WWU MÜNSTER

First Sub-eV Neutrino Mass Limit from the KATRIN Experiment

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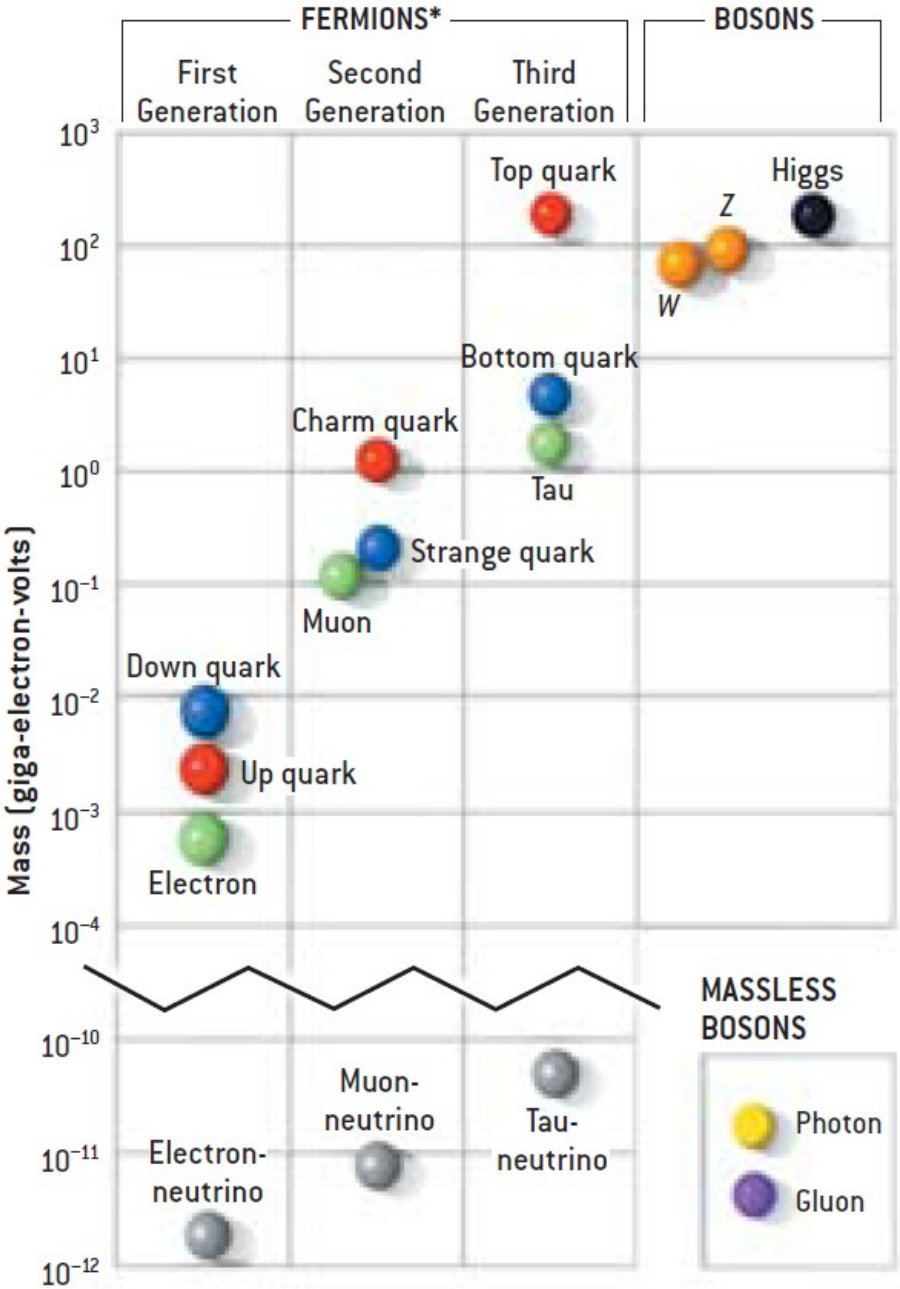
Neutrino mass in particle physics

- Nature of the neutrino: Majorana or Dirac particle, i.e. is the neutrino it's own anti-particle ?

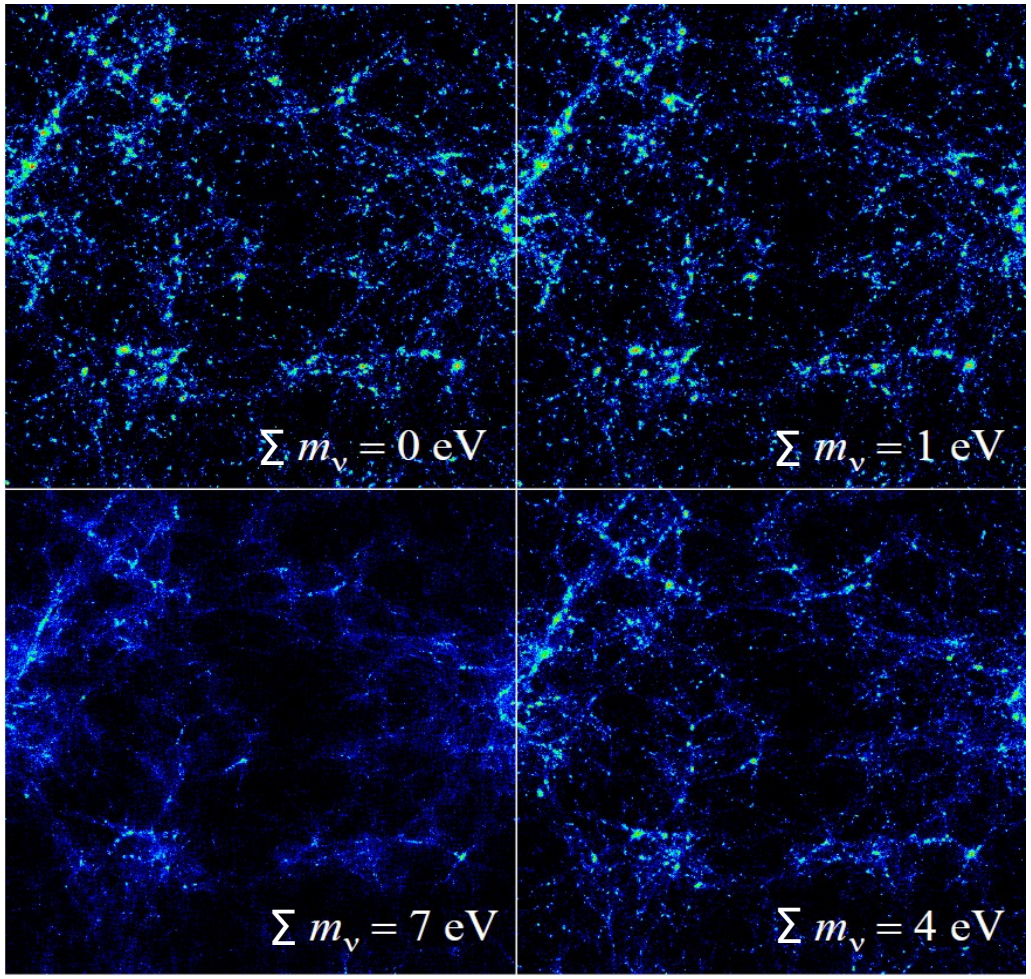
- How to explain the many orders of magnitude difference between neutrino mass limits and masses of the charged fermions of the standard model
  → sea-saw type I and type II mechanisms

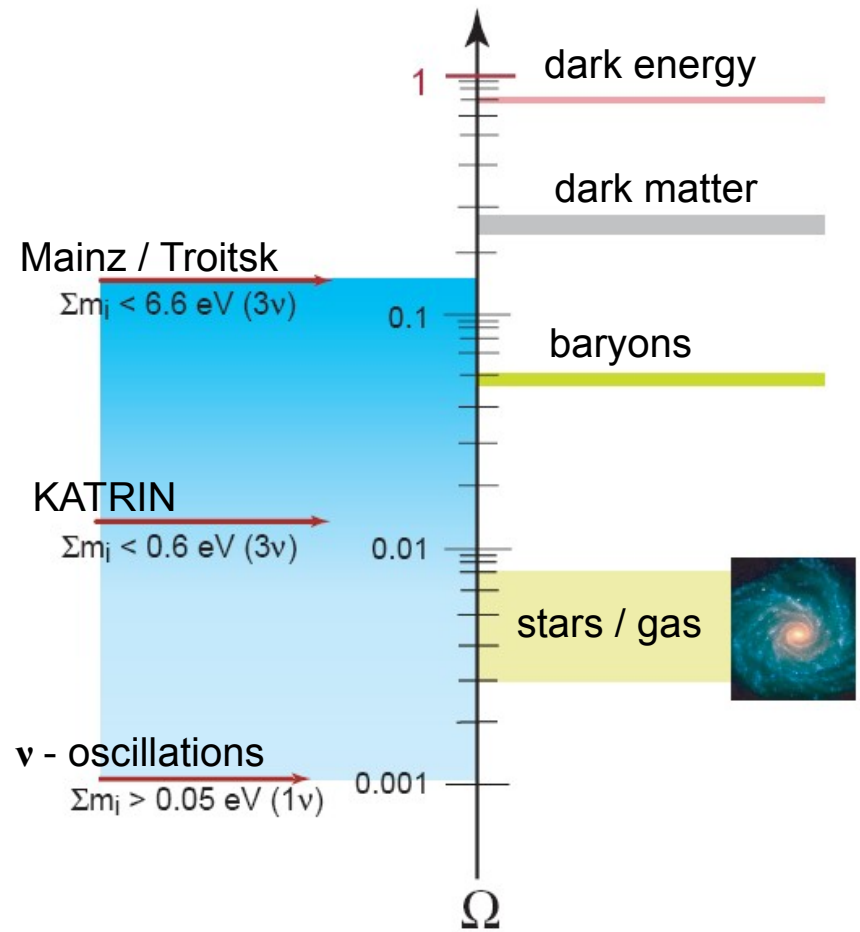
- Possible connection to the generation of the observed matter - antimatter asymmetry in the universe
  → leptogenesis



Neutrino mass in cosmology

- Neutrinos are (after γ's) the second most abundant particle species in the universe
- As part of the hot dark matter, neutrinos have a significant influence on structure formation





- For large Σm_ν values fine grained structures are washed out by the free streaming neutrinos

