Latest Results from KATRIN and Neutrino Mass

CIPANP2022, Orlando
August 29th 2022

KATRIN
Karlsruhe Tritium Neutrino Experiment

BERKELEY LAB

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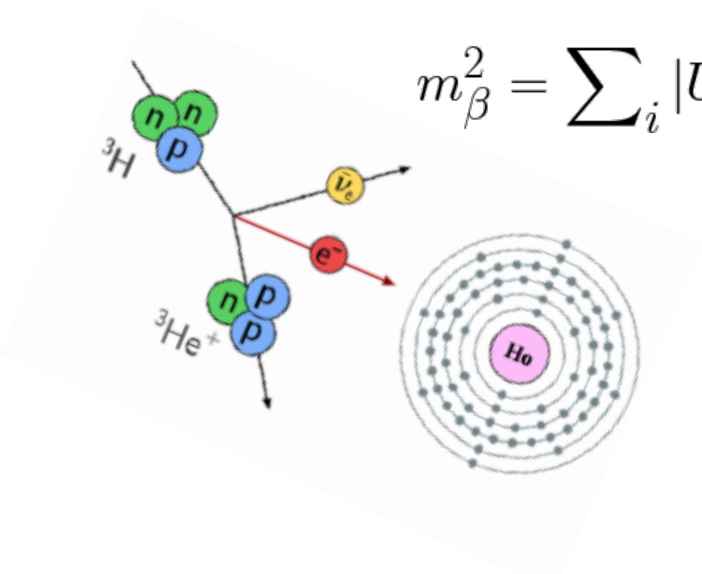
Neutrino mass observables

Complementary paths to the neutrino mass scale

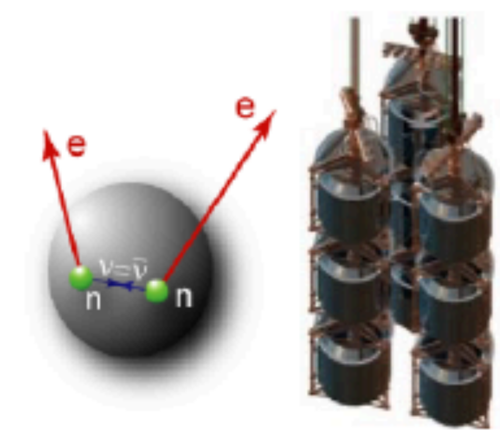
β-decay: absolute ν-mass
model independent, kinematics

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$



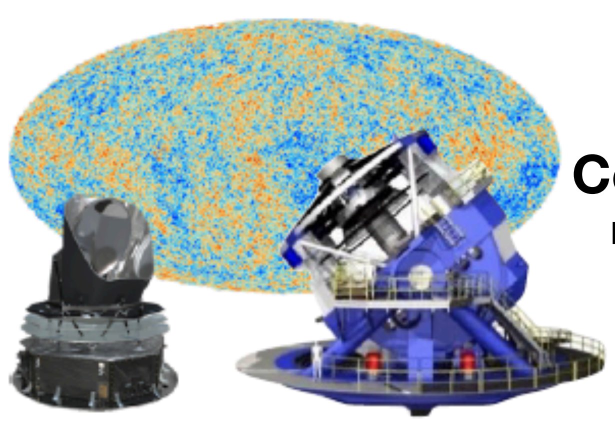
0νββ-decay: eff. Majorana mass
model-dependent (CP Phases)

$$m_{\beta\beta}^2 = \left|\sum_i U_{ei}^2 m_i\right|^2$$



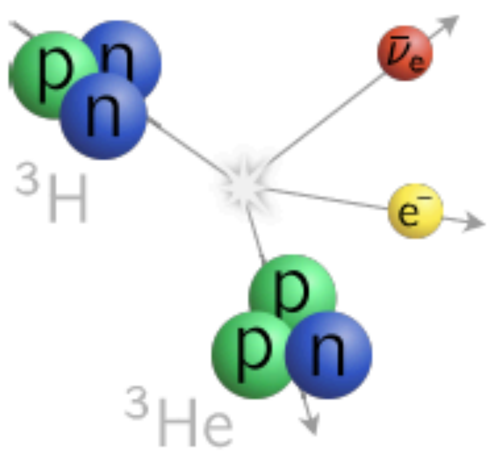
Neutrino mass measurement

$$M_\nu = \sum_i m_i$$



Cosmology: ν hot dark matter Ω_ν
model dependent, analysis of CMB and
structure formation data

Neutrino mass from β-decay kinematics



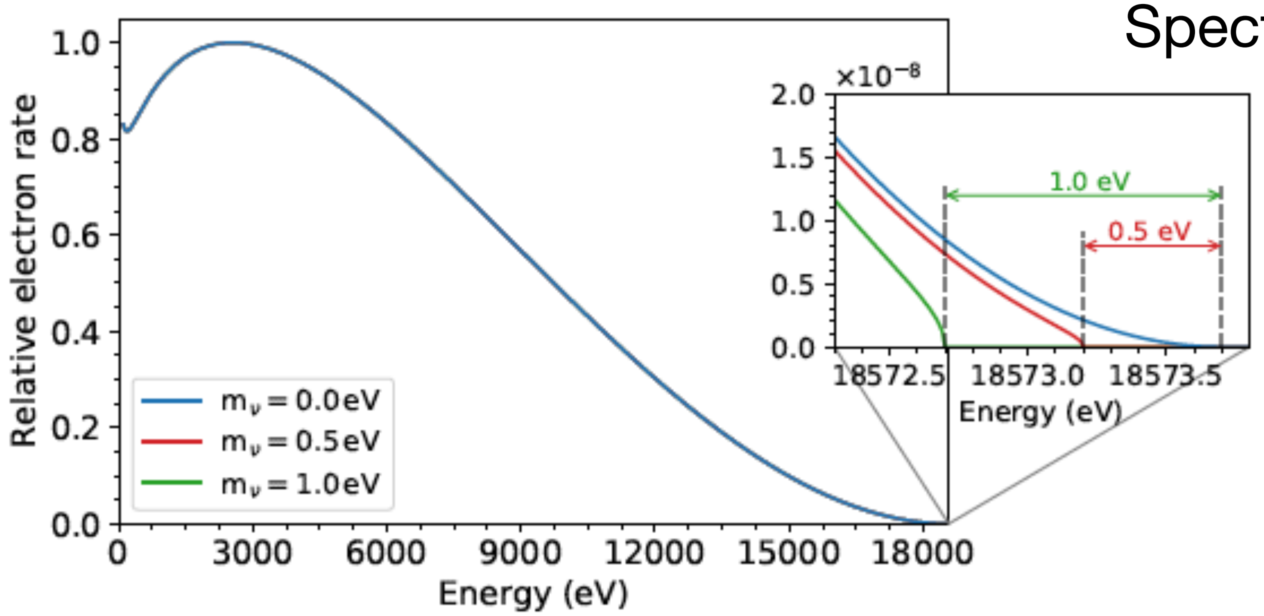
$T_2 \longrightarrow He^+ + e^- + \bar{\nu}_e$

β-decay: $n \rightarrow p + e^- + \bar{\nu}_e$

- Neutrino mass influences energy spectrum of β-decay electrons
- Neutrino mass determination via precise measurement of the spectral shape close to the endpoint
- Model independent method

