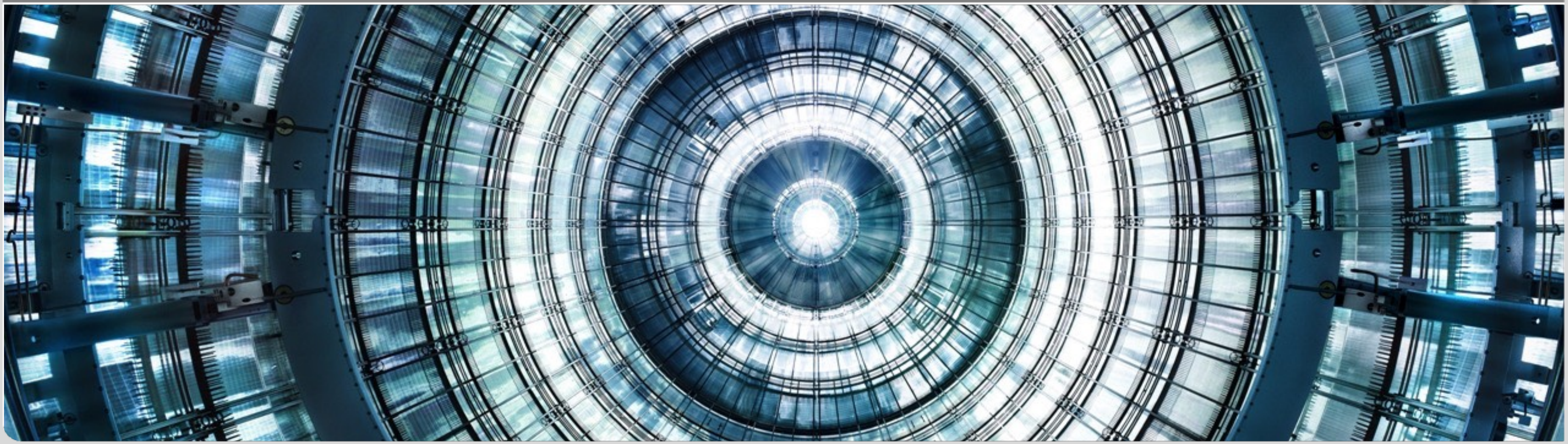
Probing the neutrino mass: latest results from KATRIN

CERN EP Seminar | July 13, 2021

KATHRIN VALERIUS, Institute for Astroparticle Physics

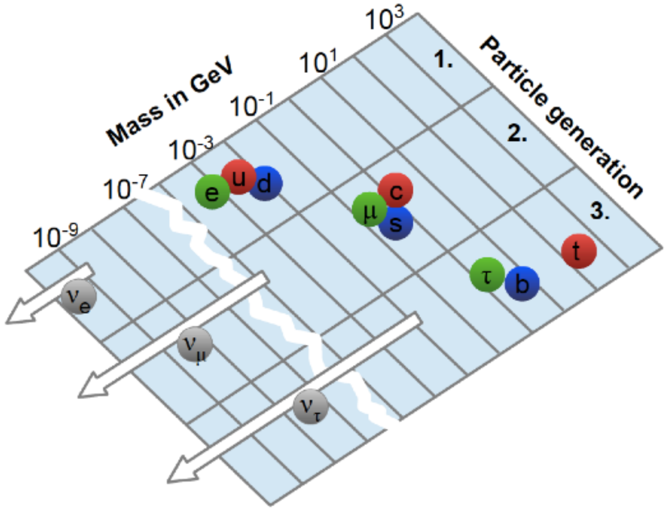


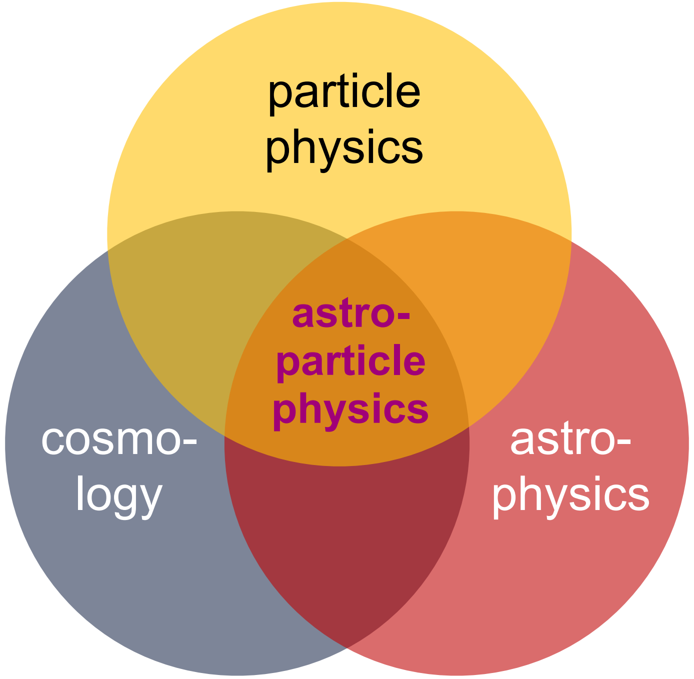
Outline of the talk

- Motivation:
  Massive neutrinos in particle and astrophysics
- Method:
  How direct neutrino-mass measurement works
- KATRIN experiment:
  First-year results and ongoing measurements
- Outlook:
  New physics opportunities beyond the neutrino mass

The role of massive neutrinos

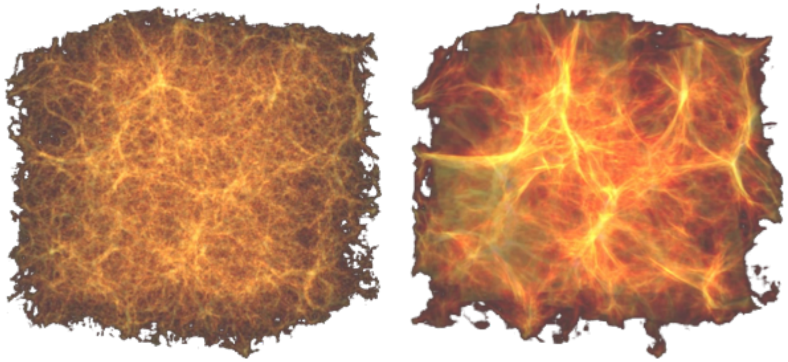
Mass generation: new concepts





Massive neutrinos as “cosmic architects”

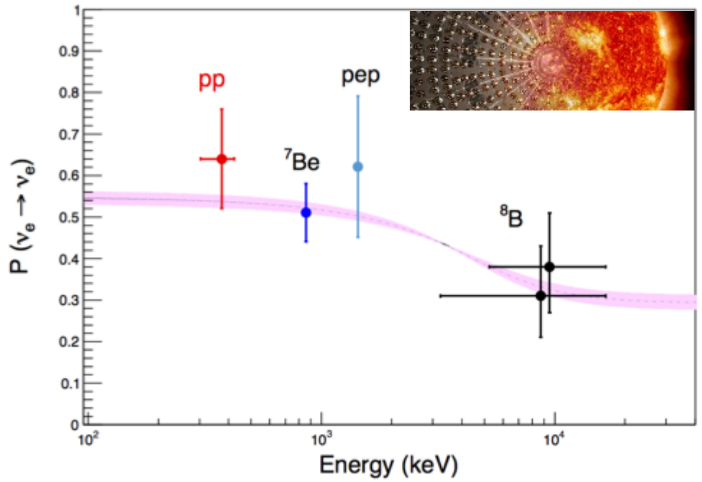
336 ν / cm³ in the Universe today



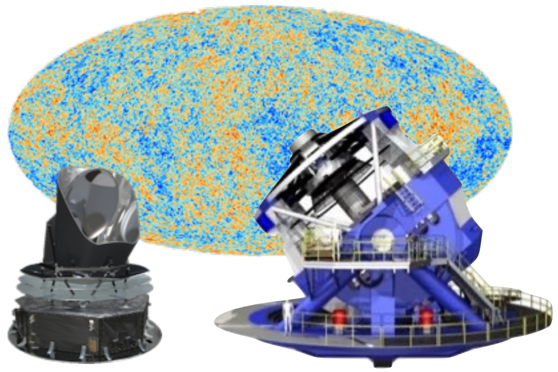
$m_\nu = 0$ $m_\nu > 0$

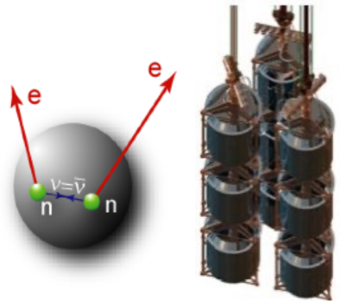
Understanding astrophysical processes

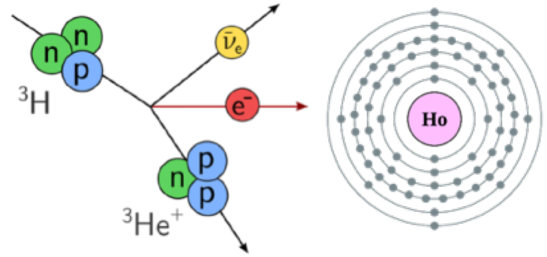
ν as probes of fusion in the sun



Complementary paths to the ν mass scale





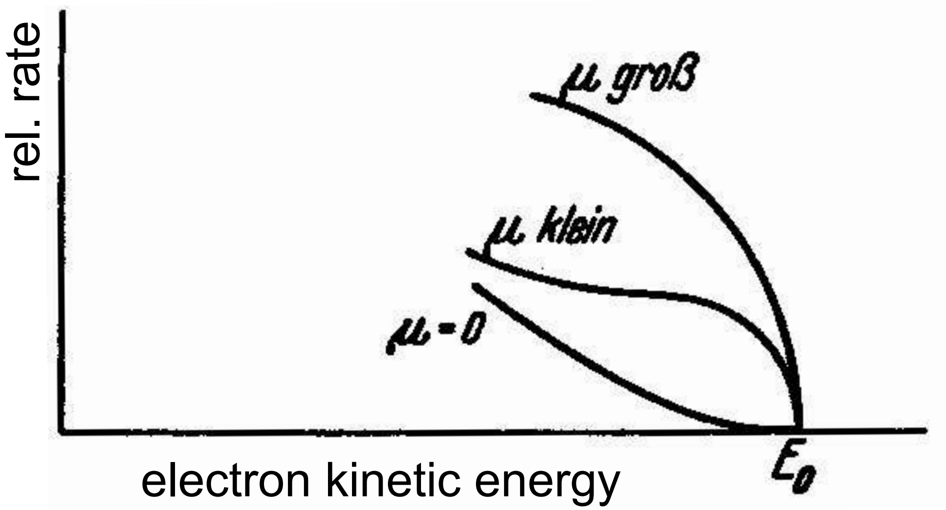


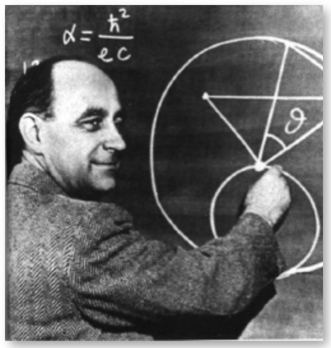
	Cosmology	Search for 0νββ	Kinematics of weak decays
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\vert\sum_i U_{ei}^2 m_i\right\vert^2$	$m_\beta^2 = \sum_i \vert U_{ei}\vert^2 m_i^2$
Model assumptions	Multi-parameter cosmological model (ΛCDM)	- Majorana nature of neutrinos? - No BSM contributions other than m(ν)?	Only kinematics; "**direct**" measurement

Neutrino mass from β-decay kinematics

Karlsruhe Institute of Technology

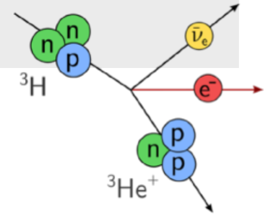
Theory: Starting from Fermi's seminal "attempt at a theory of β-rays"





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.

