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

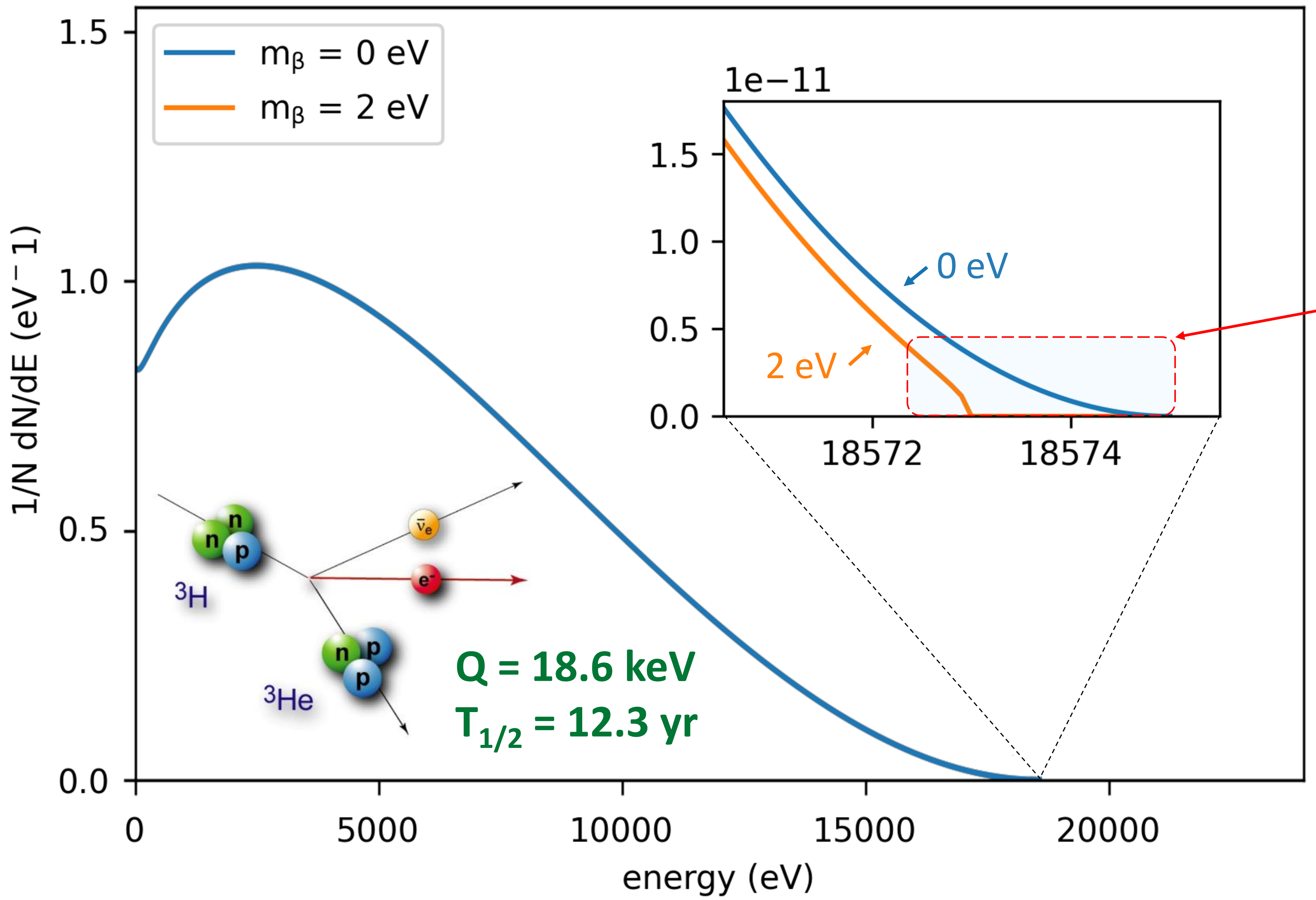
Neutrino mass measurement with tritium ß-decay kinematics

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:

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



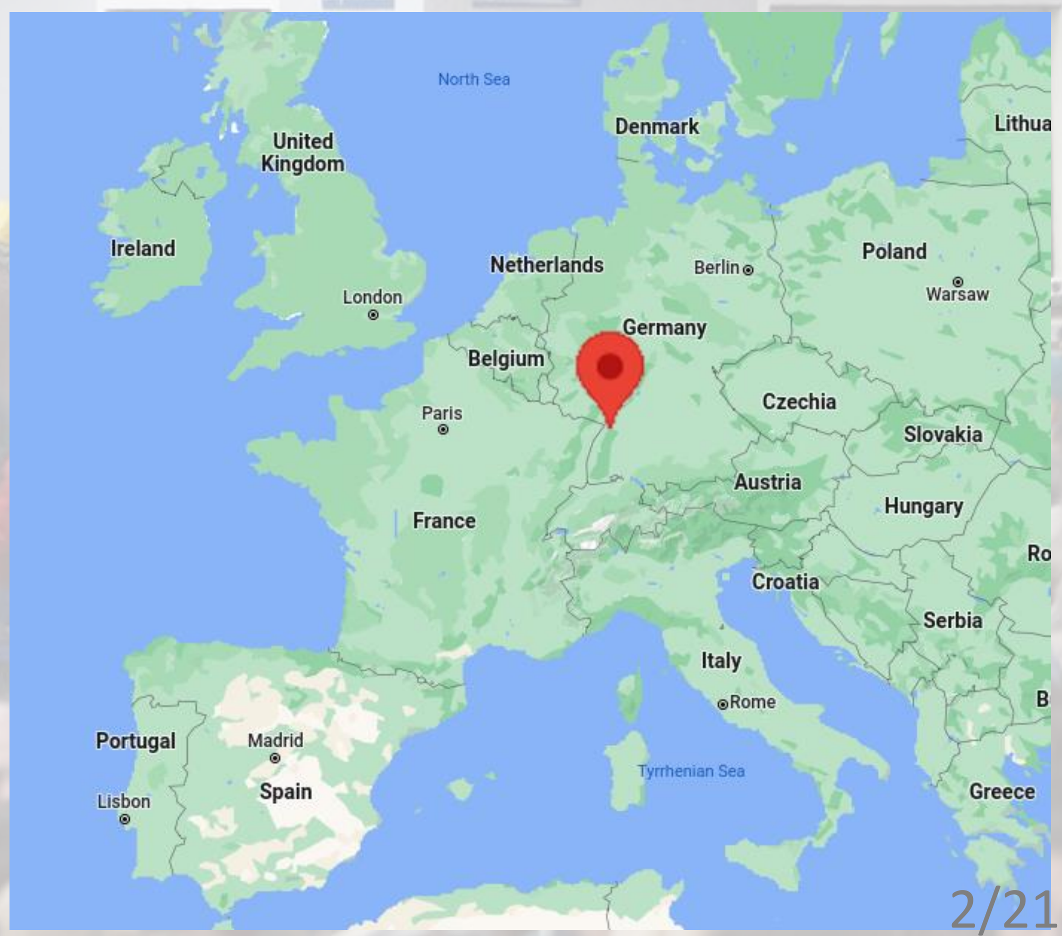
Only 10^{-13} of all decays in the last 1 eV

- 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

Karlsruhe
Tritium
Neutrino
Experiment

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)

