KATRIN experiment: first neutrino mass result and future prospects

Alexey Lokhov on behalf of KATRIN collaboration

13th European Research Conference
on Electromagnetic Interactions with Nucleons and Nuclei
Paphos, Cyprus

Institut für Kernphysik
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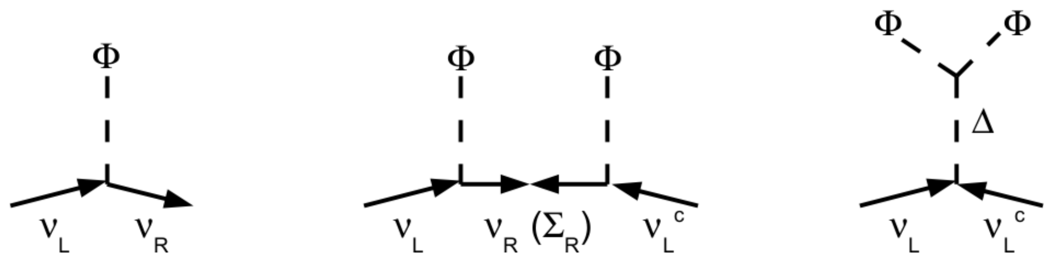
Outline

- Neutrino masses in particle physics and cosmology
- Neutrino mass measurements
  - **Complementary ways to the neutrino mass scale**
  - **Tritium β-decay spectrum**
- KATRIN experiment
  - **Setup**
  - **MAC-E-Filter Principle**
  - **Experimental response**
  - **First Tritium**
  - **First neutrino mass result**
  - **Current status and future**
- Conclusion and Outlook

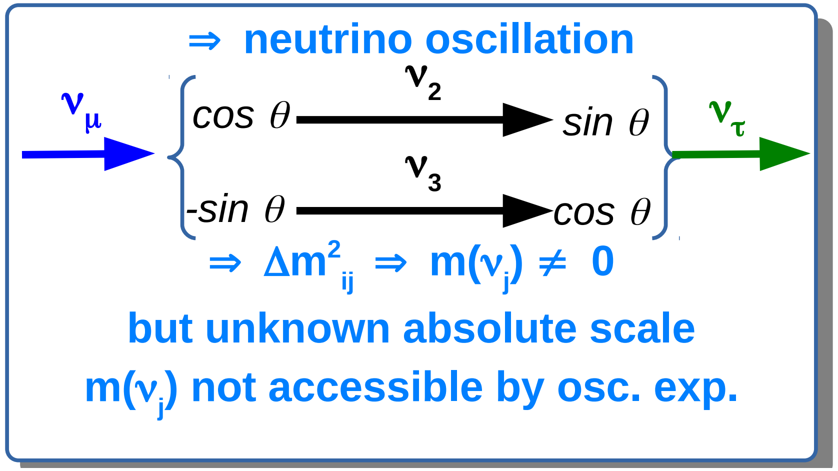
Neutrino masses in particle physics and cosmology

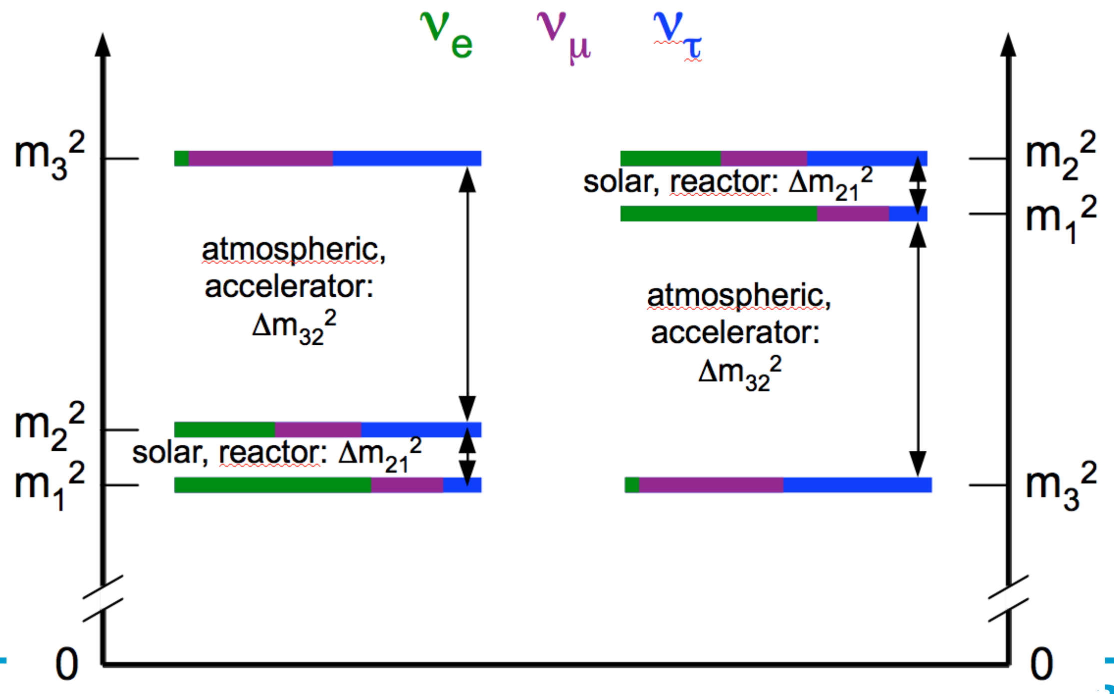
- Discovery of the neutrino oscillations
  - **non-zero neutrino masses**
  - **Physics Nobel Prize 2015:**

    Prof. Dr. T. Kajita, Prof. Dr. A.B. McDonald
- Neutrino mass ordering
- A small ν mass generation mechanism is needed, likely beyond the Standard model Higgs



- The most abundent massive particle in the Universe – 336 ν cm^{-3}
  - **only weak interaction with matter**





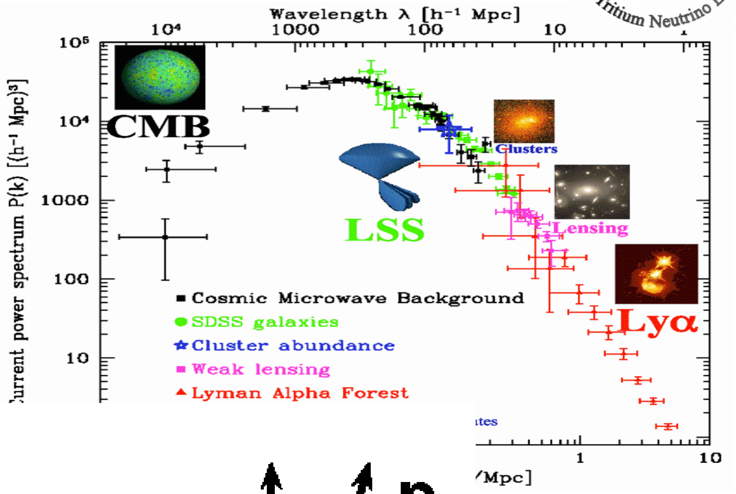
Three ways to assess the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

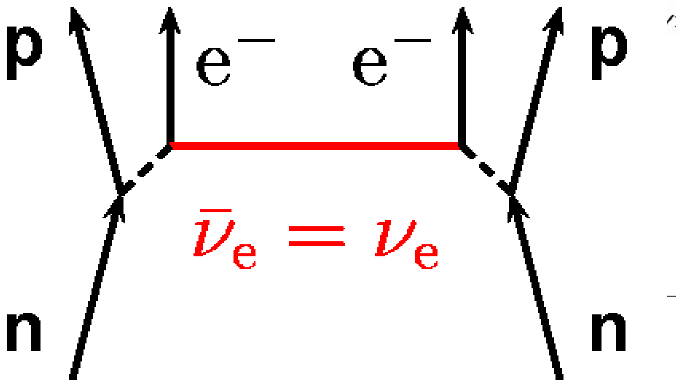
current sensitivity: $\Sigma m(\nu_i) \approx 0.12$ eV (Planck)



2) Search for 0νββ

Sensitive to Majorana neutrinos, model-dependent

Upper limits by EXO-200, KamLAND-Zen, GERDA, CUORE: $m_{\beta\beta} < 0.1\text{-}0.4$ eV



3) Direct neutrino mass determination

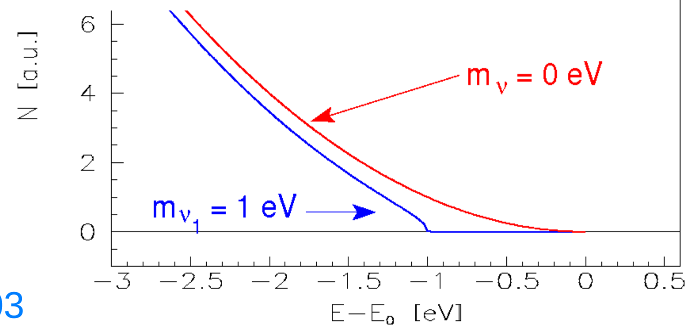
No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4$

$\Rightarrow m^2(\nu)$

Time-of-flight measurements (ν from supernova)

Kinematics of weak decays / beta decays, e.g. tritium, ^{163}Ho

best upper limits m(ν) < 2 eV (Mainz & Troitsk)



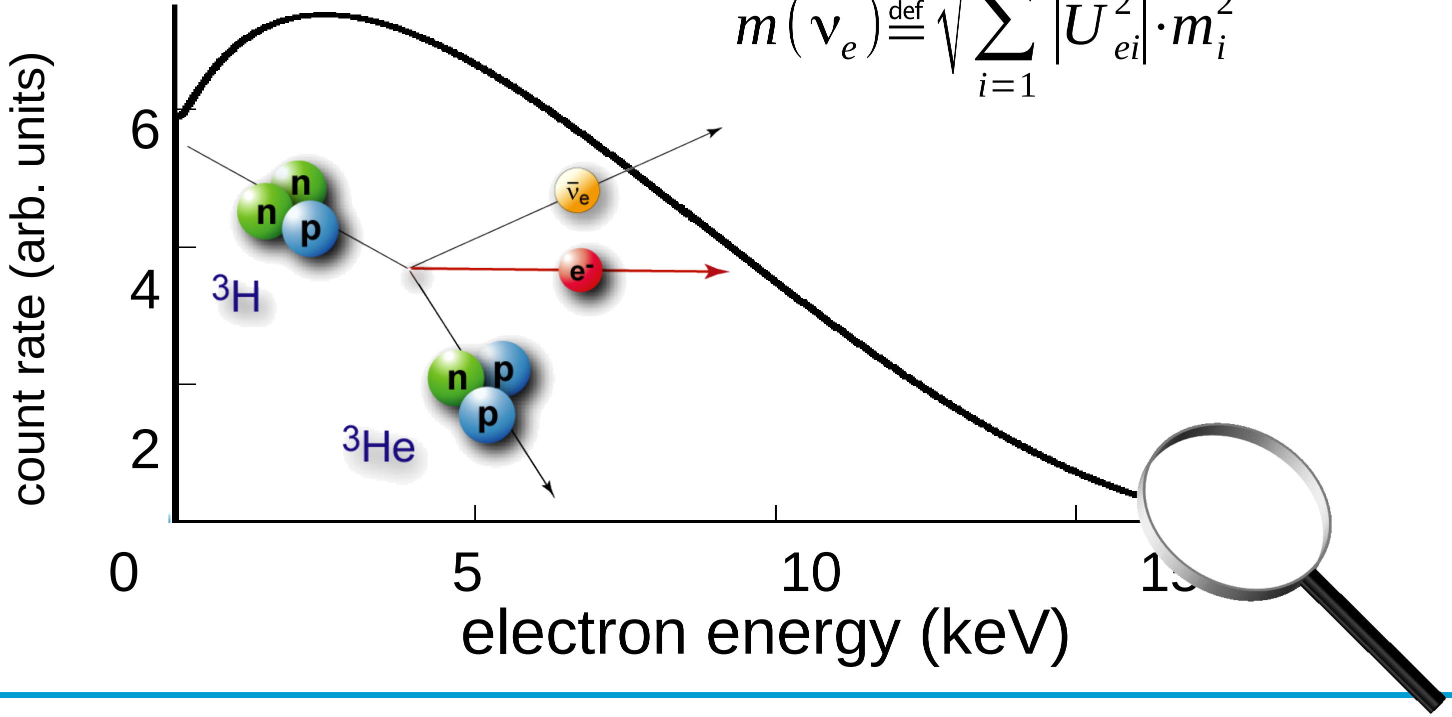
N. Aghanim et al. (Planck), (2018), arXiv:1807.06209; M. J. Dolinski, A. W. Poon, and W. Rodejohann, Annual Review of Nuclear and Particle Science 69, 219 (2019); Eur. Phys. J. C 40, 447 (2005); Phys. Rev. D 84, 112003

