

Neutrino mass measurement and sterile neutrinos search with the KATRIN experiment

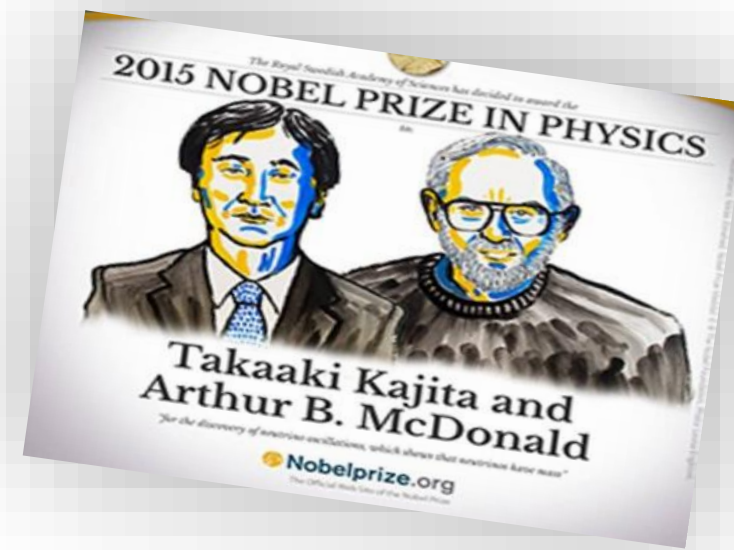
Anthony Onillon, Technical University of Munich

On behalf of the KATRIN collaboration

Neutrino mass measurement with KATRIN

Neutrino mass

- Neutrinos are massive particle



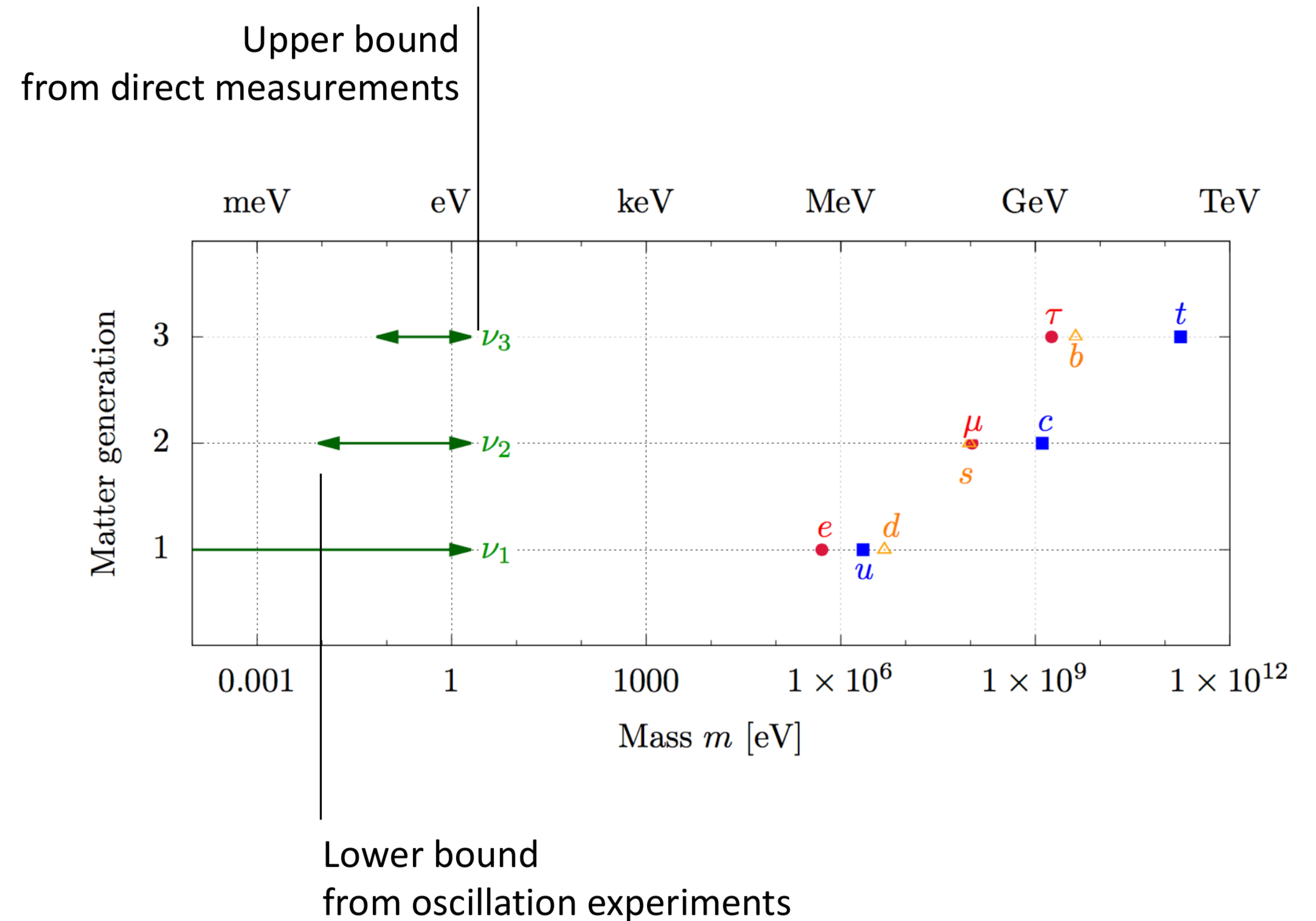
- Flavor eigenstates are linear combinations of mass eigenstates

$$v_l = \sum_i U_{li} v_i$$

- Squared mass difference measurable with neutrino oscillations experiment

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

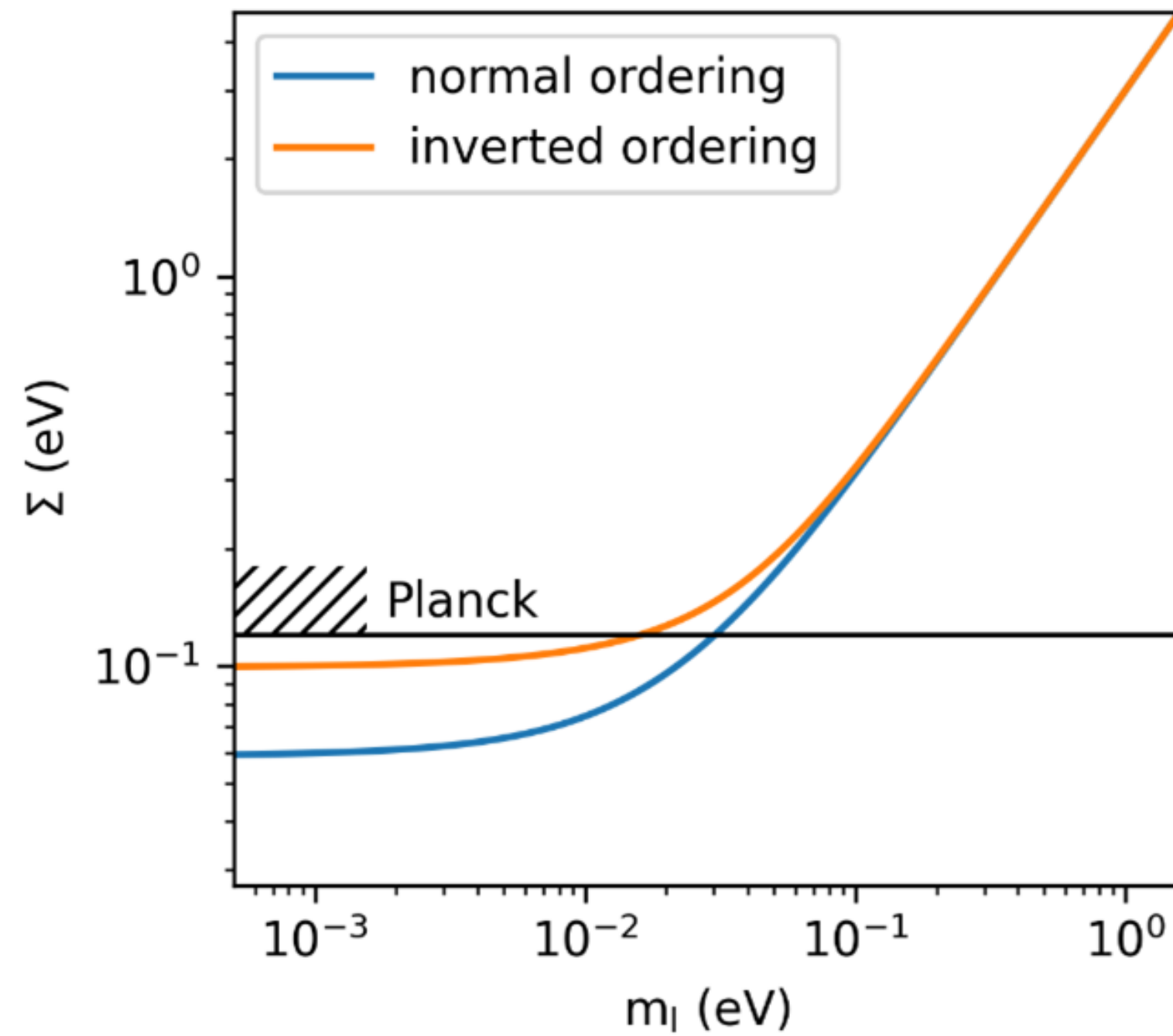
⇒ Absolute mass and mass hierarchy unknown



Neutrino mass

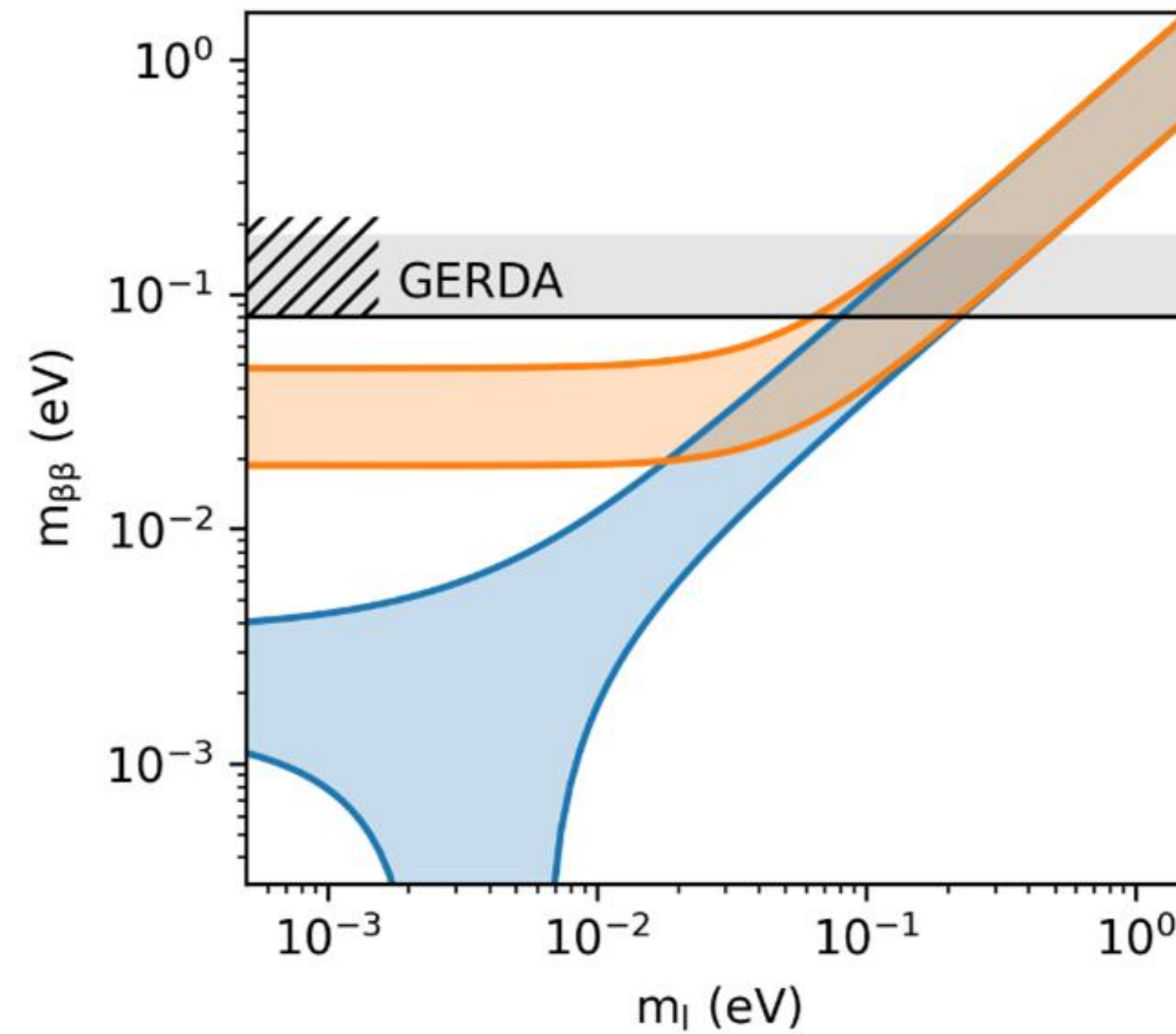
cosmology

$$\Sigma = \sum_i m_i$$



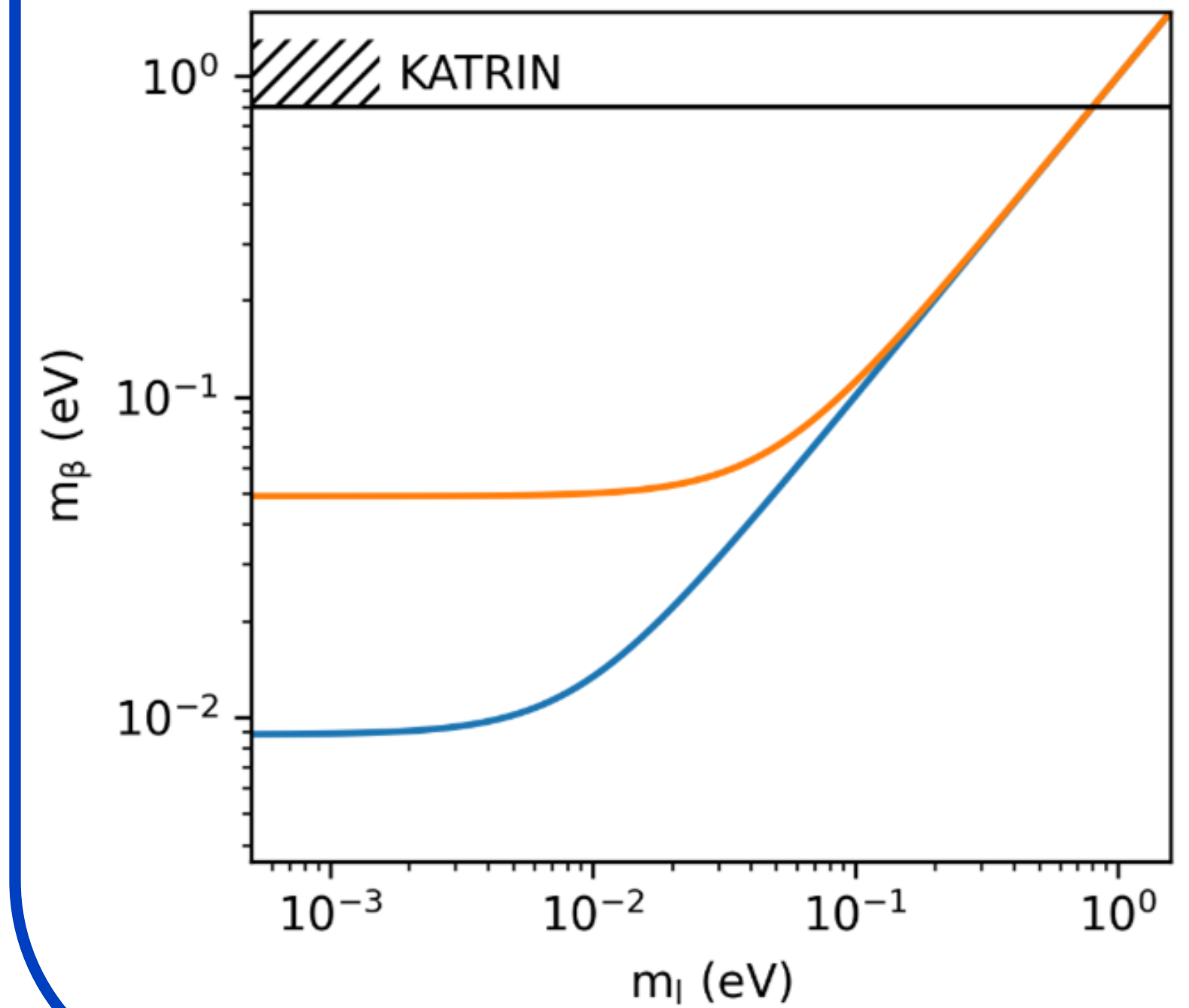
neutrinoless $\beta\beta$ -decay

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

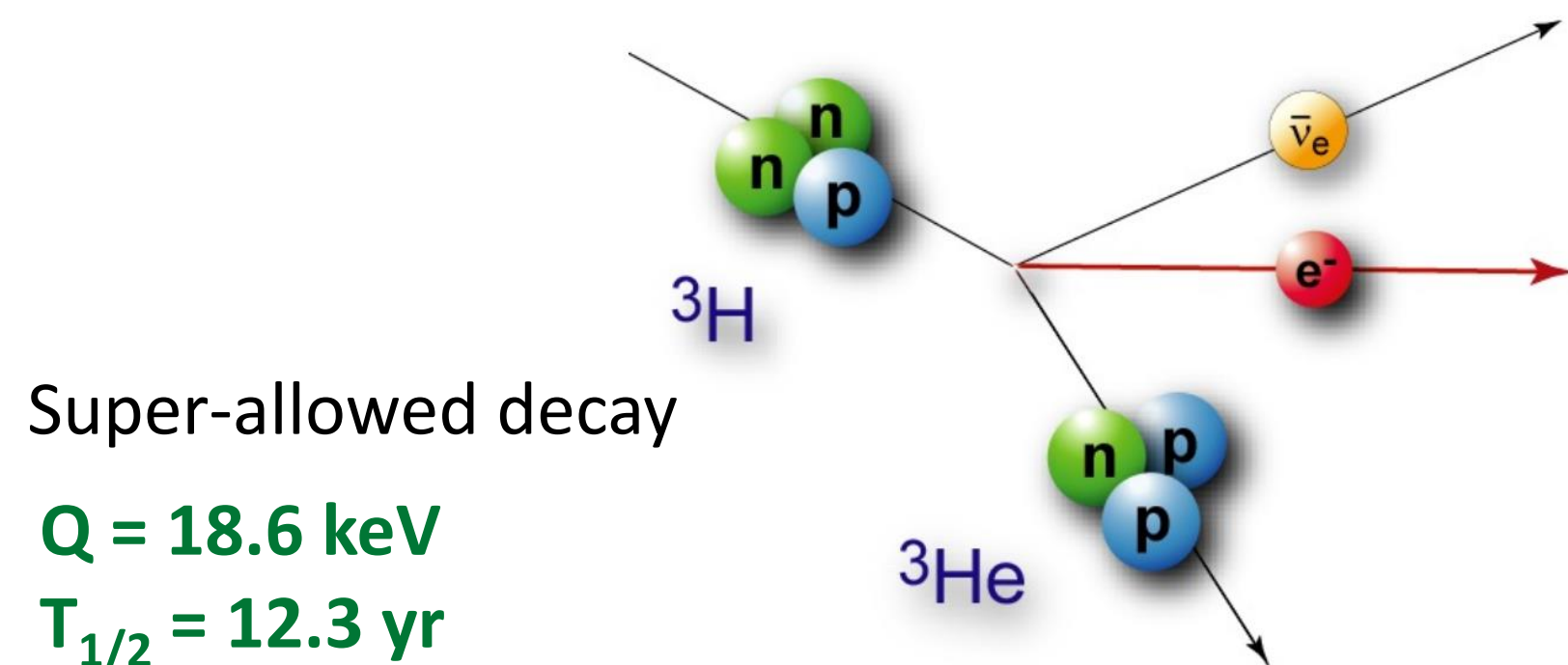


β -decay kinematics

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



β-decay kinematics



$$\frac{dN}{dE_e} \cong C \cdot F(E, Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_0 - E_e) \sqrt{(E_0 - E_e)^2 - m_v^2}$$

