Karlsruhe Institute of Technology

Tritium Laboratory Karlsruhe

Magnus Schlösser

NuMass2024, Genova, 26.02.-01.03.2024

Cristofero Colombo

KATRIN++:
Prospects for the Future

Continuing the conquest of the neutrino mass

Magnus Schlösser
for the KATRIN collaboration

NuMass2024,
Genova, 26.02.-01.03.2024

KATRIN presentations during NuMass2024

Karlsruhe Institute of Technology

2019-2025 (PoF-IV)	2026-2027 (PoF-IV)		Scientific goal
Phase 1 (Integral) Neutrino mass	Phase 2 (Differential) keV sterile ν	This talk!	Neutrino mass

- **Volker Hannen**
  (KATRIN overview)
- **Joscha Lauer**
  (Background)
- **Weiran Xu**
  (Analysis)
- **Benedikt Bieringer**
  (Calibration)

- **Anthony Onillon**
  (TRISTAN overview)
- **Daniela Spreng**
  (TRISTAN technology)
  - **Shailaja Mohanty**
    (eV-sterile neutrinos)

Outline

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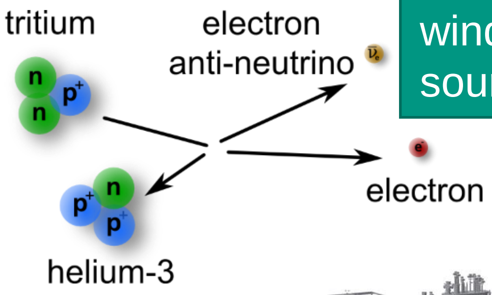
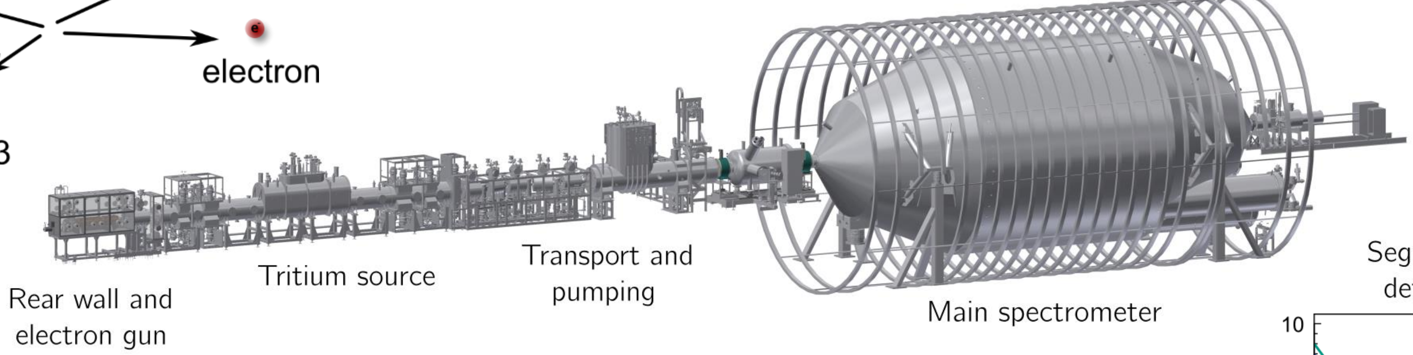
2019-2025 (PoF-IV)	2026-2027 (PoF-IV)	2028-2034 (PoF-V)	Scientific goal
Phase 1 (Integral) Neutrino mass	Phase 2 (Differential) keV sterile ν	**R&D Phase KATRIN ++** Atomic Tritium Demonstrator Quantum Sensor Demonstrator	Neutrino mass

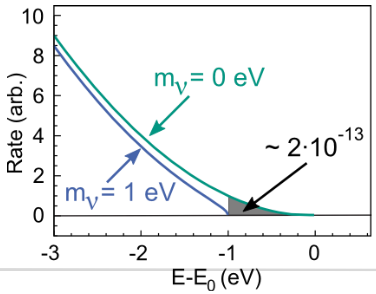
- **KATRIN** on way to achieve 1000 d measurement time **(final sensitivity m_β < 0.3 eV).**
  Next m_β result : ~ **0.5 eV sensitivity**
- We will be ready for **TRISTAN**-Operation at the end of 2025 (**Search for keV sterile neutrinos)**
- Ultimate neutrino mass experiment (Normal Ordering**; sensitivity on** m_β **< 40 meV**) requires **differential detector principle** und **an atomic tritium source → R&D Plan for PoF-V**
- KATRIN++ invites research groups for **tackling challenges together**

Karlsruhe Tritium Neutrino Experiment (KATRIN)



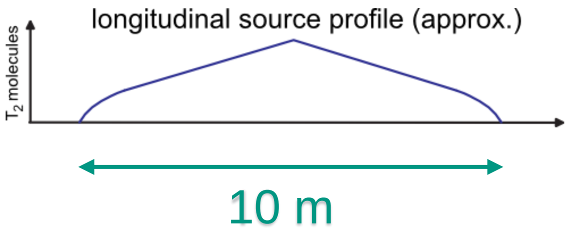
ultra-stable high-luminosity windowless gaseous tritium source (10^{11} Bq)





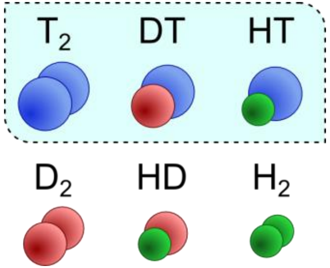
high-resolution MAC-E filter with < 1 eV energy resolution

The stable tritium source

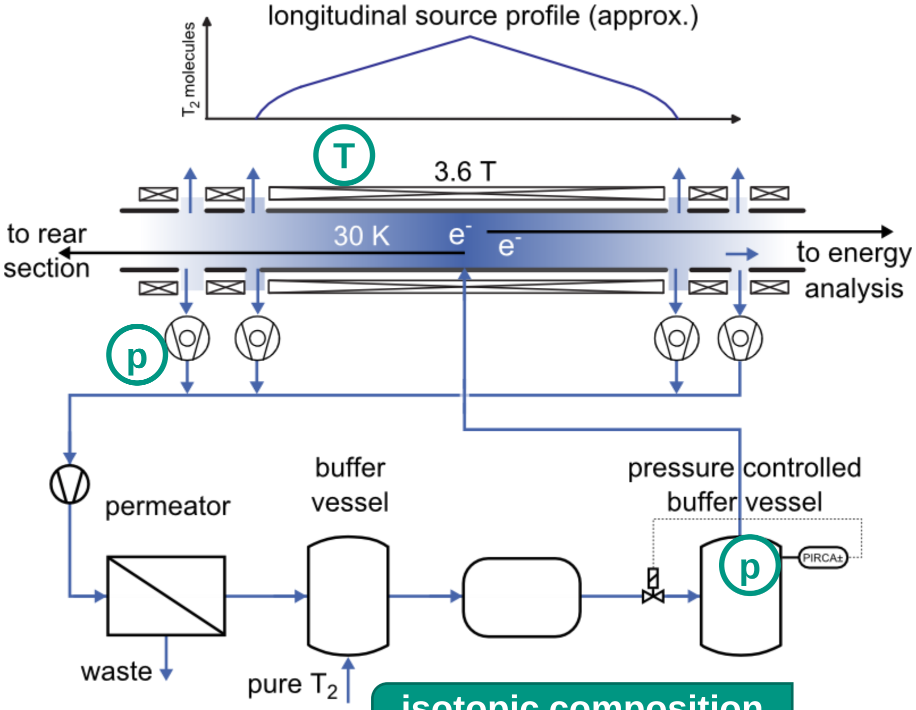


- T_2 purity > 95%
- Source activity 10^{11} Bq
- Source profile stable to 10^{-3} level

Hydrogen isotopologues



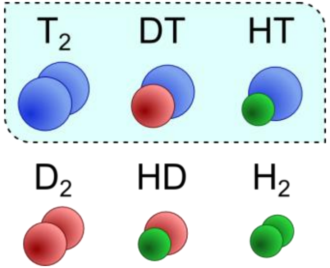
The stable tritium source



isotopic composition measurement

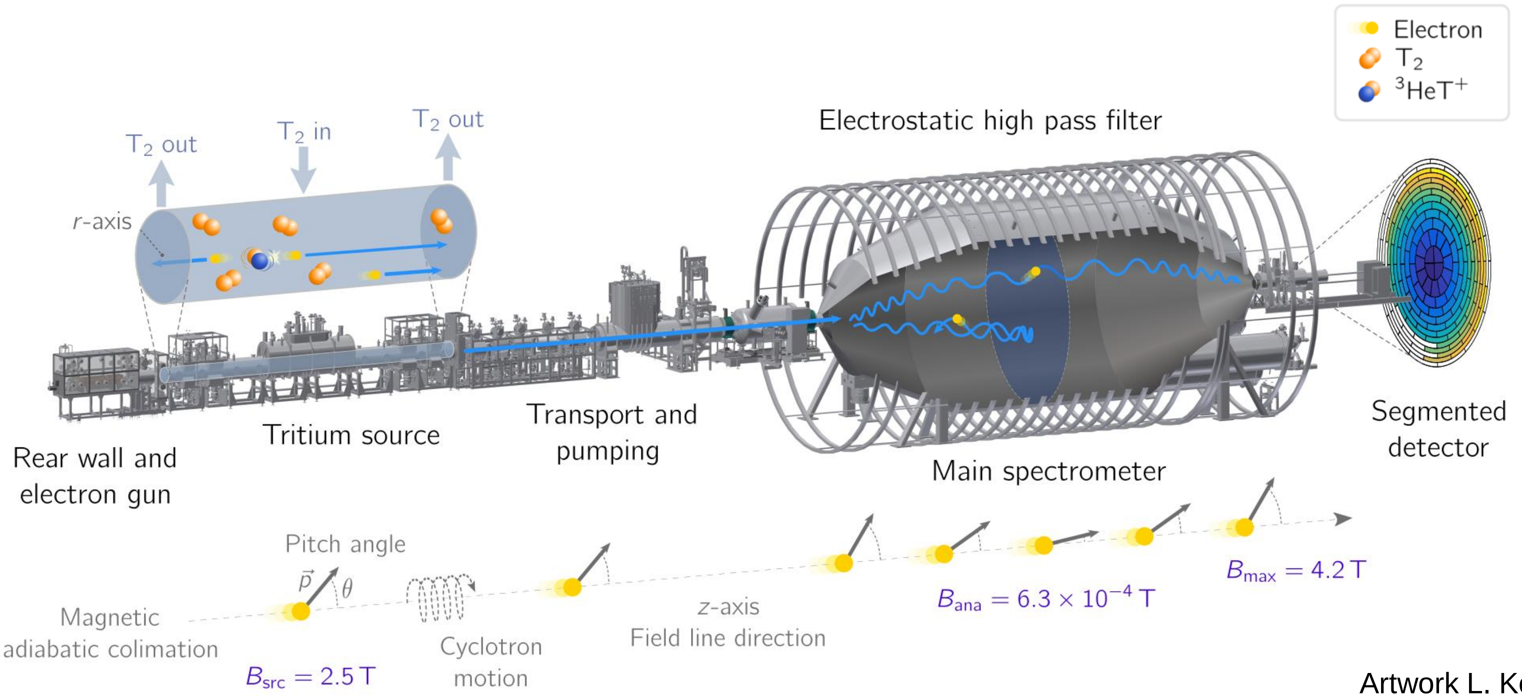
- **T_2 purity > 95%**
- **Source activity 10^{11} Bq**
- **Source profile stable to 10^{-3} level**

Hydrogen isotopologues

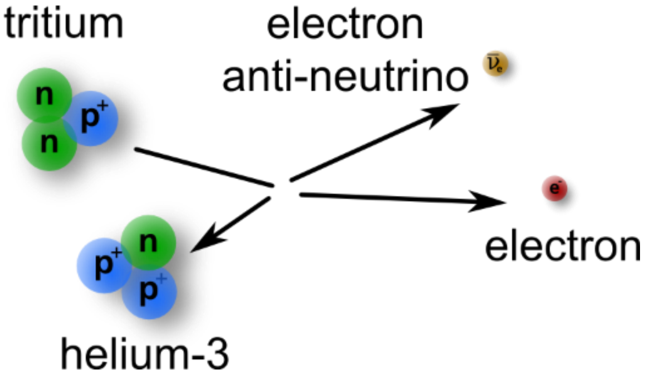


- **T_2 throughput ~ 40 g/day**
- **Operation 24/7, 60 days/run**
- **Necessary inventory >15 g**

