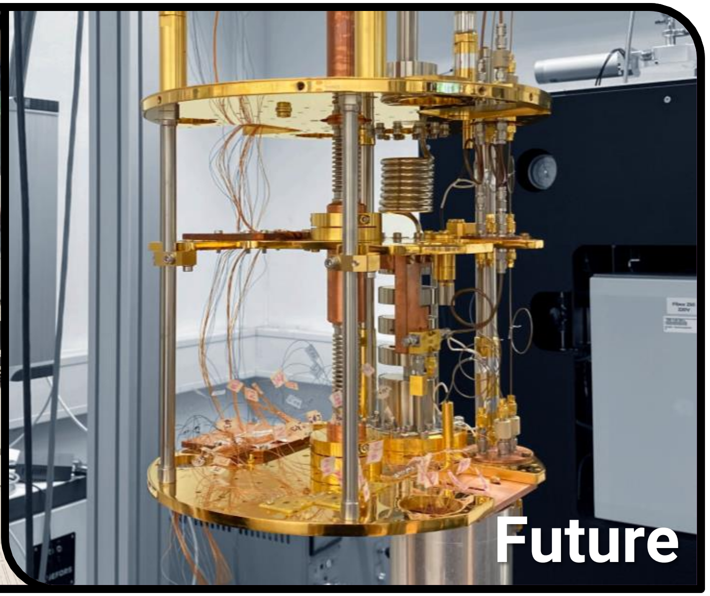
Neutrino mass measurements with KATRIN and beyond

Caroline Rodenbeck for the KATRIN Collaboration

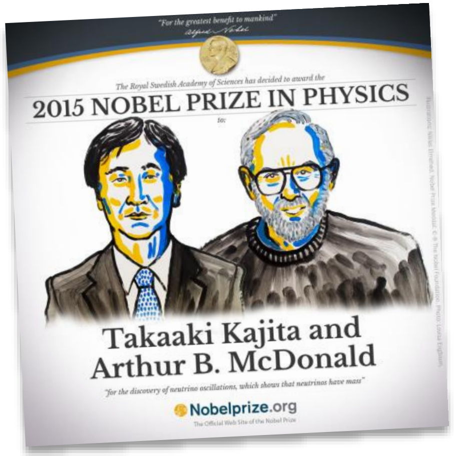
FH Particle Physics Pizza seminar, June 10, 2024

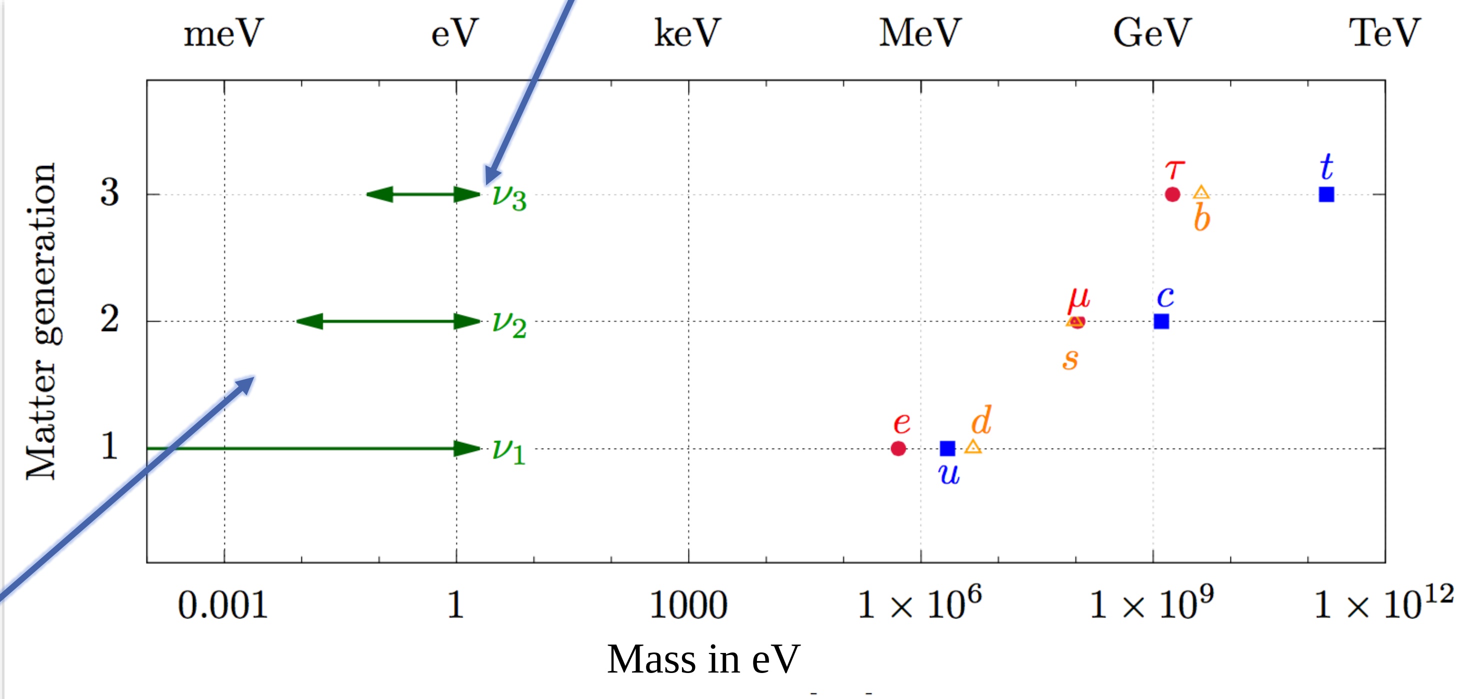


Neutrino mass

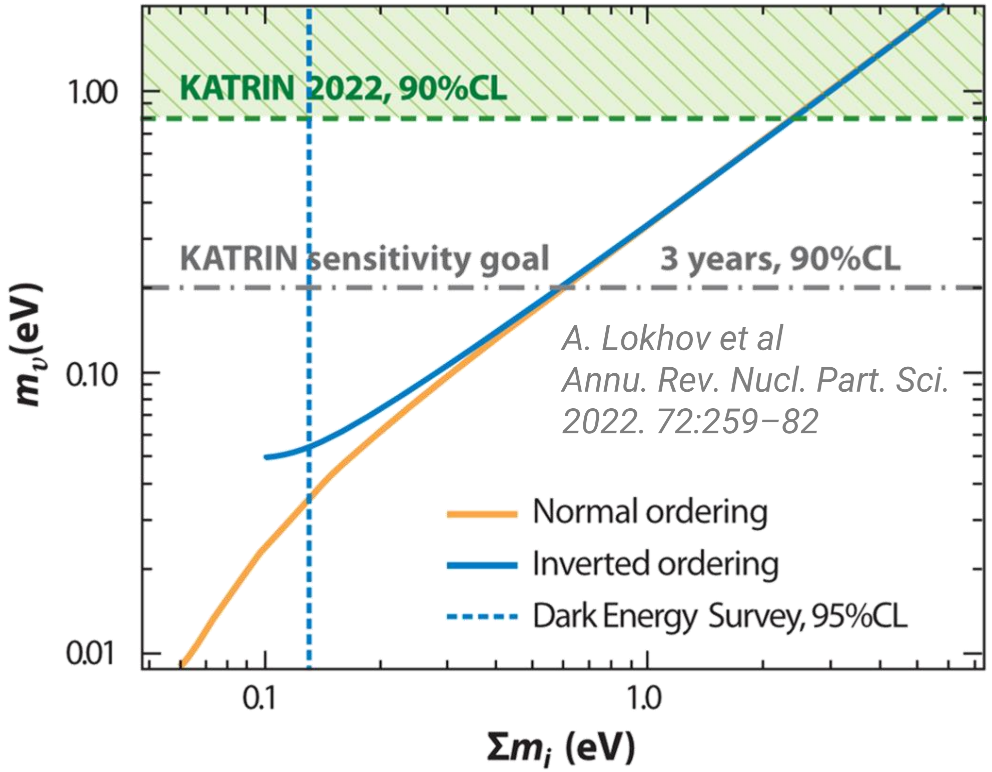
- Neutrino mass ≠ 0: proof from observation of neutrino oscillations
- Neutrino oscillation experiments:
  - sensitive on mixing angles and squared mass differences only
  - provide **lower bound** for masses

Upper bound from direct measurements



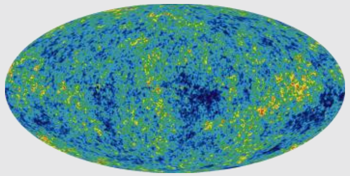


Complementary ways of determining the neutrino mass



Cosmology

- $m_\Sigma = \sum_i m_i$



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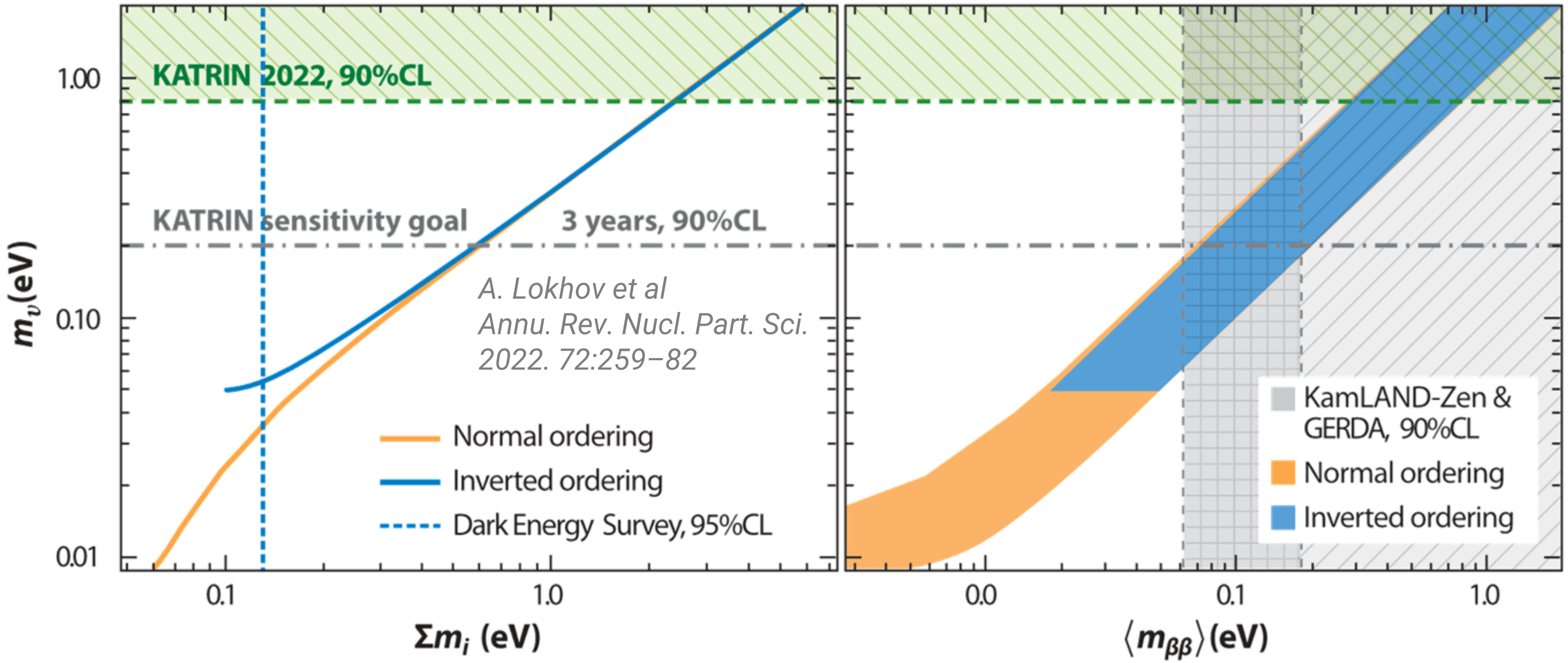

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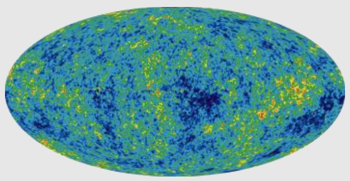
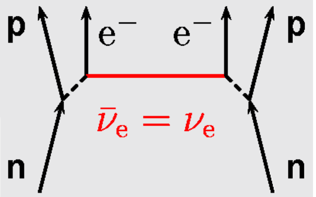


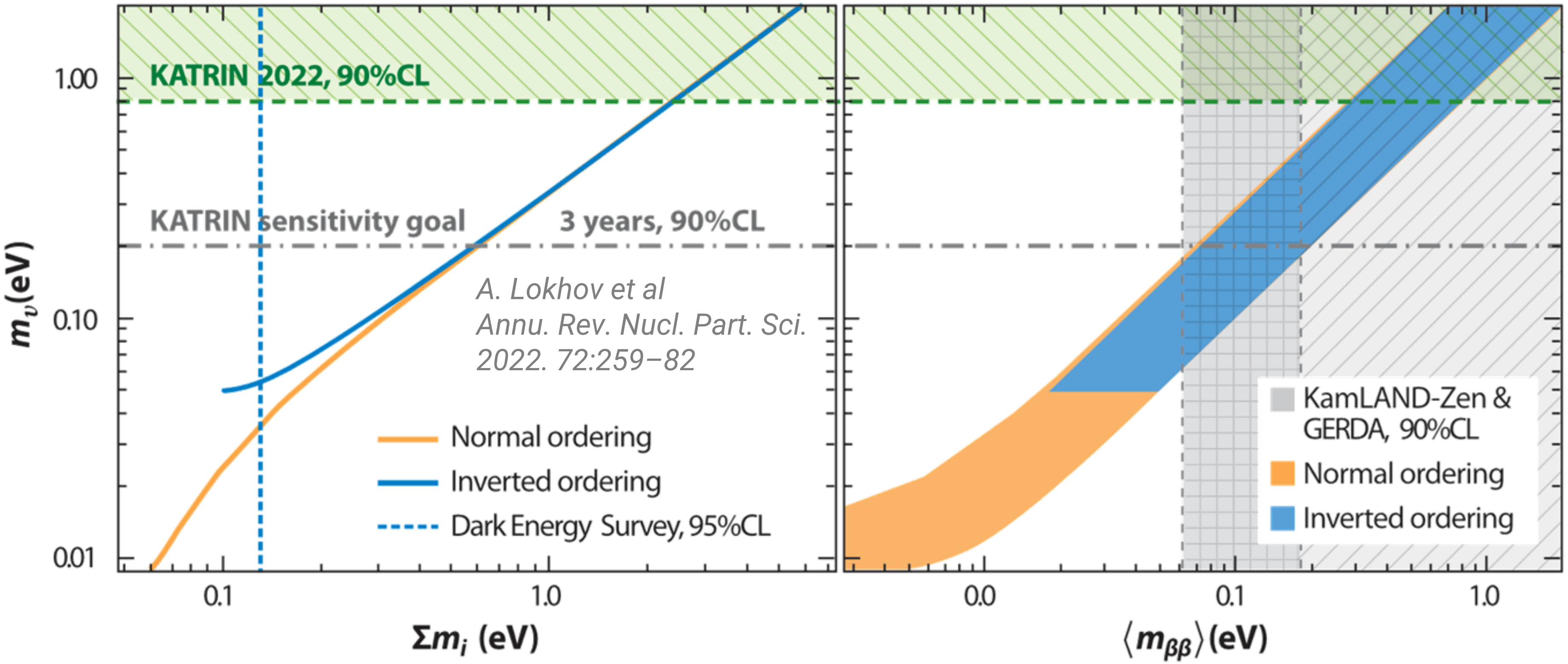
0νββ

- $m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 \right|$



Complementary ways of determining the neutrino mass

Karlsruhe Institute of Technology



Kinematic investigations

- $m_\nu = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$
- flight-time measurements (νs from supernovae)
- kinematics of weak decays

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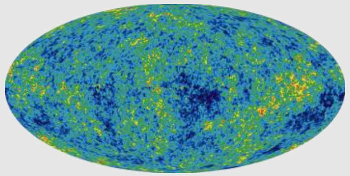

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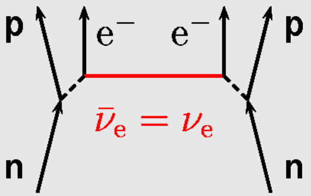

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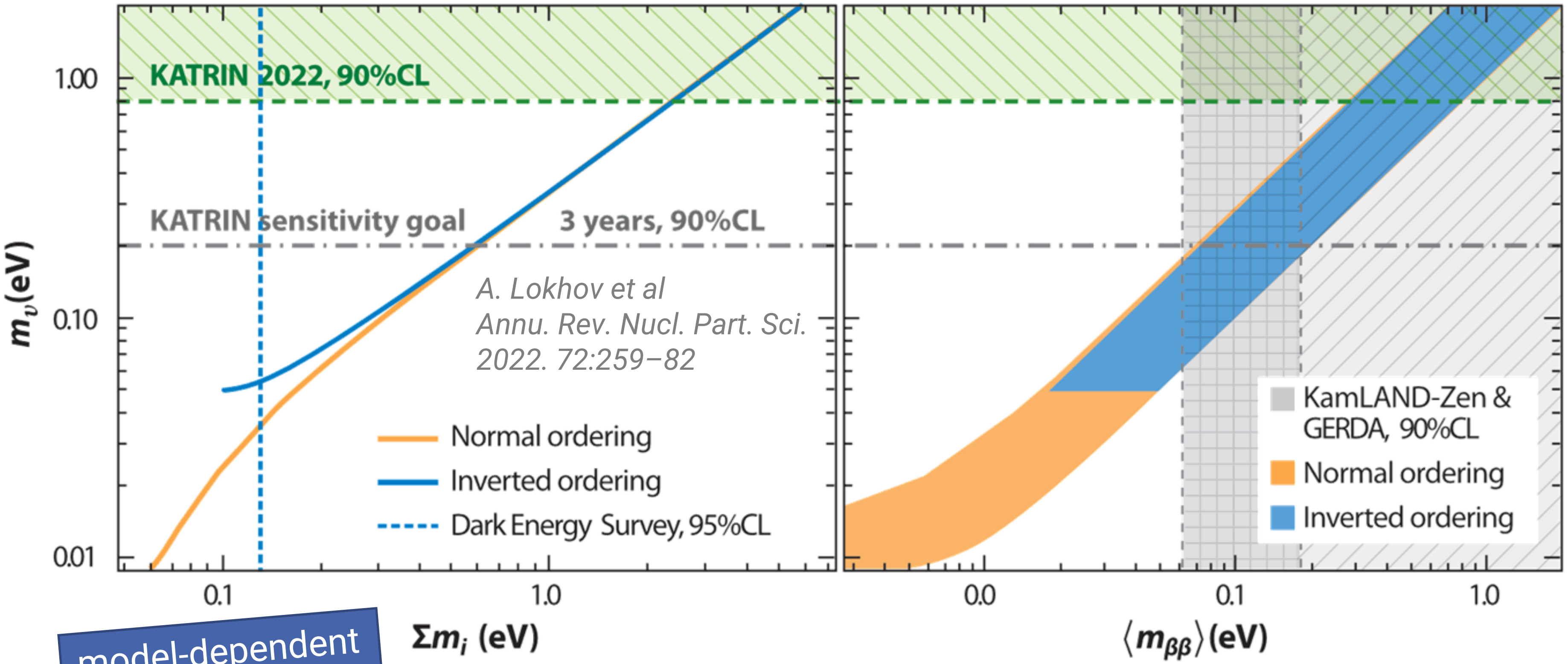
model-independent



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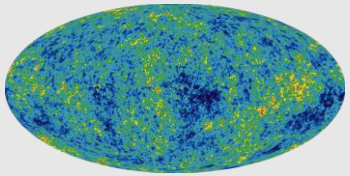

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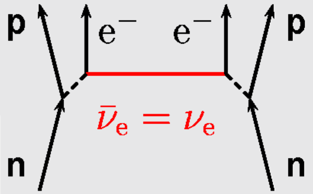

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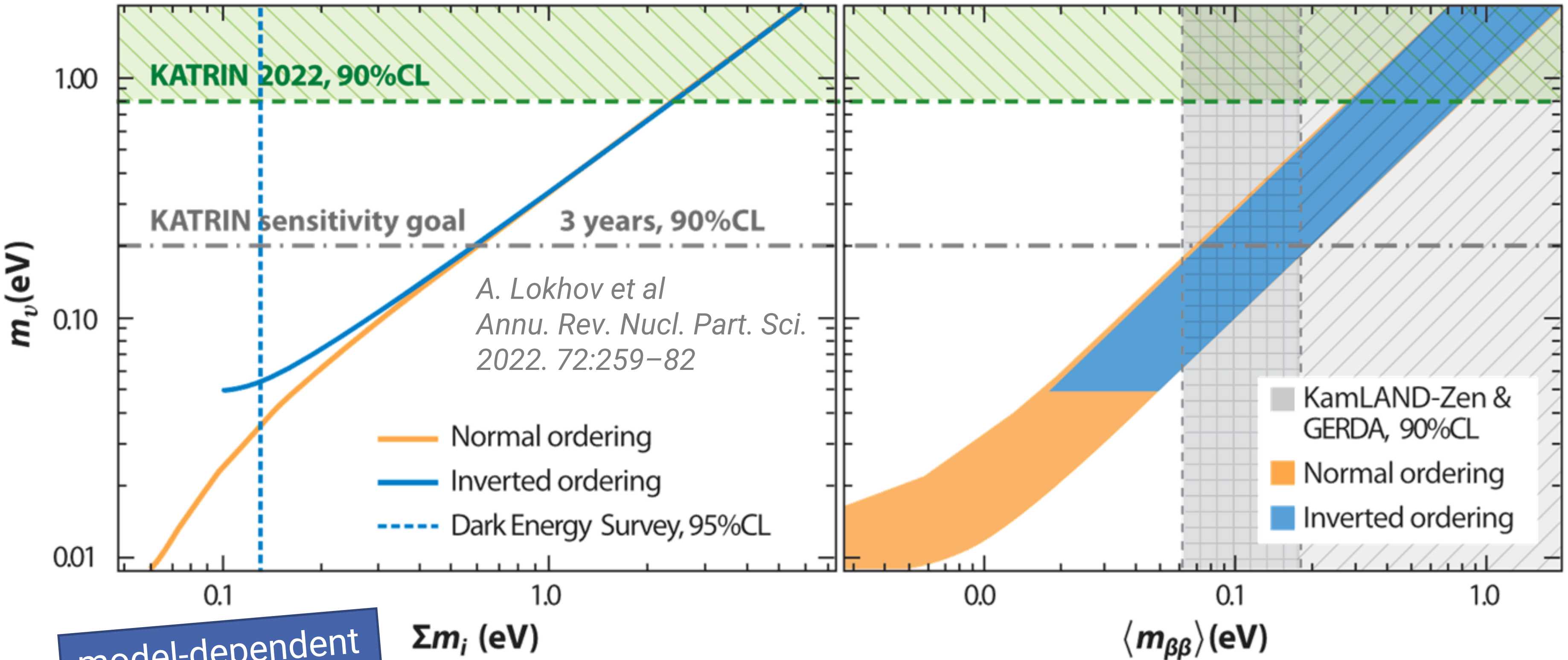

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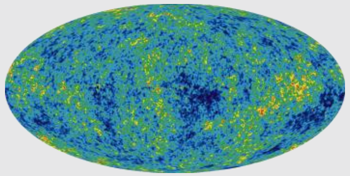

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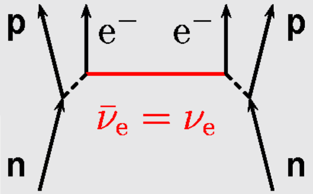
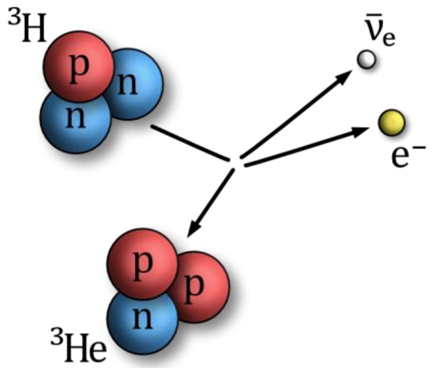


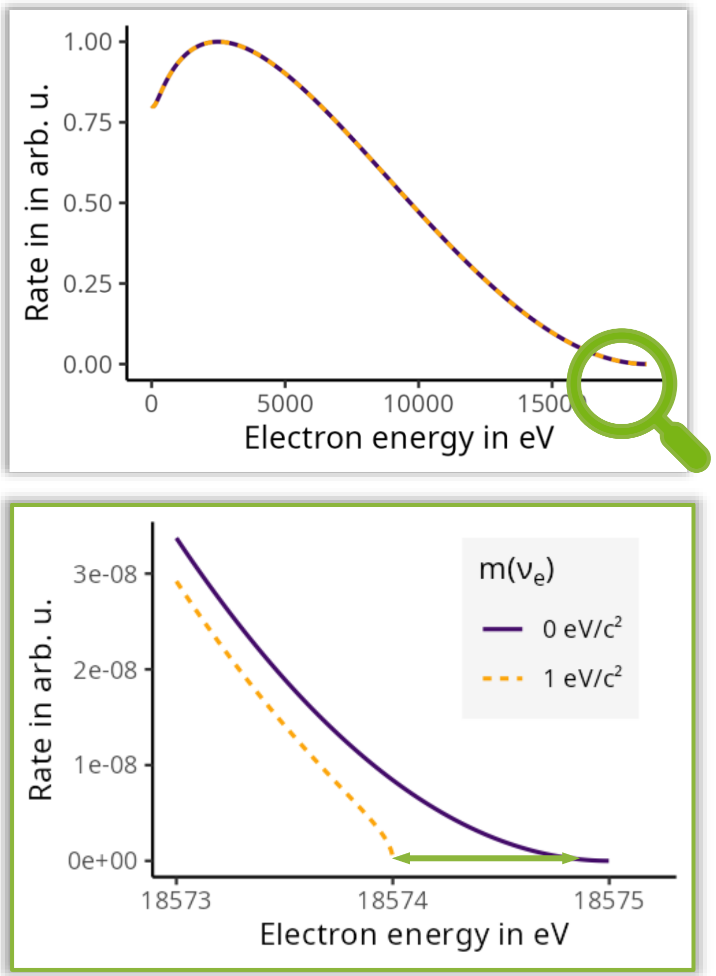
Neutrino mass determination from beta decay

- Neutrino mass influences beta-decay spectrum, especially at the endpoint ($E \approx E_0$)
- Possible beta-decay source: tritium
  - Simple structure of atomic/nuclear shell
  - Low endpoint (18.6 keV)
  - Super-allowed transition
    - High-decay rate ($T_{1/2}$ = 12.3 years)



$$\left(\frac{dN}{dE}\right) \sim (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \sum_i m_i^2 |U_{ei}|^2}$$

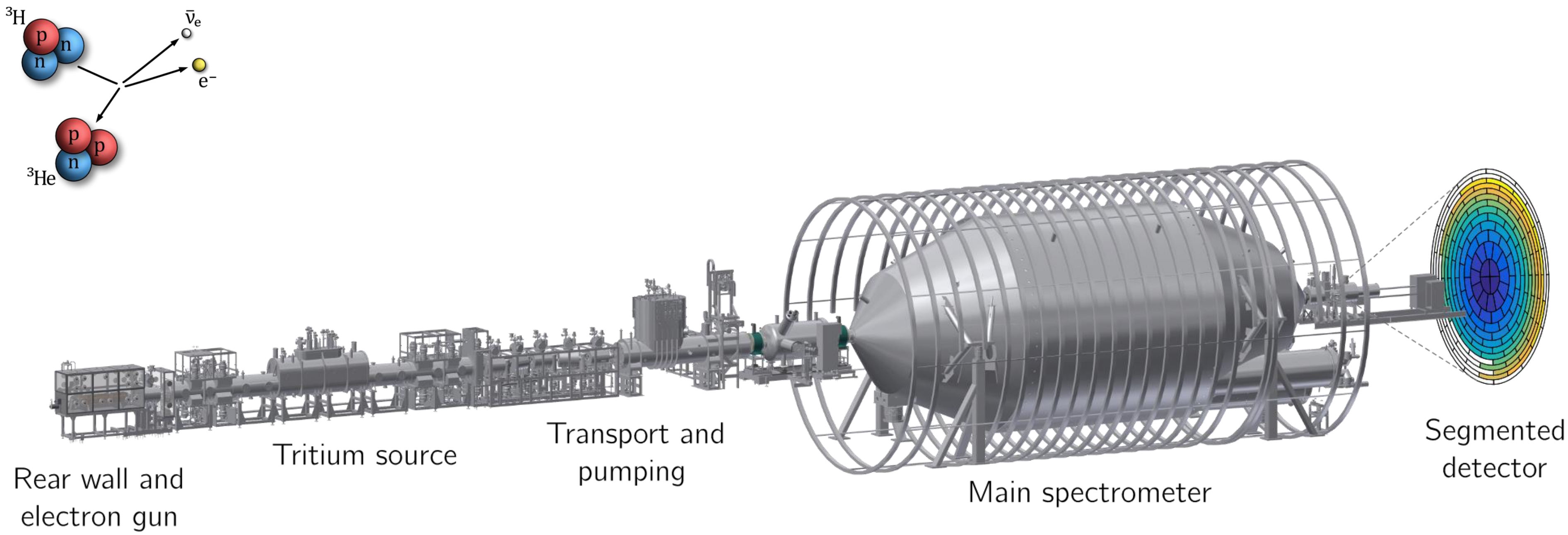
Measure kinetic energy of beta-decay electrons

