Tritium spectrum modeling for keV-sterile neutrino search with KATRIN

Poster P.260

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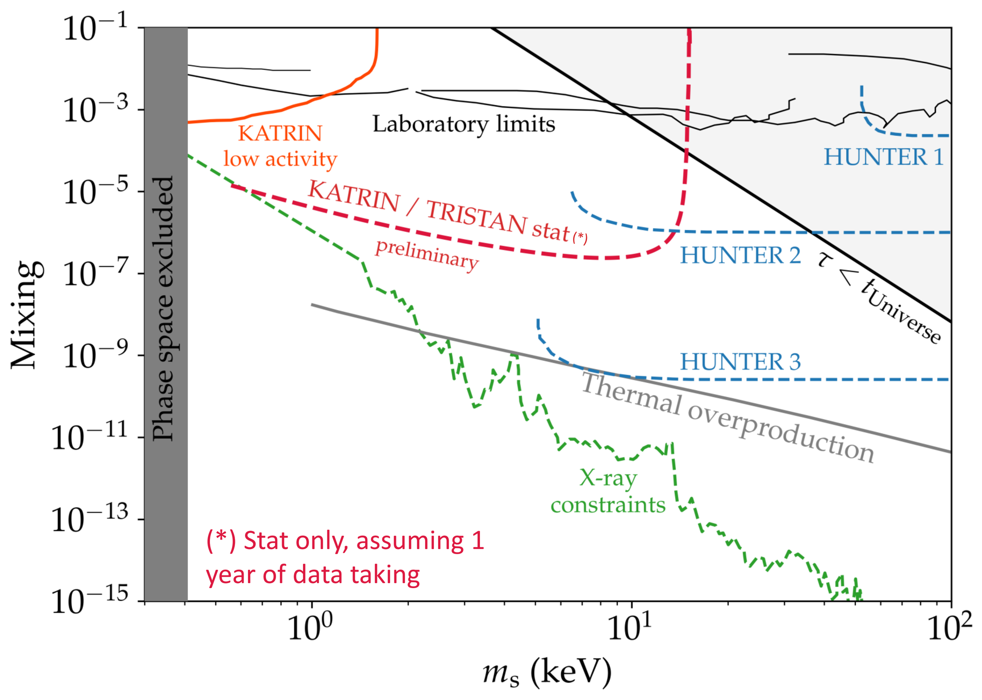
Motivation (1)

- Overwhelming cosmological evidence for dark mater, but particular nature unknown
- Sterile keV neutrino:
  - hypothetical viable candidate through minimal extension of the SM [1]
  - no weak interaction, but mixing with active neutrinos

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

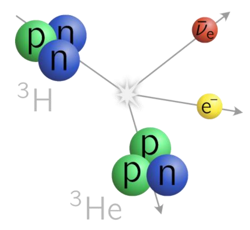
TRISTAN

- Future detector and DAQ system upgrade of the **KA**rlsruhe **TRI**tium **N**eutrino (KATRIN) experiment [2]
- Search for signature of heavy mass eigenstate mixing in tritium beta-decay spectrum
- Complementary to other projects



The KATRIN experiment (2)

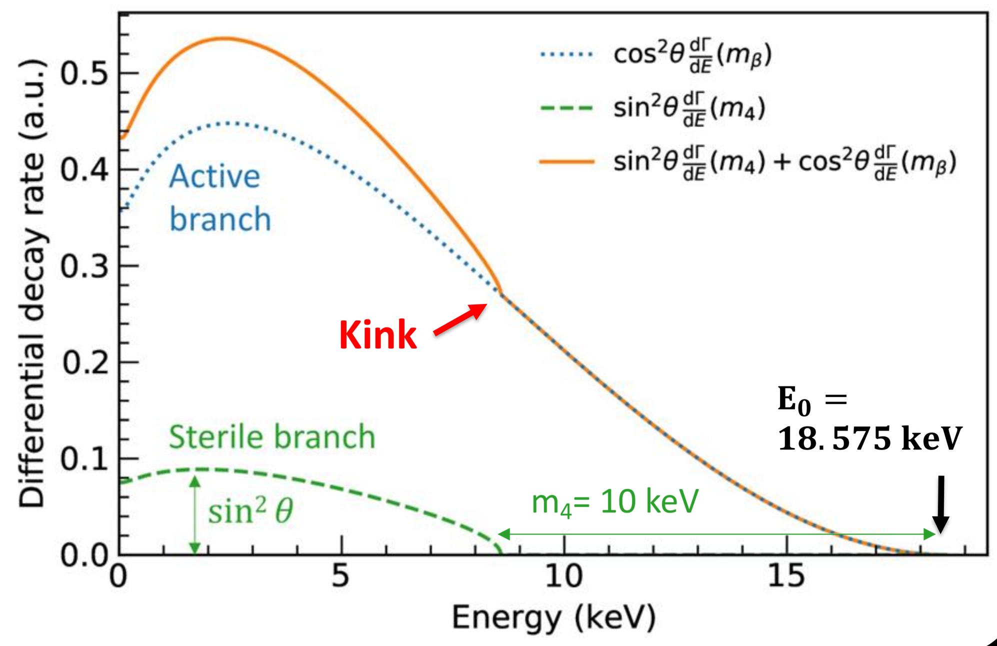
- **Neutrino mass measurement (2019 → 2025)**
  - Signature: distortion near the endpoint of the tritium beta spectrum
  - Integral measurement with high-resolution spectrometer