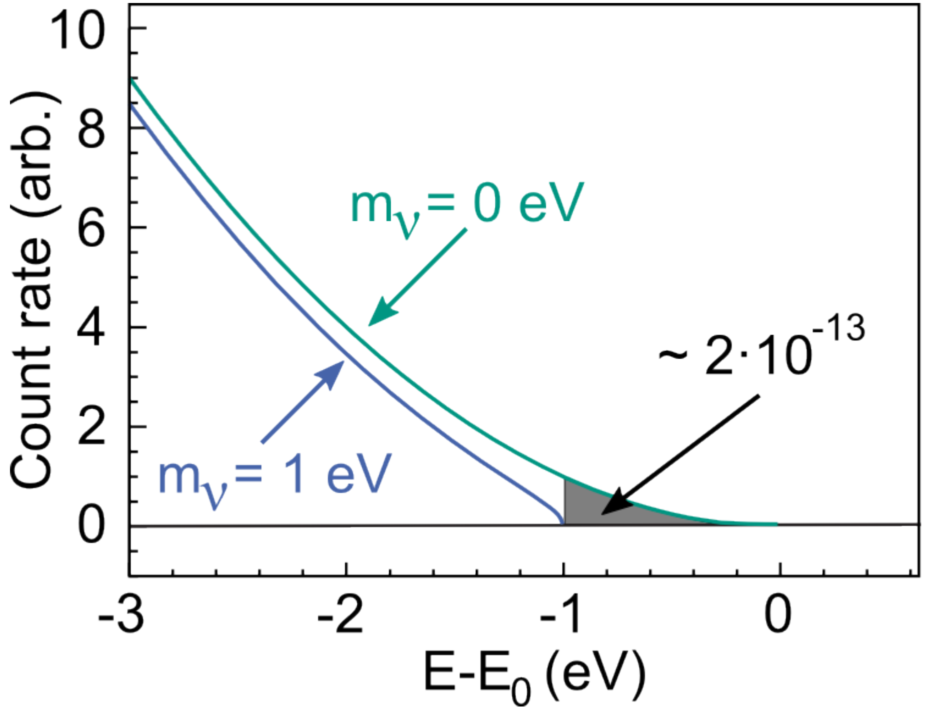
Tritium β-decay

- continuous β-spectrum described by Fermi´s Golden Rule, measurement of effective mass m(ν_e) based on **kinematic parameters & energy conservation**

$$\frac{d\Gamma}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} |U_{ei}^2| \cdot \sqrt{(E_0 - E)^2 - m_{\nu_i}^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_{\nu_i}^2)$$

$$m(\nu_e) \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}^2| \cdot m_i^2}$$





Tritium β-decay

Need: low endpoint energy ⇒ Tritium ^{3}H – 18.6 keV

short half-life (superallowed) – 12.3 yr

(^{163}Ho electron capture)

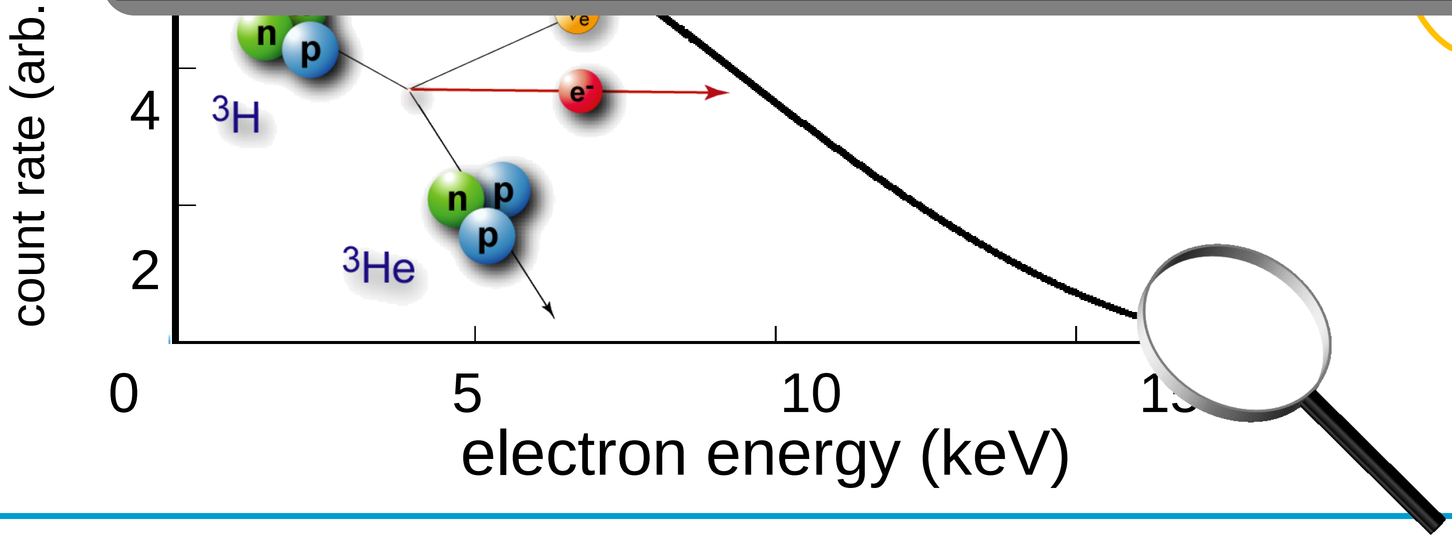
very high energy resolution &

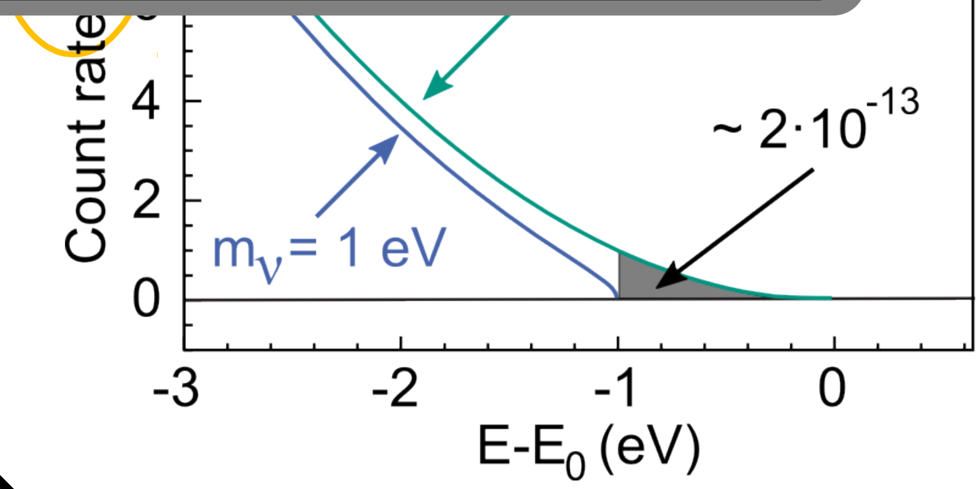
very high luminosity &

very low background

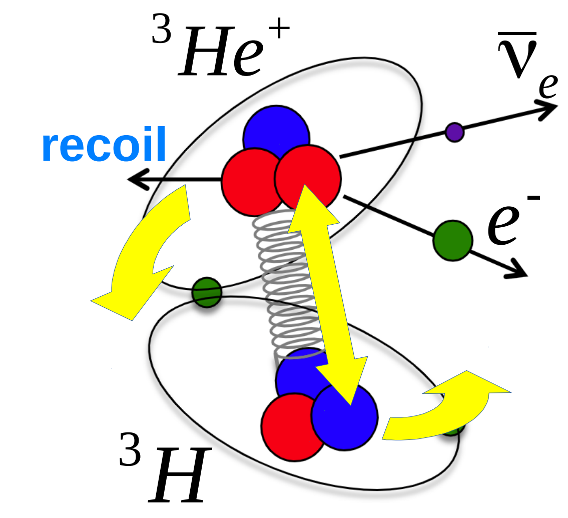
⇒ MAC-E-Filter ⇒ KATRIN

(cryogenic bolometers⇒ ECHo, HOLMES)

