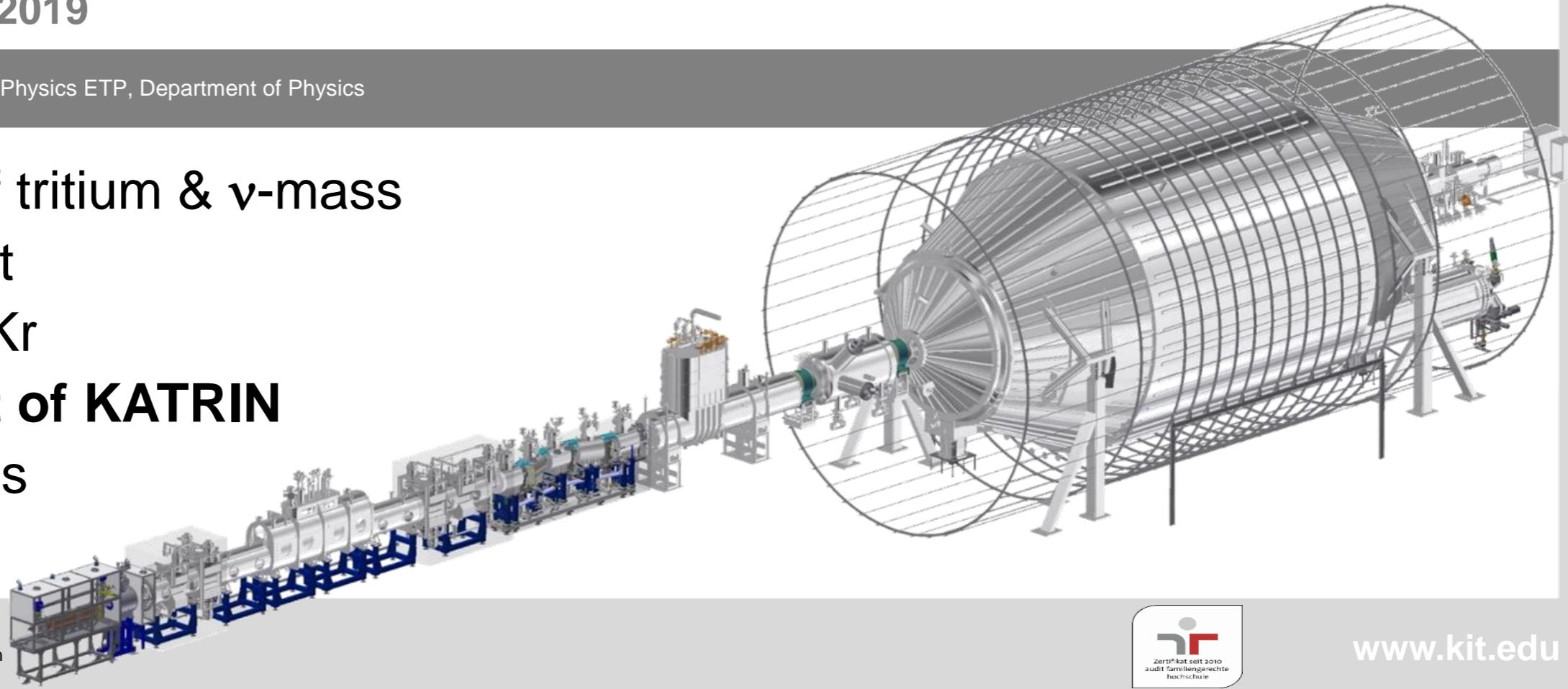


# KATRIN

5<sup>th</sup> Neutrino Colloquium: Towards CP violation in neutrino physics  
Prague, October 24-25, 2019

Guido Drexlin, Institute of Experimental Particle Physics ETP, Department of Physics

- intro: beta-decay of tritium &  $\nu$ -mass
- KATRIN experiment
- calibration with  $^{83m}\text{Kr}$
- **first  $\nu$ -mass result of KATRIN**
- keV-sterile neutrinos
- conclusion

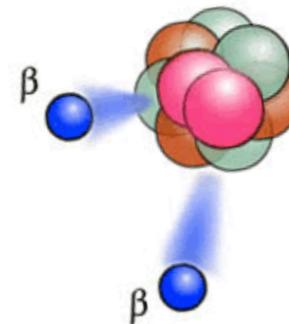


# assessing neutrino masses: the three-fold way

## 0νββ-decay

- ββ-decay:  
 $^{76}\text{Ge}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$
- model-dependent:  
**Majorana-ν**

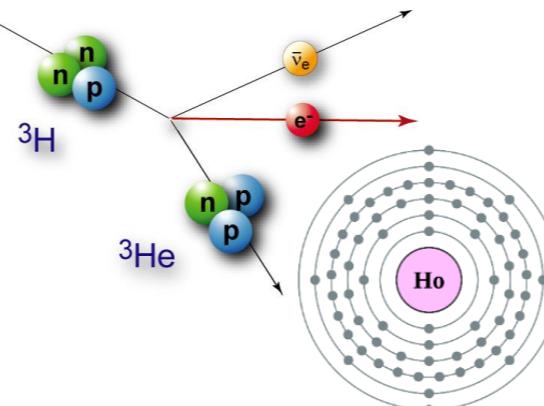
$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^3 U_{ei}^2 \cdot m_i \right|^2$$



## kinematics weak decays

- β-decay:  $^3\text{H}$
- EC:  $^{163}\text{Ho}$
- model-independent:  
**conservation of E,p**

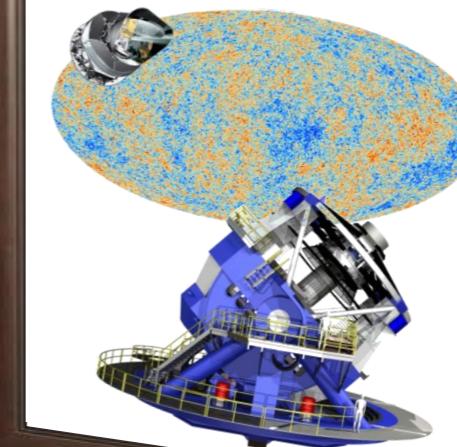
$$m(\nu_e) = \sqrt{\sum_{i=1}^3 |U_{ei}|^2 \cdot m_i^2}$$



## cosmology

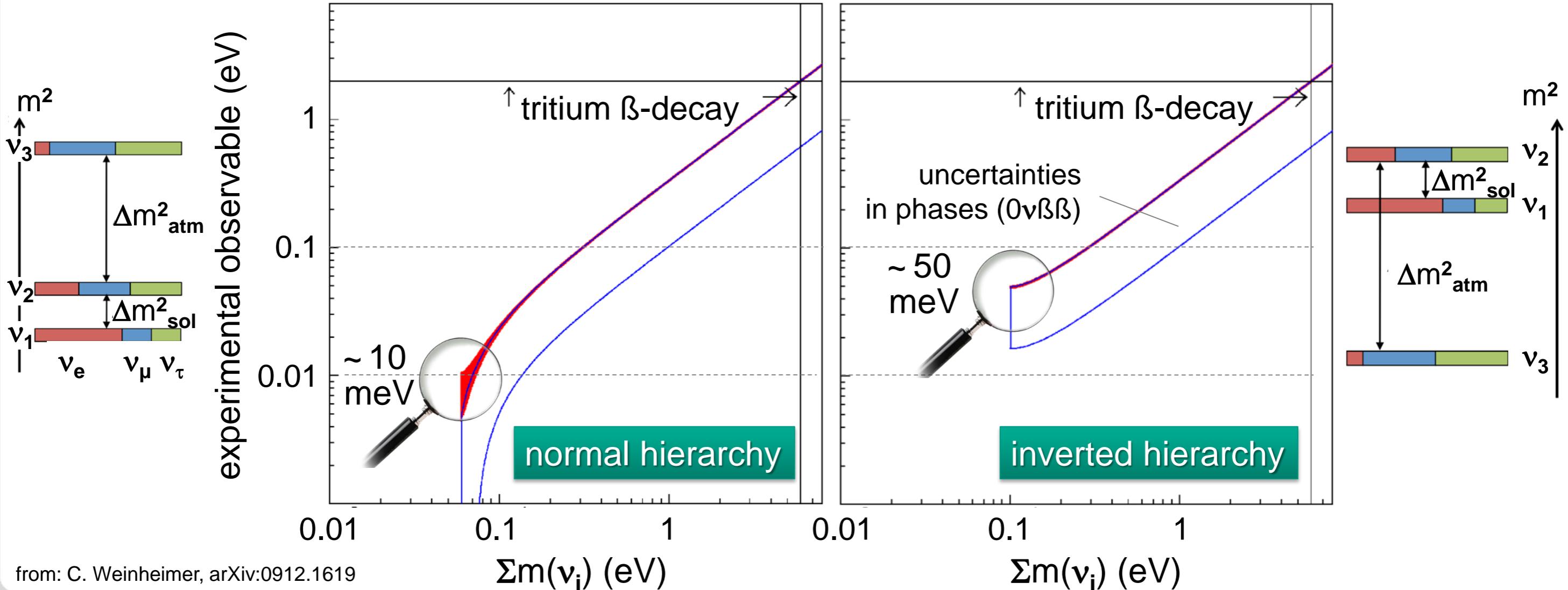
- LSS: CMB,  
GRS, lensing
- model-dependent:  
 **$\Lambda$ CDM**

$$m_{tot} = \sum_{i=1}^3 m_i$$



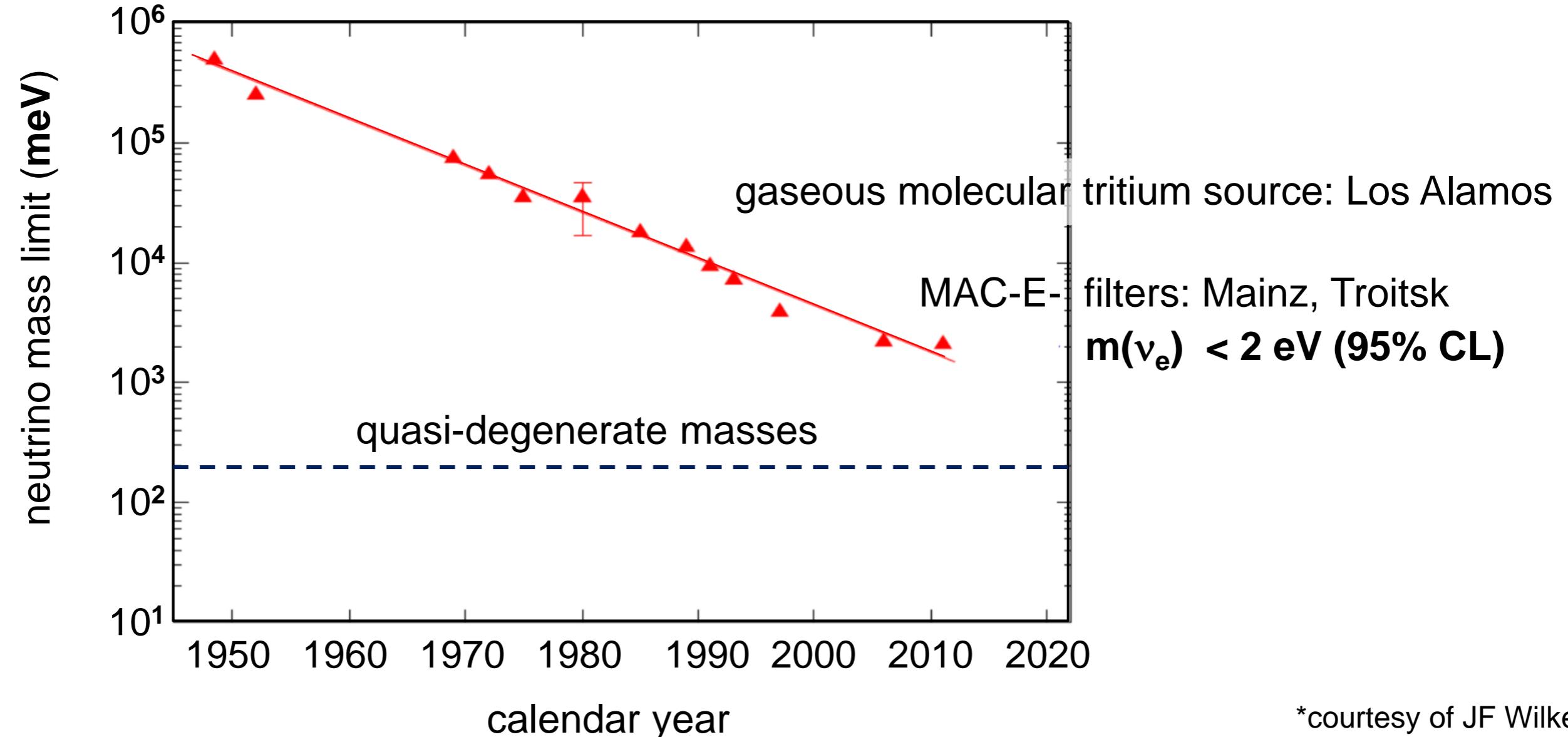
# $\nu$ -masses from kinematic studies – the challenge

- **setting the stage:** experimental observables  $m(\nu_e)$  in  $\beta$ -decay & EC  
 $m_{\beta\beta}$  in  $0\nu\beta\beta$ -searches (Majorana/CP-phases)



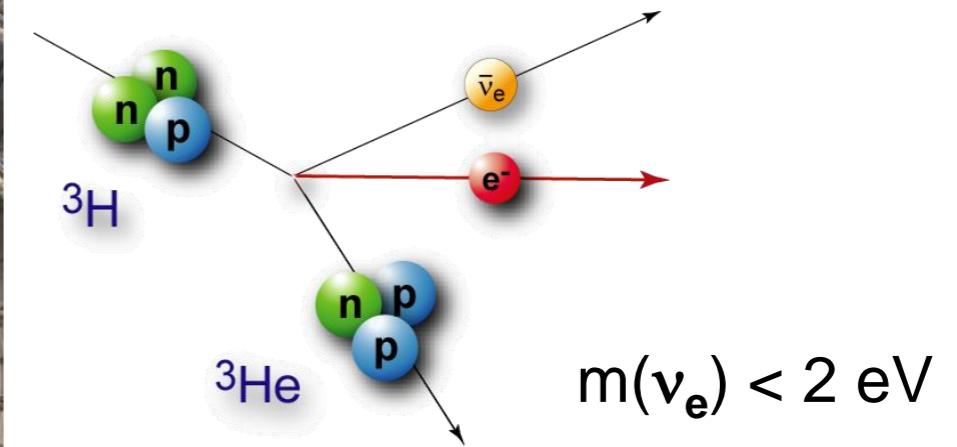
# Moore's law\* of direct $\nu$ -mass sensitivities

■ **setting the stage:** experimental progress over past decades due to **new technologies**





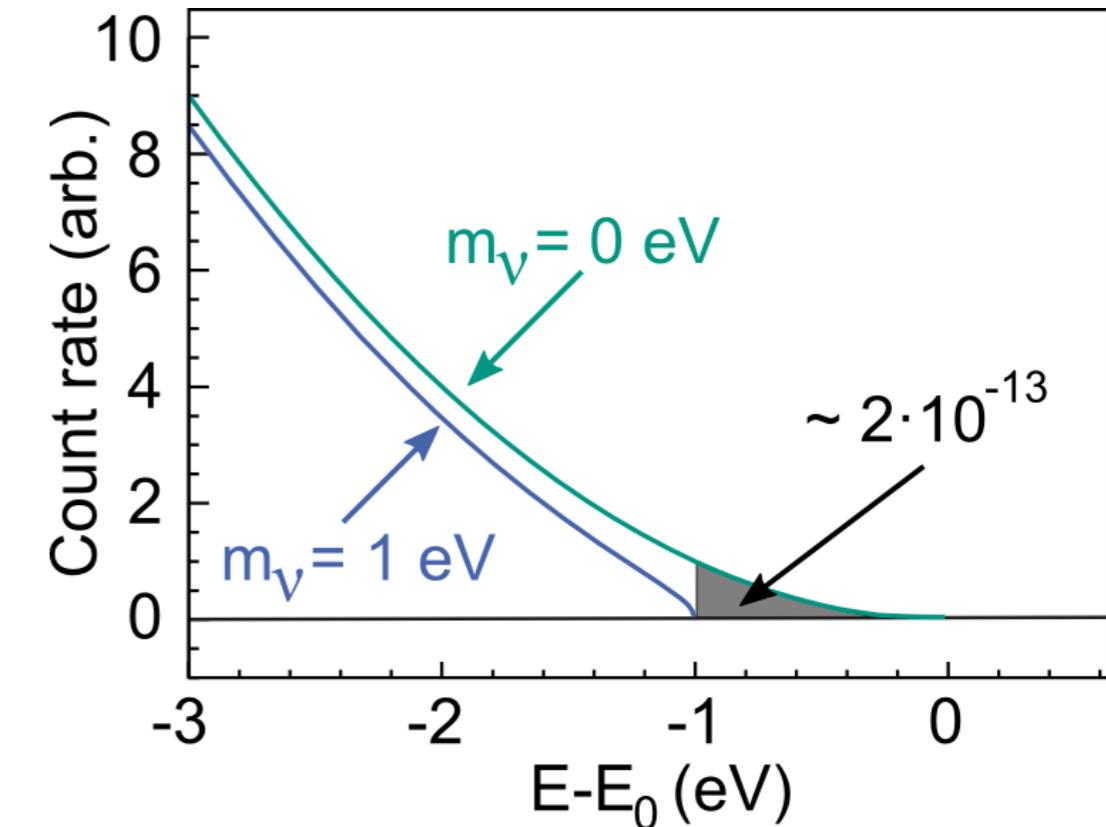
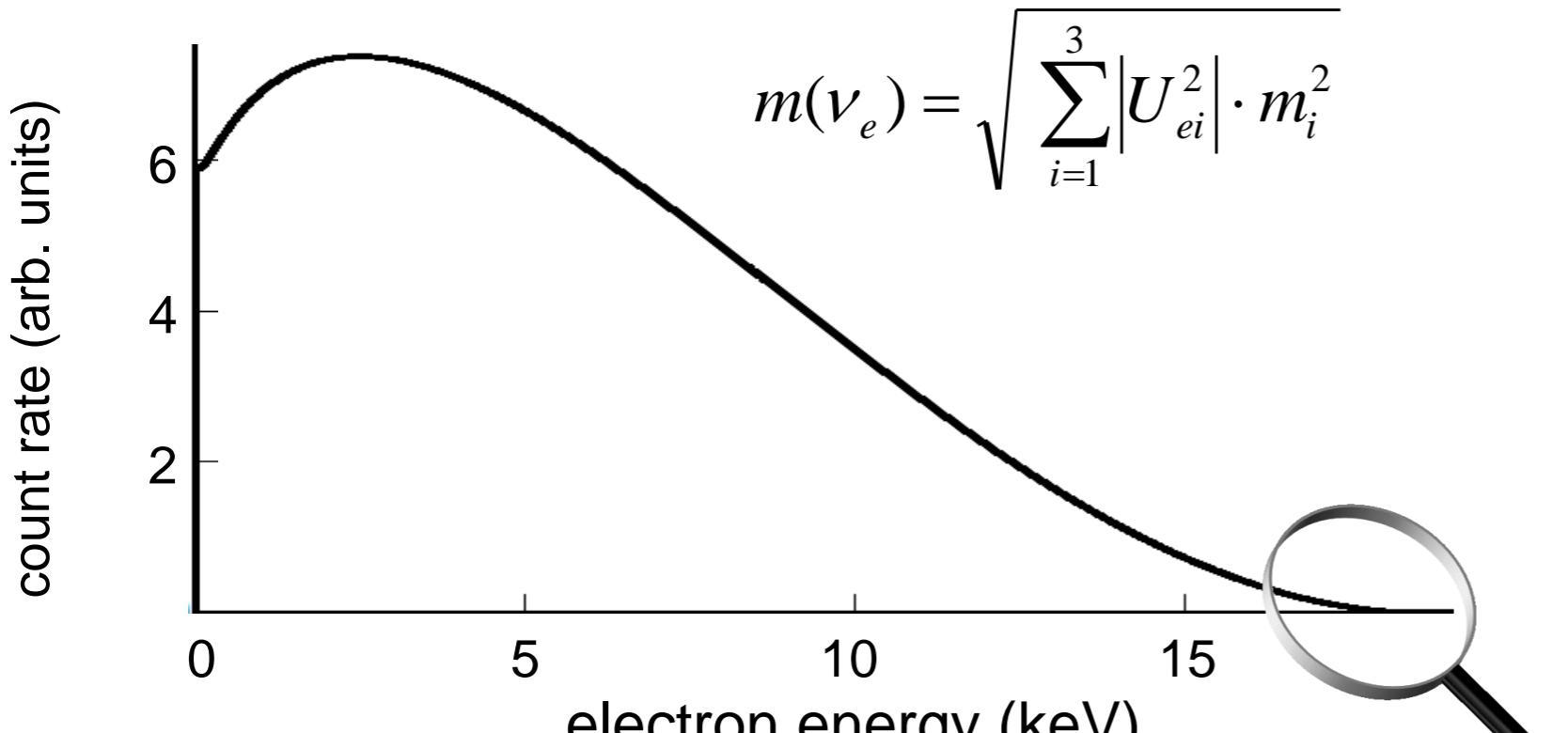
## $\beta$ -DECAY OF TRITIUM



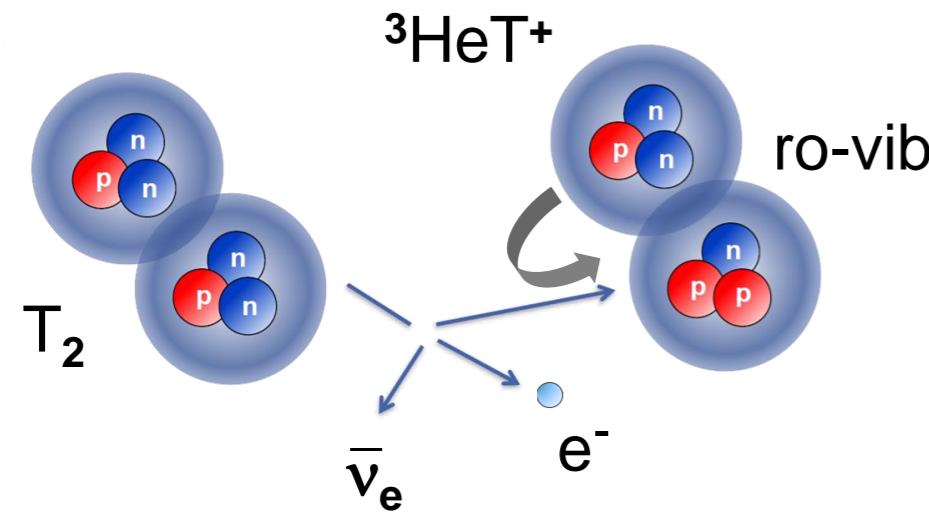
# tritium $\beta$ -decay: kinematics

- continuous  $\beta$ -spectrum described by Fermi's Golden Rule, measurement of effective mass  $m(\nu_e)$  based on **kinematic parameters & energy conservation**

$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E, Z) \cdot \theta(E_0 - E - m_i)$$

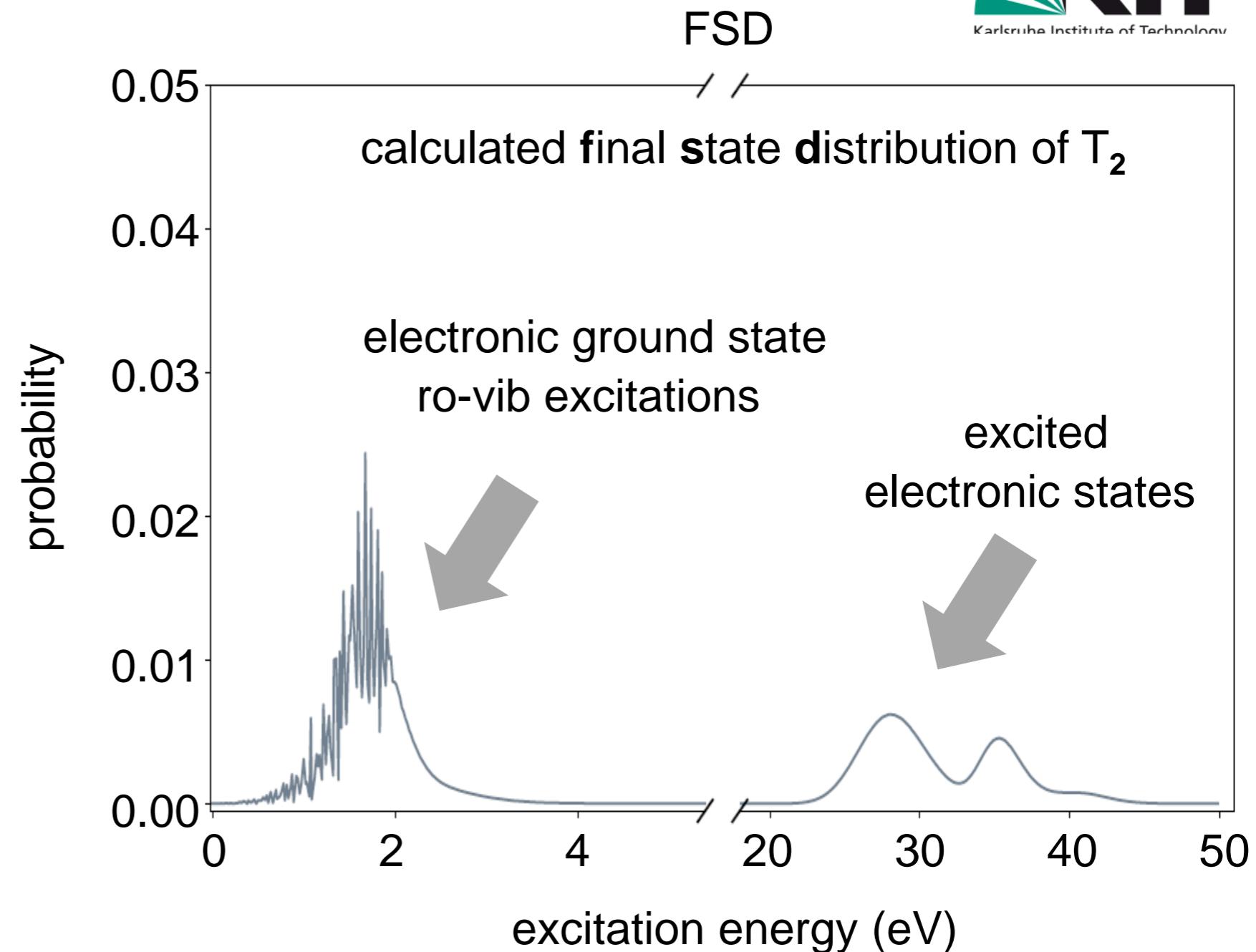
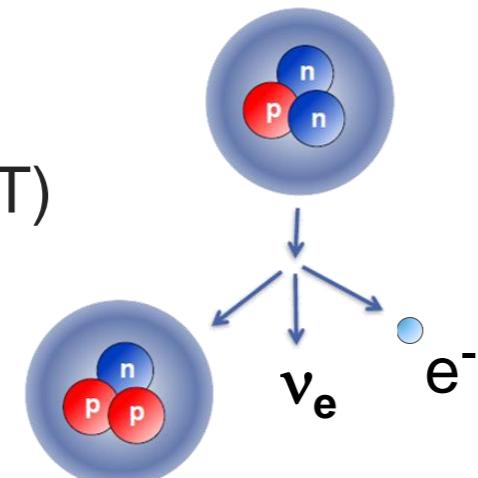


