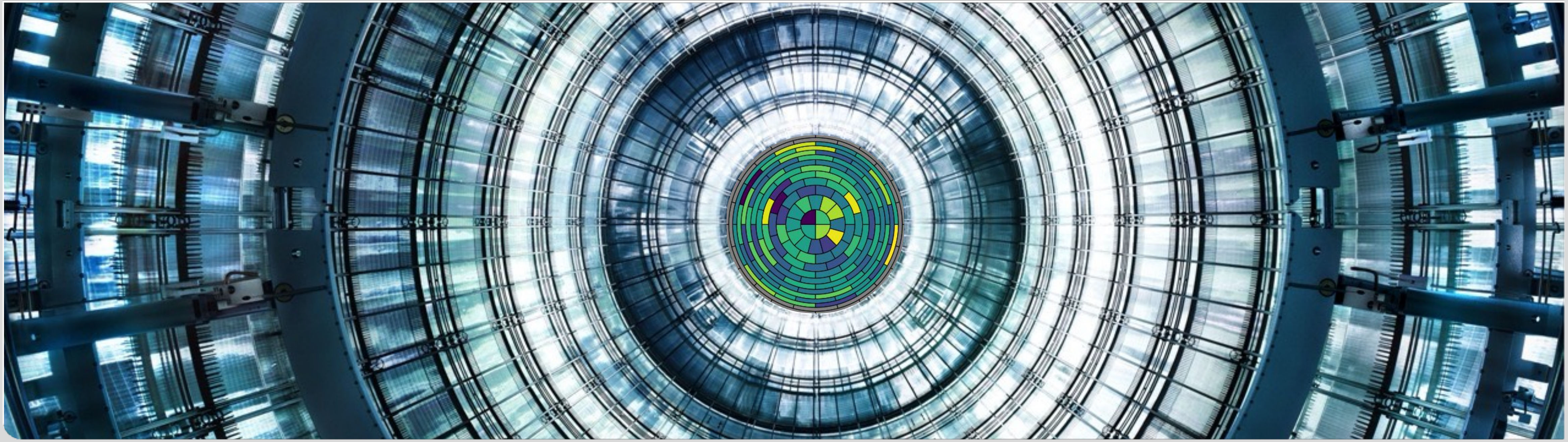
Probing the neutrino mass scale: first results and future perspectives of KATRIN

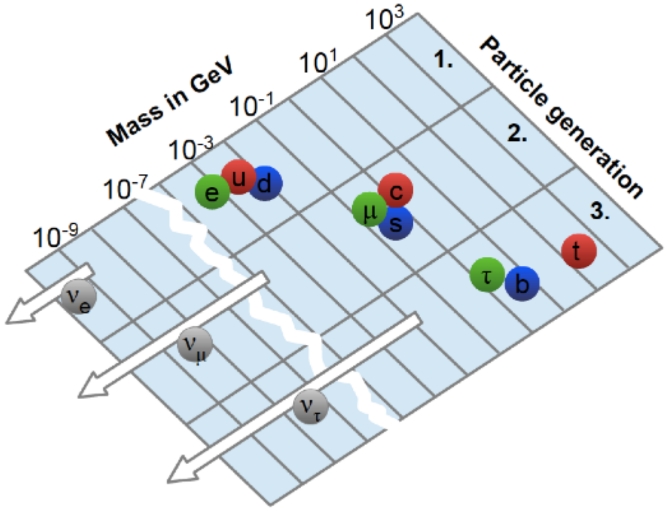
(Virtual) Particle Physics Seminar, U Liverpool
November 18th, 2020

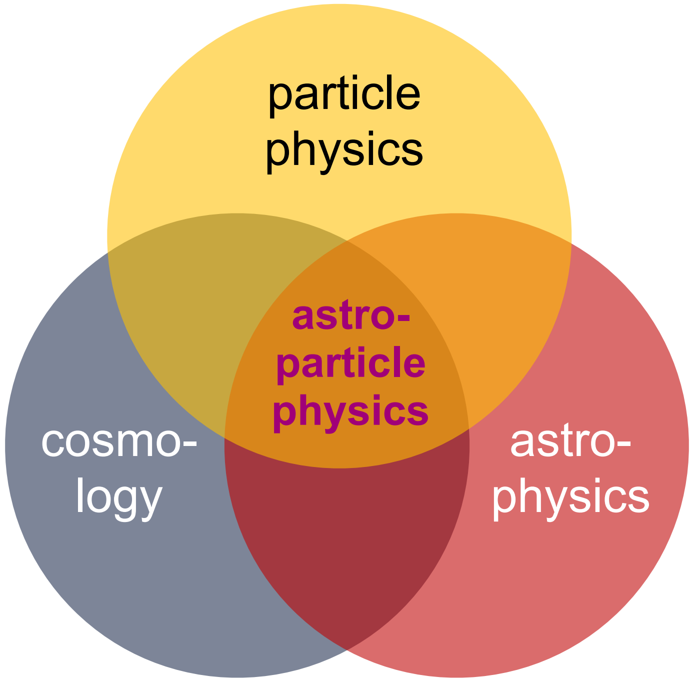
KATHRIN VALERIUS (KIT, Institute for Astroparticle Physics)



The role of massive neutrinos

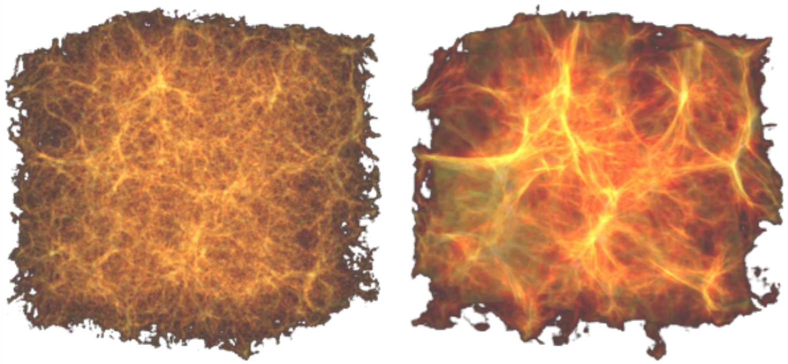
Mass generation: new concepts





Massive neutrinos as “cosmic architects”

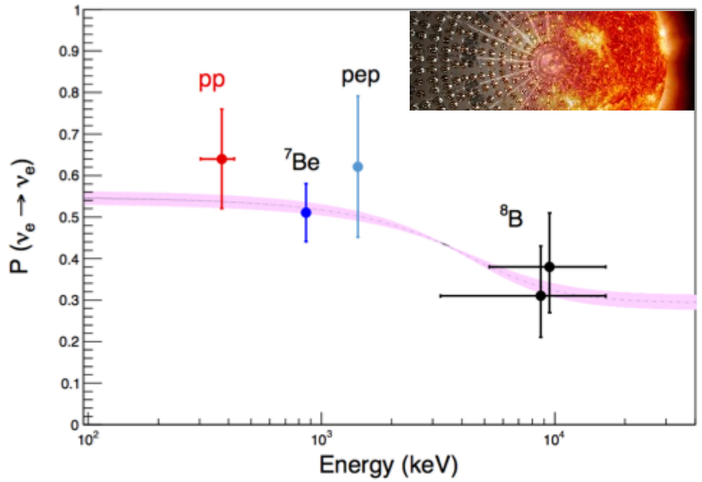
336 ν / cm³ in the Universe today



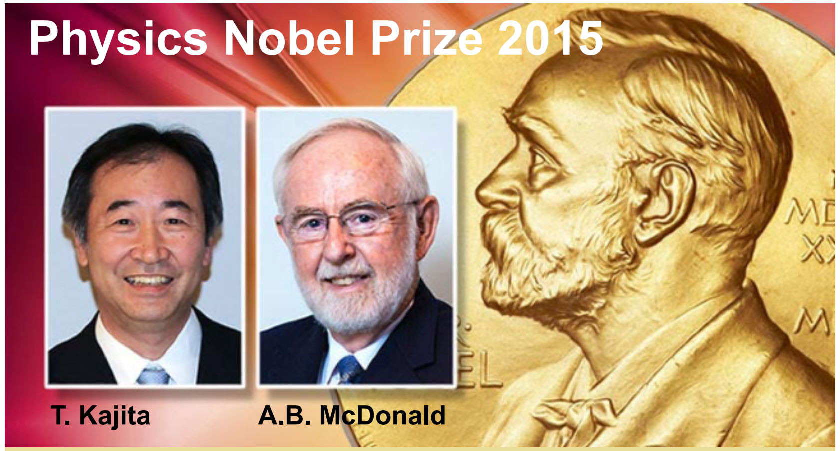
$m_\nu = 0$ $m_\nu > 0$

Understanding astrophysical processes

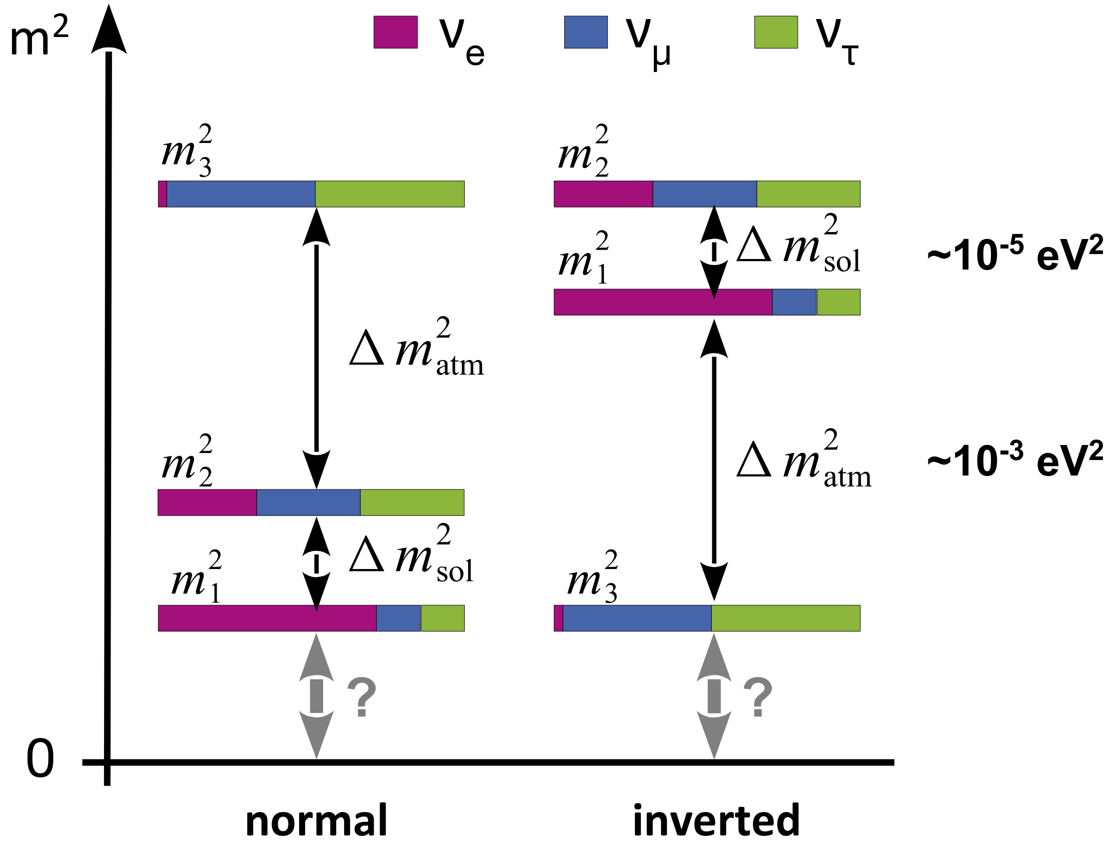
ν as probes of fusion in the sun



Neutrino masses & flavour oscillations

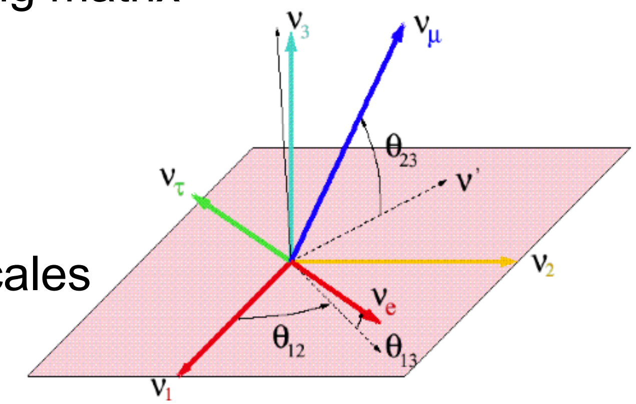


"for the discovery of neutrino oscillations, which show that neutrinos have mass"