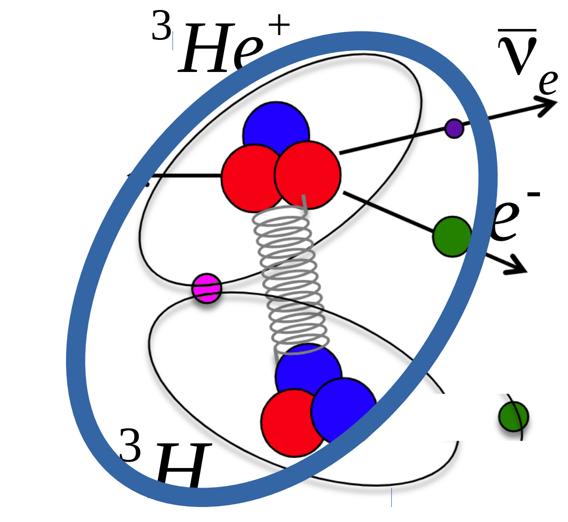




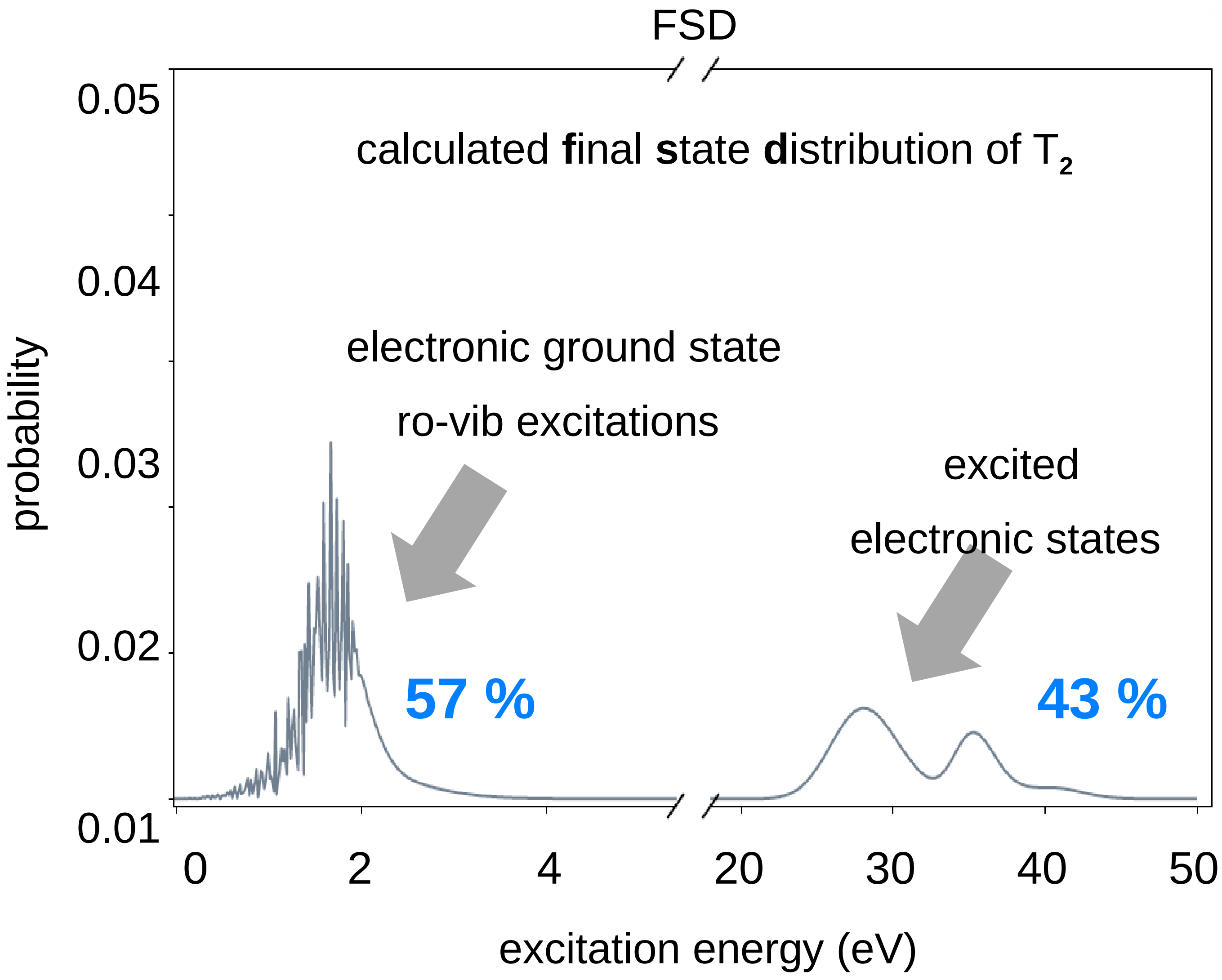
Tritium β-decay – T_2



Rotational and vibrational excitations



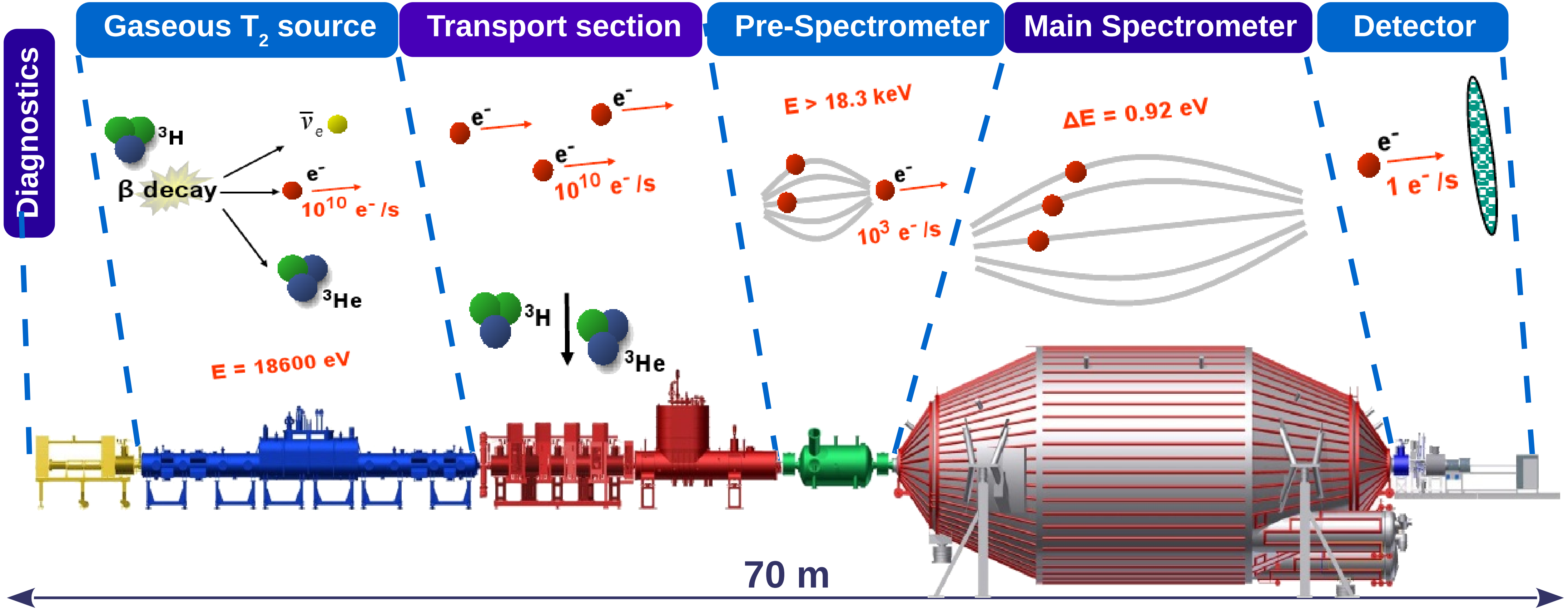
Electronic excitations and ionization due to Migdal effect → new electronic wavefunction



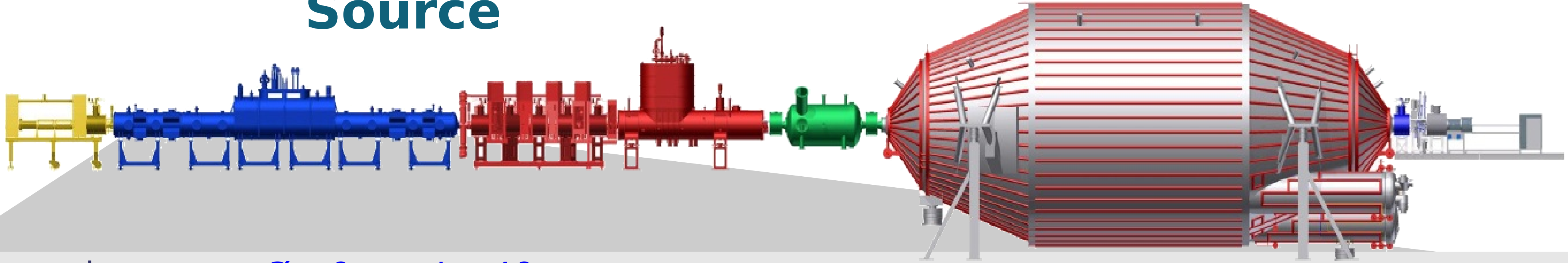
atomic source (T) would have simpler FSD but difficult to handle – PROJECT 8

A. Ashtari Esfahani et al. (Project 8), J. Phys. G 44,054004 (2017), arXiv:1703.02037

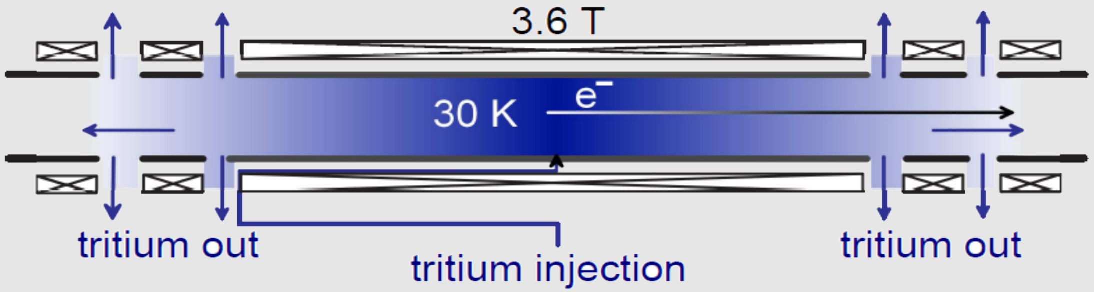
The KATRIN experiment at Karlsruhe Institute for Technology



The KATRIN Windowless Gaseous Molecular Tritium Source



beam tube	Ø = 9 cm , L = 10 m
guiding field	3.6 T (2.52 T)
temperature	T = 30 K ± 30 mK,
T_2 flow rate	$5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)
T_2 purity	95% ± 0.1 %
T_2 inlet pressure	10^{-3} mbar ± 0.1 %

