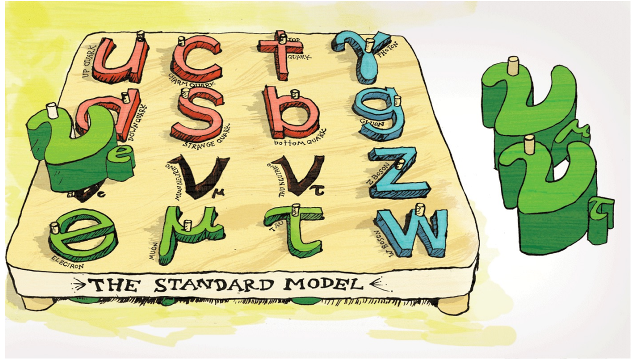
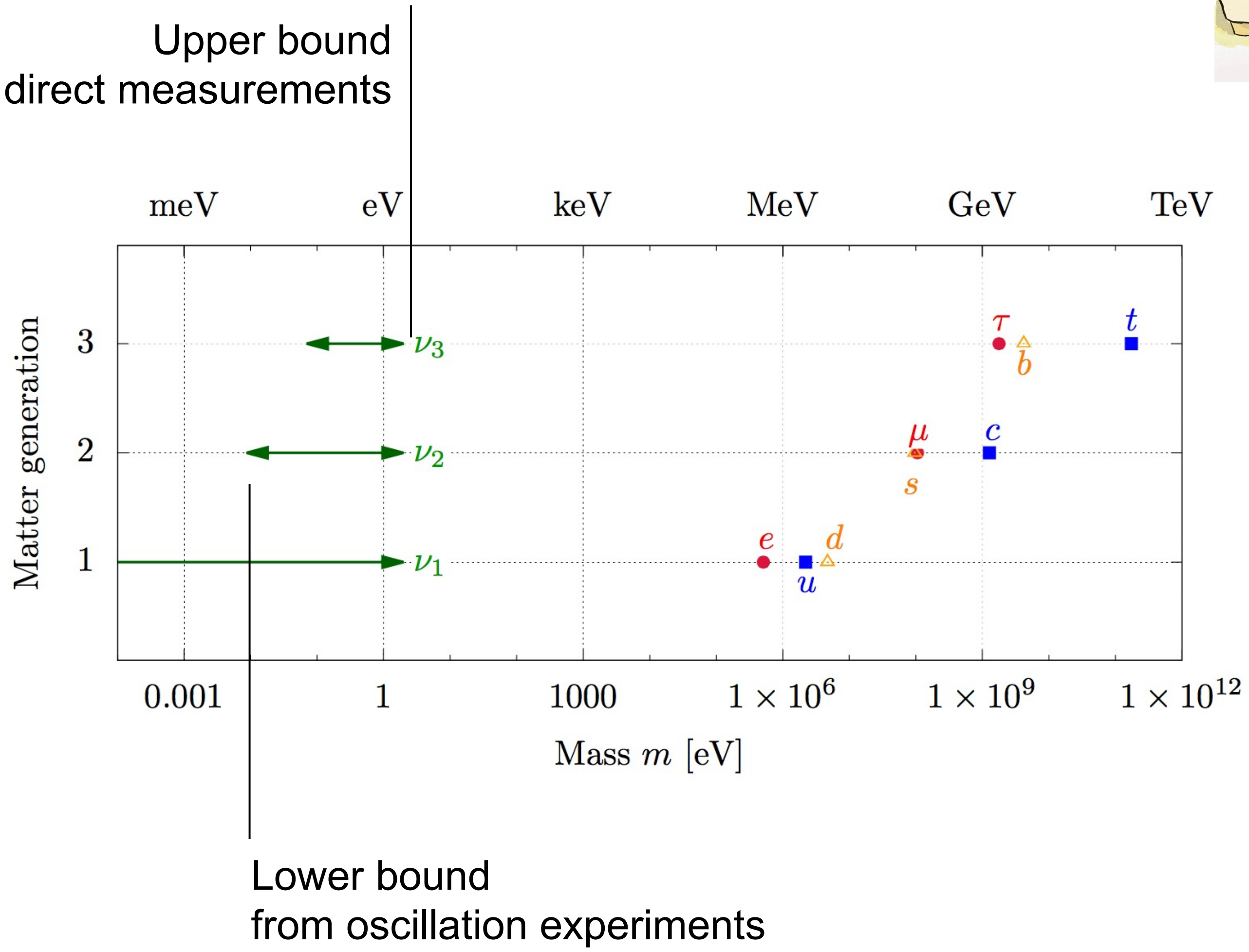
First direct neutrino-mass measurement with sub-eV sensitivity

Susanne Mertens
Max Planck Institute for Physics & Technical University Munich

Neutrino mass





Neutrino mass

Cosmology

potential: m_ν = 10 - 50 meV

$$\boldsymbol{m_\nu} = \sum_i m_i$$

Search for 0νßß

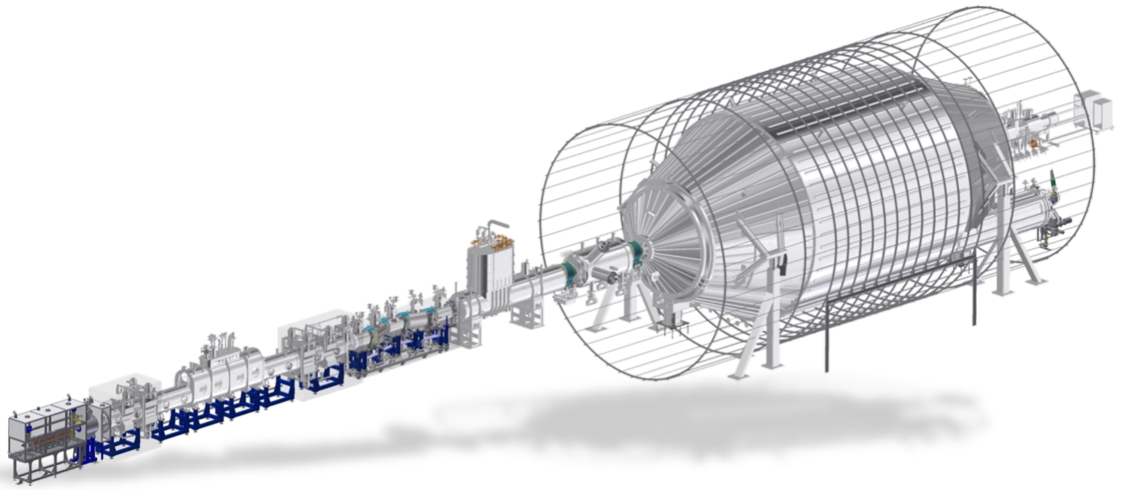
potential: $m_{ßß}$ = 7 - 17 meV

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

Kinematics of ß-decay

potential: m_β = 50 - 200 meV

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



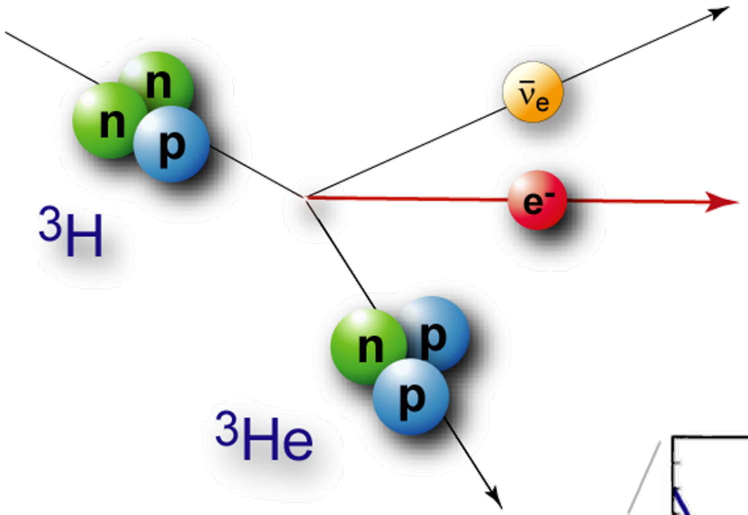
General Idea

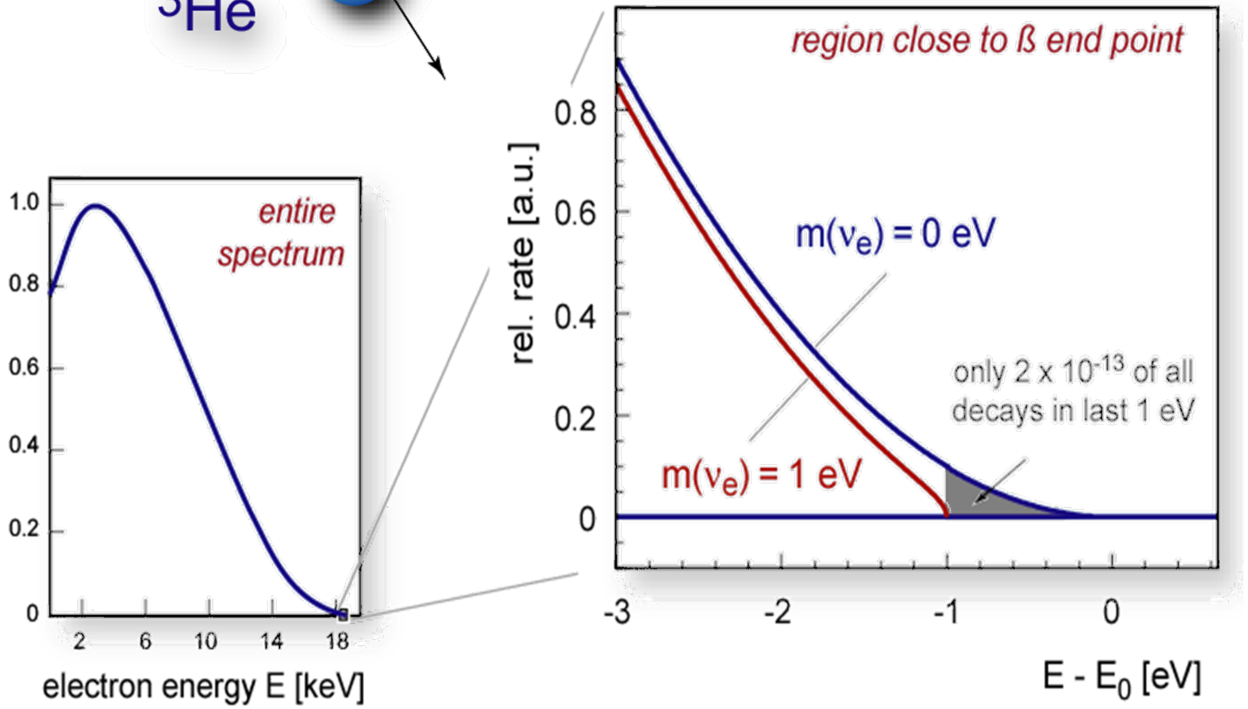
- Non-zero neutrino mass distorts the spectrum close to the endpoint

✓ Independent of cosmology

✓ Independent of neutrino nature

- Observable: $\boldsymbol{m_\nu^2} = \sum_i |U_{ei}|^2 \cdot m_i^2$

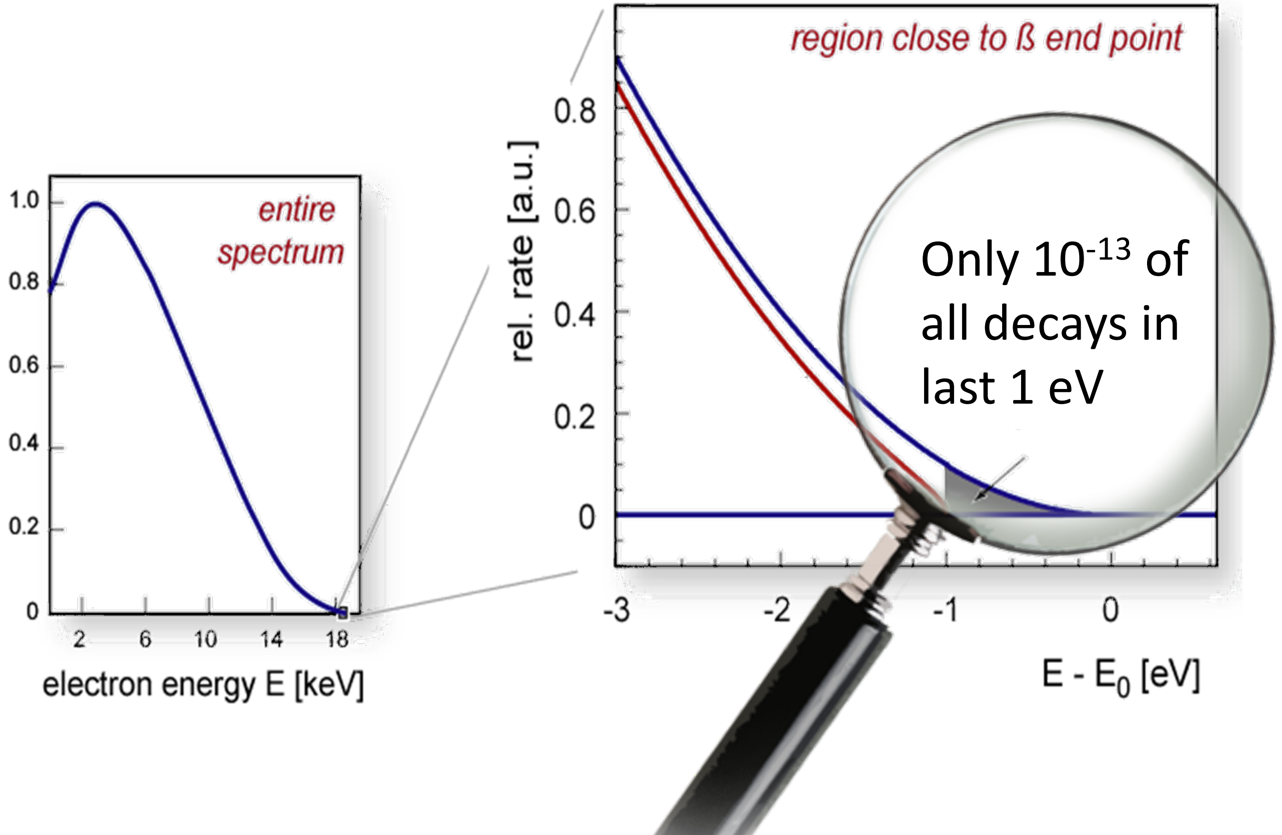




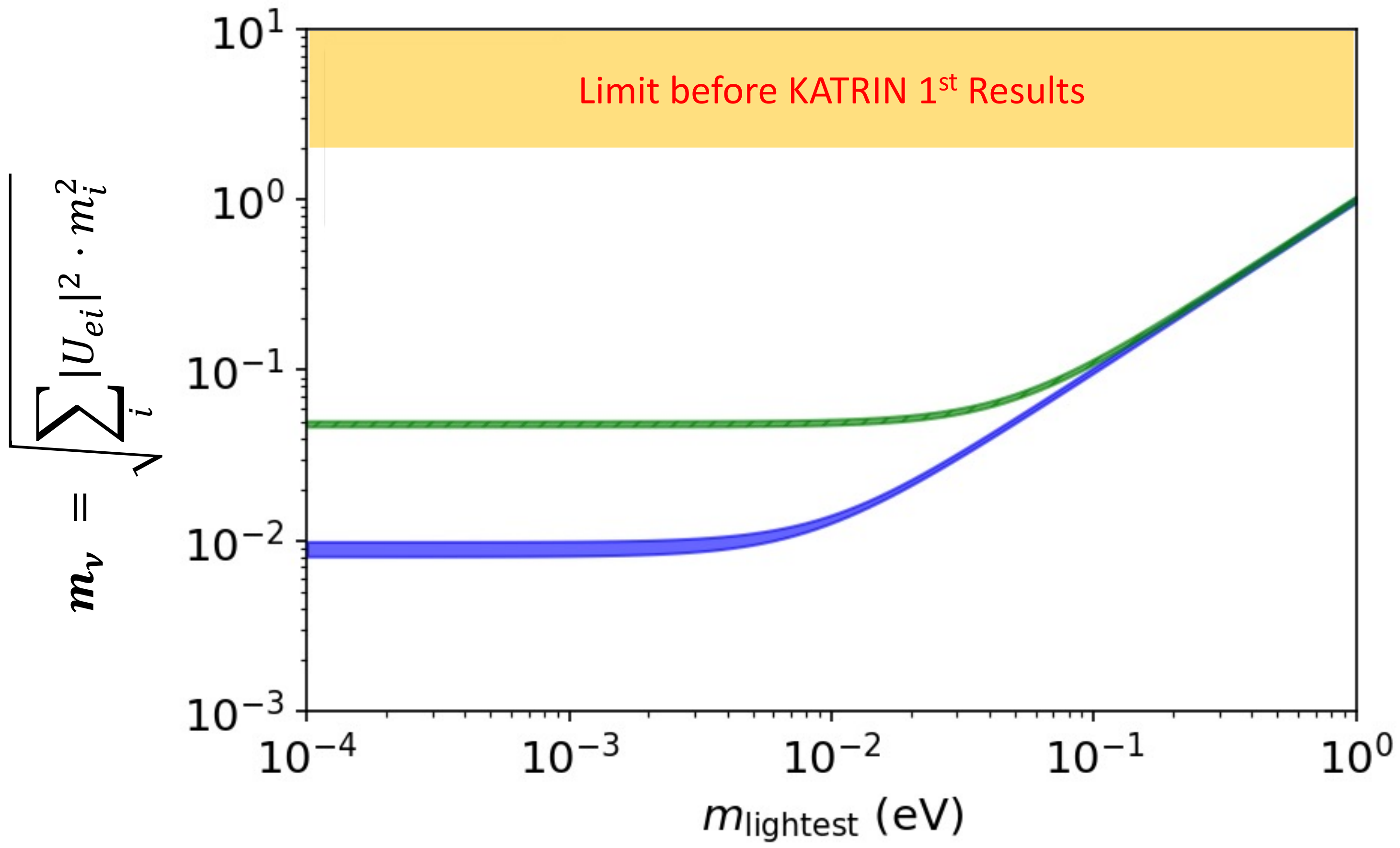
The challenge

Key requirements:

- Ultra-strong radioactive source
  - Tritium (12.3 years, E_0 = 18.6 keV)
  - Holmium (4500 years, E_0 = 2.8 keV)
- Excellent energy resolution (~ 1 eV)
- Low background (< 100 mcps)



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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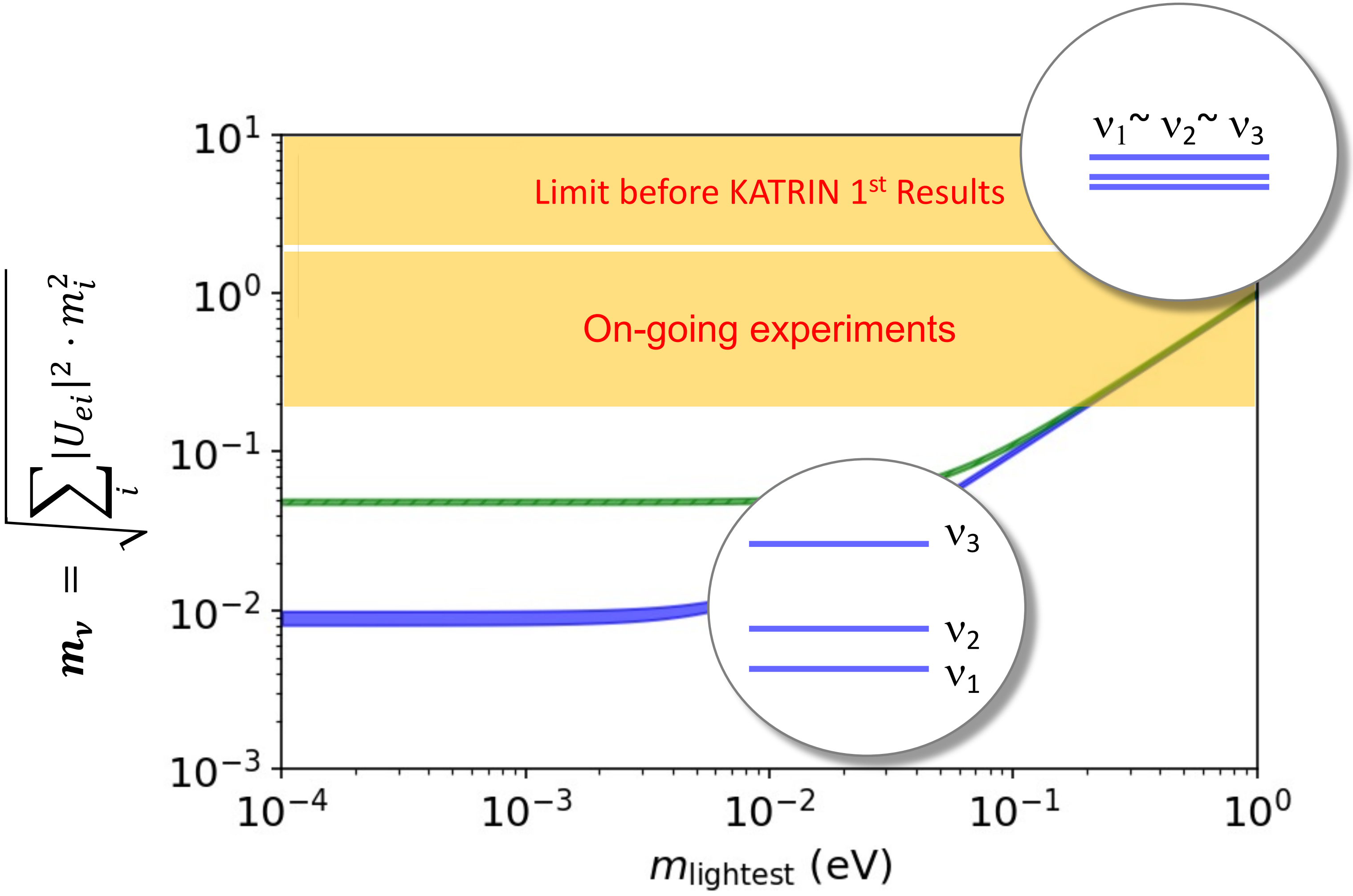

