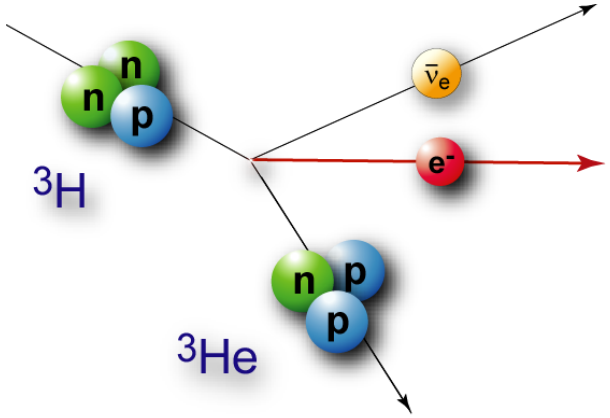
KATRIN:
Recent Results and Future Perspectives

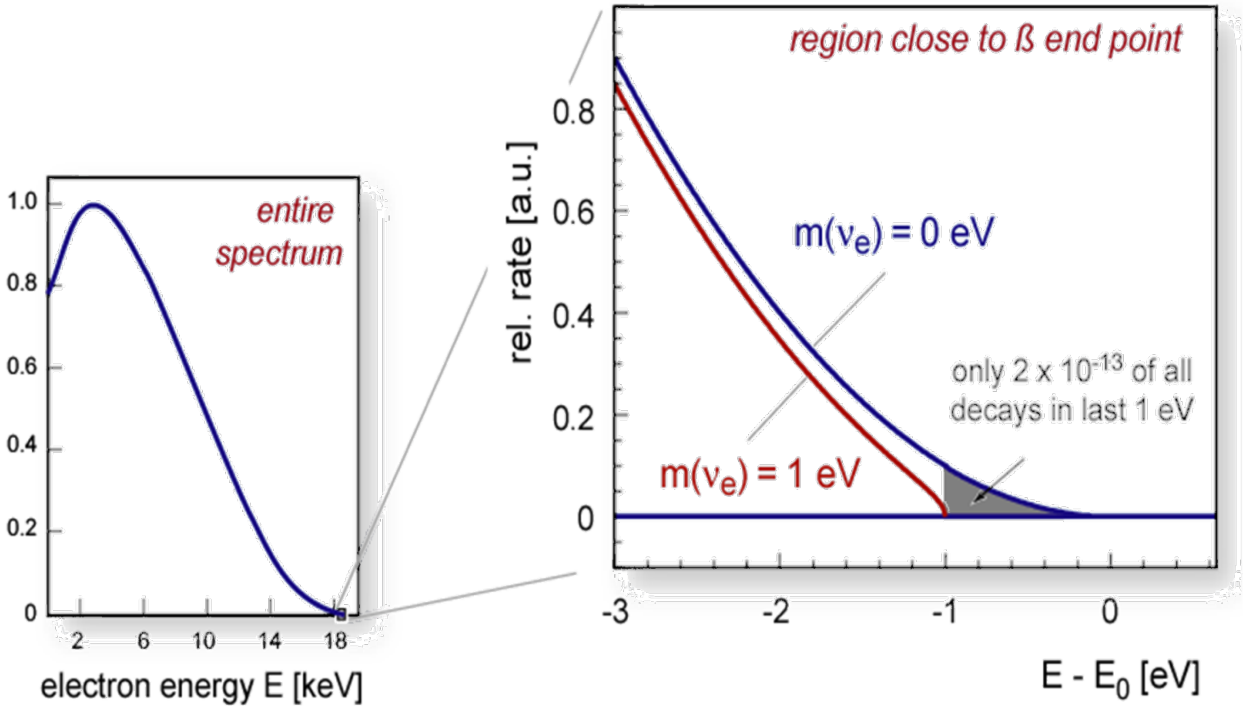
Susanne Mertens for the KATRIN collaboration
Max Planck Institute for Physics & Technical University Munich
June 2020, Neutrino-2020

General idea



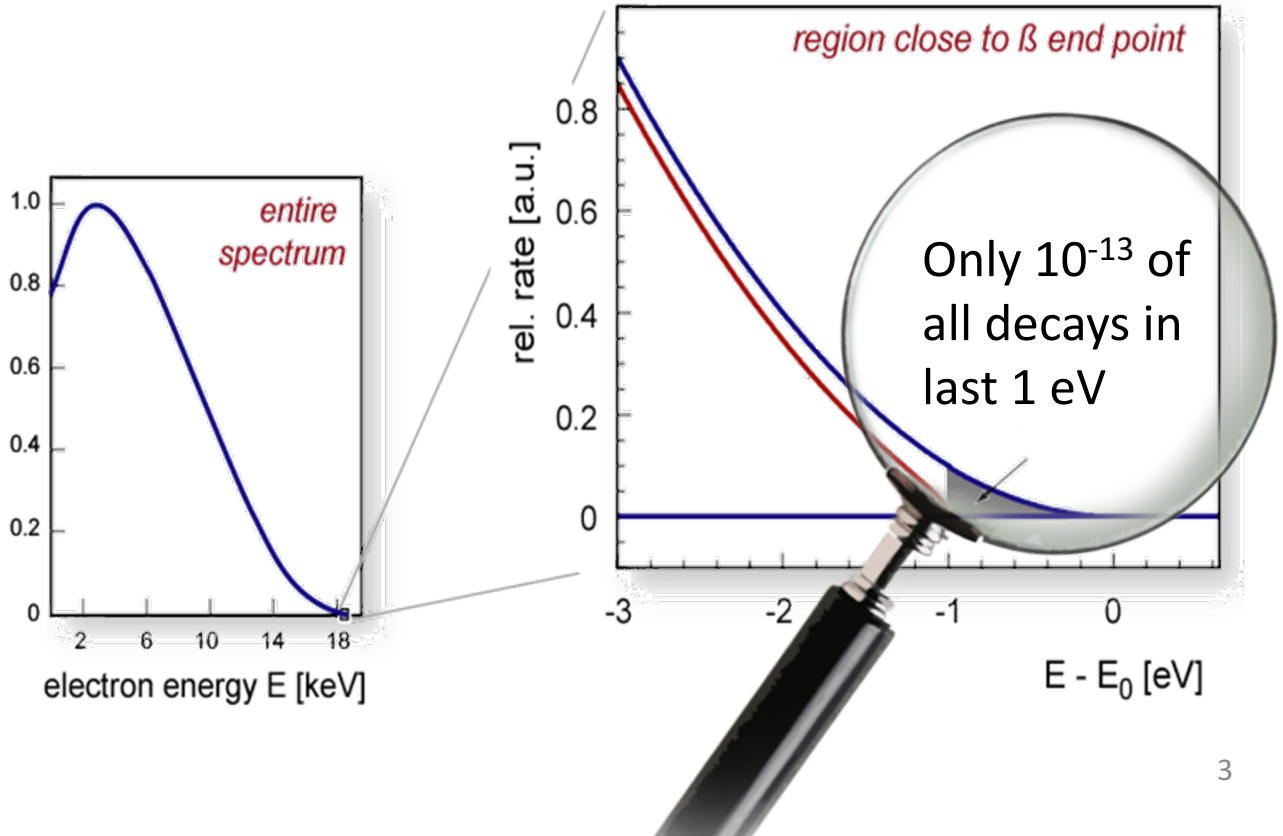
	^{3}H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.56 keV