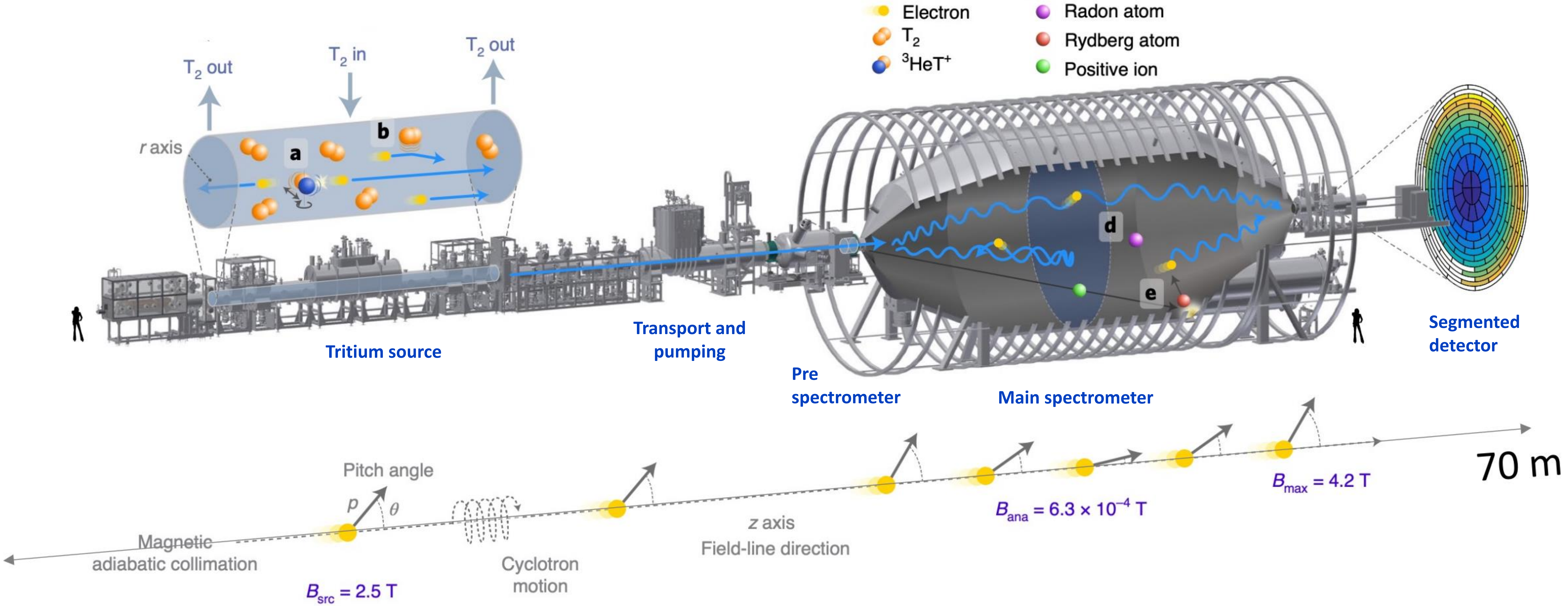
  → high resolution: O(1) eV

  → large acceptance angle: 0-51°

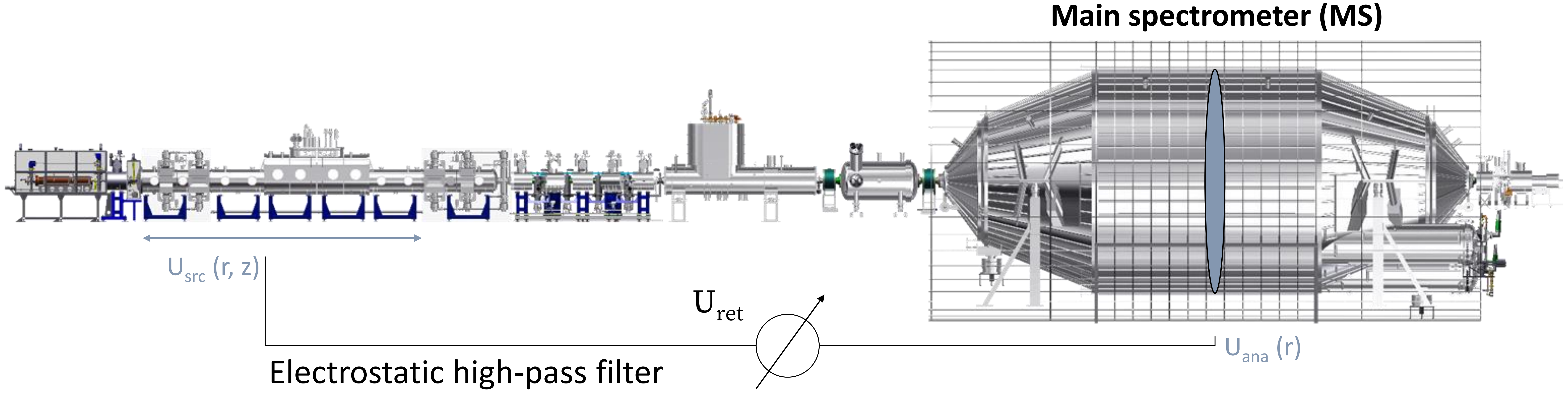
Detector section

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

  → **< 1 $e^{-}.s^{-1}$**

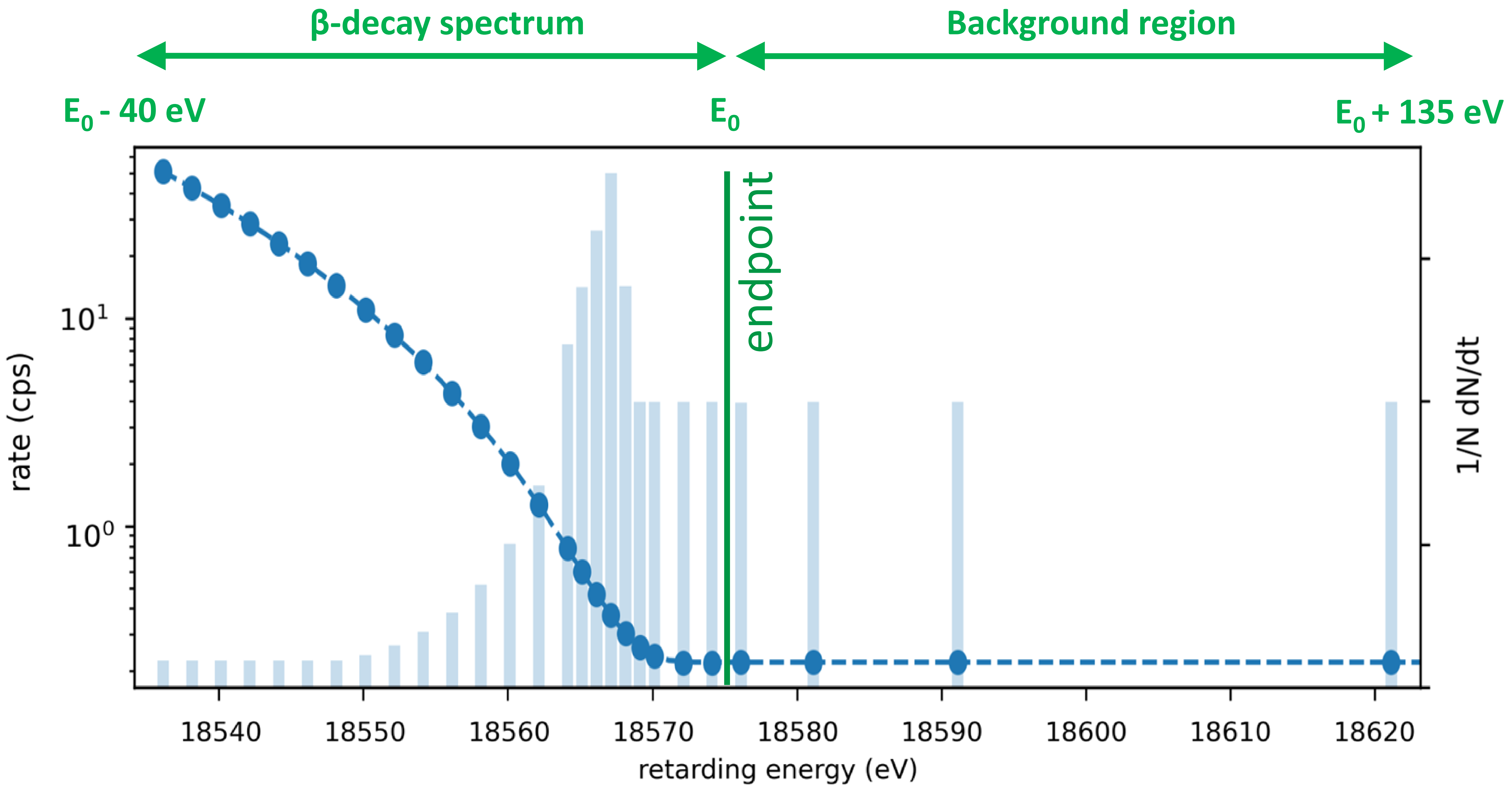


Measurement strategy



Integral spectrum measurement

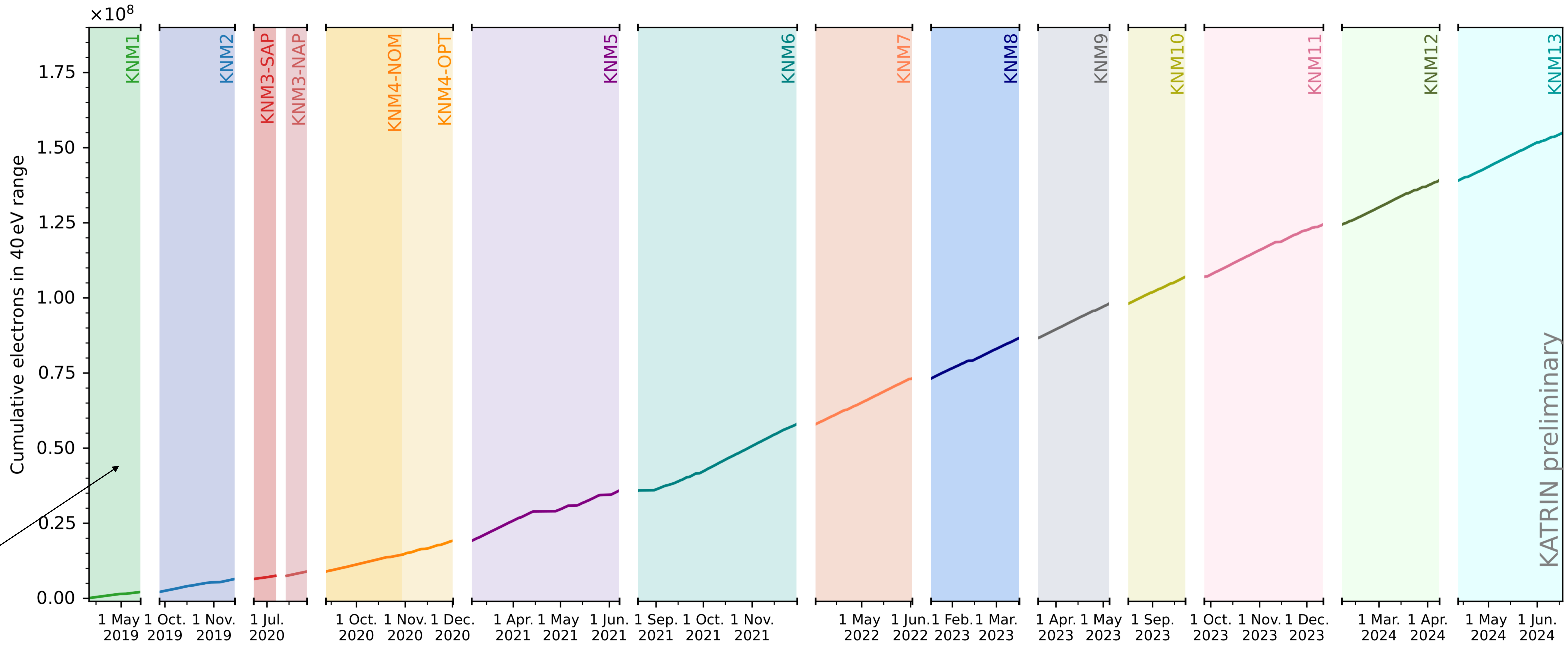
- ~30 scan steps with varying duration
- ~2 h scan duration
- scan interval: $E_0 - 40$ eV , $E_0 + 135$ eV



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

ΔE = 2.8 eV @18.6 keV

Data taking overview



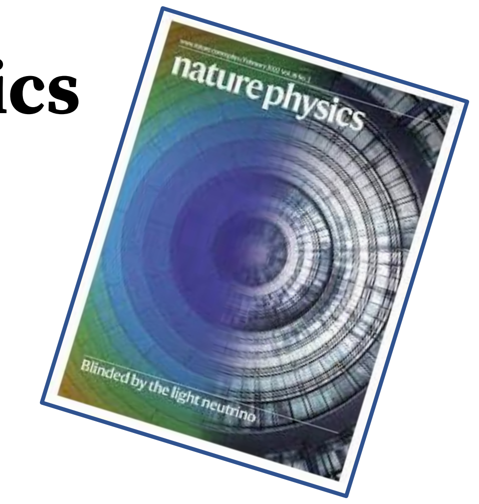
1st campaign
~2.10^6 e$^-$ in the ROI

PRL 2019

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

1st and 2nd campaigns
~6.10^6 e$^-$ in the ROI

Nature physics 2022



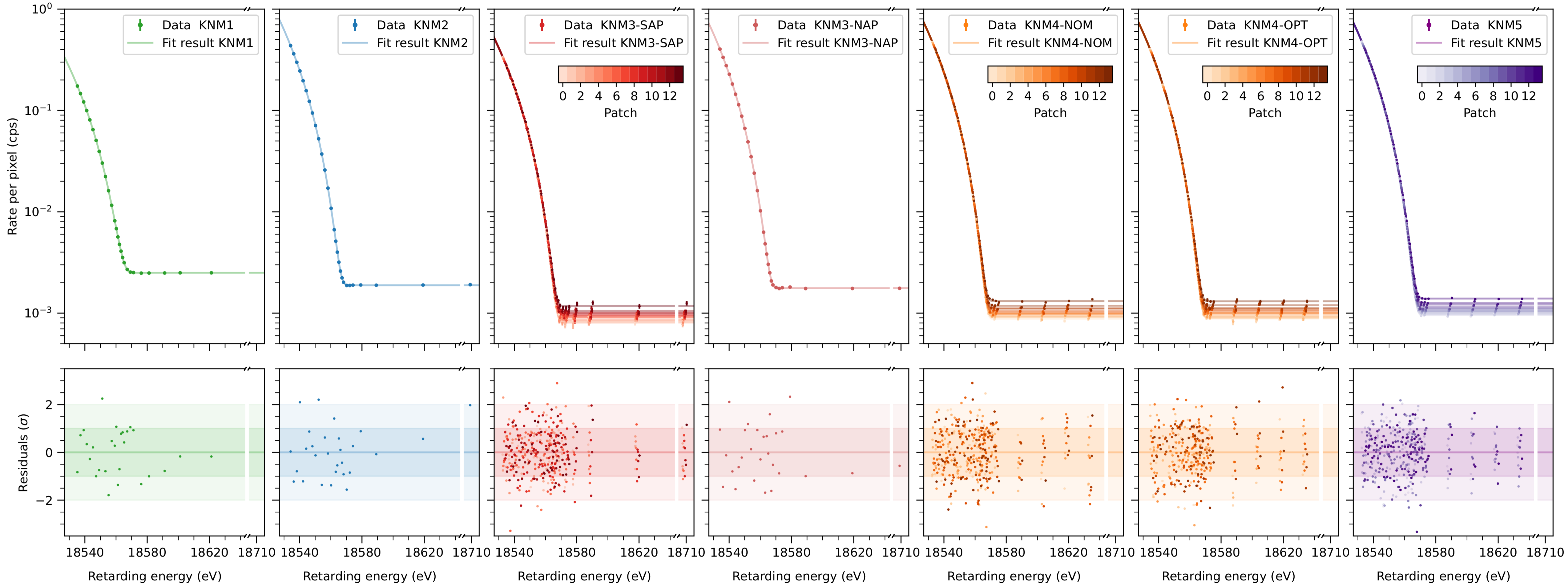
[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

New release at Neutrino 2024

1st to 5th campaigns
259 measurement days
~36.10^6 e$^-$ in the ROI

Latest ν – mass results

Preprint



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

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

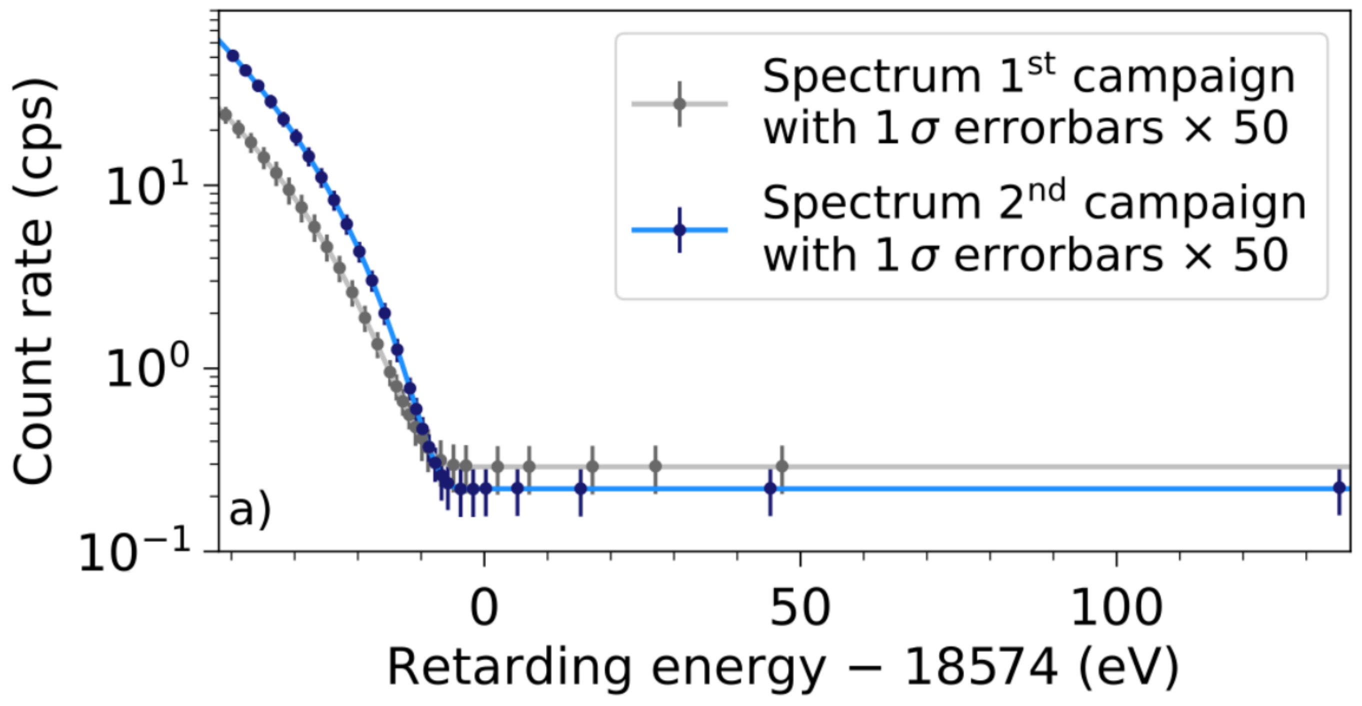
Negative m_ν^2 estimates allowed by the spectrum model to accommodate statistical fluctuations

- **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

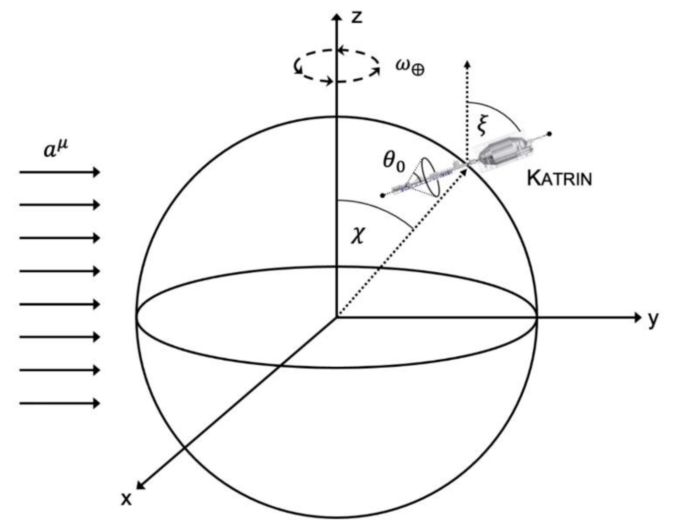
Search for exotic weak interactions

$\Rightarrow$ *shape distortion*

Search for Lorentz invariance violation

[arXiv:2112.13803]

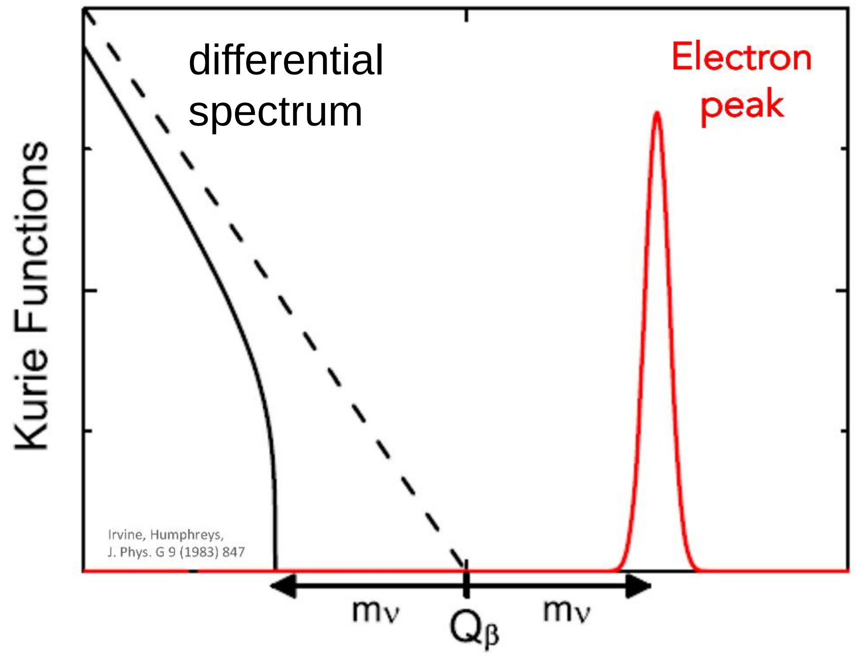
$\Rightarrow$ *sideral modulation*



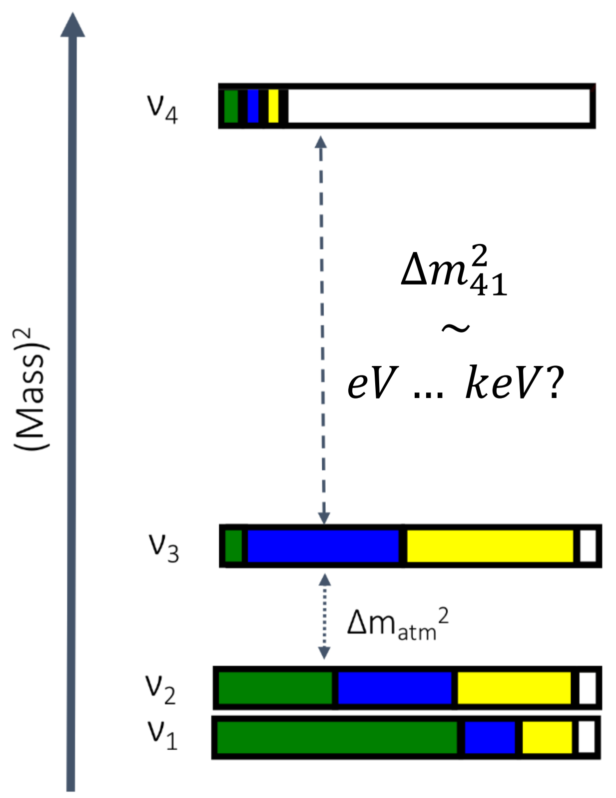
Constrain local overdensity of cosmic relic neutrinos

