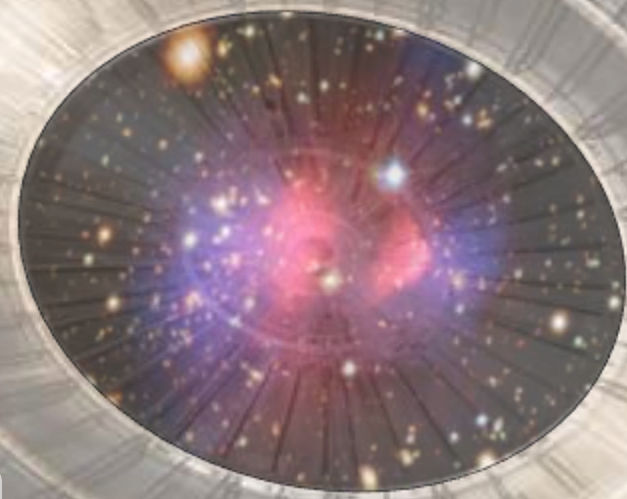
KATRIN: keV sterile neutrino search

Andrea Nava, University of Milano-Bicocca
on behalf of the KATRIN collaboration

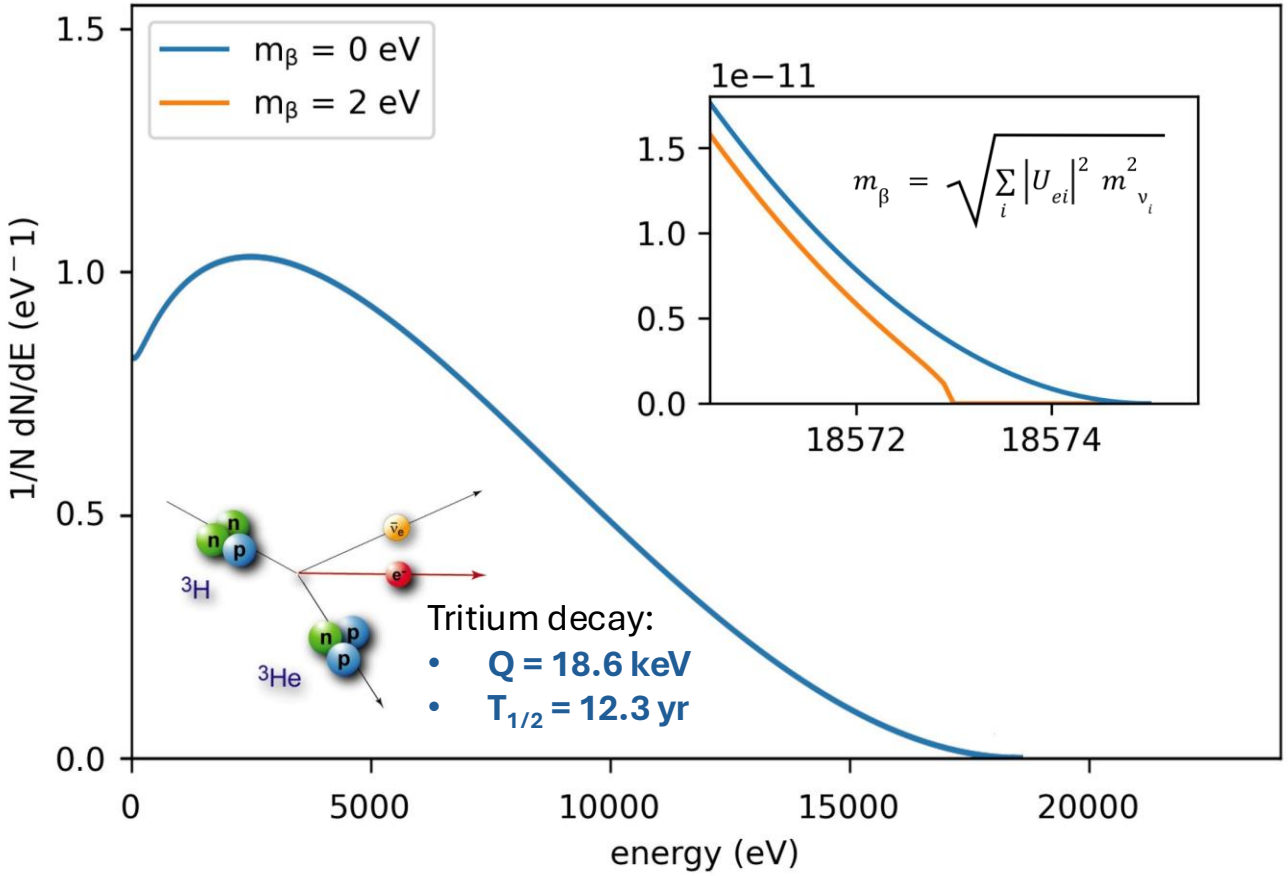


NOW 2024, 2/9/2024-8/9/2024, Otranto

Tritium β decay and neutrino mass

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

⟹ Non-zero neutrino mass induces distortion in the endpoint region



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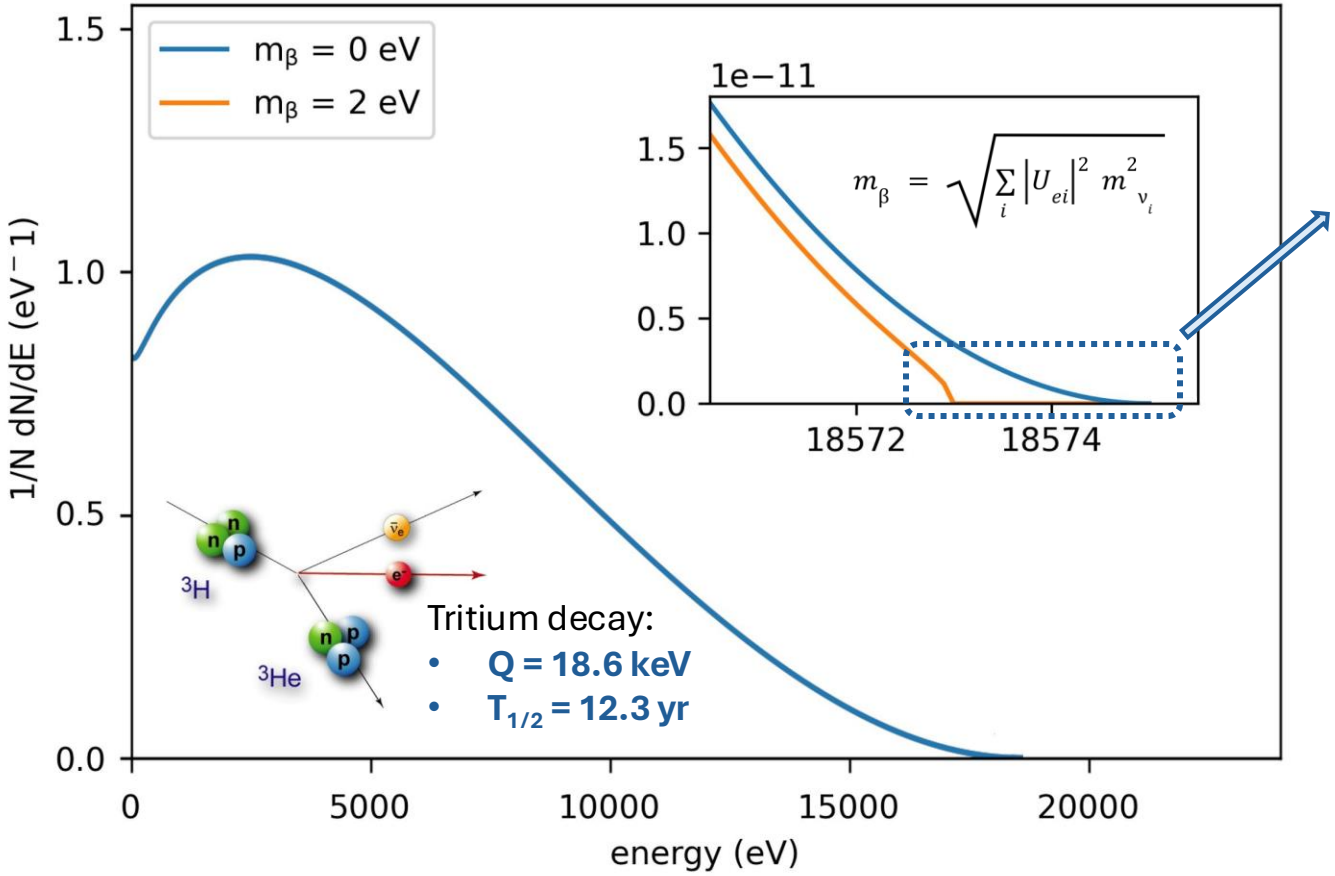