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



The challenge

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




Karlsruhe
Tritium
Neutrino
Experiment

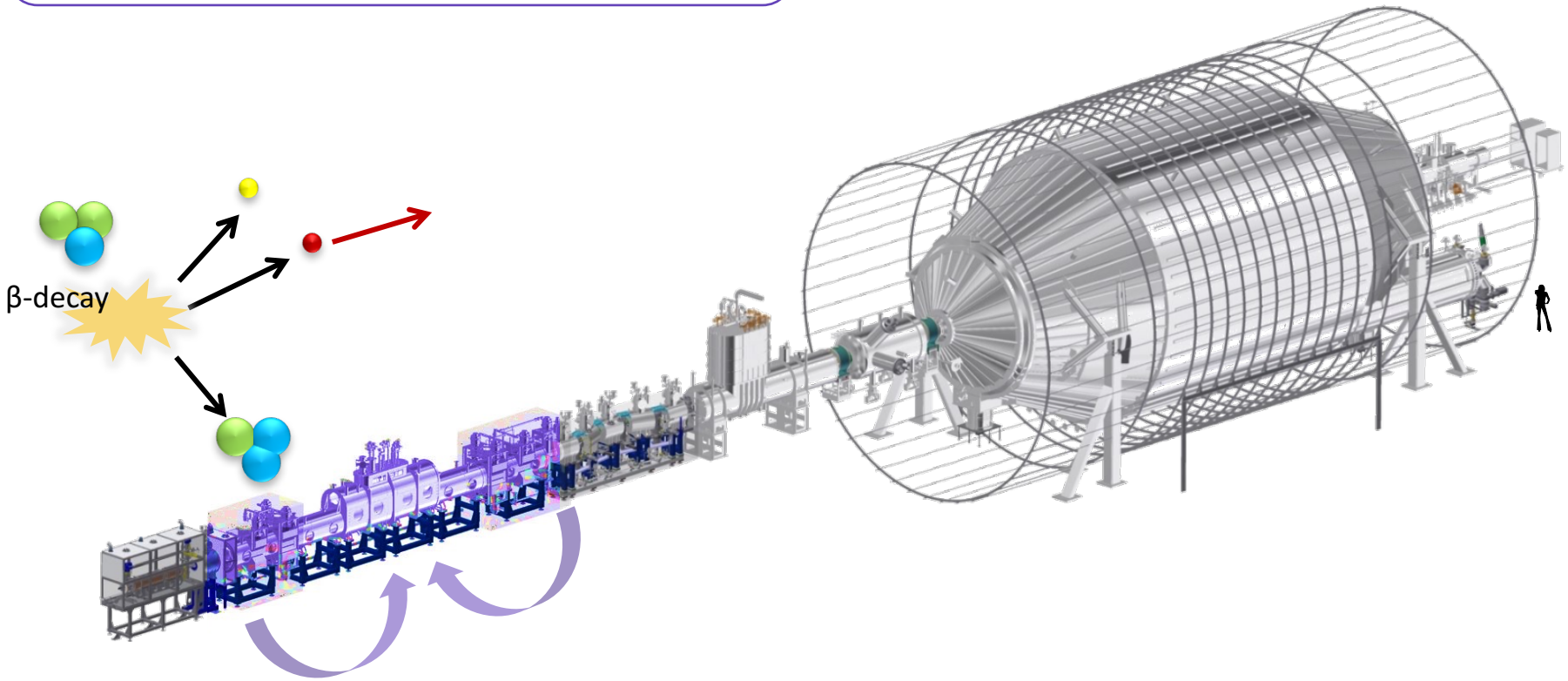
KATRIN

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

KATRIN Working Principle

Windowless gaseous tritium source

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

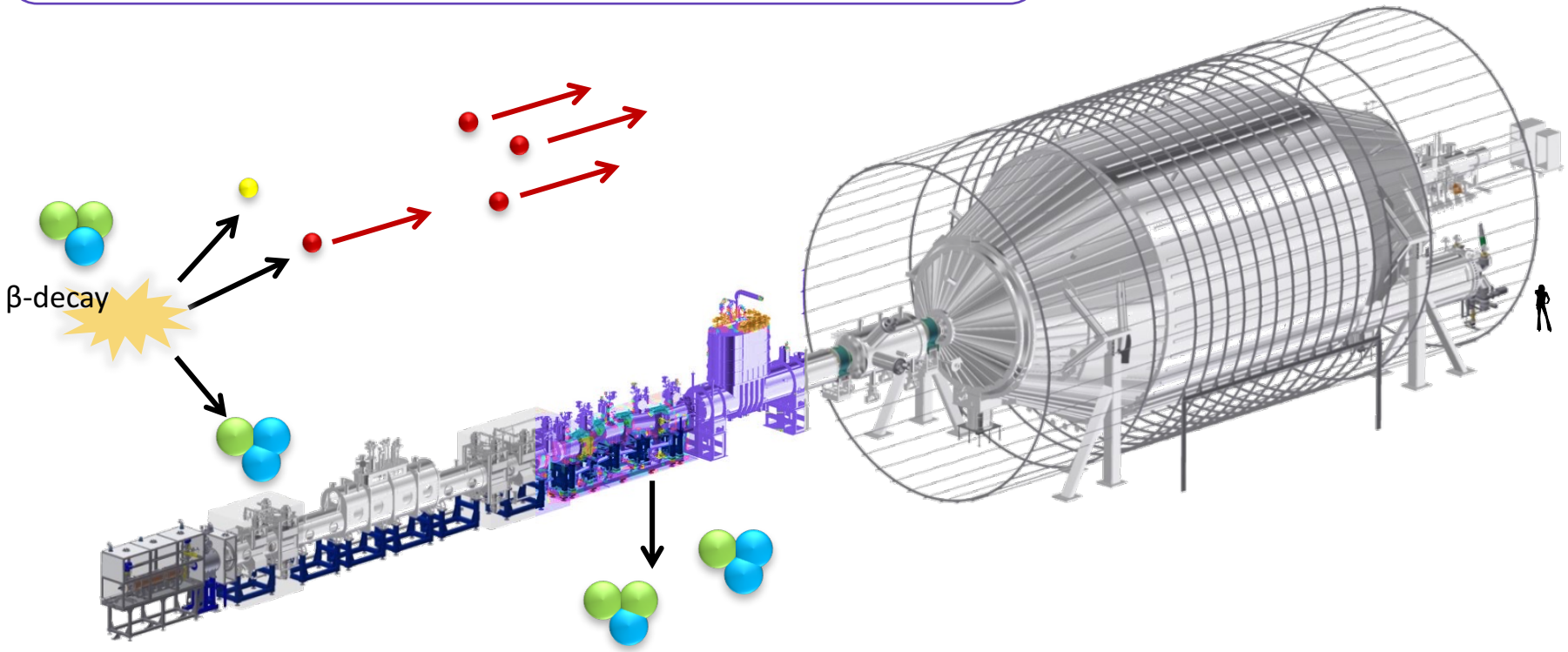


KATRIN Working Principle

Poster #115: C. Röttele et al
Poster #201: A. P. Vizcaya et al

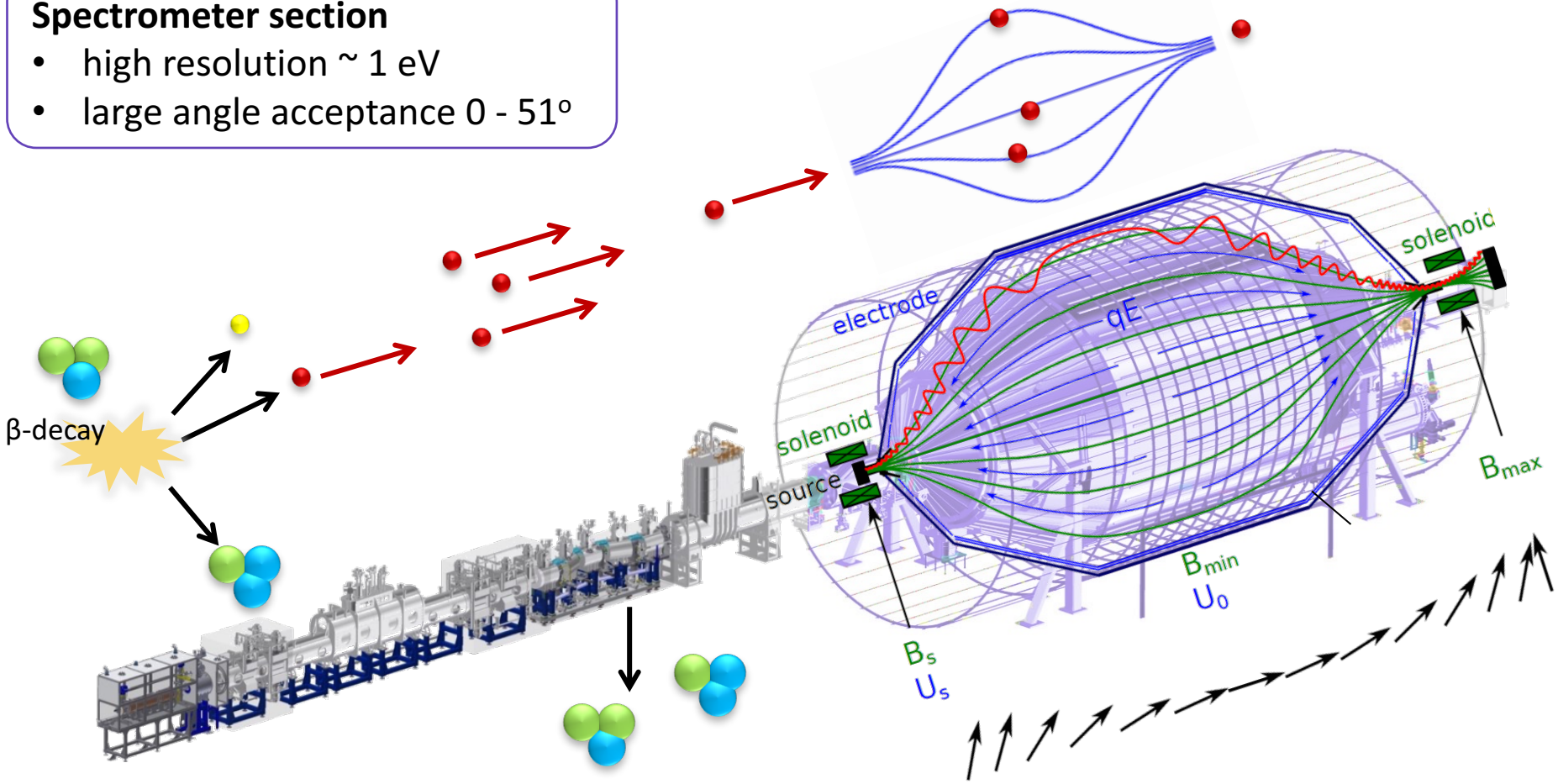
Transport section

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



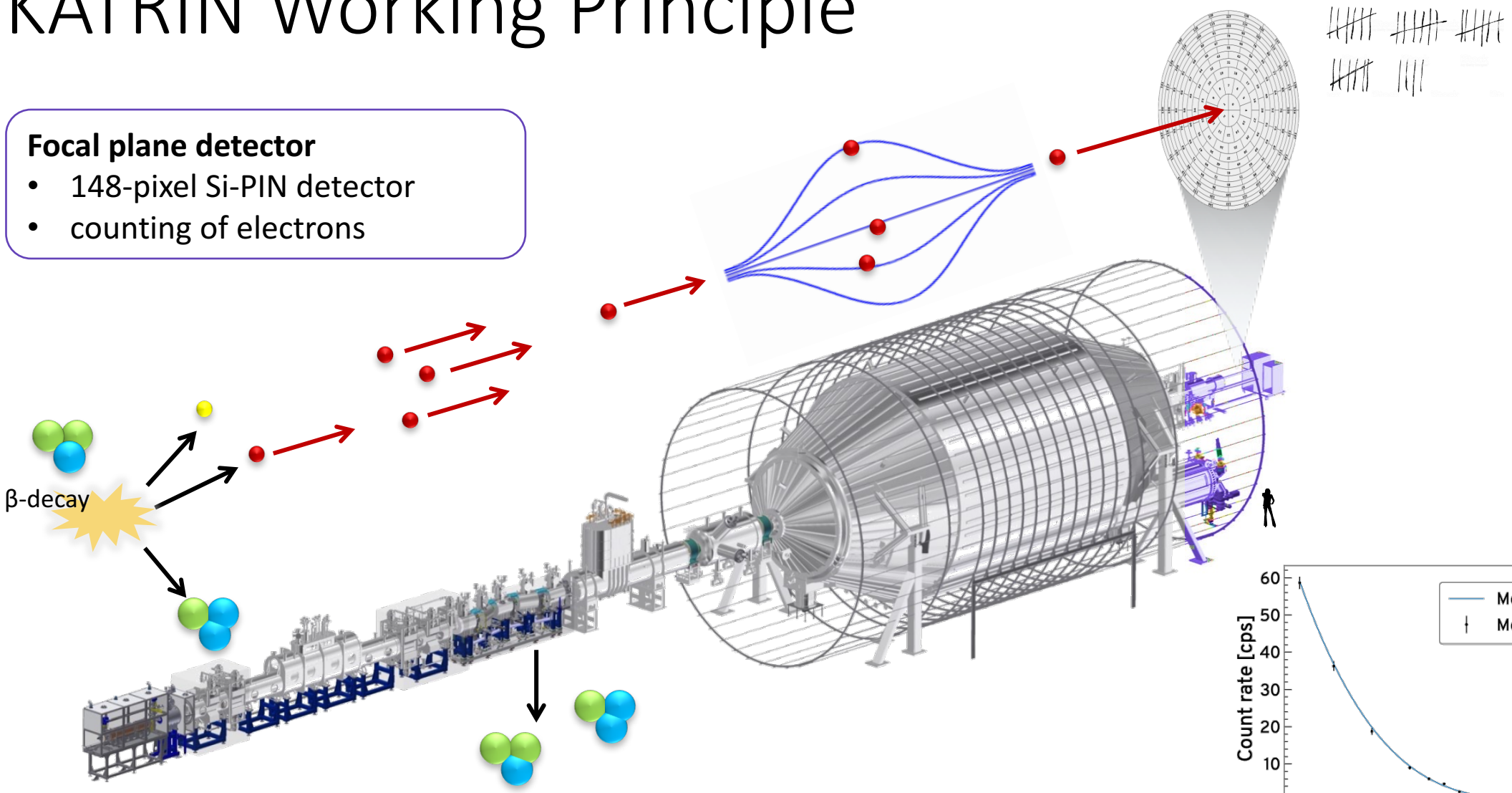
KATRIN Working Principle

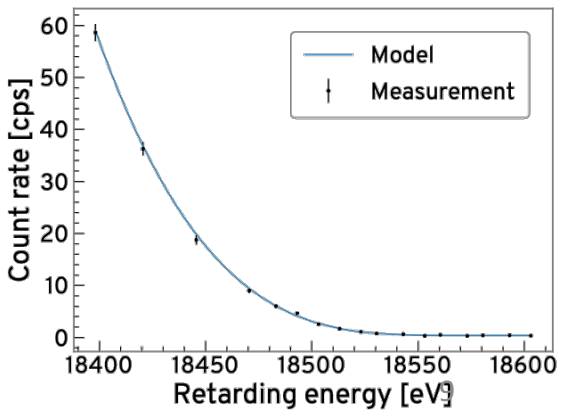
Spectrometer section
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°



KATRIN Working Principle

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

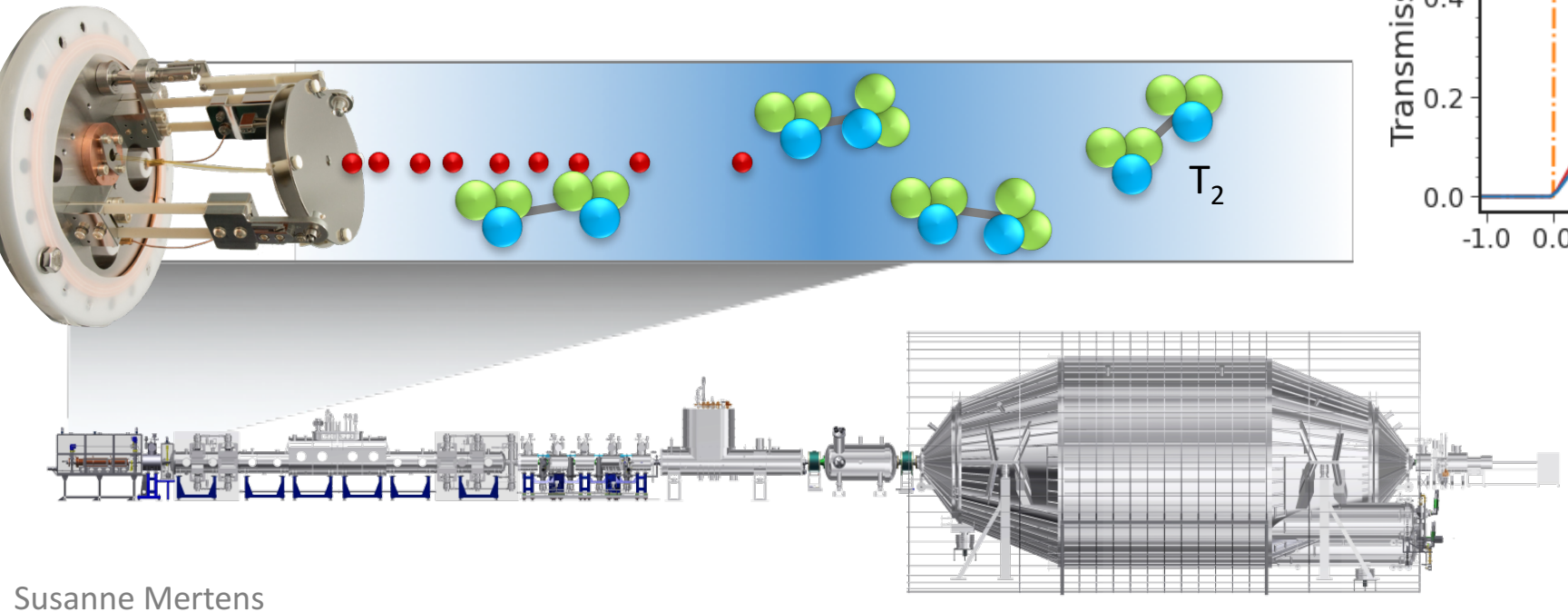


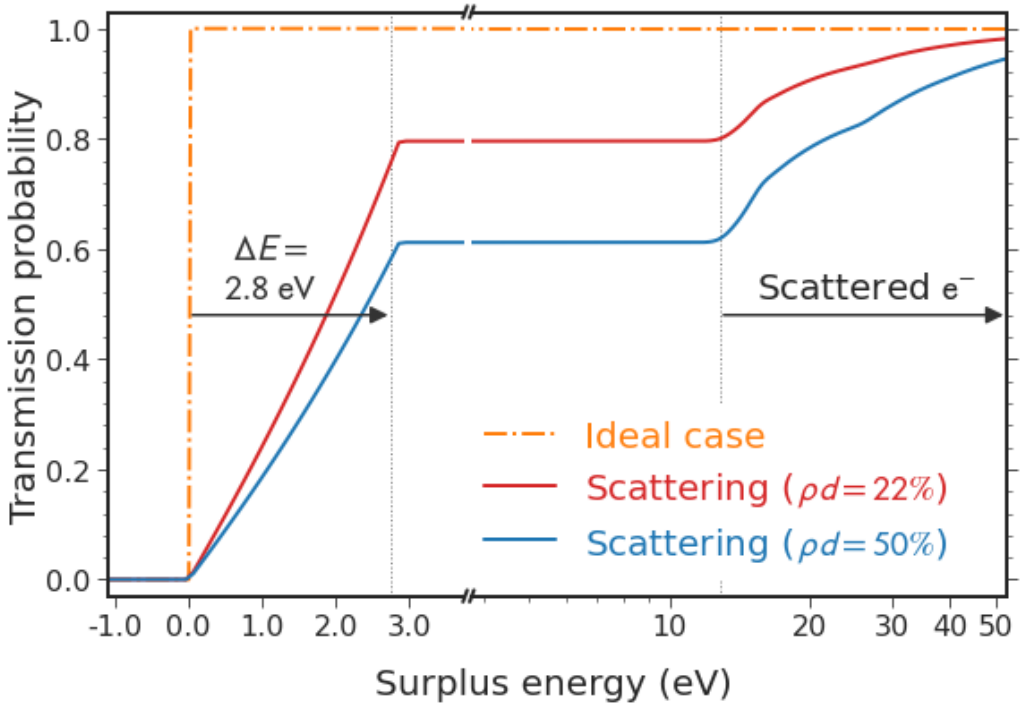


High-intensity electron gun

Poster #117
L. Schimpf et al

- Precise (< 0.25%) determination of column density
- TOF mode: Measurement of Energy-Loss PDF



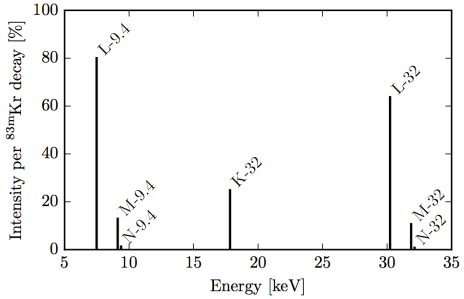


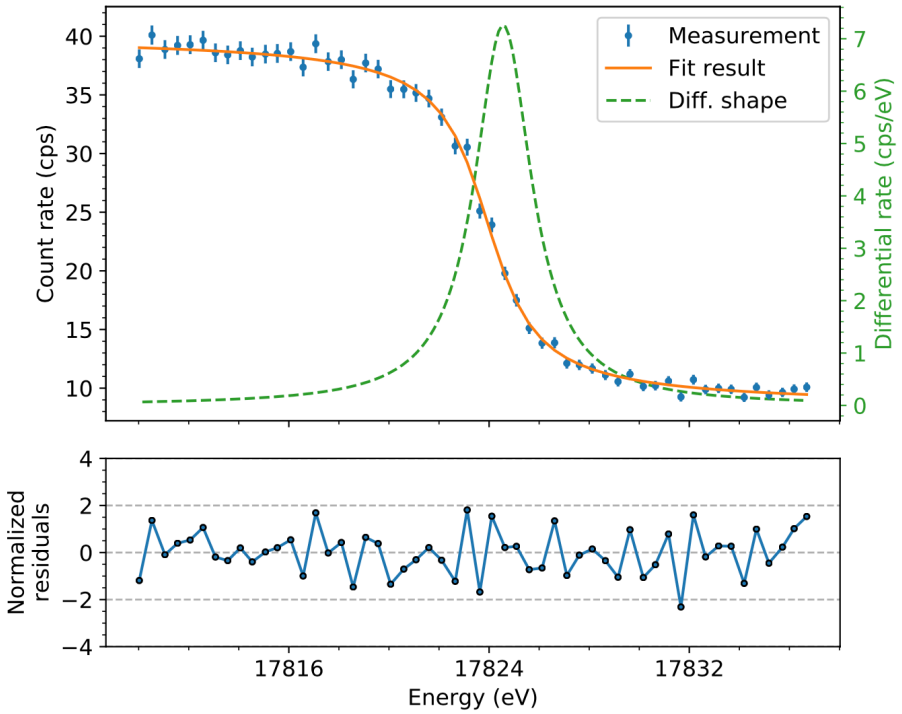
J. Behrens et al., Eur. Phys. J. C 77, 410 (2017)
V. Hannen et al., Astroparticle Physics 89 (2017) 30
J. Bonn et al., NIM A 421 (1999) 256

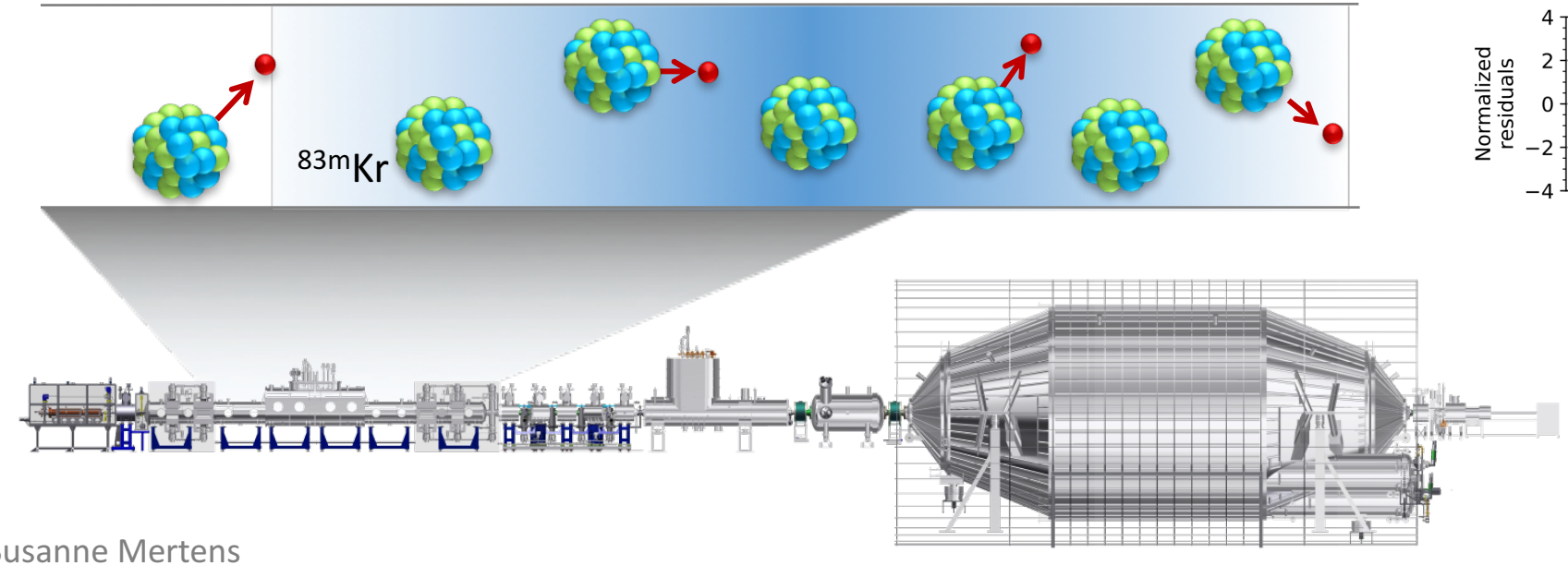
^{83m}Kr conversion electrons

Poster #20
J. Behrens et al

- Variation of electric and magnetic fields in the analyzing plane
- Variations of source electric potential
  (when used together with tritium)



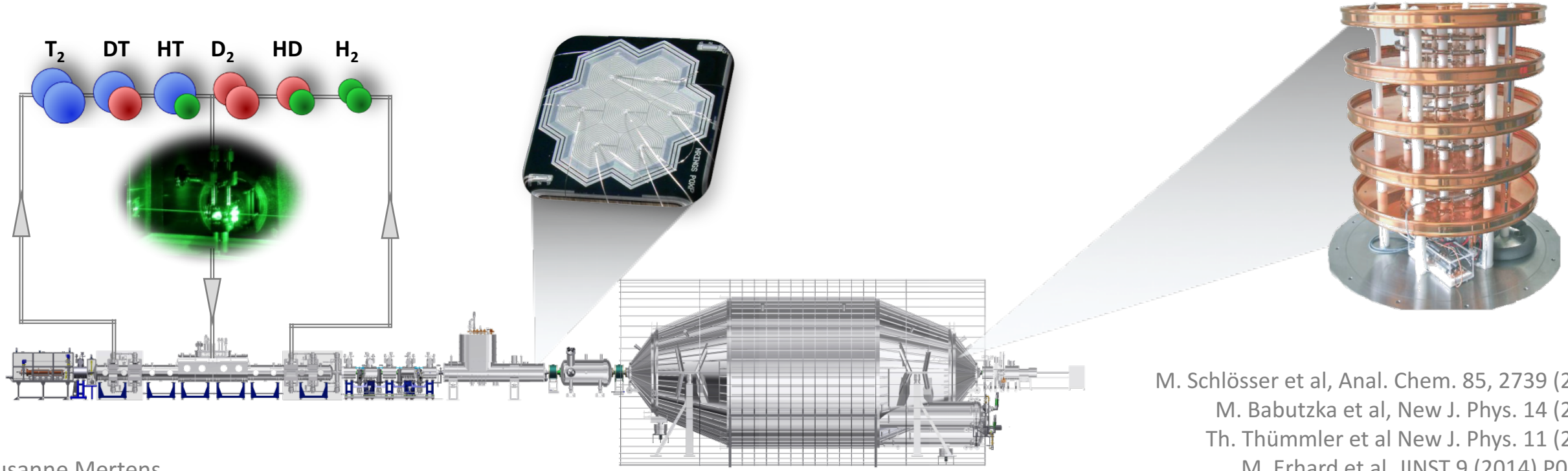




KATRIN Collab, J. Phys. G 47 (2020) 065002
KATRIN Collab, EPJ C 78 (2018) 368
J. Sentkerestiová et al, JINST 13 (2018)

