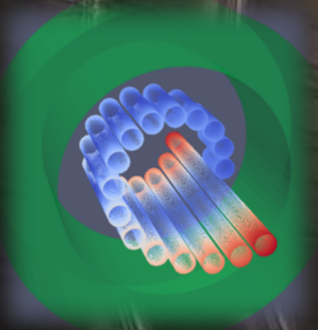
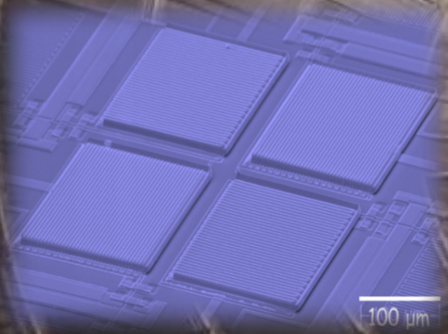
First results from the KATRIN experiment

Susanne Mertens
NDM-2020



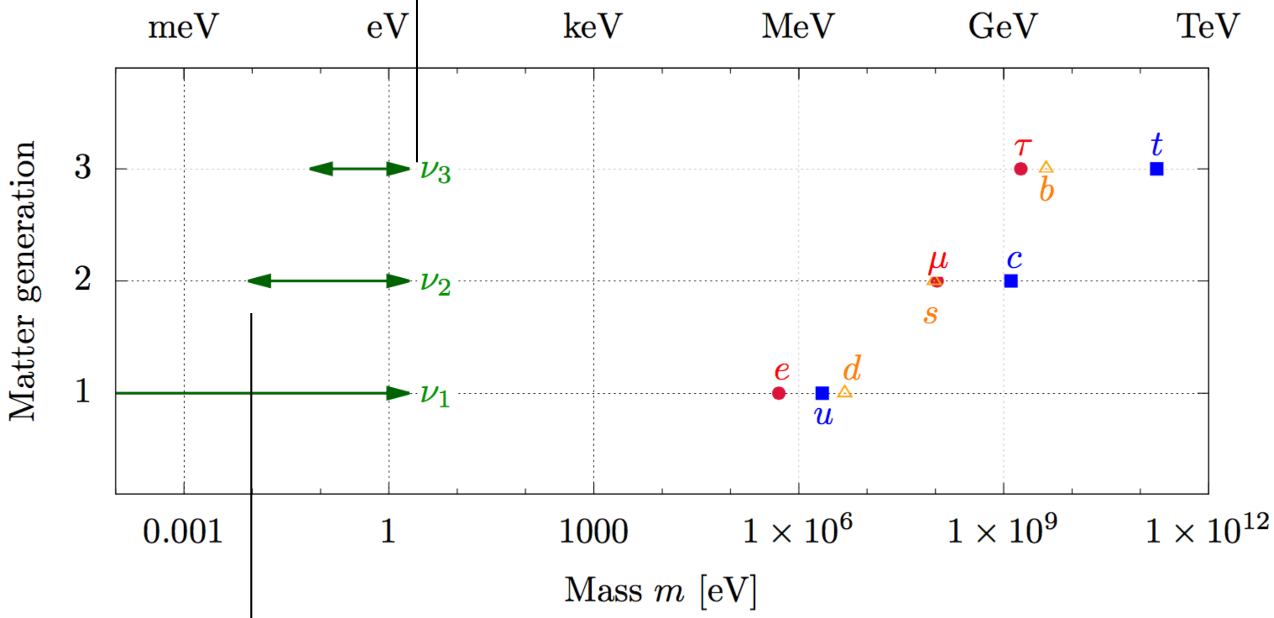


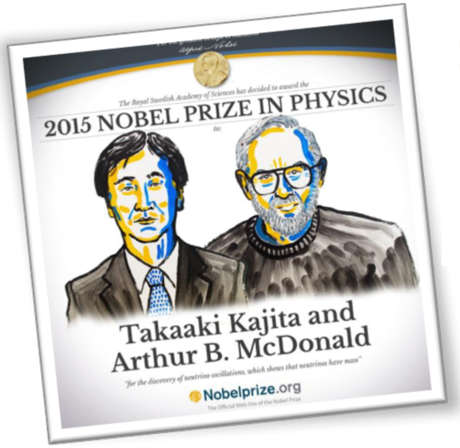
Prof. Dr. Susanne Mertens

Technical University Munich & Max Planck Institute for Physics

Neutrino mass

Upper bound
from laboratory measurements





Lower bound
from oscillation experiments

Neutrino mass

Cosmology

model-dependent
potential: m_ν = 15-50 meV
e.g. Planck

$$m_{cosmo} = \sum_i m_i$$

Search for 0νßß

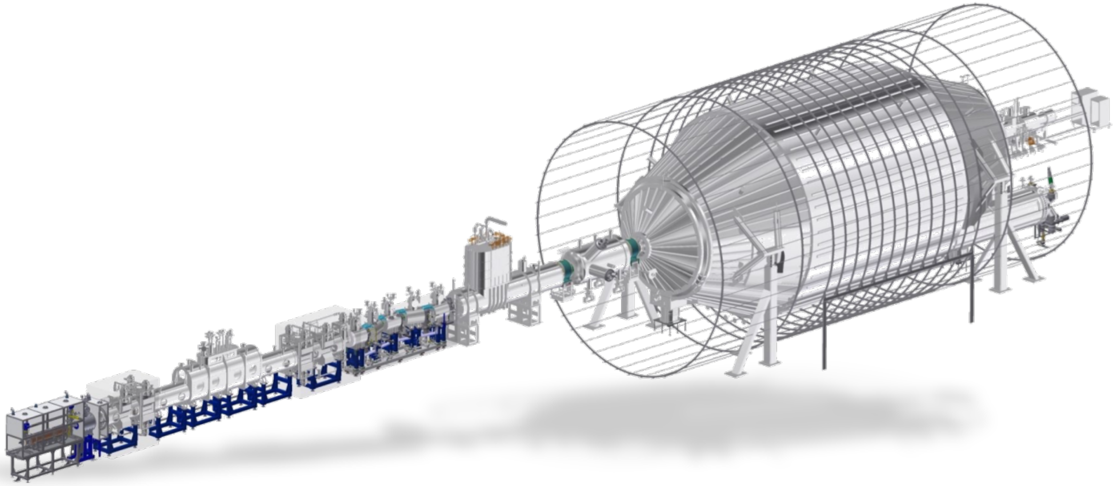
Laboratory-based
potential: $m_{ßß}$ = 15-50 meV
e.g. LEGEND

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

Kinematics of ß-decay

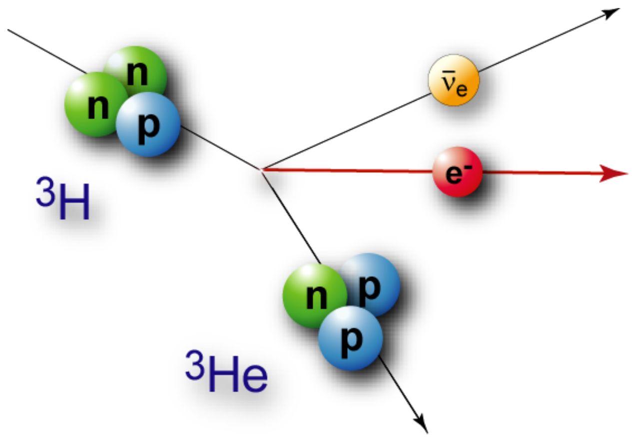
Laboratory-based
potential: m_β = 50 - 200 meV
e.g. KATRIN

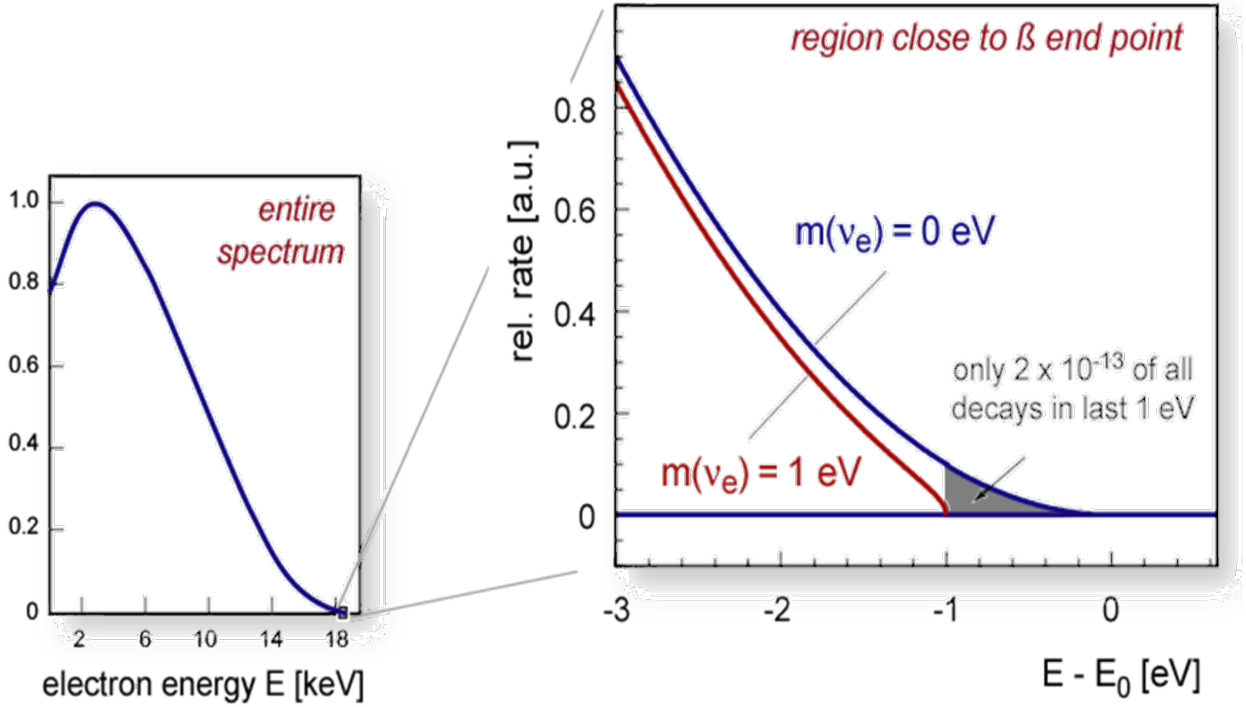
$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



General idea

- Kinematic determination of the neutrino mass
- Non-zero neutrino mass distorts the spectrum close to the endpoint





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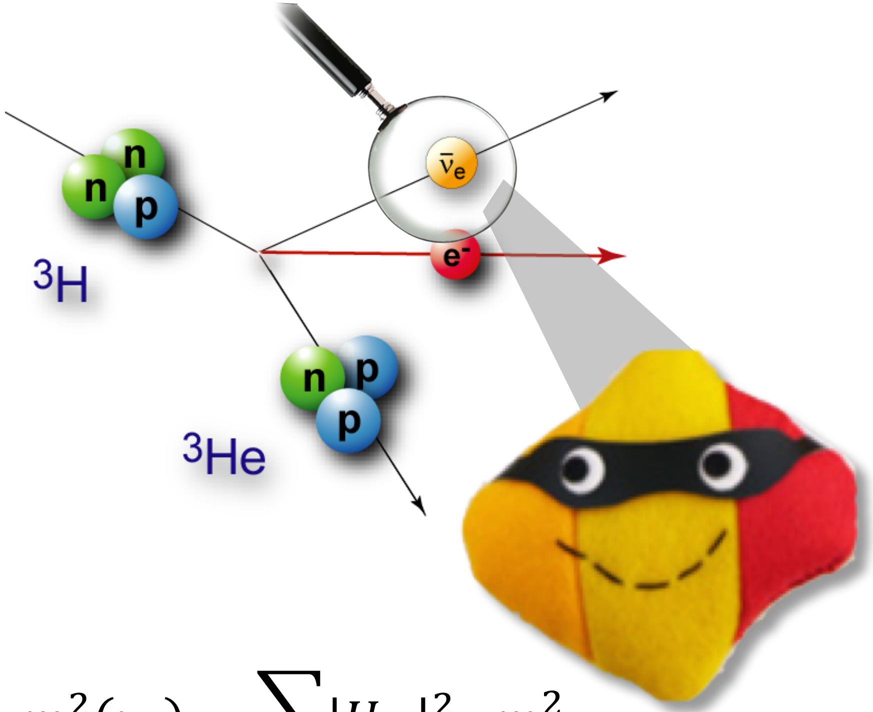
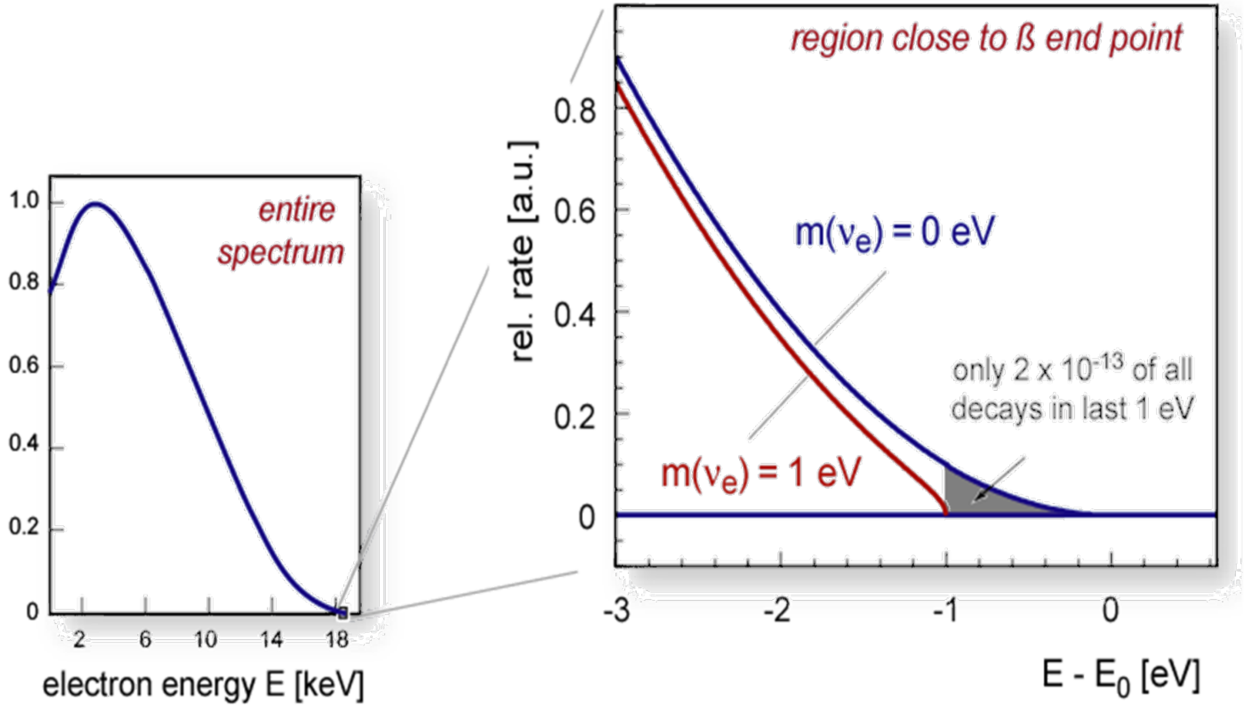


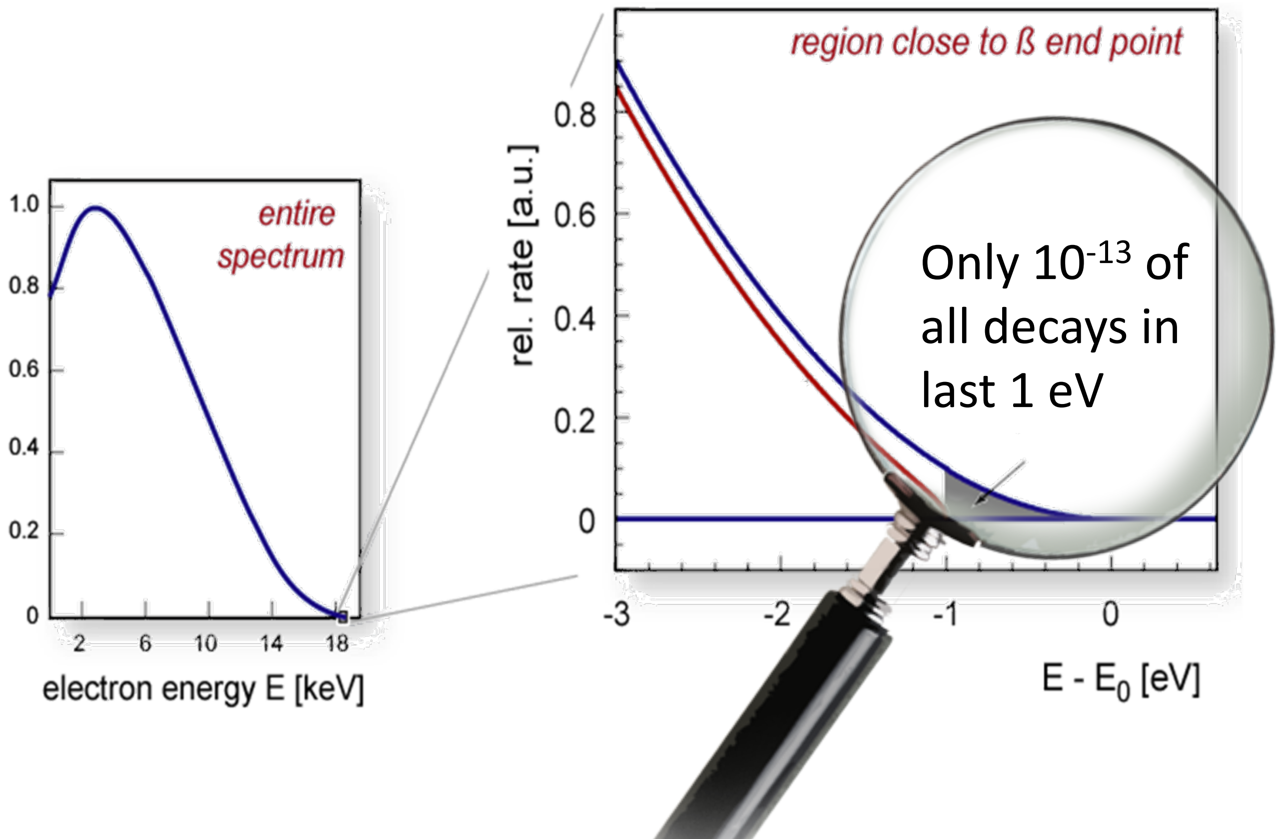
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