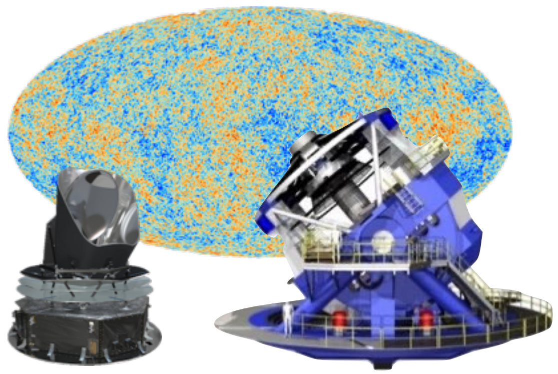
➜ 3 flavour states and 3 mass states linked by unitary mixing matrix (analogous to CKM)

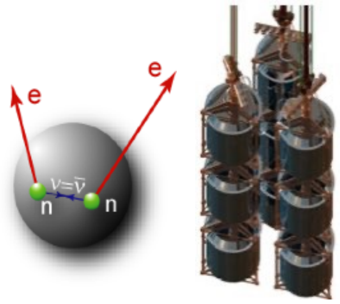
➜ 3 mixing angles θ_{ij},
1 CP phase δ,
2 independent Δm^2 scales

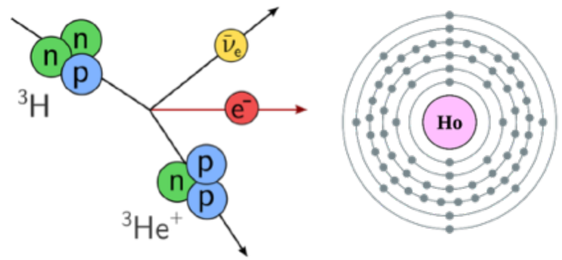


- Large neutrino mixing and tiny neutrino masses $m(\nu_i) \neq 0$ established
- Which mass ordering? CP violation?
- **What is the absolute ν mass scale?**

Complementary paths to the ν mass scale



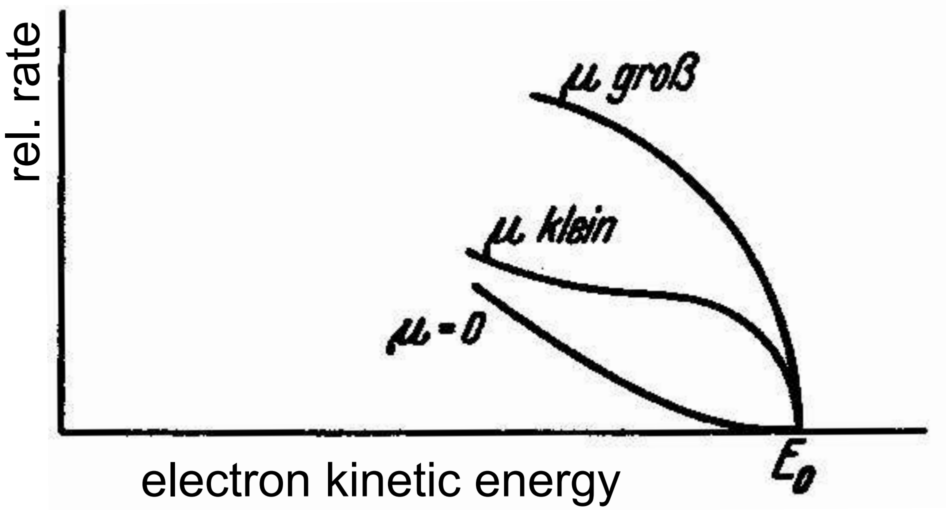


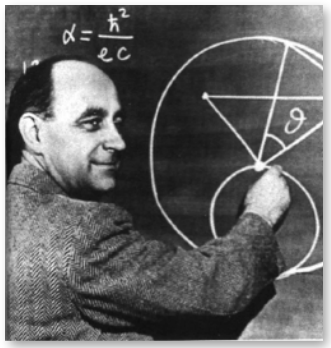


	Cosmology	Search for 0νββ	Kinematics of weak decays
Methods	CMBR, GRS, lensing, …	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\|\sum_i U^2_{ei}\, m_i\right\|^2$	$m^2_\beta = \sum_i \|U_{ei}\|^2\, m^2_i$
Model dependence	Multi-parameter cosmological model	- Majorana nature of ν, lepton number violation - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

Neutrino mass from β-decay kinematics

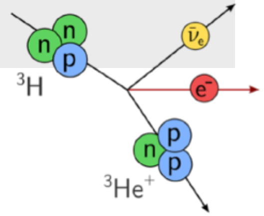
Theory: Starting from Fermi's seminal "attempt at a theory of β-rays"





Fermi, Z. Phys., 1934

Experiment: Tritium identified early on as most suitable β-emitter



NATURE August 21, 1948 Vol. 162

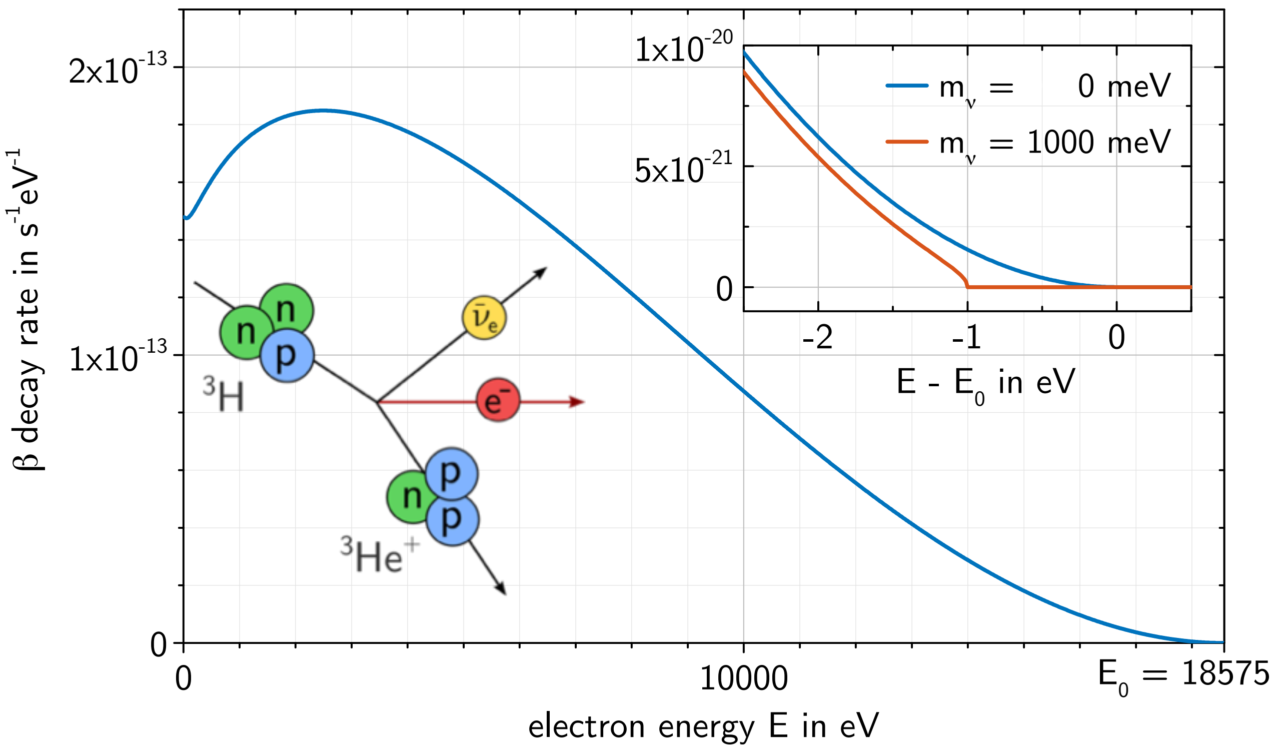
Beta Spectrum of Tritium

THE β-spectrum of tritium ($_1H^3$) is of particular interest because: (1) the relatively simple structure of the $_1H^3$ nucleus makes it well suited to a test of the Fermi theory of β-decay; (2) the unusually low energy of the β-particles means that the shape of the spectrum near the upper limit is an extremely sensitive function of the rest mass of the neutrino if the Fermi theory is confirmed; (3) a theoretical discrepancy[1] exists between the half-life[2] and the upper energy limit, as recently measured[3]; (4) the mass difference ($_1H^3$ — $_2He^3$) can be accurately determined.

Curran *et al.*

Neutrino mass from β-decay kinematics

$$\frac{d\Gamma}{dE} = K \cdot F(Z,E) \cdot \underbrace{p}_{p_e} \cdot \underbrace{E_{tot}}_{E_e} \cdot \underbrace{(E_0 - E)}_{E_\nu} \cdot \underbrace{\sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}}_{p_\nu}$$



Spectral distortion measures **"effective" mass square:**

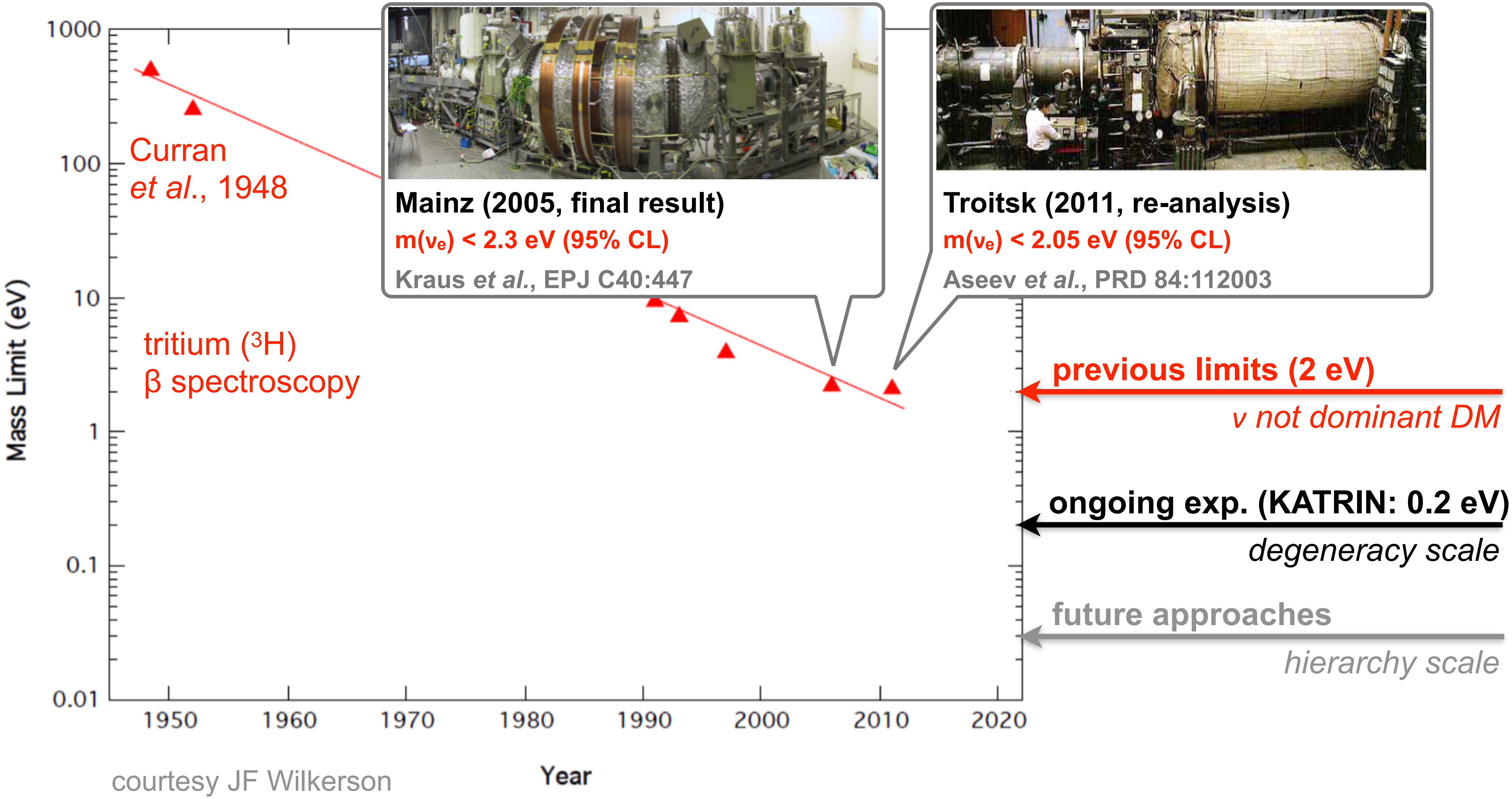
$$m^2(\nu_e) := \sum_i |U_{ei}|^2 m_i^2$$

