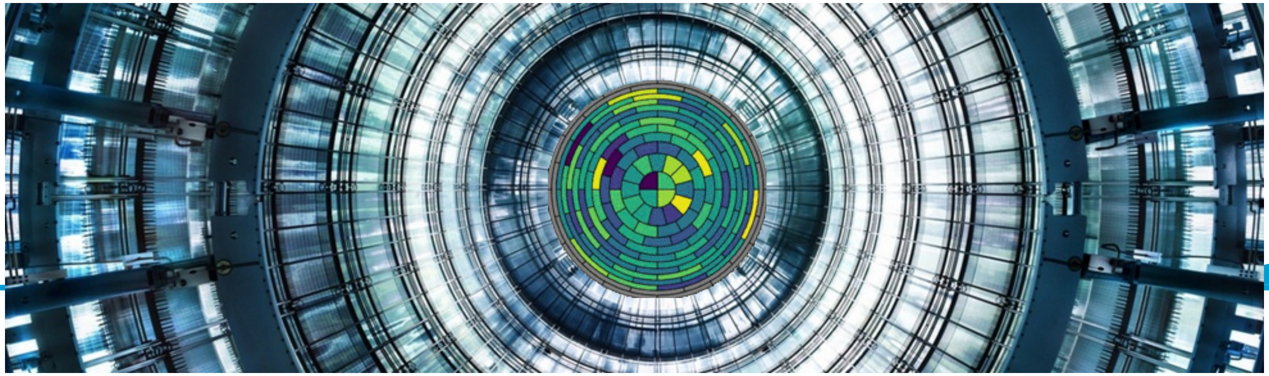
WWU MÜNSTER

First results from the neutrino mass experiment KATRIN

Christian Weinheimer – University of Münster
DESY Particle and Astroparticle Physics Colloquium, 14.1.20

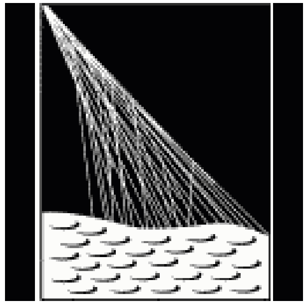
- Introduction – importance of neutrino mass
- The KArlsruhe TRItium Neutrino experiment KATRIN
- First results from KATRIN
- Future of neutrino mass measurements
- Conclusions



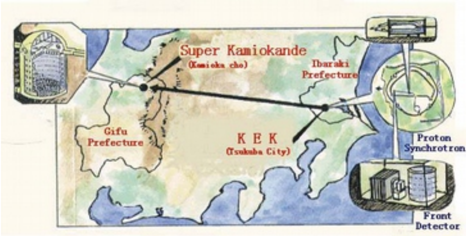
Institut für Kernphysik
Westfälische Wilhelms-Universität Münster

Positive results from ν oscillation experiments

atmospheric neutrinos
(Kamiokande, Super-Kamiokande, IceCube, ANTARES)



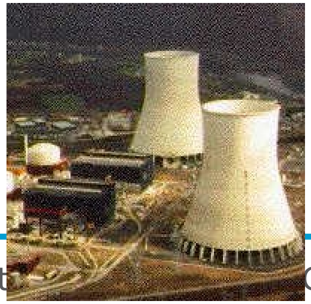
accelerator neutrinos
(K2K, T2K, MINOS, Nova, OPERA, MiniBoone)



solar neutrinos
(Homestake, Gallex, Sage,
Super-Kamiokande,
SNO, Borexino)

Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ, Daya Bay,
Double CHOOZ, RENO, ...)



⇒ non-trivial ν-mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

$0.37 < \sin^2(\theta_{23}) < 0.63$ maximal!
$0.26 < \sin^2(\theta_{12}) < 0.36$ large !
$0.018 < \sin^2(\theta_{13}) < 0.030$ 8.5°
$7.0\ 10^{-5}\ \mathrm{eV}^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ \mathrm{eV}^2$
$2.2\ 10^{-3}\ \mathrm{eV}^2 < |\Delta m_{13}^2| < 2.6\ 10^{-3}\ \mathrm{eV}^2$

⇒ $m(\nu_j) \neq 0$, but unknown

$m(\nu_j)$ not accessible by ν osc. exp.

additional sterile neutrinos ?

Current most urgent questions in neutrino physics

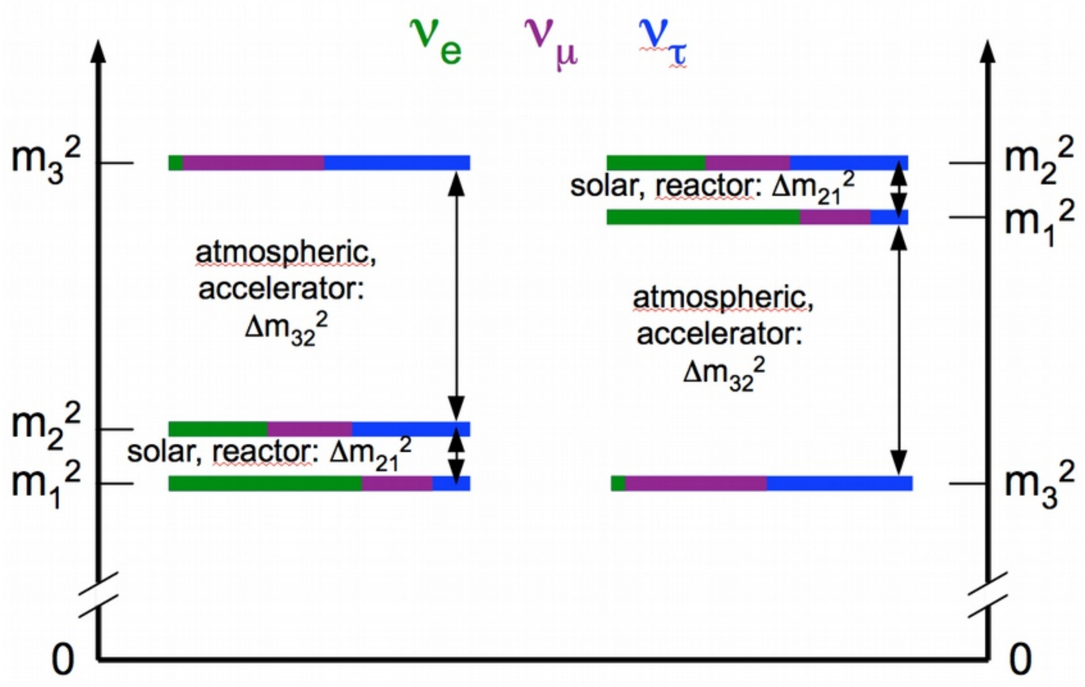
- Hierarchy: $m(\nu_3) > m(\nu_{2,1})$ or $m(\nu_{2,1}) > m(\nu_3)$?

- CP violating phase δ_{CP} ?
  3x3 unitary mixing matrix U_{PMNS}:
  3 angles and 1 CP violating phase,
  connected to BAU via leptogensis ?

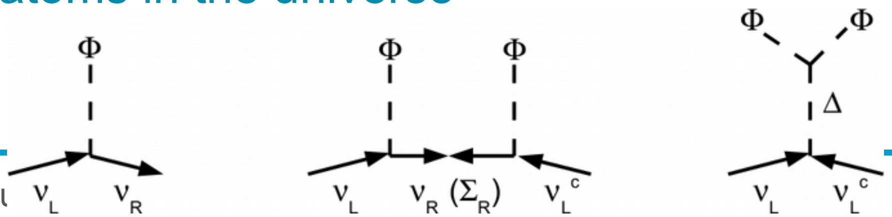
- Is there a 4th or even a 5th light
  but sterile neutrino ?

- Neutrino particle character ?
  Are neutrinos their own antiparticles
  (Majorana particles)

- **Absolute neutrino mass scale ?**
  very important since there are 1 billion times more neutrinos than atoms in the universe
  very important since the very small neutrino masses are probably
  due to more than just the Yukawa coupling to the Higgs

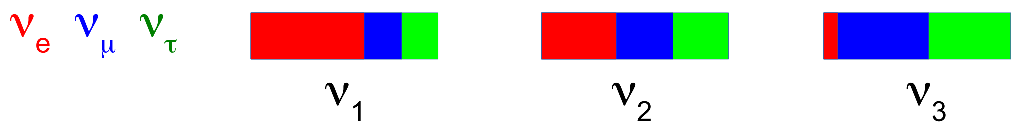


$$U_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Importance of neutrino mass for particle physics and cosmology

Results of recent oscillation experiments : Θ_{23}, Θ_{12}, Θ_{13}, $|\Delta m^2_{13}|$, Δm^2_{12} (some sensitivity to δ and sign of Δm^2_{13})



degenerated masses

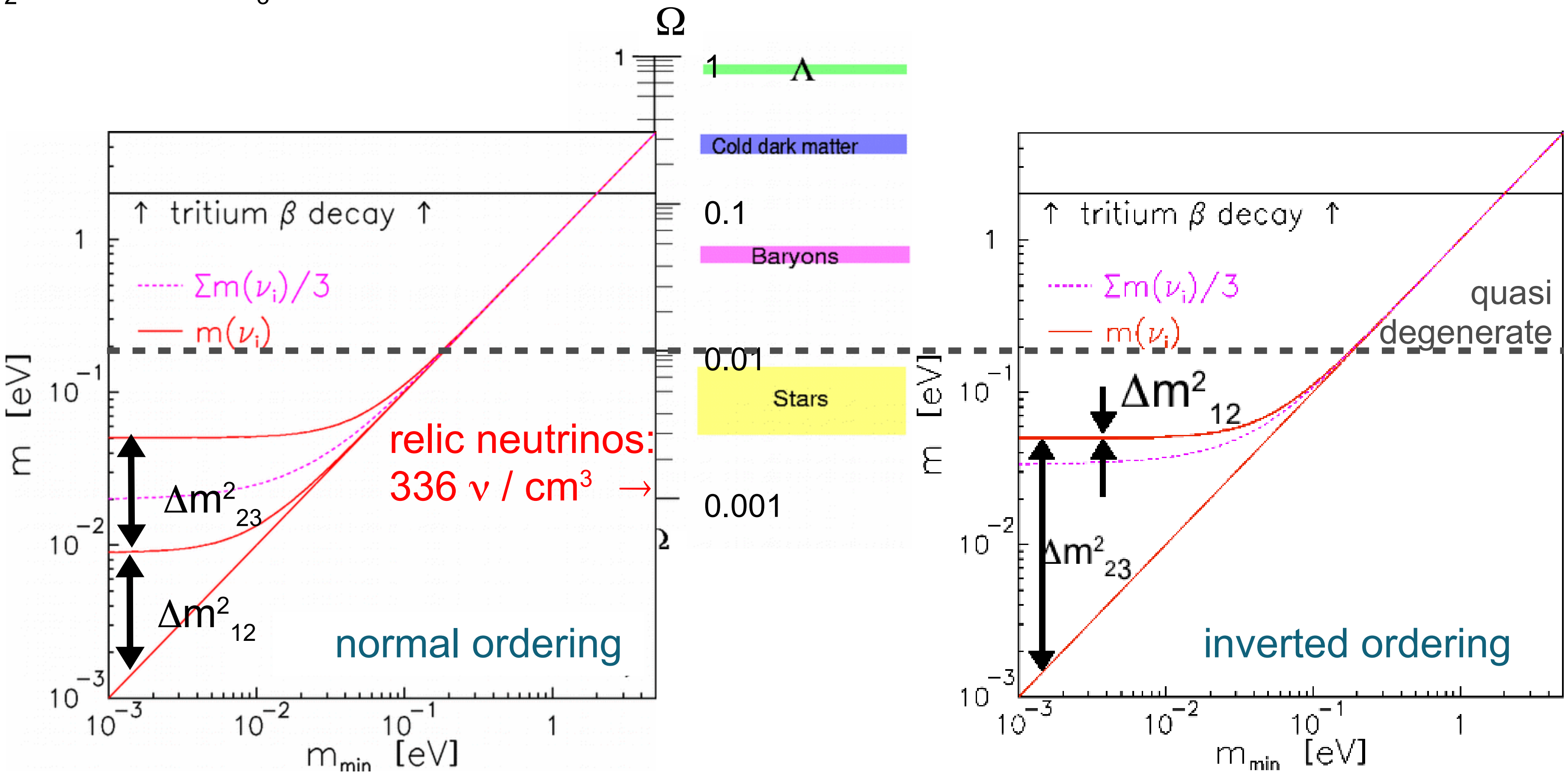
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

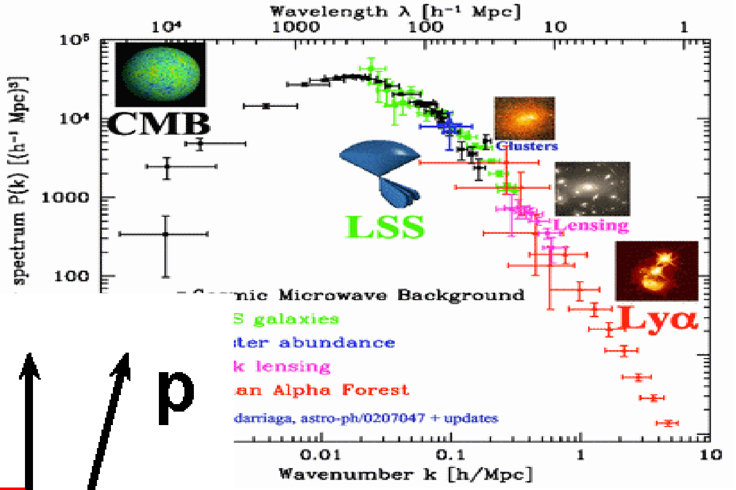
explains smallness of masses, but not large (maximal) mixing



Three complementary ways to the absolute neutrino mass scale

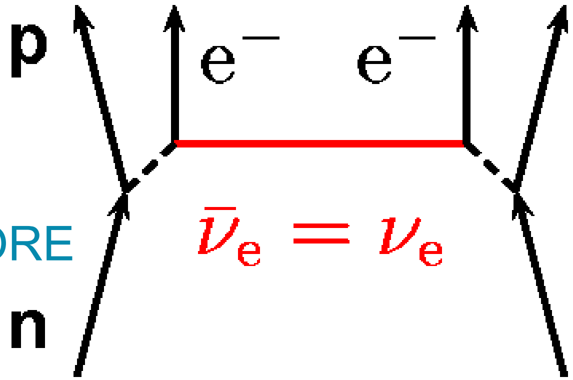
1) **Cosmology**

very sensitive, but model dependent
compares power at different scales
current sensitivity: $\Sigma m(\nu_i) \approx 0.12$ eV



2) **Search for 0νββ**

Sensitive to Majorana neutrinos, model-dependent
Upper limits by EXO-200, KamLAND-Zen, GERDA, CUORE

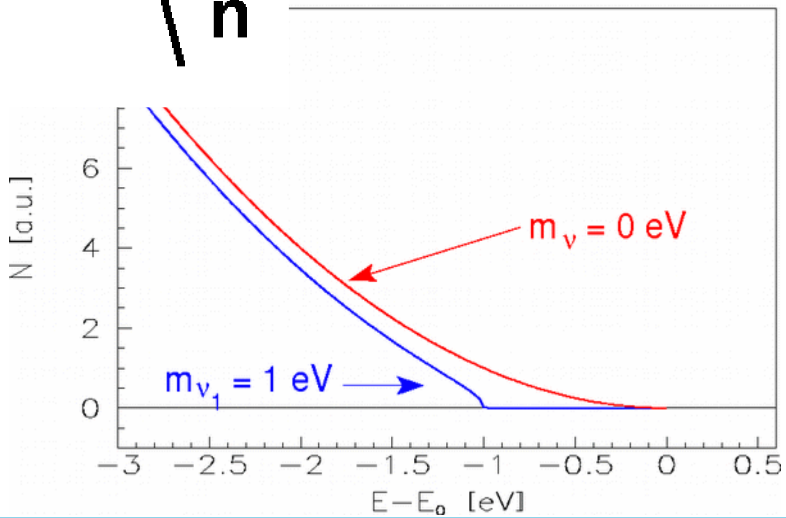


3) **Direct neutrino mass determination:**

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



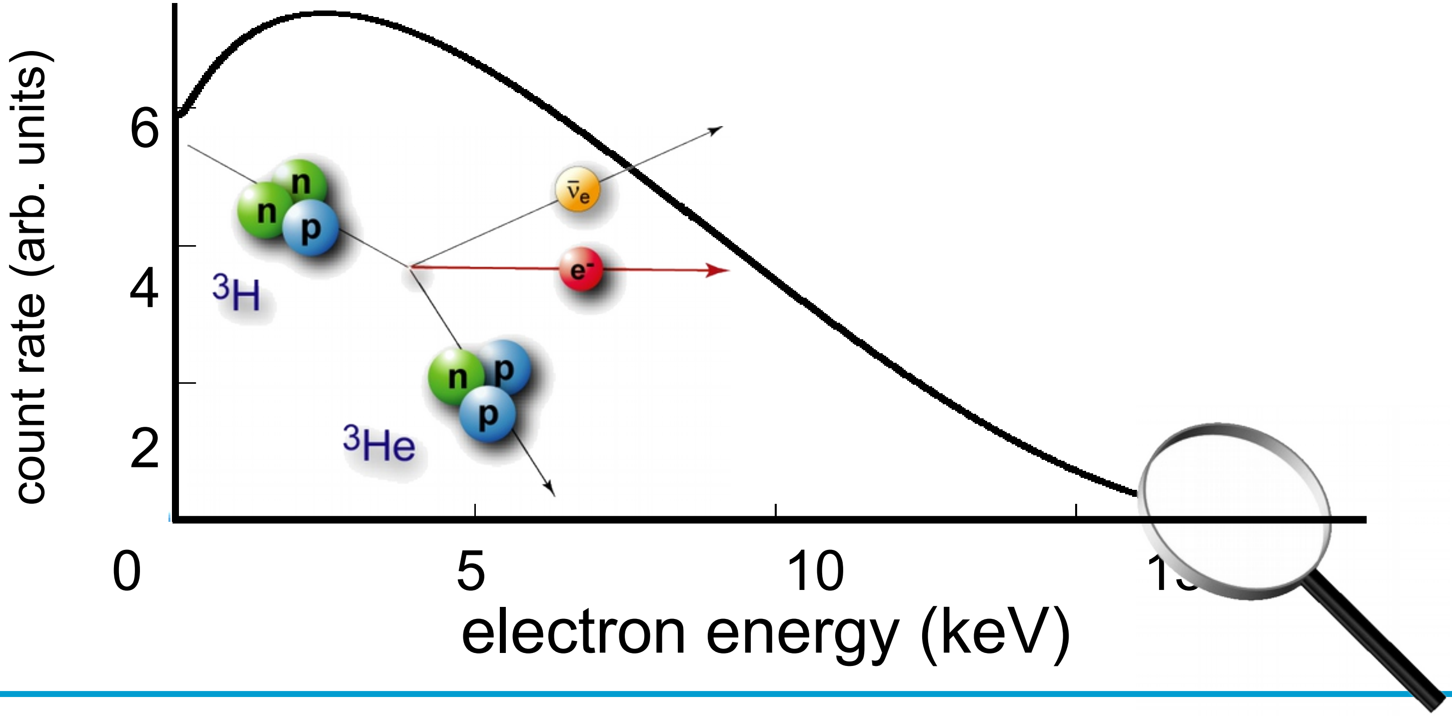
Direct determination of "$m(\nu_e)$" from β-decay (EC)