Only 10^{-13} of the electrons in the last eV

Requirements:

- high-luminosity tritium source
- very low background level
- energy resolution of O(1 eV)

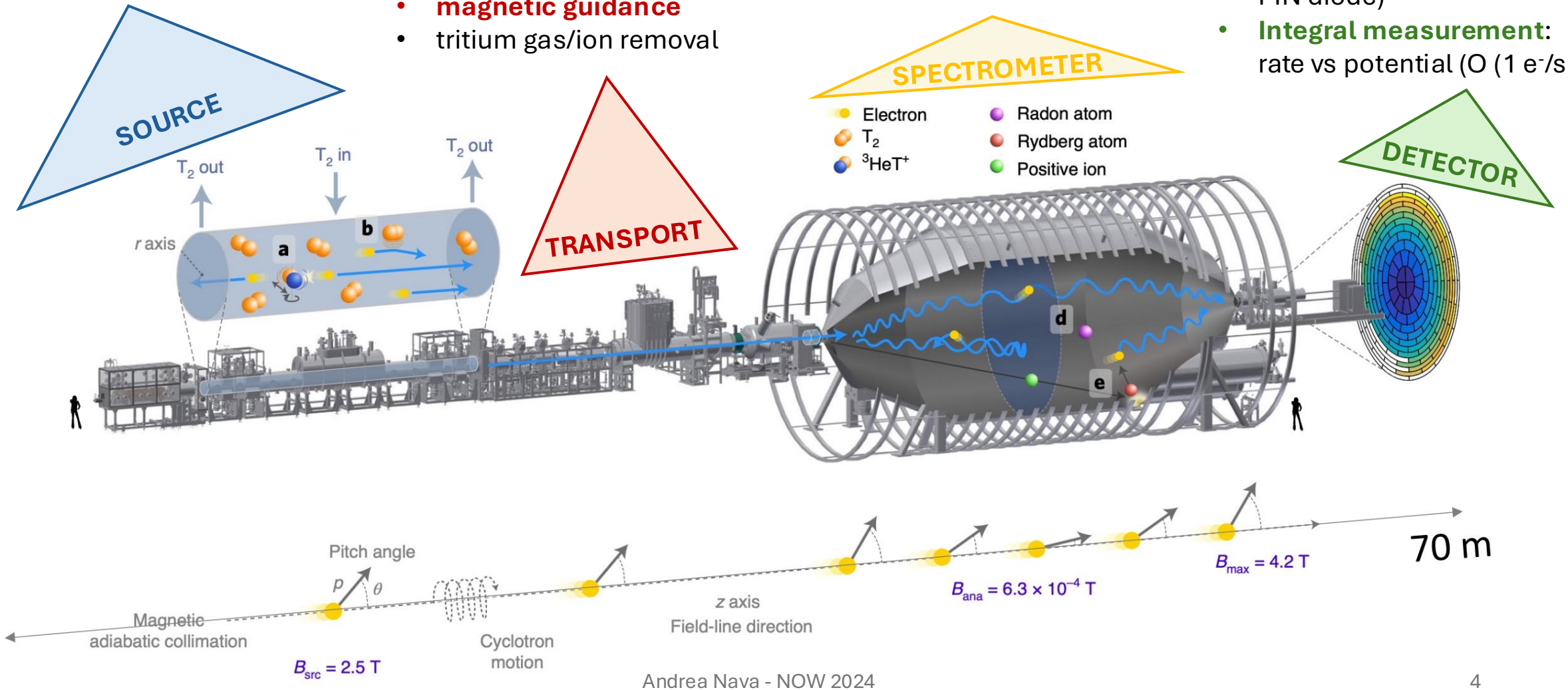
KATRIN in a nutshell

- **molecular tritium** in a closed loop
- **10^{11} decays/s**

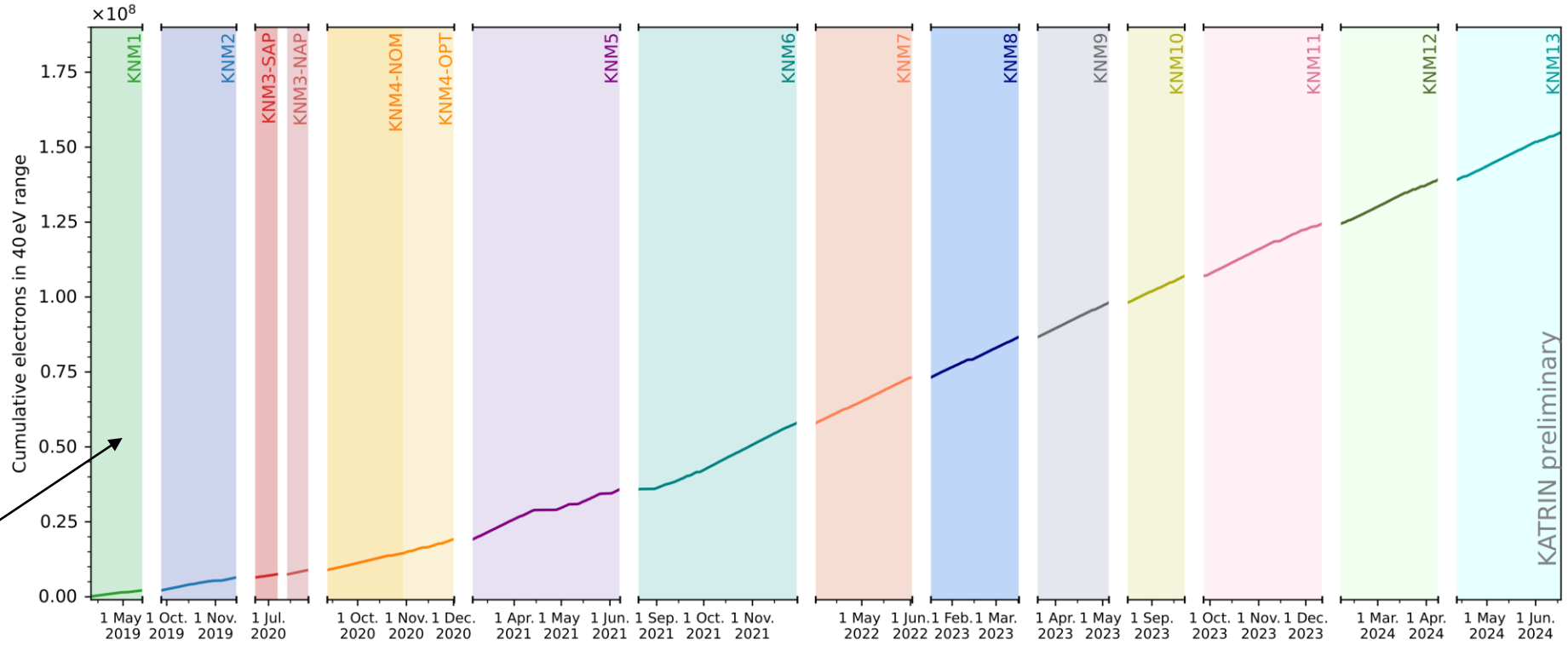
- **magnetic guidance**
- tritium gas/ion removal

- **MAC-E filter**
- **O(1 eV)** resolution
- large acceptance angle (0-51°)
- background **<0.1 cps**

- Focal Plane Detector (Si PIN diode)
- **Integral measurement**: rate vs potential (O (1 e^-/s))



