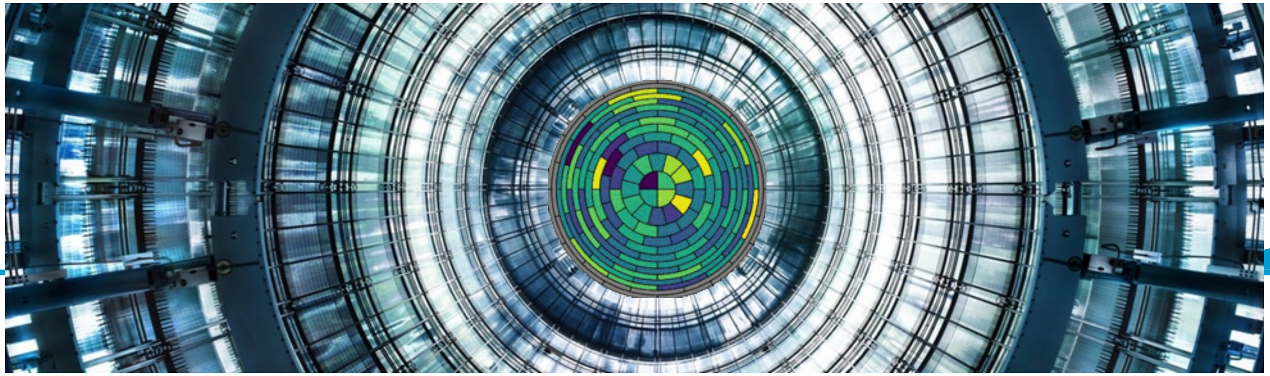
WWU MÜNSTER

First results from the neutrino mass experiment KATRIN

Christian Weinheimer – University of Münster

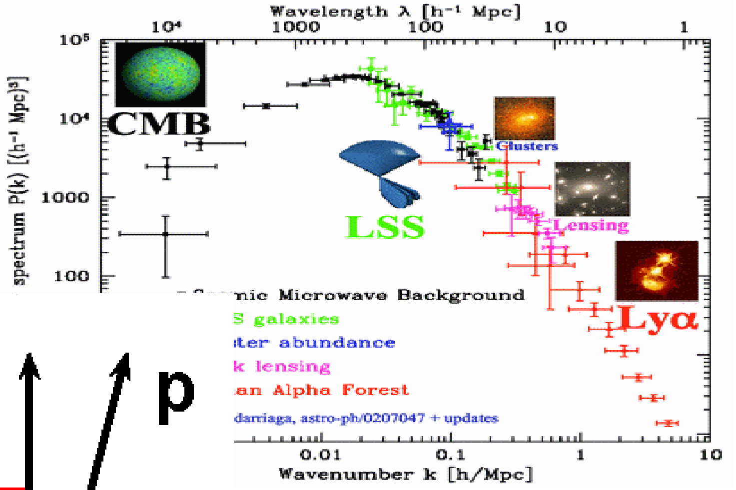
CNNP 2020, Cape Town, South Africa, February 24-28, 2020

- Introduction
- The KArlsruhe TRItium Neutrino experiment KATRIN
- First results from KATRIN
- Outlook
- Conclusions



Institut für Kernphysik
Westfälische Wilhelms-Universität Münster

Three complementary ways to the absolute neutrino mass scale



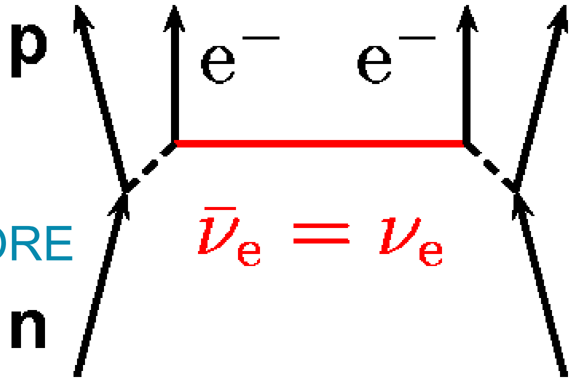
1) Cosmology

very sensitive, but model dependent

compares power at different scales

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

2) Search for $0\nu\beta\beta$



Sensitive to Majorana neutrinos, model-dependent

Upper limits by EXO-200, KamLAND-Zen, GERDA, CUORE

3) Direct neutrino mass determination:

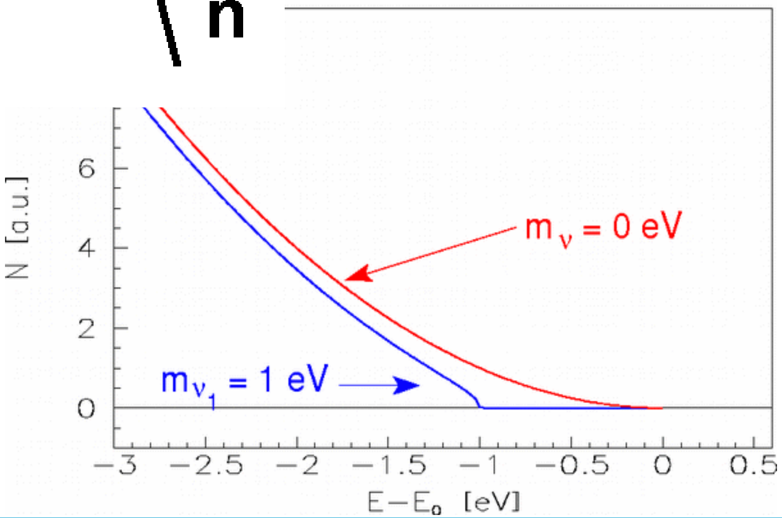
No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4$

$\Rightarrow m^2(\nu)$ is observable mostly

Time-of-flight measurements (ν from supernova)

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

measure charged decay prod., E-, p-conservation

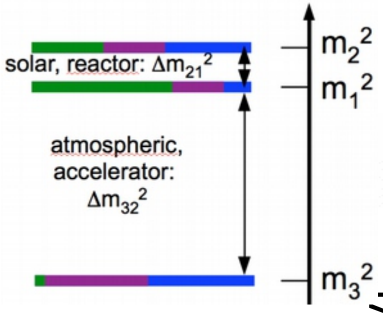


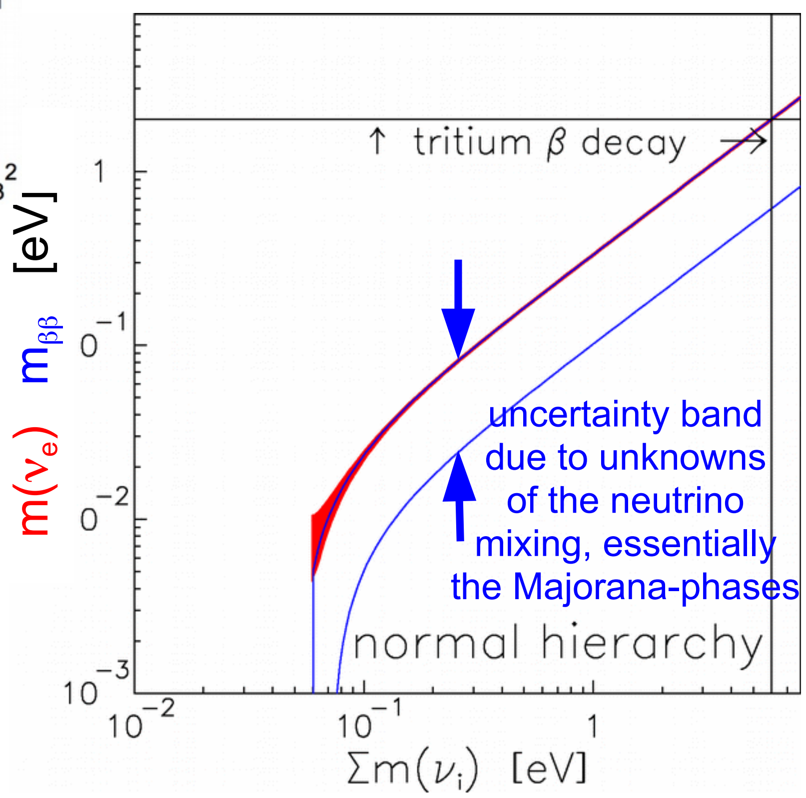
Comparison of the different approaches to m(ν)

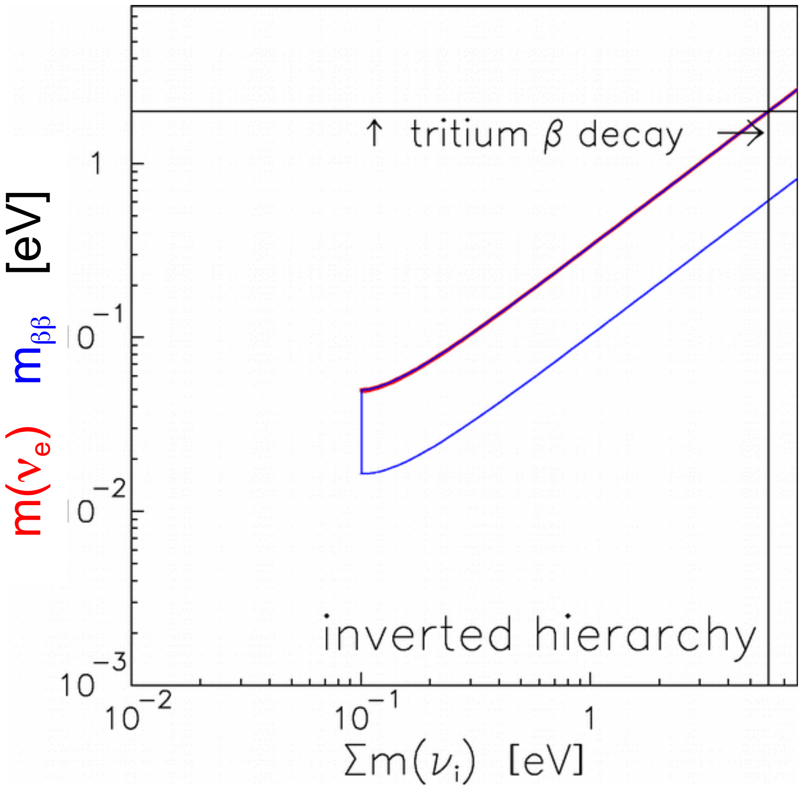
Direct kinematic measurement: $m^2(\nu_e) = \Sigma |U_{ei}{}^2|\, m^2(\nu_i)$ (incoherent)

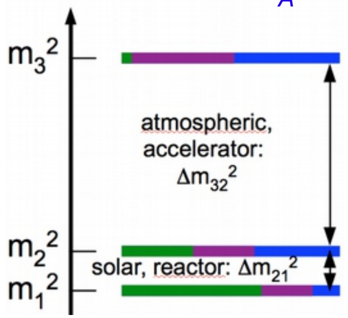
Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = |\, \Sigma |U_{ei}{}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$ (coherent)

if no other particle is exchanged (e.g. R-violating SUSY) & w/o uncertainties of NME *M* and quenching of g_A









⇒ absolute scale/ cosmological relevant neutrino mass in the lab by single β decay

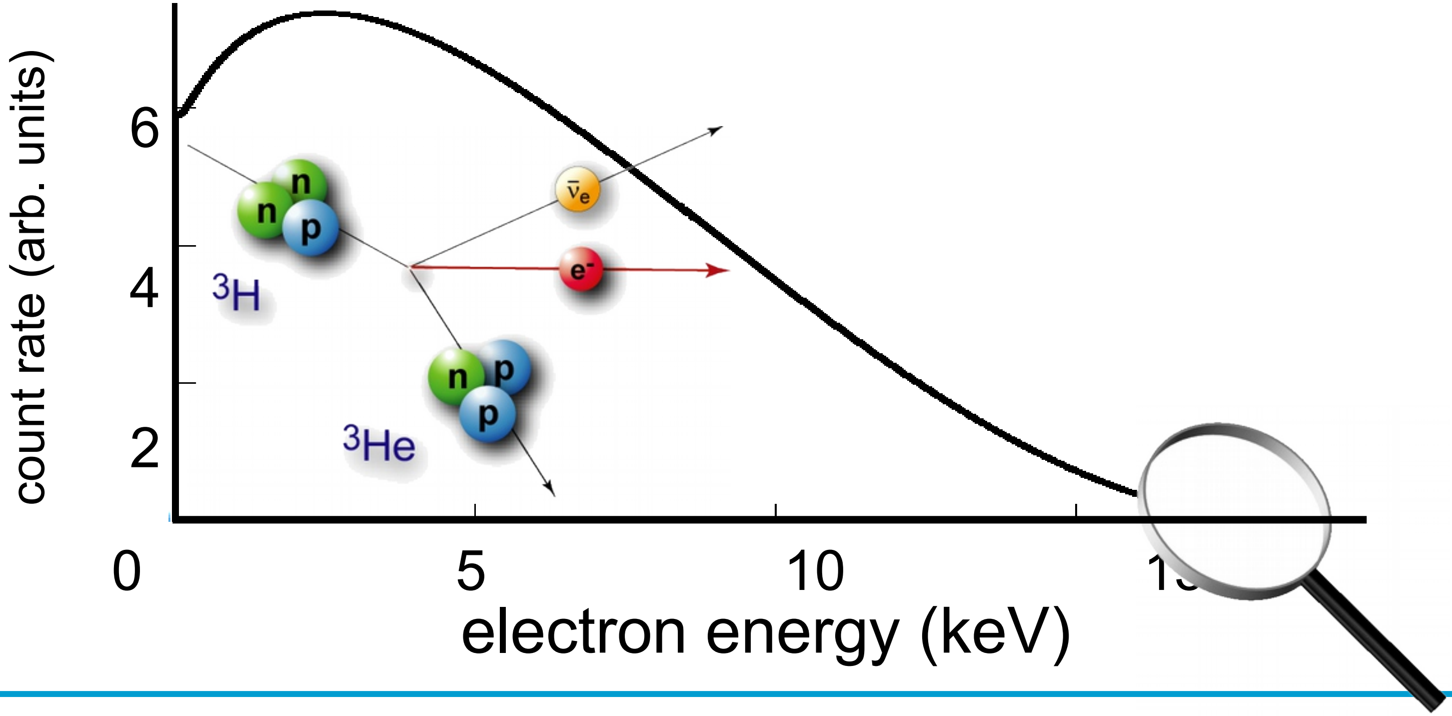
Direct determination of "$m(\nu_e)$" from β-decay (EC)

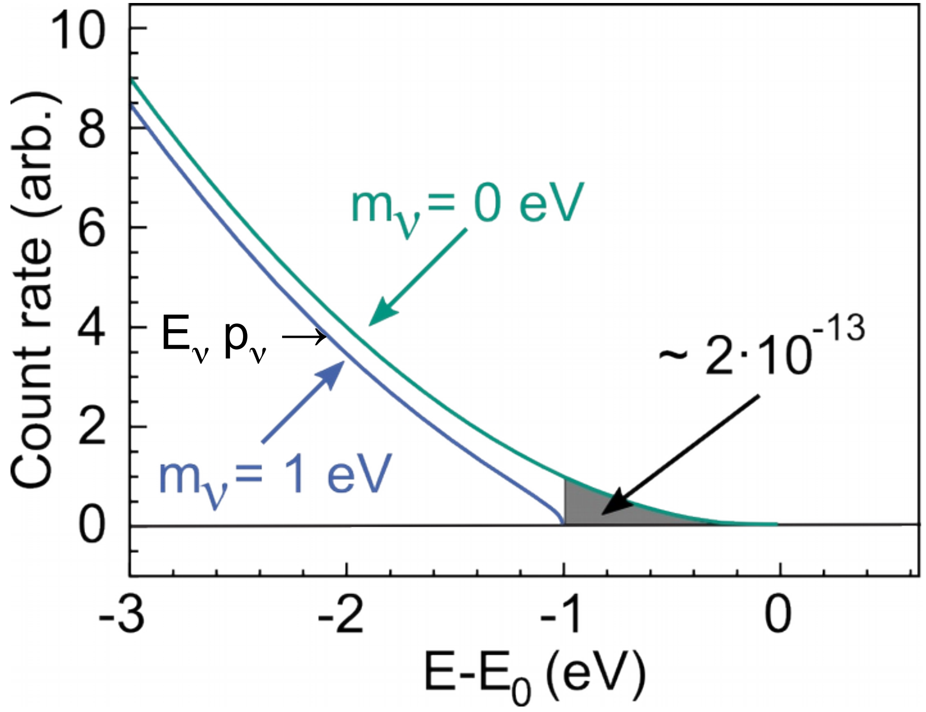
β-spectrum: $dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$

essentially phase space: p_e (under p), E_e (under E_{tot}), E_ν (under (E_0-E_e)), p_ν (under the square root)

with "electron neutrino mass": **"$m(\nu_e)^2$" := $\Sigma |U_{ei}|^2\ m(\nu_i)^2$**, complementary to 0νββ & cosmology

