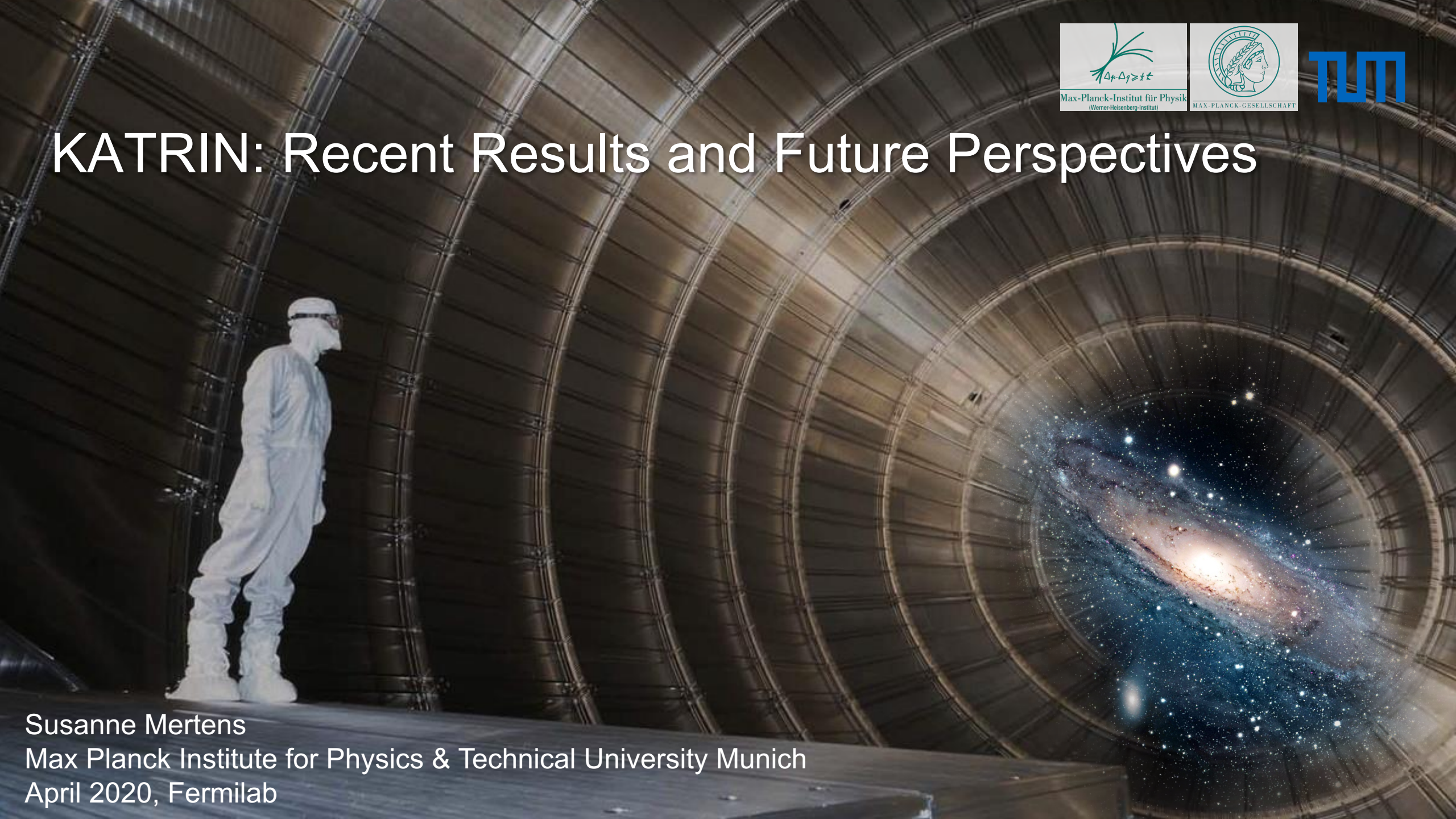
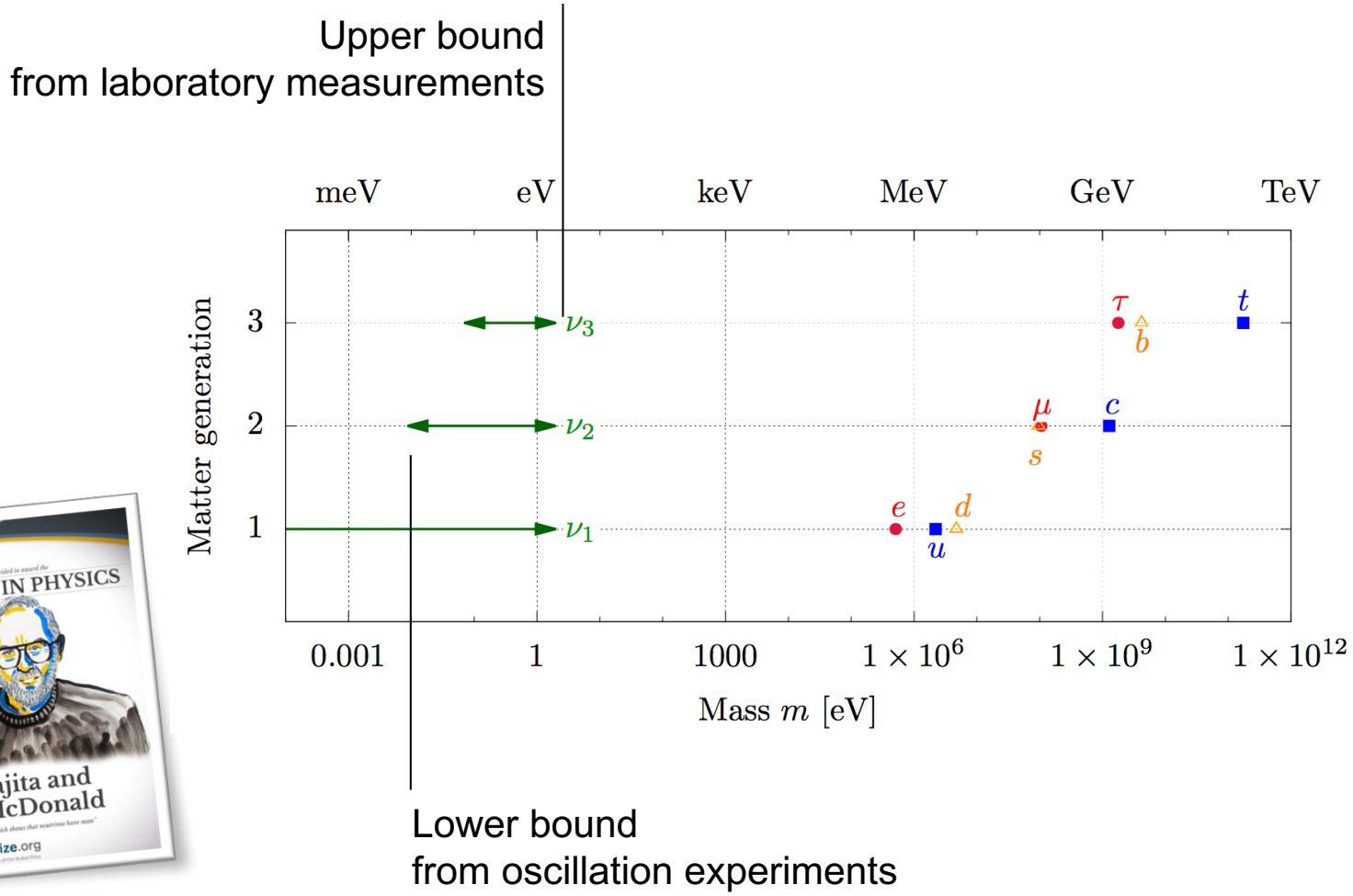
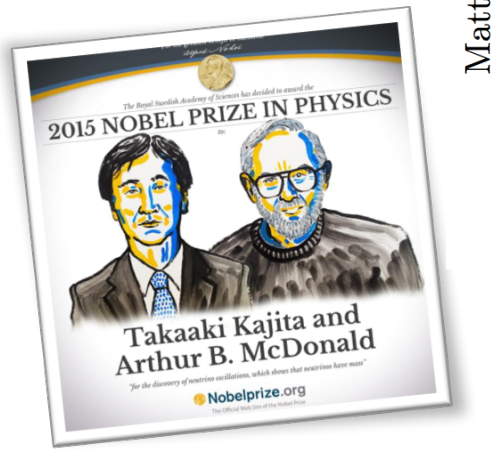


KATRIN: Recent Results and Future Perspectives

Susanne Mertens
Max Planck Institute for Physics & Technical University Munich
April 2020, Fermilab

Neutrino mass





Absolute neutrino mass

Cosmology

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

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

Search for 0νßß

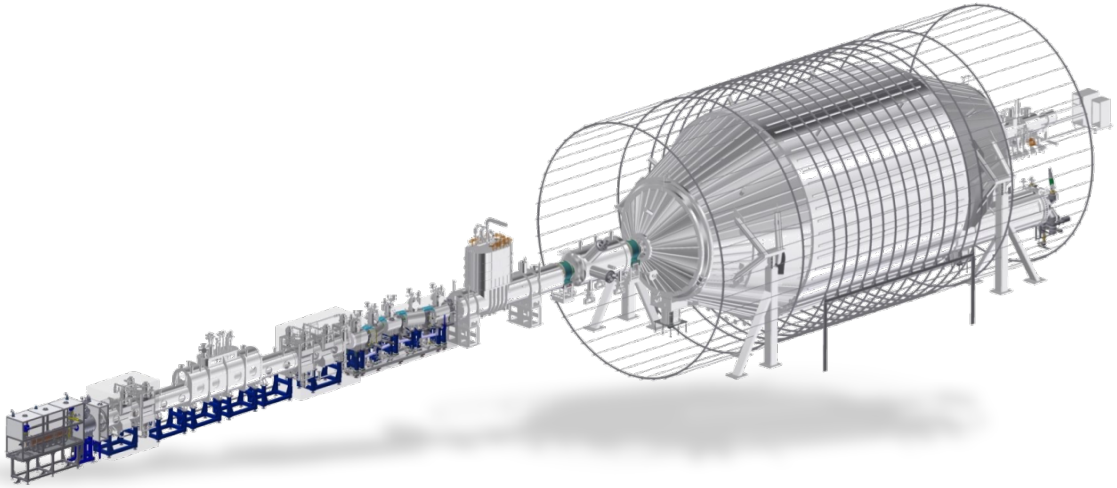
Laboratory-based
potential: $m_{ßß}$ = 15-50 meV
e.g. LEGEND

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

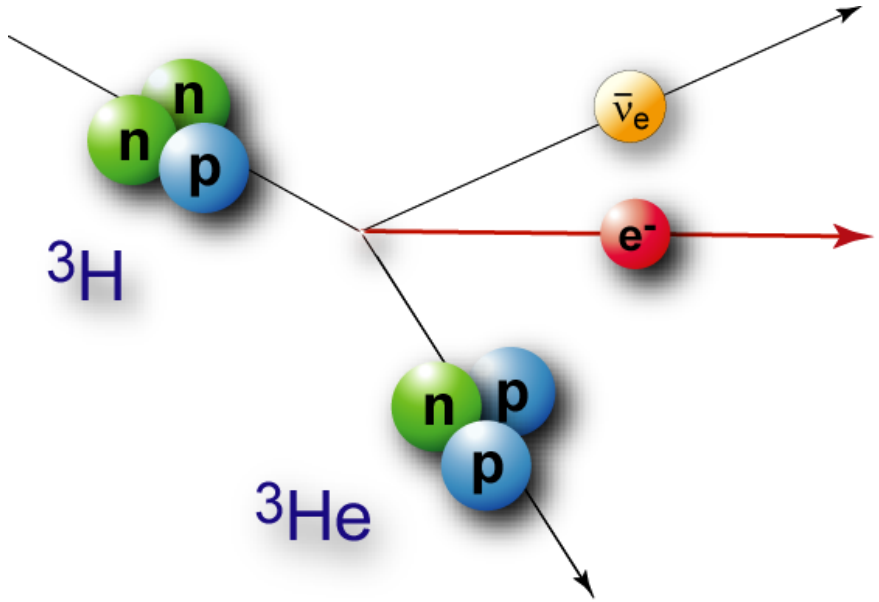
Kinematics of ß-decay

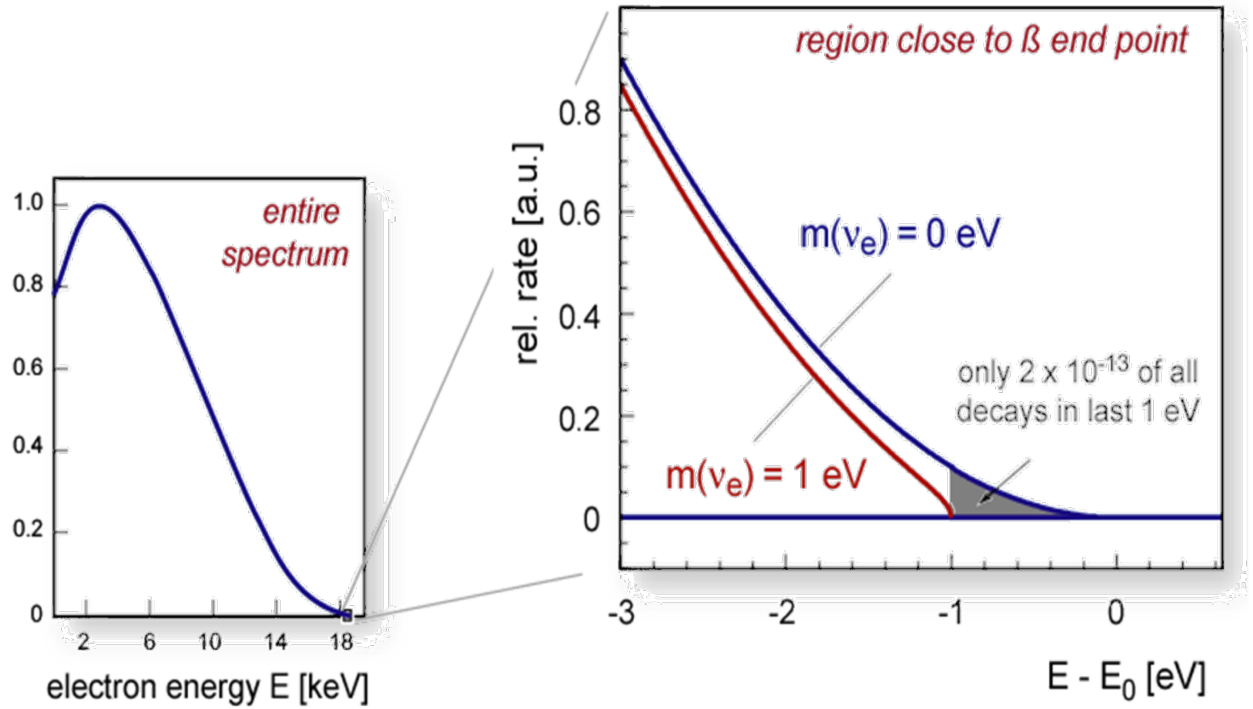
Laboratory-based
potential: m_β = 50 - 200 meV
e.g. KATRIN

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



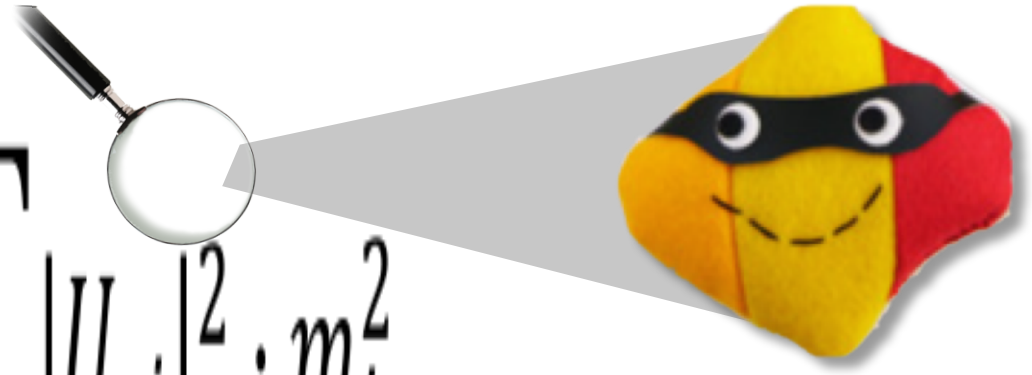
Direct neutrino mass measurement



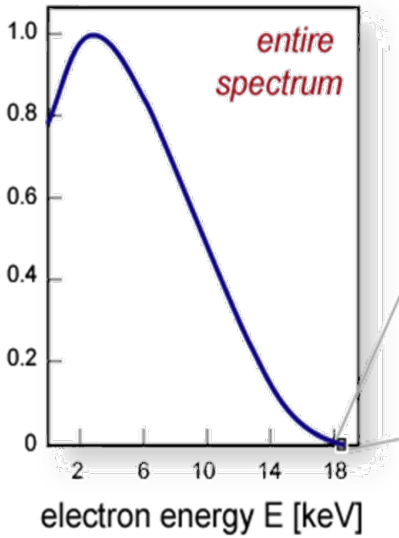


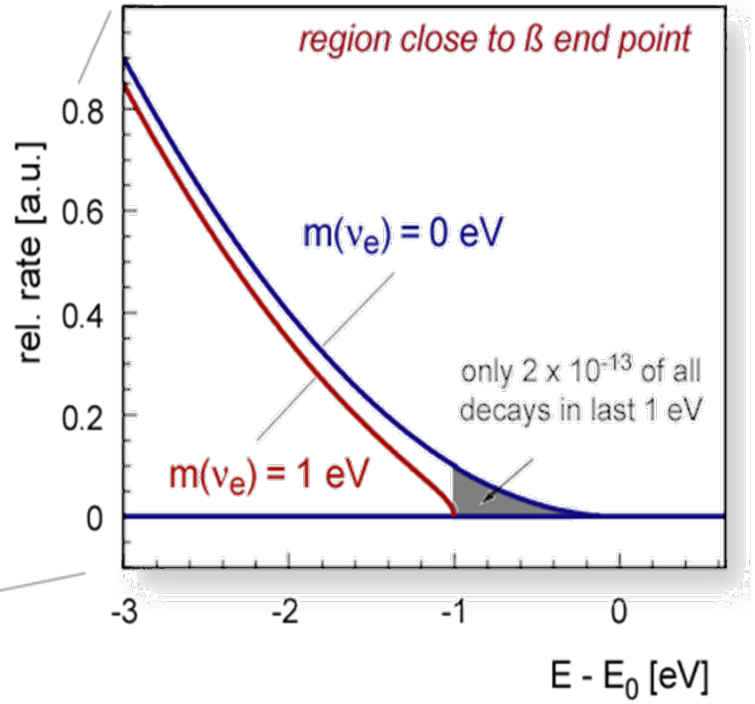
Direct neutrino mass measurement

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



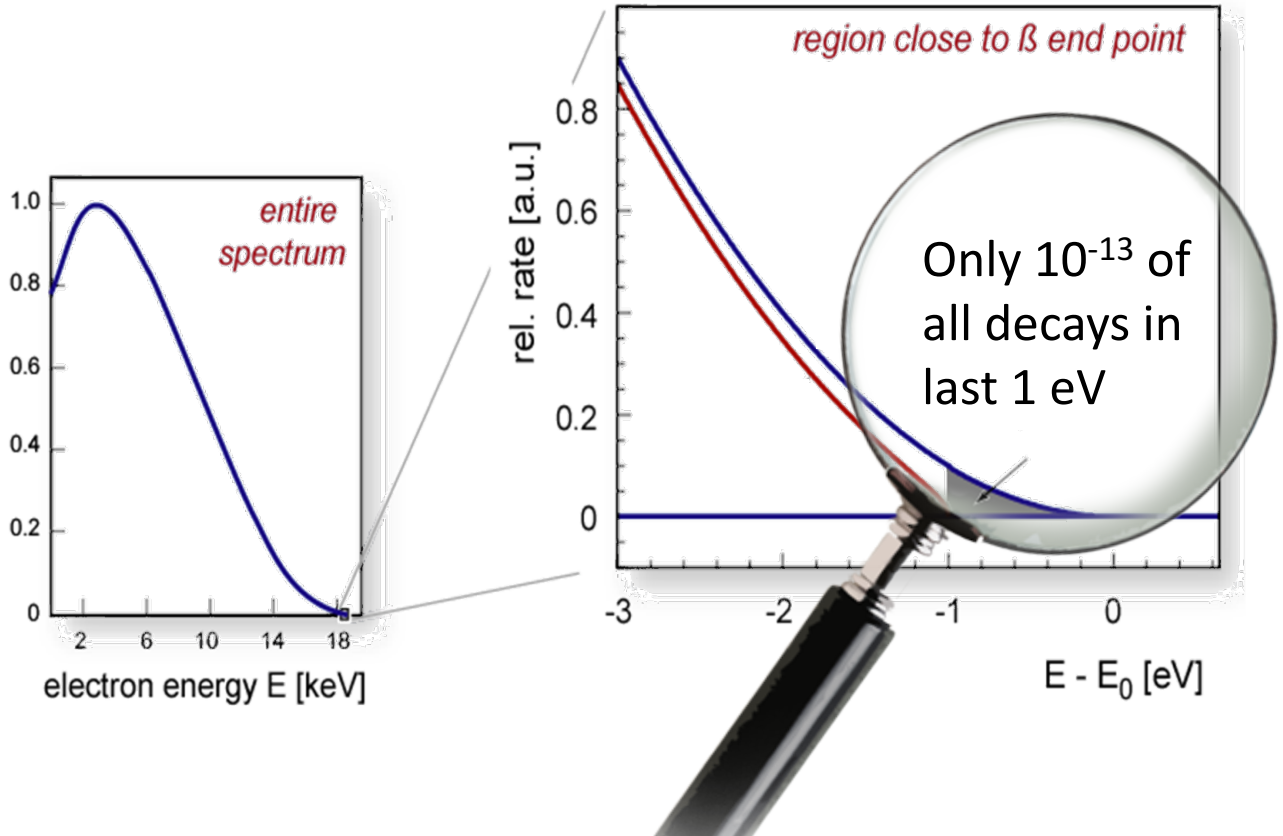
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