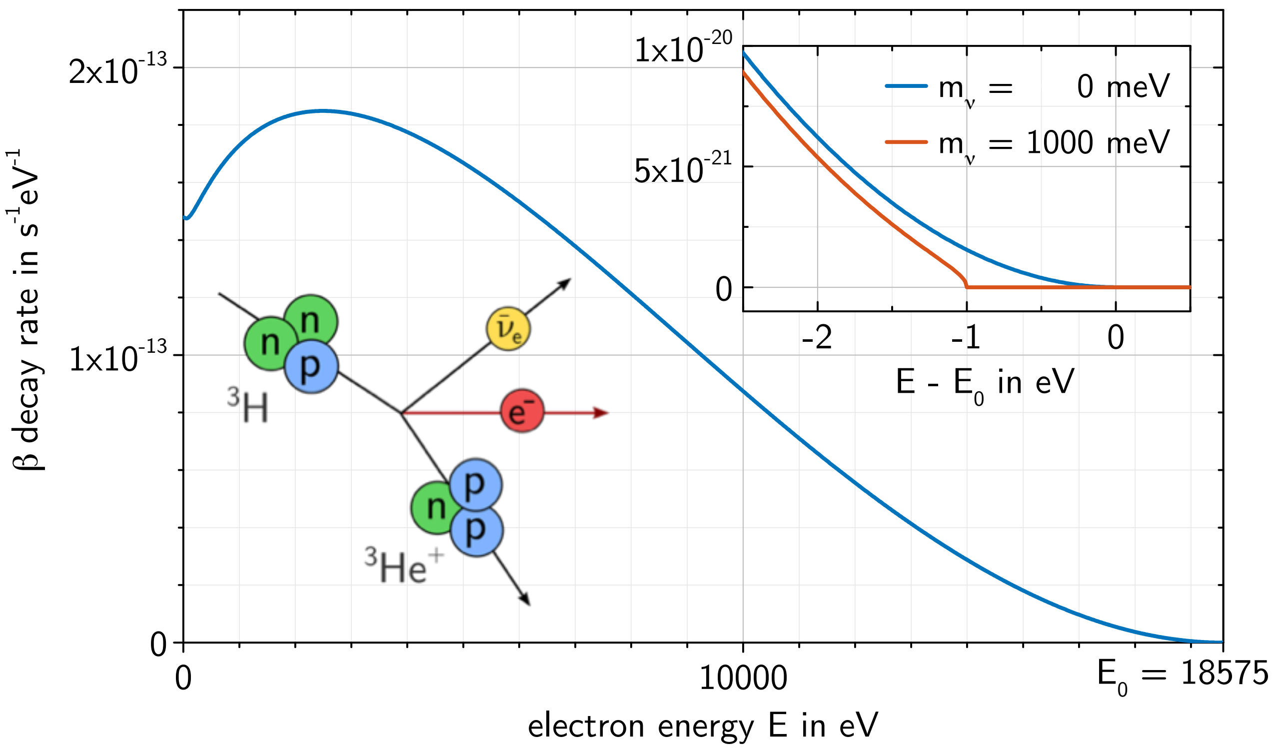
Curran *et al.*, 1948

Neutrino mass from β-decay kinematics

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

Fermi's phase space for β-decay

Modern twist: mass eigenstates m_i and neutrino mixing matrix *U*



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

$$m^2(\nu_\mathrm{e}) := \sum_i |U_{\mathrm{e}i}|^2 \, m_i^2$$

Key requirements:

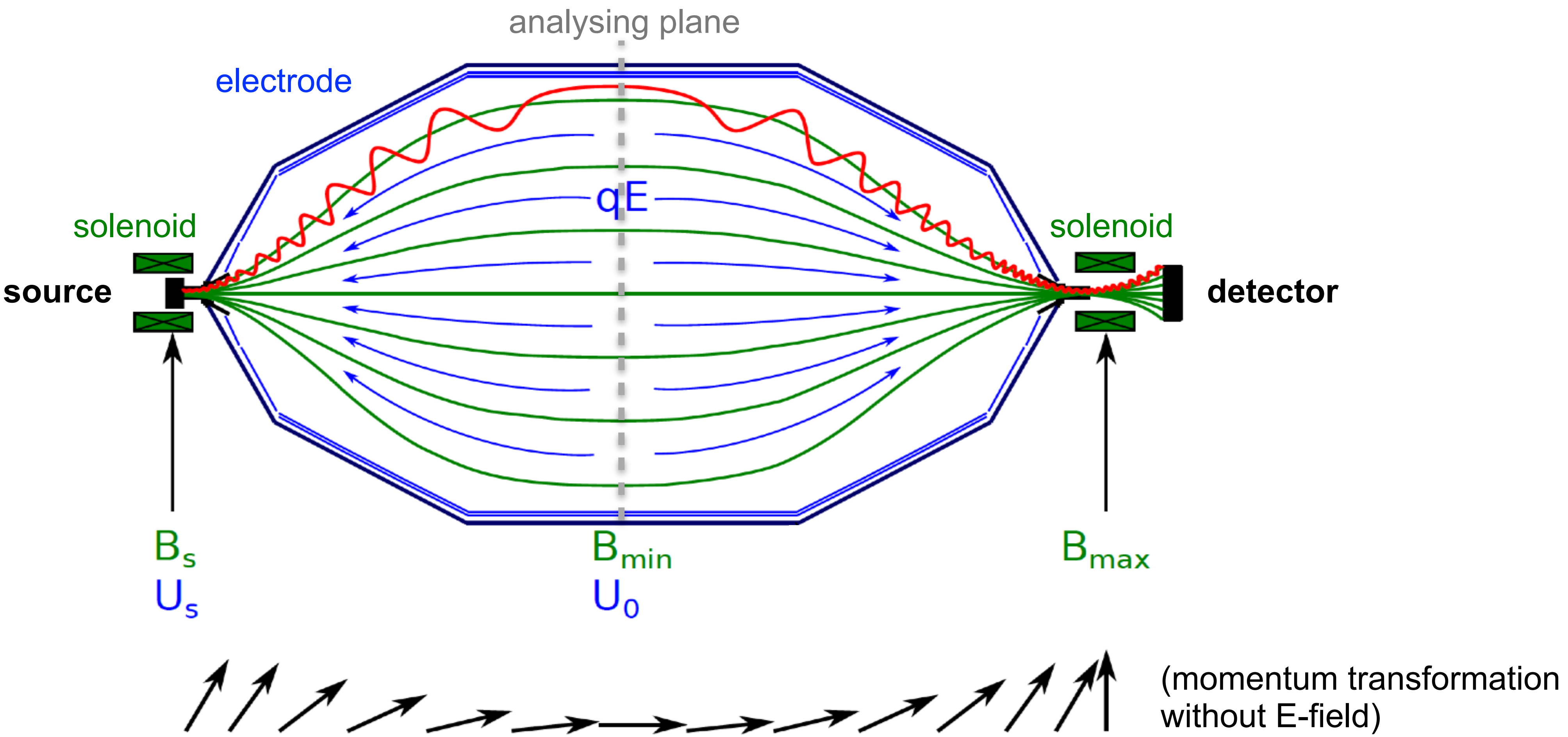
- Low endpoint energy: E_0 = 18.6 keV for ^3H
- High-activity source: $t_{1/2}$ = 12.3 yr for ^3H
- Energy resolution ~ 1 eV

High-resolution spectrometer: MAC-E filter

Magnetic **A**diabatic **C**ollimation **&** **E**lectrostatic **Filter**

- ➜ Integrating electrostatic filter ($E_{kin} > qU_0$)
- ➜ Narrow filter width ΔE ~1 eV combined with large angular acceptance

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



 Beamson et al. 1980; Kruit & Read 1983; **Lobashev 1985; Picard et al. 1992**

The Karlsruhe Tritium Neutrino Experiment

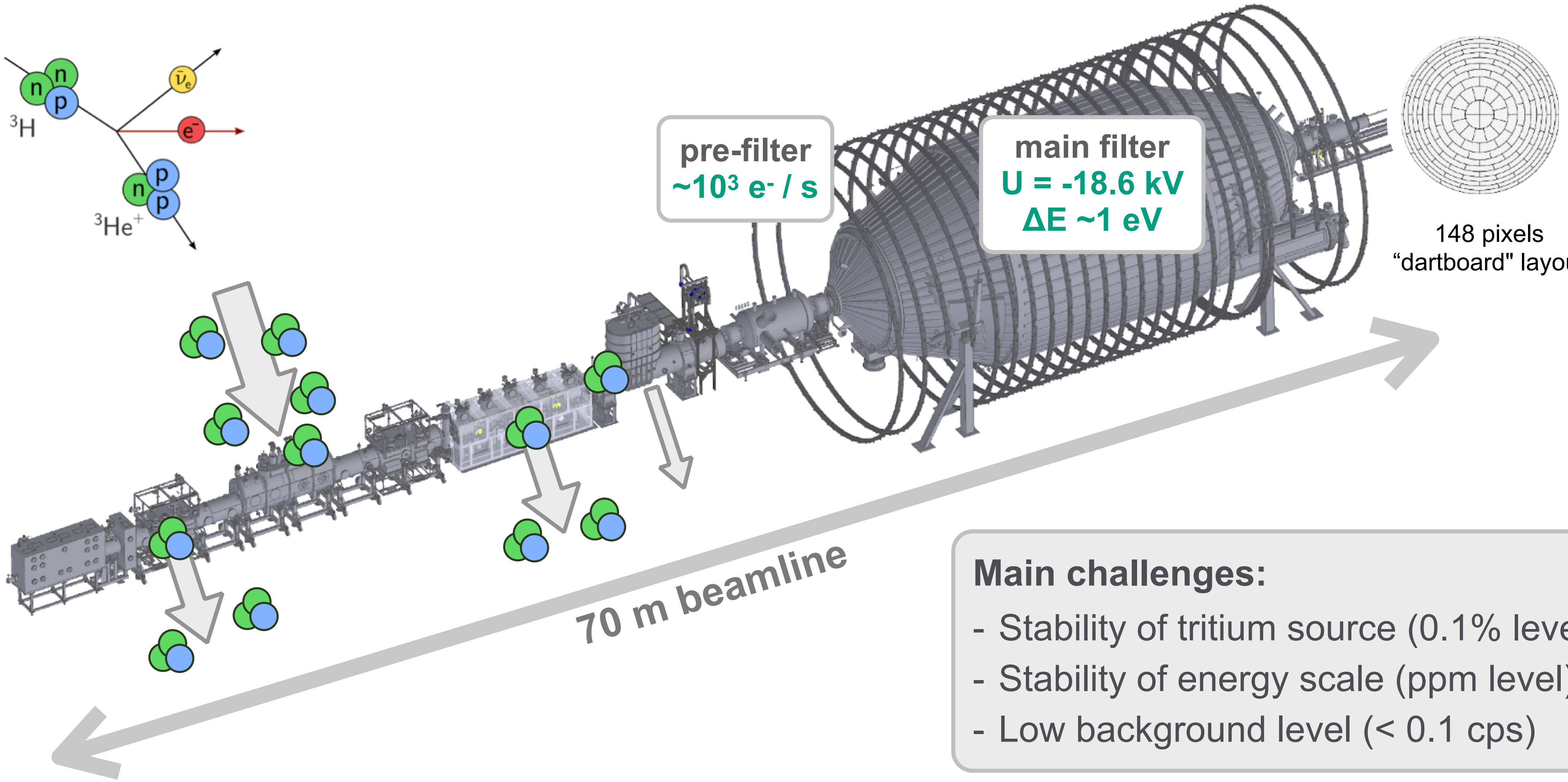
- Experimental site:
  Karlsruhe Institute of Technology (KIT)
- International collaboration:
  ~150 members from 20 institutions
  in 6 countries (D, US, CZ, RU, F, ES)
- Goal: Improve sensitivity on m(ν_e)
  from 2 eV (previous experiments) to 0.2 eV (90% CL) within 2019-2024

katrin.kit.edu

CERN Recognized
Experiment (RE14)
since 2007

Working principle of KATRIN

windowless gaseous T_2 source	tritium pumping & e^- transport	high-pass energy filters	counting detector
10^{11} e^- / s	T_2 flow reduction >10^{14}	MAC-E filter	< 1 e^- / s



Main challenges:
- Stability of tritium source (0.1% level)
- Stability of energy scale (ppm level)
- Low background level (< 0.1 cps)

