pass filter → **Transverse Energy Compensator;**
  - **Calorimetry:** measuring the deposited energy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

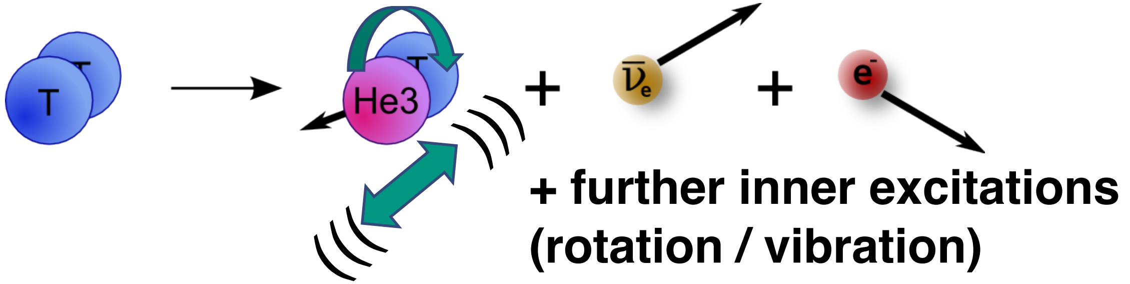
KATRIN++



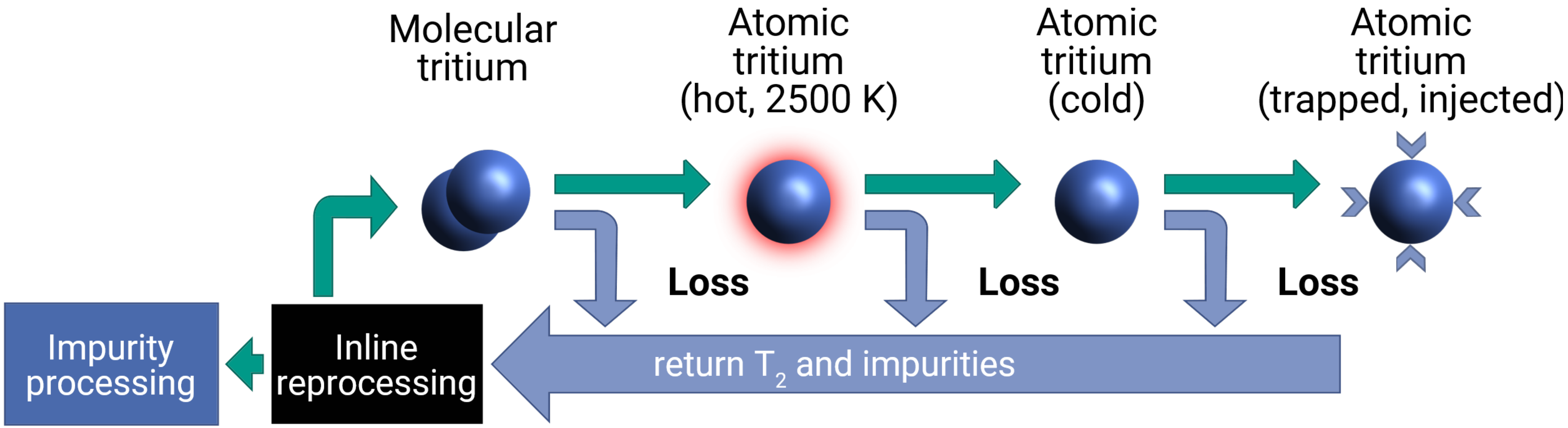
Final-state distribution



- 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).



Development of an Atomic Tritium Source



Development of an Atomic Tritium Source

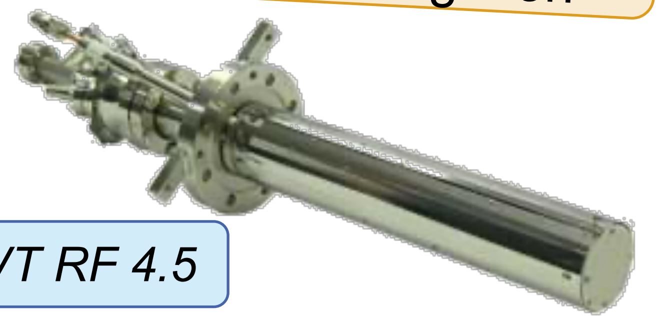
Installation of first ever atomic **tritium** source at KIT ongoing

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:

