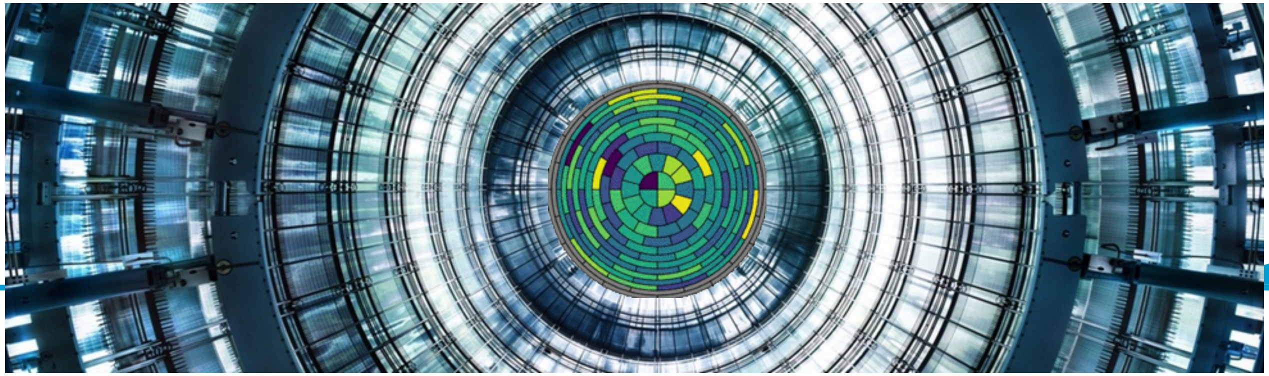
WWU MÜNSTER

First results from the neutrino mass experiment KATRIN

Christian Weinheimer – University of Münster
Colloquium, Gran Sasso Scientific Institute,11.12.19

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



Neutrinos in the Standard Model of particle physics

	generation 1	generation 2	generation 3
leptons	ν_e	ν_μ	ν_τ
	e	μ	τ
quarks	u	c	t
	d	s	b

normal matter

Neutral, spin ½,

Only weak interaction (W,Z very heavy):

$\lambda_\nu \approx$ light years at MeV scale

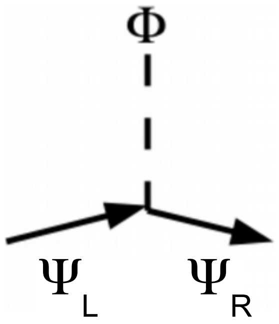
interaction rate increases linearly with E_ν usually

The most abundant particle in the universe: 336 / cm³

(together with the particle of light, the photon)

Mass terms in the Standard Model (SM):

coupling to the Higgs

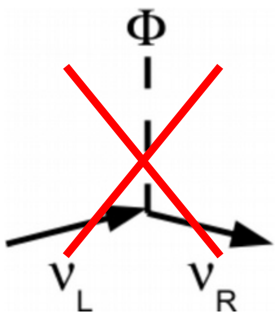


In original SM ν only left-handed: ν_L

→ difficult to account for mass term:

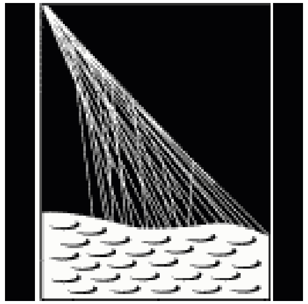
Yukawa coupling to the Higgs

did not exist in the SM

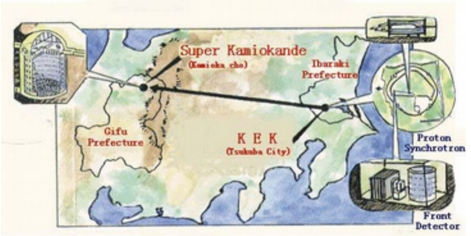


Positive results from ν oscillation experiments

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



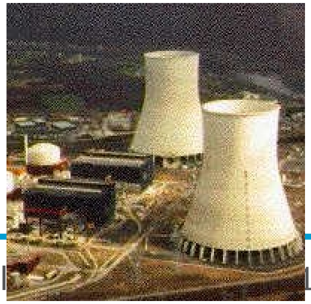
accelerator neutrinos
(K2K, T2K, MINOS, Nova, OPERA, MiniBoone)



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°

$7.0\ 10^{-5}\ eV^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ eV^2$

$2.2\ 10^{-3}\ eV^2 < |\Delta m_{13}^2| < 2.6\ 10^{-3}\ eV^2$

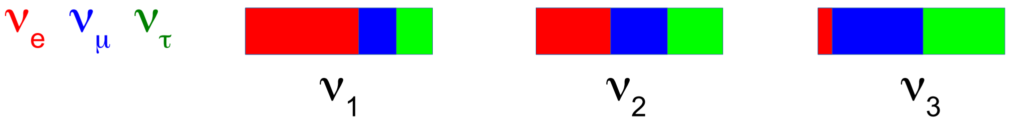
⇒ $m(\nu_j) \neq 0$, but unknown

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

additional sterile neutrinos ?

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

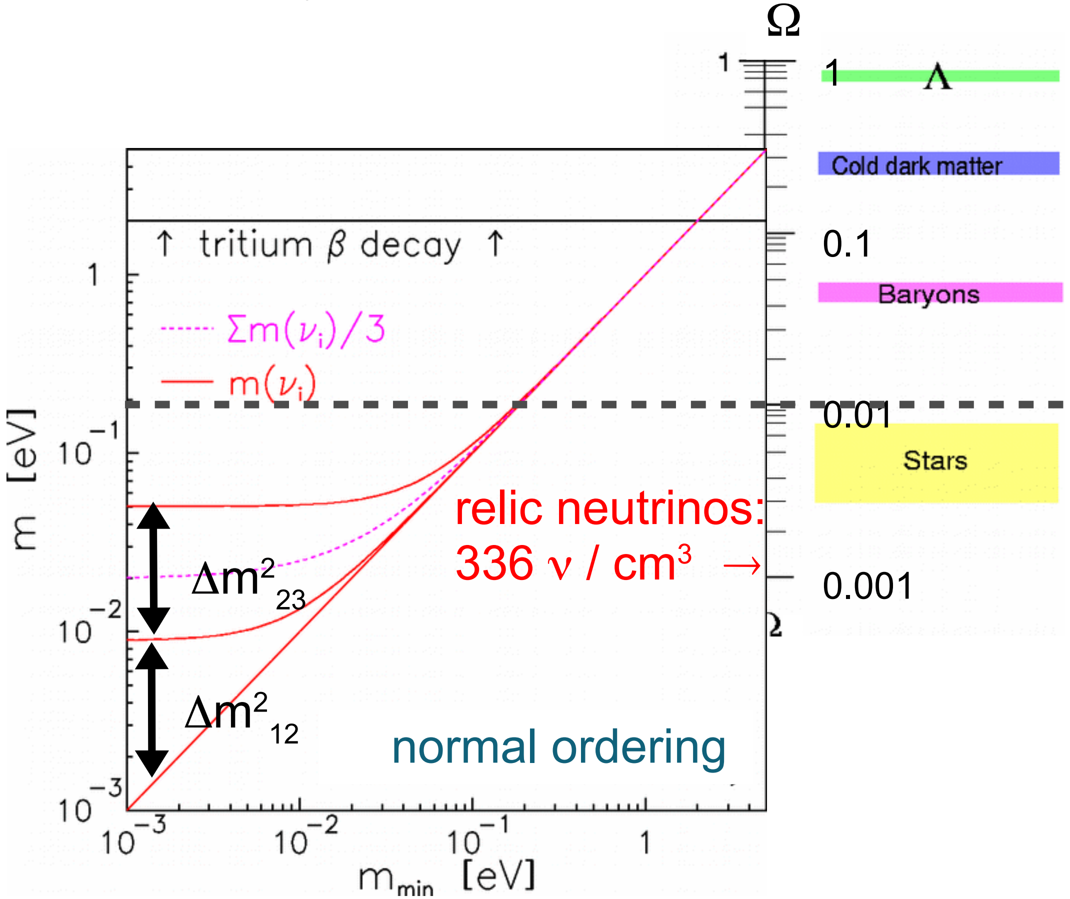
cosmological relevant

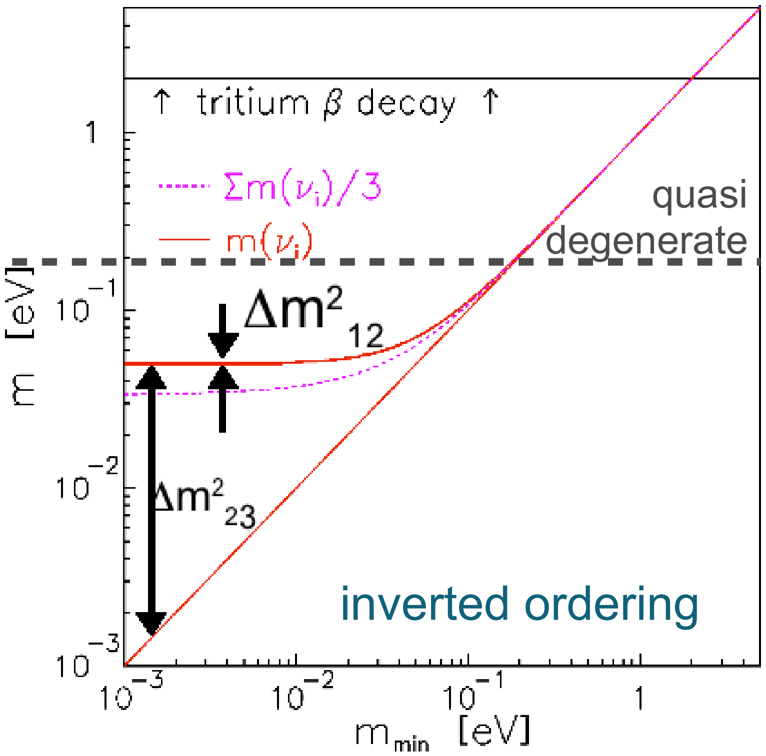
e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

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





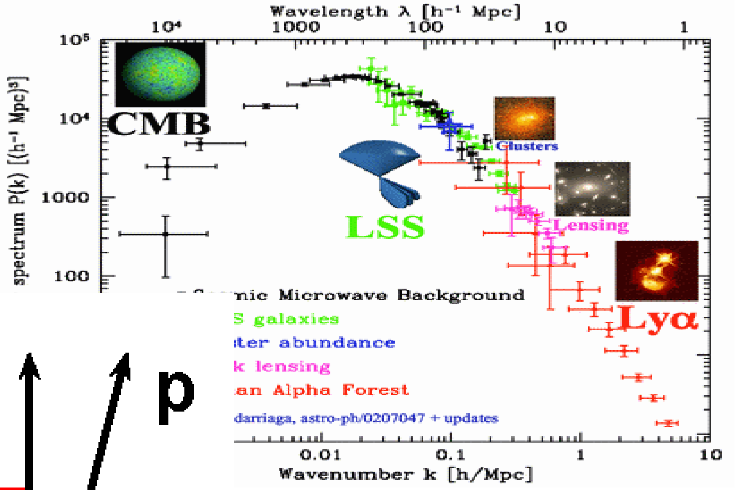
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

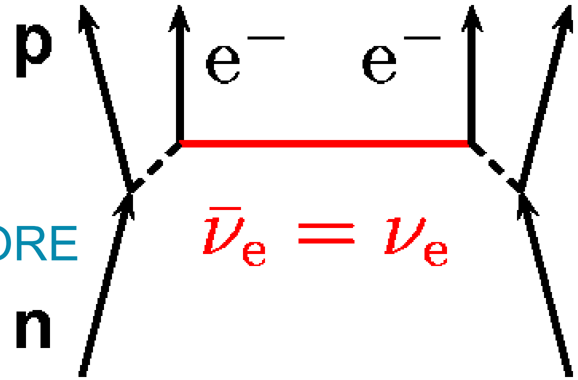
current sensitivity: $\Sigma m(\nu_i) \approx 0.12$ eV



2) Search for 0νββ

Sensitive to Majorana neutrinos, model-dependent

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



3) Direct neutrino mass determination:

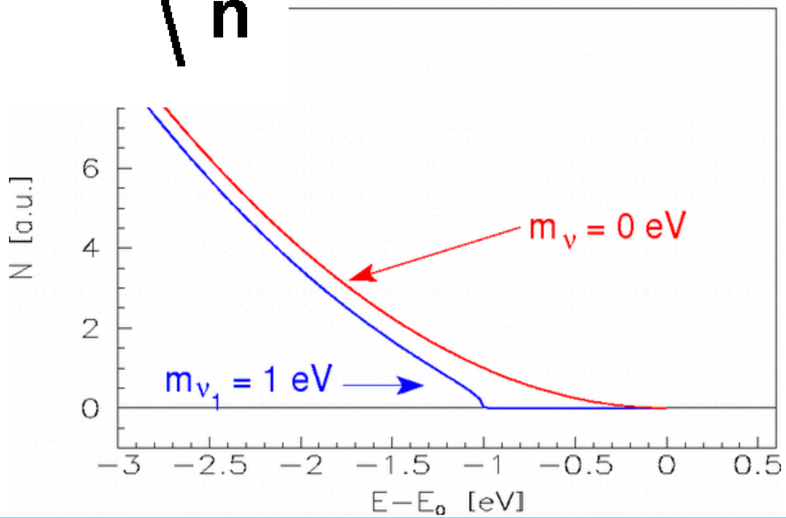
No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4$

$\Rightarrow m^2(\nu)$ 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



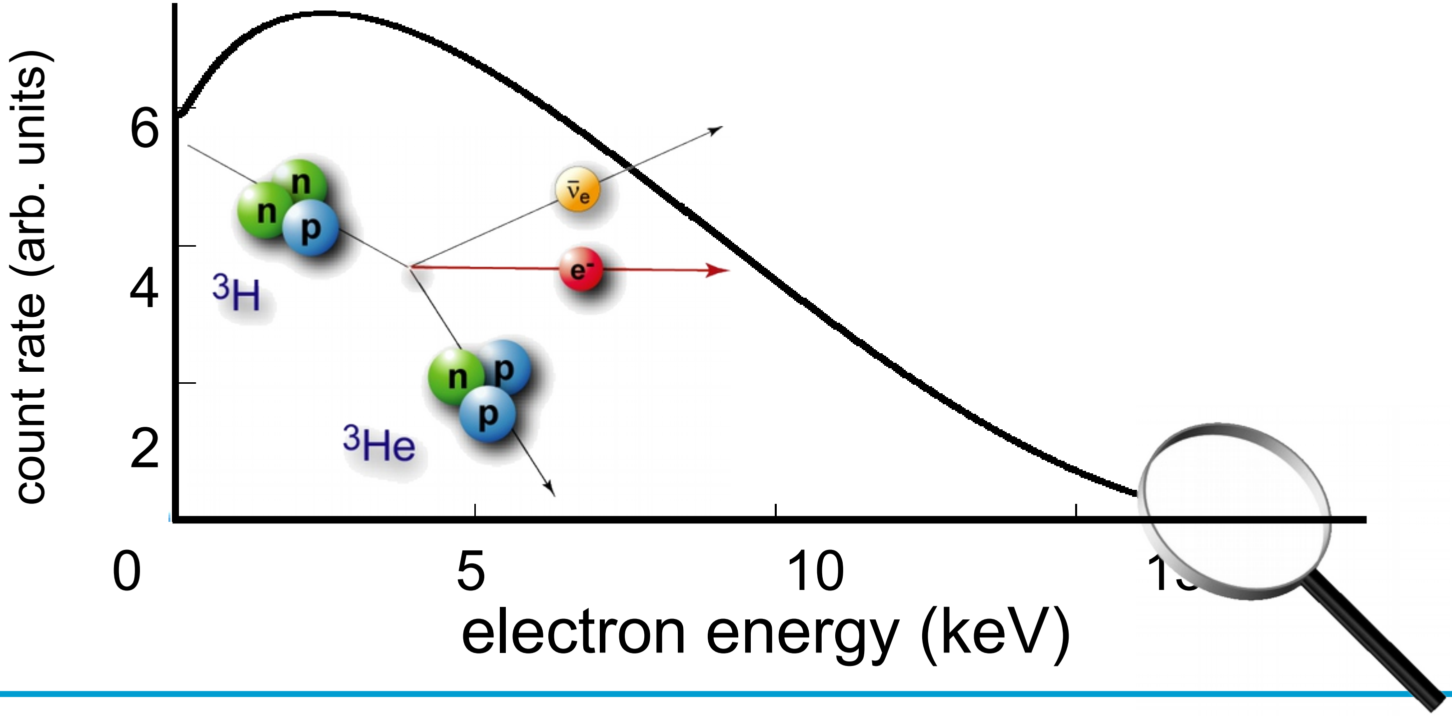
Direct determination of "$m(\nu_e)$" from β-decay (EC)

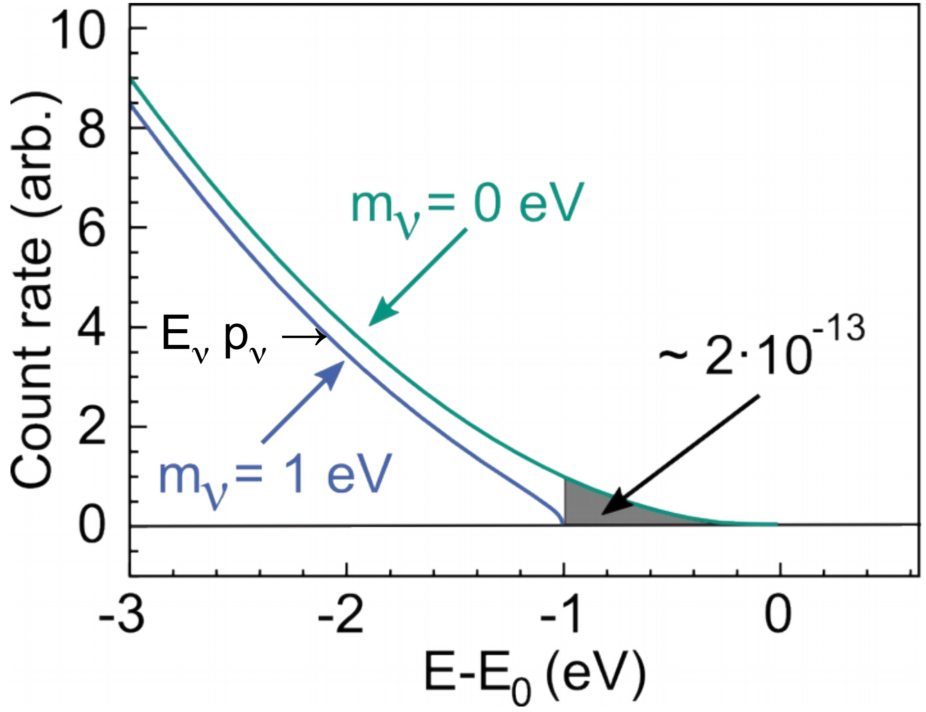
$$\beta: dN/dE = K\ F(E,Z)\ \underbrace{p}_{p_e}\ \underbrace{E_{tot}}_{E_e}\ \underbrace{(E_0-E_e)}_{E_\nu}\ \Sigma |U_{ei}|^2 \underbrace{\sqrt{(E_0-E_e)^2 - m(\nu_i)^2}}_{p_\nu}$$