Key requirements:

- Low endpoint energy: E_0 = 18.6 keV for ^3H
- High-activity source: $T_{1/2}$ = 12.3 yr for ^3H
- Energy resolution ~ 1 eV

Kinematic measurement can probe for **heavier ν states** ➜ eV- and keV-scale sterile ν

Neutrino mass from β-decay kinematics



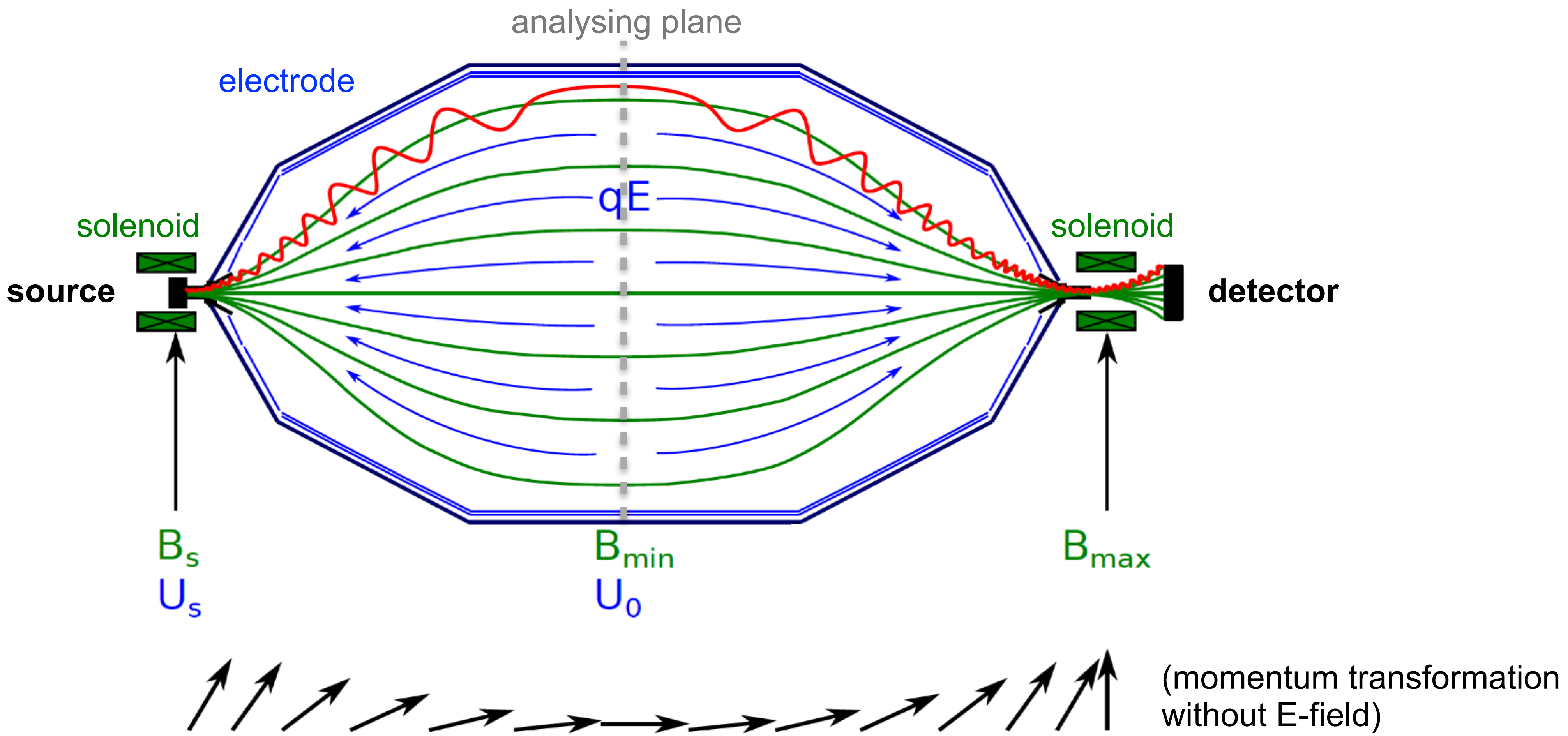
courtesy JF Wilkerson

High-resolution spectrometer: MAC-E filter

Magnetic Adiabatic Collimation & Electrostatic Filter

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

- ➜ Integrating electrostatic filter ($E_{kin} > eU_0$)
- ➜ High resolution ΔE ~1 eV combined with large angular acceptance 0° …51°



The Karlsruhe Tritium Neutrino Experiment

- Experimental site:
  Karlsruhe Institute of Technology (KIT)
- International collaboration:
  ~150 members from 20 institutions
  in 6 countries (D, US, CZ, RU, F, ES)
- Goal: Improve sensitivity on $m(\nu_e)$
  from 2 eV (previous experiments) to 0.2 eV (90% C.L.) within 2019-2024