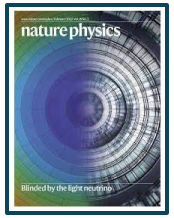
KATRIN status



PRL 2019

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

Nature physics 2022

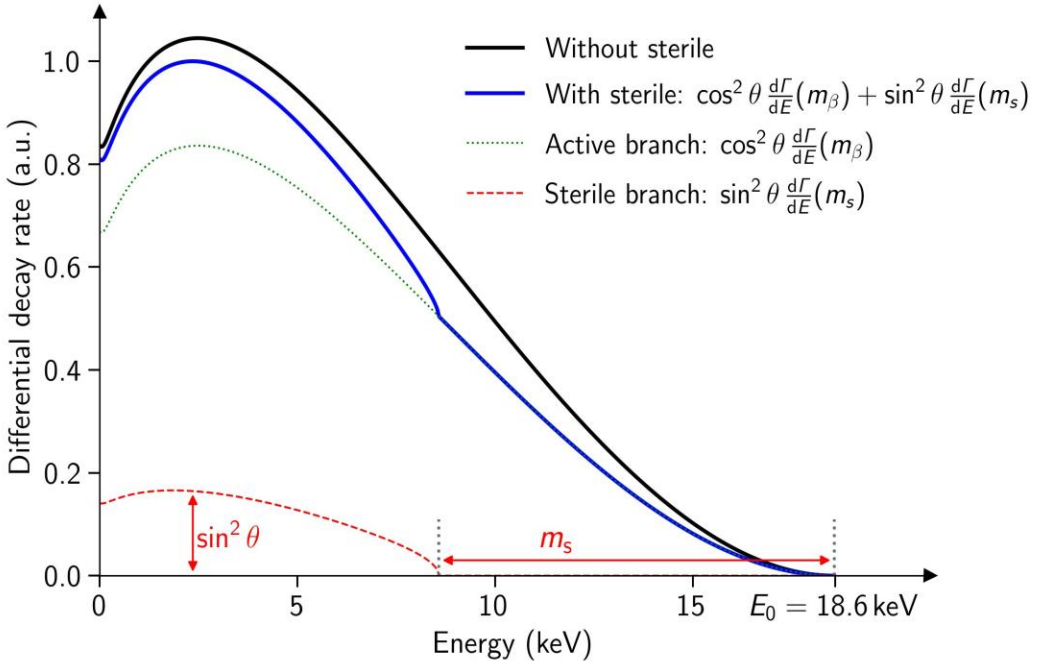


[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

Results from 1st to 5th campaign announced at Neutrino2024!

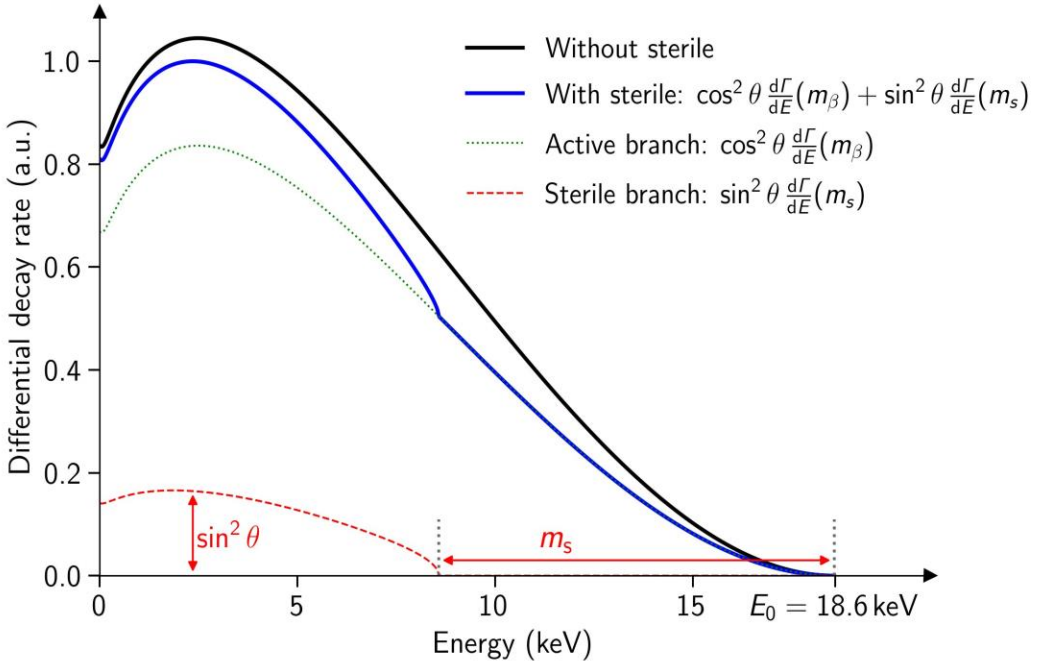
See M. Schlösser and R. Salomon talks!

keV sterile neutrinos



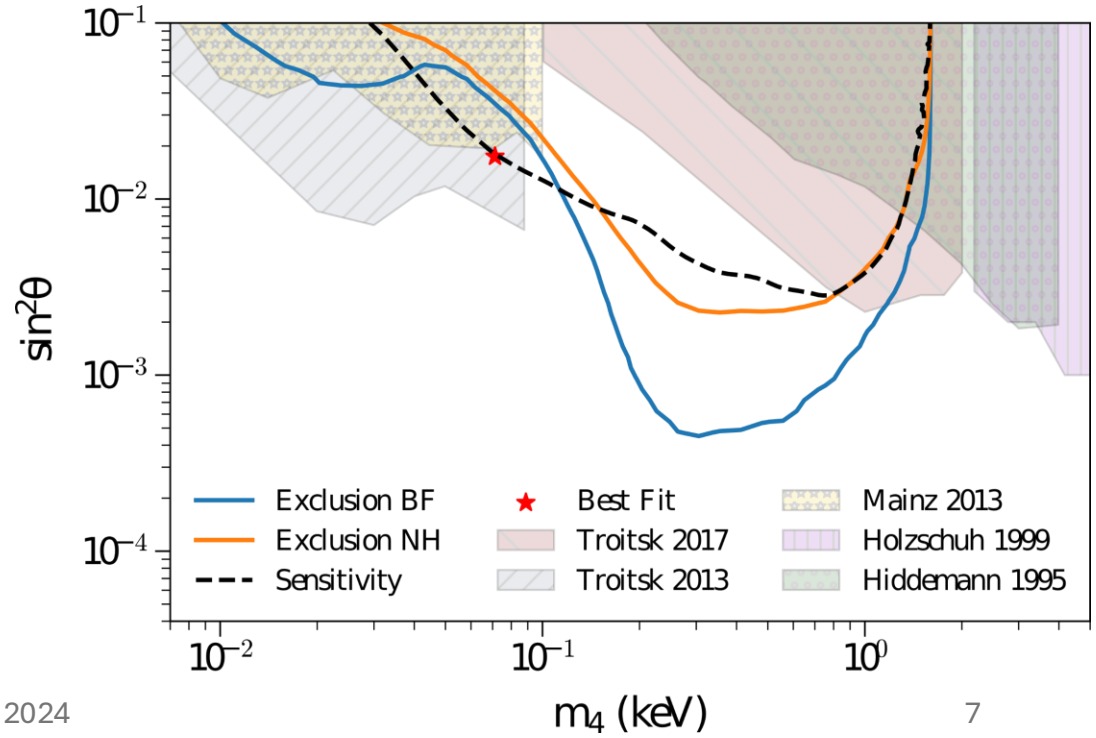
- **keV sterile neutrinos are WDM candidates**
- Their existance would lead to a global distortion (+ kink) in the β spectrum
- Kink's position and amplitude are related to sterile neutrino parameters

keV sterile neutrinos

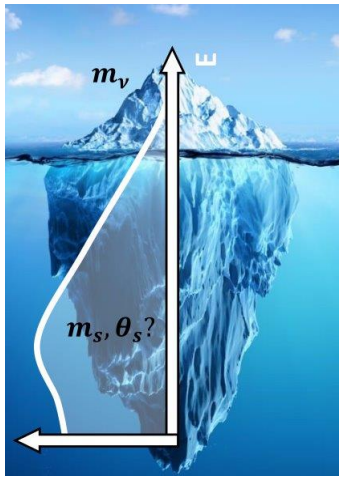


- **keV sterile neutrinos are WDM candidates**
- Their existance would lead to a global distortion (+ kink) in the β spectrum
- Kink's position and amplitude are related to sterile neutrino parameters

