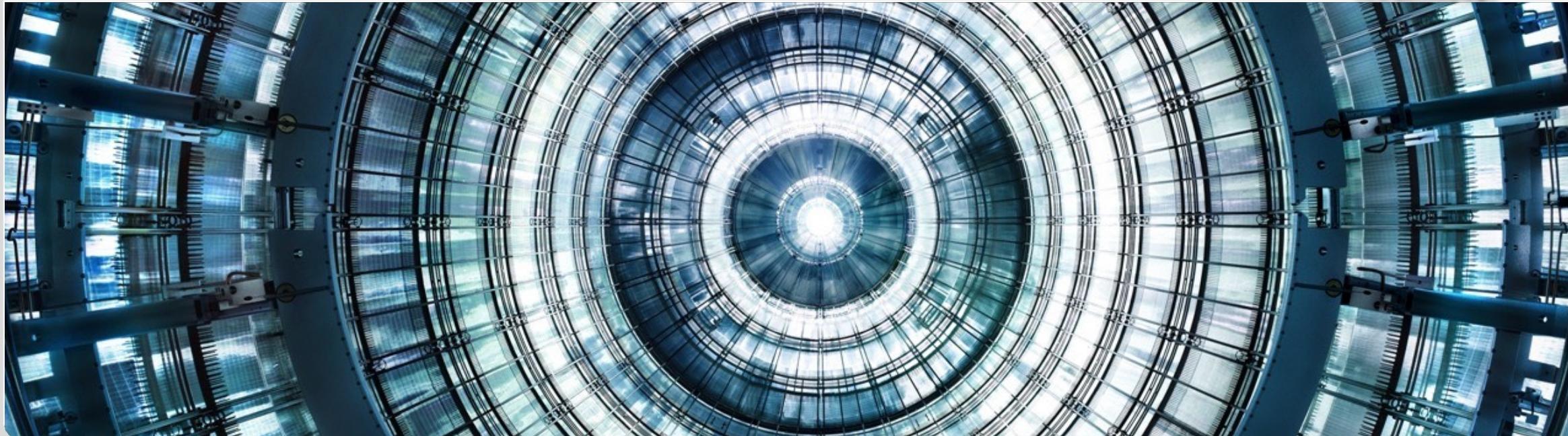


Probing the neutrino mass: latest results from KATRIN

DPNC Seminar, *UNIGE* | Jan. 19, 2022

KATHRIN VALERIUS, Institute for Astroparticle Physics



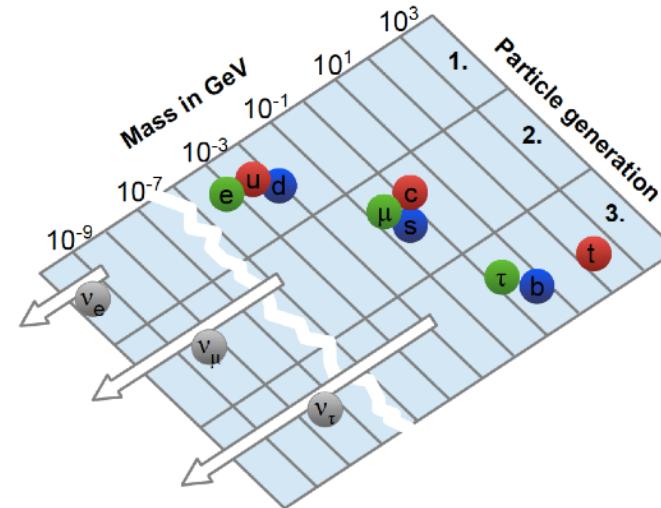
Outline of the talk

- > 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



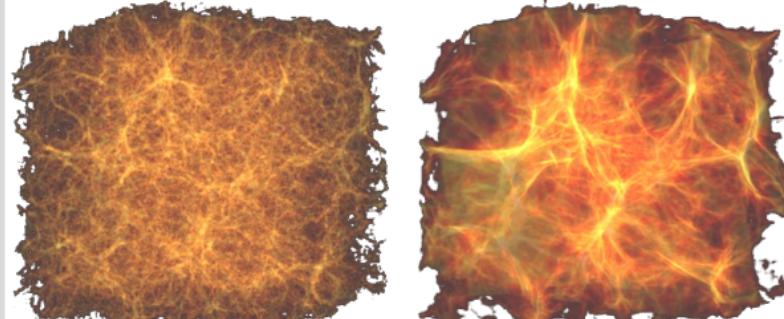
The role of massive neutrinos

Mass generation: new concepts



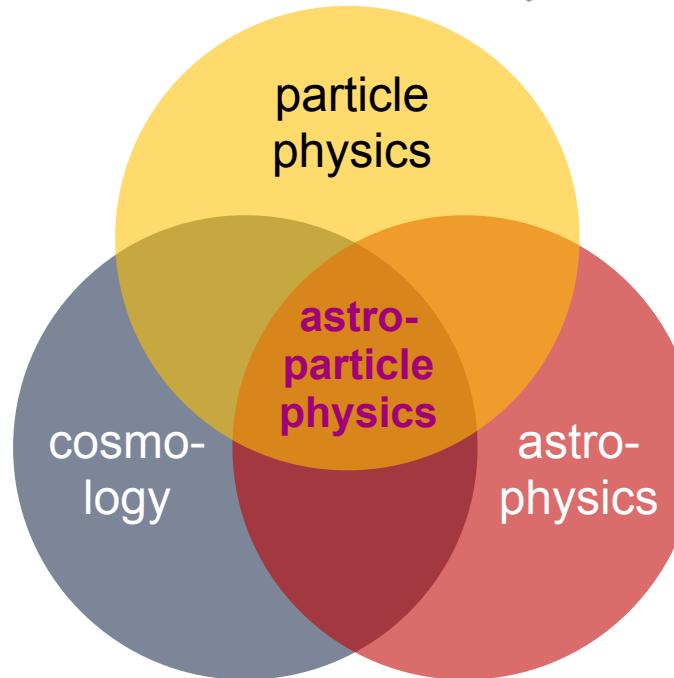
Massive neutrinos as “cosmic architects”

336 ν / cm³ in the Universe today



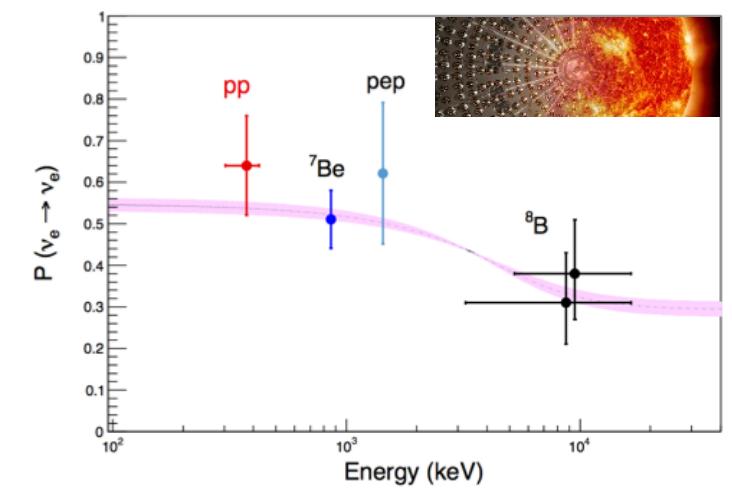
$$m_\nu = 0$$

$$m_\nu > 0$$

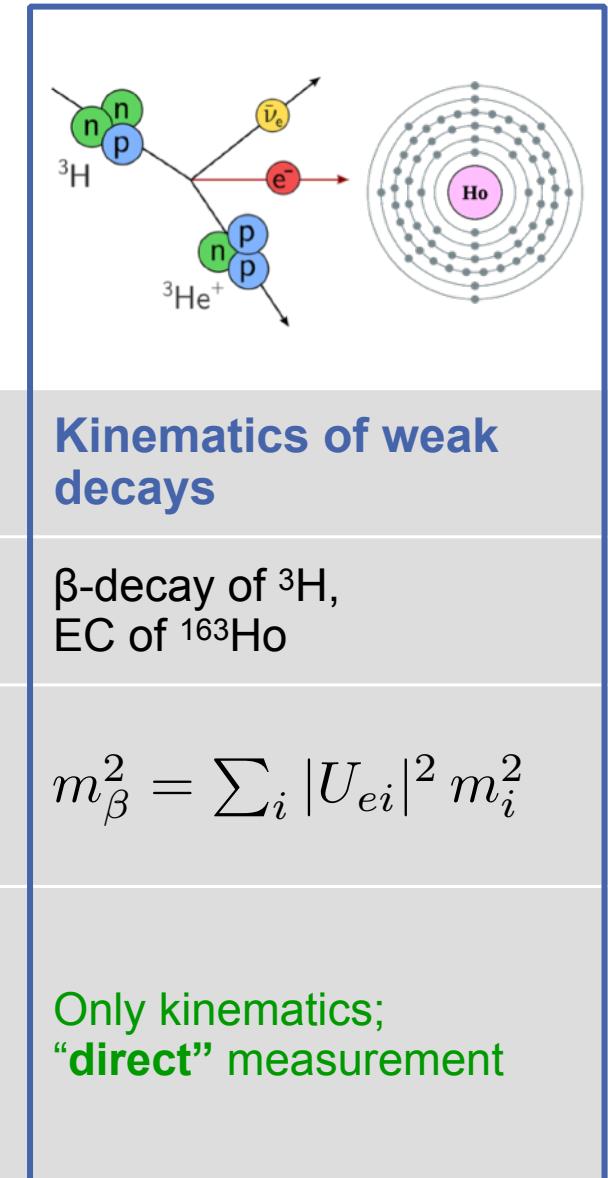
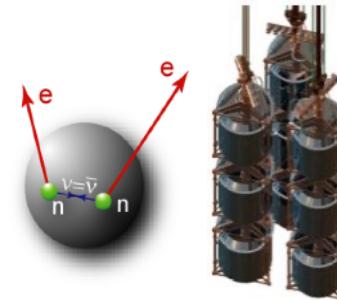
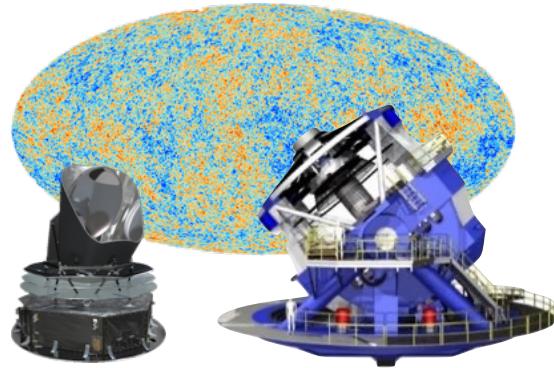


