Karlsruhe Institute of Technology

THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

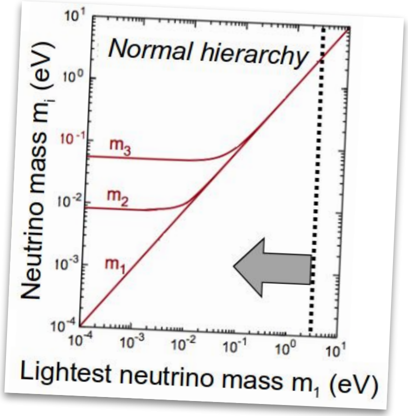
The KATRIN experiment:

The Challenge of Determining the Absolute Neutrino Mass

Jan Behrens | KIT-IKP | Nuclear Particle Astrophysics Seminars – Wright Lab at Yale University, New Haven, CT | September 10, 2020

Outline

- Direct neutrino mass measurements
  - Neutrinos from beta-decay
    - The KATRIN experiment
      - Systematic uncertainties
        - Recent measurement results
          - Timeline & future perspectives



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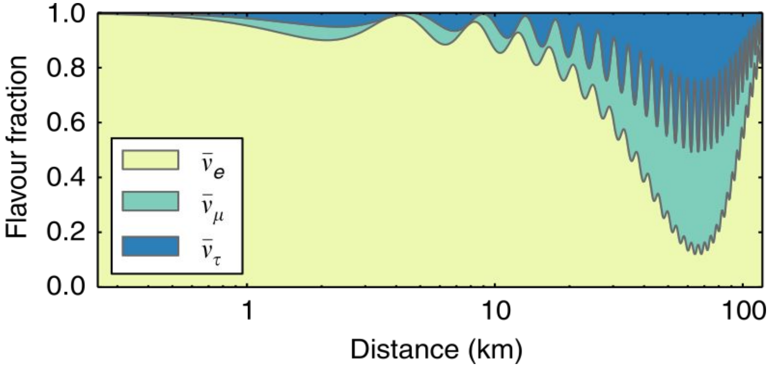
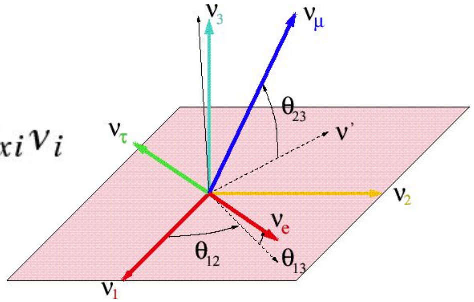
Neutrinos in the Standard Model

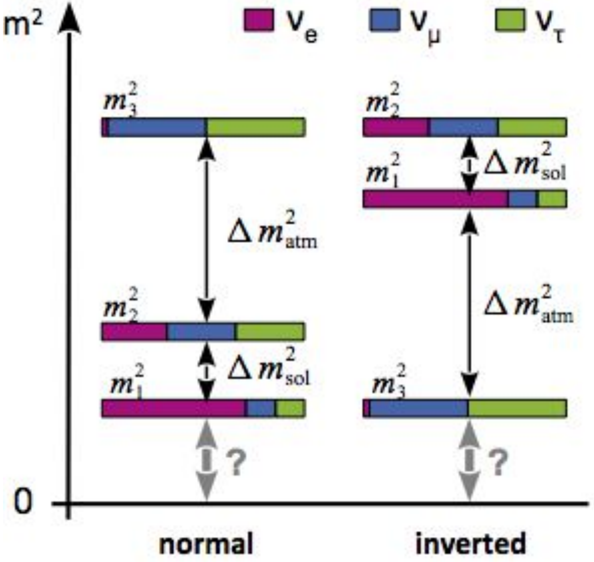
- PMNS neutrino mixing matrix, $m \neq 0$
- Neutrino oscillations sensitive to mass differences
- Two mass ordering scenarios are possible



- Mass of the lightest eigenstate is unknown
- Hints for sterile neutrinos?

$$\nu_x = \sum_i U_{xi} \nu_i$$





Determining the neutrino mass

Absolute neutrino mass scale is one of the “big open questions”

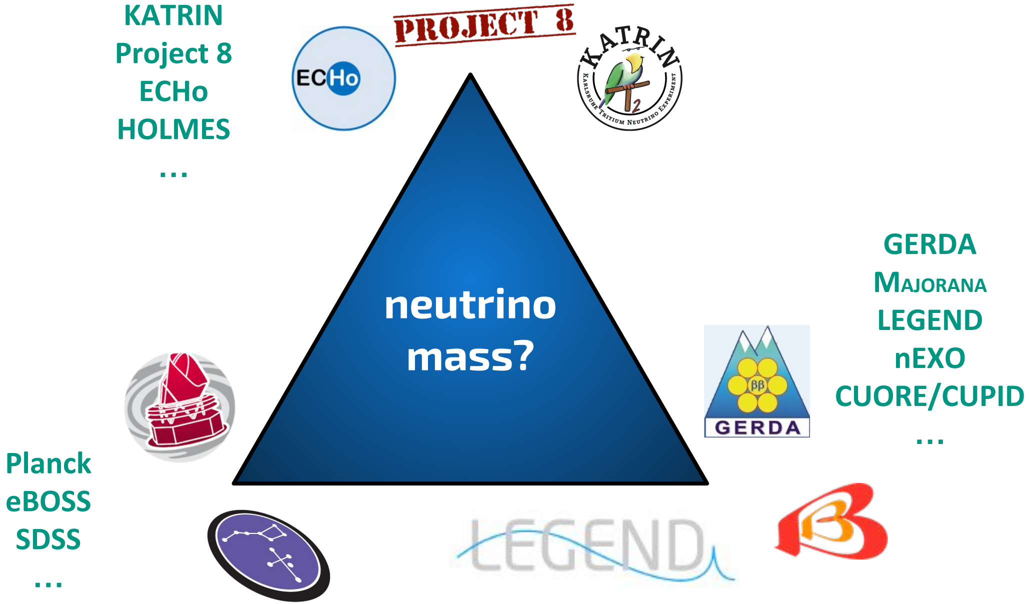
- Neutrinos are massive particles
- … but we only know mass limits

- Three different approaches:

$$M_\nu = \sum_i m_i$$

$$m_{\beta\beta}^2 = \left|\sum_i U_{ei}^2 m_i\right|^2$$

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$



Neutrinos in cosmology

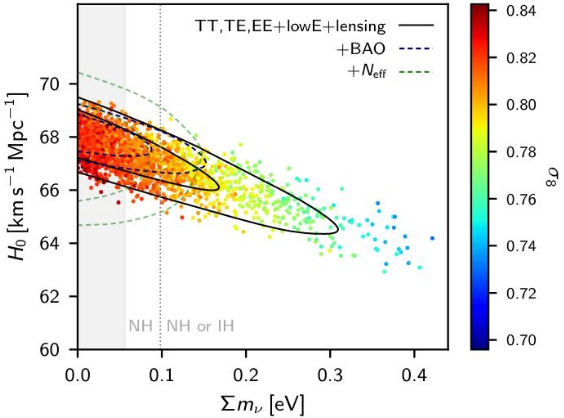
Cosmology provides best current upper limit:

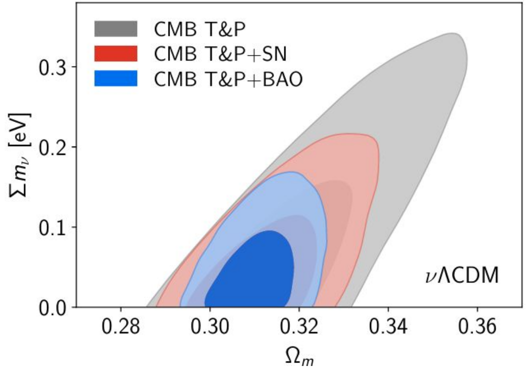
M_ν < 0.09 … 0.54 eV

- Current experiments: Planck, SDSS, BOSS
- Combine various observables (CMB, BAO, SN, …)
- Rules out inverted ordering at 0.1 eV limit

- Interpretation is based on ΛCDM standard model
- Extended scenarios weaken bounds on M_ν

- Direct mass measurements are complementary
- Neutrino mass can be tested in laboratory experiments
  ⇒ informs standard model of particle physics + ΛCDM





eBOSS collab., arXiv:2007.08991

Planck collab., arXiv:1807.06209

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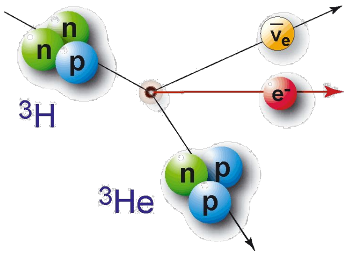
Neutrino mass from tritium beta-spectrum

$$\frac{dN}{dE} = C \cdot F(E, Z=2) \cdot p\,(E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_{\bar{\nu}}^2} \qquad m_{\bar{\nu}}^2 = \sum_{i=1}^{3} |U_{ei}|^2\, m_i^2$$

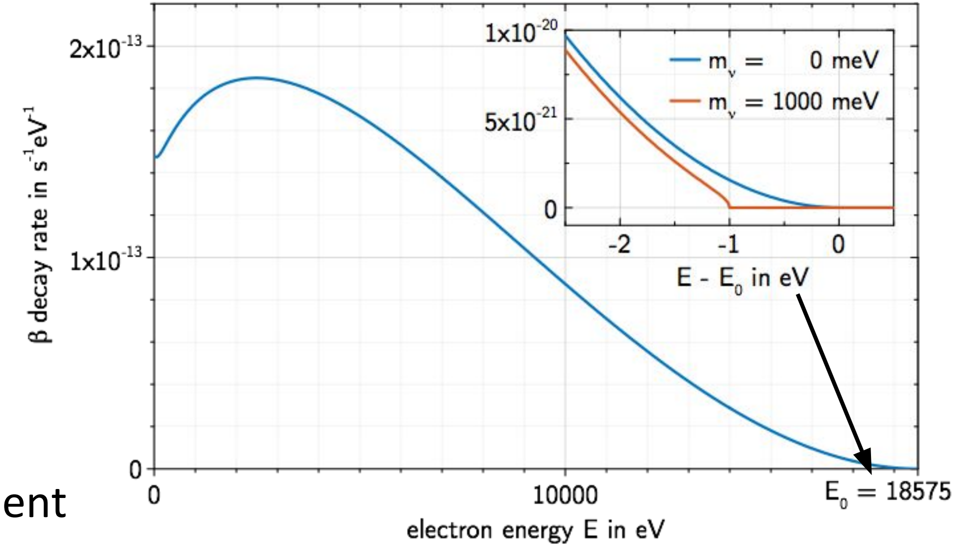
Observable: squared effective mass of the electron neutrino



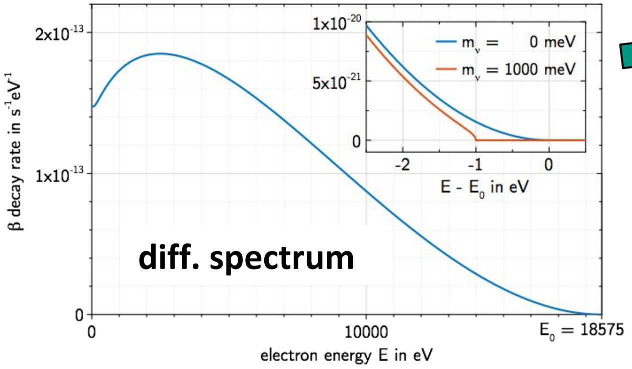
$$^3H \Rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

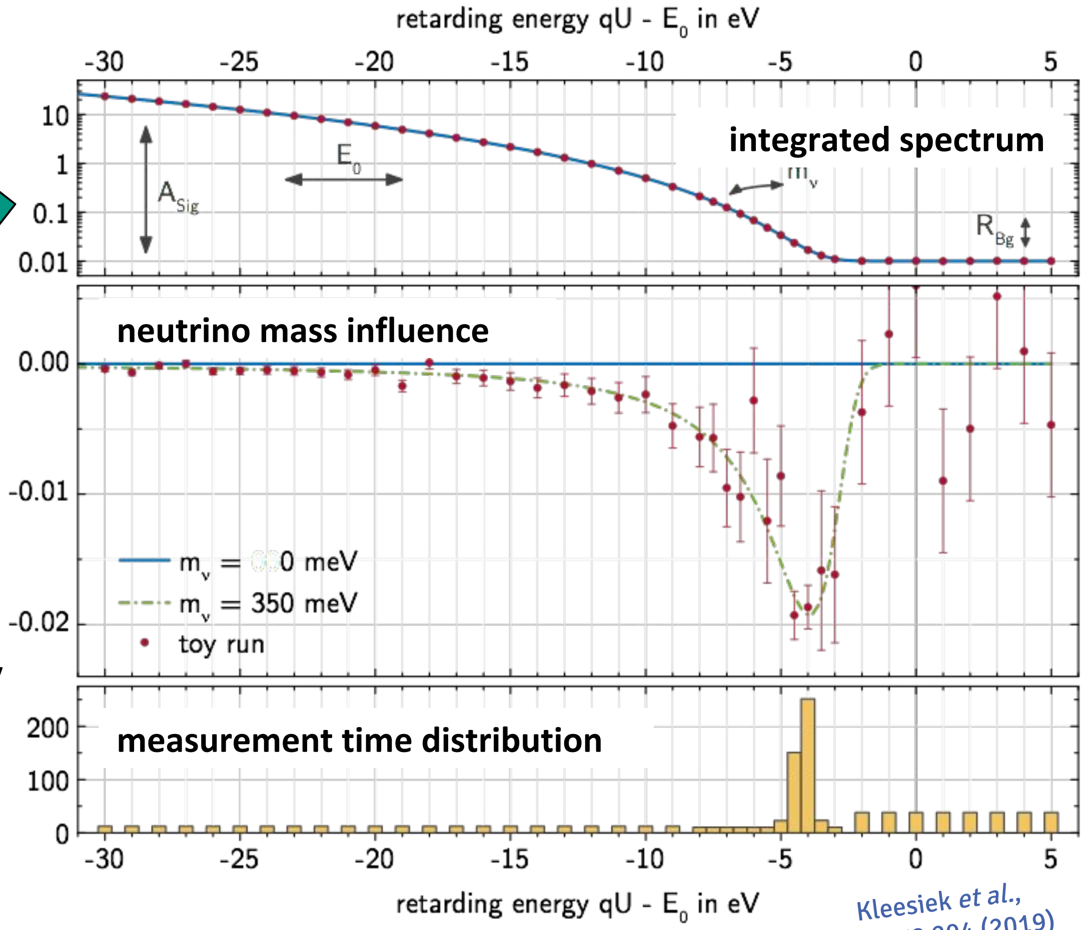
$T_{1/2}$ = 12.32 yr
E_0 = 18574 eV

- **Neutrino mass** determined from spectral shape near endpoint
- **KATRIN: kinematic measurement** of β-electron spectrum: model-independent