Full system description & commissioning paper: 2103.04755

Working principle of KATRIN

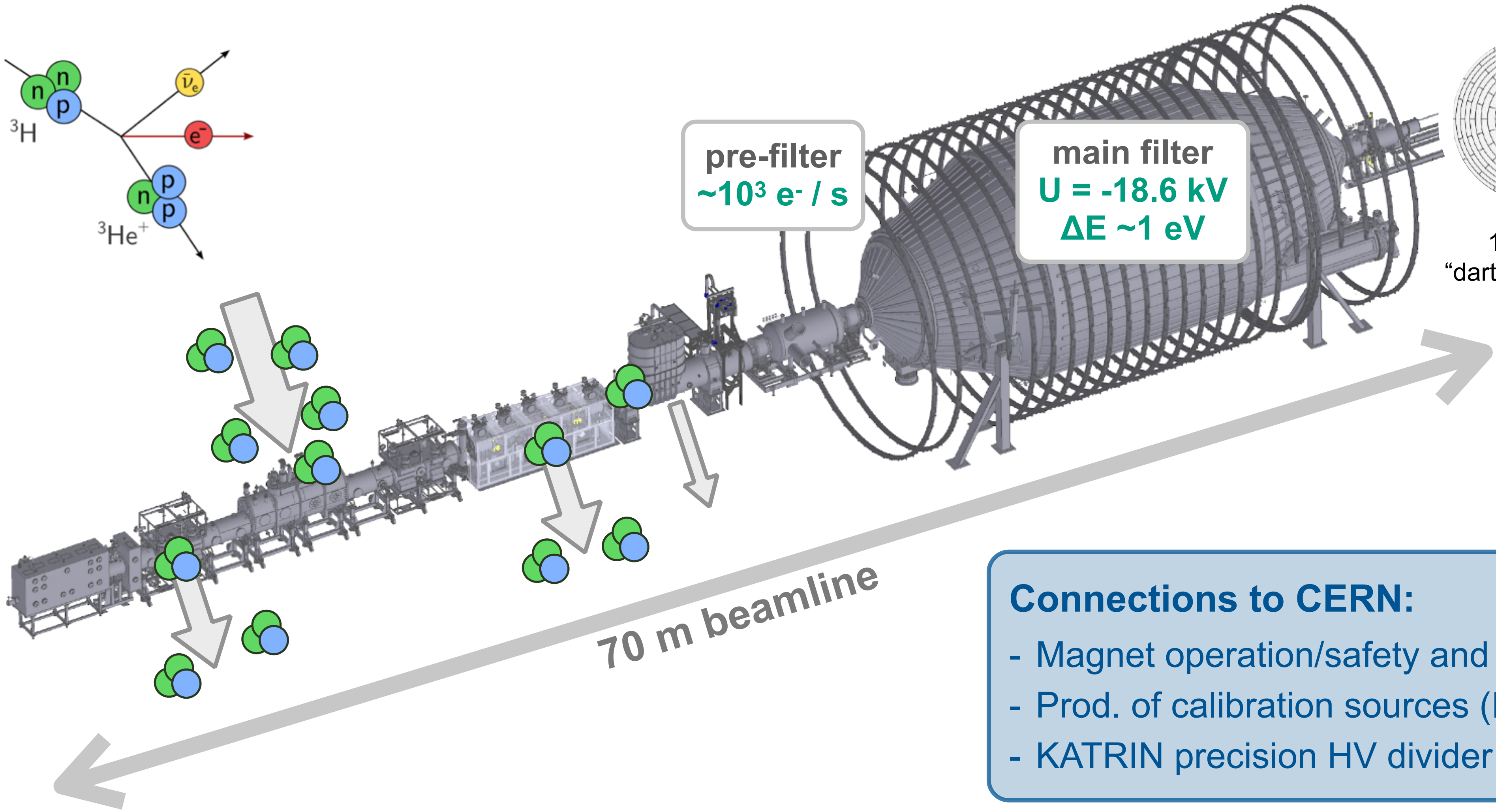
Karlsruhe Institute of Technology

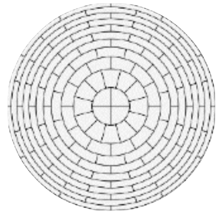
windowless gaseous T_2 source
10^{11} e^- / s

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

high-pass energy filters
MAC-E filter

counting detector
< 1 e^- / s





148 pixels
“dartboard" layout

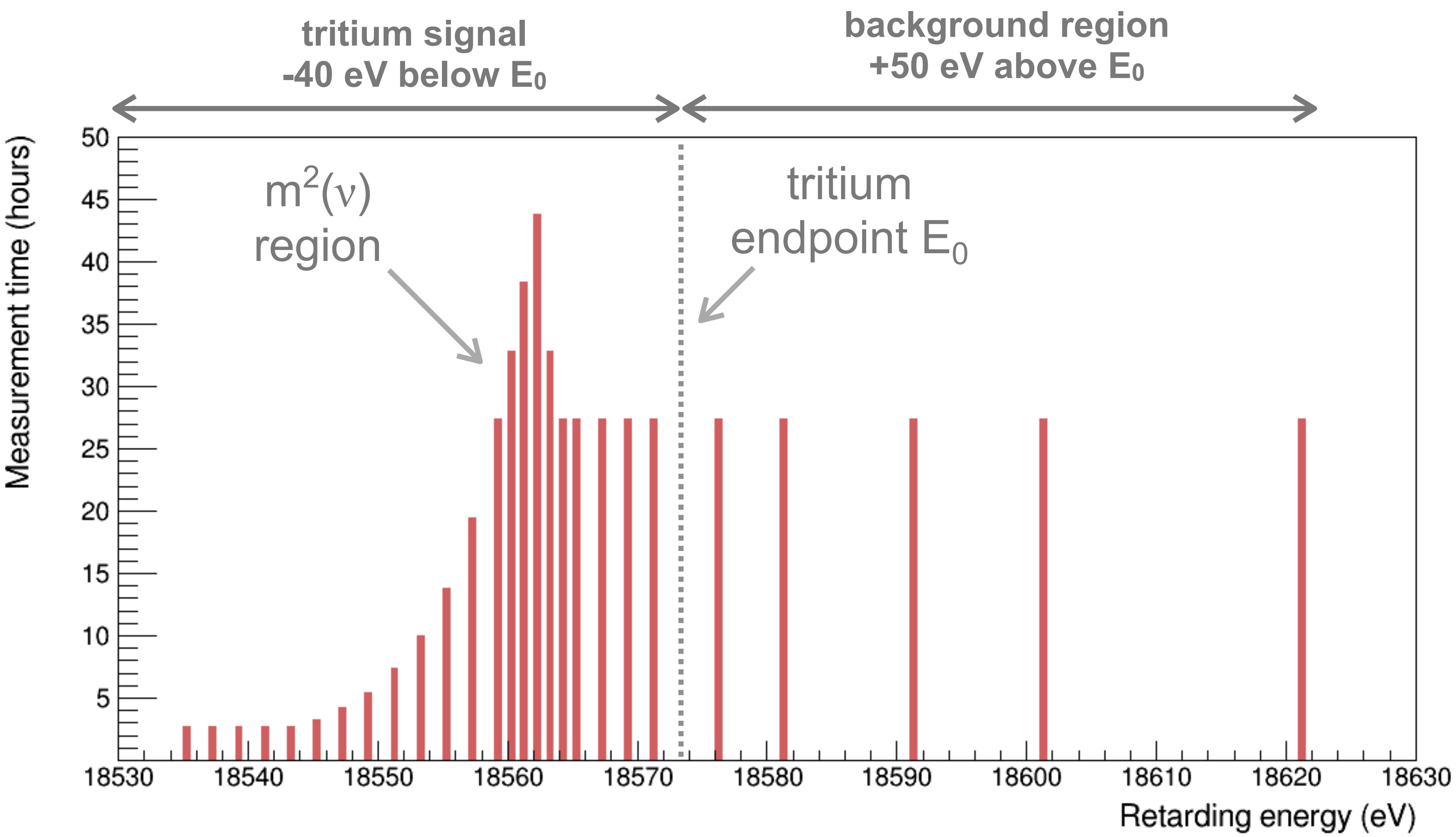
Connections to CERN:

- Magnet operation/safety and UHV
- Prod. of calibration sources (ISOLDE)
- KATRIN precision HV divider @ISOLDE

Full system description & commissioning paper: 2103.04755

Spectrum measurement: modus operandi

- Several **measurement campaigns** per year:
  each 2-3 months long, separated by calibration and maintenance breaks
- Several hundred **scans of the β-decay spectrum** in each campaign:
  each ~2.5 hours long, alternating in up/down direction



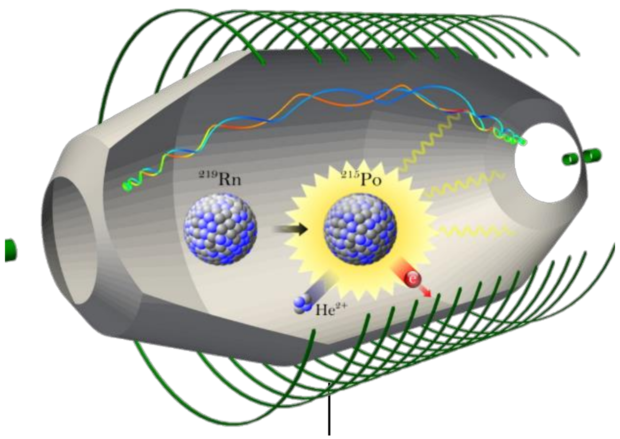
- Ca. 30 high-voltage steps in each scan
- Different regions for four fit parameters: **$m^2(\nu)$**, endpoint **E_0**, norm. **A**, background **B**
- Distribution optimized for $m^2(\nu)$ sensitivity
- Ca. 25% of time spent on background

Backgrounds in KATRIN

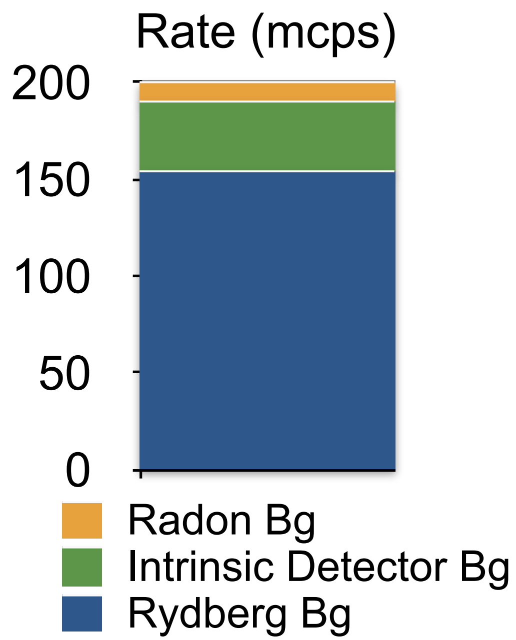
- Backgrounds from **charged particles effectively suppressed** through magnetic shielding, inner electrode system, and “trap swiper” in high-field region

  ➜ muon-induced bg [1805.12173], gamma-induced bg [1903.00563], high-field regions [1911.09633]

- **Dominant background from neutrals** traveling freely through the spectrometer and
  - undergoing decay and secondary ionization in the volume (^{219}Rn from getter pumps)
  - being ionized in the volume (Rydberg atoms liberated by surface contaminants)



➜ Background overview: 2011.05107



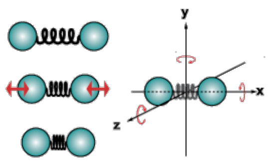
- Overall background rate ~200 mcps
- Decay statistics + electron trapping:
  - overdispersion of background rate (non-Poisson statistics)
  - potential qU-dependent slope
  - potential time slope

➜ Improve stat. and syst. uncertainties by improving on backgrounds!

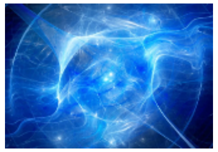
Systematics overview

- Fit model is informed by **theoretical** and **experimental** inputs,
  with systematic uncertainties determined by dedicated measurements.

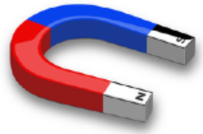
Molecular final states
- quantum-chemical computations

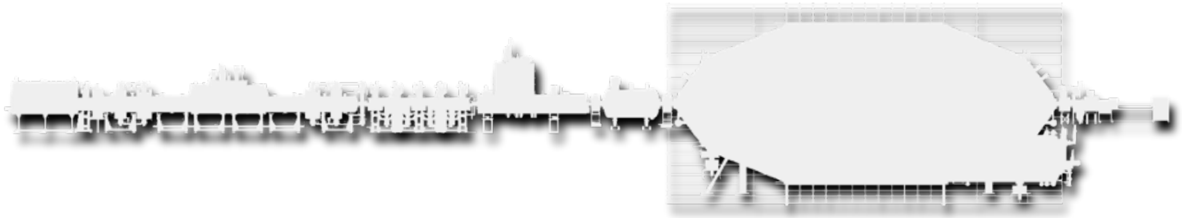


Source electric potential
- plasma properties
- surface conditions

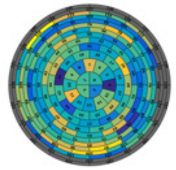


Magnetic fields
- source
- spectrometer
- detector

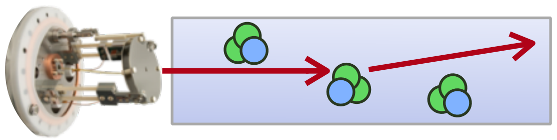




Detection efficiency



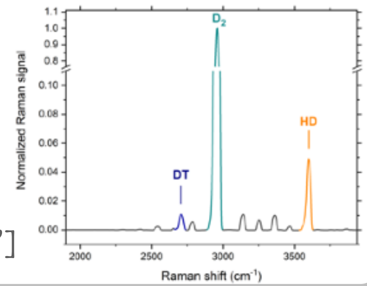
Energy loss by scattering



[EPJ C **81** (2021) 579]

Activity fluctuations
- column density
- tritium (T_2, DT, HT) concentration

[Sensors **20** (2020) 4827]