(modified by electronic final states, recoil corrections, radiative corrections)





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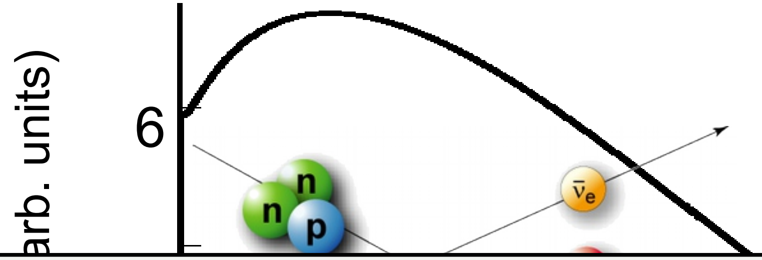
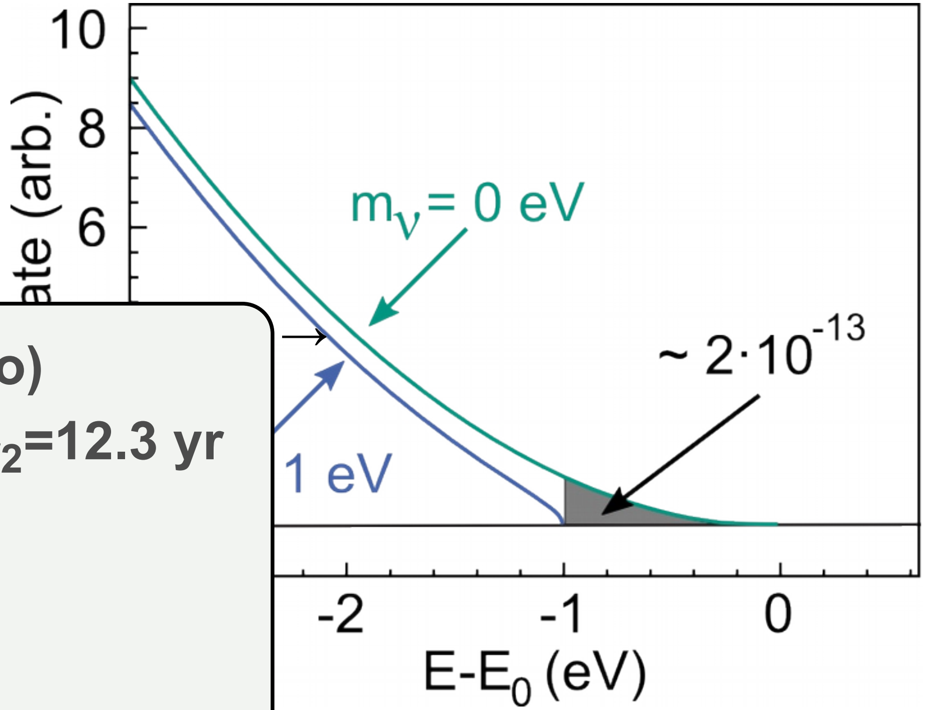
β-spectrum: $dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$

essentially phase space: p_e (from p), E_e (from E_{tot}), E_ν (from (E_0-E_e)), p_ν (from $\sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$)

with "electron neutrino mass": **"$m(\nu_e)^2$" := $\Sigma |U_{ei}|^2\ m(\nu_i)^2$**, complementary to 0νββ & cosmology

(modified by electronic final states, recoil corrections, radiative corrections)





Need: low endpoint energy ⇒ **Tritium ^3H (^{163}Ho)**
large decay rate (super-allowed) **E_0=18.6 keV, $t_{1/2}$=12.3 yr**

very high energy resolution
very high luminosity ⇒ **MAC-E-Filter**
very low background **(or cryobolometers for ^{163}Ho)**

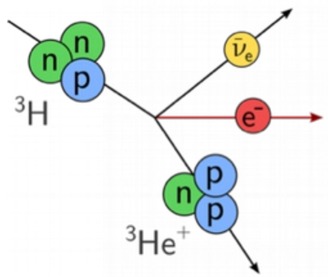
KATRIN at Karlsruhe Institute of Technology working principle

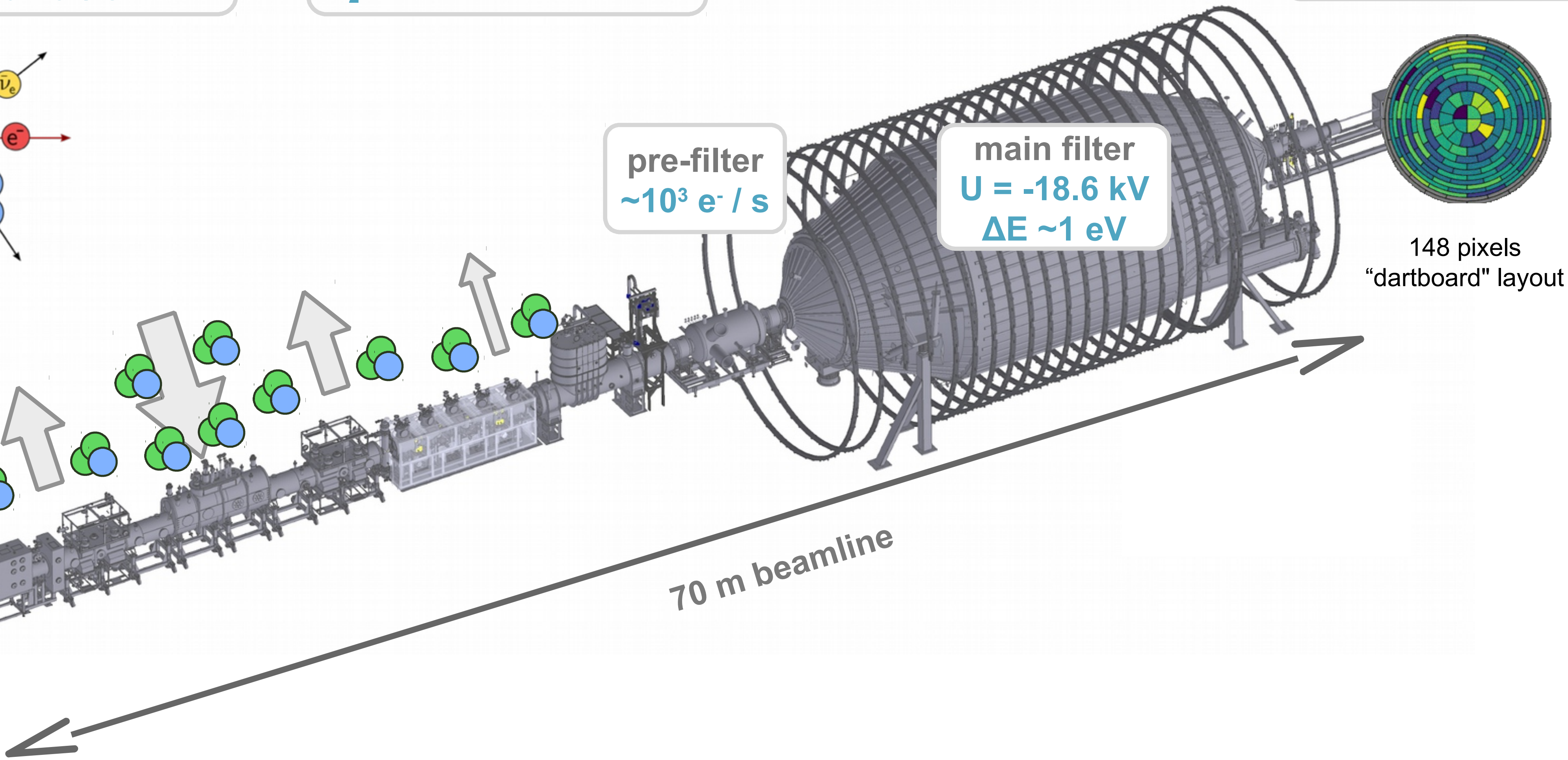
windowless gaseous T_2 source
10^{11} e$^-$ / s

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

high-pass energy filters
MAC-E-Filter

counting detector
< 1 e$^-$ / s





KATRIN at Karlsruhe Institute of Technology working principle

^3H

The international KATRIN Collaboration: 150 people from 20 (6) institutions (countries)

KIT Karlsruhe Institute of Technology
WWU MÜNSTER
CENPA
cea
Max-Planck-Institut für Physik
TUM
universität bonn
universität mainz
MIT
The University of North Carolina at Chapel Hill
Berkeley Lab
Max-Planck-Institut für Kernphysik
Case Western Reserve University
Bergische Universität Wuppertal

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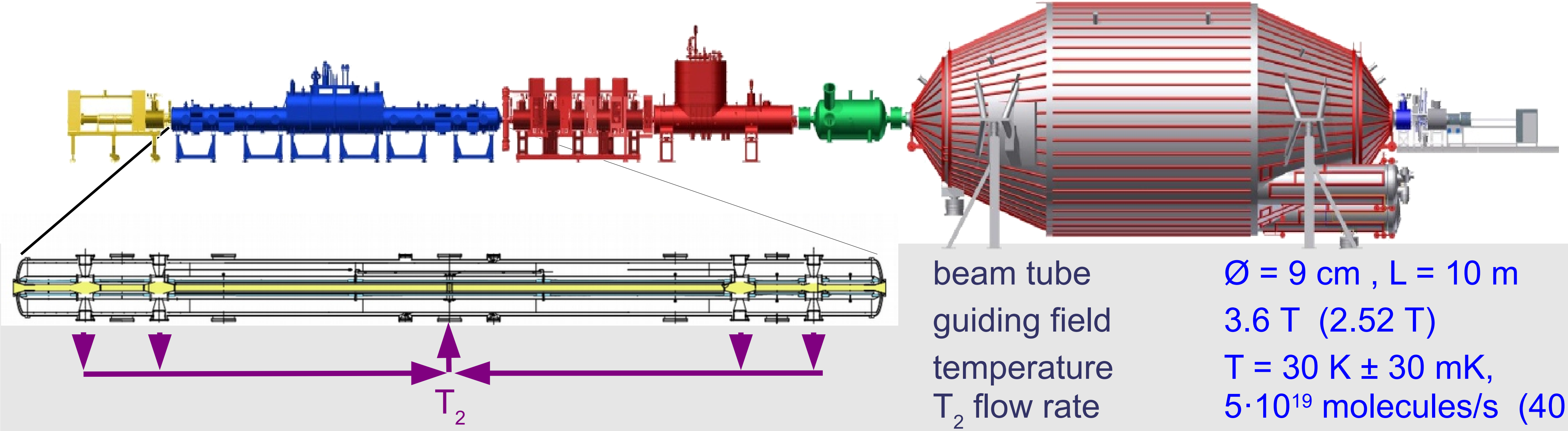
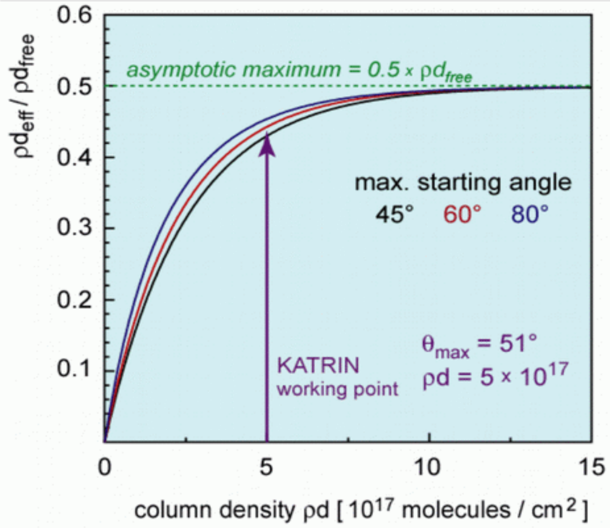
Bundesministerium für Bildung und Forschung
HELMHOLTZ GEMEINSCHAFT
DFG
MAX-PLANCK-GESELLSCHAFT
Department of Energy, United States of America
Czech Republic: MŠMT Ministry of Education Youth and Sports
Russian Academy of Sciences, Founded in 1724

The KATRIN
Windowless Gaseous Molecular Tritium Source



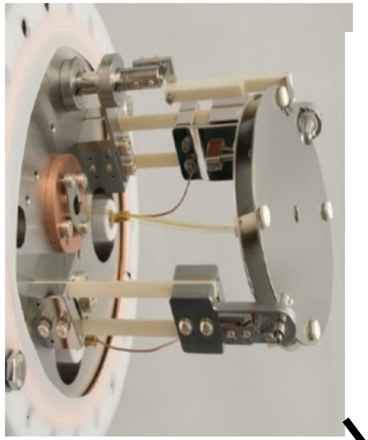
column density $5 \cdot 10^{17}$ T_2/cm^2 luminosity $1.7 \cdot 10^{11}$ Bq

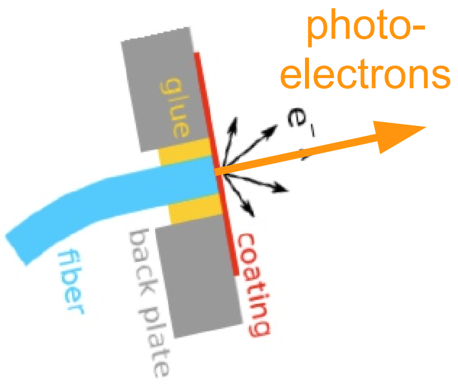
beam tube	Ø = 9 cm , L = 10 m
guiding field	3.6 T (2.52 T)
temperature	T = 30 K ± 30 mK,
T_2 flow rate	$5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)
T_2 purity	95% ± 0.1 %
T_2 inlet pressure	10^{-3} mbar ± 0.1 %