Integrated spectrum





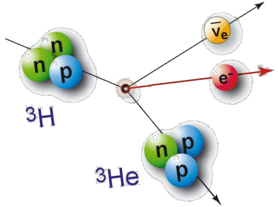
- **Energy scan** in endpoint region
- Vary retarding energy by ≈ 90 eV

- Measurement time distribution optimizes our **sensitivity**

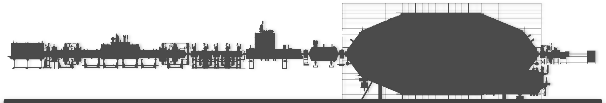
Kleesiek et al., EPJ C **79** 204 (2019)

The tritium challenge

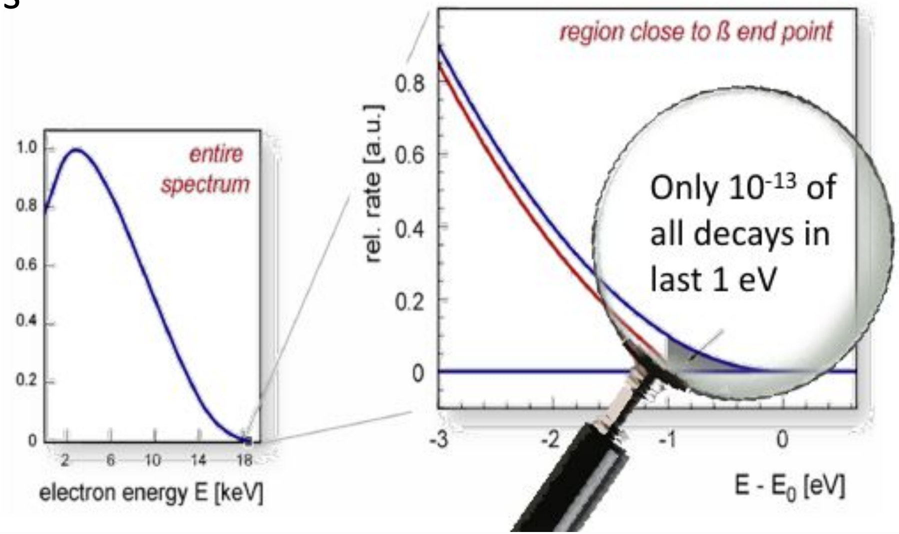
Only a fraction of tritium decays in the endpoint region!



- Design goals:
  - Ultra-strong β-source: 10^{11} decays/s
  - Low background level: < 0.1 cps
  - Excellent energy resolution: 1 eV
  - Precise understanding of spectrum



Final sensitivity goal:
0.2 eV (90% CL) / 5 yr



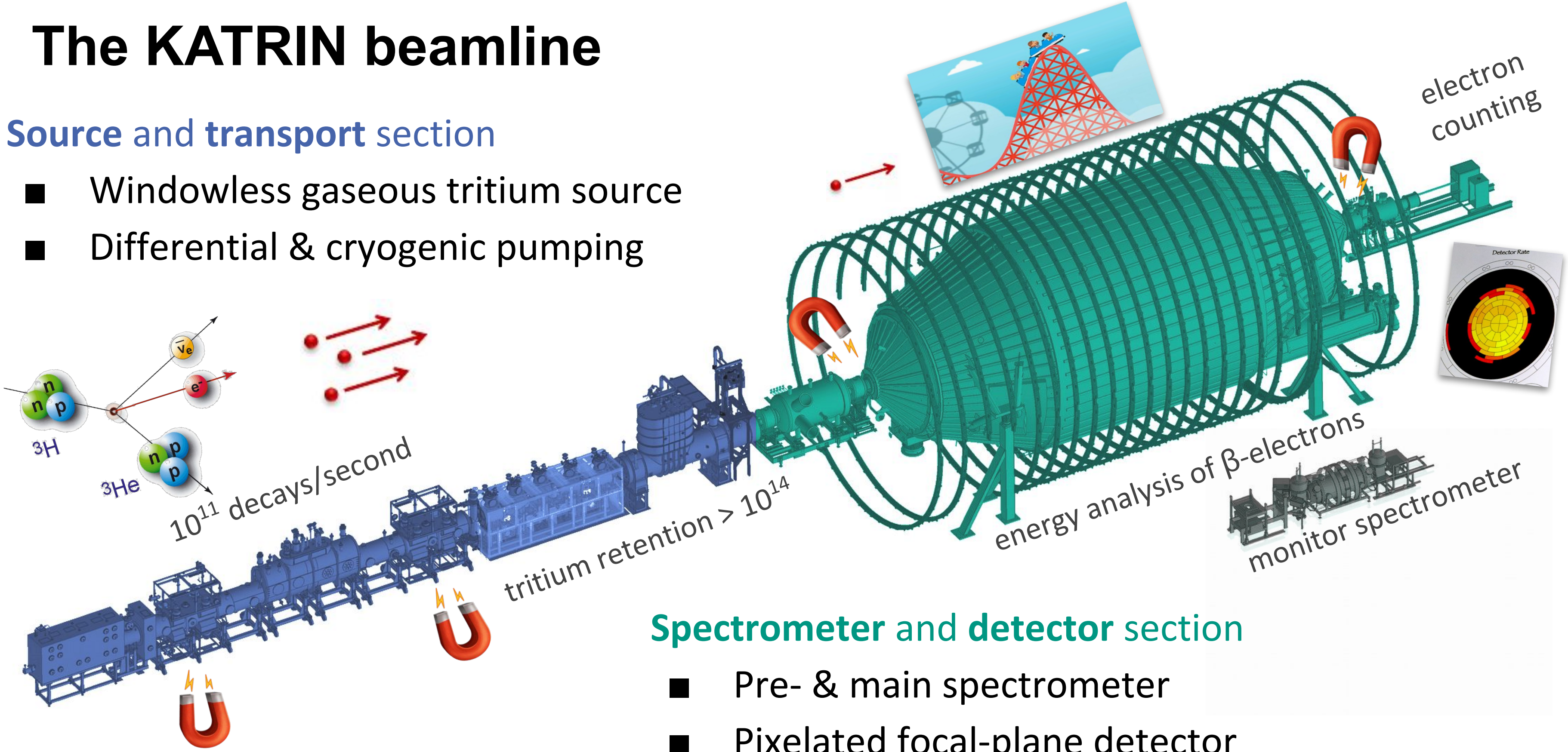
The KATRIN beamline

Source and transport section

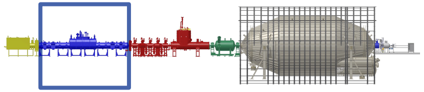
- Windowless gaseous tritium source
- Differential & cryogenic pumping

Spectrometer and detector section

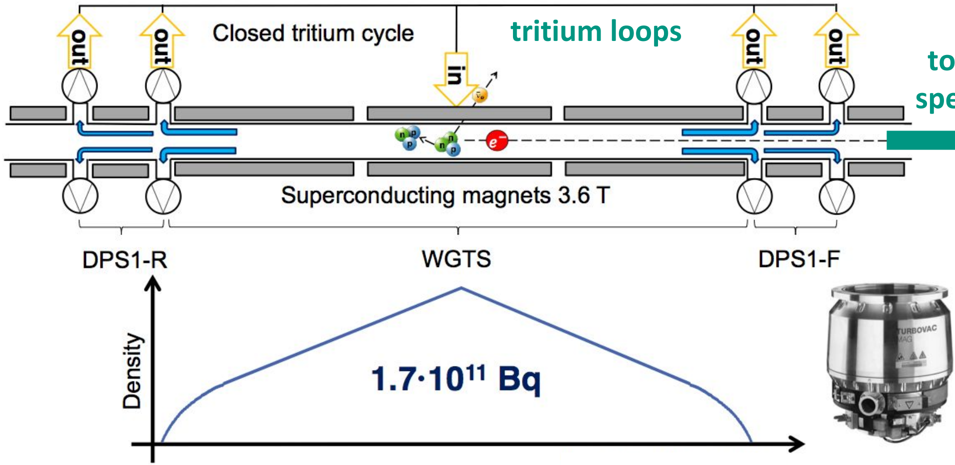
- Pre- & main spectrometer
- Pixelated focal-plane detector



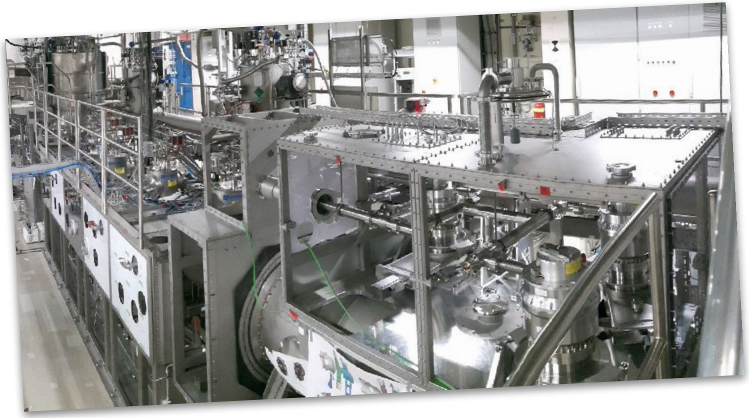
Windowless Gaseous Tritium Source



- Closed tritium cycle, 16 m long cryostat at 30 K, over 800 sensors
- 100 GBq at nominal column density $10^{17}\ \mathrm{cm}^{-2} \Rightarrow$ 40 g/day throughput (ITER scale)
- Mainly T_2 with some isotopologue fractions (H_2, HT, DT, …)
- Required stability < 0.1% at tritium purity > 95%

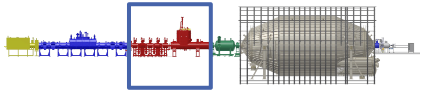


towards spectrom.