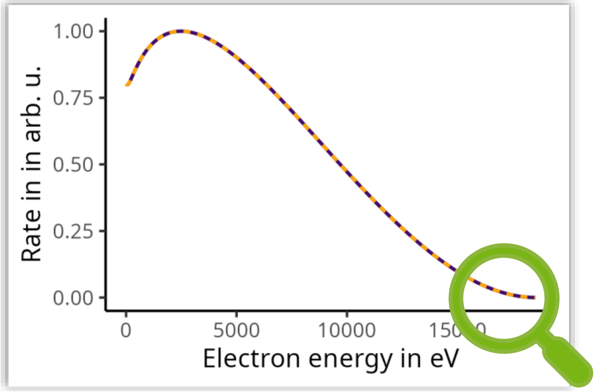


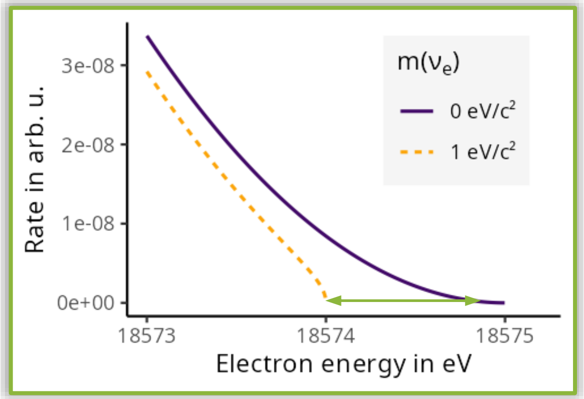
Karlsruhe Tritium Neutrino Experiment (KATRIN)

Karlsruhe Institute of Technology

- **Goal**: Determining the neutrino mass with a sensitivity of 0.2 eV/c² (90% CL)







Adapted from KATRIN Collaboration, Nat. Phys. 18, 160–166 (2022), artwork by L. Köllenberger

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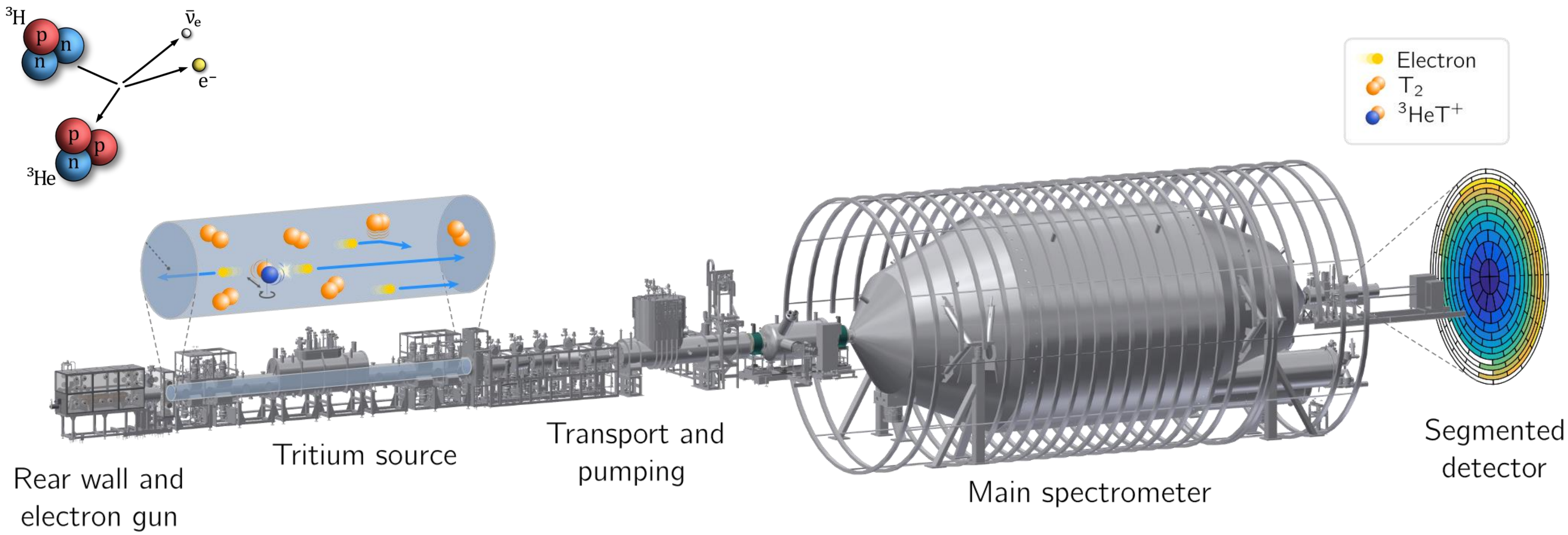

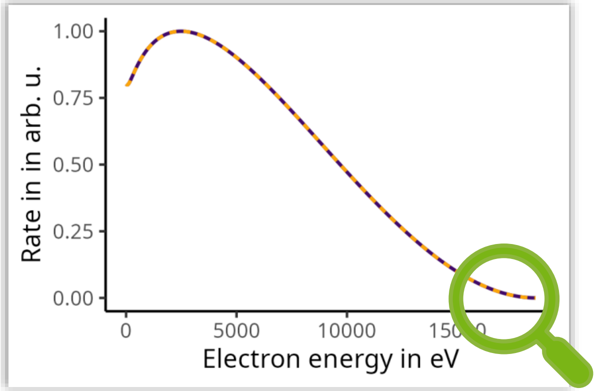

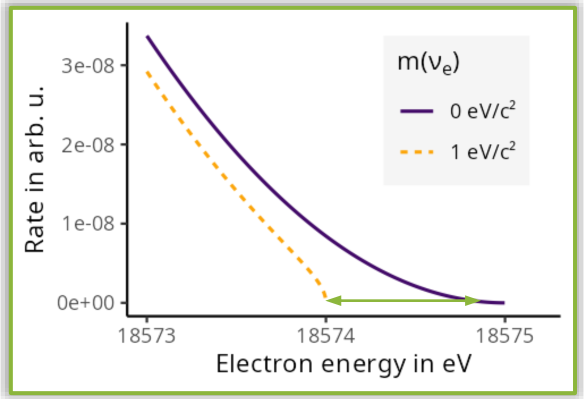

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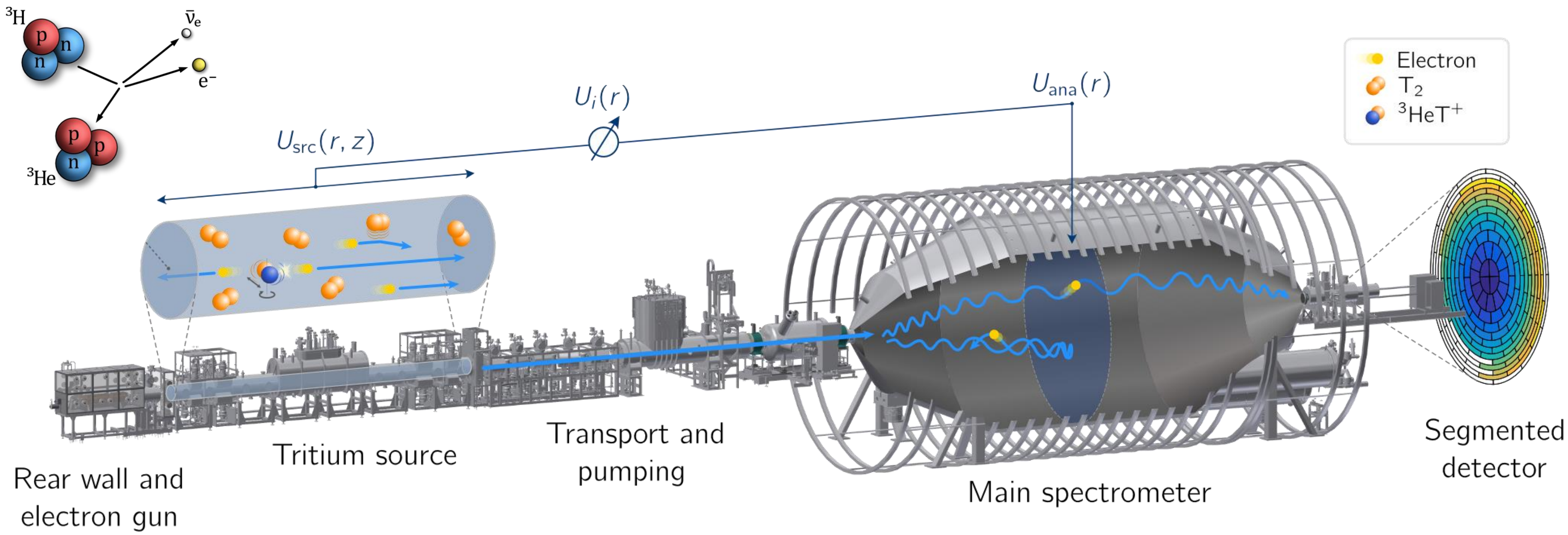

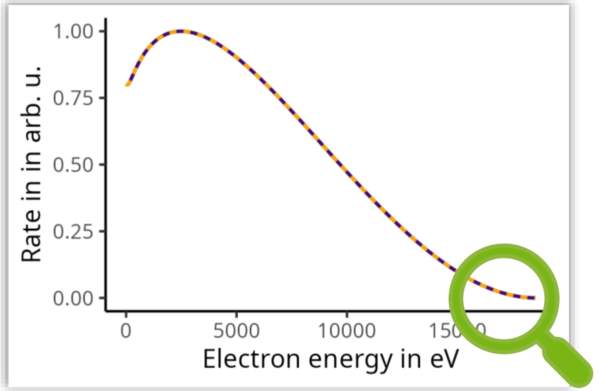

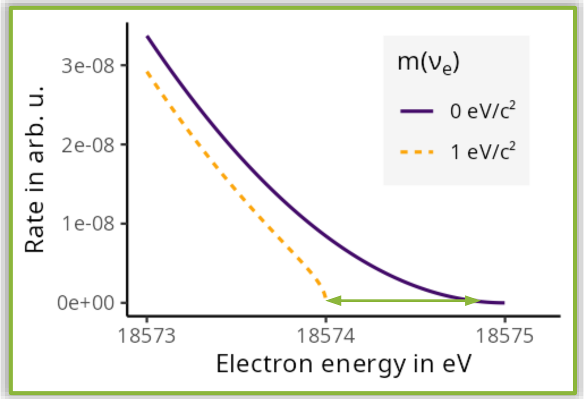

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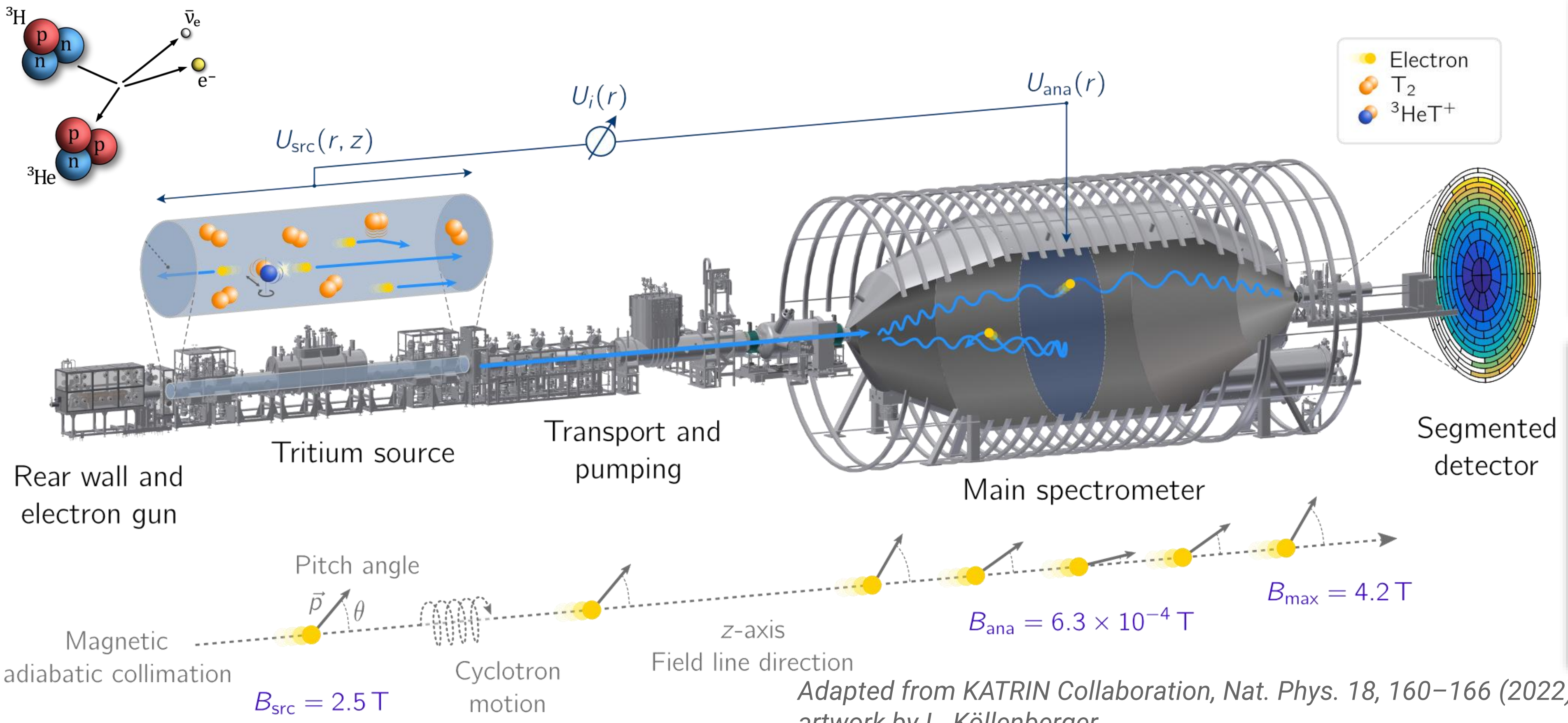

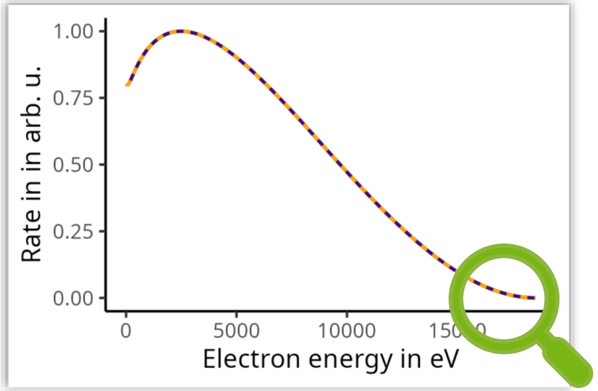

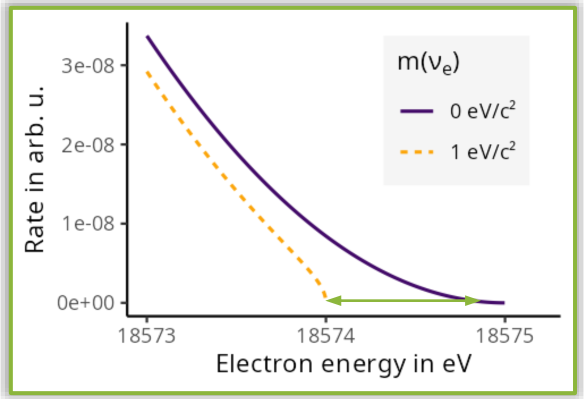

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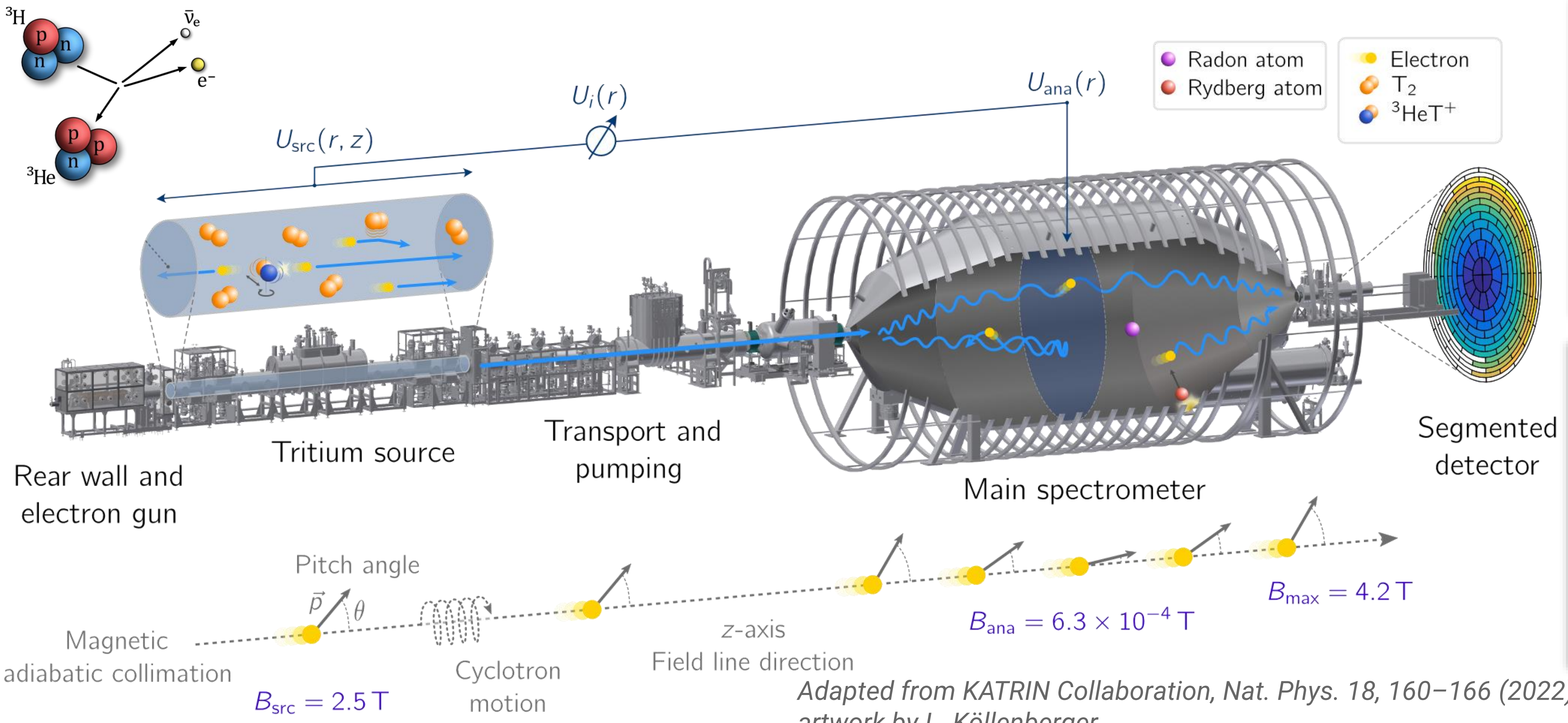

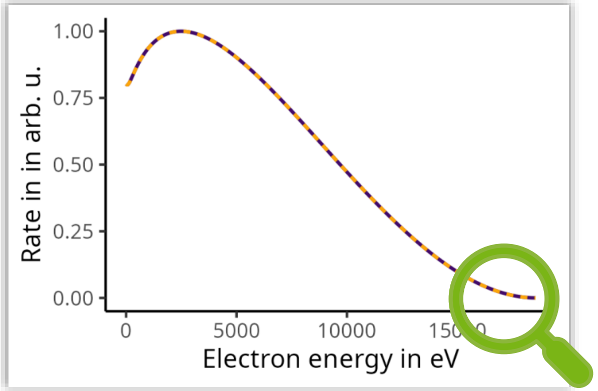

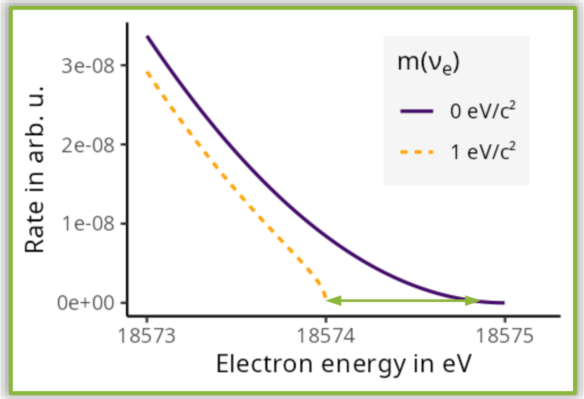

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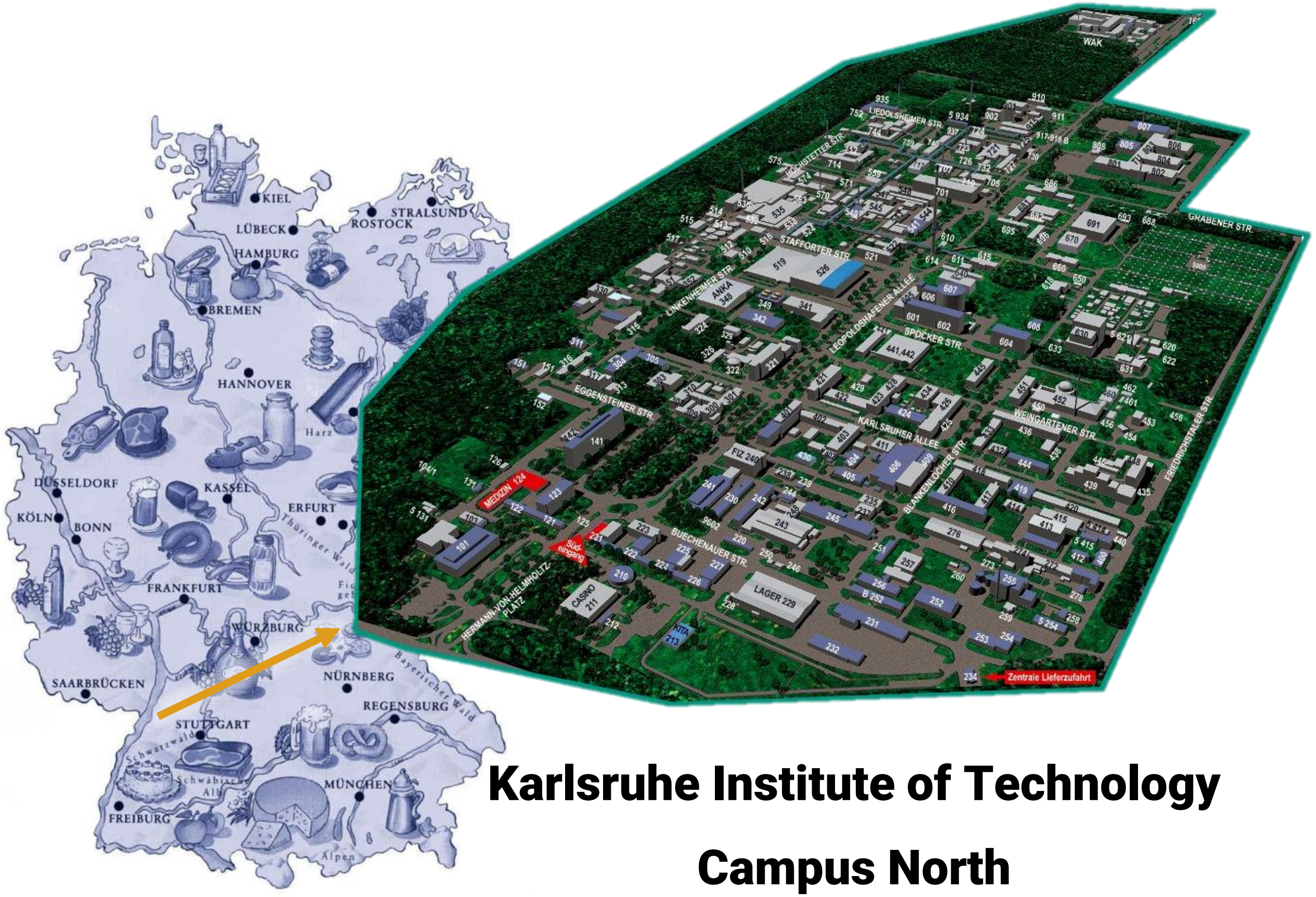
Karlsruhe Tritium Neutrino Experiment (KATRIN)

The international KATRIN collaboration:

≈150 people from 24 institutions in 7 countries

The Tritium Laboratory Karlsruhe

The Tritium Laboratory Karlsruhe



Karlsruhe Institute of Technology

Campus North

The Tritium Laboratory Karlsruhe

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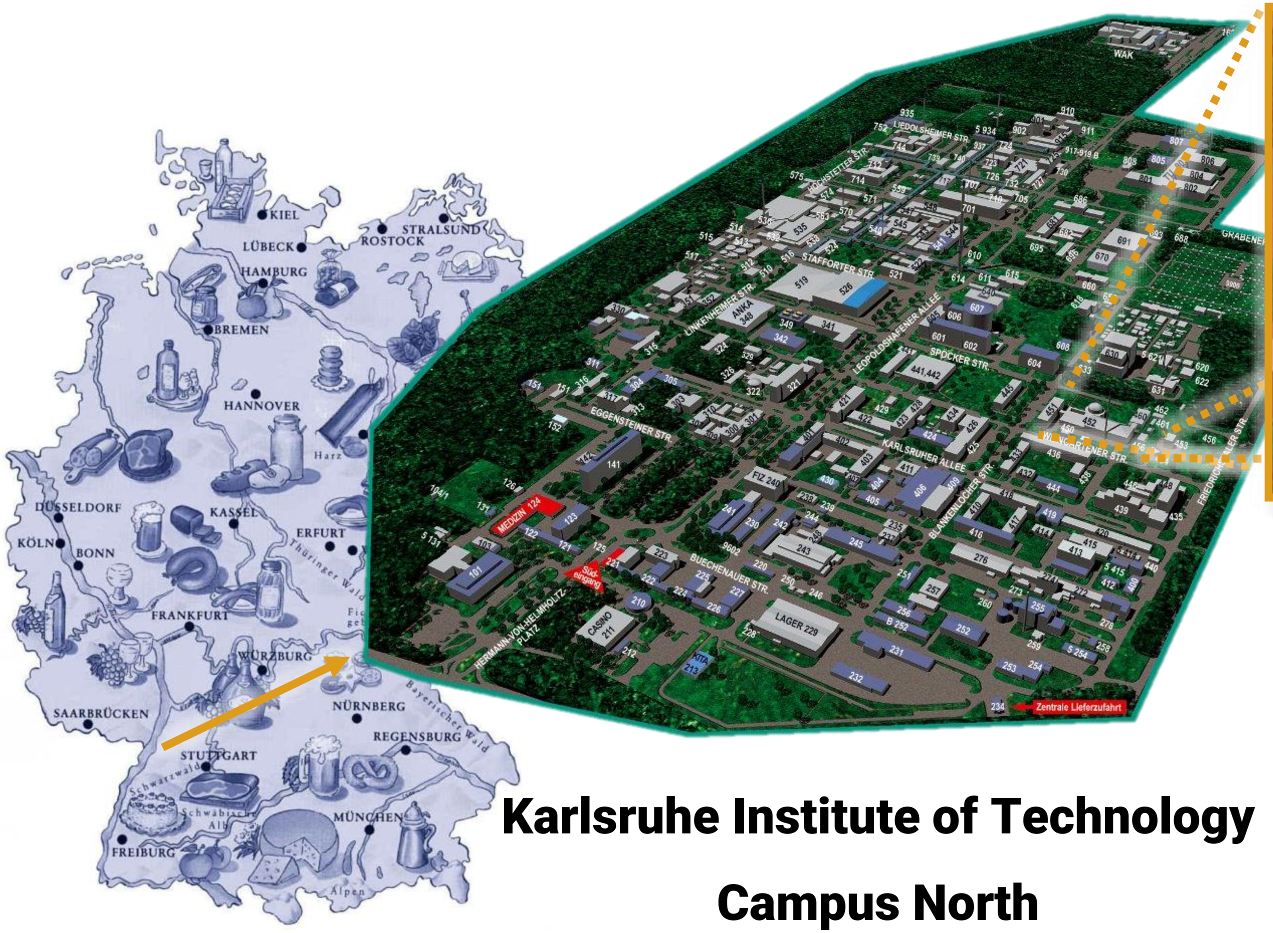
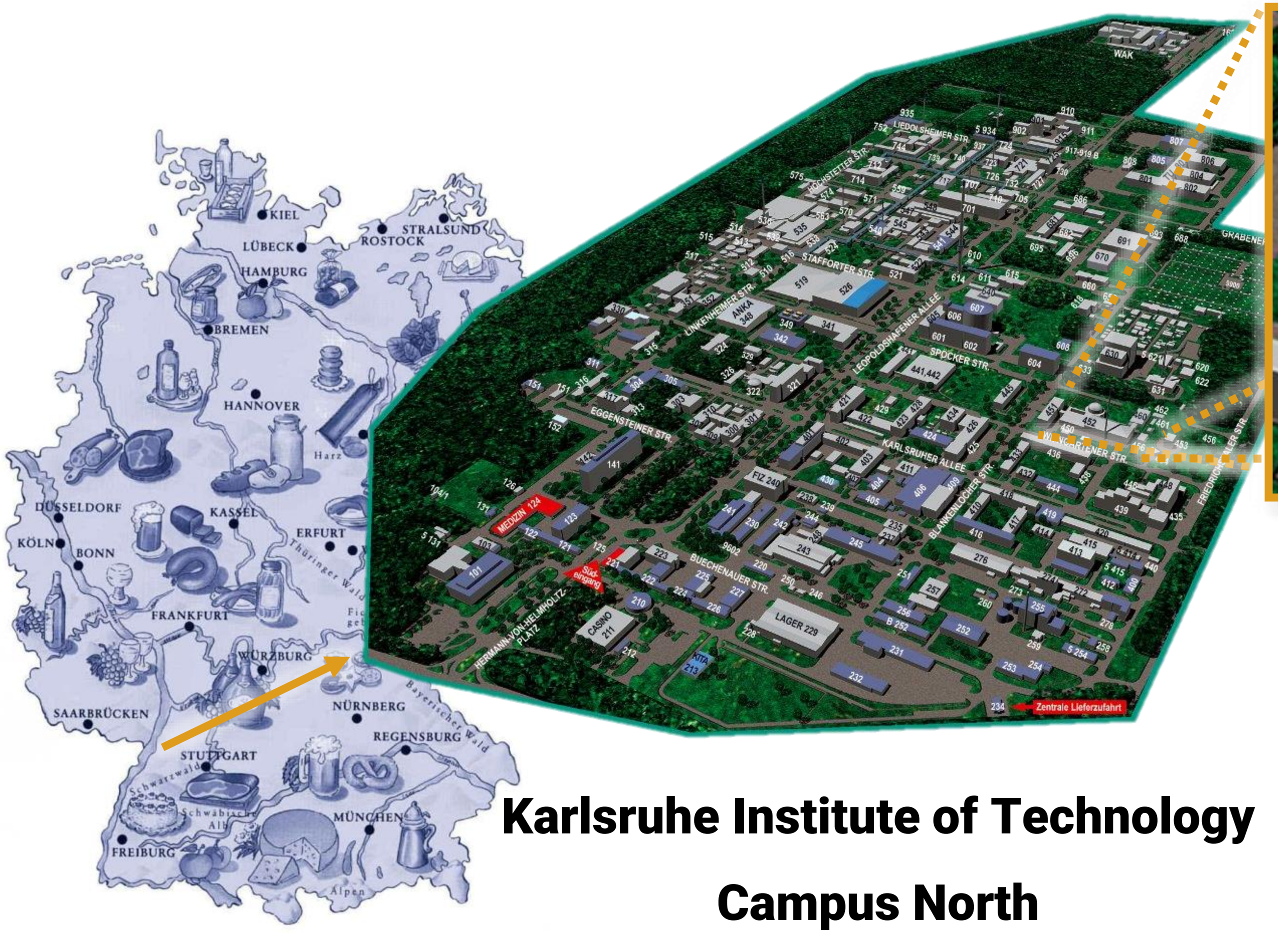


