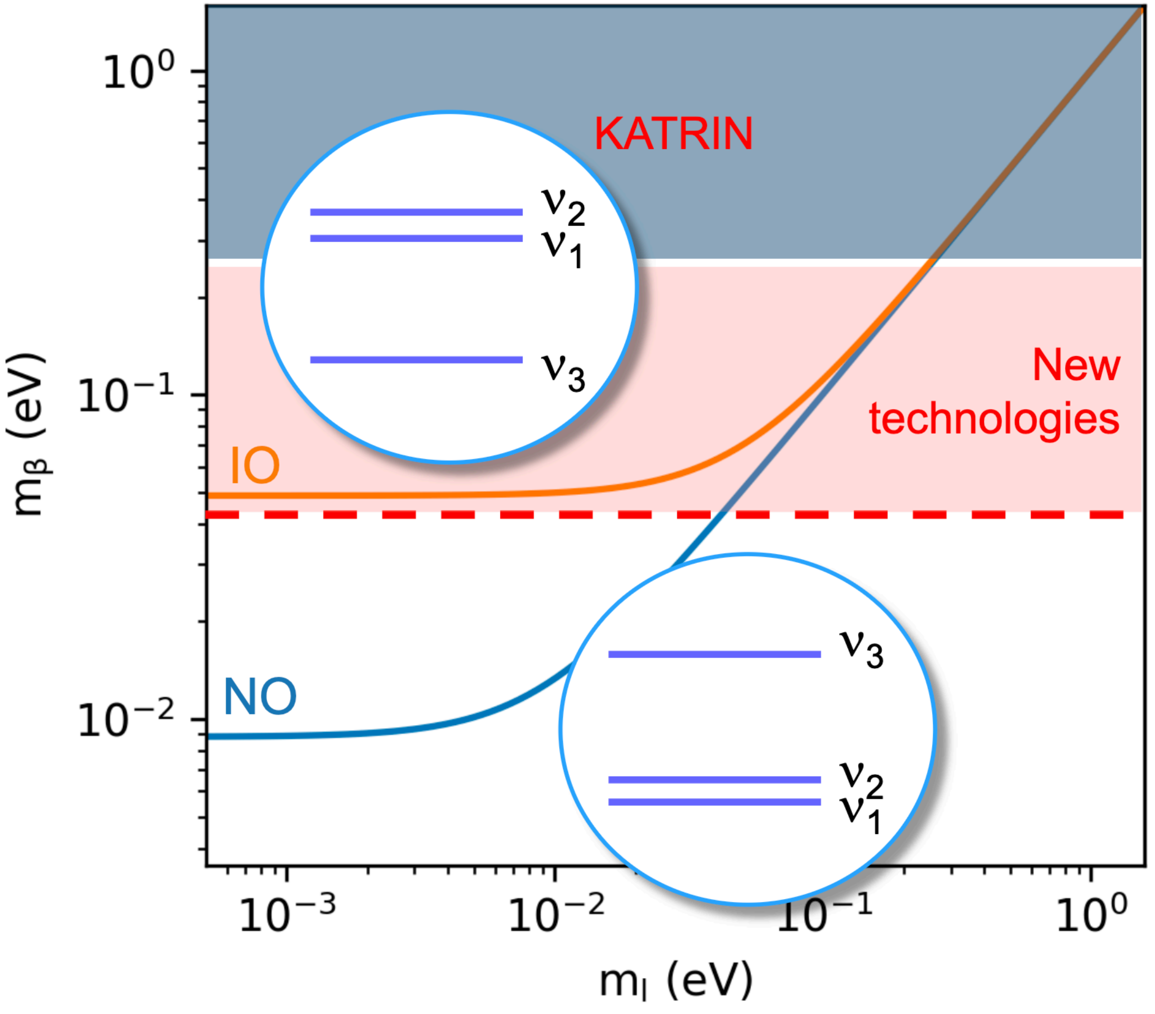
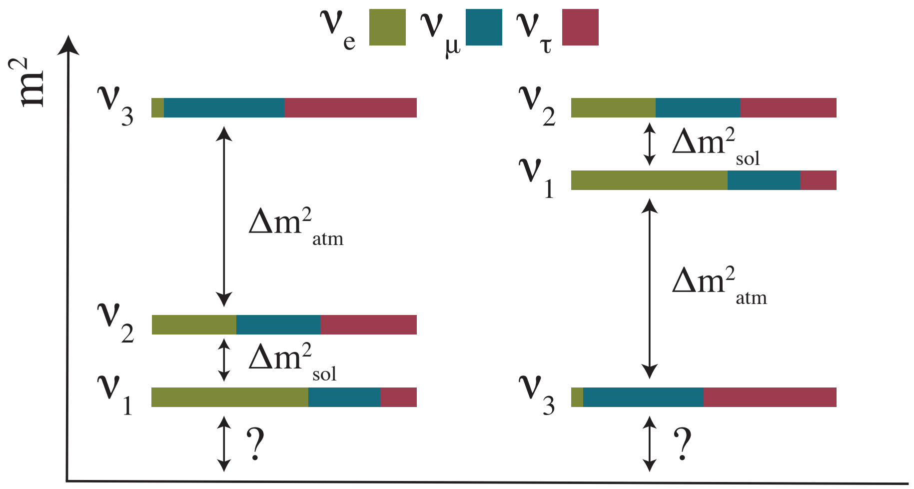
Technologies for a Future Neutrino Mass Experiment with Tritium



Neven Kovac for the KATRIN Collaboration,
Institute for Astroparticle Physics (IAP),
Karlsruhe Institute of Technology (KIT)
28.08.2025

Motivation - Massive Neutrinos

- Hunt for the absolute scale of the neutrino mass ongoing since the discovery of the neutrino oscillations at the end of last millennium!



- Neutrino mass limits
  - Cosmology (CMB + DESI BAO for λCDM)

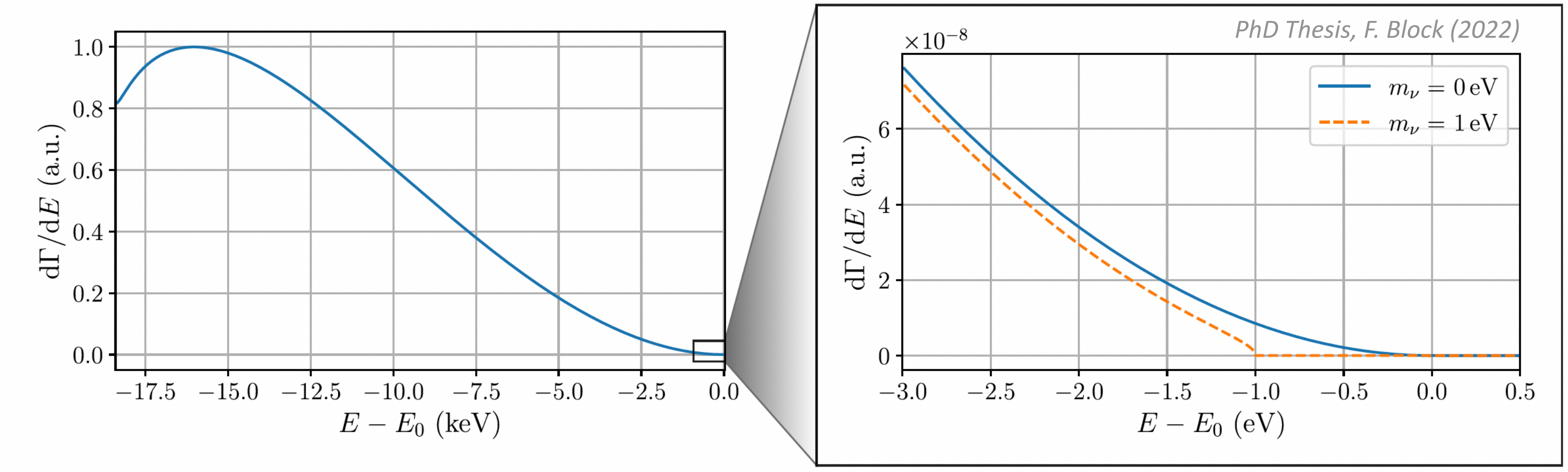
$$\sum m_{\nu,i} < 0.072\ \mathrm{eV/c^2} \quad (95\,\%\,\mathrm{C.L.})$$

The DESI Collaboration, arXiv:2406.14554

  - Direct detection:

    → (Almost) Completely model independent

    → Kinematic measurements of β - decay or electron capture spectra



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The DESI Collaboration, arXiv:2406.14554

  - Direct detection - KATRIN:

$$m_{\nu_e} \leq 0.45\ \mathrm{eV/c^2} \quad (90\,\%\,\mathrm{C.L.})$$

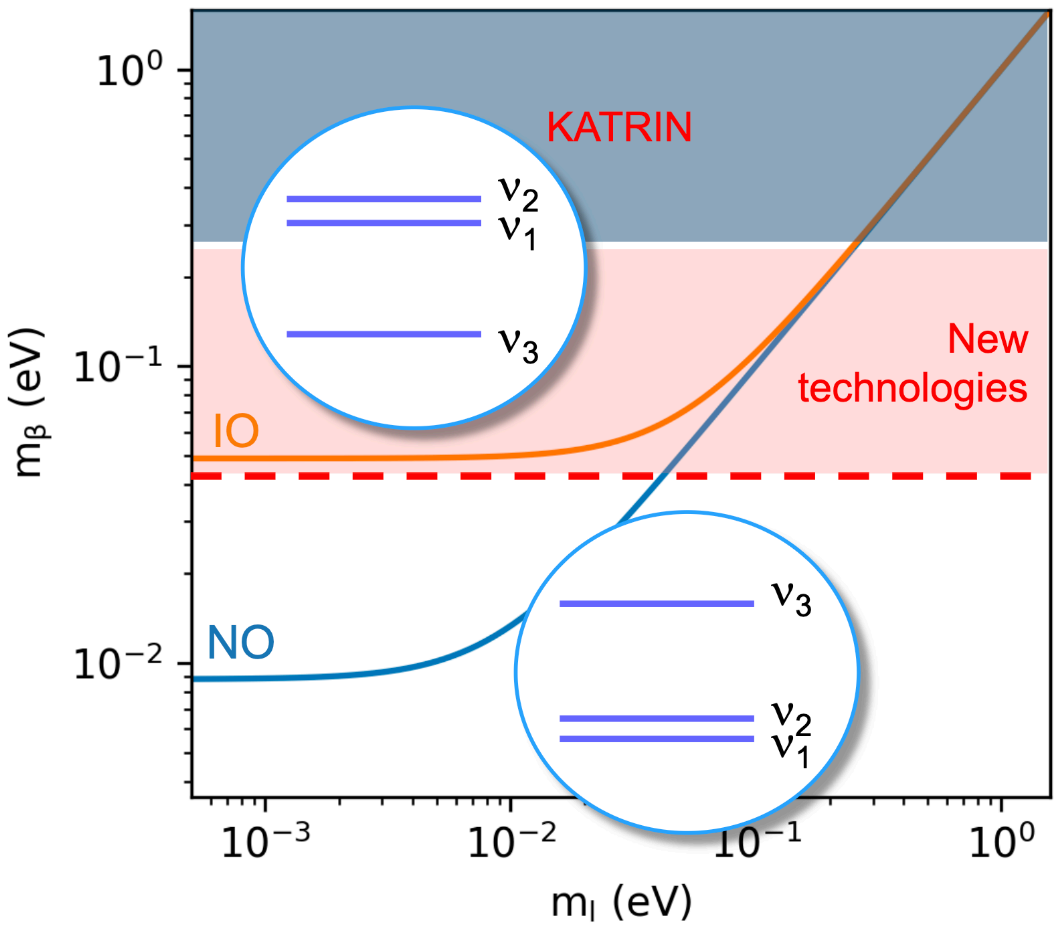
The KATRIN Collaboration, Science 388,180-185(2025)