Understanding astrophysical processes

ν as probes of fusion in the sun



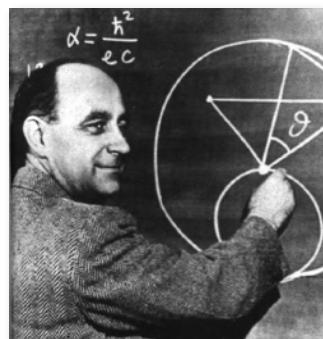
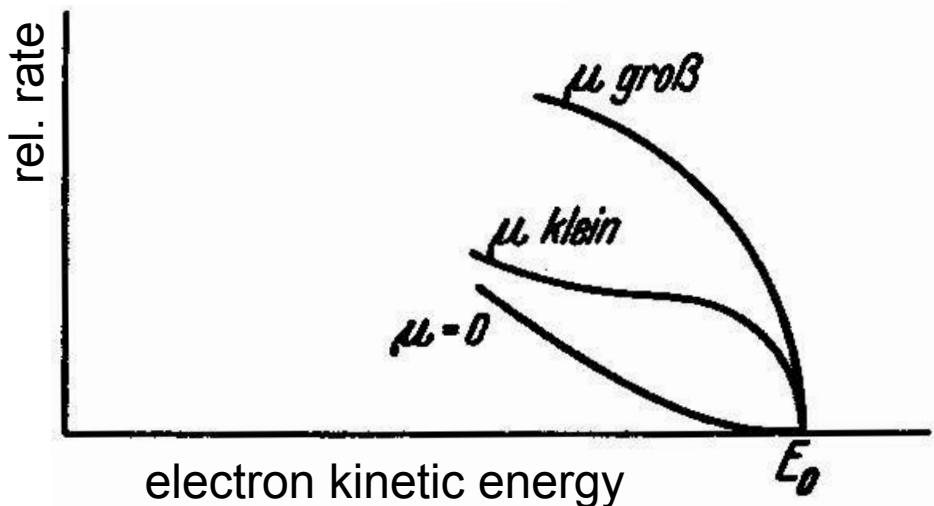
Complementary paths to the ν mass scale



	Cosmology	Search for $0\nu\beta\beta$	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	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left \sum_i U_{ei}^2 m_i \right ^2$	$m_\beta^2 = \sum_i U_{ei} ^2 m_i^2$
Model assumptions	Multi-parameter cosmological model (ΛCDM)	<ul style="list-style-type: none"> - Majorana nature of neutrinos? - No BSM contributions other than $m(\nu)$? 	Only kinematics; “direct” measurement

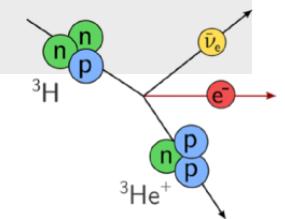
Neutrino mass from β -decay kinematics

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 (${}^3\text{H}$) is of particular interest because : (1) the relatively simple structure of the ${}^3\text{H}$ 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 discrepancy¹ exists between the half-life² and the upper energy limit, as recently measured³ ; (4) the mass difference (${}^3\text{H} - {}^3\text{He}$) can be accurately determined.

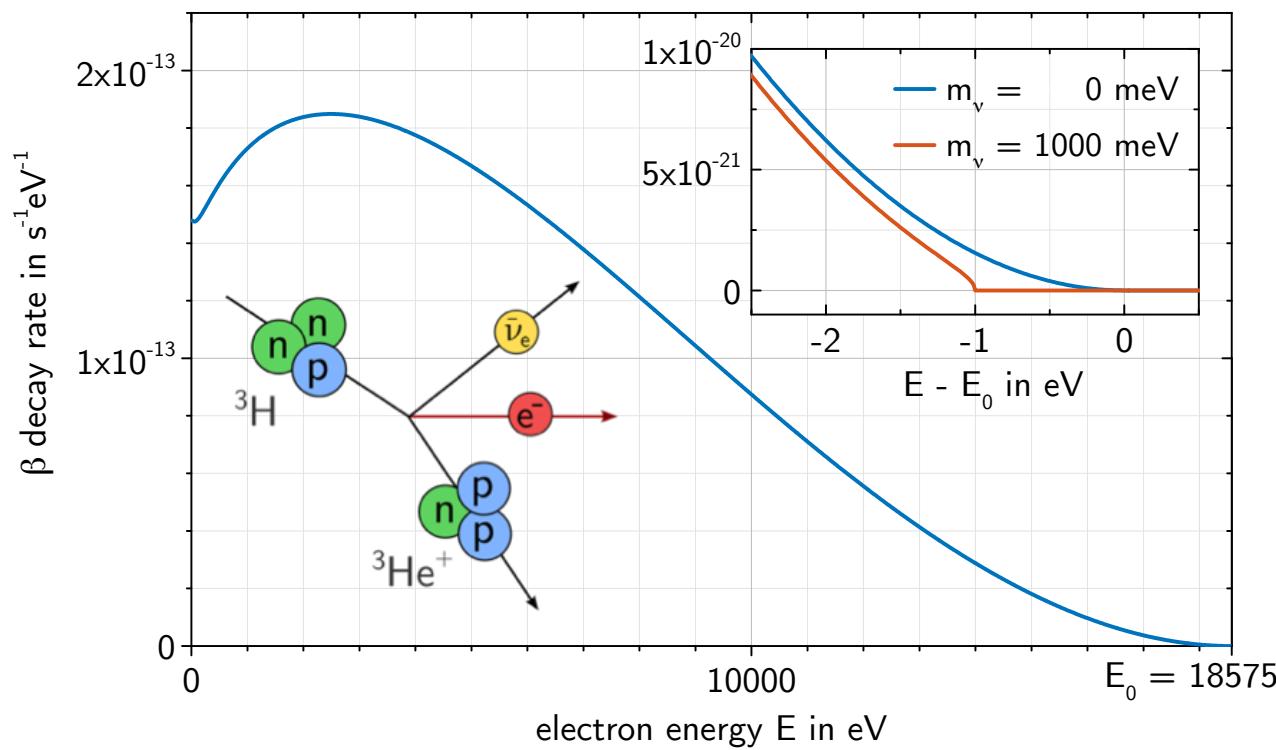
Curran *et al.*, 1948

Neutrino mass from β -decay kinematics

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

Fermi's phase space for β -decay

Modern twist: mass eigenstates m_i and neutrino mixing matrix U



Spectral distortion measures
“effective” mass square:

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

Key requirements:

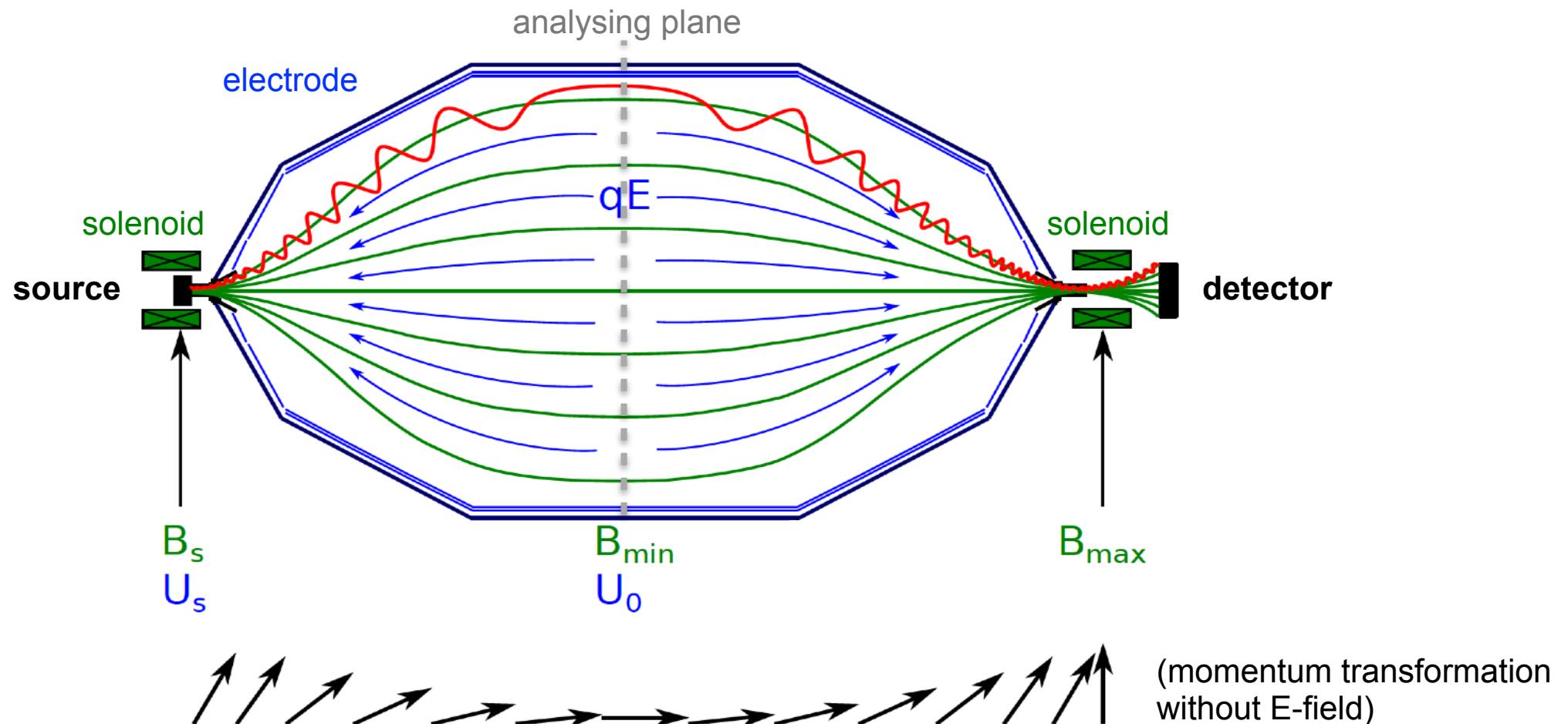
- Low endpoint energy: $E_0 = 18.6$ keV for 3H
- High-activity source: $t_{1/2} = 12.3$ yr for 3H
- Energy resolution ~ 1 eV

High-resolution spectrometer: MAC-E filter

Magnetic Adiabatic Collimation & Electrostatic Filter

- Integrating electrostatic filter ($E_{\text{kin}} > qU_0$)
- Narrow filter width $\Delta E \sim 1 \text{ eV}$ combined with large angular acceptance