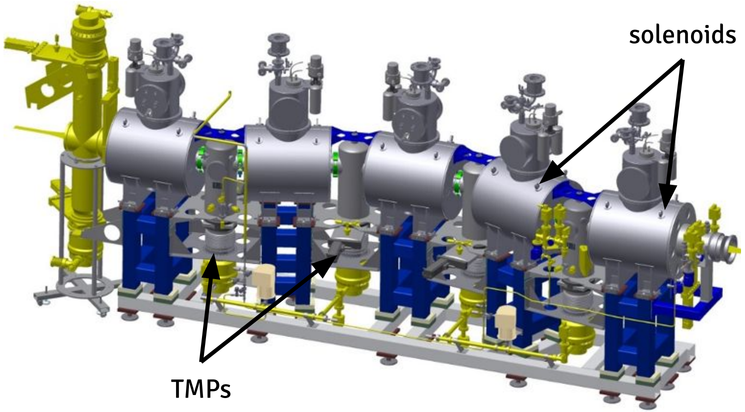
Heizmann *et al.*, JPhys Conf **888** (2017)

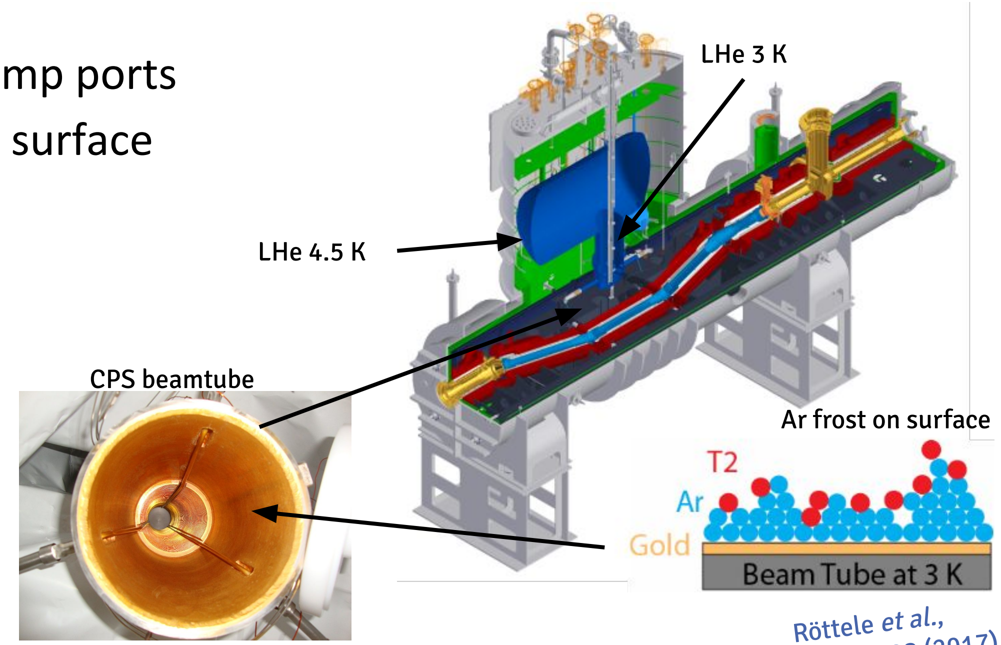
Differential & Cryogenic Pumping Sections



- Reduces tritium flow from WGTS by > 10^{12}
- Two sections with tilted beamline + ion blocking electrodes

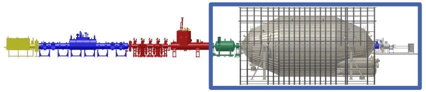
- Differential pumping: 4 TMPs in pump ports
- Cryogenic pumping: Ar frost on 3 K surface





Röttele *et al.*, JPhys Conf **888** (2017)

Spectrometer & Detector Section

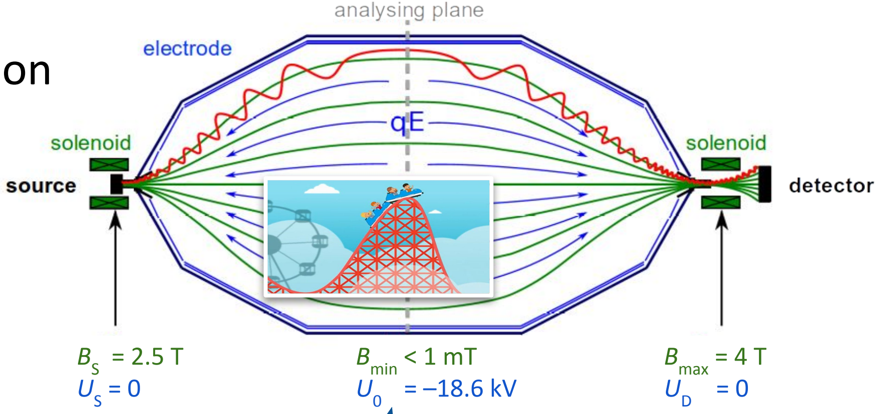


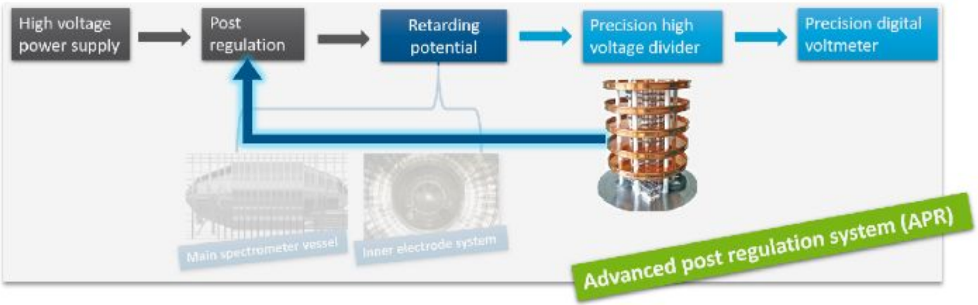
- Energy analysis of signal electrons
- Magnetic guiding field & adiabatic collimation

- MAC-E filter = sharp high-pass filter
  - Retarding potential $qU_0 \approx E_0$
  - Energy resolution 1–3 eV at E_0
  - Electron acceptance angle 51°

- Fast precision HV regulation (20 mV)

- Detector: 148-pixel Si pin-diode, 10 kV post-acceleration

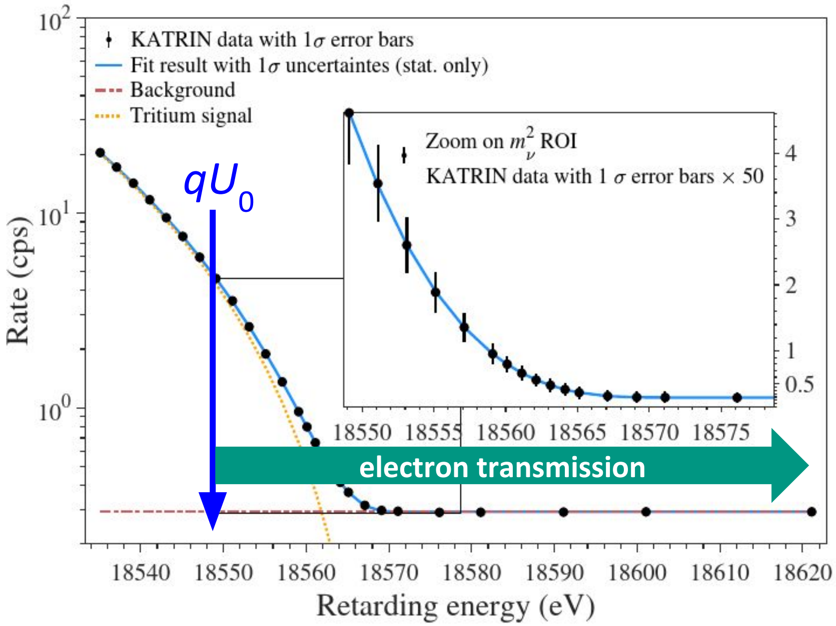


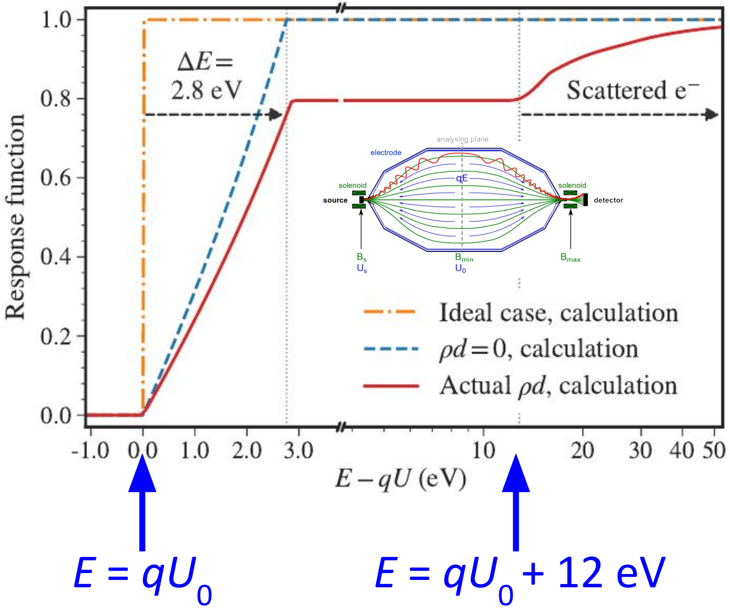


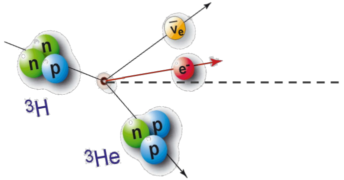
KATRIN collab., NIM A **778** (2015)

KATRIN collab., EPJ C **78** (2018)

High-resolution electron spectroscopy



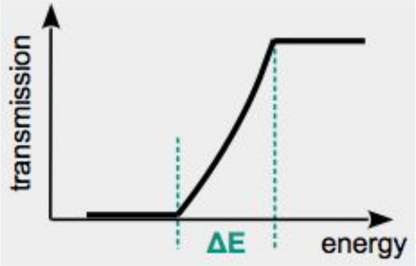


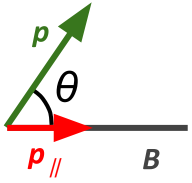


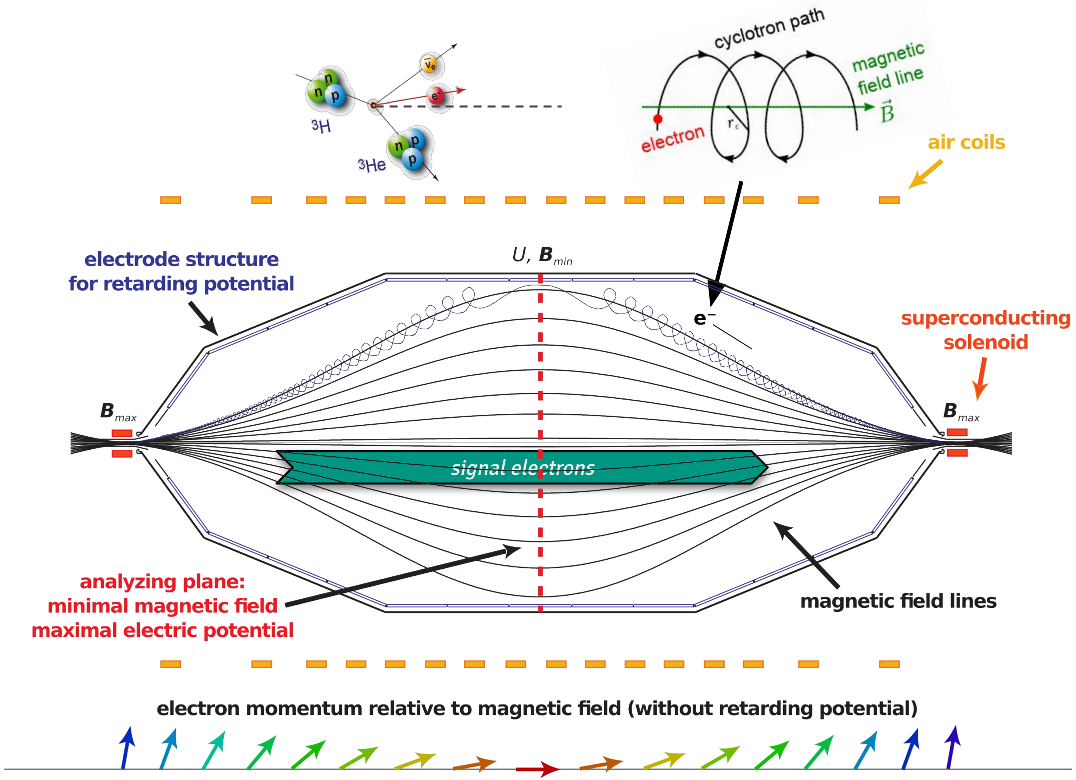
- **Integral spectrum:** count electrons above energy threshold
- MAC-E filter acts as a sharp high-pass filter for isotropic source

The MAC-E filter

- Magnetic **adiabatic collimation**
- Electrostatic **energy filter**



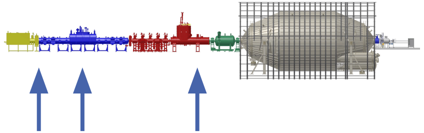




$$\mu = \frac{E_\perp}{B} = \text{const.} \qquad \frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}} \approx 1/20\,000$$

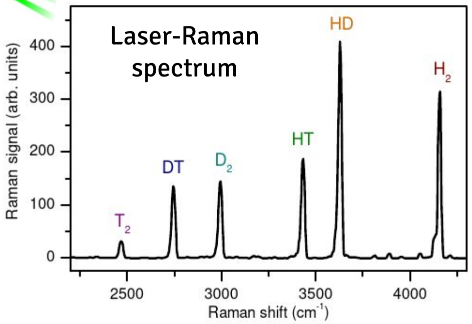
- Momentum transfer $p_\perp \dashrightarrow p_{||}$
- High acceptance angle
- Excellent energy resolution

Monitoring devices



Laser Raman system

- Monitoring of T_2 purity (0.1%)
- Monitoring of gas composition (0.1%)

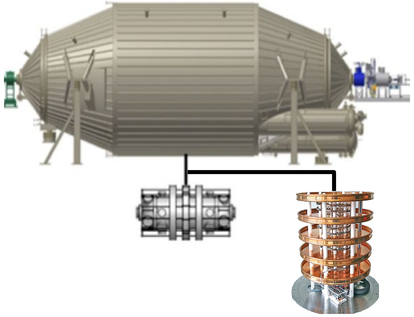


β-induced X-ray spectroscopy + **Forward Beam Monitor**

- Monitoring of source activity (0.1%)

Precision high-voltage system

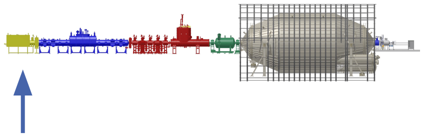
- Monitoring of retarding potential (ppm level)
- Precision high-voltage divider readout chain
- Separate spectrometer measuring ^{83m}Kr lines



Bauer *et al.*, JINST **8** (2013)