$\rightarrow$ Final projected sensitivity

$$m_{\nu_e} \leq 0.3\ \mathrm{eV/c^2} \quad (90\,\%\,\mathrm{C.L.})$$

The KATRIN collaboration et al 2021 JINST 16 T08015

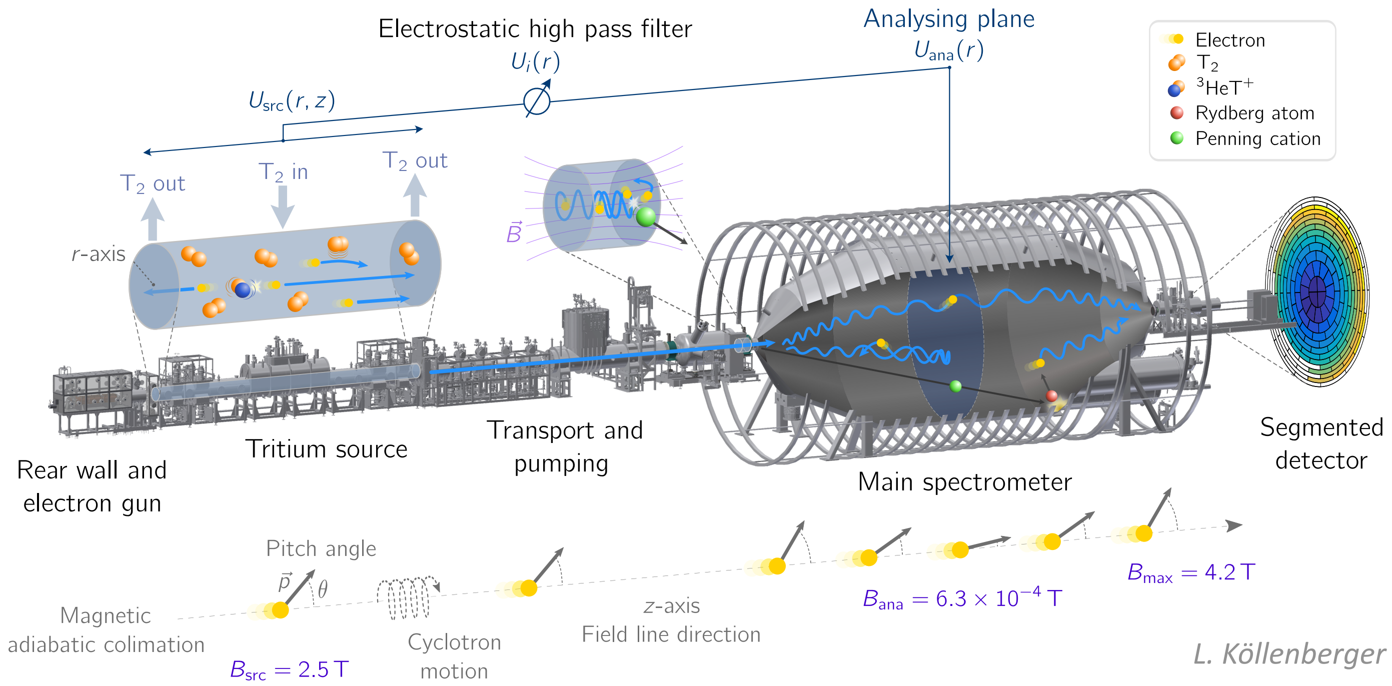
M. Schlösser



KIT

Introduction - KATRIN

- World leading experiment in direct measurement of neutrino mass



→ New neutrino mass limit: $m_{\nu_e} \leq 0.45\ \mathrm{eV/c^2}$ @ 90% C.L.

The KATRIN Collaboration, Science 388,180-185(2025)

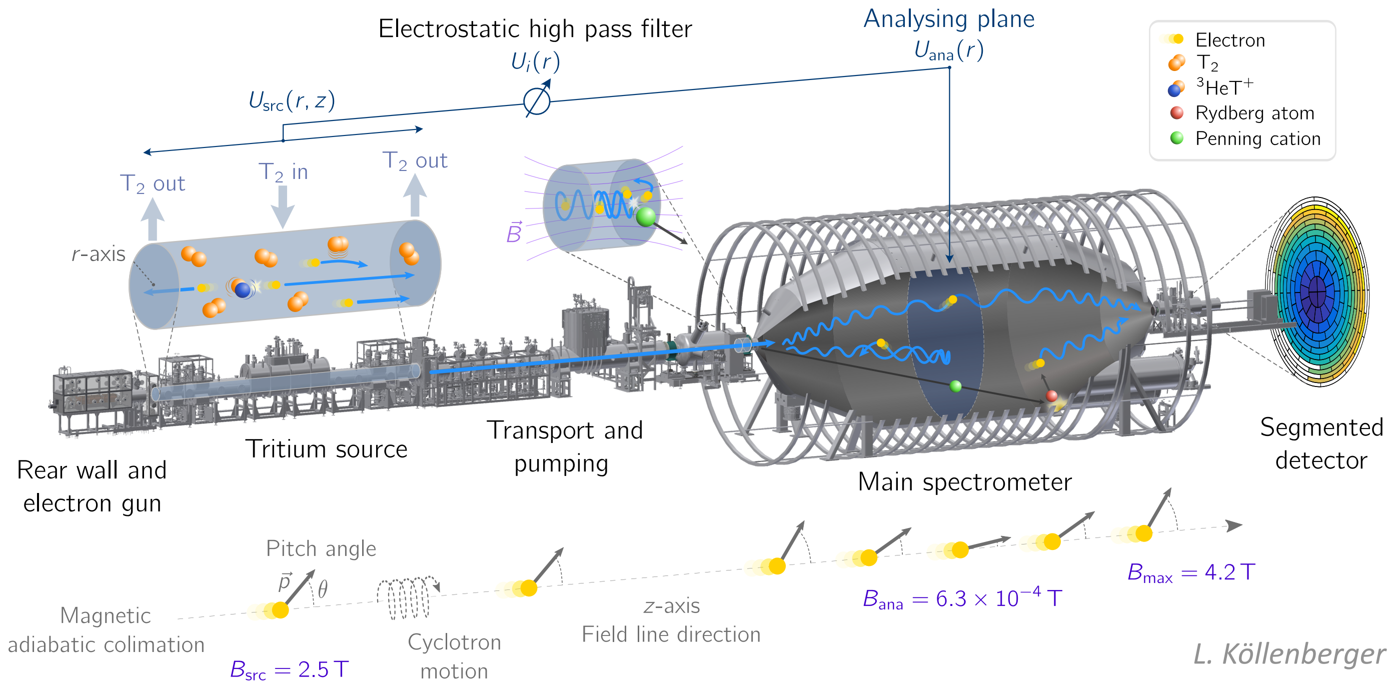
- Information on neutrino mass inferred from spectral analysis of the tritium beta-decay spectrum

$$T_2 \longrightarrow {}^3HeT^+ + e^- + \bar{\nu}_e$$

- Main features:
  - High luminosity molecular tritium source
    → 10^{11} decays/s
  - MAC-E filter principle
    → about 1 eV resolution
  - Silicon p-i-n diode counting detector
    → energy resolution ~ 1 keV

Introduction - KATRIN

- World leading experiment in direct measurement of neutrino mass



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The KATRIN Collaboration, Science 388,180-185(2025)

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$$T_2 \longrightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$$

- Final projected sensitivity:

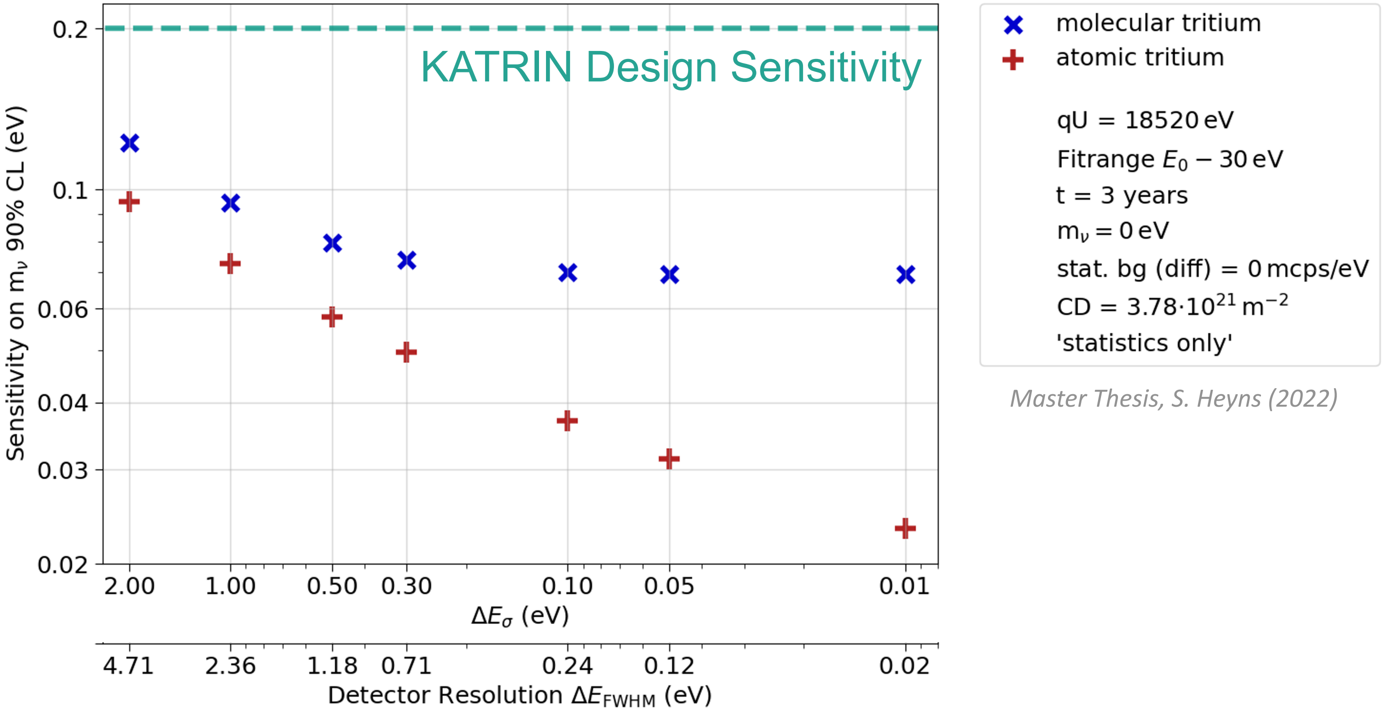
$$m_{\nu_e} \leq 0.3\ eV^2/c^2 \text{ @ } 90\,\%\,C.L.$$

→ After 1000 days of measurement
→ Should be reached at the end of this year!

