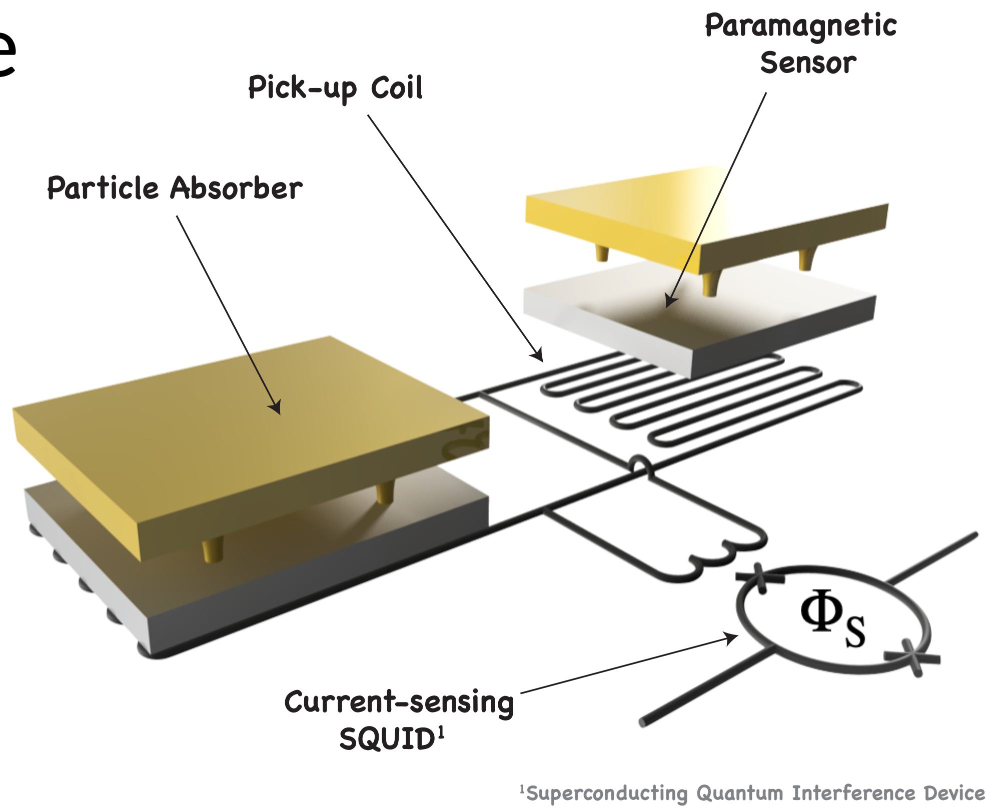
Karlsruhe Institute of Technology

ELECTRON - Development of High Resolution Metallic Microcalorimeters for a Future Neutrino Mass Experiment with Tritium



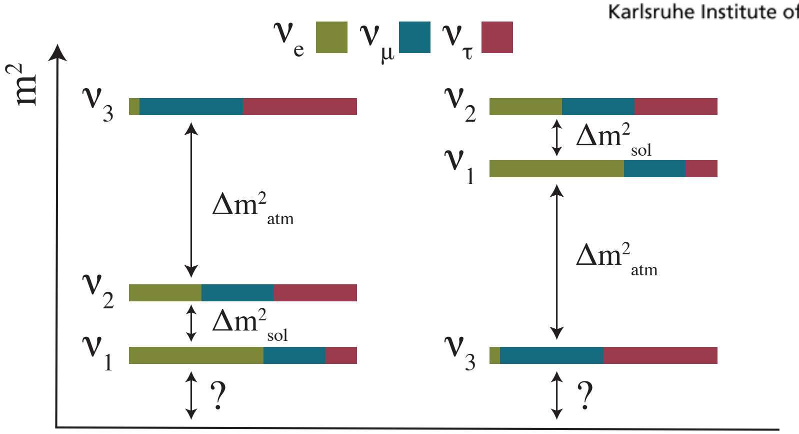
N. Kovač[1]; T. E. App[1], F. Bauer[2], B. Bornschein[1], D. de Vincenz[1], W. Gil[1], F. Glück[1], S. Heyns[1], S. Kempf[2,3], M. C. Langer[2], M. Müller[2], R. Sack[1], M. Schlösser[1], M. Steidl[1] and K. Valerius[1]

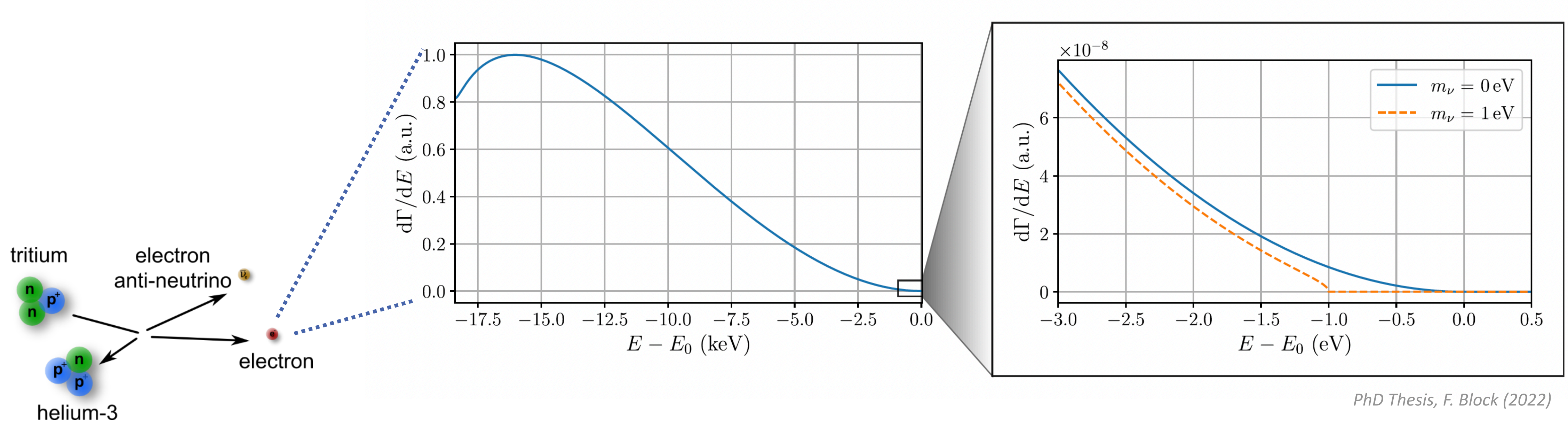
[1]*Inst. for Astroparticle Physics (IAP), Karlsruhe Institute of Technology (KIT)*
[2]*Inst. of Micro- and Nanoelectronic Systems (IMS), Karlsruhe Institute of Technology (KIT)*
[3]*Inst. for Data Processing and Electronics (IPE), Karlsruhe Institute of Technology (KIT)*

Motivation - Neutrino Mass

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

  ➡ Look for neutrino imprint in the end-point region of the beta decay (Tritium) or electron capture (Holmium) spectrum





PhD Thesis, F. Block (2022)

Motivation - Neutrino Mass

- Hunt for the absolute scale of the neutrino mass ongoing since the discovery of the neutrino oscillations at the end of last millennium
- Limit from the KATRIN experiment :

$$m_{\nu_e} \leq 0.8 \text{ eV/c}^2 \quad (90\,\%\,\text{C.L.})$$

The KATRIN collaboration, Nat. Phys. 18, 160–166 (2022)

➡ Projected final KATRIN sensitivity:

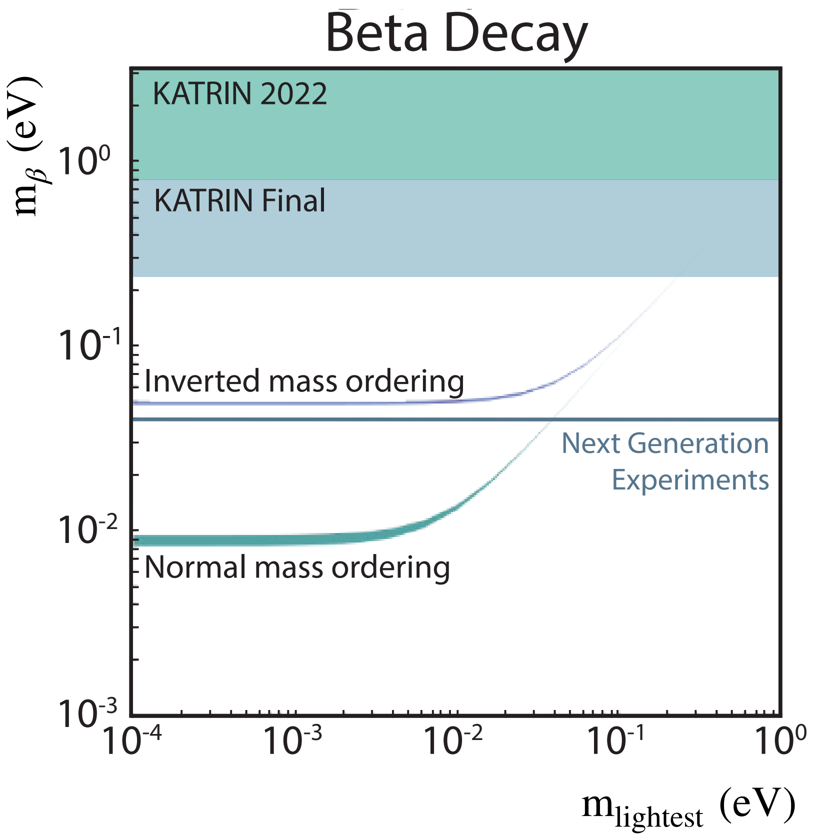
$$m_{\nu_e} \geq 0.2 \text{ eV/c}^2 \quad (90\,\%\,\text{C.L.})$$

The KATRIN collaboration et al 2021 JINST 16 T08015

- Limits from Cosmology:

$$\sum m_\nu < 0.11 \text{ eV/c}^2 \quad (95\,\%\,\text{C.L.})$$

N. Aghanim et al. (Planck), Astron. Astrophys. 641, A6 (2020)



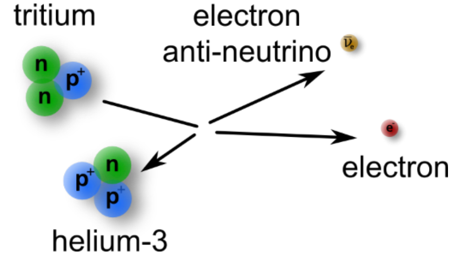
⇒ The goal of future neutrino mass experiments will be to probe the sub-100 meV region of neutrino mass!