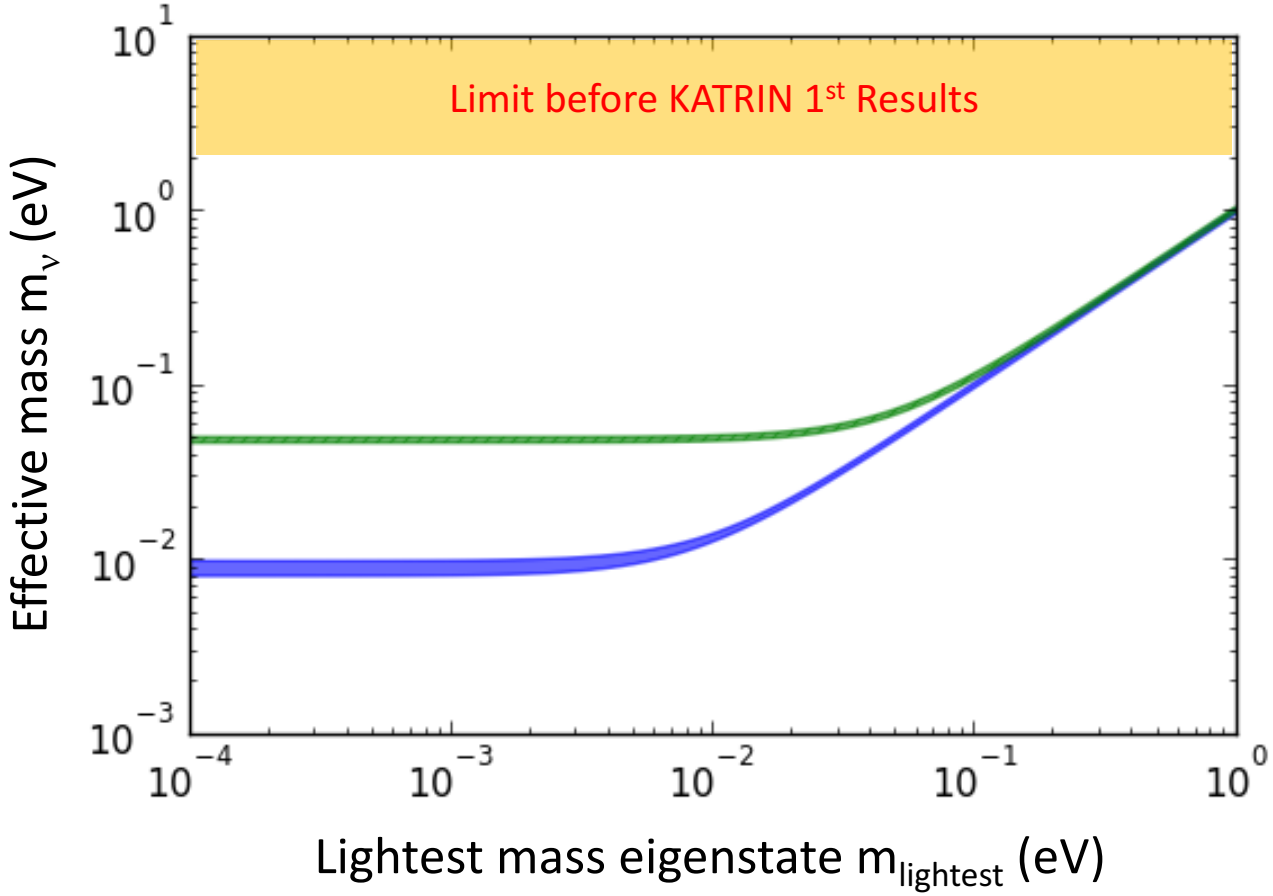


The challenge

- Ultra-strong β-source (10^{11} cps)
- Excellent energy resolution (~ 1 eV)
- Low background level (< 100 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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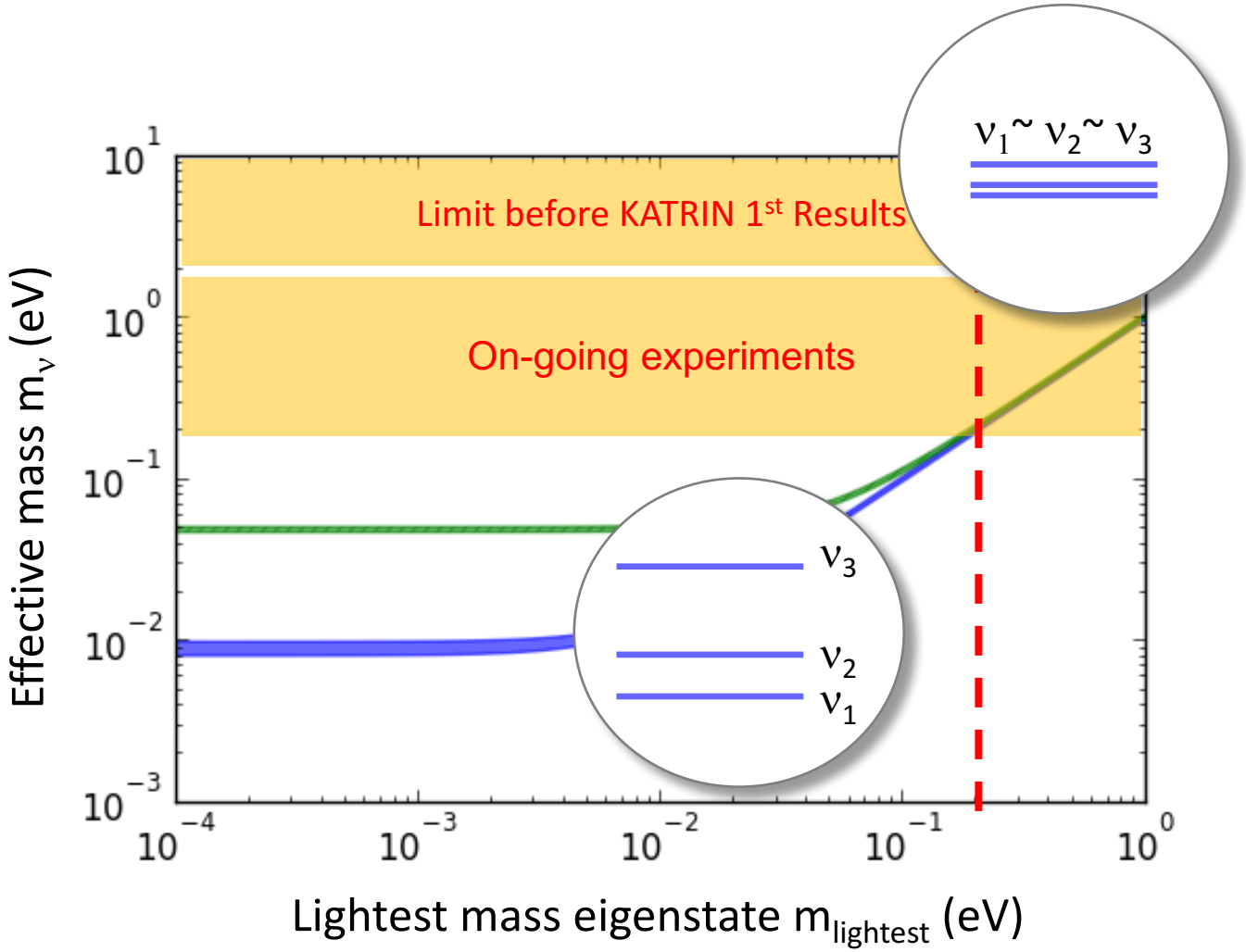

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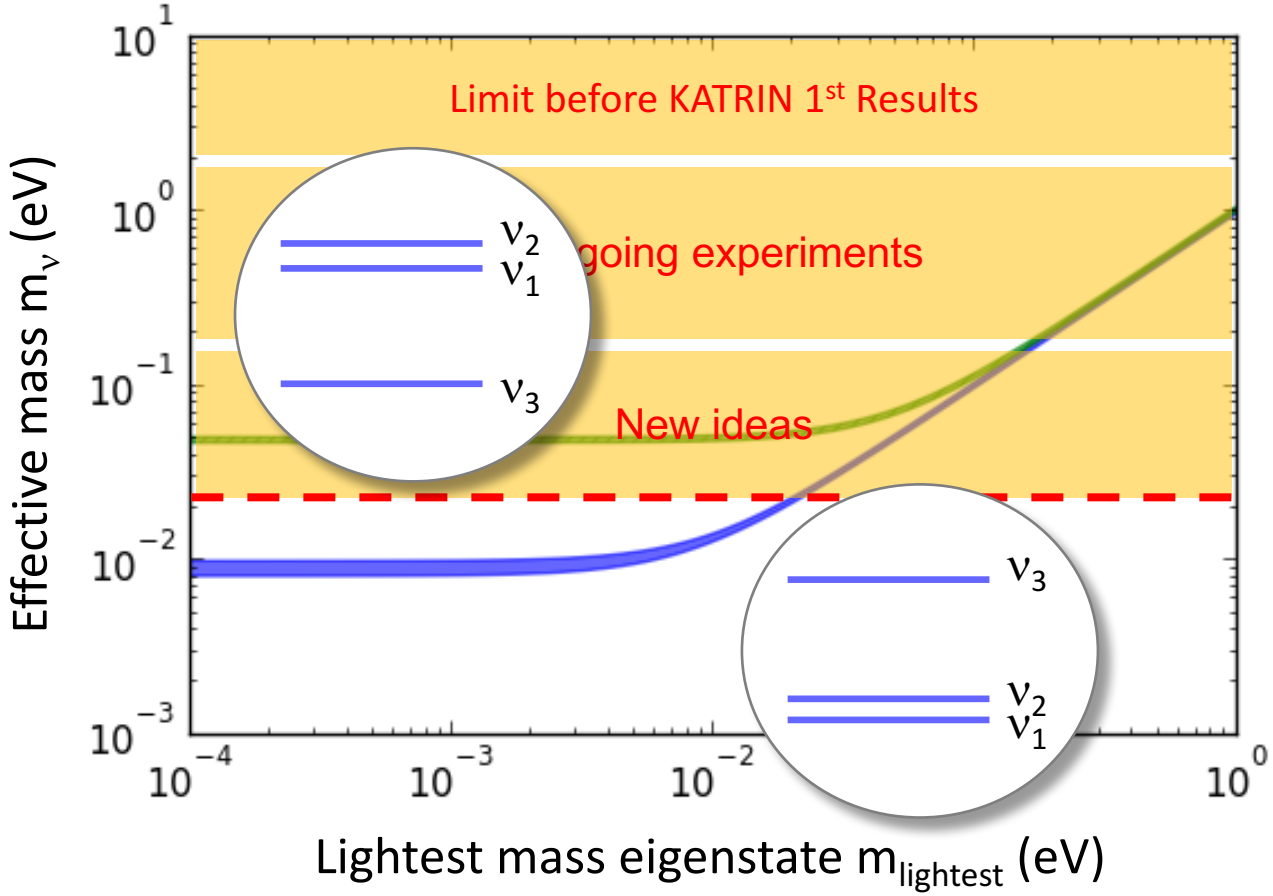
- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



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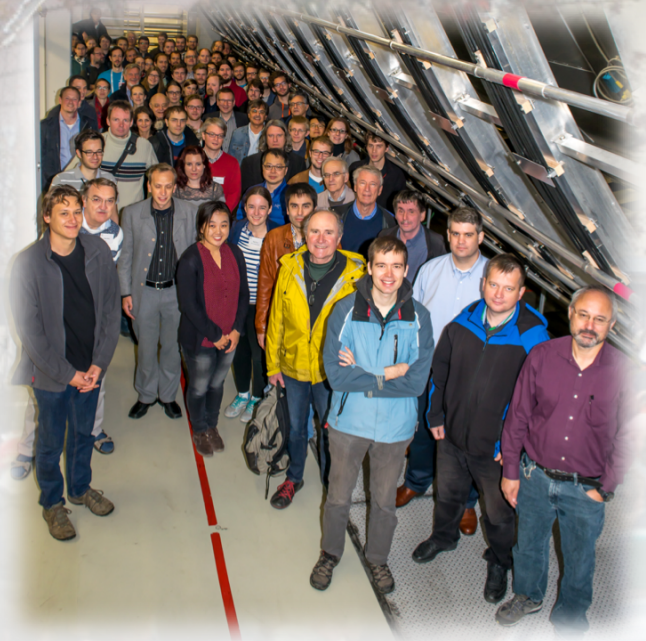
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario
- New ideas: Resolve **normal** vs **inverted** neutrino mass hierarchy

Karlsruhe
Tritium
Neutrino
Experiment

Karlsruhe Tritium Neutrino Experiment

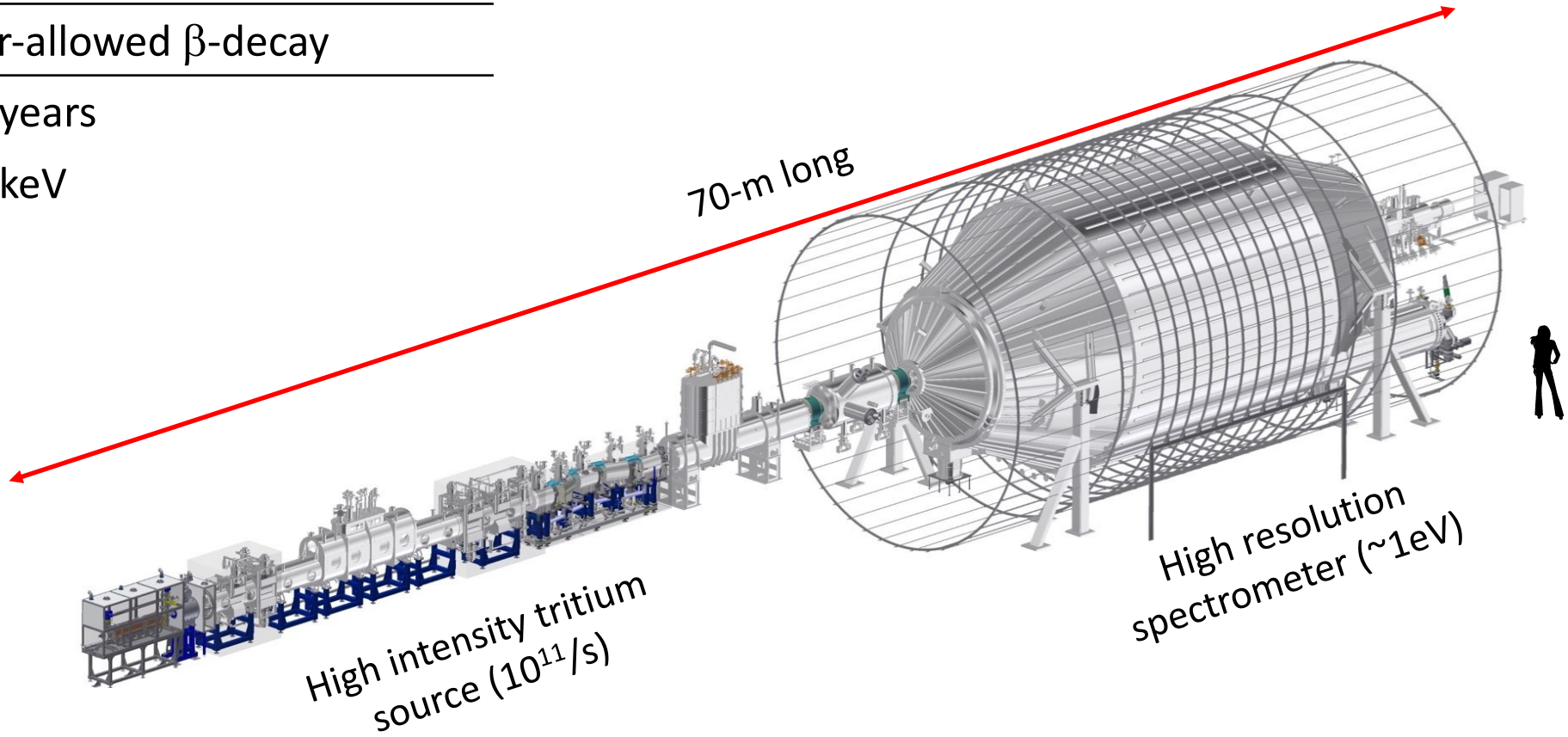


- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Sensitivity m_ν = 0.2 eV (90% CL) after 3 net-years

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 Pittsburgh Pennsylvania 1900
Universidad Complutense Madrid
Russian Academy of Sciences
JG|U Johannes Gutenberg Universität Mainz
TUM Technische Universität München
universitätbonn
Hochschule Fulda University of Applied Sciences
Bergische Universität Wuppertal
Berkeley Lab

KATRIN Working Principle

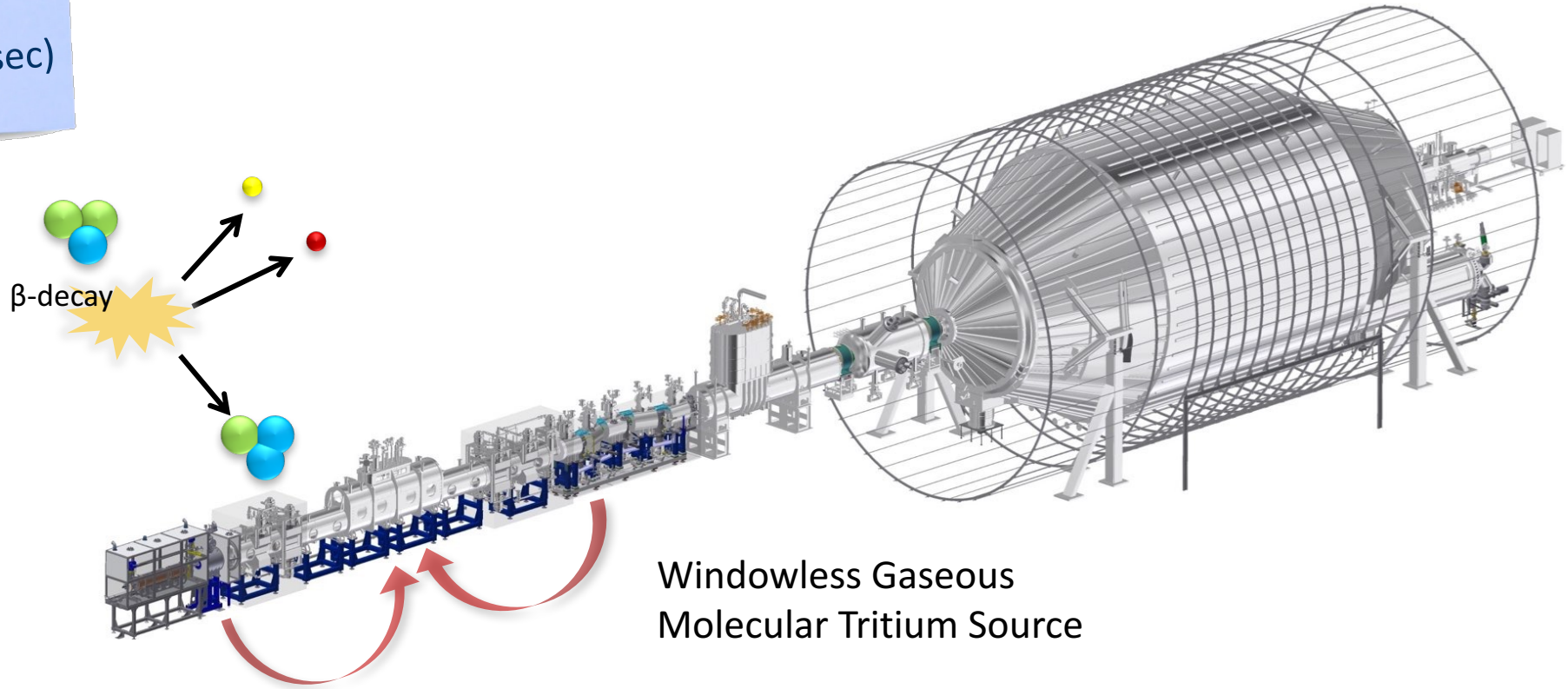
	^{3}H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV



