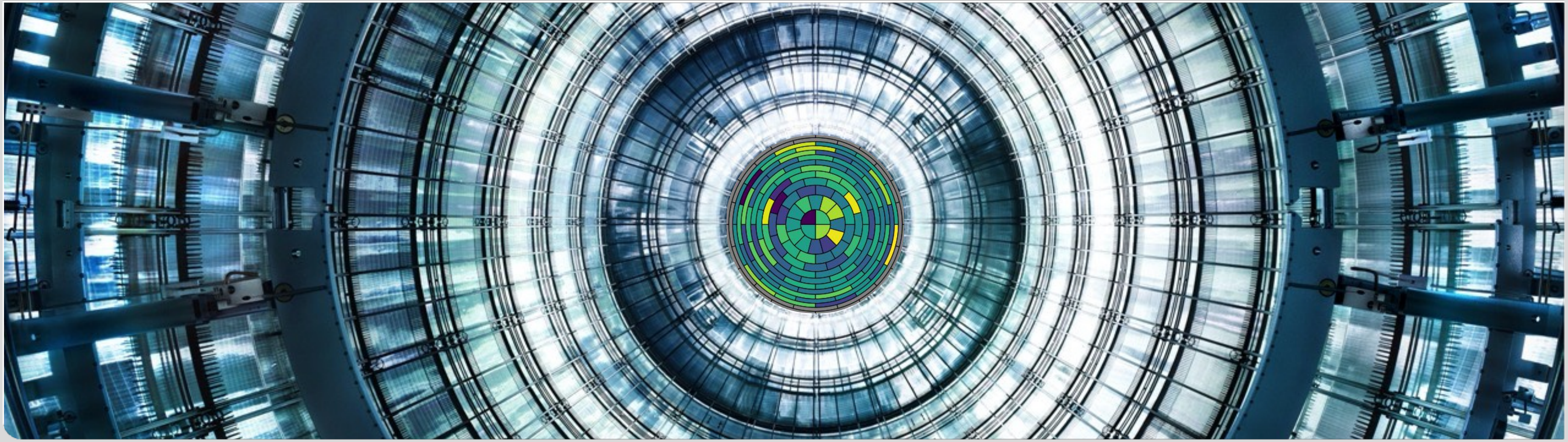
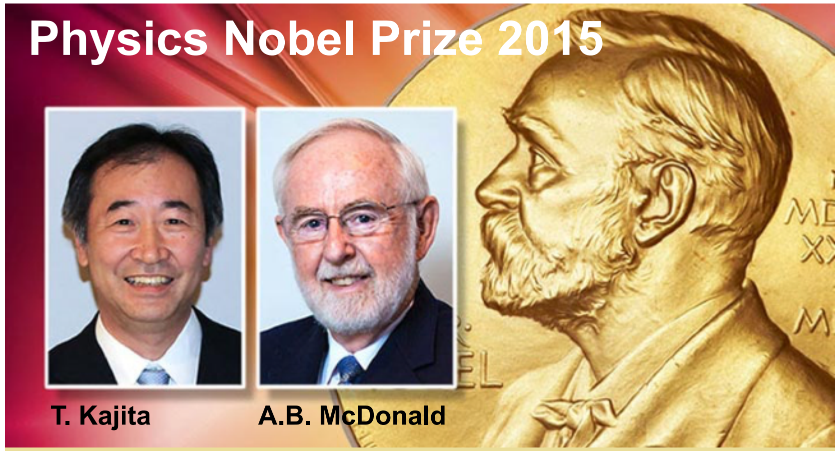
Probing the neutrino mass scale: first results from the KATRIN experiment

(Virtual) Particle Physics Seminar, Birmingham & Warwick
May 20th, 2020

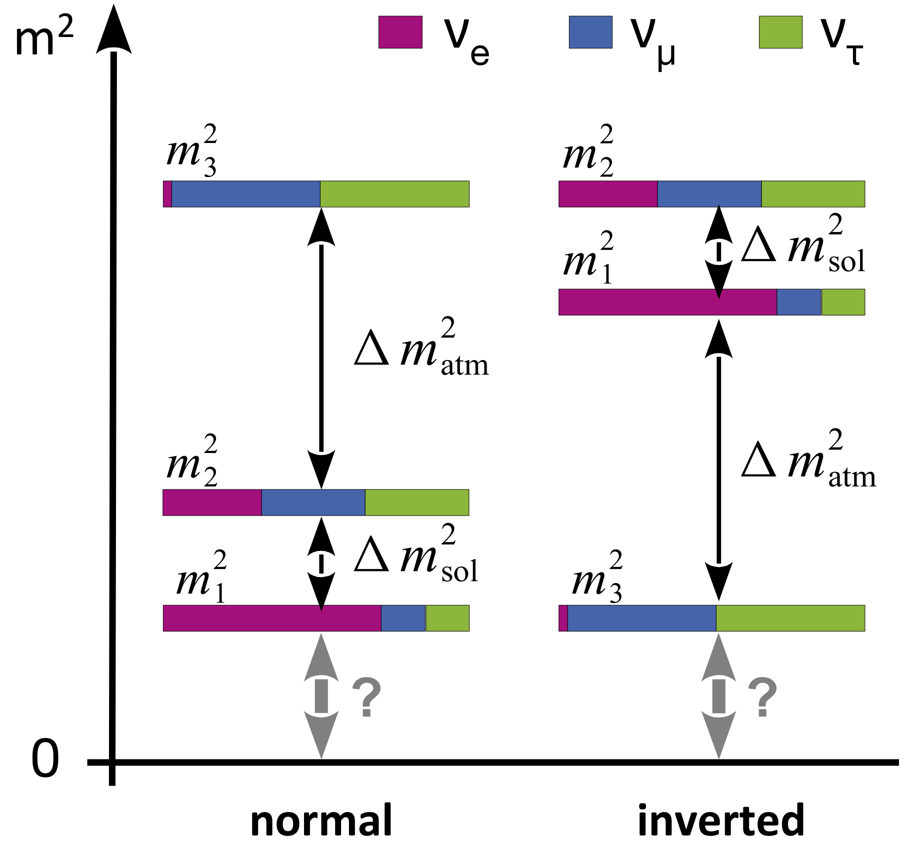
KATHRIN VALERIUS (KIT, Institute for Nuclear Physics)



Neutrino masses & flavour oscillations

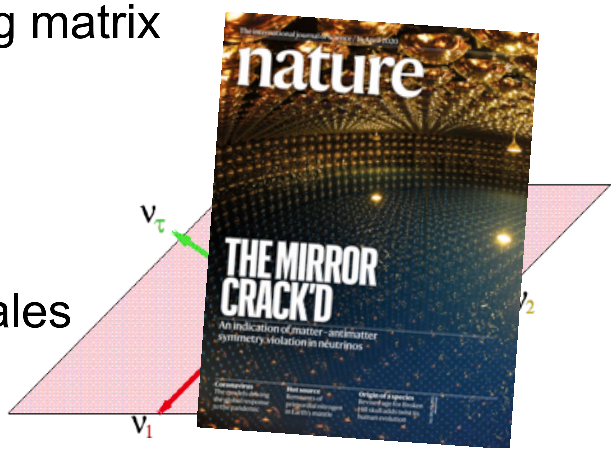


"for the discovery of neutrino oscillations, which show that neutrinos have mass"



➜ 3 flavour states and 3 mass states linked by unitary mixing matrix (analogous to CKM)

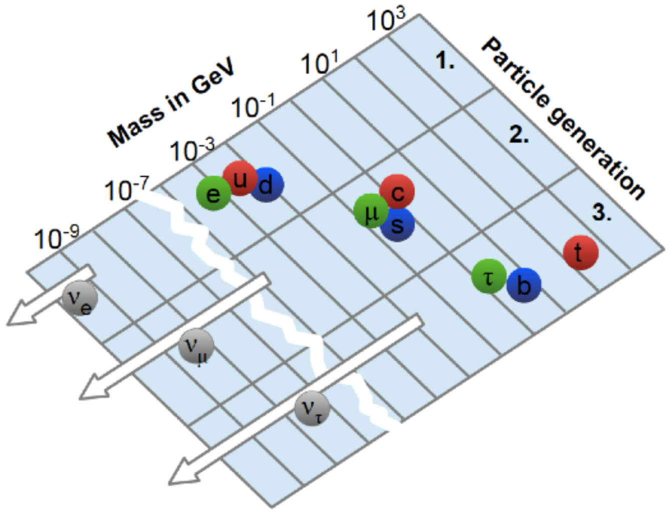
➜ 3 mixing angles θ_{ij},
1 CP phase δ,
2 independent Δm^2 scales

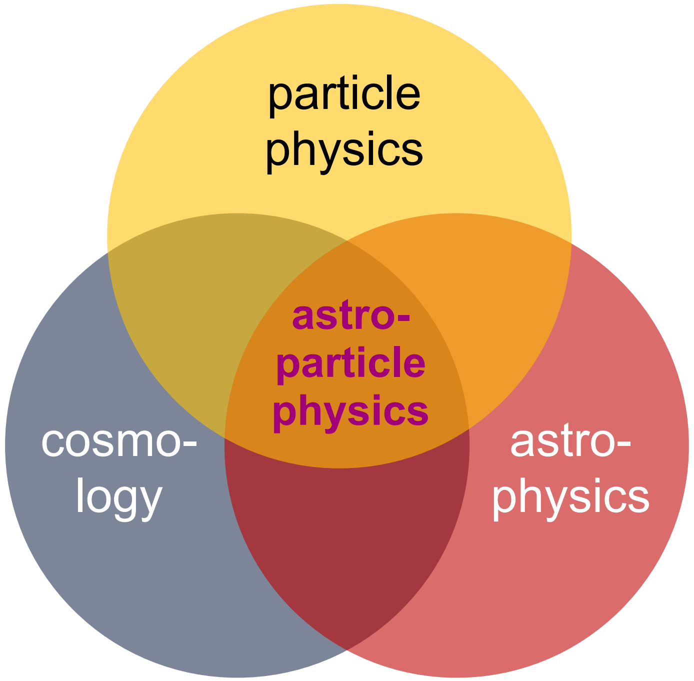


- Large neutrino mixing and tiny neutrino masses $m(\nu_i) \neq 0$ established
- Which mass ordering? CP violation?
- **What is the absolute ν mass scale?**

The role of massive neutrinos

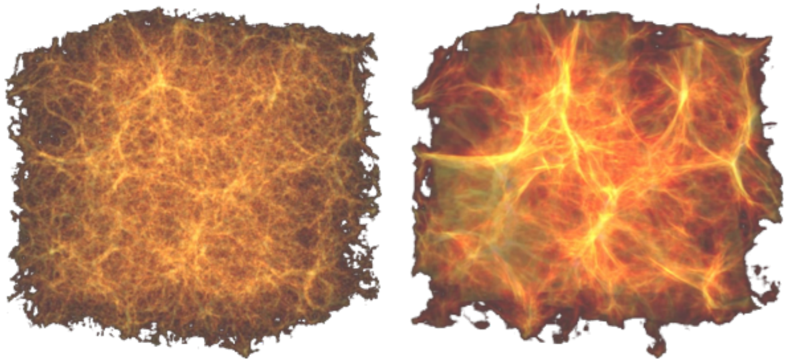
Mass generation: new concepts





Massive neutrinos as “cosmic architects”

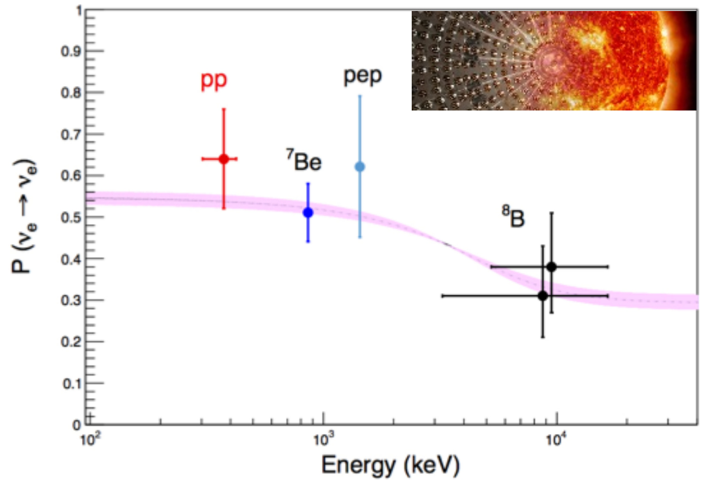
336 ν / cm³ in the Universe today



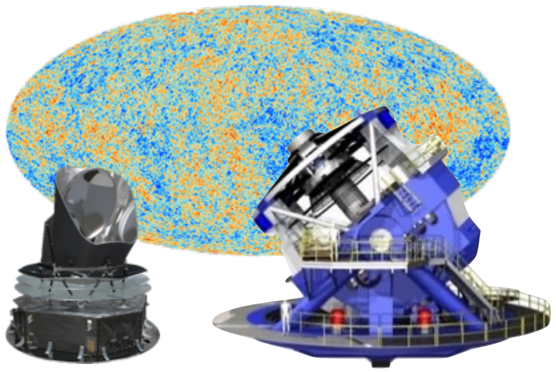
$m_\nu = 0$ $m_\nu > 0$

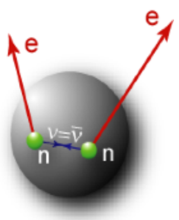
Understanding astrophysical processes

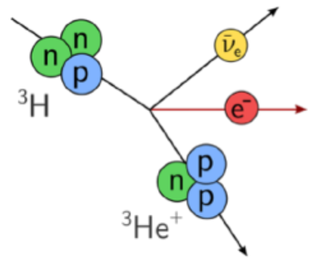
ν as probes of fusion in the sun

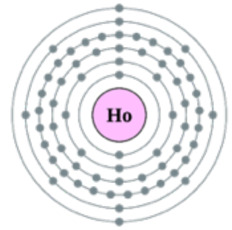


Complementary paths to the ν mass scale





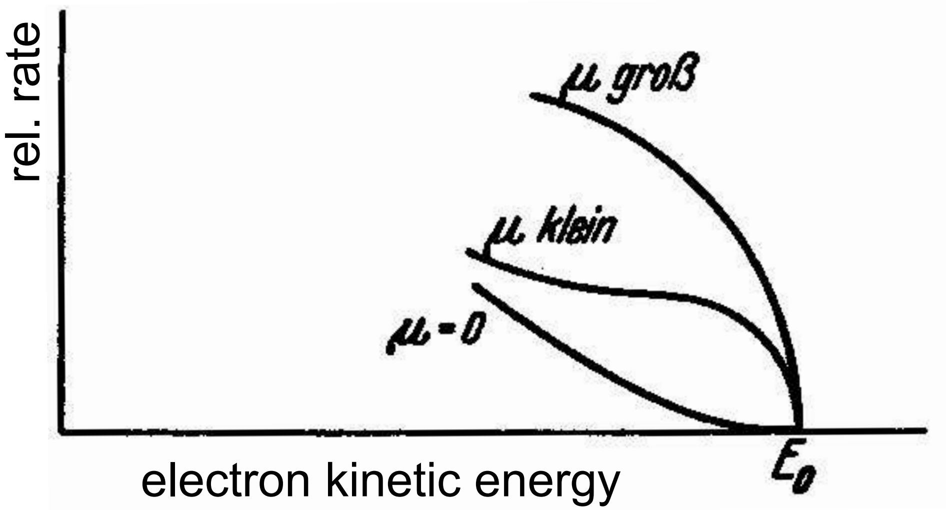


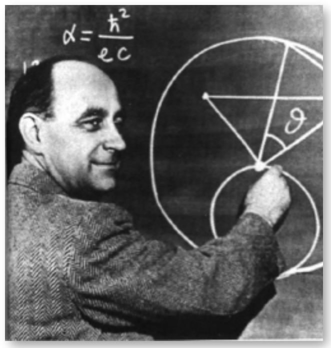


	Cosmology	Search for 0νββ	Kinematics of weak decays
Methods	CMBR, GRS, lensing, …	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$	$m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Model dependence	Multi-parameter cosmological model	- Majorana nature of ν, lepton number violation - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

Neutrino mass from β-decay kinematics

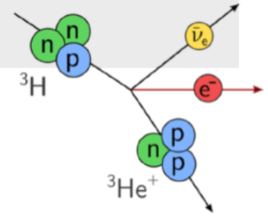
Theory: Starting from Fermi's seminal "attempt at a theory of β-rays"





Fermi, Z. Phys., 1934

Experiment: Tritium identified early on as most suitable β-emitter



NATURE August 21, 1948 Vol. 162

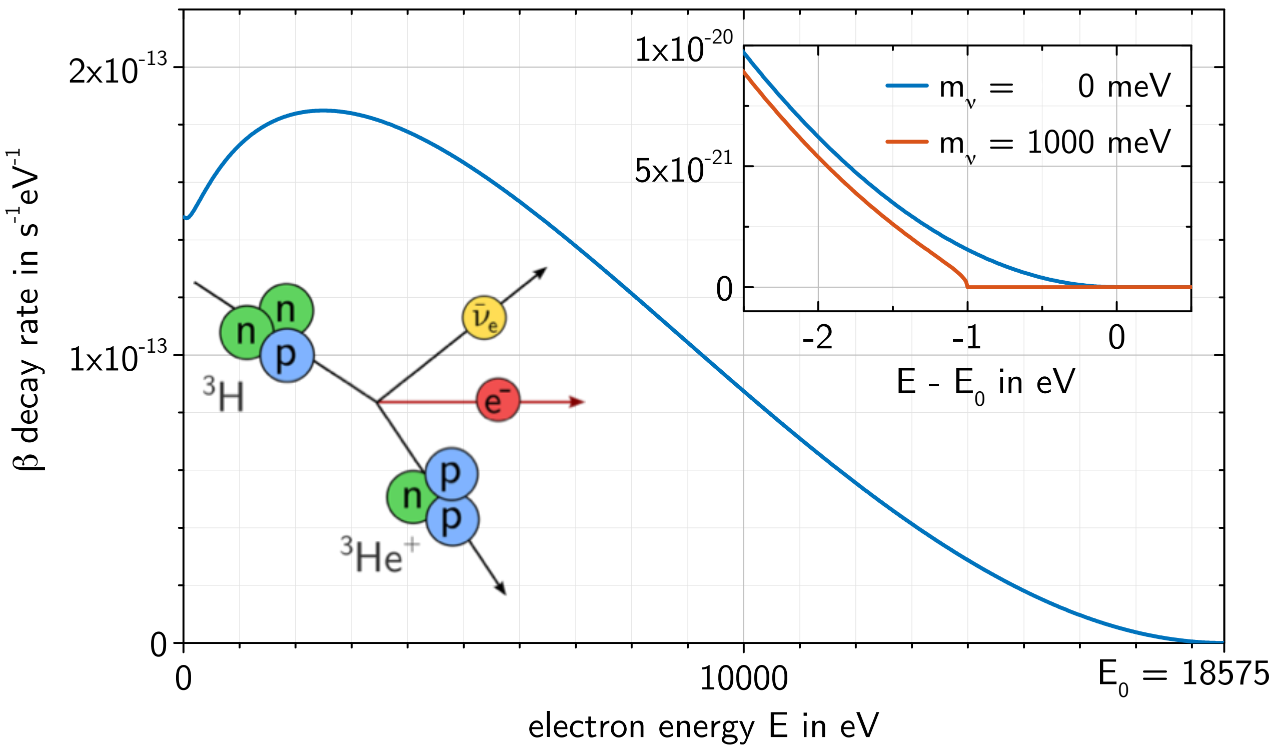
Beta Spectrum of Tritium

The β-spectrum of tritium ($_1H^3$) is of particular interest because: (1) the relatively simple structure of the $_1H^3$ nucleus makes it well suited to a test of the Fermi theory of β-decay; (2) the unusually low energy of the β-particles means that the shape of the spectrum near the upper limit is an extremely sensitive function of the rest mass of the neutrino if the Fermi theory is confirmed; (3) a theoretical discrepancy[1] exists between the half-life[2] and the upper energy limit, as recently measured[3]; (4) the mass difference ($_1H^3$ — $_2He^3$) can be accurately determined.