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



The Karlsruhe Tritium Neutrino Experiment

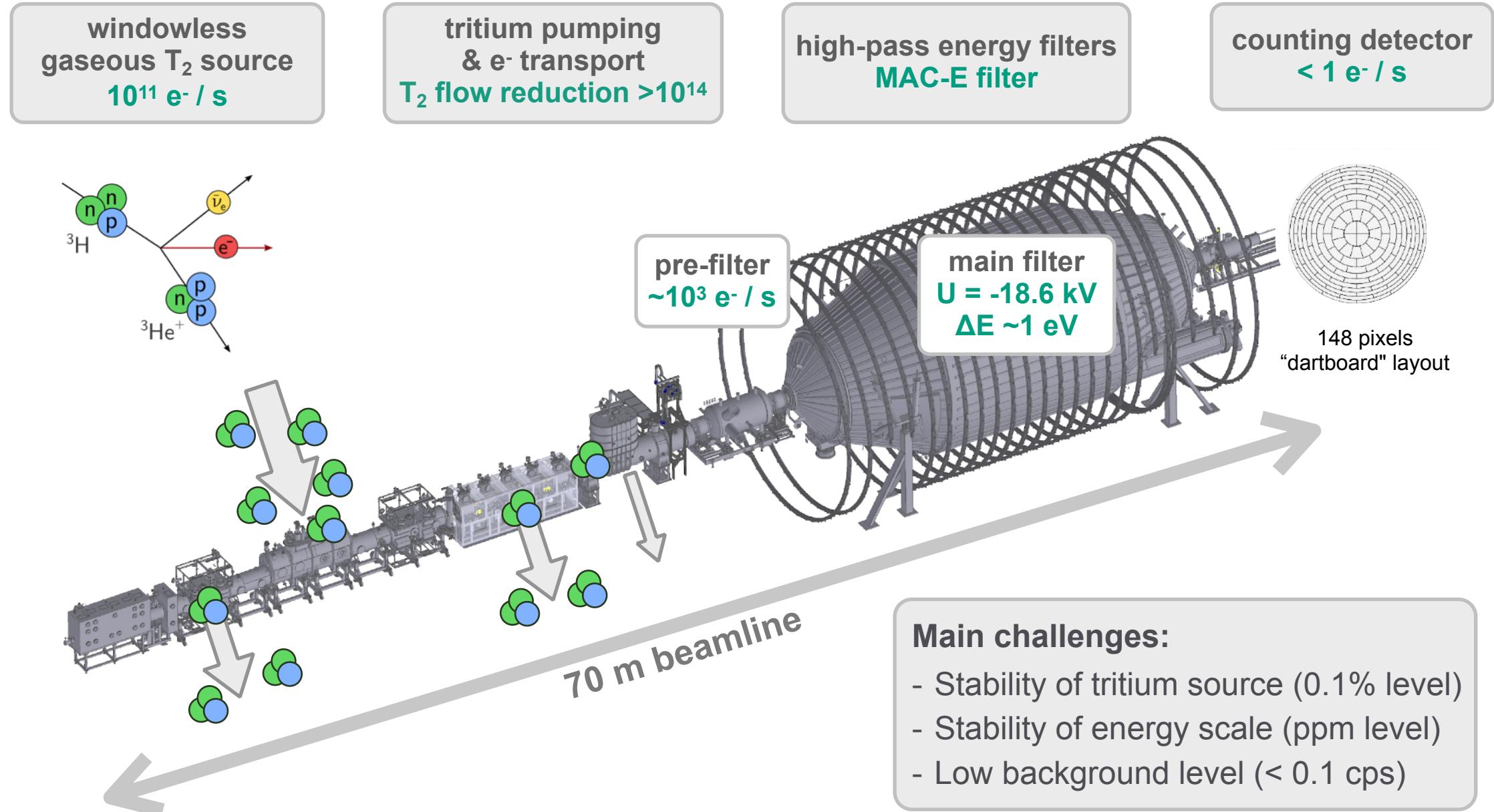


- Experimental site:
Karlsruhe Institute of Technology (KIT)
- International collaboration:
~150 members from 20 institutions
in 6 countries (D, US, CZ, RU, F, ES)
- Goal: Improve sensitivity on $m(\nu_e)$
from 2 eV (previous experiments) to 0.2 eV (90% CL) within 2019-2024

katrin.kit.edu

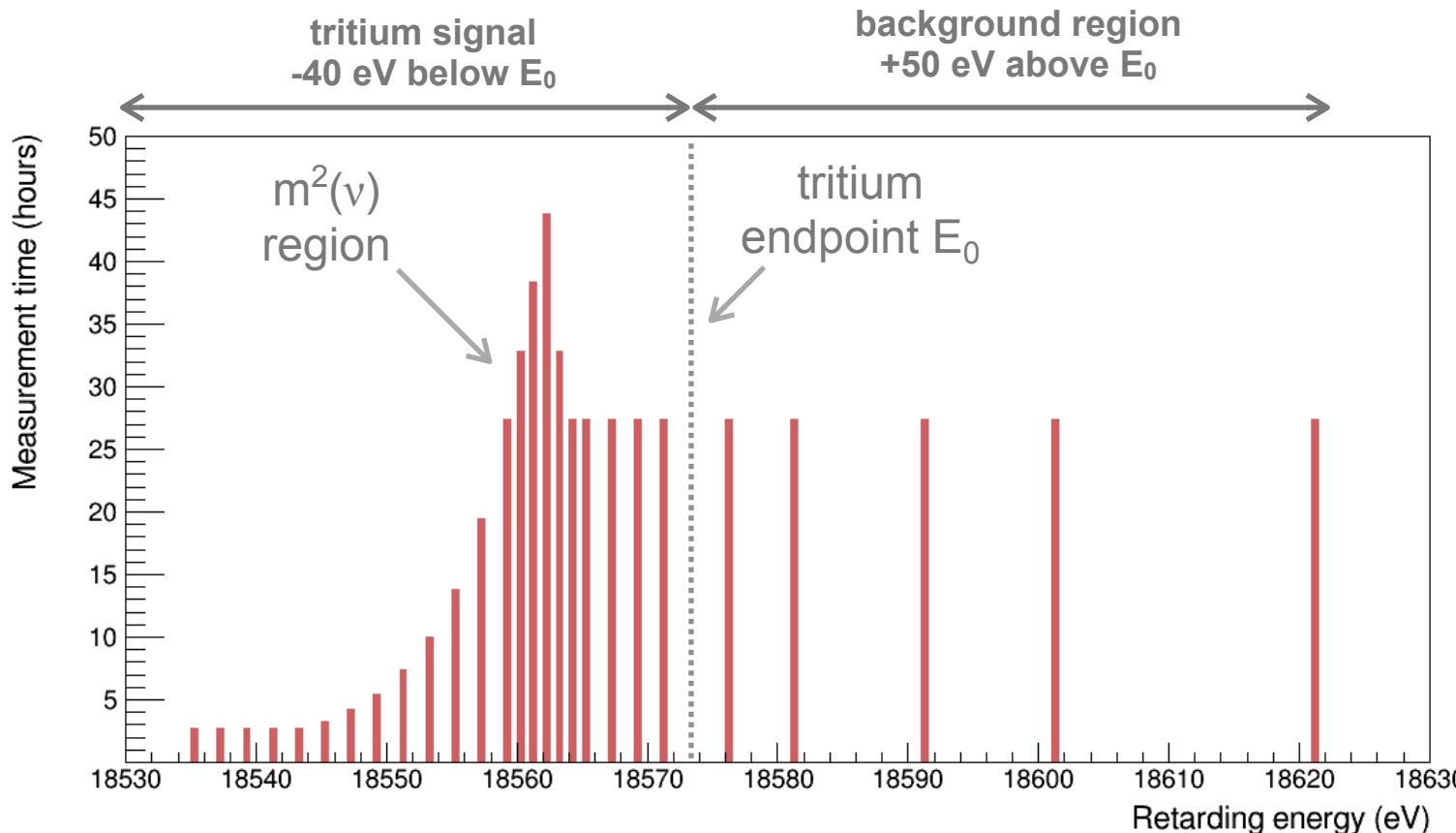


Working principle of KATRIN



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



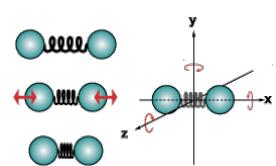
- Ca. 30 high-voltage steps in each scan
- Different regions for four fit parameters: $m^2(v)$, endpoint E_0 , norm. **A**, background **B**
- Distribution optimized for $m^2(v)$ sensitivity
- Ca. 25% of time spent on background

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

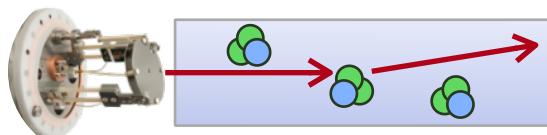


Magnetic fields

- source
- spectrometer
- detector



Energy loss by scattering

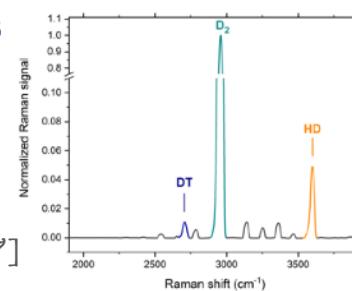


[EPJ C**81** (2021) 579]