WGTS at Tritium Laboratory Karlsruhe

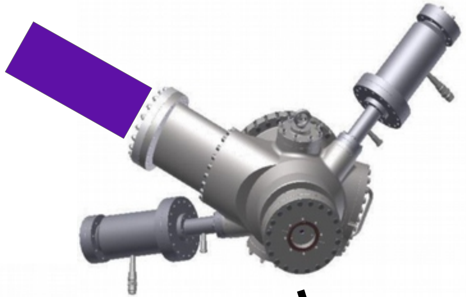
Rear calibration and monitoring system



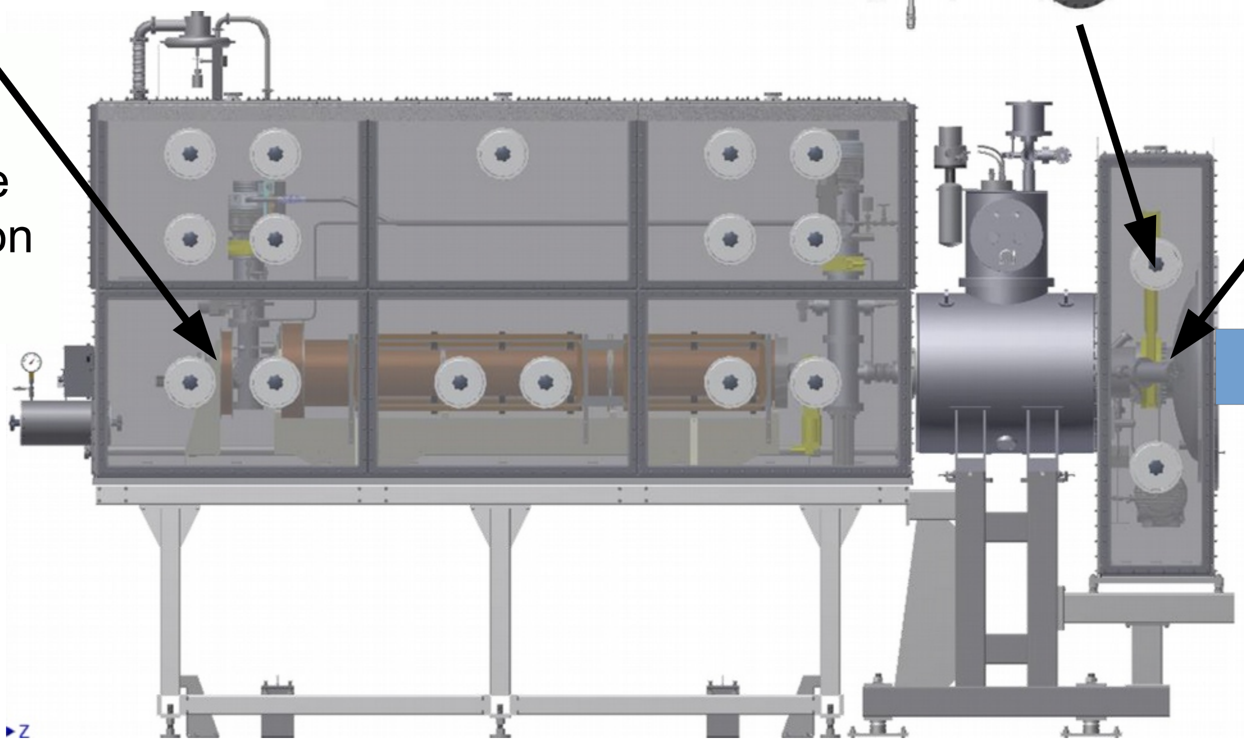


(pulsed) monoenergetic, angular-selective UV photo-electron source

VUV-illumination of rear wall & BIXS monitors



Au-surface controls magnetized cold plasma of windowless gaseous tritium source



cold tritium plasma

e$^-$ and ions: T$^+$, T3+,…, T$^-$

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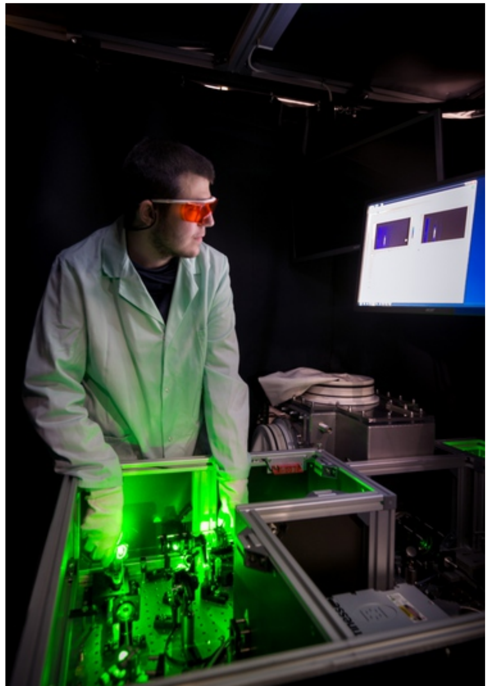
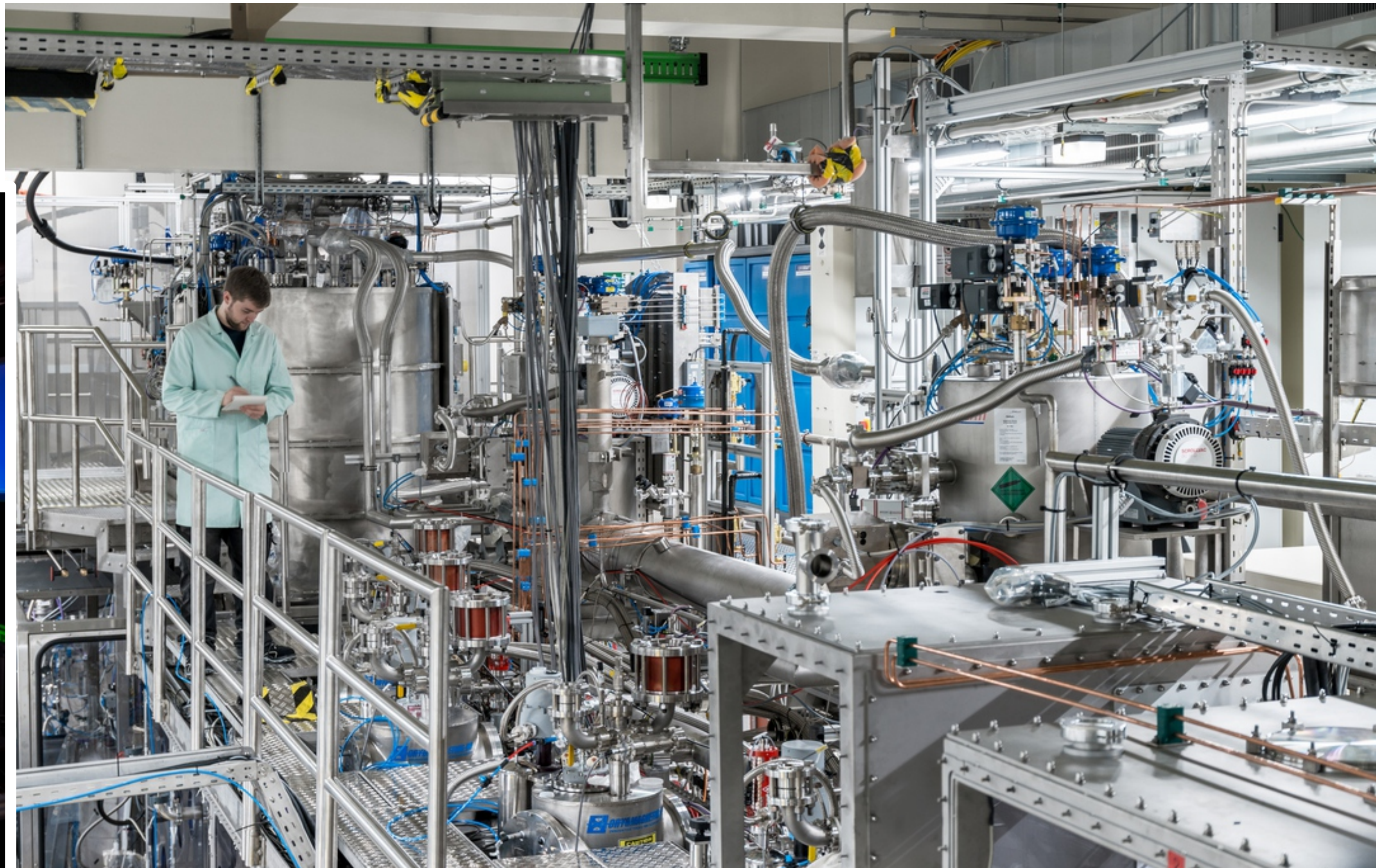
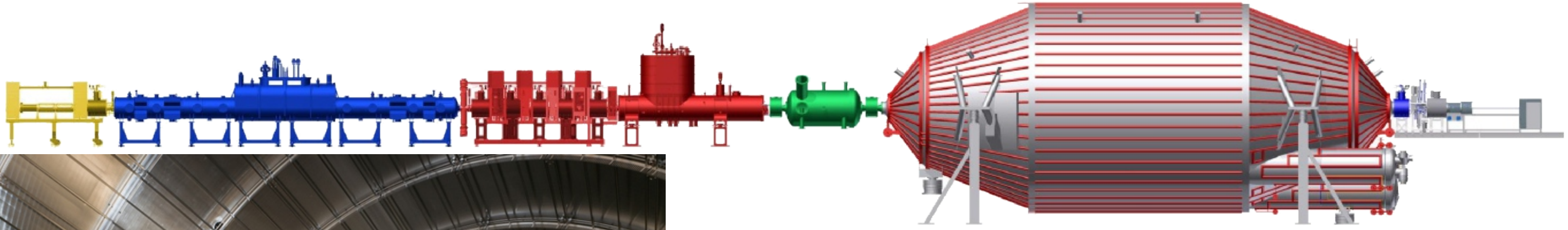
In reality: source & transport section

KATRIN Karlsruhe Tritium Neutrino Experiment





The KATRIN Main Spectrometer: an integrating high resolution MAC-E-Filter



Ultra-high vacuum, pressure $< 10^{-11}$ mbar

Retardation voltage of -18.6 kV (σ < 60 mV/years)
at vessel and double layer wire electrode system
for background reduction
and electric potential shaping

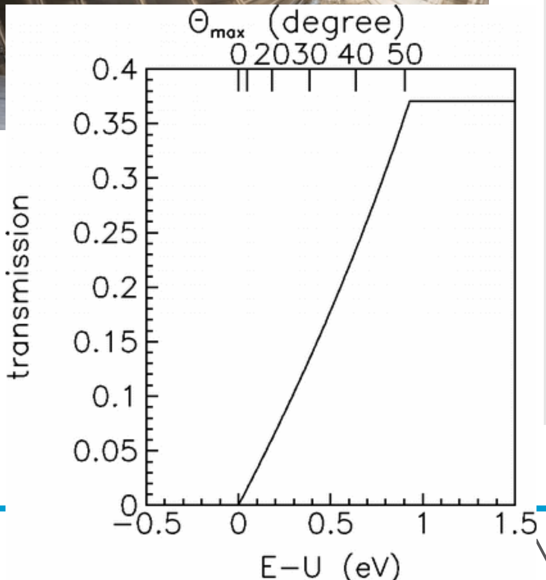
Air coils for earth magnetic
field compensation and
magnetic field shaping

Energy resolution:
(0% → 100% transmission):
0.93 (2.7) eV

→ **integral transmission function:**

$$\Delta E = E \cdot B_{min}/B_{max}$$

= 0.93 eV (2.7 eV)



Focal Plane Detector

Focal plane detection system

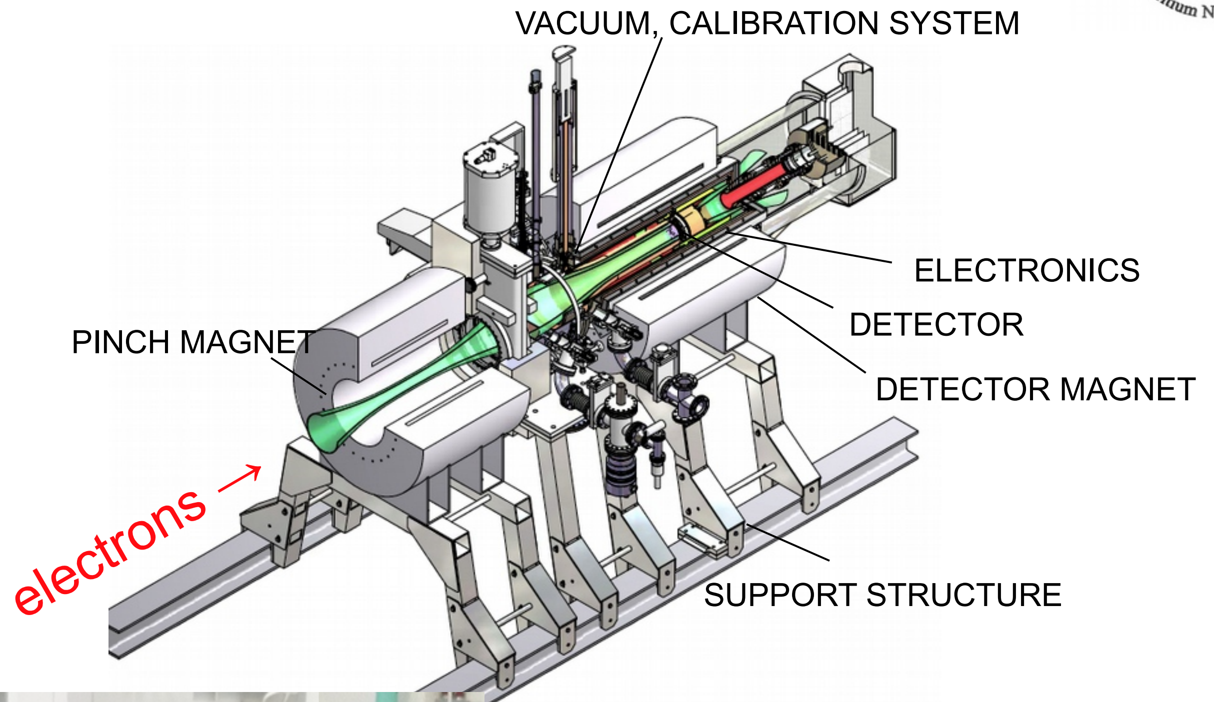
segmented Si PIN diode:
  90 mm Ø, 148 pixels, 50 nm dead layer

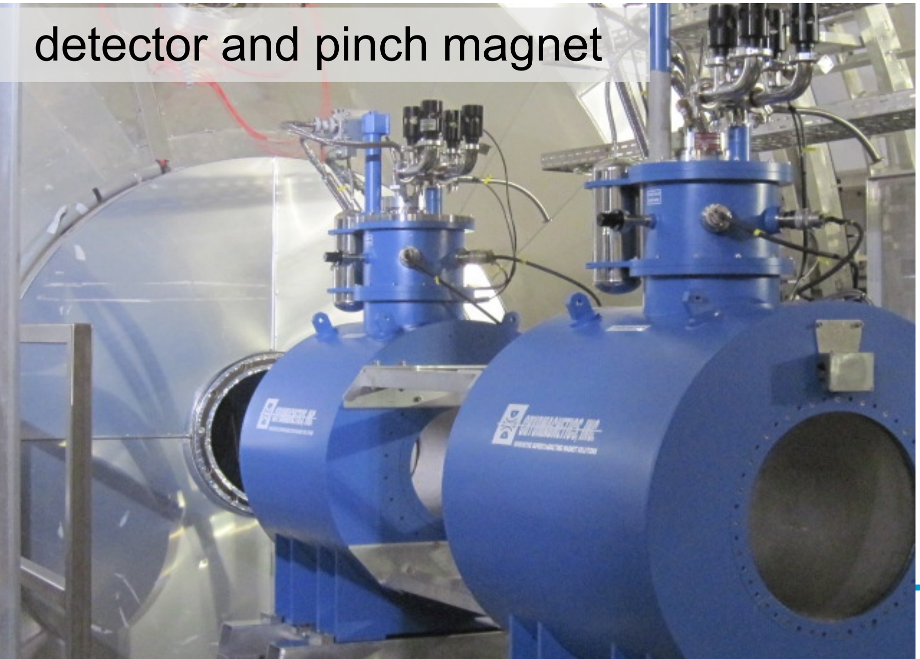
energy resolution ≈ 1 keV

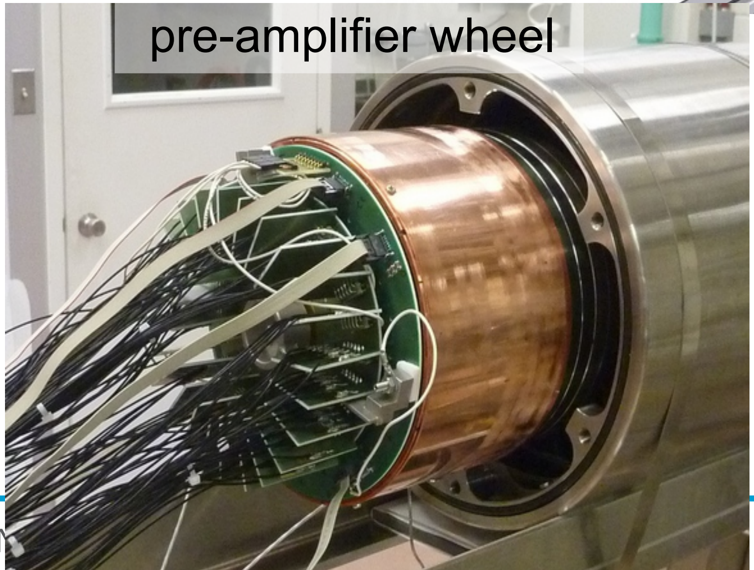
pinch and detector magnets up to 6 T

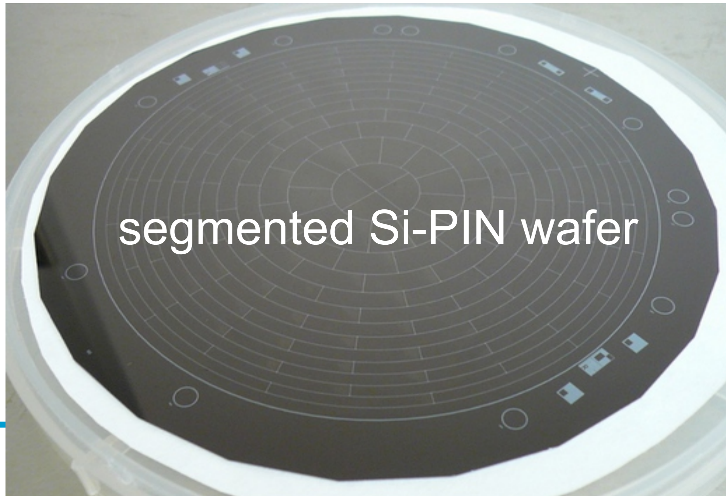
post acceleration (10kV)