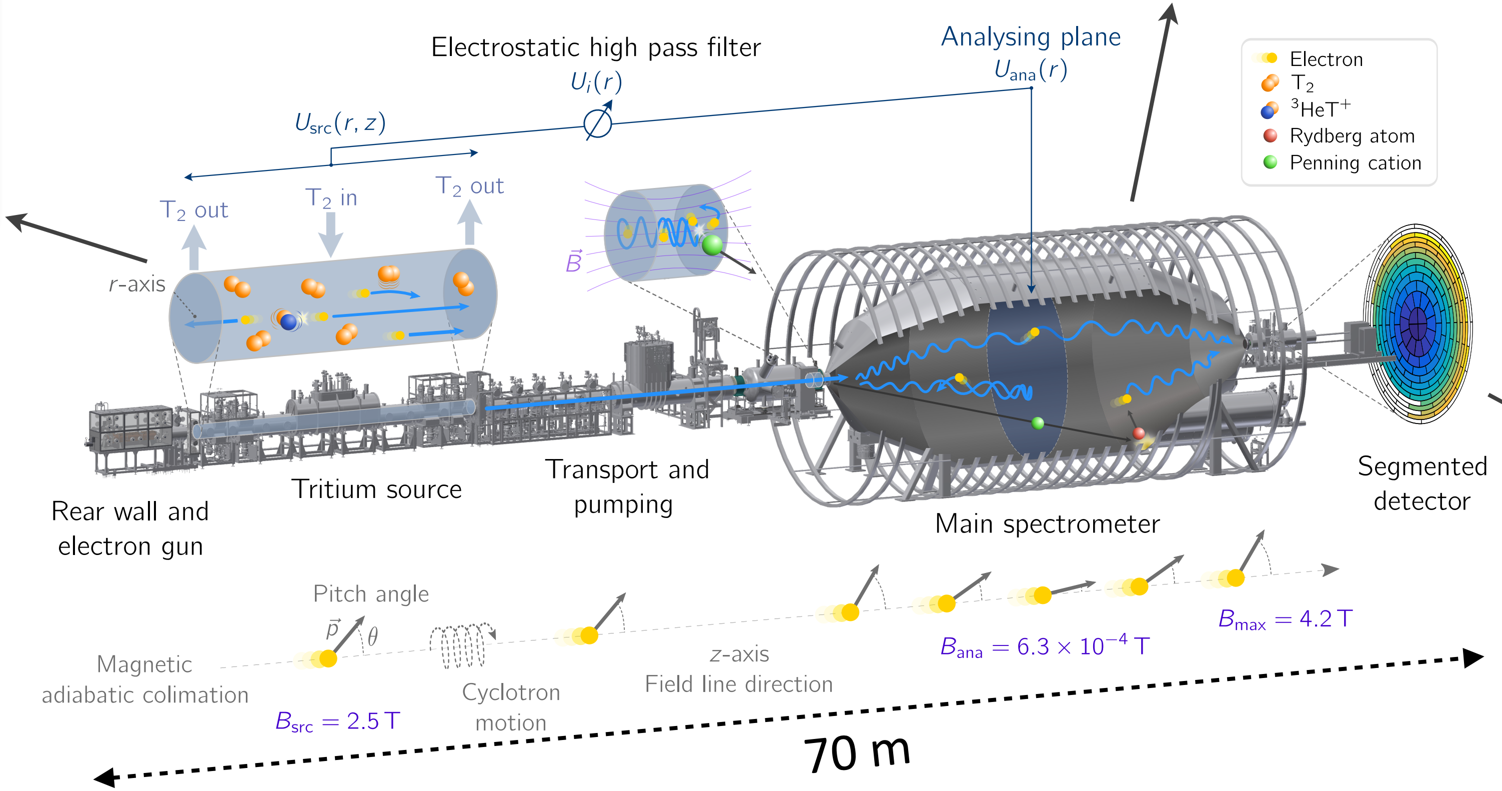
Motivation - KATRIN

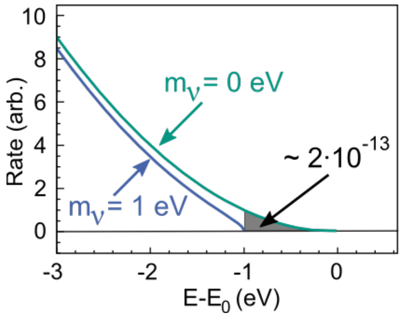
➡ **KA**rlsruhe **TRI**tium **N**eutrino Experiment

WGTS:
- → High-luminosity molecular tritium source
- → 10^{11} decays each second
- → $\rho_{cd} \approx 4 \times 10^{21}\,\mathrm{m}^{-2}$

Main Spectrometer:
- → Magnetic adiabatic collimation
- → Electrostatic energy filter
- → $\Delta E_{MS} \approx 2 - 3\,\mathrm{eV}$







FPD:
- → Silicon *p-i-n* diode array
- → 148 pixels on a 12.5 cm diameter silicon wafer
- → Energy resolution in the range of ~ few keV

⇒ Currently leading experiment in direct determination of electron (anti-)neutrino mass!

Institute for Astroparticle Physics (IAP), Karlsruhe Institute for Technology

Motivation - beyond KATRIN

Karlsruhe Institute of Technology

➡ Using KATRIN as a model for the future neutrino mass experiment

Atomic Tritium Source (ATS):

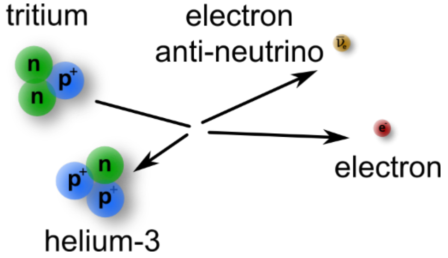
→ Generate tritium atoms at mK temperatures

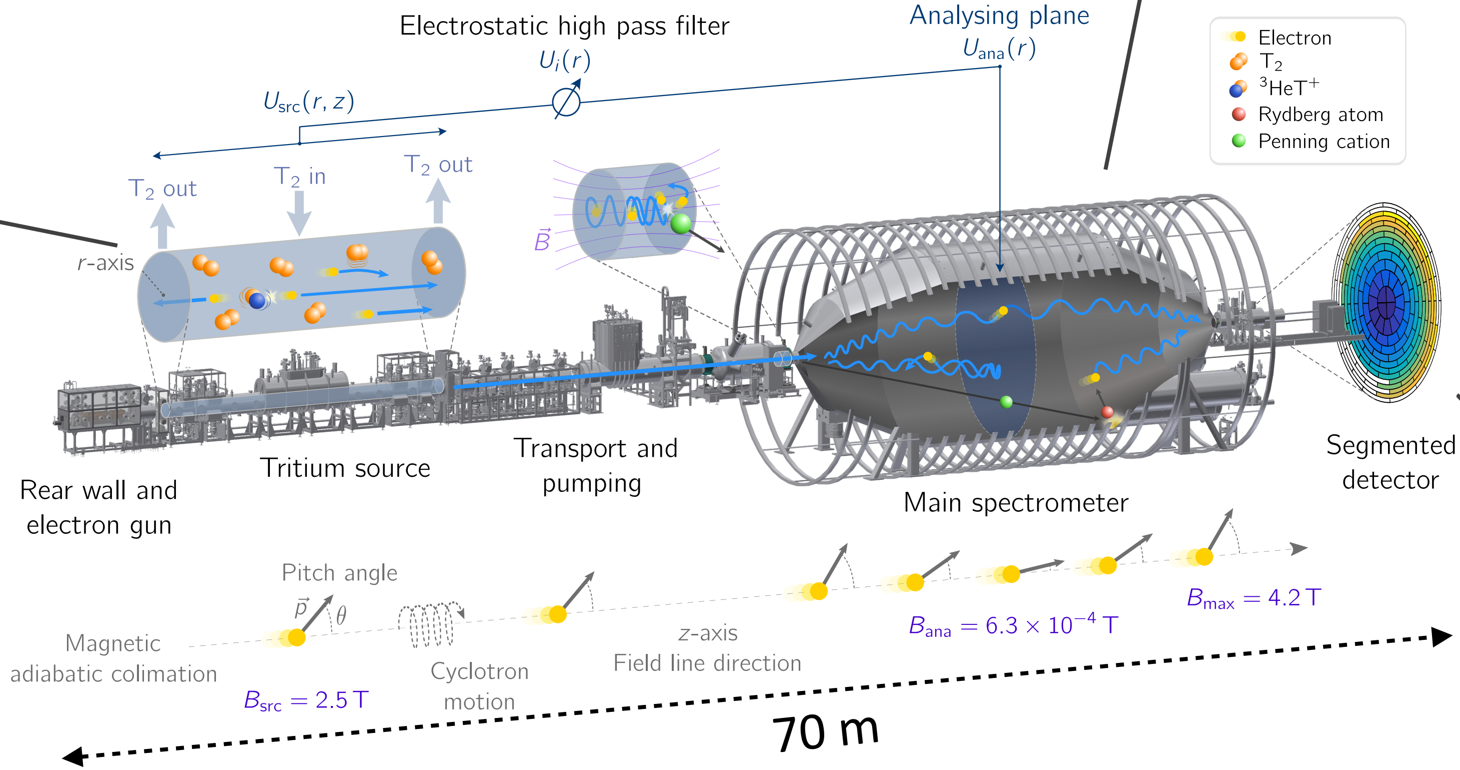
→ Trap the tritium atoms in an atomic trap

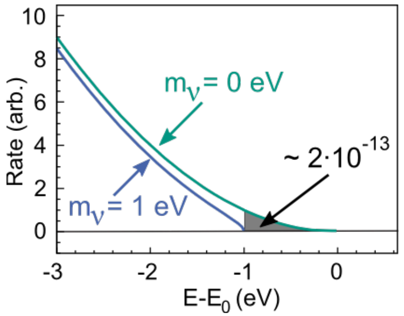
Main Spectrometer:

→ "Only pre-filter"

→ Set to fixed potential (~ 30 eV below tritium end-point)







Quantum Sensor (QS) Array:

→ Energy resolving detector

→ Ultra-high energy resolution

→ Mitigation of spectrometer induced backgrounds

Motivation - beyond KATRIN

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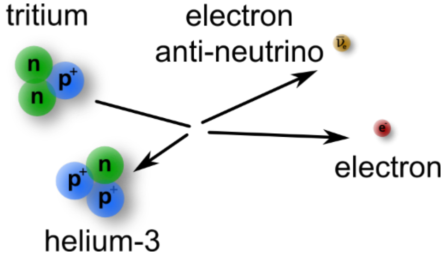

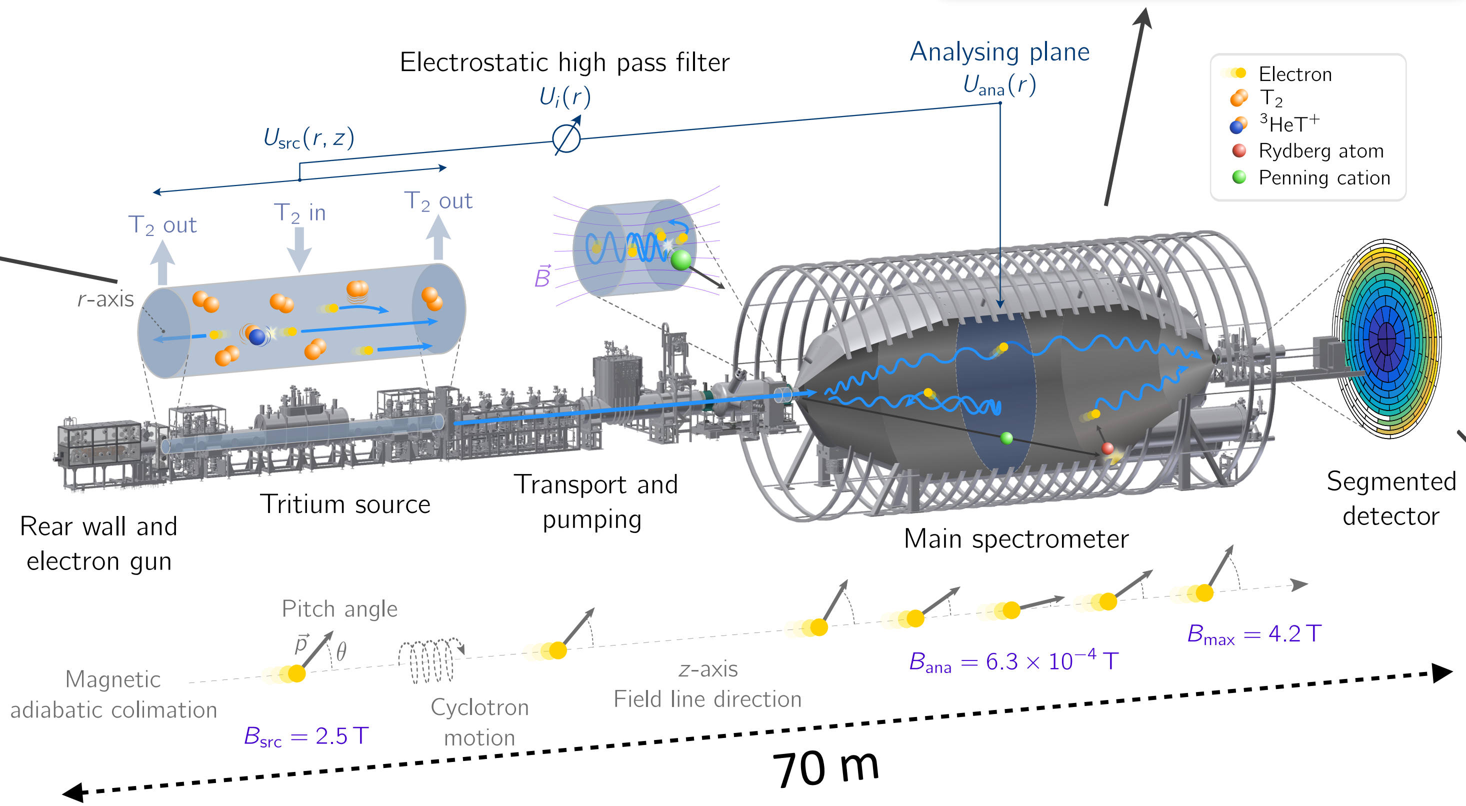

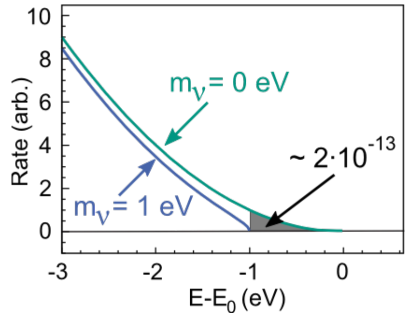

Quantum Sensor (QS) Array:
- → Energy resolving detector
- → Ultra-high energy resolution
- → Mitigation of spectrometer induced backgrounds

⇒ KATRIN beamline gives us a unique opportunity to develop new technologies!