katrin.kit.edu

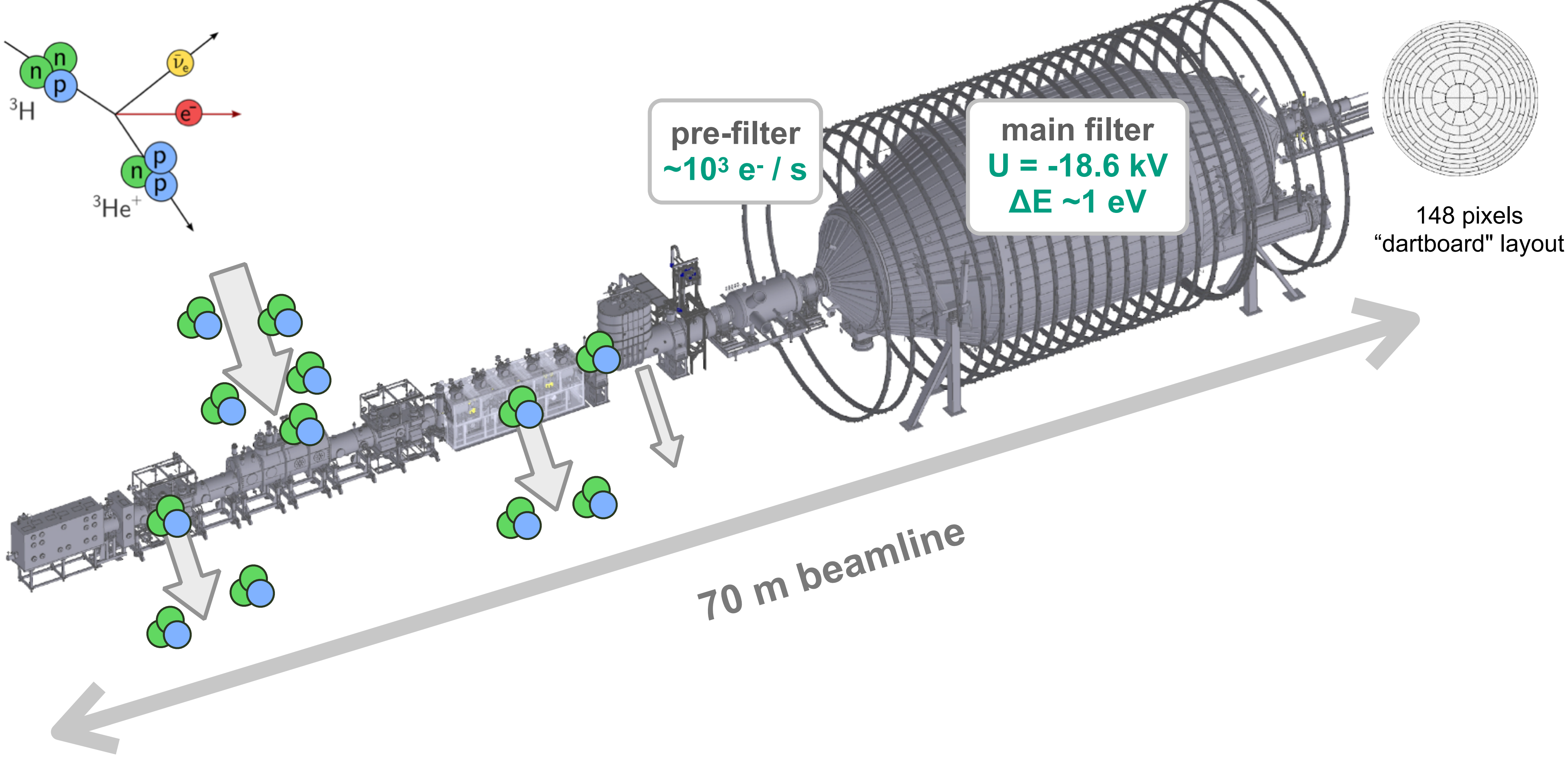
Working principle of KATRIN

windowless
gaseous T_2 source
10^{11} e^- / s

tritium pumping
& e^- transport
T_2 flow reduction $>10^{14}$

high-pass energy filters
MAC-E filter

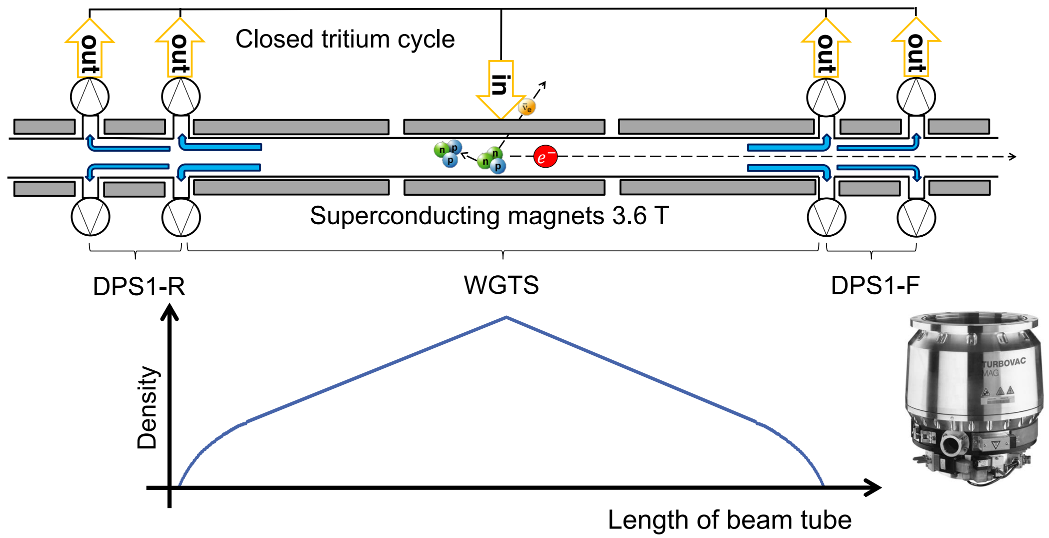
counting detector
< 1 e^- / s



KATRIN's high-luminosity tritium source

Gaseous molecular tritium source of

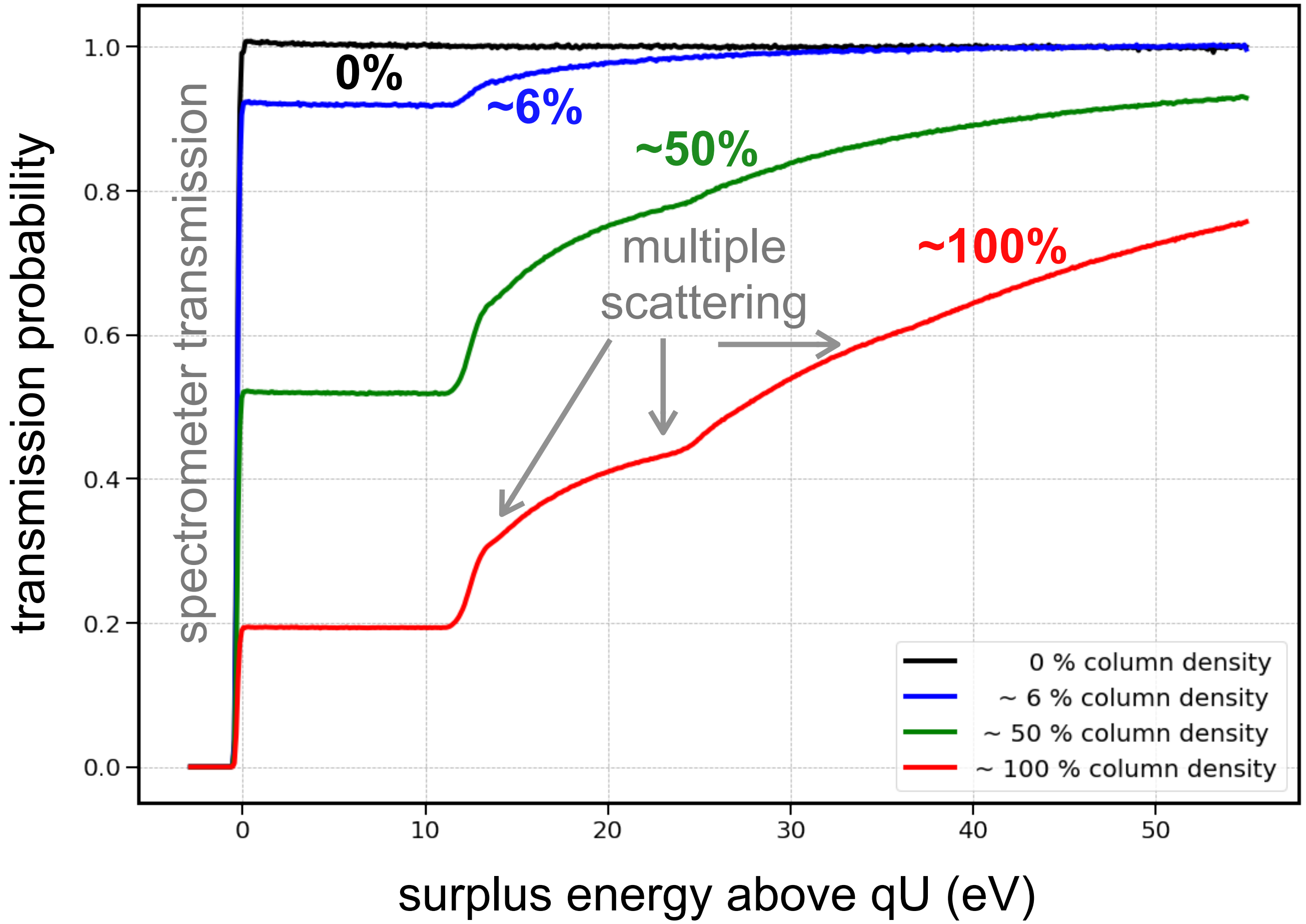
- high activity (~100 GBq)
- high gas column density ($5 \cdot 10^{17}$ cm^{-2}) and stability (0.1%)
- high isotopic purity (ε_T > 95%)



- closed tritium loops: ~100 m of piping
- instrumentation: > 800 sensors and valves

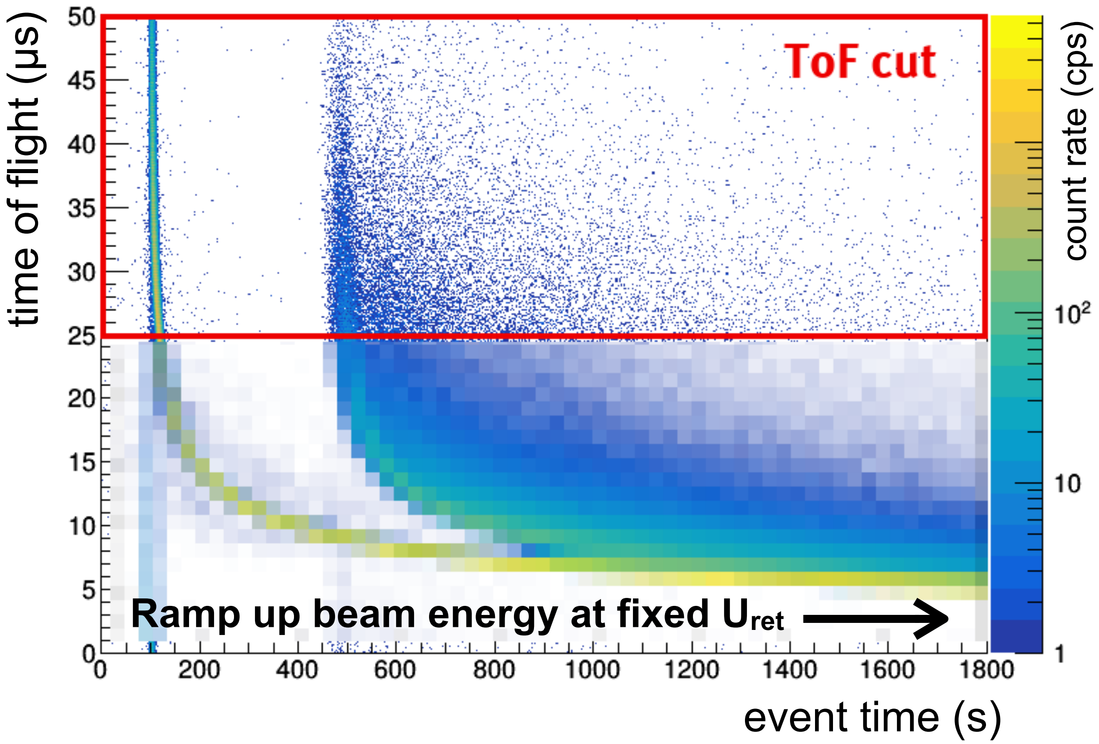
Measurement of the response function

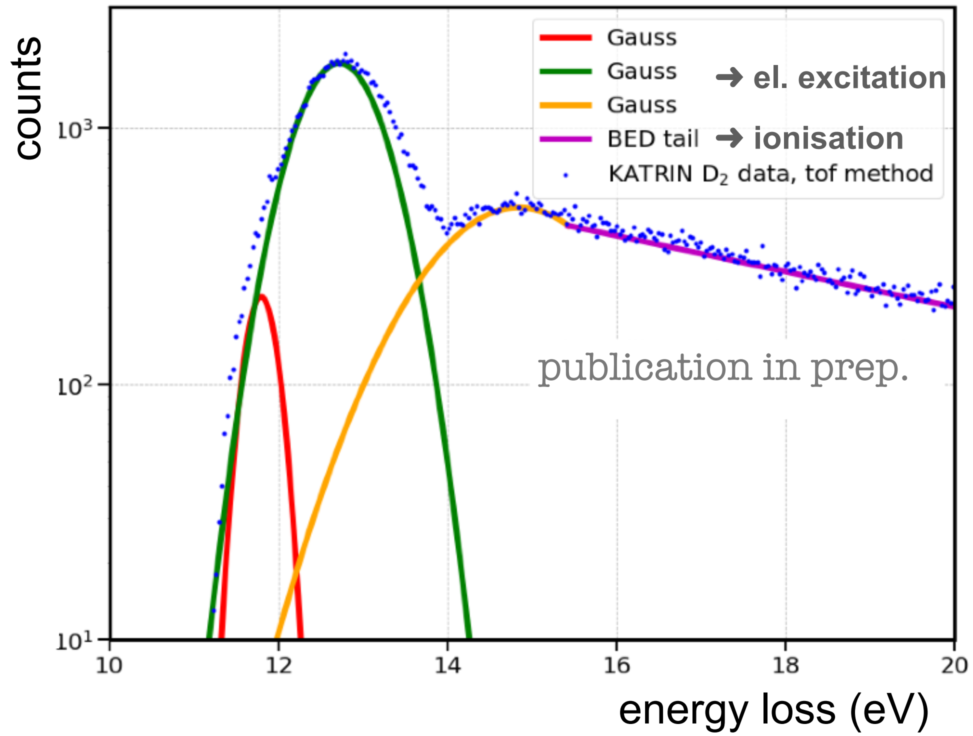
- Energy loss of electrons by inelastic scattering are key systematics in ν-mass measurement
- Measurement of “integrating” response function by precision electron source with sharp energy & defined angular range
- Time-of-flight mode adds access to differential energy loss spectrum



Energy loss function from time-of-flight

- ToF signal from pulsed e-gun (70 ns at 20 kHz):
  High-pass filter turned into narrow band-pass ➜ recover “differential” spectrum



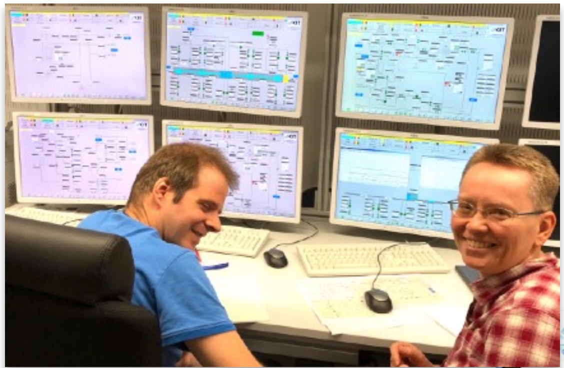


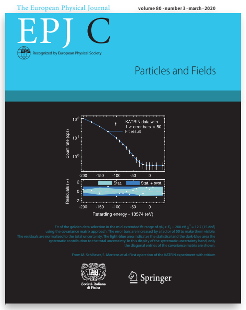
- Empirical parameterisation replaced by physics-motivated composite model
  ➜ triple Gauss for electronic excitation + ionisation tail
- Greatly improved data-driven understanding of one of the key systematics

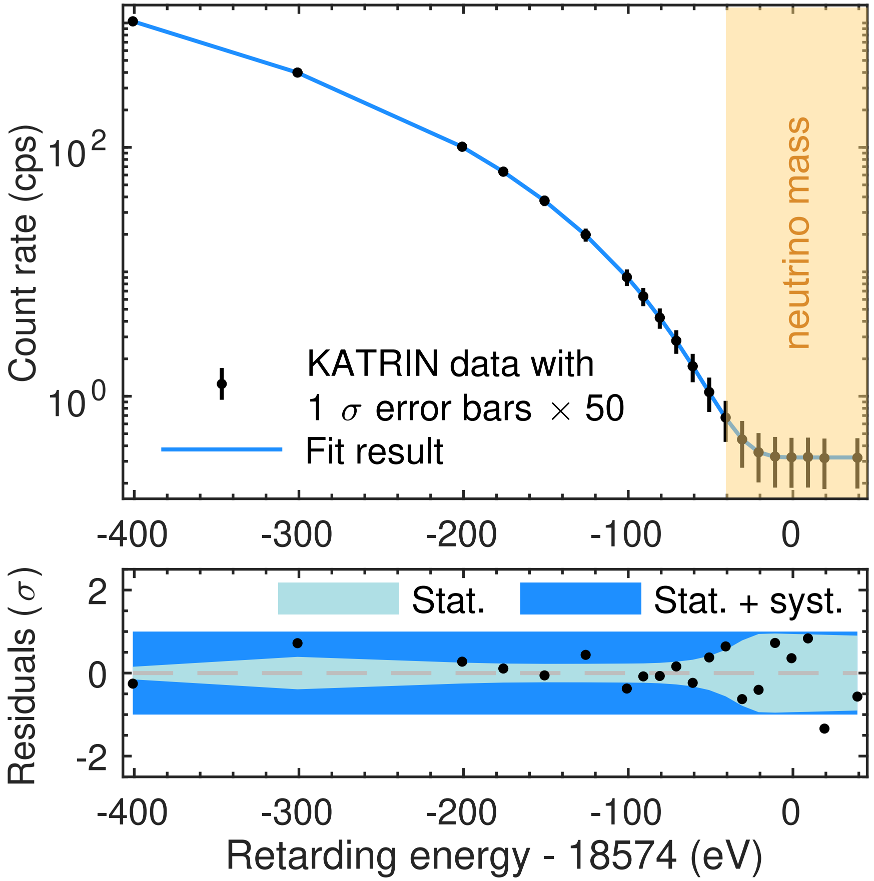
[“MAC-E-ToF” idea by J. Bonn *et al.*, NIM A421 (1999) 256; see also Steinbrink *et al.* NJP 15 (2013) 113020]

KATRIN data taking

- May/June 2018: Tritium commissioning (low activity ~500 MBq)
  ➜ First high-quality β spectra, validation of spectrum model & analysis tools
  [EPJ C 80 (2020) 264]
  ➜ Search for keV sterile neutrinos
  [forthcoming publication]