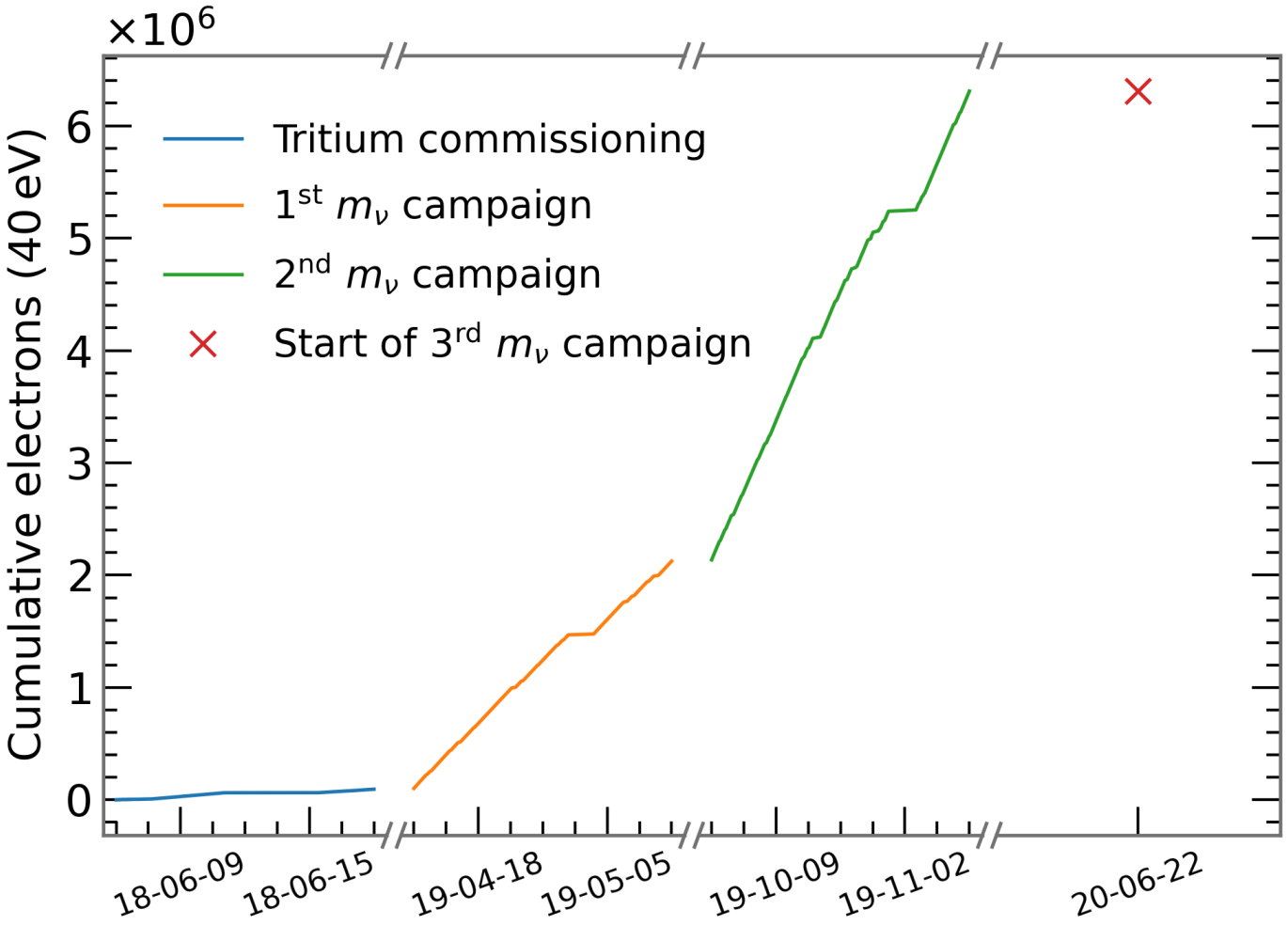
Key Monitoring Devices

- **Laser Raman system:** monitoring of tritium purity and gas composition at the 0.1% level
- **Forward beam monitor:** monitoring of activity at the 0.1% level
- **High voltage system:** monitoring of high voltage at the ppm level (20 mV)



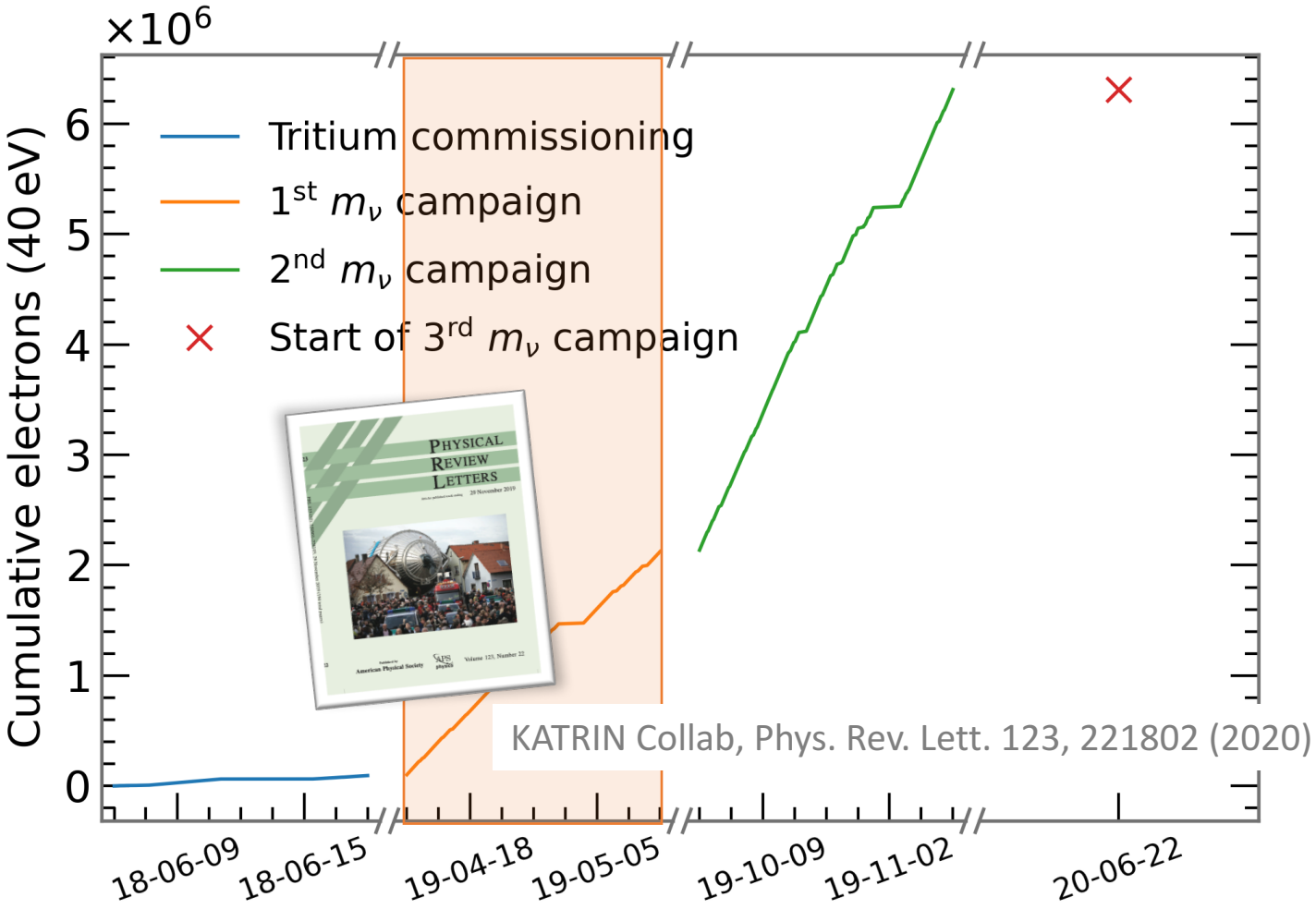
M. Schlösser et al, Anal. Chem. 85, 2739 (2013)
M. Babutzka et al, New J. Phys. 14 (2012)
Th. Thümmler et al New J. Phys. 11 (2009)
M. Erhard et al, JINST 9 (2014) P06022

KATRIN Data Taking Overview



- Demonstration of system stability
  KATRIN Collab, EPJ C 80, 264 (2020)

KATRIN Data Taking Overview



KATRIN Collab, Phys. Rev. Lett. 123, 221802 (2020)

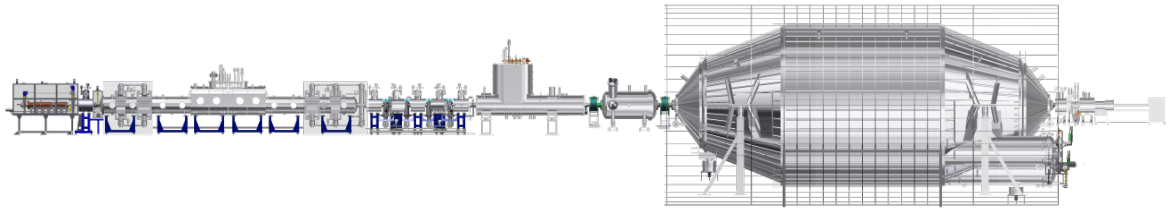
First neutrino mass campaign

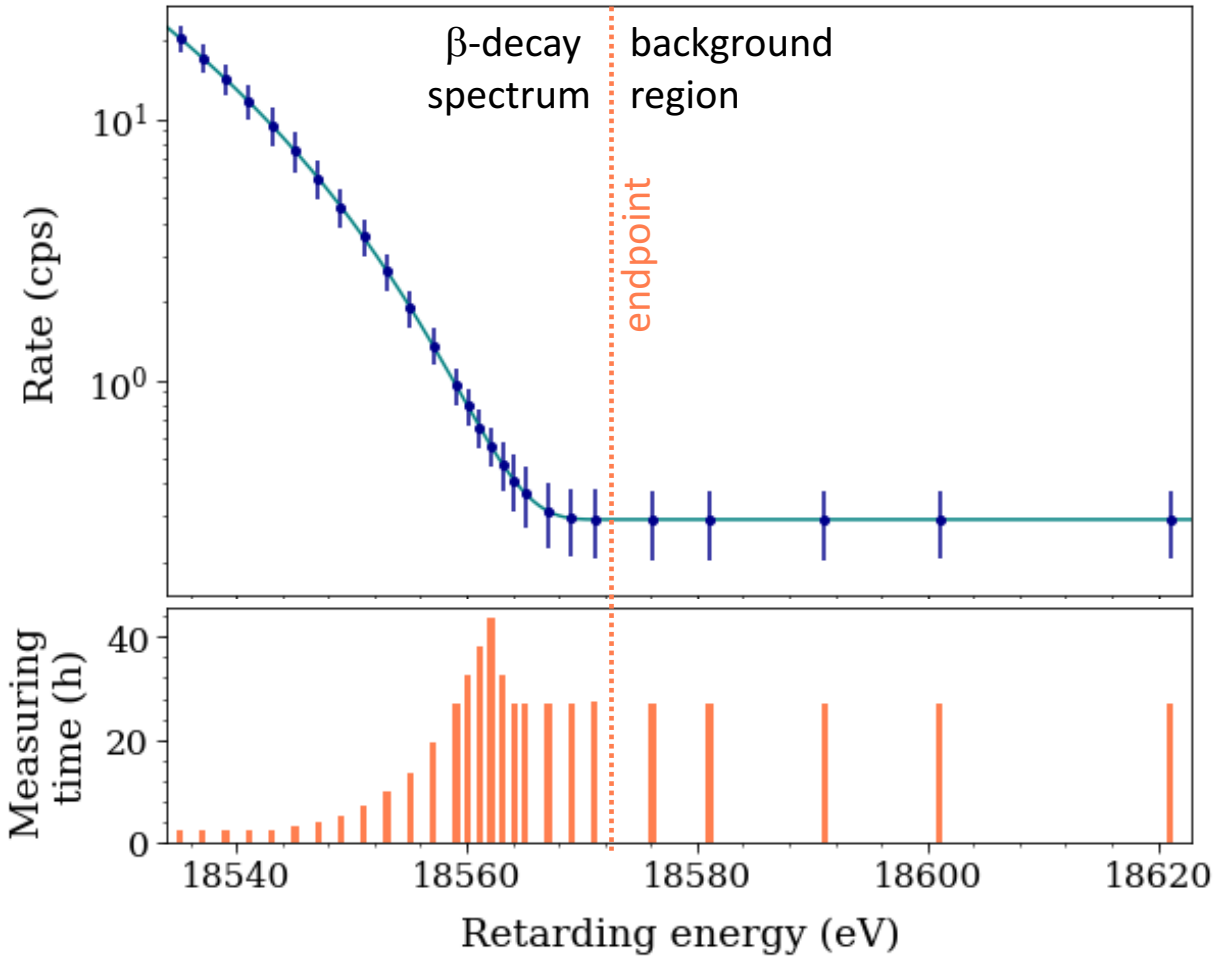
- Measurement time: **22 days**
- Gas density: **22%**
- Isotopic purity: **97.5% tritium**
- Source activity: **$2.45 \cdot 10^{10}$ Bq**
- Total statistics: **$2 \cdot 10^{6}$ e's**

column density of 22% $= 1.1 \cdot 10^{17}$ molecules/cm^2

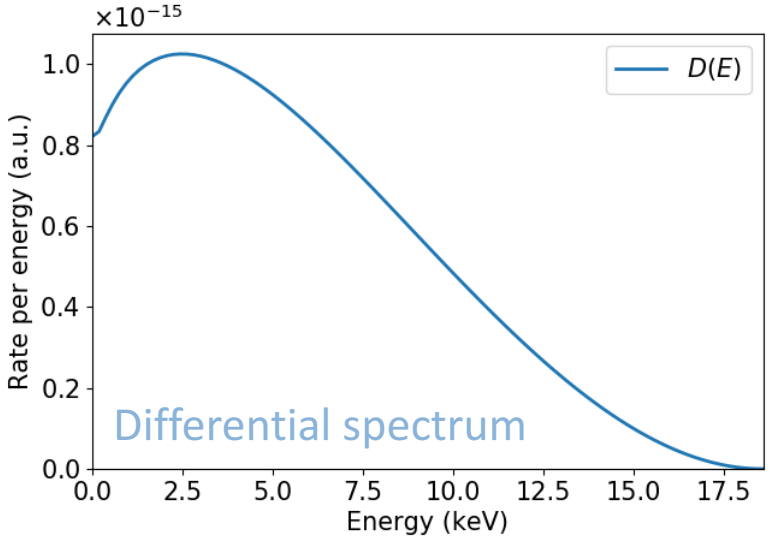
Measurement strategy

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

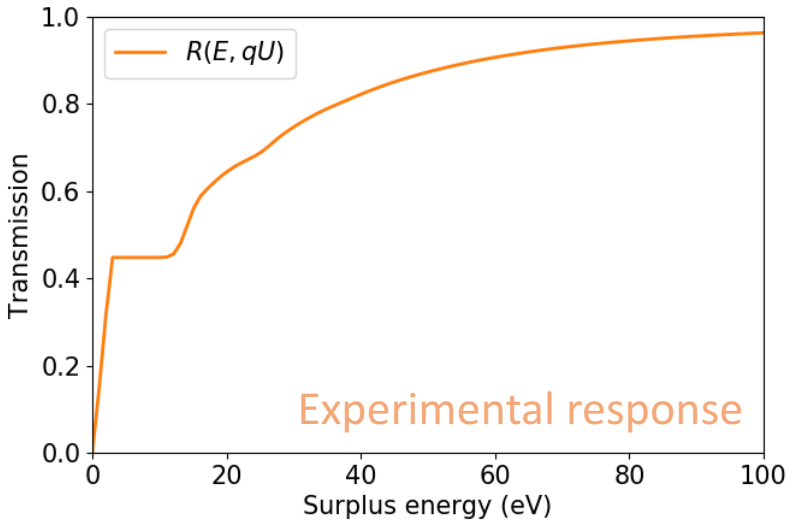




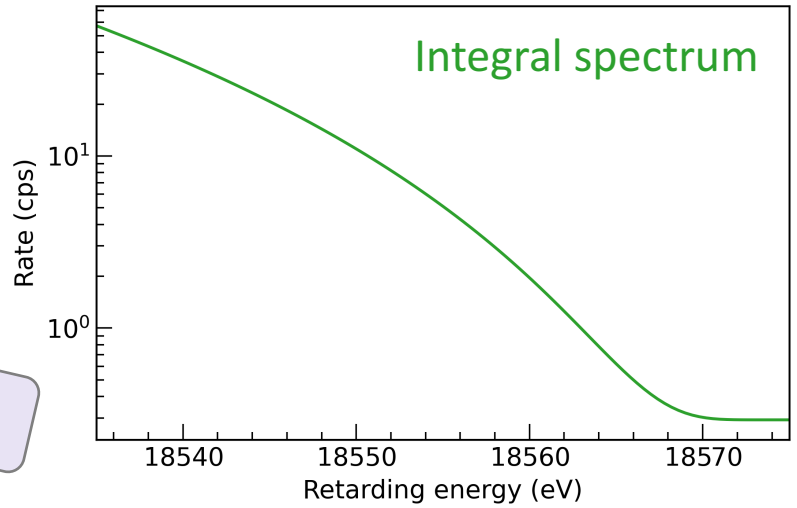
Tritium spectrum calculation



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



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



Poster #127
D. Parno et al

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

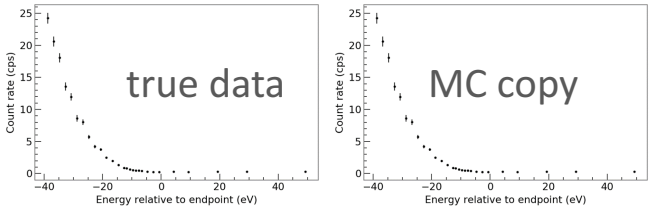
Y.-T. Lin et al, Phys. Rev. Lett. **124**, 222502 (2020)
A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000) + updates

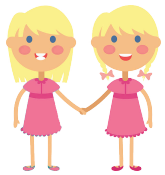
M. Kleesiek et al, EPC C, 79 (3) (2019)

Blinded analysis

Freeze analysis on MC-twin data

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

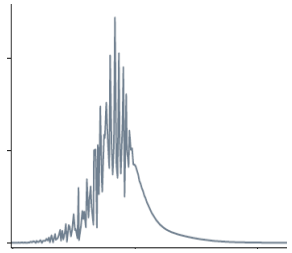


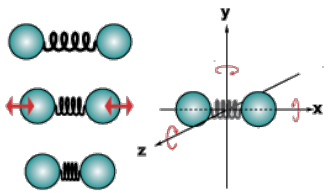


m_ν^2

Blinded model

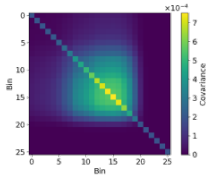
- Modified molecular final state dist.

