A model for the KATRIN differential Tritium spectrum to search for keV sterile neutrinos

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keV sterile neutrinos and β spectra

Sterile neutrinos:

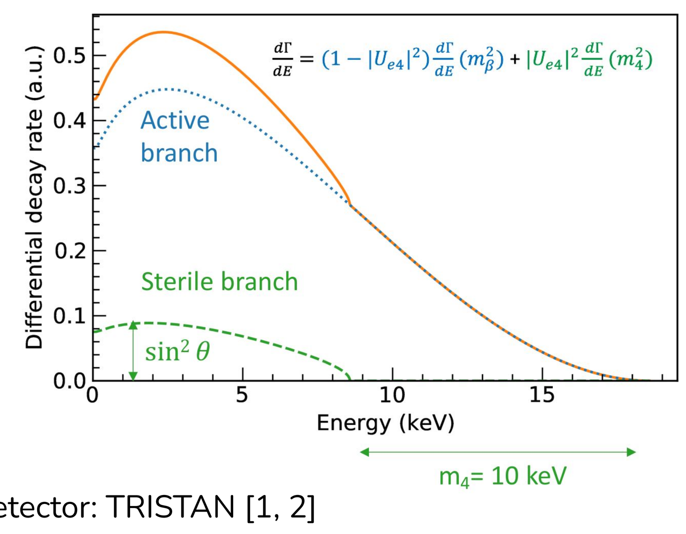
- predicted by several minimal Standard Model extensions → mixing with ν_e
- in keV range are Dark Matter candidates

in Tritium β spectrum:

- would produce a kink deep in the spectrum
- kink's position and amplitude are related to sterile mass and mixing amplitude

Technical challenge:

- the signal is small (goal: $\sin^2\theta_{e4}<10^{-6}$)
- a high-statistics differential measurement of the whole spectrum is needed



→ can be searched by KATRIN with an upgraded detector: TRISTAN [1, 2]

KATRIN (+TRISTAN): experimental setup

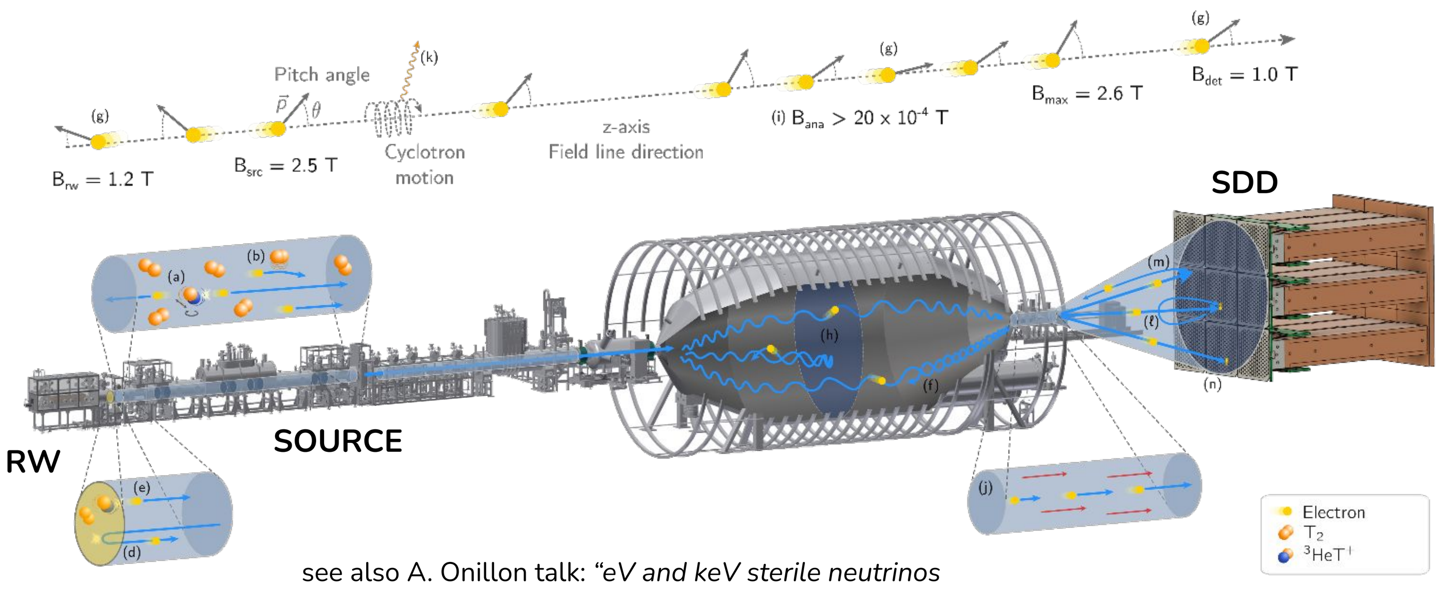
Ultra high-intensity gaseous Tritium source + adiabatic transport + MAC-E spectrometer + SDD matrix (TRISTAN detector [3][4])