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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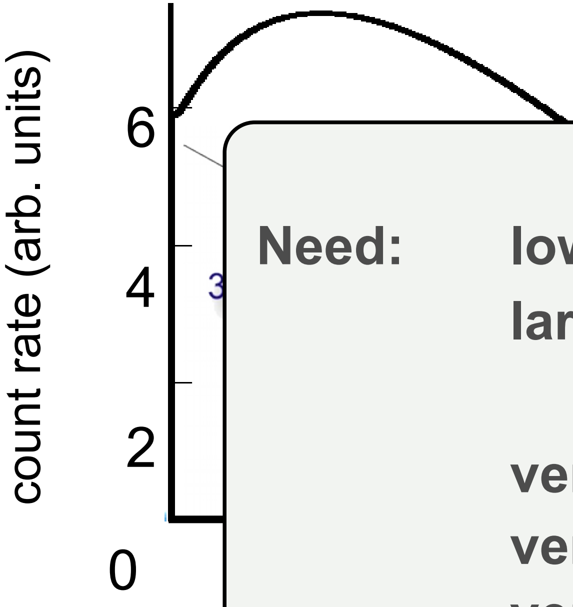
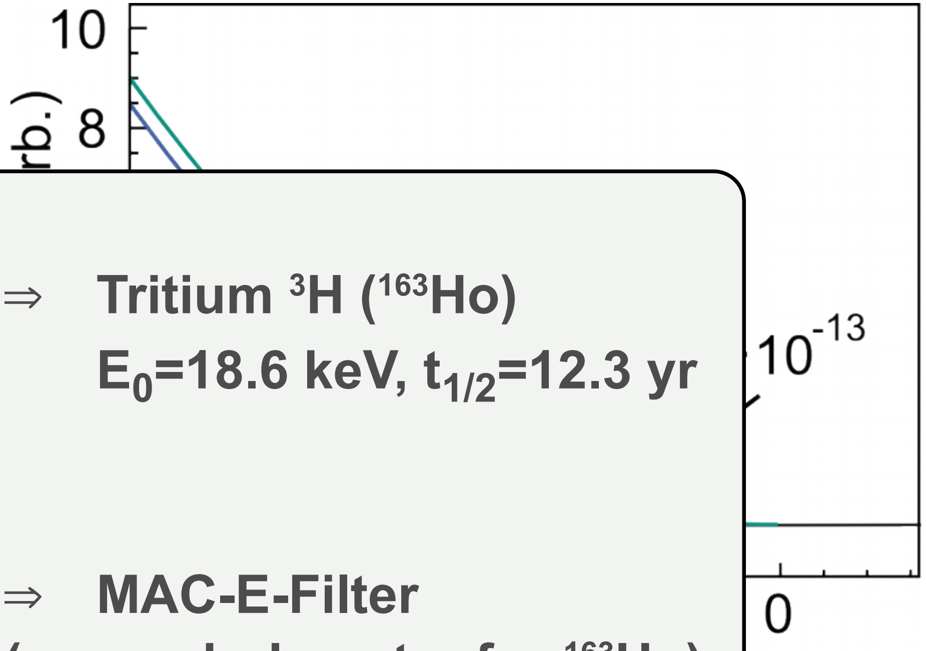




Need: low endpoint energy ⇒ Tritium ^3H (^{163}Ho)

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)

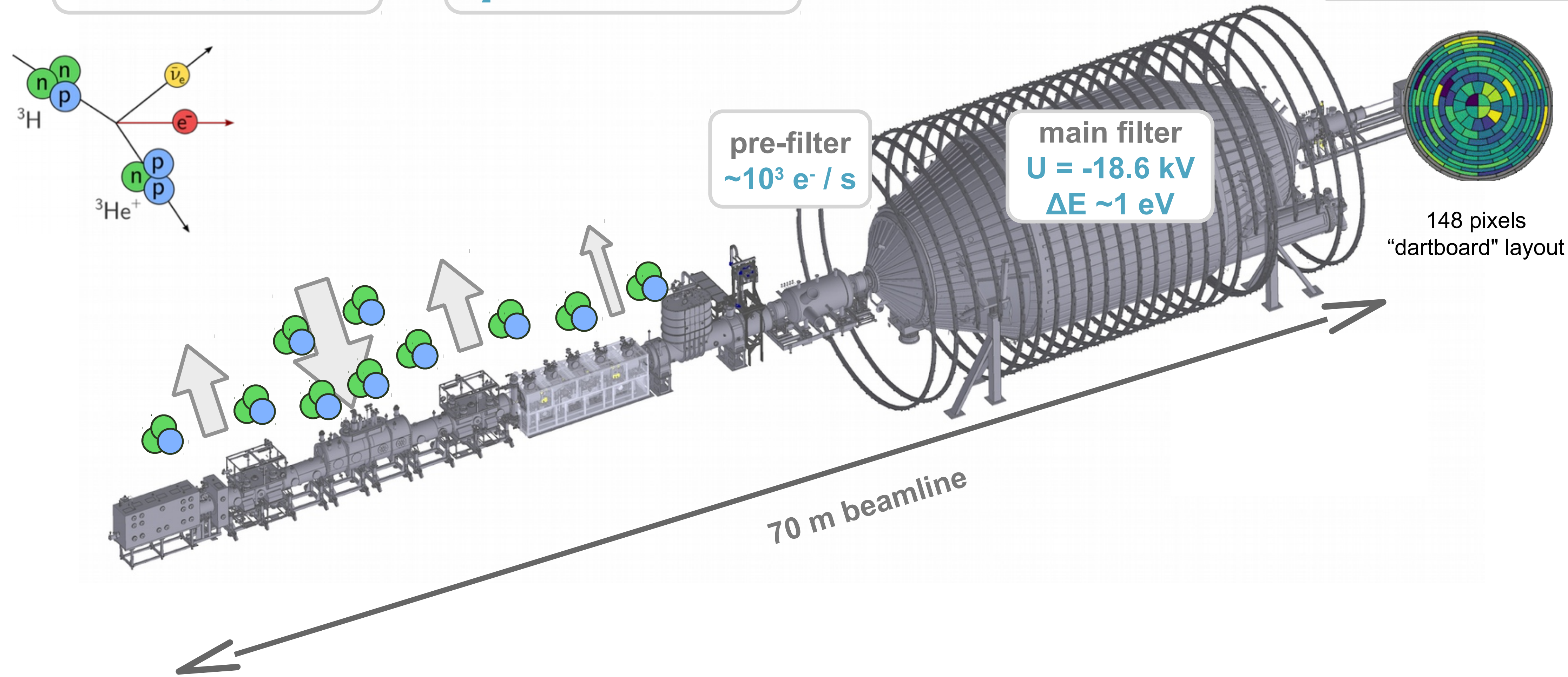
KATRIN at Karlsruhe Institute of Technology working principle

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



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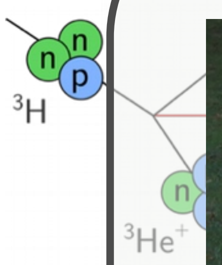
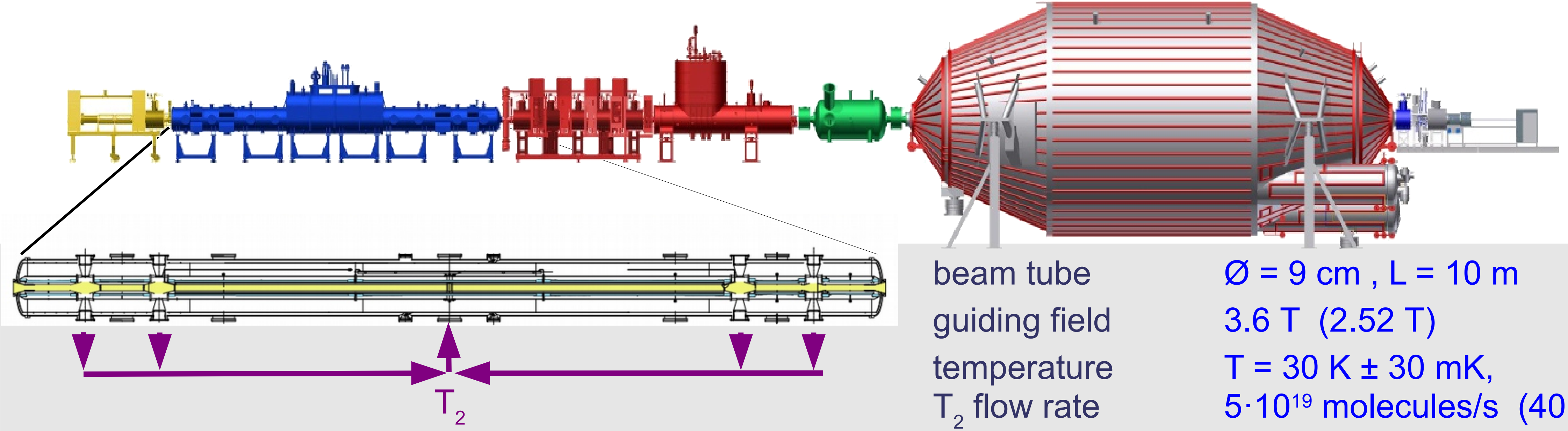


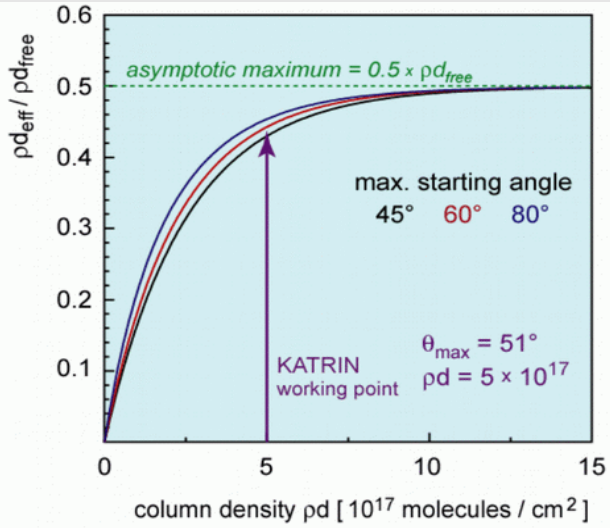
The international KATRIN Collaboration: 150 people from 20 (6) instituions (countries)

The KATRIN Windowless Gaseous Molecular Tritium Source



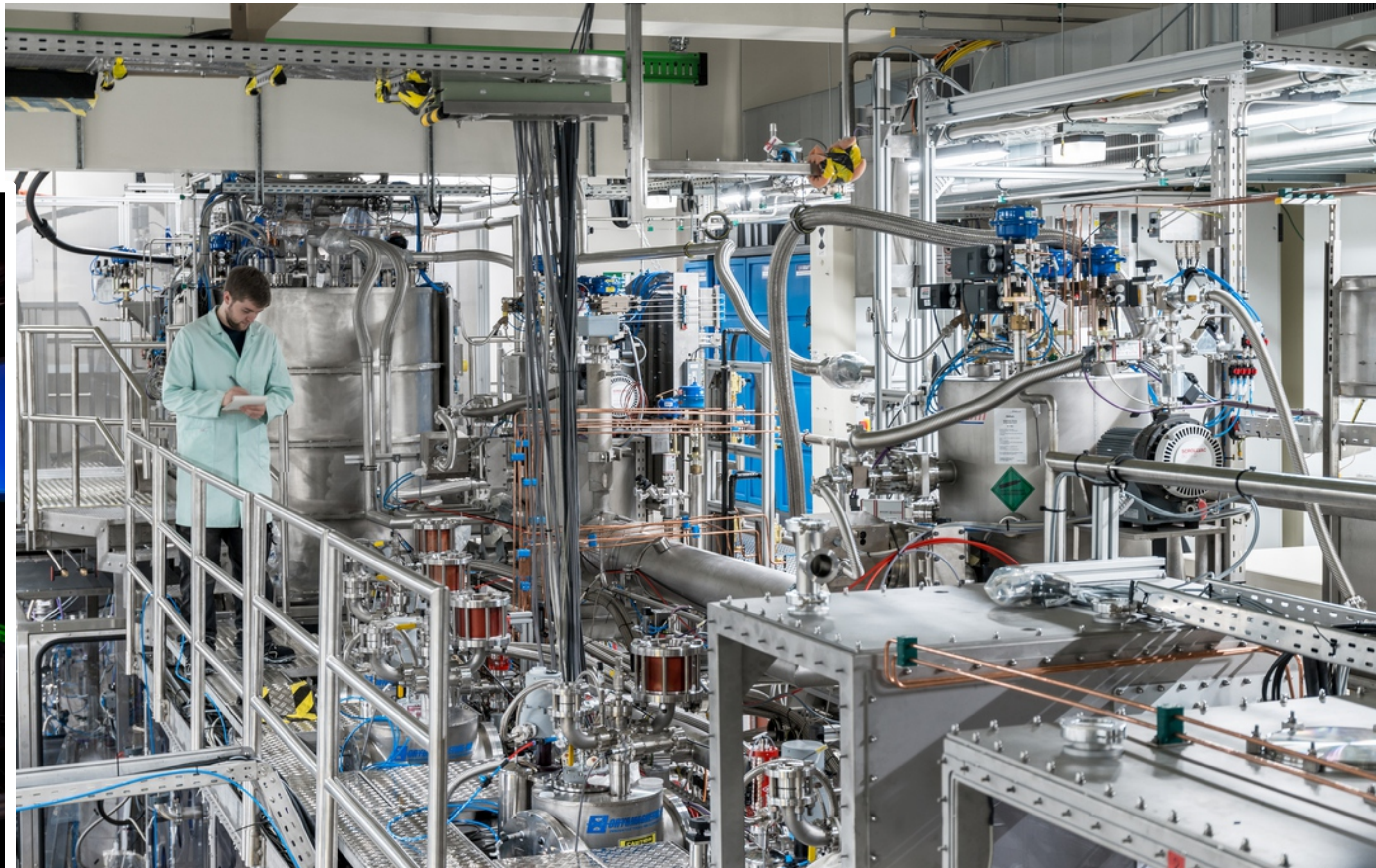
column density $5 \cdot 10^{17}$ T_2/cm^2 luminosity $1.7 \cdot 10^{11}$ Bq

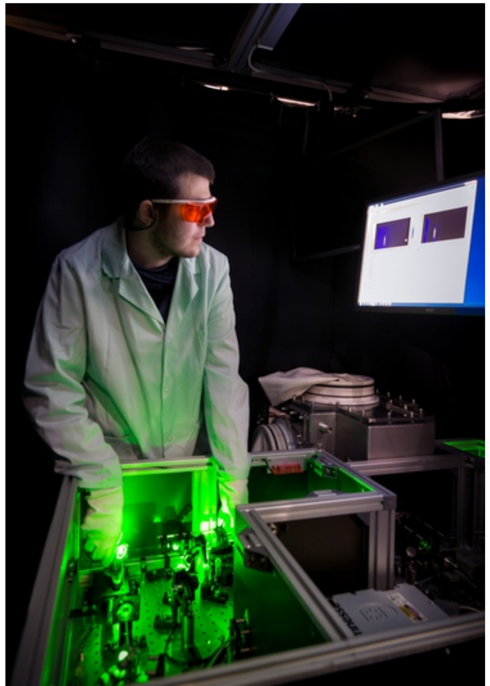
beam tube	Ø = 9 cm , L = 10 m
guiding field	3.6 T (2.52 T)
temperature	T = 30 K ± 30 mK,
T_2 flow rate	$5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)
T_2 purity	95% ± 0.1 %
T_2 inlet pressure	10^{-3} mbar ± 0.1 %



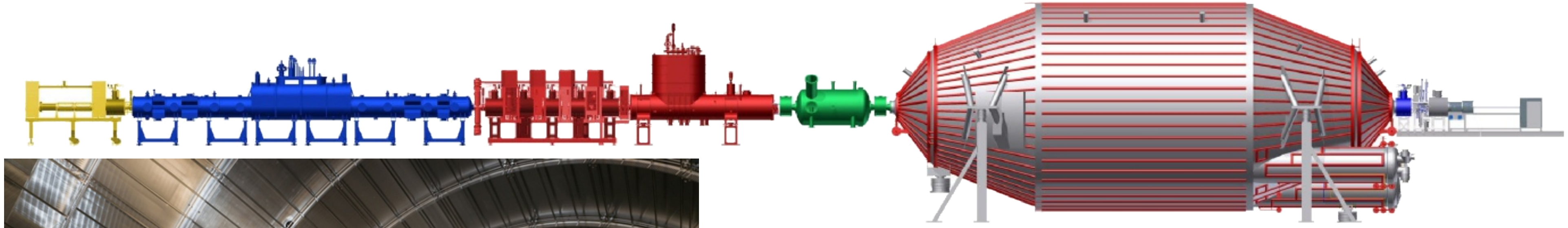
WGTS at Tritium Laboratory Karlsruhe

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

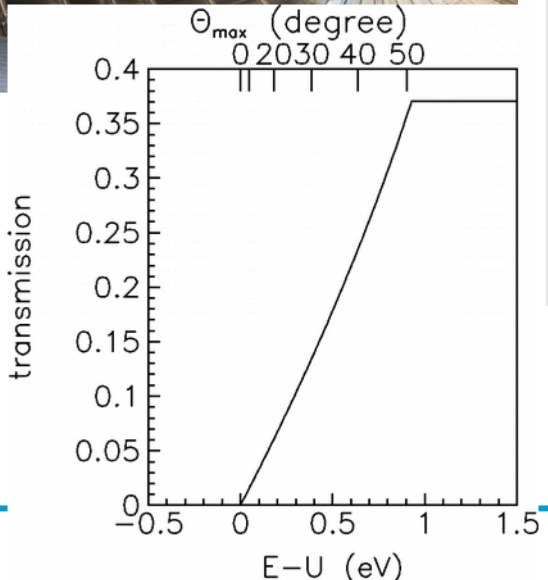
Precision voltage (ppm) at vessel and double layer wire electrode system for background reduction and field shaping