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

Fermi's phase space for β-decay



Spectral distortion measures effective mass square

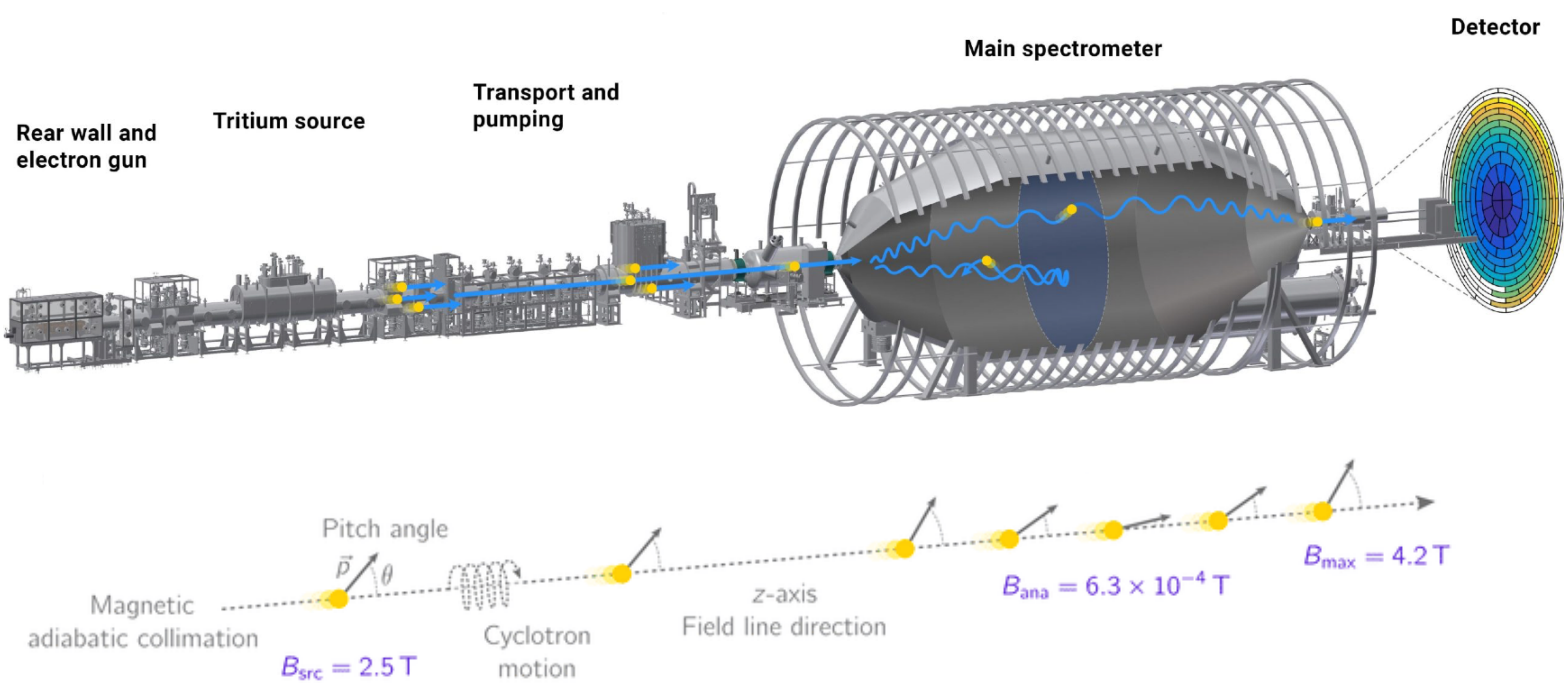
Observable $m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$

Experimental Challenge

- Convenient isotope: half-life, Q-value
  - Low endpoint energy: E_0 = 18.6 keV for ^{3}H
  - High-activity source: $t_{1/2}$ = 12.3 yr for ^{3}H
- High resolution ~ 1 eV
- Low background

KATRIN working principle

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 Mcps during calib runs**



Main challenges:
- Stability of tritium source
- Stability of energy scale
- Low background level

Full system description & commissioning paper: 2103.04755

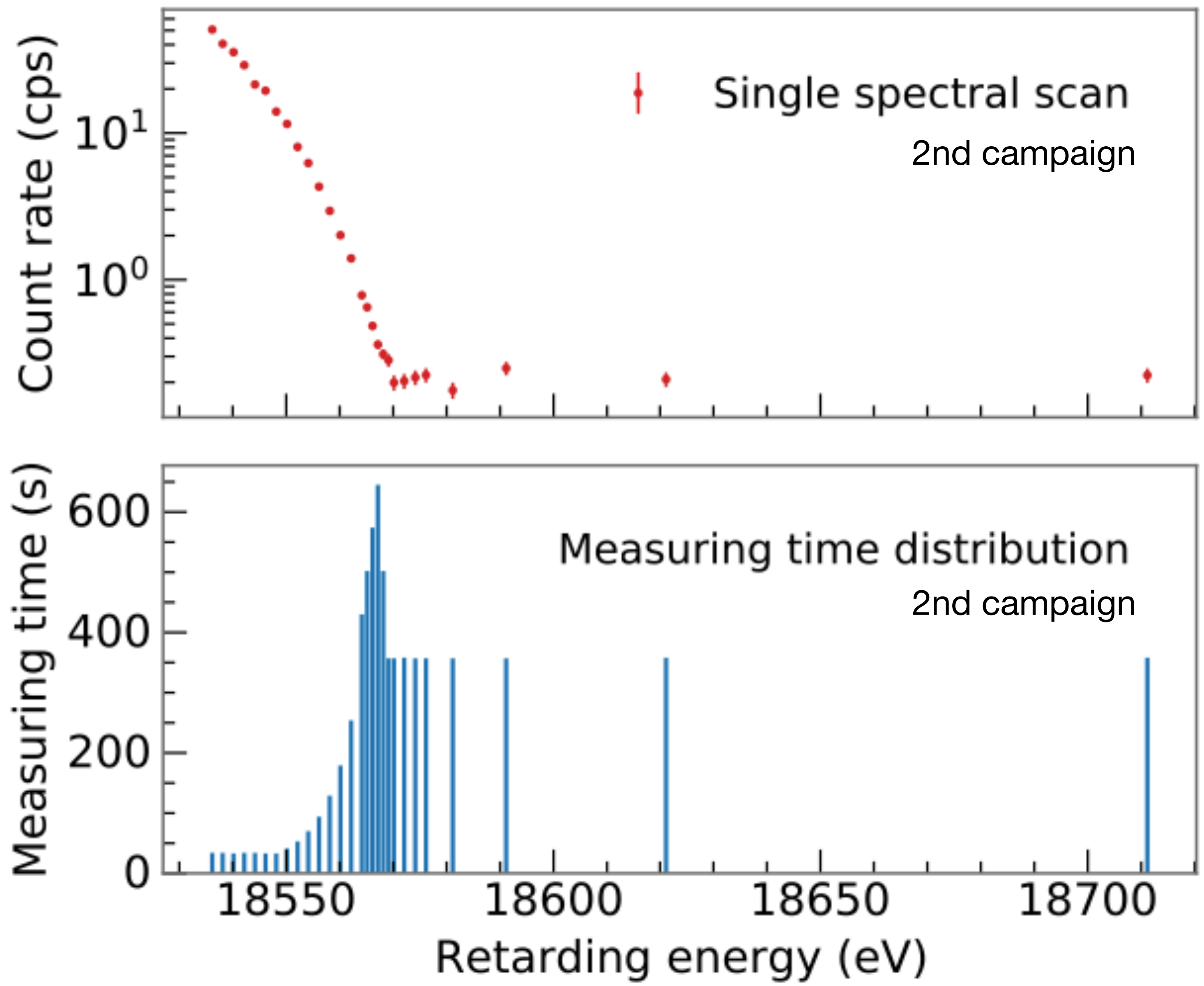
KArlsruhe TRItium Neutrino Experiment

Measurement principle

- Main spectrometer acts as high-pass filter that rejects low-energy electrons
- Set different retarding energies in the main spectrometer
- Count all electrons that pass the filter
- Integral measurement of the tritium β-spectrum