KATRIN Working Principle

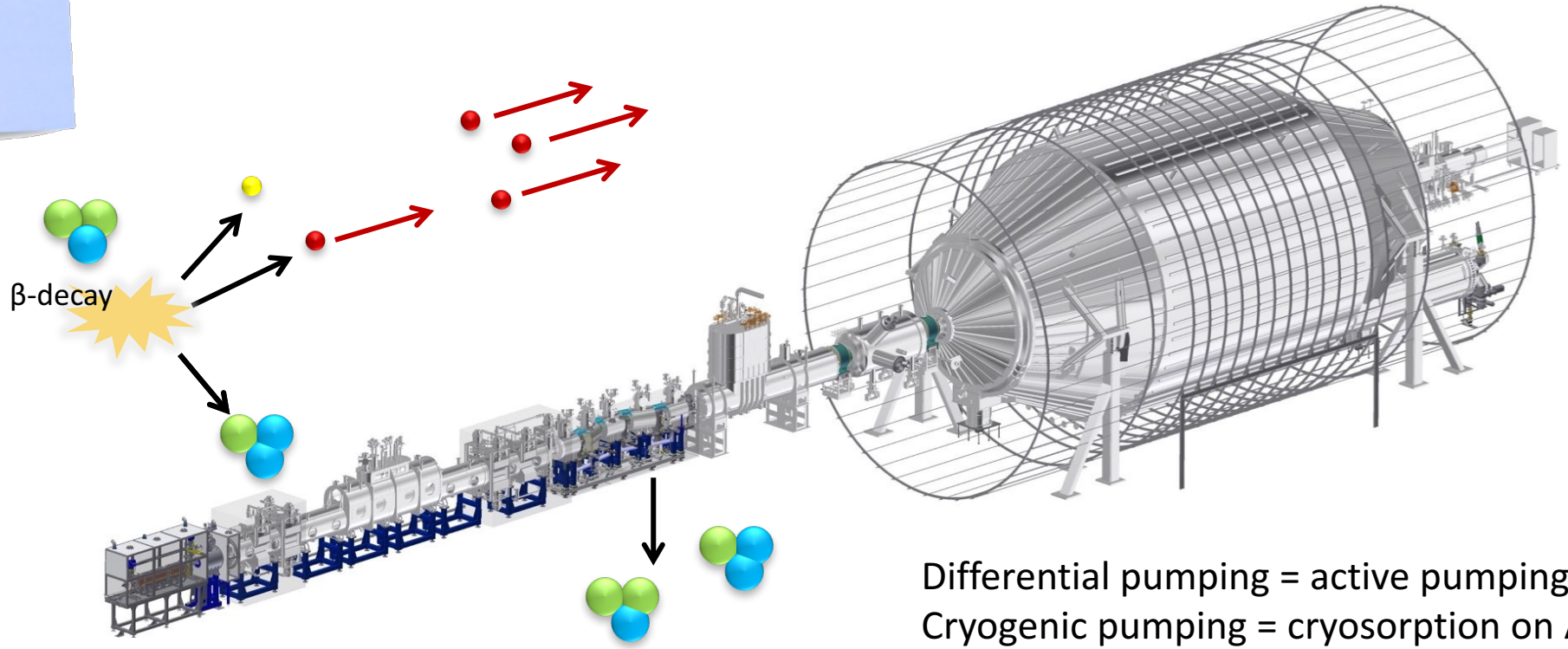
high stability
and luminosity

(10^{11} decays/sec)



KATRIN Working Principle

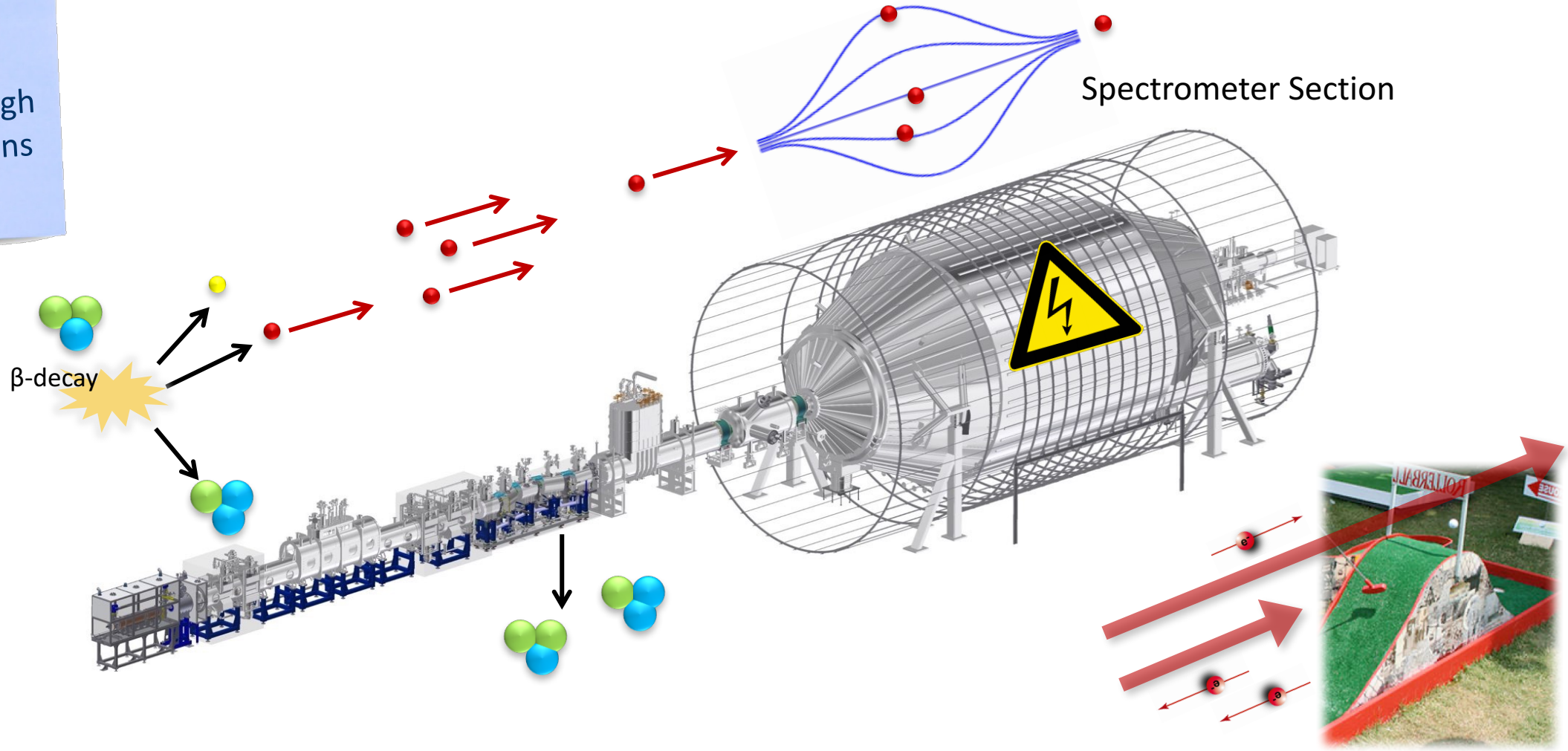
Tritium flow reduction by 14 orders of magnitude



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

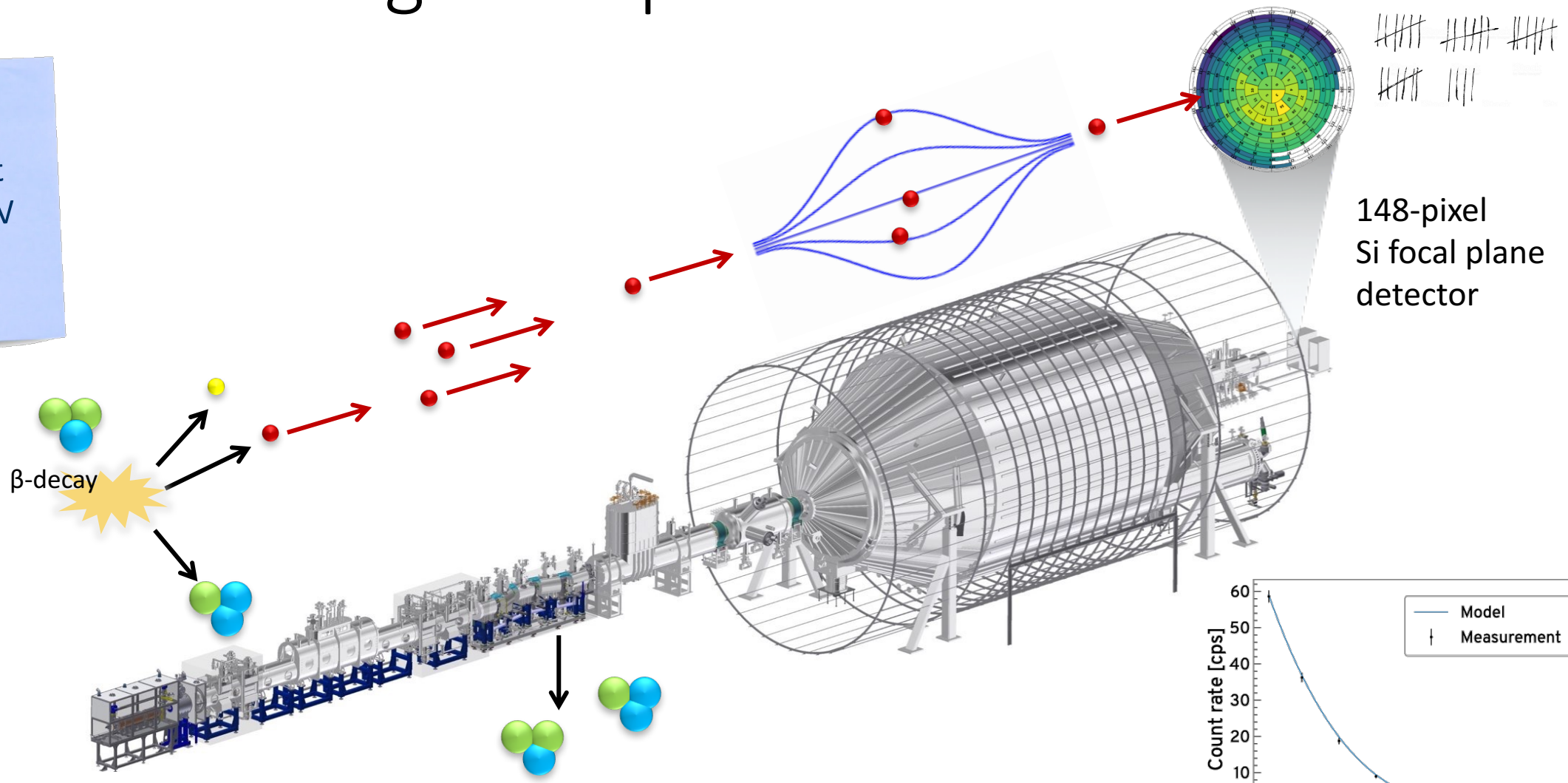
KATRIN Working Principle

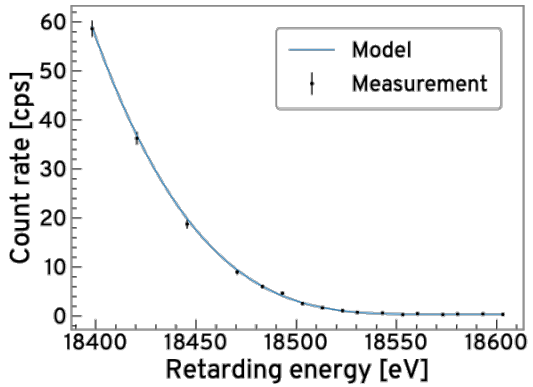
Electrostatic filter selects high energy electrons



KATRIN Working Principle

Integral measurement down to 40 eV below the endpoint

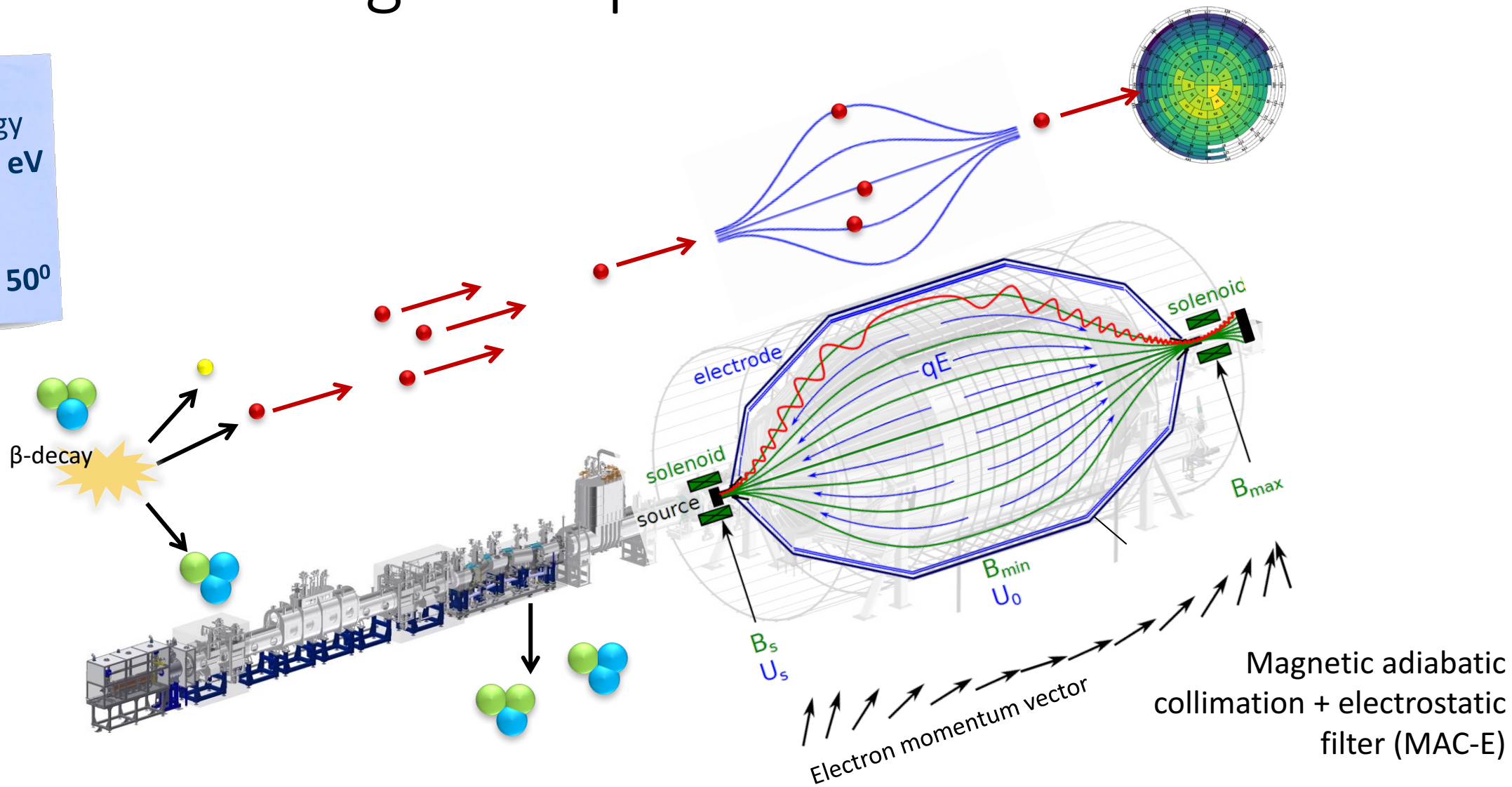




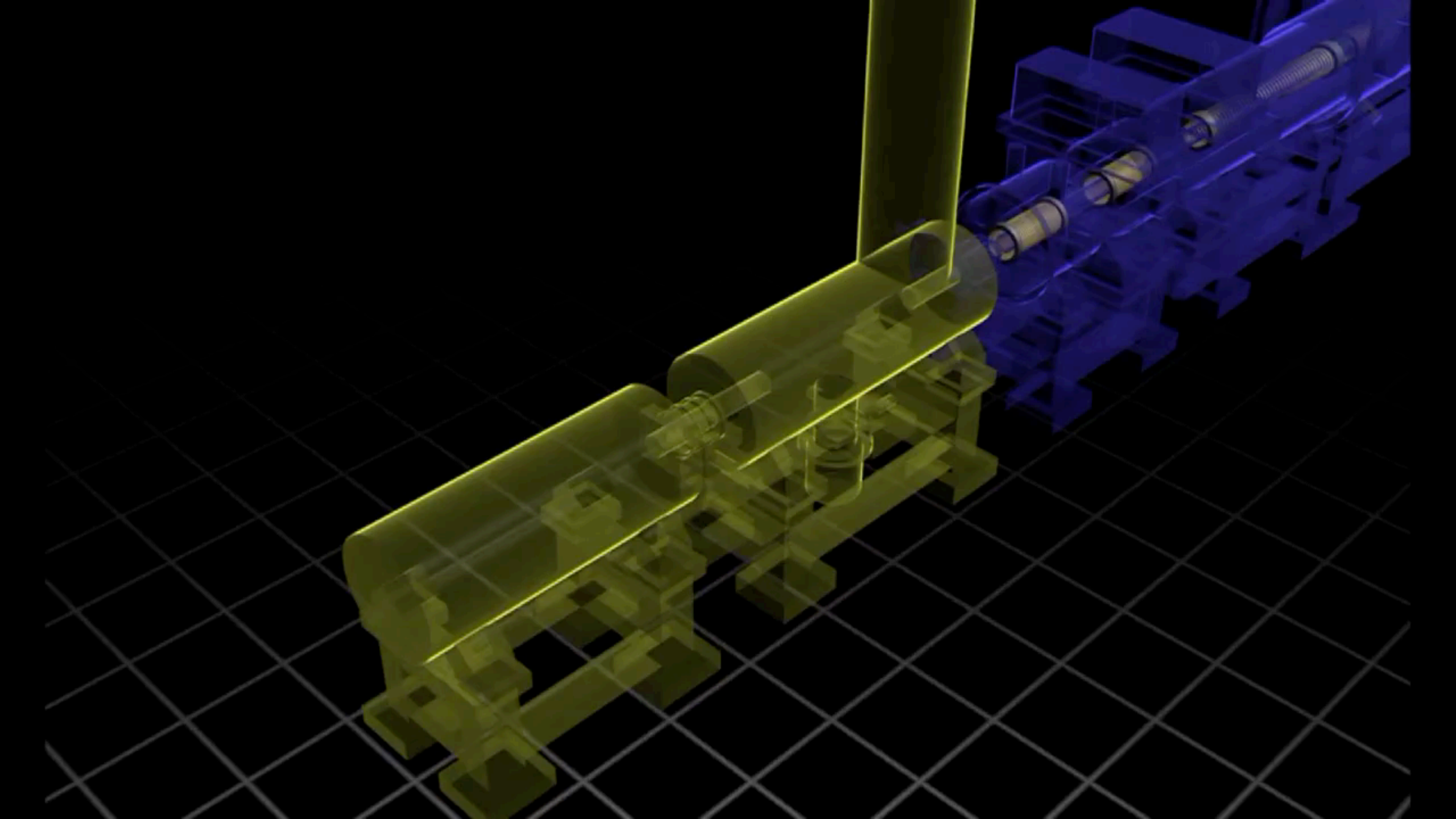
KATRIN Working Principle

excellent energy resolution: **~ 1 eV**

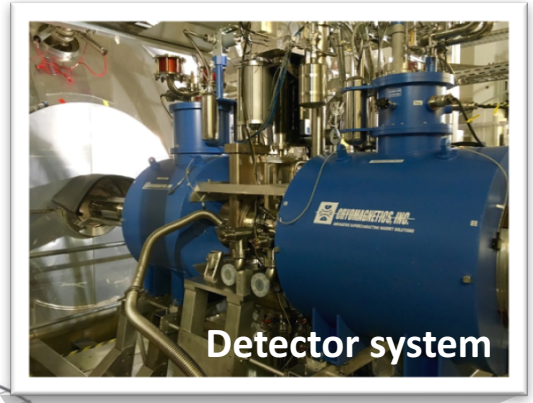
large angle acceptance: **~ 50⁰**

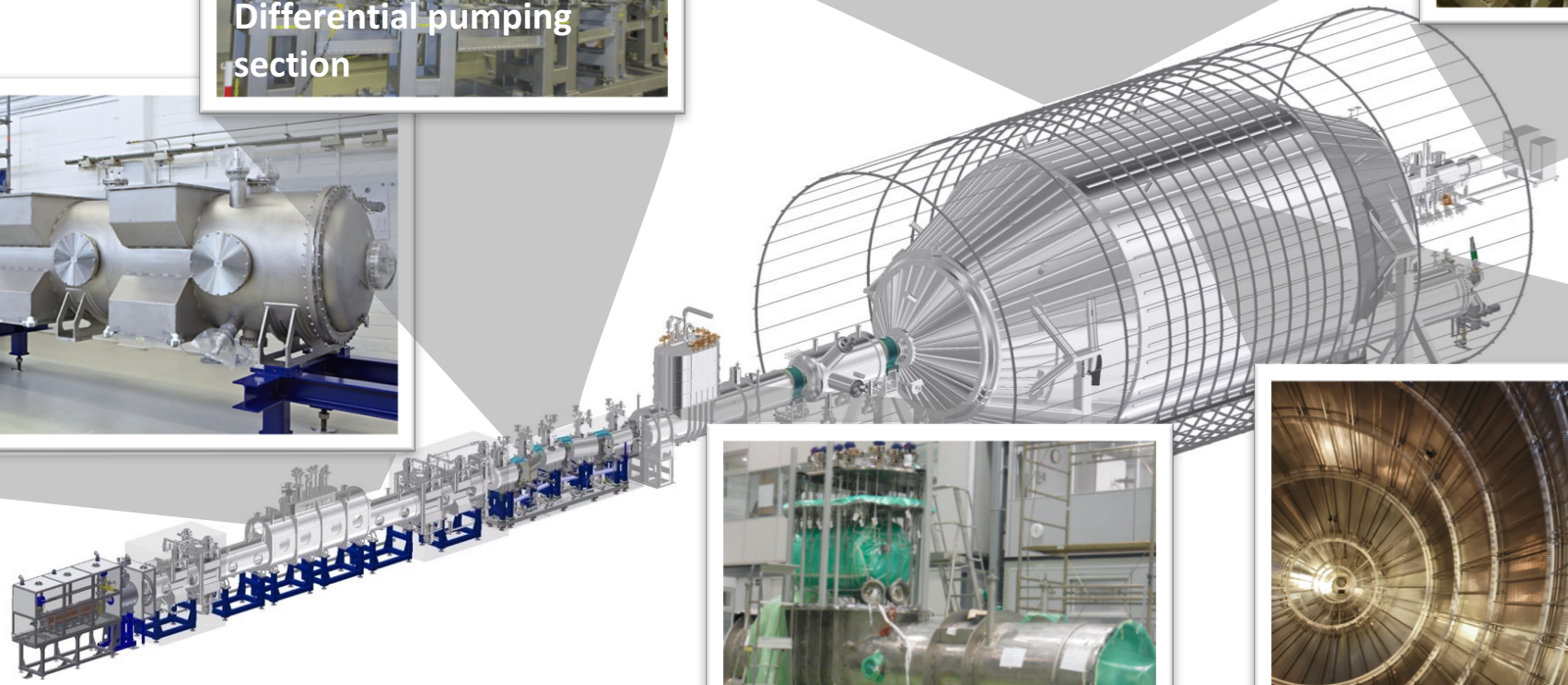


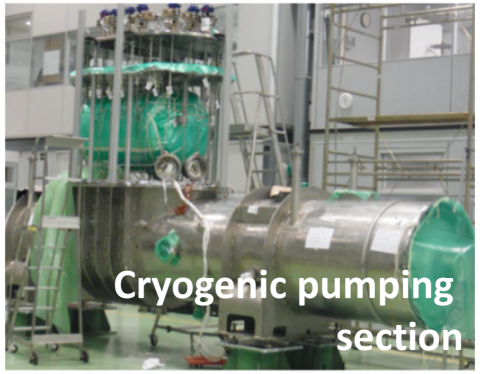
Magnetic adiabatic collimation + electrostatic filter (MAC-E)