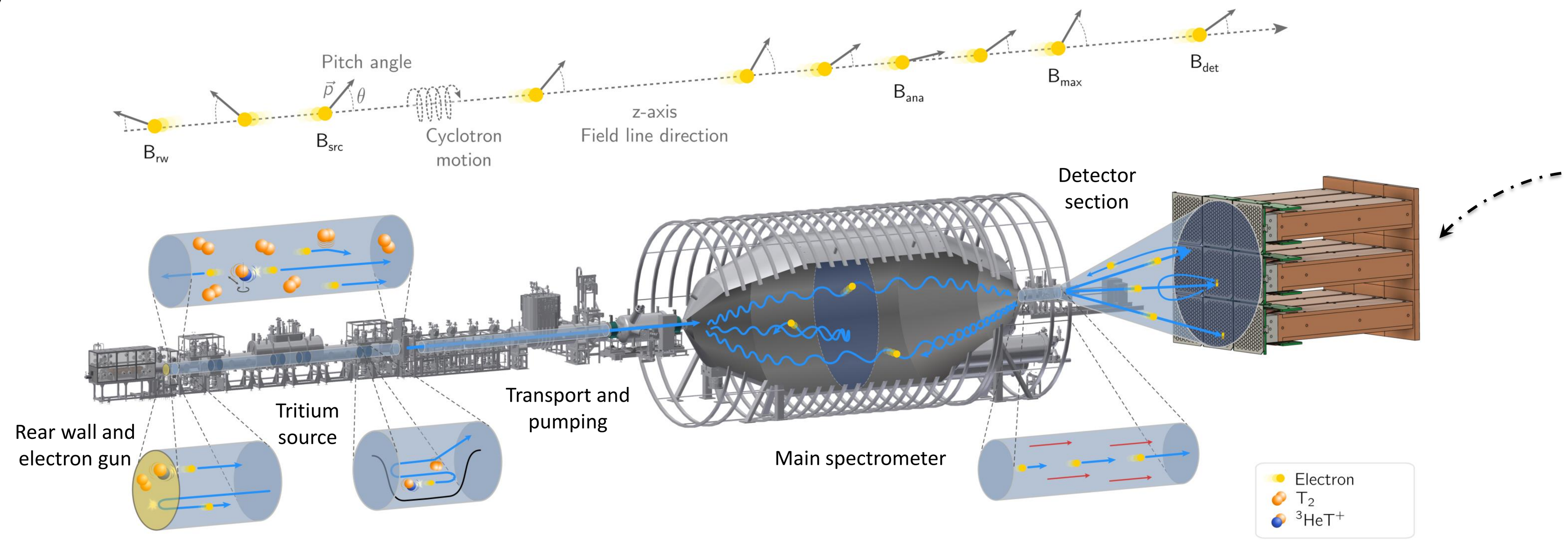
- **keV-sterile neutrino search (from ~2026)**
  - Differential measurement; search in the entire tritium beta spectrum
  - Signature: spectral distortion with kink-like feature

- Kink position: $E_{kink} = E_0 - m_s$
- Amplitude: $|U_{e4}|^2 = \sin^2\theta$

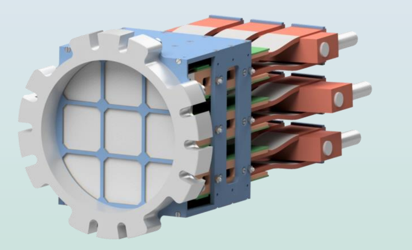
KATRIN target sensitivity: $\sin^2\theta \approx 10^{-6}$



Experimental setup and tritium spectrum modeling (3)



New detector system for high rate β-spectroscopy [3, 4, 5]