- 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
  - scanning randomly (alternating in direction)
  - scans different between campaigns



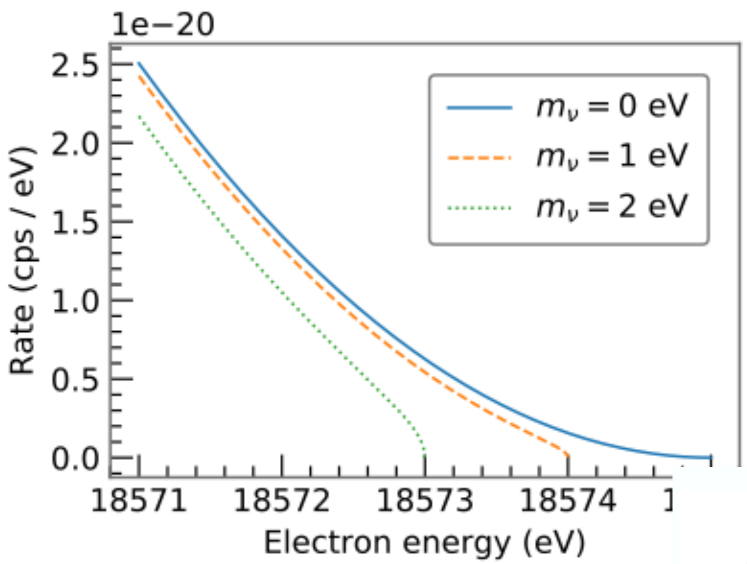
- Ca. 30 high-voltage steps in each scan
- Different regions for 4 fit parameters: **$m^2(\nu)$**, endpoint **E_0**, norm. **A**, background **B**
- Distribution optimized for $m^2(\nu)$ sensitivity - Ca. 25% of time spent on background

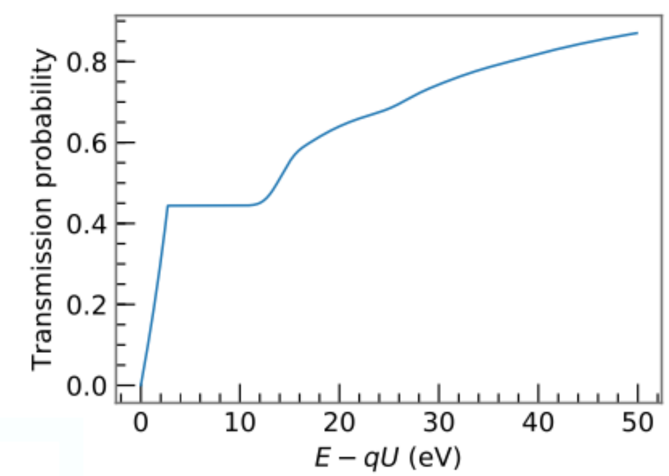
Tritium spectrum calculation

model →

- 4 parameter fit
- normalization (A), endpoint (E_0), constant background (R_{bg}), neutrino mass (m_β^2)

← data





Model of measured data

$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

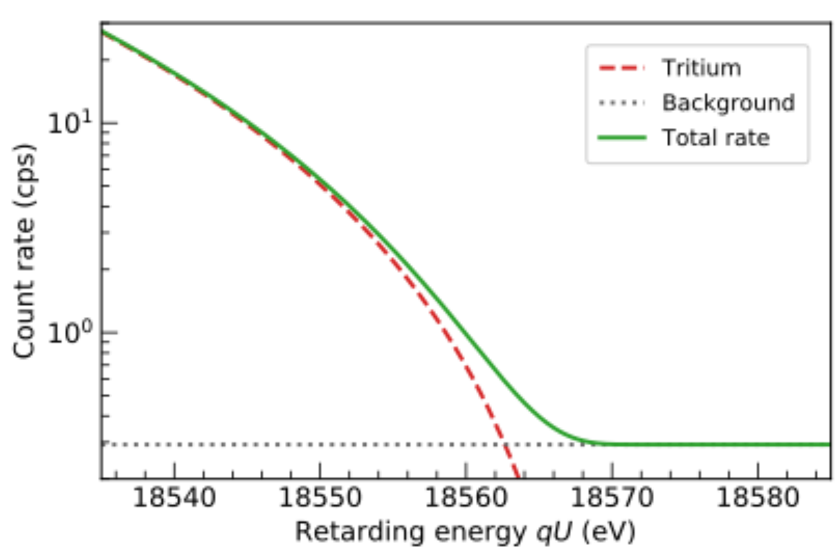
Differential β-spectrum

- Molecular final states
- Theoretical corrections
- Doppler broadening
- Neutrino mass

Experimental response

- MAC-E filter transmission
- Spectrometer resolution
- Energy loss by scattering
- Synchrotron radiation