Activity fluctuations

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

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



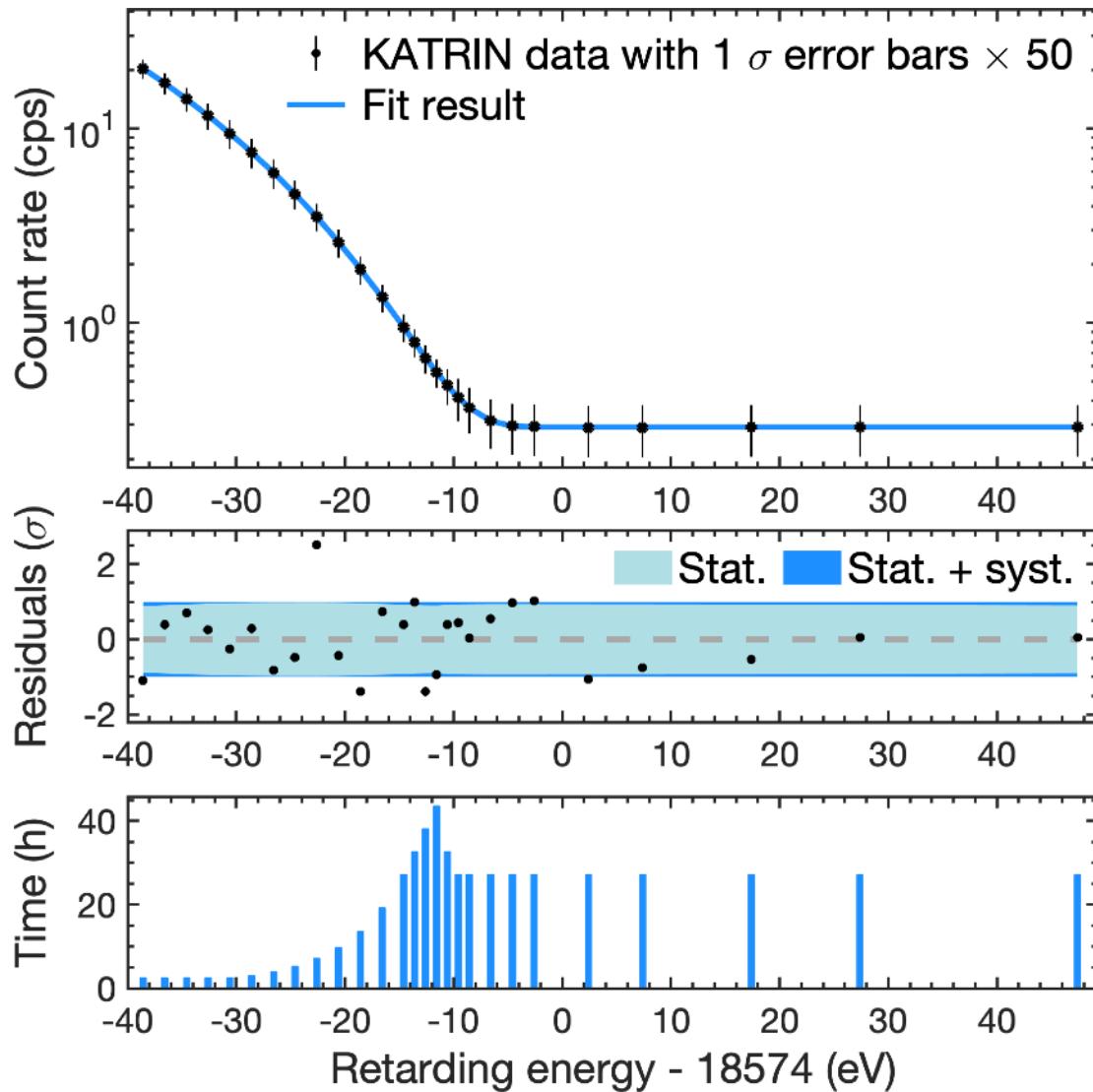
Background

- 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

First neutrino mass result



Spectrum data available on KATRIN web page

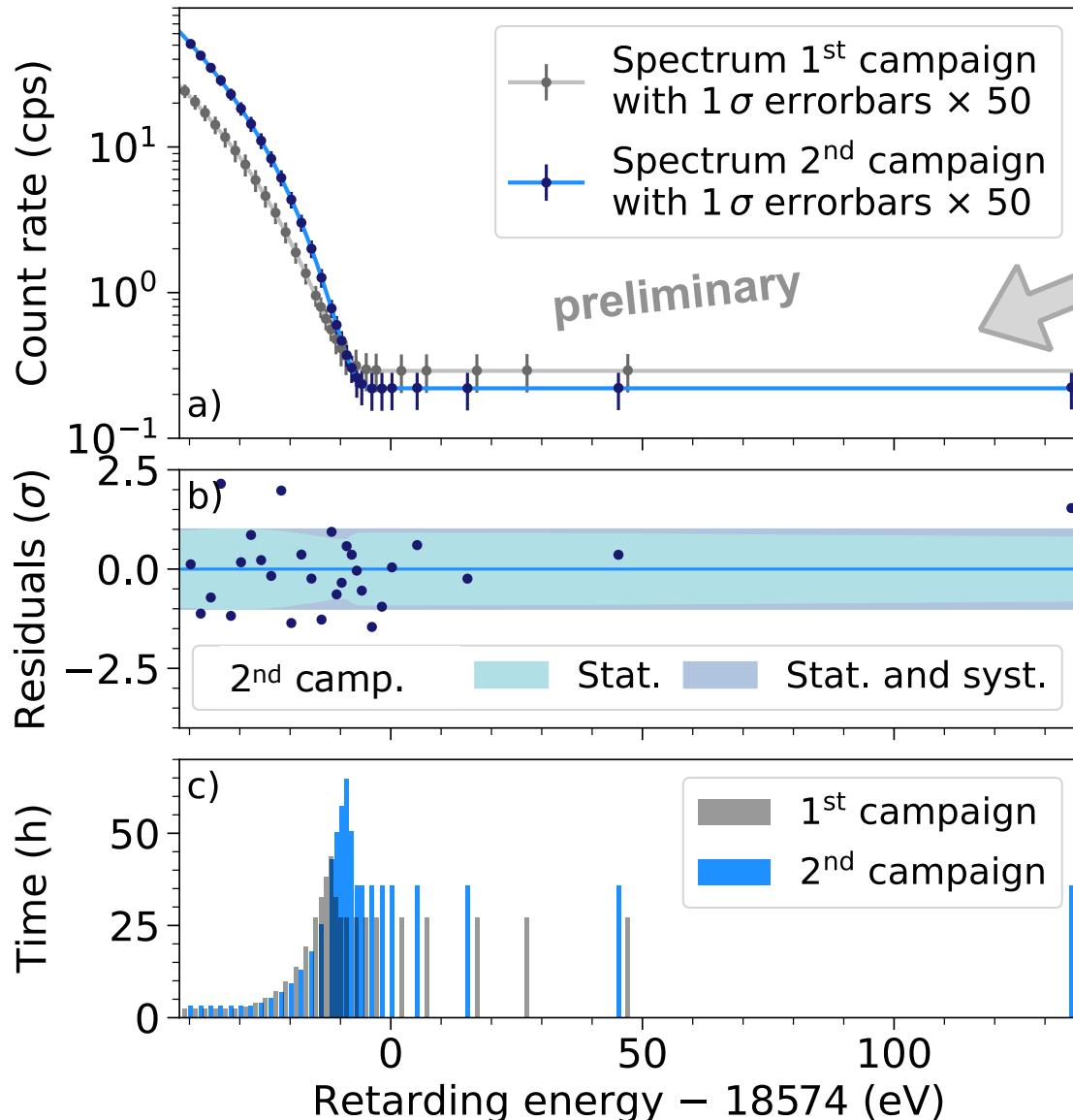
- Four-week campaign at reduced source strength (“burn-in phase”)
- 9 days of nominal KATRIN only
- Improvement over prev. experiments:
 $\sigma_{\text{stat}} = 0.97 \text{ eV}^2 \rightarrow \text{factor 2}$
 $\sigma_{\text{syst}} = 0.32 \text{ eV}^2 \rightarrow \text{factor 6}$
- Best-fit value:
$$m_\nu^2 = (-1.0^{+0.9}_{-1.1}) \text{ eV}^2$$
- Upper limit: $m_\nu < 1.1 \text{ eV}$ (90% CL)

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

KATRIN data from first two campaigns

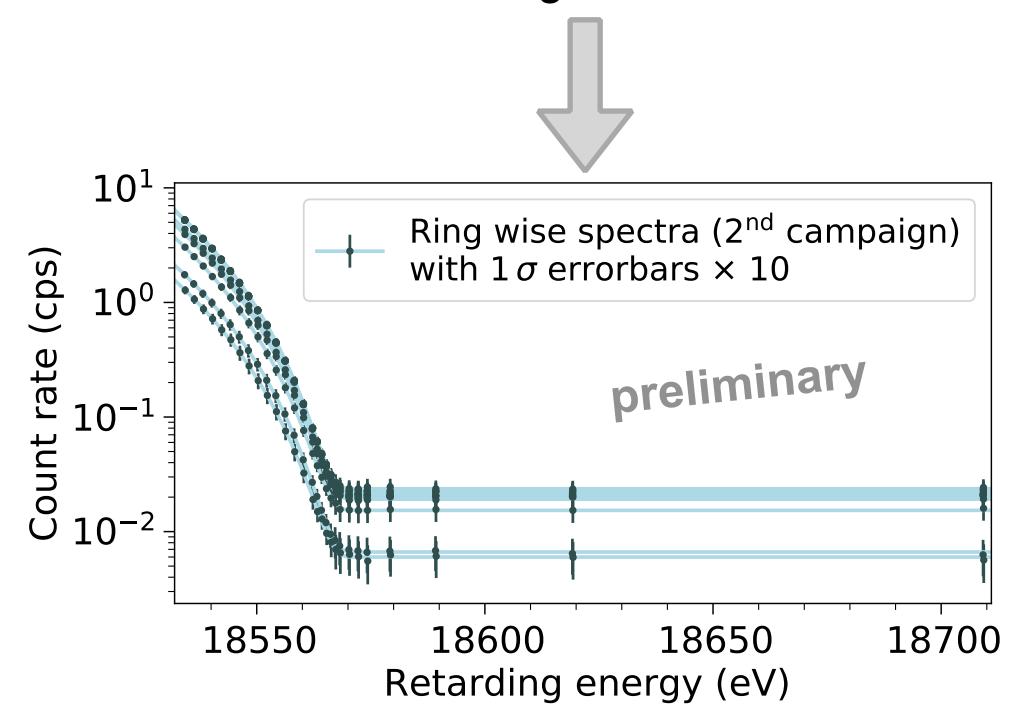
	<i>1st campaign</i> <i>PRL 123 (2019)</i>	<i>2nd campaign</i> <i>This talk</i>
Campaign date	April-May 2019	Sept-Nov 2019
Total scan time	522 h (274 scans)	744 h (361 scans)
Background	290 mcps	 reduction -25% → 220 mcps
Source activity	25 GBq	 nominal activity → 98 GBq
Tritium purity	97.6%	 raised purity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

Data from the 2nd campaign



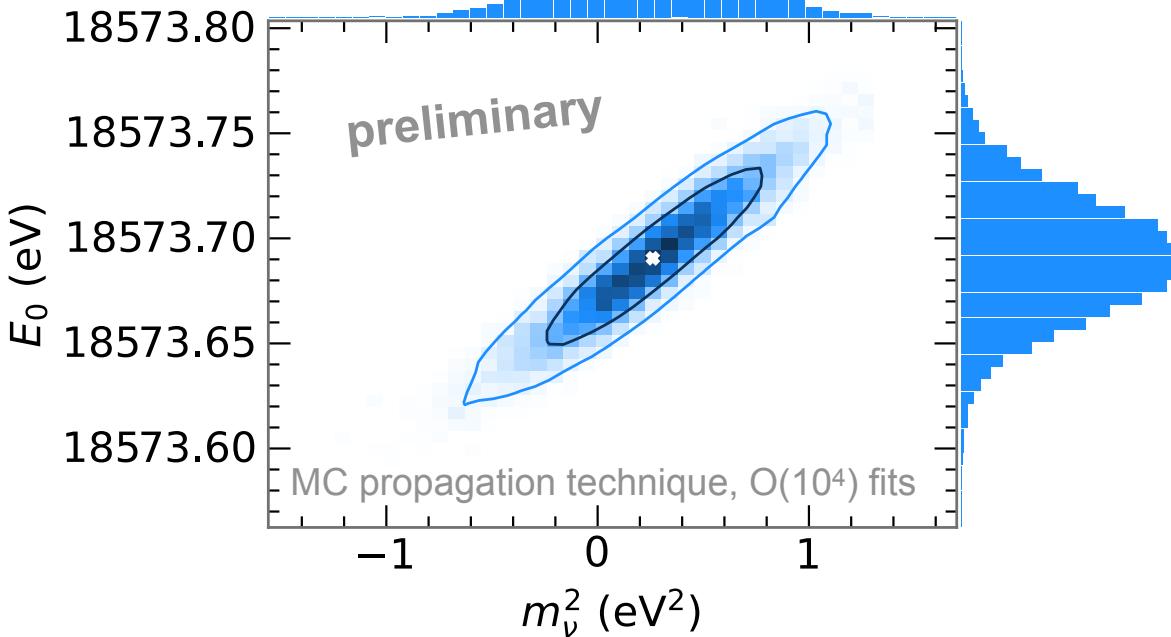
- Improved ratio of source activity to background from 1st campaign to 2nd campaign
- Overall improvement of statistics

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

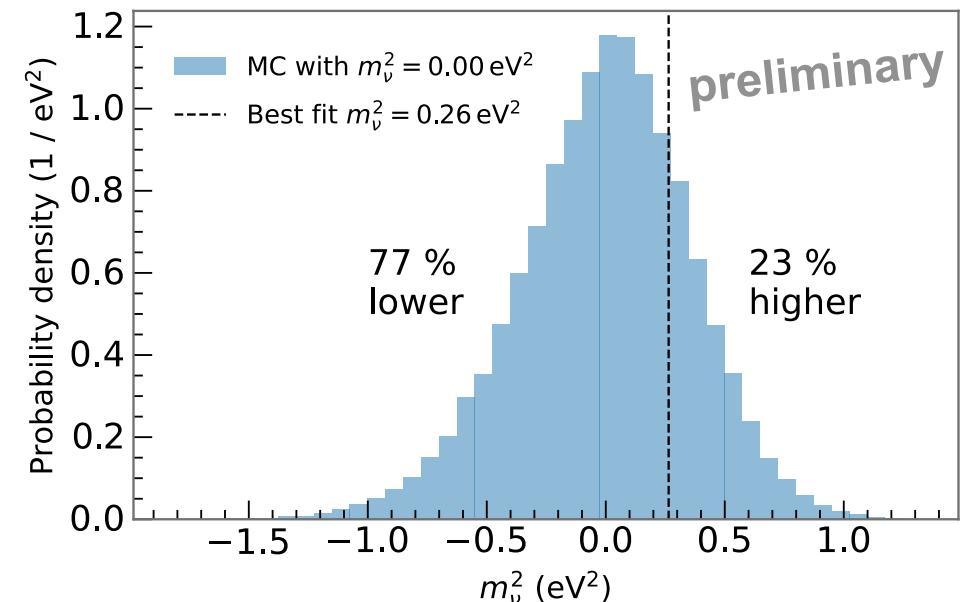


Neutrino-mass result for 2nd campaign

- Ring-wise fit with common $m^2(\nu)$, 12 x ring-dependent E_0 , background, normalization
- Best-fit value (stat. and syst.): $m^2(\nu) = 0.26 \pm 0.34 \text{ eV}^2$