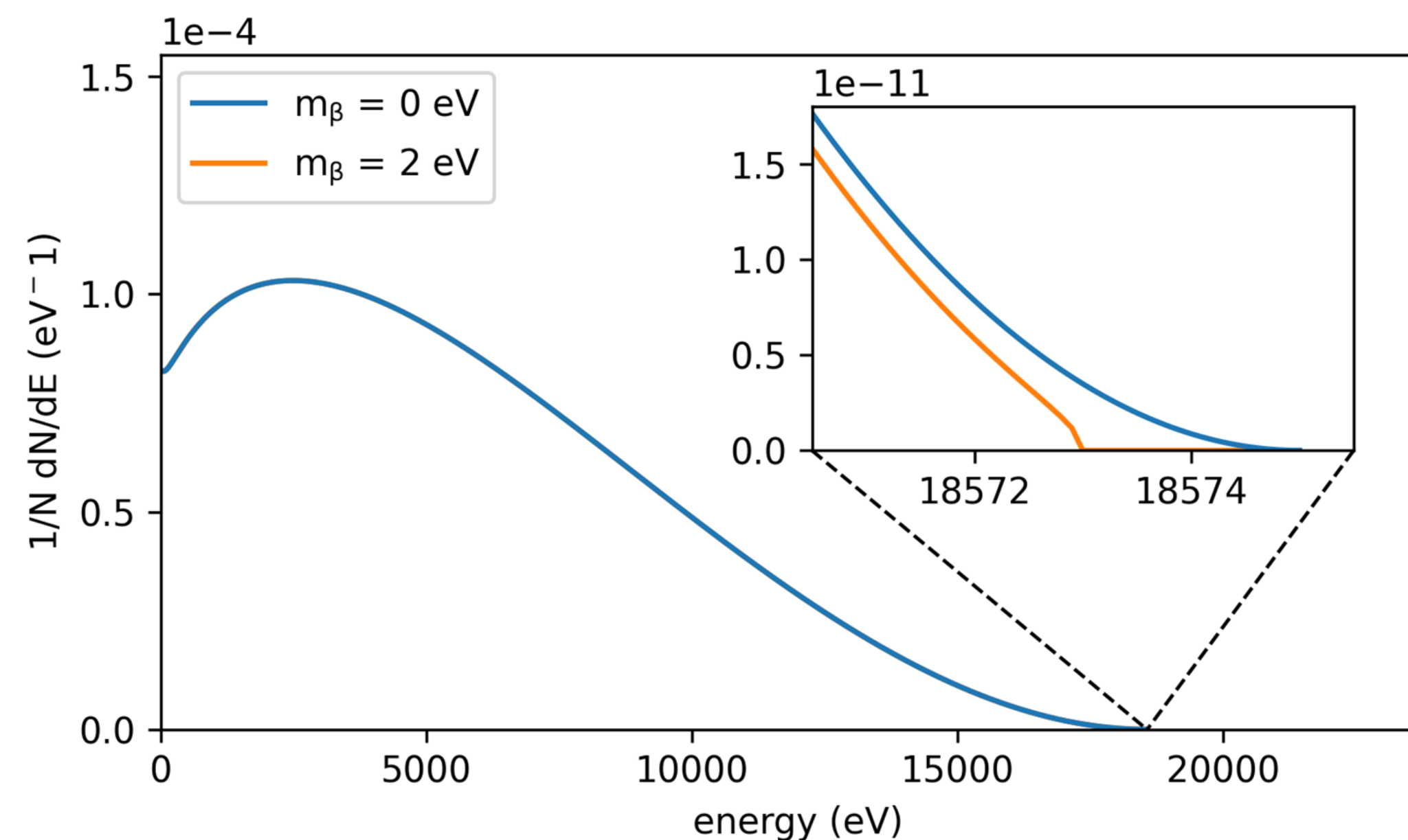
incoherent
neutrino mass:

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

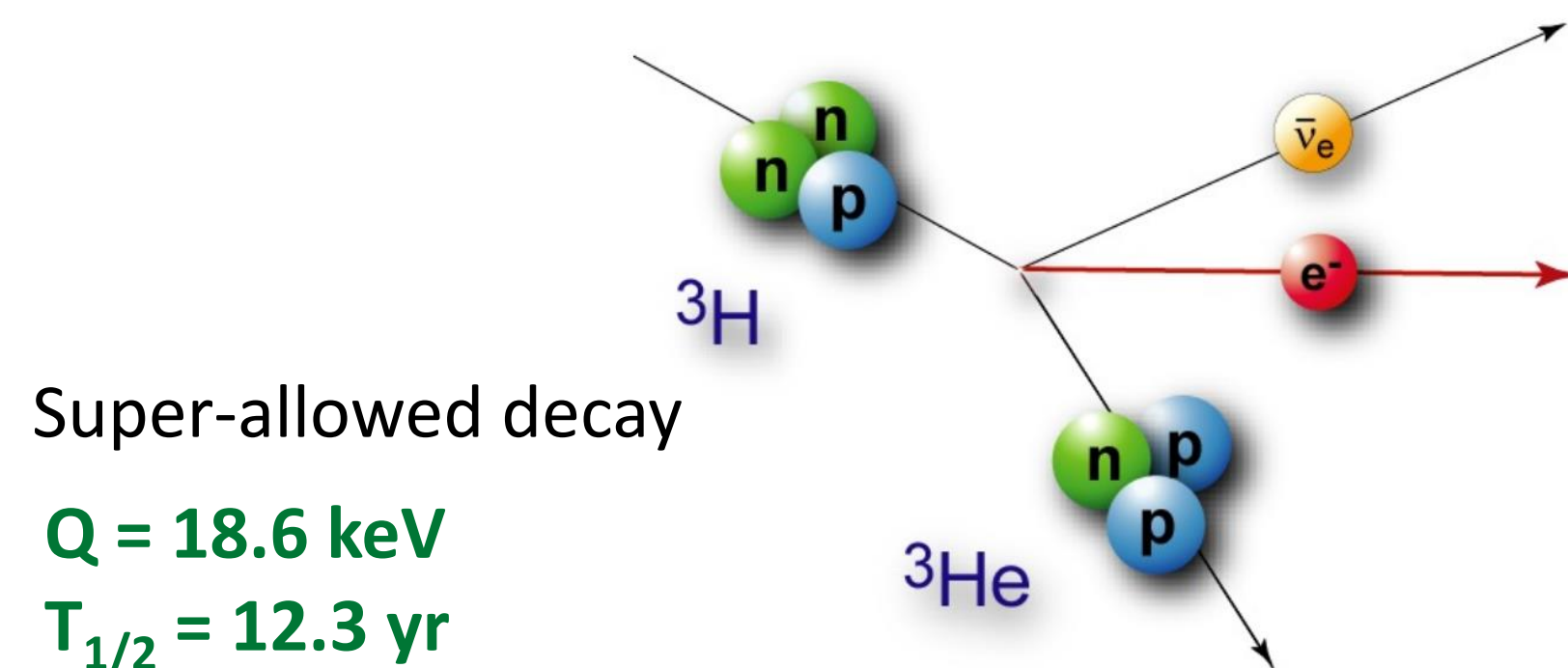
Based on kinematics and energy conservation

- independent of neutrino nature
- independent on cosmology

⇒ spectral distortion maximal at the
endpoint energy E_0

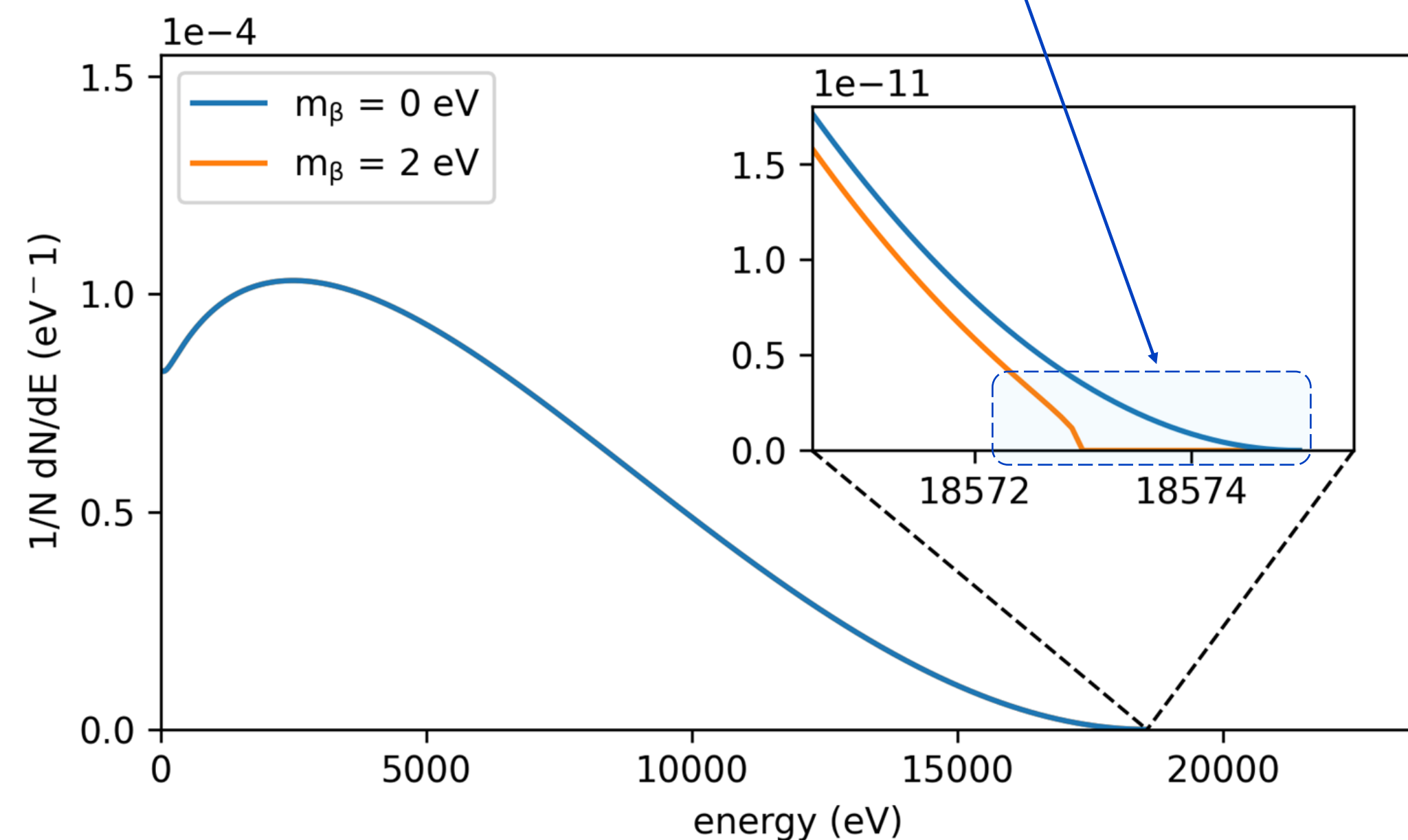


Experimental challenge



- Strong tritium source: 10^{11} decays/s
- Very low background level: $< 0.1 \text{ cps}$
- Very high energy resolution: $\sim 1 \text{ eV}$
- Precise understanding of the spectrum shape

Only 10^{-13} of all decays
in the last 1 eV

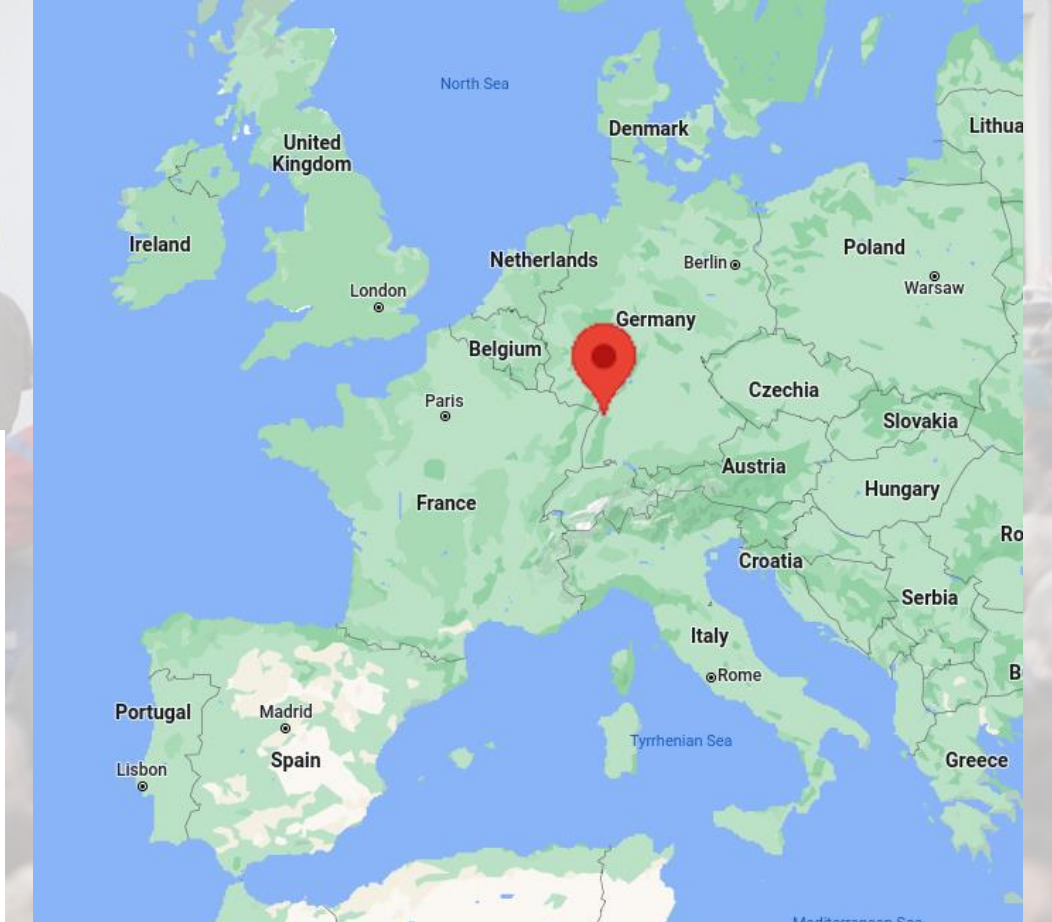


Karlsruhe Tritium Neutrino Experiment



KATRIN collaboration

- International collaboration (150 members)
- Experimental site: Karlsruhe Institute of Technology (KIT)



Working principle

Gaseous tritium source

- molecular tritium in closed loop
- 30 μg of gaseous T_2
→ 10^{11} T_2 decays/s

Transport section

- magnetic guidance
- tritium gas/ion removal
→ reduction by $> 10^{14}$

Spectrometer

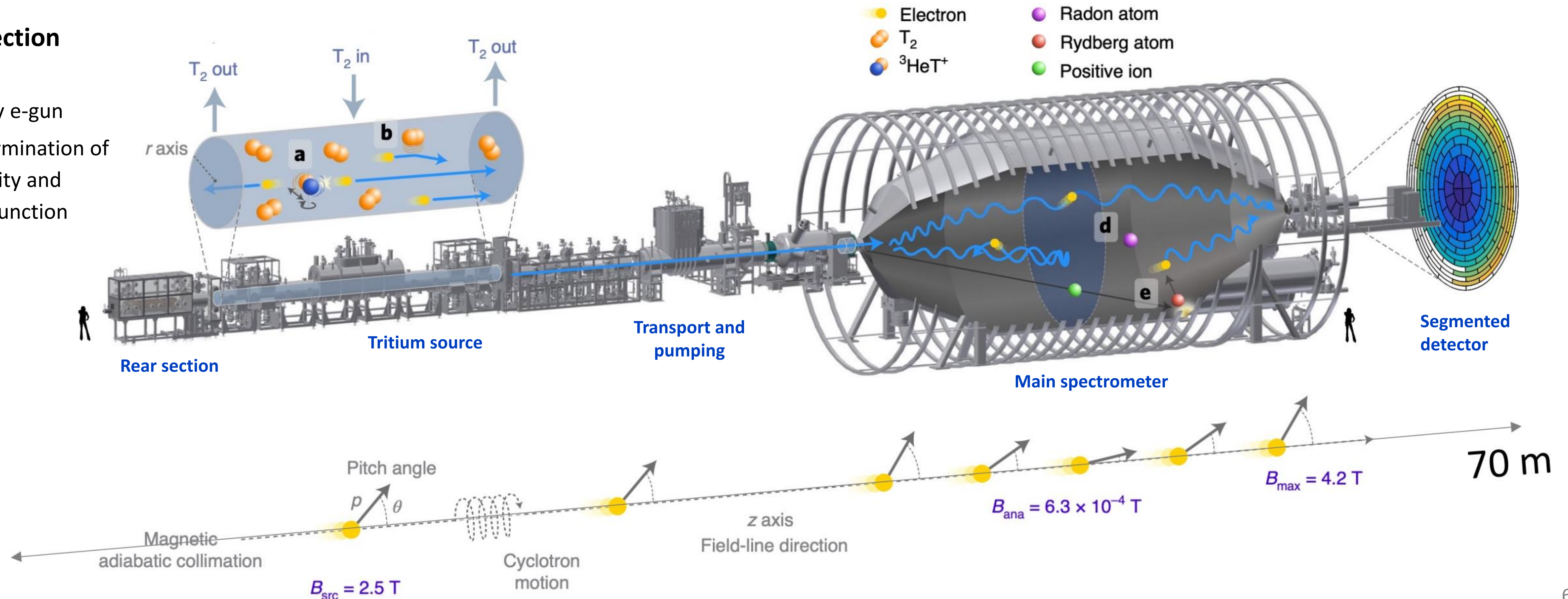
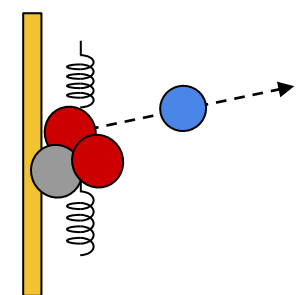
- MAC-E (Magnetic adiabatic collimation + electrostatic filter)
→ high resolution: $O(1)$ eV
→ large acceptance angle: 0 - 51°

Detector section

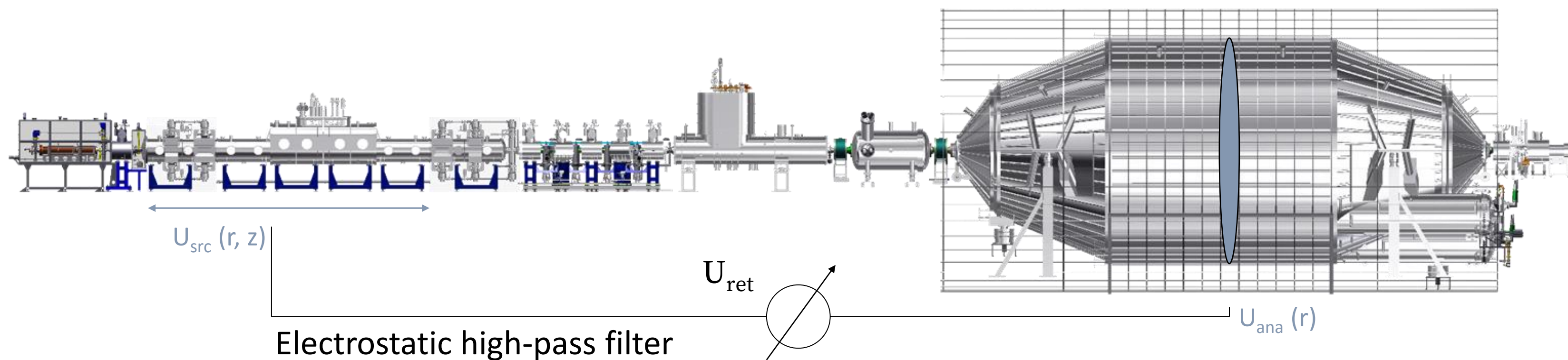
- focal plane detector, 148 pixels
PIN-diode
- counts electrons: rate vs potential
→ $< 1 \text{ e}^- \cdot \text{s}^{-1}$

Rear section

- rear wall
- high intensity e-gun
→ precise determination of column density and energy-loss function