Curran *et al.*

Neutrino mass from β-decay kinematics

$$\frac{d\Gamma}{dE} = K \cdot F(Z,E) \cdot \underbrace{p}_{p_e} \cdot \underbrace{E_{tot}}_{E_e} \cdot \underbrace{(E_0 - E)}_{E_\nu} \cdot \underbrace{\sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}}_{p_\nu}$$



Spectral distortion measures **"effective" mass square:**

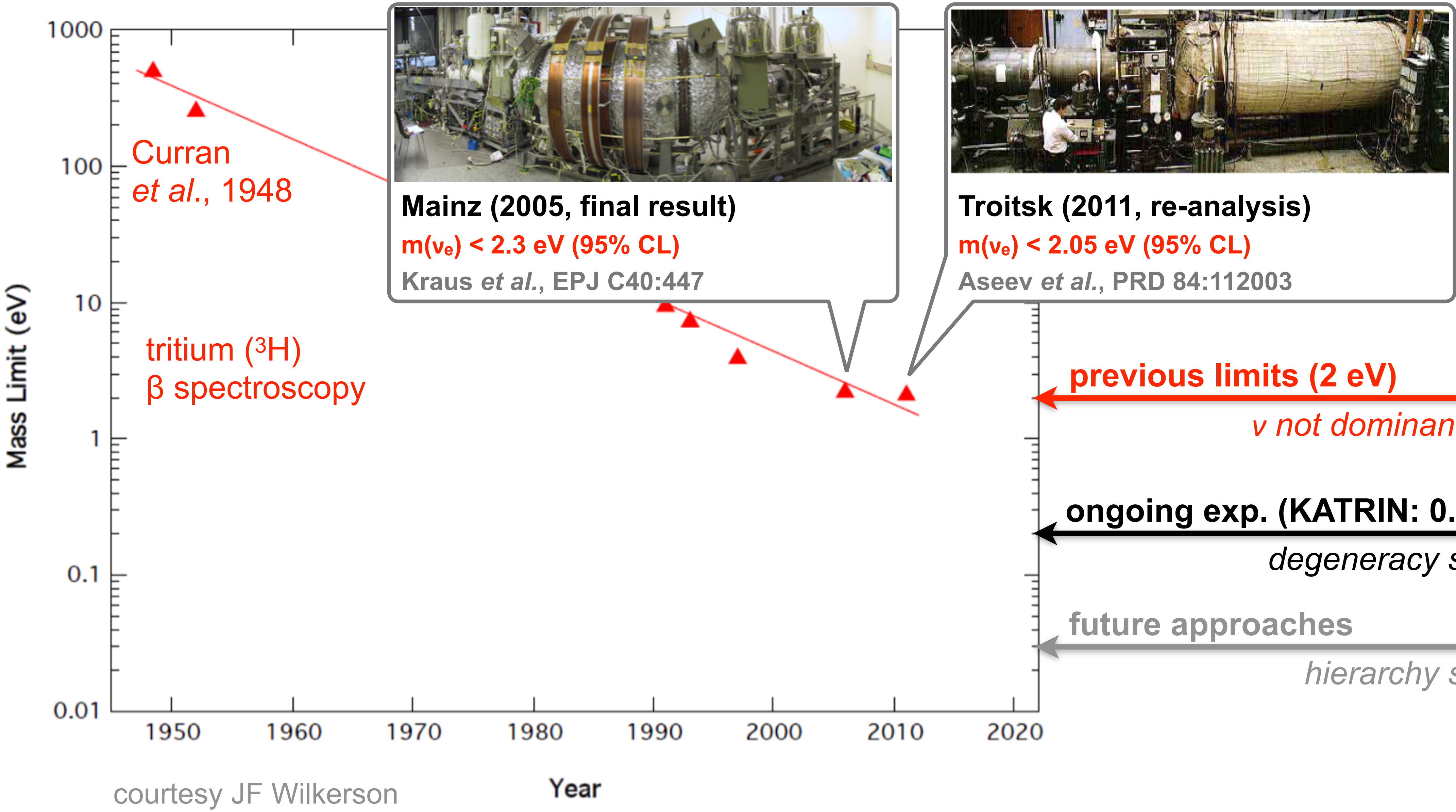
$$m^2(\nu_e) := \sum_i |U_{ei}|^2 m_i^2$$

Key requirements:

- Low endpoint energy: E_0 = 18.6 keV for ^3H
- High-activity source: $T_{1/2}$ = 12.3 yr for ^3H
- Energy resolution ~ 1 eV

Kinematic measurement can probe for **heavier ν states** ➜ eV- and keV-scale sterile ν

Neutrino mass from β-decay kinematics



courtesy JF Wilkerson

Mainz (2005, final result)
$m(\nu_e) < 2.3$ eV (95% CL)
Kraus *et al.*, EPJ C40:447

Troitsk (2011, re-analysis)
$m(\nu_e) < 2.05$ eV (95% CL)
Aseev *et al.*, PRD 84:112003

previous limits (2 eV)
ν not dominant DM

ongoing exp. (KATRIN: 0.2 eV)
degeneracy scale

future approaches
hierarchy scale

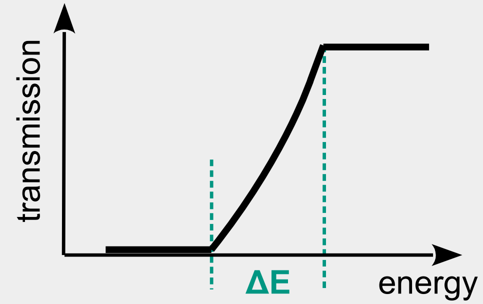
High-resolution spectrometer: MAC-E filter

Magnetic Adiabatic Collimation & Electrostatic Filter

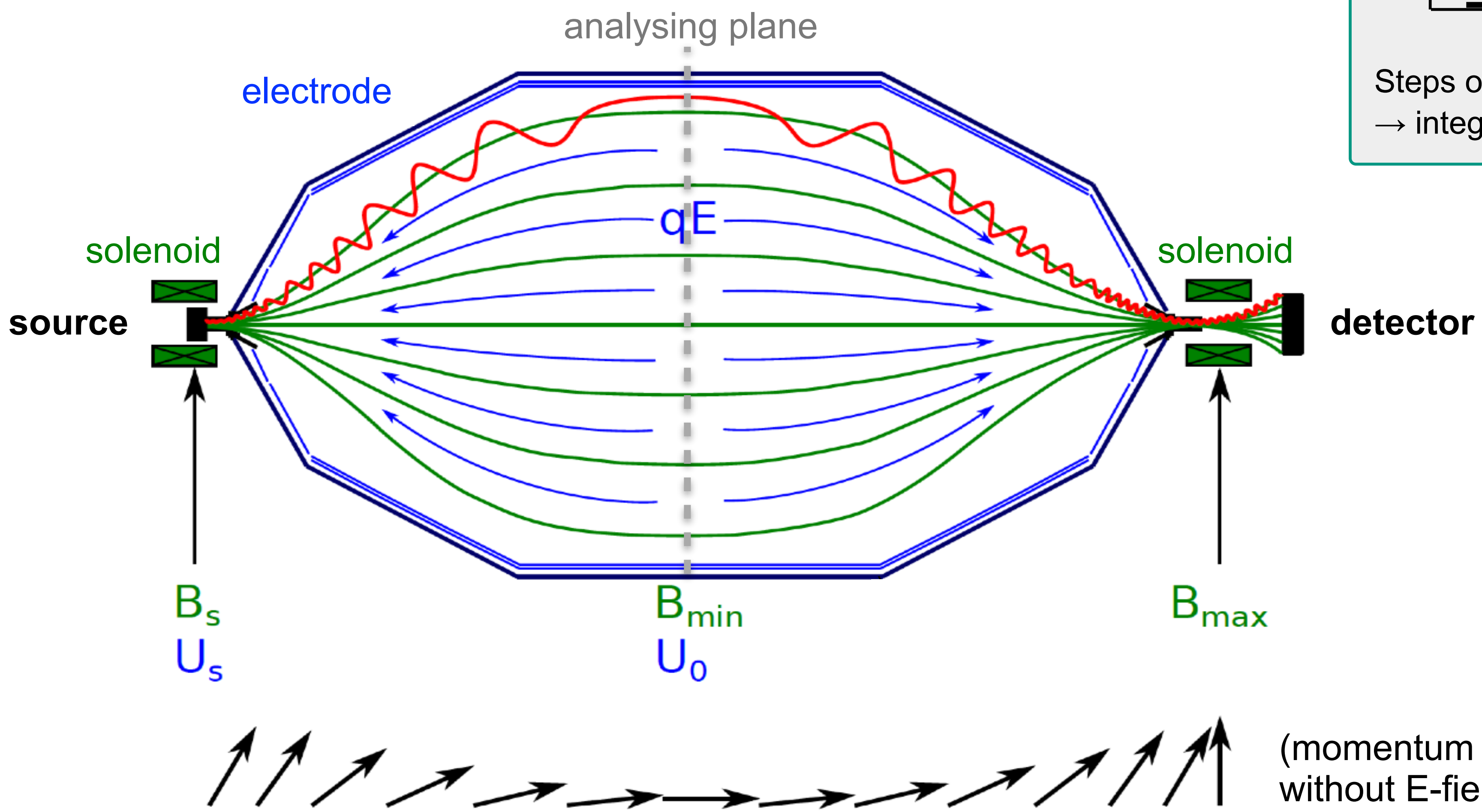
- ➜ integrating electrostatic filter ($E_{kin} > eU_0$)
- ➜ "clean" (analytic) response function

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum



(momentum transformation
without E-field)

[Beamson *et al.* 1980; Kruit & Read 1983; **Lobashev 1985; Picard *et al.* 1992**]

The Karlsruhe Tritium Neutrino Experiment

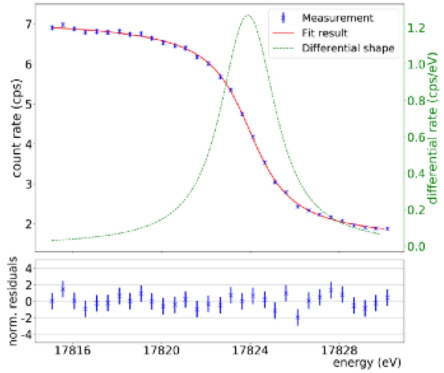
- Experimental site:
  Karlsruhe Institute of Technology (KIT)
- International collaboration:
  ~150 members from 20 institutions
  in 6 countries (D, US, CZ, RU, F, ES)
- Goal: Improve sensitivity on m(ν_e) from 2 eV (present)
  to 0.2 eV (90% C.L.) within 2019-2024

katrin.kit.edu

KATRIN timeline: the first 18 years

Letter of Intent

Main spectrometer

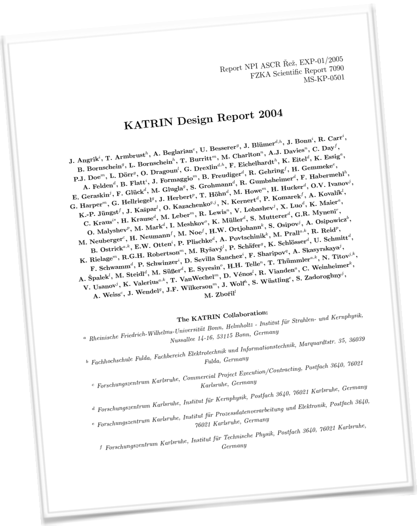


Calibration
& systematics

First neutrino mass

2001	2004	2006	2016	2017	2018	2019

Design Report

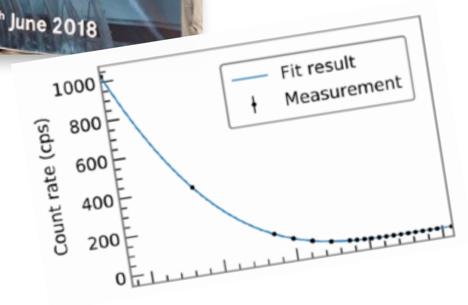

Report NPI ASCR Řež, EXP-01/2005
FZKA Scientific Report 7090
MS-KP-0501

KATRIN Design Report 2004

The KATRIN Collaboration:

First Light

First Tritium



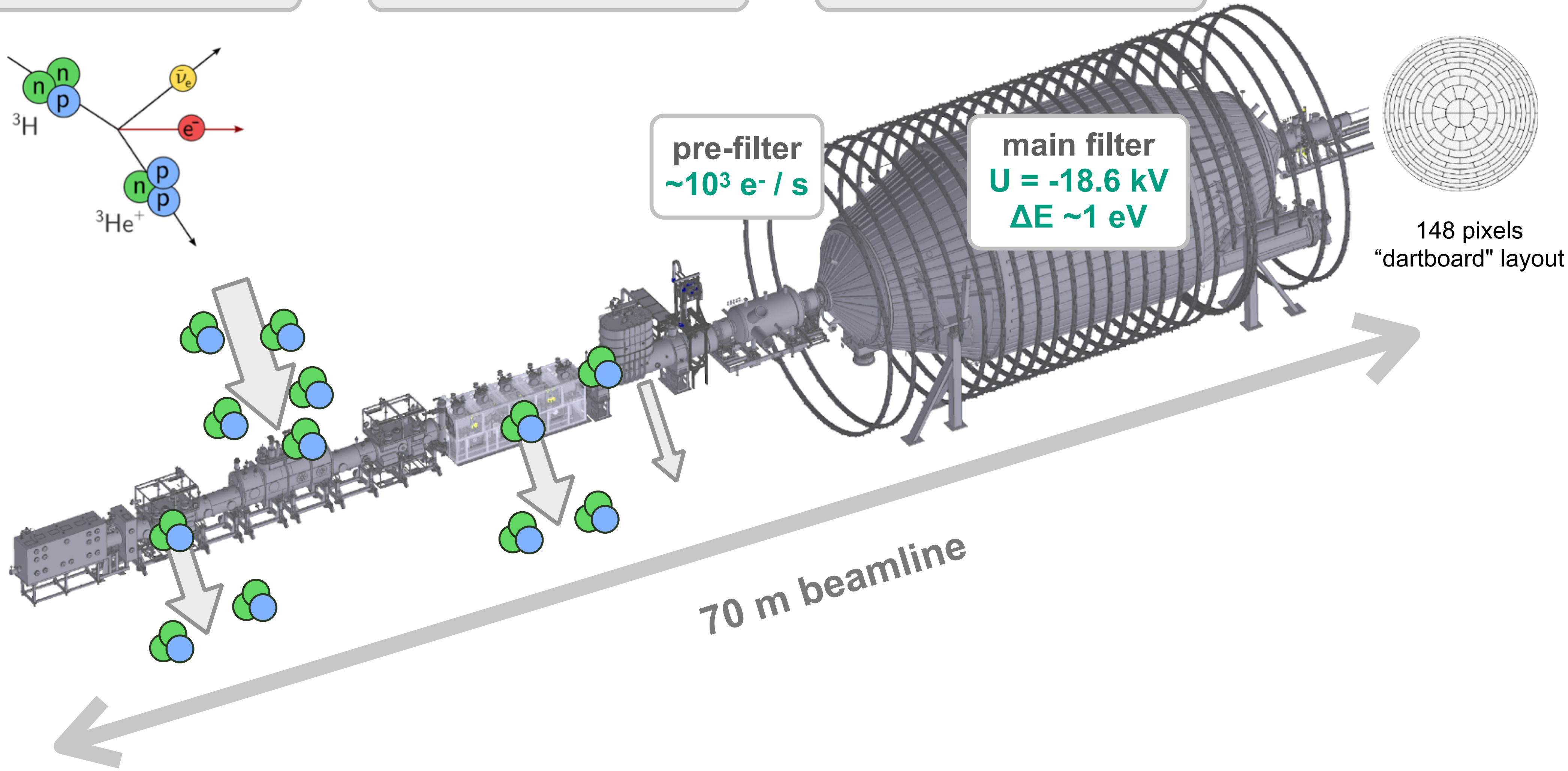
Working principle of KATRIN

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

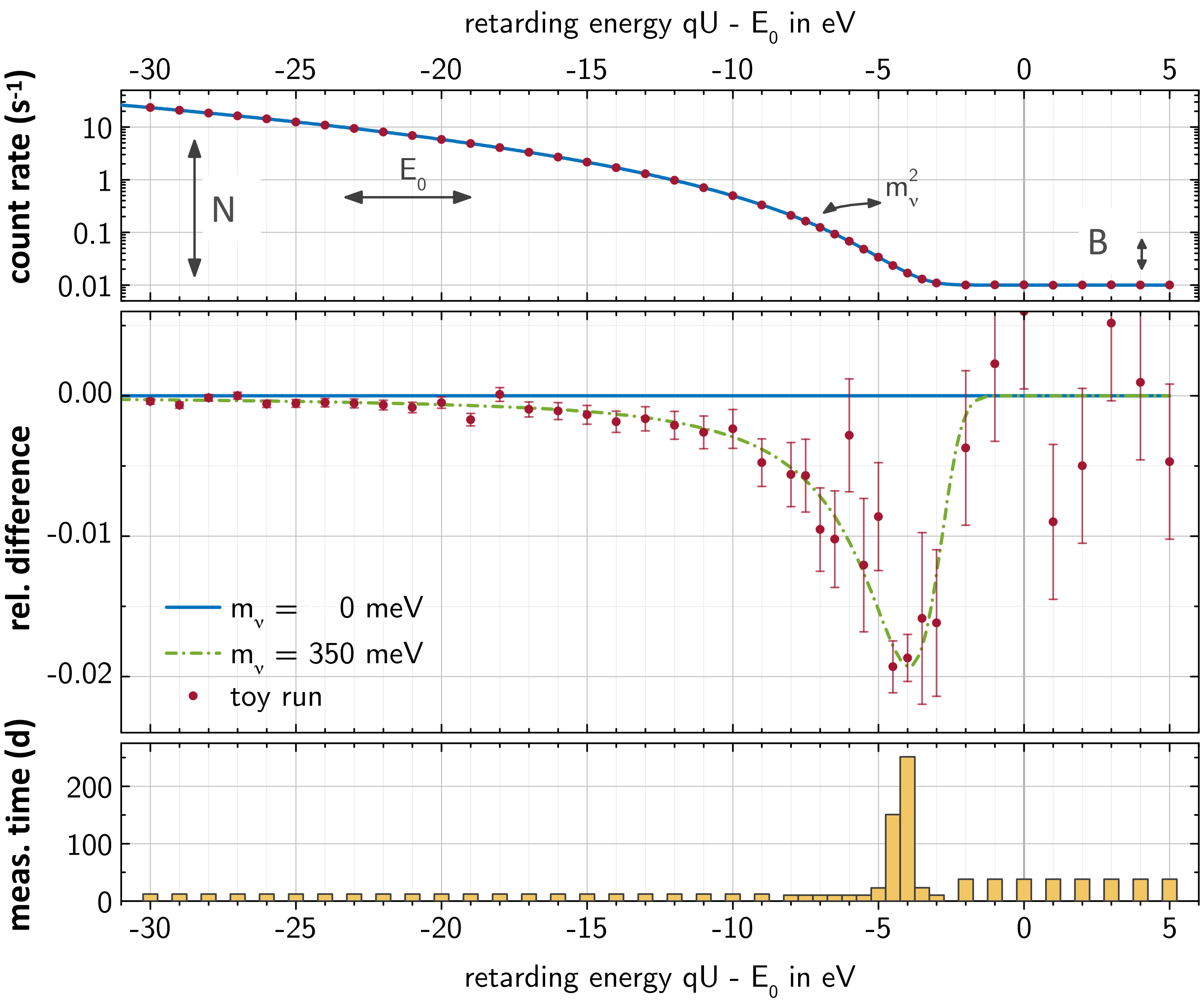
tritium pumping & e^- transport
T_2 flow reduction $>10^{14}$

high-pass energy filters
MAC-E filter

counting detector
< 1 e^- / s

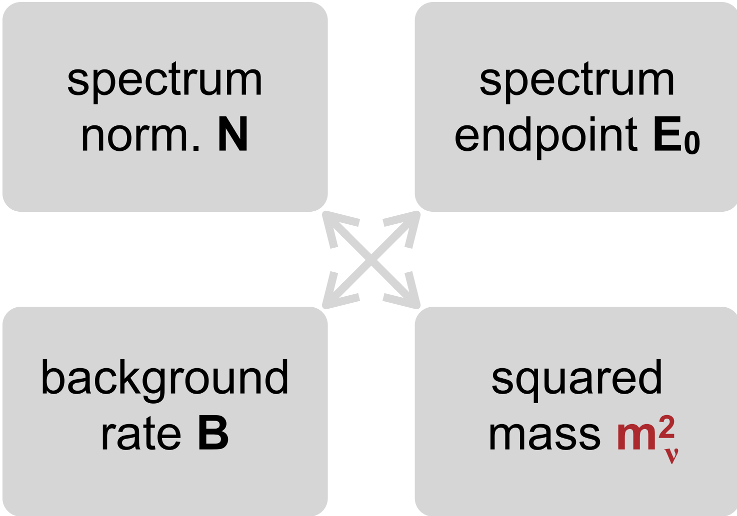


Measurement principle of KATRIN



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

Four fit parameters:



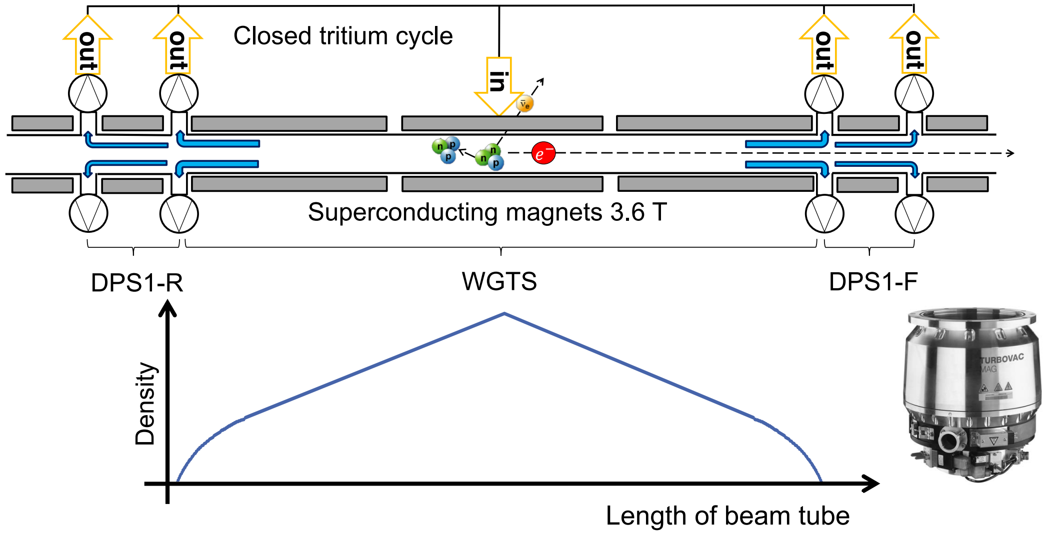
~10^{-9} of all β-decays in scan region ~40 eV below endpoint

High-intensity tritium source

Gaseous molecular tritium source of

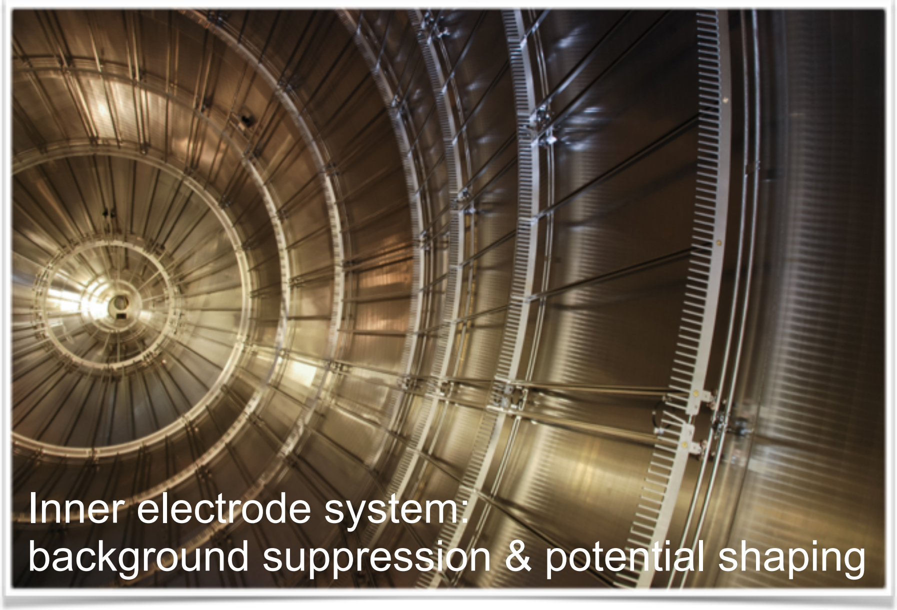
- high activity (~100 GBq)
- high isotopic purity (ε_T > 95%)
- high gas column stability (0.1%)

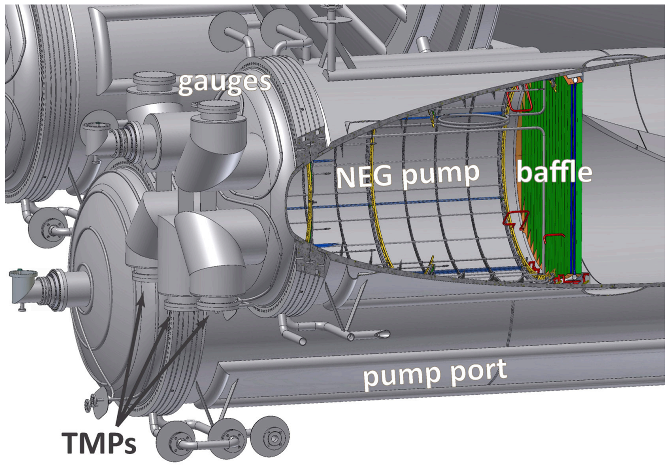
  $n \sim \varepsilon_T \cdot p \cdot V / (R \cdot T)$



- closed tritium loops: ~100 m of piping
- instrumentation: > 800 sensors and valves

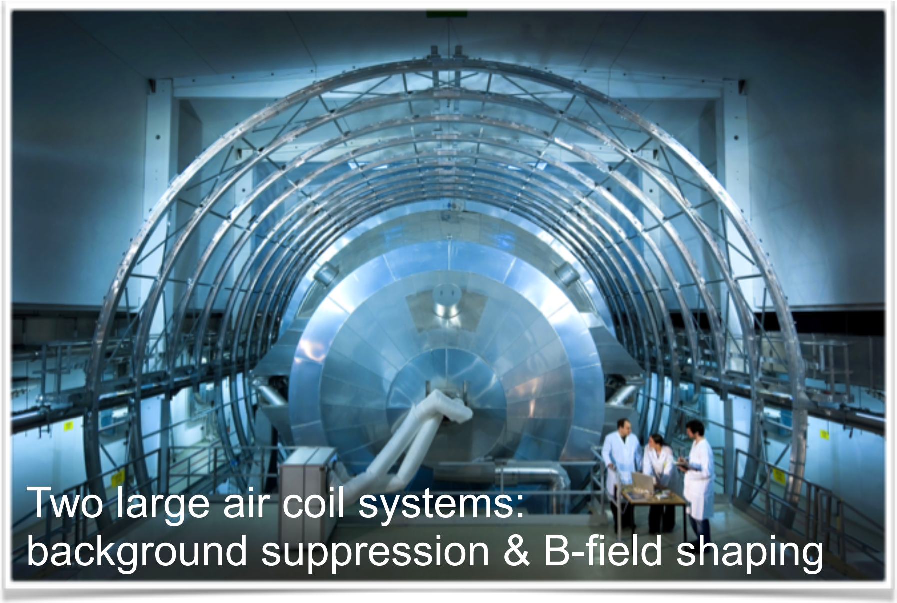
High-resolution spectrometer





UHV system for large recipient (~1240 m^3)

Large NEG pumps to reach $p \sim 10^{-11}$mbar and LN_2-cooled baffles for radon trapping

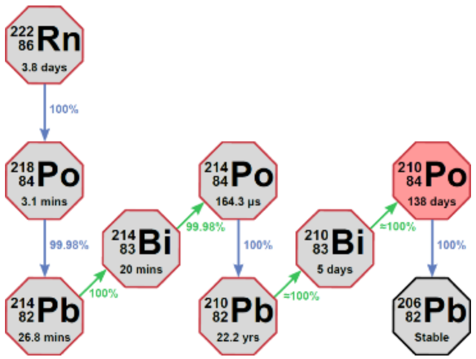


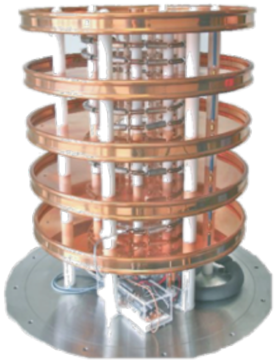
Key challenges of KATRIN

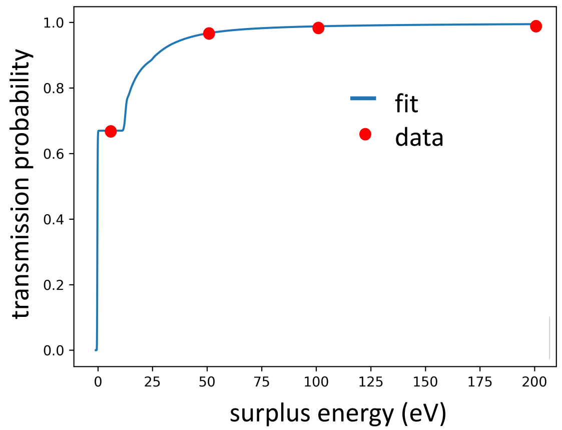
low background

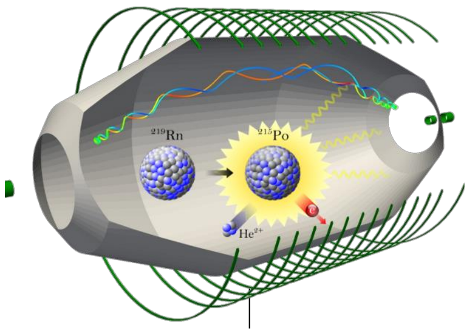
resolution and stability of energy scale

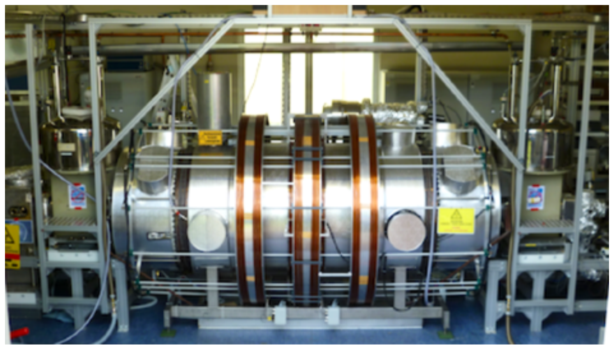
ultra-stable and pure gaseous source

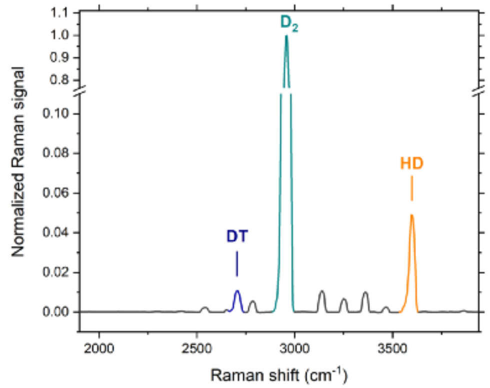






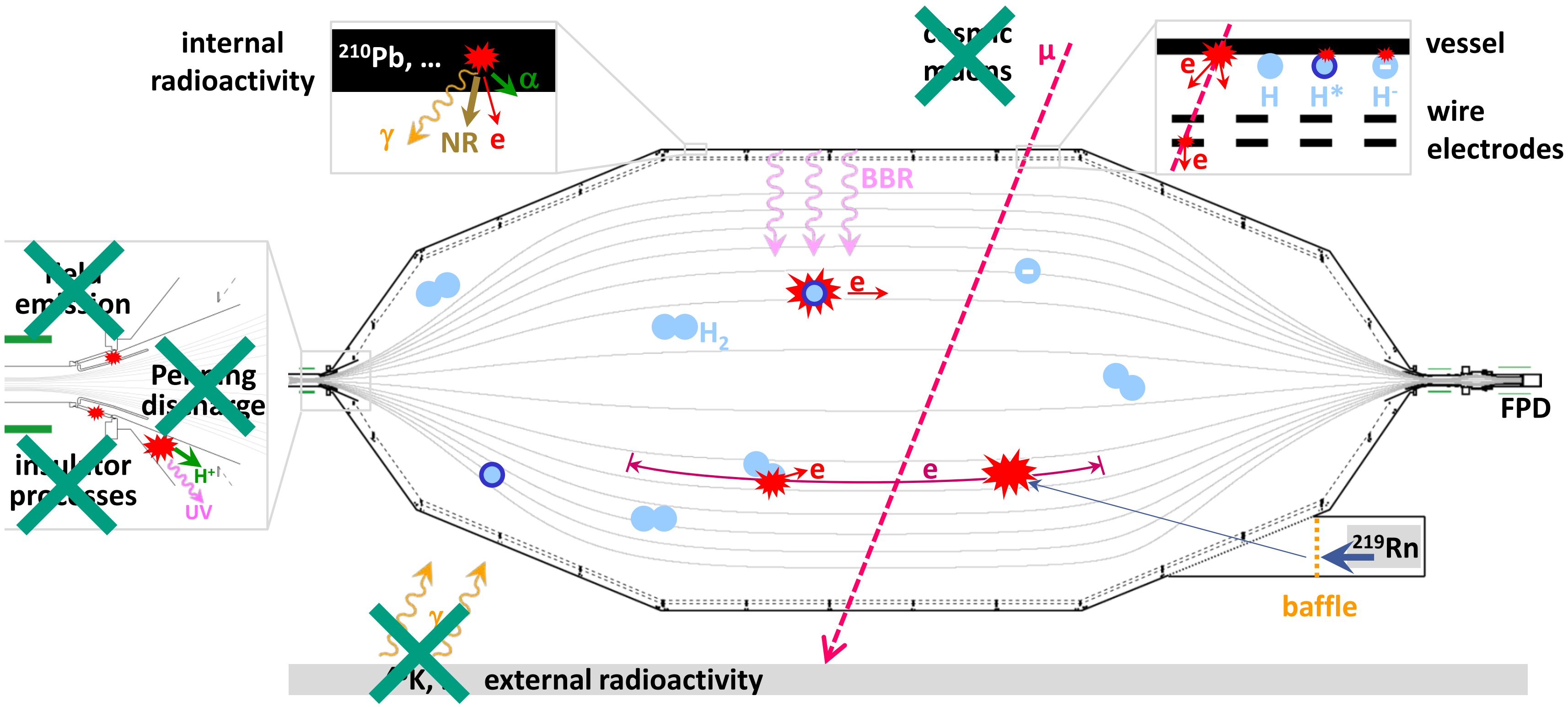






… how can we test these unique properties?