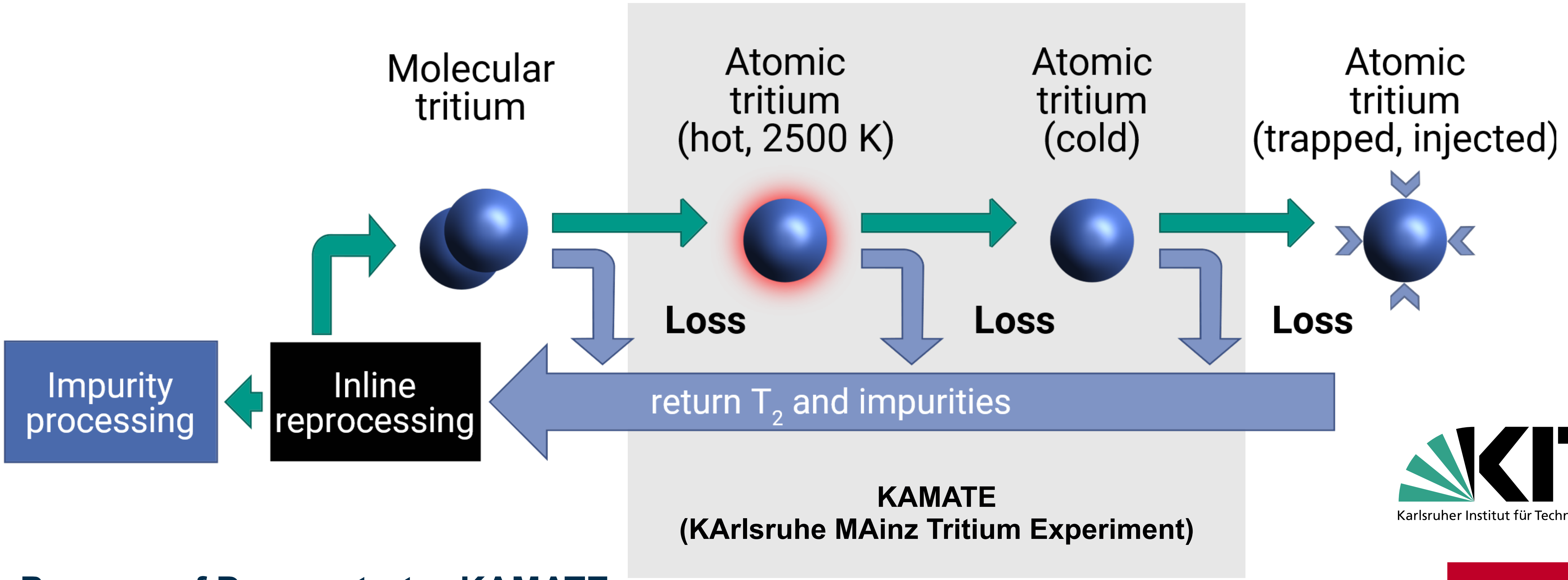
- Fine tungsten capillarity heated by electron bombardment
- **Atoms with > 2000 K**