Chung-Pei Ma 1996

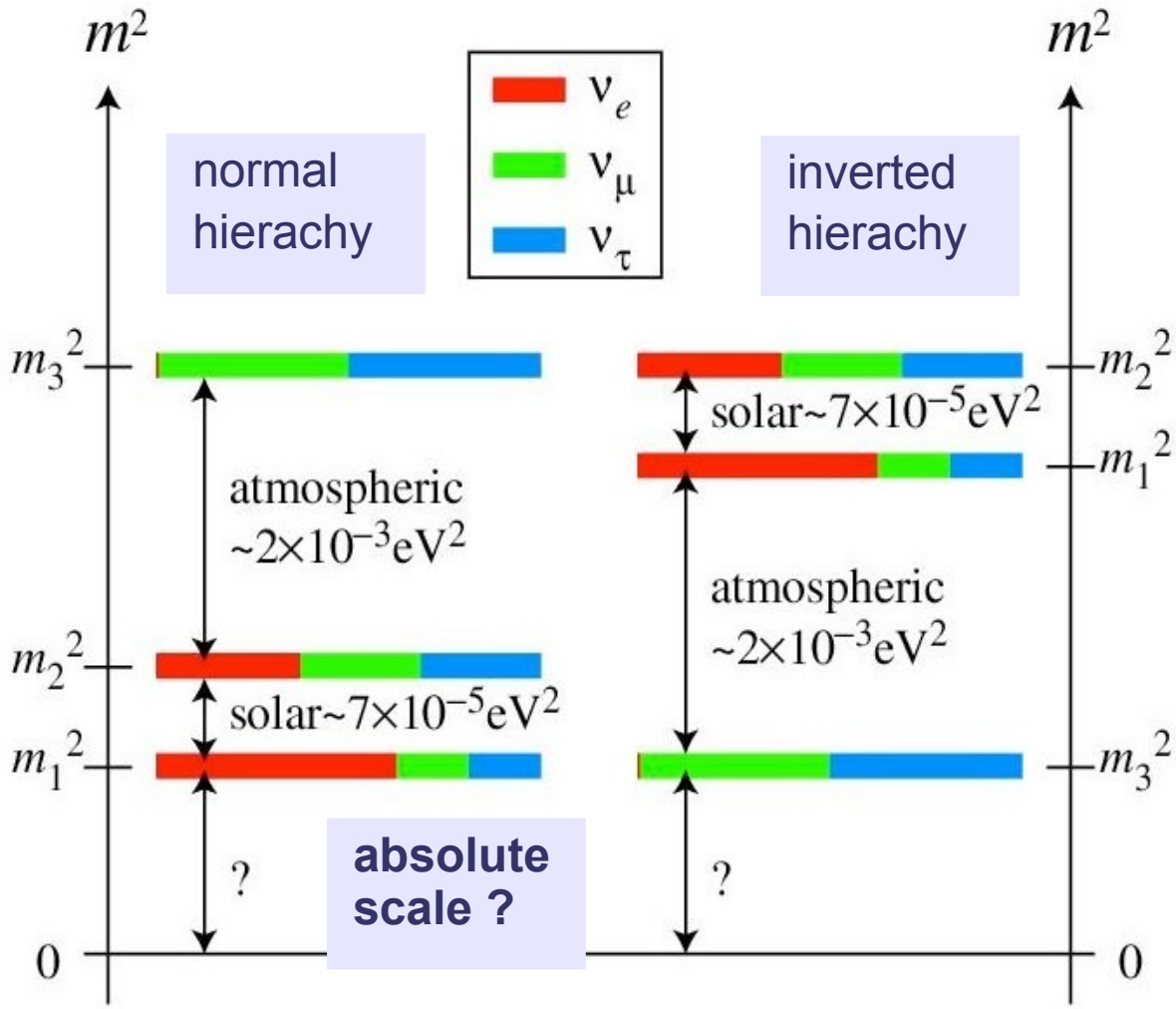
Current knowlegde and open questions

What we know (from ν oscillations):

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm^2 values known (with varying accuracies)

What we don't know :

- Normal or inverted hierachy ?
- Dirac or Majorana particle ?
- CP violating phases in mixing matrix ?
- **No information about absolute mass scale !** (only upper limits)
- Existence of sterile neutrinos ?



Search for neutrino mass

β-decay: absolute ν-mass

model independent, kinematics

status: $m_\nu < 0.8$ eV

potential: $m_\nu \approx 0.2$ eV

e.g.: KATRIN, Project-8, ECHO HOLMES, NuMECS

0νββ-decay: eff. Majorana mass

model-dependent (CP-phases)

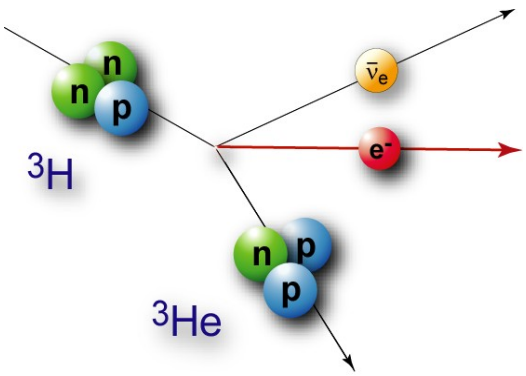
status: $m_{\beta\beta} < 61$ meV to 165 meV

(^{136}Xe, PRL 117 (2016) 082503)

potential: $m_{\beta\beta} \approx 20$-50 meV

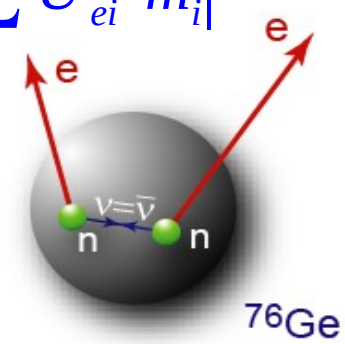
e.g.: KamLAND-Zen, GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA

$$m_\nu^2 = \sum |U_{ei}^2| m_i^2$$

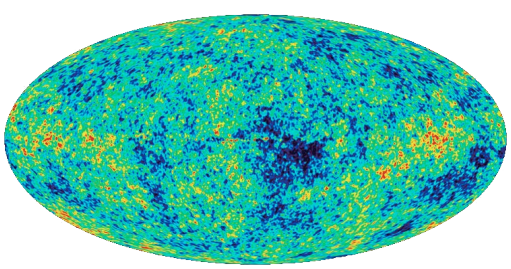


neutrino mass measurements

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



$$\sum m_i$$

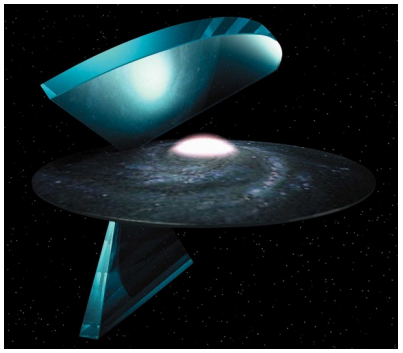


cosmology: ν hot dark matter Ω_ν

model dependent, analysis of CMB and structure formation data

status: $\Sigma m_i < 0.12$ eV

(Planck 2018 results, Astron. & Astrophys. 641 (2020) A6)



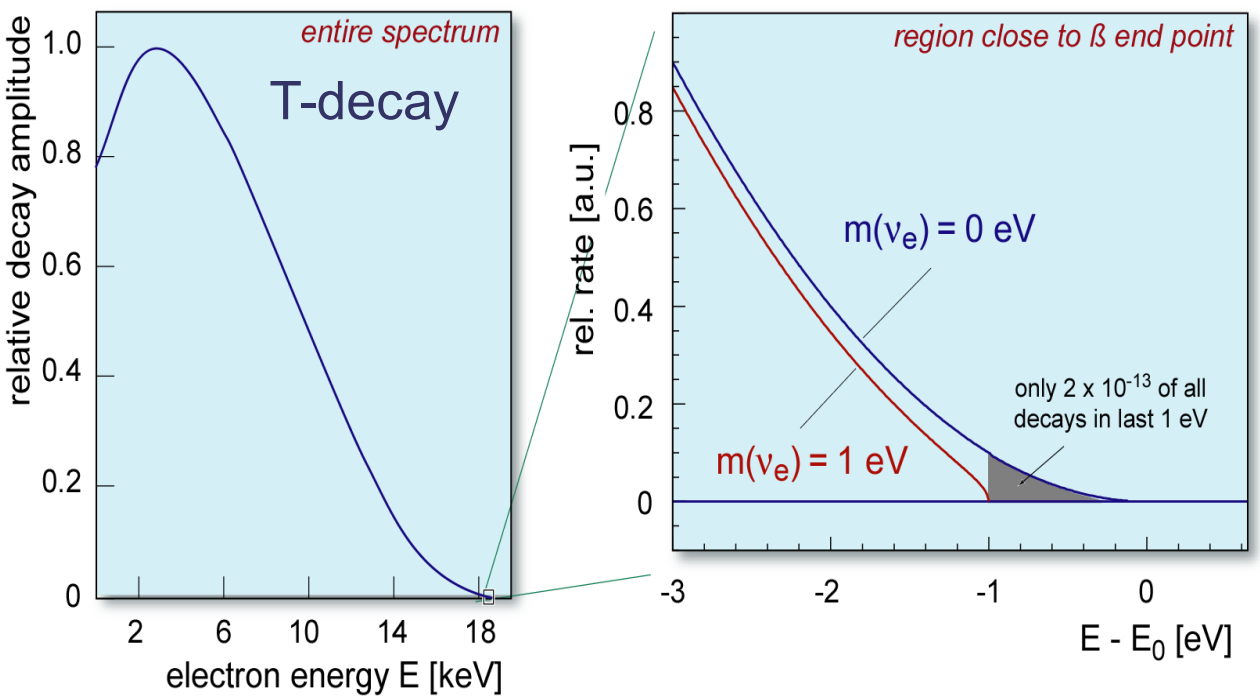
Kinematic determination of $m(\nu_e)$

$$\frac{d\Gamma}{dE} = C\, p(E+m_e)(E_0-E)\sqrt{(E_o-E)^2-m_\nu^2}\, F(Z+1,E)\,\Theta(E_0-E-m_\nu)\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C |M|^2$$

$$m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

(modified by final state distribution, recoil corrections, radiative corrections, ...)