- **KATRIN already searched for keV sterile neutrinos** in integral mode in the 0.01-1.6 keV mass range:
  - reduced isotopic abundance to handle higher rate
  - systematics dominated by source activity fluctuations
- No signal observed
- Laboratory **limit improved in the region 0.1-1 keV**



The TRISTAN detector

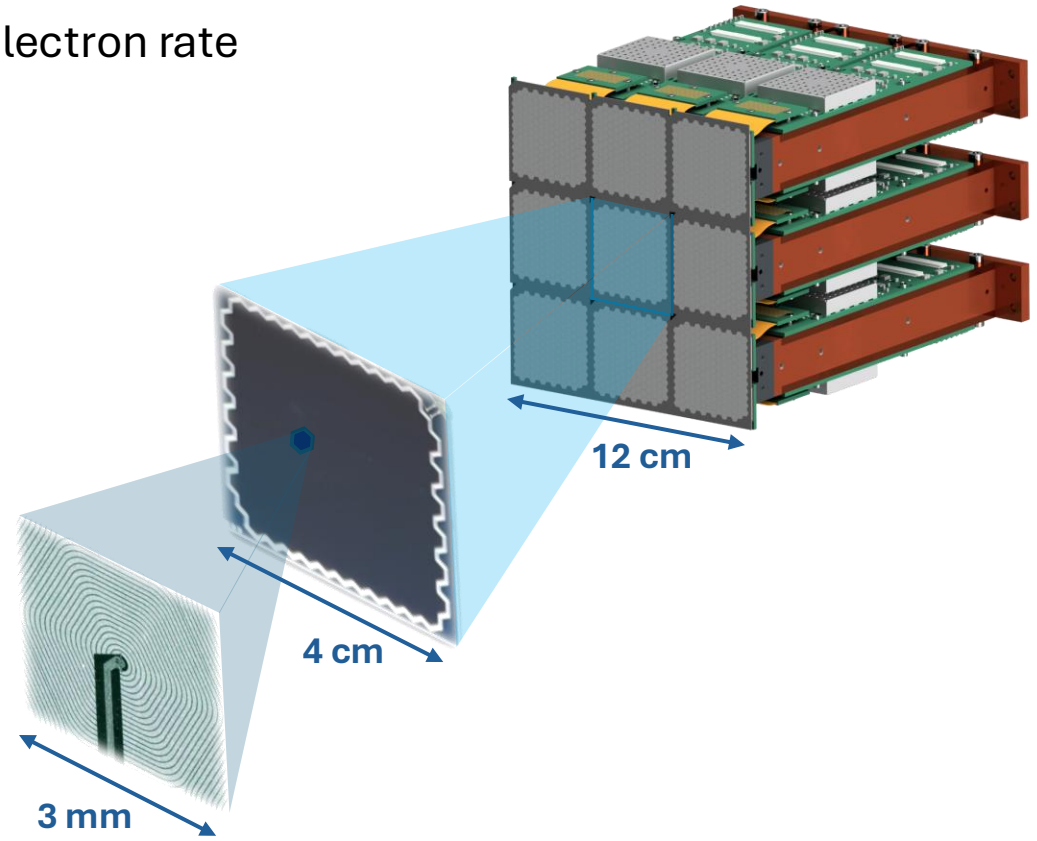


Goal: expand KATRIN physics program by measuring differentially the whole tritium spectrum

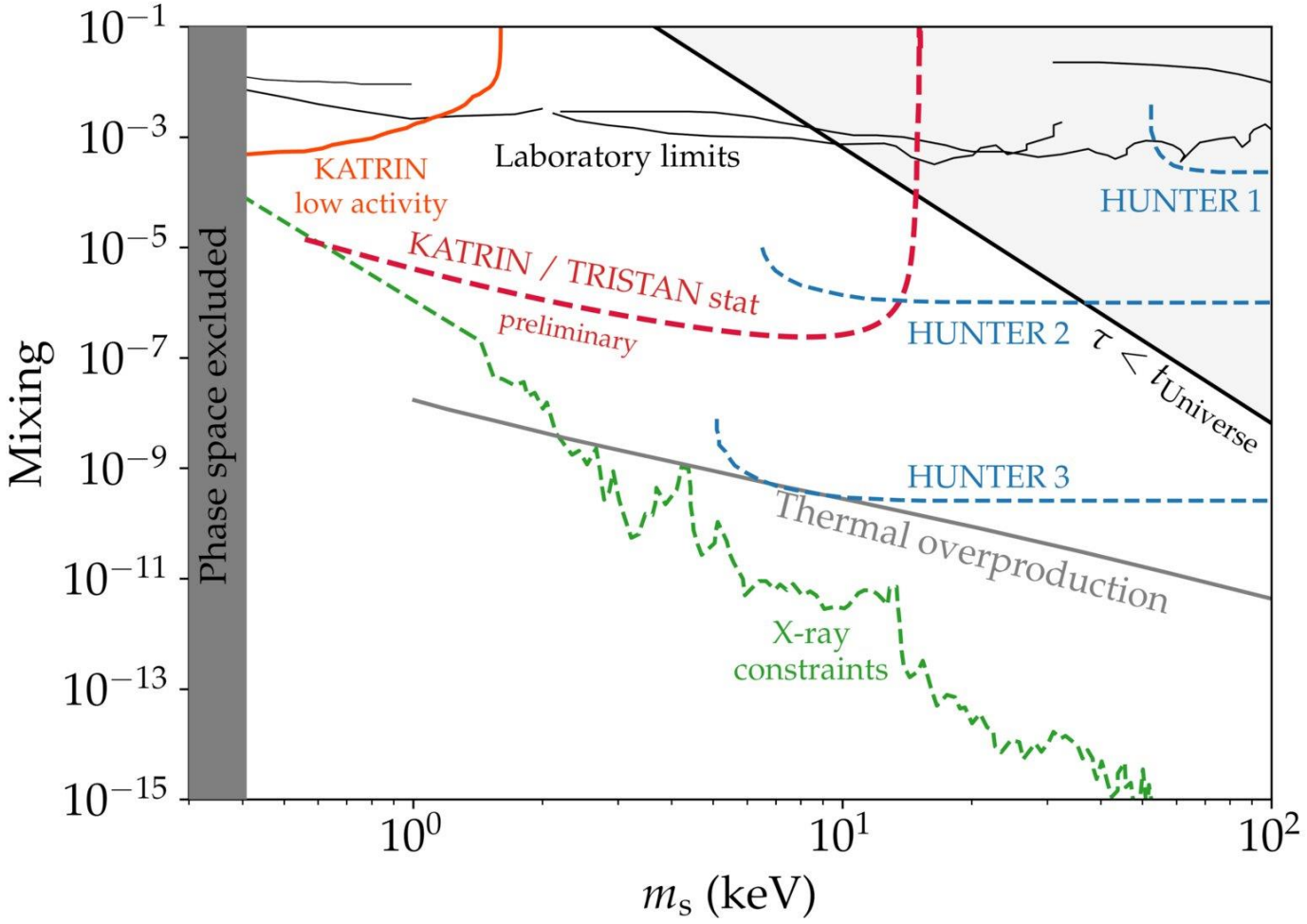
⟹ need to lower the spectrometer's potential

⟹ the current detector can't handle the electron rate

- **TRISTAN**: future upgrade of the KATRIN detector, based on the Silicon Drift Detector (SDD) technology
- Multipixel detector (>1000 SDDs)
- **Energy resolution ~10 times better** than current detector (300 eV @ 18.6 keV)
- Capable of handling **rate up to 10^5 cps/pixel**



KATRIN+TRISTAN in the sterile neutrino picture

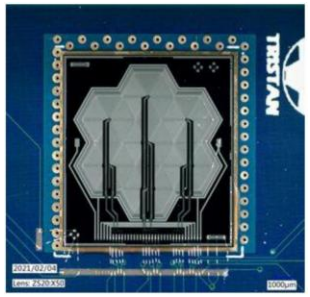


- KATRIN, equipped with the TRISTAN detector, has the statistical potential to drastically improve existing limits
- **sensitivity: $\sin^2\theta < 10^{-6}$**
- complementarity with other experimental techniques