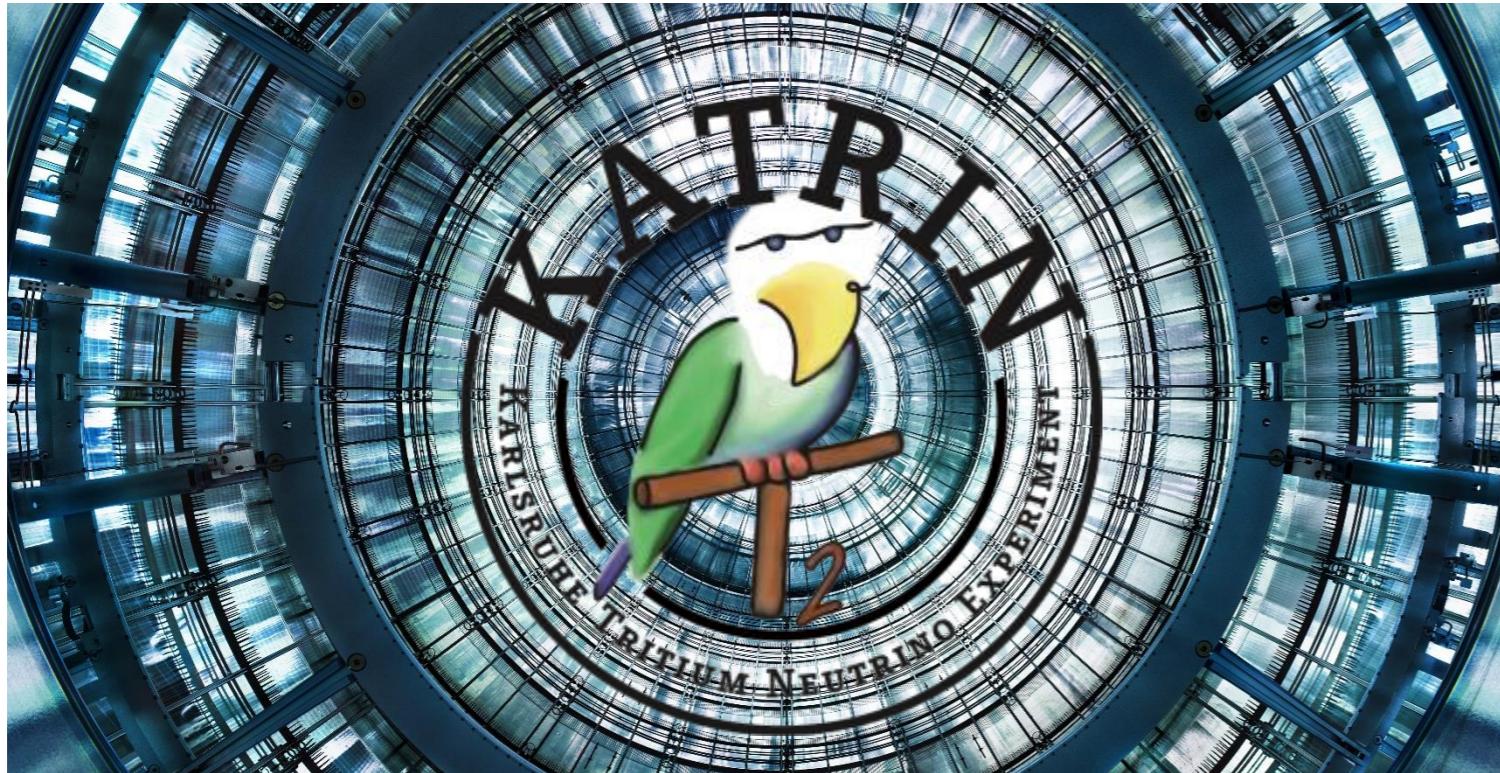
# $\beta$ -spectroscopy: molecular & atomic tritium



molecular source ( $T_2$ ) –  
sensitivity limit  $\sim 100$  meV

atomic source ( $T$ )  
sensitivity limit  
 $\sim 40$  meV (?)





# KATRIN

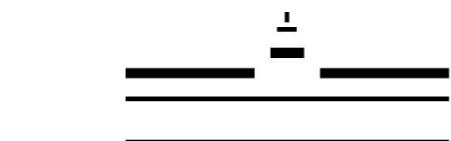
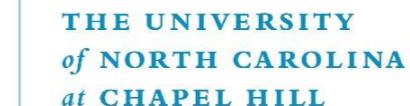
# KATRIN Collaboration – 20 institutions

## ■ Karlsruhe Tritium Neutrino Experiment

- 6 countries (D, US, CZ, RU, F, ES)
- 20 institutions, 150 collaborators



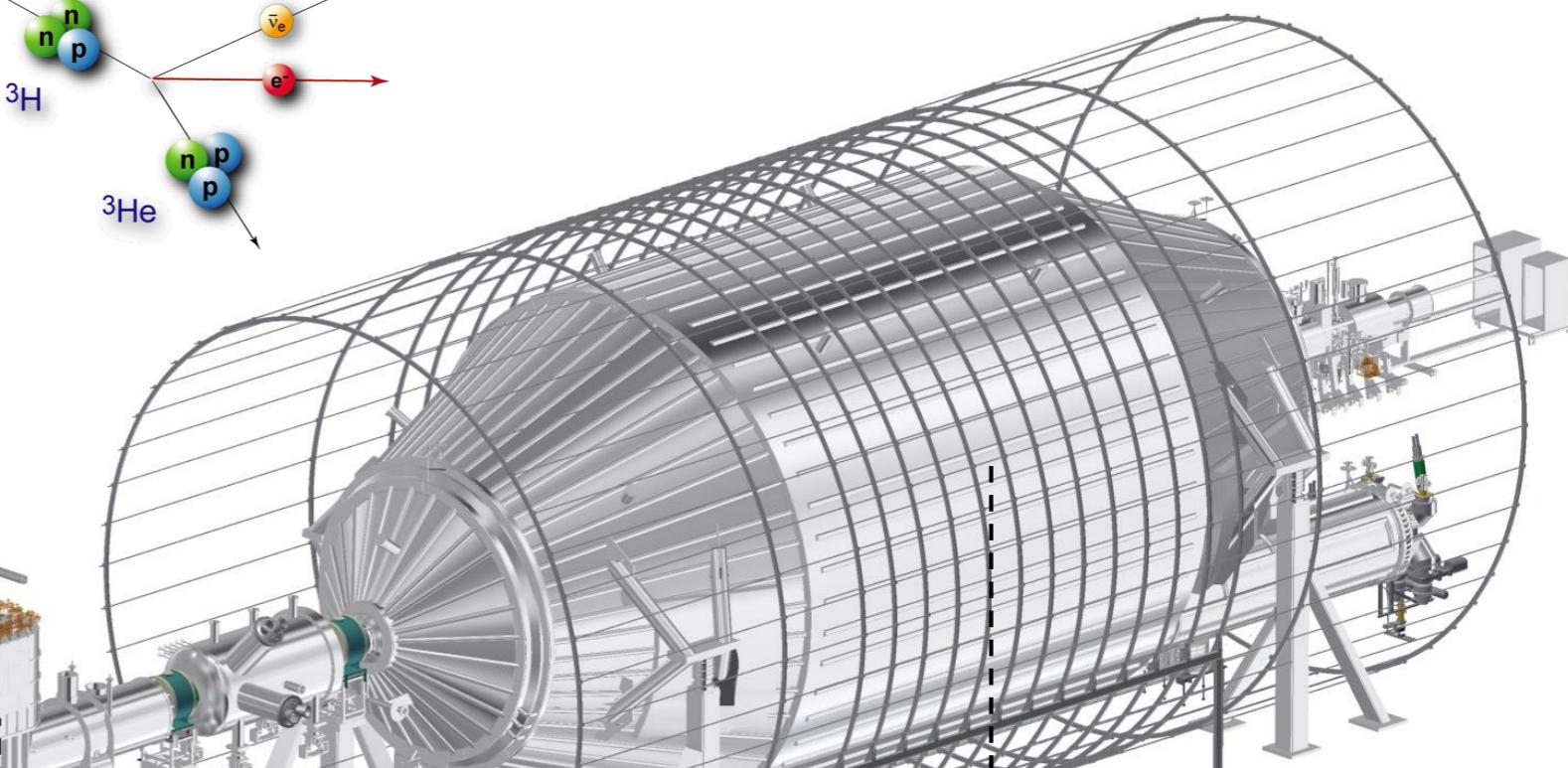
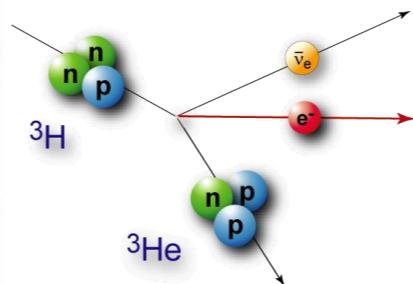
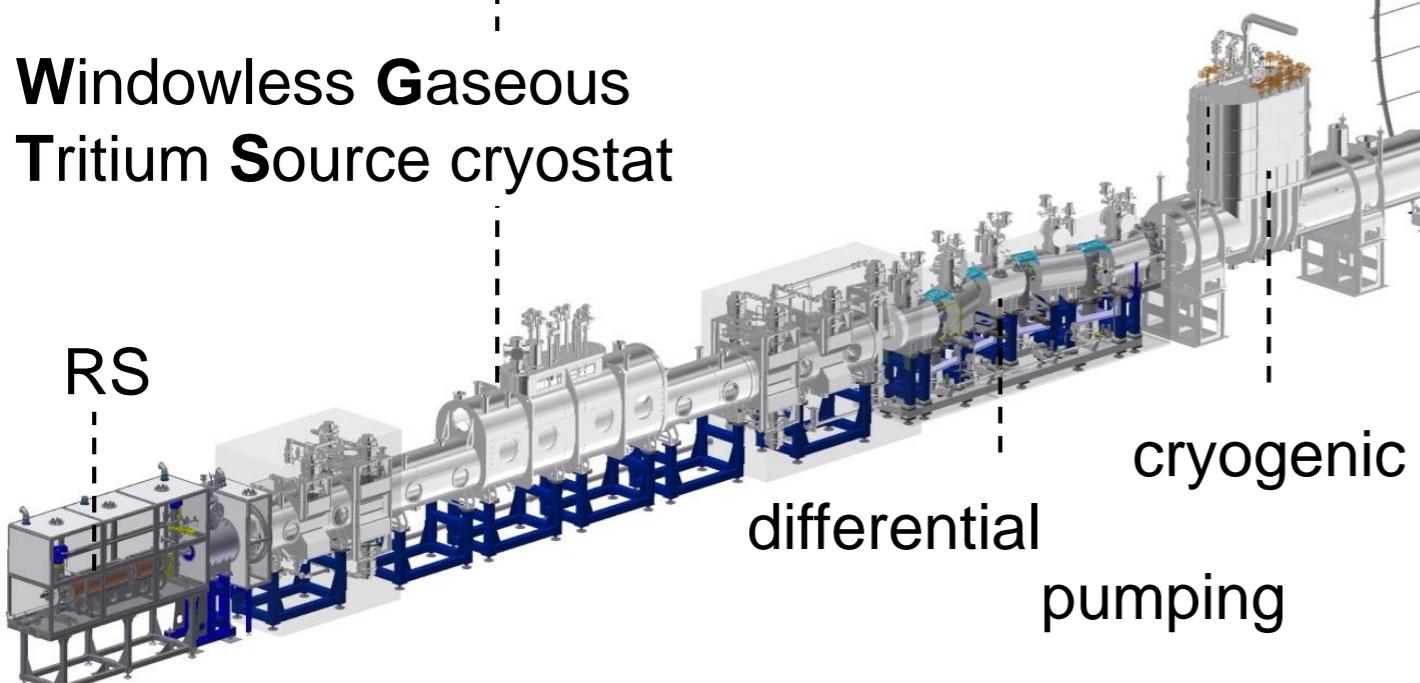
Max-Planck-Institut für Physik  
(Werner-Heisenberg-Institut)



# KATRIN overview: 70 m long beamline



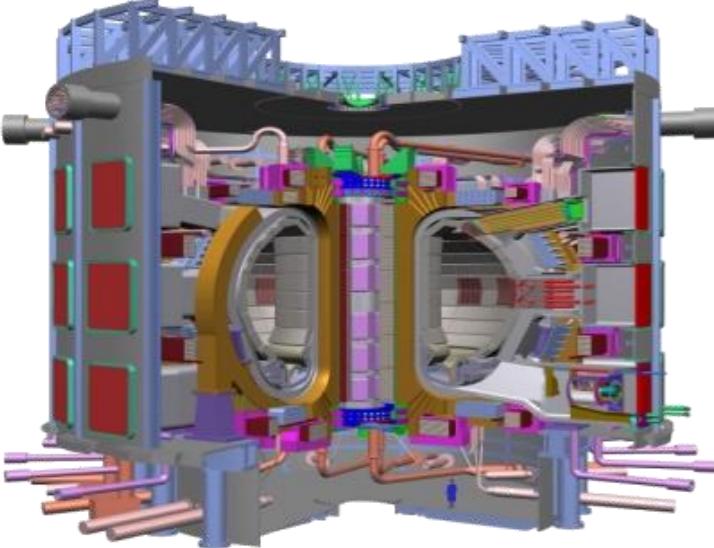
**Windowless Gaseous Tritium Source cryostat**



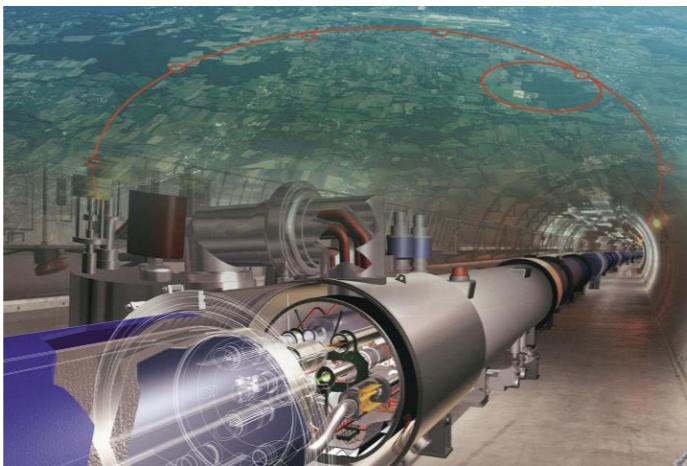
**Main Spectrometer**



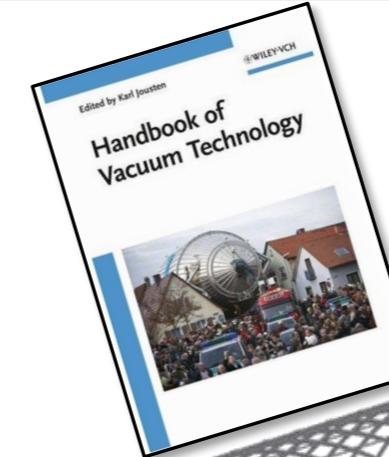
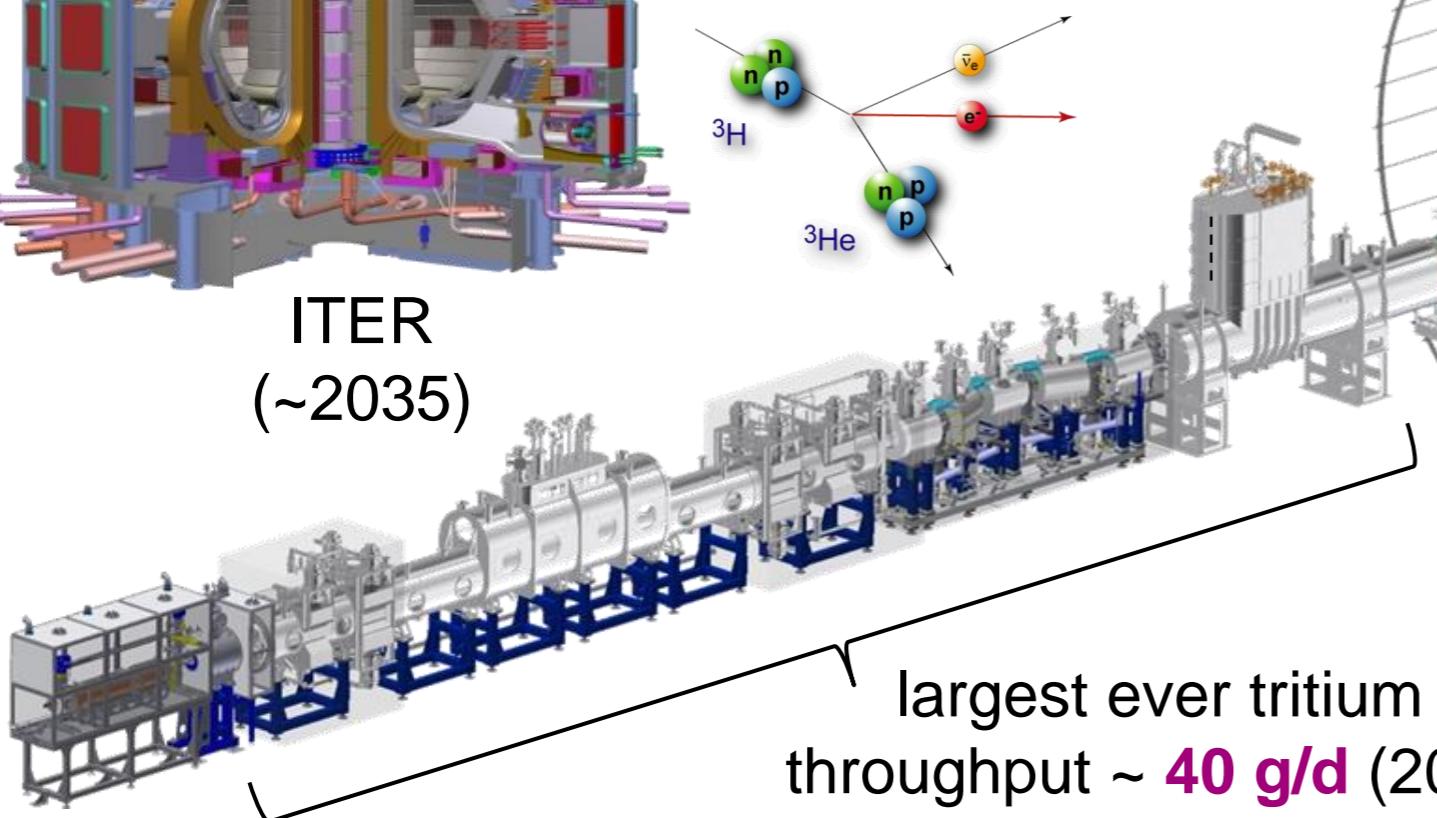
# KATRIN overview: challenges



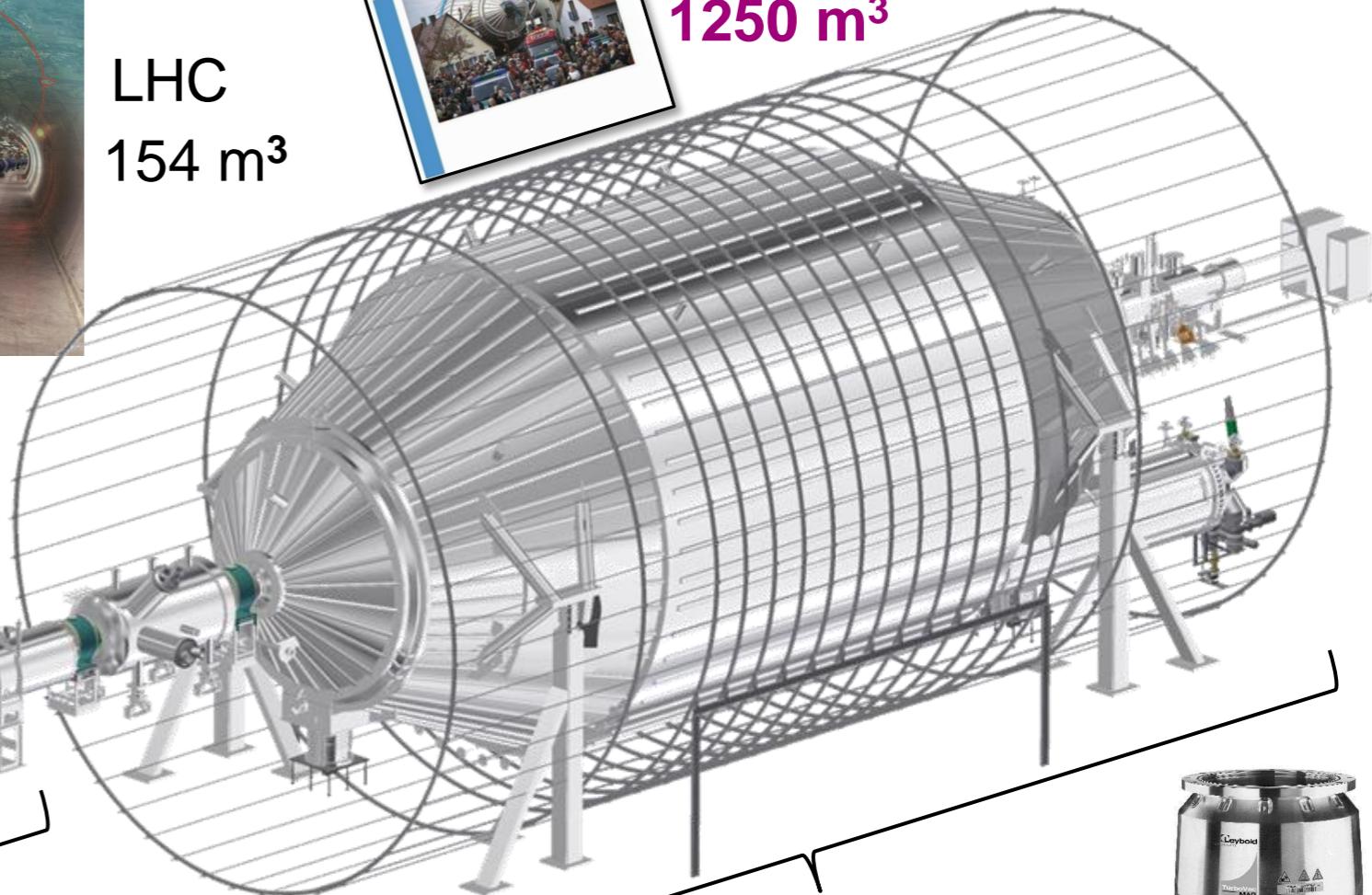
ITER  
(~2035)



LHC  
154 m<sup>3</sup>



**1250 m<sup>3</sup>**

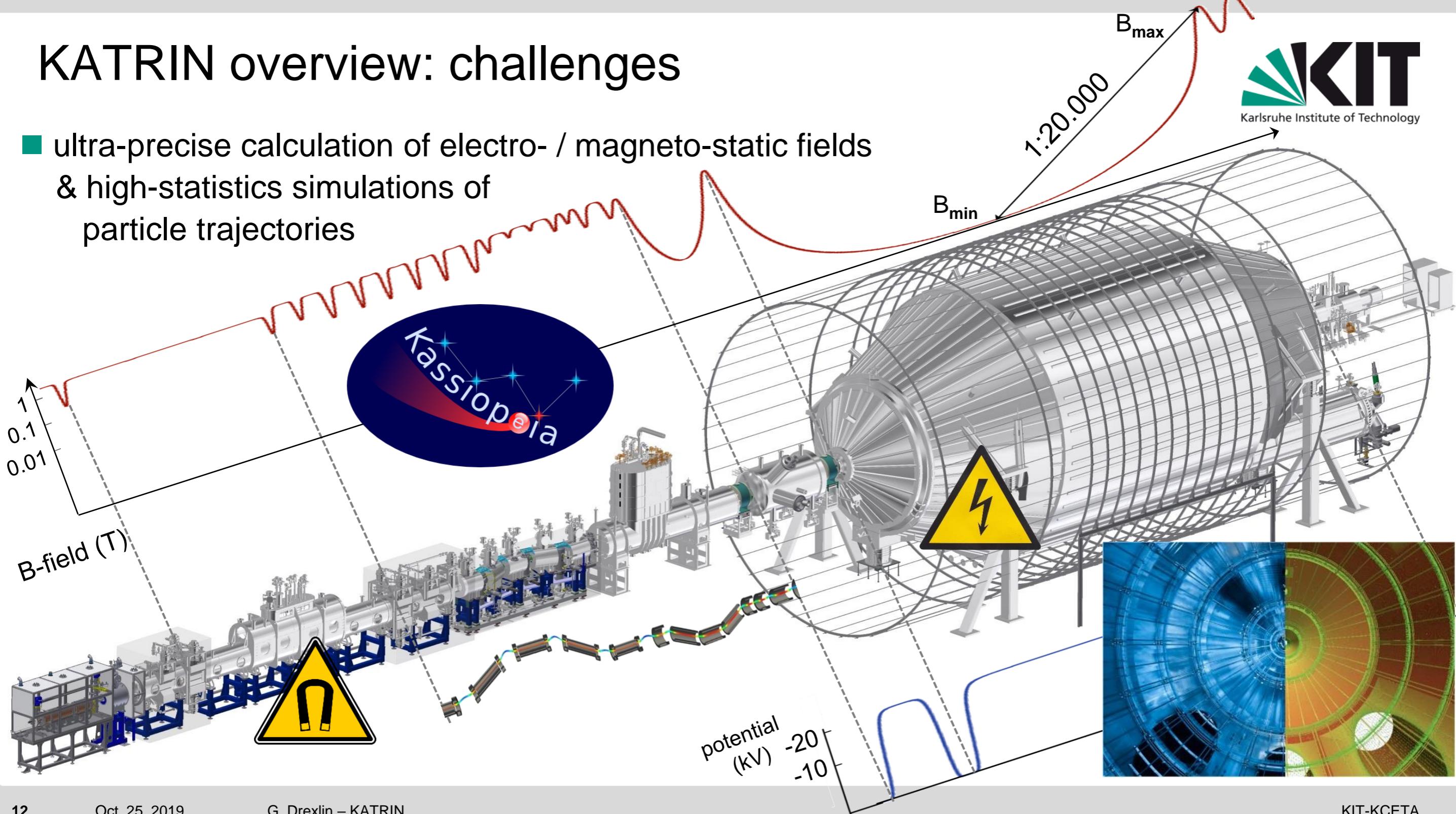


largest ever UHV recipient:  $p \sim 10^{-11}$  mbar (since 2013)