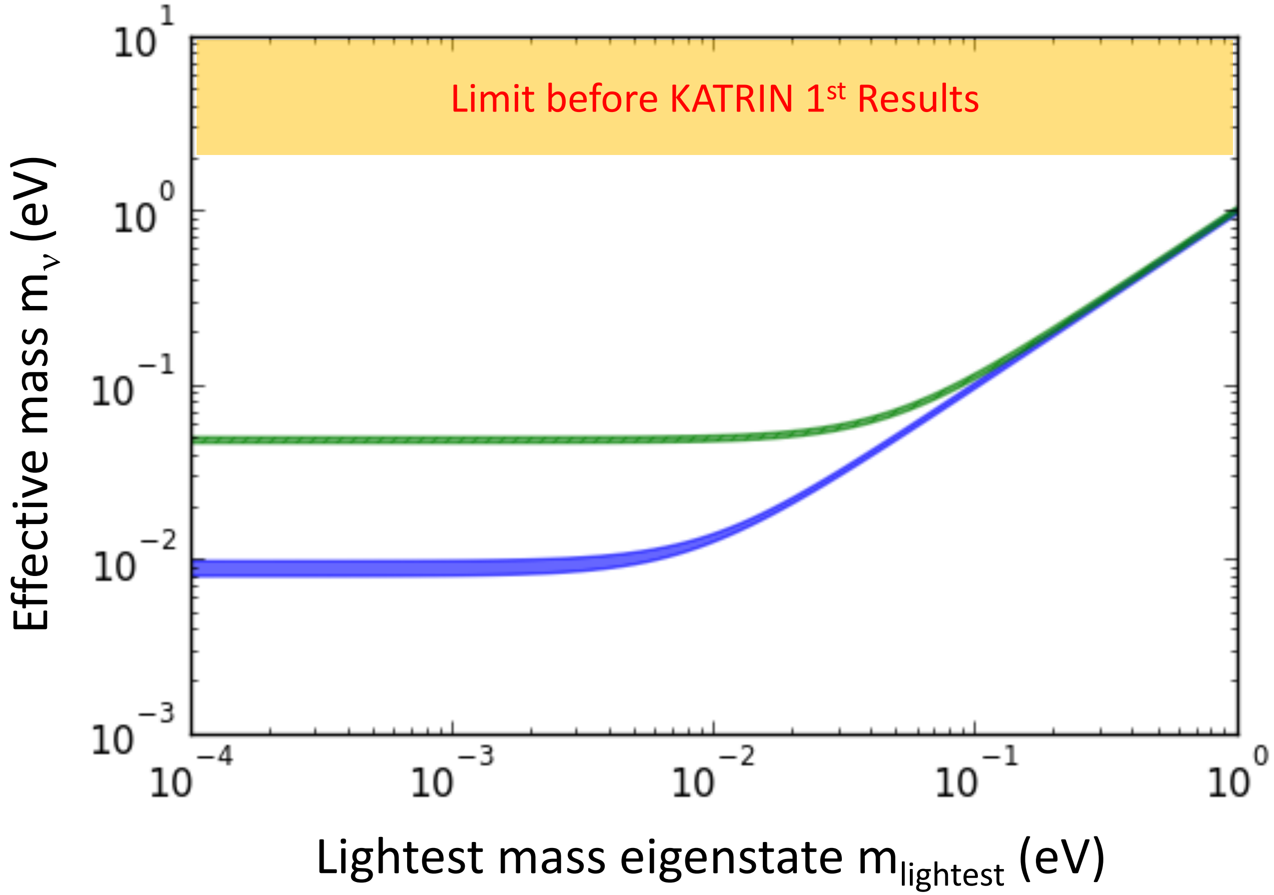
The challenge

Key requirements:

- Ultra-strong β-source (10^{11} cps)
- Excellent energy resolution (~ 1 eV)
- Low background level (~ 10 mcps)
- Precise understanding of spectrum



Where do we stand?



- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

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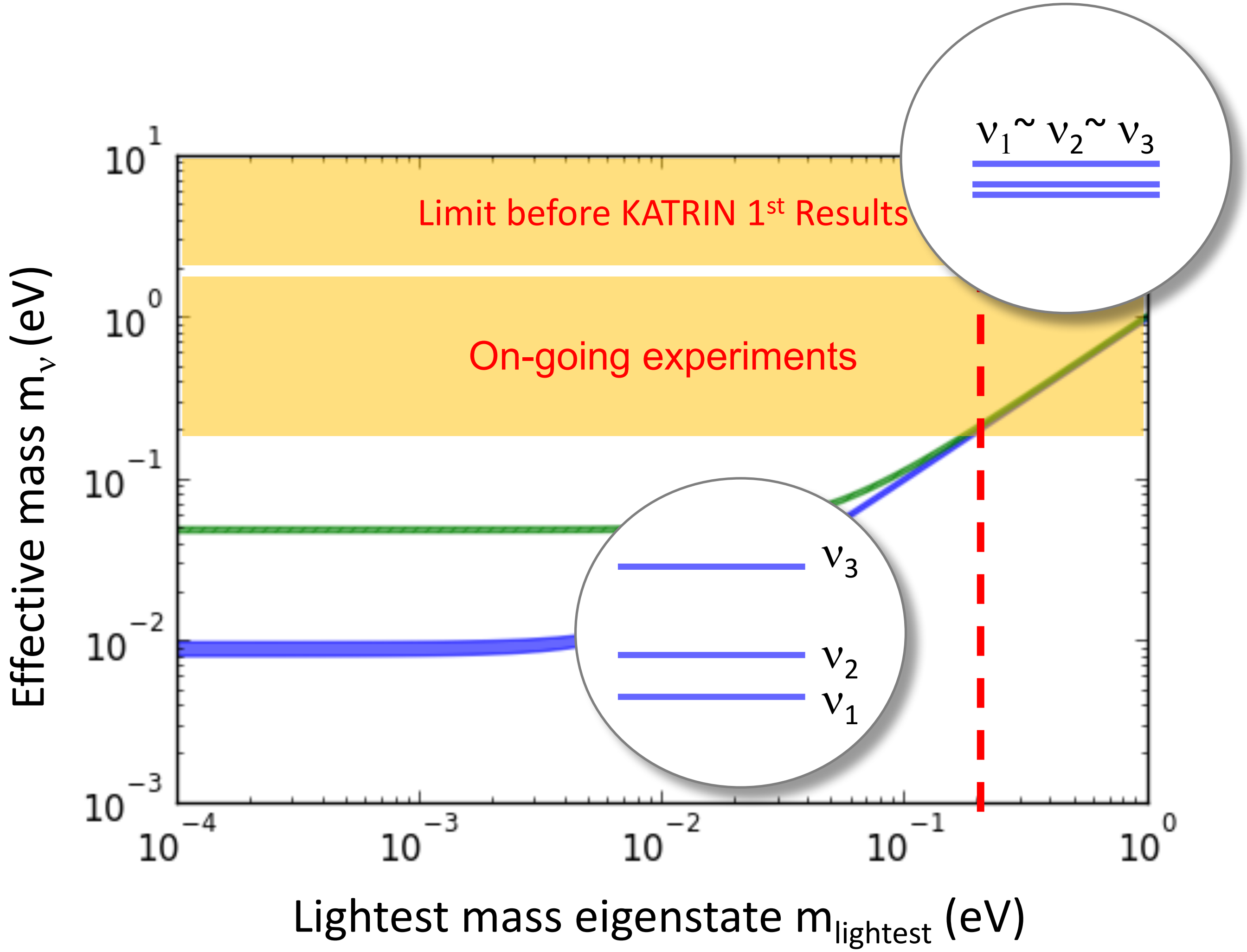

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- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario

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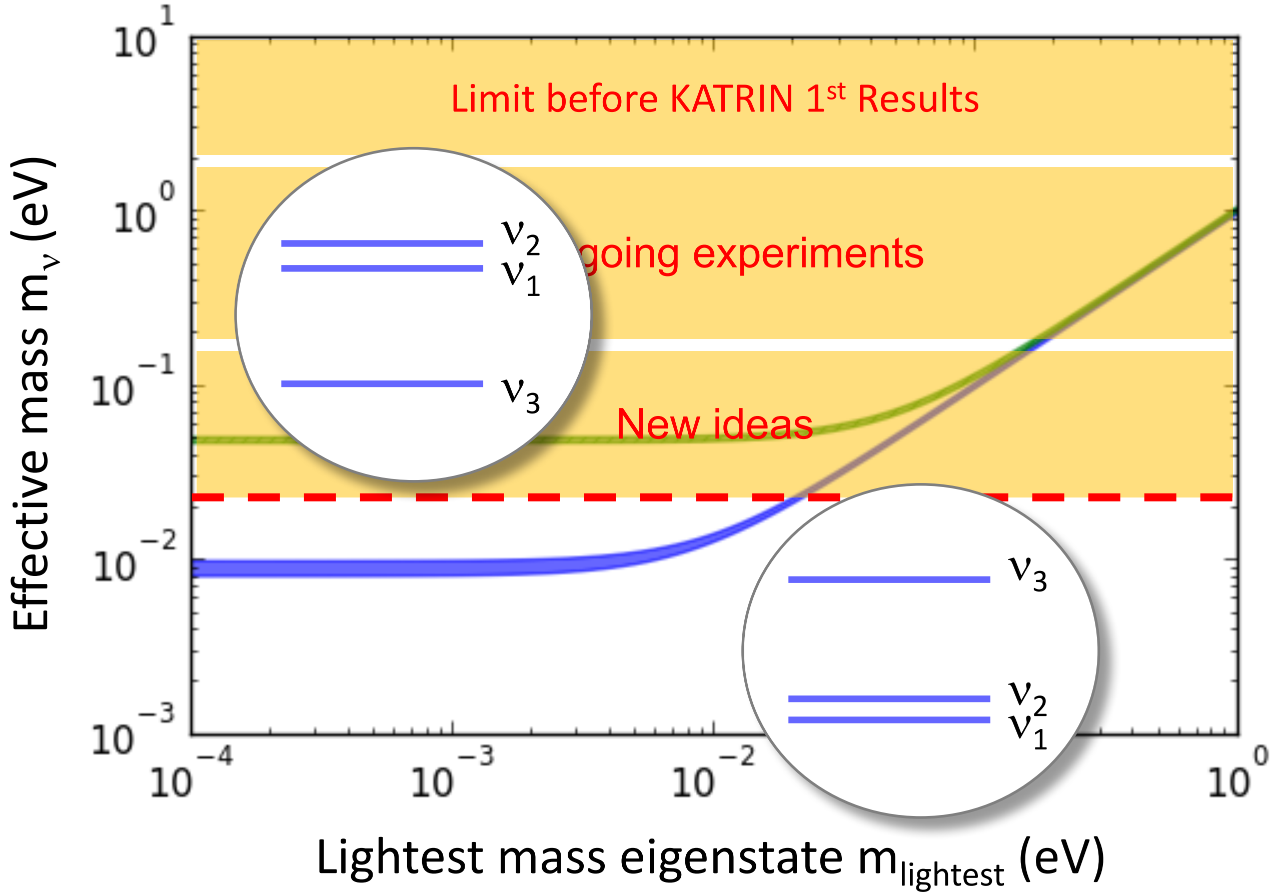

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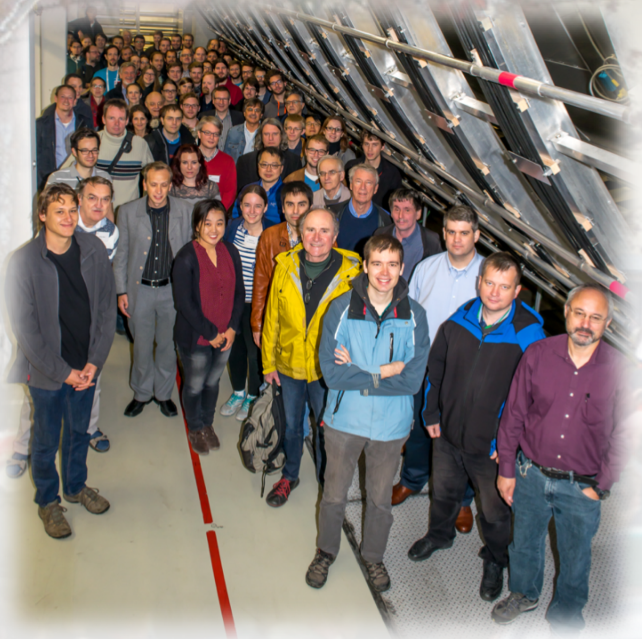
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- New ideas:
  Resolve **normal** vs **inverted** neutrino mass hierarchy

Karlsruhe
Tritium
Neutrino
Experiment

Karlsruhe Tritium Neutrino Experiment

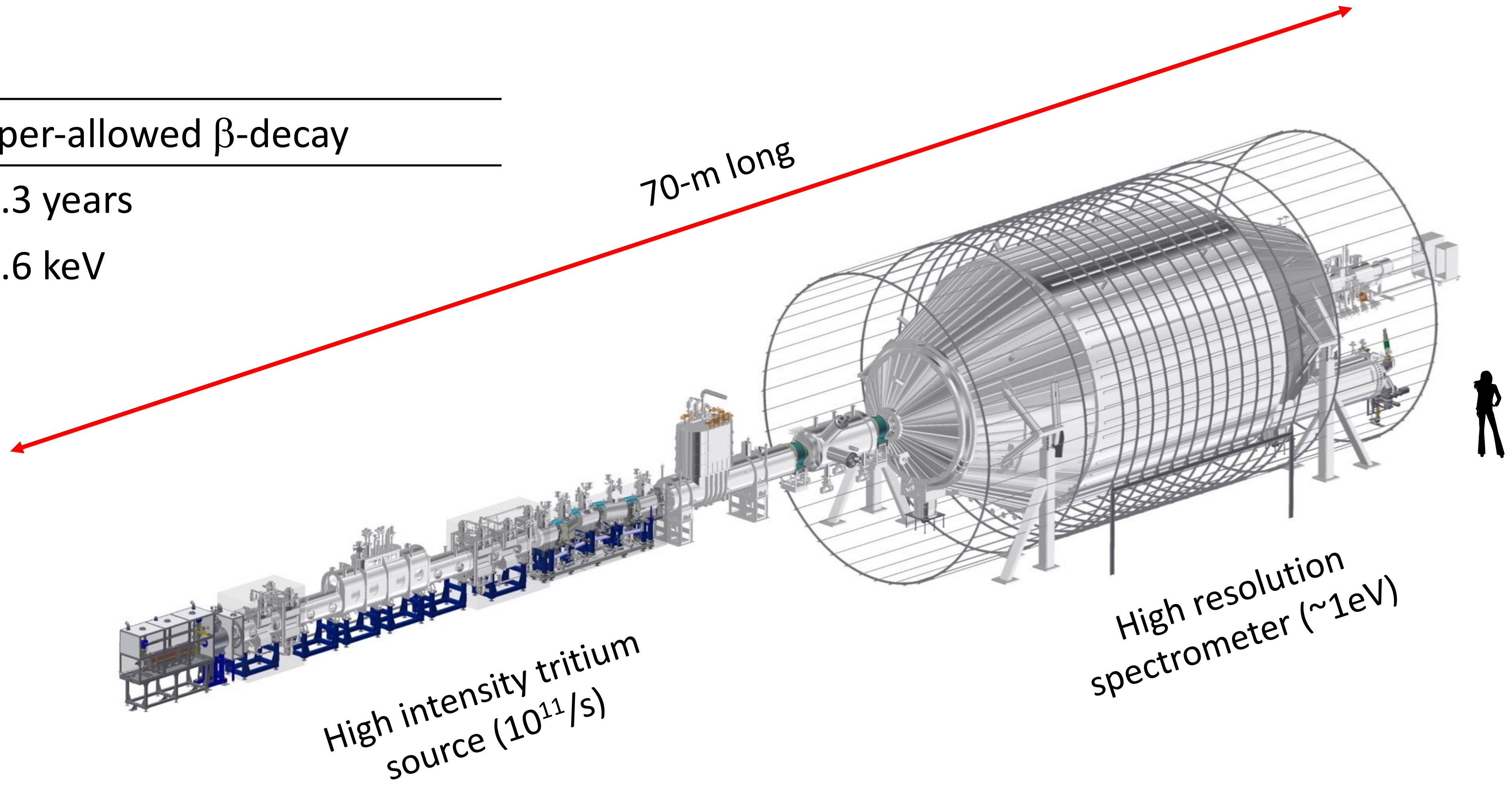


- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Sensitivity m_ν = 0.2 eV (90% CL) after 3 net-years

KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University EST. 1826 think beyond the possible
Westfälische Wilhelms-Universität Münster
Massachusetts Institute of Technology
The University of North Carolina at Chapel Hill
The Czech Academy of Sciences
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
cea
Carnegie Mellon University
Universidad Complutense Madrid
Russian Academy of Sciences
JGU Johannes Gutenberg Universität Mainz
TUM Technische Universität München
universitätbonn
Hochschule Fulda University of Applied Sciences
Bergische Universität Wuppertal
Berkeley Lab

KATRIN Working Principle

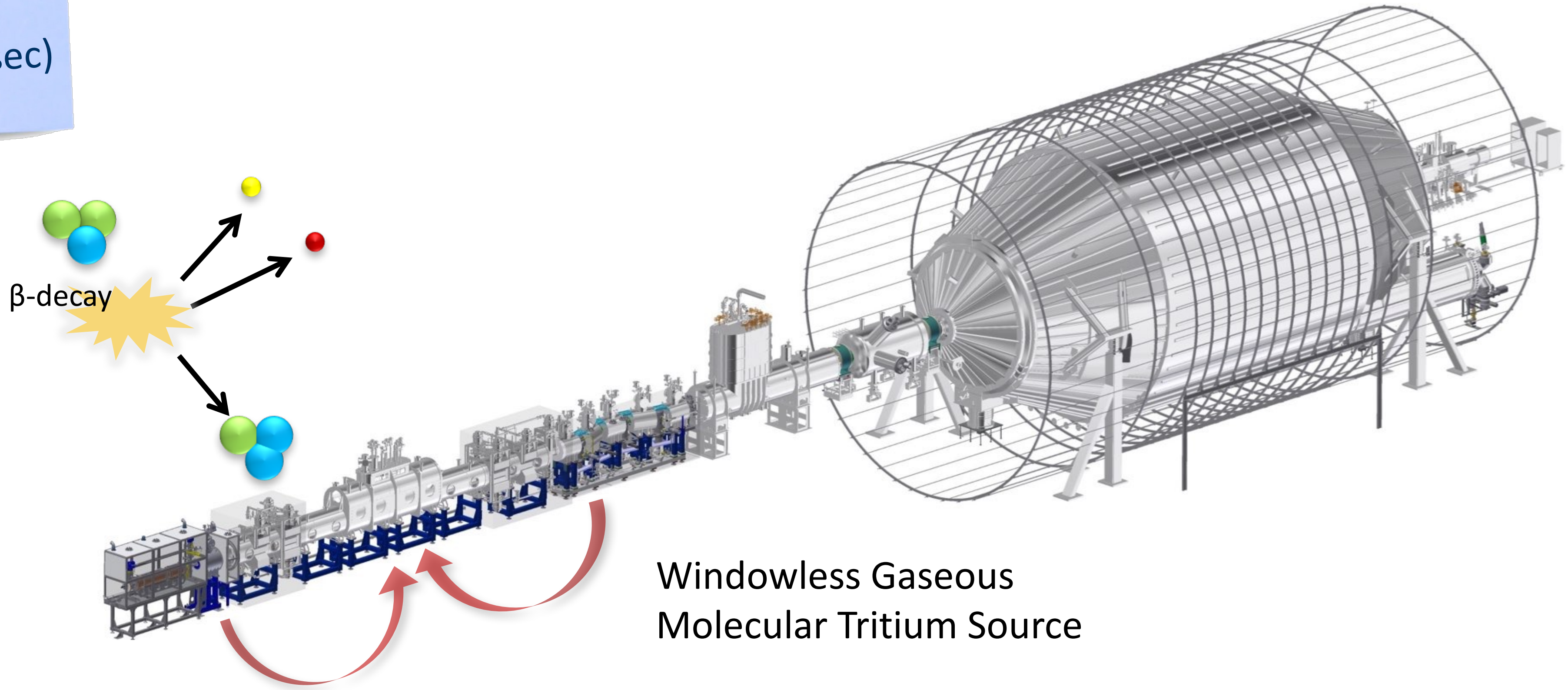
	^3H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV



KATRIN Working Principle

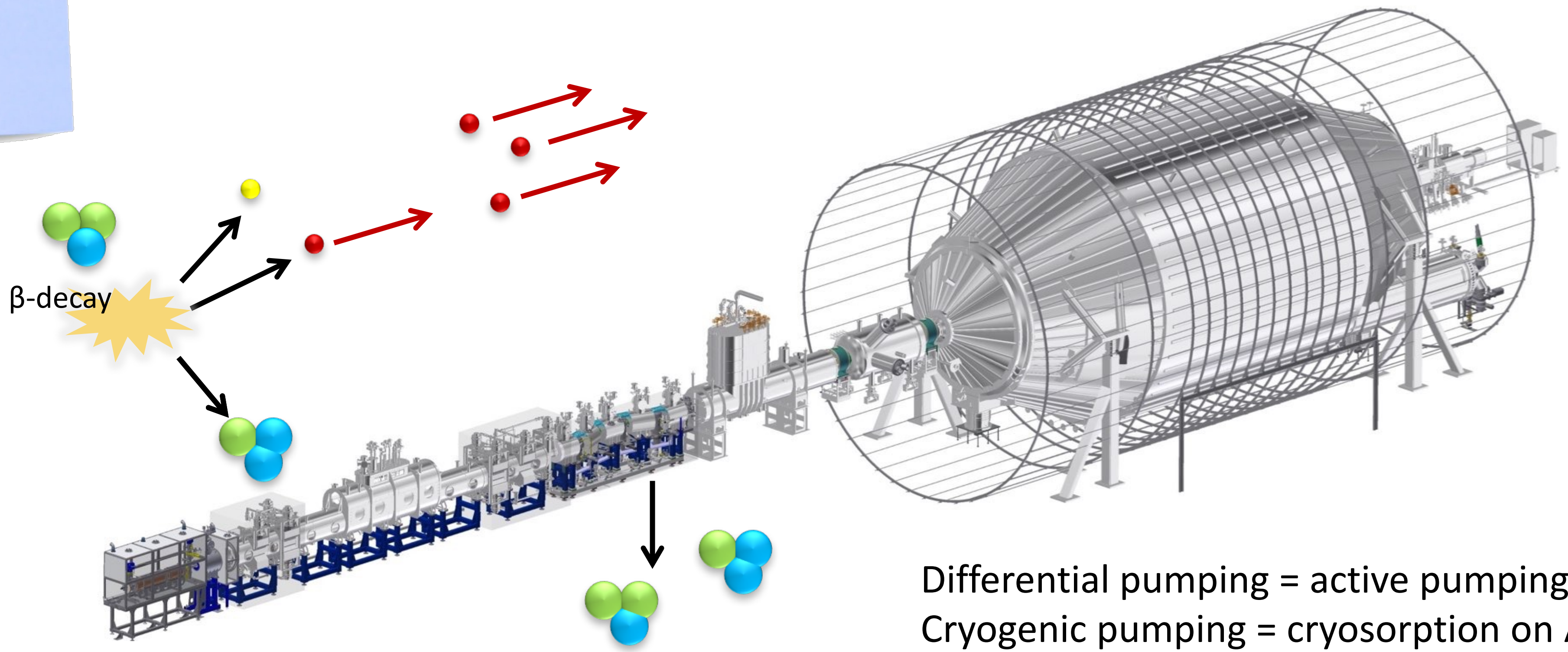
high stability
and luminosity

(10^{11} decays/sec)



KATRIN Working Principle

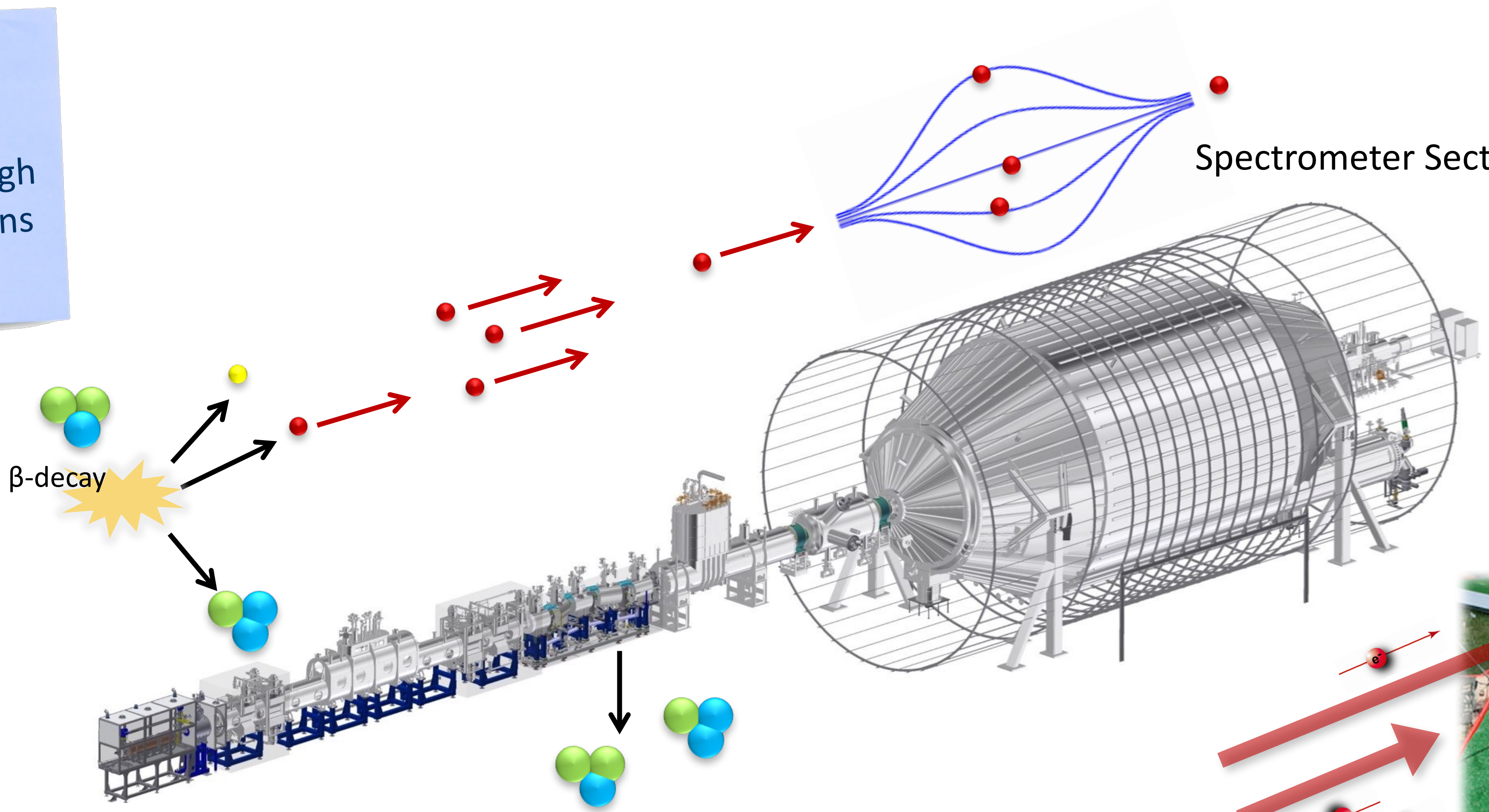
Tritium flow reduction by 14 orders of magnitude

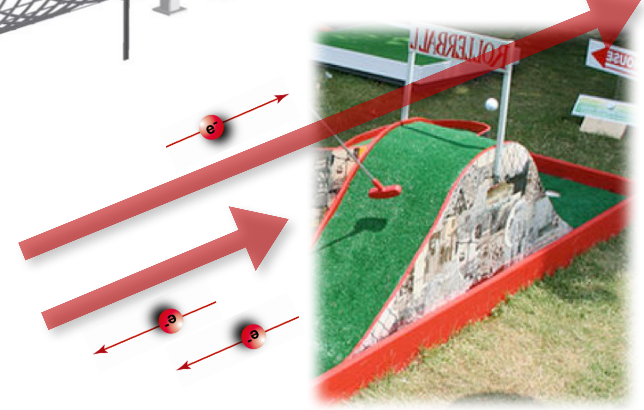


Differential pumping = active pumping by TMPs
Cryogenic pumping = cryosorption on Ar-frost

KATRIN Working Principle

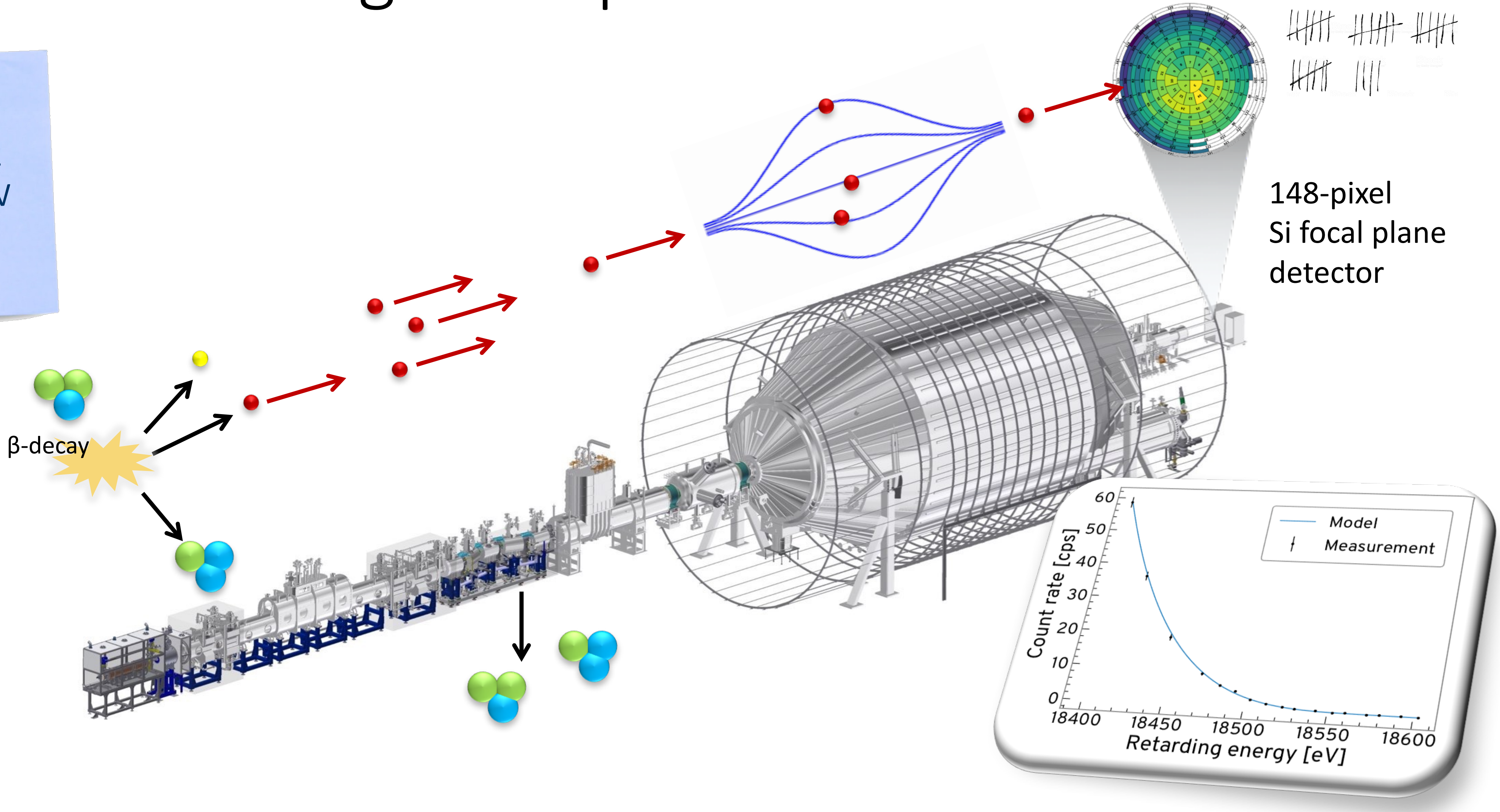
Electrostatic filter selects high energy electrons