MAC-E filter principle of KATRIN



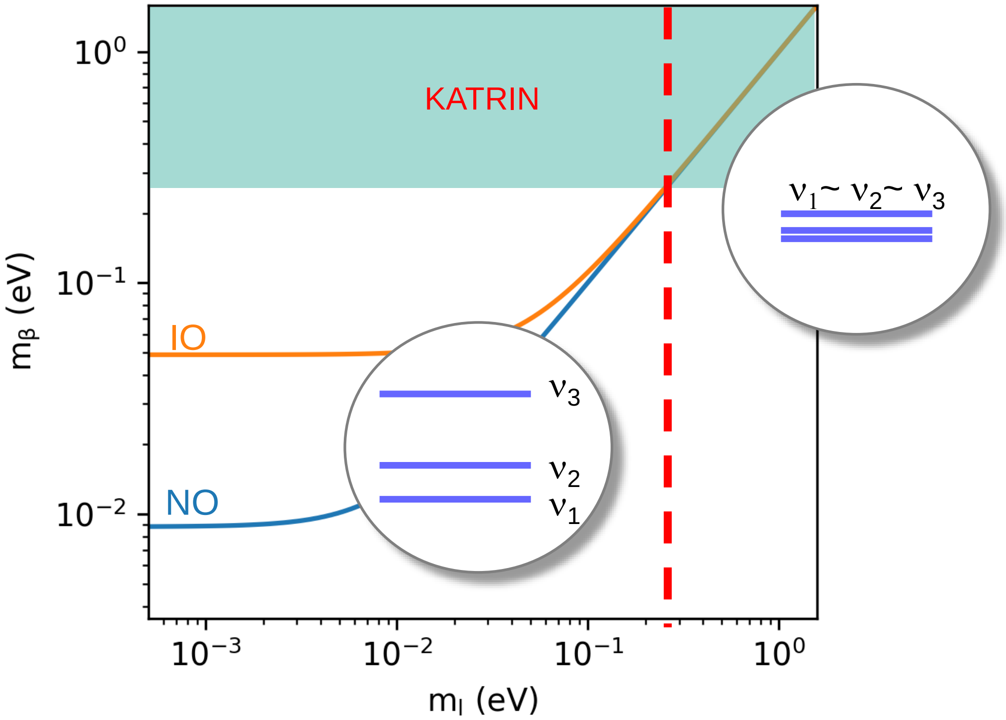
Artwork L. Köllenberger



Outlook after 2027

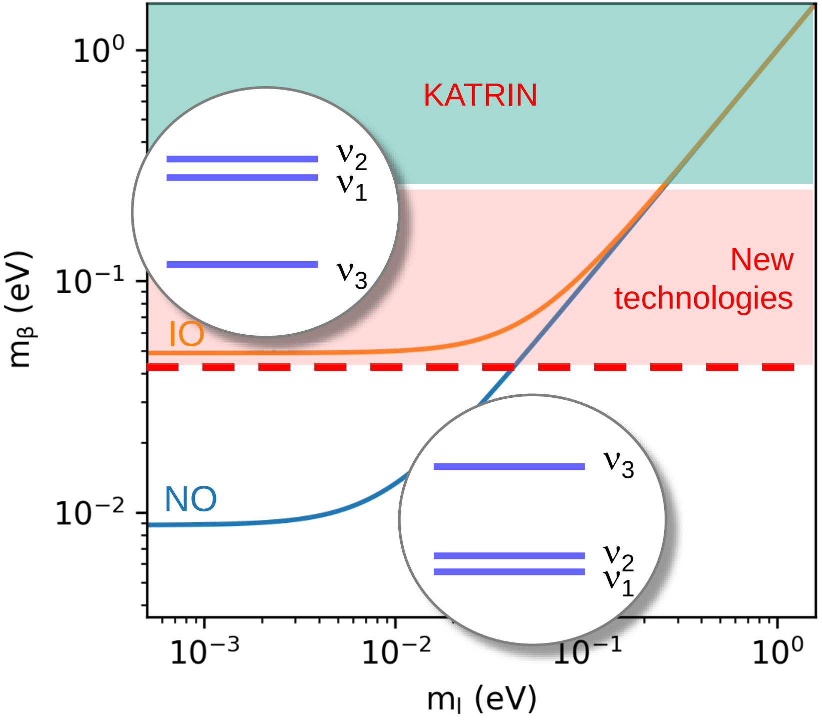
R&D for future m_ν experiments

Going beyond KATRIN



- KATRIN final: < **0.3 eV** (90% CL)
  Distinguish between **degenerate** and **hierarchical** scenario

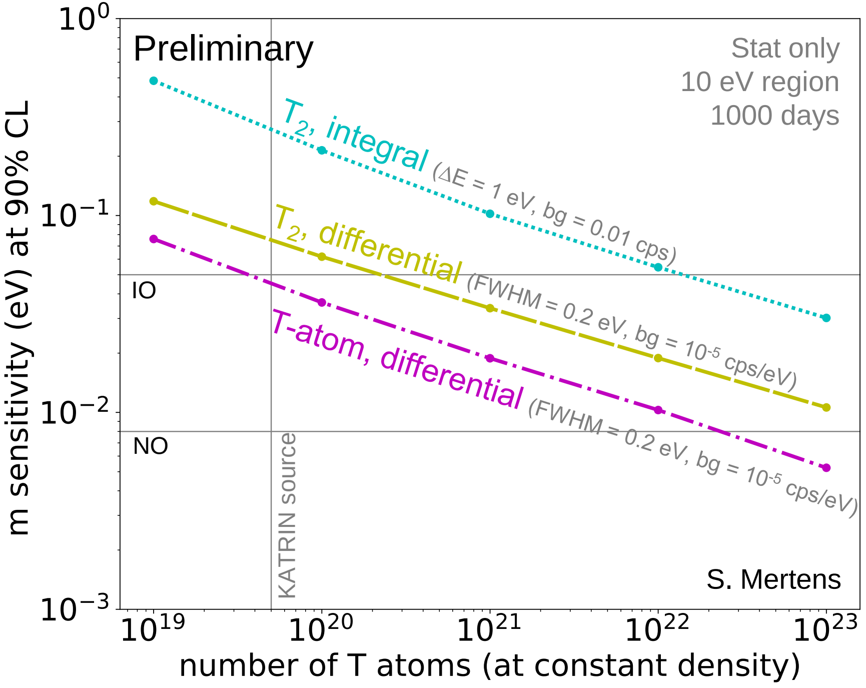
Going beyond KATRIN



- KATRIN final: < **0.3 eV** (90% CL)
  Distinguish between **degenerate** and **hierarchical** scenario

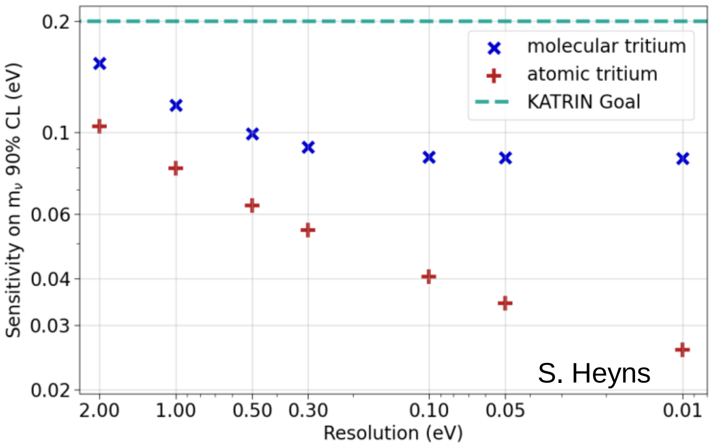
- New technologies: < **0.05 eV**
  Cover **inverted** ordering

Going beyond KATRIN



Current KATRIN performance (integral, ΔE = 2.7 eV, bg = 0.1 cps)

- **Differential measurement (FWHM < 1 eV)**
  - ✓ Better use of statistics
  - ✓ Lower background
- **Atomic tritium**
  - ✓ Avoid broadening (~ 1 eV)
  - ✓ Avoid limiting systematics of T_2



Improved measurement principle

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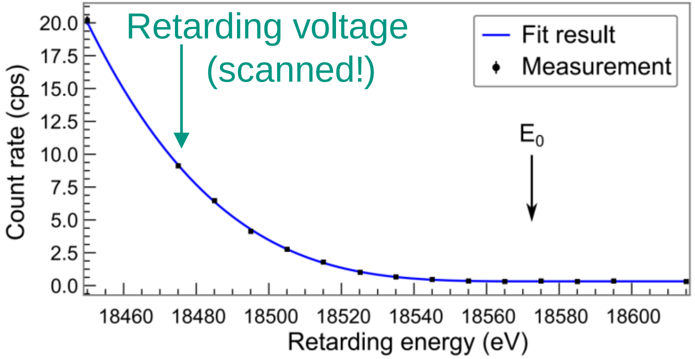
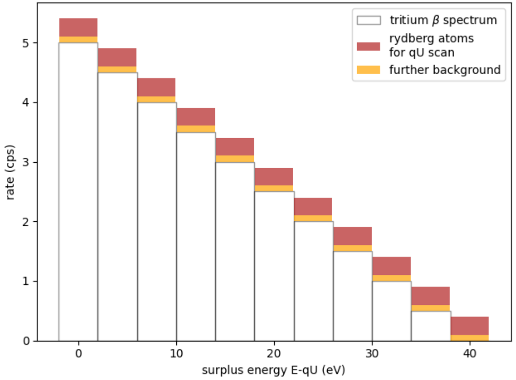
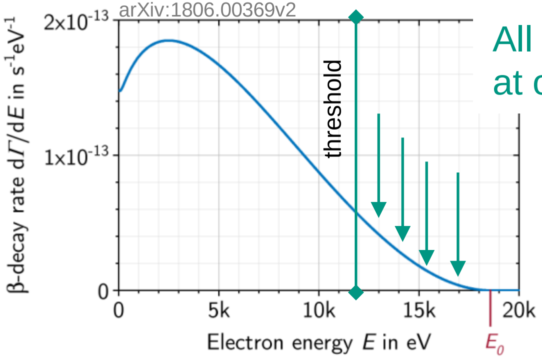
Integral measurement (high pass filter)
- Energy resolution determined by filter
- Detector „only“ counts
- Reduced statistics

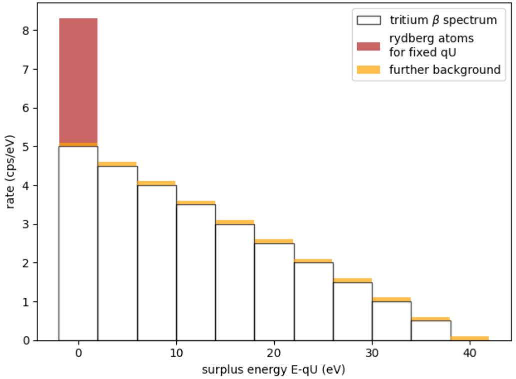




Differential measurement
- Energy resolution determined by
  - **A) detector**
  - or
  - **B) time of flight**



All energies at onces

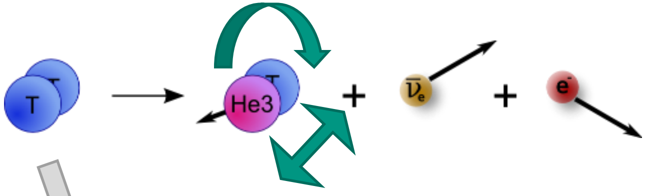


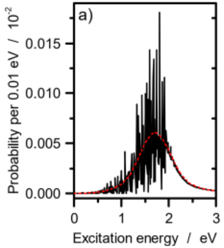
More signal

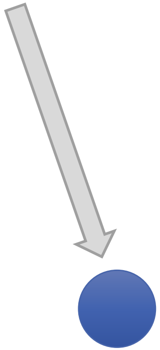
Less background

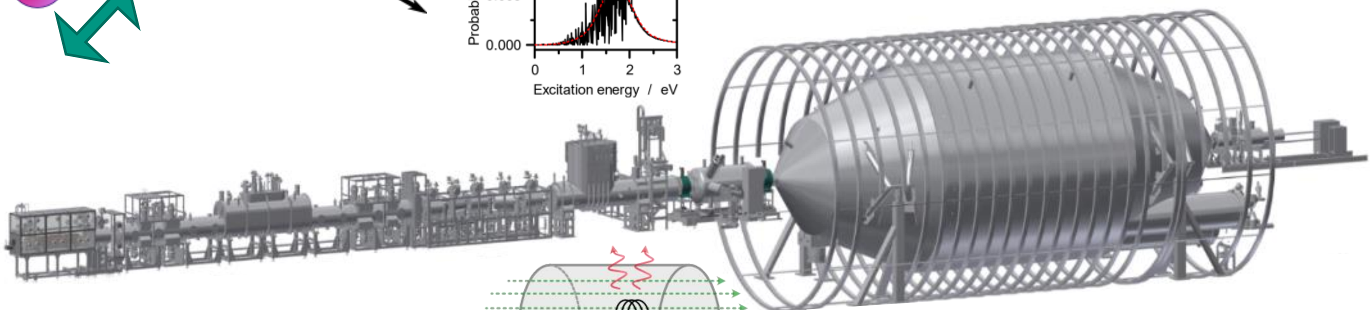
KATRIN and TLK as ideal R&D facilities

- Molecular effects → spectral broadening



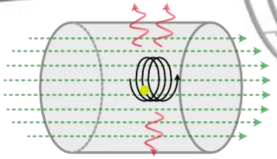






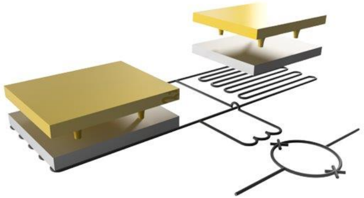
Quantum detector technology

- eV resolution for **differential** detection
- **immune to** Rydberg-like **backgrounds**



Atomic source technology

Option 2
Time-of-flight via electron tagging

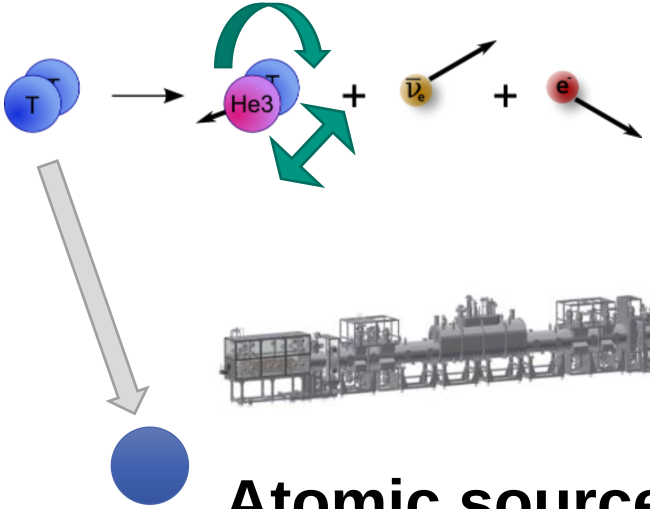


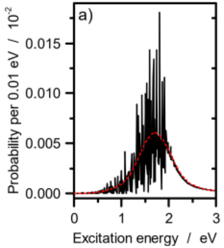
Further options?
Technologies by community?