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**

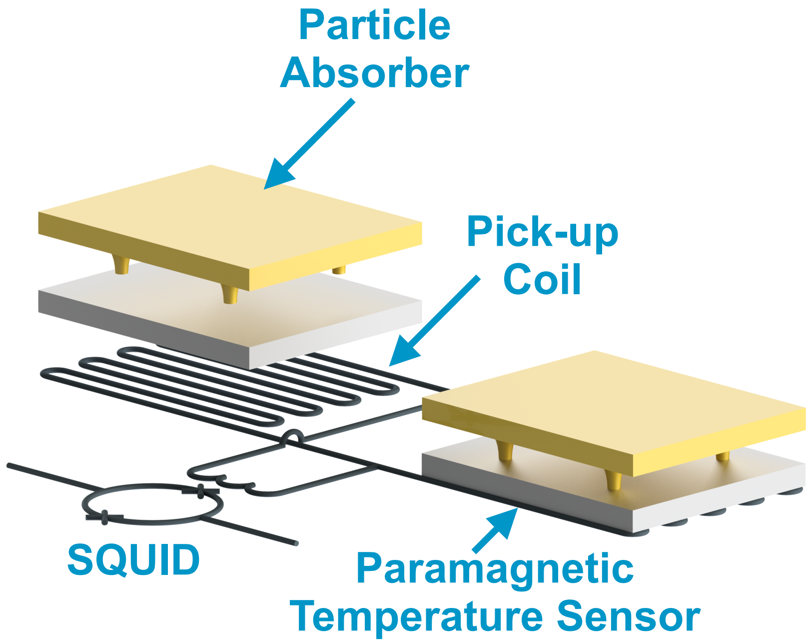
Development of an Atomic Tritium Source

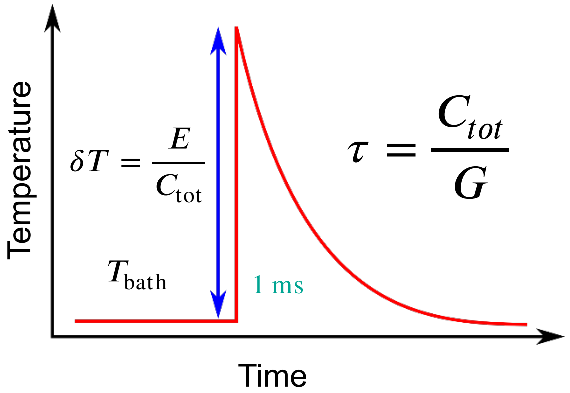


- **Propose of Demonstrator KAMATE:**
  - Develop a cooling mechanism for atoms (**≈10 mK**);
  - Generate an atom throughput on the order of **10 g day** (c.f. KATRIN: 40 g/day);
  - Investigate trapping times and maximal atom densities.

