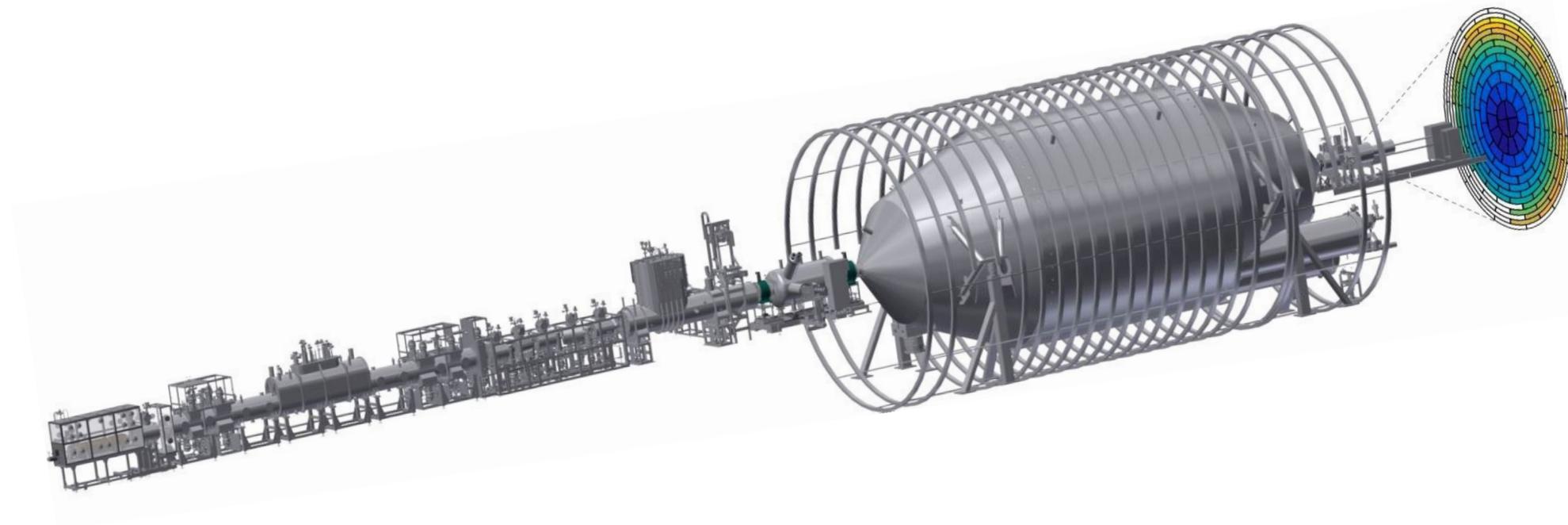


New Constraints on the Electron Antineutrino Mass from KATRIN Experiment & Beyond

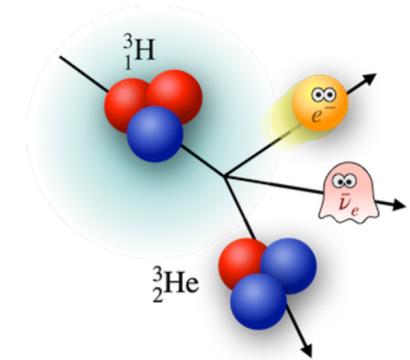
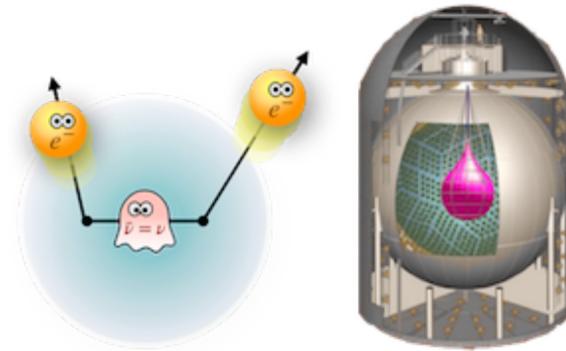
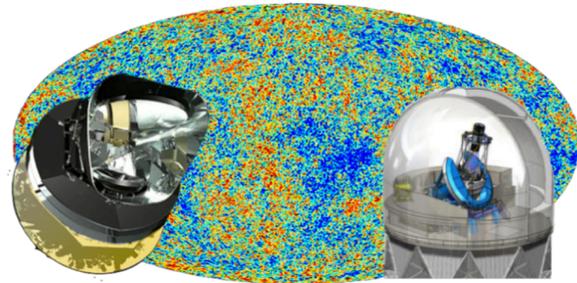


Auttakit Chatrabhuti
on behalf of the KATRIN
collaboration

High Energy Physics Research Unit
Chulalongkorn University, Bangkok
THAILAND

Three paths to the neutrino mass scale

Complementary observables and methods



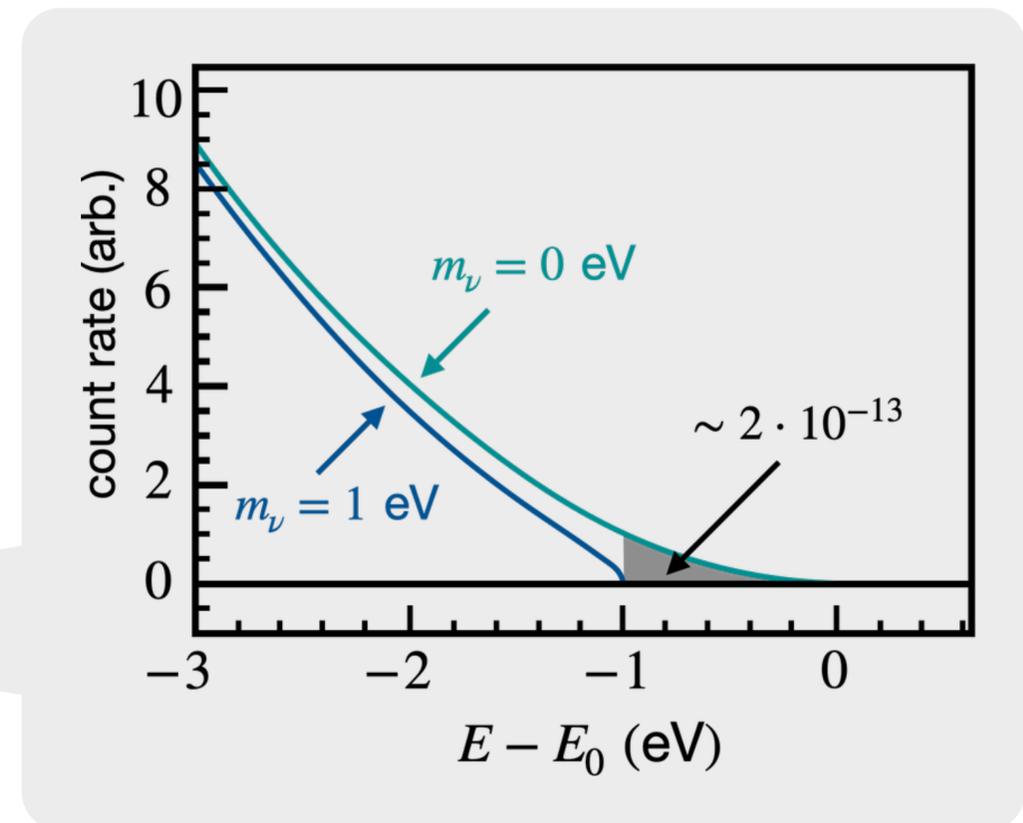
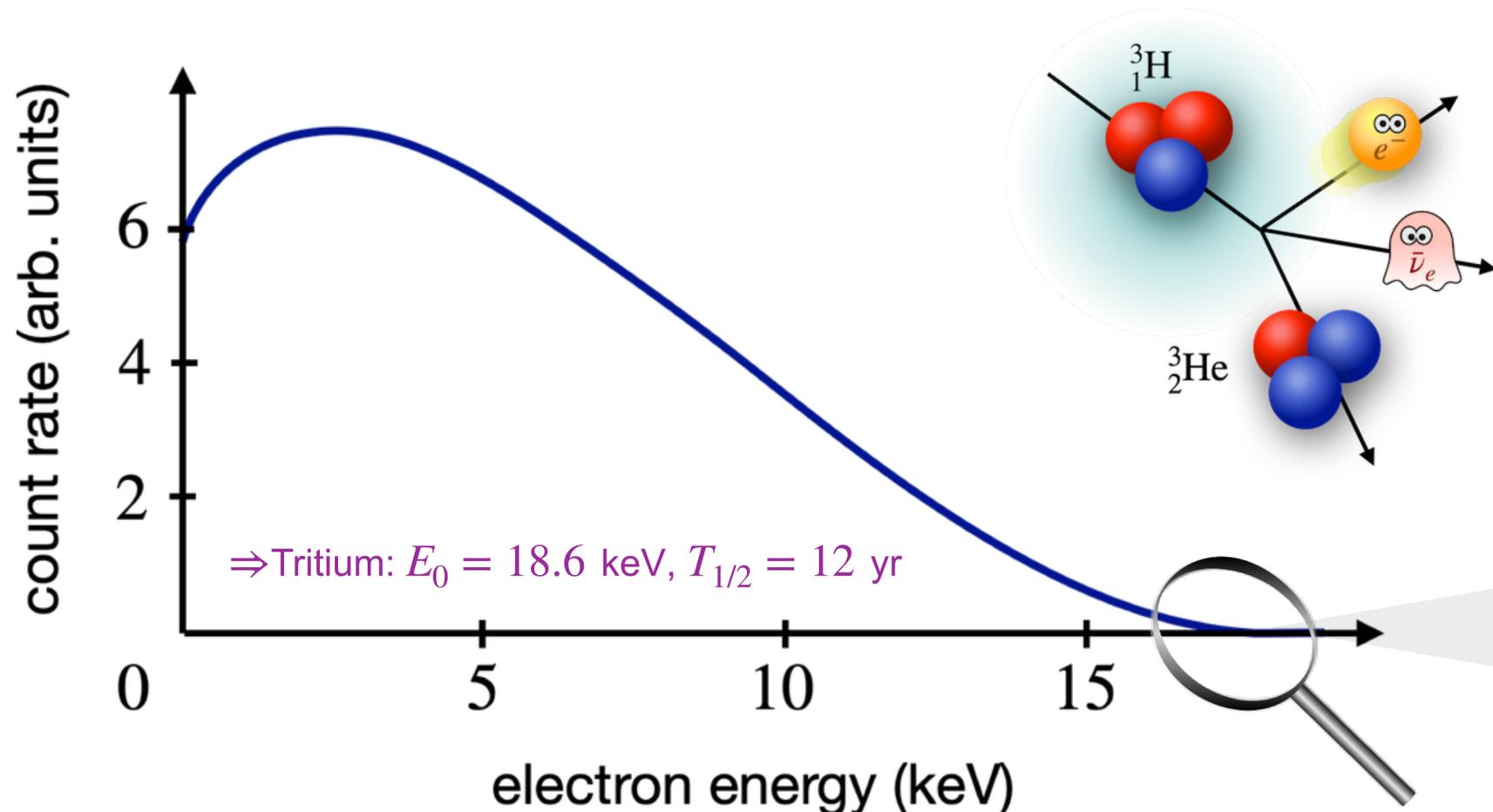
	Cosmology	Search for $0\nu\beta\beta$	Precision kinematics of weak decays
Method	Structure of Universe at early and evolved stages	$\beta\beta$ -decay of ^{76}Ge , ^{130}Te , ^{136}Xe , ...	β -decay of ^3H , EC of ^{163}Ho
Observable	$m_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left \sum_i U_{ei}^2 m_i \right ^2$	$m_\beta^2 = \sum_i U_{ei} ^2 m_i^2$
Present upper limit	0.12 eV (0.064 eV)	0.036 – 0.156 eV	0.45 eV (from ^3H)
Method assumption	Multi-parameter cosmological model (ΛCDM)	<ul style="list-style-type: none"> Majorana neutrinos Contrib. other than m_ν? Nucl. matrix elements, gA 	Direct — only kinematics; no cancellations in incoherent sum

Neutrino mass in tritium β -decay

Measurement of effective mass m_ν based on **kinematic parameters & energy conservation**

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

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



Neutrino mass in tritium β -decay

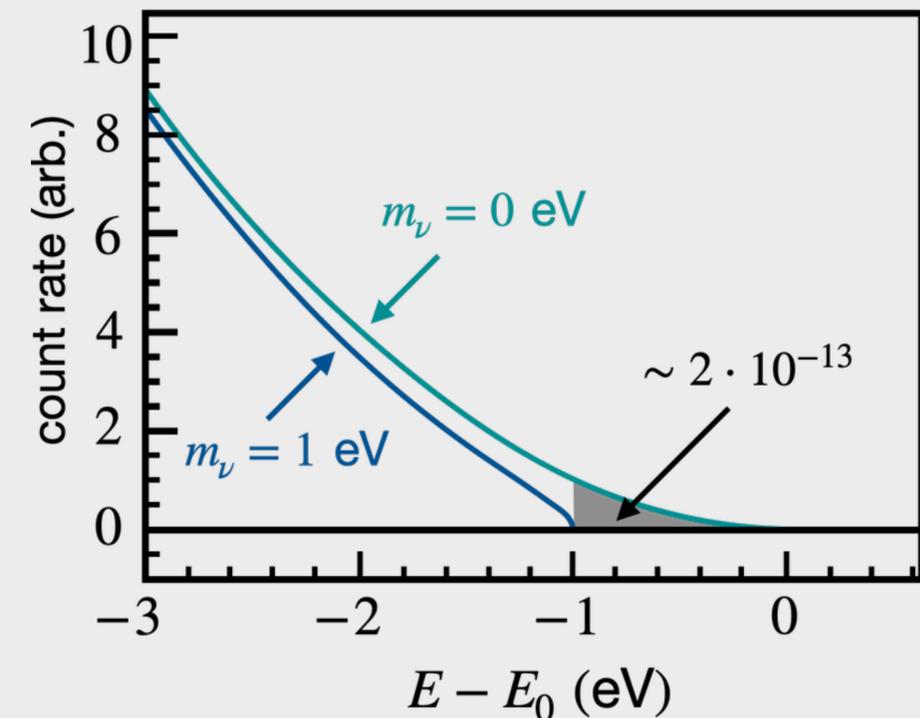
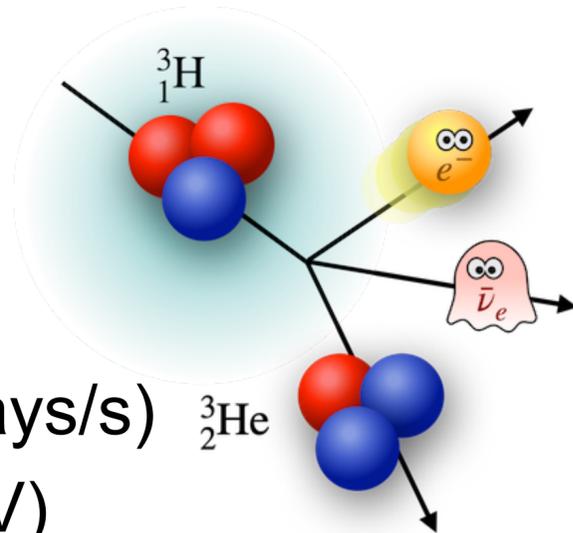
Measurement of effective mass m_ν based on **kinematic parameters & energy conservation**

