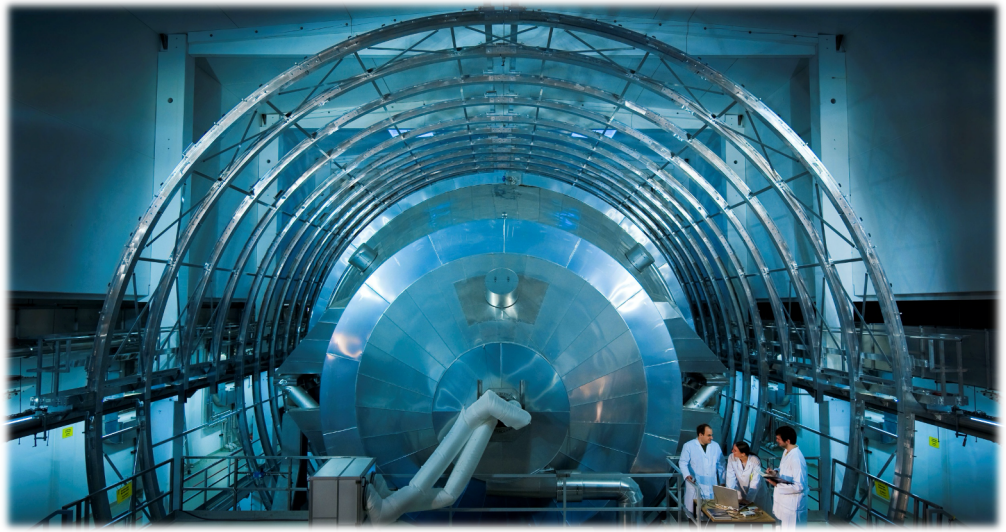
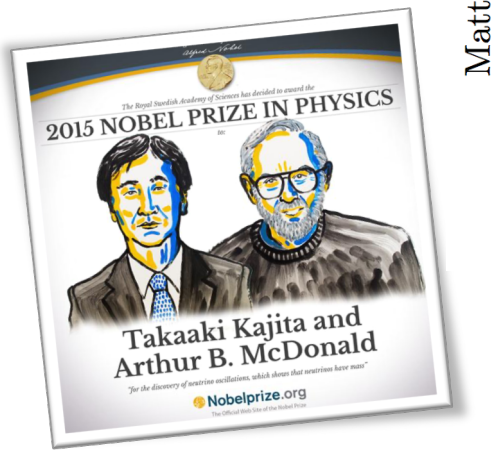
First Results from KATRIN

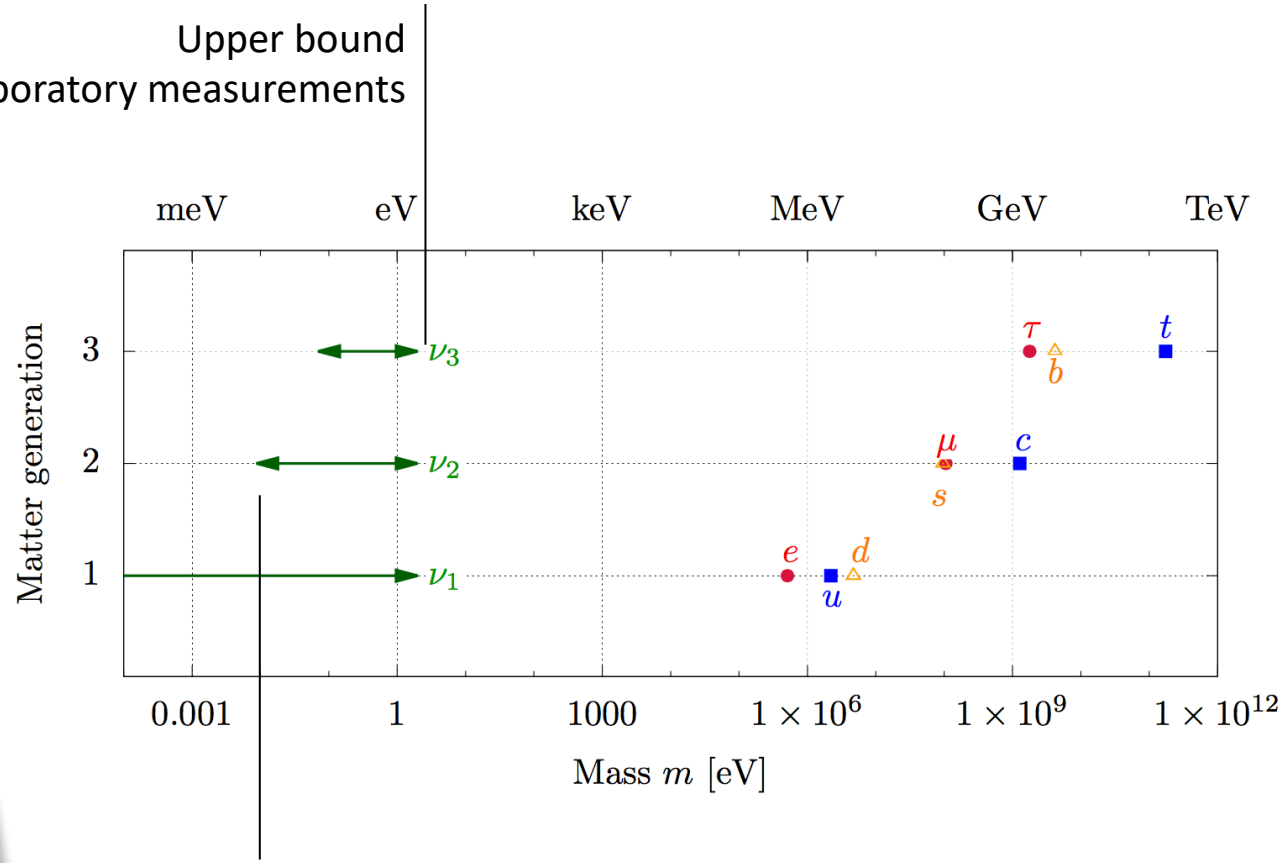


Thierry Lasserre (CEA & APC), BNL Seminar, 21/01/2021

On behalf the KATRIN collaboration

Neutrino mass





Neutrino mass

Model dependence

Laboratory-based probes

This talk

Cosmology

potential: m_ν = 10 - 50 meV

$$m_\nu = \sum_i m_i$$

Search for 0νßß

potential: $m_{ßß}$ = 7 - 17 meV

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

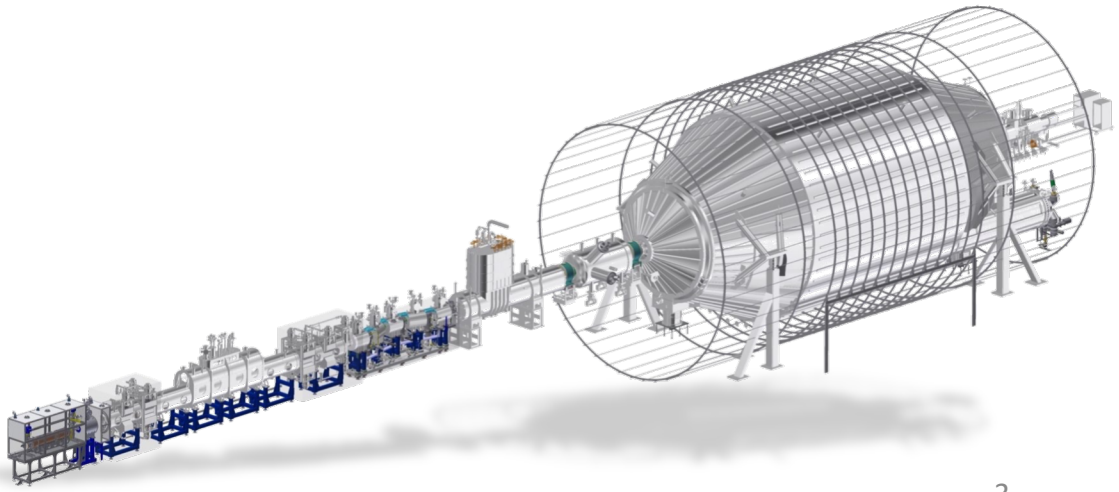
Kinematics of ß-decay

potential: m_β = 50 - 200 meV

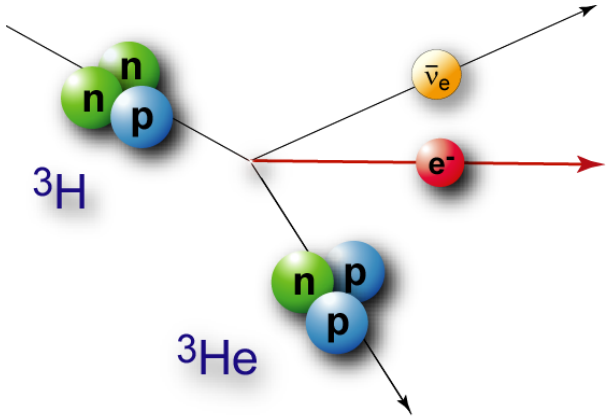
$$m_\beta^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$





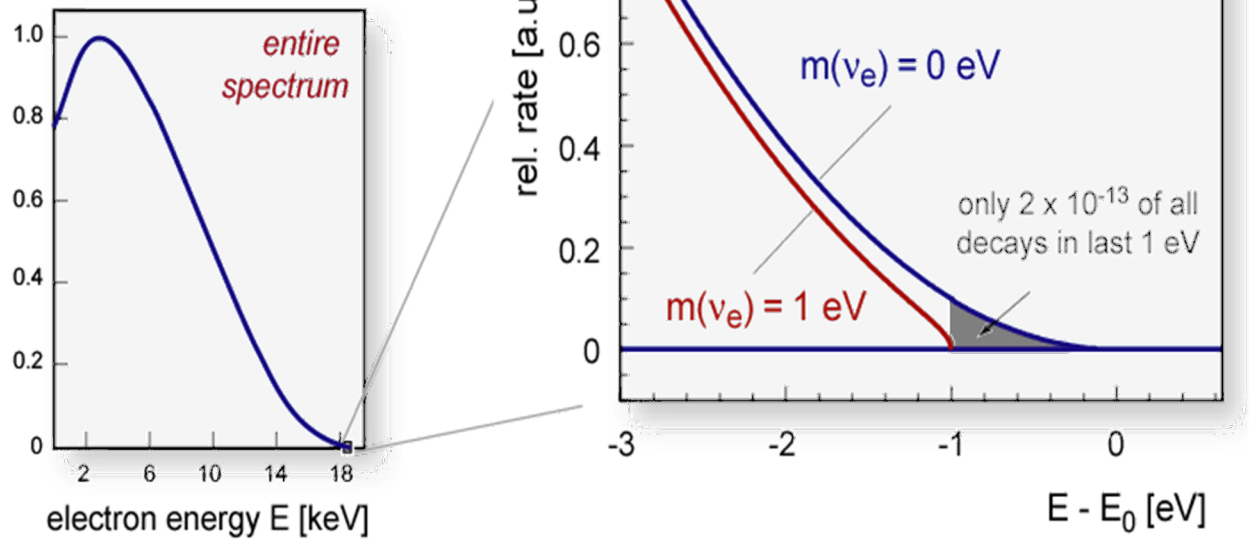


General idea



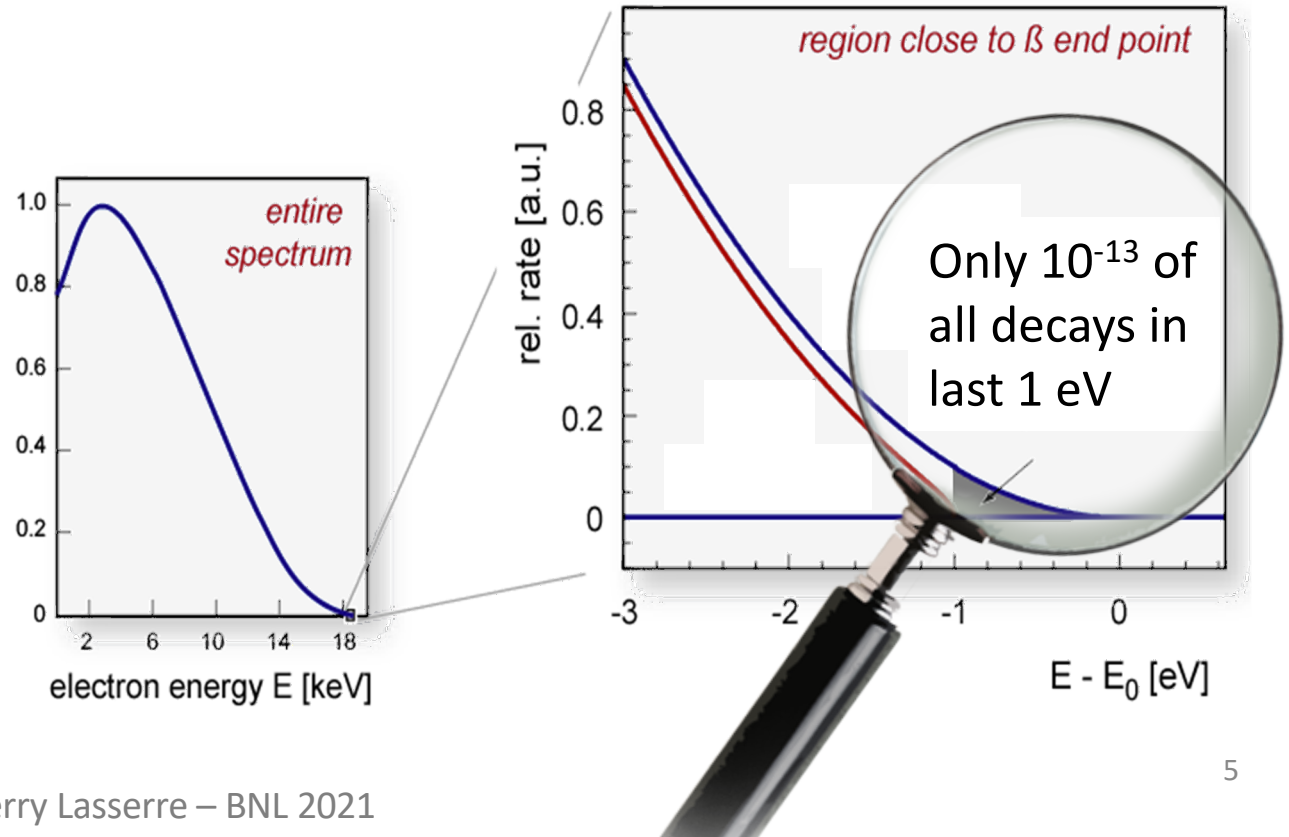
	^{3}H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.56 keV