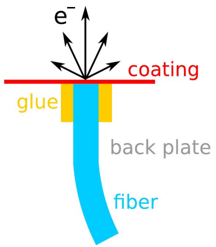
KATRIN collab., Sensors **20** (2020)

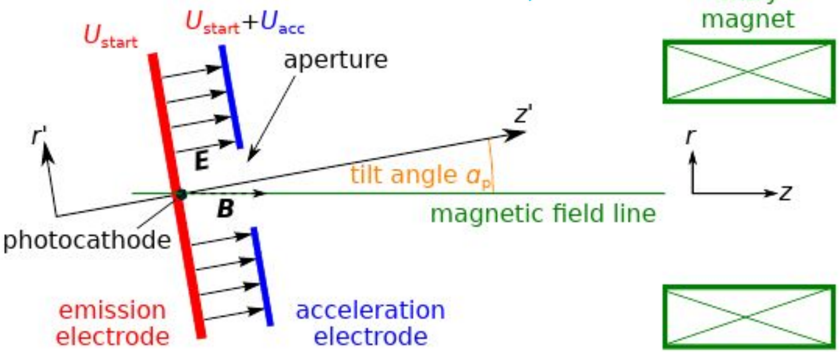
Calibration electron sources



High-intensity electron gun (e-gun)

- Mono-energetic & angular selective source
- Electrons generated via photo-electric effect
- Typical line width 0.15 eV, angular range 0° … 90°
- Pulsed UV laser for time-of-flight mode



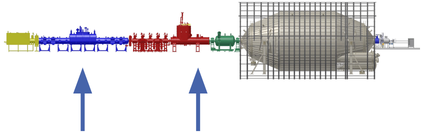


Measurements:

- Spectrometer transmission properties
- Monitoring of column density (< 0.9%)
- Energy loss function measurement

Behrens *et al.*, EPJ C **77** (2017)

Calibration electron sources



Gaseous Krypton source (GKrS)

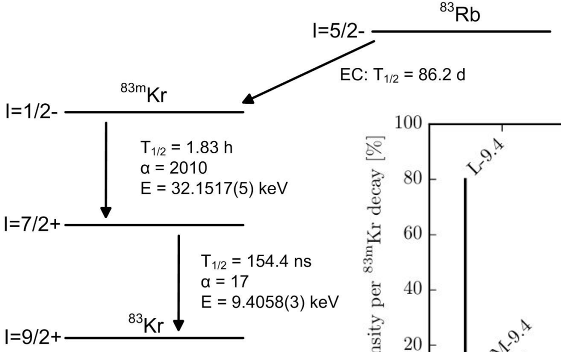
- WGTS filled with ^{83m}Kr gas at 100 K
- Can be combined with tritium mode

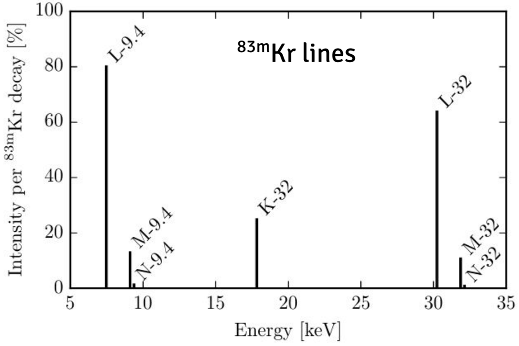
Condensed Krypton source (CKrS)

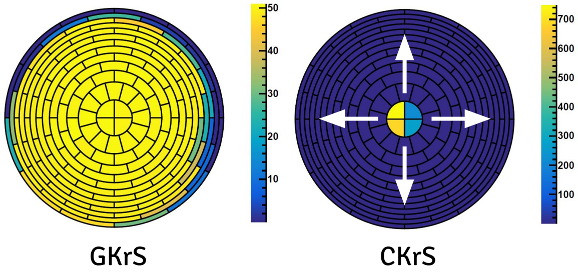
- Located behind transport section
- ^{83m}Kr condensed on cold surface (movable)

Measurements:

- Study source plasma effects
- Transmission & response function







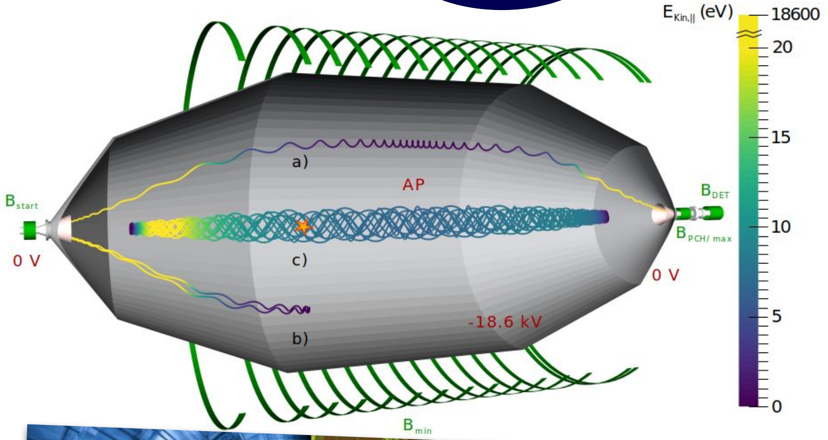
KATRIN collab., JPhys G **47** (2020)

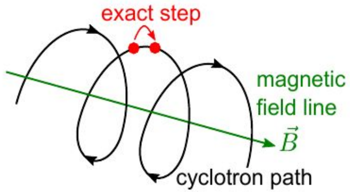
The Kassiopeia simulation software

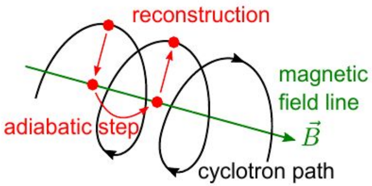
KASPER software framework developed at KATRIN

- Flexible geometry definition & configuration
- Electromagnetic fields: **KEMField**
- Particle tracking: **Kassiopeia**
  https://github.com/KATRIN-Experiment/Kassiopeia

- Precise calculation of electron trajectories
- Handles complex simulation geometries







Furse *et al.*,
NJP **19** 053012 (2017)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KATRIN's measurement timeline

Spring 2020: 3^{rd} neutrino mass run

Fall 2019: 2^{nd} neutrino mass run

Spring 2019: **1^{st} neutrino mass run**

KATRIN collab., PRL 123 221802 (2019)

Fall 2018: Systematics studies

Spring 2018: "First tritium" campaign

KATRIN collab., EPJ C **80** 264 (2020)

Spring 2017: First transmission of electrons

KATRIN collab., JINST **13** P04020 (2018)

KATRIN data-taking periods

KNM1: First neutrino mass run

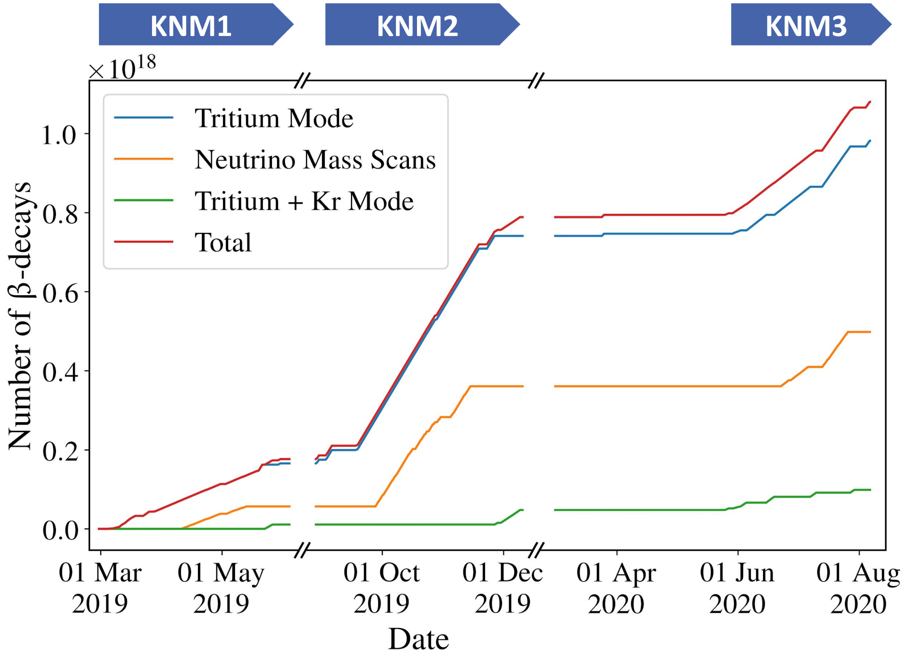
- Measurement time: 22 days
- Source activity: 2.5×10^{10} Bq

KNM2: Second neutrino mass run

- Measurement time: 31 days
- Source activity: 9.8×10^{10} Bq

KNM3: Third neutrino mass run

- Measurement time: 27 days
- Analysis is ongoing



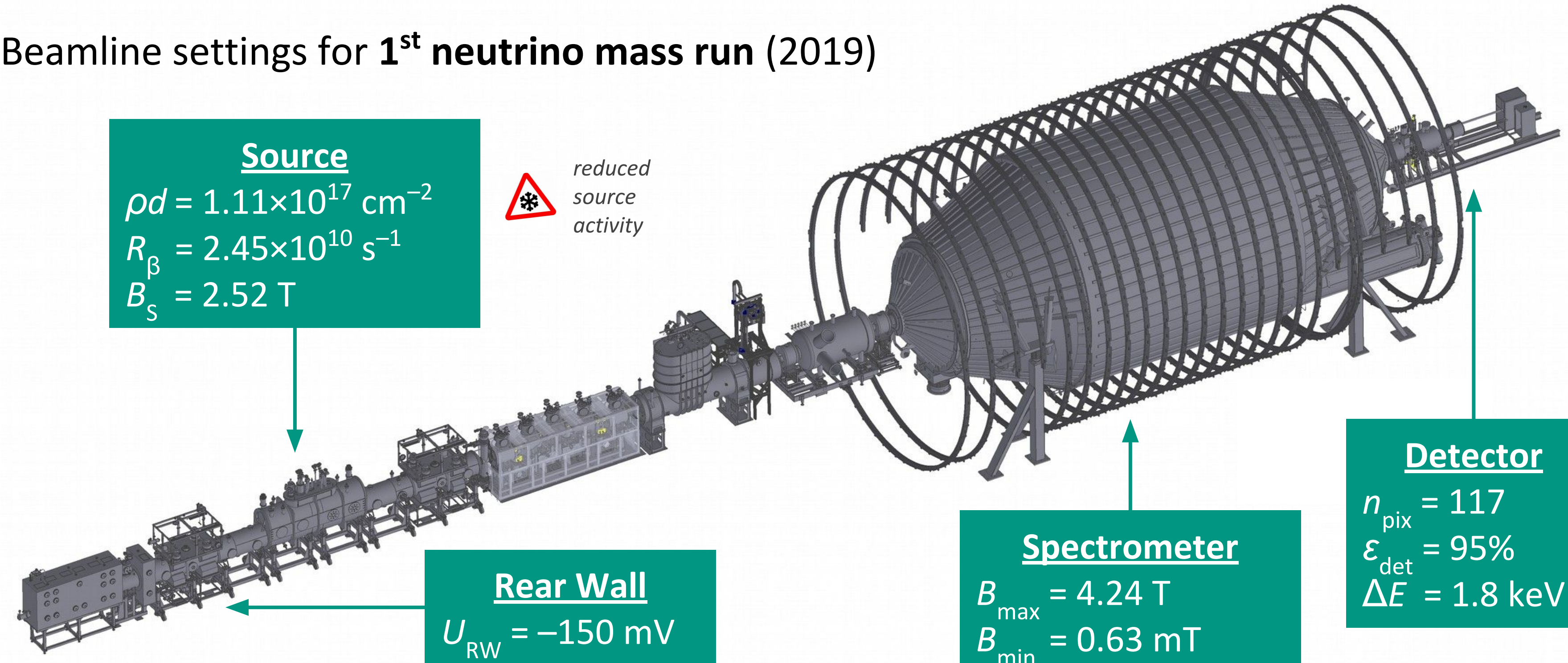
Fourth neutrino mass run started on **August 31**

KATRIN beam line configuration

Beamline settings for **1st neutrino mass run** (2019)

Source
$\rho d = 1.11\times10^{17}\ \mathrm{cm}^{-2}$
$R_\beta = 2.45\times10^{10}\ \mathrm{s}^{-1}$
$B_S = 2.52\ \mathrm{T}$

reduced source activity



Rear Wall
$U_{RW} = -150\ \mathrm{mV}$

Spectrometer
$B_{max} = 4.24\ \mathrm{T}$
$B_{min} = 0.63\ \mathrm{mT}$
$\Delta E = 2.8\ \mathrm{eV}$

Detector
$n_{pix} = 117$
$\varepsilon_{det} = 95\%$
$\Delta E = 1.8\ \mathrm{keV}$

Systematics breakdown

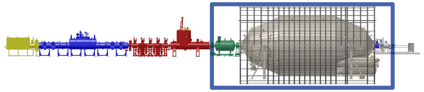
- Background — ✗ dominant
- Magnetic fields — ✓ small
- Final states — ✓ small
- Drifts & fluctuations — ✓ small
- Source scattering — ✓ small
- Energy loss — ✓ negligible

