# keV sterile neutrino search with the KATRIN experiment


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On behalf of the KATRIN collaboration



**IDM 2024**

15th International Workshop on the Identification of Dark Matter 2024

July 8-12, 2024, L'Aquila, Italy

# Neutrino mass measurement
# with KATRIN

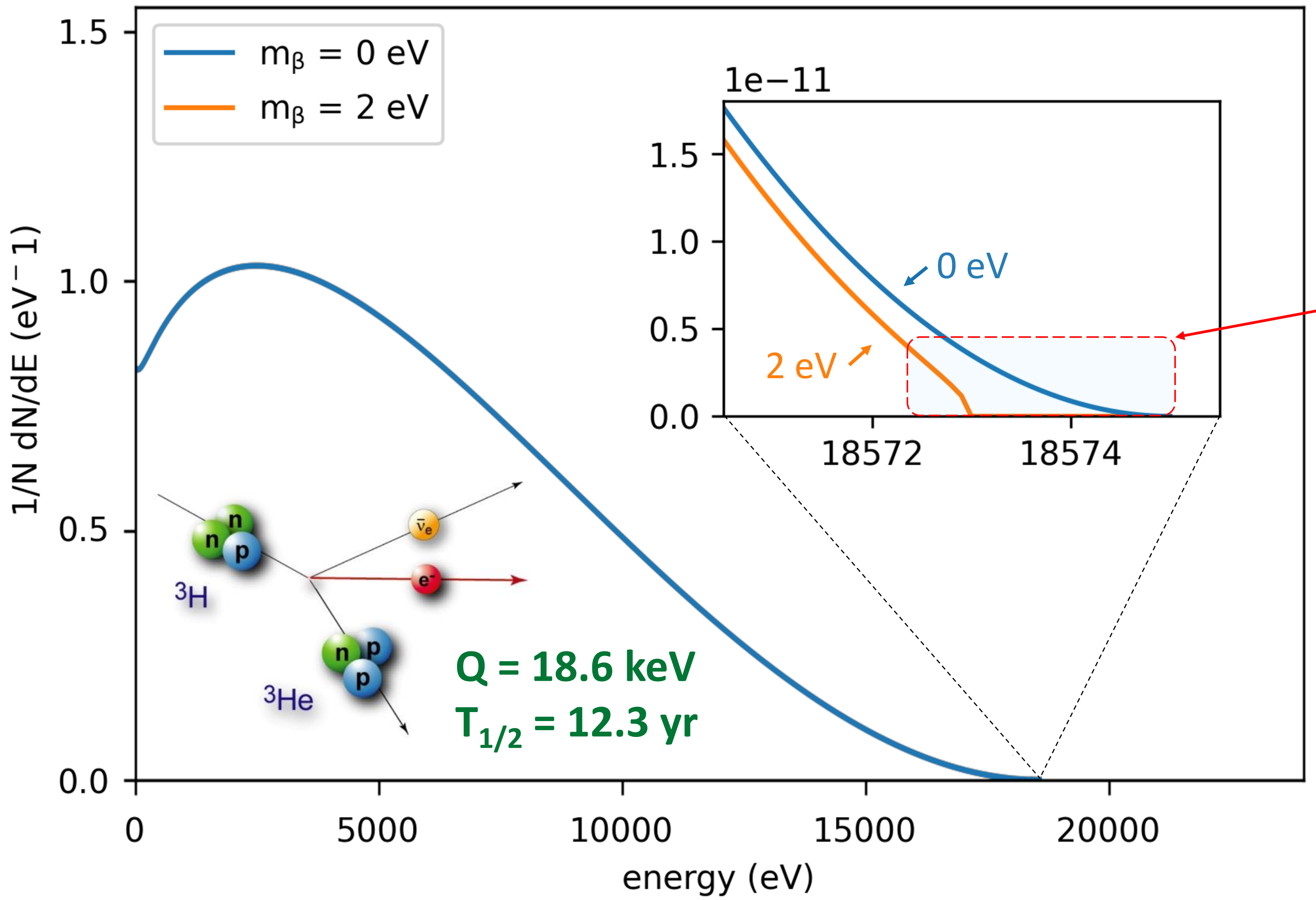
# Neutrino mass measurement with tritium ß-decay kinematics

**Super-allowed decay**

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

incoherent neutrino mass:

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




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

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

**Ka**rlsruhe
**Tri**tium
**N**eutrino
**E**xperiment

## KATRIN collaboration

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

# KATRIN experimental 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)

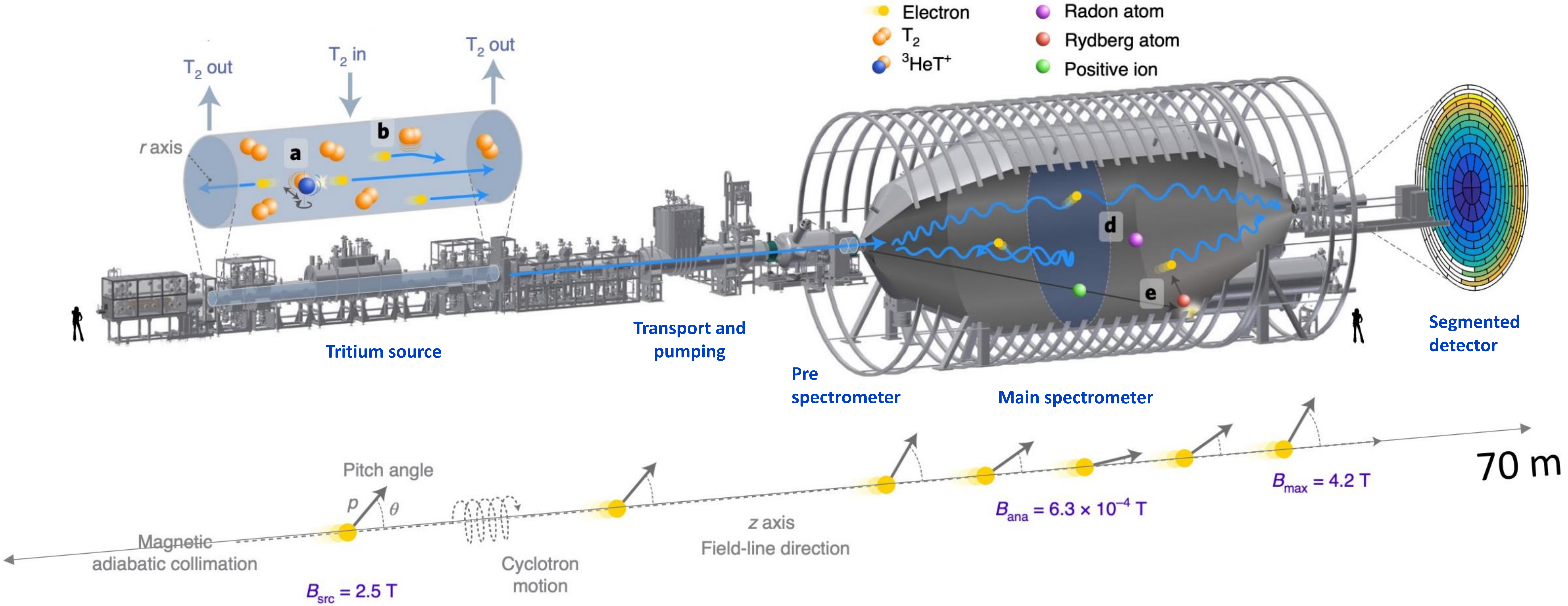
  → high resolution: O(1) eV

  → large acceptance angle: 0-51°

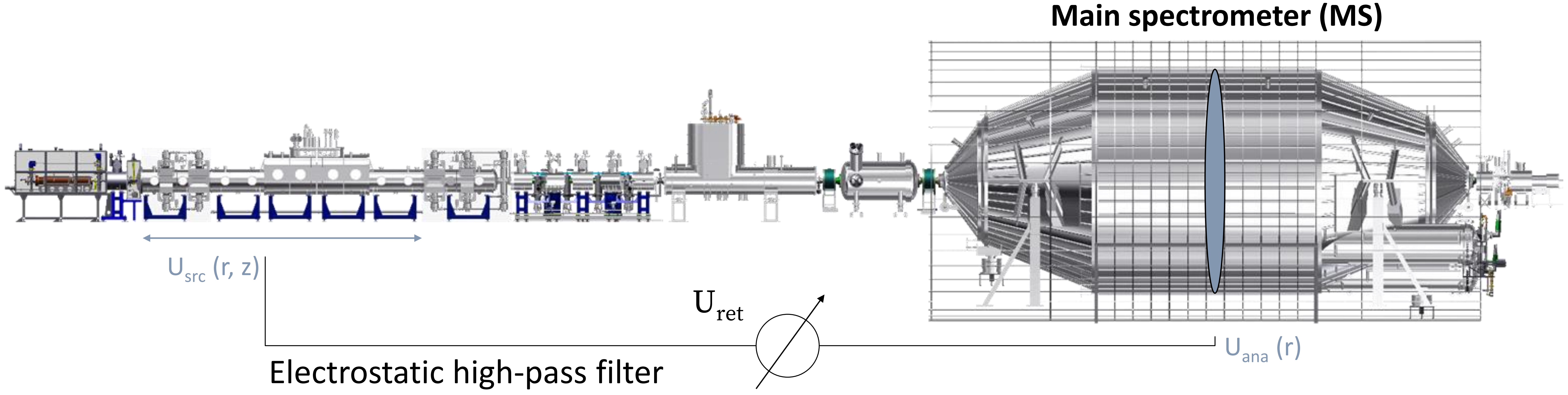
### Detector section

- focal plane detector, 148 pixels silicon PIN-diode
- counts electrons: rate vs potential

  → **< 1 $e^-.s^{-1}$**



# Measurement strategy

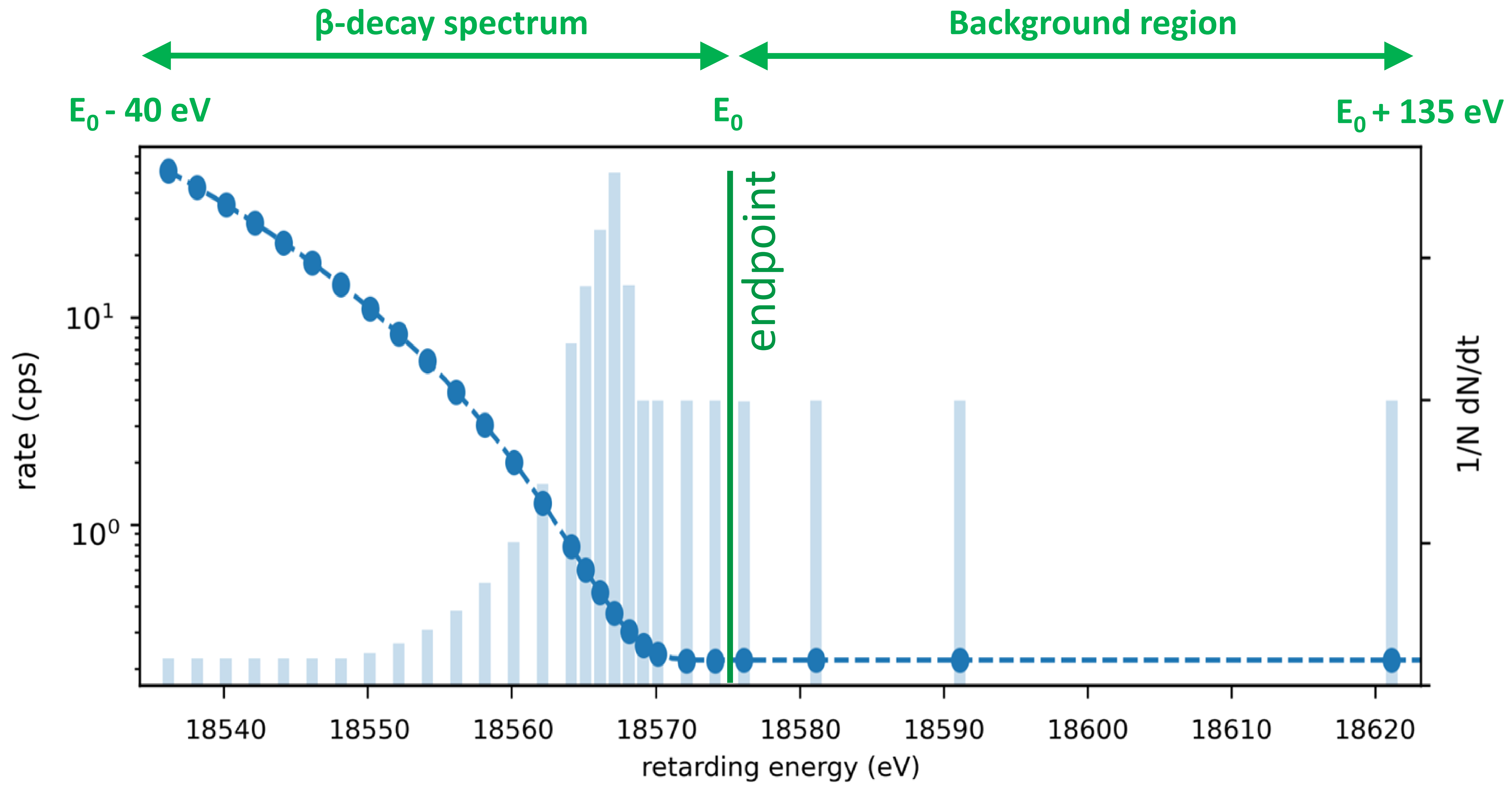



## Integral spectrum measurement

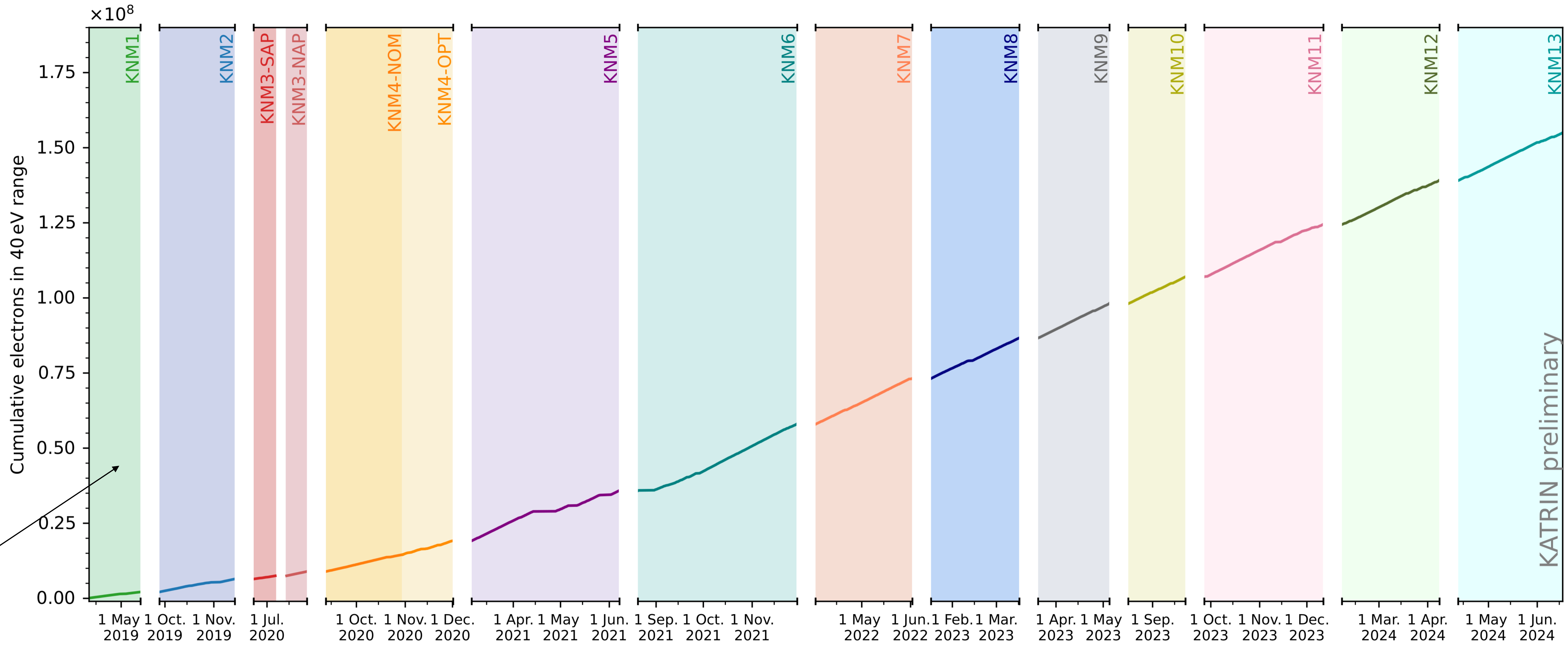
- ~30 scan steps with varying duration
- ~2 h scan duration
- scan interval: $E_0 - 40$ eV , $E_0 + 135$ eV