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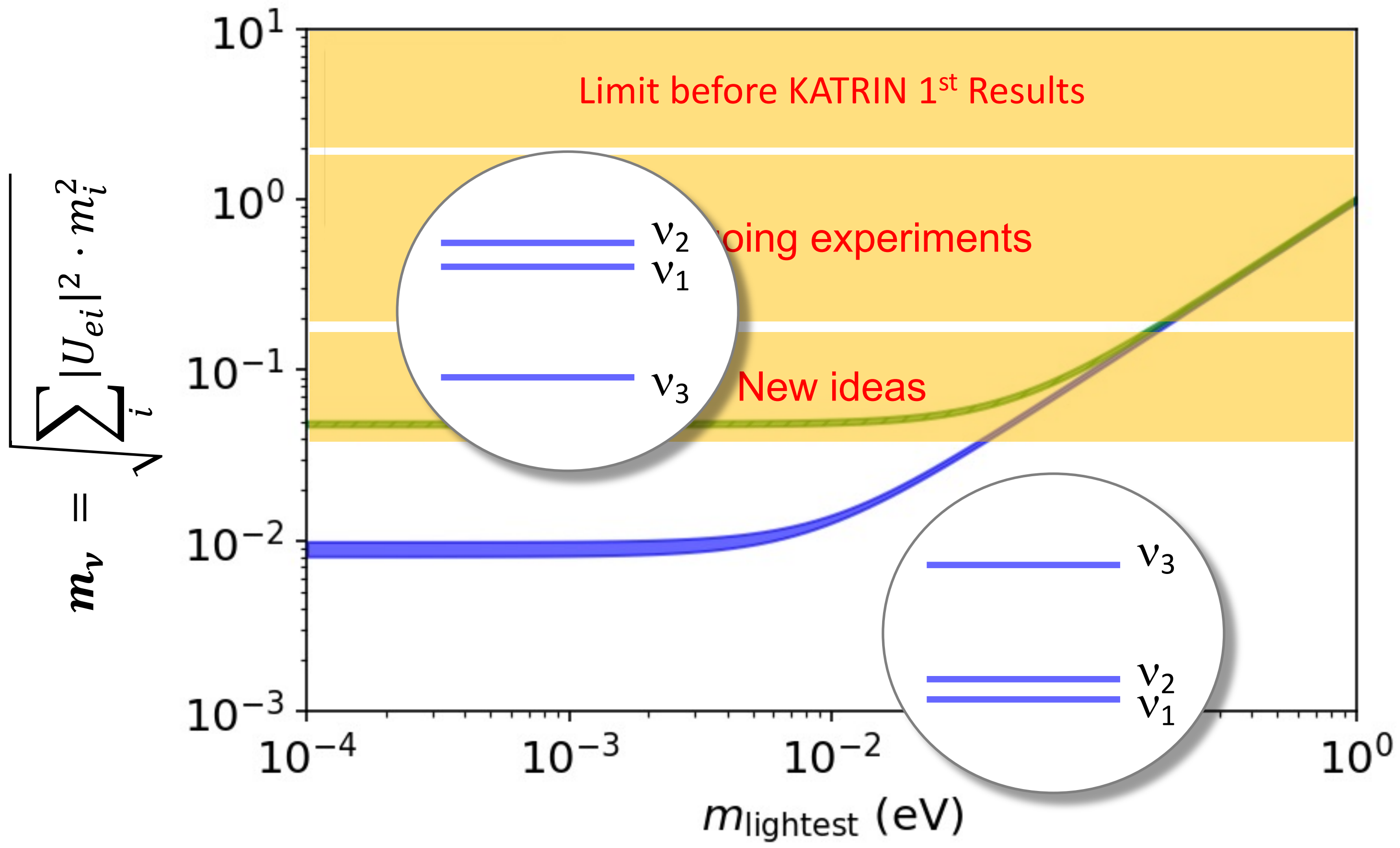
- KATRIN goal:
  Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



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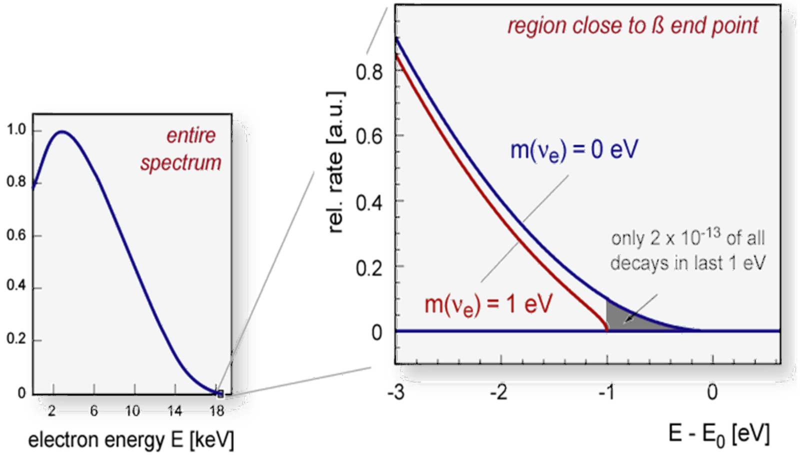
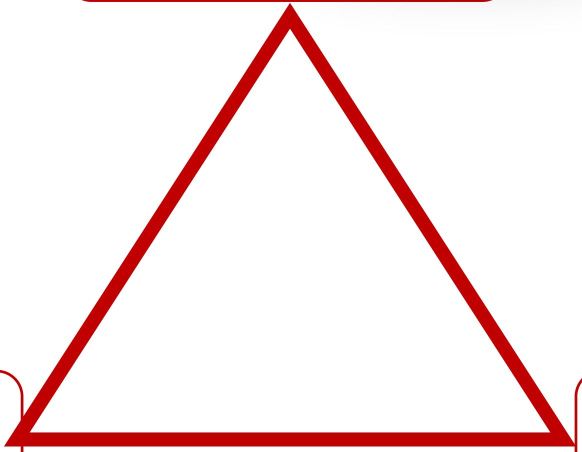
- KATRIN goal: Distinguish between **degenerate** and **hierarchical** scenario
- Future: Resolve **normal** vs **inverted** neutrino mass ordering

Experimental efforts



Electrostatic filter (MAC-E)

counting above threshold



frequency

Cyclotron Radiation

Phonons

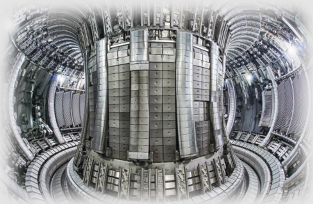
heat

Experimental efforts

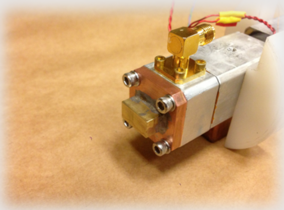
KATRIN
(Tritium)

Electrostatic filter (MAC-E)

QTNM
(Tritium)



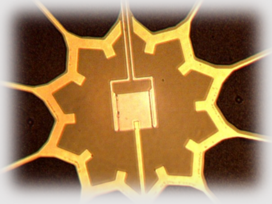
Project-8
(Tritium)



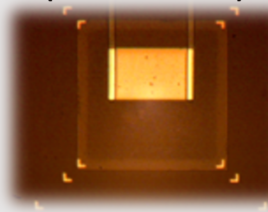
Cyclotron Radiation

Ptolemy
(Tritium)

Holmes
(Holmium)



ECHo
(Holmium)



Phonons

Karlsruhe
Tritium
Neutrino
Experiment

KATRIN

- **Experimental site: Karlsruhe Institute of Technology (KIT)**
- **International Collaboration (150 members)**
- **Design sensitivity: 0.2 eV (90% CL)**
  (1000 days of measurement time)

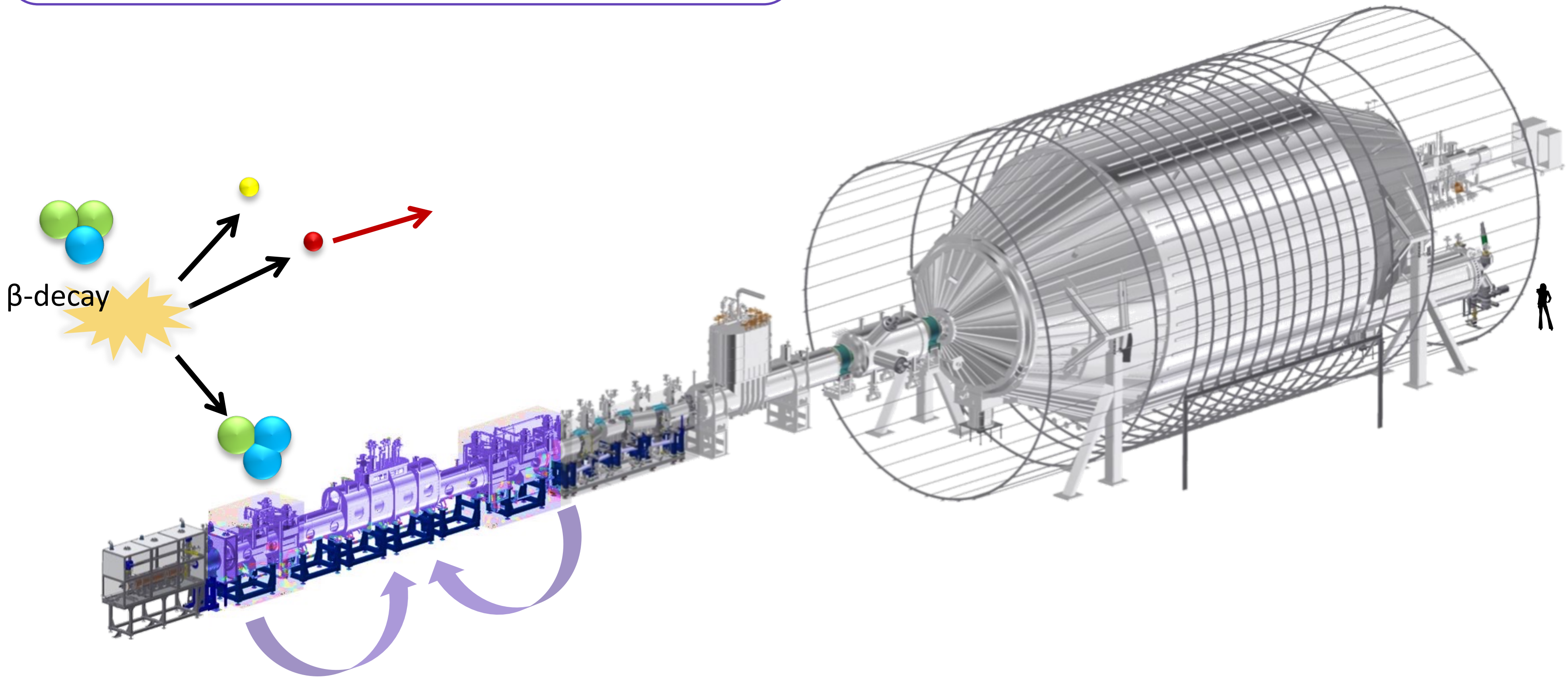
KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University
Russian Academy of Sciences
Westfälische Wilhelms-Universität Münster
Massachusetts Institute of Technology
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
The University of North Carolina at Chapel Hill
The Czech Academy of Sciences
Hochschule Fulda University of Applied Sciences
Carnegie Mellon University
Universidad Complutense Madrid
cea
Johannes Gutenberg Universität Mainz
Technische Universität München
universität bonn
Humboldt-Universität zu Berlin
Bergische Universität Wuppertal
Berkeley Lab

Overview

- How does KATRIN work ?
- What are the latest results?
- What‘s next?
- What else can we do with the data?

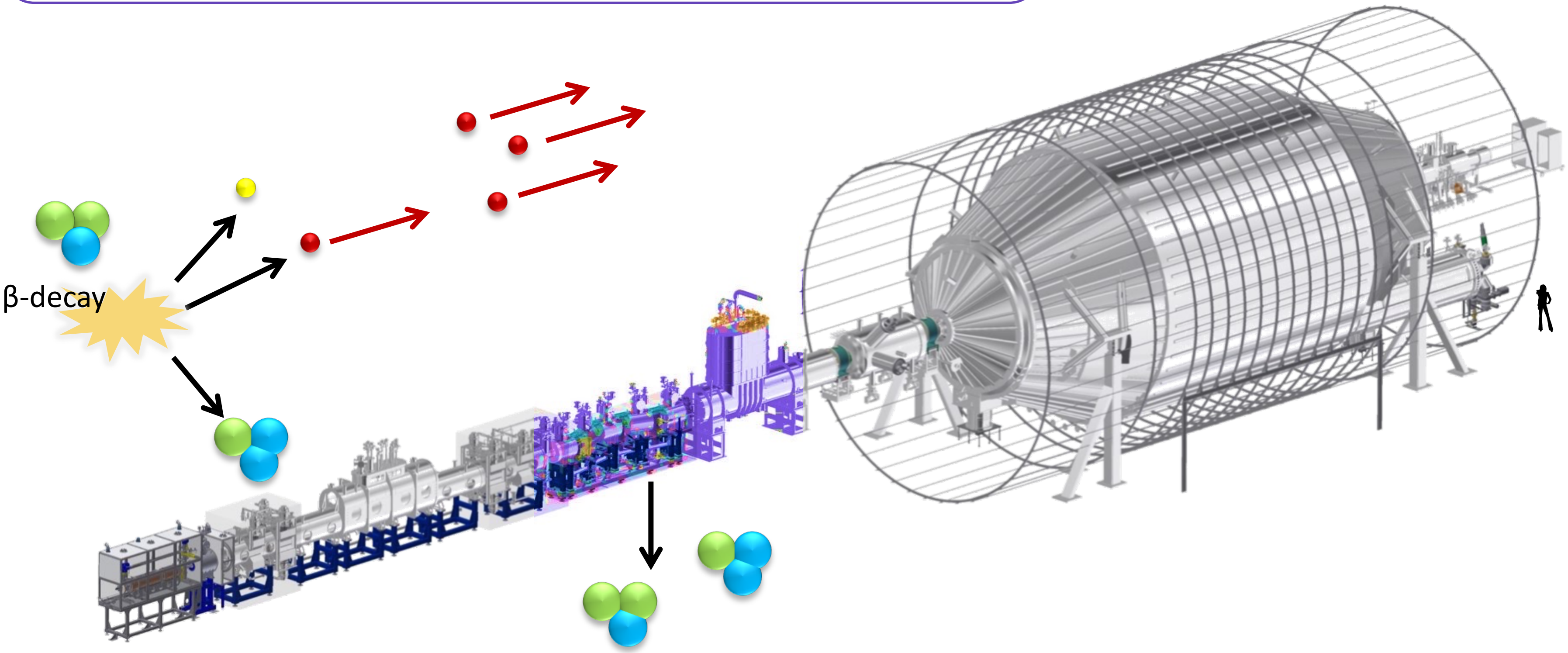
KATRIN Working Principle

Windowless gaseous tritium source
- molecular tritium in closed loop system
- 10^{11} decays/s



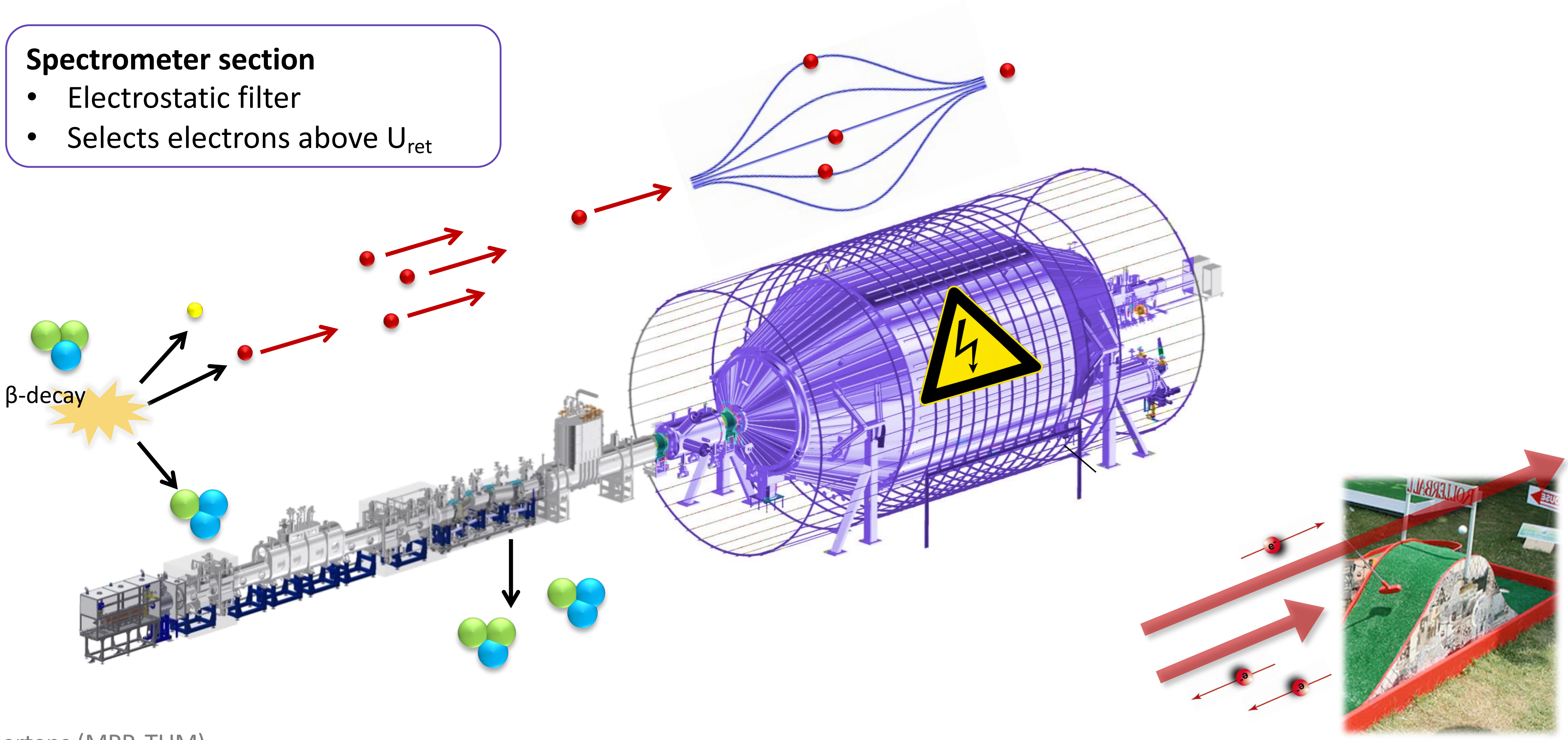
KATRIN Working Principle

Transport section
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by > 10^{14} + tritium ion removal