[Phys. Rev. Lett. 129, 011806]

$\Rightarrow$ *peak search*



Sterile neutrino search

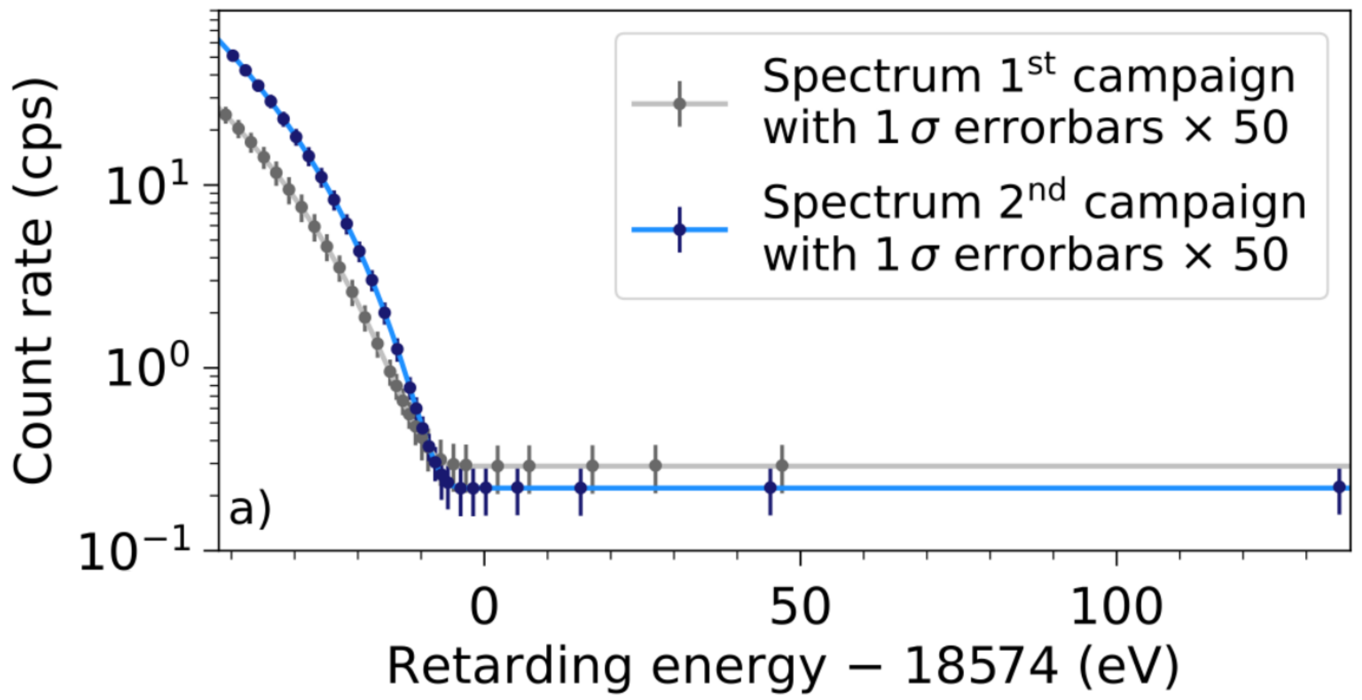


[PRD 105, 072004 (2022)]
[arXiv:2207.06337v1 [nucl-ex] (2022)]

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

$\Rightarrow$ *shape distortion*

Beyond neutrino mass in KATRIN



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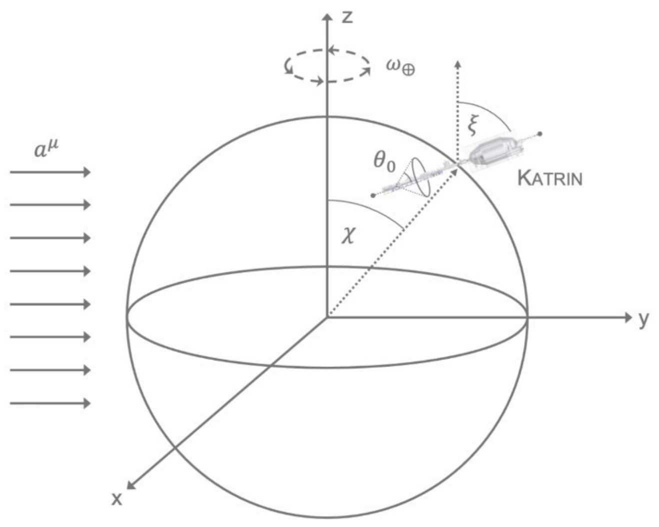
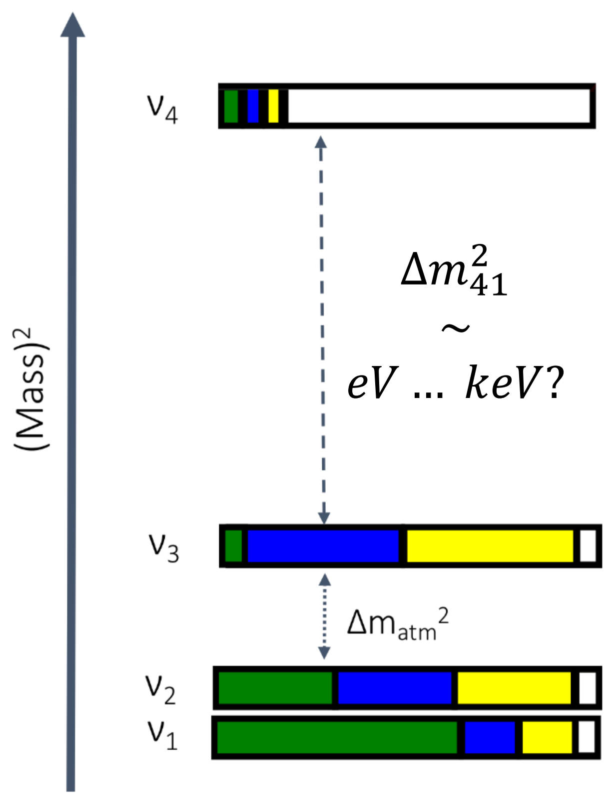


Sterile neutrino search

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



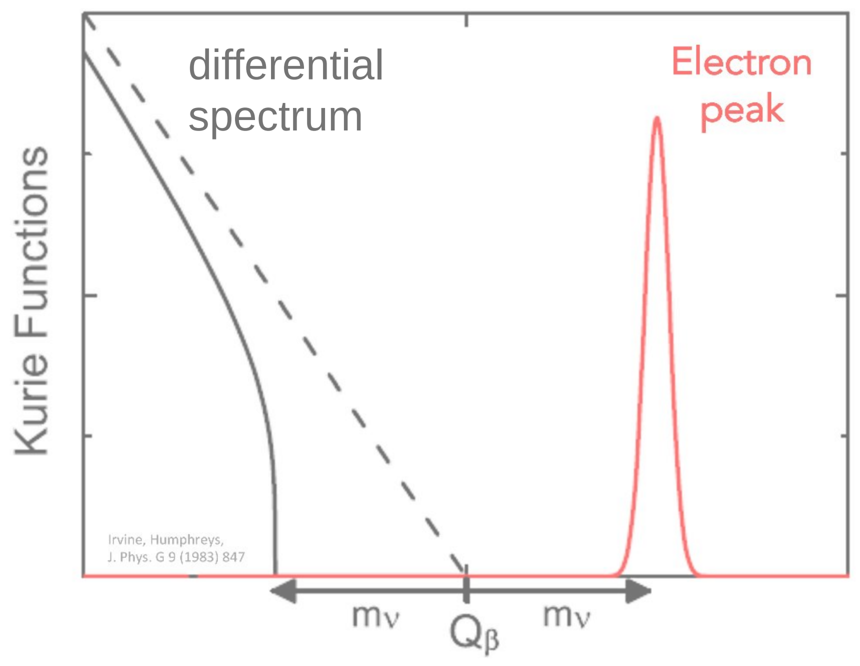
- eV-scale sterile neutrinos
- keV-scale sterile neutrinos

⇒ *shape distortion*

Constrain local overdensity of cosmic relic neutrinos

[Phys. Rev. Lett. 129, 011806]

⇒ *peak search*



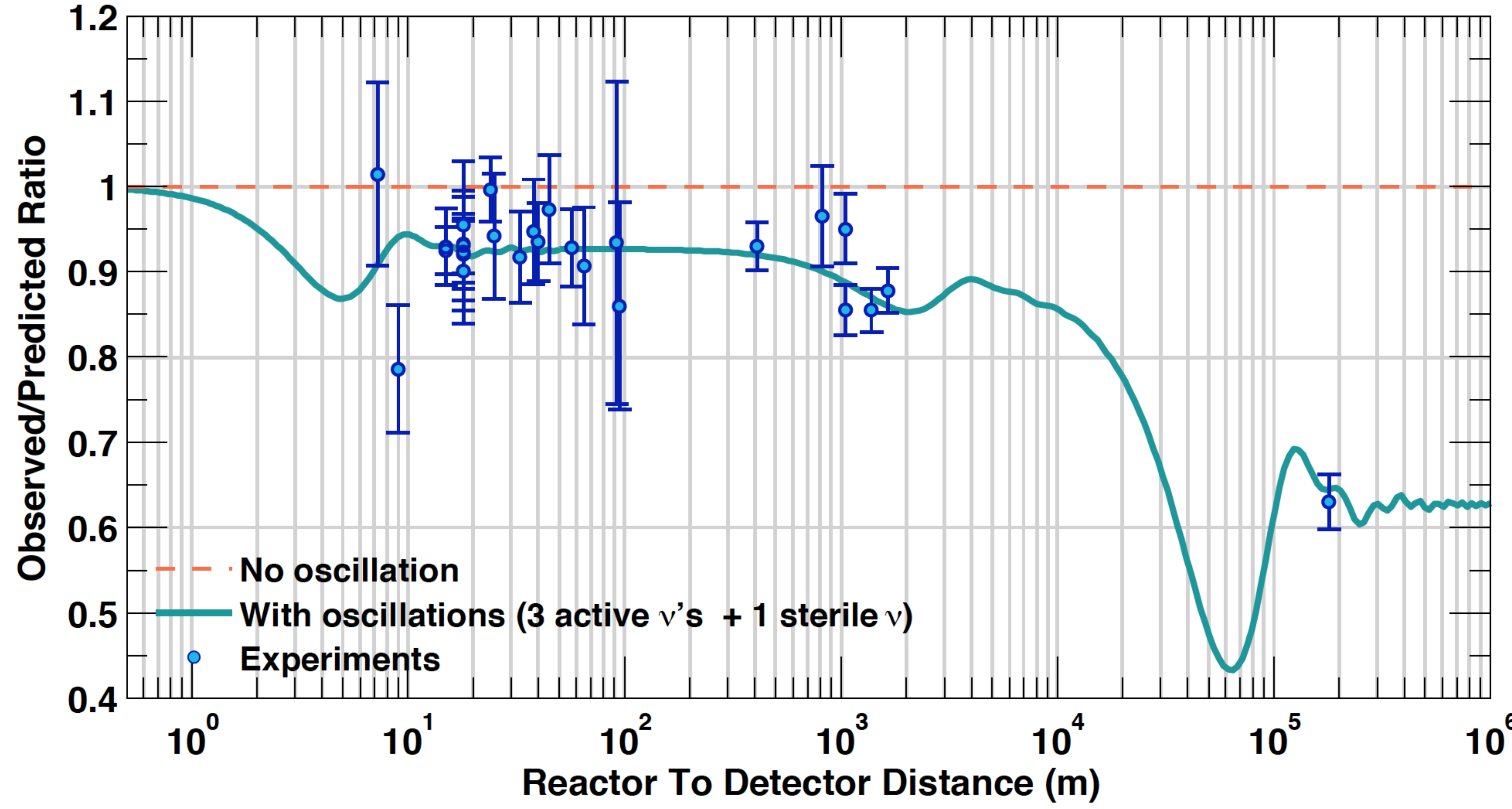
Sterile neutrino motivation

eV-scale sterile neutrino search

Several experimental anomalies

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

Reactor antineutrino anomaly (RAA)

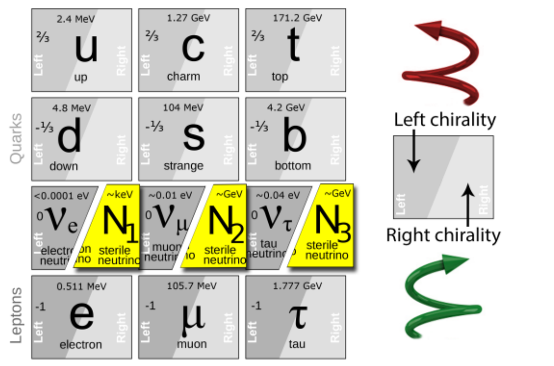


[Phys. Rev. D 83, 073006 (2011)]