Background: charged particles



observed background rate: **0 cps**

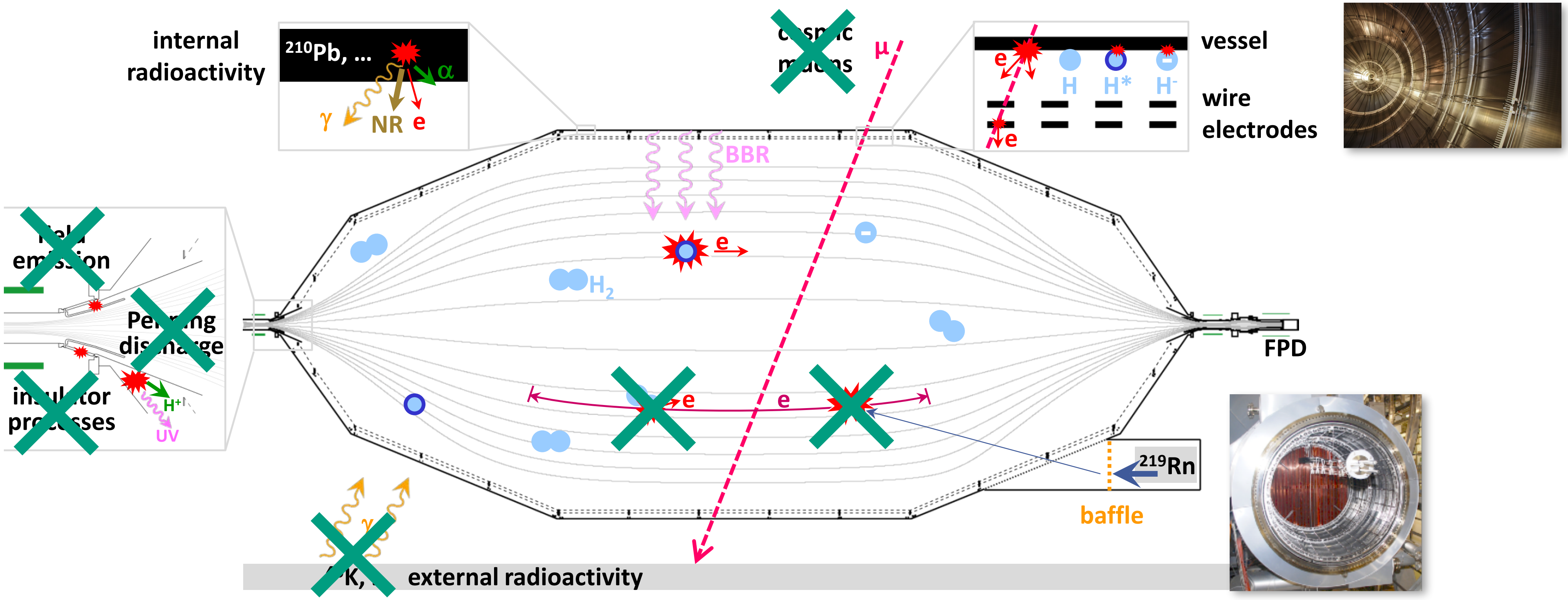
High-field region: fine-shaping of electrodes, active countermeasures (“wipers”)

- Beck *et al.*, EPJ A44 (2010) 499
- Fränkle *et al.*, JINST 9 (2014) P07028
- KATRIN Coll., arXiv:1911.09633

Charged particles from the surface: effective magnetic and electrostatic shielding

- muon-induced:
  KATRIN Coll., Astropart. Phys. 108 (2019) 40
- gamma-induced:
  KATRIN Coll., EPJ C79 (2019) 807

Background: neutral particles



Effective reduction of **radon-induced** background via nitrogen-cooled baffle system

- Görhardt *et al.*, JINST 13 (2018) T10004
- Mertens *et al.*, Astropart. Phys. 41 (2013) 52
- Wandkowsky *et al.*, J. Phys. G 40 (2013) 085102

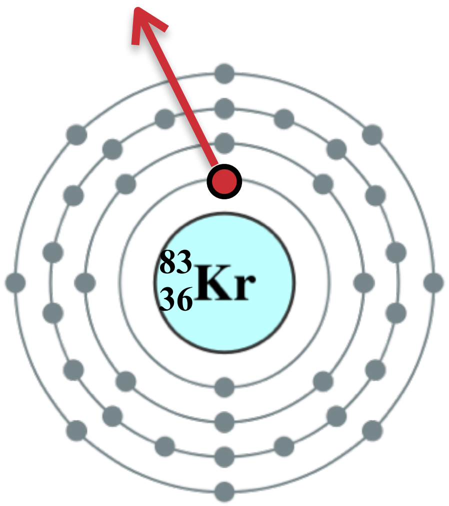
Rydberg atoms

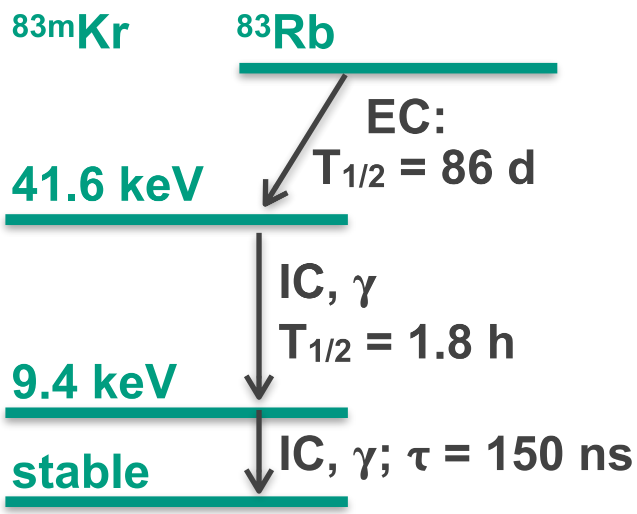
- neutrals liberated from walls after recoil from α-decay of ^{210}Po
- ionised by black-body radiation (291 K)
- mitigation by improving surface cond. (baking) and fiducialization of flux tube volume

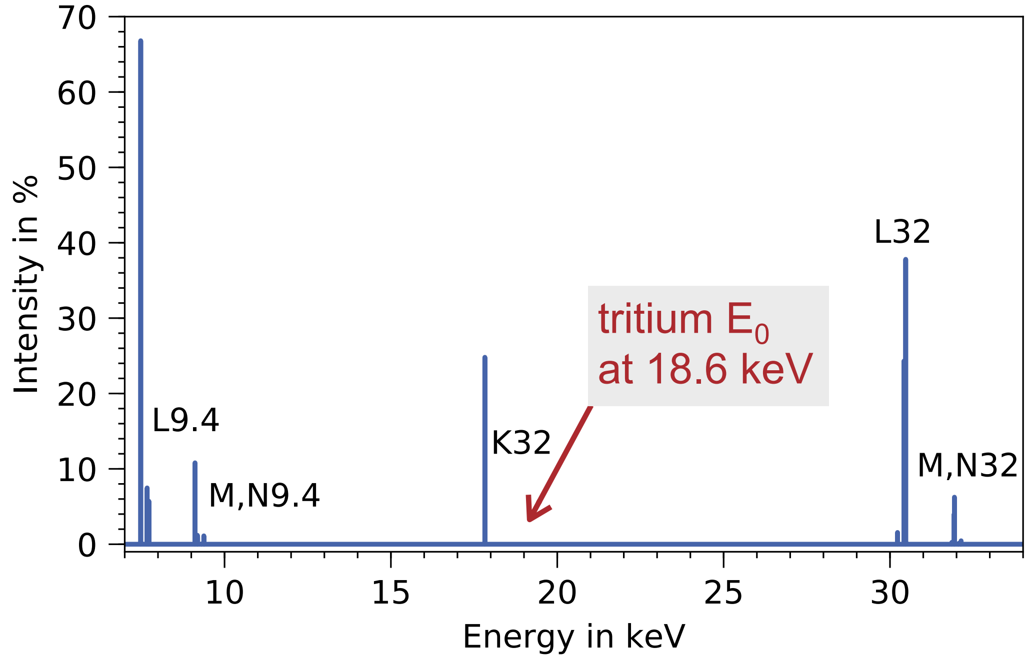
current background rate: **0.2 cps**

Precision calibration sources (1): Krypton

- Nuclear/atomic standard widely used in neutrino and dark matter experiments
- Short half-life eliminates risk of contamination
- Mono-energetic (< 3 eV) conversion electrons, isotropic angular distribution
- Convenient range of line energies



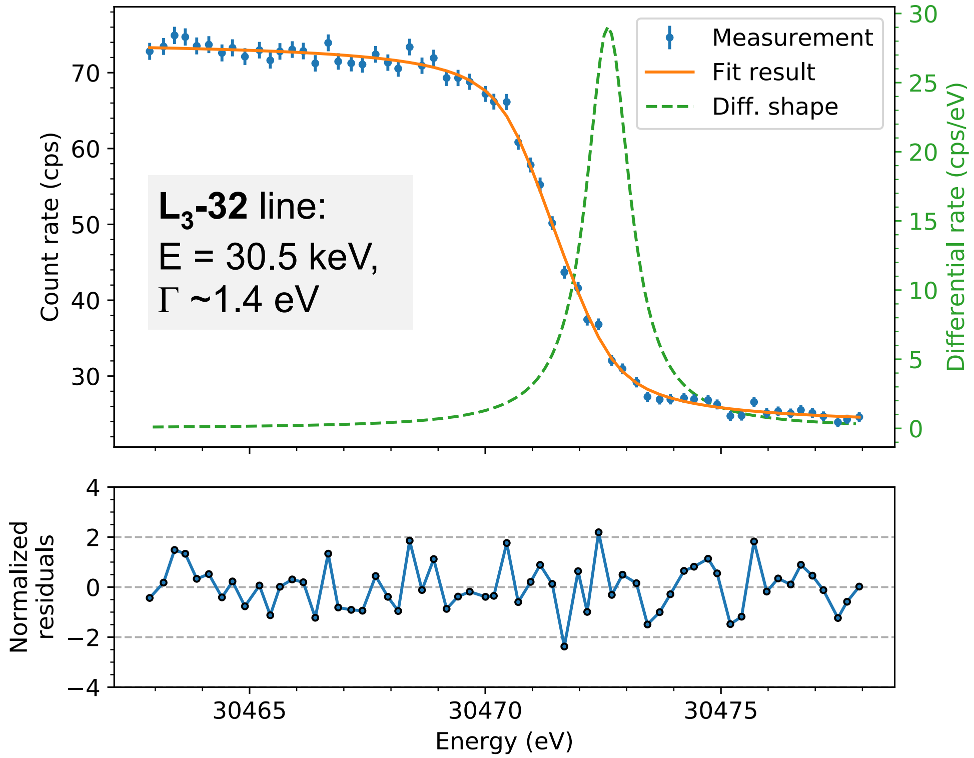


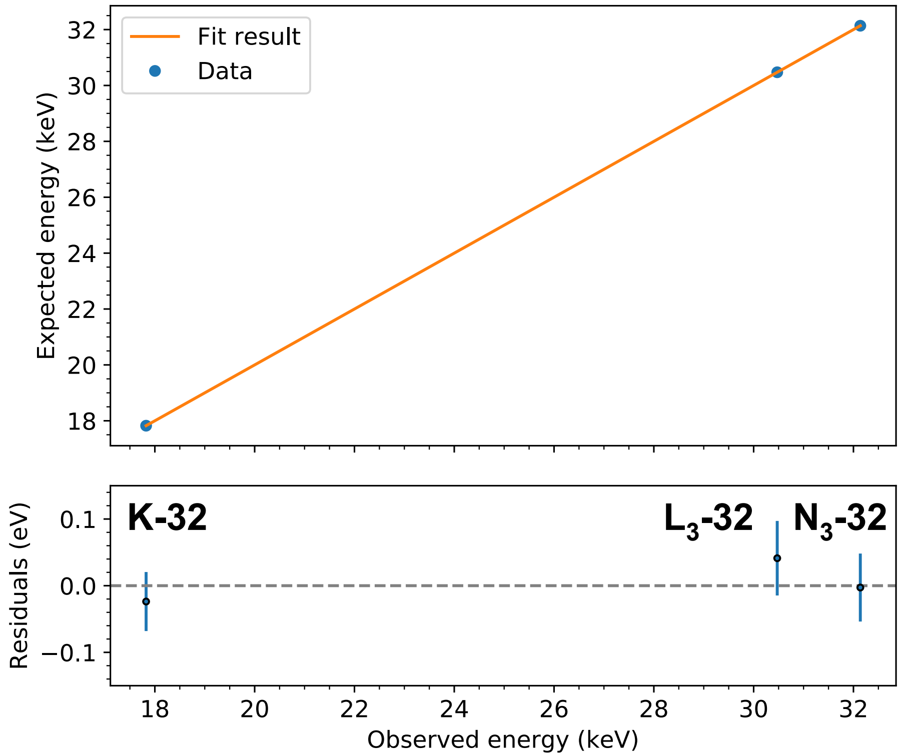


- System characterisation: transmission of MAC-E filter, detector properties, system alignment, absolute energy scale calibration, …

[JINST 13 (2018) T02012 & P04018, and further works]

Precision and linearity traced with ^{83m}Kr





- ✓ Spectrometer resolution of ~1 eV at 18 keV
- ✓ Excellent linearity of the energy scale [JINST 13 (2018) P04018; arXiv:1903.066452]
- ✓ HV calibration on the ppm level based on relative line positions [EPJ C 78 (2018) 368]
- ✓ ^{83m}**Kr** in empty beam tube, in D_2 and **in T_2 to characterise gaseous source**

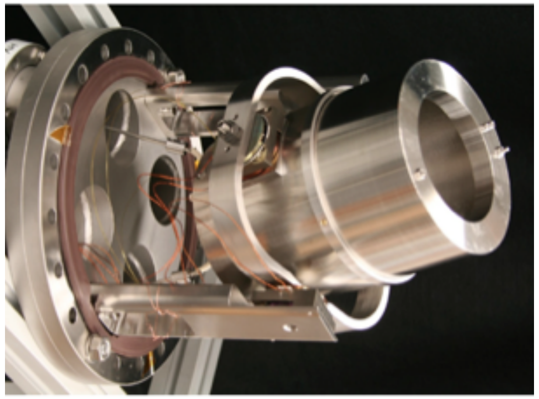
Precision calibration sources (2): e-gun

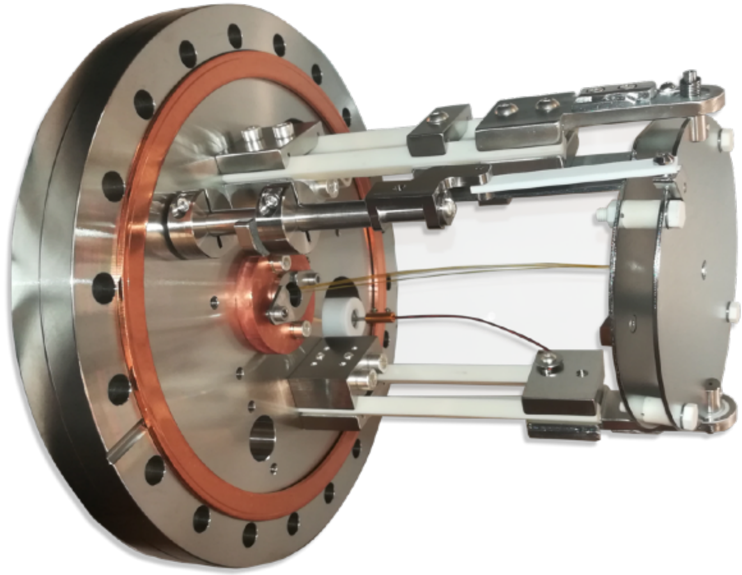
Requirements

- Tunable energy and narrow spread
- Tunable emission angle ➜ ratio $E_{||}/E_{cyc}$
- x/y beam steering over indiv. pixels
- Pulsed emission for time of flight

Custom-made solution

- UV optics for photoelectron creation
- Beam forming in staged E & B fields
- Timing by pulsed UV laser