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

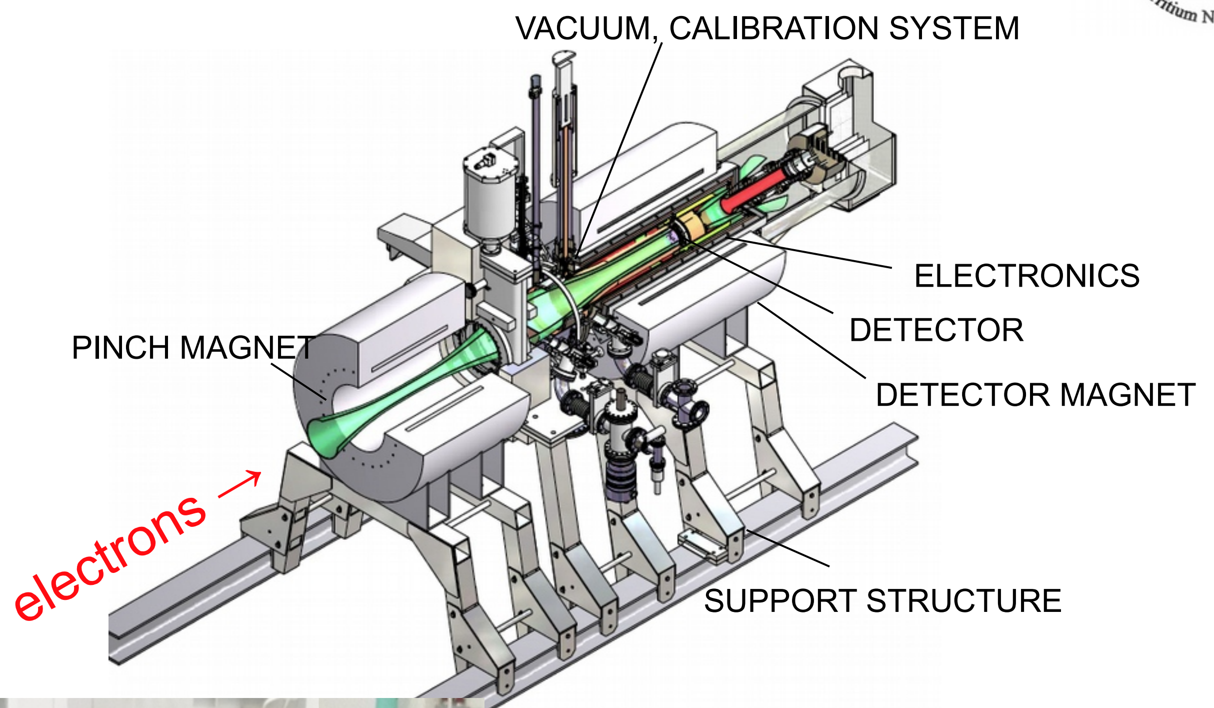
segmented Si PIN diode:
90 mm Ø, 148 pixels, 50 nm dead layer

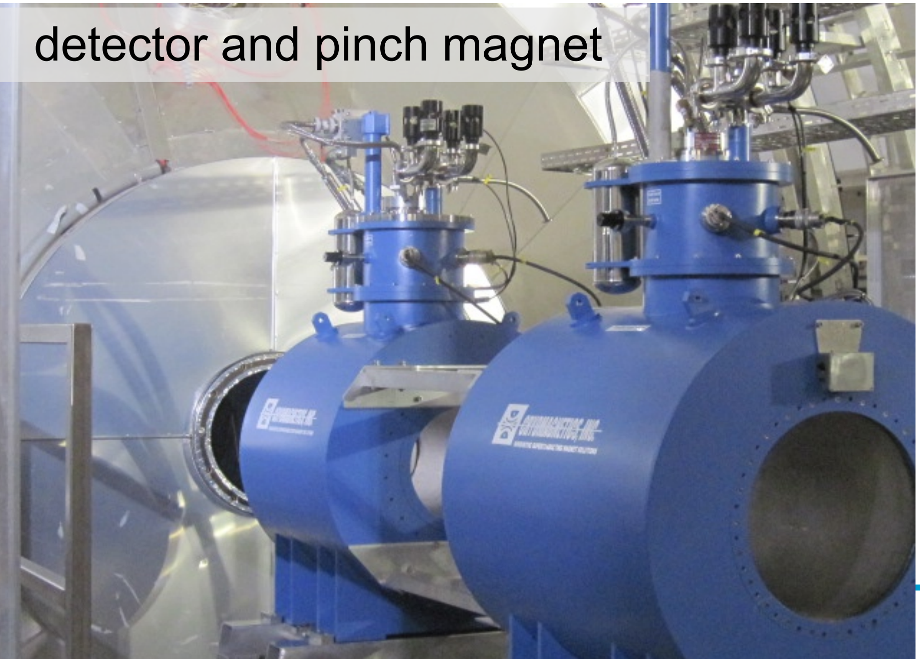
energy resolution ≈ 1 keV

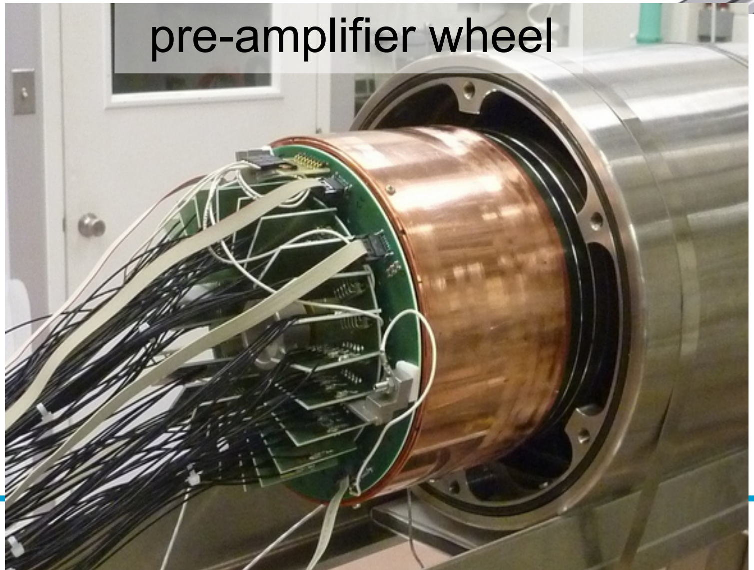
pinch and detector magnets up to 6 T

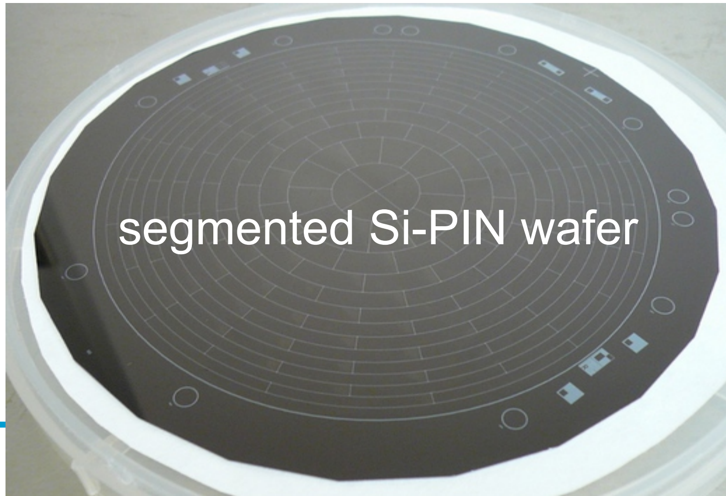
post acceleration (10kV)

active veto shield

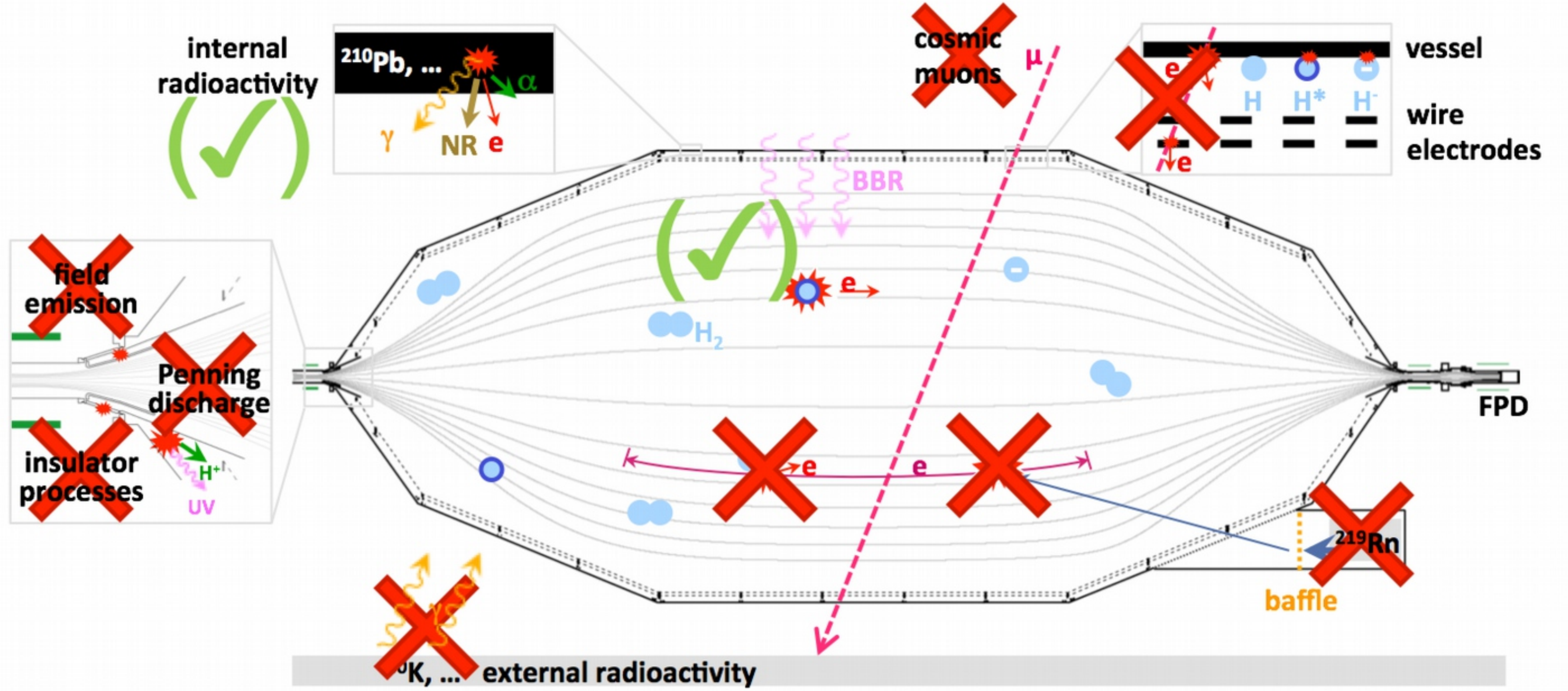








Background sources at KATRIN: detailed understanding, but …



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:

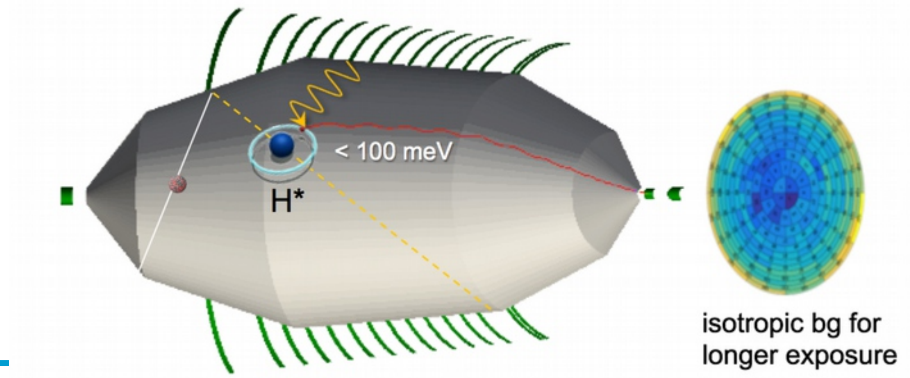
- ejected from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- ionized by black body radiation (291 K)
- non-trapped electrons on meV-scale
- bg-rate: ~0.5 cps

Countermeasures:

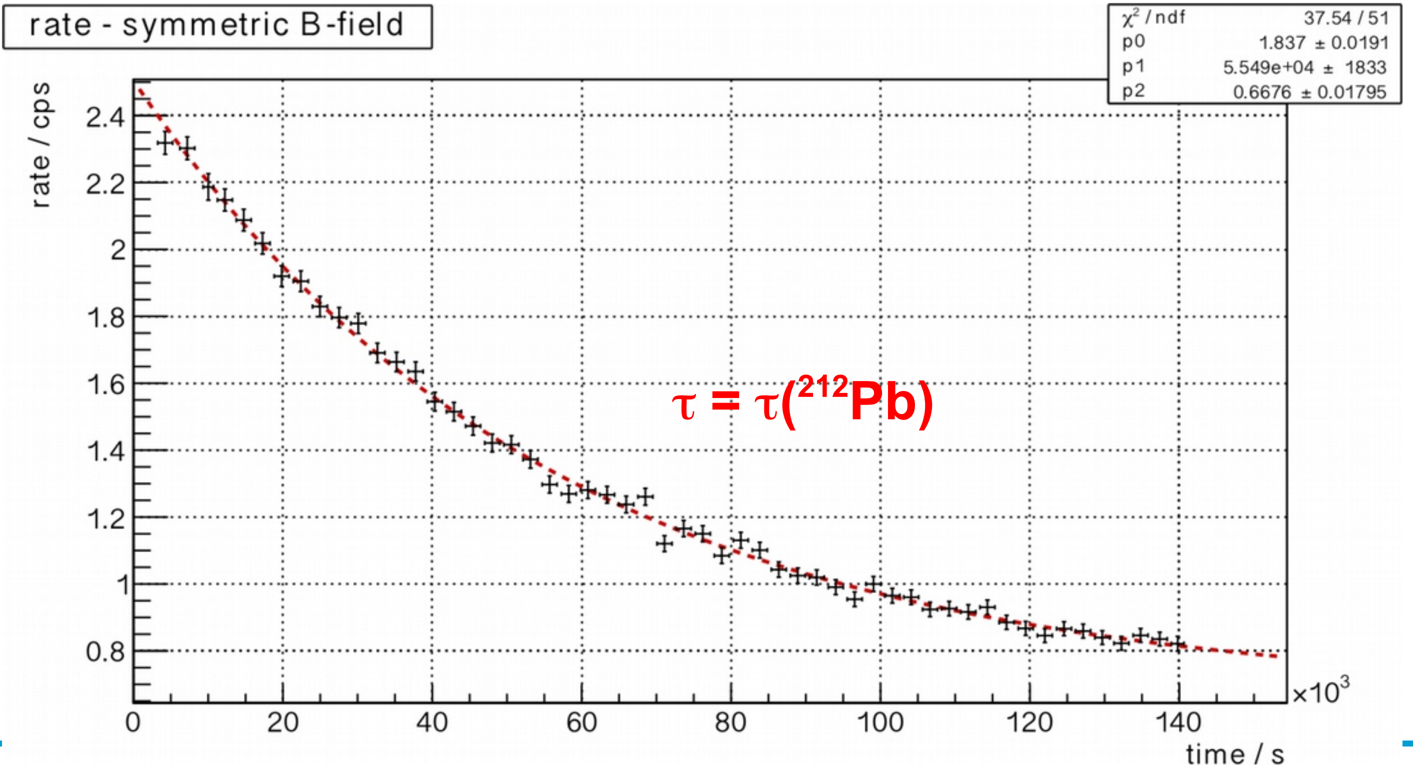
- apply stronger voltage at wires (field ionisation)
- reduce flux tube (on cost of energy resolution)
- shift analysis plane (tested, planned for 2020)
- active de-excitation ?
- coverage of surface with clean layer ?