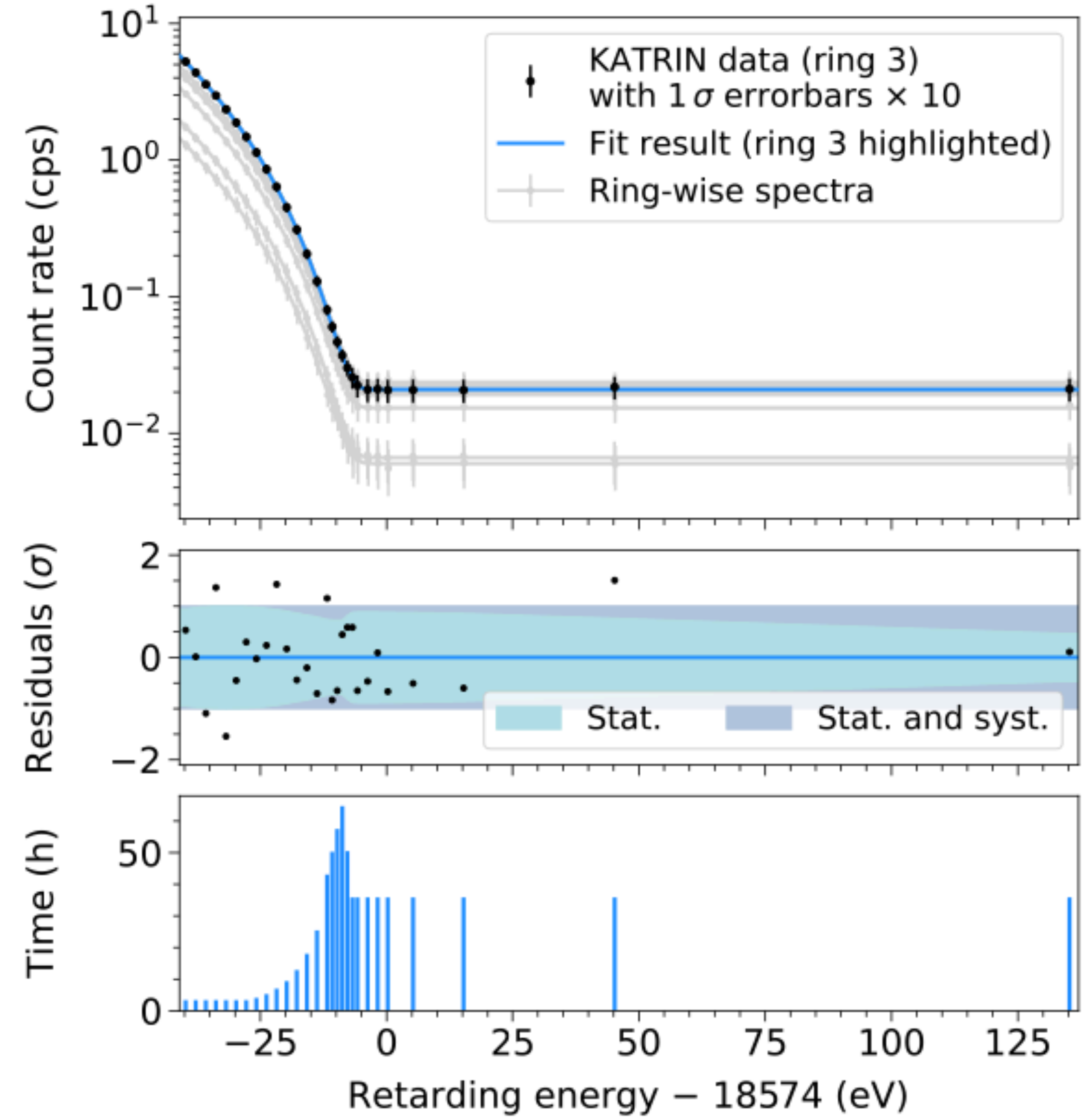
Integrated β-spectrum + bg



Neutrino-mass result for 2nd campaign

Nature Phys.18, 160 (2022)

- 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
- Frequentist limit using method of Lokhov and Tkachov which coincides with method of Feldman and Cousins upper limits with $m^2 \geq 0$
- Bayesian sampling with flat positive prior in m^2
- Best-fit effective endpoint **E_0 = 18573.69 ± 0.03 eV** consistent with mass difference $\Delta M(^3He\text{-}^3H)$ from precision Penning traps ➜ independent check of energy scale

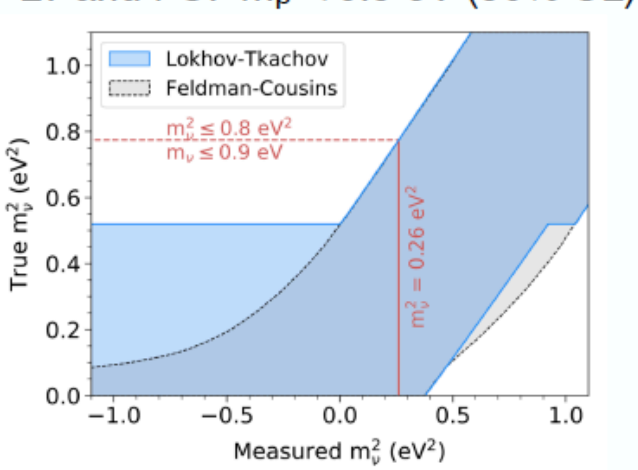


Best-fit value (stat. and syst.):

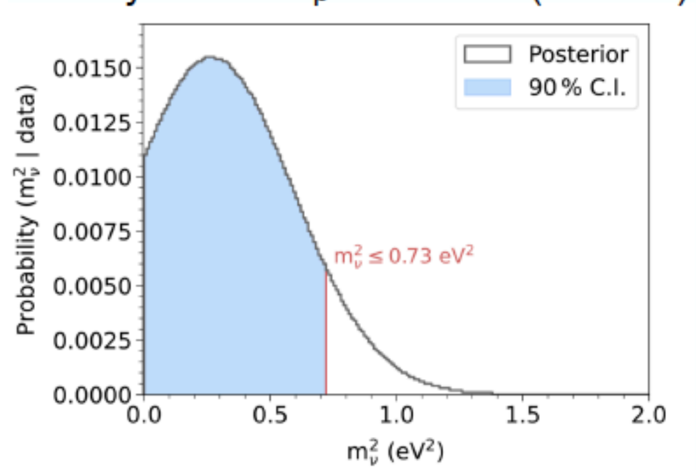
$$m_\nu^2 = 0.26 \pm 0.34 \mathrm{eV}^2$$

(0.8 σ fluctuation)

LT and FC: $m_\beta < 0.9$ eV (90% CL)



Bayesian: $m_\beta < 0.85$ eV (90% CI)



Uncertainty budget:

- Total: 0.34 eV2
- Statistics: 0.29 eV2
- Systematic: 0.18 eV2

⇒ **First sub-electronvolt direct neutrino mass measurement and sensitivity**

Results Combined 1st and 2nd campaign

Nature Phys.18, 160 (2022)

Different strategies pursued:

1. Combined fit with shared neutrino mass

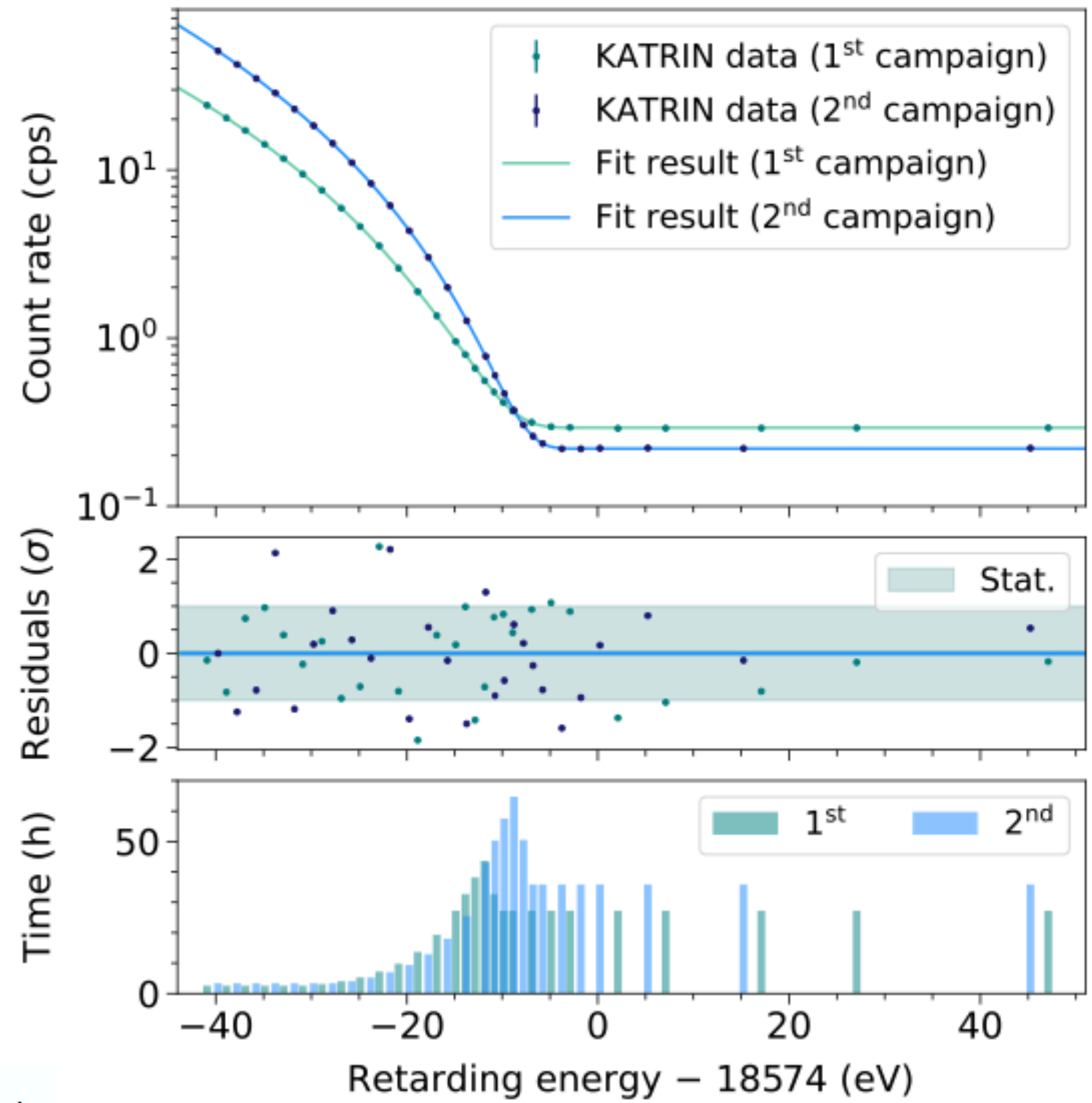
2. Multiply distributions from MC propagation