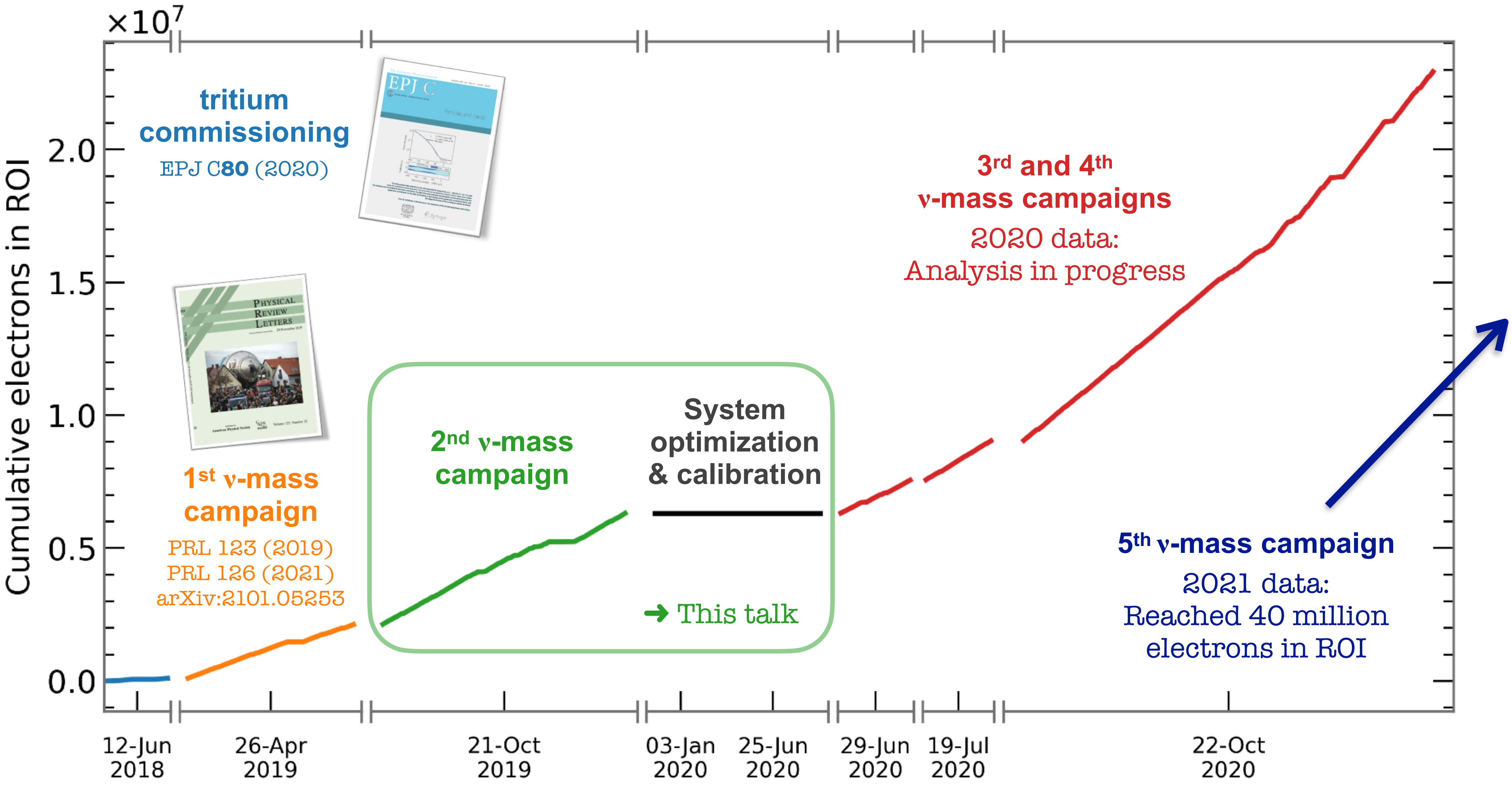
Background
- dependence on retarding potential
- time structure due to trapped electrons

[arXiv:2011.05107]

- Three complementary strategies to include systematics in the fit:
  (a) covariance matrix, (b) Monte-Carlo propagation, (c) pull-term method

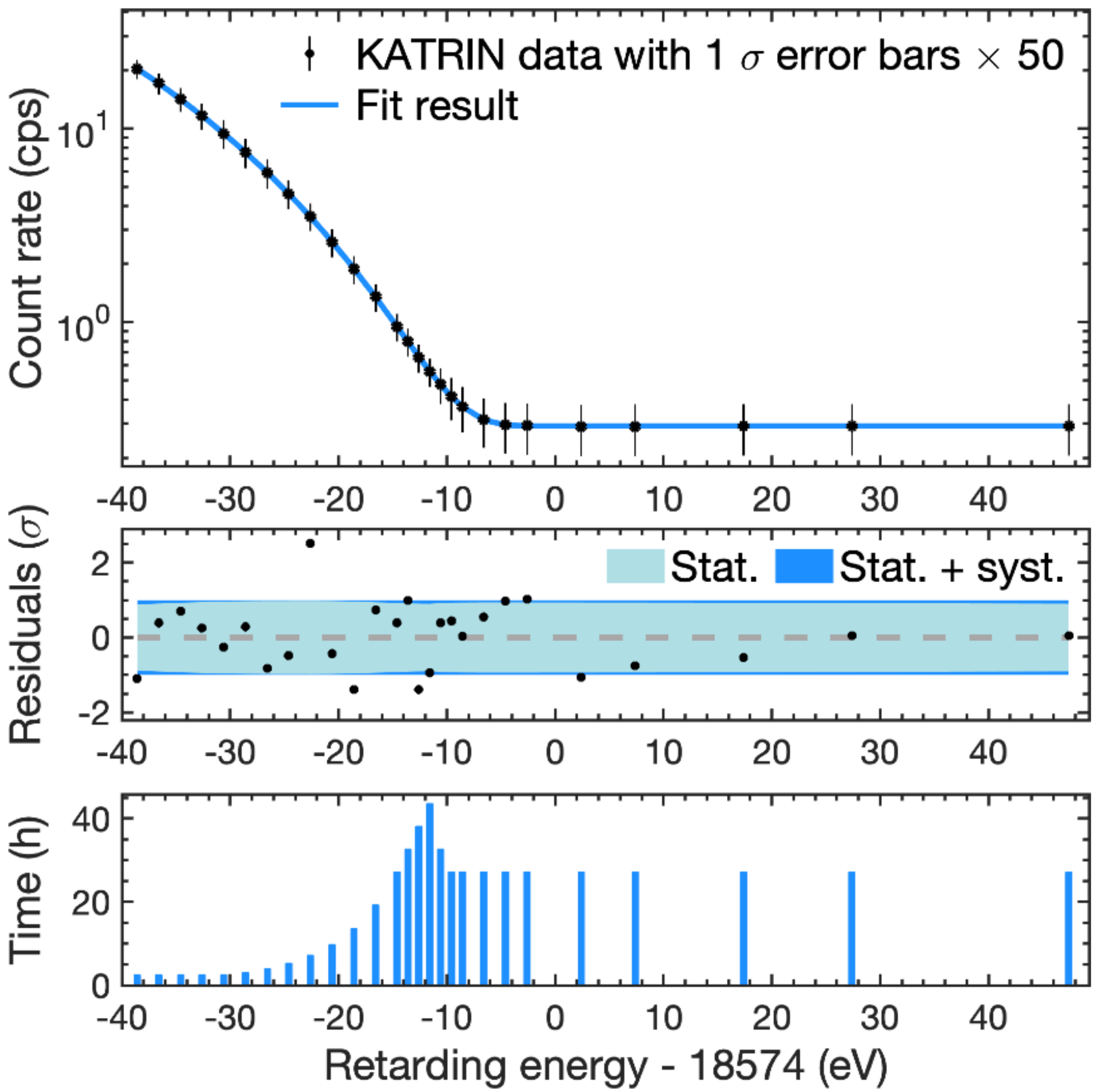
KATRIN data-taking so far

Karlsruhe Institute of Technology



Recap: First neutrino mass result

Karlsruhe Institute of Technology



Spectrum data available on KATRIN web page

- Four-week campaign at reduced source strength ("burn-in phase")
- 9 days of nominal KATRIN only
- Improvement over prev. experiments:
  σ_{stat} = 0.97 eV^2 ➜ factor 2
  σ_{syst} = 0.32 eV^2 ➜ factor 6
- Best-fit value:

$$\mathbf{m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\,eV^2}$$

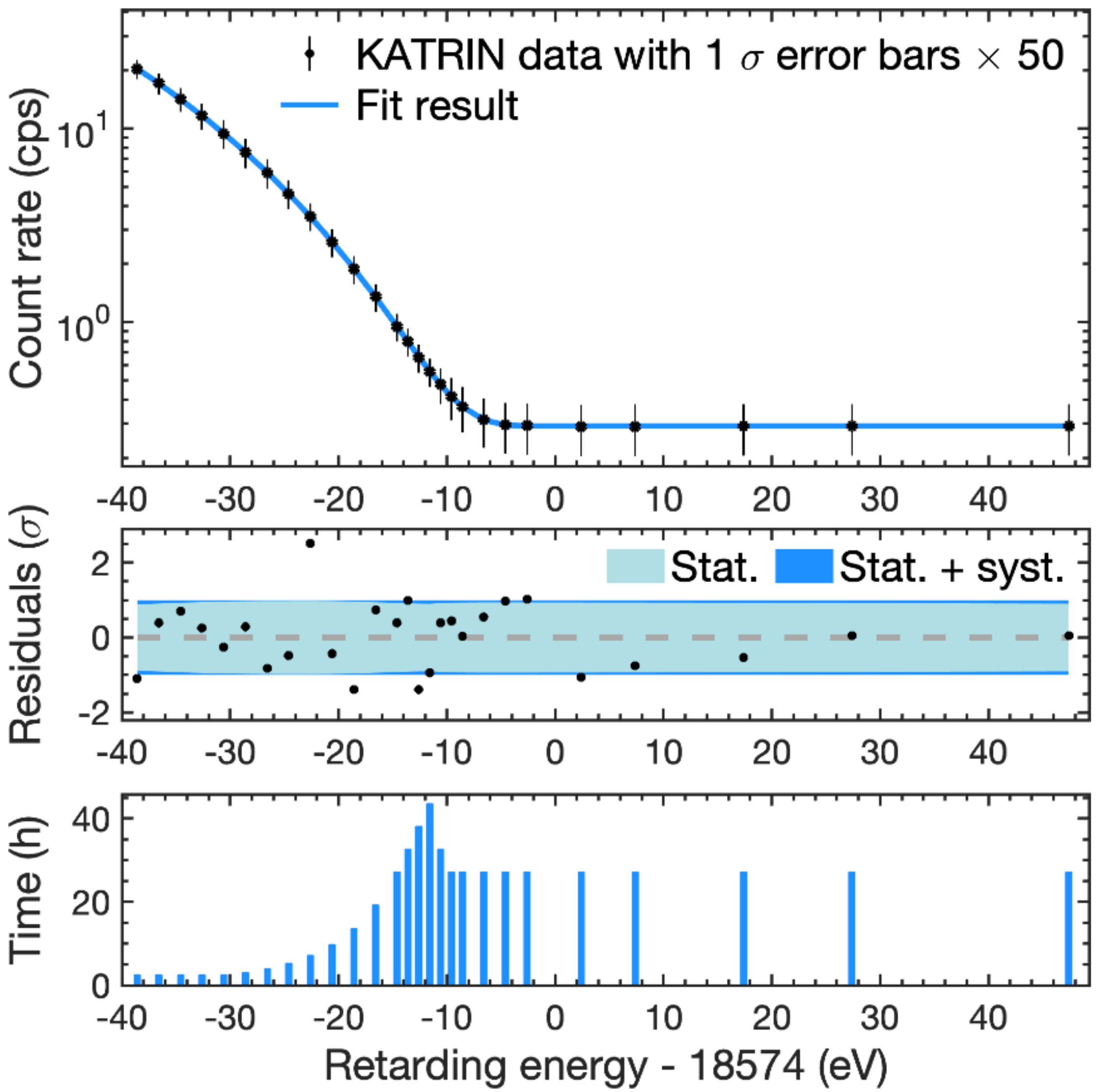
- Upper limit: $\mathbf{m_\nu}$ **< 1.1 eV (90% CL)**

New PDG reference! $\bar{\nu}$ **MASS (electron based)**

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
< 1.1	90	[1] AKER	19	SPEC	^3H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2.05	95	[2] ASEEV	11	SPEC	^3H β decay
< 5.8	95	[3] PAGLIAROLI	10	ASTR	SN1987A
< 2.3	95	[4] KRAUS	05	SPEC	^3H 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	^3H β decay

HTTP://PDG.LBL.GOV Page 4 Created: 6/1/2020 08:33

Recap: First neutrino mass result



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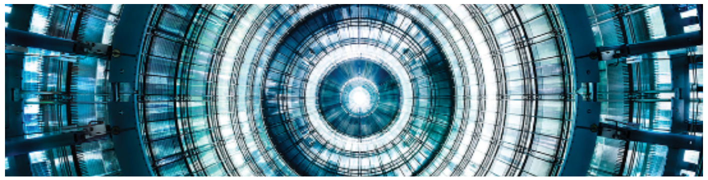
CERNCOURIER Jan. 2020



