keV sterile neutrino search with the KATRIN experiment

Anthony Onillon, Technical University of Munich

On behalf of the KATRIN collaboration

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Physics Department University of Genoa, Italy

Introduction

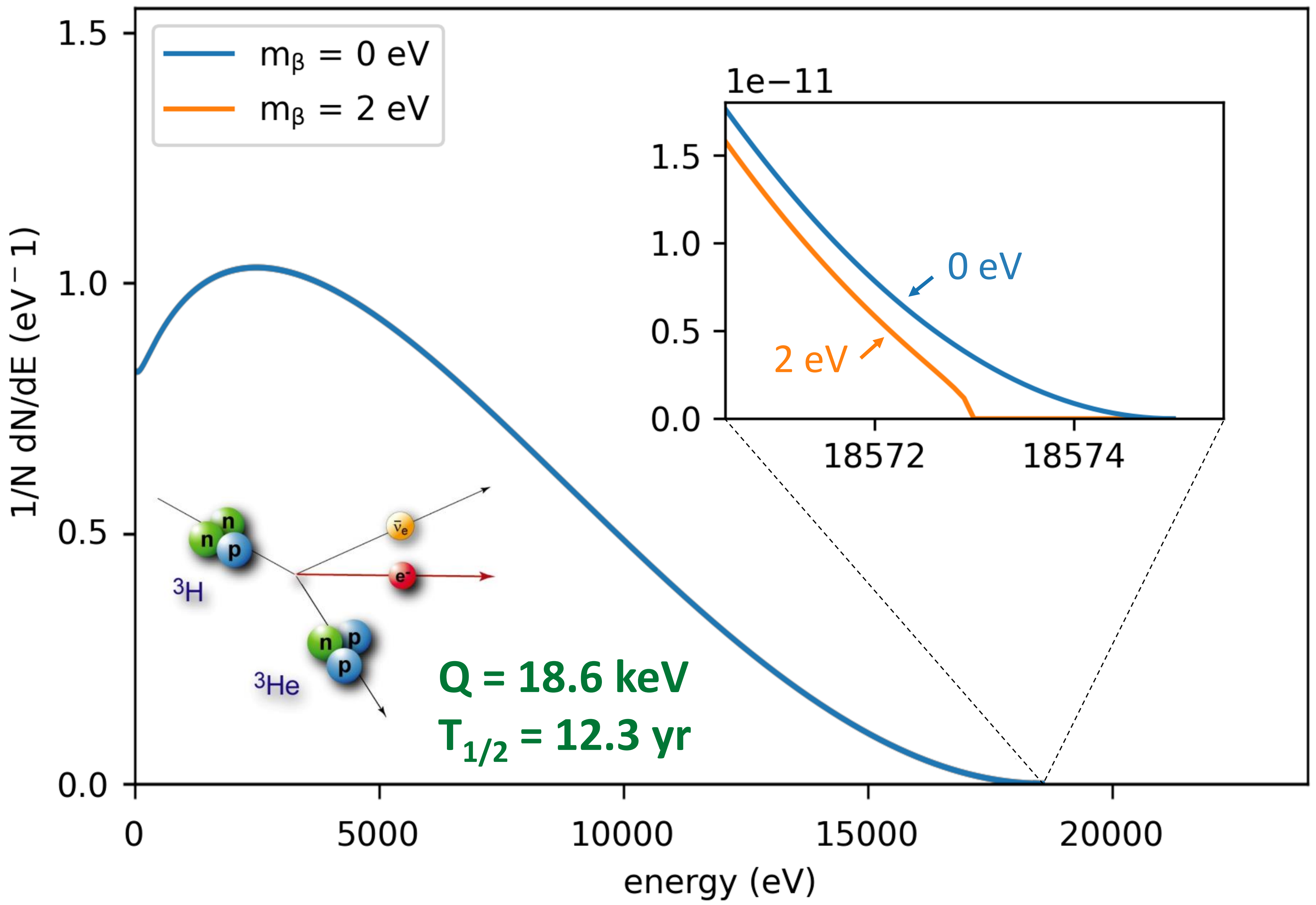
Neutrino mass measurement with tritium ß-decay kinematics

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:

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

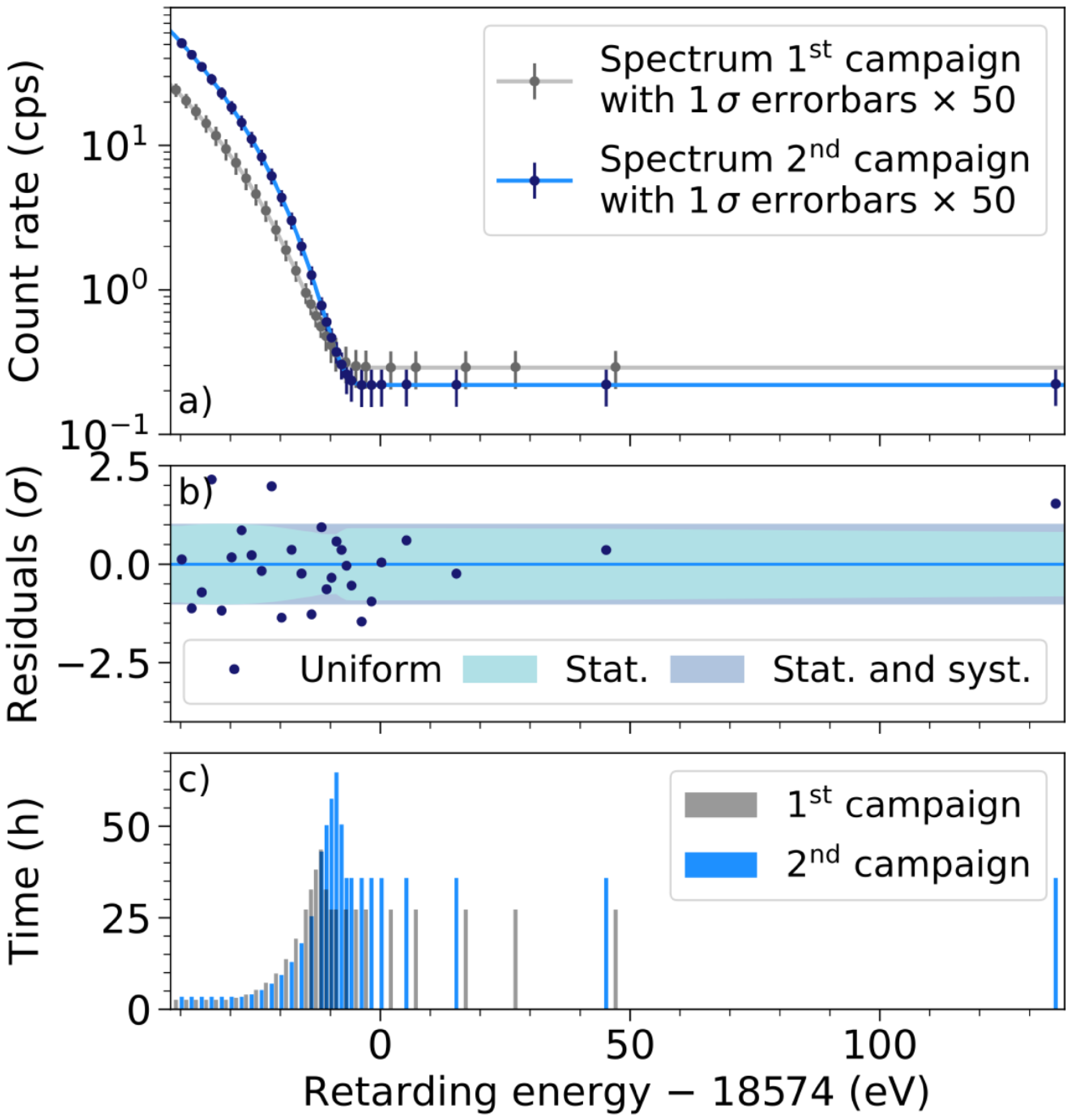


KATRIN in a nutshell

- Strong tritium source: **10^{11} decays/s**
- Very low background level: **< 0.1 cps**
- Integral measurement, very high energy resolution: **O(eV)**
- Small energy windows: **40 eV below endpoint**
- Low rate: **< 1 $e^{-}.s^{-1}$**

V. Hannen: The Karlsruhe Tritium Neutrino Experiment - an overview

ν – mass results

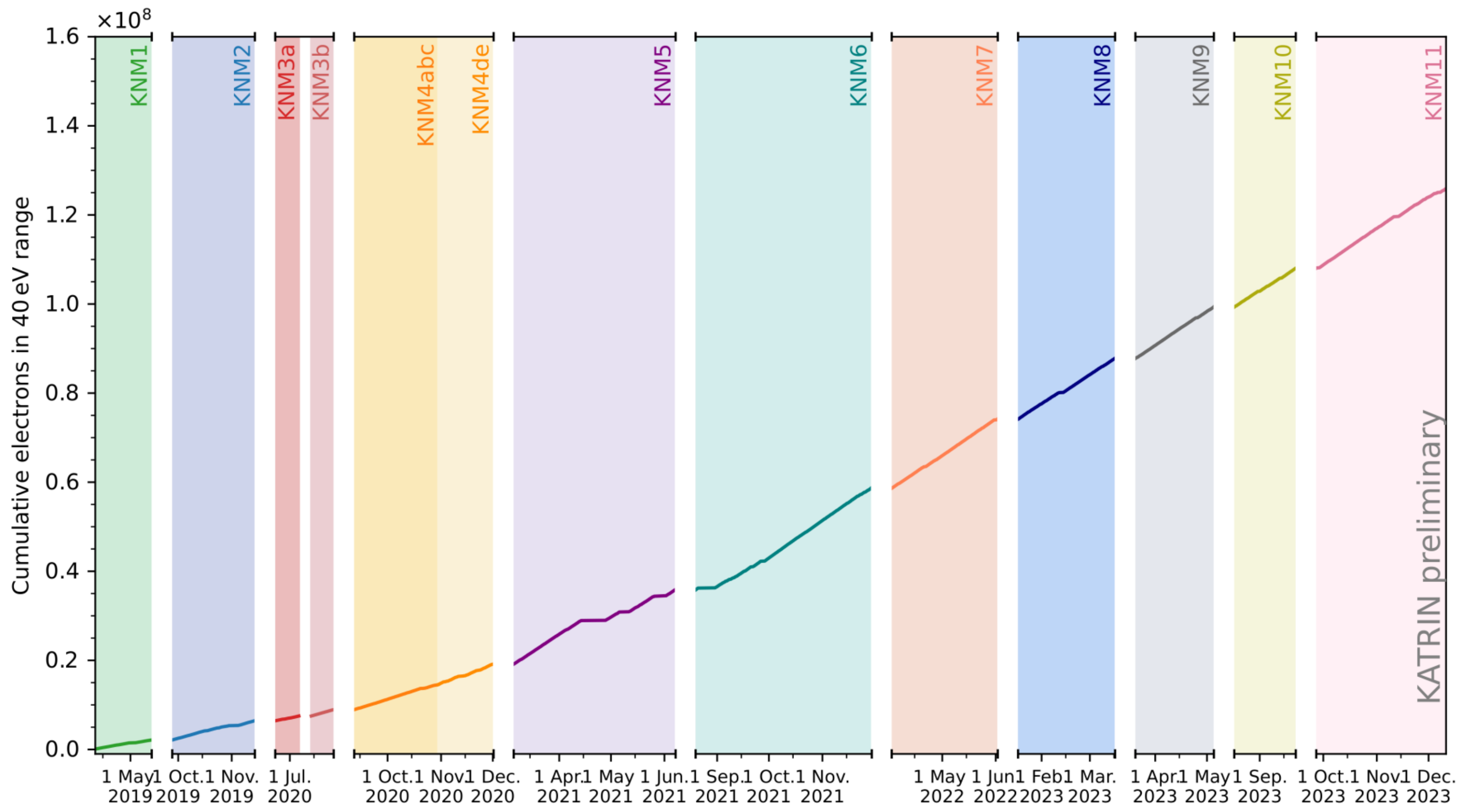


First + second campaigns:

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

- **Total statistic: 6.3 million events**
- **Best fit: $m_\nu < 0.8$ eV (90% CL)**

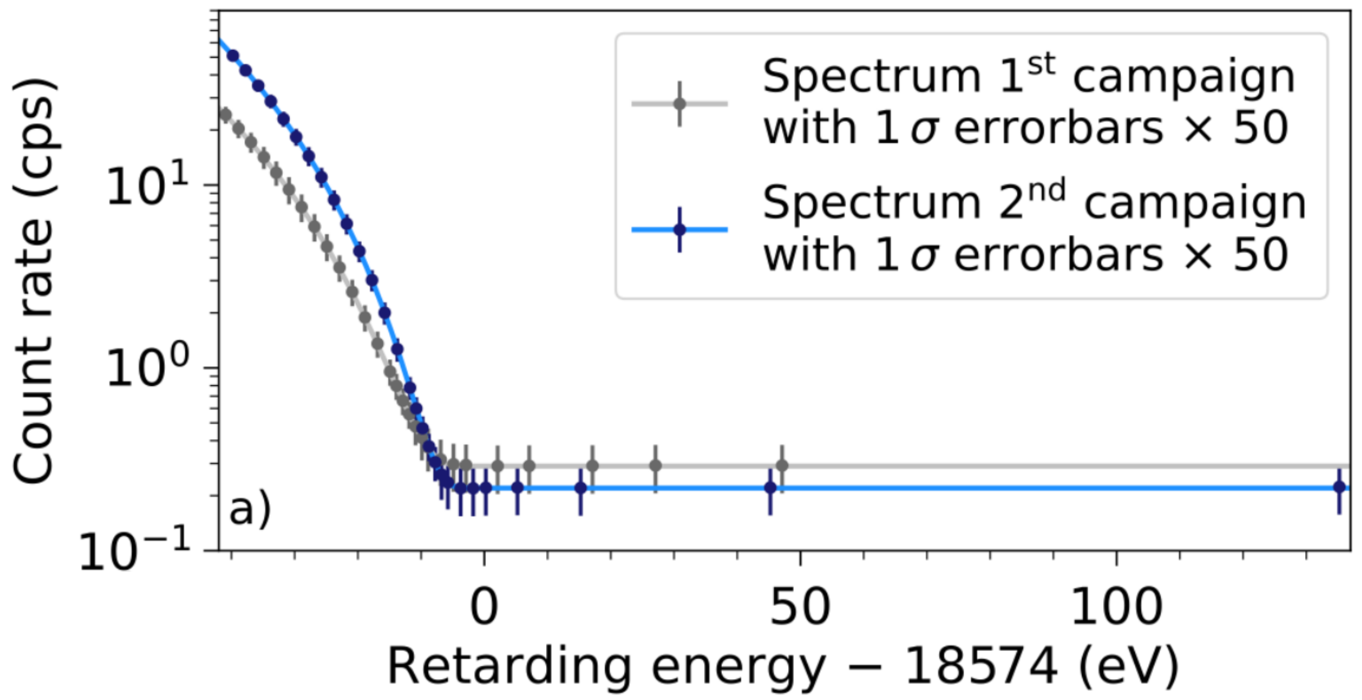
Data taking overview



1st to 11th campaigns: ~1.3x10^8 e$^-$ in the ROI

⇒ ***End of data taking: 2025 → ~2.0x10^8 e$^-$ in the ROI***

Beyond neutrino mass in KATRIN



β spectrum with high statistics and low systematics

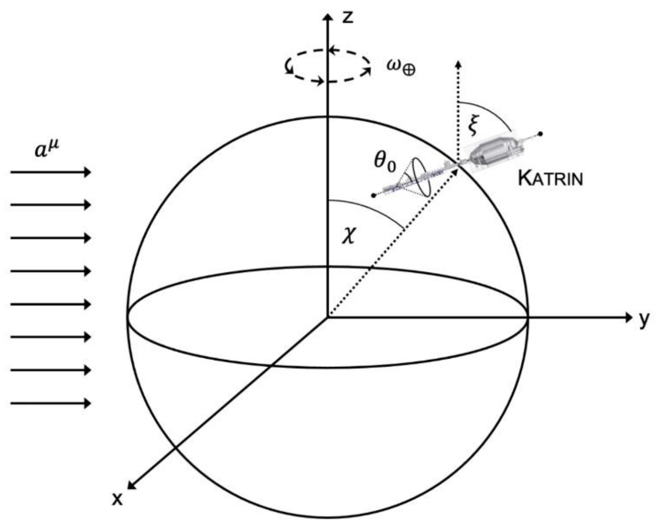
Search for exotic weak interactions

$\Rightarrow$ *shape distortion*

Search for Lorentz invariance violation

[arXiv:2112.13803]

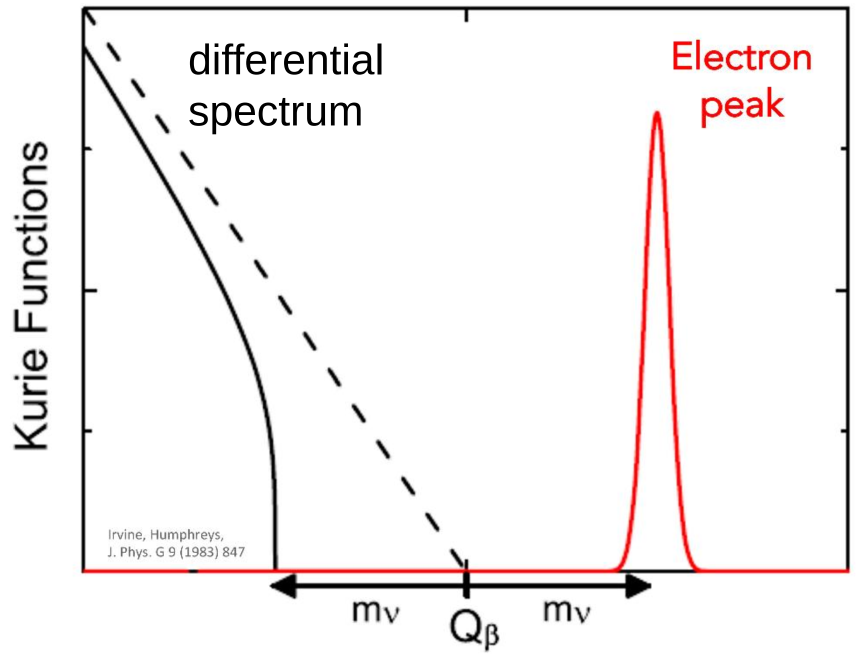
$\Rightarrow$ *sideral modulation*



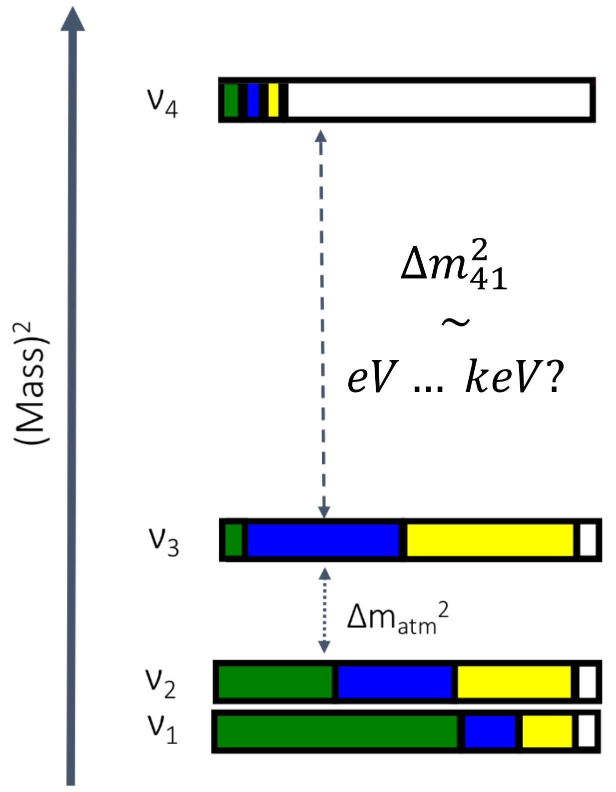
Constrain local overdensity of cosmic relic neutrinos

