

# eV and keV sterile neutrino search with the KATRIN experiment

**Anthony Onillon, Technical University of Munich**  
On behalf of the KATRIN collaboration

# Neutrino mass measurement with tritium $\beta$ -decay kinematics

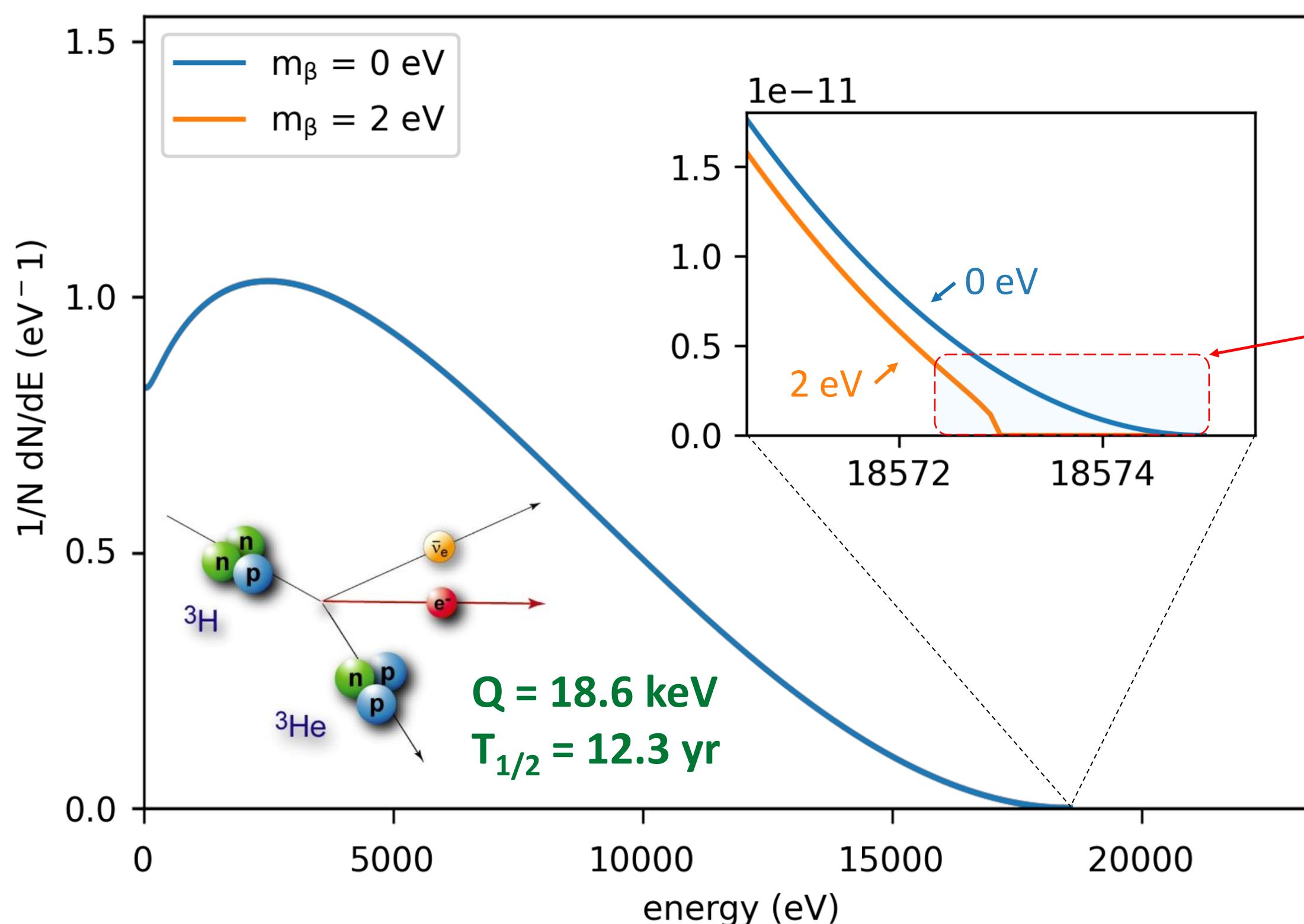
## Super-allowed decay

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

incoherent neutrino mass:

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

S. Mertens et al. (talk): Direct neutrino mass measurements – review  
 A. Lokhov (talk): Probing the neutrino mass scale with the KATRIN experiment



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:  **$O(1\text{eV})$**
- Precise understanding of the spectrum shape

# 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

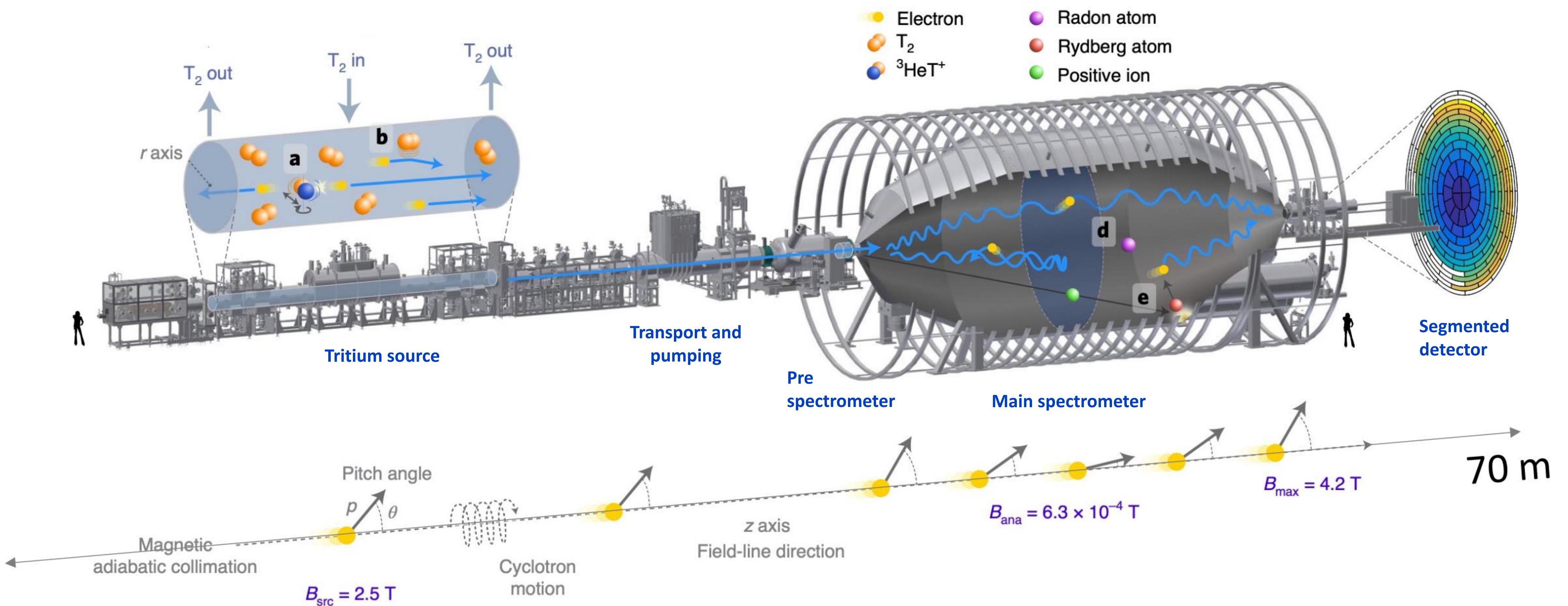
- magnetic guidance
- tritium gas/ion removal
- reduction by  $> 10^{14}$

## Spectrometer

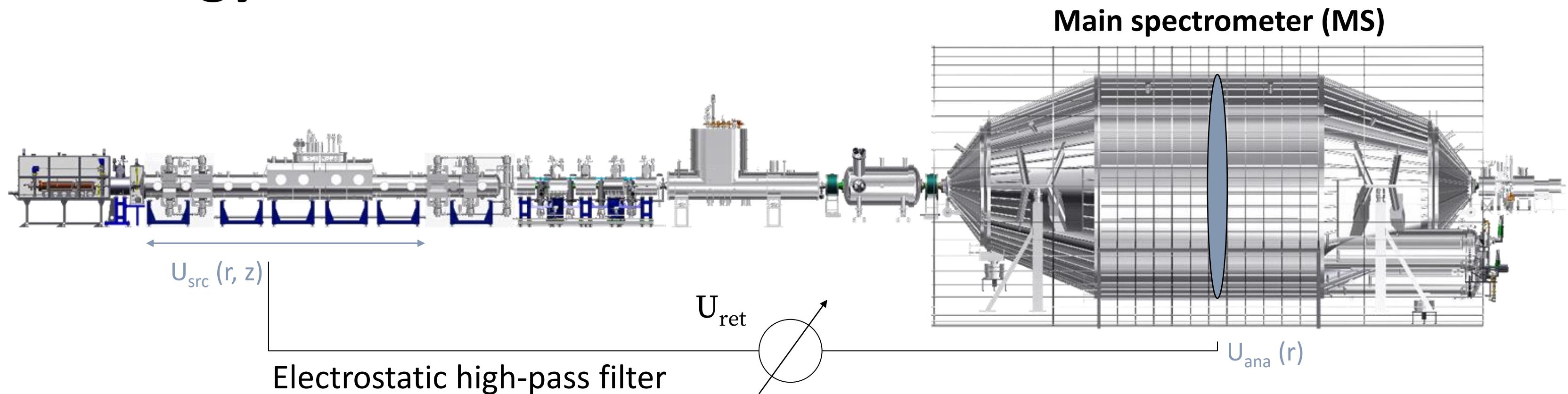
- MAC-E (Magnetic adiabatic collimation + electrostatic filter)
- high resolution:  $O(1)$  eV
- large acceptance angle:  $0\text{--}51^\circ$