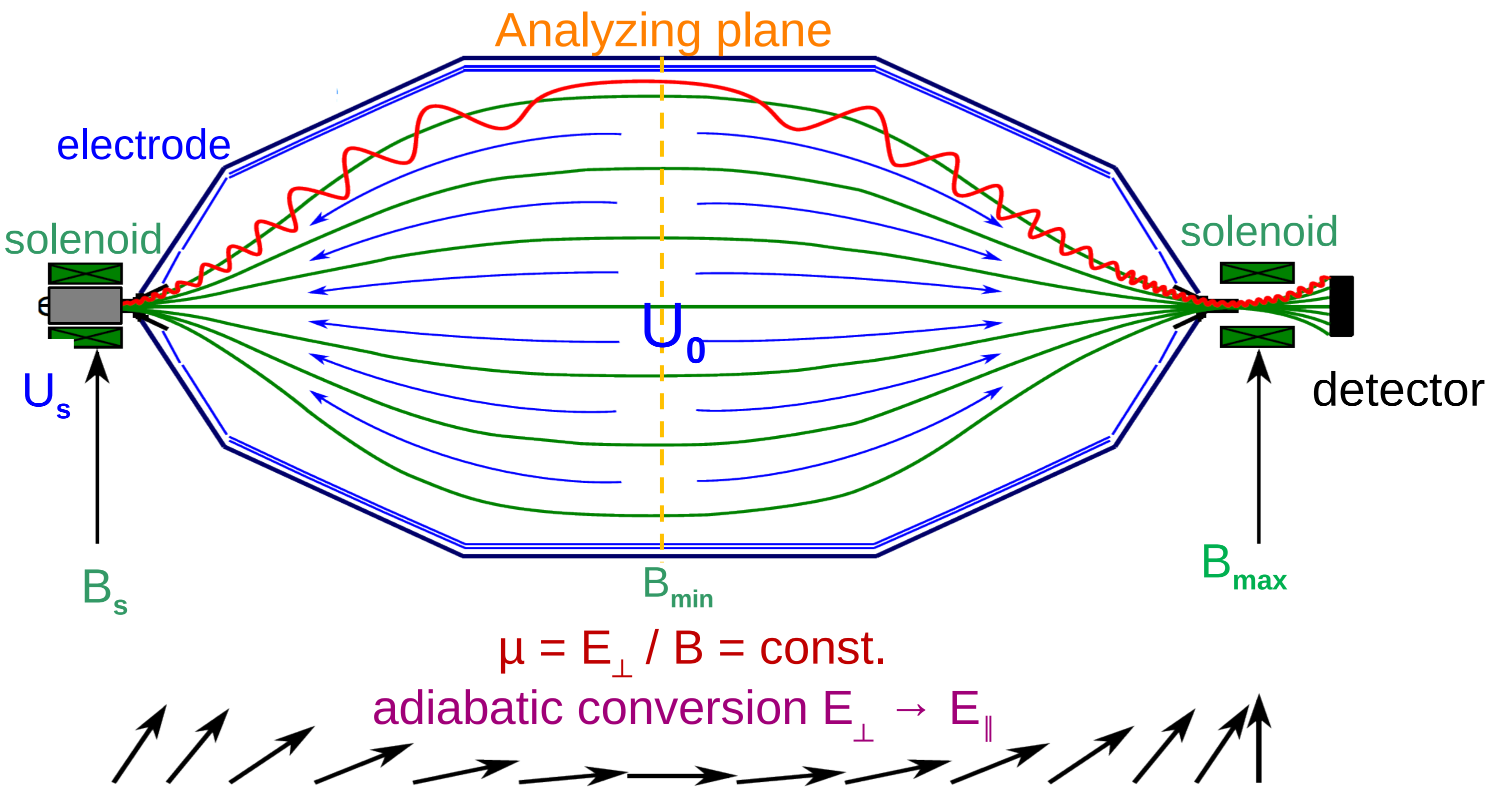


column density $5 \cdot 10^{17}$ T_2/cm^2

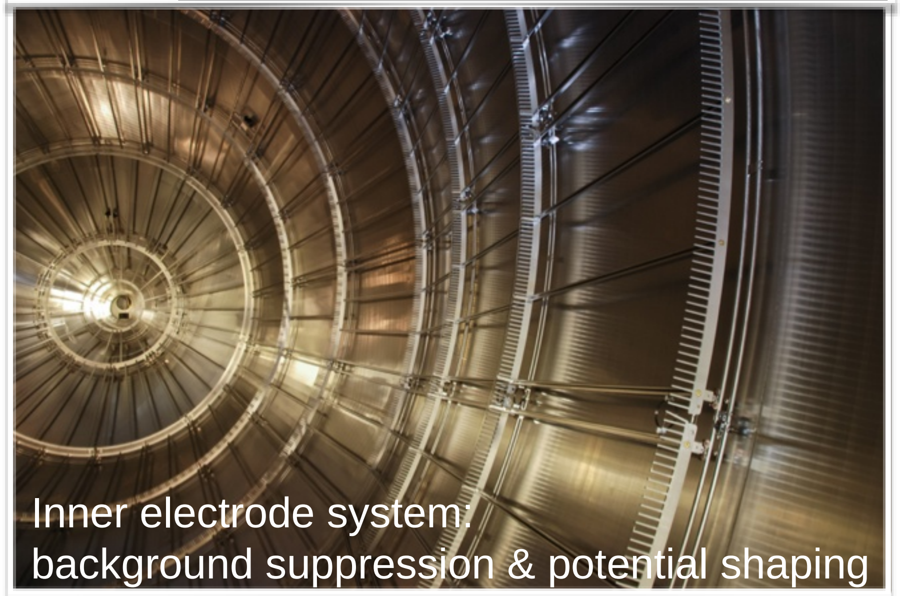
luminosity $1.7 \cdot 10^{11}$ Bq

MAC-E-Filter: high-resolution β-spectroscopy

Magnetic Adiabatic Collimation & Electrostatic Filter:



Momentum tranfsormation without the E-field



Response function of KATRIN

Shooting electrons from monoenergetic pulsed UV-laser photoelectron source through tritium column density

(Eur. Phys. J. C77 (2017) 410, Astropart. Phys. 89 (2017) 30)

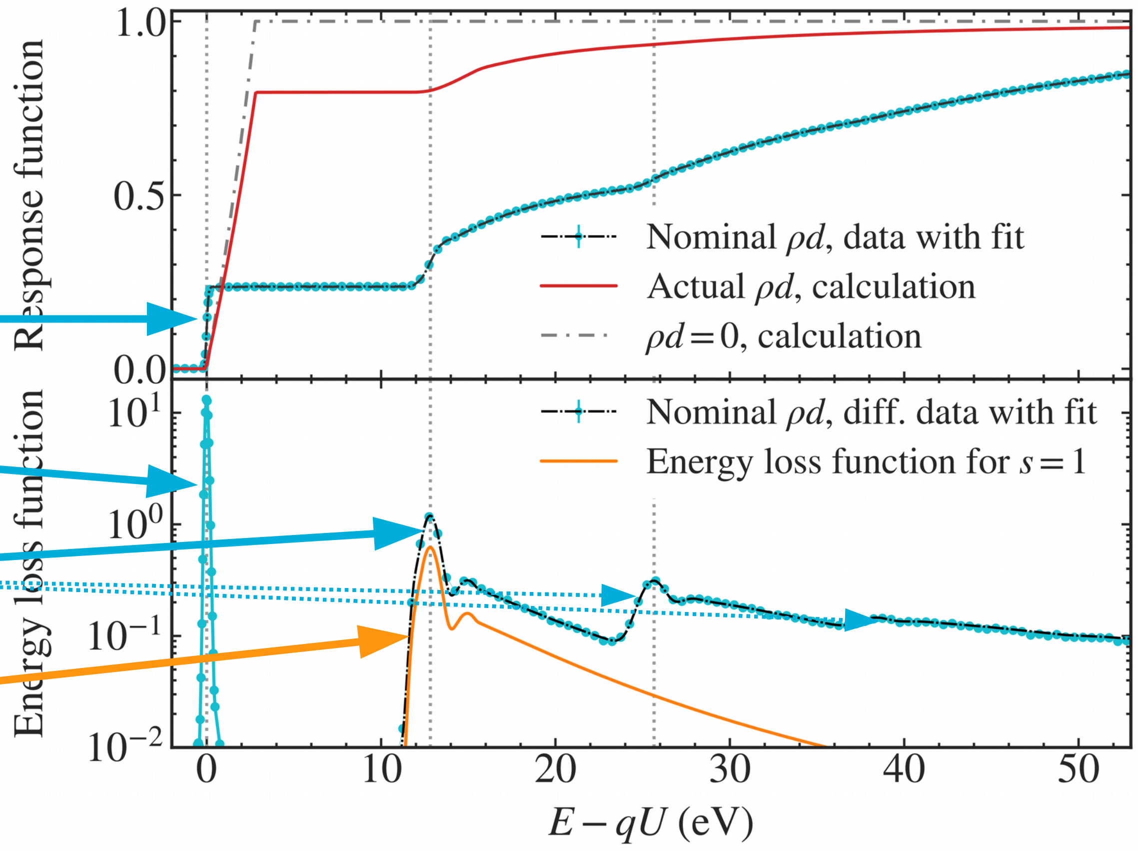
Normal integral MAC-E-Filter mode

Differential Time-of-flight mode
(Nucl. Inst. Meth. A 421 (1999) 256,
New J. Phys. 15 (2013) 113020)

1-fold, 2-fold, 3-fold inelastic scattering

Deconvoluted differential energy loss function

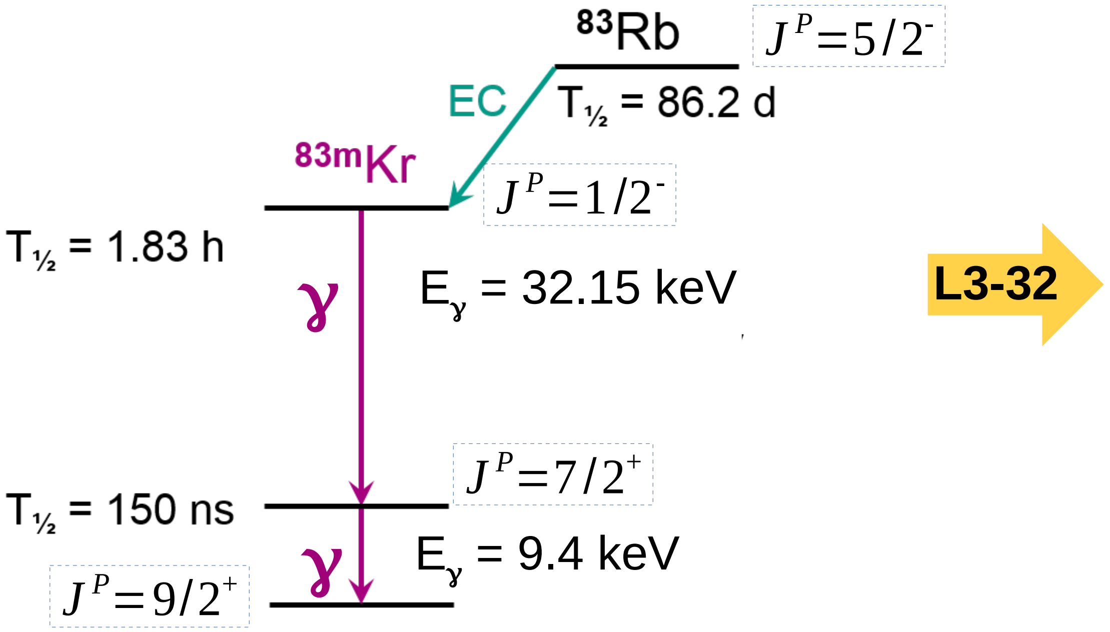
(arXiv:1909.06048, subm. to Phys. Rev. Lett.)