active veto shield

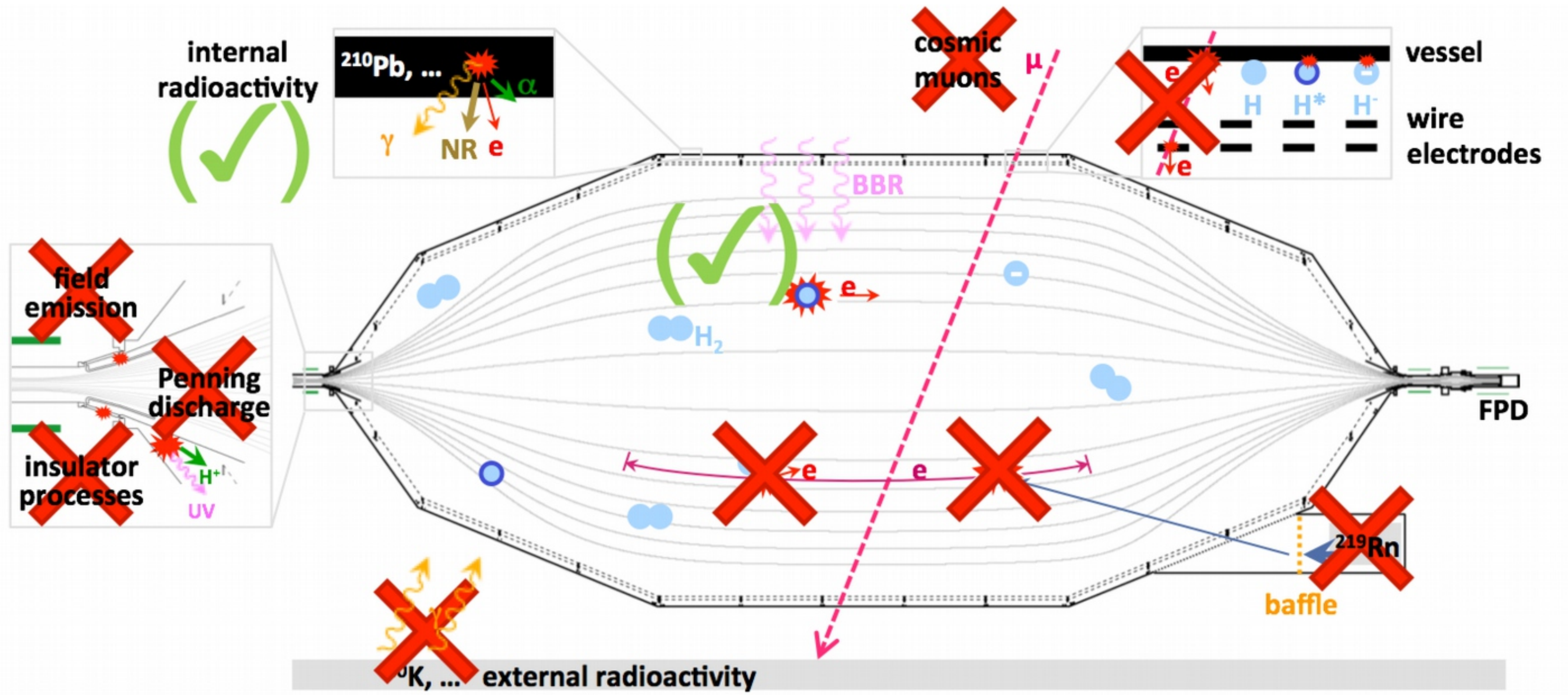








Background sources at KATRIN: detailed understanding, but …



8 sources of background investigated and understood:

7 out of 8 avoided or actively eliminated by:

- fine-shaping of electrodes
- very symmetric magnetic fields
- more negative wire electrode potentials
- LN2-cooled baffles in front of NEG pumps

1 out of 8 remaining:

caused by ^{210}Pb on spectrometer walls
neutral, but highly excited (Rydberg) atoms
ionized by black-body radiation (300K)
inside spectrometer volume

Background due to ionization of Rydberg atoms sputtered off by α decays

Rydberg (or autoionsing) atoms:

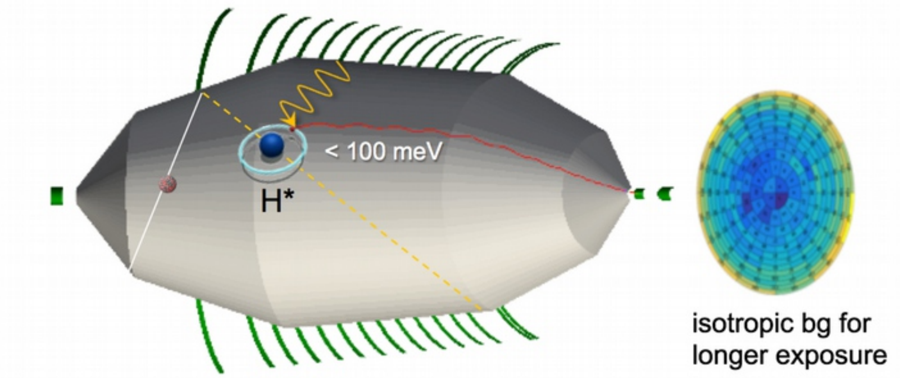
- ejected from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- ionized by black body radiation (291 K)
- non-trapped electrons on meV-scale
- bg-rate: ~0.5 cps

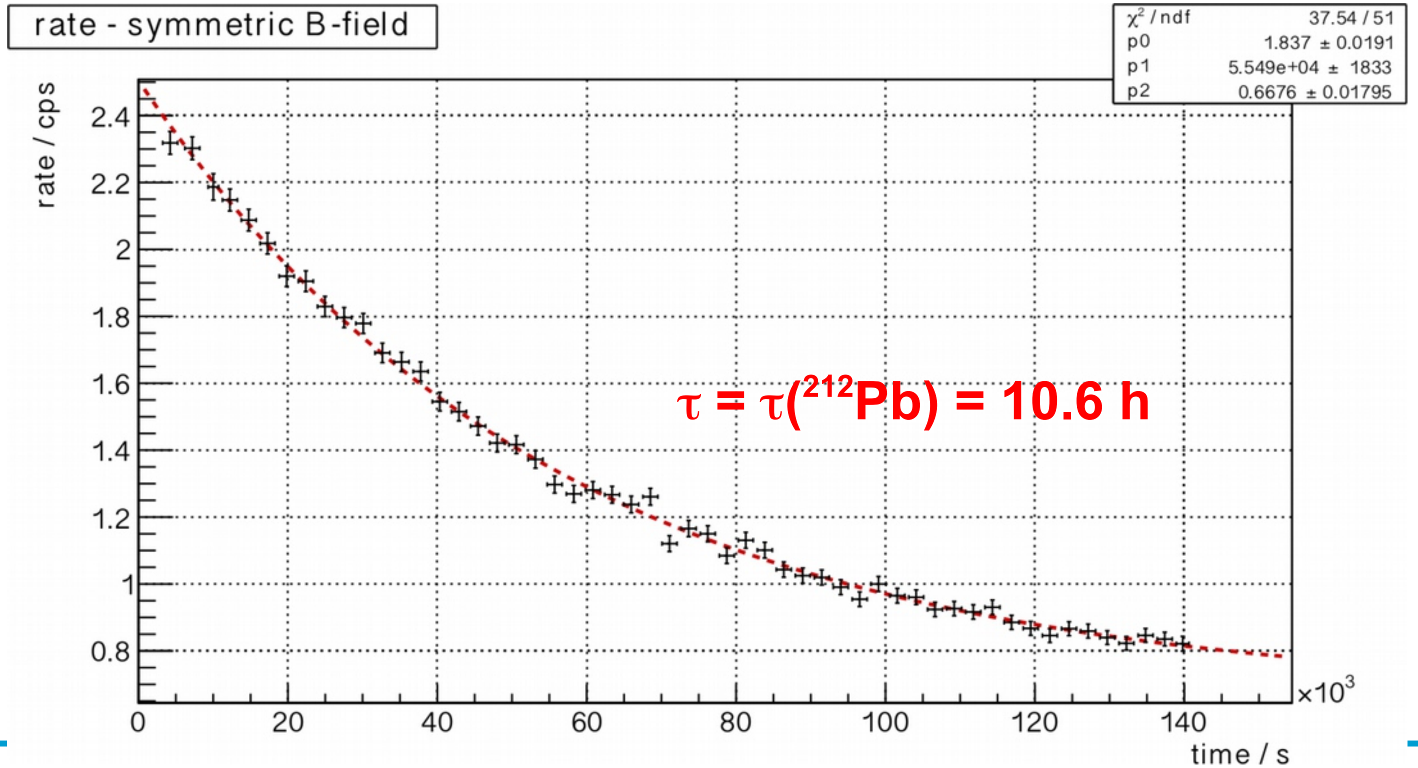
Countermeasures:

- apply stronger voltage at wires (field ionisation)
- reduce flux tube (on cost of energy resolution)
- shift analysis plane (tested, planned for 2020)
- active de-excitation ?
- coverage of surface with clean layer ?

Testing this hypothesis:

artifically contaminating the spectrometer with implanted short-living daughters of ^{220}Rn (and ^{219}Rn)

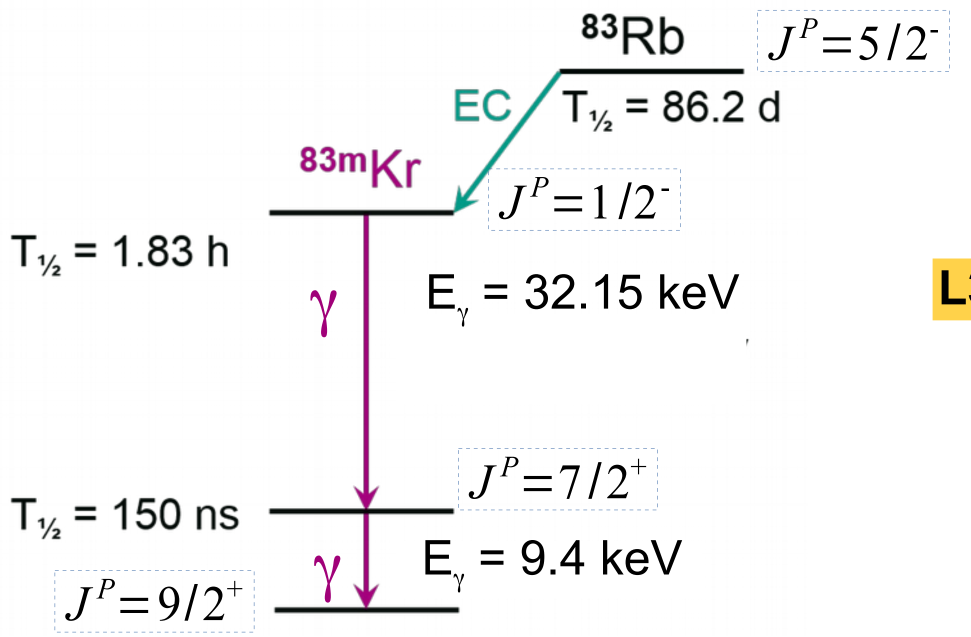




Measuring the response with ^{83m}Kr

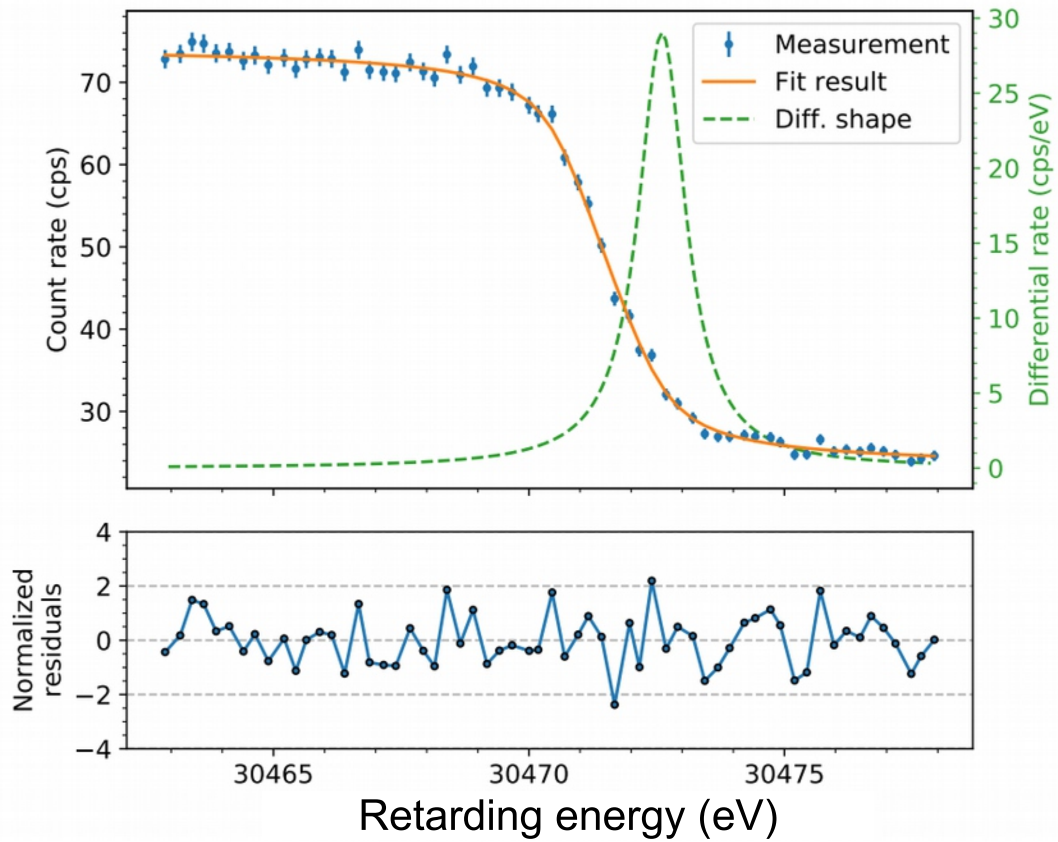
- **MAC-E filter characteristics well understood**
- **(also used to study plasma)**