## Detector section

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



# Measurement strategy

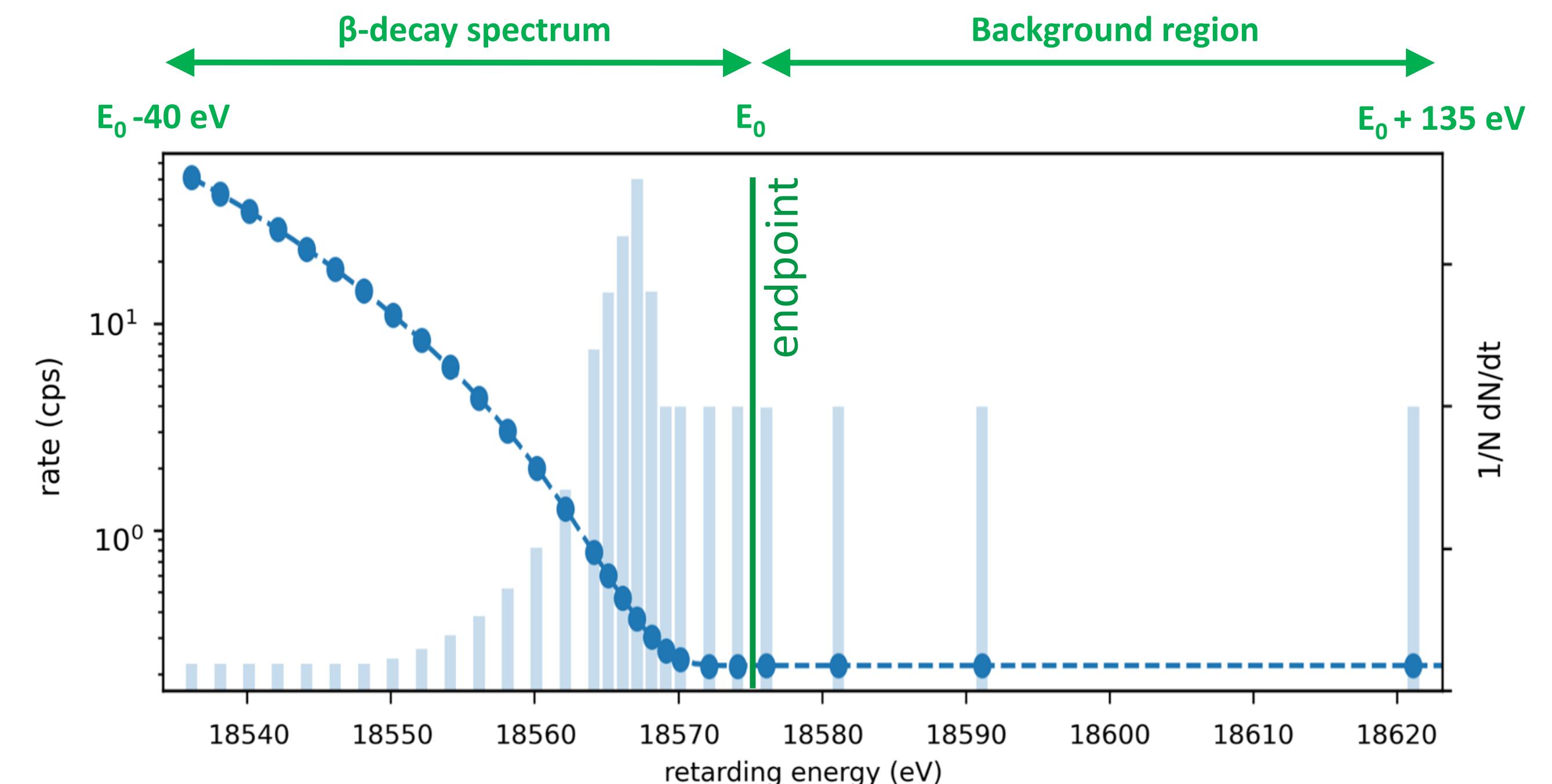


## Integral spectrum measurement

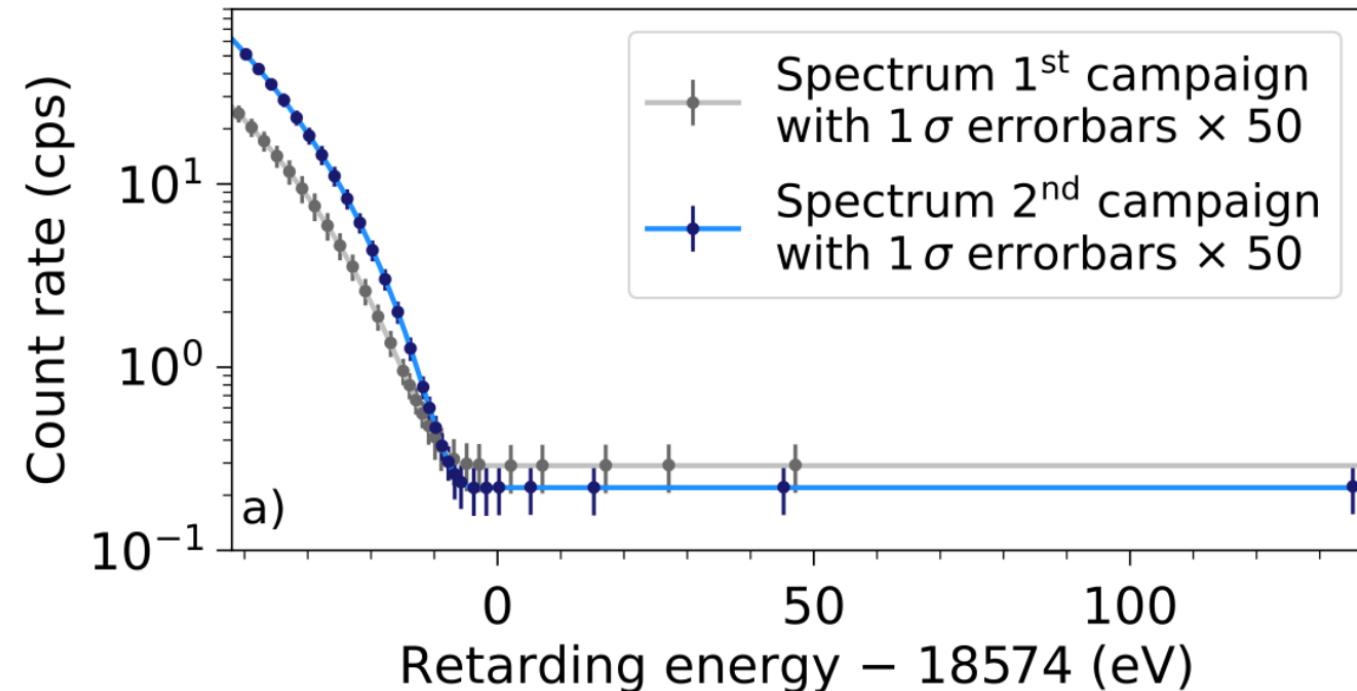
- ~30 scan steps with varying duration
- ~2 h scan duration
- scan interval:  $E_0 - 40 \text{ eV}$ ,  $E_0 + 135 \text{ eV}$

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

$$\Delta E = 2.8 \text{ eV} @ 18.6 \text{ keV}$$



# Beyond neutrino mass in KATRIN



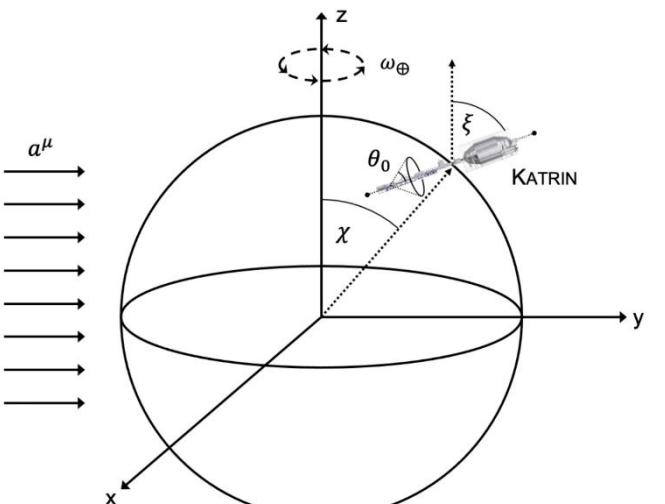
$\beta$  spectrum with high statistics  
and low systematics

**Search for exotic weak interactions**  
 $\Rightarrow$  shape distortion

**Search for Lorentz invariance violation**

[arXiv:2112.13803]

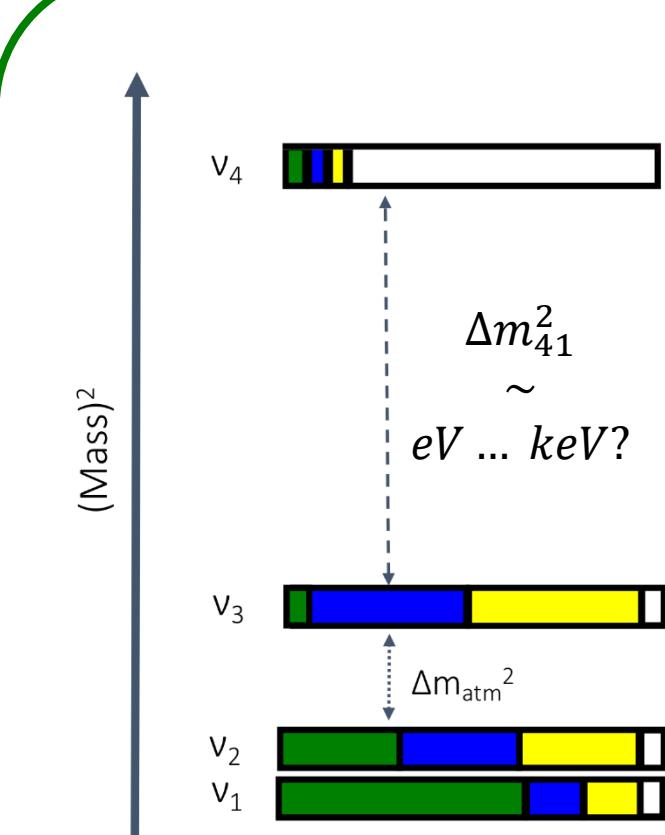
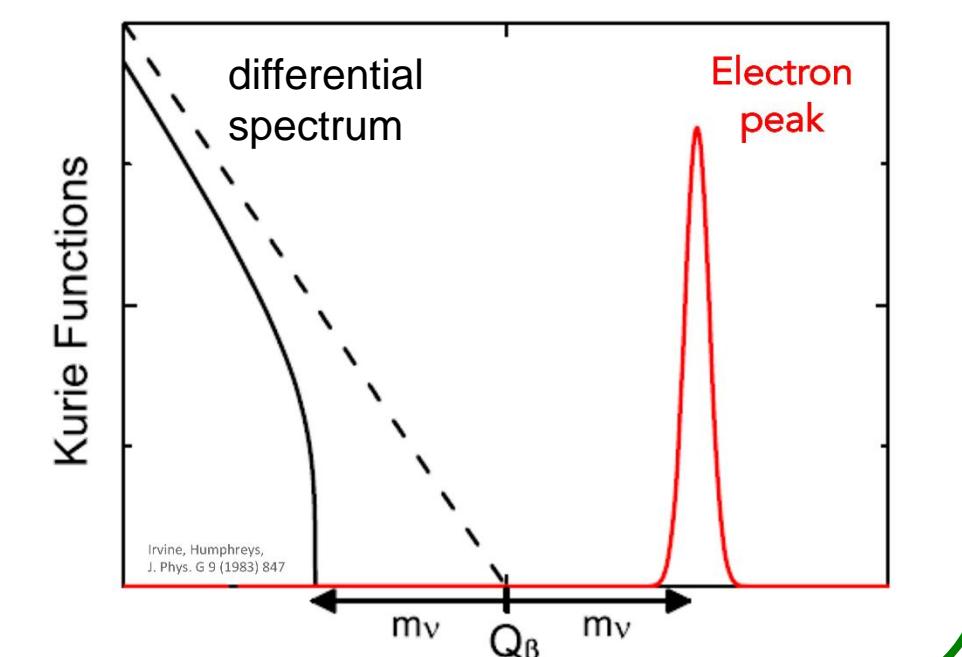
$\Rightarrow$  sidereal modulation



**Constrain local overdensity of cosmic relic neutrinos**

[Phys. Rev. Lett. 129, 011806]

$\Rightarrow$  peak search



**Sterile neutrino search**

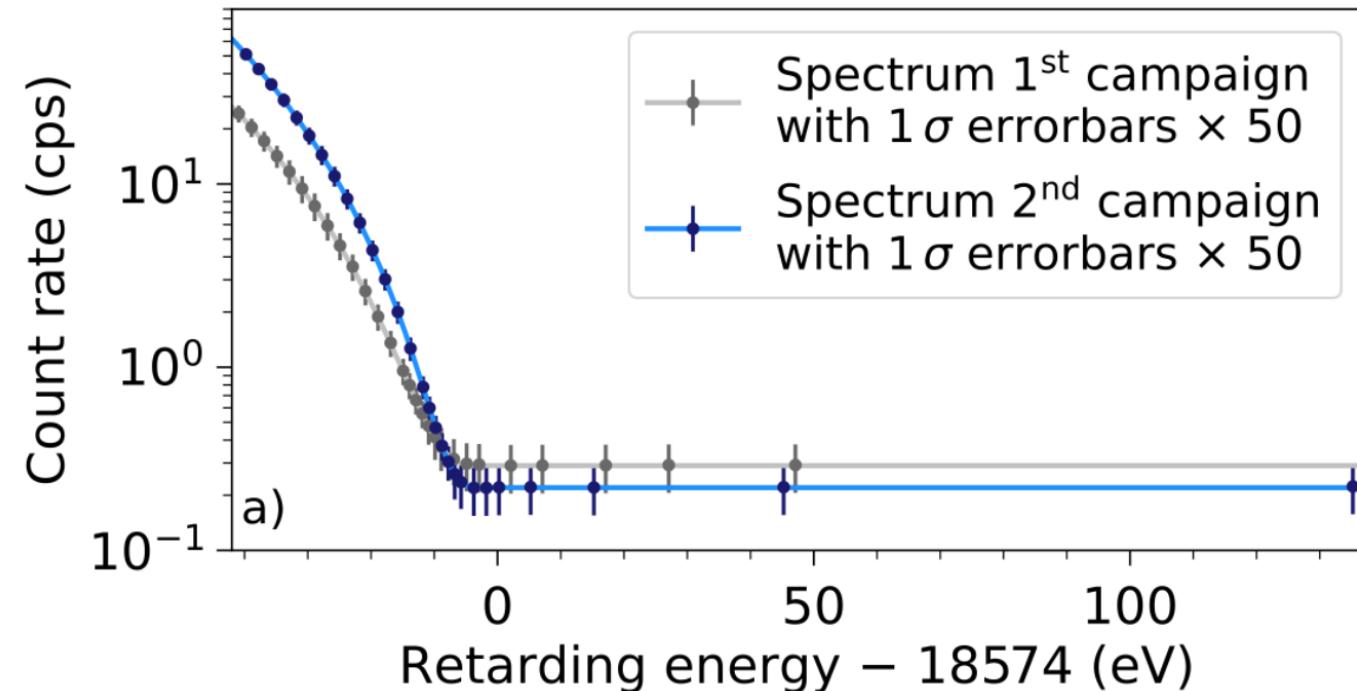
[PRD 105, 072004 (2022)]

[arXiv:2207.06337v1 [nucl-ex] (2022)]