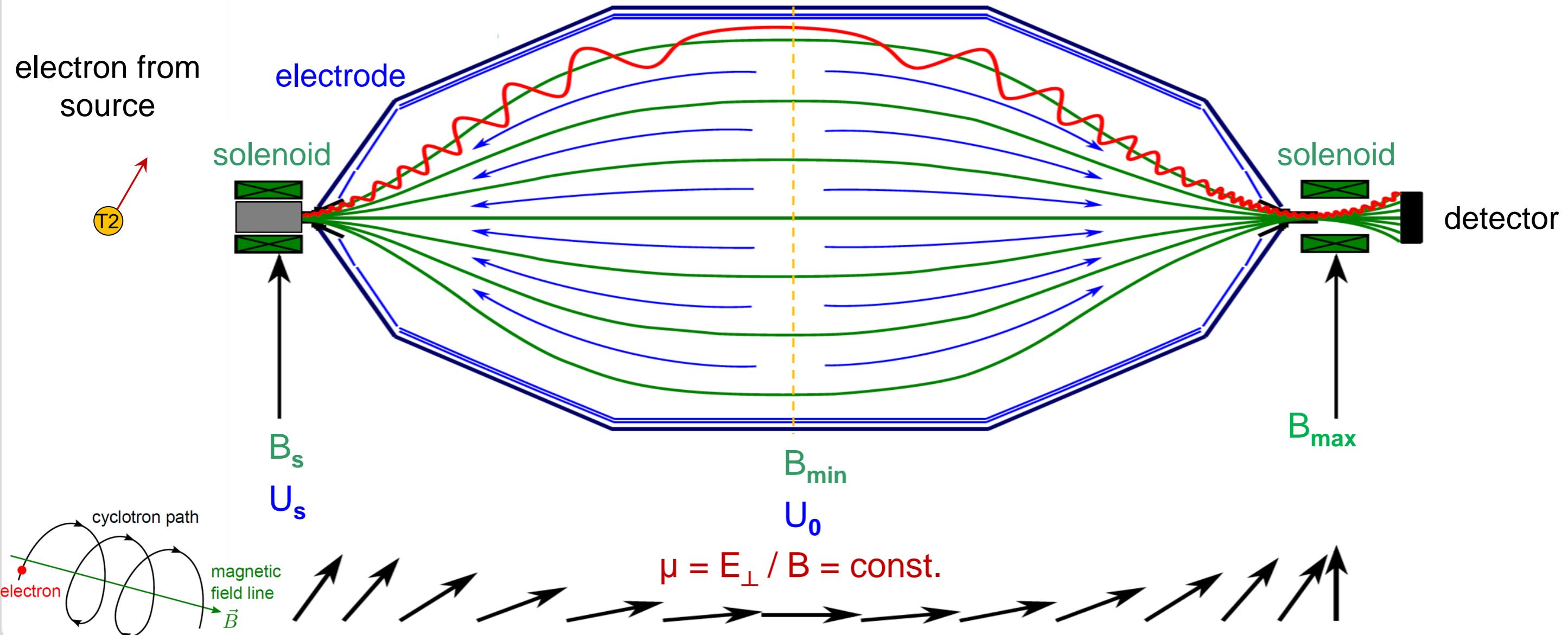
# KATRIN overview: challenges

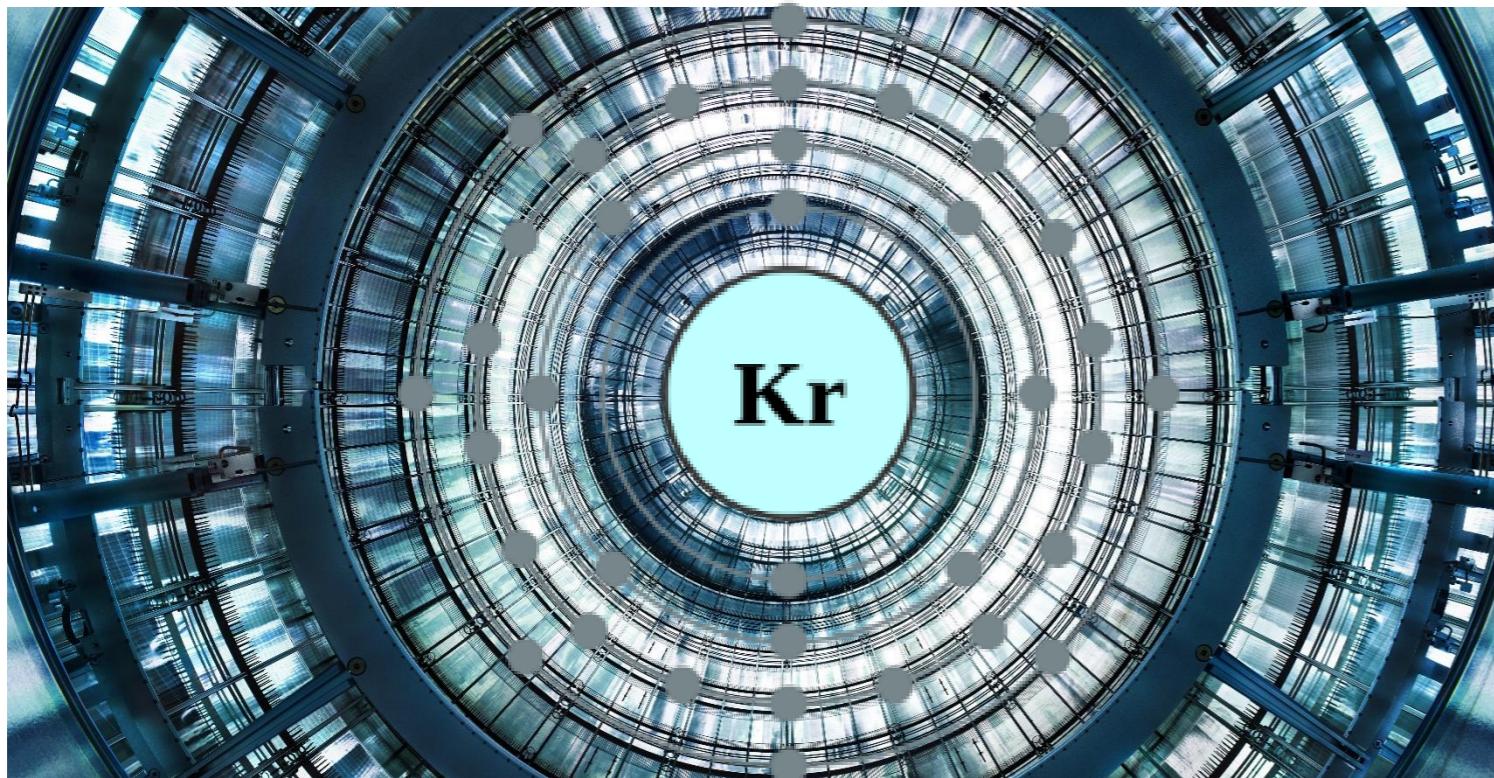
- ultra-precise calculation of electro- / magneto-static fields  
& high-statistics simulations of particle trajectories



# MAC-E principle: high-resolution tritium $\beta$ -spectroscopy

■ Magnetic Adiabatic Collimation & Electrostatic Filter: adiabatic conversion  $E_{\perp} \rightarrow E_{\parallel}$

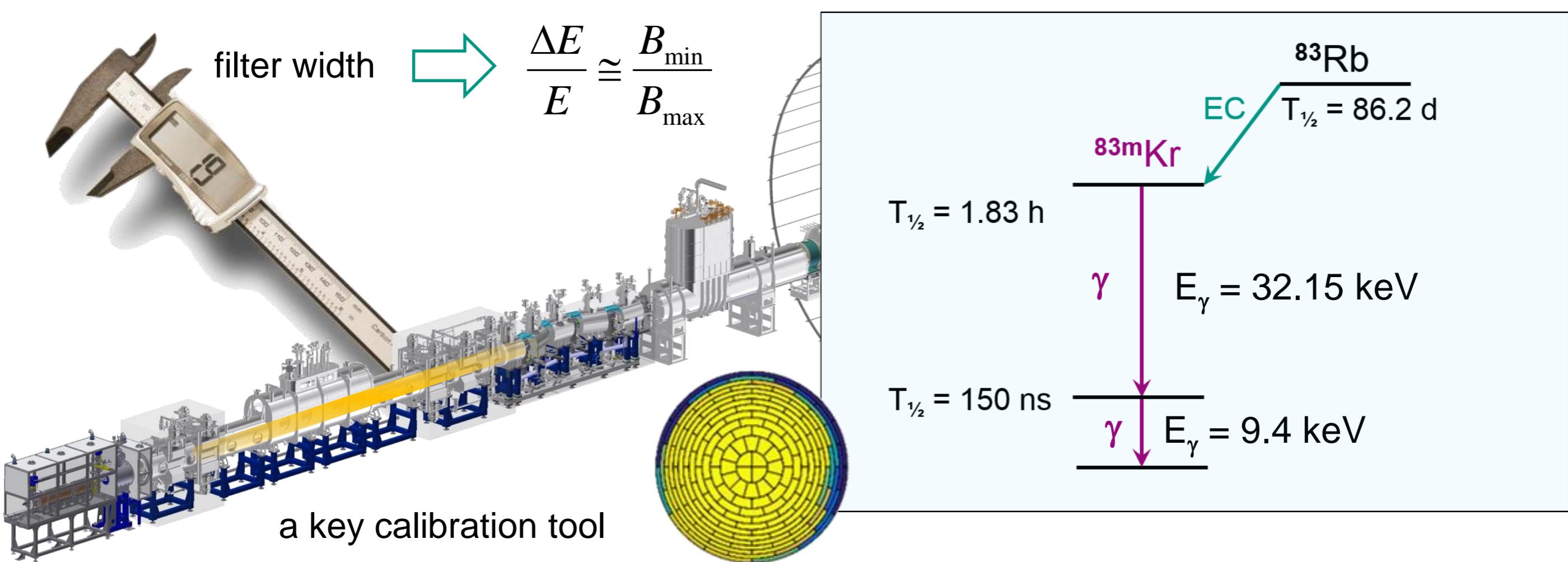




# KATRIN: CALIBRATION WITH KR-83m

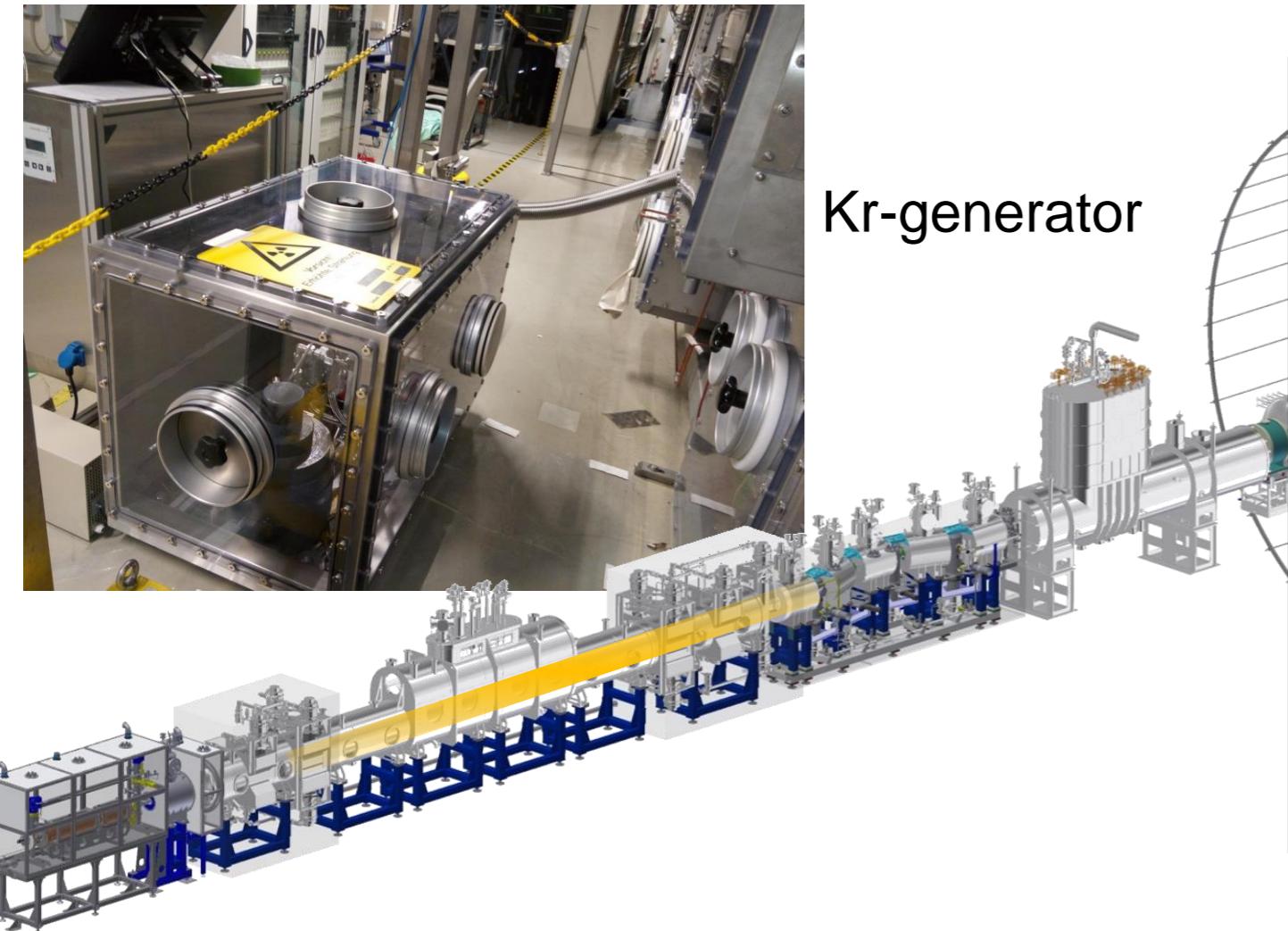
# adding $^{83m}\text{Kr}$ to tritium – a key spectroscopic test

- world-leading expertise of NPI Rez/Prague in electron & gamma spectroscopy of  $^{83m}\text{Kr}$ 
  - exact energies and line widths of **conversion electron lines** (K-32, L-32, M-32,...)

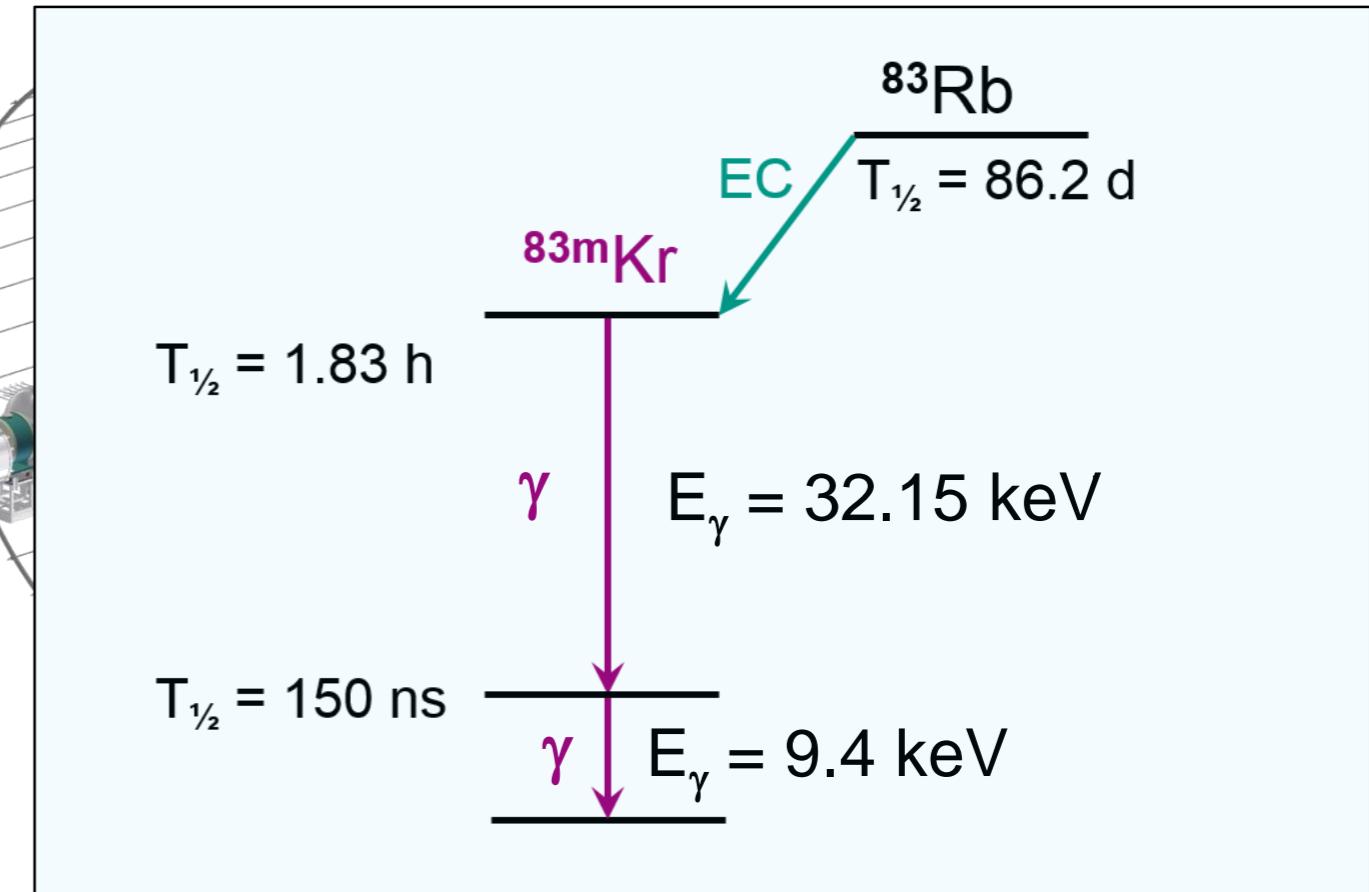


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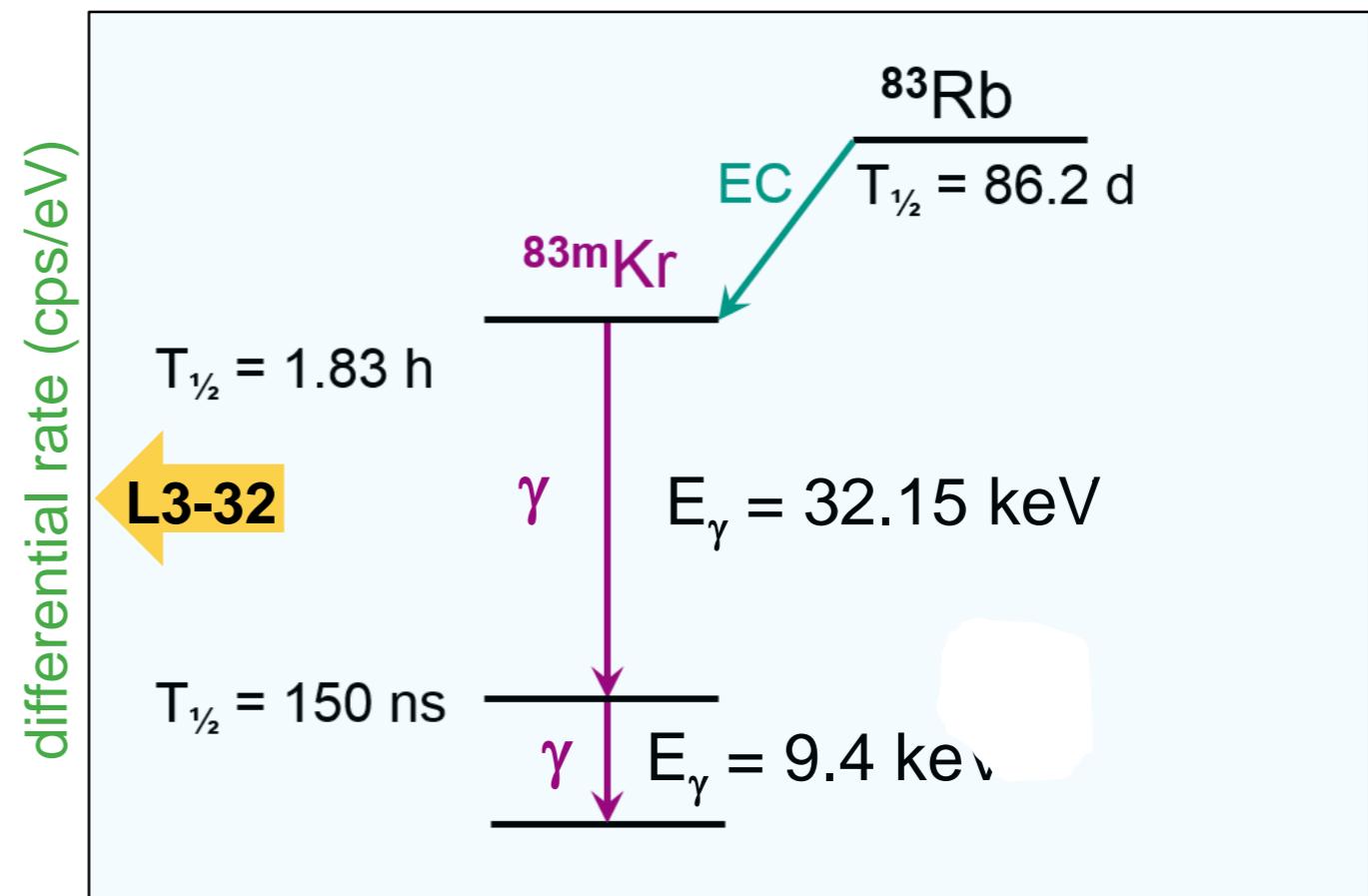
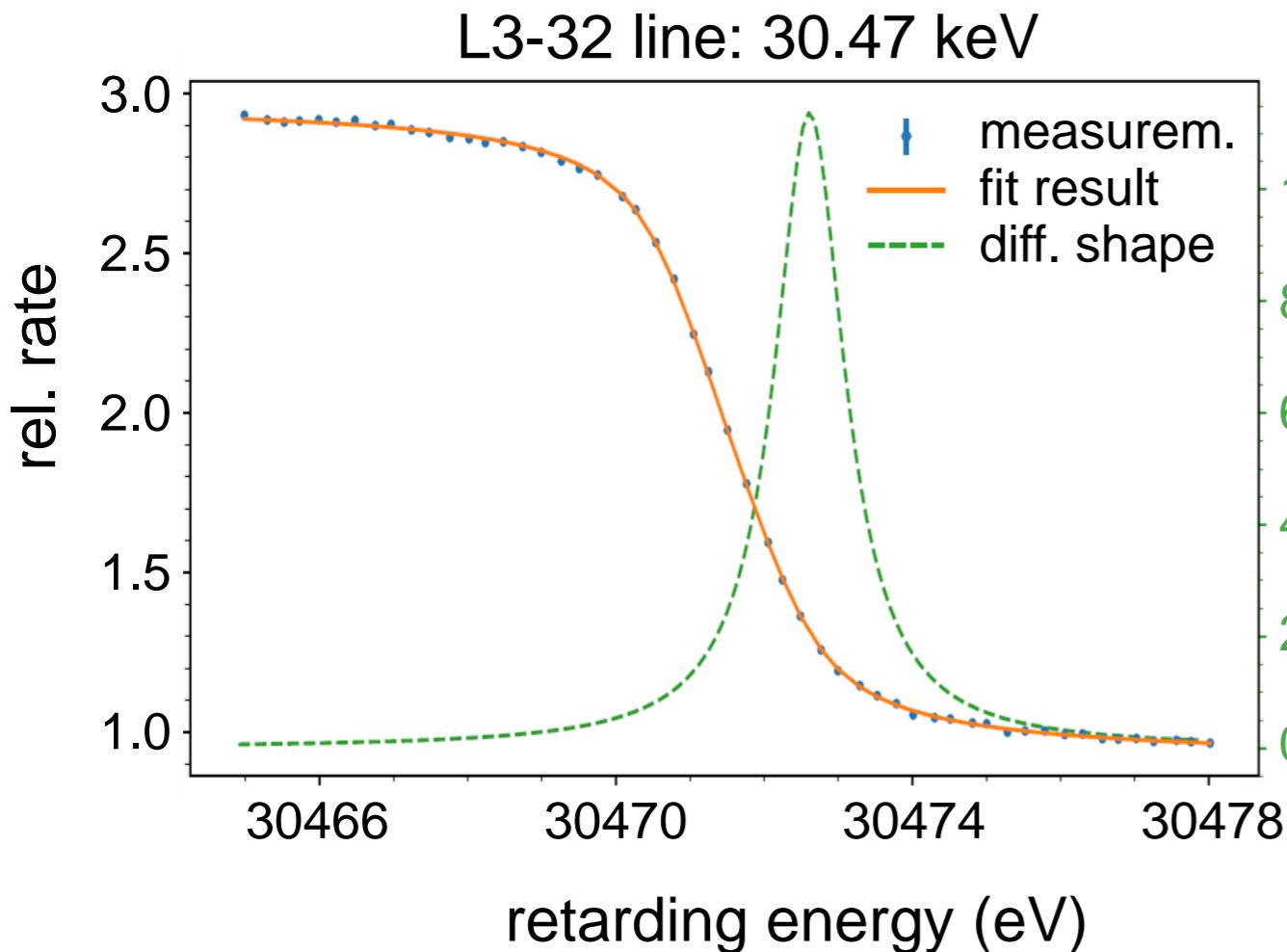