Suitable Isotopes:

Tritium

- E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a
- S(E) = 1 (super-allowed)

Rhenium

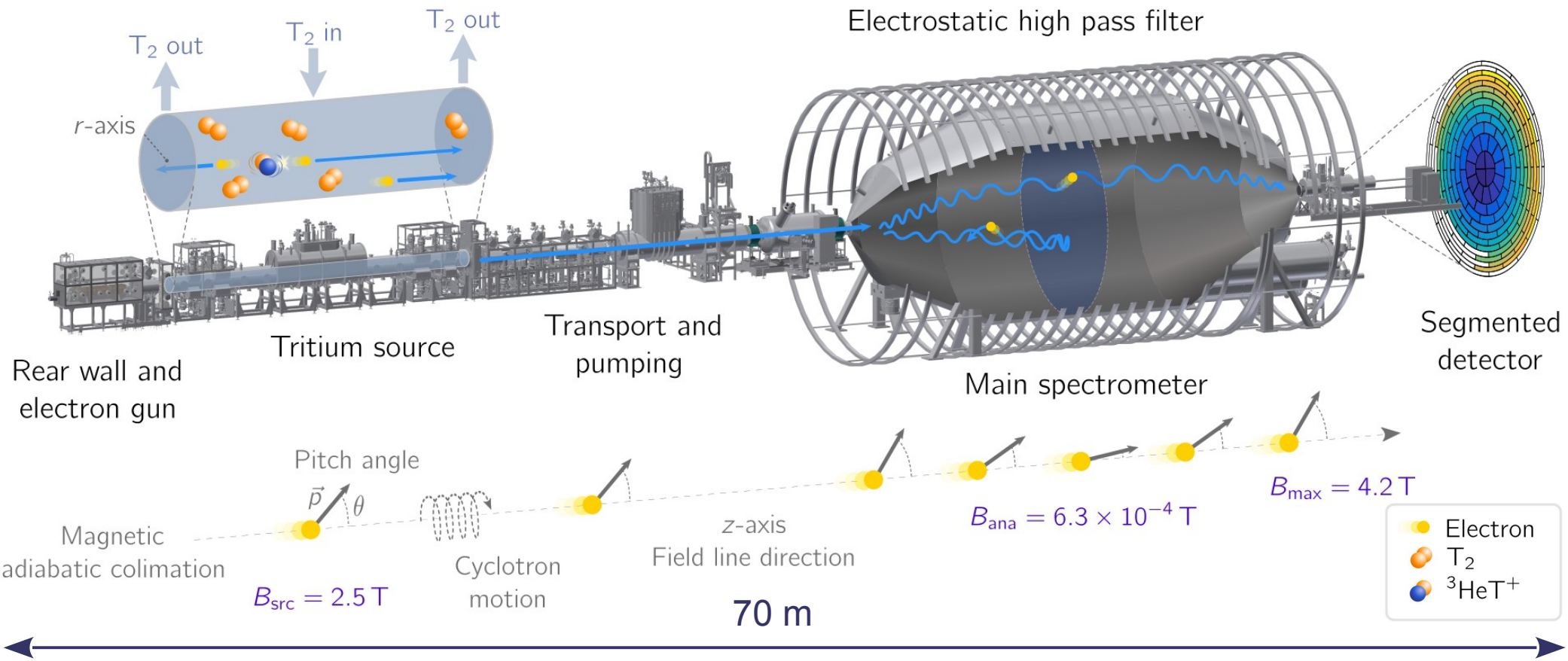
- E_0 = 2.47 keV, $T_{1/2}$ = 43.2 Gy

alternative approach:

Holmium (EC decay)

- $Q_{EC} \approx$ 2.5 keV, $T_{1/2}$ = 4570 y

KATRIN experiment at KIT

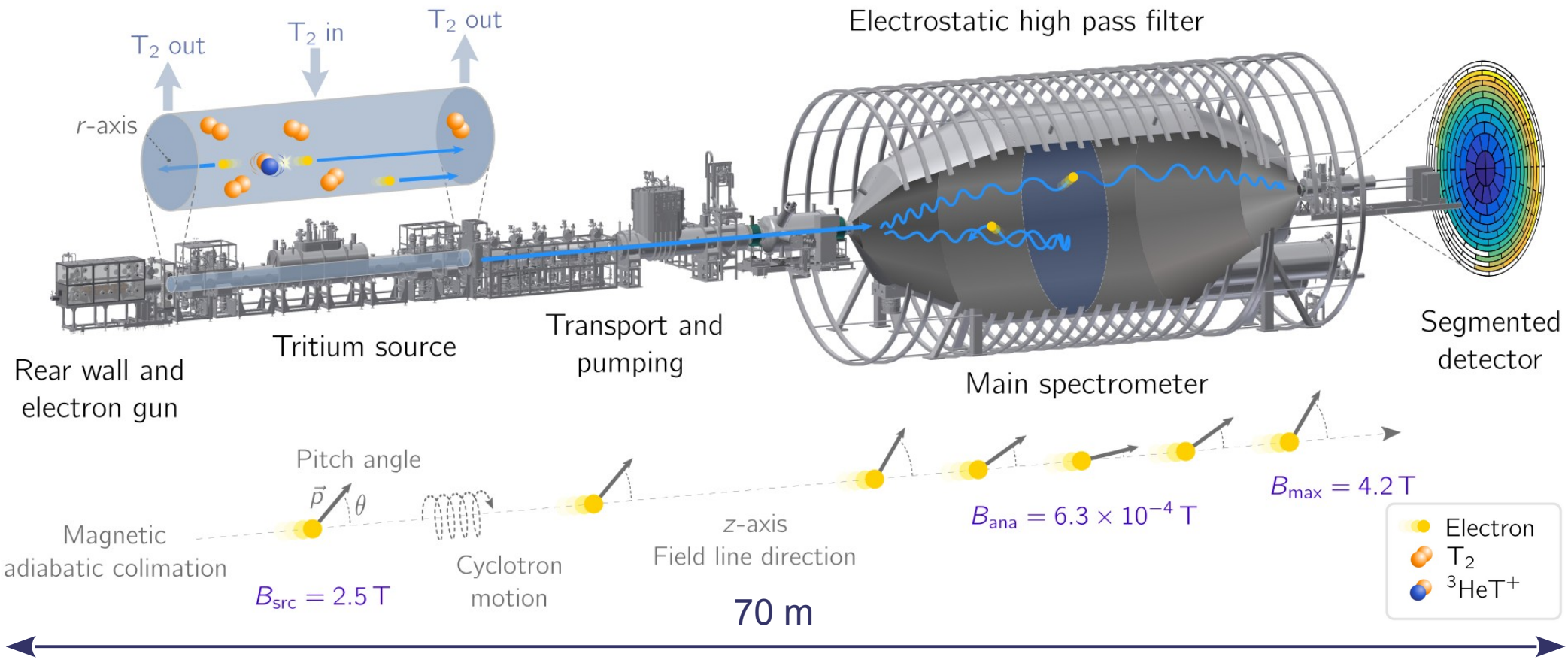


currently not active

leaving

KATRIN
Karlsruhe Tritium Neutrino Experiment

KATRIN experiment at KIT



KATRIN design goals:

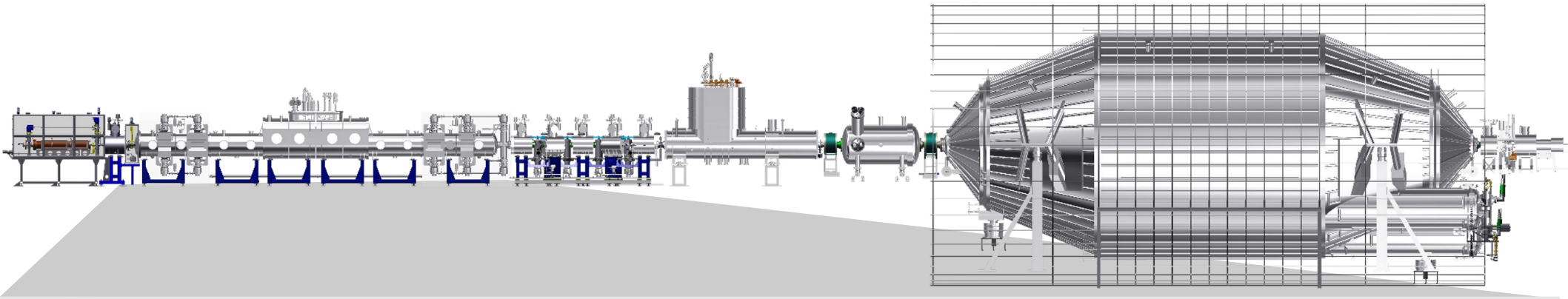
collect **1000 days** of data

statistical uncertainty $\sigma_{stat} \approx 0.018\ eV^2$

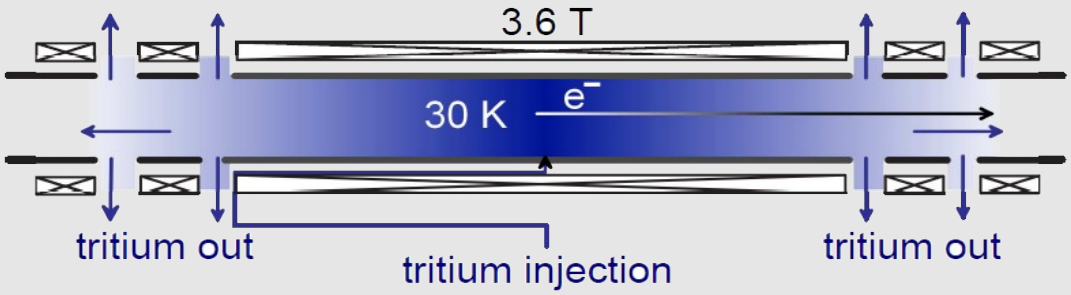
systematic uncertainty $\sigma_{sys,tot} \approx 0.017\ eV^2$

→ sensitivity for upper limit: **0.2 eV** (90% C.L.)
m_ν = 0.35 eV observable with 5σ

Windowless Gaseous Tritium Source



- beam tube Ø = 9 cm , L = 10 m
- guiding field 3.6 T
- temperature T = 30 K / 80 K ± 30 mK,
- T_2 purity 95% ± 0.1 %
- column density $5 \cdot 10^{17}$ T_2/cm^2
- luminosity $1.7 \cdot 10^{11}$ Bq



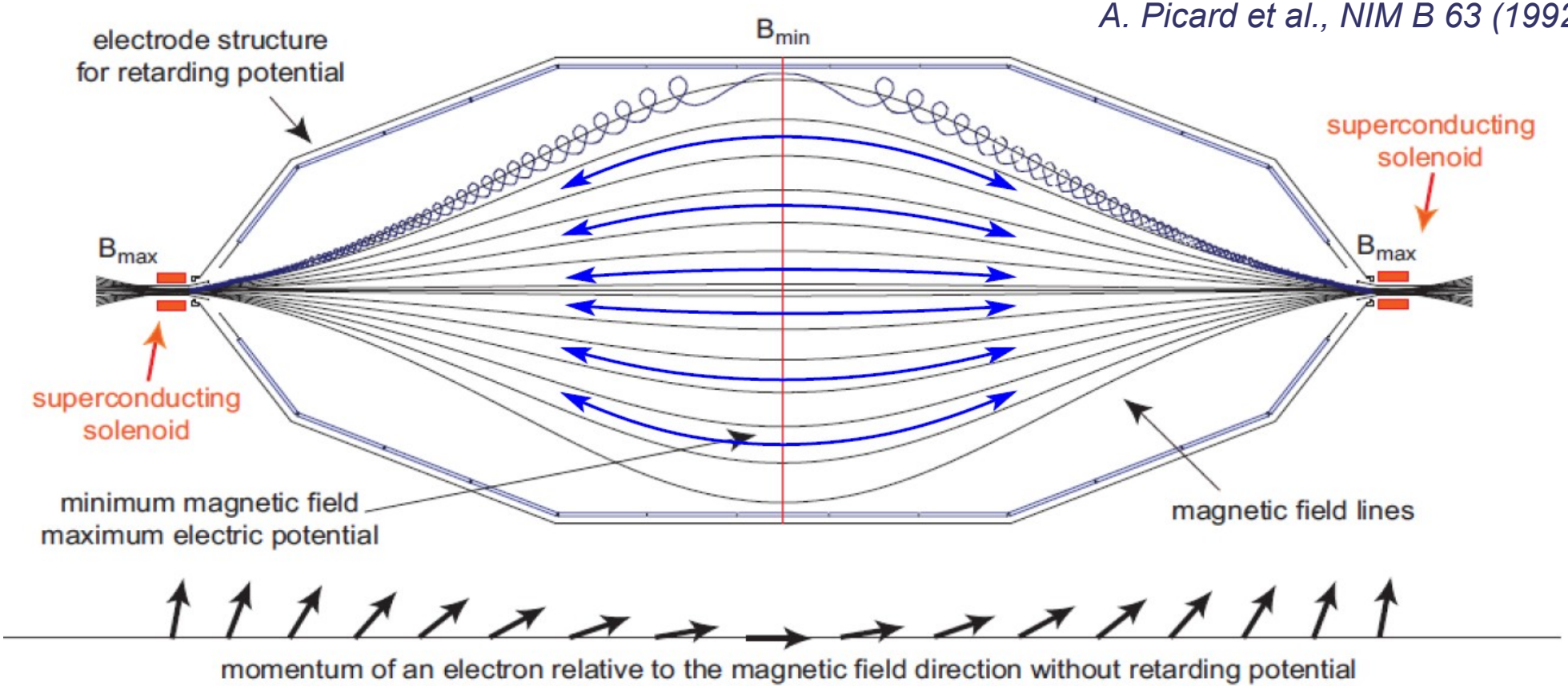
- T_2 flow rate $5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)