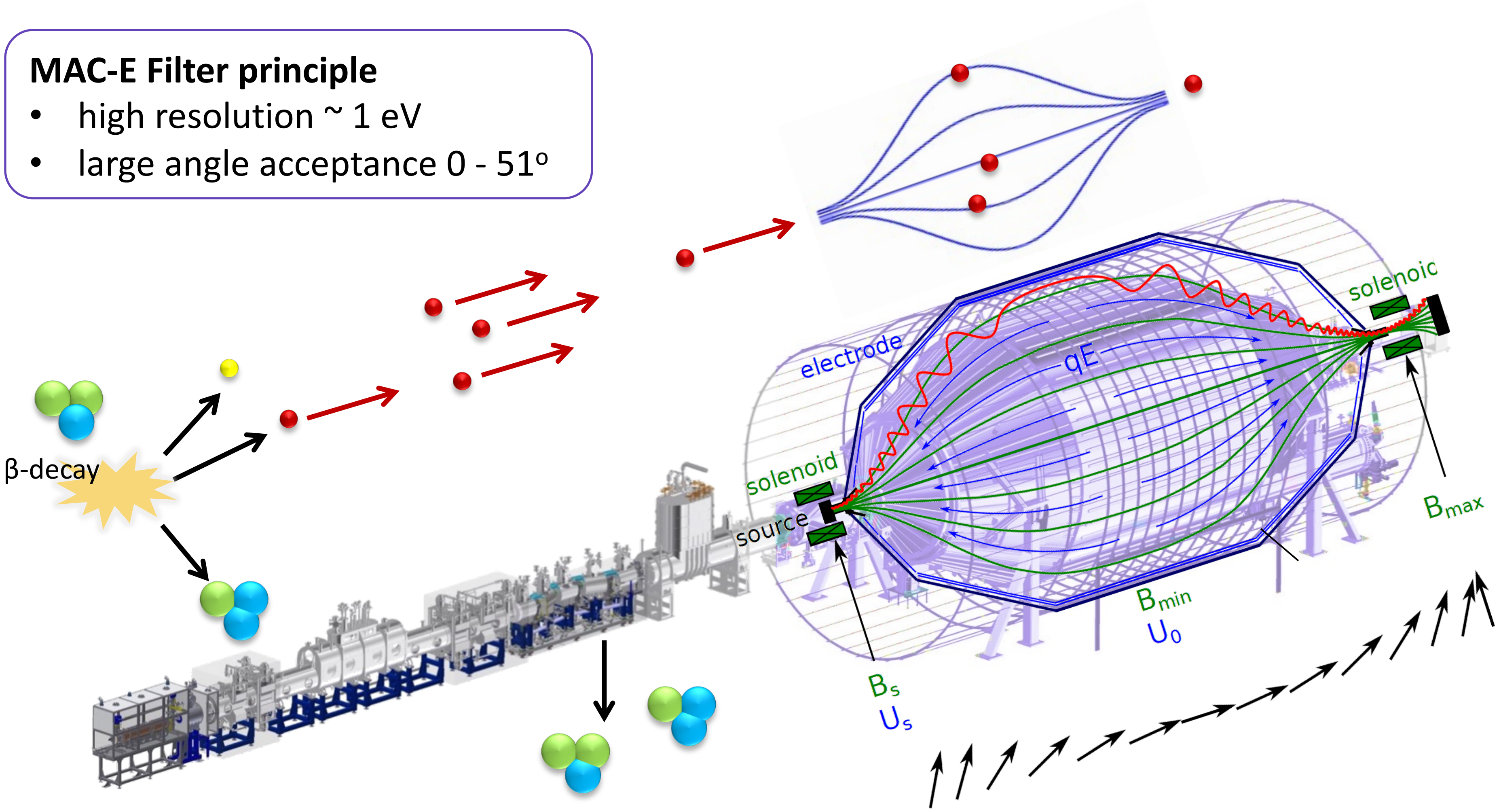
KATRIN Working Principle

Spectrometer section
- Electrostatic filter
- Selects electrons above U_{ret}



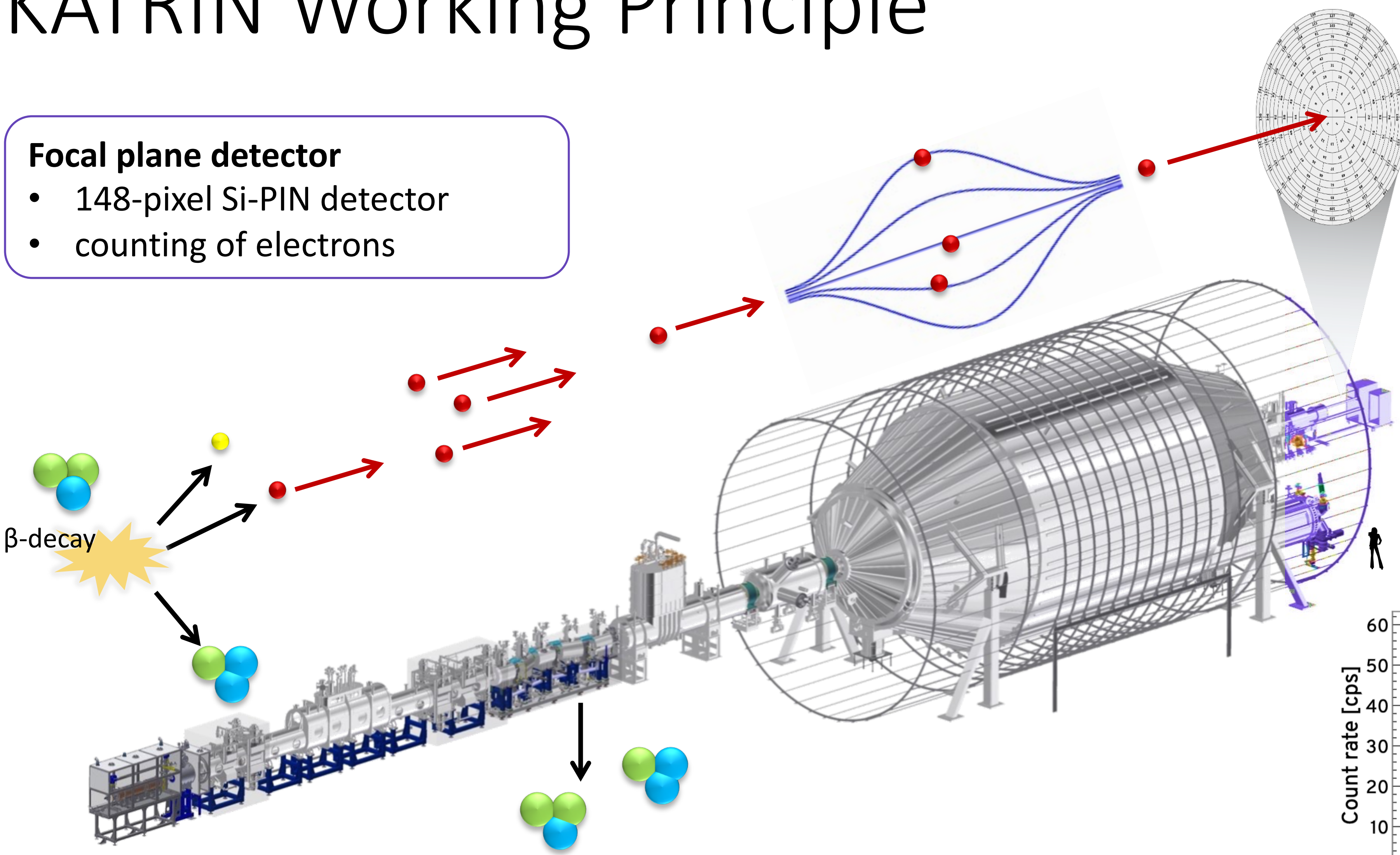
KATRIN Working Principle

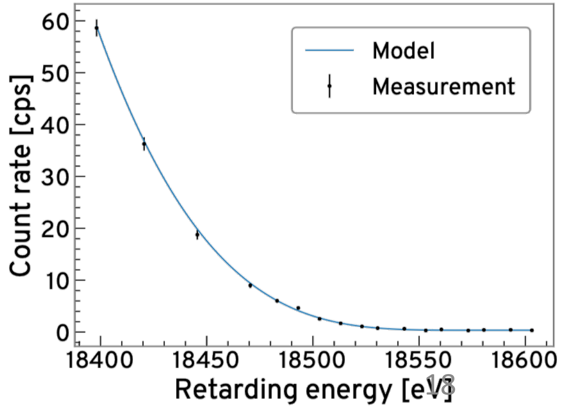
MAC-E Filter principle
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°



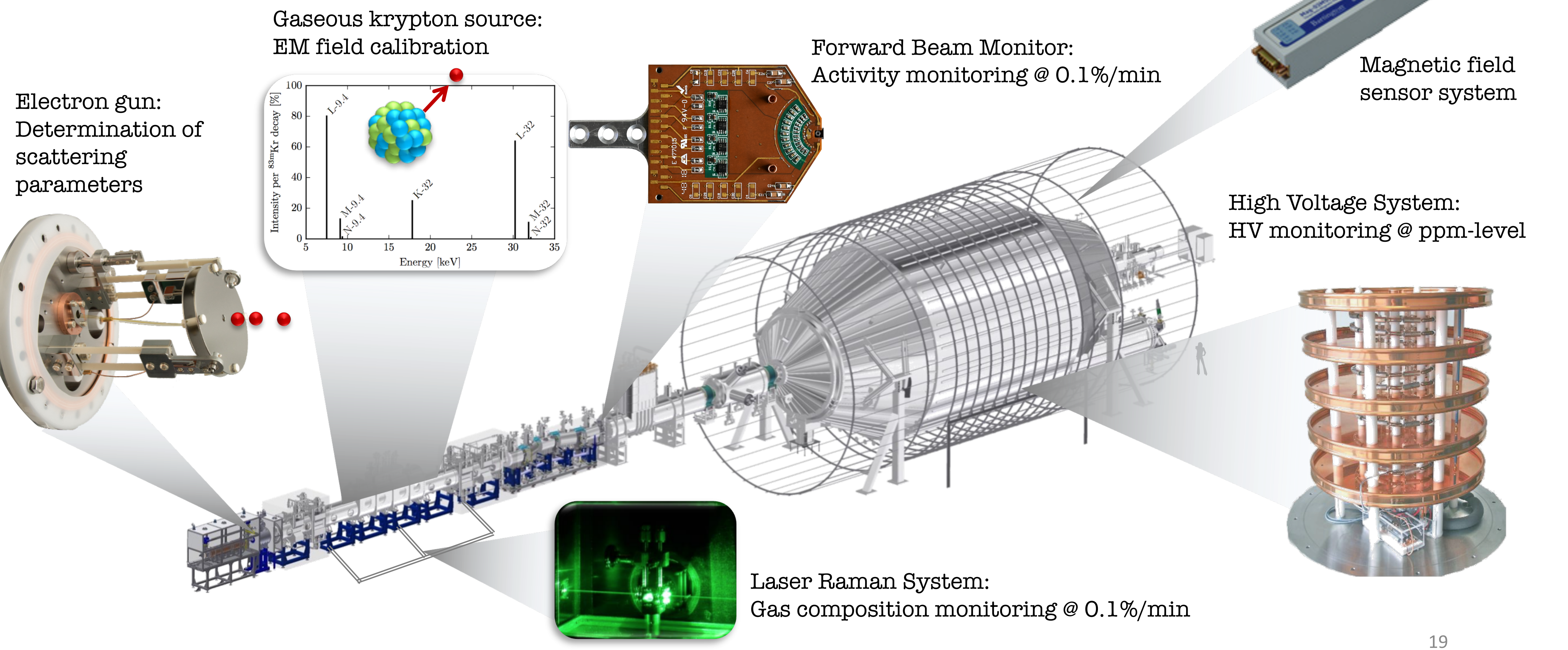
KATRIN Working Principle

Focal plane detector
- 148-pixel Si-PIN detector
- counting of electrons





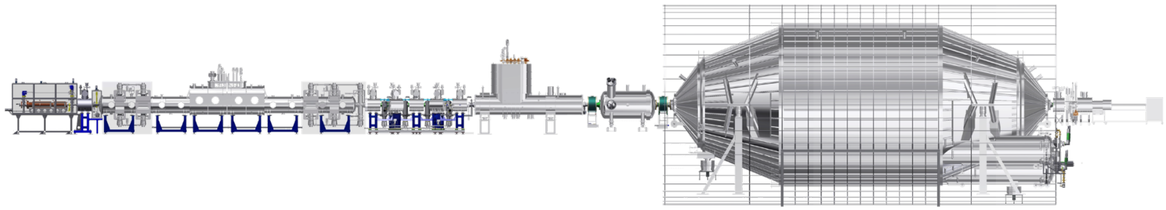
KATRIN Working Principle

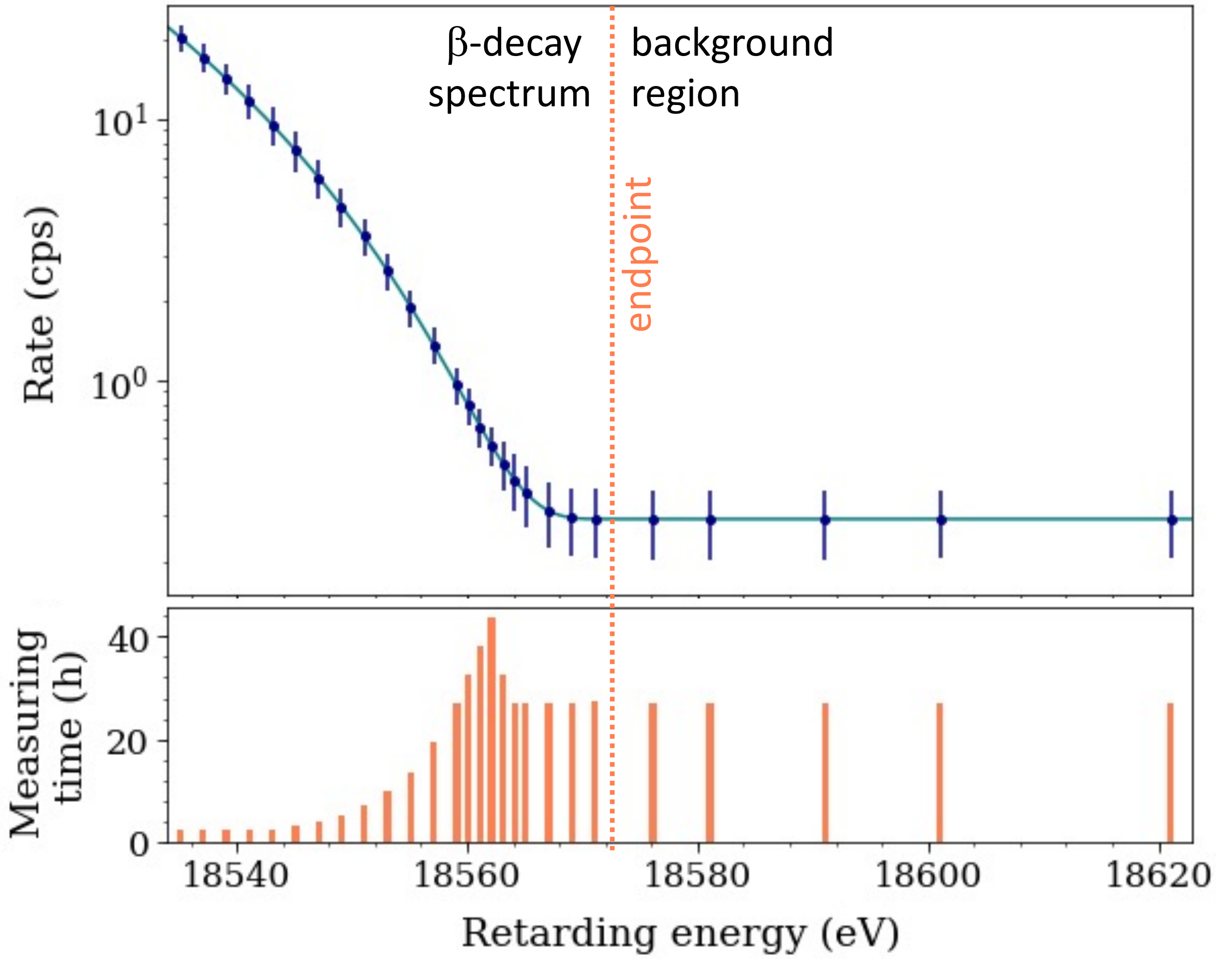


Measurement strategy

- Scan: **~ 30 HV set points**
- Scanning time: **~ 2 hours**
- Analysis interval: **E_0 – 40 eV , E_0 + 130 eV**

- Campaign: **several hundreds of scans**

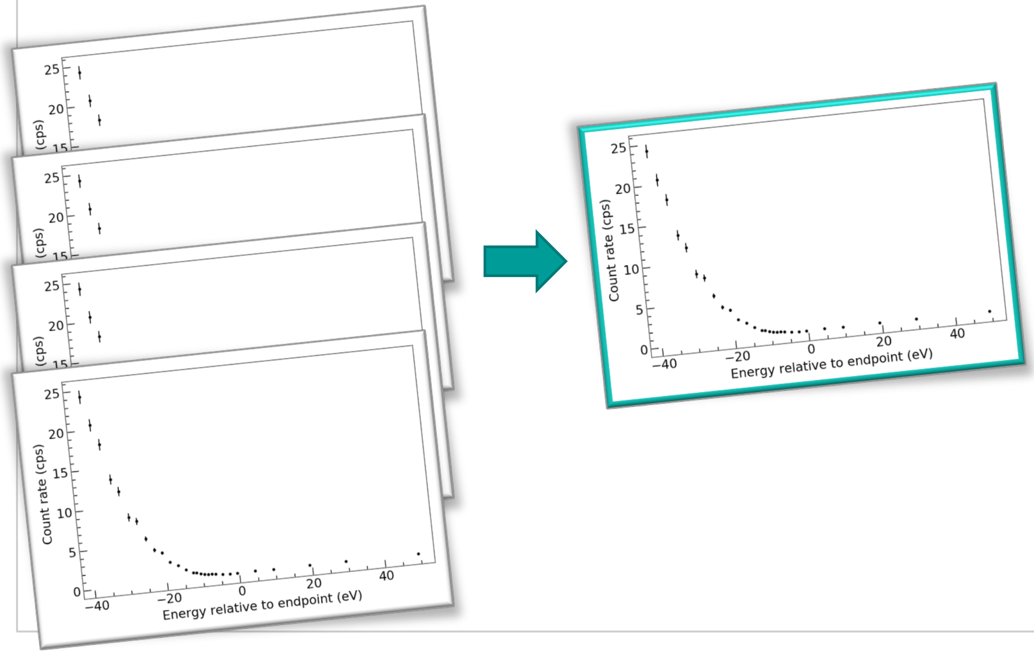




Data combination

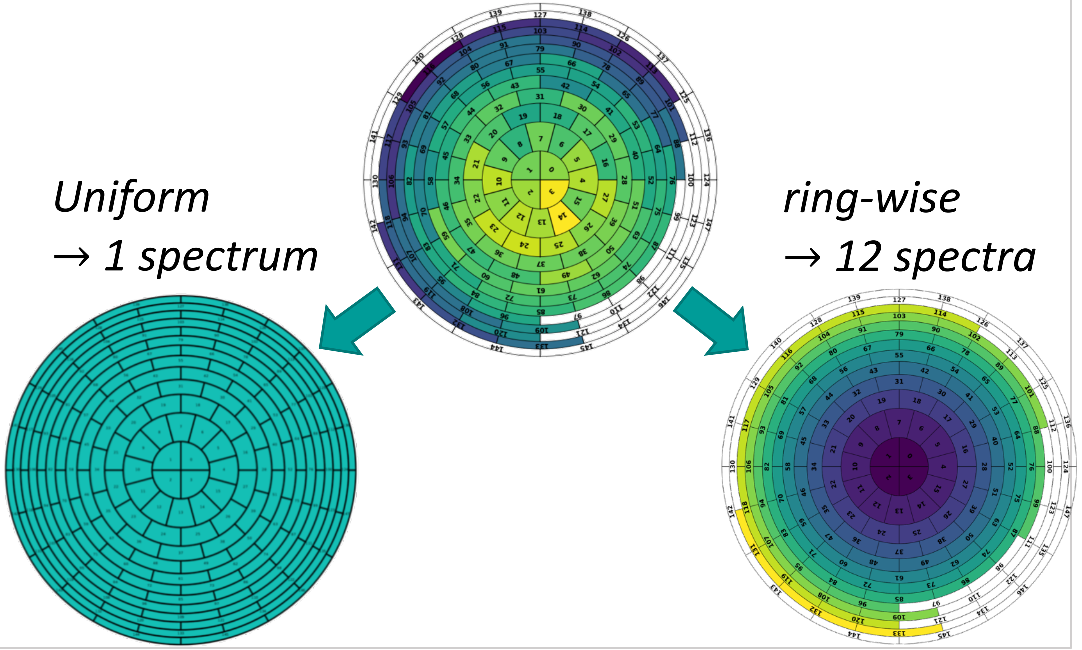
Scan combination

- sum the counts at the same HV set point
- use average HV ($\sigma_{HV} < 34\ \mathrm{mV}$)



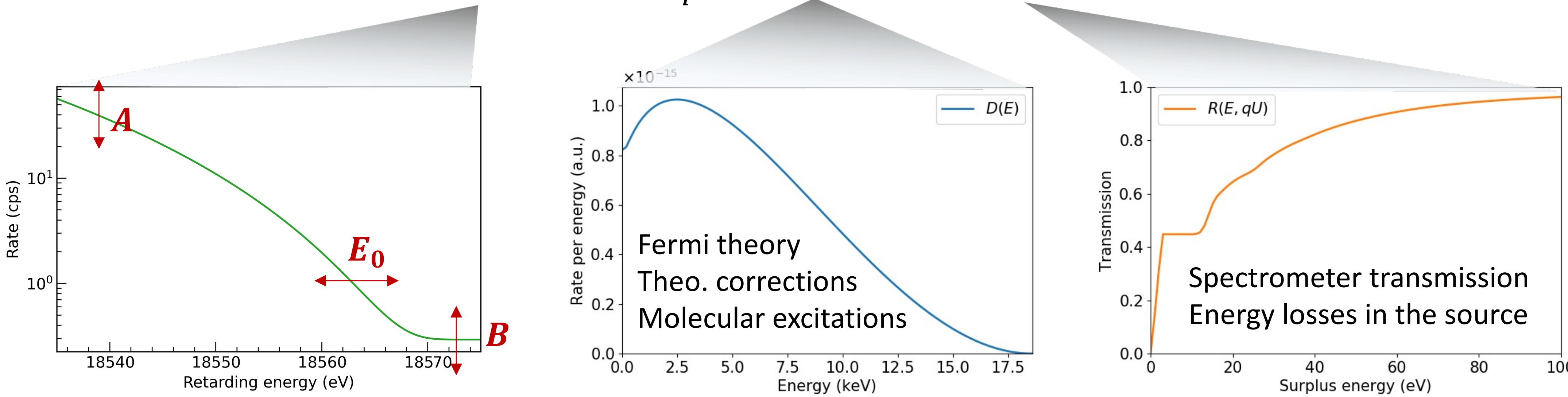
Pixel combination

- sum the counts of ALL pixels or in a ring
- use average response function



Data analysis

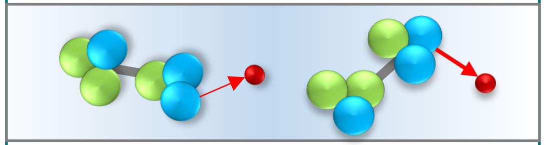
- Fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$



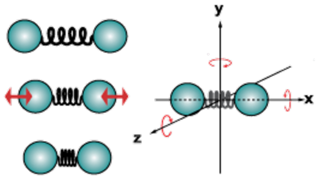
- Free parameters: $\boldsymbol{m_\nu^2}, \boldsymbol{E_0}, \boldsymbol{B}, \boldsymbol{A}$
- Fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, …)