**Energy resolution is determined by the retarding potential in the MS:**

**$\Delta E$ = 2.8 eV @18.6 keV**



# Data taking overview




**1$^{st}$ campaign**

~2.10$^6$ e$^-$ in the ROI

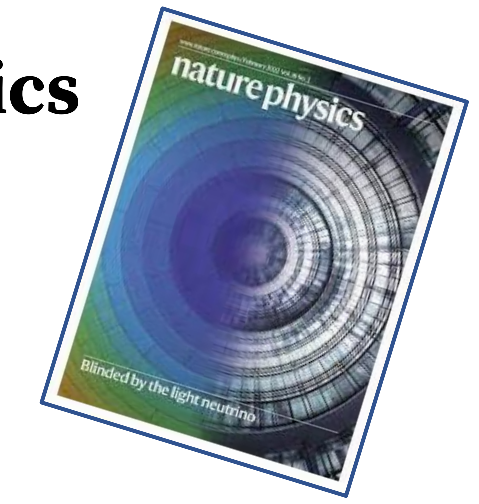

**PRL 2019**

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

**1$^{st}$ and 2$^{nd}$ campaigns**

~6.10$^6$ e$^-$ in the ROI

**Nature physics 2022**




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

**New release at Neutrino 2024**

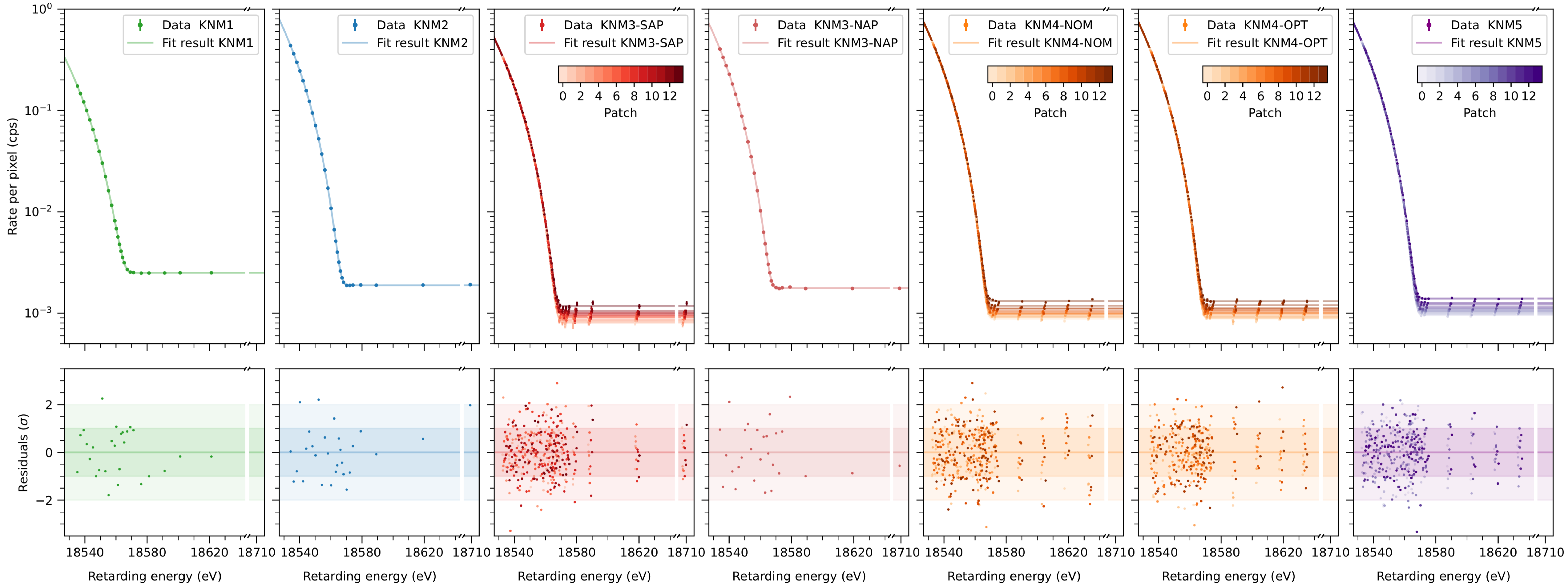
**1$^{st}$ to 5$^{th}$ campaigns**

259 measurement days

~36.10$^6$ e$^-$ in the ROI

# Latest $\nu$ – mass results

[Preprint](#)




- $\sim 36.10^6$ e⁻ in the ROI
- Simultaneous maximum likelihood fit with common $m_\nu^2$ parameter
- Excellent goodness-of-fit: p-value = 0.84

- **Best-fit value:** $\mathbf{m_\nu^2 = \left(-0.14^{+0.13}_{-0.15}\right)\ eV^2}$

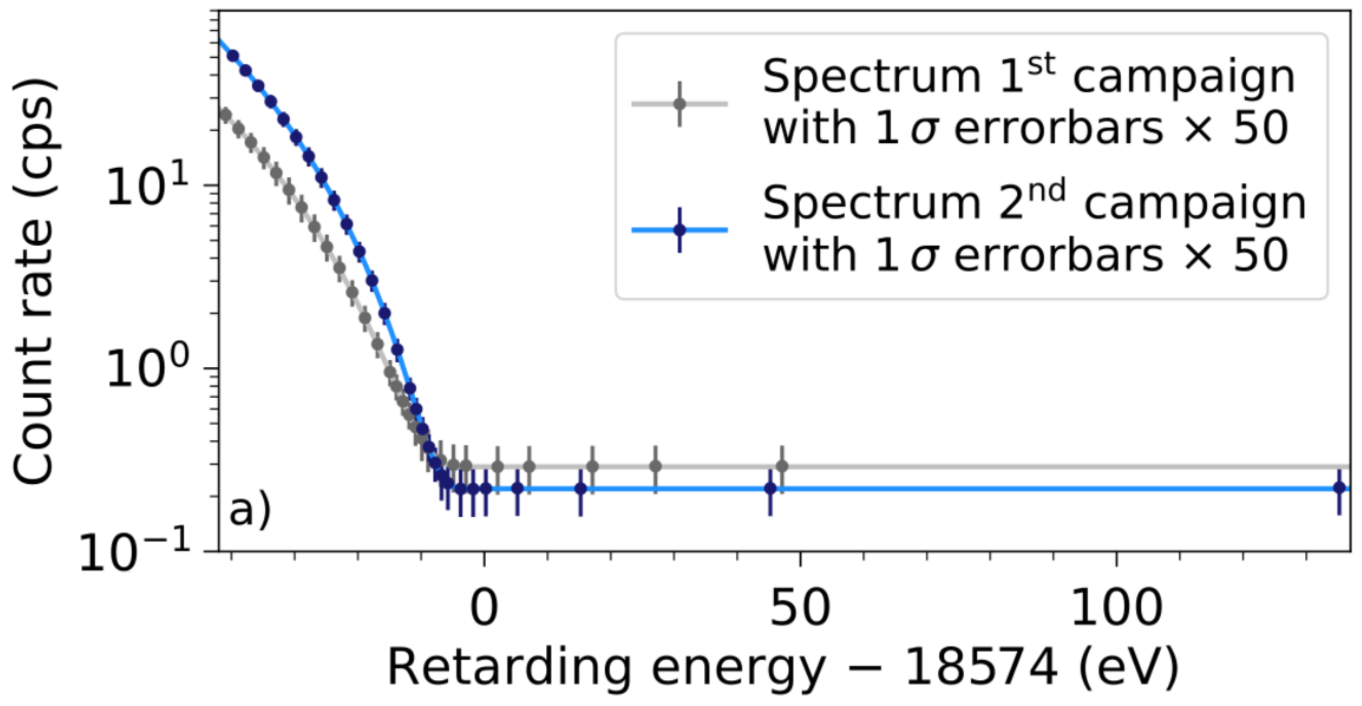
*Negative $m_\nu^2$ estimates allowed by the spectrum model to accommodate statistical fluctuations*

- **Limit:** $\mathbf{m_\nu < 0.45\ eV}$ **(90% CL, Lokhov-Tkachov construction)**

Previous limit: $m_\nu < 0.8$ eV (90% CL)

**⇒ Most stringent limit on the neutrino mass**

# Beyond neutrino mass in KATRIN




*β spectrum with high statistics and low systematics*

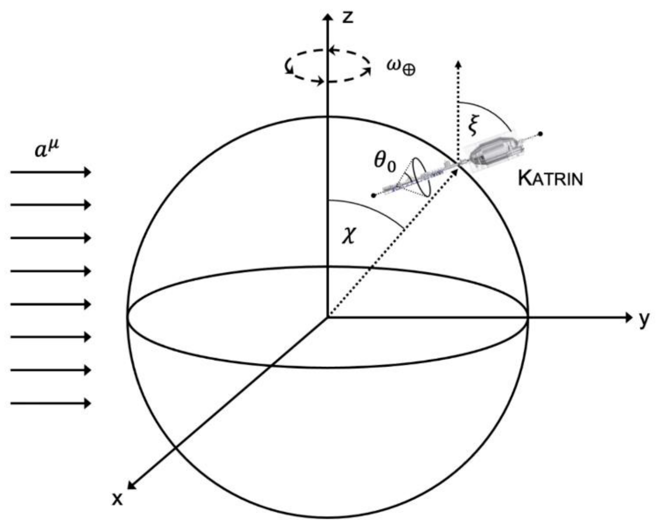
## Search for exotic weak interactions

⇒ *shape distortion*

## Search for Lorentz invariance violation

[arXiv:2112.13803]

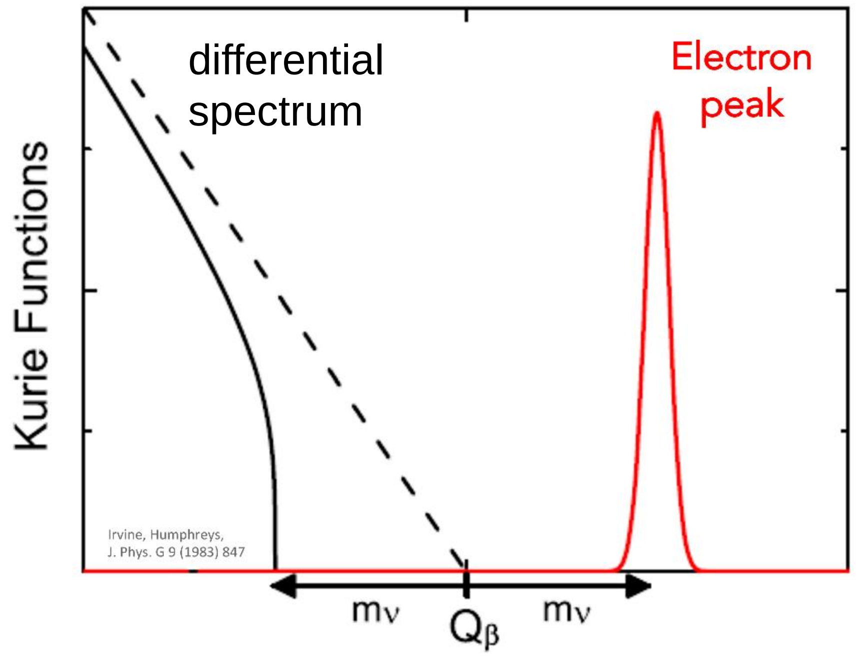
⇒ *sideral modulation*

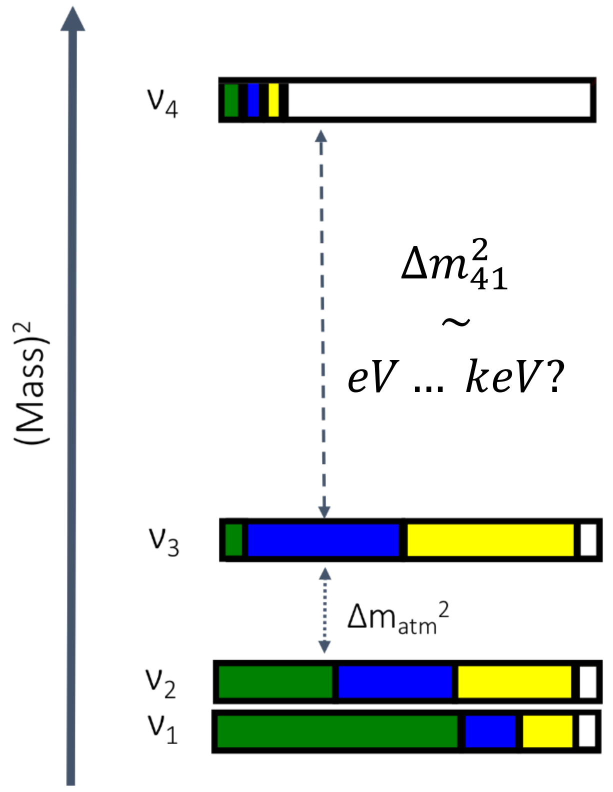



## Constrain local overdensity of cosmic relic neutrinos

[Phys. Rev. Lett. 129, 011806]

⇒ *peak search*



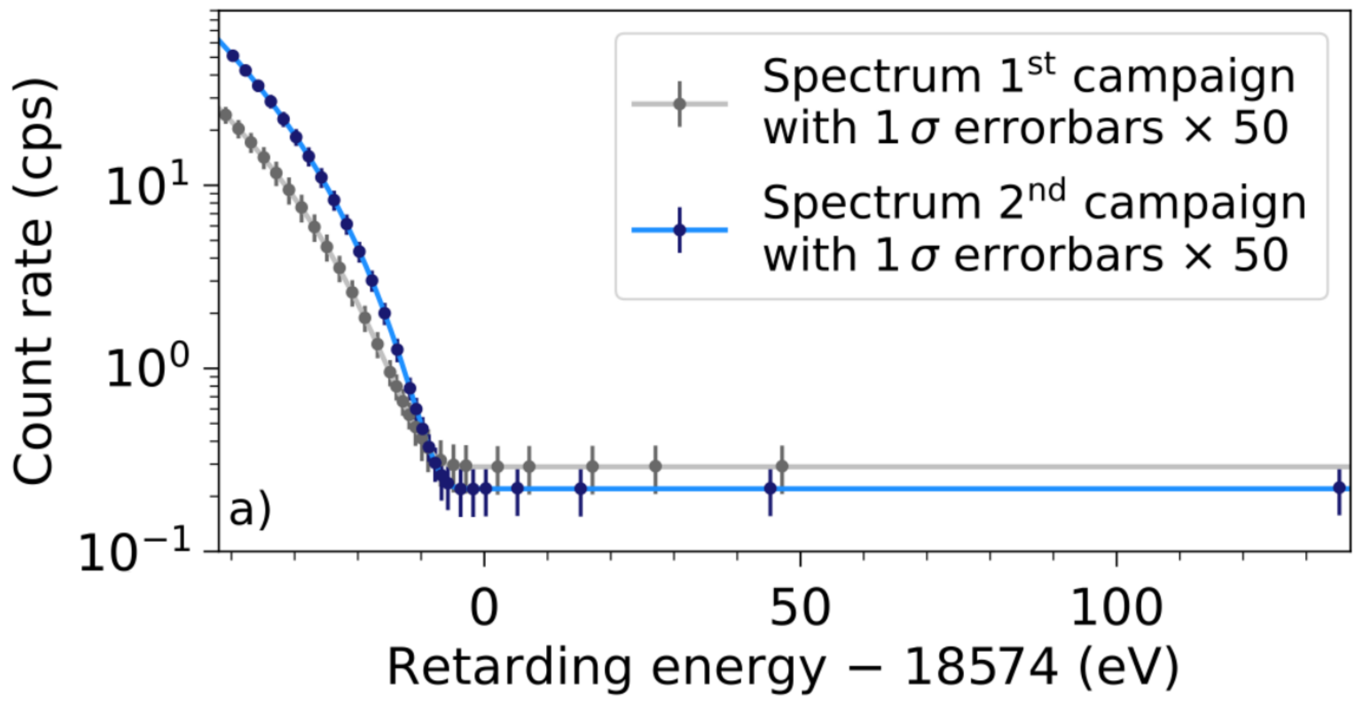

## Sterile neutrino search

[PRD 105, 072004 (2022)]
[arXiv:2207.06337v1 [nucl-ex] (2022)]