Motivation - beyond KATRIN

➡ Using KATRIN as a model for the future neutrino mass experiment

Atomic Tritium Source (ATS):

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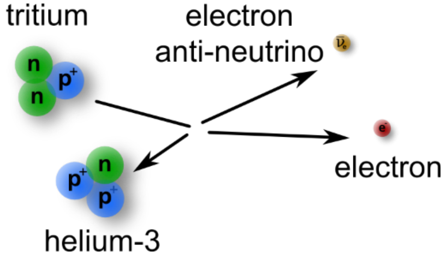
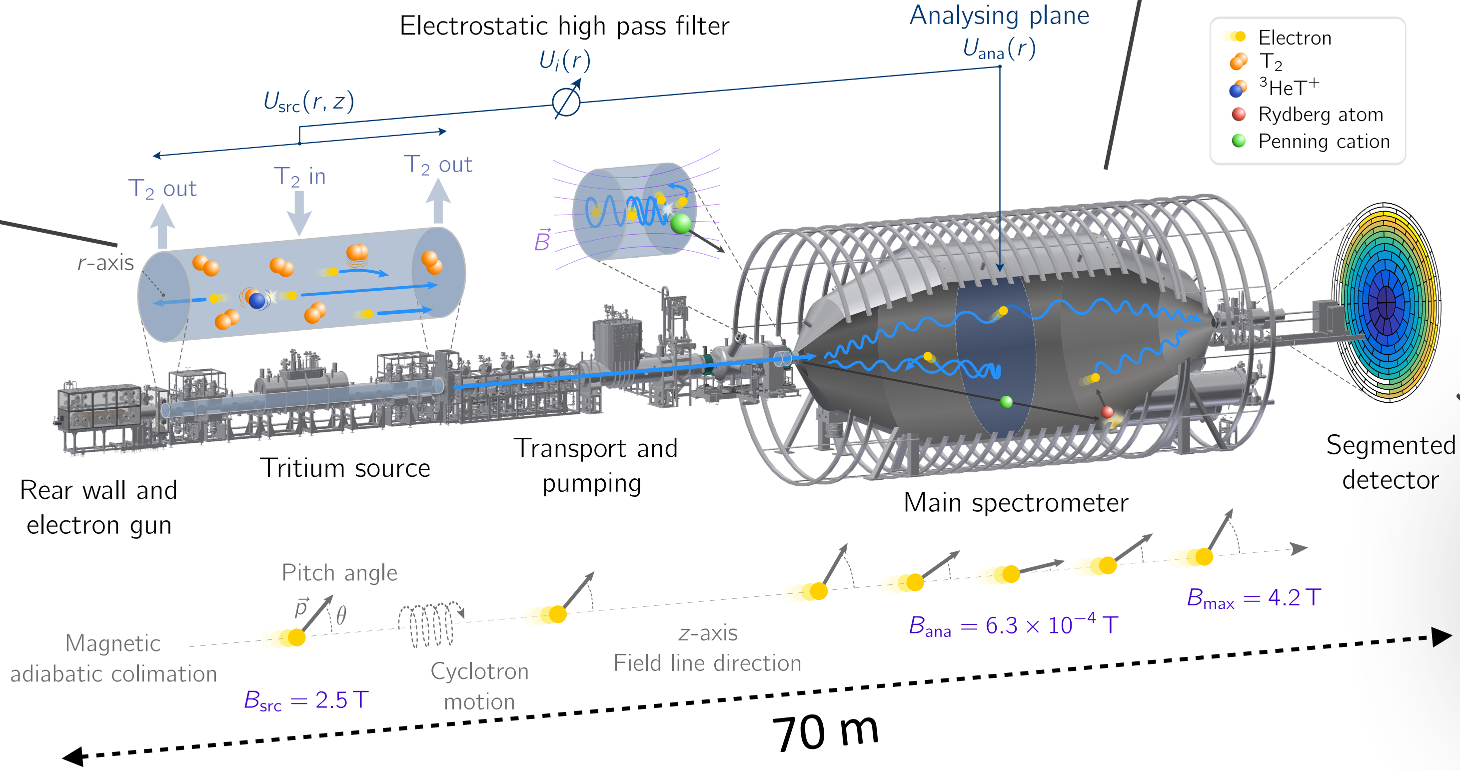
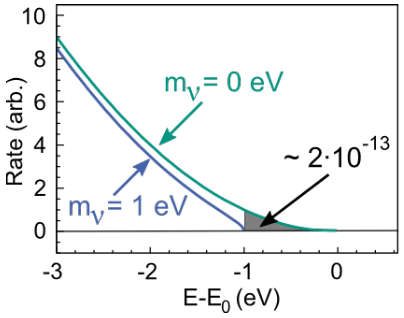






Quantum Sensor (QS) Array:

→ Energy resolving detector
→ Ultra-high energy resolution
→ Mitigation of spectrometer induced backgrounds

This talk!

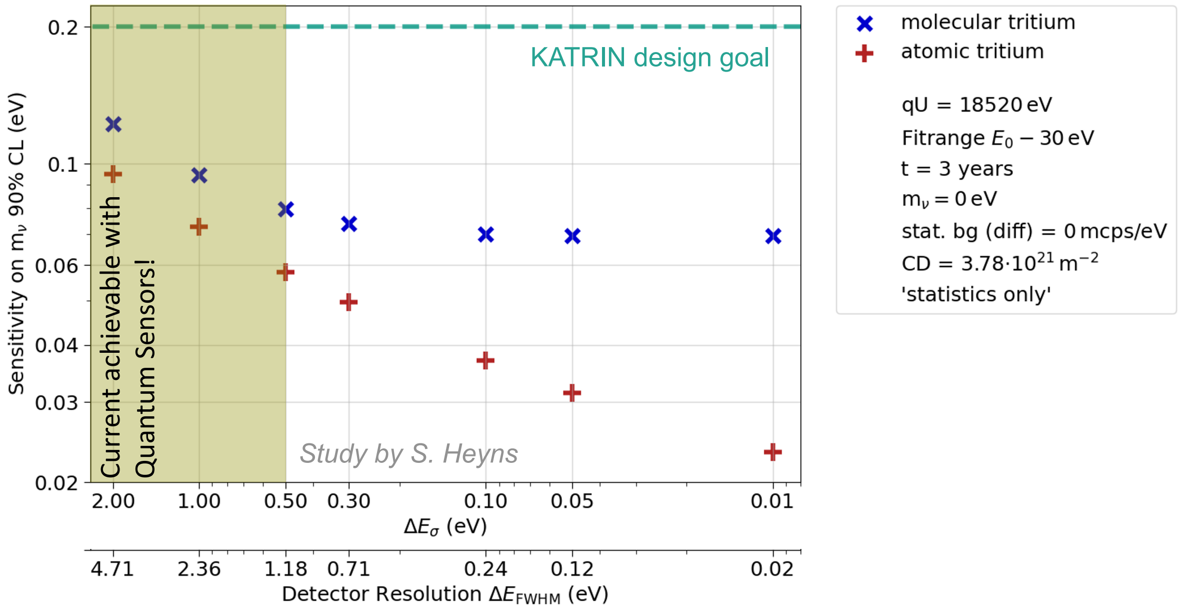
⇒ KATRIN beamline gives us a unique opportunity to develop new technologies!

Future Neutrino Mass Experiment with Tritium

Karlsruhe Institute of Technology

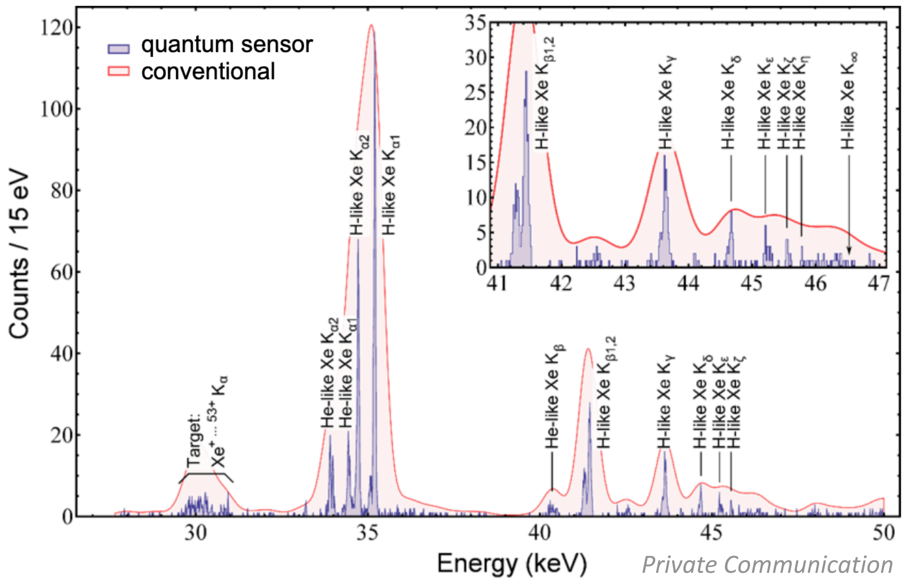
- Reaching sub-100 meV sensitivity:
  - Significant increase in the statistics
  - Reduction of the background
  - Increase in the energy resolution

⇒ Differential measurement mode is the way to go!



- Metallic Microcalorimeters:
  - Energy resolution orders of magnitude better compared to conventional detectors
  - Close to 100% quantum efficiency (for photons)
  - Near linear detector response over a wide energy range
  - No surface dead layer

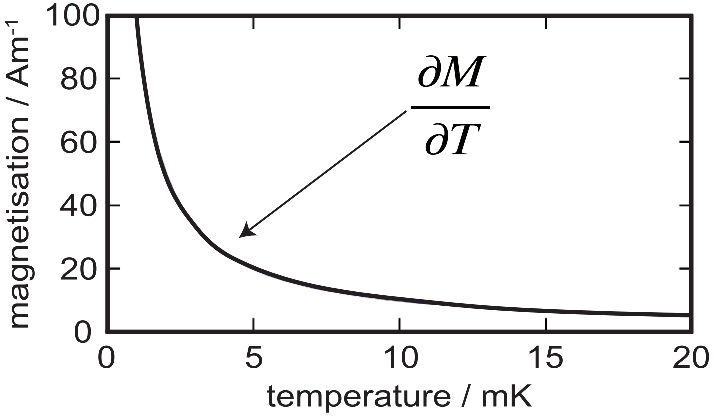
high-resolution X-ray spectroscopy

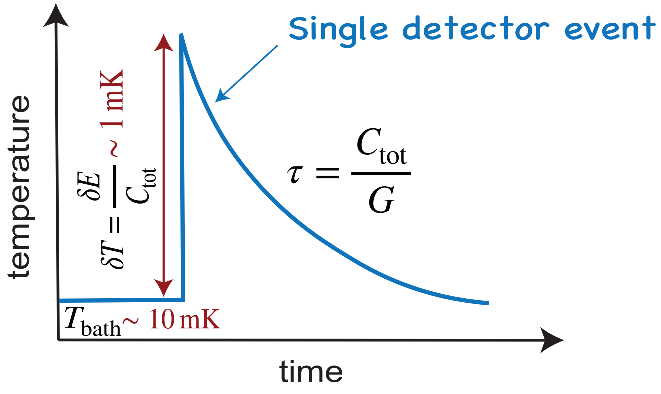


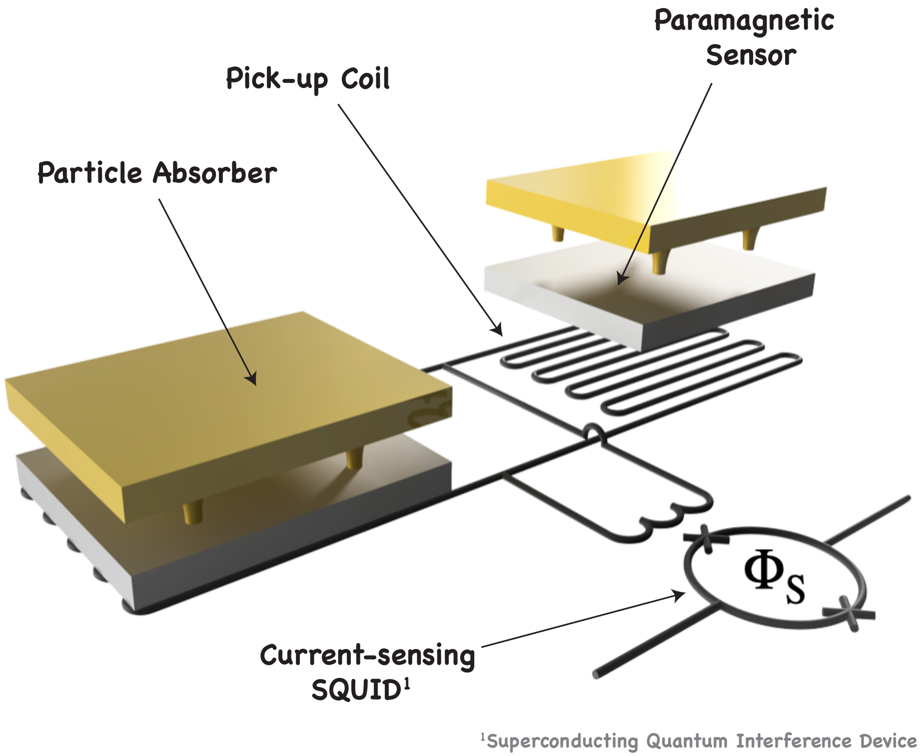
Metallic Magnetic Calorimeters (MMCs)