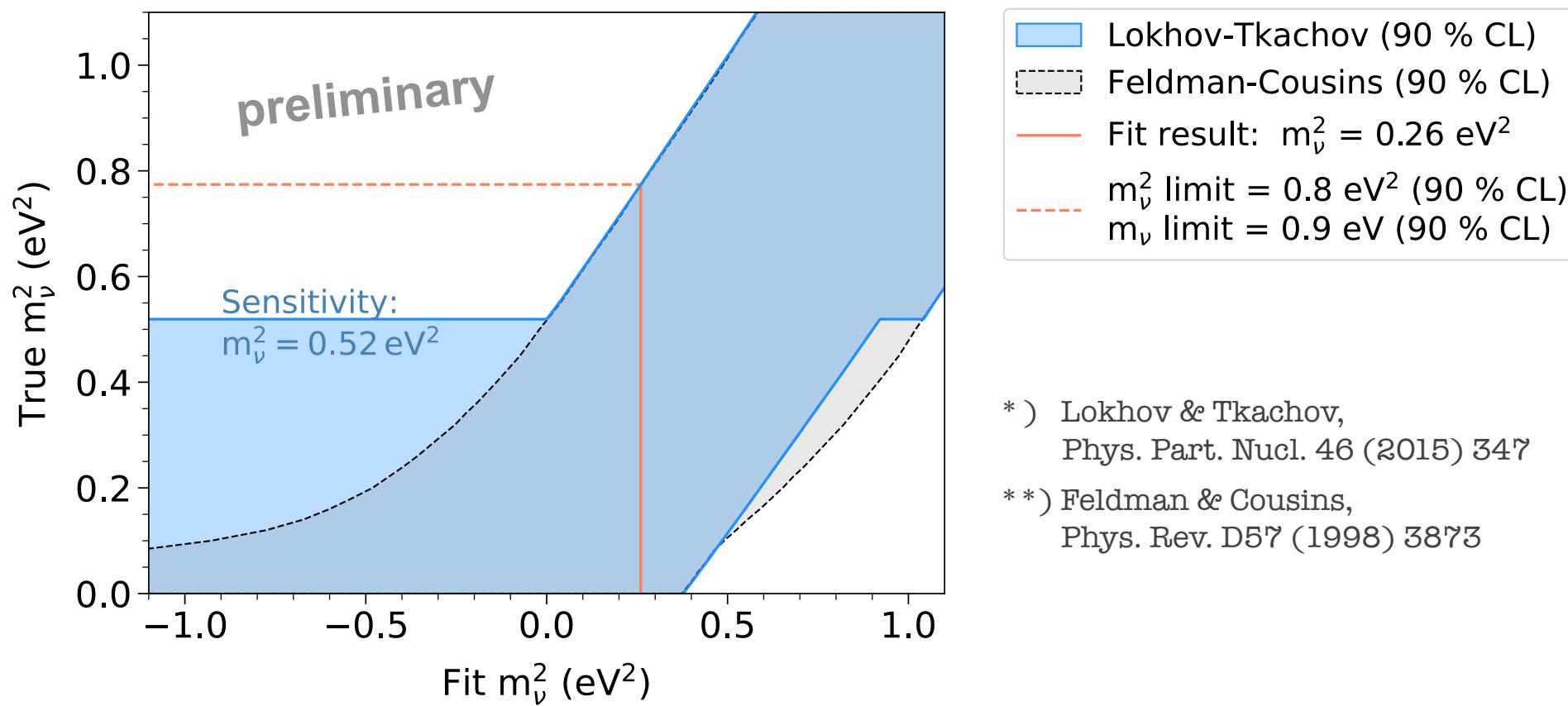
Fully compatible with expectation for $m^2(\nu) = 0$



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

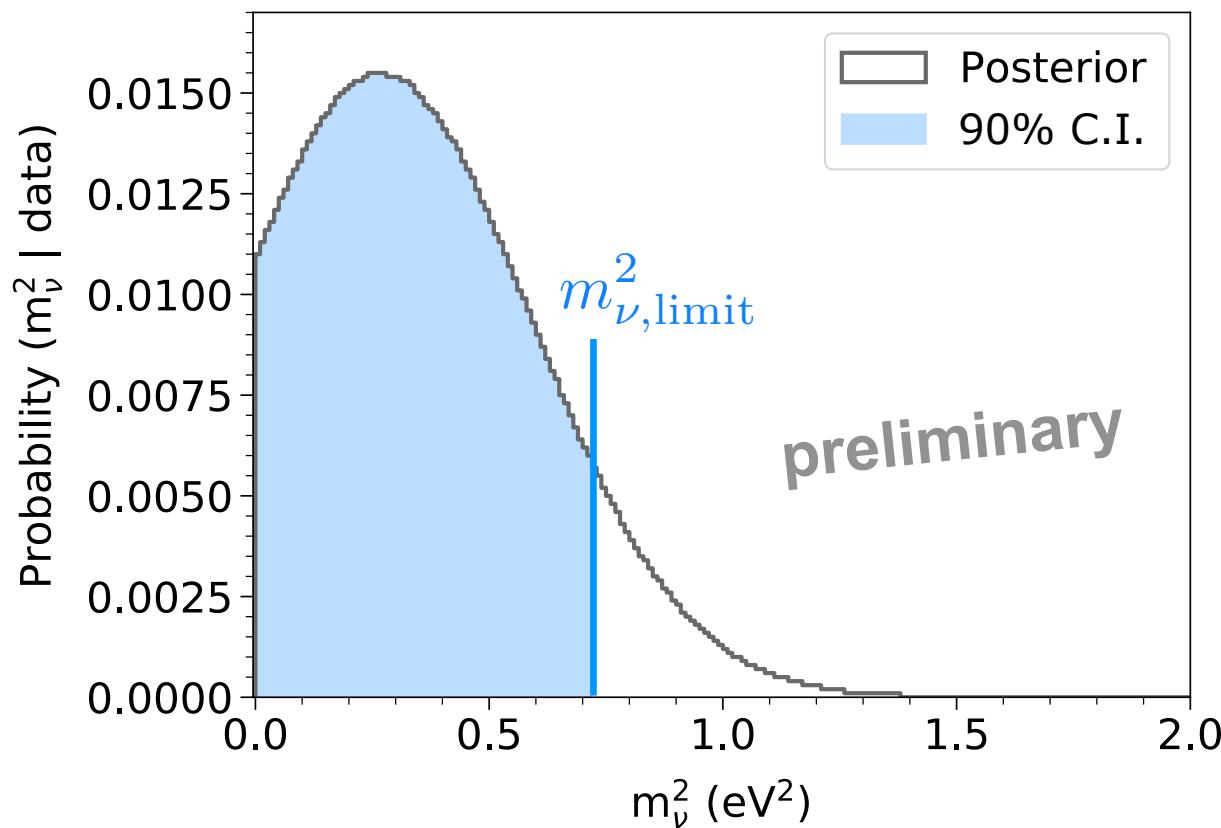
Neutrino-mass result for 2nd campaign

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



Neutrino-mass result for 2nd campaign

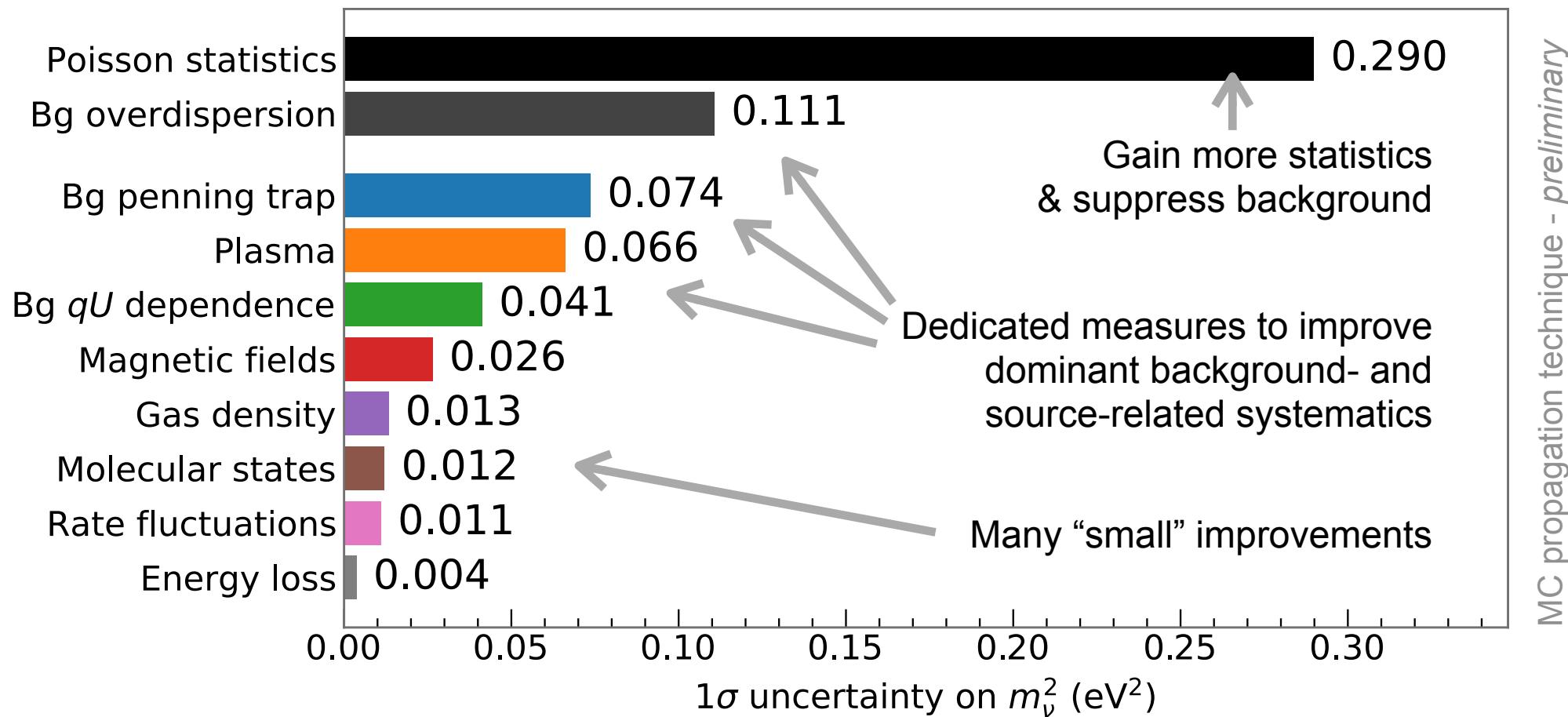
- Alternative analysis approach: Bayesian inference
- Using flat positive prior on m_ν^2
- Bayesian bound obtained by integrating posterior distribution from 0 to $m_{\nu,\text{limit}}^2$, gives $m(\nu) < 0.85 \text{ eV}$ for a 90% credible interval