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

⇒ *shape distortion*

# Beyond neutrino mass in KATRIN




*β spectrum with high statistics and low systematics*

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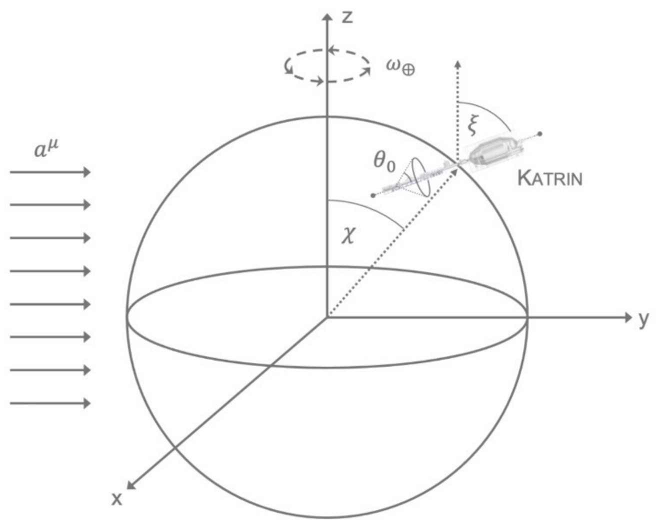


**Constrain local overdensity of cosmic relic neutrinos**

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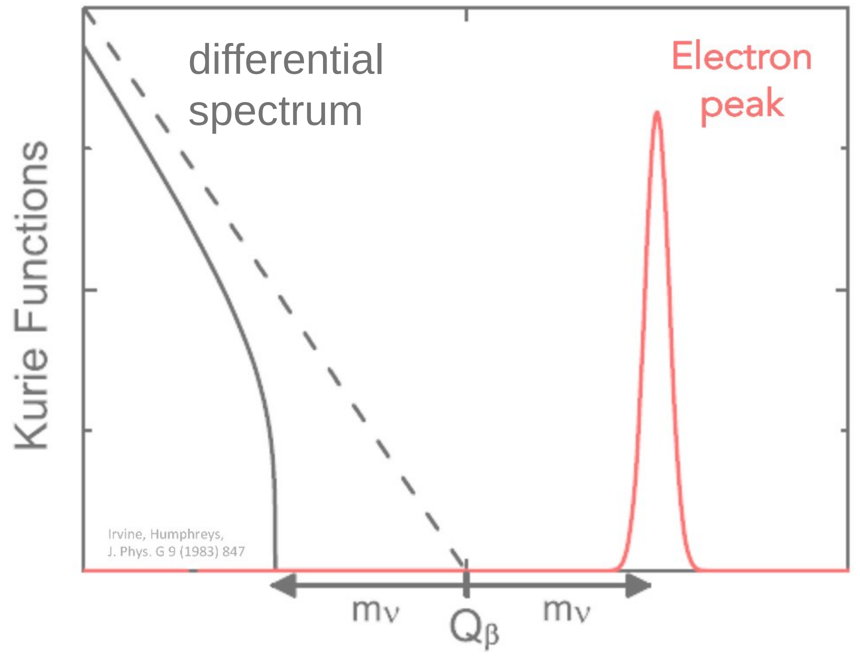
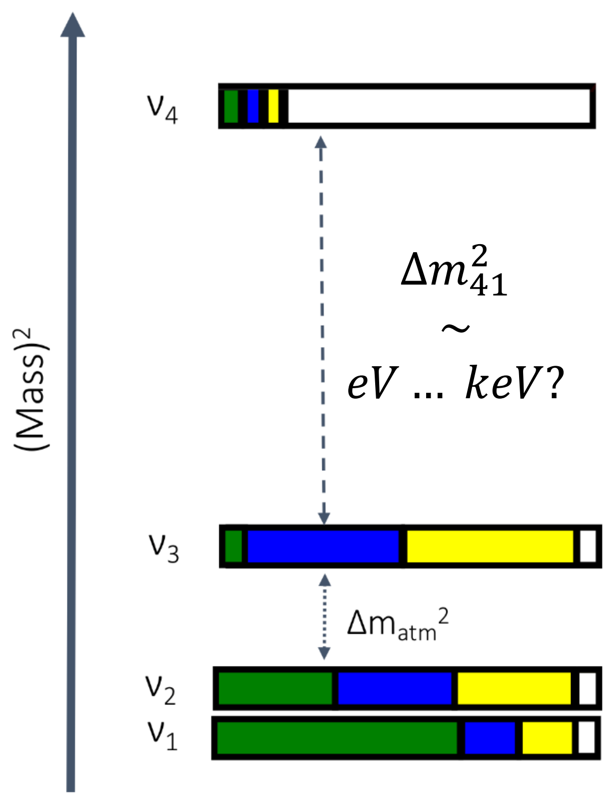



## Sterile neutrino search

[PRD 105, 072004 (2022)]
[arXiv:2207.06337v1 [nucl-ex] (2022)]

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

⇒ *shape distortion*

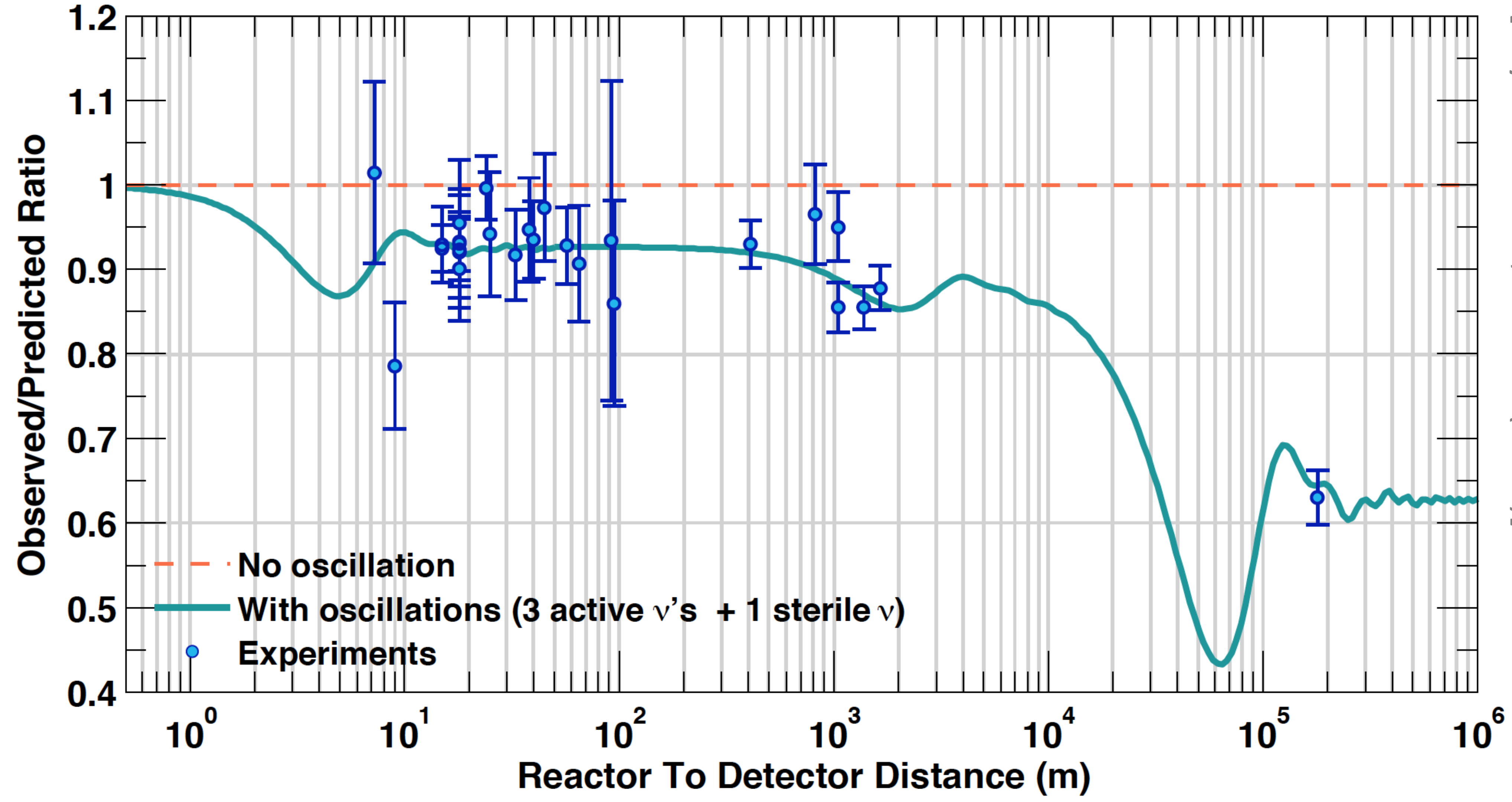
# Sterile neutrino motivation

## eV-scale sterile neutrino search

Several experimental anomalies

- deficit of reactor (RAA, ∼3σ) and Gallium flux (∼4σ) measurement to prediction

### Reactor antineutrino anomaly (RAA)

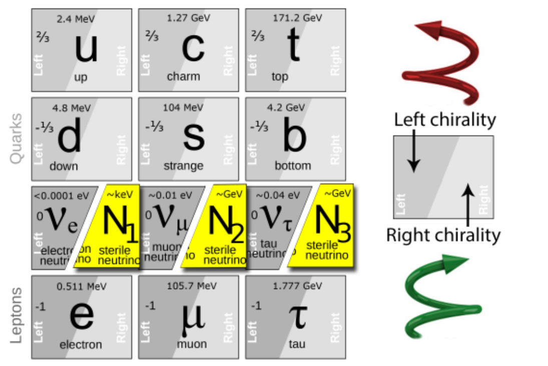



[Phys. Rev. D 83, 073006 (2011)]

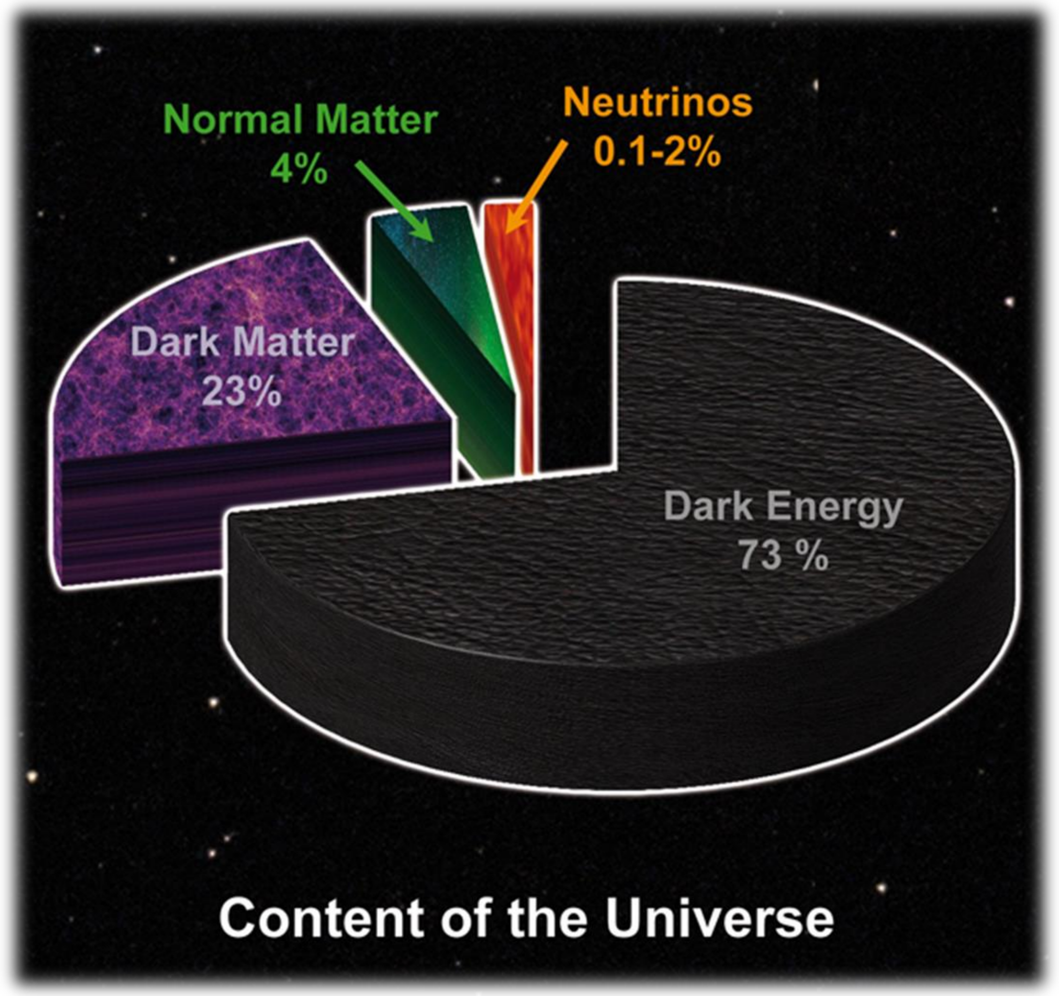
## keV-scale sterile neutrino search

Right-handed neutrinos: natural extension of SM

- straightforward way to introduce $\nu$ mass
- excellent candidate for warm dark matter
- (debated) potential hint from astrological observations for a ∼7 keV sterile $\nu$