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



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



KATRIN Setup


Karlsruhe
Tritium
Neutrino
Experiment

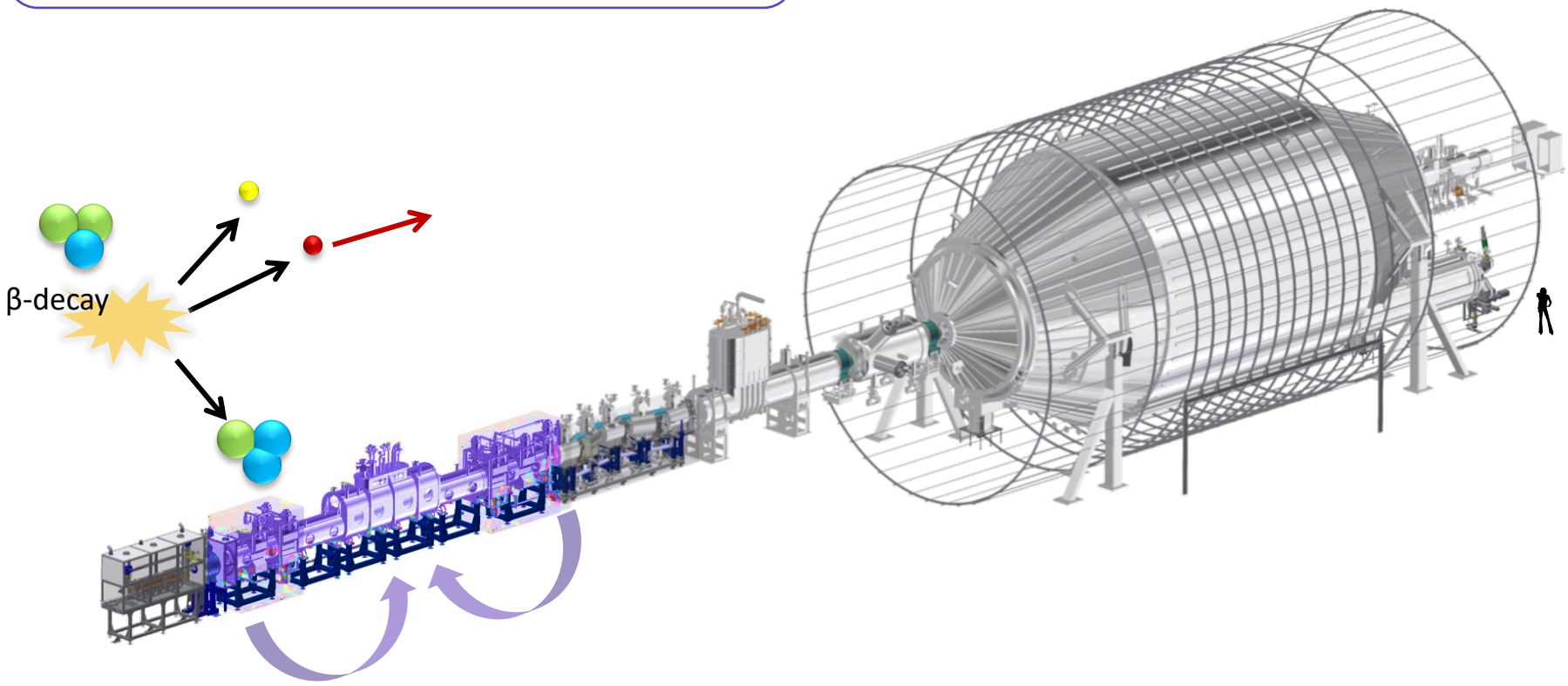
KATRIN

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



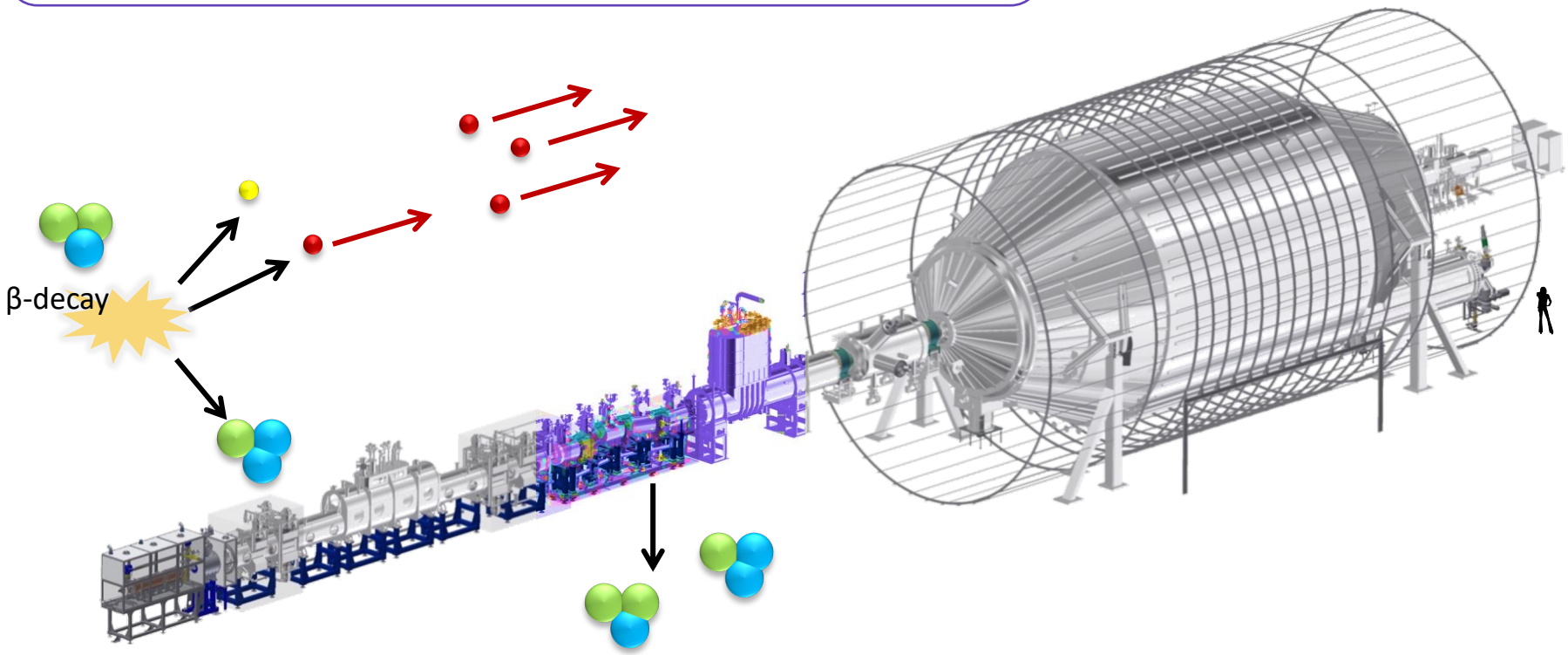
KATRIN Working Principle

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



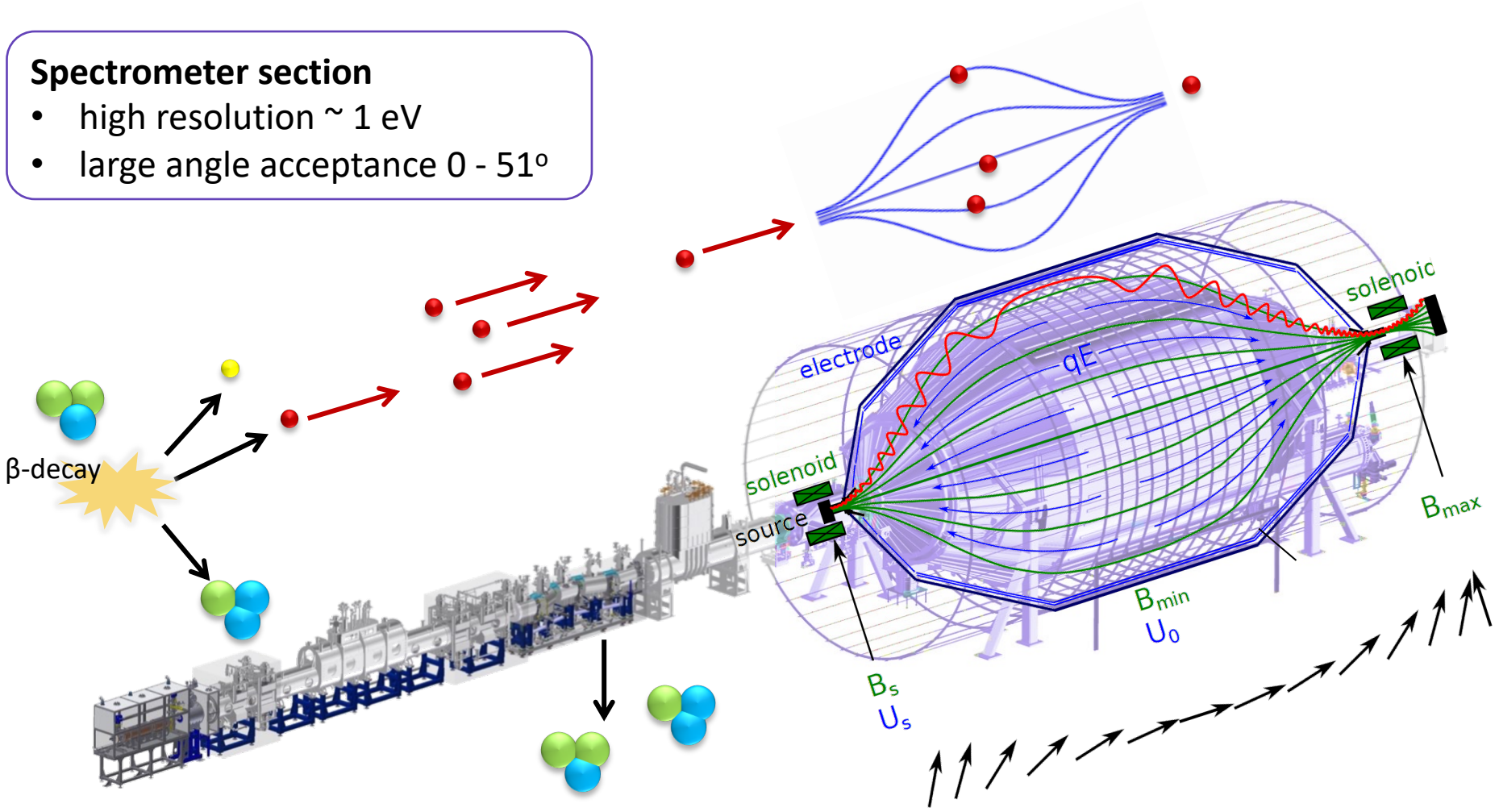
KATRIN Working Principle

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



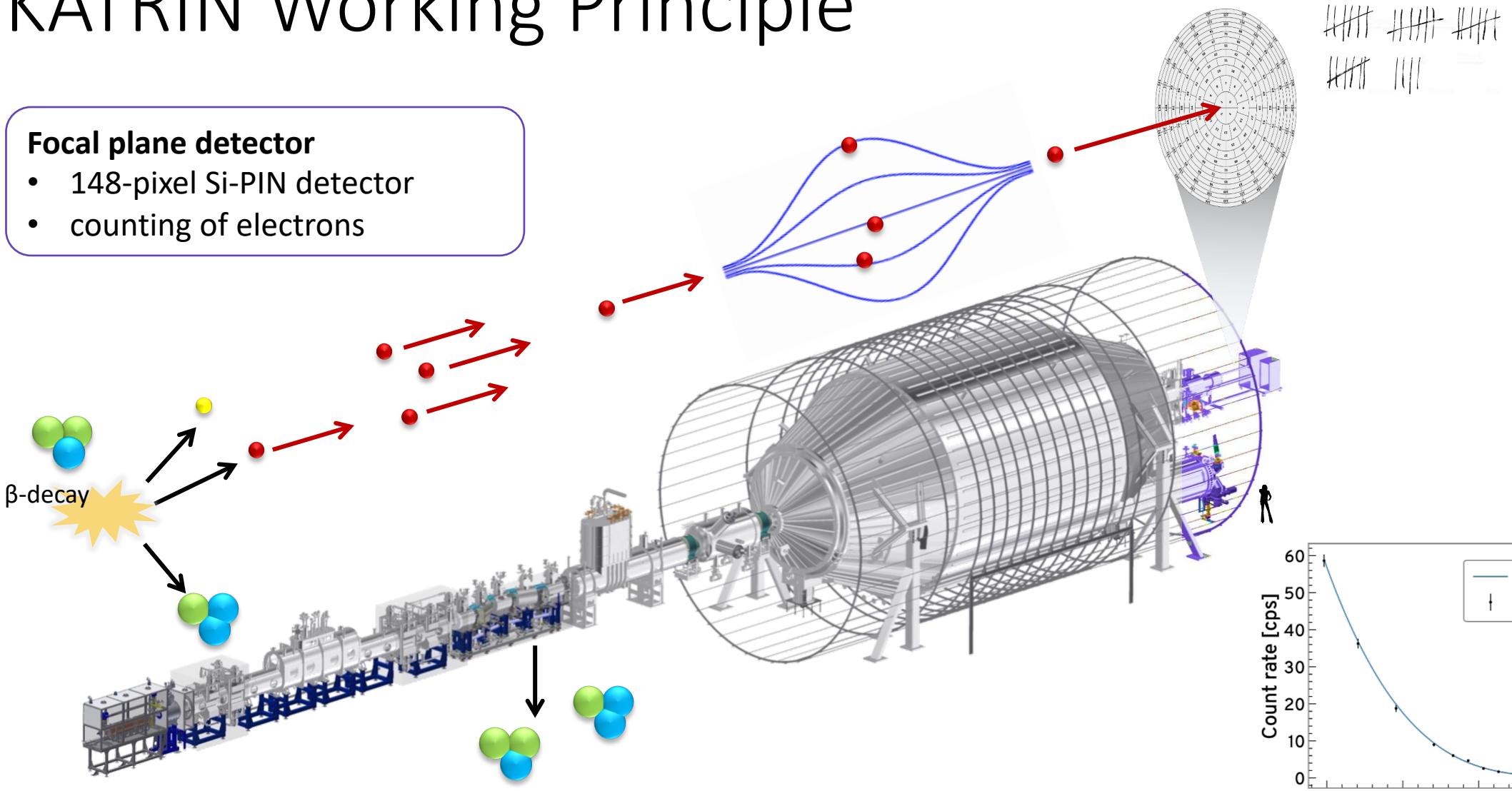
KATRIN Working Principle

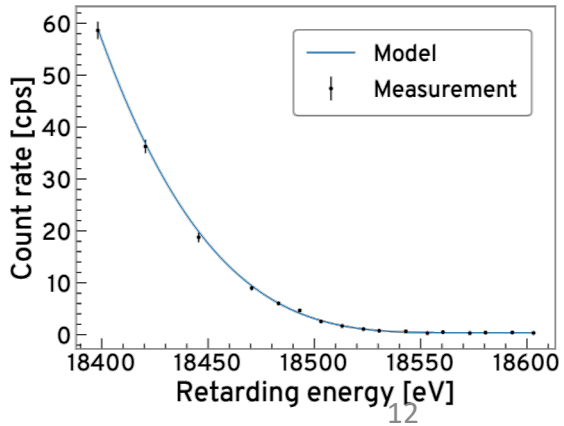
Spectrometer section
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°