- Cryogenic micro-calorimeters $\Rightarrow$ $\mathrm{T_{opt}} \sim 10\,\mathrm{mK}$
- Working principle based on the magnetisation response of the paramagnetic sensor

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





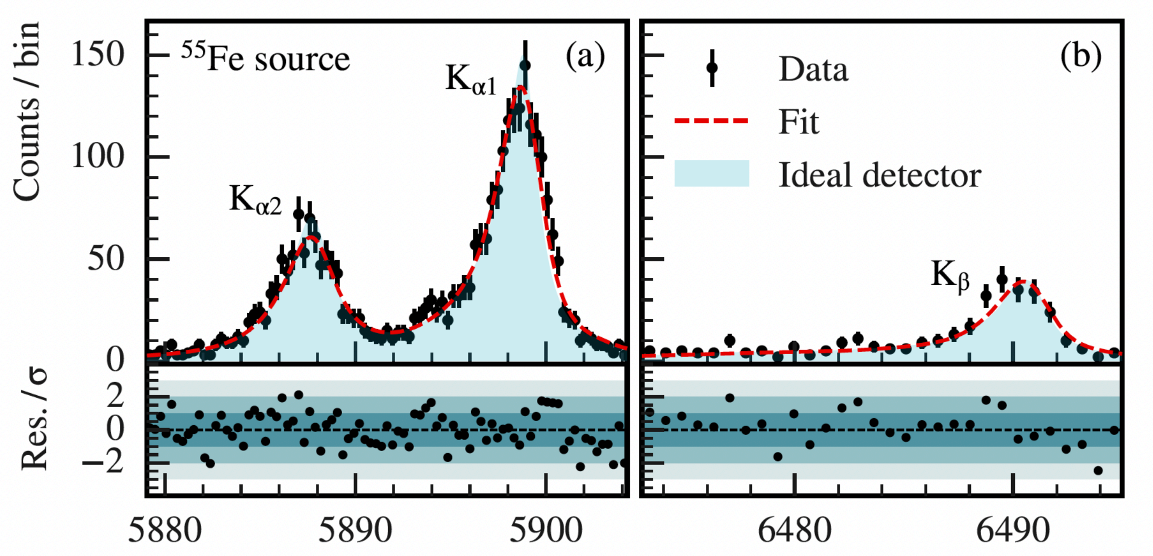


$$\Delta E_{\mathrm{FWHM}} \approx 2\sqrt{2\ln(2)}\sqrt{4\,k_{\mathrm{B}}C_{\mathrm{e}}T^2}\left(\frac{1}{\beta(1-\beta)}\frac{\tau_r}{\tau_d}\right)^{1/4}$$

C. Enss et al., Cryogenic Particle Detection, pp. 151-216. Springer Berlin Heidelberg, 2005

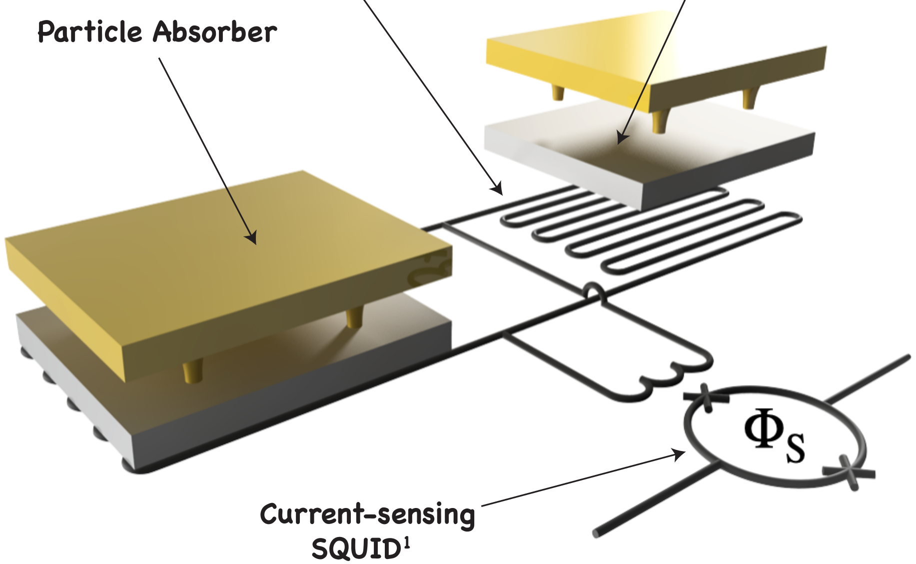
Metallic Magnetic Calorimeters (MMCs)

- Cryogenic micro-calorimeters $\Rightarrow$ $T_{opt} \sim 10\,\mathrm{mK}$
- World leading in energy resolution!



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

$$\Delta E_{\mathrm{FWHM}}^{@\,5.9\,\mathrm{keV}} = \left(1.25 \pm 0.17_{stat.}\,{}^{+0.07_{syst.}}_{-0.05_{syst.}}\right)\,\mathrm{eV}$$



[1]Superconducting Quantum Interference Device

$$\Delta E_{\mathrm{FWHM}} \approx 2\sqrt{2\ln(2)}\sqrt{4\,k_B C_e T^2}\left(\frac{1}{\beta(1-\beta)}\frac{\tau_r}{\tau_d}\right)^{1/4}$$

C. Enss et al., Cryogenic Particle Detection, pp. 151-216. Springer Berlin Heidelberg, 2005

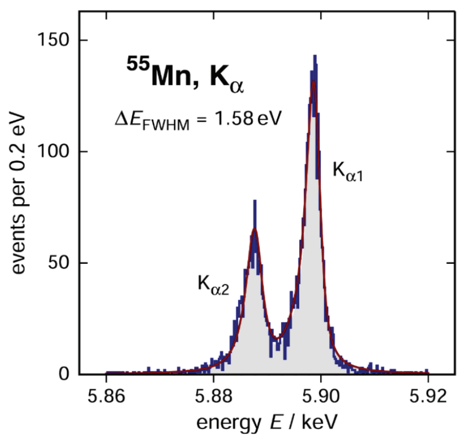
Metallic Magnetic Calorimeters (MMCs)

Karlsruhe Institute of Technology

- For KATRIN++ we need a differential detector able to perform electron spectroscopy with ultra-high energy resolution!
- MMCs not tested with external electron sources! Until now…

Photons

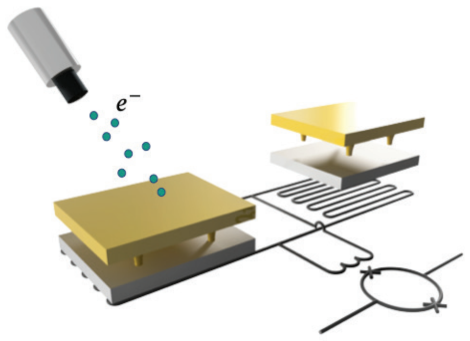
Gaussian detector response



Experiment: performed
Simulation: validated
✓

External Electrons

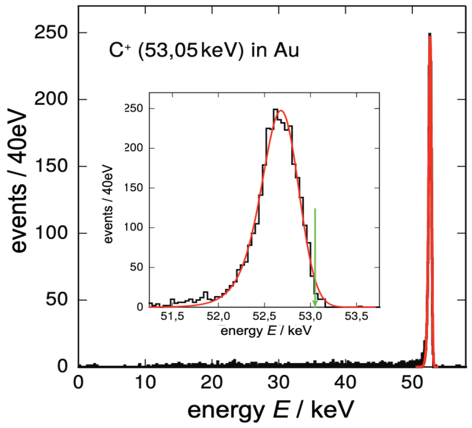
Gaussian detector response



Experiment: not yet performed
Simulation: not yet validated
✗

Heavy Ions

Non-Gaussian detector response



Experiment: performed
Simulation: validated
✓

Never used for measurements of light charged particles from external sources!

ELECTRON Project

The ELECTRON Project

- KIT internal project ⇒ funded through “***KIT Future Fields, Funding Stage 2***”
- Aims:

  I. Test whether MMC detectors can be used to measure external electrons

  II. Study the detector-electron interplay and investigate potential systematic effects

  III. First ever measurement of the differential tritium spectrum with a cryogenic micro-calorimeter

Electron sources:

(I) Electron-gun

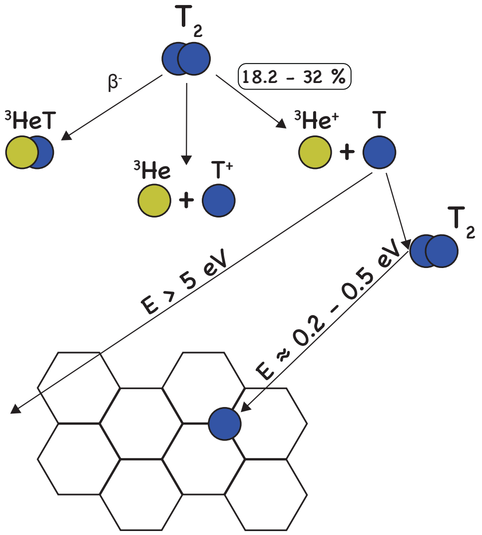
(II) $^{83}\mathrm{Rb}/^{83m}\mathrm{Kr}$ - source