Testing this hypothesis:

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



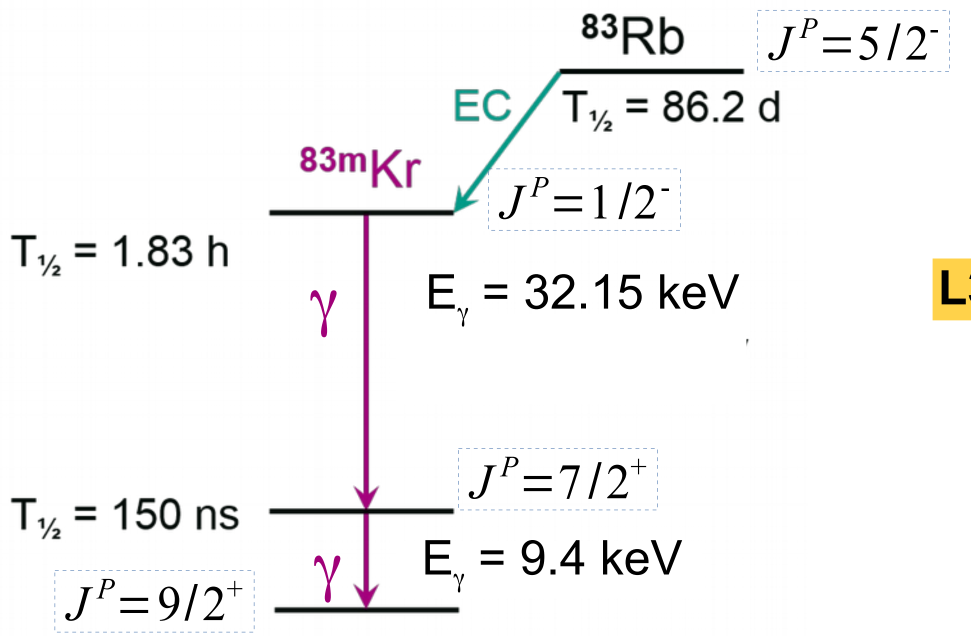
isotropic bg for longer exposure



Measuring the response with ^{83m}Kr

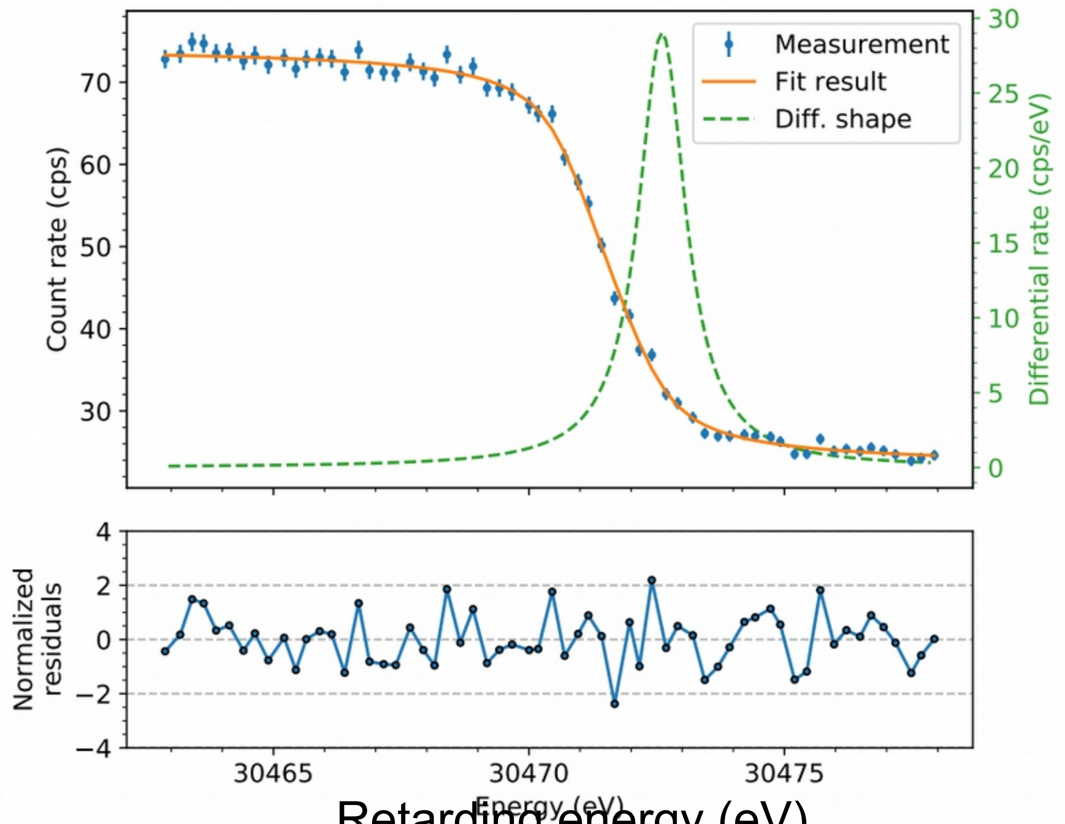
- **MAC-E filter characteristics well understood**
- **(also used to study plasma)**

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



L3-32 ⇒

L3-32 line: 30.47 keV



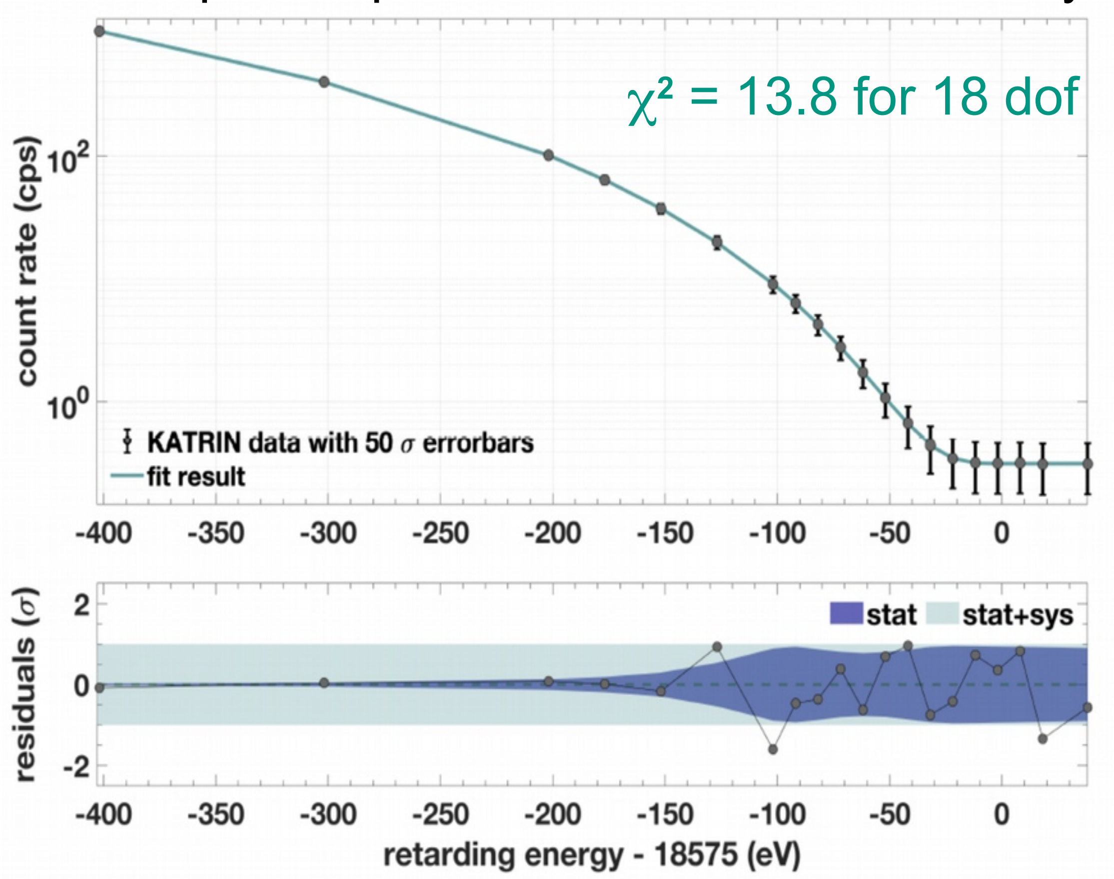
Retarding energy (eV)

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

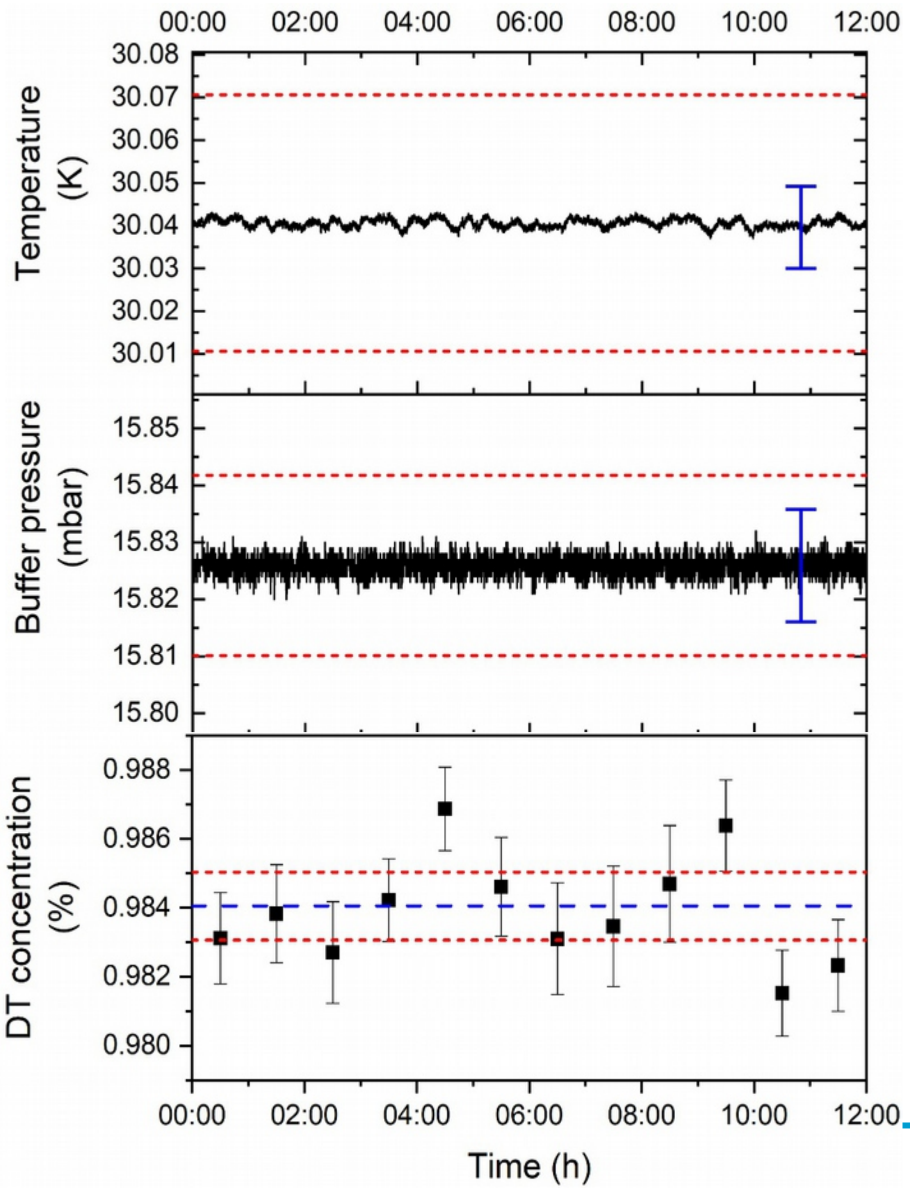


- First Tritium:

- **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

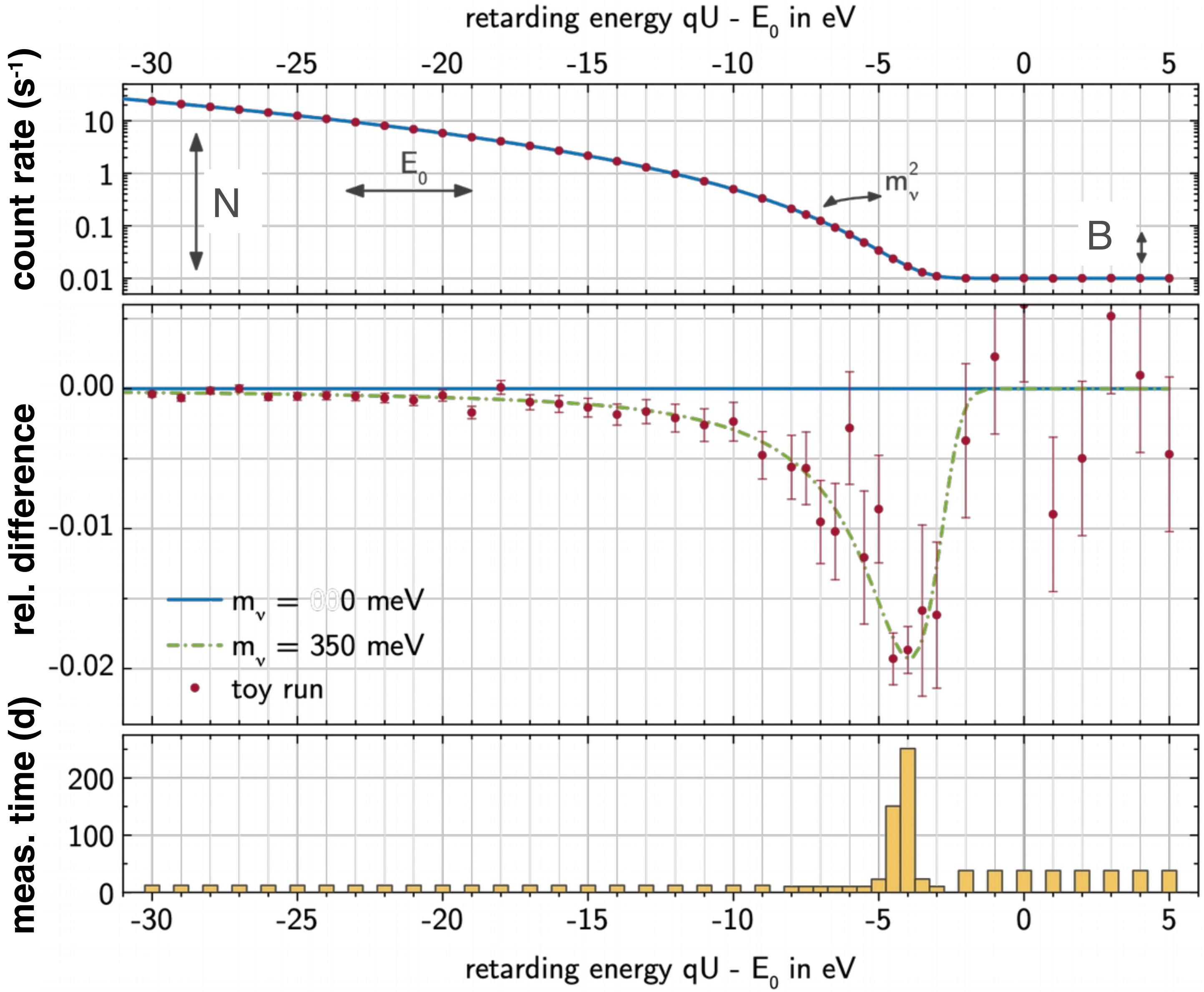


Blue arrow: systematic uncertainty

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 **E_0**
background rate **B**	squared mass **m^2_ν**

~10^{-9} 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

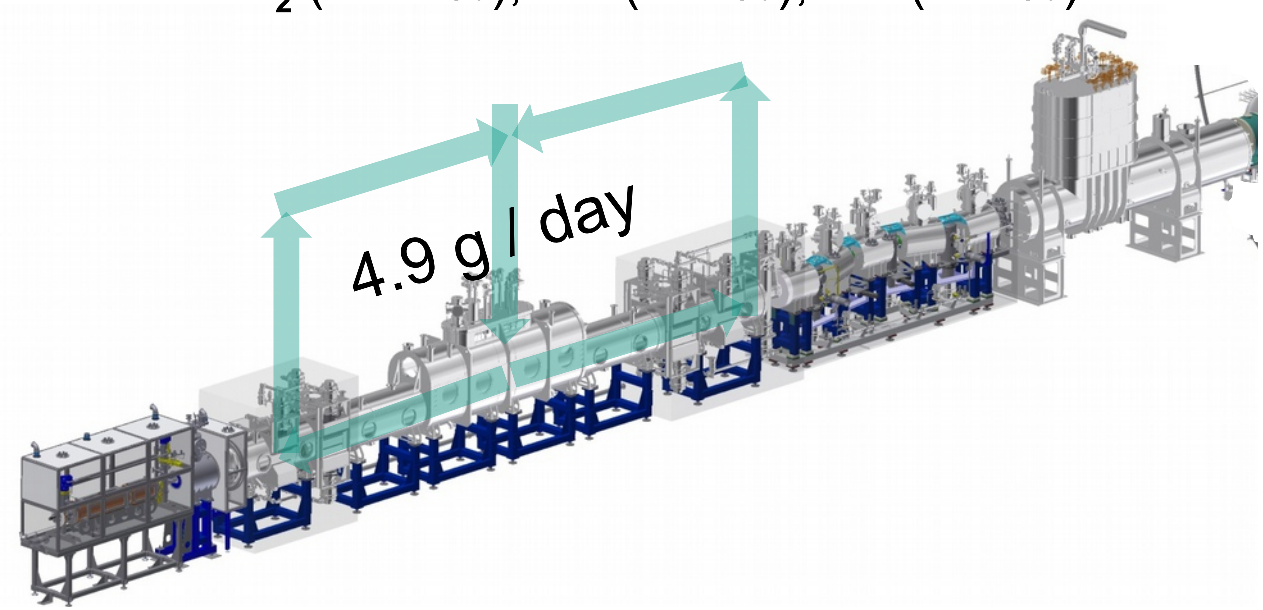
- high-quality data collected

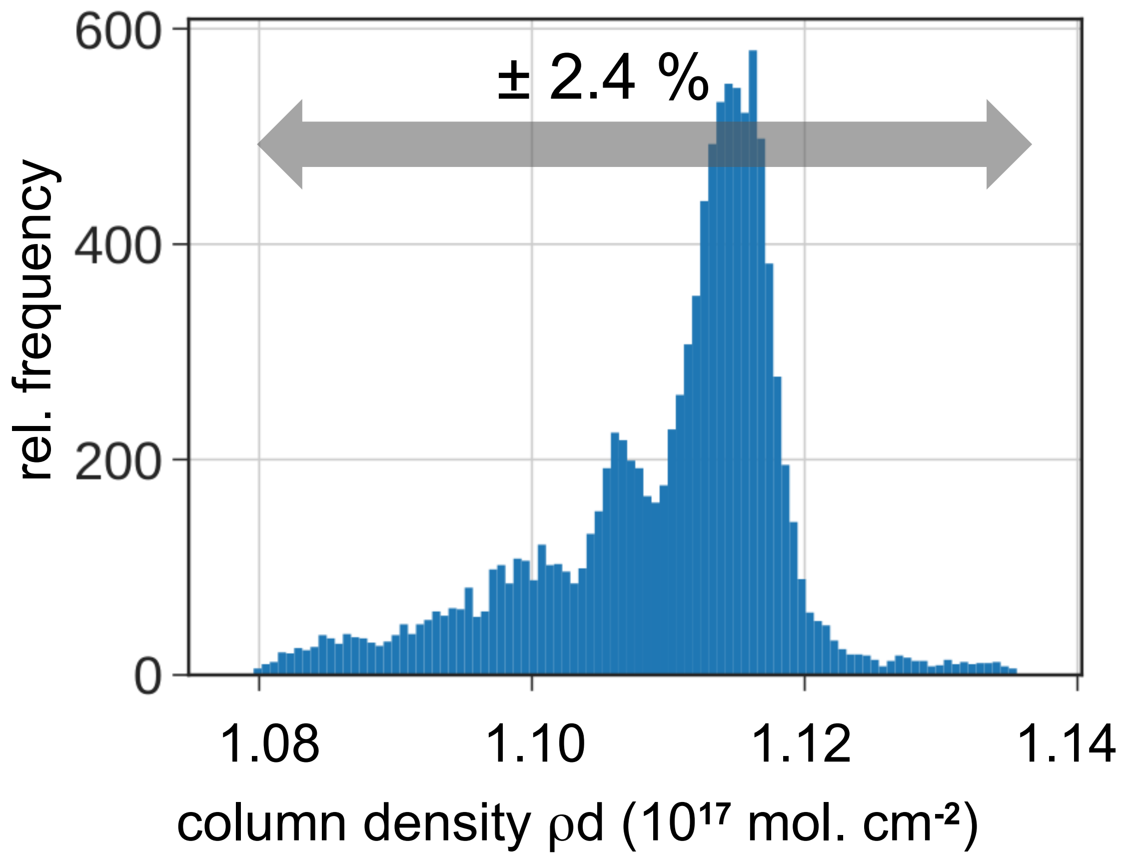
- full analysis chain using two
  independent methods