Kr-generator



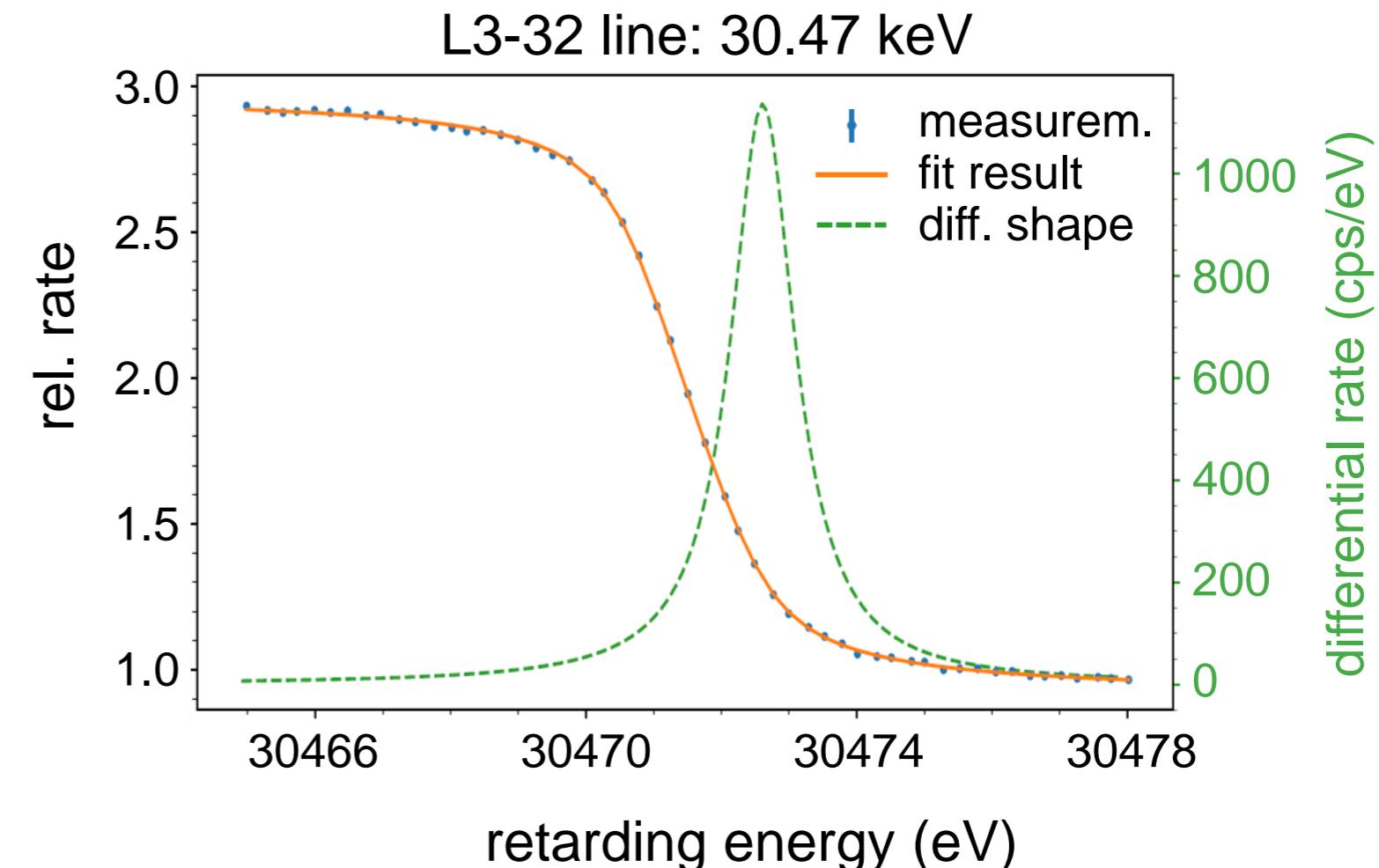
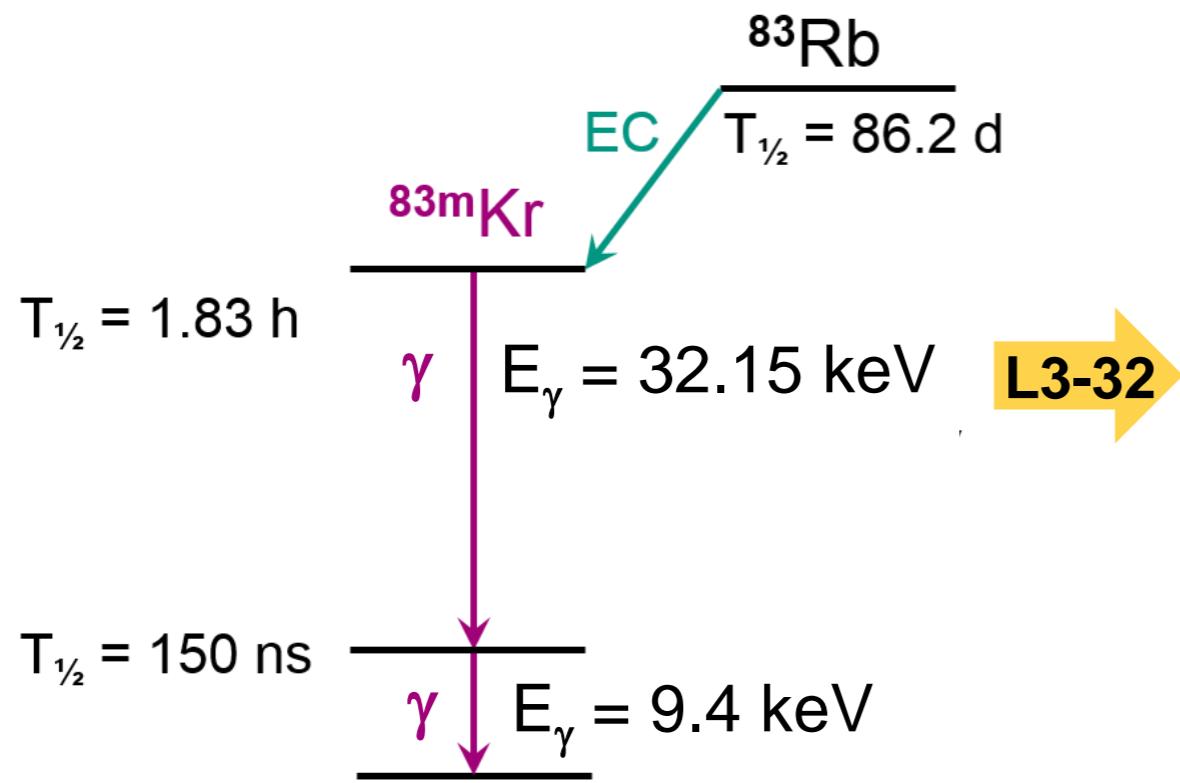
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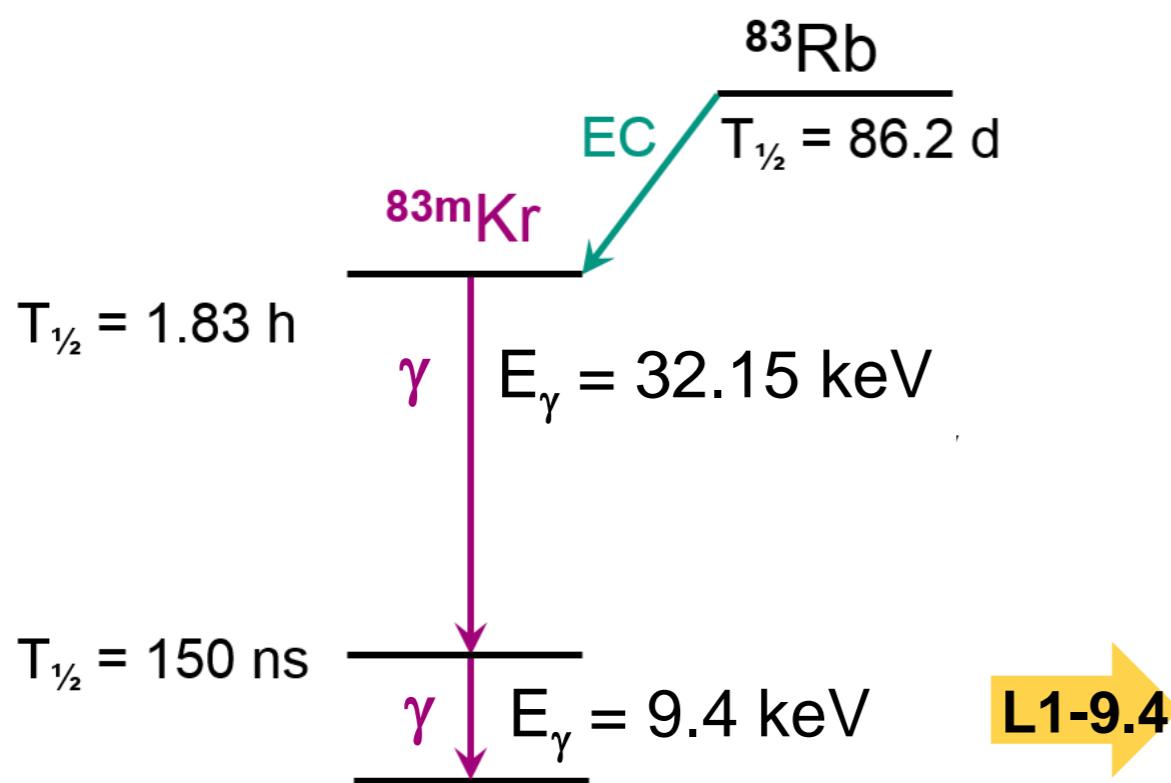
# response to quasi-monoenergetic electrons

- MAC-E filter characteristics well understood (also used to study plasma)

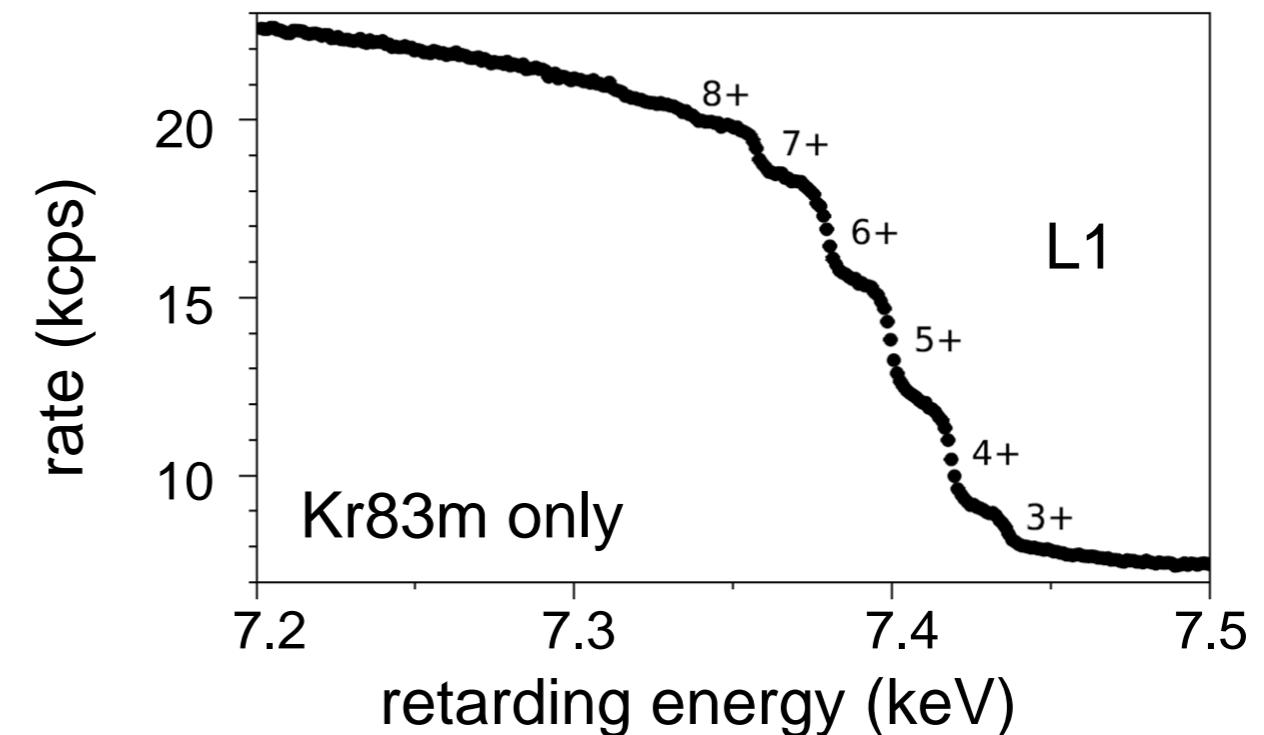


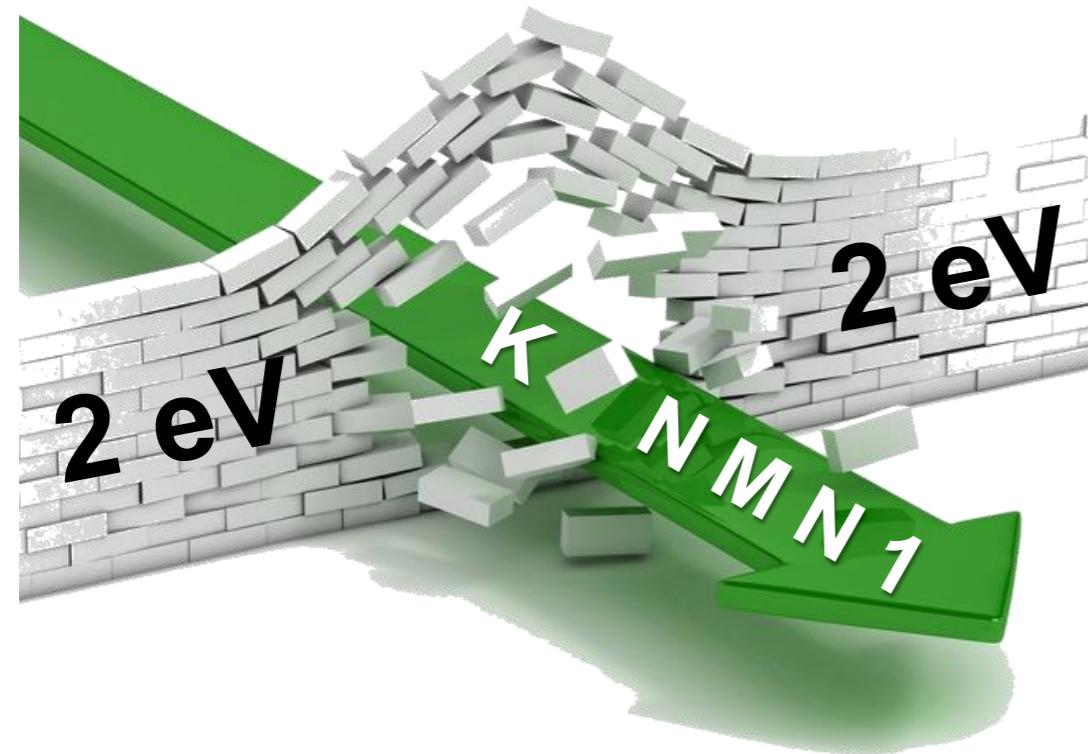
# response to quasi-monoenergetic electrons

## ■ MAC-E filter characteristics well understood (also used to study plasma)



- after conversion of 32 keV transition:  
an Auger explosion generates ions  
⇒ high charge states up to  $> 8+$
- L-lines are split, depending on charge state  
("the hedgehog")





# FIRST NEUTRINO MASS RESULT OF KATRIN

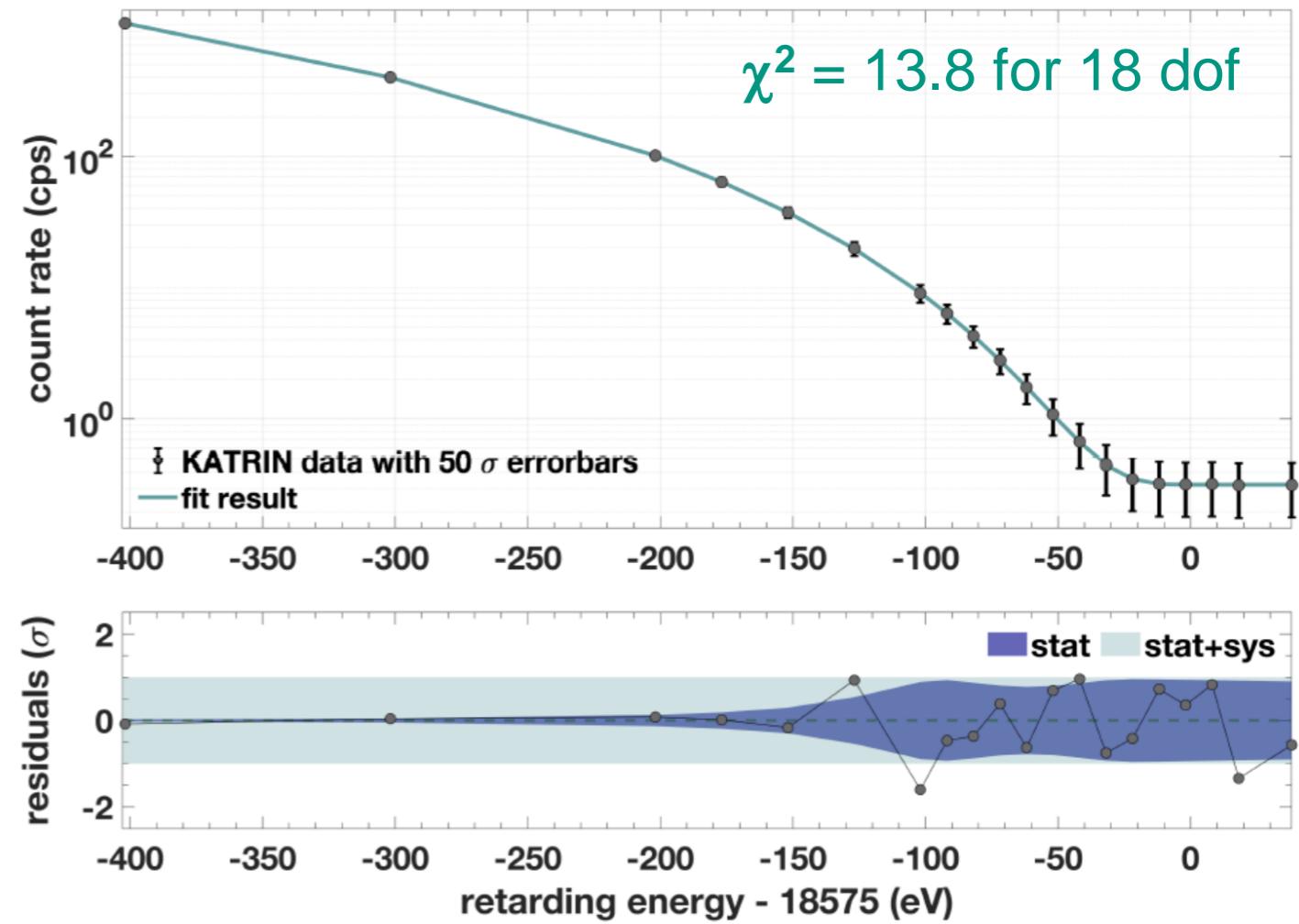
# „First Tritium“ FT (2-week engineering run in mid-2018)



## ■ First Tritium:

- low tritium concentration:  
~1% DT and ~99% D2
- functionality of all system components   
at nominal pd ( $5 \cdot 10^{17} \text{ cm}^{-2}$ )

deep scan possible due to „low“  $\beta$ -activity



KATRIN Collab., “First operation of the KATRIN experiment with tritium”, subm. to Eur. Phys. J. C

# KATRIN neutrino mass campaign #1

■ 4-week long measuring campaign in spring 2019 with high-purity tritium

- April 10 – May, 13 2019 780 h
  - high-purity tritium ( $\varepsilon_T = 97.5\%$ ) laser-Raman
  - high source activity:  $2.45 \cdot 10^{10}$  Bq
  - high-quality data collected
  - full analysis chain using two independent methods
  - target: **first neutrino mass result at TAUP 2019**



# KATRIN neutrino mass campaign #1

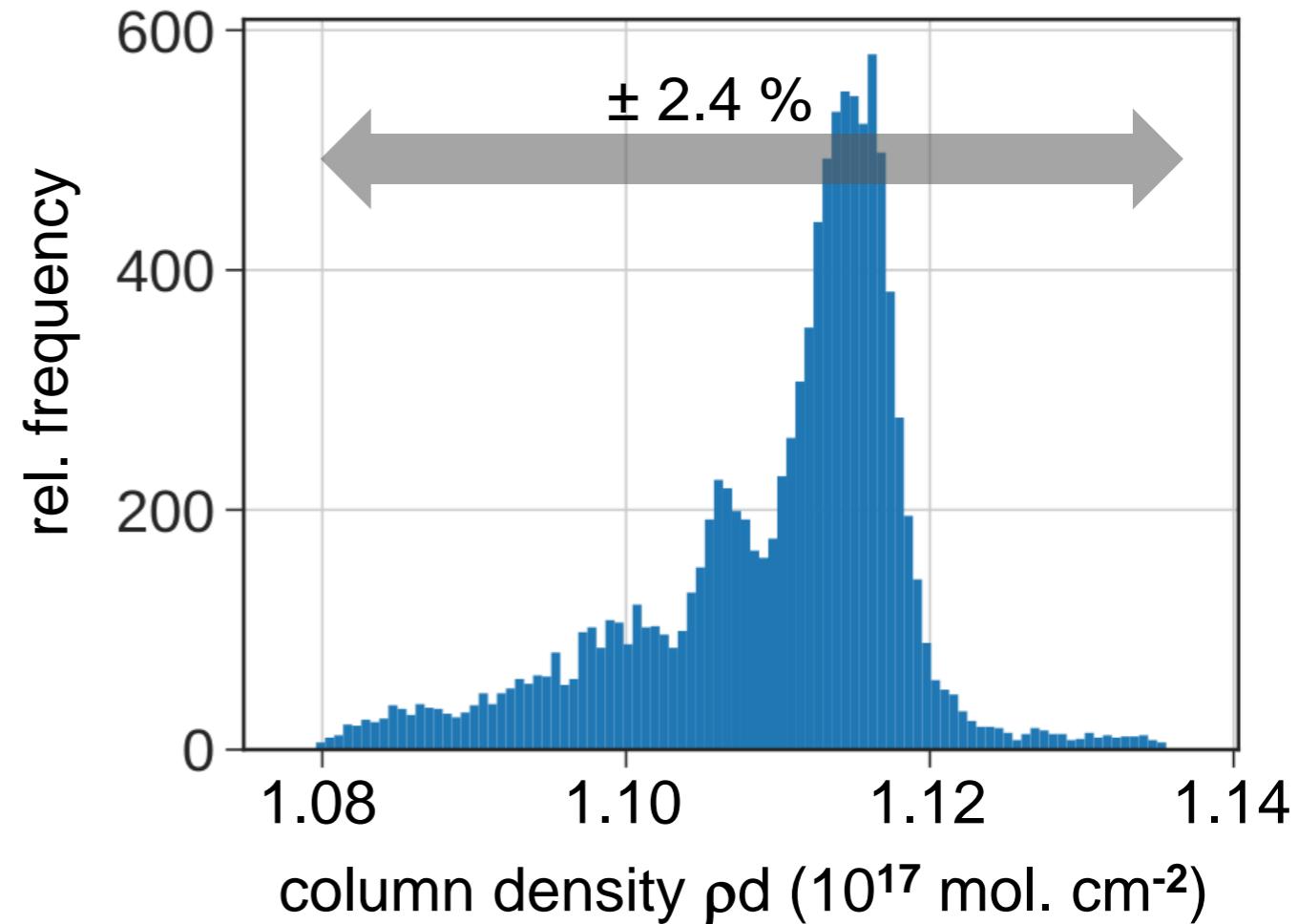
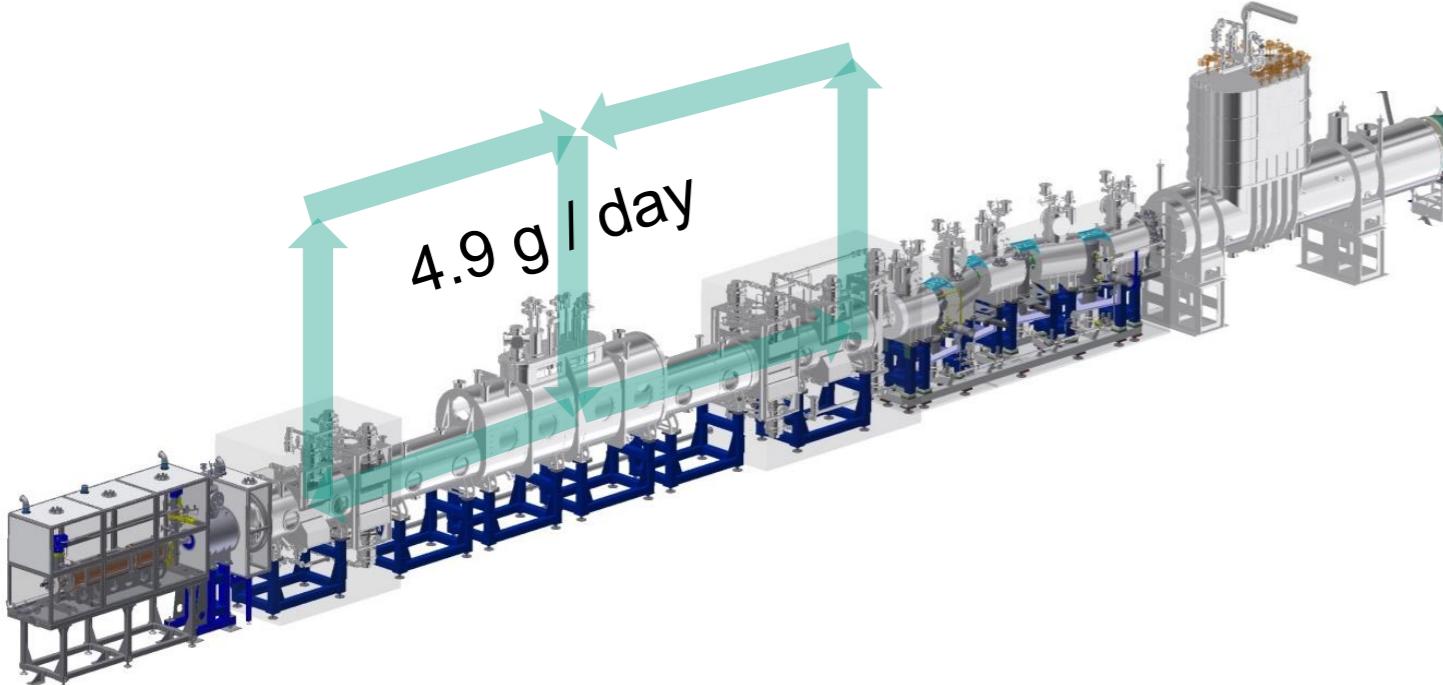
## ■ first ever large-scale throughput of high-purity tritium in closed loops

- 22% of nominal source activity (column density)

- ⇒ limits effects due to radiochemical reactions of  $T_2$  (initial „burn in“ effect)

- high isotopic tritium purity

- ⇒  $T_2$  (95.3 %), HT (3.5 %), DT (1.1 %)



# tritium scanning – strategy

## ■ 274 scans of tritium $\beta$ -decay spectrum:

- alternating up- / down- scans
- 2 h net scanning time
- analysis: 27 HV set points
- $[E_0 - 40 \text{ eV}, E_0 + 50 \text{ eV}]$