WGTS at Tritium Laboratory Karlsruhe

MAC-E filter concept

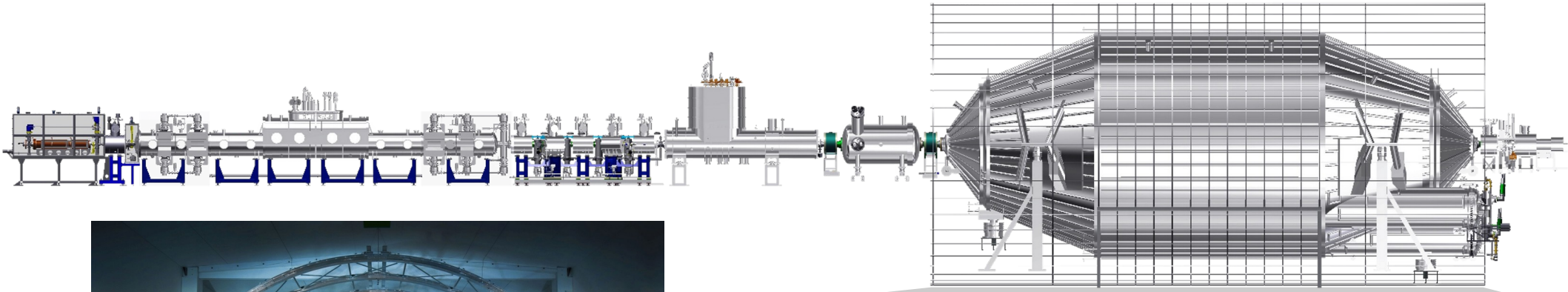
Magnetic Adiabatic Collimation with Electrostatic Filter

A. Picard et al., NIM B 63 (1992)

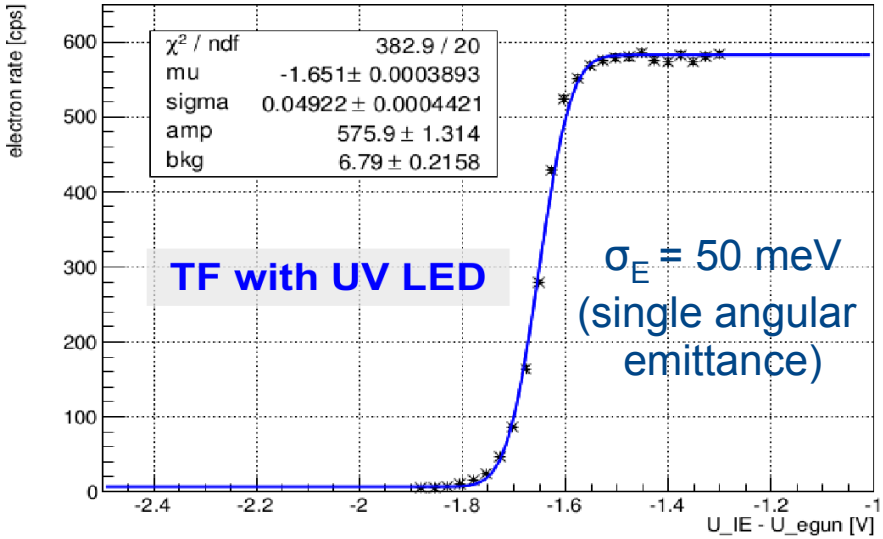


- adiabatic transport → $\mu = E_{\perp} / B = \text{const.}$
- B drops by $2 \cdot 10^4$ from solenoid to analyzing plane → $E_{\perp} \rightarrow E_{II}$
- only electrons with $E_{II} > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\perp,max,\,start} \cdot B_{min} / B_{max} < 1$ eV

Main-Spectrometer

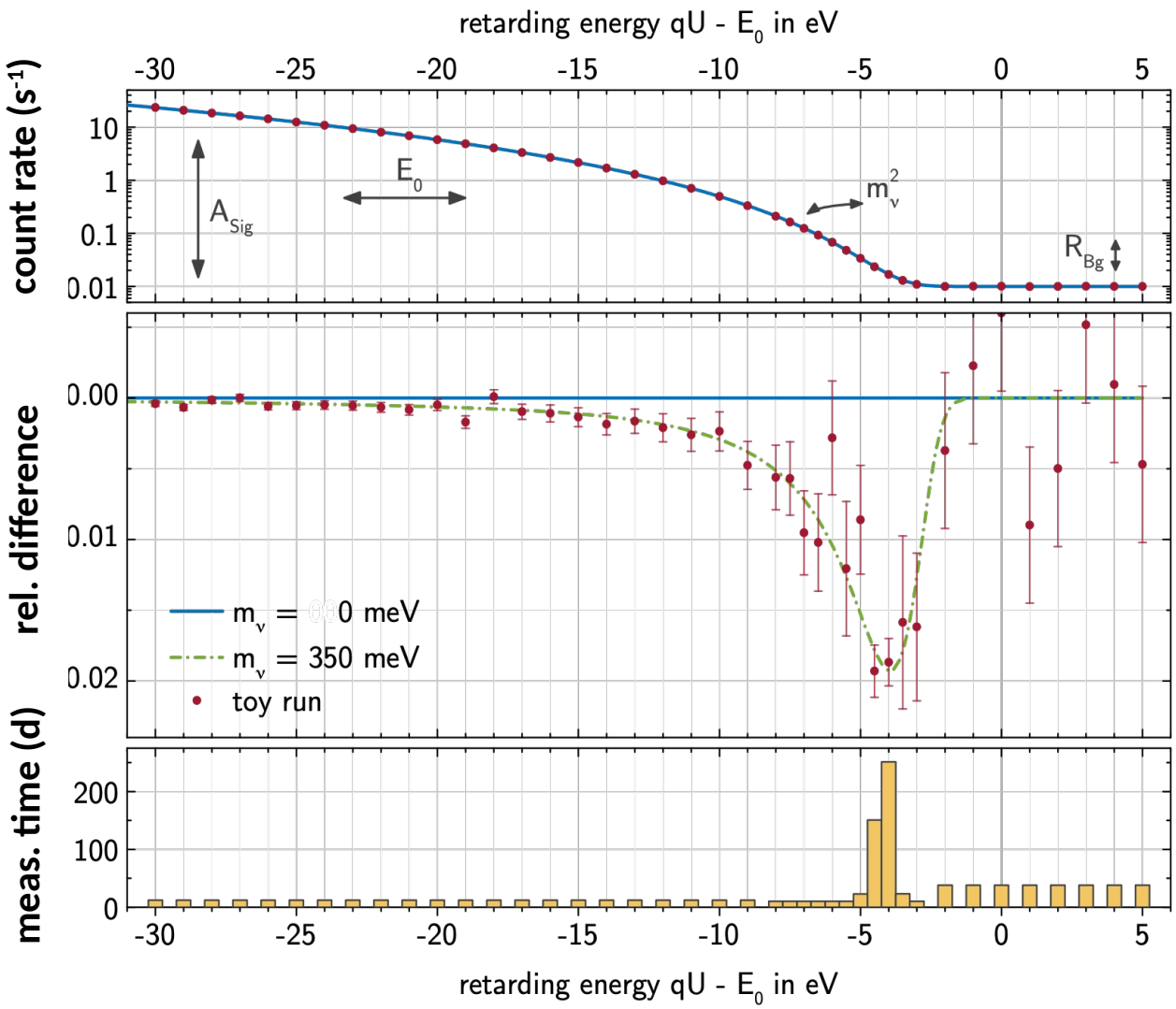


- 18.6 kV retardation voltage, $\sigma < 60$ meV
- 0.93 eV resolution
- pressure $< 10^{-11}$ mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping



Measurement principle

- Direct **shape** measurement of **integrated β spectrum**



Four fit parameters:

spectrum ampl. $\mathbf{A_{sig}}$

spectrum endpoint $\mathbf{E_0}$

background rate $\mathbf{R_{bg}}$

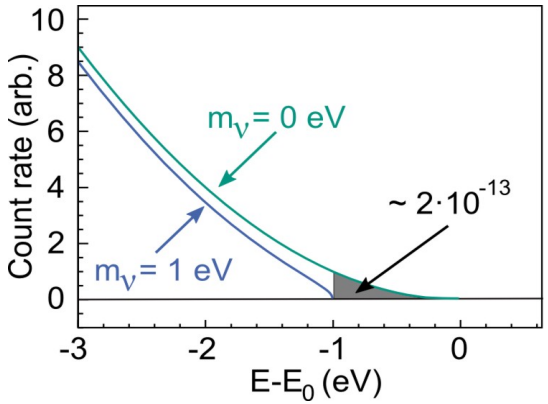
squared mass $\mathbf{m^2_\nu}$

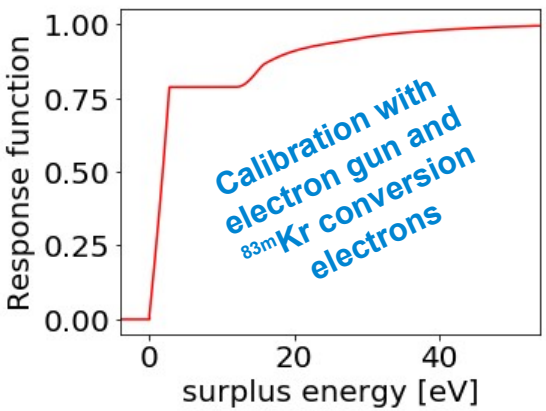
~10^{-8} of all β-decays in scan region ~40 eV below endpoint