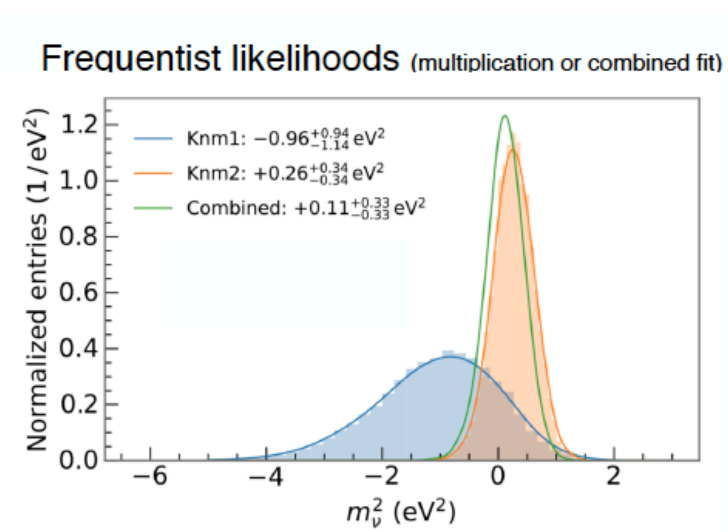
3. Bayesian analysis: use posterior of first campaign as prior for second campaign

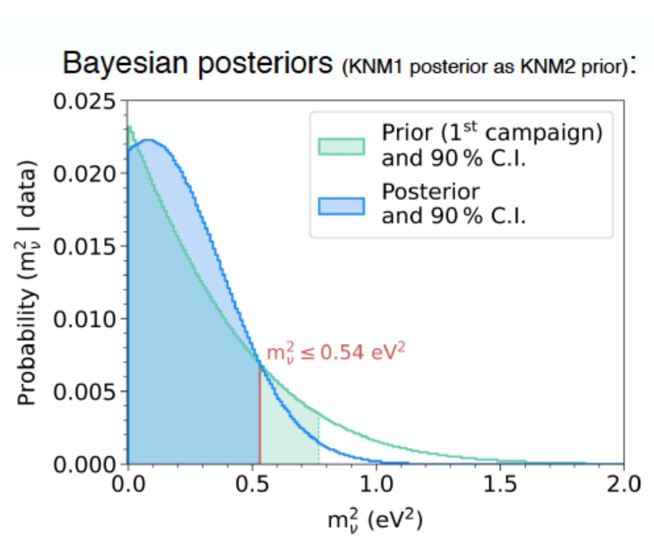
$\Longrightarrow$ Leading ***upper limit*** on neutrino mass:

$$m_\nu < 0.8 \text{ eV } (90\,\%\,\text{CL})$$

Best

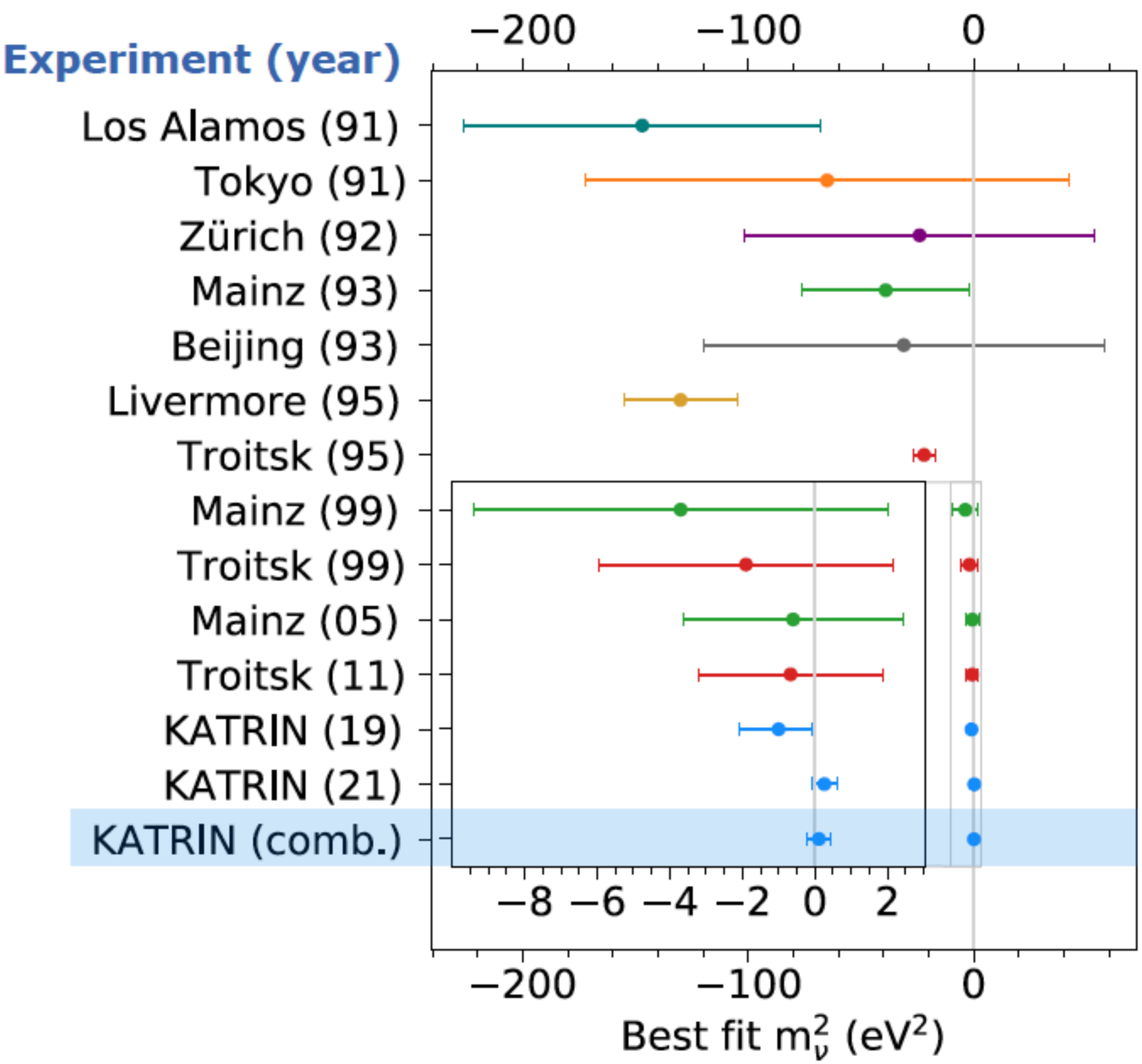






Best fit:	$m_\beta^2 = 0.1 \pm 0.3 \text{ eV}^2$
Limits LT and FC:	$m_\beta < 0.8$ eV (90% CL)
Limits Bayesian:	$m_\beta < 0.73$ eV (90% CI)