(III) Tritium bound on graphene

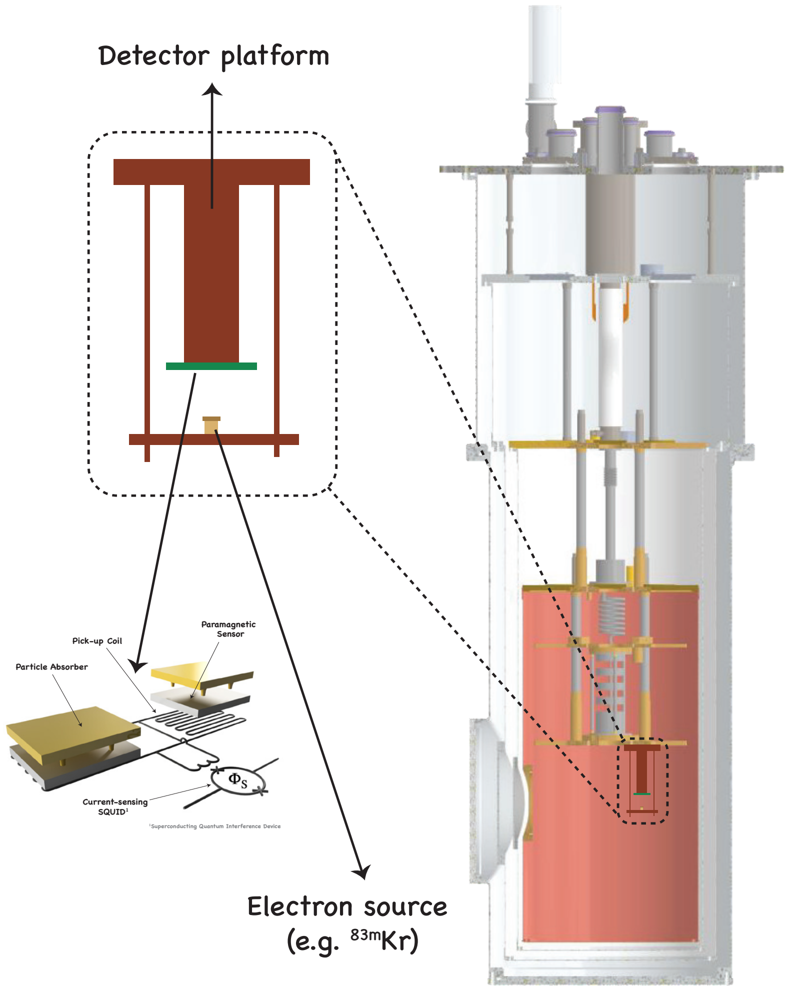
↓

Successful tritiation of graphene demonstrated at TLK, KIT (PhD G. Zeller, 2024)

https://doi.org/10.1039/D3NA00904A



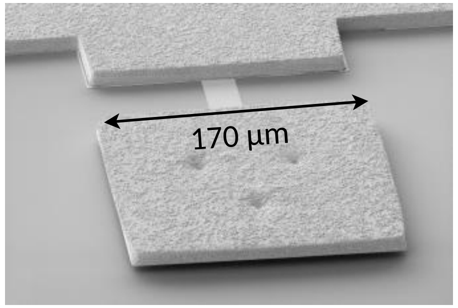
G. Zeller, arXiv:2310.16645



ELECTRON - Experimental set-up

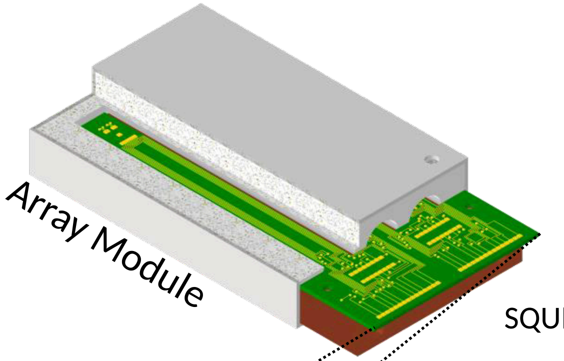
- Commercially available Bluefors $^3He/^4He$ dilution refrigerator
- Detector and read-out SQUIDs designed and fabricated at KIT-IMS

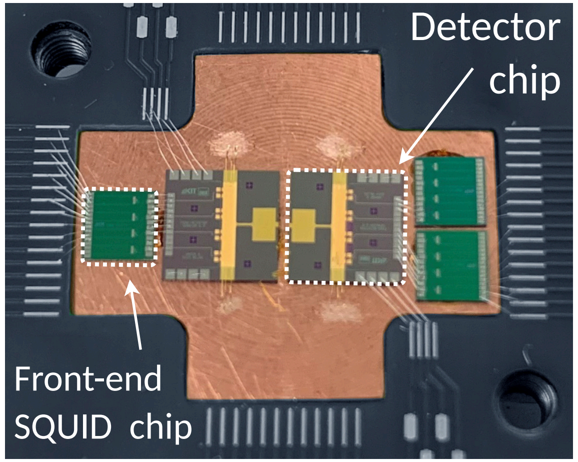
PhD Thesis M. Müller



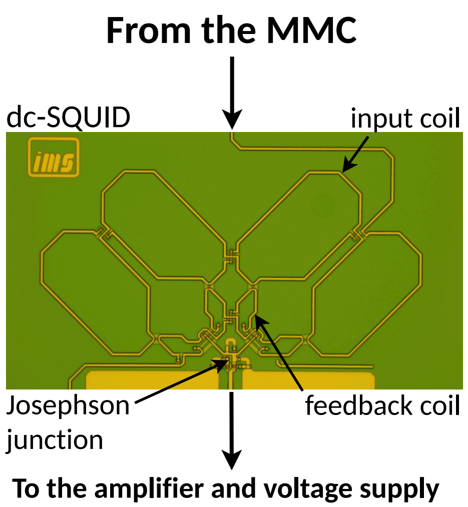
MMC pixels:

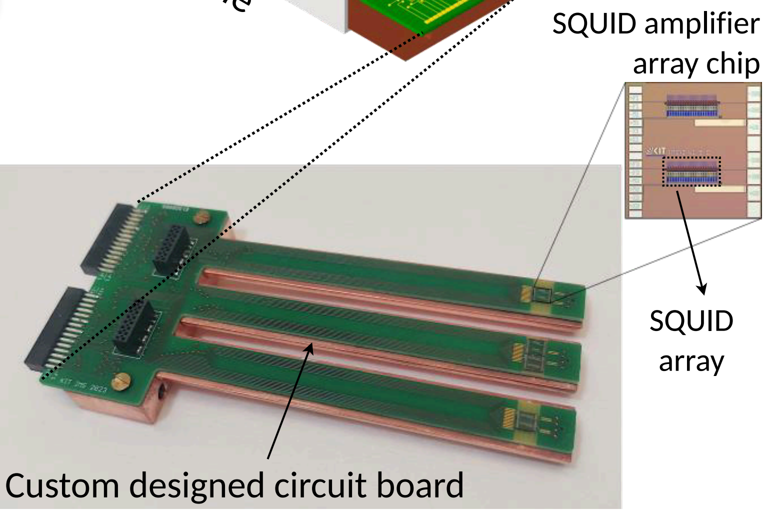
- Absorber area: 170 μm × 170 μm
- Absorber thickness: 12 μm
- Absorber material: gold

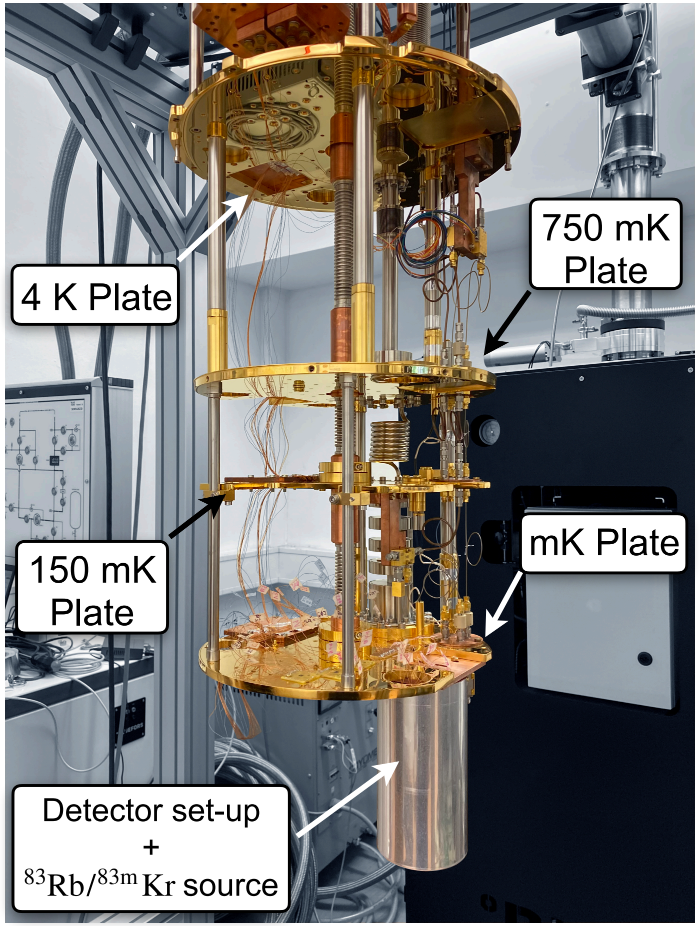




Detector set-up

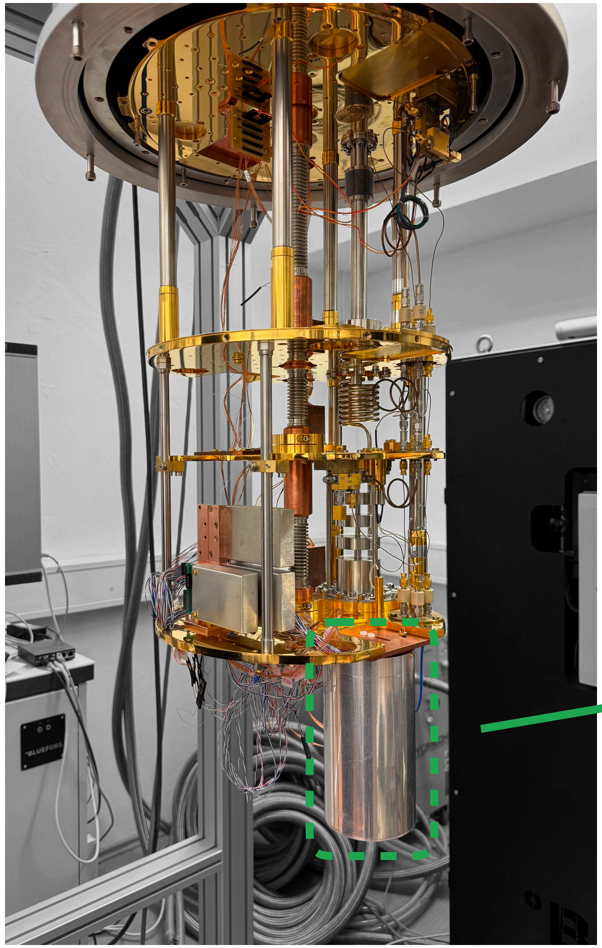




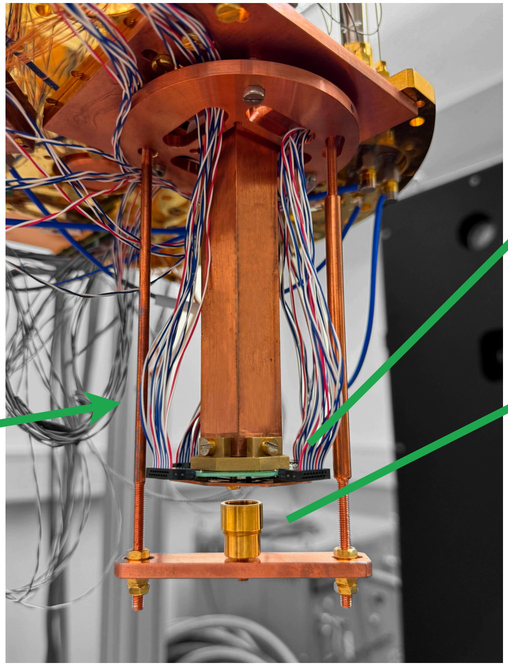


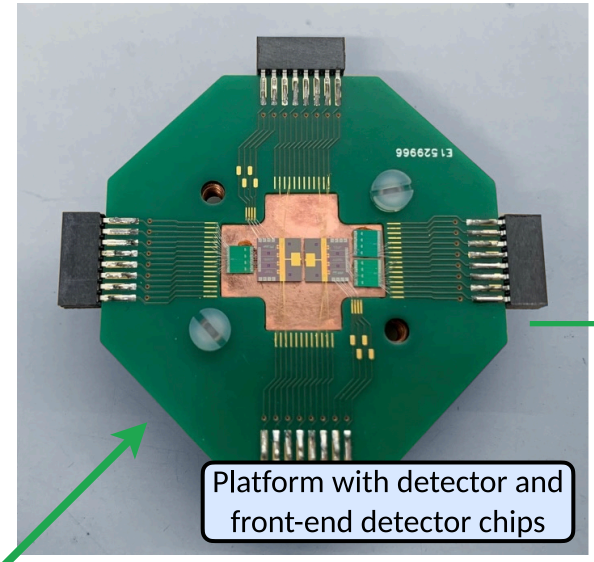
ELECTRON - First measurements with ^{83}Rb/^{83m}Kr source

- Measurement set-up at IMS



Aluminium shield prevents contamination of the cryostat
+
acts as a superconducting shield for the SQUIDs