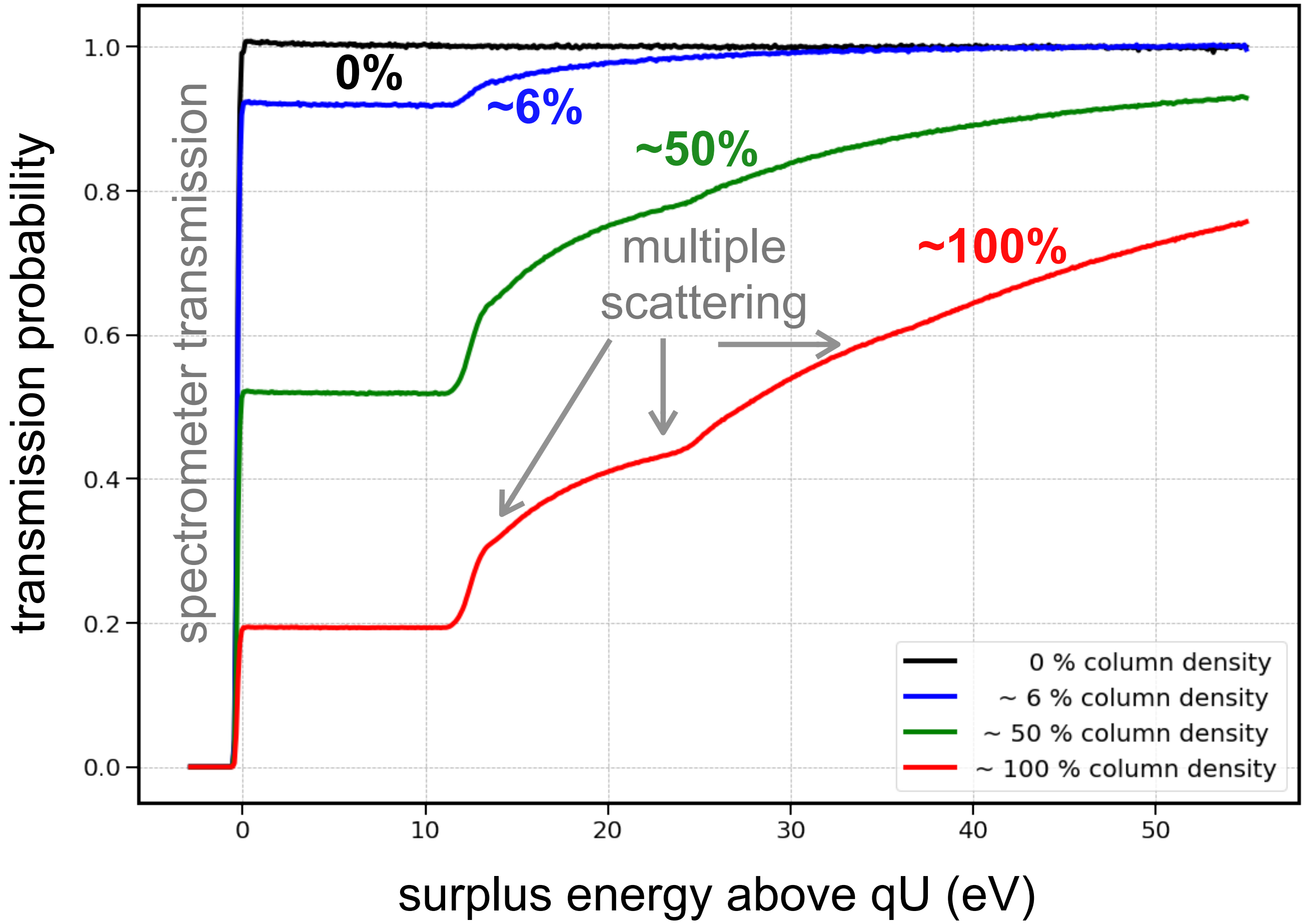




[NJP 11 (2009) 063018; PPNP 64 (2010) 288; JINST 6 (2011) P01002; EPJ C77 (2017) 410]

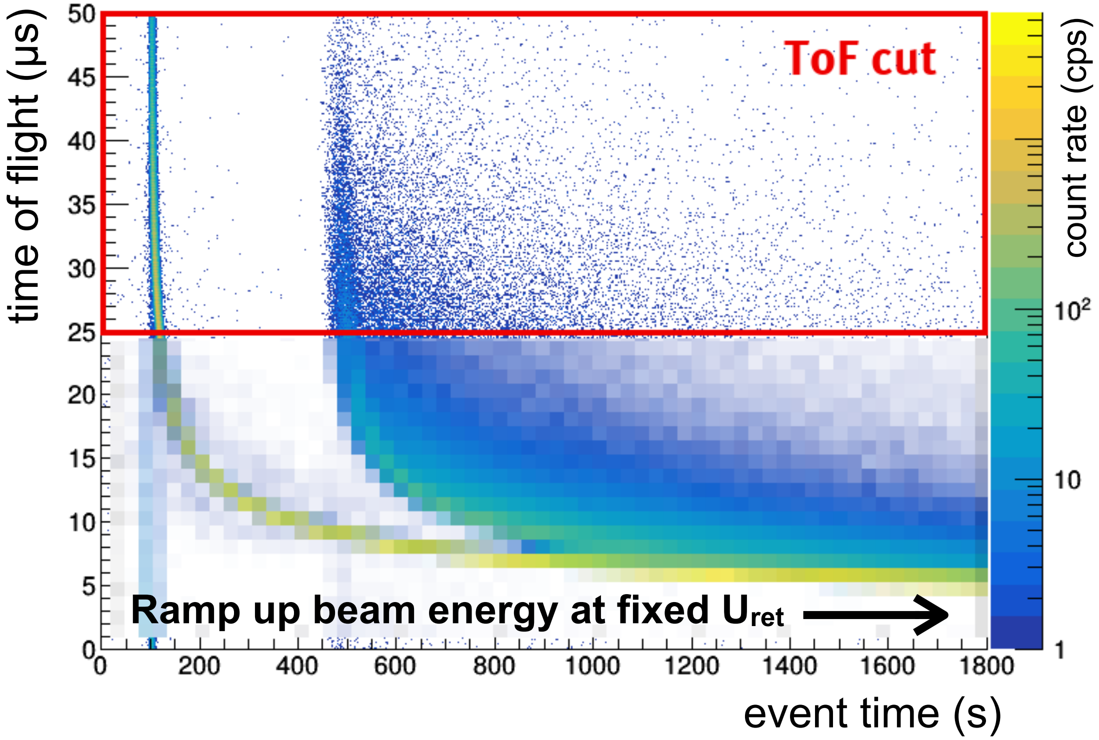
Measurement of the response function

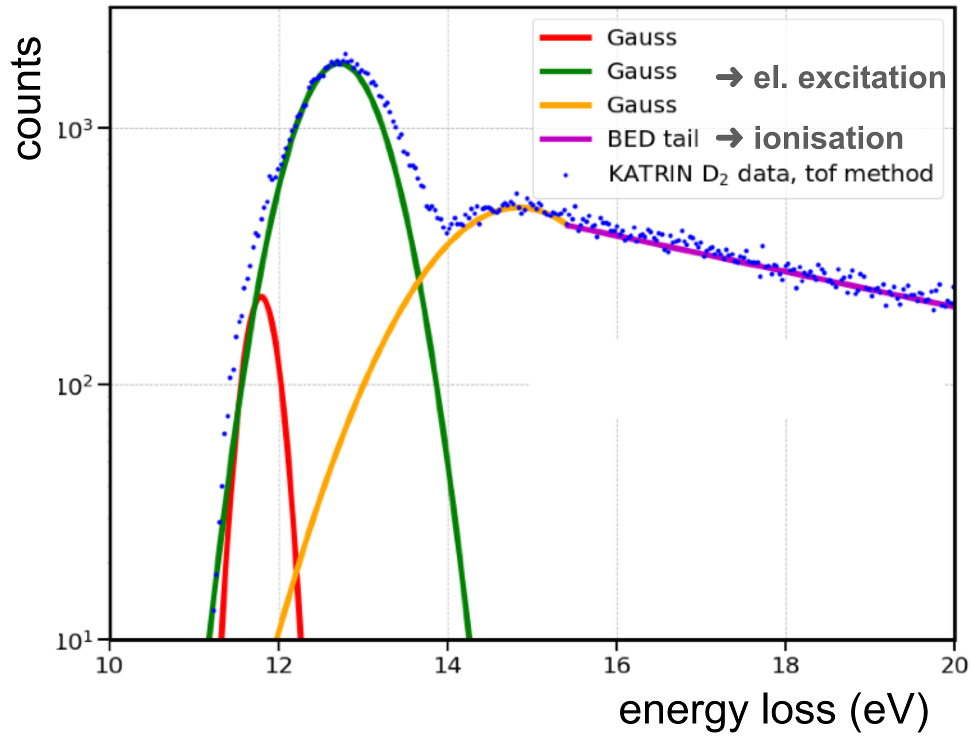
- Column density and energy loss by inelastic scattering are key systematics in ν-mass measurement
- Precision e-gun allows measurement of “response function”
- Measurements agree well with model over full range of gas densities (here: D_2)



Energy loss function from time-of-flight

- ToF signal from pulsed e-gun (70 ns at 20 kHz):
  High-pass filter turned into narrow band-pass ➜ recover "differential" spectrum.



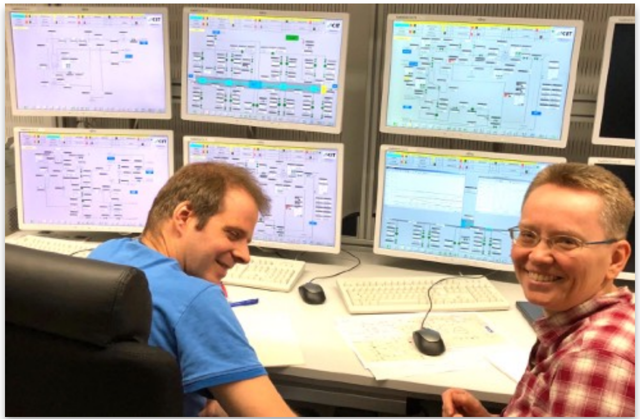


- Empirical parameterisation replaced by physics-motivated composite model
  ➜ triple Gauss for electronic excitation + ionisation tail (BED model)
- Greatly improved data-driven understanding of one of the key systematics

["MAC-E-ToF" idea by J. Bonn *et al.*, NIM A421 (1999) 256; see also Steinbrink *et al.* NJP 15 (2013) 113020]

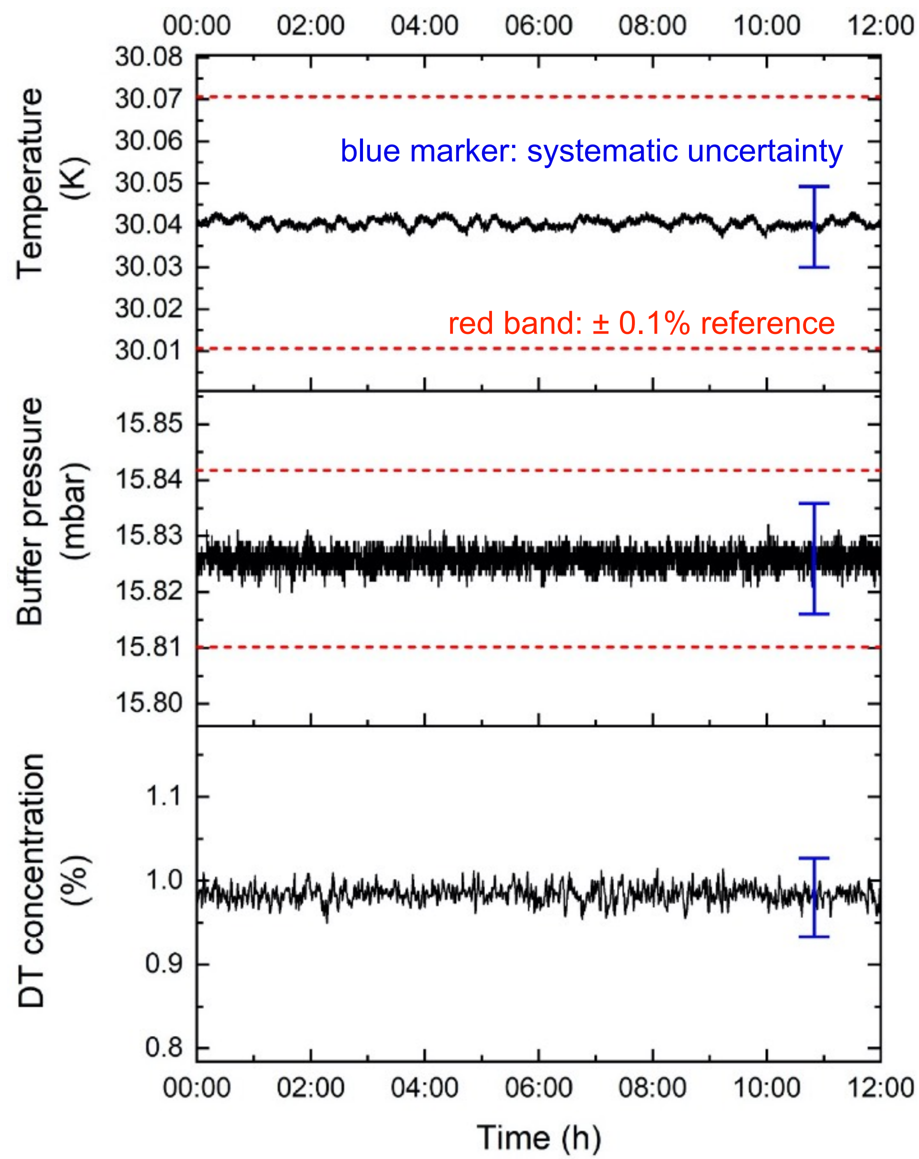
May 2018: *First Tritium* campaign

- Commissioning with nominal gas flow, but with D_2 (99%) + DT (1%)
- Demonstration of global system stability
- Test of analysis strategies
- First high-quality beta spectra with good statistics (activity ~500 MBq)



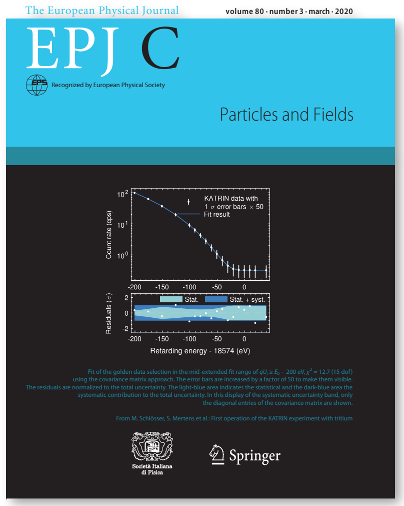
First tritium injection
Friday, May 18th, 7:48 UTC

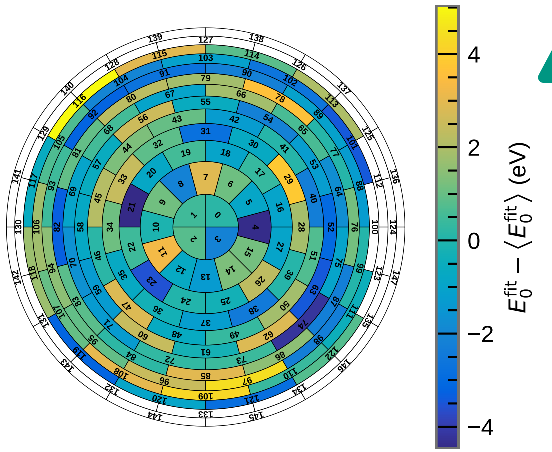
14 days of stable, reliable operation

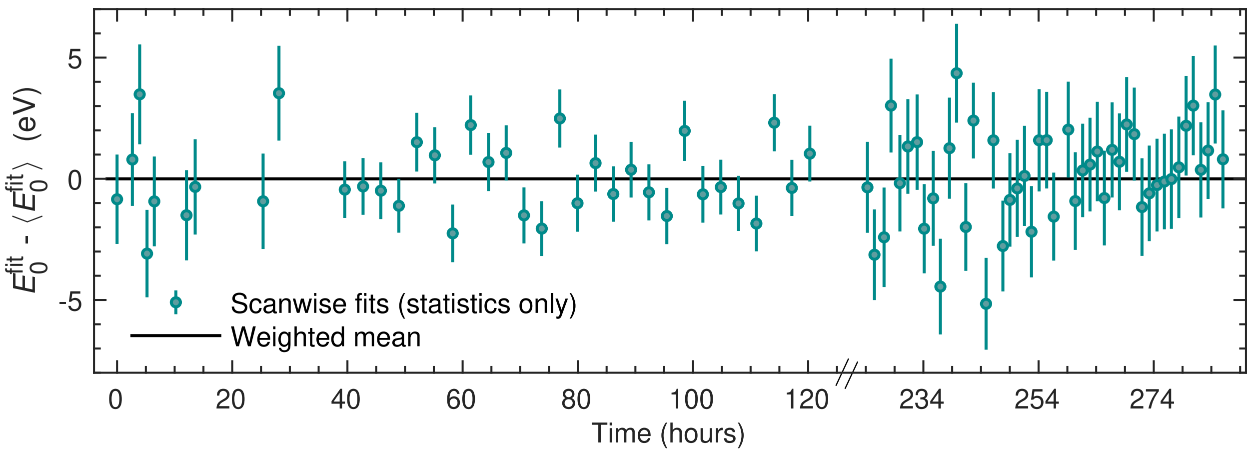


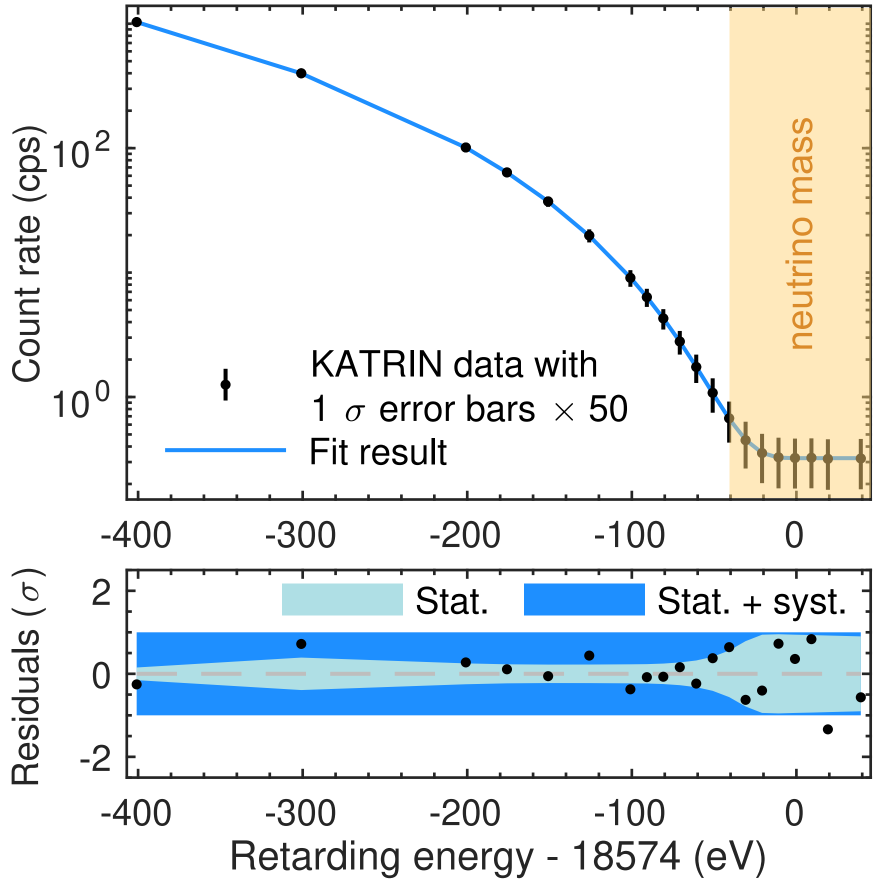
First tritium β-spectra

- Good agreement of model with with data even over extended range of 400 eV
- No relevant statistical sensitivity to $m^2(\nu)$ ➜ fixed to zero
- Parameter of interest E_0 ➜ no radial or time dependence