Effect	relative uncertainty	$\sigma(m_\nu^2)$ in eV^2
Source properties		
$\rho d \cdot \sigma$	0.85%	0.05
energy loss $\varepsilon(\delta E)$	$\mathcal{O}(1\%)$	negligible
Beamline		0.05
B_{WGTS}	2.5 %	
B_{min}	1 %	
B_{max}	0.2 %	
Final state distribution	$\mathcal{O}(1\%)$	0.02
Fluctuations in scan k		0.05
HV stacking	2 ppm	
ρd variation	0.8%	
isotopologue fractions	0.2%	
Background		
background slope	1.7%/keV	0.07
non-Poisson background	6.4%	0.30

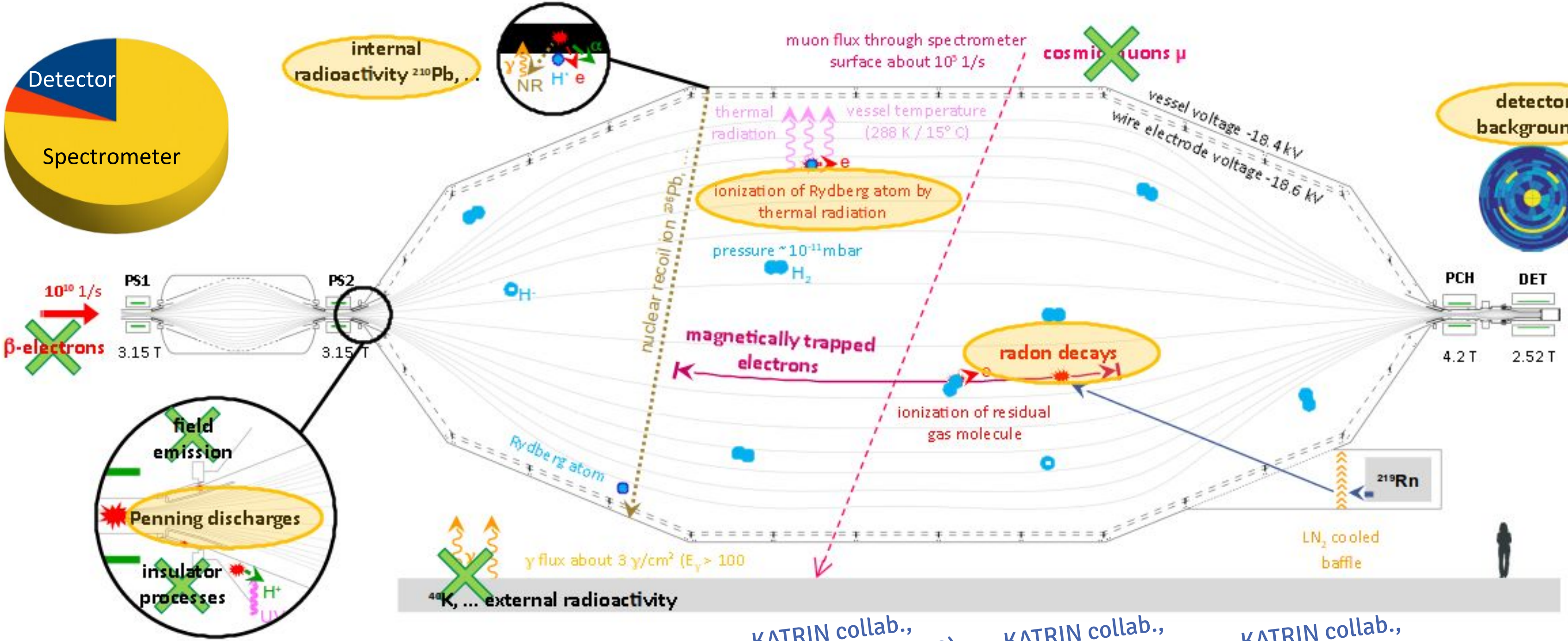
Total systematic uncertainty: **0.32 eV^2**
Total statistical uncertainty: **0.97 eV^2**

KATRIN collab., PRL **123** 221802 (2019)

Background sources at the spectrometer



Majority of spectrometer background sources are under control!



KATRIN collab., AstroP Phys **108** (2019)

KATRIN collab., EPJ C **79** (2019)

KATRIN collab., arXiv:1911.09366

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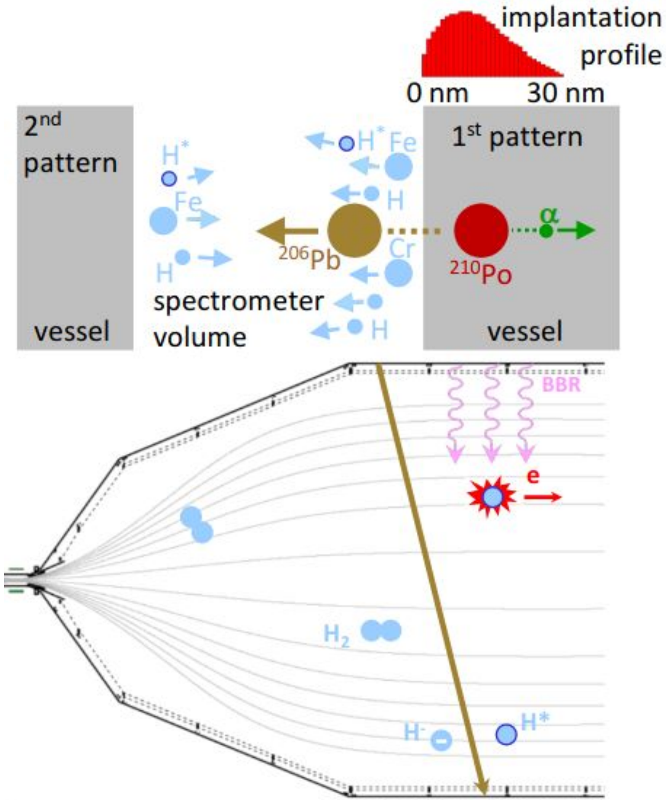
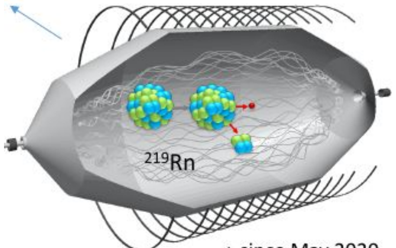
Background from Rydberg atoms



Surprise! – increased background level

- Rn background suppressed
- Volume effect
- ~~Radioactive decays~~
- ~~Trapped particles~~



→ since May 2020
improved radon-retention system

Rydberg background model:

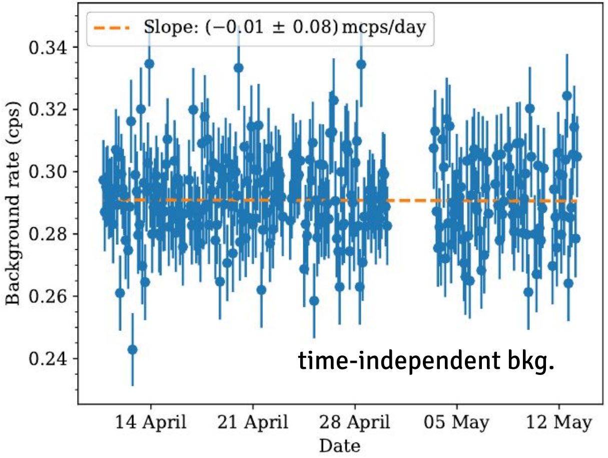
- Rydberg atoms created by ^{210}Pb decay
- Neutral particles can enter spectrometer
- Ionization by thermal radiation (≈ 300 K)
- Electrons gain energy from el. potential

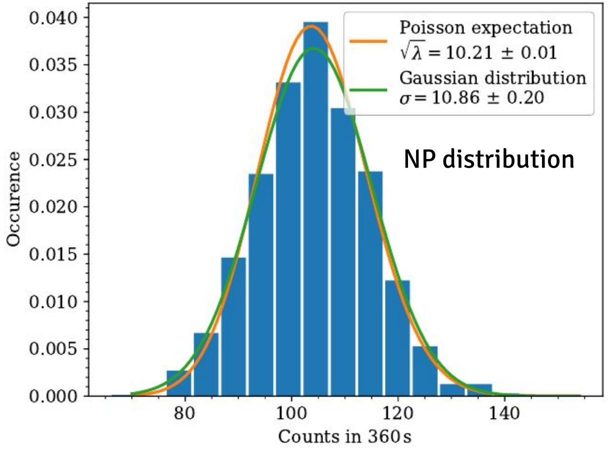
Fränkle *et al.*, J Phys Conf **888** (2017)

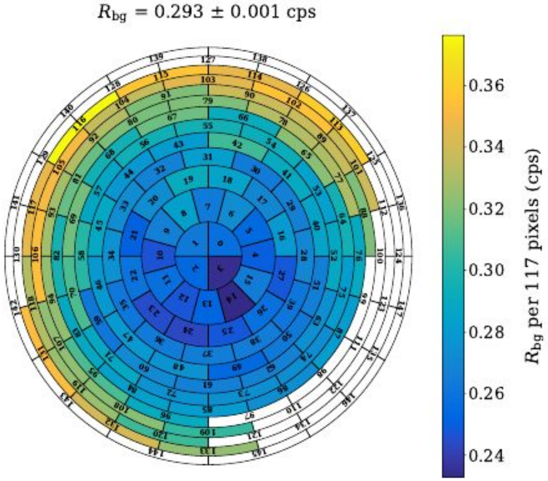
Remaining background & countermeasures

Two remaining sources: **Rydberg ionization & Radon decays**

- Very stable rate during first neutrino-mass runs
- Non-Poissonian distribution increases sensitivity impact
- Some countermeasures exist – further improvements!



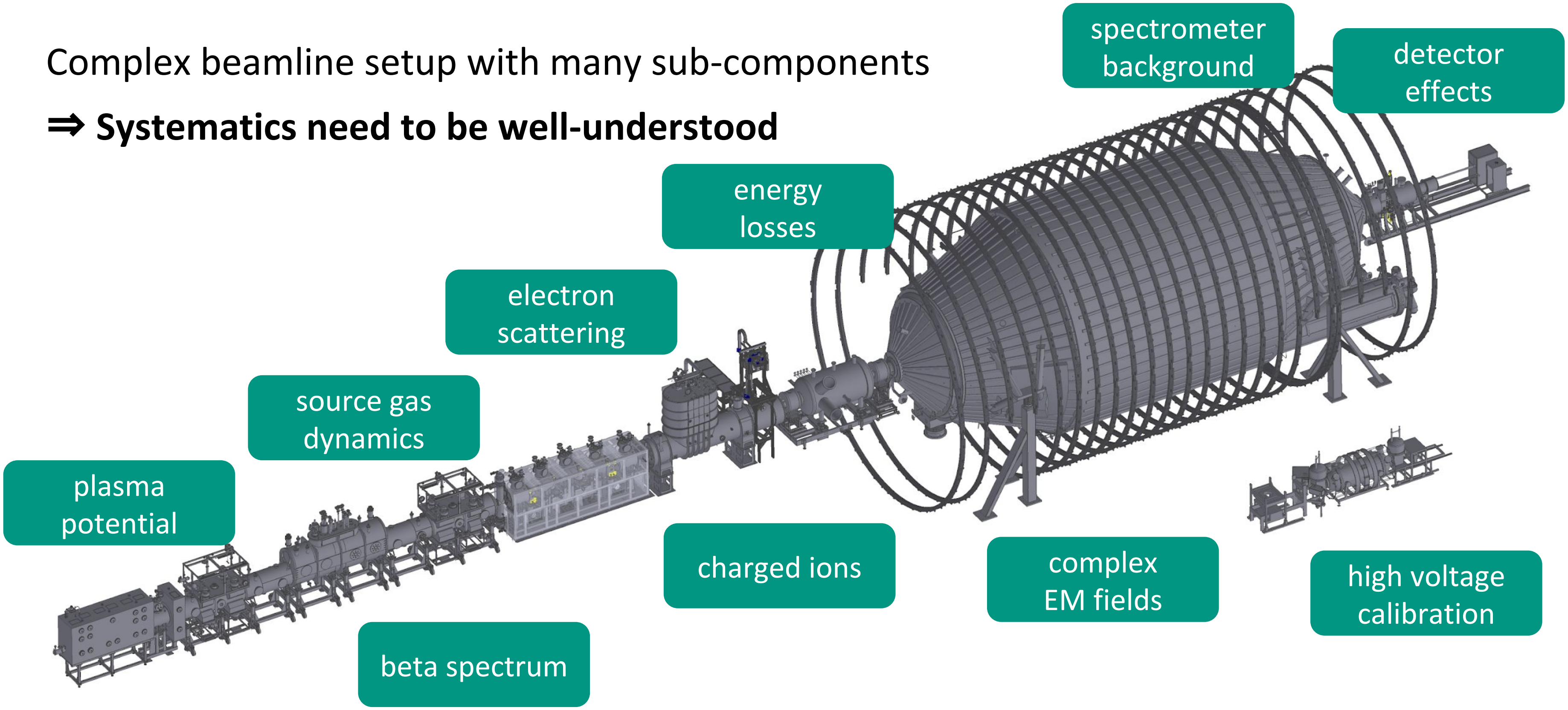




Sources of systematics

Complex beamline setup with many sub-components

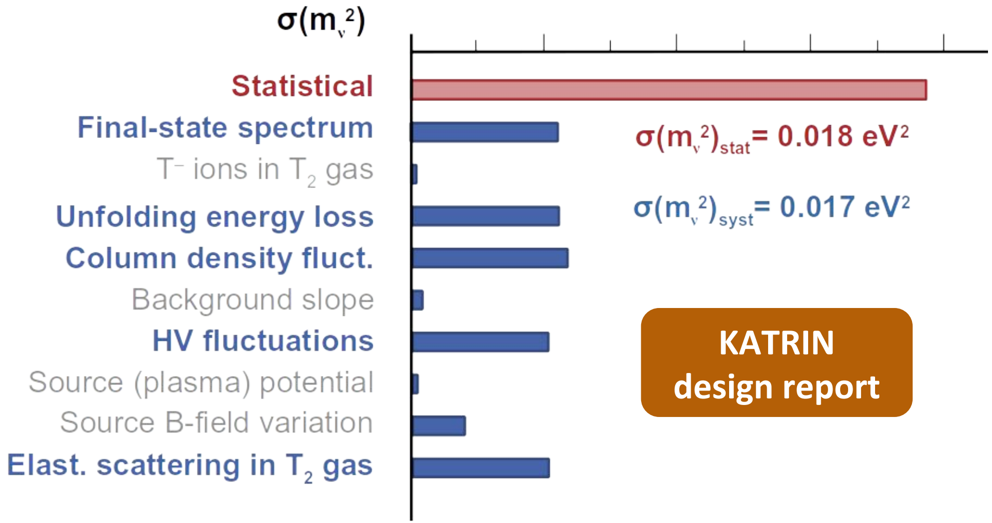
⇒ **Systematics need to be well-understood**