[Phys. Rev. Lett. 129, 011806]

$\Rightarrow$ *peak search*



Sterile neutrino search



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

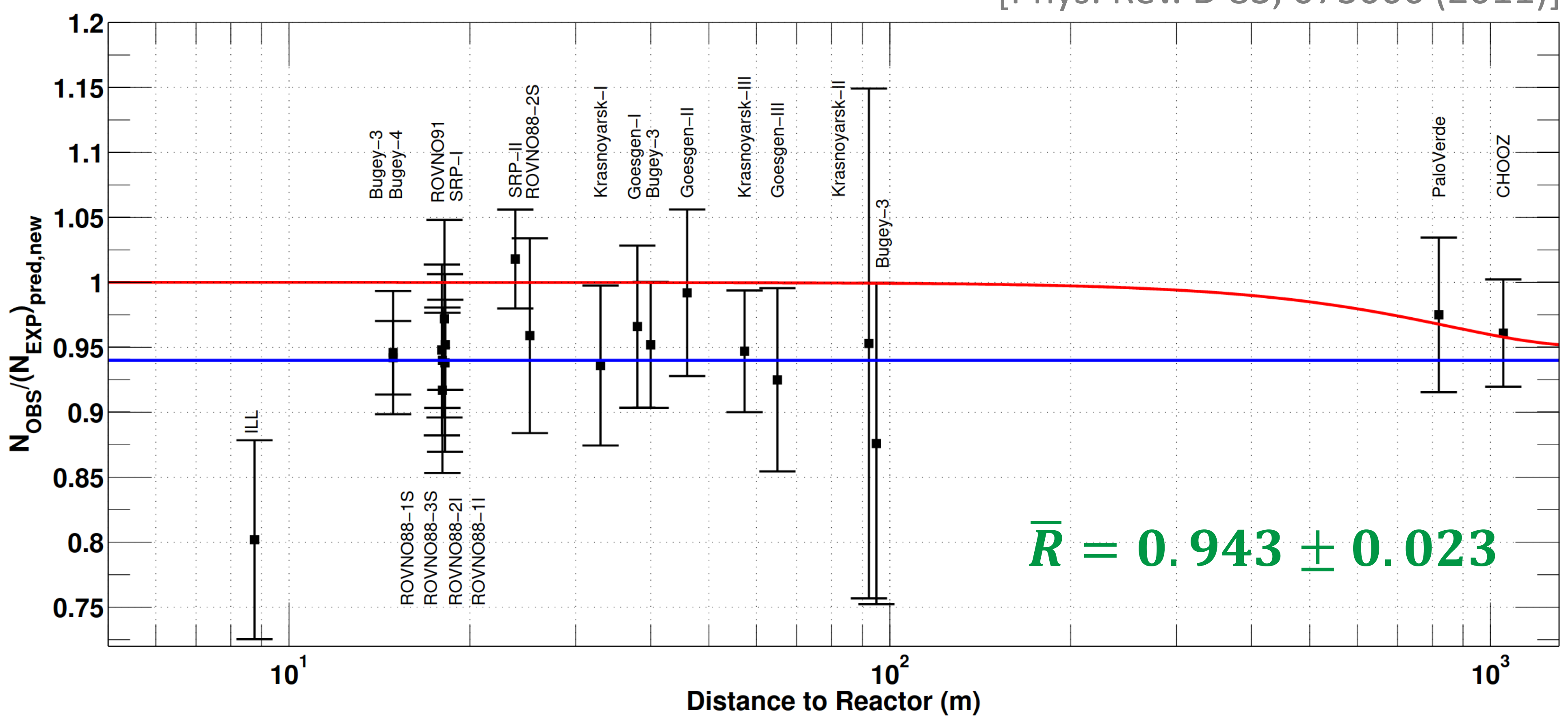
- eV-scale sterile neutrinos
- keV-scale sterile neutrinos

$\Rightarrow$ *shape distortion*

eV-scale sterile neutrino search motivation

Reactor antineutrino anomaly (RAA)

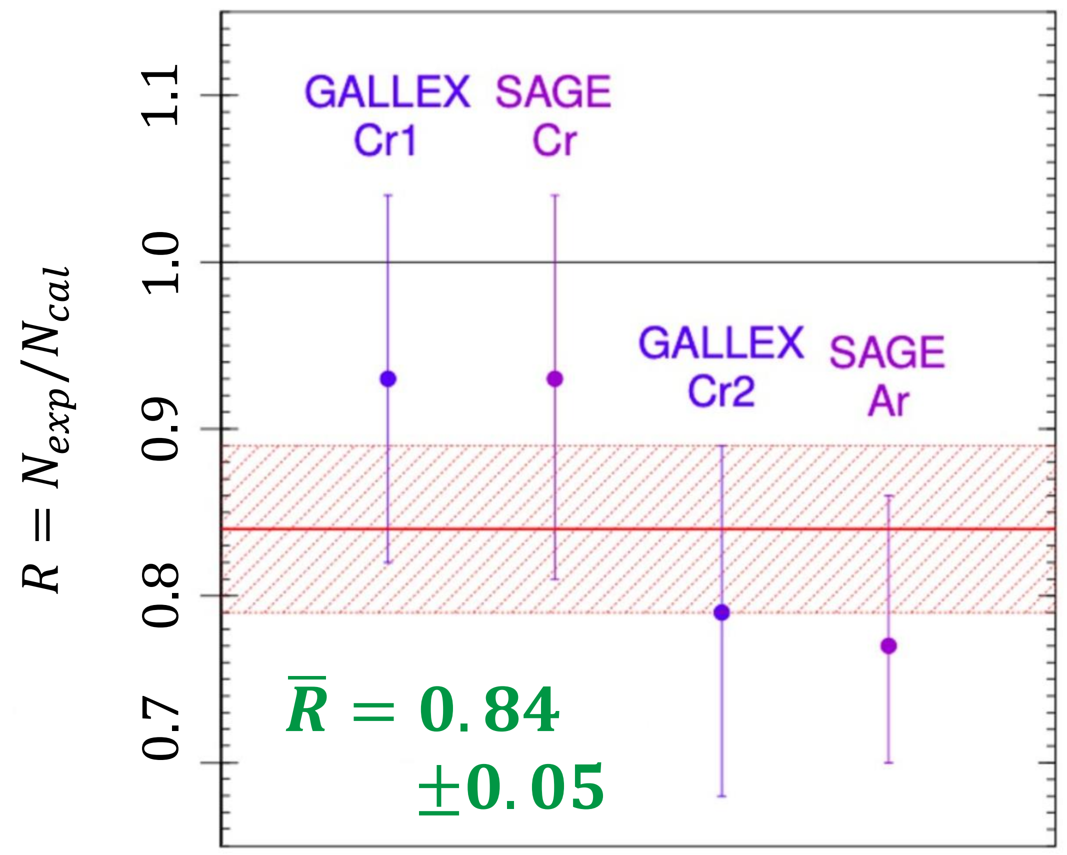
[Phys. Rev. D 83, 073006 (2011)]



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

Gallium anomaly

[Phys. Rev. C 83, 065504 (2011)]



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

[PhysRevLett.128.232501 (2021)]

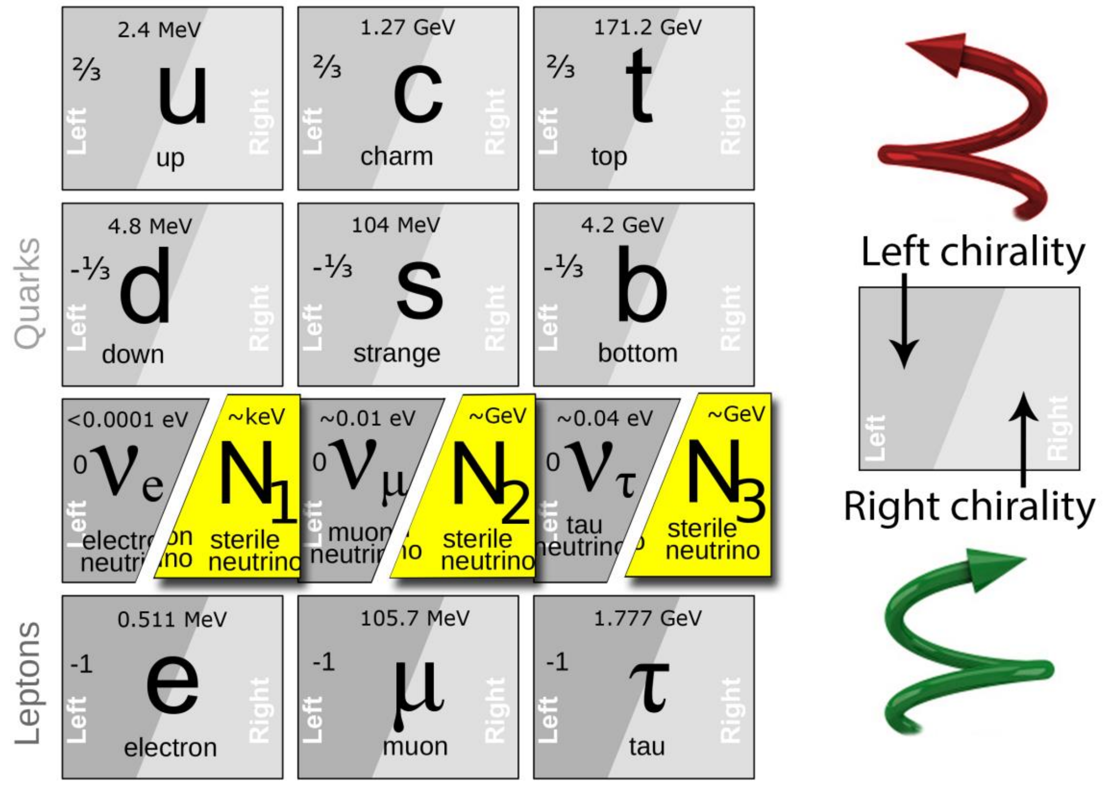
$\sim 3\sigma$ deficit of reactor and Gallium flux measurement to prediction

S. Mohanty: Search for eV Sterile Neutrinos in KATRIN data

$\Rightarrow$ Hint for the existence of light sterile neutrino?

keV-scale sterile neutrino search motivation

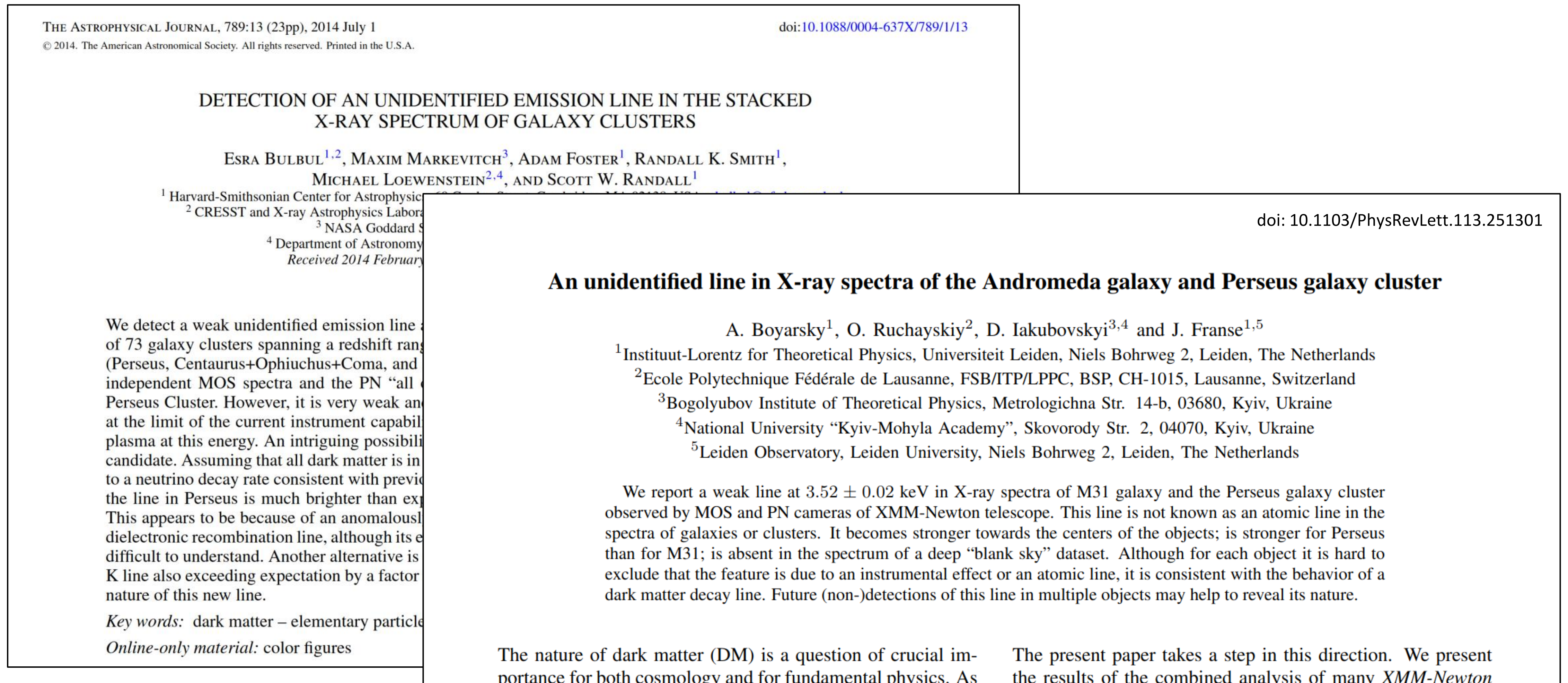
- Right-handed neutrinos: natural extension of SM and straightforward way to introduce neutrino mass
- Excellent candidate for warm dark matter: ~1-50 keV



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

↳ hint from astrological observations for a ~7 keV sterile ν ⇒ Interpretation remains inconclusive

↳ … or anything else? [Dessert et al., Science 367, 1465–1467 (2020)]


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

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

ESRA BULBUL[1,2], MAXIM MARKEVITCH[3], ADAM FOSTER[1], RANDALL K. SMITH[1], MICHAEL LOEWENSTEIN[2,4], AND SCOTT W. RANDALL[1]

doi: 10.1103/PhysRevLett.113.251301

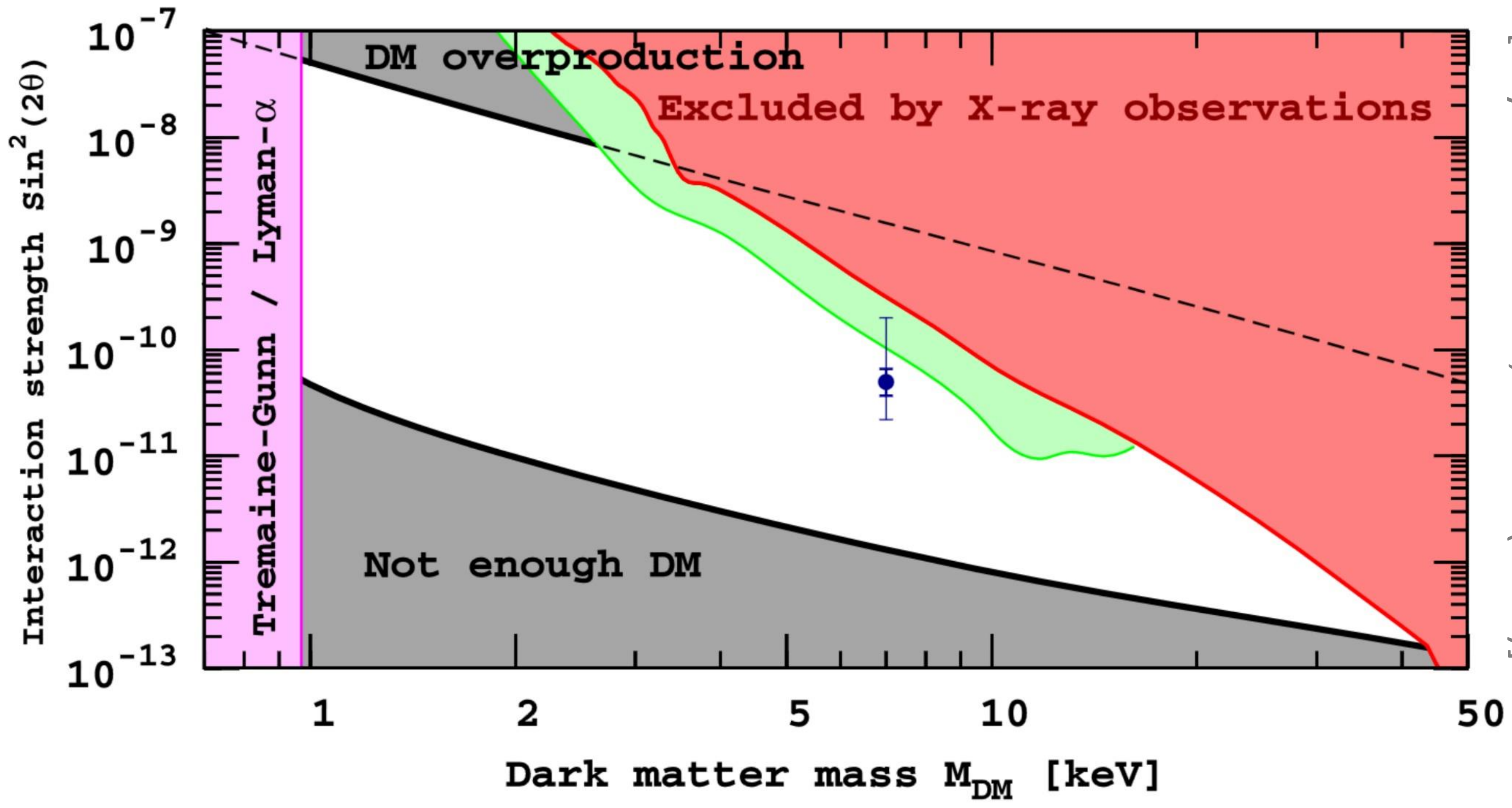
An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[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.