KATRIN Working Principle

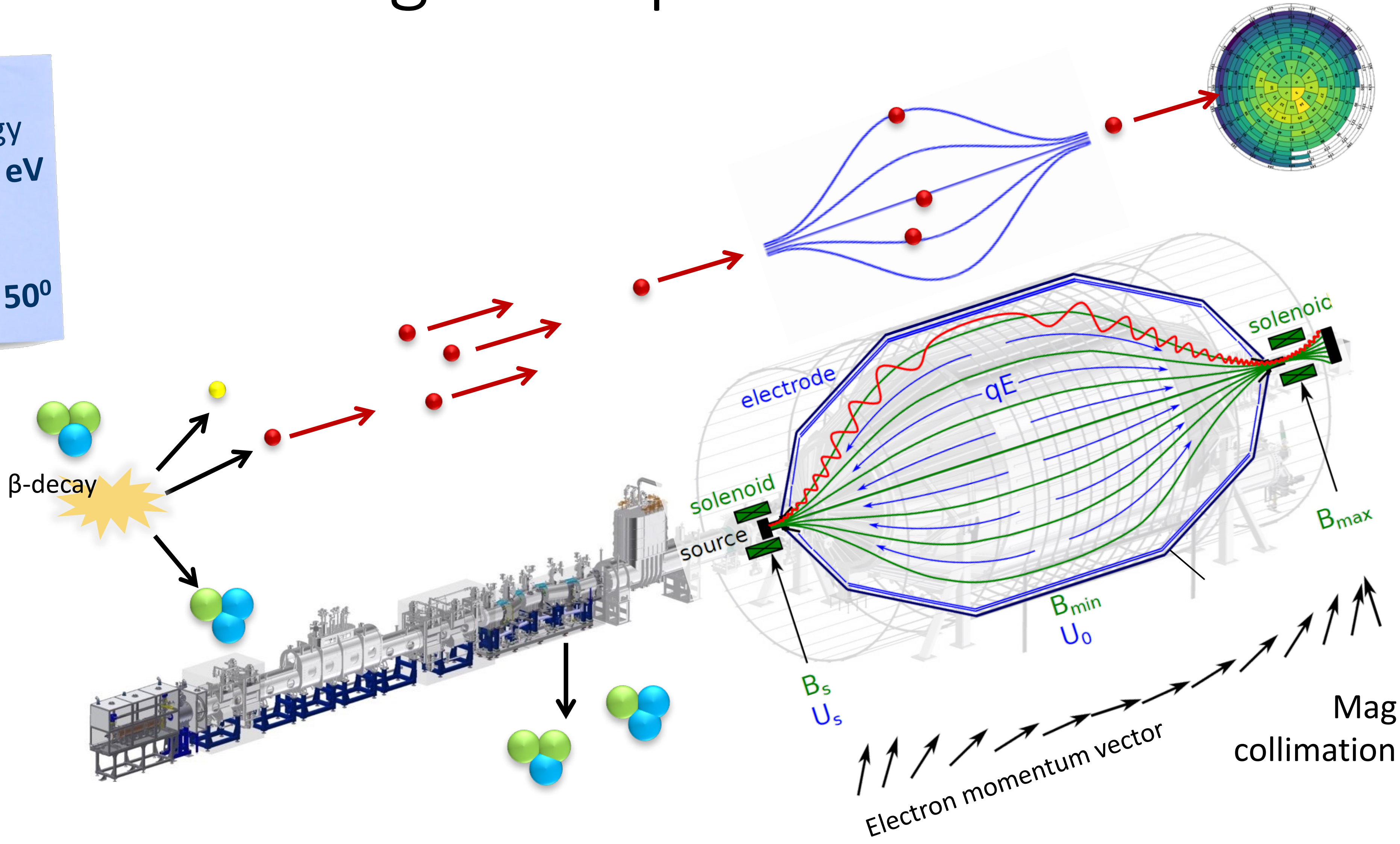
Integral measurement down to 40 eV below the endpoint



KATRIN Working Principle

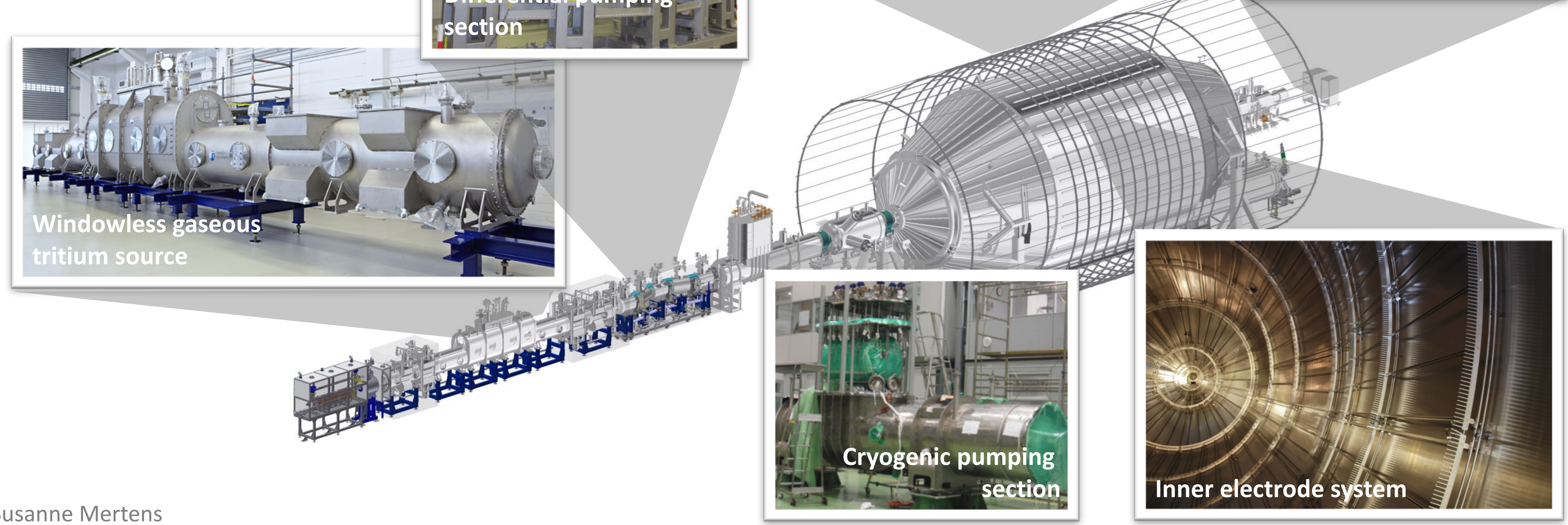
excellent energy resolution: **~ 1 eV**

large angle acceptance: **~ 50⁰**



Magnetic adiabatic collimation + electrostatic filter (MAC-E)

KATRIN (in real)



18-years of KATRIN history

Letter of Intent

Design Report


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

KATRIN Design Report 2004

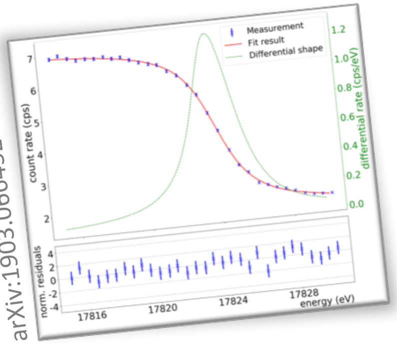
The KATRIN Collaboration

Main spectrometer

First light

JINST 13 (2018) P04018

EPJ C 78 (2018) 368
arXiv:1903.066452



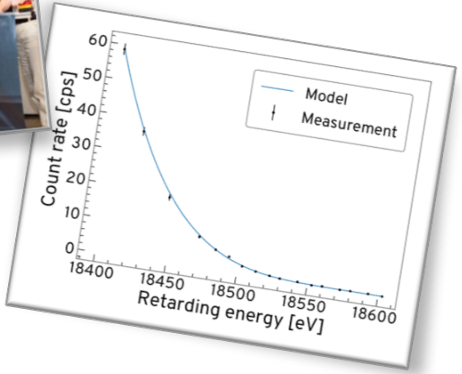
Krypton calibration

First tritium

arXiv:1909.06069

Phys. Rev. Lett. 123, 221802

First neutrino mass



2001 | 2004 | 2006 | 2016 | 2017 | 2018 | 2019

18-years of KATRIN history

Letter of Intent

Main spectrometer

EPJ C 78 (2018) 368
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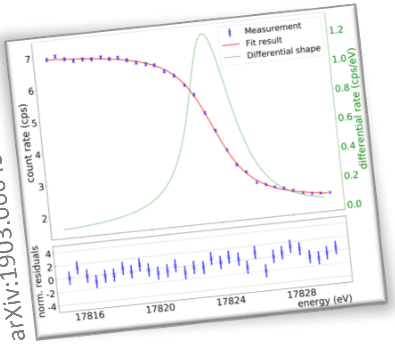

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2001 2004 2006 2016 2017 2018 2019

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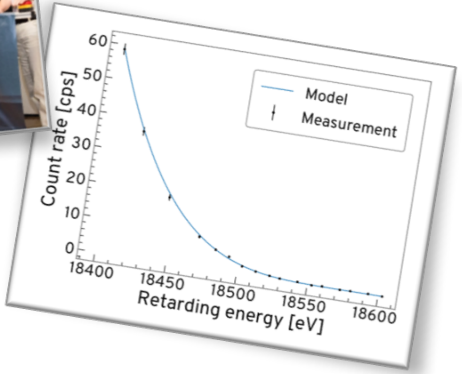


Susanne Mertens

KATRIN neutrino mass campaign #1 (KNM-1)

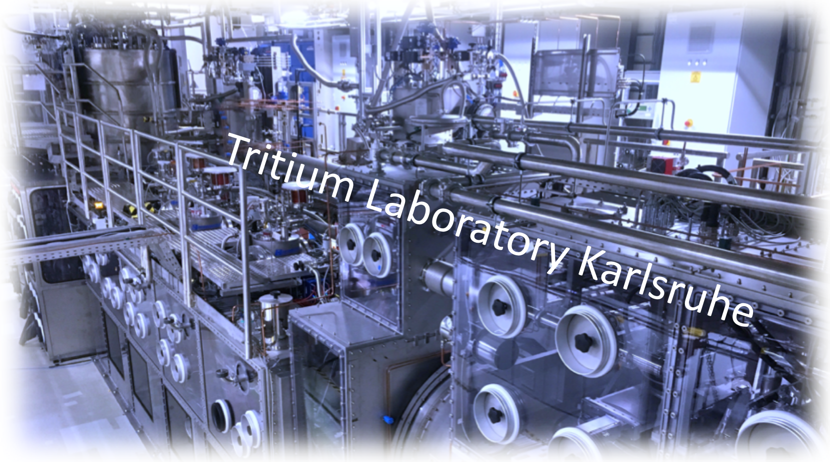
- First ever high-activity tritium operation of KATRIN
- April 10 – May 13 2019: **780 h (~4 weeks)**
- high-quality data collected **2 million electrons**

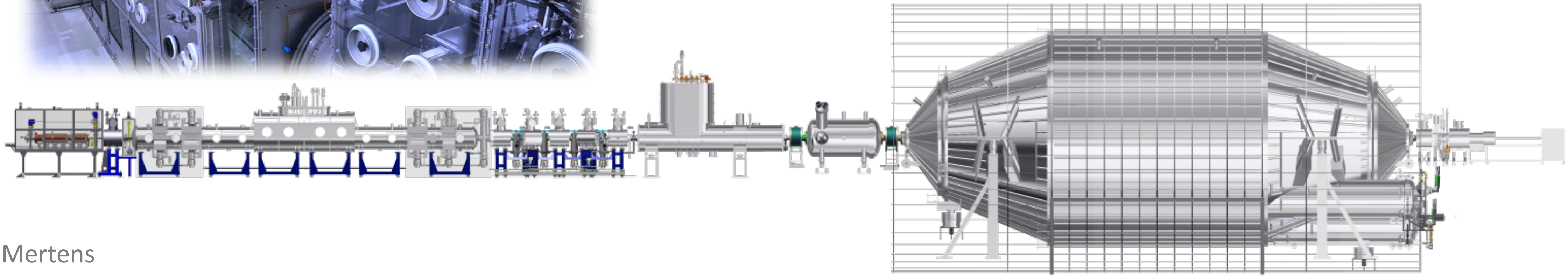
✓ **First neutrino mass result ☺**

arXiv:1909.06048

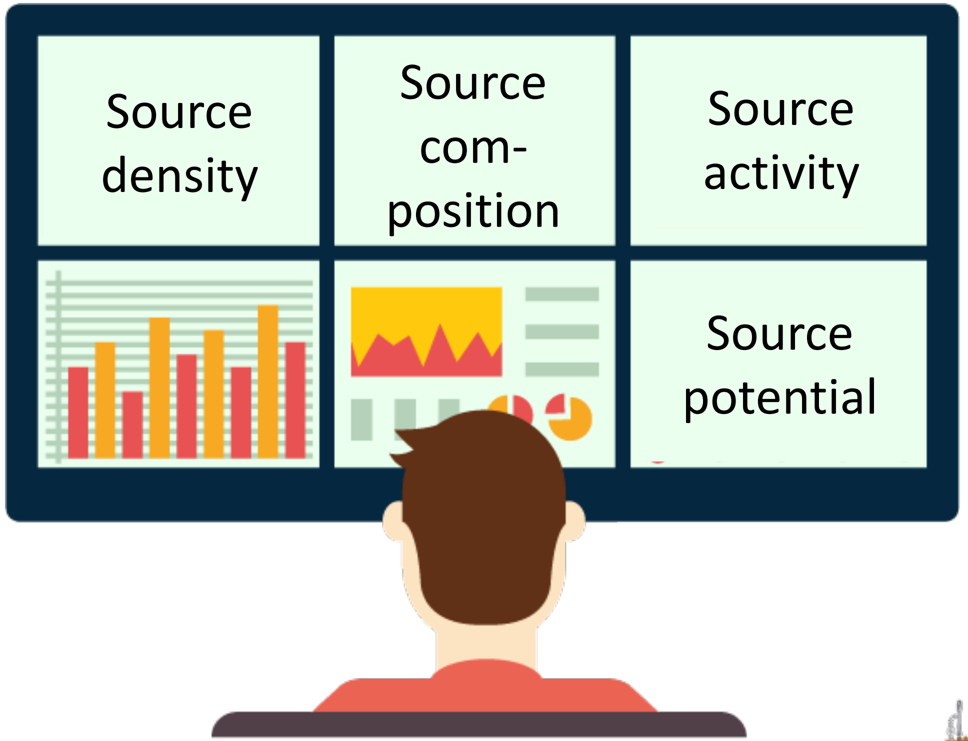
Tritium source operation

- tritium gas density: **22% of nominal (burn-in period)**
- high isotopic tritium purity: **97.5%**
- high source activity: **$2.45 \cdot 10^{10}$ Bq (24.5 GBq), throughput: 4.9 g/day**

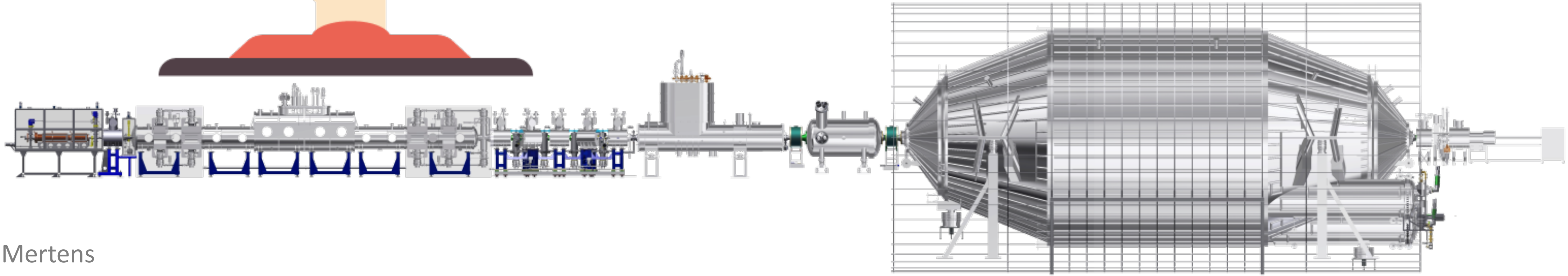




Tritium source operation



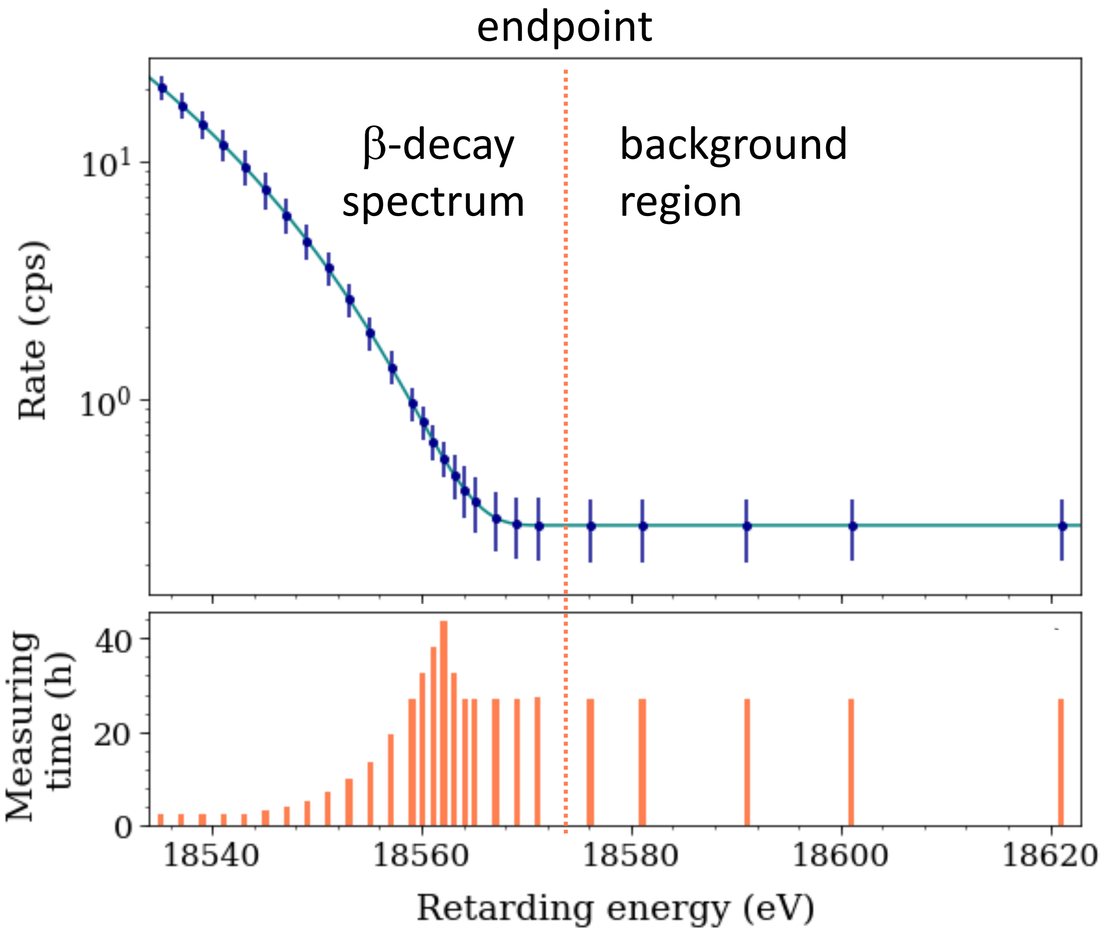
- Electron gun
- Laser Raman Cell
- Forward beam monitor
- Krypton sources