Option 1
µm-size calorimeters

KATRIN and TLK as ideal R&D facilities

- Molecular effects → spectral broadening





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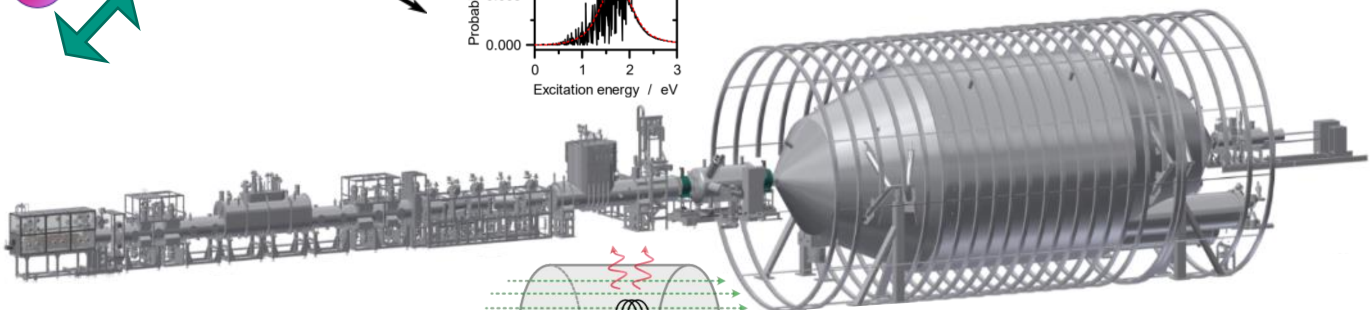
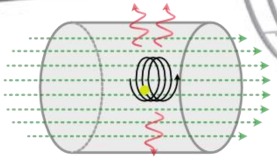
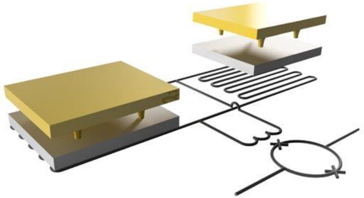




Option 2
Time-of-flight via electron tagging

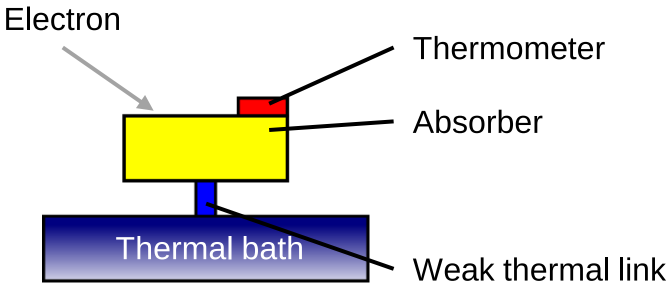


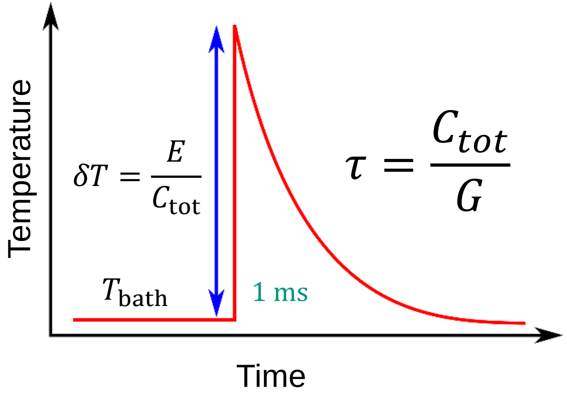
Option 1
µm-size calorimeters

Atomic source technology

Further options?
Technologies by community?

Quantum sensors as high resolution differential detectors



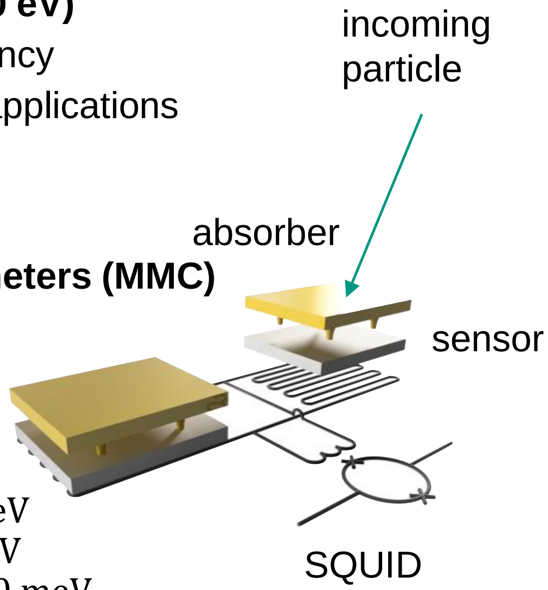


Advantages

- Energy resolution ***O*(eV)** compared to conventional detectors ***O*(100 eV)**
- Nearly 100% quantum efficiency
- Broad spectrum of possible applications

e.g. Metallic Magnetic Calorimeters (MMC)

- Temperature-dependence in sensor magnetization
- Read-out by SQUID
- Energy resolution:
  - Current: $\Delta E \lesssim 2$ eV
  - Midterm: $\Delta E \lesssim 1$ eV
  - Future: $\Delta E \sim 100$ meV

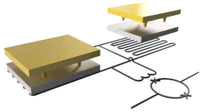


Not yet tested with external electrons

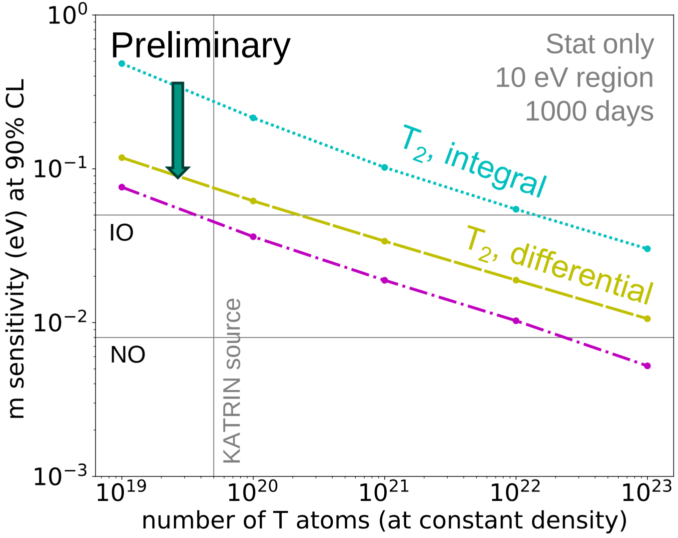
Next R&D goal:
Demonstrate KATRIN with a quantum sensor array

Use existing / well-characterised beamline

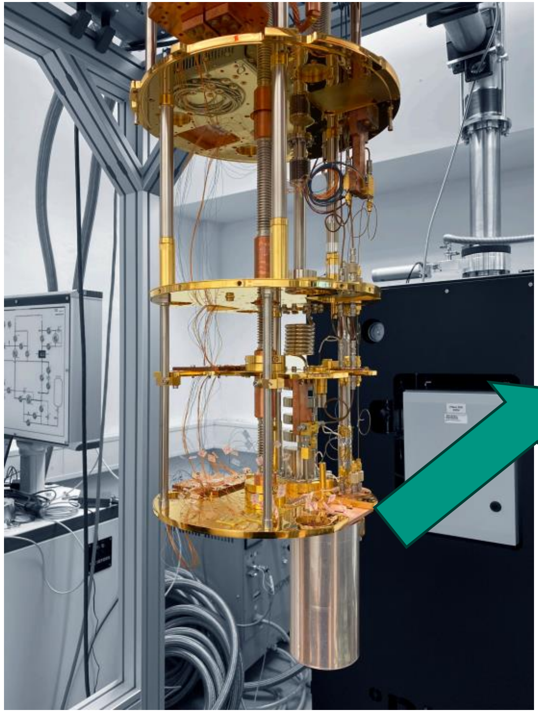
+ *10⁶ x*



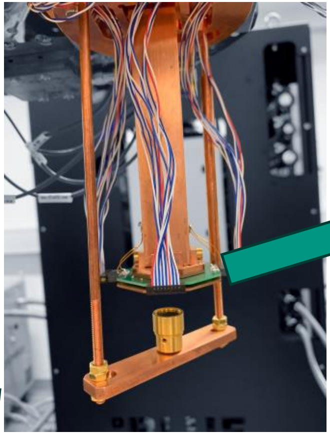
- Challenges of coupling **quantum sensor detector array** to **KATRIN infrastructure**
  - **Type** of quantum sensor
  - Operation in **magnetic field**
  - Coupling of **mK cryo-platform** with RT spectrometer
  - Large area detector and **multiplexing of ~1e6 channels**
  - **Limits to energy resolution**

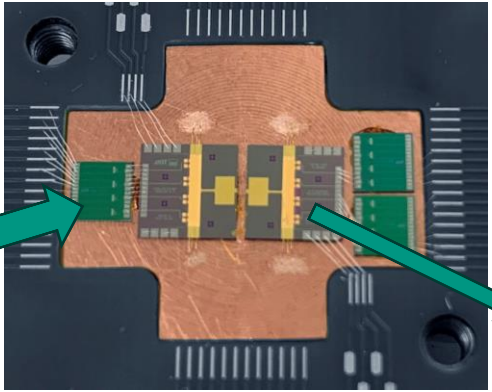


ELECTRON – proof of principle detection

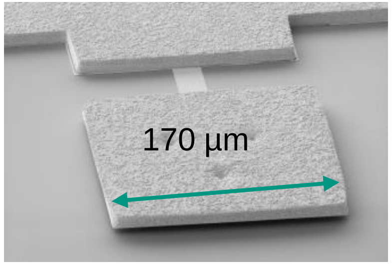


KIT-IMS cyrostat (Kempf group)



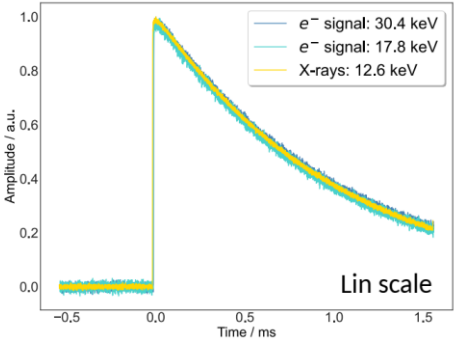


8 channel detector chips
& front-end SQUID chips



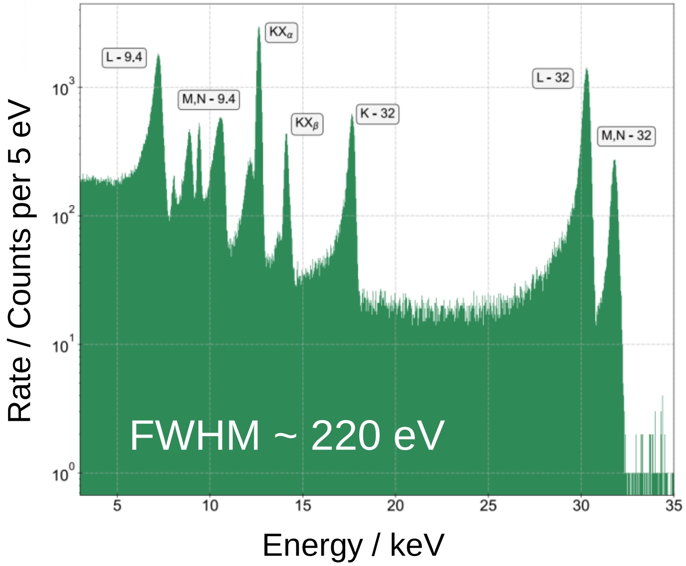
- Ongoing: ^{83m}Kr spectroscopy
- Next step: tritium spectroscopy

First results: Detector response to external electrons and X-ray photons consistent!