The nature of dark matter (DM) is a question of crucial importance for both cosmology and for fundamental physics. As … The present paper takes a step in this direction. We present the results of the combined analysis of many XMM-Newton

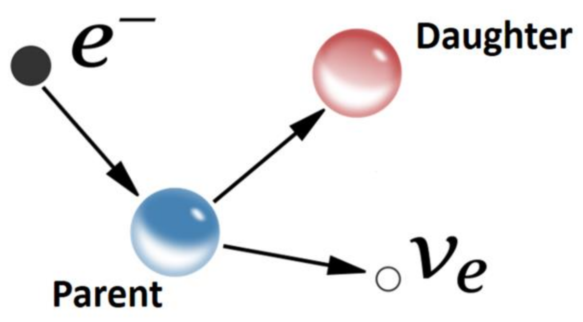


[Phys Rev Lett 113, 251301 (2014)]

Laboratory search for keV sterile

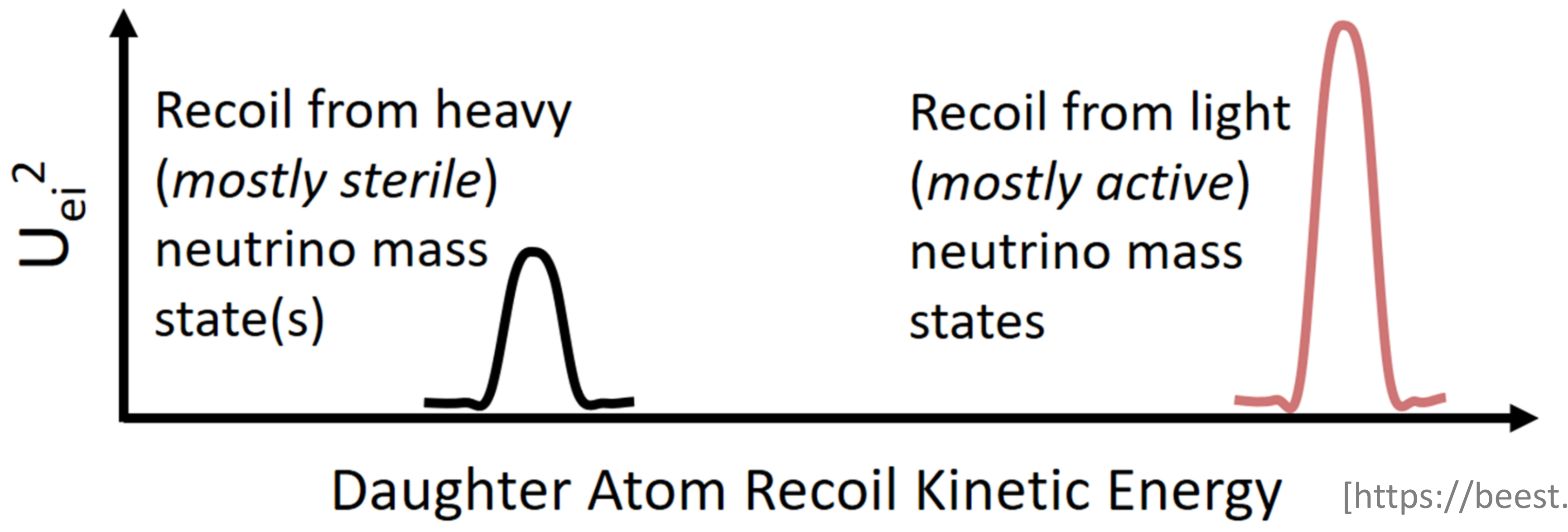
Full kinematic reconstruction

- Possible decay modes:
  - Beta decay
  - **Electron capture (EC)**



$${}_{-1}^{0}e + {}_{1}^{1}p \rightarrow {}_{0}^{1}n$$

- Measure energy and momentum of electron and daughter nucleus



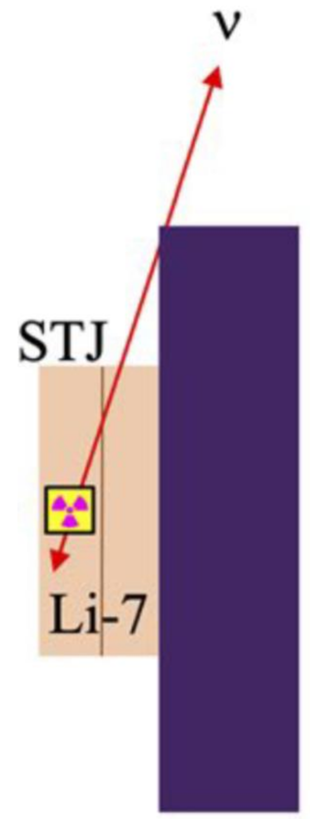
[https://beest.mines.edu]

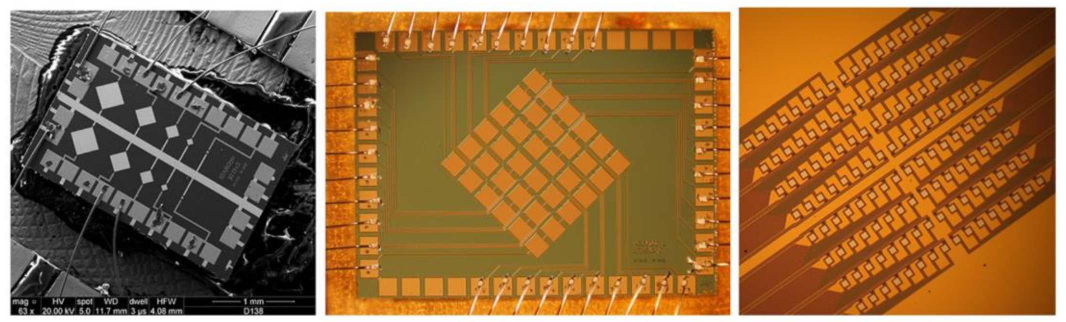
⇒ Reconstruct missing mass

BeEST

$$e^- + {}^{7}Be \rightarrow \nu_s + {}^{7}Li$$

- High count-rate STJ radiation detectors
- Be implantation into the substrate



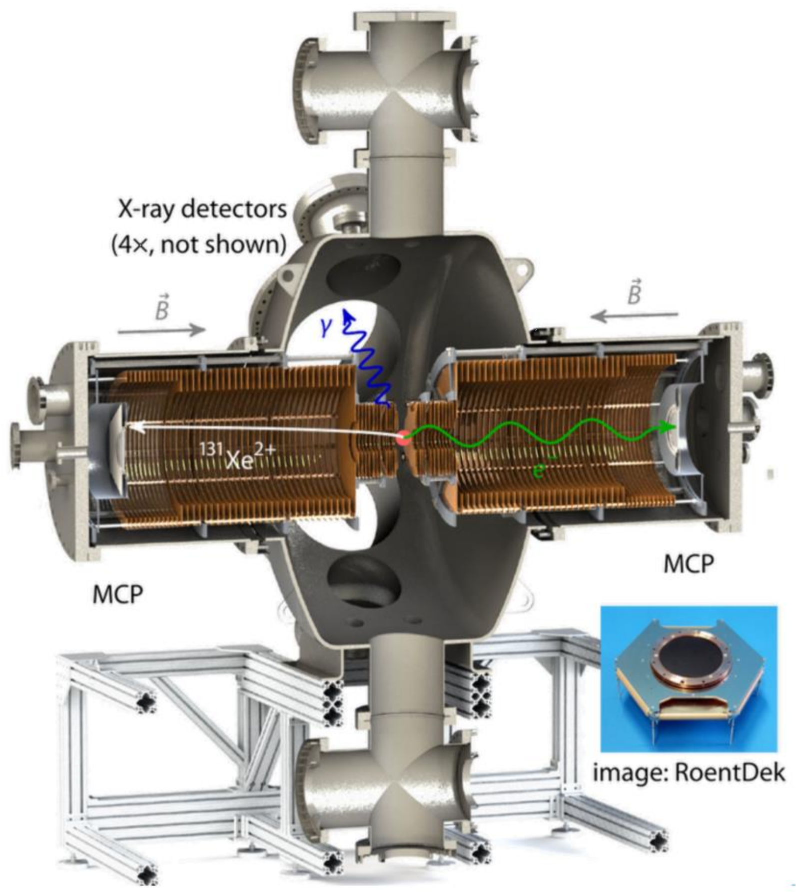


[BeEst S. Friedrich et al., Phys. Rev. Lett. 126, 021803 (2021)]

Hunter

$$e^- + {}^{131}Cs \rightarrow \nu_s + {}^{131}Xe$$

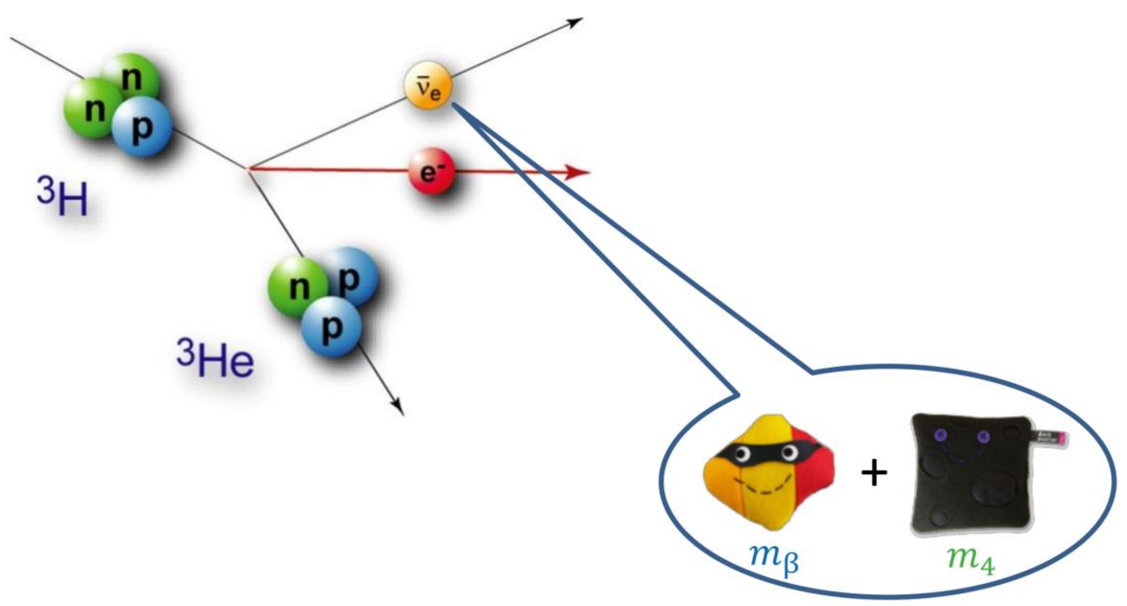
- Magneto optical trapping of atomic Cs
- Missing υ mass through reconstruction of vector momenta of decay products:
  - precision timing
  - position sensitive detectors

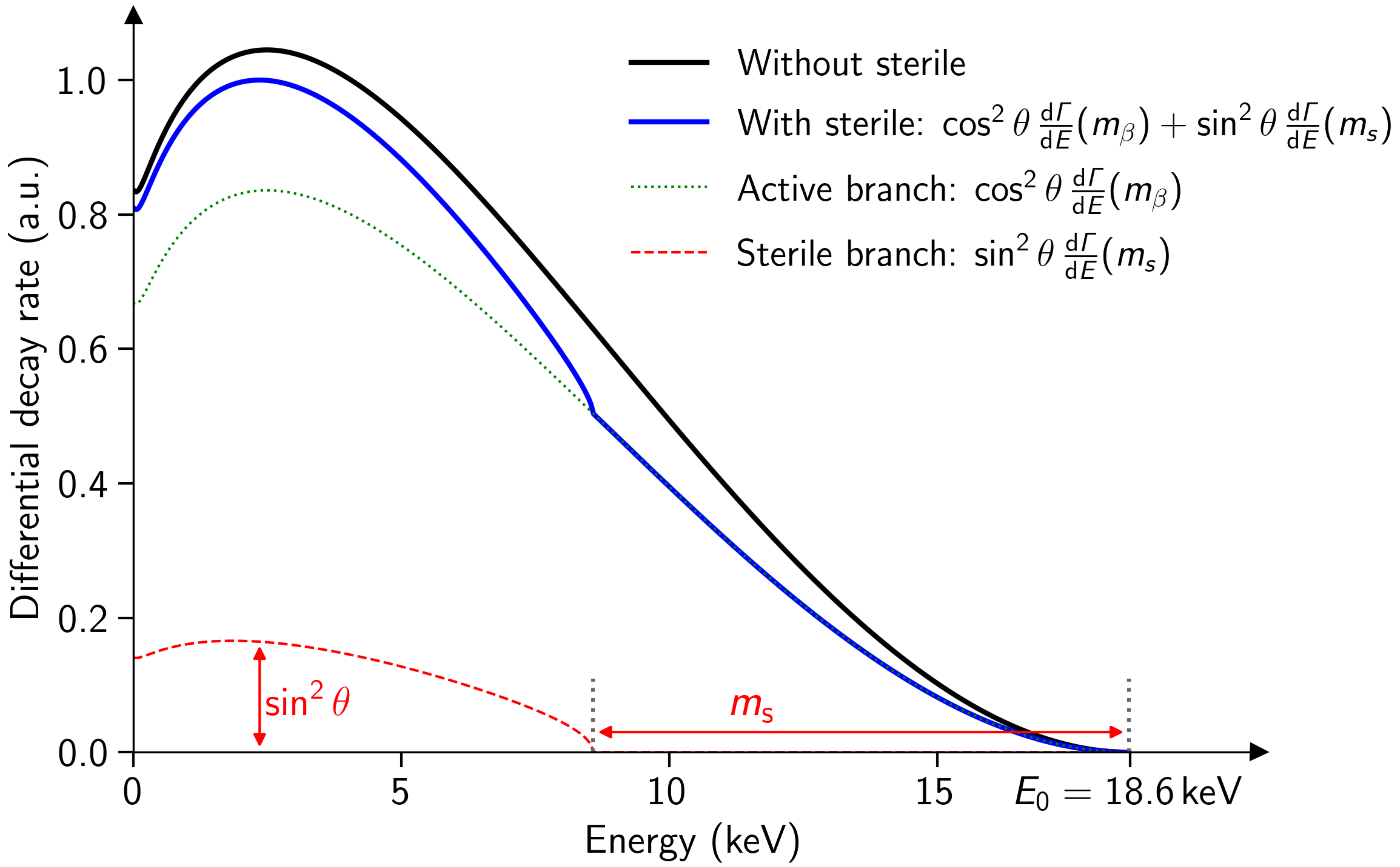


|Hunter Martoff et al., Quantum Sci. Technol. 6 024008 (2021)]

Laboratory search for keV sterile

Production in β decays



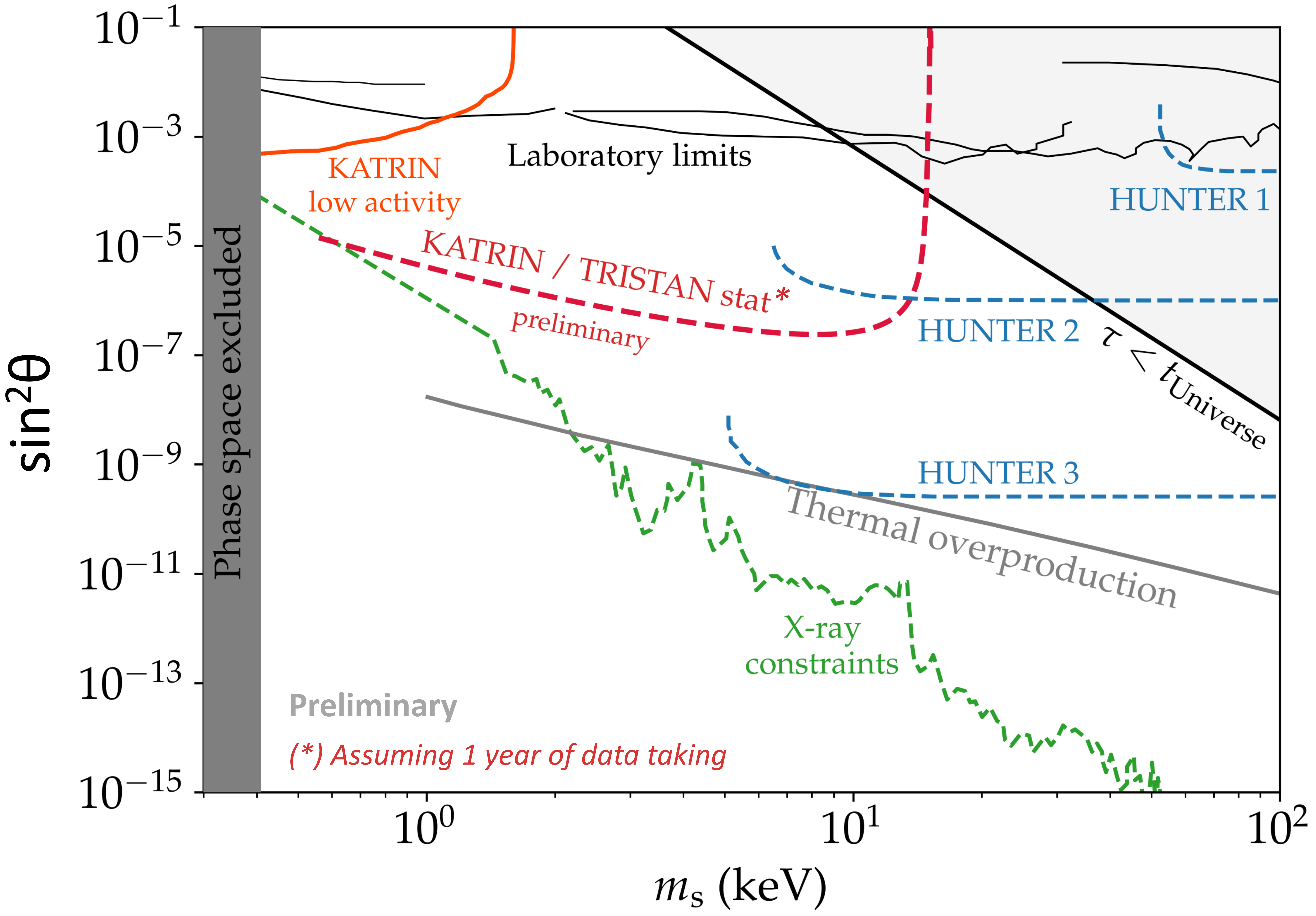


- 4^{th} mass state appear as a kink in the spectral shape
- Spectral distortion can extent deep into spectrum
- Candidate isotopes:
  - ^{3}H: E_0 = 18.5740(1) keV ⇒ **KATRIN**
  - ^{241}Pu: E_0 = 20.78(17) keV ⇒ **MAGNETO-ν**

[https://indico.cern.ch/event/118875]

⇒ Search for a spectral distortion

Current limits and projections

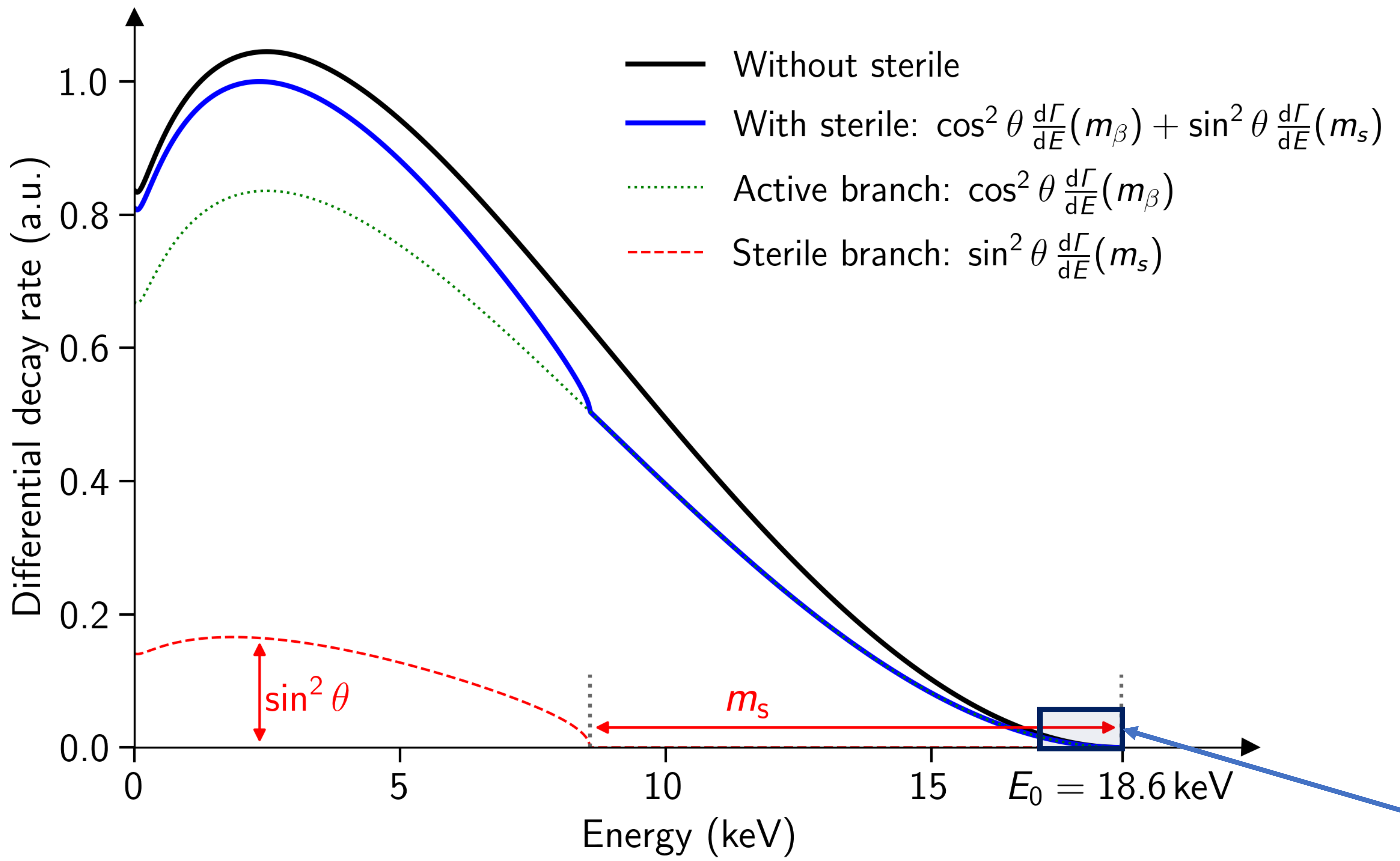


data from:
- F. Benso et al., Phys. Rev. D 100, 115035 (2019)
- F. Bezrukov et al., JCAP 06, 051 (2017)
- Abdurashitov et al., JETP Letters 105, 12 (2017)
- Martoff et al., Quantum Sci. Technol. 6 024008 (2021)
- S. Friedrich et al., Phys. Rev. Lett. 126, 021803 (2021)
- M. Aker et al, Eur. Phys. J.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