Eur. Phys. J. C 79 (2019) 204

Model of the experimental spectrum

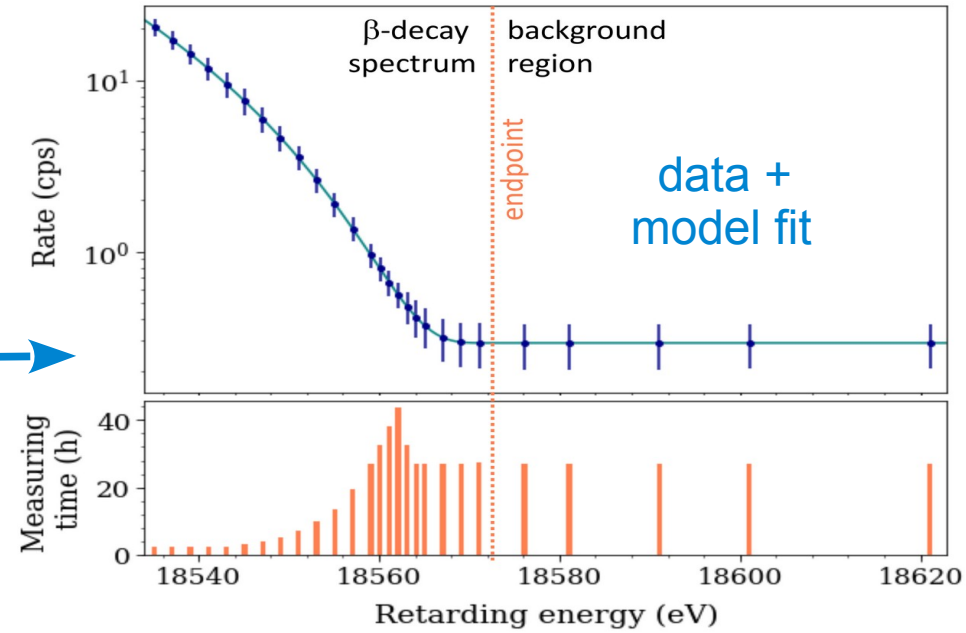
Beta spectrum: $R_\beta(E,m^2(\nu_e))$





Experimental response: **f(E-qU)**

KATRIN β-scan

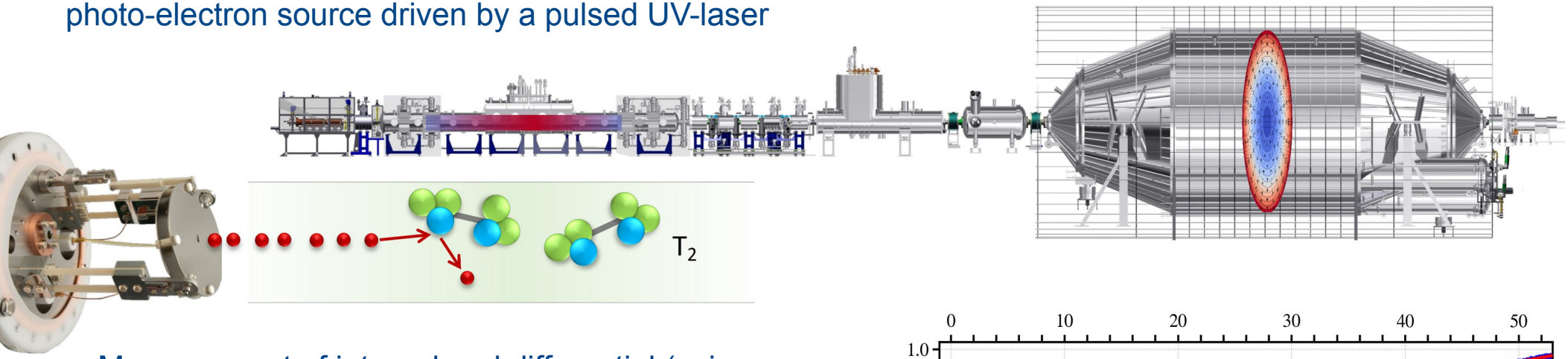


$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E-qU)\, dE + R_{bg}$$

PRL 123 (2019) 221802, EPJ C 79 (2019) 204
+ detailed analysis PRD 104 (2021) 012005
+ energy loss measurement EPJ C 81 (2021) 579

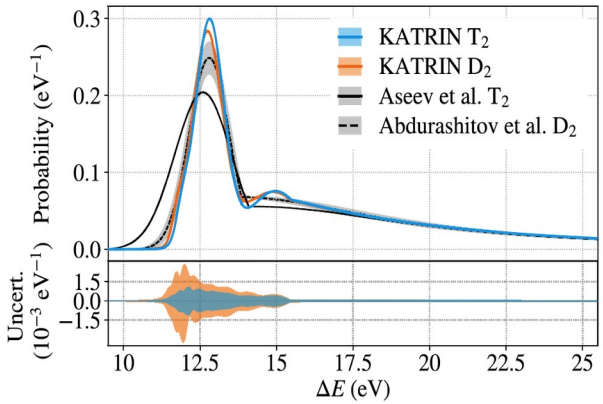
Response function measurement

- Determination of the experimental response function using a mono-energetic, angular selective photo-electron source driven by a pulsed UV-laser

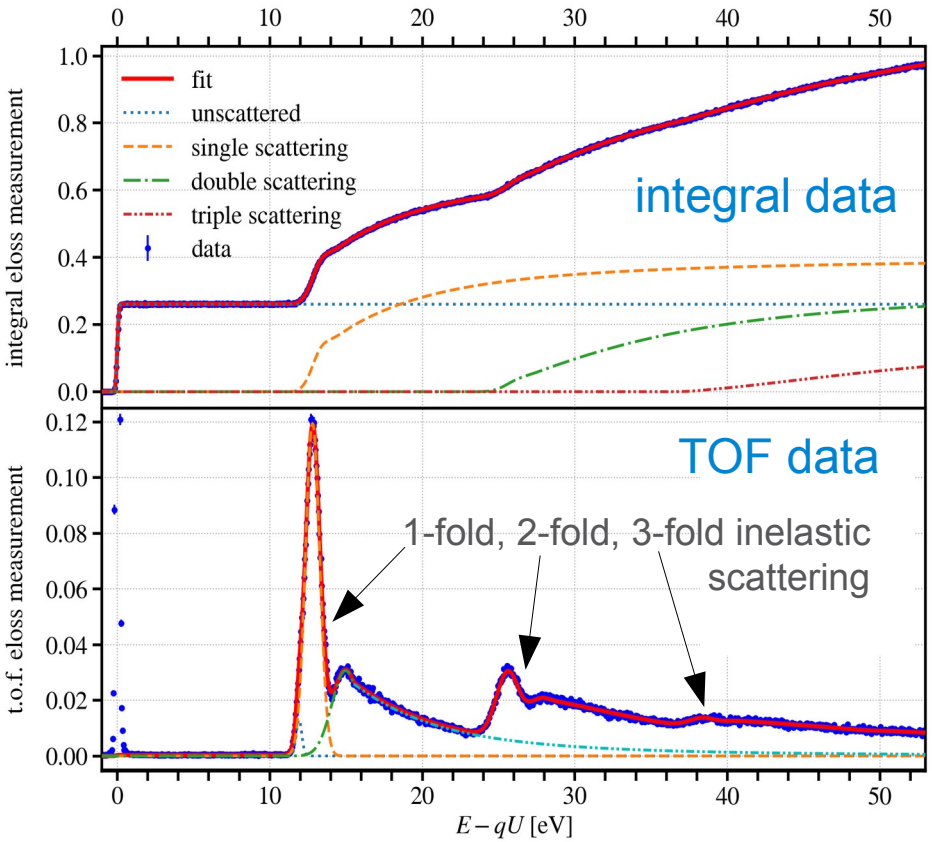


- Measurement of integral and differential (using TOF method) spectra at different column densities
  → Extraction of spectrometer transmission function and energy losses due to scattering *(EPJ C 81 (2021) 579)*

- Additional measurements with a gaseous ^{83m}Kr source to investigate plasma potential *(J. Phys. G 47 (2020) 065002)*

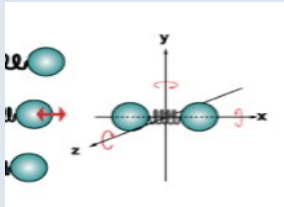


Extract differential energy loss function



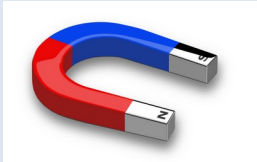
Main systematic uncertainties

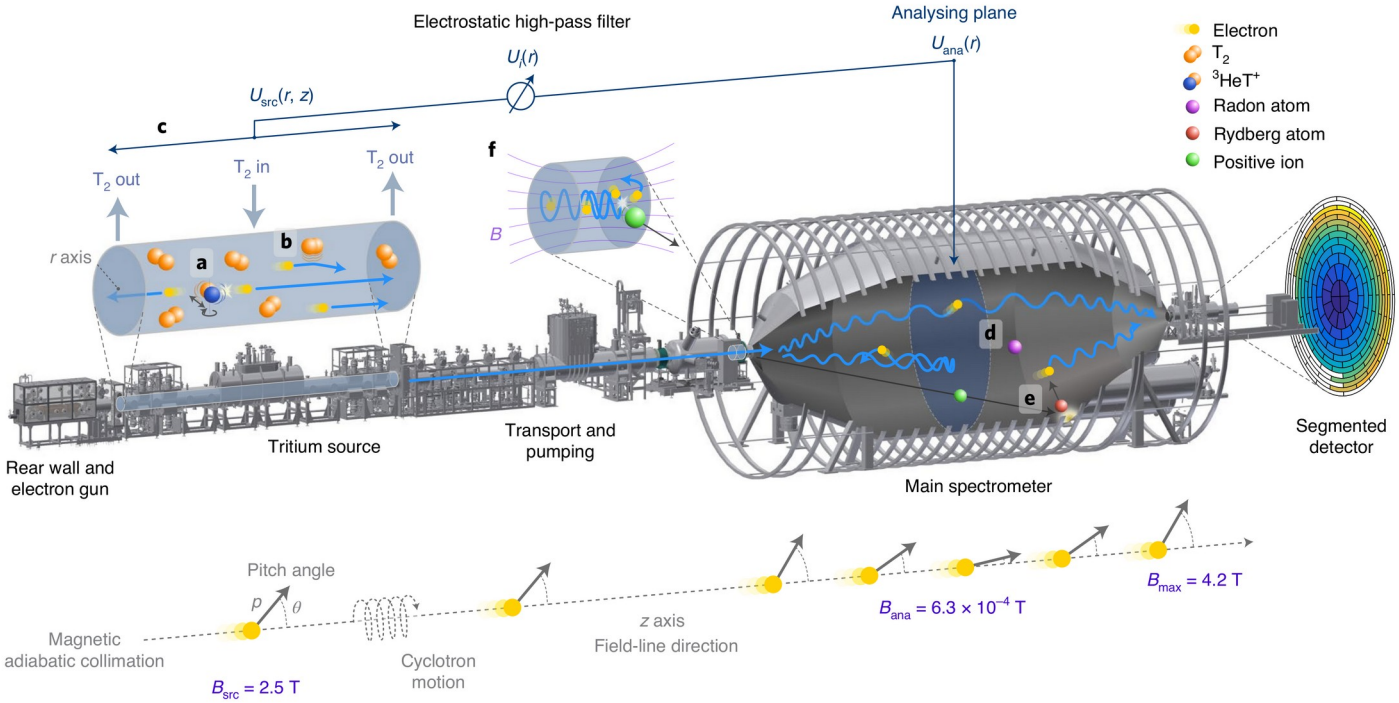
Molecular final states
- Quantum-chemical computations