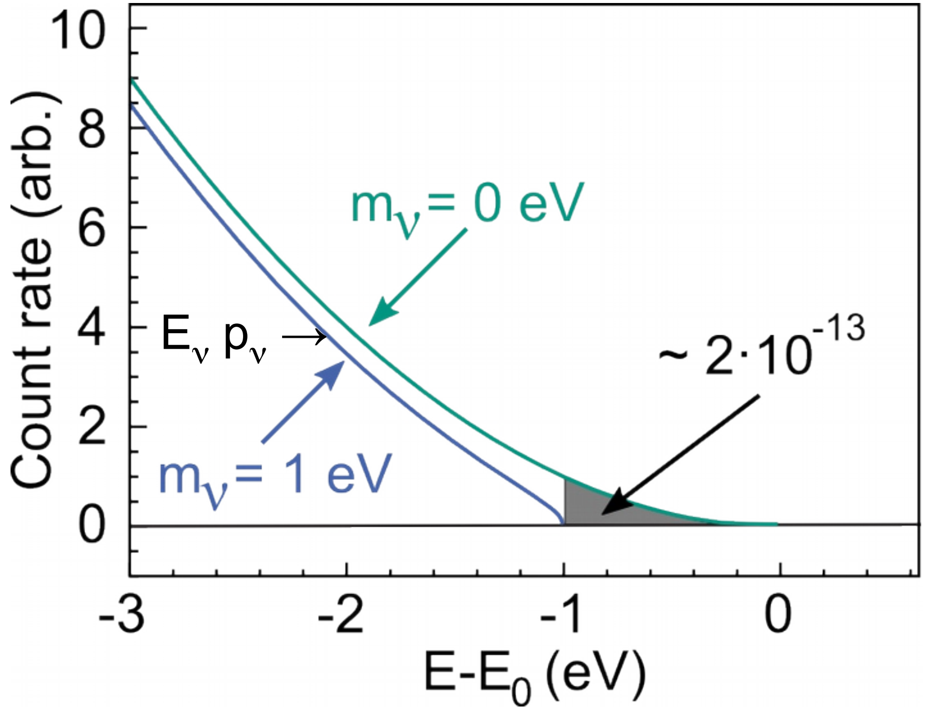
$$\beta:\ dN/dE = K\ F(E,Z)\ \underbrace{p}_{p_e}\ \underbrace{E_{tot}}_{E_e}\ \underbrace{(E_0-E_e)}_{E_\nu}\ \Sigma\,|U_{ei}|^2\ \underbrace{\sqrt{(E_0-E_e)^2 - m(\nu_i)^2}}_{p_\nu}$$

essentially phase space: p_e E_e E_ν p_ν

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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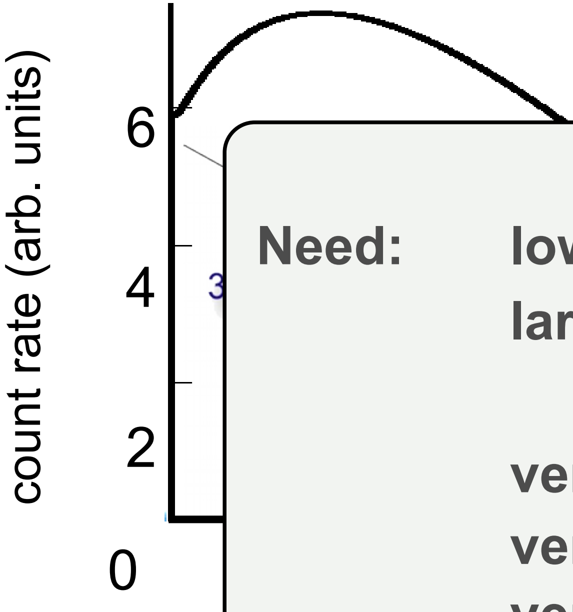
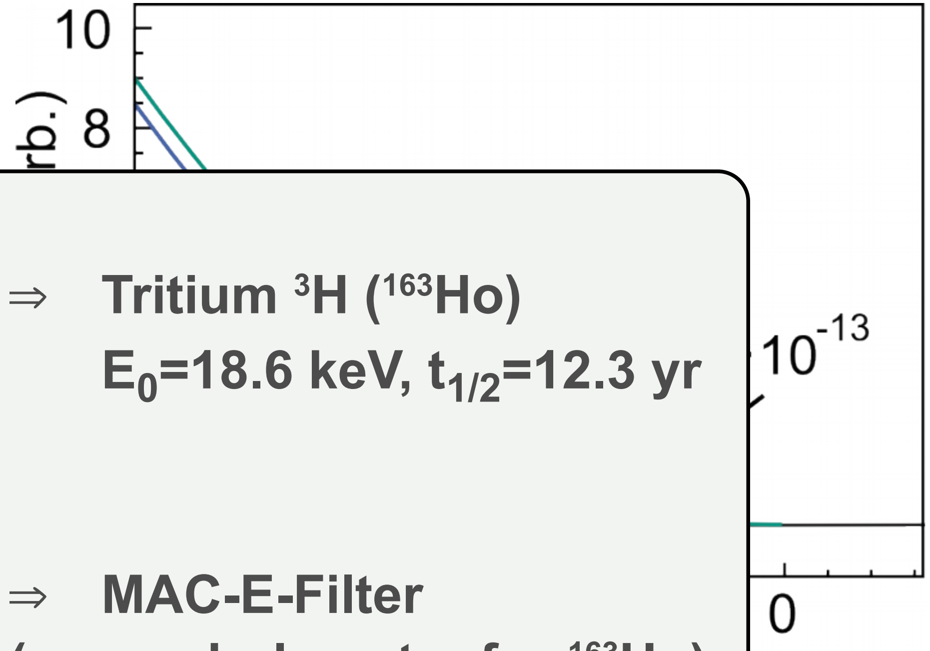
essentially phase space: p_e E_e E_ν p_ν

with "electron neutrino mass": **"$m(\nu_e)^2$" := $\Sigma\,|U_{ei}|^2\ m(\nu_i)^2$**, complementary to $0\nu\beta\beta$ & 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
very low background
} ⇒ MAC-E-Filter (or cryobolometer for ^{163}Ho)

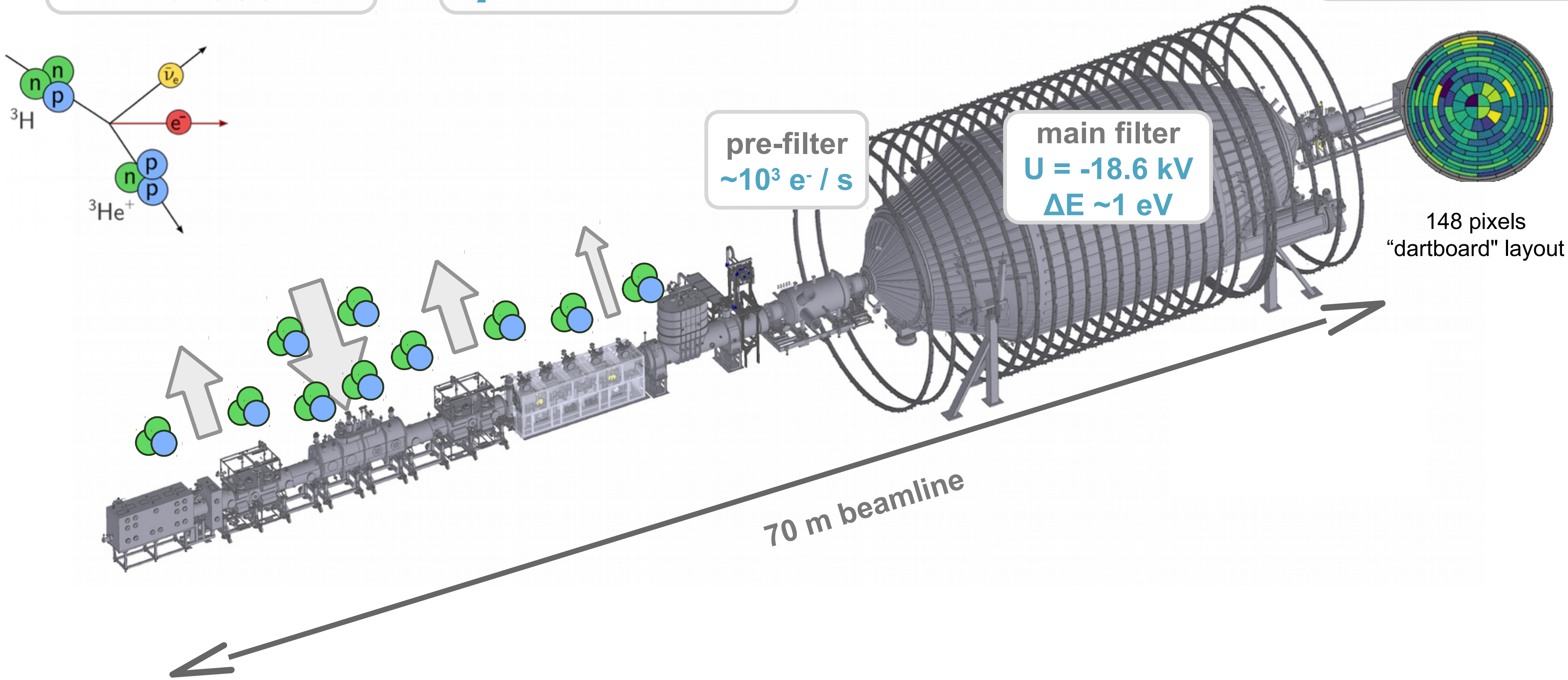
KATRIN at Karlsruhe Institute of Technology working principle

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



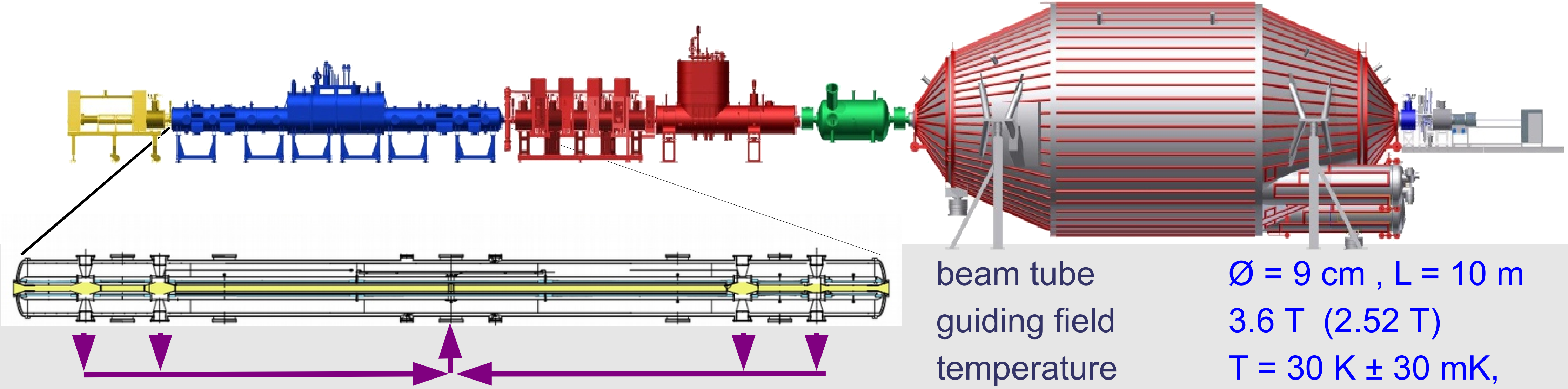
KATRIN at Karlsruhe Institute of Technology working principle

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

Funded by:

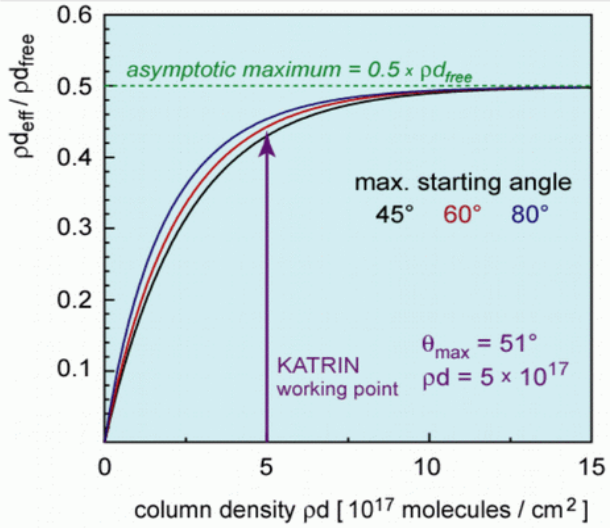
Czech Republic:

The KATRIN
Windowless Gaseous Molecular Tritium Source



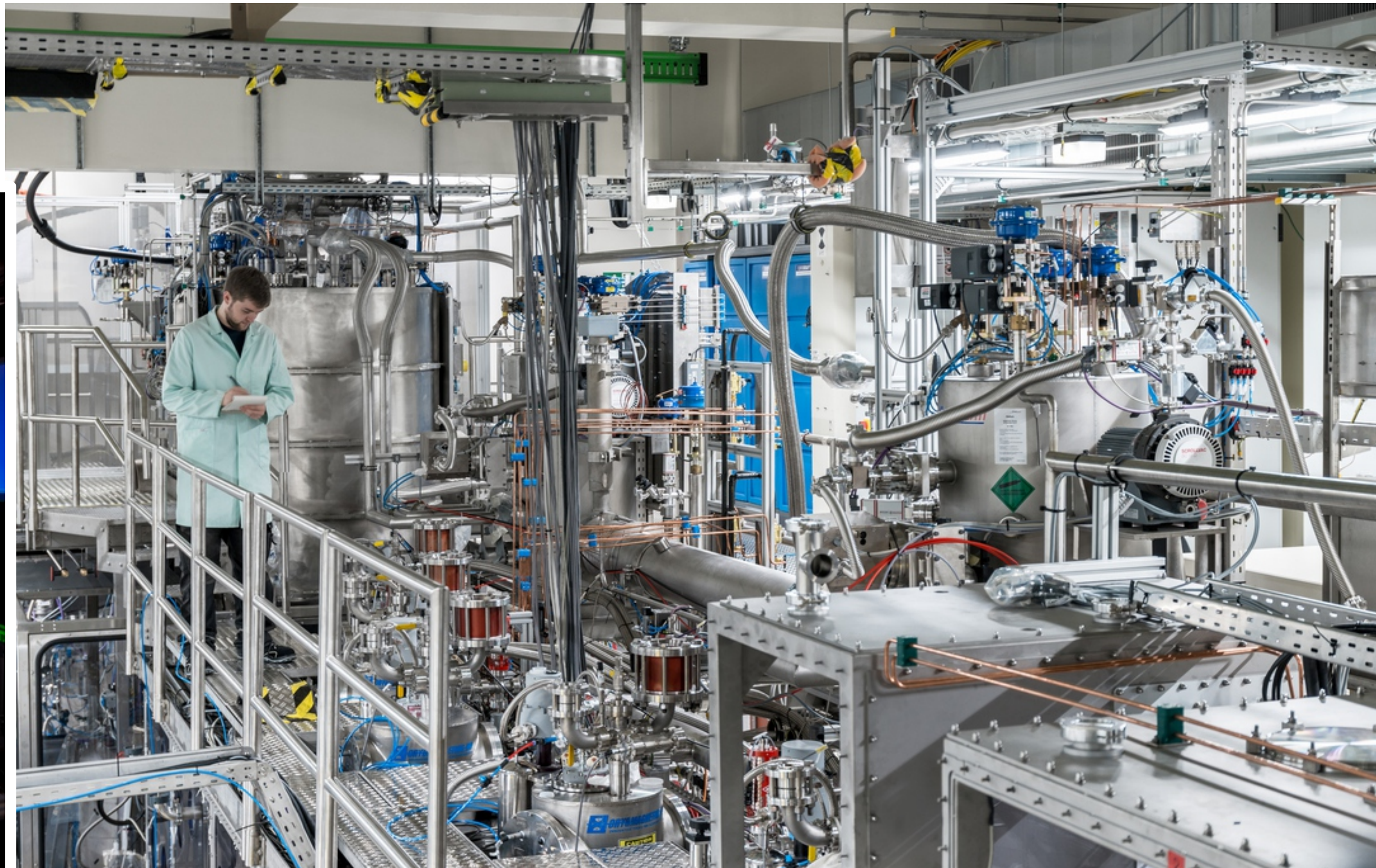
column density $5 \cdot 10^{17}$ T_2/cm^2 luminosity $1.7 \cdot 10^{11}$ Bq

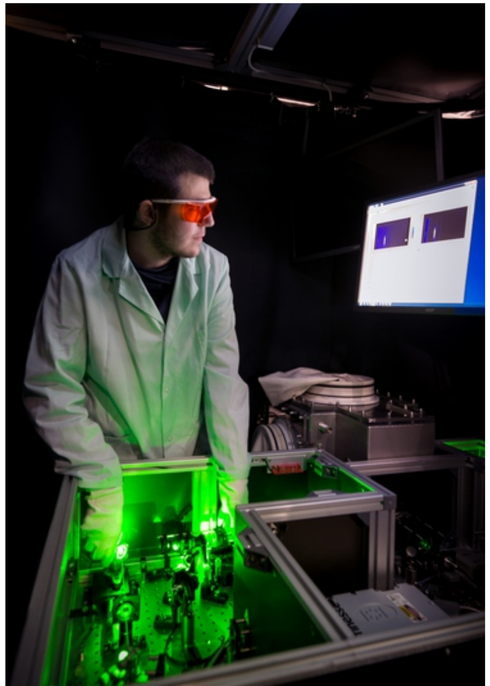
beam tube	Ø = 9 cm , L = 10 m
guiding field	3.6 T (2.52 T)
temperature	T = 30 K ± 30 mK,
T_2 flow rate	$5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)
T_2 purity	95% ± 0.1 %
T_2 inlet pressure	10^{-3} mbar ± 0.1 %