How can we go beyond?

Going Beyond KATRIN

- Going beyond KATRIN final sensitivity requires paradigm shift in measurement approach

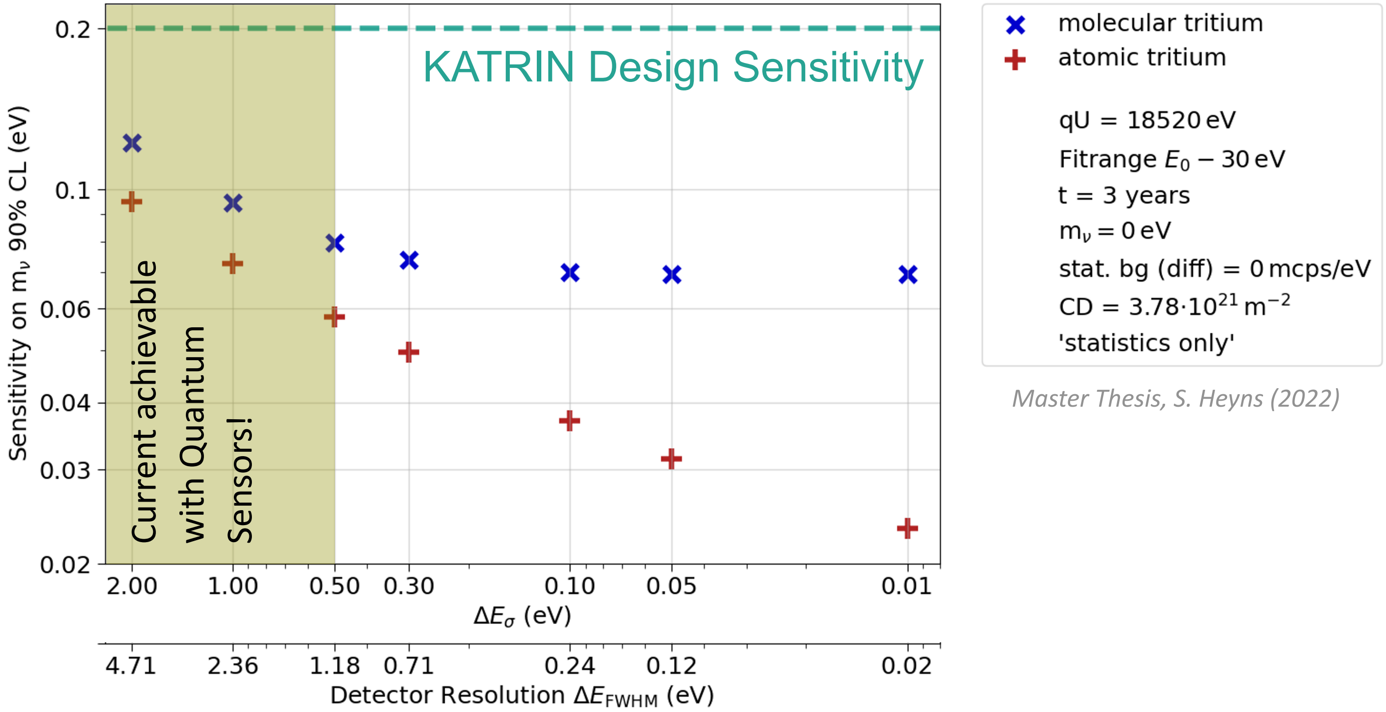


Master Thesis, S. Heyns (2022)

- Two directions forward:
  - Differential measurement mode:
    - → Significant increase in statistics
    - → Reduction of backgrounds
    - → Increase in energy resolution
  - Change from molecular tritium source to an atomic one:
    - → Eliminate effects due to molecular final states

Going Beyond KATRIN

- Going beyond KATRIN final sensitivity requires paradigm shift in measurement approach



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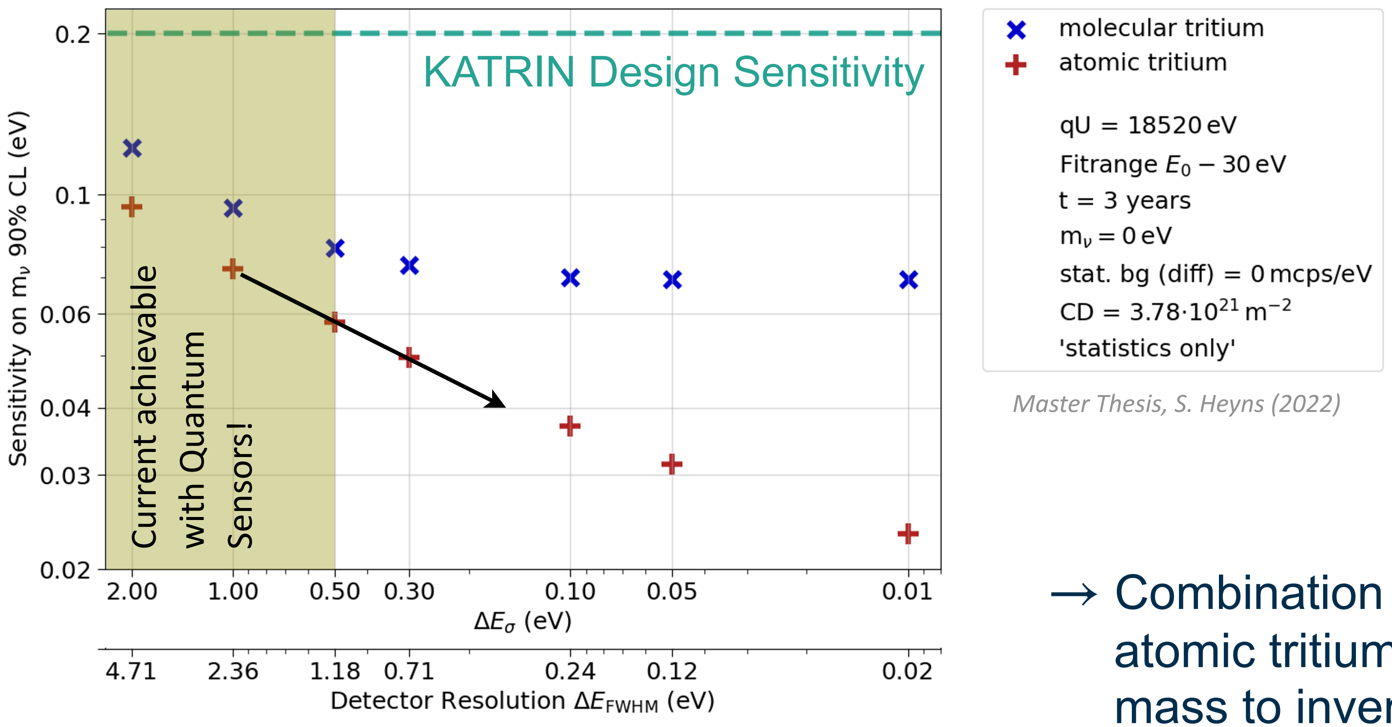

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  - Change from molecular tritium source to an atomic one:
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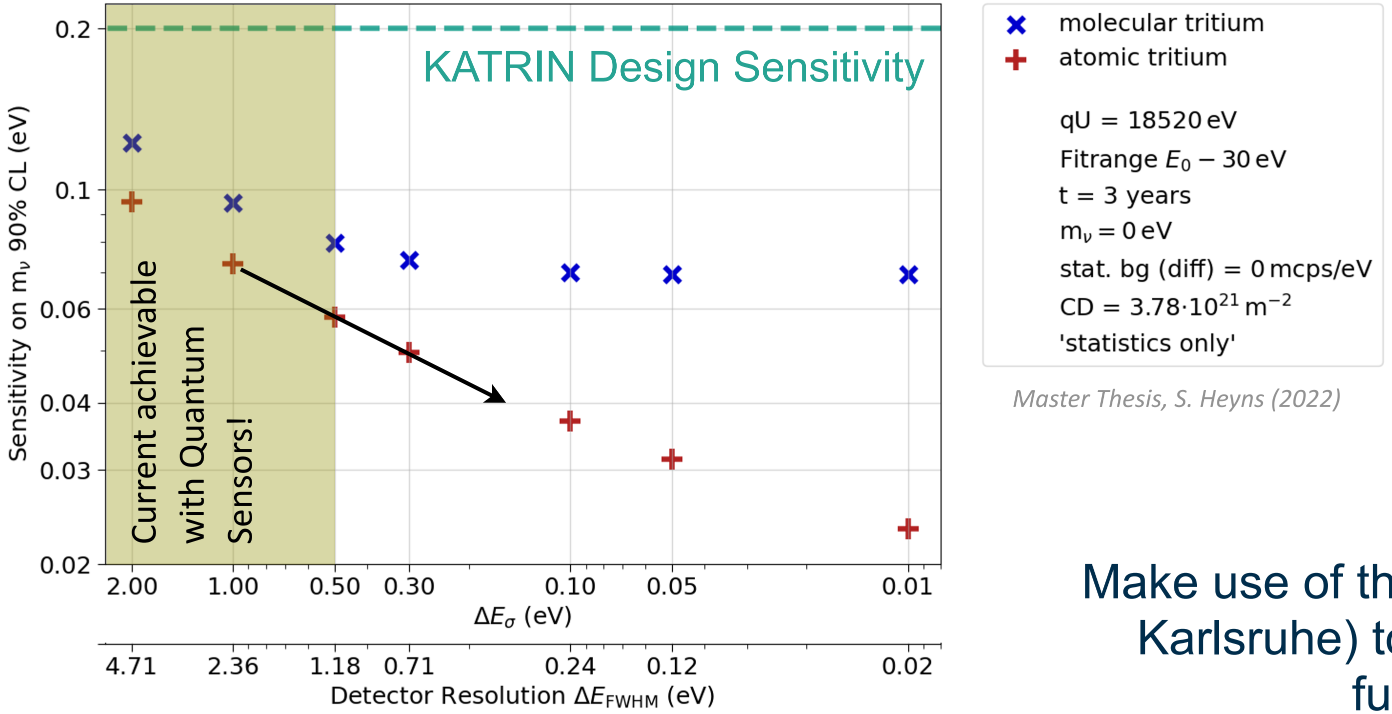
→ Combination of a differential measurement mode with an atomic tritium source allows for the probing of the neutrino mass to inverted ordering and beyond!