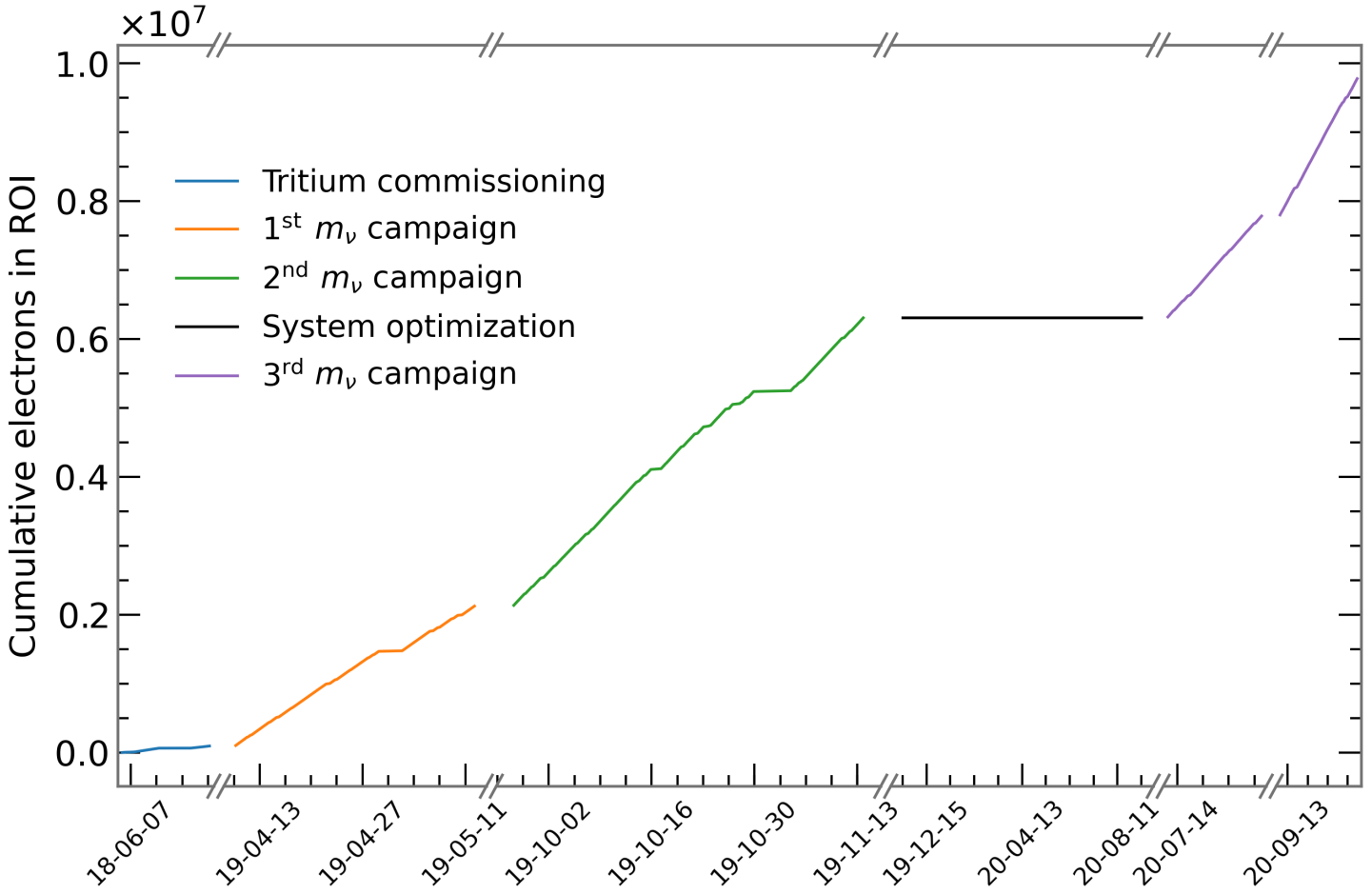
KATRIN Working Principle

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





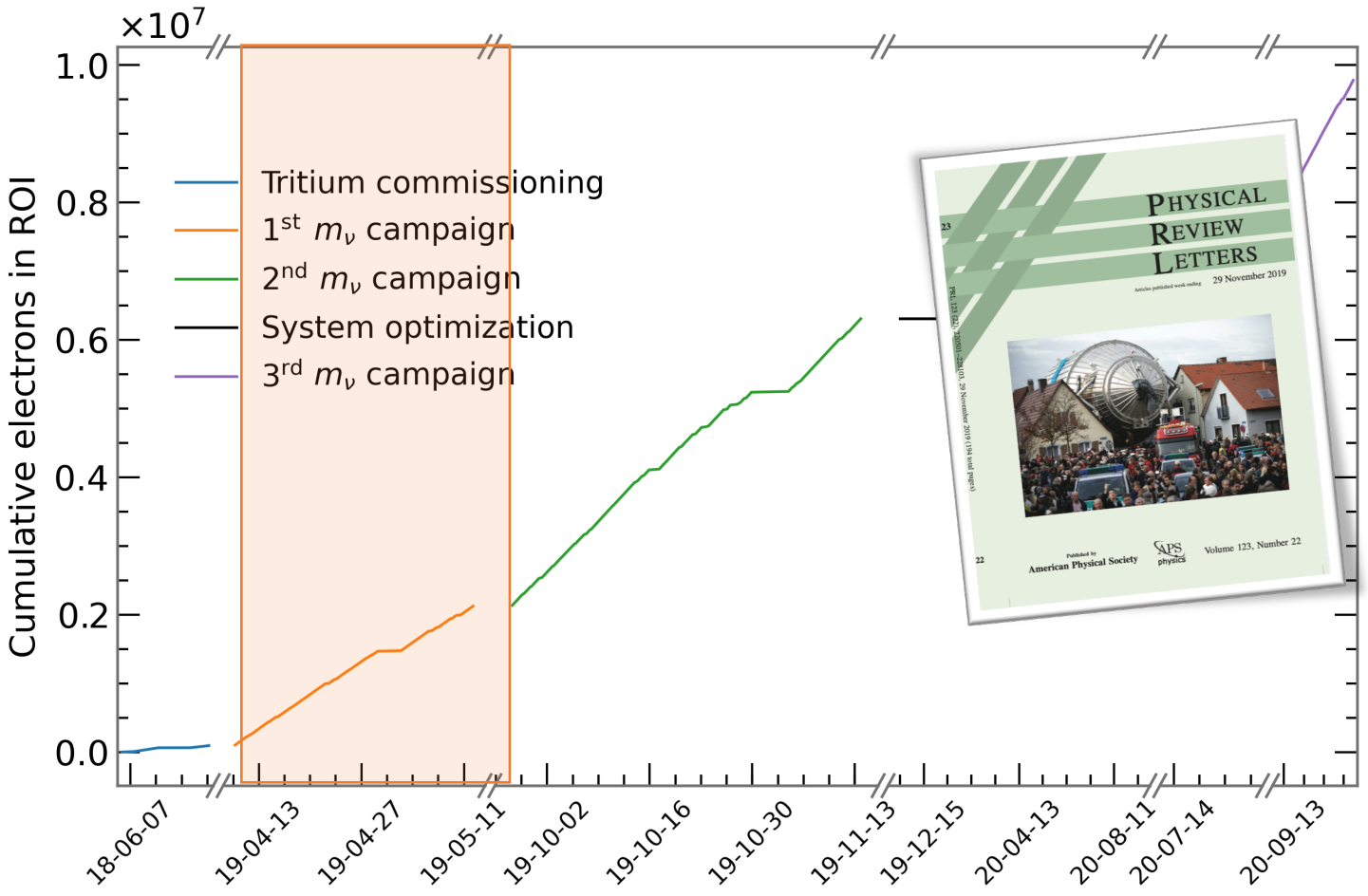
KATRIN Data Taking Overview



← 10 millions of electrons in the Neutrino mass ROI

First KATRIN Neutrino Mass Measurement

First neutrino mass campaign

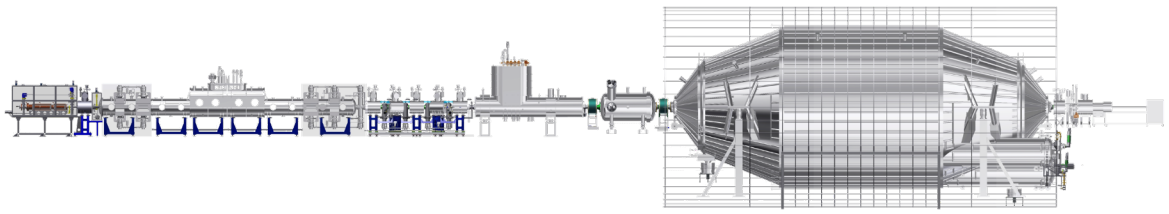


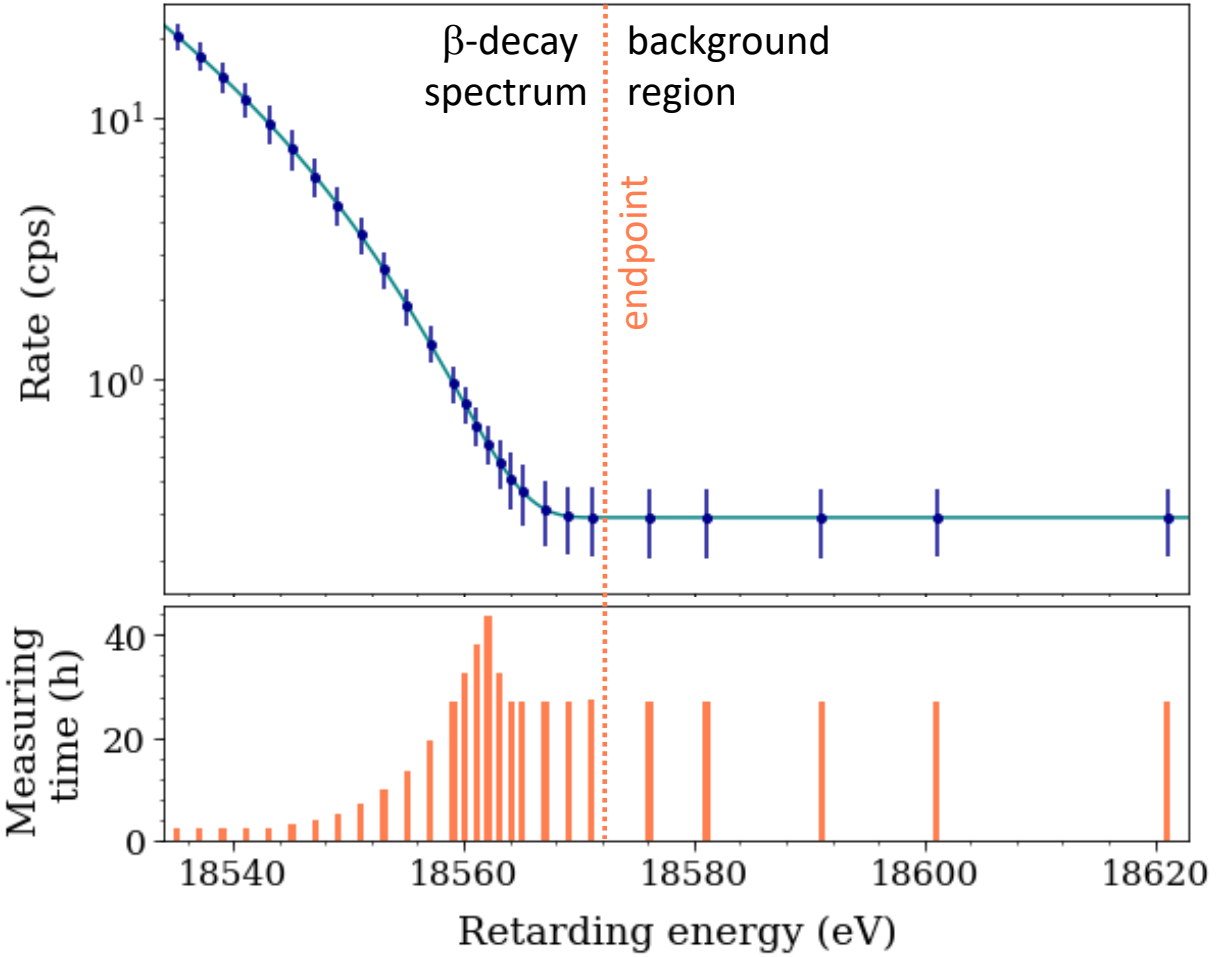
- Measurement Time: **22 days**
- Isotopic purity: **97.5% tritium**
- Gas density: **22%**
- Source activity: **$2.45 \cdot 10^{10}$ Bq**
- Total statistics: **$2 \cdot 10^{6}$ e's**

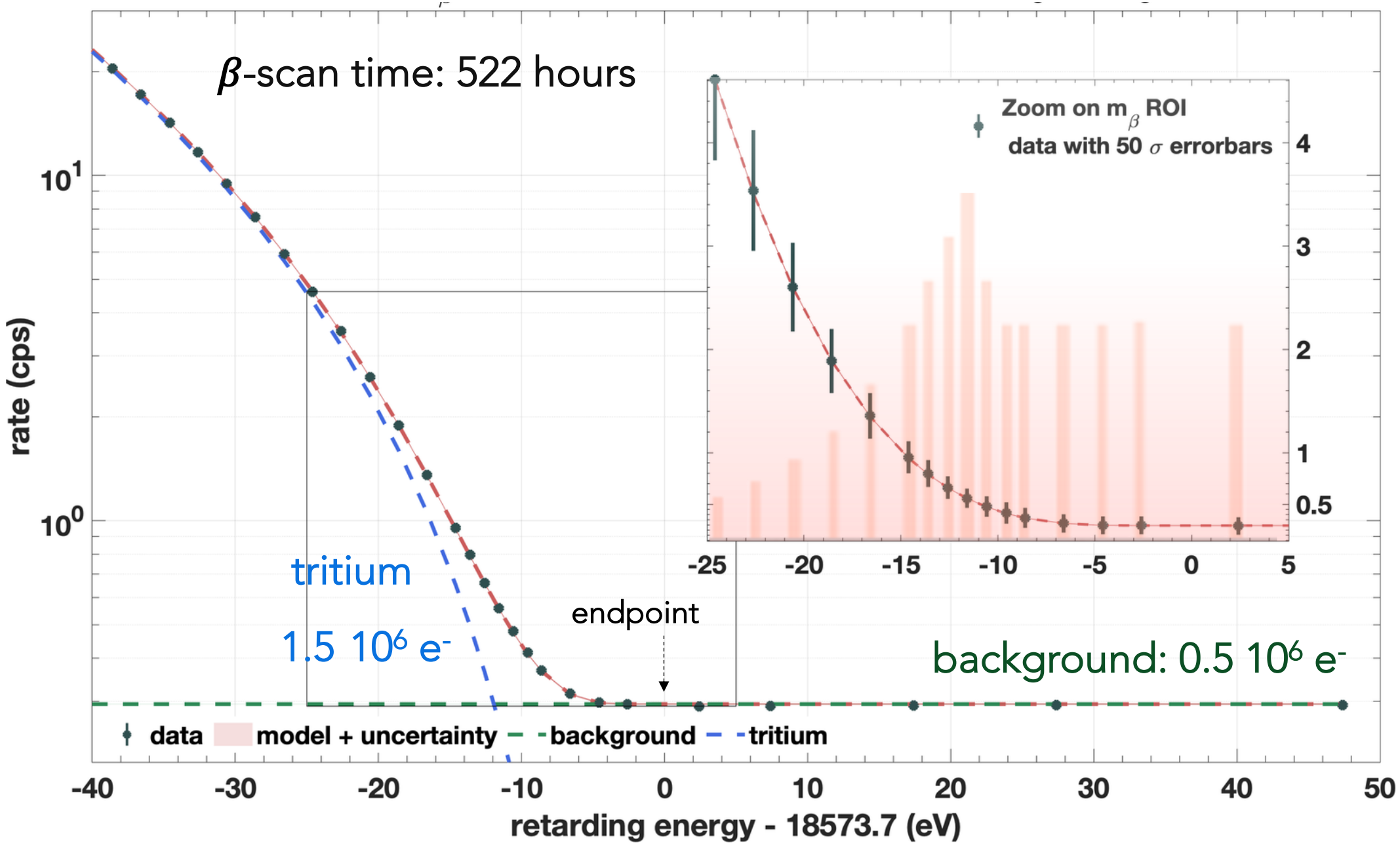
KATRIN Collab, Phys. Rev. Lett. 123, 221802 (2019)

Measurement strategy

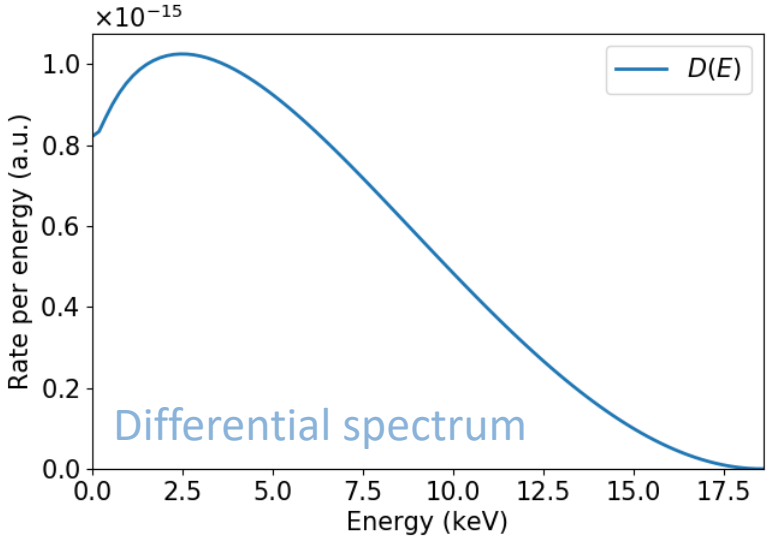
- # HV set points: **27**
- interval: **E_0 – 40 eV , E_0 + 50 eV**
- scanning time: **2 hours**
- # scans: **274**
- HV stability: **35 mV (ppm-level)**
- Background: **293 mcps**



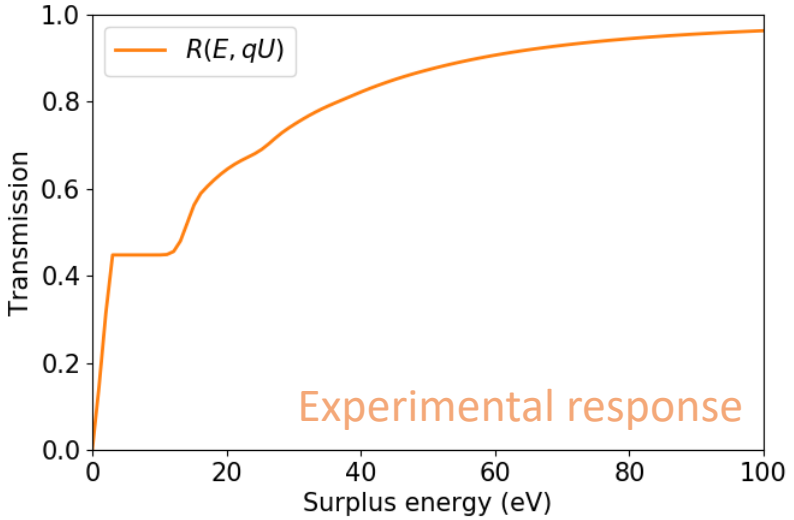



β-scan time: 522 hours
Zoom on m β ROI
data with 50 σ errorbars
tritium
1.5 10⁶ e⁻
endpoint
background: 0.5 10⁶ e⁻
data
model + uncertainty
background
tritium
rate (cps)
retarding energy - 18573.7 (eV)