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

Experimental challenges:

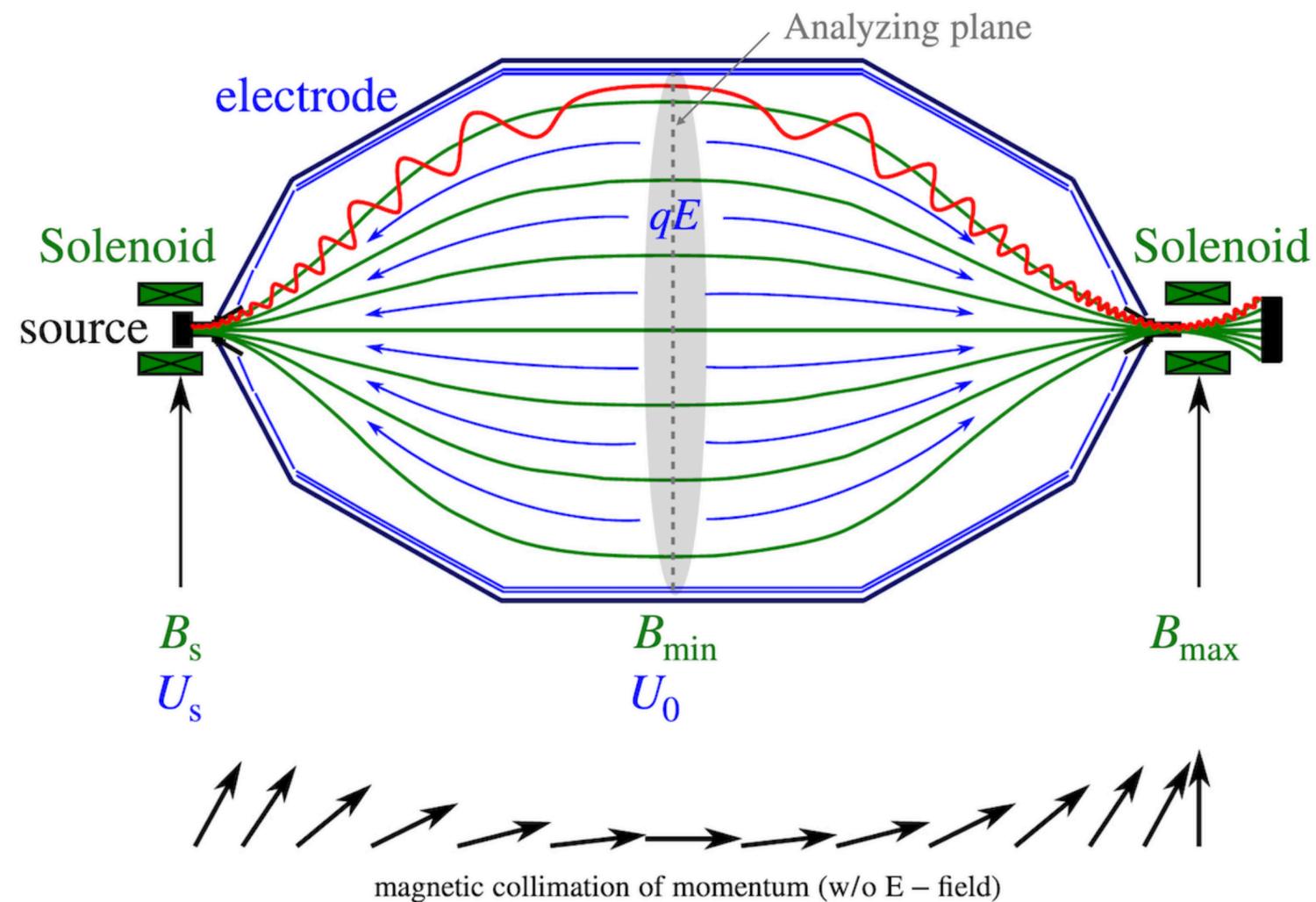
- High source activity ($\sim 10^{11}$ decays/s)
- Excellent energy resolution (~ 1 eV)
- Low background ($\ll 1$ cps)
- Spectrum and response model
- Hardware stability over years



High-resolution spectrometer

Magnetic Adiabatic Collimation with Electrostatic Filter ("MAC-E")

(see Picard et al., NIM B 1992; Lobashev & Spivak, NIM A 1985)



Key feature:

Combines large acceptance with eV-scale energy resolution

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}} \approx \frac{1}{20,000}$$

Challenge:

Size of a multi-story building

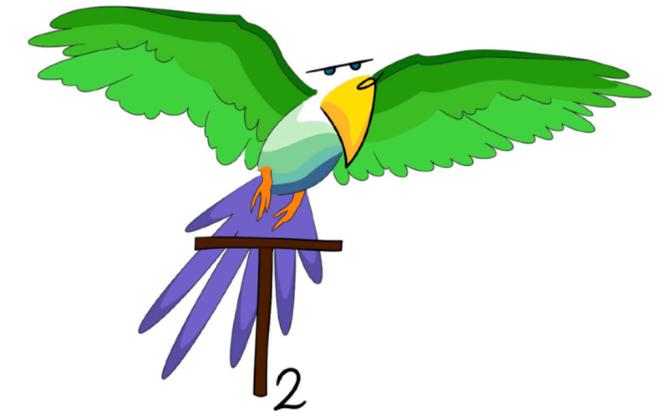


KATRIN: Karlsruhe Tritium Neutrino Experiment

- Experimental site: Karlsruhe Institute of Technology (KIT)
- International collaboration founded in 2001:
~150 members from ~20 institutions in 7 countries
- Reach: m_{ν_e} sensitivity of < 0.3 eV (90% CL)



KATRIN collaboration



Collaboration meeting, October 2024, KIT



KATRIN @ Tritium Laboratory Karlsruhe



Tritium Laboratory Karlsruhe (TLK)

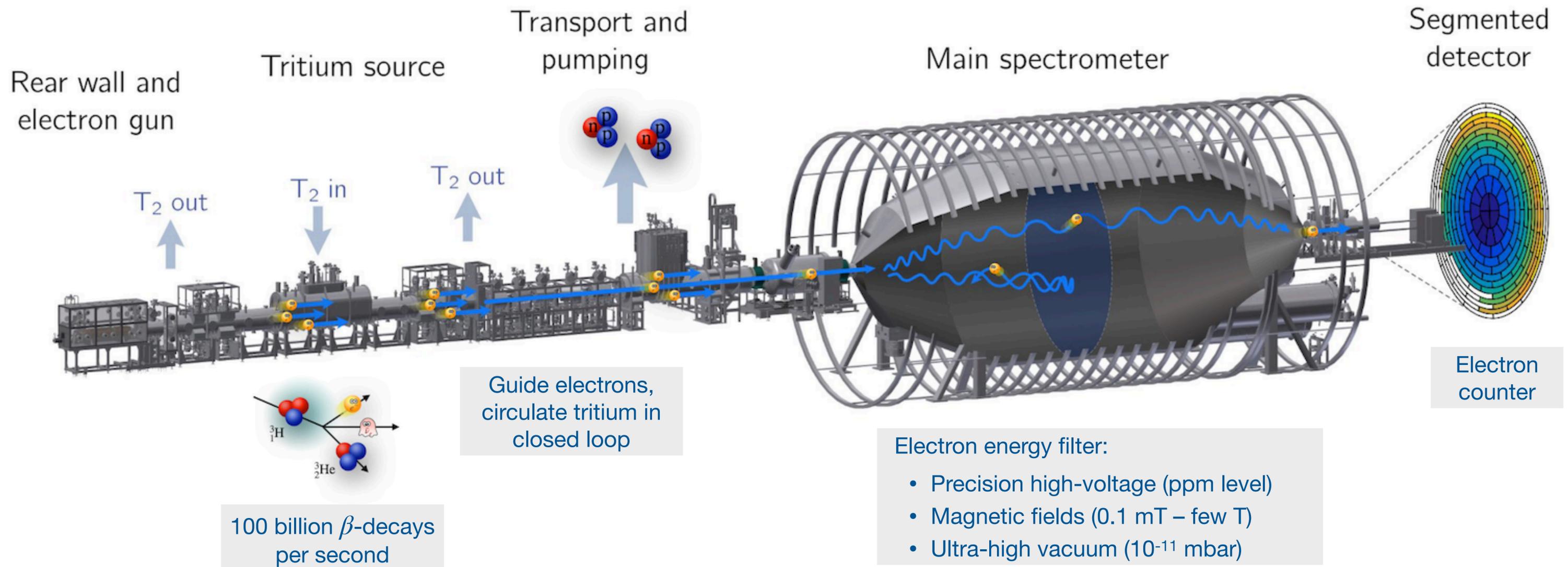
A unique research facility in Europe with 30 years of experience:

- Development of tritium fuel cycle for nuclear fusion
- Closed-loop source operation (~10 kg/year) for KATRIN

(e.g., Hillesheimer et al., *Fusion Sci. Tech.* 80 (2023) 465)

Overview of the KATRIN experiment

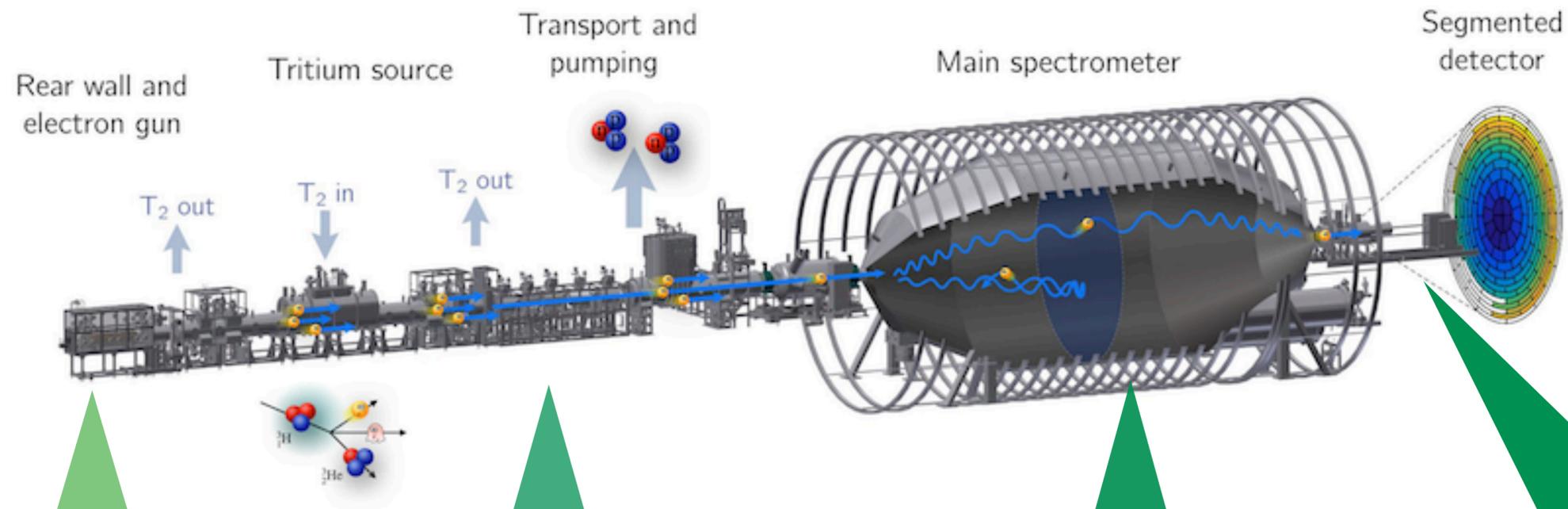
70 m long beam-line: ultra-pure gaseous T₂ source combined with high-resolution electron spectrometer



Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

Overview of the KATRIN experiment

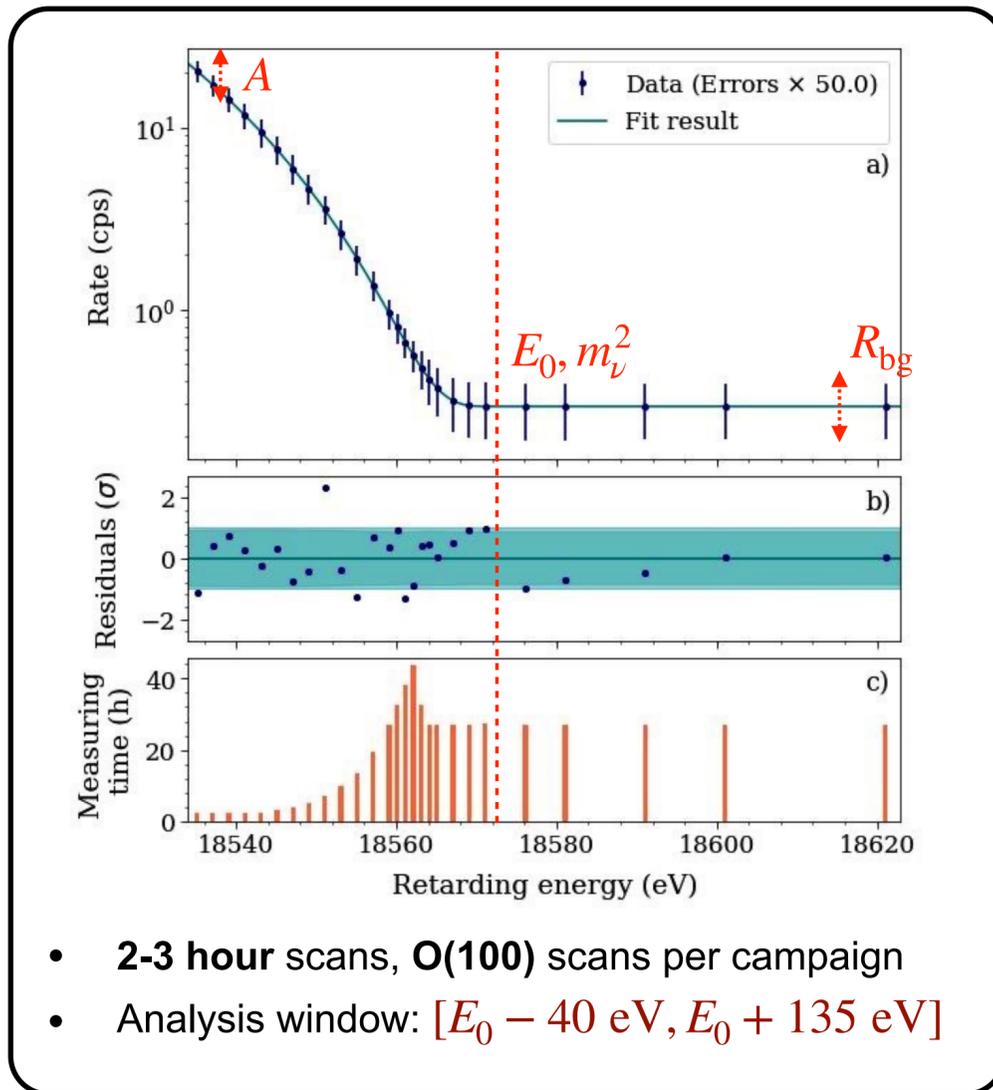
70 m long beam-line: ultra-pure gaseous T_2 source combined with high-resolution electron spectrometer



Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

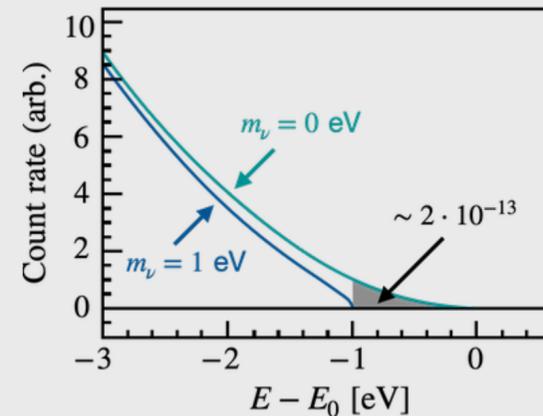
Modelling the tritium spectrum

- Convolution of theoretical spectrum with experimental response

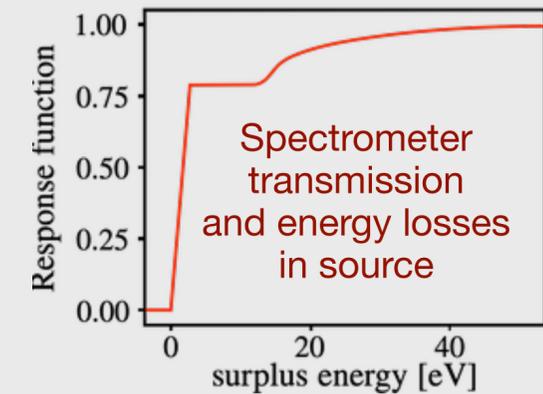


$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E) dE + R_{bg}$$

Beta decay spectrum



Experimental response



- fitting parameters for neutrino mass: m_ν^2, E_0, A, R_{bg}
- fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, ...)

KATRIN data releases

2019: $m_\nu < 1.1$ eV (90 % CL)

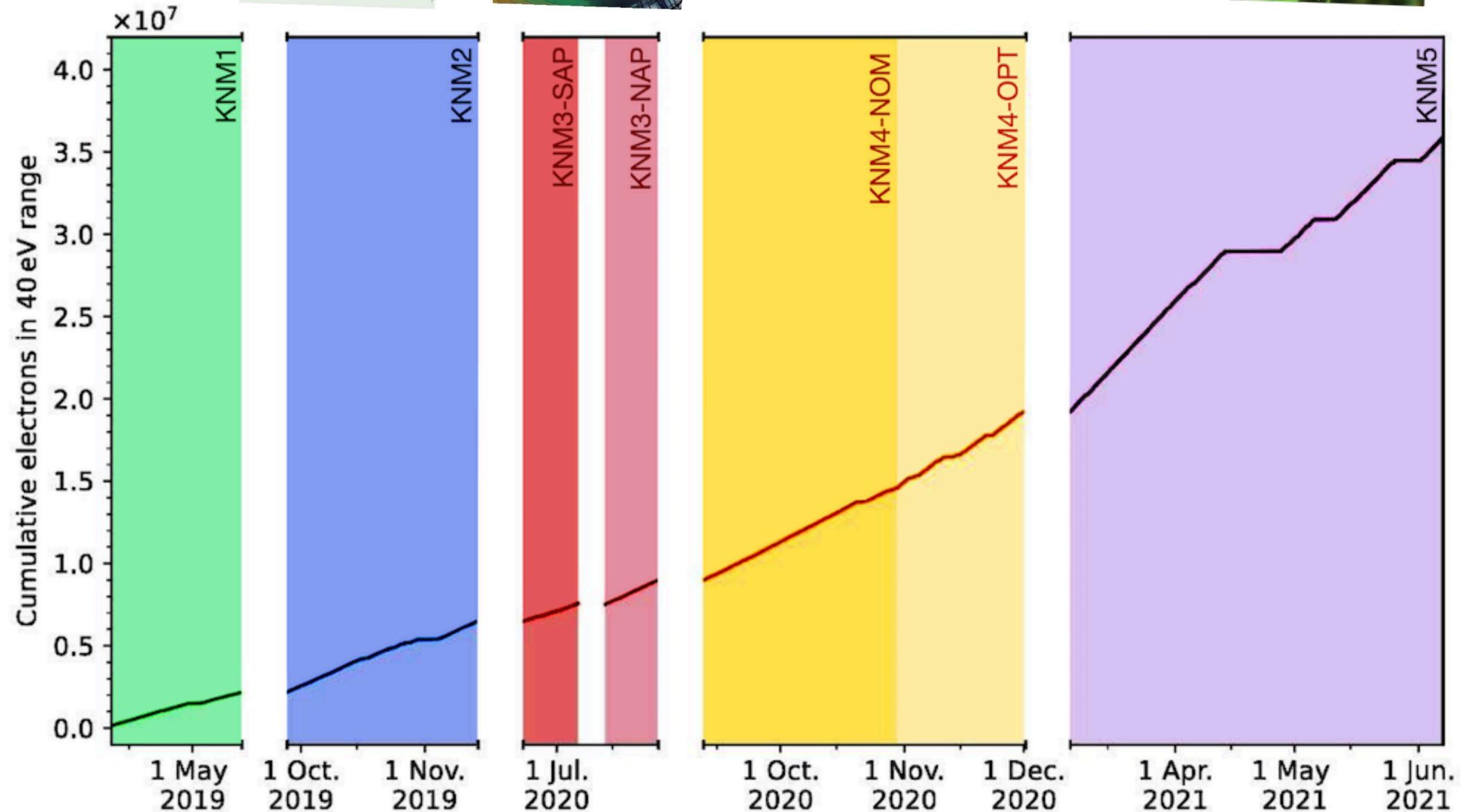
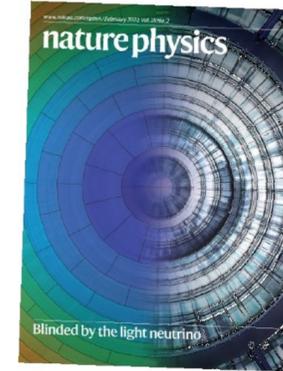
2022: $m_\nu < 0.8$ eV (90 % CL)

- $\sim 6 \times 10^6$ counts

2024:

- 259 measurement days
- 1757 β -scan
- $\sim 36 \times 10^6$ counts

Expected sensitivity < 0.5 eV



PRL 123 (2019) 221802
PRD 104 (2021) 012005

Nature Phys. 18 (2022) 160

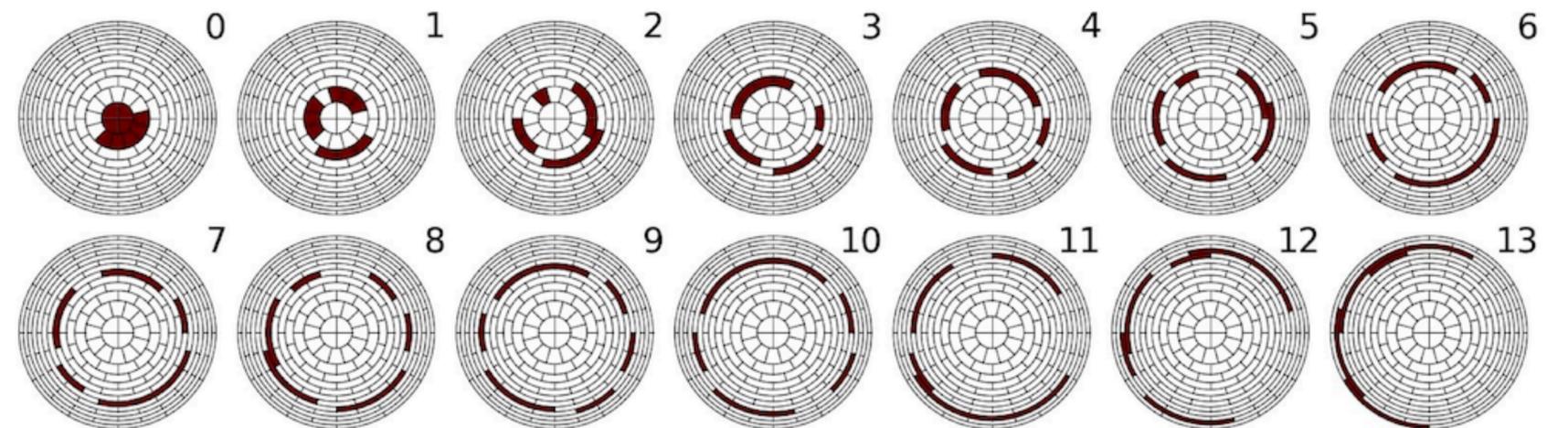
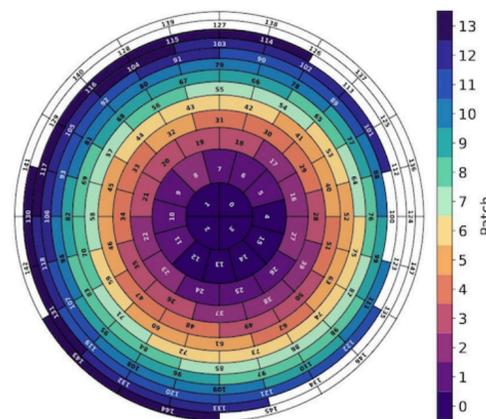
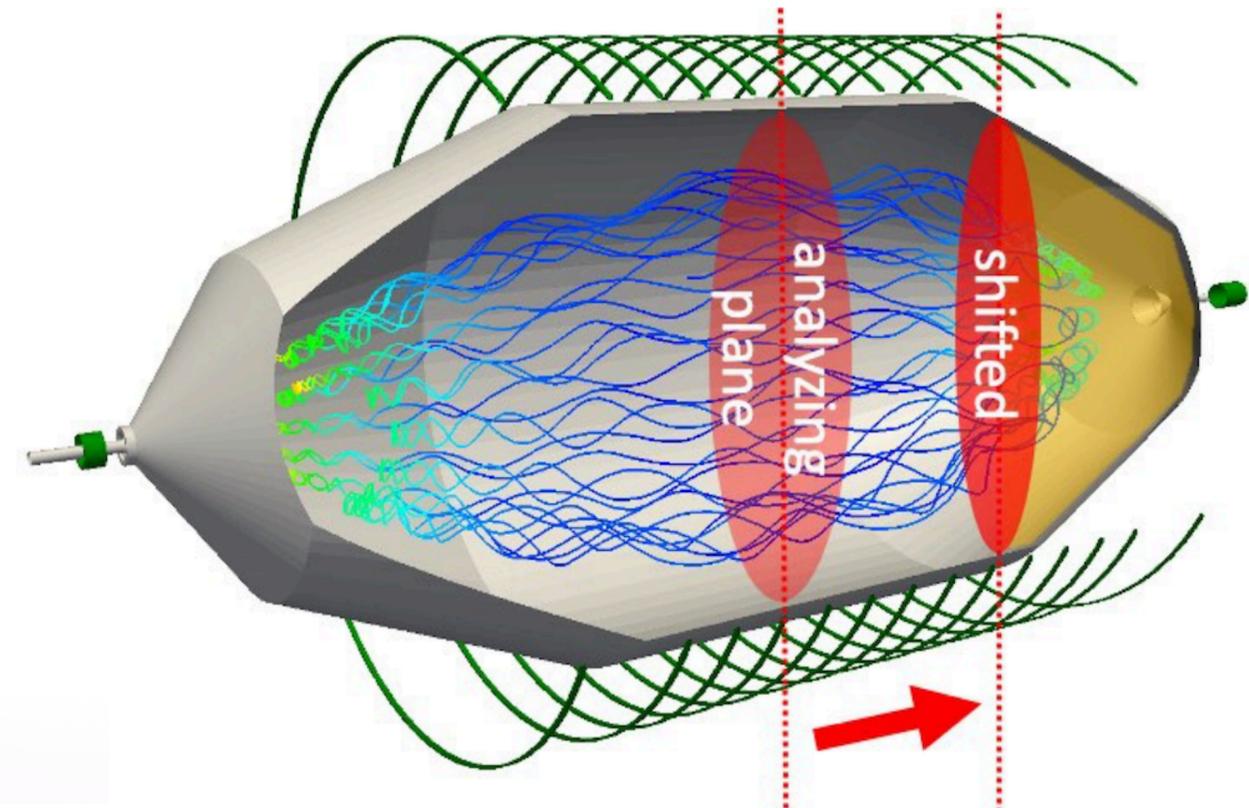
SCIENCE 388 (2025) 180