Karlsruhe Institute of Technology

Campus North

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

The Tritium Laboratory Karlsruhe



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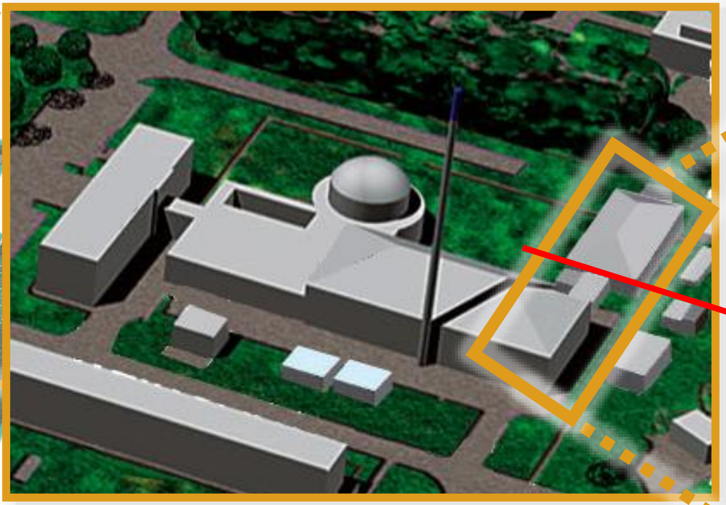

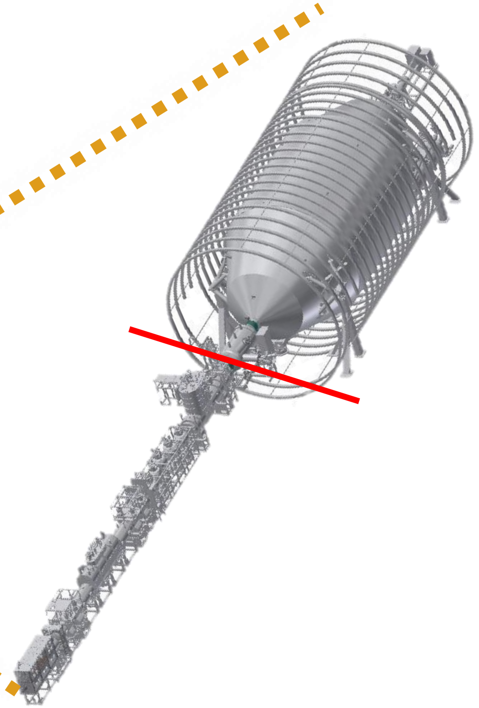

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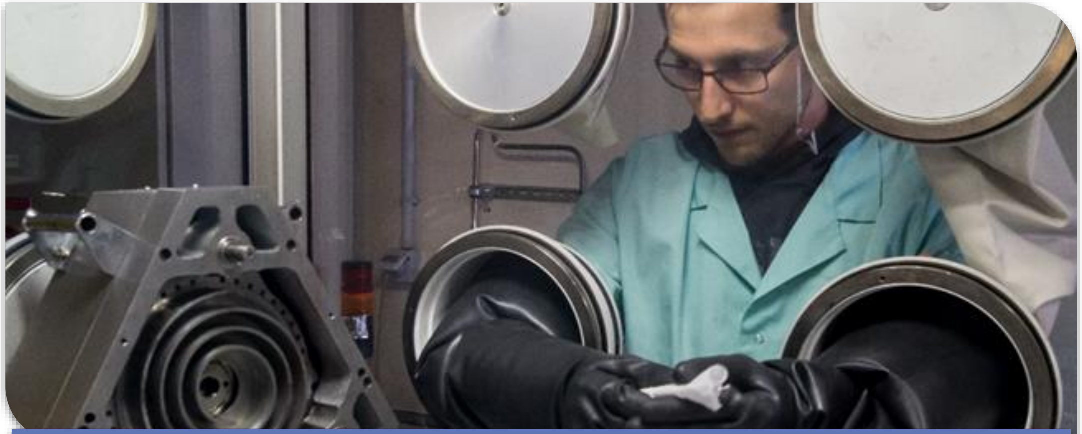
TLK – A facility for high-activity tritium experiments

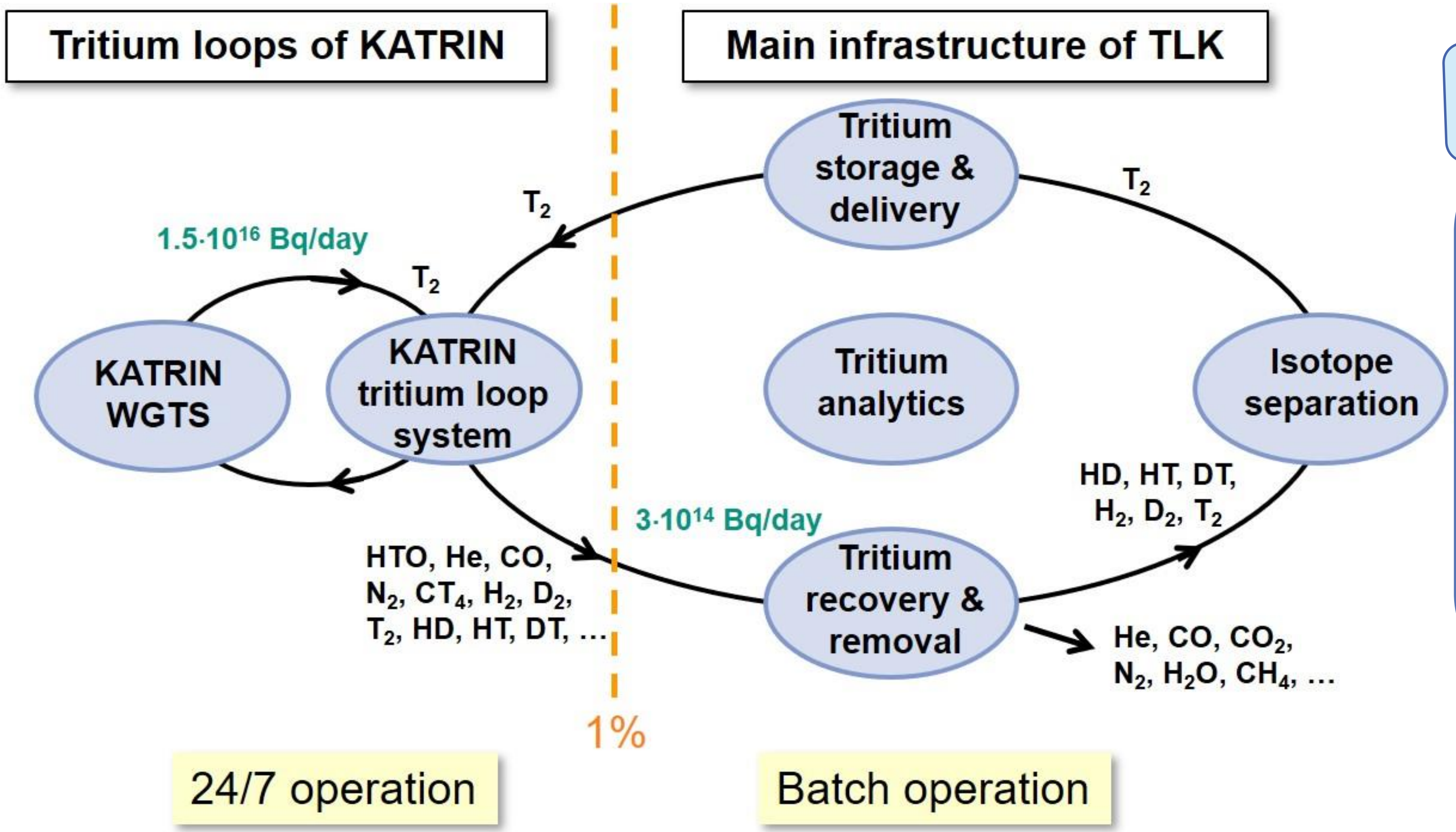
- Closed tritium cycle for recycling and purifying tritium in gram amounts
- 57 people including graduate/PhD students
- 2.2 M€/year base funding for operation
- 38 FTE base funding for personnel



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

Overview of the tritium supply structure



Tritium operation in numbers
2019 – now

- 982 days of circulation (T_2, Kr)
- 157 gas transfers to KATRIN
- 289 gas transfers to infrastructure

31.3 kg integral tritium throughput:

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

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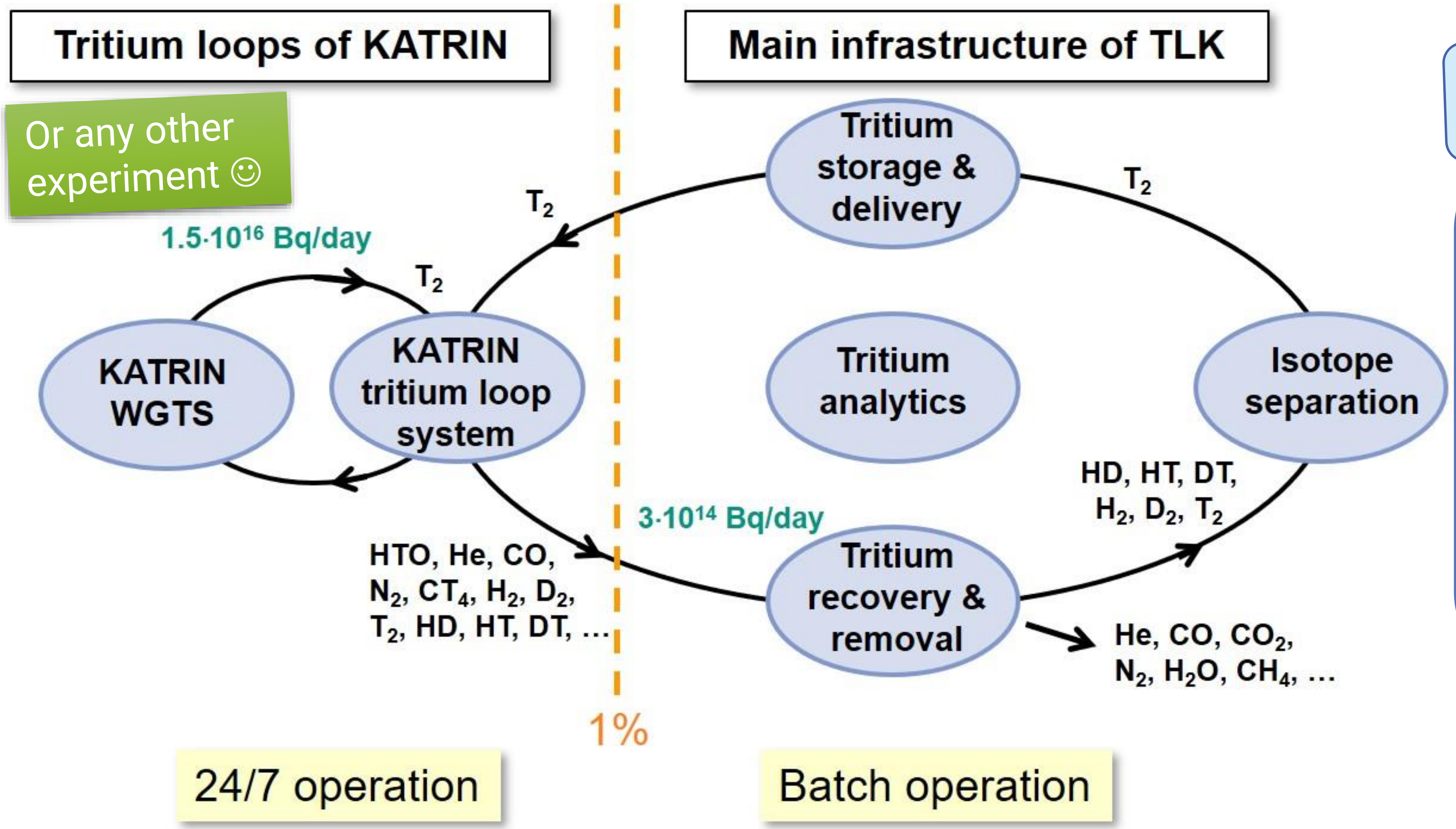

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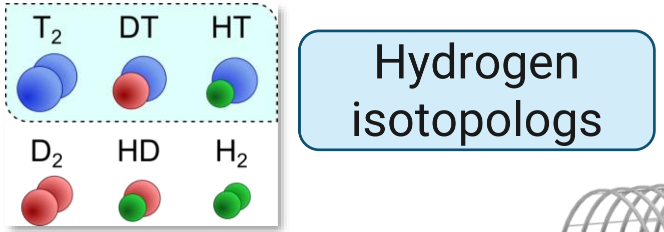
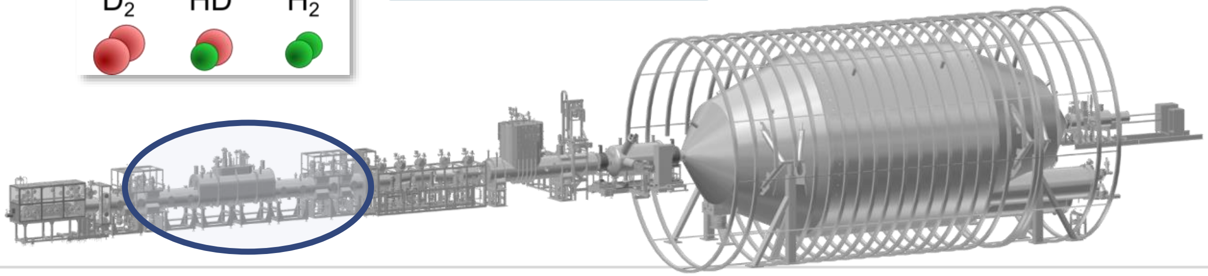
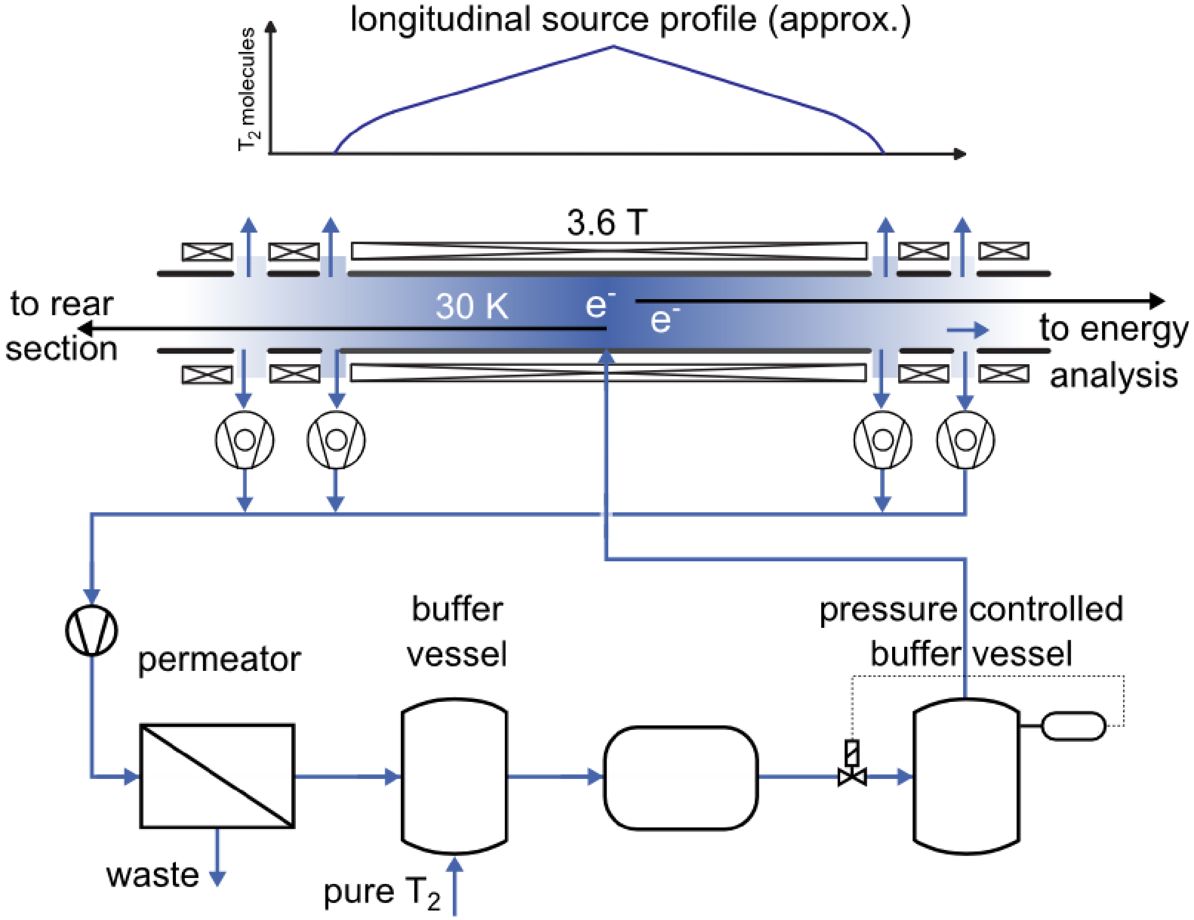
Gaseous molecular tritium source for KATRIN

- Source activity: 10^{11} Bq
  - Tritium throughput ≈ 40 g/day
  - Necessary inventory > 15 g
  - Operation 24/7, 60 days/run
- Source profile stable to 10^{-3} level
- T_2 purity > 98%







Measurement principle of the MAC-E filter spectrometer

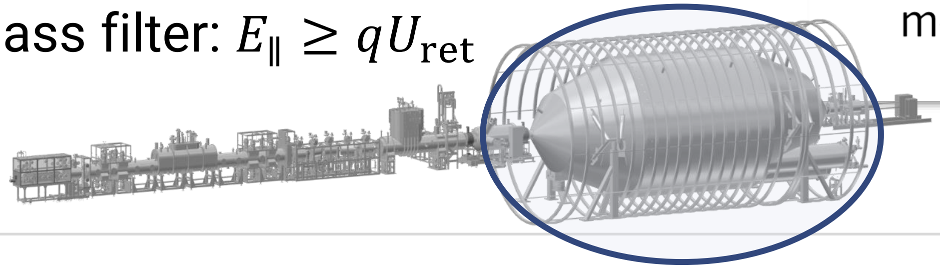
MAC Magnetic adiabatic collimation:

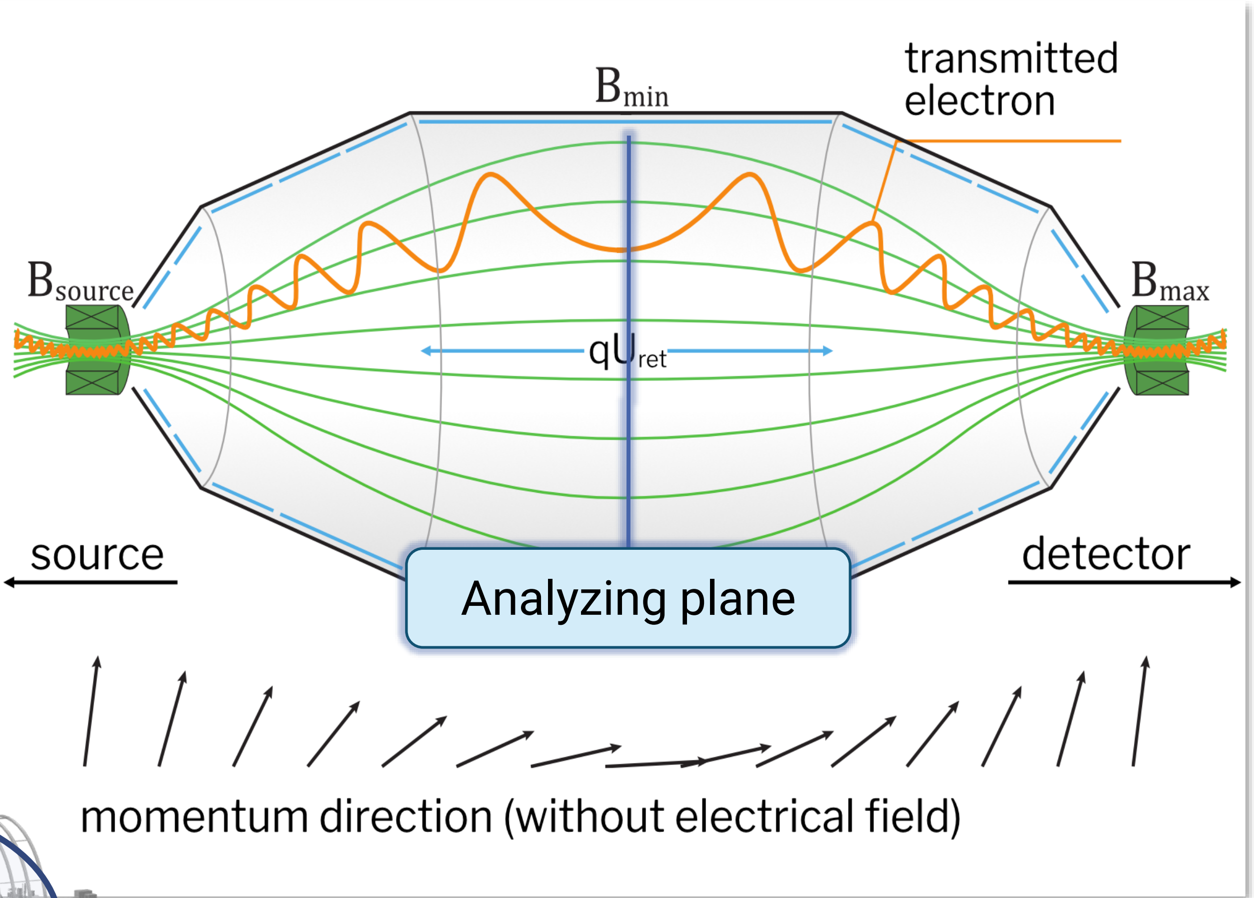
- Axially symmetric and smoothly diverging magnetic field
- Magnetic moment $\mu = \frac{e}{2m_e}\left|\vec{L}\right| = \frac{E_\perp}{B}$ is invariant
- At analyzing plane, transversal energy $E_\perp$ is minimal and

$$E_{\perp,\mathrm{Ana}} = E_{\mathrm{kin}} \cdot \sin^2\theta_{\mathrm{source}} \frac{B_{\mathrm{min}}}{B_{\mathrm{source}}}$$

E Electrostatic filter

- High-pass filter: $E_\parallel \geq qU_{\mathrm{ret}}$





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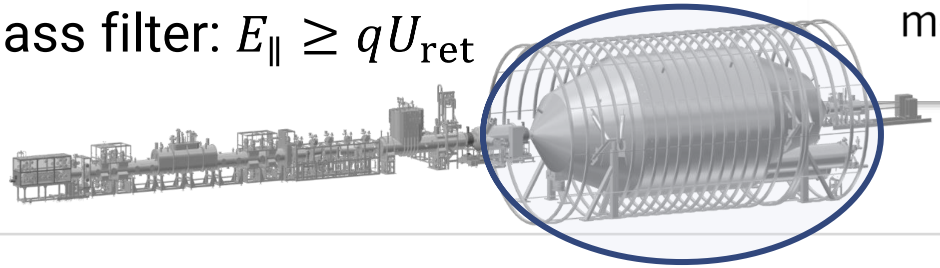
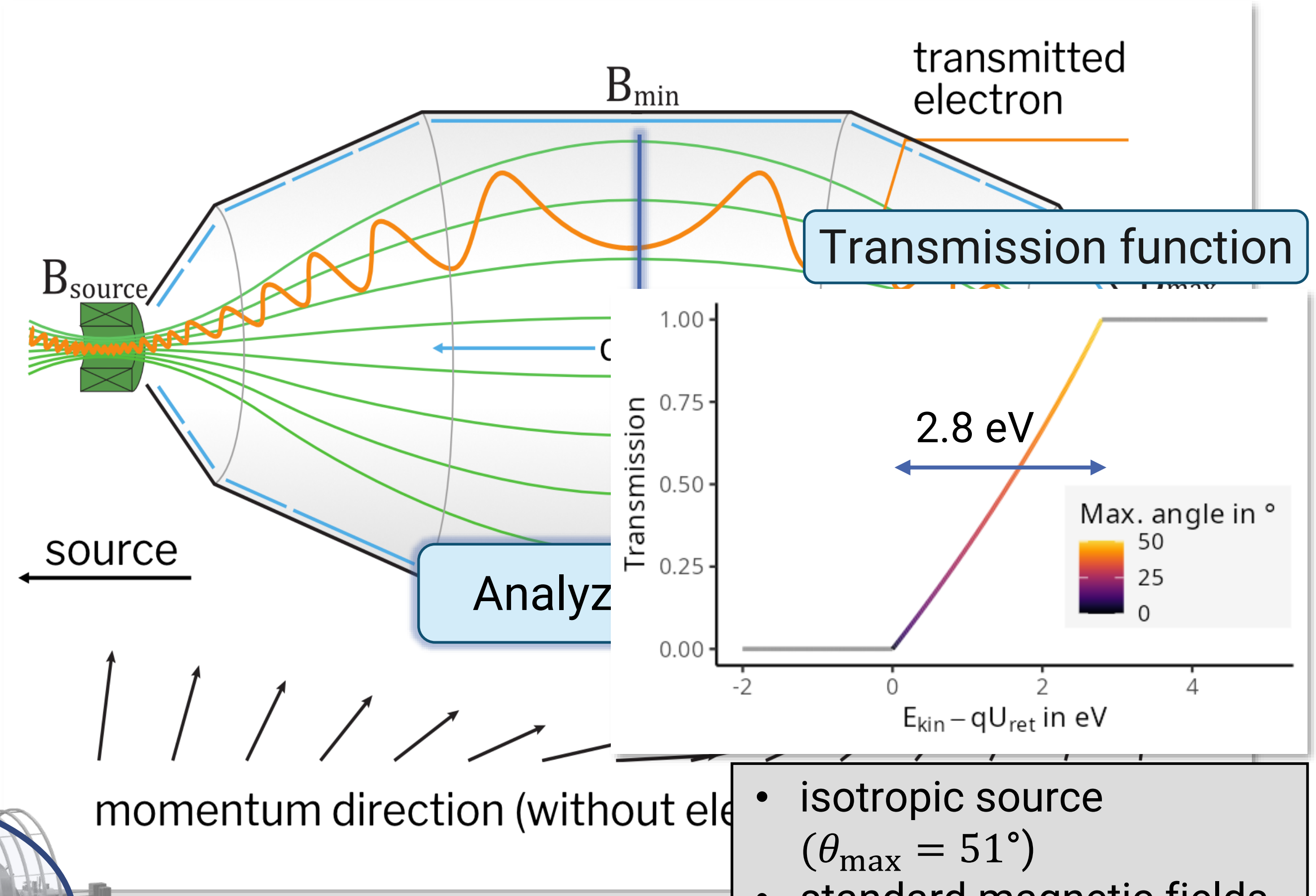
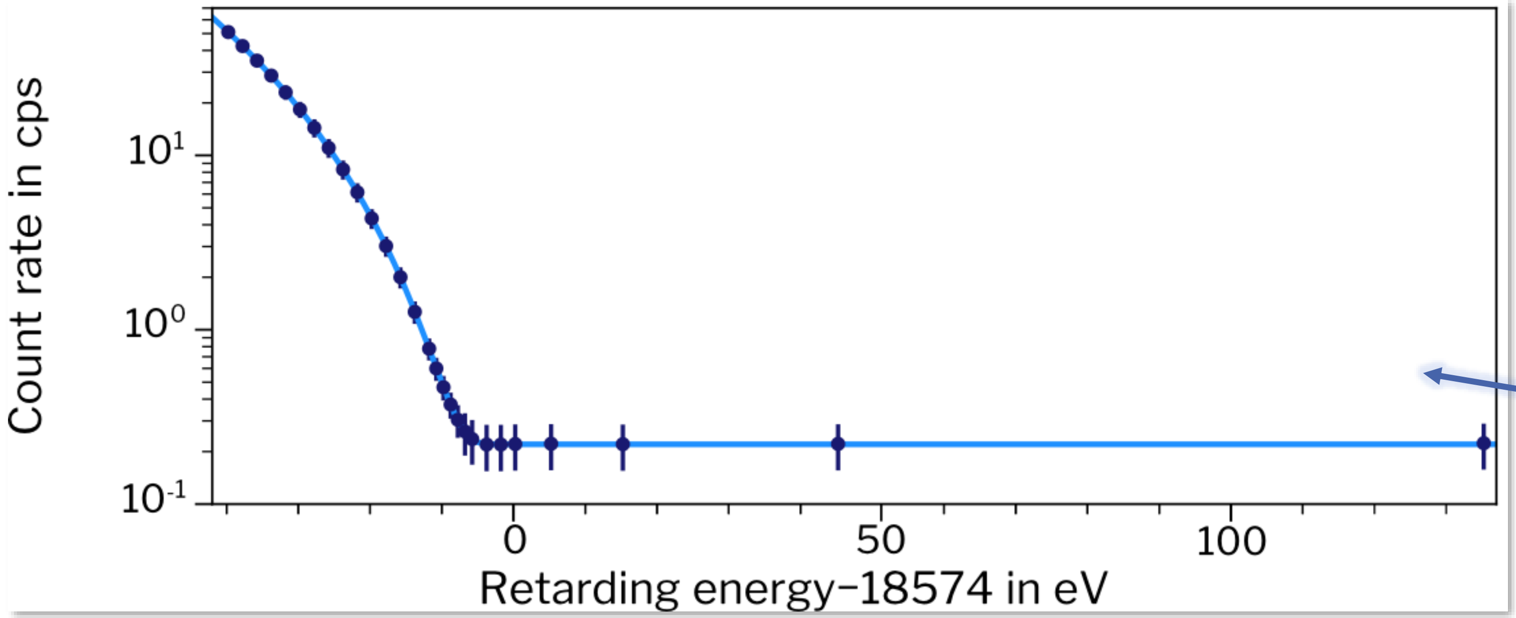