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

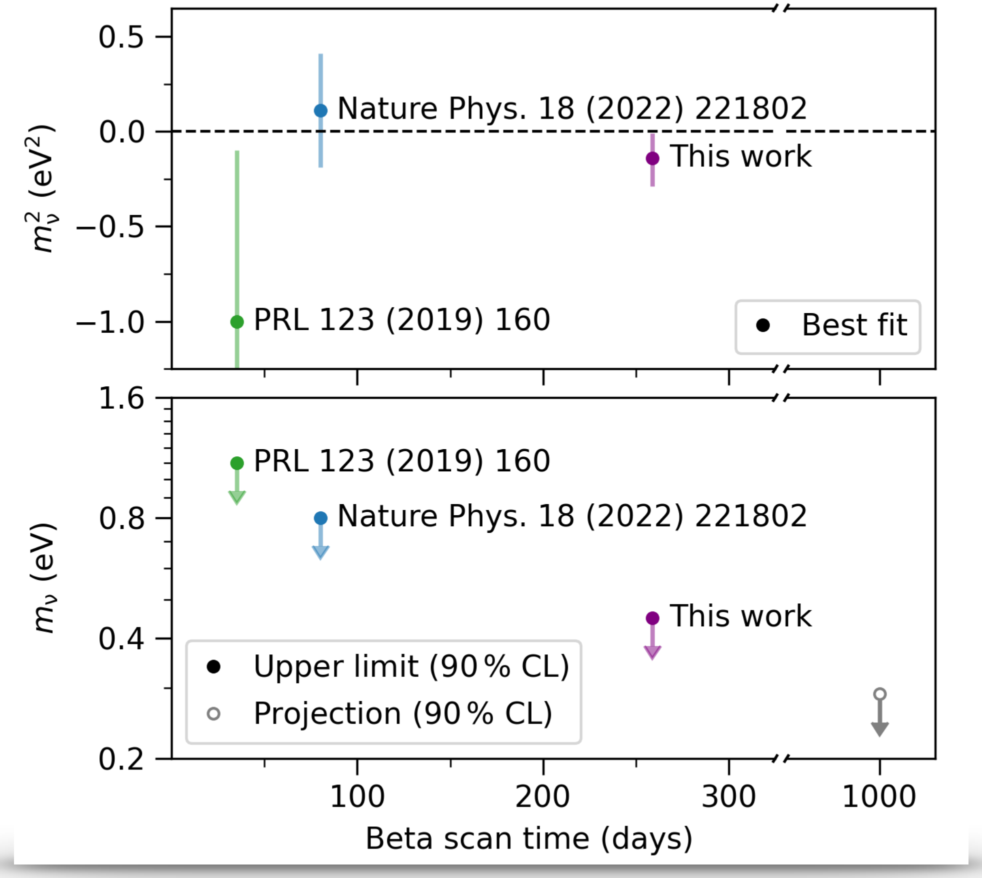
Conclusion and Outlook

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

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

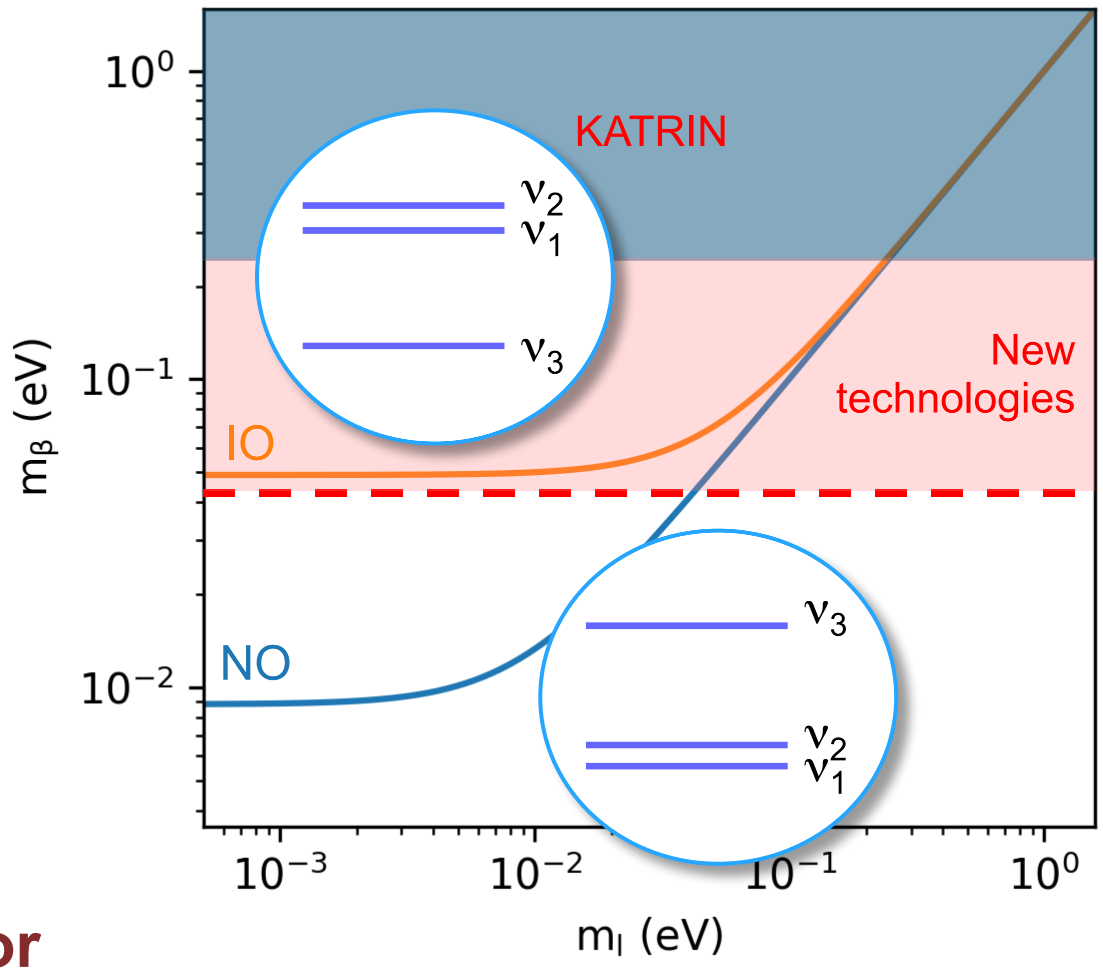
- keV sterile search ruled-out most of the parameter space allowed by the gallium anomaly and a large section of the **RAA allowed region**.
- Ongoing data taking through 2025 → **1000 days**
  - Targeting a sensitivity below 0.3 eV.

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



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.



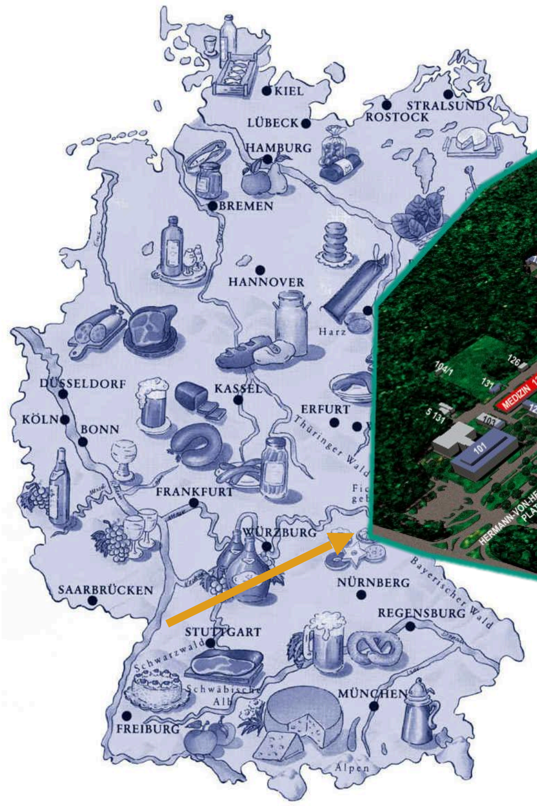
Thank you for your attention!