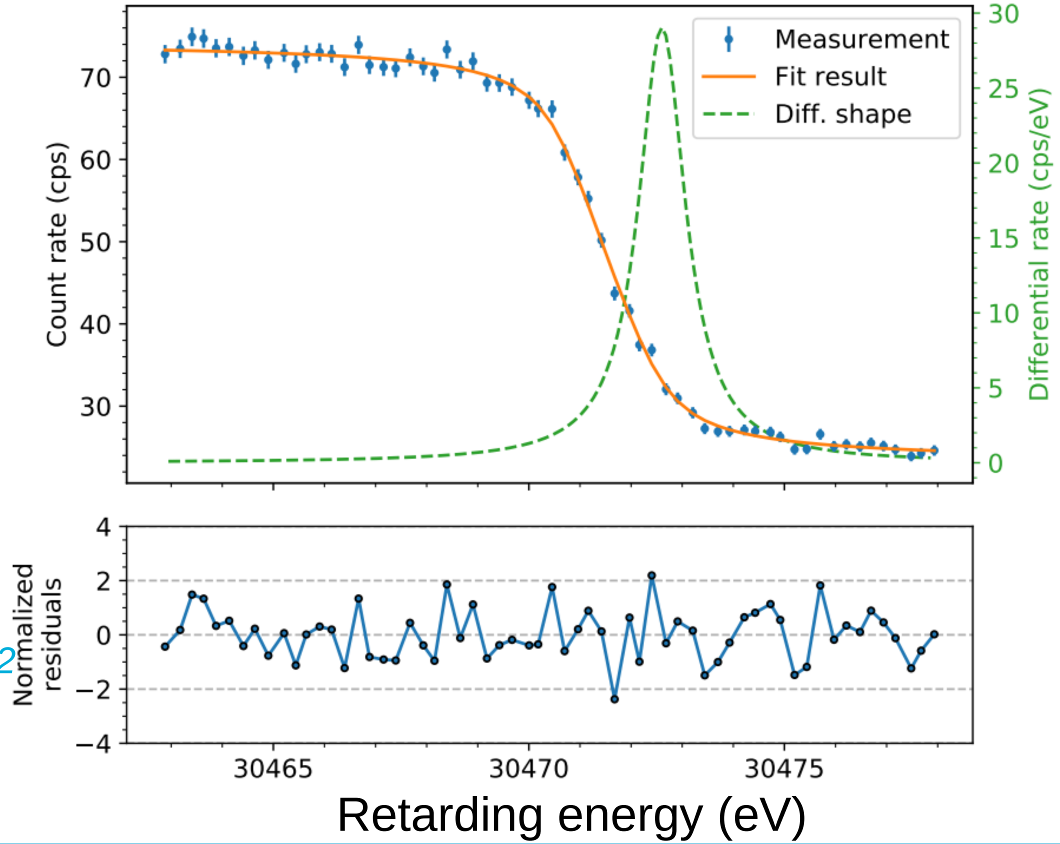
Measuring the response with ^{83m}Kr

- **MAC-E filter characteristics well understood**
- **(also used to study plasma)**

filter width ⇒ $$\frac{\Delta E}{E} \cong \frac{B_{min}}{B_{max}} \cdot E$$



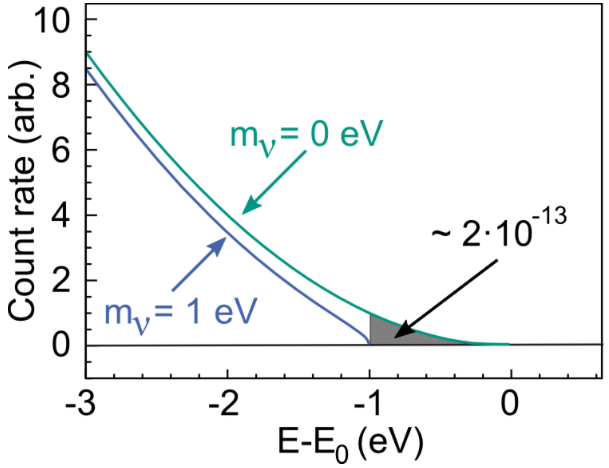
L3-32 line: 30.47 keV



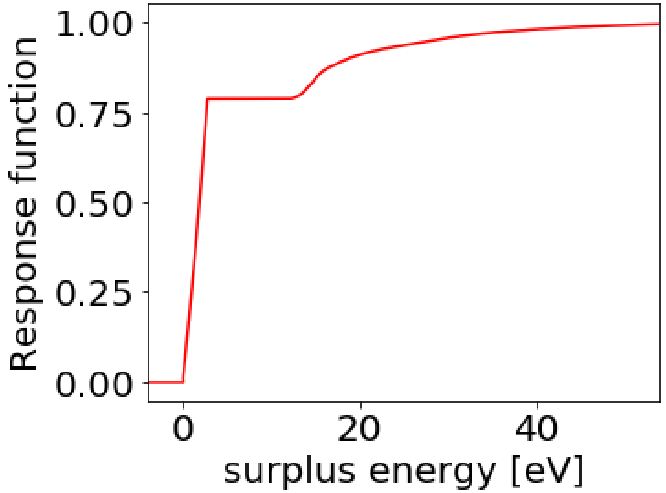
KATRIN Collab., "High-resolution spectroscopy of gaseous ^{83m}Kr conversion electrons with the KATRIN experiment", arXiv:1903.06452
"Calibration of high voltages at the ppm level by the difference of 83mKr conversion electron lines at the KATRIN experiment", Eur. Phys. J. C (2018) 78:368

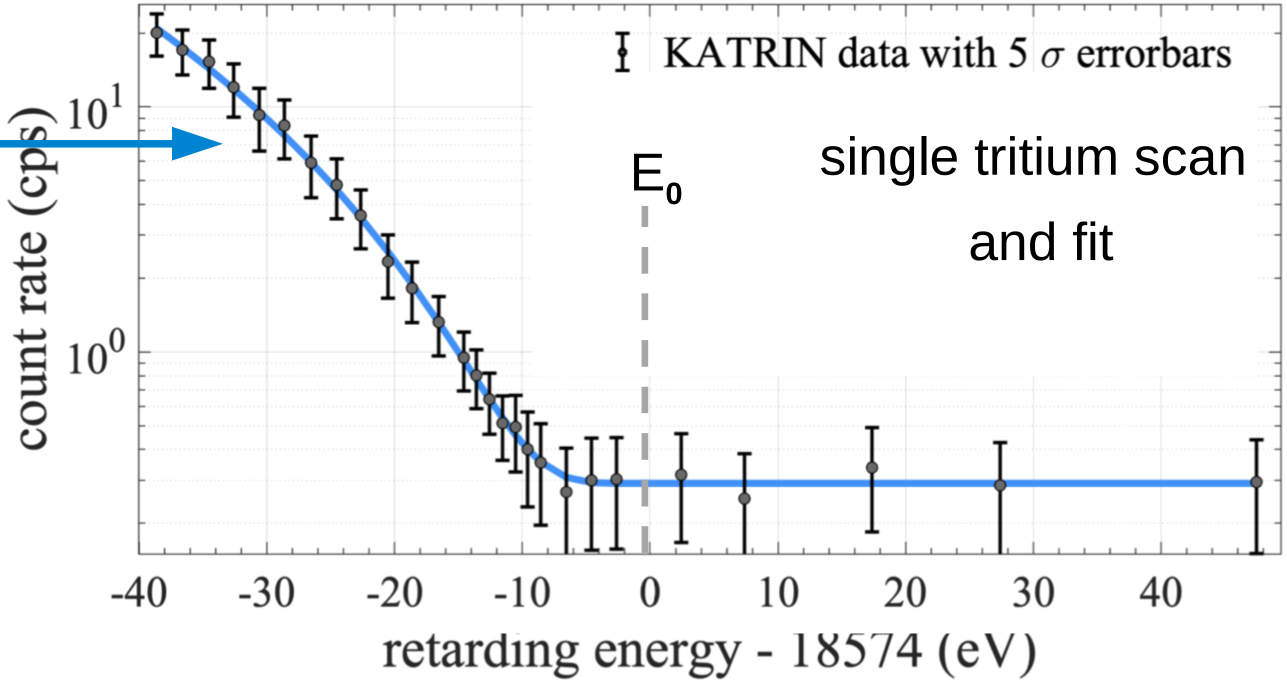
Model of the experimental spectrum

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



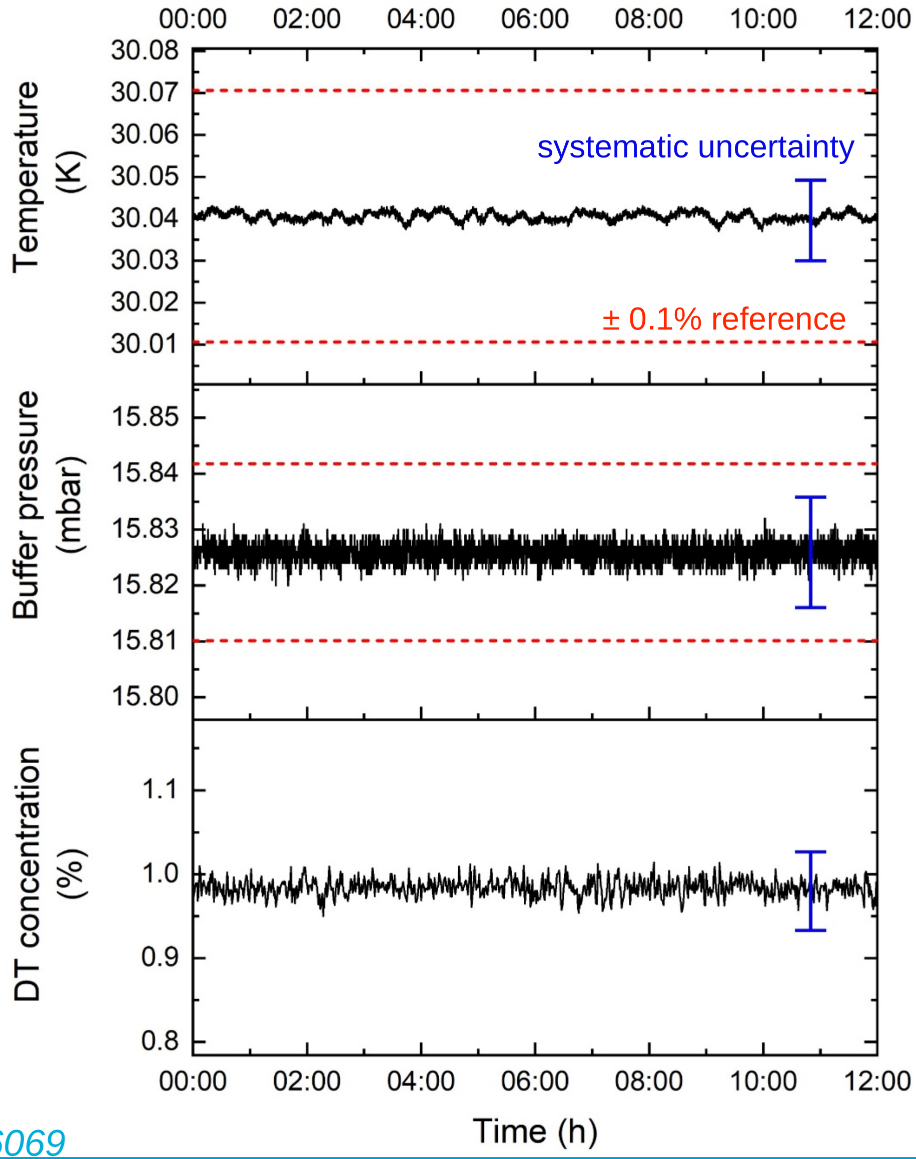
- **Experimental response: f(E-qU)**





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

First Tritium (2-week engineering run in 2018)



First Tritium:

- **low tritium concentration**:
  ~1% DT and ~99% D_2
- functionality of all system components at nominal column density ρd ($5 \cdot 10^{17}$ cm^{-2})
- stability of the source parameters
  → sub per mille level