Spectrometer operation

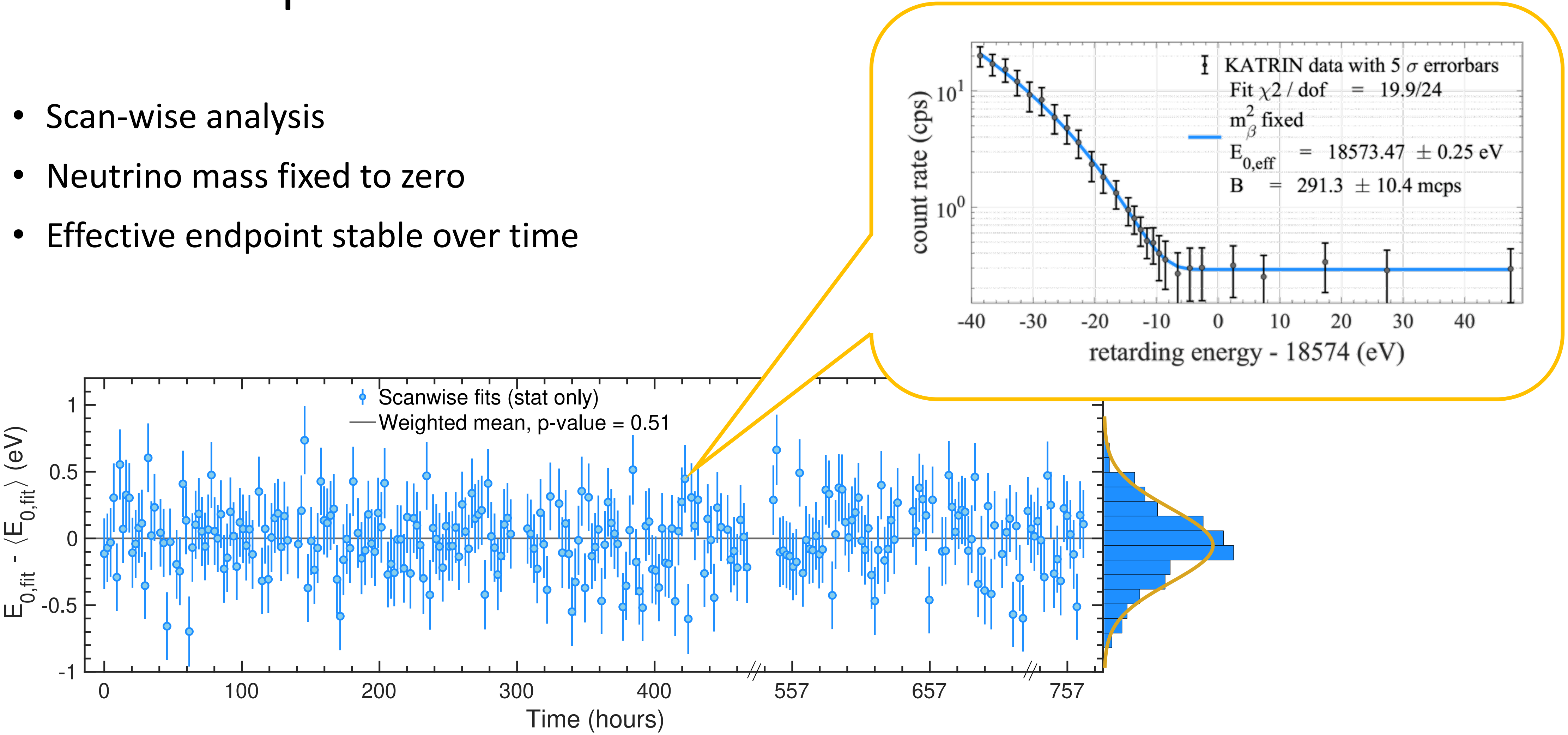
- interval: **E_0 – 40 eV , E_0 + 50 eV**
- # HV set points: **27**
- scanning time: **2 hours**
- Number of scans: **274**
- Sequence of scans: **alternating up/down**
- HV stability: **20 mV (ppm-level)**

➢ **One β-decay spectrum for each scan**

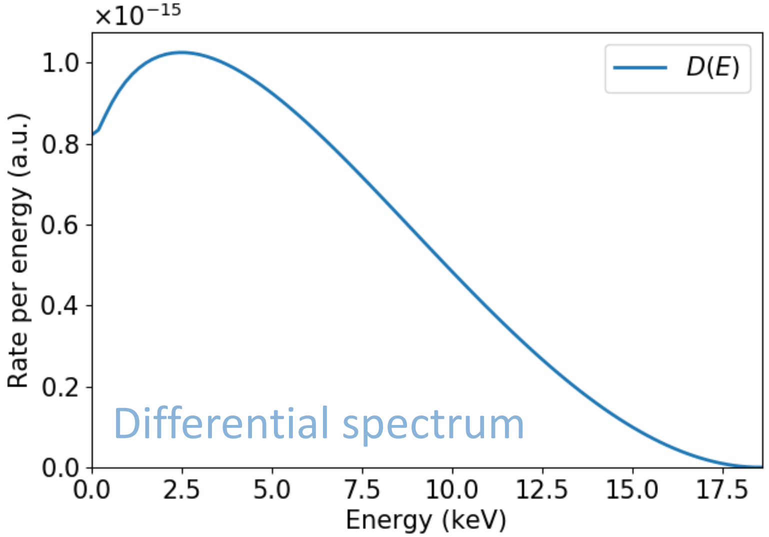


Stable operation

- Scan-wise analysis
- Neutrino mass fixed to zero
- Effective endpoint stable over time

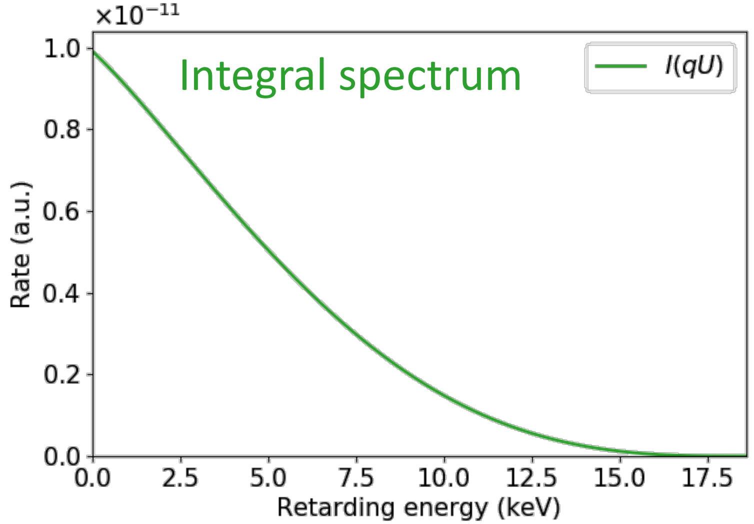


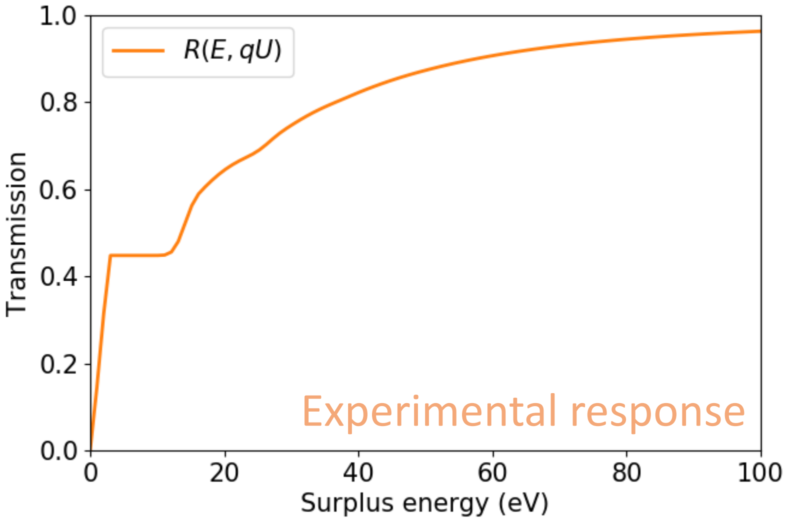
Tritium spectrum calculation



- Molecular final states
- Theoretical corrections
- Doppler broadening
- …

$$I(qU) = \int_{qU}^{E_0} D(E)R(E,qU)dE$$

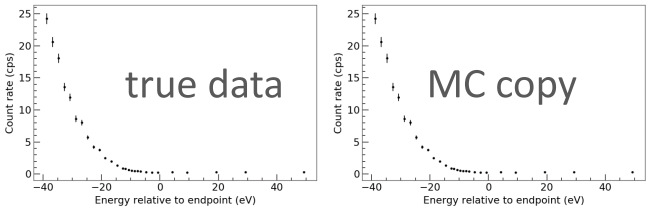


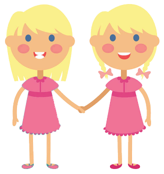


- Spectrometer resolution
- Scattering in the source
- Synchrotron radiation
- …

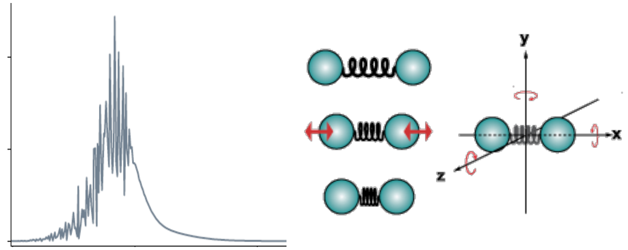
3-fold bias free analysis

Freeze analysis on fake data
- Generate MC-copy of each scan



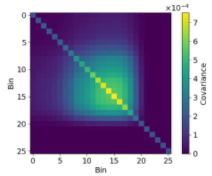


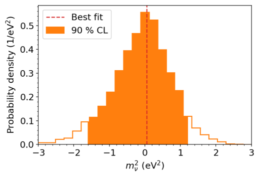
Blinded model
- Modified molecular final state dist.



m_ν^2

Two independent analysis strategies
- Covariance matrix
- Monte Carlo propagation

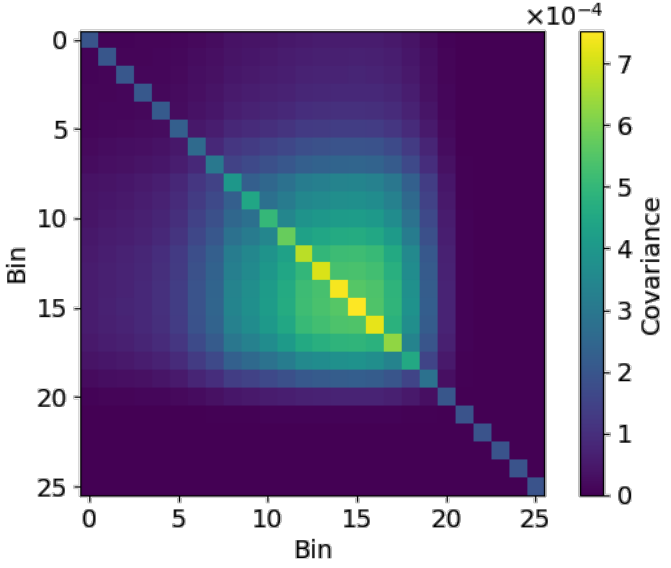




Two independent analysis approaches

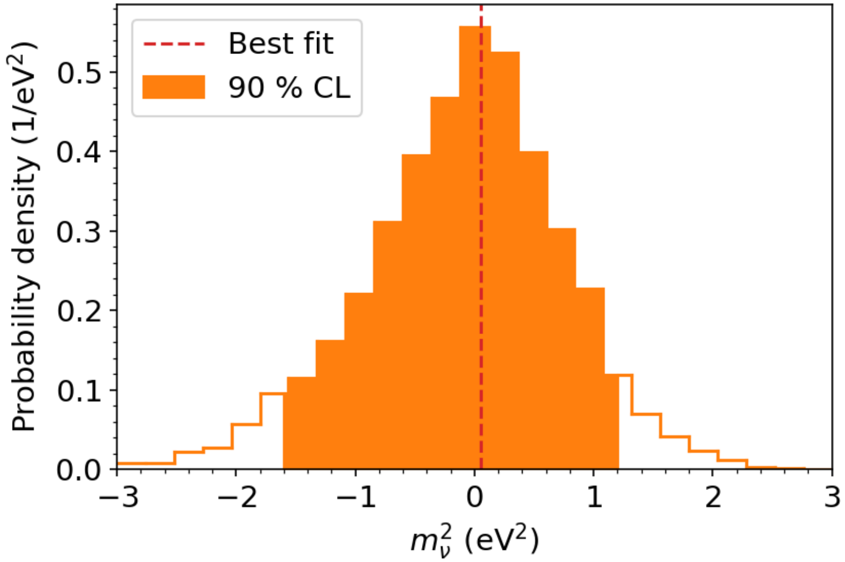
Covariance matrix

- Systematic: **Spectrum** computed 10^5 times
- $\chi^2 = (\vec{m} - \vec{d})^T V_{tot}^{-1} (\vec{m} - \vec{d})$