- isotropic source ($\theta_{\mathrm{max}} = 51°$)
- standard magnetic fields
- $U_{\mathrm{ret}} = -18.6\ \mathrm{kV}$

Measurement of the neutrino mass



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

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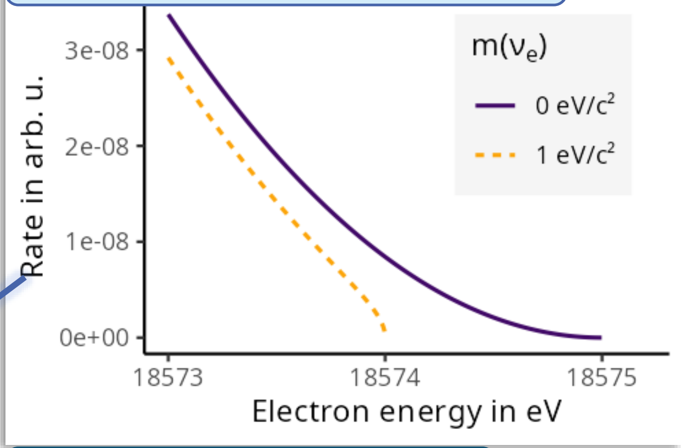
Beta decay spectrum



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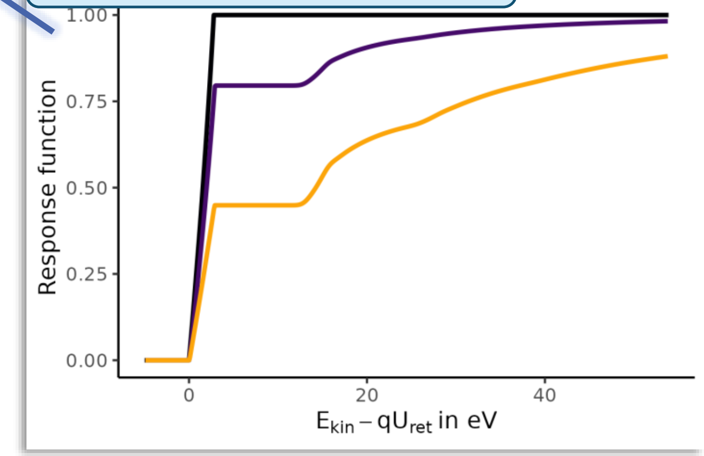
Response function



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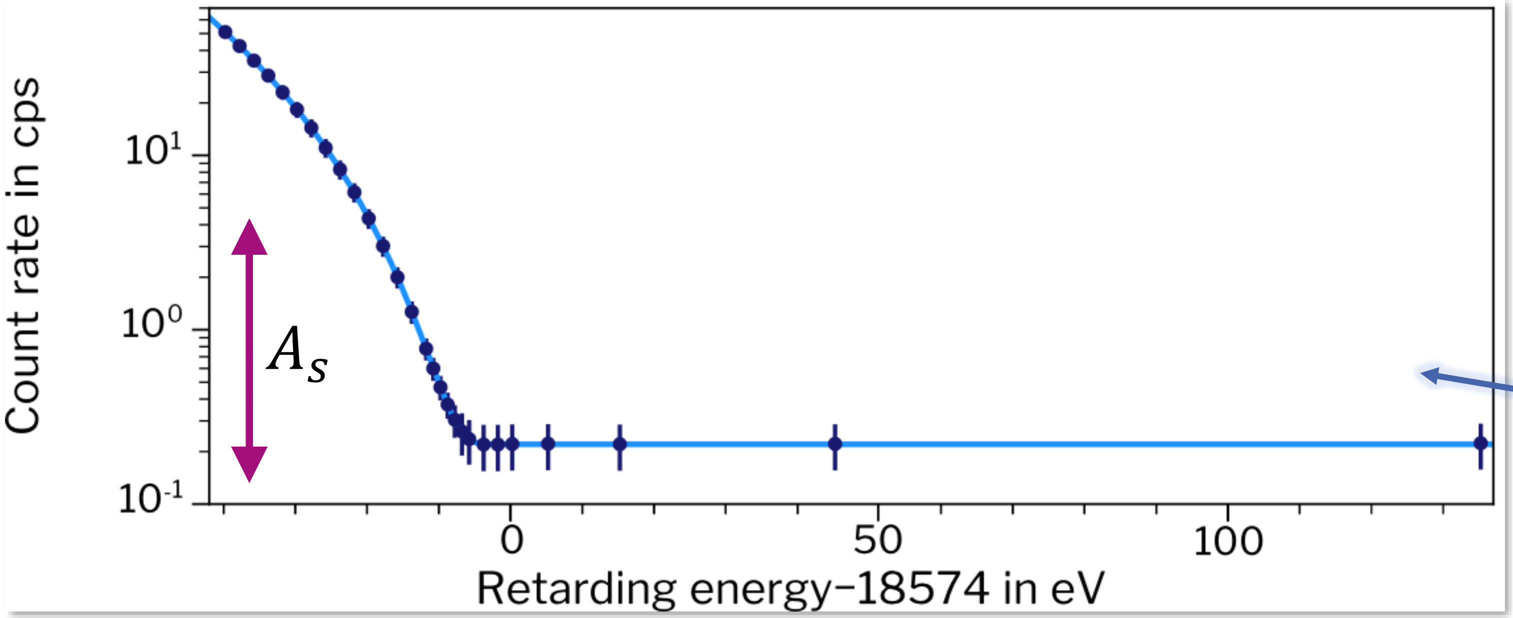

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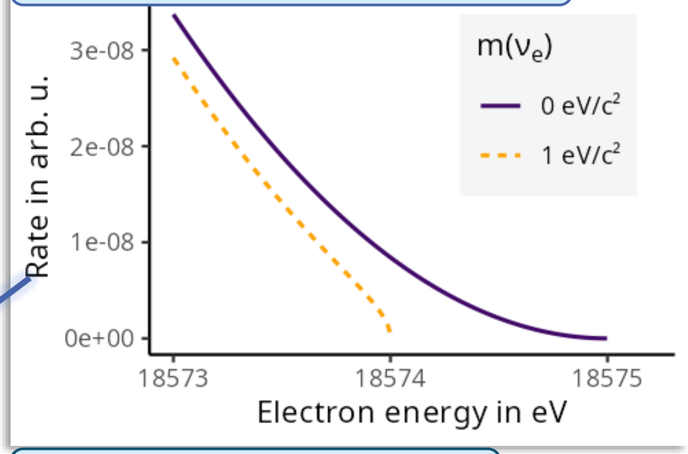
Beta decay spectrum



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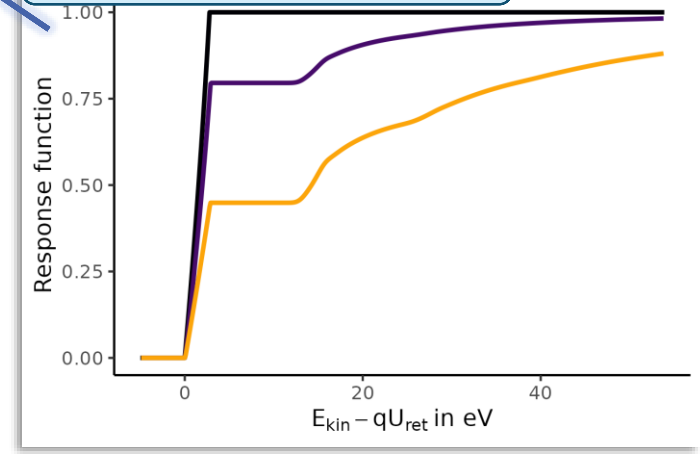
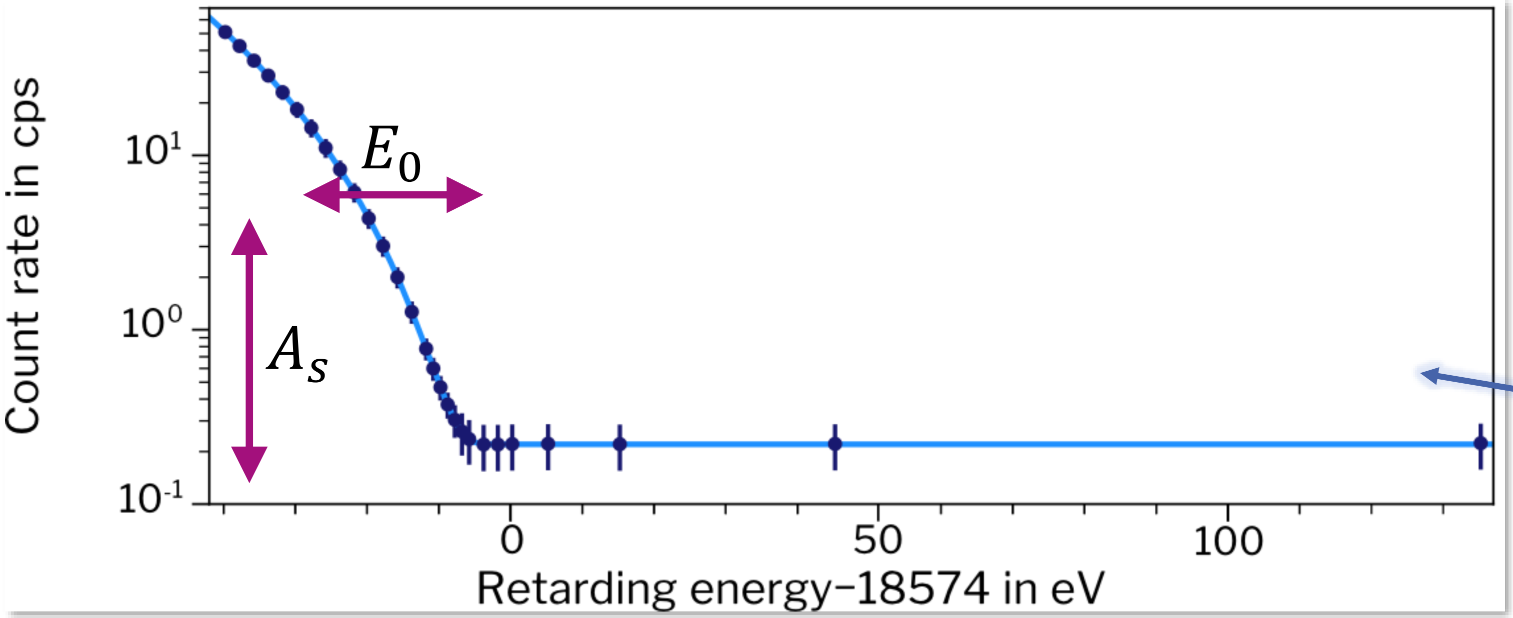
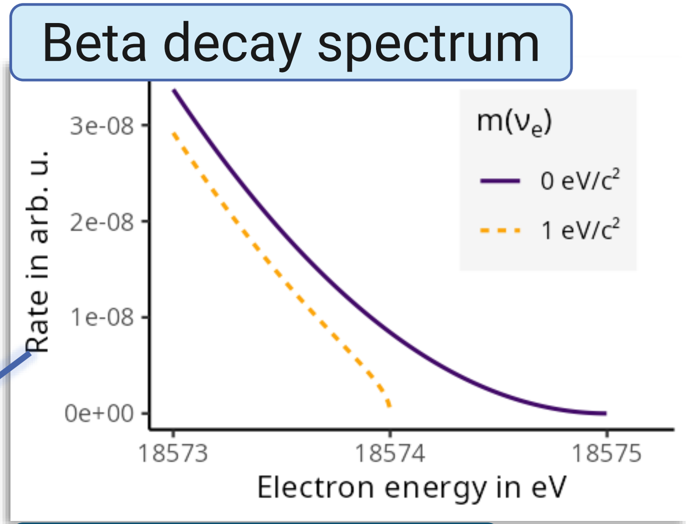
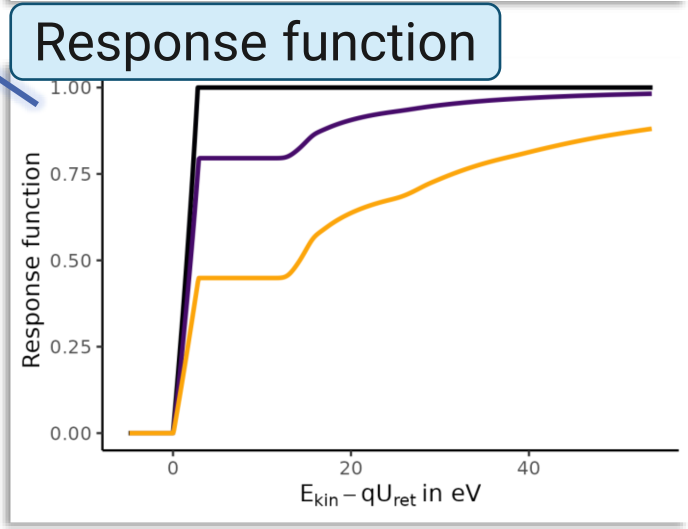


Measurement of the neutrino mass



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





$$R(qU_{\text{ret}}) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E, qU_{\text{ret}})\mathrm{dE} + R_{\text{bg}}(qU_{\text{ret}})$$

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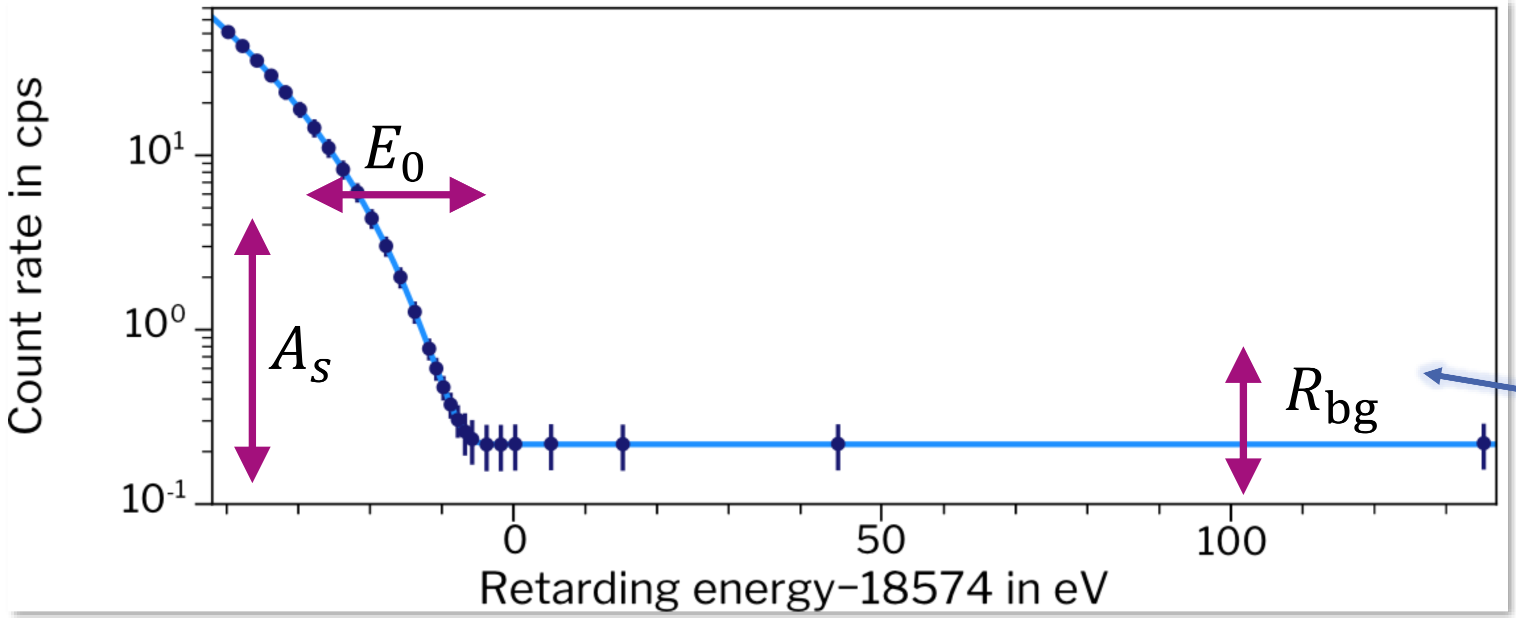

KATRIN Collaboration, Nat. Phys. 18, 160–166 (2022)

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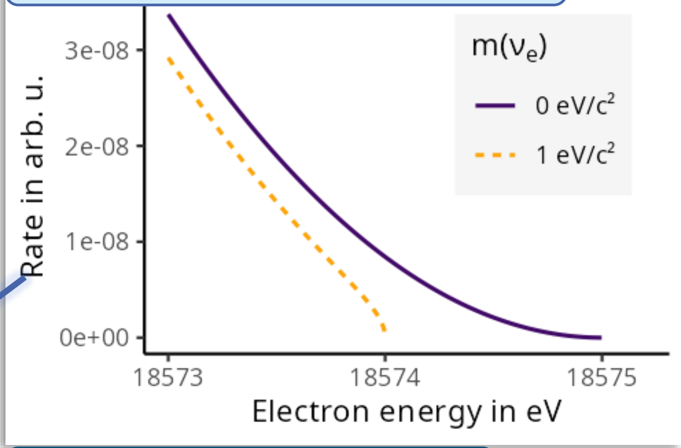
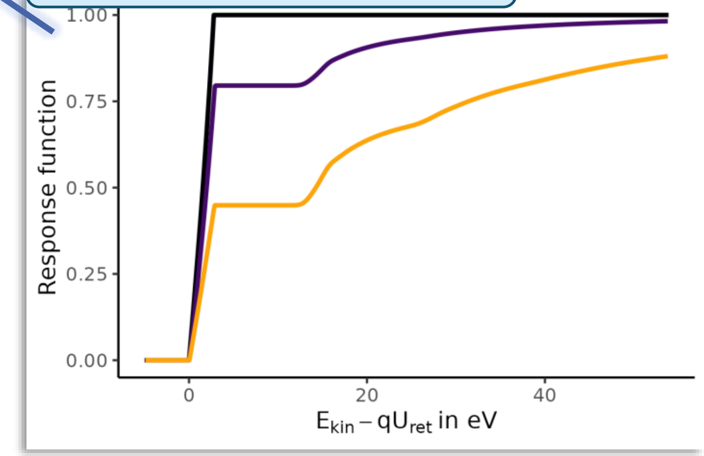
Beta decay spectrum

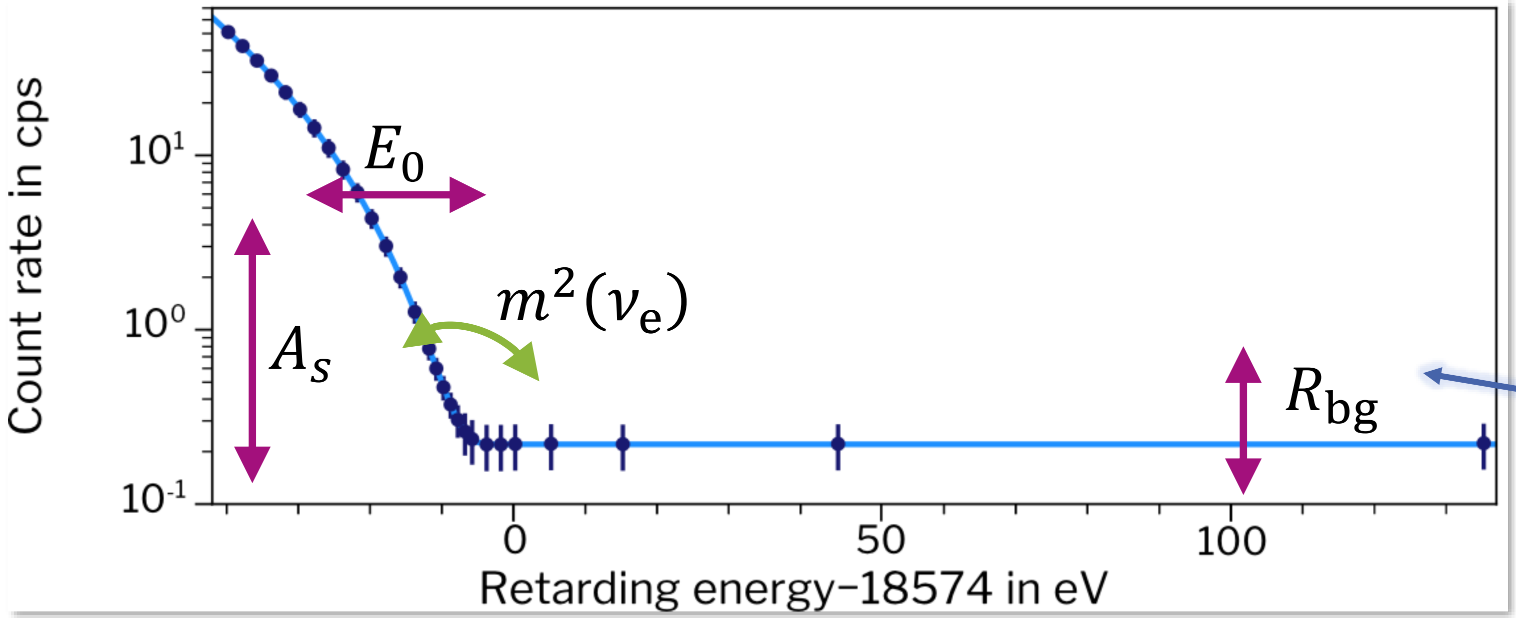


$\otimes$

Response function



Measurement of the neutrino mass



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

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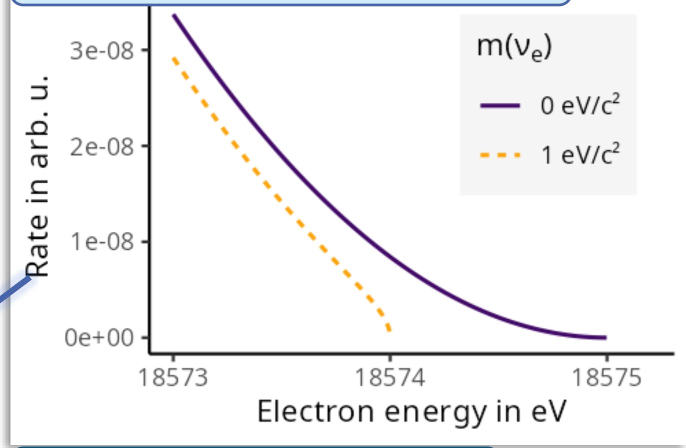

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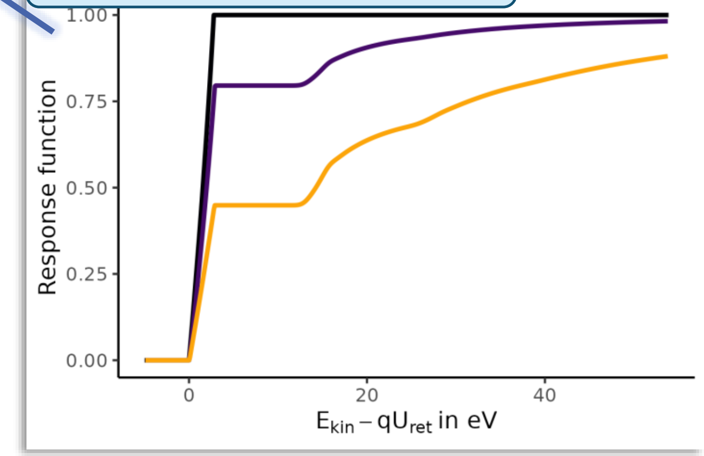

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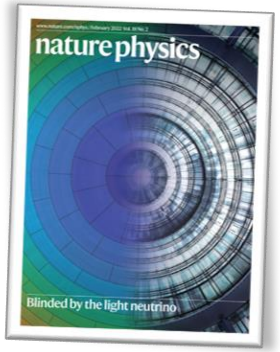
Recent results from KATRIN

- First campaign
  (“KNM1”, spring 2019)
  - total stat.: 2 million events
  - best fit: $m^2(\nu_e) = -1.0^{+0.9}_{-1.1}\text{eV}^2$
  - limit: $m(\nu_e) < 1.1$ eV (90% C.L.)

Phys. Rev. Lett. 123, 221802 (2019)
Phys. Rev. D. 104 (1), 012005 (2021)

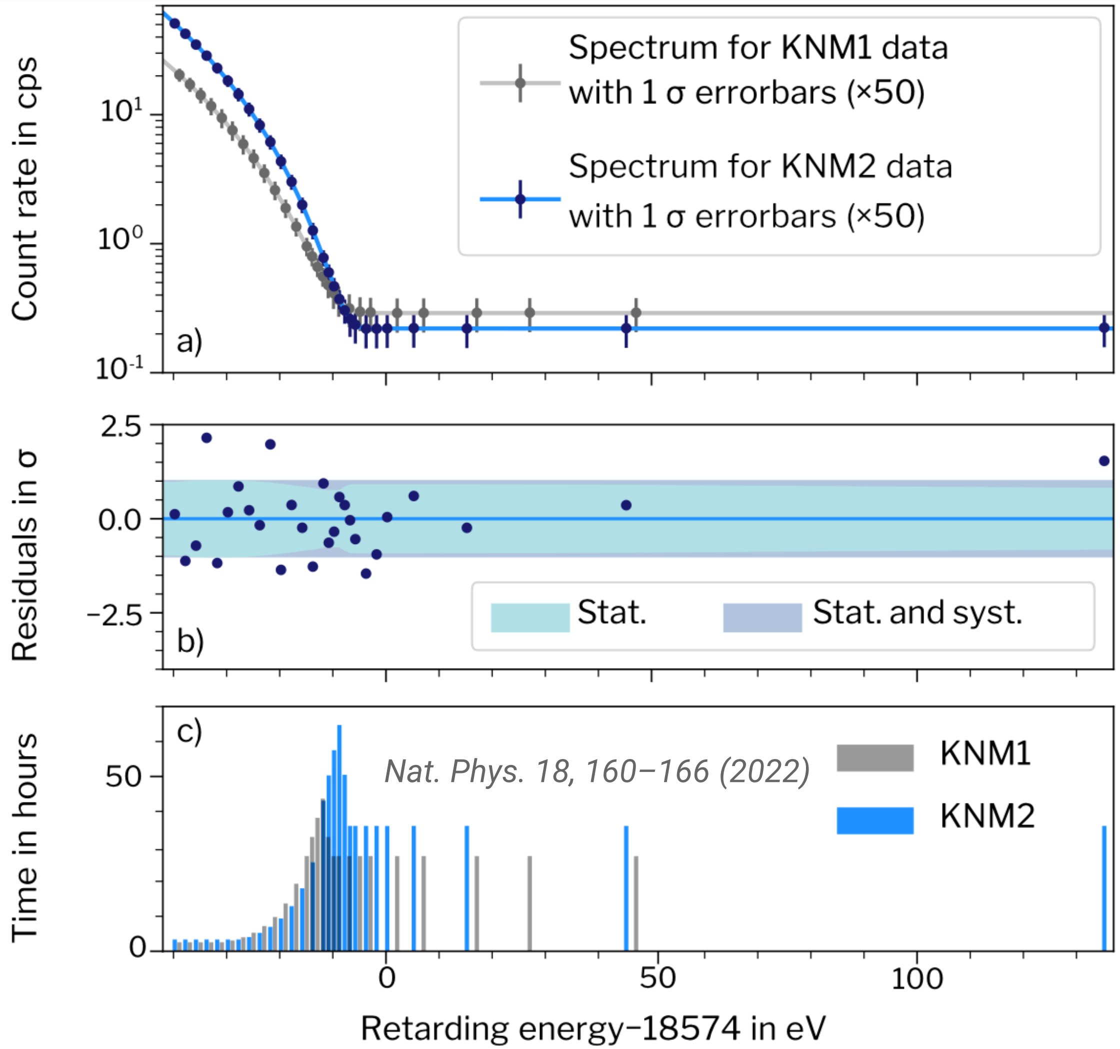
- Second campaign
  (“KNM2”, autumn 2019)
  - total stat.: 4.3 million events
  - best fit: $m^2(\nu_e) = 0.26^{+0.34}_{-0.34}\text{eV}^2$
  - limit: $m(\nu_e) < 0.9$ eV (90% C.L.)