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

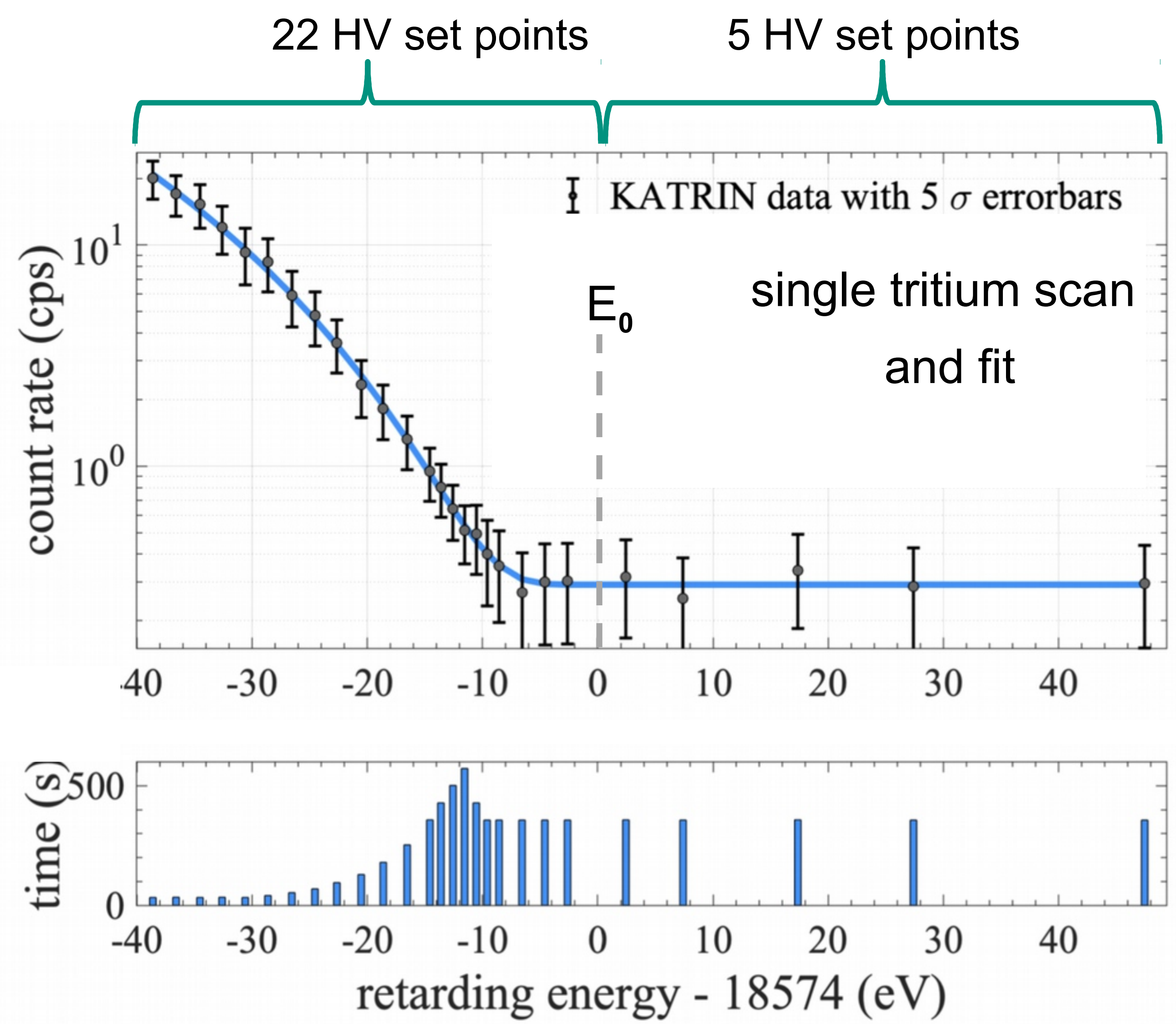
- **274 scans of tritium ß-spectrum**:

  - 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

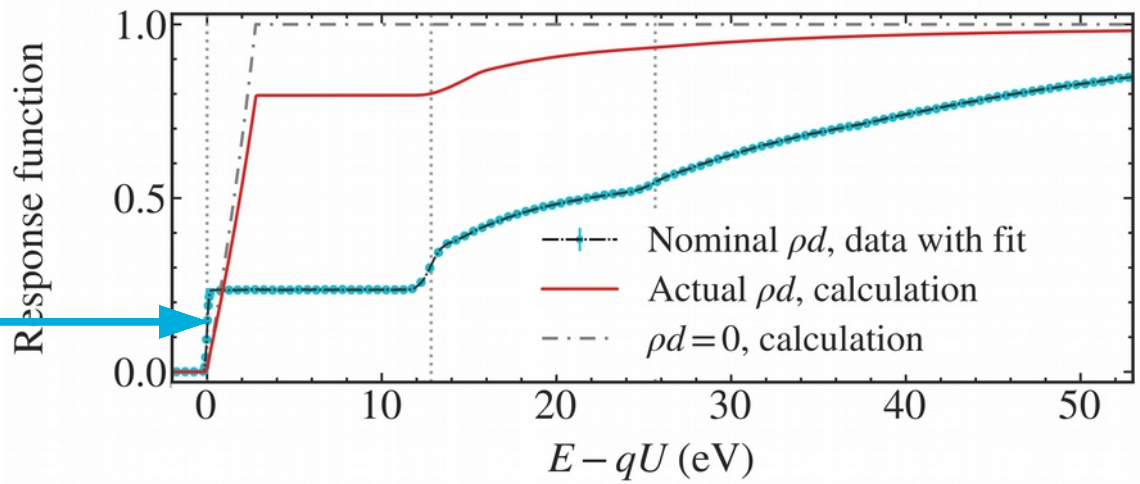


Determination of response function

- **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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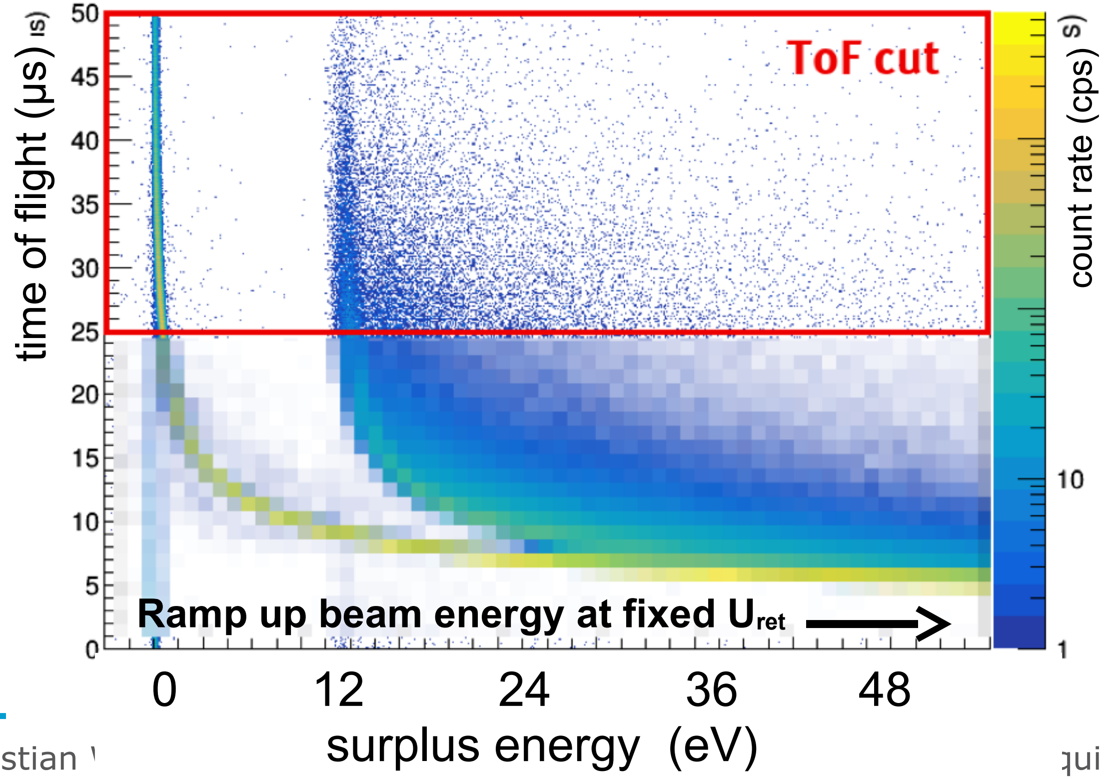

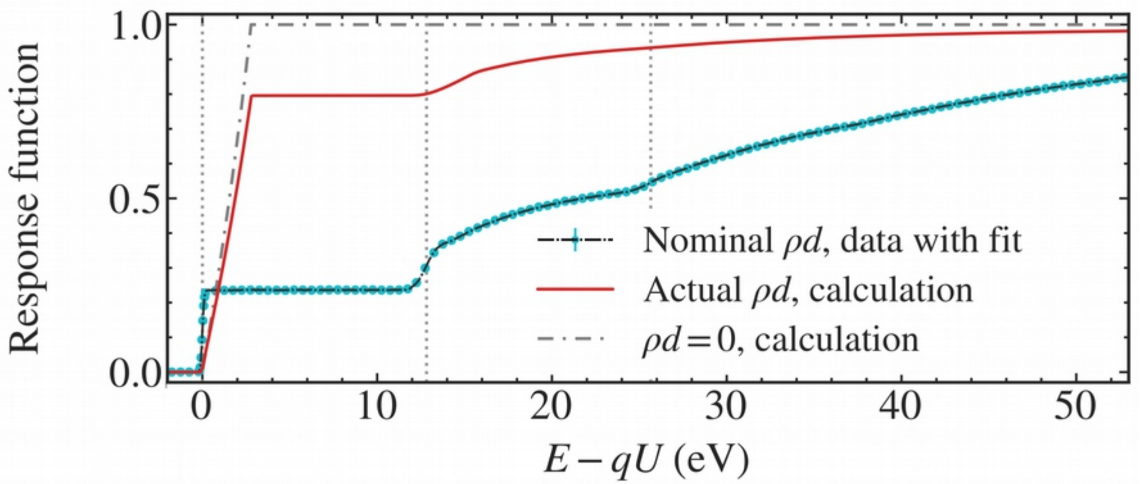

Time-of-flight of electrons from pulsed e-gun (70 ns at 20 kHz):
→ High-pass filter turned into narrow band-pass
→ recover "differential" spectrum

"Differential Time-of-flight mode"

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

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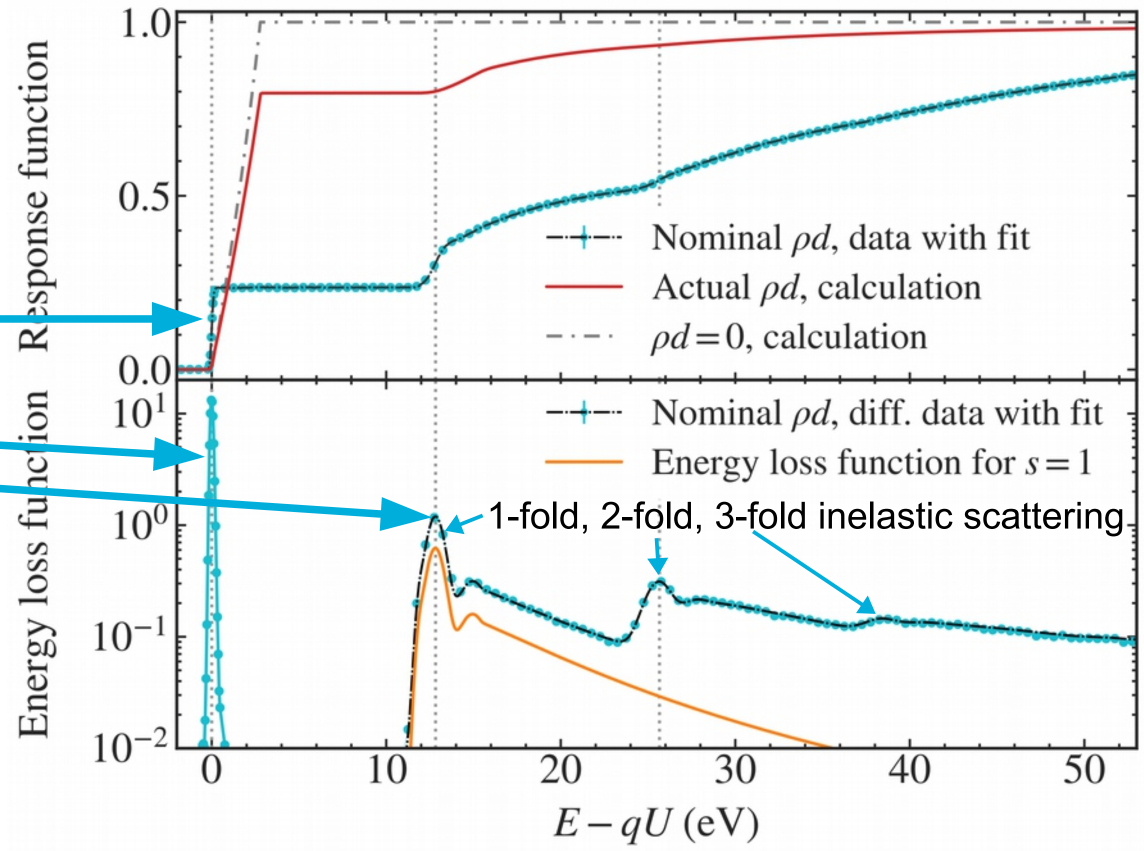

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Normal integral MAC-E-Filter mode

Differential Time-of-flight mode

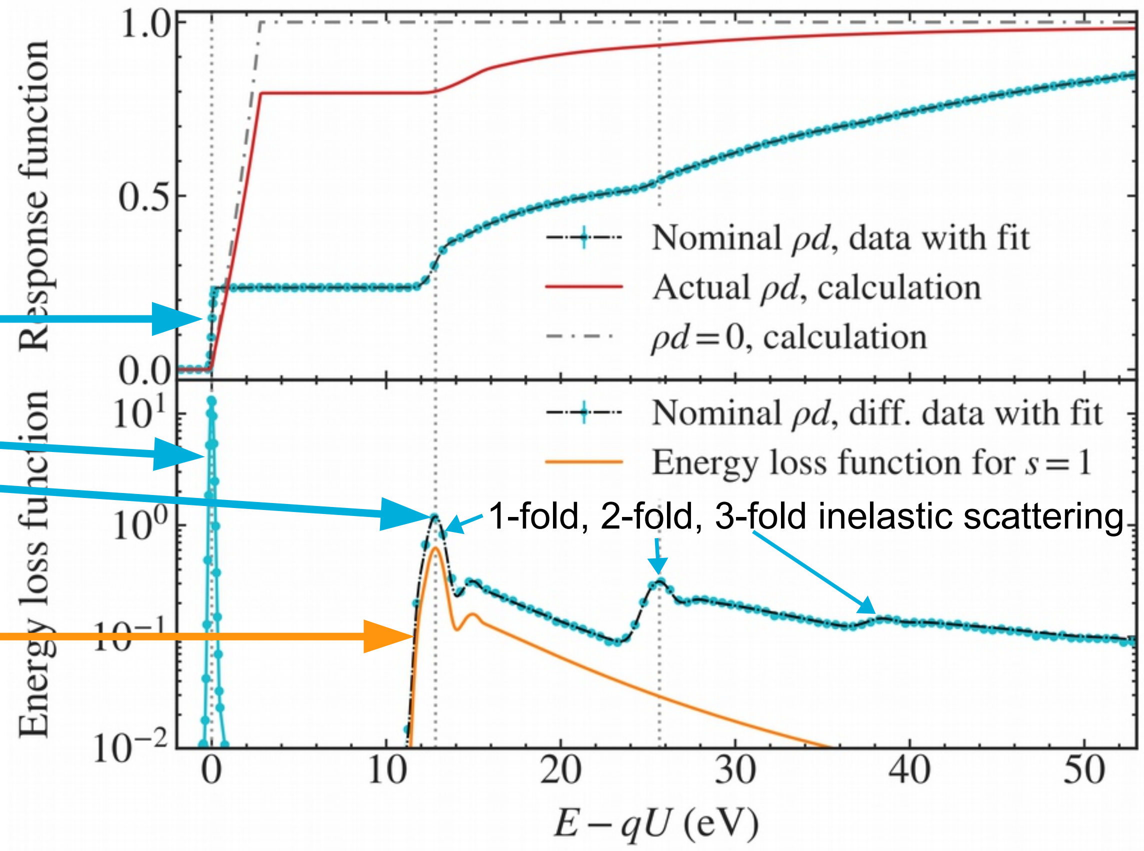
Nucl. Inst. Meth. A 421 (1999) 256,

New J. Phys. 15 (2013) 113020

Deconvoluted differential energy loss function

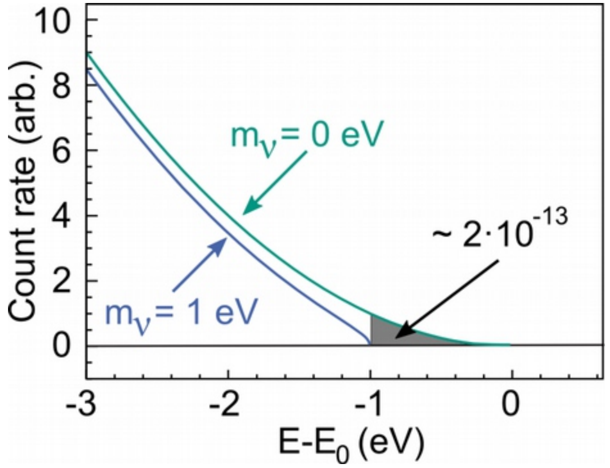
M. Aker et al. (KATRIN Collaboration)