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

$\Rightarrow$  shape distortion

# Beyond neutrino mass in KATRIN



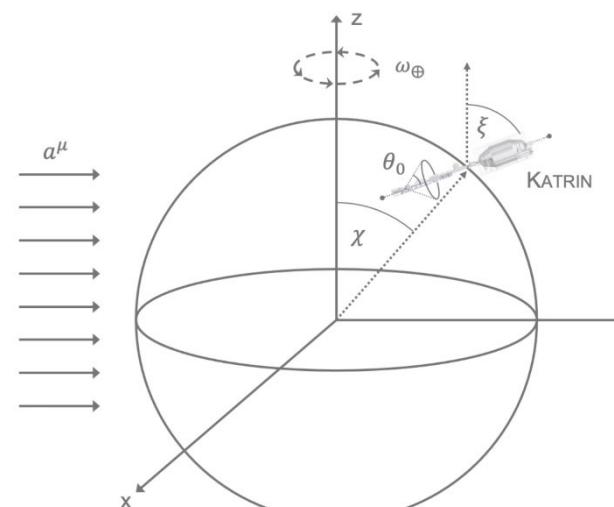
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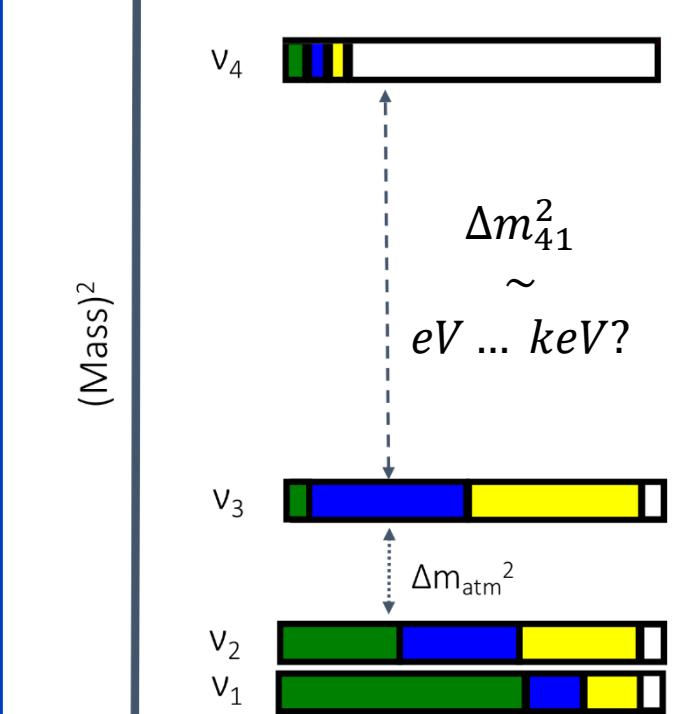
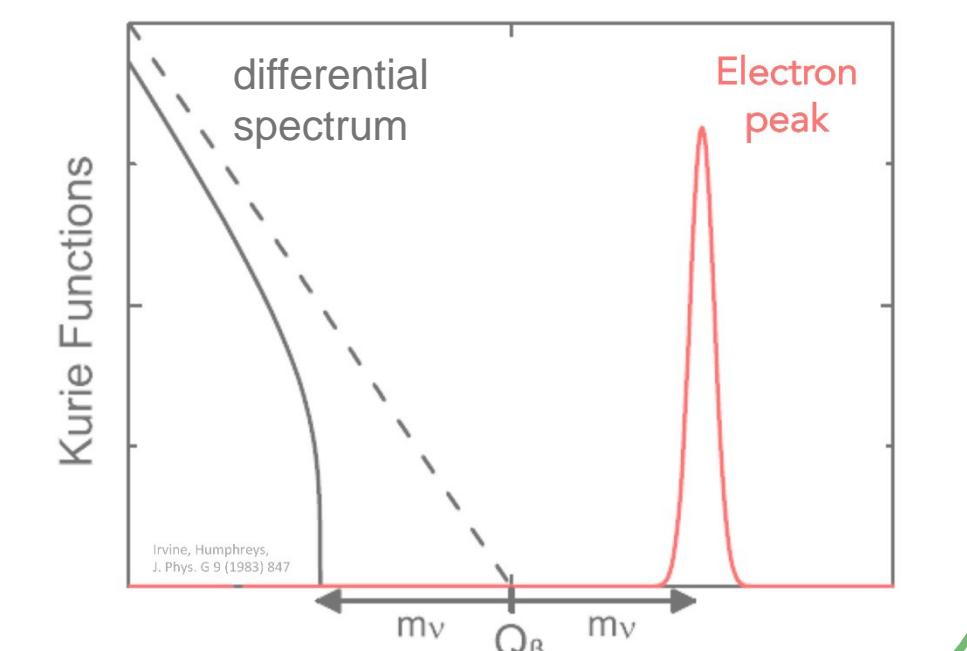
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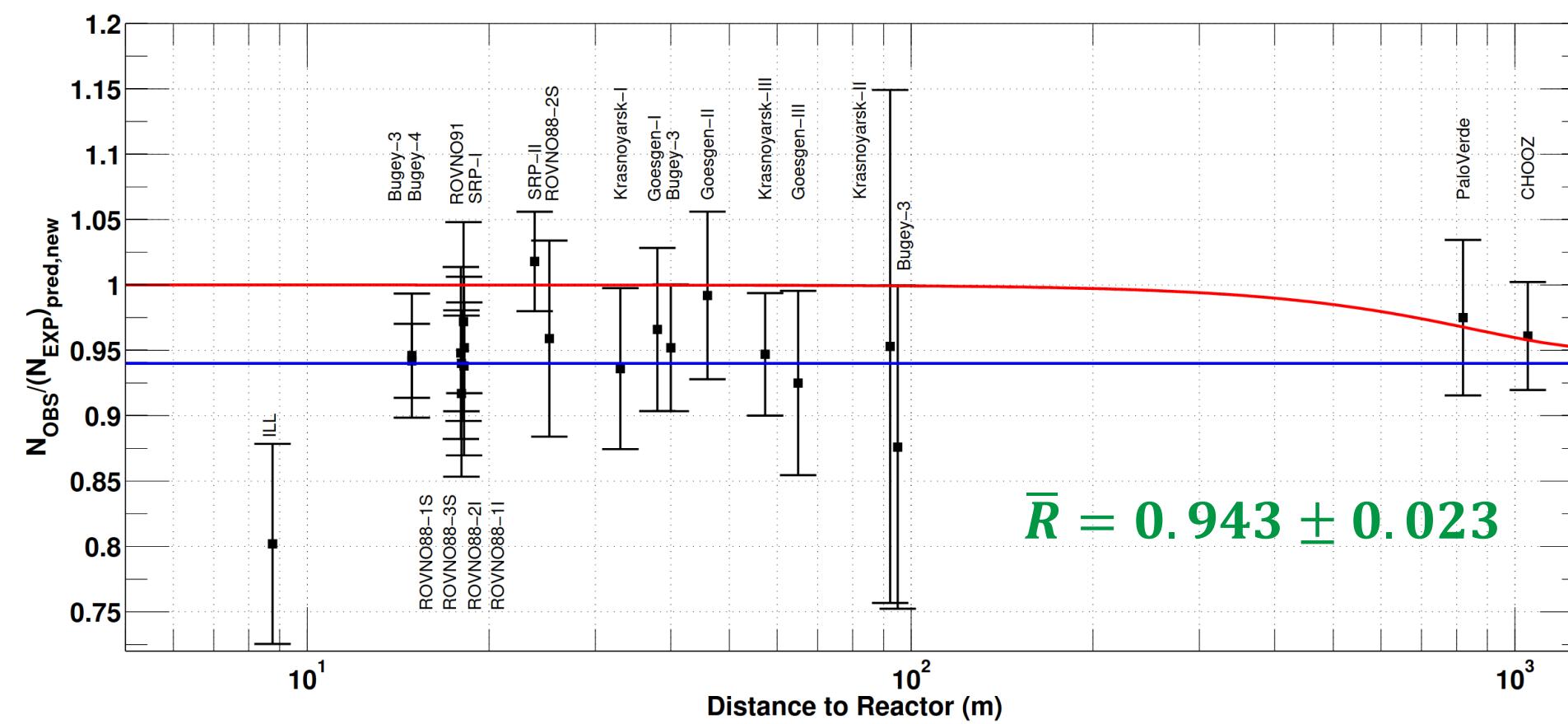
# Sterile neutrino motivation

## eV-scale sterile neutrino search

Several experimental anomalies

- deficit of reactor (RAA,  $\sim 3\sigma$ ) and Gallium flux ( $\sim 4\sigma$ ) measurement to prediction

### Reactor antineutrino anomaly (RAA)

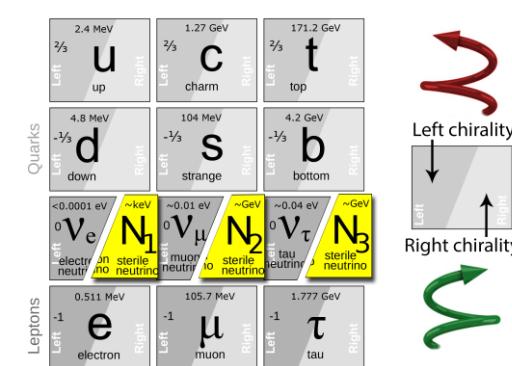


[Phys. Rev. D 83, 073006 (2011)]

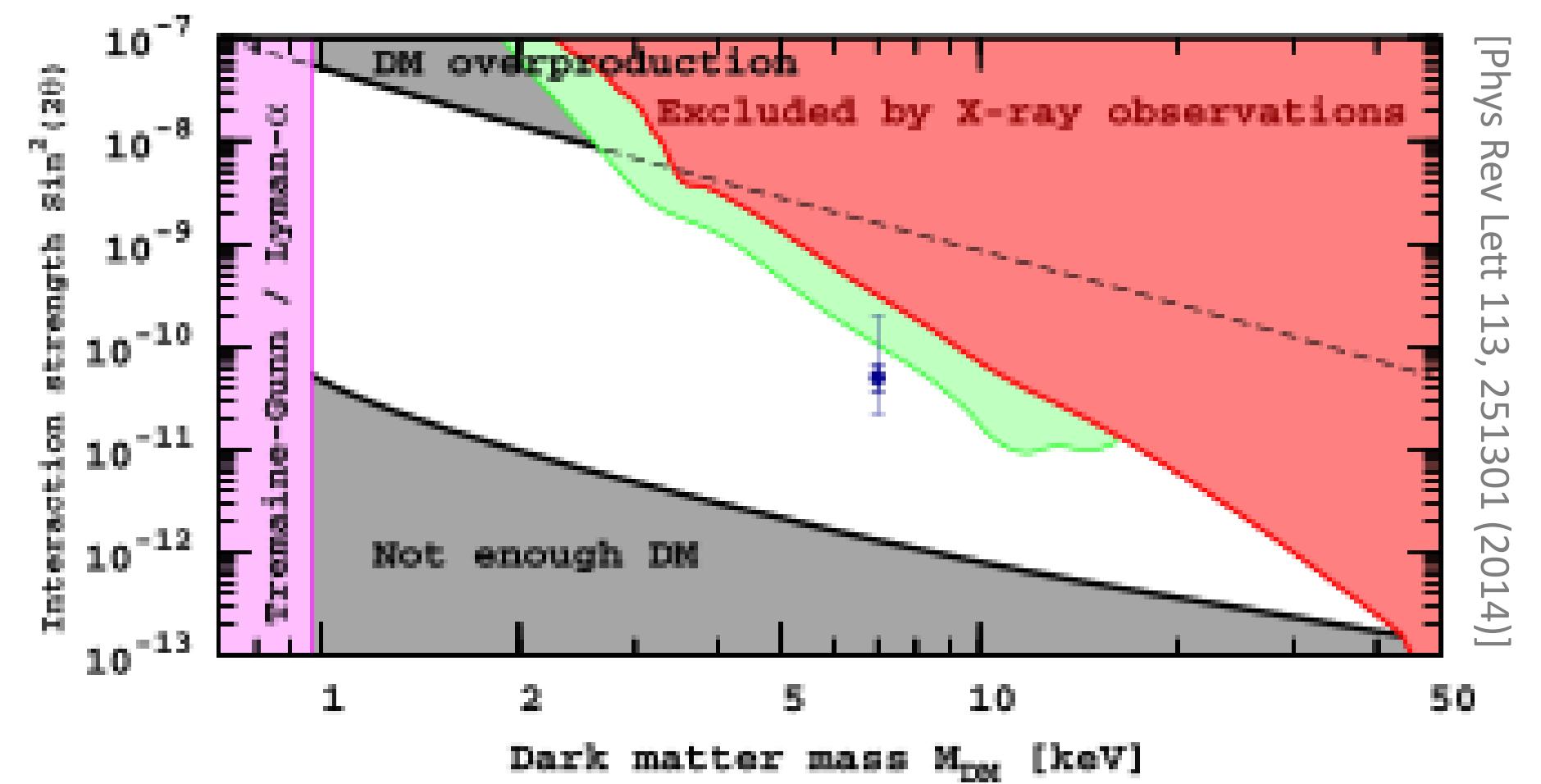
## keV-scale sterile neutrino search

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  $\sim 7$  keV sterile  $\nu$