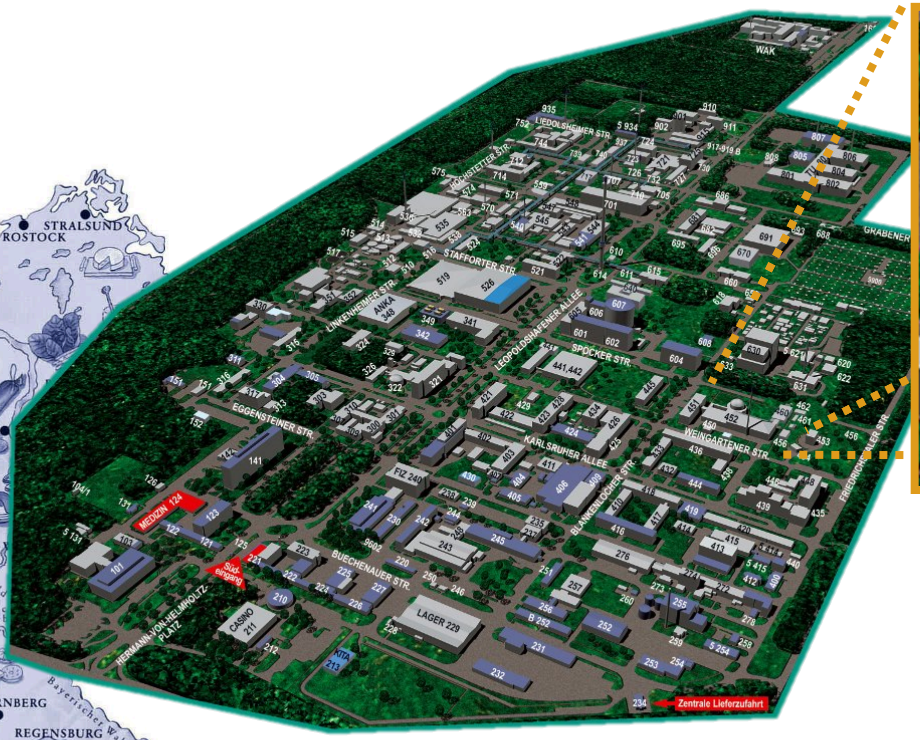
Backup Slides

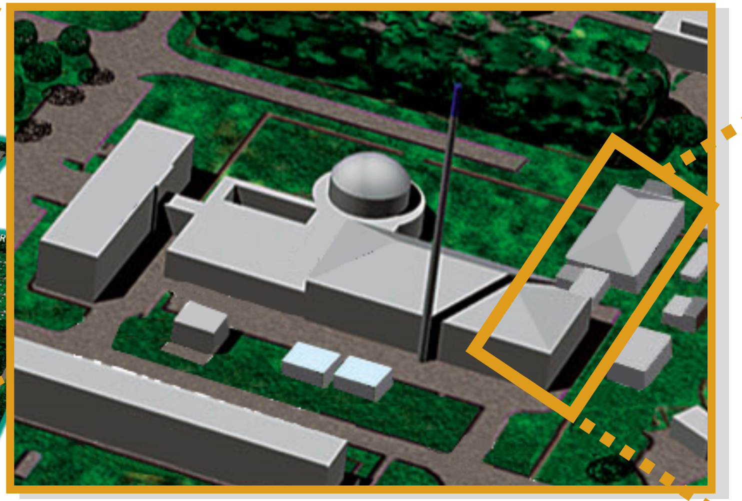
KATRIN at Karlsruhe

FIDELITAS

Karlsruher Institut für Technologie







Karlsruhe Institute of Technology Campus North

TLK Tritiumlabor Karlsruhe:

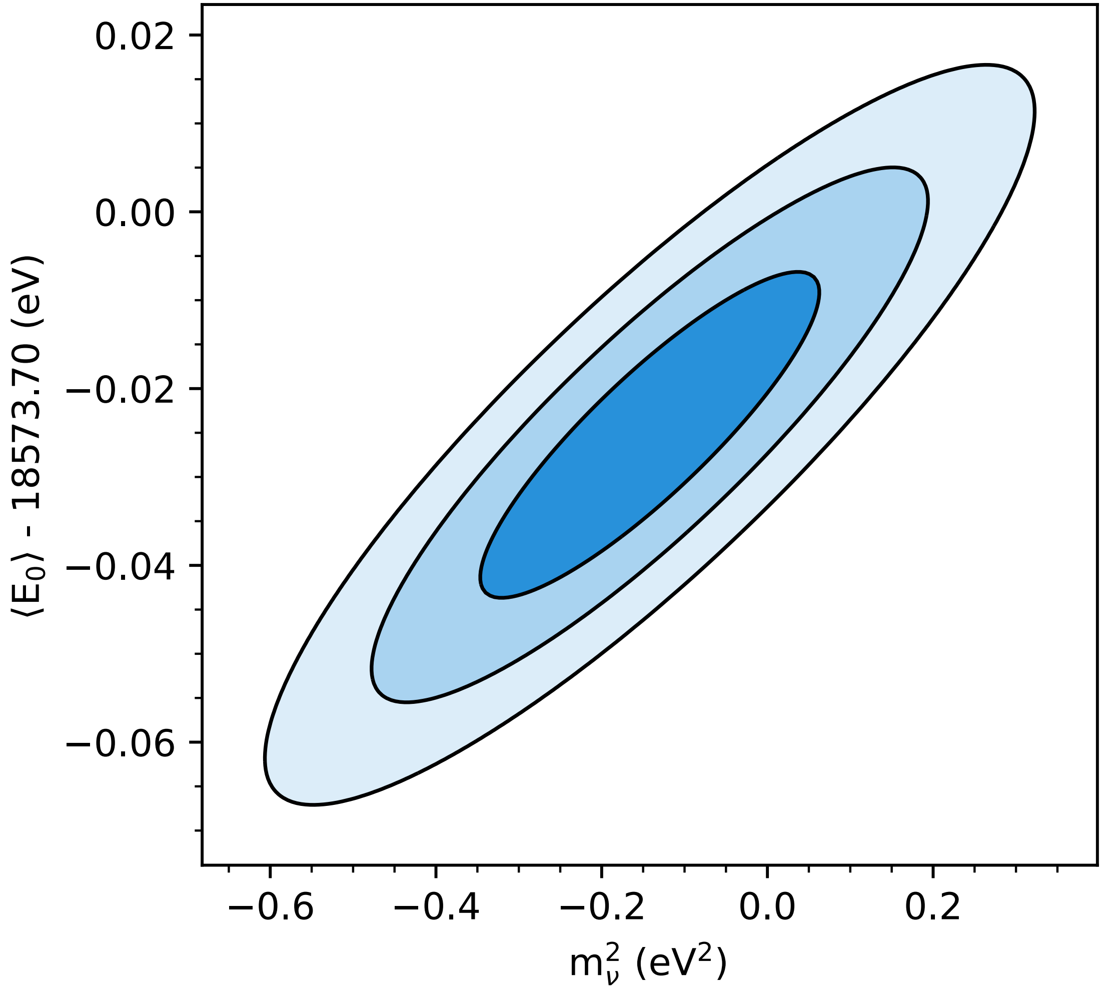
- Commissioned in 1993;
- Licensed for 40 g of Tritium
- Two missions:
  - KATRIN experiment
  - Fusion reactors