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



L3-32

L3-32 line: 30.47 keV

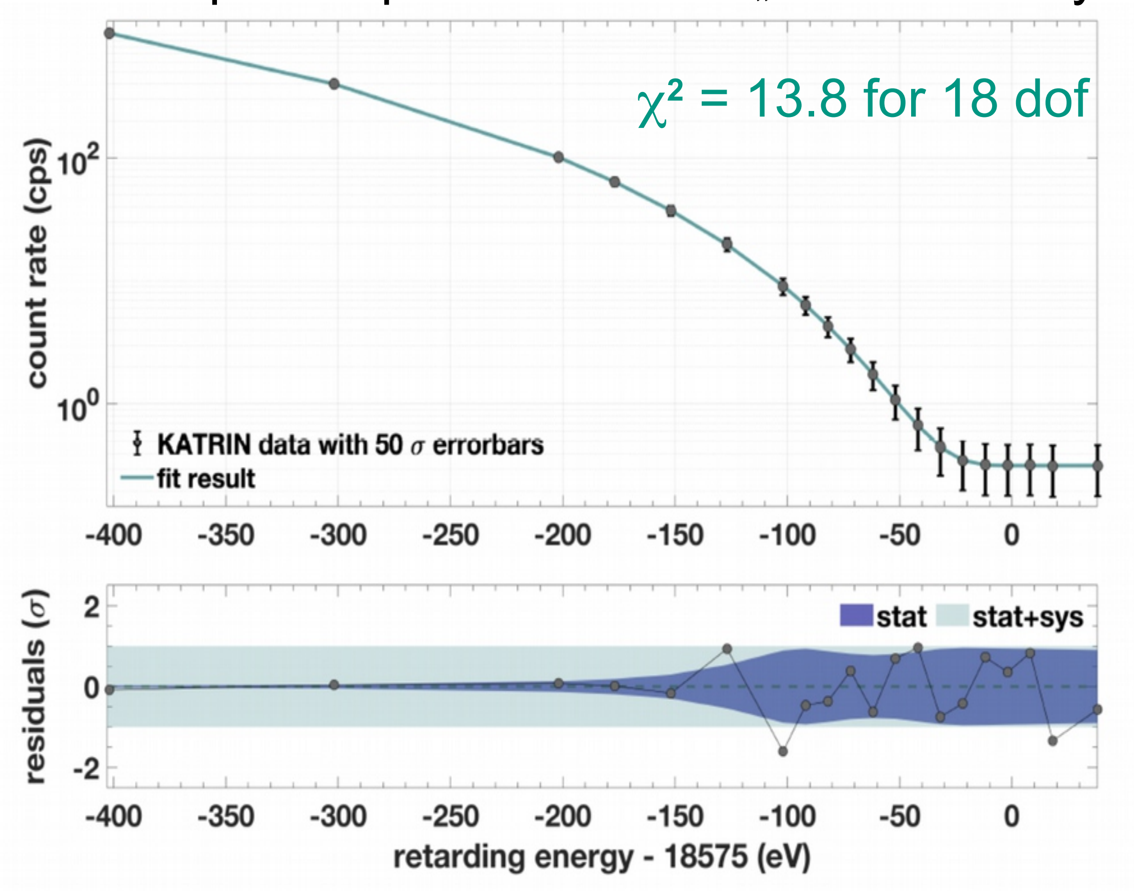


KATRIN Collab., "High-resolution spectroscopy of gaseous ^{83m}Kr conversion electrons with the KATRIN experiment", arXiv:1903.06452

KATRIN Collab.,"Calibration of high voltages at the ppm level by the difference of 83mKr conversion electron lines at the KATRIN experiment", Eur. Phys. J. C 78 (2018) 368

First Tritium (2-week engineering run in 2018)

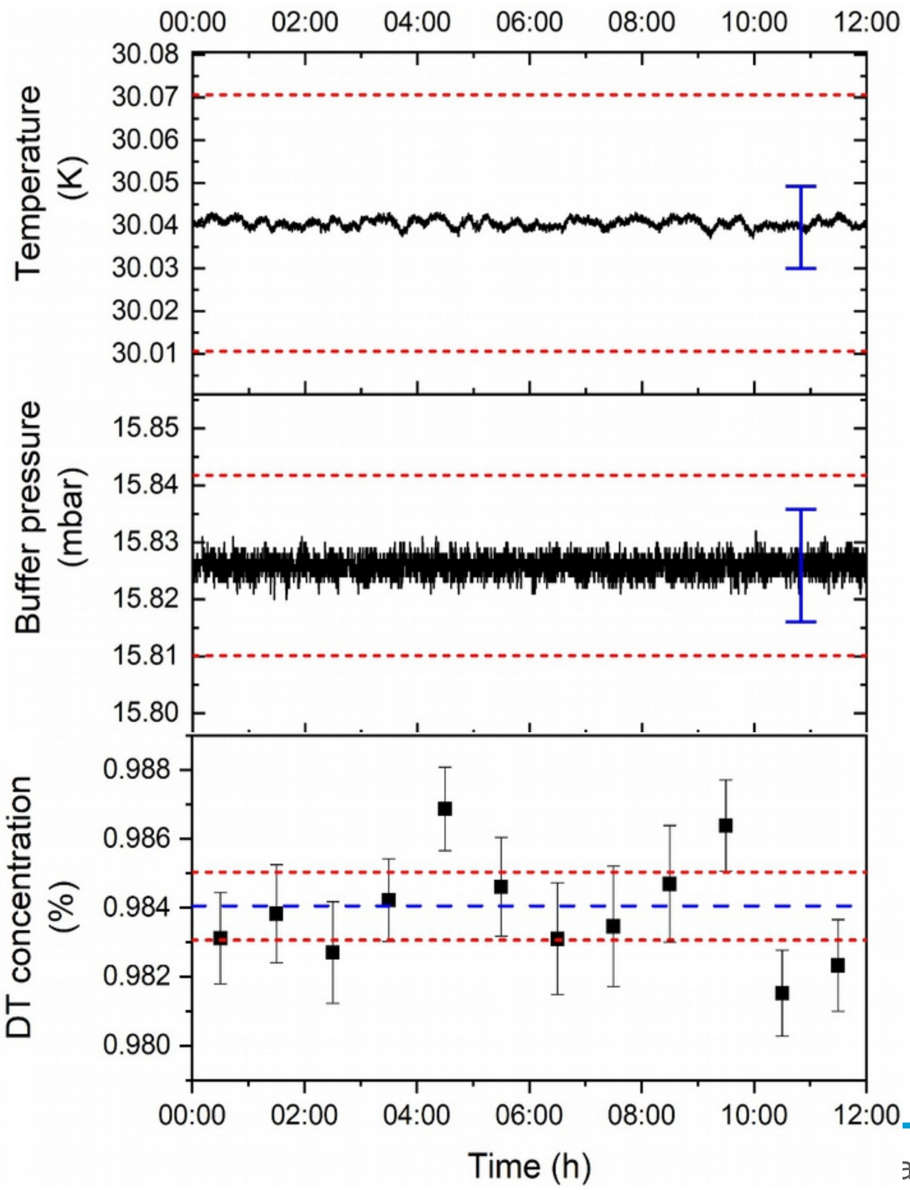
deep scan possible due to „low“ ß-activity



- **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})

KATRIN Collab., “First operation of the KATRIN experiment with tritium”, arXiv:1909.06069, accepted for publication by EPJ C

First tritium campaign:
Stability of source parameters during 12 h



Blue arrow: systematic uncertainty

Red dashed line: ± 0.1 % stability required for neutrino mass data taking

→ **source parameters were proven to be stable and within the specifications**

KATRIN science 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

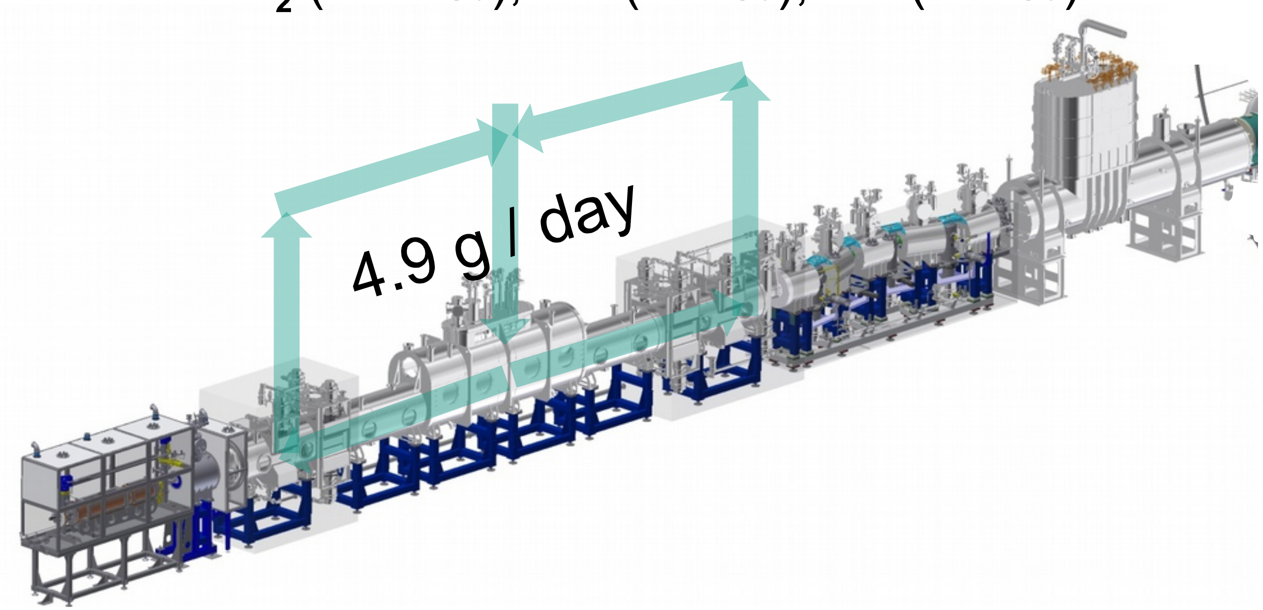
- high-quality data collected

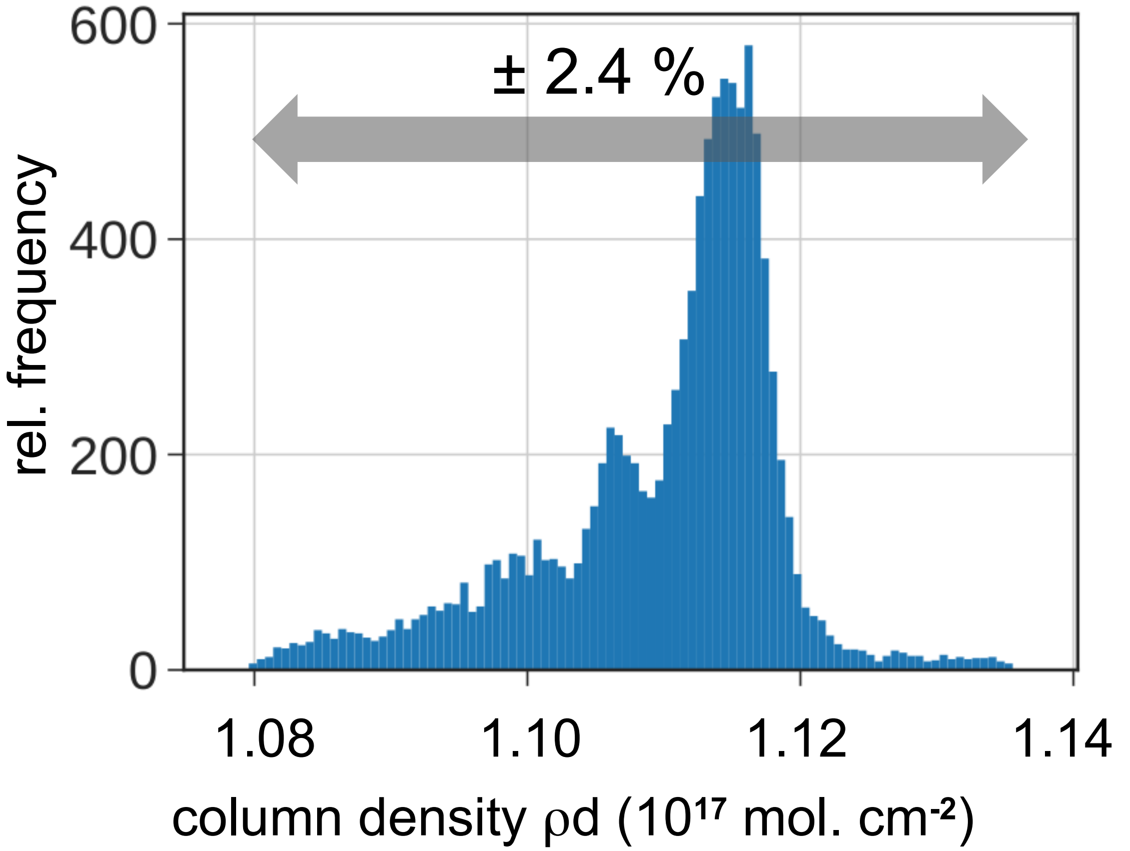
- full analysis chain using two
  independent methods

KATRIN science run #1

first ever large-scale throughput of high-purity tritium in closed loops

- **22% of nominal source activity (column density)**
  - ⇨ limits effects due to radiochemical reactions of T_2 (initial „burn in“ effect)
- **high isotopic tritium purity**
  - ⇨ T_2 (95.3 %), HT (3.5 %), DT (1.1 %)





Tritium scanning strategy

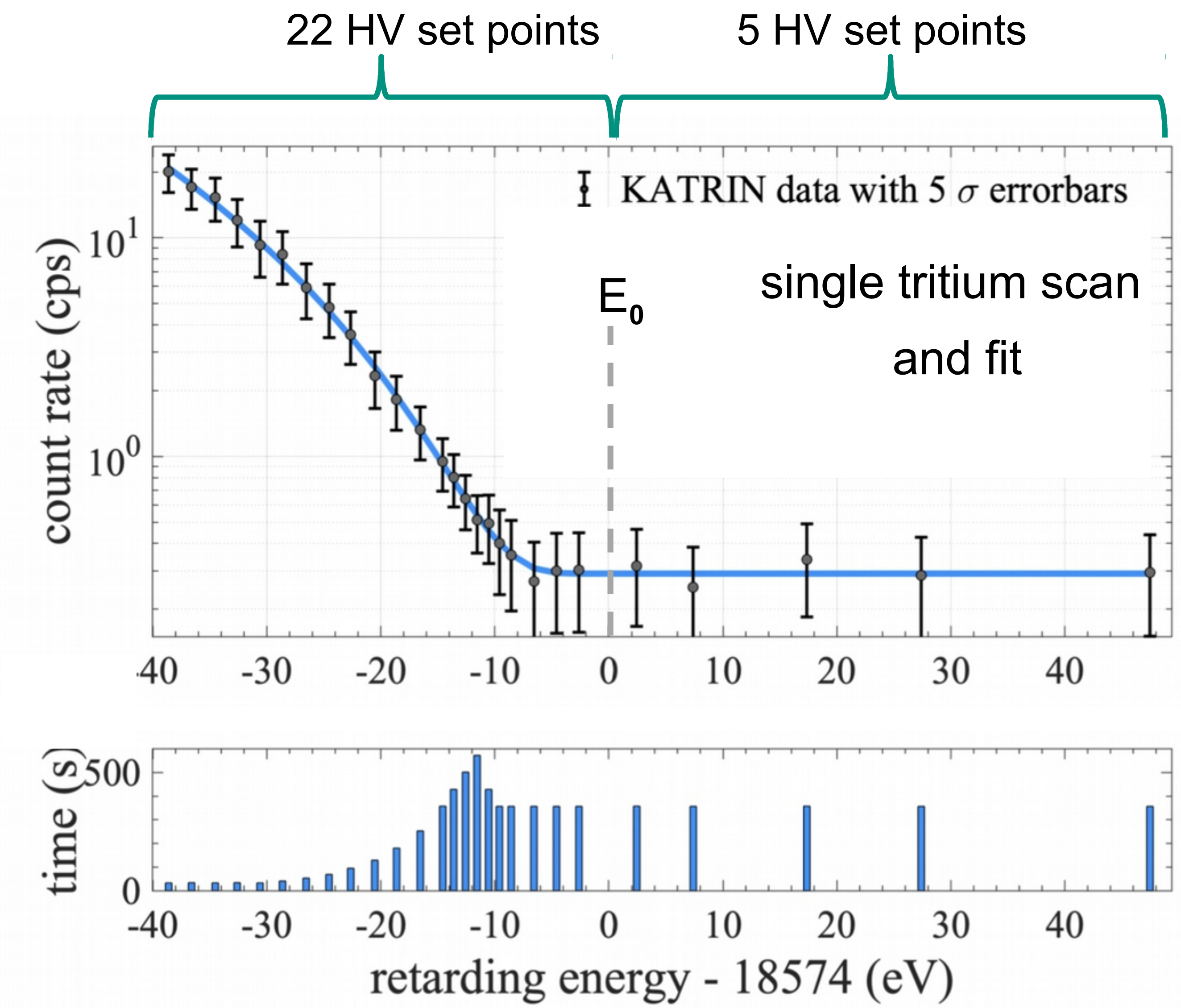
- **274 scans of tritium ß-spectrum**:

- 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

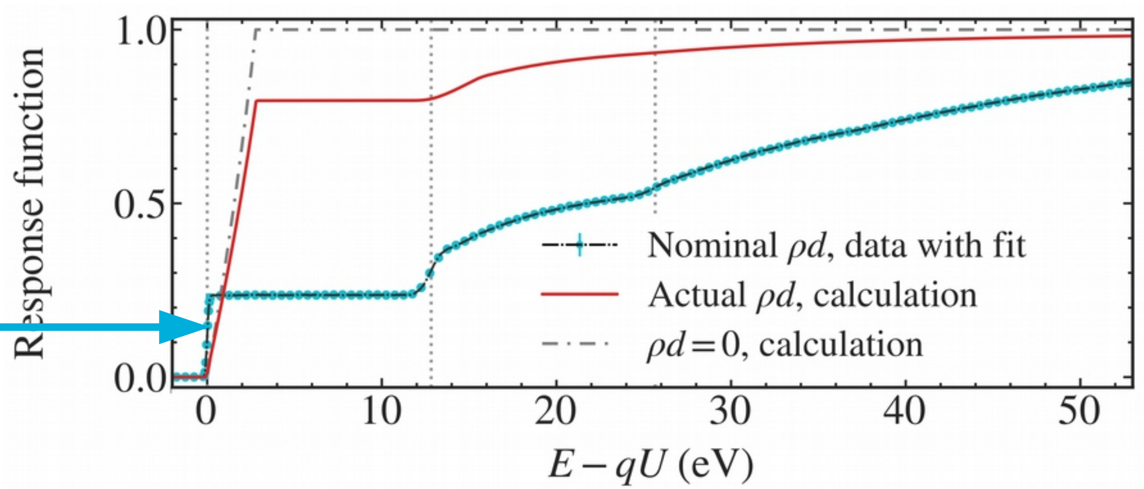


Determination of response function

- **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



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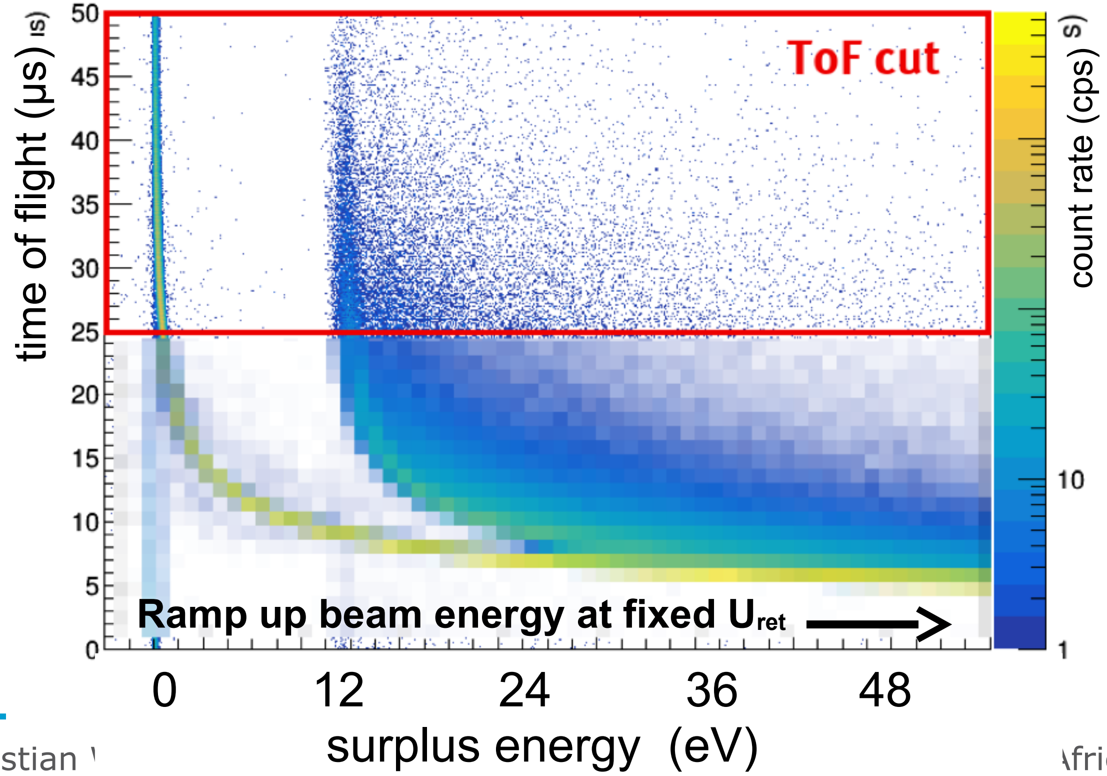

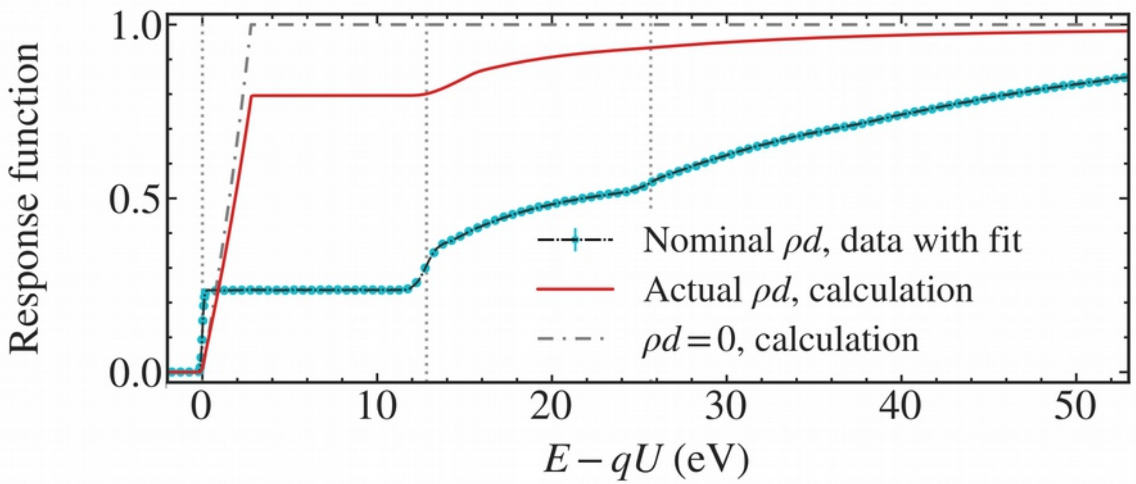

Time-of-flight of electrons from pulsed e-gun (70 ns at 20 kHz):
→ High-pass filter turned into narrow band-pass
→ recover "differential" spectrum

"Differential Time-of-flight mode"
Nucl. Inst. Meth. A 421 (1999) 256,

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

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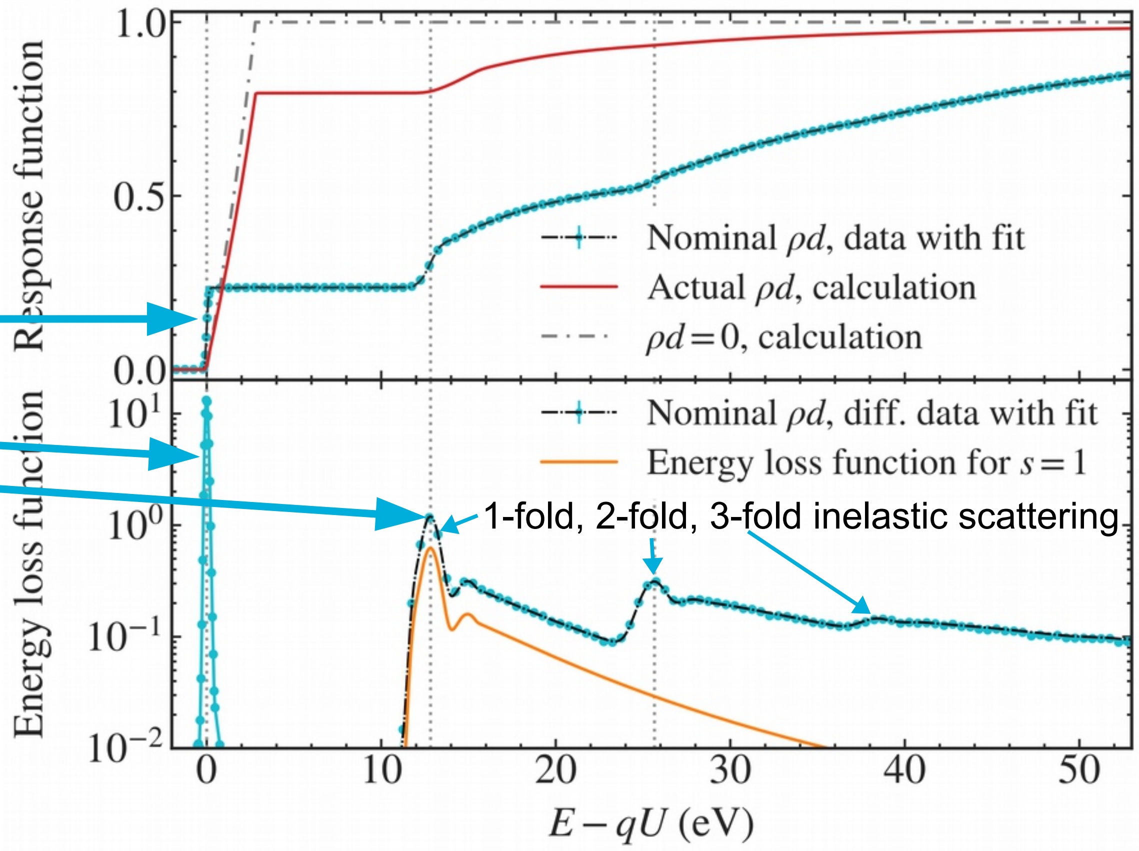
Differential Time-of-flight mode
(Nucl. Inst. Meth. A 421 (1999) 256)



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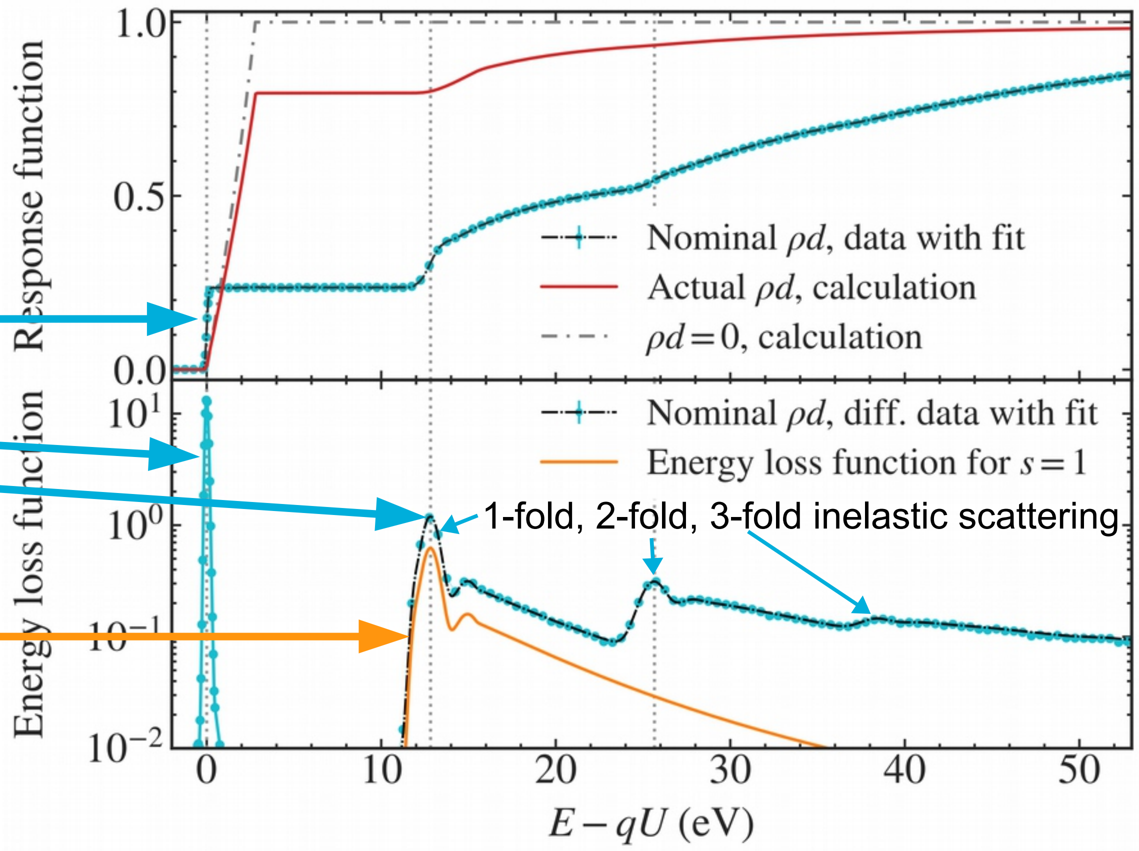
Normal integral MAC-E-Filter mode