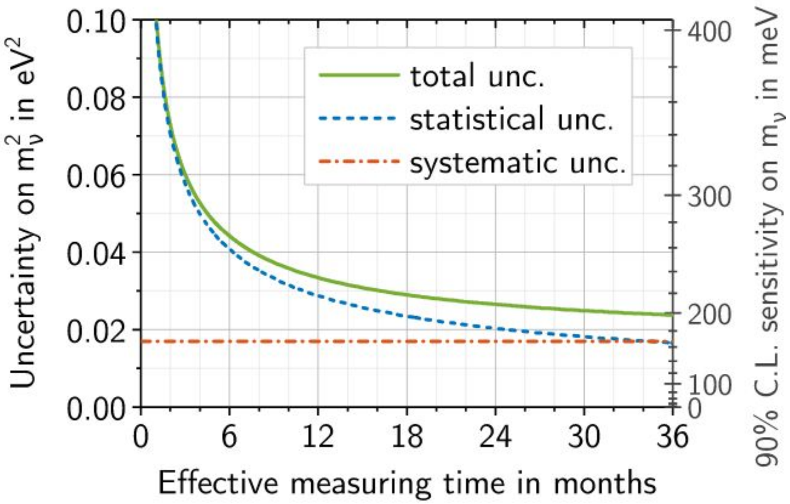


Systematic uncertainty budget

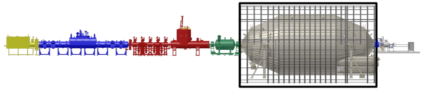
KATRIN design report (2004) identified five major systematics

- Systematic budget 0.017 eV^2 matches statistical uncertainty for 3 yrs data
- First science runs dominated by statistical uncertainty



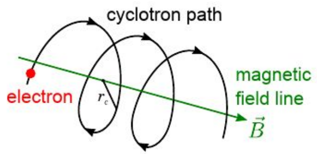


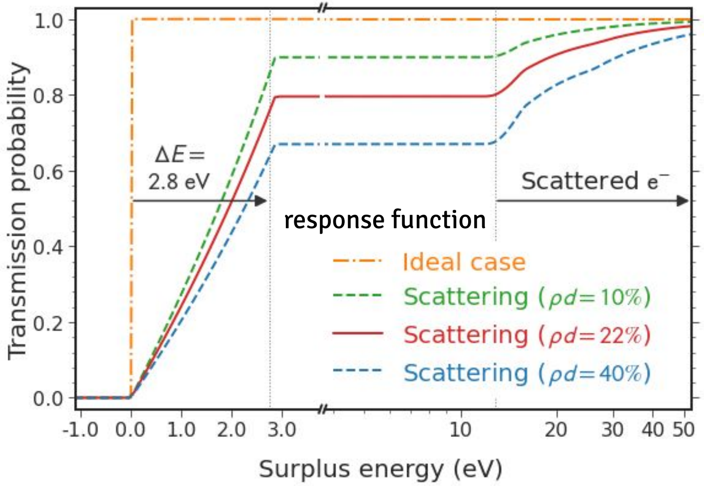
Transmission & response function



MAC-E filter transmission + energy losses

- Radial inhomogeneity of spectrometer fields
- Cyclotron radiation over 70 m flight path
- Electron scattering on tritium molecules

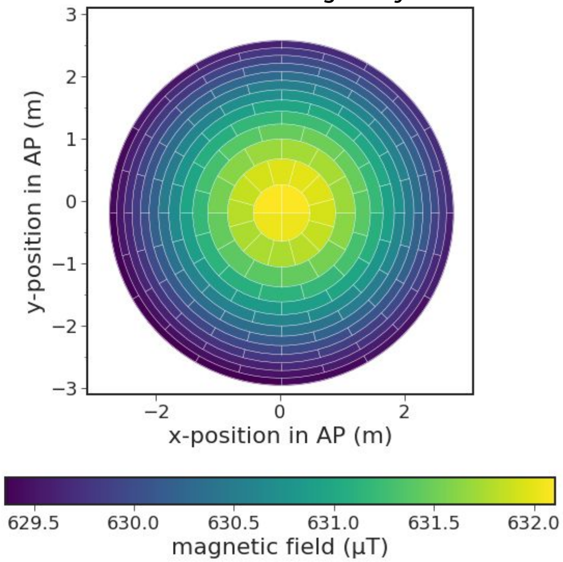




$$\frac{\Delta E}{E} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}$$

$$P_s = \frac{(\rho d \sigma)^s}{s!} \mathrm{e}^{-\rho d \sigma}$$

radial inhomogeneity



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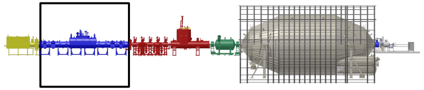
Source column density

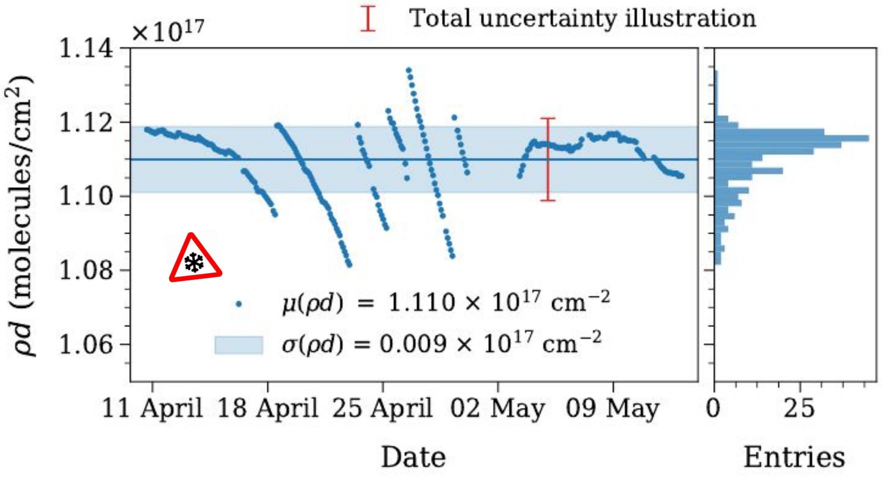


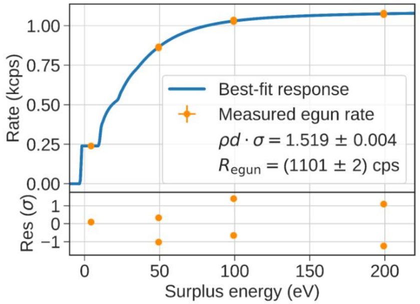
- Determines source activity & electron scattering
- Regular calibration measurements with e-gun

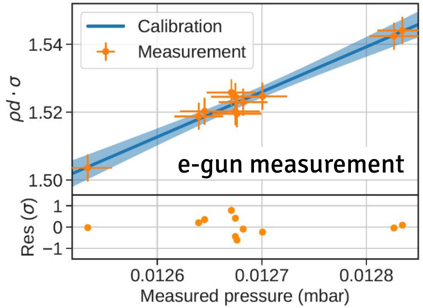
$$N_T = 2\epsilon_\mathrm{T} \cdot \rho d \cdot A$$

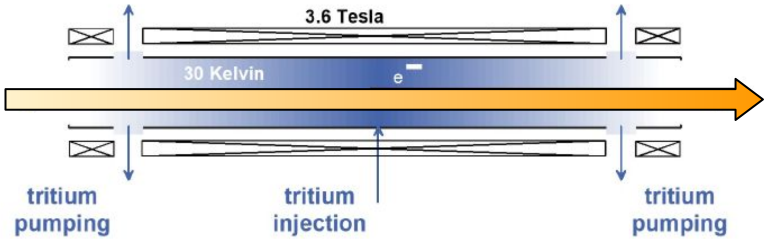
$$P_s = \frac{(\rho d \sigma)^s}{s!} \mathrm{e}^{-\rho d \sigma}$$

- Fluctuations due to TH_4 freezing → *solved!*

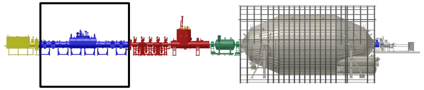






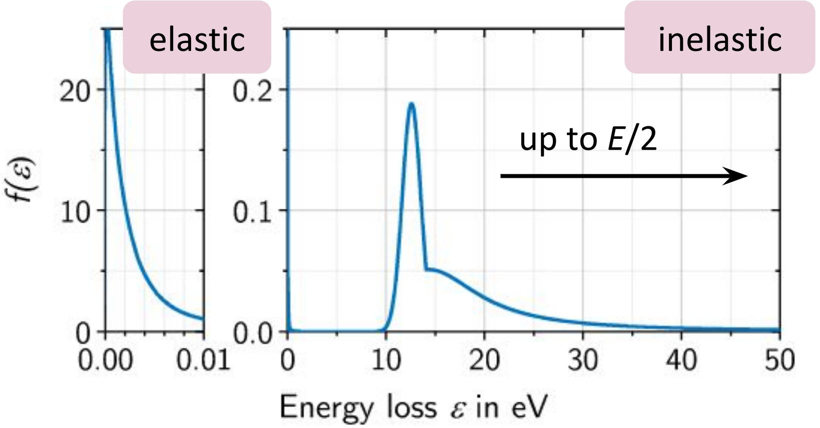


Source electron scattering



- Elastic + inelastic scattering on tritium gas
- Described by energy loss function $f(\epsilon)$

- Convoluted for multiple scatterings
- Poisson statistics: scattering probabilities P_s



$$R(E,U) = \int_{\epsilon=0}^{E-qU} T(E-\epsilon, U) \cdot \left[P_0 + P_1\, f(\epsilon)\, \delta(\epsilon) + P_2\, (f \otimes f)(\epsilon) + \ldots \right] \mathrm{d}\epsilon$$

spectrometer transm. function | no scattering | scattered once | scattered twice

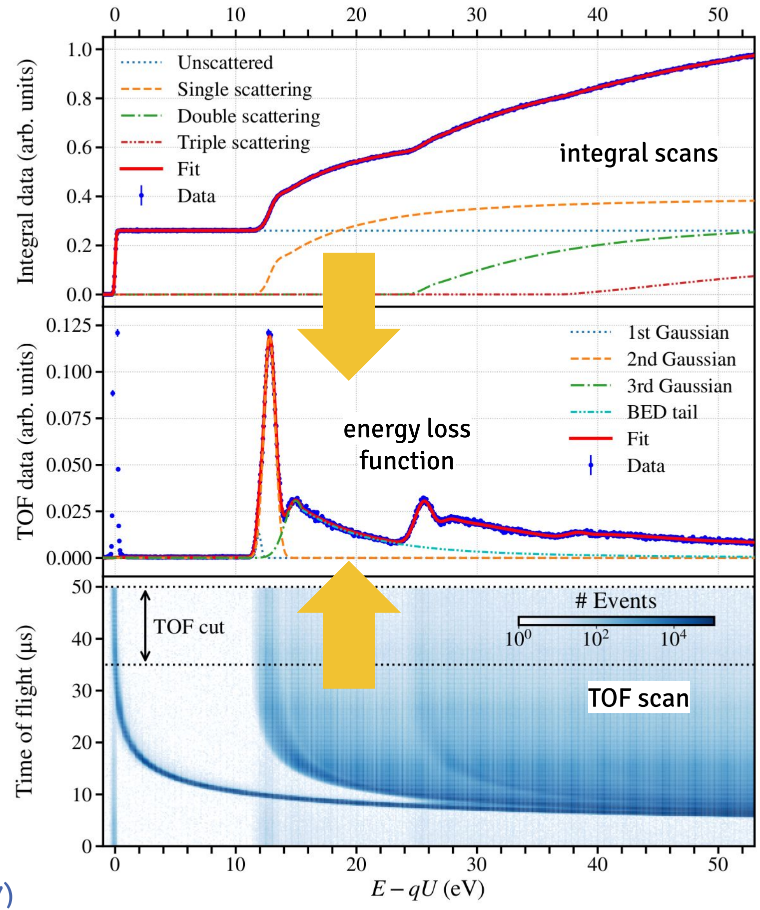
Energy loss function

Measurements with calibration sources

- Electrons provided by pulsed e-gun
- Integral (rate) or differential (TOF) mode