Overview of the KATRIN Runs

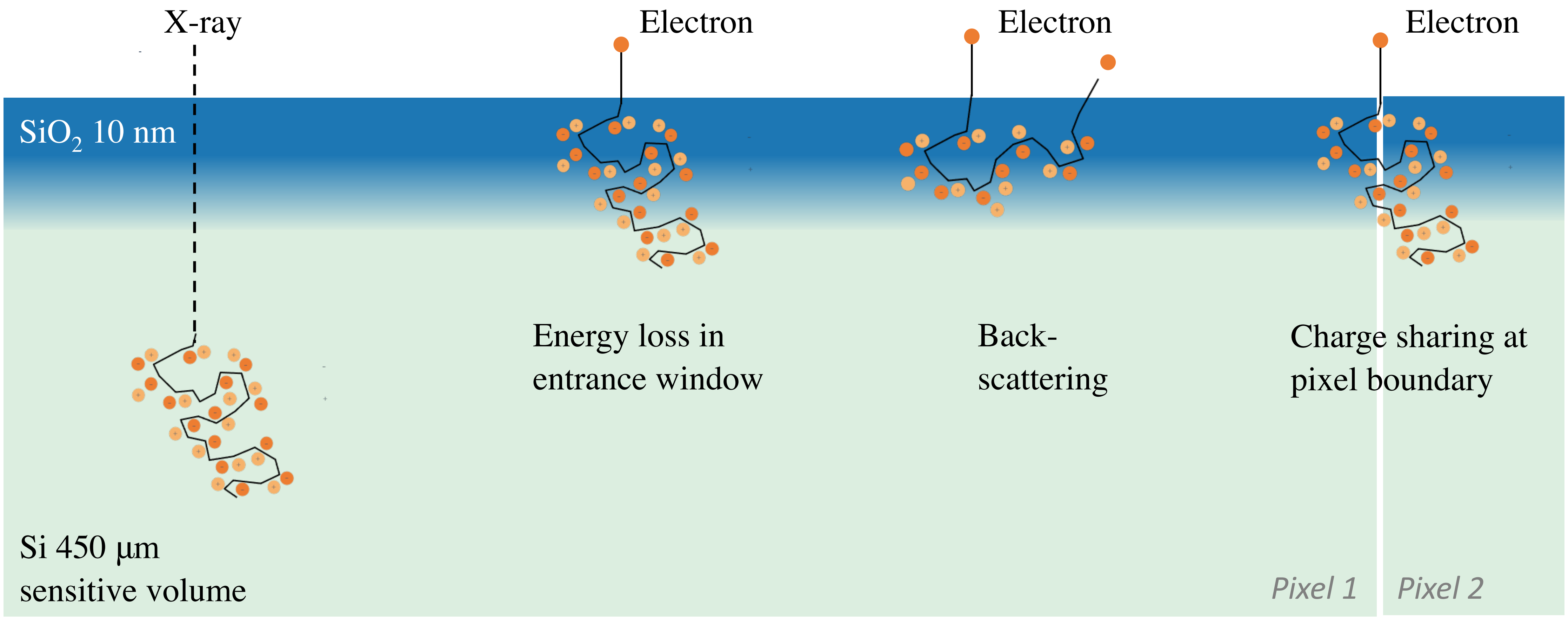
Table 1: Key features of the measurement campaigns. The live time corresponds to the data used for analysis. The values are quoted for the number of active pixels in each measurement campaign and all the scan-steps above $E_0 - 40\,\mathrm{eV}$.