Systematic uncertainties

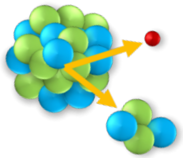
Source electric potential

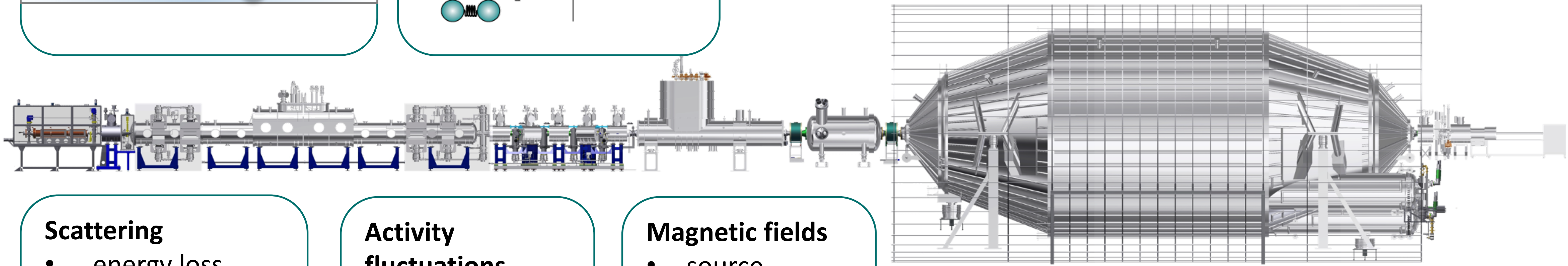


Molecular Final States

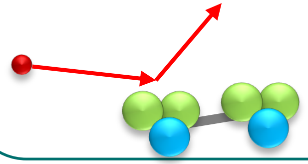


Background:
- time correlation (radon, penning trap)
- retarding potential dependence

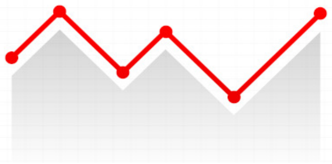




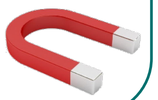
Scattering
- energy loss
- column density



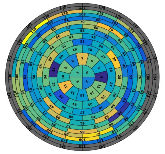
Activity fluctuations



Magnetic fields
- source
- spectrometer
- detector



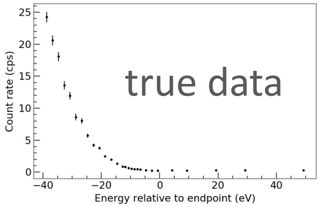
Detection efficiency

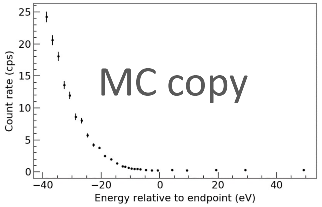


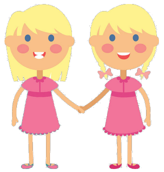
Blinded analysis

Freeze analysis on MC-twin data

- MC-copy of each scan (with m_ν = 0 eV)

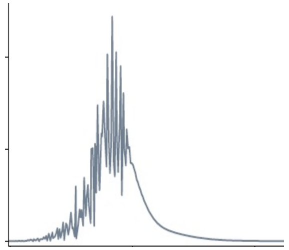


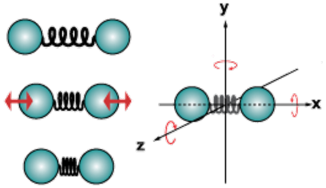




Blinded model

- Modified molecular final state dist.

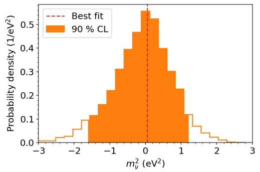


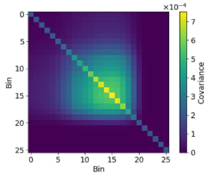


m_ν^2

Independent analysis strategies

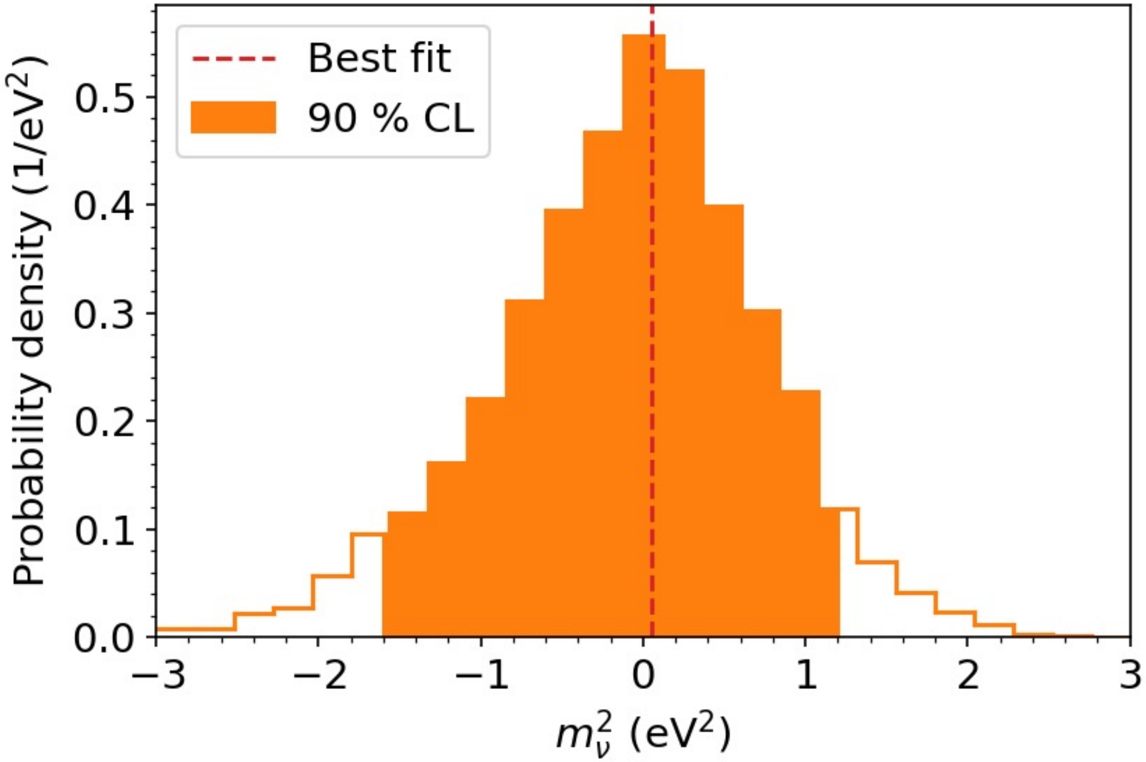
- Covariance matrix
- Monte Carlo propagation
- Pull term





MC propagation of uncertainties

- Fit performed 10^5 times
- Each time the systematic parameter is varied according to its uncertainty
- Width of m_ν^2 distribution reflects systematic uncertainty from this effect



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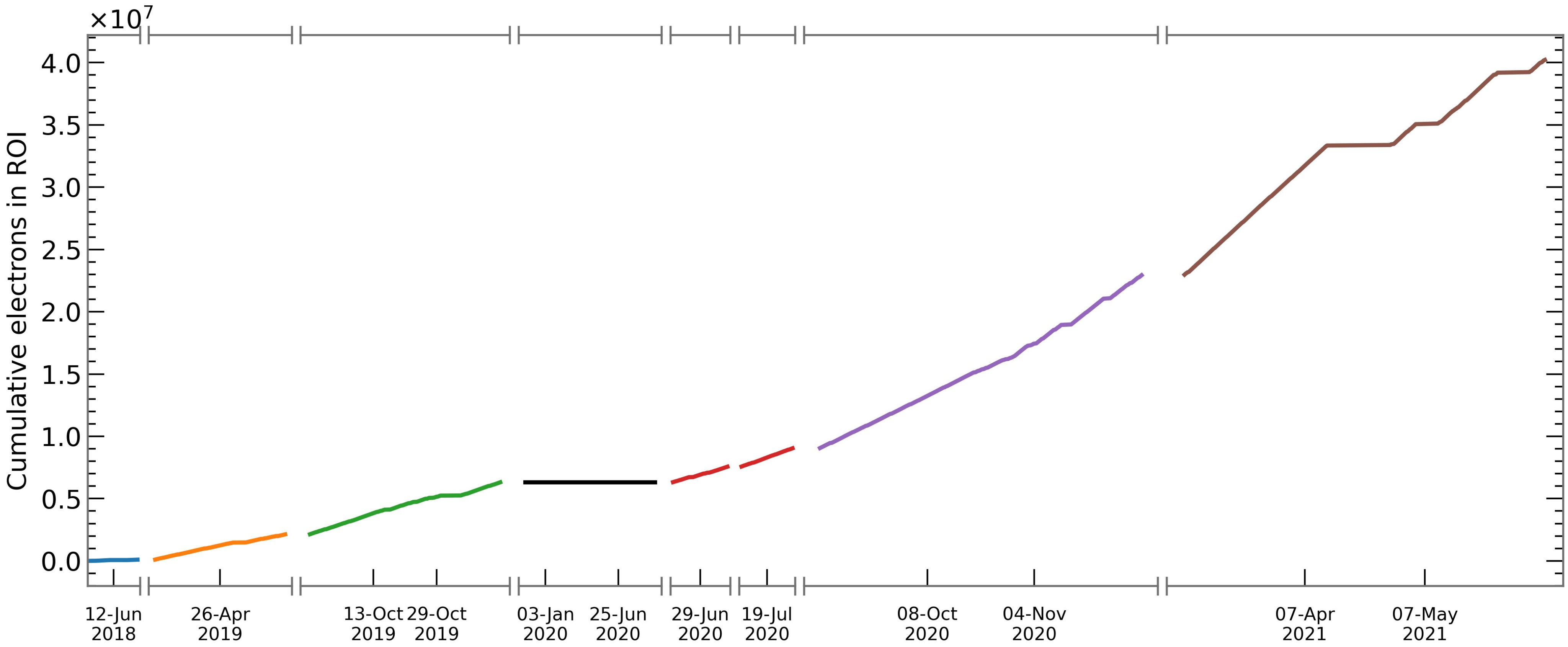
KATRIN Data Taking Overview



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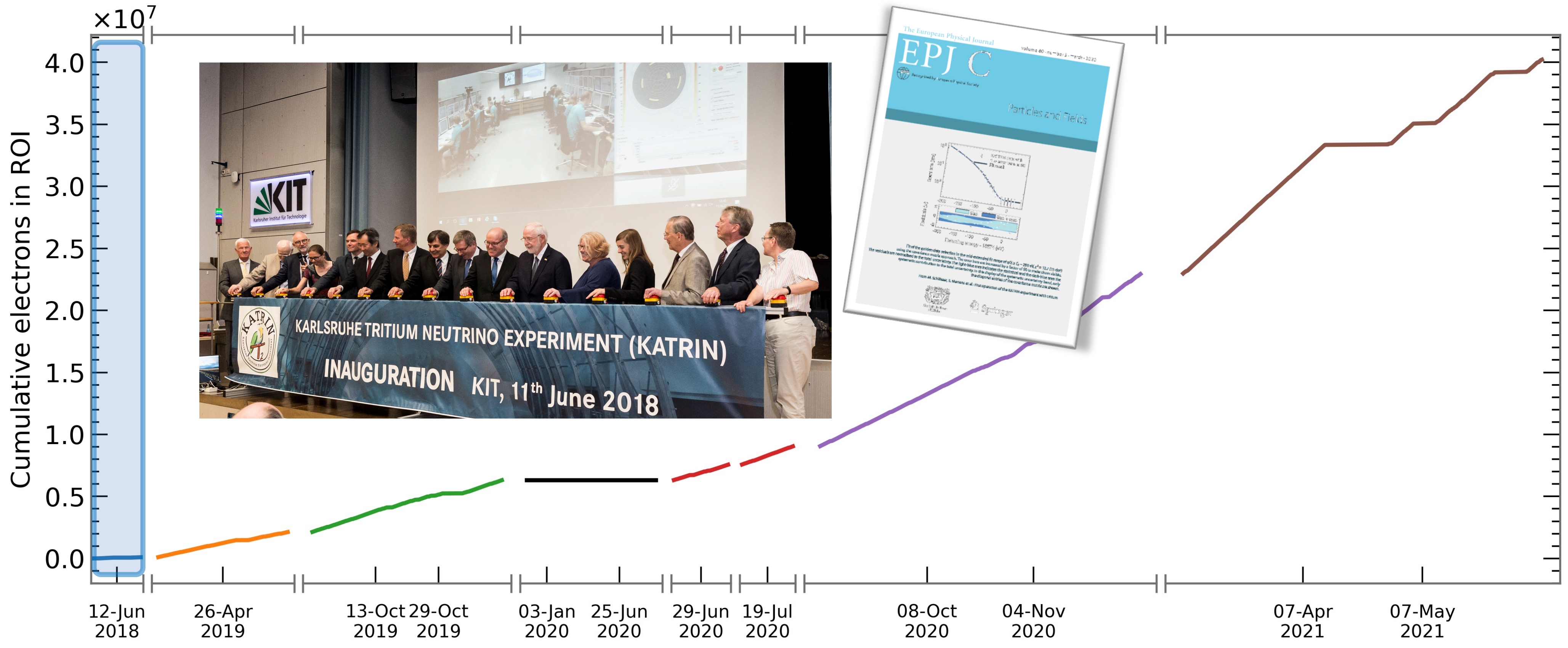

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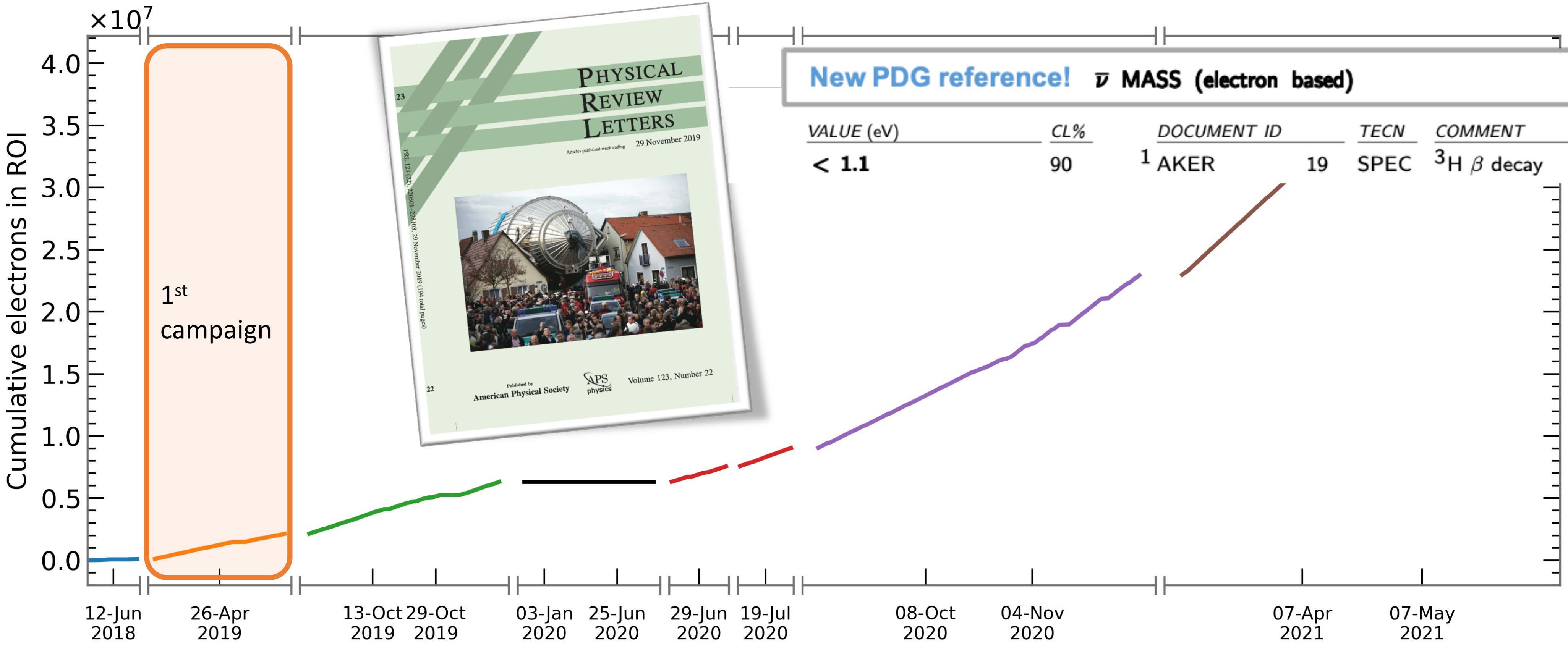
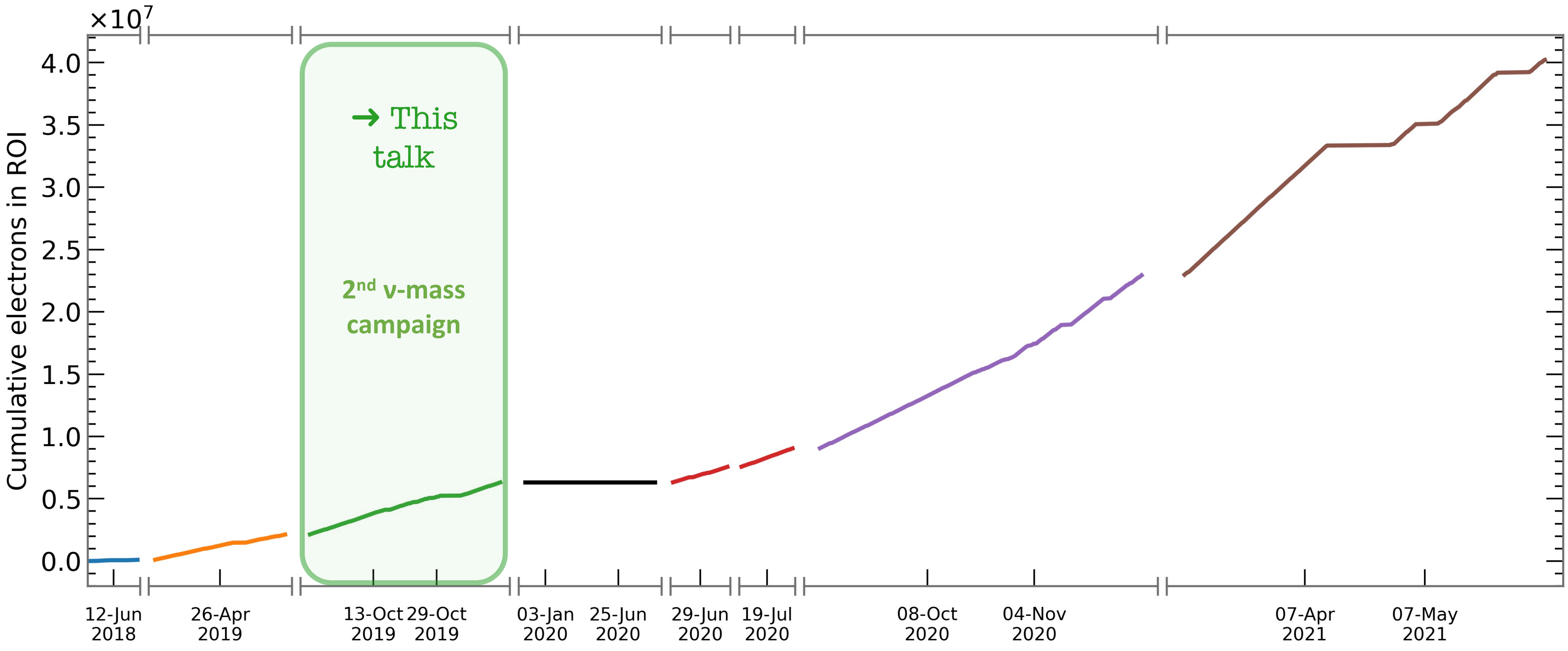


New PDG reference! $\bar{\nu}$ **MASS (electron based)**

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
< 1.1	90	[1] AKER 19	SPEC	^3H β decay