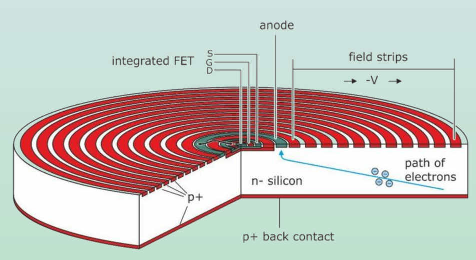


Silicon drift detector (SDD)

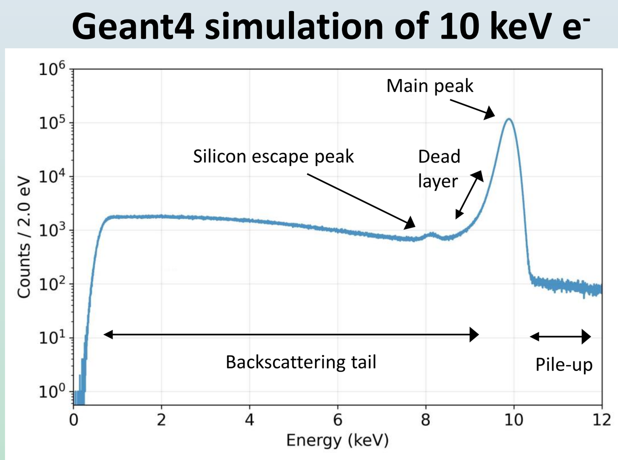
- good energy resolution: 300 eV @20 keV
- handling of high rate: >10^5 cps/pixel
- large area coverage: ~20x20 cm²

9 modules detector

- 166 pixel per module
- ~1000 golden pixels
- new detector chamber
- dedicated DAQ system



Geant4 simulation of 10 keV e⁻



Theoritical beta spectrum (Fermi theory)

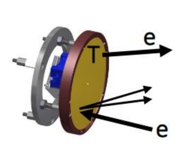
$$\frac{d\Gamma(E;m_{\beta_i})}{dE} \propto C \cdot F(Z,E) \cdot (E+m_e) \cdot p \cdot (E_0 - E) \cdot \sum_i |U_{ei}|^2 \sqrt{(E_0-E)^2 - m_{\beta_i}^2}$$

- $F(Z,E)$: Fermi function
- U_{ei}: mixing between the electron neutrino and the i-th neutrino mass eigenstate
- m_{β_i}: mass of the i-th mass eigenstate

Experimental effects

Gold rear wall

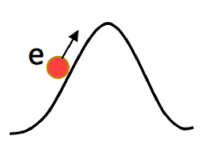
- Backscattering
- Surface activity



⇒ *Geant4 simulations*

Spectrometer

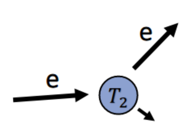
- Retarding potential
- HV stability
- Adiabatic transport



⇒ *Analytical description*

Source

- Scattering
- Stability
- Magnetic traps



⇒ *Analytical description + MC*

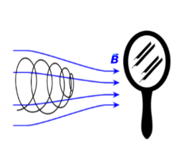
Detector section

- Post-acceleration
- SDD response
- Backscattering, backreflection

⇒ *Geant4 + KASSIOPEIA simulations*

Transport

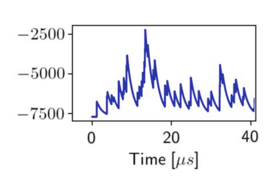
- Magnetic mirror
- Magnetic collimation
- Synchrotron radiation