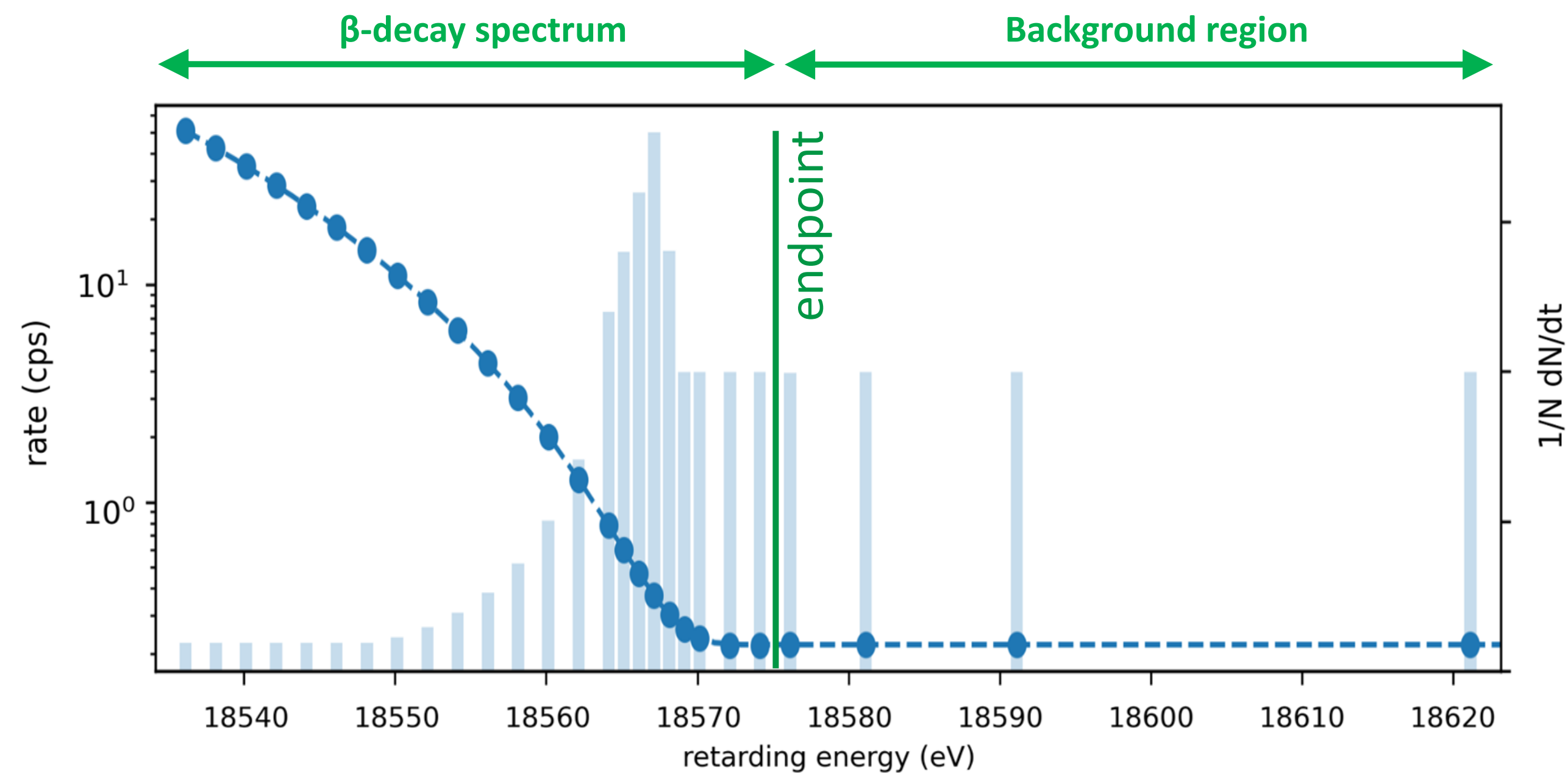


Measurement strategy

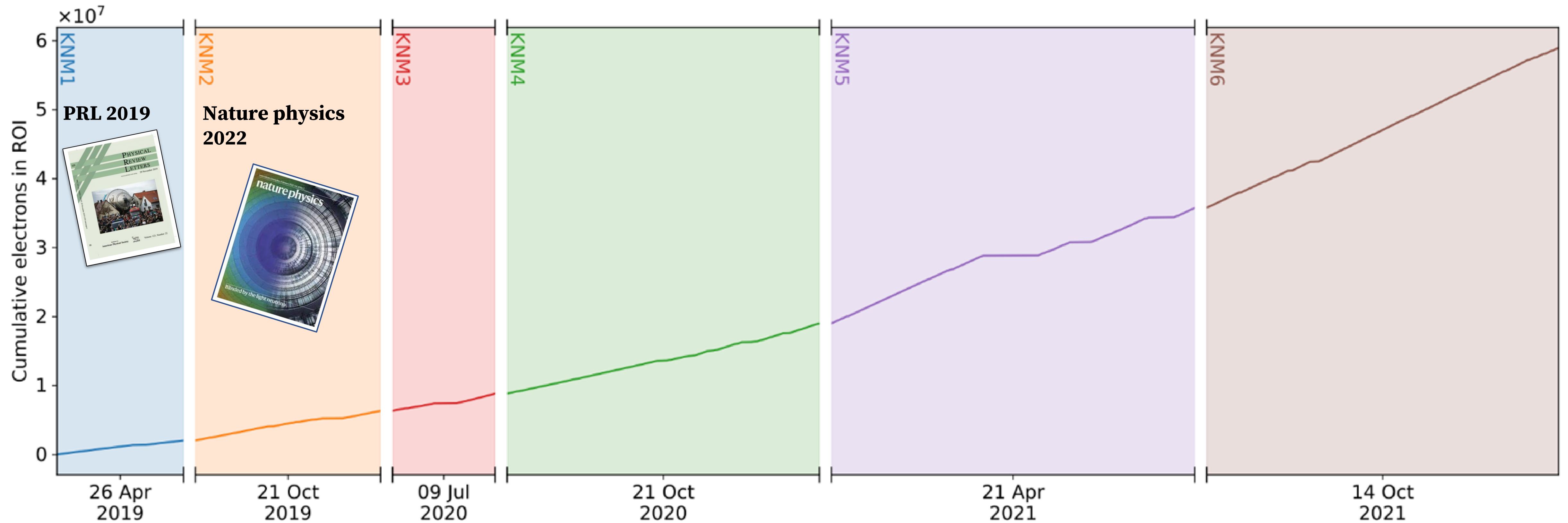


Integral spectrum measurement

- ~ 30 scan steps with varying duration
- ~ 2 h scan duration
- scan interval: $E_0 - 40$ eV , $E_0 + 135$ eV
- several campaigns per year



Data taking overview



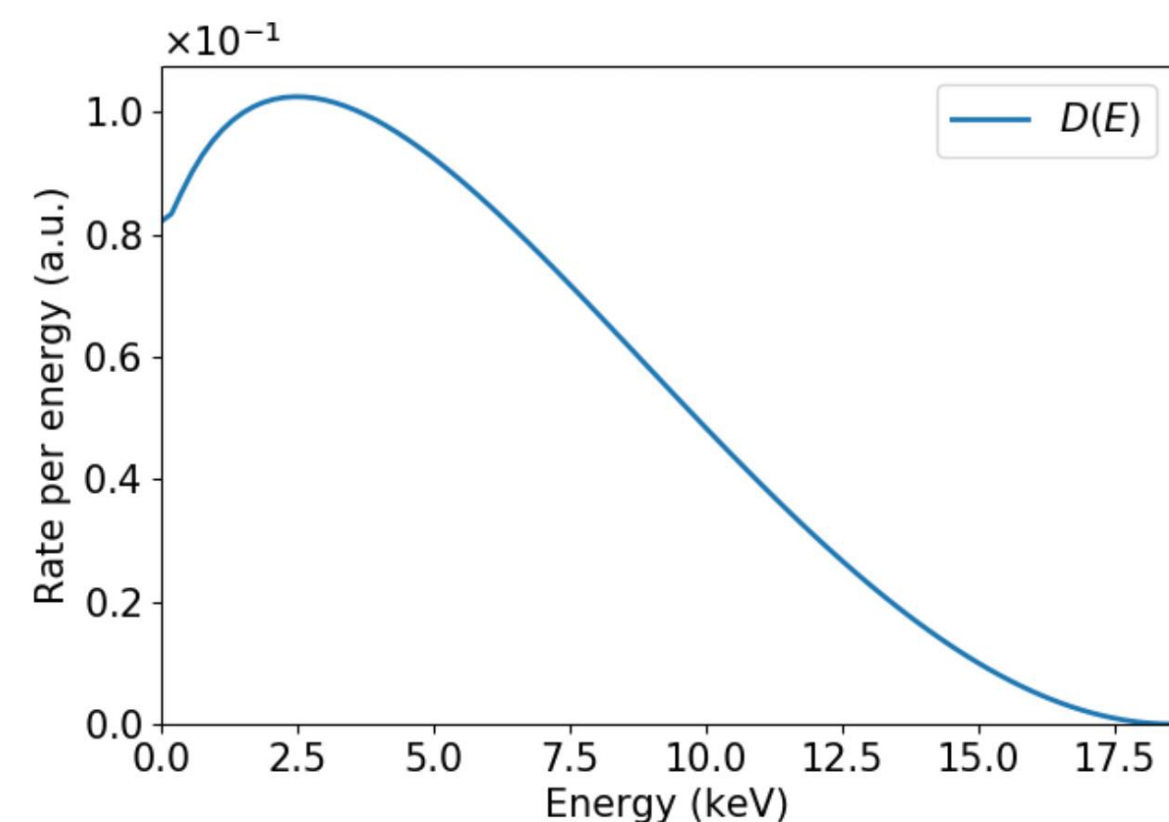
1st and 2nd campaigns
 $6 \cdot 10^6$ e⁻ in the ROI
- published -

1st to 5th campaigns
 $\sim 30 \cdot 10^6$ e⁻ in the ROI
- analysis in progress -

Analysis strategy

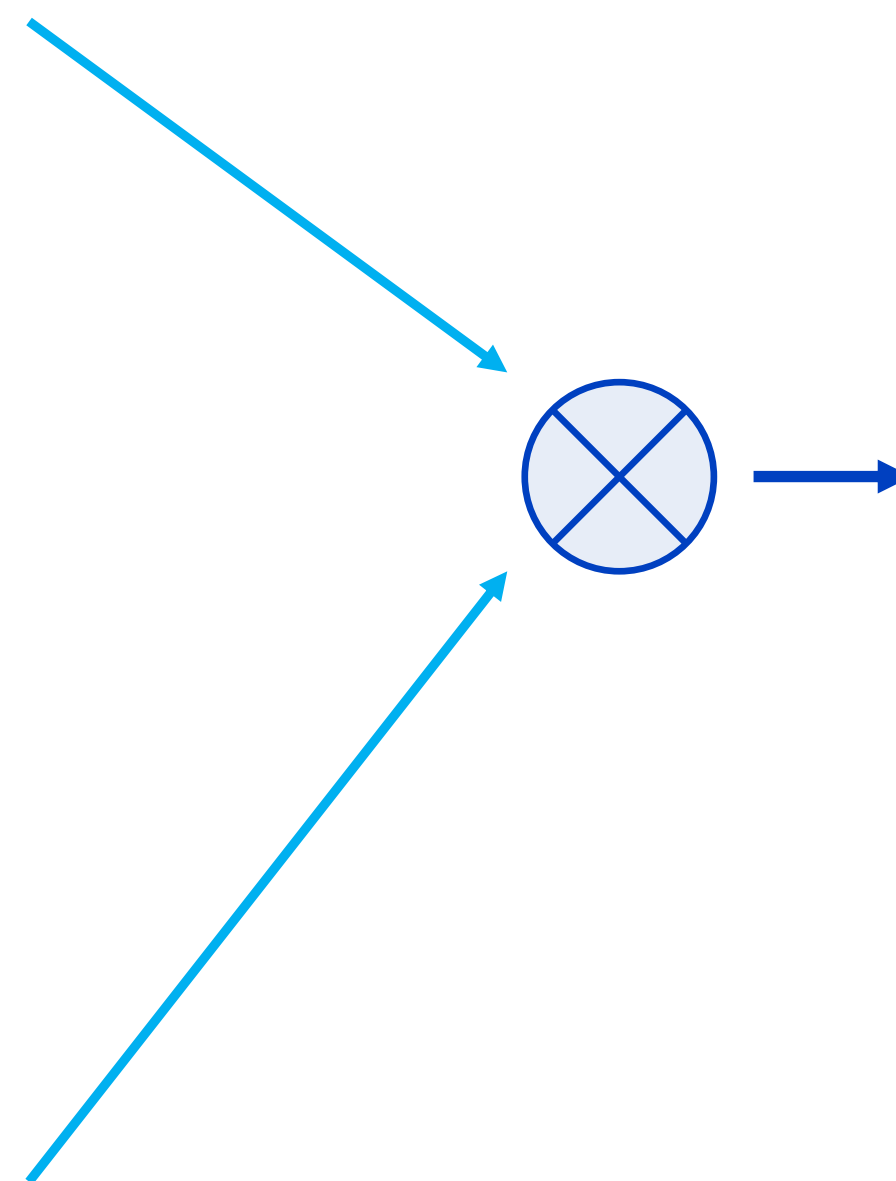
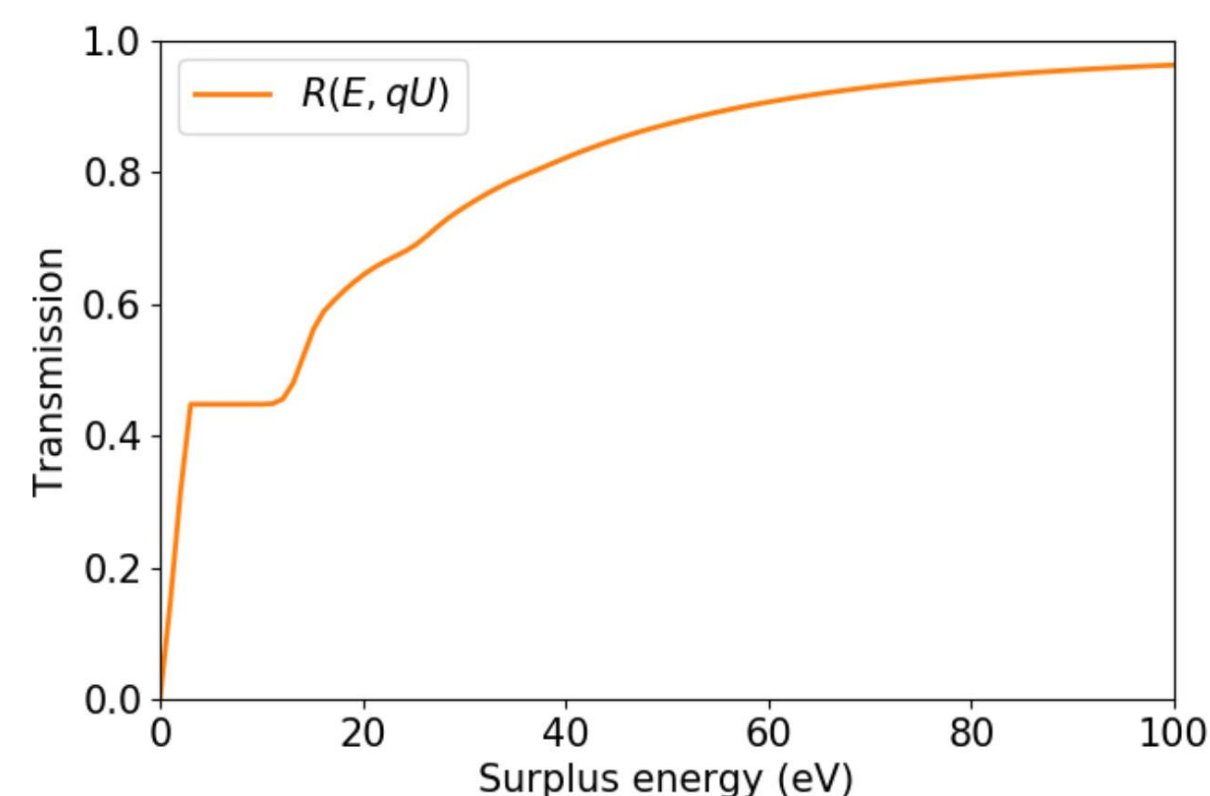
Beta spectrum:

theoretical inputs (Fermi theory, molecular excitations)



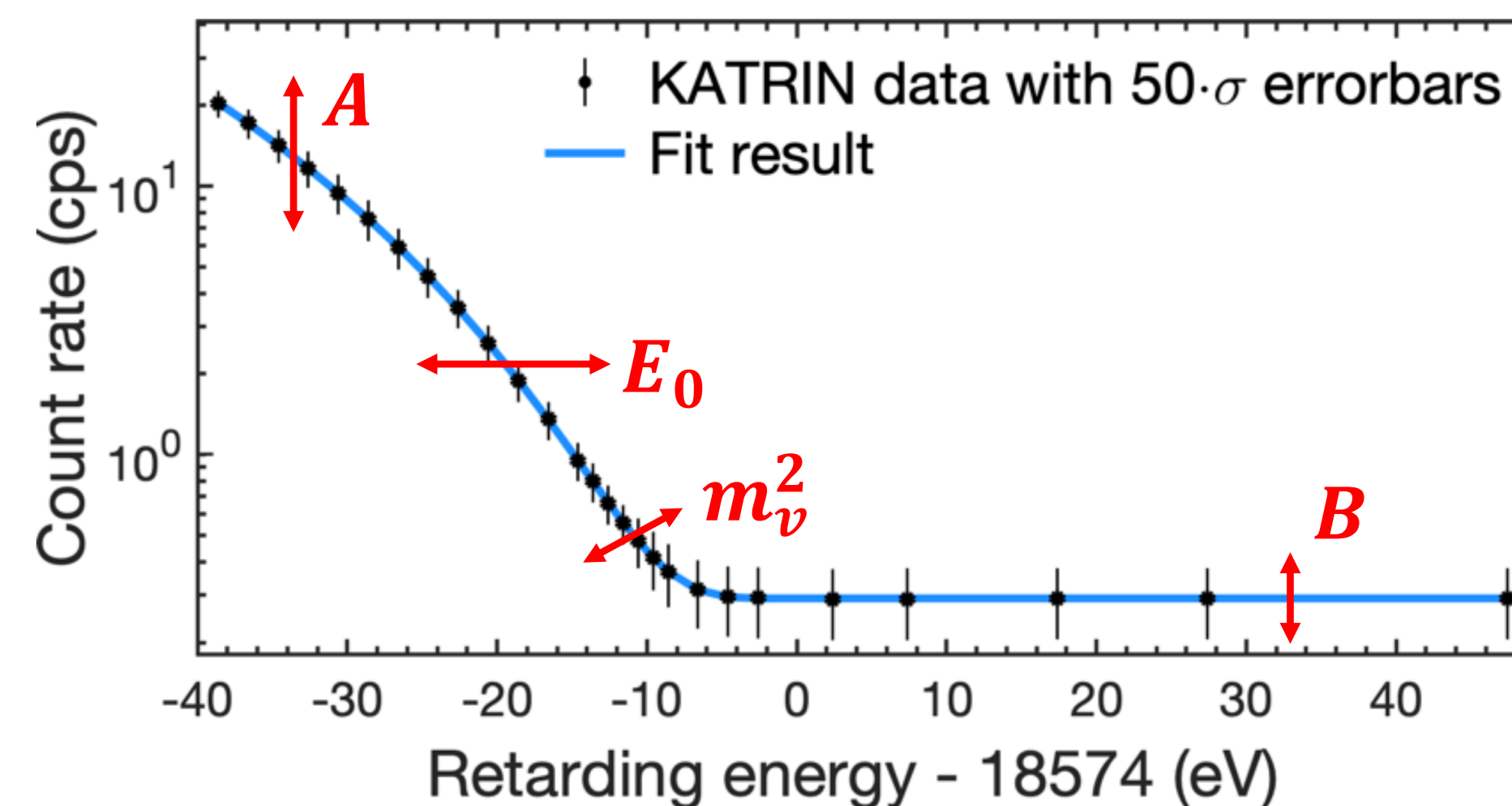
Response function

experimental data: calibration with e^- - gun and ^{83m}Kr conversion electrons



Expected measured rate:

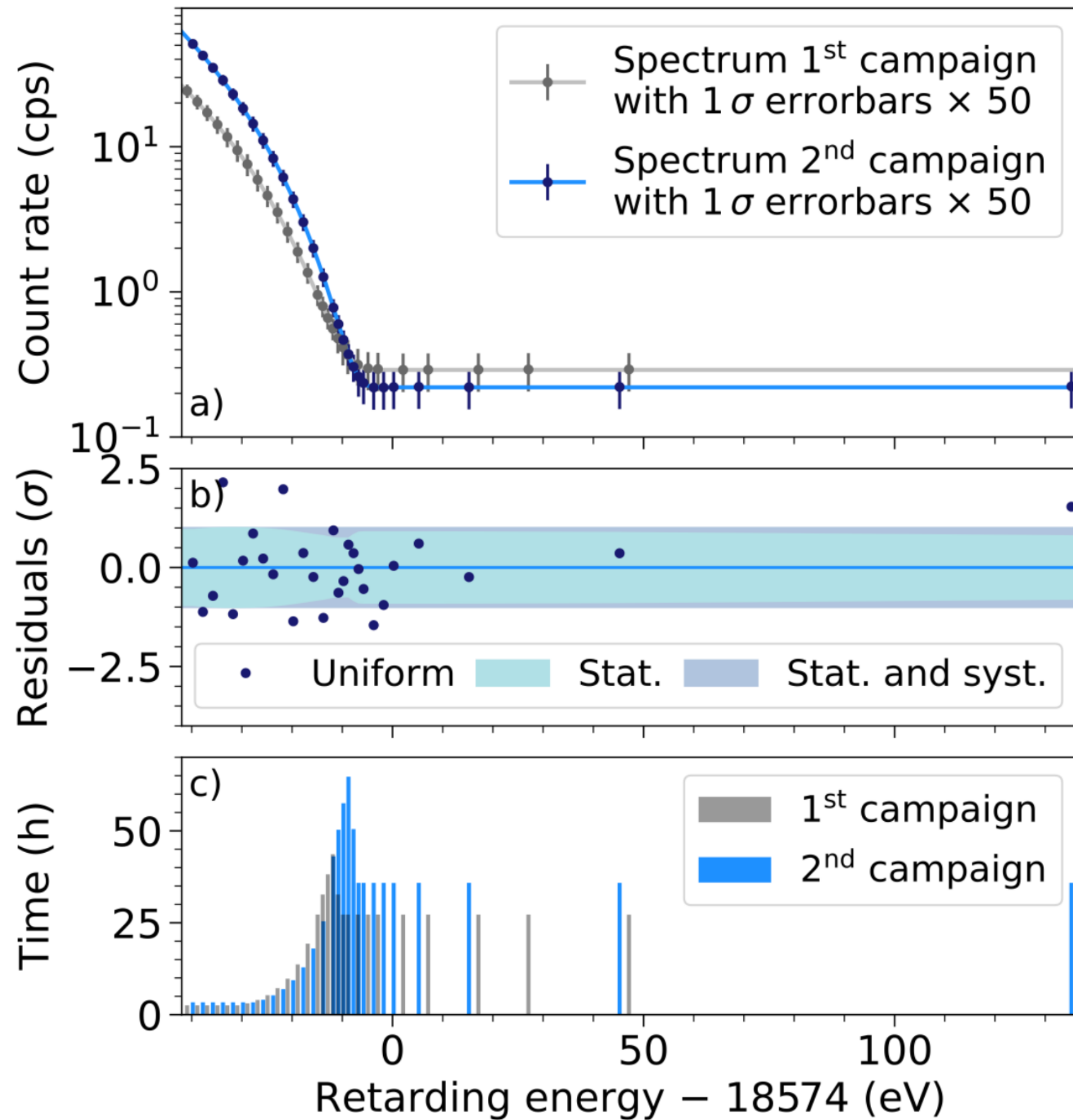
$$\Gamma(qU) = \mathbf{A} \int_{qU}^{E_0} D_{\beta}(E, \mathbf{m}_{\nu_e}^2, \mathbf{E}_0) \cdot R(E, qU) dE + \mathbf{B}$$



Maximum likelihood fit of model

- free amplitude A
- endpoint E_0
- background rate B
- **squared neutrino mass m_{ν}^2**

Latest ν – mass results



First campaign:

[Aker et al., PRL 123 (2019) 22, 221802]

- **Total statistic: 2 million events**
- **Best fit:** $m_\nu^2 = (-1.0^{+0.9}_{-1.1}) \text{ eV}^2$
- **Limit:** $m_\nu < 1.1 \text{ eV (90\% CL)}$

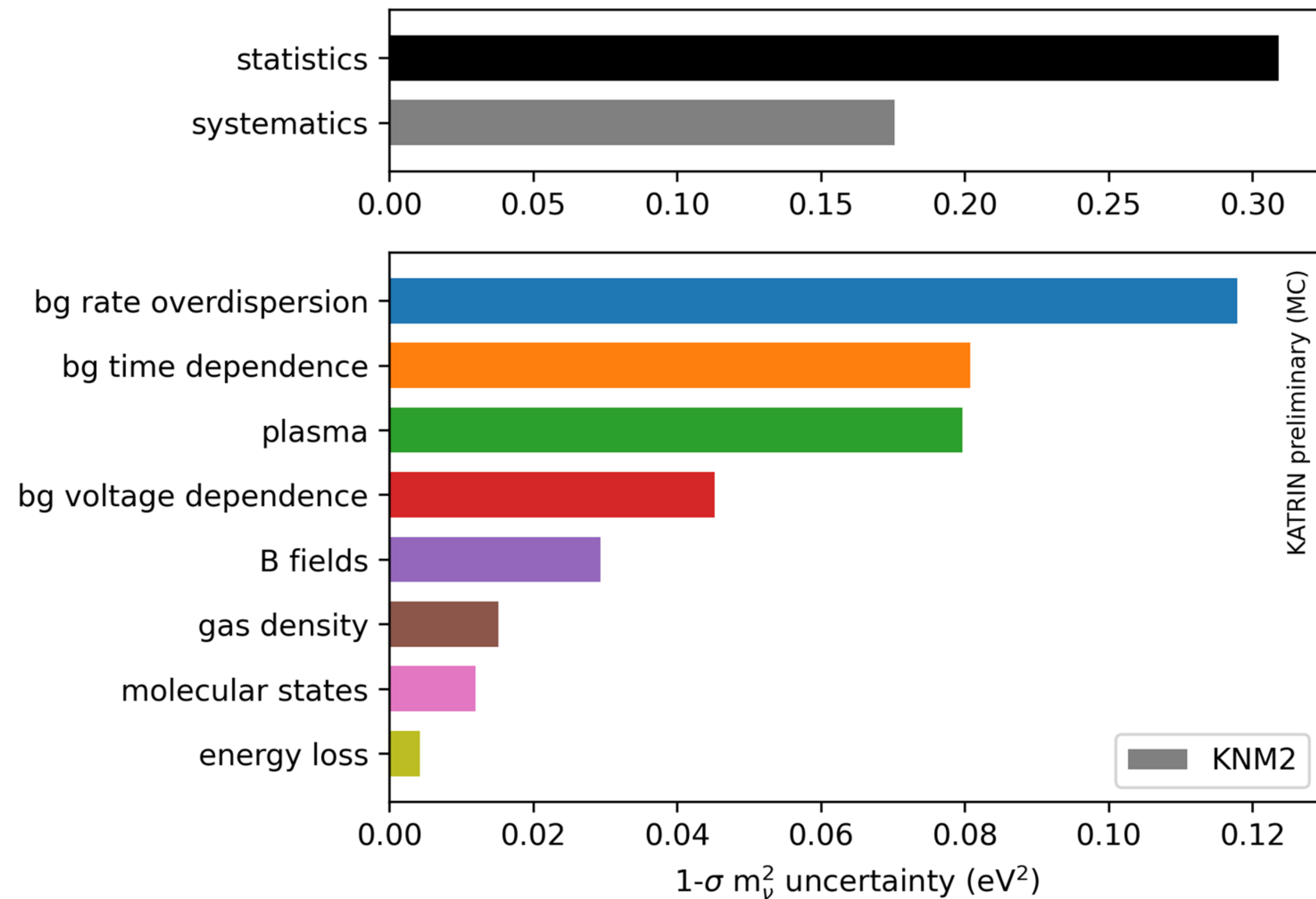
Second campaign:

[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

- **Total statistic: 4.3 million events**
- **Best fit:** $m_\nu^2 = (0.26^{+0.34}_{-0.34}) \text{ eV}^2$
- **Limit:** $m_\nu < 0.9 \text{ eV (90\% CL)}$

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

Systematic breakdown



➤ **Total uncertainty dominated by statistical uncertainty**

- **Significant systematics**
- dominated by background-related uncertainties
 - significant source plasma uncertainty

ν – mass outlook

1st and 2nd campaigns combined

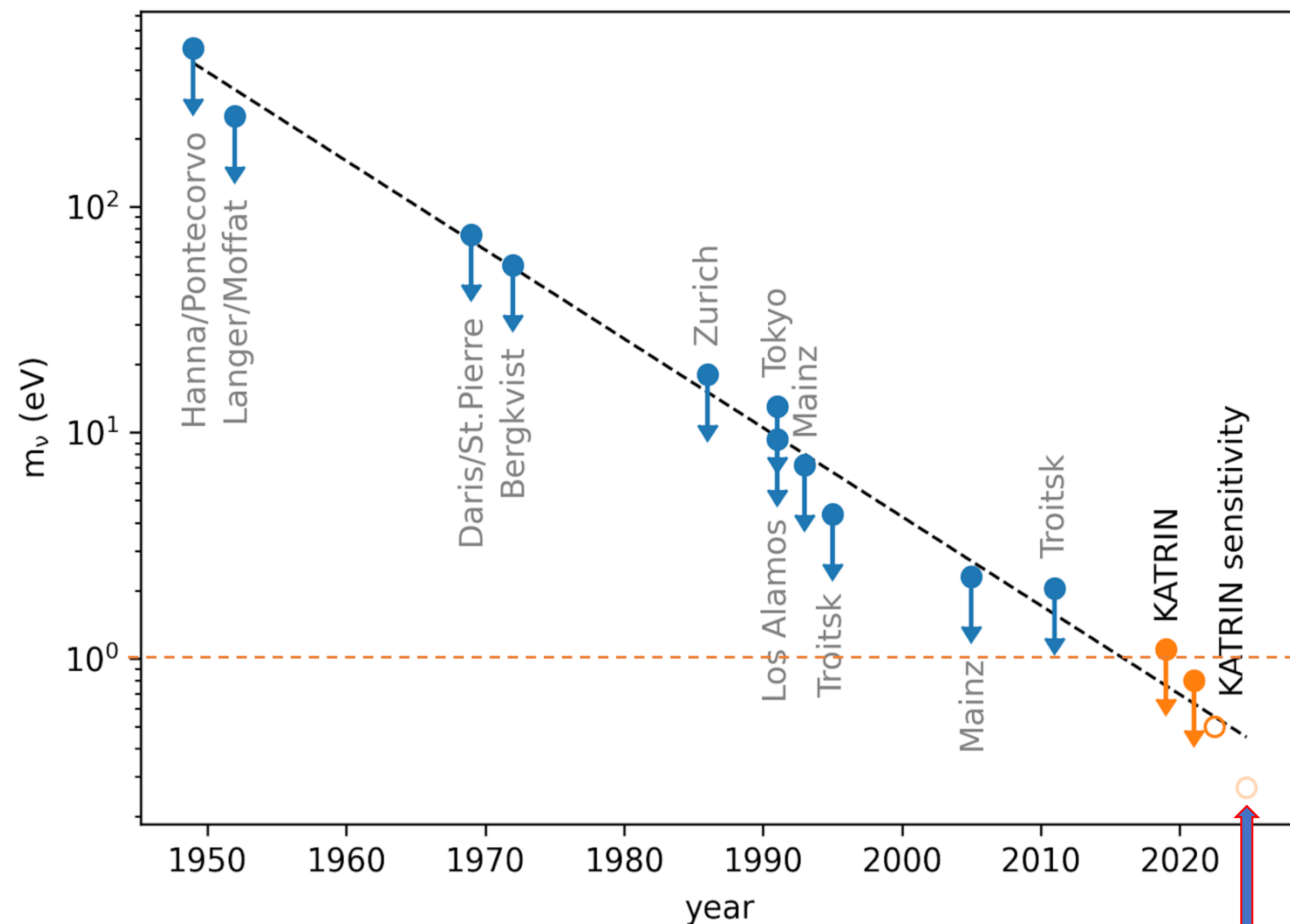
- $6 \cdot 10^6$ e⁻ in ROI
- $m_\nu < 0.8$ eV (90% CL) – statistic dominated
- first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

First five campaigns (work in progress)

- $\sim 30 \cdot 10^6$ e⁻ in ROI
- $m_\nu < 0.5$ eV (90% CL)
- data unblinded during the summer

Final target (2025)

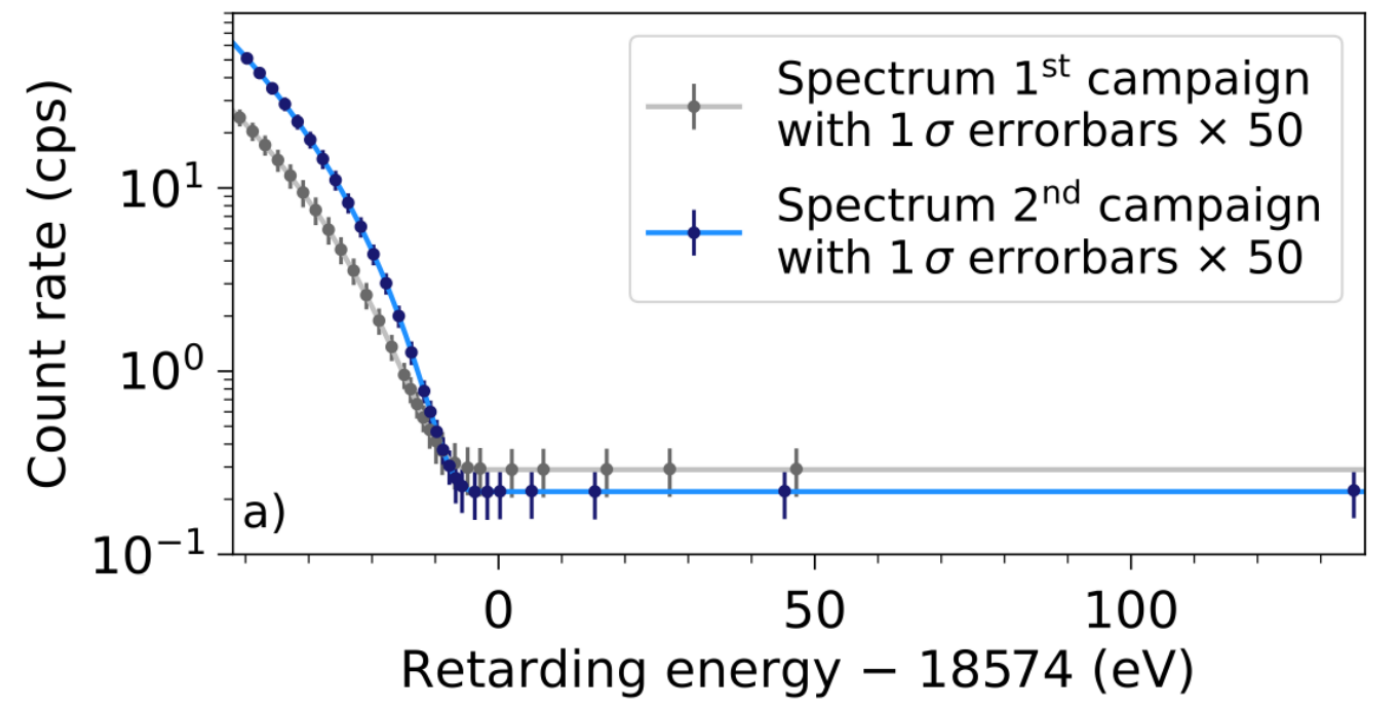
- $\sim 70 \cdot 10^6$ e⁻ in ROI
- $m_\nu < 0.2 - 0.3$ eV (90% CL)



KATRIN final target

**Beyond the neutrino mass:
sterile neutrino search with KATRIN**

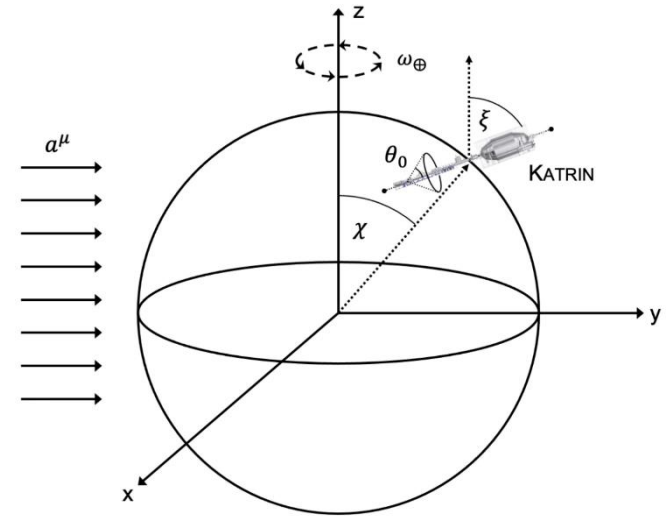
Beyond neutrino mass in KATRIN



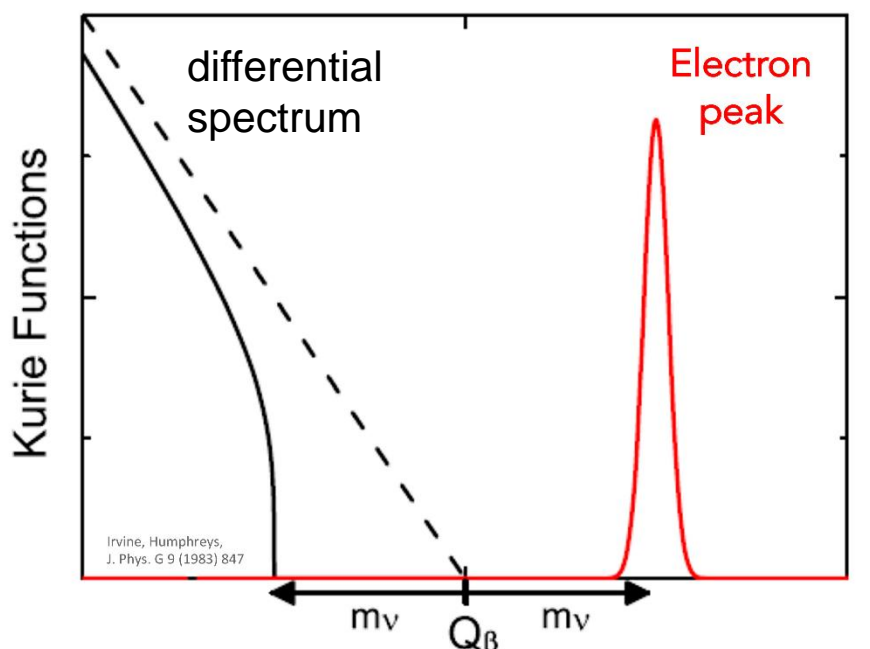
β spectrum with high statistics and low systematics

Search for exotic weak interactions
 \Rightarrow *shape distortion*

Search for Lorentz invariance violation
 [arXiv:2112.13803]
 \Rightarrow *sideral modulation*



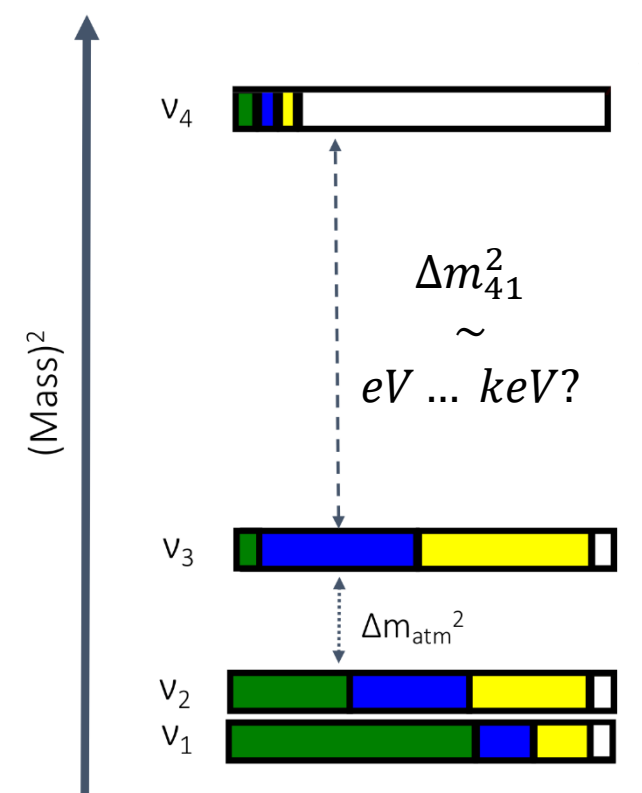
Constrain local overdensity of cosmic relic neutrinos
 [Phys. Rev. Lett. 129, 011806]
 \Rightarrow *peak search*