Going Beyond KATRIN

- Going beyond KATRIN final sensitivity requires paradigm shift in measurement approach



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- Two directions forward:
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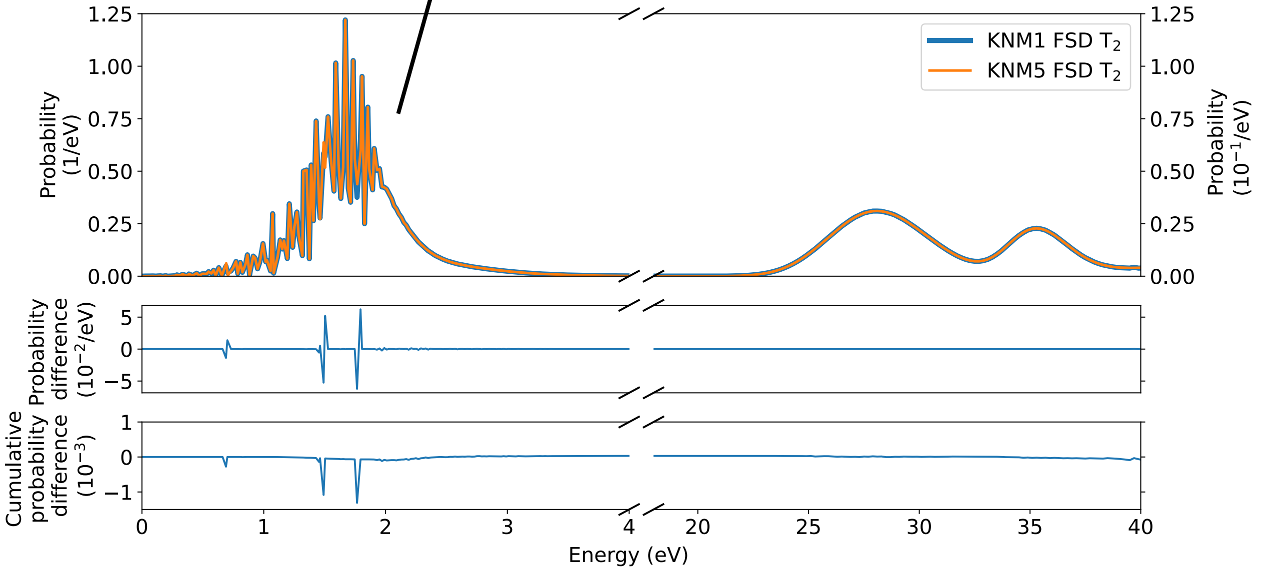
    - → Increase in energy resolution
  - Change from molecular tritium source to an atomic one:
    - → Eliminate effects due to molecular final states

Make use of the existing KATRIN & TLK (Tritium Laboratory Karlsruhe) to develop new and scalable technology for future neutrino mass experiments!

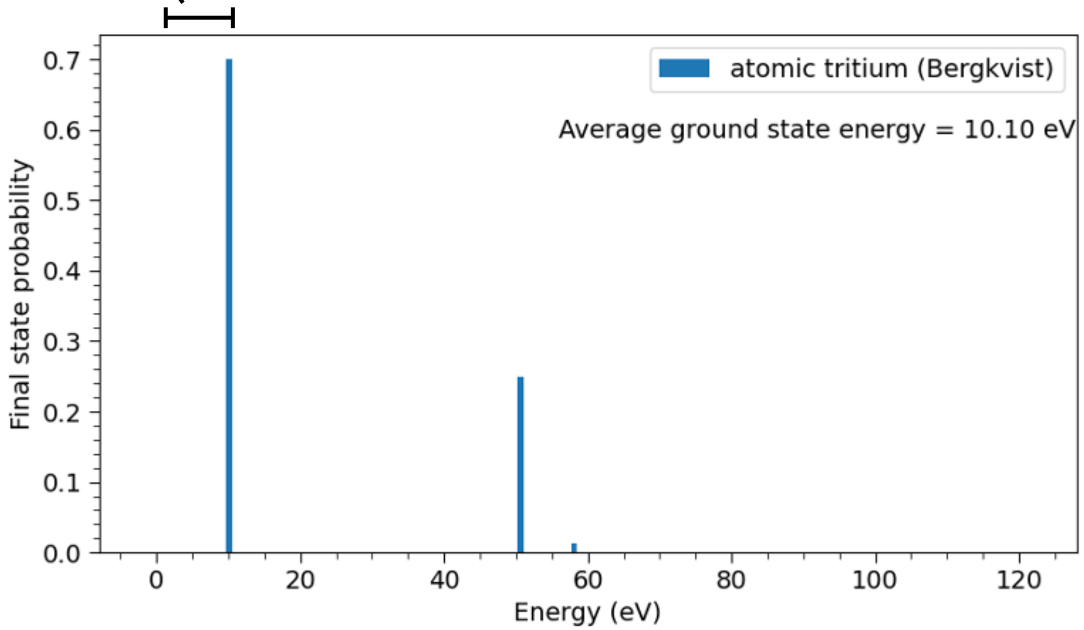
Atomic Tritium Source

- Molecular tritium source
  - 57% of decays in to electronic ground state
  - Intrinsic broadening of the end point on the level of 1 eV

The KATRIN Collaboration, Science 388,180-185(2025)



- Atomic tritium source
  - 70% decays in to electronic ground state
  - ~ 8 eV shift of the end point

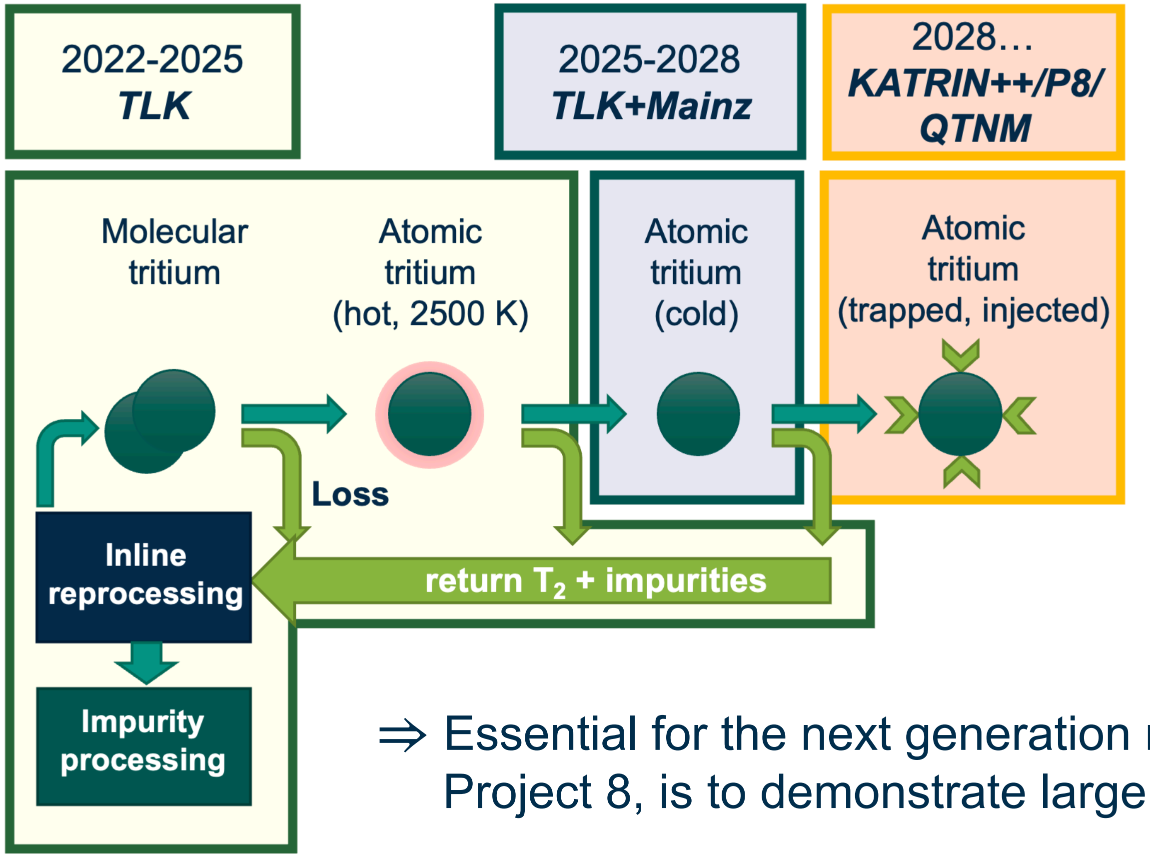


Atomic Tritium Source

Collaboration of KATRIN and Project 8

- Atomic tritium pathfinder at Tritium Laboratory Karlsruhe (TLK)

M. Schlösser

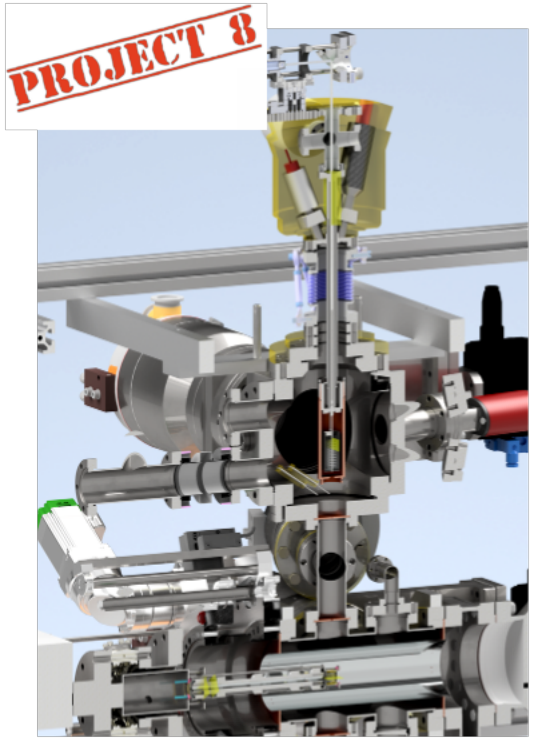


- Main Objectives:
  - Develop atom cooling mechanism
  - Trapping times / max. Densities
  - Interplay of beta-driven plasma (meV - eV) and ultra cold trapped atoms (neV)

→ Ultimately: tritium atom throughput on the order of 10 g/day (ref. current KATRIN throughput is 40 g/ day)

⇒ Essential for the next generation neutrino mass experiments, such as KATRIN++ and Project 8, is to demonstrate large scale generation and cooling (~ 10 mK) of atomic tritium

Atomic Tritium Source



- KAMATE: **KA**rlsruhe **M**ainz **A**tomic **T**ritium experiment
  - Joint effort by KATRIN (TLK) and Project8 (Mainz) to develop atomic tritium source for the future neutrino mass experiments!
  - Atomic Tritium Pathfinder: Global mission to develop atomic tritium for different applications → New groups and expertise are welcome to join!