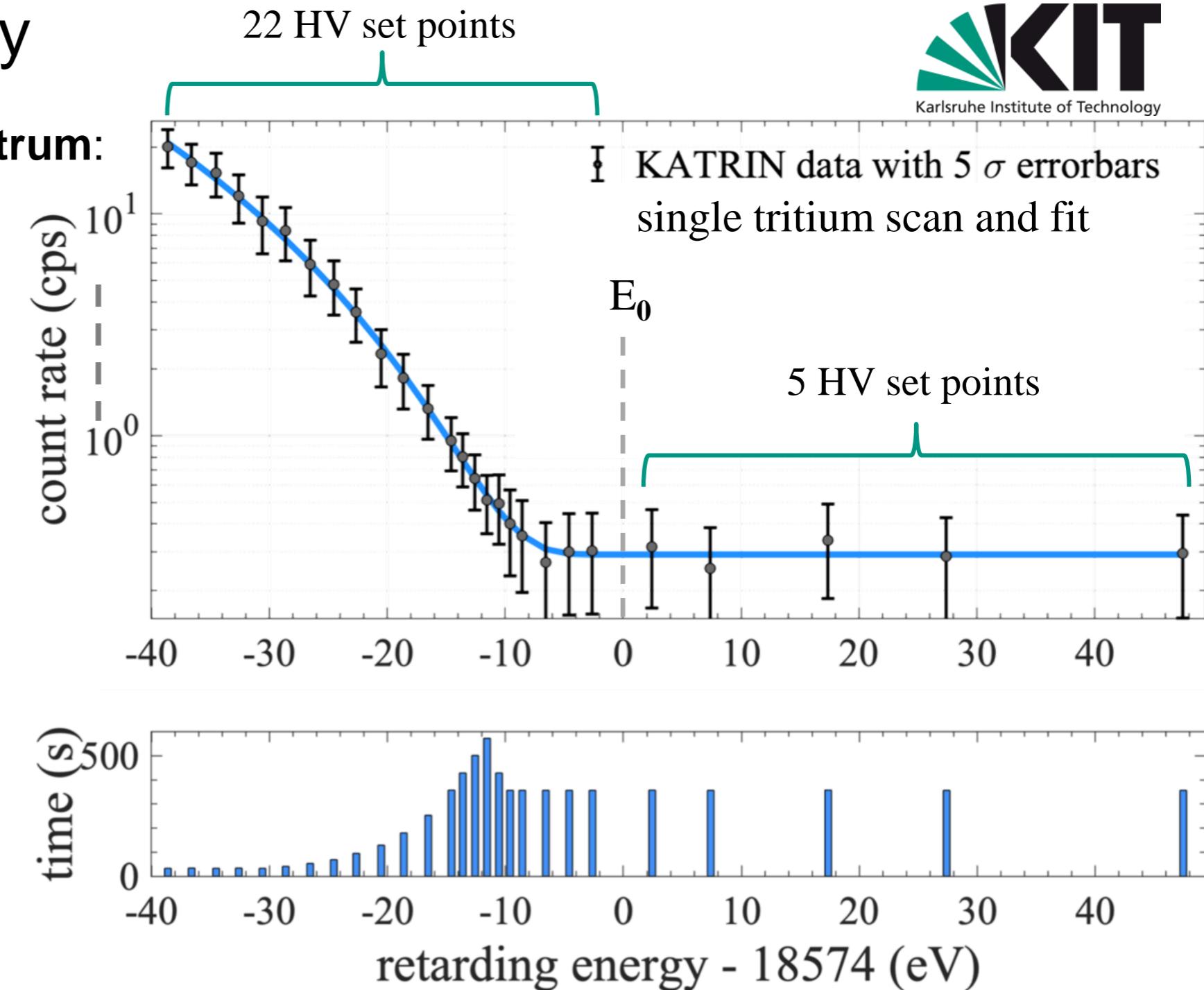
FSD



bg-slope

## ■ MTD maximises $\nu$ -mass sensitivity

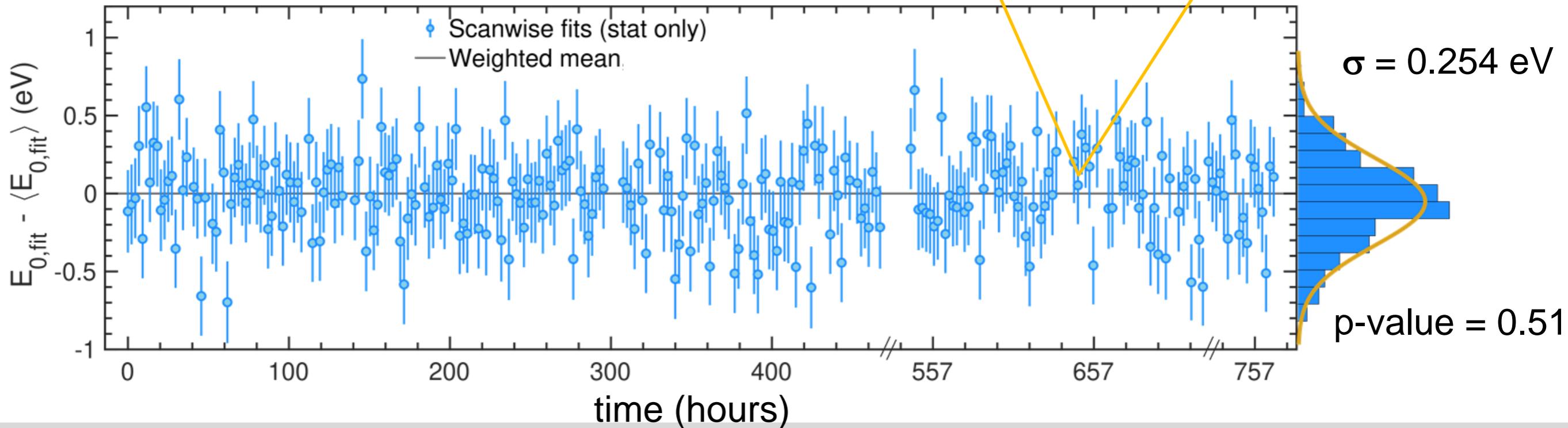
- focus on region close to  $E_0$



# tritium scanning

## ■ excellent stability of scanning over entire 4-week period

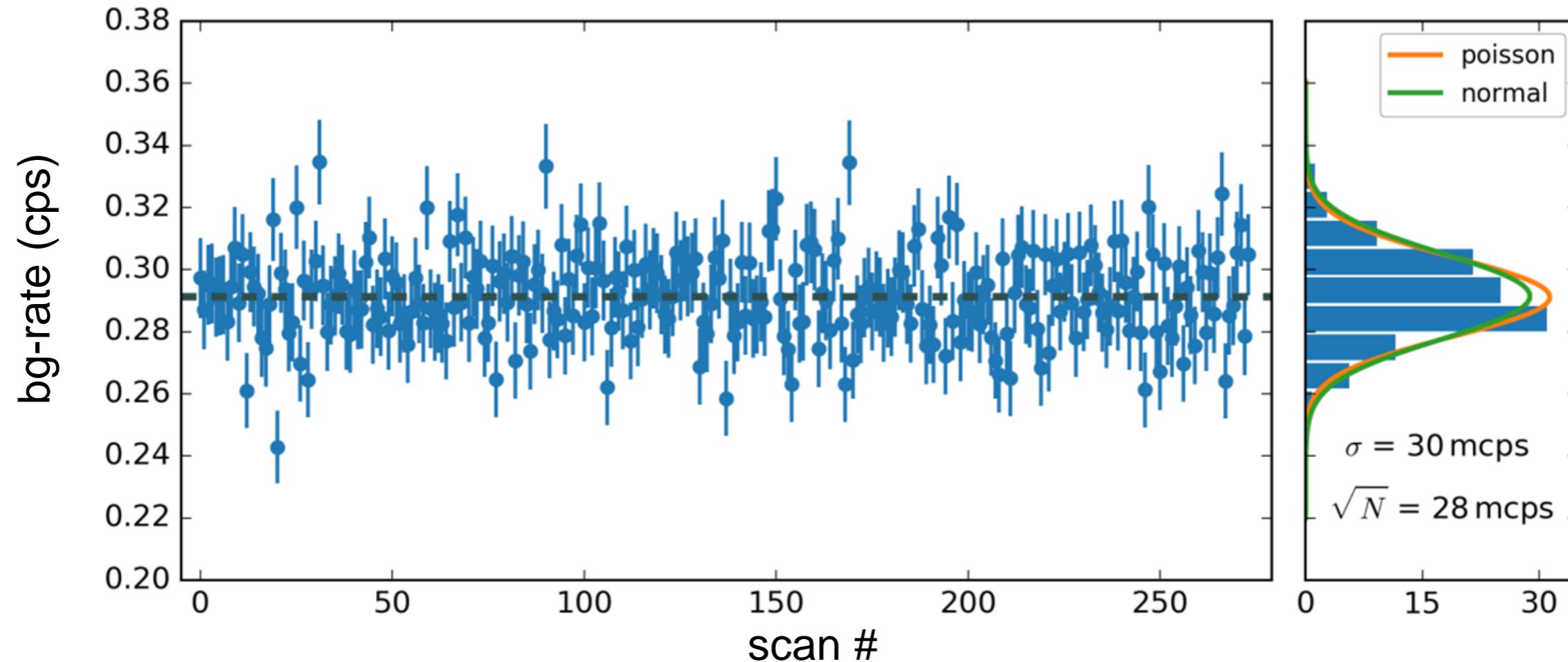
- fits to  $\beta$ -decay endpoints  $E_0$  of all 274 tritium scans:  
⇒ Gaussian distribution



# systematics: background

## ■ background due to neutral, excited atoms in active flux-tube volume

- ionisation of Rydberg states due to BBR       $\Rightarrow$  purely Poisson component
- $\alpha$ -decays of  $^{219}\text{Rn}$  atoms from NEG pump       $\Rightarrow$  with small non-Poisson part



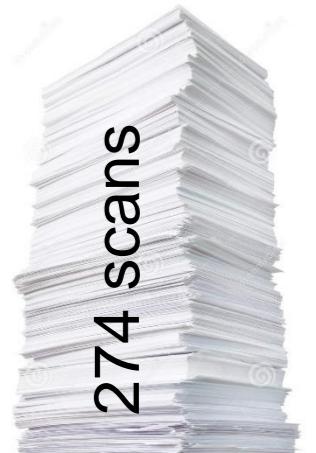
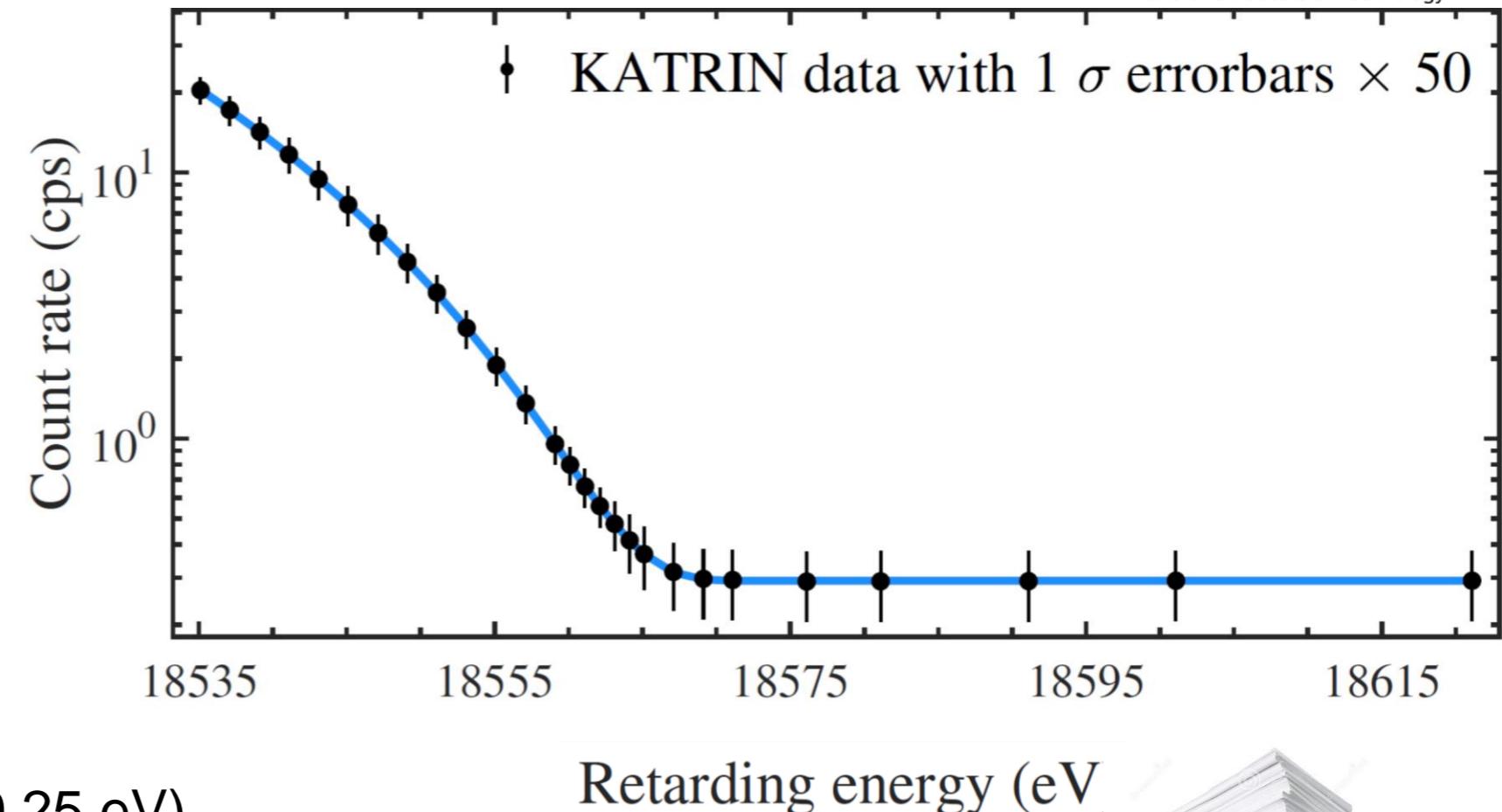
# Integral tritium $\beta$ -decay spectrum - merged

## ■ High-statistics $\beta$ -spectrum

- 2 million events in  
in 90-eV-wide interval  
(522 h of scanning)

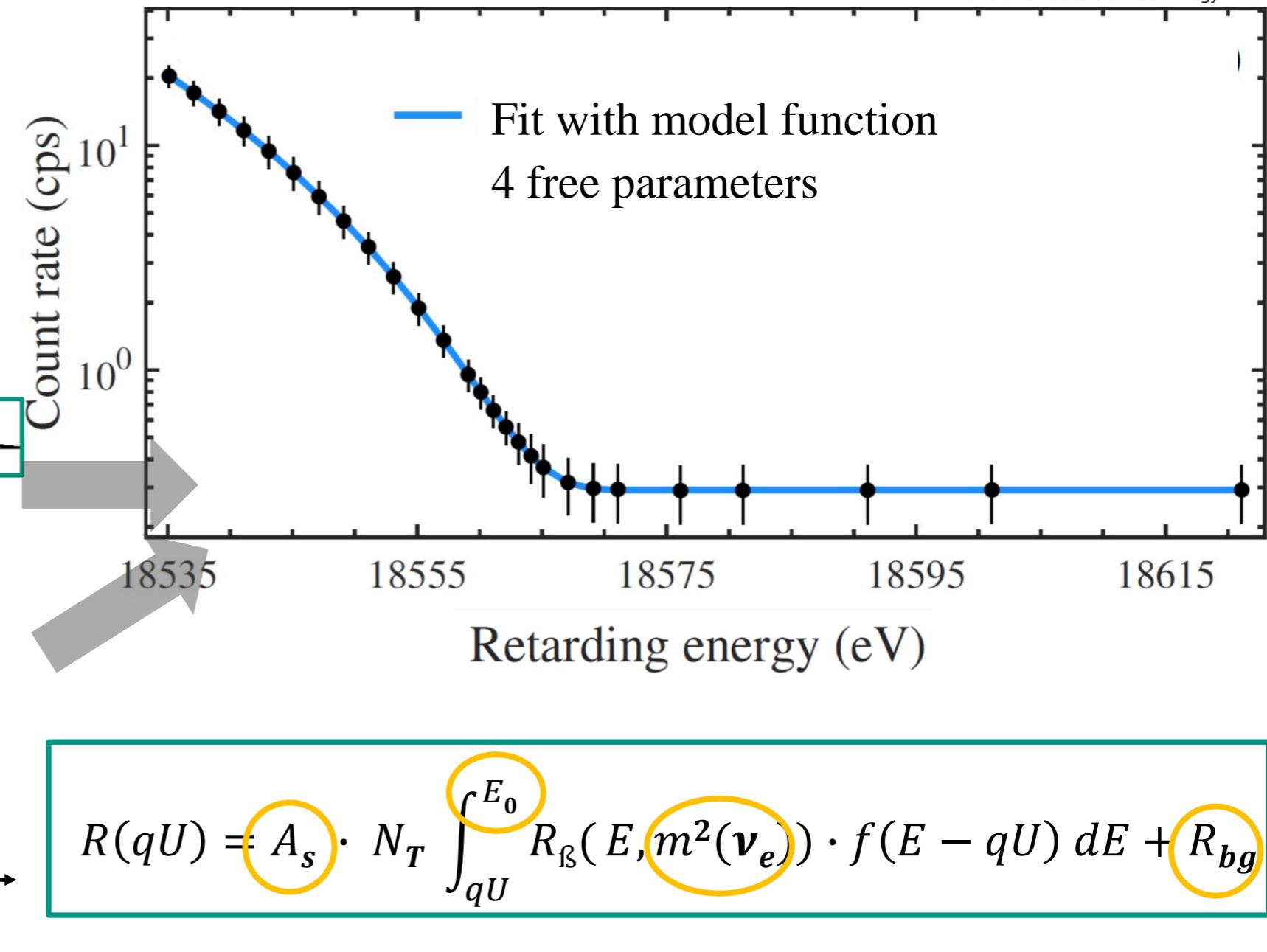
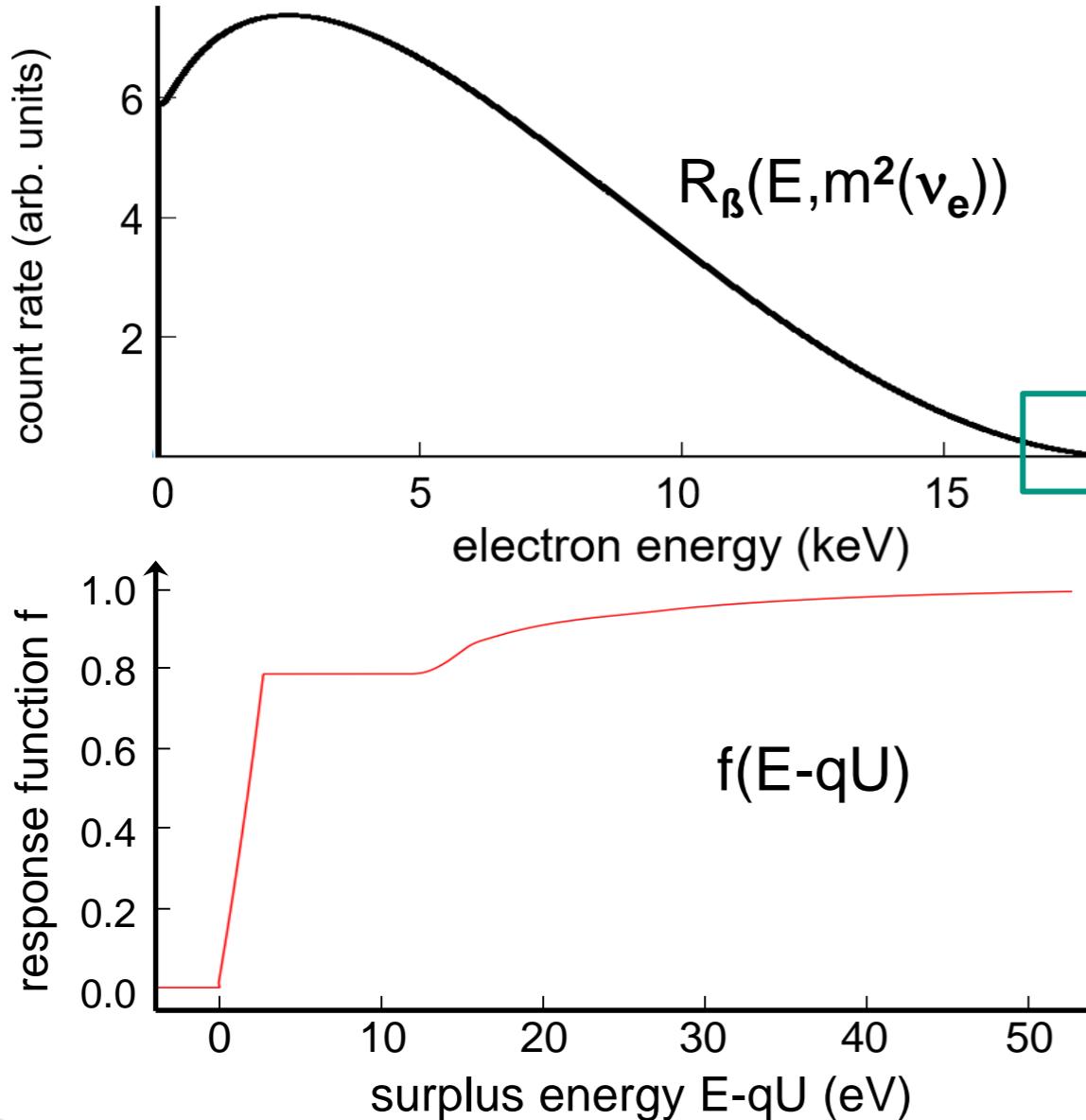
## ■ merged data set

- combine all 274 scans:  
excellent stability of all  
fitted  $\beta$ -decay endpoints  $E_0$  ( $\sigma = 0.25$  eV)  
 $\Rightarrow$  “stacking” of events at mean HV set-point  
(excellent reproducibility: RMS = 34 mV)



# modelling of experimental data

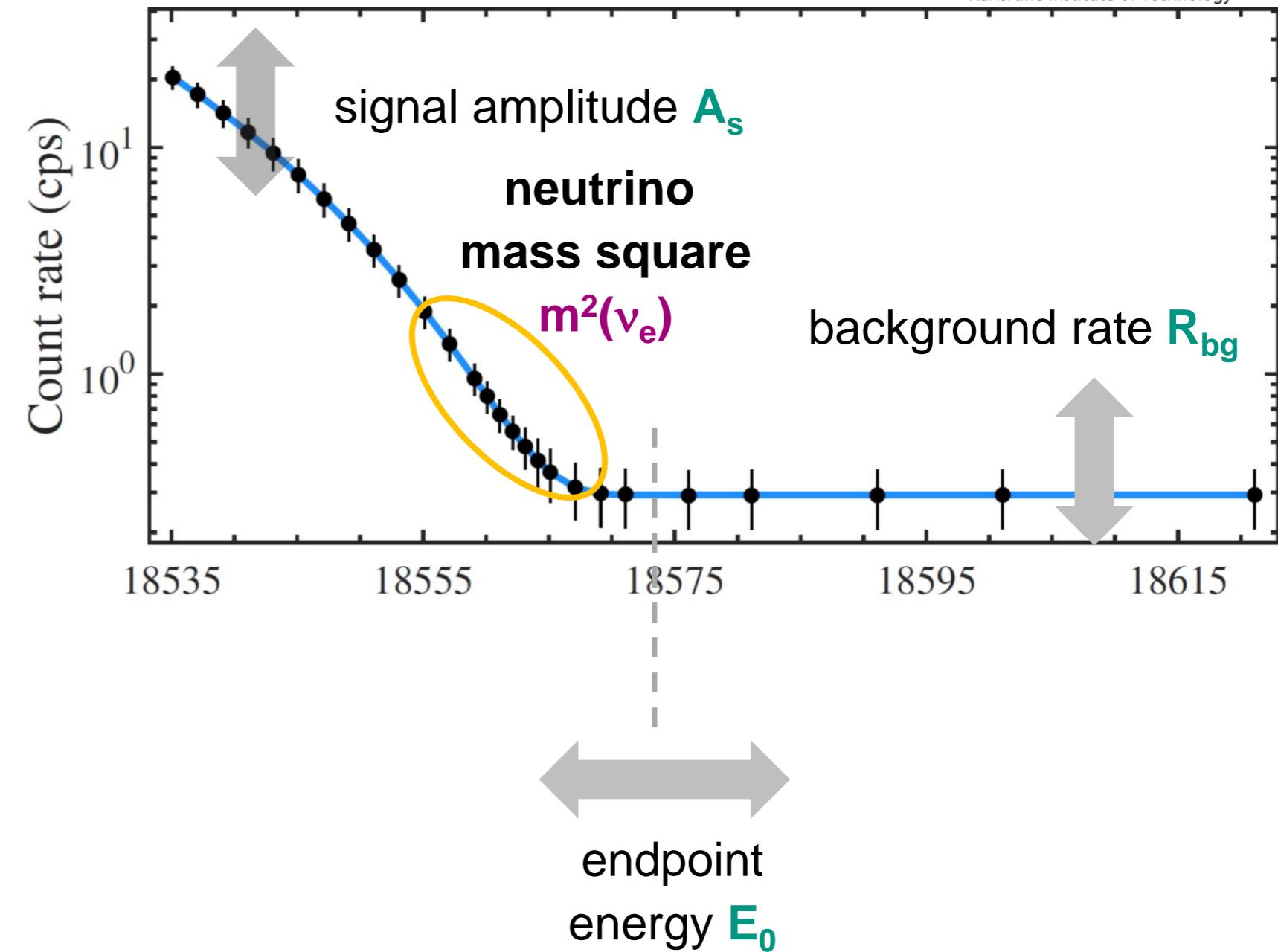
## ■ $\beta$ -spectrum $\otimes$ response function



# tritium scanning – fitting of spectrum

- fit of integrated experimental energy spectrum to theoretical model with **4 free parameters**

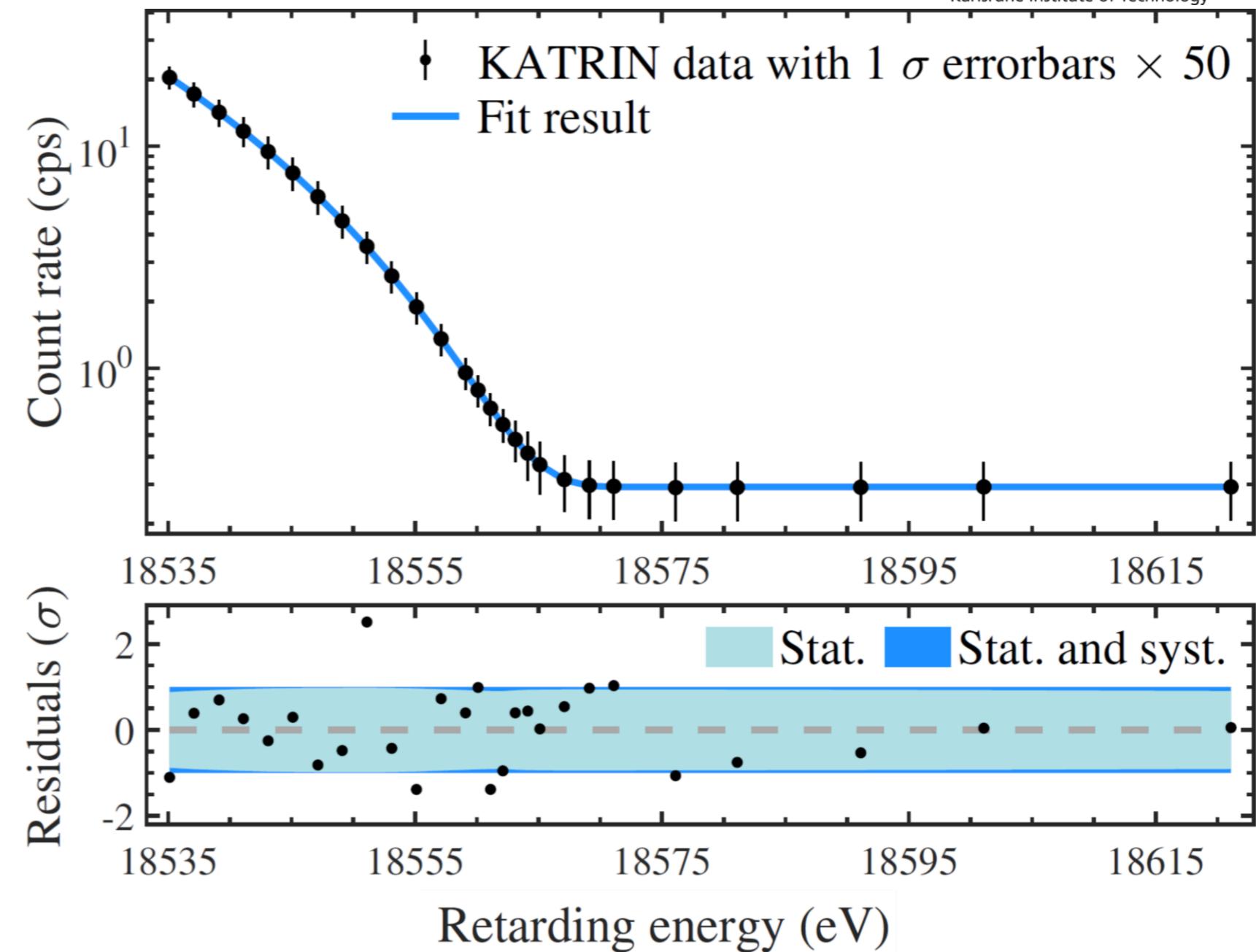
- leave parameters  $A_s$  and  $E_0$  unconstrained  
**'shape-only'** fit
- excellent goodness-of-fit  
 $\chi^2 = 21.4$  for 23 d.o.f.  
(p-value = 0.56)