Sterile neutrino search

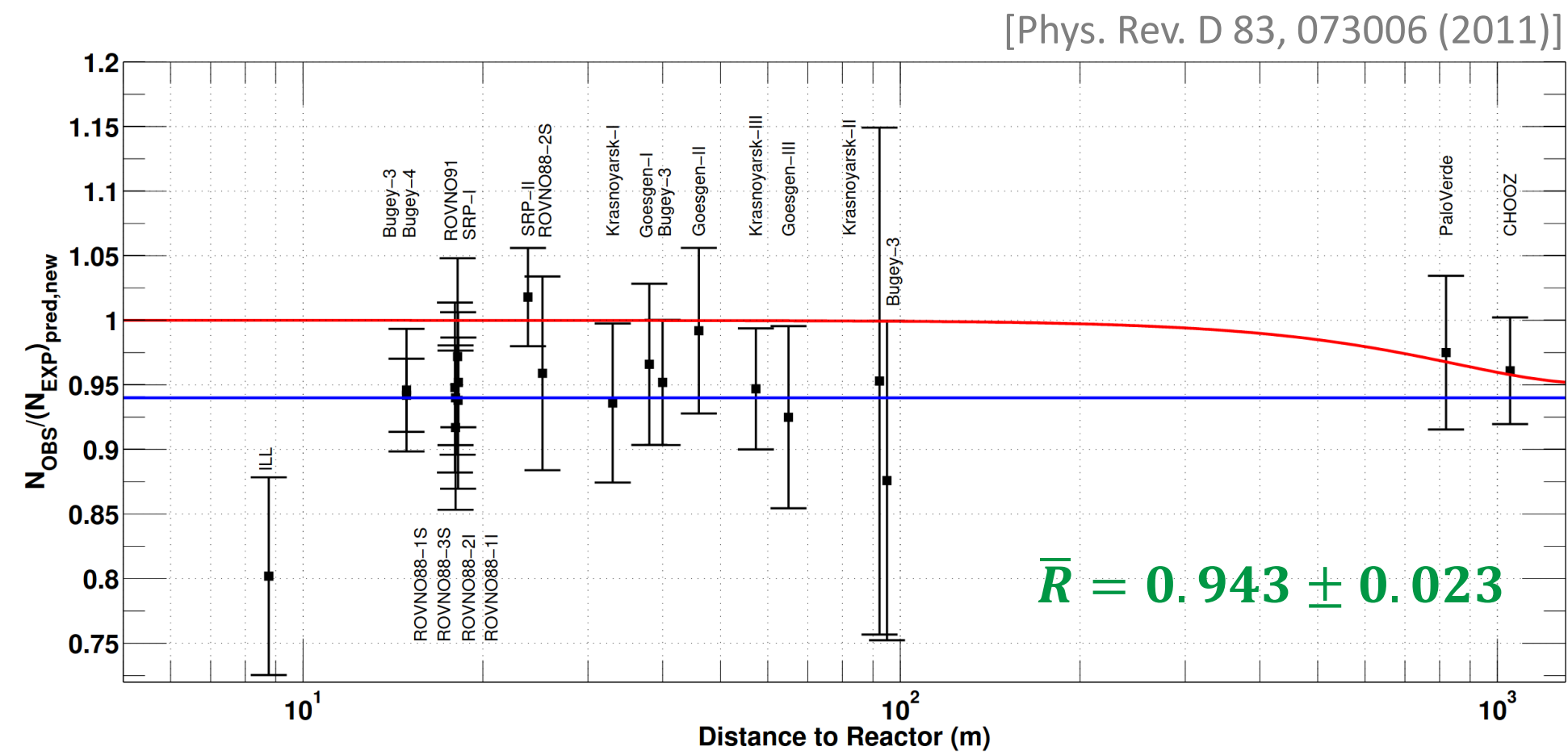
- eV-scale sterile neutrinos
- keV-scale sterile neutrinos

\Rightarrow *shape distortion*



eV-scale sterile search motivation

Reactor antineutrino anomaly (RAA)

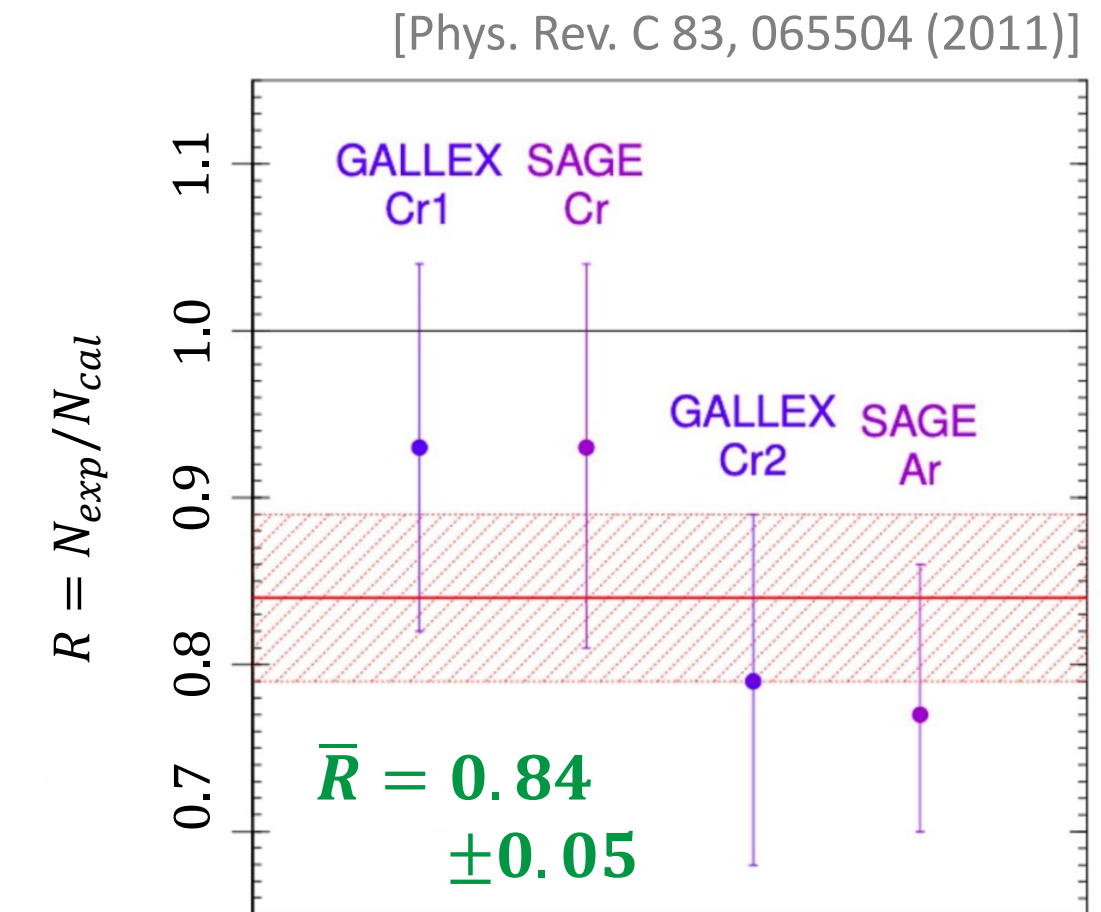


Systematic deficit of the reactor $\bar{\nu}_e$ flux measurements with respect to the predictions of ~ 20 experiments

$\sim 3\sigma$ deficit of reactor and Gallium flux measurement to prediction

⇒ Hint for the existence of light sterile neutrino?

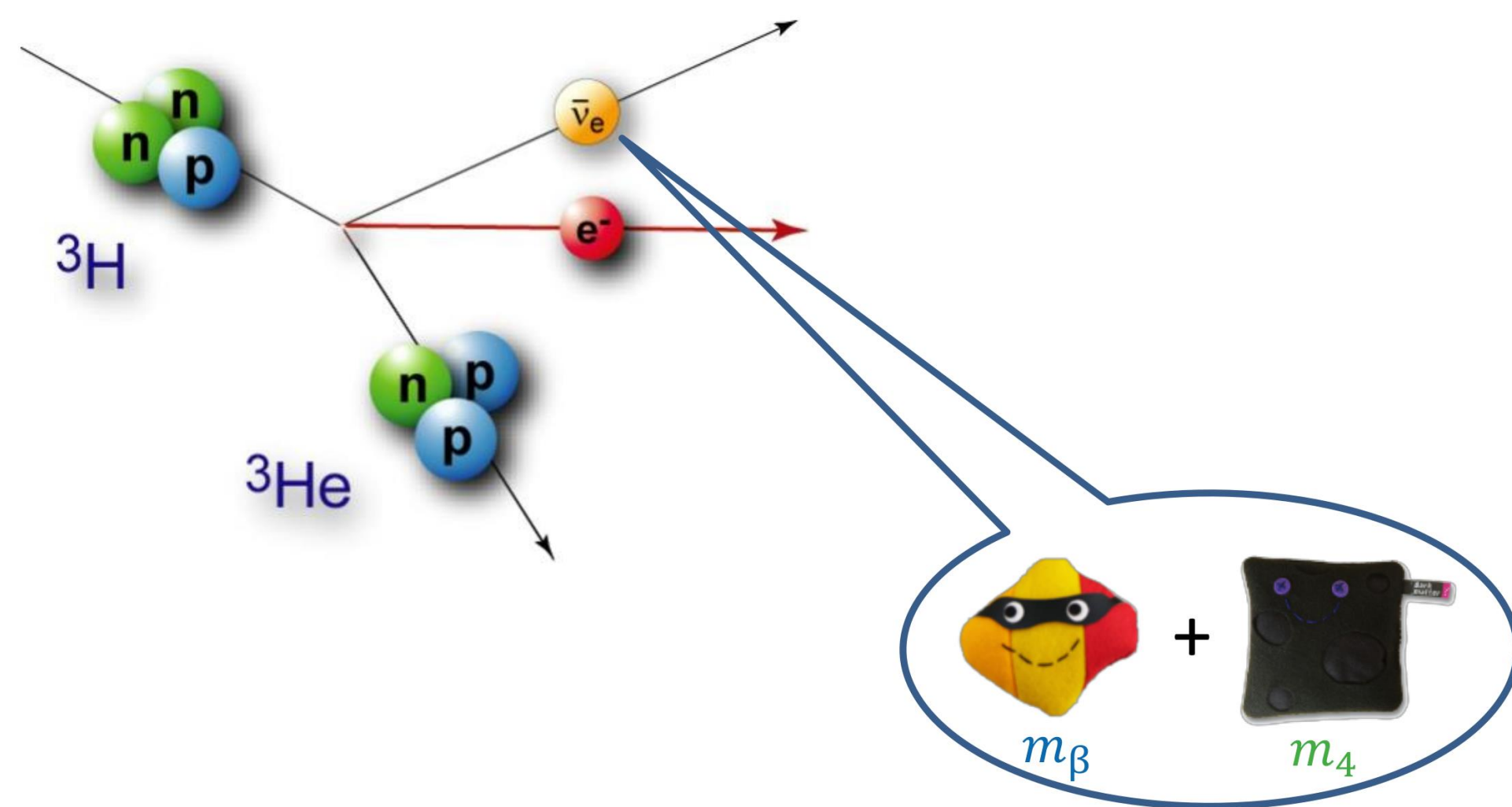
Gallium anomaly



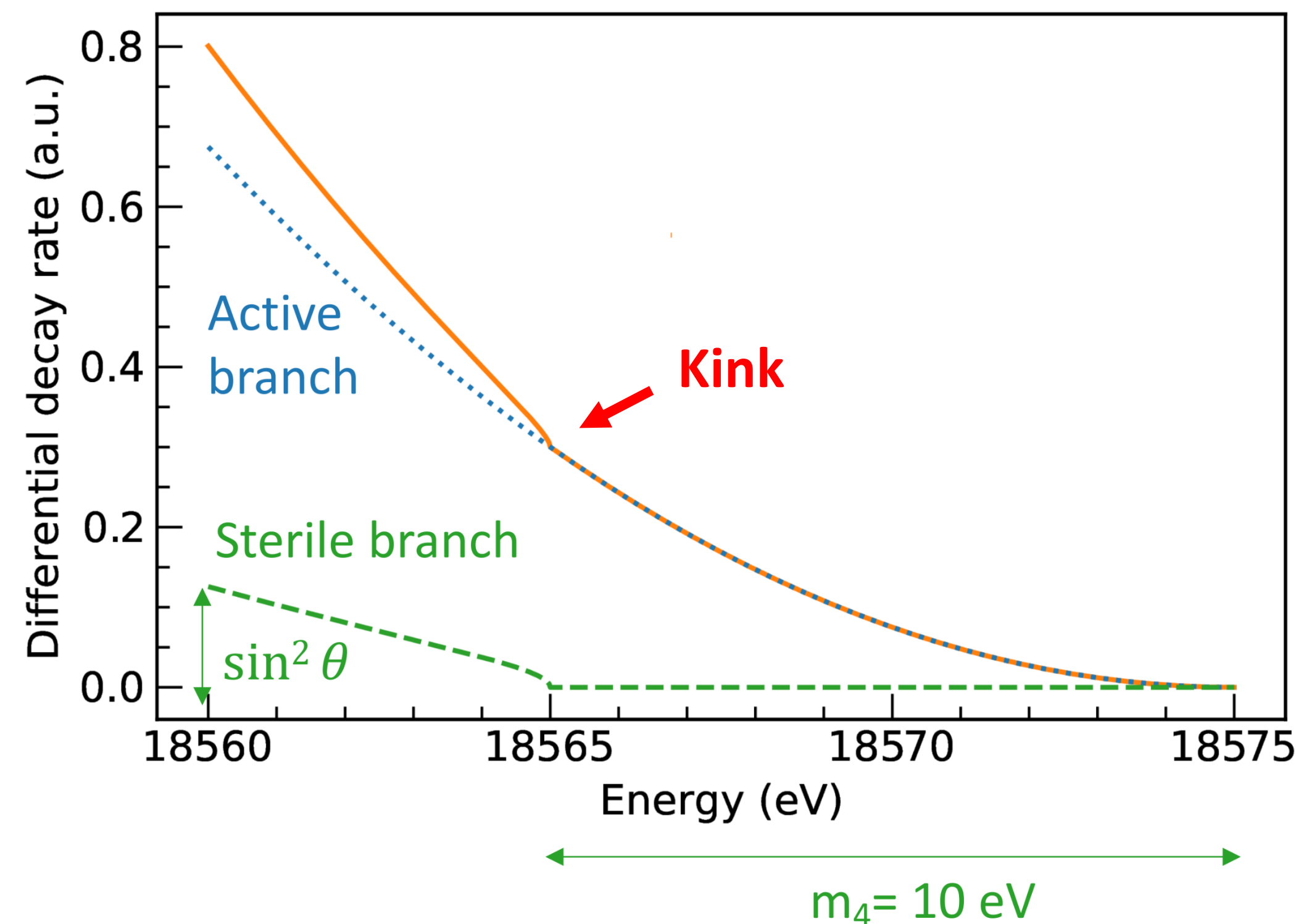
Systematic deficit of $\bar{\nu}_e$ from very short baseline measurements with Gallium

Imprint of sterile ν on β -decay spectrum

- 4th mass state will appear as a kink in the spectral shape
- Kink close to the endpoint: excellent energy resolution required



$$\frac{d\Gamma}{dE} = (1 - |U_{e4}|^2) \frac{d\Gamma}{dE}(m_\beta^2) + |U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)$$

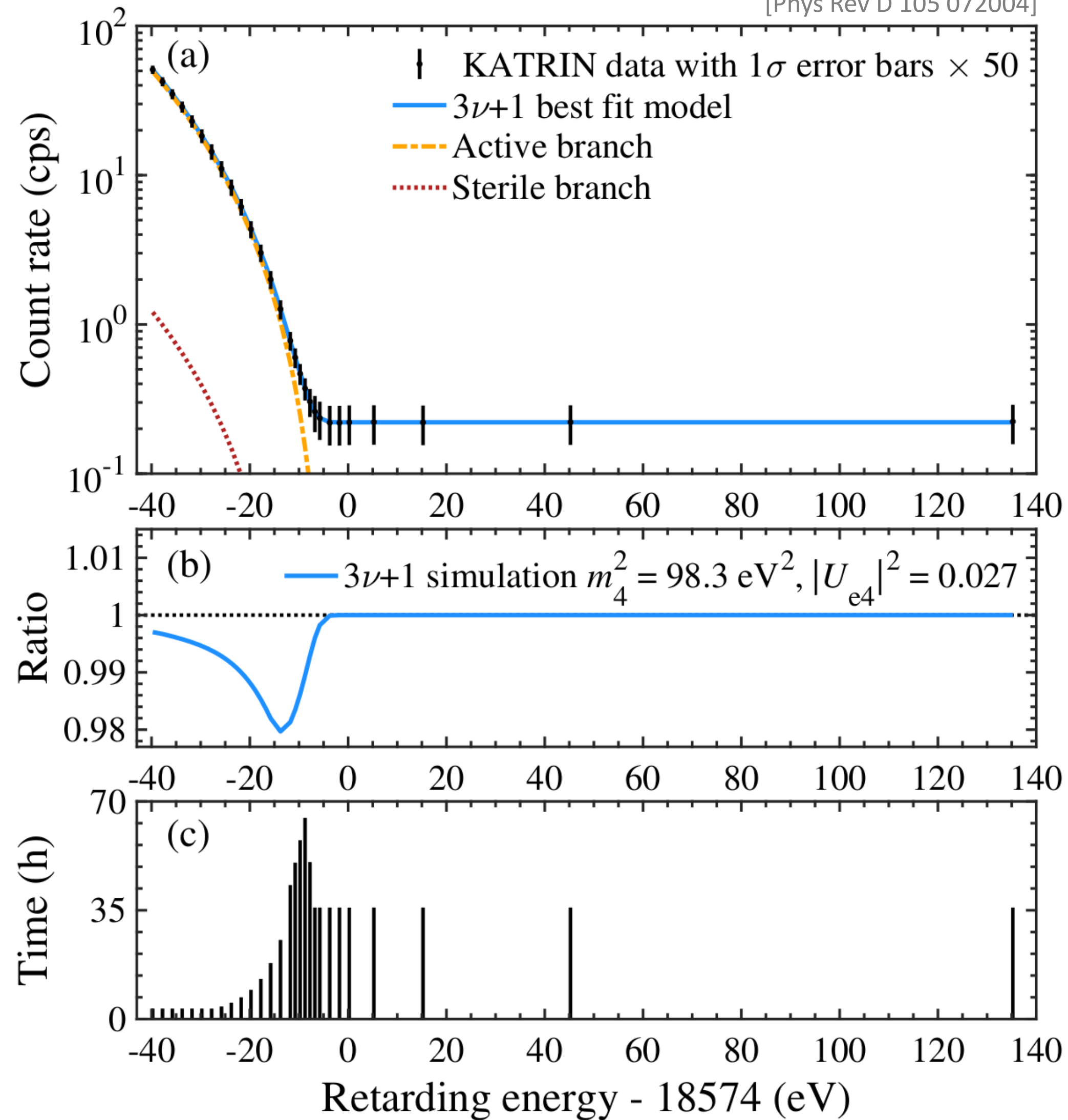


⇒ Accessible in current data sets

analysis published for the first 2 campaigns of KATRIN combined

Sterile neutrino fit

[Phys Rev D 105 072004]



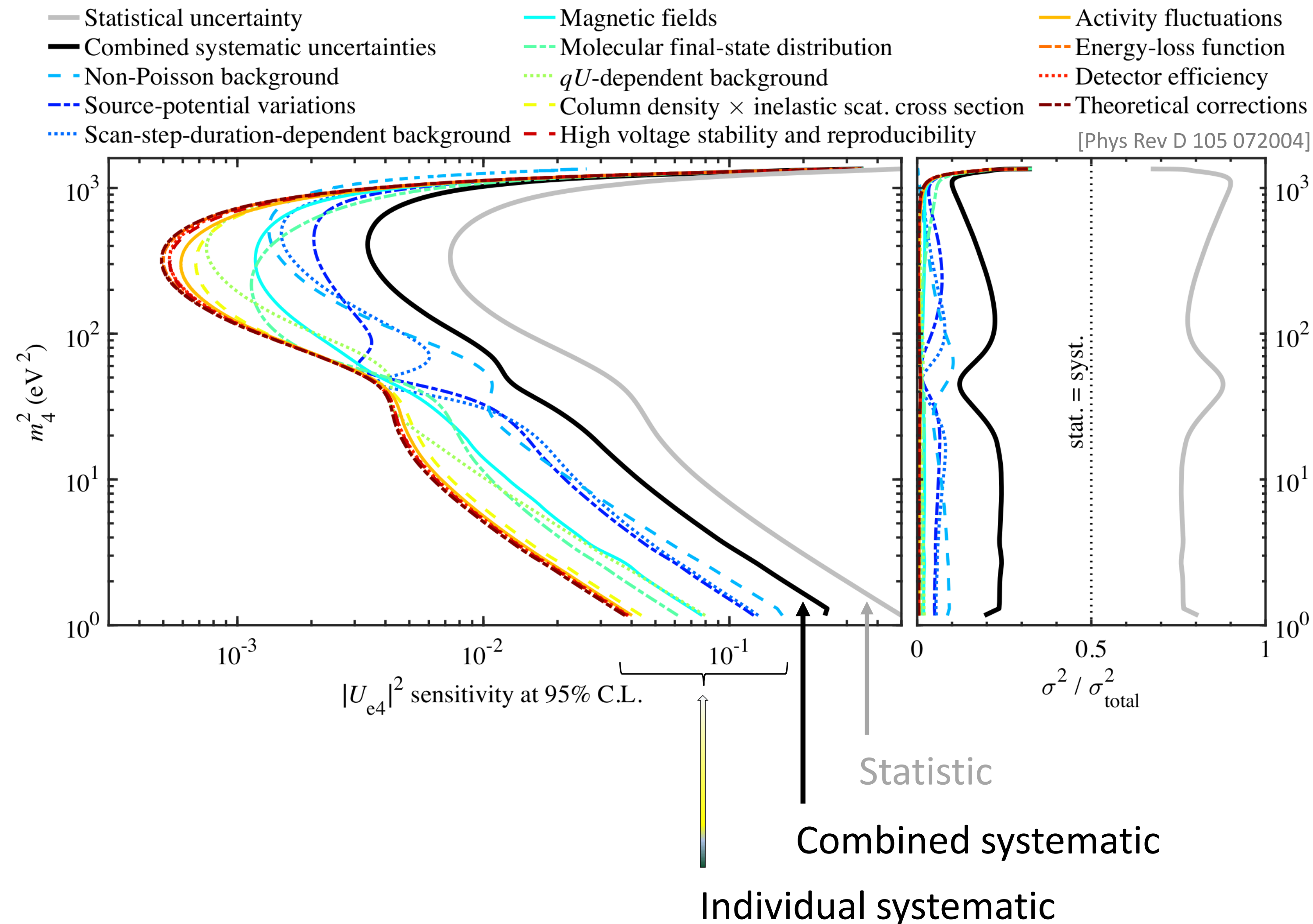
$$\Gamma(qU) = \mathbf{A} \int_{qU}^{E_0} D_{\beta}(E, \mathbf{m}_{\nu_e}^2, \mathbf{E}_0, |\mathbf{U}_{e4}|^2, \mathbf{m}_4^2) \cdot R(E, qU) dE + \mathbf{B}$$