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  [EPJ C 80 (2020) 264]
  ➜ Search for keV sterile neutrinos
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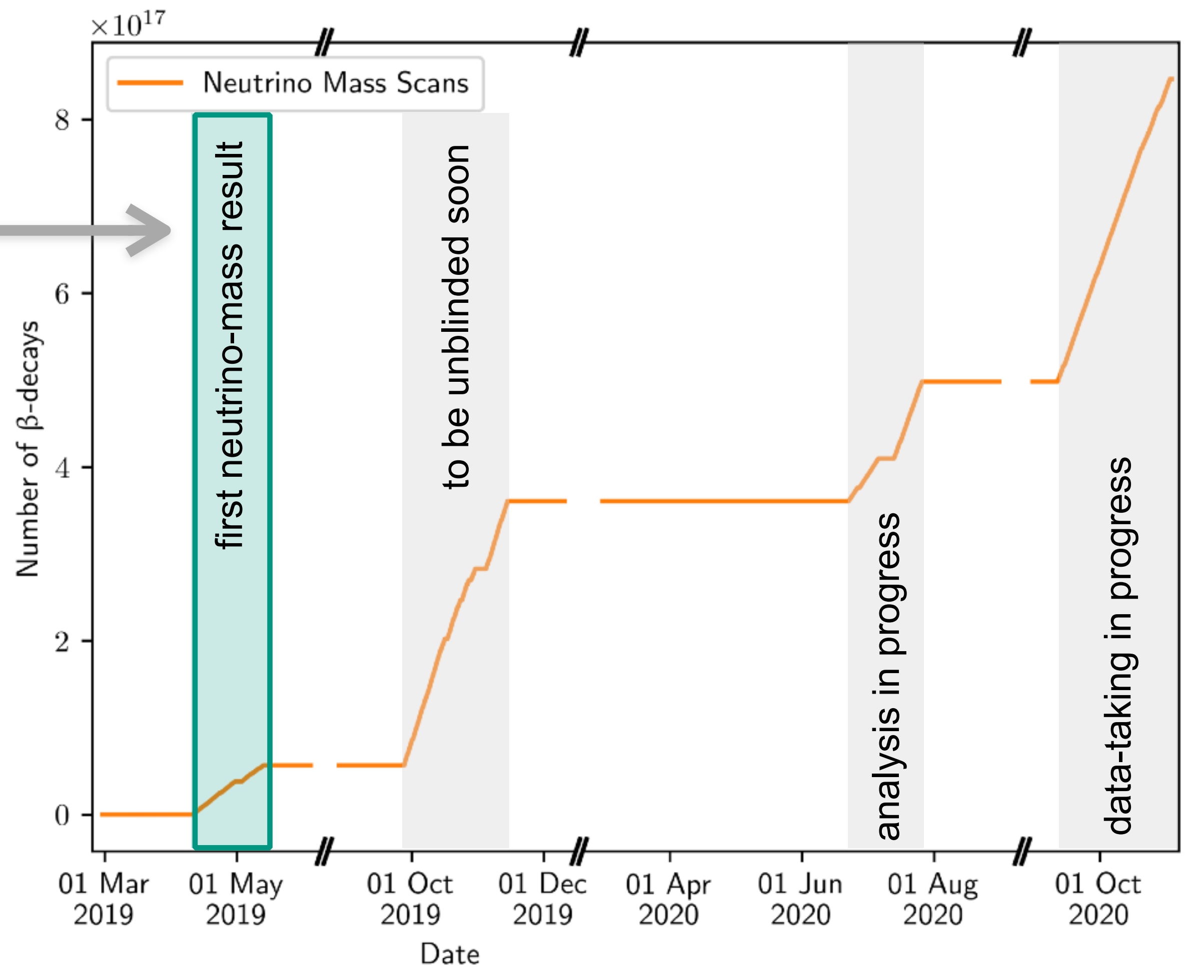
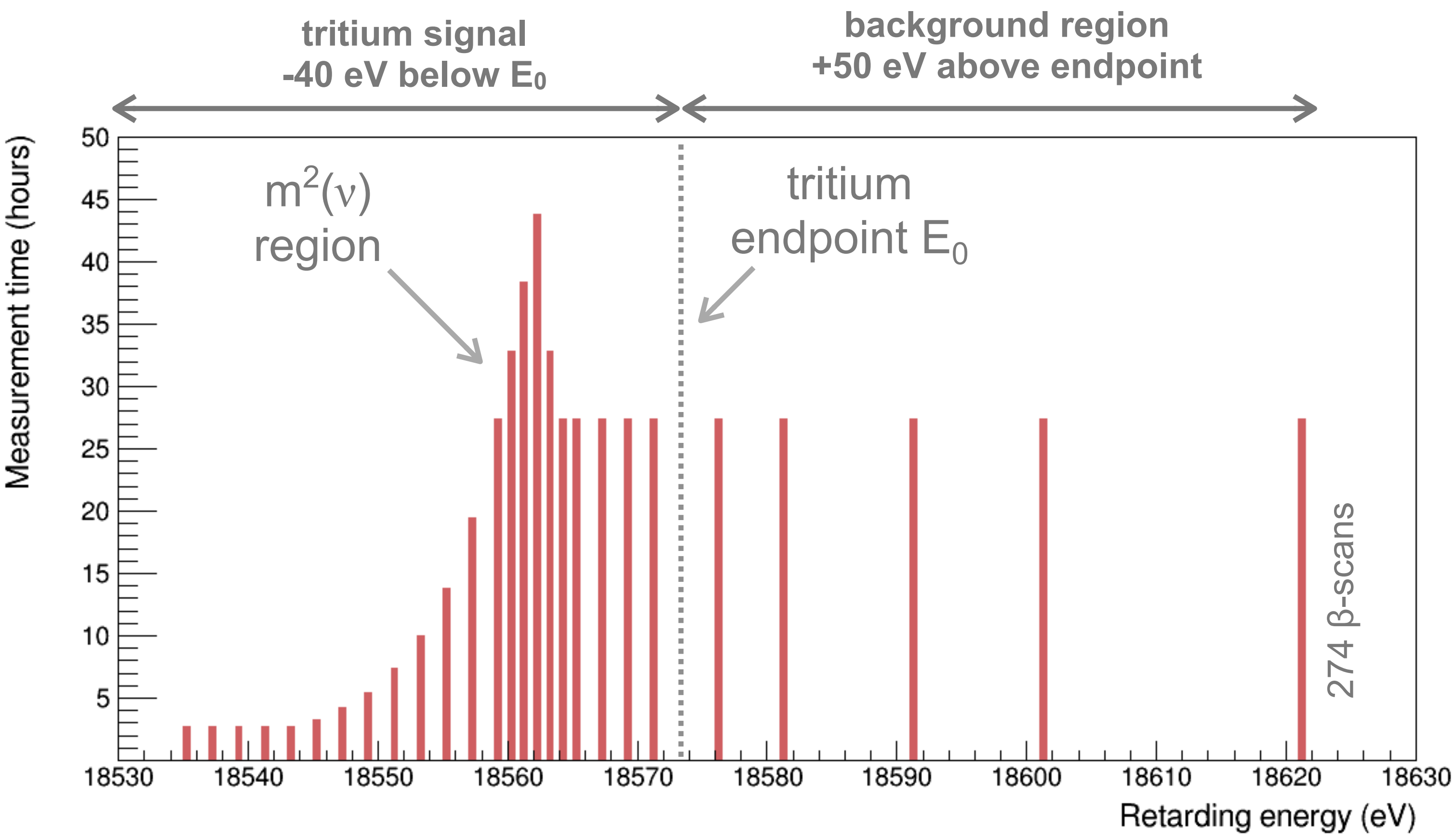
- April/May 2019: Start of neutrino-mass measurements.
  Since then:
  - Ramp-up of source strength
  - Improved background suppression
  - In-depth systematics studies, e.g. plasma properties
  - Improved calibration methods



KATRIN’s first neutrino mass campaign

- **March 4, 2019:**
  Start large-scale throughput of high-purity tritium in closed loop (4.9 g/day)

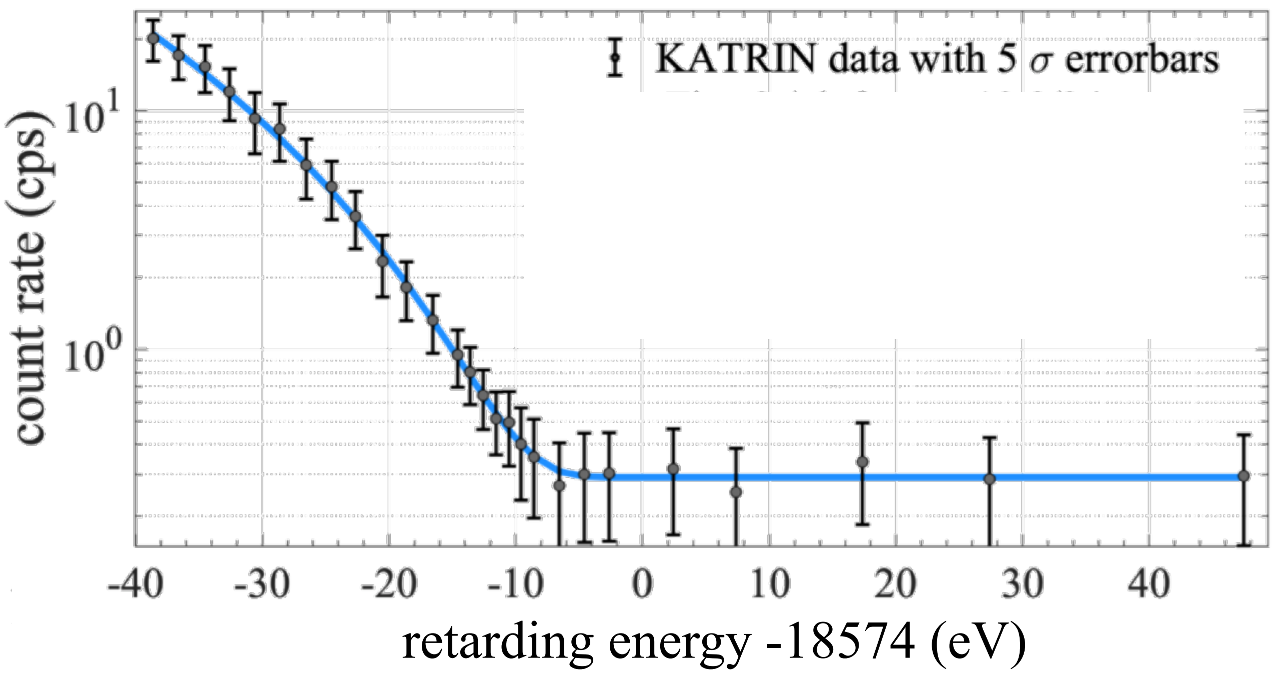
- **April 10 - May 13, 2019:** four weeks (780 hrs) of β-scans at 24.5 GBq
  ➜ equivalent to few days out of 1000 planned days at nominal activity (100 GBq)

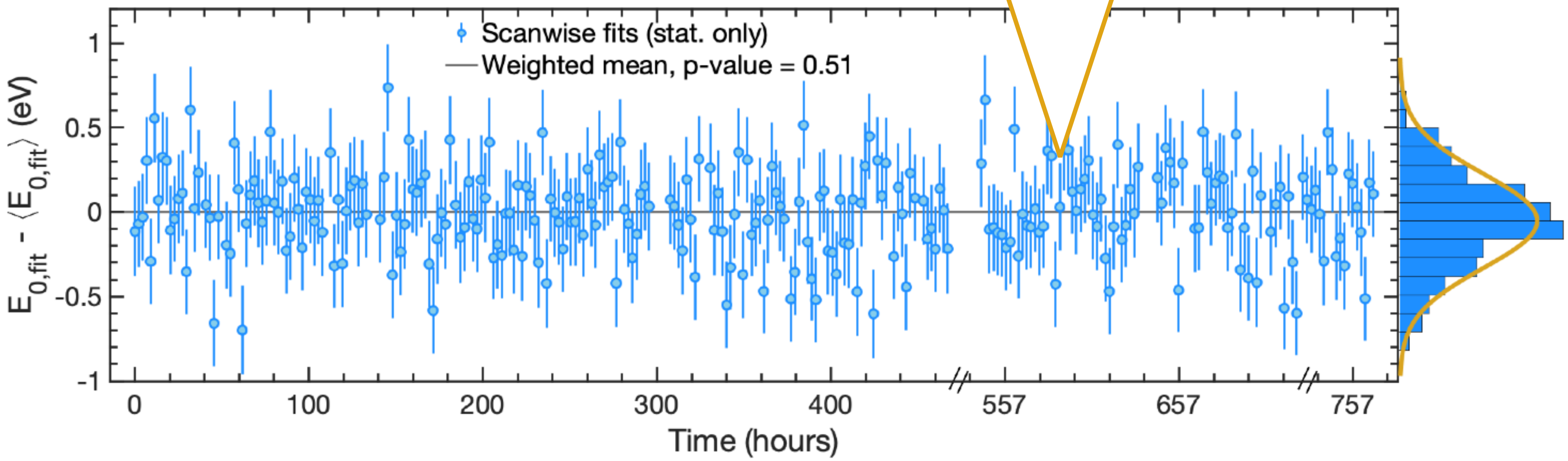


- After quality selection:
  274 β-scans x 2.5 hrs
- Alternating up/down scans
- 27 HV set-points per scan
- Event sample:
  2 Million electrons