White Paper on keV Sterile Neutrino Dark Matter, arXiv:1602.04816

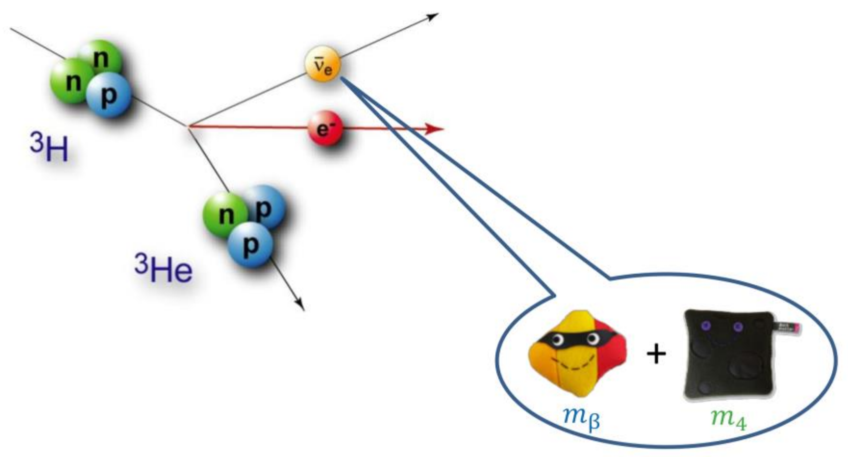



**⇒ Need for model-independent experiments across a wide mass range**

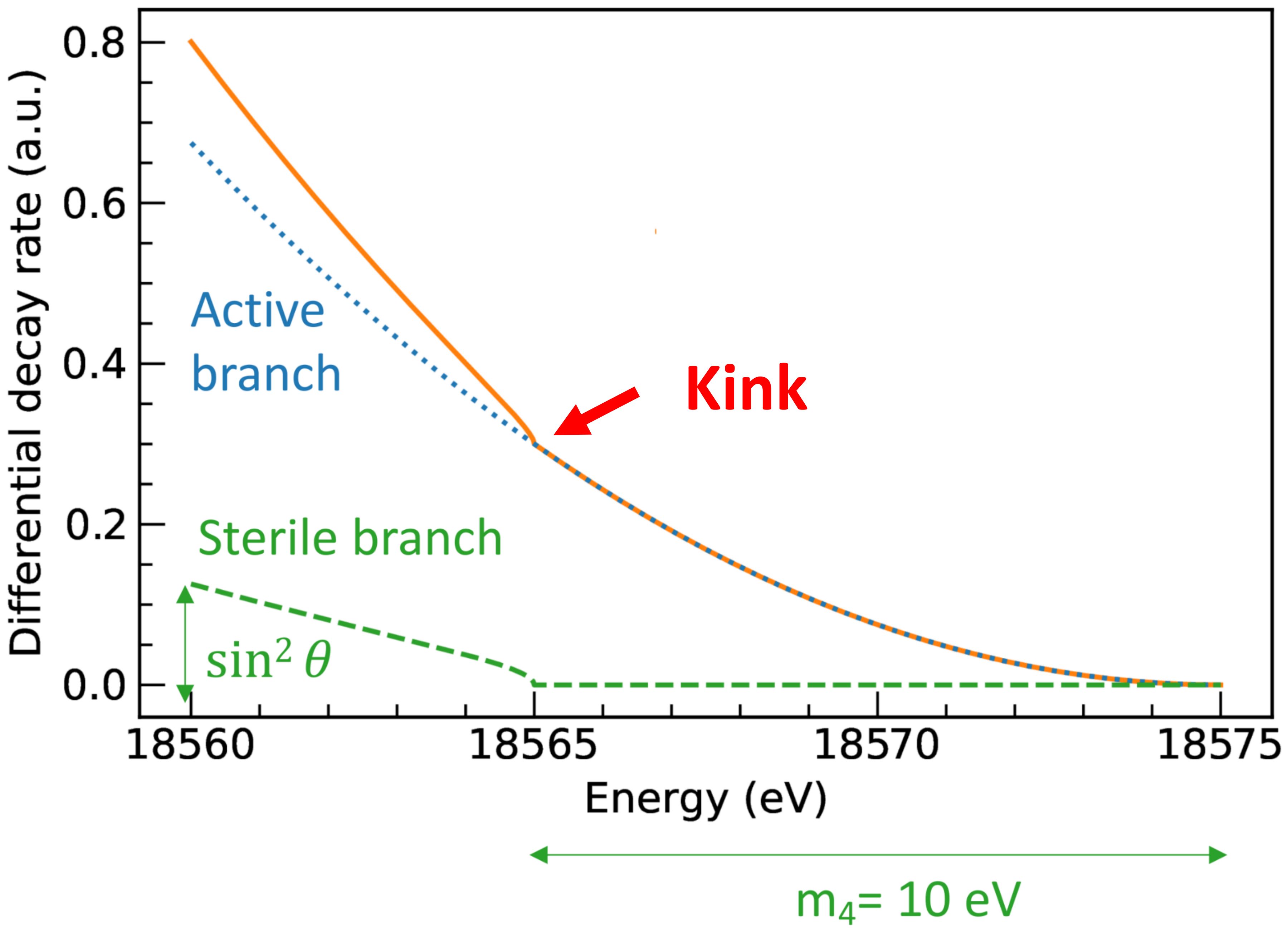
# Imprint of eV sterile $\nu$ on β-decay spectrum

Emitted neutrino in β-decay is admixture of mass eigenstates

$$\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\\|\nu_S\rangle\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\U_{S1} & U_{S2} & U_{S3} & U_{S4}\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\\|\nu_4\rangle\end{pmatrix}$$

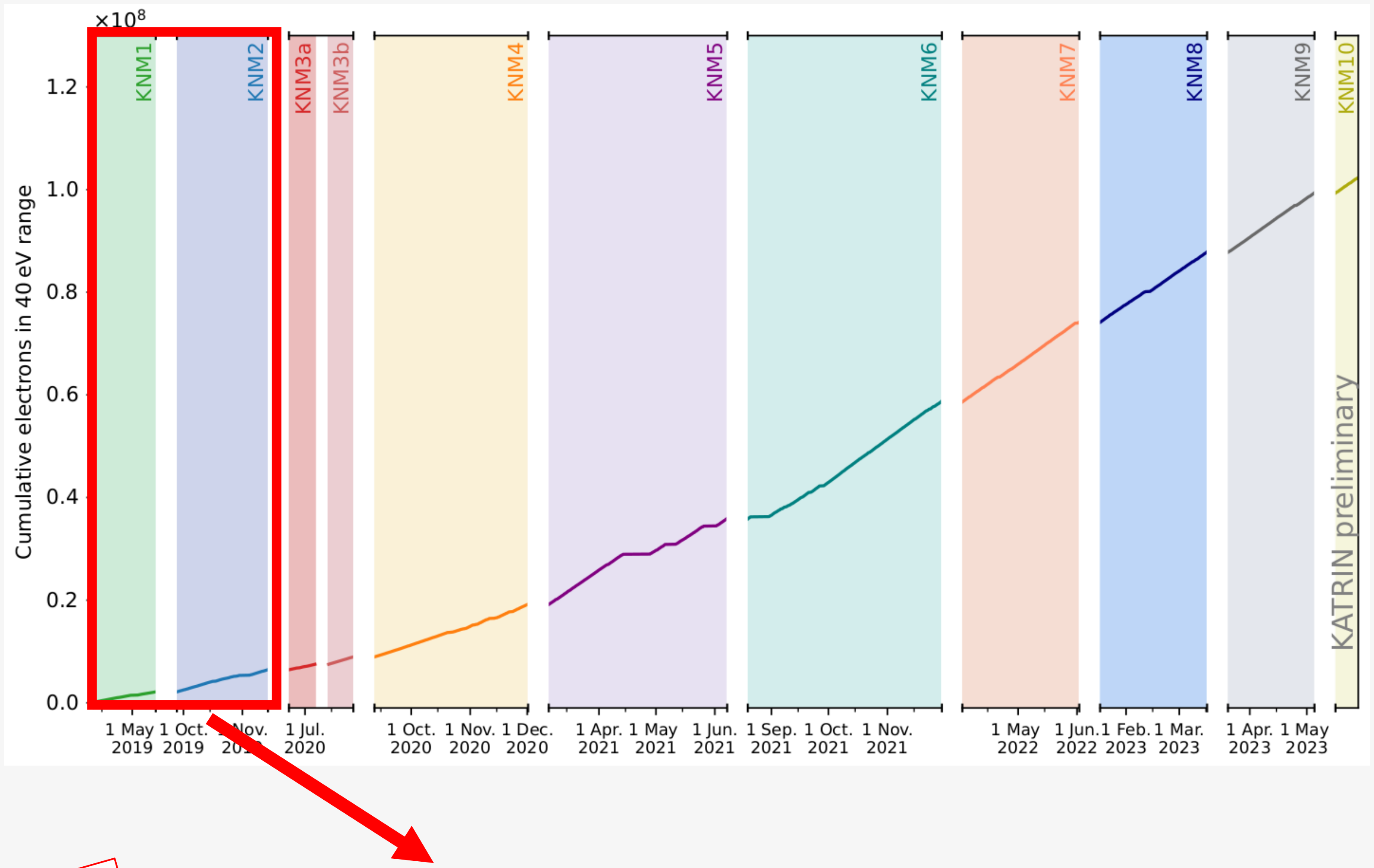


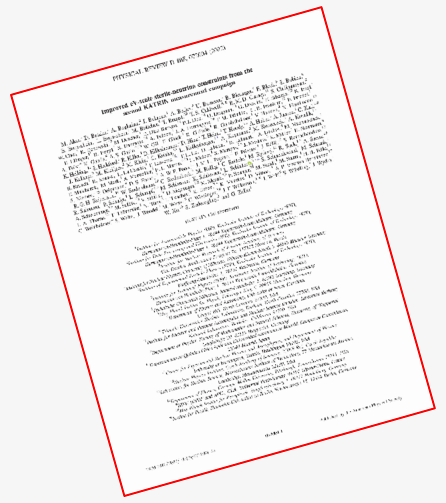

$$\frac{d\Gamma}{dE} = (1-|U_{e4}|^2)\frac{d\Gamma}{dE}(m_\beta^2) + |U_{e4}|^2\frac{d\Gamma}{dE}(m_4^2)$$




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

**⇒ Accessible in $\nu$-mass data sets**



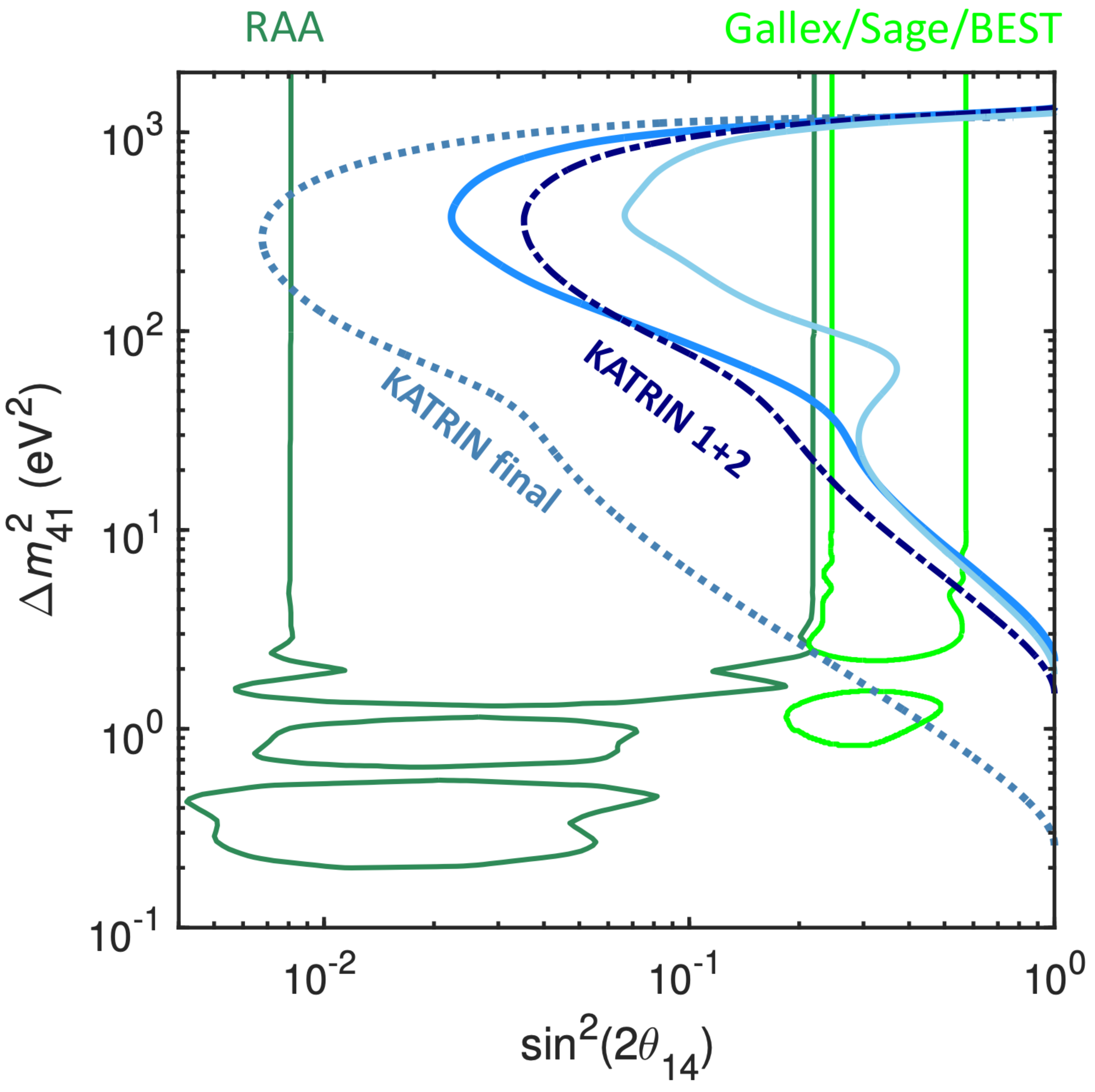



**1st + 2nd campaign**

- ~1265 h of data
- ~6.10⁶ e⁻ in the ROI
- < 5% of the expected final statistic

Phys Rev D 105 072004 (2022)

# Overview of sterile experiment results

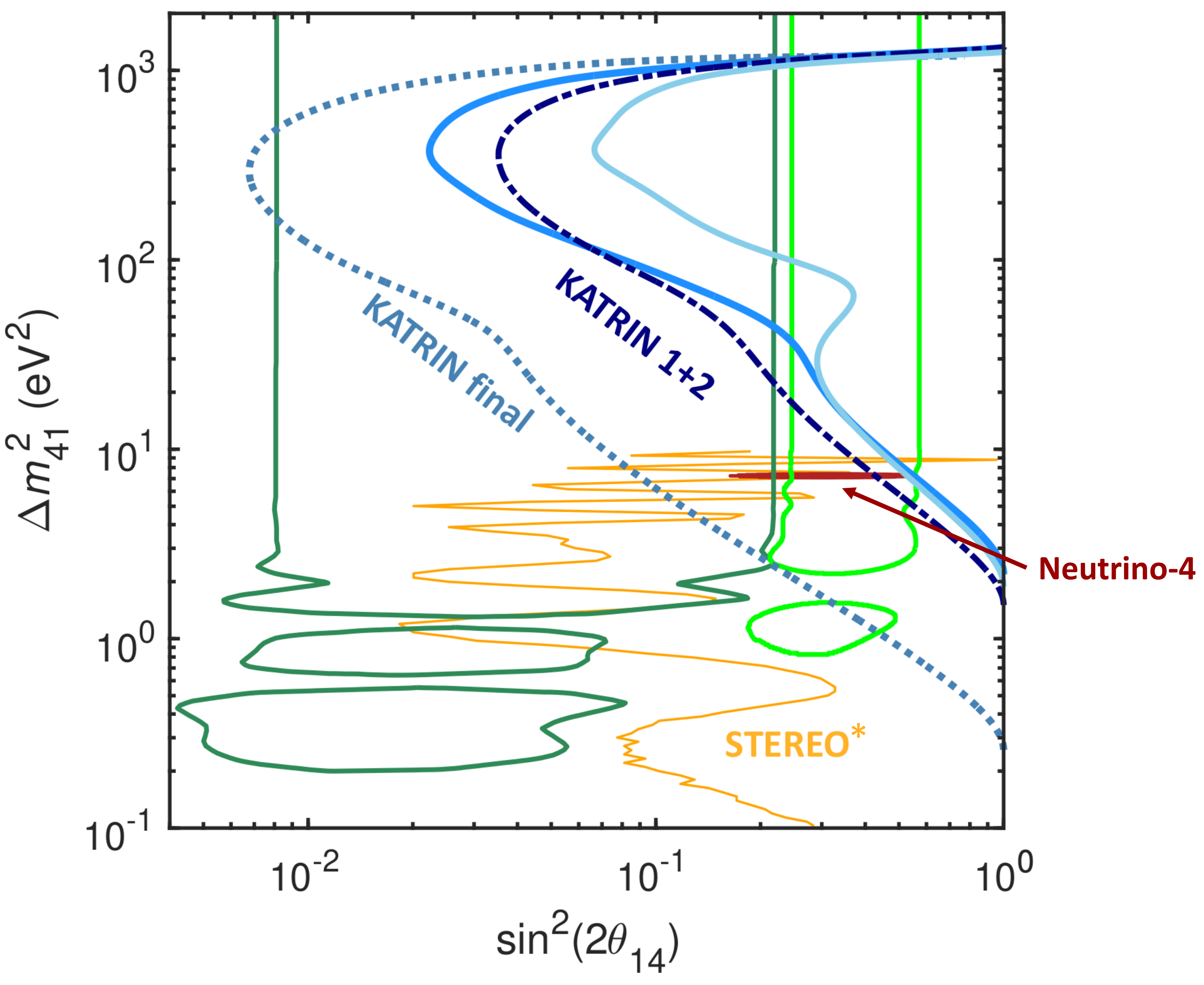



**95% C.L. exclusion contours**

- No eV-sterile neutrino signal observed
- Exclude large $\Delta m_{41}^2$ solutions from the reactor antineutrino and gallium anomaly