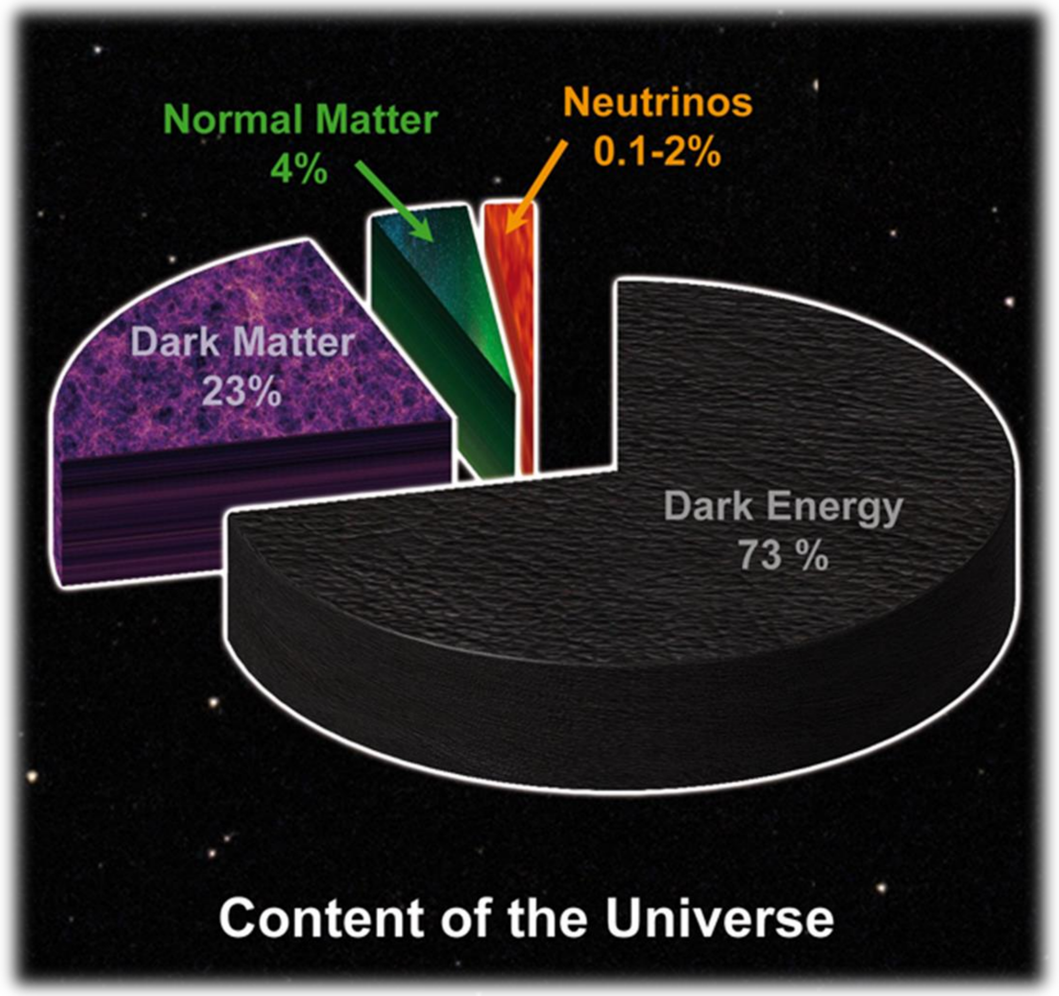
keV-scale sterile neutrino search

Right-handed neutrinos: natural extension of SM

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



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

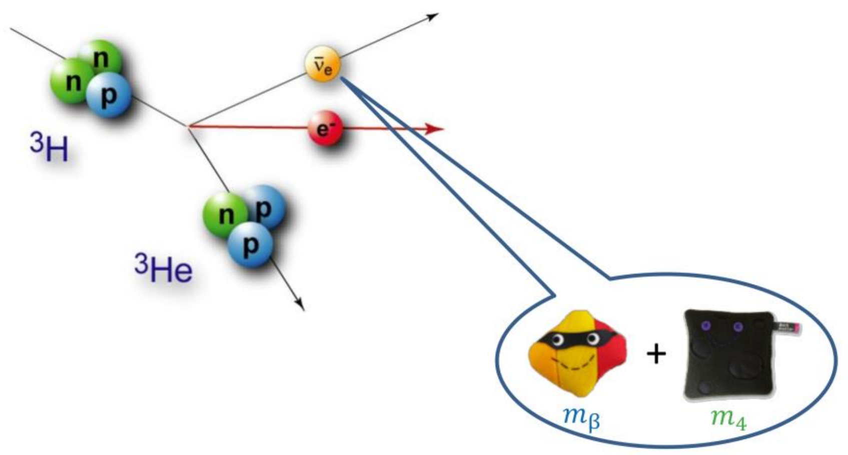


⇒ **Need for model-independent experiments across a wide mass range**

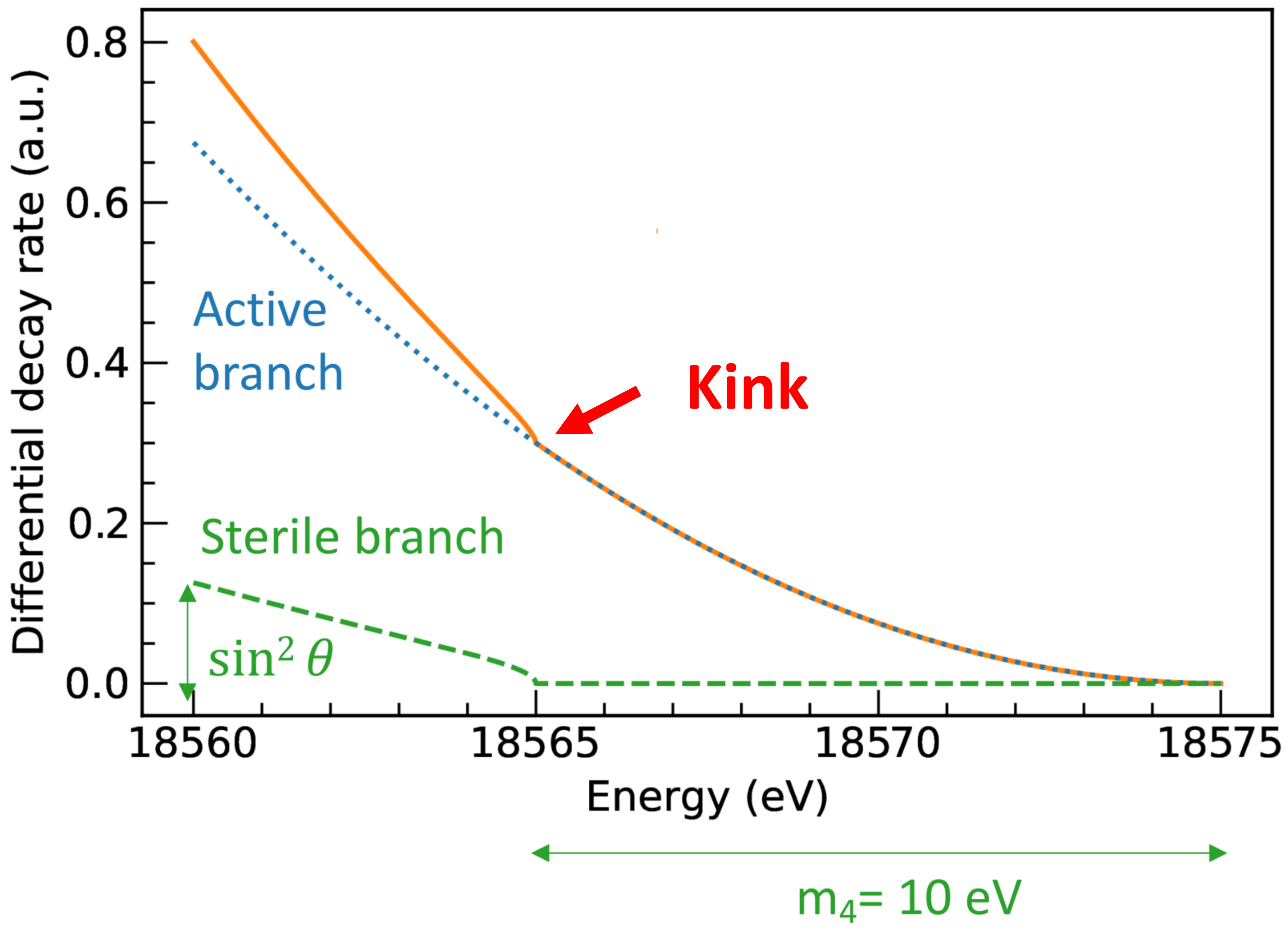
Imprint of eV sterile ν on β-decay spectrum

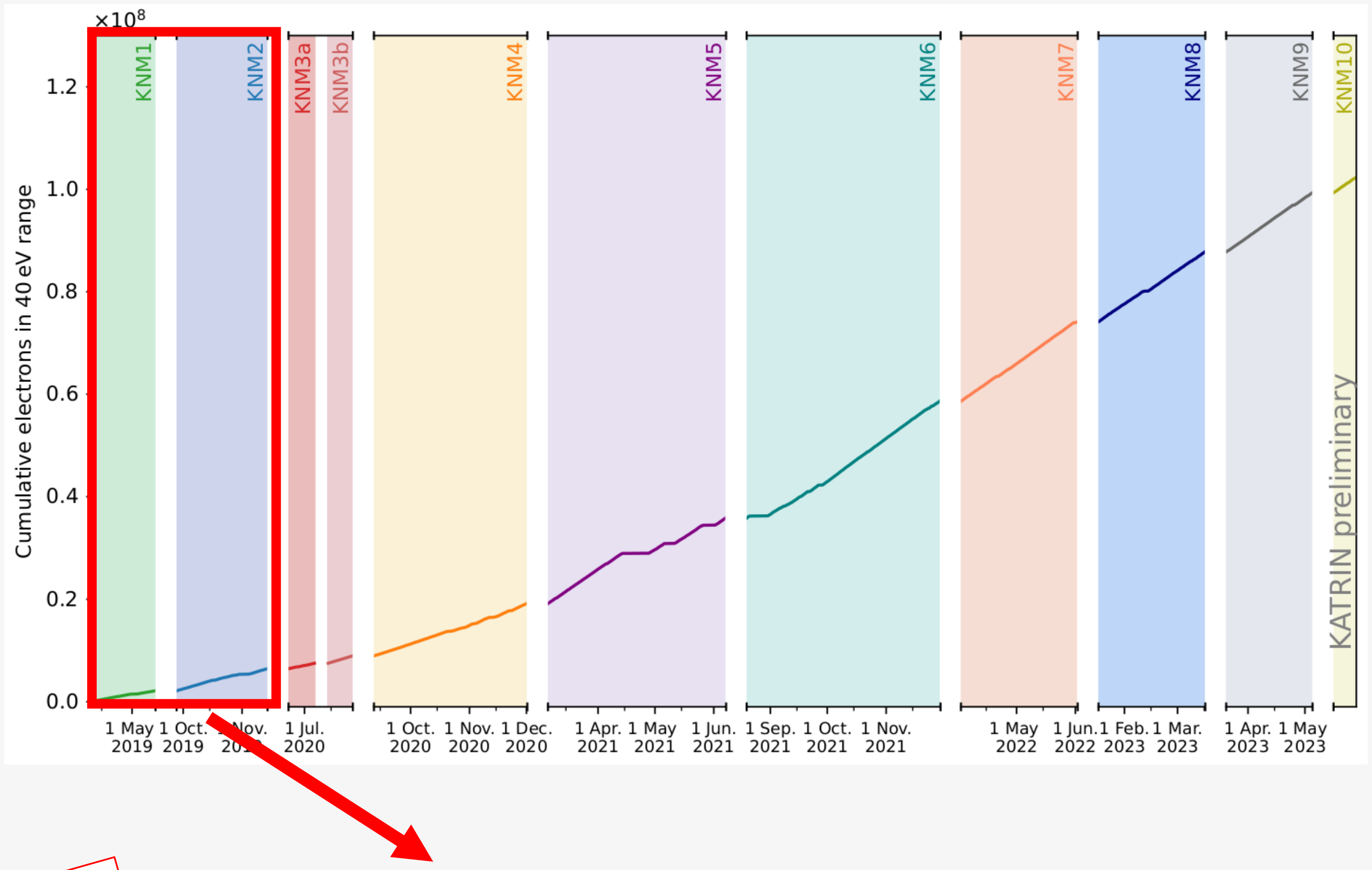
Emitted neutrino in β-decay is admixture of mass eigenstates

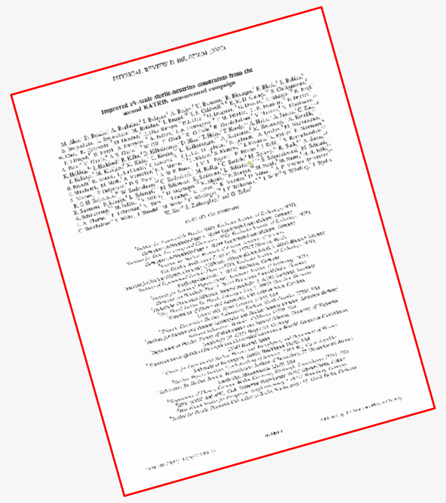
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_S\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{S1} & U_{S2} & U_{S3} & U_{S4} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \end{pmatrix}$$



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







1st + 2nd campaign

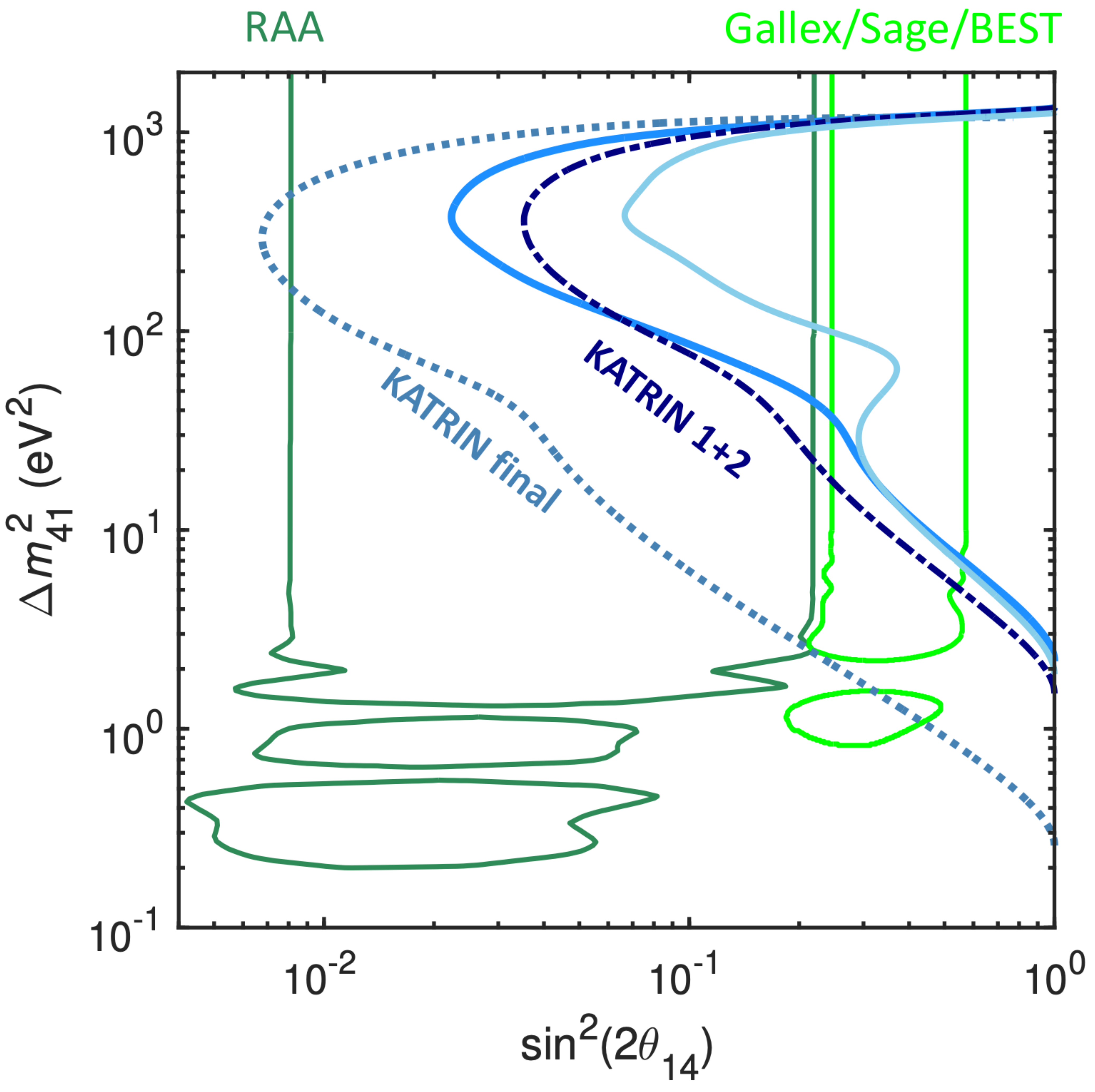
- ~1265 h of data
- ~6.10⁶ e⁻ in the ROI
- < 5% of the expected final statistic

Phys Rev D 105 072004 (2022)