⇒ *Analytical description*

DAQ

- Threshold
- Electronics noise
- Pileup, non-linearities

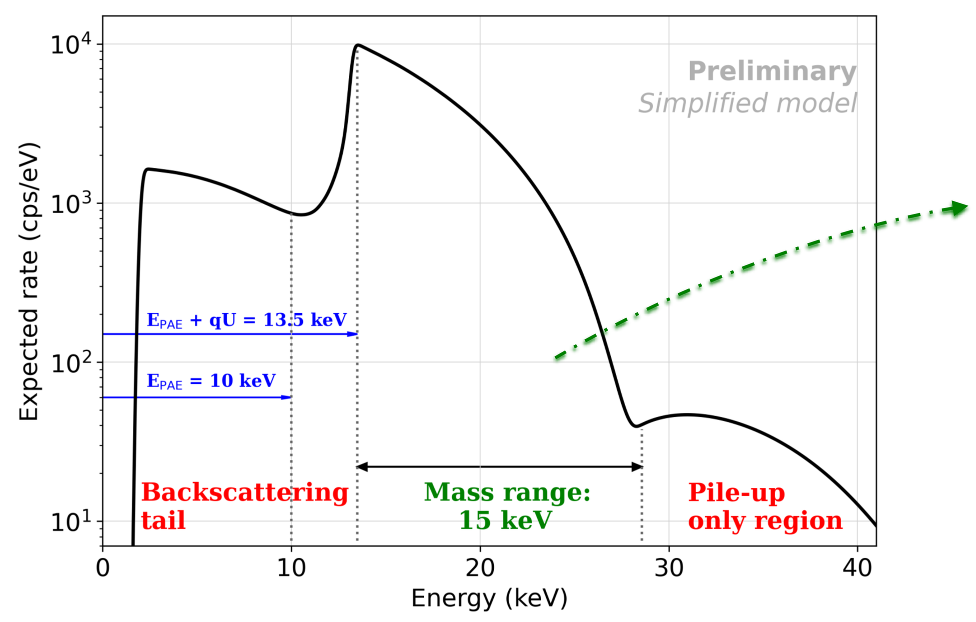


⇒ *Analytical description*

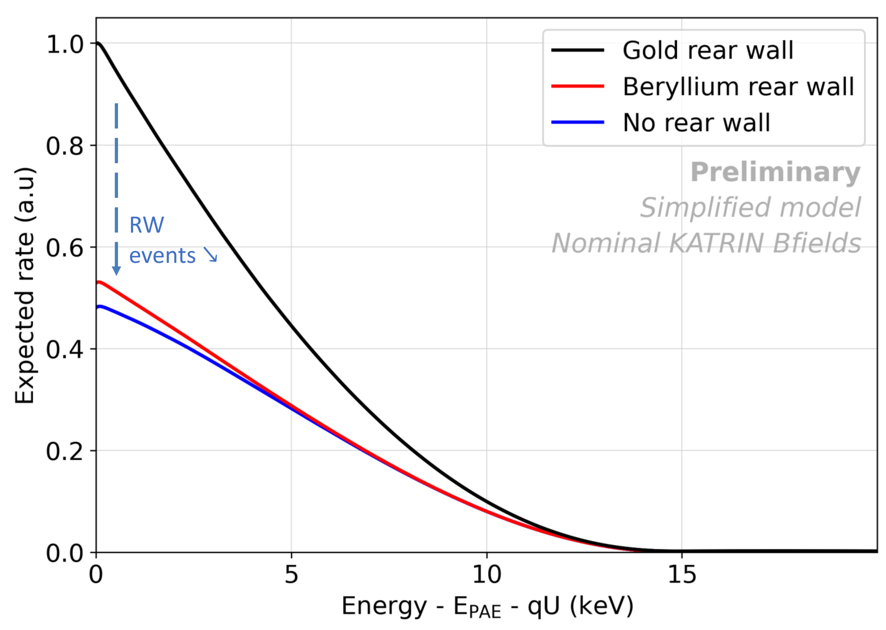
Tritium model at the detector:

Using a theoretical tritium beta spectrum, all experimental effects are accounted for through precalculated response matrix libraries.

Predicted spectrum – full range



Predicted spectrum – ROI



Most significant experimental effects accounted for in the model - model refinement in progress

⇒ Model suitable for sensitivity study

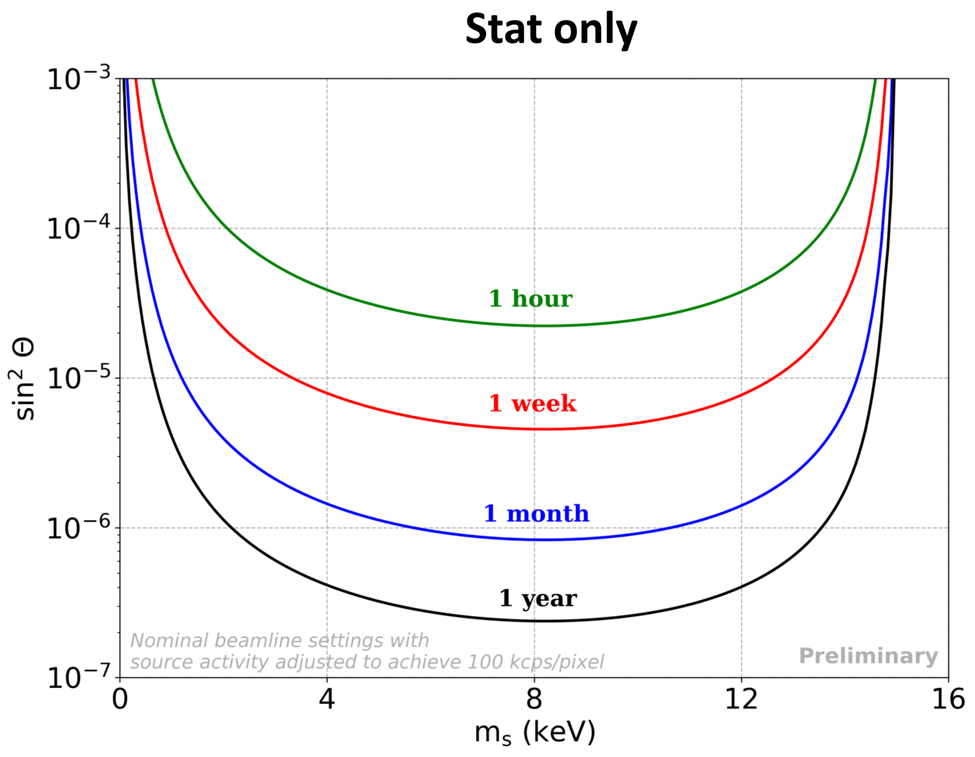
⇒ **Dominant systematic effect: rear wall events. Mitigable with new material (Au → Be) and optimized magnetic fields → contribution of < 1% in ROI**