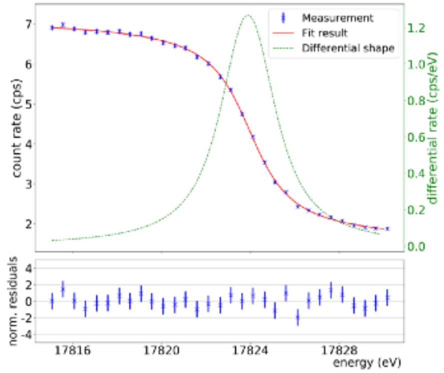


[KATRIN Coll., EPJ C 80 (2020) 264]

KATRIN timeline: the first 18 years

Letter of Intent

Main spectrometer

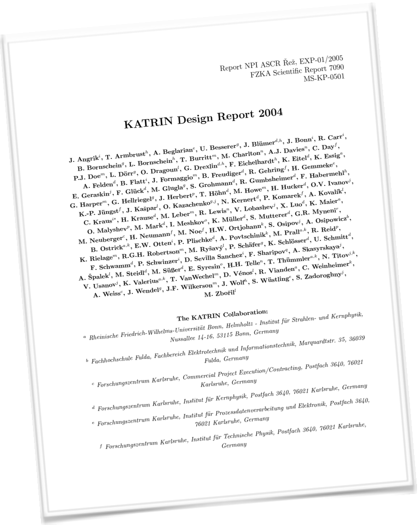


Calibration & systematics

First neutrino mass

2001 — 2004 — 2006 — 2016 — 2017 — 2018 — 2019

Design Report

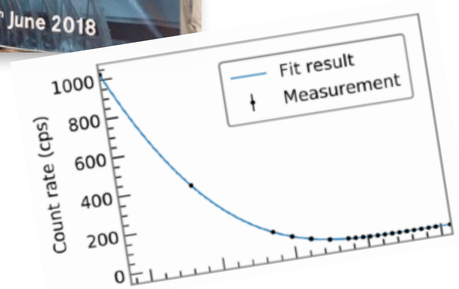

Report NPI ASCR Řež, EXP-01/2005
FZKA Scientific Report 7090
MS-KP-0501

KATRIN Design Report 2004

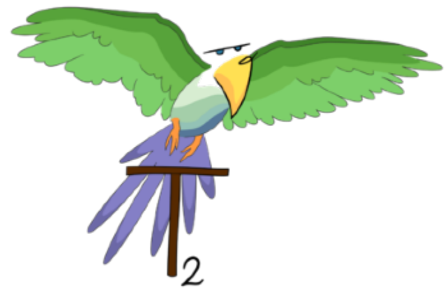
The KATRIN Collaboration:

First Light

First Tritium

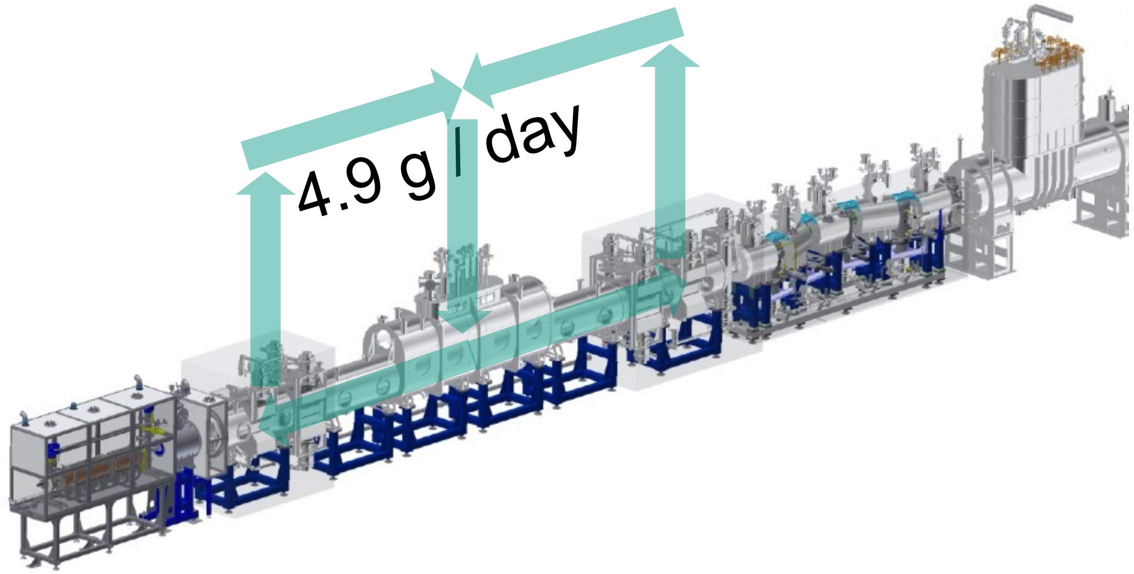


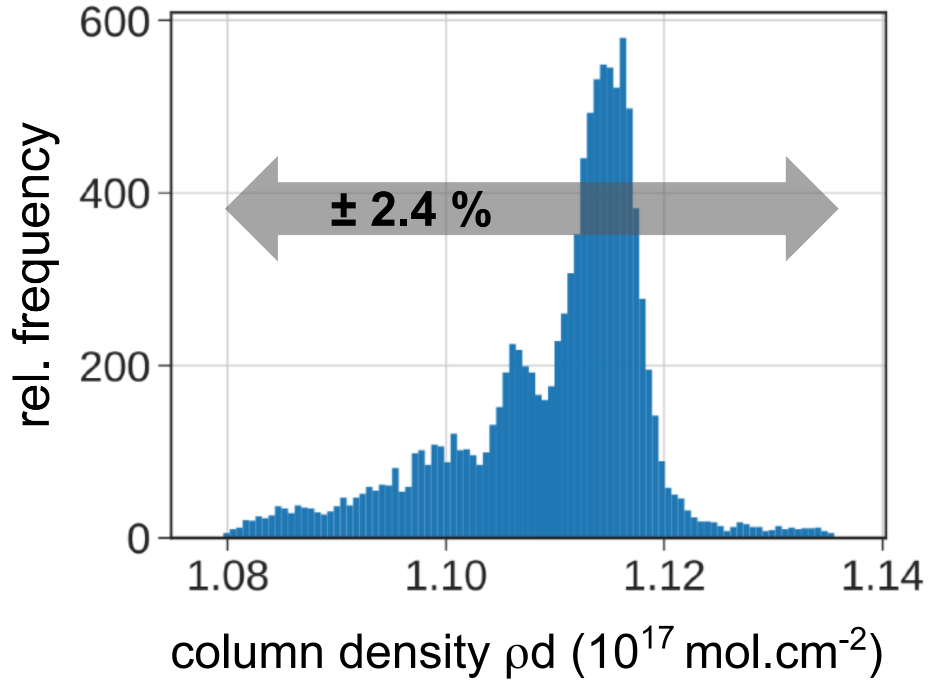
KATRIN's first Science Run



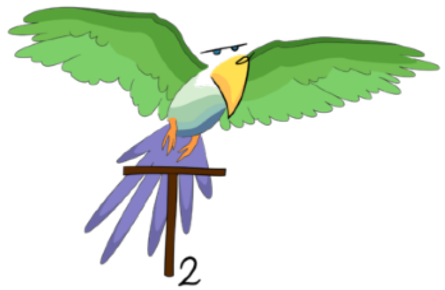
- **March 4, 2019:**
  First ever large-scale throughput of high-purity tritium in closed loop

  - 22% of nominal column density (activity ~50 x "First Tritium")
    ➜ 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 %)

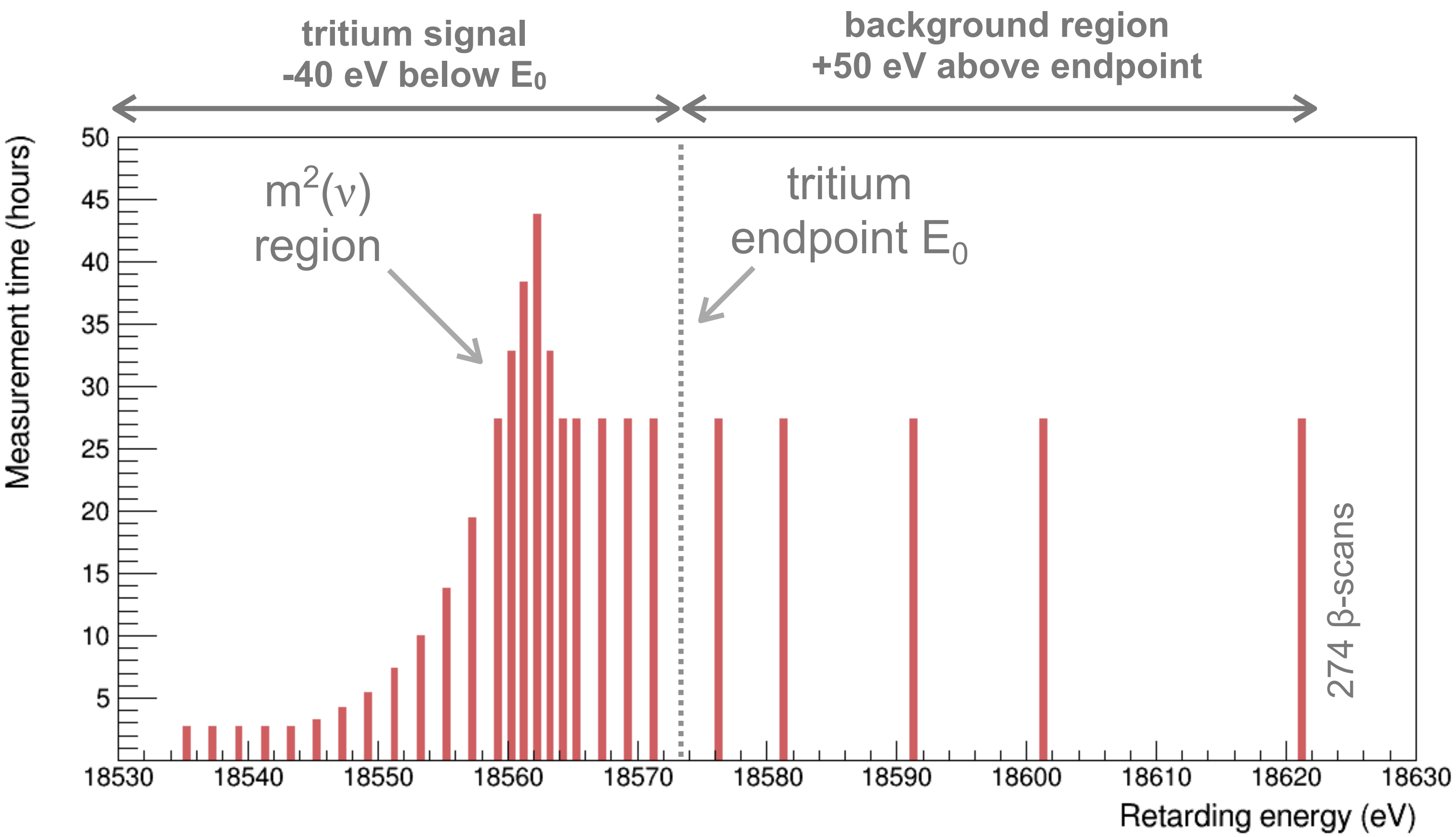




KATRIN's first Science Run

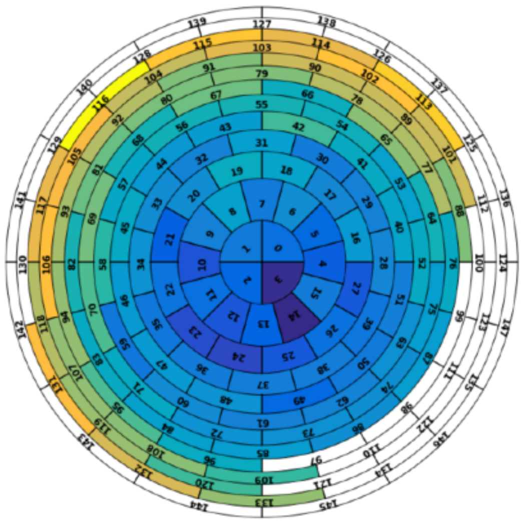


- **March 4, 2019:**
  First ever large-scale throughput of high-purity tritium in closed loops
- **April 10 - May 13, 2019:** four weeks (780 hrs) of β-scans at 24.5 GBq
  ➜ equivalent to few days out of 1000 planned days at nominal activity (100 GBq)



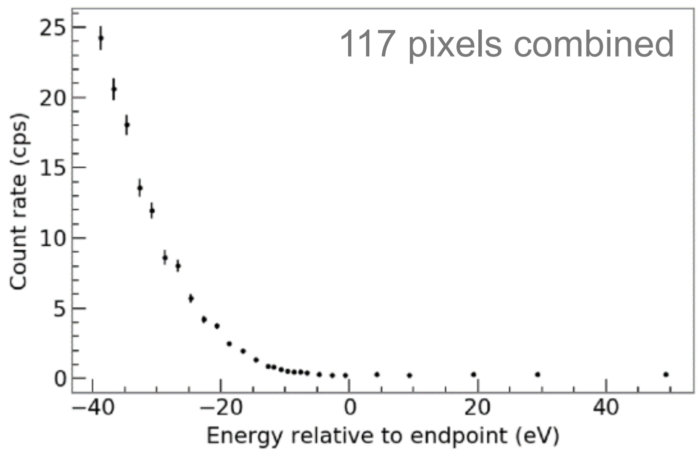
- After quality selection: 274 β-scans x 2.5 hrs
- Alternating up/down scans
- 27 HV set-points per scan
- Event sample: $2.03 \cdot 10^6$

Data combination strategy



Segmented Si-PIN detector:

- 117 out of 148 pixels used (79%)
- high, uniform detection efficiency (> 90%)
  with negligible dependence on retarding potential
- one β-spectrum per pixel = 117 spectra



Sequence of 274 scans:

- 117 x 274 = 32,058 spectra for one $m^2(\nu)$!
- high system stability allows
  - stacking of data for each HV point
  - uniform fit across detector

first-campaign approach

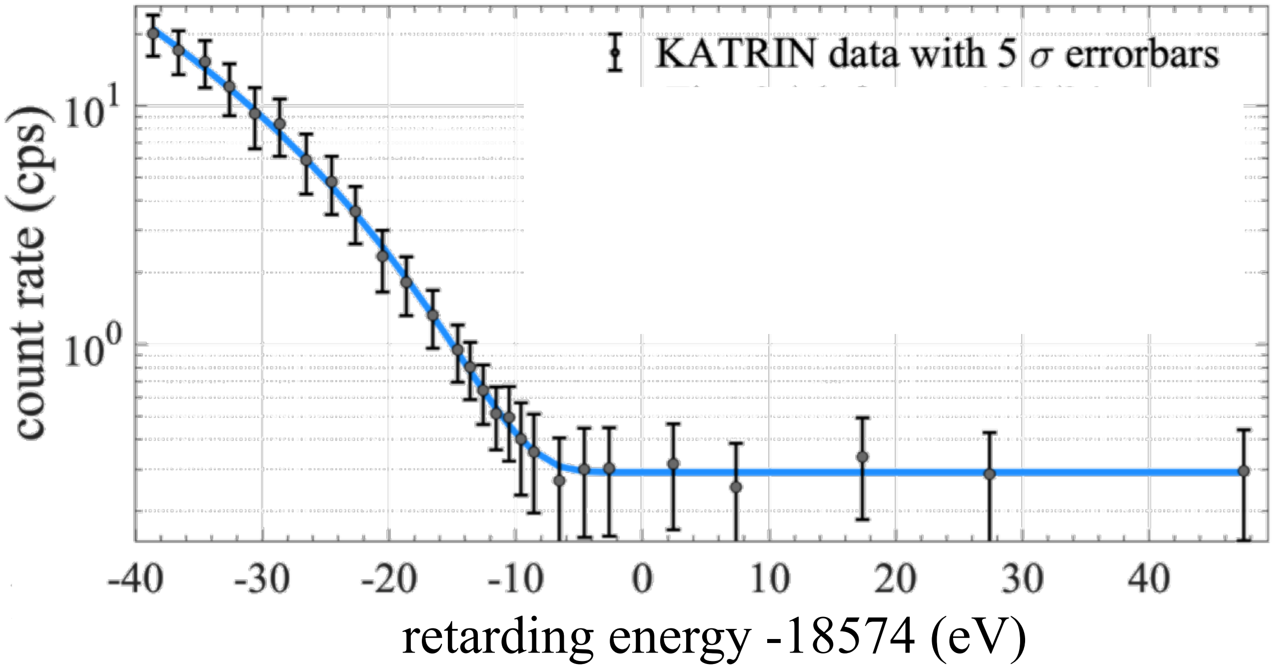
- other data combination strategies:
  multi-ring/multi-pixel fit, appended runs, …