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

⇒ Accessible in ν-mass data sets

Overview of sterile experiment results

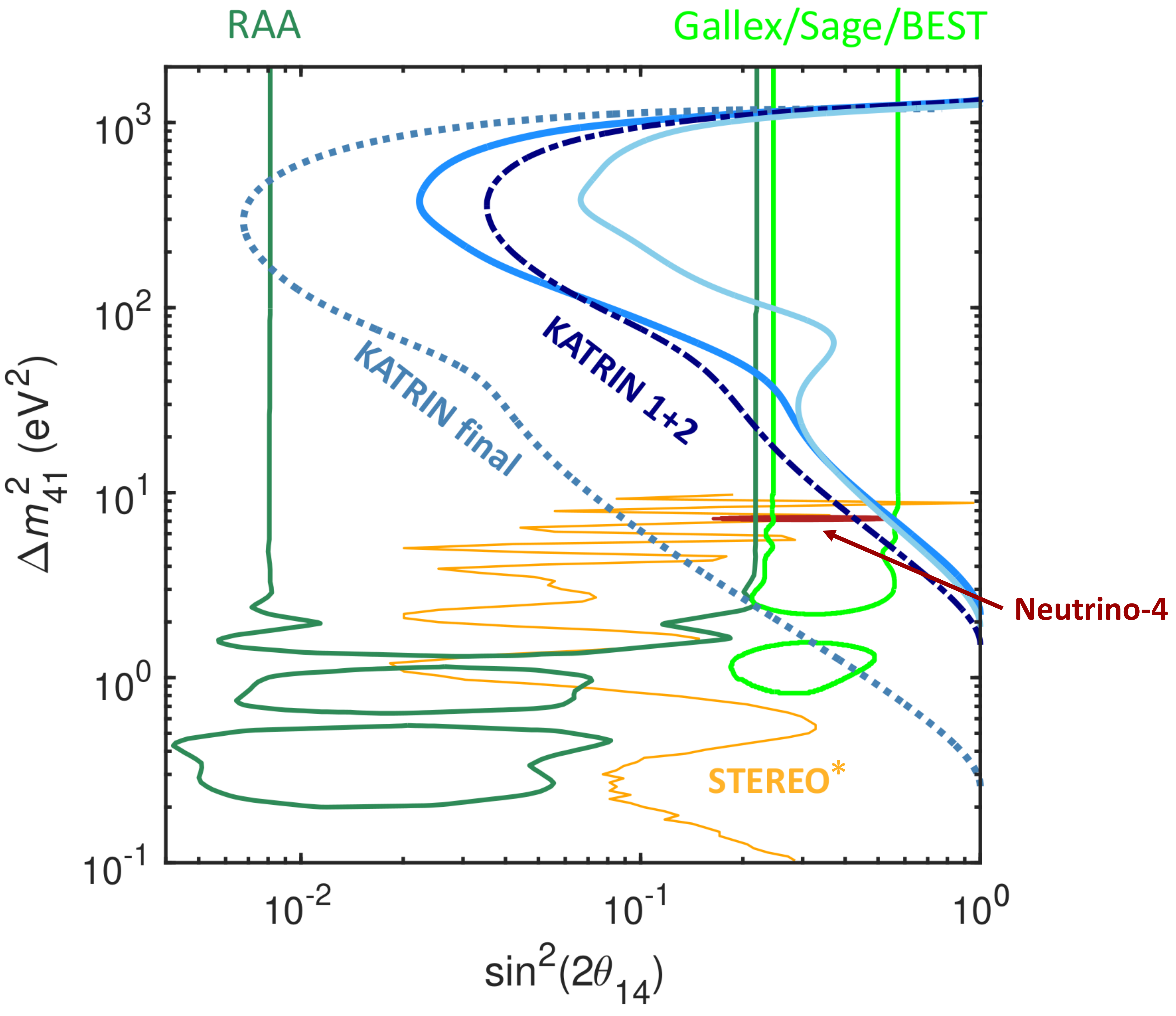


95% C.L. exclusion contours

- No eV-sterile neutrino signal observed
- Exclude large Δm_{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 Δm^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**

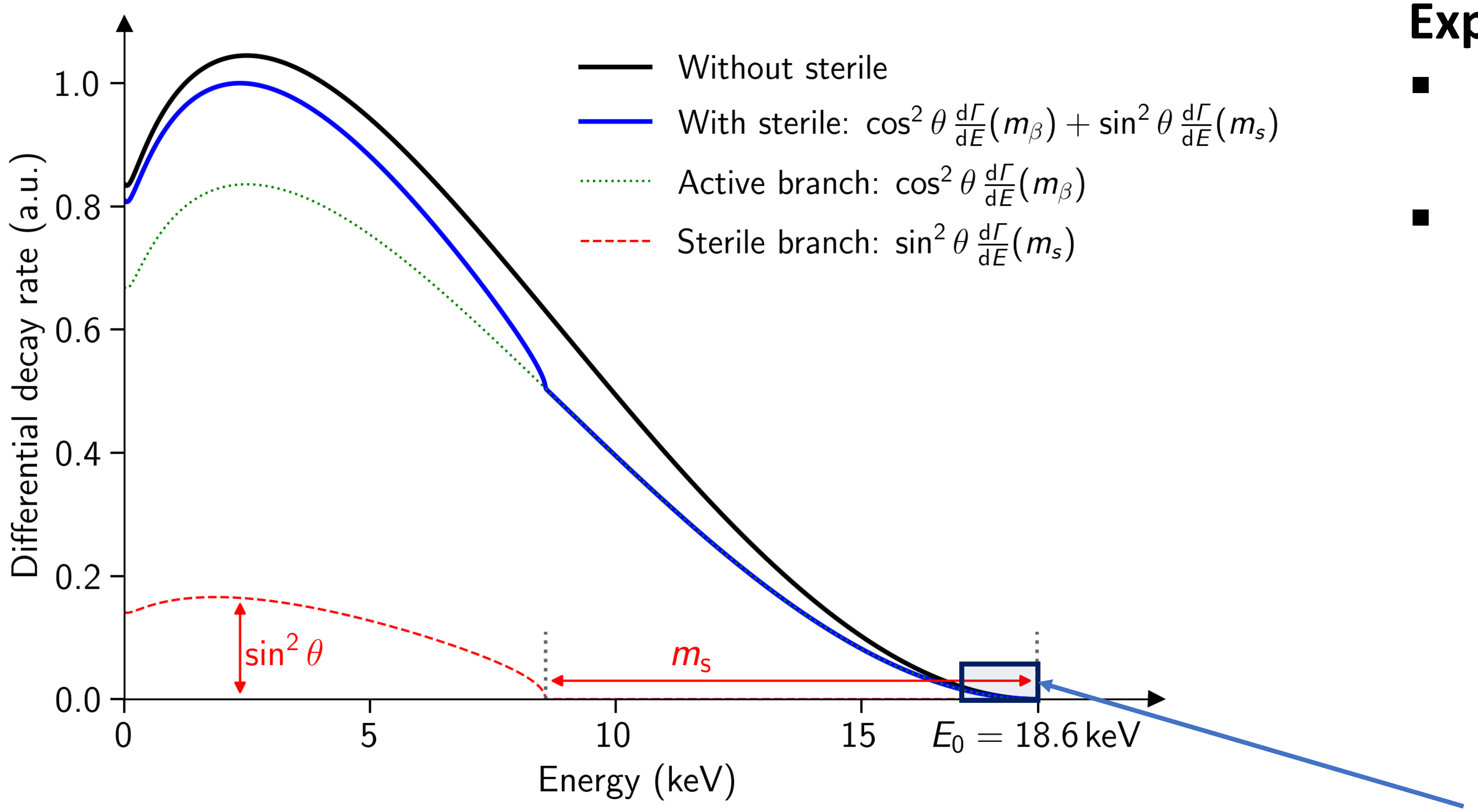
Updated analysis with the first 5th campaigns in progress

(*) 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



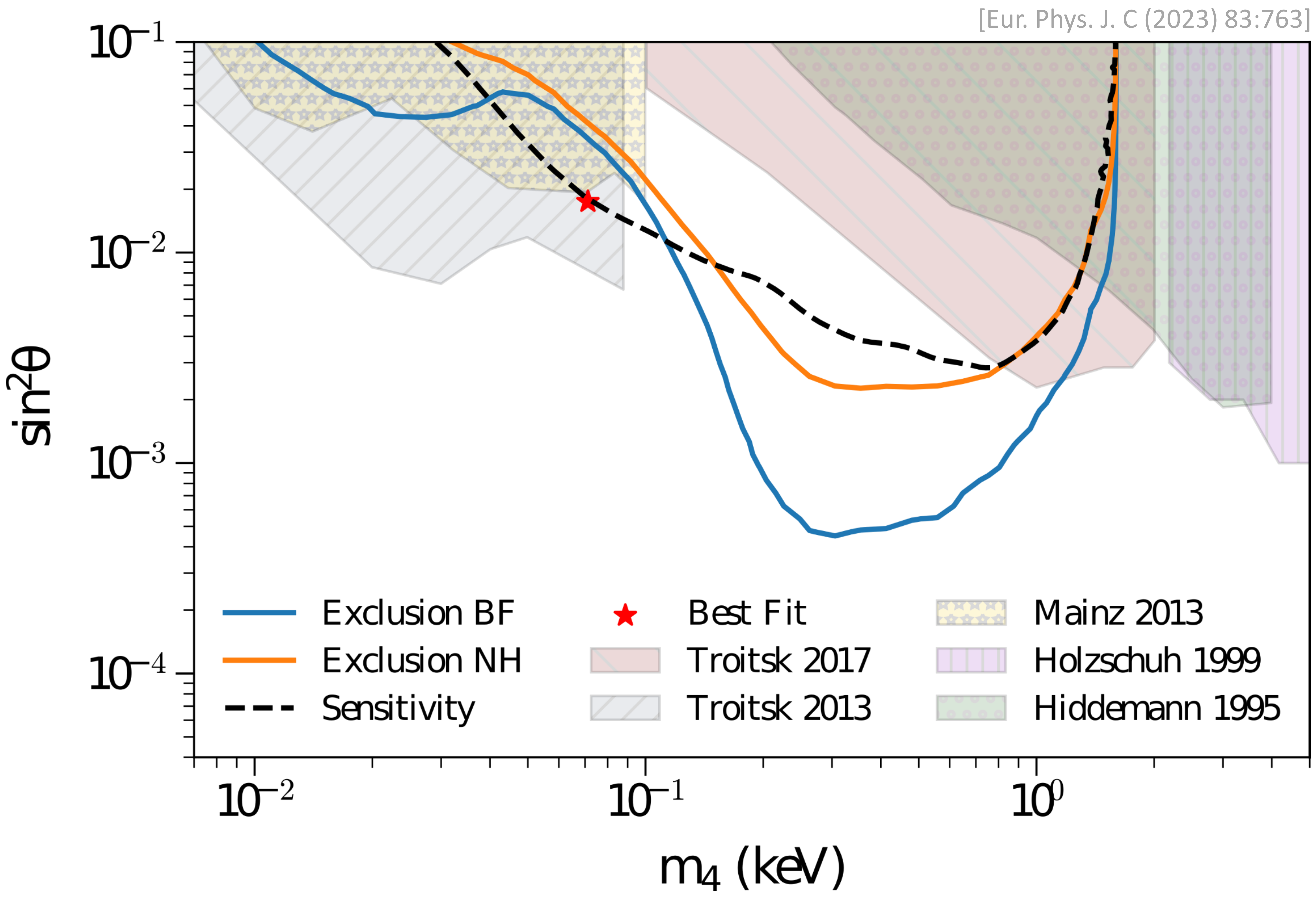
Experimental challenge:

- Energy windows of ν-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

1^{st} 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 keV < m_4 < 1.0 keV
- Dominant syst.: source activity fluctuation

Successful demonstration of feasibility using current KATRIN detector ✓

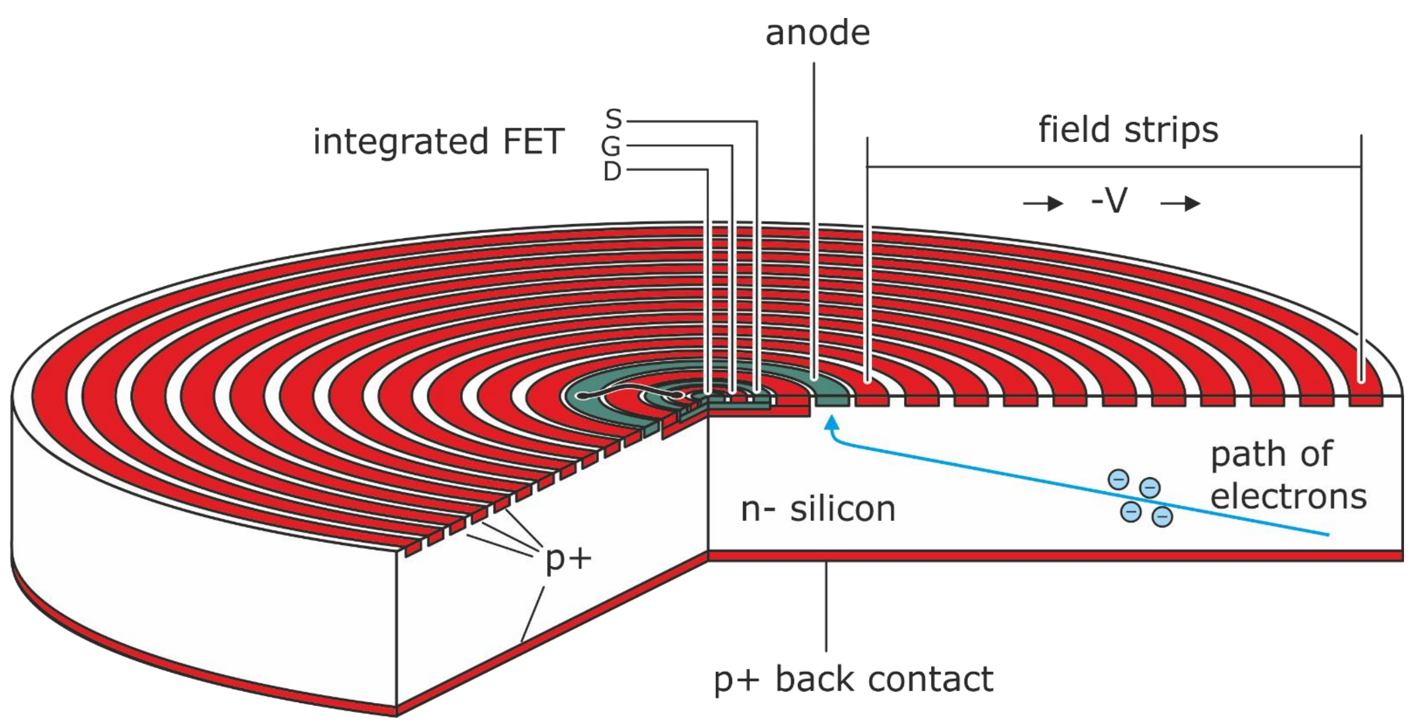
⇒ **New detector required for high rate β-spectroscopy**