Tritium spectrum calculation

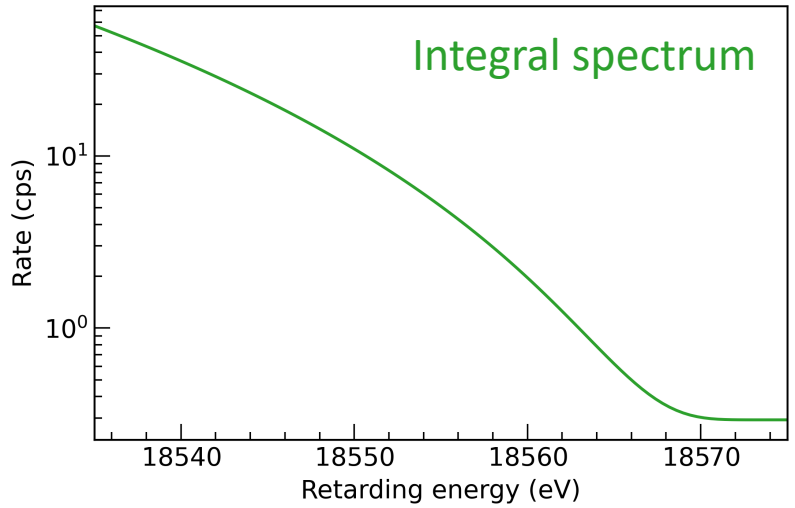


$$\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$$



- Molecular final states
- Doppler broadening
- Radiative corrections

(theory uncertainties)



- Spectrometer resolution
- Scattering in the source
- Synchrotron radiation

(experimental uncertainties)

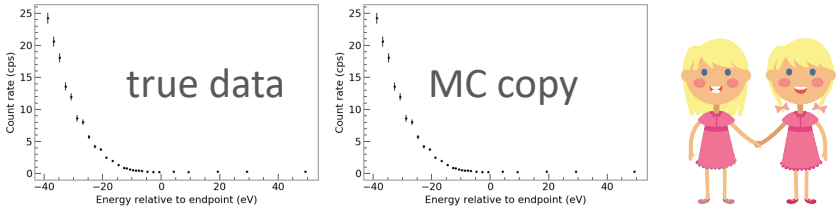
Y.-T. Lin et al, Phys. Rev. Lett. **124**, 222502 (2020)
A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000) + updates

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

Blinded analysis

Freeze analysis on MC-twin data

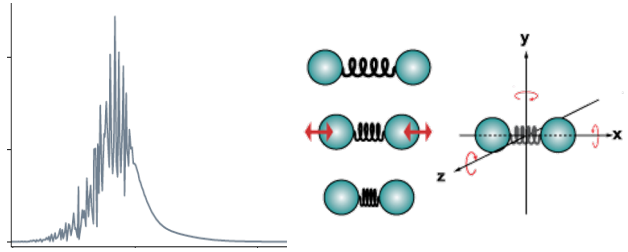
- MC-copy of each scan (with m_ν = 0 eV)



m_ν^2

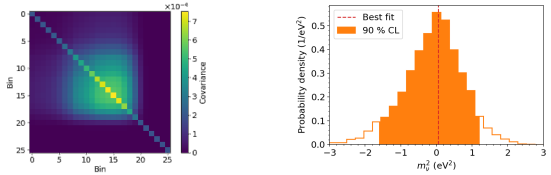
Blinded model

- Modified molecular final state dist.



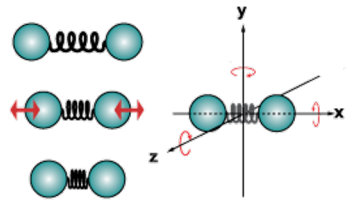
Two independent analysis strategies

- Covariance matrix
- Monte Carlo propagation



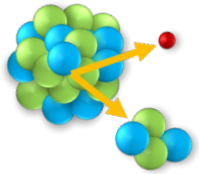
Systematic uncertainties

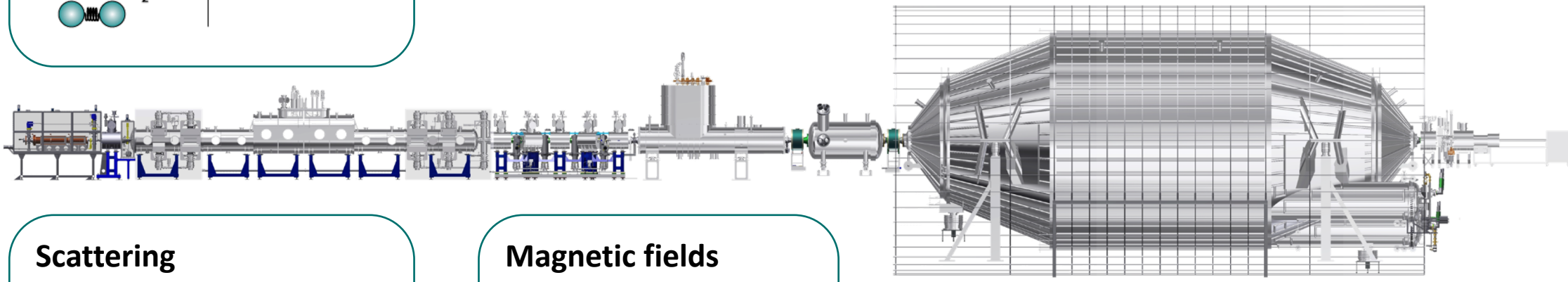
Molecular Final States



Background:

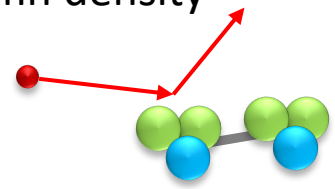
- time correlation
- retarding potential dependence





Scattering

- energy loss
- column density



Magnetic fields

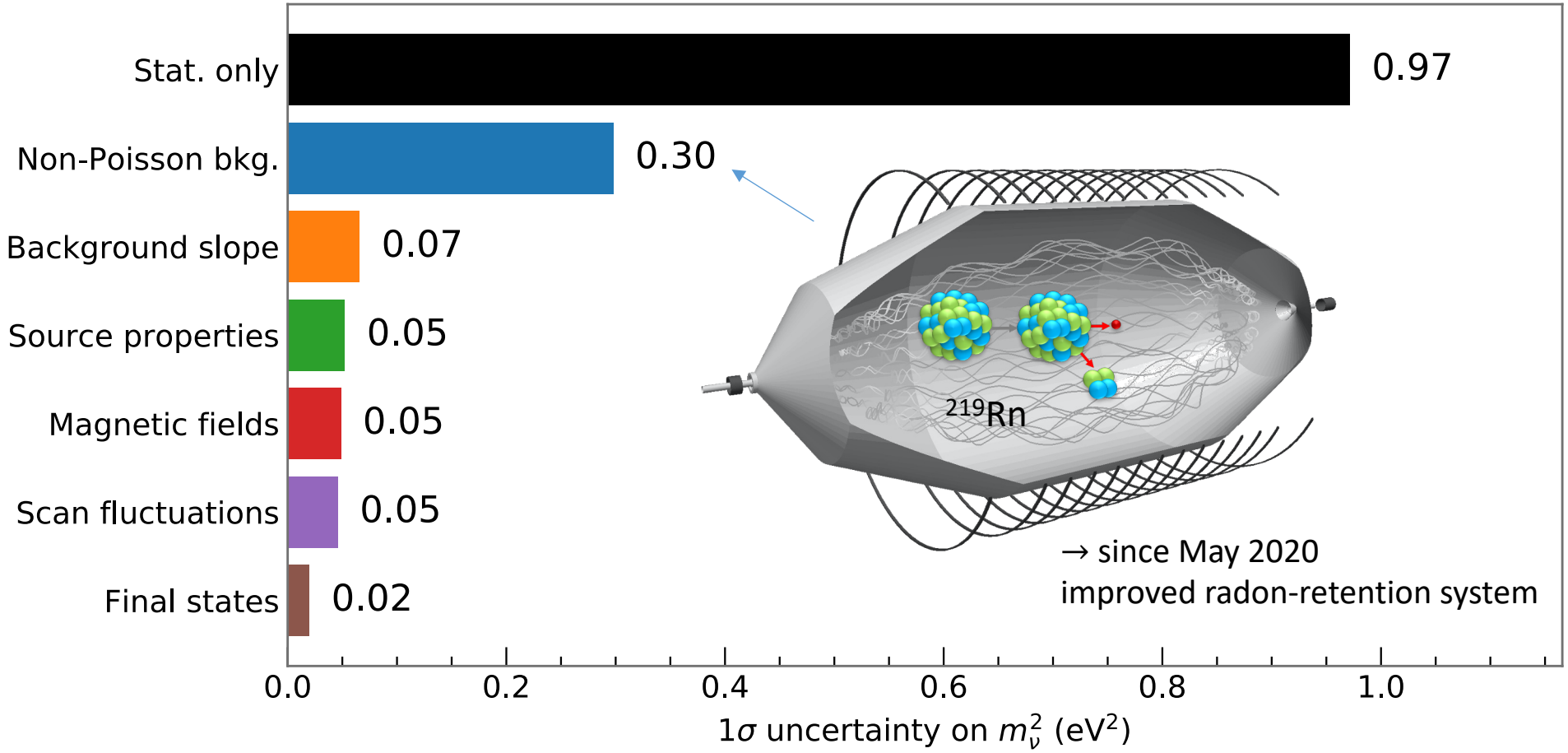
- source
- spectrometer
- detector



Data combination



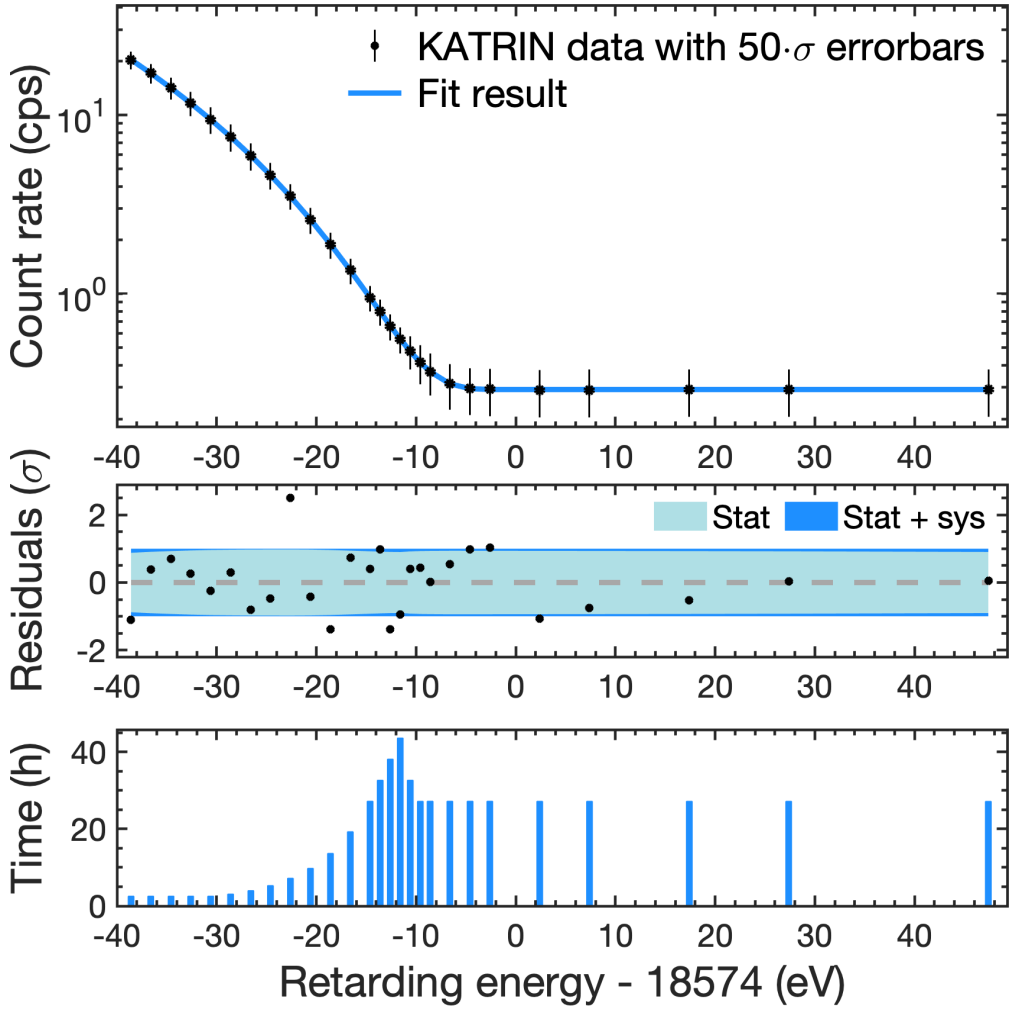
Budget of uncertainties



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



Best fit results:

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

→ compatible with zero

→ probability of 16%, if true $m_\nu = 0$ eV

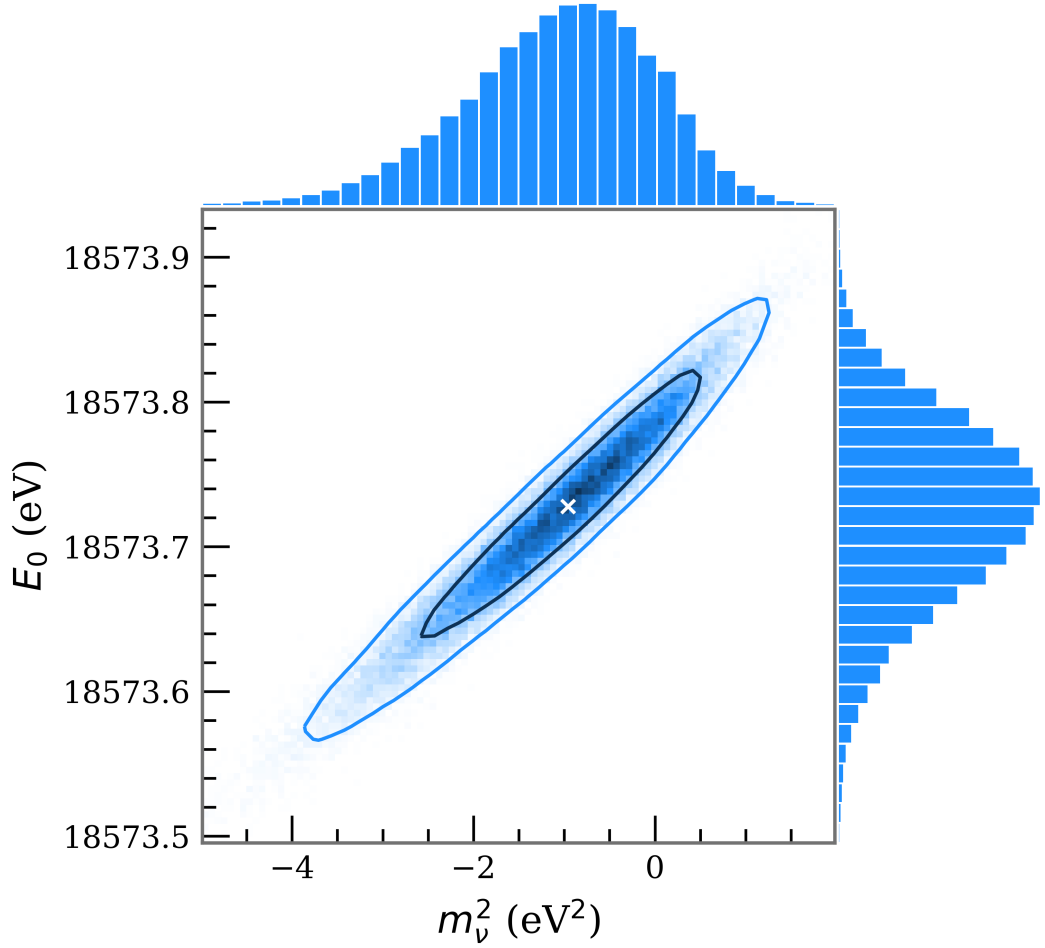
$$E_0 = 18573.7 \pm 0.1\ \text{eV}$$

→ 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)