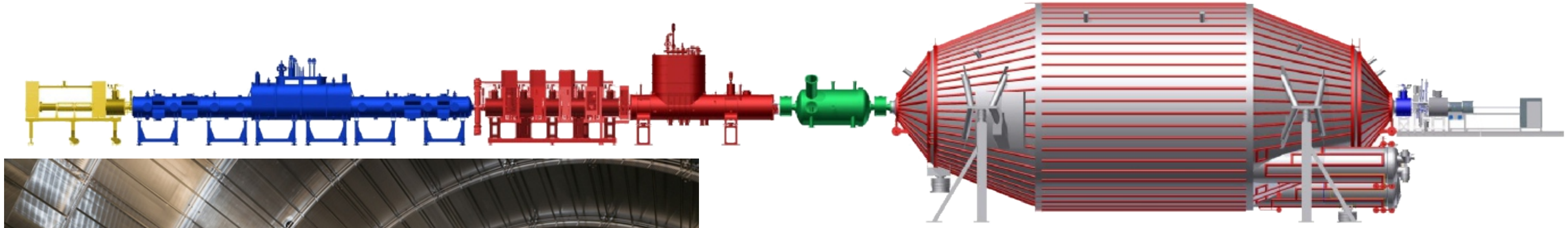
WGTS at Tritium Laboratory Karlsruhe

Photos: source & transport section





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



18.6 kV retardation voltage, σ < 60 meV/years

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

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

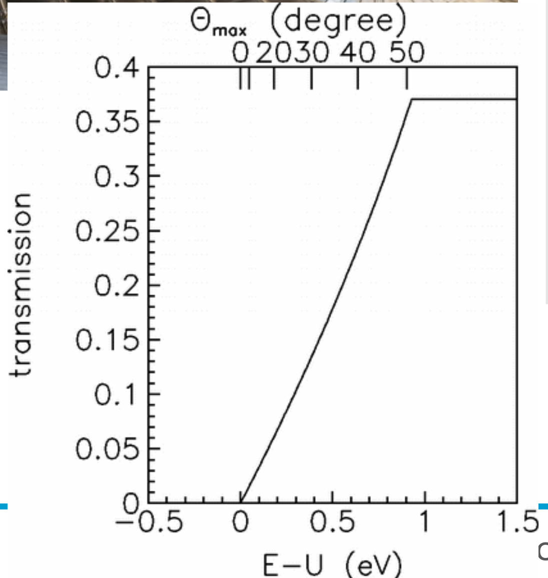
Precision voltage (ppm) at vessel and double layer wire electrode system for background reduction and field shaping

Air coils for earth magnetic field compensation

→ integral transmission function:

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

= 0.93 eV (2.7 eV)



Focal Plane Detector

Focal plane detection system

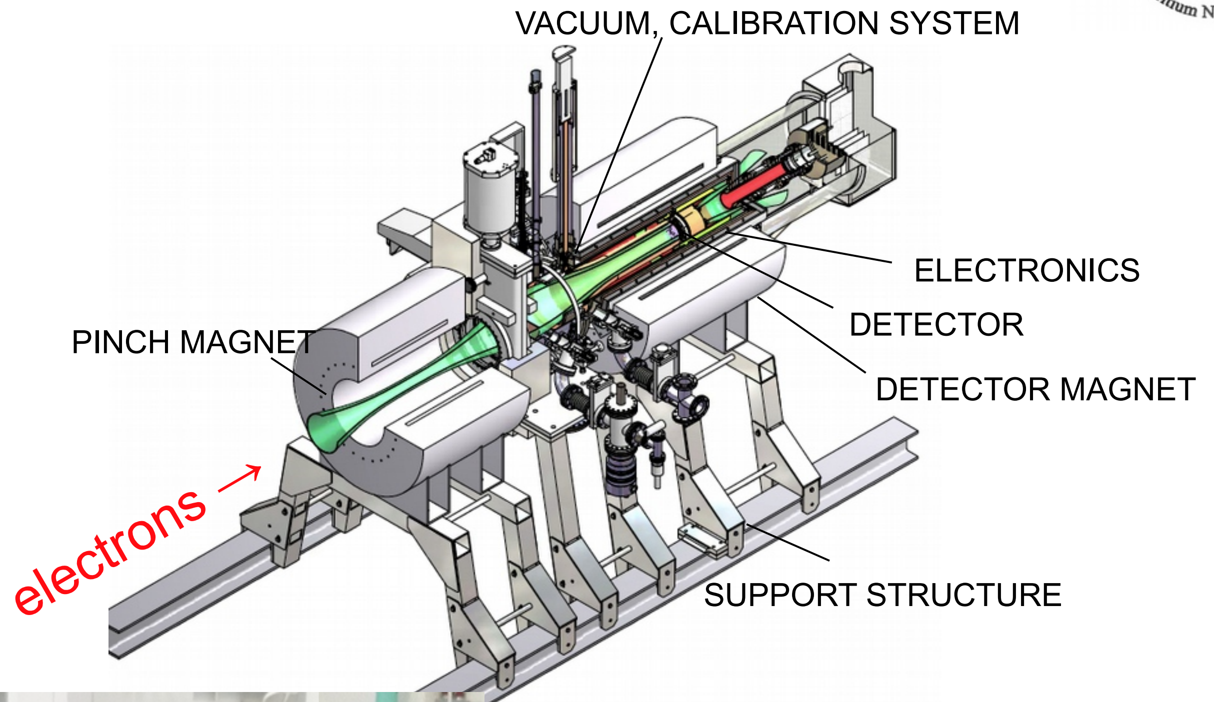
segmented Si PIN diode:
  90 mm Ø, 148 pixels, 50 nm dead layer

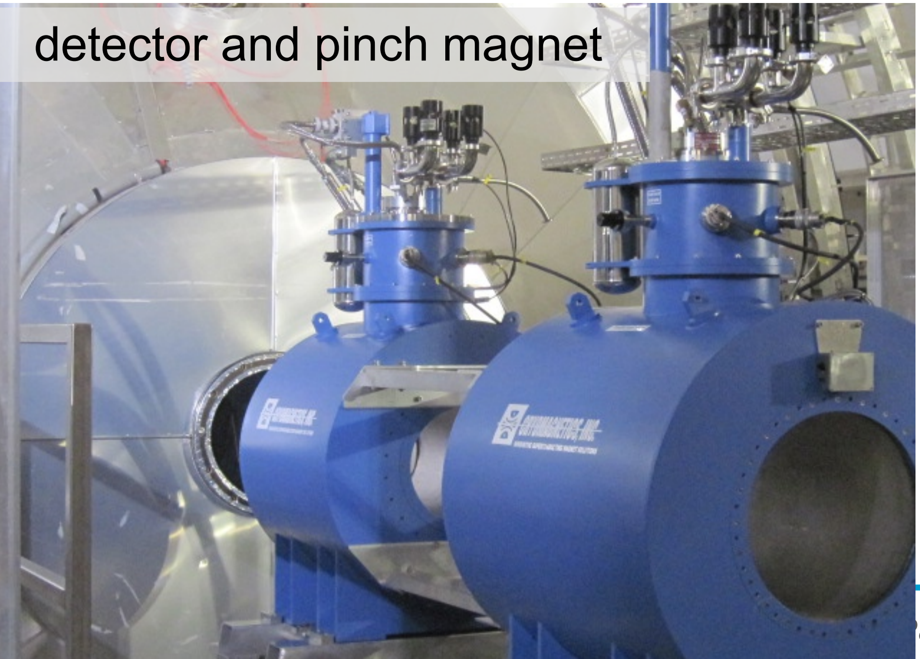
energy resolution ≈ 1 keV

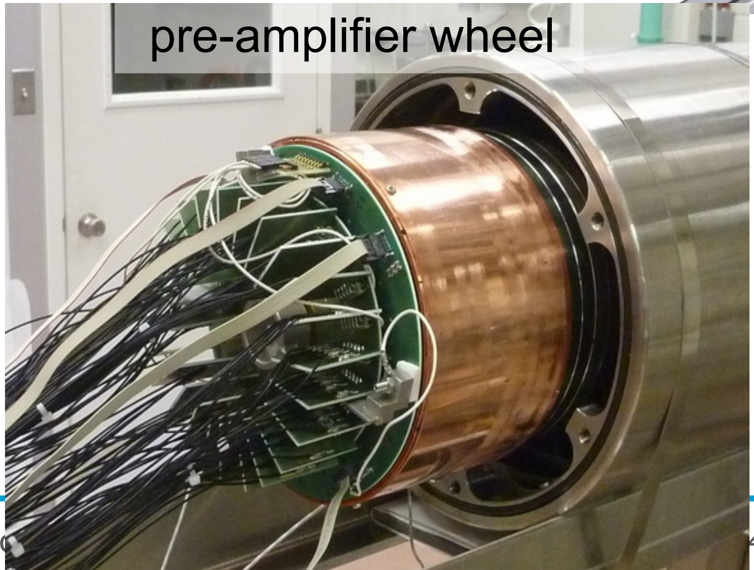
pinch and detector magnets up to 6 T

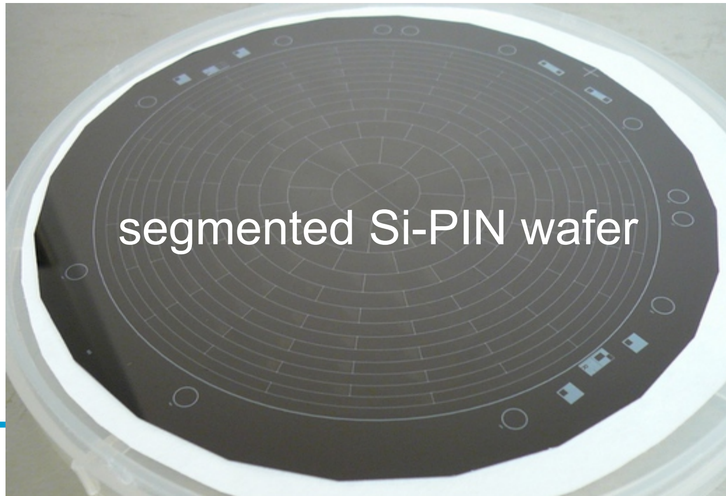
post acceleration (10kV)

active veto shield

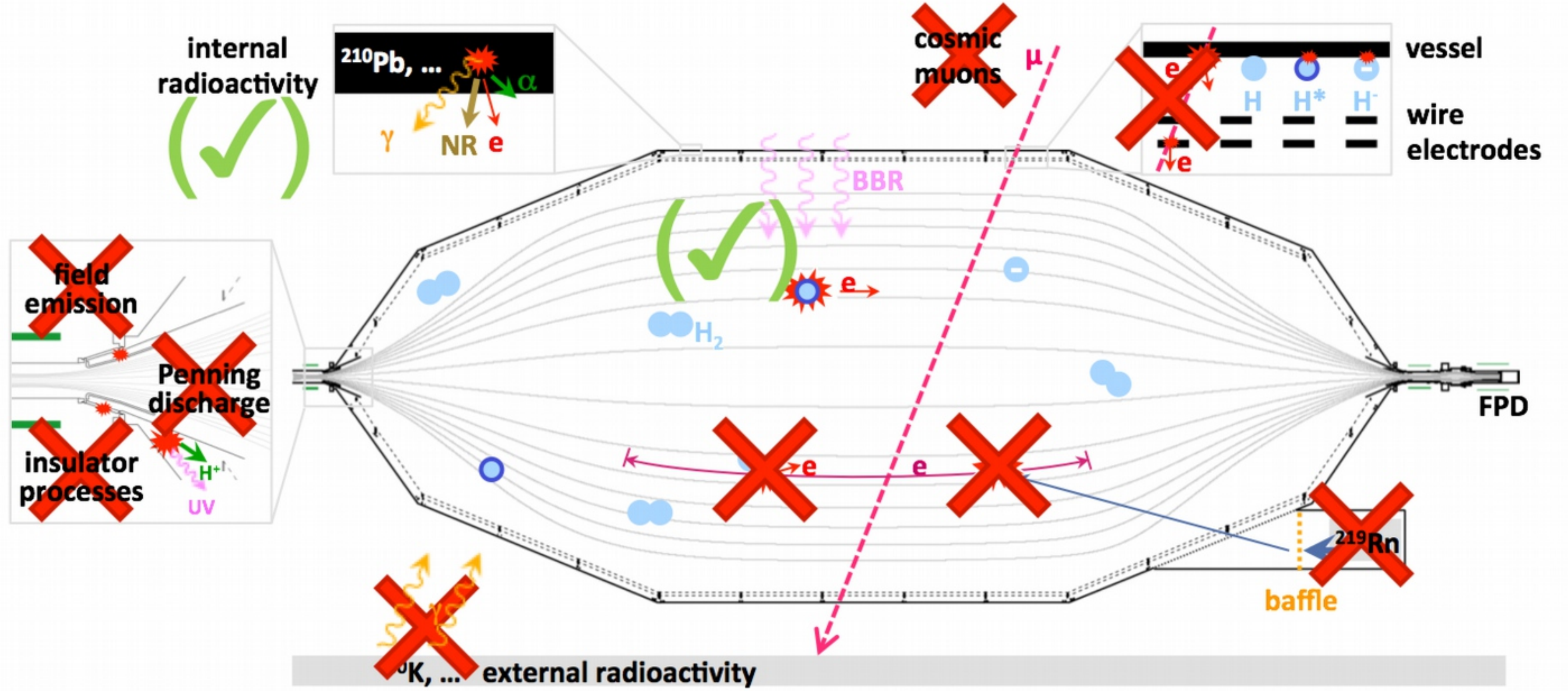








Background sources at KATRIN: detailed understanding, but …



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:

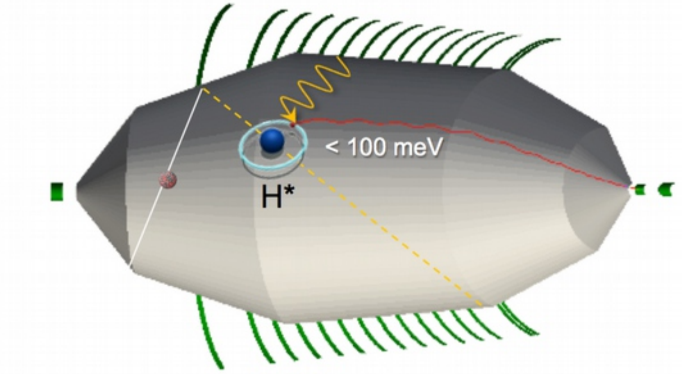
- ejected from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- ionized by black body radiation (291 K)
- non-trapped electrons on meV-scale
- bg-rate: ~0.5 cps

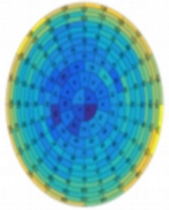
Countermeasures:

- 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 ?

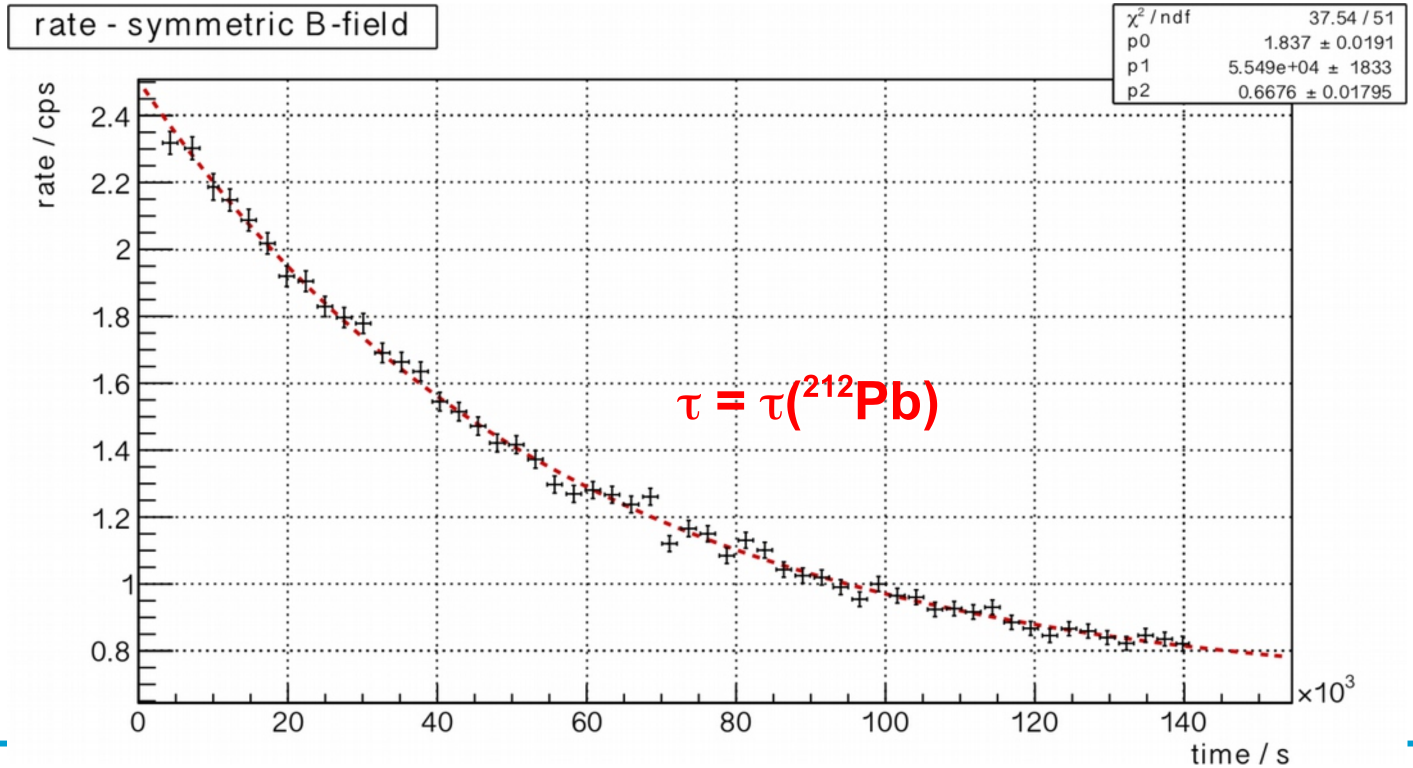
Testing this hypothesis:

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





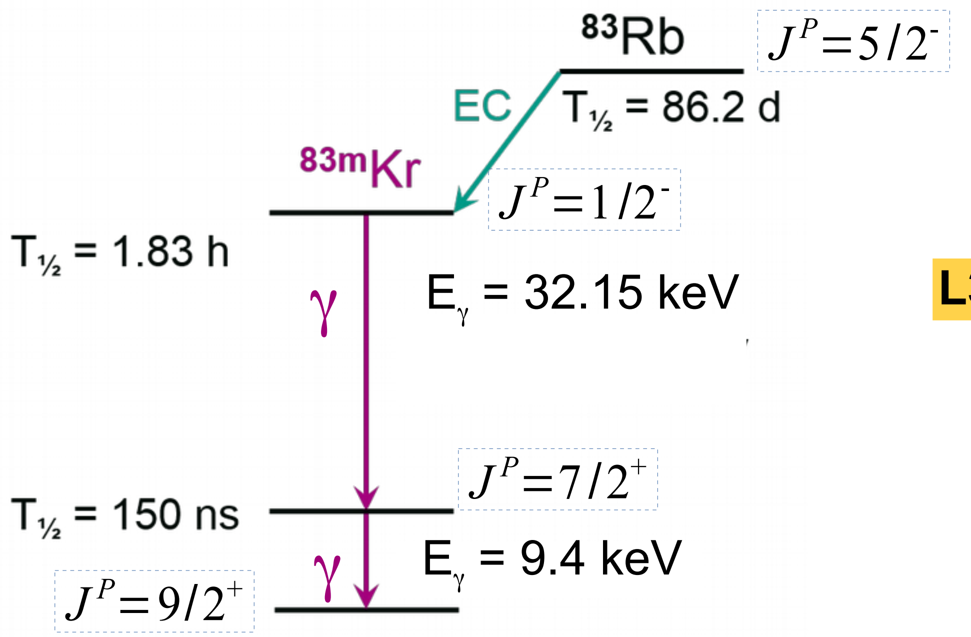
isotropic bg for longer exposure



Measuring the response with ^{83m}Kr

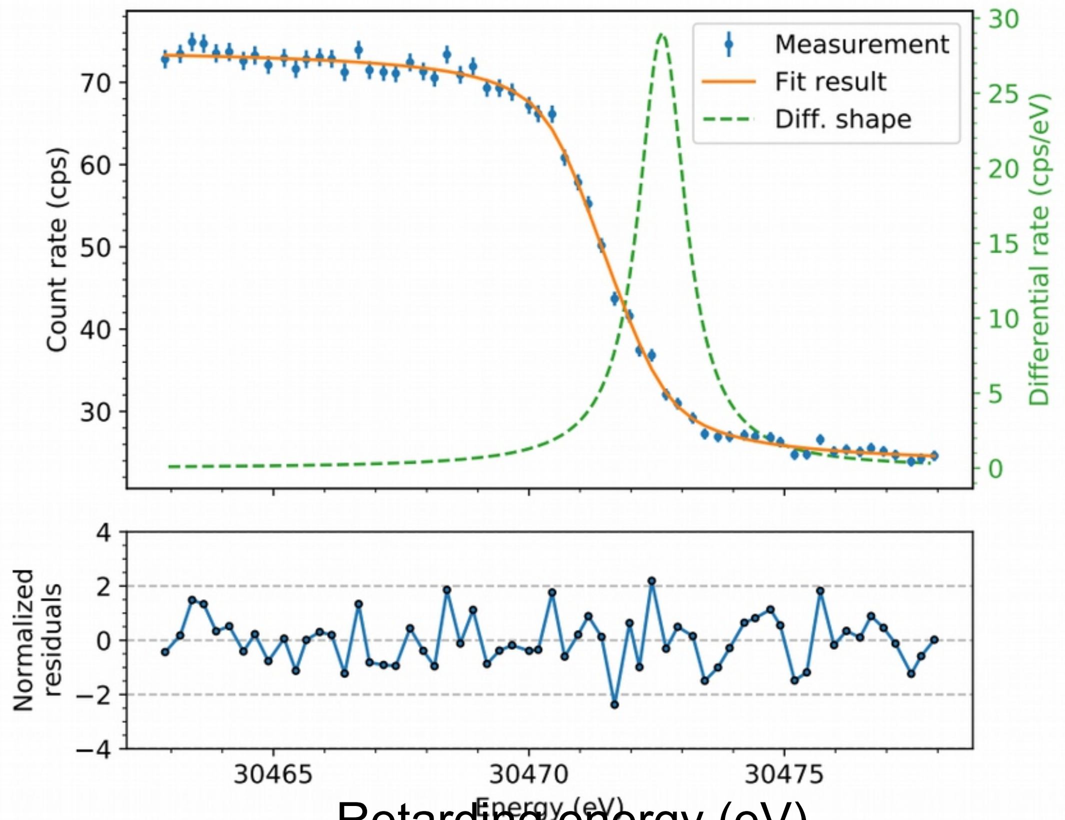
- **MAC-E filter characteristics well understood**
- **(also used to study plasma)**

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



L3-32

L3-32 line: 30.47 keV

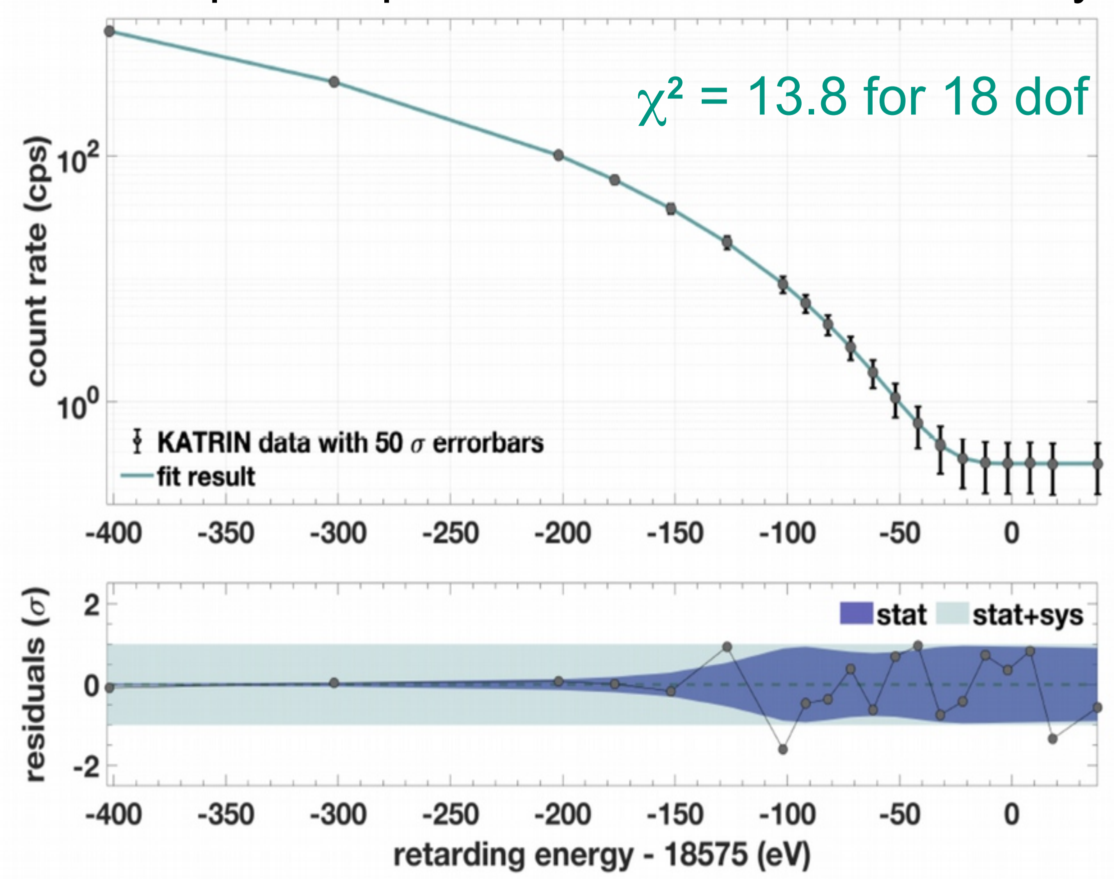


Retarding energy (eV)

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

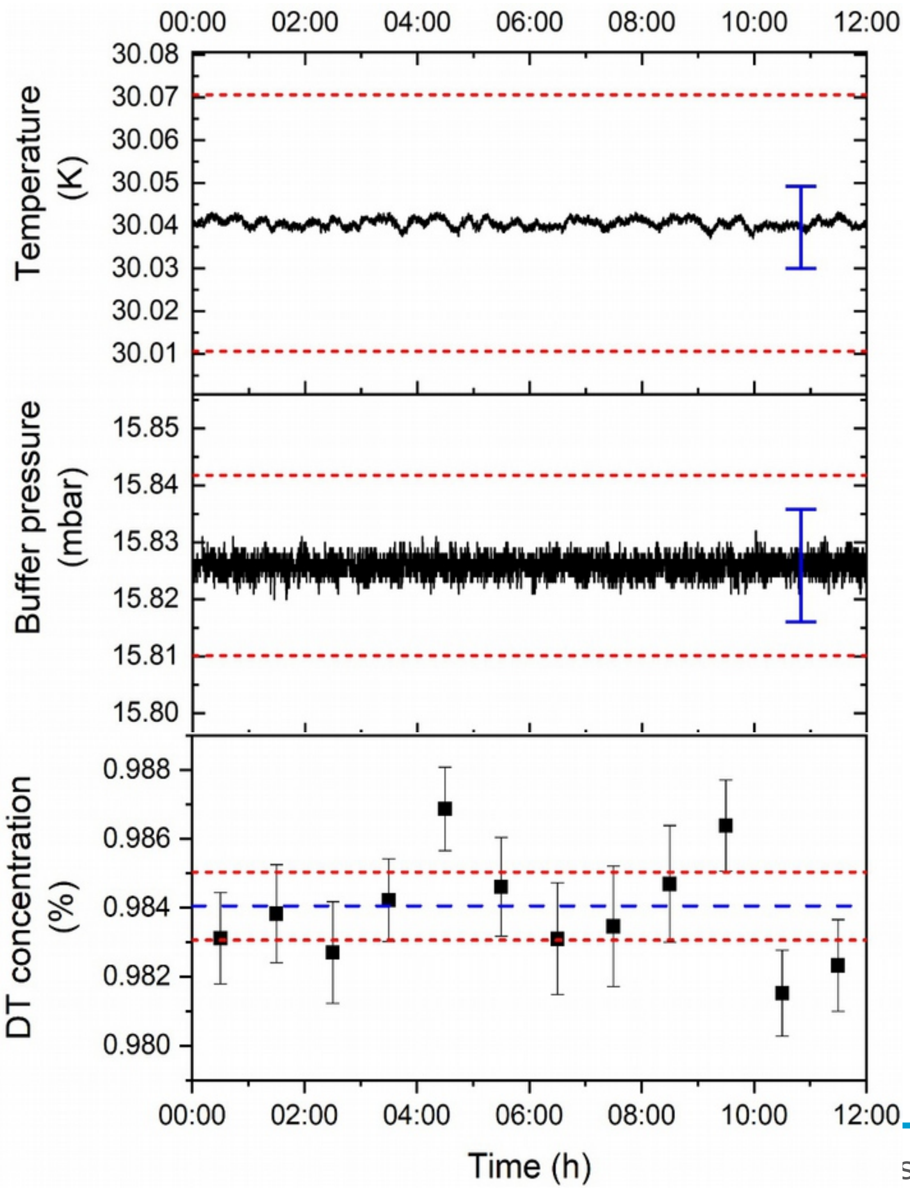


- First Tritium:

- **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})

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

First tritium campaign: Stability of source parameters during 12 h

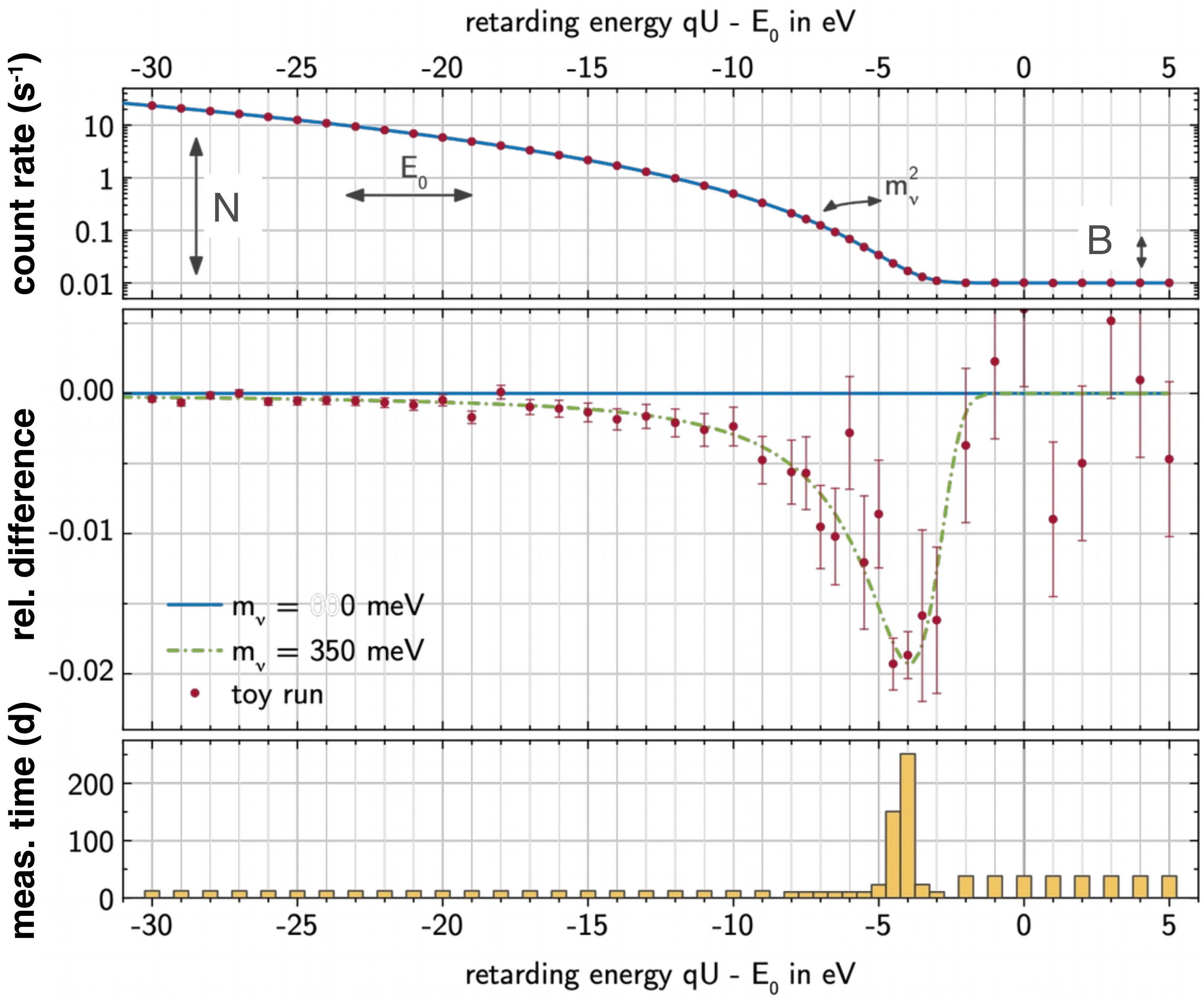


Blue arrow: systematic uncertainty

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

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

The measurement principle



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

Four fit parameters:

spectrum norm. **N**	spectrum endpoint $\mathbf{E_0}$
background rate **B**	squared mass $\mathbf{m^2_\nu}$

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

M. Kleesiek et al., Eur.Phys.J. C79 (2019) 204

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

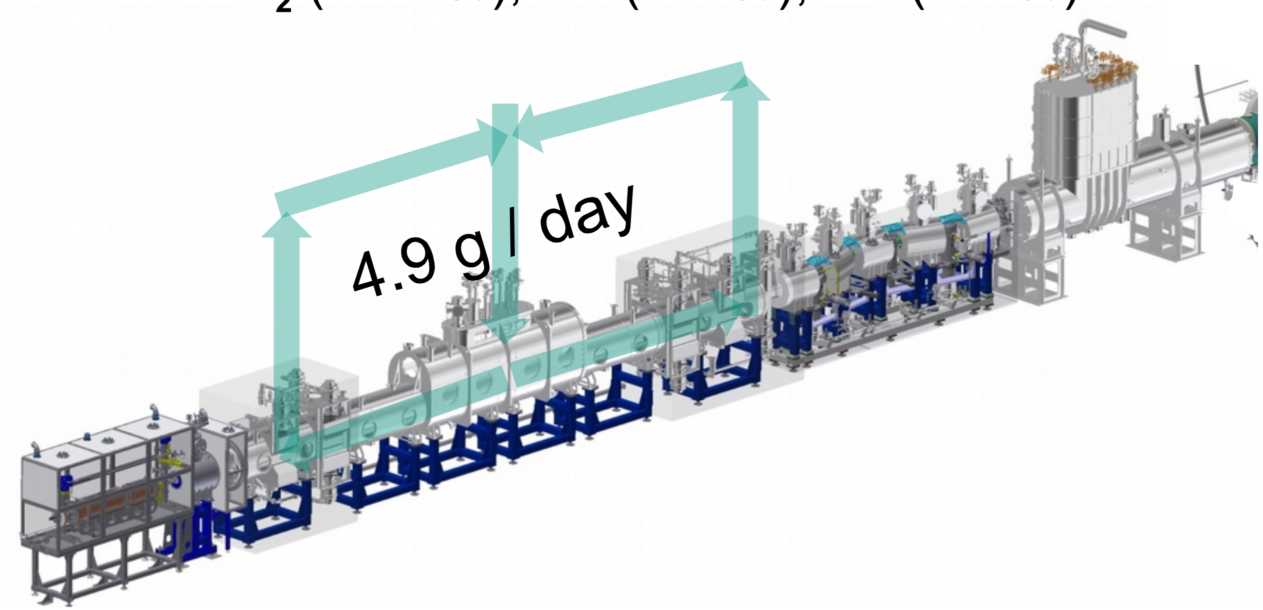
- high-quality data collected

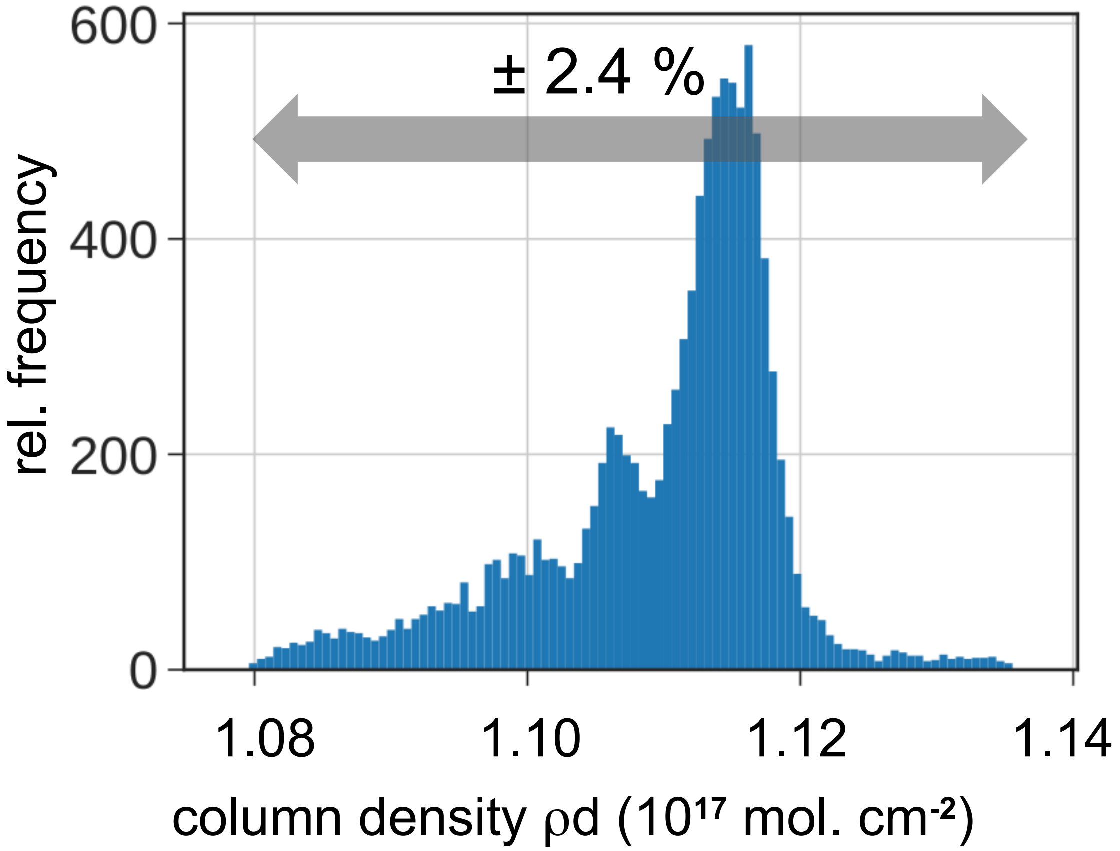
- full analysis chain using two
  independent methods