RAA, Phys. Rev. D 83, 073006 (2011), STEREO, Phys. Rev. D 102, 052002 (2020)
Neutrino-4, JETP Lett. 109 (2019) 4, 213-221, Gallex, Phys. Lett. B 342, 440 (1995); 420, 114 (1998)
Sage, Phys. Rev. Lett. 77, 4708 (1996); Phys. Rev. C 59, 2246 (1999), BEST, Phys. Rev. Lett. 128, 232501 (2022)

# Overview of sterile experiment results




**95% C.L. exclusion contours**

- No eV-sterile neutrino signal observed
- Exclude large $\Delta m^2_{41}$ solutions from the reactor antineutrino and gallium anomaly
- Improve the exclusion bounds set by short-baseline oscillation experiments for $\Delta m^2_{41} \gtrsim 10\ \mathrm{eV}^2$
- Uncertainty budget dominated by the statistic: KATRIN will probe the positive result claimed by Neutrino-4

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

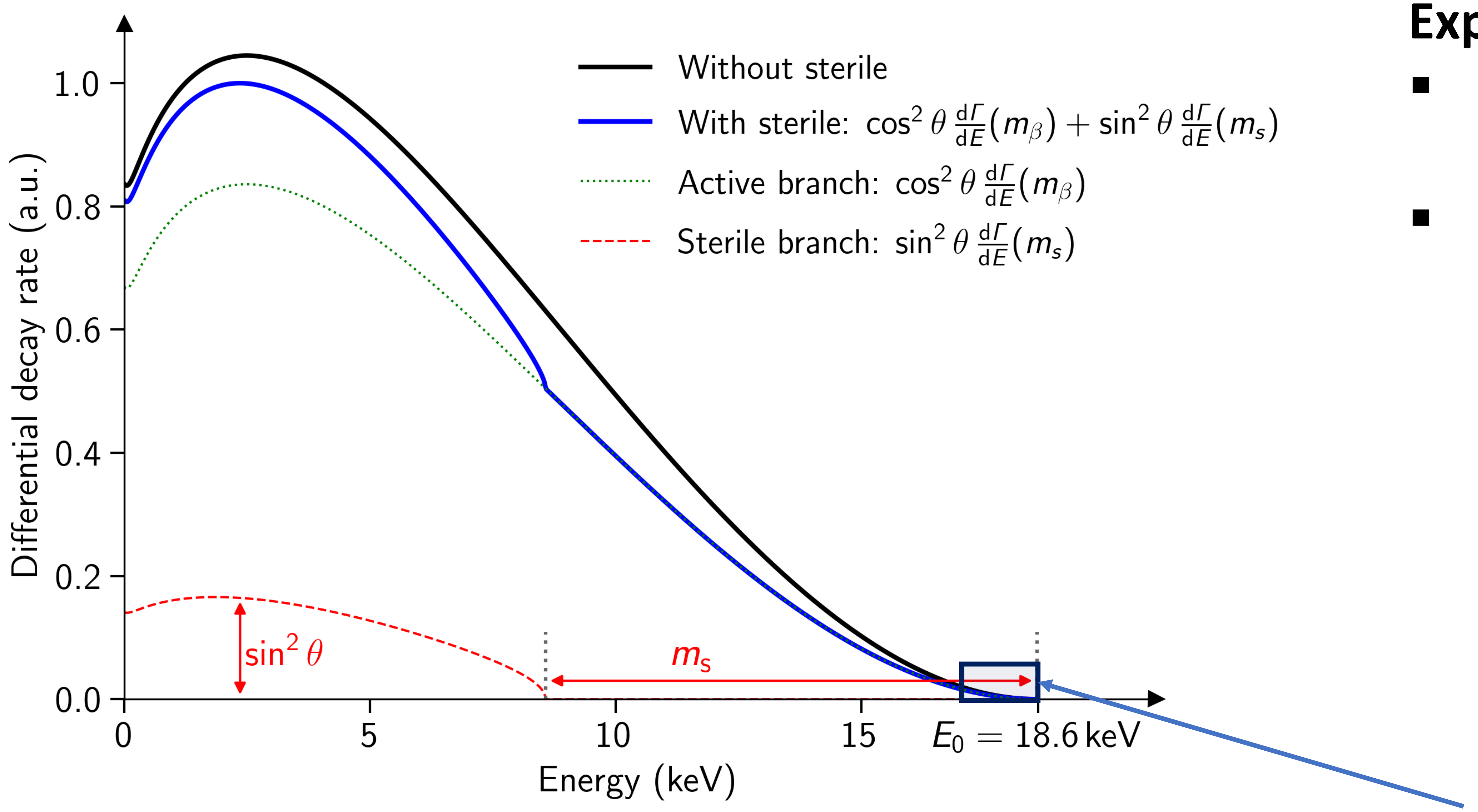
*Updated analysis with the first 5th campaigns in progress*

**(*) Most recent limit from STEREO not included in this plot**

RAA, Phys. Rev. D 83, 073006 (2011), STEREO, Phys. Rev. D 102, 052002 (2020)
Neutrino-4, JETP Lett. 109 (2019) 4, 213-221, Gallex, Phys. Lett. B 342, 440 (1995); 420, 114 (1998)
Sage, Phys. Rev. Lett. 77, 4708 (1996); Phys. Rev. C 59, 2246 (1999), BEST, Phys. Rev. Lett. 128, 232501 (2022)

# keV-scale sterile neutrinos
# with the first KATRIN data

# keV search with the first KATRIN data



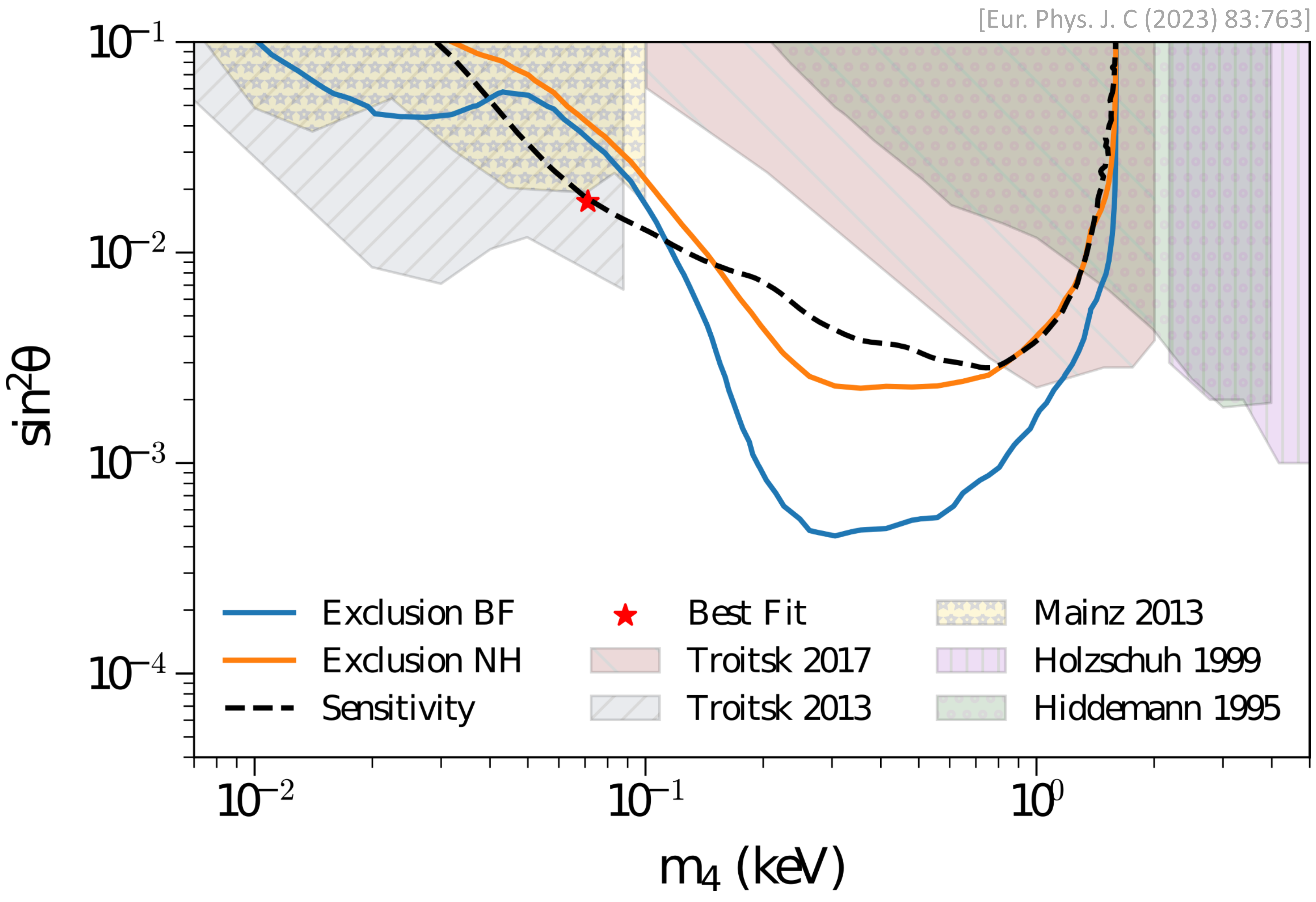

**Experimental challenge:**

- Energy windows of $\nu$-mass data set too small for keV sterile neutrino search
- detector system not designed to handle very high data rates that would occurs with large energy window

**12 days commissioning campaign in 2018**

- Reduced isotopic abundance of 0.5%
- Integral measurement: 0.01 - 1.6 keV mass

# 1st KATRIN results for keV sterile




**95% C.L. exclusion contours**

- No significant keV-sterile neutrino signal observed
- Exclusion limits competitive with previous laboratory-based searches
- Improved laboratory-based bounds for $0.1\ \text{keV} < m_4 < 1.0\ \text{keV}$
- Dominant syst.: source activity fluctuation

Successful demonstration of feasibility using current KATRIN detector ✓

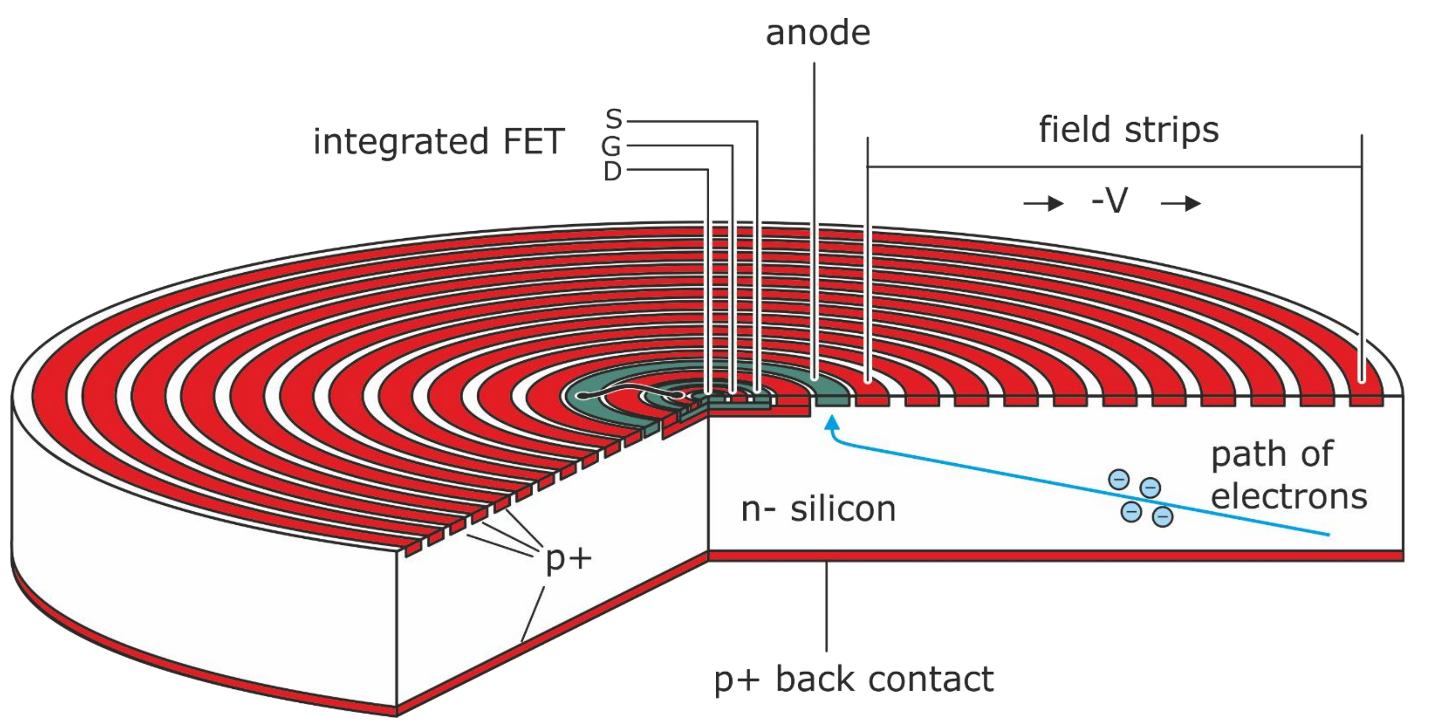
⇒ **New detector required for high rate β-spectroscopy**

# keV sterile neutrino search
# with the TRISTAN detector

# TRISTAN project

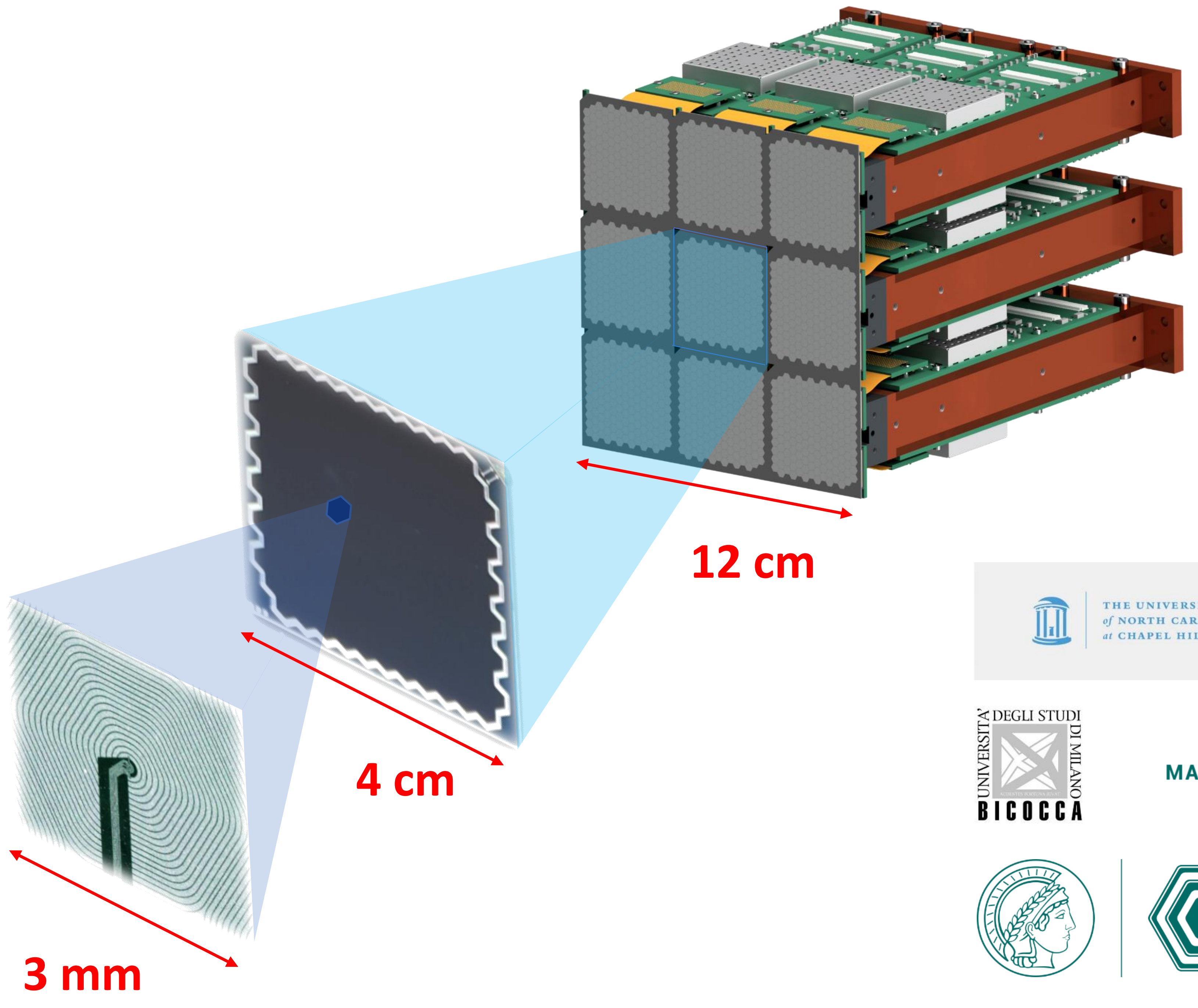
**Tritium Beta Decay to Search for Sterile Neutrinos**