30 years retrospective on tritium experiments



Instrument development
Dedicated systematics experiments
Theoretical model

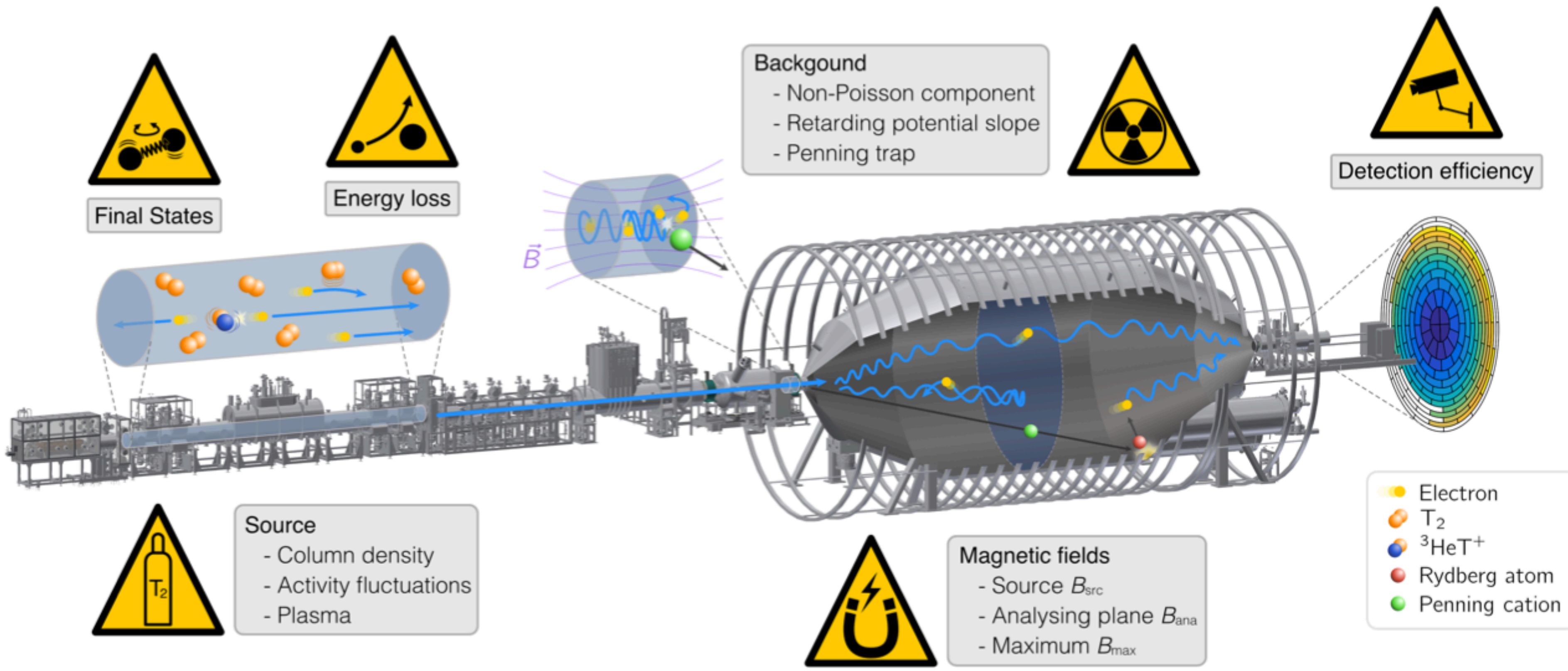
Scale-up & further development of MAC-E technique with gaseous source

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

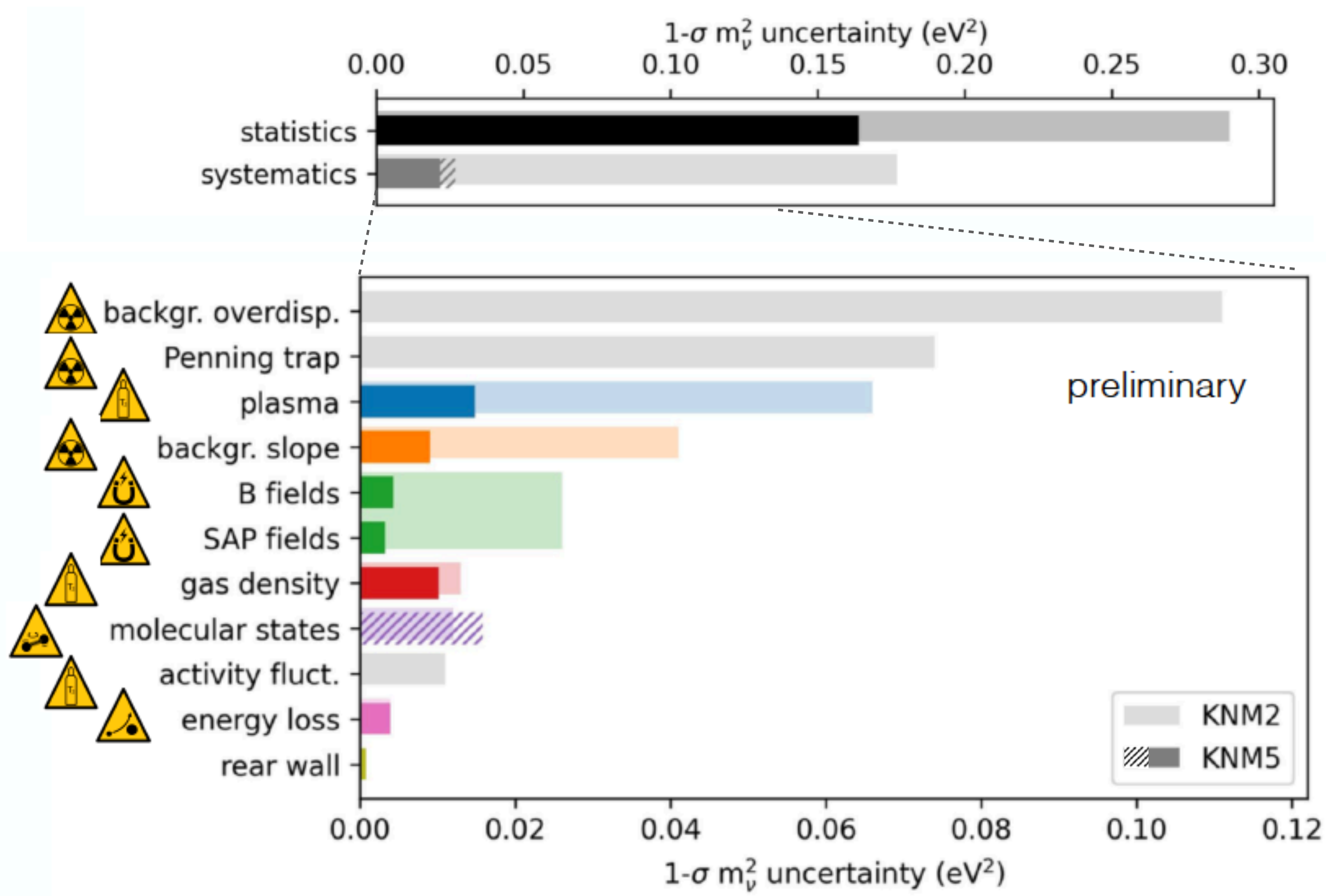
Combined limit: $m_\nu < 0.8\ eV\,(90\%\ \mathrm{CL})$

3 months KATRIN data better than Mainz, Troitsk
- Statistics x6, systematics x12
- First sub-eV neutrino mass sensitivity in lab
- Multiple independent blind analyses

Systematics overview



Design requirement for KATRIN final:
σ_{total} = 0.024 eV², σ_{stat} = σ_{syst} = 0.017 eV²