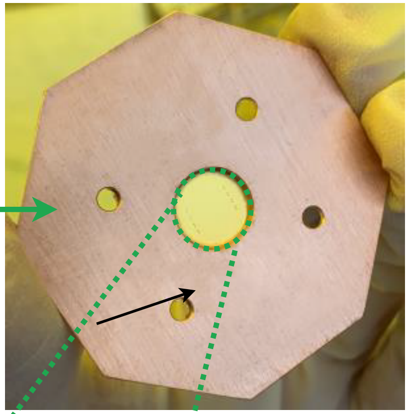


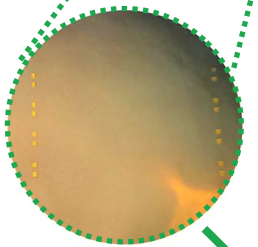


Platform with detector and front-end detector chips

Implanted ^{83}Rb/^{83m}Kr source used as a source of external electrons and X-rays

Activity adjusted by changing the distance between the source and detector





Gold foil collimator prevents charging up of the detector substrate

ELECTRON - Measurements with ^{83}Rb/^{83m}Kr source

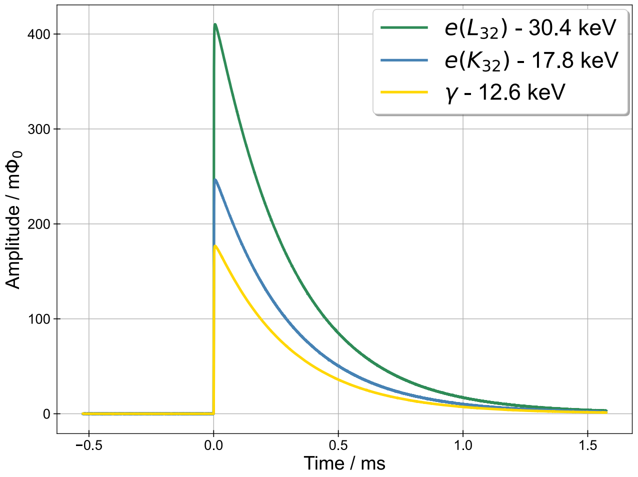
Karlsruhe Institute of Technology

- Analysis of the signal pulse shape
- Averaging several signals corresponding to:

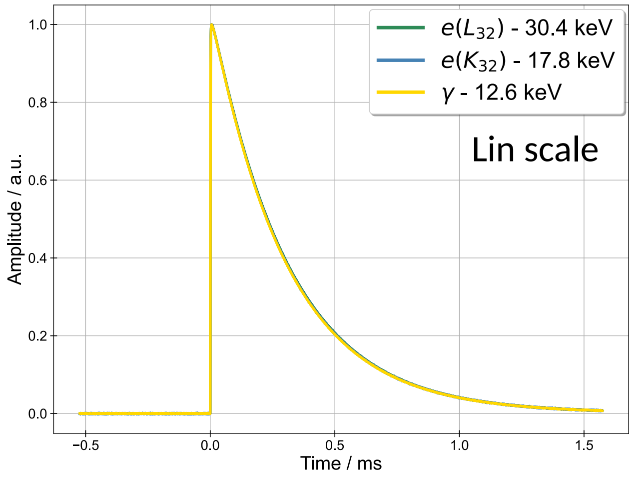
  I. 30.4 keV L-32 conversion electrons
  II. 17.8 keV K-32 conversion electrons
  III. 12.6 keV K_α X-rays

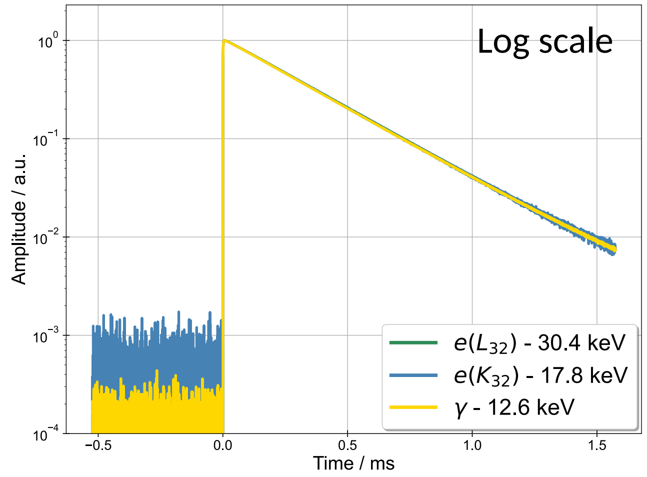
  } ⇒ From the ^{83}Rb/^{83m}Kr spectrum

Consistency between detector responses to electrons and photons is important for the first stage analysis of the measured spectra!



⇒ Scale pulses to unitary amplitude

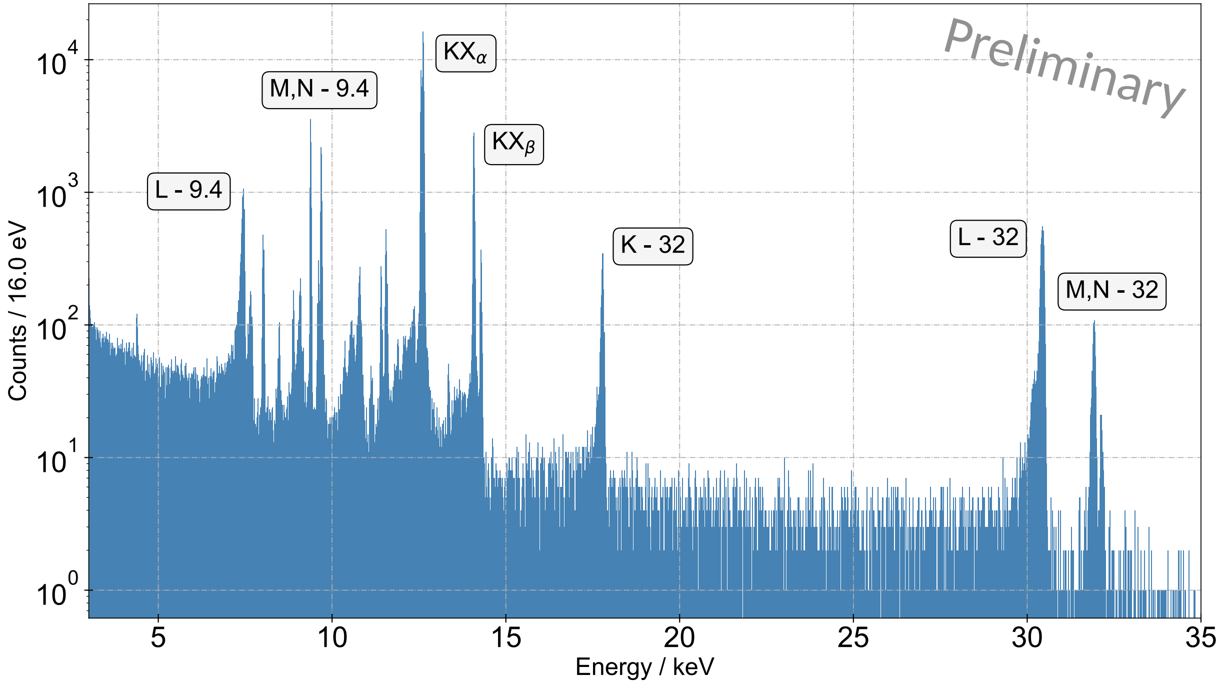


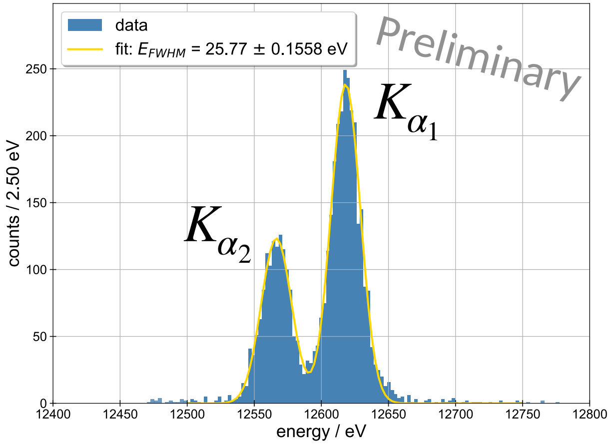


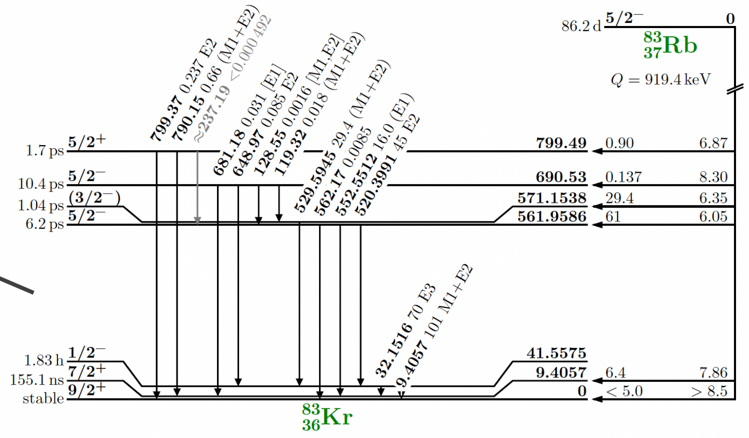
⇒ Detector response to external electrons and X-ray photons shown to be consistent!

ELECTRON - ^{83}Rb/^{83m}Kr Spectrum

- Differential ^{83}Rb/^{83m}Kr spectrum with the highest resolution ever recorded
  - ➡ Successful identification of individual spectral lines
  - ➡ Achieved resolution (X-ray lines): $\Delta E_{FWHM} = 25\,\mathrm{eV}$ @ $12.6\,\mathrm{keV}$
  - ➡ Resolution expected to be below 10 eV in the next runs!