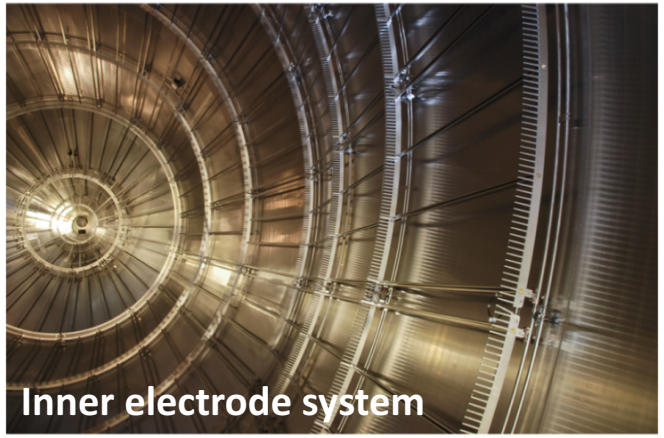


KATRIN (in real)









JINST 11 P04011 (2016)
JINST 13 P04020 (2018)

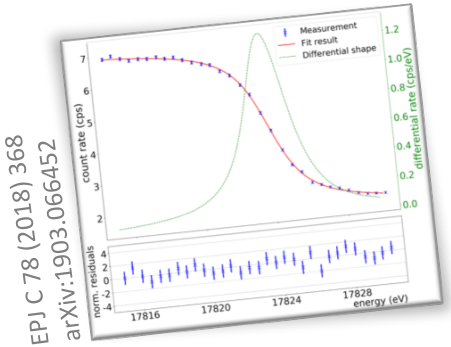
18-years of KATRIN history

Letter of Intent

2001

Main spectrometer

2006



EPJ C 78 (2018) 368
arXiv:1903.066452

Krypton calibration

2016

2017

Phys. Rev. Lett. 123, 221802

First neutrino mass

2018

2019

Design Report

2004

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

KATRIN Design Report 2004

J. Angrik[1], T. Armbrust[1], A. Beglarian[1], U. Bauerer[1], J. Blümer[1,3], J. Bonn[1], R. Carr[1], B. Bornschein[1], L. Bornschein[1], T. Burritt[14], M. Charlton[7], A.J. Davies[7], C. Day[1], P.J. Doe[10], L. Dörr[1], O. Dragoun[1], G. Drexlin[1,3], F. Eichelhardt[1], K. Eitel[1], K. Essig[1], A. Felden[1], B. Flatt[1], J. Formaggio[10], B. Freudiger[1], R. Gumbsheimer[1], F. Habermehl[1], E. Geraskin[1], F. Glück[1], M. Glugla[1], S. Grohmann[1], H. Hucker[1], O.V. Ivanov[1], G. Harper[10], G. Helbrägel[1], J. Herbert[1], T. Höhn[1], M. Howe[10], H. Hucker[1], A. Kovalik[1], K.-P. Jüngst[1], J. Kaiser[1], O. Kazachenko[1,4], N. Kernert[1], P. Komarek[1], A. Osipowicz[1], C. Kraus[10], H. Krause[1], M. Leber[10], R. Lewis[7], V. Lobashev[4], X. Luo[1], K. Maier[1], O. Malyshev[7], M. Marx[1], I. Moskov[4], K. Müller[1], S. Mutterer[1], G.R. Myneni[7], M. Neuberger[1], H. Neumann[1], M. Noe[1], H.W. Ortjohann[1], S. Osipov[4], A. Osipowicz[1], B. Ostrick[1,3], E.W. Otten[1], P. Plischke[1], A. Pomaroski[1], A. Pretzschner[1], R. Reid[7], K. Riesinger[10], R.G.H. Robertson[10], M. Rysavý[2], P. Schäfer[1], K. Schlösser[1], U. Schmitt[1], F. Schwamm[1], P. Schwinzer[1], D. Sevilla Sanchez[1], F. Sharipov[4], A. Skasyrskaya[4], A. Špalek[1], M. Steidl[1], M. Süßer[1], E. Syresin[4], H.H. Telle[1], T. Thümmler[1,3], N. Titov[1,3], V. Umanov[1], K. Valerius[1,3], T. VanWechel[10], D. Vénos[1], R. Vianden[1], C. Weinheimer[1], A. Weiss[1], J. Wendel[1], J.F. Wilkerson[10], J. Wolf[1], S. Wüstling[1], S. Zadoroghny[4], M. Zbořil[2]

The KATRIN Collaboration:

[1] Rheinische Friedrich-Wilhelms-Universität Bonn, Helmholtz - Institut für Strahlen- und Kernphysik, Nussallee 14-16, 53115 Bonn, Germany

[2] Fachhochschule Fulda, Fachbereich Elektrotechnik und Informationstechnik, Marquardtstr. 35, 36039 Fulda, Germany

[3] Forschungszentrum Karlsruhe, Commercial Project Execution/Contracting, Postfach 3640, 76021 Karlsruhe, Germany

[4] Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany

[5] Forschungszentrum Karlsruhe, Institut für Prozessdatenverarbeitung und Elektronik, Postfach 3640, 76021 Karlsruhe, Germany

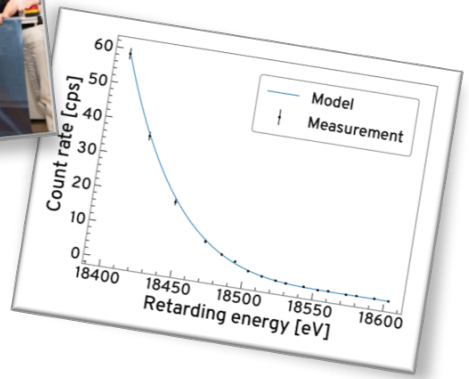
[7] Forschungszentrum Karlsruhe, Institut für Technische Physik, Postfach 3640, 76021 Karlsruhe, Germany

First light

JINST 13 (2018) P04018

First tritium

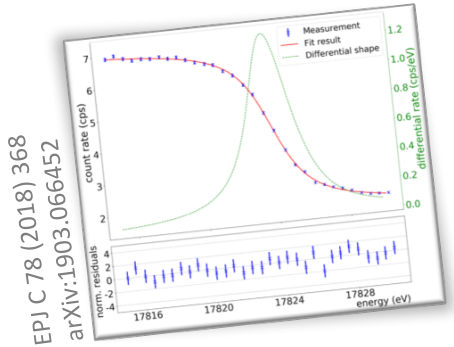
arXiv:1909.06069



18-years of KATRIN history

Letter of Intent

Main spectrometer



EPJ C 78 (2018) 368
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Krypton calibration

Phys. Rev. Lett. 123, 221802

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

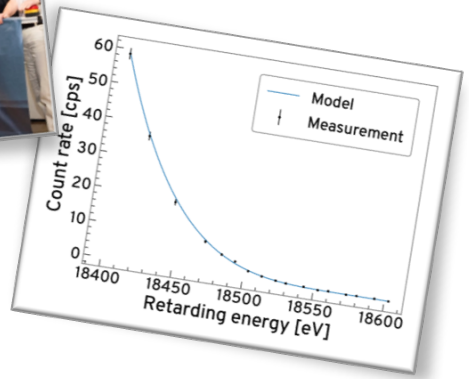
The KATRIN Collaboration:

First light

JINST 13 (2018) P04018

First tritium

arXiv:1909.06069



KATRIN neutrino mass campaign #1 (KNM-1)

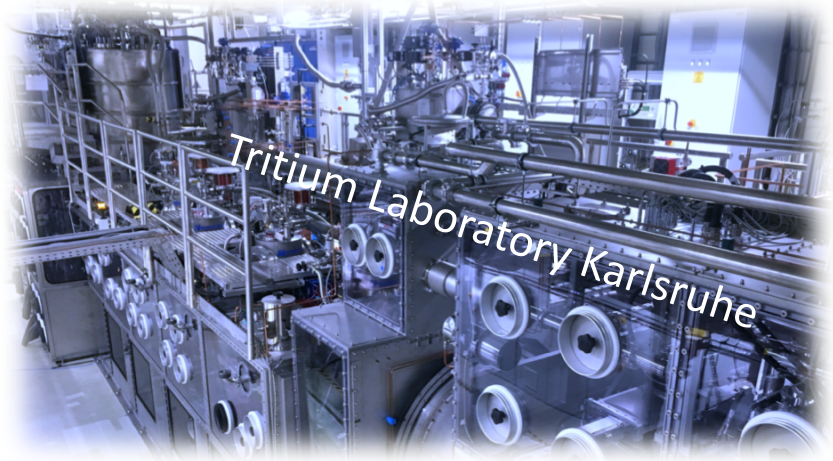
- First ever high-activity tritium operation of KATRIN
- April 10 – May 13 2019: **780 h (~4 weeks)**
- high-quality data collected **2 million electrons**

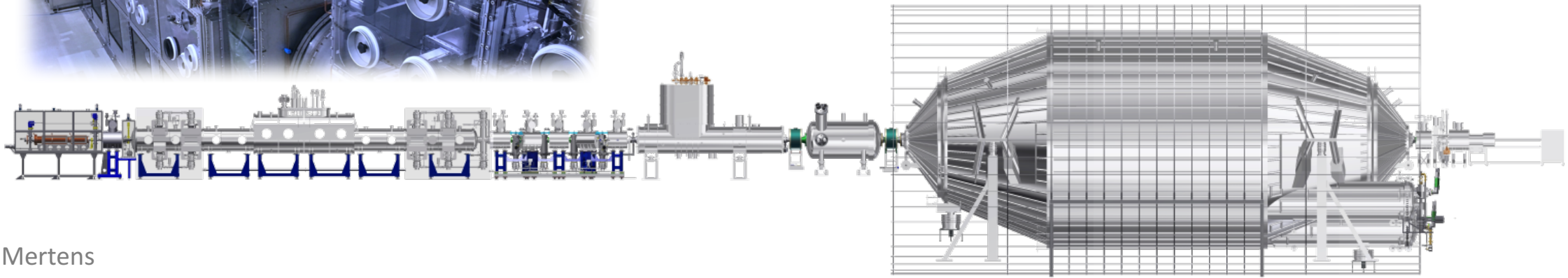
✓ **First neutrino mass result ☺**

Phys. Rev. Lett. 123, 221802

Tritium source operation

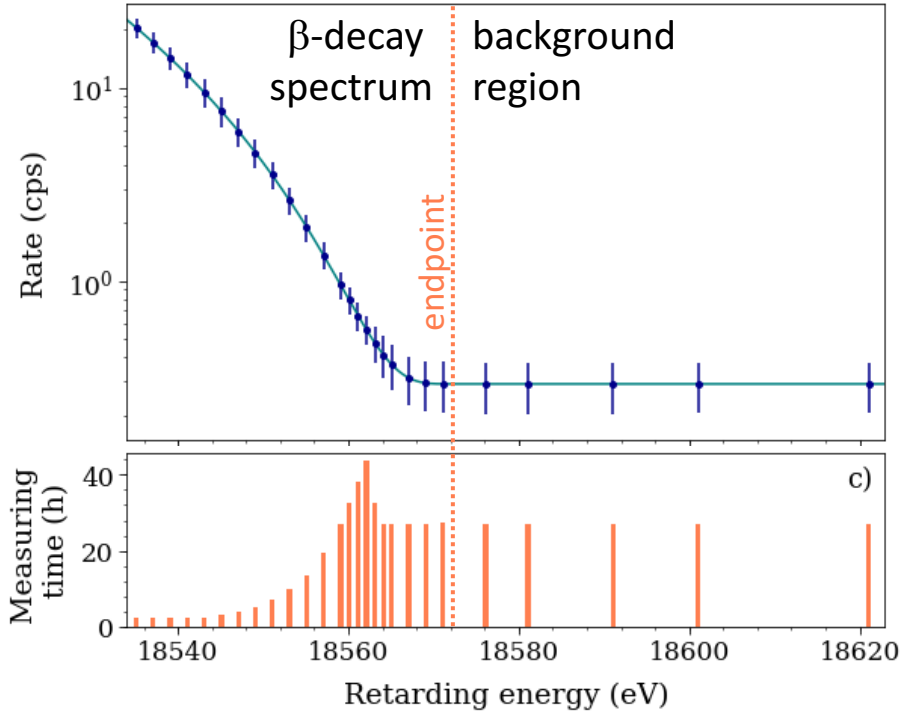
- tritium gas density: **22% of nominal (burn-in period)**
- high isotopic tritium purity: **97.5%**
- high source activity: **$2.45 \cdot 10^{10}$ Bq (24.5 GBq), throughput: 4.9 g/day**