NEUTRINOS | FEATURE

A voyage to the heart of the neutrino

10 January 2020

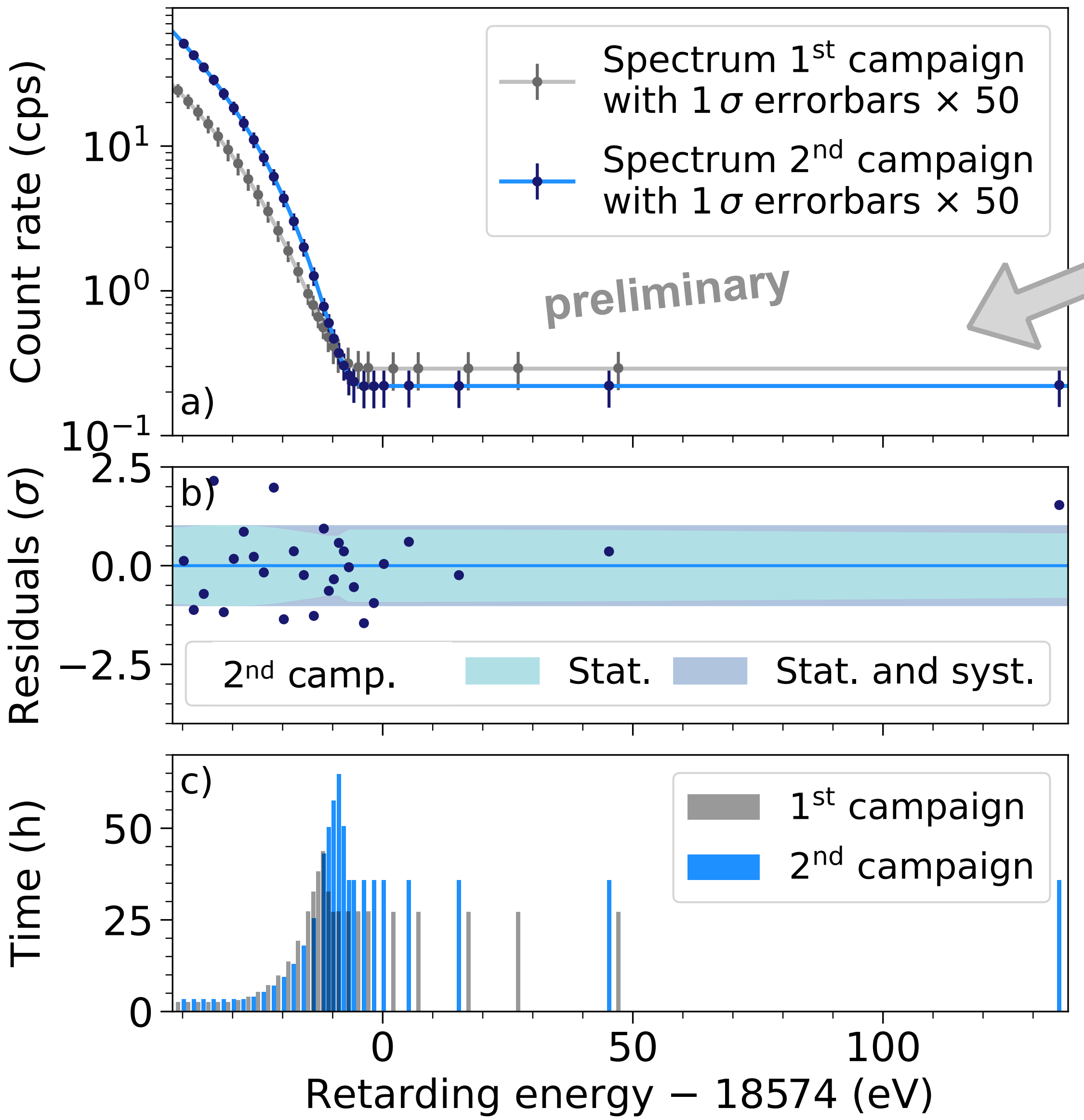
The Karlsruhe Tritium Neutrino (KATRIN) experiment has begun its seven-year-long programme to determine the absolute value of the neutrino mass.

PRL **123** (2019) 221802 + detailed analysis PRD **104** (2021) 012005

KATRIN data-taking: 2019 in numbers

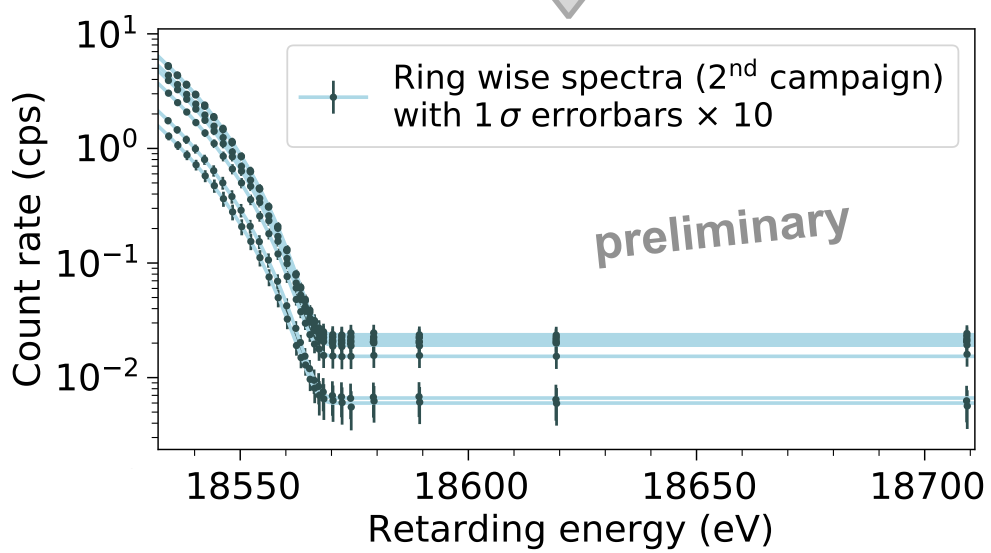
	1st campaign *PRL 123 (2019)*		*2nd campaign* *This talk*
Campaign date	April-May 2019		Sept-Nov 2019
Total scan time	522 h (274 scans)		744 h (361 scans)
Background	290 mcps	**reduction -25%** →	220 mcps
Source activity	25 GBq	**nominal activity** →	98 GBq
Tritium purity	97.6%	**raised purity** →	98.7%
Electrons in RoI	2 Mio	**stats doubled** →	4.3 Mio

Data from the 2nd campaign



- Improved ratio of source activity to background from 1st campaign to 2nd campaign
- Overall improvement of statistics

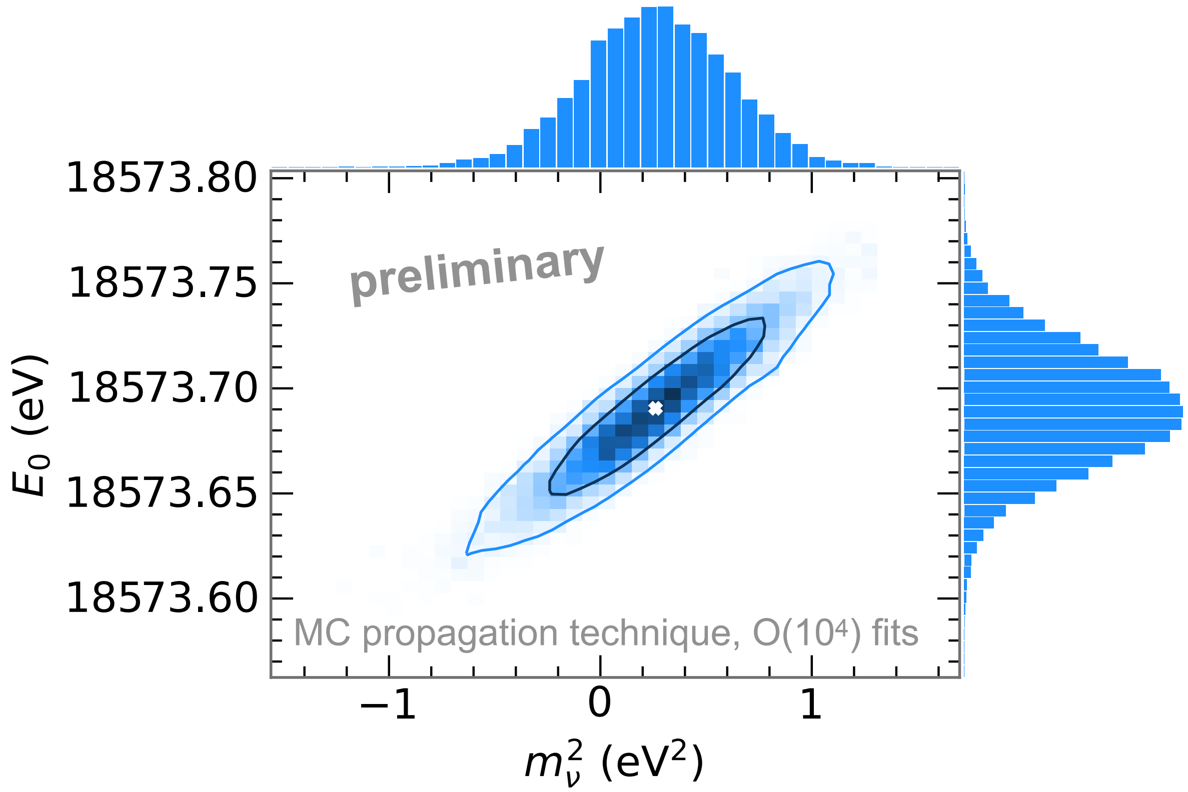
- High quality of 12 ring-wise spectra and excellent agreement with model



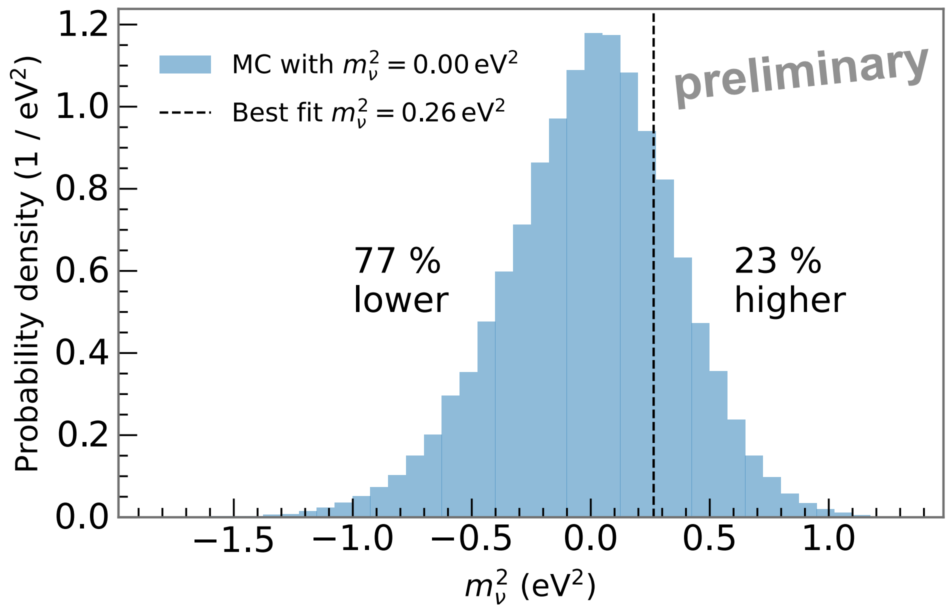
[arXiv:2105.08533]

Neutrino-mass result for 2nd campaign

- Ring-wise fit with common **m²(ν)**, 12 x ring-dependent E₀, background, normalization
- Best-fit value (stat. and syst.): **$m^2(\nu) = 0.26 \pm 0.34\ \mathrm{eV}^2$**