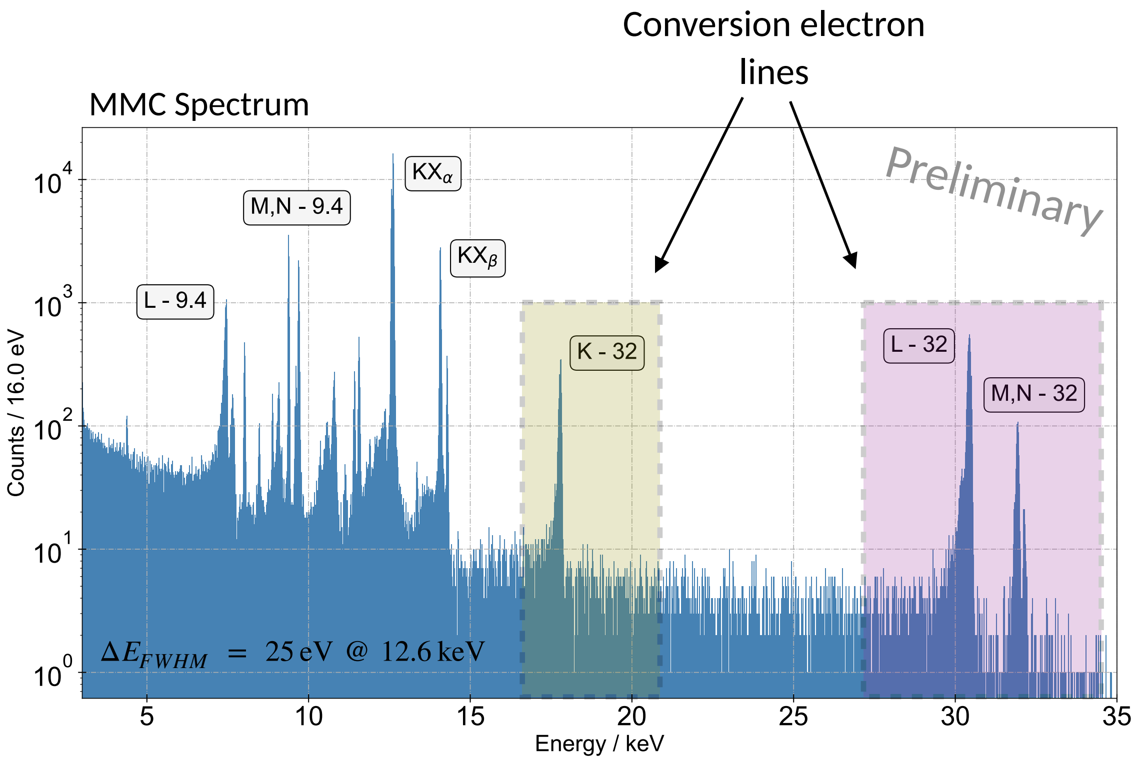


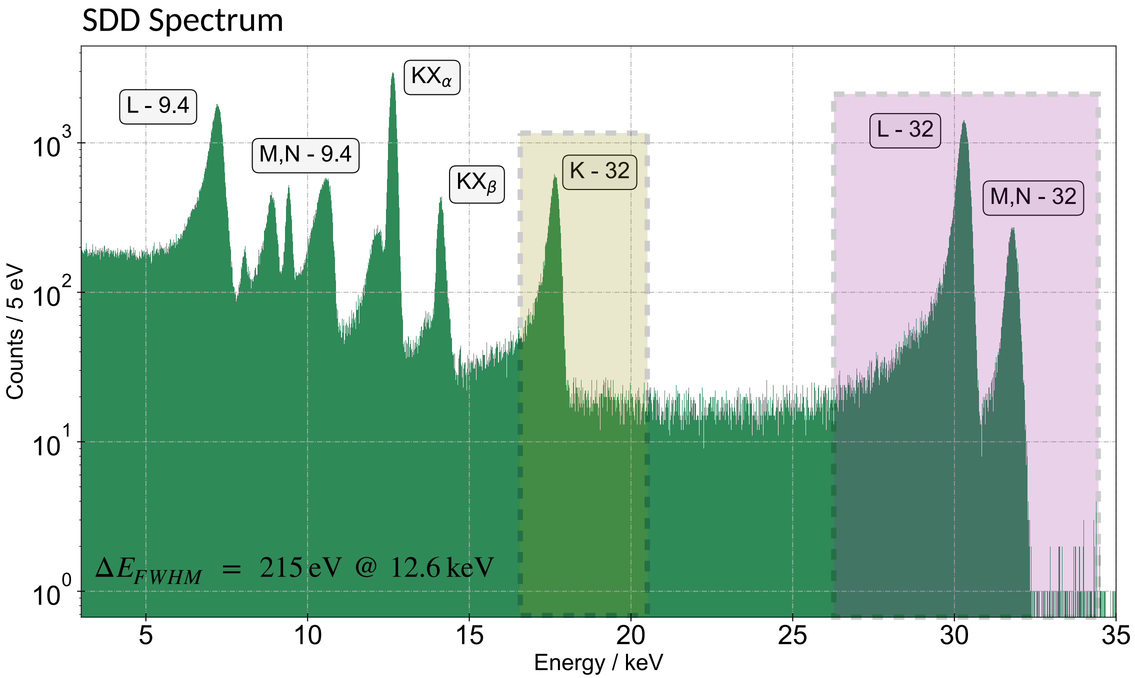
D. Vénos et al 2018 JINST 13 T02012

ELECTRON - $^{83}\mathrm{Rb}/^{83m}\mathrm{Kr}$ Spectrum

- Analysis of the acquired spectra

➡ Comparison with the spectrum measured with the Silicon Drift Detector (SDD) detector using the same $^{83}\mathrm{Rb}/^{83m}\mathrm{Kr}$ source

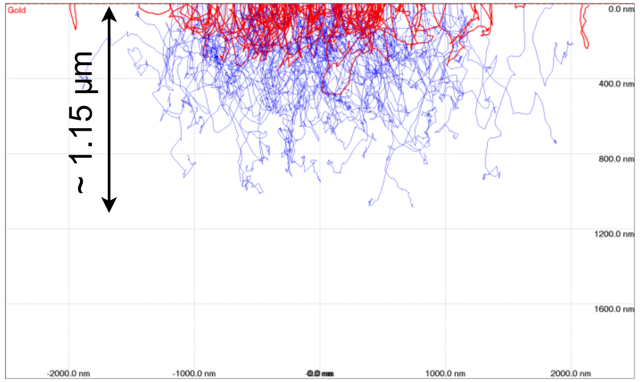




ELECTRON - Further Steps

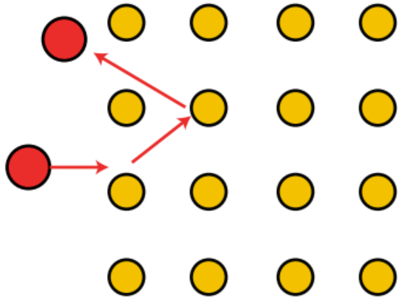
- Next steps:
  1. Measurement with sub-10 eV resolution (improved thermalization of the detector platform)
  2. Investigation of the systematic effects, such as backscattering and sputtering

12 µm Au layer

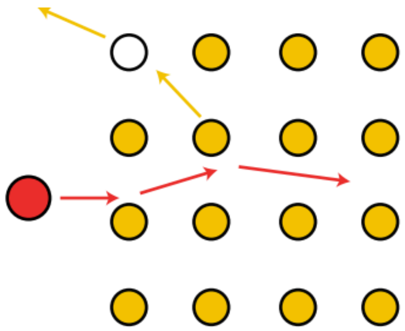


Simulations by F. Bauer

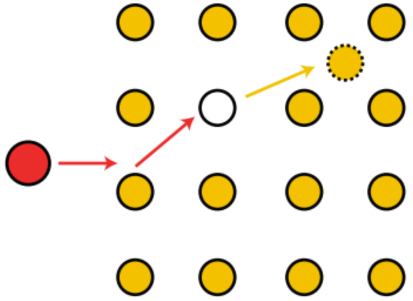
Backscattering

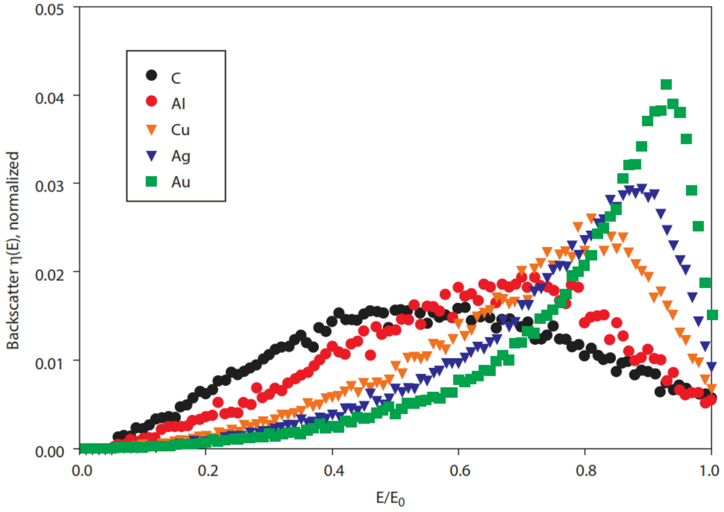


Sputtering



Frenkel Pairs





Scanning Electron Microscopy and X-Ray Microanalysis, Springer New York, NY, 2018

ELECTRON - Further Steps

- Next steps:
  1. Measurement with sub-10 eV resolution (improved thermalization of the detector platform)
  2. Investigation of the systematic effects, such as backscattering and sputtering

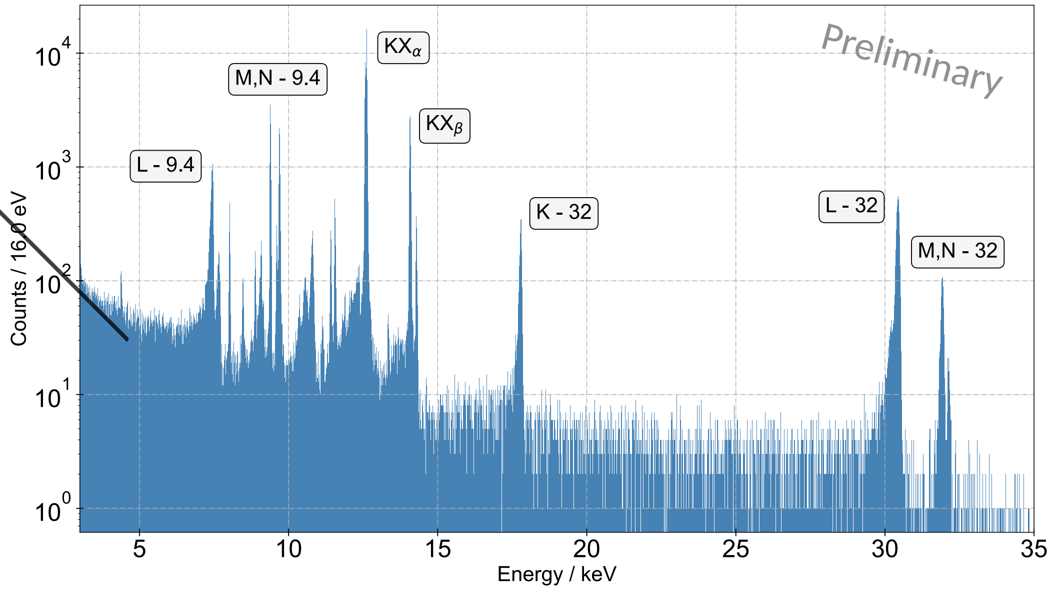
Energy deposited by backscattered electrons?

↓

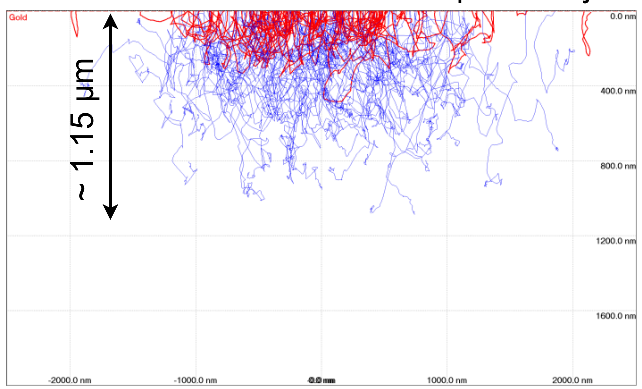
Under investigation!

↓

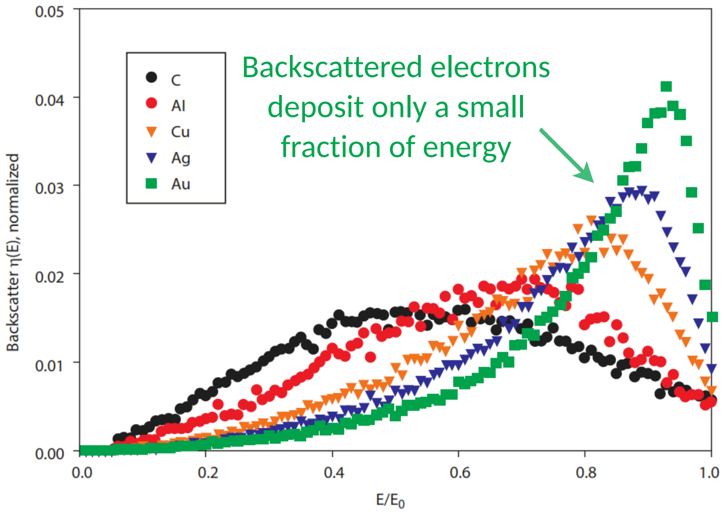
Measurements with the electron gun!