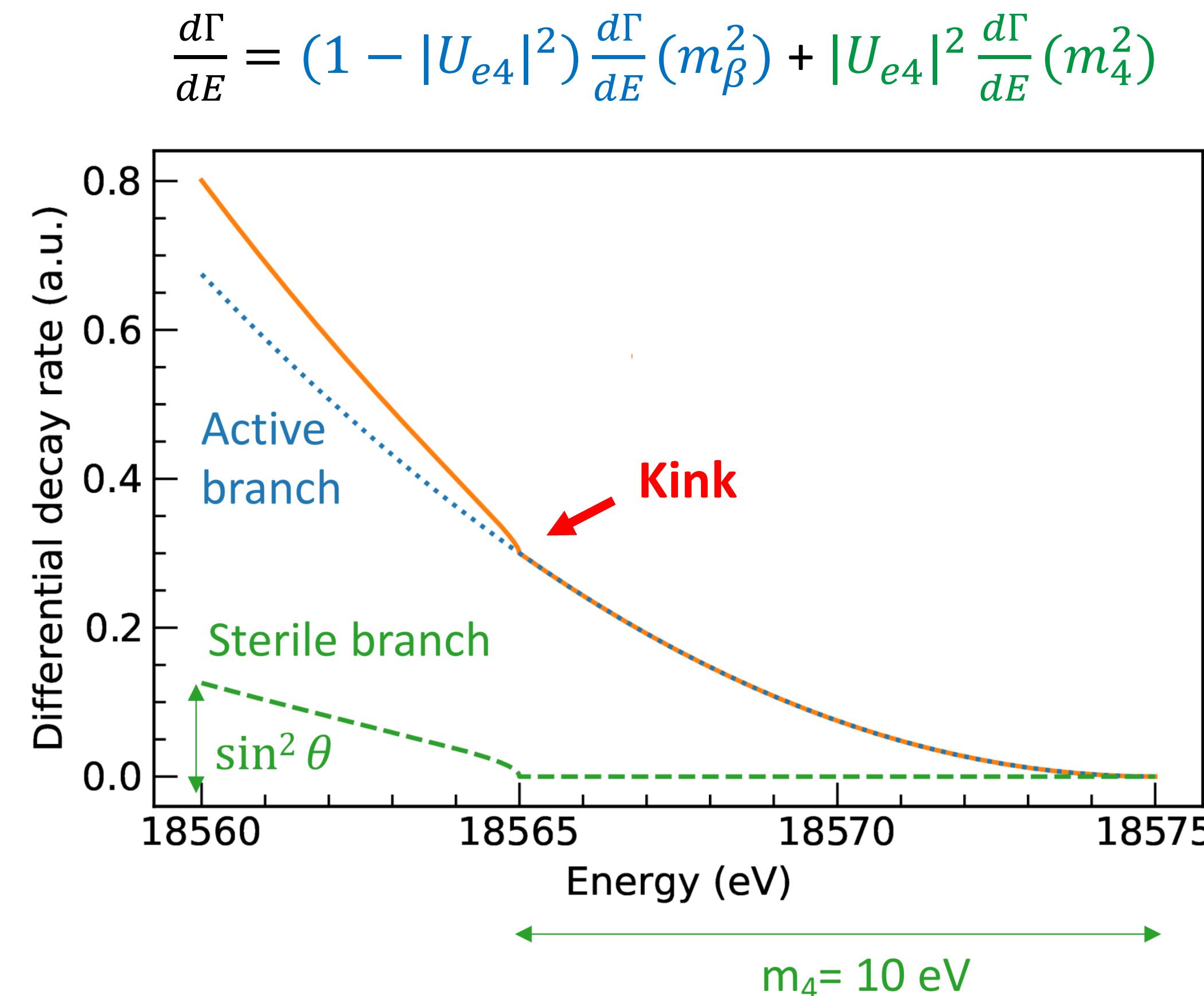
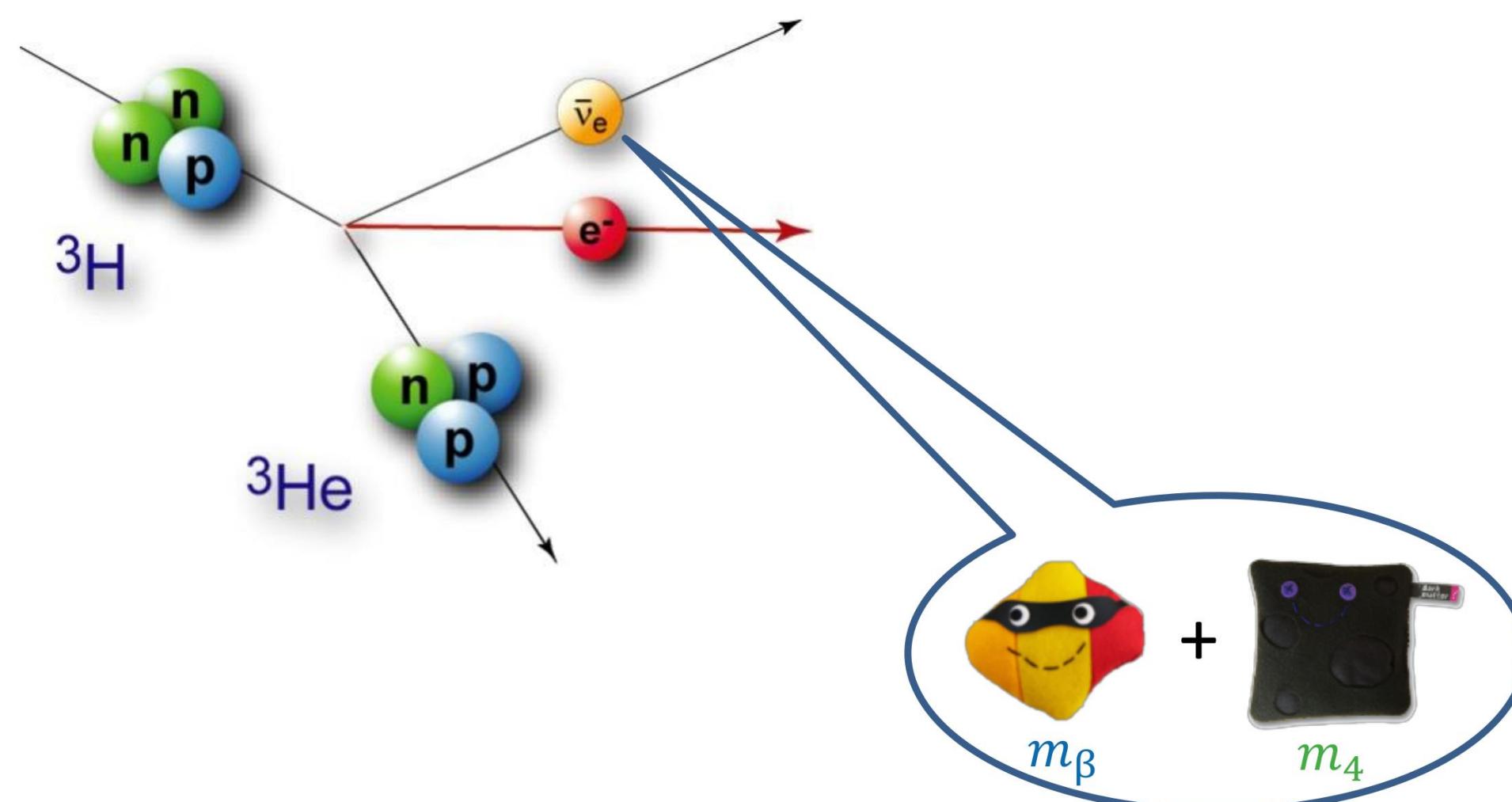
White Paper on keV Sterile Neutrino Dark Matter, arXiv:1602.04816



⇒ Need for model independent experiment across a wide range of mass

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

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

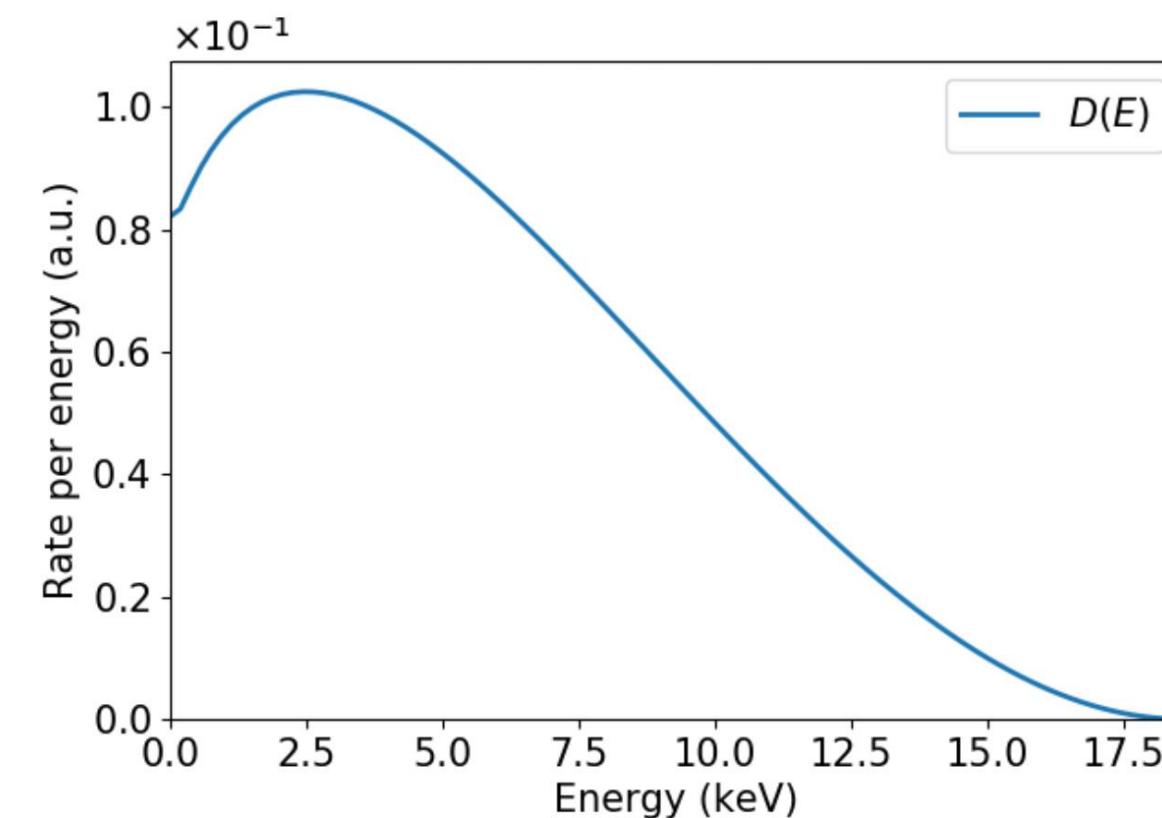


⇒ Accessible in  $\nu$ -mass data sets

# Analysis strategy

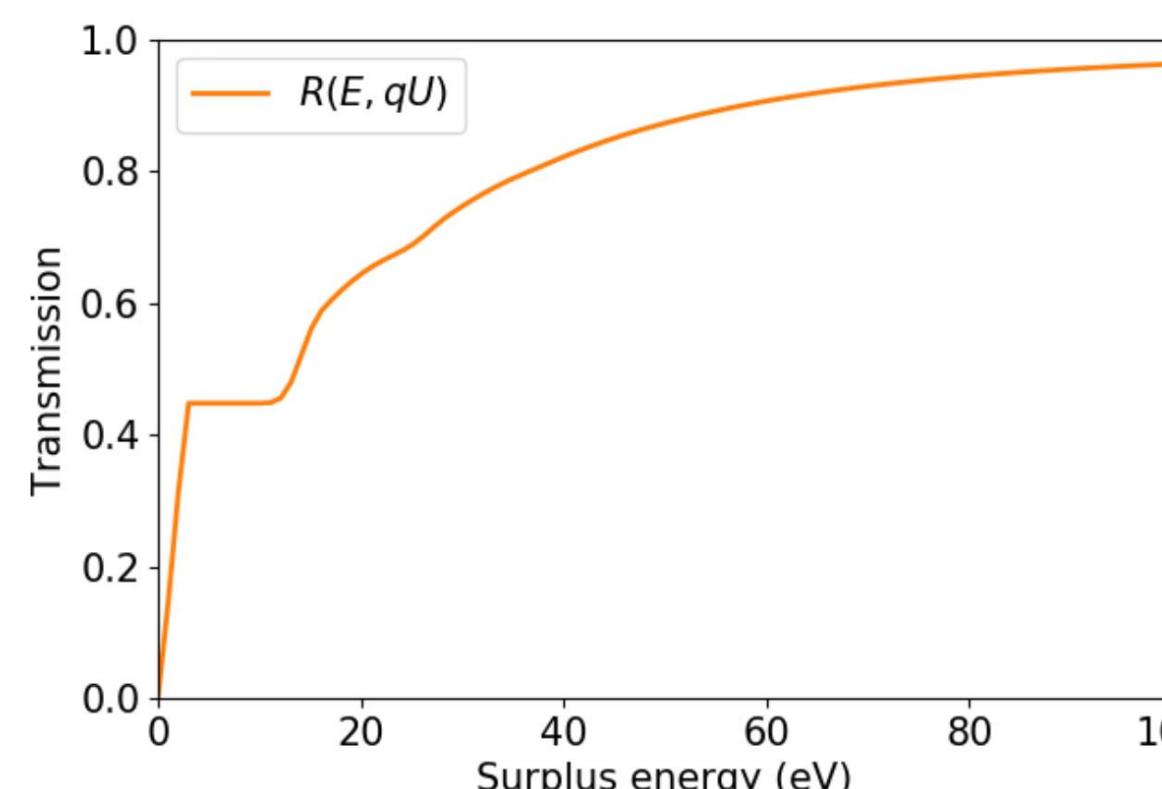
## Beta spectrum

theoretical inputs (Fermi theory, molecular excitations)  
 [Eur. Phys. J. C 79, 204 (2019)]