# Integral tritium $\beta$ -decay spectrum

## ■ bias-free analysis

- blinding of FSD  
(Final State Distribution)  
important: data are  
left untouched  
blinding only on model !
- full analysis chain first on  
MC data sets  
(MC twins for each  $\beta$ -scan)
- final step: unblinded FSD  
for experimental data



# analysis chain & $\nu$ -mass result

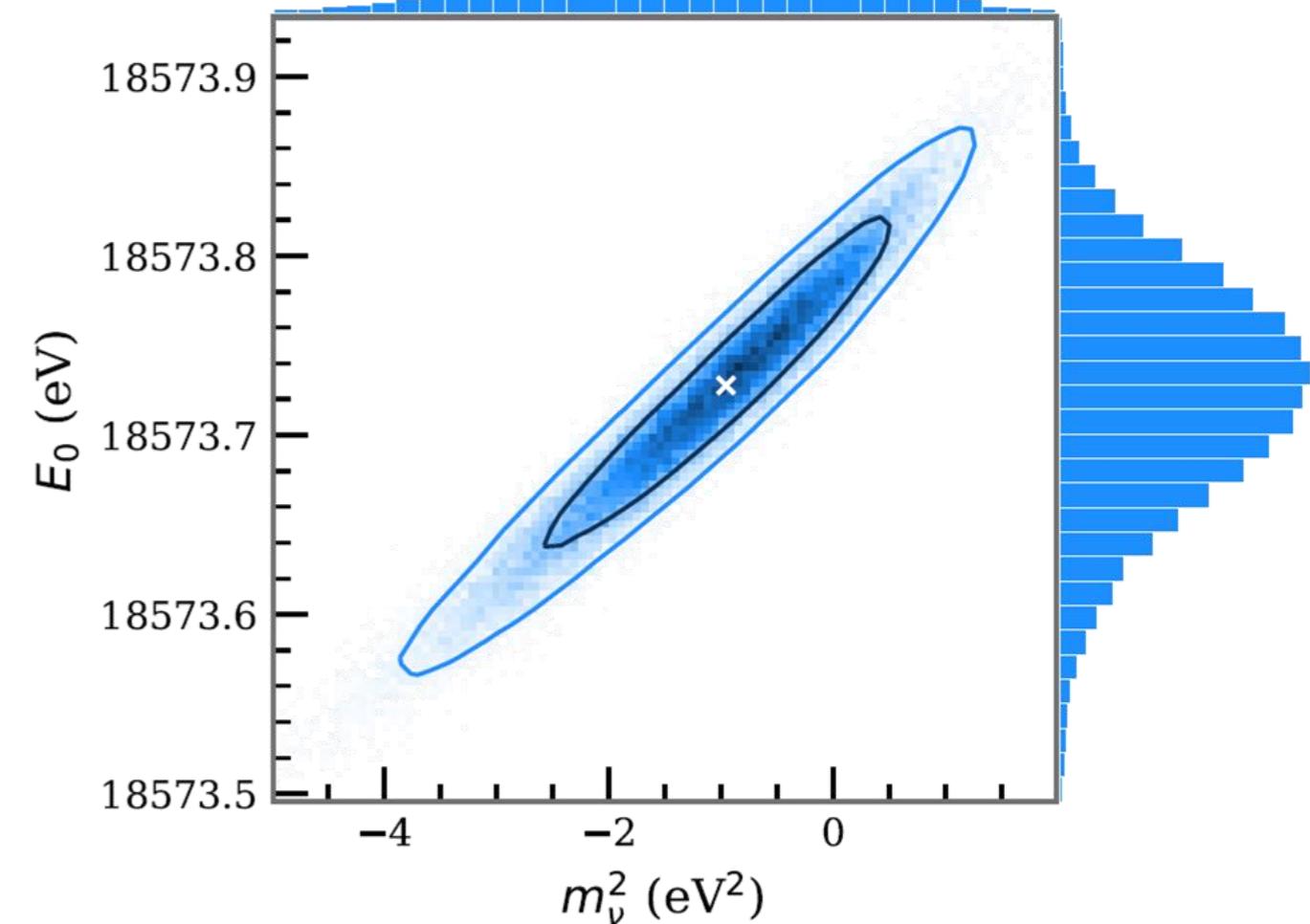
- two independent analysis methods  
to propagate uncertainties & infer parameters

- Covariance matrix:  
covariance matrix +  $\chi^2$ -estimator

- MC propagation:  
 $10^5$  MC samples + likelihood ( $-2 \ln \mathcal{L}$ )
  - both methods agree to a few percent

- $\nu$ -mass and  $E_0$ : best fit results

$$m^2(\nu_e) = \left( -1.0 \begin{array}{l} +0.9 \\ -1.1 \end{array} \right) \text{eV}^2 \text{ (90% CL)}$$



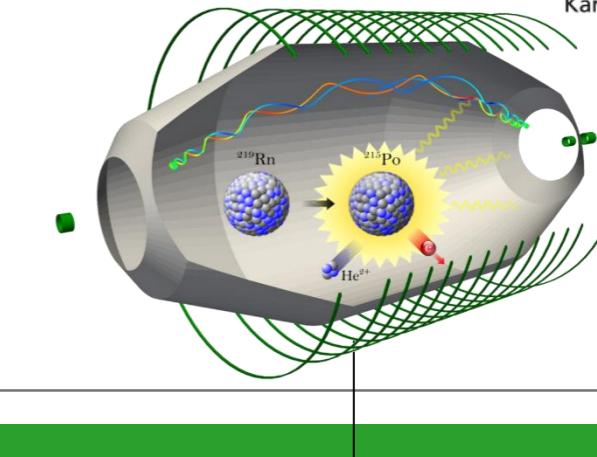
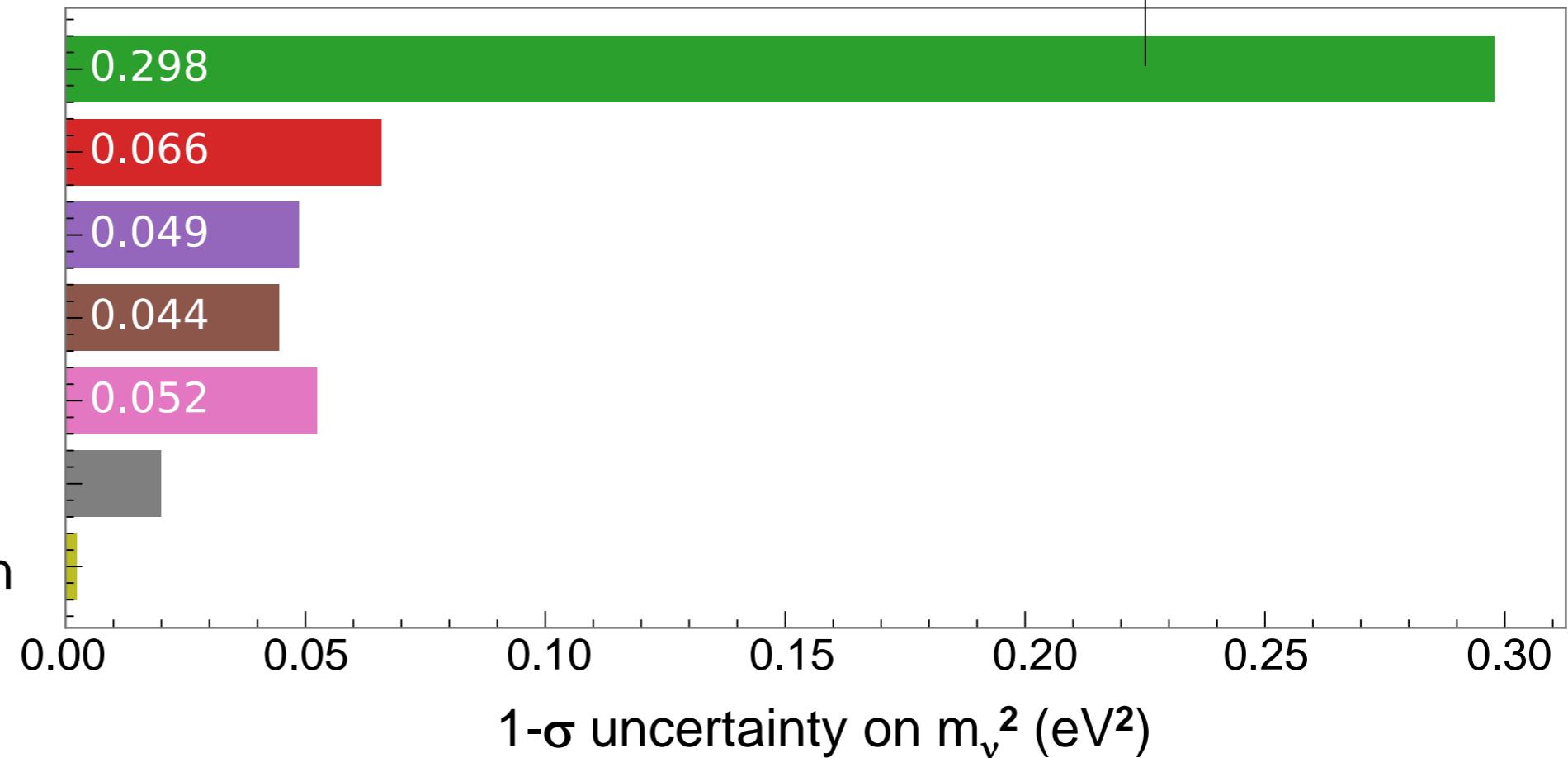
$$E_0 = (18573.7 \pm 0.1) \text{ eV} \Rightarrow \text{Q-value : } (18575.2 \pm 0.5) \text{ eV} \quad \text{Q-value } [\Delta M(^3\text{H}, ^3\text{He})]: (18575.72 \pm 0.07) \text{ eV}$$

# systematics breakdown

## ■ well-understood systematics budget $\sigma_{\text{syst}}$ (with $\sigma_{\text{syst}} < \sigma_{\text{stat}}$ )

- total statistical uncertainty budget  $\sigma_{\text{stat}} = 0.97 \text{ eV}^2$
- total systematic uncertainty budget  $\sigma_{\text{syst}} = 0.32 \text{ eV}^2$

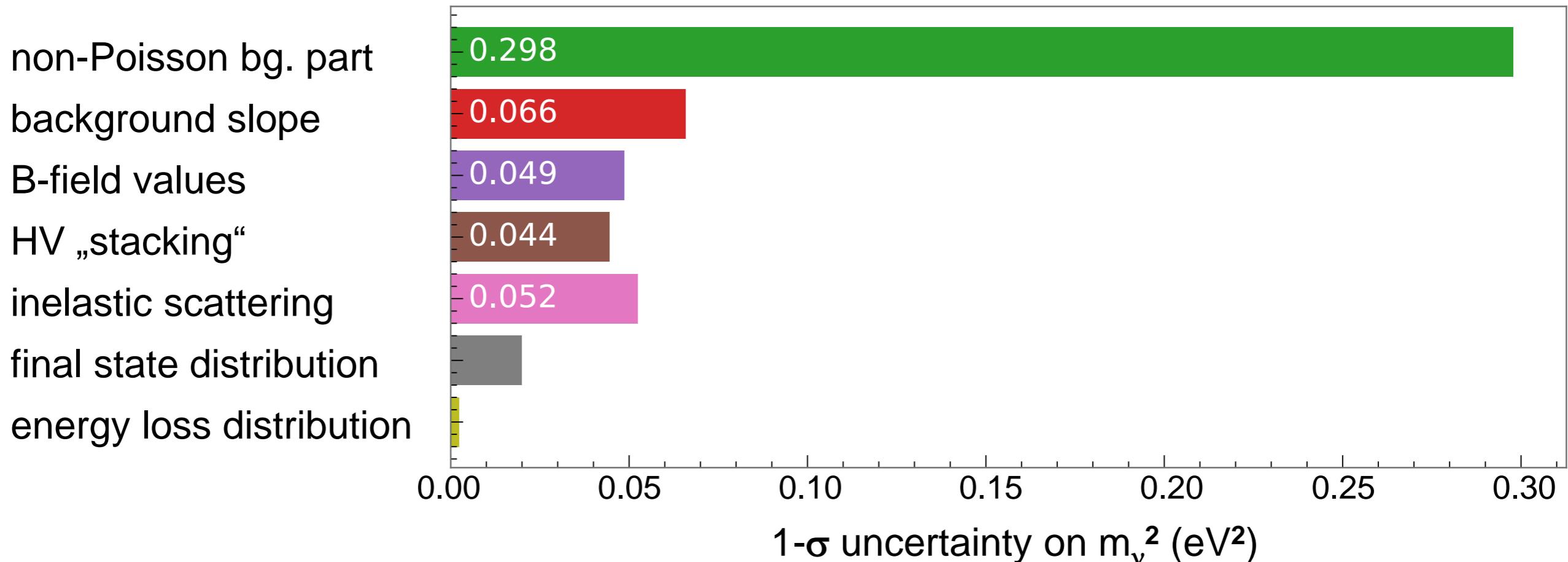
non-Poisson bg. part  
 background slope  
 B-field values  
 HV „stacking“  
 inelastic scattering  
 final state distribution  
 energy loss distribution



# systematics breakdown

## ■ well-understood systematics budget $\sigma_{\text{syst}}$ based on only 4 weeks of data

- total statistical uncertainty budget  $\sigma_{\text{stat}} = 0.97 \text{ eV}^2$
  - total systematic uncertainty budget  $\sigma_{\text{syst}} = 0.32 \text{ eV}^2$
- improves on Mainz/Troitsk by
- factor 2  
factor 6

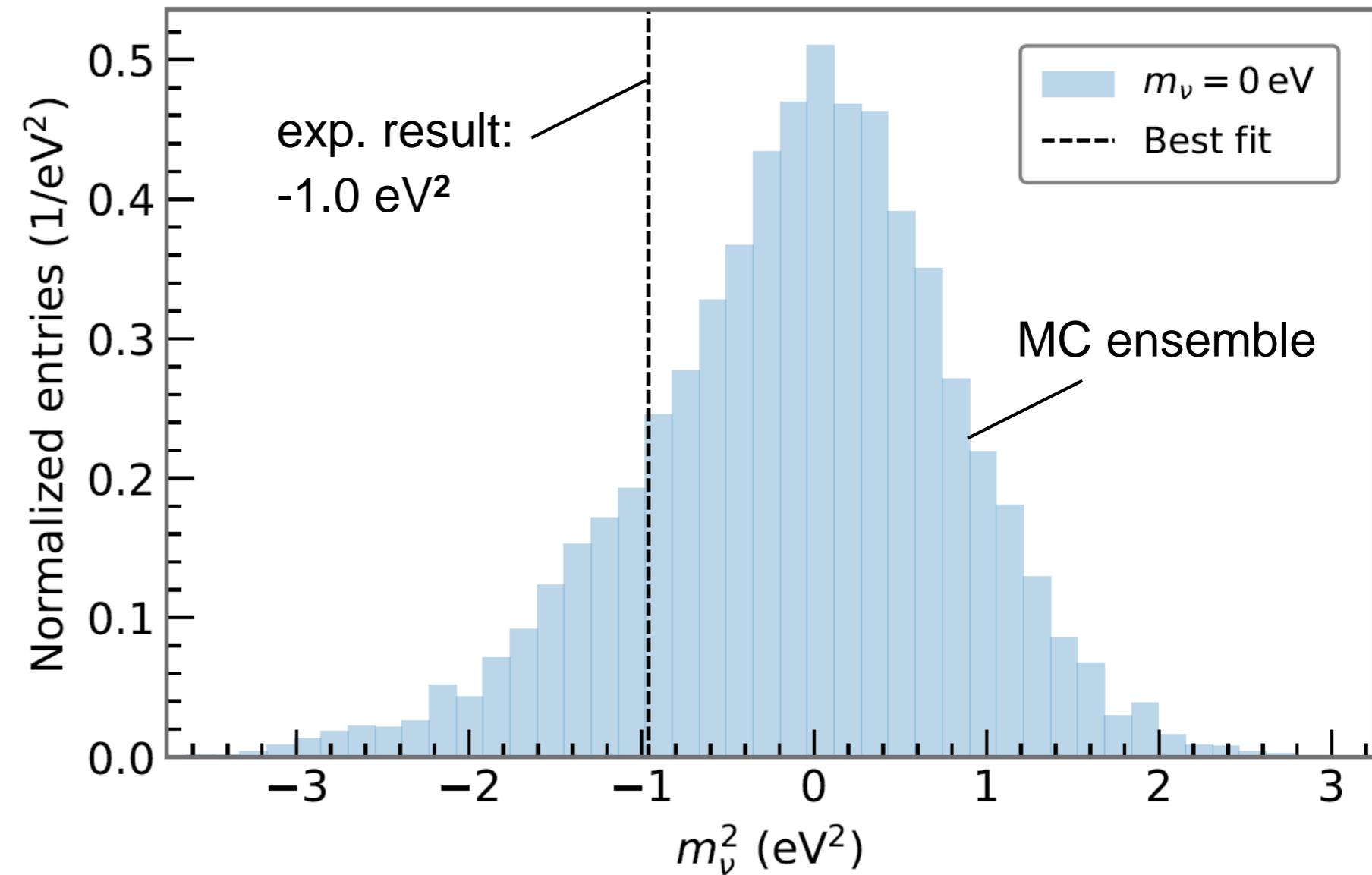


# KATRIN result and expectation

■ best-fit result corresponds to a  $1-\sigma$  statistical fluctuation to negative  $m^2(\nu_e)$

- p-value is derived from 13 000 MC samples with  $m^2(\nu_e) = 0$  and properly fluctuated  $\sigma_{\text{stat}}$  and  $\sigma_{\text{syst}}$

p-value = 0.16



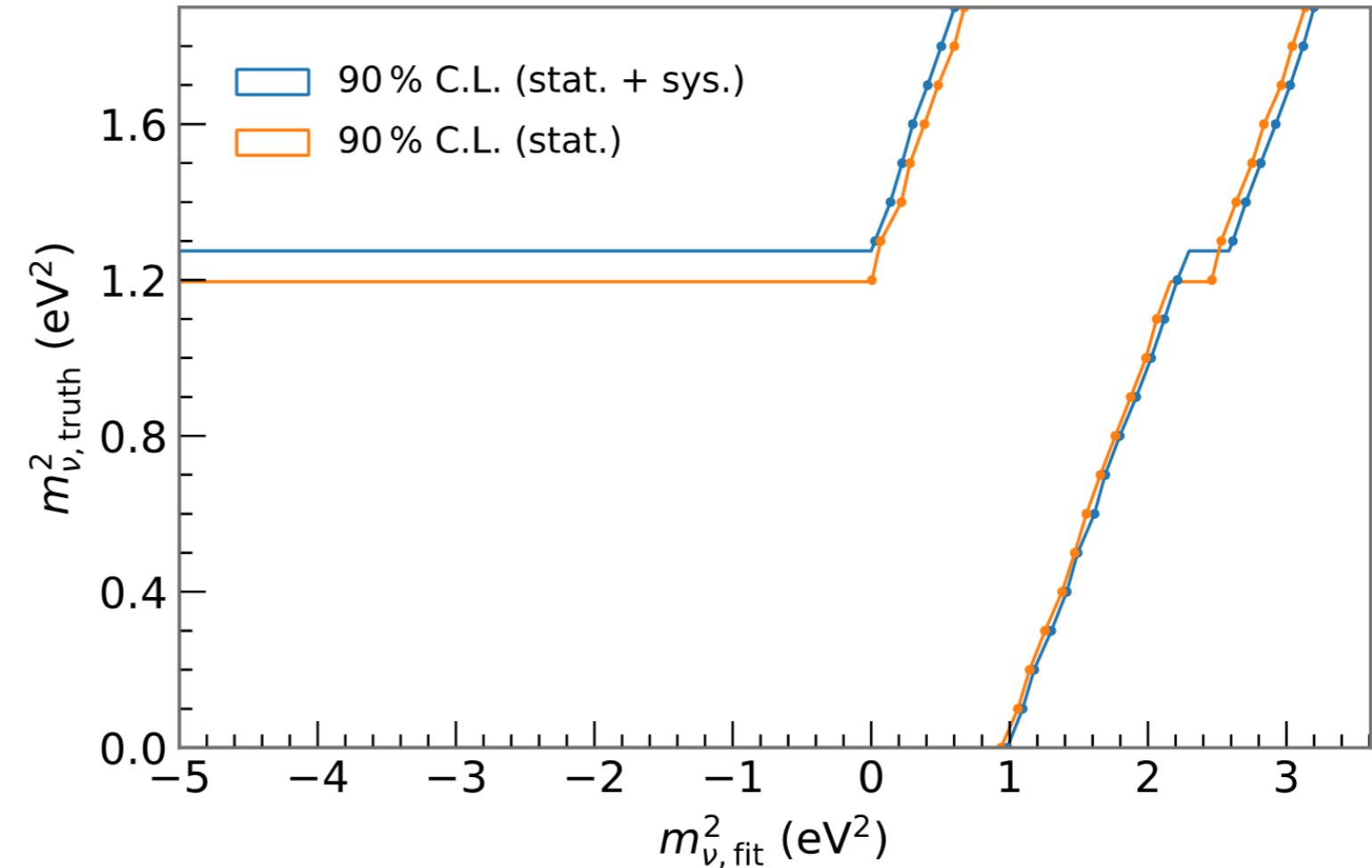
# neutrino mass upper limit

■ **confidence belts:** procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC)

- for this first result we follow the robust LT method
- LT yields experimental sensitivity by construction for  $m^2(\nu_e) < 0$
- **KATRIN upper limit on neutrino mass:**

LT     $m(\nu) < 1.1 \text{ eV (90\% CL)}$

FC     $m(\nu) < 0.8 \text{ eV (90\% CL)}$   
       $< 0.9 \text{ eV (95\% CL)}$



A.V. Lokhov, F.V. Tkachov, Phys. Part. Nucl. 46 (2015) 347

# neutrino mass upper limit

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 $< 0.9 \text{ eV (95\% CL)}$

M. Aker et al. (KATRIN Collab.), *An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN, acc. for publ. in PRL*

An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN

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Ryšavý,<sup>17</sup> R. Sack,<sup>8</sup> A. Saenz,<sup>25</sup> P. Schäfer,<sup>1,2</sup> L. Schimpf,<sup>6</sup> K. Schlösser,<sup>1</sup> M. Schlösser,<sup>1,2</sup> L. Schlüter,<sup>10,3</sup> H. Schön,<sup>2</sup> K. Schöning,<sup>11,1,2</sup> M. Schrank,<sup>1</sup> B. Schulz,<sup>25</sup> J. Schwarz,<sup>1</sup> H. Seitz-Moskaliuk,<sup>6</sup> W. Seller,<sup>20</sup> V. Sibile,<sup>7</sup> D. Siegmann,<sup>10,3</sup> A. Skasyrskaya,<sup>21</sup> M. Slezák,<sup>10,17</sup> A. Špalek,<sup>17</sup> F. Spanier,<sup>1</sup> M. Steidl,<sup>1</sup> N. Steinbrink,<sup>8</sup> M. Sturm,<sup>1,2</sup> M. Suesser,<sup>2</sup> M. Sun,<sup>16</sup> D. Tcherniakhovski,<sup>9</sup> H. H. Telle,<sup>23</sup> T. Thümmler,<sup>1,8</sup> L. A. Thorne,<sup>18</sup> N. Titov,<sup>21</sup> I. Tkachev,<sup>21</sup> N. Trost,<sup>1</sup> K. Urban,<sup>10,3</sup> D. Vénos,<sup>17</sup> K. Valerius,<sup>1,8</sup> B. A. VanDevender,<sup>16</sup> R. Vianden,<sup>5</sup> A. P. Vizcaya Hernández,<sup>18</sup> B. L. Wall,<sup>16</sup> S. Wüstling,<sup>9</sup> M. Weber,<sup>9</sup> C. Weinheimer,<sup>8</sup> C. Weiss,<sup>24</sup> S. Welte,<sup>1,2</sup> J. Wendel,<sup>1,2</sup> K. J. Wierman,<sup>13,14</sup> J. F. Wilkerson,<sup>13,14,21</sup> J. Wolf,<sup>6</sup> W. Xu,<sup>7</sup> Y.-R. Yen,<sup>18</sup> M. Zacher,<sup>8</sup> S. Zadorozhny,<sup>21</sup> M. Zbořil,<sup>8,17</sup> and G. Zeller,<sup>1,2</sup>