TRISTAN:

- 9 modules (~1500 Silicon Drift Detectors)
- high rate (~100kcps/SDD)
- energy resolution ~145eV @6keV

β electrons can lose energy and change angle due to:

- scattering in the source
- scattering on the rear wall
- EM transport
- backscattering on SDD
- **Need to model these effects**



see also A. Onillon talk: *"eV and keV sterile neutrinos search with the KATRIN experiment"*

Spectrum model workflow

Input:

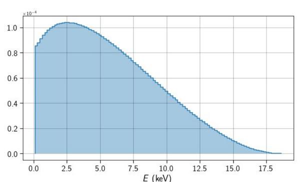
- 1D Theoretical spectrum (Fermi theory + corrections)
- isotropic decay

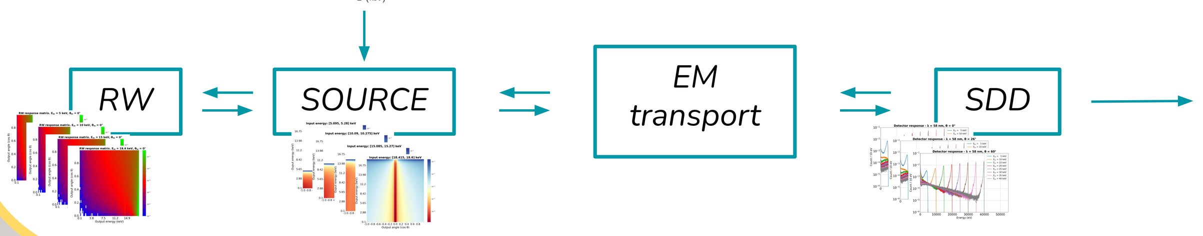
Propagation:

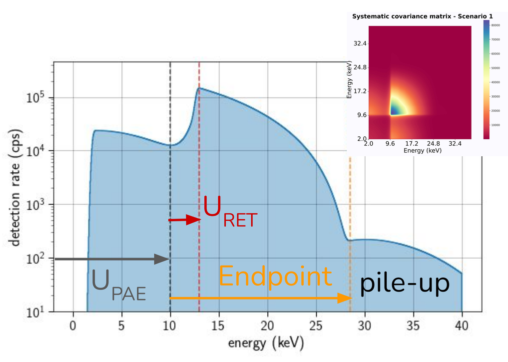
- 2D pdf (E, cosθ)
- probability to lose energy and change angle computed with MC and stored in response matrices
- multiple scatterings modeled through iterative multiplications with response matrices

Output:

- 1D expected spectrum
- energy covariance matrix describing the effect of systematics uncertainties on the predicted spectrum