KATRIN Collab., "First operation of the KATRIN experiment with tritium", arXiv:1909.06069

KATRIN neutrino mass run # 1

4-week long measuring campaign in spring 2019 with high-purity tritium

- April 10 – May, 13 2019: 780 h
- high-purity tritium
  (ε_T = 97.5 % by laser-Raman spectr.)
- high source activity (22% nominal):
  $2.45 \cdot 10^{10}$ Bq
- high-quality data collected
- full analysis chain using two
  independent methods

Tritium scanning strategy

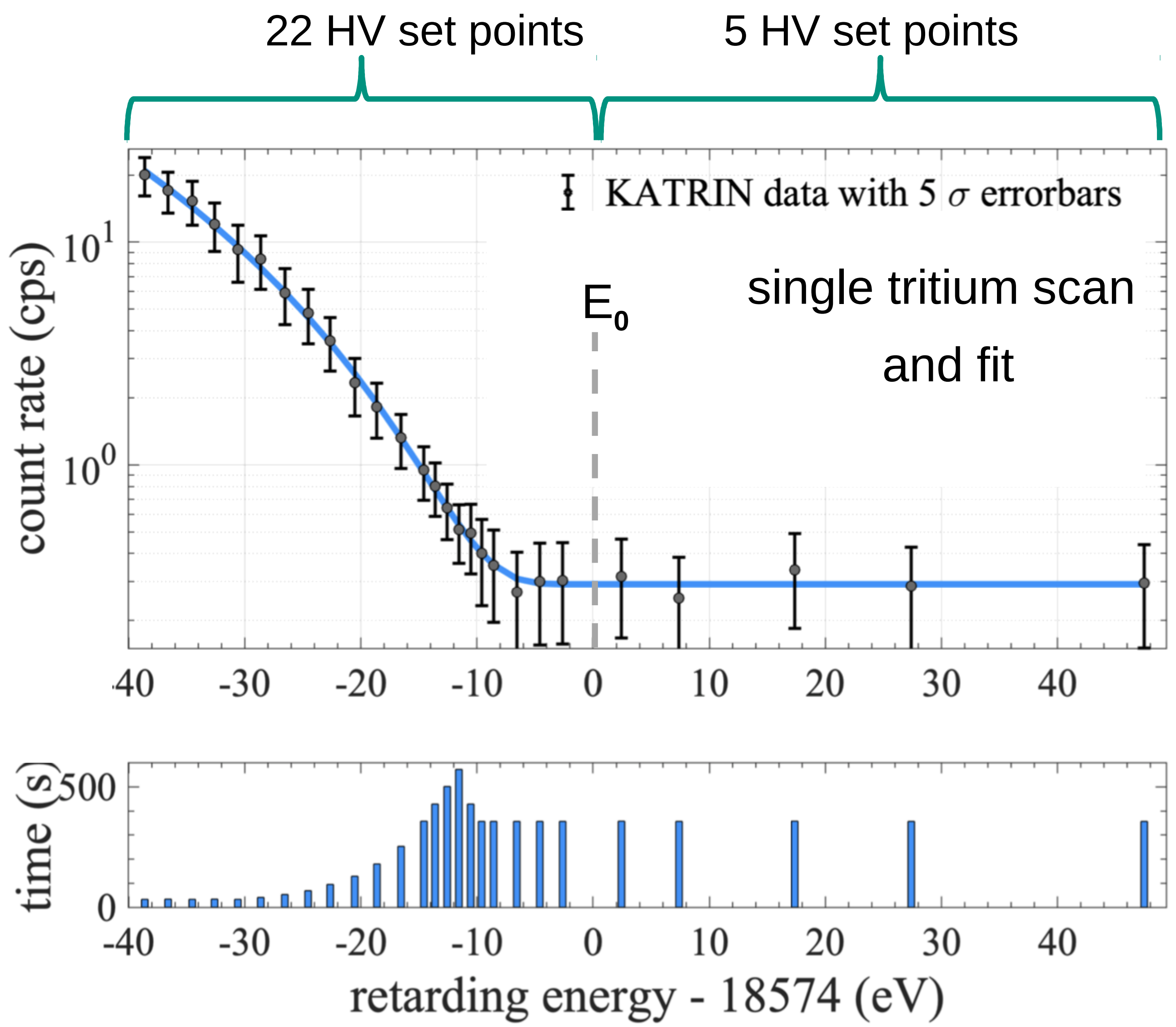
274 scans of tritium β-spectrum:

- alternating up- / down- scans
- 2 h net scanning time
- analysis: 27 HV set points
- [E_0 – 40 eV , E_0 + 50 eV]

still limited　　bg-slope

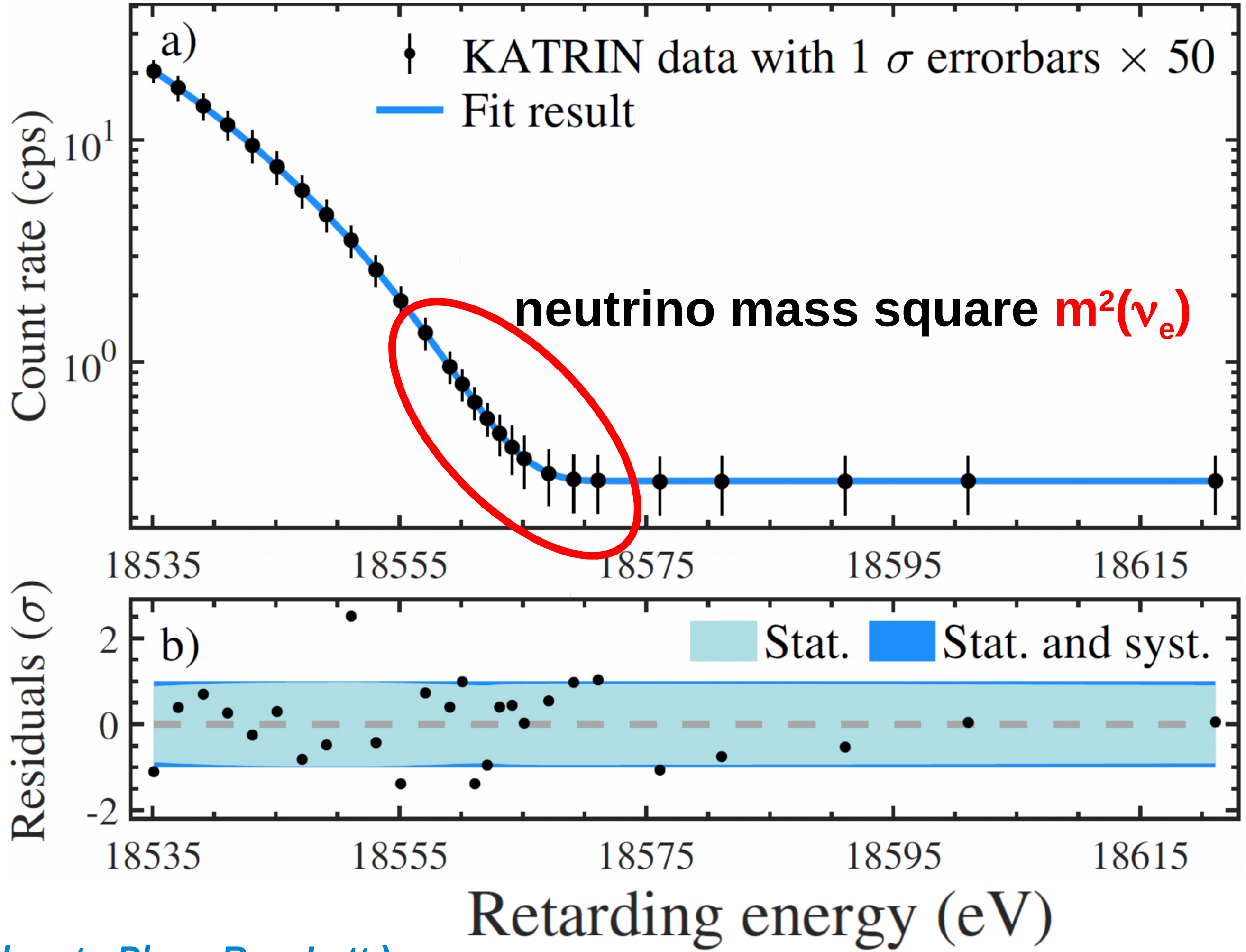
Measurement point distribution maximises ν-mass sensitivity

- focus on region close to E_0



Fitting tritium β-decay spectrum

- **High-statistics β-spectrum**
  - 2 million events in
    in 90-eV-wide interval
    (522 h of scanning, 274 indiv. scans)
  - fit with 4 free parameters:
    $m^2(\nu_e)$, R_{bg}, A_s, E_0
    excellent goodness-of-fit
    χ^2 = 21.4 for 23 d.o.f.
    (p-value = 0.56)
- **Bias-free analysis**
  - blinding of FSD
  - full analysis chain first on
    MC data sets
  - final step: unblinded FSD
    for experimental data



(arXiv:1909.06048, subm. to Phys. Rev. Lett.)

Analysis methods and ν-mass result

- **two independent analysis methods**
  to propagate uncertainties & infer parameters

  - Covariance matrix:
    covariance matrix + χ^2-estimator

  - MC propagation:
    10^5 MC samples + likelihood (-2 ln L)

  - both methods agree to a few percent

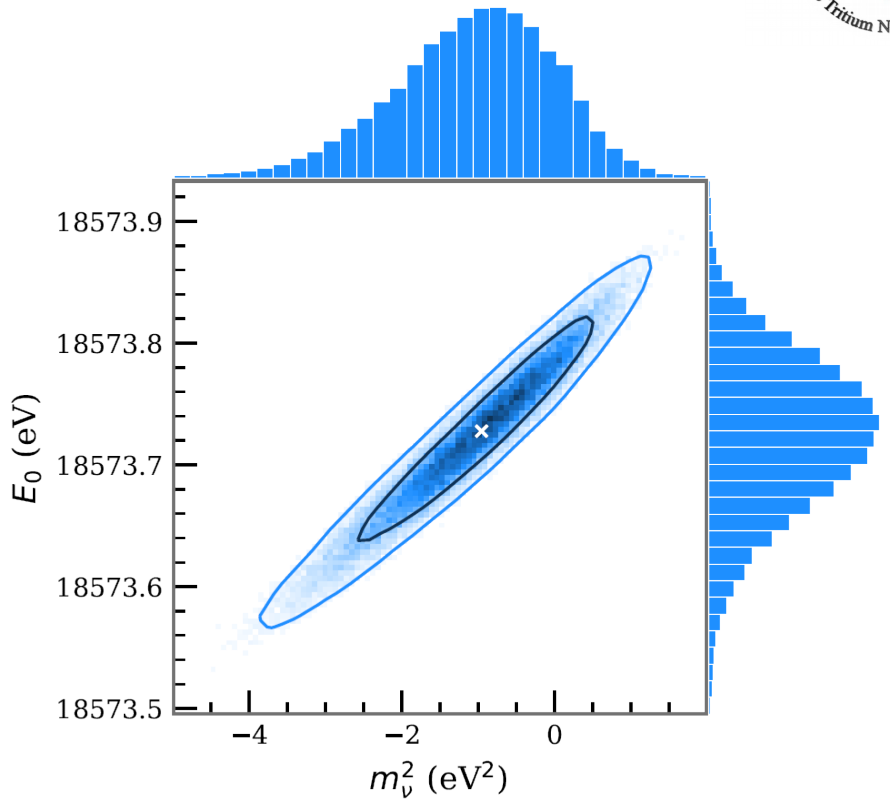
- **ν-mass and E_0: best fit results**

$$m^2(\nu_e) = -1.0\ ^{+0.9}_{-1.1}\ \text{eV}^2$$

$$E_0 = (18573.7 \pm 0.1)\ \text{eV}$$

→ Q-value: (18575.2 ± 0.5) eV

→ Q-value[$\Delta M(^3H,^3He)$]: (18575.72 ± 0.07) eV



KATRIN collab.
arXiv:1909.06048
subm. to Phys. Rev. Lett.