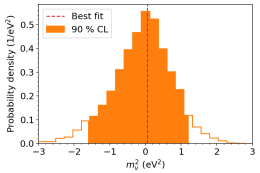




Two independent analysis strategies

- Covariance matrix
- Monte Carlo propagation

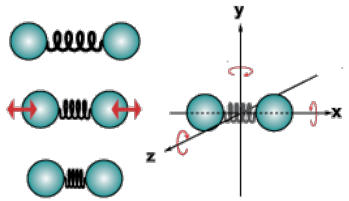




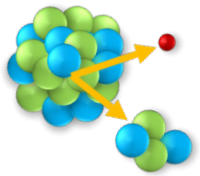
Poster #211: S. Hickford et al
Poster #109: L. Schlüter et al
Poster #114: C. Karl et al

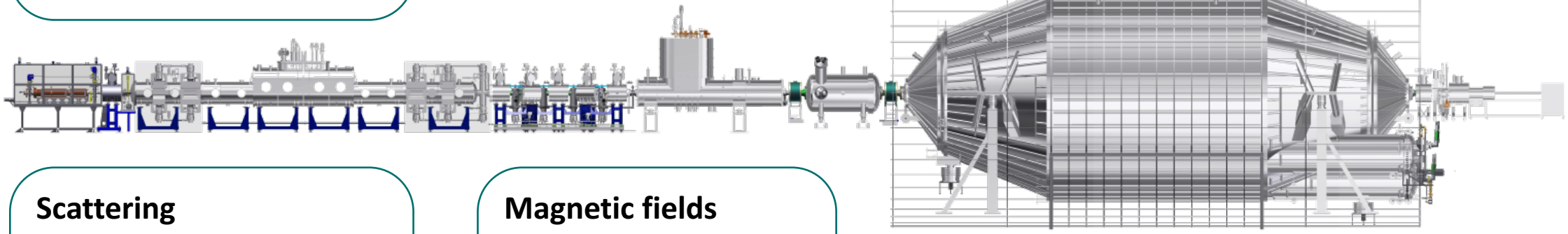
Systematic uncertainties

Molecular Final States

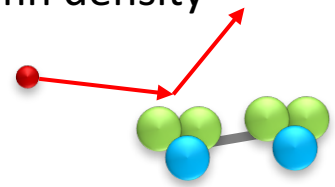


Background:
- time correlation
- retarding potential dependence





Scattering
- energy loss
- column density

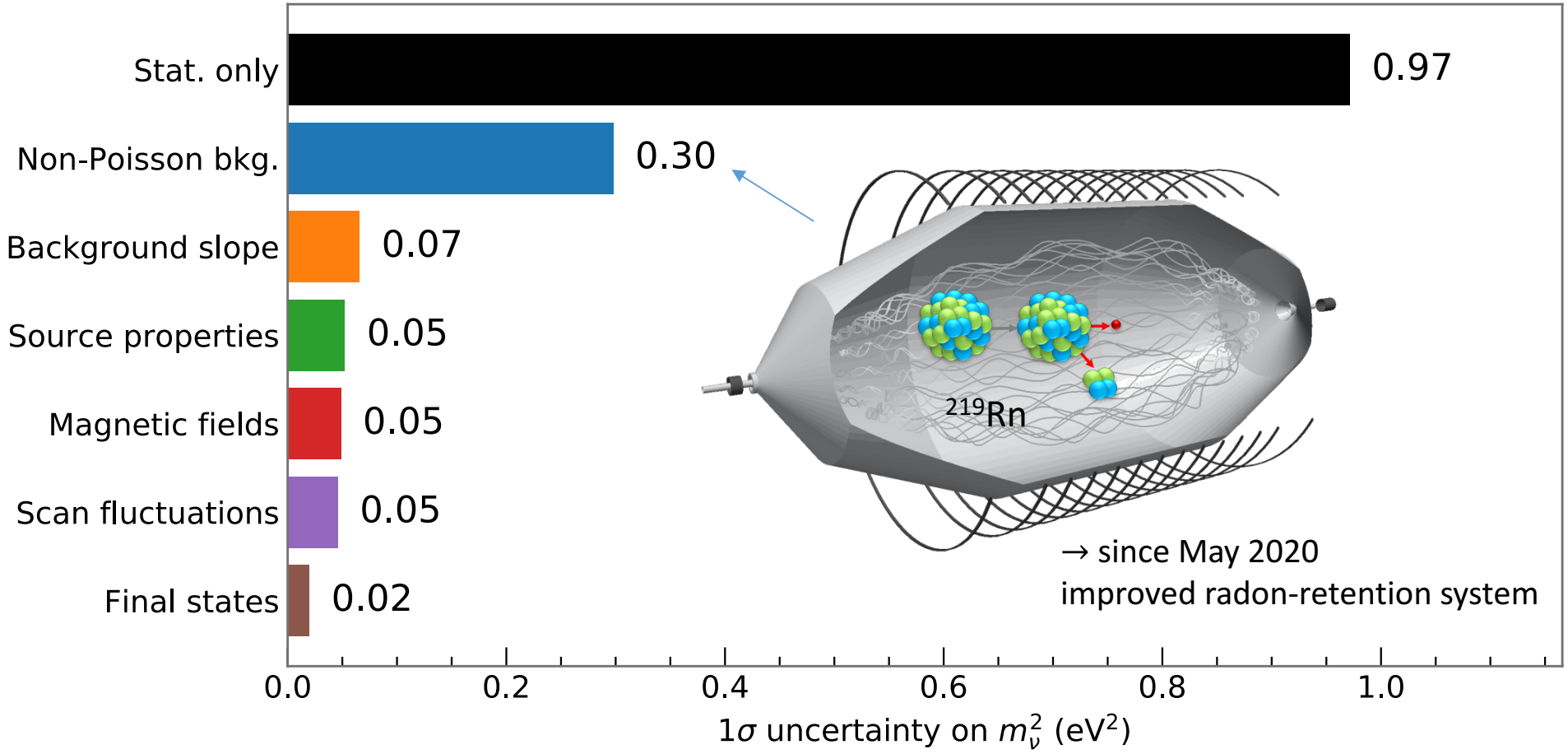


Magnetic fields
- source
- spectrometer
- detector

Data combination

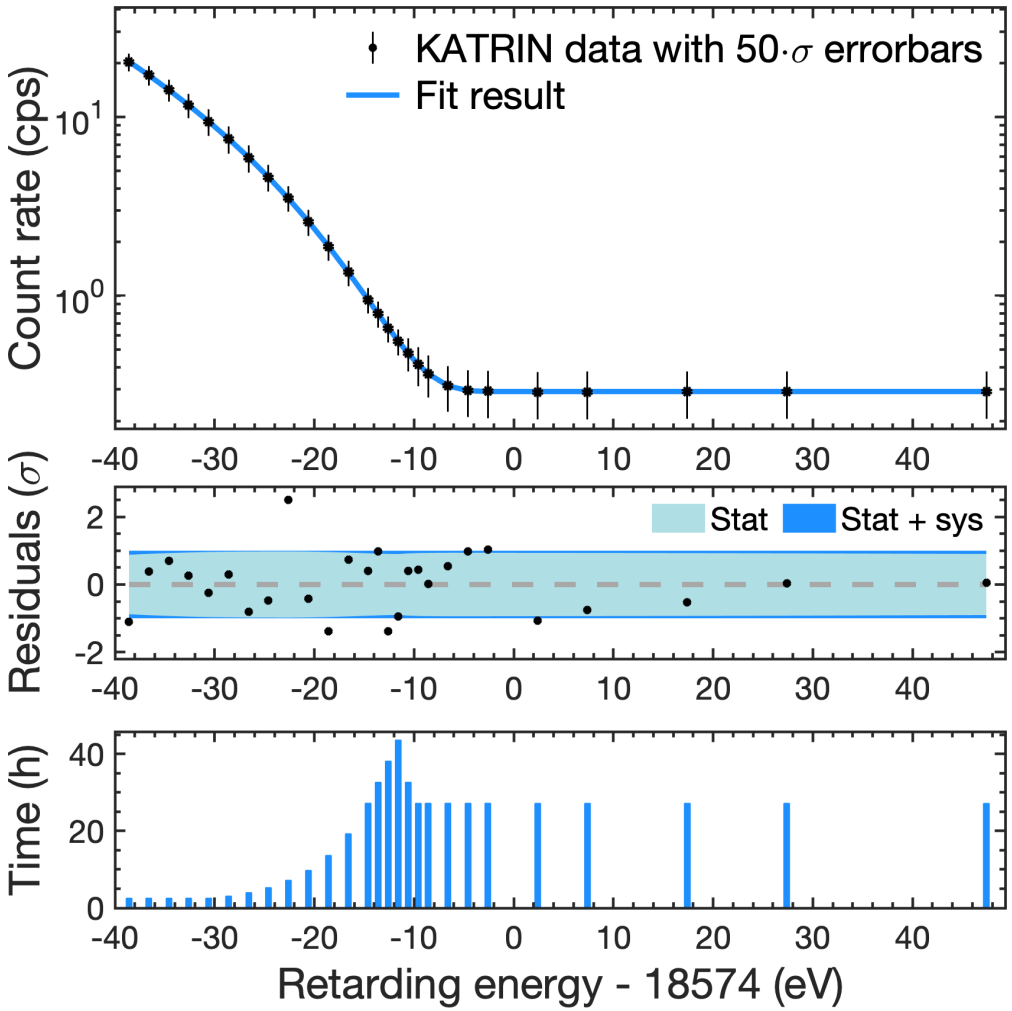
Budget of uncertainties

we are largely statistics dominated !!!



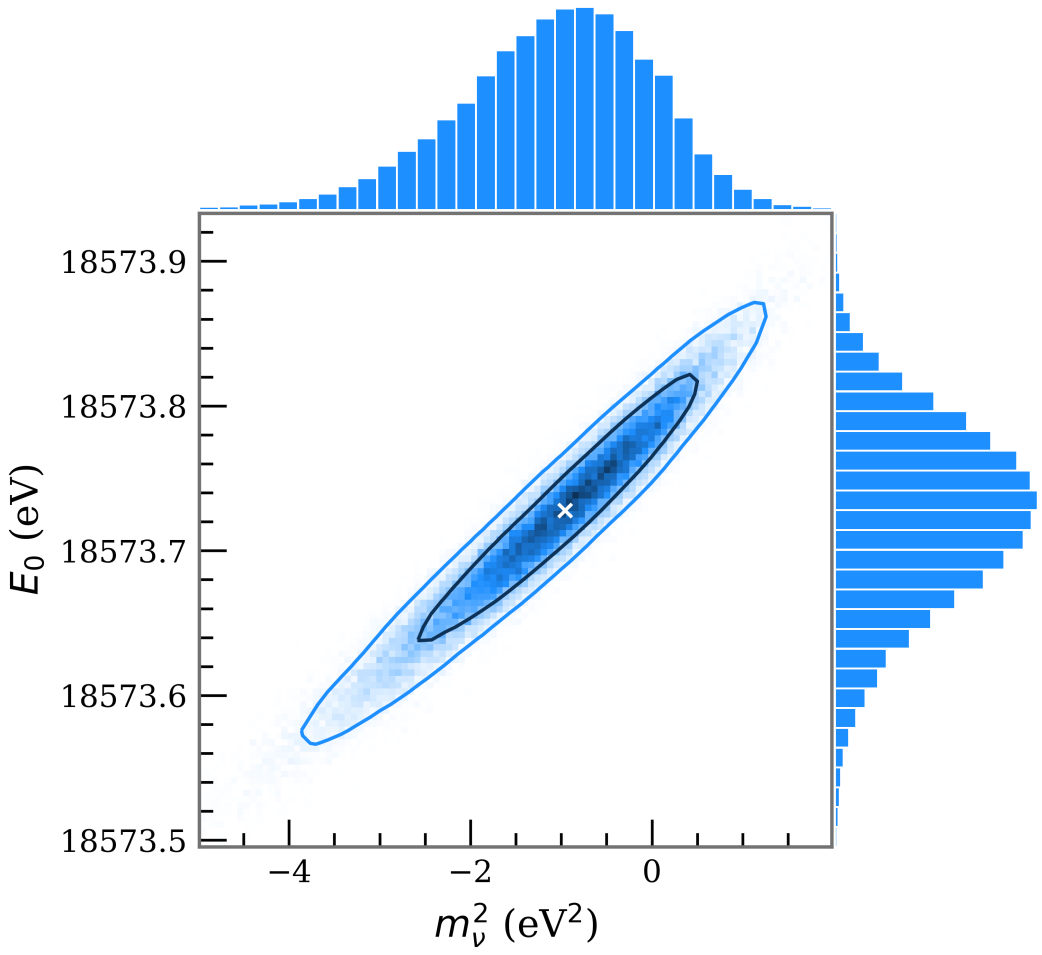
S. Goerhardt et al., JINST 13 (2018) no.10, T10004
S. Mertens et al, Astropart. Phys. 41 (2013), 52–62

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
- note: error bar increased by factor 50 (for visibility)!

Final fit result



Best fit results:

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

→ compatible with zero

→ probability of 16%, if true m_ν = 0 eV

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

→ 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)

Improved neutrino mass limit

Lokhov-Tkachov

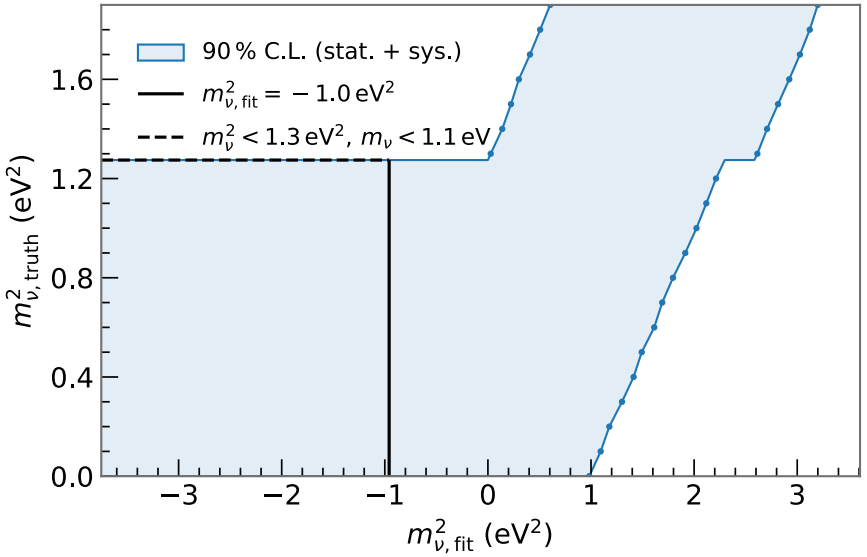
- $m_\nu < 1.1$ eV (90% CL) = sensitivity

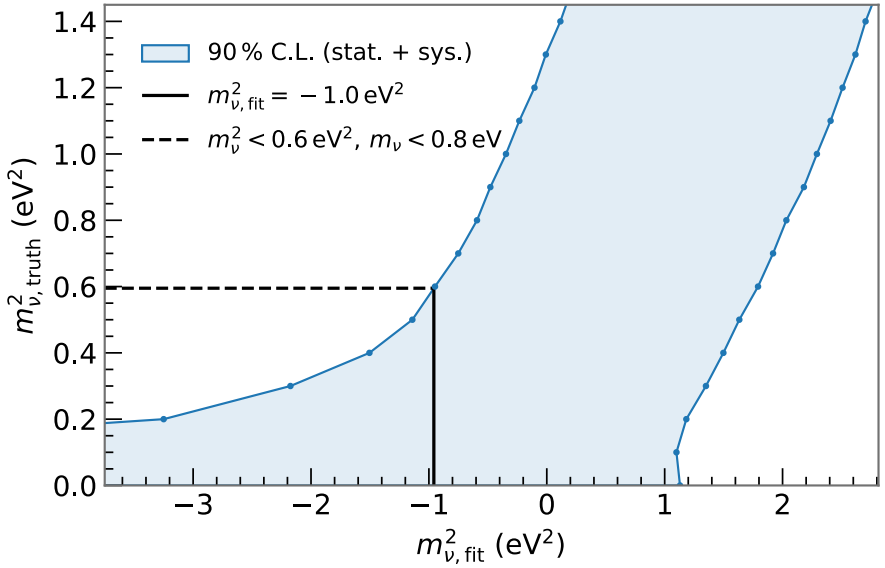
Feldman-Cousins

- $m_\nu < 0.8$ eV (90% CL)

Bayesian Confidence Interval ($m_\nu^2 > 0$, flat)

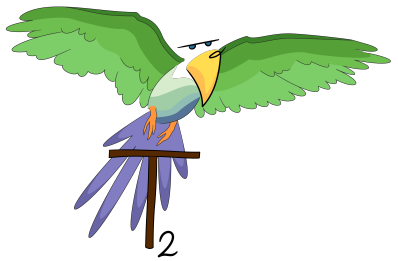
- $m_\nu < 0.9$ eV (90% CI)