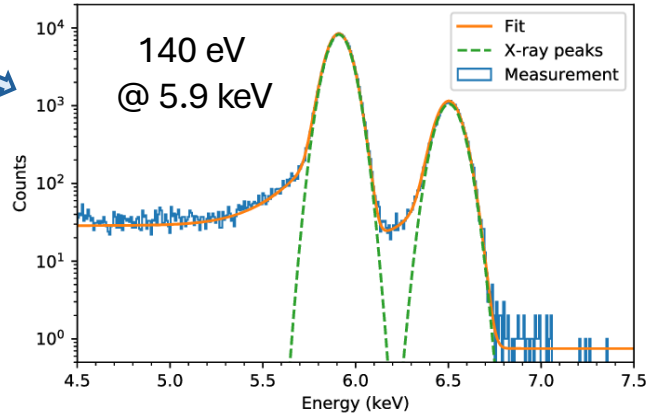
The experimental challenge

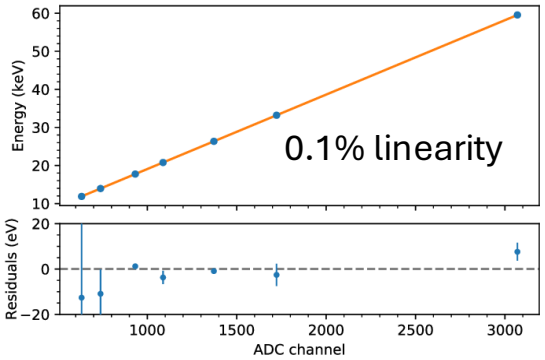
Build and operate a large SDD array in the KATRIN beamline

2017
First prototypes



- optimization of the design
- first studies of SDD response



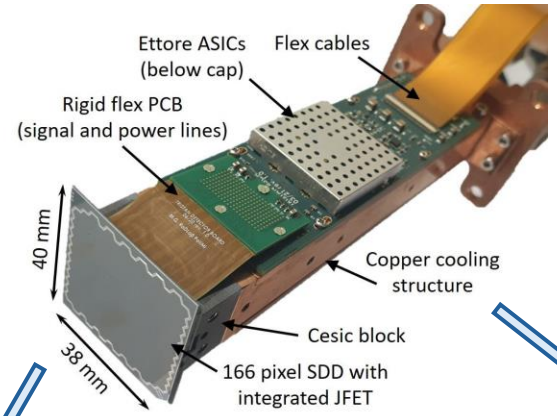


SDD performances meet expectations!

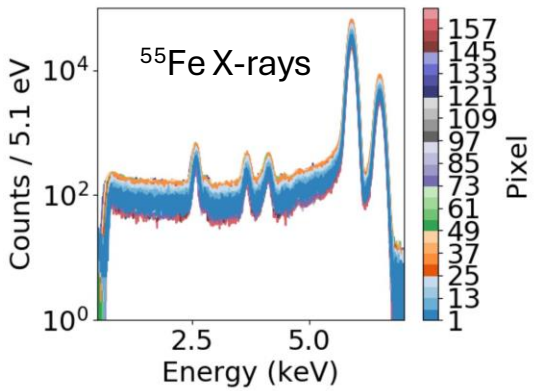
The experimental challenge

Build and operate a large SDD array in the KATRIN beamline

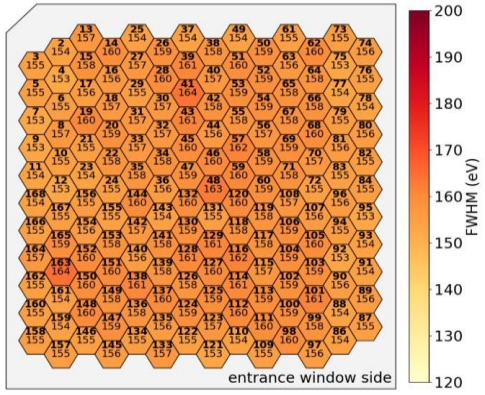
2021
Assembly of a 3D TRISTAN module



- final design for TRISTAN
- multipixel SDD response studies



Largest SDD array ever operated!

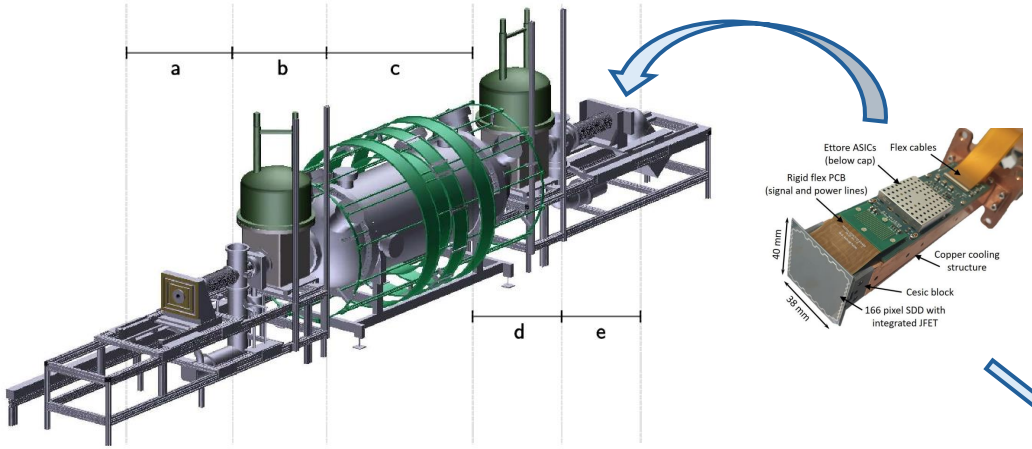


The experimental challenge

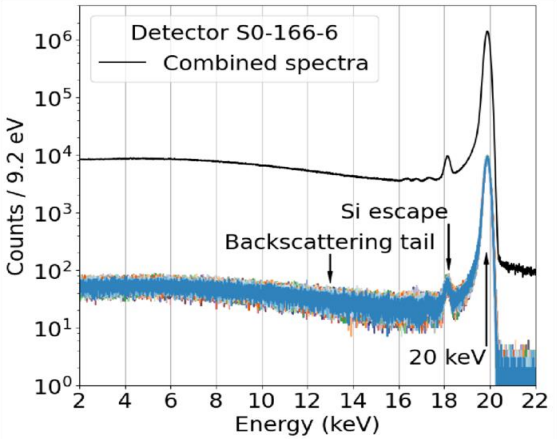
Build and operate a large SDD array in the KATRIN beamline

2022

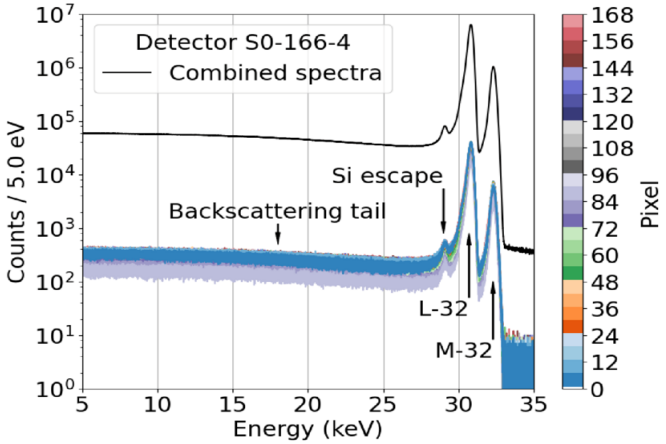
Operation in a KATRIN-like environment



- KATRIN monitor spectrometer (ex Mainz)
- O(T) magnetic fields and O(kV) potential
- first test in a realistic environment



e-gun electrons in the lab



^{83m}Kr electrons in MoS

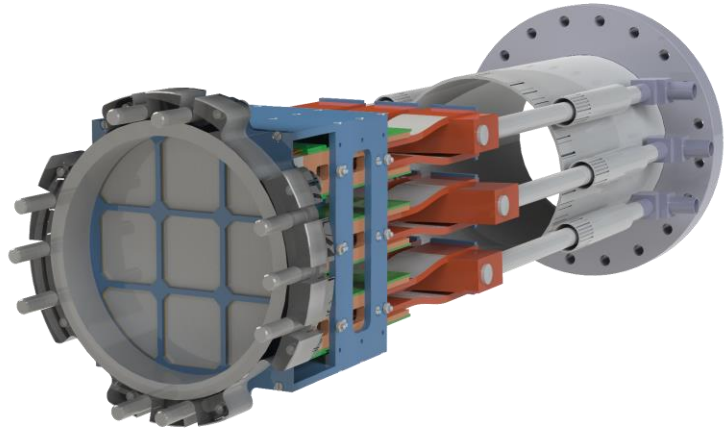
The experimental challenge

Build and operate a large SDD array in the KATRIN beamline

Autumn 2024
Operation in
the detector replica

- exact replica of the KATRIN detector section
- test in the final environment
- Test-bench for new technical solutions (e.g. post acceleration up to 20 keV)