keV-sterile neutrino sensitivity (4)

- Grid scan method: χ^2 test between the model with and without the sterile admixture
- Sensitivity @95% CL
- Statistical and systematic uncertainties accounted for via covariance matrices

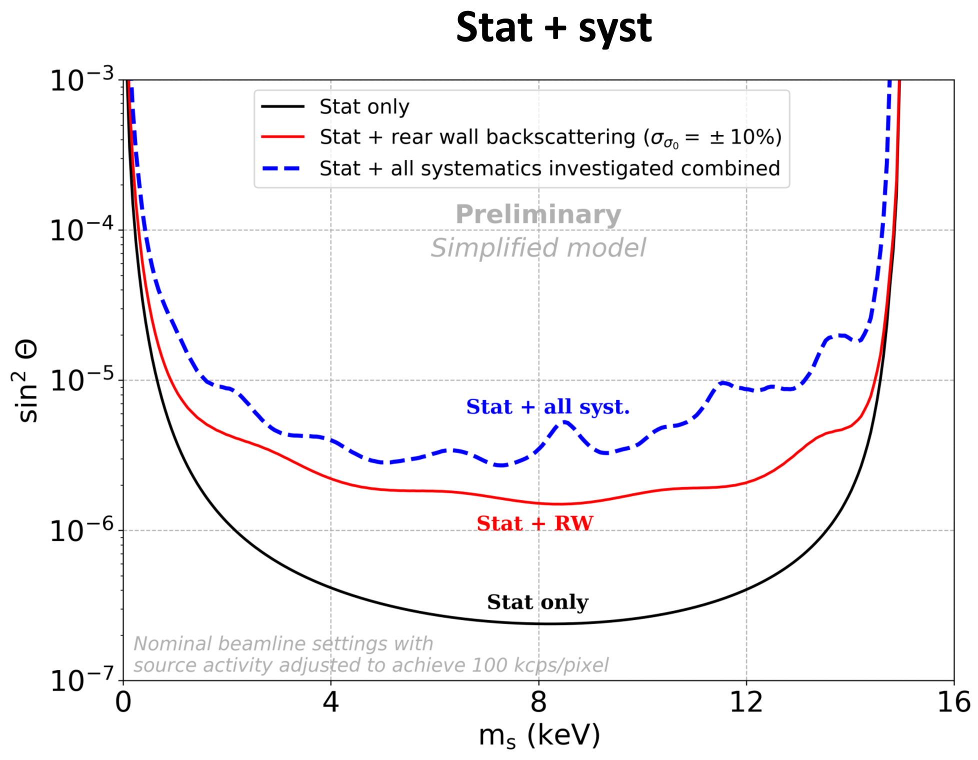
Nominal beamline settings = beamline settings of ν-mass measurement but qU = 3.5 kV

Stat only



- ~2×10^{-7} reachable in 1 year at the center of the mass range

Stat + syst



- Systematics dominated by rear wall events
- Systematic effects reduce the statistical sensitivity by at least one order of magnitude

⇒ **Ongoing simulation and R&D efforts to mitigate impact of rear wall events and other systematic effects**

Summary (5)

- KATRIN transitions from absolute neutrino mass measurements to keV sterile neutrino search using tritium β-decay spectrum
- New TRISTAN detector and readout system commissioning planned for early 2026
- Sensitivity goal: $\sin^2\theta \approx 10^{-6}$
- Sensitivity limited by systematic uncertainties → simulation and R&D efforts to mitigate their impact

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References

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