	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

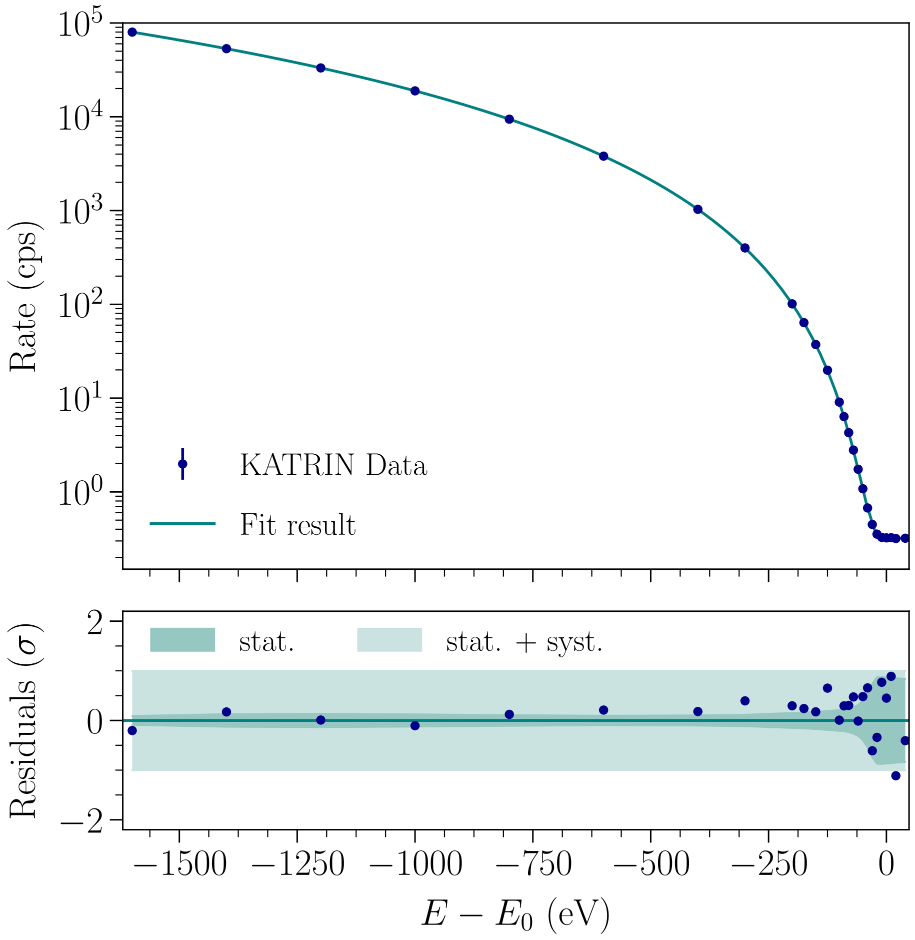
Correlation Between Mass and Endpoint

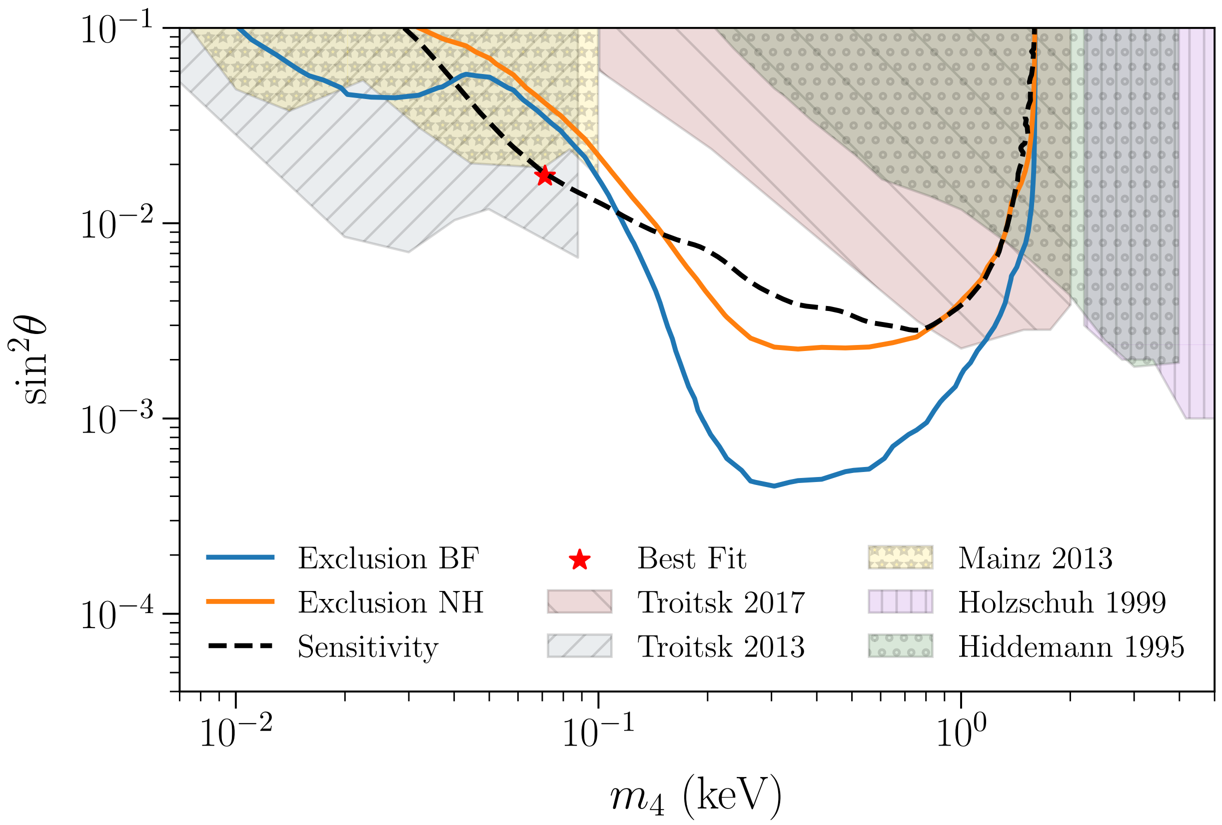


Interaction in the SDD Detector



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.

Eur. Phys. J. C (2023) 83:763