Phys. Rev. Lett. 23 (2019) 221802

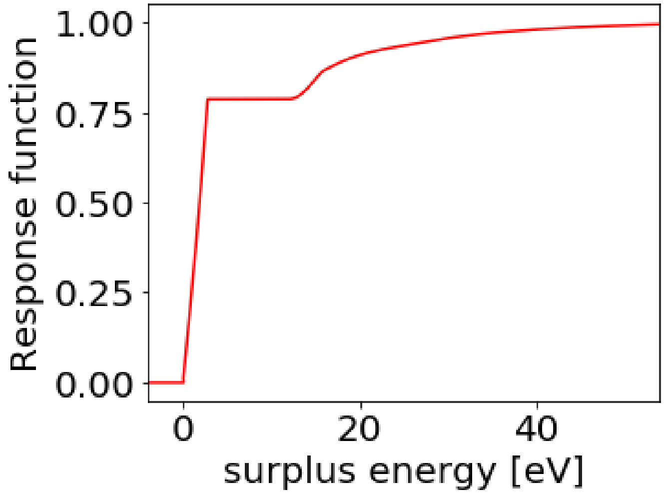


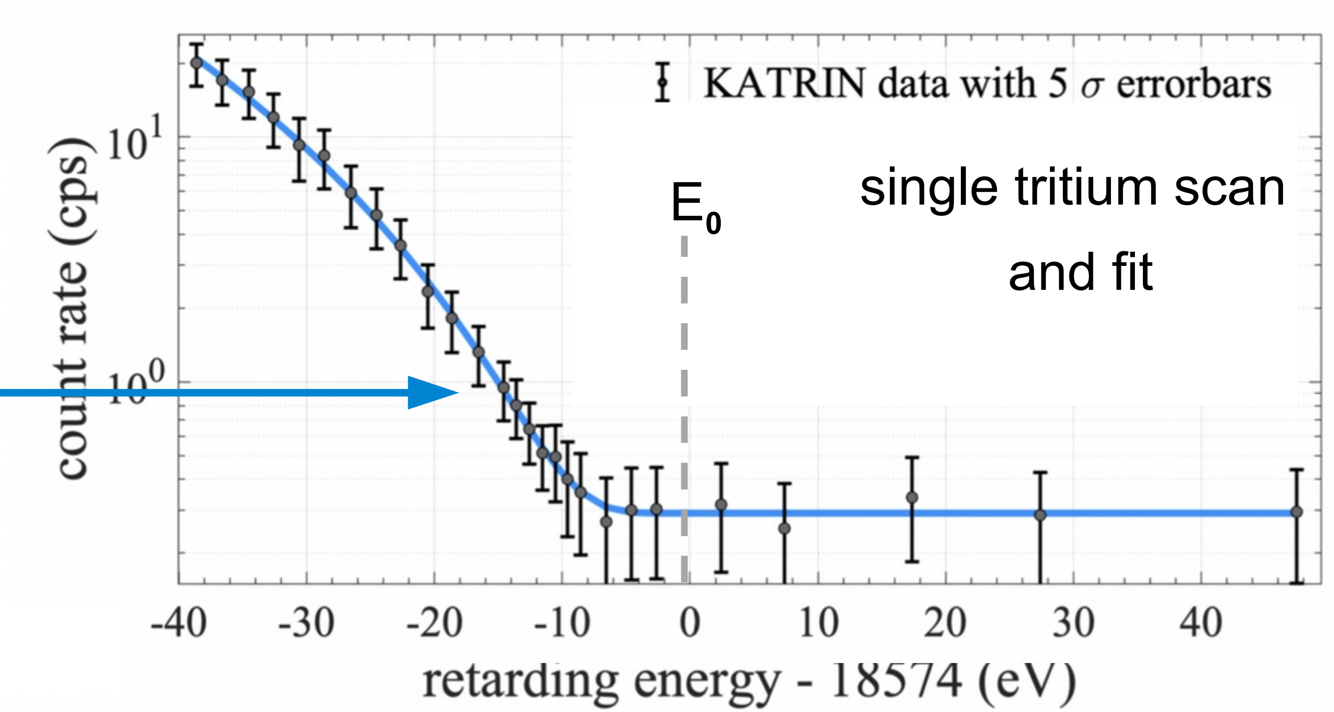
Modeling of experimental data

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



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

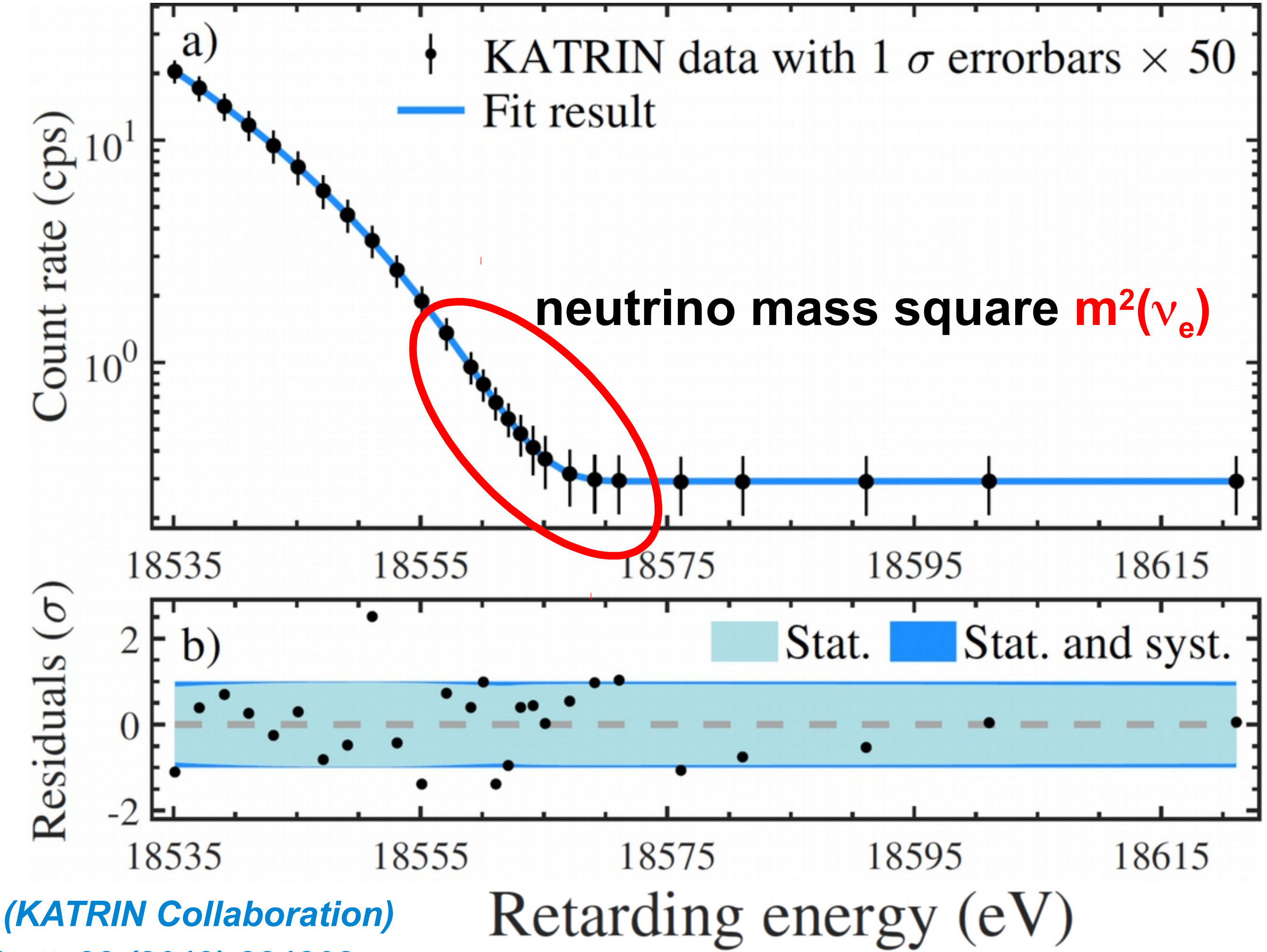




$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_{ß}(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

Fitting tritium ß-decay spectrum

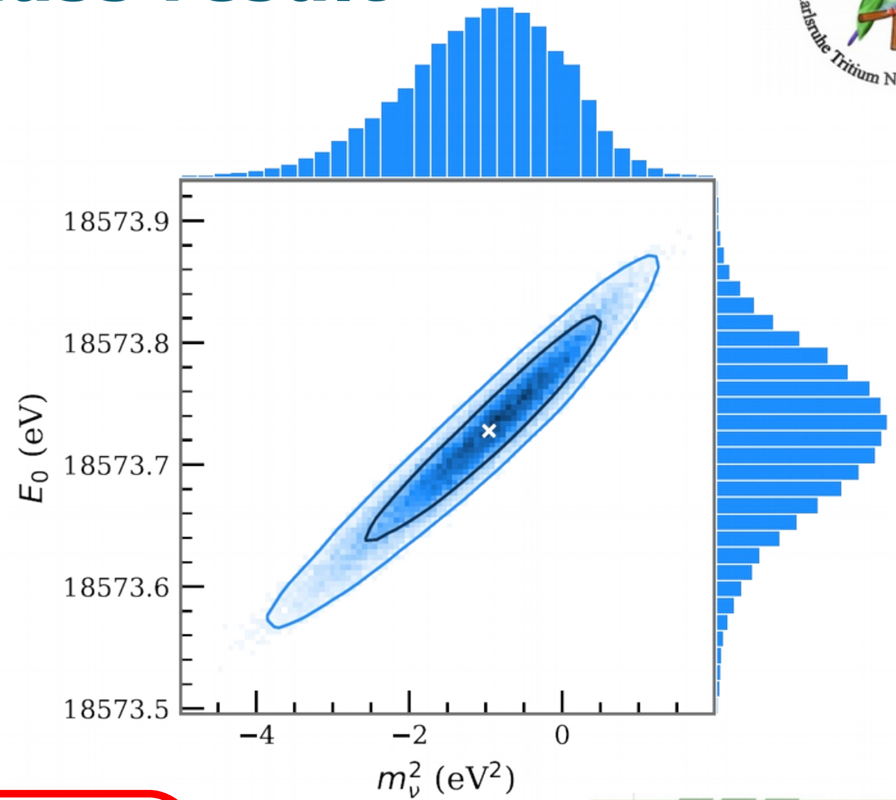
- **High-statistics ß-spectrum**
  - 2 million events in
    in 90-eV-wide interval
    (522 h of scanning, 274 indiv. scans)
  - fit with 4 free parameters:
    $m^2(\nu_e)$, R_{bg}, A_s, E_0
    excellent goodness-of-fit
    $\chi^2 = 21.4$ for 23 d.o.f.
    (p-value = 0.56)
- **Bias-free analysis**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

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

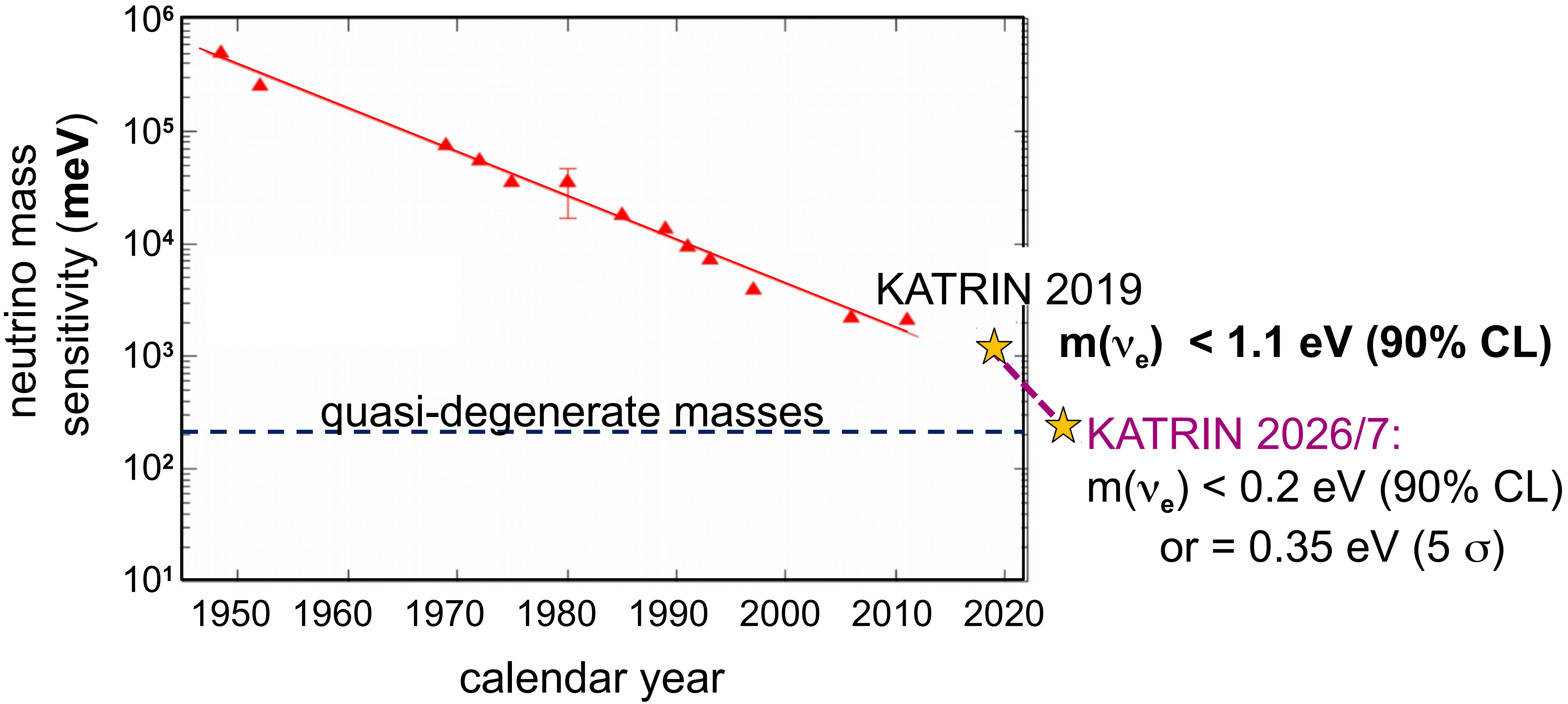
E_0 = (18573.7 ± 0.1) eV

→ 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

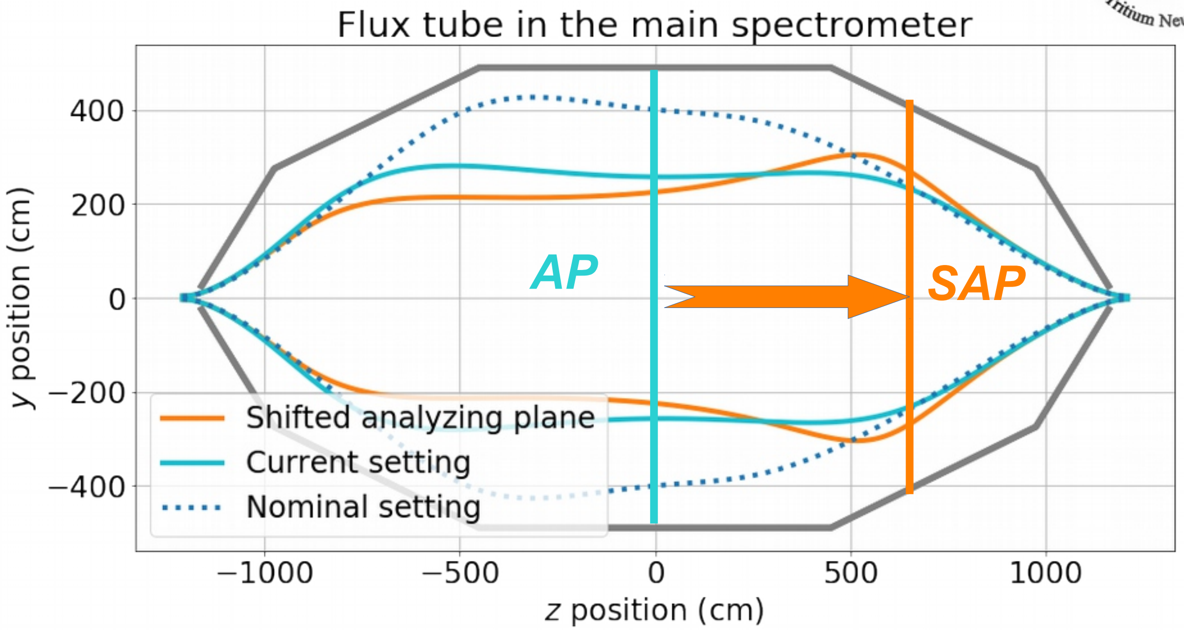
Moore´s law of direct ν-mass sensitivities