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

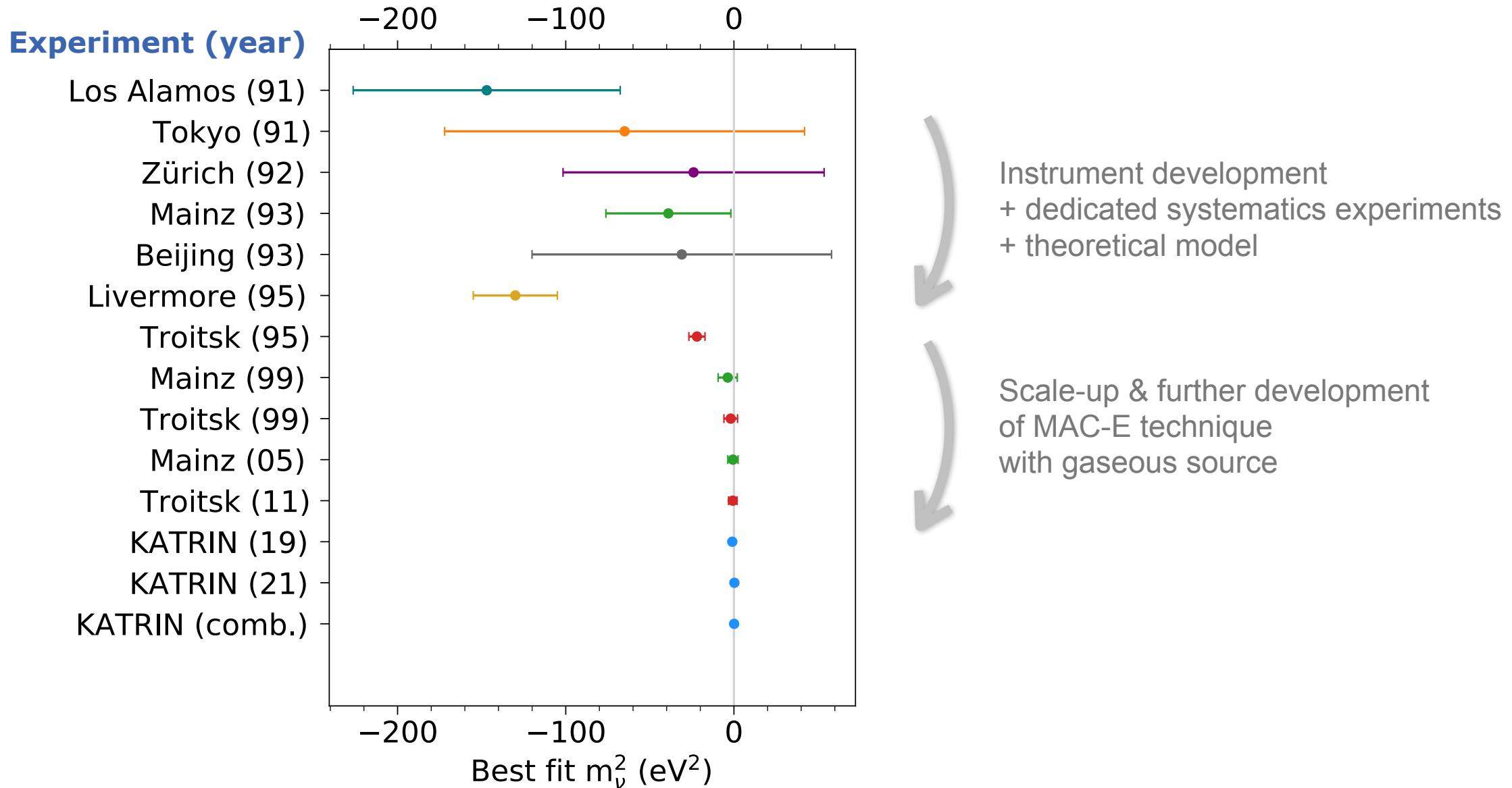
Systematic uncertainties

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

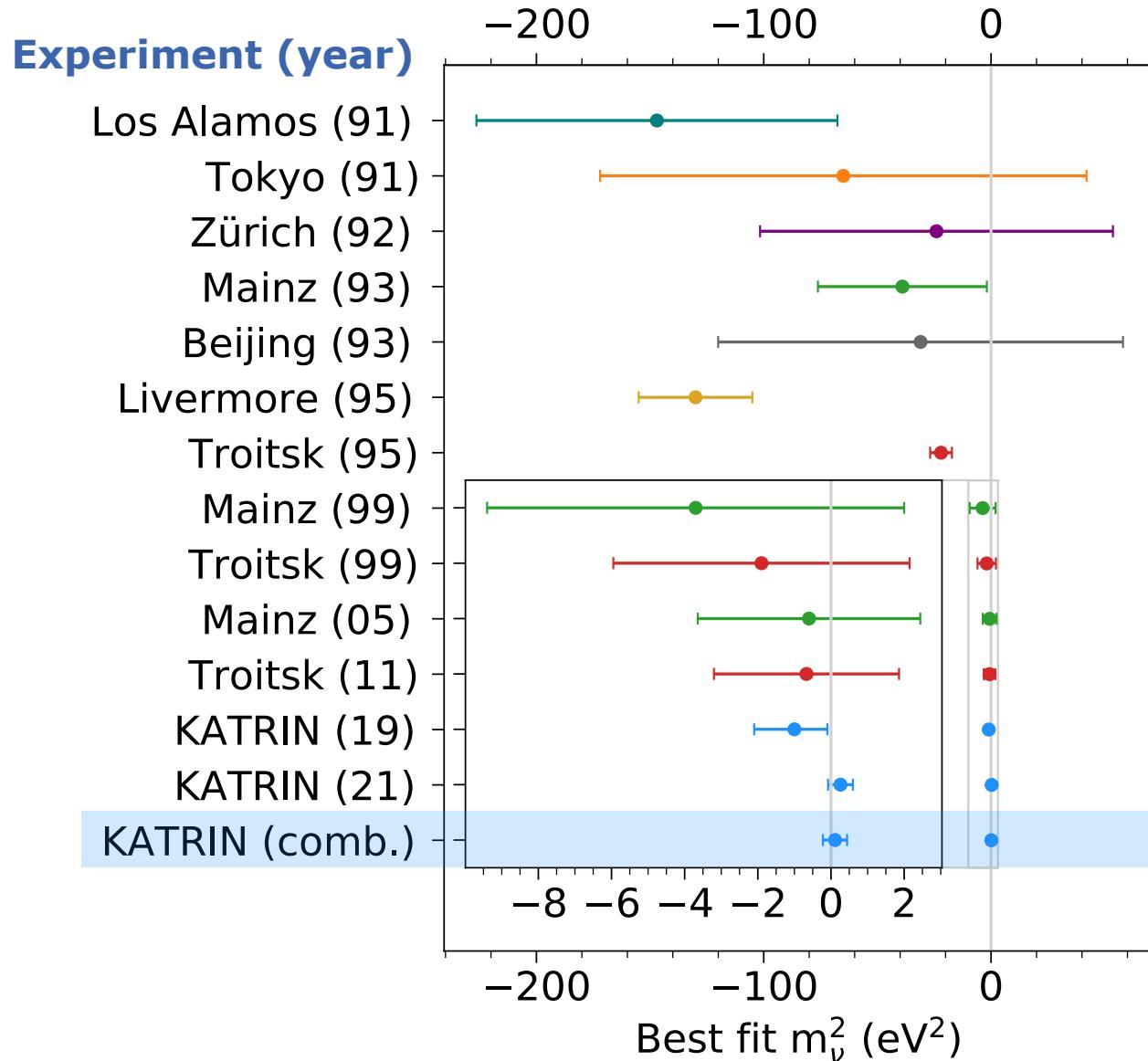


→ Substantial improvements already from 3rd campaign onwards.

30-year retrospective on tritium experiments



30-year retrospective on tritium experiments



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

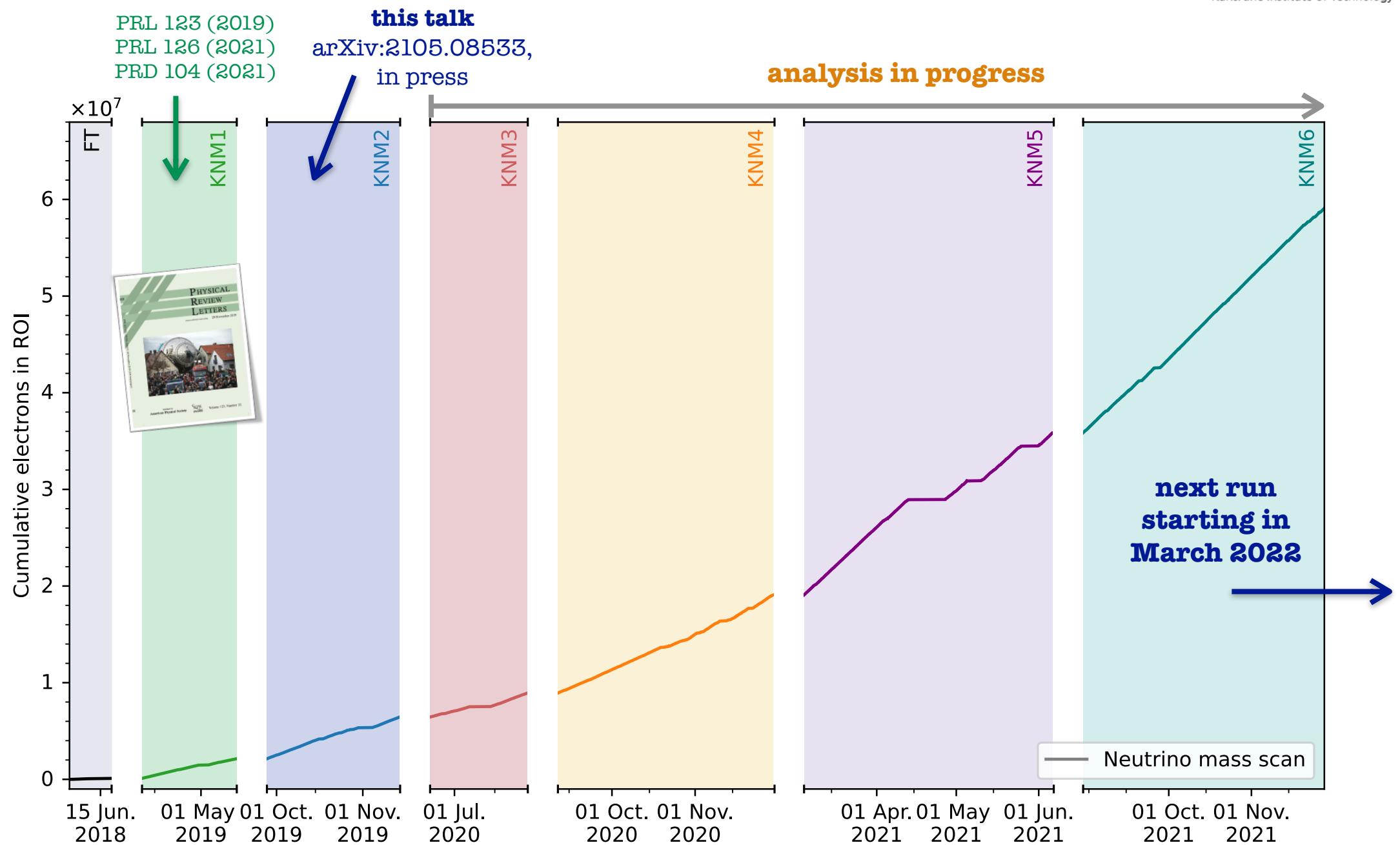
Combined limit: $m_{\nu} < 0.8 \text{ eV}$ (90% CL)