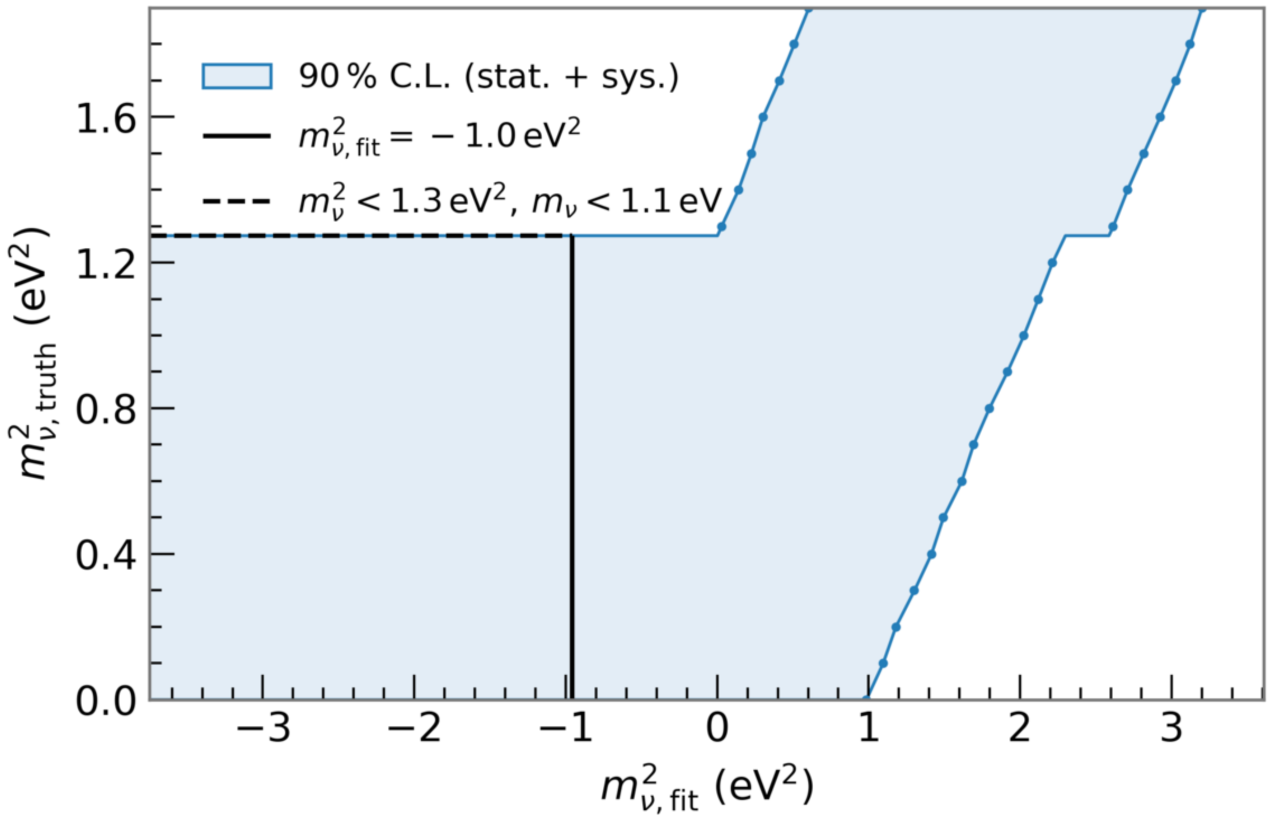
E.G. Myers, A. Wagner, H. Kracke, B.A. Wesson,
Phys. Rev. Lett. 114, 013003 (2015)

New upper limit on neutrino mass

confidence belts: procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC)

- for this first result we follow the robust LT method
- LT yields experimental sensitivity by construction for $m^2(\nu_e) < 0$
- **KATRIN upper limit on neutrino mass:**

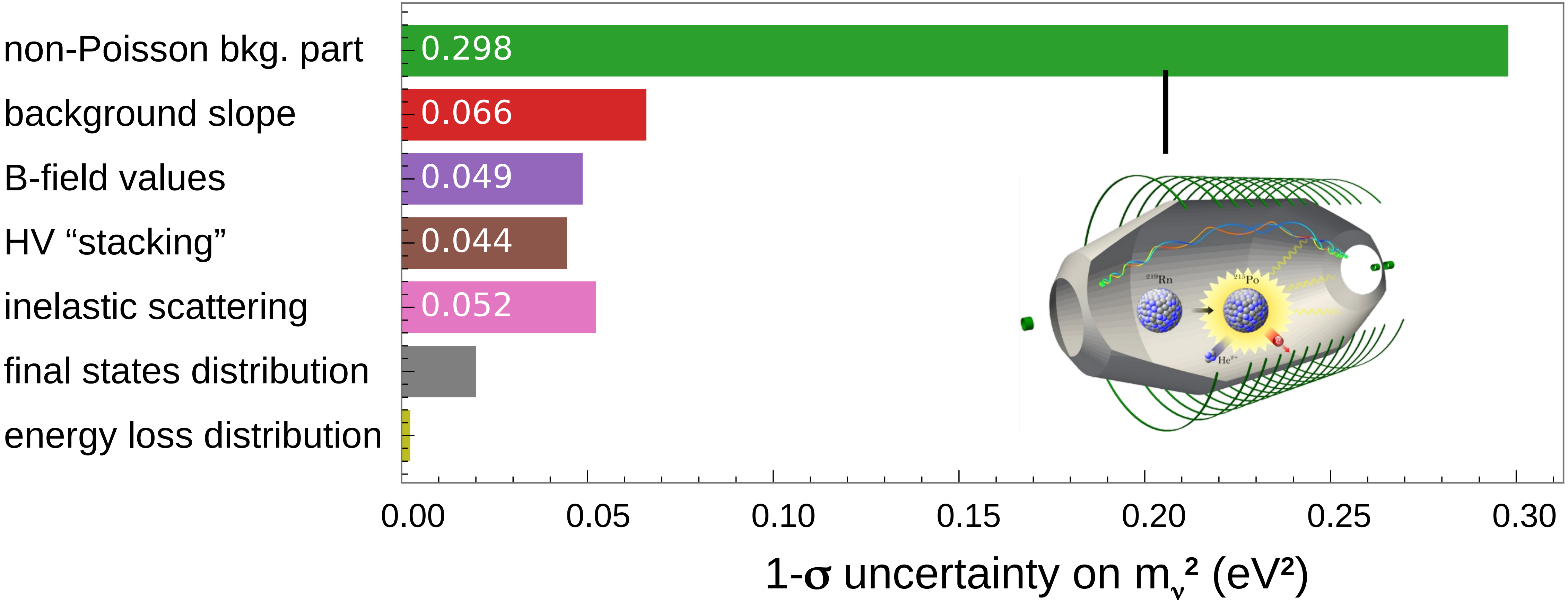
LT	**m(ν) < 1.1 eV (90% CL)**
FC	m(ν) < 0.8 eV (90% CL)
	< 0.9 eV (95% CL)



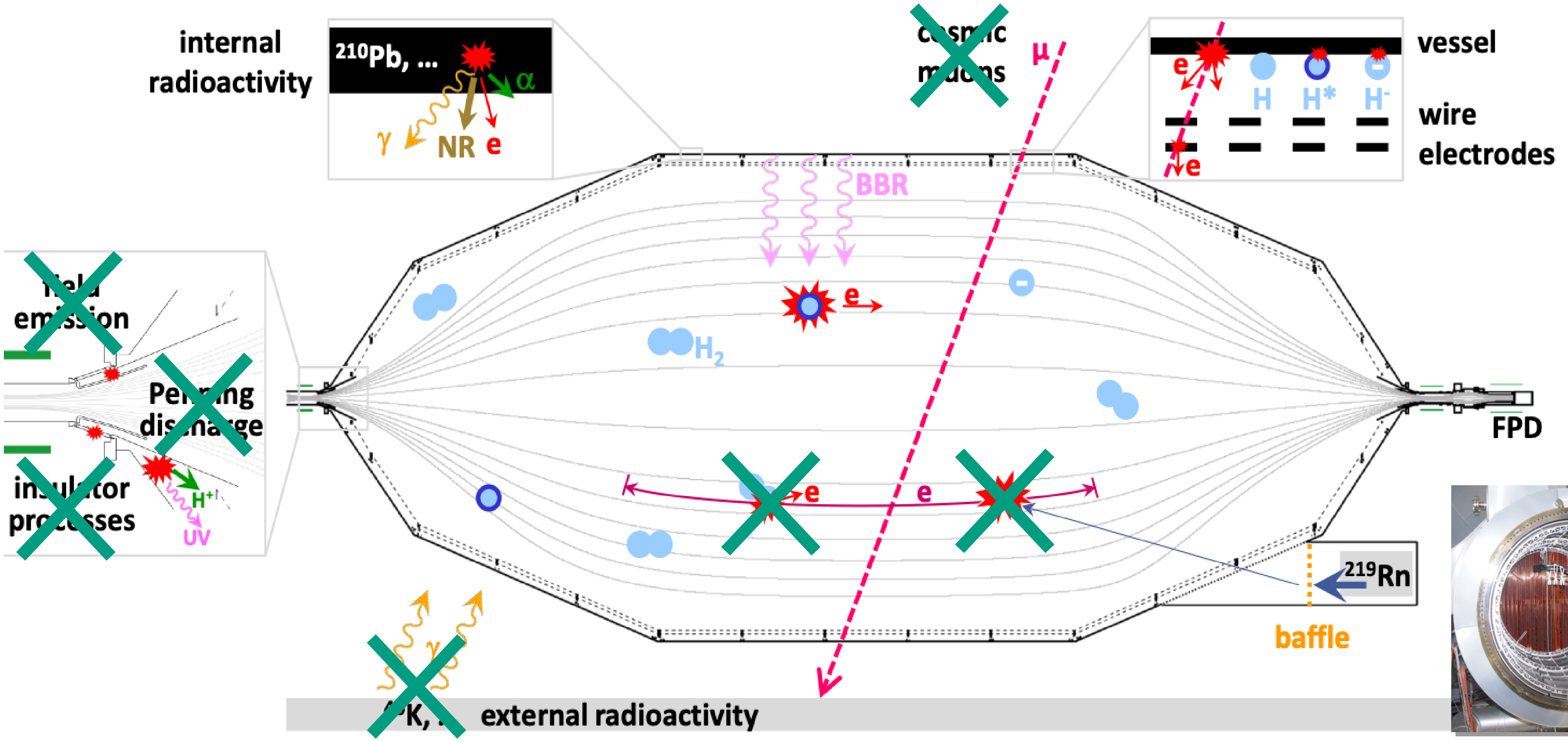
A.V. Lokhov, F.V. Tkachov, Phys. Part. Nucl. 46 (2015) 347
G. J. Feldman and R. D. Cousins, Phys. Rev. D 57 (1998) 3873
M. Aker et al. (KATRIN Collab.), An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN; arXiv:1909.06048