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

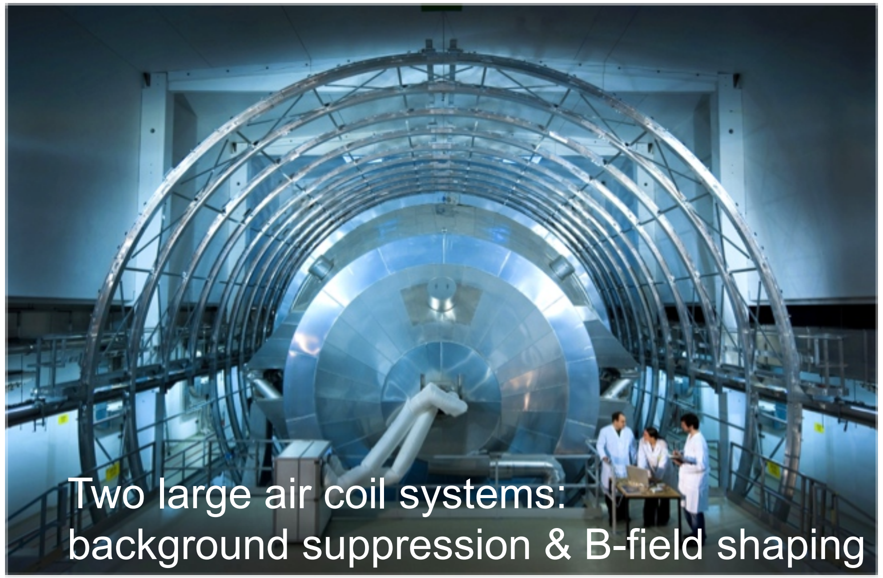


Outlook: Background reduction

- **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



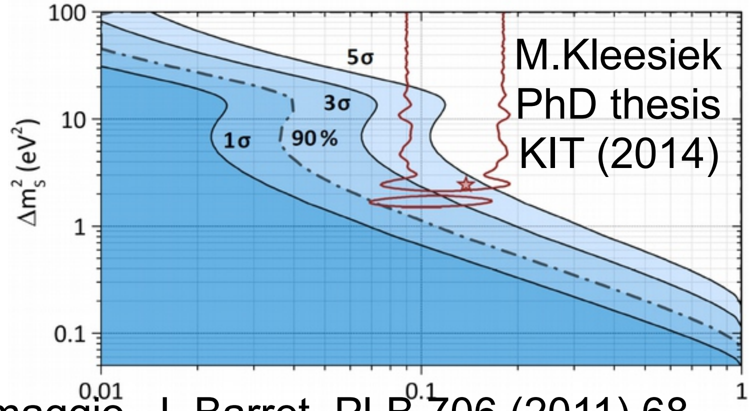
Two large air coil systems:
background suppression & B-field shaping

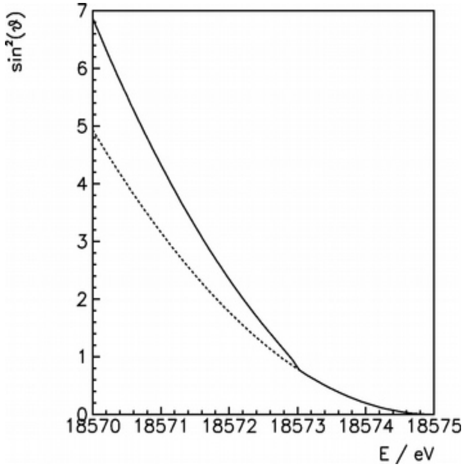
Other interesting searches for physics beyond the Standard Model

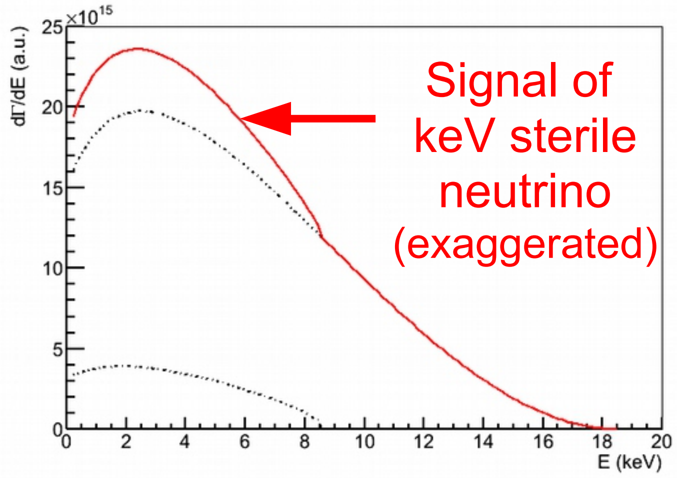
Sterile neutrinos

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

eV ν:



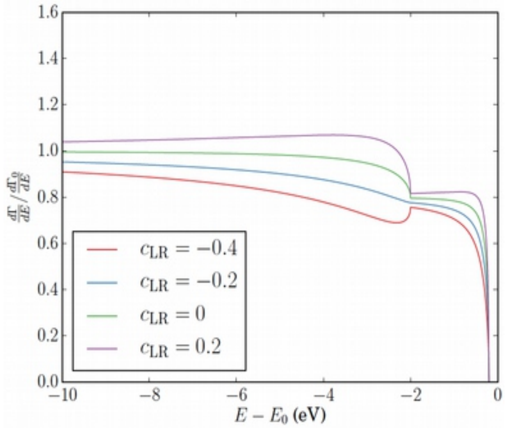


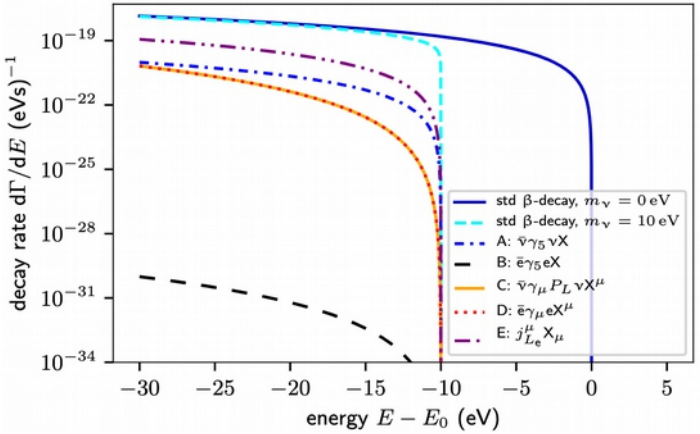


see e.g.:
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

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, ...

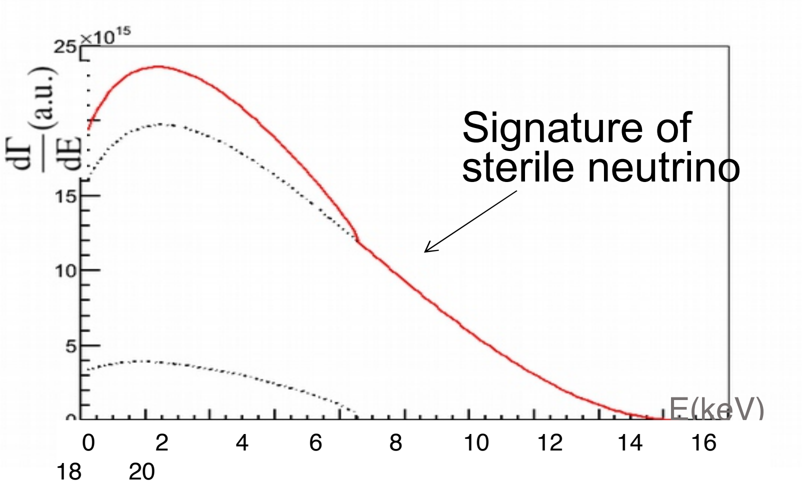
see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν), G. Arcadi et al., JHEP 1901 (2019) 206 (light bosons)

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

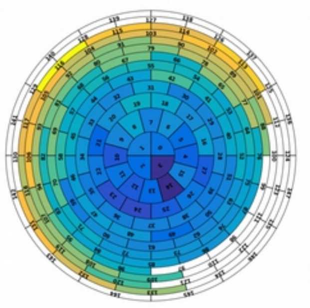
$$\frac{dN}{dE} = \cos^2\theta_s \cdot \frac{dN}{dE}(m_{active}) + \sin^2\theta_s \cdot \frac{dN}{dE}(m_{sterile})$$



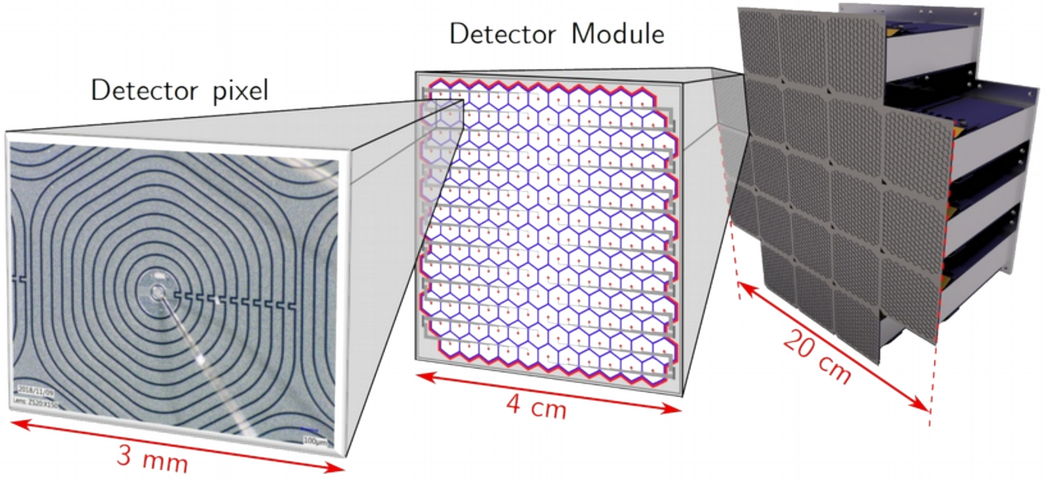
- **Look for the kink in the β-spectrum**
- **TRISTAN project in KATRIN**

  - developing a new detector & DAQ system

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



segmented Si-PIN wafer

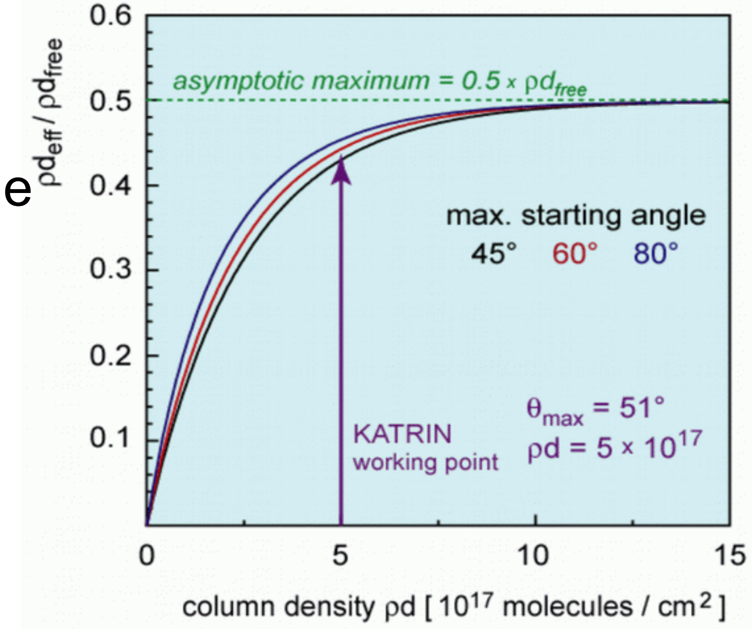


S. Mertens et al., J.Phys. G46 (2019) 065203; T. Brunst et al., JINST 14 (2019) P11013

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



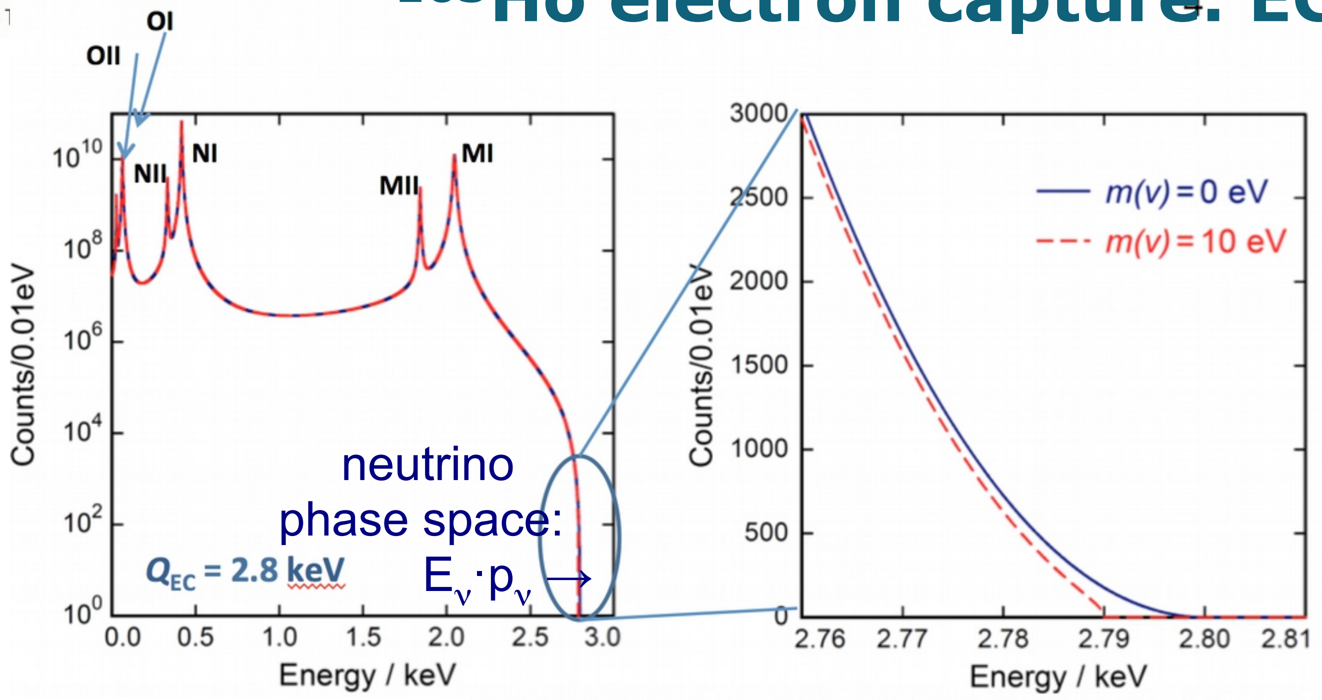
Possible ways out:

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

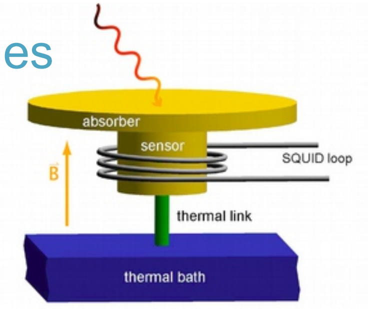
$^{163}Ho + e^- \rightarrow$
$^{163}Dy^* + \nu_e \rightarrow$
$^{163}Dy + \gamma/e^- + \nu_e$



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

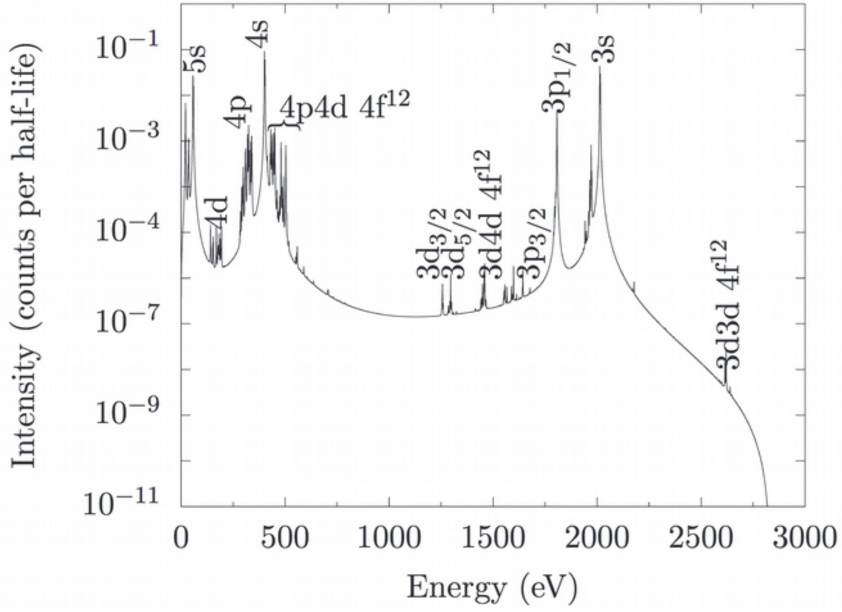
$\Delta T = \Delta E/C$, $C \propto T^3$