- Commissioning of first 3 modules in the replica by the end of 2024
- Full detector (9 modules) to be installed in the replica in first semester of 2025



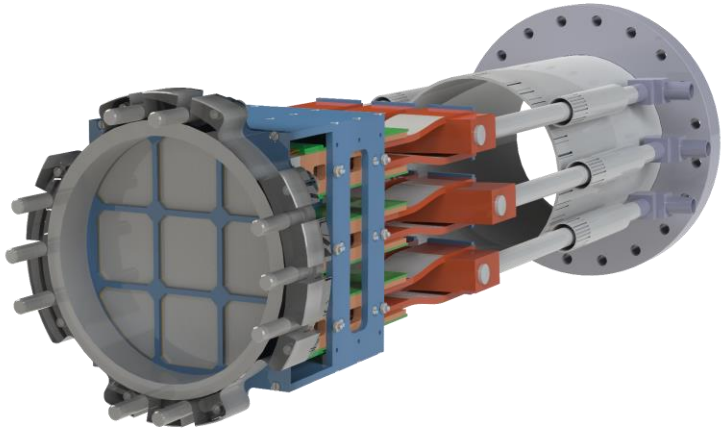
The experimental challenge

Build and operate a large SDD array in the KATRIN beamline

2026
TRISTAN installation in the KATRIN beamline

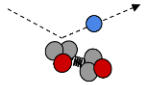
- exact replica of the KATRIN detector section
- test in the final environment
- Test-bench for new technical solutions (e.g. post acceleration up to 20 keV)

- Commissioning of first 3 modules in the replica by the end of 2024
- Full detector (9 modules) to be installed in the replica in first semester of 2025

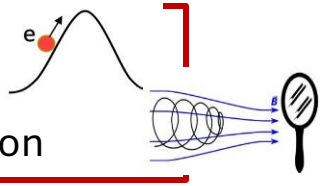


Systematics for the keV sterile search

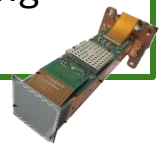
Source:
- scattering
- magnetic traps

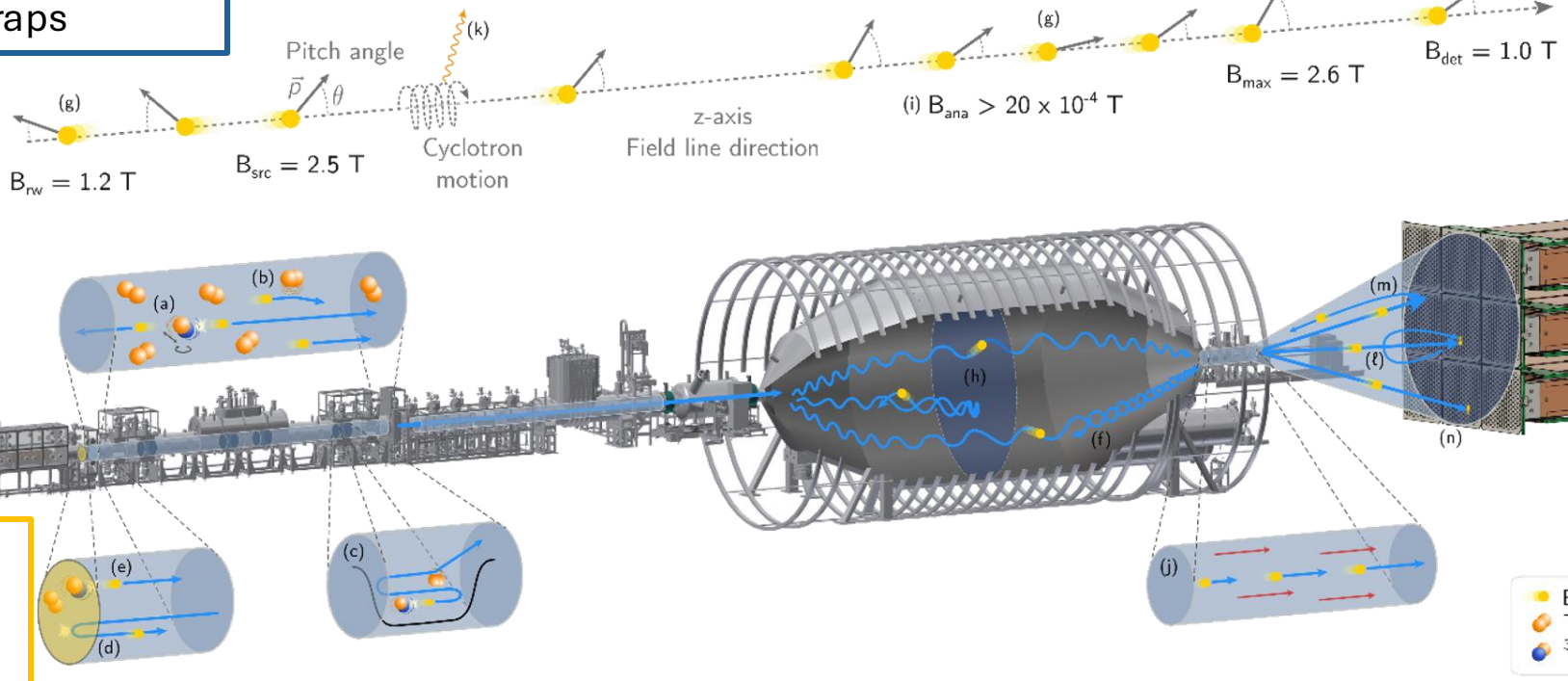


Transport:
- Motion in EM fields
- transmission condition

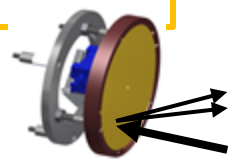


Detector response:
- Dead-layer
- Backscattering and reflections
- Energy resolution
- Charge-sharing
- DAQ





Rear Wall:
- scattering on the surface
- residual tritium activity



- Very different set of systematics wrt integral neutrino mass measurements
- The whole spectrum is measured: energy/angular dependences of the systematic effects are crucial

The model challenge

- **Rear Wall**: scattering and activity modeled through GEANT4 simulations
- **Source**: scattering modeled through custom MC simulation based on theoretical electron-tritium cross-section
- **Transport**: analytical formulae
- **Detector response**: GEANT4 simulations + analytical models for detector non-idealities

Energy/angle dependence = Lot of simulations!