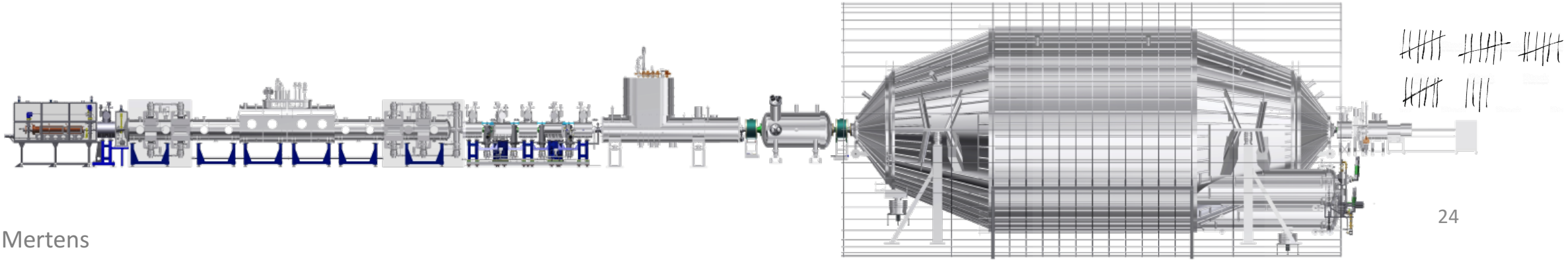




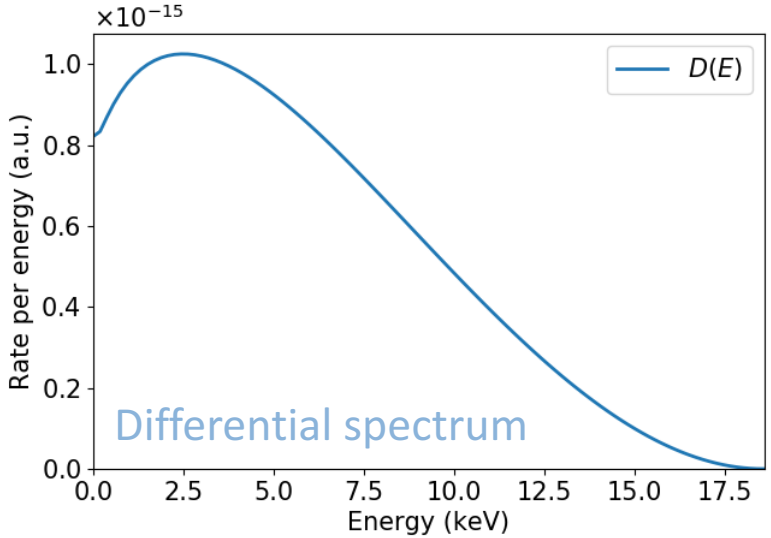
Spectrometer operation

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

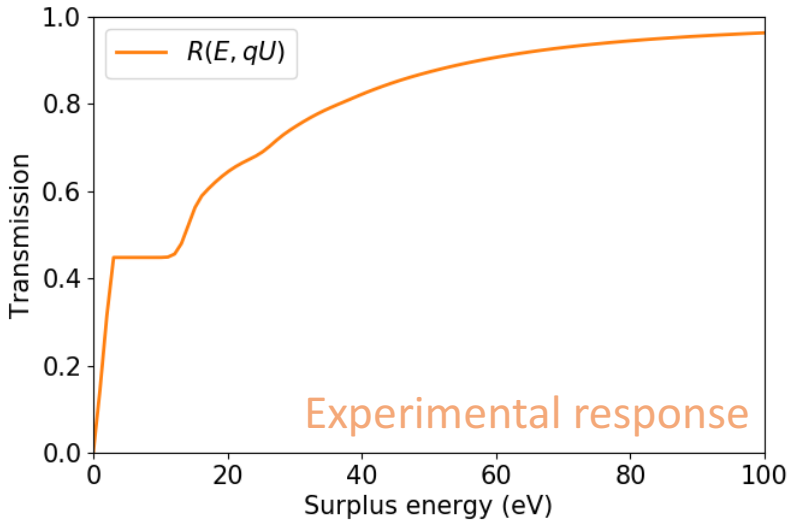


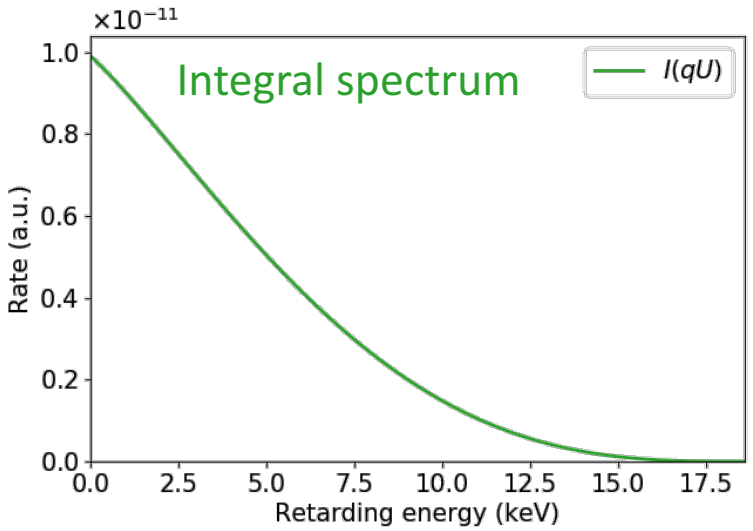


Tritium spectrum calculation



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

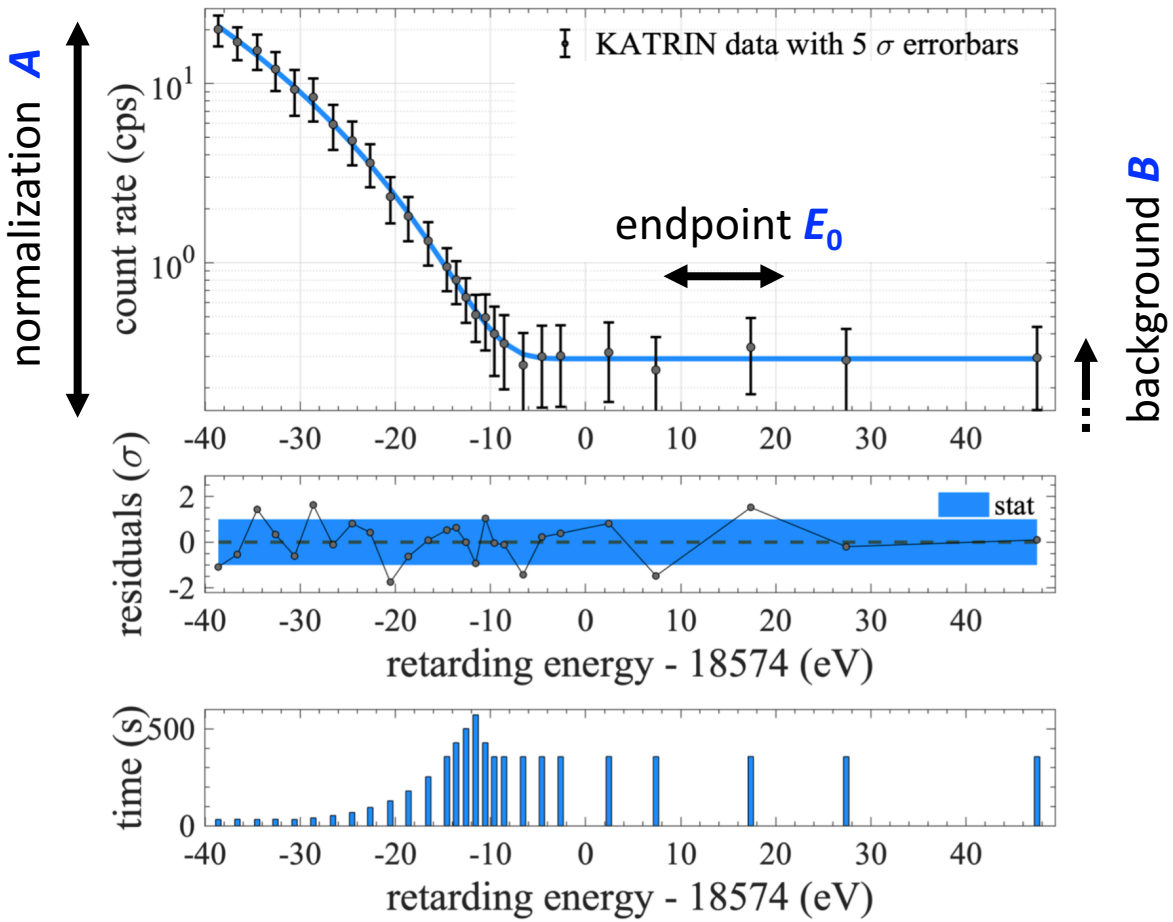




- Molecular final states
- Theoretical corrections
- Doppler broadening
- …

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

Fit of a single 2-h beta-scan

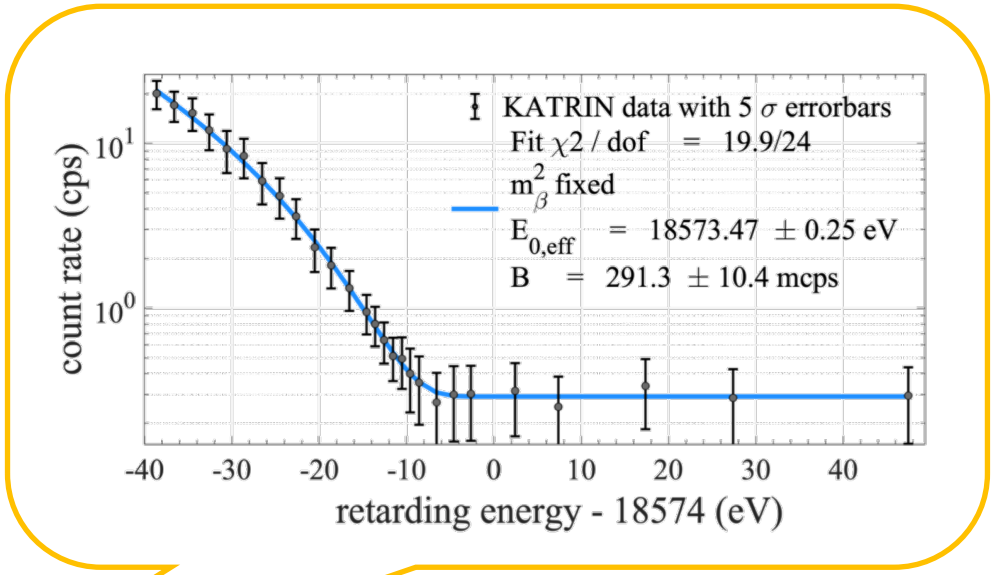


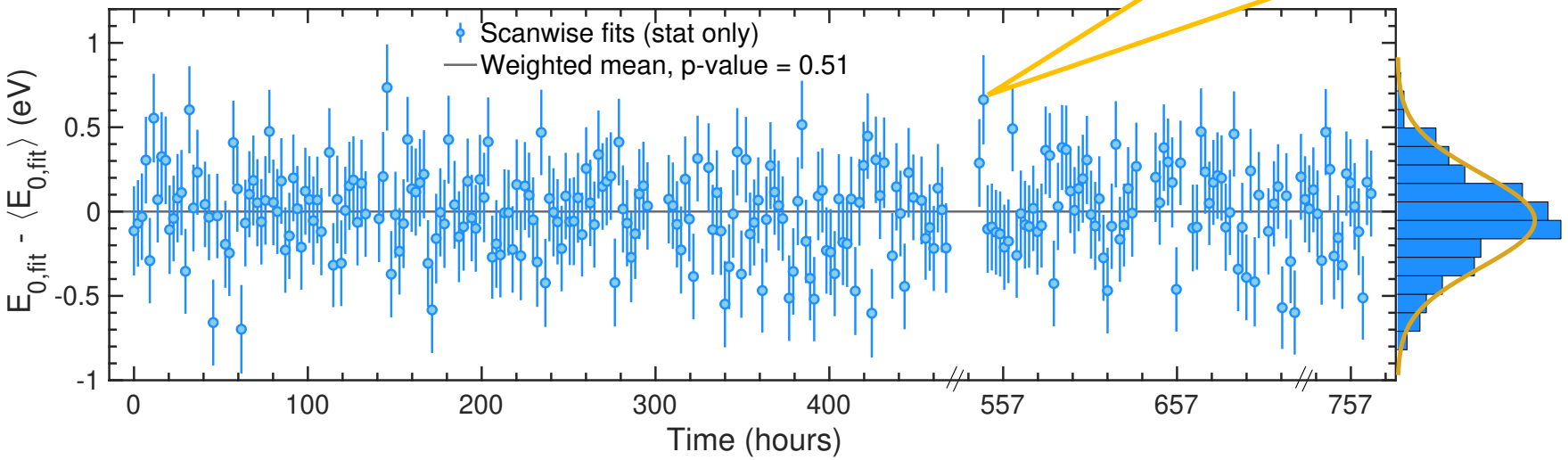
$$\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$$

- 3 parameter fit – stat. only
- neutrino mass fixed to zero
- Check for stability of fits before combining data

Stability Test

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

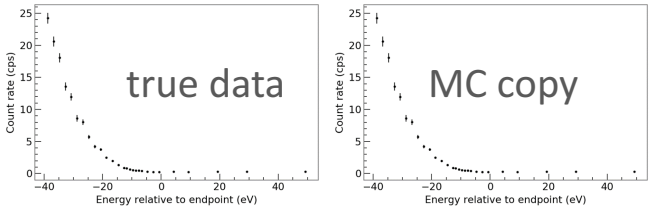


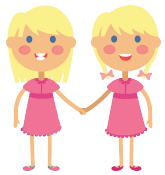


Blinded analysis

Freeze analysis on fake data

- Generate MC-copy of each scan

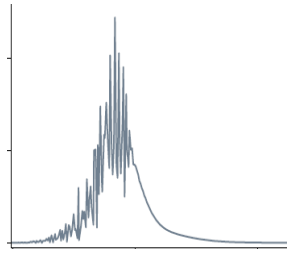


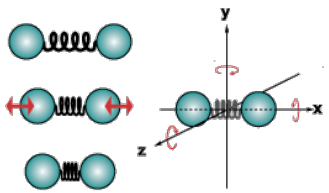


m_ν^2

Blinded model

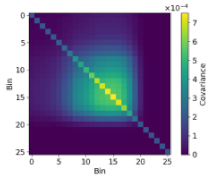
- Modified molecular final state dist.

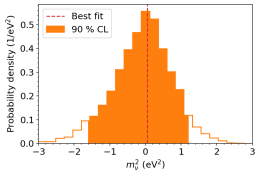




Two independent analysis strategies

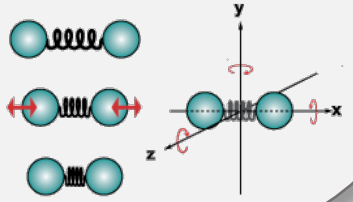
- Covariance matrix
- Monte Carlo propagation





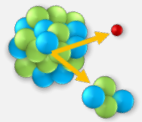
Systematic uncertainties

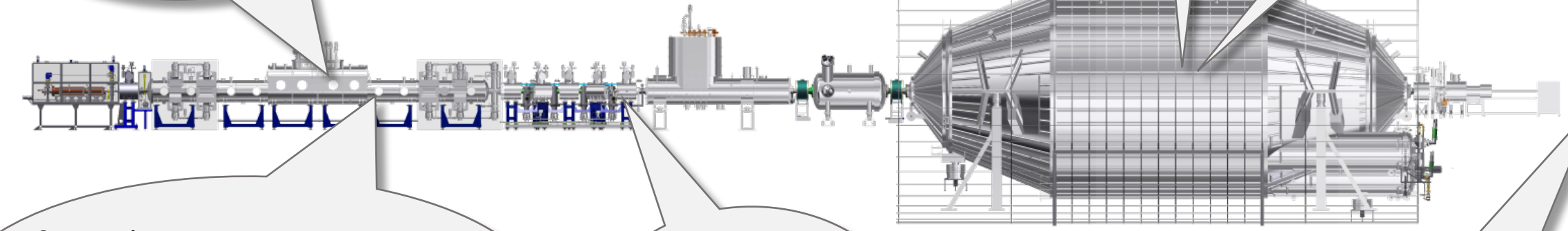
Molecular excitations (FSD)



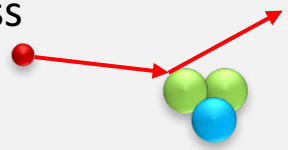
Background-slope

Non-Poisson background





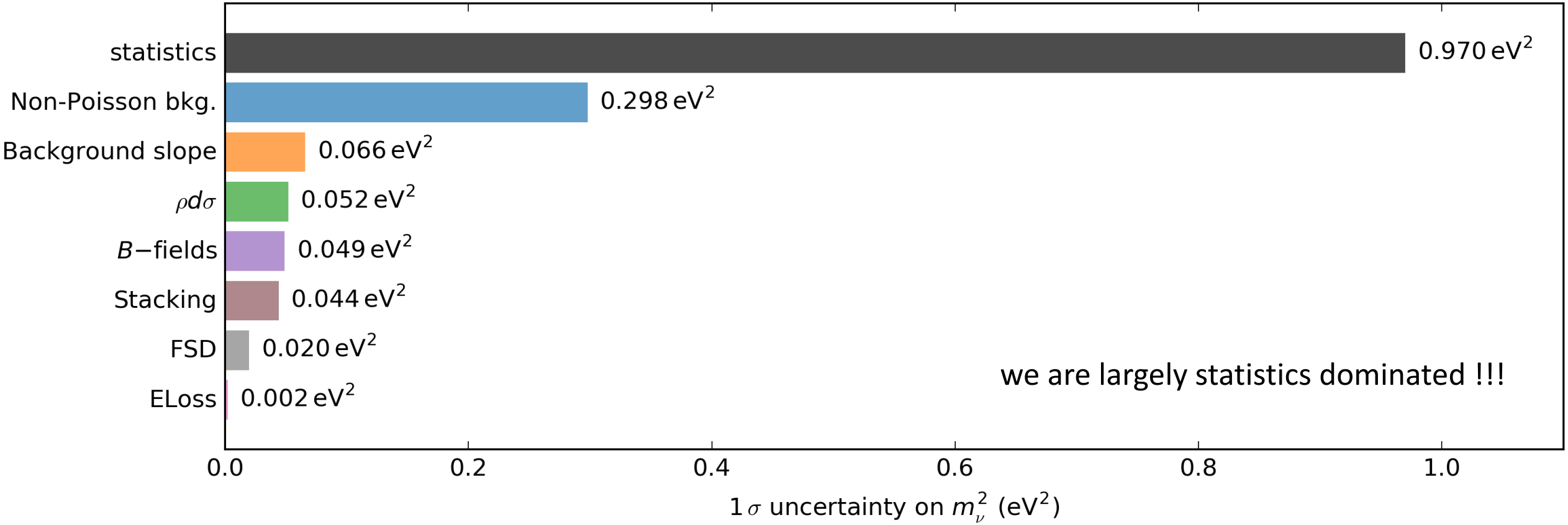
Scattering:
column density x cross-section,
energy loss



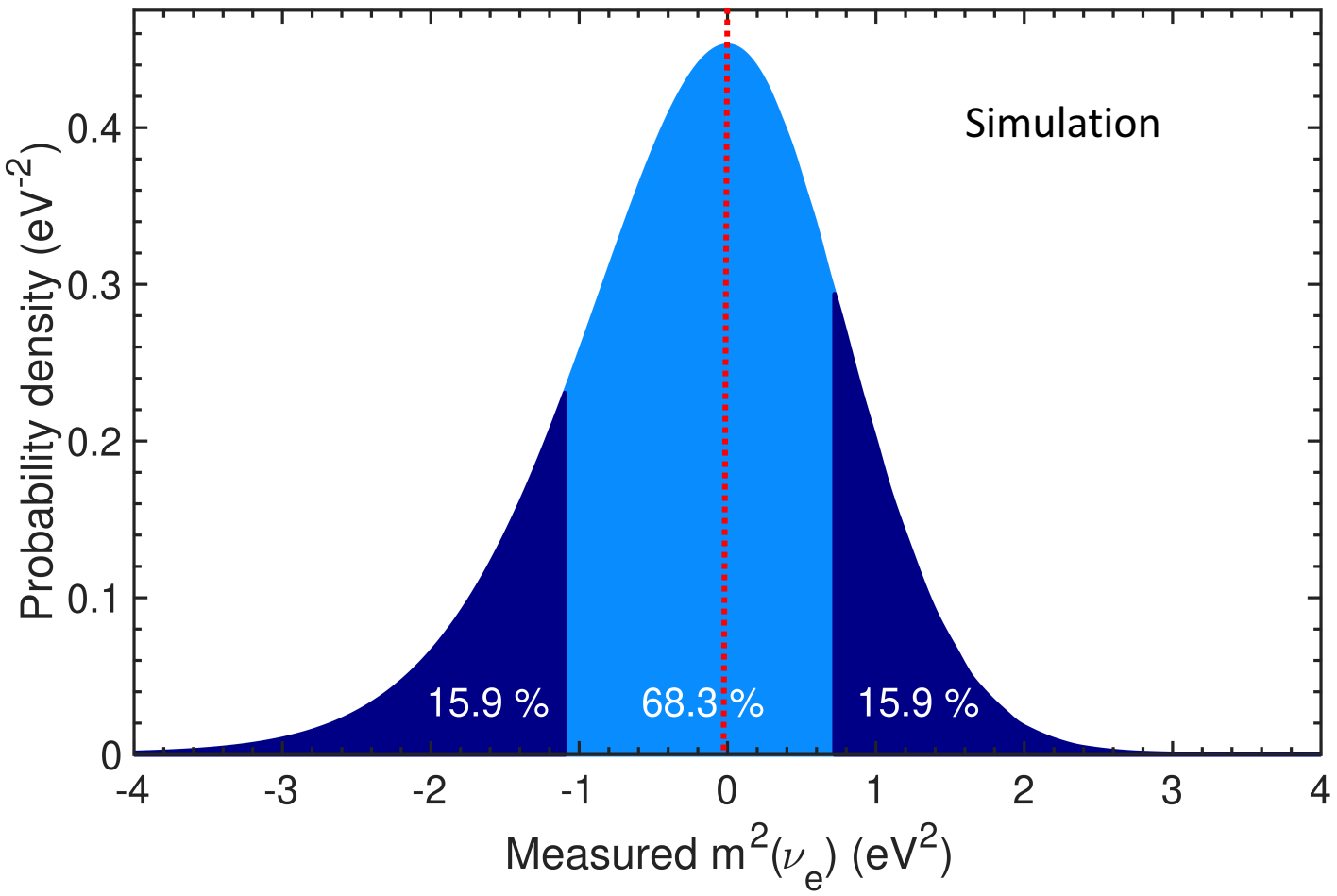
Magnetic fields

Data combination

Budget of uncertainties

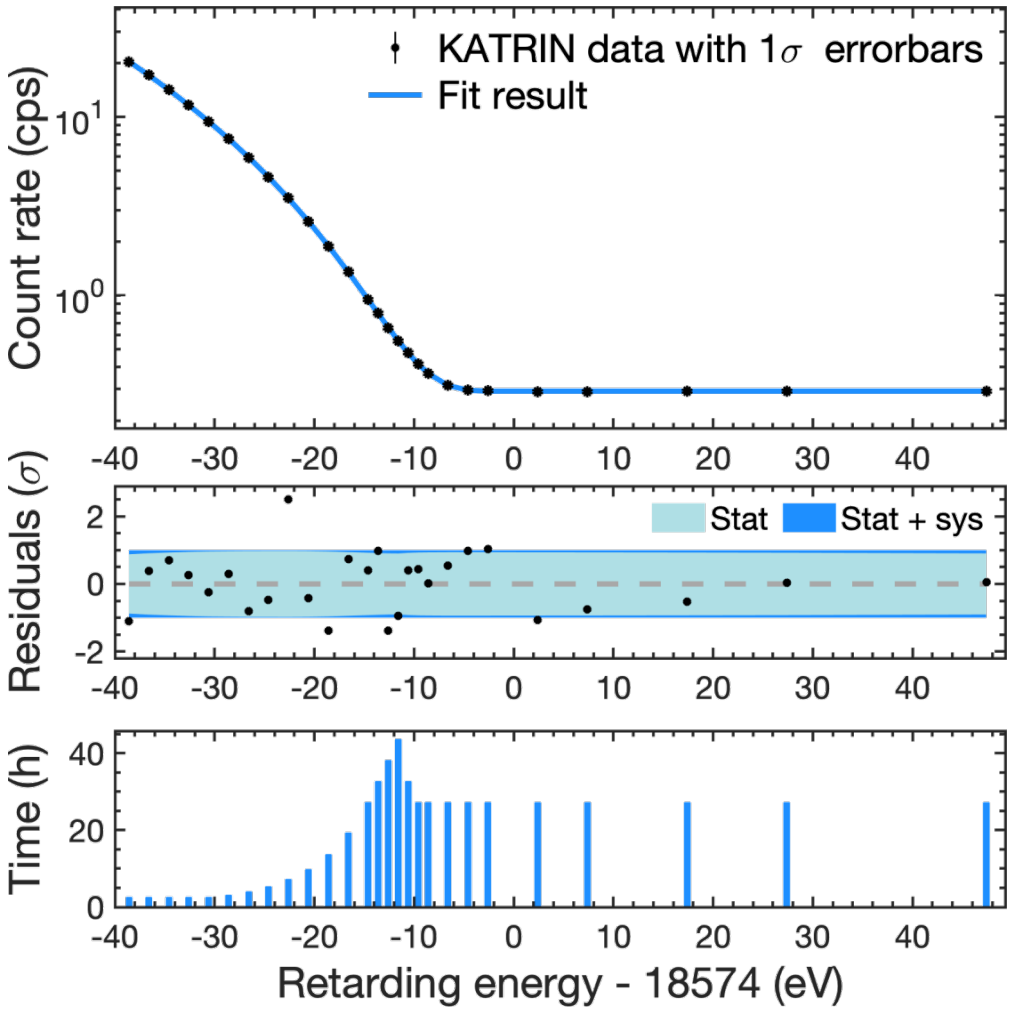


What do we expect to measure?