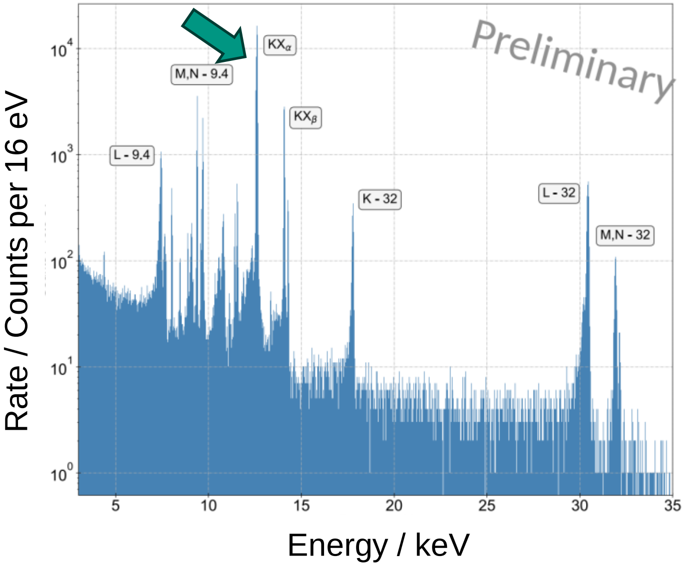


First krypton-83m spectrum with MMC

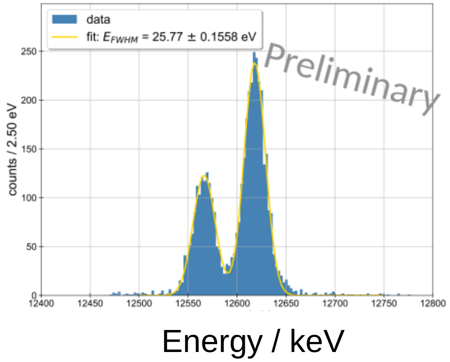
Silicon Drift Detector (SDD)



Metallic Magnetic Calorimeters (MMC)



FWHM ~ 25 eV

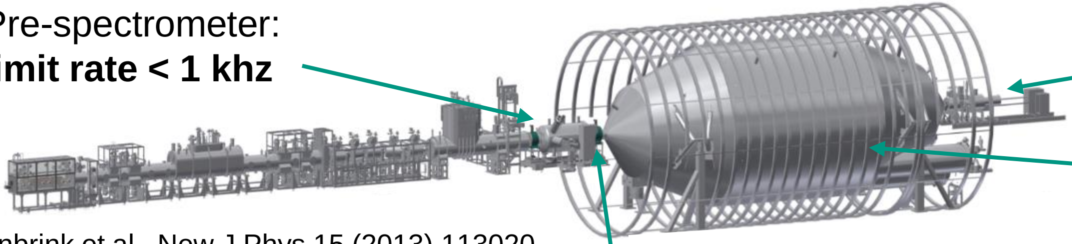


Copper support limits thermalization (~45 mK instead of 10 mK at detector)

Calorimetric Kr-83m spectrum with highest resolution
Next: Improve cooling → significant improvement anticipated

Next R&D goal:
Demonstrate single electron tagging for ToF

Pre-spectrometer:
limit rate < 1 khz

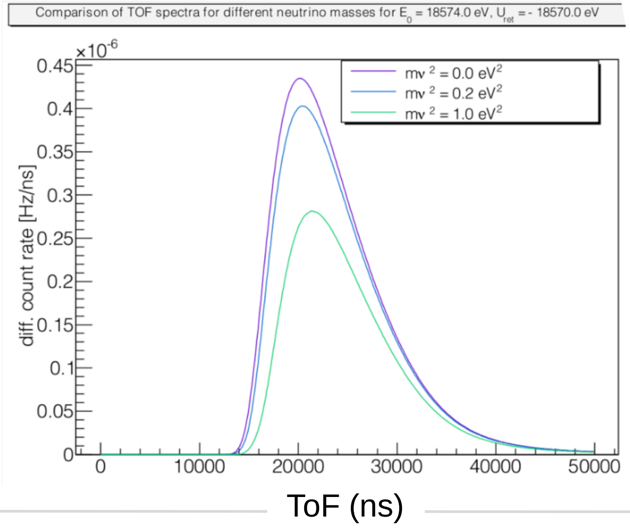


Fast detector: **stop**

Main spectrometer:
delay line due to retardation pot.

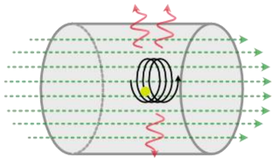
Tagger: **start** (~1000 Hz)

Steinbrink et al., New J Phys 15 (2013) 113020



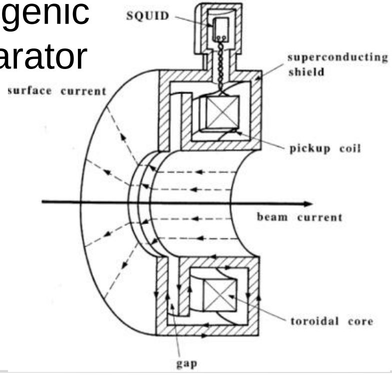
Single electron tagging is challenging

Cyclotron radiation emission detection



Coreless cryogenic current comparator

Tiny signals vs minimal noise floor

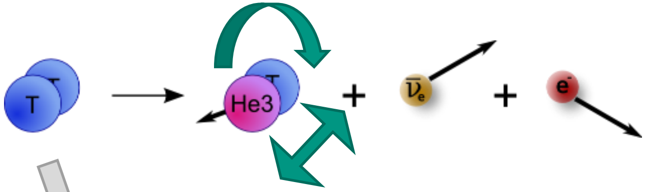


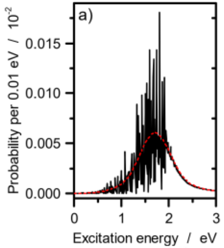
T. Tanabe et al., Nucl. Instr. Meth. A 427 (1999) 455

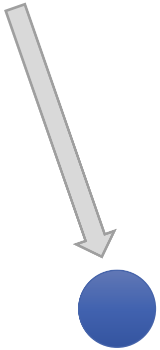
R&D ongoing at U North Carolina

KATRIN and TLK as ideal R&D facilities

- Molecular effects → spectral broadening

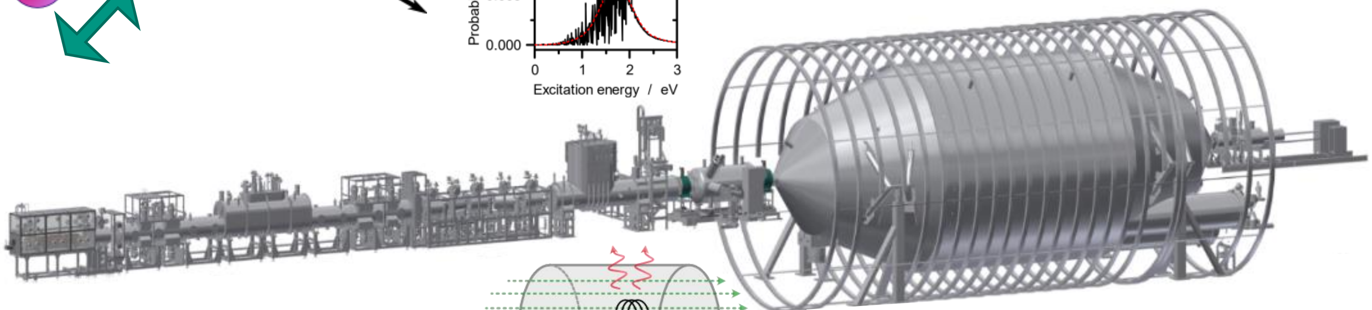


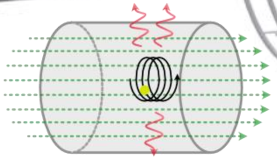




Quantum detector technology

- eV resolution for **differential** detection
- **immune to** Rydberg-like **backgrounds**

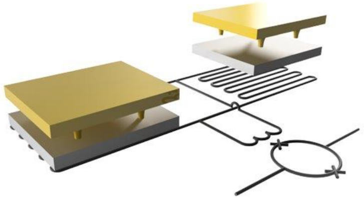




Option 2
Time-of-flight via electron tagging

Atomic source technology

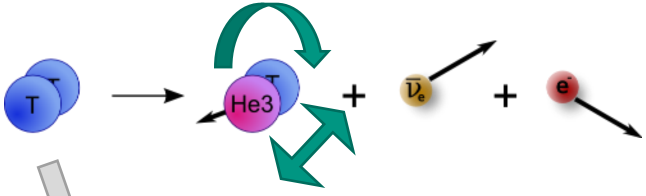
Further options?
Technologies by community?

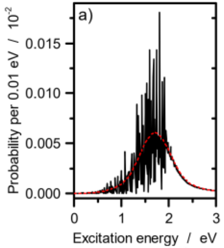


Option 1
µm-size calorimeters

KATRIN and TLK as ideal R&D facilities

- Molecular effects → spectral broadening





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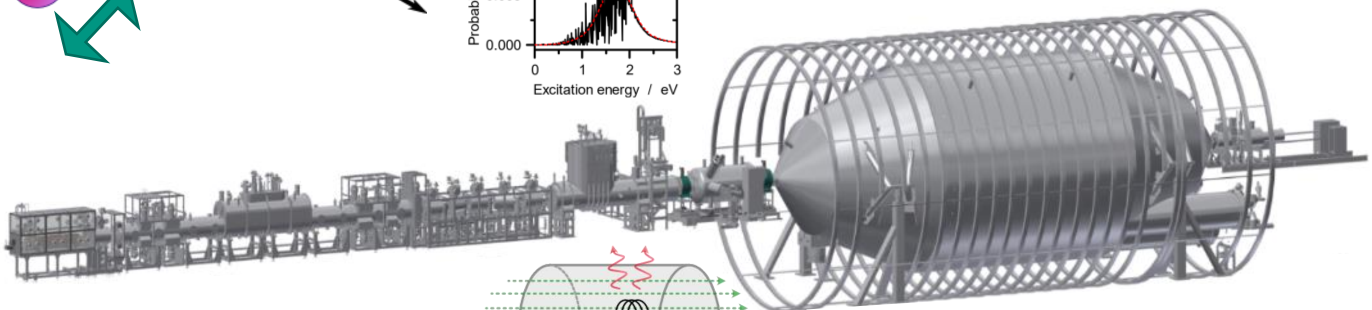
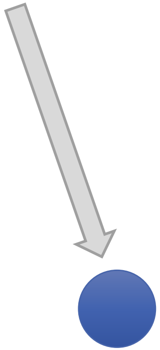
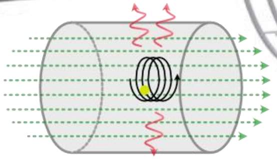




Atomic source technology



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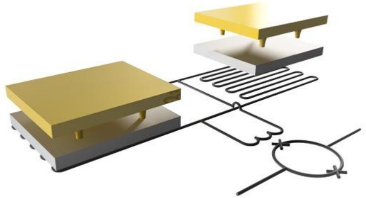
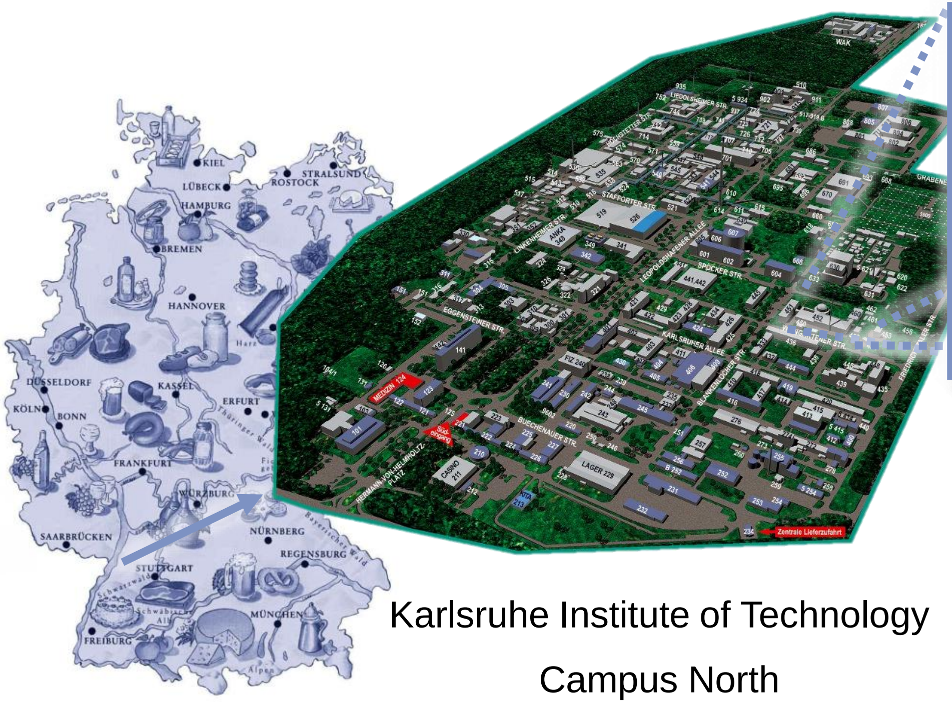


Further options?
Technologies by community?