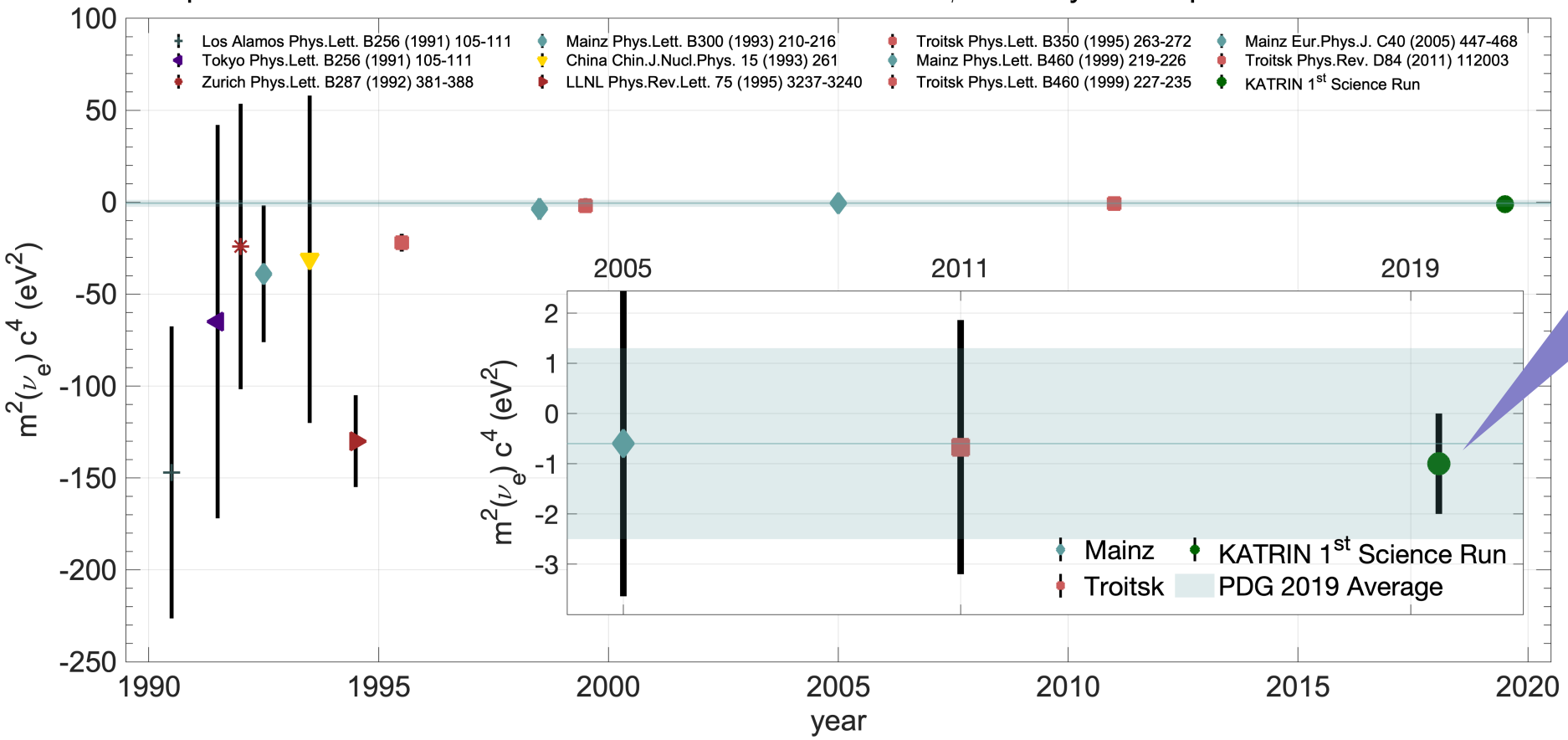


KATRIN Collab, Phys. Rev. Lett. 123, 221802 (2020)

Historical context



Squared neutrino mass values obtained from tritium β -decay in the period 1990-2019

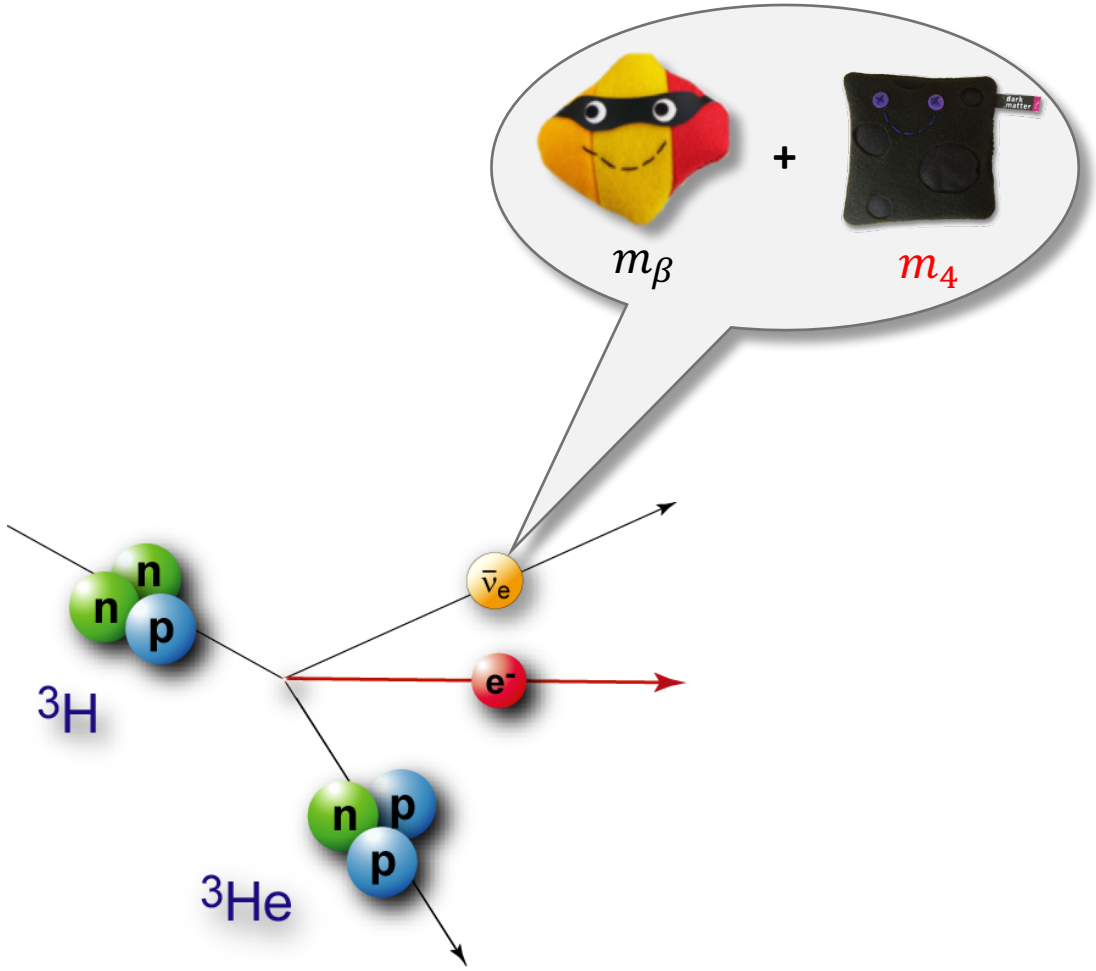


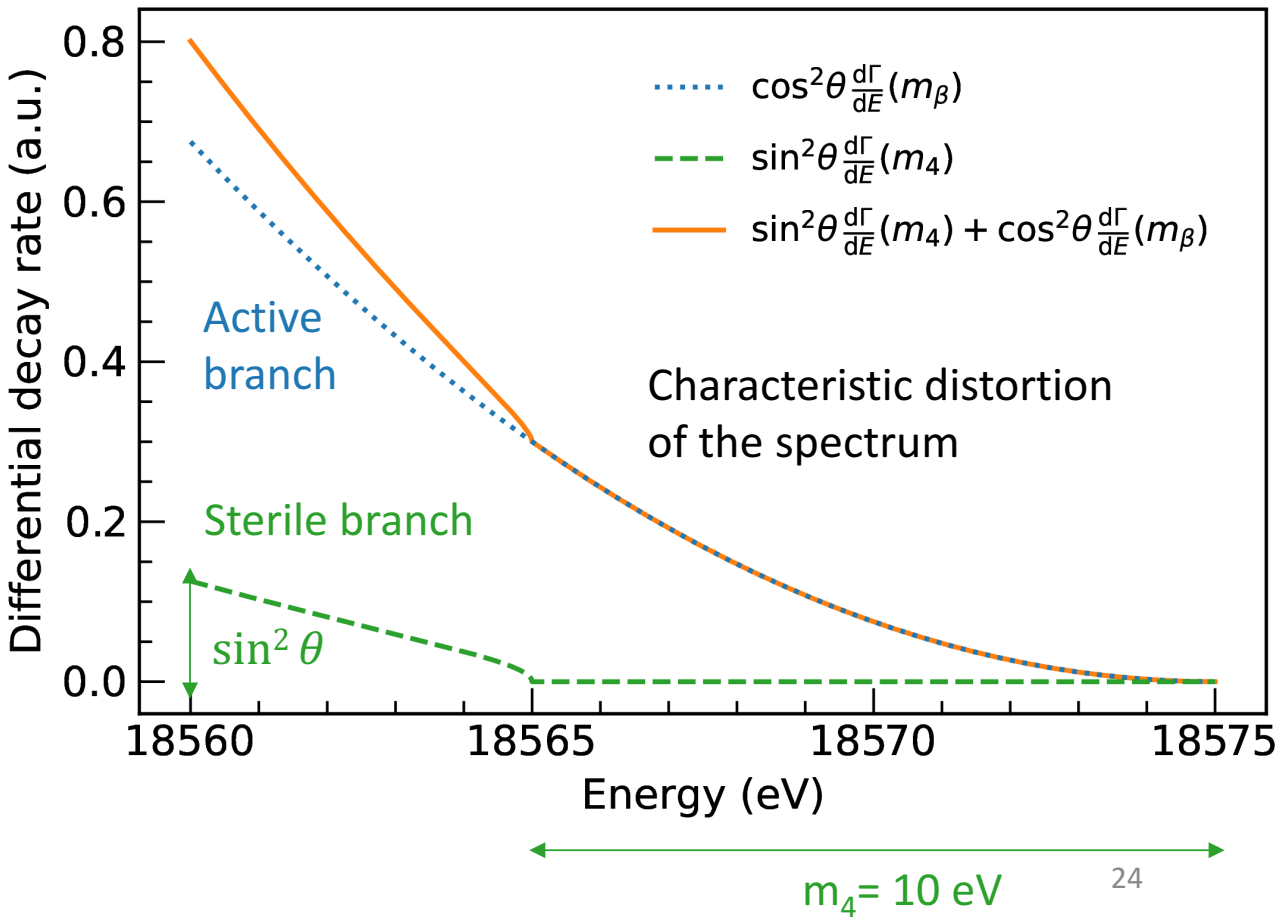
Effective 5 days of data
- Stat. error: ÷ 2
- Syst. error: ÷ 6

KATRIN Collab, Phys. Rev. Lett. 123, 221802

Signature of light sterile neutrino

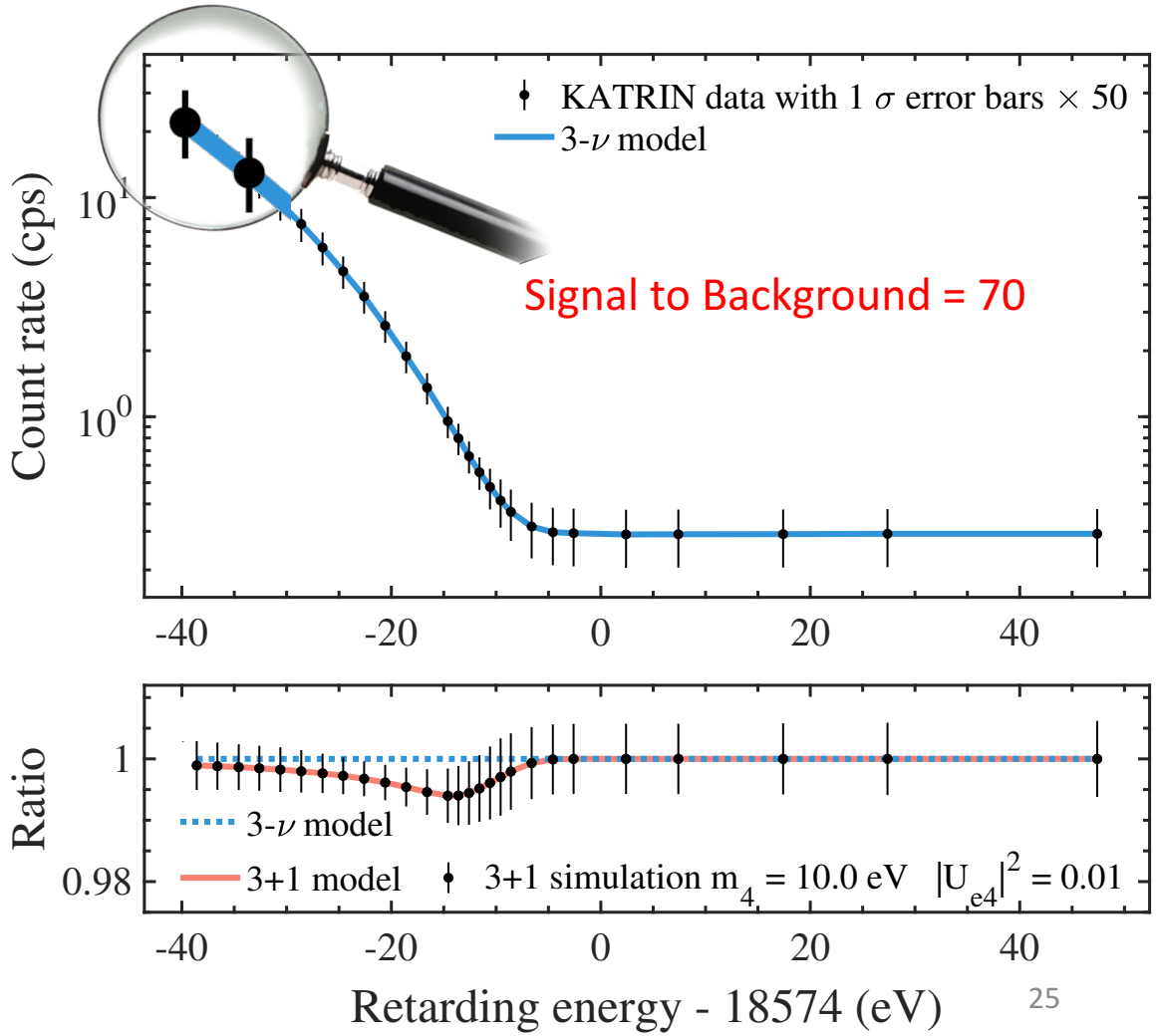
→ See **Reactor and Geo ν** session on **25 June**
→ See **sterile ν** session on **2 July**





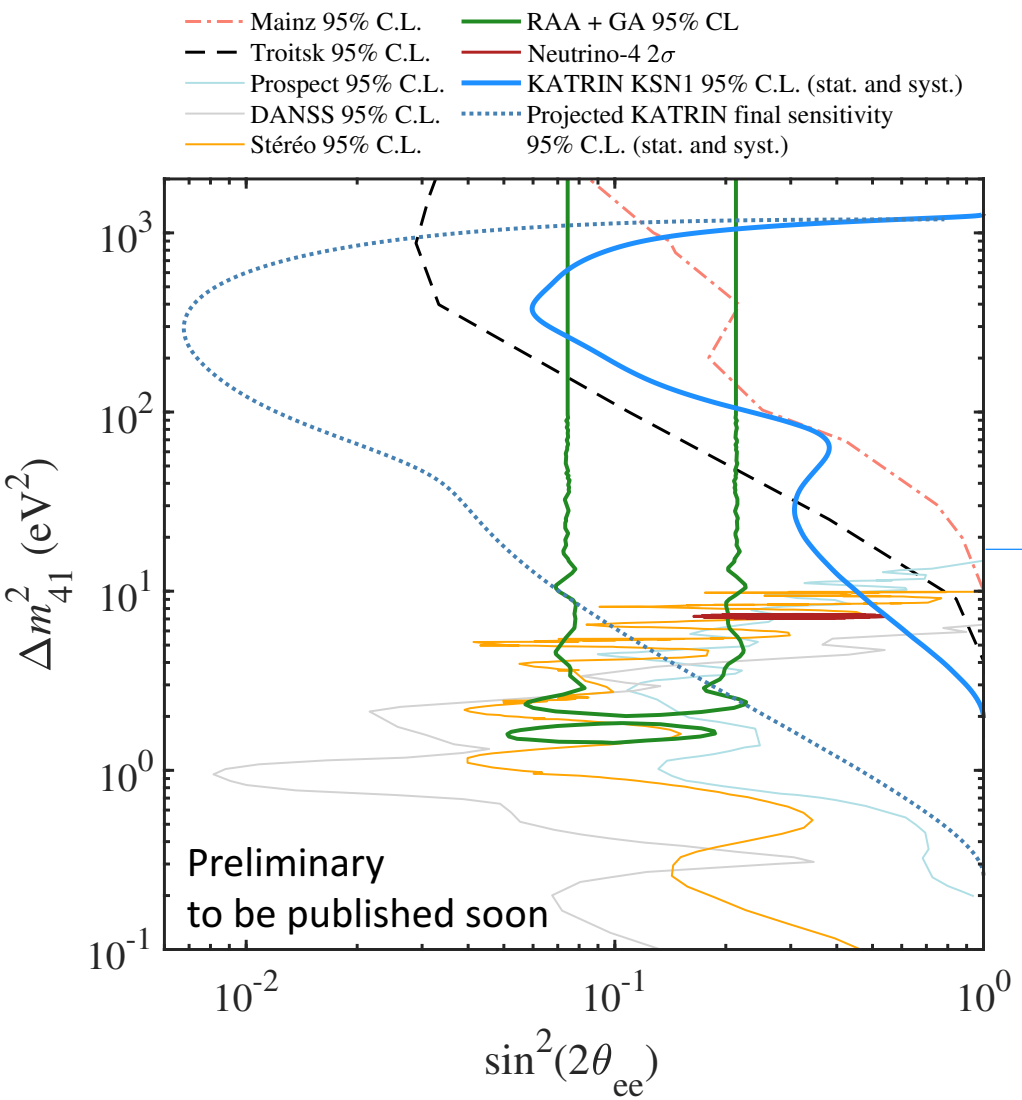
eV-scale sterile neutrino search

- same data set as for neutrino mass
- 3+1 sterile neutrino model
- grid search in $m_4, |U_{e4}|^2$ plane
- m_ν fixed to minimal allowed value (0.009 eV)



eV-scale sterile neutrino search

Poster #108
T. Lasserre et al



High Δm_{41} region:

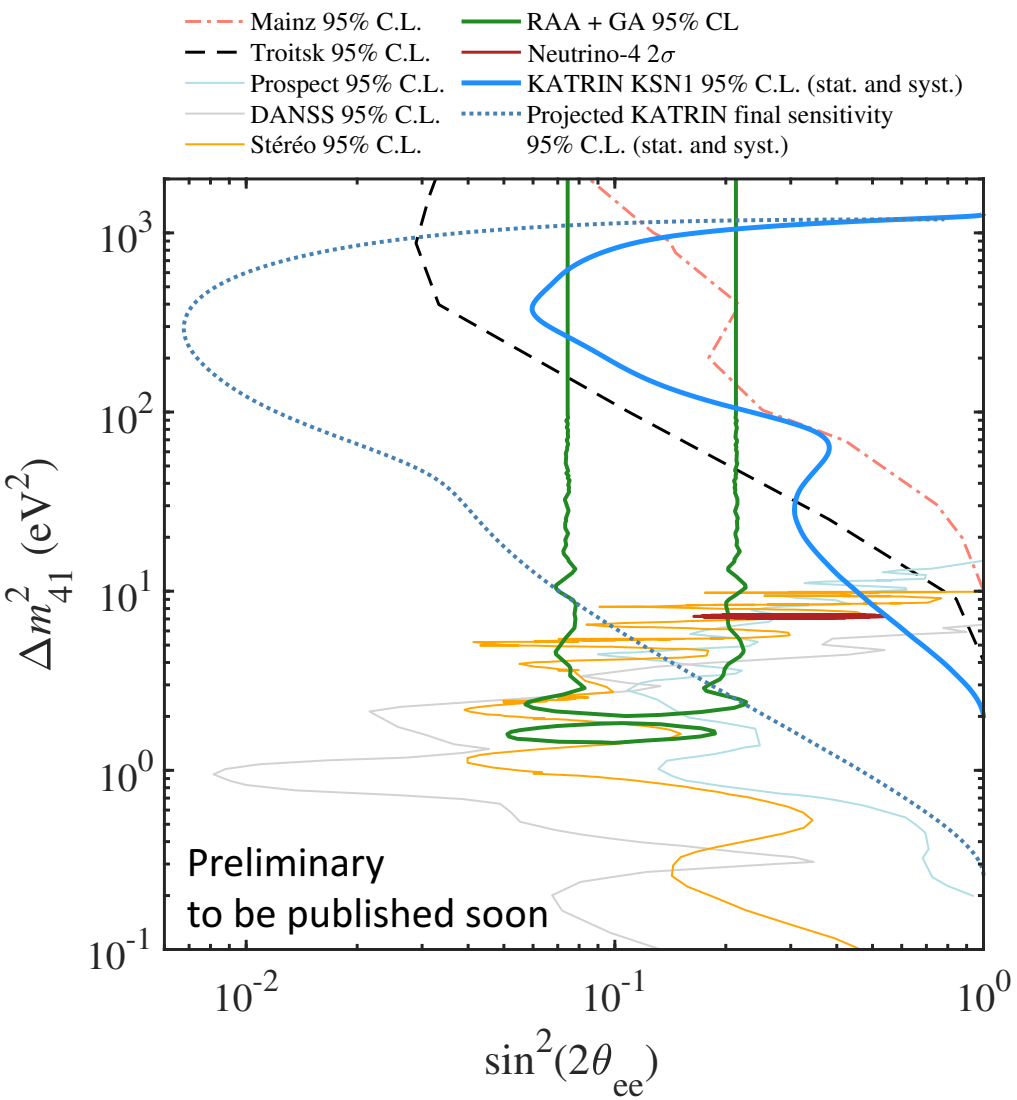
- ✓ Improve exclusion with respect to DANSS, PROSPECT, and STEREO
- ✓ Exclude parameter space of Reactor Anomaly (RAA)

Low Δm_{41} region:

- ✓ Improve MAINZ and TROITSK limit
- ✓ The NEUTRINO-4 hint at the edge of exclusion limit

eV-scale sterile neutrino search

Poster #108
T. Lasserre et al

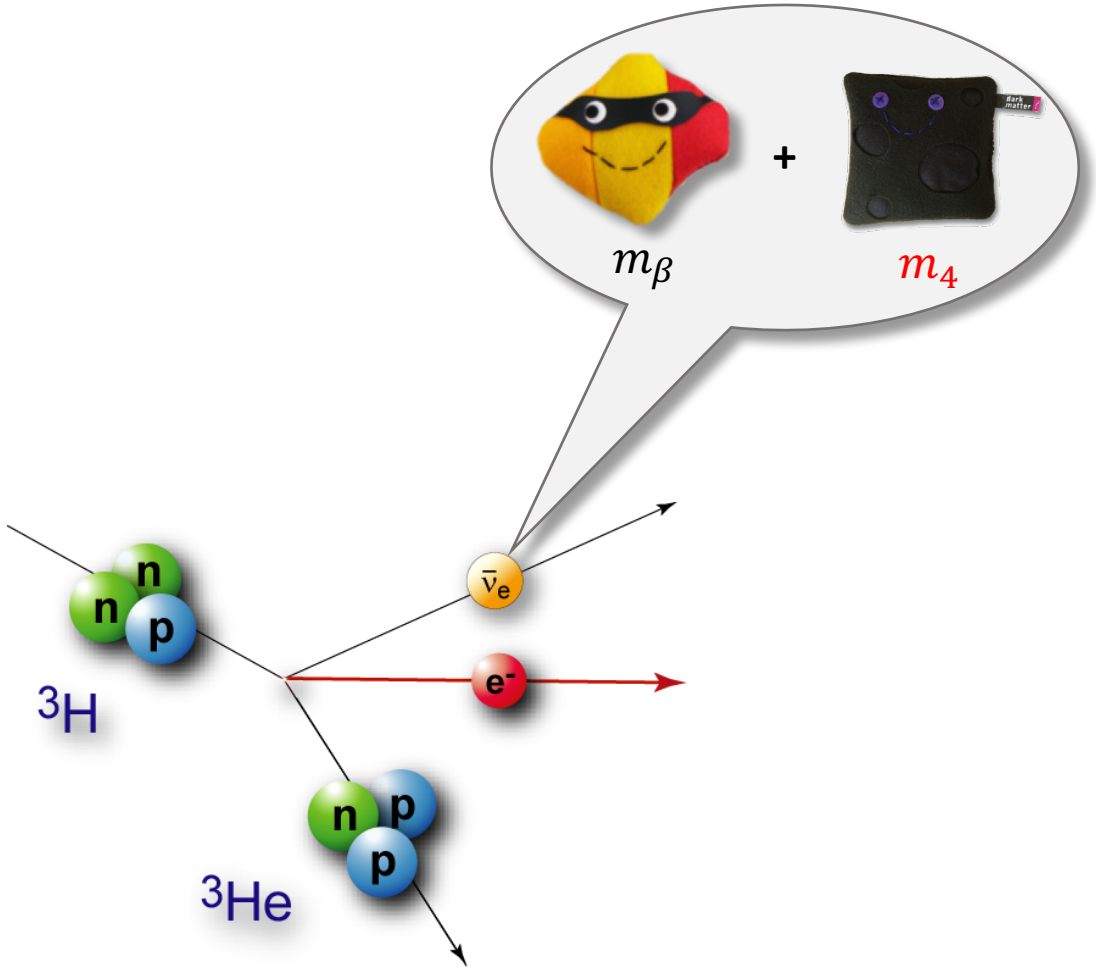


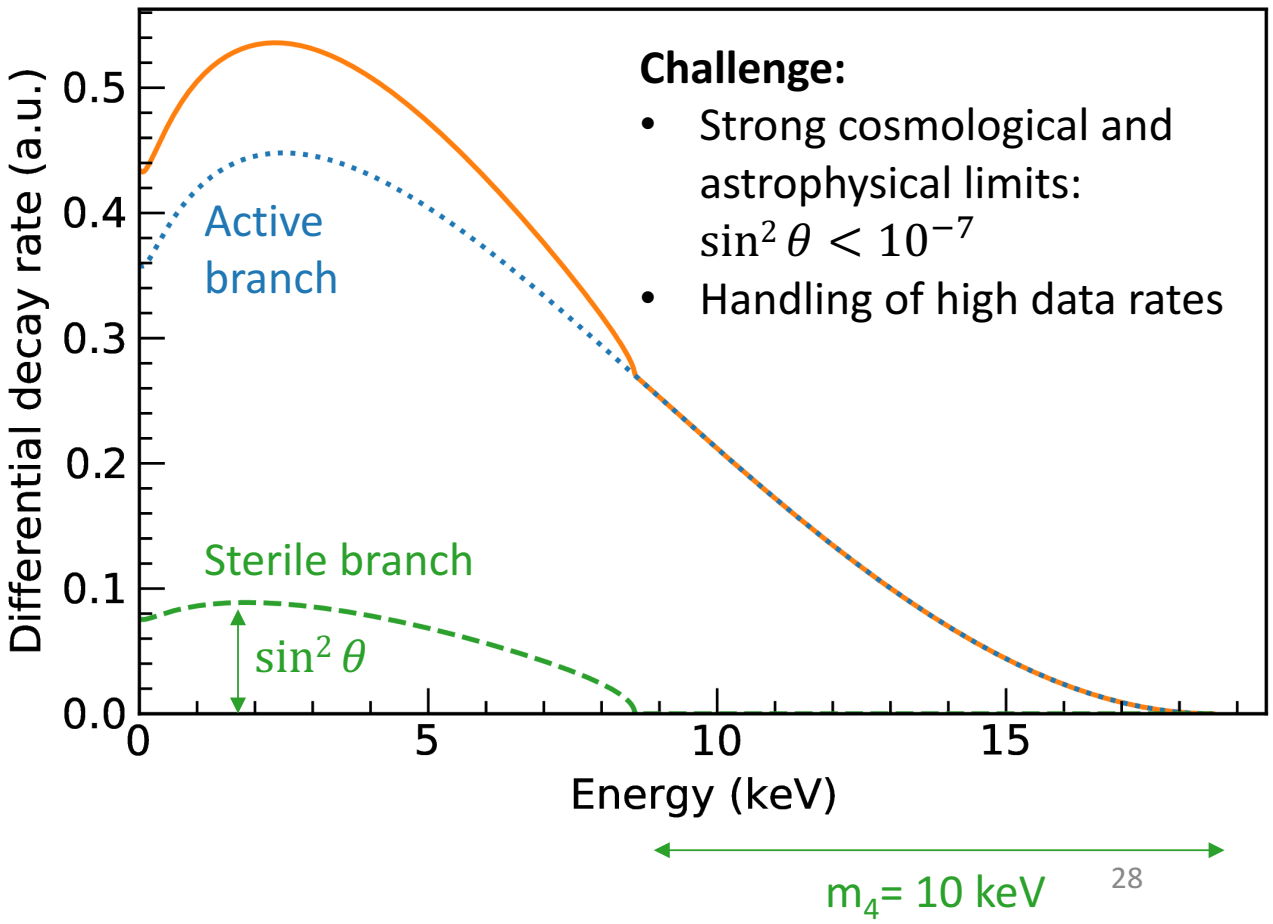
Demonstrate **potential** and **complementarity** of KATRIN to probe the sterile-ν hypothesis

Future: A large fraction of RAA region of interest will be probed with upcoming campaigns

Signature of keV sterile neutrino

→ See talk by Kev Abazajian, June 24





Challenge:

- Strong cosmological and astrophysical limits: $\sin^2\theta < 10^{-7}$
- Handling of high data rates

keV-scale sterile neutrino search

Proof of principle: Deep scan (1.6 keV below E_0) with low-activity commissioning data

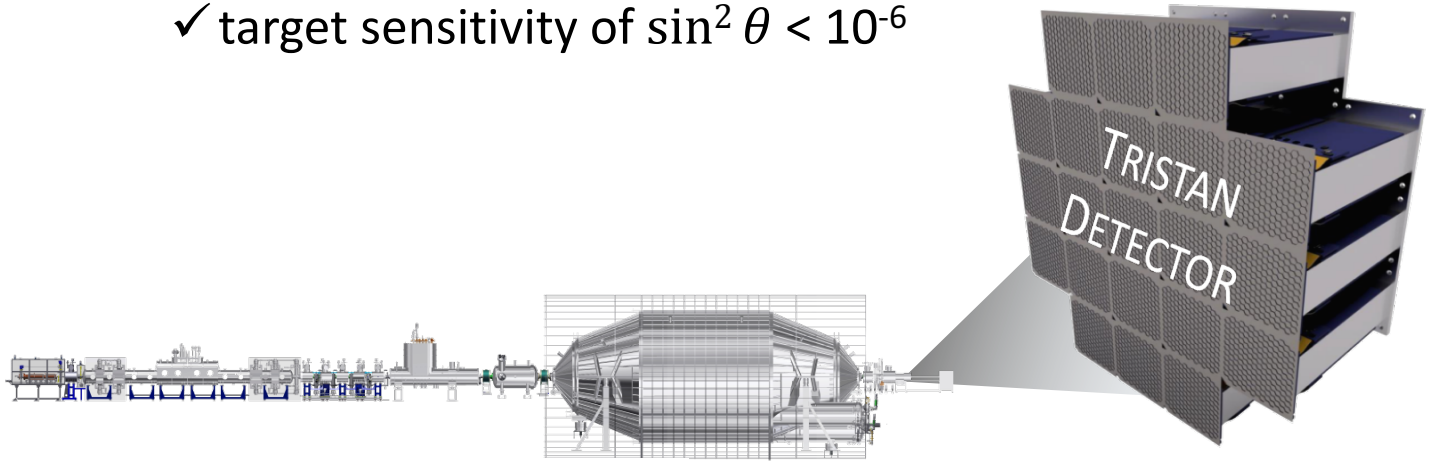
✓ excellent agreement of model and data (p-value = 0.6)

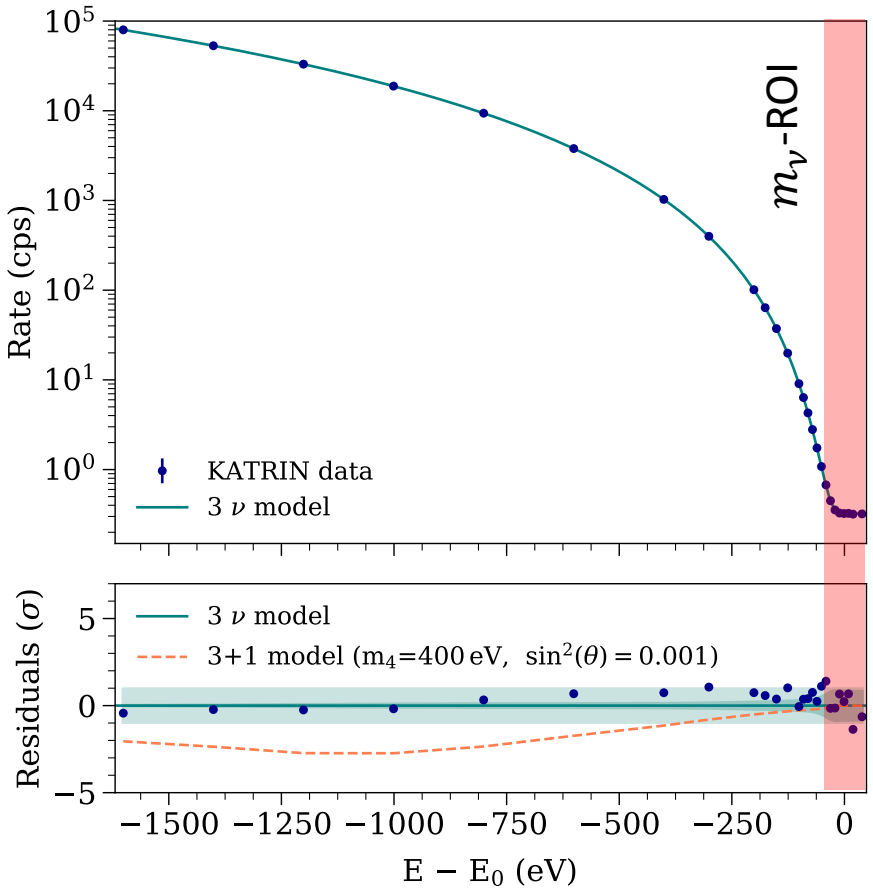
✓ sensitivity to $\sin^2\theta < 10^{-3}$ @ m_4 = 0.4 keV

Future: Novel multi-pixel Silicon Drift Detector array (TRISTAN)

✓ high-statistics search

✓ target sensitivity of $\sin^2\theta < 10^{-6}$

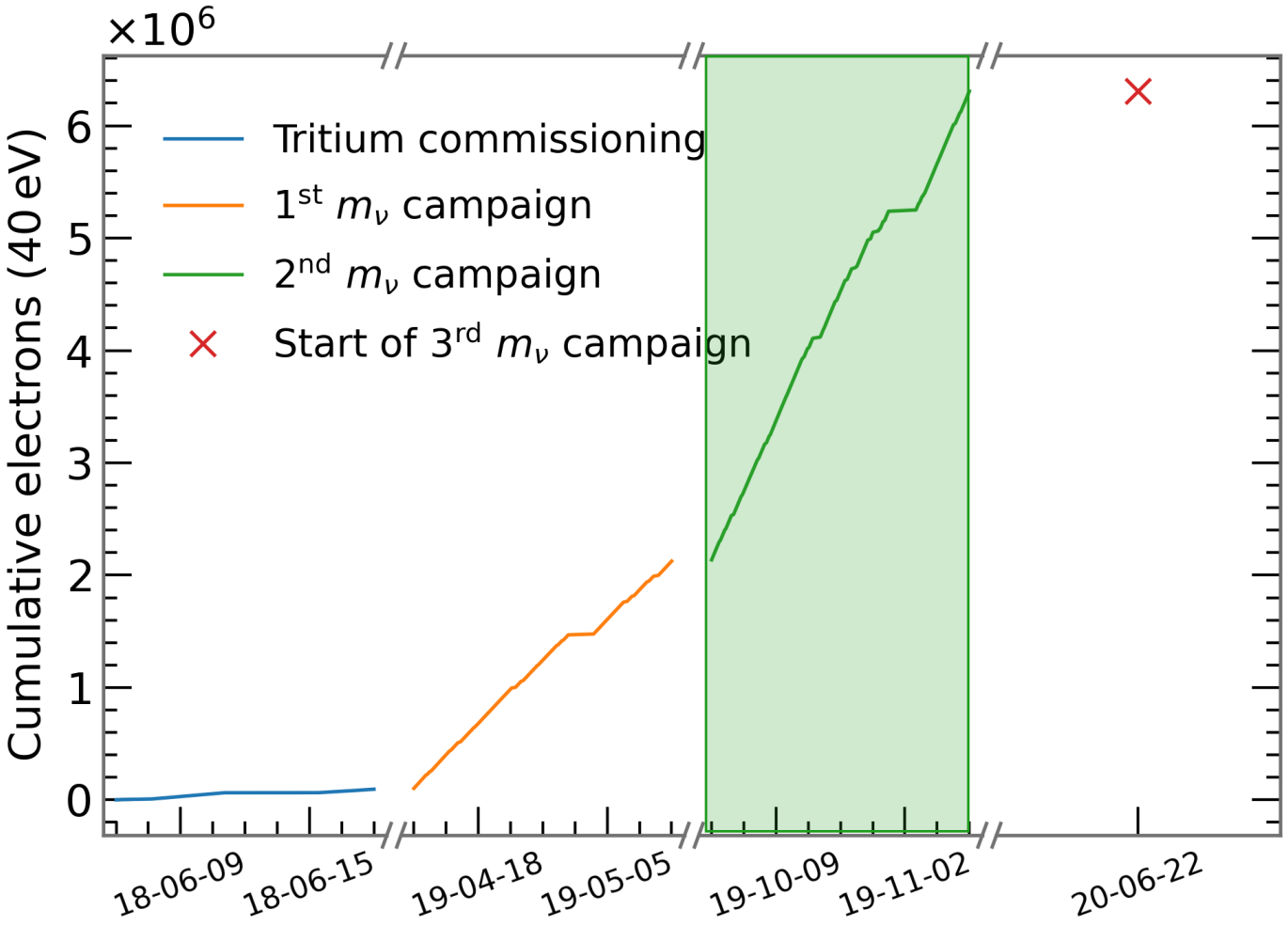




Mertens et al, JCAP 1502 (2015)
Mertens et al, J. Phys. G46 (2019)