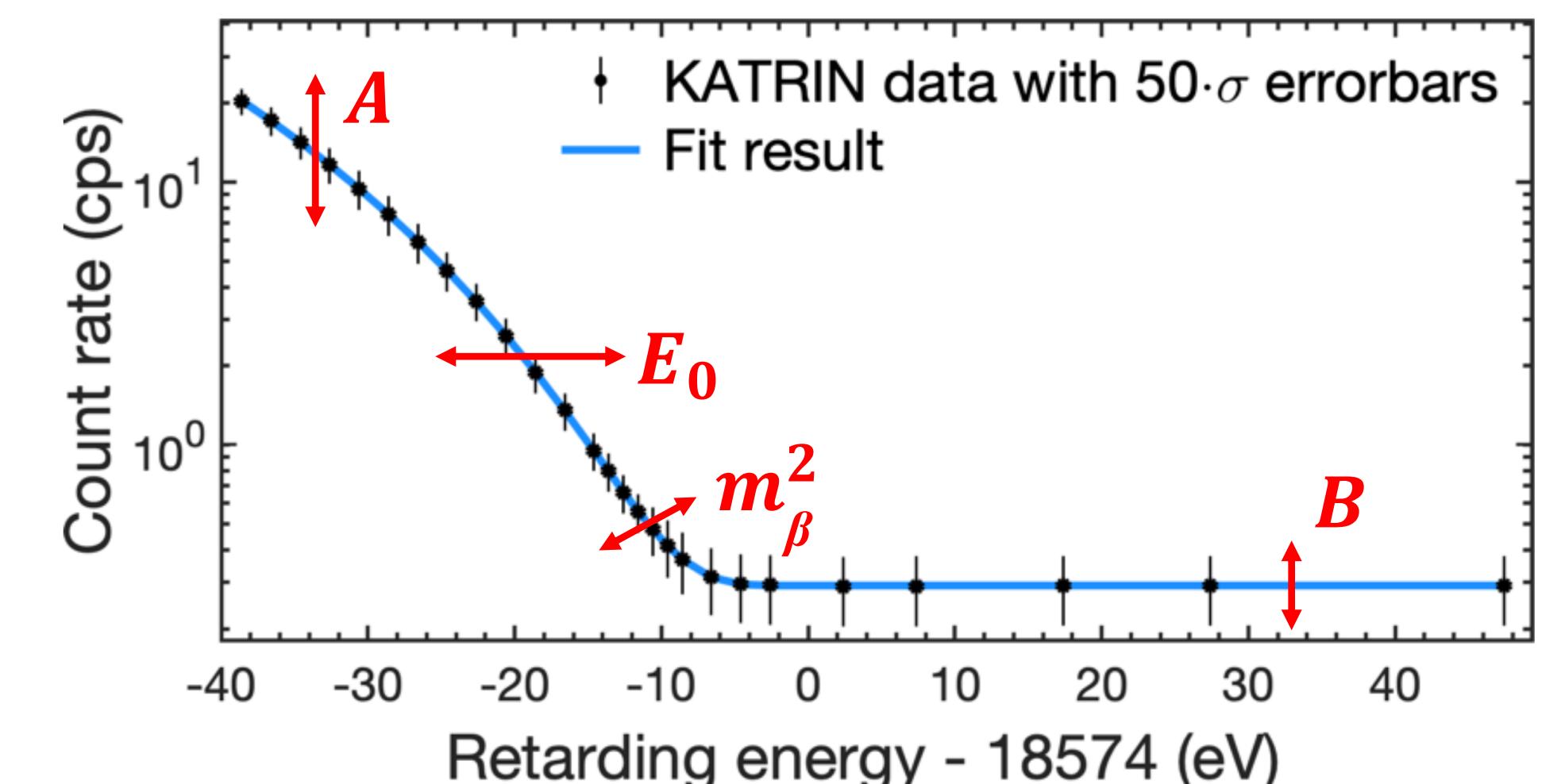
## Response function

experimental data: calibration with  $e^-$ -gun and  $^{83m}\text{Kr}$  conversion electrons [PRD. D 104, 012005 (2021)]



## Expected measured rate

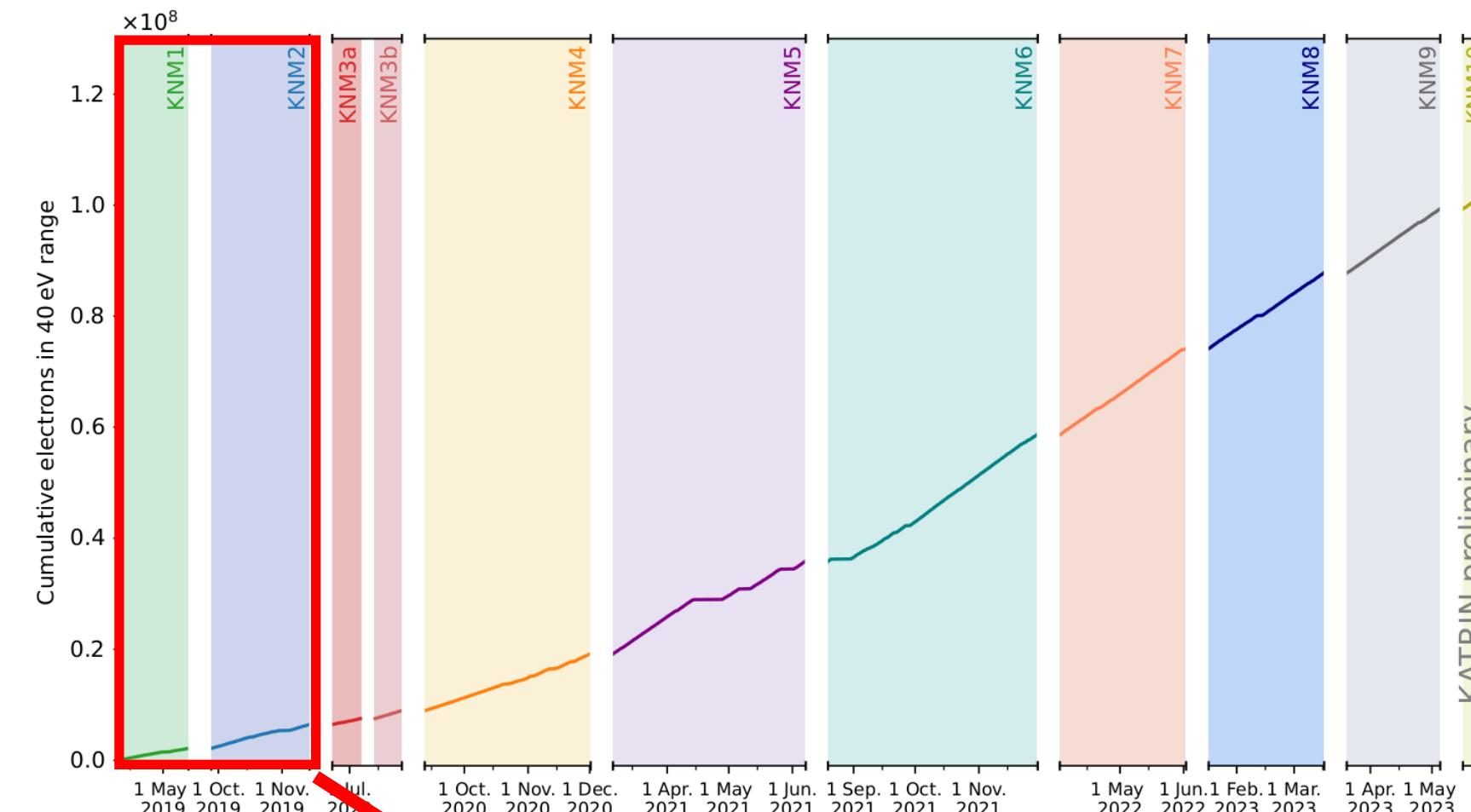
$$\Gamma(qU) = \mathbf{A} \int_{qU}^{E_0} D_\beta(E, \mathbf{m}_{\nu_e}^2, E_0, |U_{e4}|^2, \mathbf{m}_4^2) \cdot R(E, qU) dE + \mathbf{B}$$



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

- free amplitude  $\mathbf{A}$
- endpoint  $E_0$
- background  $\mathbf{B}$
- squared neutrino mass  $\mathbf{m}_\beta^2$
- 4<sup>th</sup> neutrino mass and mixing:  $|U_{e4}|^2, \mathbf{m}_4^2$

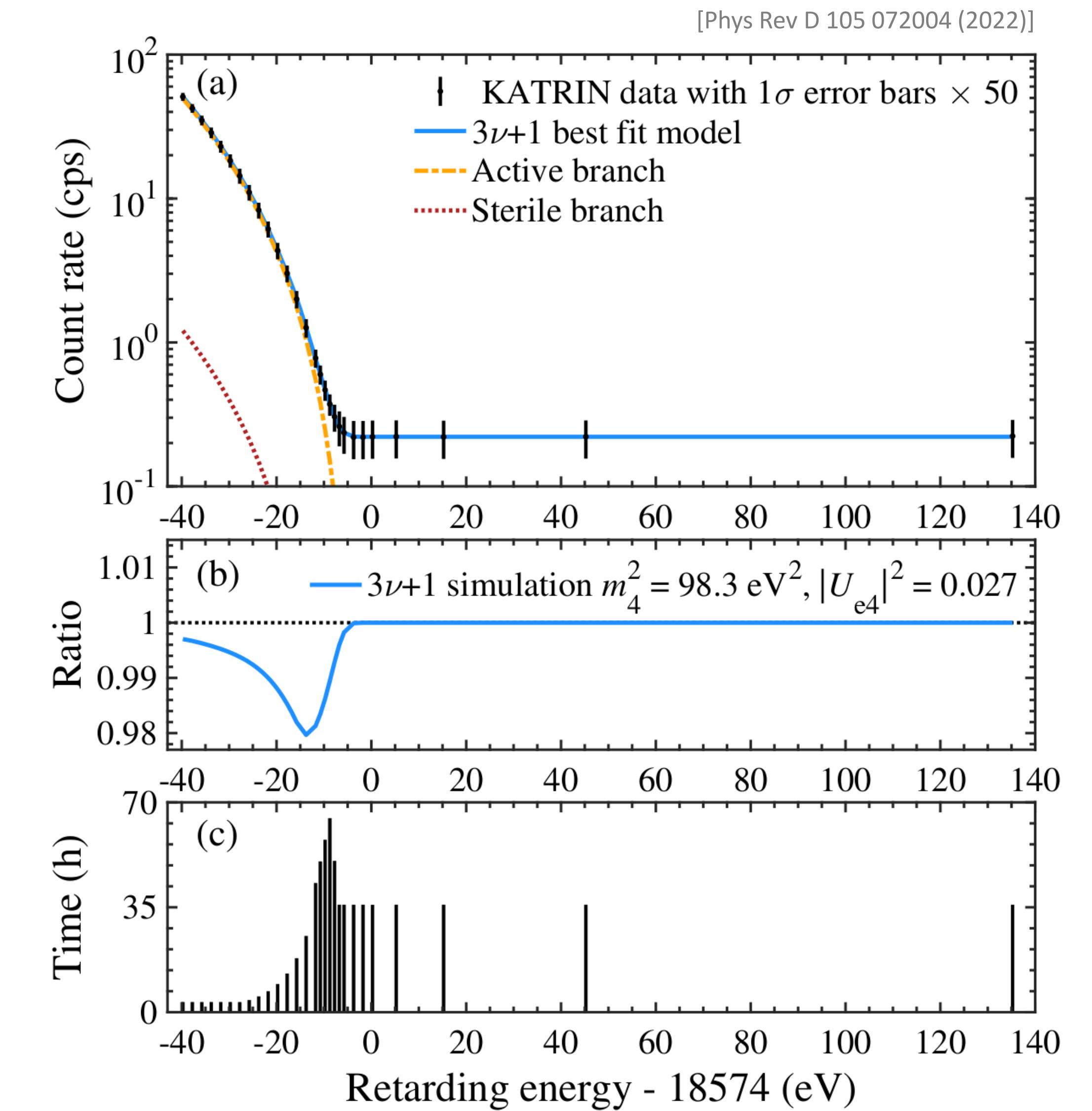
# Sterile neutrino fit – 1<sup>st</sup> + 2<sup>nd</sup> campaign