Experimental improvements in new data (I)

Factor 2 lower background using

“shifted analyzing plane” configuration

- Smaller volume mapped onto detector
- Inhomogeneous EM-fields
 - More segmented data x 14
 - Calibration of fields needed



Experimental improvements in new data (II,III)

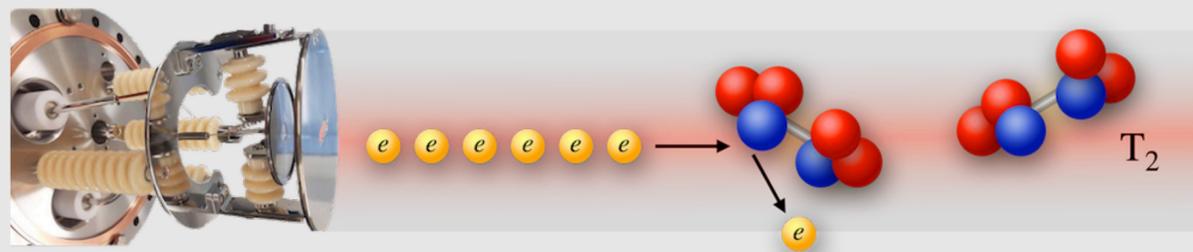
Precise calibration measurements with ^{83m}Kr co-circulation:

- Probe of electric potential variation in the source
- Field mapping in the spectrometer
- Source temperature: 30K \rightarrow 80K

KATRIN collab, Eur. Phys. J. C 85, 757 (2025)

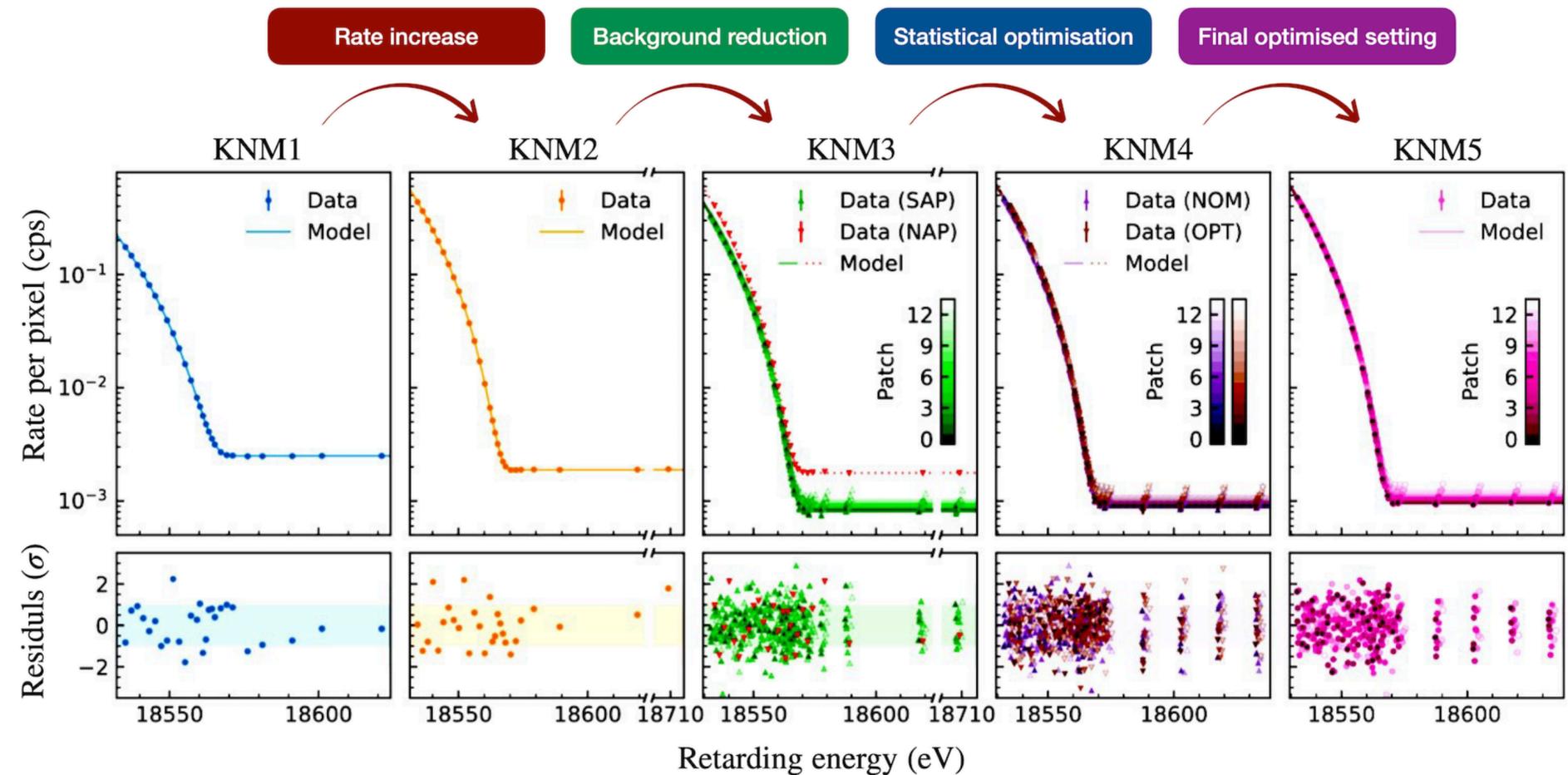
And with the **electron gun**:

- Energy loss through scattering
- Tritium gas density



Marsteller et al., JINST 17, P12010 (2022);

KATRIN collab, Eur. Phys. J. C 81, 579 (2021)



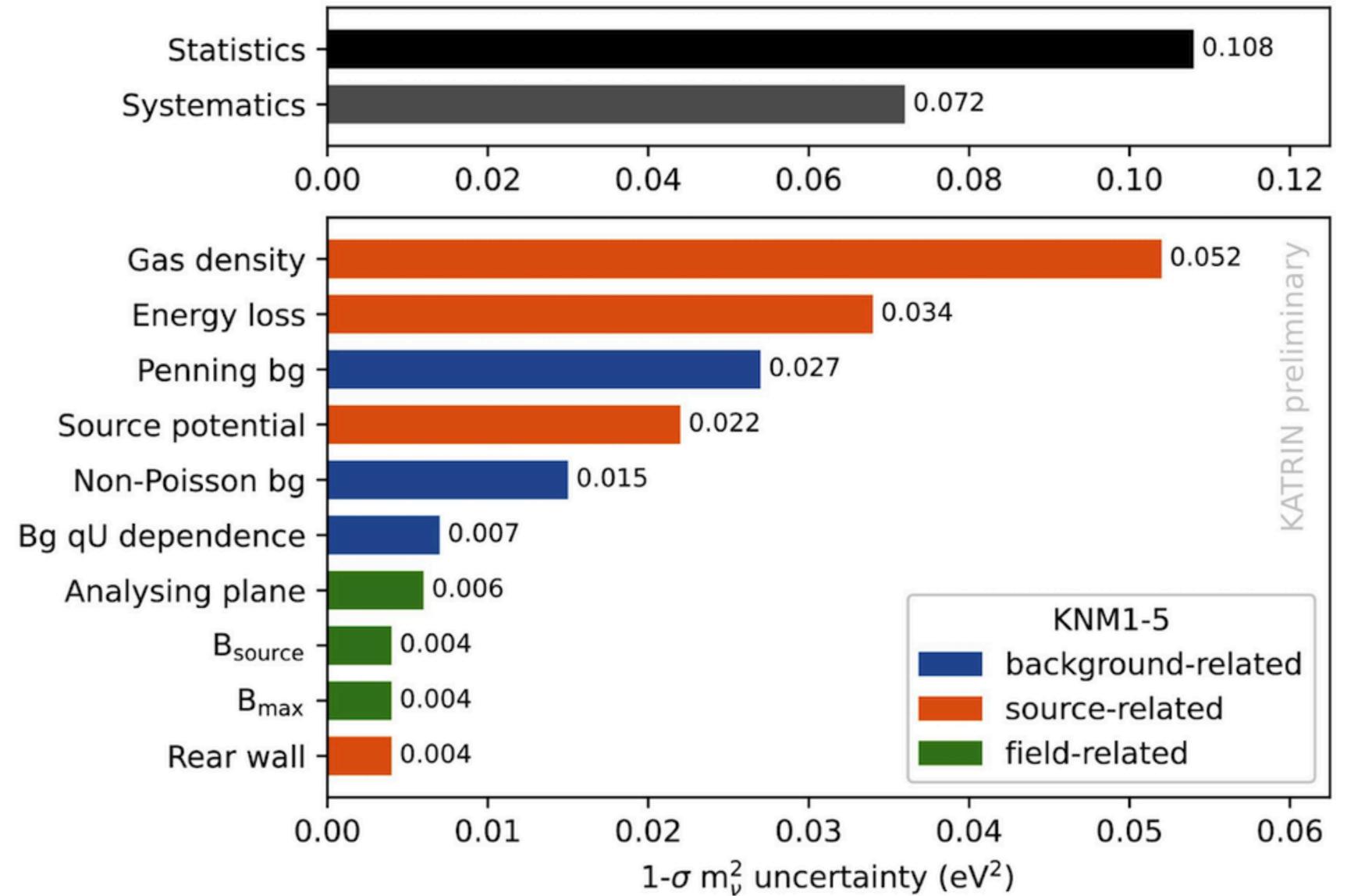
In measurement campaigns 4 and 5:

- **Improved** statistical sensitivity by optimized scan-time distribution
- **Eliminated** trapped particle background by lowering pre-spectrometer voltage
- Measured the residual tritium activity on the gold-plated **rear wall** and reduced it with ozone cleaning

M. Aker et al., Fusion Science and Technology 80, 303 (2024)

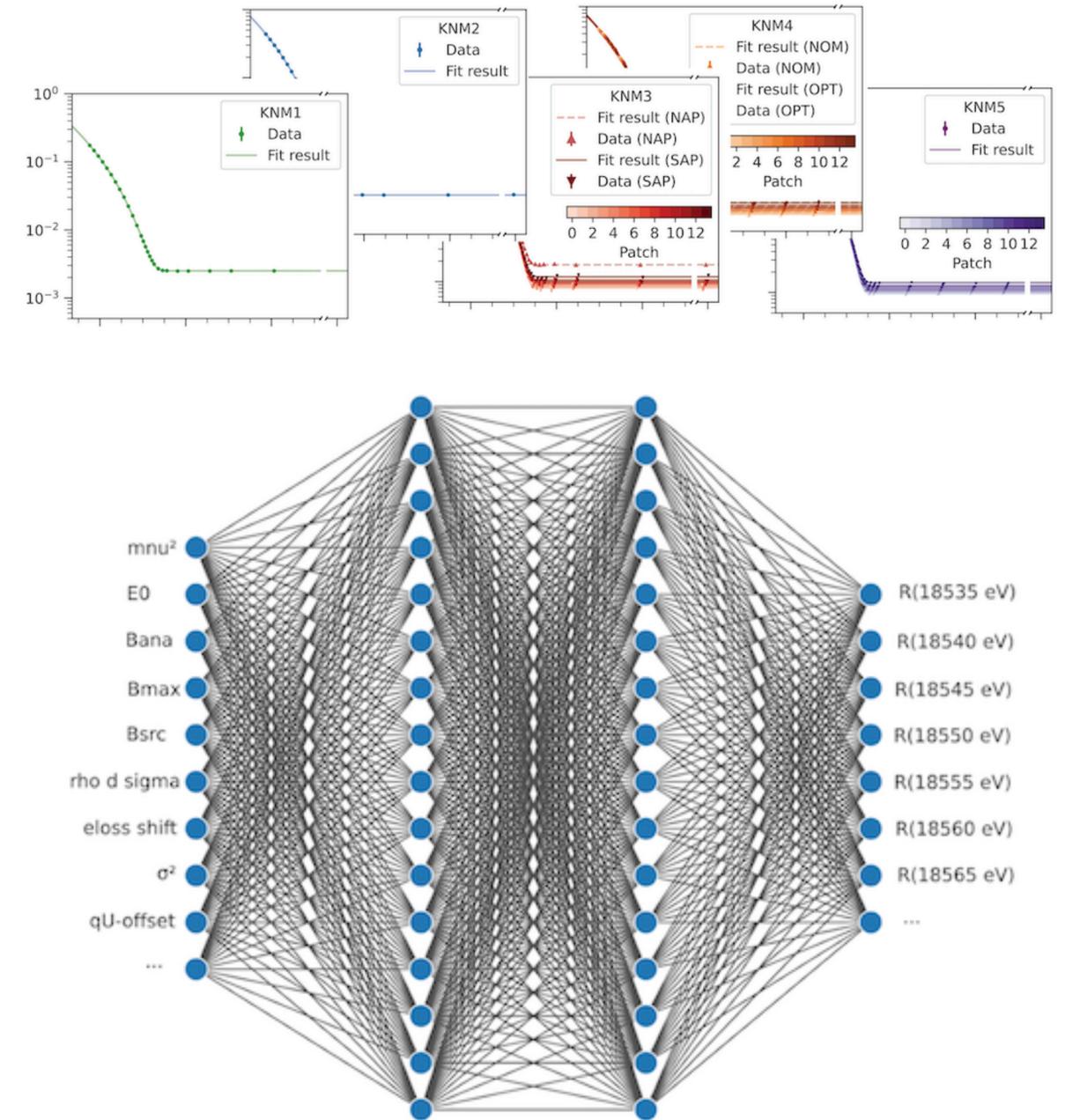
Systematic uncertainties

- Sensitivity dominated by statistical uncertainties
- Reduction of background-related systematics
- More precise calibration: new e-gun and the new krypton-tritium co-circulation mode to examine the source plasma potential
- Reduction of molecular final-states uncertainties by refined theoretical reassessment