Progress of data-taking

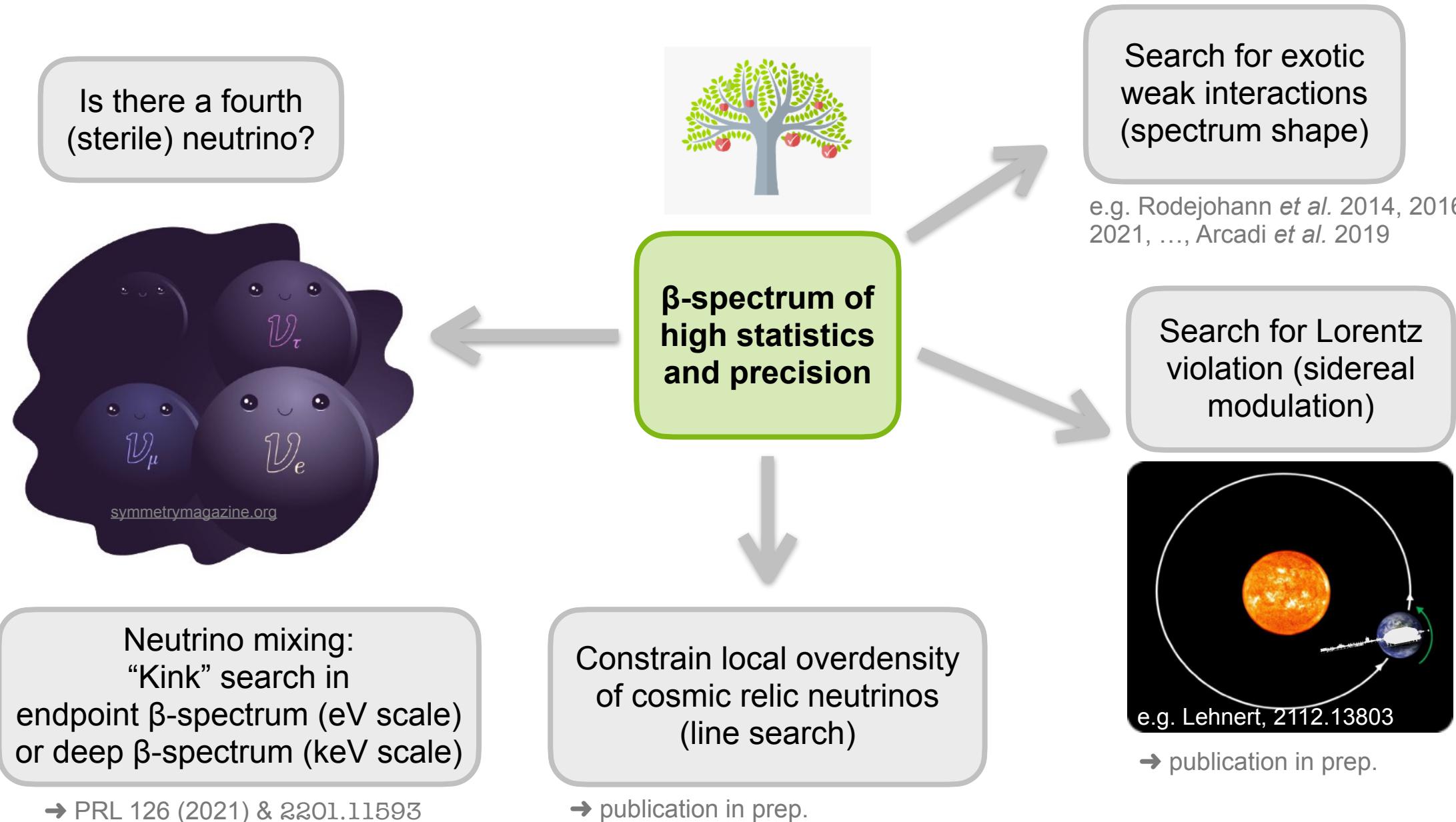
Six measurement campaigns (+ extensive calibration phase) since the start of the pandemic, carried out under all necessary precautions



Progress of data-taking



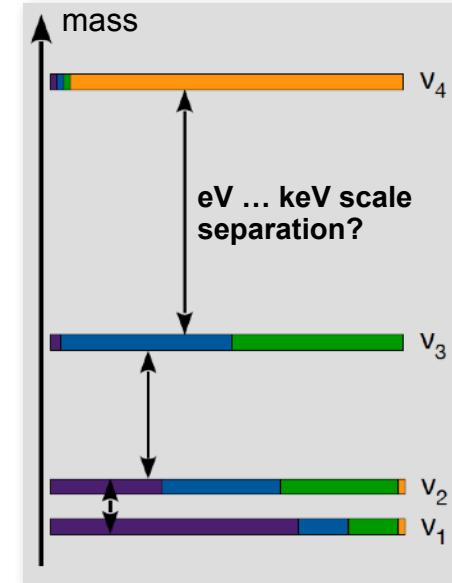
Physics “beyond the neutrino mass” with KATRIN



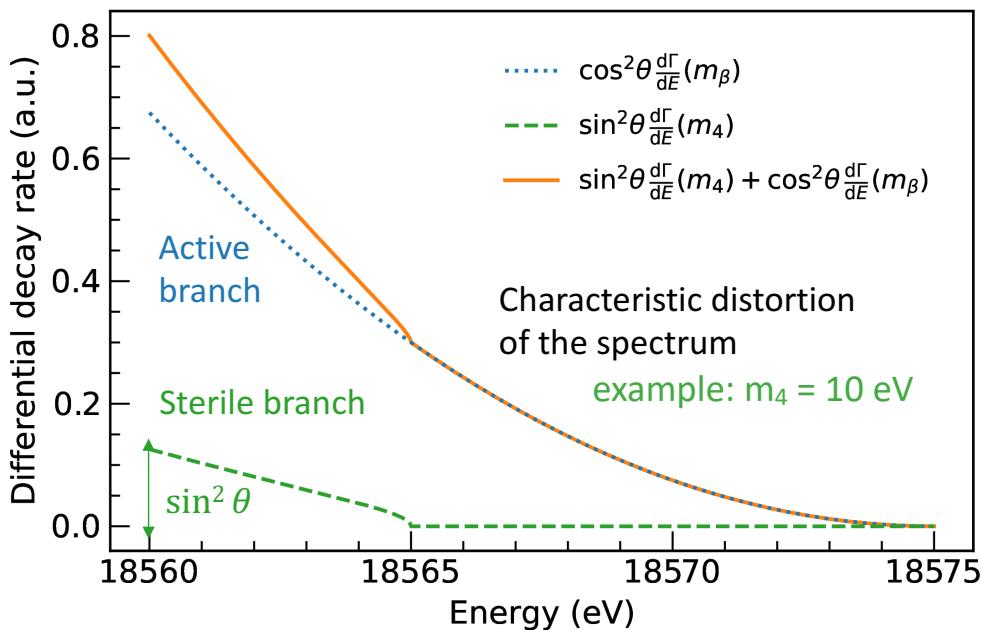
Physics reach of KATRIN: search for extra neutrino states

$$\frac{d\Gamma}{dE} = \cos^2(\theta_s) \frac{d\Gamma}{dE}(m_\beta^2) + \boxed{\sin^2(\theta_s) \frac{d\Gamma}{dE}(m_s^2)}$$

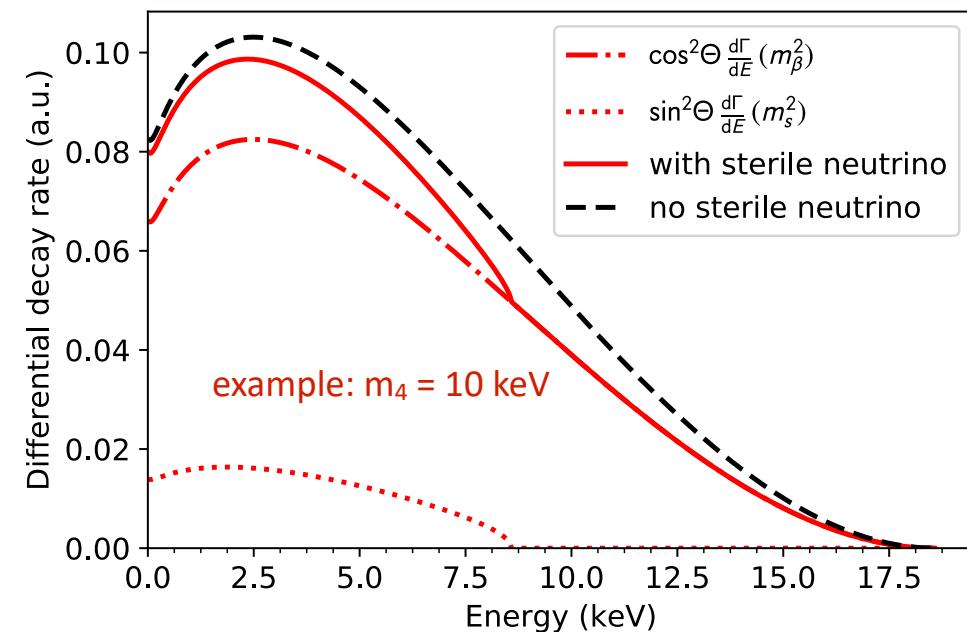
Neutrinos mix: generate “kink” in β spectrum at $E = E_0 - m_s$



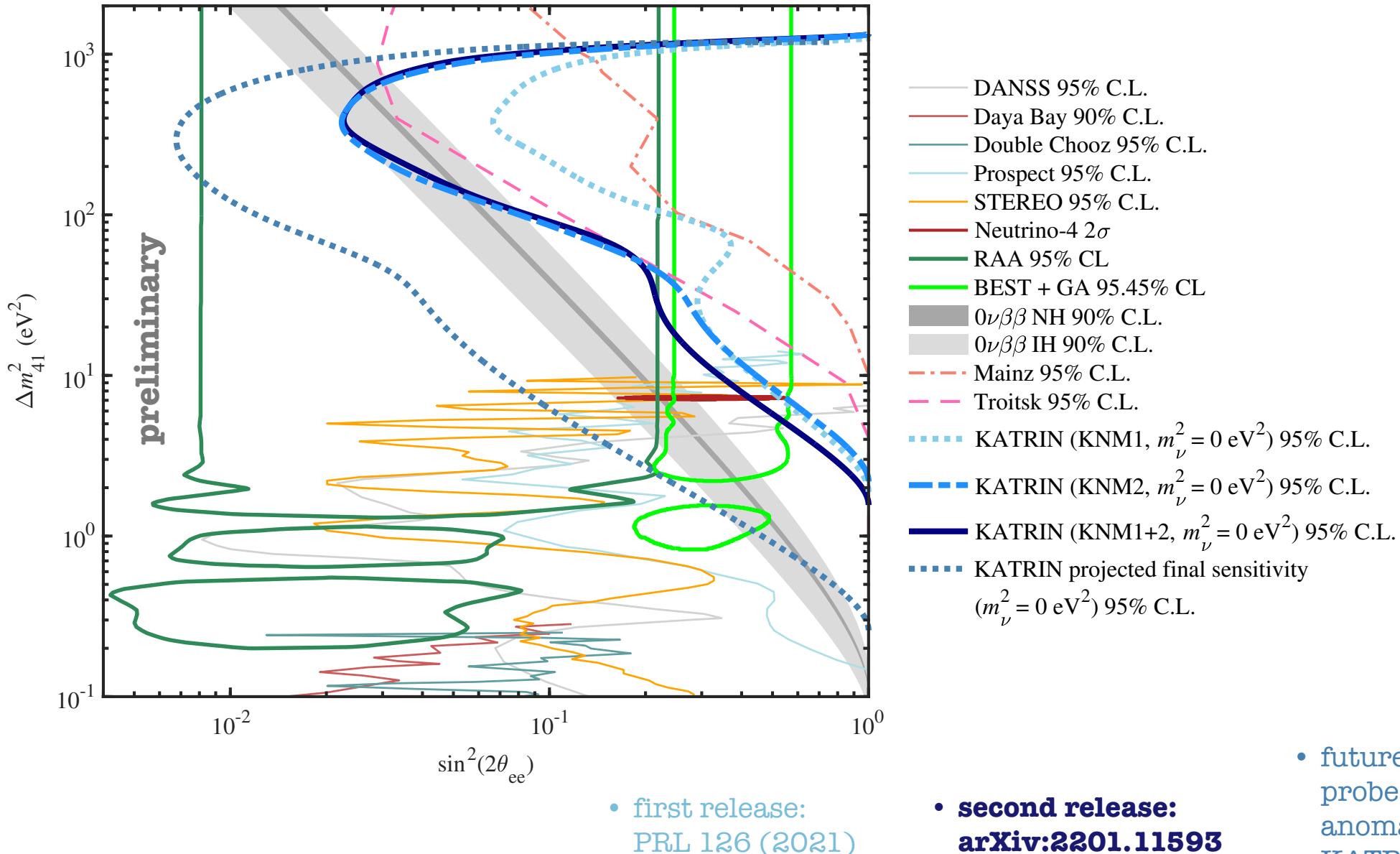
light sterile ν , $m_s \sim$ few eV
motivated by oscillation anomalies