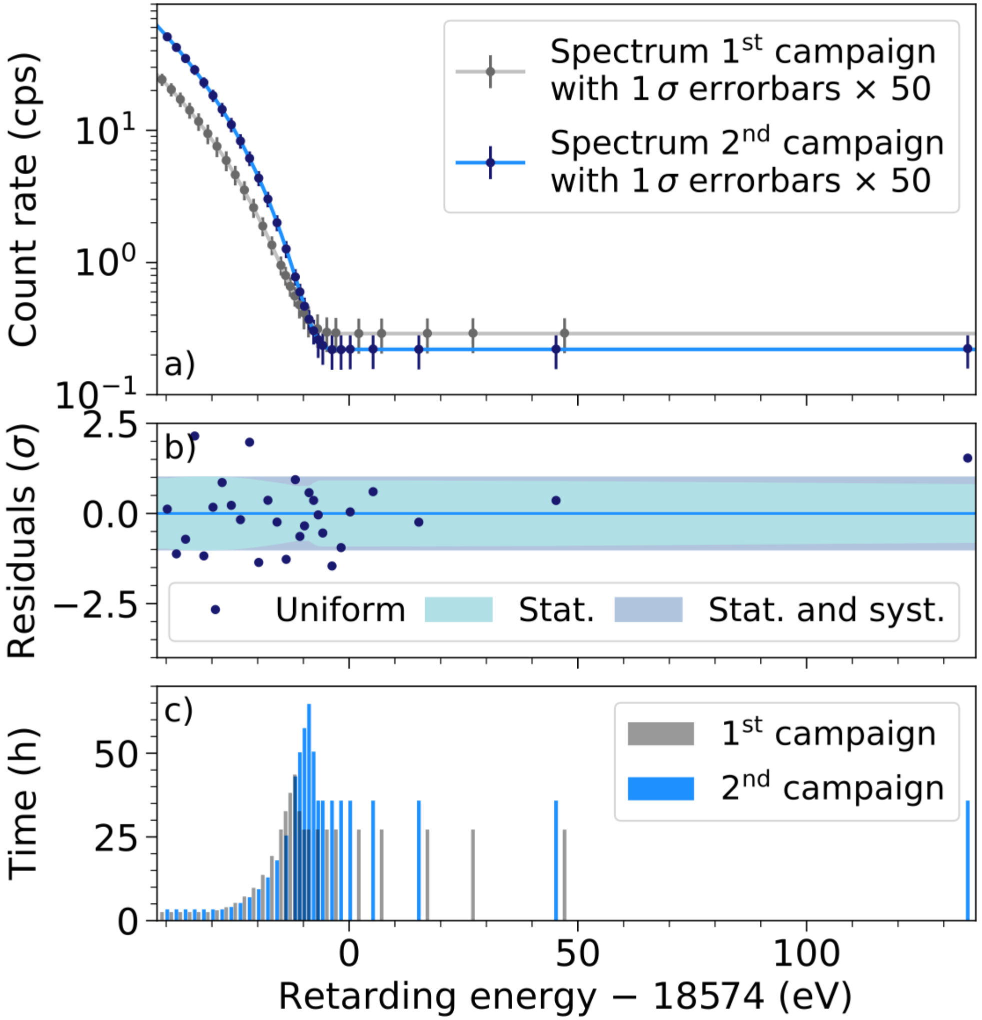
KATRIN Data Taking Overview



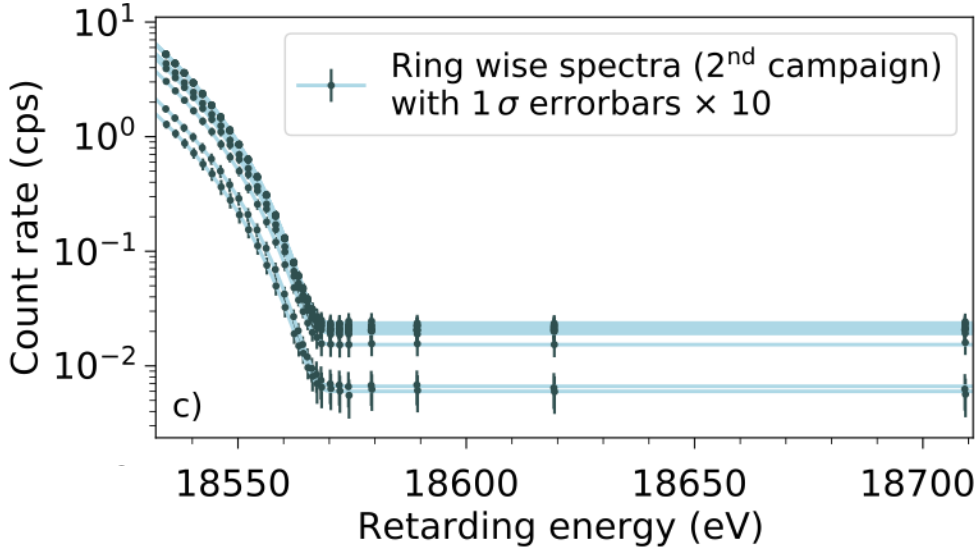
Improvements wrt 1st campaign

	1st campaign PRL 123 (2019)		2nd campaign This talk
Campaign date	April-May 2019		Sept-Nov 2019
Total scan time	522 h (274 scans)		744 h (361 scans)
Source activity	25 GBq	**nominal activity** →	98 GBq
Background	290 mcps	**reduction -25%** →	220 mcps
Tritium purity	97.6%	**raised purity** →	98.7%
Electrons in RoI	2 Mio	**stats doubled** →	4.3 Mio

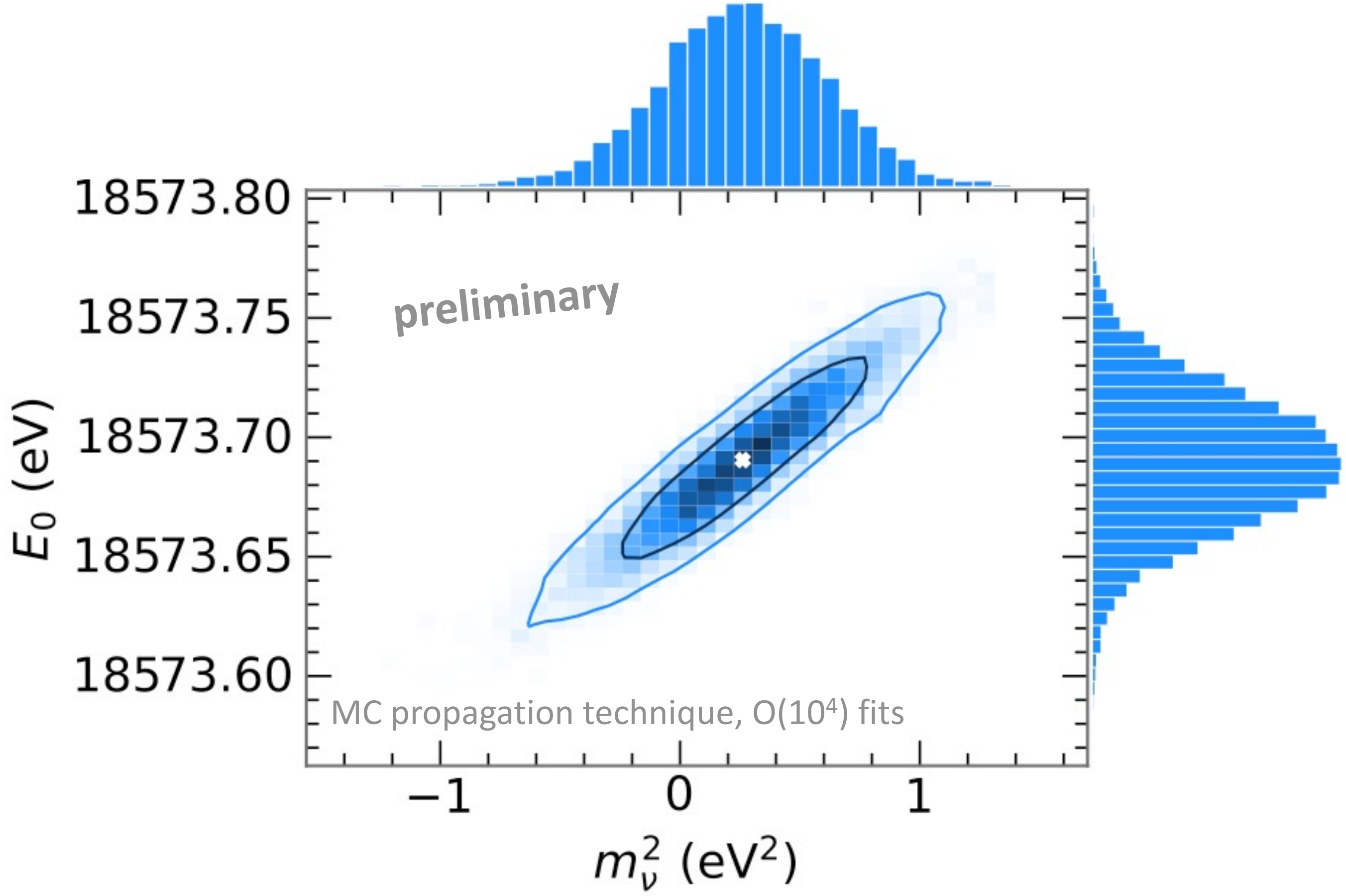
New data release

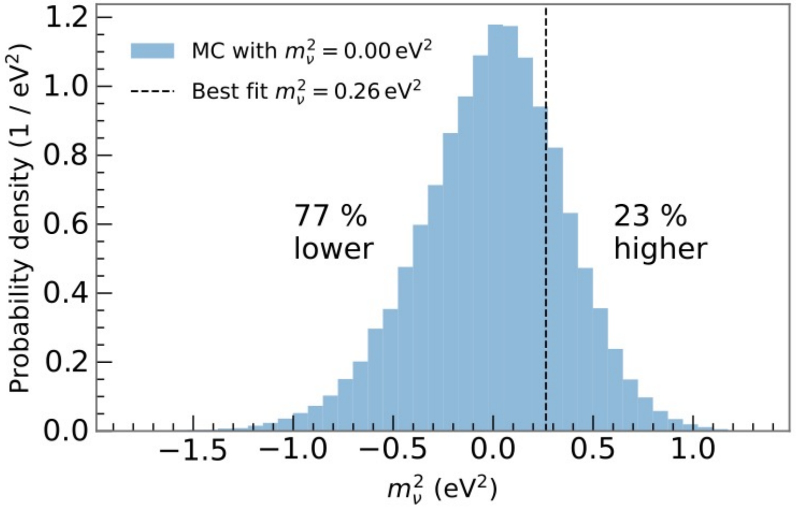


- total statistics: 4 million events
- excellent goodness-of-fit: p-value = 0.8
- Uncertainties are statistics dominated
- *Uniform* and *ring-wise* fit lead to consistent results



Best Fit





$$m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)\mathrm{eV}^2$$

✓ compatible with zero

$$E_0 = 18573.69 \pm 0.03\ \mathrm{eV}$$

✓ Q-value : 18575.2 ± 0.5 eV

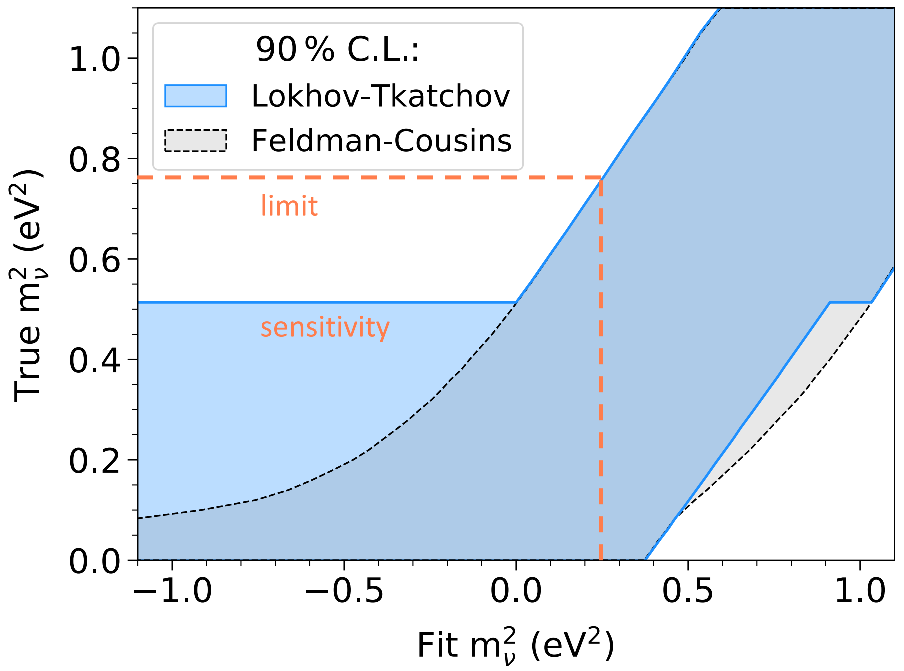
✓ good agreement with literature

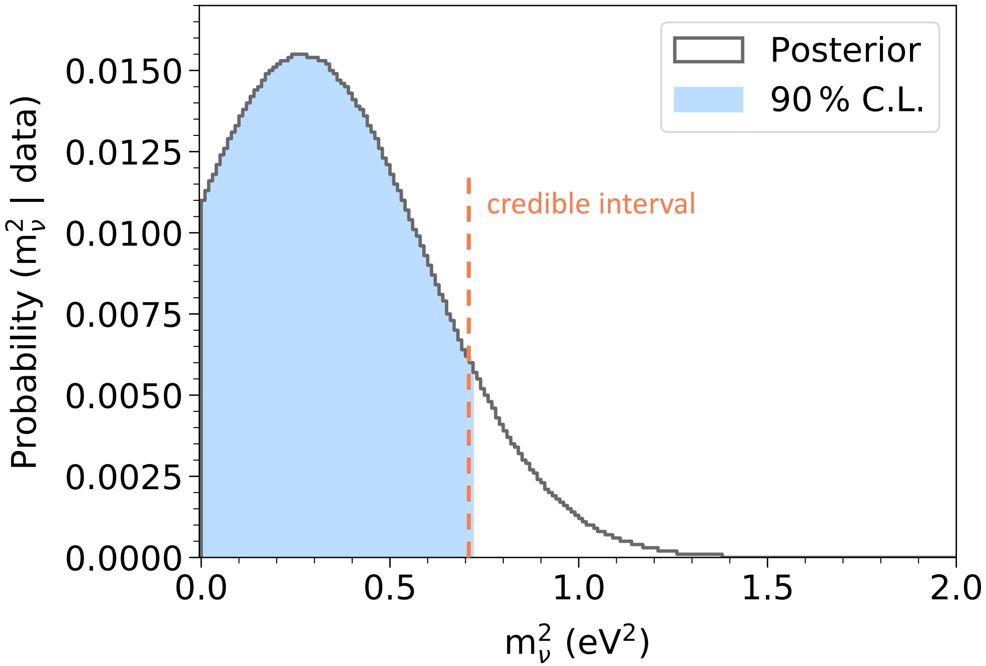
Q = 18575.72 ± 0.07 eV

E. Myers et al. Phys. Rev. Lett. 114, 013003 (2015)

New upper limit

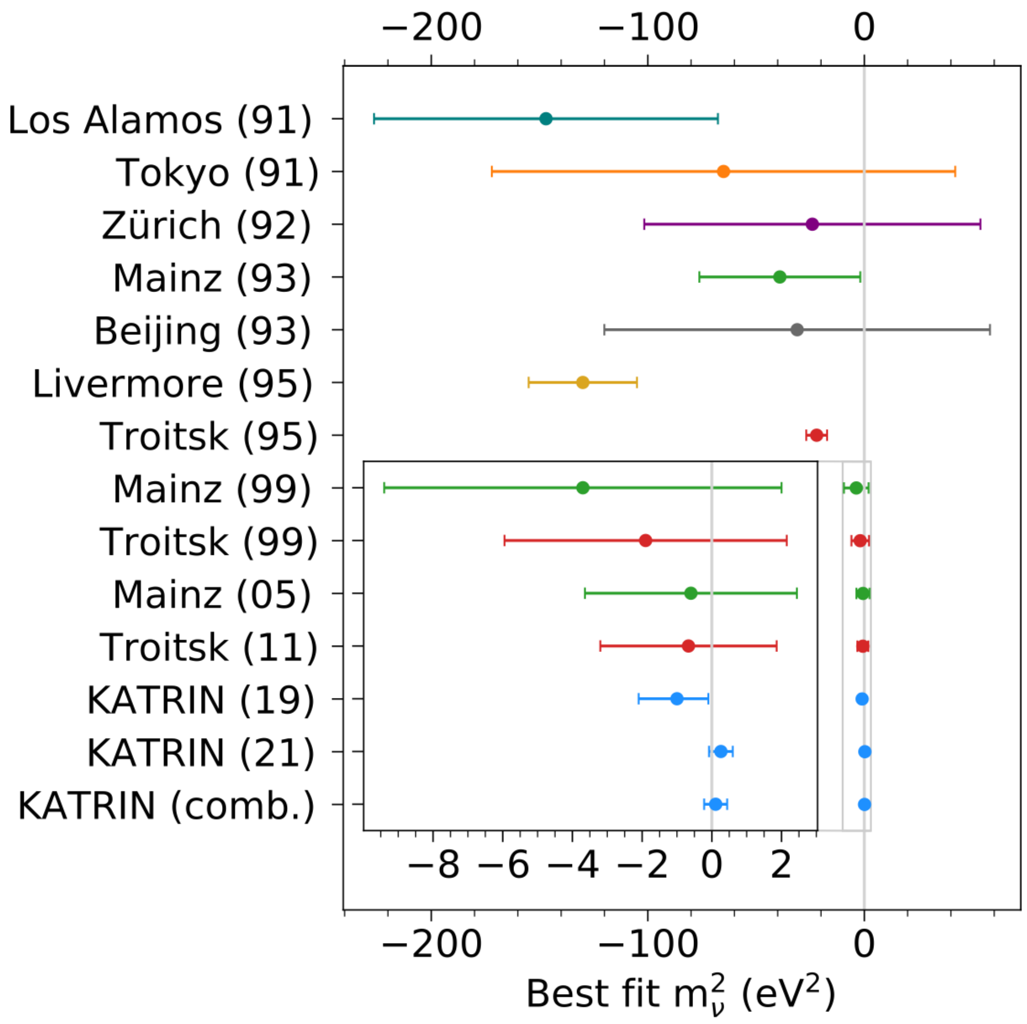
- Frequentist limit: $m_\nu < 0.9$ eV (90% CL)
- Bayesian: $m_\nu < 0.85$ eV (90% CI)
- Sensitivity: $m_\nu < 0.7$ eV (90% CL)





Lokhov & Tkachov, Phys. Part. Nucl. 46 (2015) 347
Feldman & Cousins, Phys. Rev. D57 (1998) 3873

Historical context



- KATRIN (2021):

  first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

- 1st and 2nd campaign combined result:

$$m_\nu^2 = \left(0.11^{+0.33}_{-0.33}\right)\text{eV}^2$$

- 1st and 2nd campaign combined limit:

$$m_\nu < 0.8\ \text{eV (90\% CL)}$$

KATRIN Collab. arXiv:2105.08533 [hep-ex]

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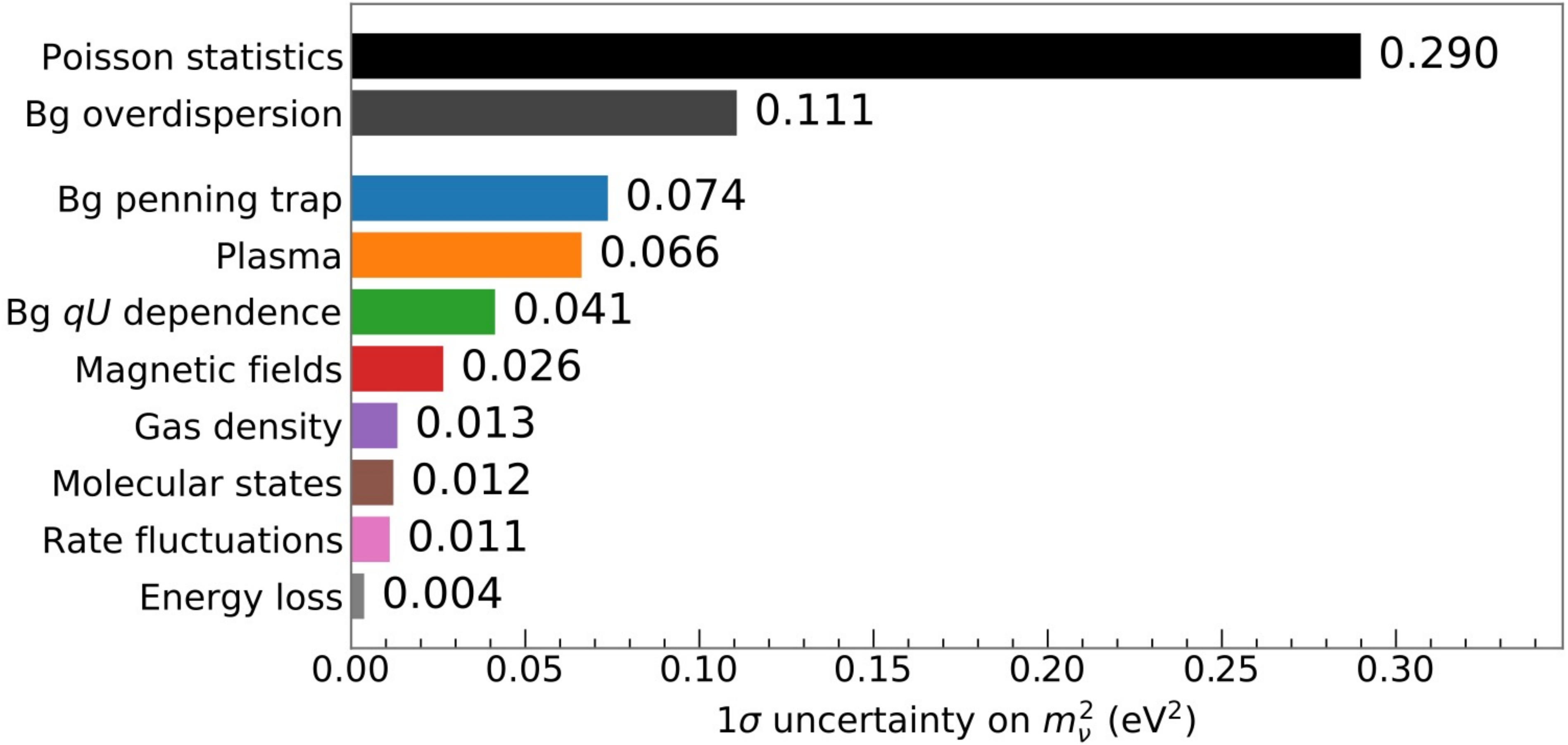
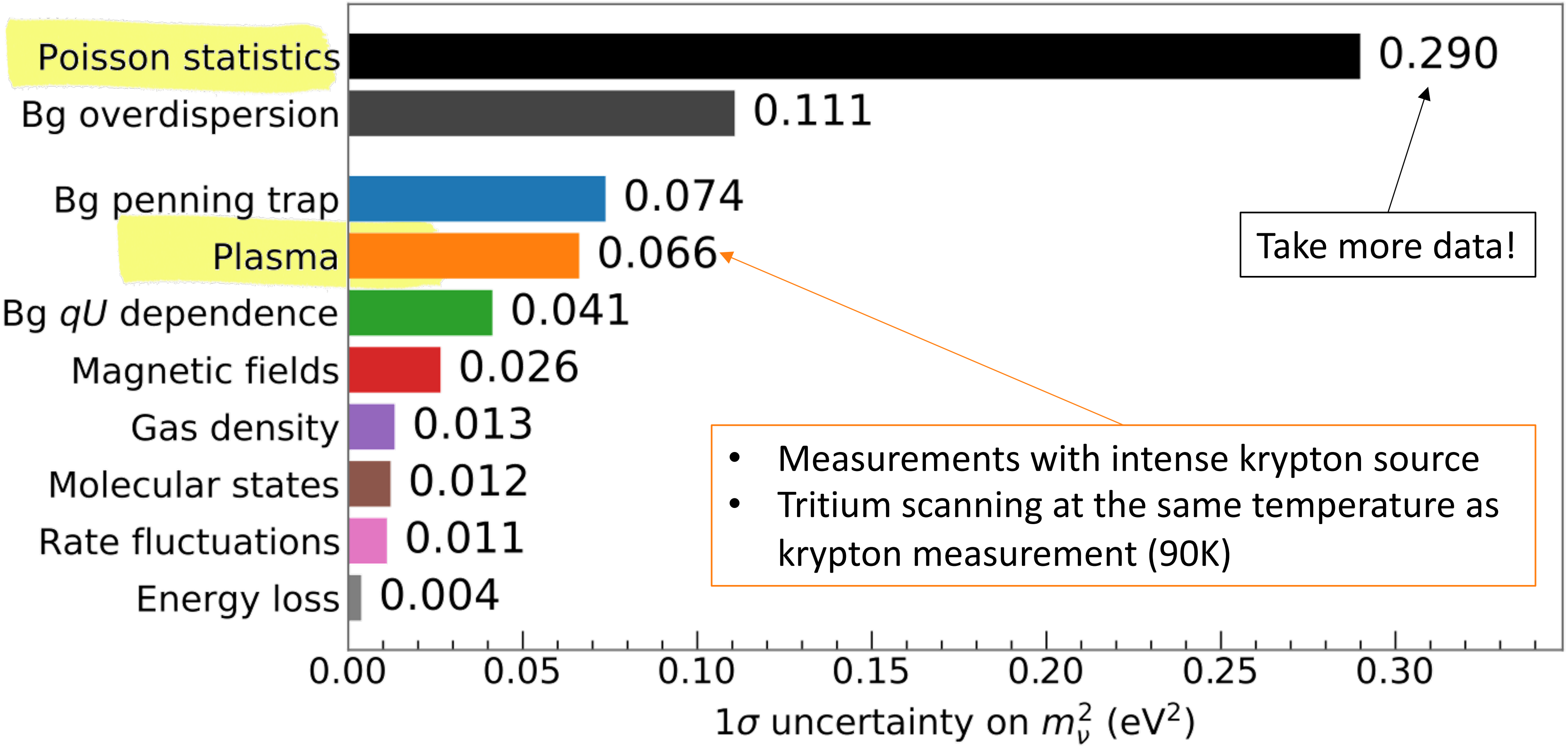
- What else can we do with the data?