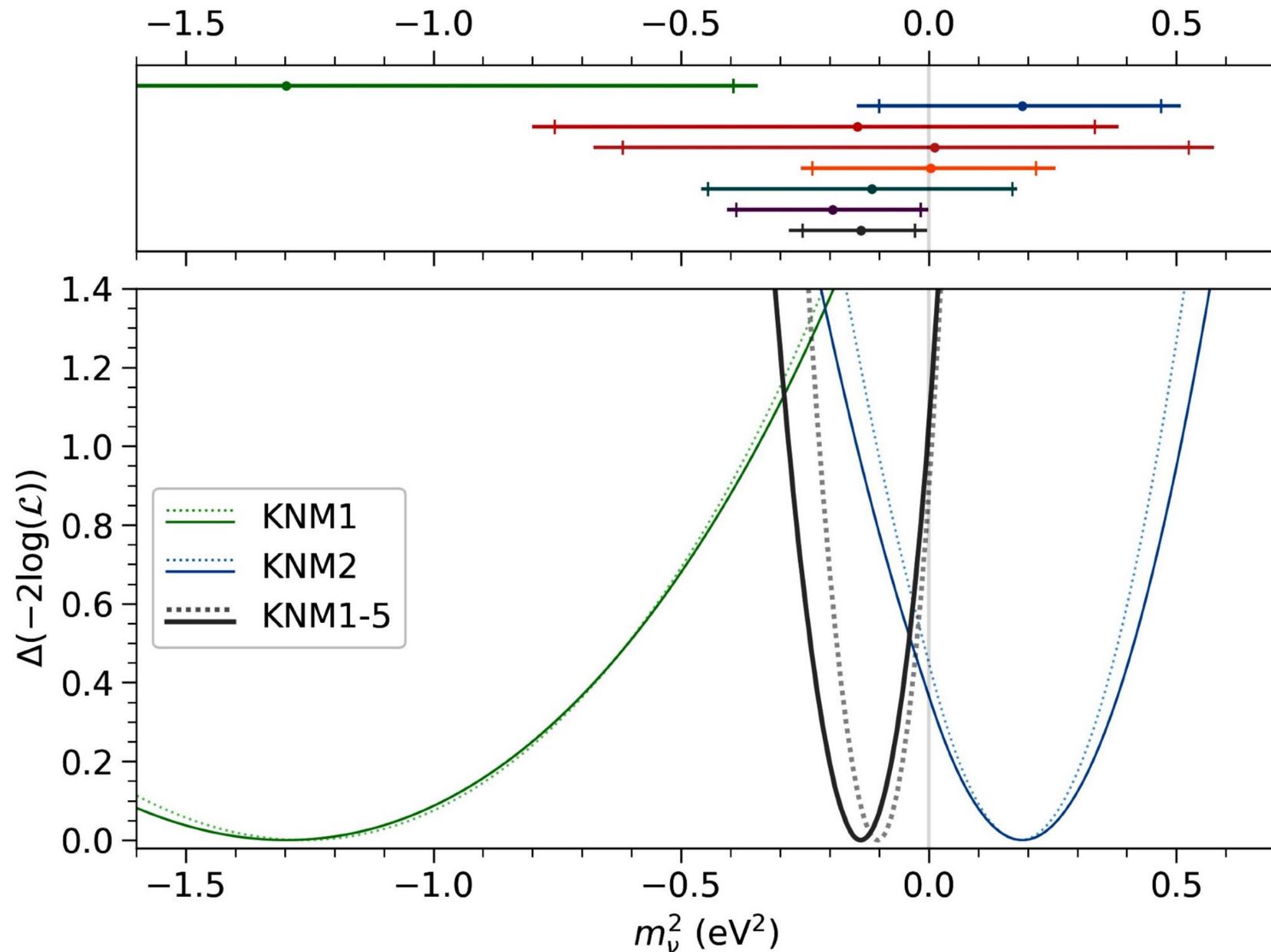
Analysis challenges

- Multiple campaigns, different operating configurations
- Highly segmented data(1609 datapoints)
- 144 correlated systematic parameters
- Computationally expensive model evaluations
 - Optimized direct model evaluation
 - Fast model prediction with a neural network
- Two independent analysis teams, double-layer blinding scheme
 - Different strategies and codes
 - Fixing analysis procedure on MC data
 - Using model blinding, undisclosed modification of final states



Karl et al., EPJ C 82 (2022) 439

Result of combined spectral fit



- Combined best-fit value:

$$m_\nu^2 = -0.14^{+0.13}_{-0.15} \text{ eV}^2$$

- Compatible with zero within uncertainties
- Excellent goodness-of-fit (p-value = 0.84)
- The m_ν^2 estimation that yields negative value, reflects the statistical fluctuations allowed by the spectral model.
- Agreement between both analysis teams

New Upper limit

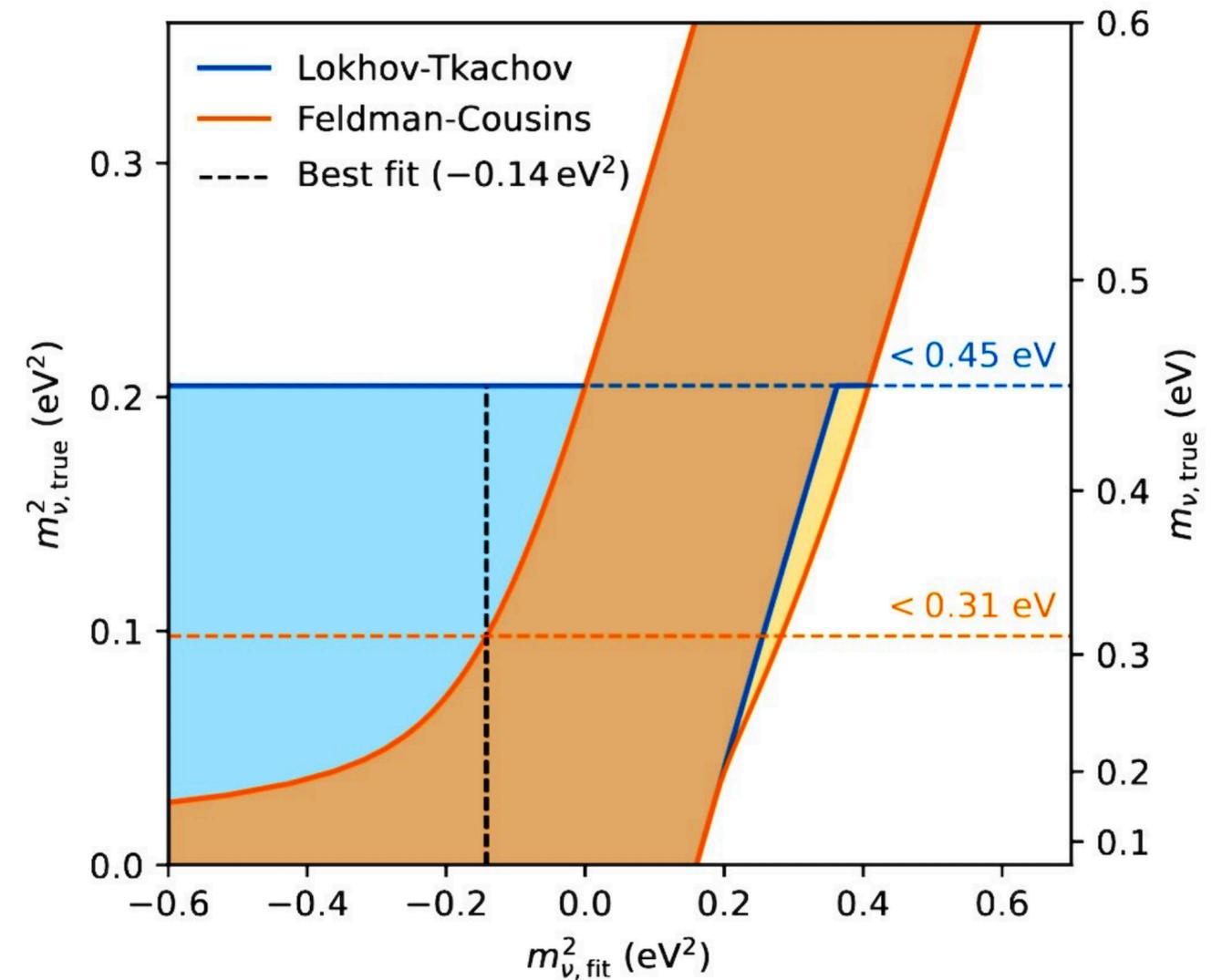
- best-fit value:

$$m_\nu^2 = -0.14^{+0.13}_{-0.15} \text{ eV}^2$$

- New upper limit: from

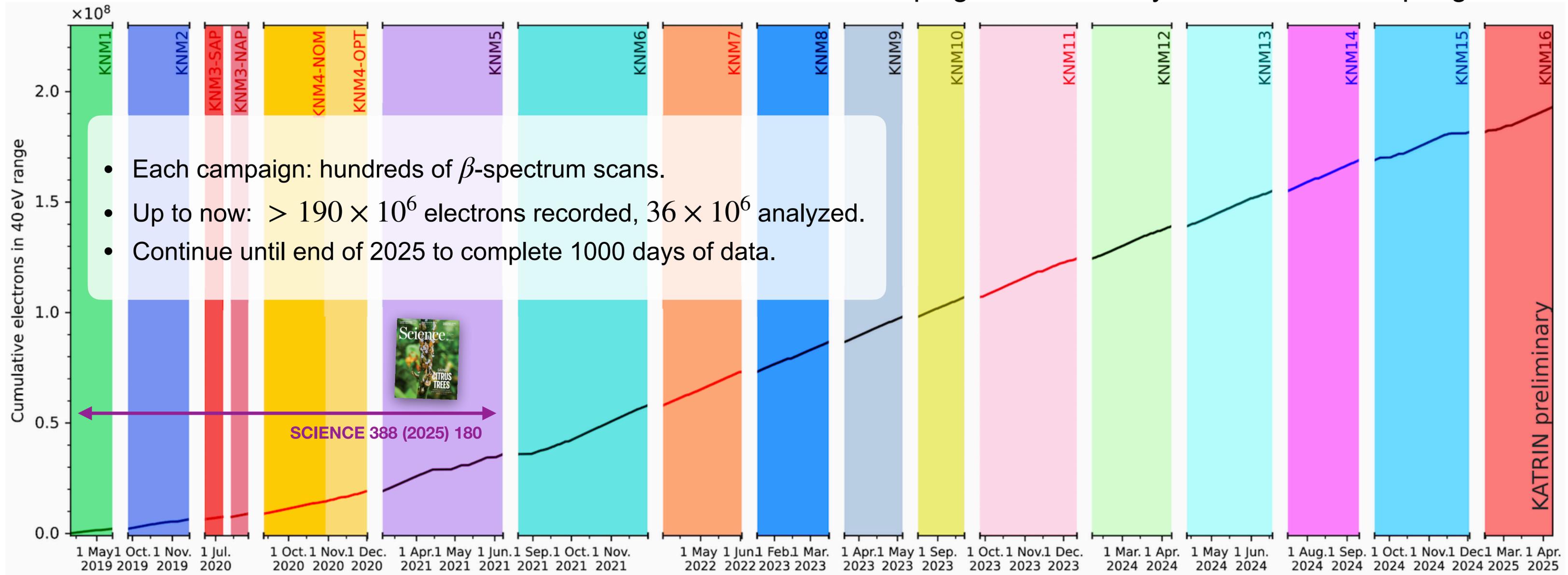
$$m_\nu < 0.45 \text{ eV (90 \% CL)}$$

Lokhov-Tkachov ~ sensitivity



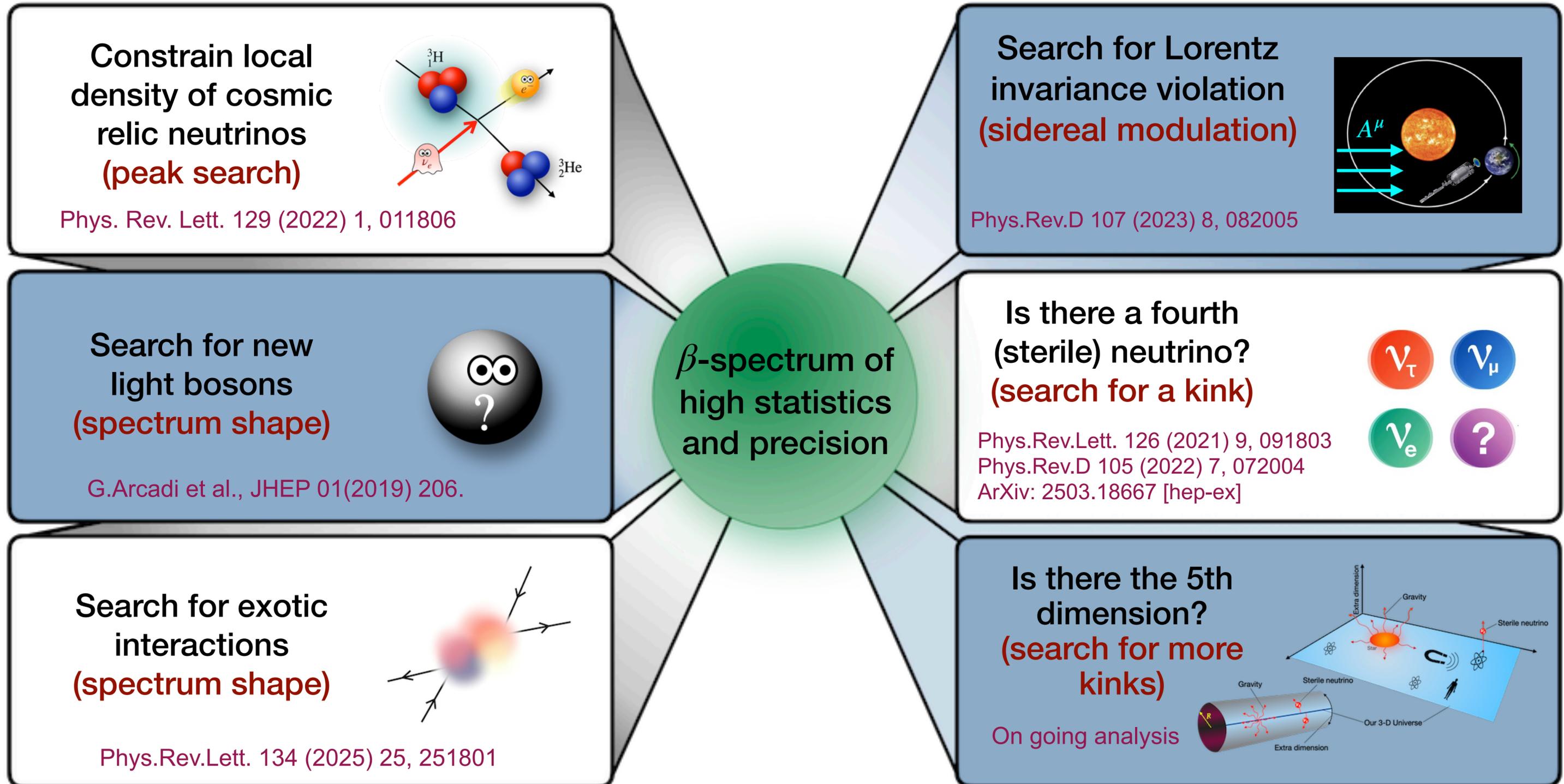
Progress of KATRIN data taking

16 measurement campaigns successfully concluded as of spring 2025.