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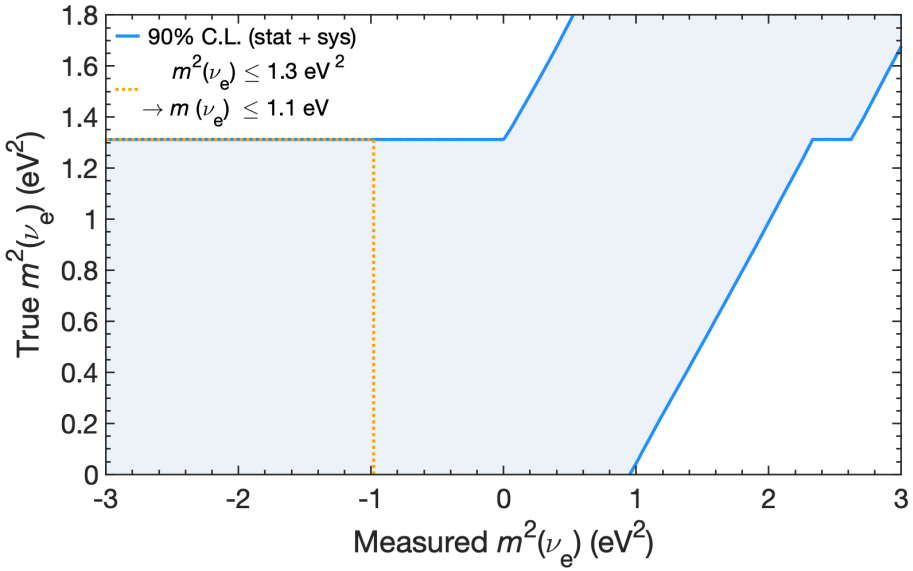
E. Myers et al. Phys. Rev. Lett. 114, 013003 (2015)

Improved neutrino mass limit



Lokhov-Tkachov

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

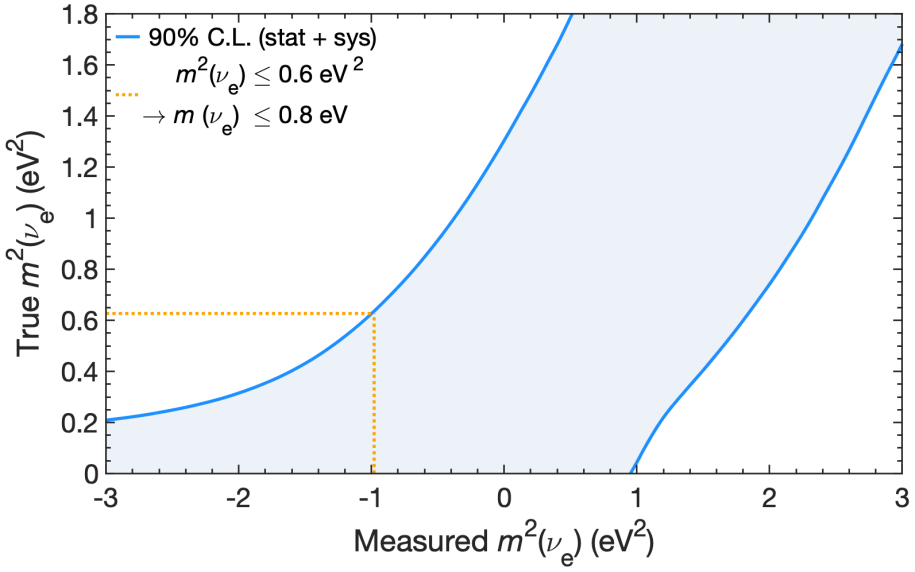


Feldman-Cousins

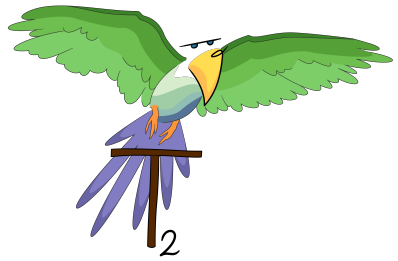
- $m_\nu < 0.8$ eV (90% CL)

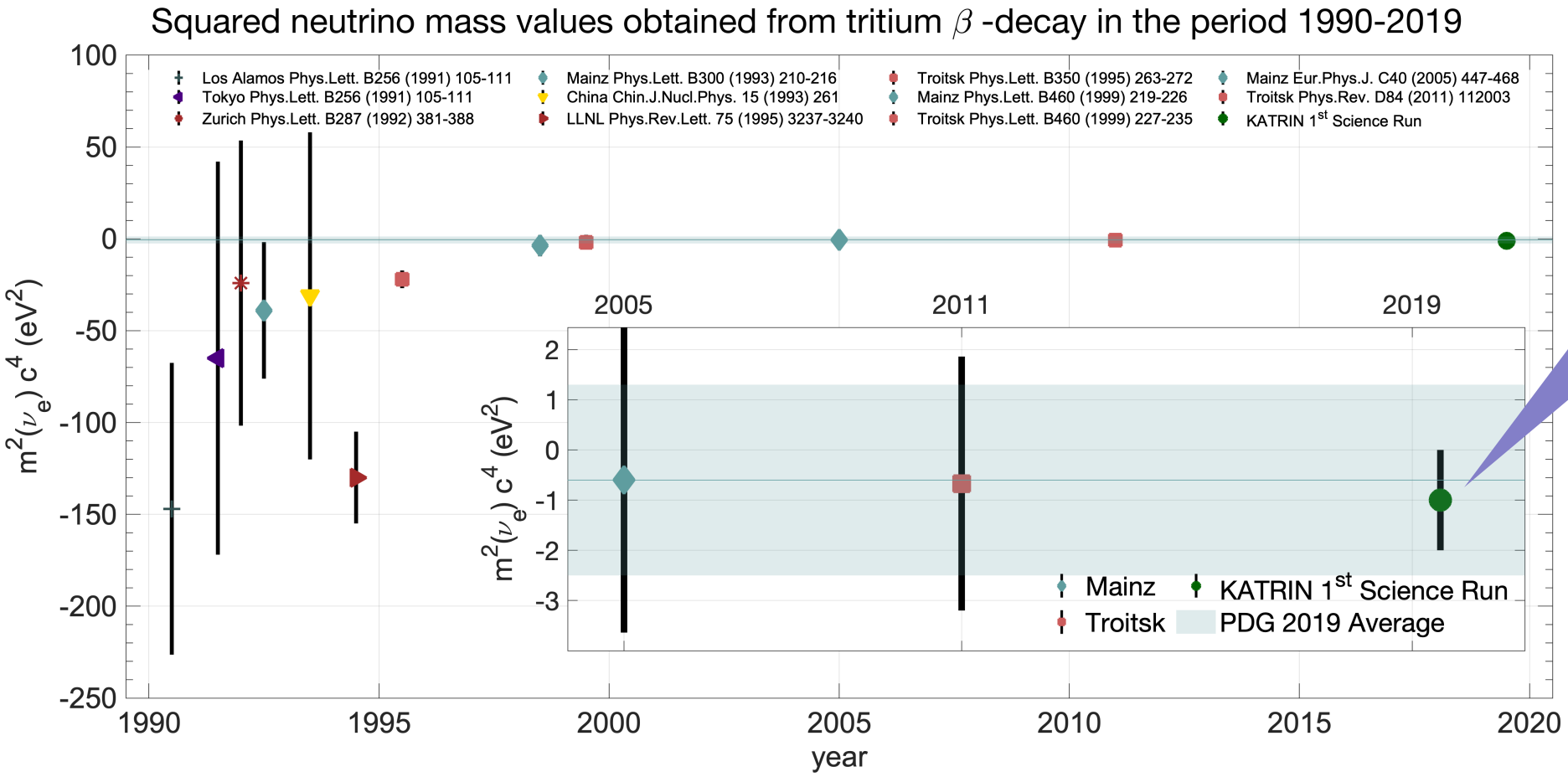
Bayesian Confidence Interval ($m_\nu^2 > 0$, flat)

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



Historical context

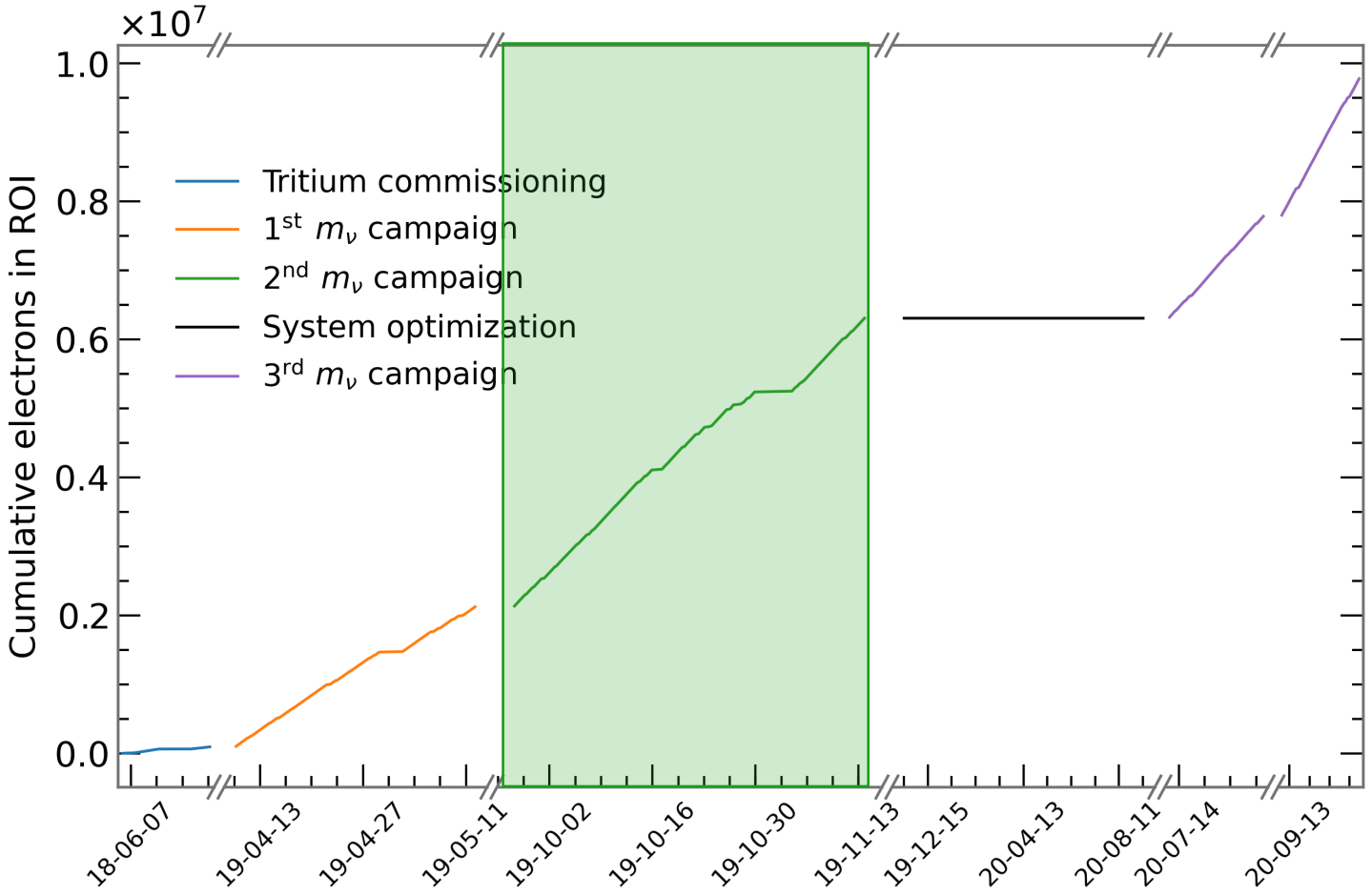




Effective 5 days of data
- Stat. error: ÷ 2
- Syst. error: ÷ 6

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

2nd neutrino mass campaign (2019-2020)



- 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**
- **m_ν–sensitivity:** **0.7 eV (90% CL)**

✓ Data unblinded in January!

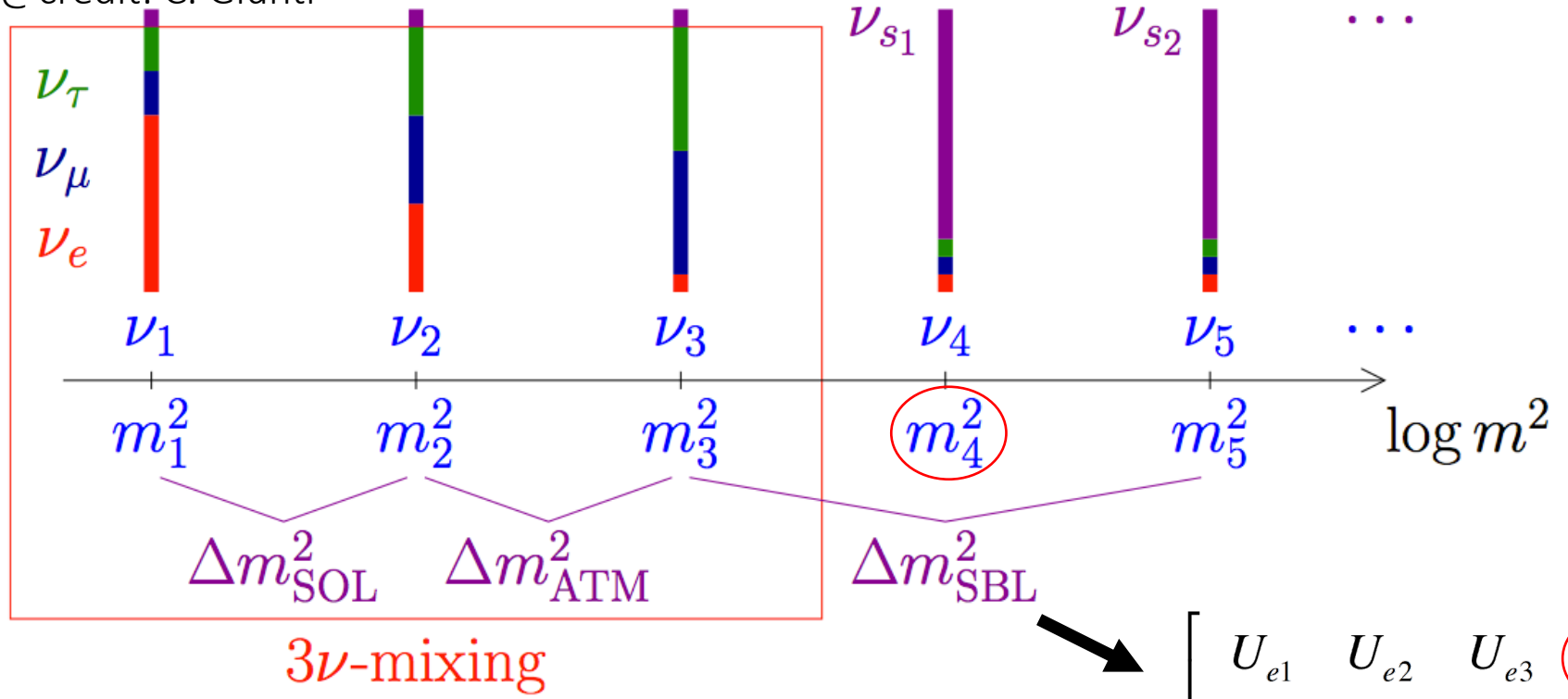
sub-eV sensitivity

First KATRIN Light Sterile Neutrino Search

Sterile Neutrinos – General Idea

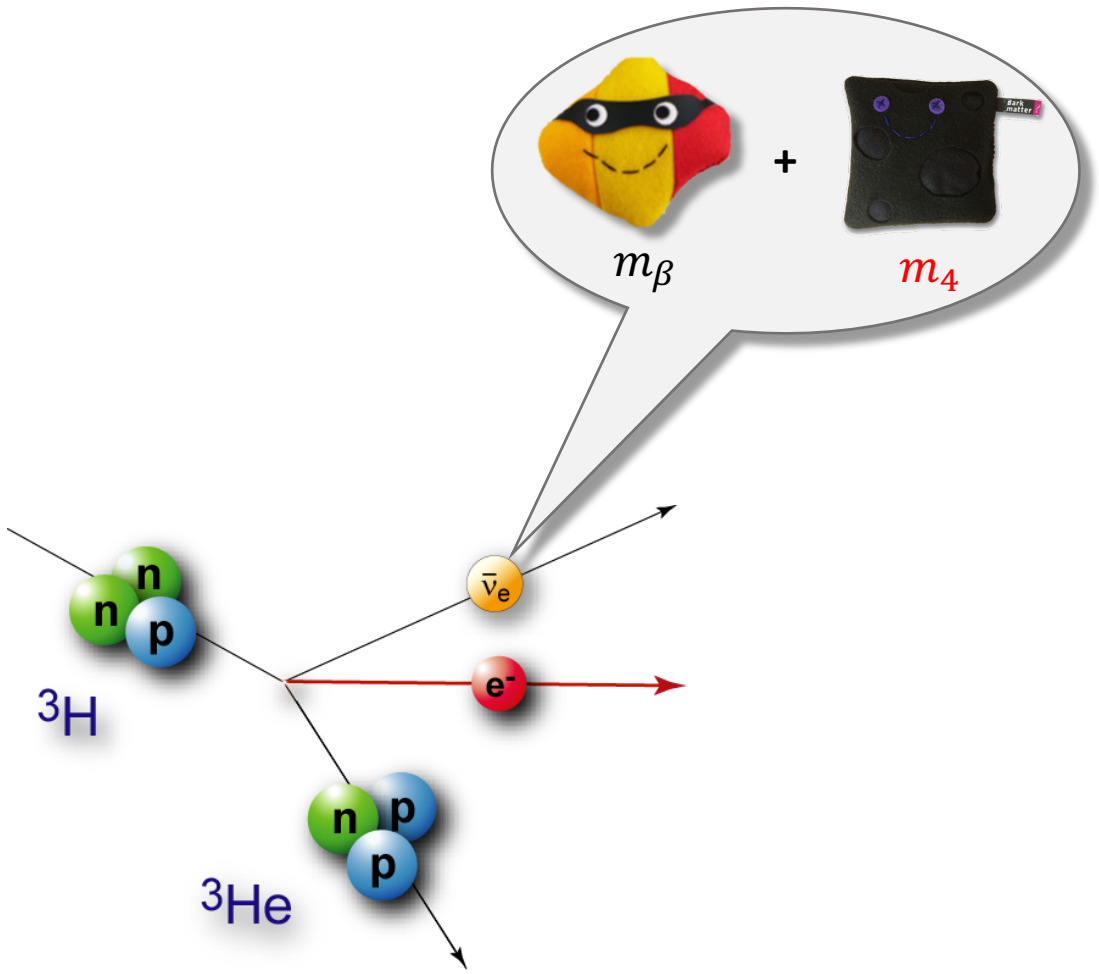
No – or extra-weak SM interaction
Mixing with active ν's