Uncertainty budget of 2nd campaign

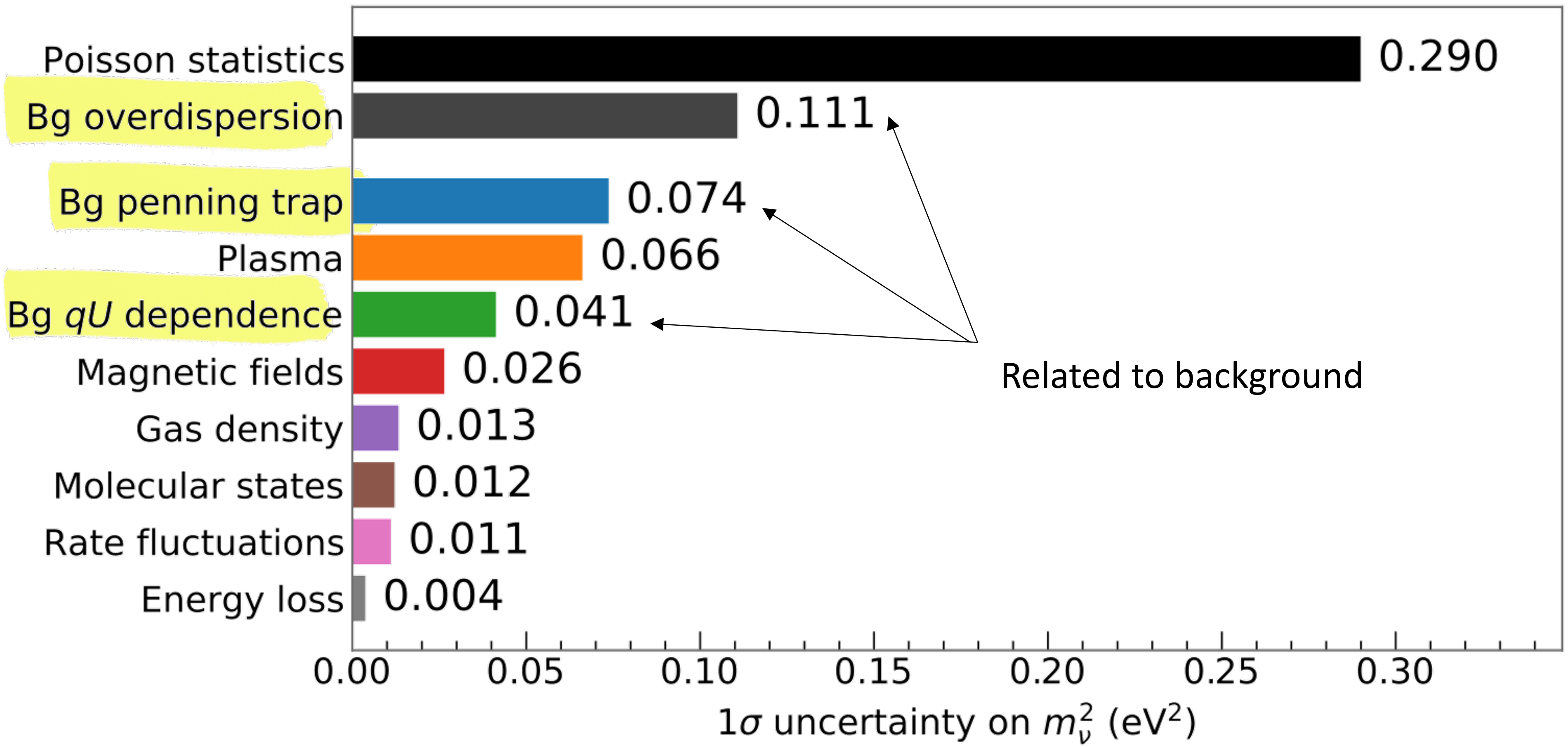


Uncertainty budget of 2nd campaign



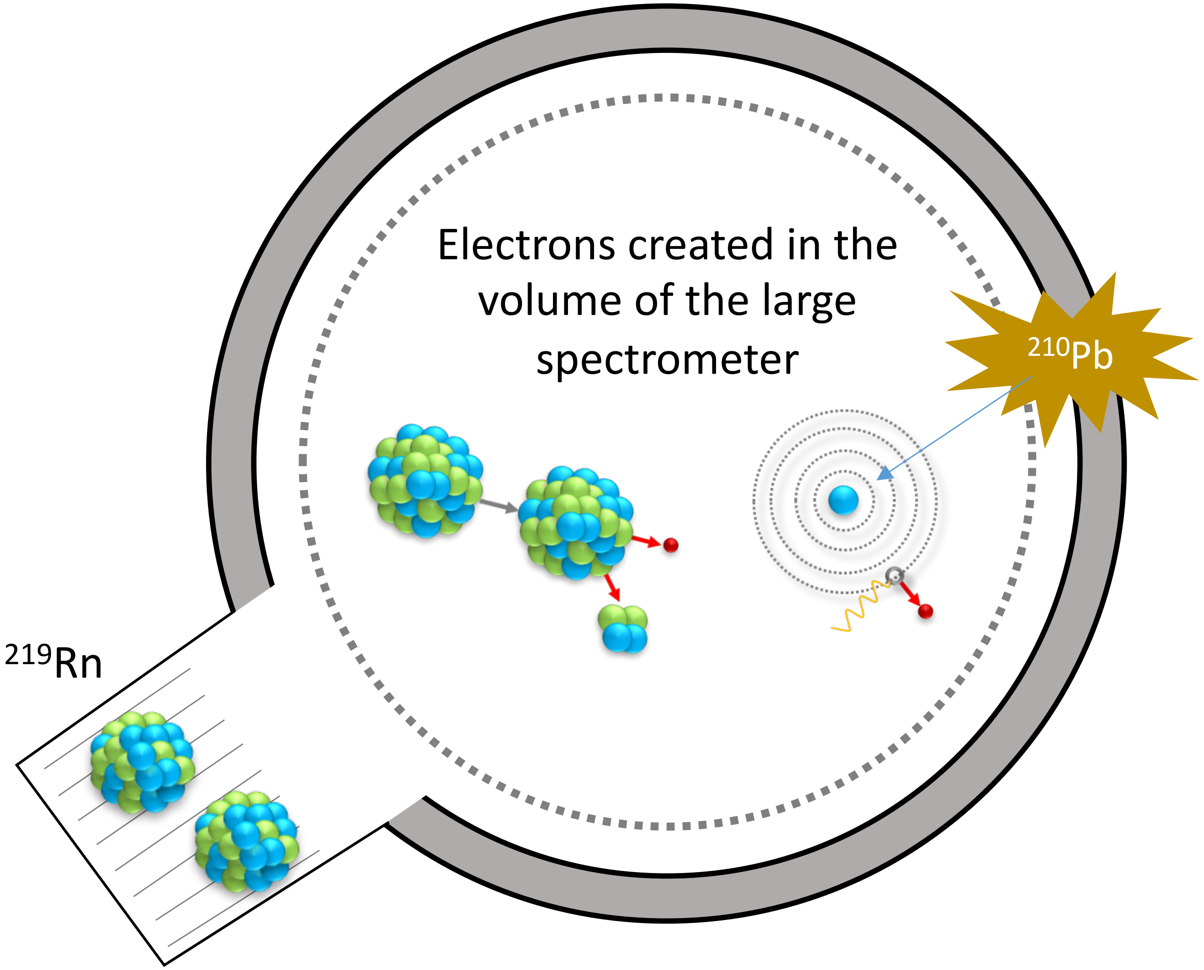
- Measurements with intense krypton source
- Tritium scanning at the same temperature as krypton measurement (90K)

Uncertainty budget of 2nd campaign

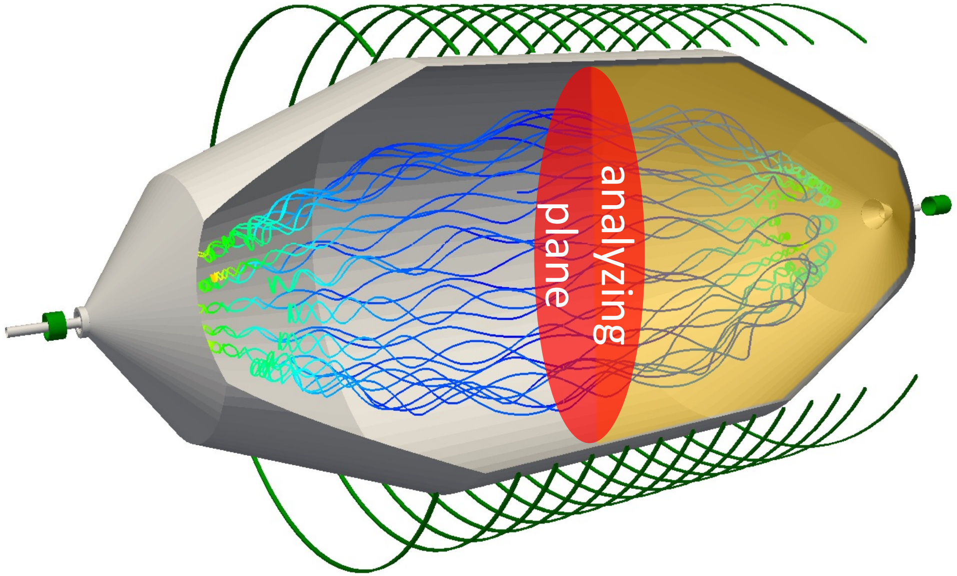


KATRIN backgrounds

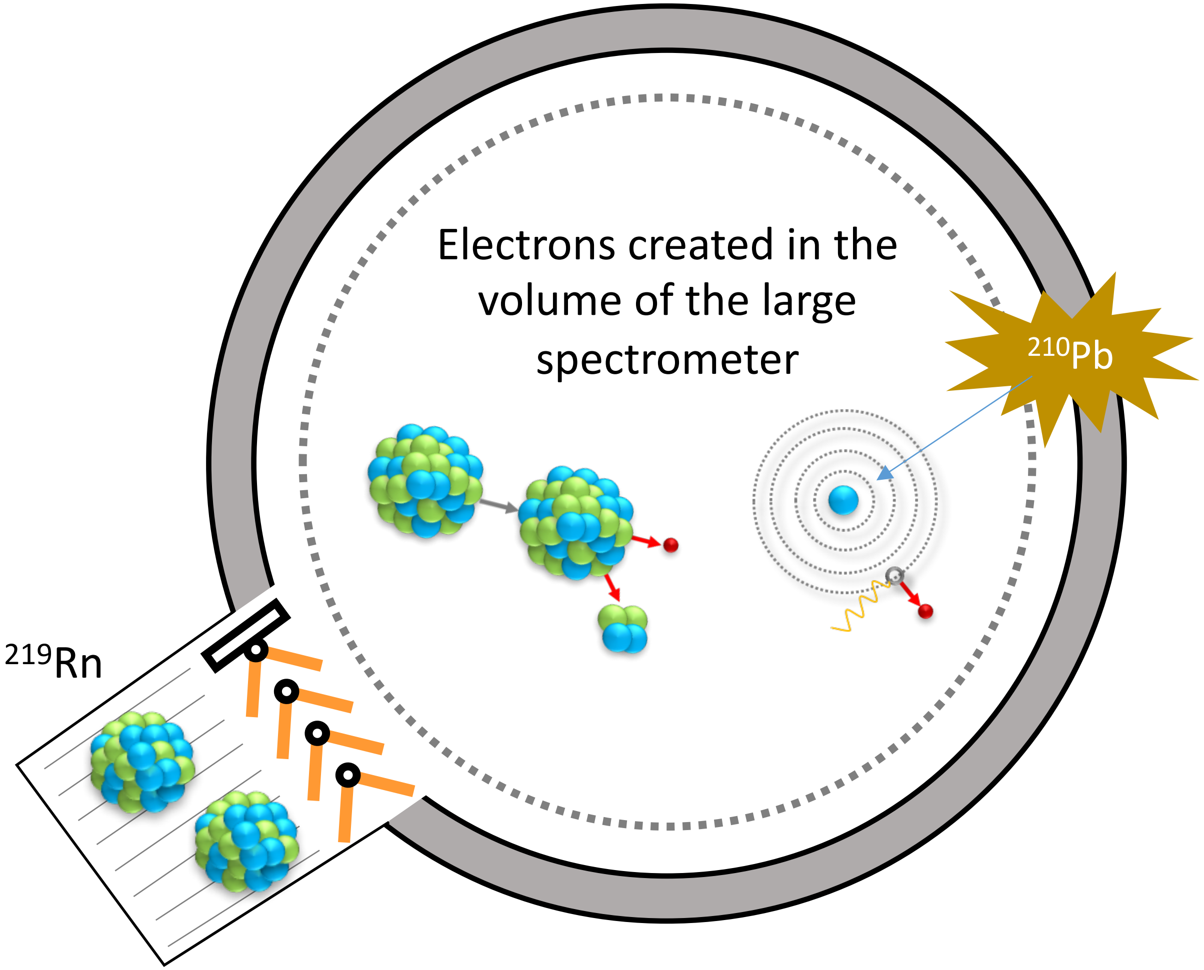
KATRIN backgrounds



- ^{219}Rn-induced background
- ^{210}Pb-induced background



KATRIN background mitigation

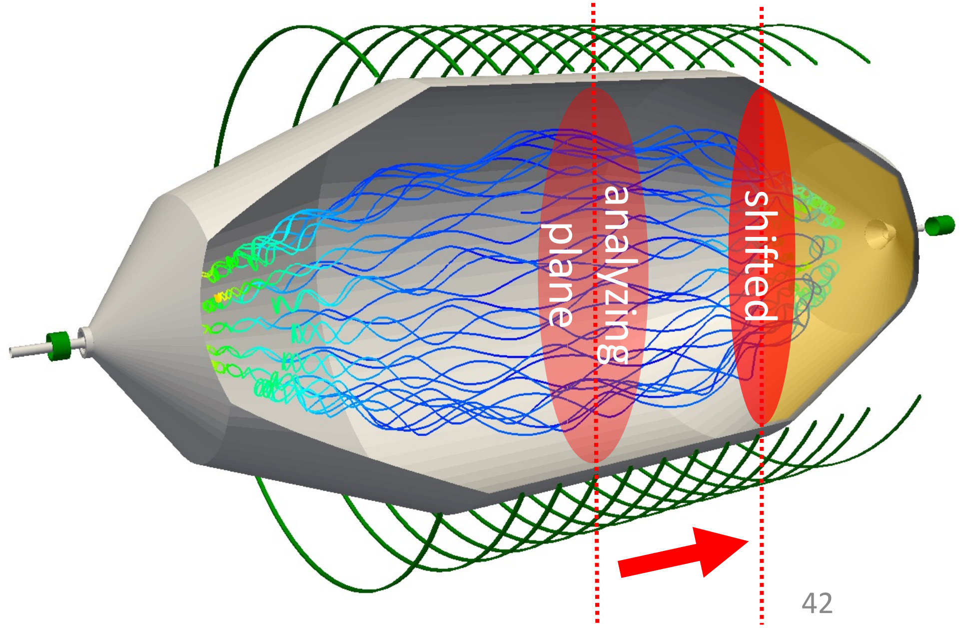


✓ LN cooled baffle + shifted analyzing plane

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

✓ Background reduction by factor of 2.3 to about 130 mcps (original design: 10 mcps)

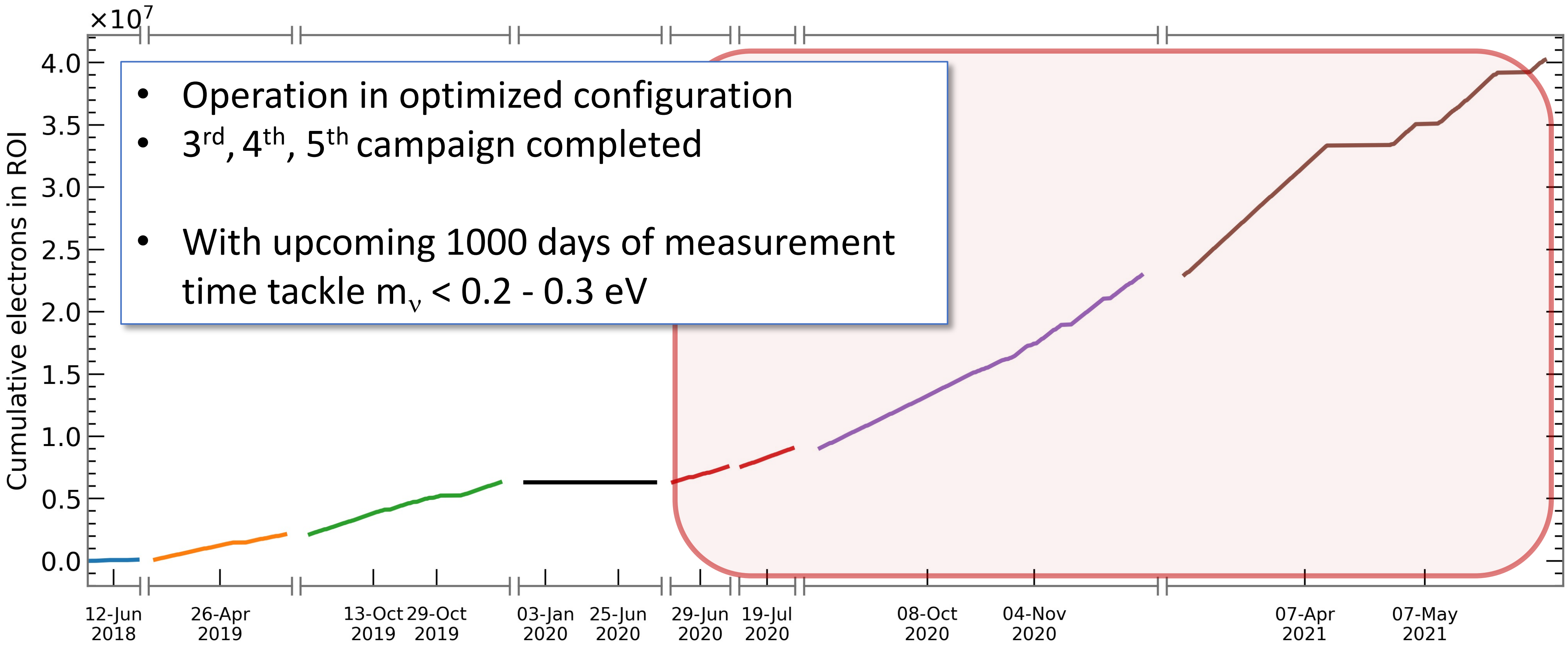
✓ Further R&D ongoing



Outlook

- Operation in optimized configuration
- 3rd, 4th, 5th campaign completed

- With upcoming 1000 days of measurement time tackle $m_\nu < 0.2 - 0.3$ eV

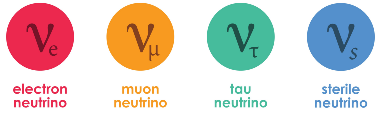


Overview

- How does KATRIN work ?
- What are the latest results?
- What‘s next?
- What else can we do with the data?