12 µm Au layer



Simulations by F. Bauer



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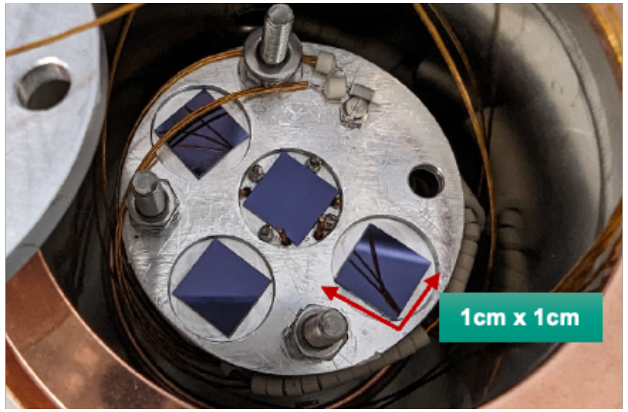
ELECTRON - Further Steps

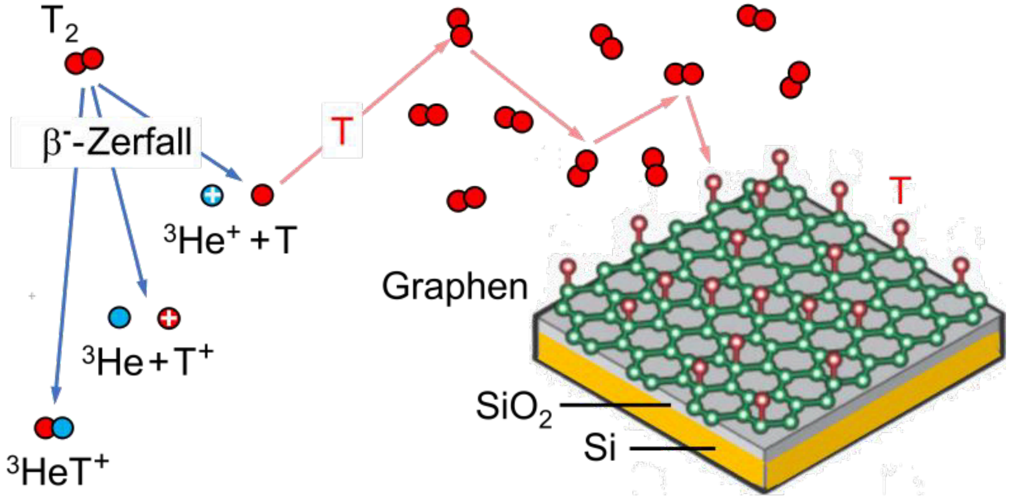
Karlsruhe Institute of Technology

- Next steps:

  1. Measurement with sub-10 eV resolution (improved thermalization of the detector platform)
  2. Investigation of the systematic effects, such as backscattering and sputtering
  3. Measurement of the novel compact tritium source → Tritium bound on graphene

G. Zeller, arXiv:2310.16645





- Tritium graphene source - quasi atomic tritium source
  - Tritium atoms are covalently bound on graphene substrate
  - Samples developed and fabricated at Tritium Laboratory Karlsruhe
  - Compact tritium source → can be mounted directly in the cryostat
  - Specially designed detector-source enclosure required to prevent contamination of the cryostat!

Motivation - beyond KATRIN

Karlsruhe Institute of Technology

- Using KATRIN as a model for the next generation neutrino experiments with tritium

  ➡ KATRIN approaches the target goal of 1000 days of Tritium beta scans → final sensitivity just above 200 meV

  ➡ By the end of 2025, TRISTAN keV-sterile neutrino search will start —> see talk by F. Edzards

  ➡ Next generation neutrino mass experiments will require years of research and development of new technologies

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 2026 2028 2034

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time: 2019, 2022, 2026, 2028, 2034

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

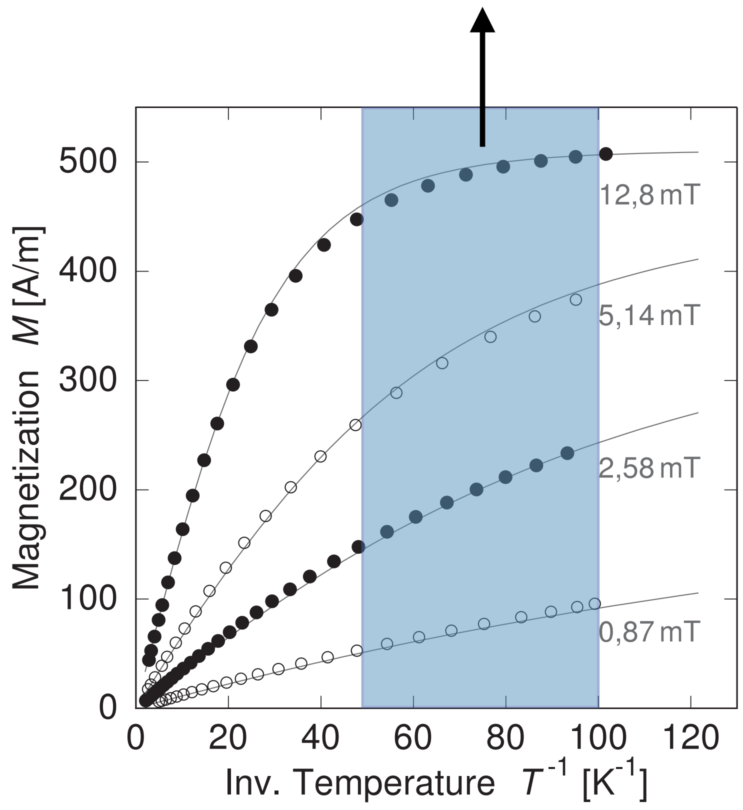
Quantum Sensor Array at KATRIN beamline

- KATRIN beamline as a test facility for next generation neutrino mass experiments with tritium
- MMCs (and TESs) highly sensitive to external magnetic fields:
  - ➡ Sensitivity of detectors decreases with the higher magnetic fields
  - ➡ MMCs can be optimised to operate at ~ 20 mT fields
- Quantum Sensor Arrays have to be operated at cryogenic (mK) temperatures
  - ➡ Interface between source at room temperature and detector array at mK temperatures needed
  - ➡ Graduate cooling of the beamline after the spectrometer needed
  - ➡ Cryostat powerful enough to cool down large detector array and keep it stable for several months of operation

Idea from the Qantum Sensor workshop last October:

- ➡ Cold chicane to move the detector array from direct line of sight from the spectrometer + to gradually cool the beamline
  A. Nava and M. Biassoni

Operational range of the MMC-based detectors



C. Enss et al., Cryogenic Particle Detection, pp. 151-216. Springer Berlin Heidelberg, 2005

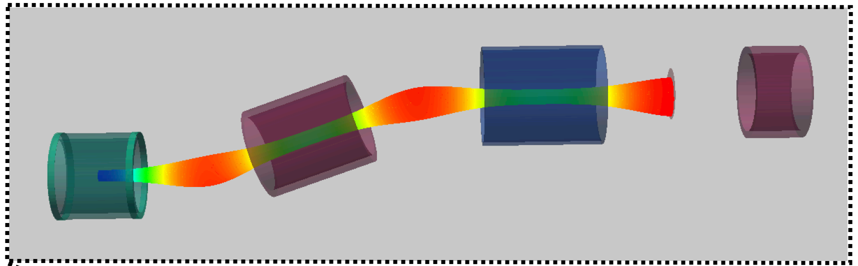
Quantum Sensor Array at KATRIN beamline

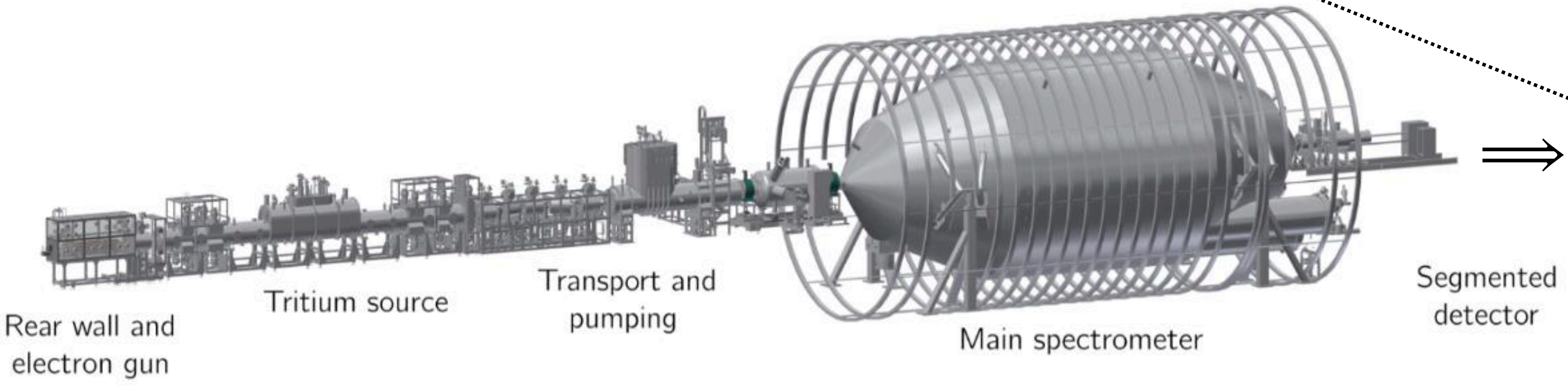
- Modifications of the KATRIN beamline for quantum sensor integration currently under investigation

  ➡ Global magnetic field needs to be decreased by a factor of 10

  ➡ Cryostat hosting the detector array needs to be integrated in the beamline, but off-axis from the (room-temperature) main spectrometer

  ➡ Beamline needs to be pre-cooled before the cryostat





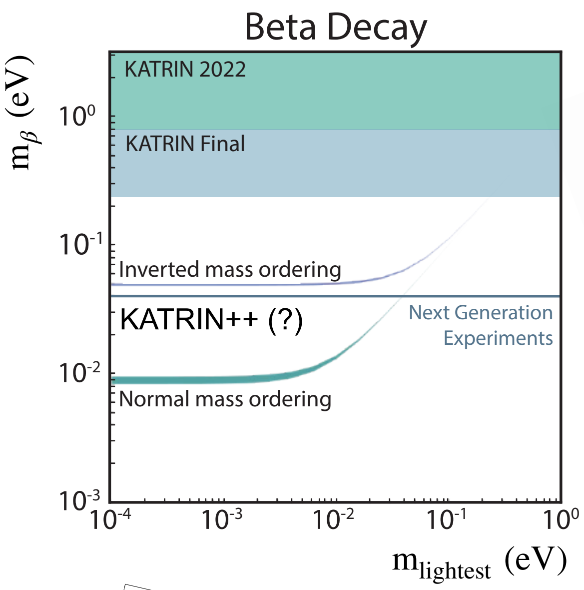
⟹ Cold chicane with detector cryostat

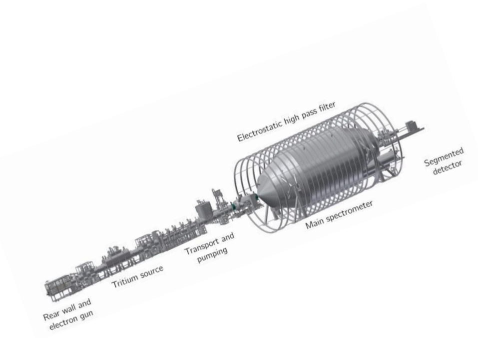
Global magnetic field decreased by factor of 10 ⇒ ~ 20 mT magnetic field at detector position

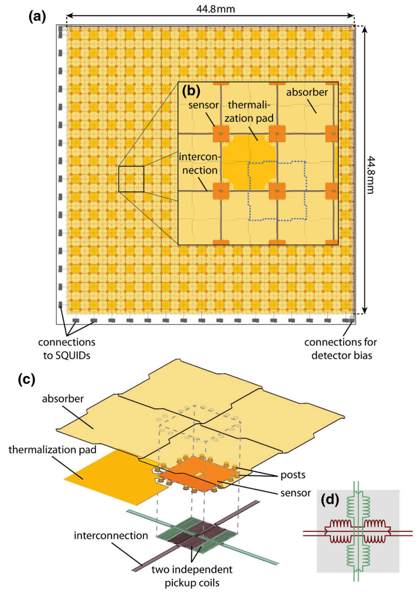
Conclusion and Outlook

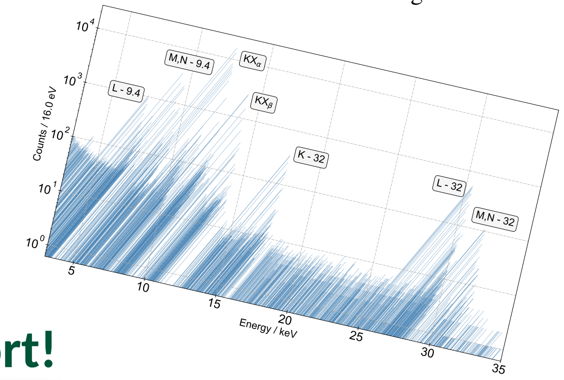
- ELECTRON
  - ➡ Showed that Metallic Magnetic Calorimeters can be employed for measurements of the external light charged particles
  - ➡ Upcoming measurement aim at sub-10 eV resolution
  - ➡ In the near future first measurements of the tritium spectrum with the cryogenic microcalorimeters

- Many challenges still ahead of us
  - ➡ Development of large quantum sensor arrays (order of 10^6 pixels) and accompanying read-out, compatible with low magnetic fields (10s of mT)
  - ➡ Design and construction of a large dilution refrigerator to house the detector array
  - ➡ Integration of the quantum sensor array at the KATRIN beamline
  - ➡ Development of the atomic tritium source









L. Gamer et al., J Low Temp Phys (2016) 184:839–844

⇒ KATRIN invites interested groups and individuals to join the effort!