spring 2019

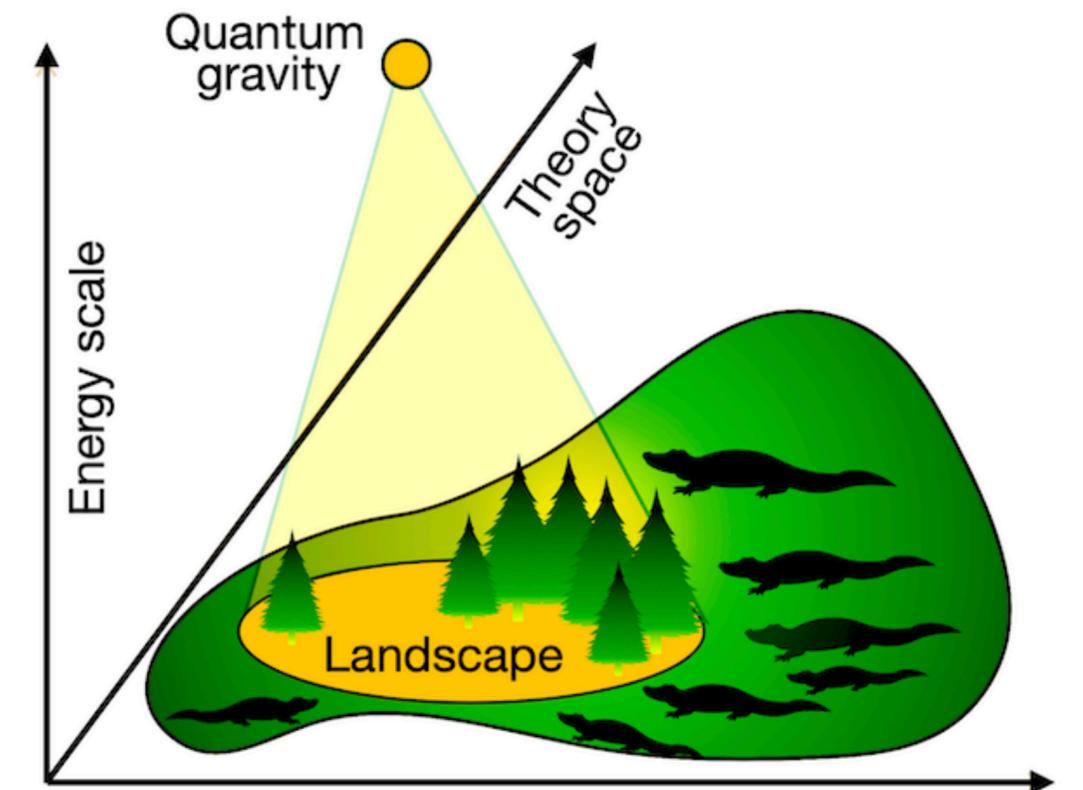
KATRIN “beyond neutrino mass”



String Landscape and Swampland Program

- Not all effective field theories can consistently coupled to gravity
 - Anomaly cancellation is not sufficient
 - Consistent ultraviolet completion can bring non-trivial constraints
- **Swampland Program:** searching for conditions on EFTs that can consistently coupled to gravity

criteria \Rightarrow conjectures supported by arguments based on string theory and black-hole physics
- **Swampland conjectures** provide bridge from quantum gravity to astrophysics, cosmology, and particle physics



“Good” theory lives in the landscape and “bad” ones lives in swampland

Vafa, hep-th/0509212

Where Do We Live in The String Landscape?

⇒ Distance Conjecture Ooguri-Vafa, Nucl.Phys.B766, 21 (2007)

- At large distance in field space $\phi \Rightarrow$ tower of exponentially light states

$$m \sim e^{-\alpha\phi} \text{ with } \alpha \sim \mathcal{O}(1) \text{ in Planck units}$$

- Provides a weakly coupled description up to the species scale:

$$M_* = M_P / \sqrt{N}$$

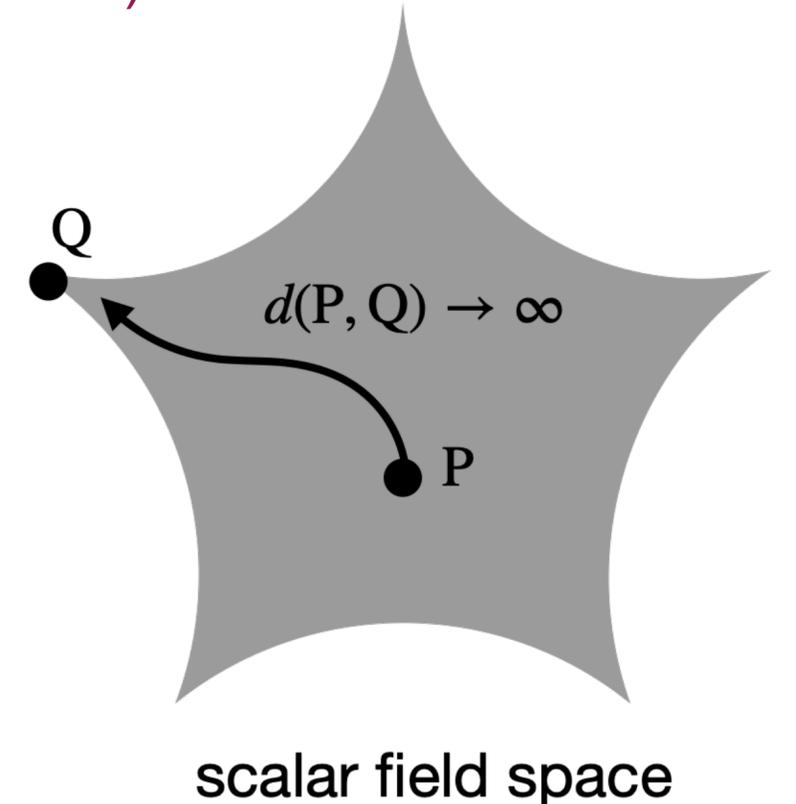
- Tower can be either:

- A Kaluza-Klein tower (decompactification of d extra dimensions)

$$m \sim 1/R, \quad \phi = \ln R; \quad M_* = M_P^{4+d} = (m^d M_P^2)^{1/(d+2)} \text{ and } N = (M_* R)^d$$

- A tower of string excitation (not discuss here!)

- Smallness of some physical parameters might signal a large distance corner in string landscape of vacua?



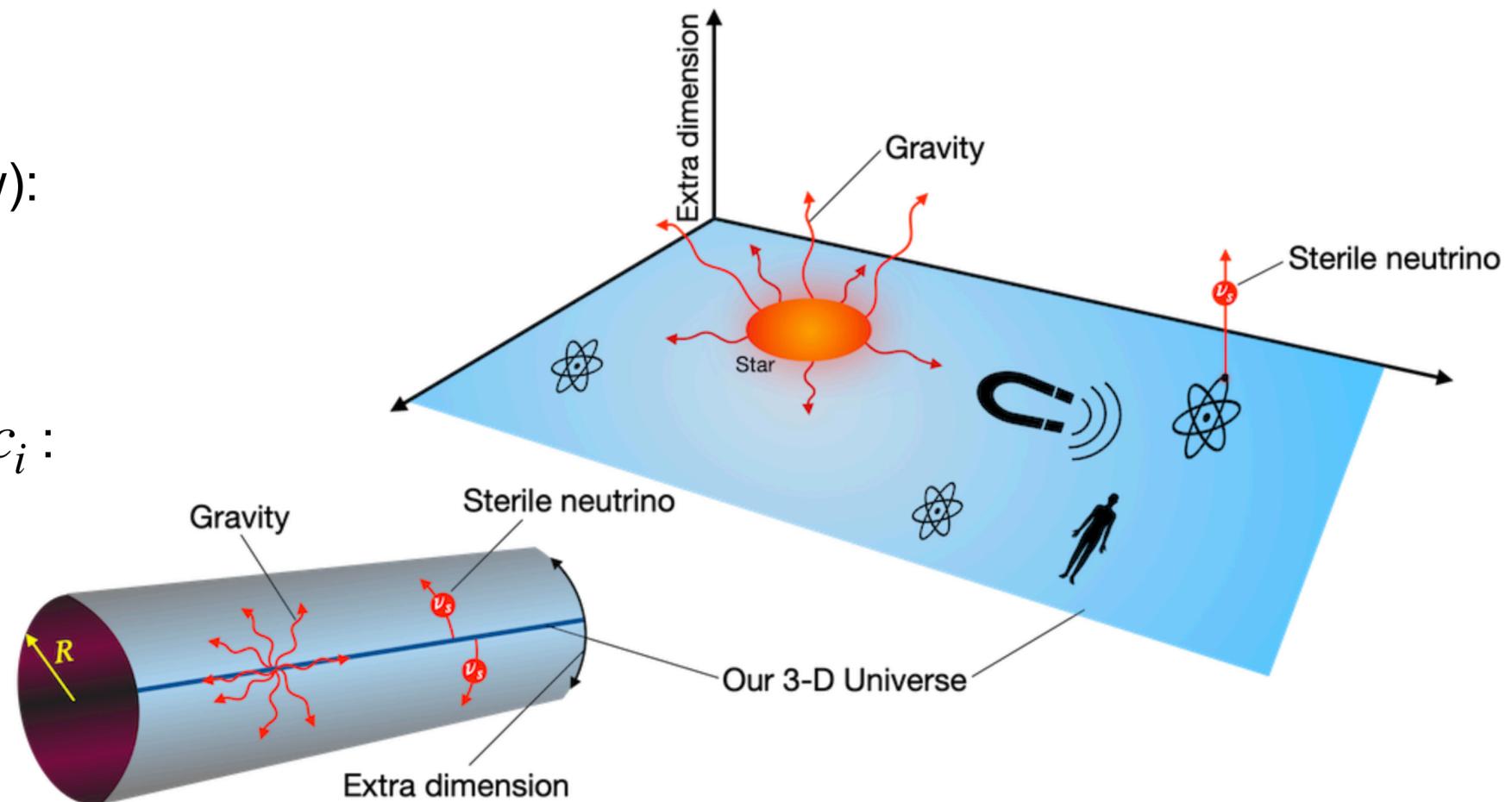
Dark Dimension proposal for the dark energy

- By combining swampland conjectures with observational data, **the cosmological hierarchy problem** (i.e. the smallness of the dark energy $\Lambda \sim 10^{-120} M_P$) could be understood as an asymptotic limit in field space, corresponding to a decompactification of **one extra (dark) dimension of a size in the micron range**
 - (Montero-Vafa-Valenzuela, JHEP02(2023)022)
 - (Anchordoqui-Antoniadis-Lüst, Phys.Rev.D107(2023)083530)
- Our observable universe should be localized on **“3-brane”**
 - ⊥ to the Dark dimension

- Tabletop experiment (deviations from Newton’s law):
 - constraints $R < 30 \mu\text{m}$

- The action for bulk fermions with mass parameter c_i :

$$S_{5D} = \int d^4x \int_0^{\pi R} dz \left(\sum_{i=1}^3 i\bar{\Psi}_i \Gamma^M \partial_M \Psi_i - \sum_{i=1}^3 c_i \bar{\Psi}_i \Psi_i \right)$$



Dark Dimension & Neutrino Physics

- Neutrino masses originate in 5D bulk brane interactions of the form

$$S_Y = - \frac{1}{\sqrt{\Lambda_{\text{QG}}}} \int d^4x \left(\sum_i y_i \bar{L}_i^L \tilde{H} \Psi_{iR} + c.c. \right)$$

- Expand Ψ_j into canonically normalized modes leads to 4D Yukawa coupling (suppressed by square root of bulk volume)

$$Y_{i0} = \mu_i \sqrt{\frac{2\pi R c_i}{e^{2\pi R c_i} - 1}} \quad \text{and} \quad \mu_i \equiv \frac{v y_i}{\sqrt{\pi R \Lambda_{\text{QG}}}} \quad (v = 174 \text{ GeV}, \quad \Lambda_{\text{QG}} \sim 10^9 \text{ GeV})$$