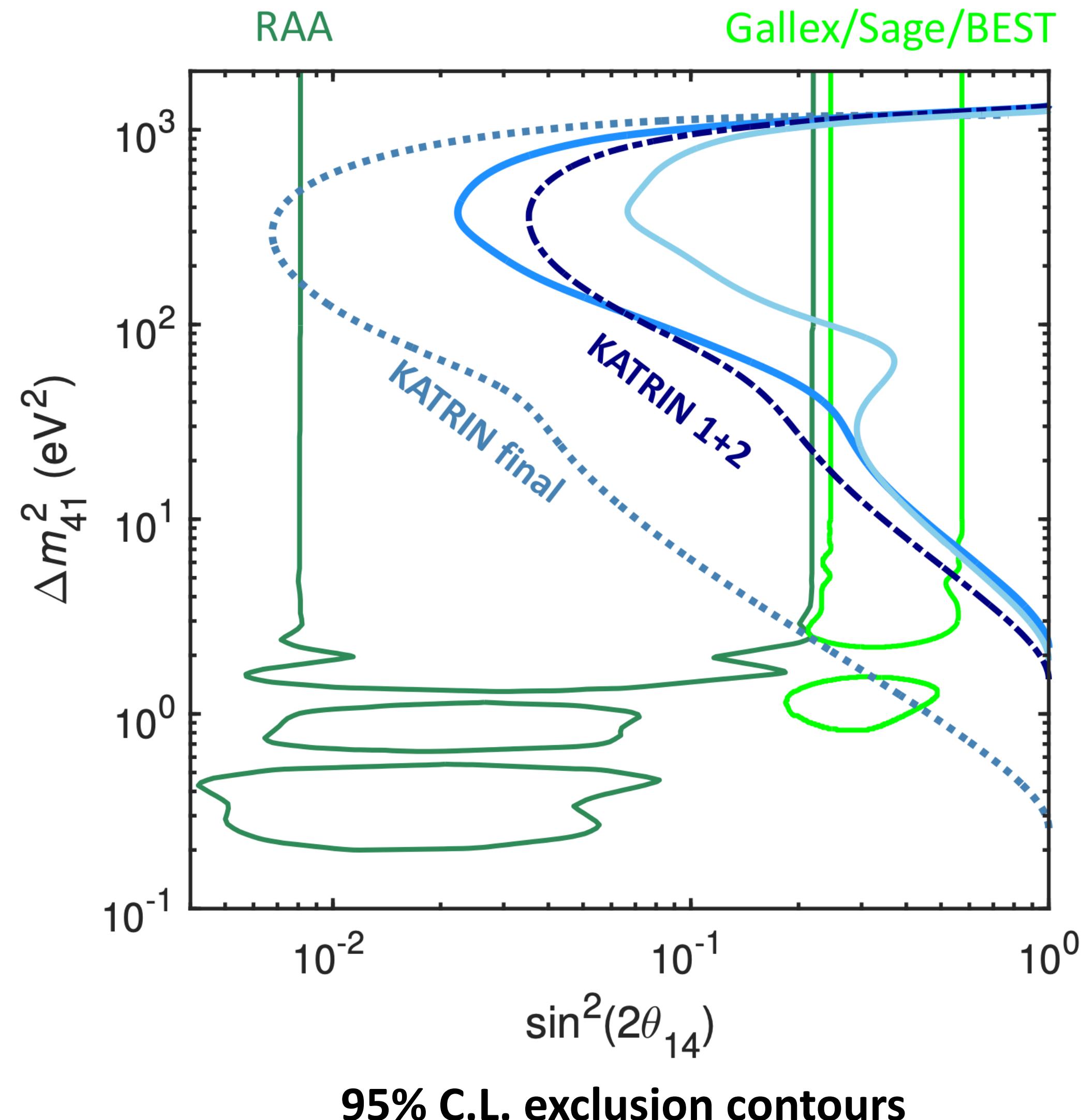
## 1<sup>st</sup> + 2<sup>nd</sup> campaign

- ~1265 h of data
- ~ $6 \cdot 10^6$  e<sup>-</sup> in the ROI
- ~5% of the expected final statistic

⇒ No significant sterile-neutrino signal  
is observed in KATRIN

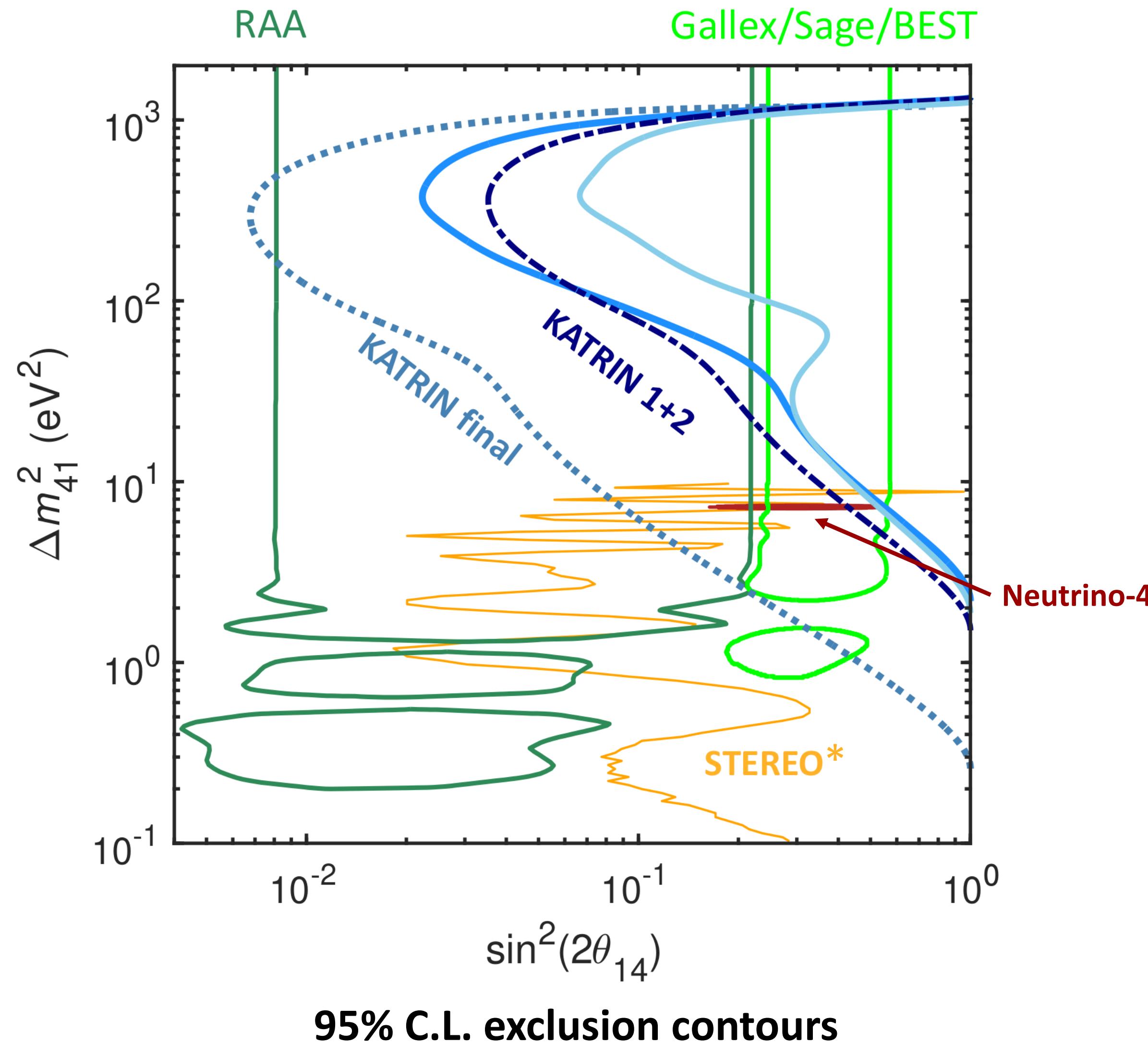


# Overview of sterile experiment results



- KATRIN uncertainty dominated by the statistic
- Exclude large  $\Delta m_{41}^2$  solutions from the reactor antineutrino and gallium anomaly

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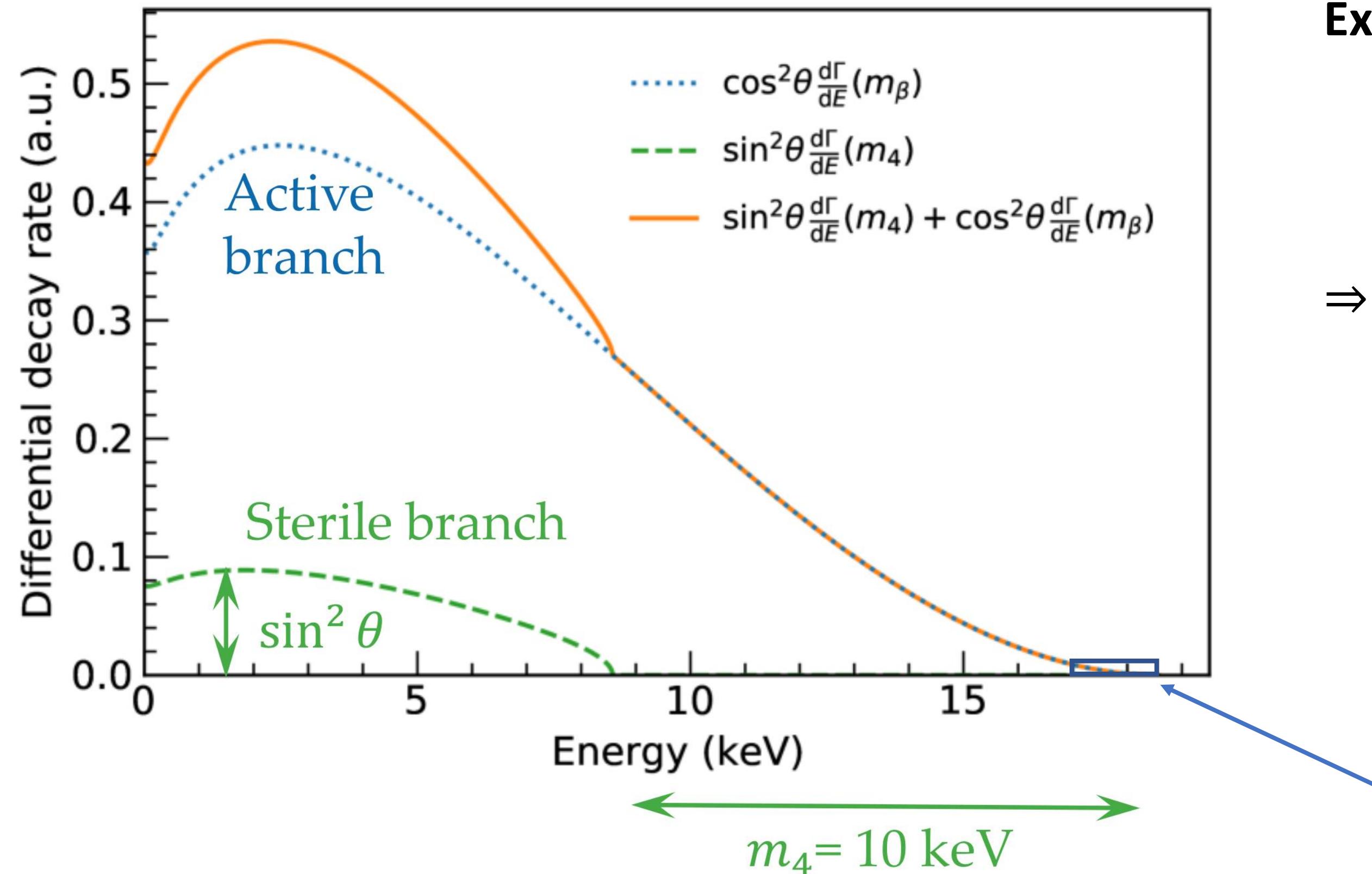


- KATRIN uncertainty dominated by the statistic
- Exclude large  $\Delta m_{41}^2$  solutions from the reactor antineutrino and gallium anomaly
- Improve the exclusion bounds set by short-baseline oscillation experiments for  $\Delta m_{41}^2 \gtrsim 10$  eV<sup>2</sup>
- KATRIN will probe the positive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