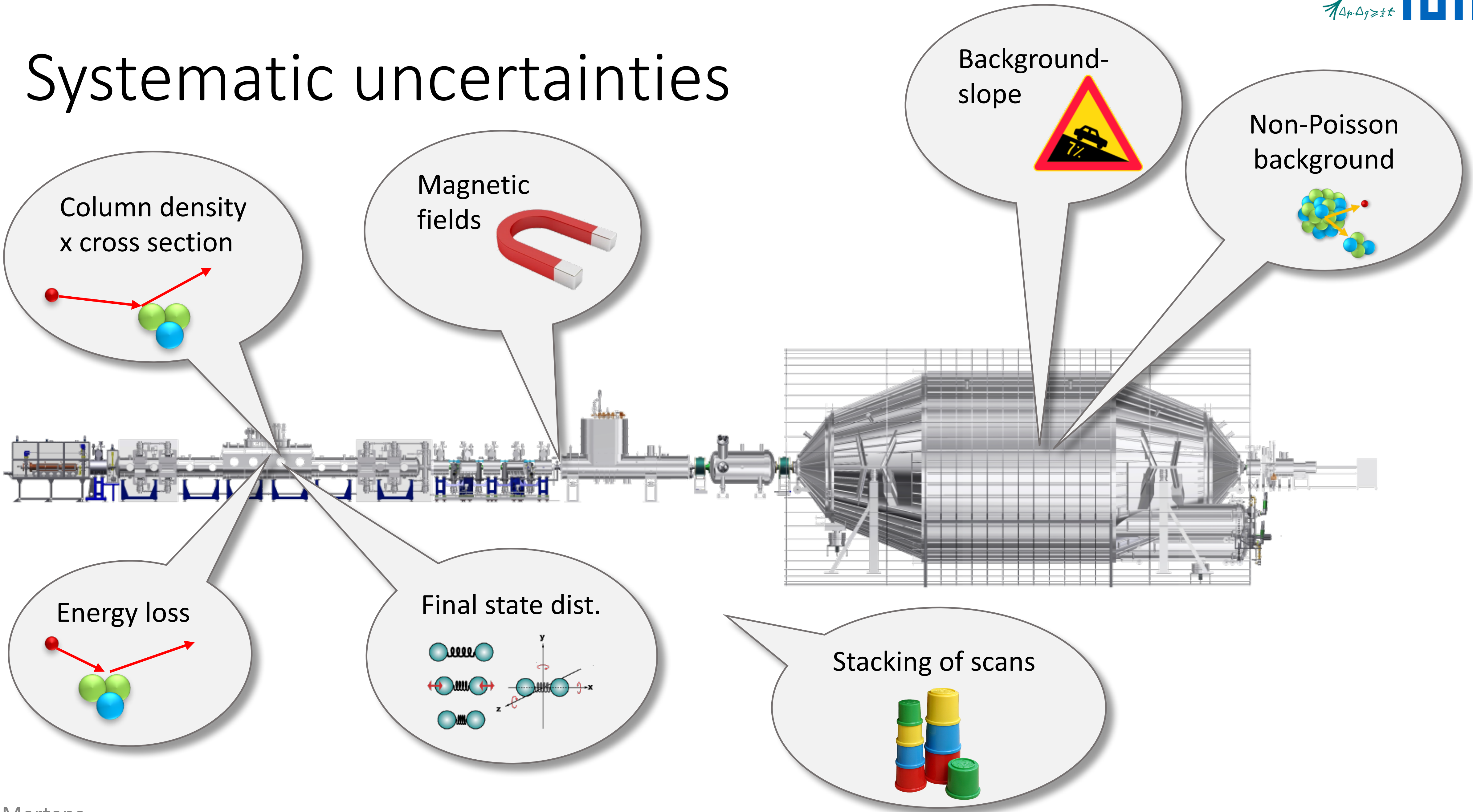


MC propagation

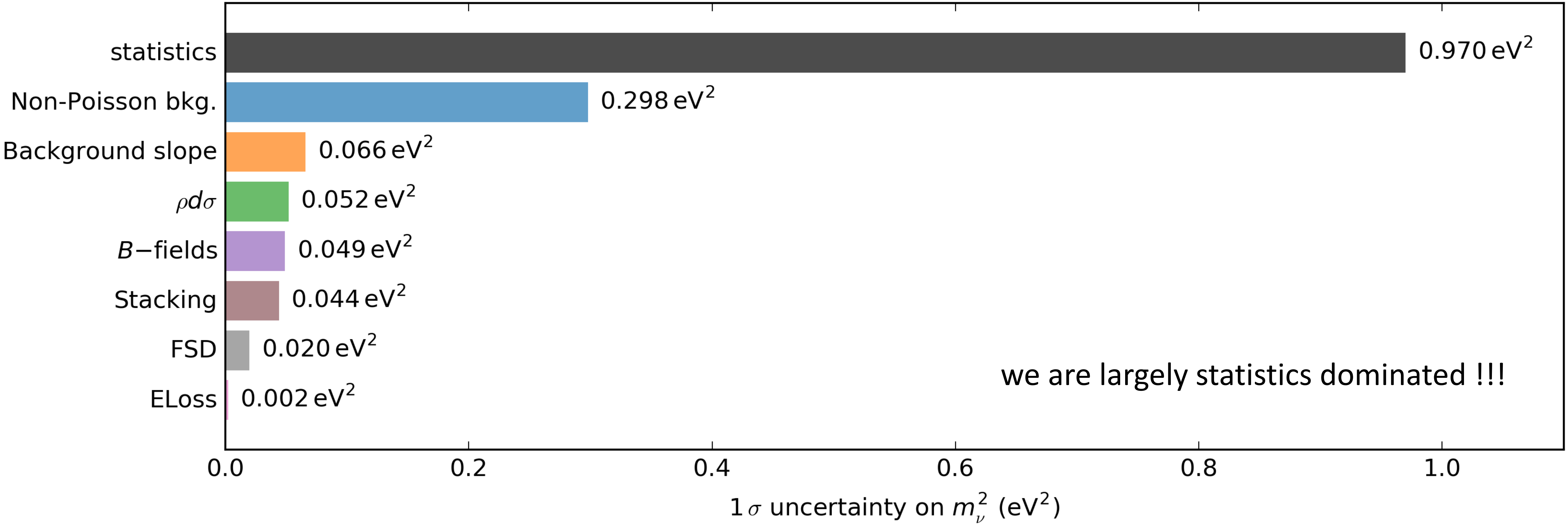
- Systematics: **Fit** performed 10^5 times
- $-2\log\mathcal{L} = 2\sum_i [m_i - d_i + d_i \log(d_i/m_i)]$



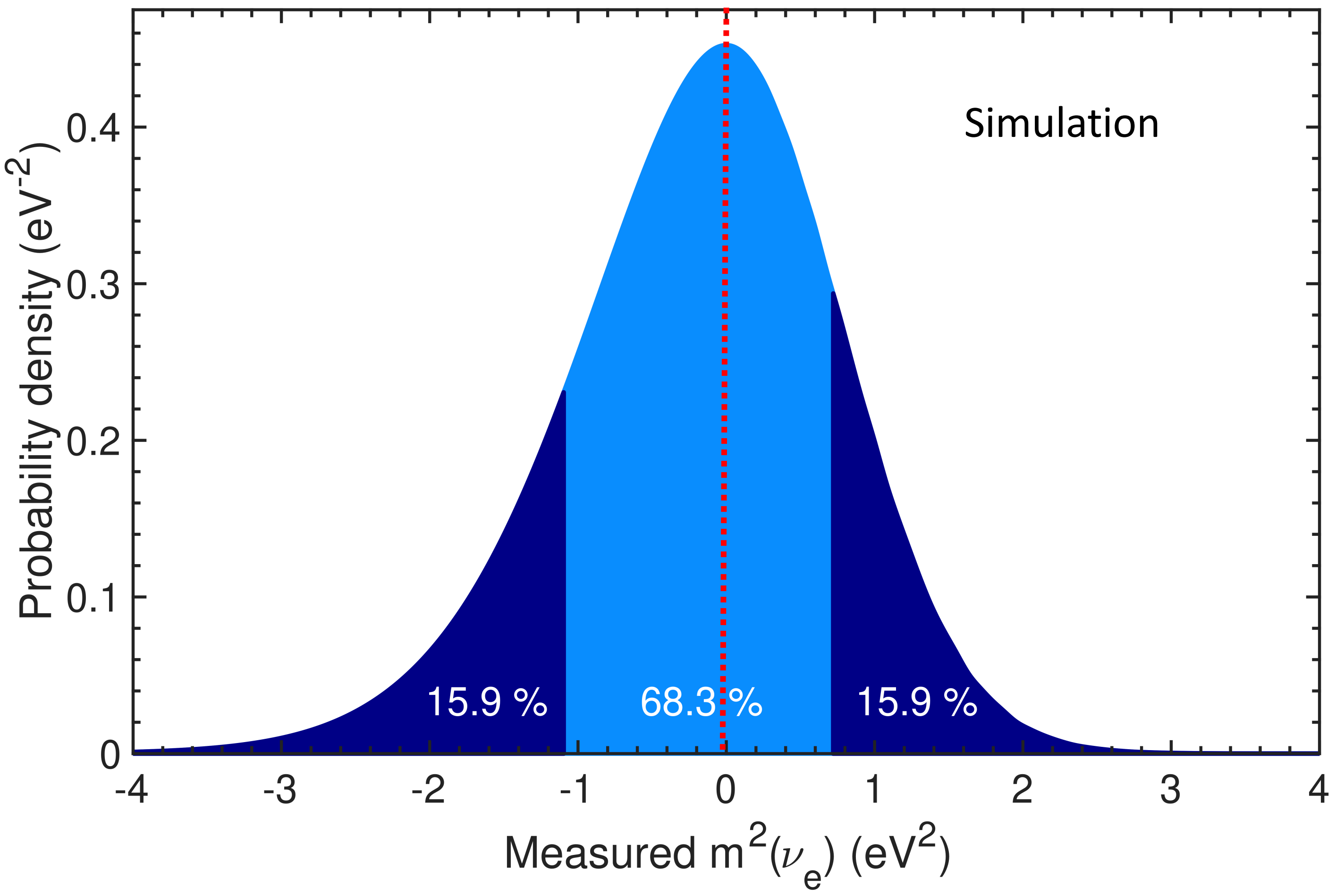
Systematic uncertainties



Budget of uncertainties

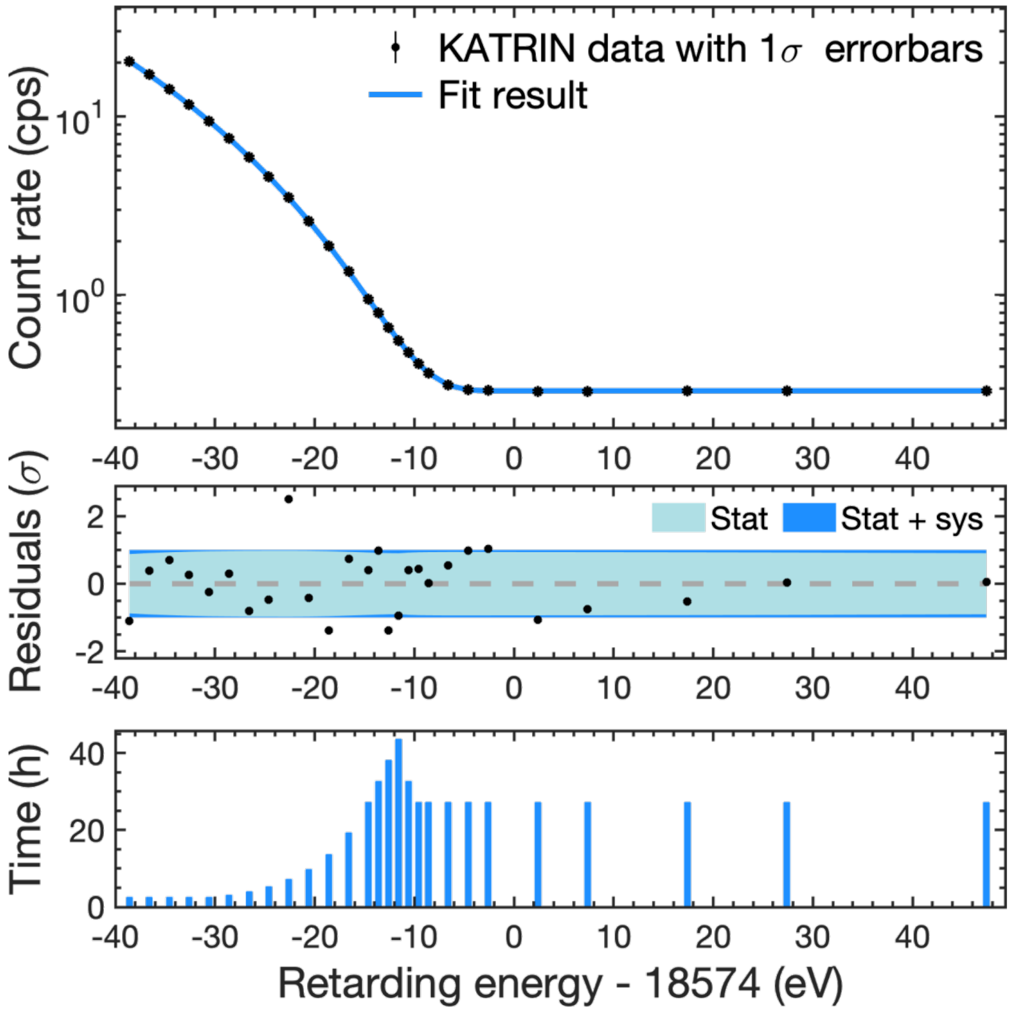


What do we expect to measure?



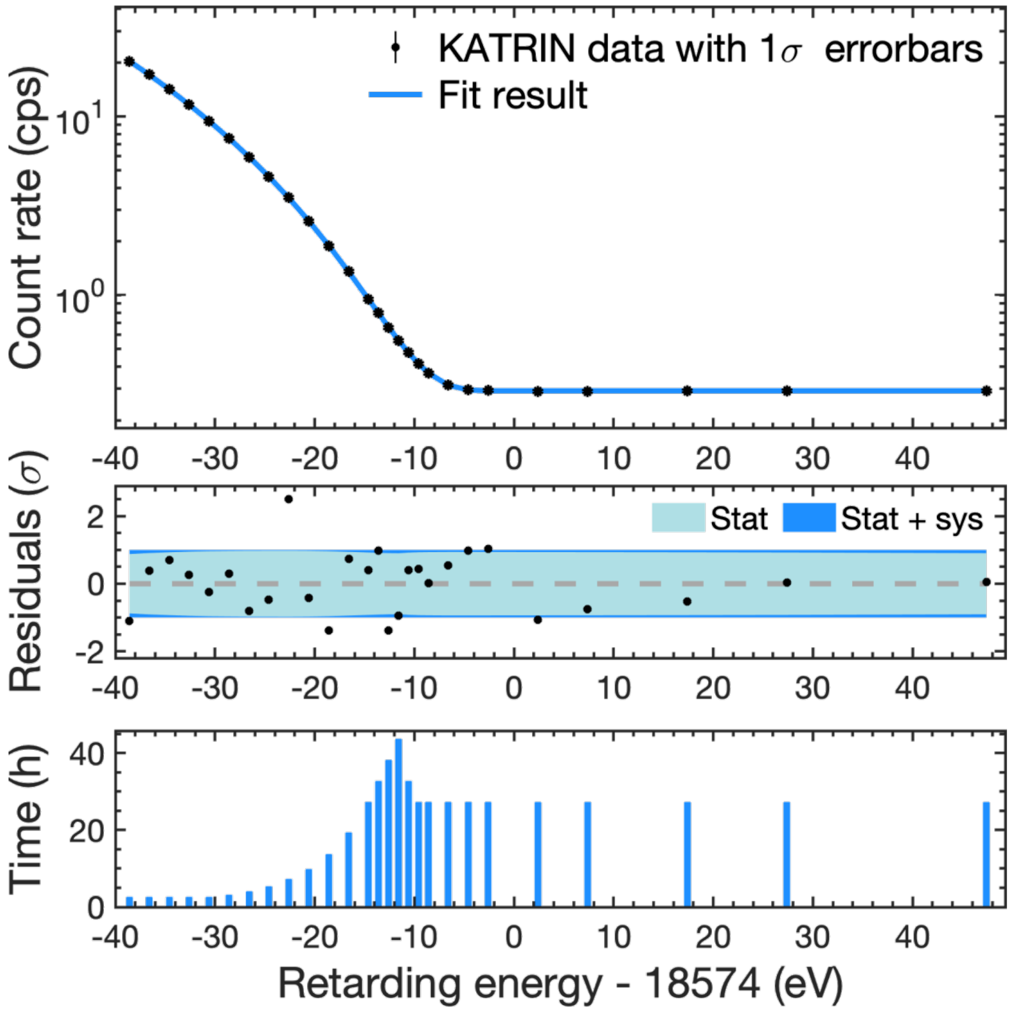
- If the neutrino mass was zero…
- … and we would repeat KATRIN 1 000 000 times…
- 68% probability: m_ν^2 in $[-1; +1]$eV²
- 95% probability: m_ν^2 in $[-2; +2]$eV²

Final fit result



- 2 million events
- 4 free parameters: background, signal normalization, E_0, m_ν^2
- excellent goodness-of-fit: p-value = 0.56
- Blind-analysis, 2 independent analysis methods
- Neutrino mass best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\mathrm{eV}^2$

Final fit result



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- Improved upper limit:
  $m_\nu < 1.1$ **eV @ 90% CL**

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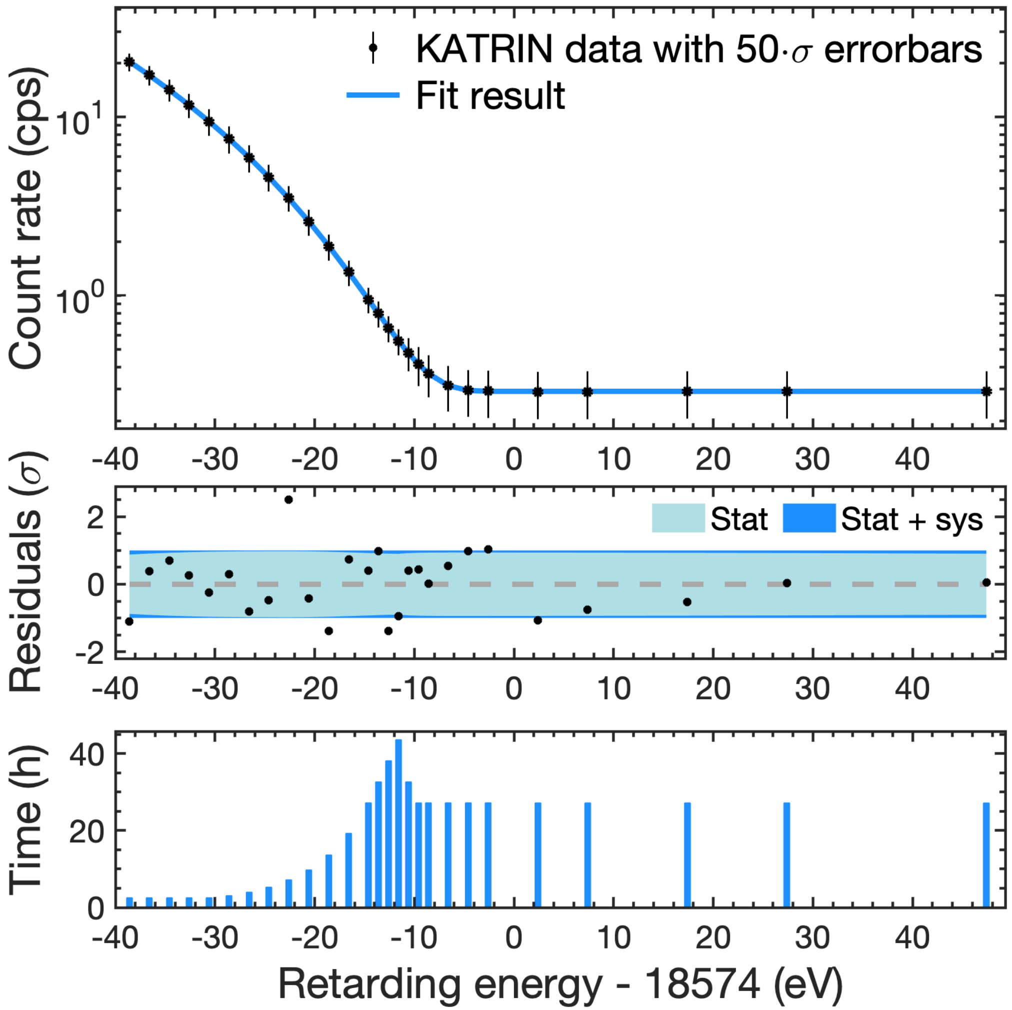