ECHo:
metallic magnetic calorimeters: change of magnetic properties

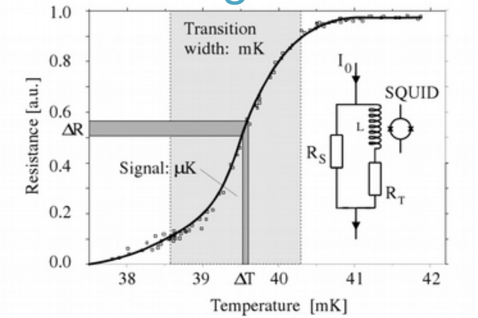


New ab initio spectral calculation: M. Braß et al., PRC **97** (2018) 054620

→ much better agreement with experimental data from ECHo



HOLMES:
sc. transition edge sensors



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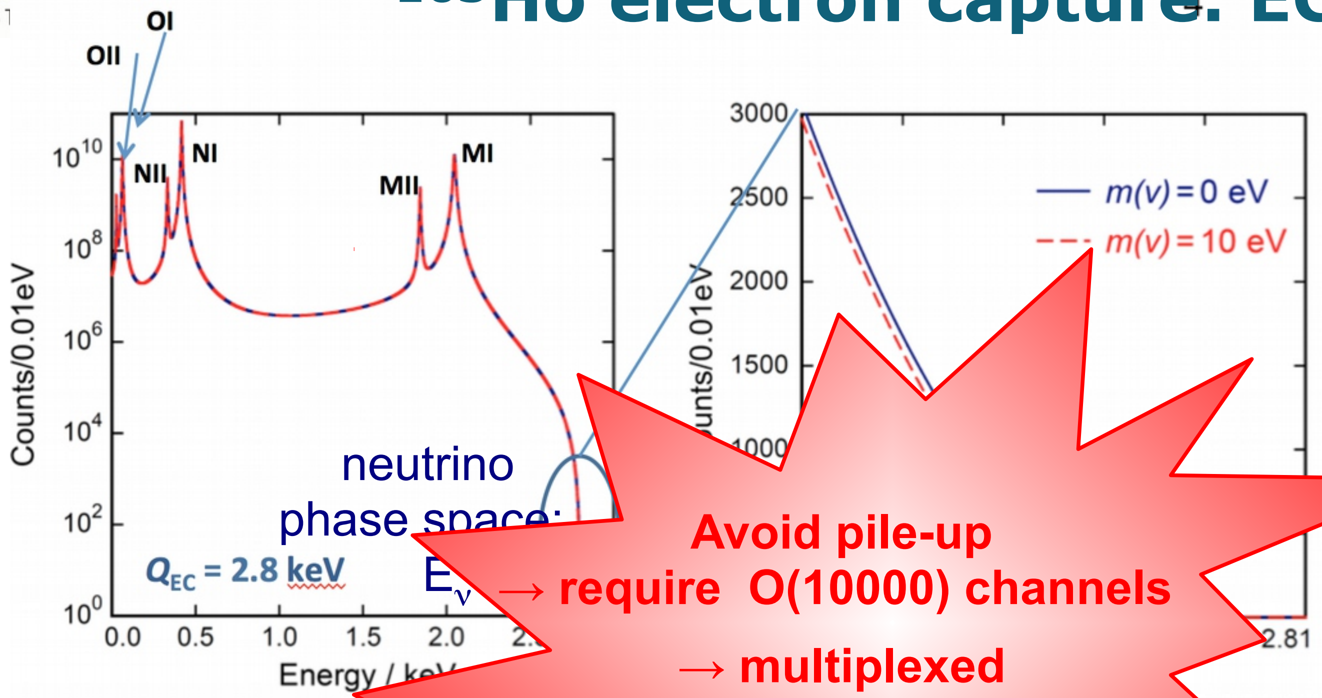

Avoid pile-up
→ require O(10000) channels
→ multiplexed read-out

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

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ECHo:
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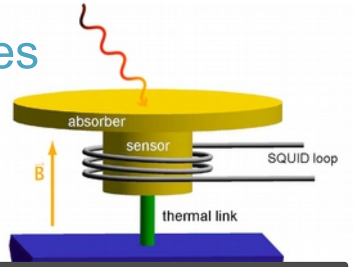

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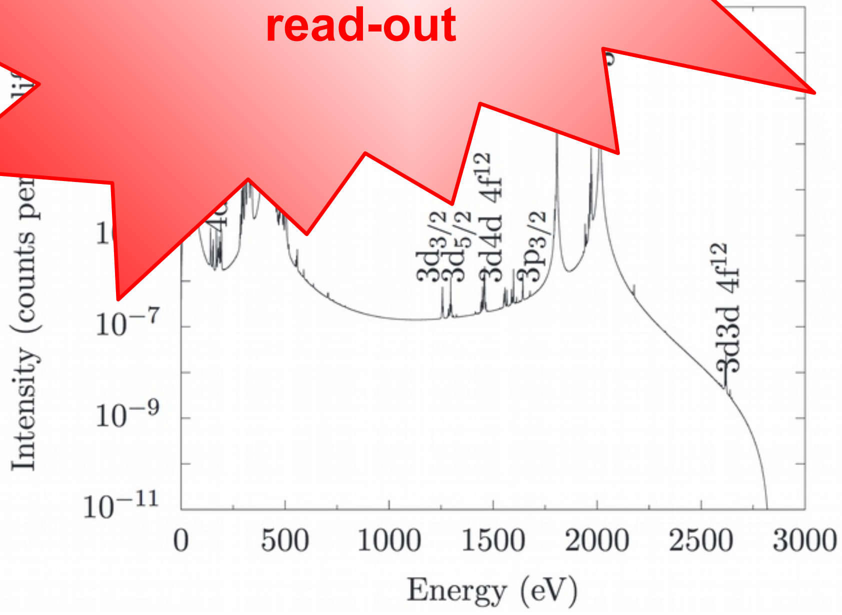

ECHo: *First measurement of 4 pixels for 4 days at LSM (L. Gastaldo, TAUP 2019):*

Q_{EC} = (2838 ± 14) eV

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

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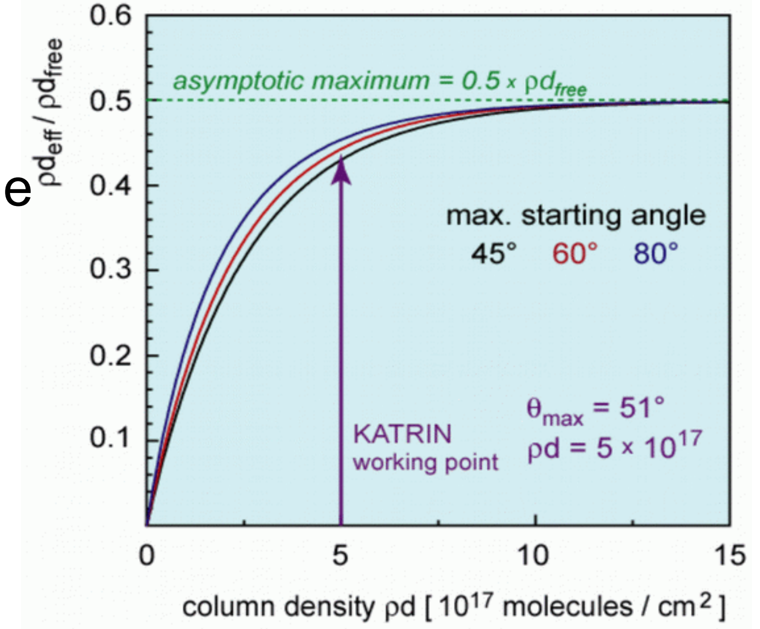

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c) hand-over energy information of b electron to other particle (radio photon), which can escape tritium source (Project 8)

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

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

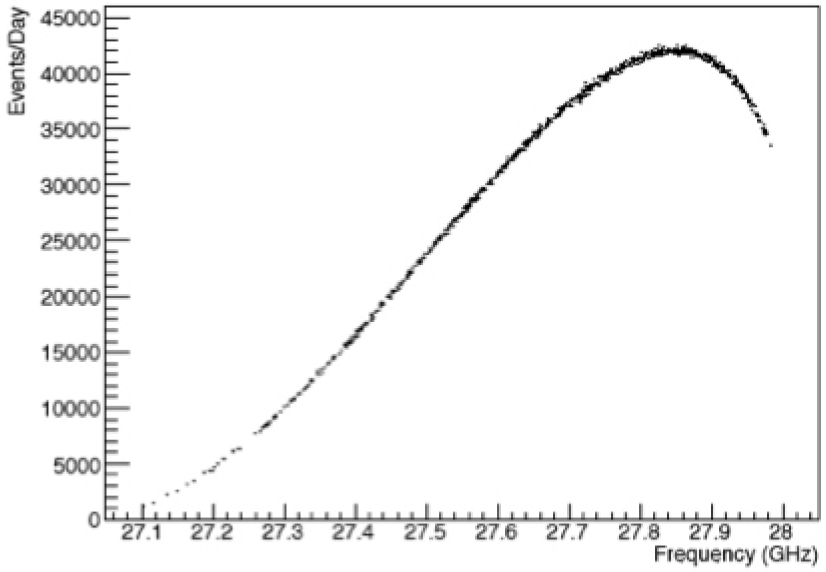
- Source = KATRIN tritium source technology :

uniform B field + low pressure T_2 gas

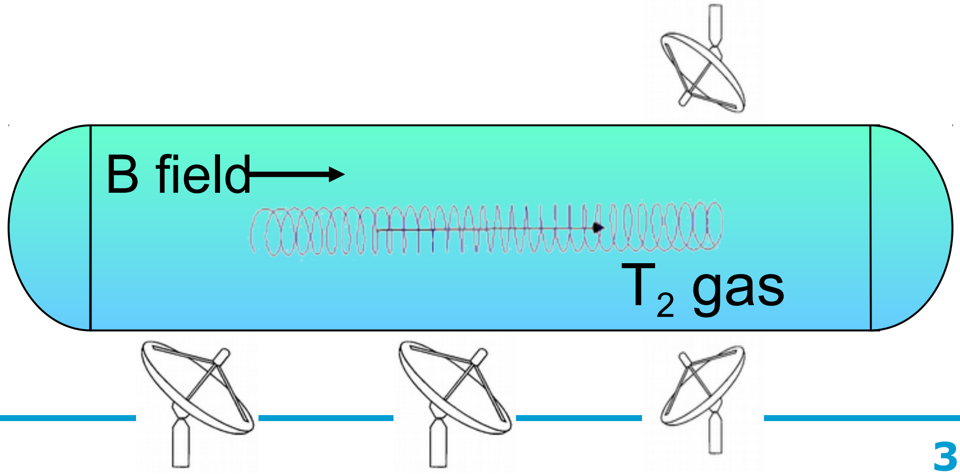
β electron radiates coherent cyclotron radiation

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

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

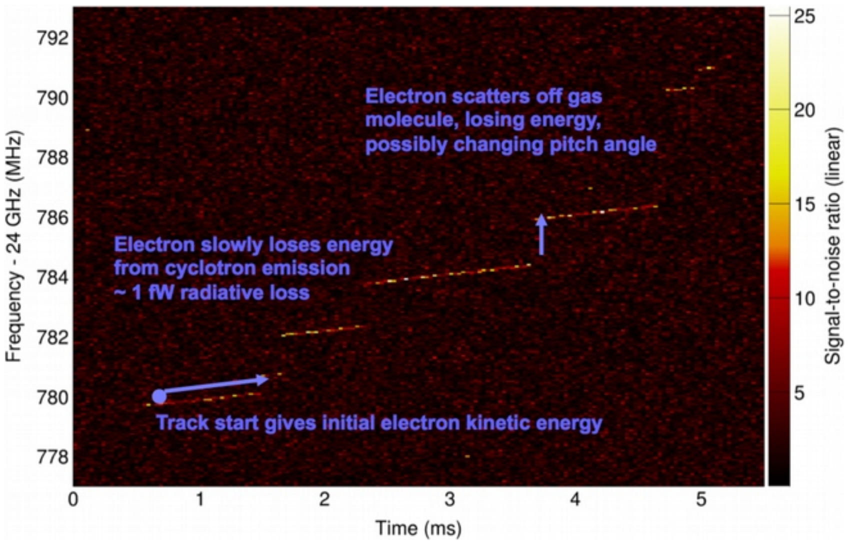


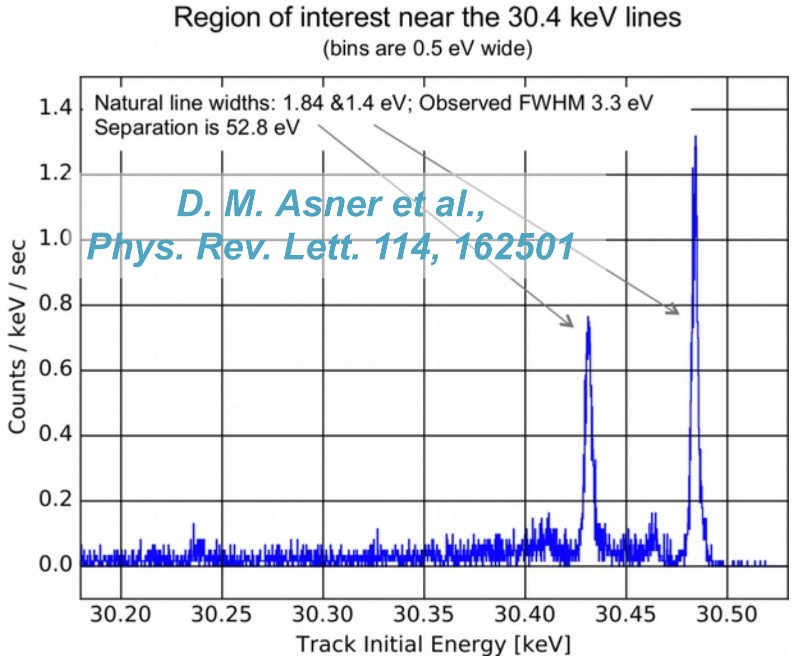
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and carries out the information of the β-electron energy



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

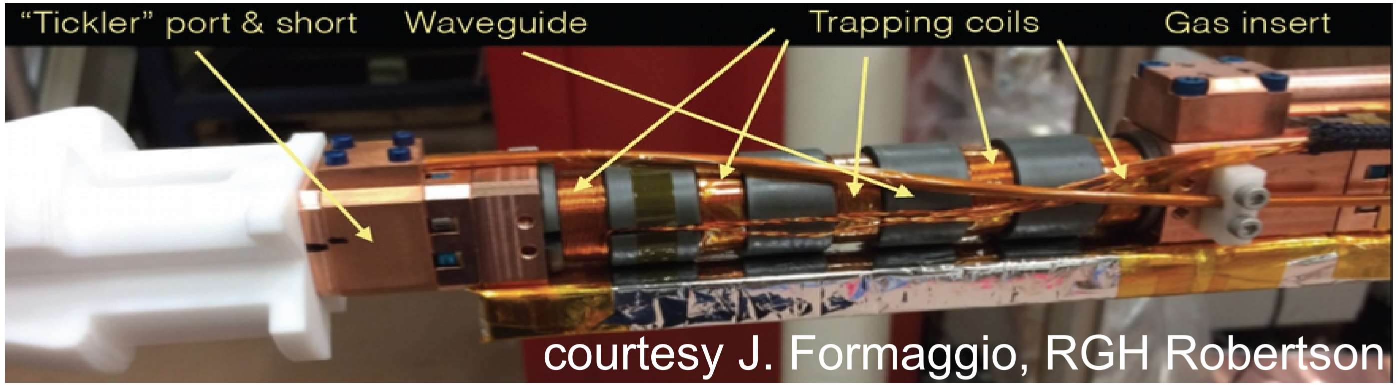
Phase I (^{83m}Kr)

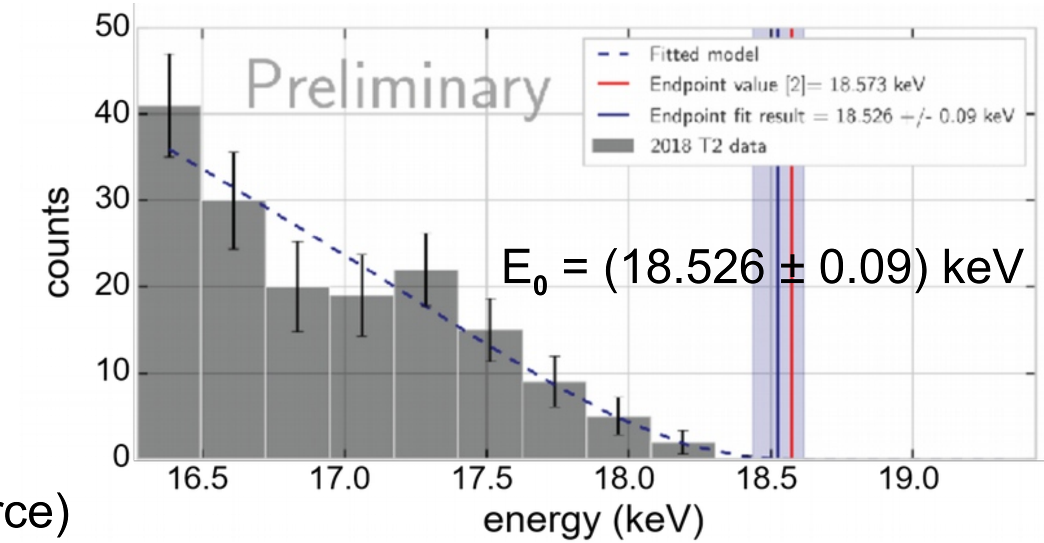




magnetic bottle to trap decay electrons long enough

Phase II (tritium test)





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

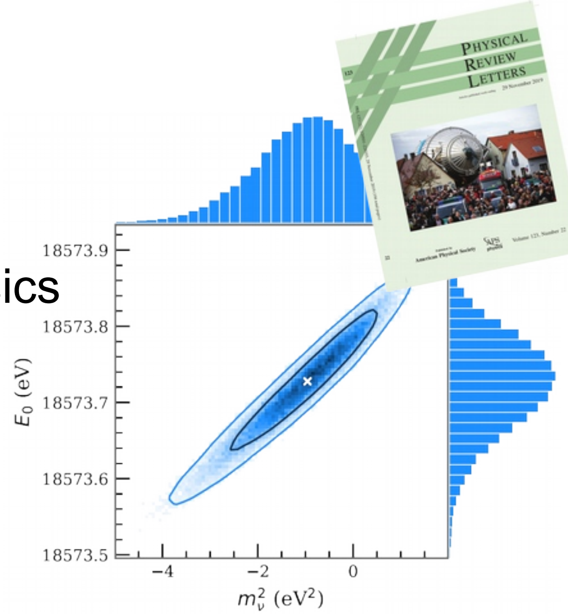
Conclusions

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 0νββ 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 currently performing science run 2 with higher statistics
- 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