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

keV-scale sterile neutrinos
with the first KATRIN data

keV search with the first KATRIN data



Experimental challenge:

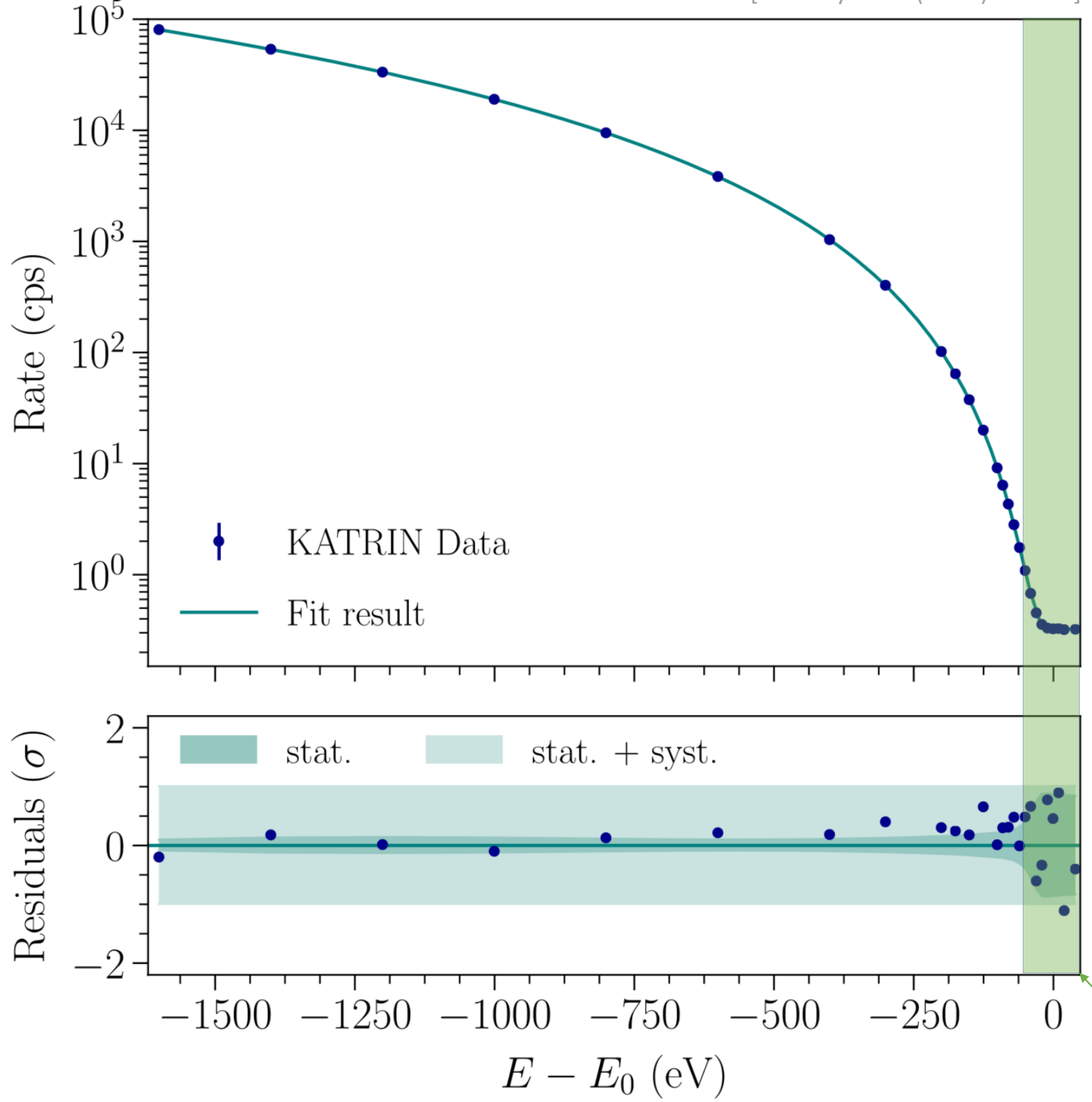
- Energy windows of ν-mass data set too small for keV sterile neutrino search
- detector system not designed to handle very high data rates that would occurs with large energy window

12 days commissioning campaign in 2018

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

Sterile neutrino fit - commissioning campaign

[Eur. Phys. J. C (2023) 83:763]



ROI for ν mass search

$$R_{calc}(qU) = A_s N_T \int_{qU}^{E_0} R_\beta(E, m_\nu^2, E_0, |U_{e4}|^2, m_4^2) \cdot f_{calc}(E, qU) dE + R_{bg}$$

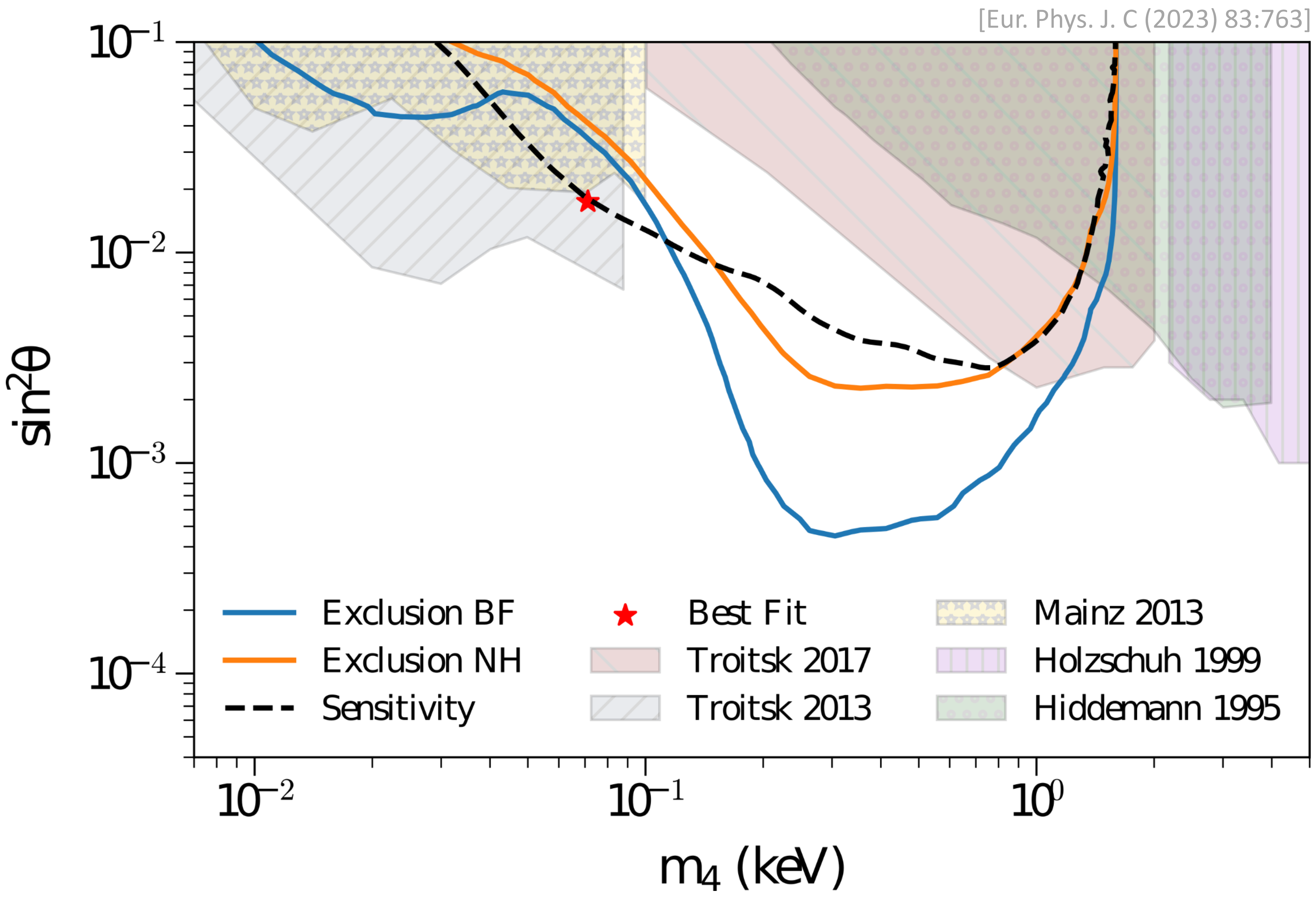
Maximum likelihood fit of model for $3\nu + 1$

- Signal normalization A_s
- endpoint E_0
- background R_{bg}

- **4th neutrino mass and mixing: $|U_{e4}|^2, m_4^2$**

No significant keV sterile-neutrino signal is observed in KATRIN ⇒ sensitivity

1^{st} KATRIN results for keV sterile



95% C.L. exclusion contours

- No 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 ✓

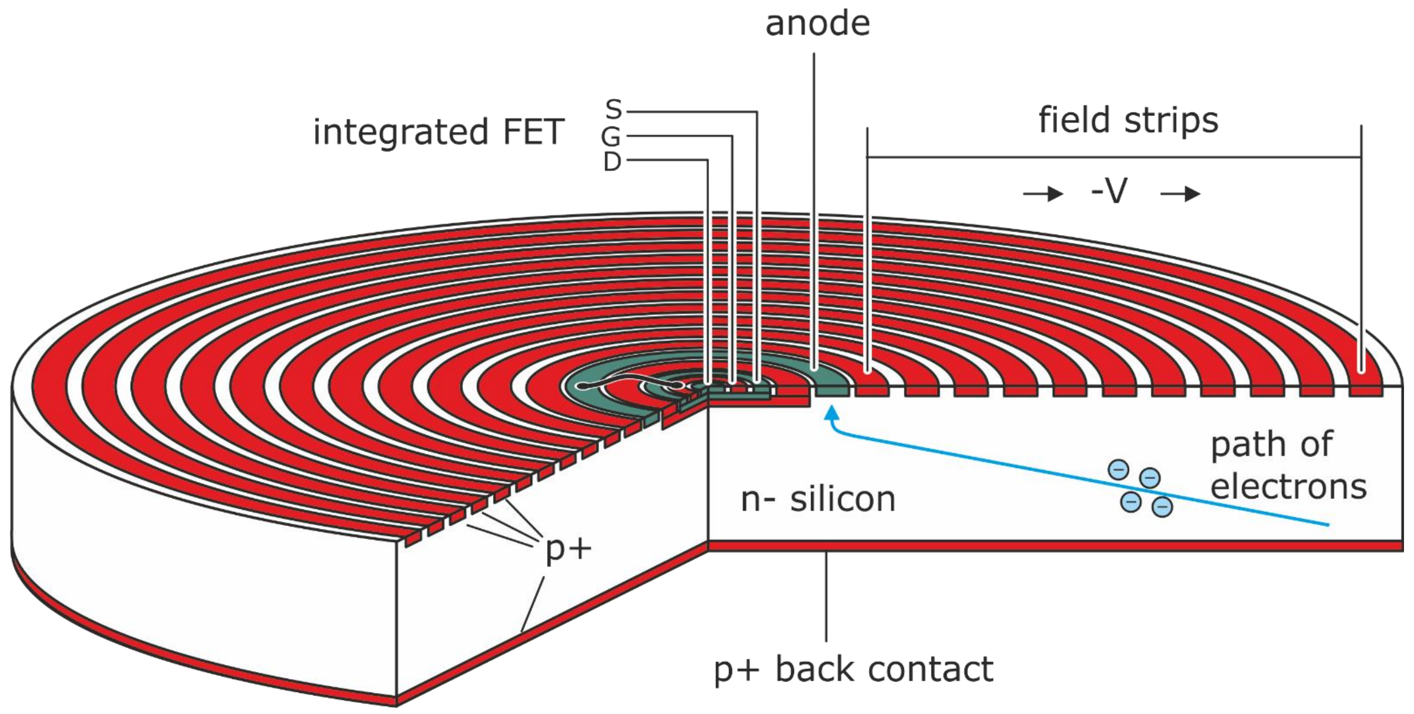
⇒ **New detector required for high rate β-spectroscopy**

keV sterile neutrino search with the TRISTAN detector

TRISTAN project

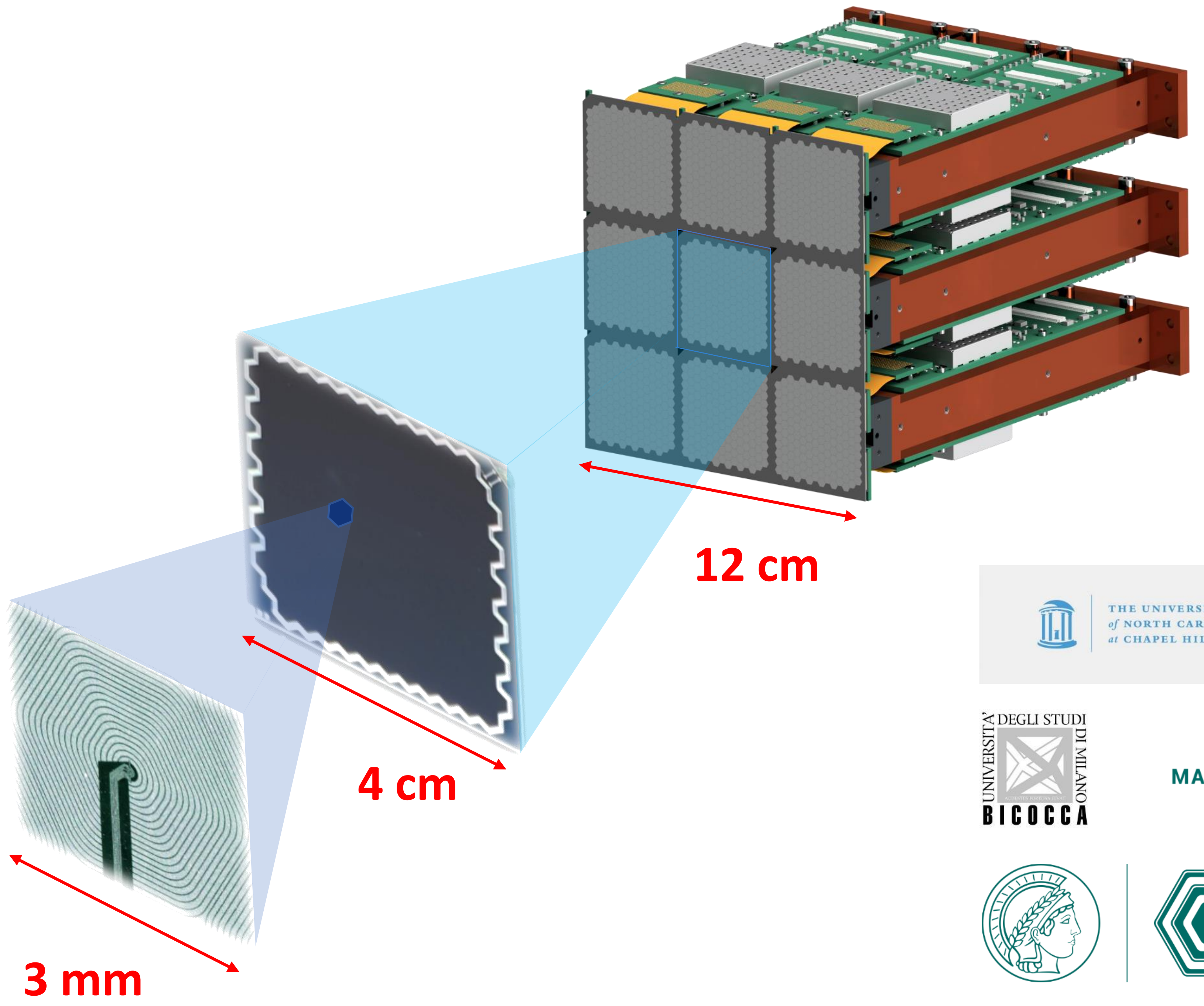
Tritium Beta Decay to Search for Sterile Neutrinos

- 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 $\sin^2\theta$

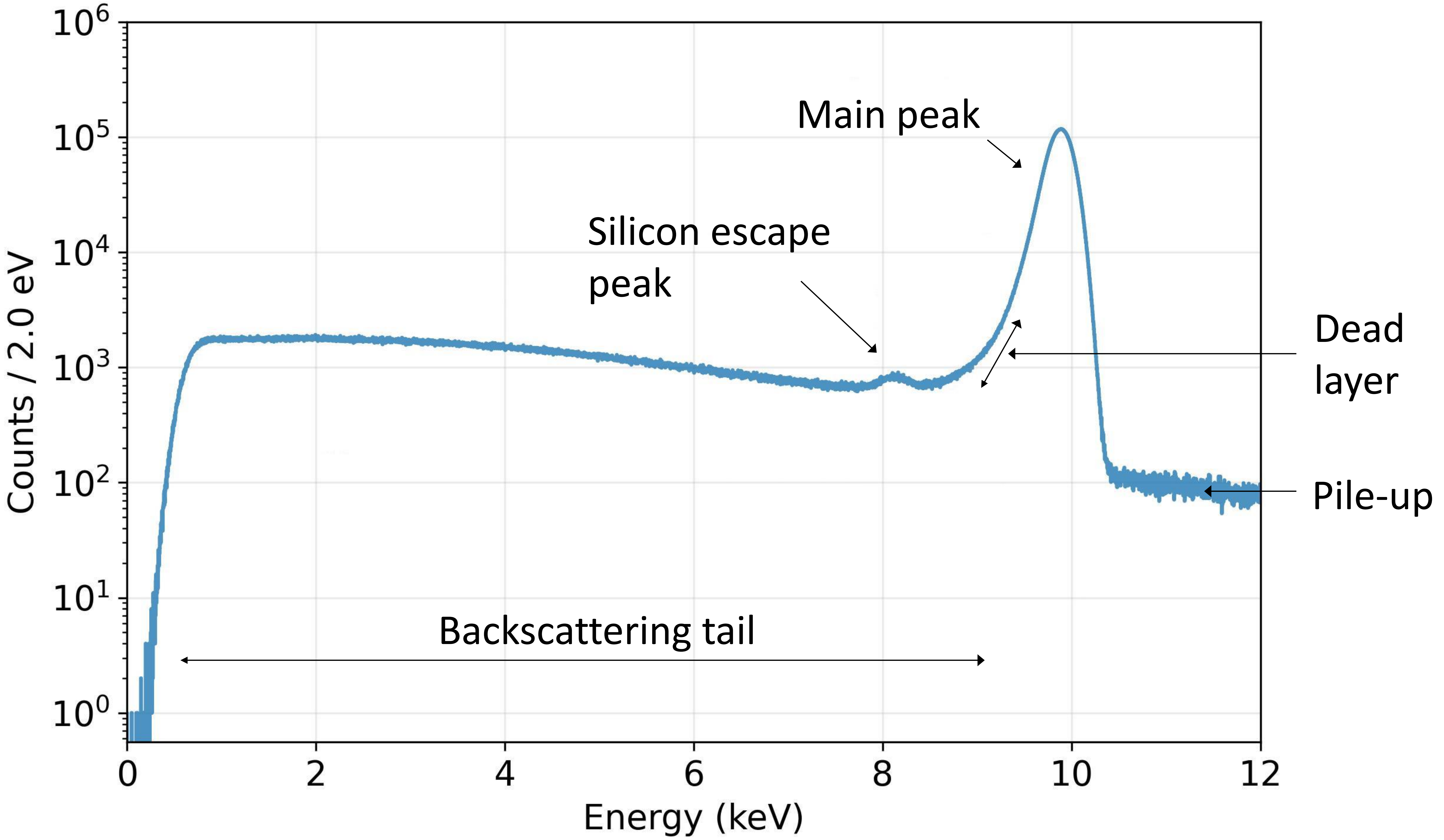
S. Mertens et al., J. Phys. G46 (2019)
S. Mertens et al., J. Phys. G48 (2020)