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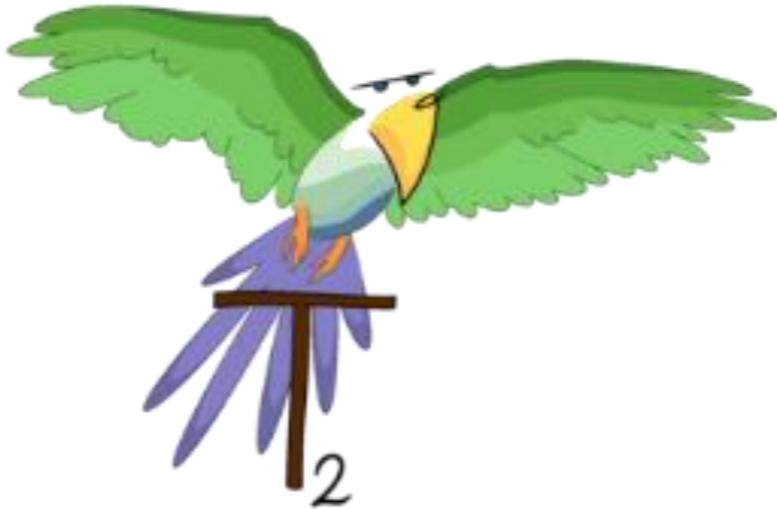
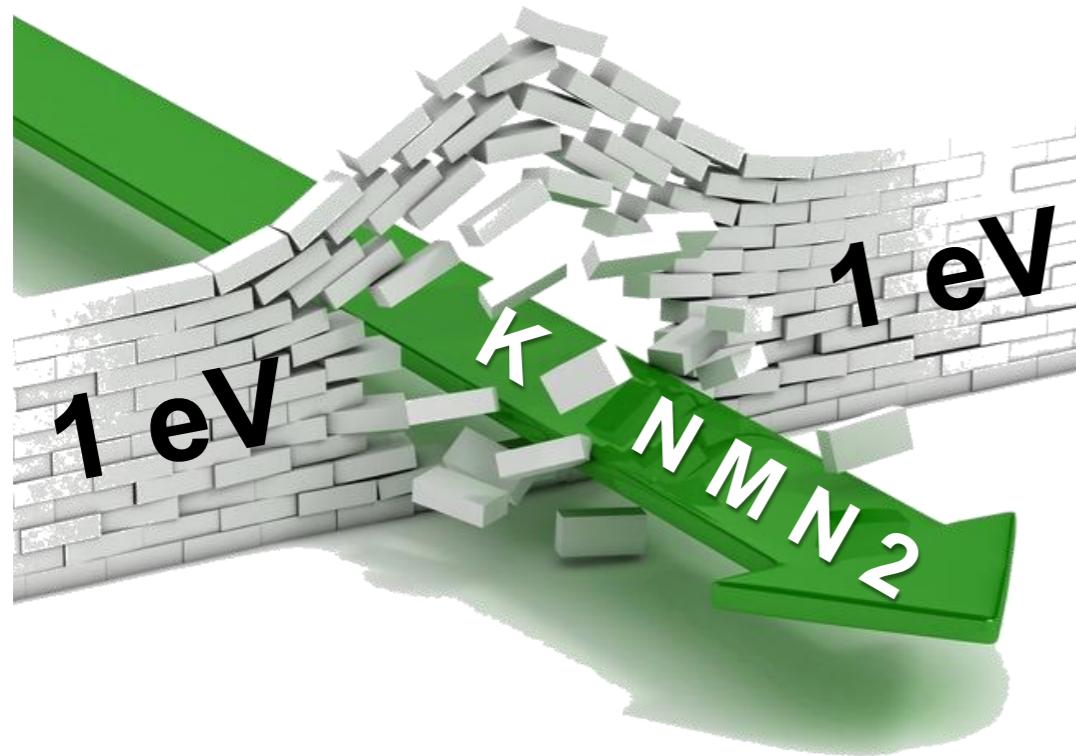
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arXiv:1909.06048v1 [hep-ex] 13 Sep 2019



# KATRIN FUTURE

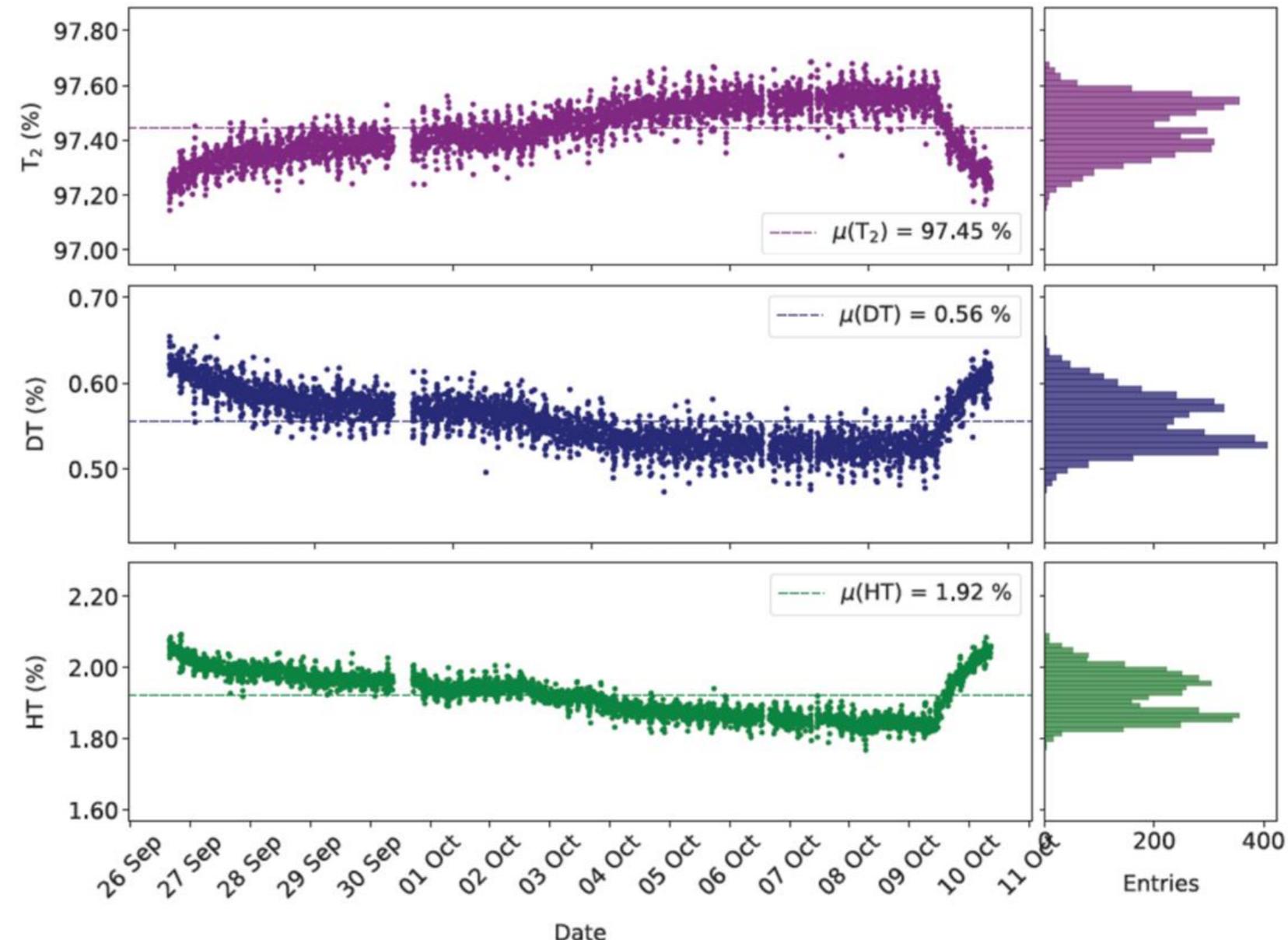
# actual KNM2 measurement campaing

## ■ **KNM2**: since Sept. 27, 2019

- first campaign with quasi-nominal column density (~60 days)
- improved HV-reproducibility (34 mV → few mV)
- reduced background rate after spectrometer bake-out



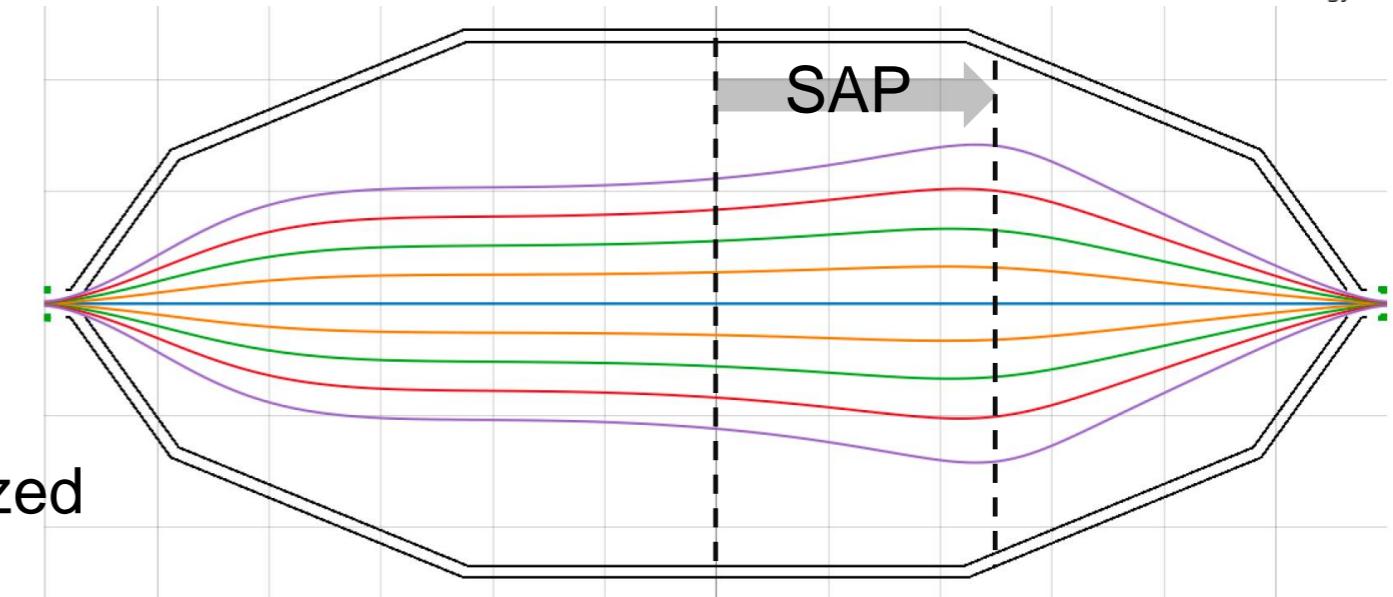
- **significantly improved S/B relative to KNM1 (goal: factor 10)**



# KATRIN – future plans

## ■ KATRIN near- and long-term future :

- even further reduction of background from decays of Radon & Rydberg atoms  
⇒ upgraded aircoil system   
„shifted analysis plane“ (SAP)  
bg-studies & tritium scans being analyzed



- further reduction of systematics  
energy loss via egun in ToF modus, ...



R&D works on ToF-technique  
for differential tritium scanning

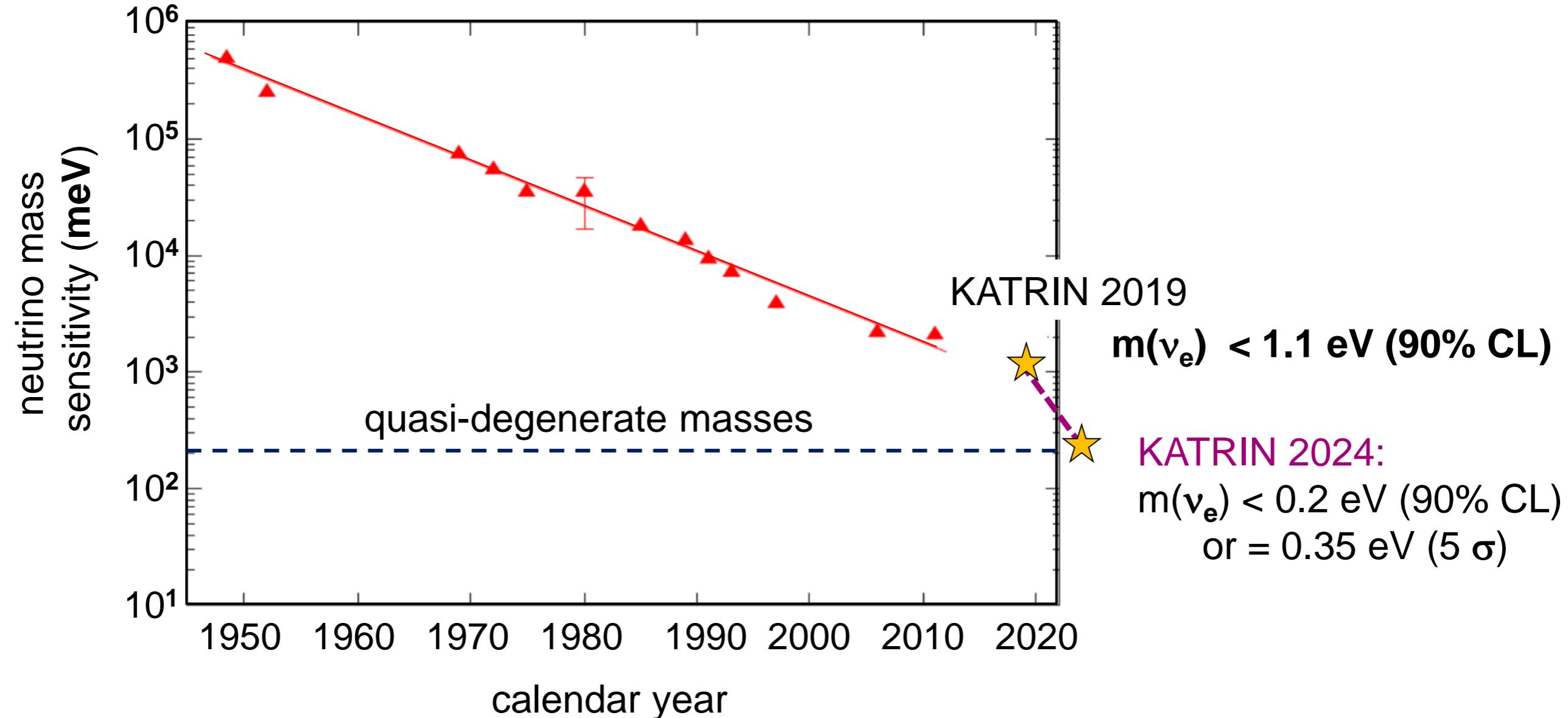
- 1000 days of measurements at nominal  $\rho d$  ( $5 \cdot 10^{17}$  molecules  $\text{cm}^{-2}$ )  
3 tritium campaigns (65 days each)  
per calendar year over next 5 years

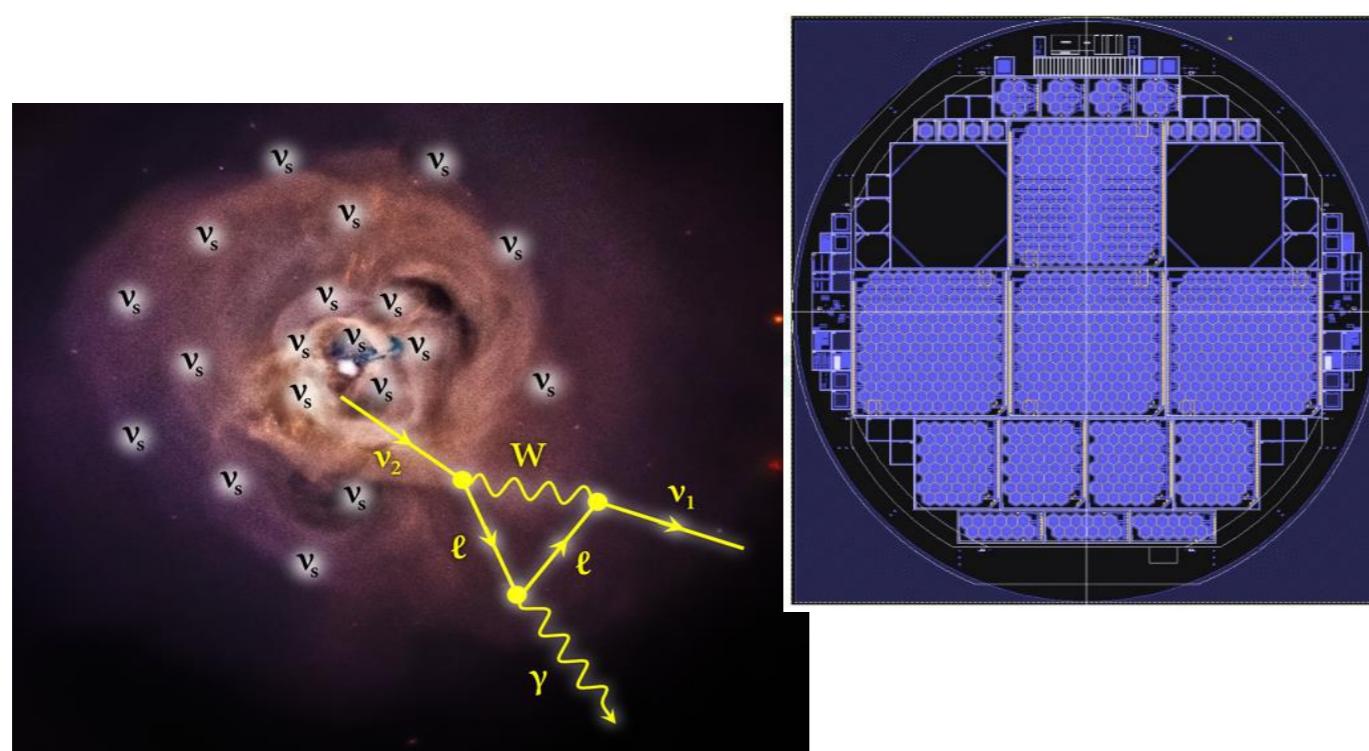
sensitivity  $m(\nu_e) = 0.2 \text{ eV (90\% CL)}$

$0.35 \text{ eV (5}\sigma\text{)}$

# future Moore's law of direct ν-mass sensitivities

■ KATRIN 2019 – 2024: a new, much steeper slope for Moore's law





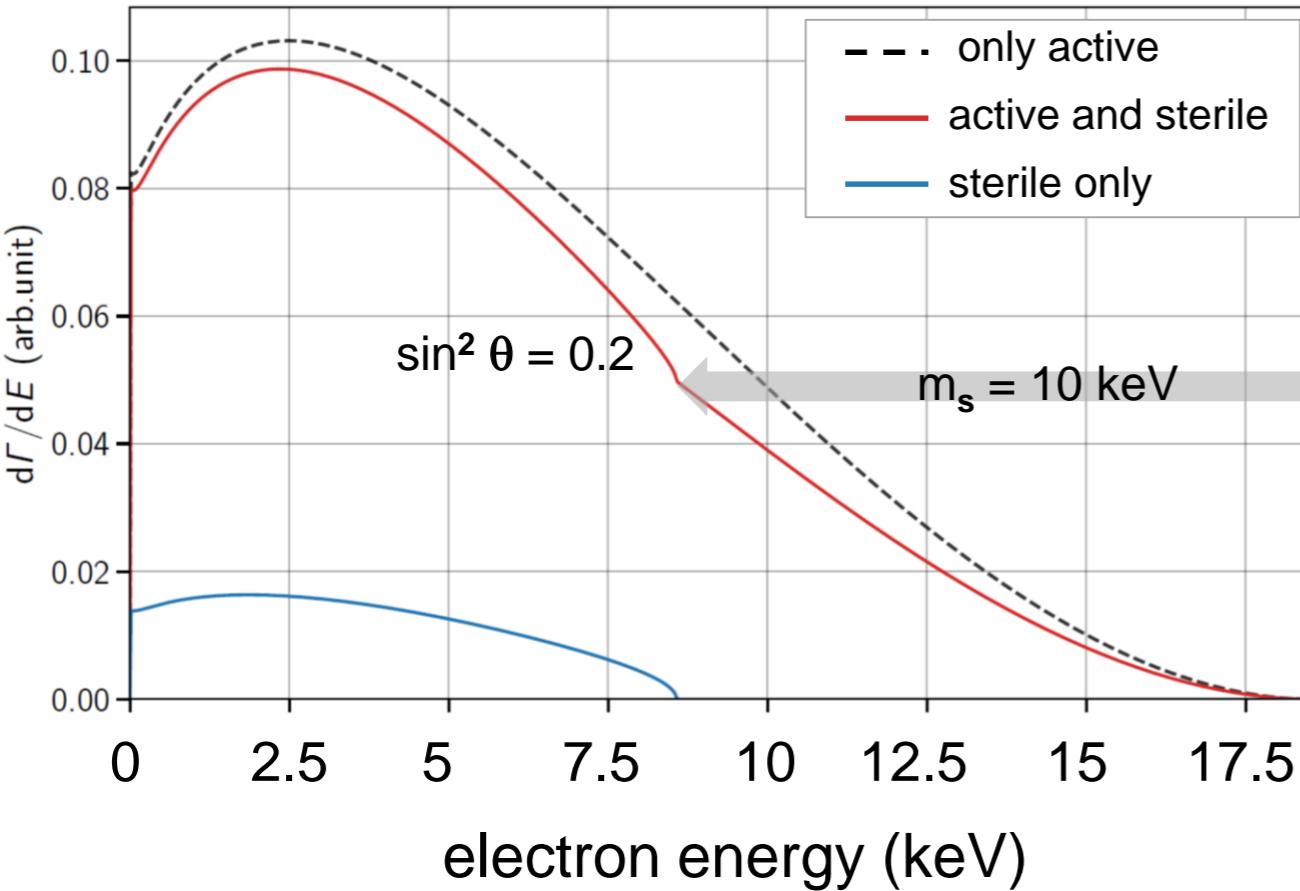
# SEARCH FOR KEV STERILE NEUTRINOS

# Tritium $\beta$ -decay and dark fermions

## ■ BSM particles (sterile neutrinos, light fermionic DM)

in keV-mass scale would produce a 'kink' in the  $\beta$ -spectrum

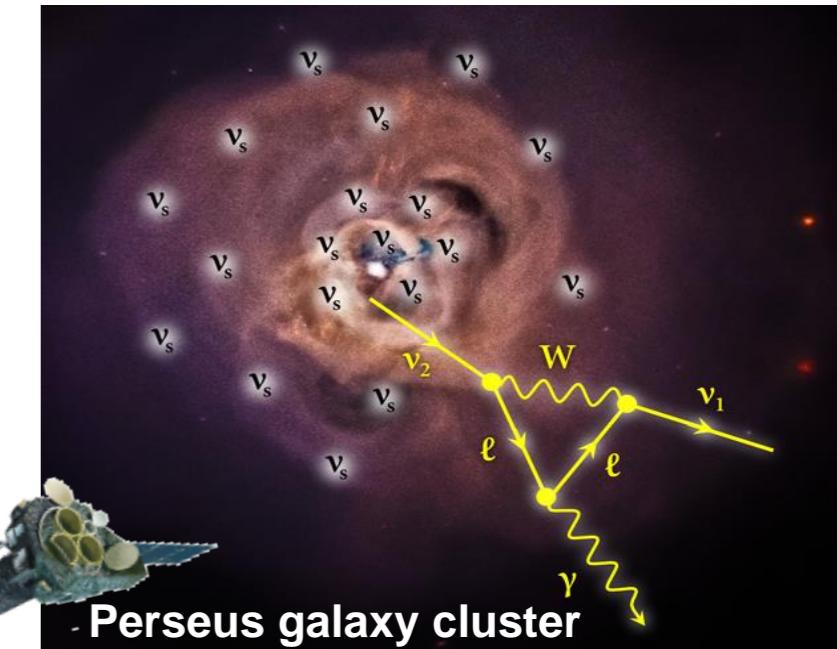
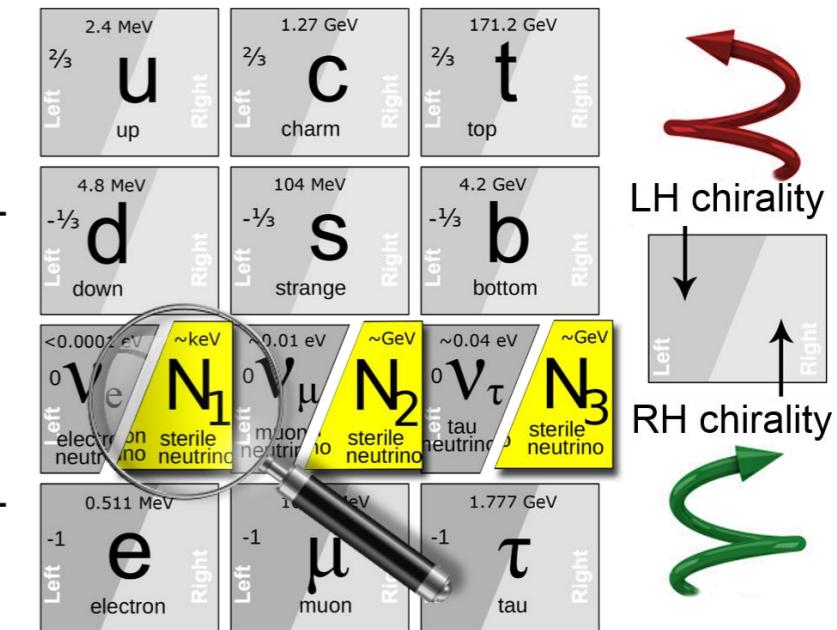
- cover entire phase space (masses up to 18 keV)
- cover tiny couplings ( $\sim 10^{-7}$ )  $\Rightarrow$  left-right couplings (Rodejohann)



$$\frac{dN}{dE} = \cos^2 \theta_s \cdot \frac{dN}{dE}(m_{\text{active}}) + \sin^2 \theta_s \cdot \frac{dN}{dE}(m_{\text{sterile}})$$