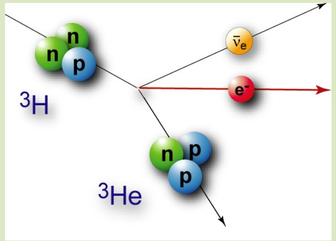
New Physics with KATRIN

neutrino mass
(endpoint shape)



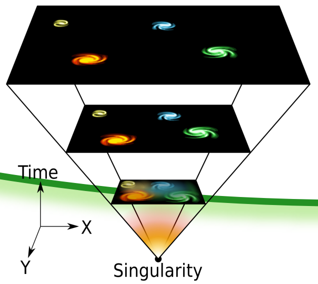
Search for eV-keV sterile neutrinos *(kink search)*

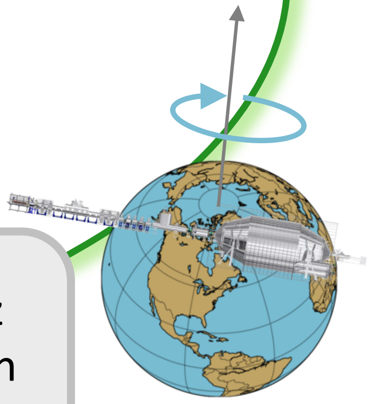
Search for exotic weak interactions
(spectrum shape)



β-spectrum of high statistics and precision

Constrain local overdensity of cosmic relic neutrinos
(peak search)

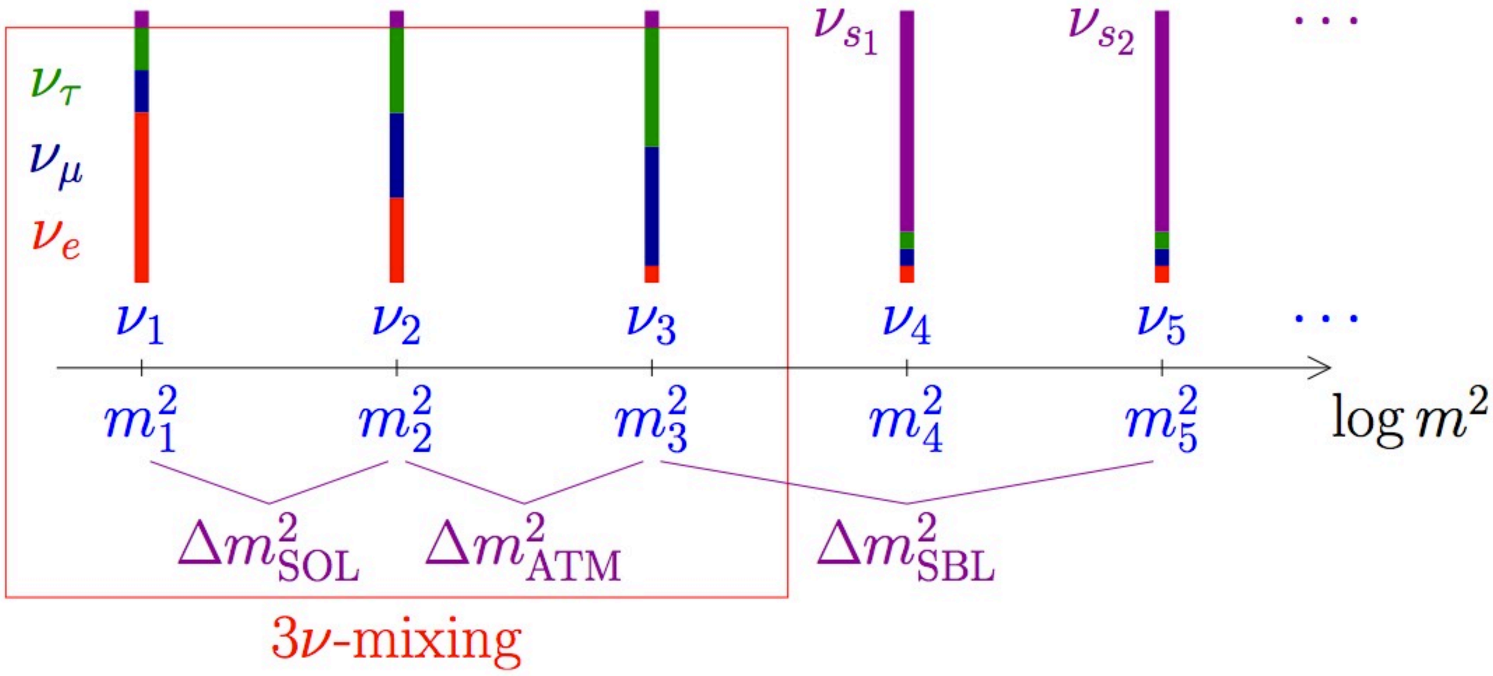




Search for Lorentz invariance violation
(sidereal modulation)

Sterile neutrinos

- Additional neutrino mass eigenstates or arbitrary scale
- Interaction via their mixing with active states



Sterile neutrinos

Heavy sterile neutrinos (> GeV)

- Lightness of neutrinos
  + Matter/Anti-matter asymmetry

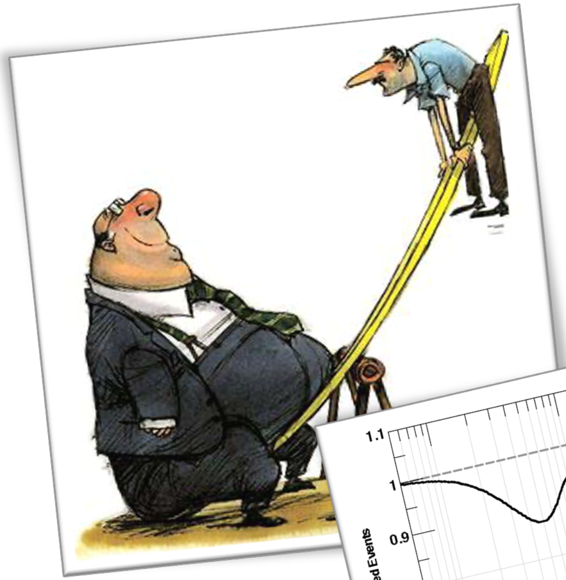
Light sterile neutrinos (~1 eV)

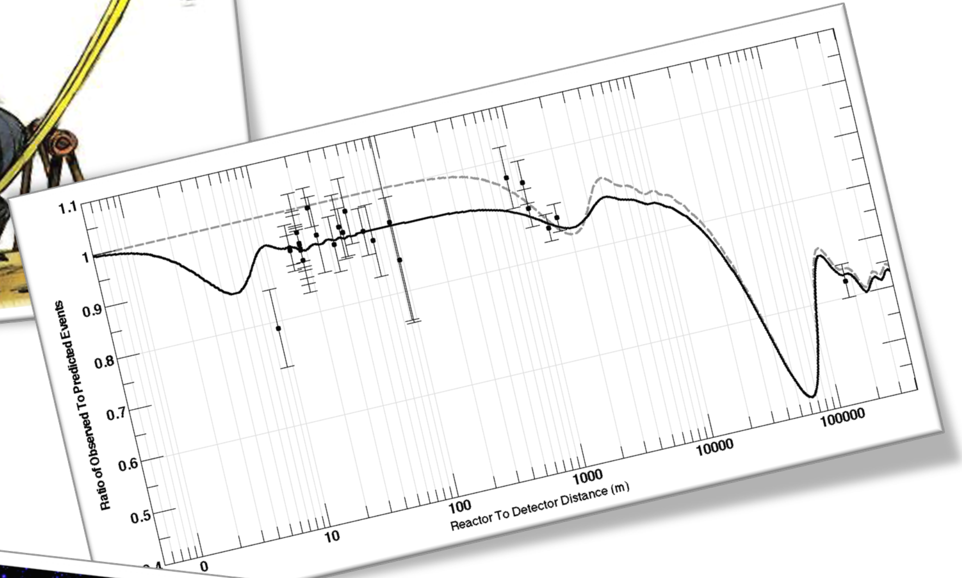
- Short-baseline neutrino oscillation anomalies

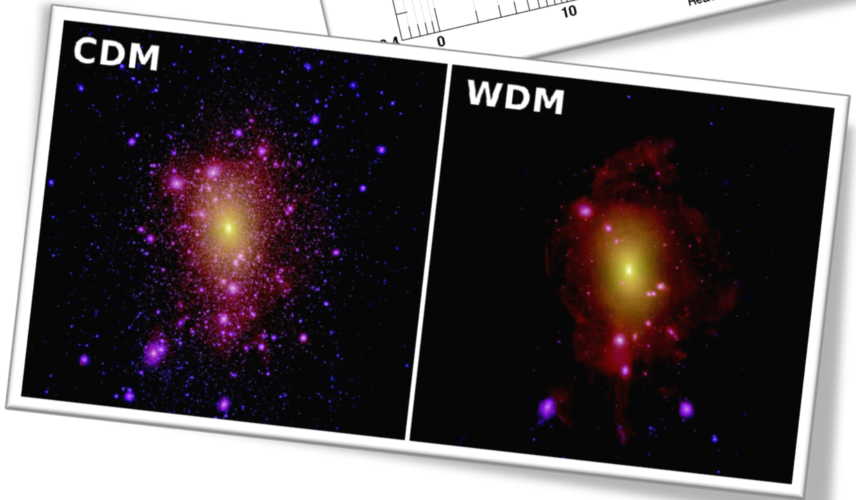
KeV-scale sterile neutrinos (~ 1 - 50 keV)