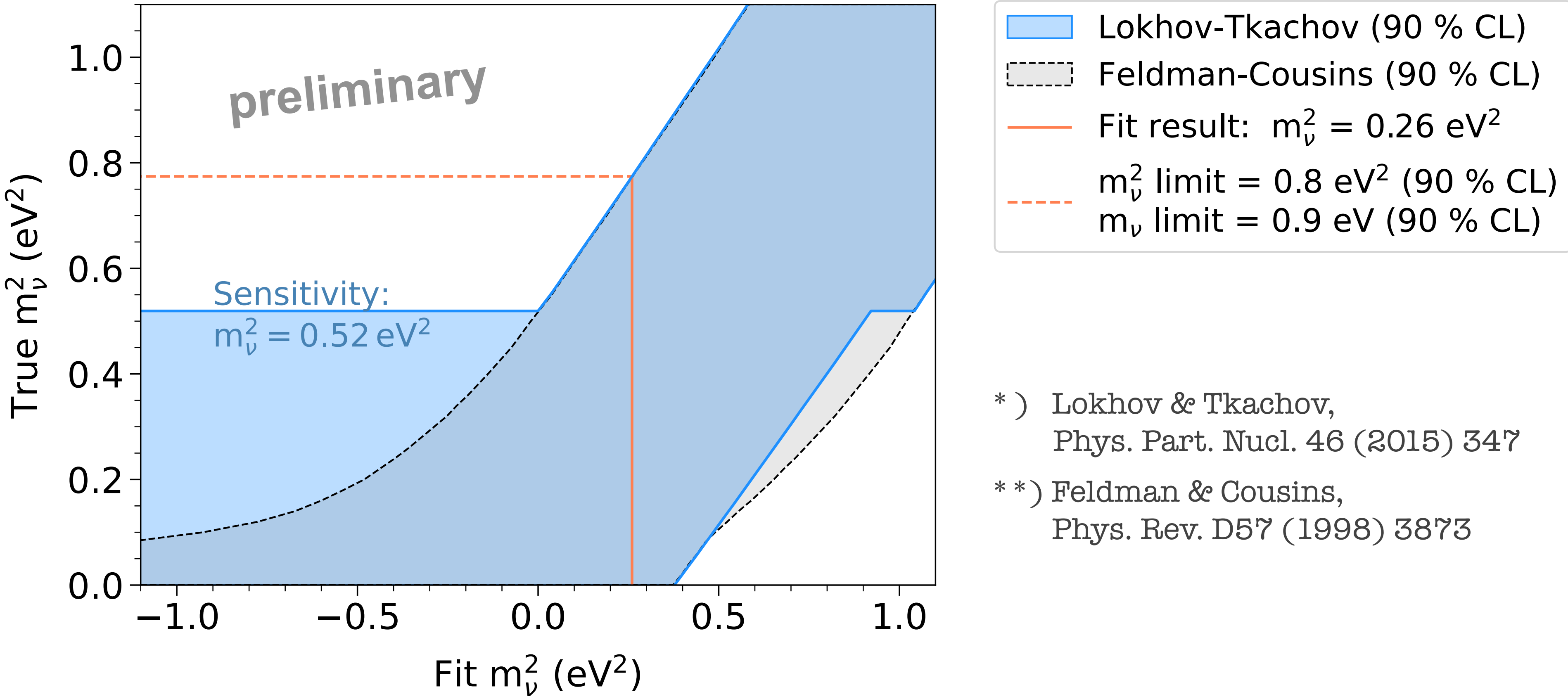
Fully compatible with expectation for $m^2(\nu) = 0$



- Best-fit effective endpoint **$E_0 = 18573.69 \pm 0.03$ eV** consistent with mass difference $\Delta M(^3He-^3H)$ from precision Penning traps ➜ independent check of energy scale

Neutrino-mass result for 2nd campaign

- Two frequentist limit construction techniques (Lokhov-Tkachov* and Feldman-Cousins**) to obtain upper limit: **m(ν) < 0.9 eV (90% CL)**
- Sensitivity of 2nd campaign: 0.7 eV (90% CL)



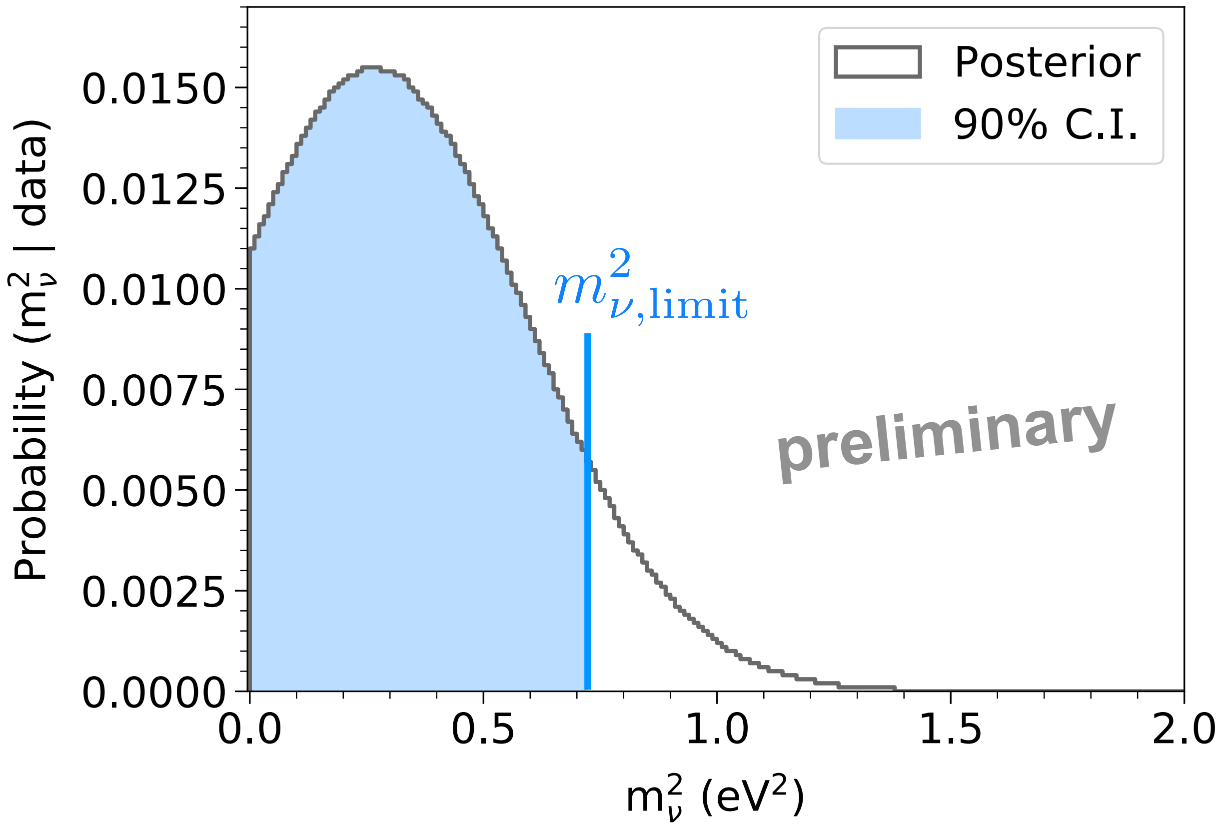
*) Lokhov & Tkachov, Phys. Part. Nucl. 46 (2015) 347

**) Feldman & Cousins, Phys. Rev. D57 (1998) 3873

[arXiv:2105.08533]

Neutrino-mass result for 2nd campaign

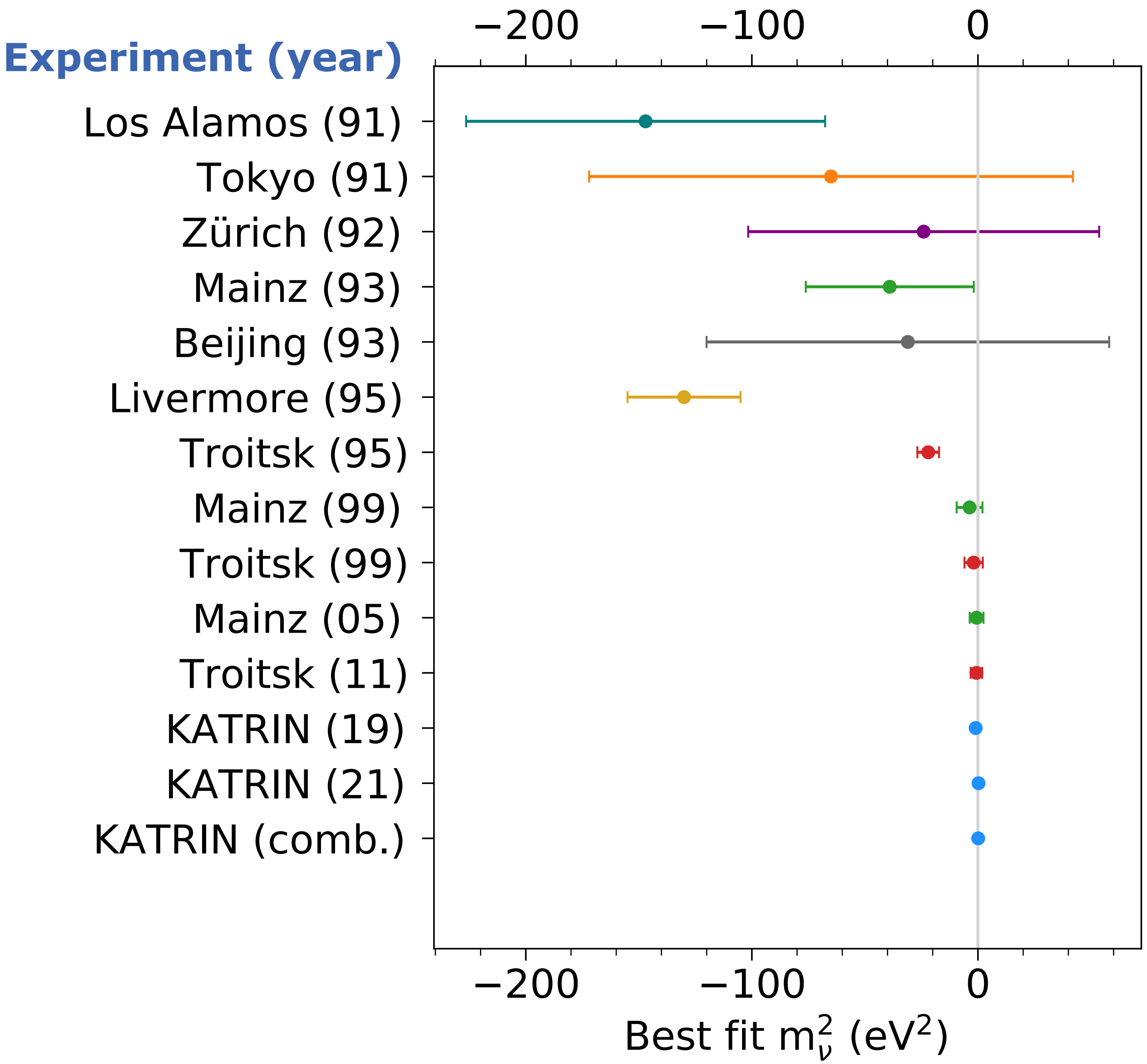
- Alternative analysis approach: Bayesian inference
- Using flat positive prior on m_ν^2
- Bayesian bound obtained by integrating posterior distribution from 0 to $m^2_{\nu,\mathrm{limit}}$ gives m(ν) < 0.85 eV for a 90% credible interval



(Note:
different interpretation of bounds in frequentist vs. Bayesian approach)

[arXiv:2105.08533]

30-year retrospective on tritium experiments



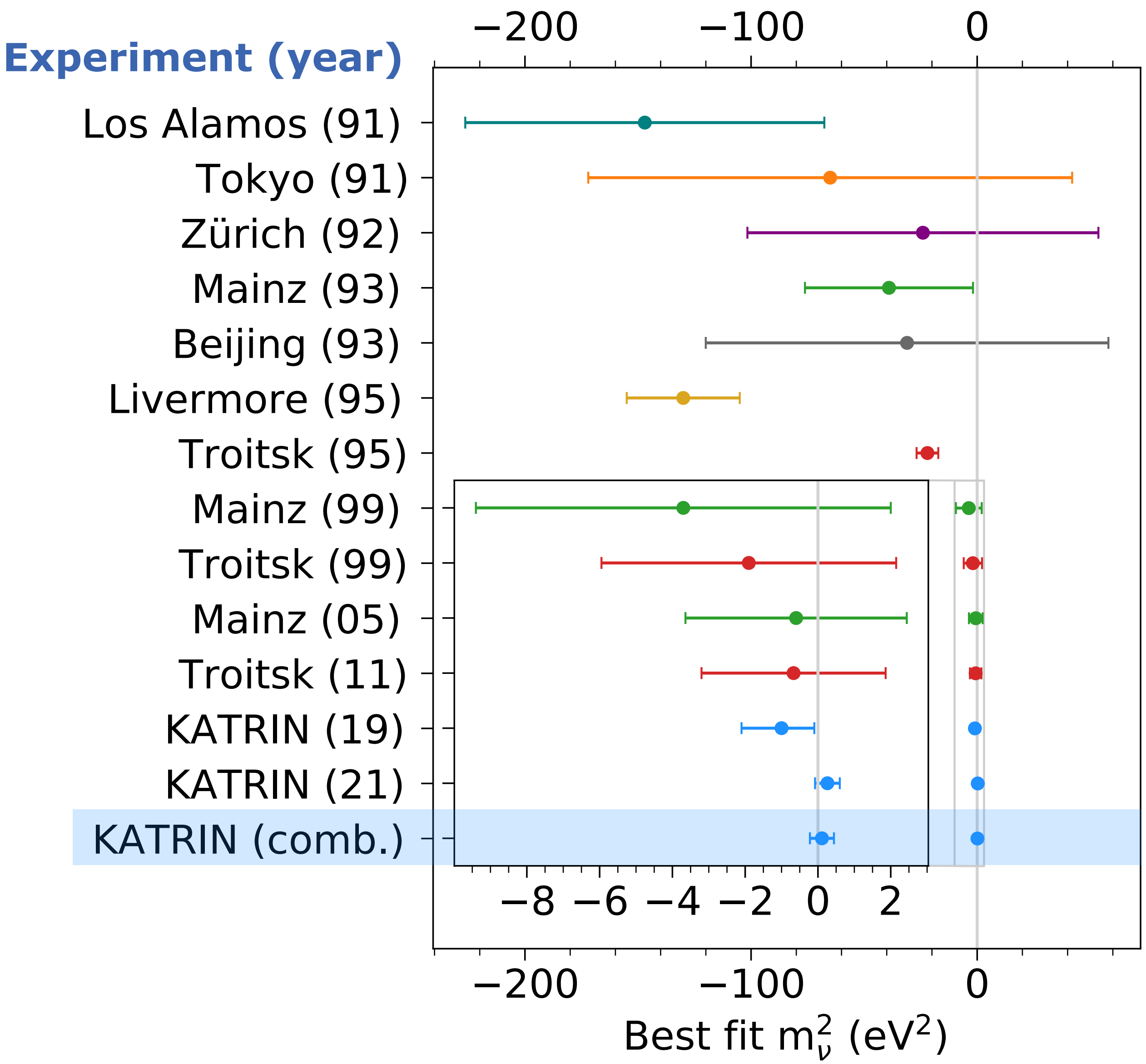
Instrument development
+ dedicated systematics experiments
+ theoretical model