KAMATE 0.5: Identify the best source at MATS with H/D at Mainz

KAMATE 1.0: Operate KAMATE 0.5 with tritium at TLK
T (beam) ~ 2500 K

KAMATE 2.0: Add accommodator as first stage cooling
T (beam) ~ 150 K

KAMATE 3.0: Add nozzle for second stage cooling and beam temp. measurement set-up

2024 2025 2026 2027 2028

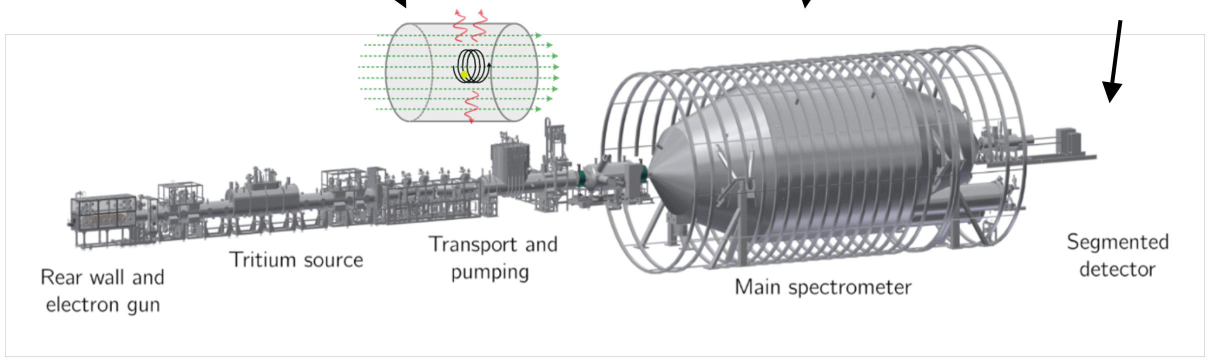
Differential Detection Method

- Time-of-Flight (ToF) Measurements
  - Tag electrons as they pass through the beam line
  - Combine this information with arrival time at the detector to reconstruct differential spectrum
  - 1000 Hz single electron tagger with high Signal-to-Noise ration required!

Tag Electrons

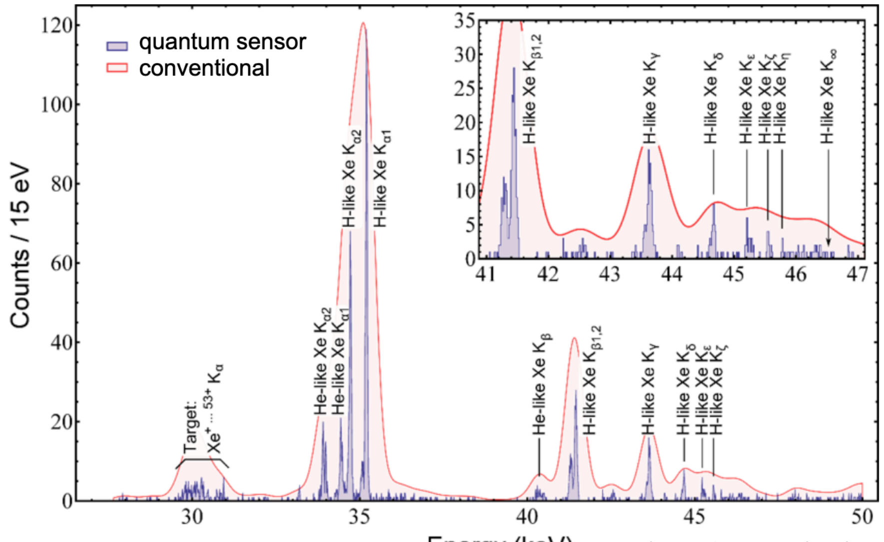
Delay line due to retarding potential

Measure Electrons



- Quantum Sensors - Metallic Microcalorimeters (MMCs)
  - Orders of magnitude better energy resolution compared to conventional detectors
  - Close to 100% quantum efficiency
  - Near-linear detector response over broad energy range
  - No surface dead layer

high-resolution X-ray spectroscopy

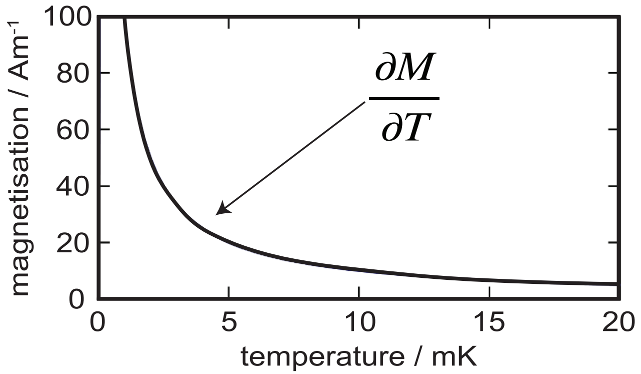


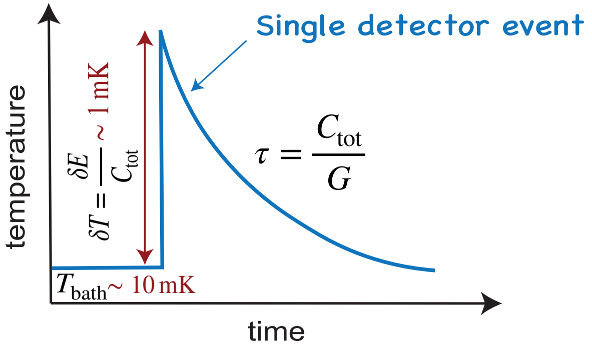
Private Communication

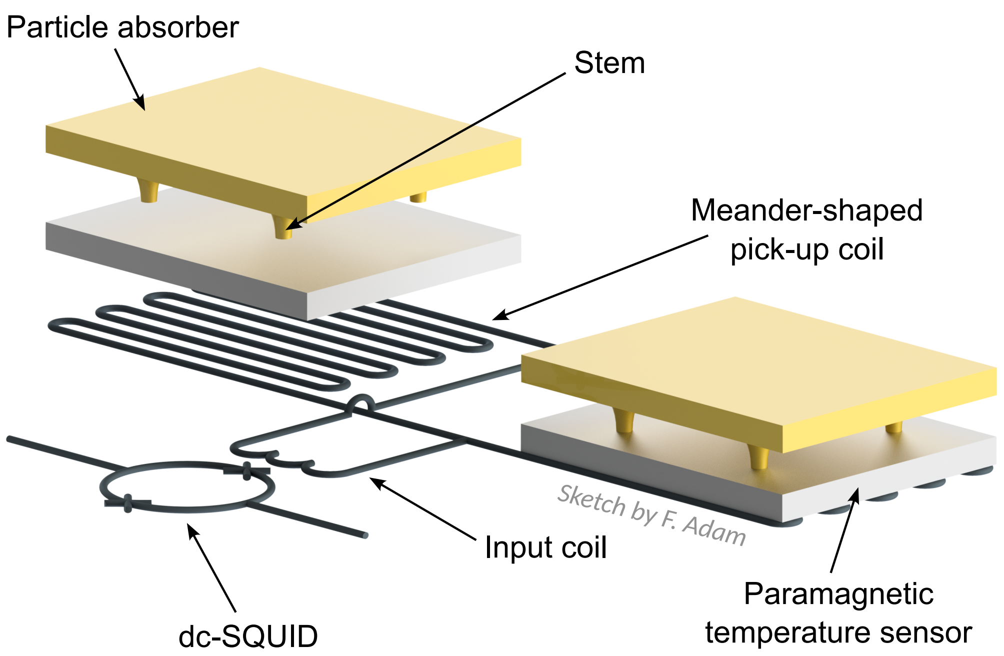
Quantum Sensors

- Metallic Microcalorimeters (MMCs)
  - Cryogenic particle detectors → operational temperature < 100 mK
  - Working principle based on magnetization response of paramagnetic sensor

$$\delta\Phi \propto \delta M \propto \frac{\partial M}{\partial T}\delta T \propto \frac{\partial M}{\partial T}\frac{\delta E}{C_{\mathrm{tot}}}$$







→ **World leading energy resolution (6 keV photons)!**

$$\Delta E = \left(1.25 \pm 0.17_{stat.}\ {}^{+0.07_{syst.}}_{-0.05_{syst.}}\right)\ \mathrm{eV}$$

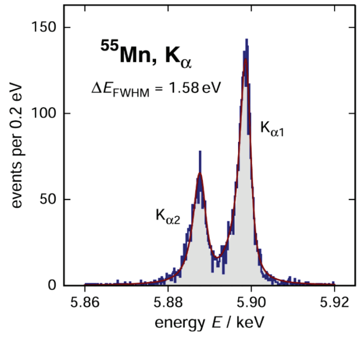
M. Krantz et al., Appl. Phys. Lett. 124, 032601 (2024)
F. Toschi et al, PRD (2024)

Electron Spectroscopy with MMCs

- What has been done so far?
  - Measurements of photon radiation
  - Measurements of heavy ions
  - Never tested with external electrons!