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

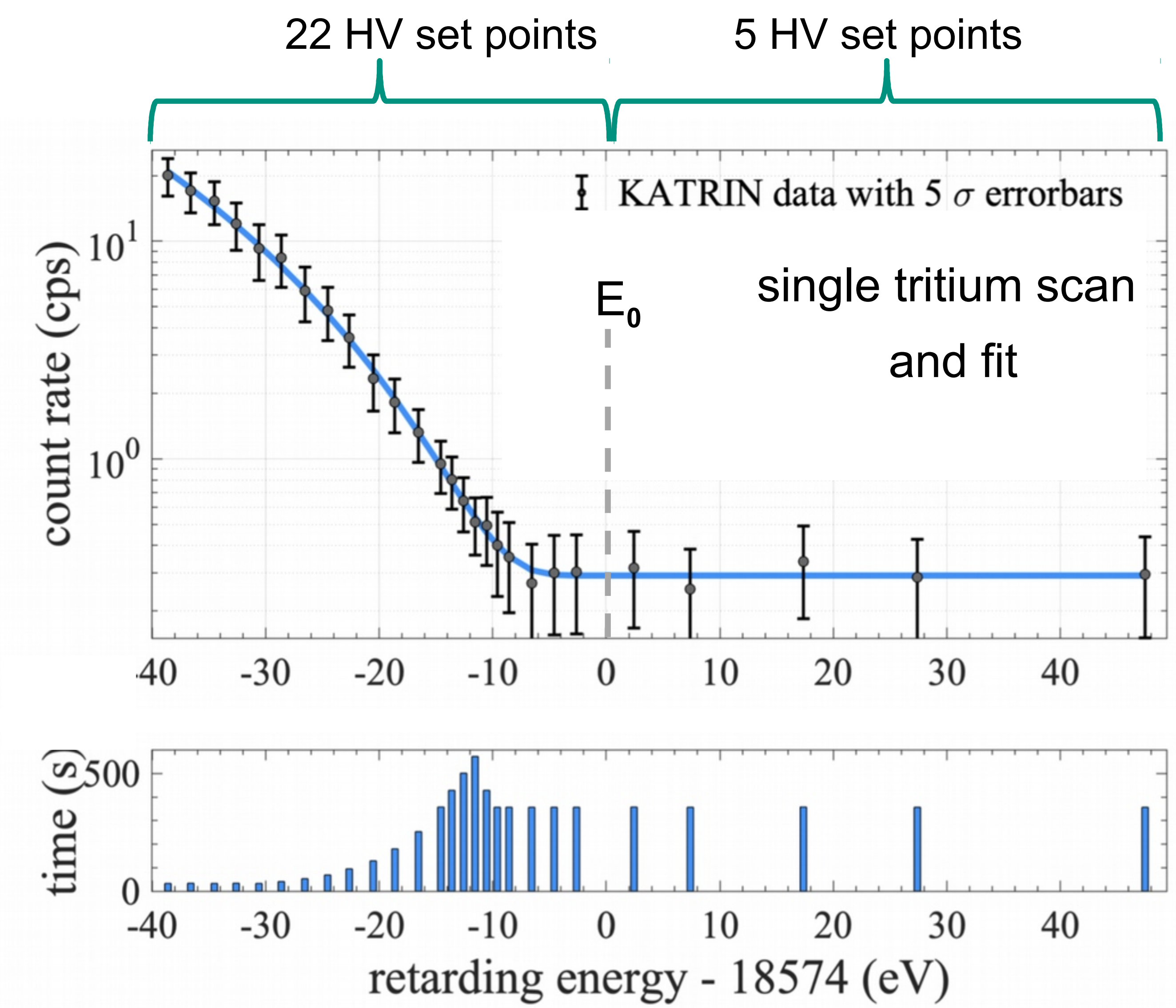
- **274 scans of tritium ß-spectrum**:

  - 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

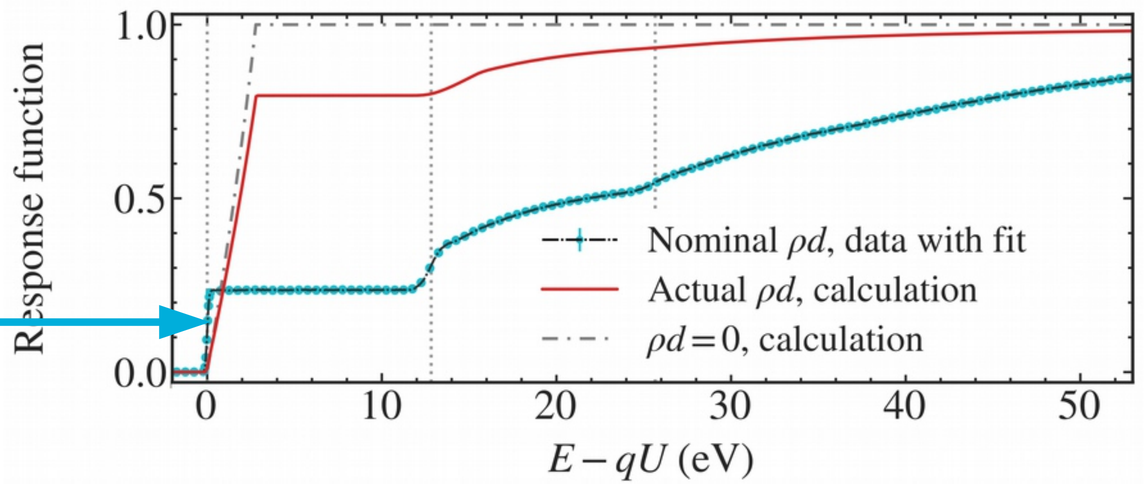


Determination of response function

- **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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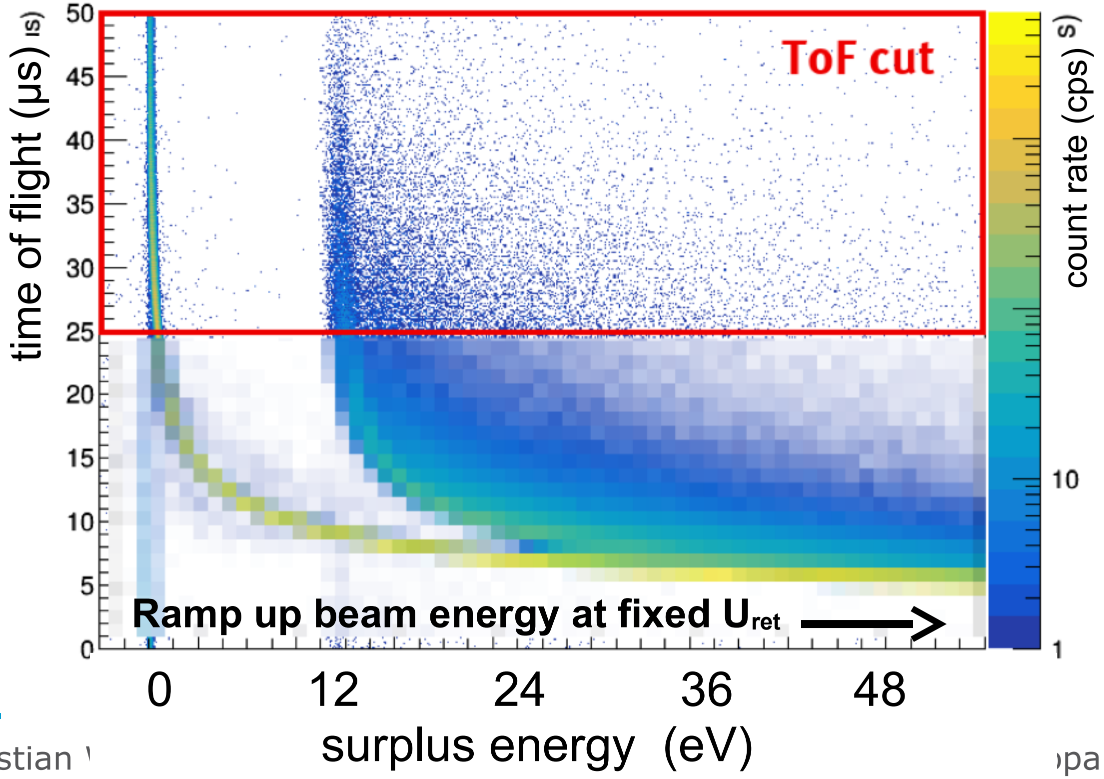
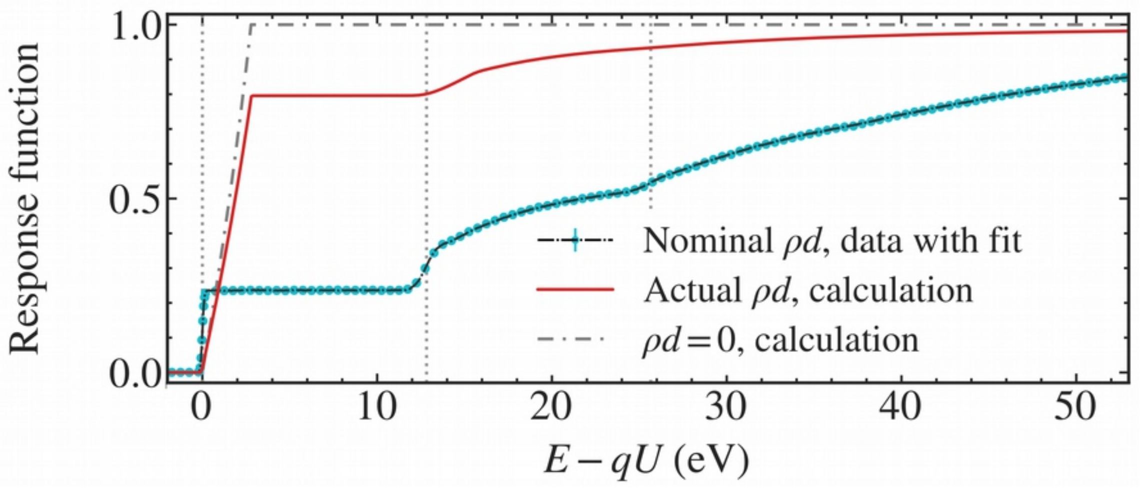


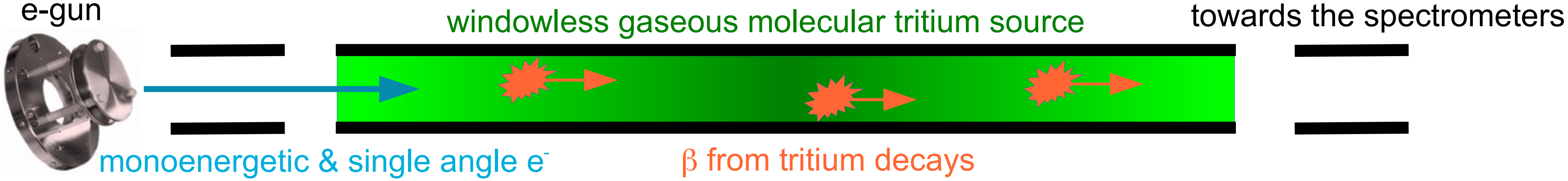


Time-of-flight of electrons from pulsed e-gun (70 ns at 20 kHz):
→ High-pass filter turned into narrow band-pass
→ recover "differential" spectrum

"Differential Time-of-flight mode"

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

Determination of response function



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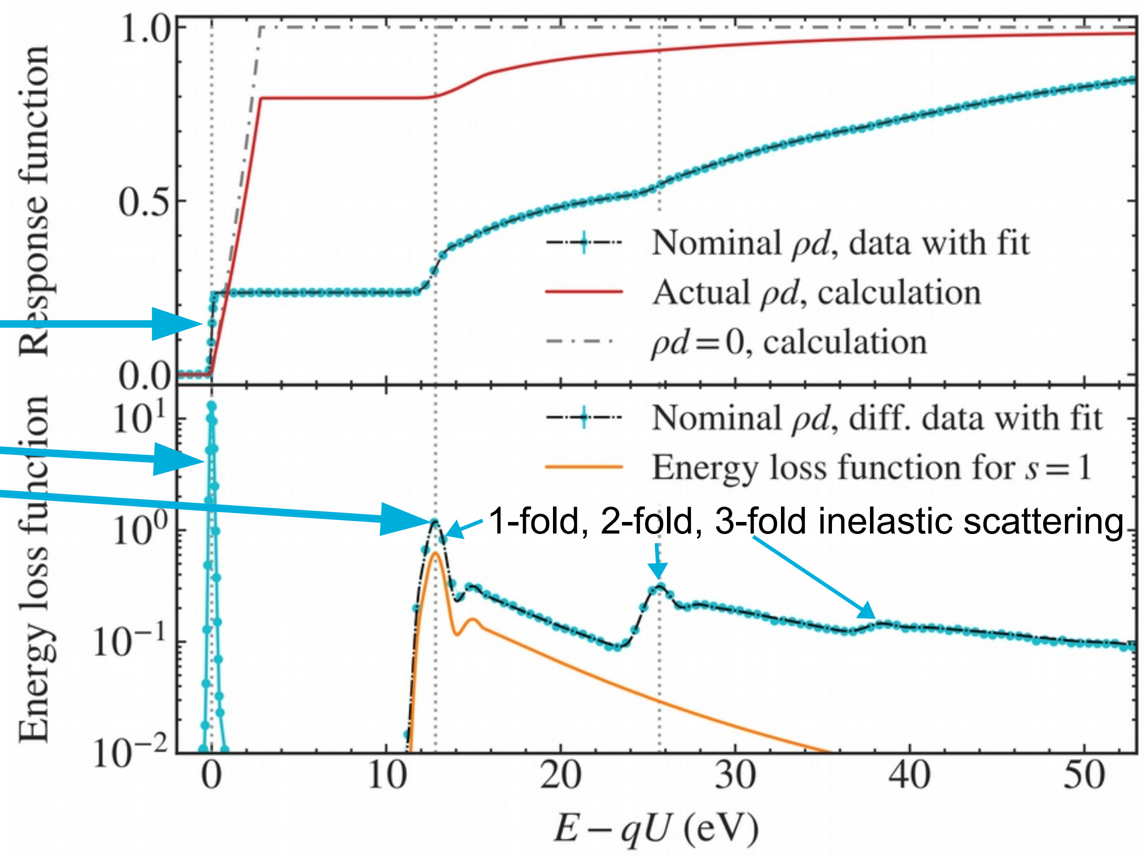
  (Eur. Phys. J. C77 (2017) 410, Astropart. Phys. 89 (2017) 30)

Normal integral MAC-E-Filter mode

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



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)