⇒ KATRIN provide a complementary probe of eV sterile neutrino

L. Köllenberger & al. (poster): Search for light sterile neutrinos with the KATRIN experiment

# keV sterile neutrino search with KATRIN



## Experimental challenge:

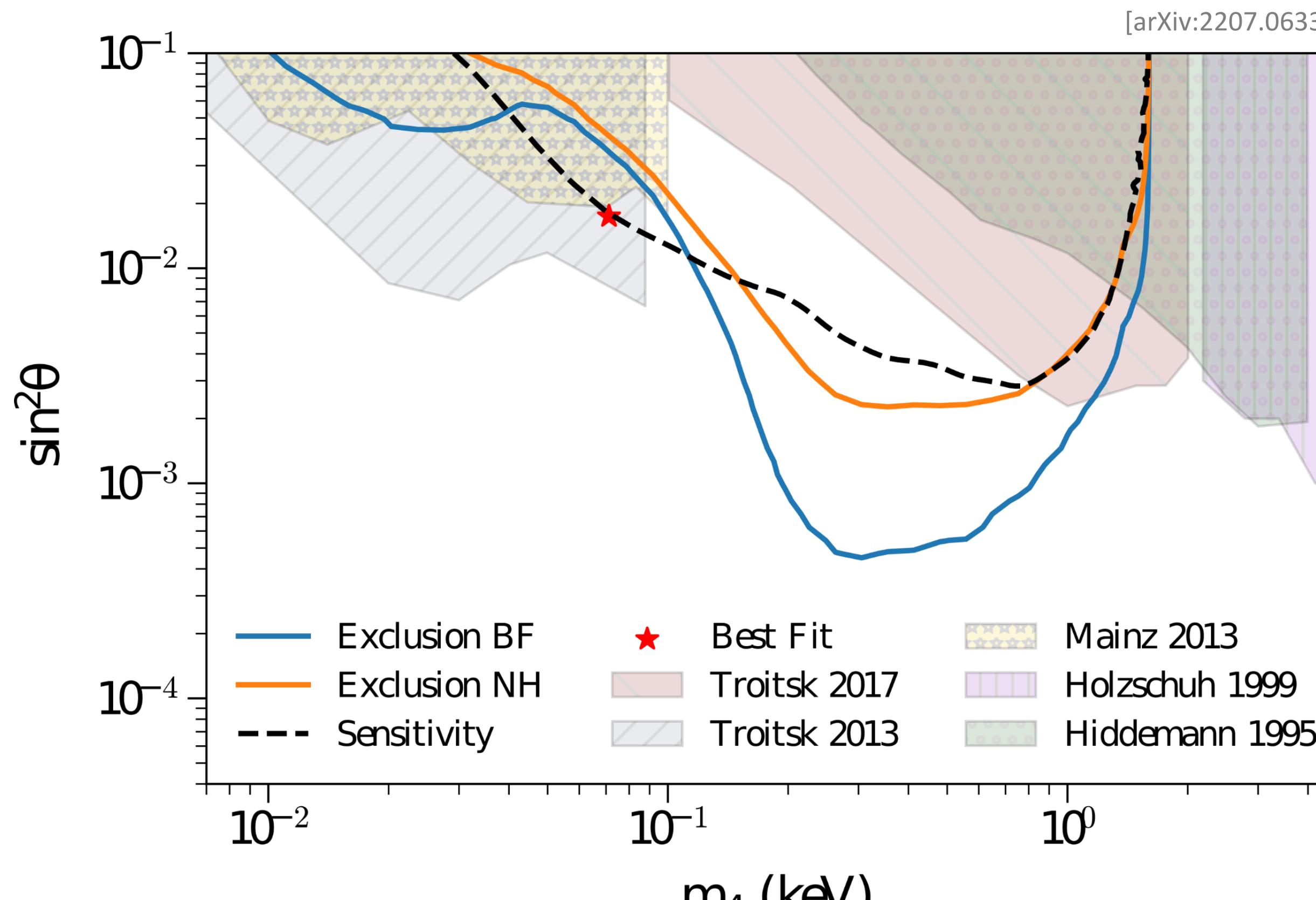
- detector system not design to handle very high data rates
- source activity stability limit sensitivity with integral measurement

⇒ Search not possible in  $\nu$ -mass data set

12 days commissioning campaign in 2018

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

# 1<sup>st</sup> KATRIN results for keV sterile



- No keV-sterile neutrino signal was observed
- Exclusion limits competitive with previous laboratory-based searches
- Improved laboratory-based bounds for  $0.1 \text{ keV} < m_4 < 1.0 \text{ keV}$

Successful demonstration of feasibility using current KATRIN detector ✓  
 ⇒ New detector required for high rate β-spectroscopy

# TRISTAN project

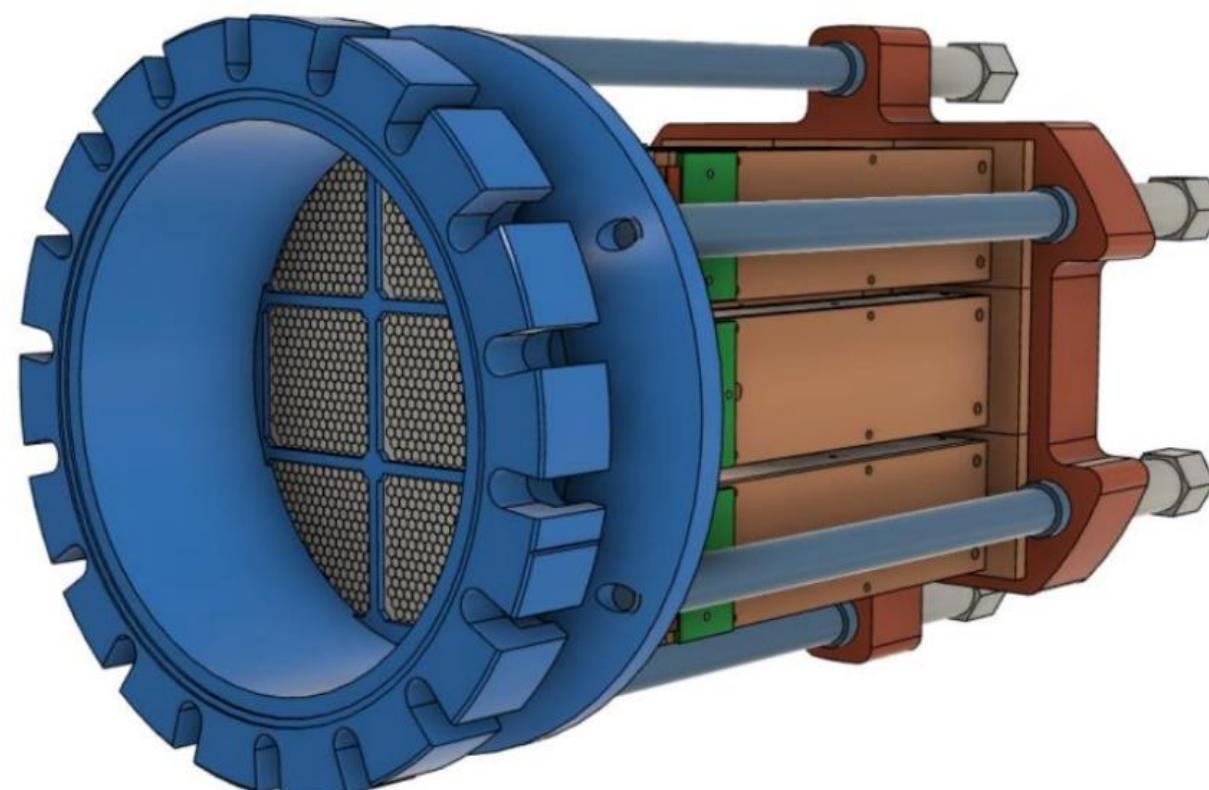
## Tritium Beta Decay to Search for Sterile Neutrinos

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

→ Beamline integration planned for 2025: largest SDD array ever operated

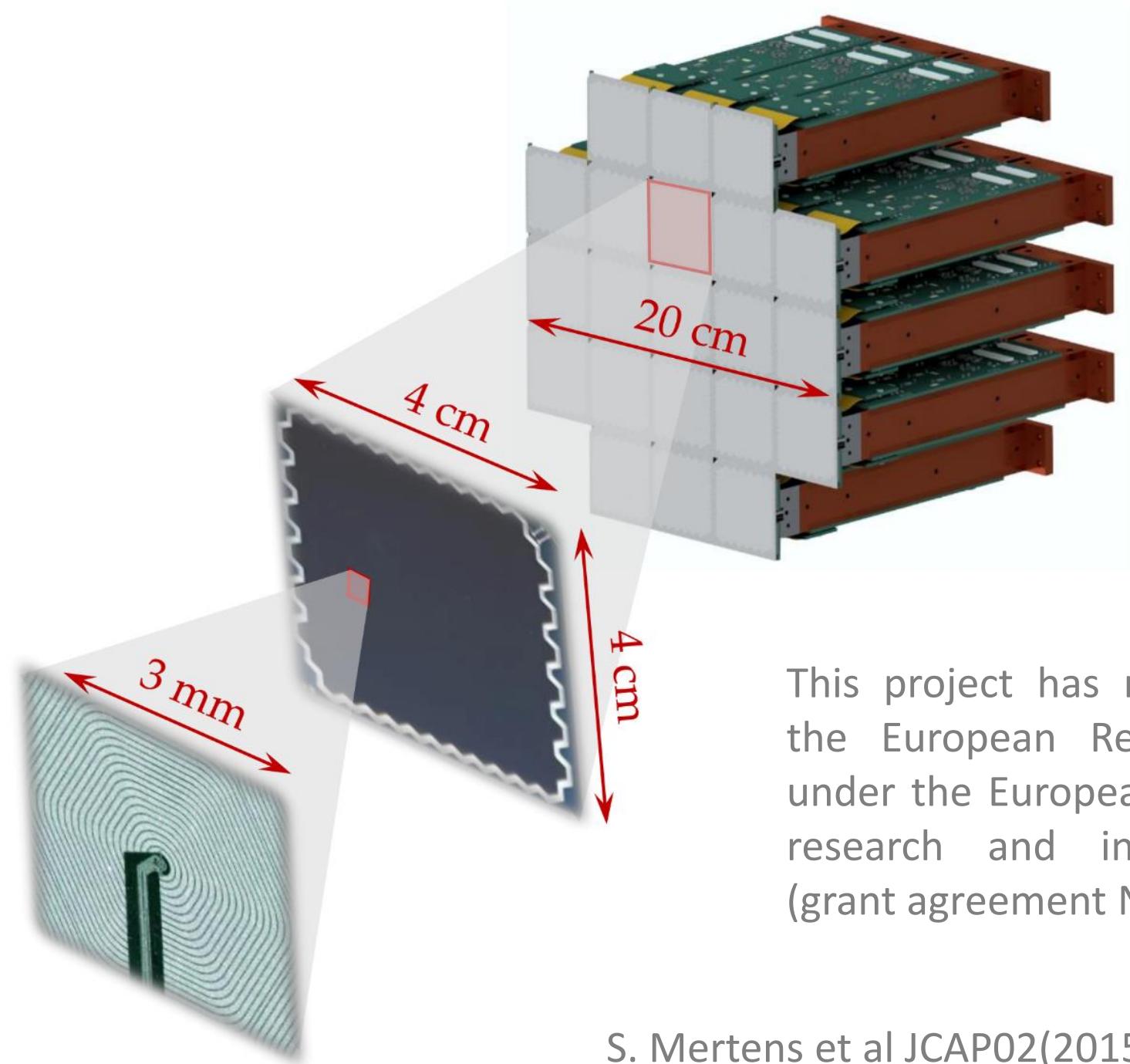
### Phase 1

- 9 modules
- 1500 pixels



### Phase 2

- 21 modules
- 3500 pixels



This project has received funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme (grant agreement No. 852845)

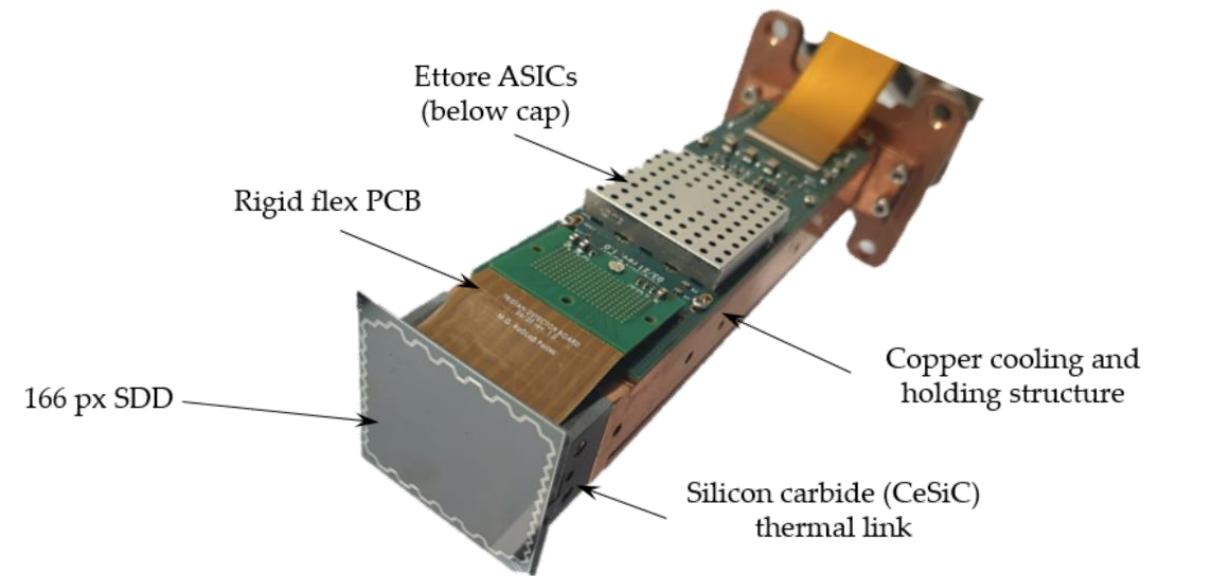
S. Mertens et al JCAP02(2015)020  
 Mertens et al, J. Phys. G46 (2019)



⇒ Measurement of tritium differential energy spectrum

# Detector performance

- SDD production started
- Performance characterization with X-rays, electrons and laser sources: *energy resolution, linearity, timing....*