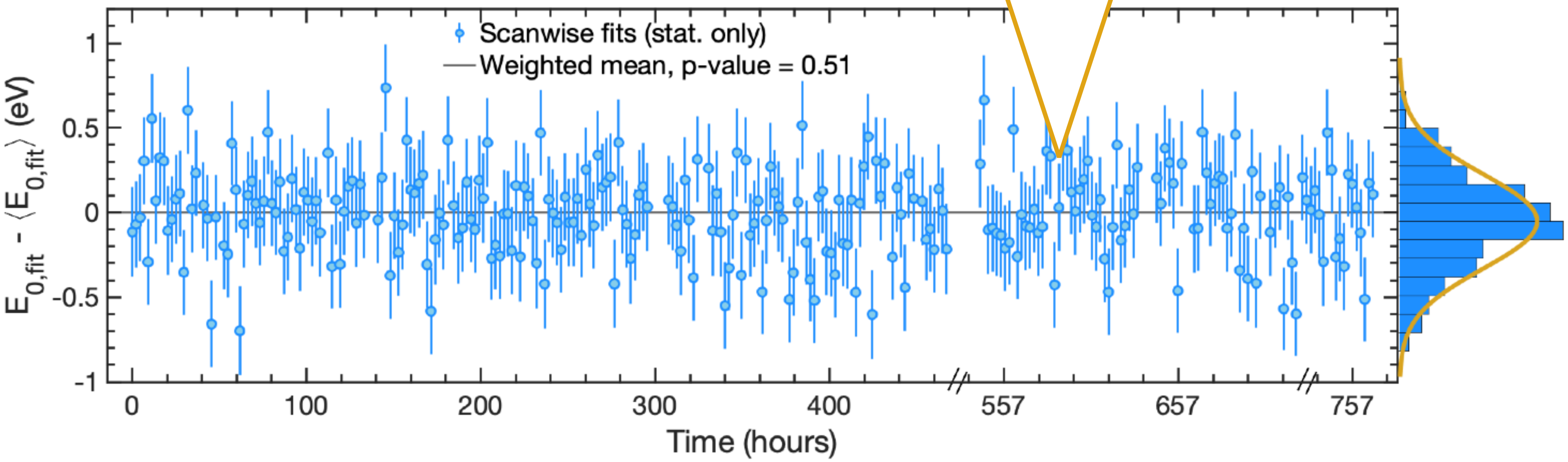
more resource-demanding

Stability of spectral scans

Fit of 274 individual scans (with $m^2(\nu) = 0$ fixed):

➜ β-spectrum endpoint shows excellent stability over entire 4-week period



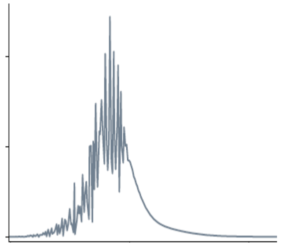


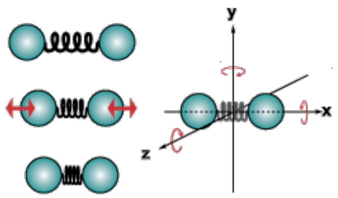
std. deviation $\sigma = 0.255$ eV

Ingredients for an unbiased ν-mass analysis

1. Bias protection by Monte Carlo

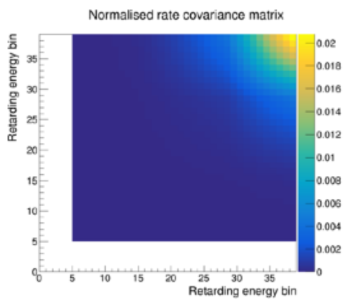
- Use slow-control input to generate “MC twin” of each scan
- Freeze analysis on MC before turning to real data

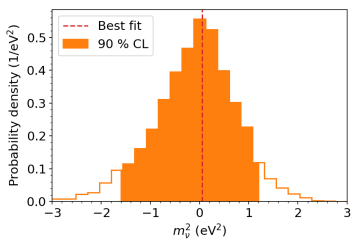




2. Model-based blinding scheme

- Molecular final states distribution with artificial smearing unknown to analysts
- Hides true $m^2(\nu)$, but leaves other parameters unaltered





3. Complementarity

Two independent methods for treatment of systematics

- Covariance matrix approach (chi^2 estimator)
- Monte-Carlo propagation (likelihood estimator)

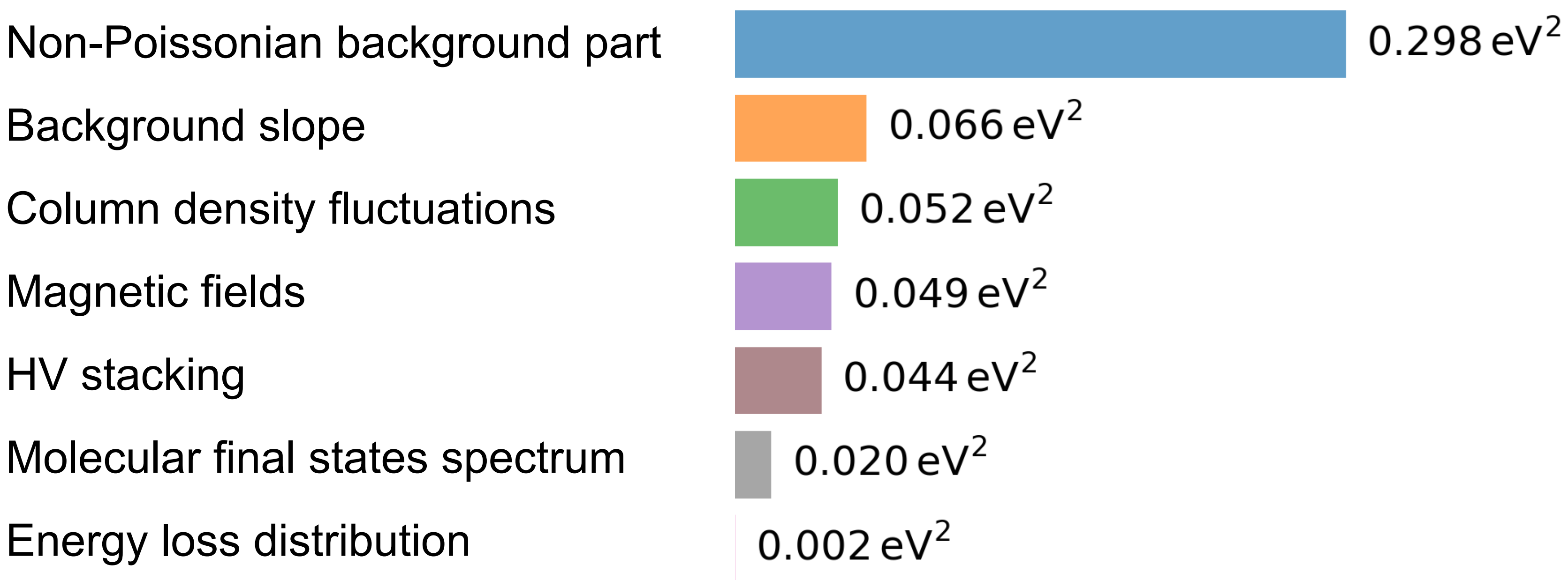
Statistical and systematic uncertainties

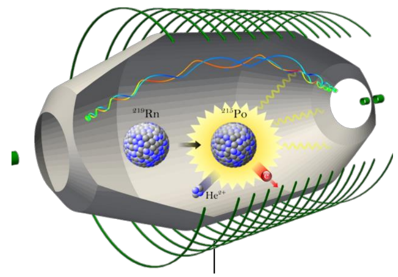
- Current dataset is strongly statistics-dominated (5 days nominal KATRIN only …).
  Total statistics budget: σ_{stat} = 0.97 eV² **factor 2**

  improves on Mainz &Troitsk by

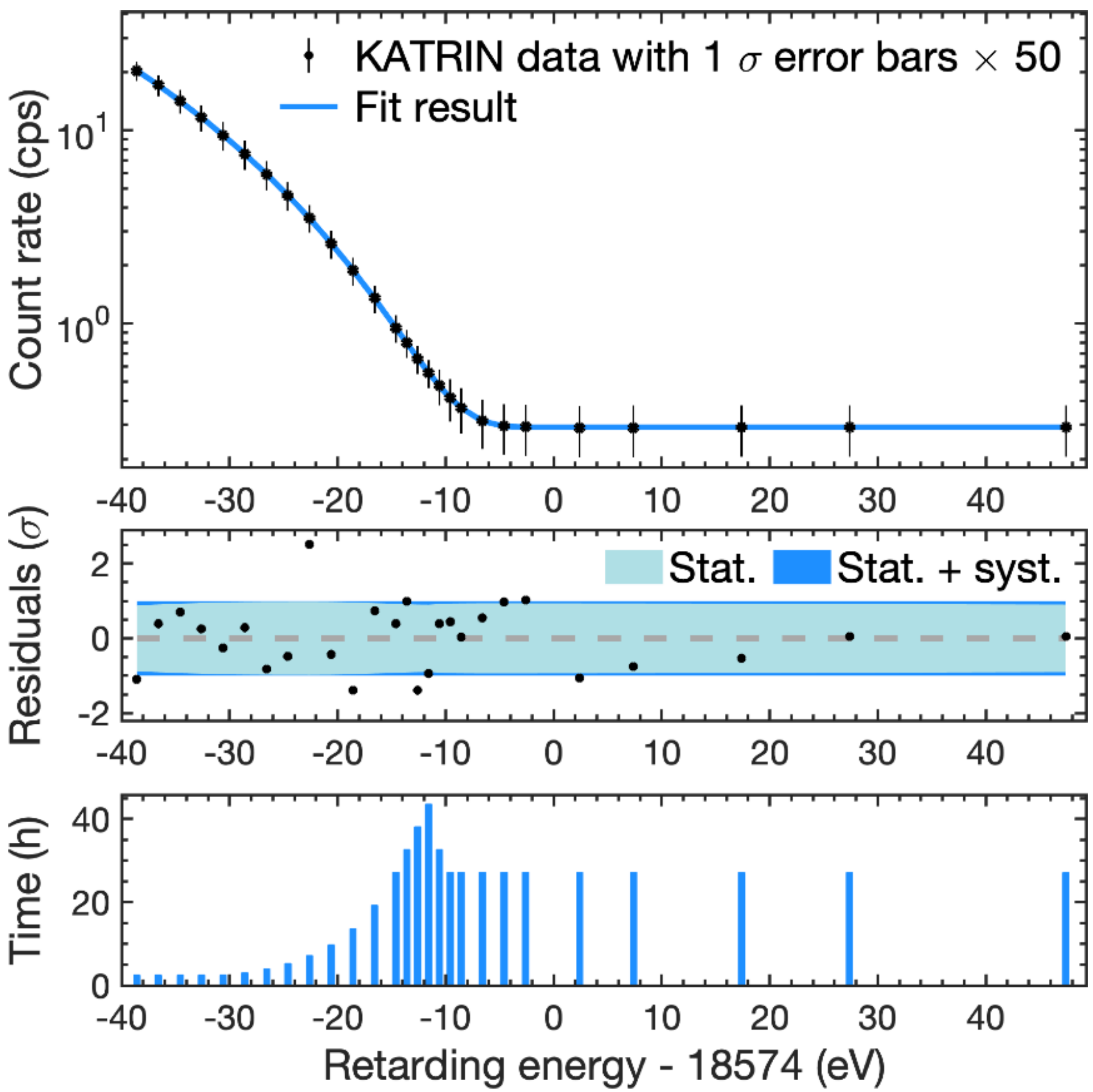
- Systematic uncertainties are well understood.
  Total systematics budget: σ_{syst} = 0.32 eV² **factor 6**

- Systematics breakdown for first Science Run:





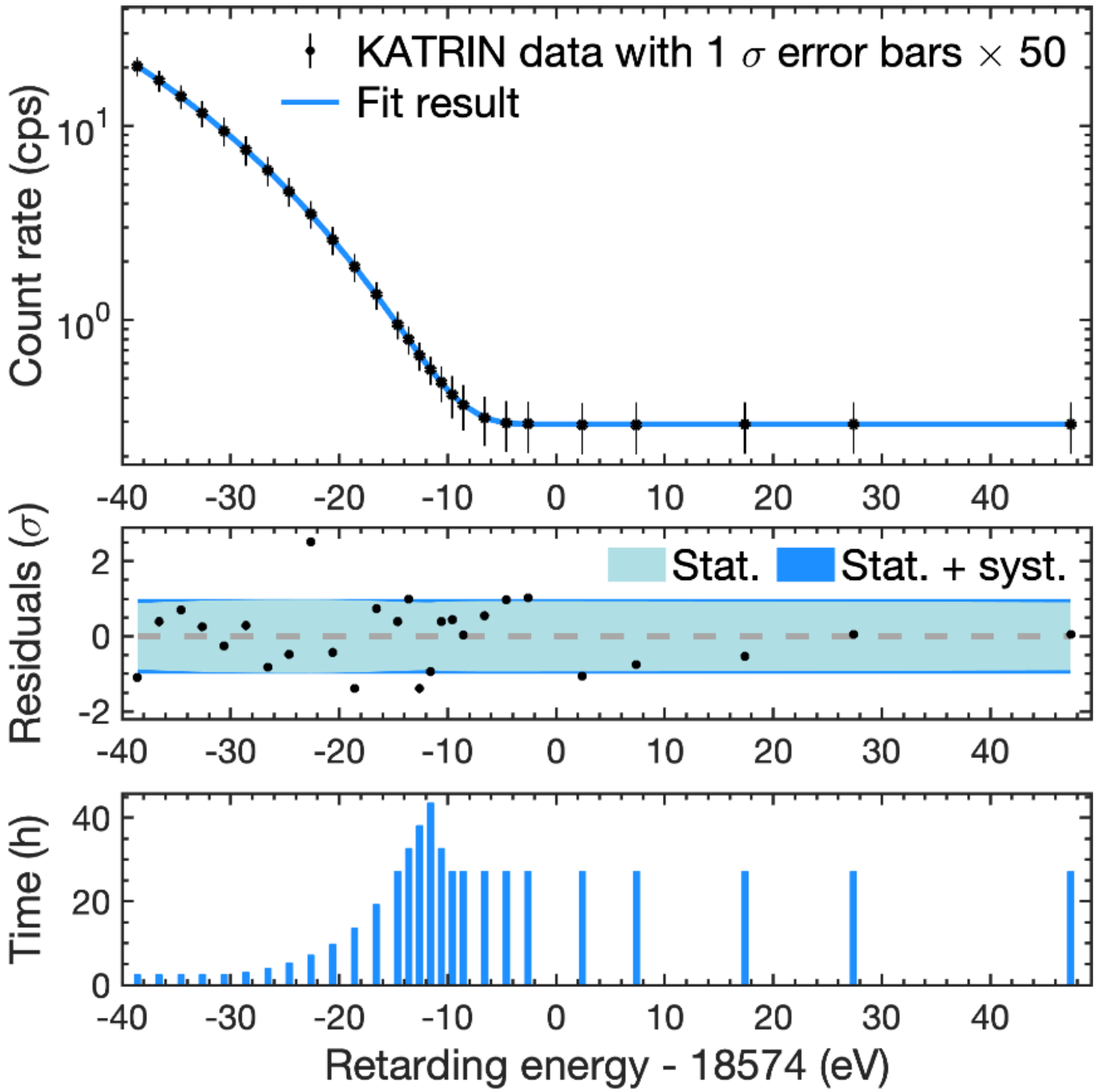
First neutrino mass result

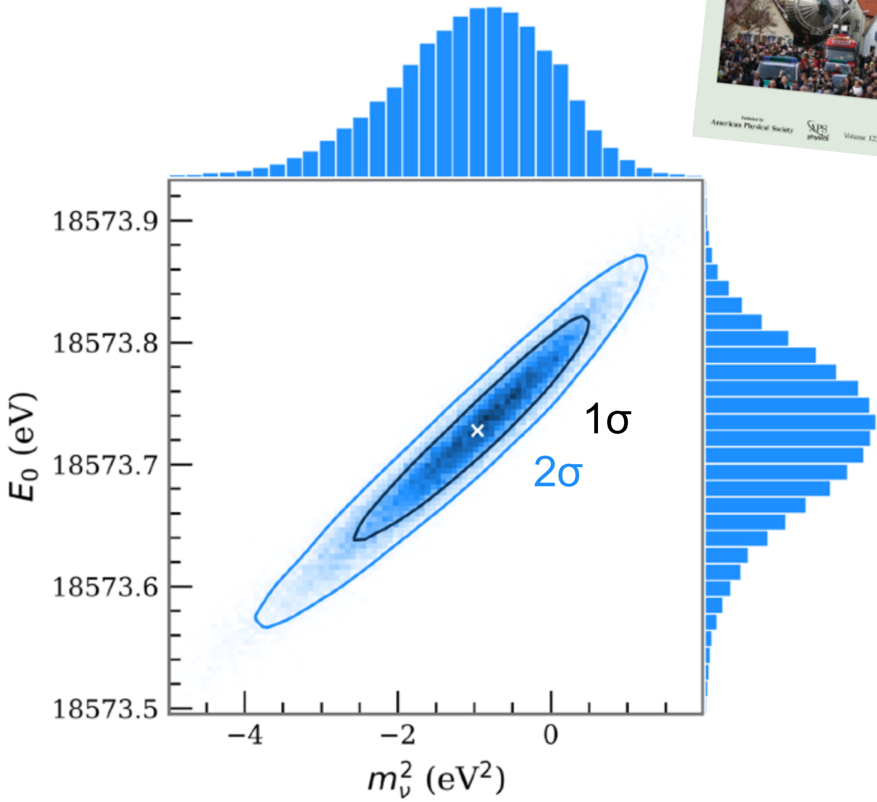


- 2 million events in total
- 4 free parameters, shape-only fit
  $m^2(\nu)$, E_0, background, signal normalisation
- Excellent goodness-of-fit:
  $\chi^2 = 21.4$ for 23 d.o.f. $(p = 0.56)$
- Best-fit value: $\mathbf{m_\nu^2} = \left(-\mathbf{1.0}^{+\mathbf{0.9}}_{-\mathbf{1.1}}\right)\,\mathrm{eV}^{\mathbf{2}}$
- New upper limit:
  m_ν < 1.1 eV
  (90% CL, Lokhov-Tkachev*)
- m_ν < 0.8 eV (0.9 eV) at 90% (95%) CL (Feldman-Cousins)