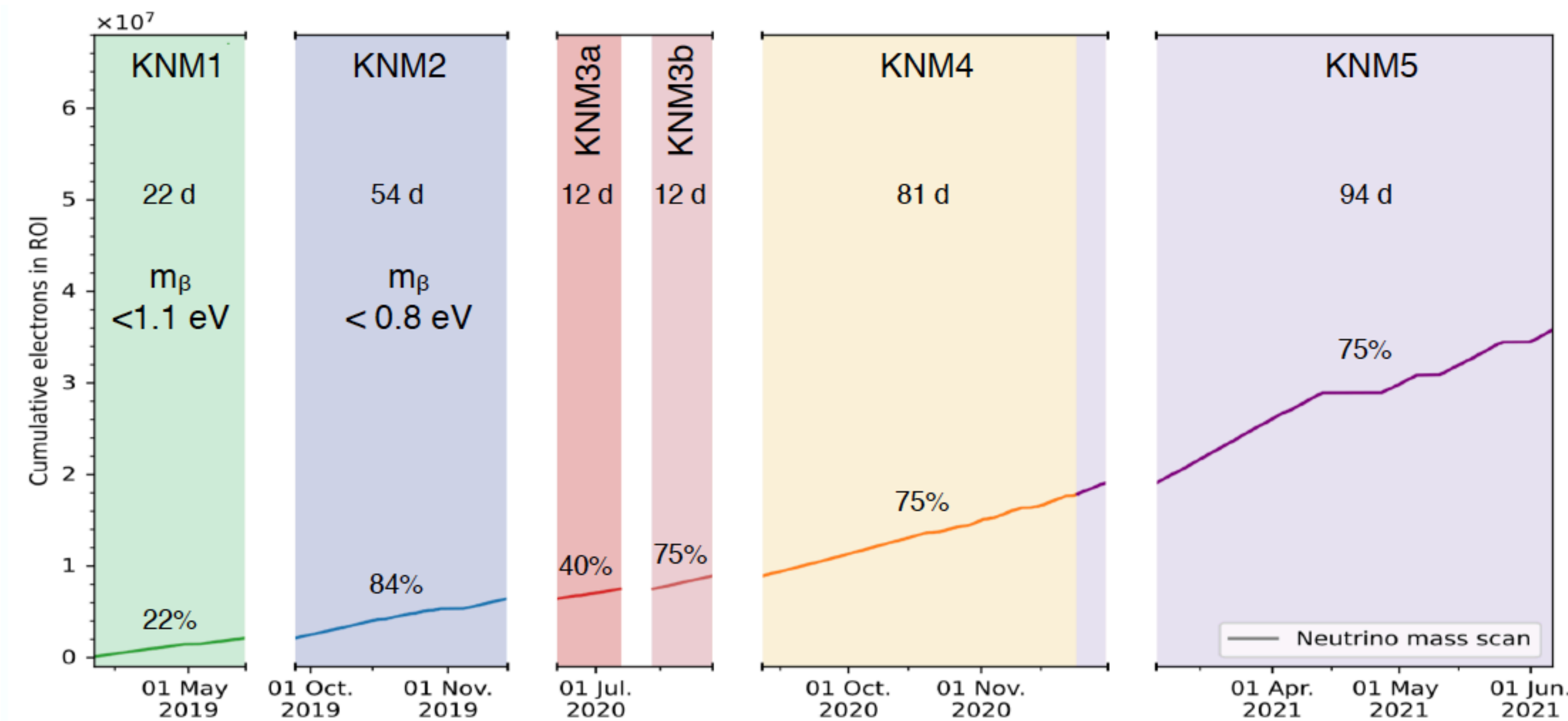
- Gain more statistics & suppress background
- Dedicated measures to improve dominant background- and source-related systematics
- Many “incremental” improvements

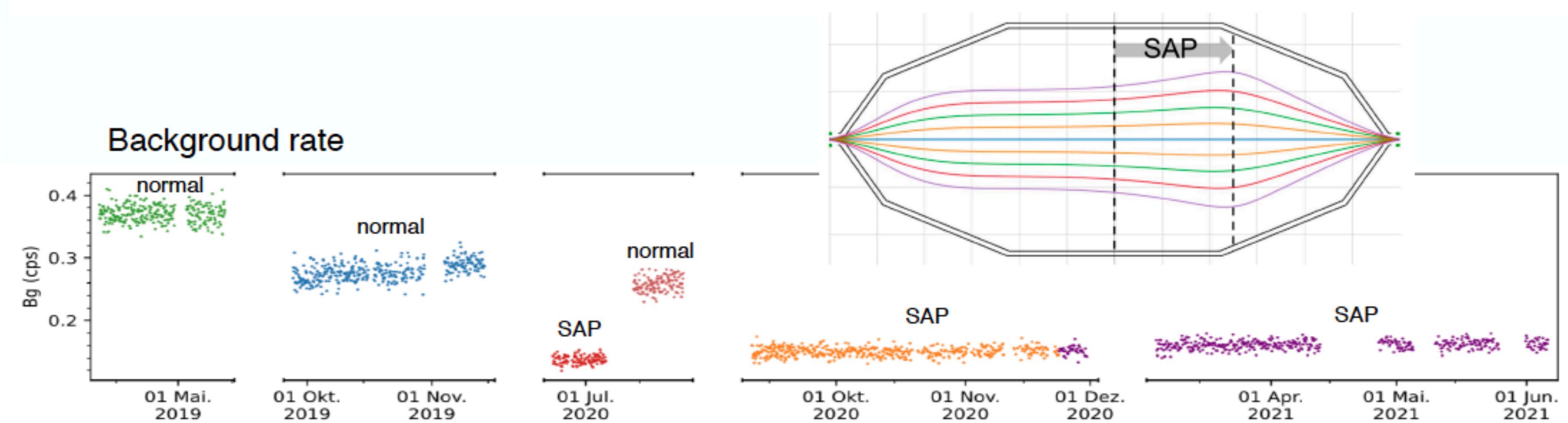
Largest future systematic:

- Plasma effects

Outlook: next neutrino mass campaigns

5th ν-mass campaign 2021 data: Reached 40 million electrons in ROI





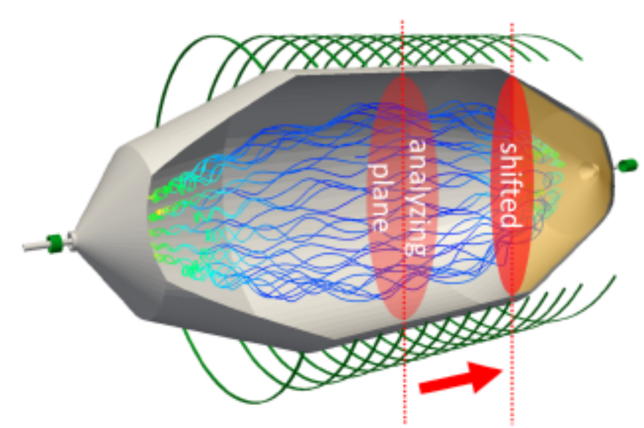
50% of background reduction by SAP

KNM6 & 7 on disk
KNM8 will start soon

Coming next:
- Next data release [1-5]
  ETA end of 2022
- Statistics increased by ≈ x3.6
- Background reduction by ≈ x2
- Systematics reduction by ≈ x6