T. Houdy et al

KATRIN Data Taking Overview



2nd neutrino mass campaign

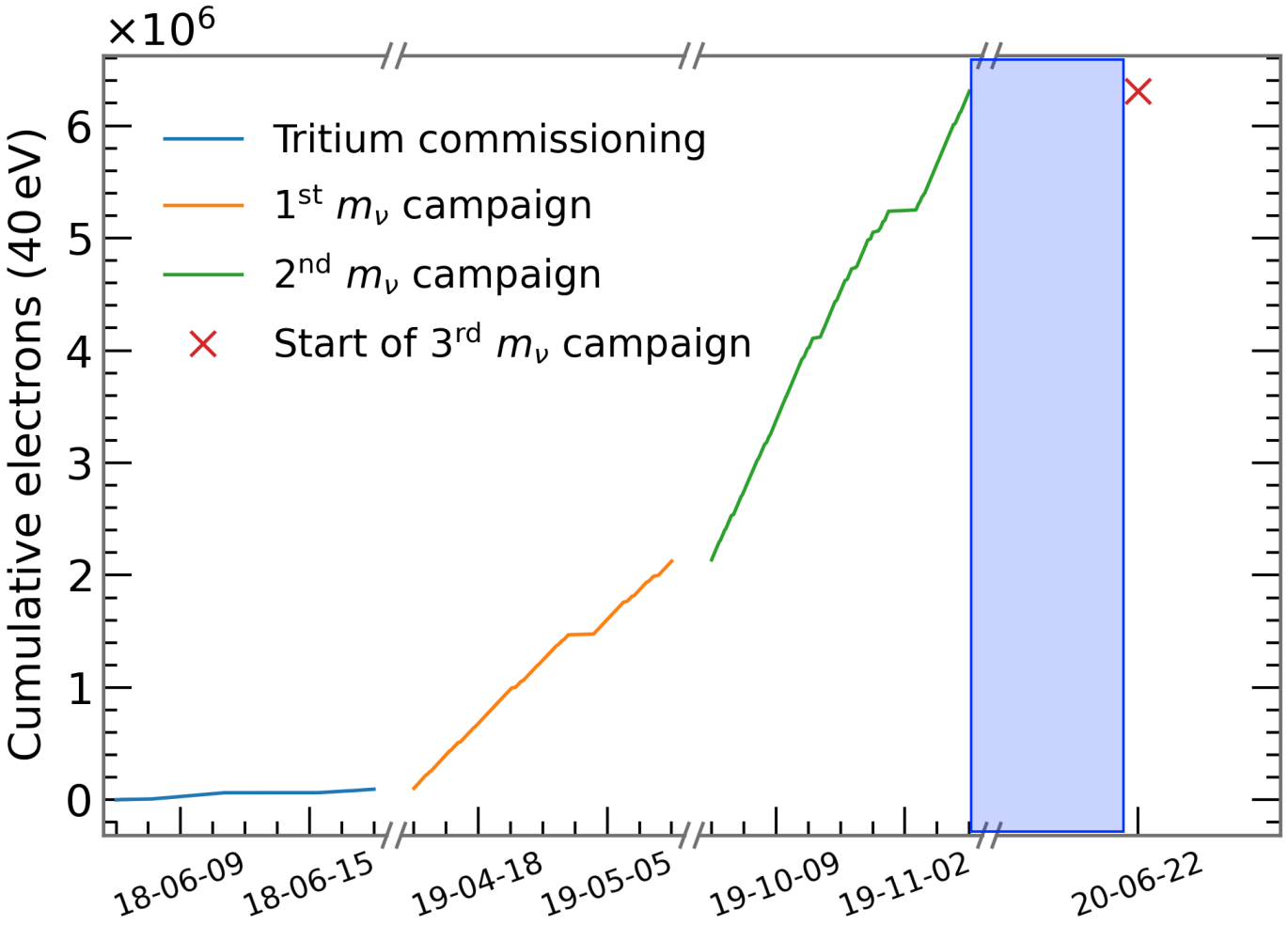
- Measurement time: 31 days
- **Gas density: 84%**
- Isotopic purity: 98.6% tritium
- **Source activity: $9.8 \cdot 10^{10}$ Bq**
- Total statistics: $4 \cdot 10^6$ e's

➢ Data soon to be un-blinded

column density of $100\% = 5 \cdot 10^{17}$ molecules/cm²

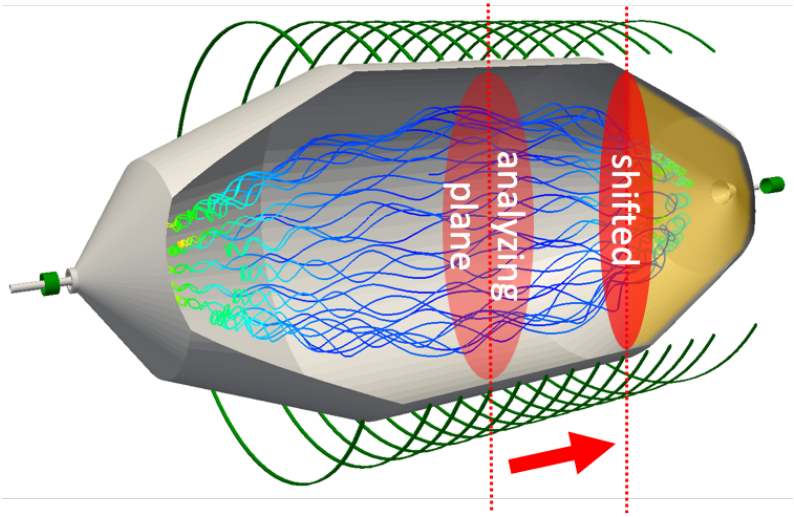
KATRIN Data Taking Overview

Poster #125: D. Hinz et al
Poster #361: E. Ellinger et al

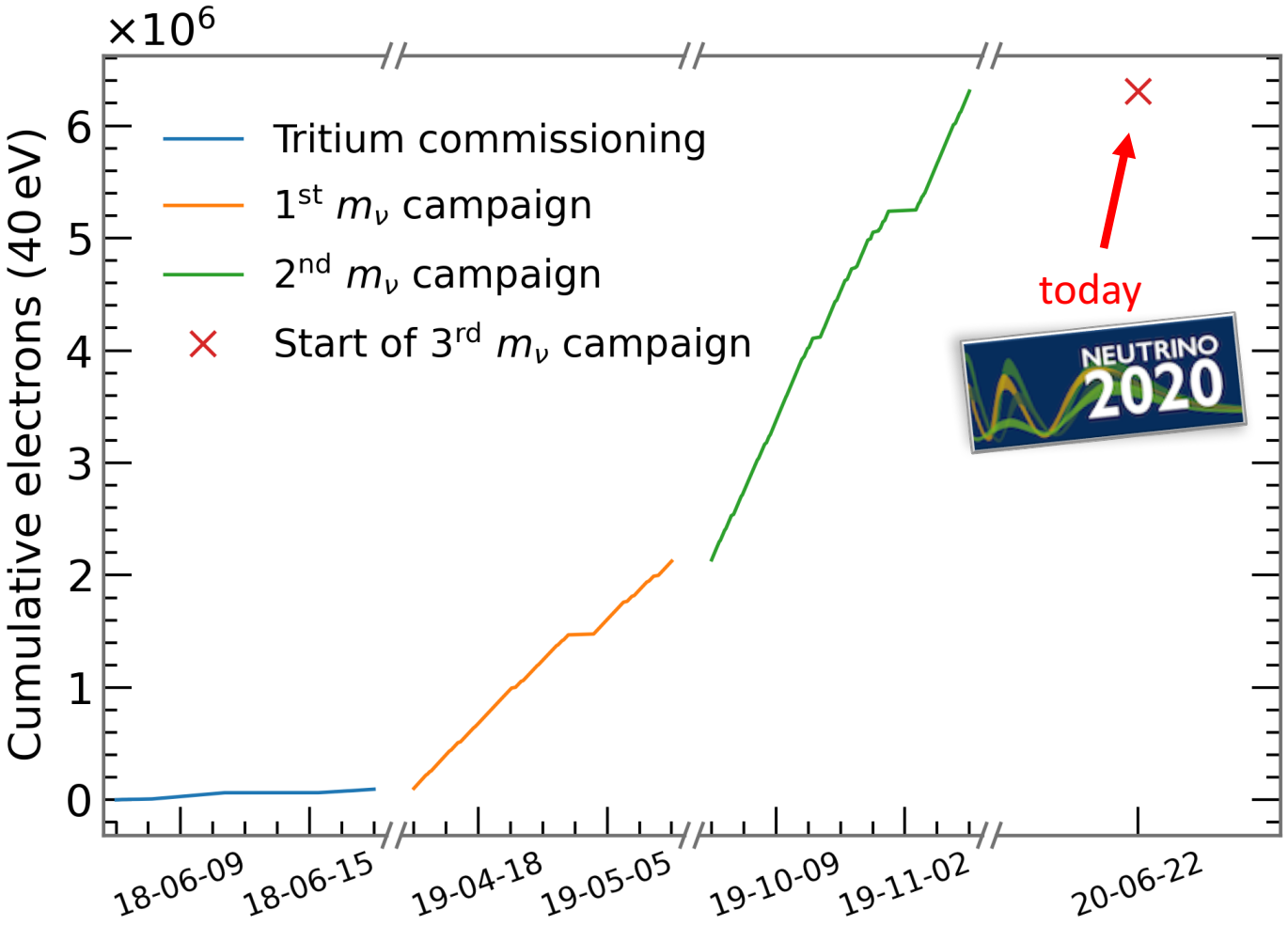


Calibration and Optimization

- Extensive study of plasma properties at different gas densities, temperature and boundary conditions
- Improved el.mag. field config. to reduce background (÷ 2) → 150 mcps

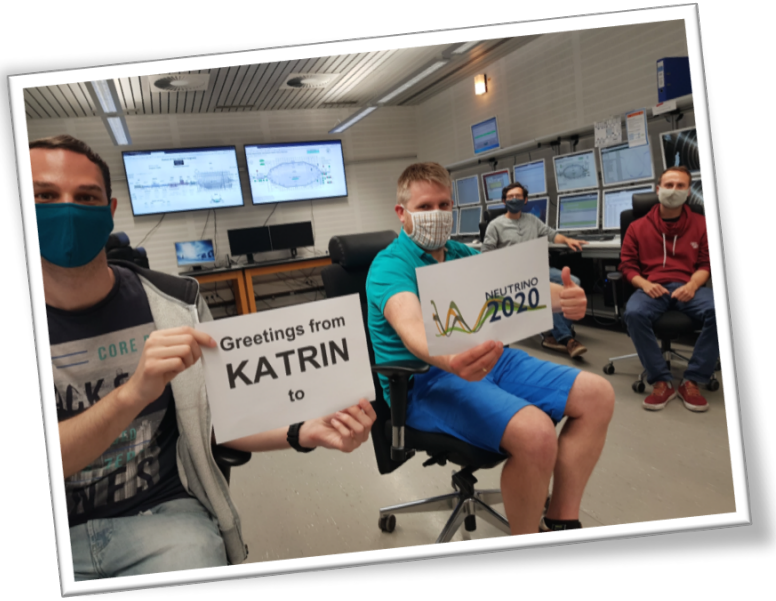


KATRIN Data Taking Overview



3rd neutrino mass campaign

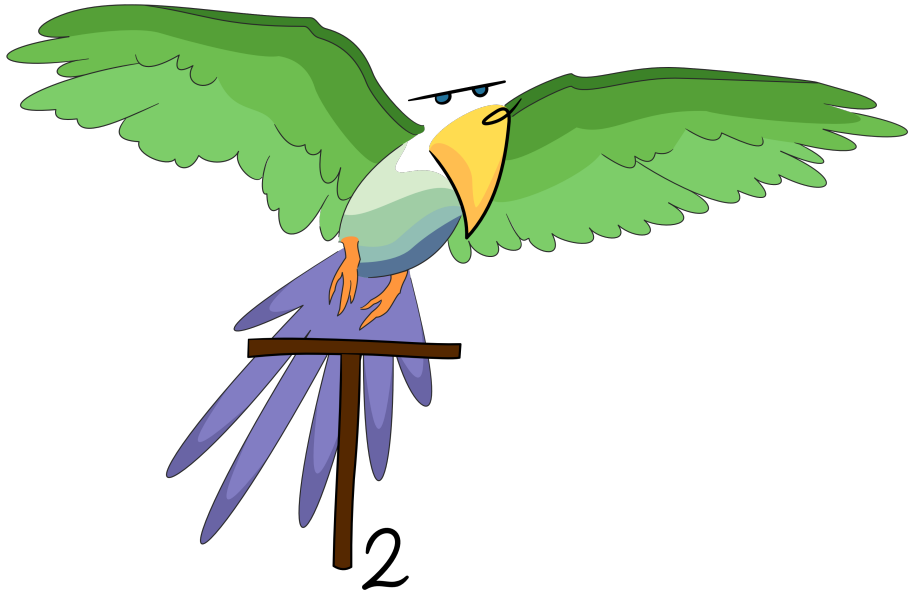
- m_ν - measurement started today



Conclusion

- New world-best direct neutrino mass measurement: **m_ν < 1.1 eV (90% C.L.)**
- With upcoming 1000 days of measurement time

  tackle low sub-eV sensitivity



- First constraints on **eV sterile neutrinos**
- Promising potential to search for **keV sterile neutrinos**
- New data release expected soon
- Next KATRIN run (with optimized settings) has started today

Thank you for your attention

Prof. Dr. Susanne Mertens for the KATRIN collaboration

Technical University Munich & Max Planck Institute for Physics

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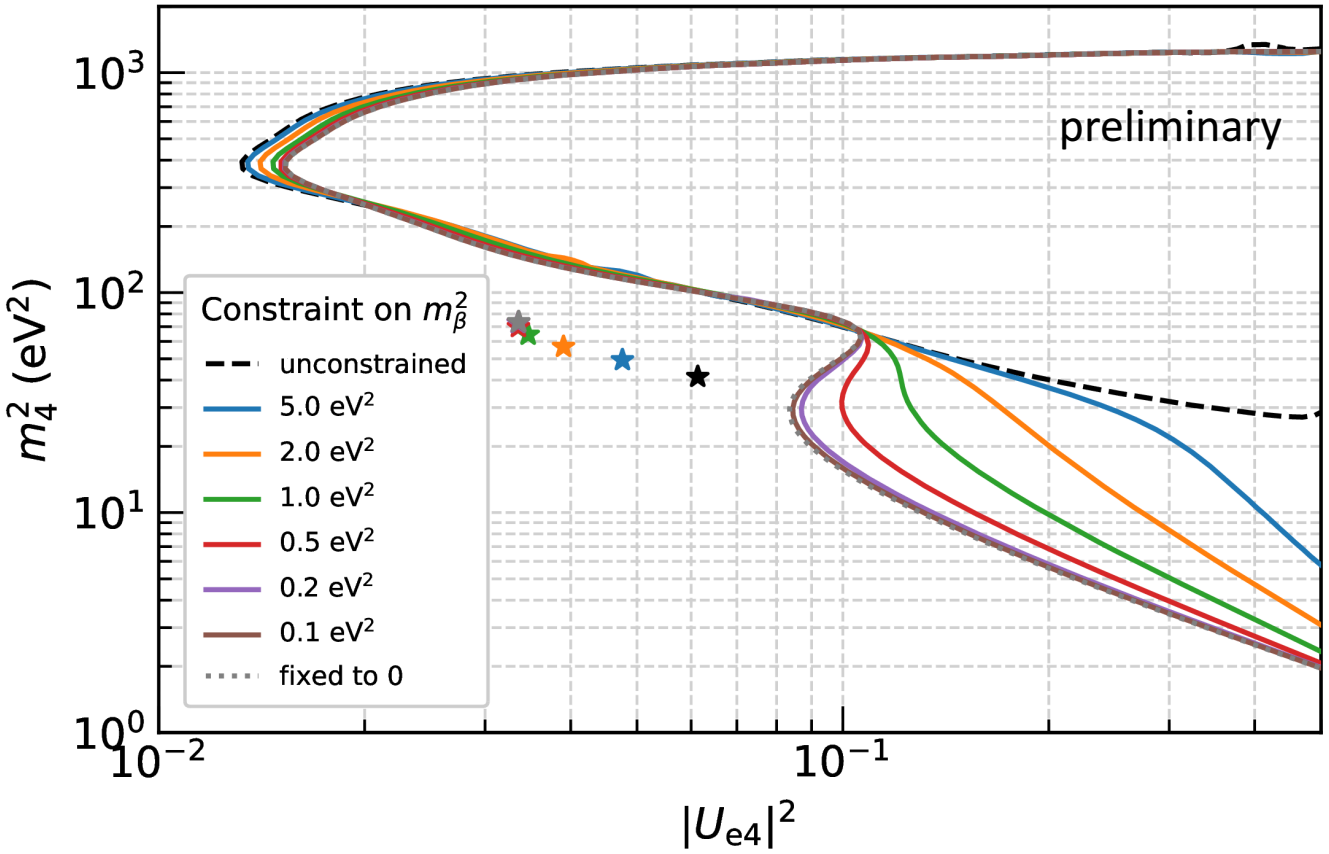
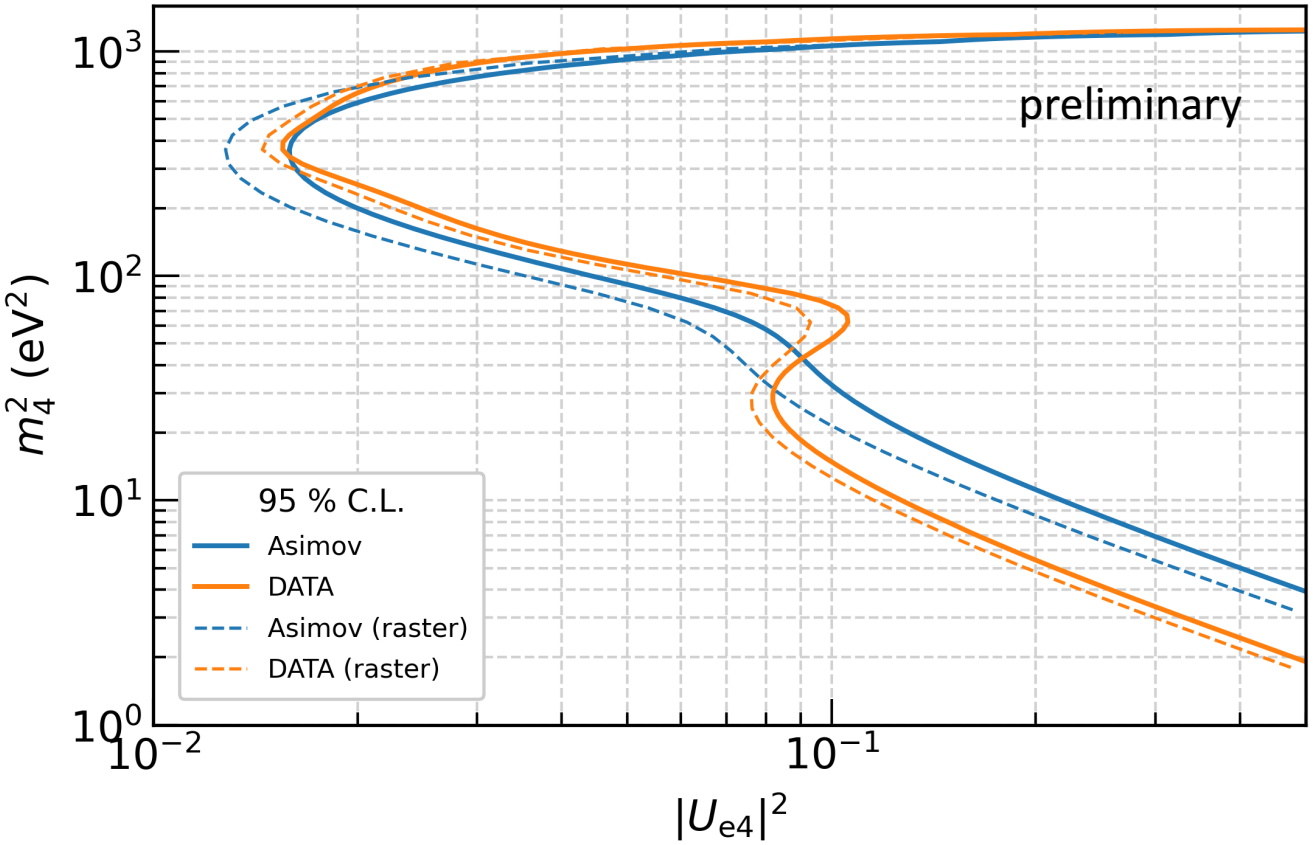
eV-sterile neutrino search