The model challenge

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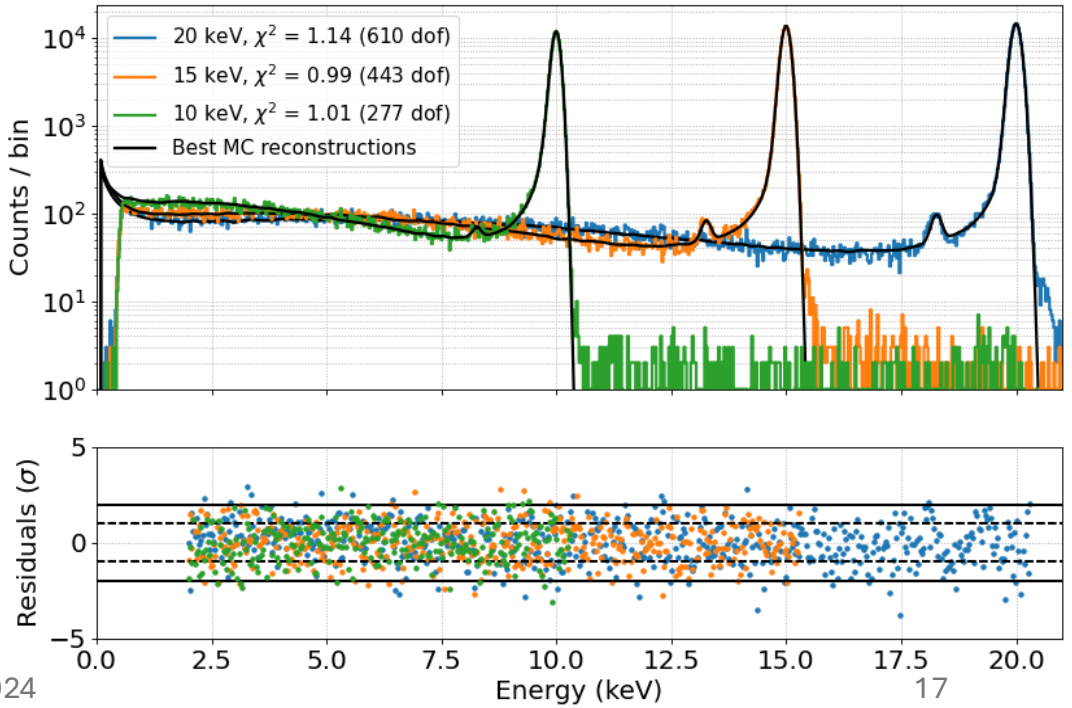
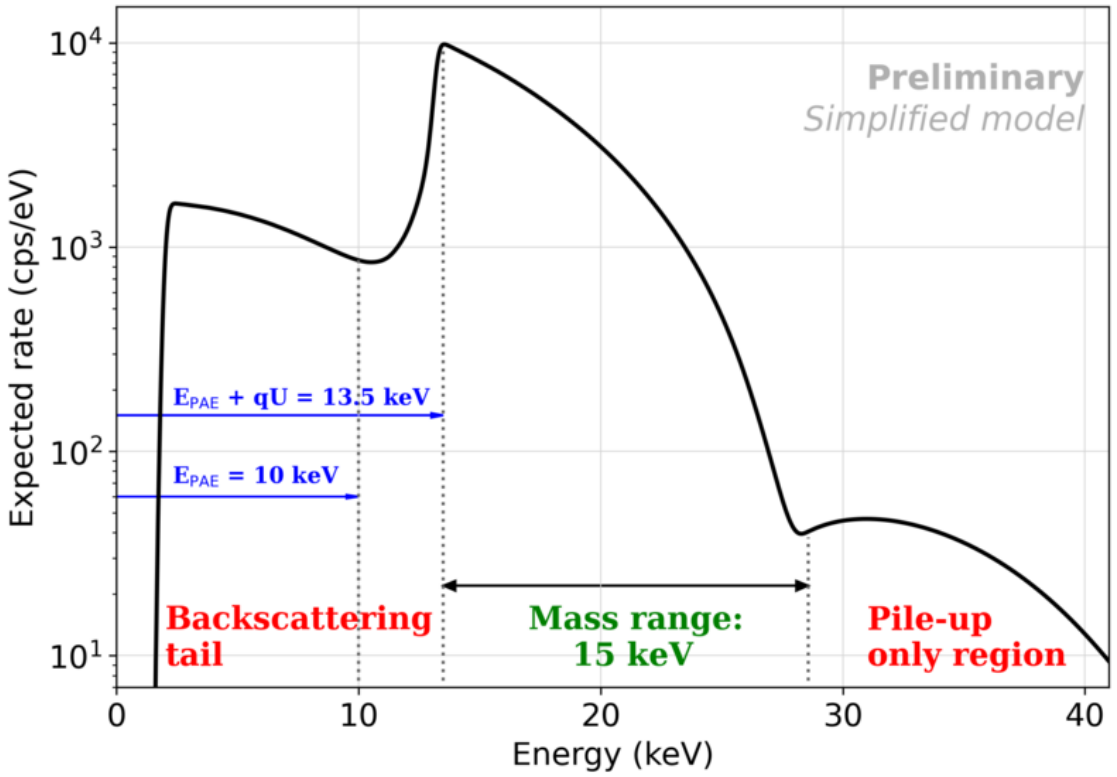
Energy/angle dependence = Lot of simulations!

- **MC simulations must be tested** with experimental data to assess the accuracy
- here the example of the SDD response to electrons measured in the lab with an e-gun
- Calibration data (especially in-situ) will be fundamental to test the components of the model



Towards a deep model

Apply systematics effects to the tritium spectrum: pre-compute a database of response matrices and perform iterative convolutions



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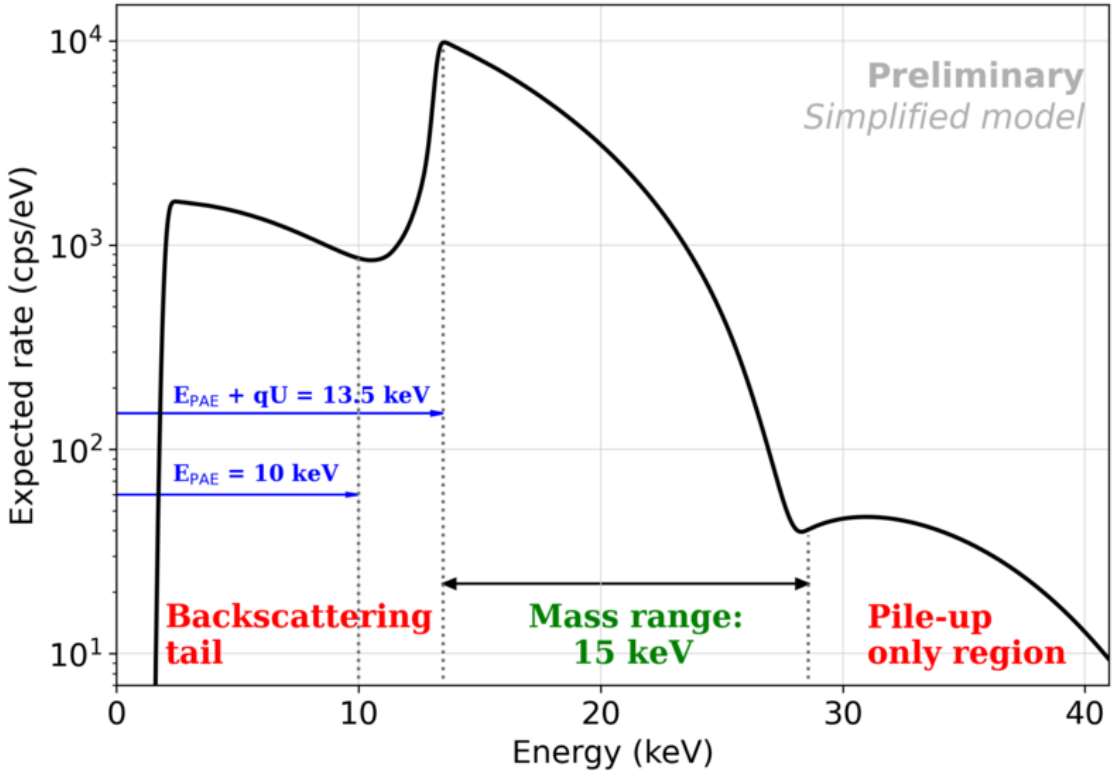
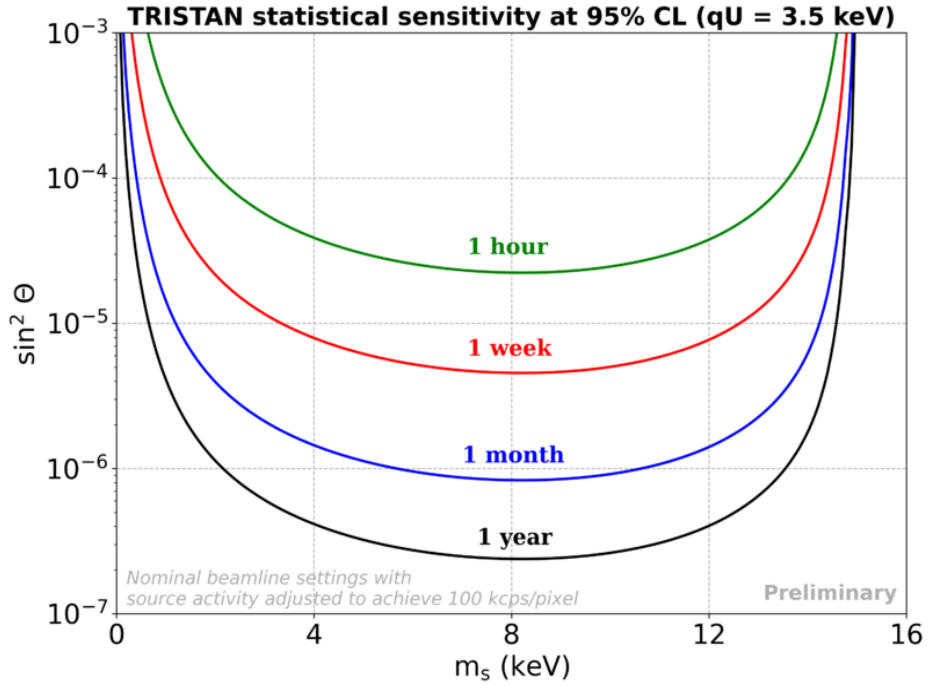