Sensitivity studies

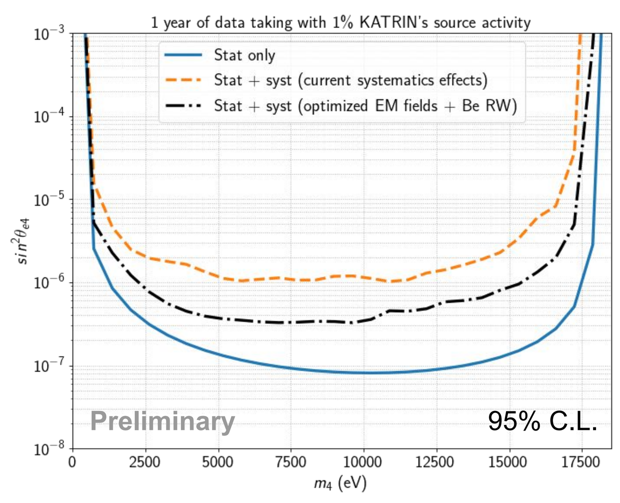
The main goal of this model is to compute KATRIN's sensitivity to keV sterile neutrinos

Statistical sensitivity:

- grid scan in (m_4, $\sin^2\theta_{e4}$) phase-space
- for each grid point compute $\Delta\chi^2$ with respect to null hypothesis (no sterile)
- find 95% C.L. contour → $\sin^2\theta_{e4}<10^{-6}$ achievable

Systematics treatment:

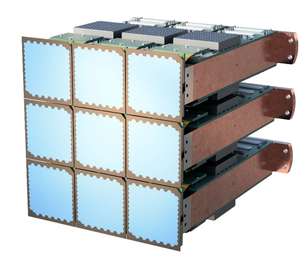
- compute energy covariance matrix by varying model parameters
- $Cov_{tot} = Cov_{stat} + Cov_{syst}$
- include Cov_{tot} in $\Delta\chi^2$ calculation → sensitivity loss



Conclusion: with this model it is possible to rank the most critical systematics and find hardware optimizations to mitigate them and recover sensitivity to sterile neutrinos

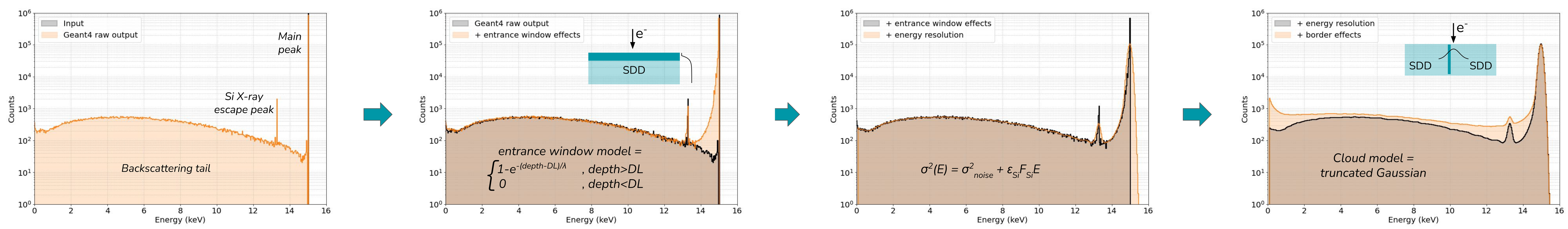
The accuracy challenge

- all the main effects are included and parametrized in the Tritium Model → this is enough for sensitivity studies and systematics mitigation
- nevertheless, this model will not be used only for sensitivity studies, but also for data analysis once the TRISTAN detector will be installed in the KATRIN beamline
- this means that dedicated calibration measurements must be done to assess the accuracy of each part of the model (scattering in the source, scattering on RW, EM transport and detector response)
- a big effort, in particular, has been done to model the detector response of SDDs, since it is one of the main systematics effects for a differential measurement