Photons

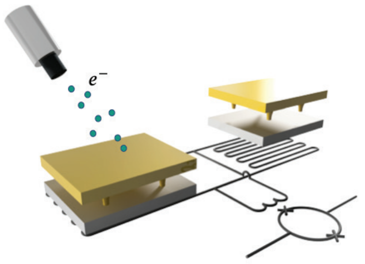
Gaussian detector response



Experiment: performed
Simulation: validated

External Electrons

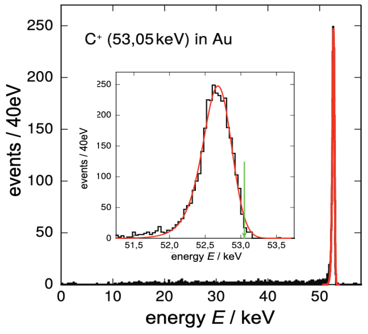
Gaussian detector response



Experiment: not yet performed
Simulation: not yet validated

Heavy Ions

Non-Gaussian detector response



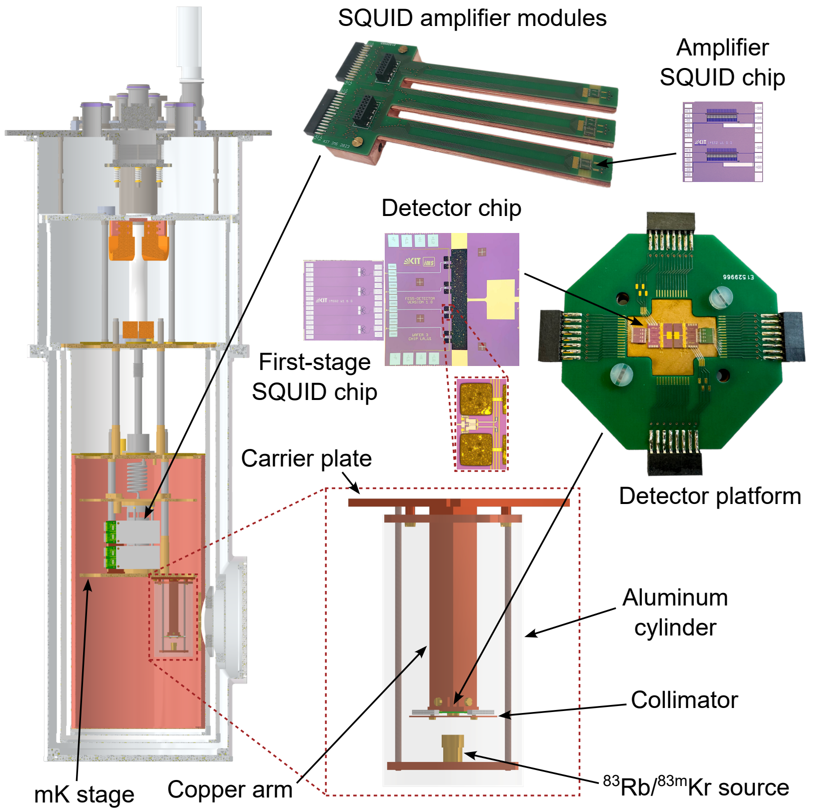
Experiment: performed
Simulation: validated

Electron Spectroscopy with MMCs

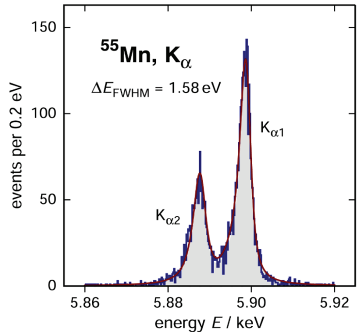
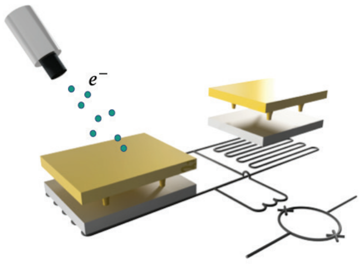
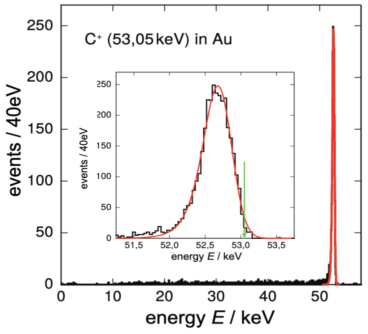
- What has been done so far?
  - Measurements of photon radiation
  - Measurements of heavy ions
  - **Never tested with external electrons!**

ELECTRON Project

- Experimental Set-Up for characterization with external electrons



Sketch by F. Adam

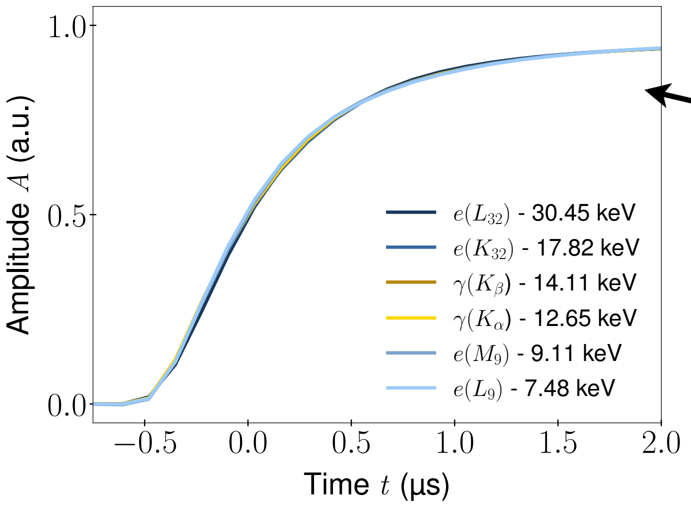
Photons	External Electrons	Heavy Ions
Gaussian detector response	Gaussian detector response	Non-Gaussian detector response
		
Experiment: performed **Simulation:** validated ✓	**Experiment:** not yet performed **Simulation:** not yet validated ✗	**Experiment:** performed **Simulation:** validated ✓

Response of MMCs to External Electrons

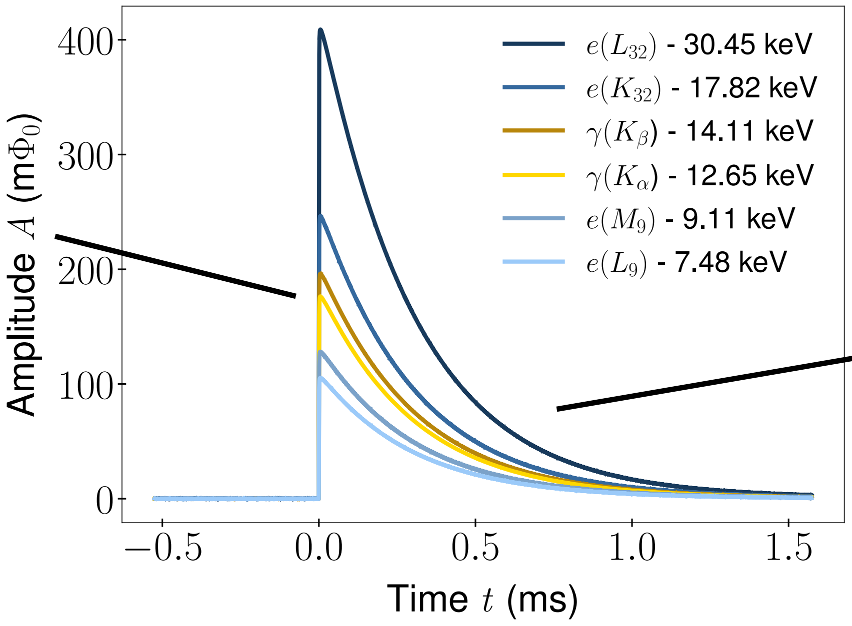
- ^{83}Rb/^{83m}Kr source
  - Conversion electrons → detector response to external electrons
  - X-ray photons → well understood from past measurements

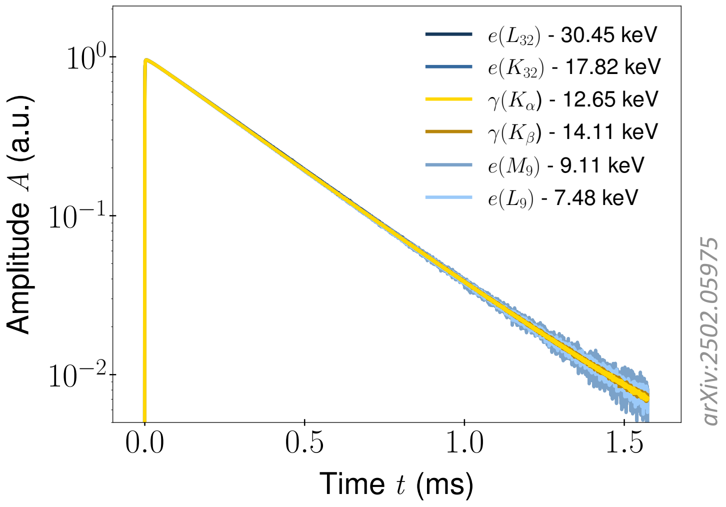
→ Allows for comparison between signals from external electrons and X-ray photons with the same radioactive source!

Consistency in signal rise!



arXiv:2502.05975





Consistency in signal decay!