- **Stat-sensitivity better than current lab limits already after 1 hour of data-taking**
- Work in progress to accurately evaluate the systematics impact on sensitivity
- Still need to upgrade the model to handle the KATRIN+TRISTAN expected statistics (~10^{15} electrons in the ROI)

Conclusion and outlook

- **sterile neutrino** are predicted by several BSM theories. With a mass in the keV scale they would be dark matter candidates

- **KATRIN already set the best laboratory limit in the 0.1-1 keV interval** performing an integral measurement

- **from 2026 KATRIN will switch into a differential mode** after the commissioning of the TRISTAN detector to search for keV sterile neutrinos with a mixing down to 10^{-6}

- The TRISTAN detector is in the assembly procedure and will be installed in a replica of the KATRIN detector section in 2025

- The model of the whole differential spectrum is ongoing

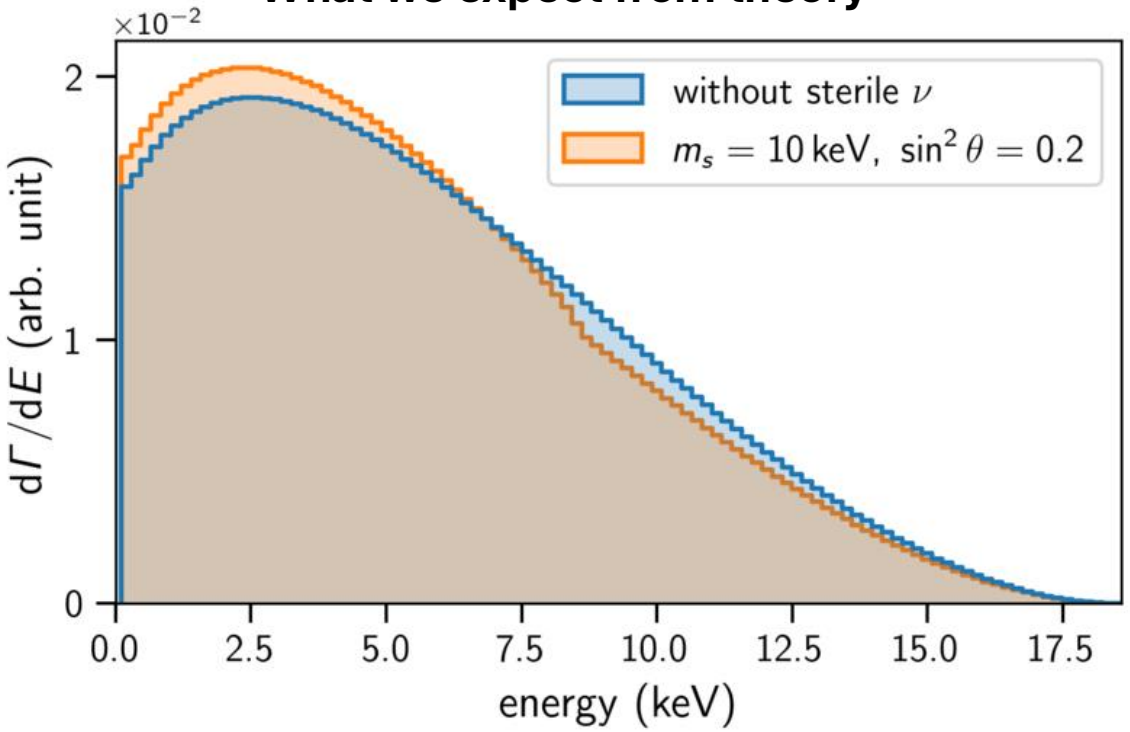
- The development of an analysis pipeline for differential electron measurements may also be beneficial for future neutrino mass experiments!

Thanks for the attention!

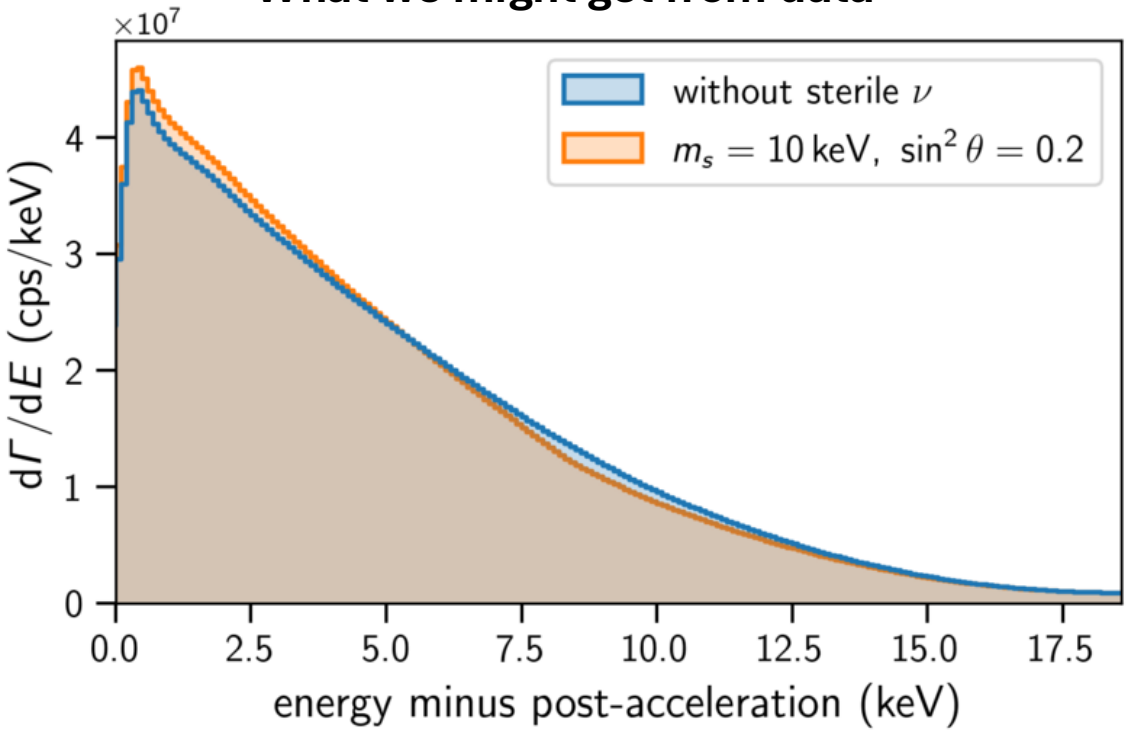
The model challenge

It's possible to infer sterile neutrino parameters from the β spectrum by comparing the best fit in the no sterile neutrino case with the best fit for a given alternative hypothesis:

What we expect from theory



What we might get from data



Need to develop a model for systematics!