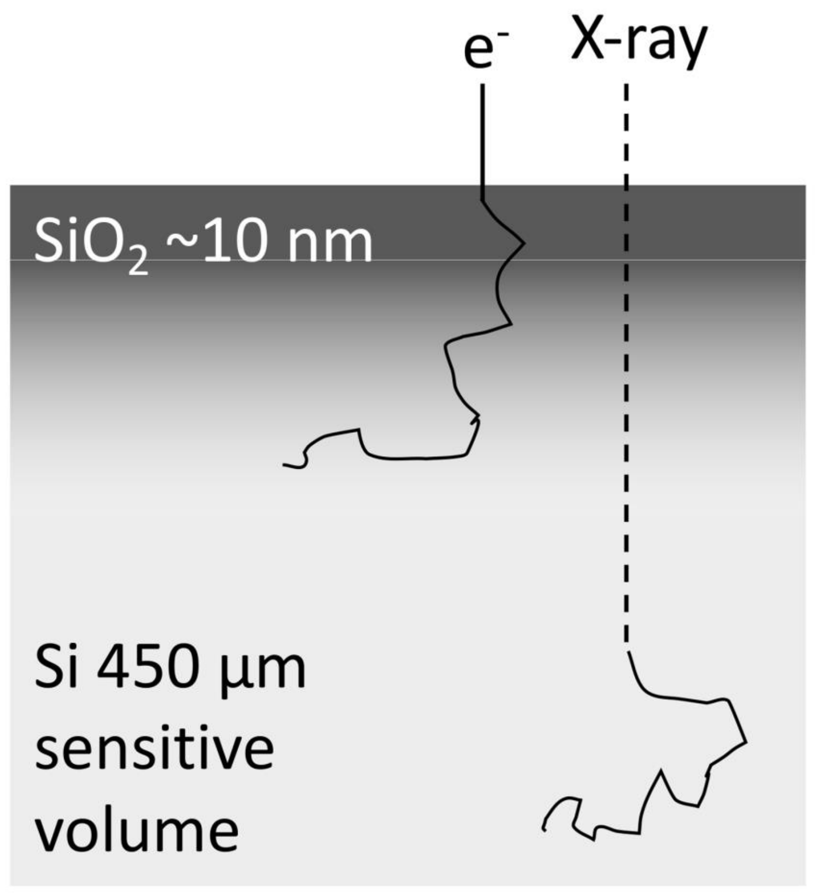


- 9 modules
- ~1500 pixels

Detector response

Illustration for monoenergetic e$^-$ of 10 keV (e-gun data)





D. Spreng: TRISTAN detector overview

M. Gugiatti et al., NIM-A 979 (2020)
M. Biassoni et al., EPJ. Plus 136 (2021)
P. King et al., JINST 16 T07007 (2021)
D. Siegmann et al., arXiv:2401.14114v1 (2024)

Working principle

Transport section
- magnetic guidance
- tritium gas/ion removal

  → **reduction by > 10^{14}**

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

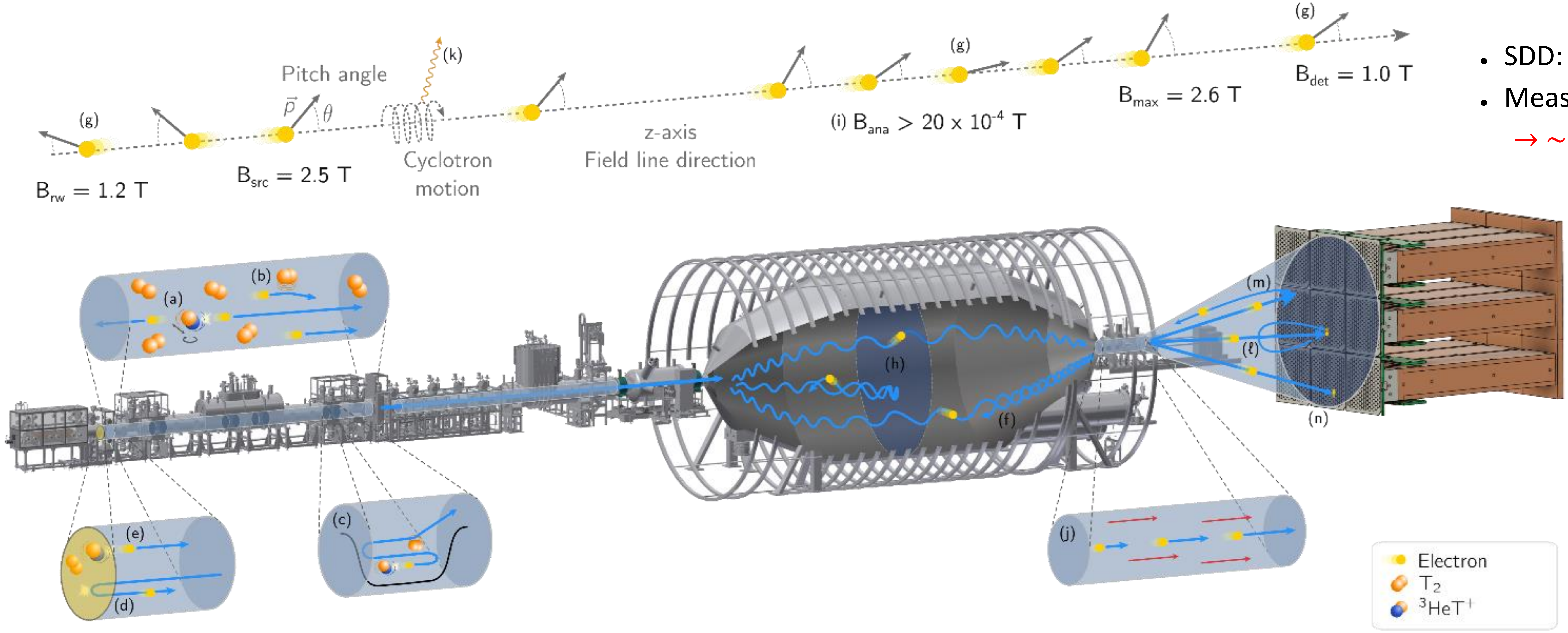
  → **aim for low qU value: look deep into spectrum**

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

Detector section
- SDD: ~1500 pixels
- Measure differential spectrum

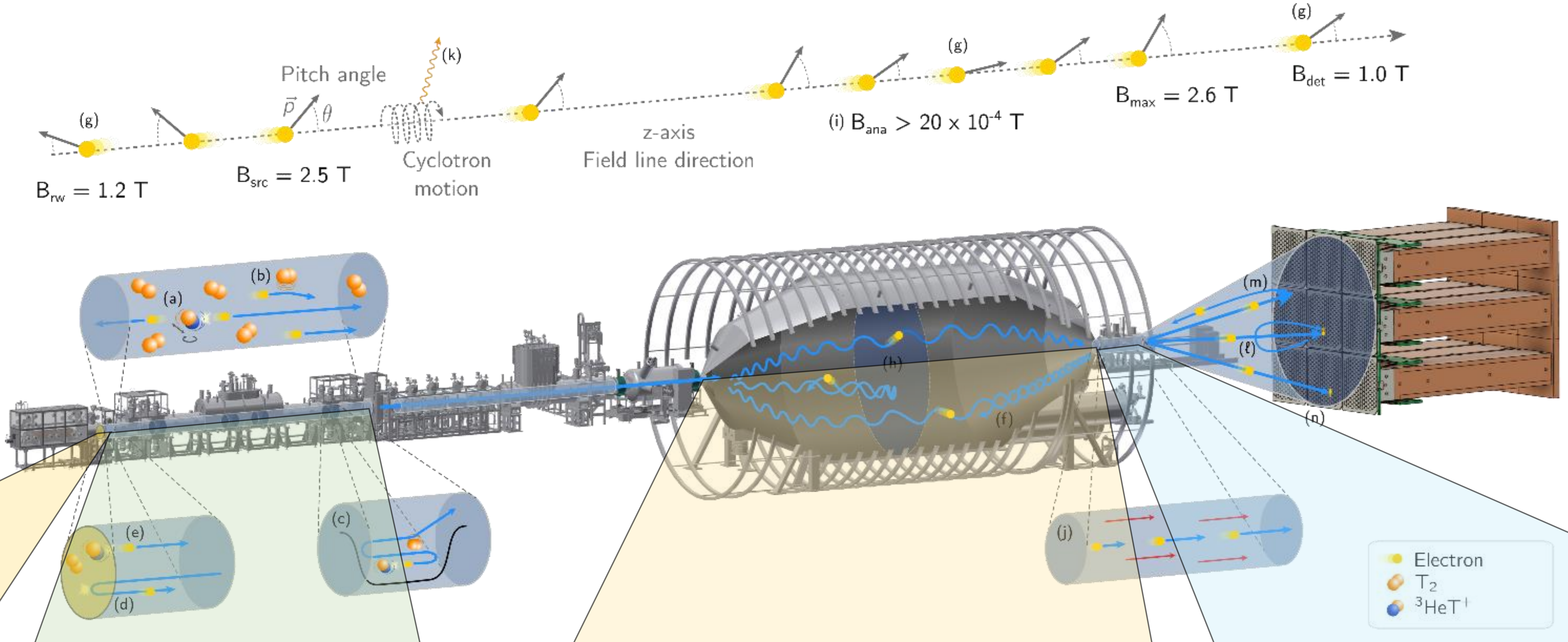
  → **~10^8 $e^-.s^{-1}$**

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

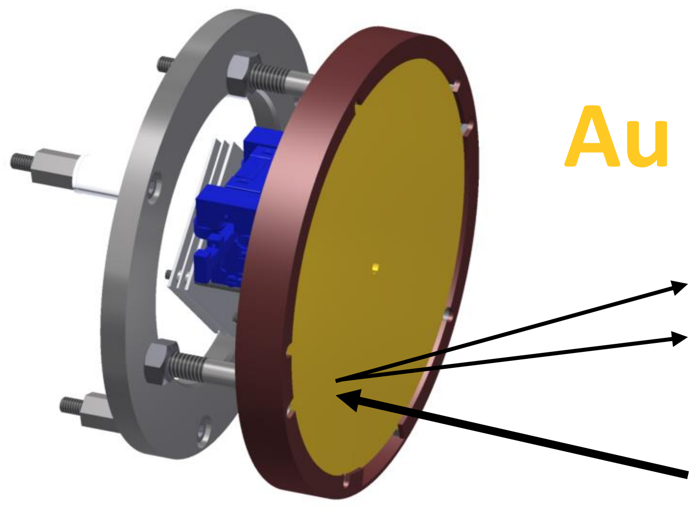
- Scattering
- Magnetic trapping

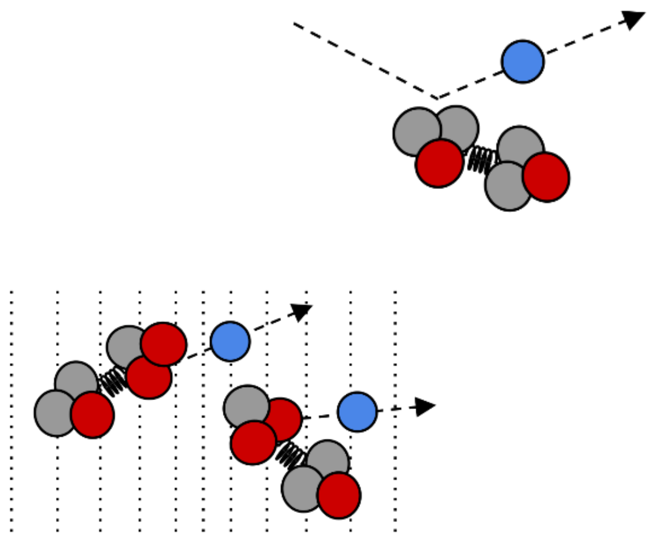
Spectrometer

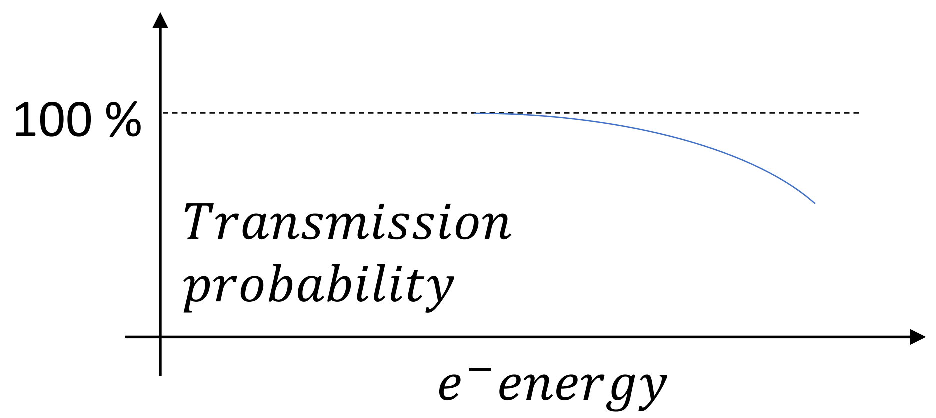
- Magnetic mirror and collimation
- Spectrometer adiabaticity