Option 1
µm-size calorimeters

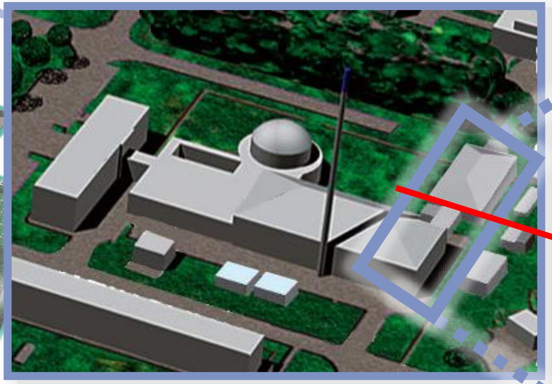
The Tritium Laboratory Karlsruhe

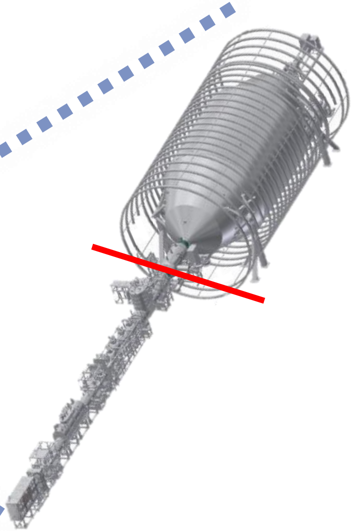


Karlsruhe Institute of Technology

Campus North

Tritium Laboratory Karlsruhe (TLK)





- Commissioned in 1993
- Licensed for 40 g Tritium
- Two missions:
  - Fuel cycle for fusion reactors
  - KATRIN Experiment

TLK – A facility for high activity tritium experiments

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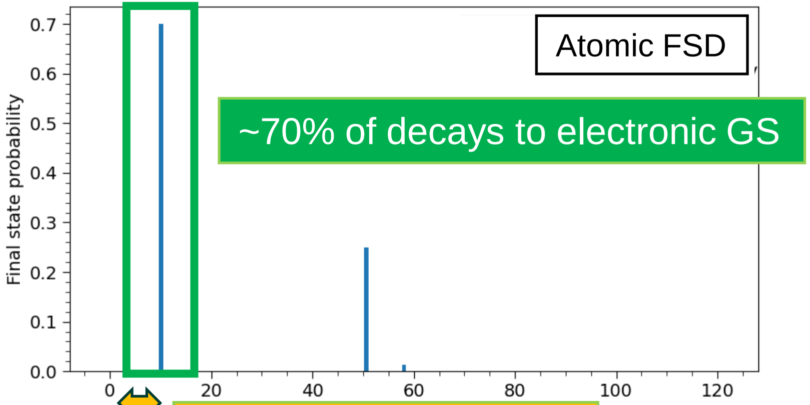
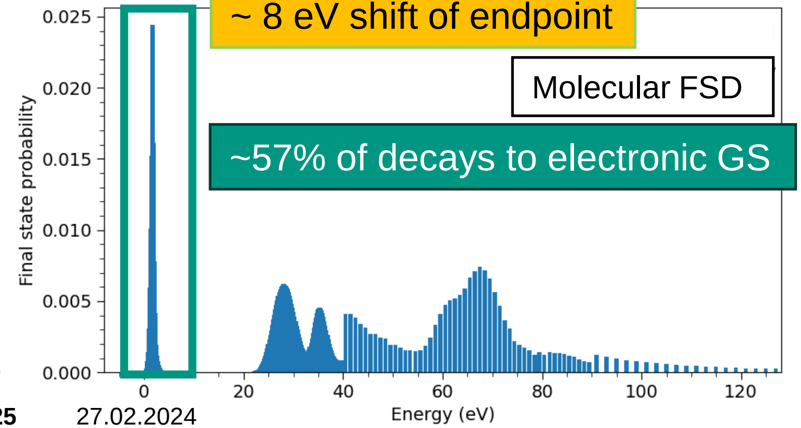
- Closed tritium cycle for recycling and purifying tritium in gram amounts
- Currently 57 people "on board" including 8 doctoral researchers and 13 students
- Baseline cost for lab (w/o any R&D or KATRIN source) O(2 M€/year) operations & O(25 FTE) manpower

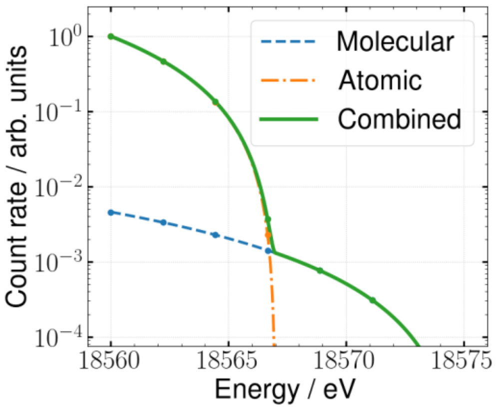
We develop safe tritium technology and versatile tritium analytics since 1993

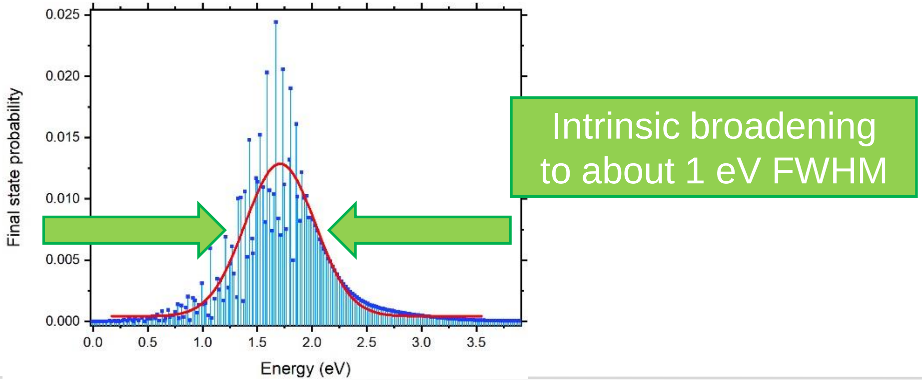
We are able to setup and operate a large variety of experiments with tritium

Atomic vs molecular tritium

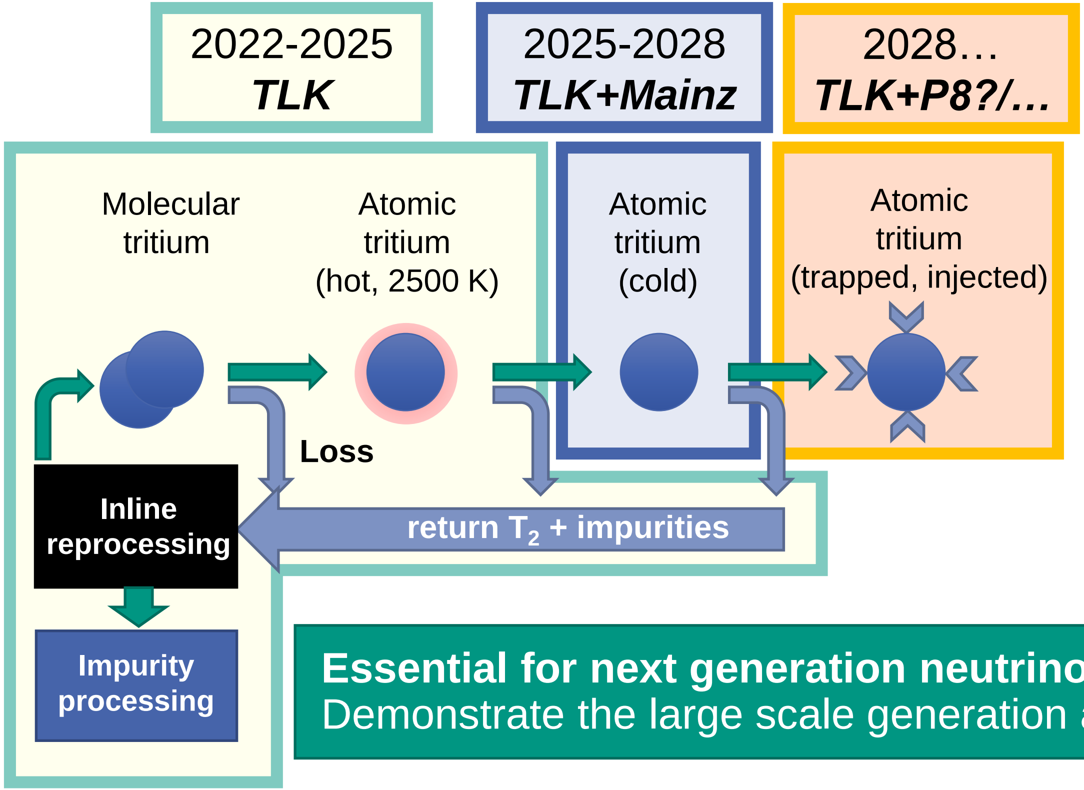








Atomic tritium demonstrator at TLK

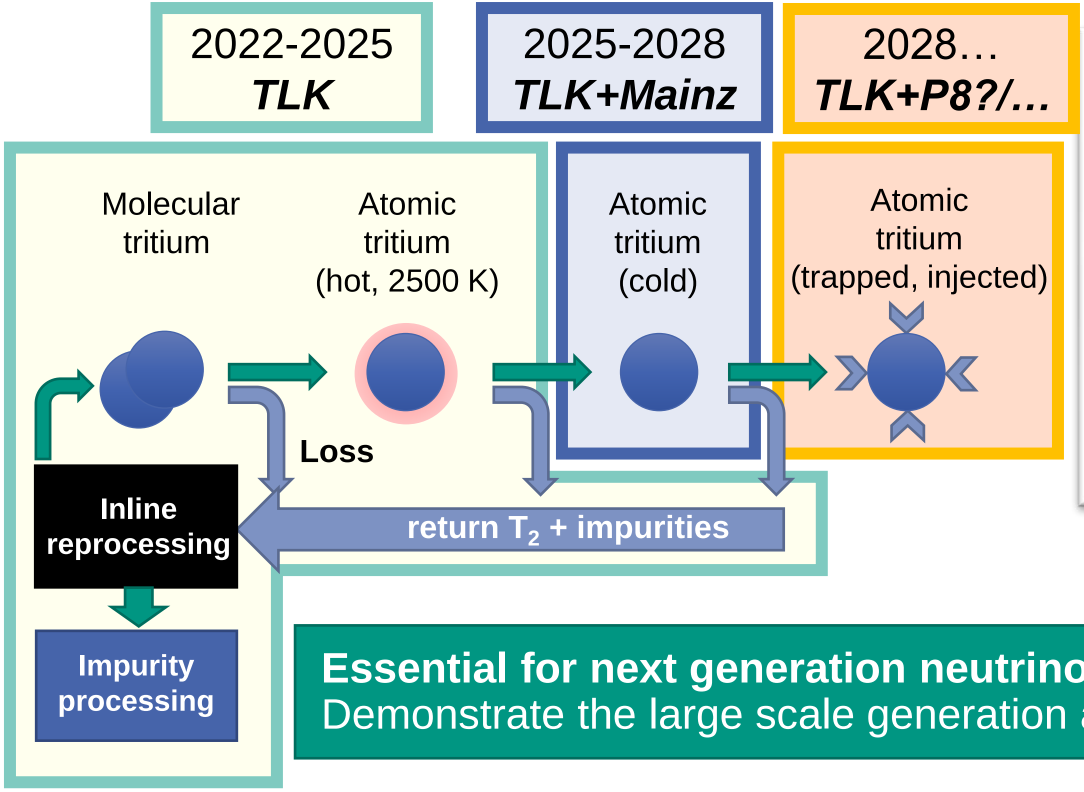


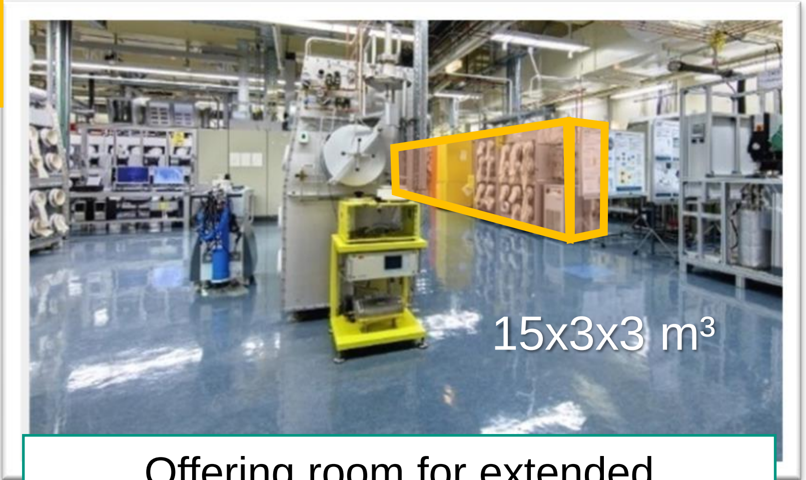
- **Aim for investigation**
  - Develop atom cooling mechanism
  - Trapping times / max. densities
  - Interplay of beta-driven plasma (meV—eV) and ultra-cold trapped atoms (neV)