- **Combined result:**
  $\mathbf{m(\nu_e) < 0.8}$ **eV (90% C.L.)**

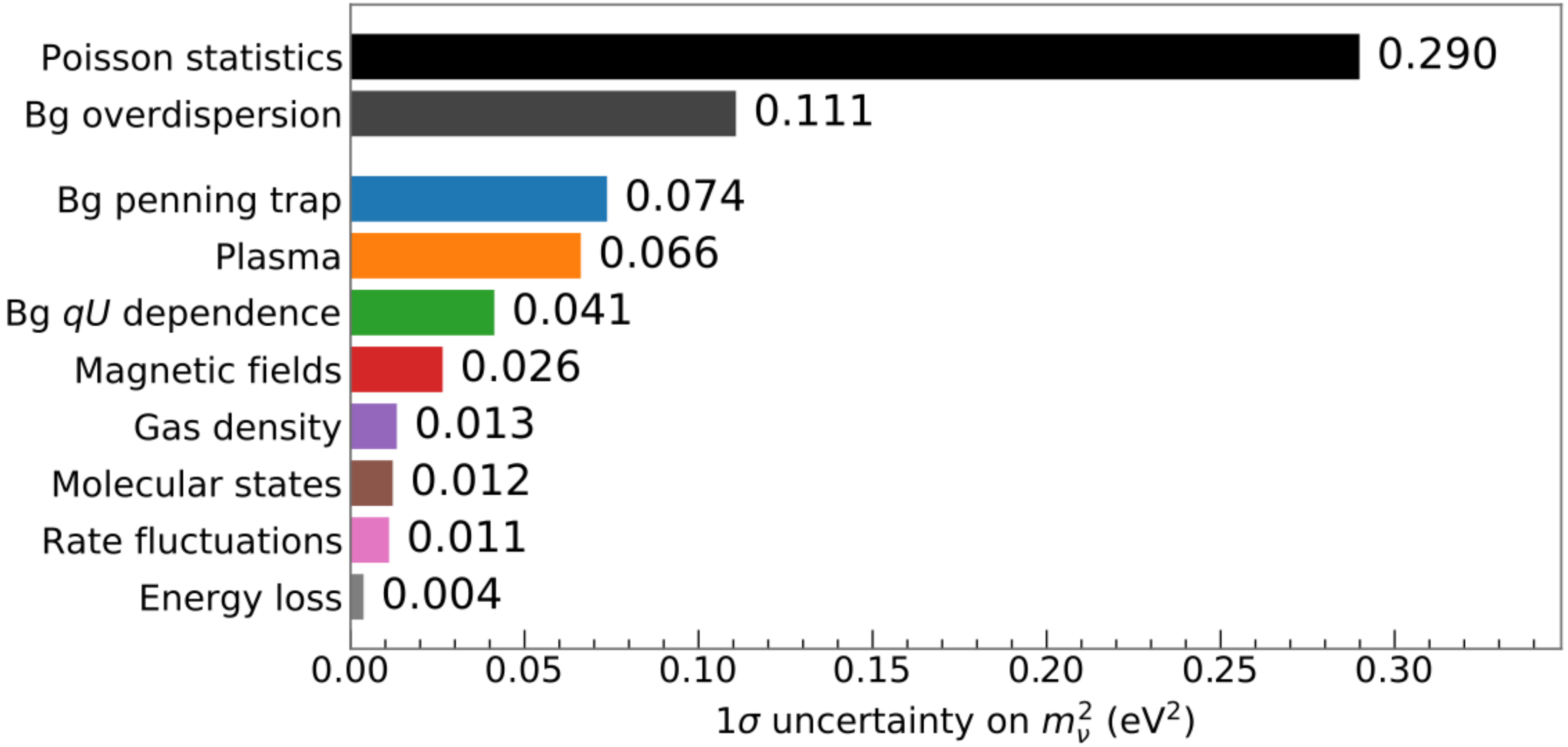
Nat. Phys. 18, 160–166 (2022)

KNM: KATRIN Neutrino Mass measurement

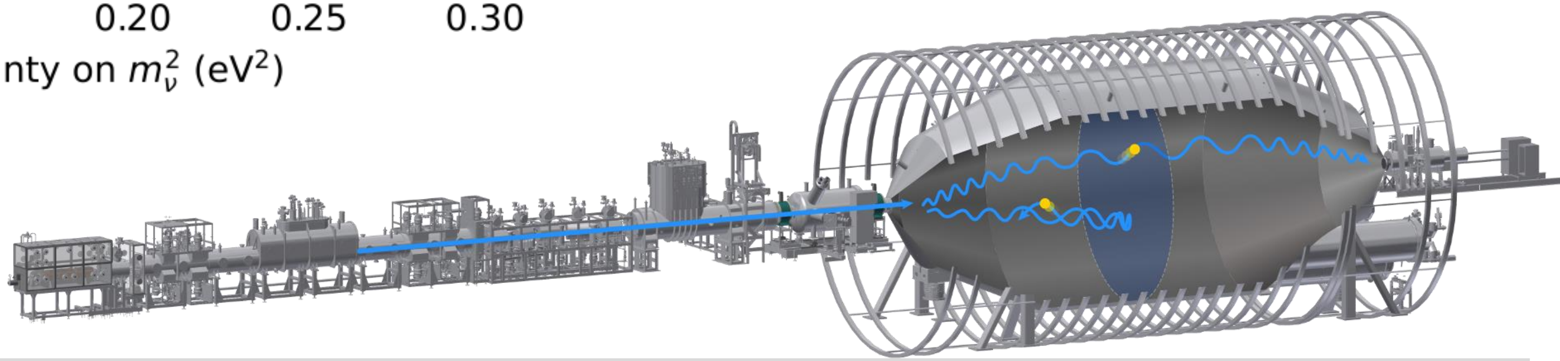


Nat. Phys. 18, 160–166 (2022)

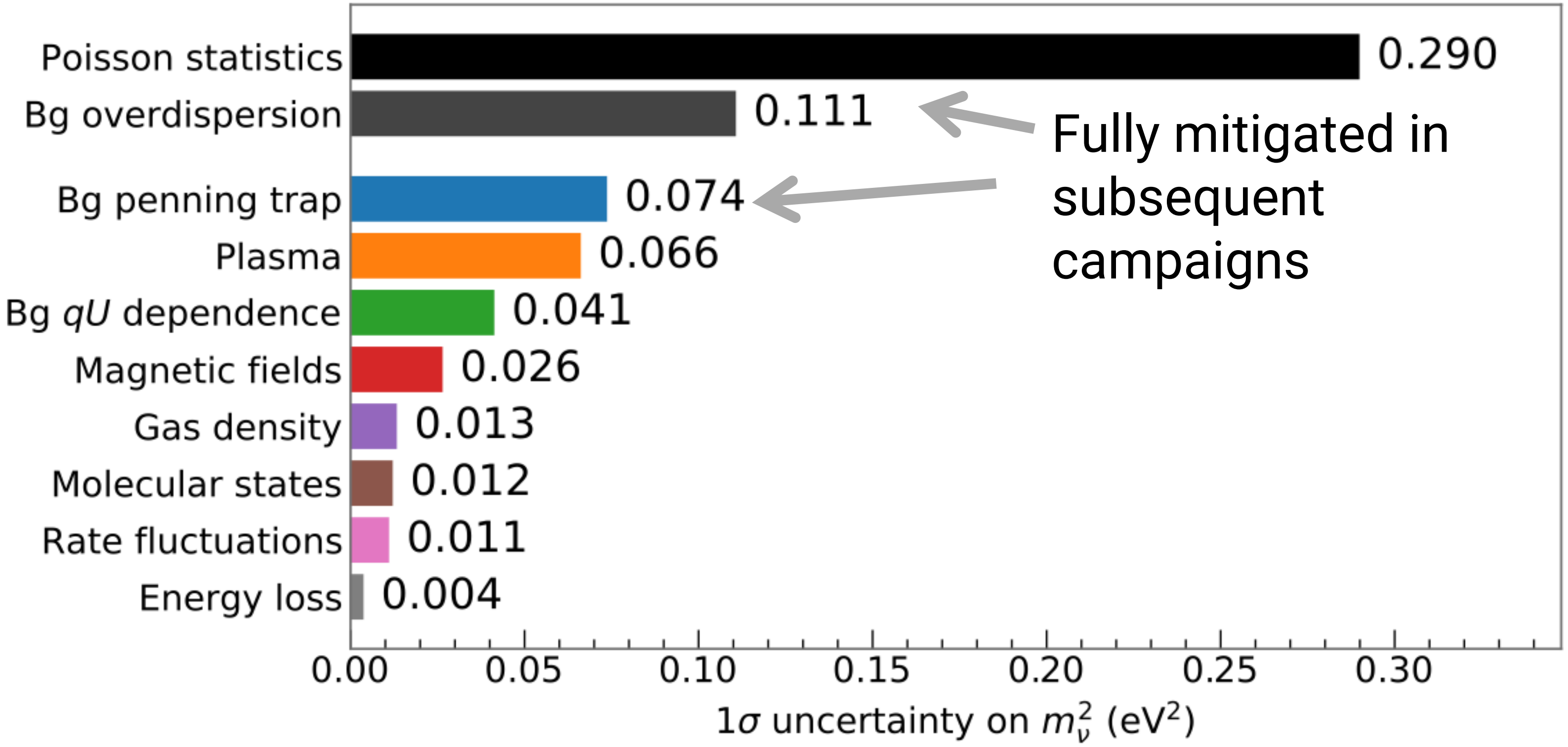
Systematic uncertainties



Status of systematic uncertainties for initial data taking of KNM2, substantial improvements from KNM3 on.



Systematic uncertainties



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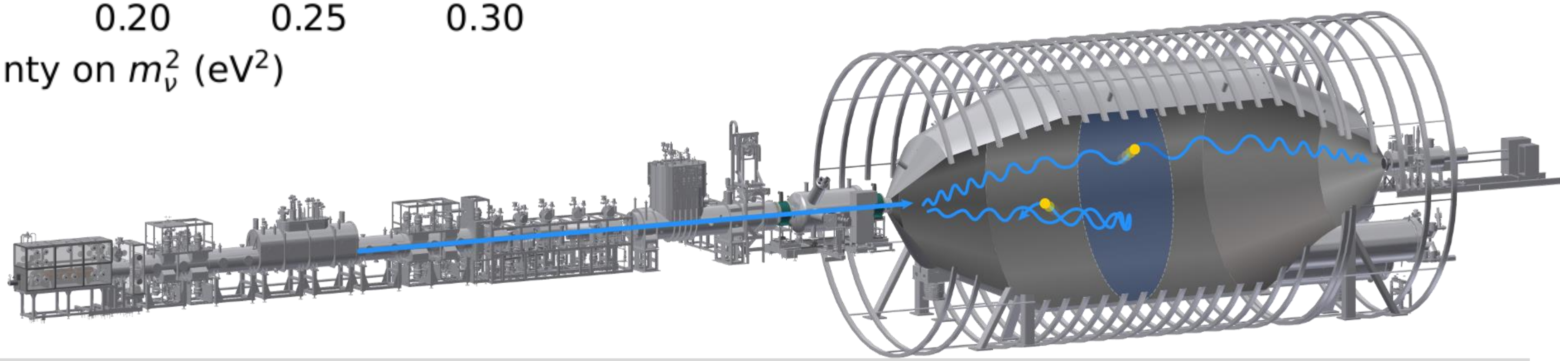
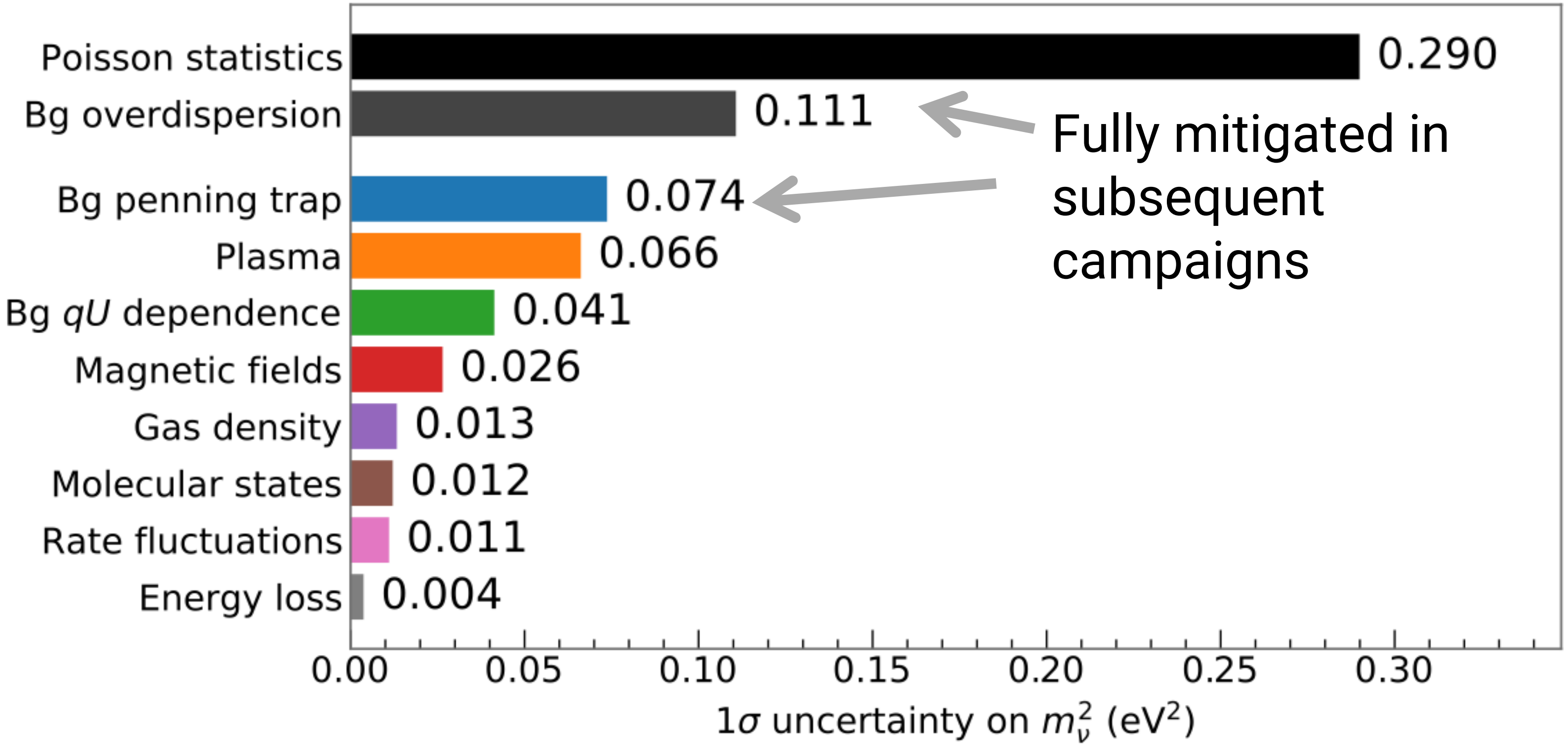


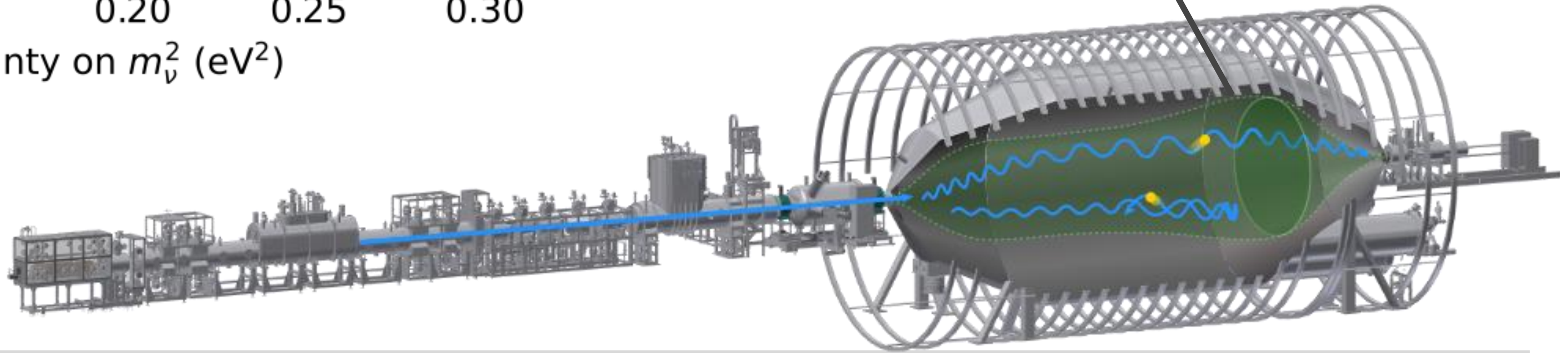
Systematic uncertainties



Status of systematic uncertainties for initial data taking of KNM2, substantial improvements from KNM3 on.

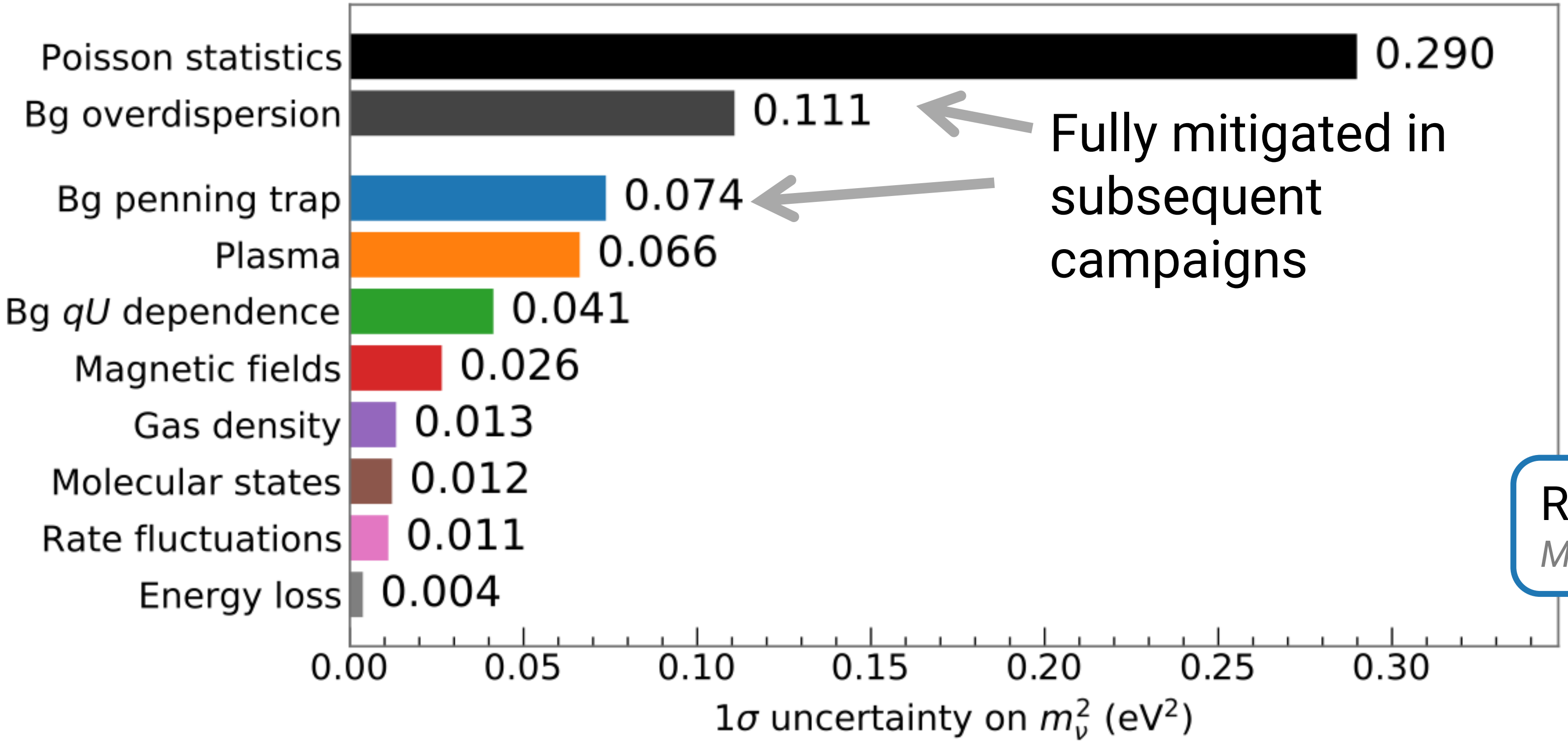
Shifted analyzing plane

A.Lokhov et al. Eur. Phys. J. C 82:258 (2022)



Systematic uncertainties

Karlsruhe Institute of Technology

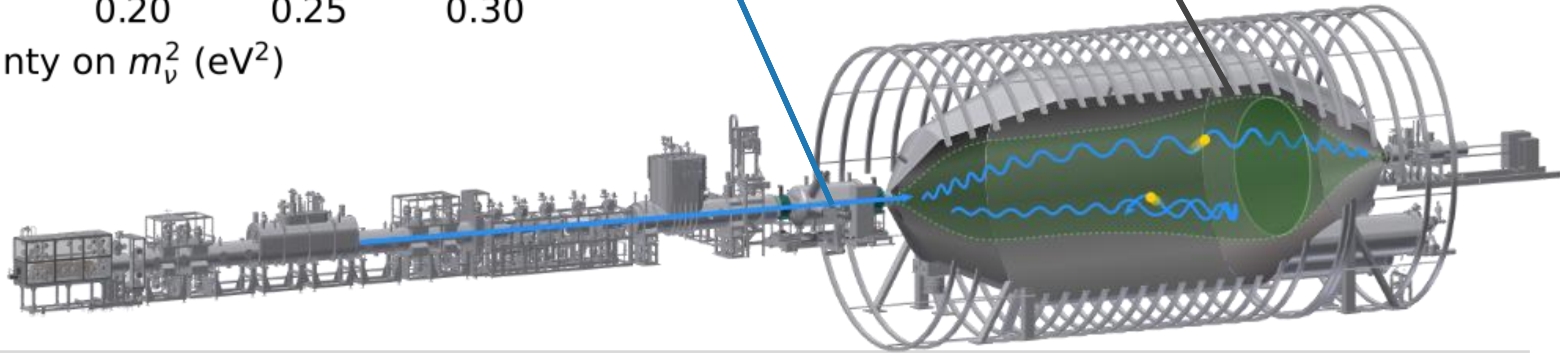


Fully mitigated in subsequent campaigns

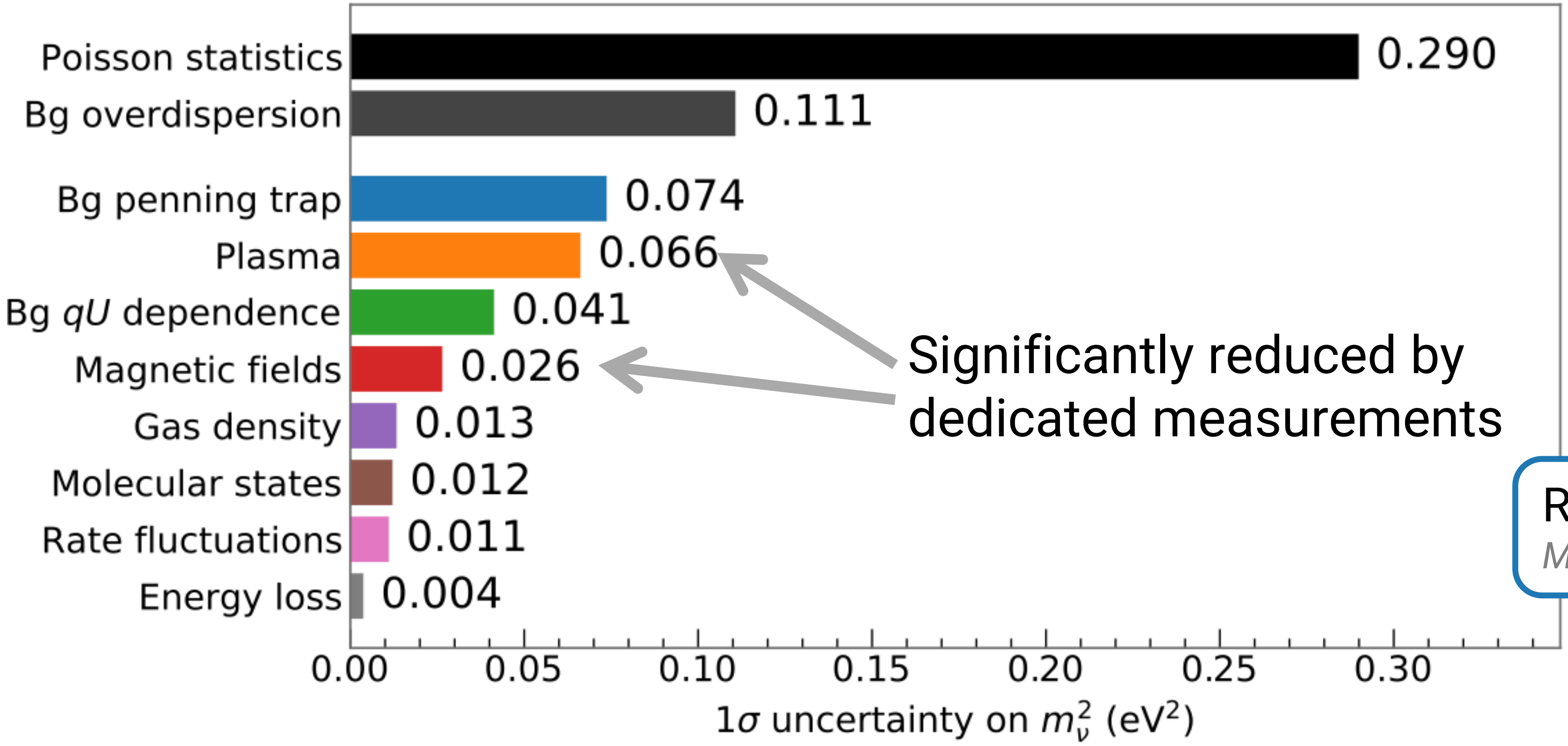
Status of systematic uncertainties for initial data taking of KNM2, substantial improvements from KNM3 on.