- Mesoscopic extra dimensions produces suppression of 4-dimensional Yukawa couplings yielding naturally light Dirac neutrinos (Note that for $c_i \gg 1/R$, the mass of active ν_i is exponentially suppress)
- Recent analysis of ν -oscillation data with 3 bulk neutrino [Forero-Giunti-Ternes-Tyagi, Phys.Rev.D106 \(2022\), 035027](#)

$$m \gtrsim 2.5 \text{ eV}, \quad R \lesssim 0.4 \mu\text{m}$$

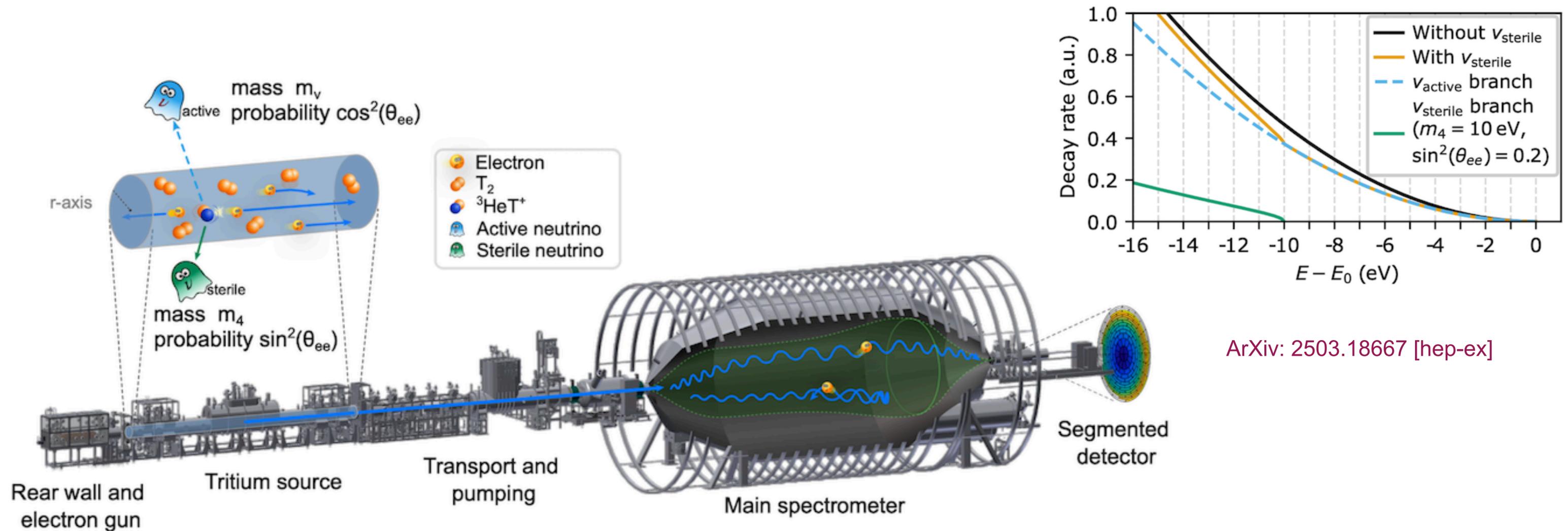
- Bound can be relaxed in the presence of bulk 5D neutrino mass ($c_i \neq 0$)

[Anchoroqui-Antoniadis-Cunat, Phys.Rev.D109 \(2024\), 016028](#)

[Antoniadis-Chatrabhuti-Isono-Pongkitivanichkul-Thongyoi, work in progress](#)

Search for Sterile Neutrino @ KATRIN

- **Light sterile neutrinos (eV mass scale):** motivated by short-baseline oscillation anomalies
- **Heavy sterile neutrinos (keV mass scale):** motivated as a dark matter candidate



Search for the Dark Dimension @ KATRIN ??

- Expect Kaluza-Klein (KK) “sterile” neutrino
- Model parameters:

- Extra dim radius: R ($\sim \mu\text{m}$)

- 5-dim fermion mass: c

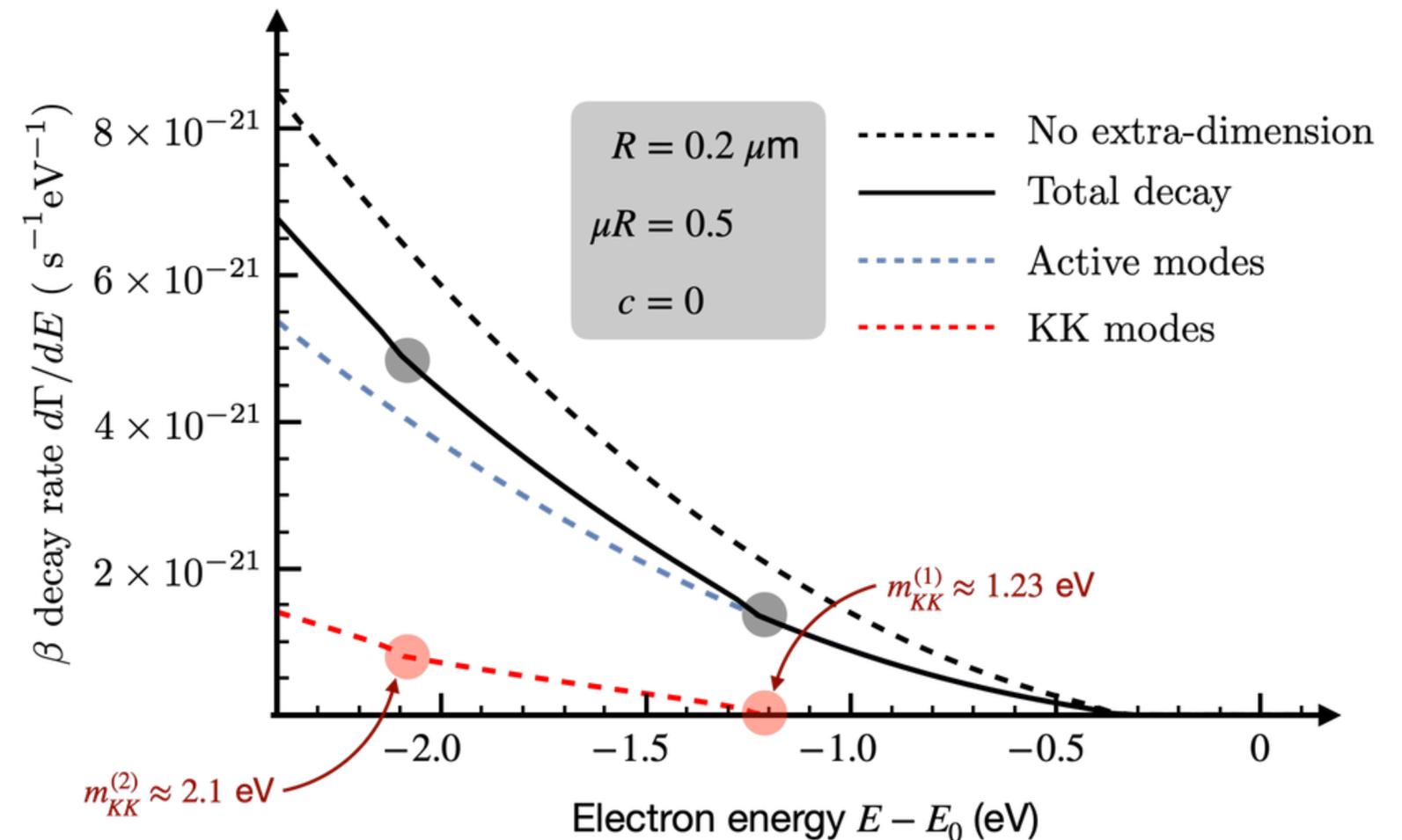
- Yukawa coupling: μ

- For small coupling, the n^{th} KK sterile is

$$m_{KK}^{(n)} \approx \frac{1}{R} \sqrt{n^2 + c^2 R^2}$$

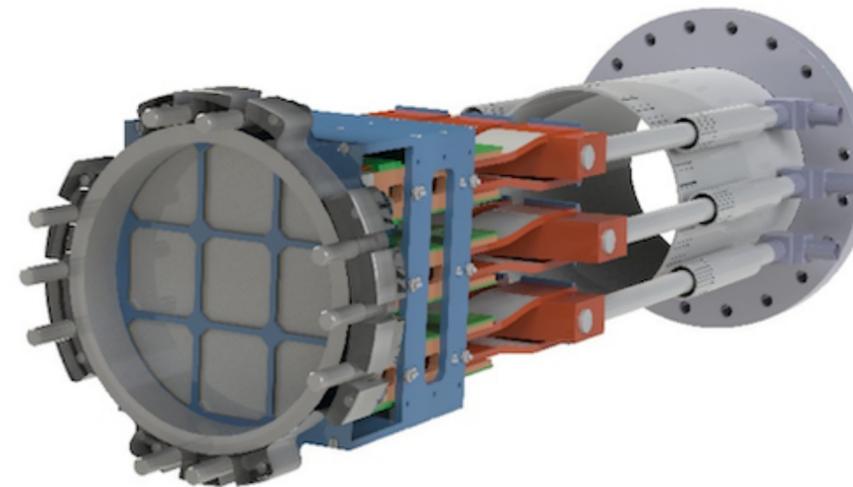
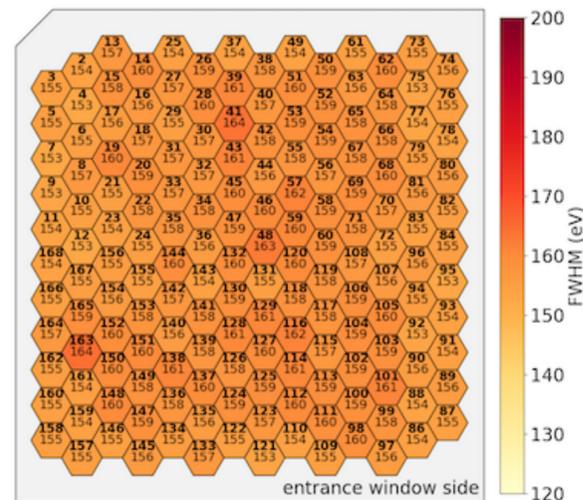
- The mixing matrix $\simeq \frac{n\mu R}{n^2 + c^2 R^2}$

- Expect to see **more kinks** in the spectrum



TRISTAN @ KATRIN

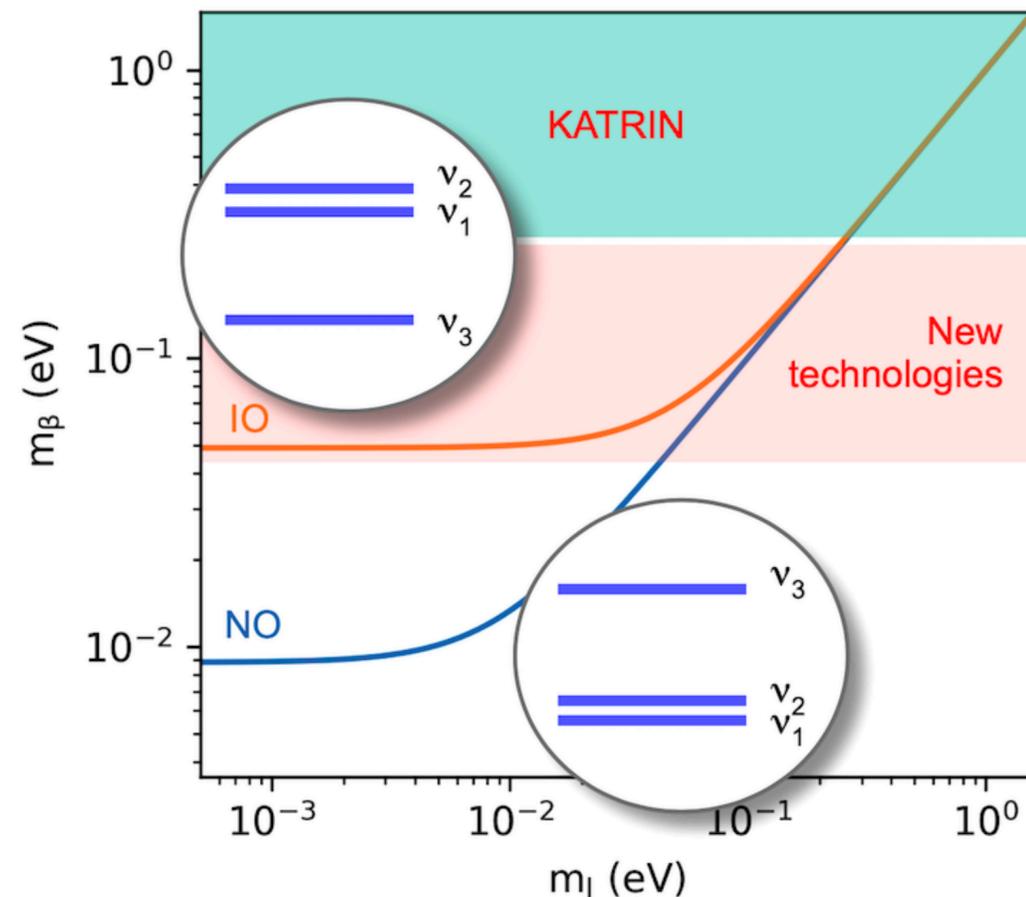
- **Aim:** Measure the **full tritium spectrum** to search for **keV steriles**
- **Challenges:** Energy range x 400, electron rate $\times 10^6$, high energy resolution, control of systematics
- **Technology:** Silicon Drift Detector (SDD) array with > 1000 pixels



- Capacity to handle high rates (> 108 cps)
- Excellent energy resolution (160 eV @ 5.9 keV)

- **Timeline:** Implement in KATRIN beam line for **measurements** during **2026-2027**

Towards a next-generation experiment

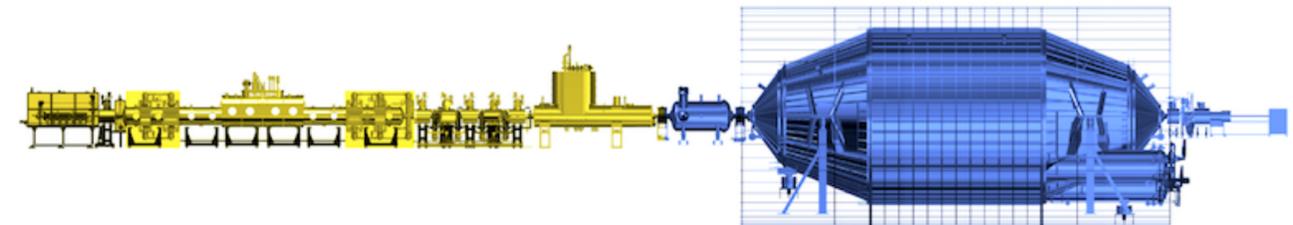


Many ideas with exciting potential:

e.g. CRES technology (Project 8), quantum sensor arrays & readout (ECHO, HOLMES), time-of-flight with electron tagger, ...

Goals: Develop new technologies to fully cover inverted mass ordering (I.O.), and eventually (N.O.) of ν masses

Will a new experiment look like KATRIN??