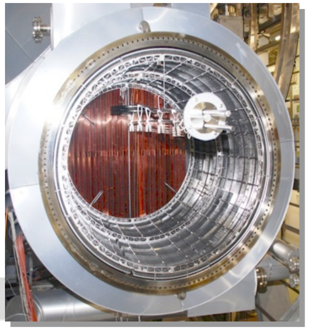
Systematics breakdown

- **well-understood systematics budget σ_{syst} (with $\sigma_{syst} < \sigma_{stat}$)**
  - total statistical uncertainty budget σ_{stat} = 0.97 eV² x2 better than Mainz & Troitsk
  - total systematic uncertainty budget σ_{syst} = 0.32 eV² x6 better than Mainz & Troitsk



Outlook: Background reduction

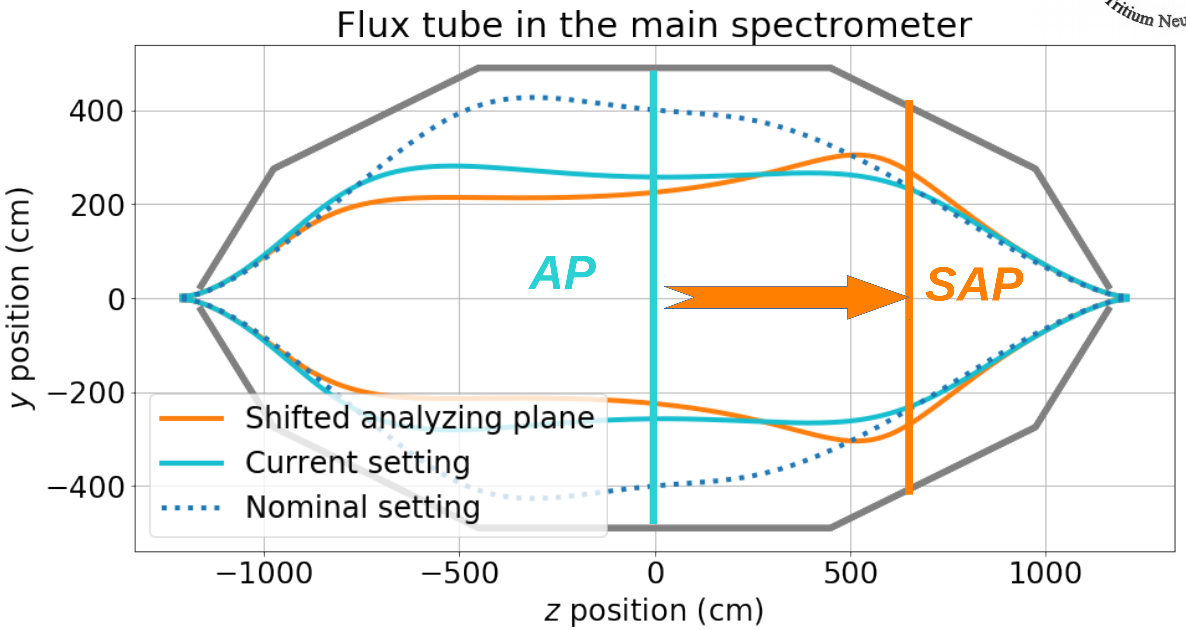




- Secondary electrons from ^{219}Rn decays
  - **Efficient reduction via nitrogen-cooled baffle system**
- Highly excited H atoms, „Rydberg“ states, ionized by thermal radiation
  - **current: 0.36 cps (design: 0.01 cps)**

Outlook: Background reduction

- **Further background reduction**
  - ⇨ spectrometer bake-out successful ☑
  - ⇨ more effective baffles
    - – cooled by under-pressured LN
    - – better ^{219}Rn retention
- **Volume dependent background rate**
  - **reduce the volume of the flux**
  - ⇨ upgraded air coil system ☑
  - ⇨ „shifted analyzing plane“ (SAP) ☑
    - – factor 2 signal/background improvement
    - – background & calibration & tritium scans

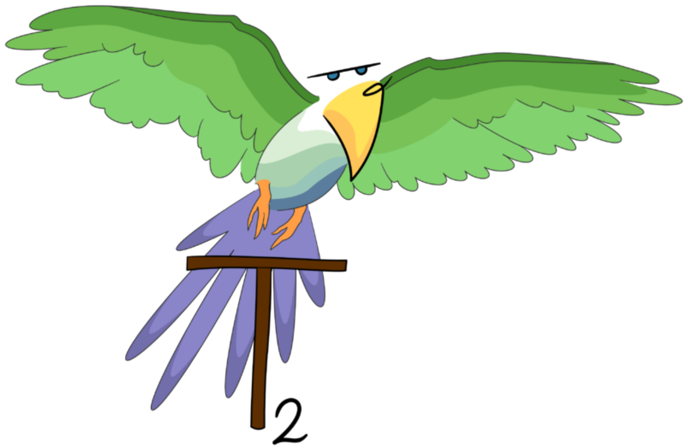


Two large air coil systems:
background suppression & B-field shaping

WWU MÜNSTER

Outlook: KATRIN – future plans

- **Currently taking T_2 data (~30 days) of the 2nd science run at 4x more tritium in the source**
- **Further reduction of systematics**
  - ⇨ energy loss via egun in ToF modus
  - ⇨ plasma effects in the source
  - ⇨ …
- **R&D works on ToF-technique for differential tritium scanning**



- **1000 days of measurements** at nominal ρd ($5 \cdot 10^{17}$ molecules cm^{-2}) 3 tritium campaigns (65 days each) per calendar year

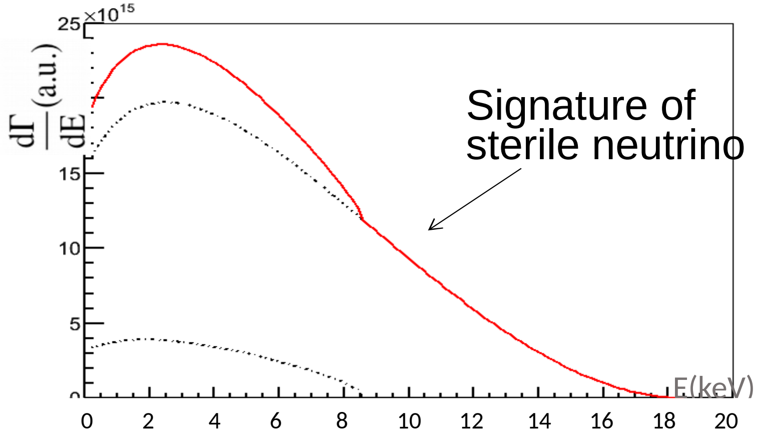
sensitivity $m(\nu_e)$ = 0.2 eV (90% CL)

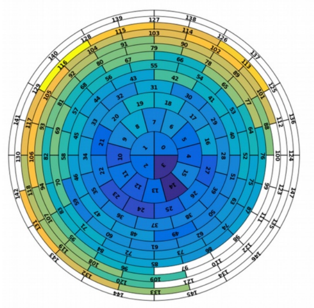
0.35 eV (5σ)

Outlook: keV sterile neutrino search with KATRIN

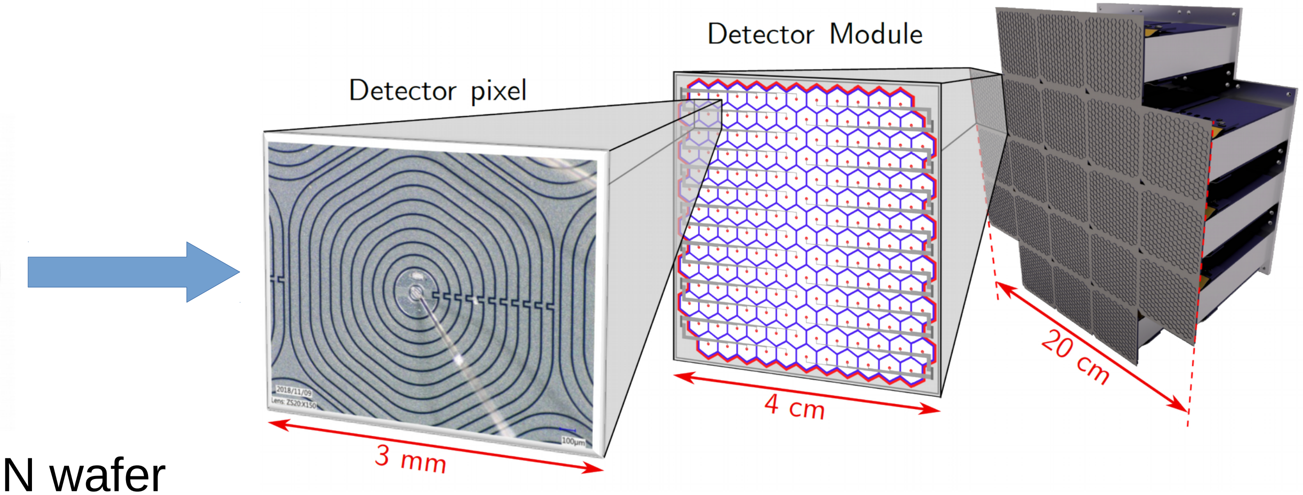
- 4-th mass eigenstate of neutrino
  - **particle beyond the standard model**
  - **DM candidate**
- Look for the kink in the β-spectrum
- TRISTAN project – developing a new detector & DAQ system
  - **large count rates**
  - **good energy resolution**
  - **Silicon Drift Detector**

$$\frac{dN}{dE} = \cos^2\theta_s \cdot \frac{dN}{dE}(m_{active}) + \sin^2\theta_s \cdot \frac{dN}{dE}(m_{sterile})$$





segmented Si-PIN wafer



S. Mertens et al., arXiv: 1810.06711; T.Brunst et al., arXiv: 1909.02898

Conclusion

- First neutrino mass result by KATRIN:

  m_ν < 1.1 eV (90 % C.L.)

  - **Statistical error reduced by x2, systematic error x6**
  - **Stable operation at high tritium purity and source activity**
  - **Further reduction of systematics and background**
- KATRIN is taking data (3 cycles/year) to reach the ultimate sensitivity of 0.2 eV (90 % C.L.)
- Background reduction techniques are being tested (SAP, ToF)
- Search for the BSM physics (light and heavy sterile neutrinos, light bosons, etc.)
- Stay tuned for the new results KATRIN

Thank you for your attention!