Tritium atom throughput on the order of 10 g/day (c.f. KATRIN: 40 g/day)

Essential for next generation neutrino mass experiment (e.g. KATRIN++) : Demonstrate the large scale generation and cooling (~10 mK) of atomic tritium

Atomic tritium demonstrator at TLK





Offering room for extended atomic tritium experiments

Essential for next generation neutrino mass experiment (e.g. KATRIN++) :
Demonstrate the large scale generation and cooling (~10 mK) of atomic tritium

Atomic source R&D progress

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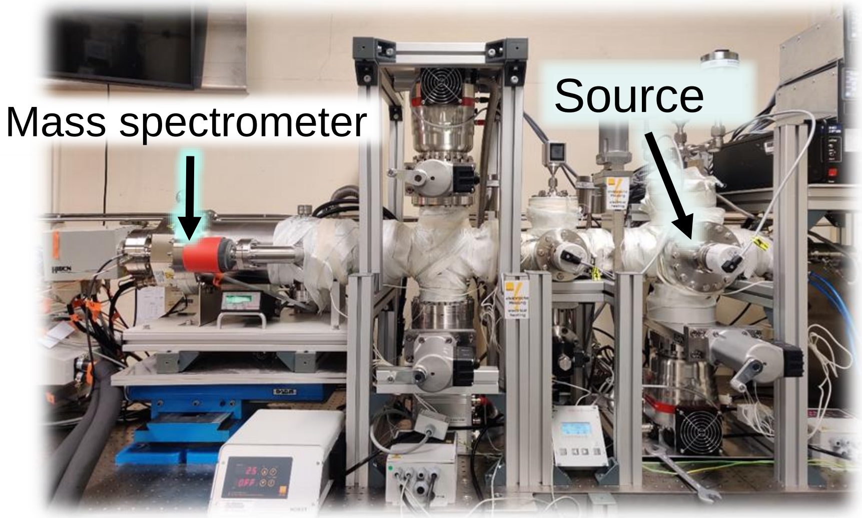
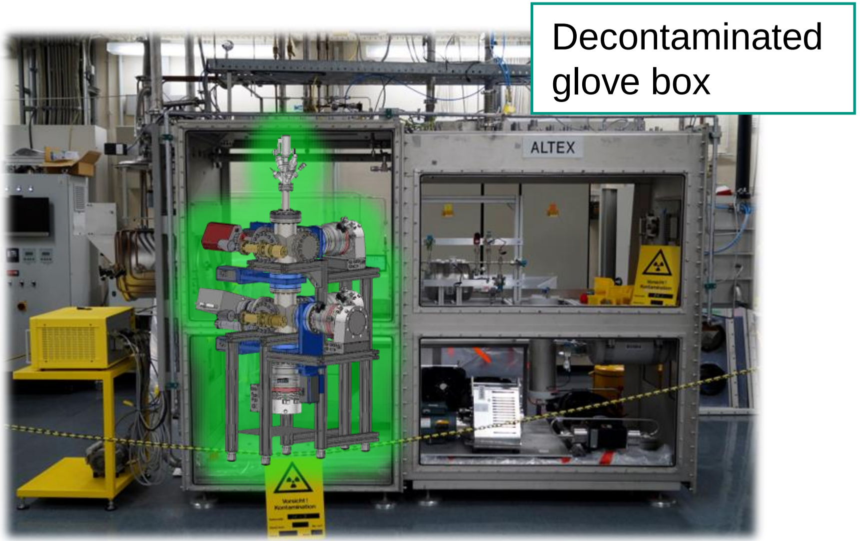


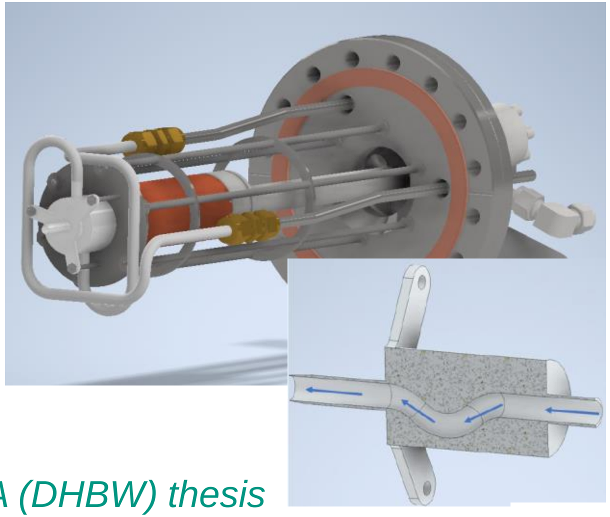


- Non-tritium hydrogen cracker being operated
- **Characterization measurements for tritium beamline ongoing**

- Installation of first ever atomic **tritium** source at TLK ongoing
- **First results expected in 2024**

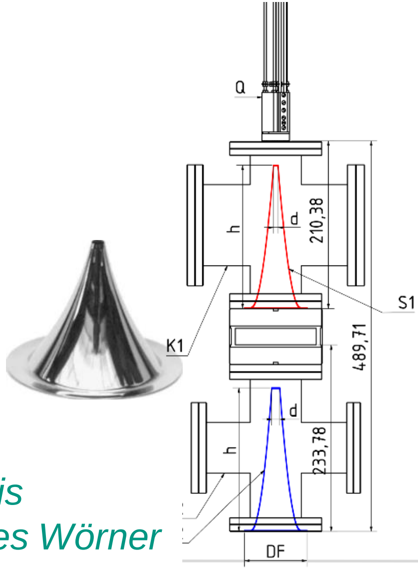
Further R&D progress

Design of nitrogen cooled accommodator



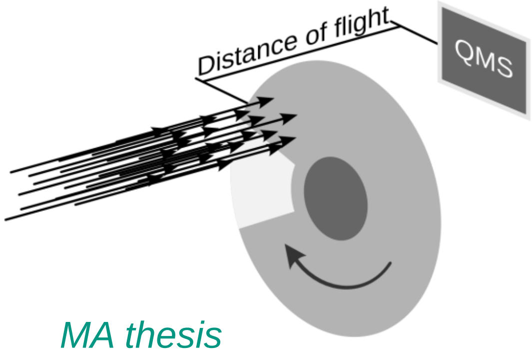
BA (DHBW) thesis
Florian Hanß

Skimmer design for suppression of molecular background



BA thesis
Johannes Wörner

Time-of-flight measurement for temperature studies



MA thesis
Sebastian Koch

KAMATE –
Karlsruhe Mainz Atomic Tritium experiment

Scientific / technical goals

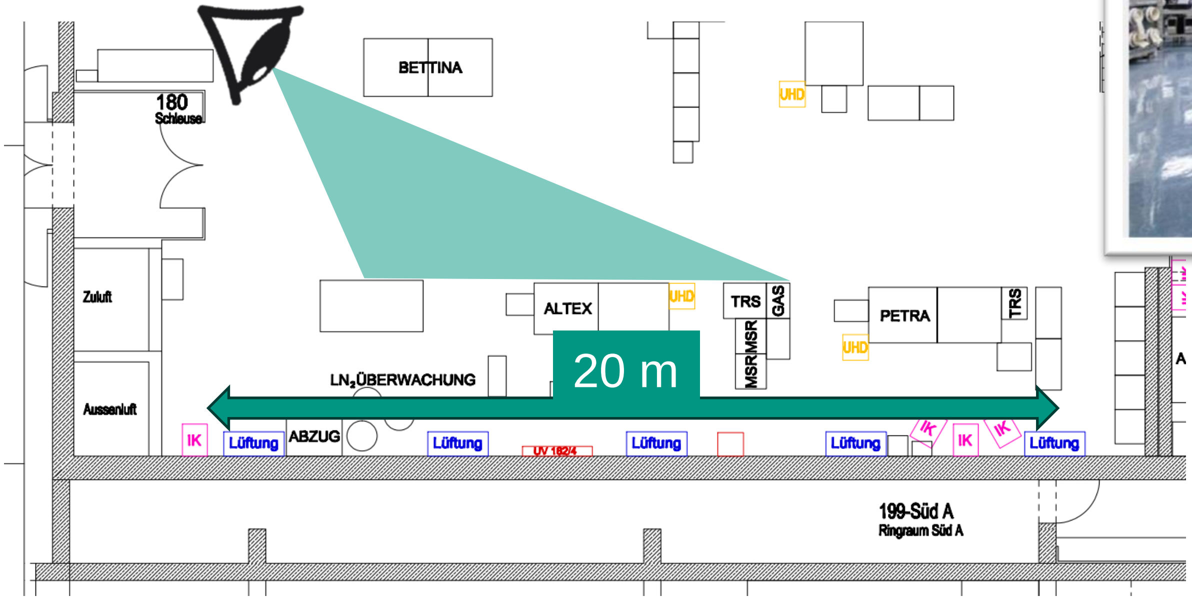
- **Atomic beam characterization**
  - Atomic fraction
  - Maximal flow rates / pressure limits
  - Isotopic effects
  - **Angular dispersion**
  - **Time-of-flight (upgrade)**
  - **Wire-detector**
- **Cooling / accommodation (upgrade)**
  - **Velocity measurement**
  - **Recombination**

Karlsruhe

Mainz

Sophisticated setup based on Mainz setup
Multi chamber / collimation design, tilting mechanism, beam control, source parameter control, beam analytics

Preparing TLK for the atomic tritium demonstrator



Preparing TLK for Atomic Tritium Demonstrator

ALTEX Box

- Decontamination completed
- Installation ongoing

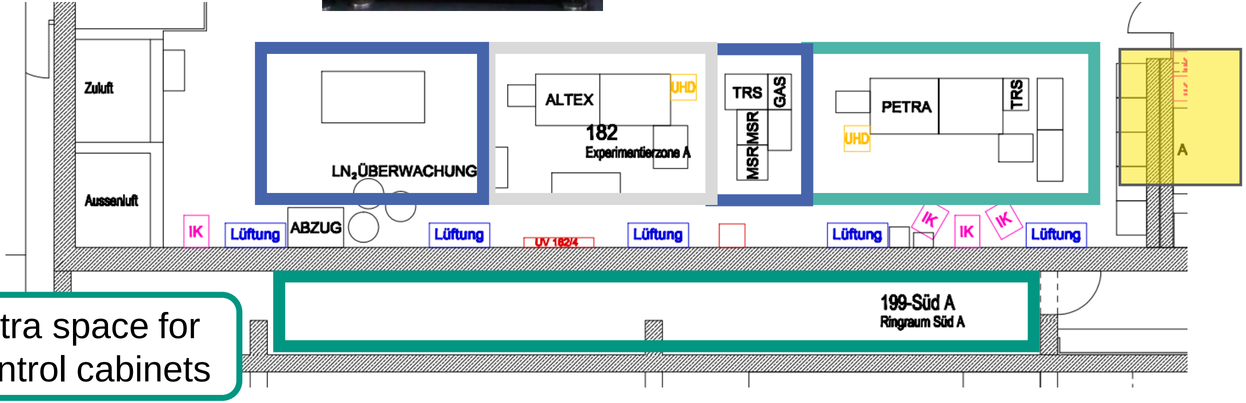
PETRA box

- In process of disposal/repurposing of former experiment
- Next step: decontamination

Other systems

e.g. tritium retention system, gas bottles, control cabinets, …
→ Will be relocated

Mrs. Bornschein, tear down this wall!