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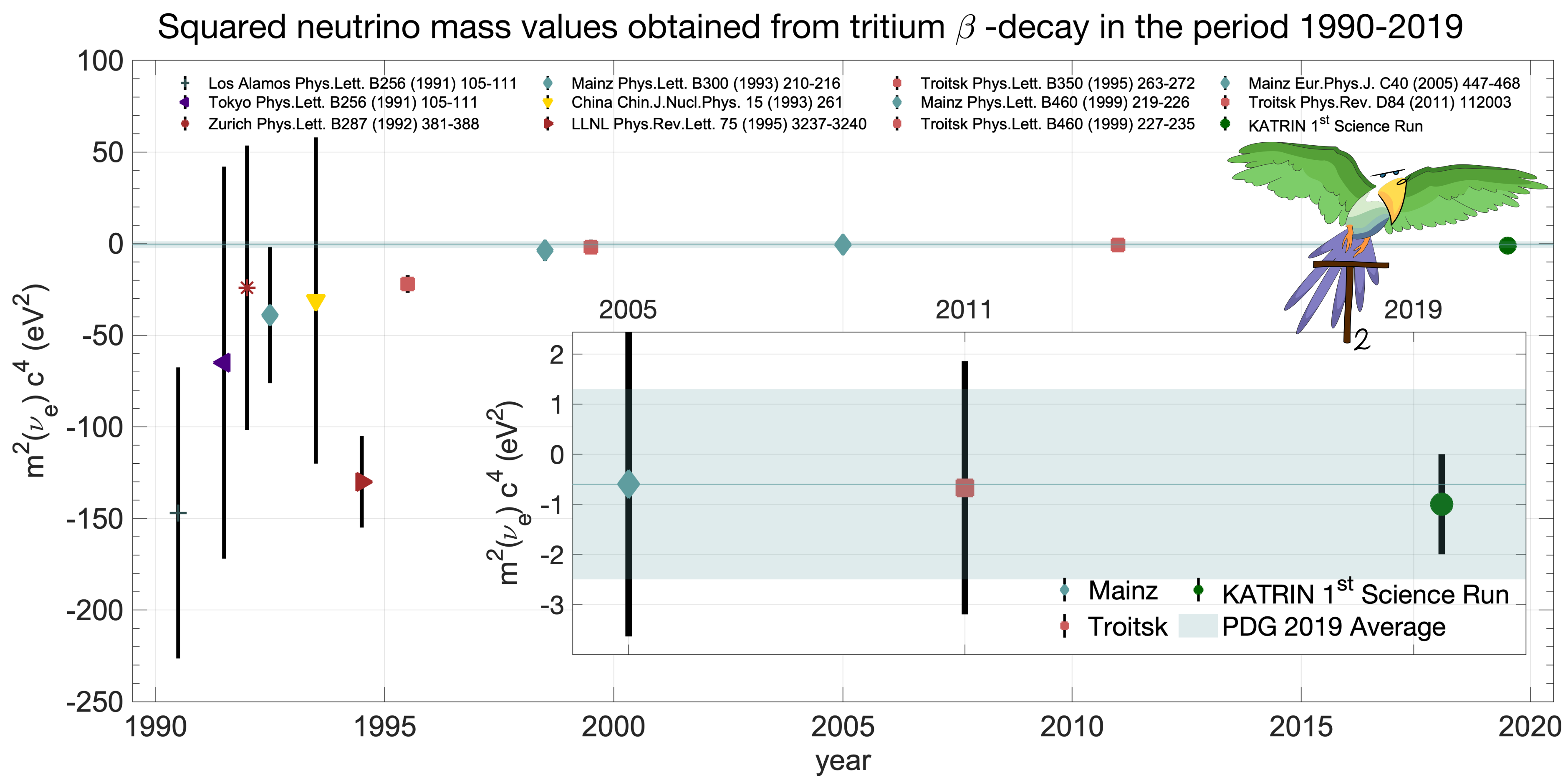
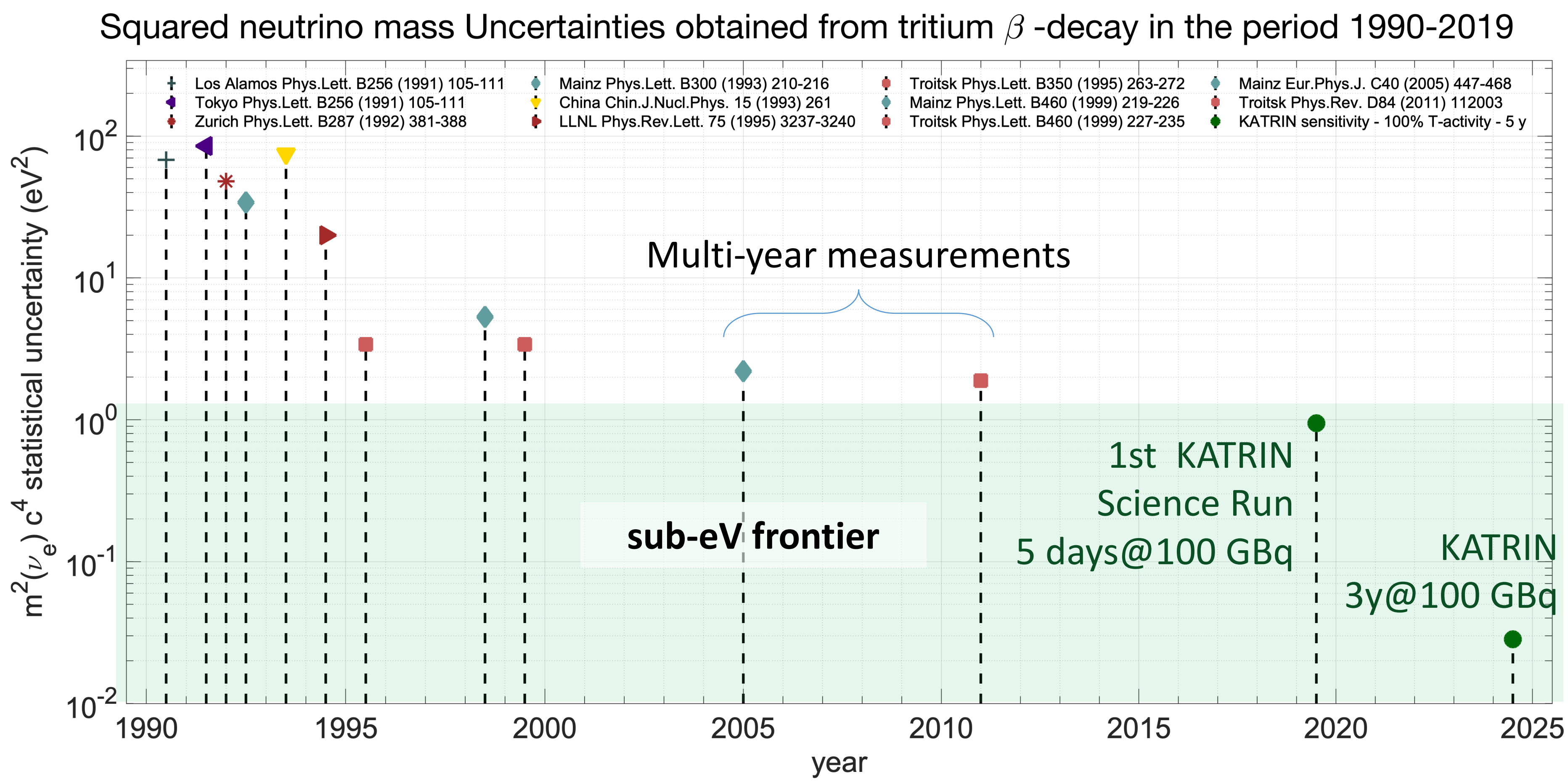
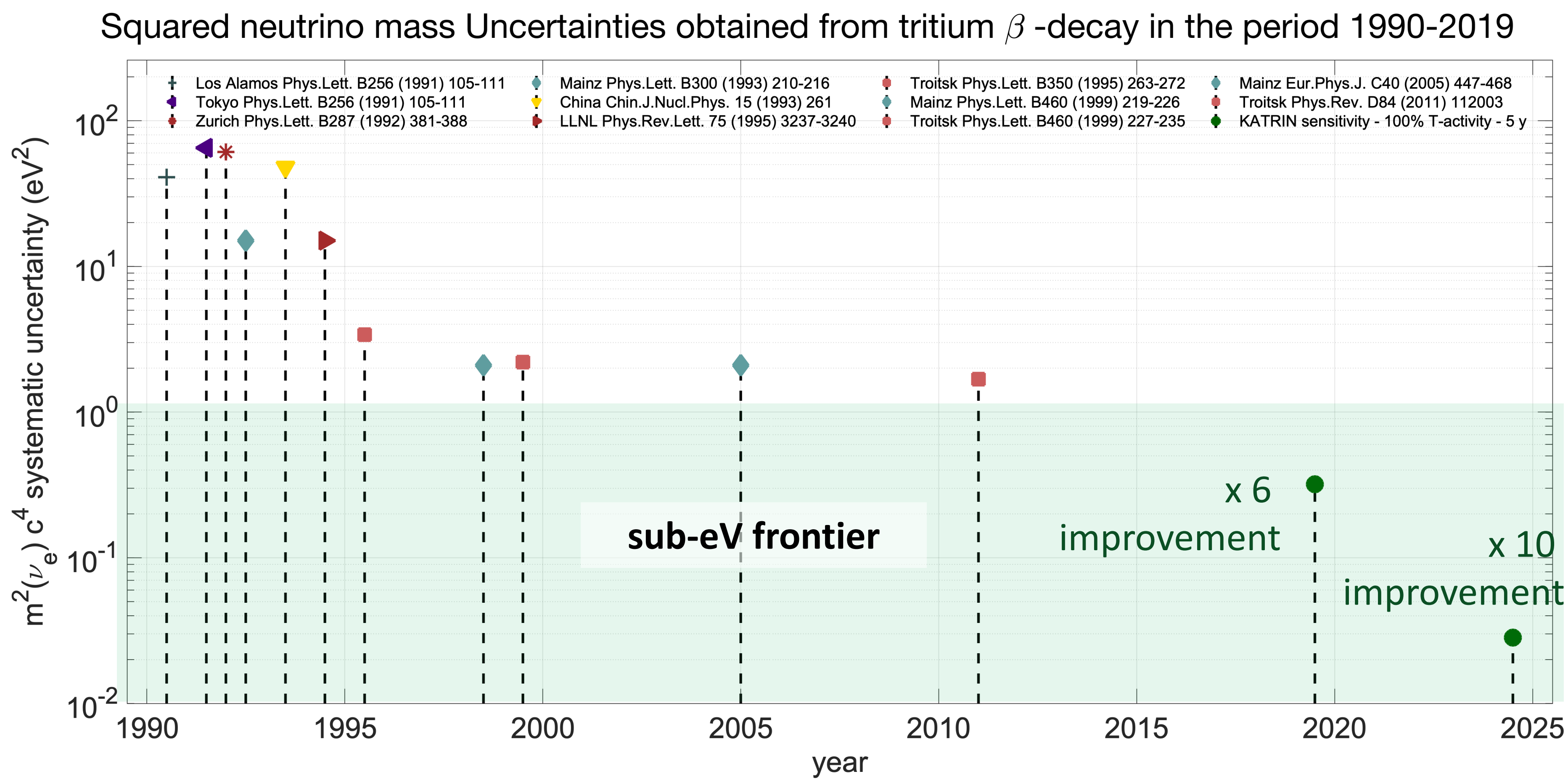
Historical context