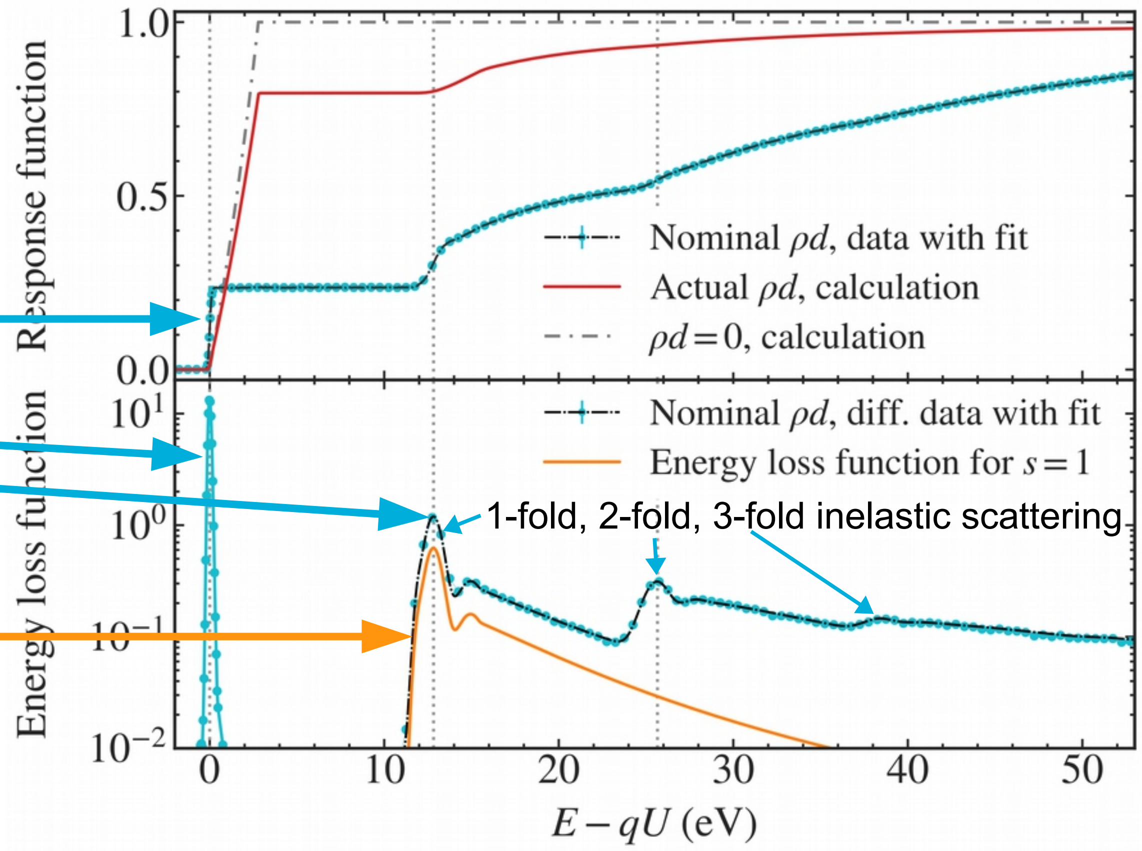
Normal integral MAC-E-Filter mode

Differential Time-of-flight mode

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

New J. Phys. 15 (2013) 113020

Deconvoluted differential energy loss function

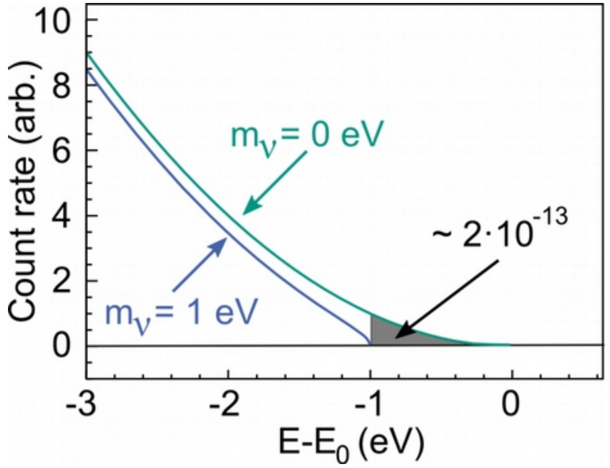


M. Aker et al. (KATRIN Collaboration)

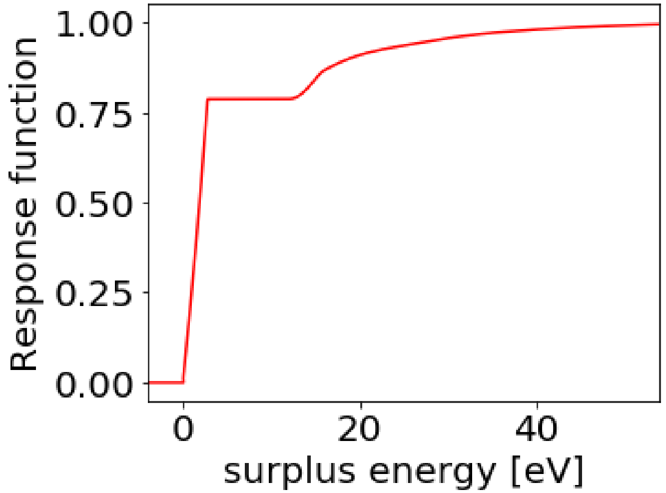
Phys. Rev. Lett. 23 (2019) 221802

Modeling of experimental data

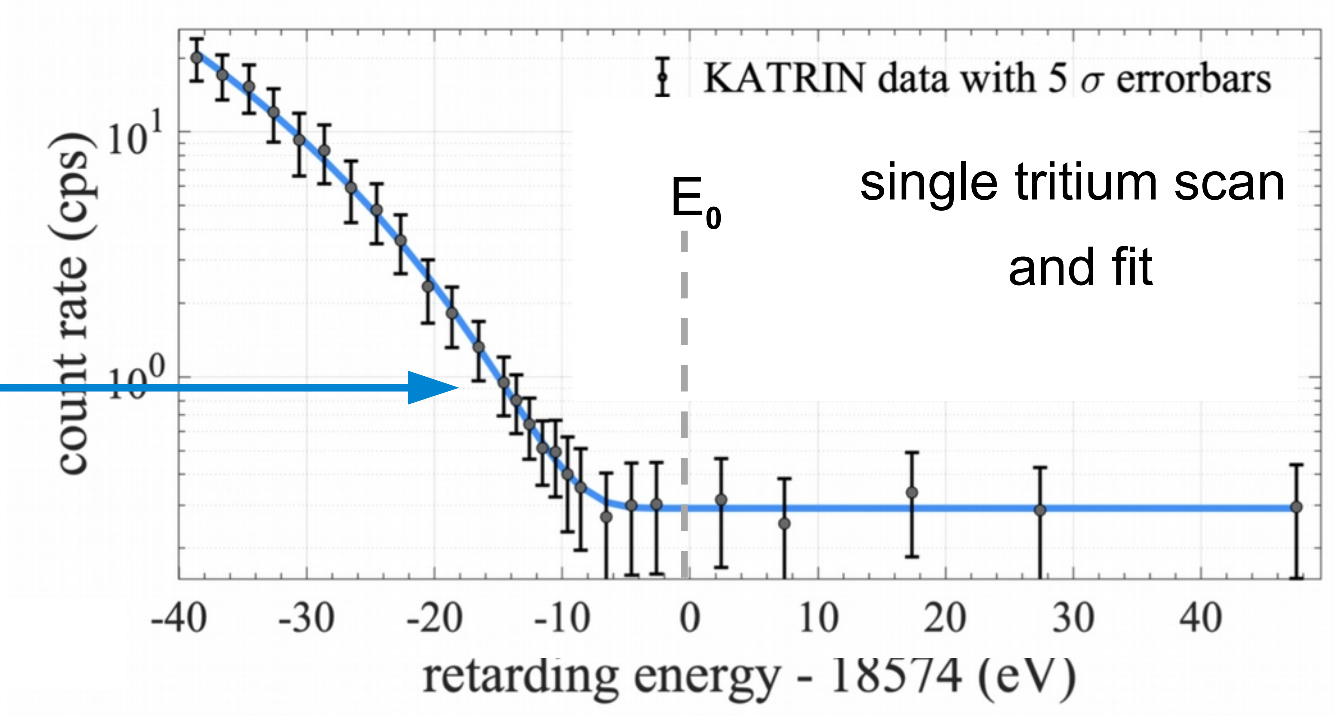
- **Beta spectrum: $R_\beta(E, m^2(\nu_e))$**



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



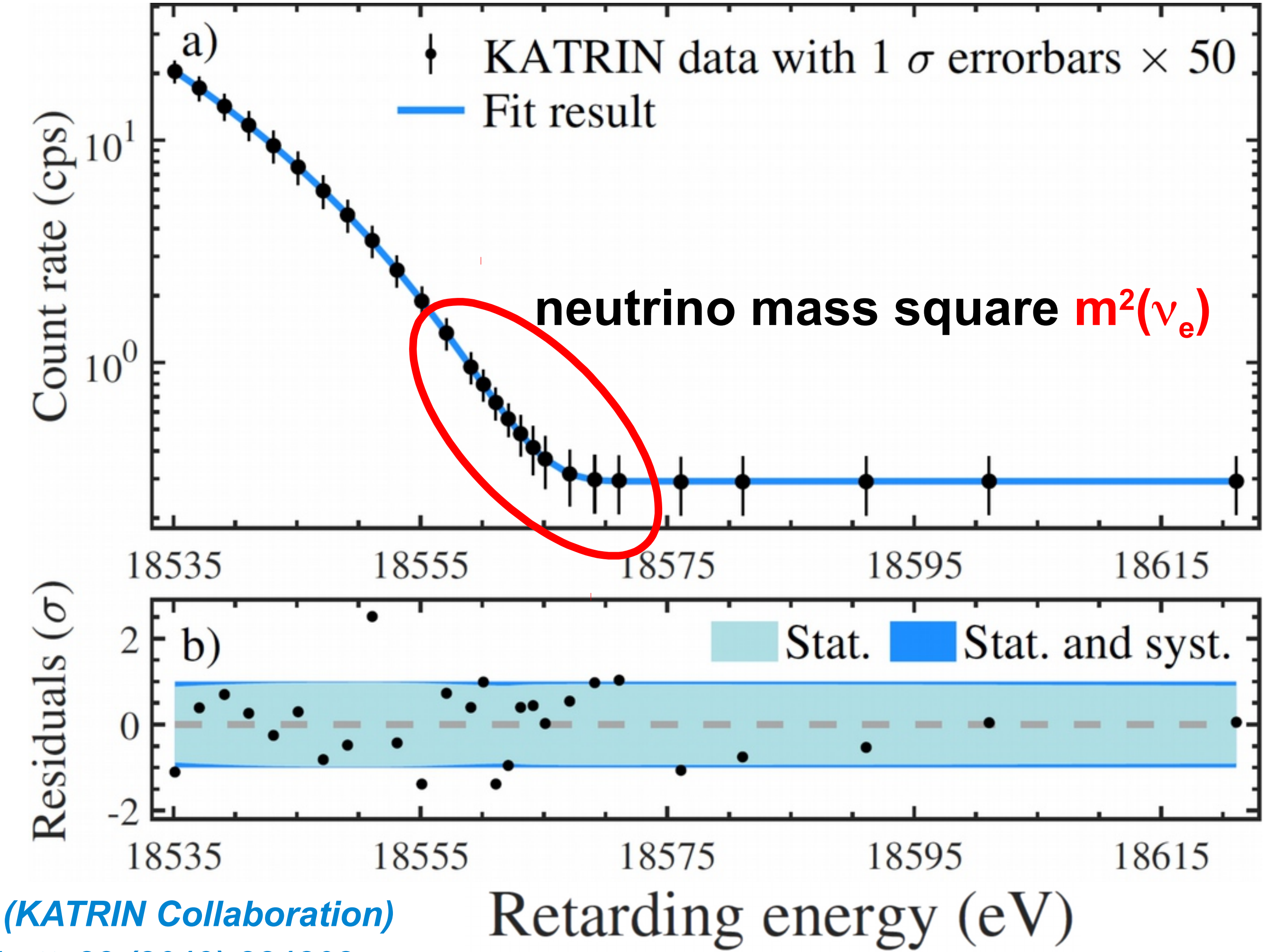
$\otimes$



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

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. 23 (2019) 221802

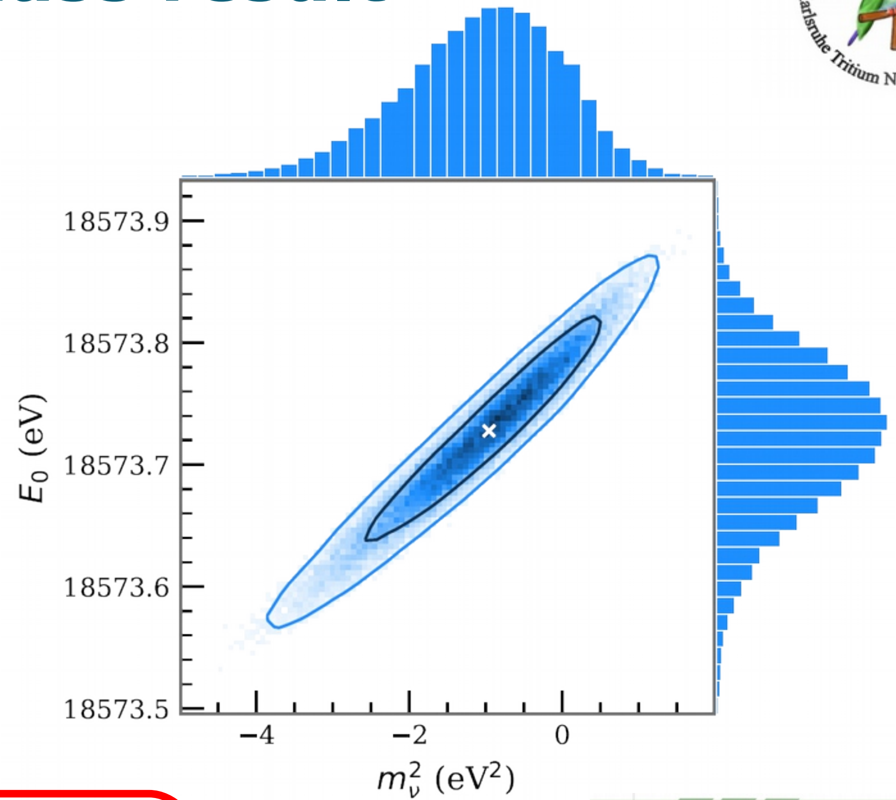
Analysis methods and ν-mass result

- **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**

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

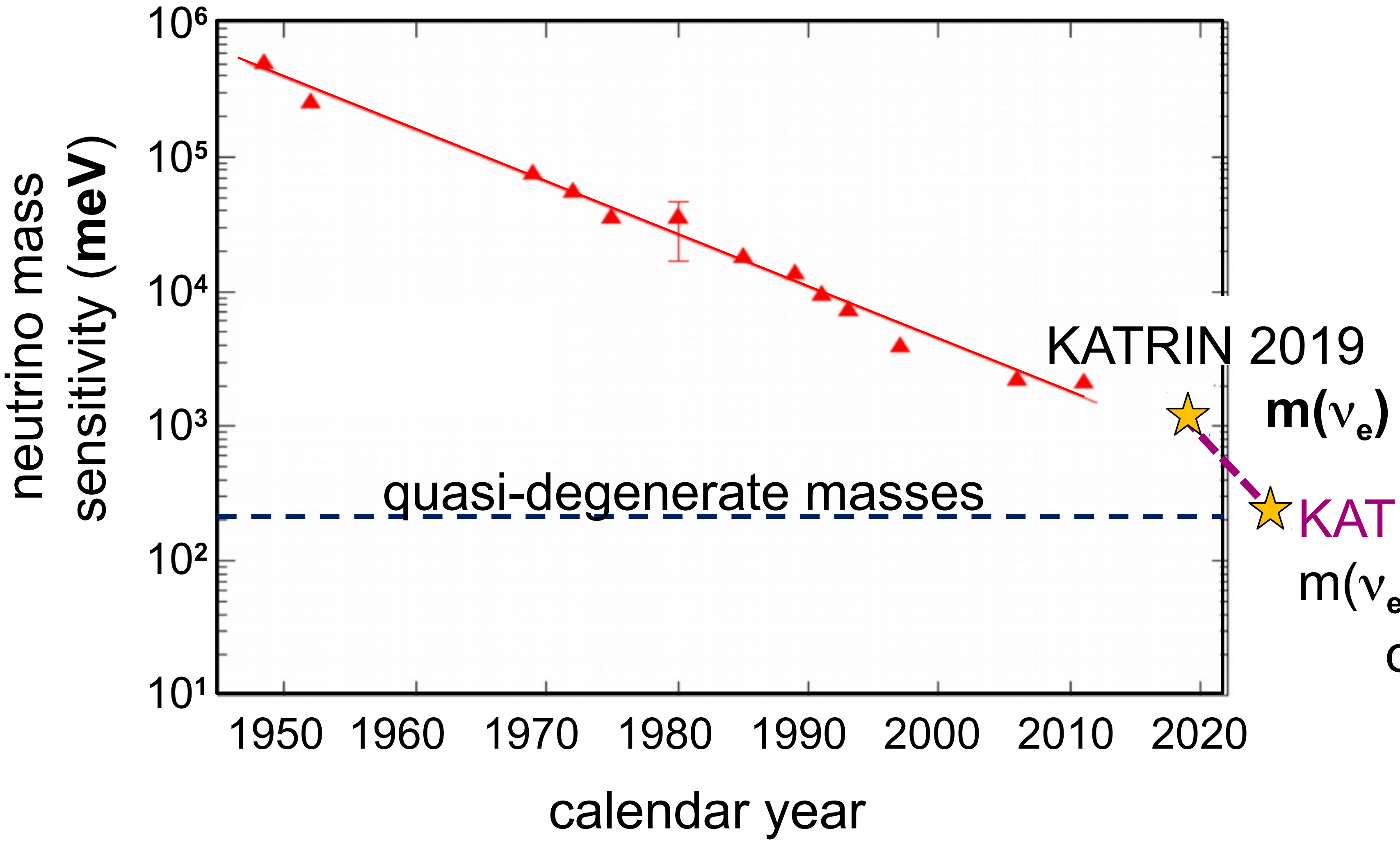
$E_0 = (18573.7 \pm 0.1)$ eV

→ Q-value : (18575.2 ± 0.5) eV Q-value [$\Delta M(^3H,^3He)$]: (18575.72 ± 0.07) eV

M. Aker et al. (KATRIN Collab.) Phys. Rev. Lett. 23 (2019) 221802

Moore´s law of direct ν-mass sensitivities

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

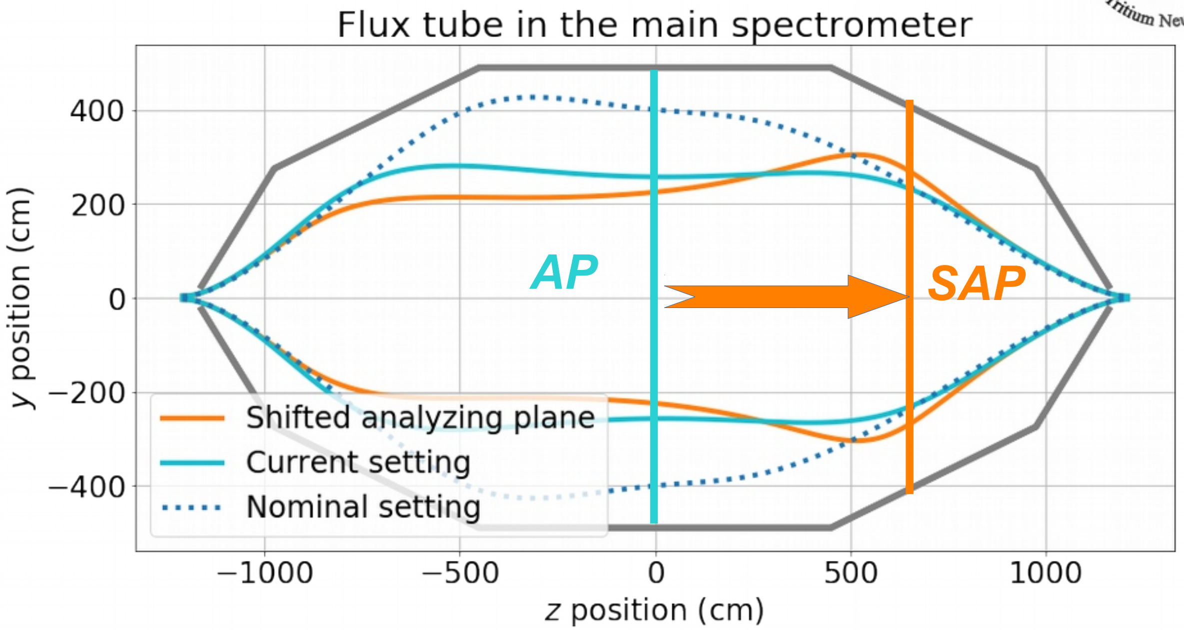


$m(\nu_e)$ < 1.1 eV (90% CL)