Differential Time-of-flight mode

Nucl. Inst. Meth. A 421 (1999) 256,

New J. Phys. 15 (2013) 113020

Deconvoluted differential energy loss function

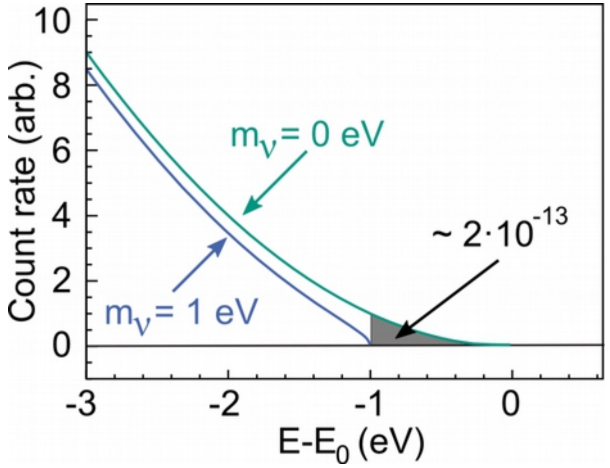


M. Aker et al. (KATRIN Collaboration)

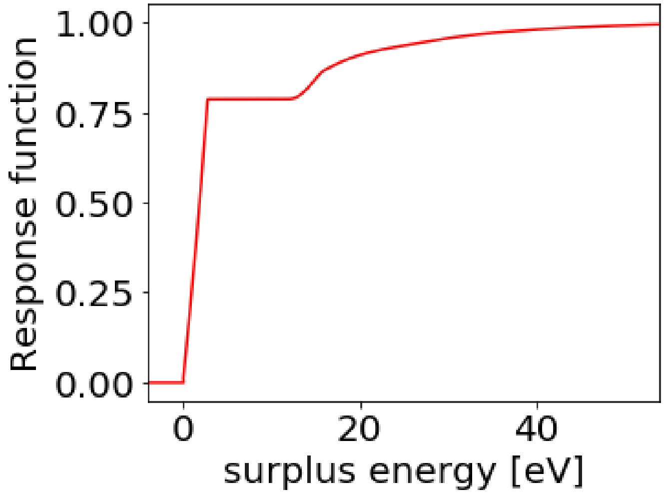
Phys. Rev. Lett. 123 (2019) 221802

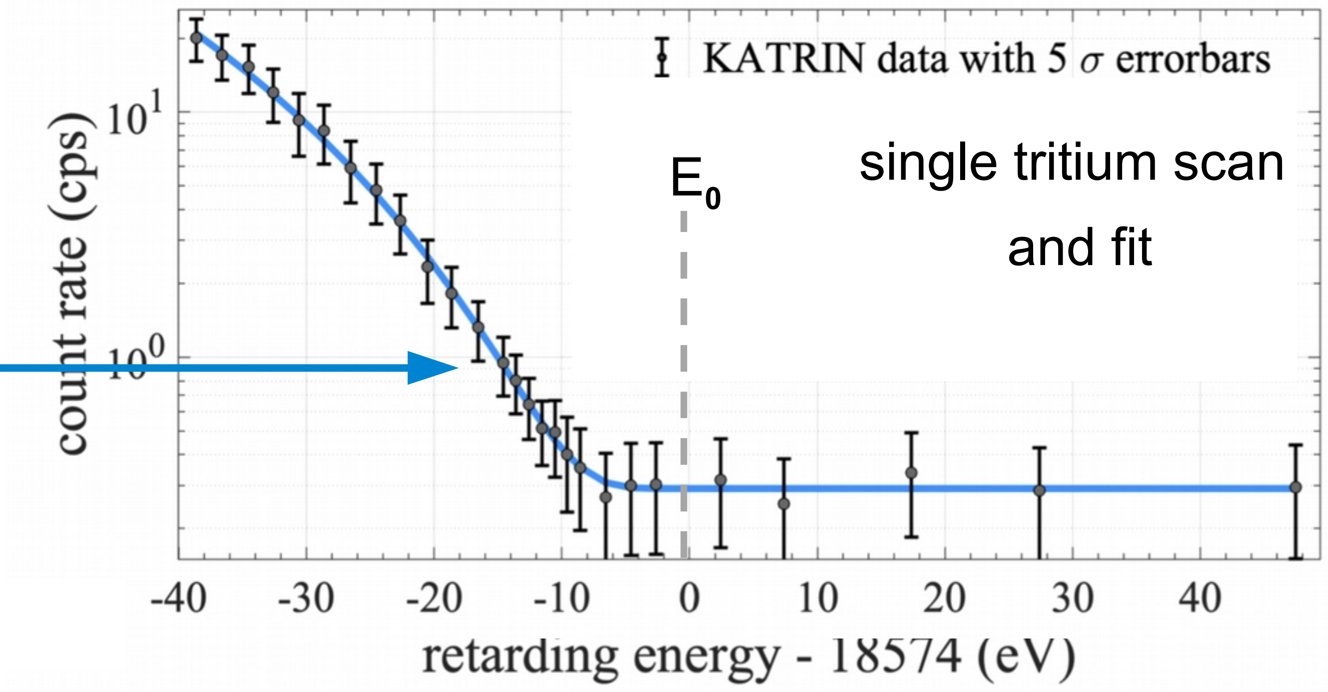
Modeling of experimental data

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



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

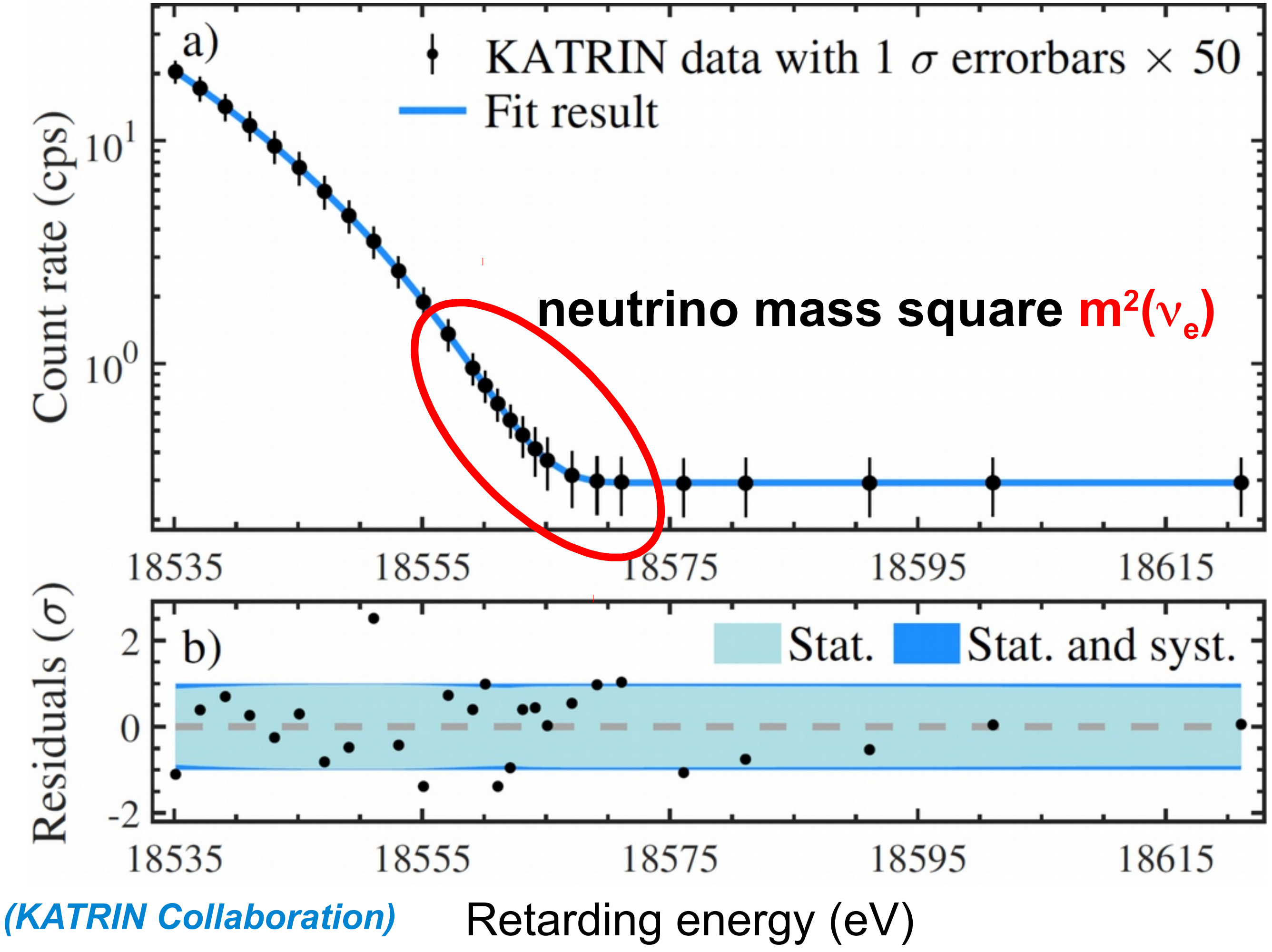




$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_ß(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

Fitting tritium ß-decay spectrum

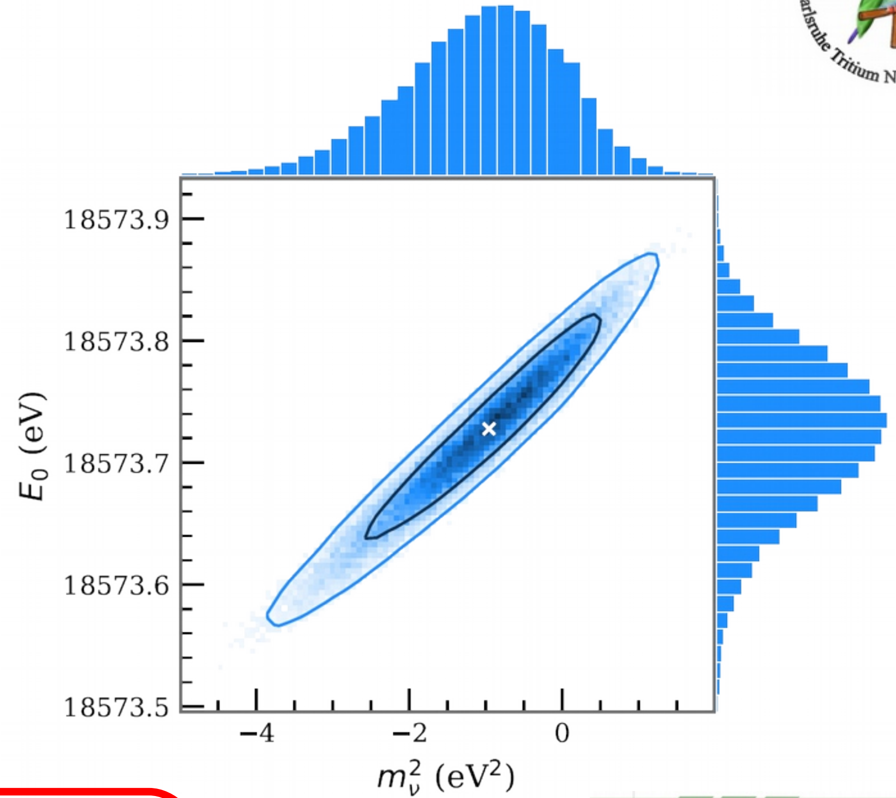
- **High-statistics ß-spectrum**
  - 2 million events in
    in 90-eV-wide interval
    (522 h of scanning, 274 indiv. scans)
  - fit with 4 free parameters:
    $m^2(\nu_e)$, R_{bg}, A_s, E_0
    excellent goodness-of-fit
    $\chi^2 = 21.4$ for 23 d.o.f.
    (p-value = 0.56)
- **Bias-free analysis**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



M. Aker et al. (KATRIN Collaboration)
Phys. Rev. Lett. 123 (2019) 221802

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**

$m^2(\nu_e) = -1.0\ ^{+0.9}_{-1.1}$ eV^2 (90% C.L.)

→ $m(\nu_e) < 1.1$ eV at 90% CL (Lokhov-Tchakev)

→ $m(\nu_e) < 0.8$ eV (0.9 eV) at 90% (95%) CL (Feldman-Cousins)

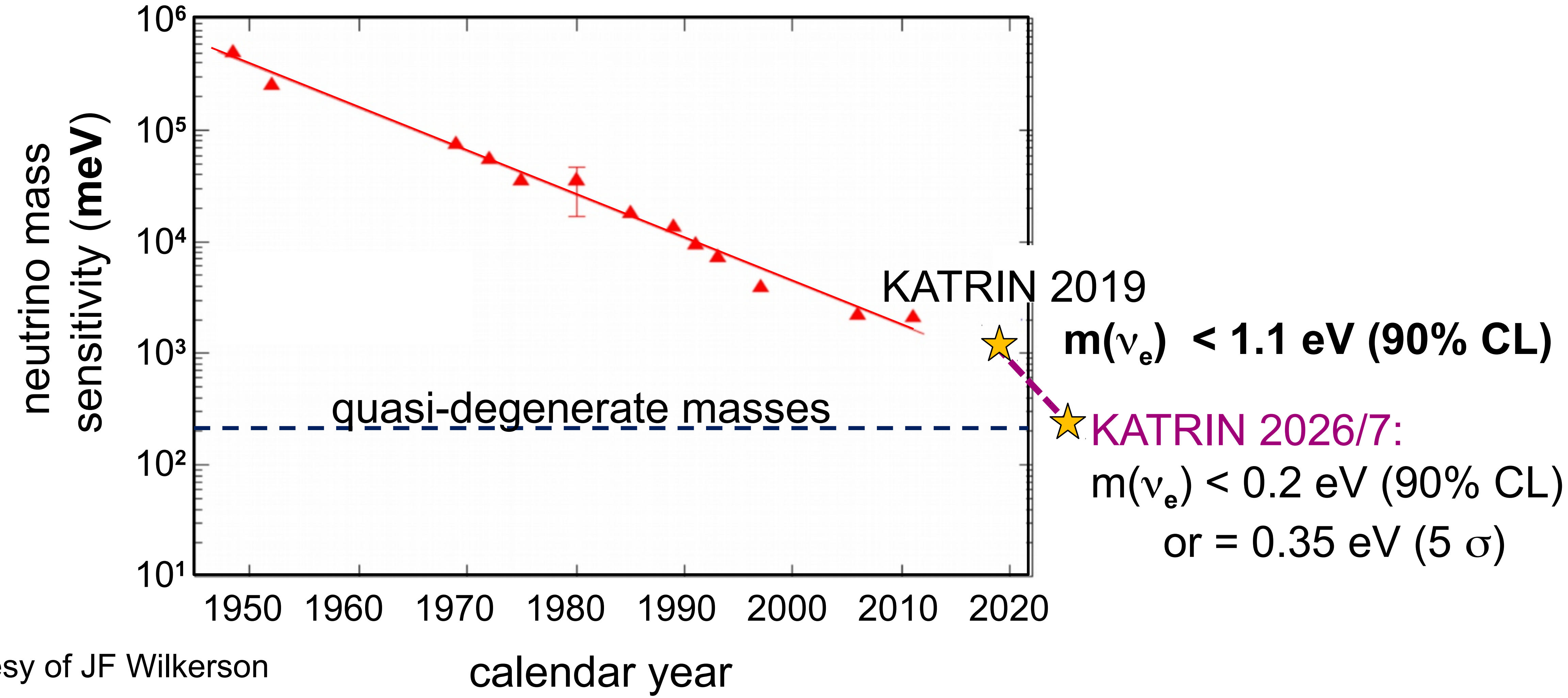
M. Aker et al. (KATRIN Collab.) Phys. Rev. Lett. 123 (2019) 221802

E_0 = (18573.7 ± 0.1) eV → Q-value : (18575.2 ± 0.5) eV

E.G. Myers et al., PRL 114 (2015) 013003: Q-value [$\Delta M(^3H,^3He)$]: (18575.72 ± 0.07) eV

Moore´s law of direct ν-mass sensitivities*

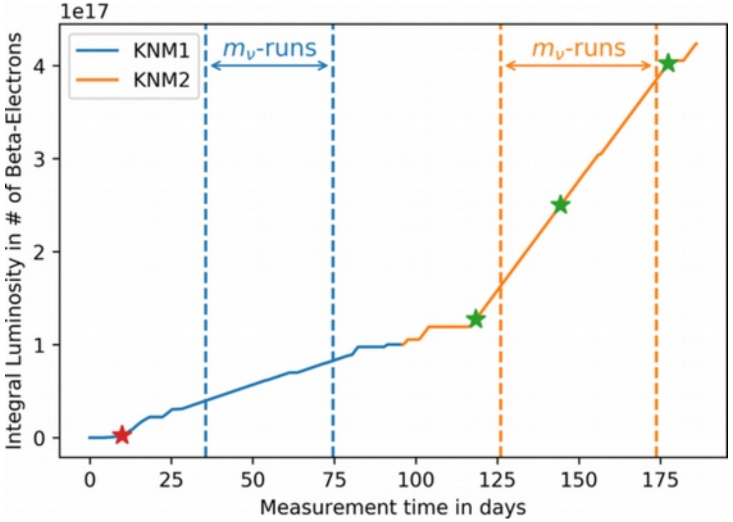
- KATRIN 2019 – 2024: **a new, much steeper slope for Moore´s law**