keV sterile neutrino search
with the TRISTAN detector

TRISTAN project

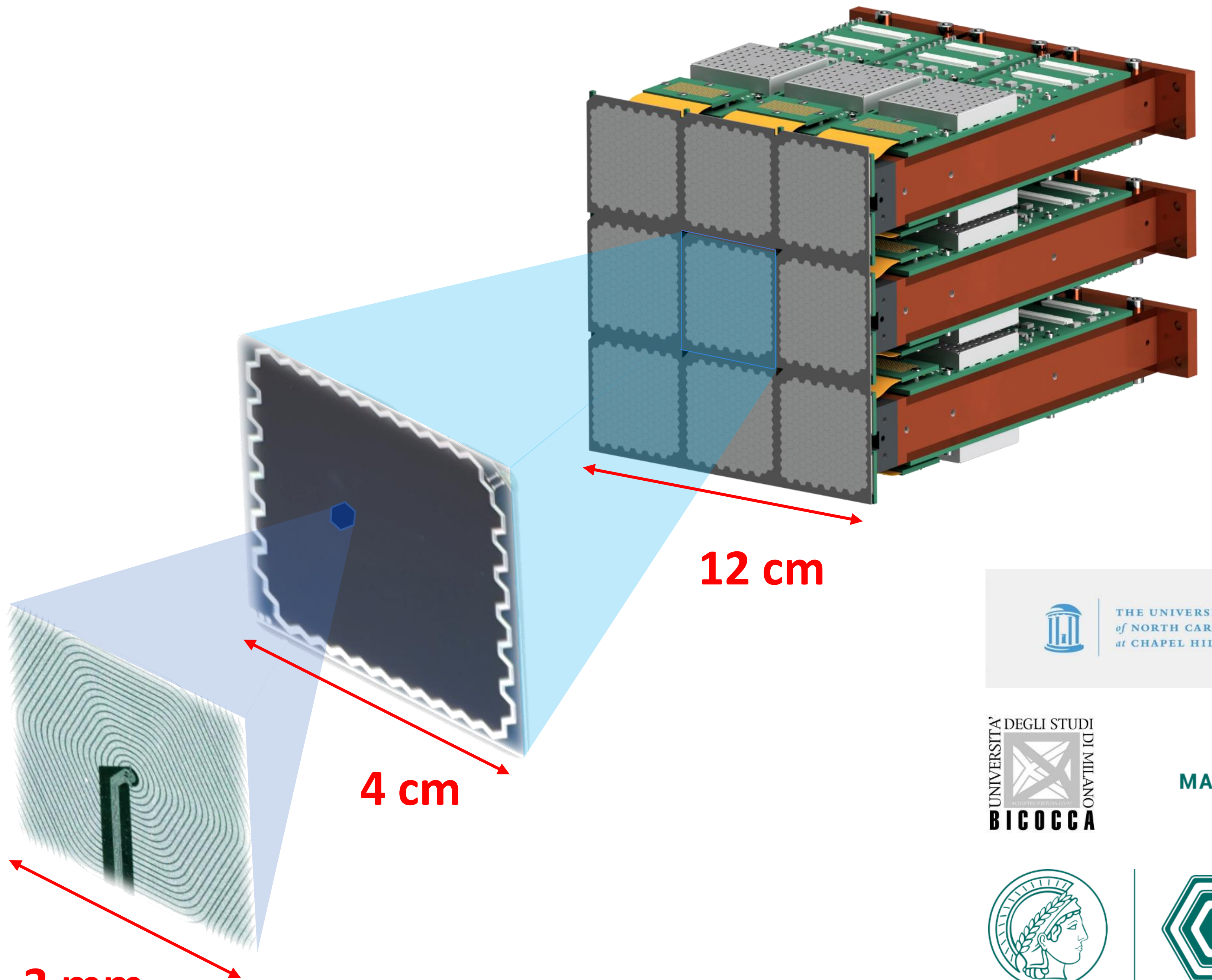
Tritium Beta Decay to Search for Sterile Neutrinos

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



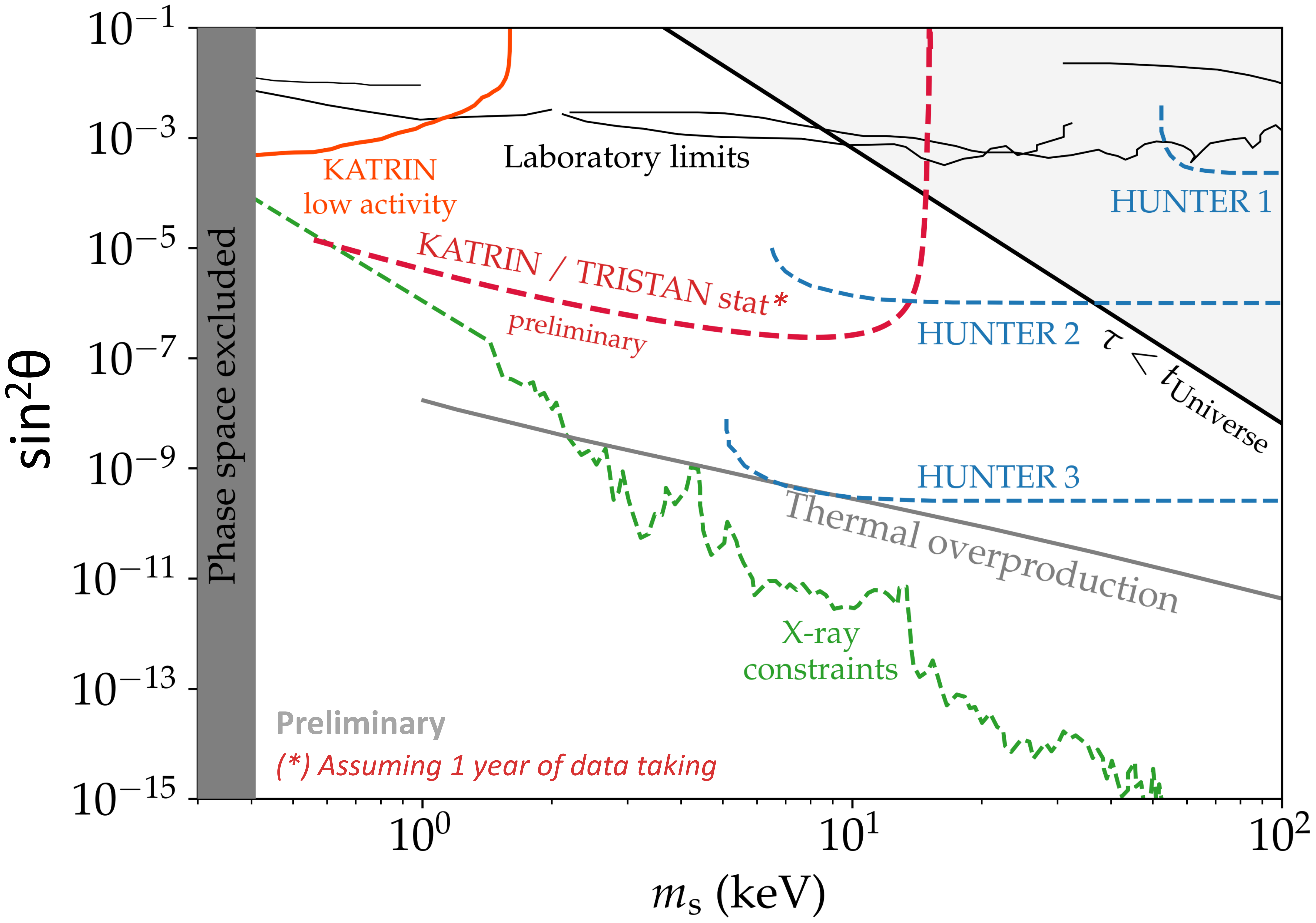
Measurement of tritium differential energy spectrum ⇒ Goal: ppm level on $\sin^2\theta$

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**

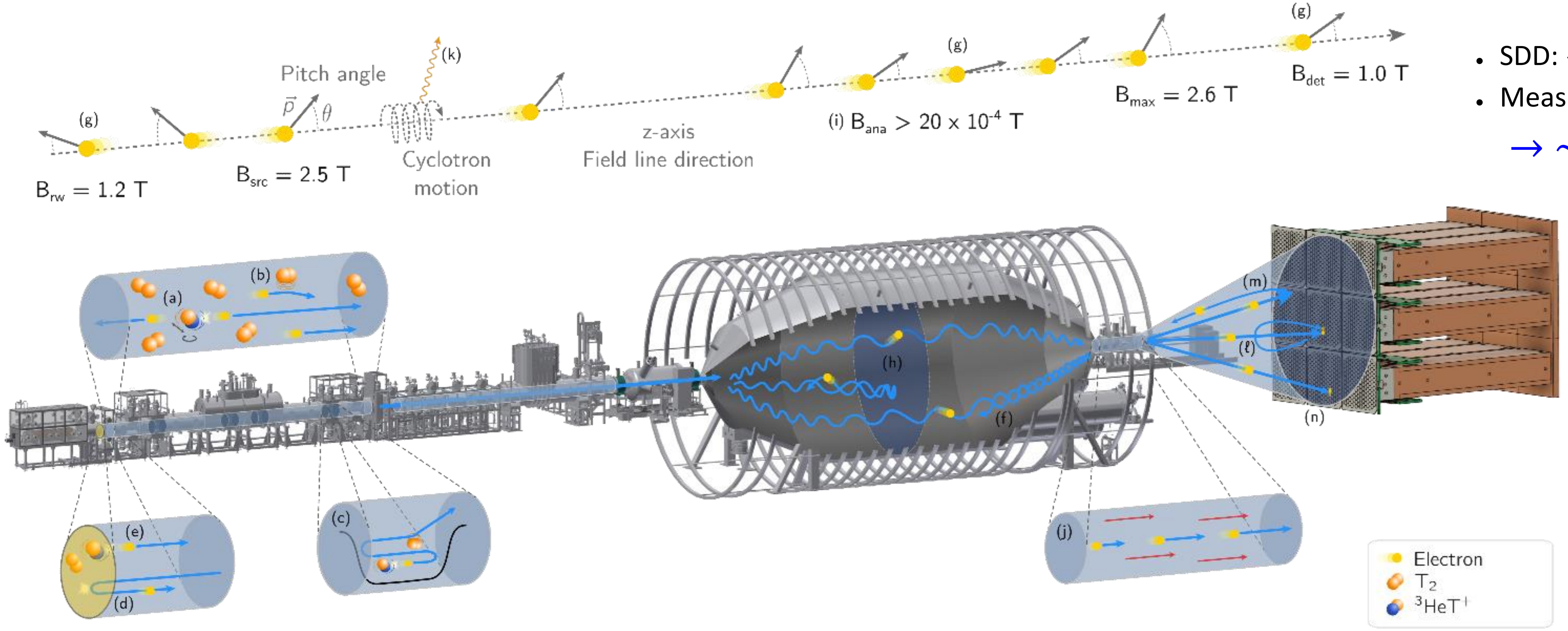
Detector section

- SDD: ~1500 pixels
- Measure differential spectrum

→ ~10^8 $e^-.s^{-1}$

Rear section

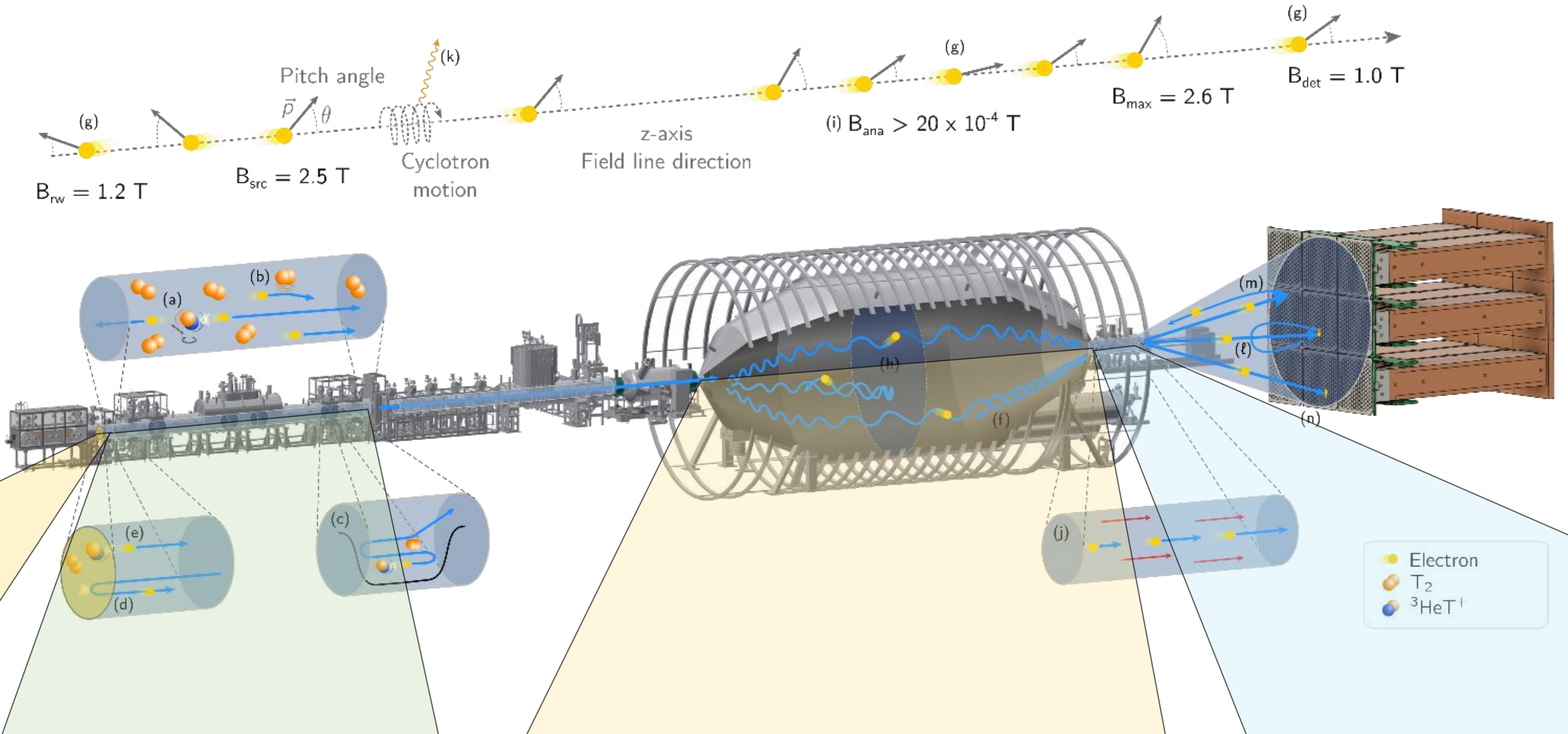
- golden rear wall
- high intensity e-gun



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

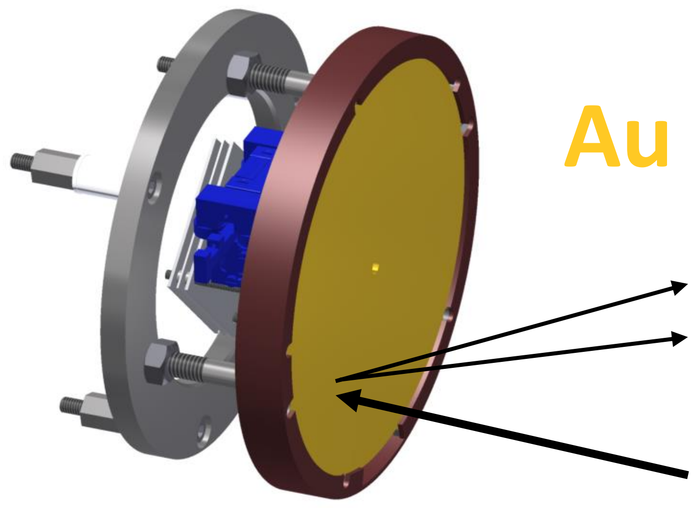
- Scattering
- Magnetic trapping

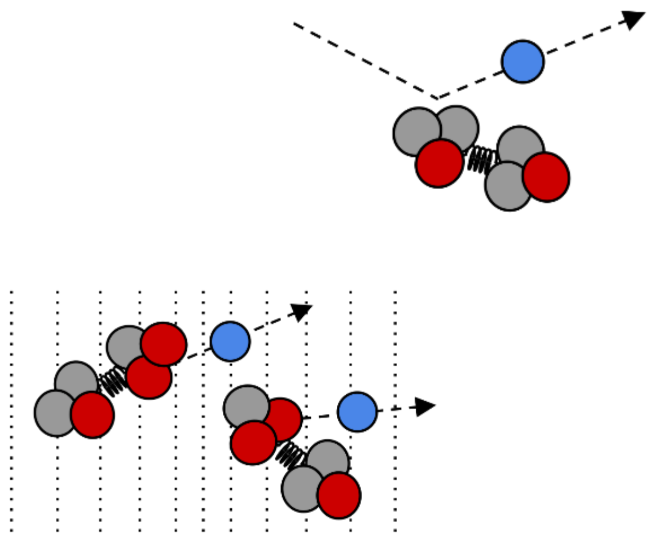
Spectrometer

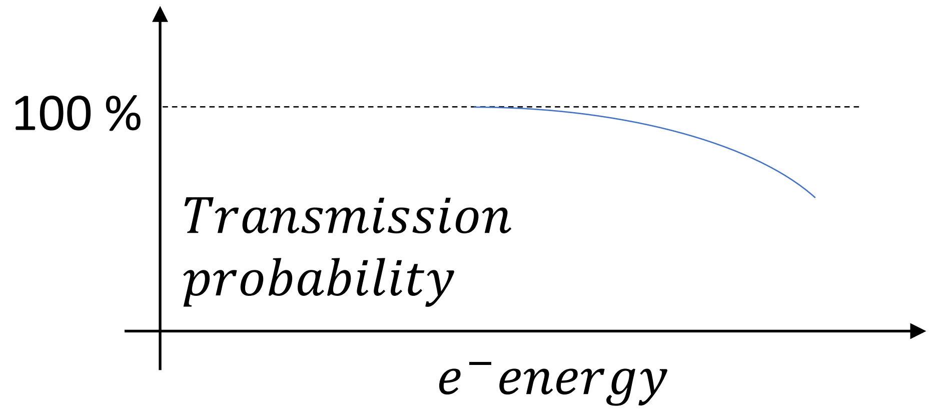
- Magnetic mirror and collimation
- Spectrometer adiabaticity