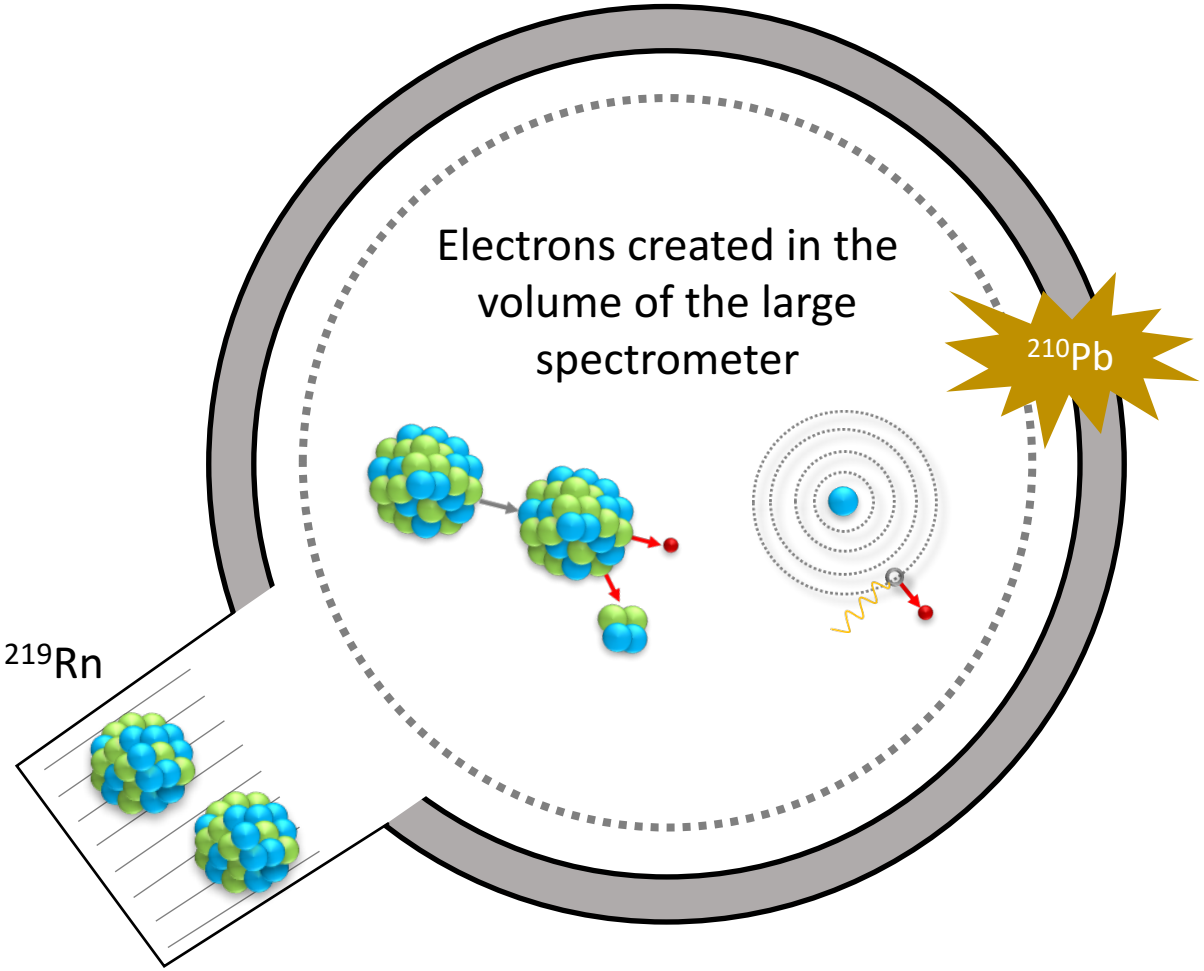


eV-sterile neutrino search

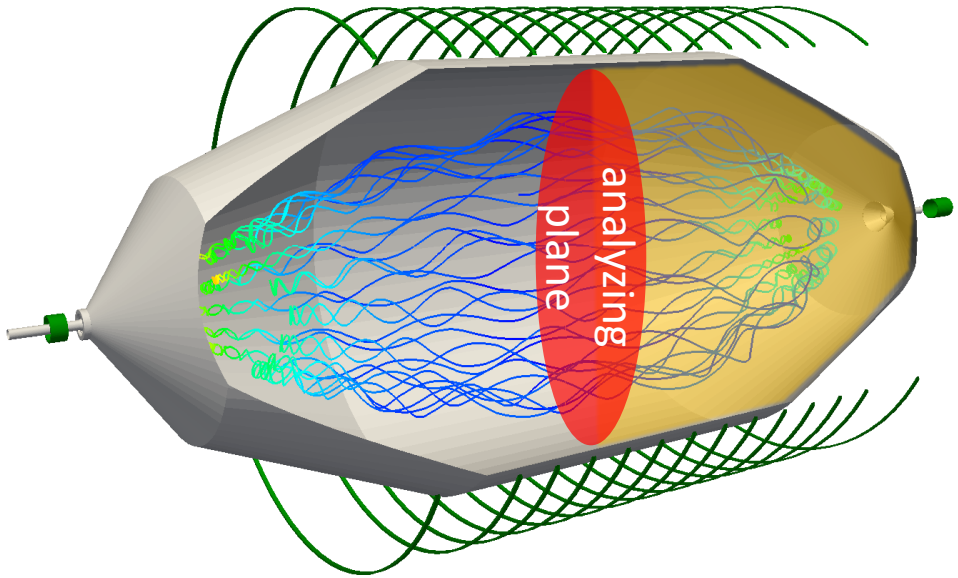


KATRIN backgrounds

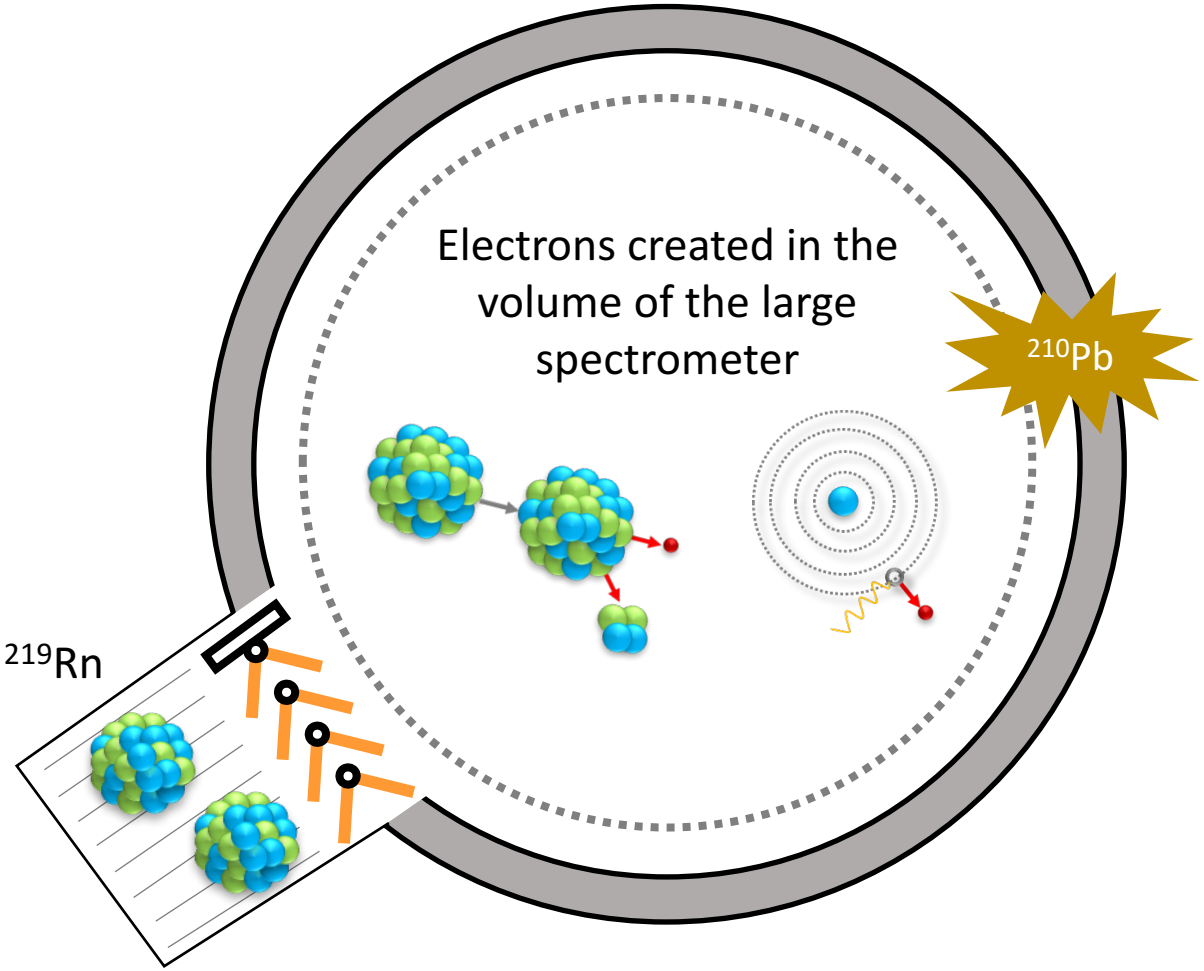
J. Wolf
E. Ellinger



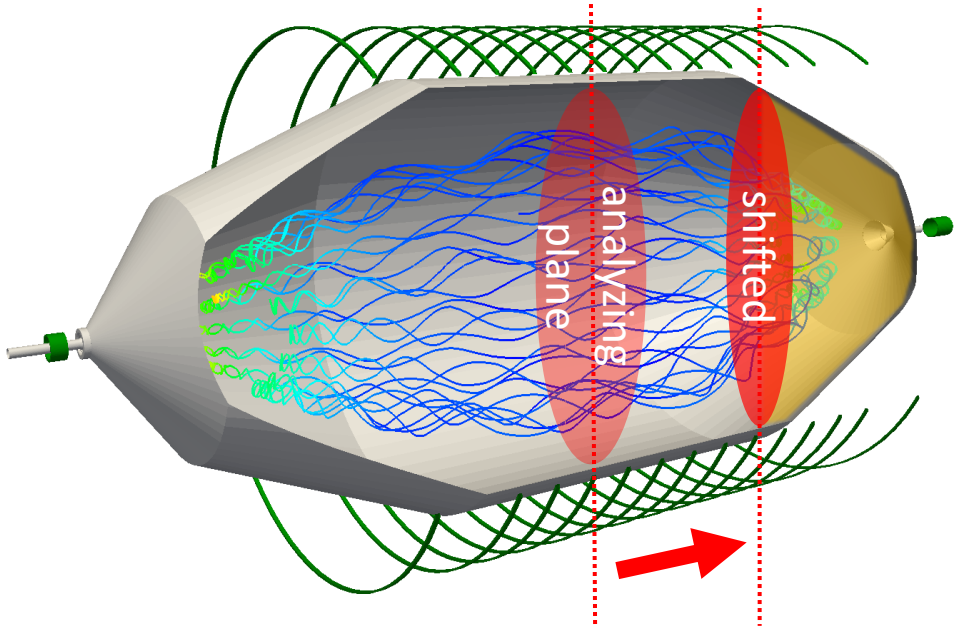
- ^{219}Rn-induced background
- ^{210}Pb-induced background



KATRIN background mitigation

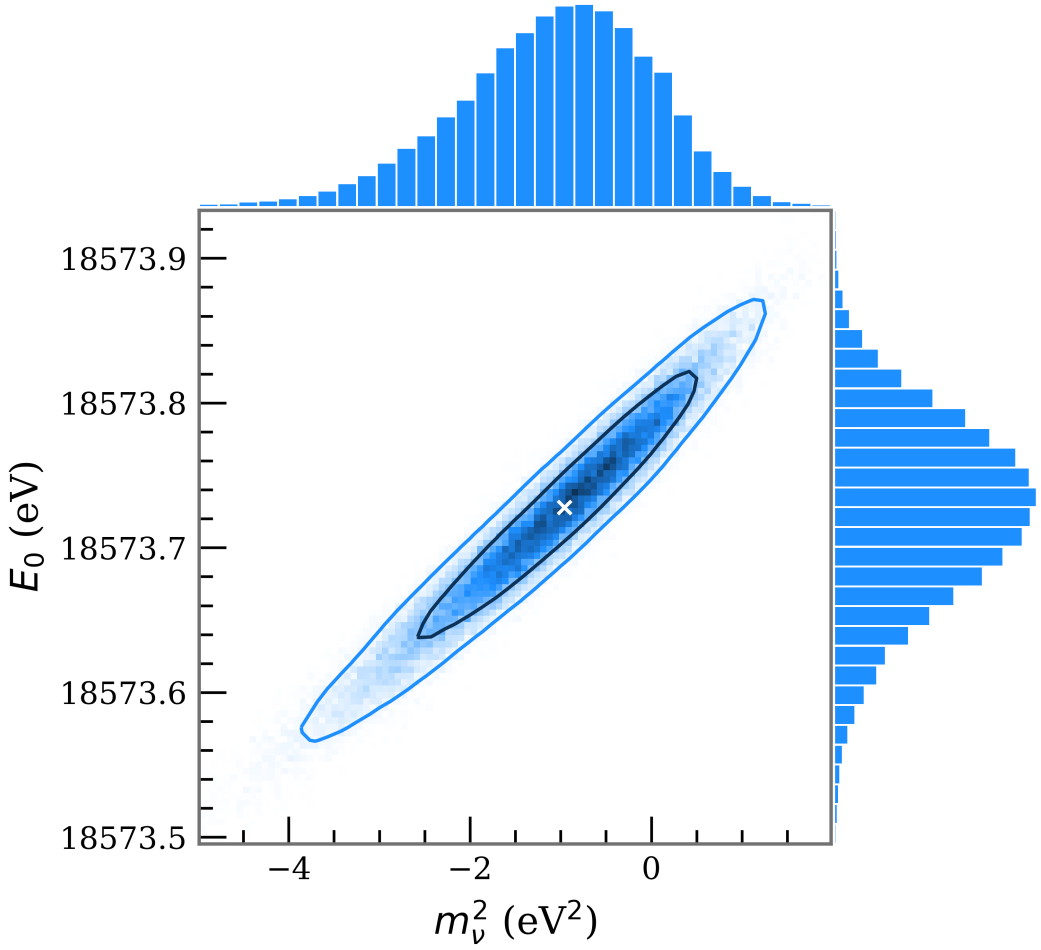


- ✓ LN cooled baffle + shifted analyzing plane
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
- ✓ Background reduction by factor of 2.3 to 153 mcps



Final fit result (endpoint)

$$E_0^{fit} = E_0 + \phi_{source} - \phi_{WF,MS}$$



- fitted E_0 = 18573.7 ± 0.1 eV
- Q-value (KATRIN): 18575.2 ± 0.5 eV
- Q-value (literature): 18575.72 ± 0.07 eV

✓ excellent agreement

✓ confidence in overall energy scale ☺

Source activity