- Future upgrade of KATRIN detector using silicon drift detector (SDD)
- Novel detector system: **high rate and high resolution $\beta$-spectroscopy**
  - ✓ Large area, small capacitance: small anode
  - ✓ Good energy resolution: 300 eV at 20 keV
  - ✓ Handling of high rates: **>10$^5$ cps/pixel**



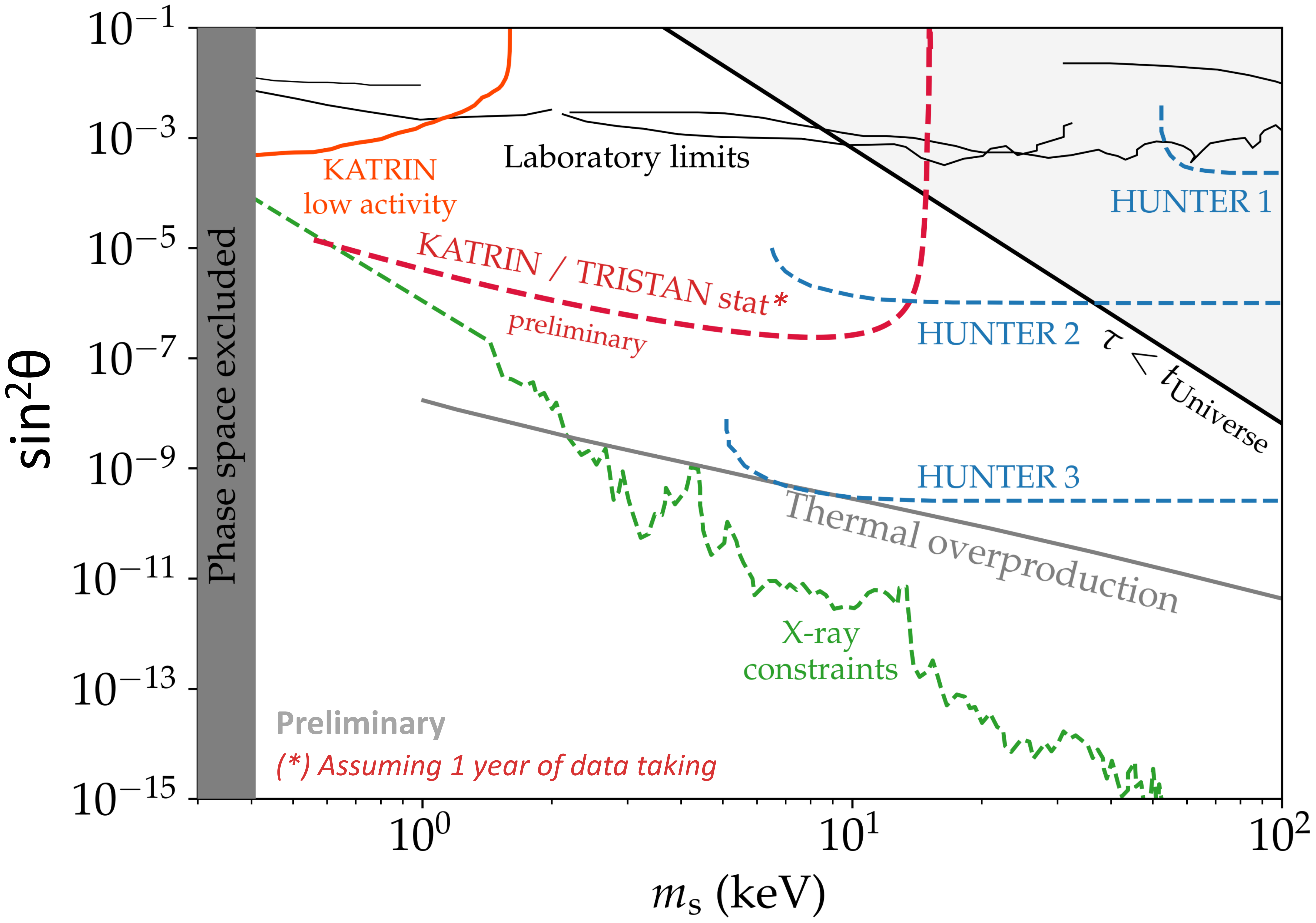

**Measurement of tritium differential energy spectrum ⇒ Goal: ppm level on $\sin^2\theta$**

S. Mertens et al., JCAP02(2015)020
S. Mertens et al., J. Phys. G46 (2019)
S. Mertens et al., J. Phys. G48 (2020)




- 9 modules
- ~1500 pixels

# TRISTAN sensitivity limit




- 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


data from:

- F. Benso et al., Phys. Rev. D 100, 115035 (2019)
- F. Bezrukov et al., JCAP 06, 051 (2017)
- Abdurashitov et al., JETP Letters 105, 12 (2017)
- Martoff et al., Quantum Sci. Technol. 6 024008 (2021)
- S. Friedrich et al., Phys. Rev. Lett. 126, 021803 (2021)
- M. Aker et al, Eur. Phys. J. C (2023) 83:763

# Working principle

### Spectrometer

- MAC-E (Magnetic adiabatic collimation + electrostatic filter): high resolution, large acceptance angle

**→ aim for low retarding potential: look deep into spectrum**

### Transport section

- magnetic guidance
- tritium gas/ion removal

**→ reduction by > $10^{14}$**

### Gaseous tritium source

- molecular tritium in closed loop
- **up to $10^{11}$ $T_2$ decays/s**

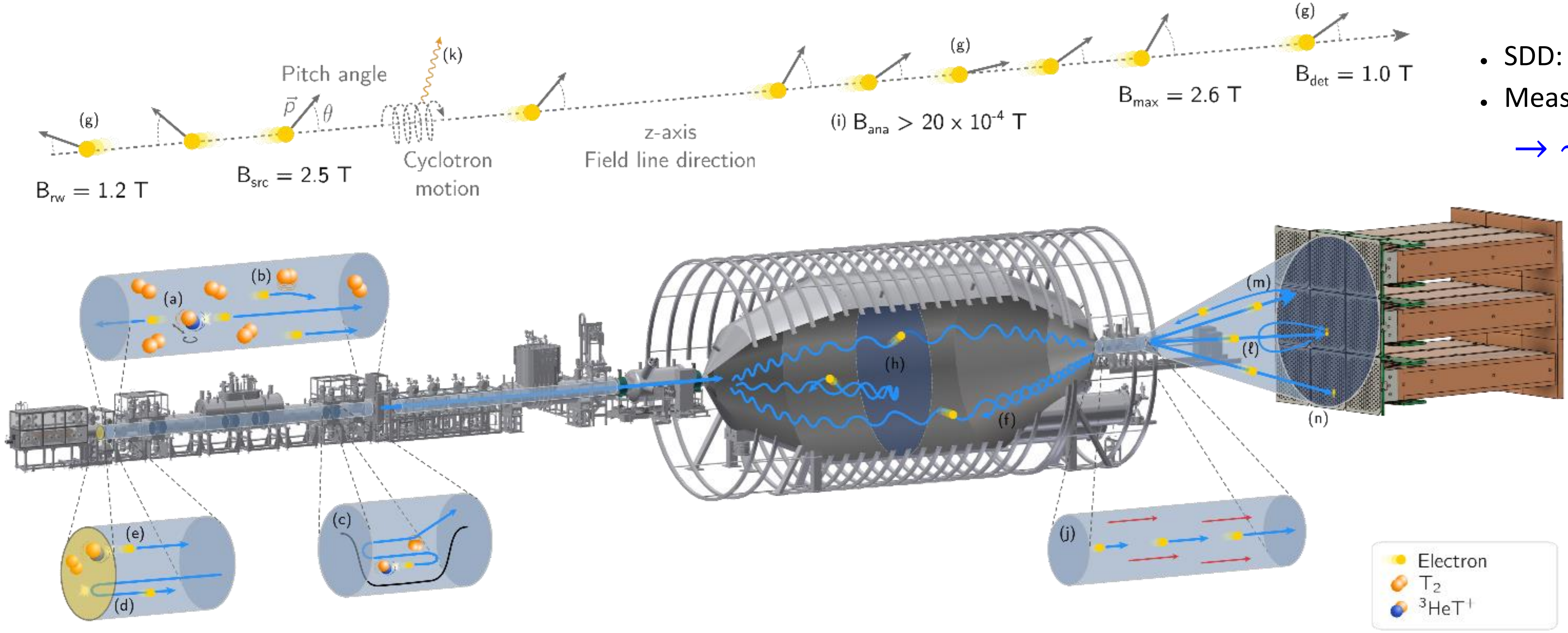
### Detector section

- SDD: ~1500 pixels
- Measure differential spectrum

**→ ~$10^8$ $e^-.s^{-1}$**

### Rear section

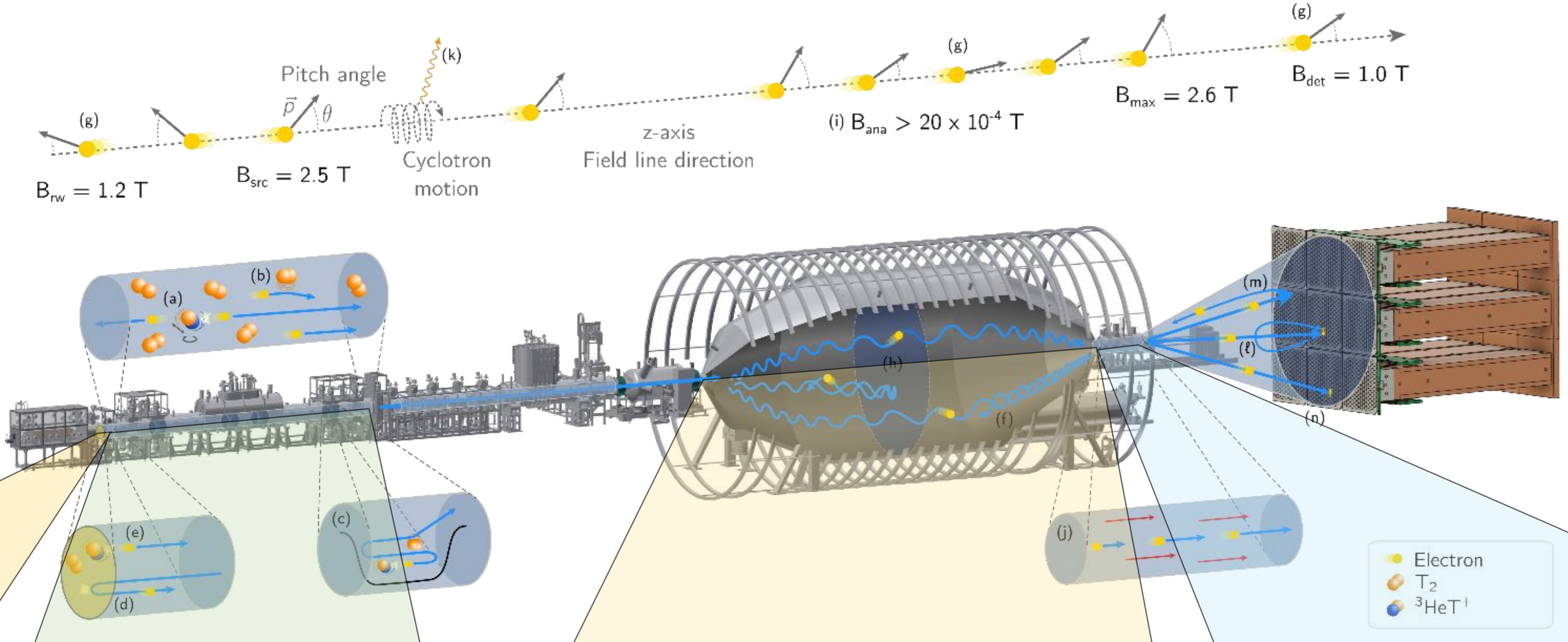
- golden rear wall
- high intensity e-gun




**Experimental & modelling challenges:**

- ➢ Set of relevant systematic effects different than for the ν mass measurement
- ➢ Full energy spectrum: energy/angular dependance of the systematic effects

# Systematic effects




**Rear wall**

- Surface activity
- Backscattering

**Source**

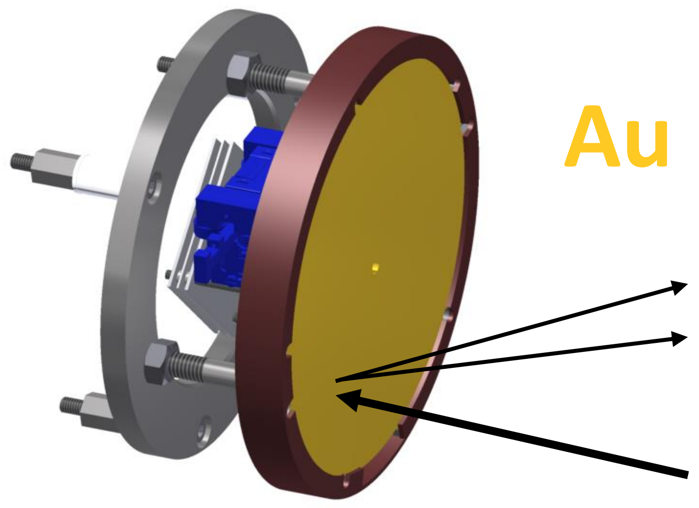
- Scattering
- Magnetic trapping

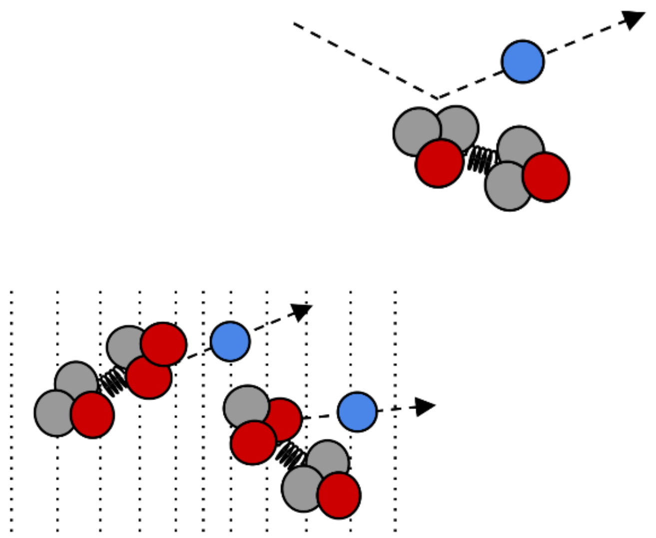
**Spectrometer**

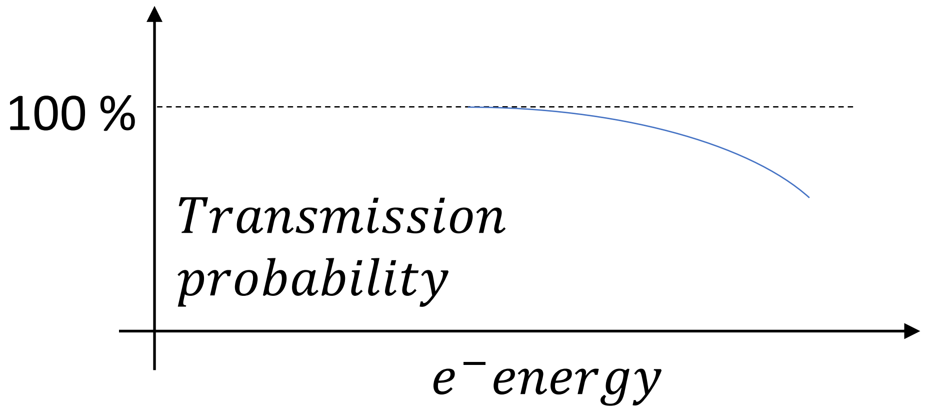
- Magnetic mirror and collimation
- Spectrometer adiabaticity