Scale-up & further development
of MAC-E technique
with gaseous source

[arXiv:2105.08533]

30-year retrospective on tritium experiments

Karlsruhe Institute of Technology



Instrument development
+ dedicated systematics experiments
+ theoretical model

Scale-up & further development
of MAC-E technique
with gaseous source

KATRIN (2021): first direct neutrino-mass experiment to reach sub-eV sensitivity

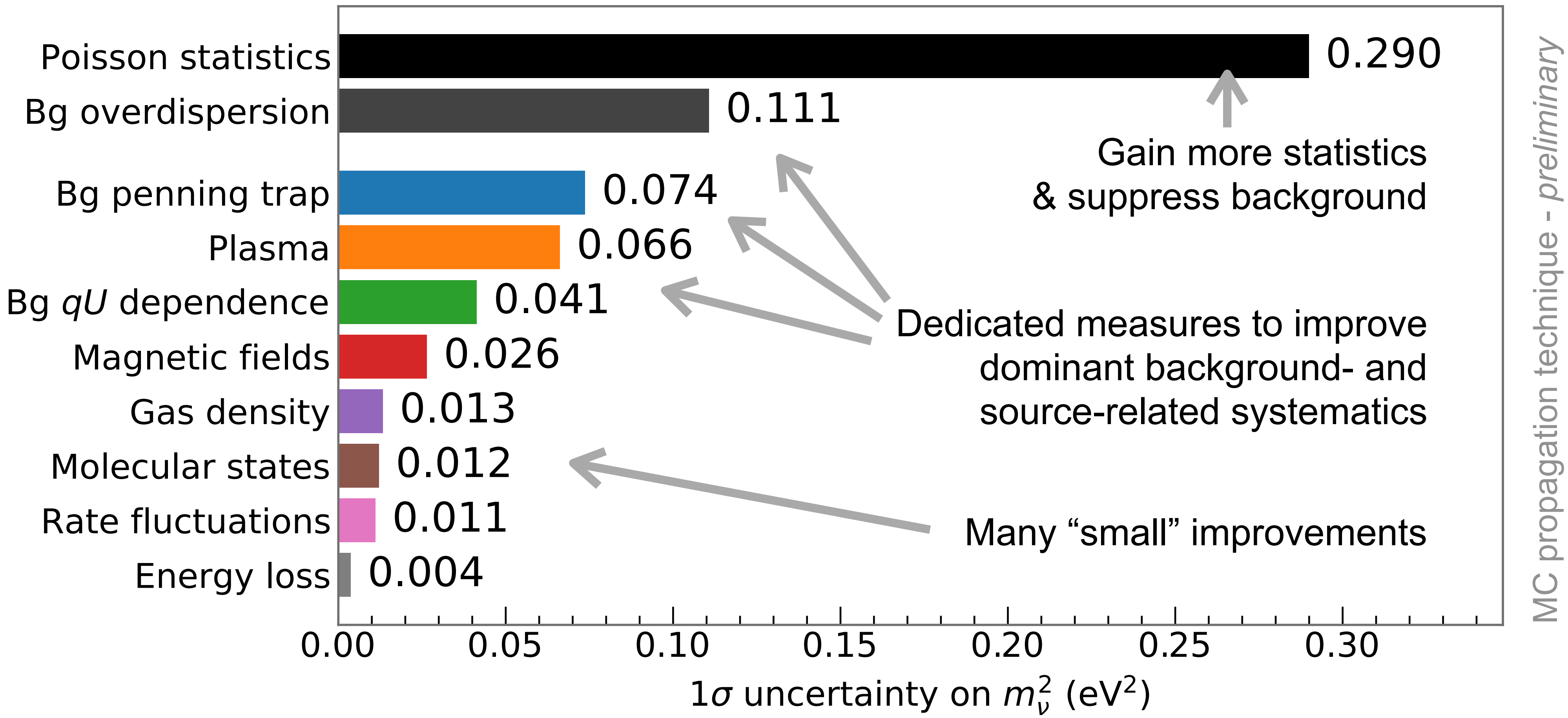
Combined result: $\mathbf{m_\nu^2 = (0.1 \pm 0.3)\ eV^2}$

Combined limit: **m_ν < 0.8 eV (90% CL)**

[arXiv:2105.08533]

Where do we go from here?

Breakdown of uncertainties for 2nd campaign (status: first out of 5 years of operations)



➜ **Further improvements already from 3rd campaign onwards.**

[arXiv:2105.08533]

Outlook: Progress of data-taking

Karlsruhe Institute of Technology

5th neutrino-mass campaign* (March-May 2021), followed by krypton calibration campaign (ongoing)

*) Third consecutive measurement campaign since beginning of the pandemic, performed under all necessary precautions.

Big *Thanks* to all operators!

Physics “beyond the neutrino mass” with KATRIN

β-spectrum of high statistics and precision

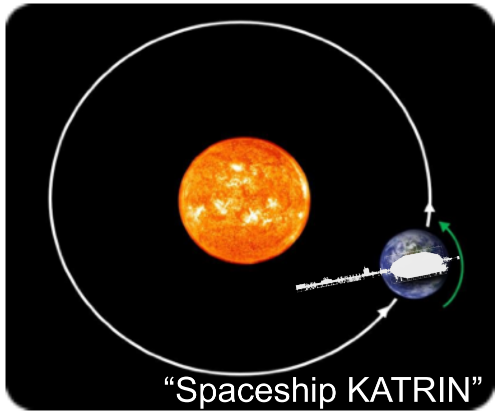
Is there a fourth (sterile) neutrino?

Neutrino mixing:
“Kink” search in
normal β-spectrum (eV scale)
or deep β-spectrum (keV scale)

Constrain local overdensity of cosmic relic neutrinos (line search)

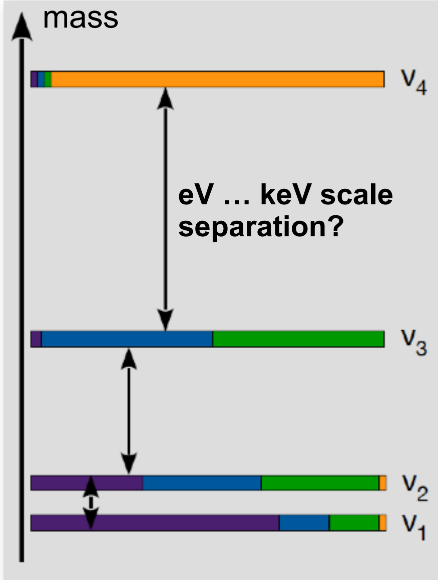
Search for exotic weak interactions (spectrum shape)

Search for Lorentz invariance violation (sidereal modulation)



Snowmass LoI: “Searches for BSM physics with KATRIN”
Snowmass LoI: “Prospects for keV sterile neutrino searches with KATRIN”

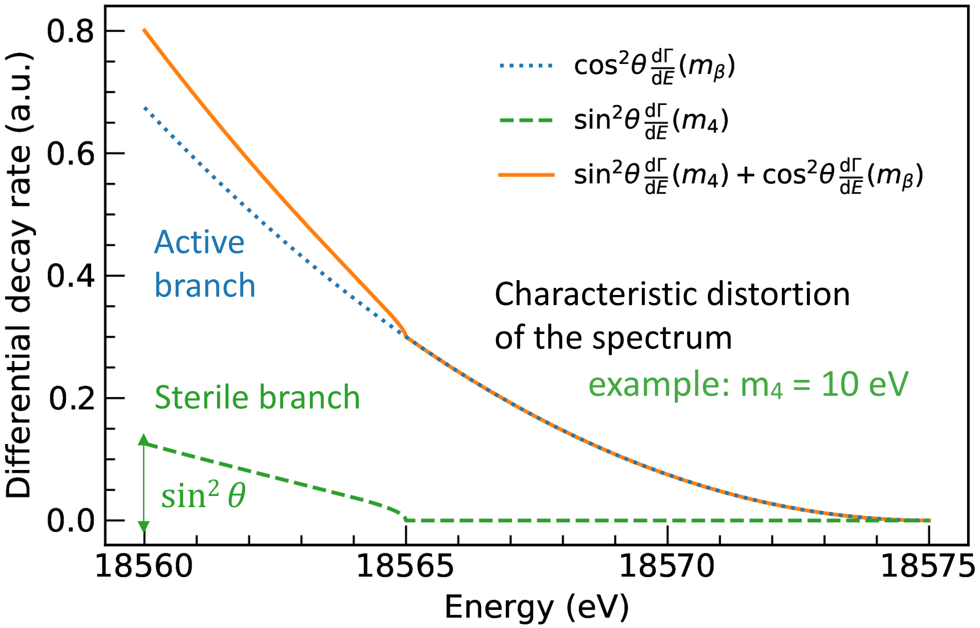
Physics reach of KATRIN: search for extra neutrino states



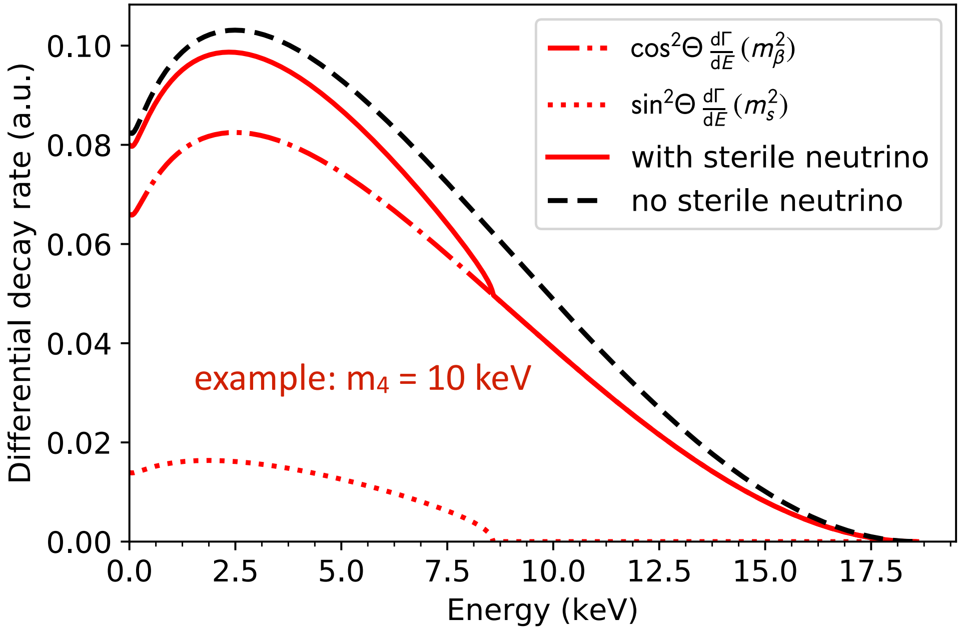
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \cos^2(\theta_s)\,\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_\beta^2) + \sin^2(\theta_s)\,\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_s^2)$$