Shifted analyzing plane
A.Lokhov et al. Eur. Phys. J. C 82:258 (2022)

Removal of the penning trap
M. Aker et al. Eur. Phys. J. C 80: 821 (2020)



Systematic uncertainties



Significantly reduced by dedicated measurements

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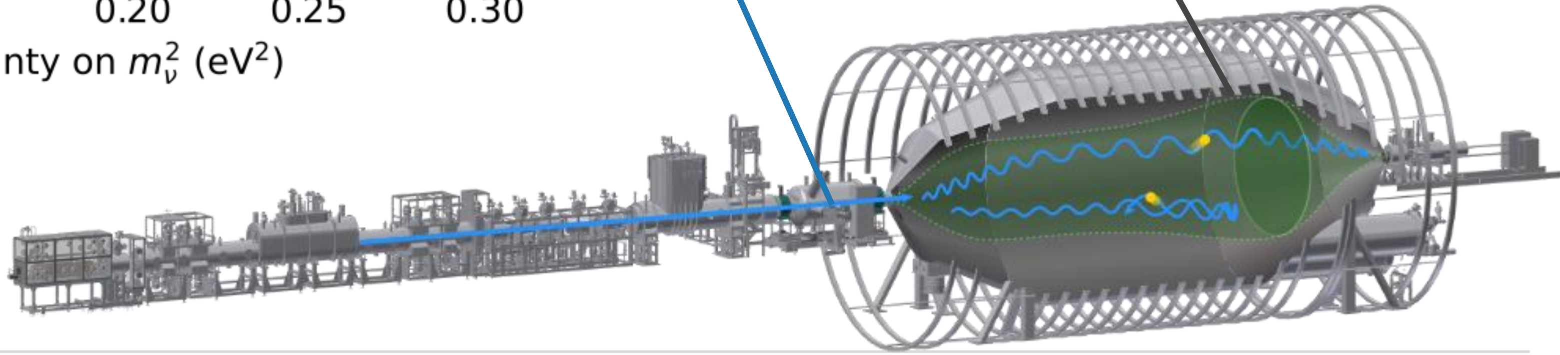

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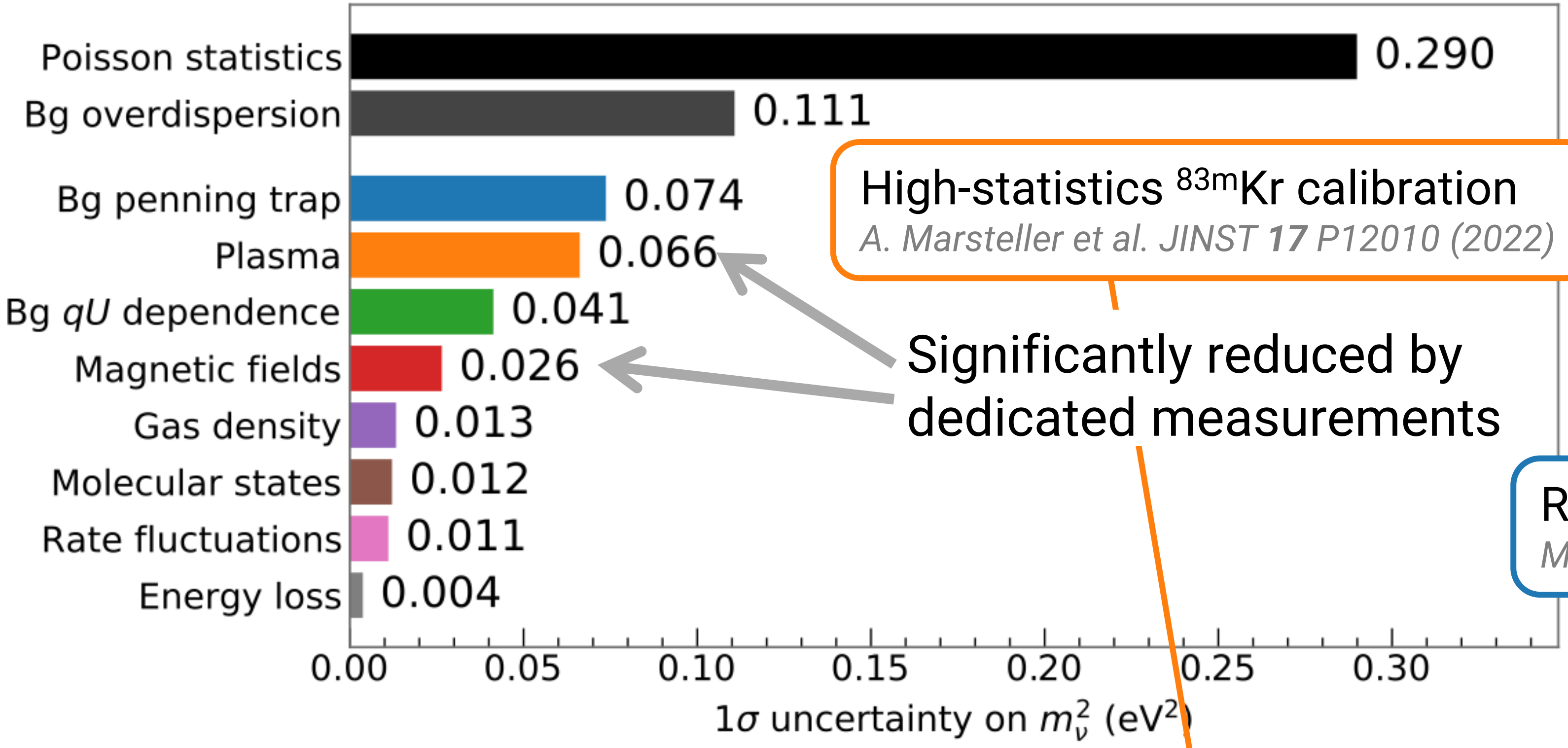

High-statistics ^{83m}Kr calibration
*A. Marsteller et al. JINST **17** P12010 (2022)*

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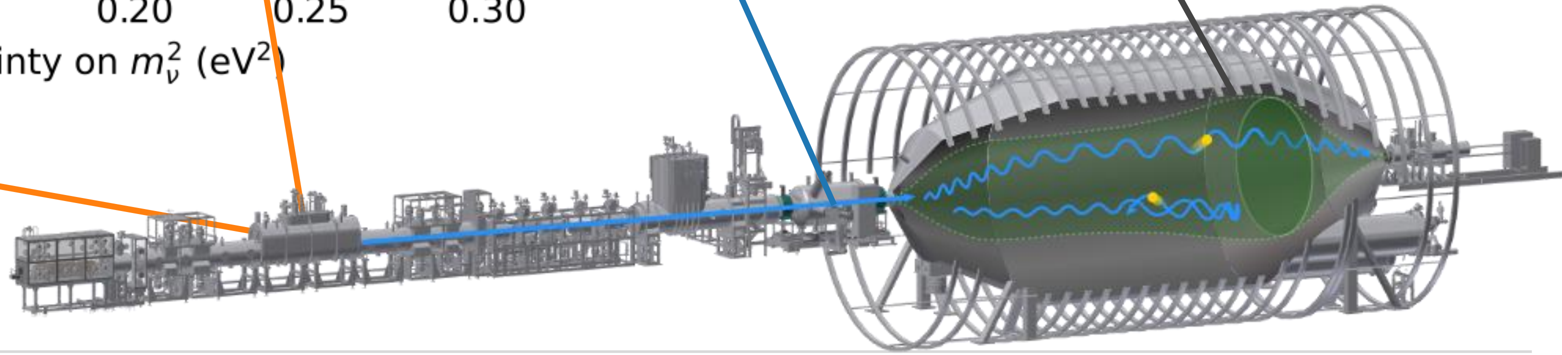
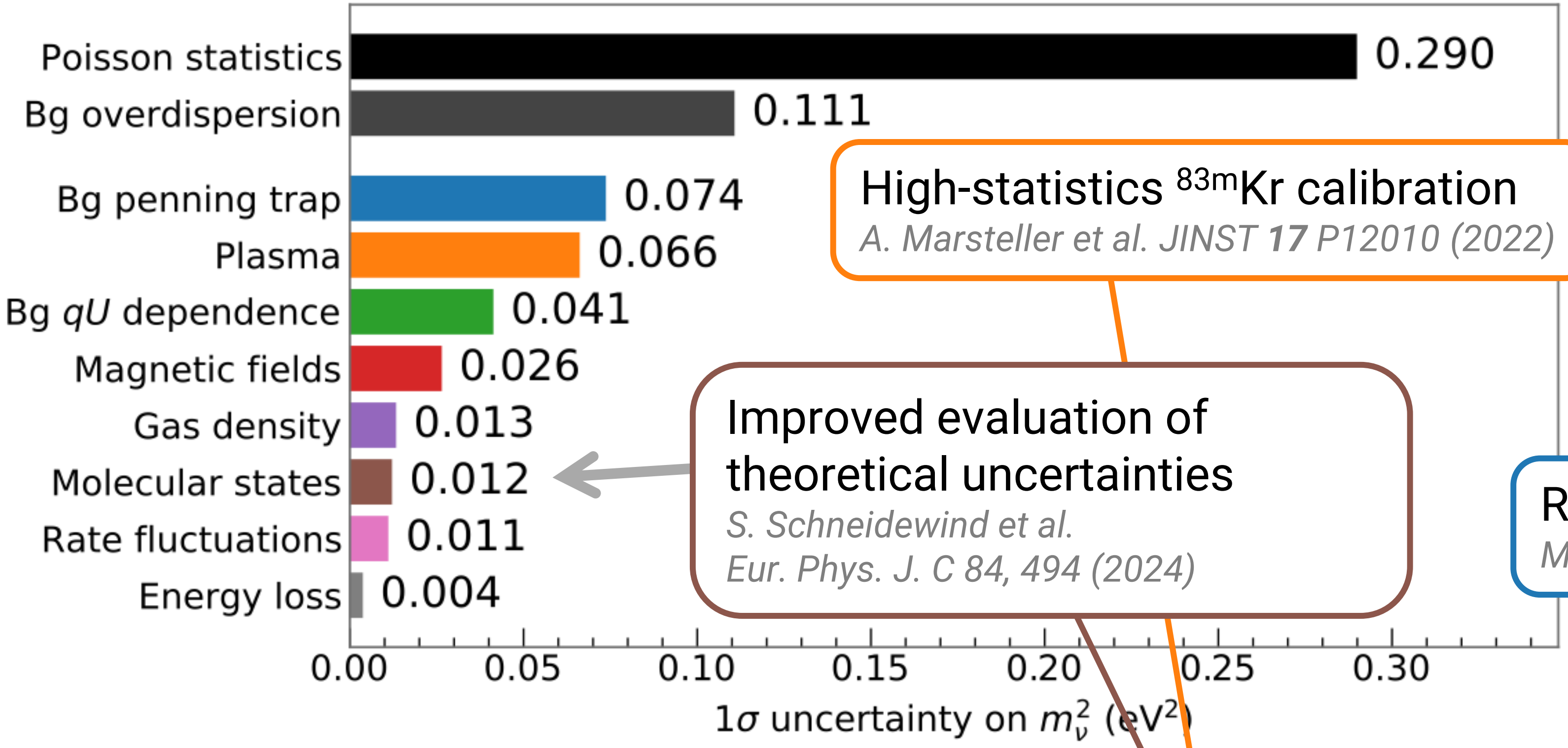
Absolute energy scale calibration
C. Rodenbeck Eur. Phys. J. C 82:700 (2022)



Systematic uncertainties



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High-statistics ^{83m}Kr calibration
*A. Marsteller et al. JINST **17** P12010 (2022)*

Improved evaluation of theoretical uncertainties
S. Schneidewind et al.
Eur. Phys. J. C 84, 494 (2024)

Shifted analyzing plane
A.Lokhov et al. Eur. Phys. J. C 82:258 (2022)

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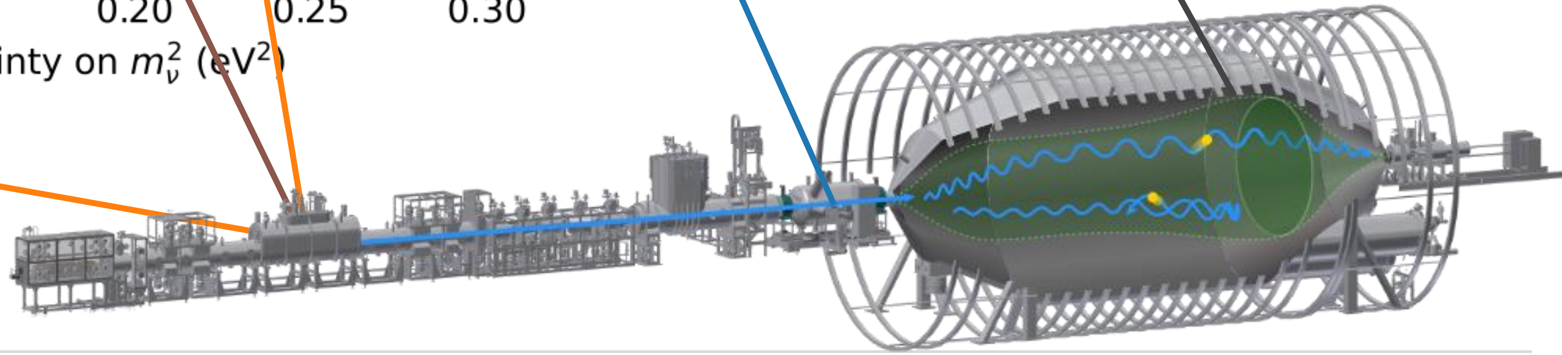
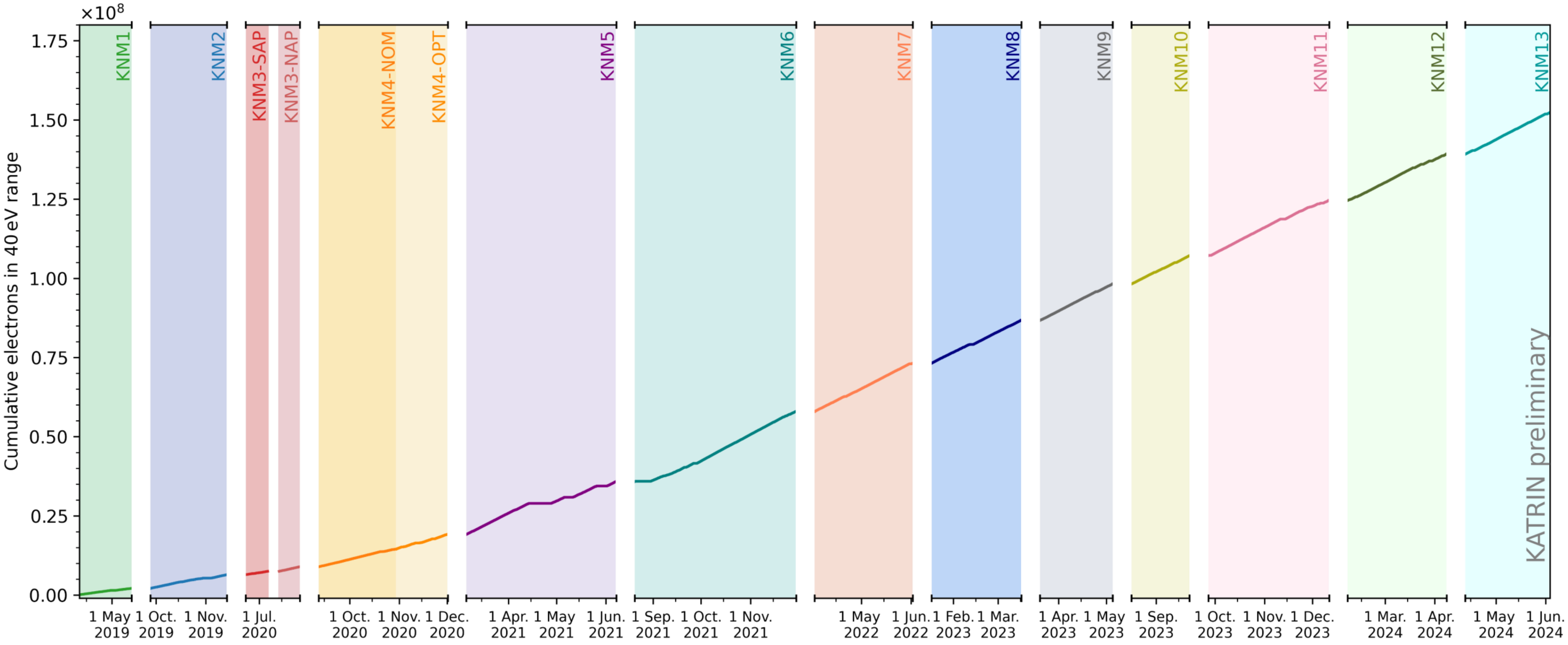
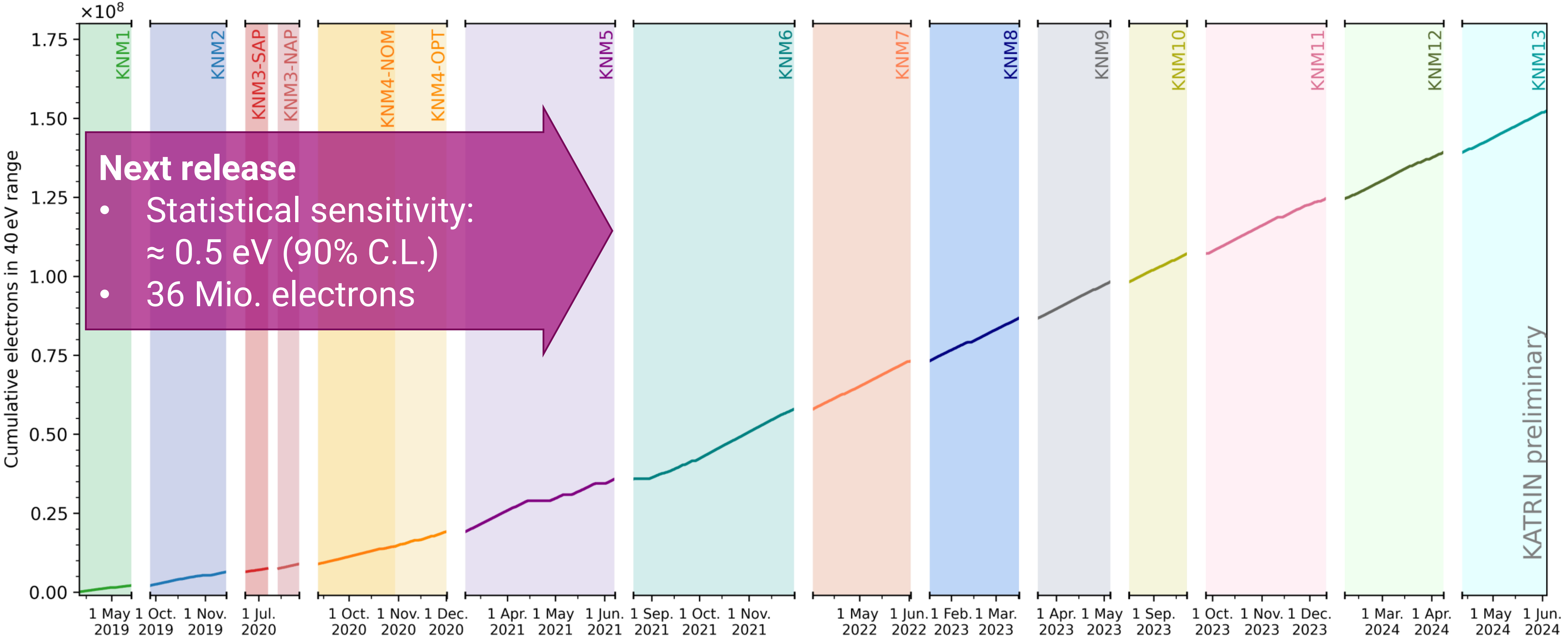


KATRIN data taking

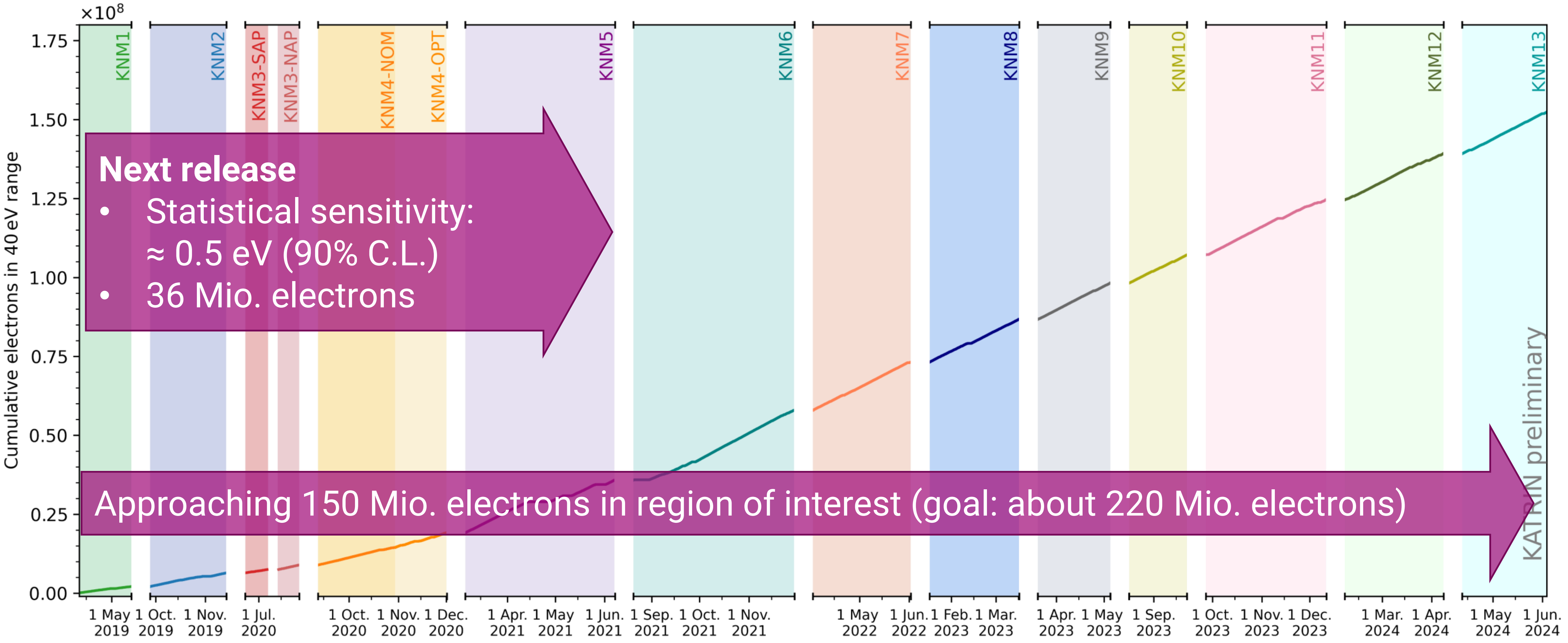


KATRIN data taking



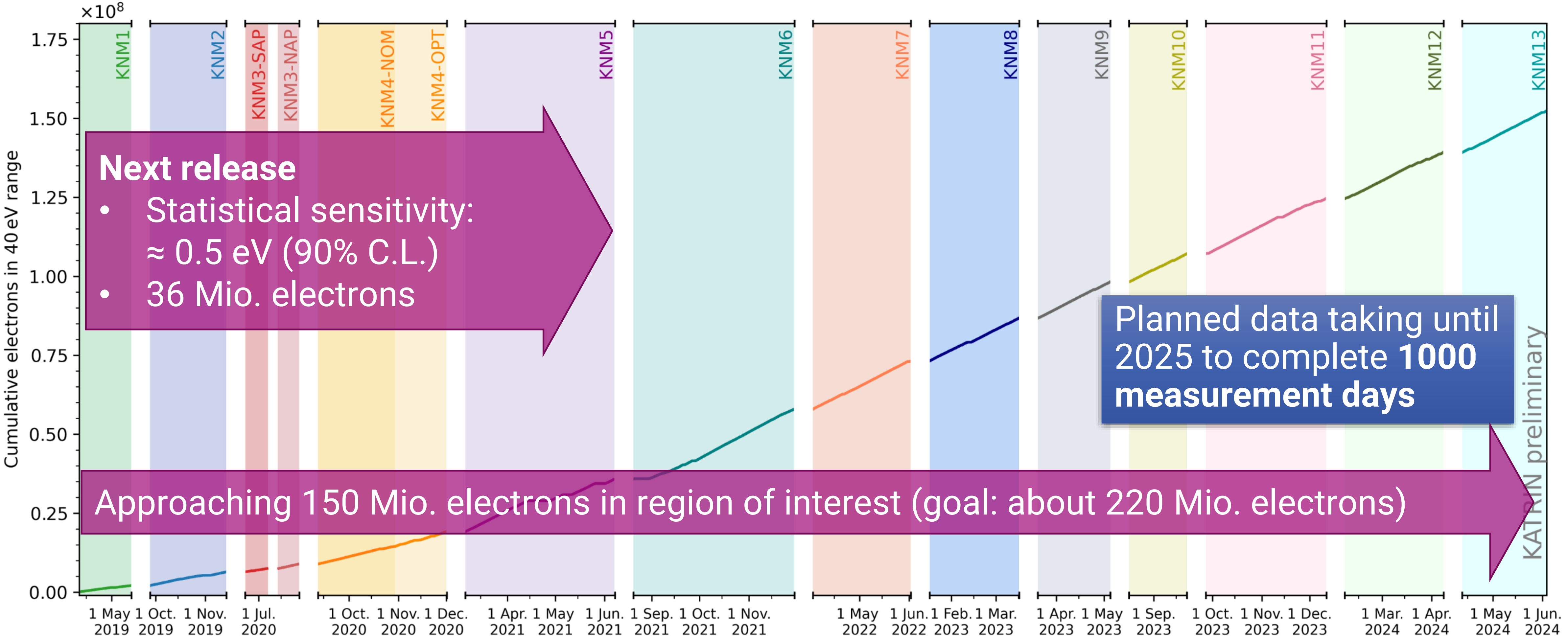
Next release
- Statistical sensitivity: ≈ 0.5 eV (90% C.L.)
- 36 Mio. electrons

KATRIN data taking



KATRIN data taking

Karlsruhe Institute of Technology



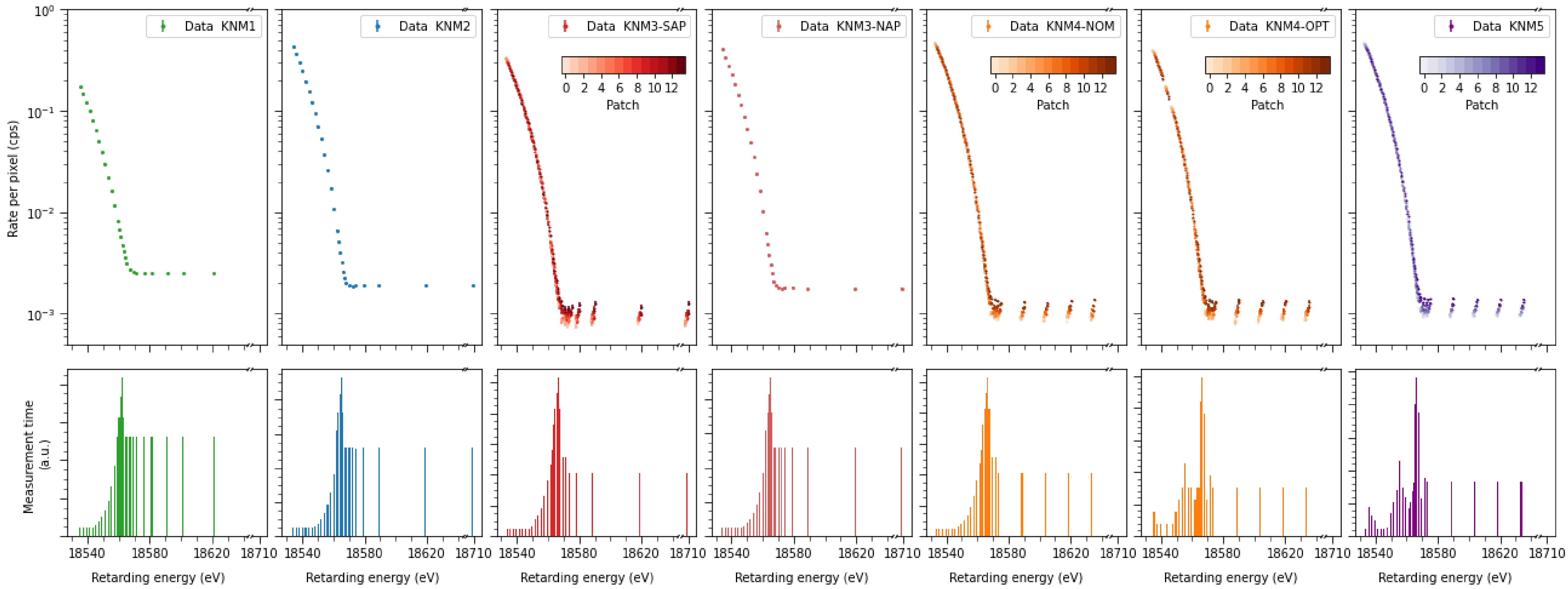
Next release

- Statistical sensitivity: ≈ 0.5 eV (90% C.L.)
- 36 Mio. electrons

Planned data taking until 2025 to complete **1000 measurement days**

Approaching 150 Mio. electrons in region of interest (goal: about 220 Mio. electrons)

Preview: upcoming release



- Analysis of first 5 campaigns (statistics x 6, improved systematics and lower background)

Neutrino mass measurements with KATRIN and Beyond

Karlsruhe Institute of Technology

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		Quantum sensor demonstrator	
Atomic tritium R&D		Atomic tritium demonstrator	