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

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

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

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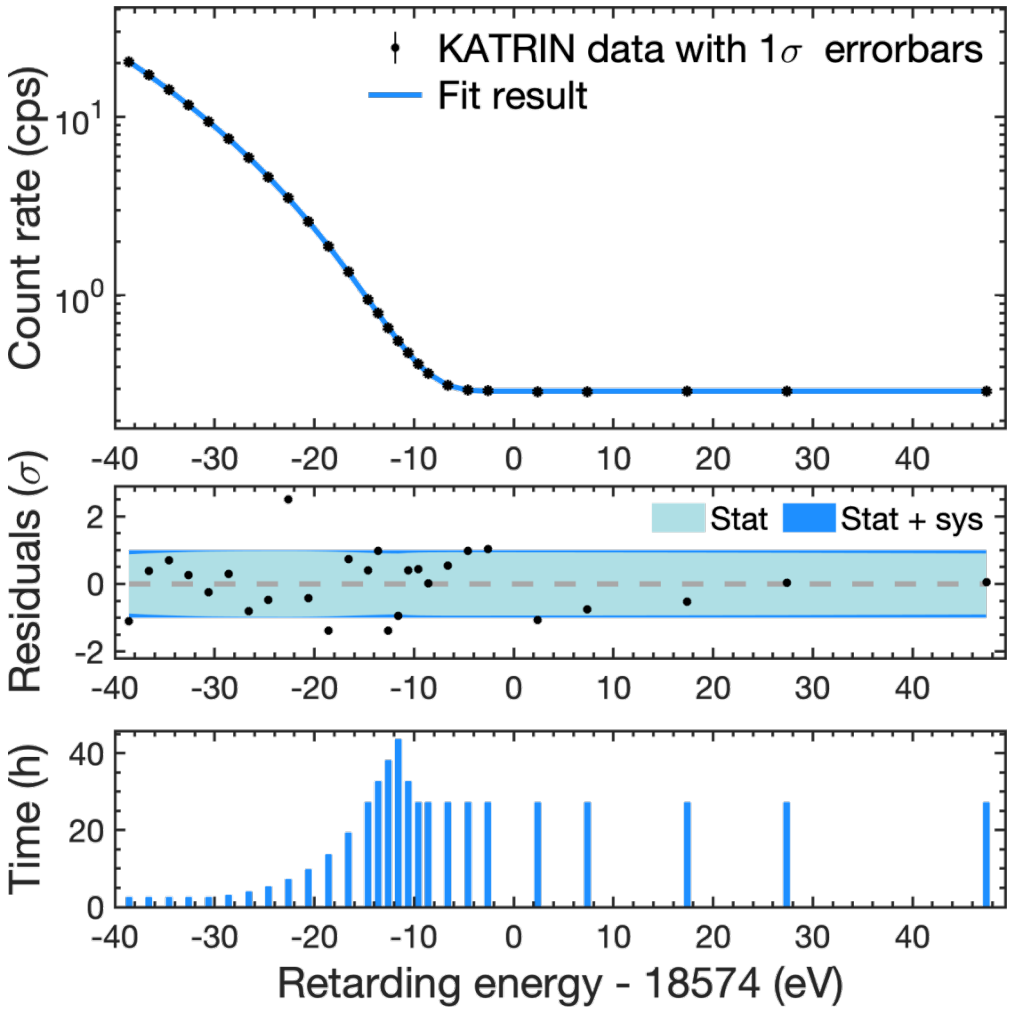

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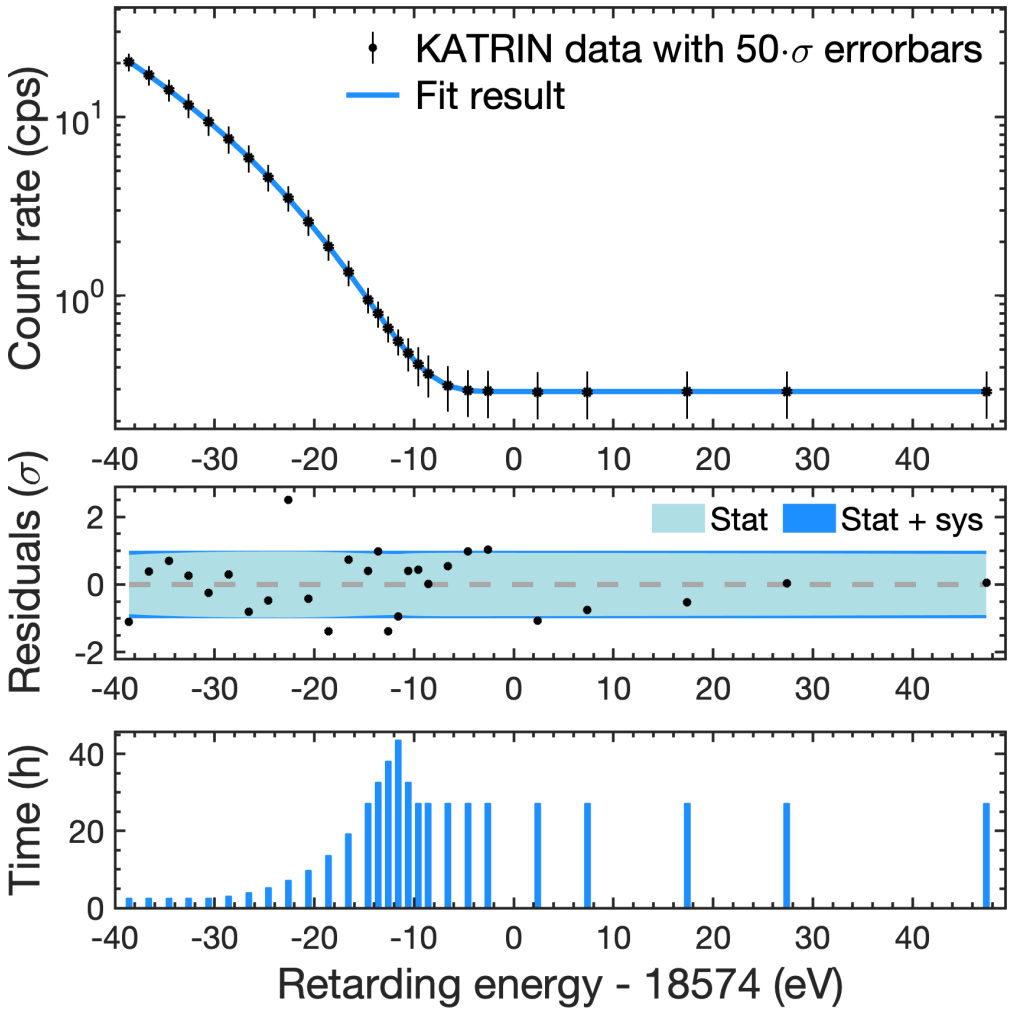

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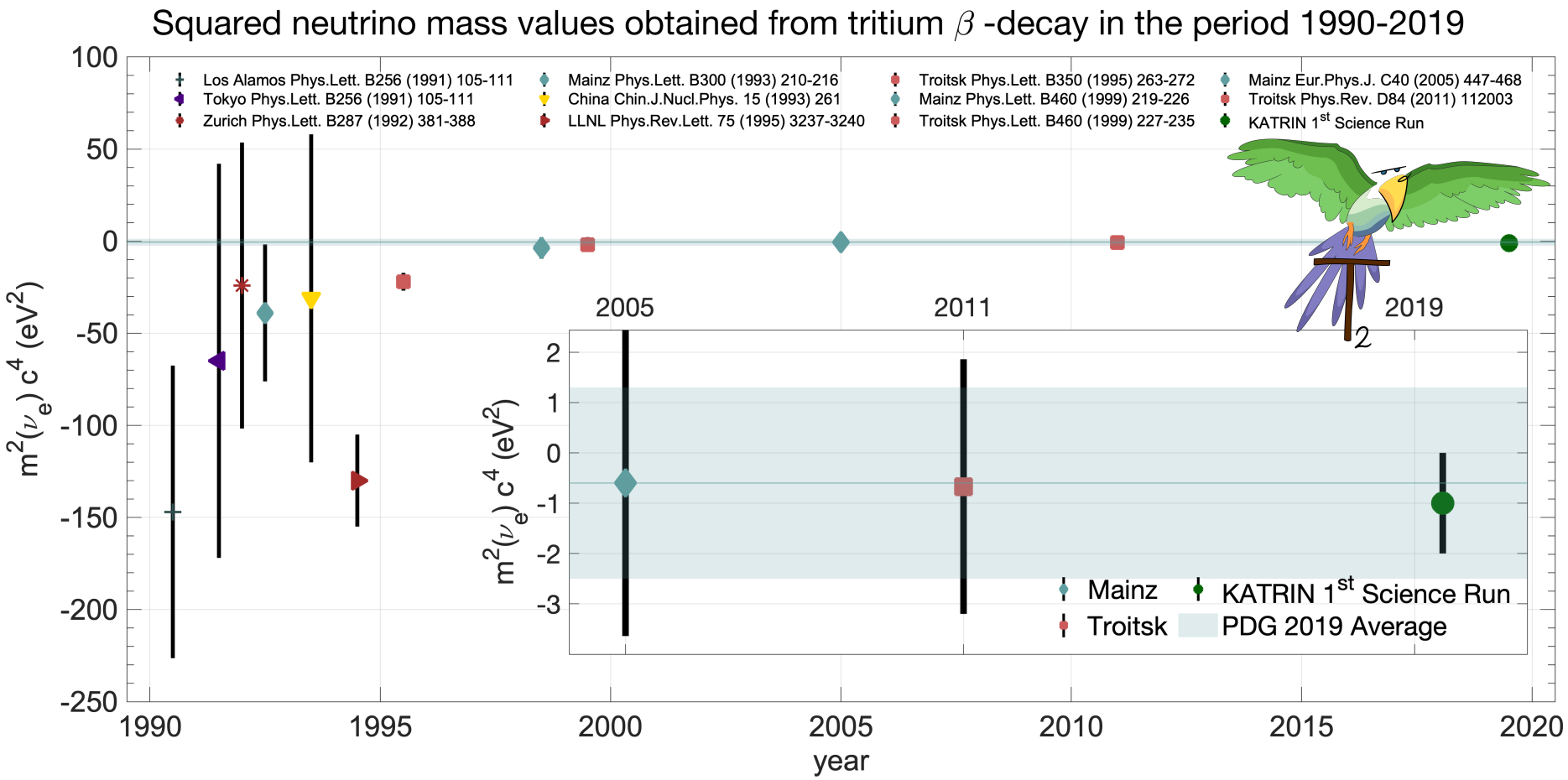
Historical context



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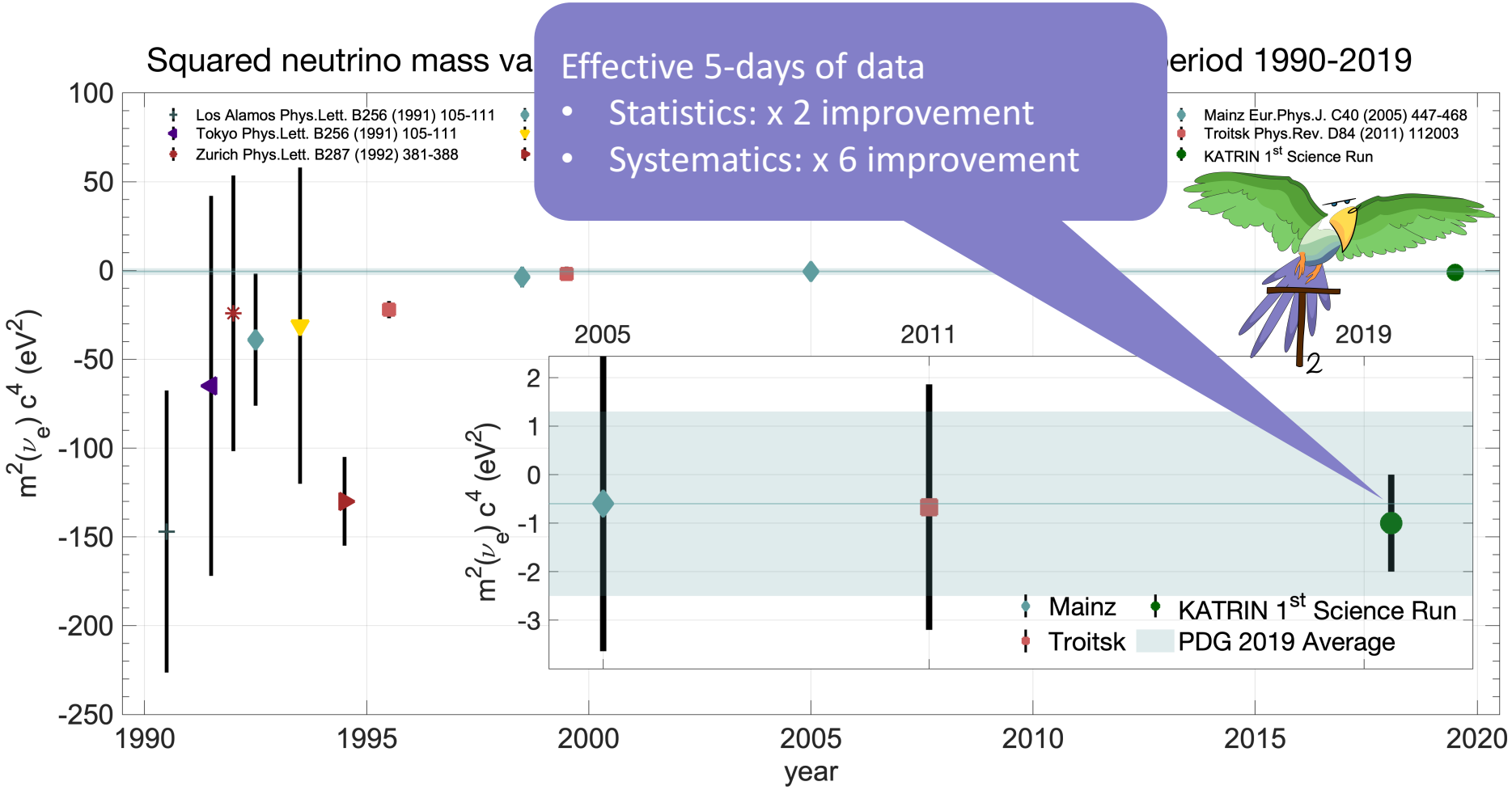


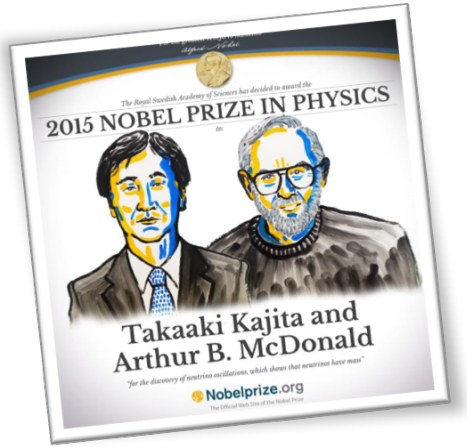
Effective 5-days of data

- Statistics: x 2 improvement
- Systematics: x 6 improvement

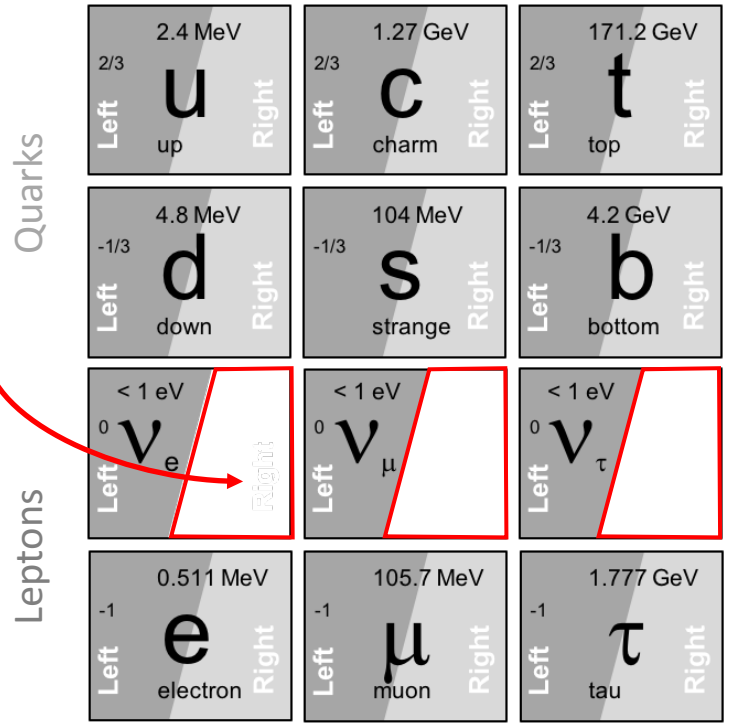
Sterile Neutrinos

Sterile Neutrinos

Something is missing

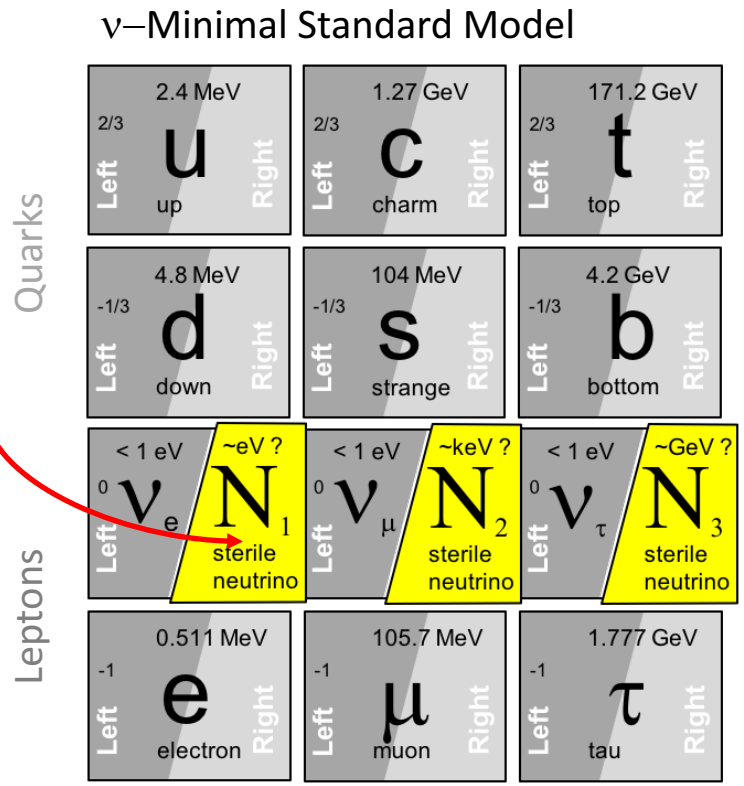


Standard Model (SM)



Sterile Neutrinos

Sterile neutrino



L. Canetti, M. Drewes, and M. Shaposhnikov, PRL **110** 061801 (2013)

Sterile Neutrinos

Heavy sterile neutrinos (> GeV)

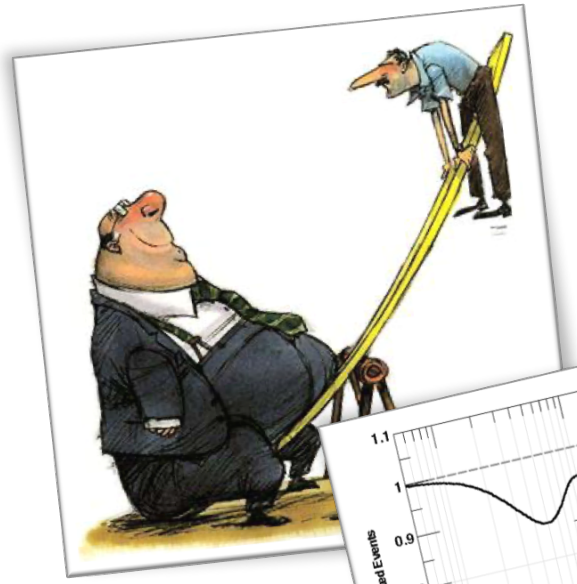
- Lightness of neutrinos
  + Matter/Anti-matter asymmetry

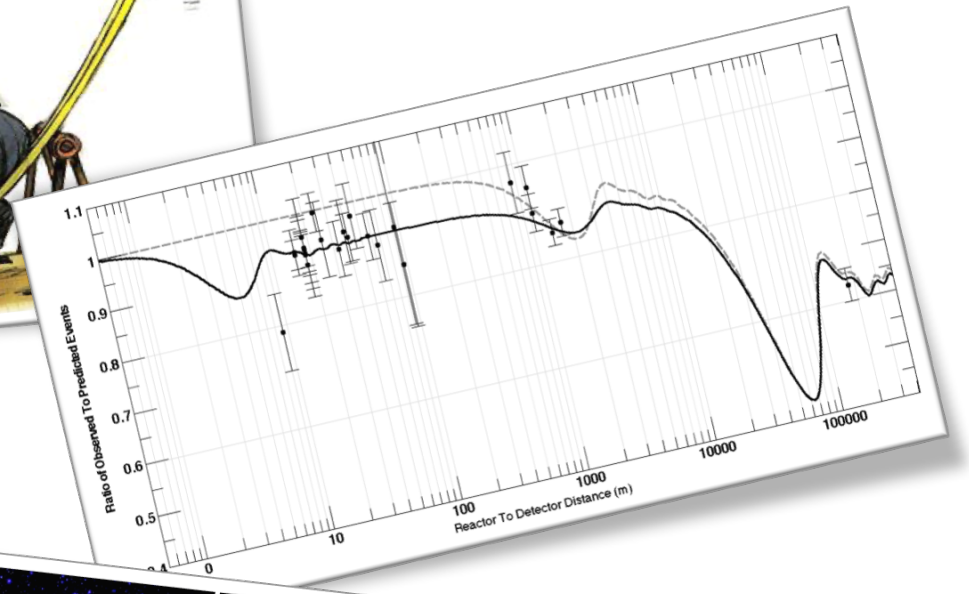
Light sterile neutrinos (~1 eV)

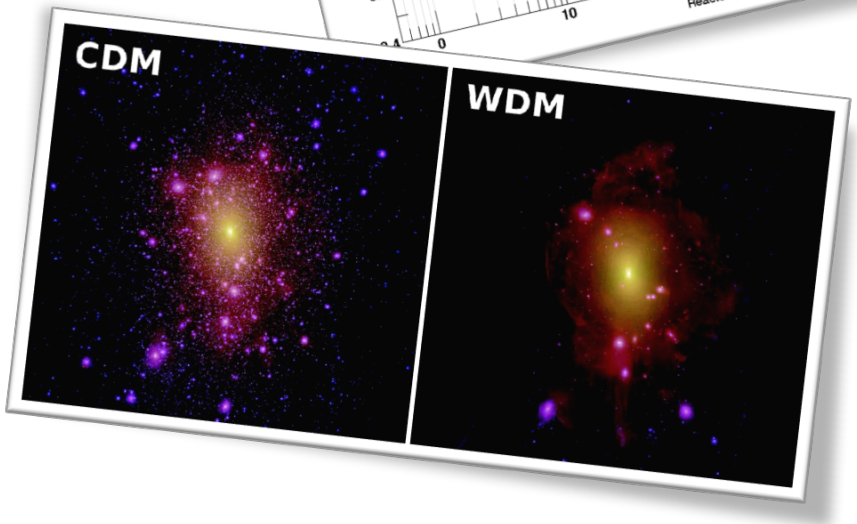
- Short-baseline neutrino oscillation anomalies
  arXiv:1901.08330v2 (2019)