Stability of spectral scans

- Fit of 274 individual scans (fixed $m^2(\nu) = 0$)
- All pixels combined into uniform pixel
- ✓ β-spectrum endpoint E_0 shows excellent stability over entire 4-week period





std. deviation $\sigma = 0.255$ eV

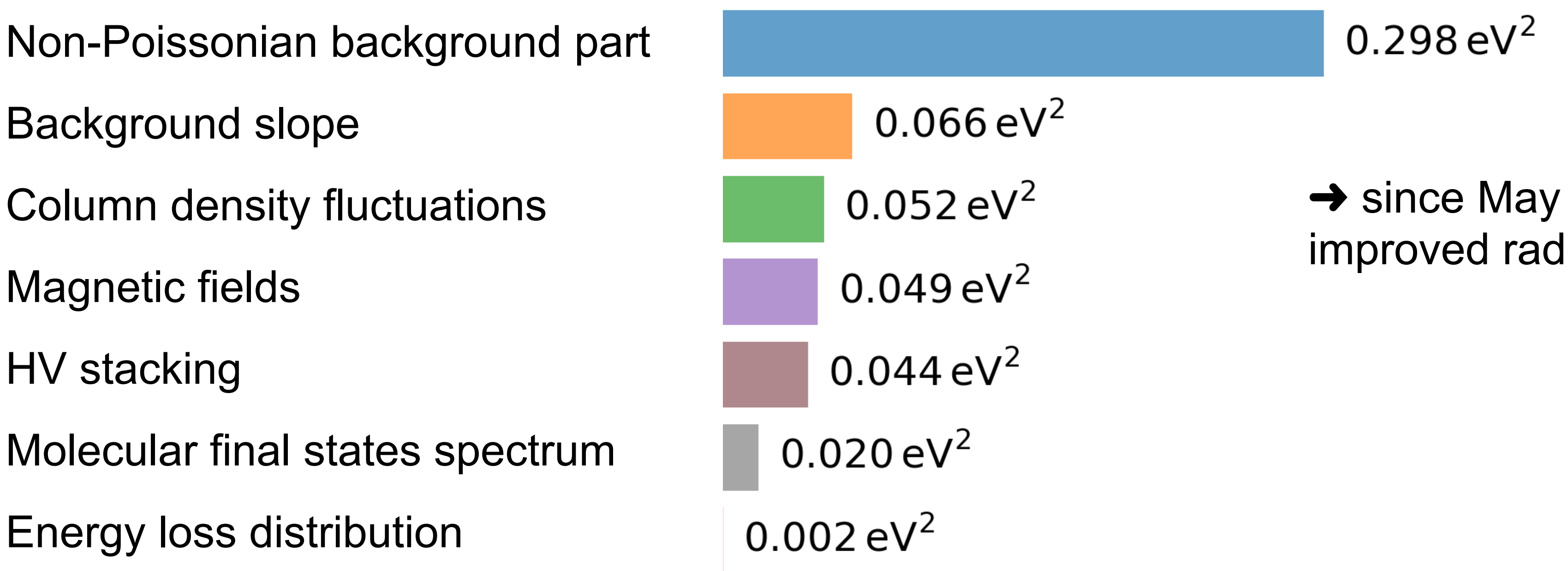
Statistical and systematic uncertainties

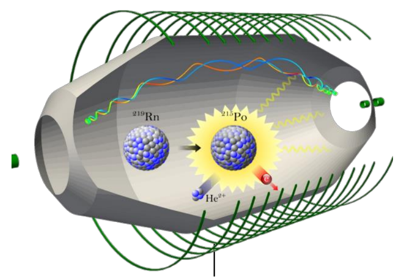
- First dataset is strongly statistics-dominated (5 days nominal KATRIN only …).
  Total statistics budget: $\sigma_{stat} = 0.97\ eV^2$ **factor 2**

improves on
Mainz &Troitsk by

- Systematic uncertainties are well understood.
  Total systematics budget: $\sigma_{syst} = 0.32\ eV^2$ **factor 6**

- Systematics breakdown for first Science Run:

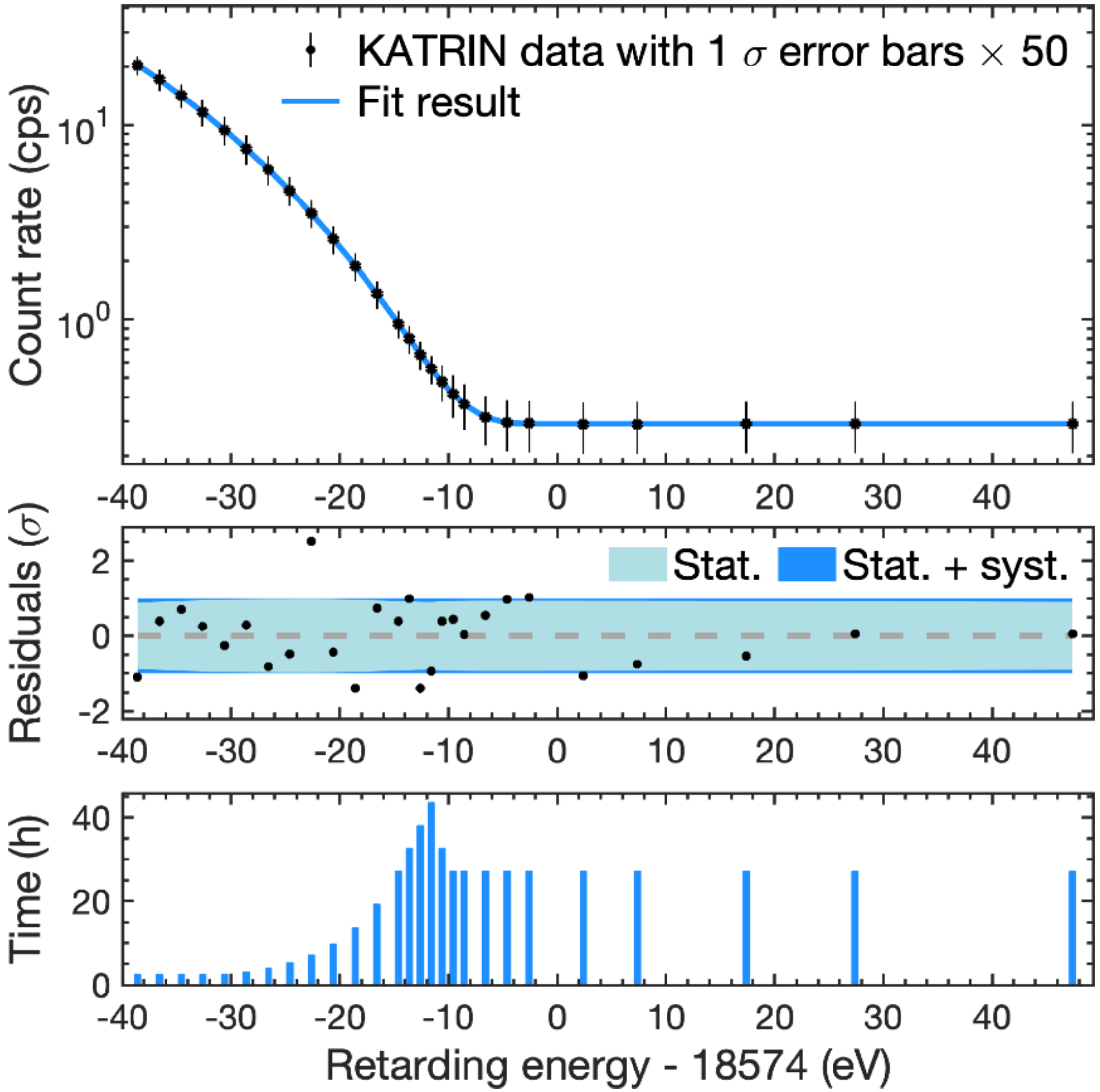




➜ since May 2020:
improved radon retention system

KATRIN Collab., PRL 123 (2019) 221802

First neutrino mass result



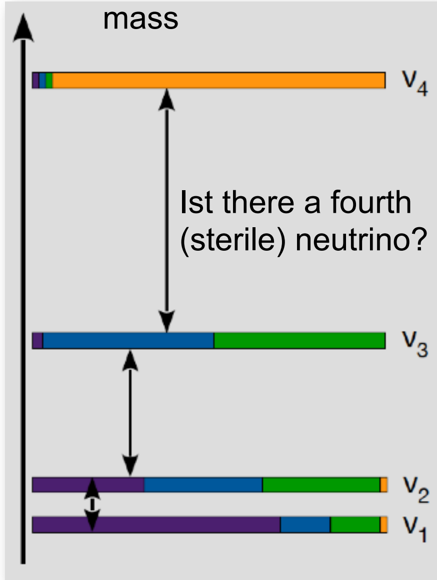
- 2 million events in total
- Shape-only fit, 4 free parameters: $m^2(\nu)$, E_0, normalisation, background
- Excellent goodness-of-fit: $\chi^2 = 21.4$ for 23 d.o.f. $(p = 0.56)$
- Best-fit value: $\mathbf{m_\nu^2} = \left(-1.0^{+0.9}_{-1.1}\right)\,\mathrm{eV}^2$
- New upper limit: **m_ν < 1.1 eV (90% C.L.) = sensitivity**
- Bayesian Credible Interval (flat prior, $m^2 > 0$) $m_\nu < 0.9$ eV (90% C.I.)

KATRIN Collab., PRL 123 (2019) 221802

Physics reach of KATRIN: search for extra neutrino states

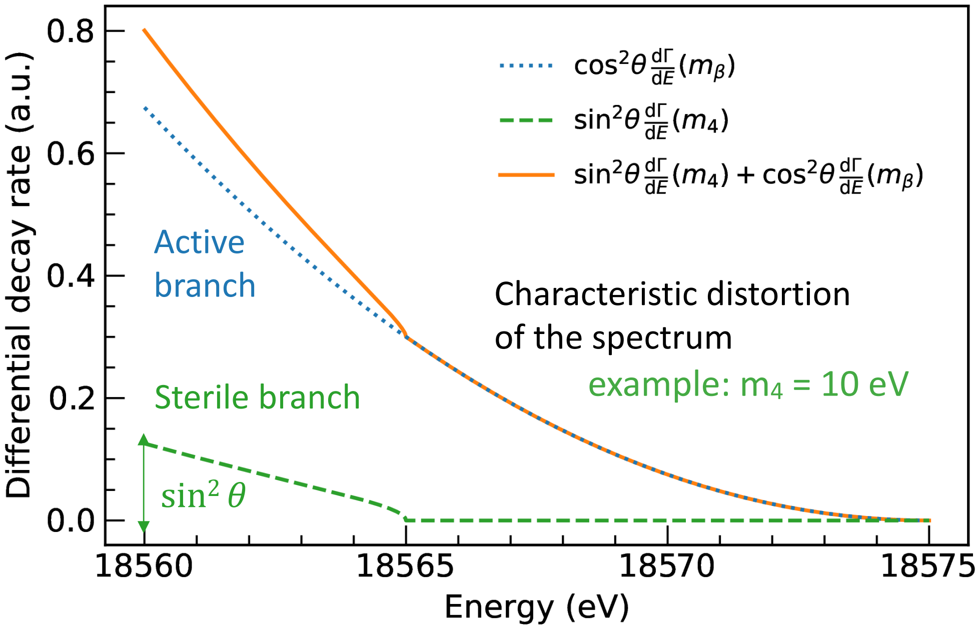
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \cos^2(\theta_s)\,\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_\beta^2) \;+\; \sin^2(\theta_s)\,\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_s^2)$$