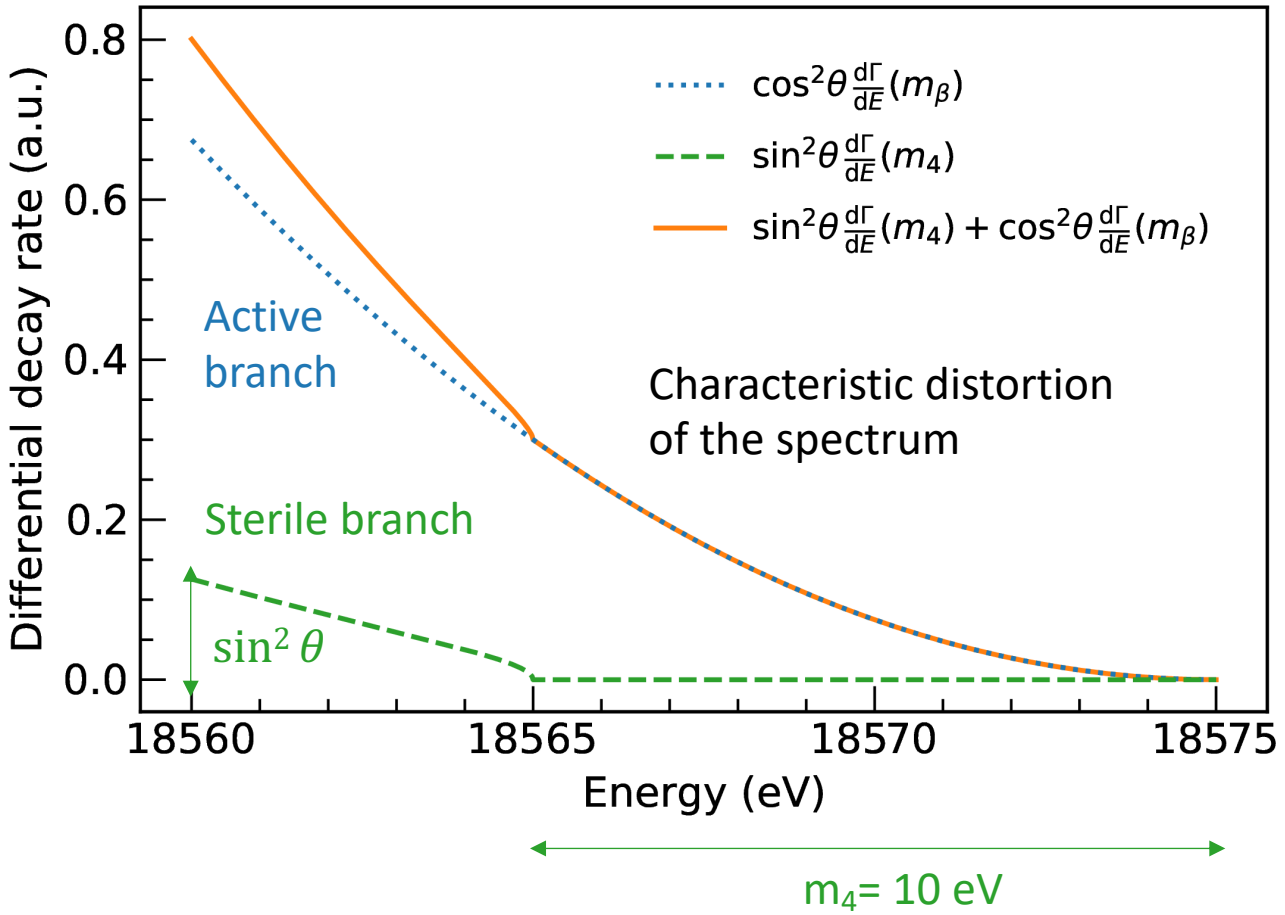
@credit: C. Giunti



$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

eV-Sterile neutrino signature in KATRIN

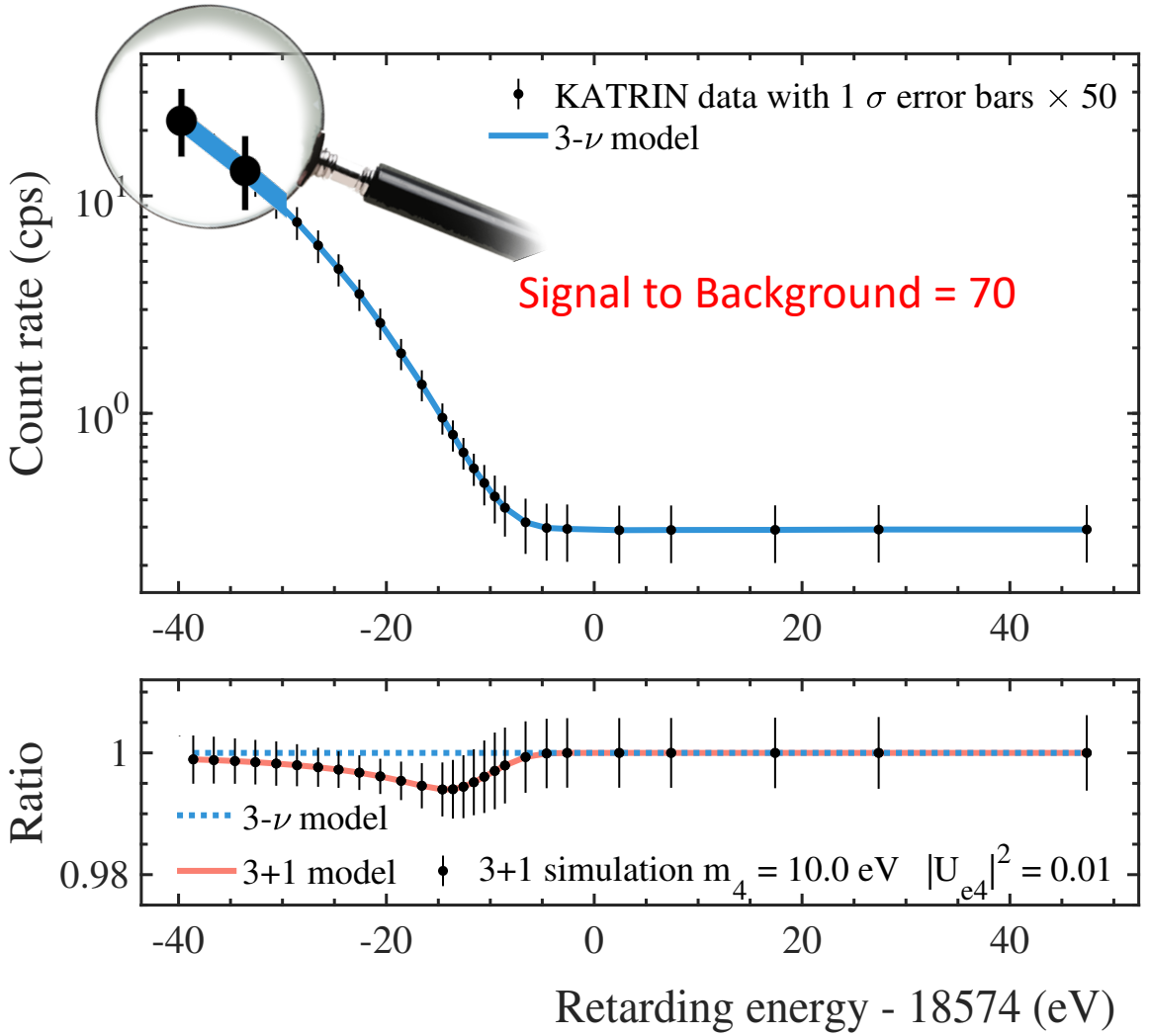




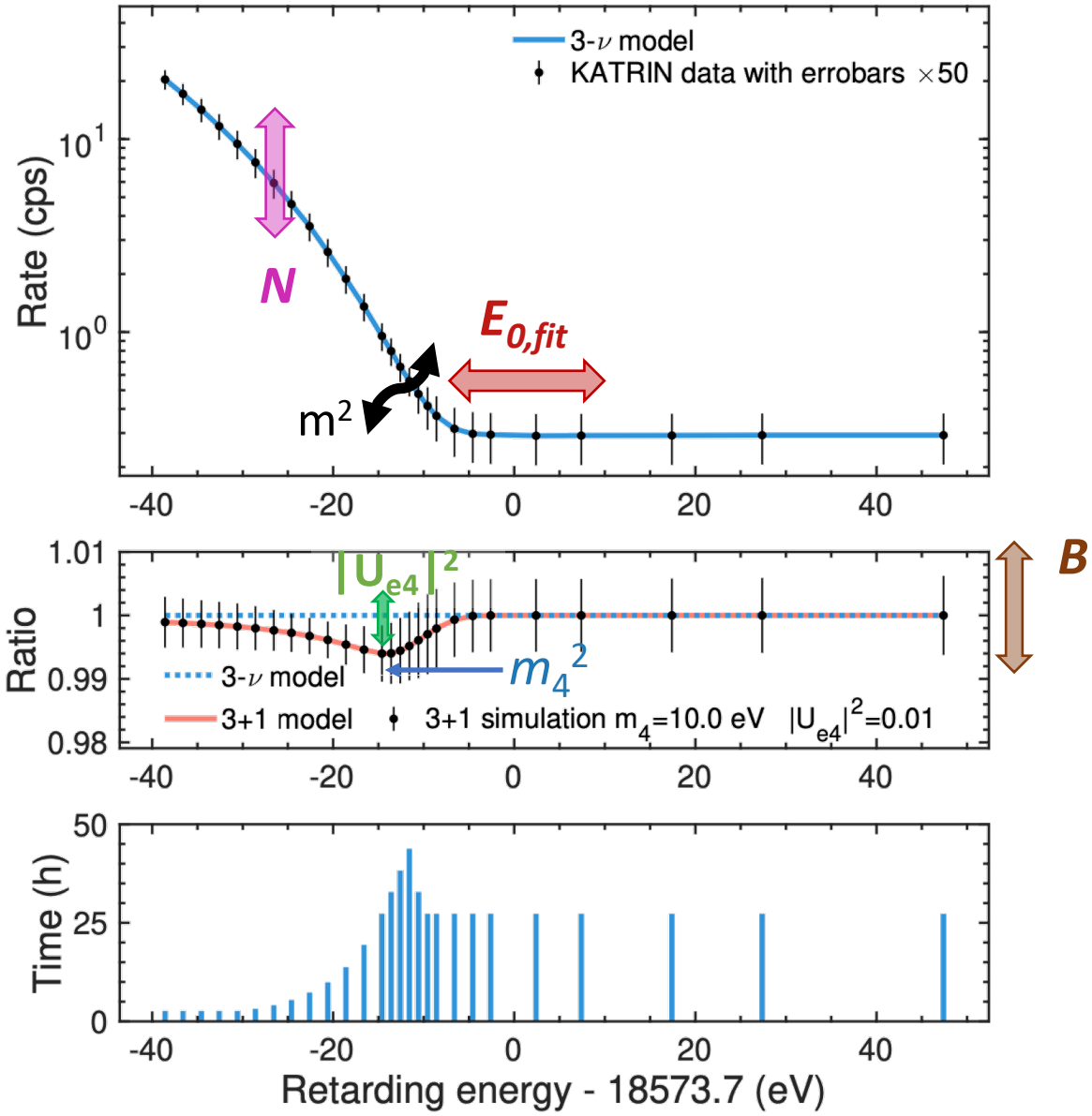
Sterile ν search in first science run

- same data set as for neutrino mass
- 3+1 sterile neutrino model
- grid search in $(m_4)^2, \sin^2\theta$ plane

simulation →



Sterile Neutrino Modeling



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

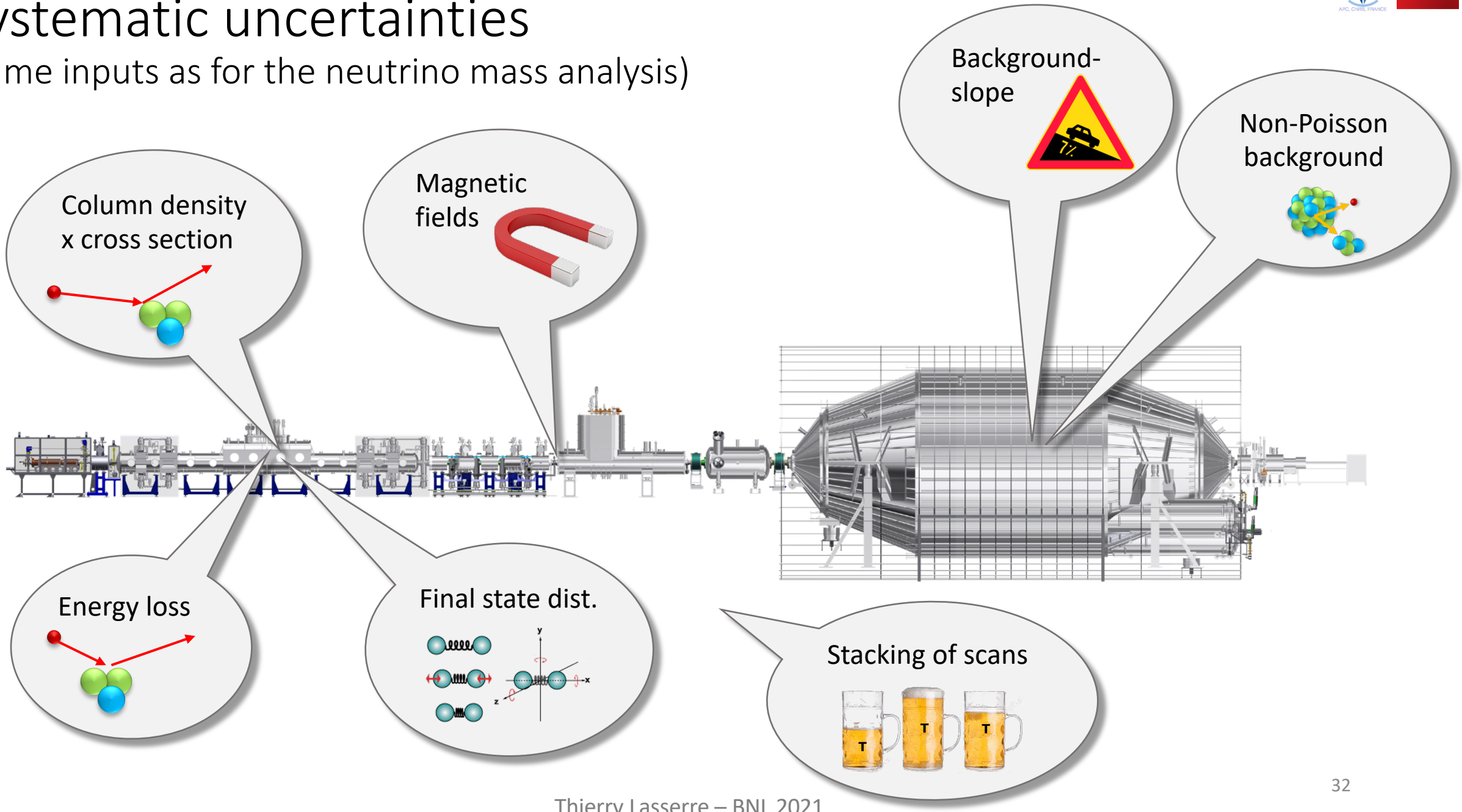
Fit Parameters:

m^2	neutrino mass (fixed/free/constrained)
$E_{0,fit}$	endpoint
N	signal normalization
B	energy-independent background rate