KeV-scale sterile neutrinos (~ 1 - 50 keV)

- Dark matter candidate
  Prog. Part. Nucl. Phys. 104 (2019)







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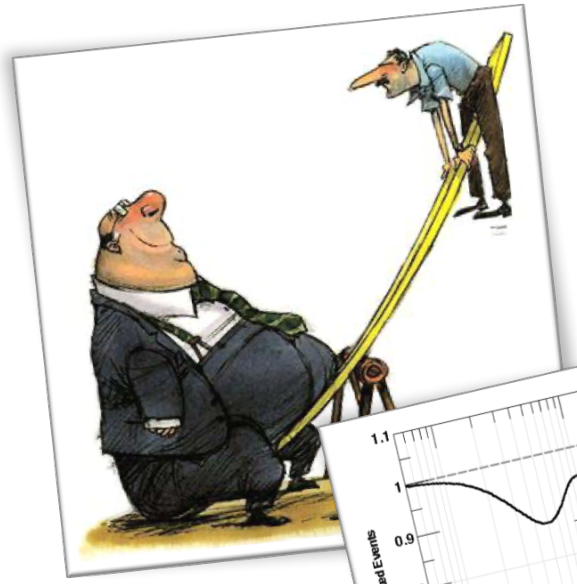
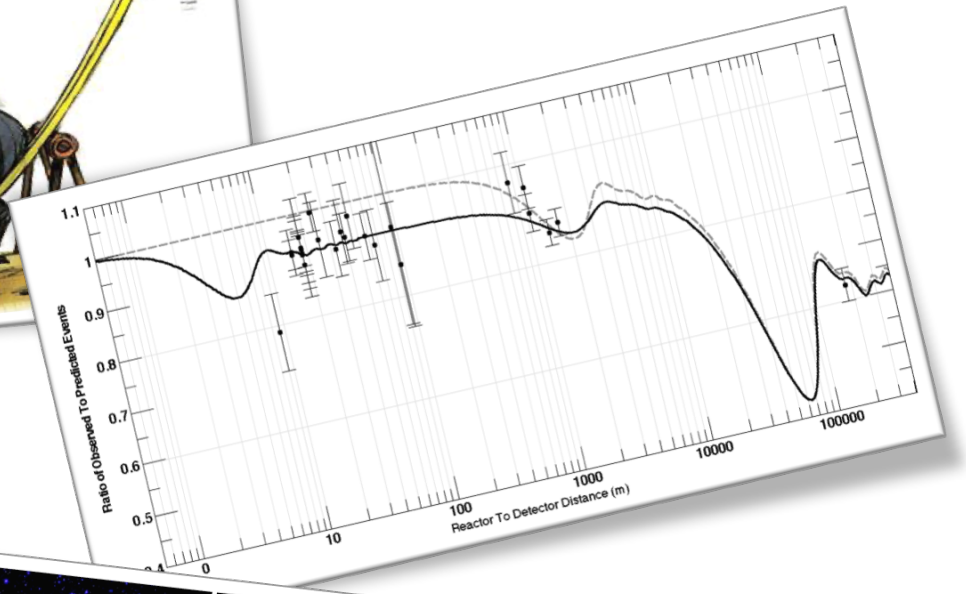
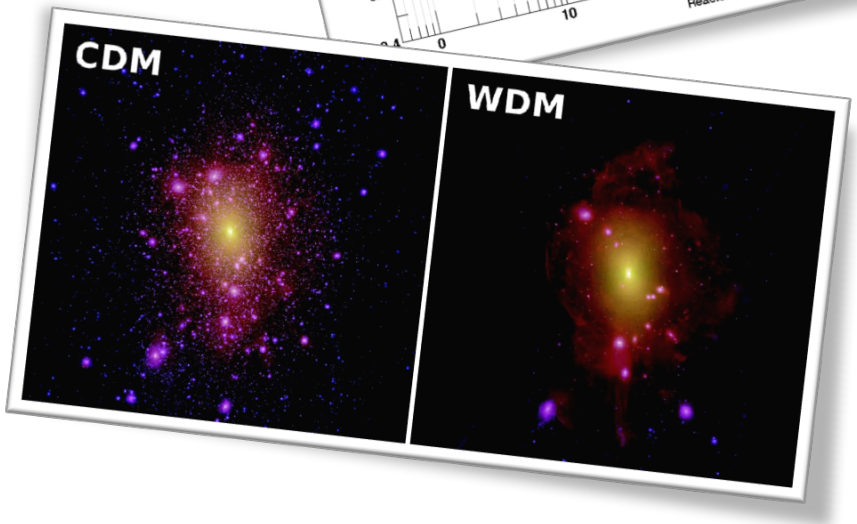
  Prog. Part. Nucl. Phys. 104 (2019)

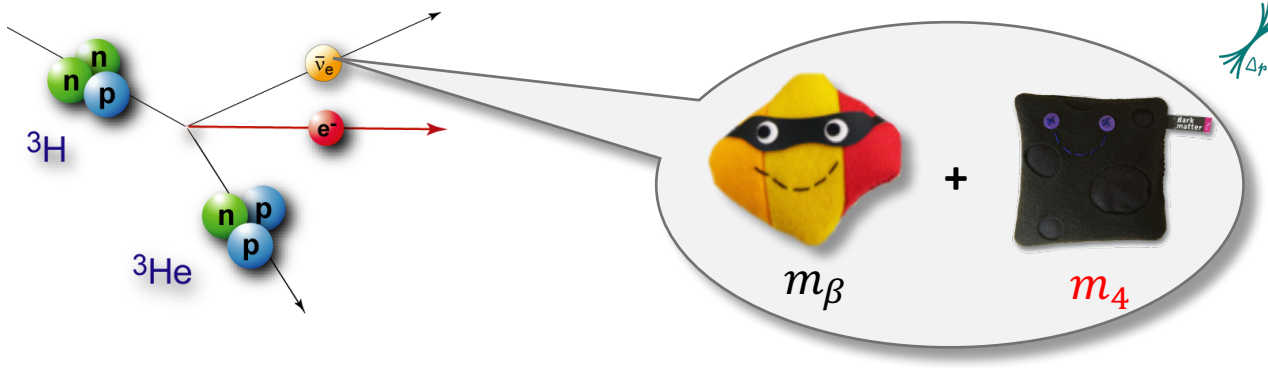
➢ accessible in β-decays



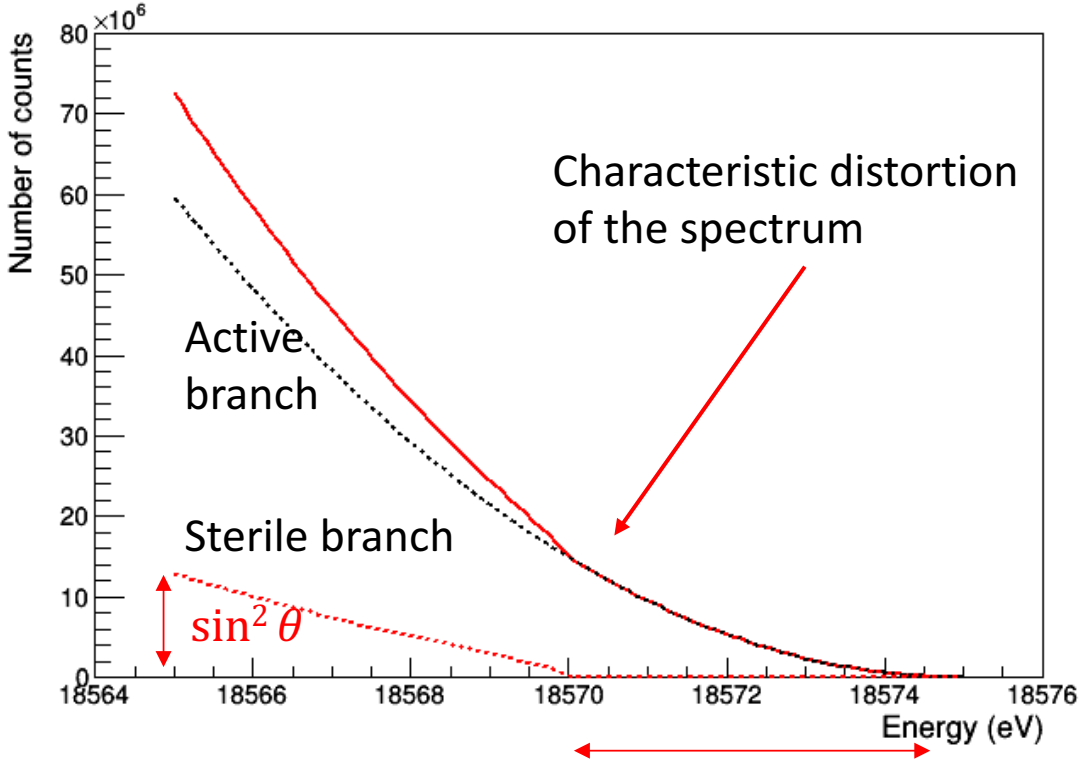




Sterile neutrinos



eV-scale sterile ν signature



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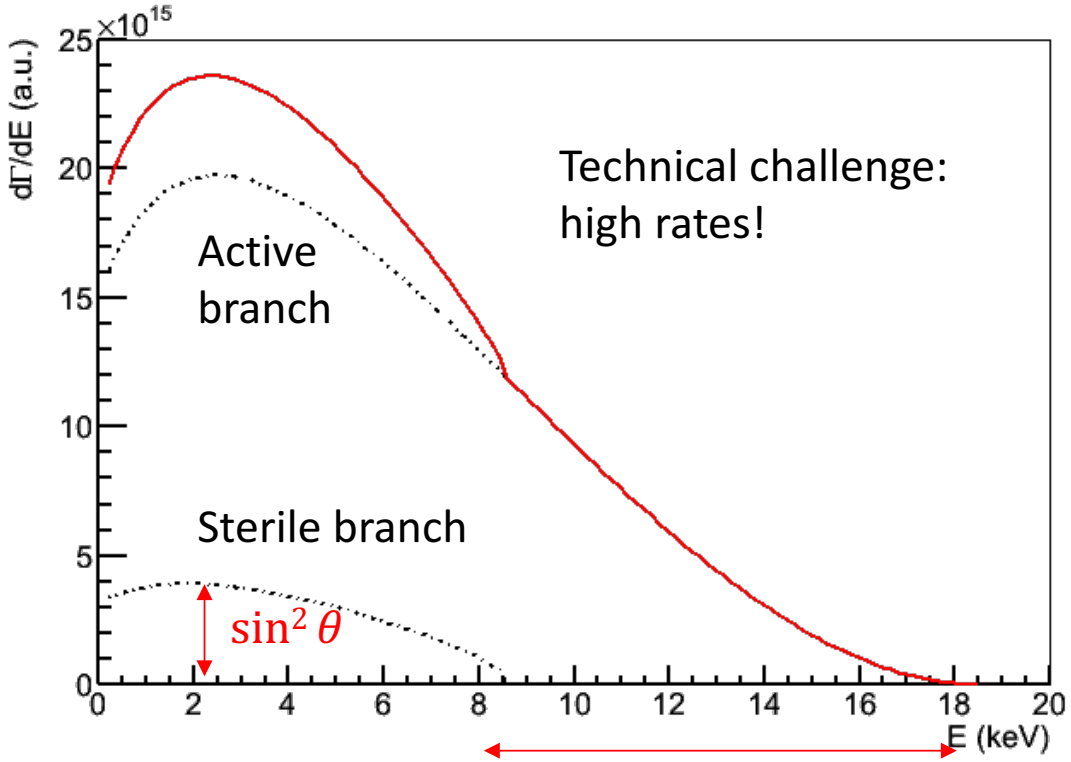
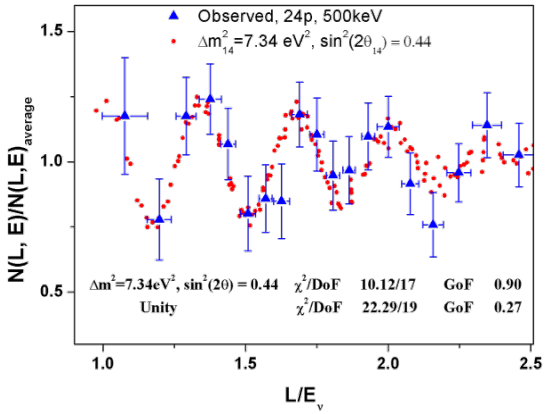


eV-scale sterile neutrino sensitivity

preliminary plot

- Based on “first-nu-mass” data set
- Statistics (5-days of full KATRIN) not enough to test best fit of Reactor-Anomaly
- But, test of *Neutrino-4* result in reach …stay tuned

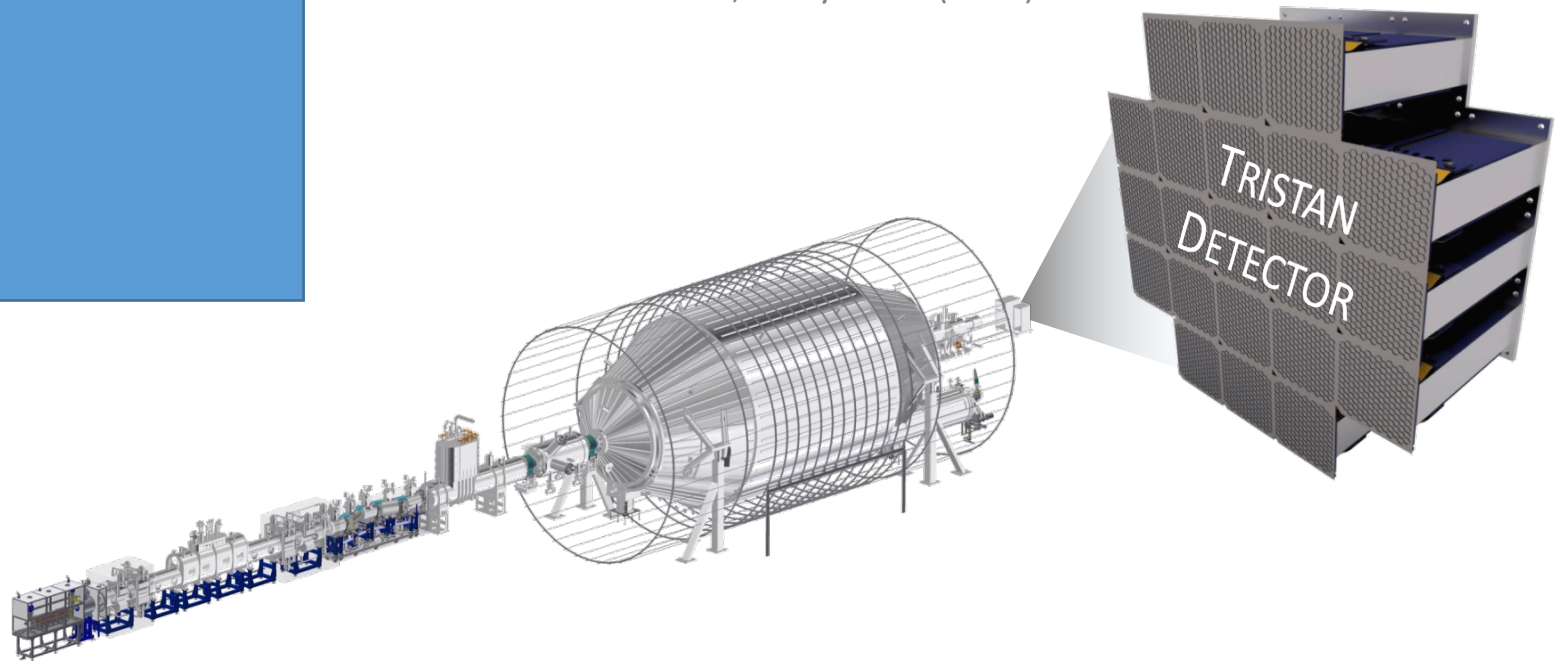


arxiv-1809.10561

keV-scale sterile neutrino sensitivity

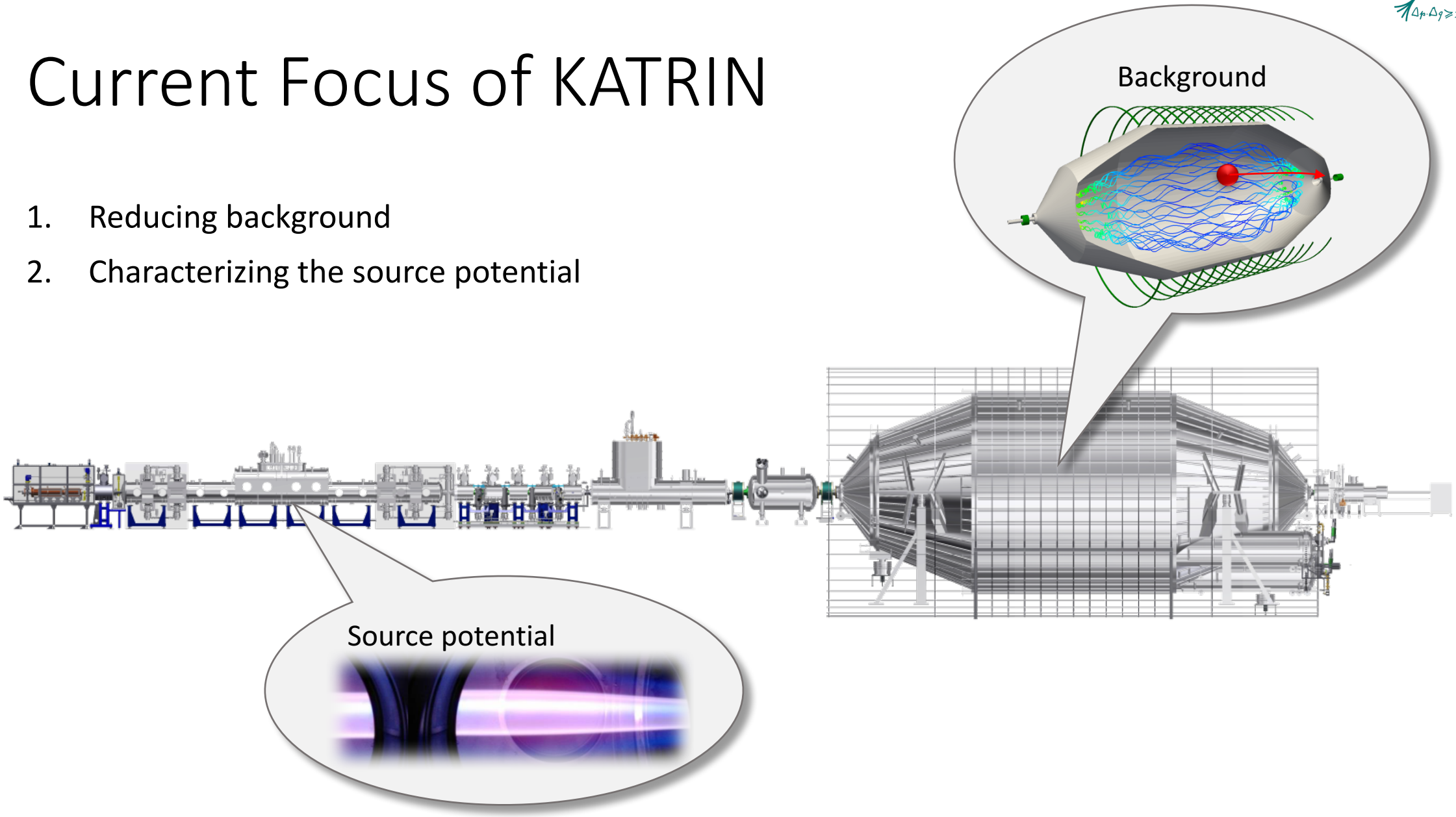
preliminary plot

- First results based on “low-activity” run in 2018
  EPJ-C, arXiv:1909.06069
- Future: Novel detector system TRISTAN → significant improvement of lab-limits
  Mertens et al. JCAP 1502 (2015)
  Mertens et al, J. Phys. G46 (2019)