Response of MMCs to External Electrons

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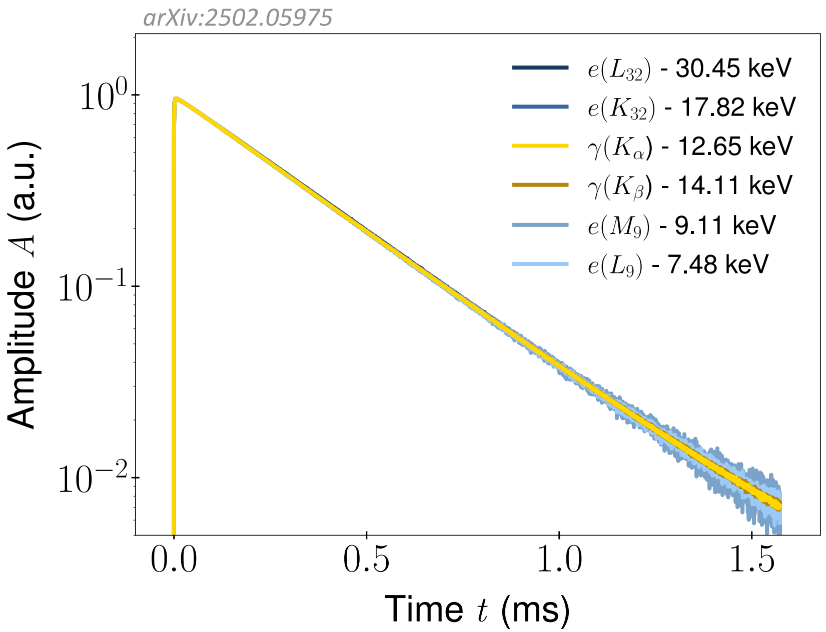
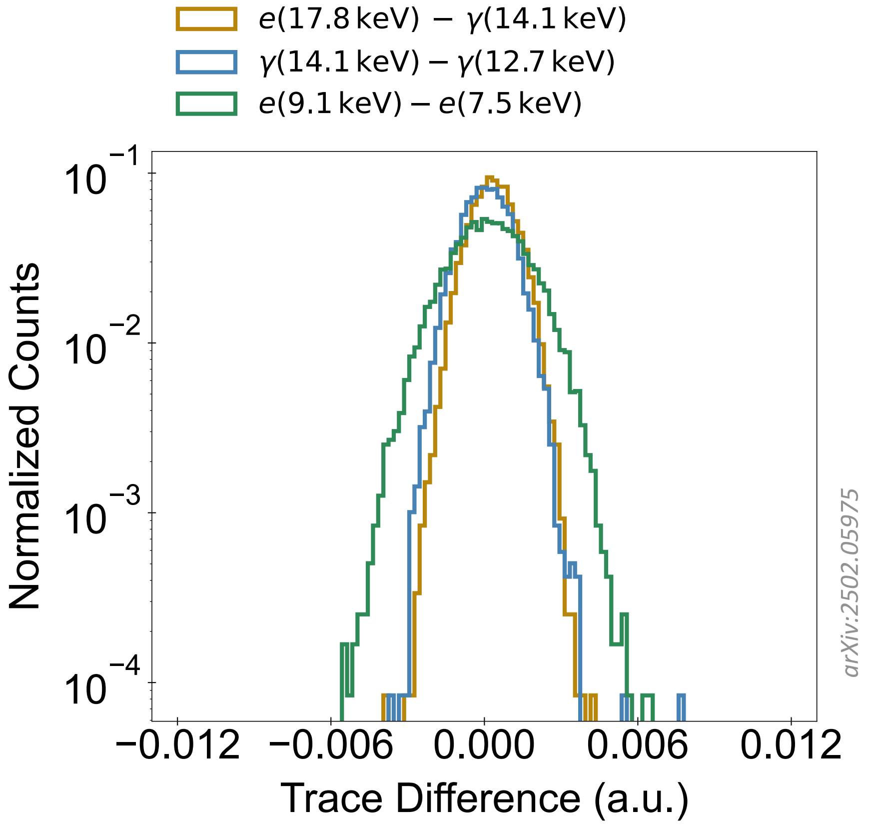
  - X-ray photons → well understood from past measurements



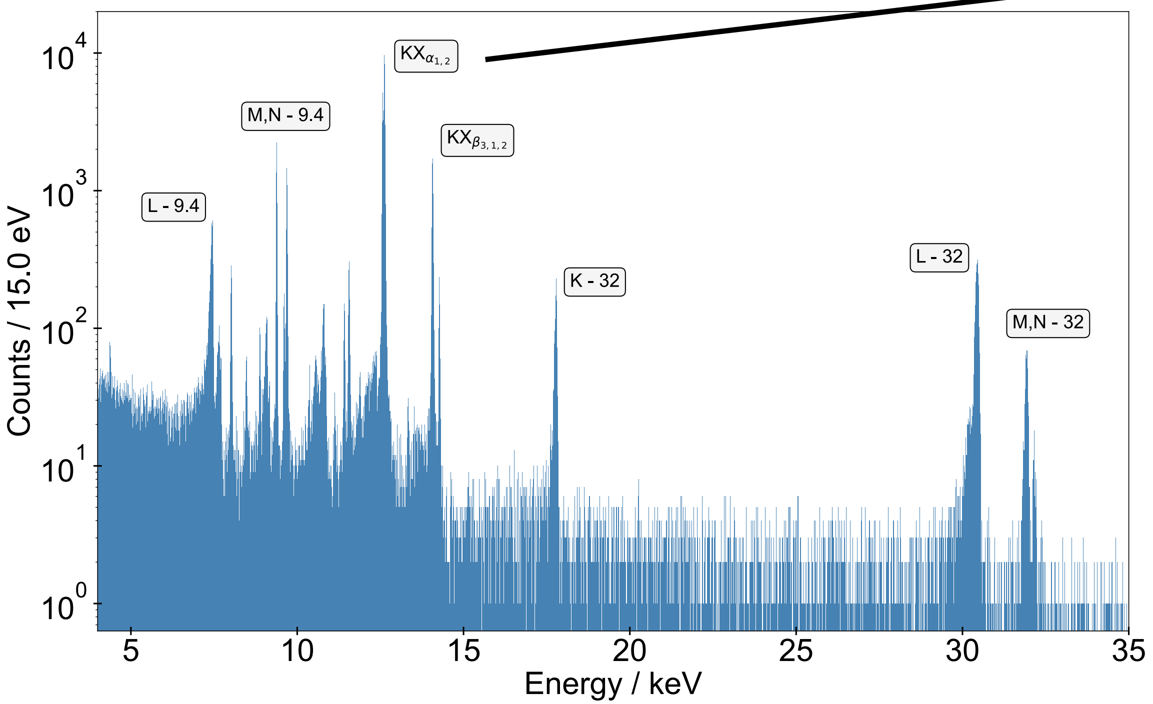
Trace difference between signal of different particle types →

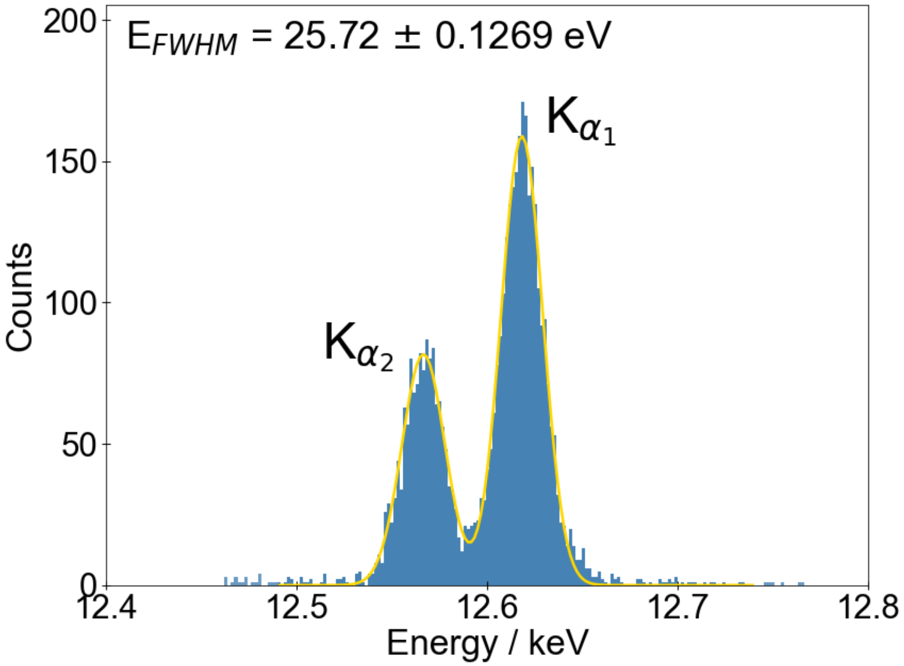


Gaussian distribution of trace difference confirms consistency in detector response to external electrons and X-ray photons!

Measurement of ^{83}Rb/^{83m}Kr Spectrum

- Measured ^{83}Rb/^{83m}Kr spectrum
  - Energy resolution at 12.6 keV → 25 eV
  - Publication in preparation



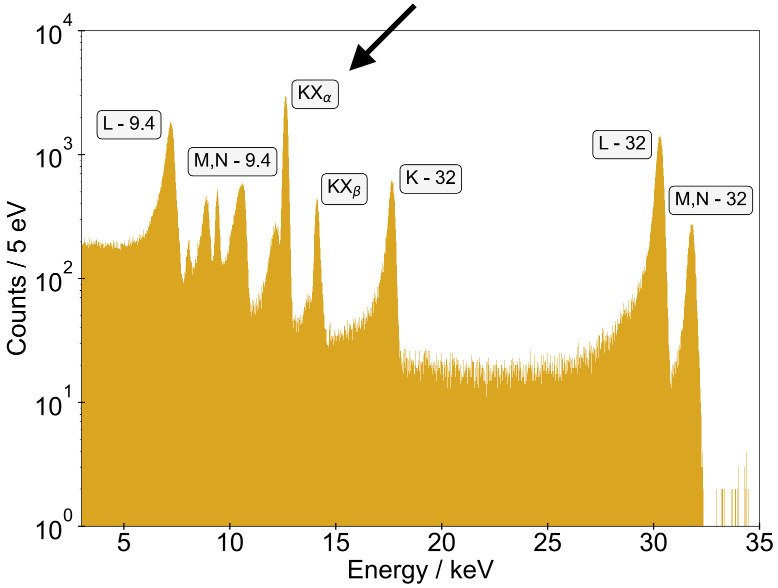


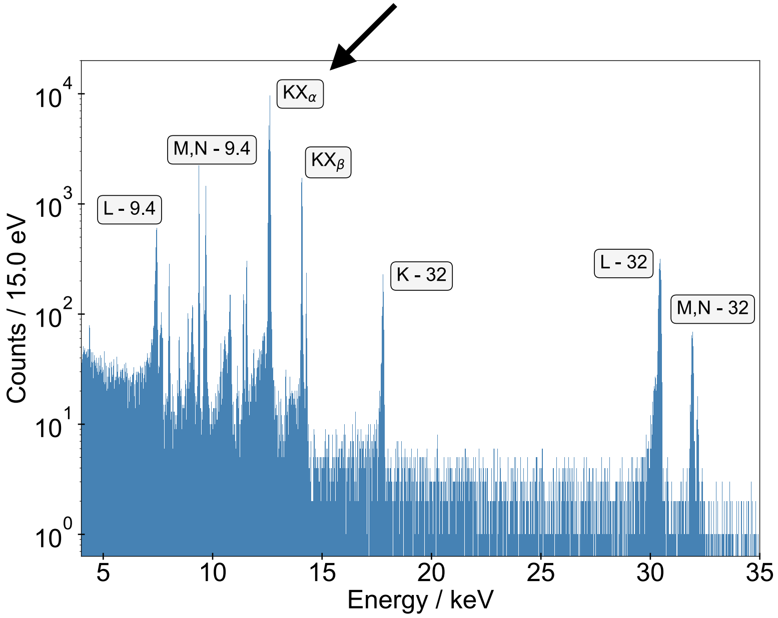
Highest resolution ^{83}Rb/^{83m}Kr spectrum measured with a differential detector!