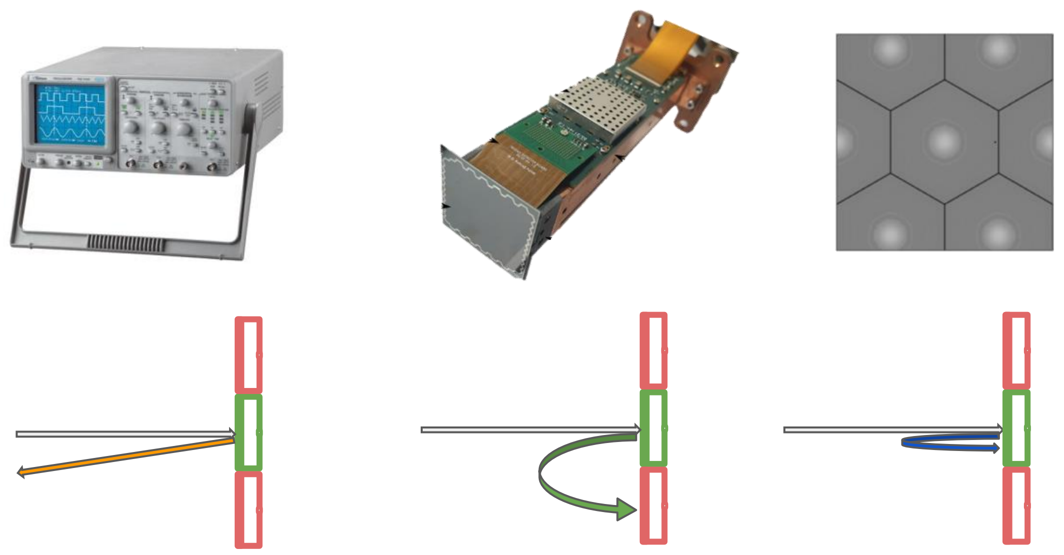
Detector section

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



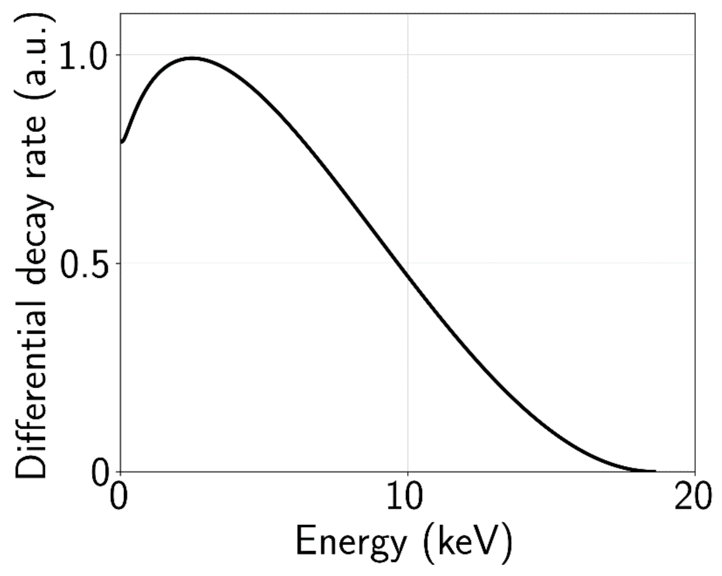




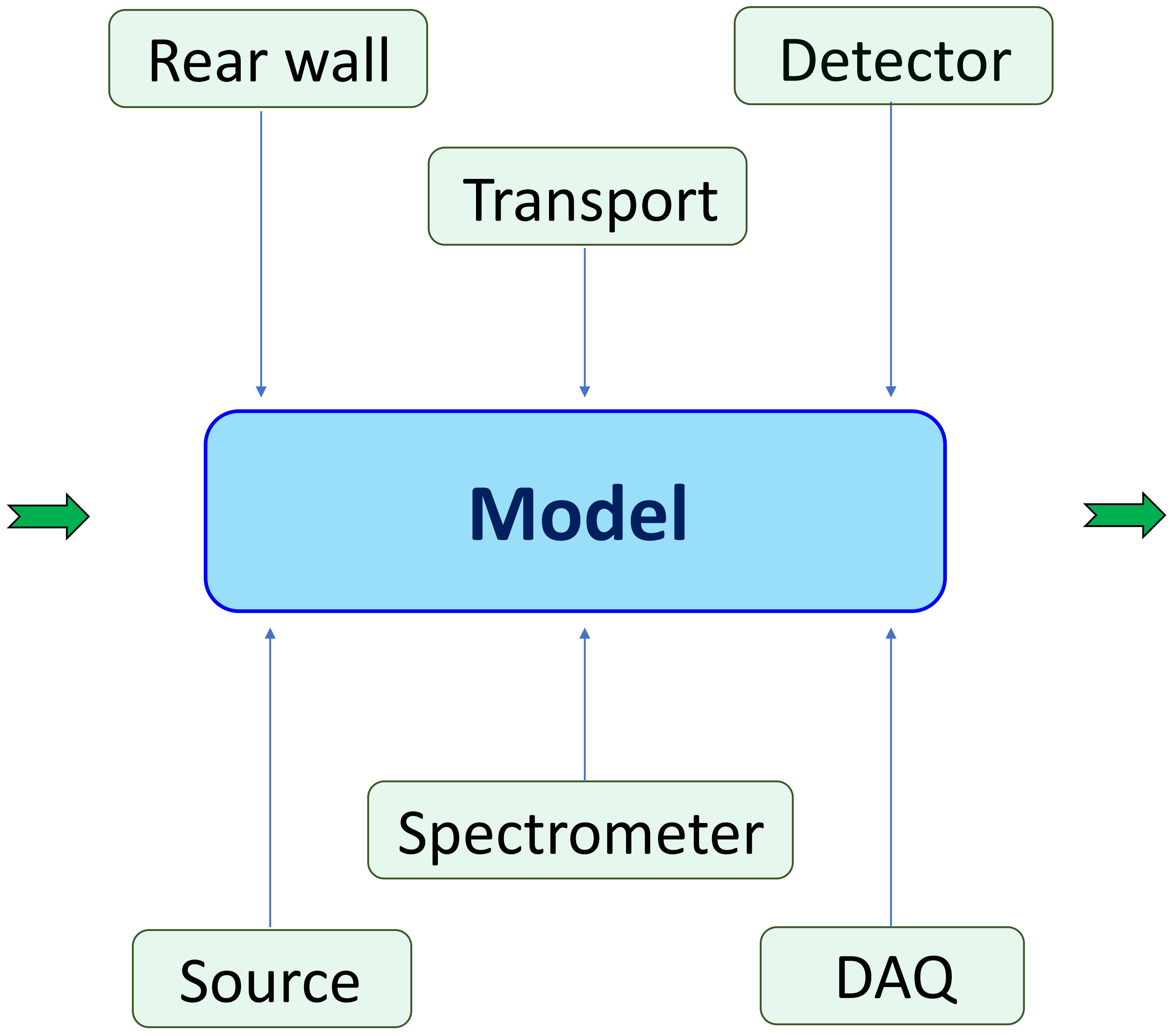


Modelling of expected spectrum

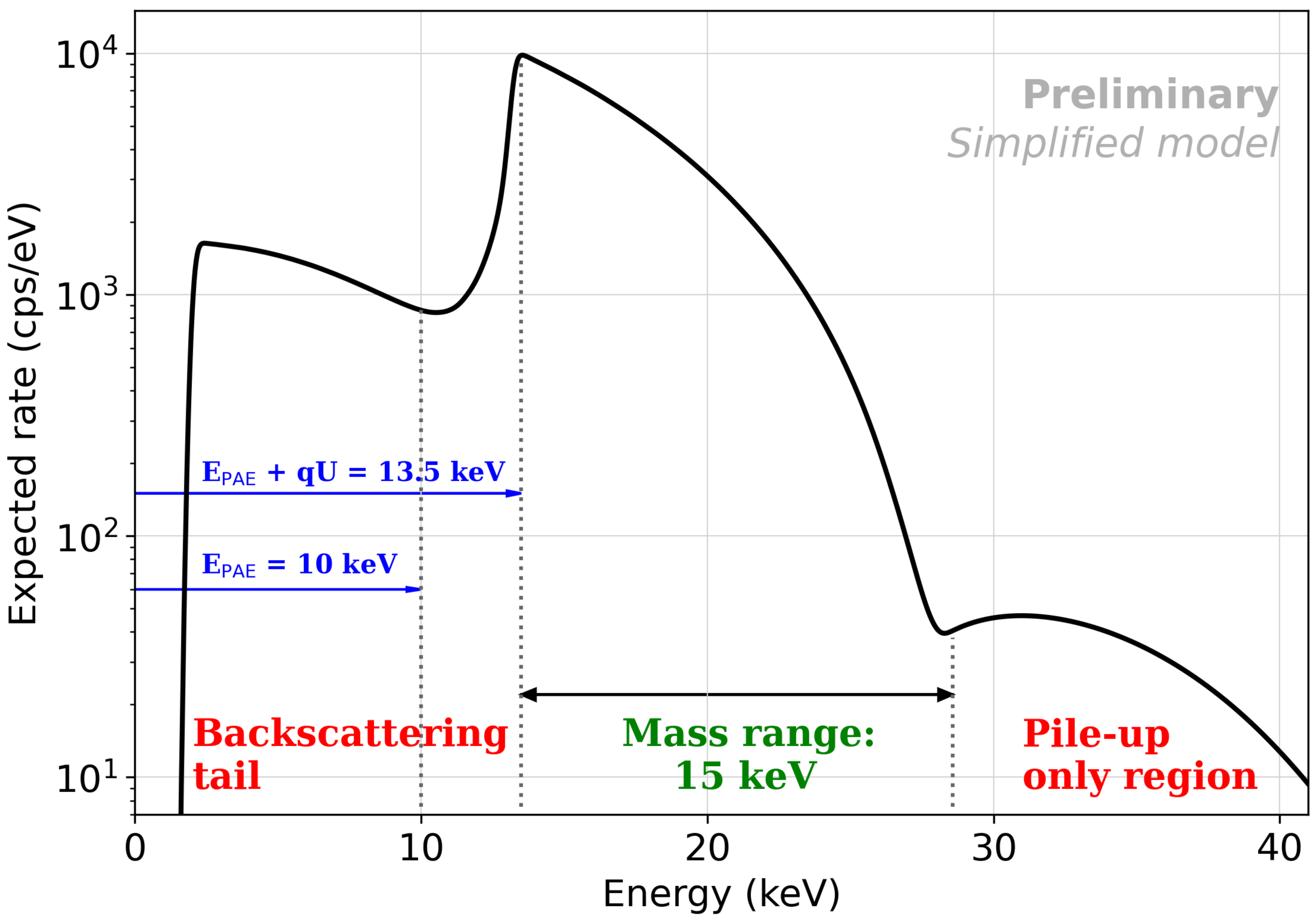
- Multipurpose / multiphysics code
- Systematic effects impact modeled by external codes (analytical / Geant4, KASSIOPEIA simulations)



Theoritical β-spectrum prediction



Expected measured spectrum (1 year of data taking)



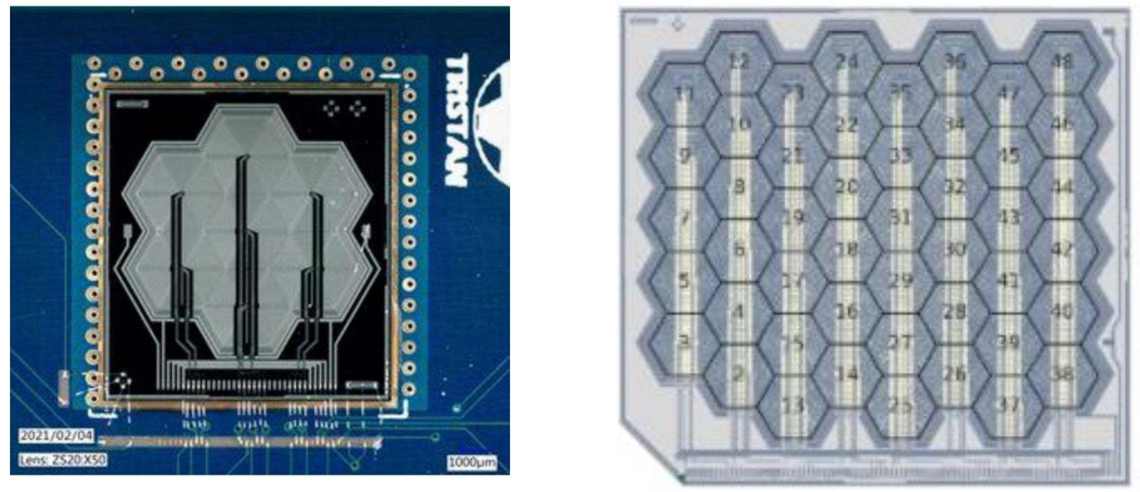
⇒ Order of magnitude: $\sim 2 \times 10^{15}$ electrons per year

Staged approached

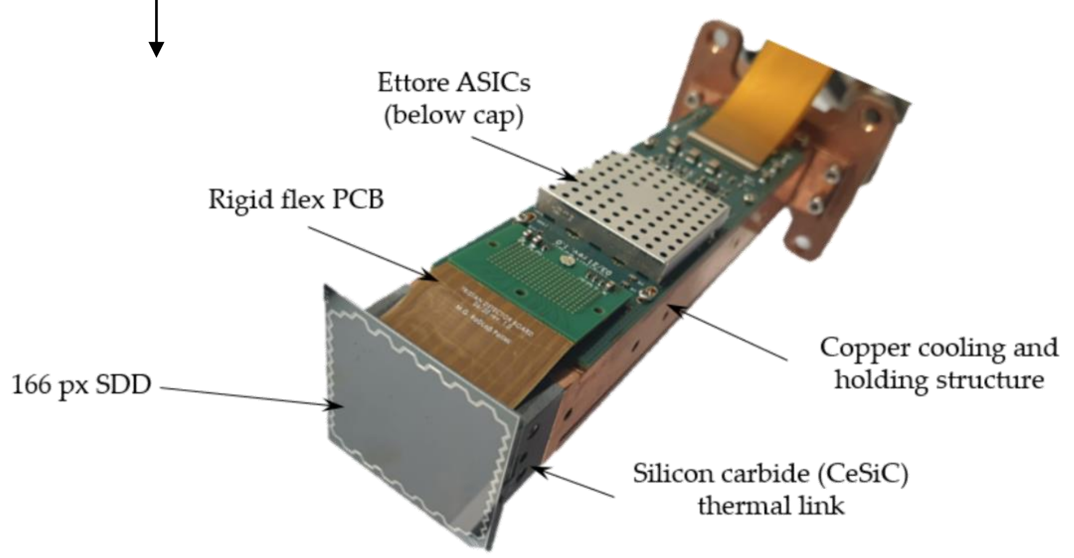
2017

1st prototype

7 and 47 pixels prototypes

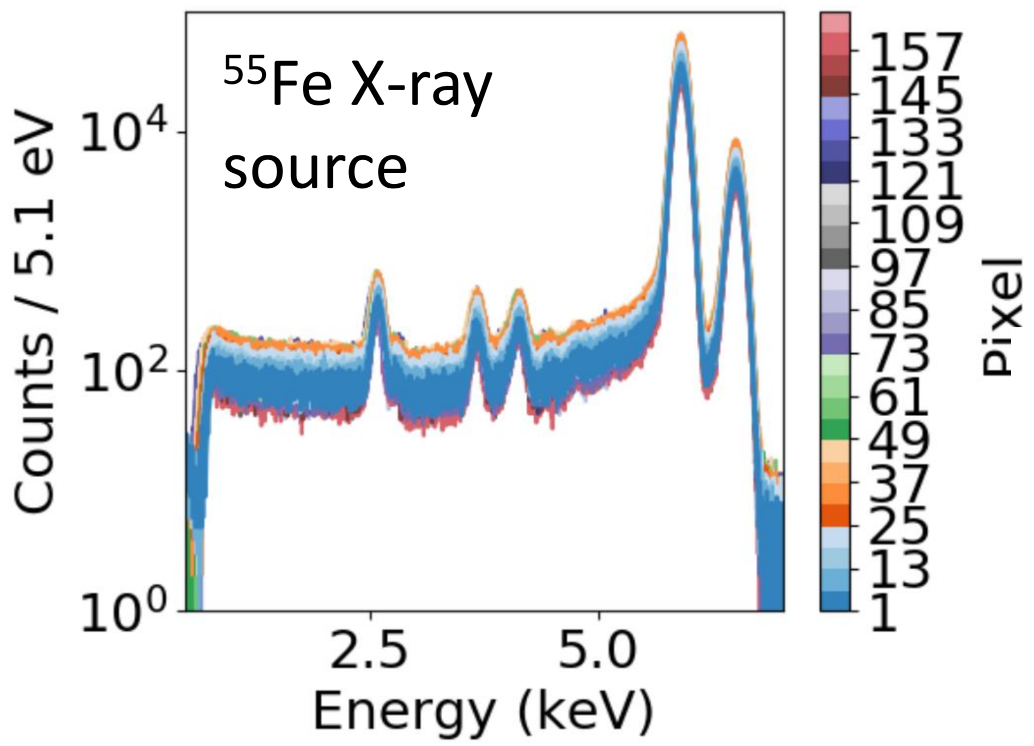


3D focal plane design with 166 pixels



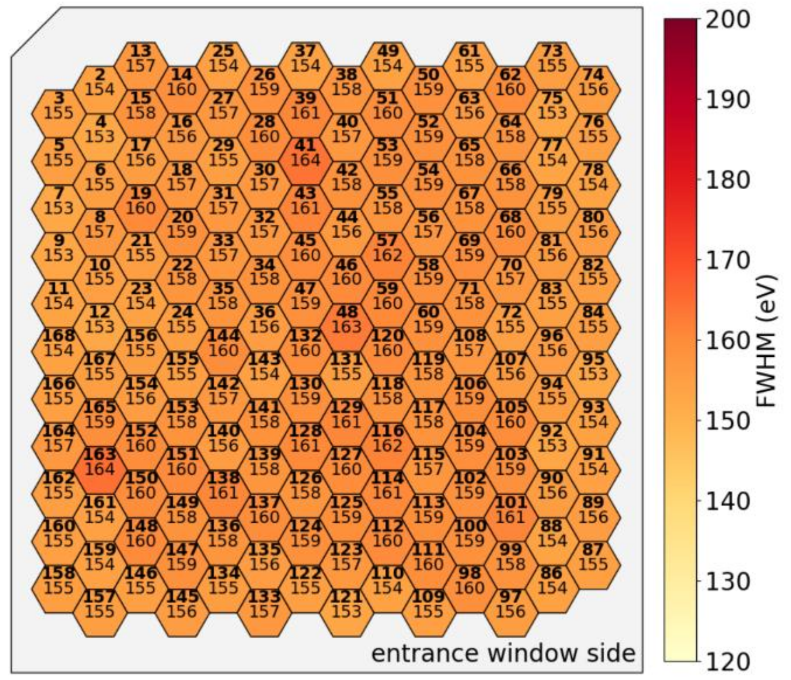
Prototypes: 7, 47, 166 pixels

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



Energy resolution @ 5.9 keV

[j.nima.2021.166102]



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

D. Spreng: TRISTAN detector overview

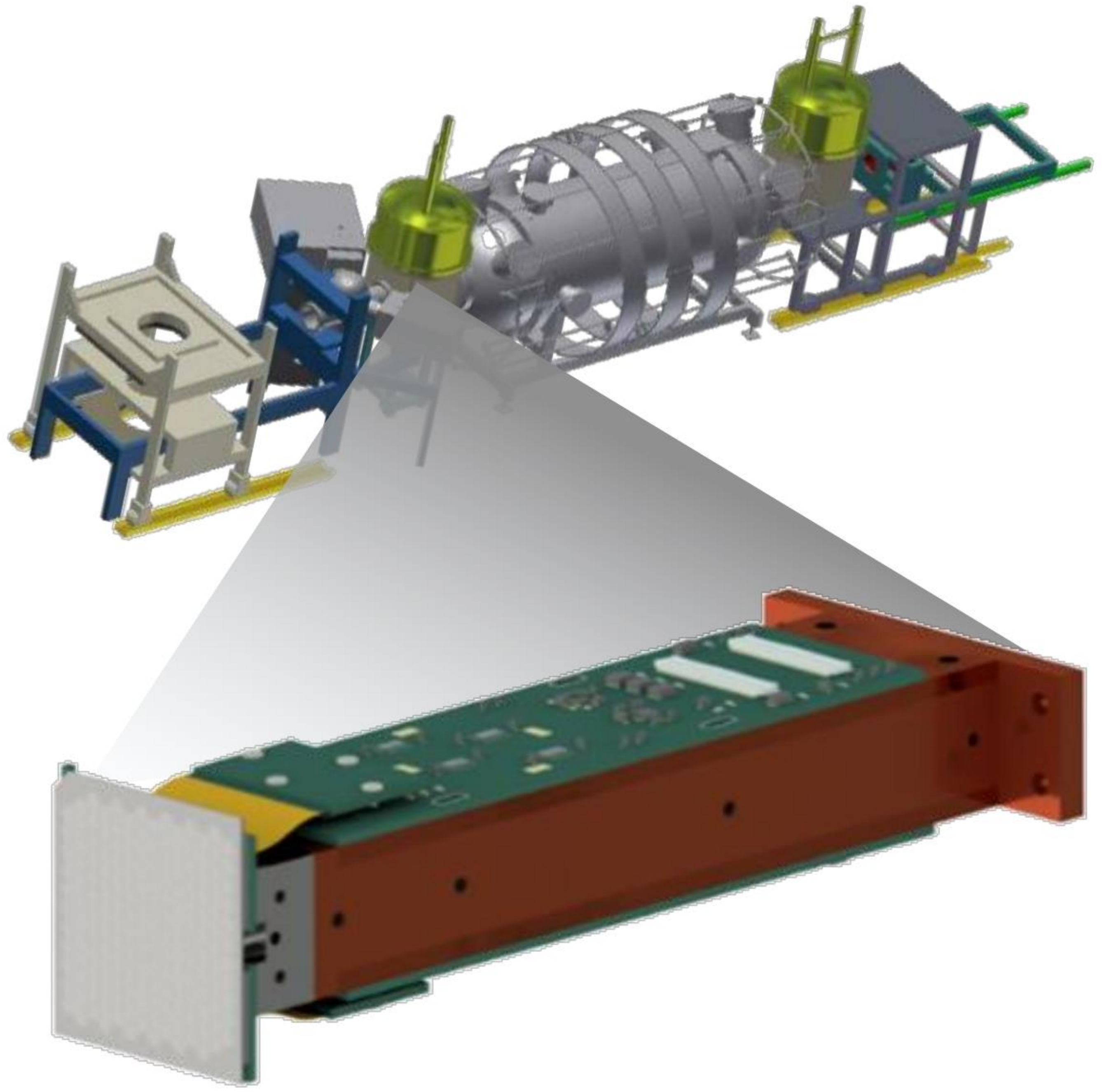
Staged approached

2017

1st prototype

2022

1st module in monitor spectrometer



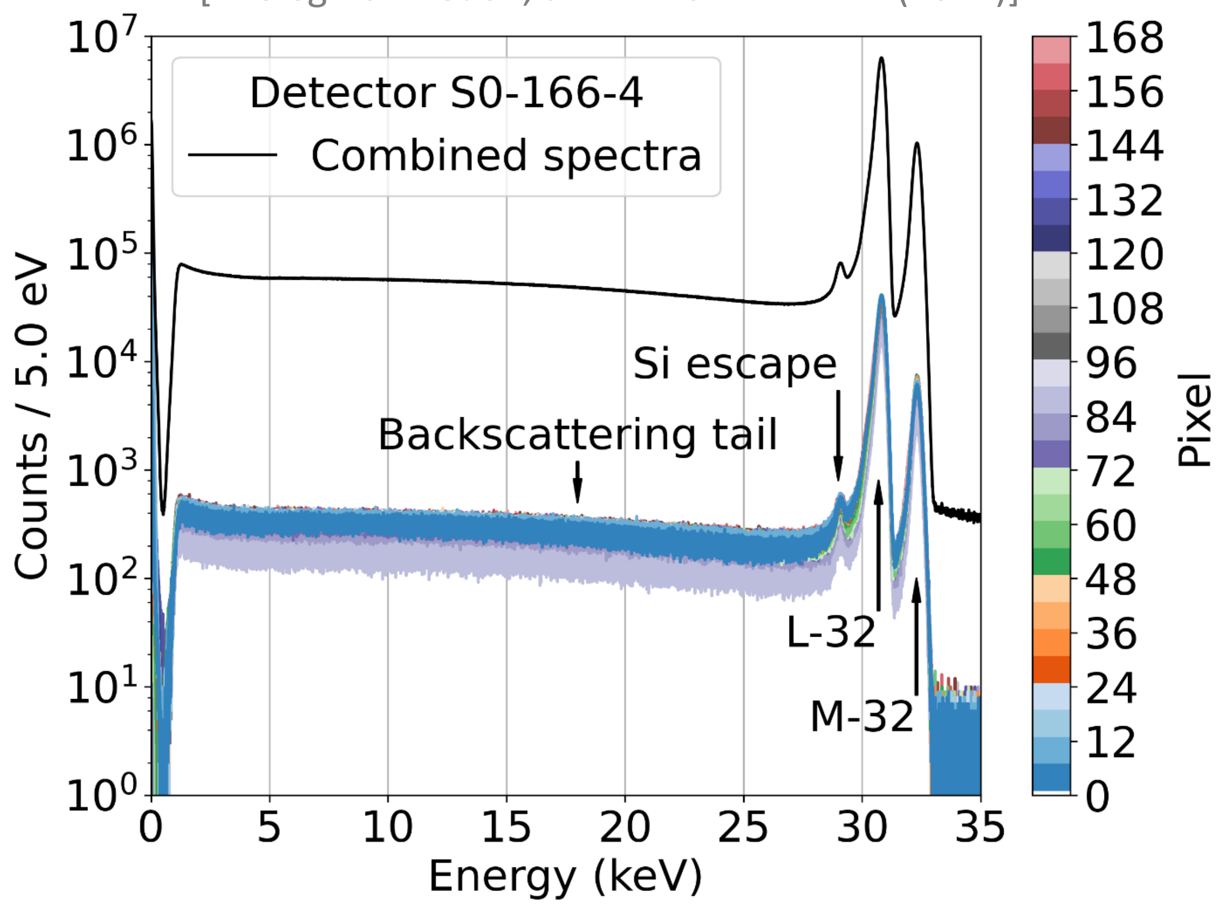
Monitor spectrometer (MoS):