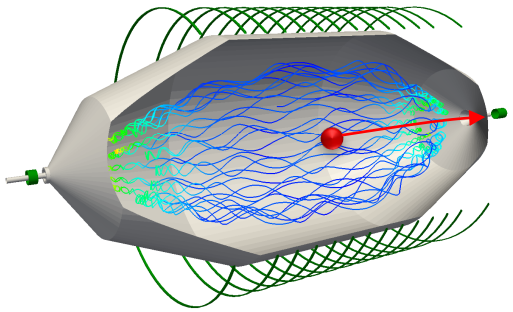


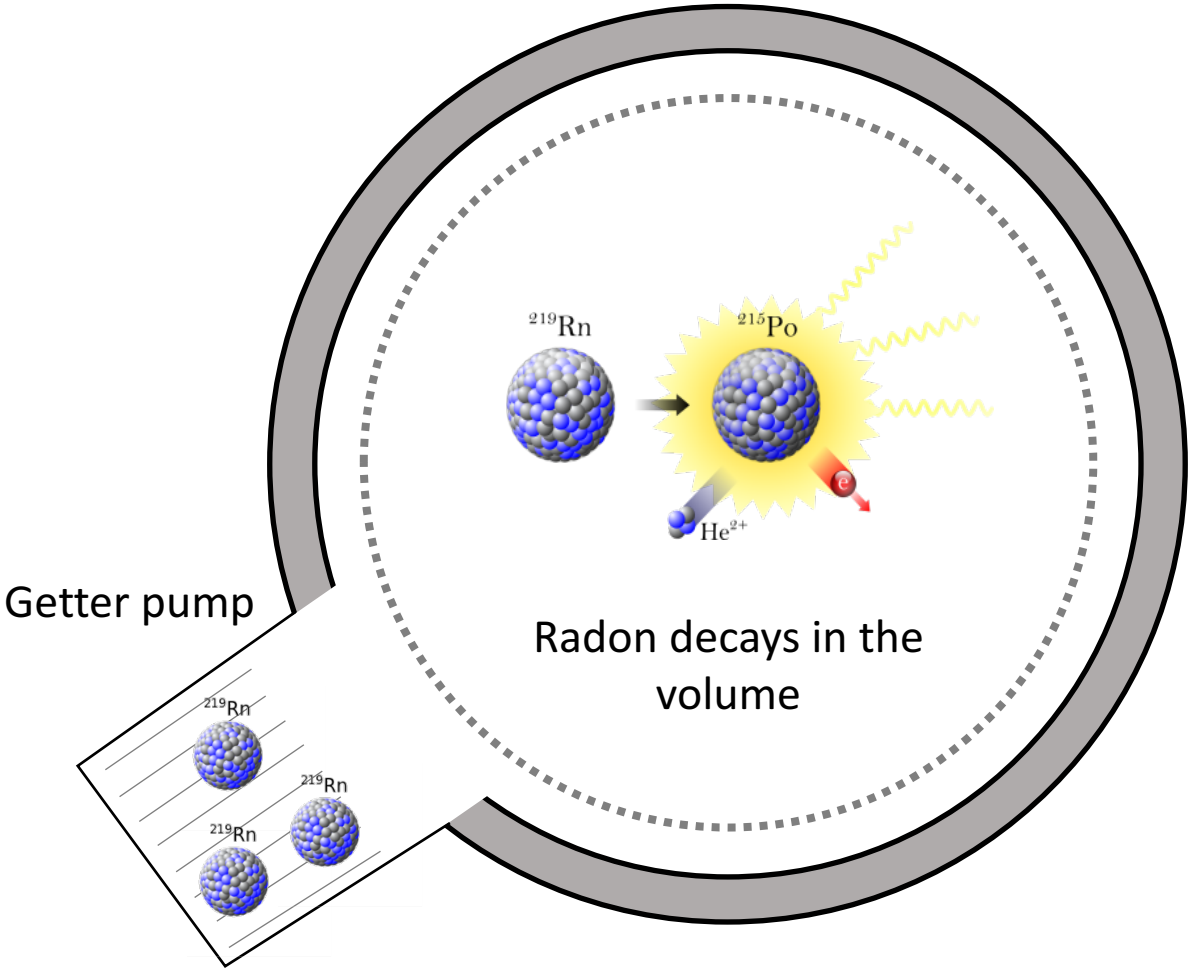
Current Focus of KATRIN

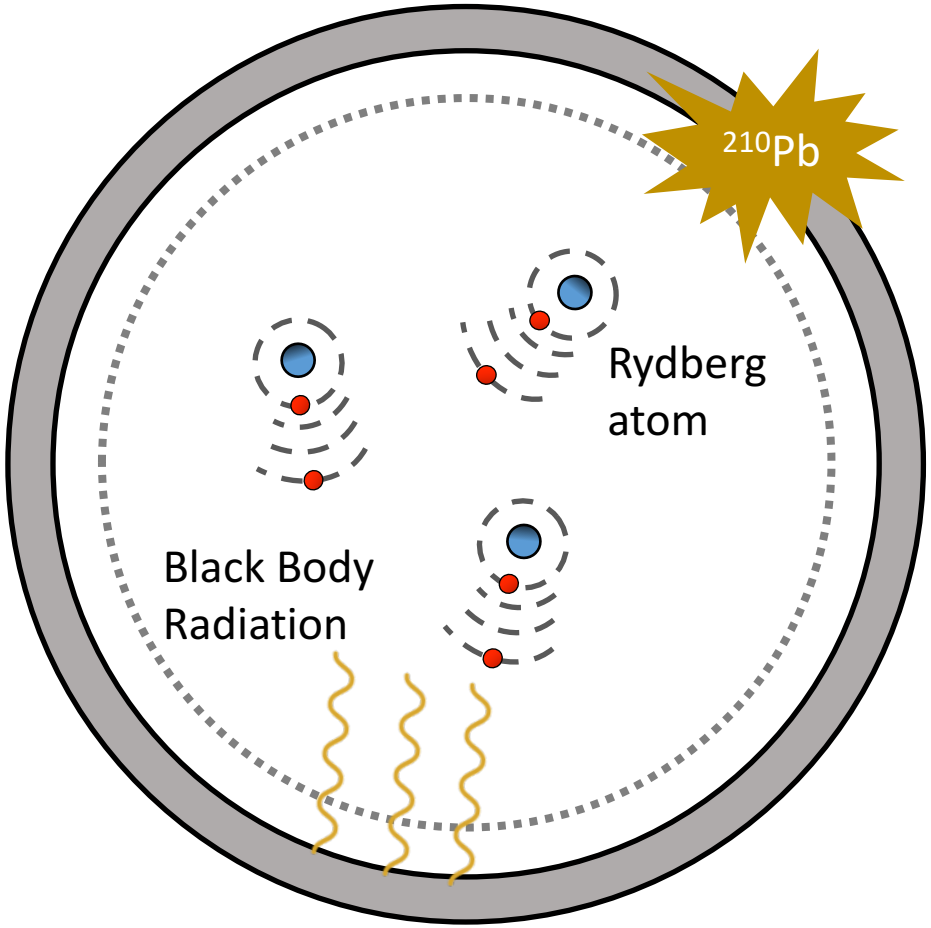
1. Reducing background
2. Characterizing the source potential



KATRIN backgrounds



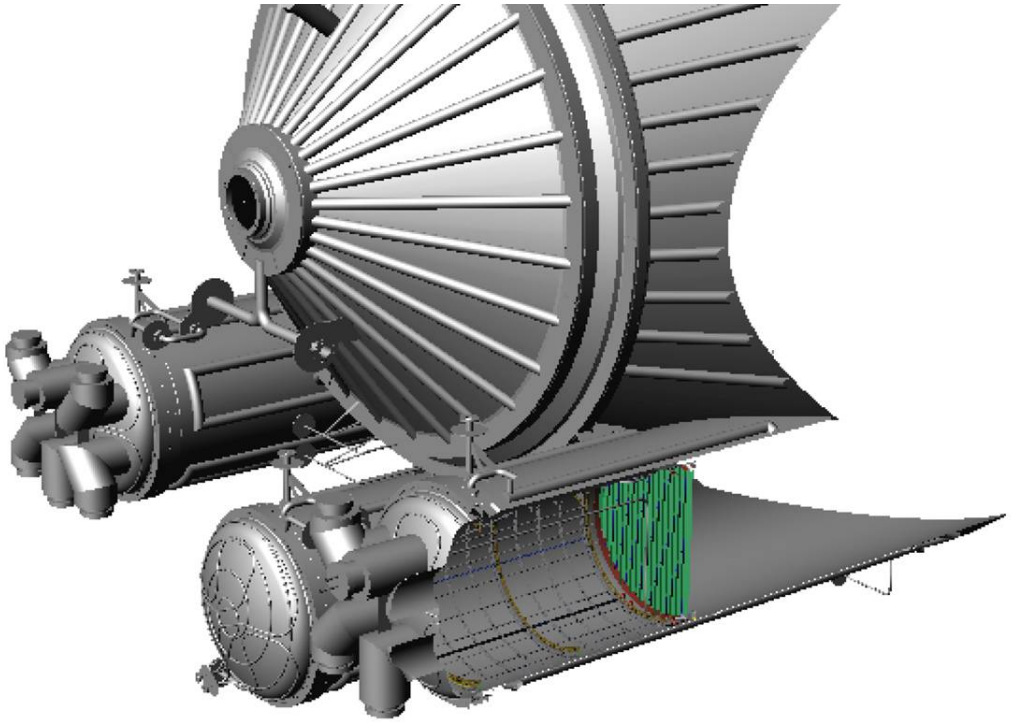


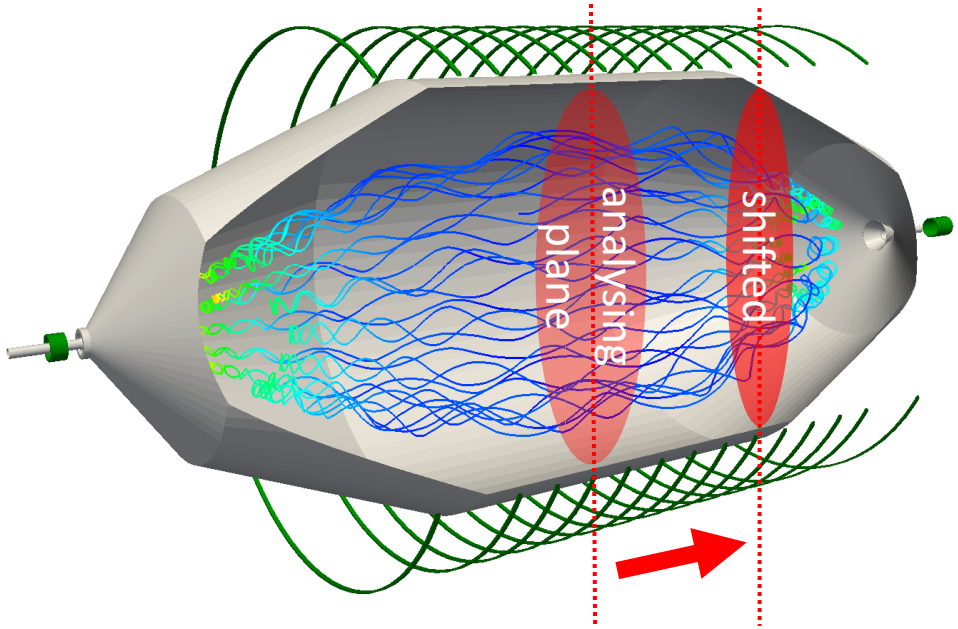


KATRIN backgrounds

- ✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004

- ✓ Mitigation of Rydberg background by shifting analyzing plane
  not yet applied, under investigation at the moment





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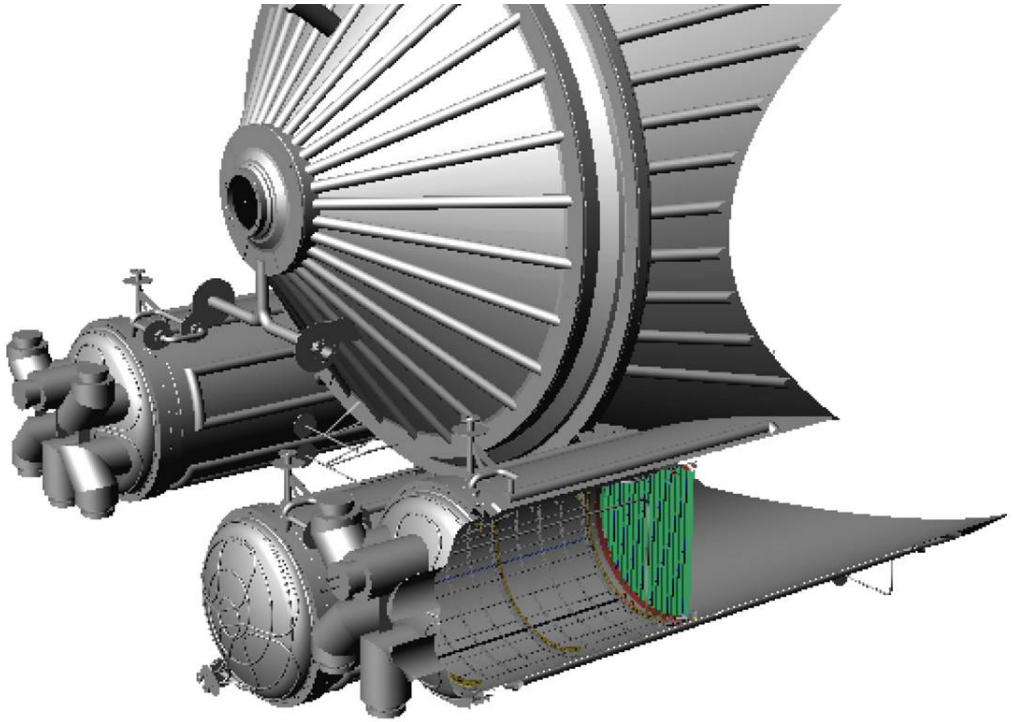
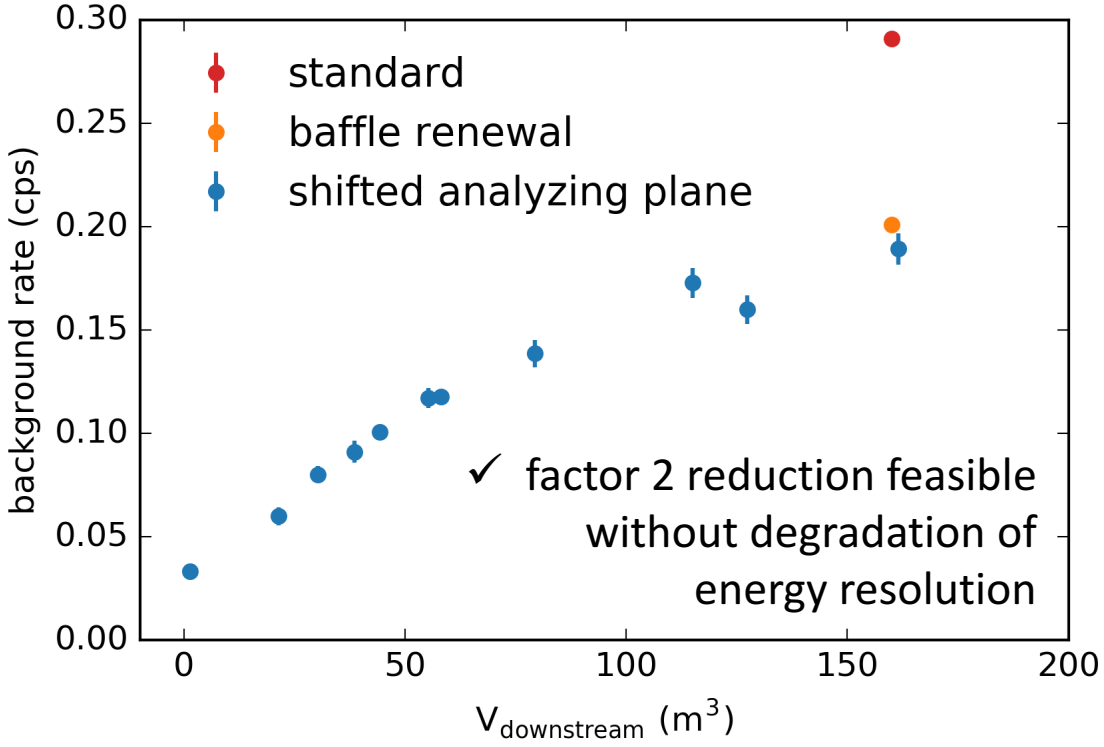
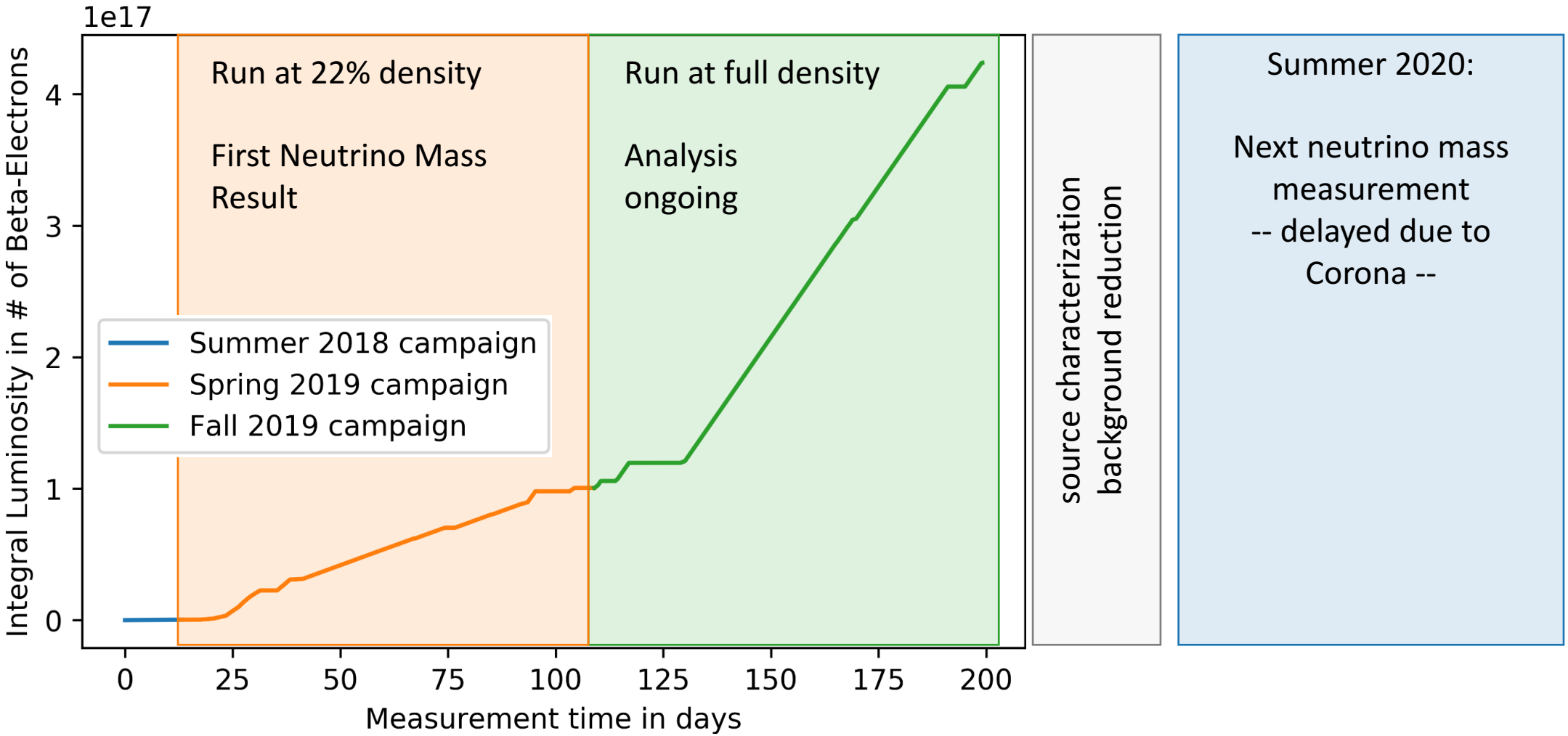


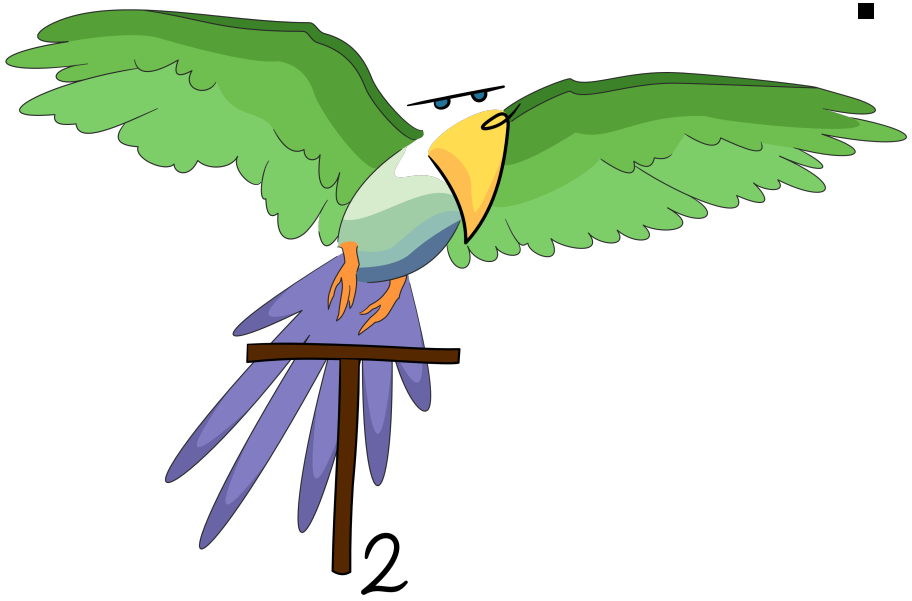


Measurement Timeline of KATRIN



Conclusion

- New world-best direct neutrino mass measurement: **m_ν < 1.1 eV (90% C.L.)**
  - Interesting perspectives to search for **eV up to keV sterile neutrinos**
    - Improving on **source characterization** and **background reduction**
      - Next KATRIN run (in optimized configuration) will start soon
        - Goal: sensitivity of < 0.3 eV reached after 5-years



Thank you for your attention

Prof. Dr. Susanne Mertens

Technical University Munich & Max Planck Institute for Physics