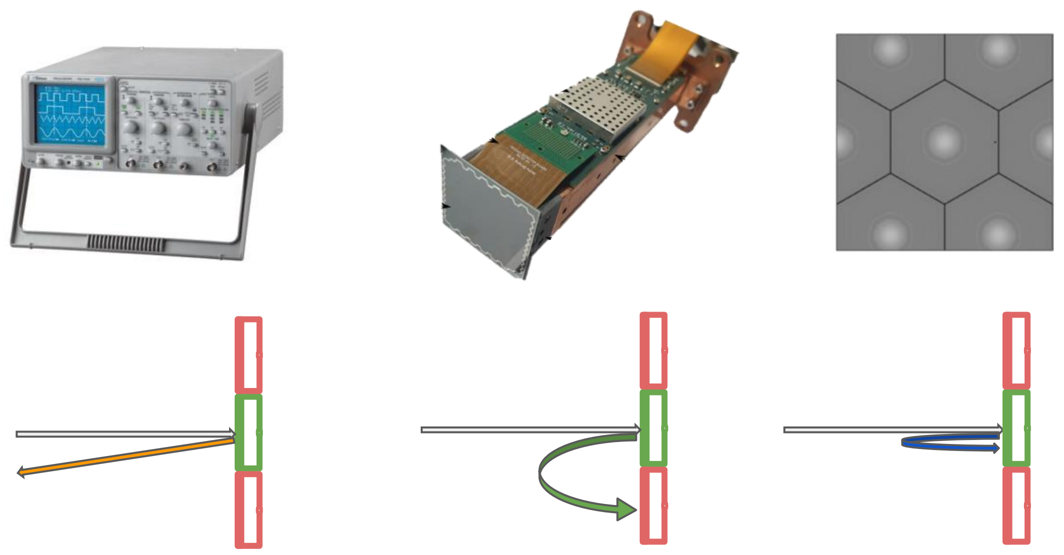
Detector section

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







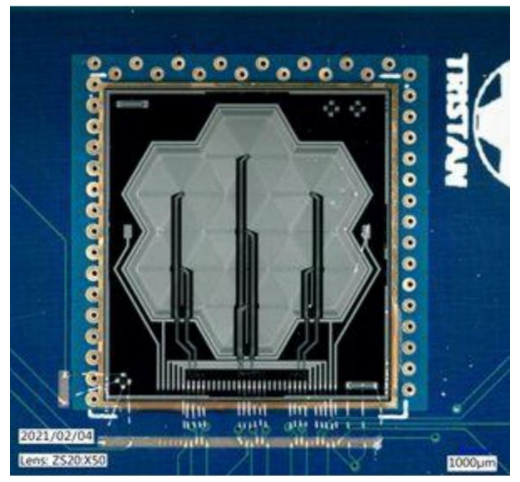


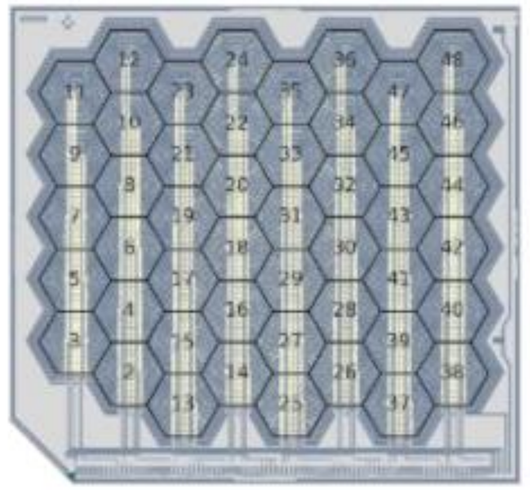
Staged approached

2017

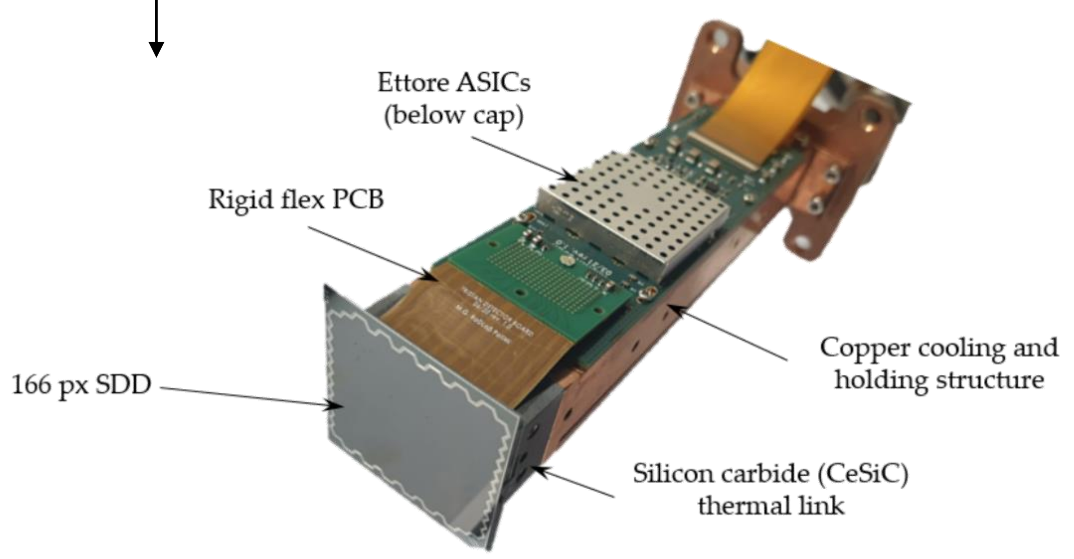
1st prototype

7 and 47 pixels prototypes



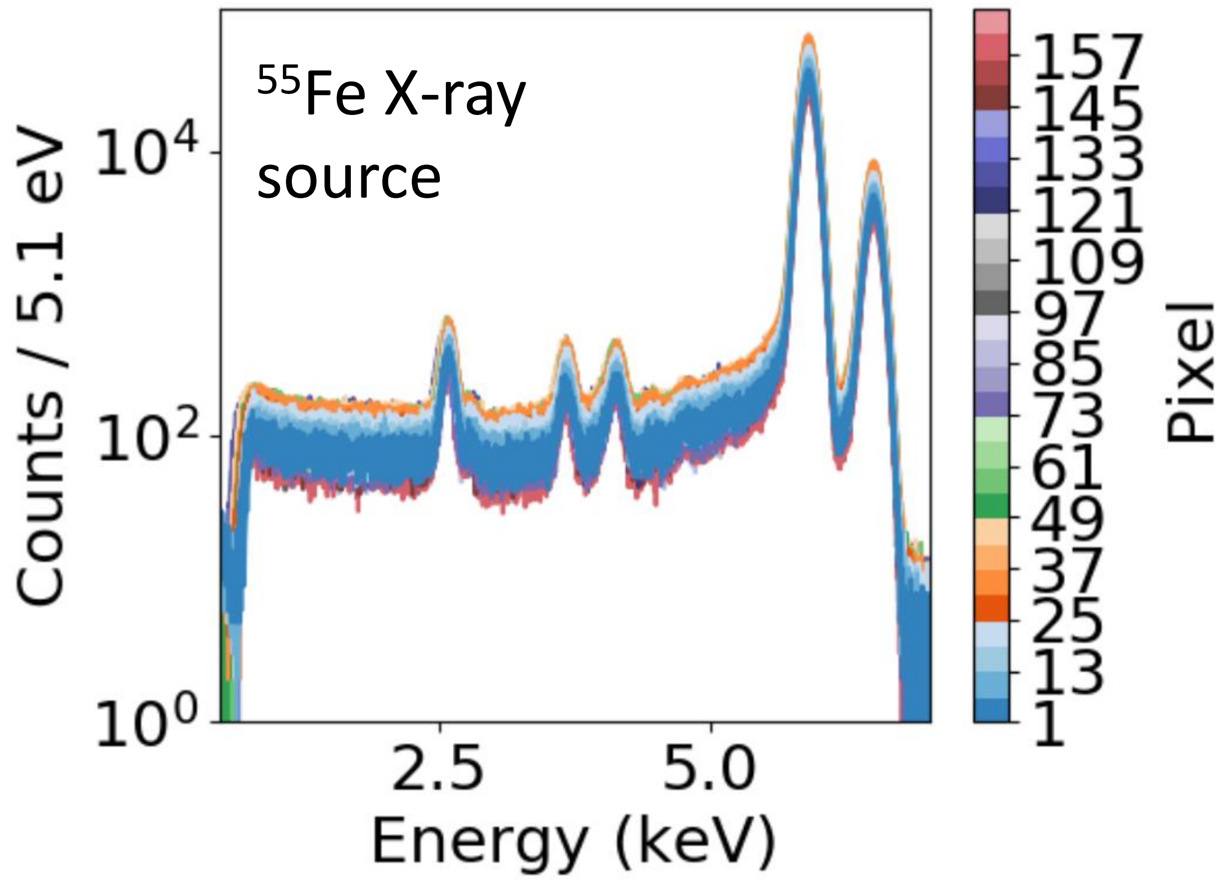


3D focal plane design with 166 pixels



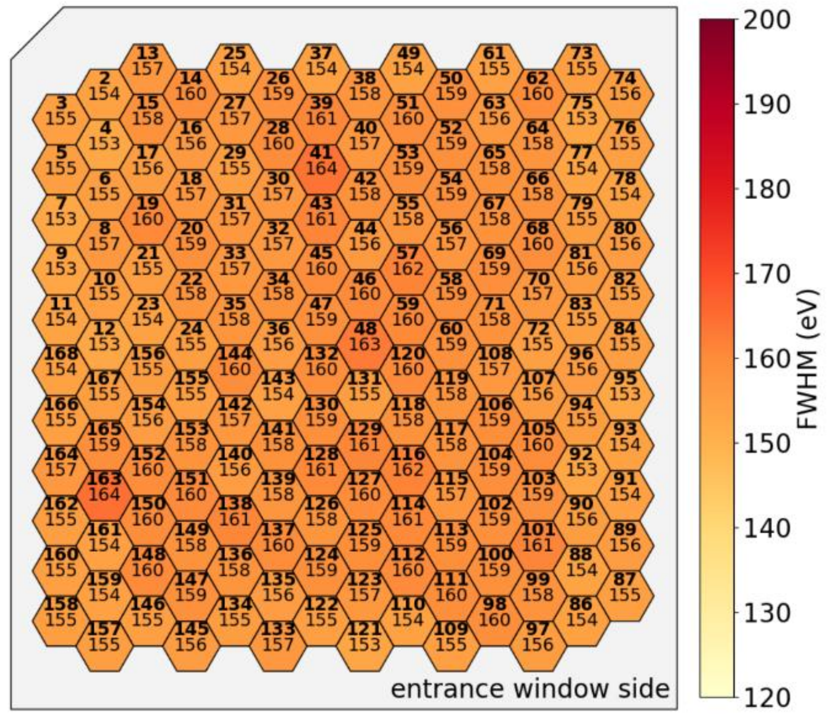
Prototypes: 7, 47, 166 pixels

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



[j.nima.2021.166102]