Measurement of ^{83}Rb/^{83m}Kr Spectrum

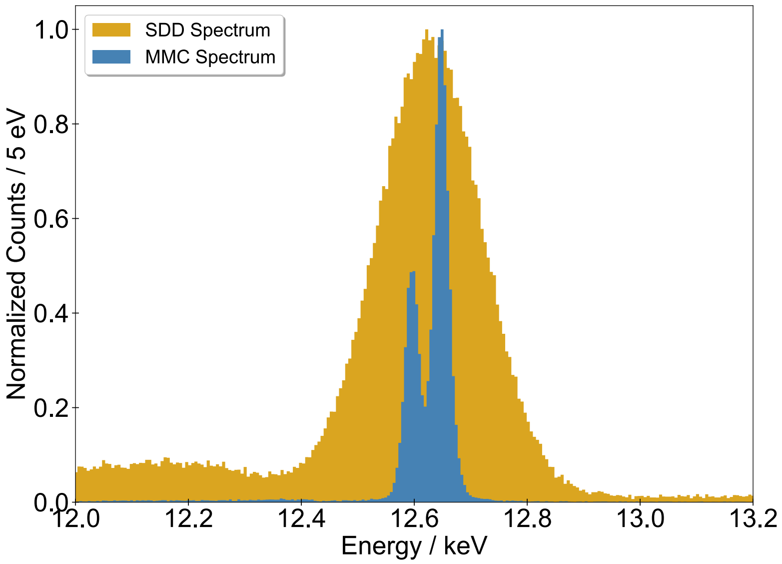
- Comparison with the spectrum measured with a classical (silicon) detector
  - Using the same ^{83}Rb/^{83m}Kr source
  - Measurements done with a state of the art silicon drift detector (SDD)

Advantage of going with a quantum sensors directly visible!





Comparison of X-ray lines



Measurement of $^{83}Rb/^{83m}Kr$ Spectrum

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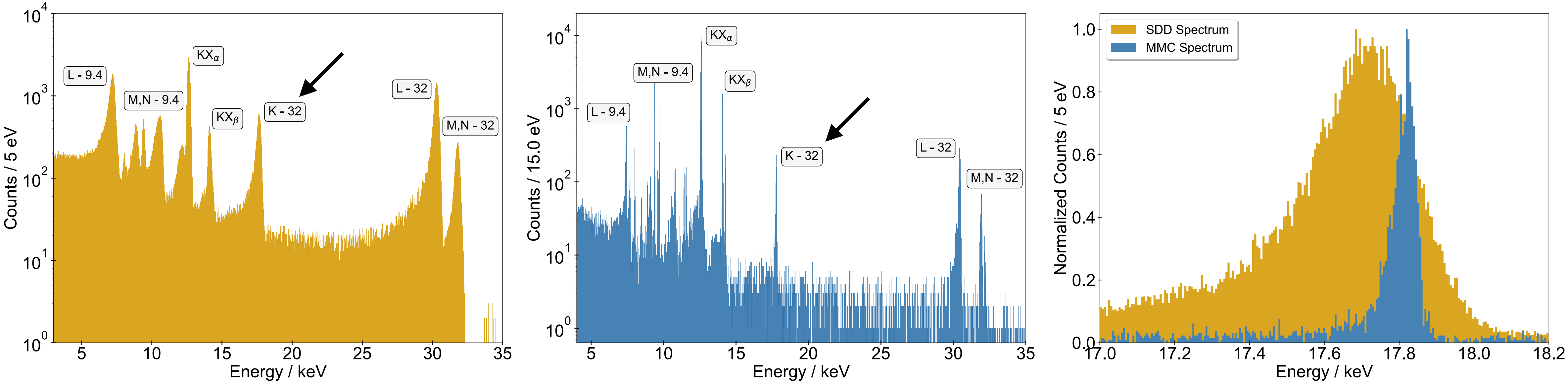
Advantage of going with a quantum sensors directly visible!

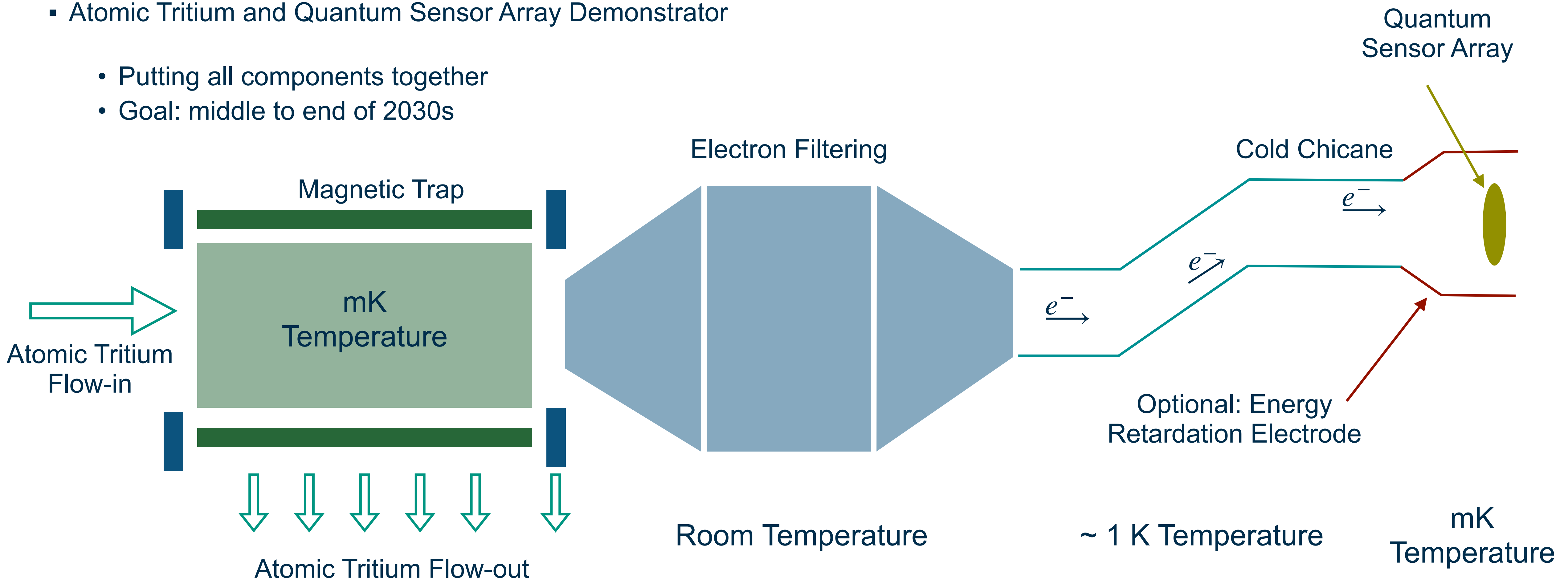
Comparison of conversion electron lines



KATRIN++ - Final R&D Goal

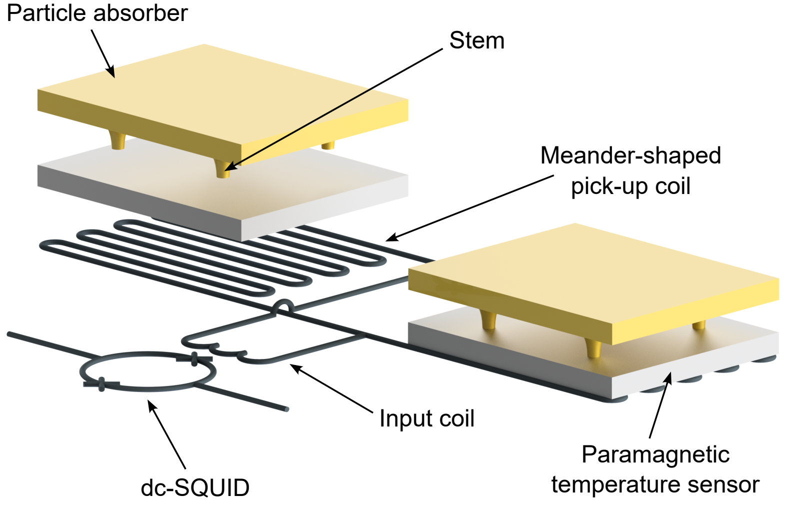
Very Rough Sketch!

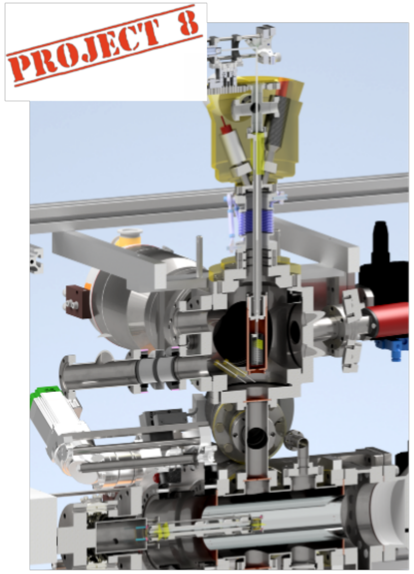
- Atomic Tritium and Quantum Sensor Array Demonstrator
  - Putting all components together
  - Goal: middle to end of 2030s



Conclusion and Outlook

- Going beyond the final KATRIN sensitivity is an extremely challenging endeavor!
- It requires paradigm shift in measurement principles
  - Differential measurement method will allow us to probe sub-100 meV region of the neutrino mass!
  - High luminosity atomic tritium source will allow us to go even further, beyond the invert mass ordering!
- Currently ongoing R&D projects under KATRIN++ umbrella:
  - Development of large area quantum sensor arrays for ultra-high resolution electron spectroscopy
  - Development of single-electron tagger for a time-of-flight measurement
  - Development of atomic tritium source





Conclusion and Outlook

KATRIN Talks:
J. Lauer , Thursday, 16:40
S. Mohanty, Thursday, 17:00
TRISTAN Talk:
A. Nava, Thursday, 16:20

- Rough timeline for KATRIN++
  - After TRISTAN experimental phase, several years of R&D are required!

KATRIN Invites all interested groups to join the effort towards the ultimate neutrino mass hunt!

Current KATRIN Scientific Phases!

KATRIN Phase 1
→ Integral measurement
→ Aim to constrain the mass of electron anti-neutrino
→ Projected sensitivity: $m_\nu \geq 200\,\mathrm{meV}$

KATRIN Phase 2 - TRISTAN
→ Differential measurement with new SDD detectors
→ Aim to probe the keV sterile neutrino mass range

R&D Towards The Future

KATRIN++ R&D Phase
→ Develop new technologies for future neutrino experiments
→ Atomic tritium demonstrator
→ Quantum Sensor demonstrator

Ultimate neutrino mass experiment
→ Determination of the neutrino mass ordering
→ Determination of the absolute values of the neutrino mass eigenstates

time
2019 | 2022 | 2026 | 2028 | 2034

2022 → R&D for Atomic Tritium Source (ATS) and next generation Quantum Sensors (QSs) already started!

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