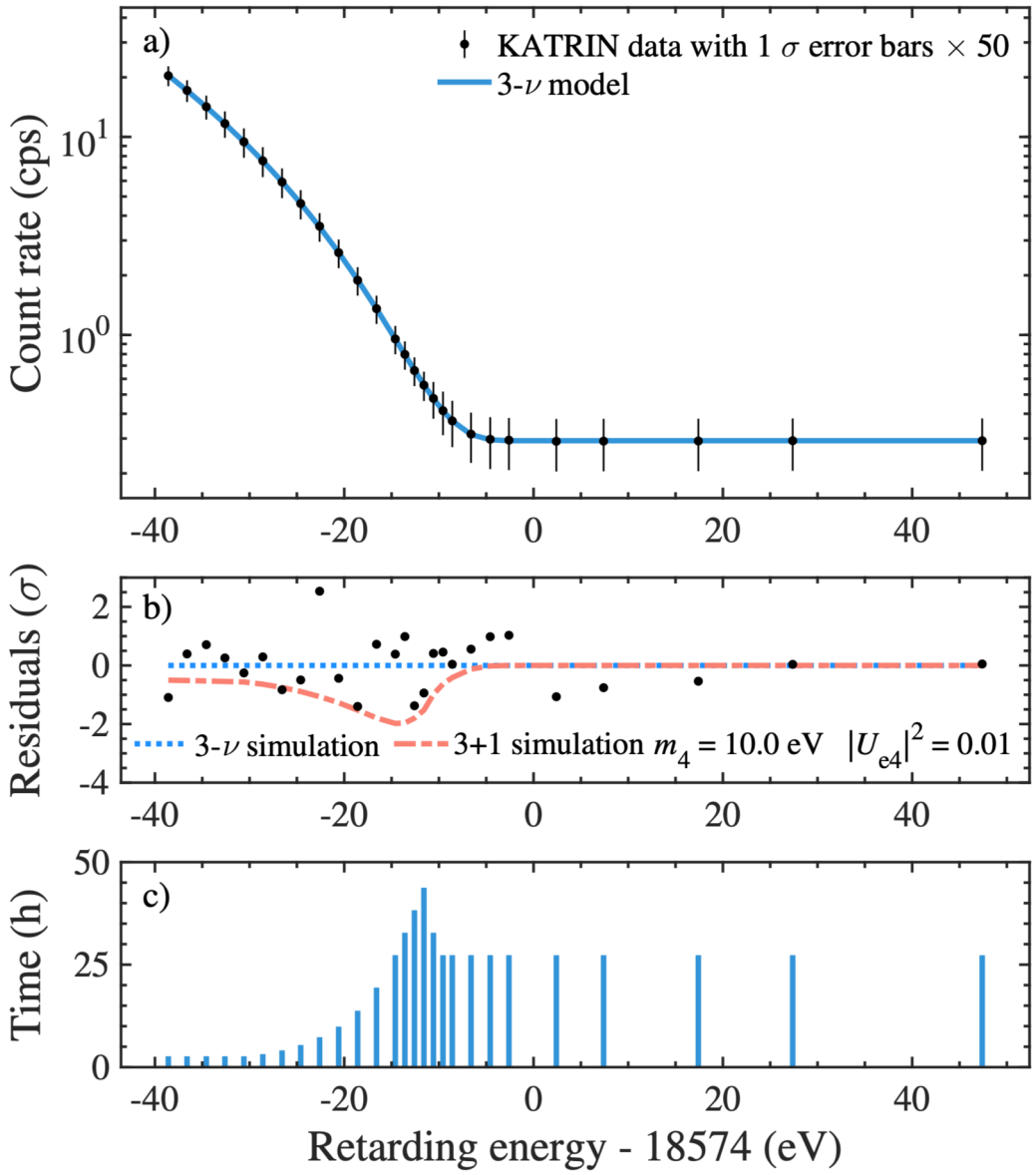
m_4^2	4th neutrino mass
$\|U_{e4}\|^2$	4th neutrino mixing

Systematic uncertainties

(same inputs as for the neutrino mass analysis)



KATRIN 3+1 Neutrino Fit (40 eV range)

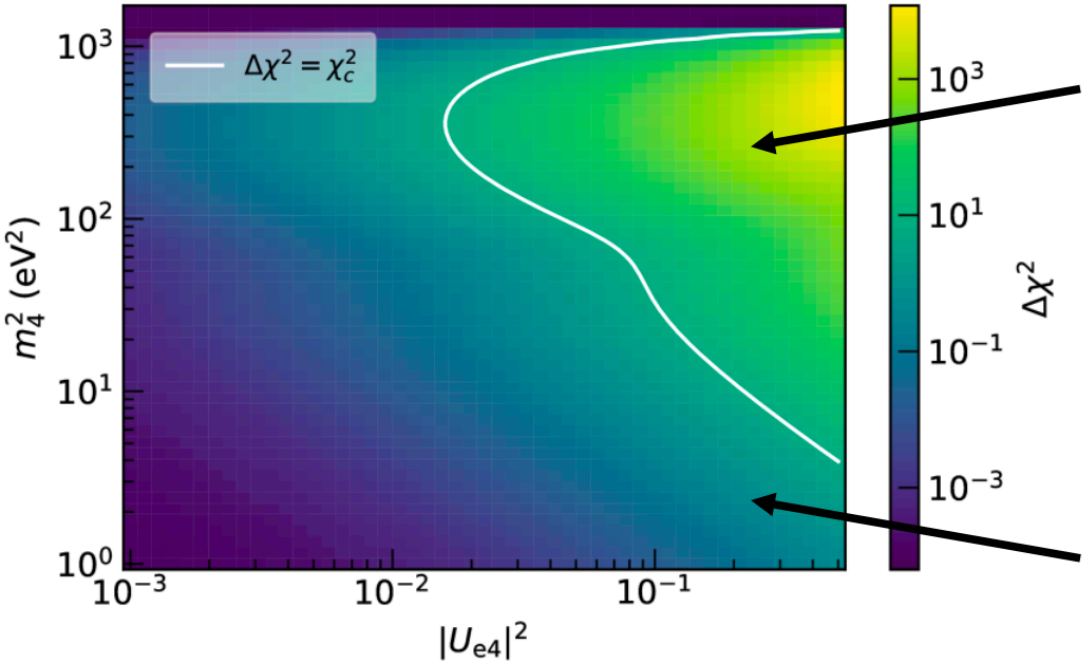


No evidence for sterile neutrino signal

Best fit	3ν (NH)	3+1
m_4^2	-	73.0
$\|Ue_4{}^2\|$	-	0.034
$p-value$	0.41	0.50
χ^2	22.9	21.3
$\Delta\chi^2$	1.6 (54.5% C.L)	

Confidence Interval (95 % C.L.)

- χ^2 analysis, systematic effects included via covariance matrix
- Likelihood ratio for given sterile parameters: $\Delta\chi^2\left(|U_{e4}|^2, m_4^2\right) = \chi^2\left(|U_{e4}|^2, m_4^2\right) - \chi^2_{\text{best}}$



parameters for which $\Delta\chi^2 > \Delta\chi^2_c$ are excluded

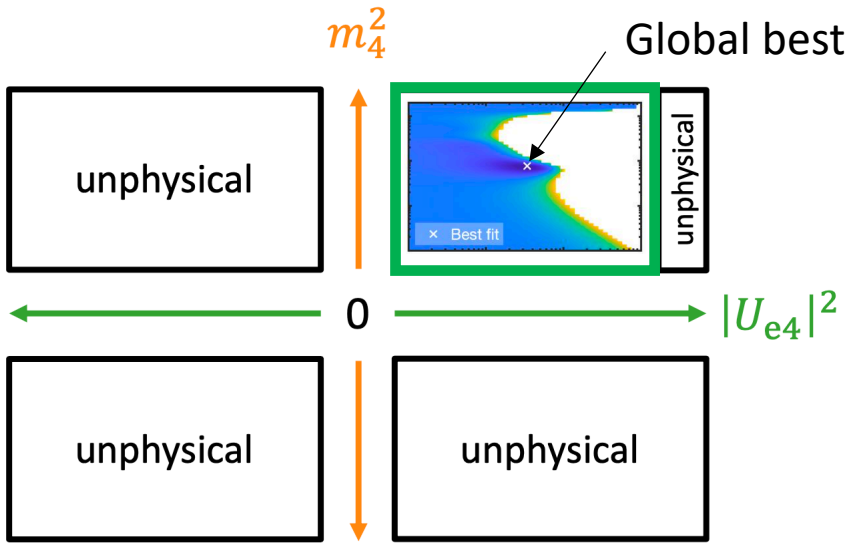
accepted

- Good approximation by Wilks' theorem: $\Delta\chi^2_c$ = 5.99 for the 95% C.L.
  95 % quantile of χ^2 distribution with 2 dof was verified with >5000 MC simulations ($\Delta\chi^2_c$ = 6.18)

Complementary Investigations

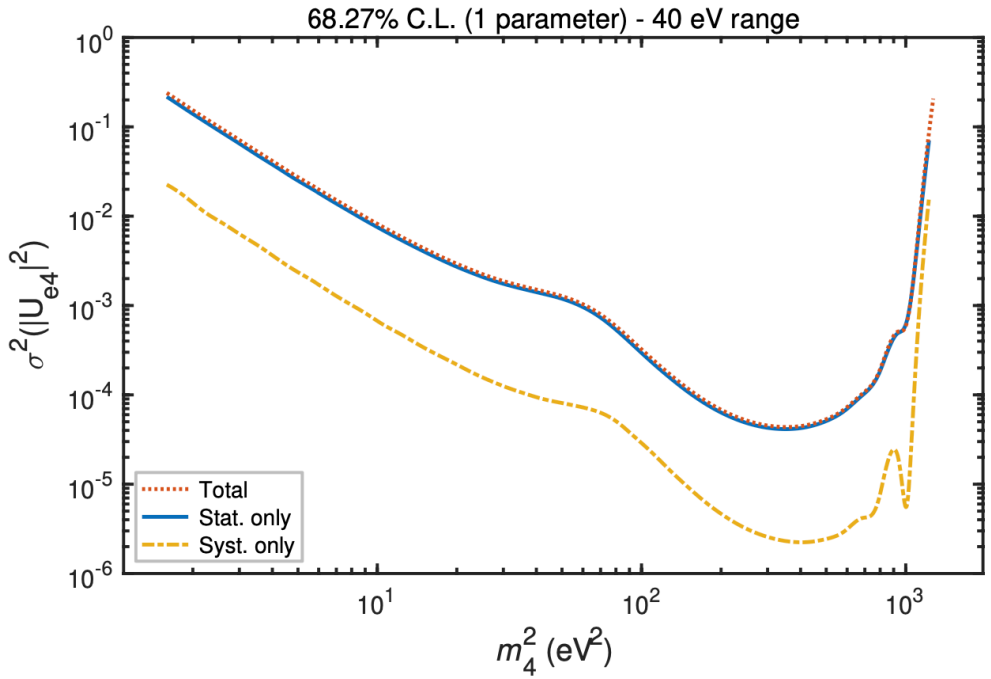
Analysis performed in non-physical regions

- $|Ue_4{}^2| < 0$ negative β-decay rate at the heavy neutrino branch
- $|Ue_4{}^2| > 0.5$ unphysical mixing
- $m_4^2 < 0$ tachyonic sterile neutrino



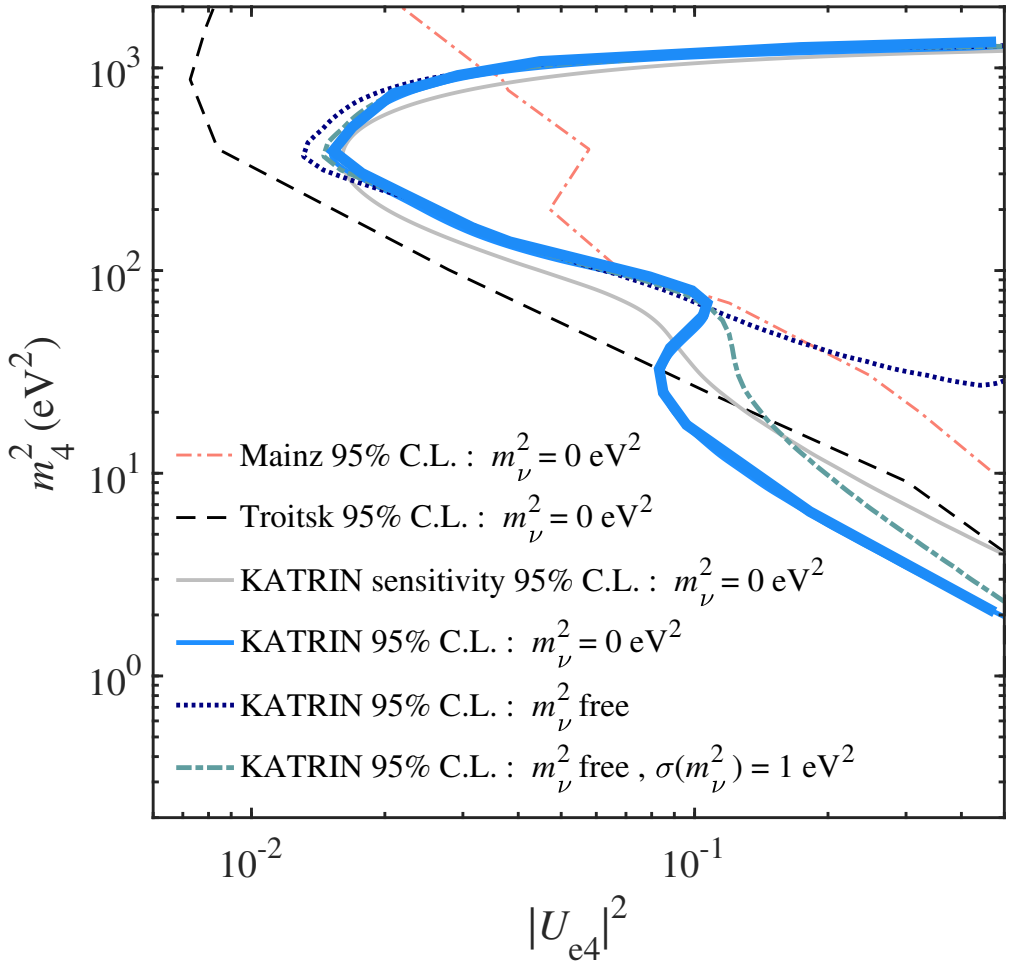
Raster scan

- choose a fixed value of m_4^2 and extract a $|Ue_4{}^2|$
- repeat for all physical m_4^2 - extract $\sigma(|Ue_4{}^2|)$