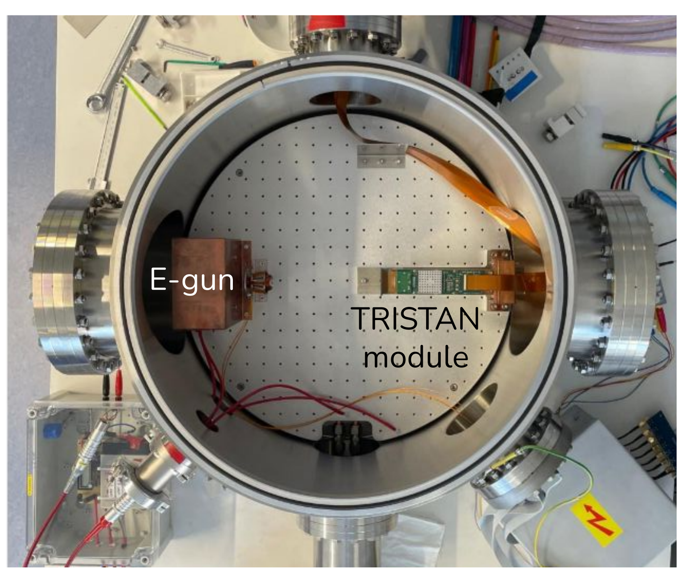


Detector model step-by-step

- keV electrons, when interacting with materials, can be backscattered without depositing all their energy → need of a MC simulation (Geant4 with Penelope model) [5][6]
- moreover, part of their energy is left close to the surface, a region with incomplete charge-collection efficiency, and part can be shared with neighboring pixels if the electron cloud crosses a border



Detector model validation with experimental data



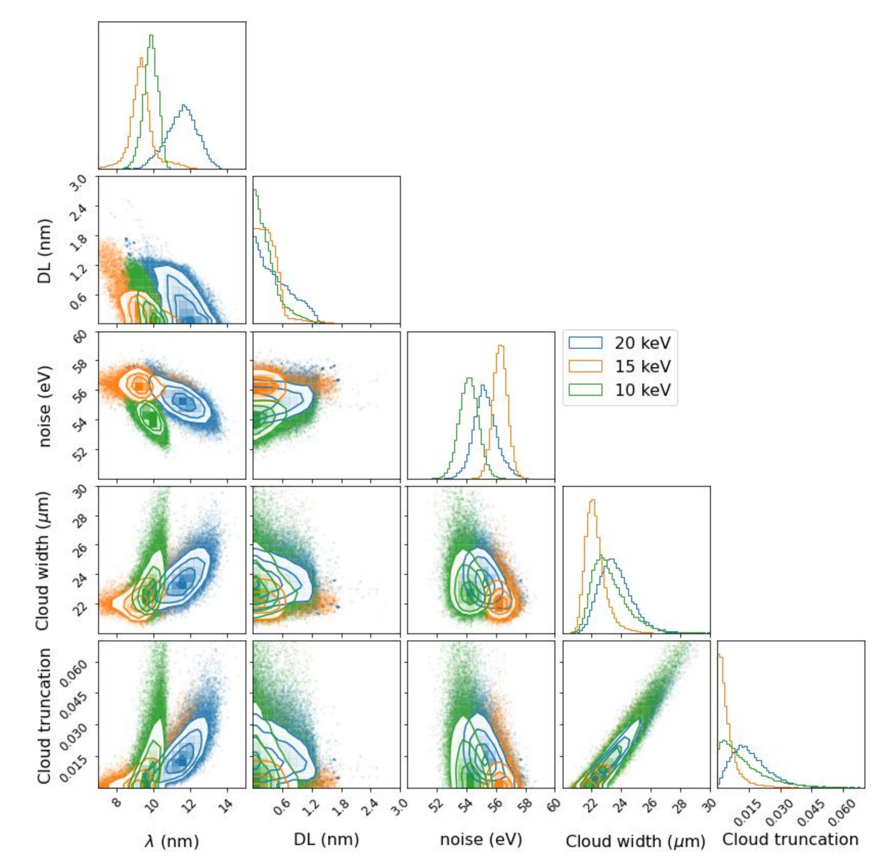
Experimental data:

- need of an ideal source to test simulations
- custom e-gun based on thermionic emission
- thanks to steering coils an homogeneous illumination on >100 pixels can be achieved
- realistic angular and spatial distributions
- different electron energies (10, 15, 20 keV)

see also K. Urban poster: *"TRISTAN: A novel detector for searching keV-sterile neutrinos at the KATRIN experiment"*