heavy sterile ν , $m_s \sim$ few keV
motivated as DM candidate



Search for sterile neutrinos at the eV scale



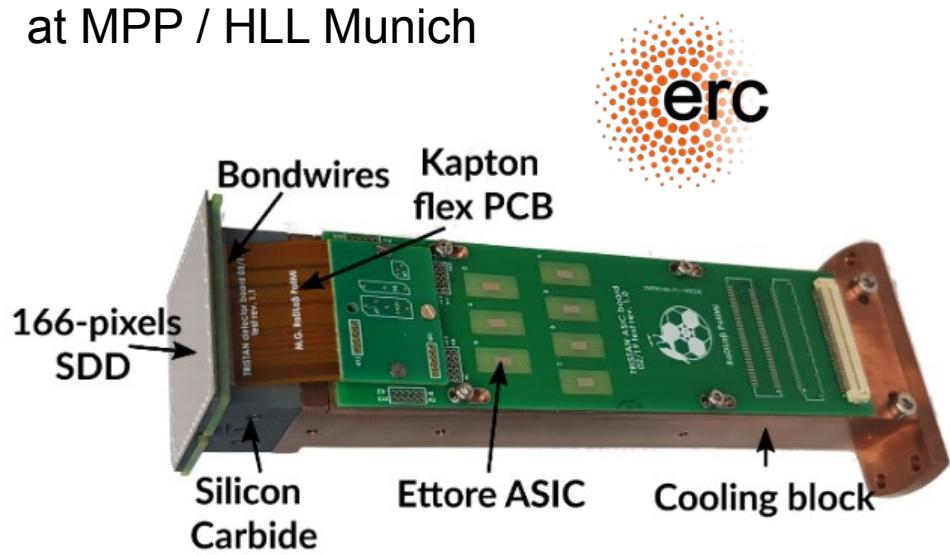
Prospects for keV sterile neutrino search

- 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

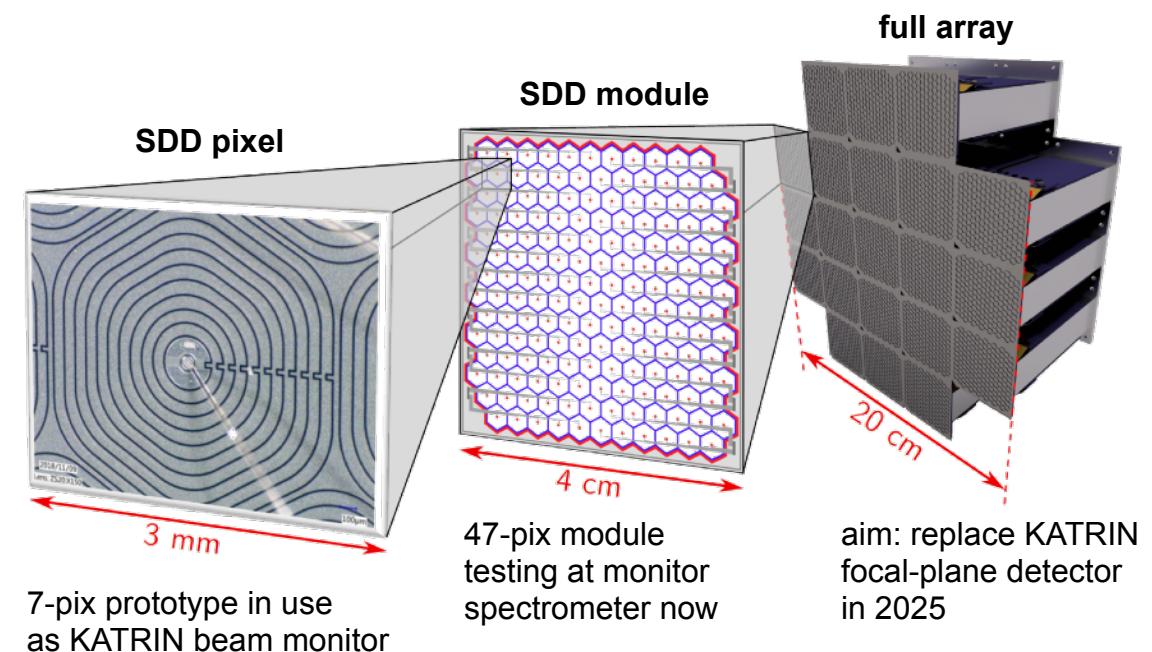
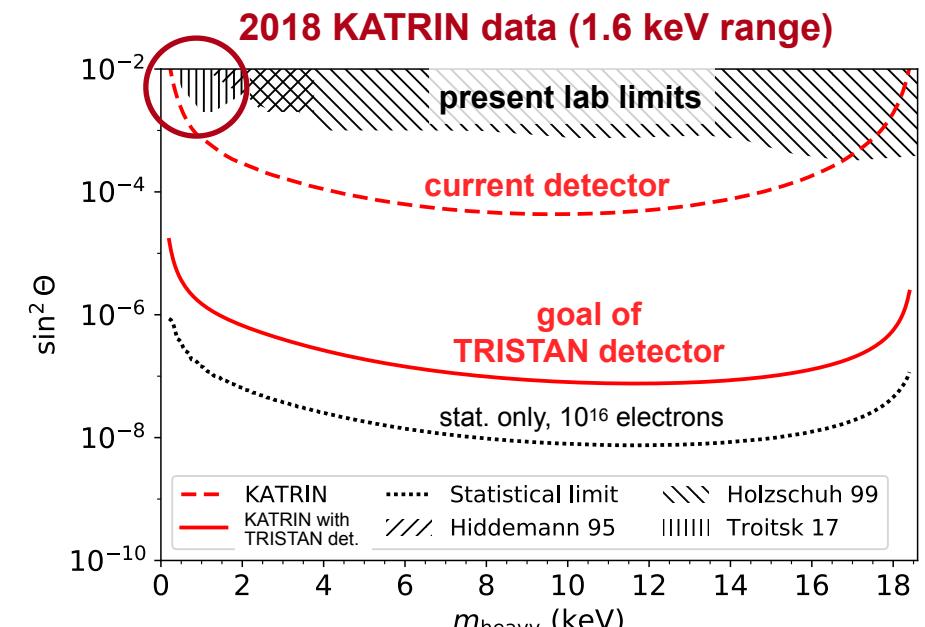


TRISTAN detector for KATRIN:

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

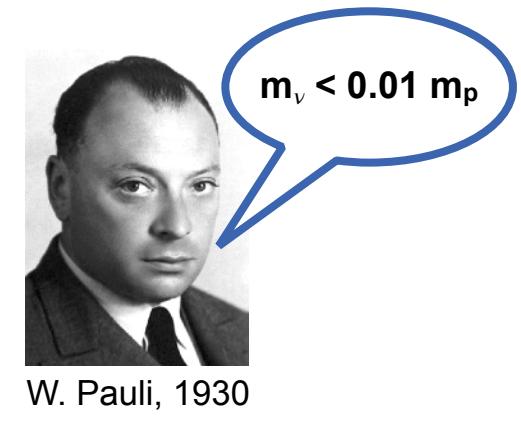


[J. Phys. G**46** (2019) 065203 & G**48** (2020) 1]

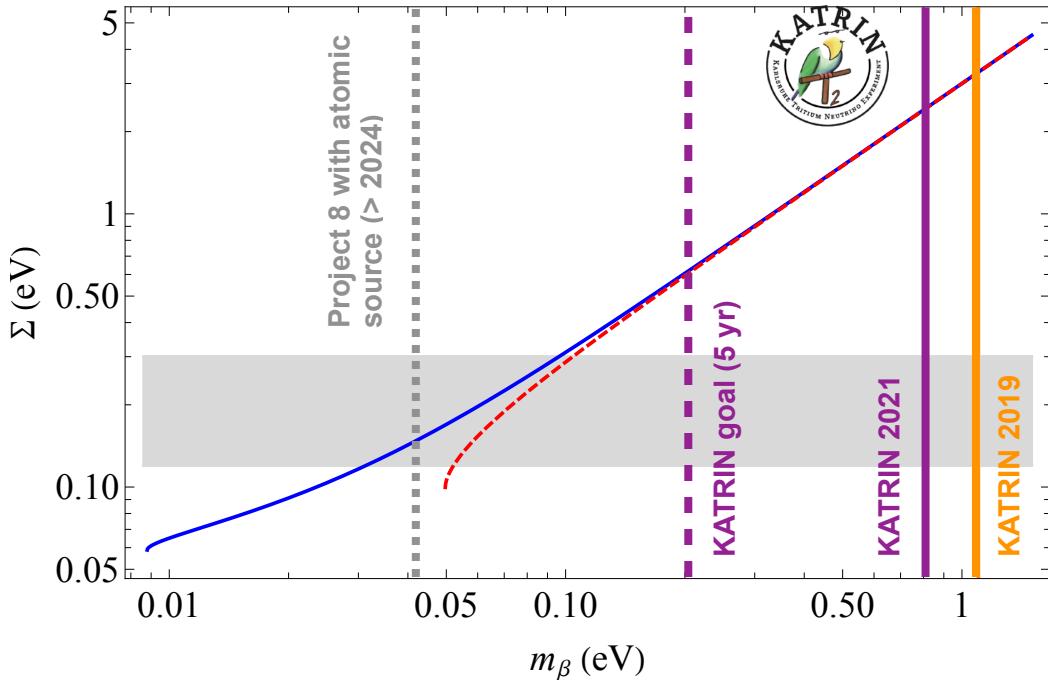


Summary and Outlook

- 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 $0\nu\beta\beta$, and *direct kinematics*
- First sub-eV result** from KATRIN:
 $m(\nu) < 0.8 \text{ eV (90% CL)}$ 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!