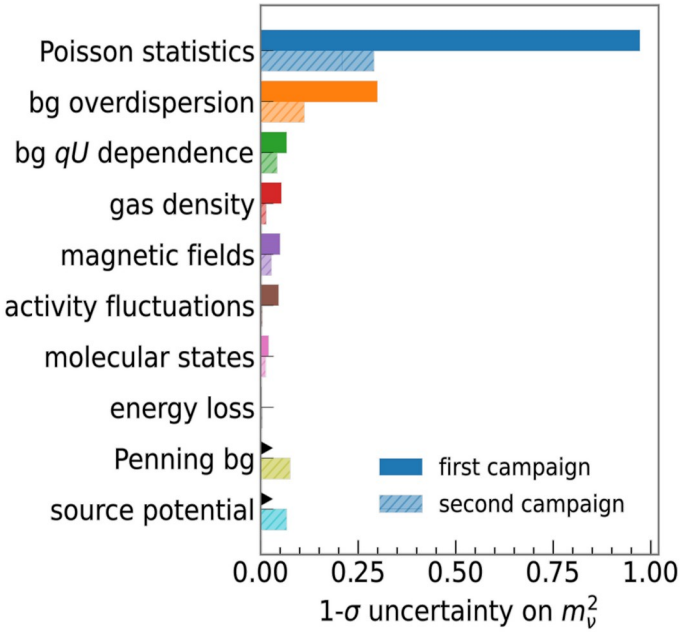


Source electric potential
- plasma properties
- surface conditions

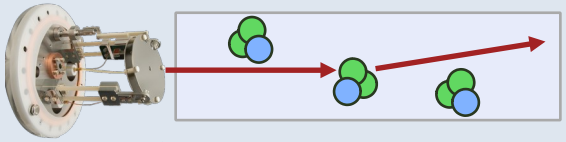
Magnetic fields
- source
- spectrometer
- detector





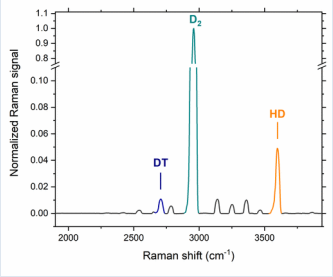


Energy loss by scattering



EPJ C 79 (2019) 204
EPJ C 81 (2021) 579

Activity fluctuations
- column density
- Tritium purity (T_2, DT, HT)

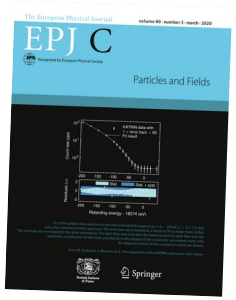


Sensors 20 (2020) 4827

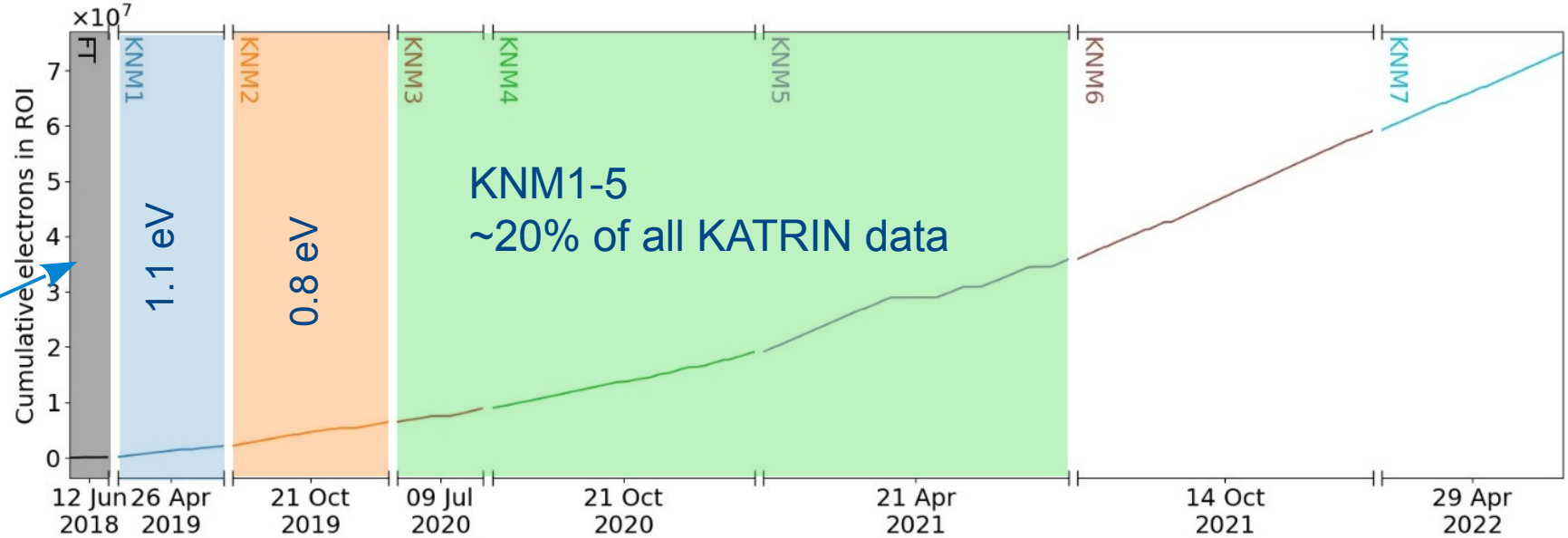
Background
- Volume dependent "Rydberg" background
- Voltage dependent background
- Background time structure due to trapped electrons

arXiv:2011.05107v1 (2020)

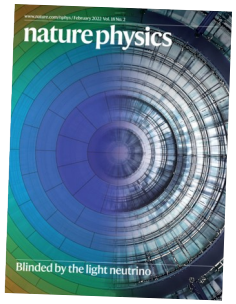
KATRIN data taking



EPJC 80 (2020) 264



PRL 123 (2019) 221802



Nat. Phys. 18 (2022) 160

Light sterile neutrinos

PR D 105 (2022) 072004

+

relic neutrinos

PRL 129 (2022) 011806

+

- analysis of runs KNM3 to KNM5 ongoing, expected statistical sensitivity ~ 0.5 eV (90% CL)
- data unblinding will happen soon

Extracted neutrino mass limits

1st campaign (spring 2019)

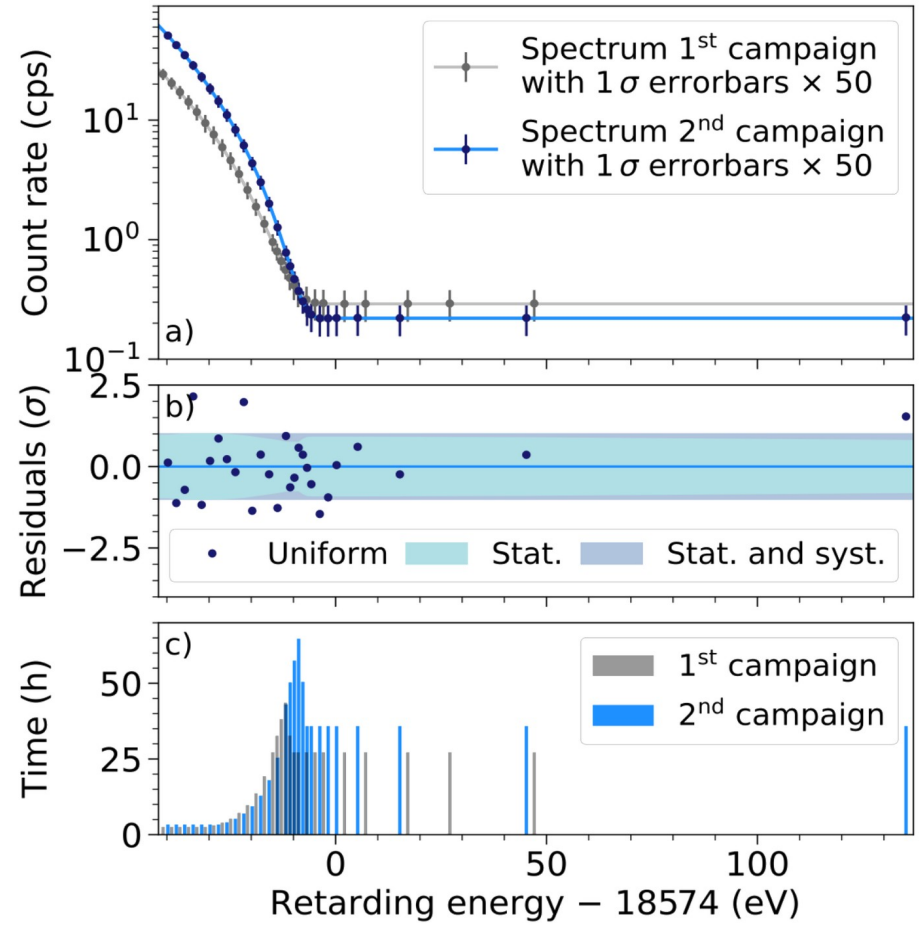
- total statistics: 2 million events
- best fit result: $m_\nu^2 = -1.0^{+0.9}_{-1.1}\ \mathrm{eV}^2$
- mass limit: $m_\nu < 1.1\ \mathrm{eV}\ (90\%\,CL)$

2nd campaign (autumn 2019)

- total statistics: 4.3 million events
- best fit result: $m_\nu^2 = 0.26^{+0.34}_{-0.34}\ \mathrm{eV}^2$
- mass limit: $m_\nu < 0.9\ \mathrm{eV}\ (90\%\,CL)$

Combine 1st and 2nd campaign:

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

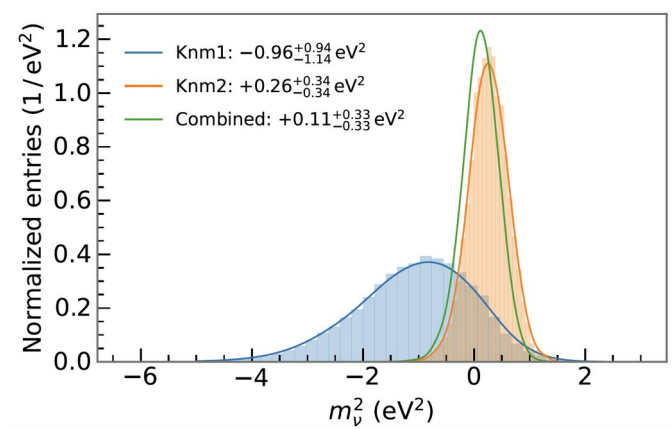


Cross-check: endpoint energy

E_0 = 18573.69 ± 0.03 eV → Q-value: 18575.2 ± 0.5 eV

→ good agreement with Penning trap experiments:

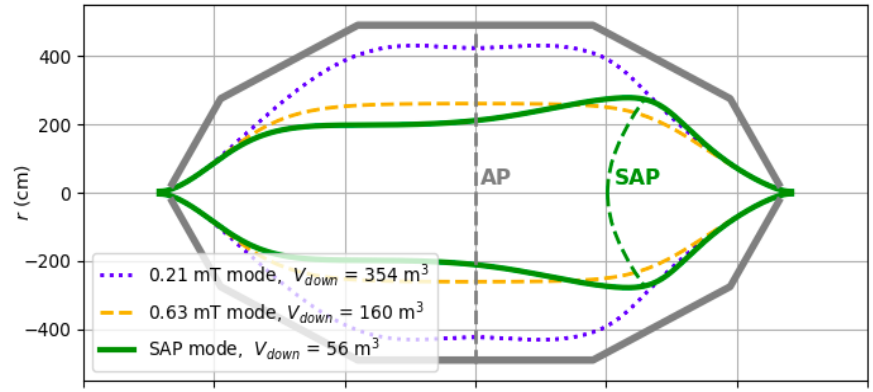
Q = 18575.72 ± 0.07 eV *(PRL 114 (2015) 013003)*



Nature Physics 18 (2022) 160

KATRIN improvements

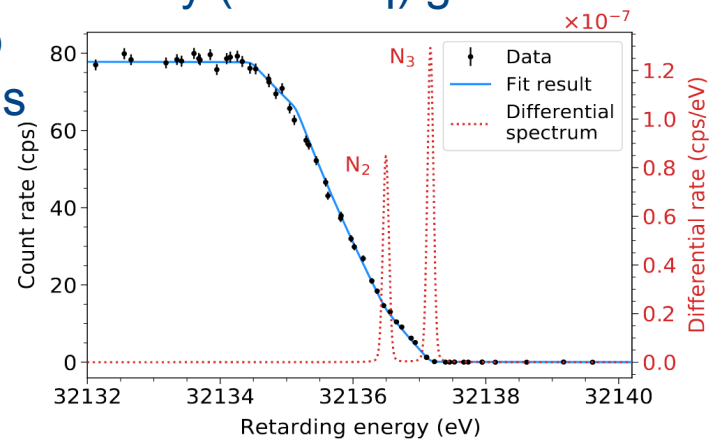
- New spectrometer field configuration (shifted analysis plane) reduced background by factor 2 and removes non-poissonian backgrounds



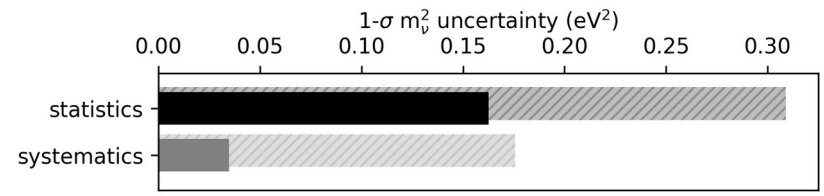
Eur. Phys. J. C 82 (2022) 258

- Calibration with high intensity (10 GBq) gaseous ^{83m}Kr source to map out source potentials

  → co-circulation with T_2 for simultaneous monitoring



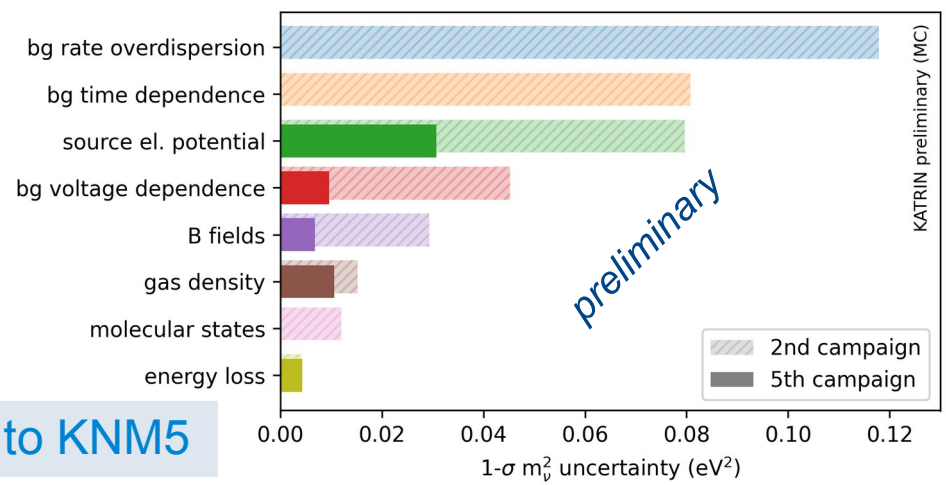
J. Phys. G 47 (2020) 065002



- Removal of inter-spectrometer Penning trap to eliminate background time dependence

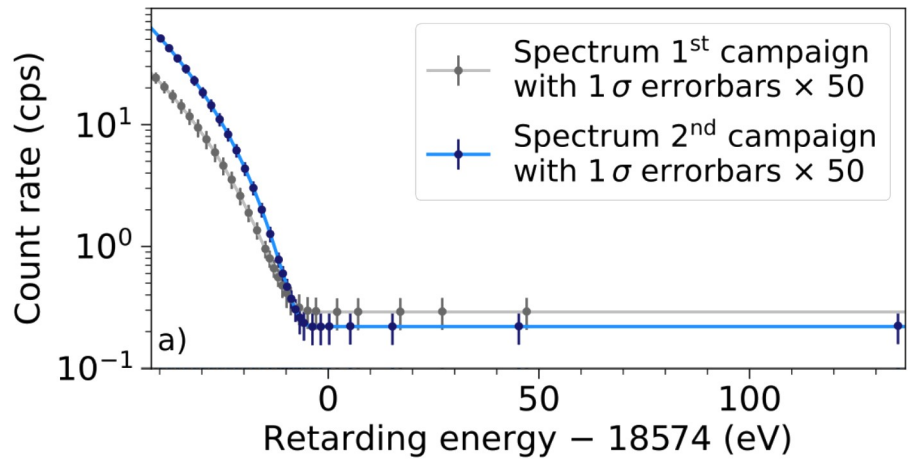
- New calculations of molecular final states in progress

- Many additional accuracy improvements ...

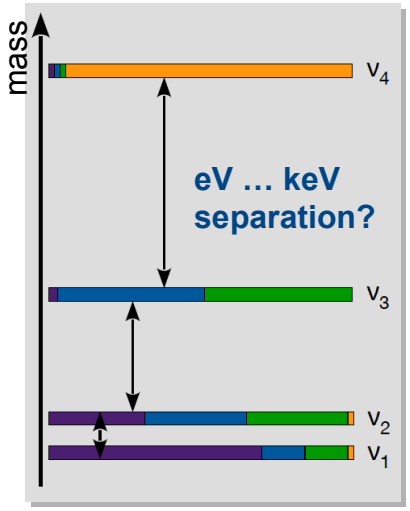


Expected uncertainty budget for KNM3 to KNM5

Beyond neutrino mass searches



Is there a fourth (sterile) neutrino?



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

Phys. Rev. D 105 (2022) 072004
arXiv:2207.06337v1 (2022)

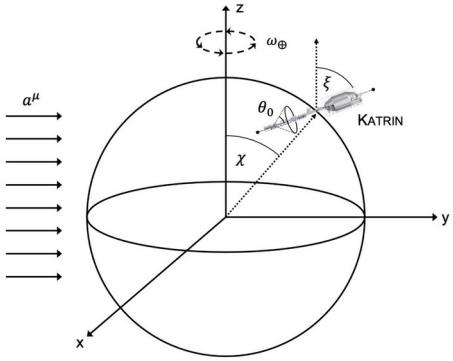
High statistics, high precision β spectrum

Constrain local over-density of cosmic relic neutrinos (peak search)

PRL 129 (2022) 011806

Search for exotic weak interactions (spectrum shape)

Search for Lorentz invariance violation (sidereal modulation)

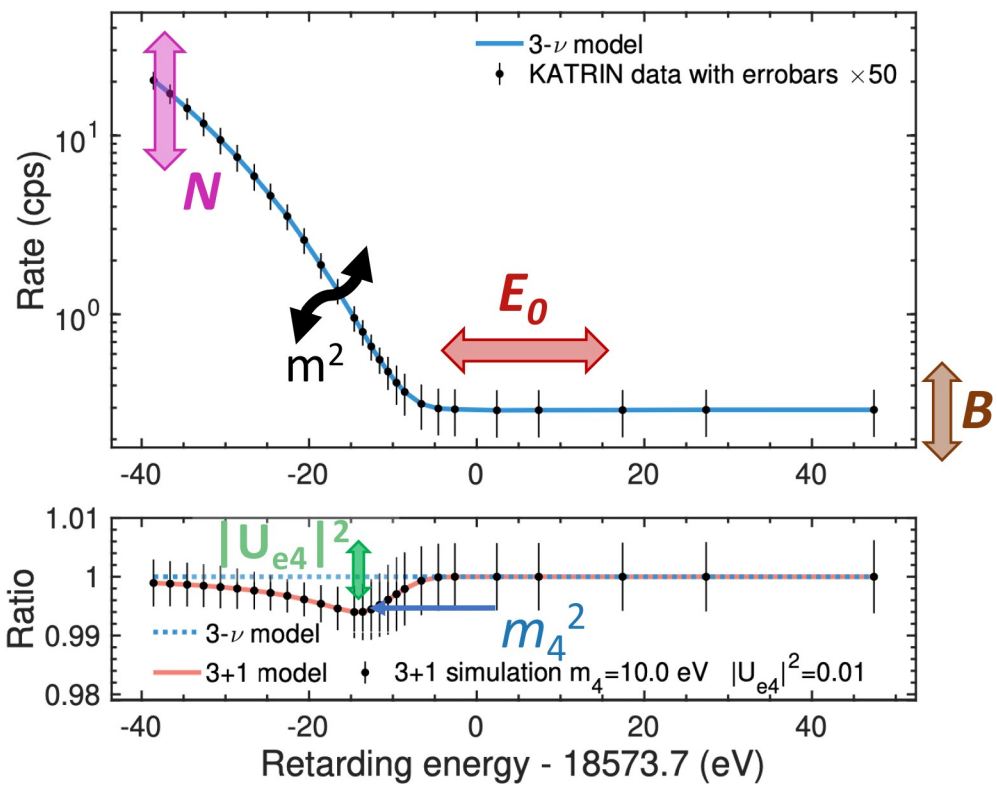


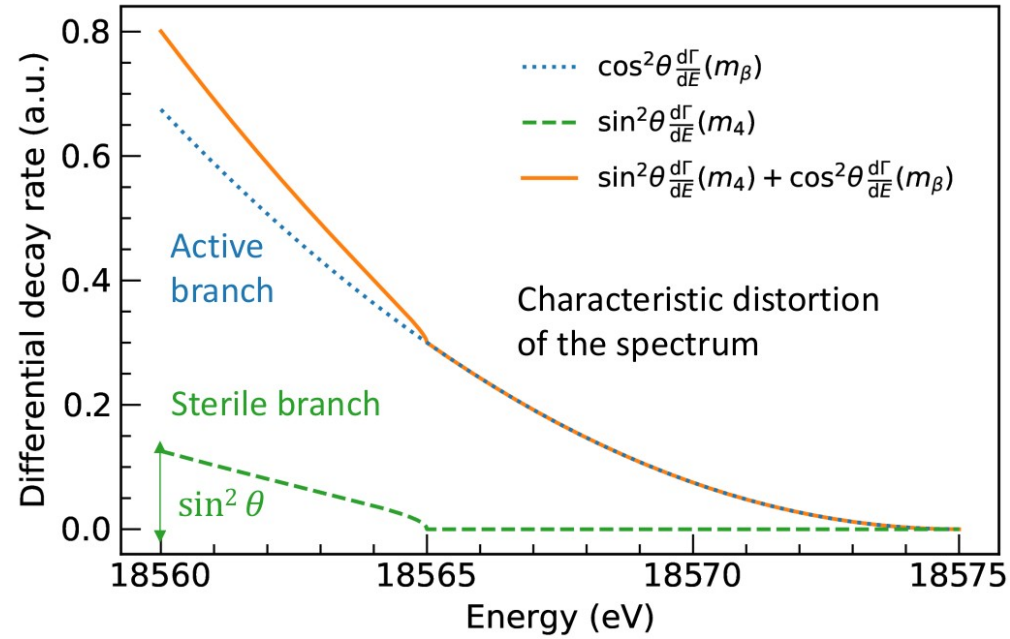
arXiv:2207.06326v1 (2022)