- Energy loss due to scattering reduces rate
- Direct measurement of p.d.f. in TOF mode
- Combined fit yields energy loss function

- Semi-empirical parameterization (peaks + tail)
- Systematic uncertainties under investigation

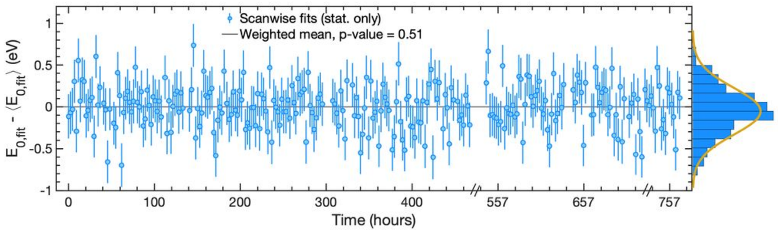


Hannen *et al.*, AstroP Phys **89** (2017)

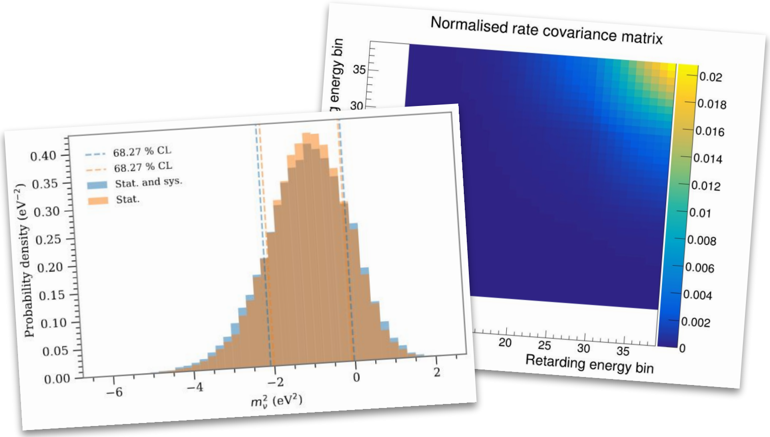
Data analysis

First **22 days of KATRIN data** with sensitivity to neutrino mass

endpoint stability



- New analysis & unblinding procedure:
  - Analysis on "MC twin" data sets (m=0)
  - Run fits on blinded data sets
  - Extract final results from unblinded data

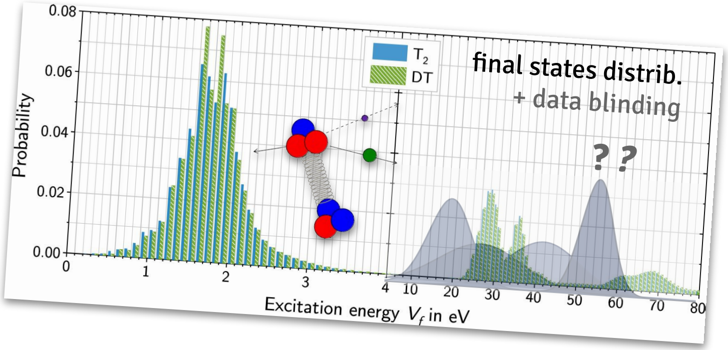


- Inclusion of systematic uncertainties:
  - Covariance matrix
  - MC propagation

Unblinding strategy

KATRIN is not the usual low-background counting experiment!

- Before unblinding: Fix all inputs & run fits on Monte Carlo data
- After unblinding: Fit to measurement data with free neutrino mass



- Need full spectral data to study systematics
- Requires novel approach to data blinding

- Solution for **data-blinding at KATRIN**:
  - Model spectrum includes final state excitations in molecular T_2
  - Final states distribution partially replaced by unknown Gaussian
  - Systematic studies with inaccessible $m_{\bar{\nu}}^2$

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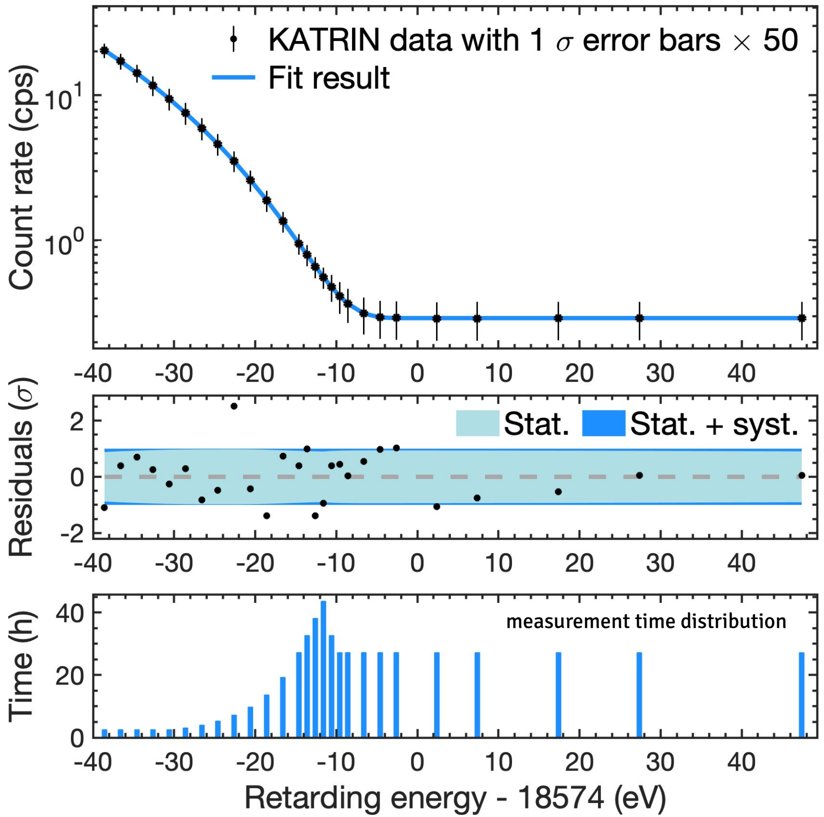
New upper limit on the neutrino mass



- Integral beta spectrum over **90 eV** range
- Data displayed with **50 × 1-σ** error bars
- Residuals relative to 1-σ band of best-fit

Quick facts:

- Single fit with 4 parameters
- 27 voltage set points × 274 runs
- Total scanning time 521.7 h ≈ 22 d
- 2.03×10^6 events after cuts

KATRIN collab., PRL **123** 221802 (2019)

New upper limit on the neutrino mass

Final result obtained from **best-fit value** using **MC propagation**

Best-fit results:

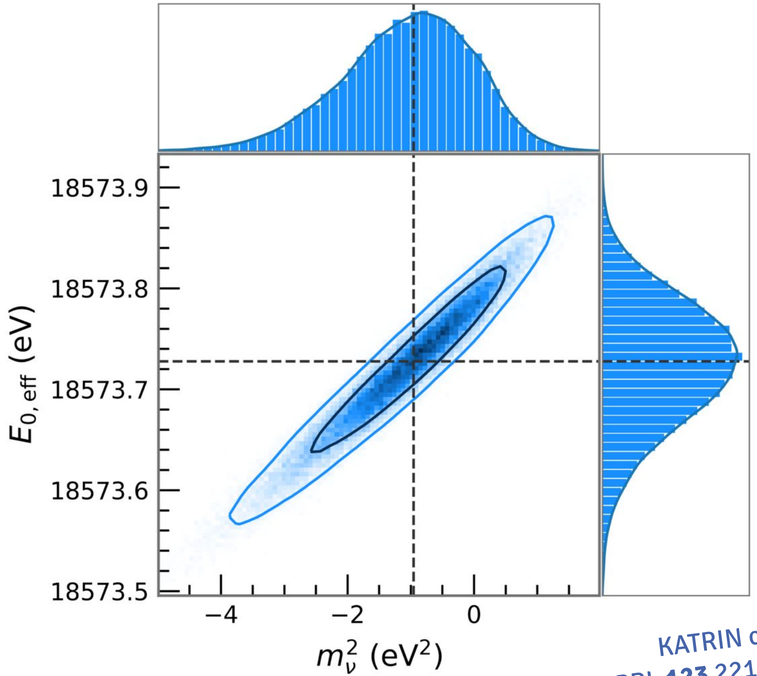
$$m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\ \mathrm{eV}^2$$

- compatible with zero
- 16% probability if true *m* = 0

$$E_0 = 18573.7 \pm 0.1\ \mathrm{eV}$$

- *Q*-value: 18575.2 ± 0.5 eV
- Good agreement with literature

(reference: *Q* = 18575.72 ± 0.07 eV) Myers et al., PRL **114** 013003 (2015)



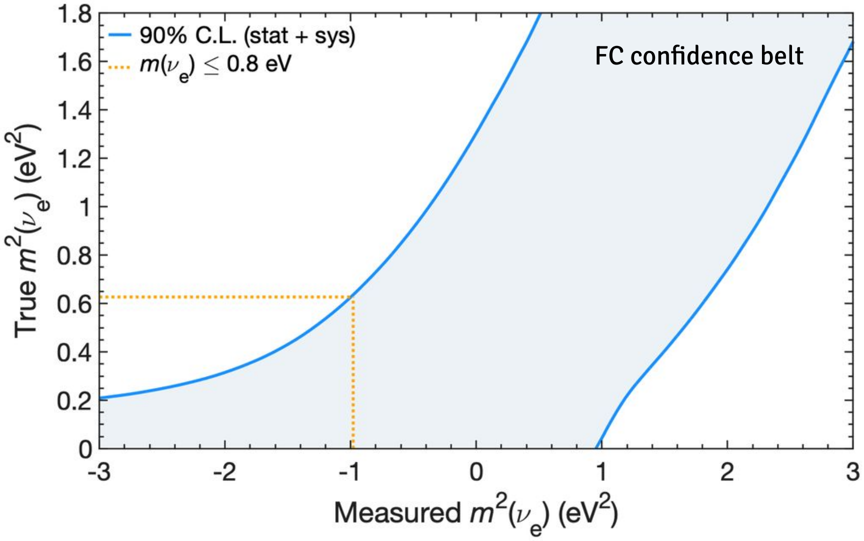
KATRIN collab., PRL **123** 221802 (2019)

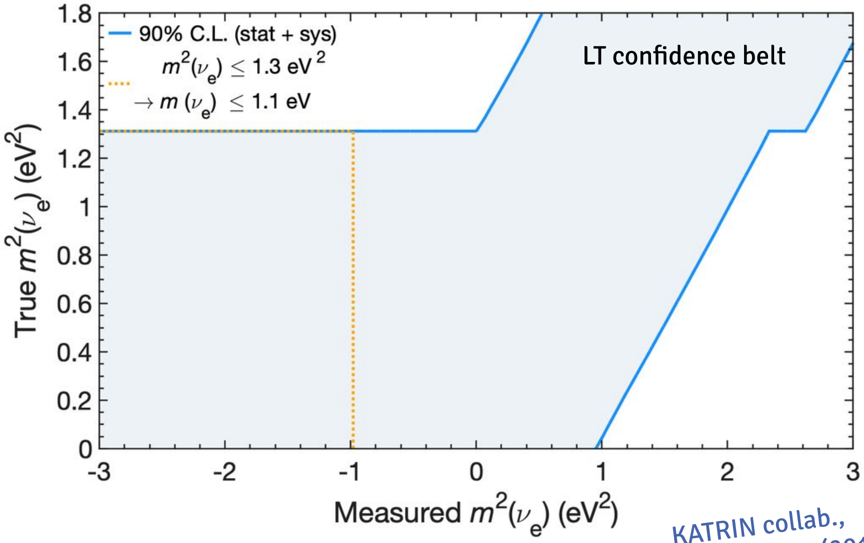
New upper limit on the neutrino mass

Final result obtained from **best-fit value** using **MC propagation**

- Fully dominated by statistical uncertainty
- Upper limit: $m_\nu < 1.1$ eV (90% CL) = sensitivity (*Lokhov-Tkachov* approach)

Lokhov & Tkachov, PP Nuc. **46** 347 (2015)





KATRIN collab., PRL **123** 221802 (2019)

Sterile neutrinos

Kinematic method opens window to sterile neutrinos

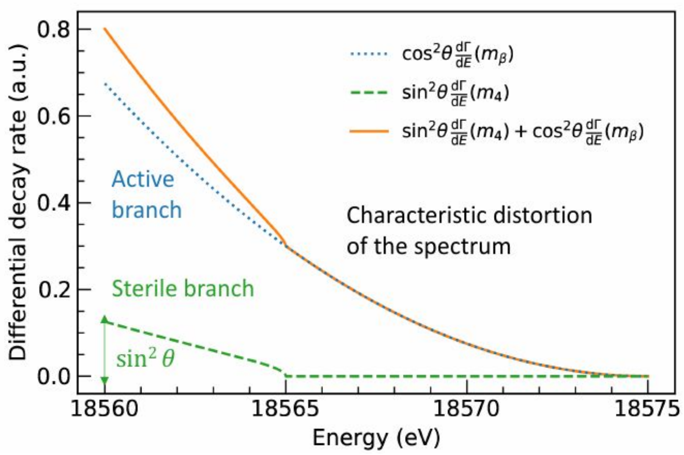
- Characteristic signature: spectral distortion