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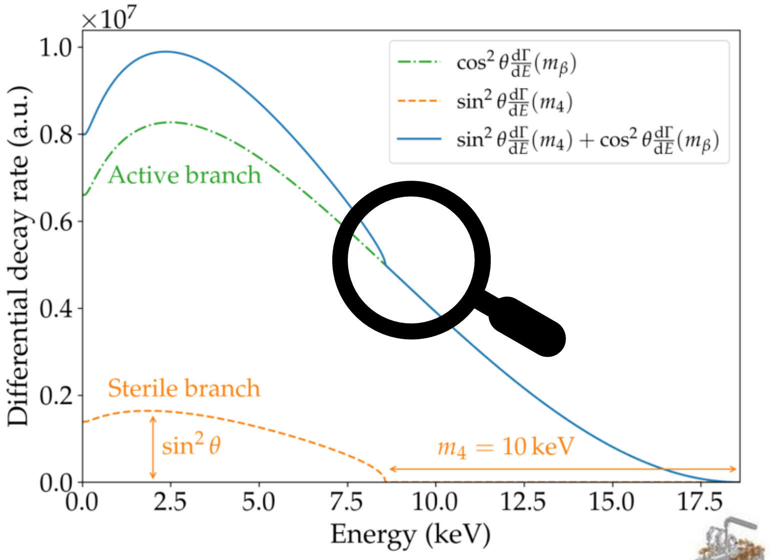
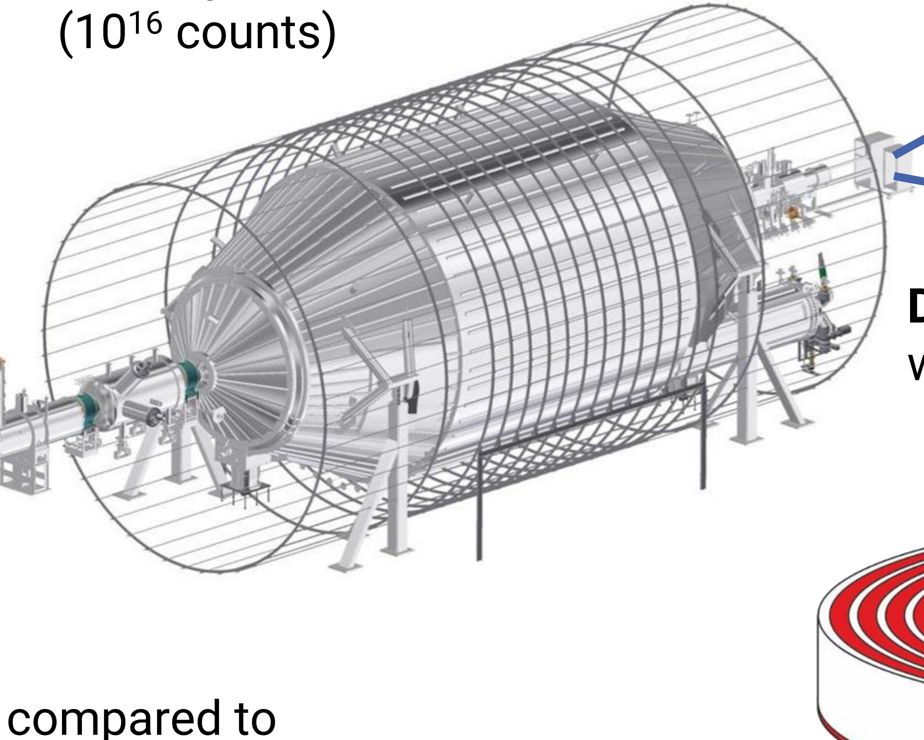
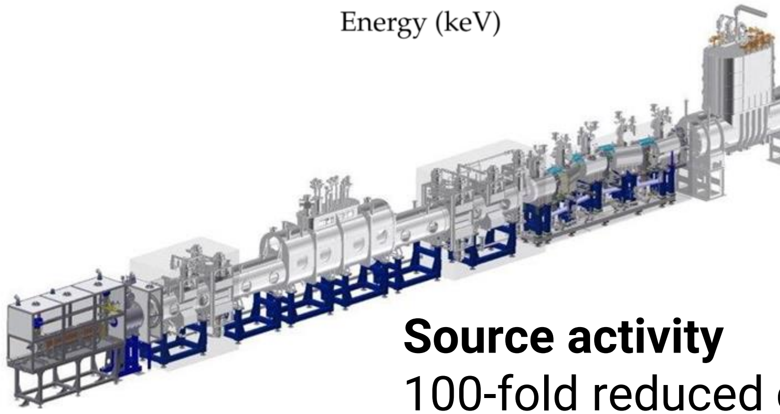
Search for keV-sterile neutrinos with TRISTAN detector

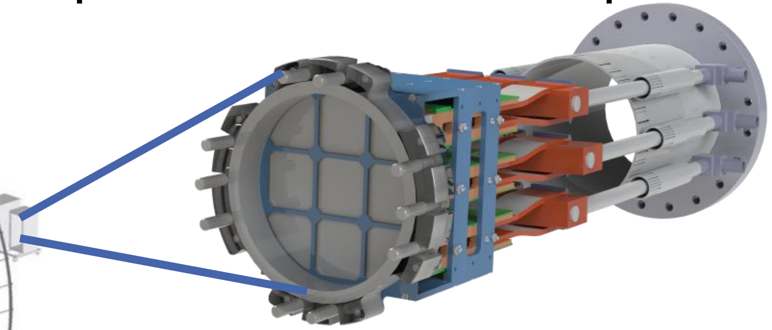


Full spectral coverage
with high statistics
(10^{16} counts)

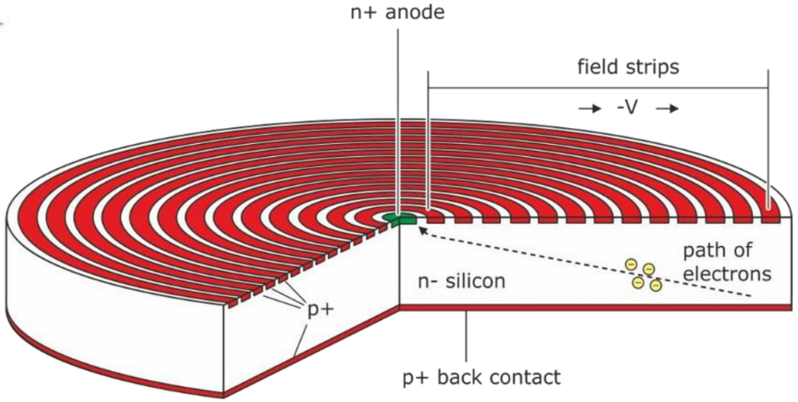
New 9 module detector
1500 pixel, 100k counts/s/pixel







Differential measurement
with about 300 eV resolution



Source activity
100-fold reduced compared to
neutrino mass measurements

Neutrino mass measurements with KATRIN and Beyond

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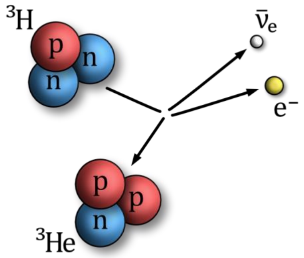

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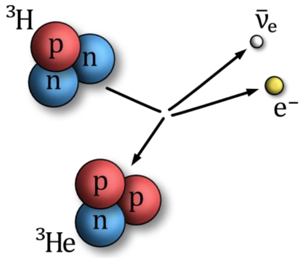
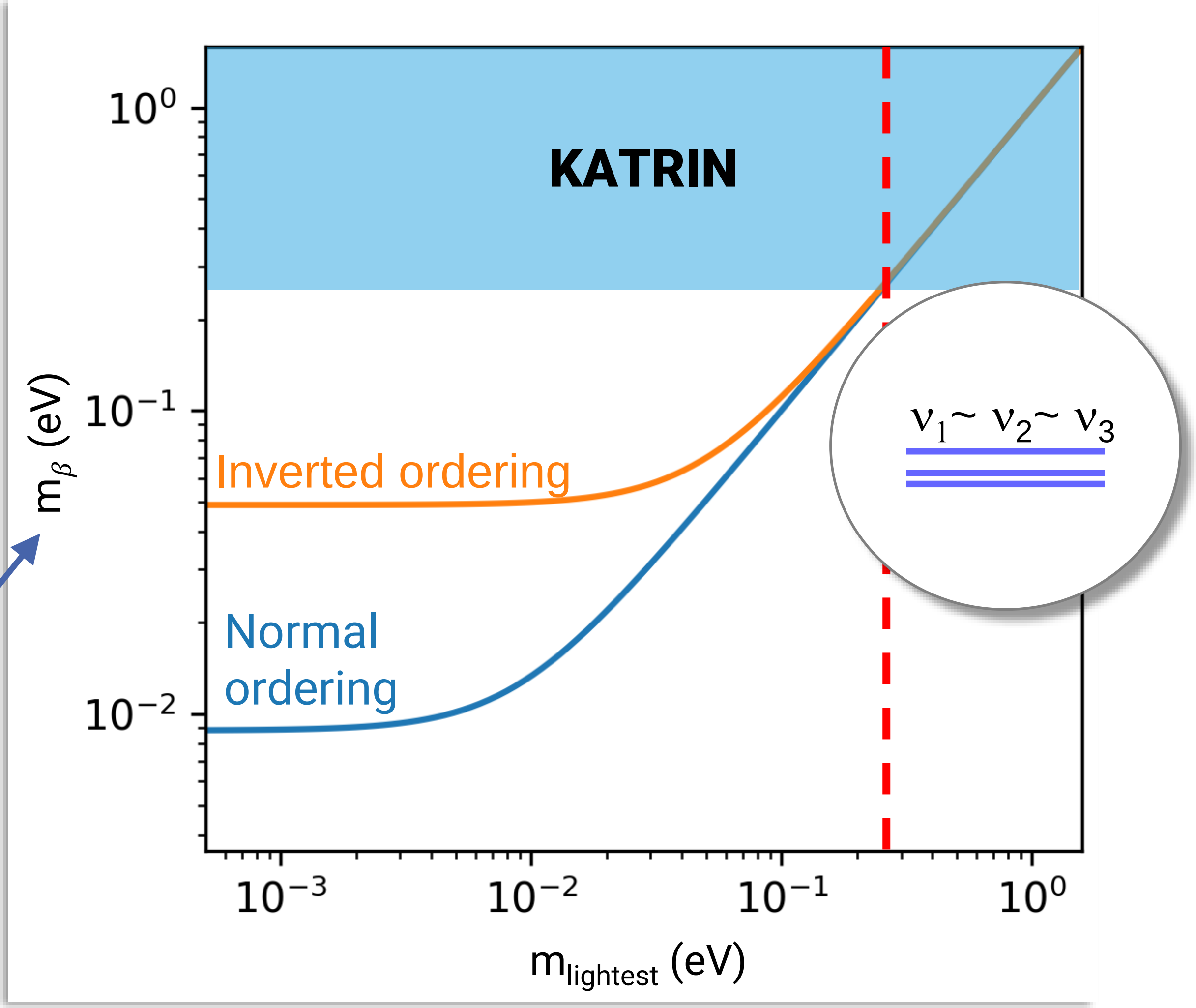


Neutrino mass measurements beyond KATRIN

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

$$m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$$



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- New technologies are necessary to cover **inverted** ordering < **0.05 eV**

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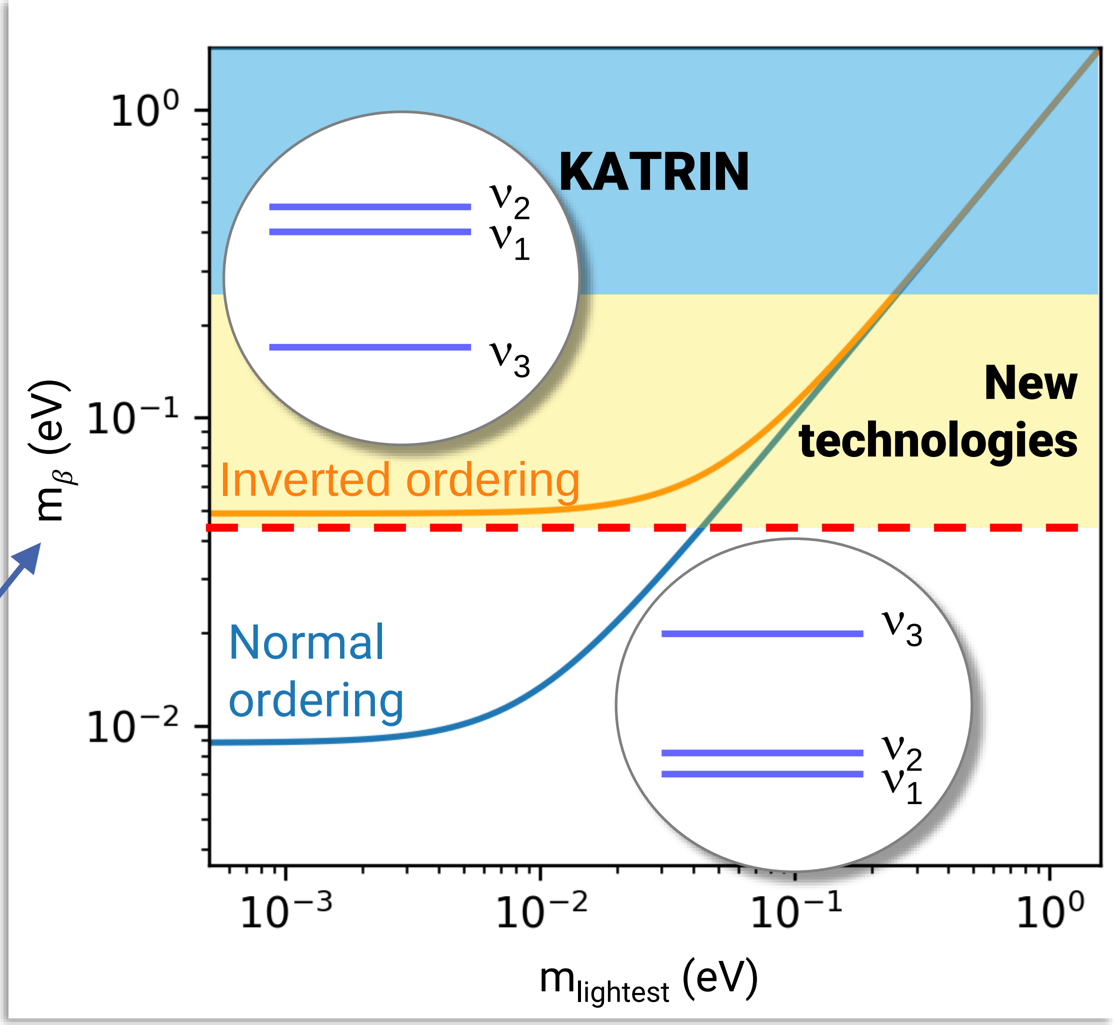

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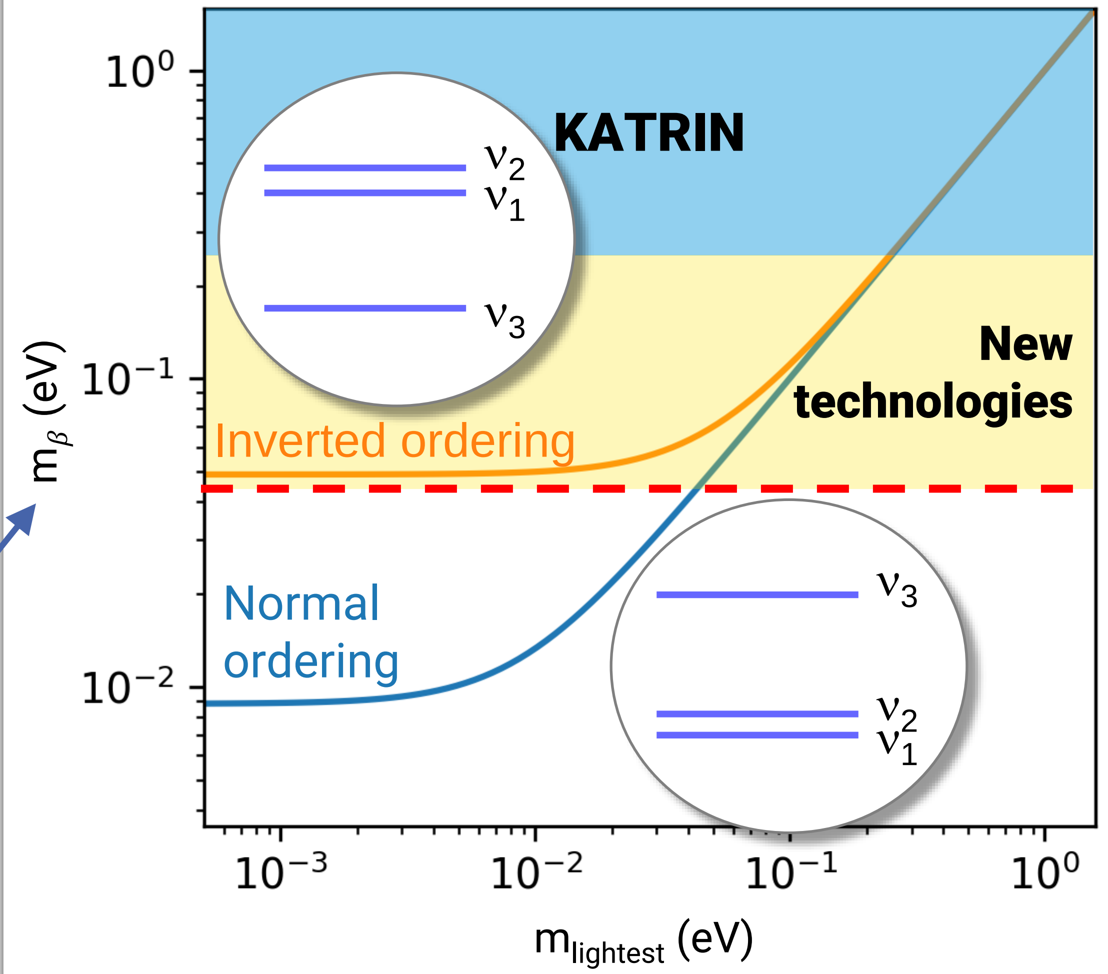
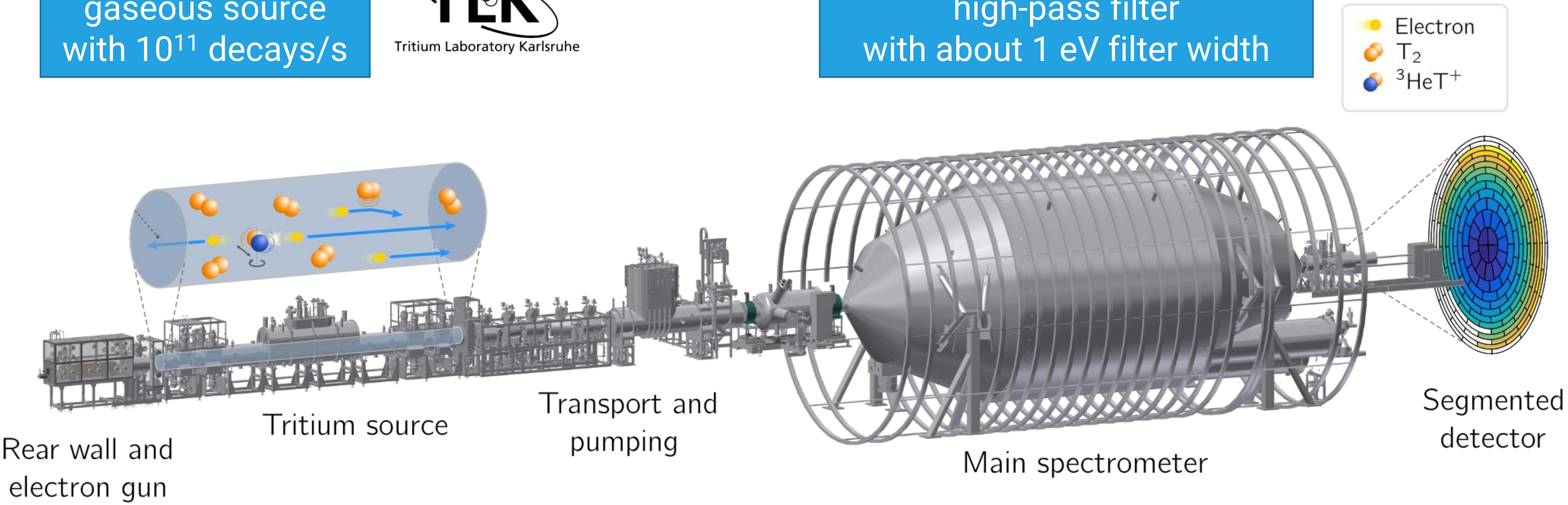


New technologies:
1. Differential detector
2. Atomic tritium source

KATRIN and TLK as ideal research facilities

High-luminosity gaseous source with 10^{11} decays/s

Precision spectroscopy by high-pass filter with about 1 eV filter width

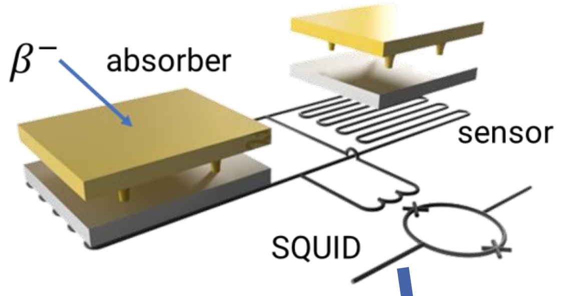


Differential measurement at KATRIN

- Upgrade detector to differential detector (e.g. MMC)

S. Kempf et al, J Low Temp Phys 193, 365–379 (2018)

R&D ongoing at KIT group of S. Kempf

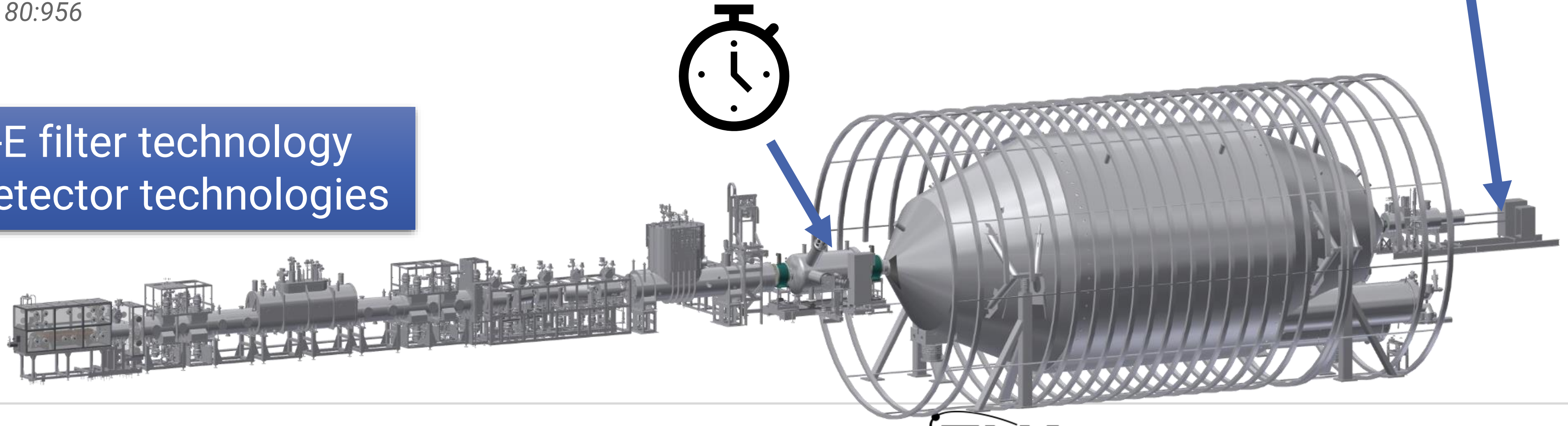


- Enable time-of-flight measurements with a tagger or time-focusing time-of-flight technique

R&D ongoing at UNC group of R. Henning and U Münster group of Ch. Weinheimer

J. Bonn et al, Nucl. Inst. and Meth. A 421.1, pp. 256–265 (1999)
N. Steinbrink et al, 2013 New J. Phys. 15 113020
A. Fulst et al, Eur. Phys. J. C (2020) 80:956

Use established MAC-E filter technology to characterize new detector technologies



Quantum detector technology

Advantages

- ✓ O(1 eV) resolution (conventional detectors O(100 eV))
- ✓ Near 100% quantum efficiency
- ✓ Immune to spectrometer background

Ongoing

Characterization of prototype detectors (MMC) with external electron sources (^{83m}Kr, e-gun, tritium on graphene)

MMCs as one possibility

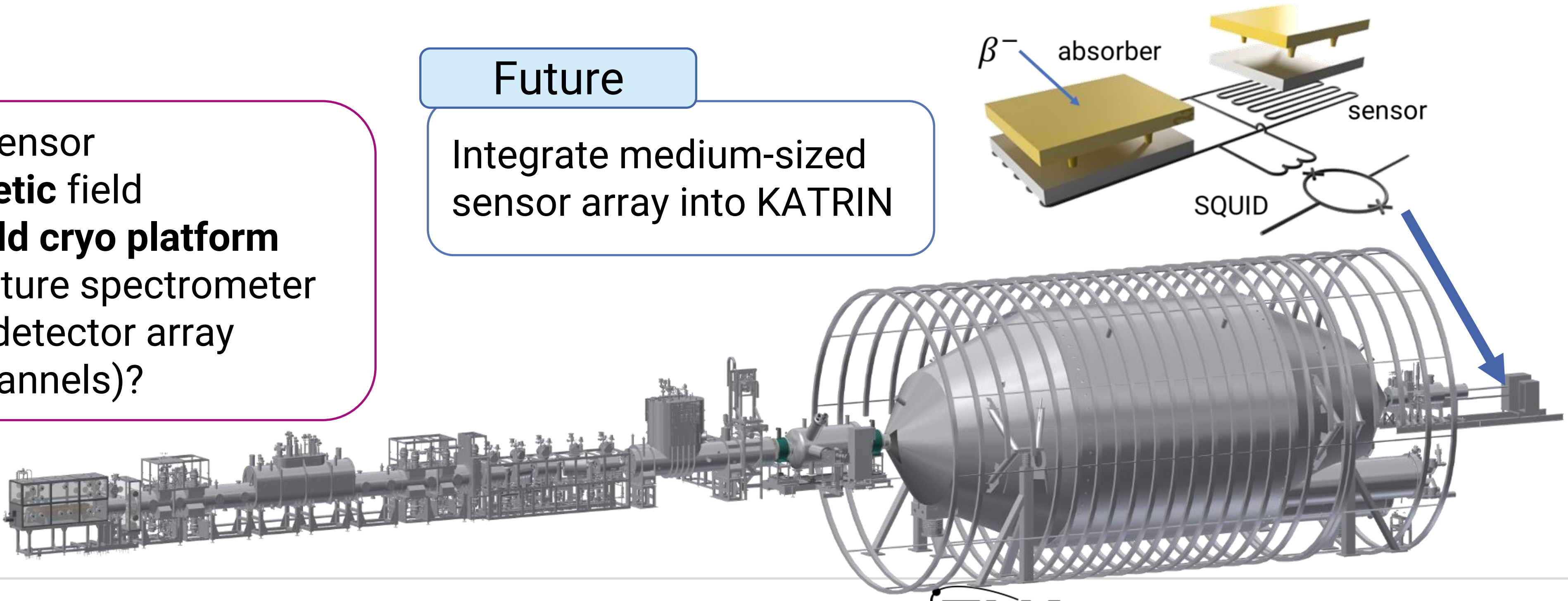
MMC: metallic magnetic microcalorimeters

Challenges

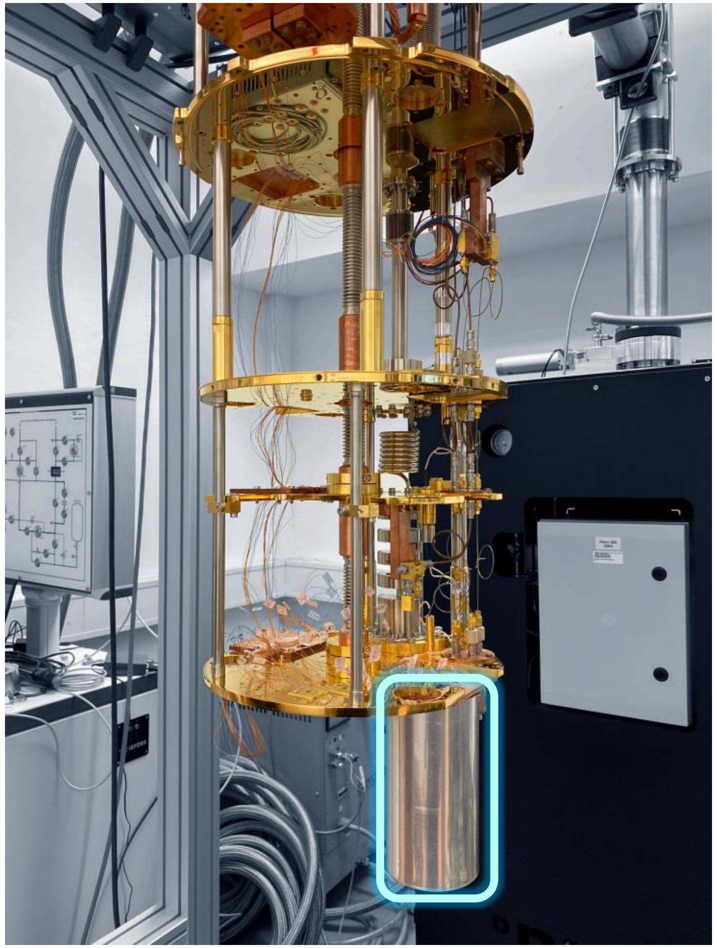
- ? Type of quantum sensor
- ? Operation in **magnetic** field
- ? Coupling of **mK-cold cryo platform** with room temperature spectrometer
- ? Multiplexing large detector array (about $10^5 - 10^6$ channels)?