* Lokhov & Tkachov, Phys. Part. Nucl. 46 (2015) 347

First neutrino mass result





- Strong correlation of E_0 and $m^2(\nu)$ from 10^5 pseudo-experiments, as expected
- Agreement with ^3H-^3He mass difference ➜ consistency check of energy scale

eff. Q-value from fit: **(18575.2 ± 0.5) eV**; from* $\Delta M(^3H,^3He)$: **(18575.72 ± 0.07) eV**

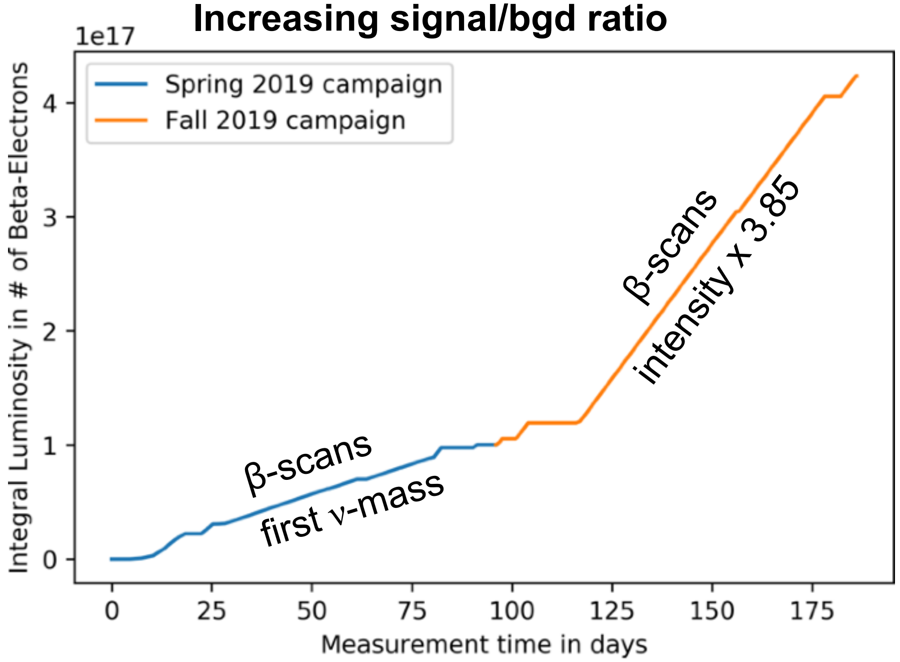
* Myers *et al.*, PRL 114 (2015) 013003

Ongoing work and next plans

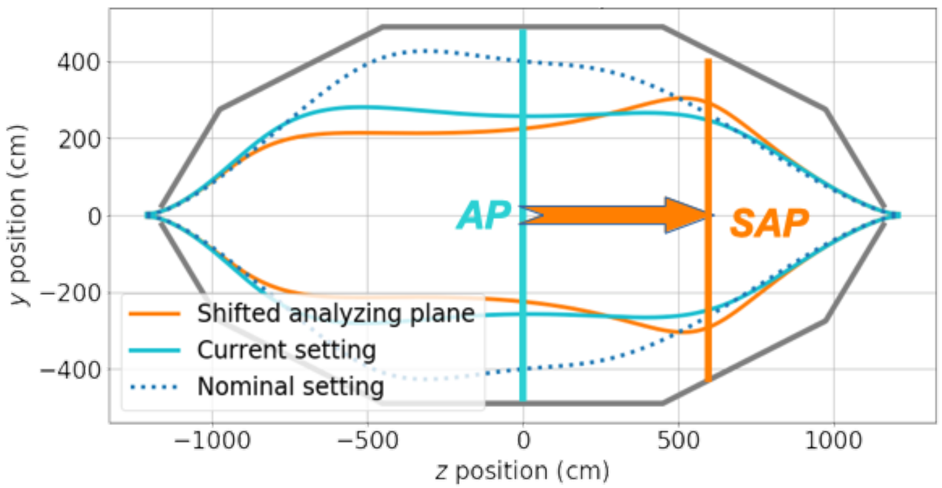
- **2nd Science Run (fall 2019)**
  - Improved stability (HV, gas density)
  - 83% of nominal column density
- **3rd Science Run (spring 2020)**

  - Reduction of backgrounds through flux-tube fiducialization
  - Very promising first tests: 200 mcps → 100 mcps
- **Full data set :1000 days**
  - Collect data over 5 years (3 campaigns per calendar year)
  - Sensitivity $m(\nu_e)$ = 0.2 eV (90% C.L.)

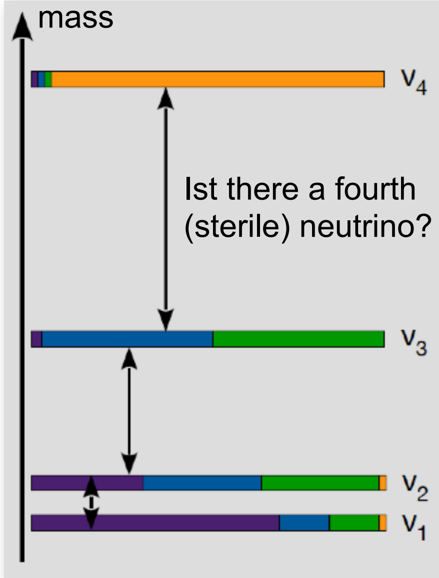
Increasing signal/bgd ratio



Fiducialization of main spectrometer flux tube



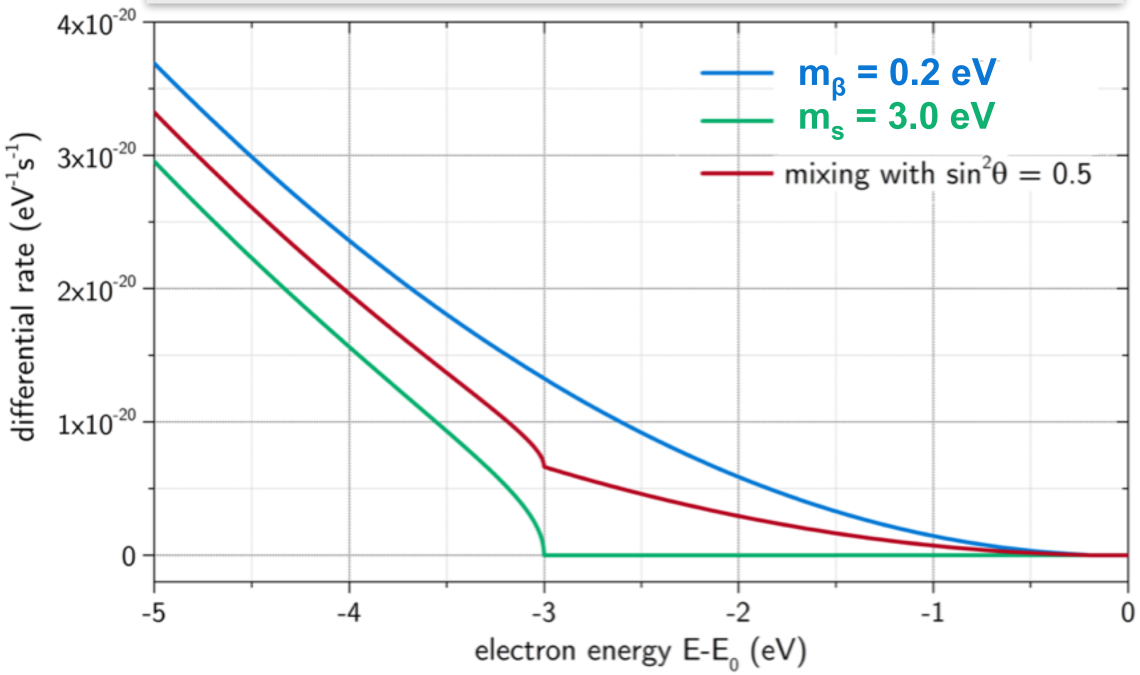
Physics reach of KATRIN: search for extra neutrino states



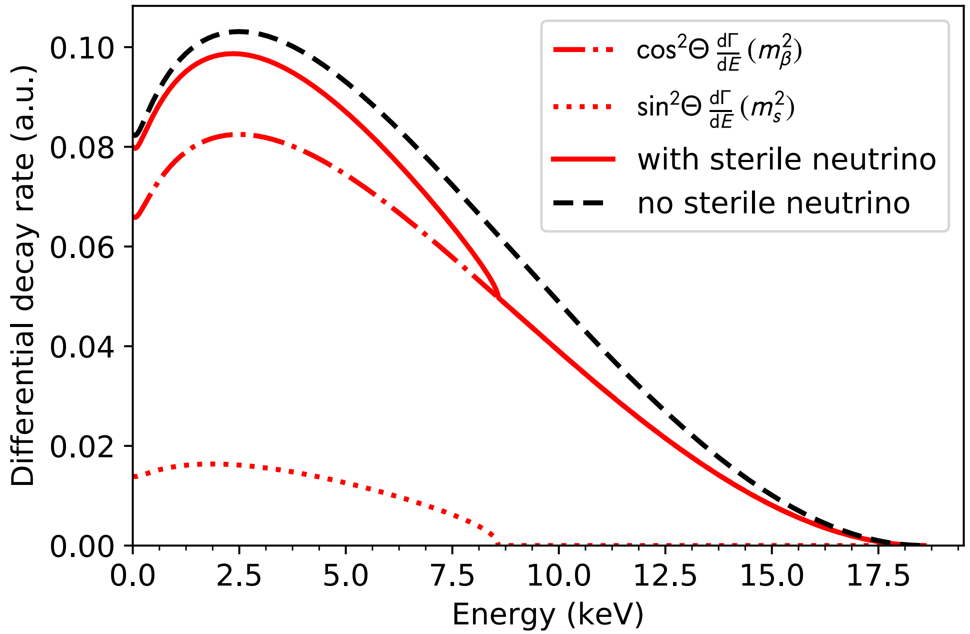
$$\frac{d\Gamma}{dE} = \cos^2(\theta_s)\,\frac{d\Gamma}{dE}(m_\beta^2) + \sin^2(\theta_s)\,\frac{d\Gamma}{dE}(m_s^2)$$

neutrinos mix: generate "kink" in β spectrum at $E = E_0 - m_s$

light sterile ν, m_s ~ few eV
motivated by oscillation anomalies



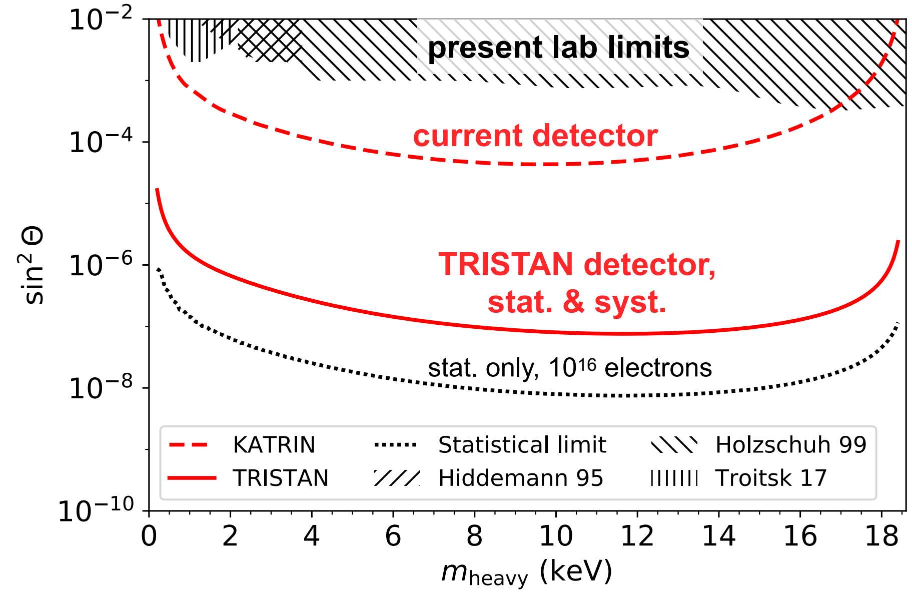
heavy sterile ν, m_s ~ few keV
motivated as DM candidate



Search for keV sterile neutrinos with KATRIN

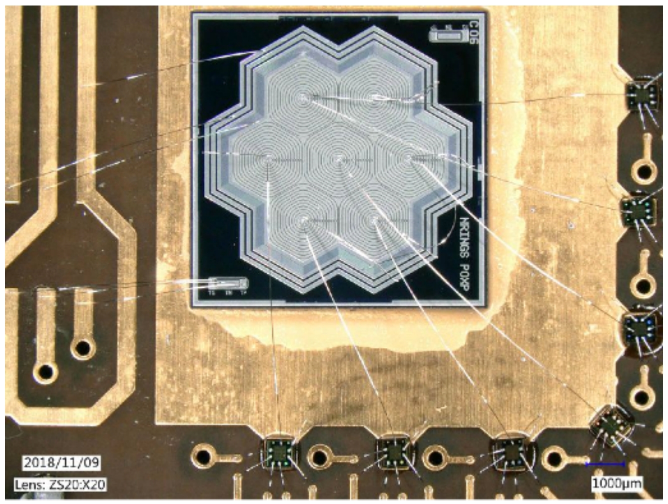
Goal: search for sterile neutrinos and other BSM physics deeper in the tritium β-spectrum

- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for differential measurement, need energy resolution ~300 eV or better



TRISTAN detector for KATRIN: SDD layout

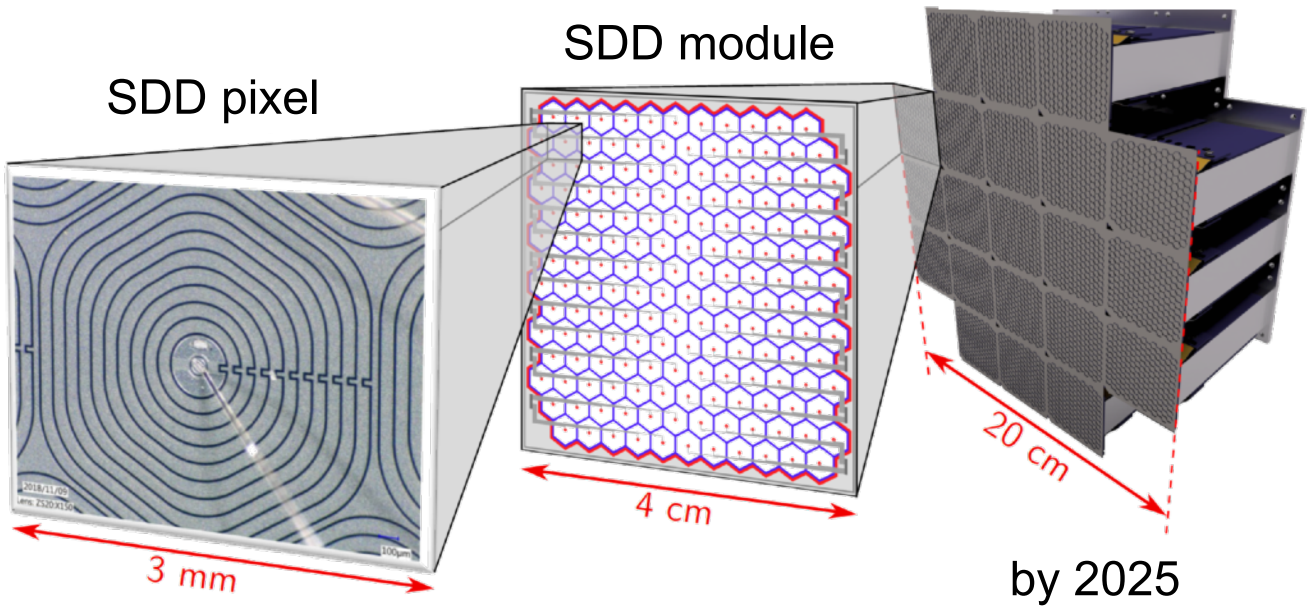
prototype (HLL, MPP)



SDD pixel

SDD module

full array

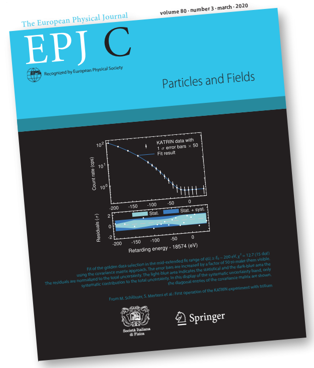


by 2025

[Mertens *et al.*, J. Phys. G 46 (2019) 065203]

Summary & Outlook

- **Neutrino mass scale:** fundamental relevance from cosmology to particle physics
- **KATRIN:** direct, kinematic neutrino-mass search complementary to cosmology and $0\nu\beta\beta$
  - Successful first science run in spring 2019, yielding new limit: **$m(\nu) < 1.1$ eV (90% C.L.)**
  - Analysis of science run 2 (higher statistics) in progress, just launching science run 3 (lower background) in May 2020
  - Sensitivity goal: **$m(\nu) < 0.2$ eV (90% C.L.)** for 5 years of data
  - Promising BSM physics avenues: eV and keV sterile ν (with future detector upgrade TRISTAN), non-standard weak interactions, LIV, …



Stay tuned!

- **Beyond KATRIN:**
  - Electron capture: ^{163}Ho micro-calorimeters (ECHo, HOLMES, …)
  - Beta spectroscopy: Time-of-flight upgrade? New ideas, like Project 8, …