Maximum likelihood fit of model for $3\nu + 1$

- free amplitude A
- squared neutrino mass m_{β}^2
- endpoint E_0
- background B
- **4th neutrino mass and mixing: $|U_{e4}|^2, m_4^2$**

No significant sterile-neutrino signal is observed in KATRIN \Rightarrow sensitivity

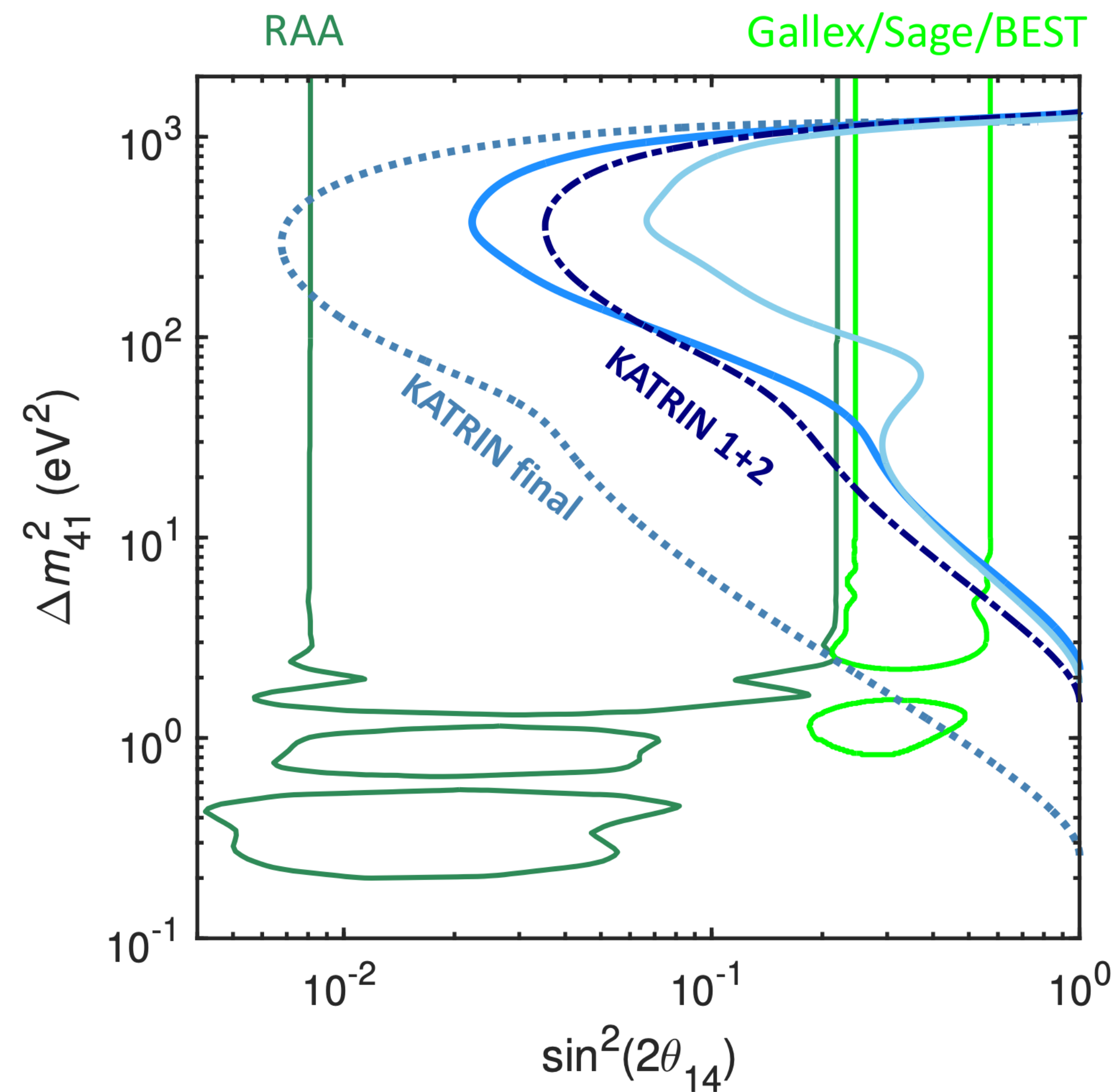
Sterile neutrino systematic breakdown



$$\sigma_{\text{syst}}(|U_{e4}|^2) = \sqrt{\sigma_{\text{stat+syst}}^2 - \sigma_{\text{stat}}^2}$$

- Uncertainty budget dominated by the statistic for all masses
- Dominant systematics:
 - background
 - source plasma potential

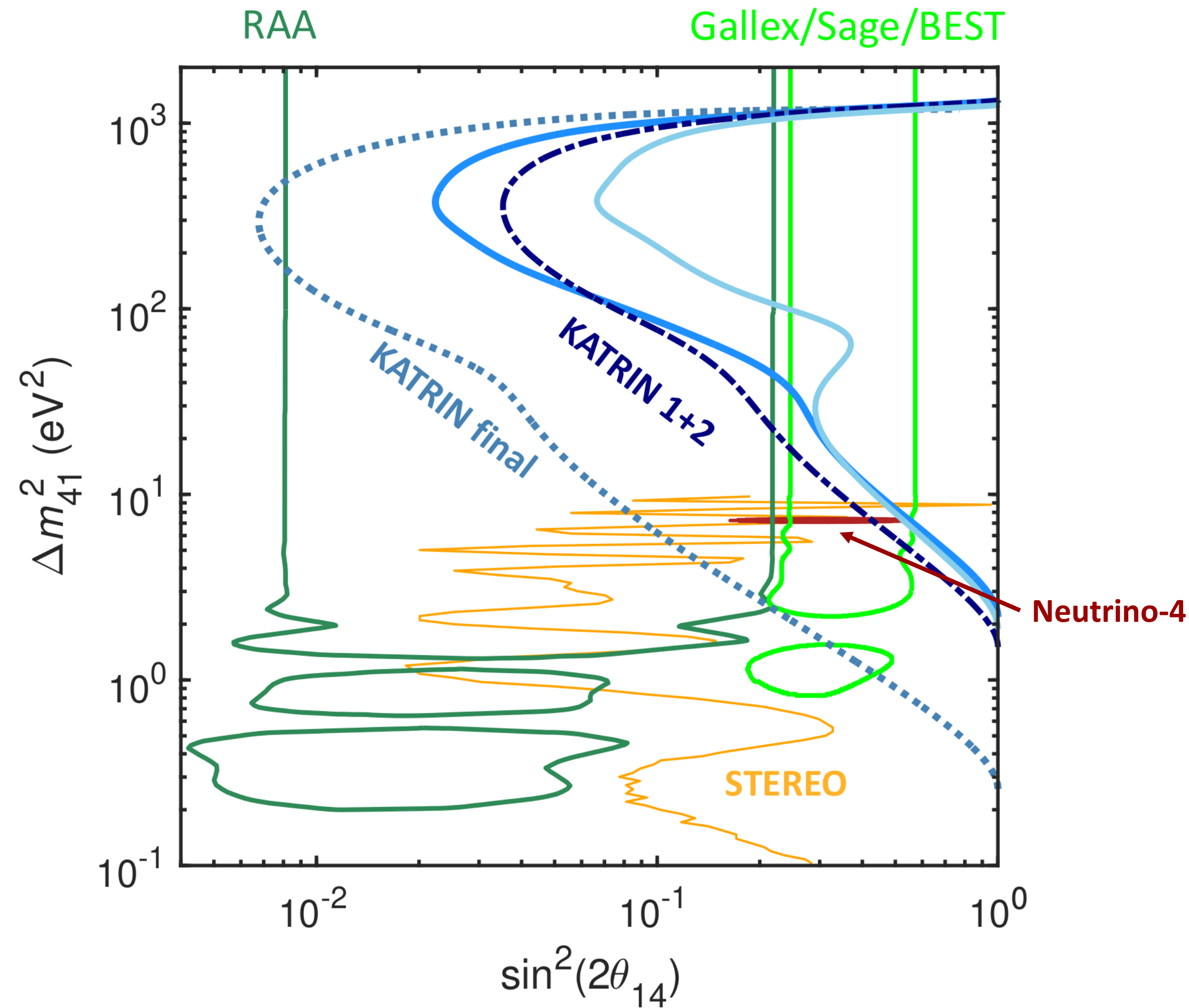
Overview of sterile experiment results



95% C.L. exclusion contours

- Exclude large Δm_{41}^2 solutions from the reactor antineutrino and gallium anomaly

Overview of sterile experiment results

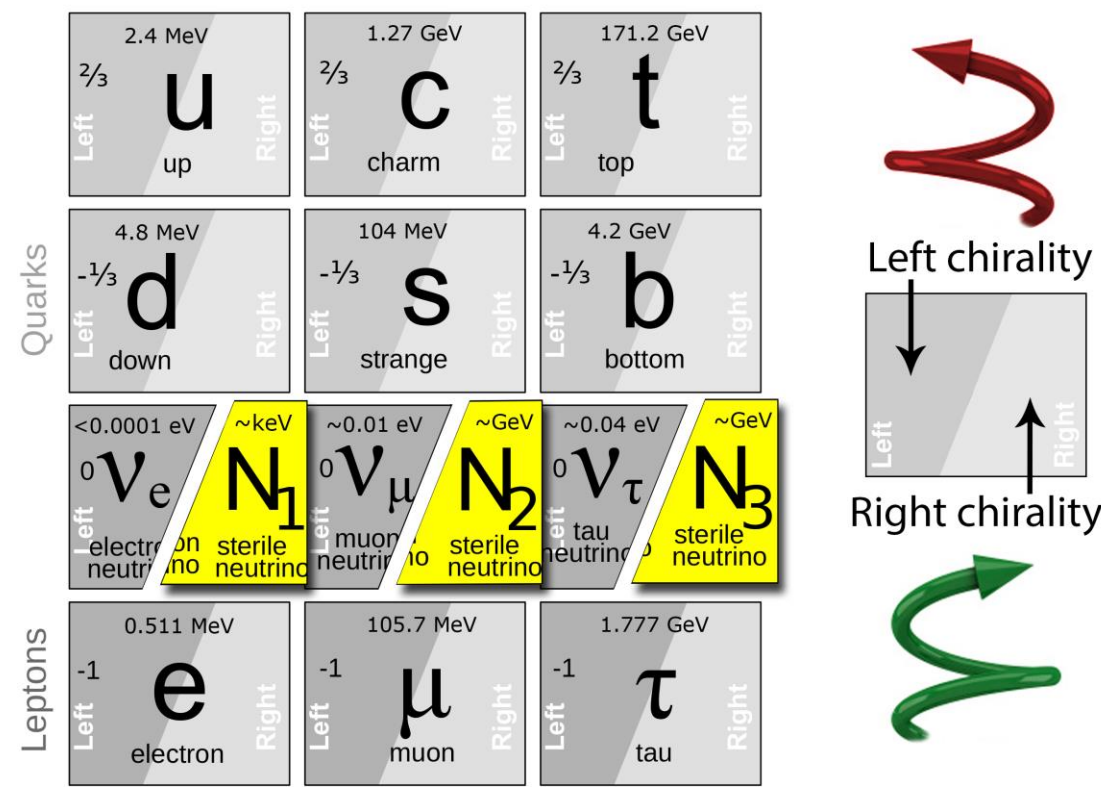


- Exclude large Δm_{41}^2 solutions from the reactor antineutrino and gallium anomaly
- Improve the exclusion bounds set by short-baseline oscillation experiments for $\Delta m_{41}^2 \gtrsim 10 \text{ eV}^2$
- KATRIN will probe the positive result claimed by Neutrino-4

⇒ **KATRIN provide a complementary probe of sterile neutrino**

keV-scale sterile neutrino search motivation

- Right-handed neutrinos: natural extension of SM and straightforward way to introduce neutrino mass
- Excellent candidate for warm dark matter



Unexpected x-ray emission line around 3.5 keV observed in nearby galaxy

Hint of sterile neutrinos with a mass around 7 keV?
 ... or anything else? [Dessert et al., Science 367, 1465–1467 (2020)]

⇒ Need of model independent measurements across a wide range of mass

THE ASTROPHYSICAL JOURNAL, 789:13 (23pp), 2014 July 1
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doi:10.1088/0004-637X/789/1/13

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

ESRA BULBUL^{1,2}, MAXIM MARKEVITCH³, ADAM FOSTER¹, RANDALL K. SMITH¹,
 MICHAEL LOEWENSTEIN^{2,4}, AND SCOTT W. RANDALL¹

¹ Harvard-Smithsonian Center for Astrophysics
² CRESST and X-ray Astrophysics Laboratory
³ NASA Goddard Space Flight Center
⁴ Department of Astronomy
 Received 2014 February 10

We detect a weak unidentified emission line of 73 galaxy clusters spanning a redshift range from $z=0.05$ to $z=0.15$ (Perseus, Centaurus, Ophiuchus, and Coma, and independent MOS spectra and the PN “all-sky” Perseus Cluster. However, it is very weak and at the limit of the current instrument capabilities. This appears to be because of an anomalous dielectronic recombination line, although its exact nature is difficult to understand. Another alternative is a K line also exceeding expectation by a factor of 10.

doi: 10.1103/PhysRevLett.113.251301

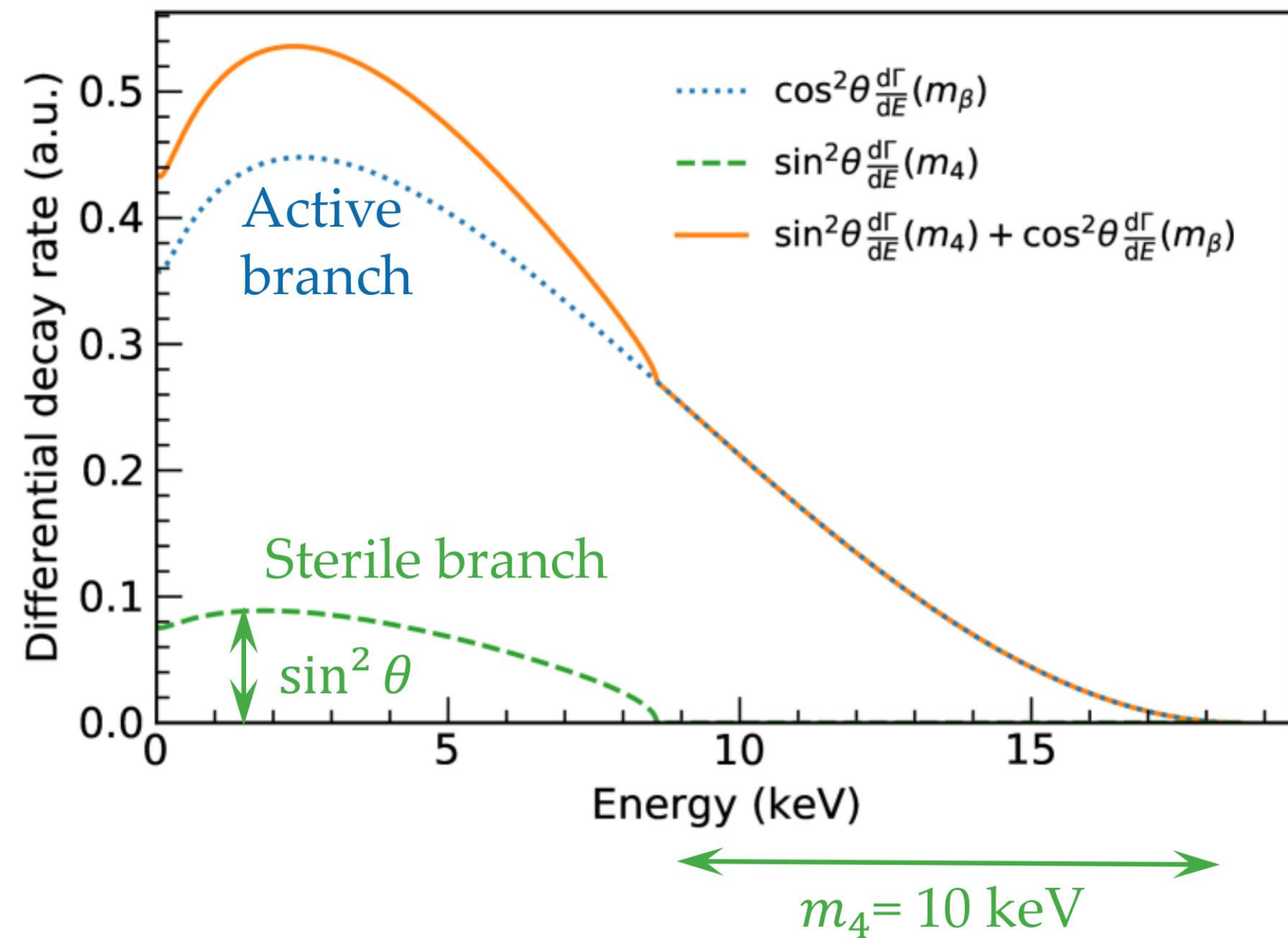
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky¹, O. Ruchayskiy², D. Iakubovskiy^{3,4} and J. Franse^{1,5}

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² Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
³ Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
⁴ National University “Kyiv-Mohyla Academy”, Skovorody Str. 2, 04070, Kyiv, Ukraine
⁵ Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

We report a weak line at 3.52 ± 0.02 keV in X-ray spectra of M31 galaxy and the Perseus galaxy cluster observed by MOS and PN cameras of XMM-Newton telescope. This line is not known as an atomic line in the spectra of galaxies or clusters. It becomes stronger towards the centers of the objects; is stronger for Perseus than for M31; is absent in the spectrum of a deep “blank sky” dataset. Although for each object it is hard to exclude that the feature is due to an instrumental effect or an atomic line, it is consistent with the behavior of a dark matter decay line. Future (non-)detections of this line in multiple objects may help to reveal its nature.

keV sterile neutrino search with KATRIN



Experimental challenge

- Handling of high data rates: $10^8 \text{ e}^- \cdot \text{s}^{-1}$
- Good energy resolution: $< 300 \text{ eV}$
- Low energy threshold: $E_{\text{thr}} < 2 \text{ keV}$