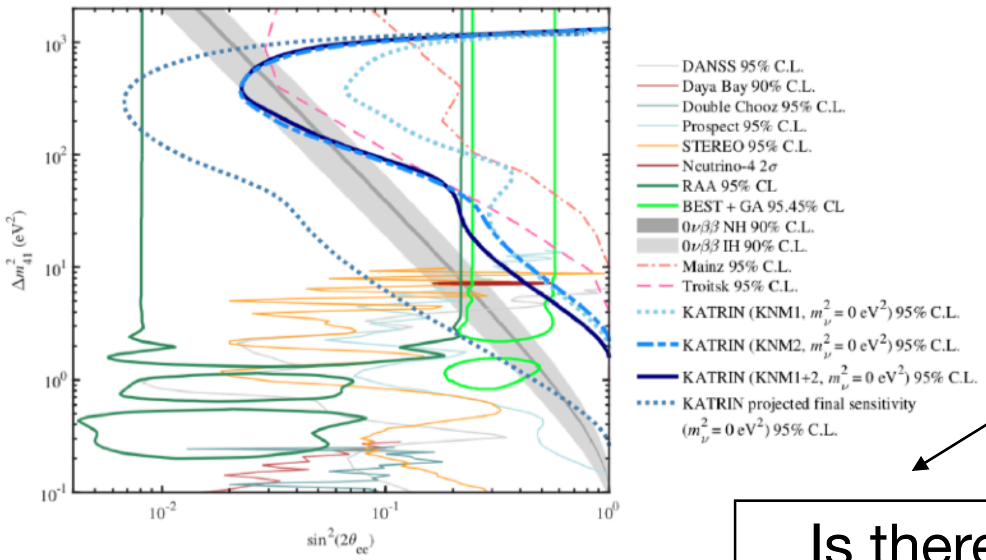
Background reduction:
- All low energy e- in main spectrometer volume can mimic signal
- MAC-E filter can store fast e- through “magnetic bottle” effect
- Stored e- ionize residual gas creating low energy secondary electrons

➡ **Shifted analyzing plane (SAP)**



Background overview: 2011.05107

Physics “beyond the neutrino mass” with KATRIN



Light sterile neutrino
Phys. Rev. Lett. **129**, 061801

β-spectrum of high statistics and precision

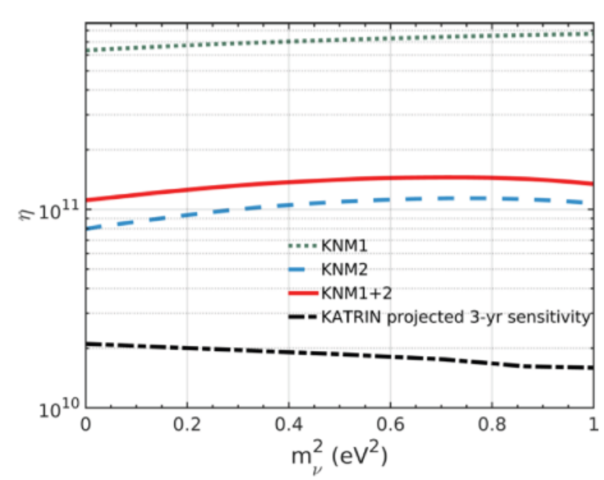
Is there a fourth (sterile) neutrino?

Search for exotic weak interactions (Spectrum shape)

Search for Lorentz invariance violation (sidereal modulation)

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)



Phys. Rev. Lett. **129**, 011806

Summary & Outlook

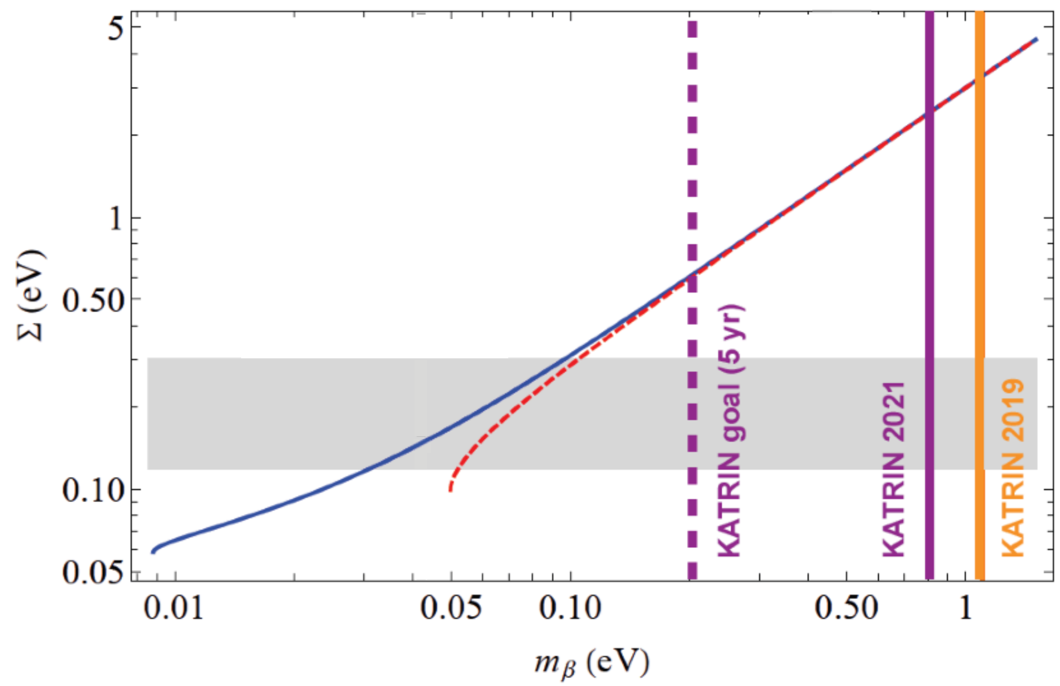
- Latest KATRIN results: (1st and 2nd datasets combined) **Nature Phys.18, 160 (2022)**

$$m_\beta^2 = 0.1 \pm 0.3\ \mathrm{eV}^2 \qquad m_\beta < 0.8\ \mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

  - Still strongly dominated by statistics

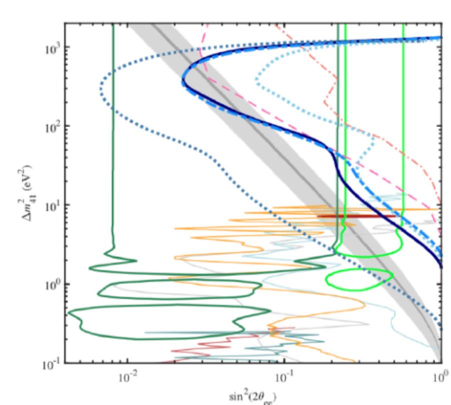
- Statistics dominated, largest systematic from background
- Complementary with Cosmology and Double Beta Decay
- Currently only leading experiment (Future: Project8, ECHo, HOLMES)

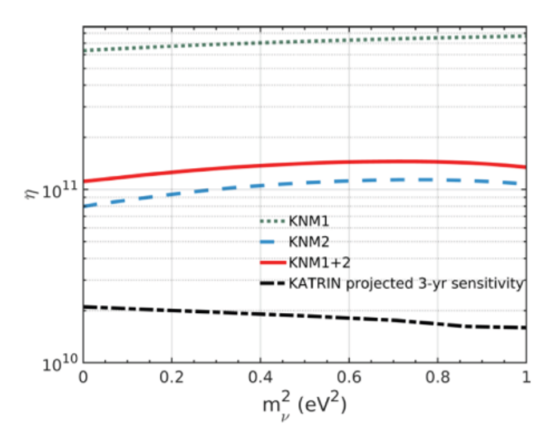
Future measurements:
- 8th measurement campaign will start soon
- Improvements on background reduction established
- Full KATRIN sensitivity (1000 d): 0.2 eV (90% CL)



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

- 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, …





K. Valerius