KATRIN 2026/7:
$m(\nu_e)$ < 0.2 eV (90% CL)
or = 0.35 eV (5 σ)

Outlook: Background reduction

- **Further background reduction**
  - ⇨ spectrometer bake-out successful ☑
  - ⇨ more effective LN_2-cooled baffles
    - – by pumping → lowering temperature
    - → 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

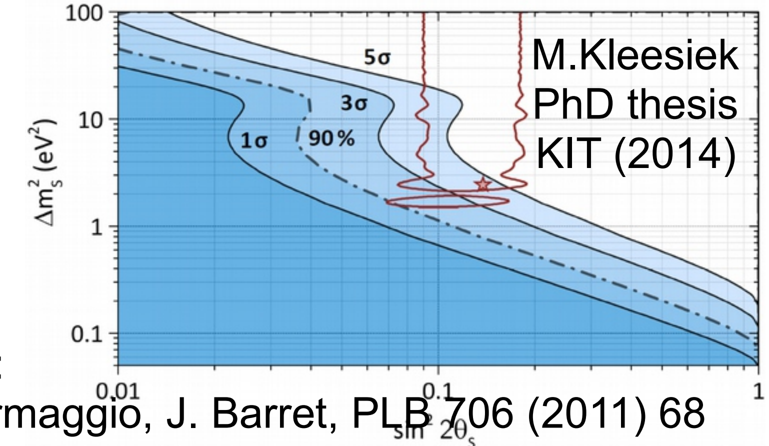
Two large air coil systems:
background suppression & B-field shaping

Other interesting searches for physics beyond the Standard Model

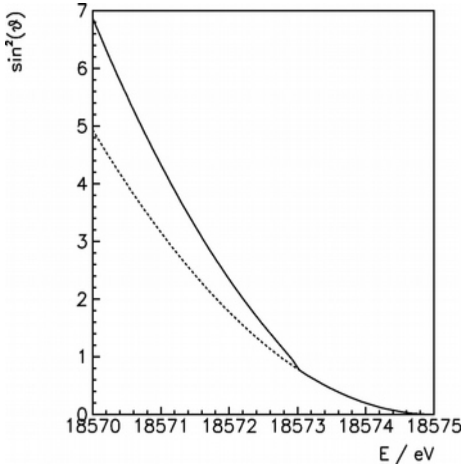
Sterile neutrinos

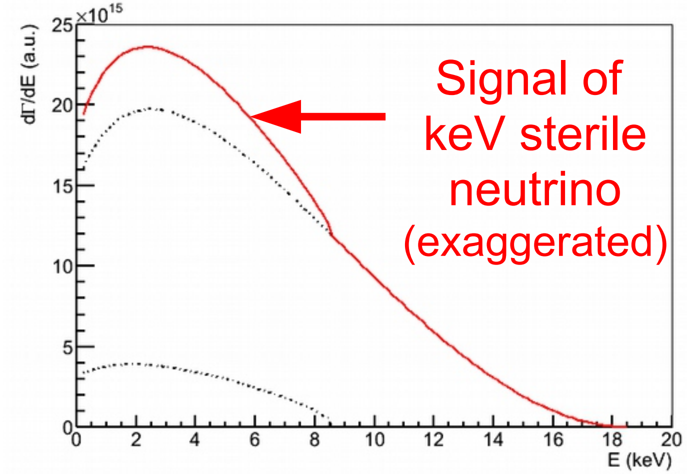
$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2}\right)$$

eV ν:



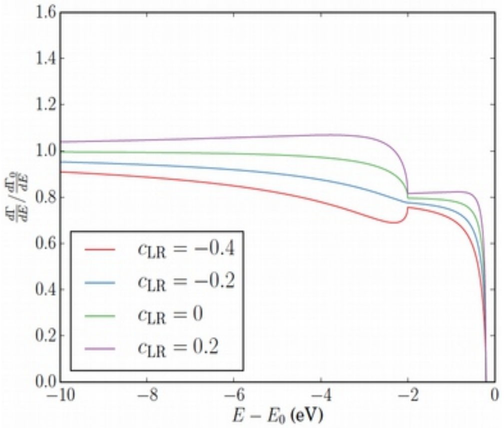
see e.g.:
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

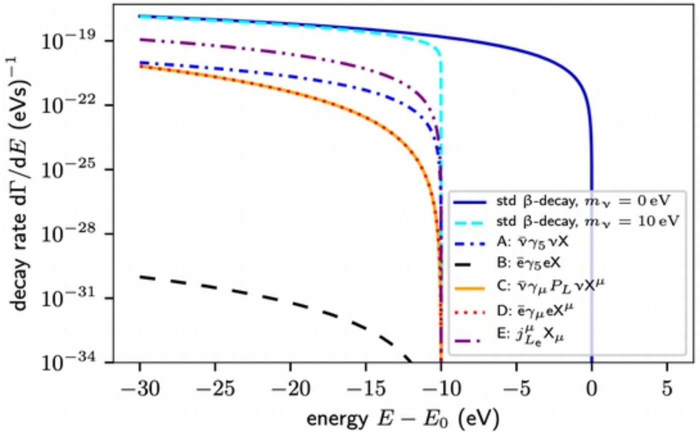




keV ν:

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

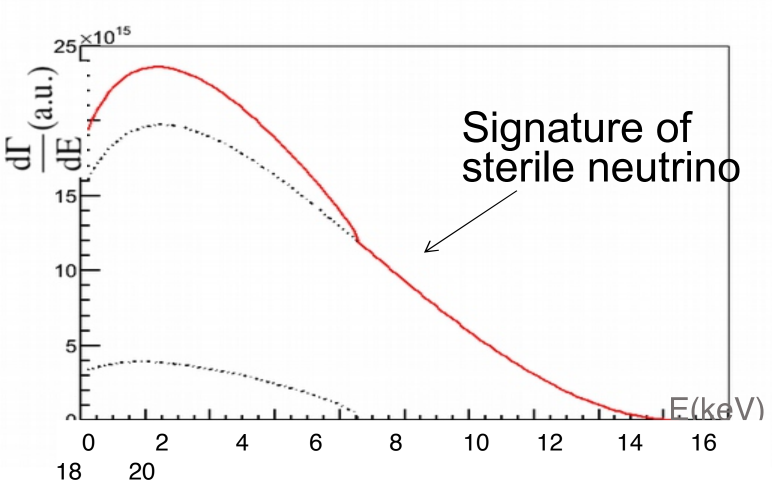
  - particle beyond the standard model
  - Dark matter candidate

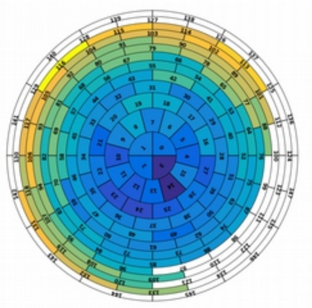
- **Look for the kink in the β-spectrum**
- **TRISTAN project in KATRIN**

  - developing a new detector & DAQ system

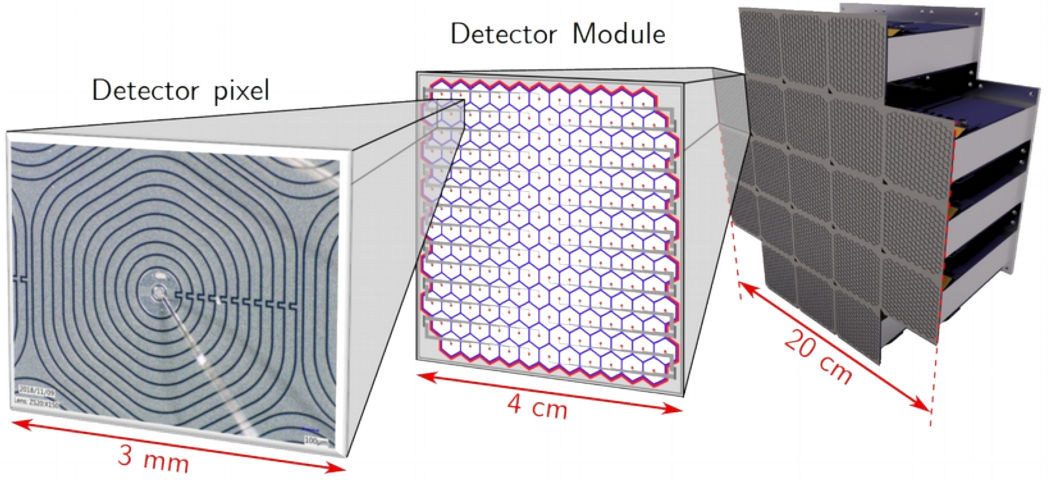
- **large count rates**
- **good energy resolution**
- **Silicon Drift Detector**

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





segmented Si-PIN wafer

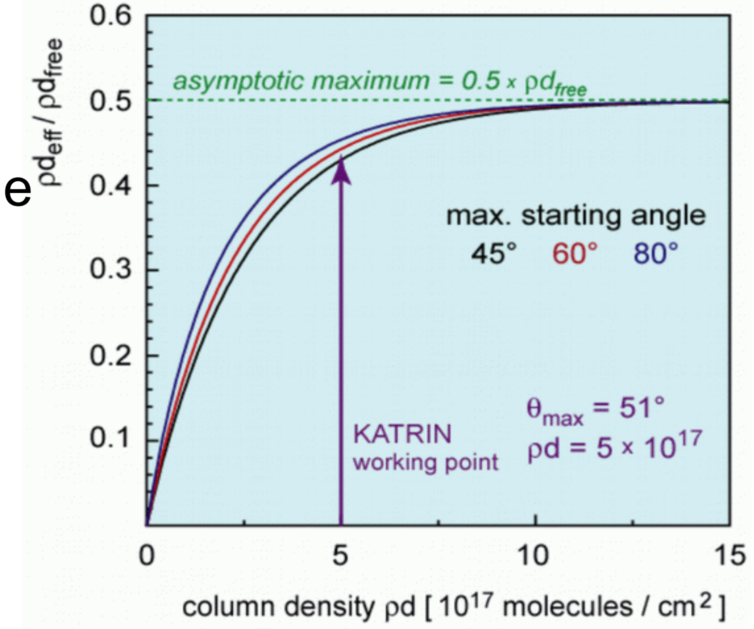


S. Mertens et al., J.Phys. G46 (2019) 065203; T. Brunst et al., JINST 14 (2019) P11013

KATRIN's sensitivity of 200 meV might not be enough
Can we go beyond or improve KATRIN ?

Problem: The KATRIN source is already opaque

→ need to increase size transversally magnetic flux tube conservation requests larger spectrometer, but a Ø100m spectrometer is not feasible



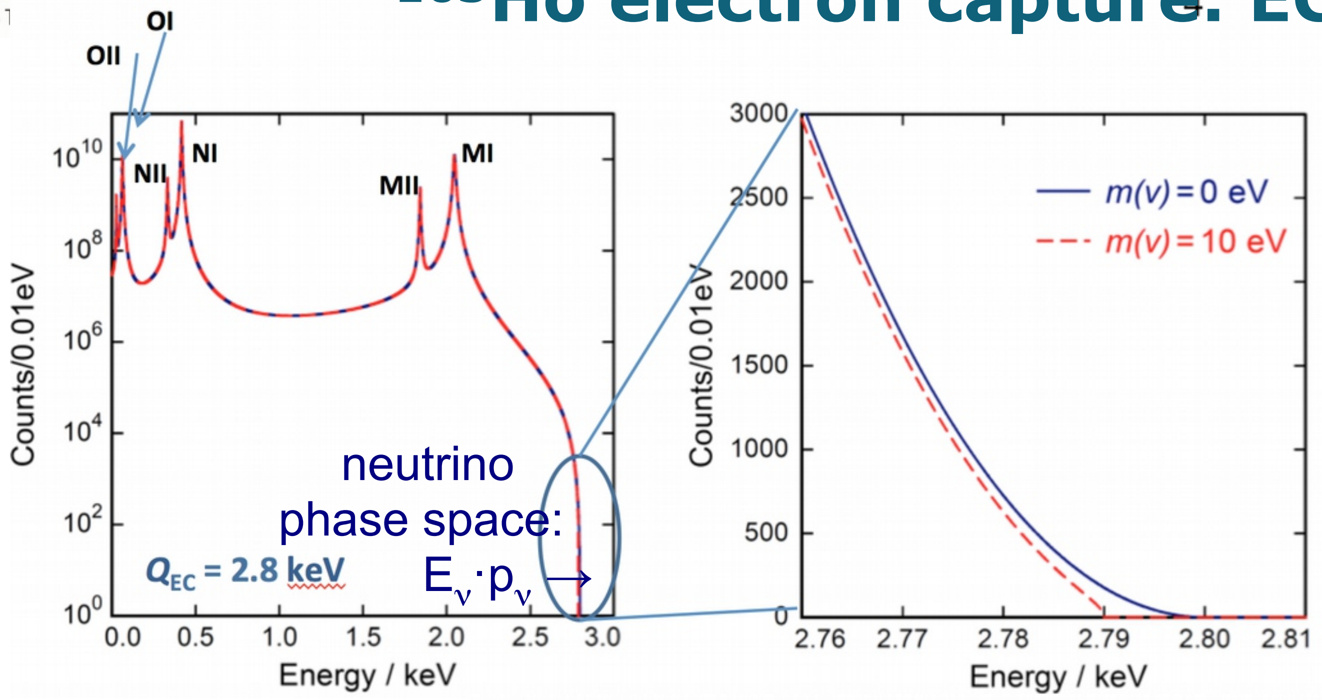
Possible ways out:

a) make better use of the electrons by differential measurement (e.g. cryo bolometer array or TOF) additional to integral threshold:
→ measure all retarding voltage settings at once
additional benefit: significant background reduct.

b) source inside detector (compare to $0\nu\beta\beta$) using cryogenic bolometers (ECHo, HOLMES, ..)

Direct neutrino mass measurement from ^{163}Ho electron capture: ECHo, HOLMES

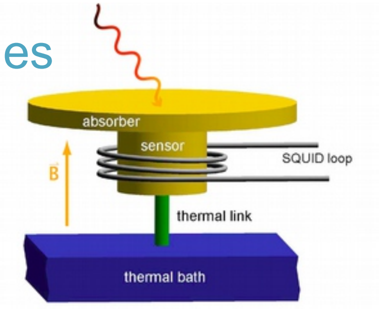
$^{163}Ho + e^- \rightarrow$
$^{163}Dy^* + \nu_e \rightarrow$
$^{163}Dy + \gamma/e^- + \nu_e$



^{163}Ho source inside cryo calorimeter → determine ΔE by temp change ΔT:

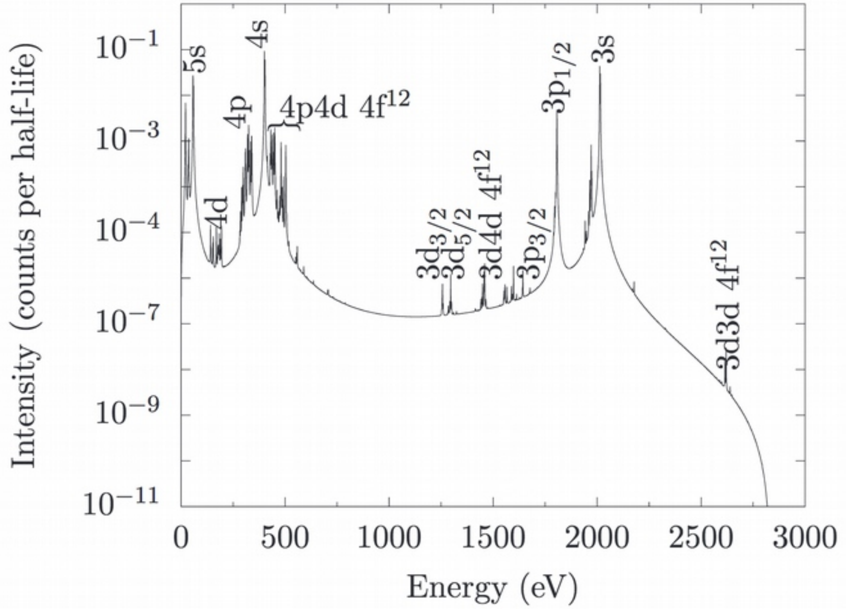
$\Delta T = \Delta E / C,\ C \propto T^3$