- 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

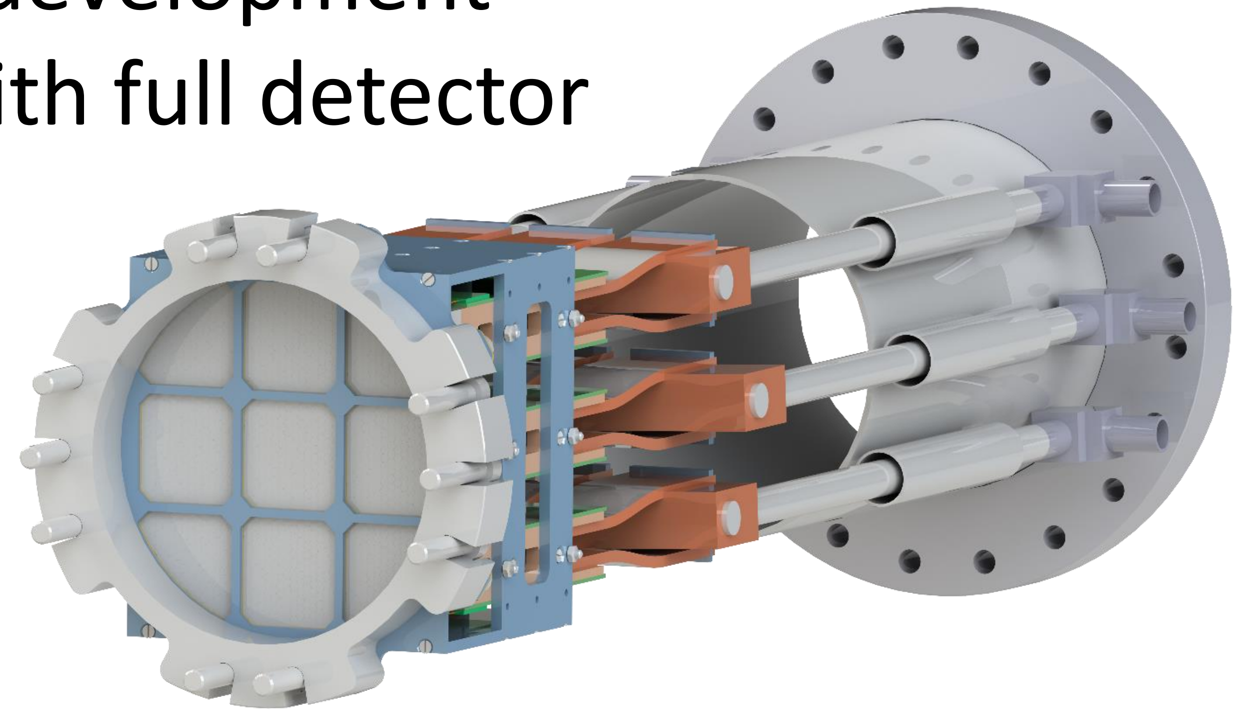
1st module in monitor spectrometer

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

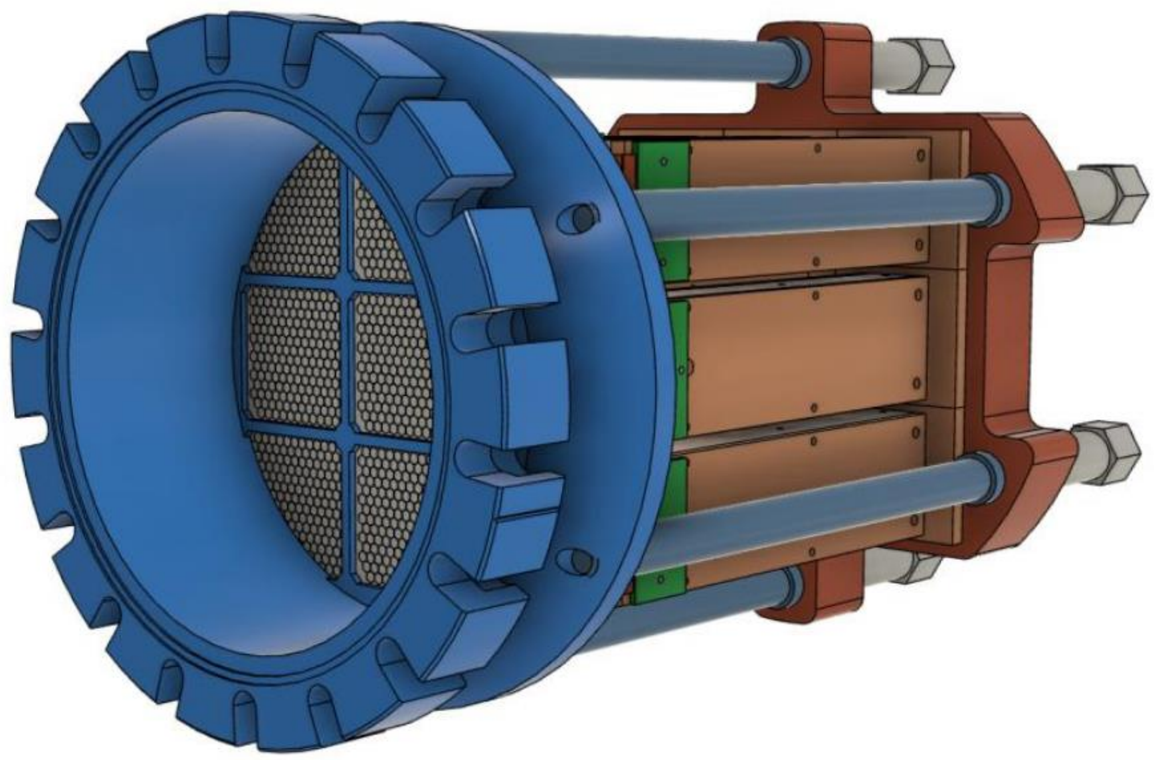


Multi-modules calibration

- 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

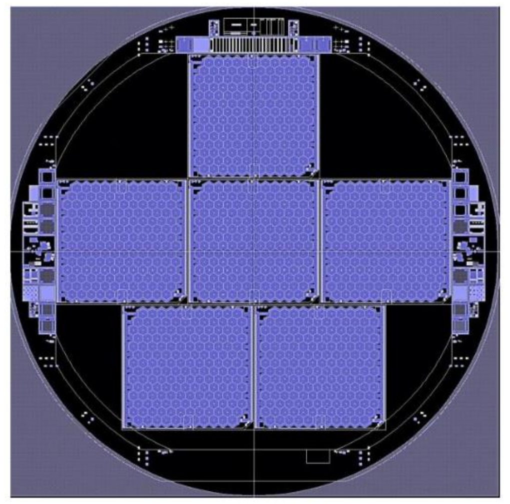


- 9 modules
- 1500 pixels

Detector commissioning in 2026

- Almost final module design
- SSD production started

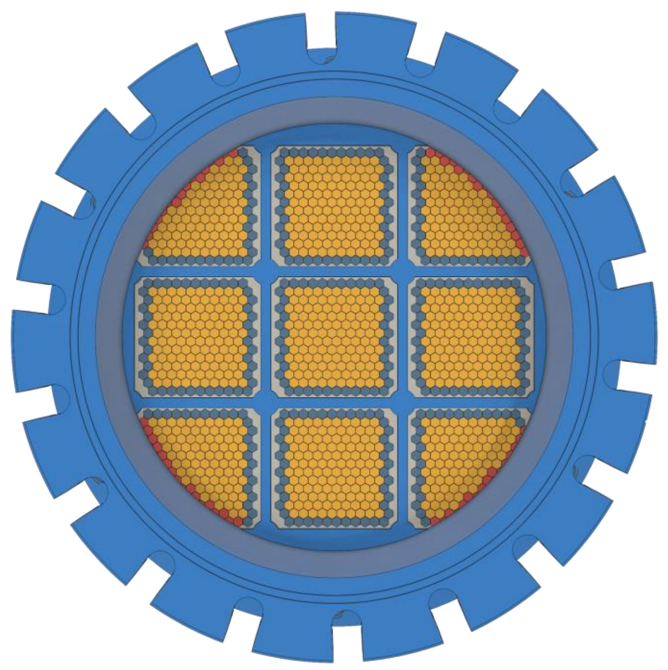
SSD wafer prototype



⇒ First KATRIN keV sterile neutrino search with TRISTAN

KATRIN sensitivity to keV sterile neutrino with TRISTAN

Rate consideration

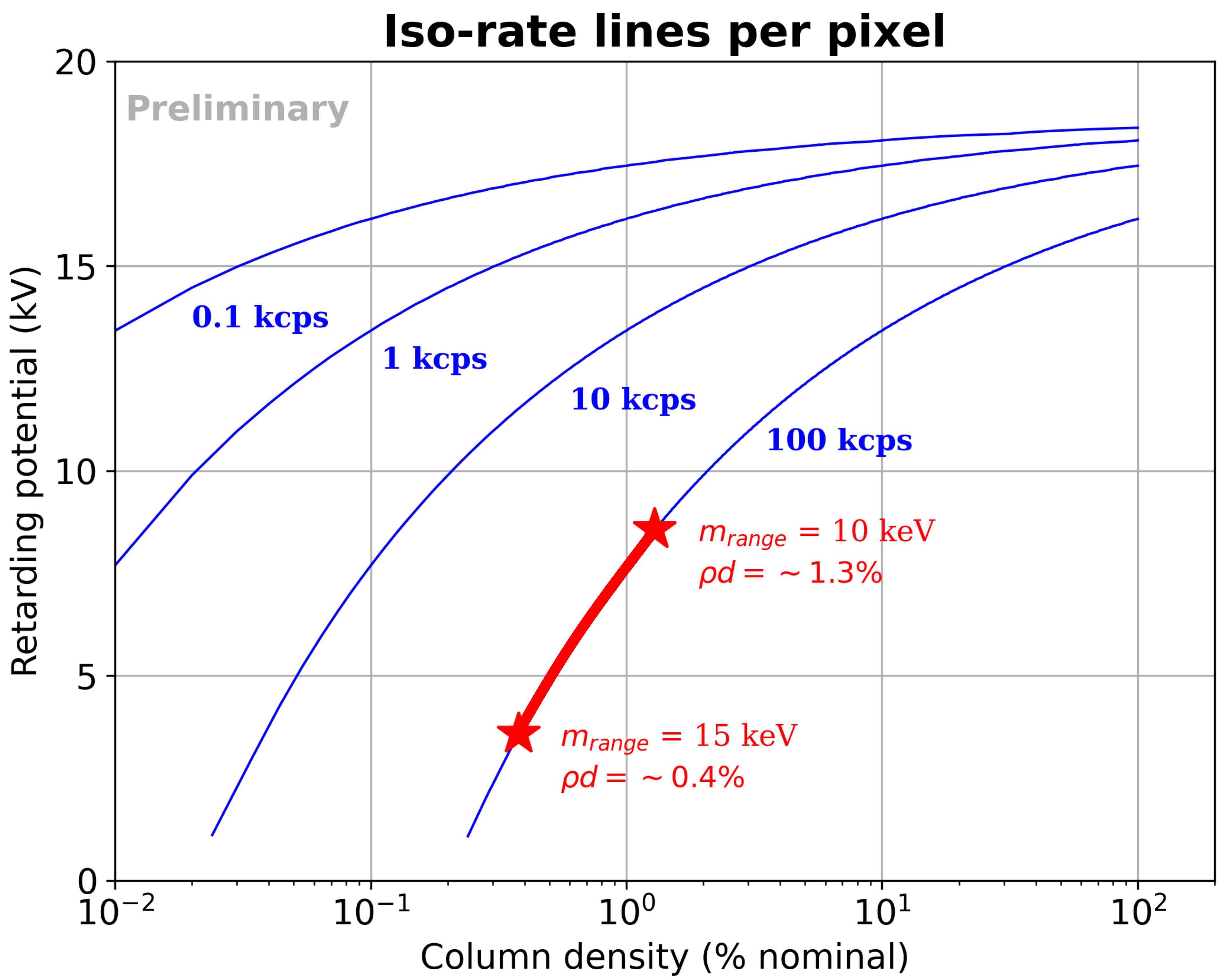


TRISTAN 9 modules

- Total pixels: 1494
- Golden pixels: 936 (63%)

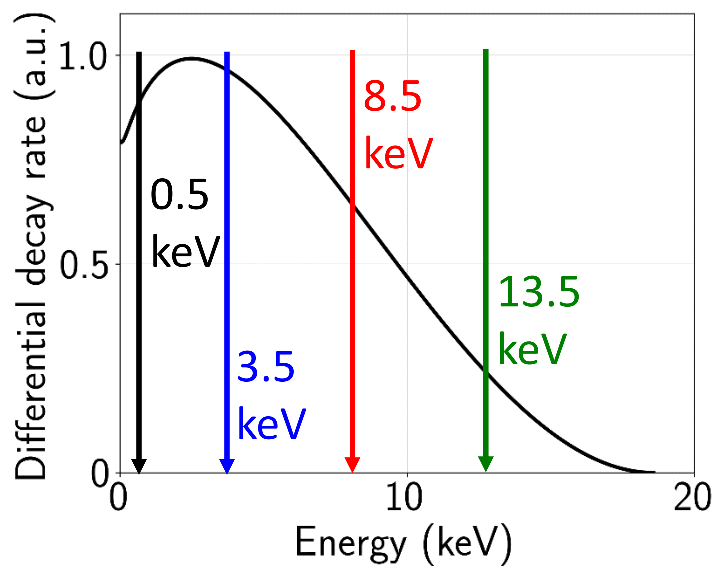
Rate per pixel limited to 100 kcps due to dead time
⇒ Maximal total rate: $\sim 10^8$ cps

Rate can be adjusted via
- Source activity (Column density)
- Retarding potential (mass range)
- Magnetic fields (acceptance angles)



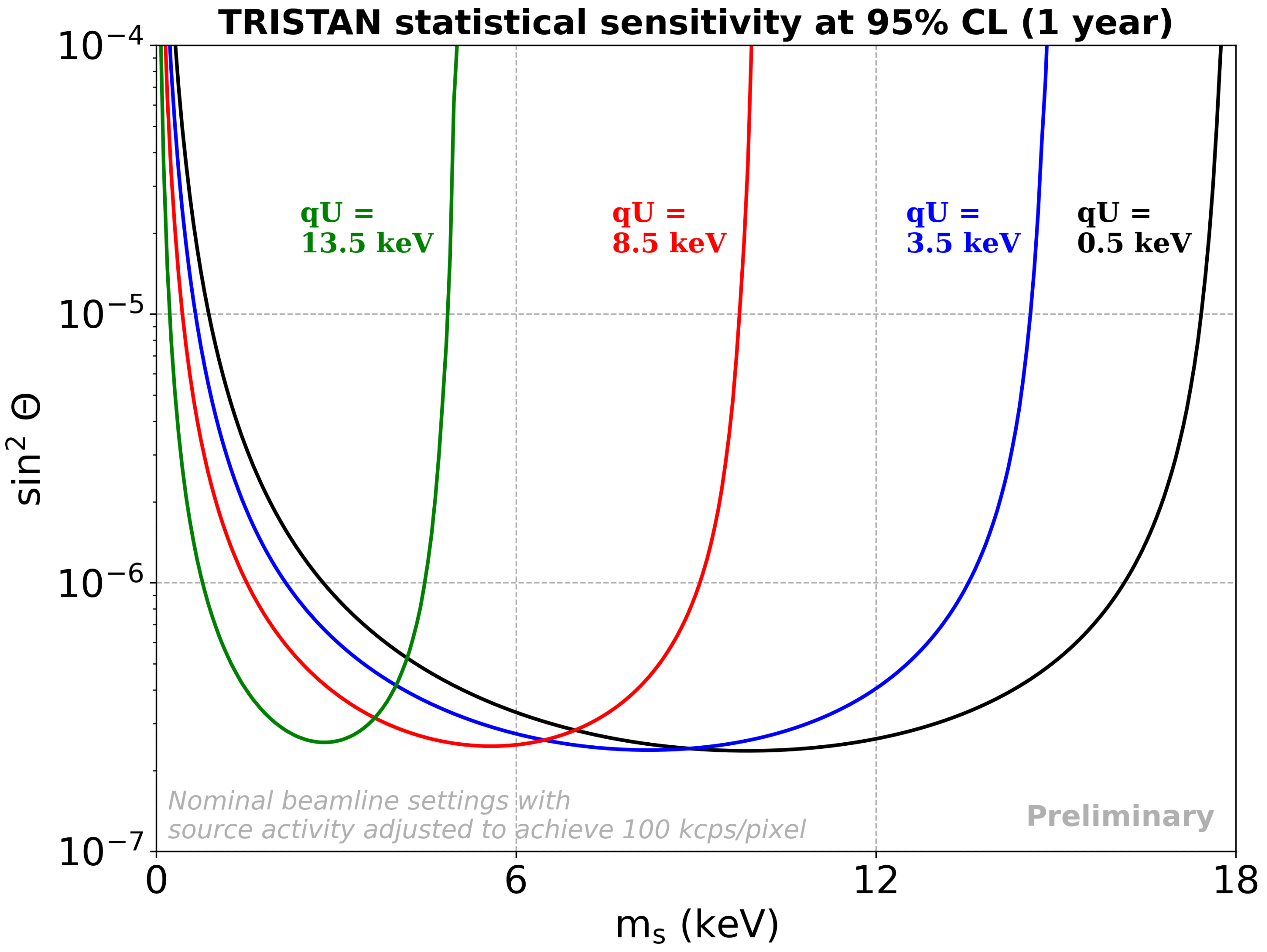
⇒ Optimal column density for TRISTAN: percent level of nominal source activity