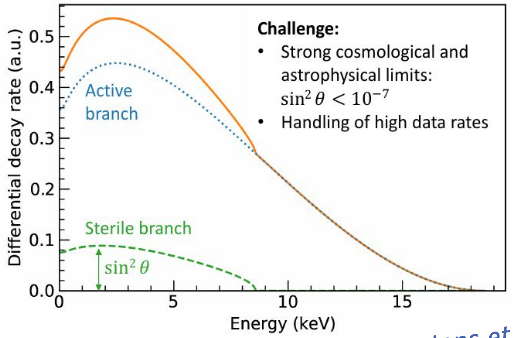
Search for **eV-scale sterile neutrinos**

- Improve current exclusion limits
- Probe RAA region in future campaigns
- Investigate Neutrino-4 hint

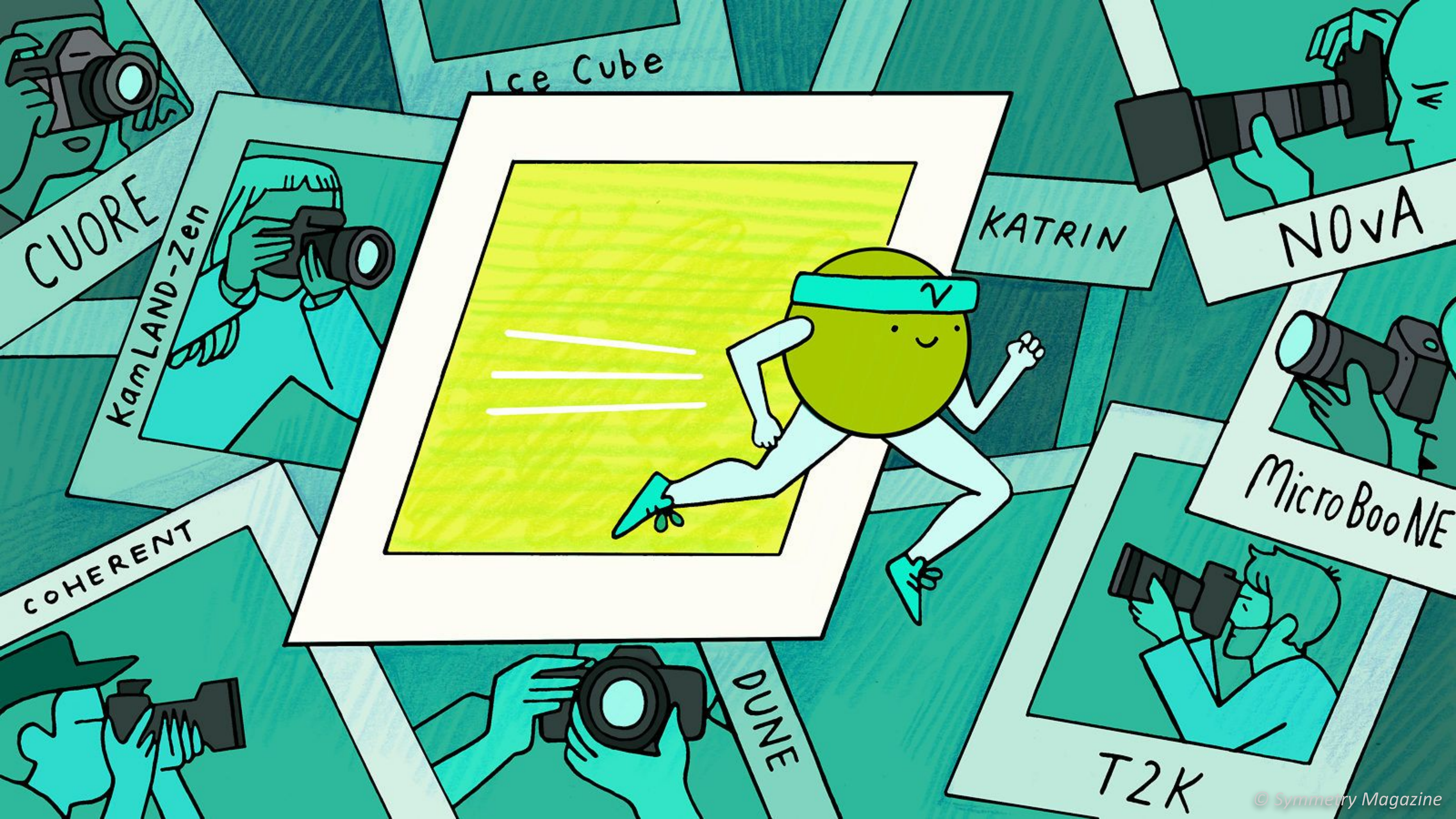
Search for **keV-scale sterile neutrinos**

- Proof-of-principle (KATRIN deep scan)
- Future upgrade: TRISTAN detector

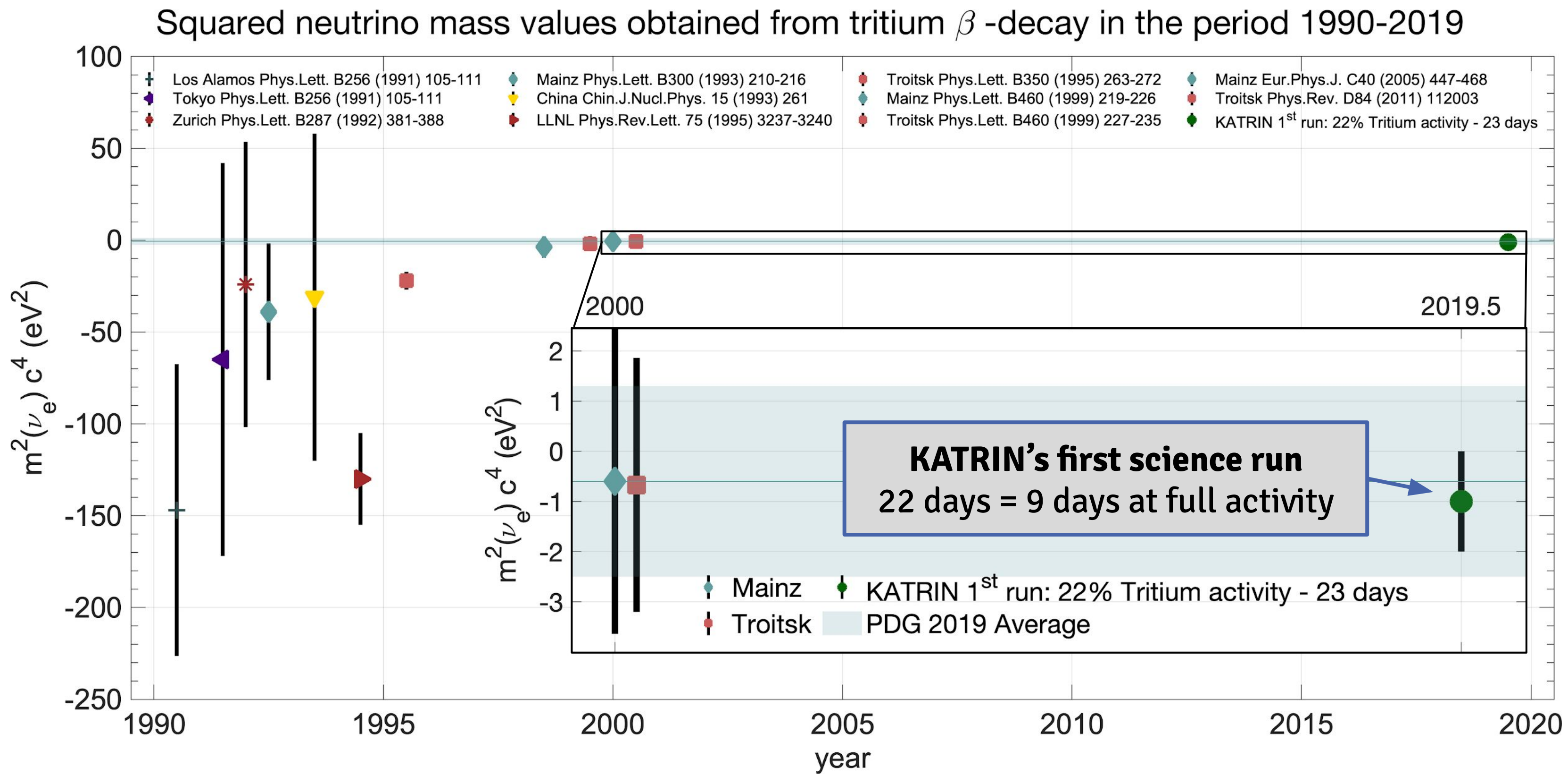




Mertens *et al.*, JPG **46** 065203 (2019)


Ice Cube
CUORE
KamLAND-Zen
KATRIN
NOvA
ν
MicroBooNE
COHERENT
DUNE
T2K

Direct neutrino mass measurements



KATRIN's measurement timeline

2020 & beyond: *successive data-taking*

Spring 2020: 3rd neutrino mass run

Fall 2019: 2nd neutrino mass run

Spring 2019: 1st neutrino mass run

Fall 2018: Systematics studies

Spring 2018: "First tritium" campaign

Spring 2017: First transmission of electrons

KATRIN collab., PRL 123 221802 (2019)

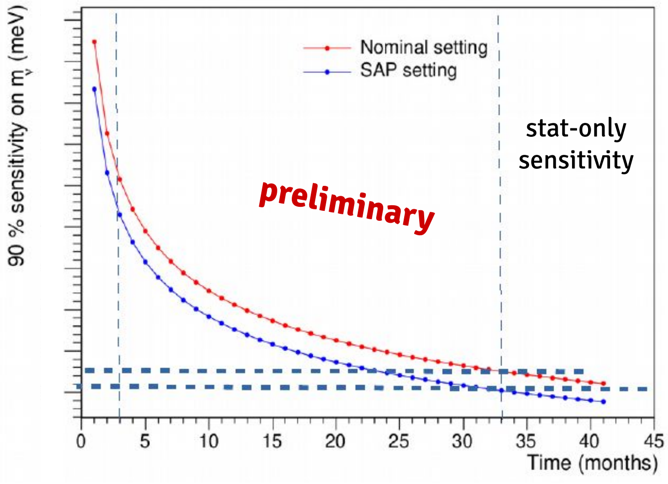
KATRIN collab., EPJ C **80** 264 (2020)

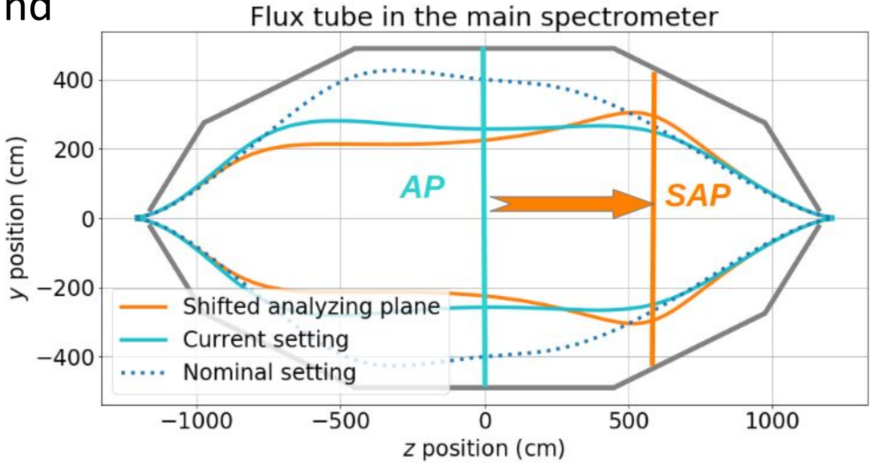
KATRIN collab., JINST **13** P04020 (2018)

Background with Shifted Analyzing Plane

Spectrometer background is volume-dependent

- Smaller "fiducial" volume reduces background
- Flexible operation: shifted analyzing plane
- Strong impact on NP background





Next data-taking run in "SAP" mode

- Improves statistical uncertainty
- Systematics under investigation

Outlook

THANK YOU!

- **KATRIN** published first **upper limit** in 2019
  - 1.1 eV sensitivity after only 22 days – goal: 3 years
  - Already 2× improvement on prior upper limits

- Latest **data-taking** period started just now
- Analysis ongoing, publications in preparation :-)

- Next steps to improve experiment & model:
  - Non-Poisson background reduction
  - Precision final state calculations
  - Understanding of source plasma effects
  - *… and more!*

The KATRIN experiment is now up & running!

Final sensitivity goal:
0.2 eV (90% CL)

Funding and support from: *Helmholtz Association (HGF), Ministry for Education and Research BMBF (05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), Helmholtz Alliance for Astroparticle Physics (HAP), and Helmholtz Young Investigator Group (VH-NG-1055) in Germany; Ministry of Education, Youth and Sport (CANAM-LM2011019), cooperation with the JINR Dubna (3+3 grants) 2017–2019 in the Czech Republic; and the Department of Energy through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, DE-SC0011091, and DE-SC0019304 in the United States.*