⇒ New detector required for high rate β -spectroscopy

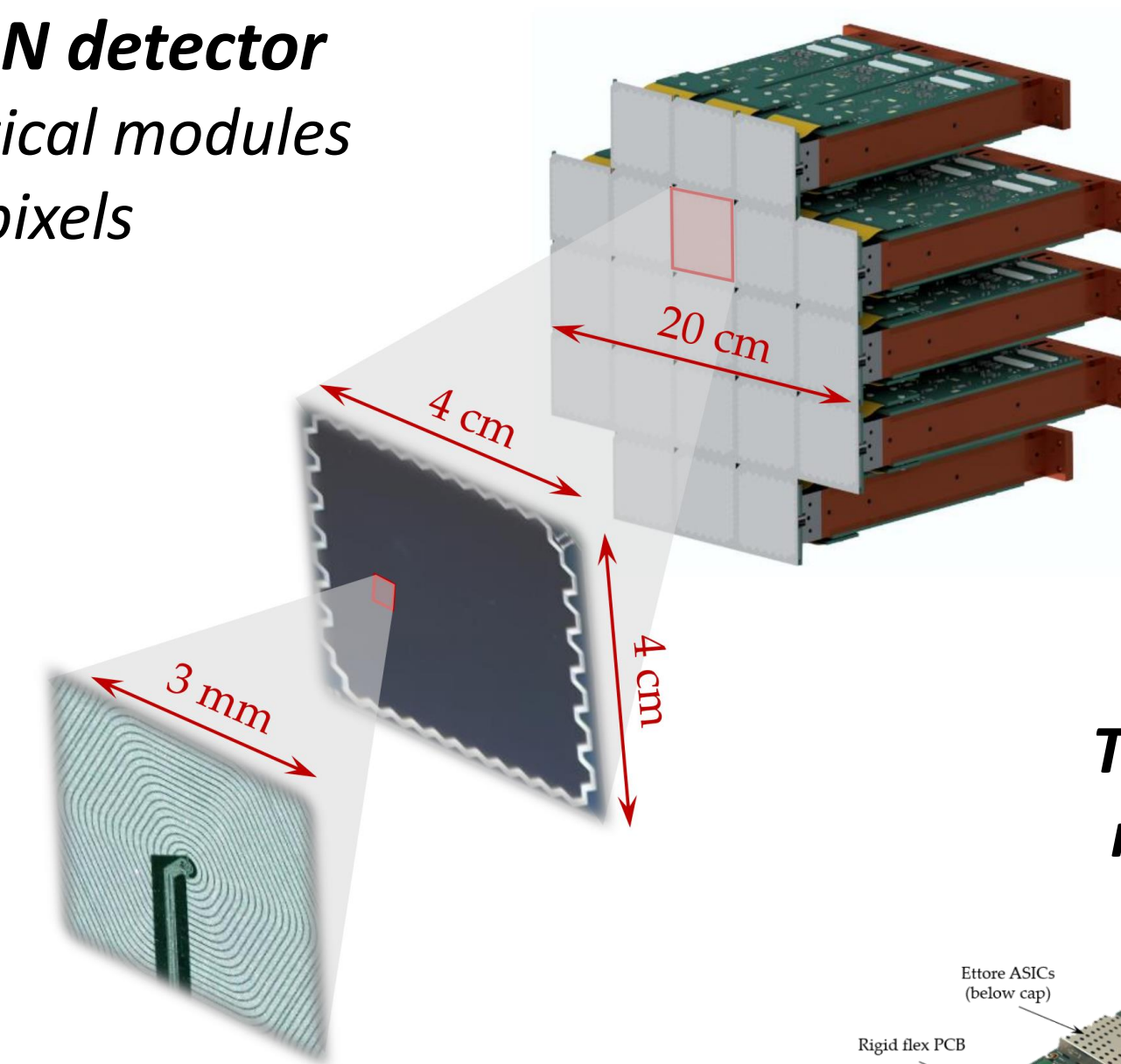
TRISTAN project: “Tritium Beta Decay to Search for Sterile Neutrinos”

- Future upgrade of KATRIN detector using silicon drift detector (SDD) technology
- goal: ppm level on $\sin^2 \theta$

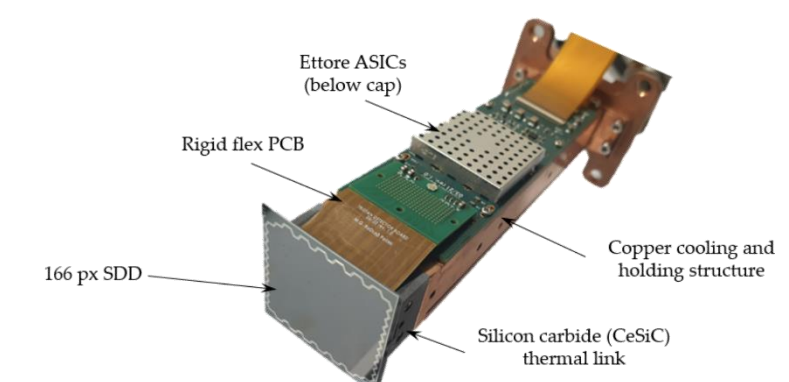


Full TRISTAN detector

- 21 identical modules
- ~3500 pixels



TRISTAN detector module with 166 pixels



S. Mertens et al JCAP02(2015)020
Mertens et al, J. Phys. G46 (2019)

Staged approached

Characterization

Prototype bench test
(7, 47, 166 px)

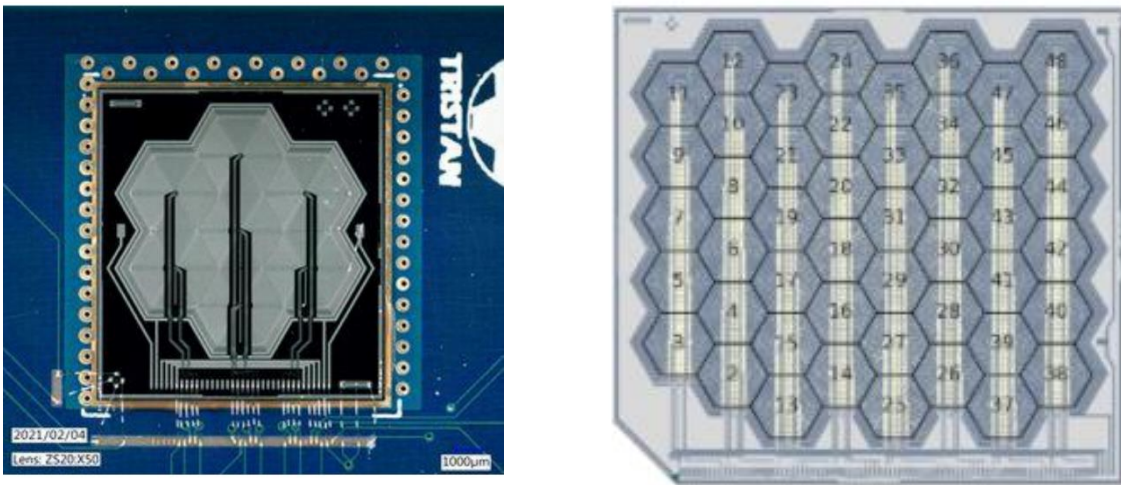
Phase 0

One module in monitor
spectrometer (166 px)

Phase 1 | Phase 2

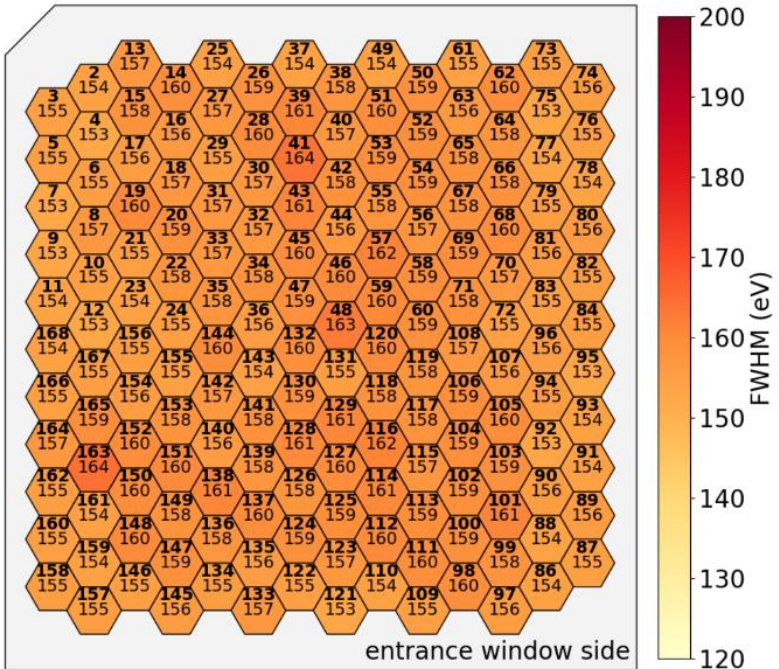
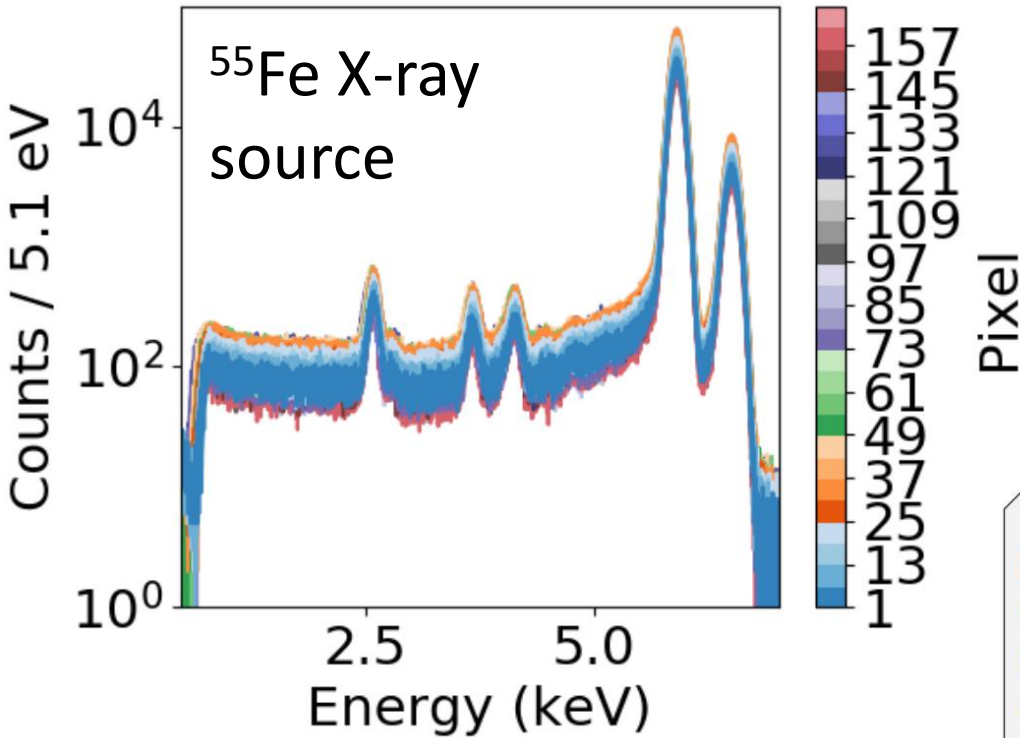
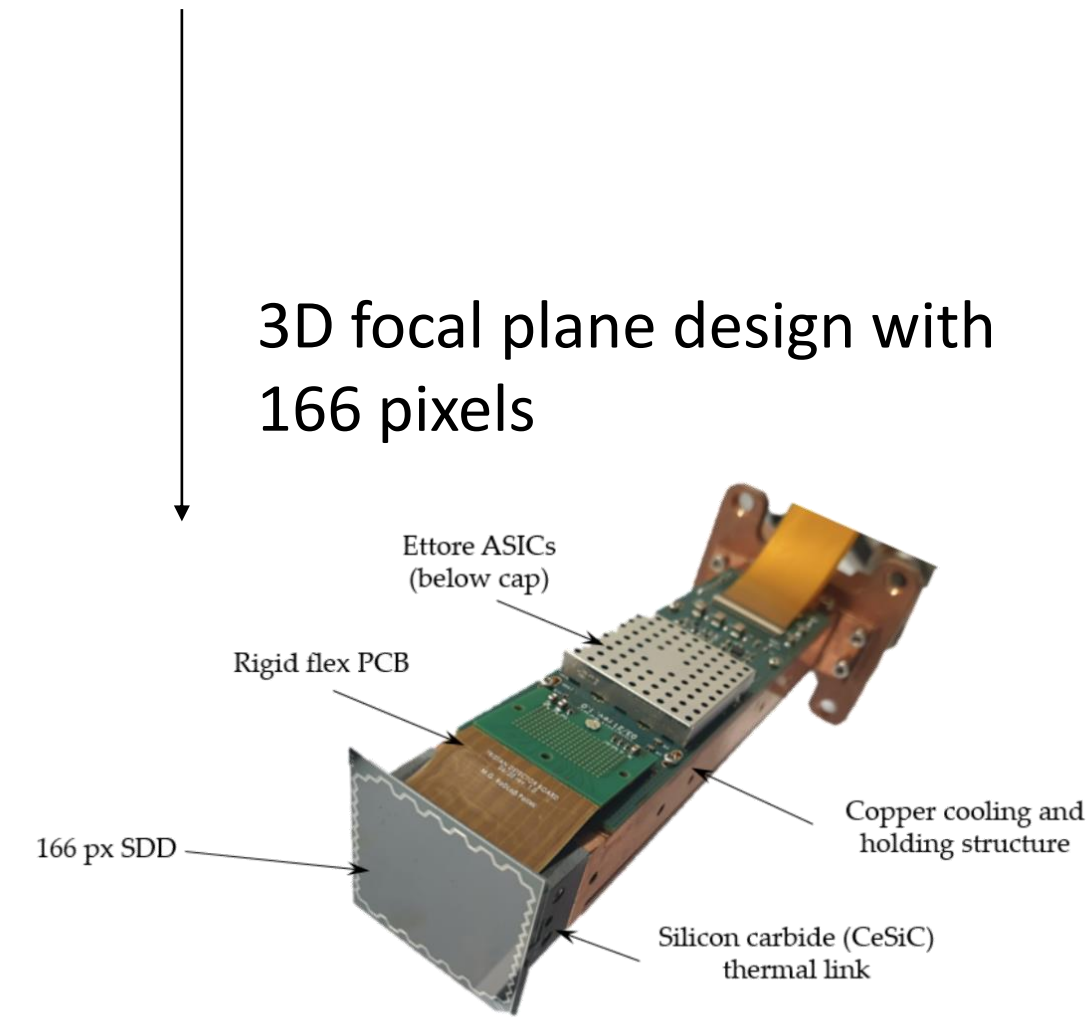
detector in KATRIN beamline
9 modules (1500 px) 21 modules (3500 px)

7 and 47 pixels prototypes



Prototypes: 7, 47, 166 px

- design definition and optimization
- performance characterization with X-rays, electrons and laser sources
 - ↳ *energy resolution, linearity, timing, boundary effects*



Energy resolution
@ 5.9 keV

⇒ **Good performance demonstrated**
↳ *match TRISTAN requirement*

Staged approach

Characterization

Prototype bench test
(7, 47, 166 px)

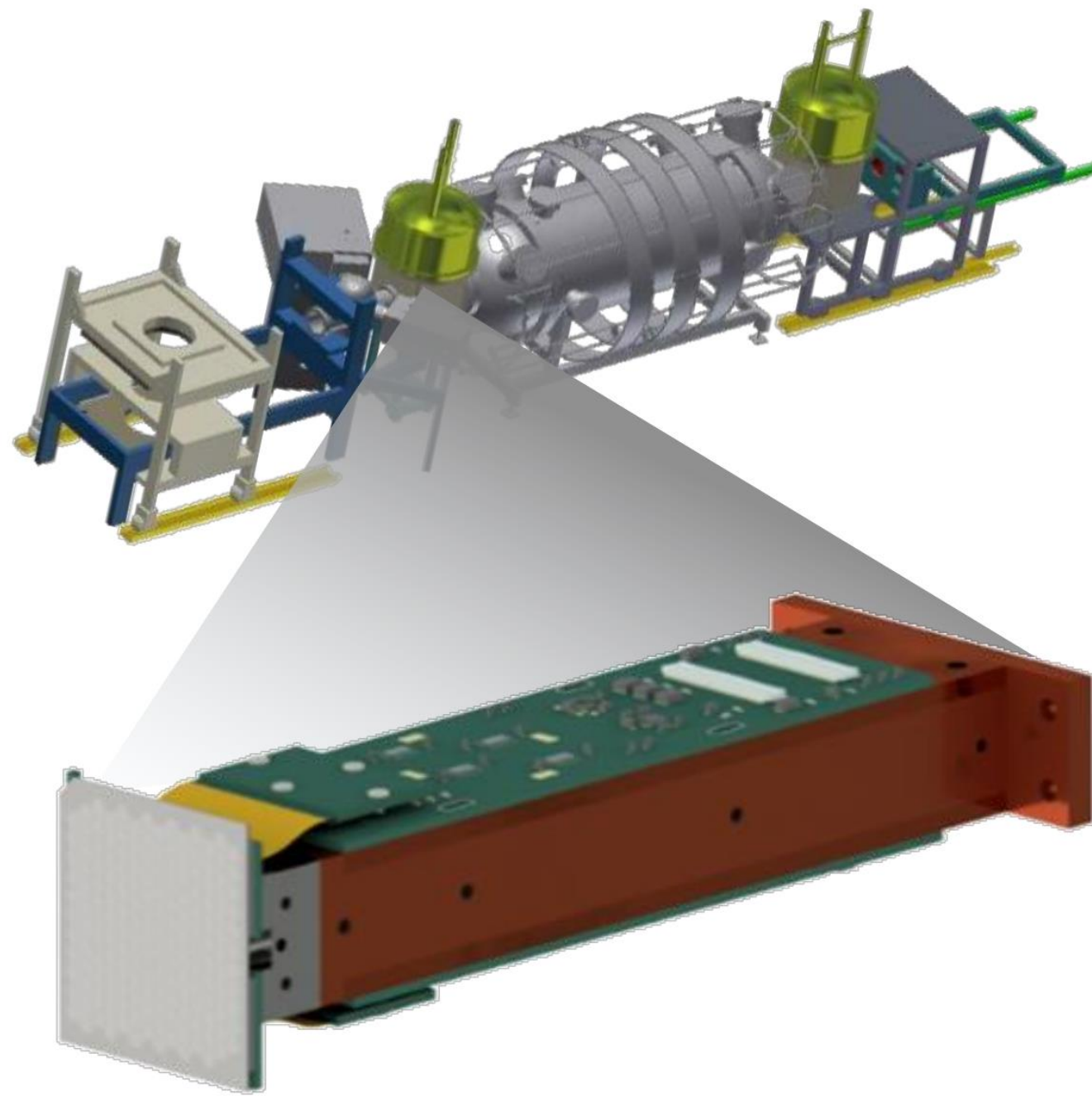
Phase 0

One module in monitor
spectrometer (166 px)

Phase 1 | Phase 2

detector in KATRIN beamline

9 modules (1500 px) 21 modules (3500 px)



Monitor spectrometer (MoS):

- refurbished MAC-E filter from Mainz experiment reassembled in KIT
- similar energy resolution as KATRIN main spectrometer

⇒ Integration and first electron in september 2022!