- New **source** concepts (molecular \rightarrow atomic tritium)
- New **detector** technologies (differential spectroscopy, high energy resolution)

Conclusion and Outlook

New KATRIN release improves direct neutrino-mass bound by a factor of 2:

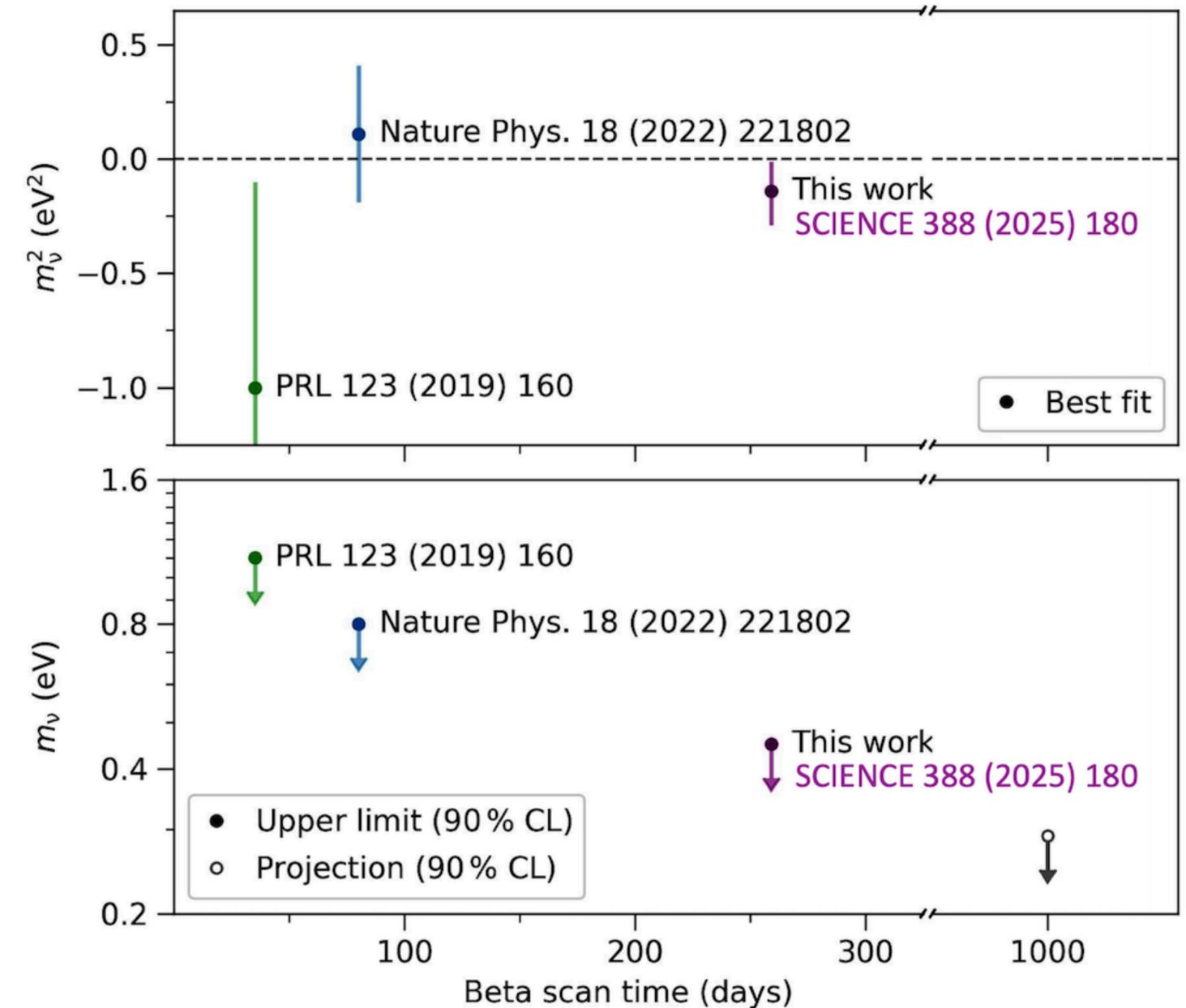
$$m_\nu < 0.45 \text{ eV (90 \% CL)}$$

Ongoing analysis:

- 70 % of total anticipated data recorded, improvements in systematics
- Several BSM physics searches: eV-sterile, exotic interactions, extra dimension, light bosons, relic ν , etc ...

Ongoing data taking through 2025 \rightarrow Σ 1000 days

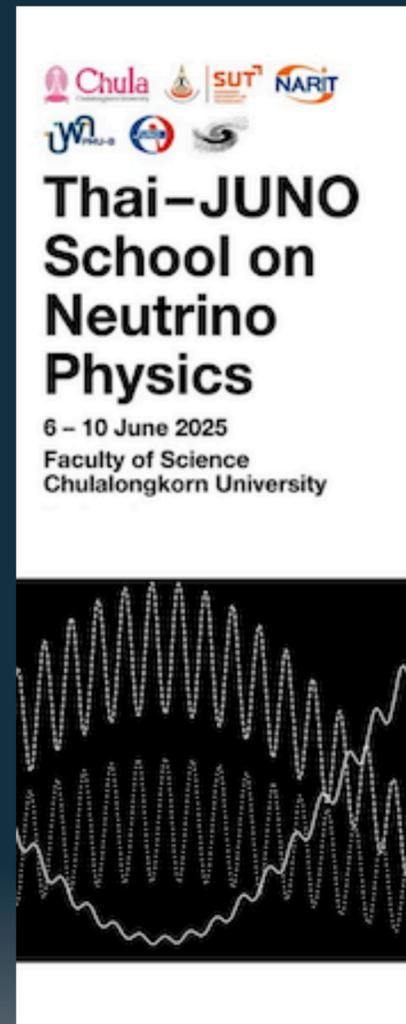
- Target sensitivity below 0.3 eV



Neutrino Physics in Thailand

Neutrino Experimental Research Group:

Chulalongkorn U. (KATRIN, JUNO, SND@LHC), Suranaree U. (KATRIN, JUNO), NARIT (JUNO)
Chiang Mai U. (Ice Cube, TRIDENT, SND@LHC)





Thank you
Cảm ơn
ขอบคุณครับ



Back up

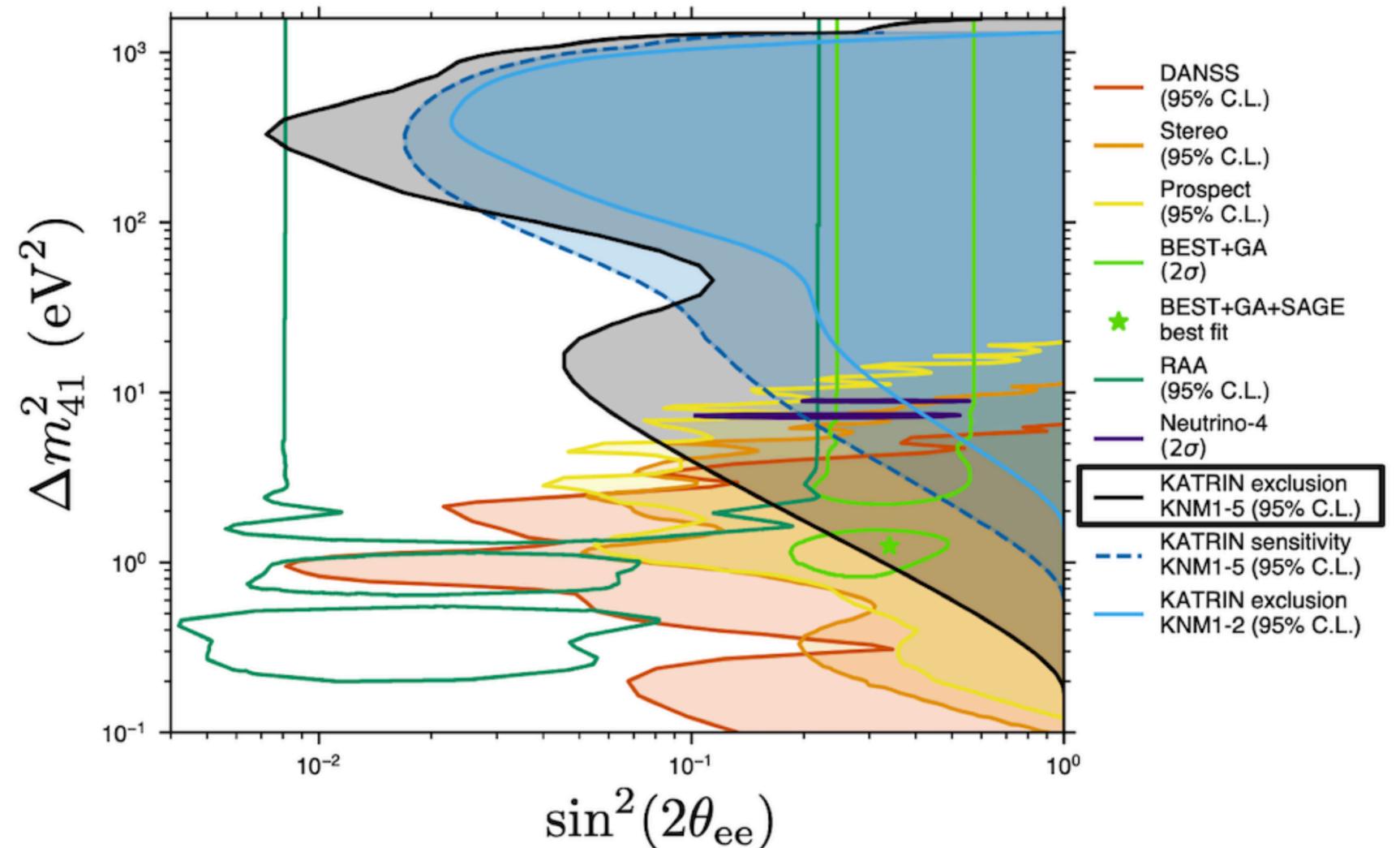
New direct bounds on light sterile neutrinos

- Improvement in statistics (X6 compared to previous release)
- Synergy with short-baseline reactor experiments (Prospect, Stereo, DANSS)

- KATRIN bound dominates for

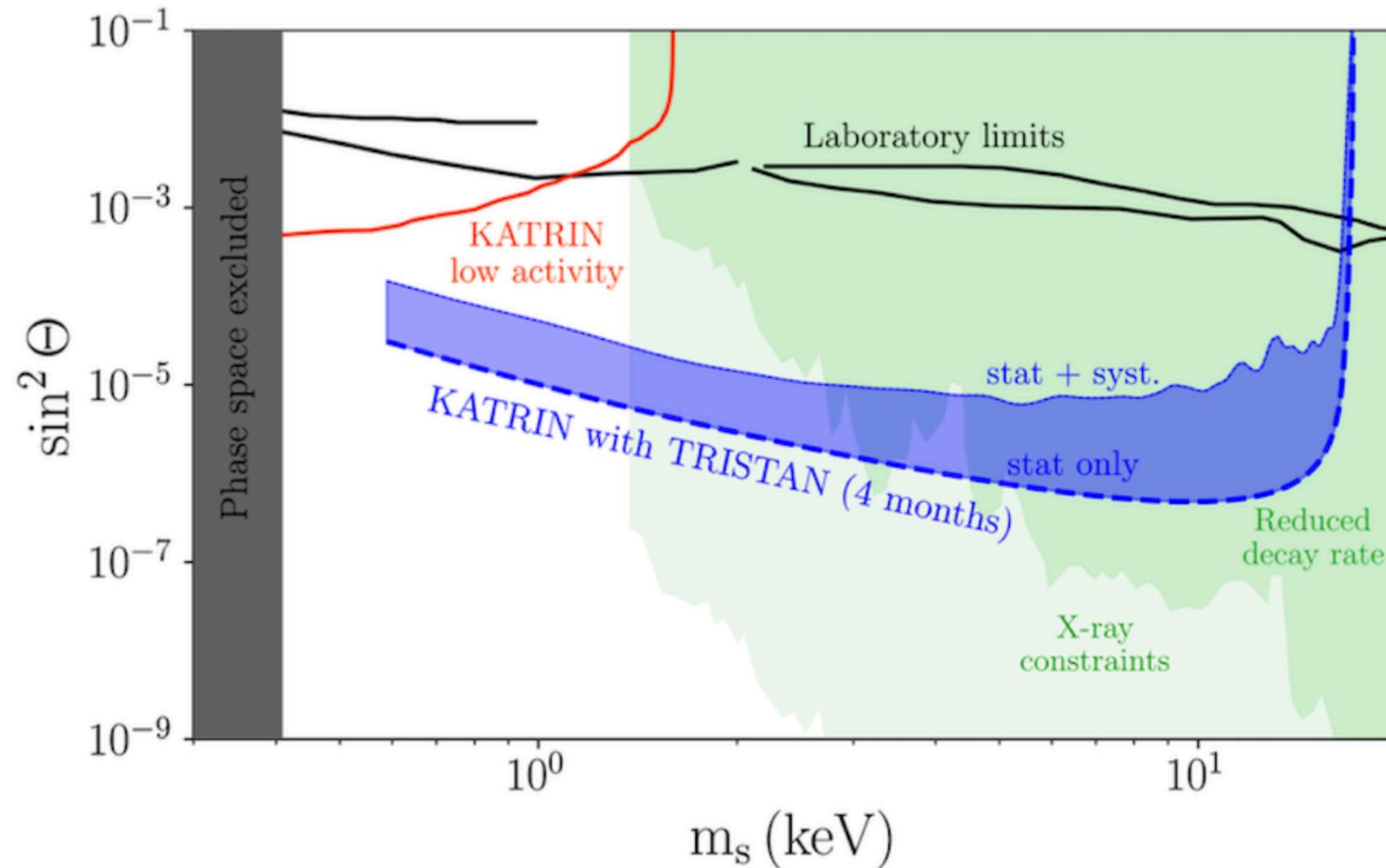
$$\Delta m_{41}^2 \approx m_4^2 - m_\beta^2 > 5 \text{ eV}^2$$

- Expect further improvement of sensitivity with full data set



ArXiv: 2503.18667 [hep-ex]

Sensitivity to keV sterile neutrinos



- Present direct lab-based constraints: mixing sensitivity $\sim 10^{-3}$ (e.g. from **KATRIN commissioning**, at reduced source strength)
- **KATRIN with TRISTAN detector** will reach $\sim 10^{-6}$ statistical sensitivity with few months of data
- Key systematics under scrutiny (hardware adaptations, dedicated measurements)