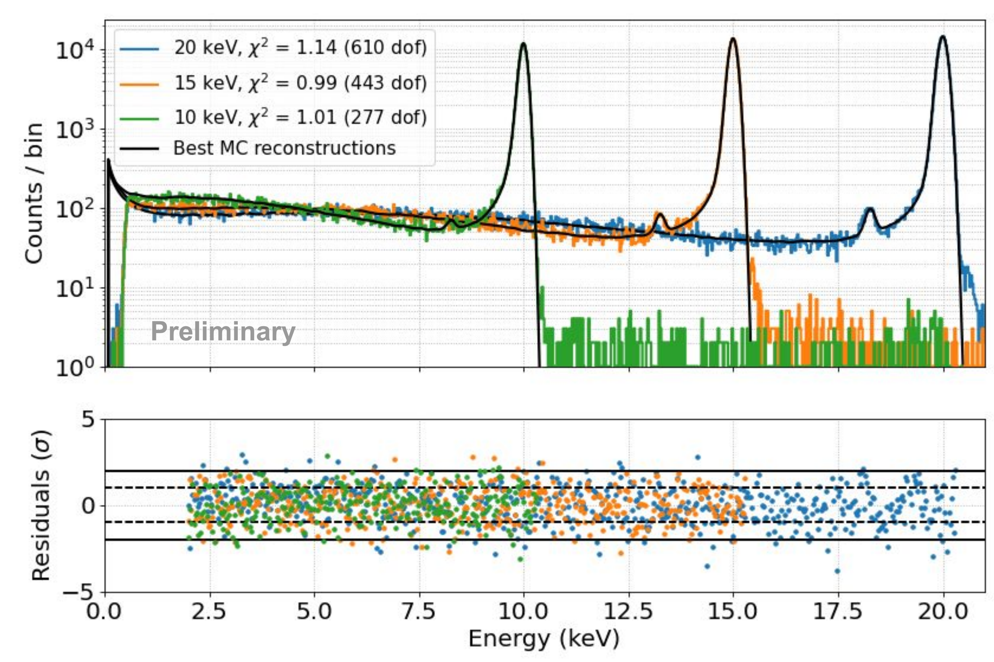
Fit technique:

- Bayesian fit with flat priors by varying 5 physical parameters
- MCMC (Goodman & Weare) sampling of Poissonian likelihood
- median as best fit estimator
- 68% intervals and correlations will be used to construct realistic covariance matrices for sensitivity studies



Results:

- all the structures in the spectra are well reproduced
  - **main peak**: entrance window, border effects
  - **tail**: incomplete charge collection due to backscattering and border effects + Si X-ray escape



Conclusion:

- very good understanding of detector response to electrons in the lab
- next steps: investigate even higher energies and with higher statistics
- test response in a KATRIN-like environment

[1] S. Mertens et al. *"Sensitivity of next-generation tritium beta-decay experiments for keV-scale sterile neutrinos"*. In: Journal of Cosmology and Astroparticle Physics (Feb. 2015)

[2] S. Mertens et al. *"A novel detector system for KATRIN to search for keV-scale sterile neutrinos"*. In: Journal of Physics G: Nuclear and Particle Physics 46.6 (May 2019)

[3] M. Gugiatti et al. *"Characterisation of a silicon drift detector for high-resolution electron spectroscopy"*. In: Nuclear Instruments and Methods in Physics Research (Nov 2020)

[4] S. Mertens et al. *"Characterization of silicon drift detectors with electrons for the TRISTAN project"*. In: J. Phys. G: Nucl. Part. Phys. (2021)

[5] M. Biassoni et al. *"Electron spectrometry with Silicon drift detectors: a GEANT4 based method for detector response reconstruction"*. In: Eur. Phys. J. Plus (2021)

[6] A. Nava et al. *"A Geant4-based model for the TRISTAN detector"*. in: J. Phys.: Conf. Ser. (2021)