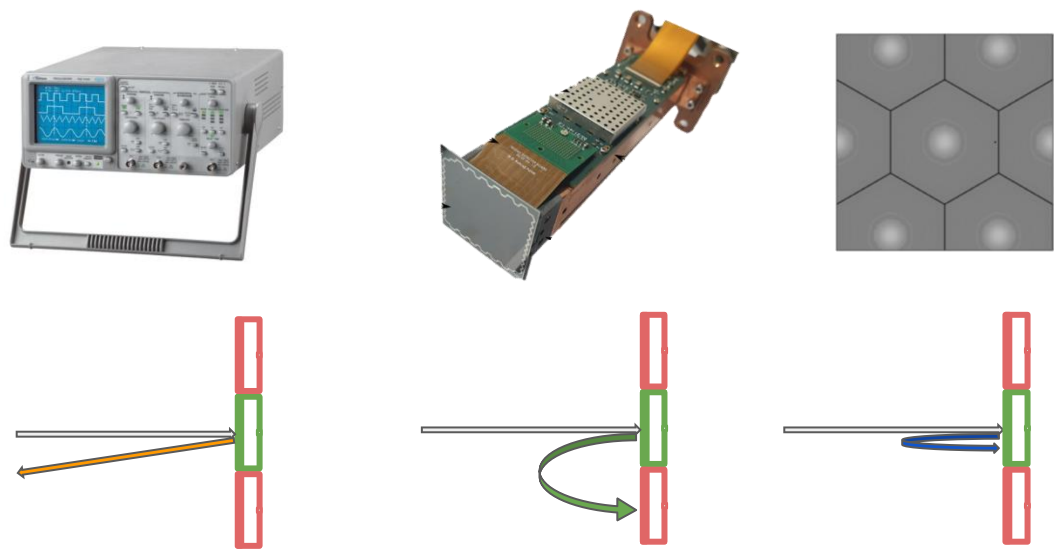
**Detector section**

- Det.: charge collect. (noise, dead layer, pixel sharing) , backscattering escape
- DAQ: pileup, noise, Escale
- Backscattering and backreflexion



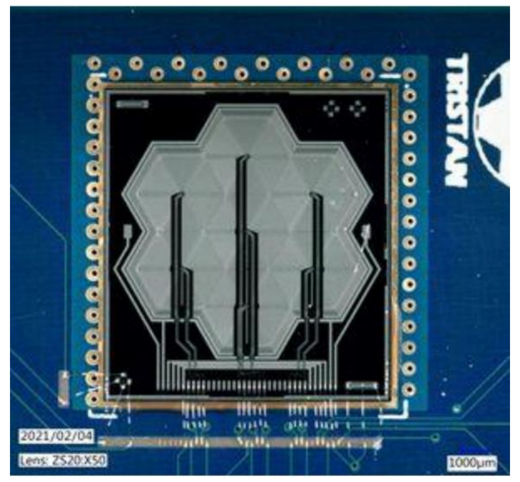



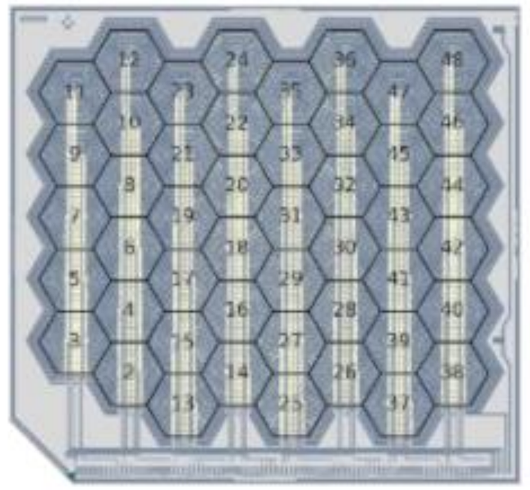
# Staged approached

2017

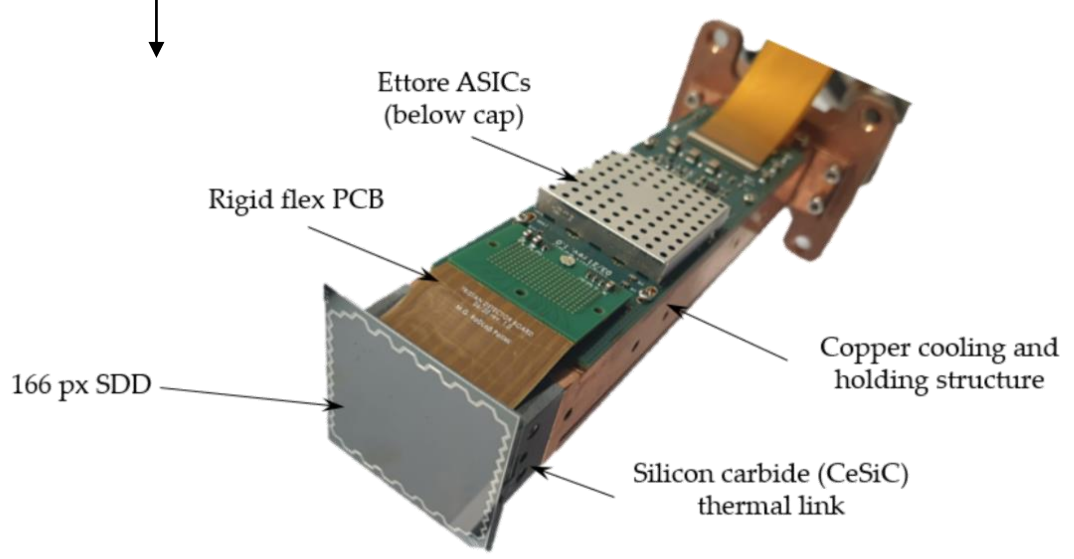
**$1^{st}$ prototype**

7 and 47 pixels prototypes



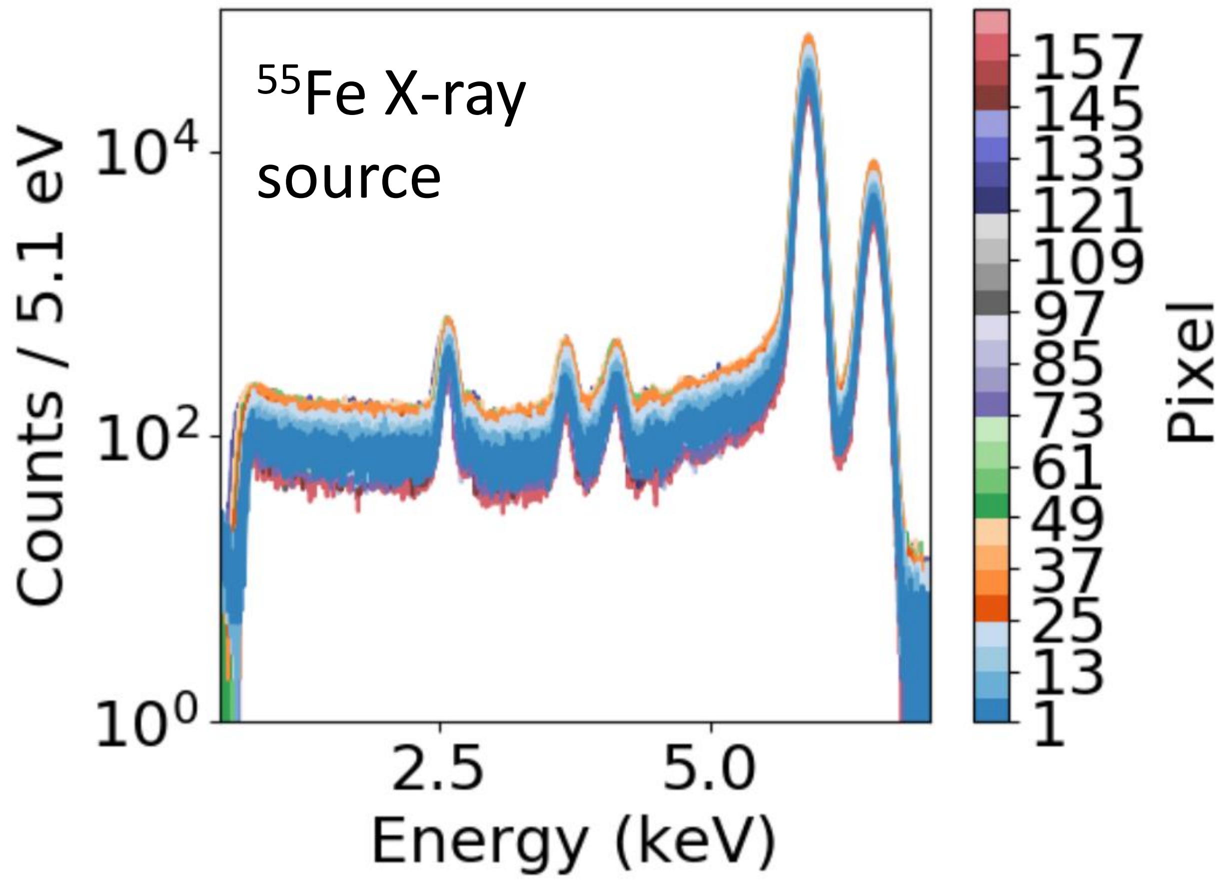


3D focal plane design with 166 pixels



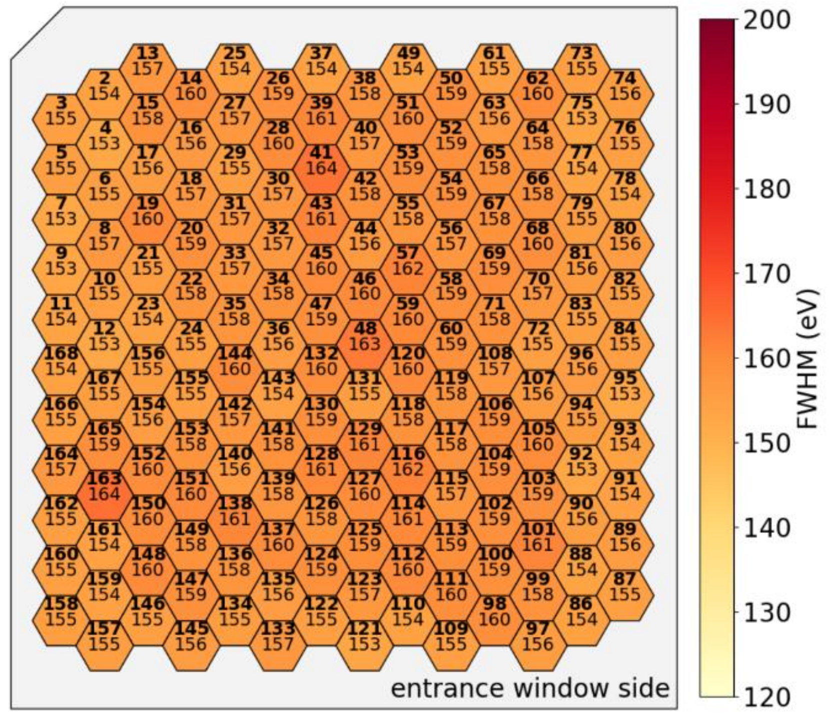

**Prototypes: 7, 47, 166 pixels**

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




*Energy resolution @ 5.9 keV*

[j.nima.2021.166102]