(Light) sterile neutrino signature

- 3+1 sterile neutrino model
- Same data-set as for the neutrino mass
- Grid search in m_4, $|U_{e4}|^2$ plane

$$\frac{d\Gamma}{dE} = \underbrace{\left(1-|U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2\frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$





6 Fit Parameters:

m^2	- neutrino mass (free/constrained)
E_0	- endpoint
N	- amplitude
B	- background rate
m_4^2	- 4th neutrino mass
$\|U_{e4}\|^2$	- 4th neutrino mixing

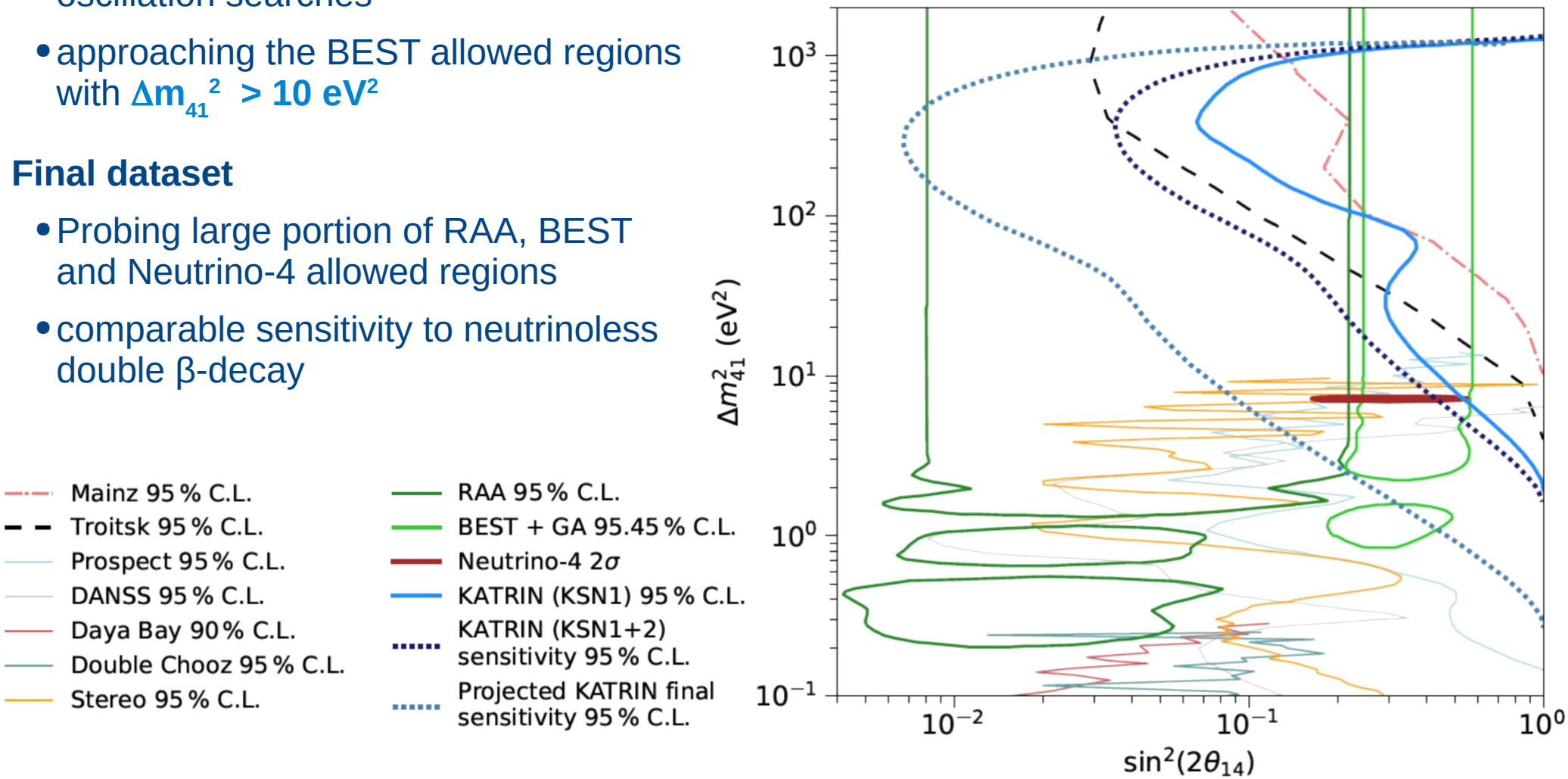
Limits on light sterile neutrinos

Current dataset

- KATRIN starts to probe very interesting parameter space, complementary to oscillation searches
- approaching the BEST allowed regions with $\Delta m_{41}^2 > 10\ eV^2$

Final dataset

- Probing large portion of RAA, BEST and Neutrino-4 allowed regions
- comparable sensitivity to neutrinoless double β-decay



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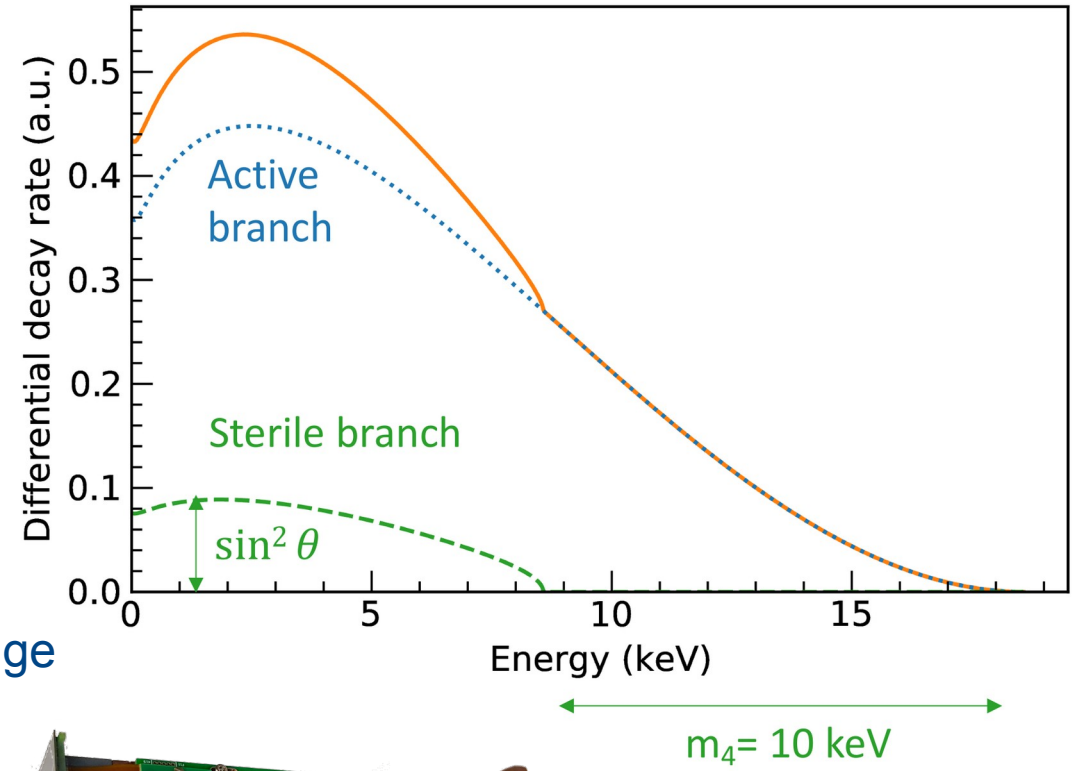
$$\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1-|U_{e4}|^2)$$

Future plans: keV scale sterile neutrinos

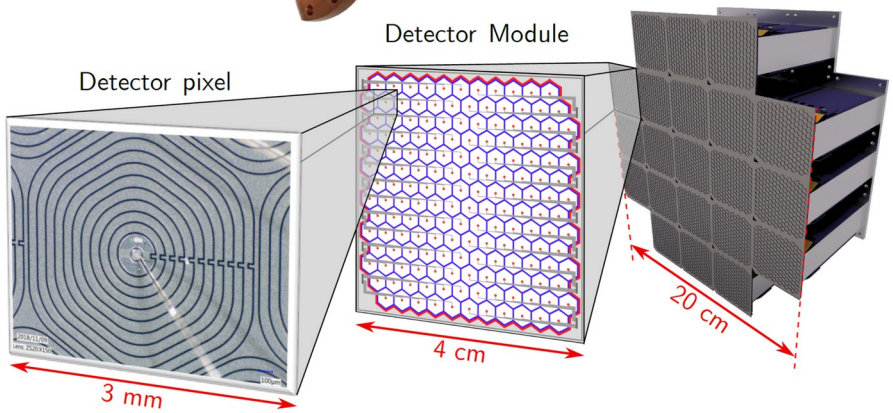
keV-scale sterile neutrino search:

- sterile neutrinos on keV-scale are a viable candidate for dark matter in the universe (WDM)
- First scans deep into the β-spectrum during FT campaign at 0.5% c.d. *arXiv:2207.06337v1 (2022)*
- high-sensitivity search requires new high-rate detector system (TRISTAN) to handle huge electron rates from WGTS over large spectral range



TRISTAN project in KATRIN:

- novel multi-pixel Silicon Drift Detector array
- large count rates
- excellent energy resolution
- prototypes installed as monitoring devices @ KATRIN
- target sensitivity: **$\sin^2\theta < 10^{-6}$**



Summary

- Studies of β-decay kinematics offer a model-independent way to determine the neutrino mass, complementary to cosmology and 0νββ searches
- The KATRIN experiment has finalized the analysis of the first two science runs and published the first sub-eV neutrino mass limit with **m_ν < 0.8 eV**
- Several improvements allowed to strongly reduce experimental background and systematic uncertainties
- Analysis of KNM3 to KNM5 science runs ongoing, unblinding will happen soon
- KATRIN has the capability to study several physics topics beyond neutrino mass:
  - eV-scale sterile neutrinos (first upper limits published)
  - keV scale sterile neutrinos (future project with new focal plane detector TRISTAN)
  - upper limit on local relic neutrino overdensity
  - investigations of Lorentz invariance
  - search for exotic weak interactions