Neutrinos mix: generate “kink” in β spectrum at $E = E_0 - m_s$



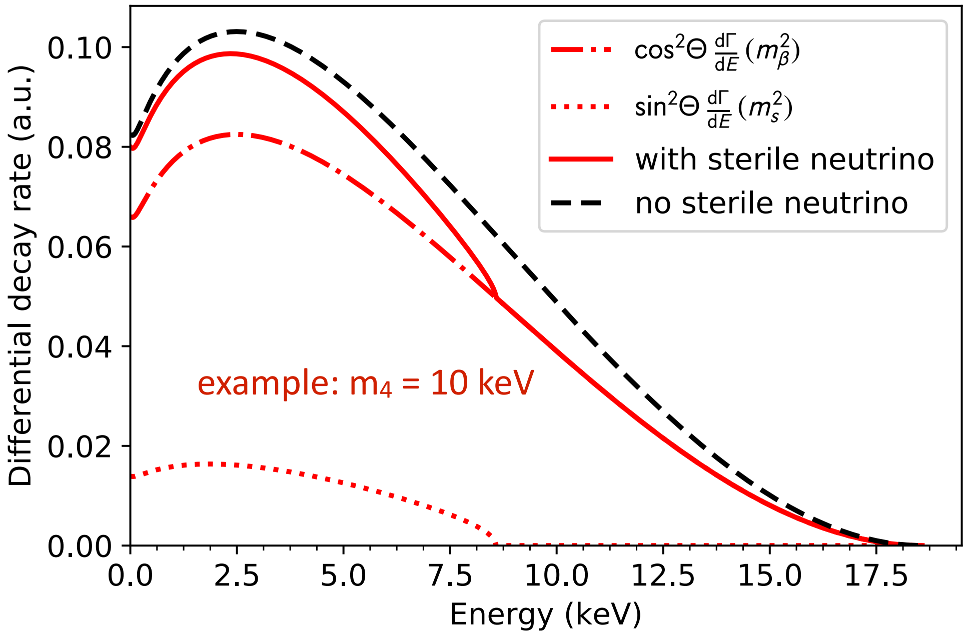
light sterile ν, m_s ~ few eV

motivated by oscillation anomalies



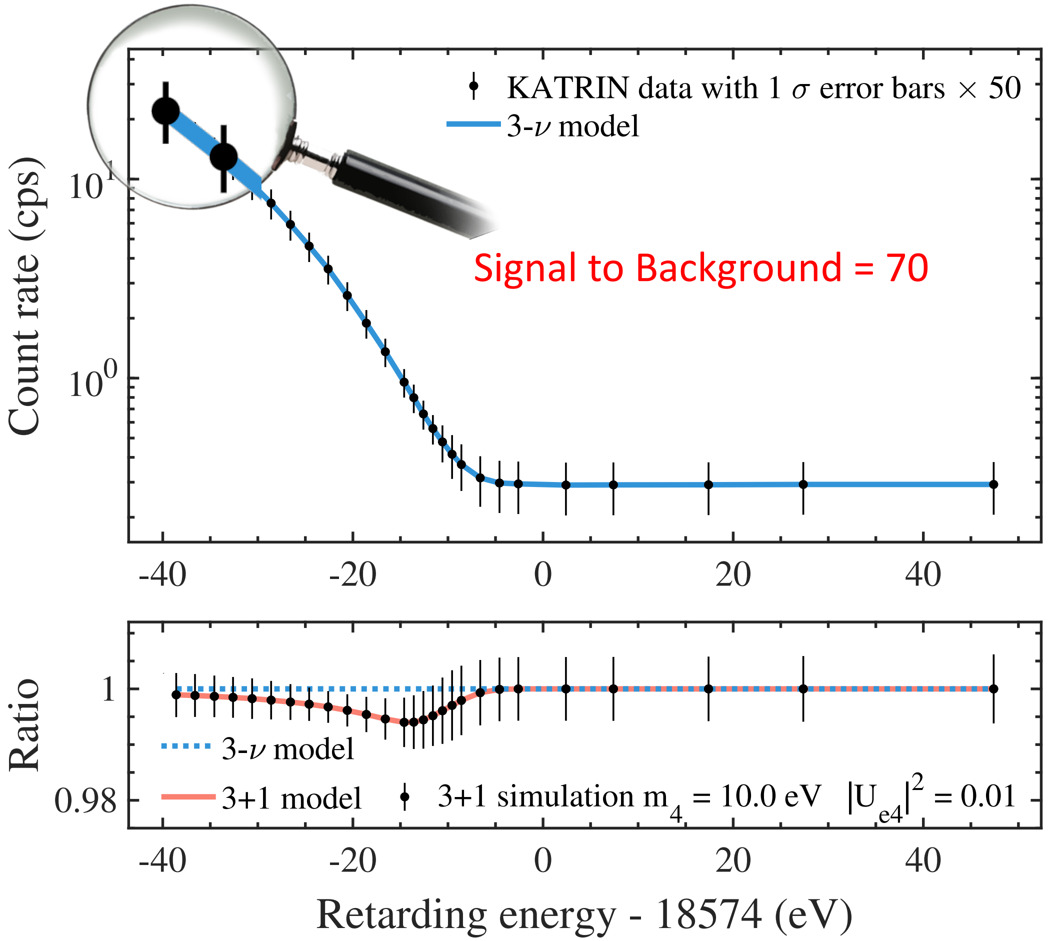
heavy sterile ν, m_s ~ few keV

motivated as DM candidate



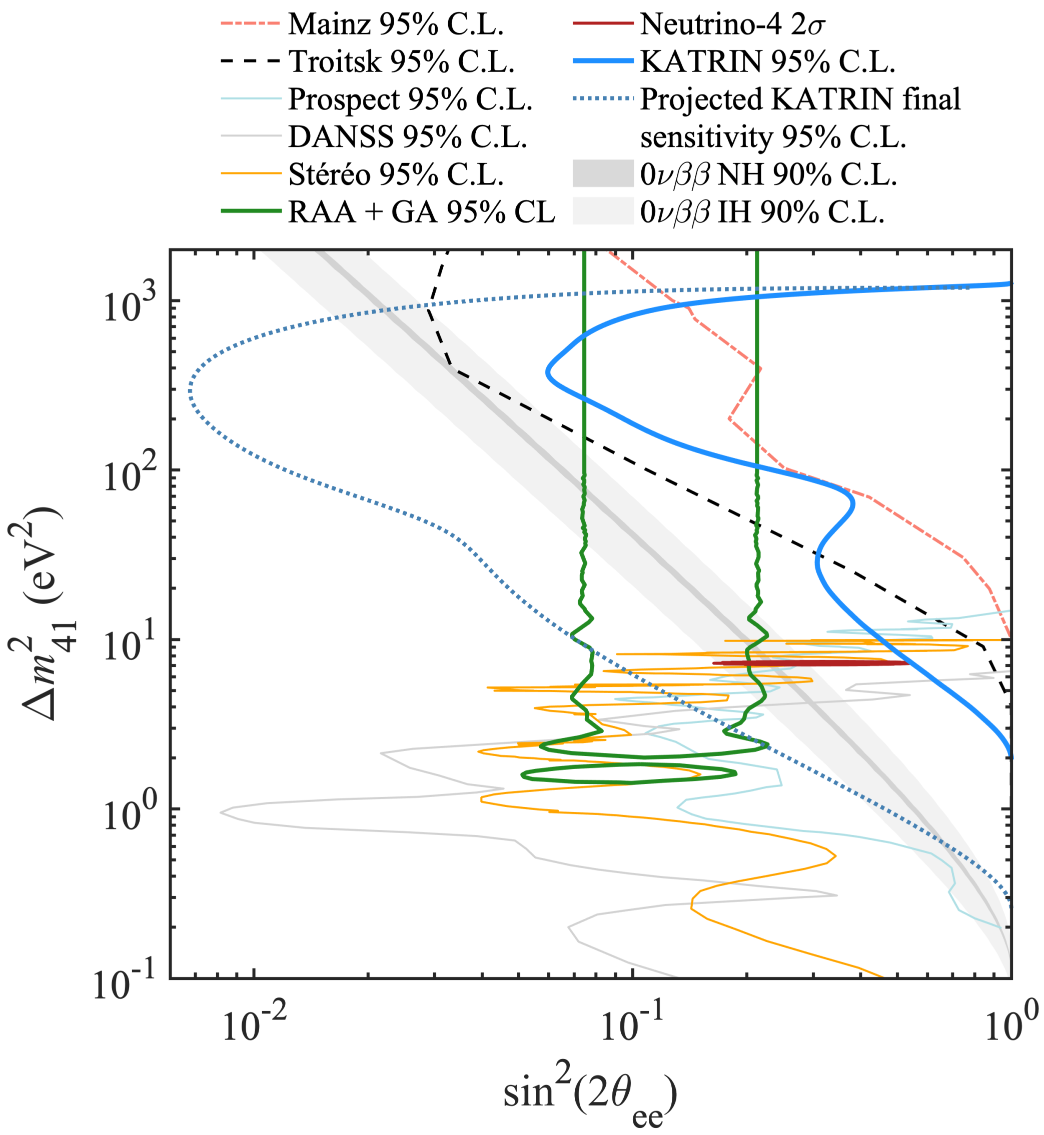
Illustrations c. S. Mertens

Search for sterile neutrinos at the eV scale



- Same data set and basic analysis procedure as for "m_β" neutrino mass search
- At E_0-40 eV, signal to background ratio is ~70 (favourable compared to typical oscillation experiments)
- Apply 3+1 sterile neutrino model
- Grid search in (m_4, $|U_{e4}|^2$) plane
- m_β fixed to minimum allowed value (0.009 eV) according to oscillations

Search for sterile neutrinos at the eV scale



KATRIN Collab., arXiv:2011.05087

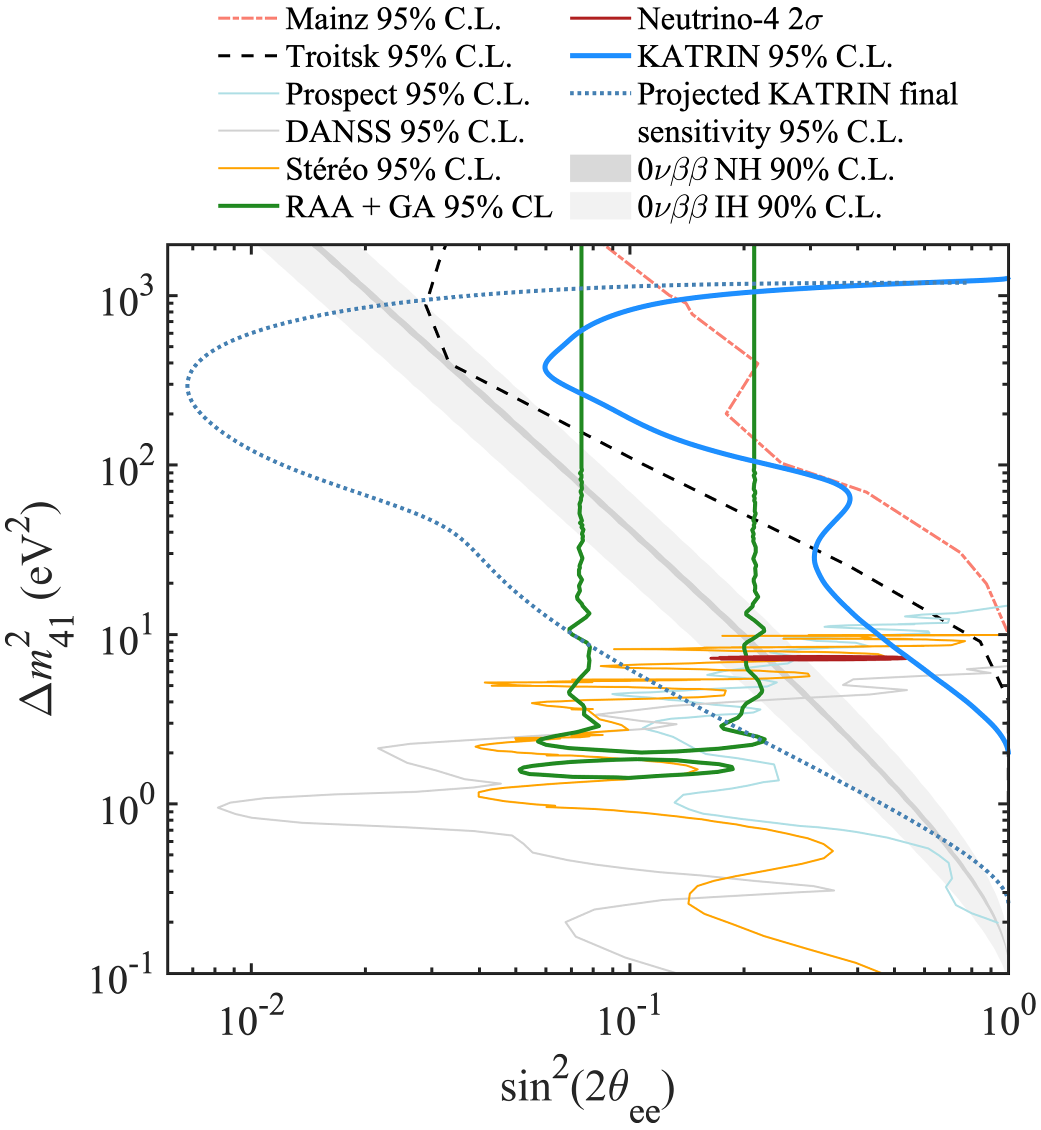
Region of high Δm^2:

- Improve exclusion with respect to DANSS, PROSPECT, STÉRÉO
- Exclude large Δm^2 solution preferred by reactor and gallium anomalies

Region of low Δm^2:

- Improve limits by Mainz and Troitsk
- Neutrino-4 hint at the edge of 95% exclusion

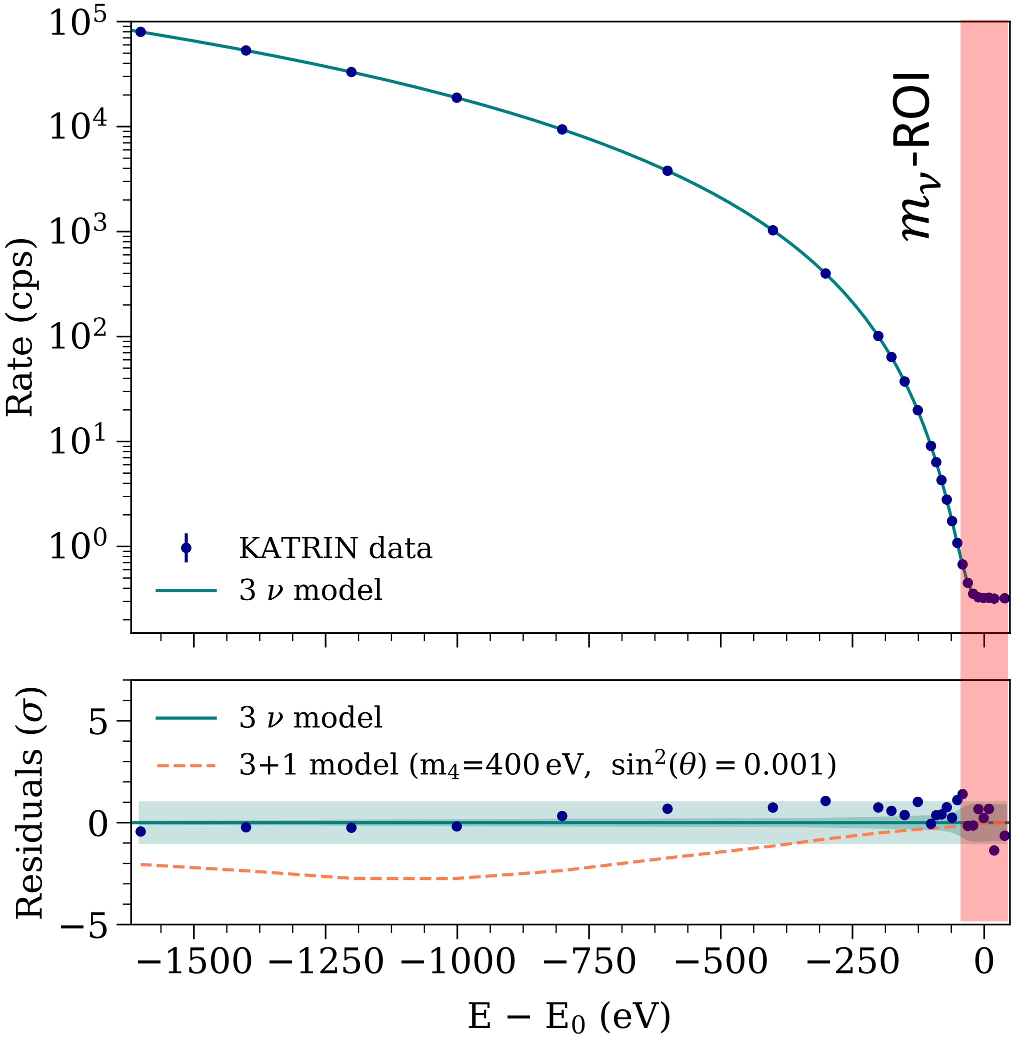
Search for sterile neutrinos at the eV scale



KATRIN Collab., arXiv:2011.05087

- **Demonstrate potential** of KATRIN to probe sterile neutrino hypothesis
- **Complementarity** with short-baseline oscillation experiments
- **Future prospects:** large fraction of reactor & gallium anomaly and Neutrino-4 region of interest will be probed with full KATRN data set

Prospects for keV sterile neutrino search



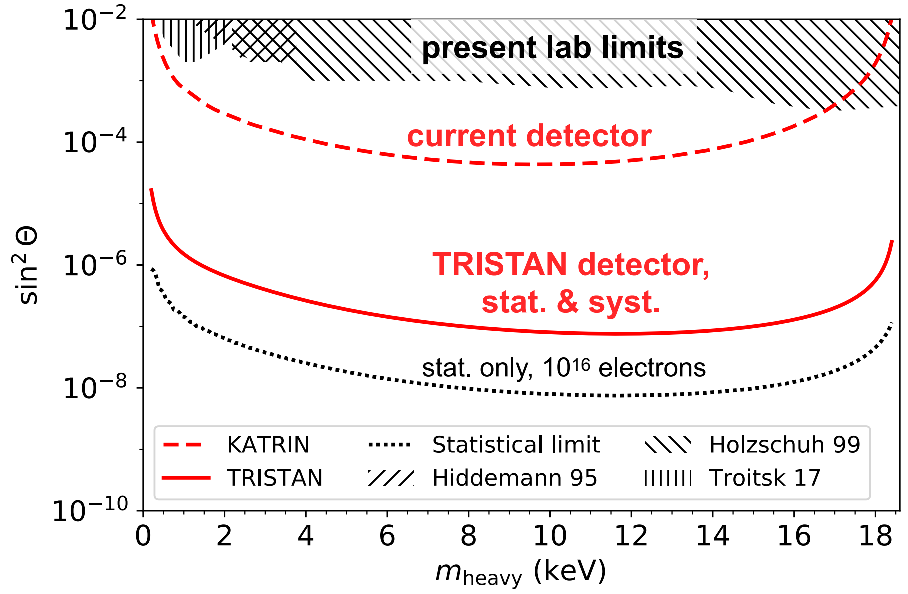
publication in preparation

- **Proof of principle:**
  - Deep scan (1.6 keV below E_0)
  - low-activity commissioning data
- Excellent agreement of model and data (p-value = 0.6)
- Sensitivity to $\sin^2\theta = 10^{-3}$ at m_4 = 0.4 keV

- **Future perspectives:** Novel multi-pixel Silicon Drift Detector array (TRISTAN)
  - High-statistics search
  - Target sensitivity of $\sin^2\theta < 10^{-6}$

Prospects for keV sterile neutrino search

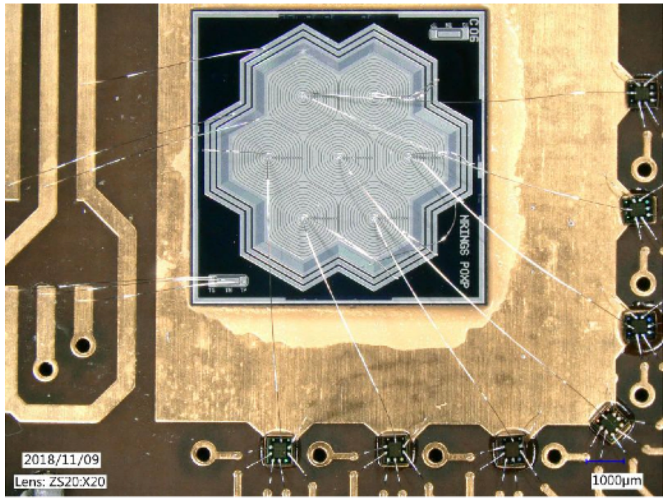
- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for differential measurement, need energy resolution ~300 eV or better

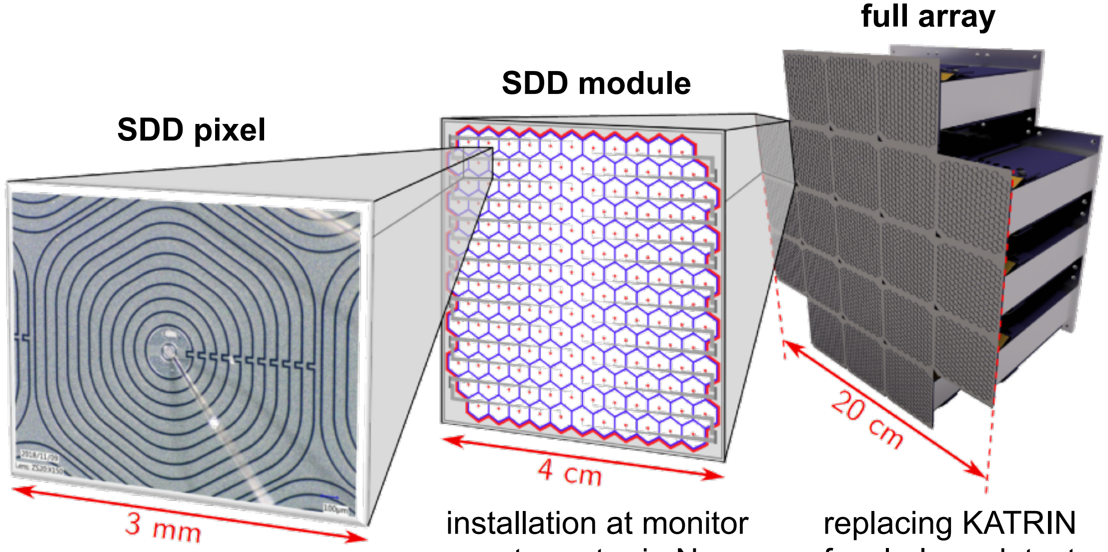


TRISTAN detector for KATRIN:

Silicon Drift Detector (SDD) arrays developed at MPP / HLL Munich

[Mertens *et al.*, J. Phys. G 46 (2019) 065203 & 2007.07136]





7-pix prototype in use as KATRIN beam monitor

installation at monitor spectrometer in Nov. 2020

replacing KATRIN focal-plane detector in 2025

Summary and Outlook

- Spring 2019: Inaugurational neutrino-mass campaign (4 weeks, at reduced source strength)
- New upper limit $m(\nu) < 1.1$ eV (90% CL) improves on previous experiments by factor ~2
- Ongoing analyses: more data sets
  - at increased source luminosity (2019)
  - with improved background reduction (2020)
- Ongoing data-taking: Collecting ~200 measurement days in 2020 towards target sensitivity of 200 meV (~5 cal. years)
- Beginning to explore KATRIN's physics potential beyond the neutrino mass:
  - search for sterile neutrinos at eV to keV scales
  - search for exotic weak interactions, Lorentz invariance violation, …

Stay tuned!

New PDG reference value:

$\bar{\nu}$ MASS (electron based)

Those limits given below are for the square root of $m^{2(\mathrm{eff})}_{\nu_e} \equiv \sum_i |U_{ei}|^2 m^2_{\nu_i}$. Limits that come from the kinematics of $^3\mathrm{H}\beta^- \bar{\nu}$ decay are the square roots of the limits for $m^{2(\mathrm{eff})}_{\nu_e}$. Obtained from the measurements reported in the Listings for "$\bar{\nu}$ Mass Squared," below.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
< 1.1	90	[1] AKER	19	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2.05	95	[2] ASEEV	11	SPEC	^{3}H β decay
< 5.8	95	[3] PAGLIAROLI	10	ASTR	SN1987A
< 2.3	95	[4] KRAUS	05	SPEC	^{3}H β decay
<21.7	90	[5] ARNABOLDI	03A	BOLO	^{187}Re β decay
< 5.7	95	[6] LOREDO	02	ASTR	SN1987A
< 2.5	95	[7] LOBASHEV	99	SPEC	^{3}H β decay

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