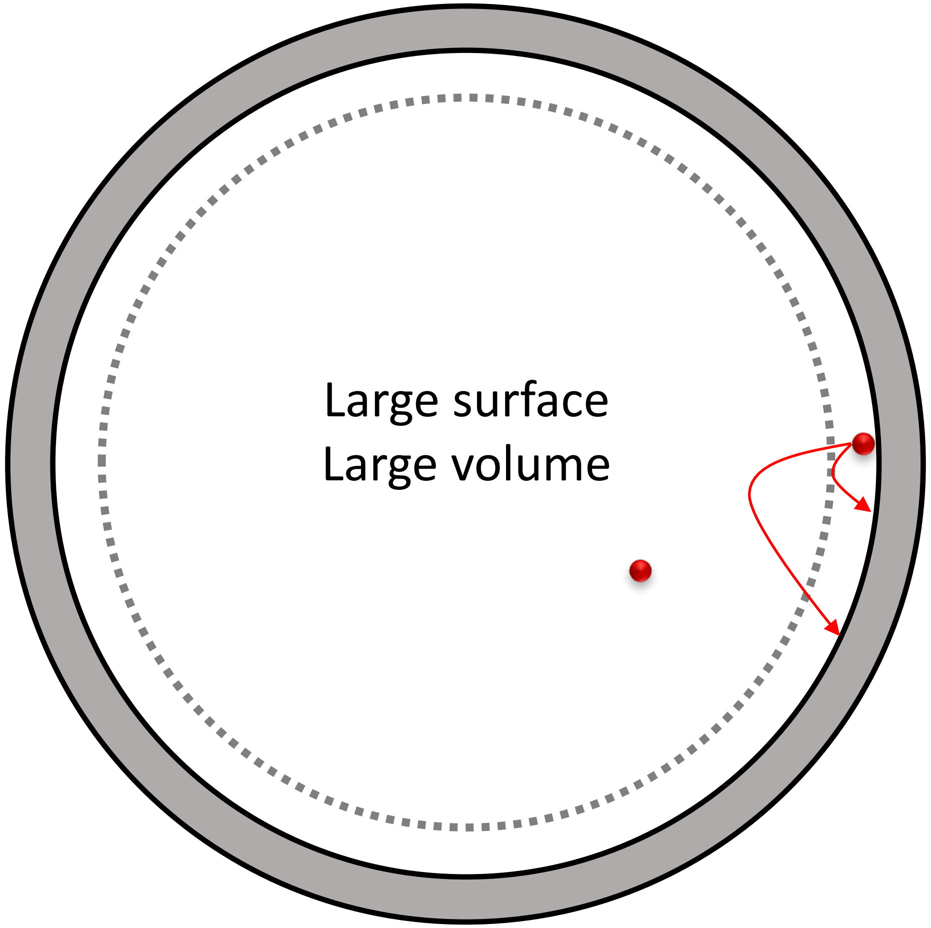
Improvements in statistics

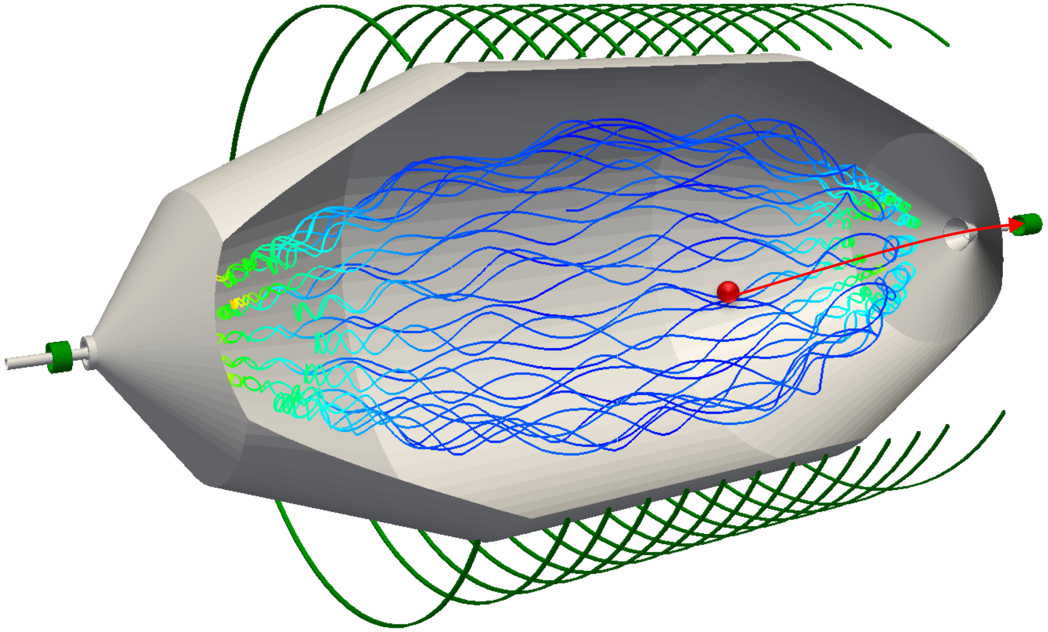


Improvements in systematics

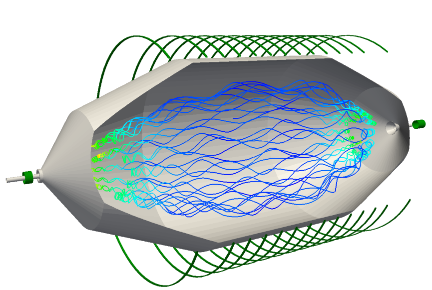


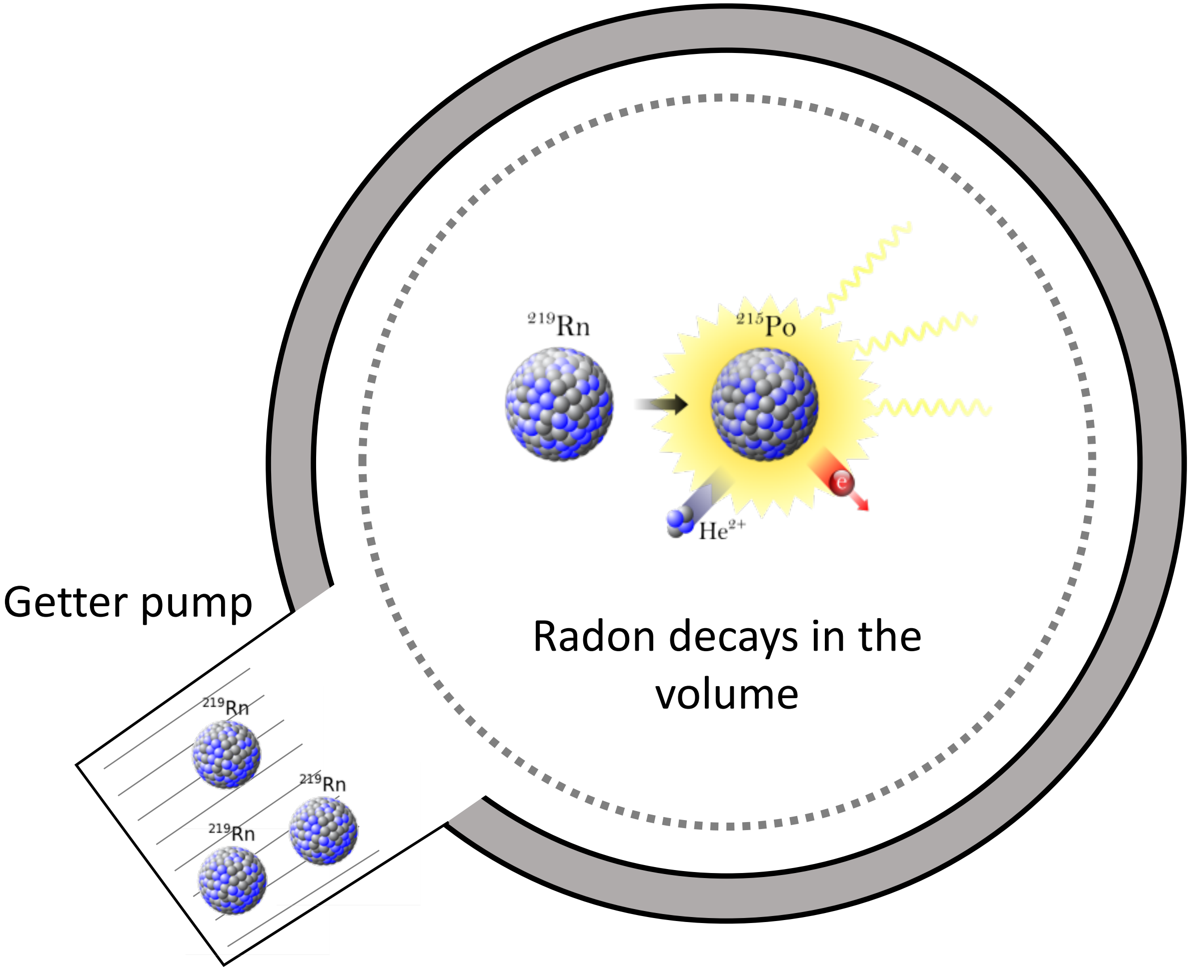
KATRIN backgrounds

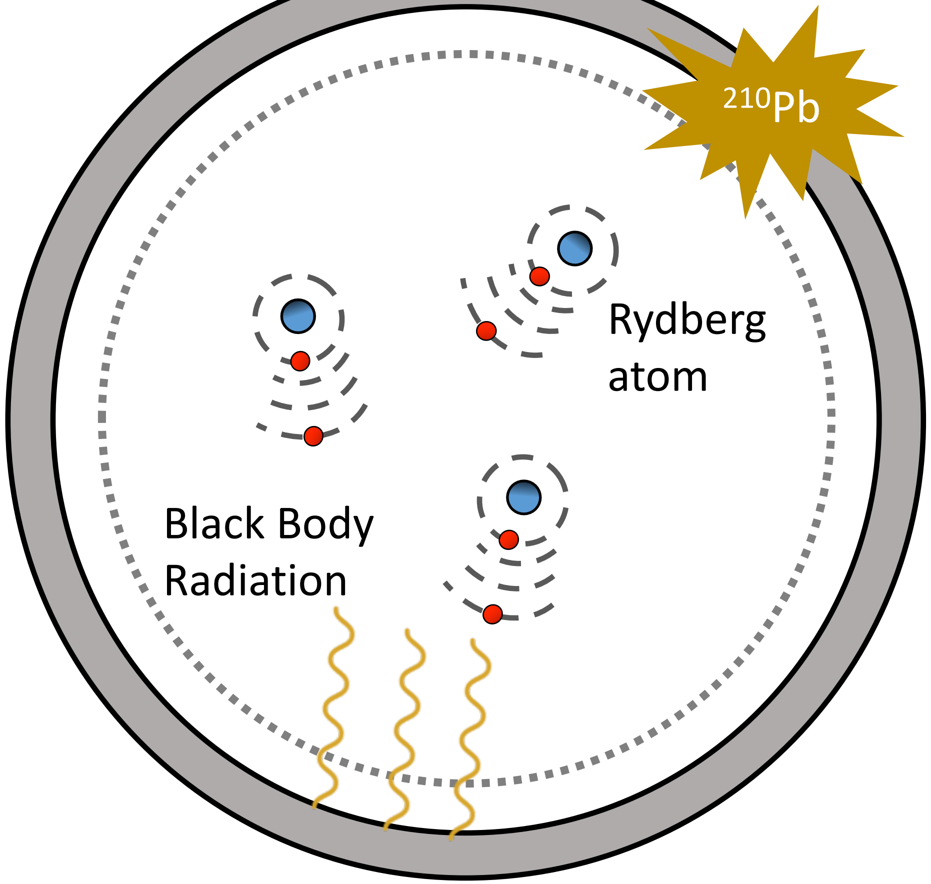




KATRIN backgrounds







Susanne Mertens

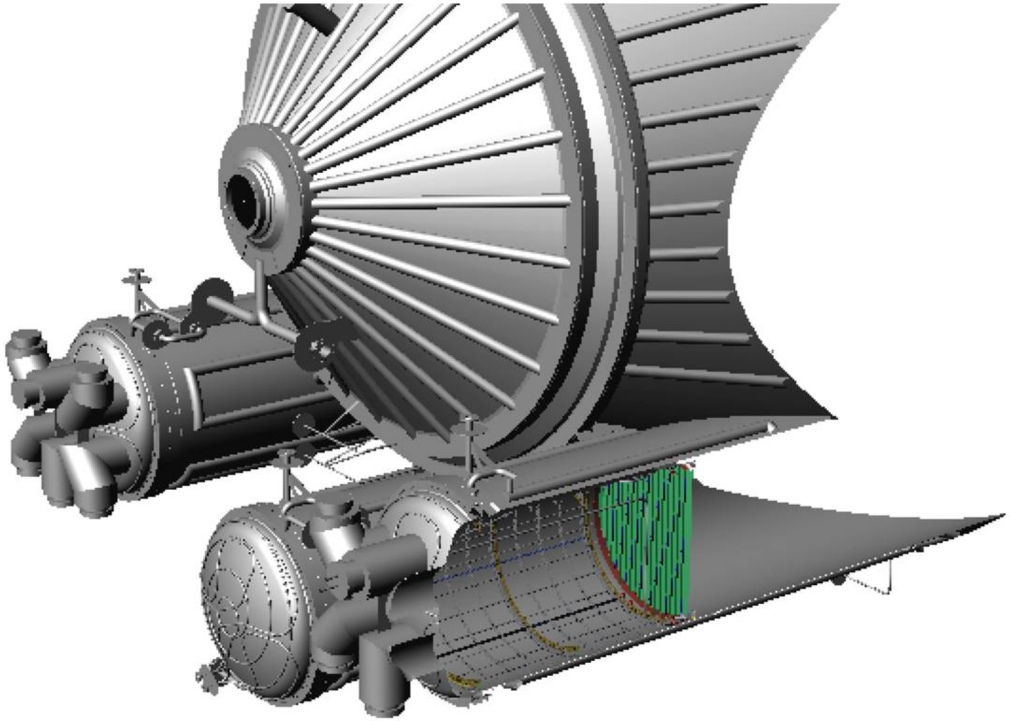
KATRIN backgrounds

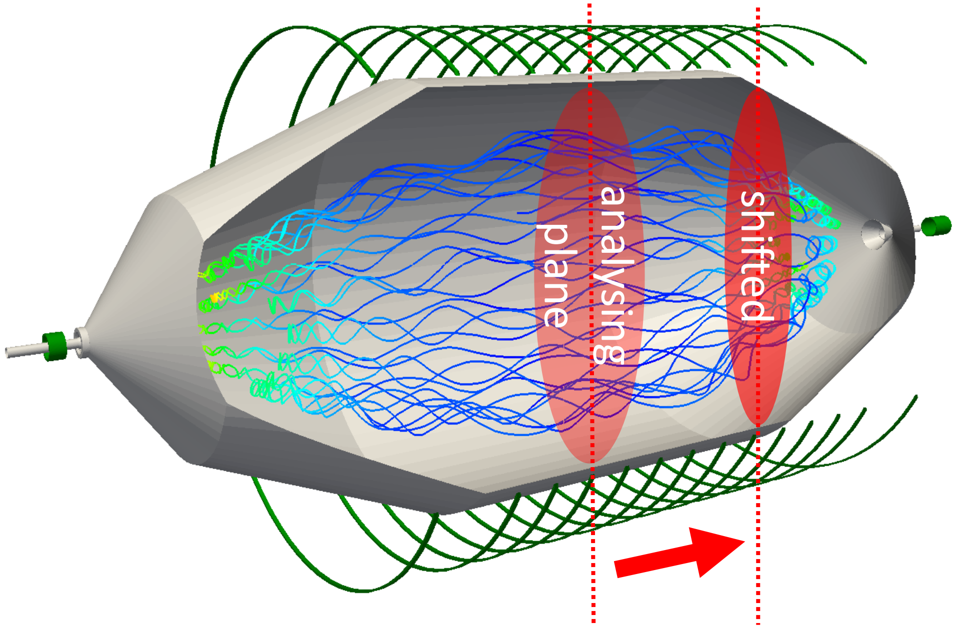
✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system

S. Goerhardt, et al., JINST 13 (2018) no.10, T10004

✓ Effective mitigation of Rydberg background by shifting analyzing plane

not yet applied, under investigation at the moment

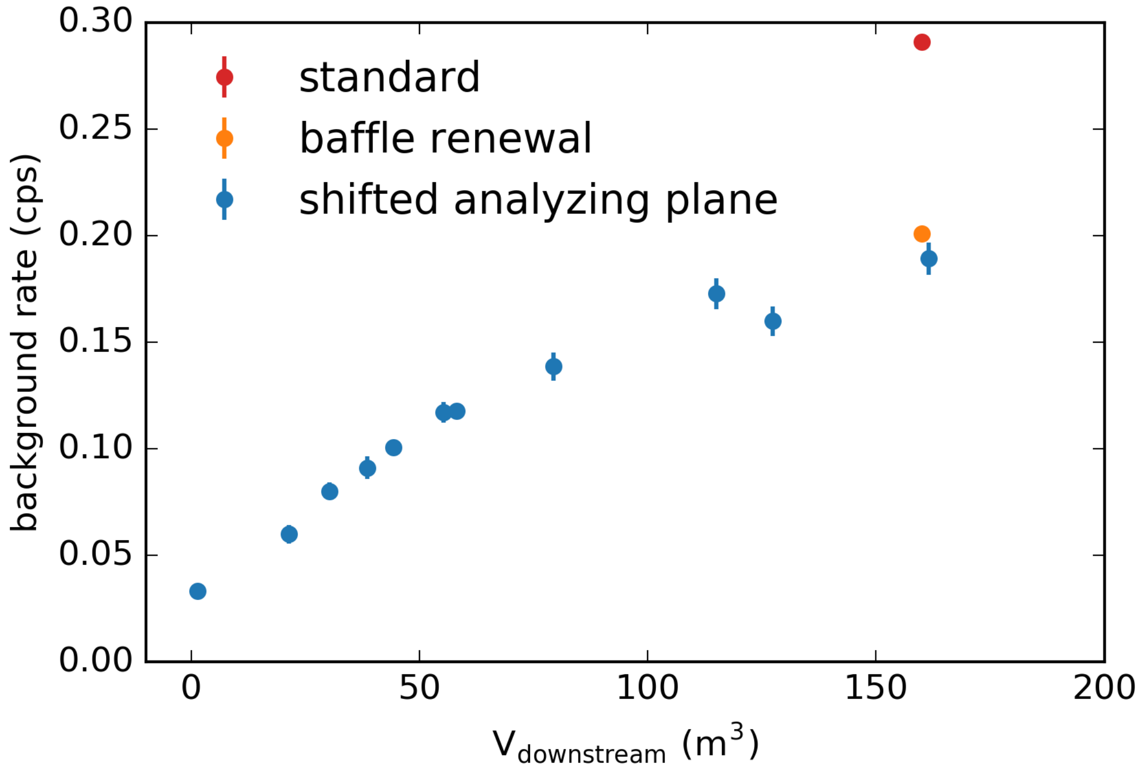




KATRIN backgrounds

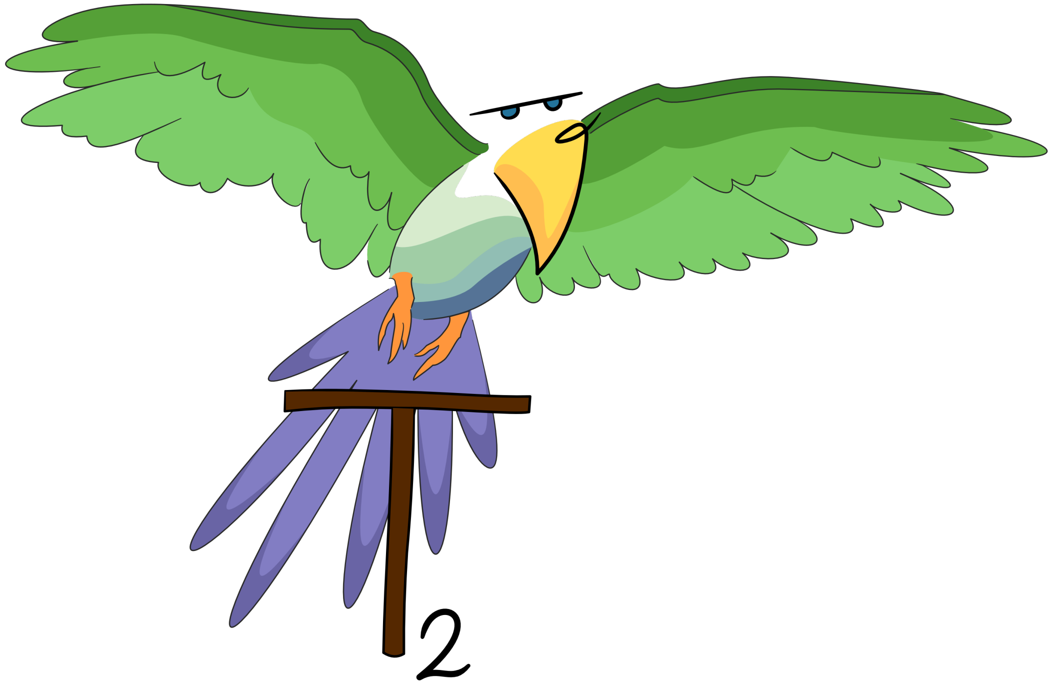
1. Effective reduction of radon-induced background via nitrogen-cooled baffle system
2. Effective mitigation of Rydberg background by shifting analyzing plane

✓ Successful test measurements show feasibility of the technique



Conclusion

- New World Best Direct Neutrino Mass Measurement: m_ν < 1.1 eV (90% C.L.)
- 2nd measurement campaign completed
- Calibration runs ongoing
- Final sensitivity of 0.2 eV reached after 5-years



Thank you for your attention

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