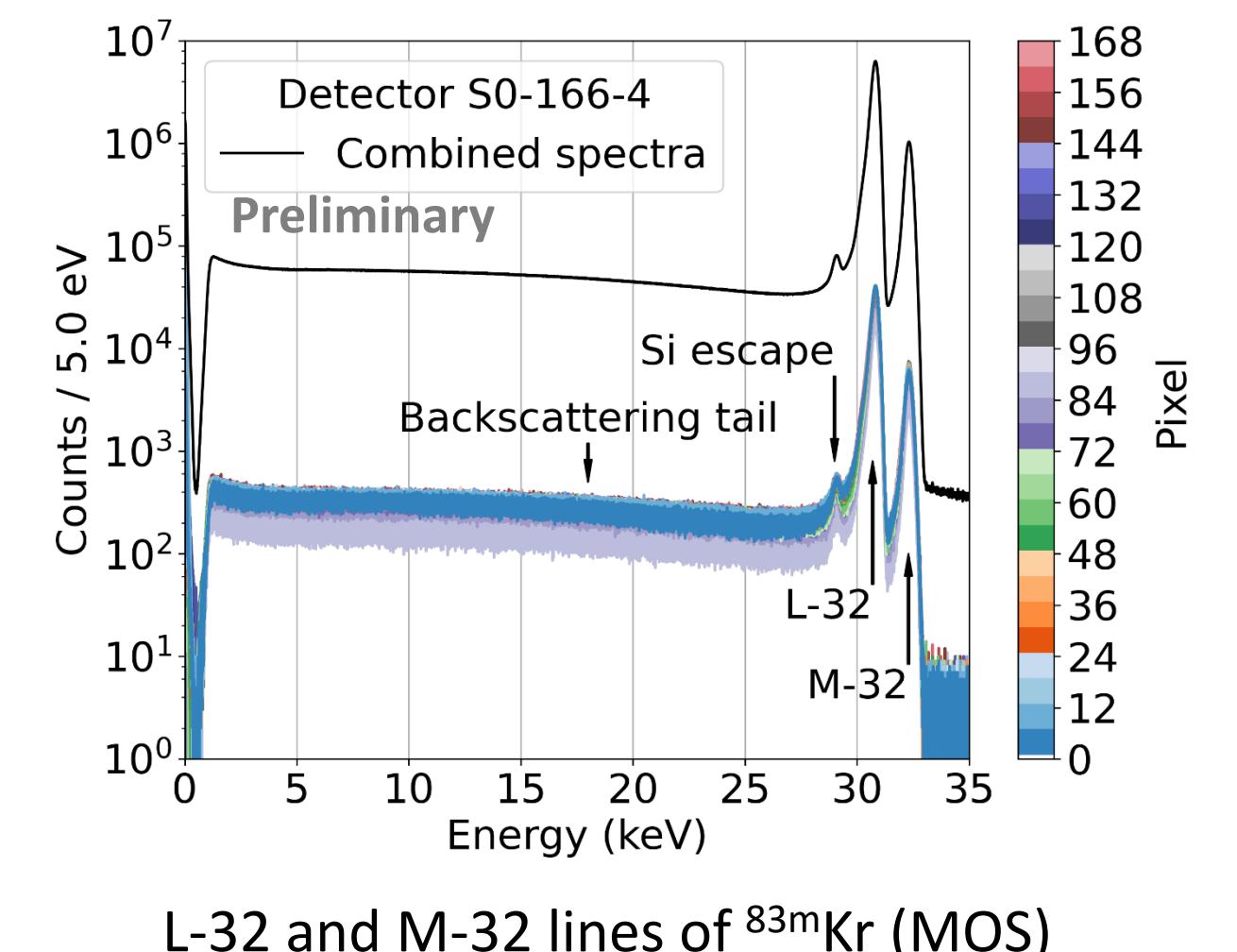
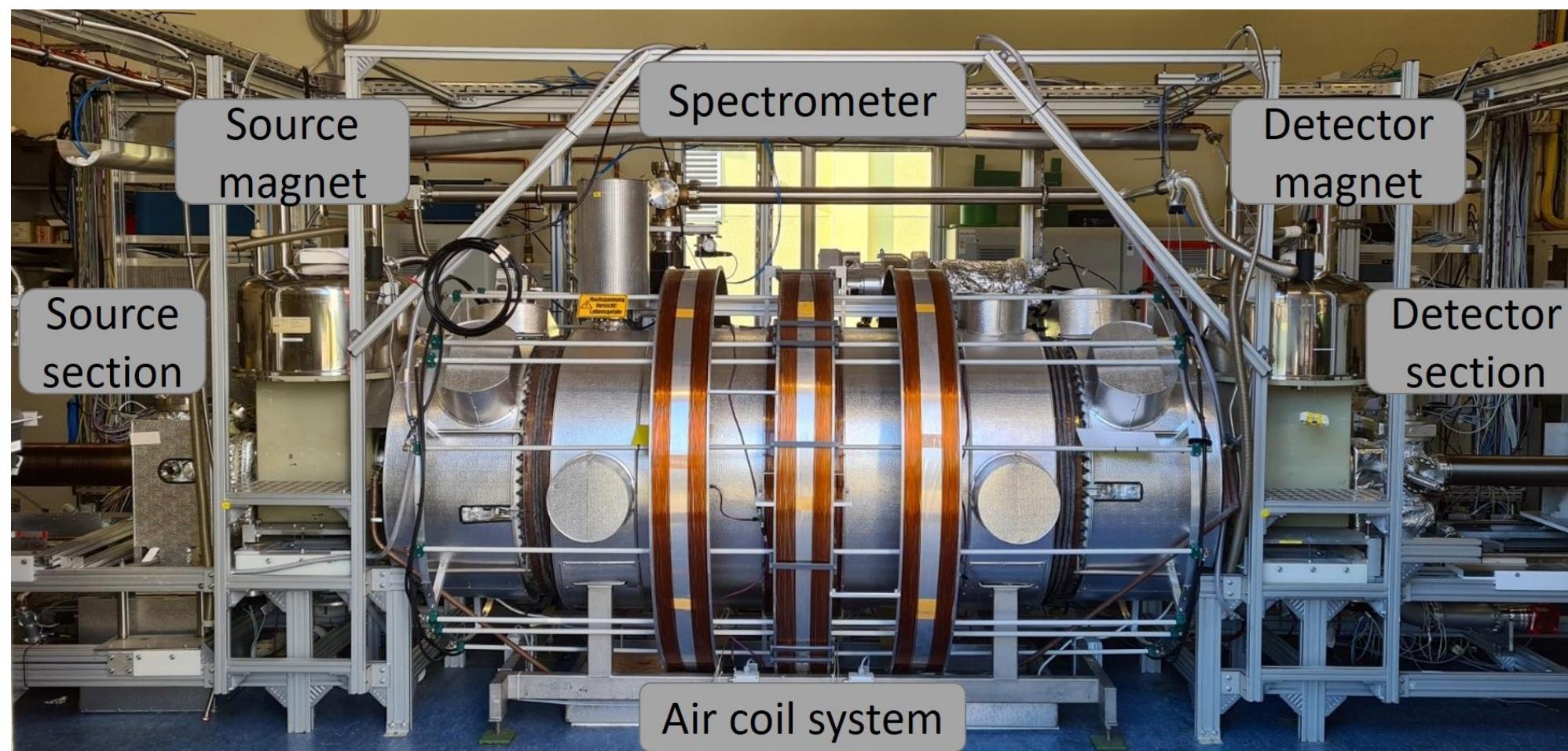


**TRISTAN detector module** with 166 pixels

## First measurement at MOnitor Spectrometer (MOS)

*Test setup for potential hardware upgrades of KATRIN*

*Publication in preparation!*

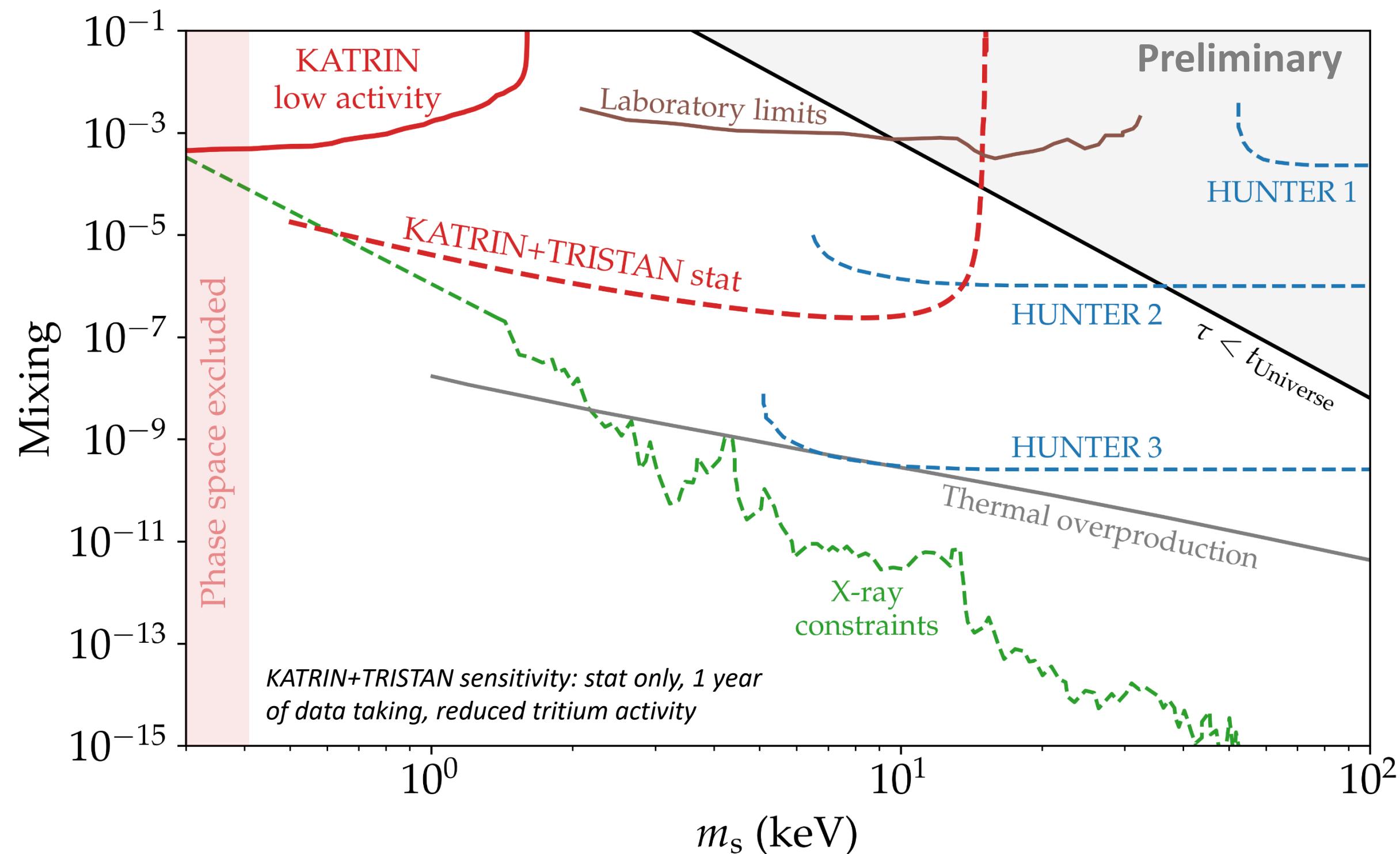


## Good performance matching requirement demonstrated ✓

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

K. Urban (poster): A novel detector for searching keV-sterile neutrinos at the KATRIN experiment  
A. Nava (poster): A model for the KATRIN differential Tritium spectrum to search for keV sterile neutrinos

# 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

Data from:

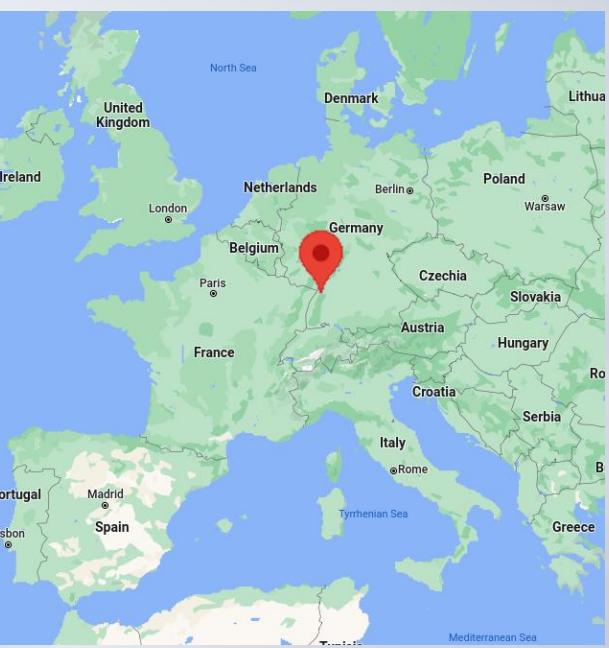
- F. Bezrukov et al., JCAP 06, 051 (2017)  
 J. N. Abdurashitov et al., JETP Letters 105, 12 (2017)  
 F. Benso et al., Phys. Rev. D 100, 115035 (2019)  
 C. J. Martoff et al., Quantum Sci. Technol. 6 024008 (2021)  
 S. Friedrich et al., Phys. RM. Aker et al., arXiv:2207.06337 (2022)  
 ev. Lett. 126, 021803 (2021)

# Conclusion and outlook

KATRIN design to measure neutrino mass

- Suitable to search for eV-sterile neutrinos with current setup
  - ↳ competitive and complementary results to short baseline experiments
- Search for keV-sterile neutrinos with novel TRISTAN detectors after 2025
  - ↳ successful demonstration of feasibility achieved using current KATRIN detector. Improved laboratory-based bounds for  $0.1 \text{ keV} < m_4 < 1.0 \text{ keV}$
  - ↳ Several order of magnitude improvement of current laboratory limits expected with TRISTAN

# Karlsruhe Tritium Neutrino Experiment



*Thank you for your attention!*