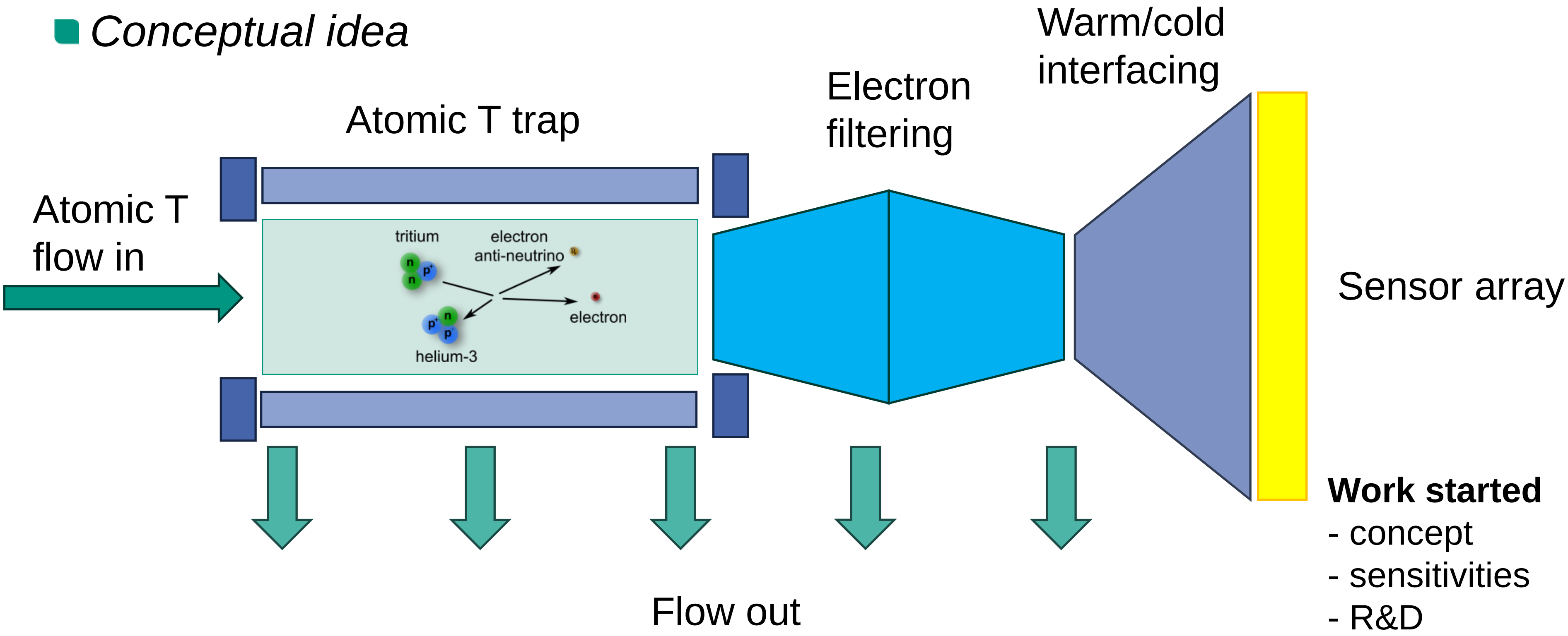


Extra space for control cabinets

A wall is in principle not the limit

Final R&D goal
Atomic tritium with Quantum sensor array

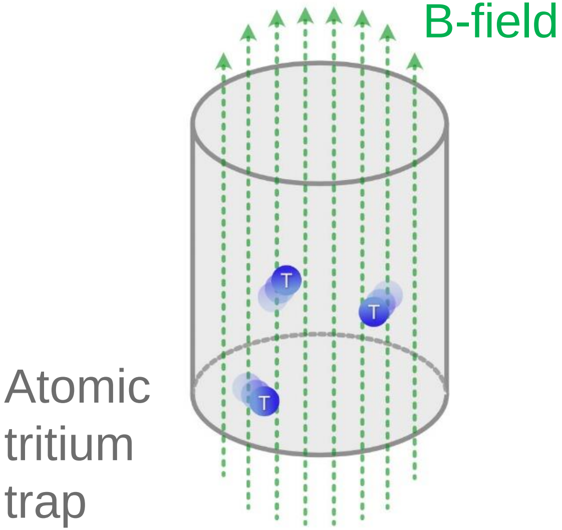
- *Conceptual idea*



Work started
- concept
- sensitivities
- R&D

KATRIN++ and Project8 – future collaborators?

- Currently, **no technology proven** to reach ultimate sensitivity
- Neutrino mass detection must be confirmed by **independent technologies**
- **Atomic tritium trap** is key for both detection techniques



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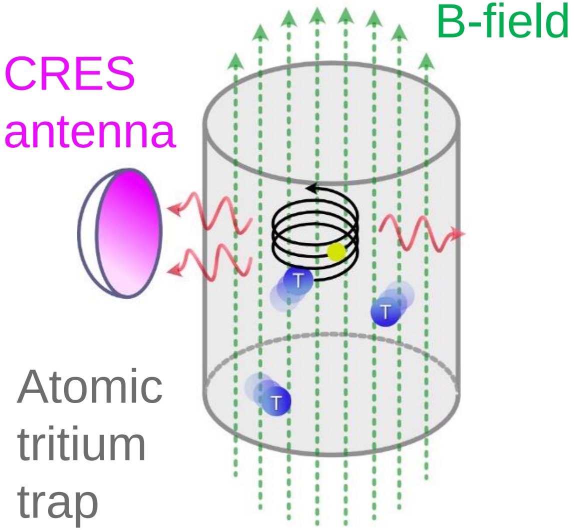

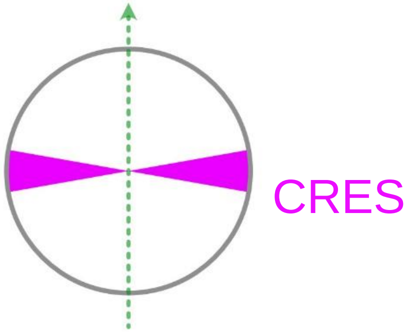

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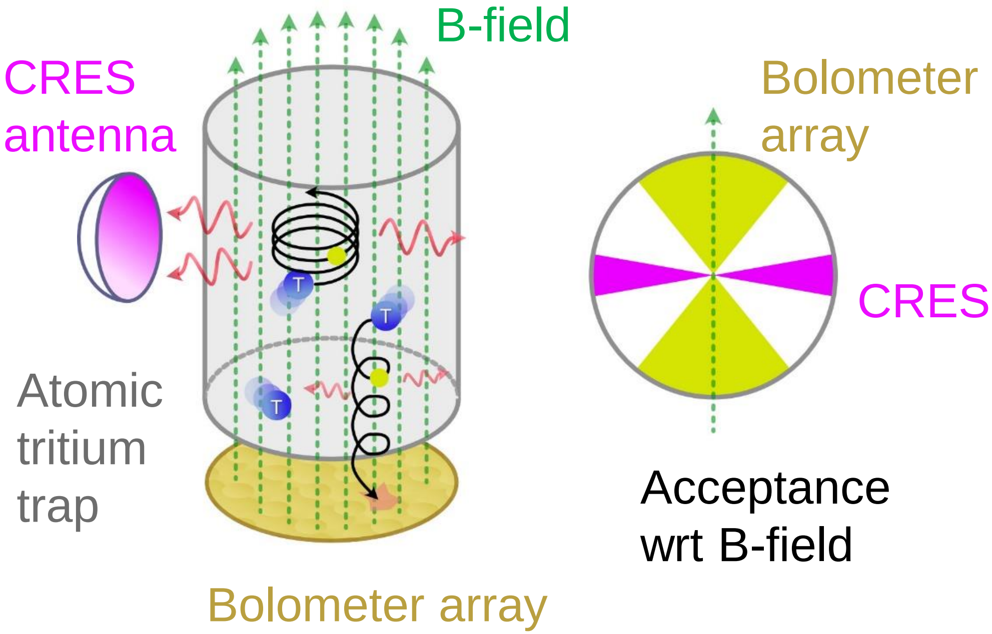
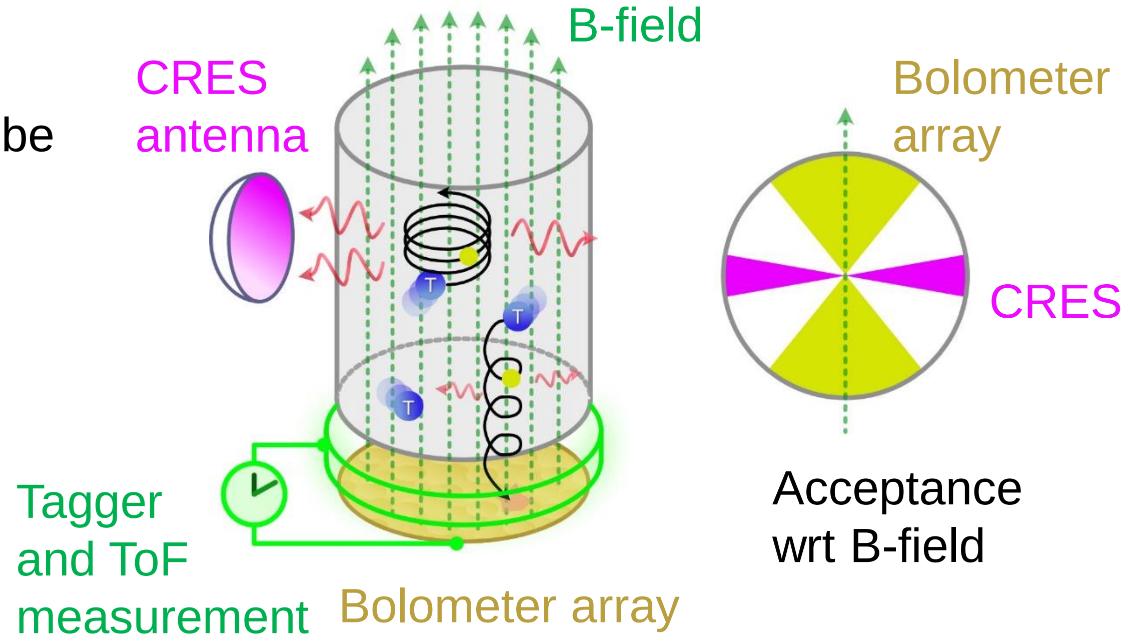
- CRES and bolometer **complementary**



KATRIN++ and Project8 – future collaborators?

Disclaimer: current P8 baseline forsees cavity design

- Currently, **no technology proven** to reach ultimate sensitivity
- Neutrino mass detection must be confirmed by **independent technologies**
- **Atomic tritium trap** is key for both detection techniques
- CRES, bolometer and ToF **complementary**



Possible future tritium sources

	Molecular tritium T_2
Type of source	Dynamic injection
Scalability to higher luminosity	
Effective limitation of resolution	
Final-state-distribution	
Baseline for	KATRIN

Possible future tritium sources

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	Molecular tritium T_2	Atomic tritium T
Type of source	Dynamic injection	Long-lifetime trap
Scalability to higher luminosity		Challenging
Effective limitation of resolution		
Final-state-distribution		
Baseline for	KATRIN	PROJECT 8 KATRIN QTNM

Possible future tritium sources

Karlsruhe Institute of Technology

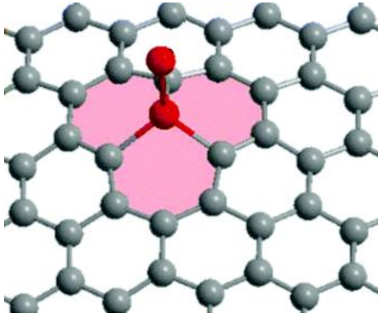
	Molecular tritium T_2	Atomic tritium T	Quasi-atomic tritium (tritiated graphene)
Type of source	Dynamic injection	Long-lifetime trap	Surface-bound
Scalability to higher luminosity	👎	Challenging	Promising
Effective limitation of resolution	👎	👍	?
Final-state-distribution	👉	👍	?
Baseline for		QTNM Quantum Technologies for Neutrino Mass	PTOLEMY

Driving question: Can graphene be tritiated?

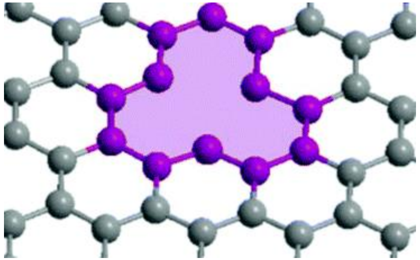
Tritiation of graphene

- Aim:
  Perform first tritiation of graphene
- Tritium != hydrogen/deuterium

Study effect of tritium radiochemistry on carbon monolayer

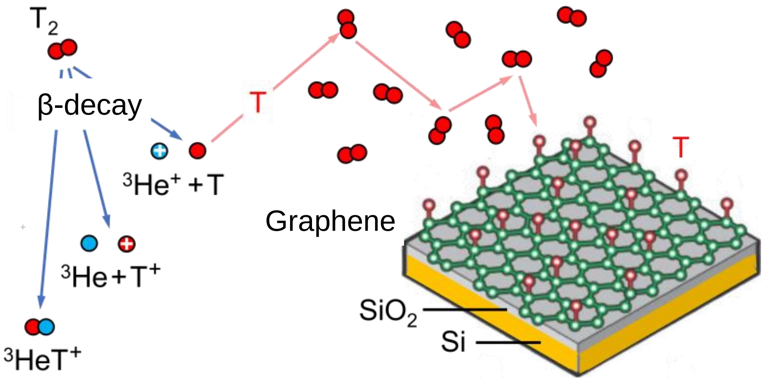


Tritium binding?



Defect generation?