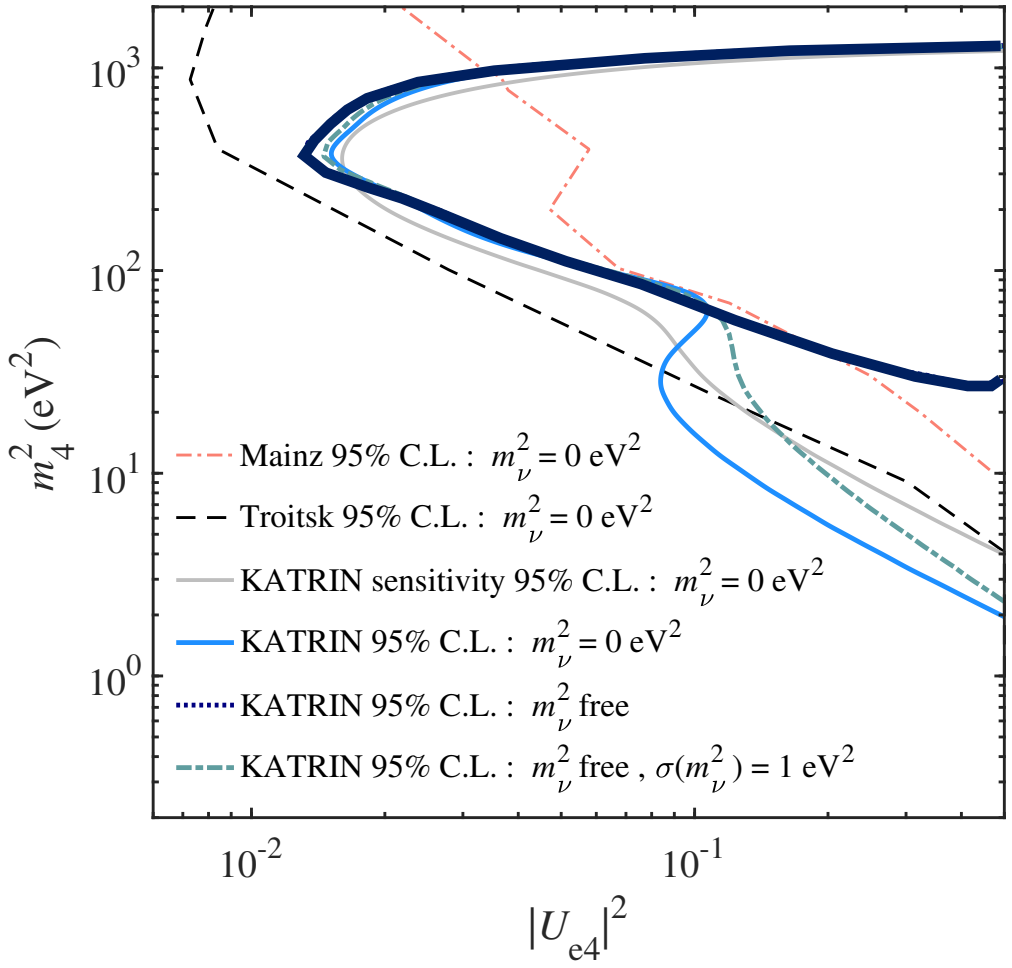
Systematic uncertainties are negligible for all m_4

Case i) 40 eV fit range, m_β= 0 eV fixed



- Results in the $|U_{e4}{}^2|$ - m_4^2 plane
- m_β= 0 eV fixed
- Sensitive to
  - m_4^2 < 1000 eV^2
  - $|U_{e4}|^2 > 0.02$
- Limit directly comparable to Mainz/Troitsk

Case ii) 40 eV fit range, free m_β



- Free m_β

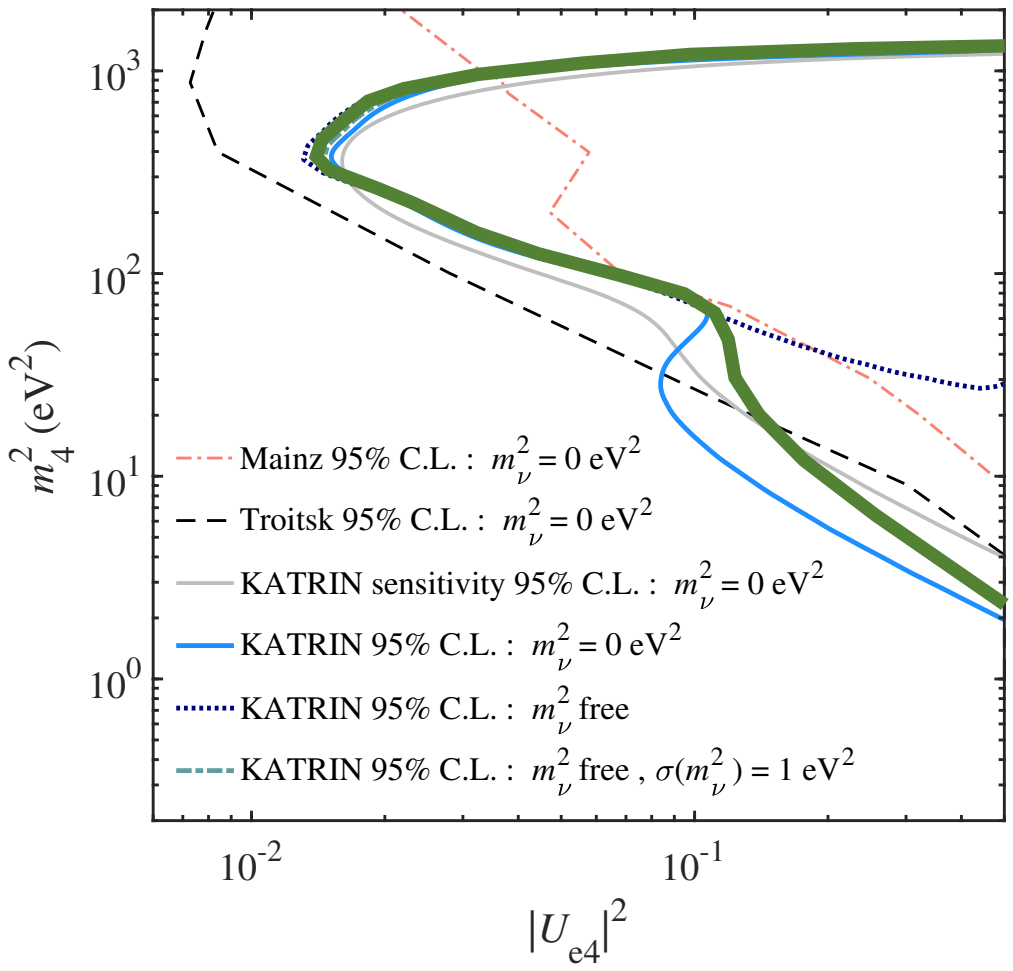
  → m_β can be negative

- The most generic analysis

- Loosing sensitivity w.r.t. case i) for $m_4^2 < 60$ eV^2

  → m_β and m_4 correlation at large $|\mathrm{Ue}_4{}^2|$

Case iii) 40 eV fit range, constrained m_β



- Constrained m_β

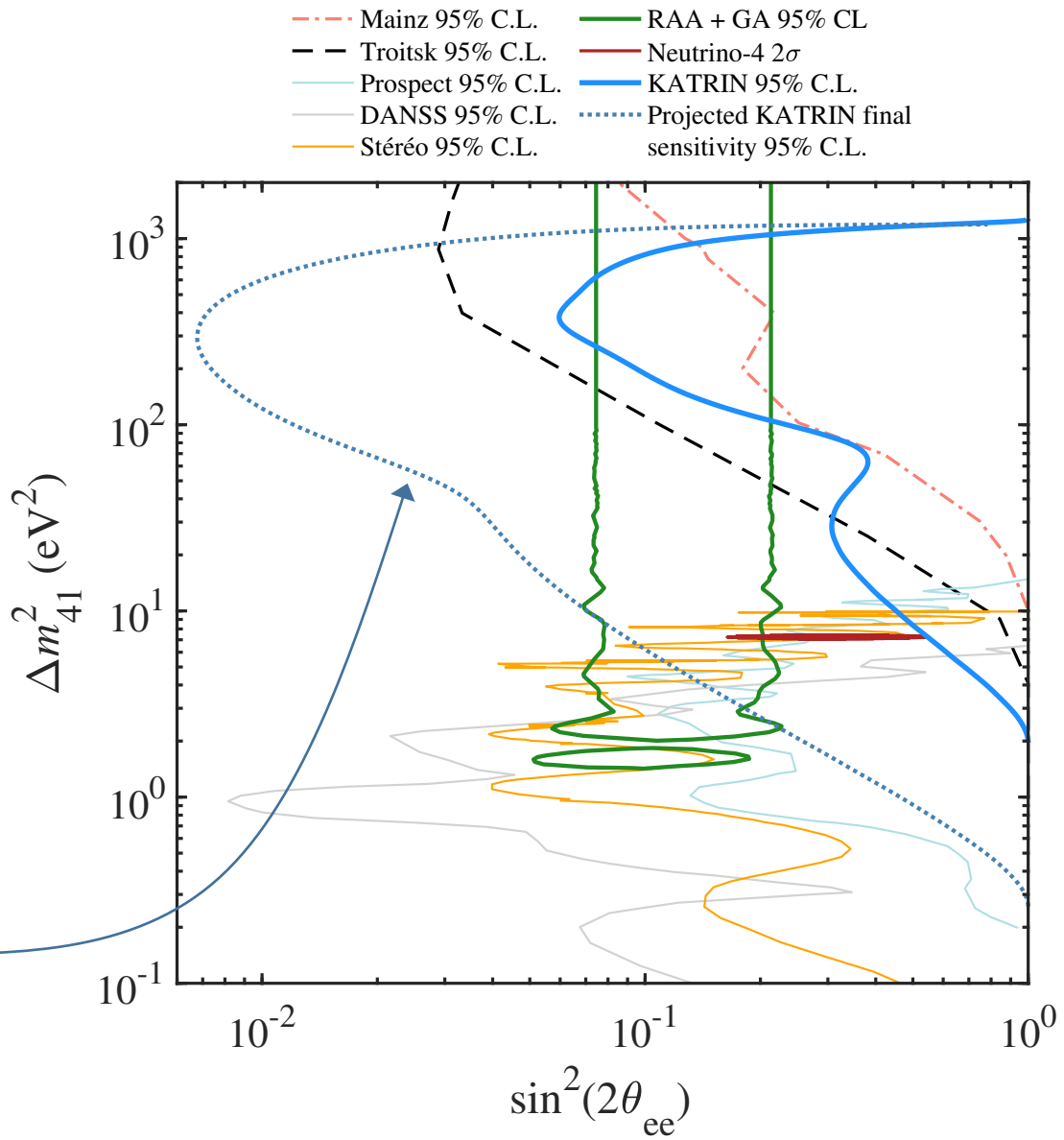
  Arbitrary constraint value, for illustration : 1 eV^2

- Intermediate case, for illustration of the impact of an external constraint (here $m_\beta < 1$ eV)

- Could be later used with with a bound from cosmology for instance

Synergy with oscillation experiments

- **Oscillation Electron Disappearance Experiments**
  - $\Delta m_{41}^2 = m_4^2 - m_1^2 \approx \Delta m_{42}^2 \approx \Delta m_{43}^2$
  - $\sin^2 2\Theta = 4|U_{e4}|^2(1-|U_{e4}|^2)$
- **KATRIN**
  - m_β and m_4
  - $\sin^2\Theta = |U_{e4}|^2$
- Conversion KATRIN -to- Oscillation
  - $\Delta m_{41}^2 \simeq m_4^2 - m_\beta^2$
  - $\sin^2 2\Theta = 4\sin^2\Theta(1-\sin^2\Theta)$
- Projected KATRIN final sensitivity
  (1000 days of data – reduced background)



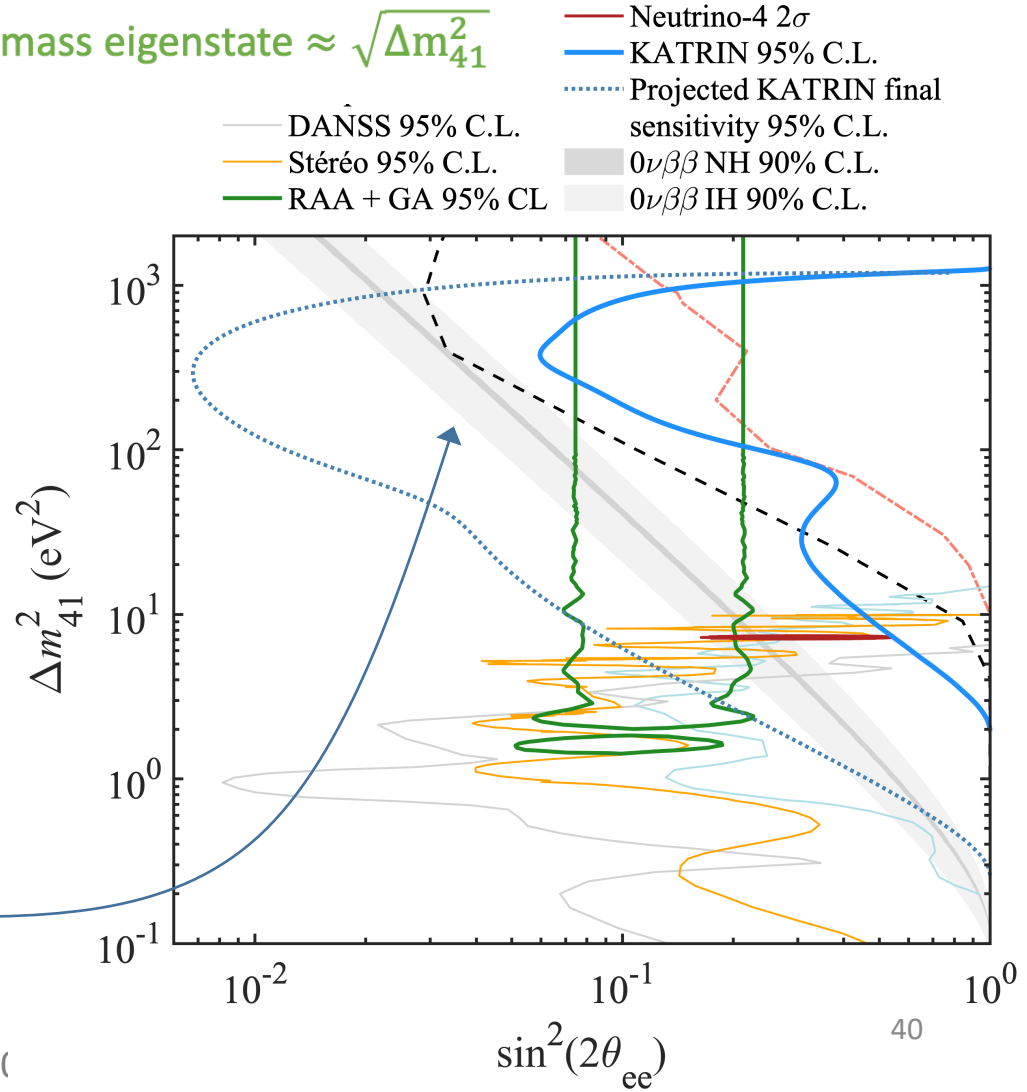
Interplay with 0νββ experiments

- $m_{\beta\beta}^{4\nu} = \left|(1 - |U_{e4}|^2) \cdot m_{\beta\beta}^{3\nu} + e^{i\varphi}\ |U_{e4}|^2\ m_4\ \right|$

complex phase with $\varphi \in [-\pi, \pi]$ — active-to-sterile mixing — 4^{th} mass eigenstate $\approx \sqrt{\Delta m_{41}^2}$

- Experimental constraint: $m_{\beta\beta}^{exp} < 0.165$ eV at 90% C. L.
- $m_{\beta\beta}^{exp} = m_{\beta\beta}^{4\nu} = \left|(1 - |U_{e4}|^2) \cdot m_{\beta\beta}^{3\nu} + e^{i\varphi}\ |U_{e4}|^2\ \sqrt{\Delta m_{41}^2}\ \right| < 0.165$ eV

- MC: Calculate $m_{\beta\beta}^{exp}$ for each each grid point, sampling
  - $m_{\beta\beta}^{3\nu} \in [0, 0.005\ \text{eV}]$ (NH), $m_{\beta\beta}^{3\nu} \in [0.01, 0.05\ \text{eV}]$ (IH)
  - $\varphi \in [-\pi, \pi]$
- Grey bands show all $(\Delta m_{41}^2, |U_{e4}|^2)$ combinations for which $m_{\beta\beta}^{exp}$ <0.165 eV

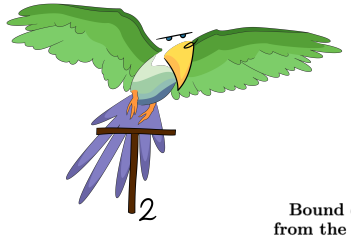


Conclusion

- High-quality data collected over 780 hours @25 GBq in 2019
- 2019: World Best Direct Neutrino Mass Measurement:

  $m_\nu < 1.1$ eV (90% C.L.), Phys. Rev. Lett. 123, 221802
- 2020: First Results on the light sterile neutrino search, arXiv:2011.05087
- Currently : x 10 more statistics already acquired,

  → New data release expected soon



arXiv:2011.05087v1 [hep-ex] 10 Nov 2020

Bound on 3+1 active-sterile neutrino mixing from the first four-week science run of KATRIN

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(Dated: November 11, 2020)

We report on the light sterile neutrino search from the first four-week science run of the KATRIN experiment in 2019. Beta-decay electrons from a high-purity gaseous molecular tritium source are analyzed by a high-resolution MAC-E filter down to 40 eV below the endpoint at 18.57 keV. We consider the framework with three active neutrinos and one sterile neutrino of mass m_4. The analysis is sensitive to a fourth mass state $m_4^2 \lesssim 1000$ eV^2 and to active-to-sterile neutrino mixing

Thank you for your attention



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