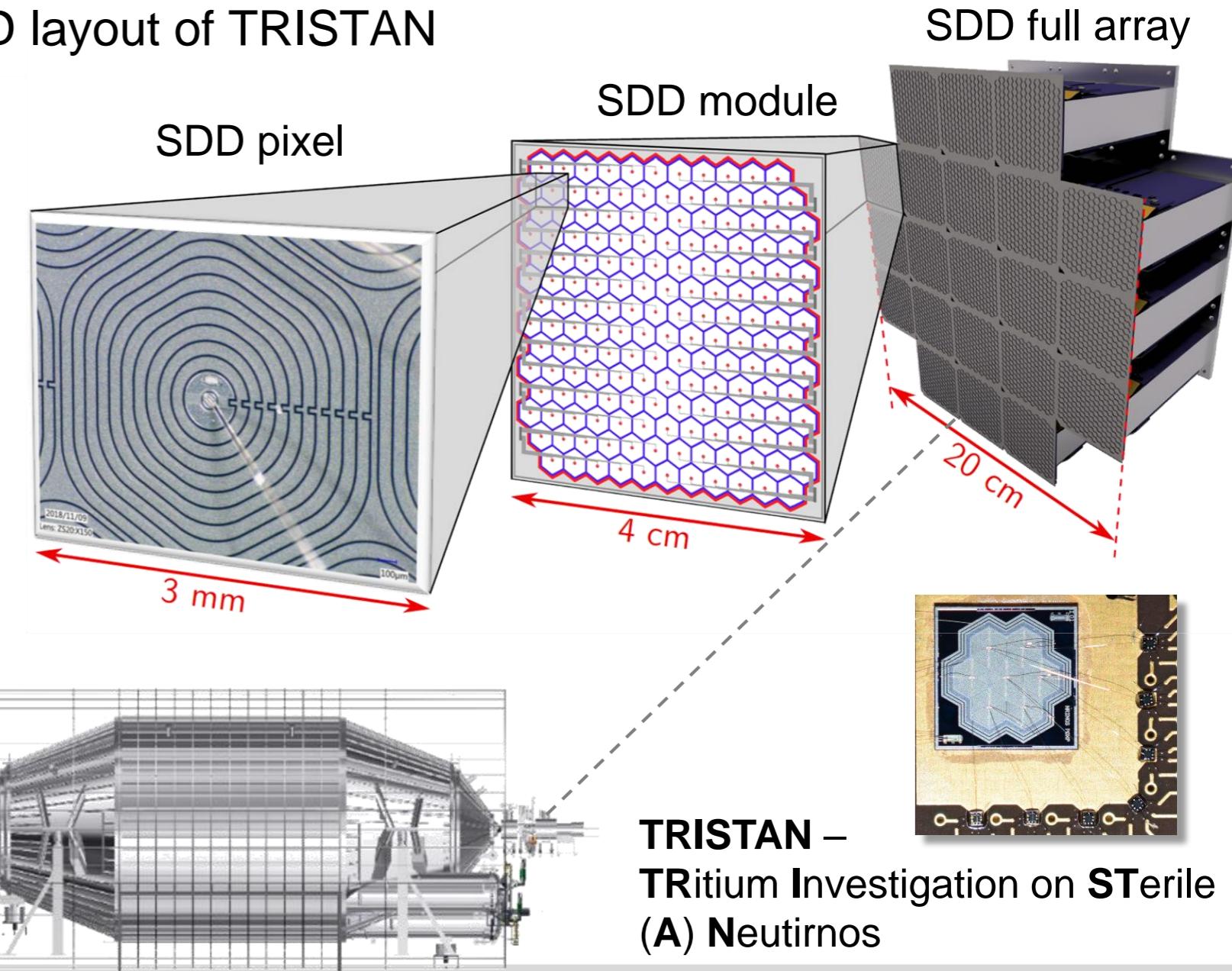
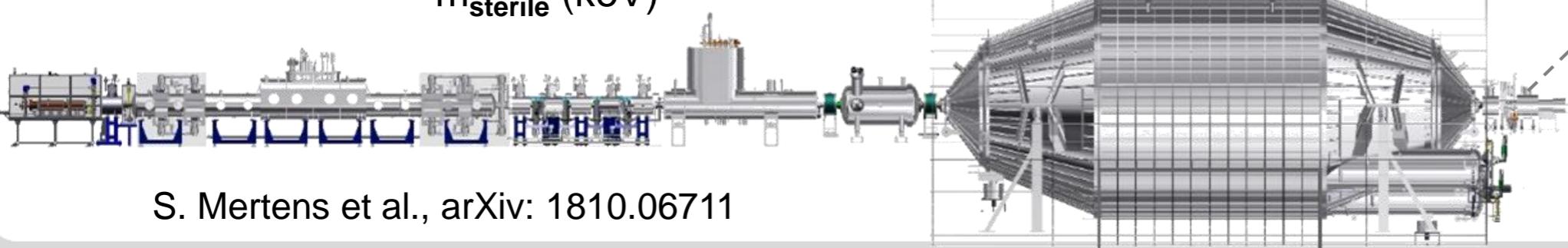
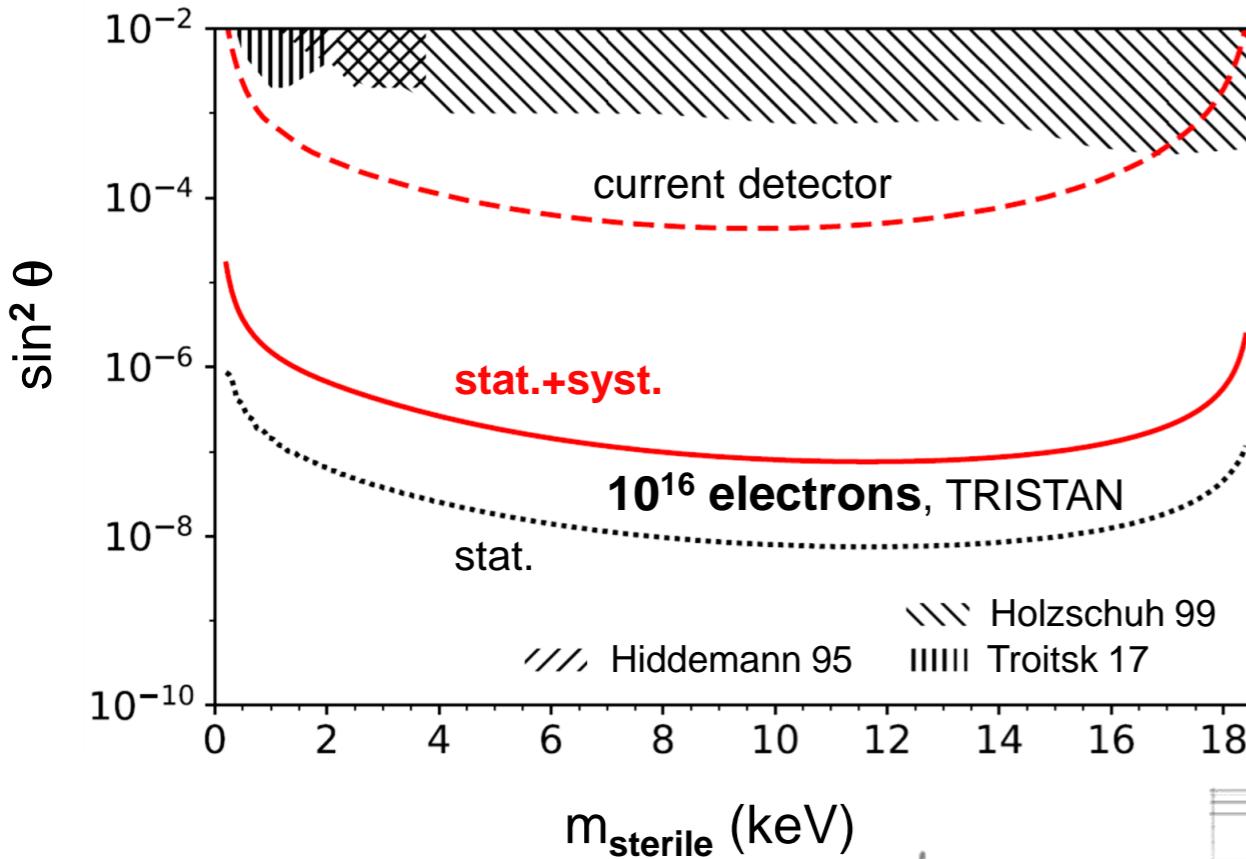


vMSM



# Science reach of KATRIN with new detector array

■ estimated **KATRIN sensitivity** and SDD layout of TRISTAN



# Conclusion

## ■ major experimental progress of KATRIN & future improvements

**KATRIN:**

**first neutrino mass result**

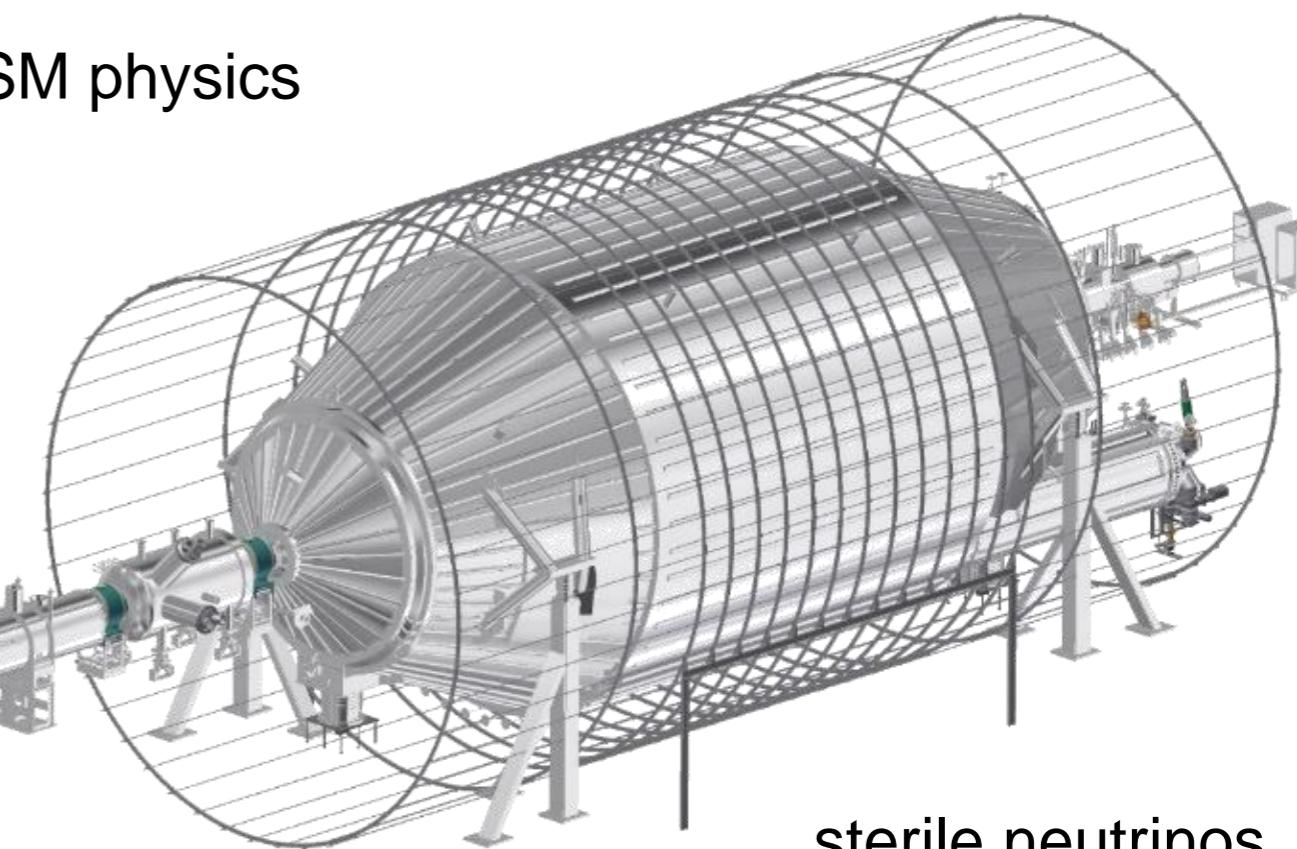
$m_\nu < 1.1 \text{ eV (90 \% CL)}$

3 cycles / year



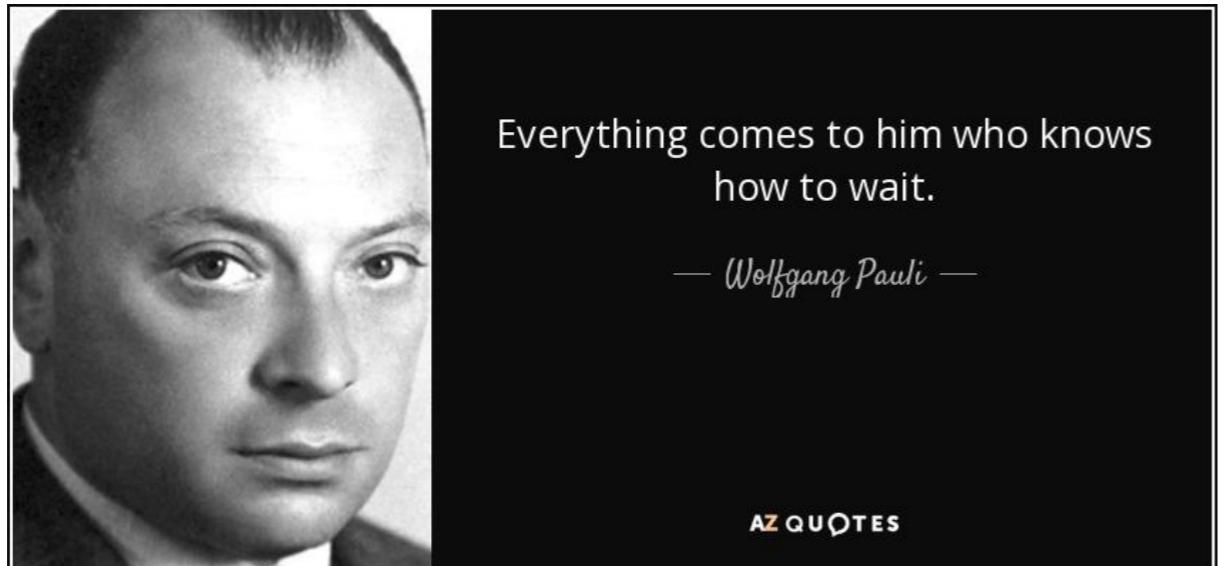
BSM physics

exotic CC



Lorentz violation

sterile neutrinos  
eV...keV scale

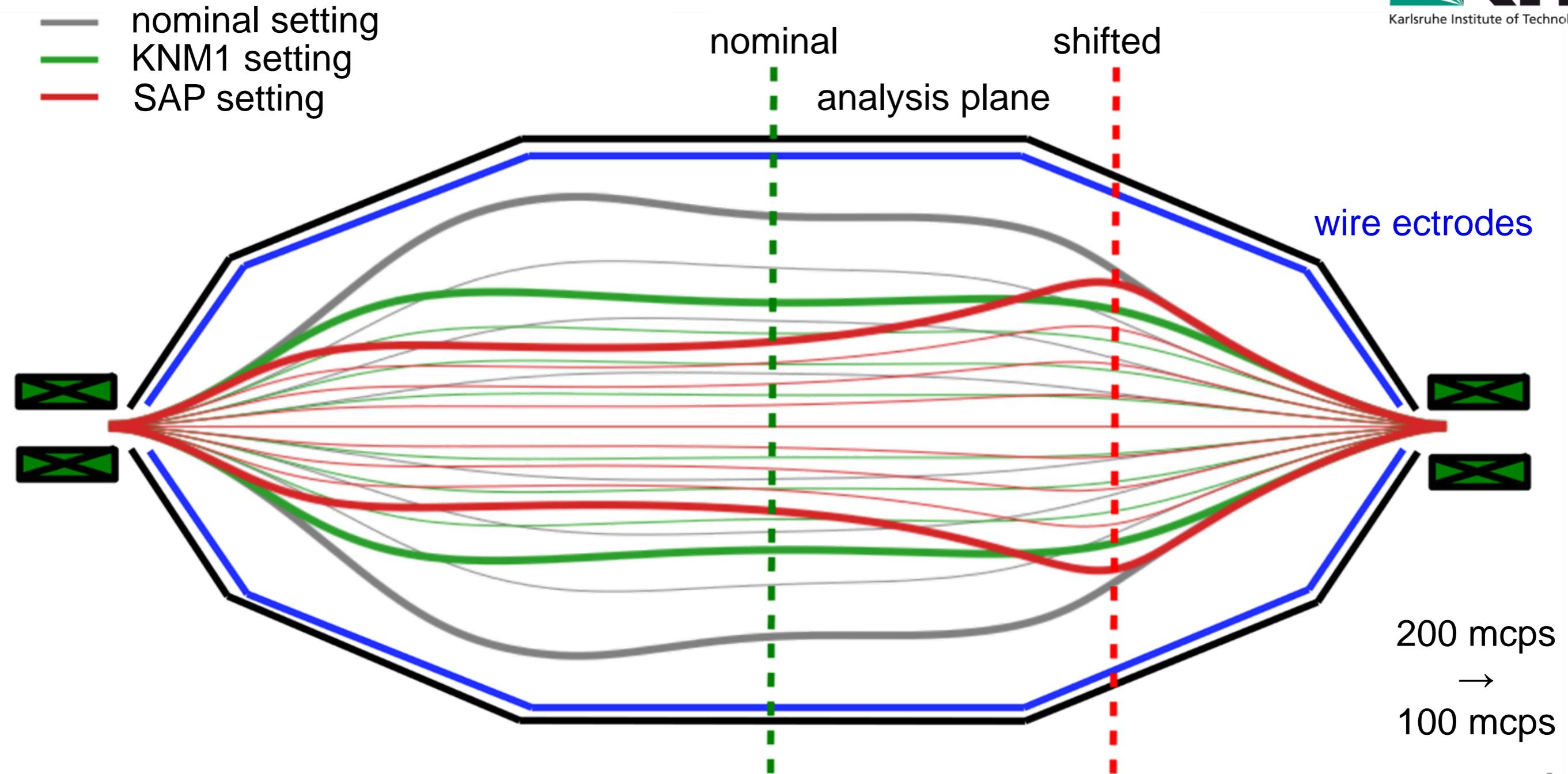


# THANK YOU!

this talk is dedicated to our wonderful Czech Collaborators!

# ADDITIONAL TRANSPARENCIES

# Background mitigation: shifted analysis plane (SAP)



# neutrino mass upper limit

## ■ calculation of confidence belts

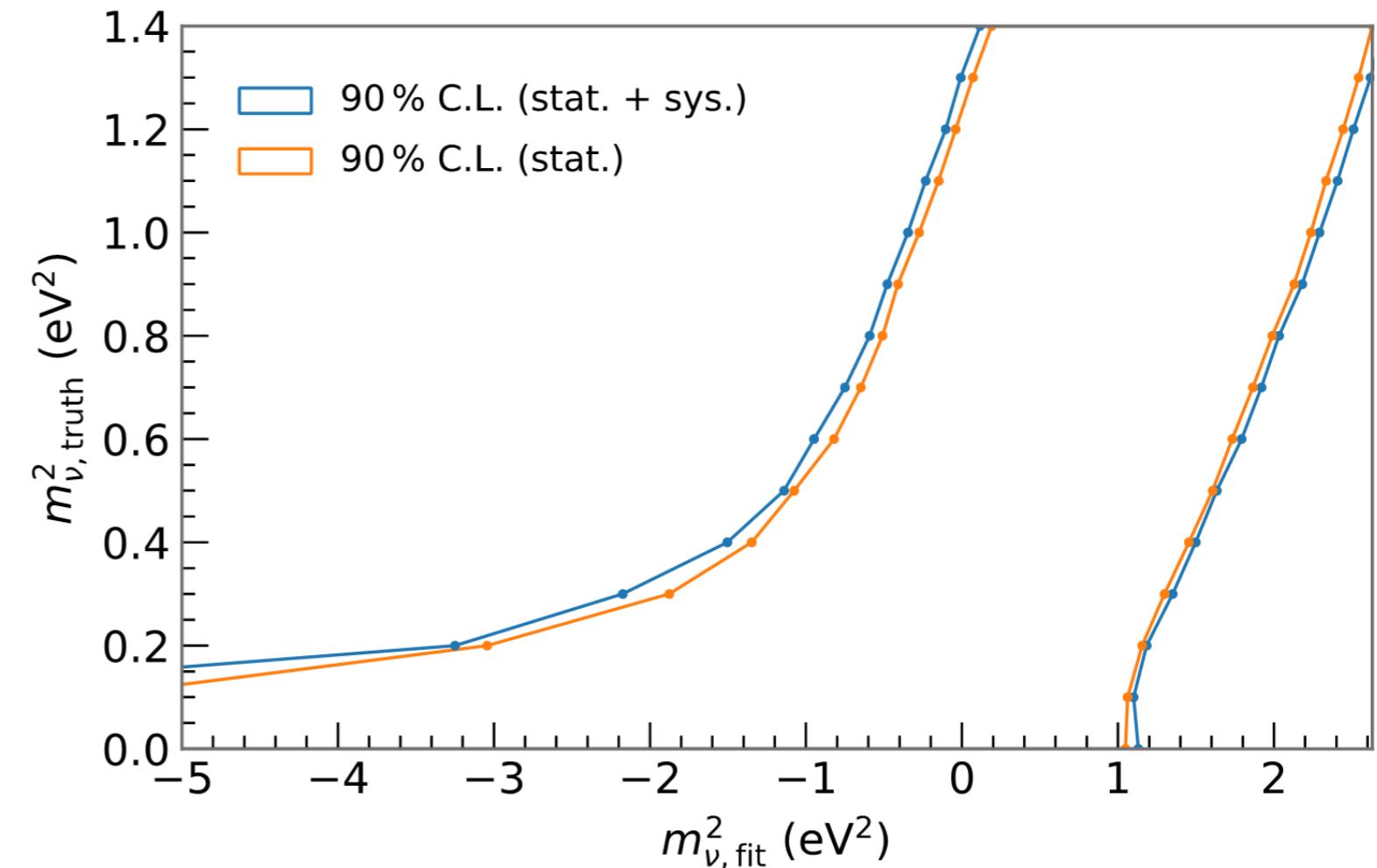
- procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC):  
no empty confidence intervals for  
fluctuations into region  $m^2(\nu_e) < 0$

- **KATRIN upper limit on neutrino mass (LT)**

$m(\nu) < 1.1 \text{ eV (90\% CL)}$

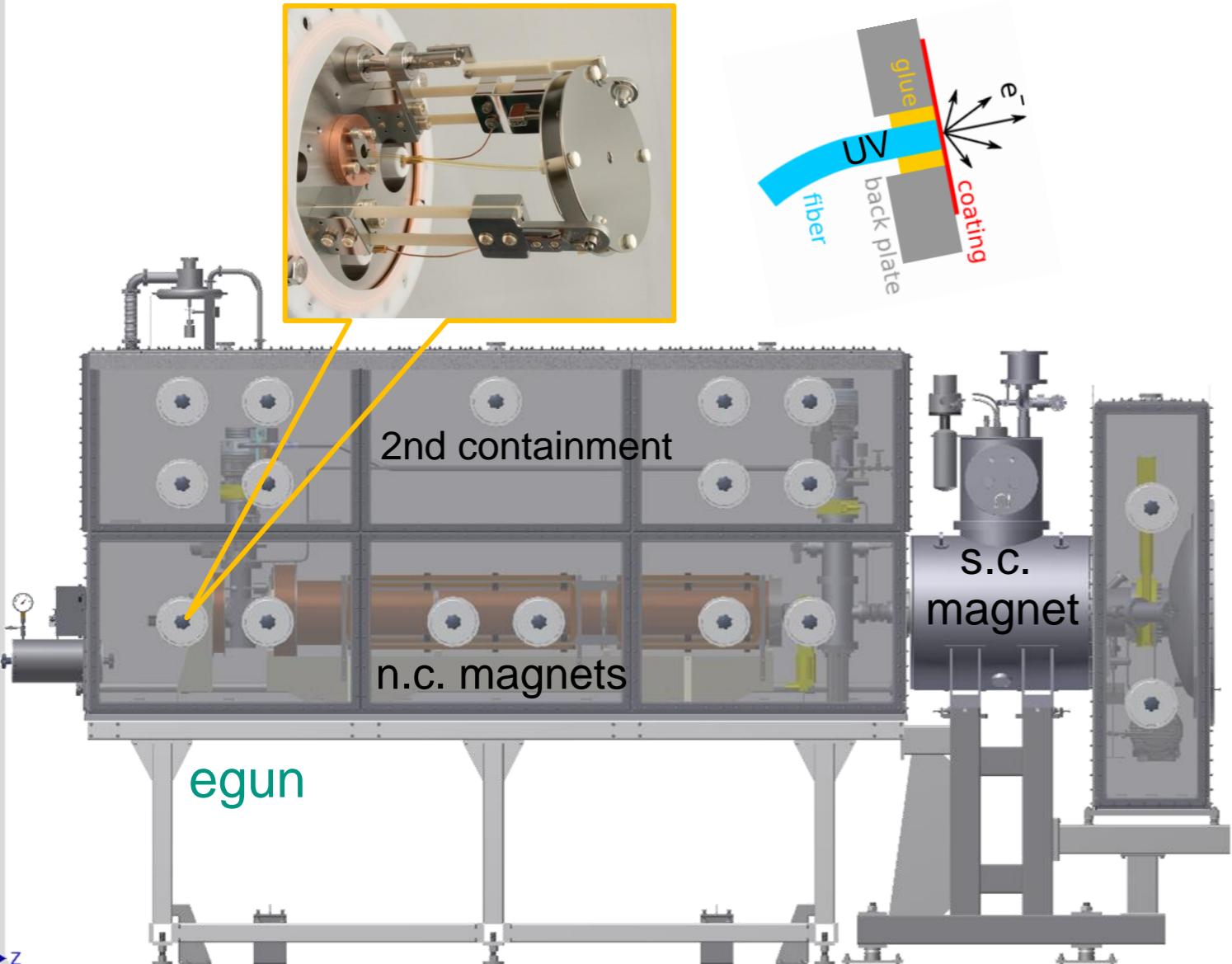
- KATRIN upper limit on neutrino mass (FC)

$m(\nu) < 0.8 \text{ eV (90\% CL)}$   
 $< 0.9 \text{ eV (95\% CL)}$

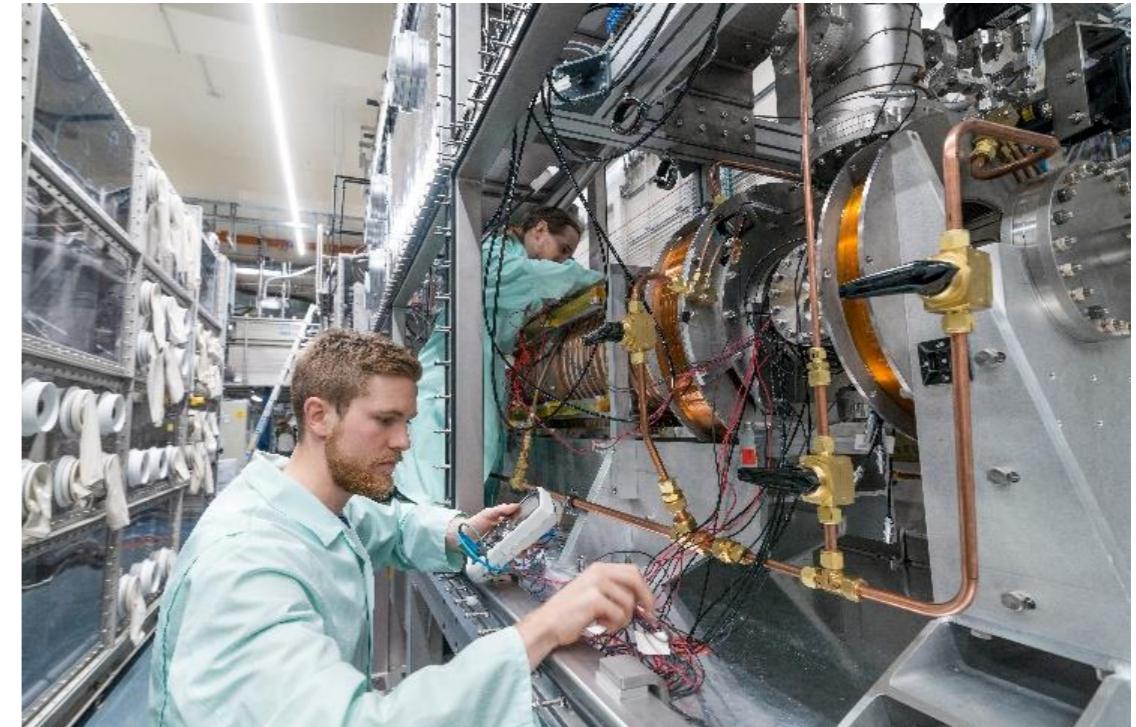


# electron gun to measure electron energy losses

■ **Angular selective precision egun:** determine nelastic energy losses in source & pd



- well-defined pitch angle  $\Delta\theta$
- narrow energy spread  $\Delta E$
- excellent stability at high rates



egun during commissioning phase

# systematics due to column density

## ■ column density $\rho d$ – in situ measurement of transmission function with egun