Statistical sensitivity



Impact of the retarding potential

- Stat only
- Retarding potential ↗: mass range ↘



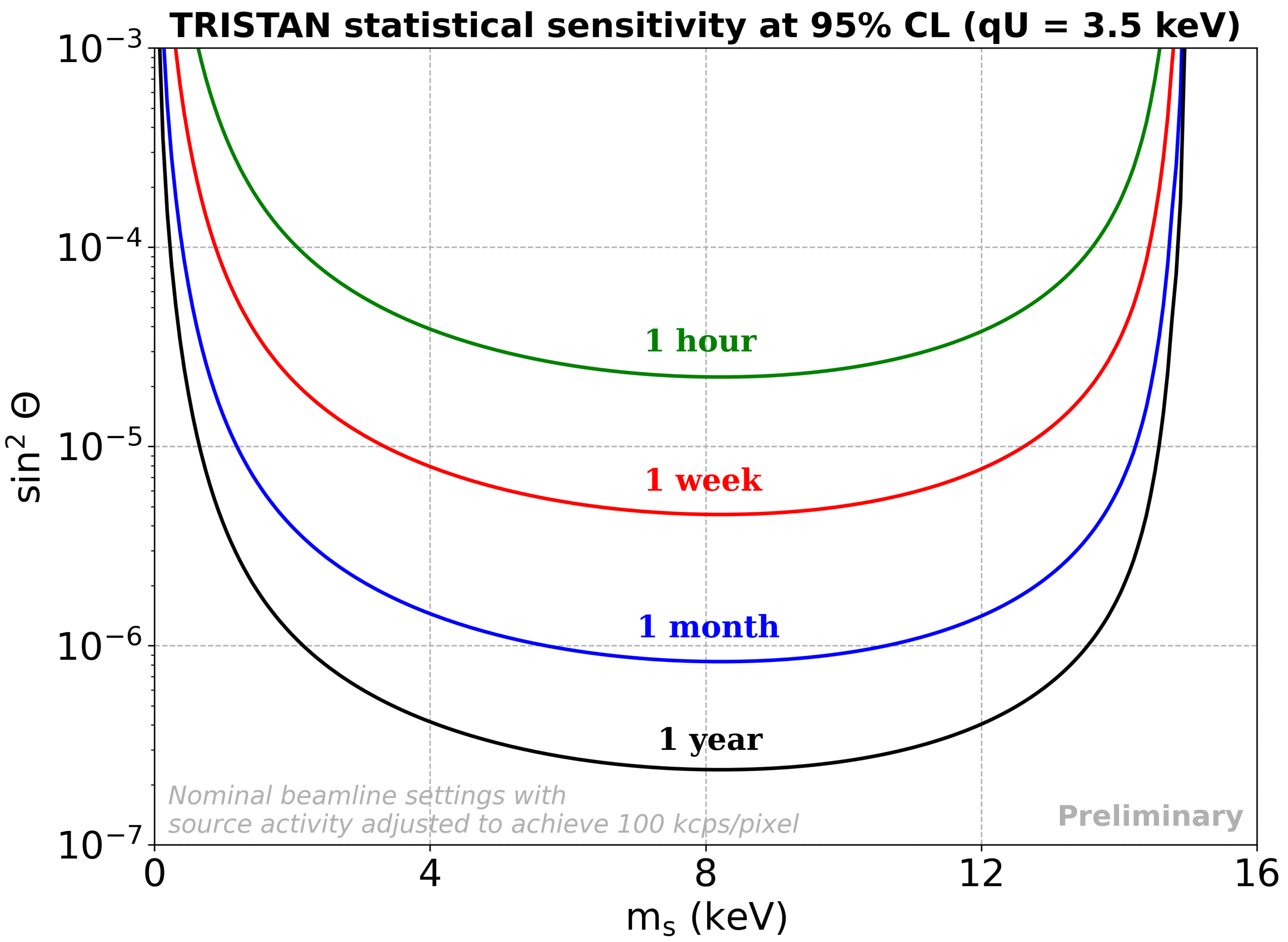
⇒ With high retarding potential, low statistical limit can be maintain by increasing the source activity

Statistical sensitivity

Impact of the measurement time

- Stat only
- Sensitivity improve as $\sqrt{N_{event}}$
- 10^{-5} level reachable within days

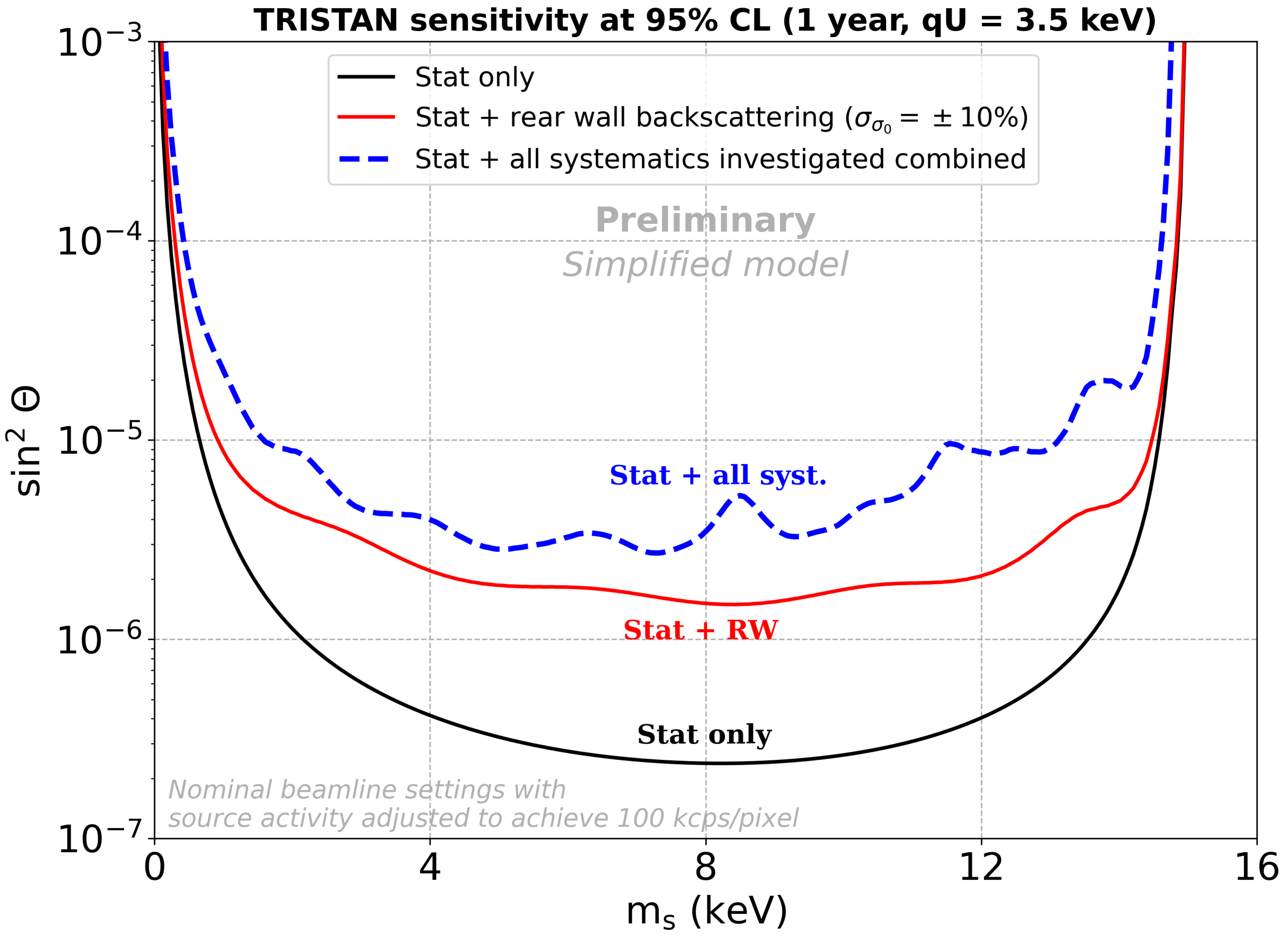
⇒ ~2.10^{-7} reachable in 1 year at the center of the mass range (N_{event} ~ 10^{15} in ROI)



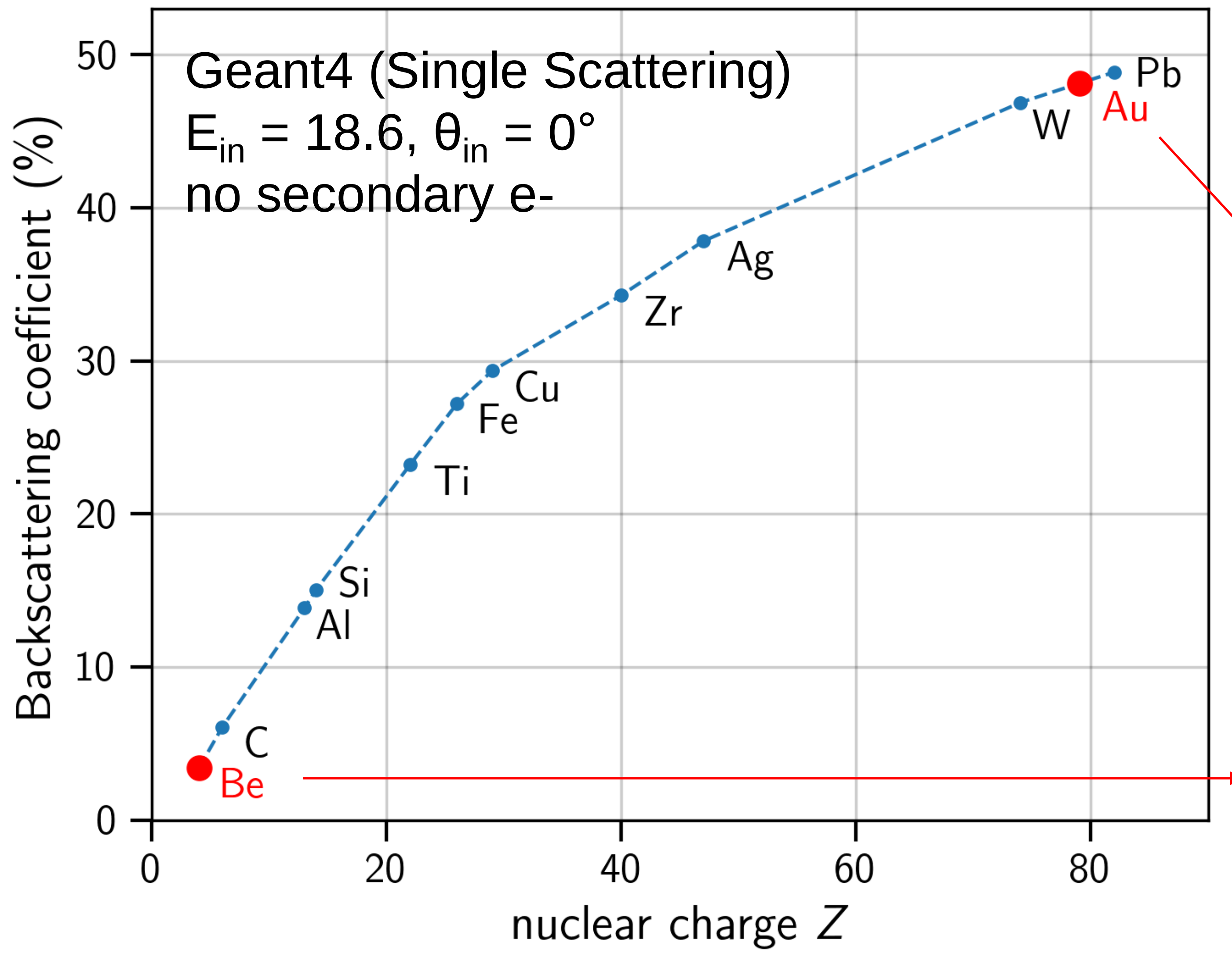
Systematic uncertainties

- Systematic effects reduced the statistical sensitivity by at least one order of magnitude when the same beamline settings are used as for the ν-mass measurement.
- Systematics are dominated by Rear Wall events.

⇒ On-going simulations and R&D efforts to mitigate impact of RW events and other systematic effects



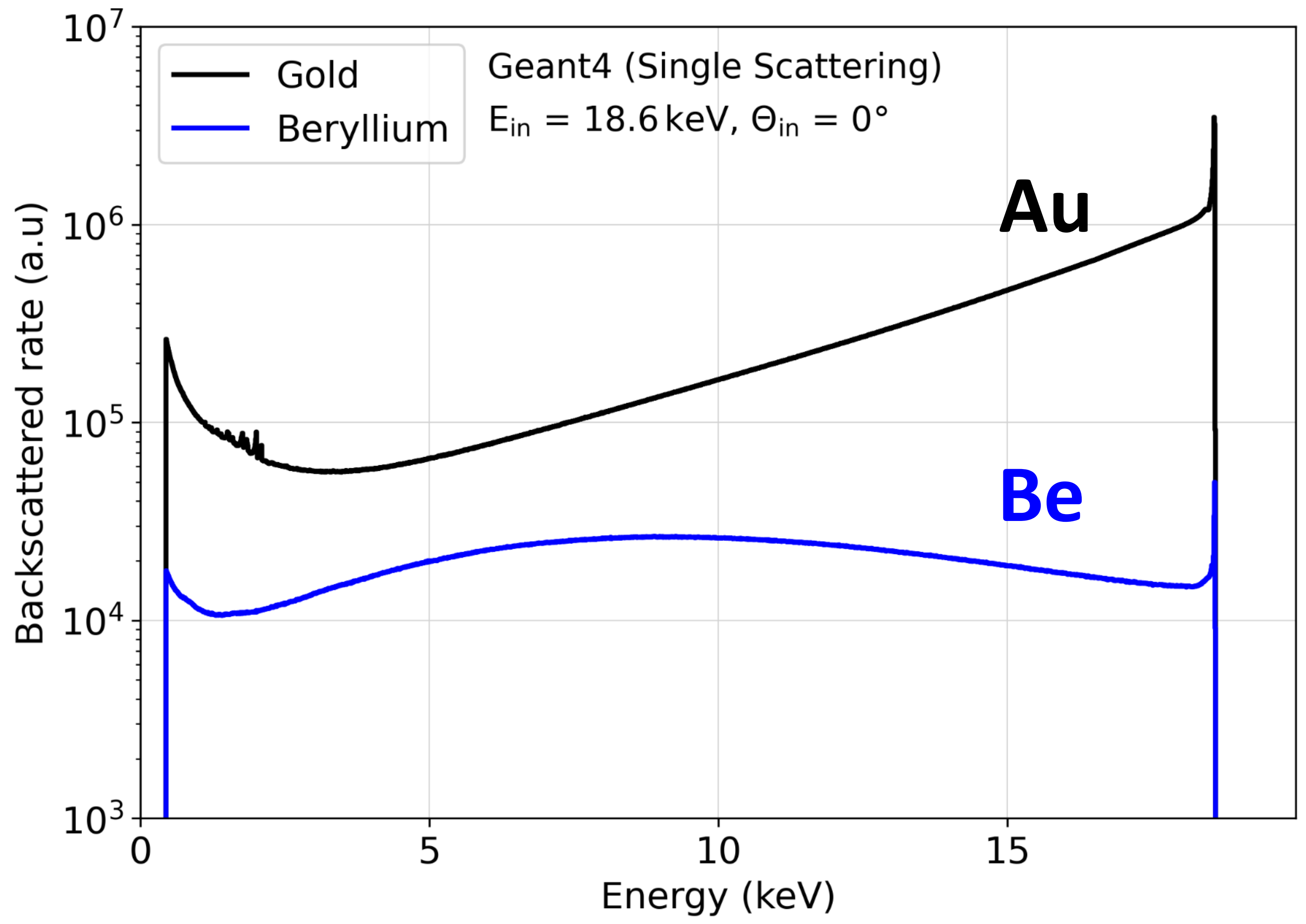
Rear wall events mitigation

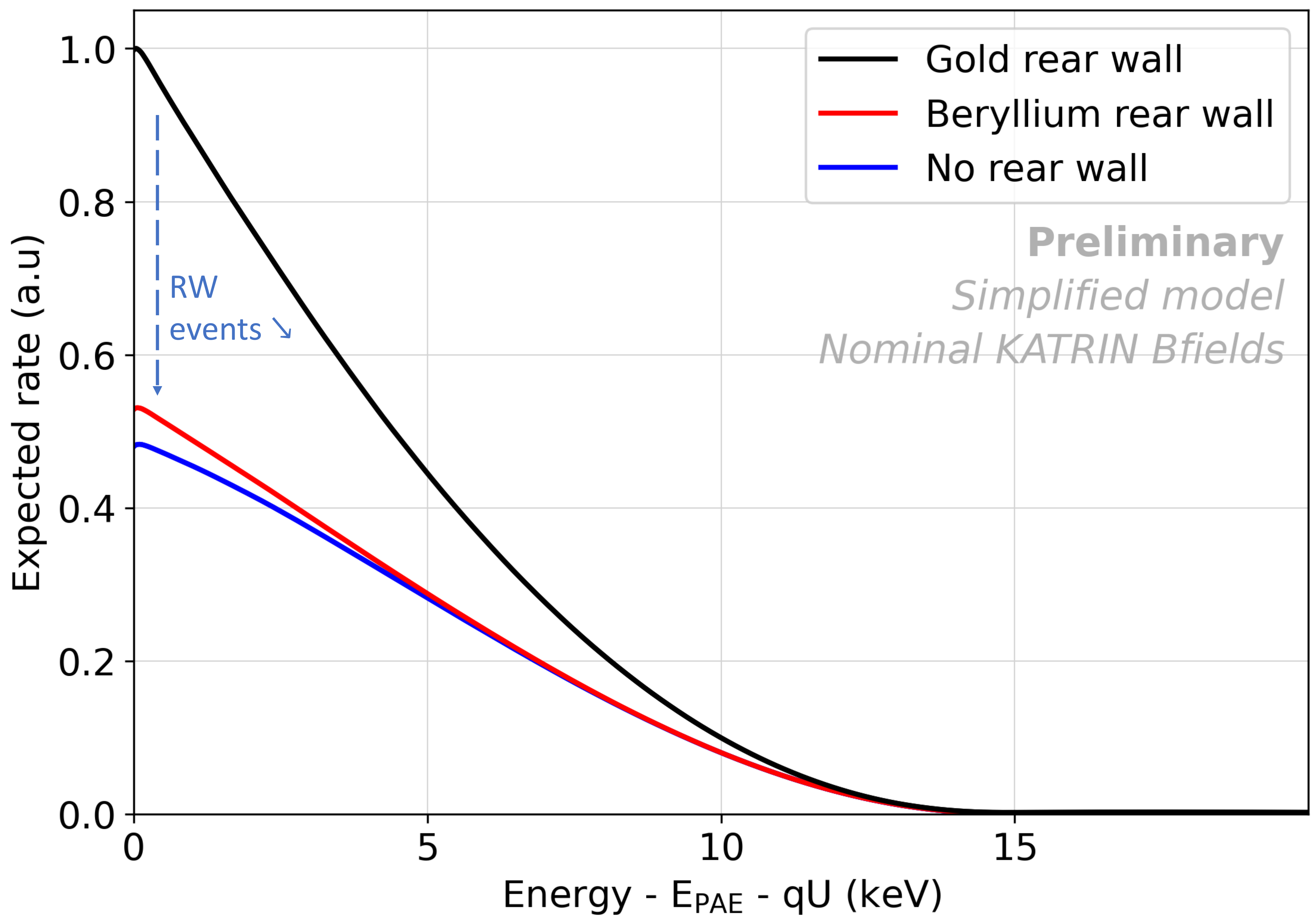


Backscattering probability

Au: ~48%

Be: ~3%





High contribution of RW events with Au

- **Mitigable with new material. Further reduction with optimised magnetic fields possible for a contribution < 1% in ROI**
- More technicaly challenging optimisation also investigated: blocking electric potential before rear wall

Conclusion

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 keV < m_4 < 1.0 keV
  - ↳ Several order of magnitude improvement of current laboratory limits expected with TRISTAN Goal: ppm level on $\sin^2\theta$

Thank you for your attention!

Acknowledgement:

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