- Dark matter candidate

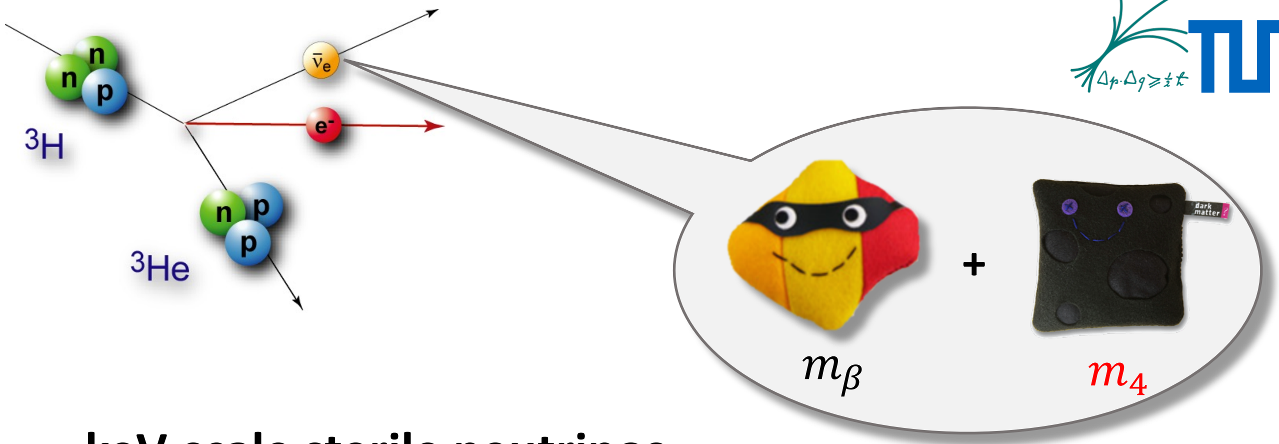
➢ Accessible in beta-decays



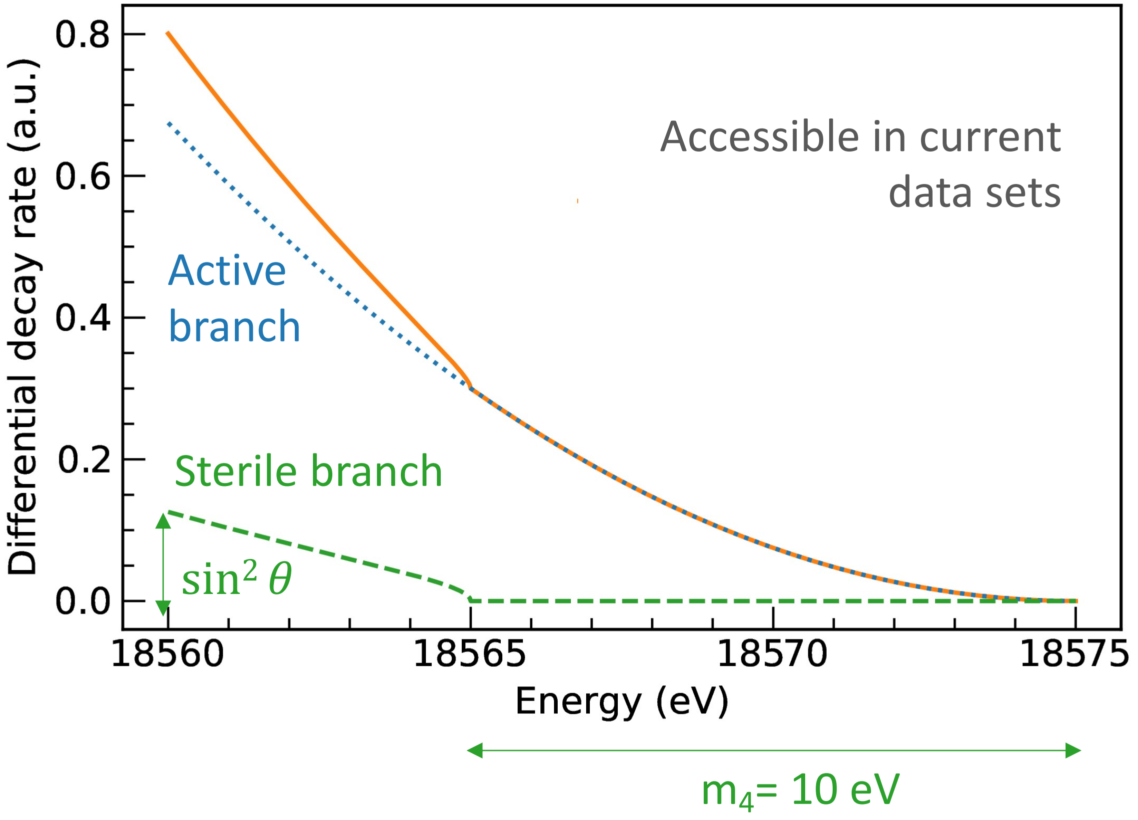




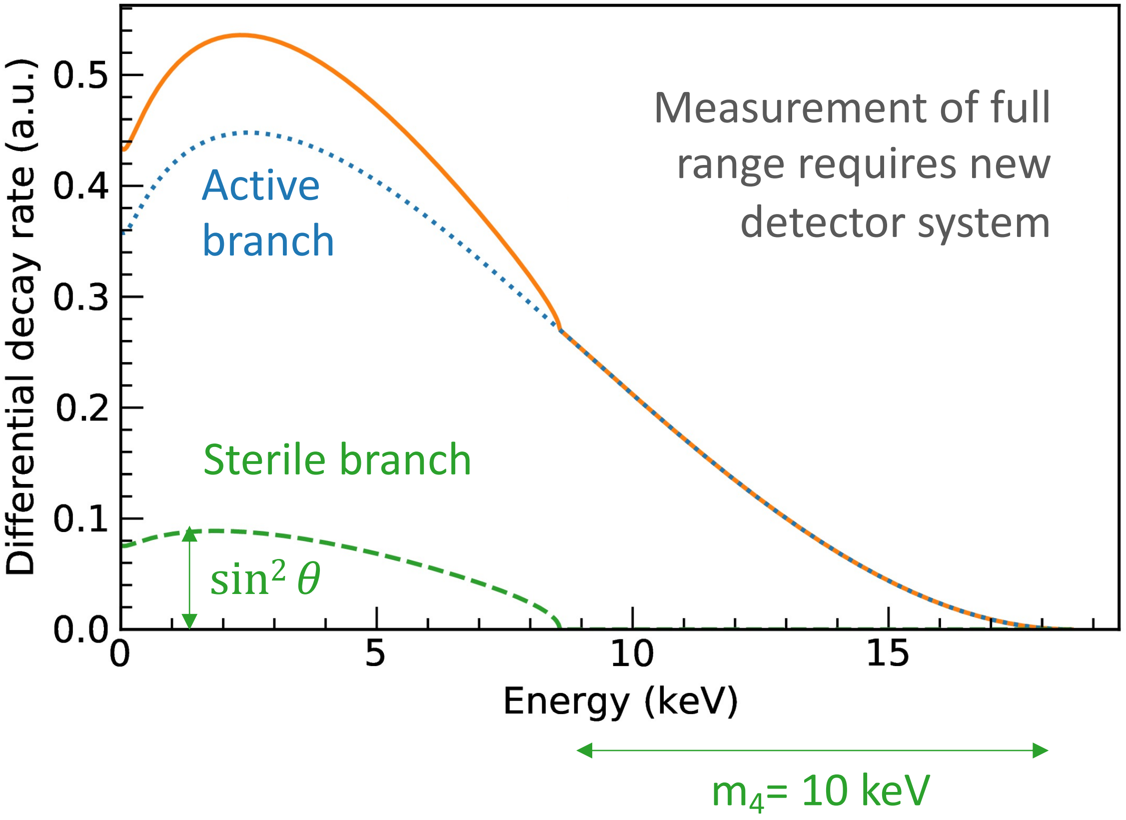
Sterile neutrinos



Light sterile neutrinos



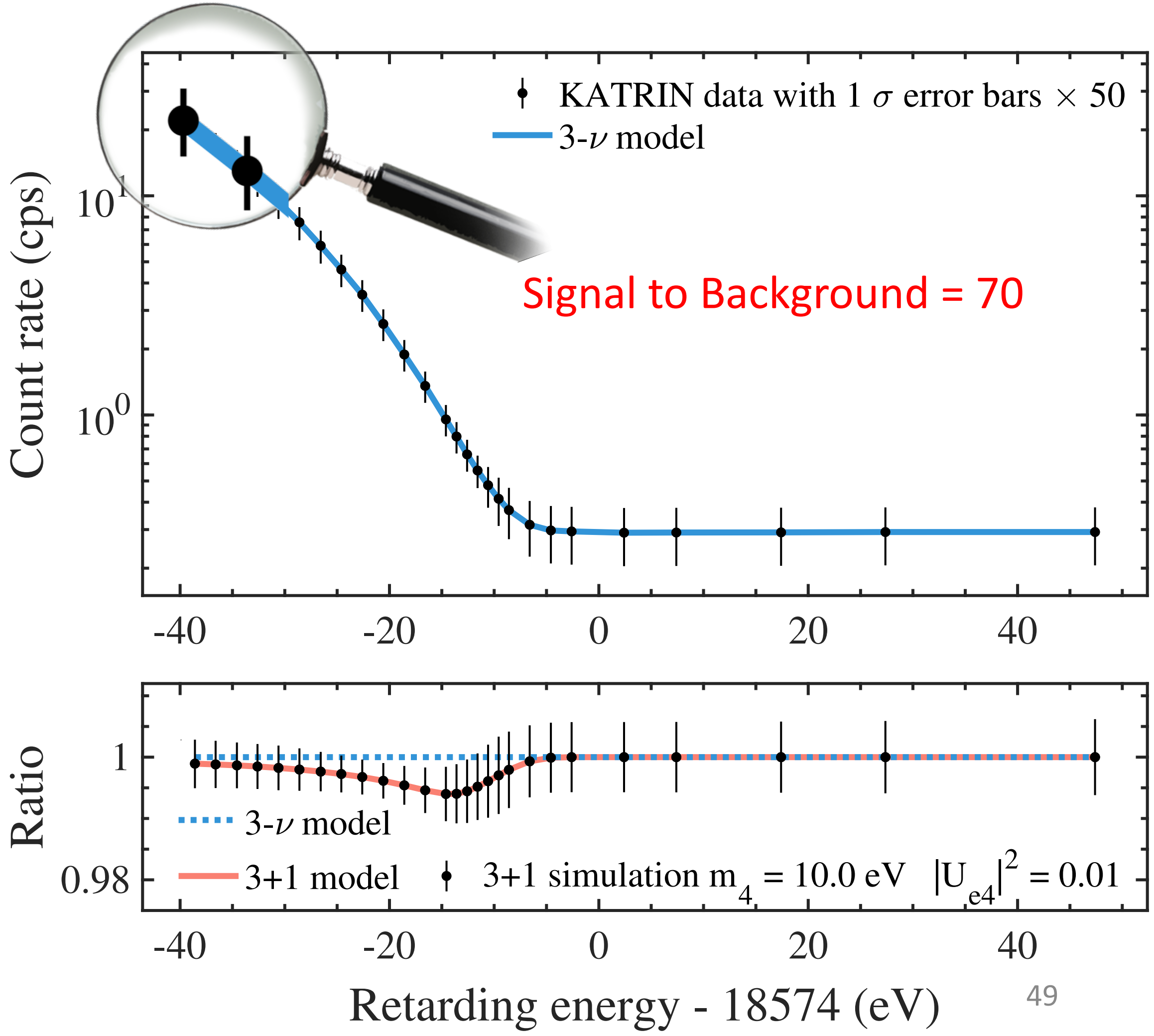
keV-scale sterile neutrinos



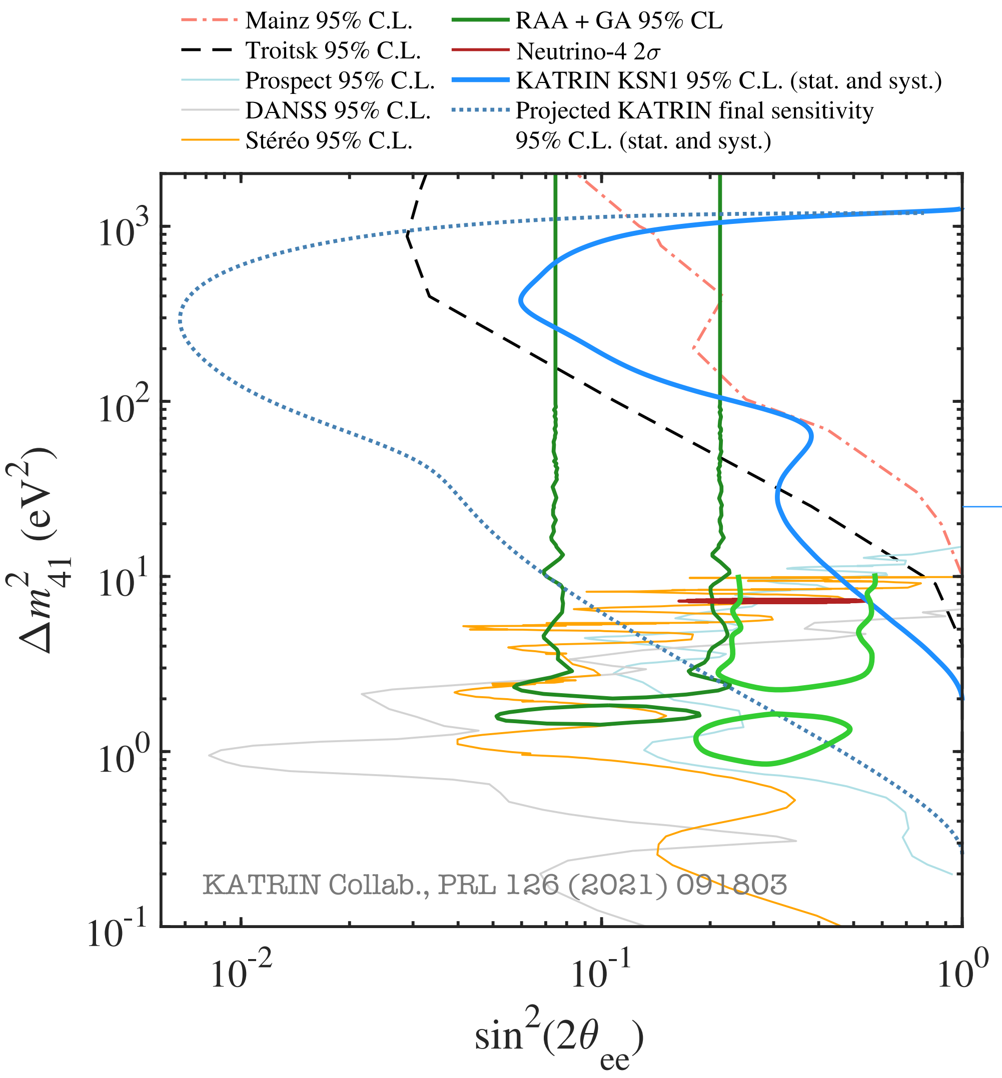
eV-scale sterile neutrino search

- Search performed on data set of **first** and **second** neutrino mass campaign
- 3+1 sterile neutrino model
- Grid search in m_4, $|U_{e4}|^2$ plane

$$\frac{d\Gamma}{dE} = \underbrace{\left(1-|U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2\frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$



eV-scale sterile neutrino search (1st campaign)



High Δm_{41} region:

- ✓ Improve exclusion with respect to DANSS, PROSPECT, STEREO
- ✓ Exclude parameter space of Reactor Anomaly (RAA)

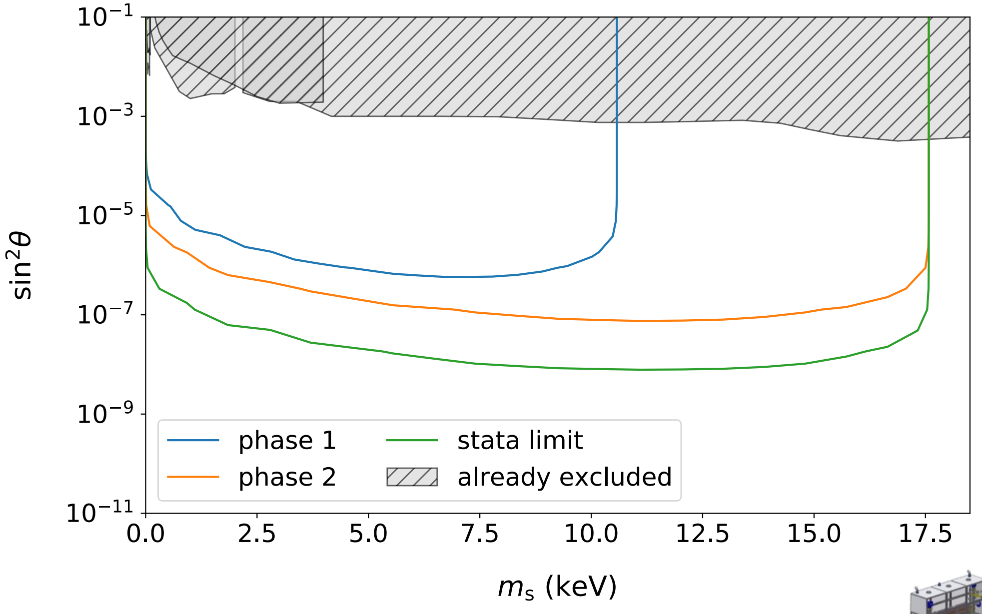
Low Δm_{41} region:

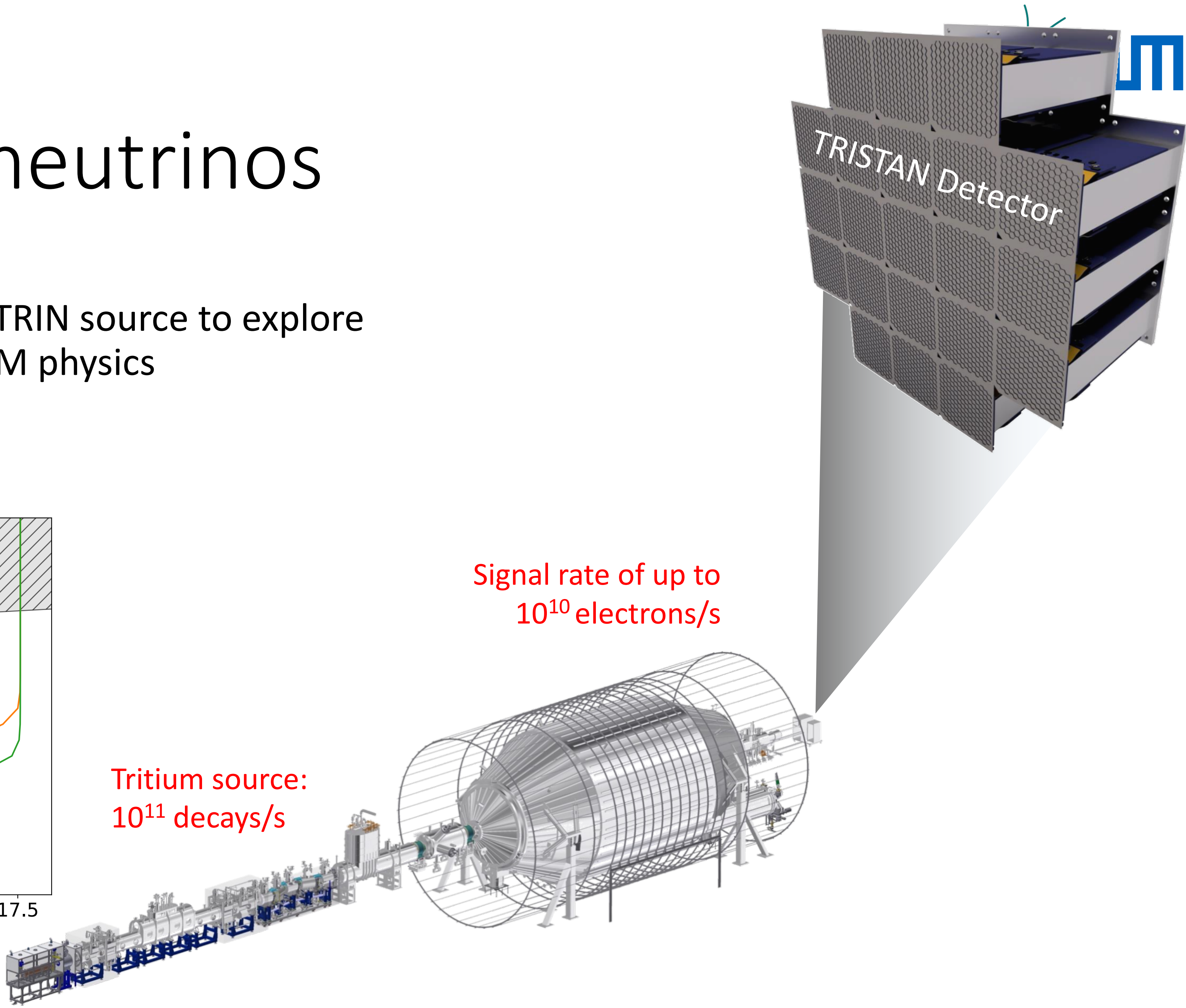
- ✓ Improve MAINZ and TROITSK limit
- ✓ The NEUTRINO-4 hint at the edge of exclusion limit
- ✓ Test part of BEST result with future data

keV-scale sterile neutrinos

- Idea: make use of the luminous KATRIN source to explore full beta spectrum to search for BSM physics

➢ Develop a novel detector system

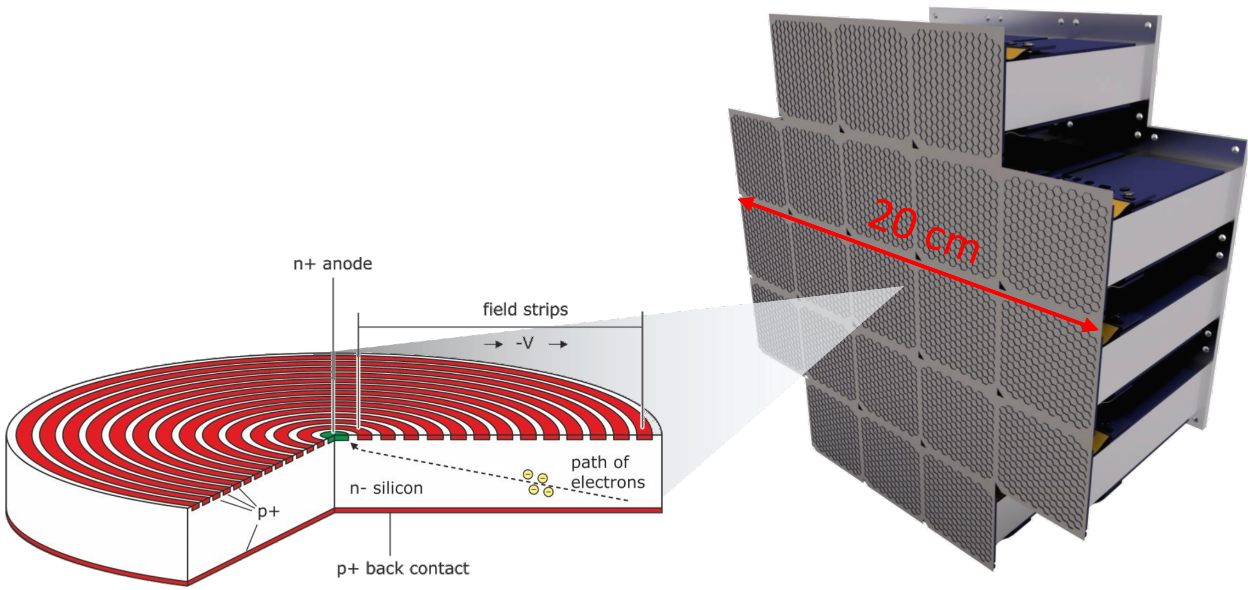


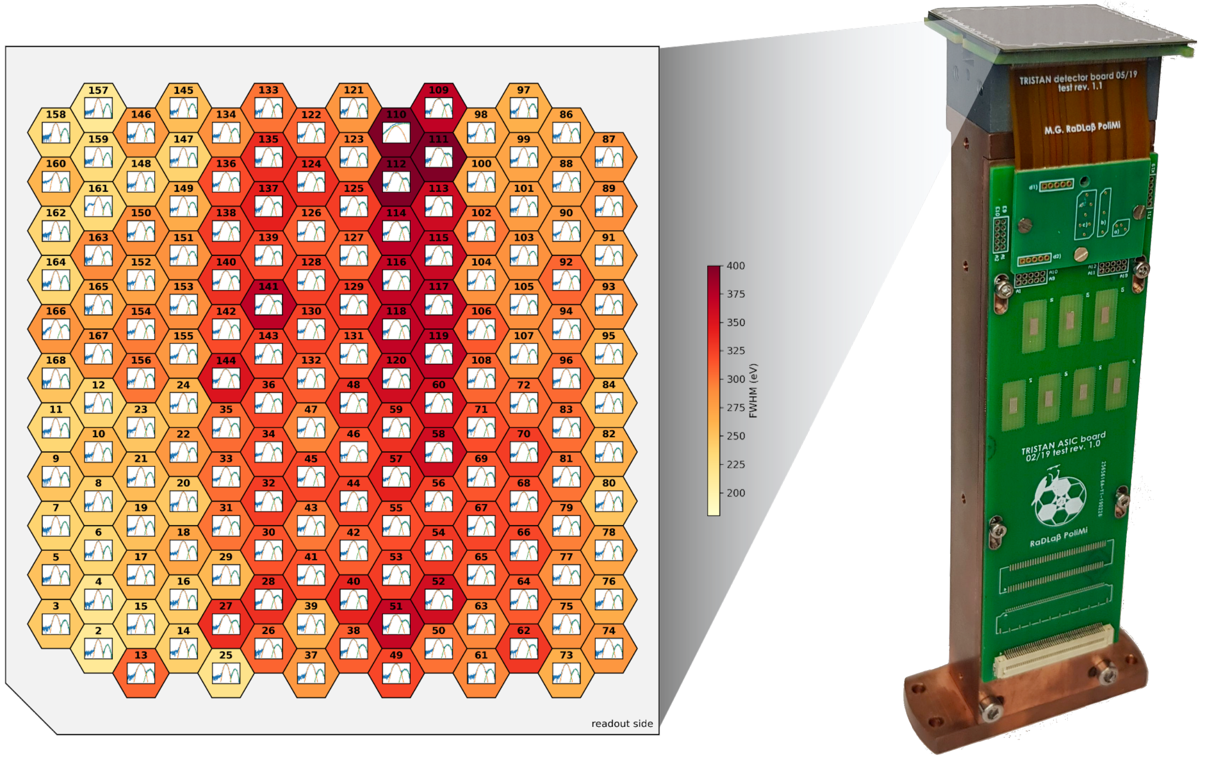


Mertens et al, Phys.Rev. D91 (2015) 4, 042005
Mertens et al, JCAP 1502 (2015) 02, 020

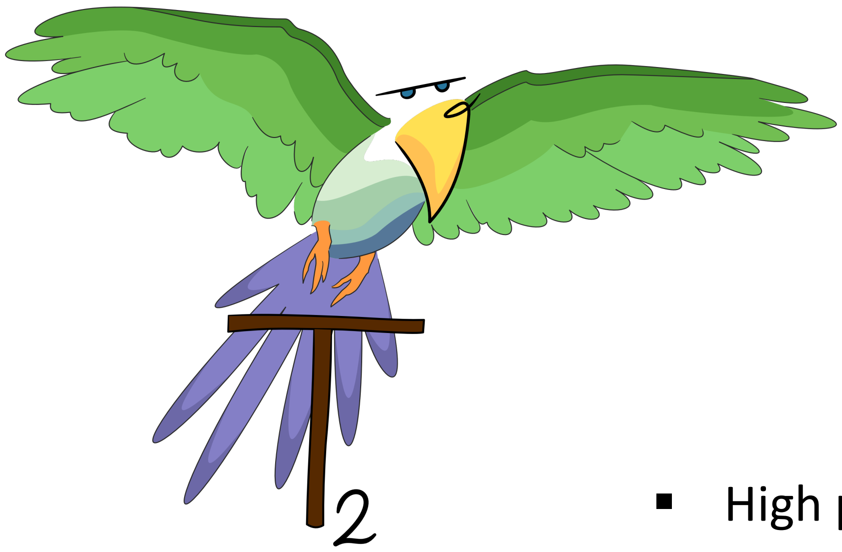
TRISTAN detector

- Silicon drift detector (SDD) technology
  - ✓ Capability of handling high rates (> 10^8 cps)
  - ✓ Excellent energy resolution (300 eV @ 20 keV)
- Challenge
  - Control of systematics at the ppm-level
  - Operation of 3500 pixel focal plane array
- Status
  - ✓ Excellent performance of prototypes
    S. Mertens et al, J. Phys. G46 (2019)
    S. Mertens et al, J. Phys. G48 (2020)
    M. Gugiatti et al, NIM-A 979 (2020)
    M. Biassoni et al, Eur. Phys. J. Plus 136, 125 (2021)
    P. King et al JINST 16 T07007 (2021)
  - ✓ Operation of 166-pixel module (largest SDD module ever operated) – thanks to Polimi and Bicocca



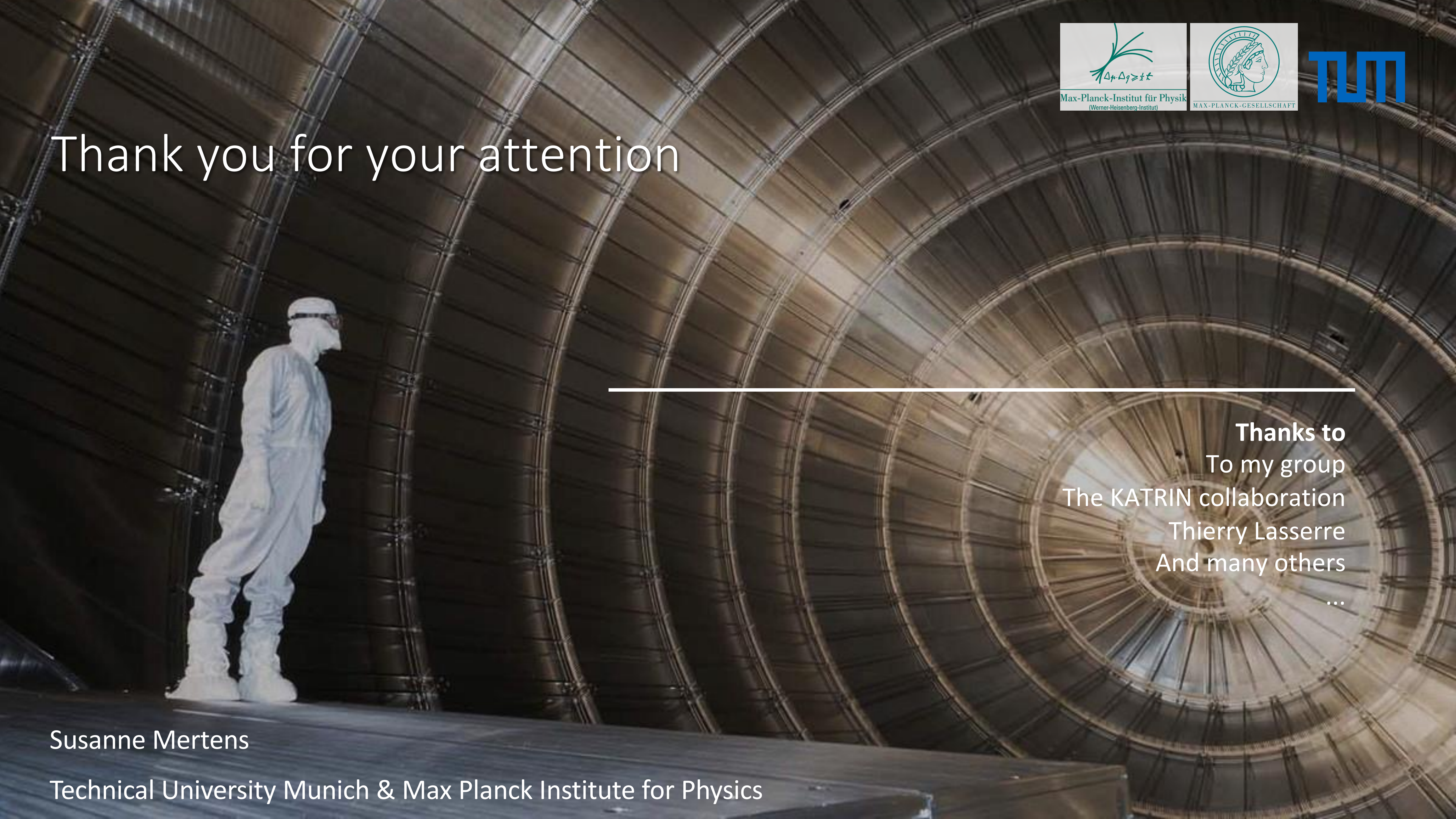


Conclusion



- First sub-eV neutrino mass limit from a direct experiment
- Various improvements of systematics and background in place
- Sensitivity close to 0.2 eV (90% CL) targeted within next years

- High precision KATRIN data available for interesting new physics searches
- Upgrade of KATRIN beamline with SDD array will allow to extend the measurement interval



Thank you for your attention

Thanks to
To my group
The KATRIN collaboration
Thierry Lasserre
And many others
…

Susanne Mertens

Technical University Munich & Max Planck Institute for Physics