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

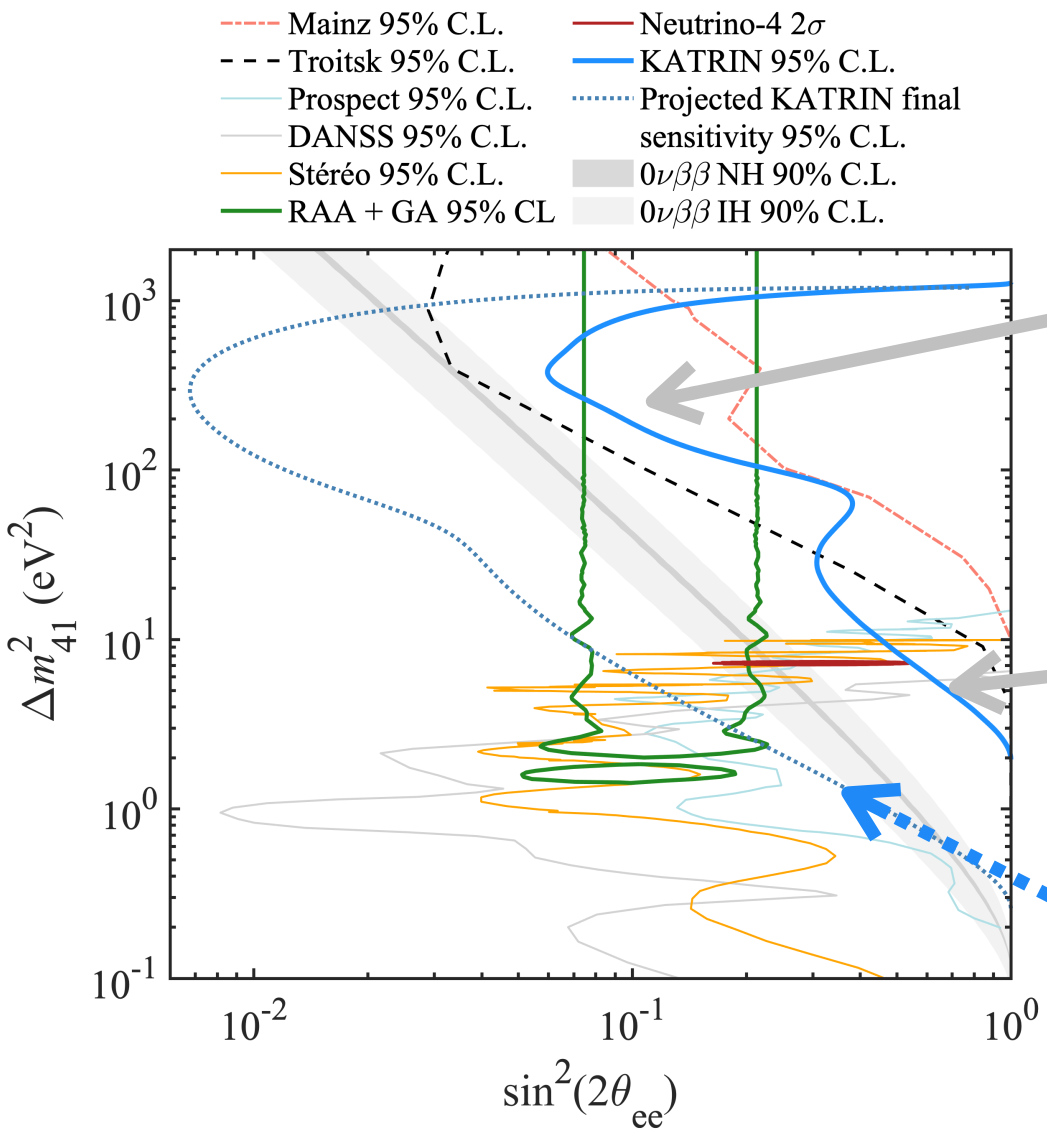
light sterile ν, m_s ~ few eV
motivated by oscillation anomalies



heavy sterile ν, m_s ~ few keV
motivated as DM candidate



Search for sterile neutrinos at the eV scale



[KATRIN Collab., PRL **126** (2021) 091803]

Region of high Δm²:

- Improve exclusion with respect to DANSS, PROSPECT, STÉRÉO
- Exclude large Δm² solution preferred by reactor and gallium anomalies

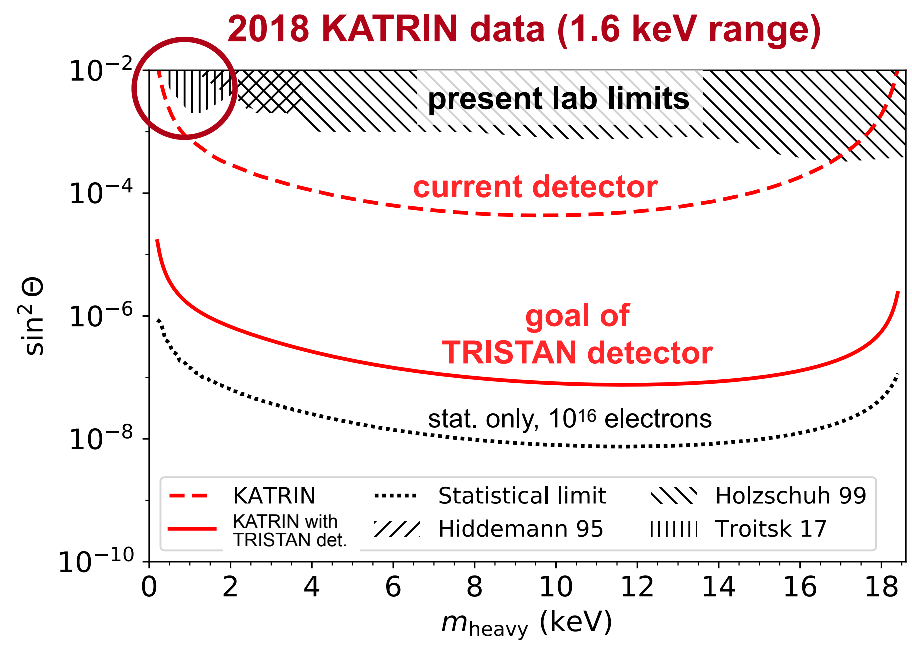
Region of low Δm²:

- Improve limits by Mainz and Troitsk

Future prospects:
eV-scale anomalies will be probed with full KATRIN data set

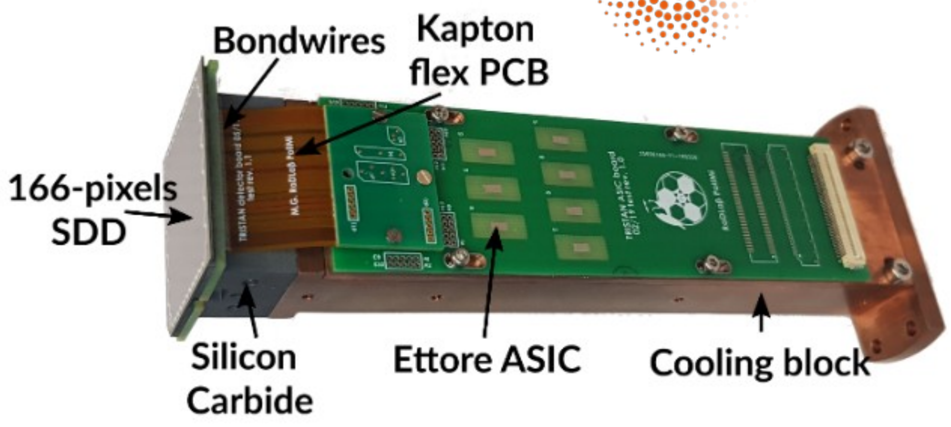
Prospects for keV sterile neutrino search

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

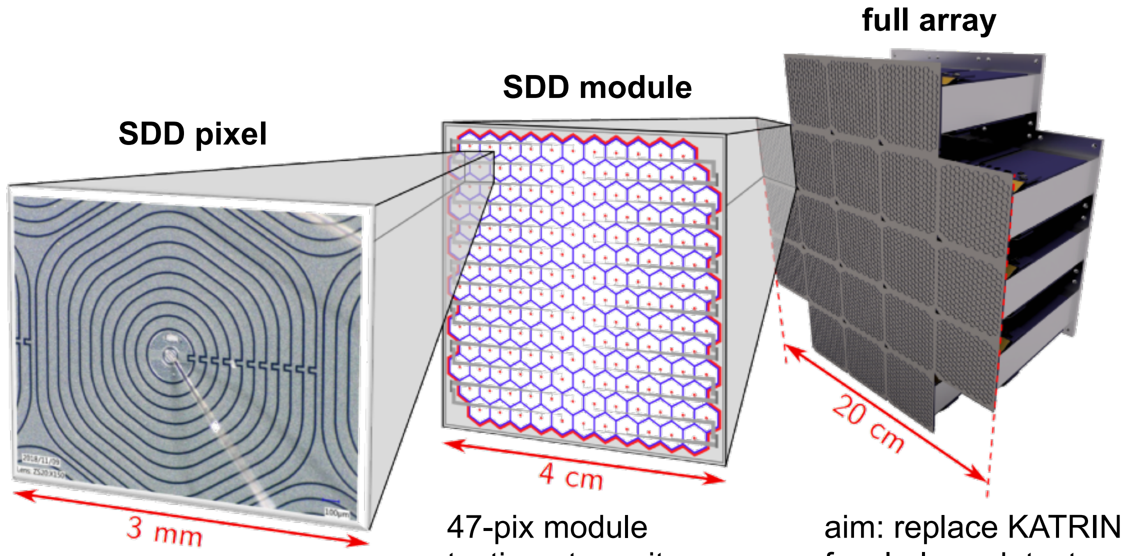


TRISTAN detector for KATRIN:

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



[J. Phys. G**46** (2019) 065203 & G**48** (2020) 1]



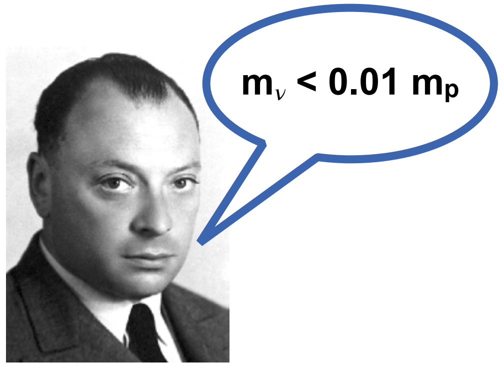
7-pix prototype in use as KATRIN beam monitor

47-pix module testing at monitor spectrometer now

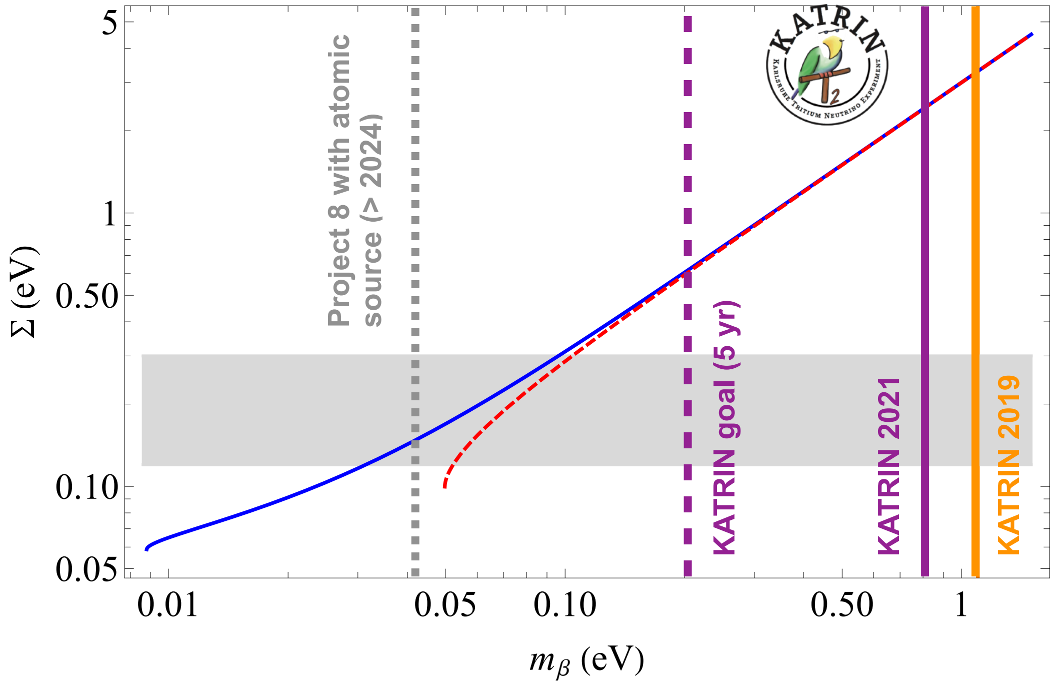
aim: replace KATRIN focal-plane detector in 2025

Summary and Outlook

- Since 90 years, the absolute neutrino mass scale is a fundamental open question with implications from particle physics to cosmology
- The last decade has seen tremendous progress from three angles: observational cosmology, search for 0νββ, and *direct kinematics*
- **First sub-eV result** from KATRIN:
  m(ν) < 0.8 eV (90% CL) from just few months of data



W. Pauli, 1930



- Five-year target sensitivity: 0.2 eV (90% CL)
- Precision β-kinematics: great perspectives for new physics “beyond the neutrino mass”, e.g. eV- and keV-scale sterile neutrinos, Lorentz invariance, relic ν overdensities, exotic weak interactions, …

Exciting times ahead!

Formaggio, de Gouvea, Robertson,
Physics Reports **914** (2021) 1 [2102.00594]