Currently, atomic tritium source not available

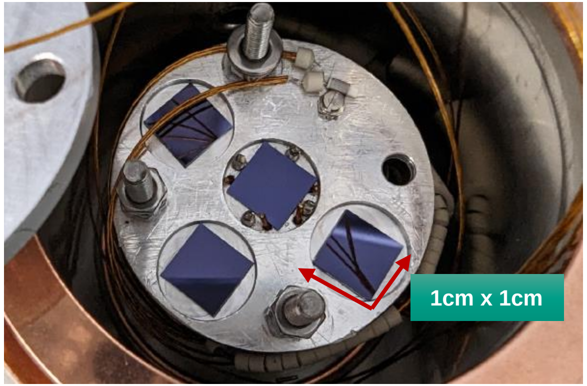


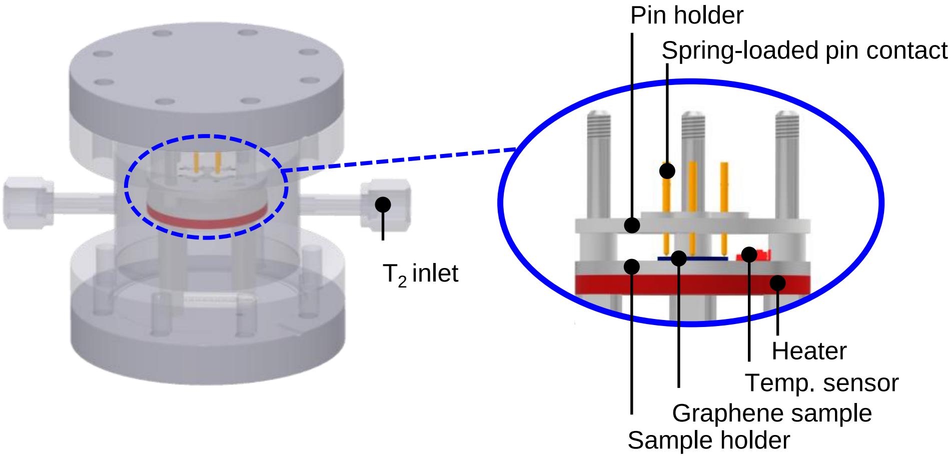
Use autoradiolysis for generation of tritium atoms and ions

Zeller et al. (2024). arXiv:2310.16645, under Review at Nanoscale Advances

Loading experiment

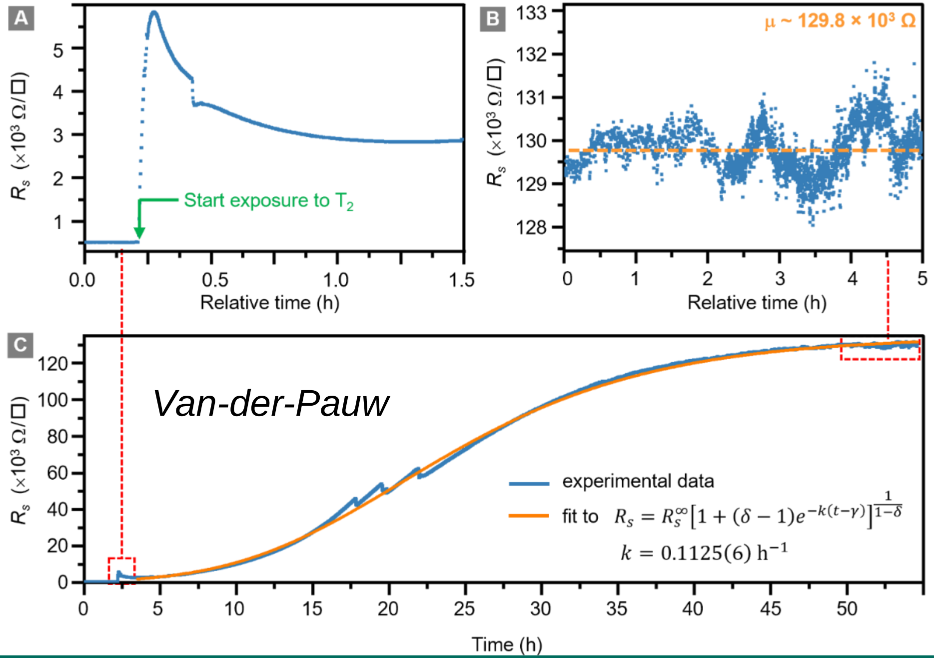
- 4x mono-layer graphene on Si/SiO_2-substrate *(Graphenea, ES)*
- ~400 mbar T_2 (≙ ca. $7{,}6 \times 10^{12}$ Bq ≙ 10^4 Legal limits)
- 55h exposure time



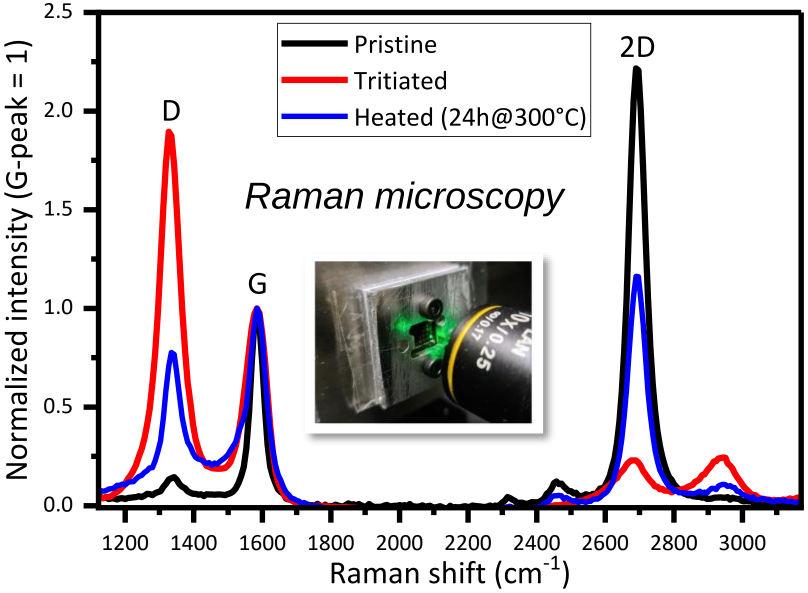


In-situ sheet resistivity measurement on central sample with Van-der-Pauw-methode

Results after exposition (3.4×10^{10} Bq/cm^3 for 55h)



Significant tritiation of graphene (~6-10%)



Tritiation induces defects (~2-8%) (Autoradiolysis, ion, …)

Zeller et al. (2022). arXiv:2310.16645, in Review bei Nanoscale Advances

Overview on KATRIN++

2019-2025 | 2026-2027 | 2028-2034 (PoF-V) | Scientific goal

Phase 1 (integral) neutrino mass

Phase 2 (differential) keV-sterile ν

R&D phase KATRIN ++

Neutrino mass

Quantum sensor R&D

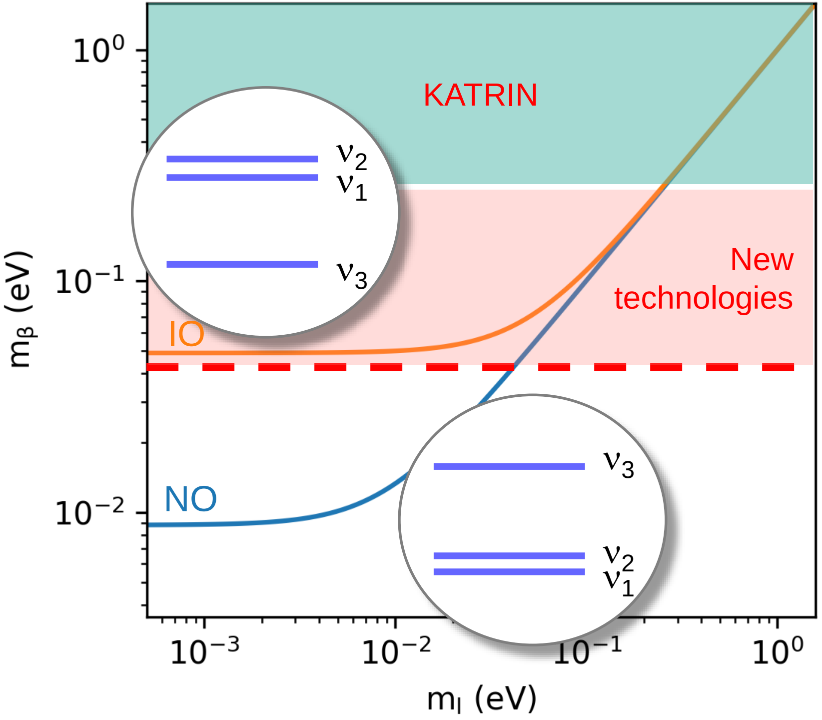
Atomic tritium R&D

Quantum sensor demonstrator

Atomic tritium demonstrator

- **KATRIN** on way to achieve 1000 d measurement time (final sensitivity m_β < 0.3 eV).
  Next m_β result : ~ **0.5 eV sensitivity**
- We will be ready for **TRISTAN**-Operation at the end of 2025 (**Search for keV sterile neutrinos)**
- Ultimate neutrino mass experiment (Normal Ordering**; sensitivity on m_β < 40 meV**) requires **differential detector principle** und **an atomic tritium source → R&D Plan for PoF-V**
- KATRIN invites research groups for **tackling challenges together**

Start the voyage for the final discovery



Credits (KATRIN++ R&D groups)

Atomic Tritium Source

Hassan Abdulahi Ali
Albert Braun
Beate Bornschein
Robin Größle
Leonard Hasselmann
David Hillesheimer
Sebastian Koch
Daniel Kurz
Elias Lütkenhorst
Florian Priester
Marco Röllig
Caroline Rodenbeck
Magnus Schlösser
Michael Sturm
Nancy Tuchscherer
Stefan Welte

ELECTRON / MMCs

Fabienne Bauer
Neven Kovac
Sebastian Kempf
Michael Müller
Marie Langer
Rudolf Sack
Magnus Schlösser
Markus Steidl
Kathrin Valerius
Daniel de Vincenz

Tagger / ToF

Andrew Gavin
Reyco Henning
Eric Martin
Christian Weinheimer

Tritiated graphene

Deseada Diaz Barrero
Simon Niemes
Magnus Schlösser
Helmut Telle
Paul Wiesen
Genrich Zeller

Simulations

Svenja Heyns
Ferenc Glück
Woosik Gil
Susanne Mertens

Cryogenics

Matteo Biassoni
Andrea Nava

Overview of the tritium supply structure

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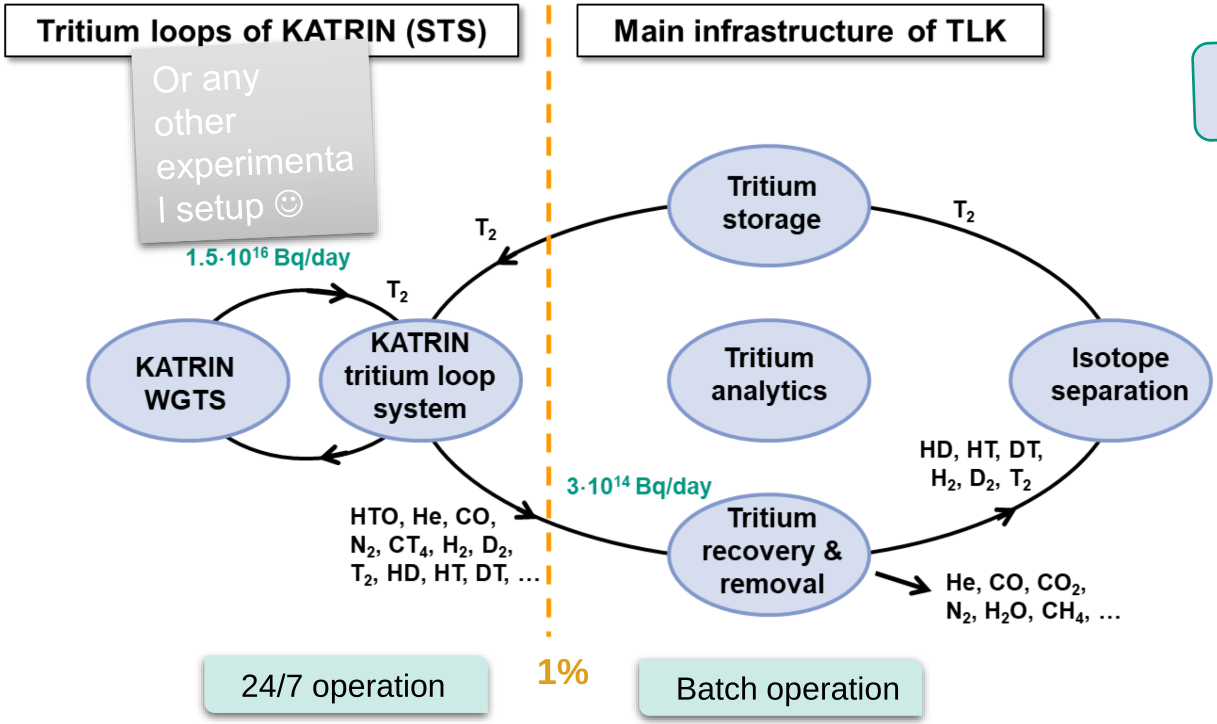

Tritium operation in numbers 2019 – now

- 873 days of circulation (T_2, Kr)
- 141 gas transfers to KATRIN
- 254 gas transfers to infrastructure

27.3 kg integral tritium throughput:

- Tritium purity > 98%
- Necessary tritium inventory: 15 g
- TLK license: 40 g (≈ 1.5×10^{16} Bq)