**⇒ Good performance demonstrated to match requirement**

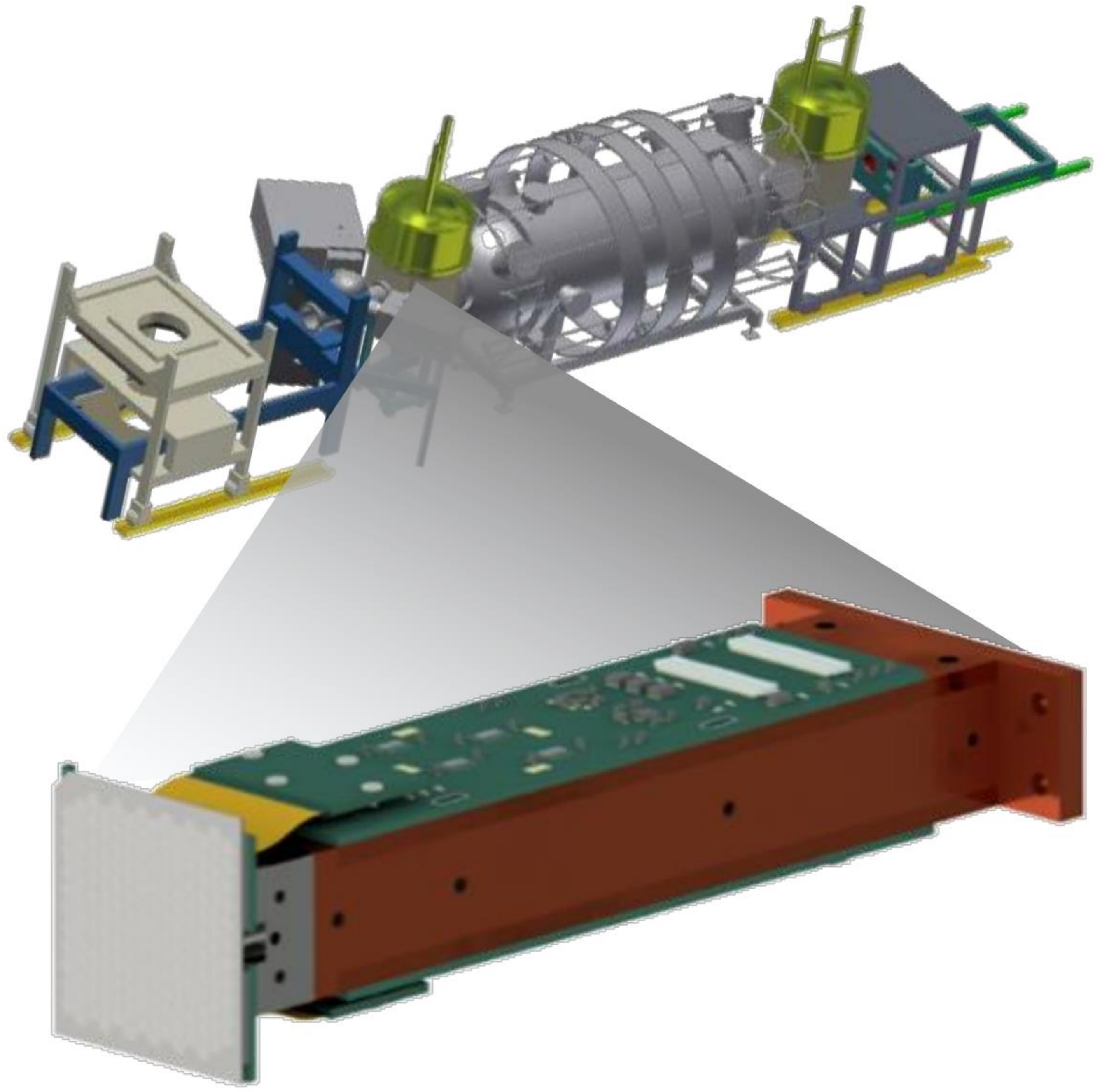
# Staged approached

*2017*

**1st prototype**

*2022*

**1st module in monitor spectrometer**



**Monitor spectrometer (MoS):**

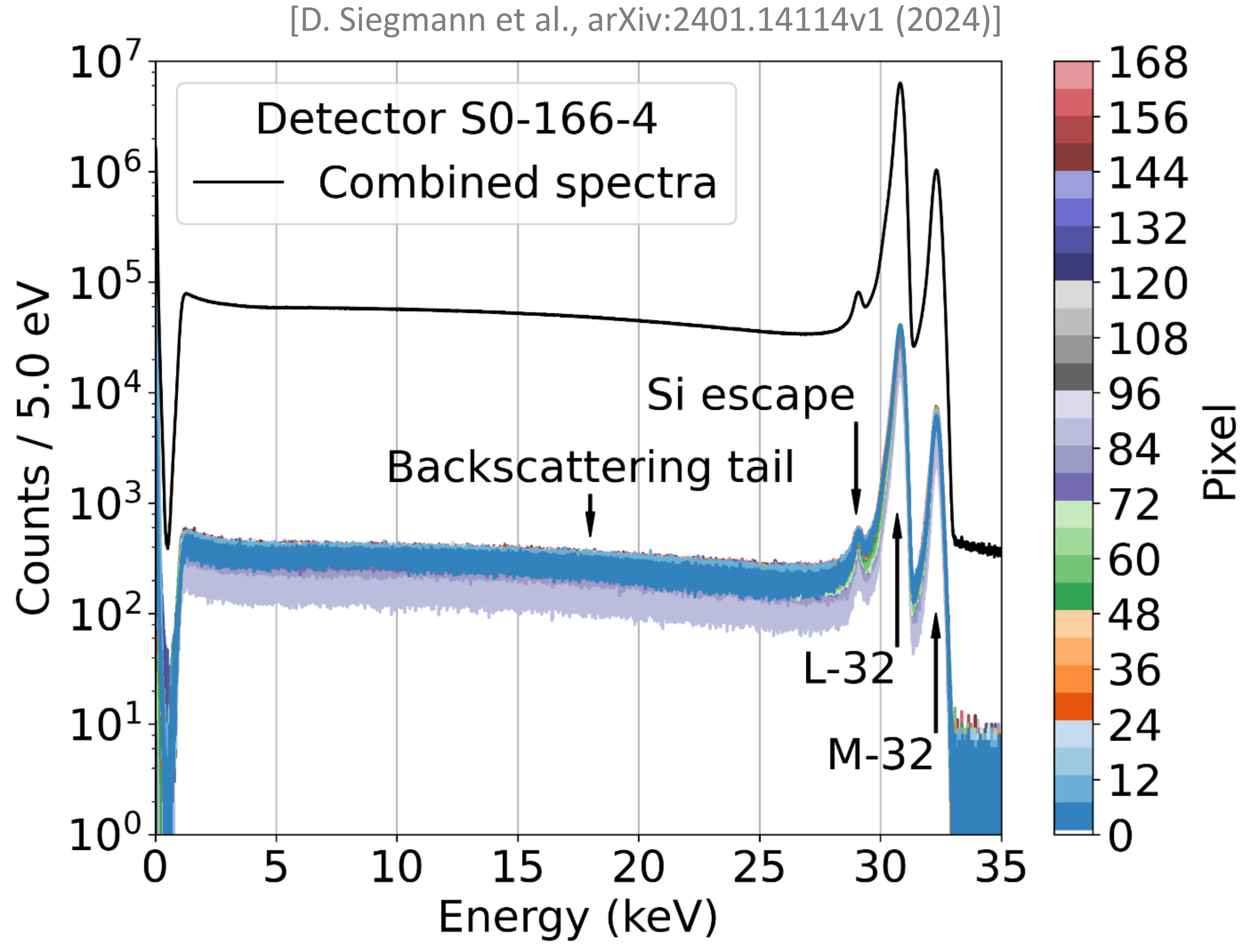
- Refurbished MAC-E filter from Mainz experiment reassembled in KIT
- Similar energy resolution as KATRIN main spectrometer

➢ Integration and first electron in september 2022

➢ Largest SDD array ever operated

**⇒ Successful operation in KATRIN-like environment ✓**

[D. Siegmann et al., arXiv:2401.14114v1 (2024)]




L-32 and M-32 lines of $^{83m}$Kr (MOS)

# Staged approached

2017

1st prototype

2022

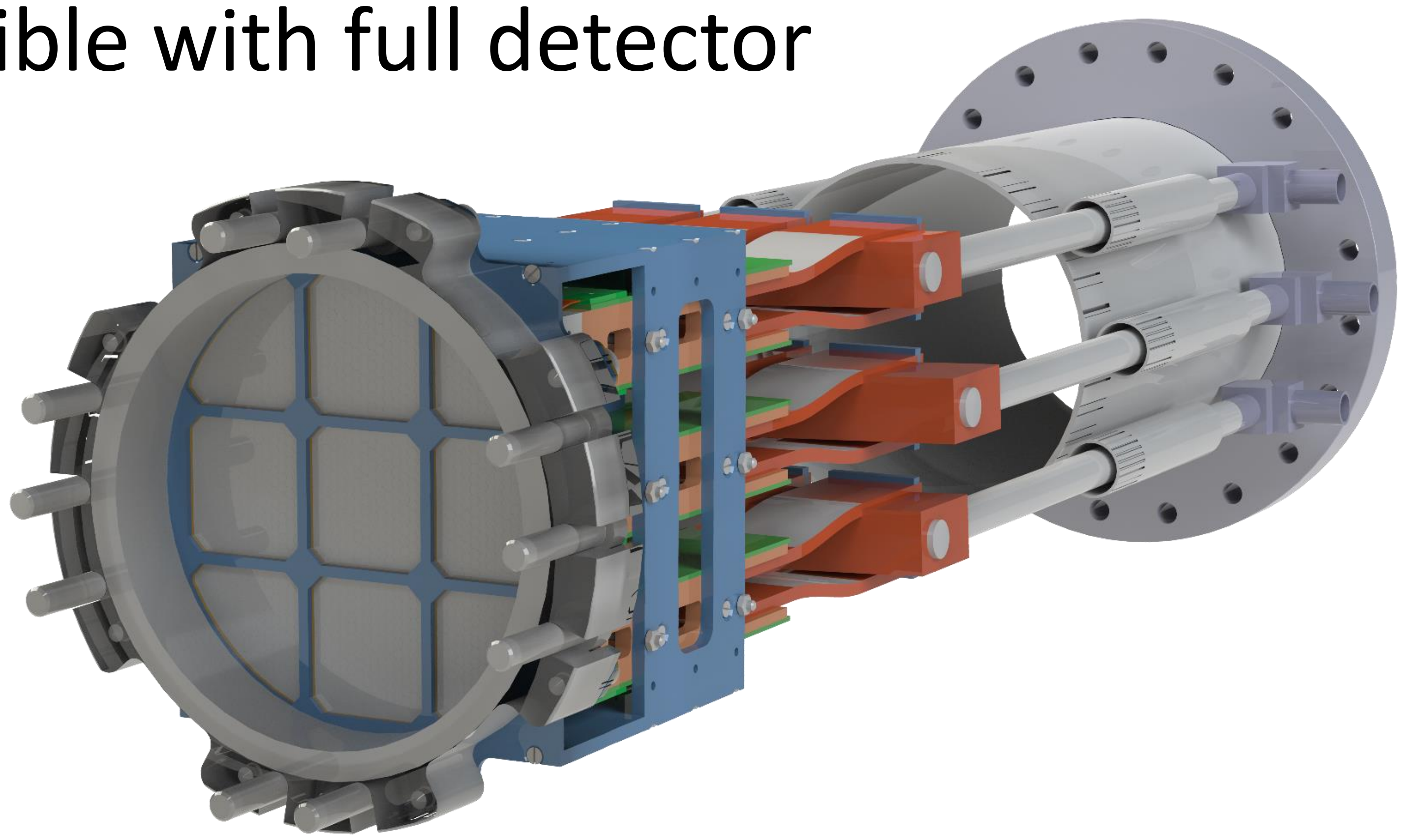
1st module in monitor spectrometer

2024-2025

3-9 modules in detector replica


**Detector replica:**

- Old magnet from KATRIN: up to 4.2 T
- New post-acceleration system under development
- Large vacuum chamber compatible with full detector



Multi-modules calibration

- 2nd semester 2024 → 3 modules deployment
- 1st semester 2025 → 9 modules deployment

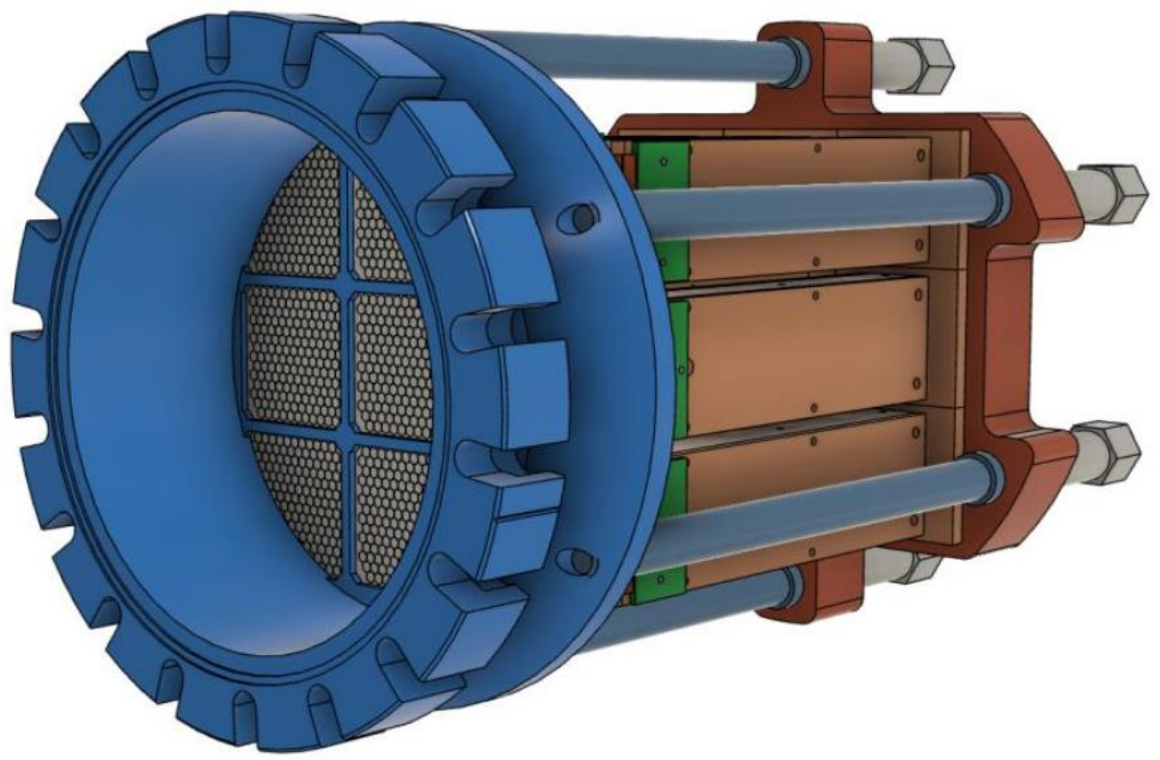
# Staged approached

2017
1st prototype

2022
1st module in monitor spectrometer

2024-2025
3-9 modules in detector replica

2026
detector in KATRIN beamline

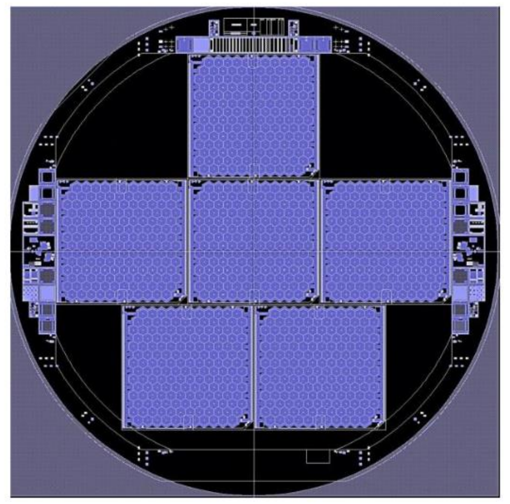


- 9 modules
- 1500 pixels

**Detector commissioning in 2026**

- Almost final module design
- SSD production started

*SSD wafer prototype*



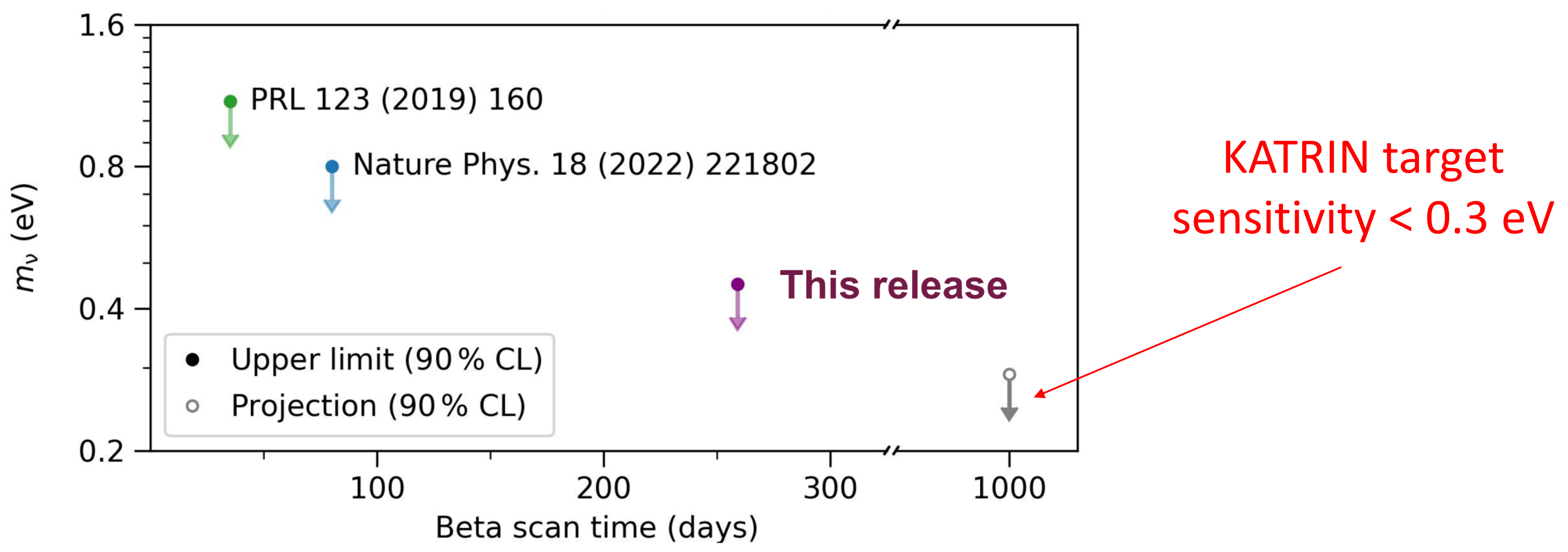
**⇒ First KATRIN keV sterile neutrino search with TRISTAN**

# Conclusion

# Conclusion and outlook

- New KATRIN release; most accurate laboratory based neutrino mass limit to date

$$m_\nu < 0.45 \text{ eV (90\% CL)}$$




- eV-sterile neutrinos search possible with current setup
  - ↳ competitive and complementary results to short baseline experiments

- Search for keV-sterile neutrinos
  - ↳ Proof-of-concept achieved in 2018 using current KATRIN detector. Improved laboratory-based bounds for 0.1 keV < $m_4$ < 1.0 keV
  - ↳ Search for keV-sterile neutrinos with novel TRISTAN detector will start in 2026

    Mixing angle sensitivity goal down to $10^{-6}$ with extended mass range

**Ka**rlsruhe
**Tri**tium
**N**eutrino
**E**xperiment

# *Thank you for your attention!*