ECHo:
metallic magnetic calorimeters: change of magnetic properties

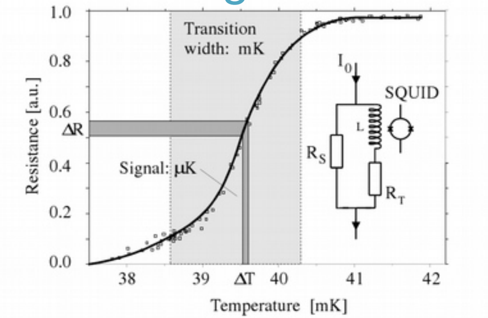


New ab initio spectral calculation: M. Braß et al., PRC **97** (2018) 054620

→ much better agreement with experimental data from ECHo



HOLMES:
sc. transition edge sensors



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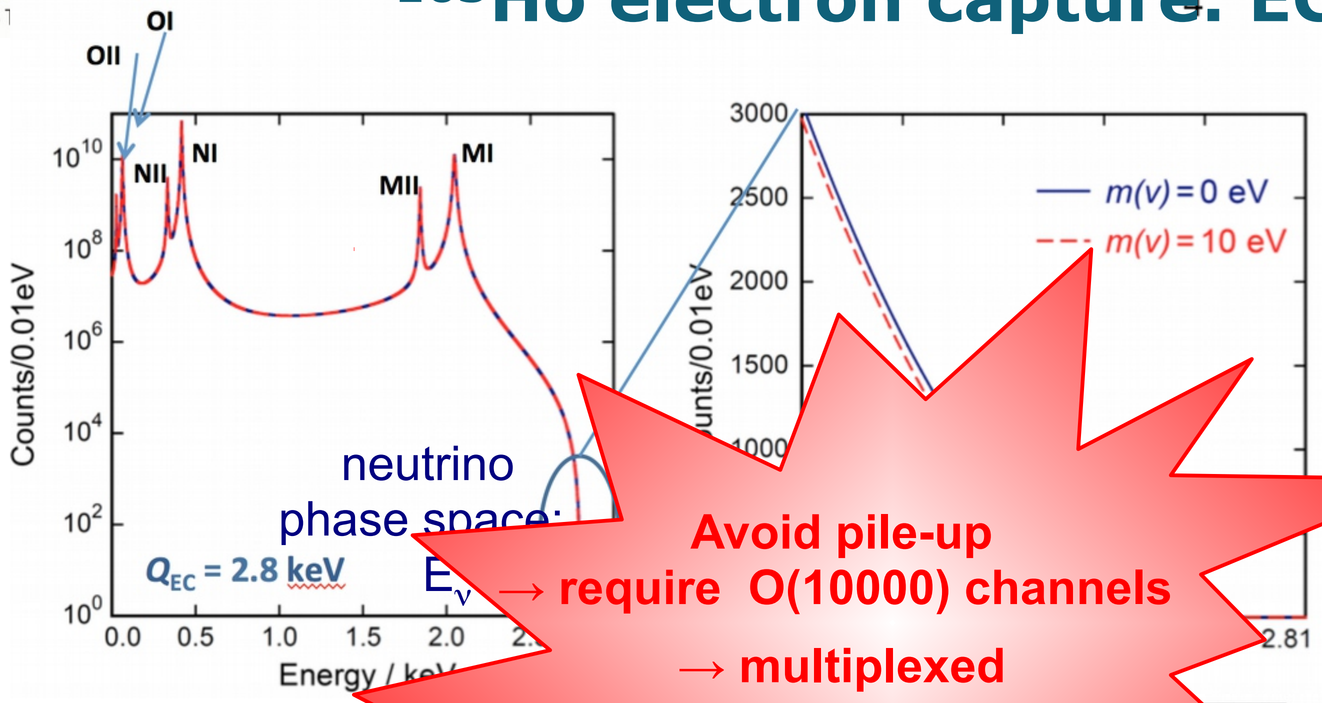
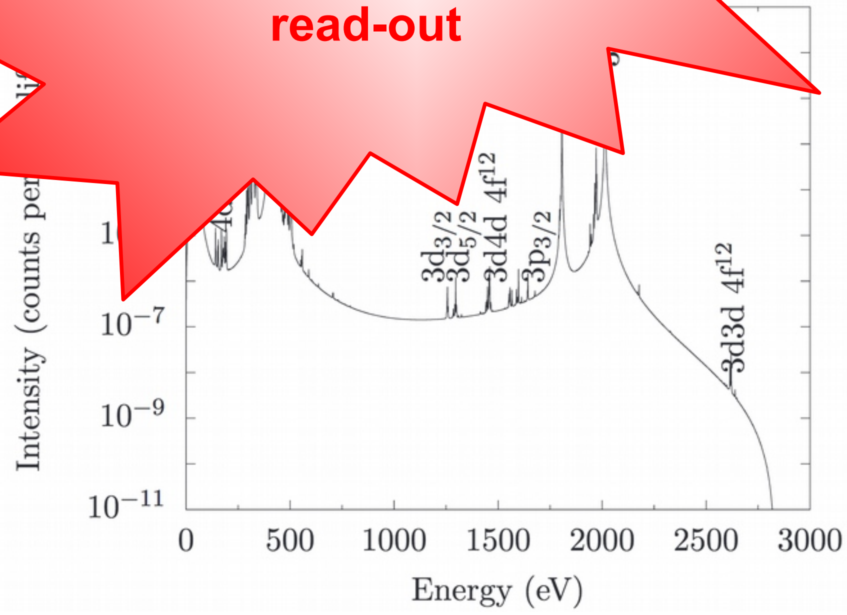


Avoid pile-up
→ require O(10000) channels
→ multiplexed read-out



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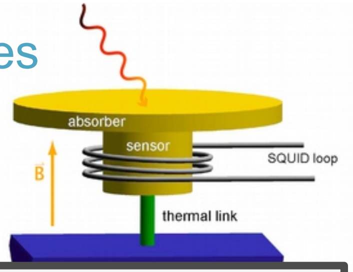

ECHo: *First measurement of 4 pixels for 4 days at LSM (L. Gastaldo, TAUP 2019):*

Q_{EC} = (2838 ± 14) eV

$m(\nu_e) < 150$ eV (95% C.L.)

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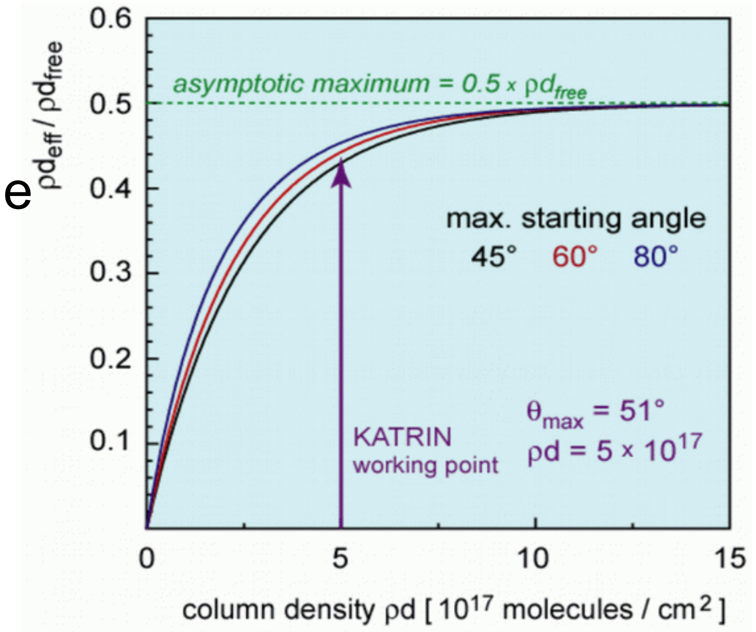

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b) source inside detector (compare to $0\nu\beta\beta$)
using cryogenic bolometers (ECHo, HOLMES, ..)

c) hand-over energy information of β-electron
to other particle (radio photon),
which can escape tritium source (Project 8)

Project 8's goal: Measure coherent cyclotron radiation of tritium β-electrons

General idea: *B. Monreal and J. Formaggio, PRD 80 (2009) 051301*

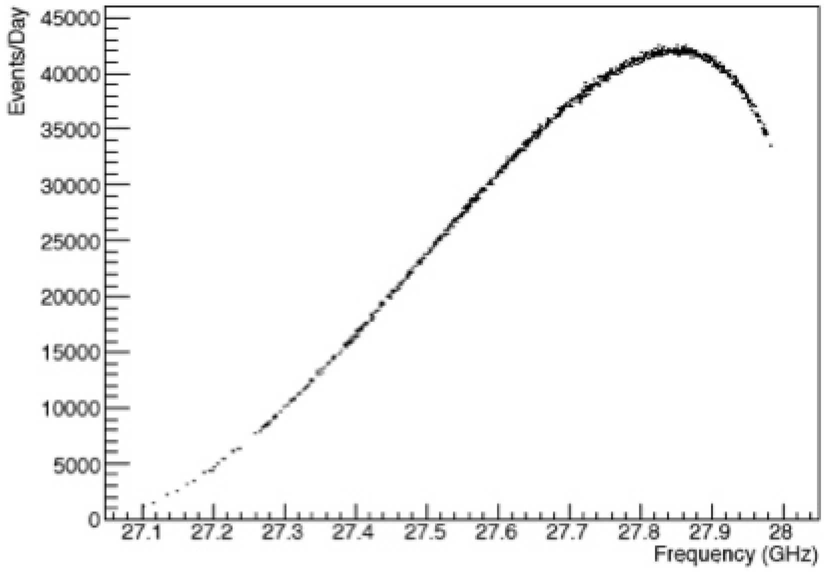
- Source = KATRIN tritium source technology :

  uniform B field + low pressure T_2 gas

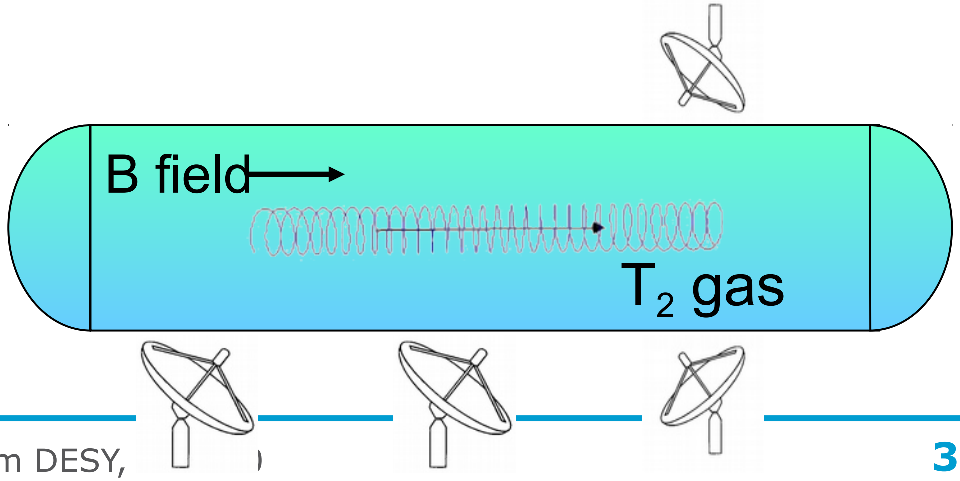
  β electron radiates coherent cyclotron radiation

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{e\,B}{K + m_e}$$

But tiny signal: P (18 keV, θ=90°, B=1T) = 1 fW

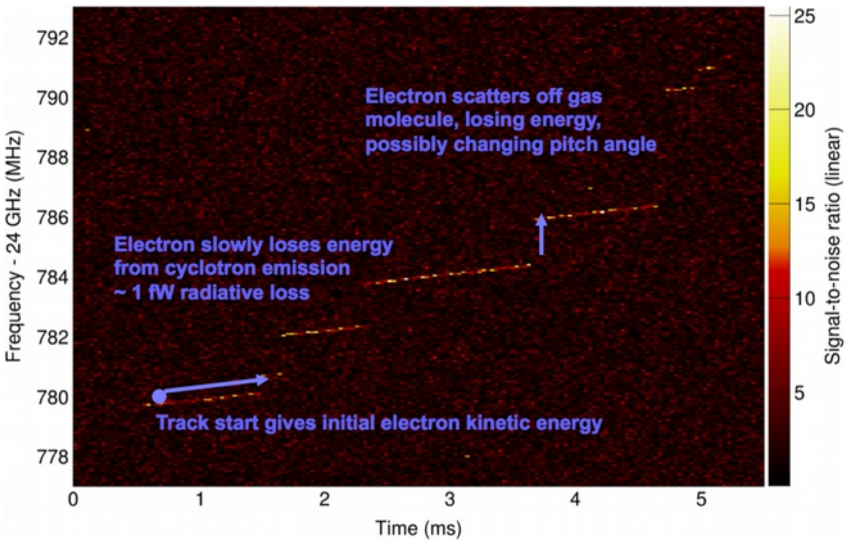


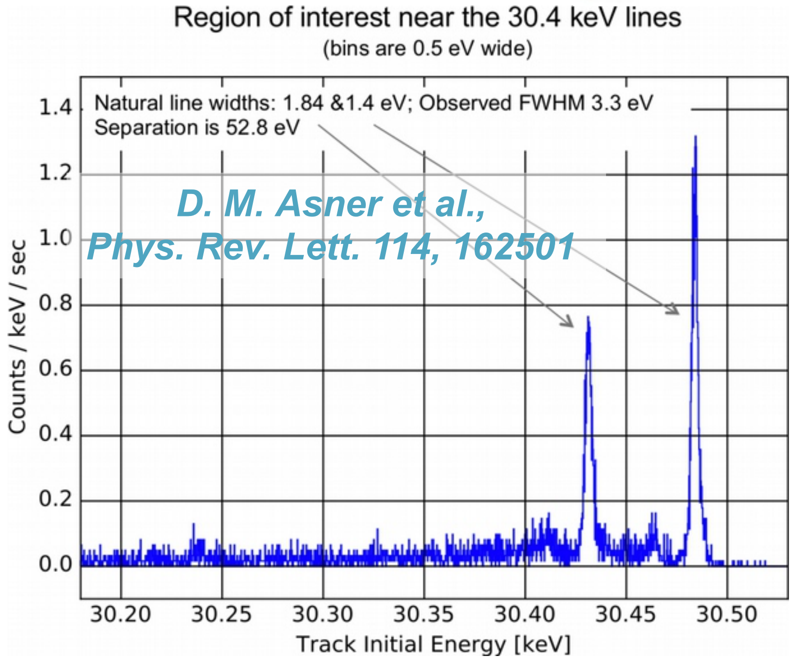
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and carries out the information of the β-electron energy



Project 8: phase I (^{83m}Kr) and II (tritium) Proof of principle

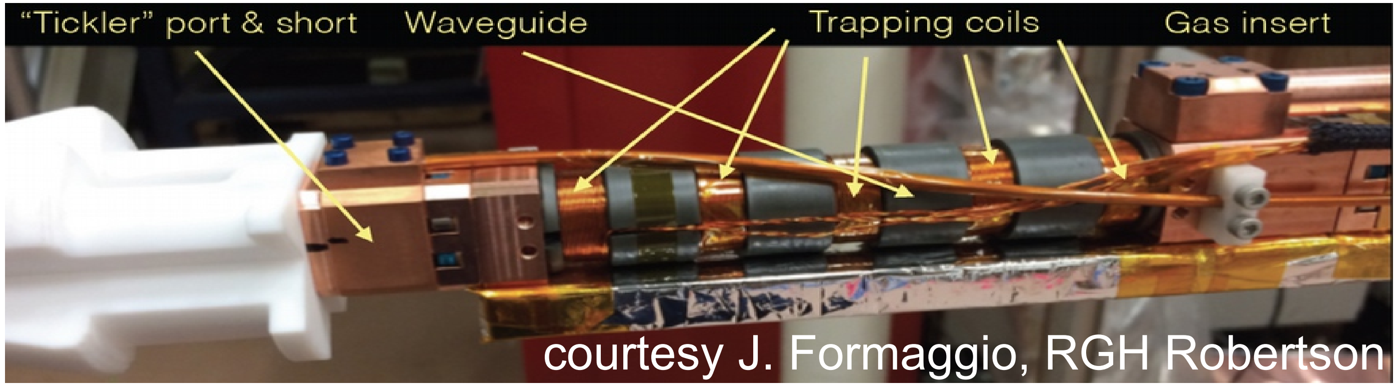
Phase I (^{83m}Kr)

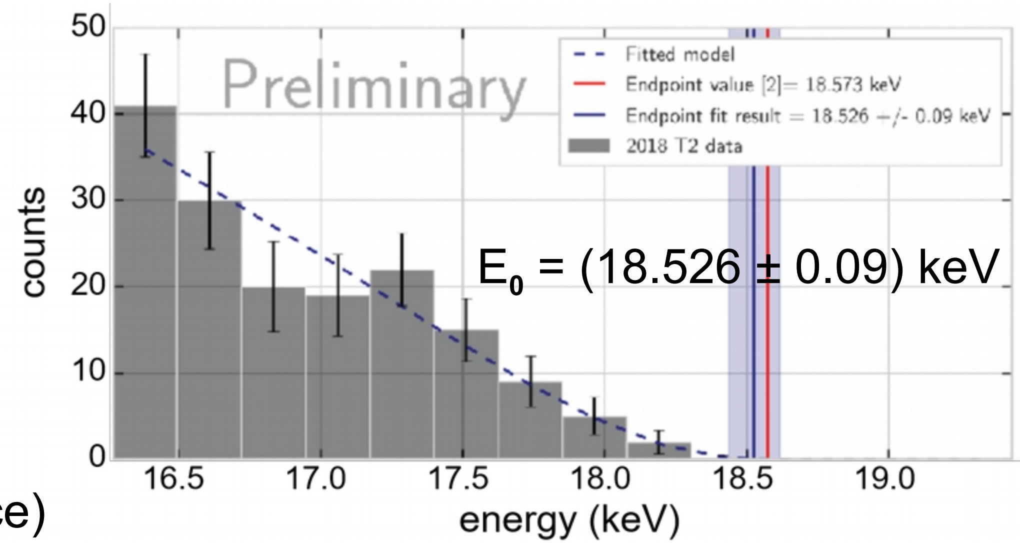




magnetic bottle to trap decay electrons long enough

Phase II (tritium test)



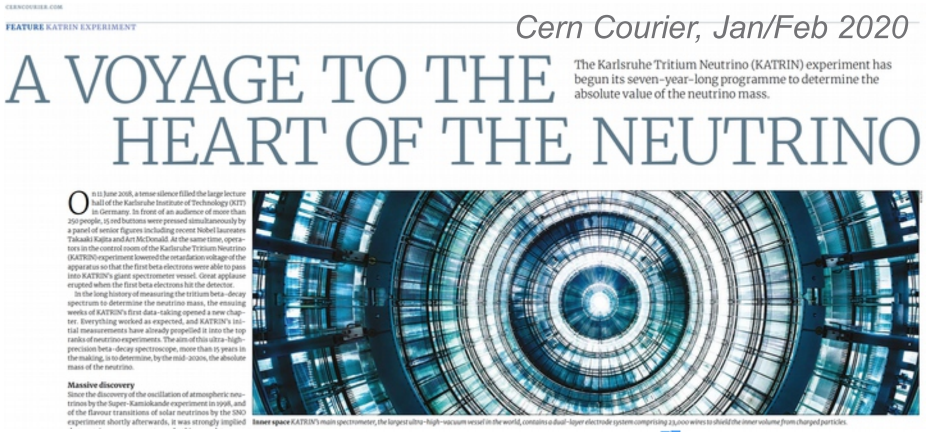


$E_0 = (18.526 \pm 0.09)$ keV

Phase III (tritium demonstrator) – Phase IV (atomic tritium source)

Conclusions

Cern Courier, Jan/Feb 2020


FEATURE KATRIN EXPERIMENT

A VOYAGE TO THE HEART OF THE NEUTRINO

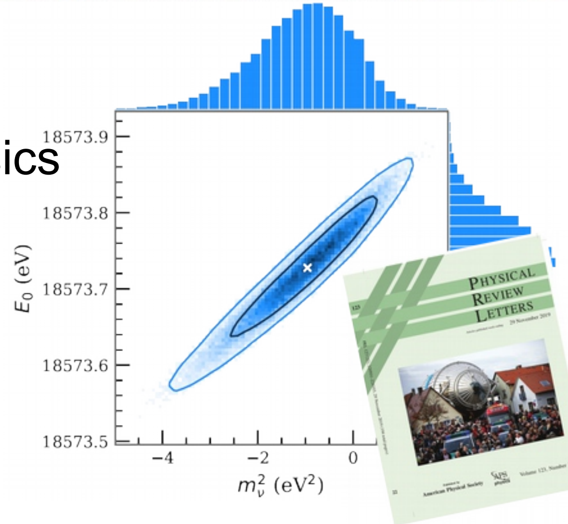
The Karlsruhe Tritium Neutrino (KATRIN) experiment has begun its seven-year-long programme to determine the absolute value of the neutrino mass.

Neutrino masses are non-zero:

- and 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
- can also look for sterile neutrinos (eV, keV with TRISTAN detector) and other BSM physics
- 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



Thank you for your attention !

Beyond KATRIN:

- Can we upgrade KATRIN by time-of-flight or cryo-bolometer?
- ^{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