Energy resolution @ 5.9 keV



⇒ Good performance demonstrated to match requirement

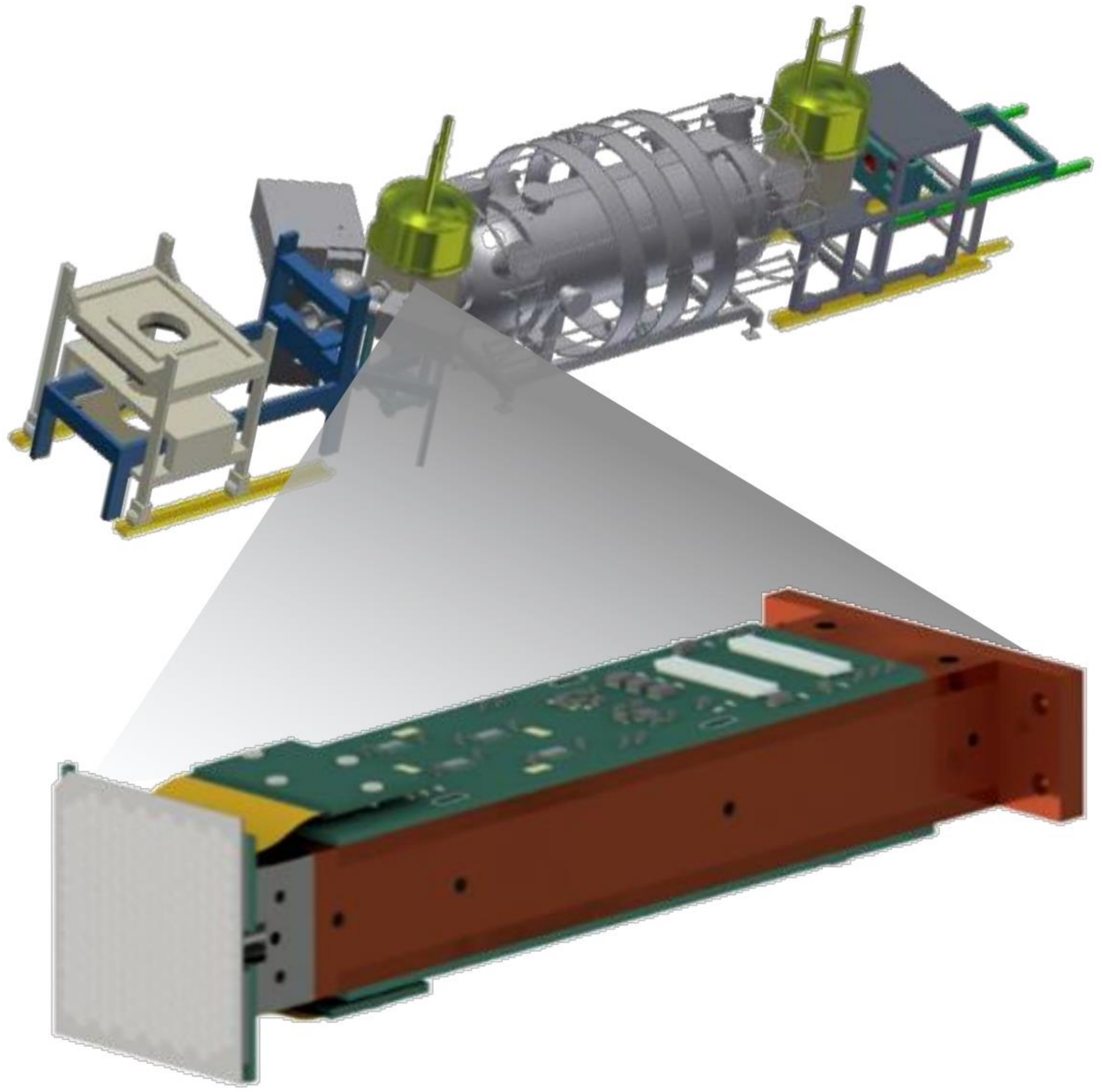
Staged approached

2017

1st prototype

2022

1st module in monitor spectrometer



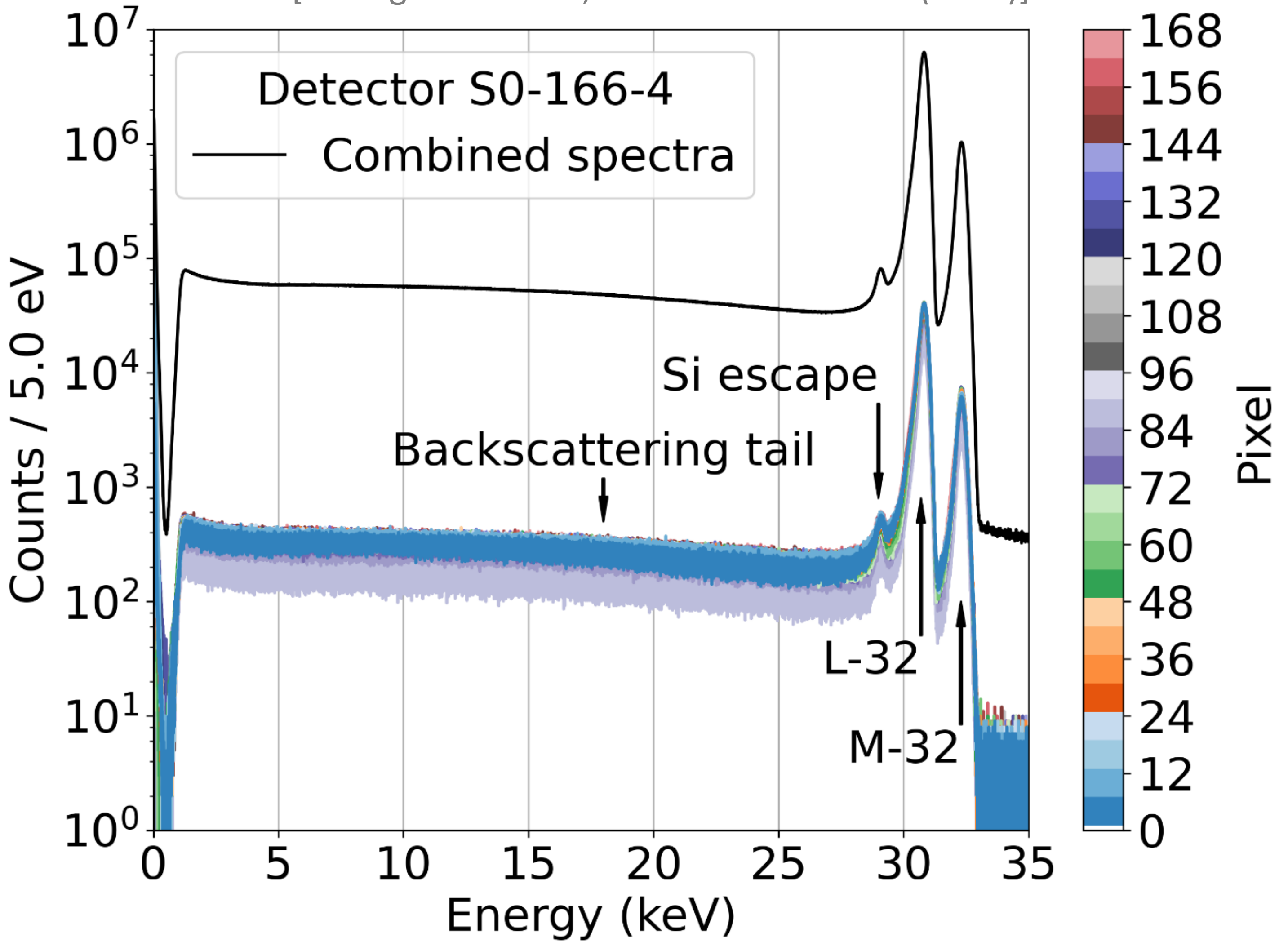
Monitor spectrometer (MoS):

- 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

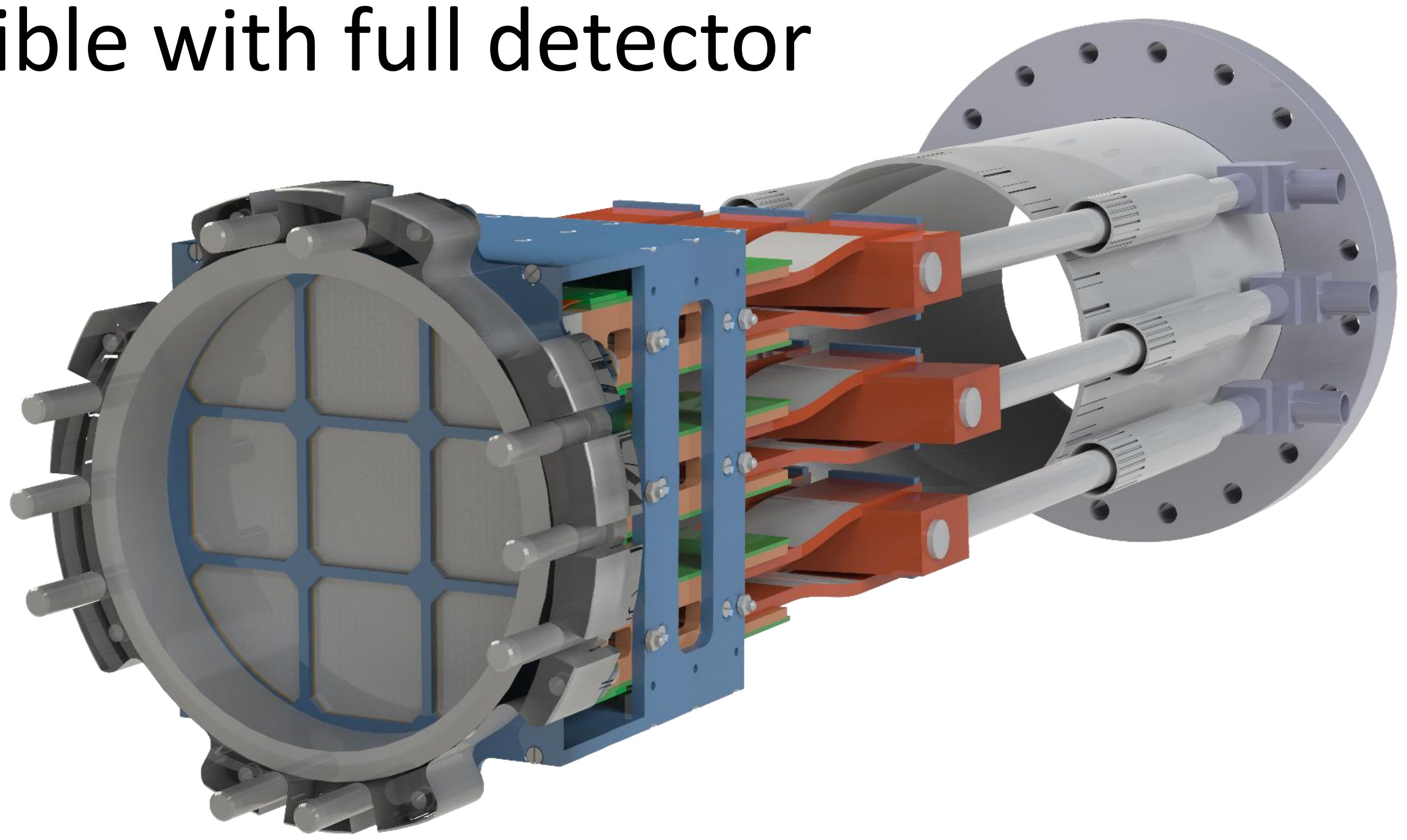
1st module in monitor spectrometer

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

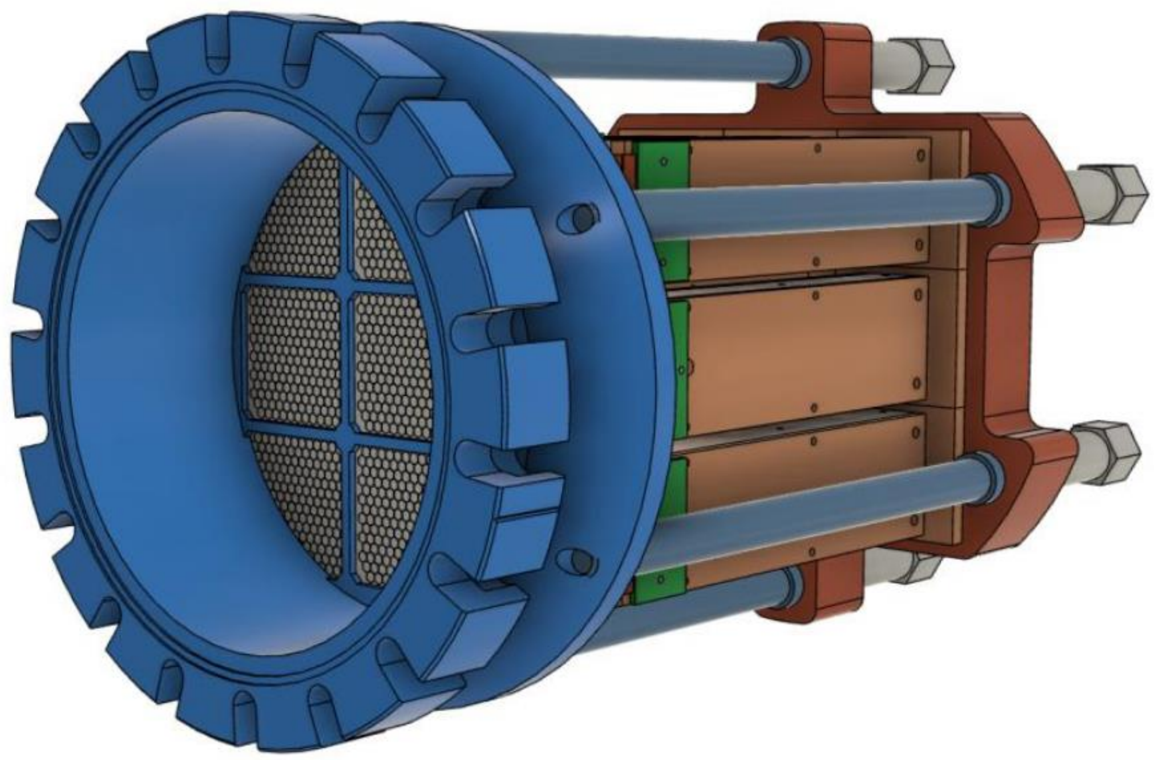


Multi-modules calibration

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

Staged approached

2017	2022	2024-2025	2026
1st prototype	1st module in monitor spectrometer	3-9 modules in detector replica	detector in KATRIN beamline

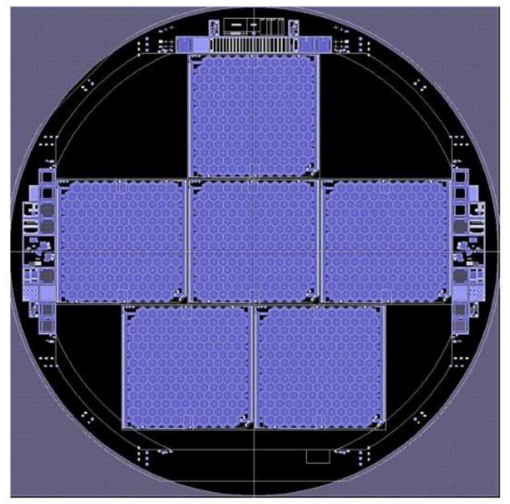


- 9 modules
- 1500 pixels

Detector commissioning in 2026

- Almost final module design
- SSD production started

SSD wafer prototype



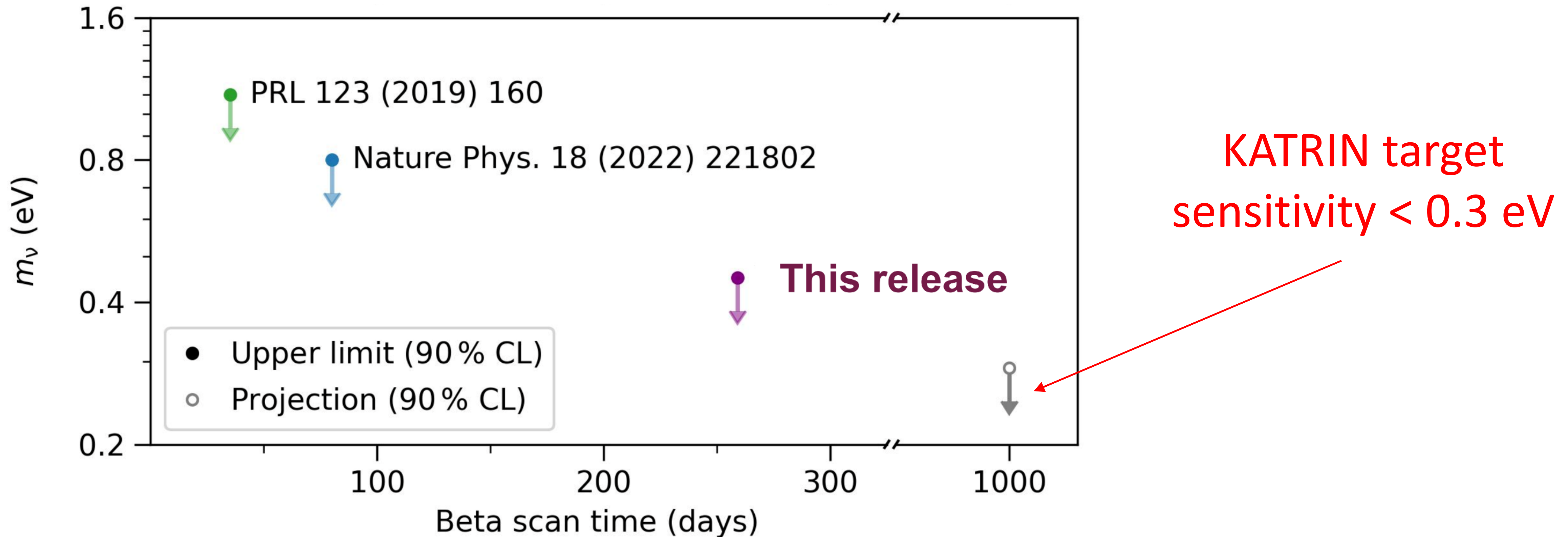
⇒ First KATRIN keV sterile neutrino search with TRISTAN

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

Karlsruhe
Tritium
Neutrino
Experiment

Thank you for your attention!