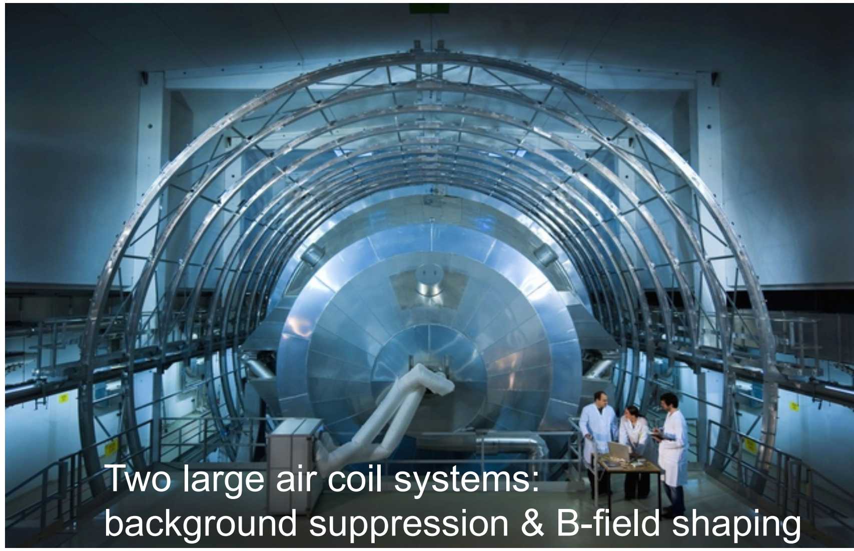


*courtesy of JF Wilkerson

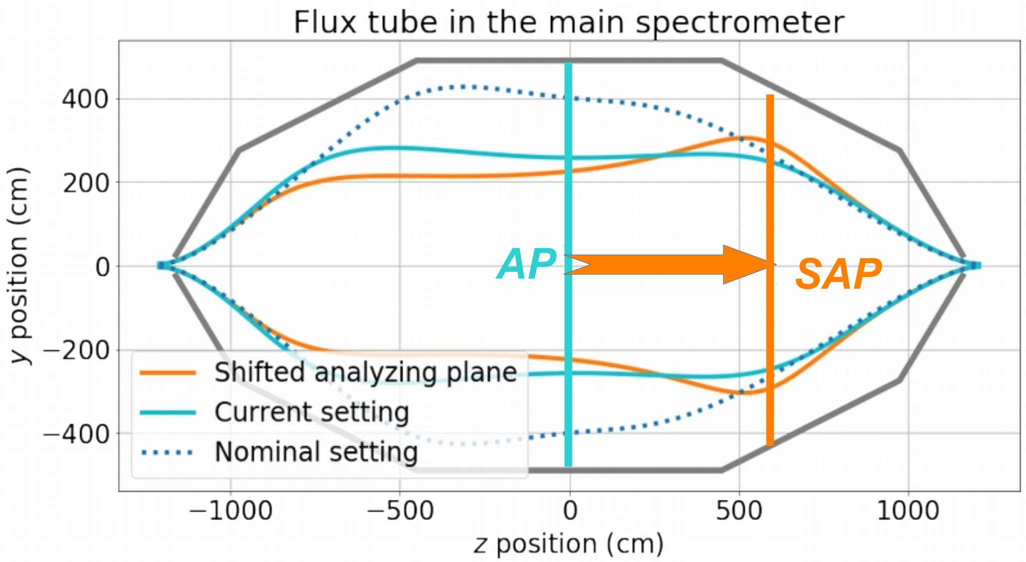
Improving signal-to-background ratio

- **Signal increase**
  ⇨ science run 2 in fall 2019 with
  83% nominal column density





- **Background reduction**
  ⇨ „shifted analyzing plane" (SAP)
  by segemented wire electrode system
  & upgraded air coil system ☑
  → factor >2 signal-to-background improvement
  ⇨ spectrometer bake-out successful ☑
  ⇨ more effective LN_2-cooled baffles
  – by pumping → lowering temperature
  → better ^{219}Rn retention

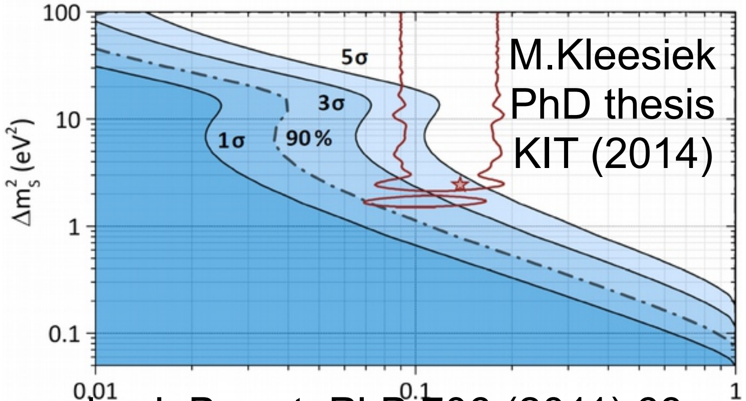


Other interesting searches for physics beyond the Standard Model

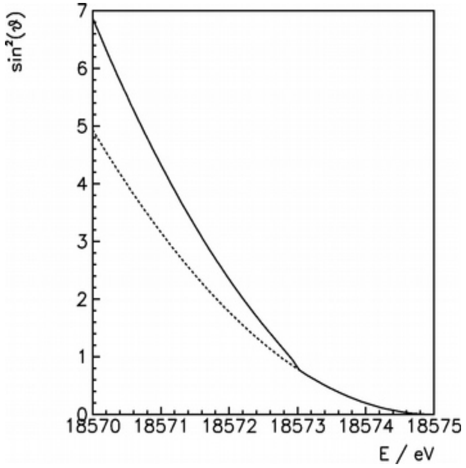
Sterile neutrinos

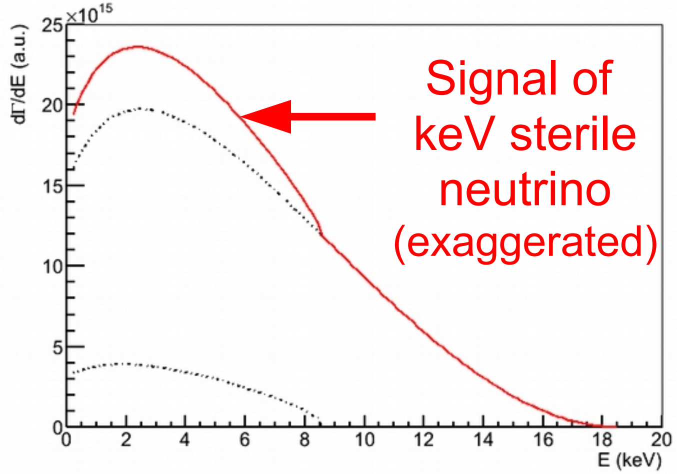
$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2}\right)$$

eV ν:



see e.g.:
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

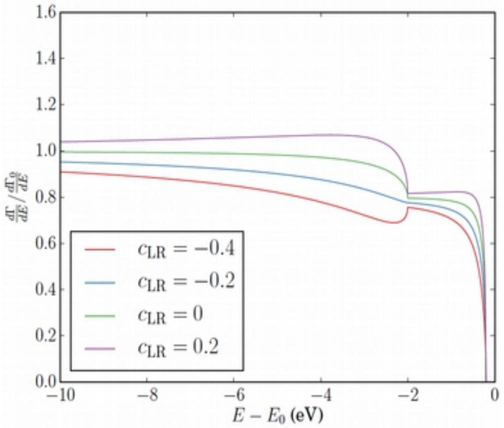


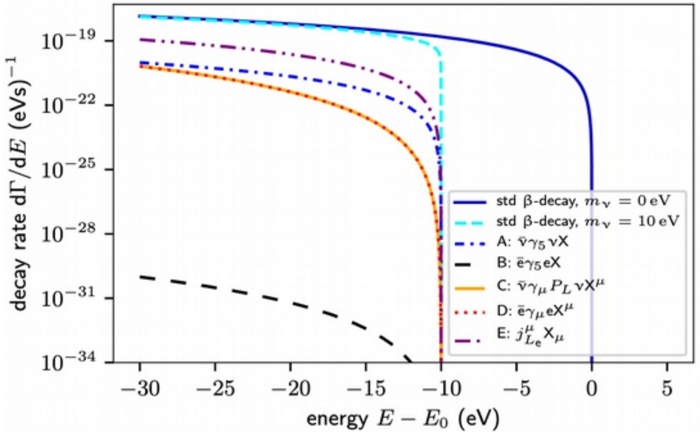


keV ν:

see e.g.

S. Mertens et al., JCAP 02 (2015) 020
M. Drewes et al. JCAP 01 (2017) 025





non SM currents, additional light bosons, ...

see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν), G. Arcadi et al., JHEP 1901 (2019) 206 (light bosons)

Outlook:
keV sterile neutrino search with KATRIN

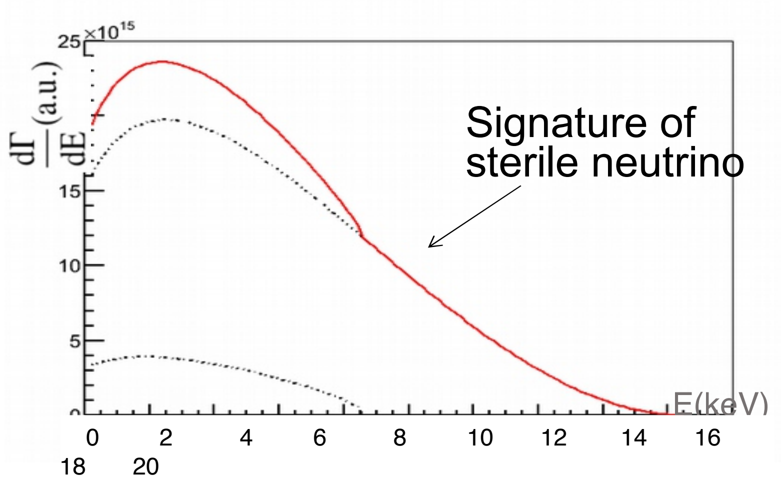
- 4-th mass eigenstate of neutrino mixed with the flavour eigenstates

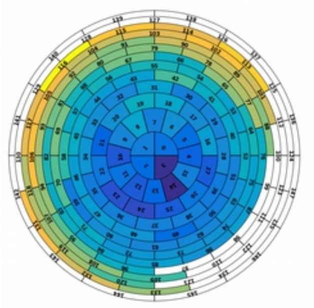
  - particle beyond the standard model
  - Dark matter candidate
- **Look for the kink in the β-spectrum**
- **TRISTAN project in KATRIN**

  - developing a new detector & DAQ system

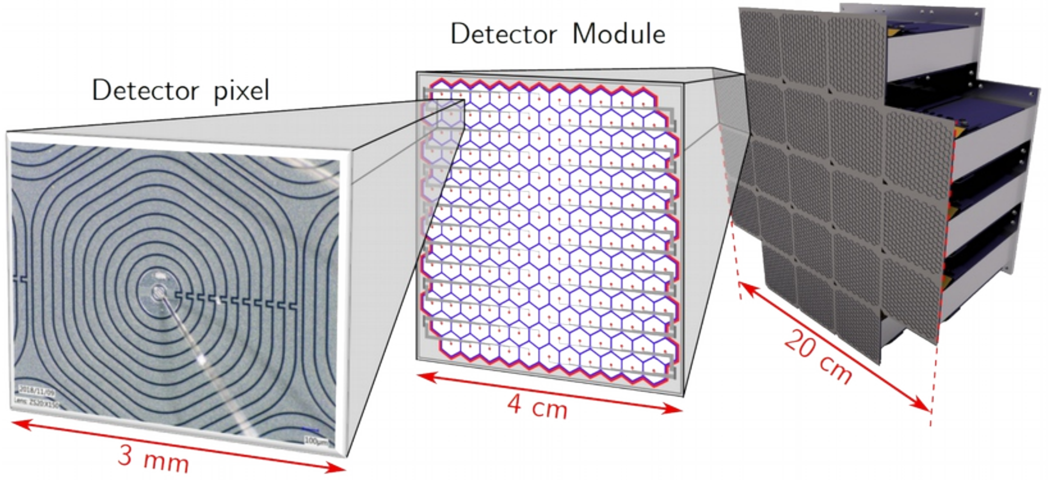
- **large count rates**
- **good energy resolution**
- **Silicon Drift Detector**

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





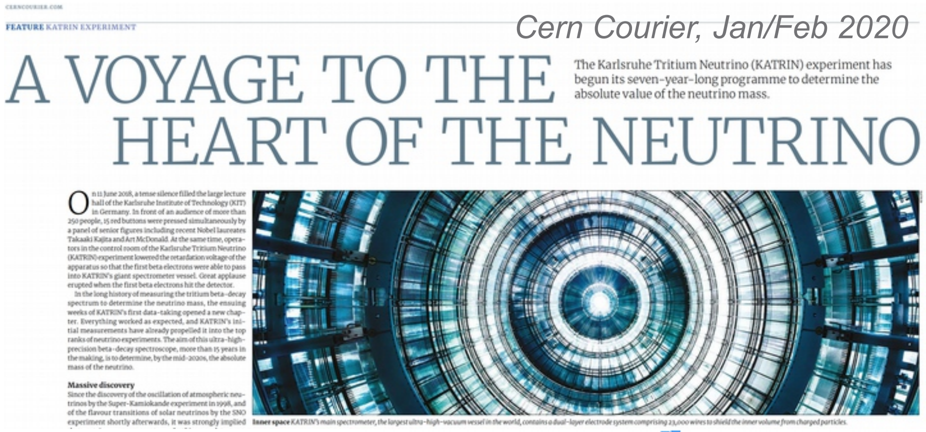
segmented Si-PIN wafer



S. Mertens et al., J.Phys. G46 (2019) 065203; T. Brunst et al., JINST 14 (2019) P11013

Conclusions

Cern Courier, Jan/Feb 2020


FEATURE KATRIN EXPERIMENT

A VOYAGE TO THE HEART OF THE NEUTRINO

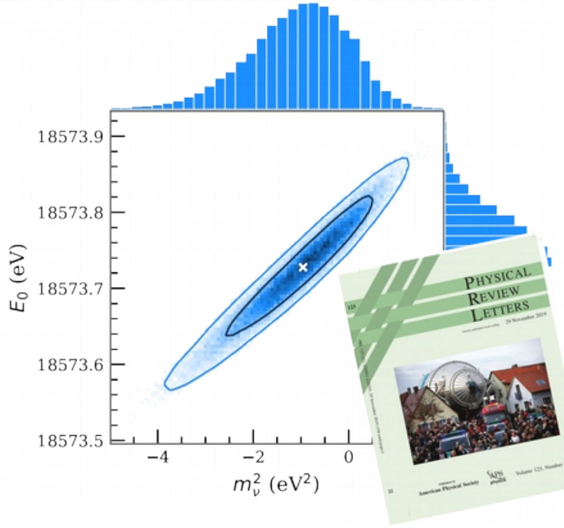
The Karlsruhe Tritium Neutrino (KATRIN) experiment has begun its seven-year-long programme to determine the absolute value of the neutrino mass.

Neutrino masses are

- very important for astrophysics & cosmology & particle physics

KATRIN:

- is the direct neutrino mass experiment complementary to cosmological analyses and $0\nu\beta\beta$ searches
- has performed successful first neutrino mass science run in 2019 yielding a limit of 1.1 eV for the neutrino mass
- is analyzing science run 2 (higher statistics) and is preparing science run 3 (lower bg)
- has the sensitivity goal of 200 meV for 5 years running
- can also look for sterile neutrinos (eV, keV with TRISTAN det.) and other BSM physics



Thank you for your attention !

Beyond KATRIN:

- Can we upgrade KATRIN by time-of-flight or cryo-bolometer to differential mode?
- ^{163}Ho micro calorimeters (ECHo, HOLMES, …)
- New ideas like Project 8, ..


Dr. Jochen Bonn 1944 - 2012


Prof. Dr. Vladimir M. Lobashev 1934 - 2011


Prof. Dr. Dr. h.c. Ernst-W. Otten 1934 - 2019

3 very important founding members passed away on the long road of KATRIN