- environment close to the final setup – realistic condition
- largest SDD array ever operated

Staged approached

Characterization

Prototype bench test
(7, 47, 166 px)

Phase 0

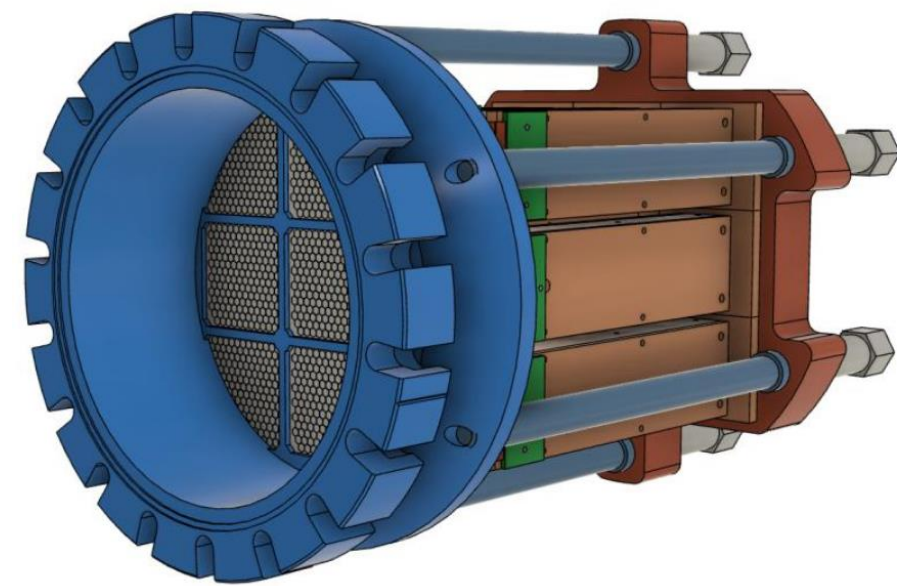
One module in monitor
spectrometer (166 px)

Phase 1 | Phase 2

detector in KATRIN beamline

9 modules (1500 px)

21 modules (3500 px)



Phase 1

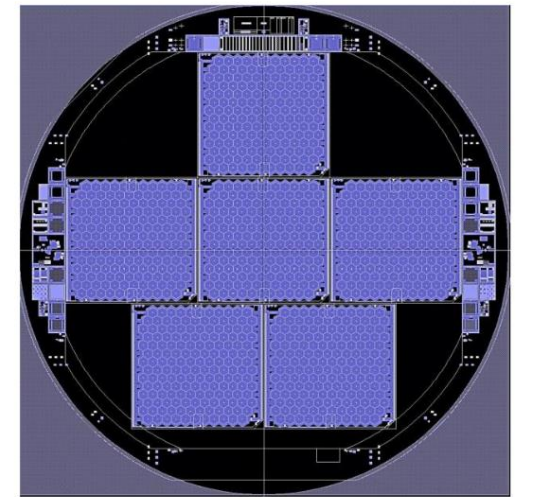
- 9 modules
- 1500 pixels

Phase 1 → start in 2025

- Almost final module design
- SSD production started: *final detectors in 2023*

⇒ **First keV sterile neutrino search with KATRIN**

SSD wafer prototype

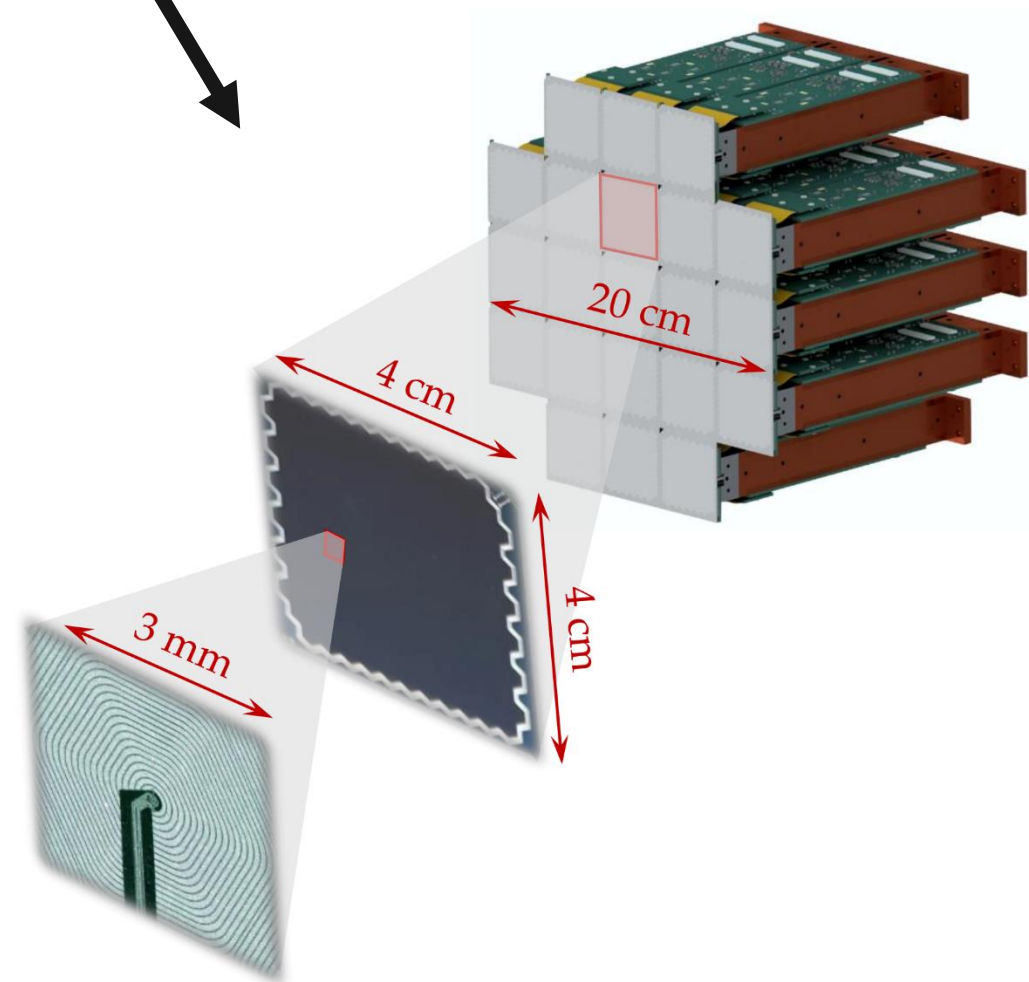


Phase 2

- 21 modules
- 3500 pixels

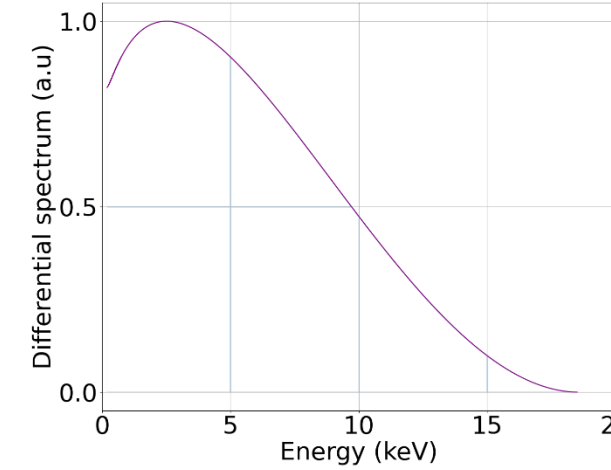
Phase 2

- Optimal experimental setup → reduced systematics
- 3 years of data taking → improved statistics

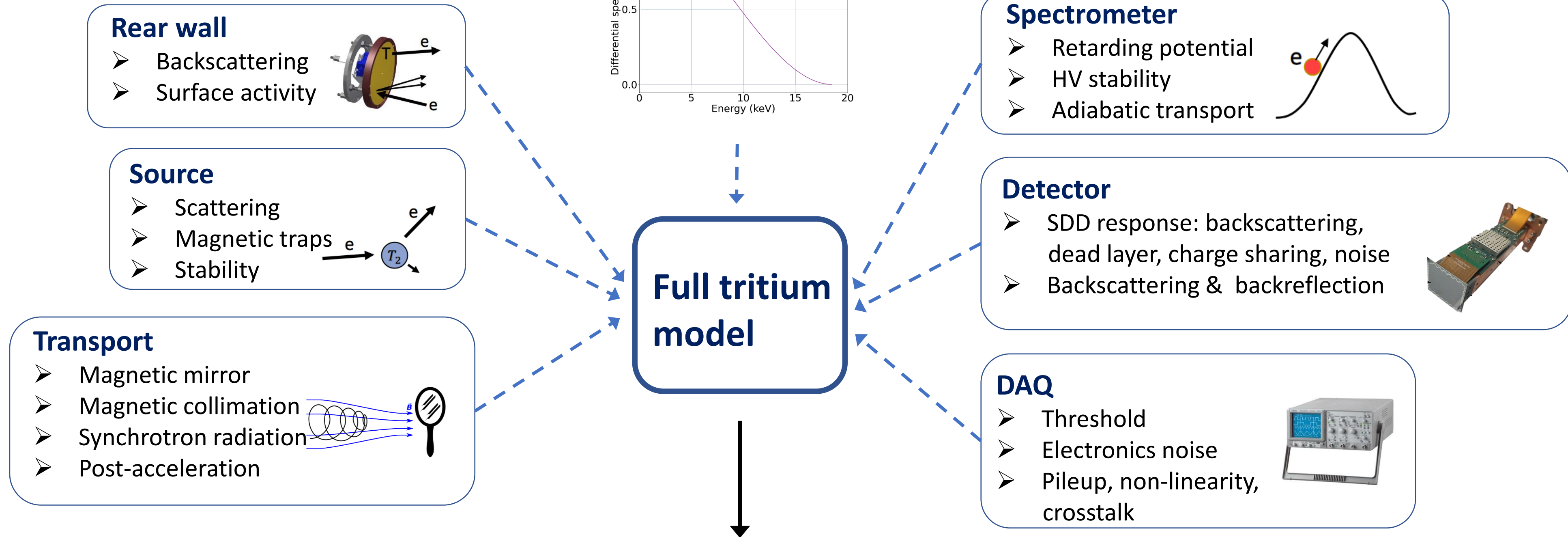


Spectrum modeling

Theoretical β spectrum



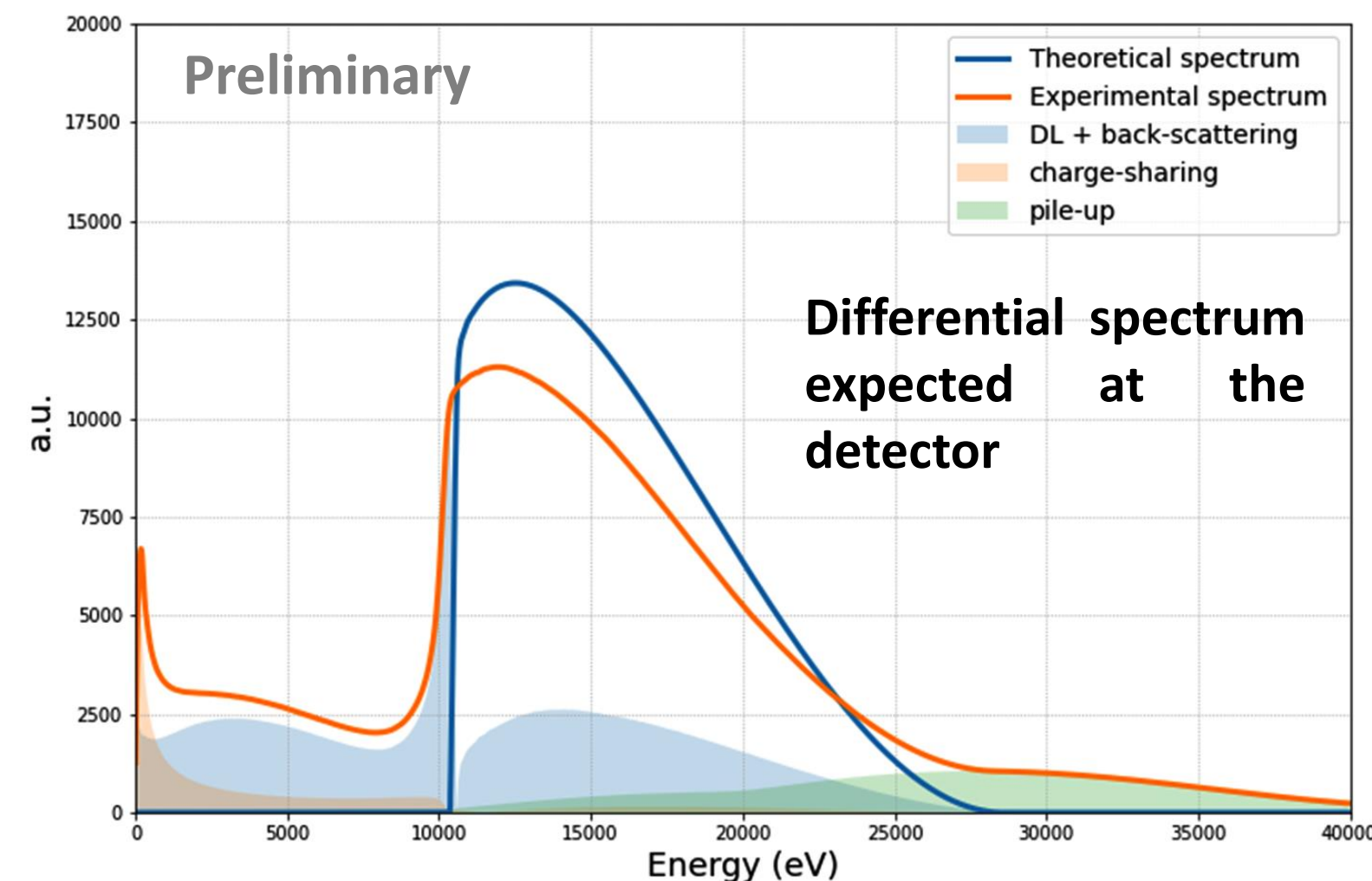
Experimental effects



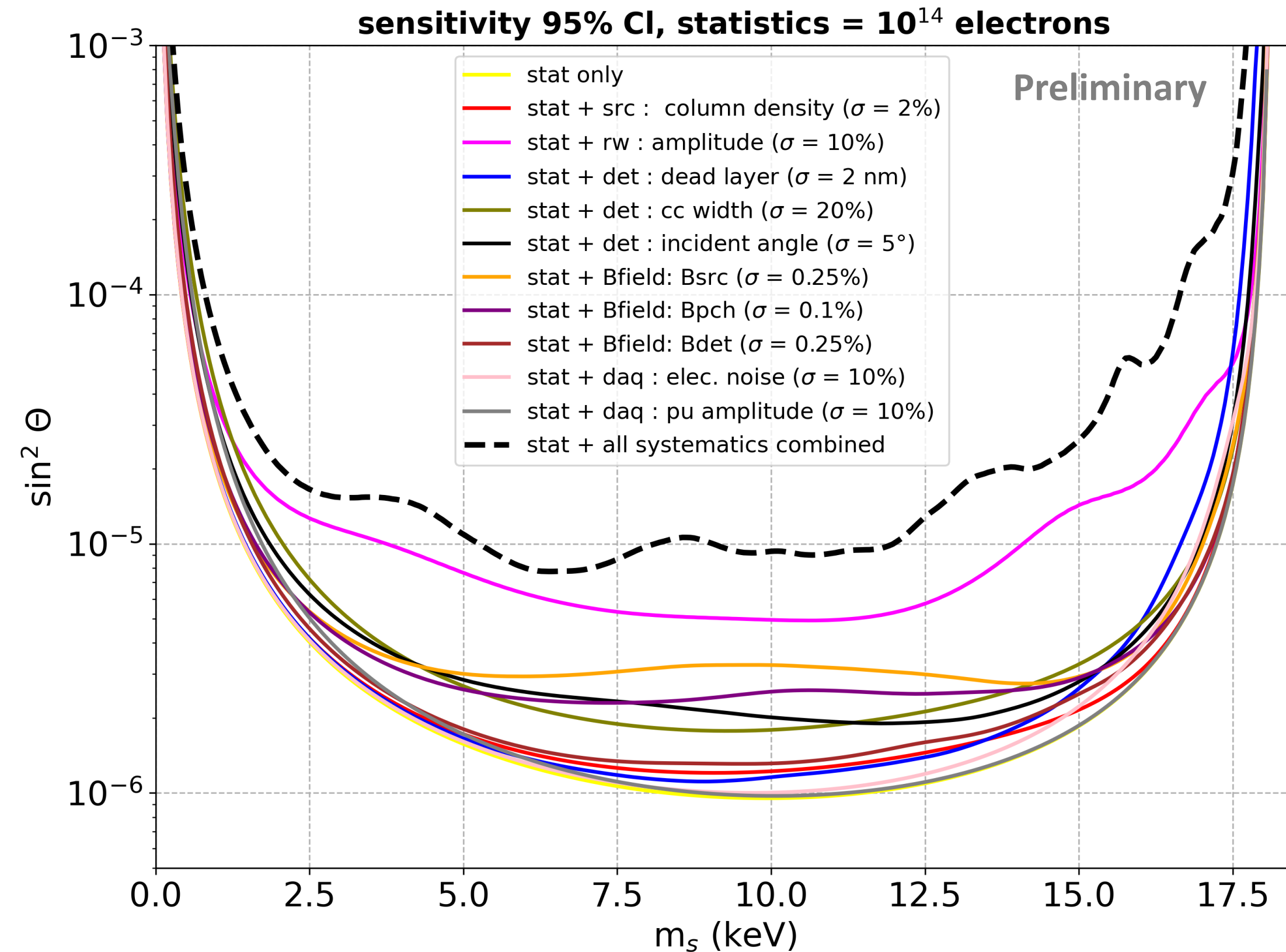
Model:

- Analytical calculations + simulations
- Non trivial effects:
 - backscattered e^- at the rear wall
 - backscattered and backreflected e^- at the detector

⇒ **Systematic effects smear the sterile signature**



KATRIN sensitivity on keV sterile neutrino – Phase 1

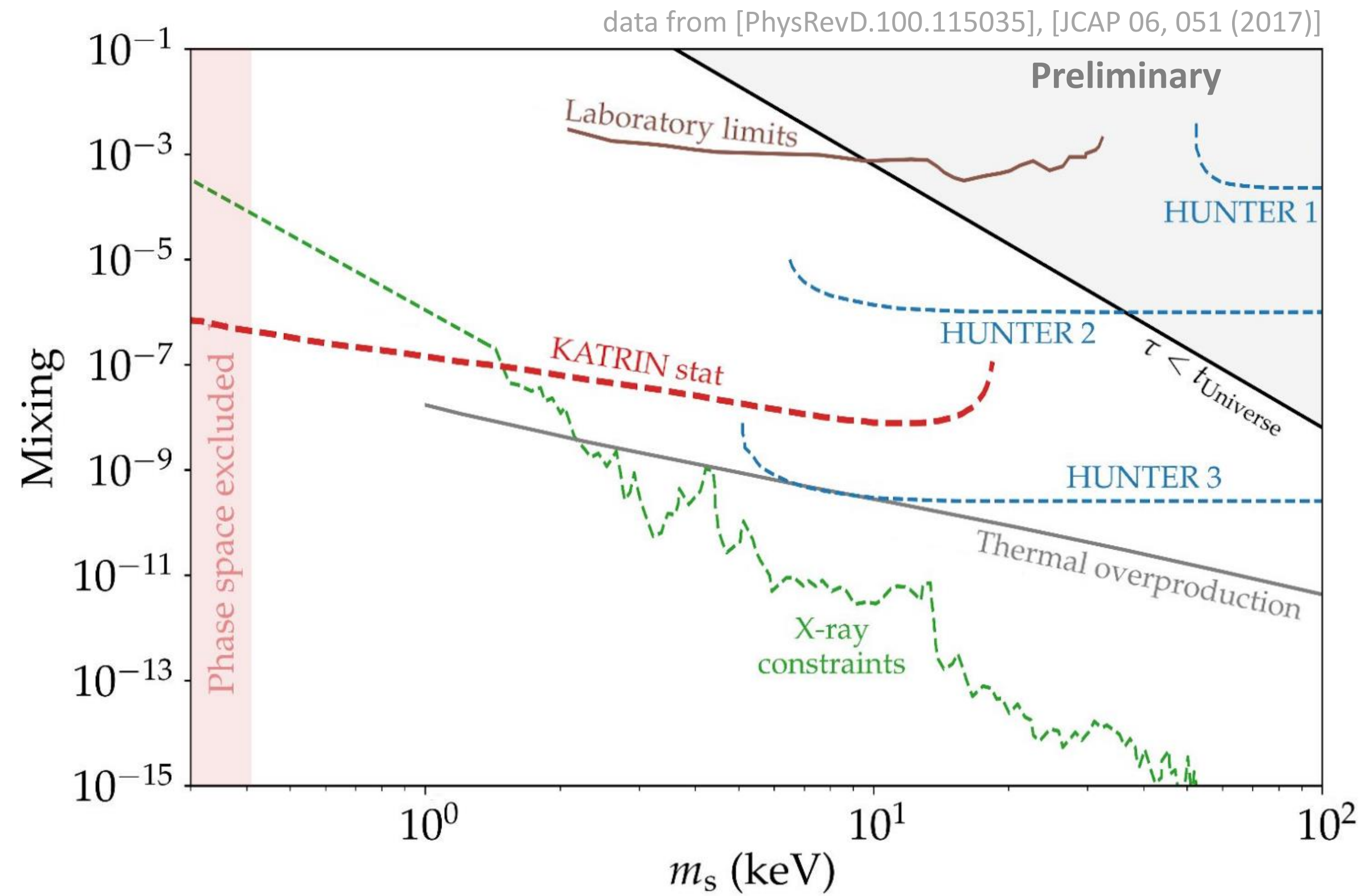


- Statistical sensitivity at $1 \cdot 10^{-6}$ reachable in ~ 1 month
- Systematic effects reduce the sensitivity by (at least) one order of magnitude
 - rear wall dominate
 - important contribution of Bfields and detector effects
- Work in progress
 - model refinement
 - missing systematics
 - experimental setup optimization

Scenario hypothesis:

- Current KATRIN Bfield / rear wall configuration

KATRIN target sensitivity on keV sterile neutrino



- Several order of magnitude improvement of current laboratory limits expected
- Competitive and complementary to other keV sterile experiment
- Work in progress to evaluate impact of systematic uncertainties

KATRIN stat hypothesis:

- 3 years of data taking: 10^{18} e^- collected

Conclusion and outlook

- First direct sub-eV neutrino mass limit

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

- Targeted sensitivity with increased statistics and improved systematics

$$m_\nu < 0.2\text{-}0.3 \text{ eV by 2025}$$

- search for eV-sterile neutrinos with current setup, complementary results to short baseline experiments probe
- search for keV-sterile neutrinos with novel TRISTAN detectors after 2025
- *But also... relic neutrino overdensity, Lorentz invariance violation in current KATRIN data*

Thank you for your attention!