Future

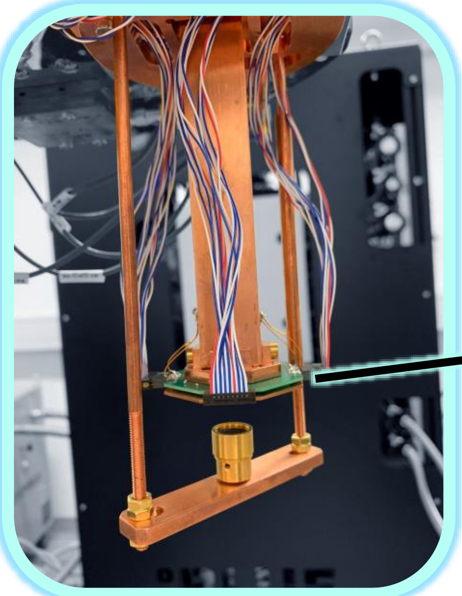
Integrate medium-sized sensor array into KATRIN

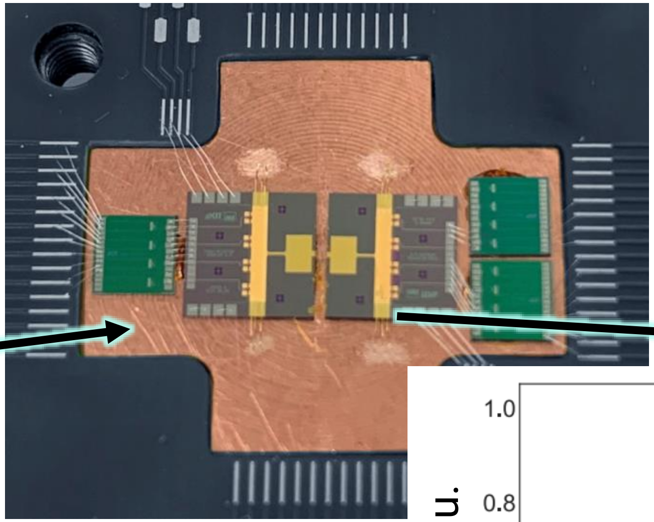


Project ELECTRON – Proof of principle

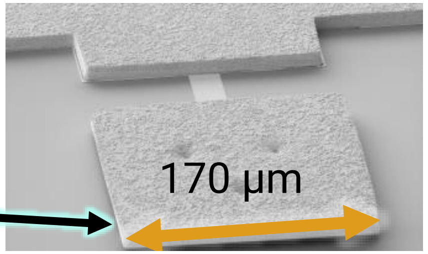


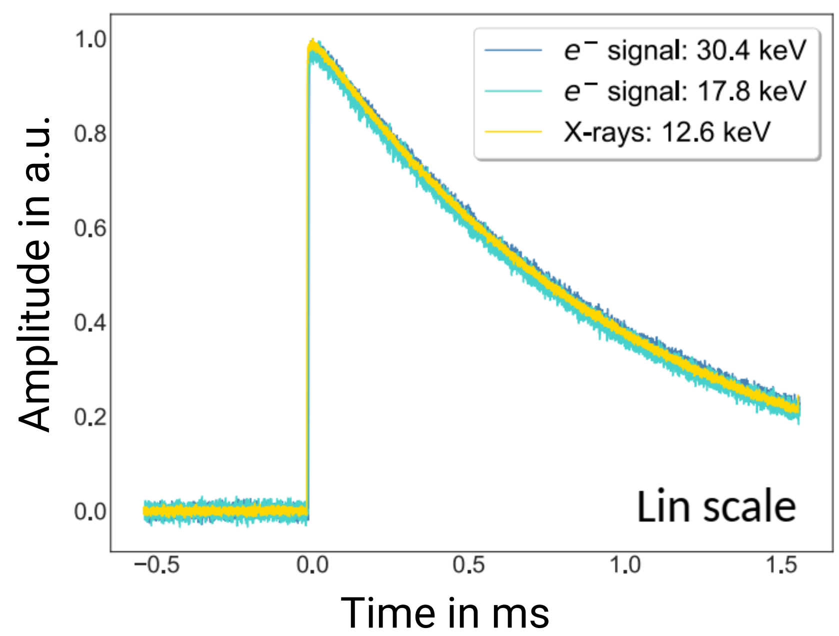
KIT-IMS cyrostat





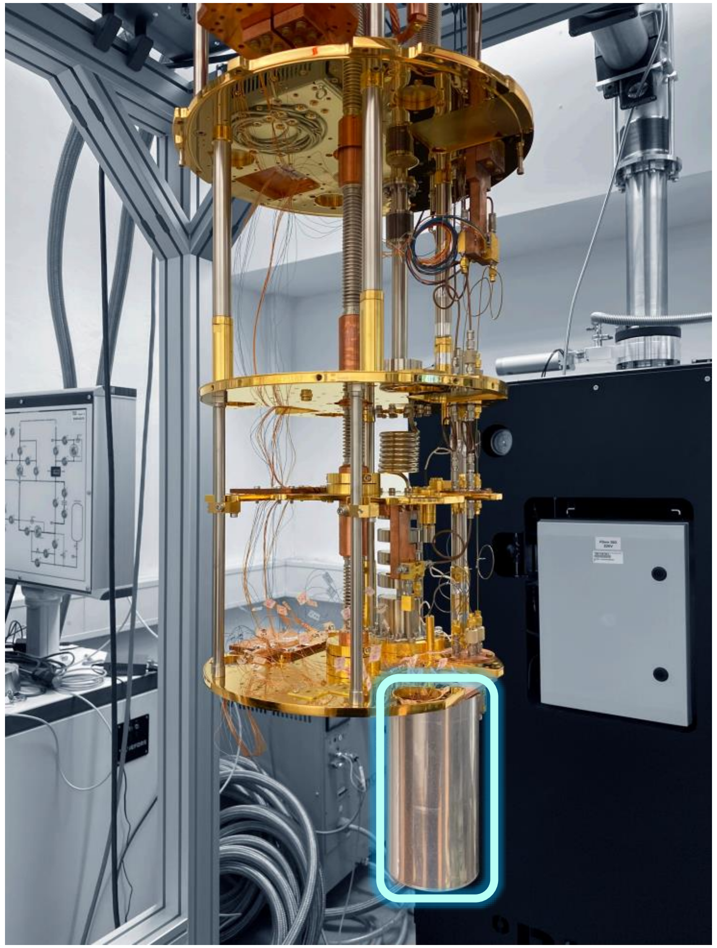
8 channel detector chips
& front-end SQUID chips



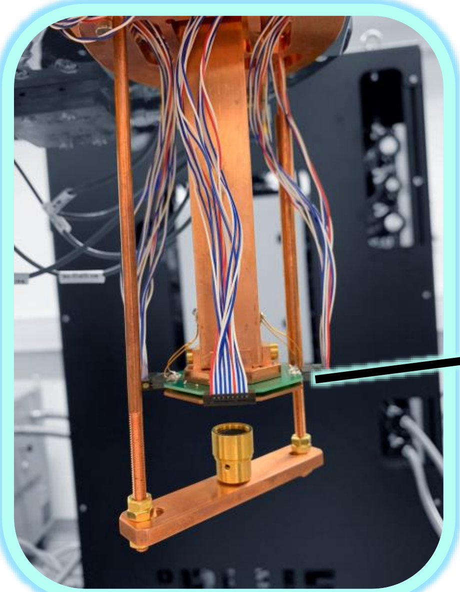


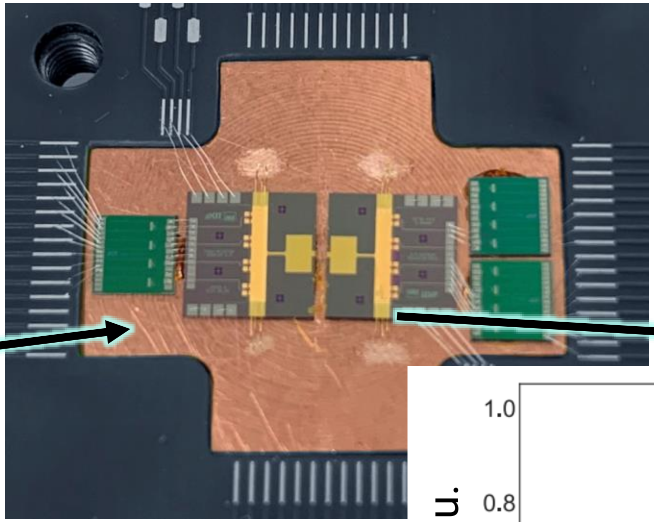
- **Ongoing:** ^{83m}Kr spectroscopy
- **Next step:** tritium spectroscopy

Project ELECTRON – Proof of principle

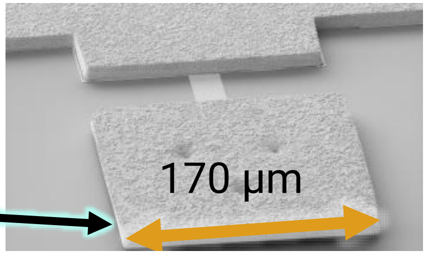


KIT-IMS cyrostat



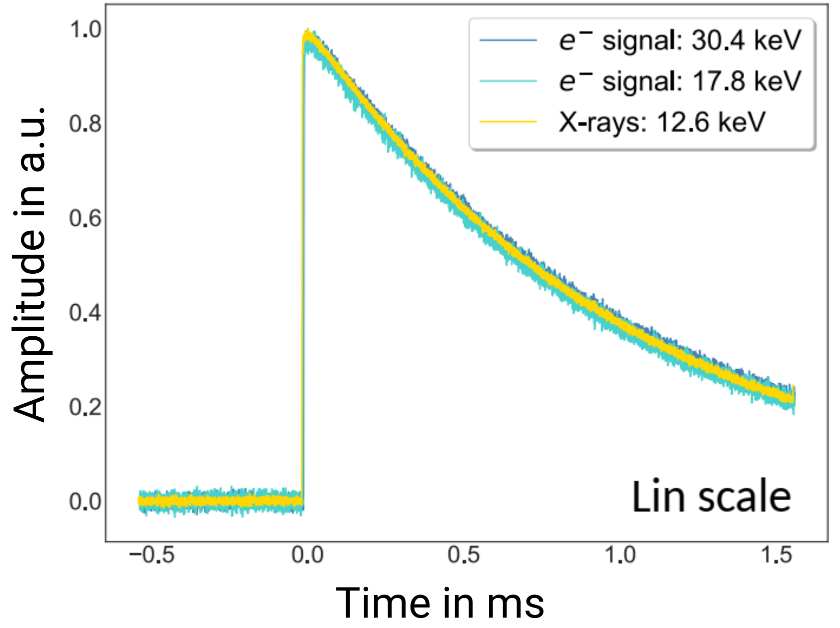


8 channel detector chips
& front-end SQUID chips

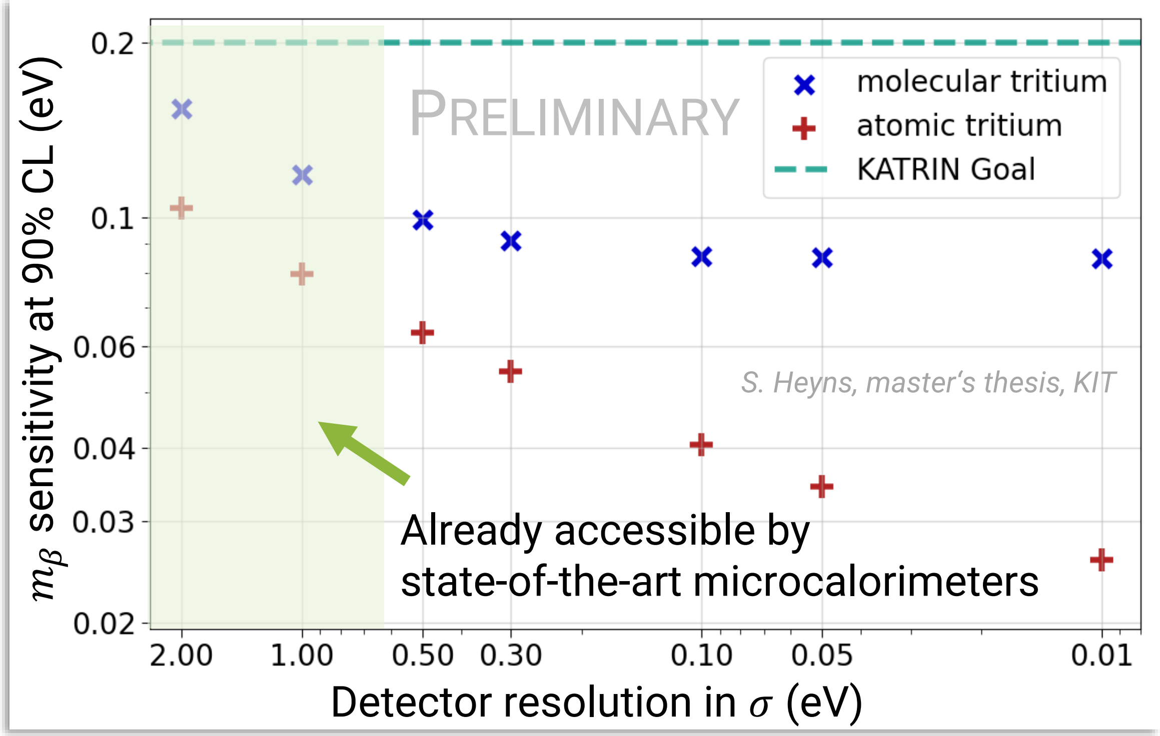


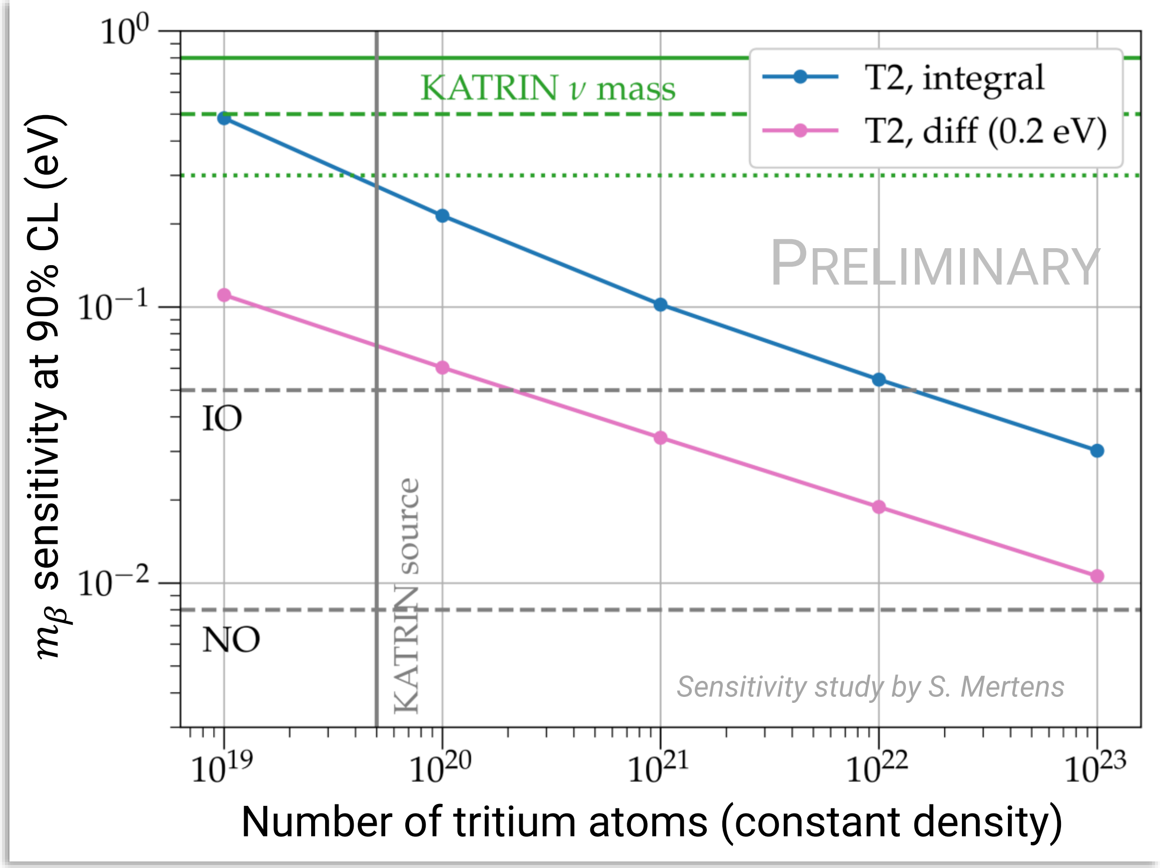
- **Ongoing:** ^{83m}Kr spectroscopy
- **Next step:** tritium spectroscopy

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



Neutrino mass sensitivities

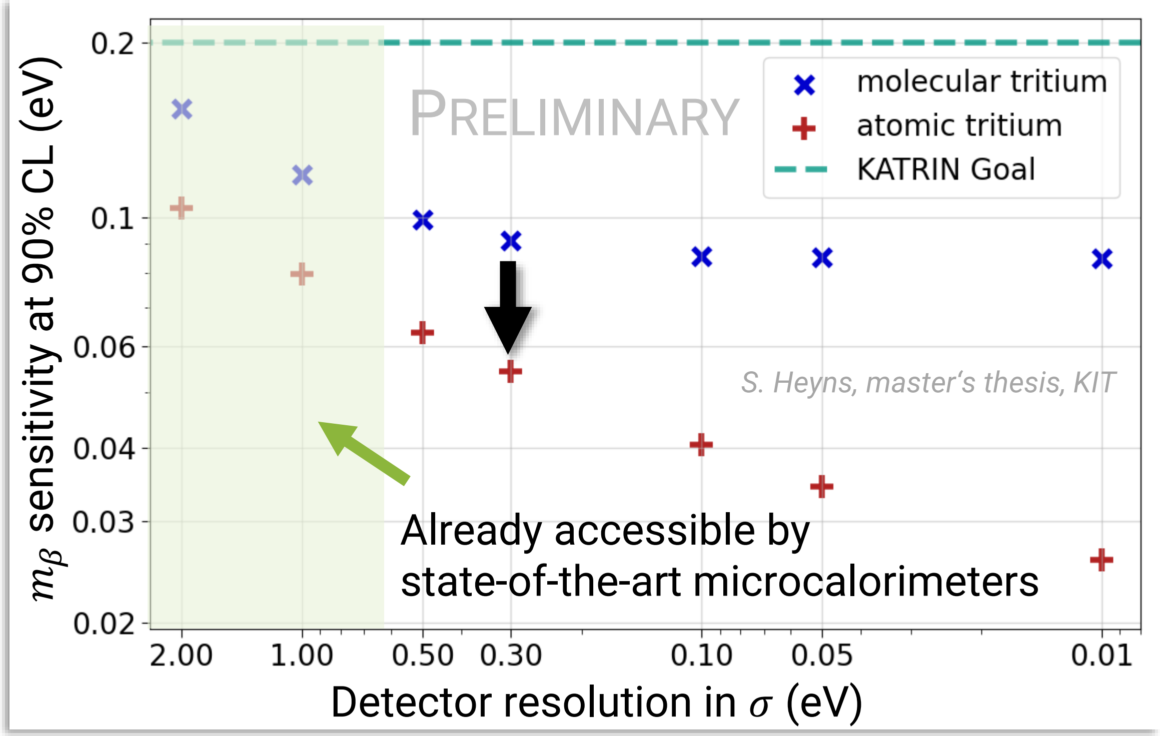


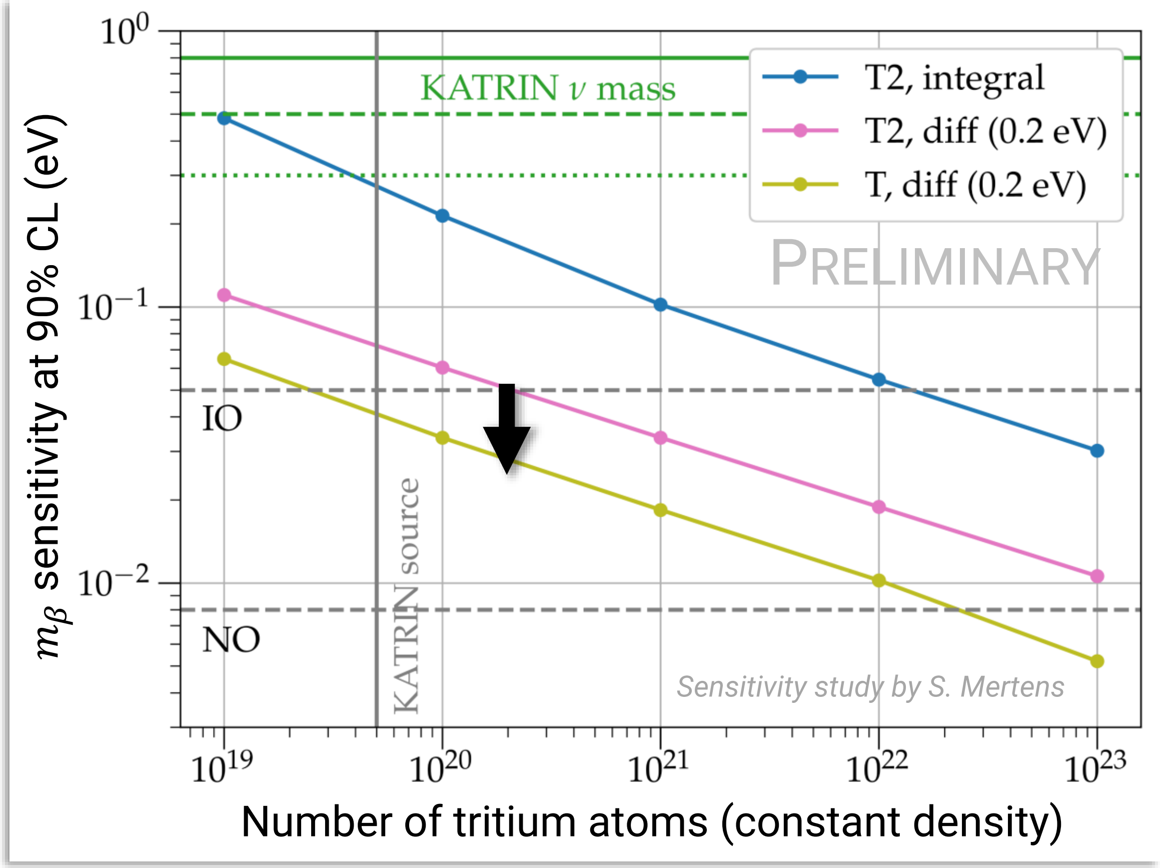


KATRIN-like setup with a differential detector upgrade:

- $t = 3$ years, $m_\nu = 0$ eV, stat. bg. $= 0$ mcps/eV

Neutrino mass sensitivities





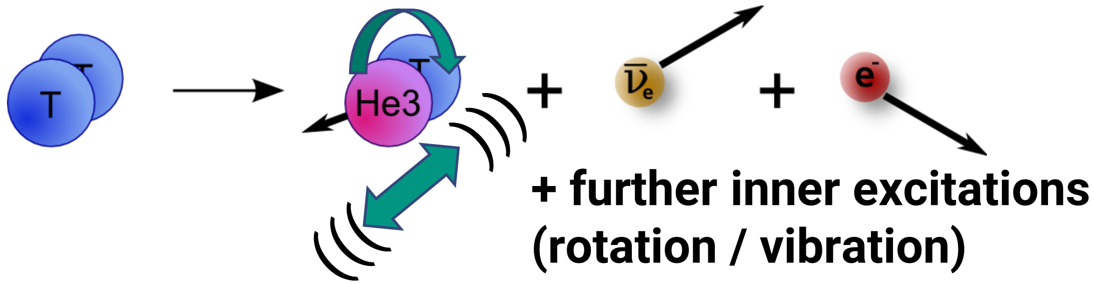
KATRIN-like setup with a differential detector upgrade:

- $t = 3$ years, $m_\nu = 0$ eV, stat. bg. $= 0$ mcps/eV

Gaining in sensitivity with atomic tritium source

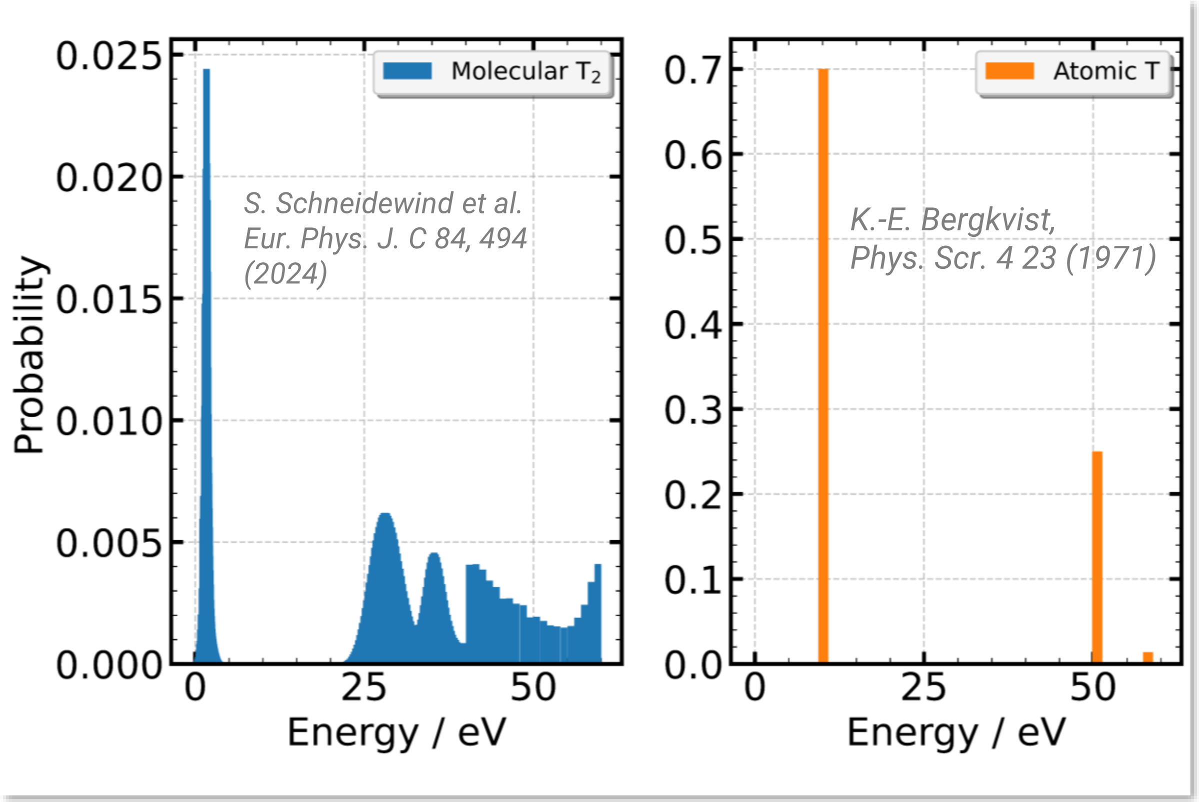
Tritium source – molecular vs. atomic

- Daughter molecule ^{3}HeT+ exhibits inner excitations after tritium beta decay



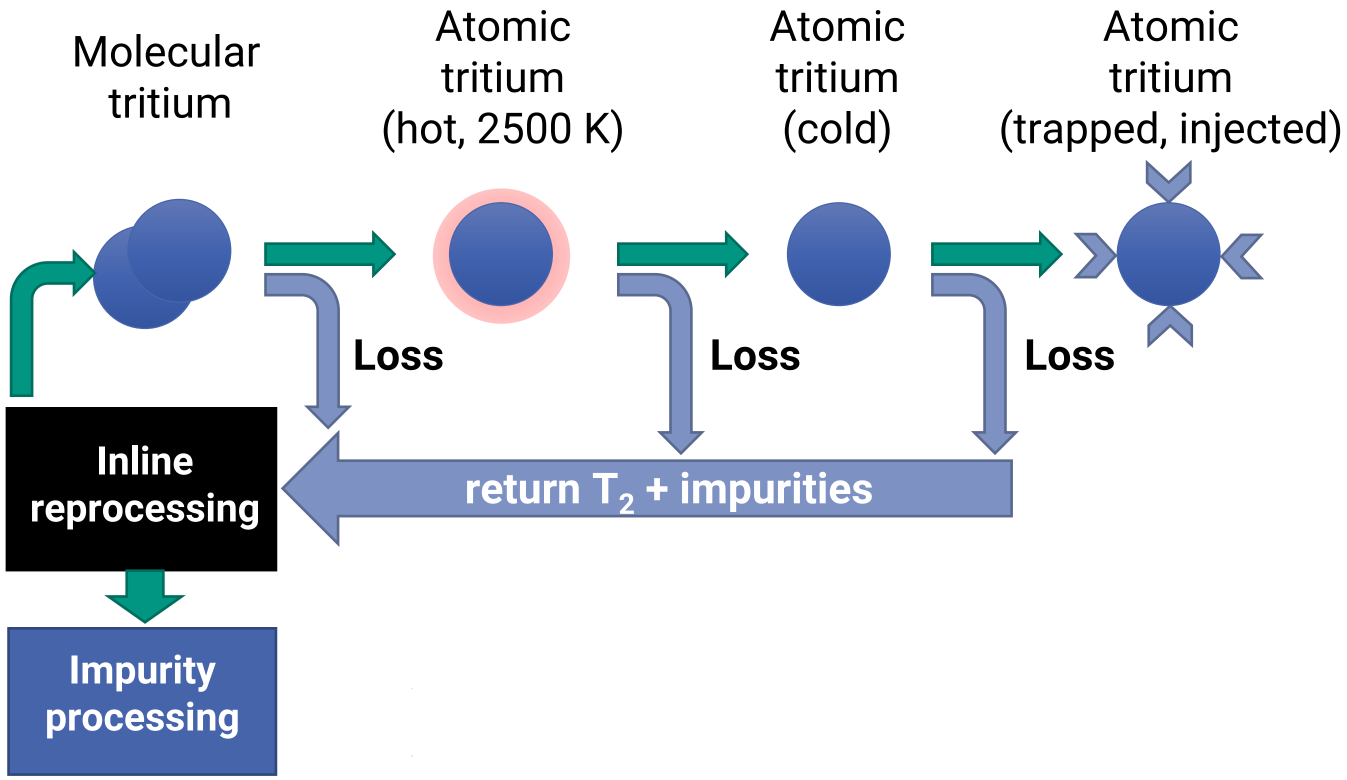
- Intrinsic broadening of ground state (std. dev. of about 0.4 eV)

Future neutrino mass experiments need an atomic tritium source.



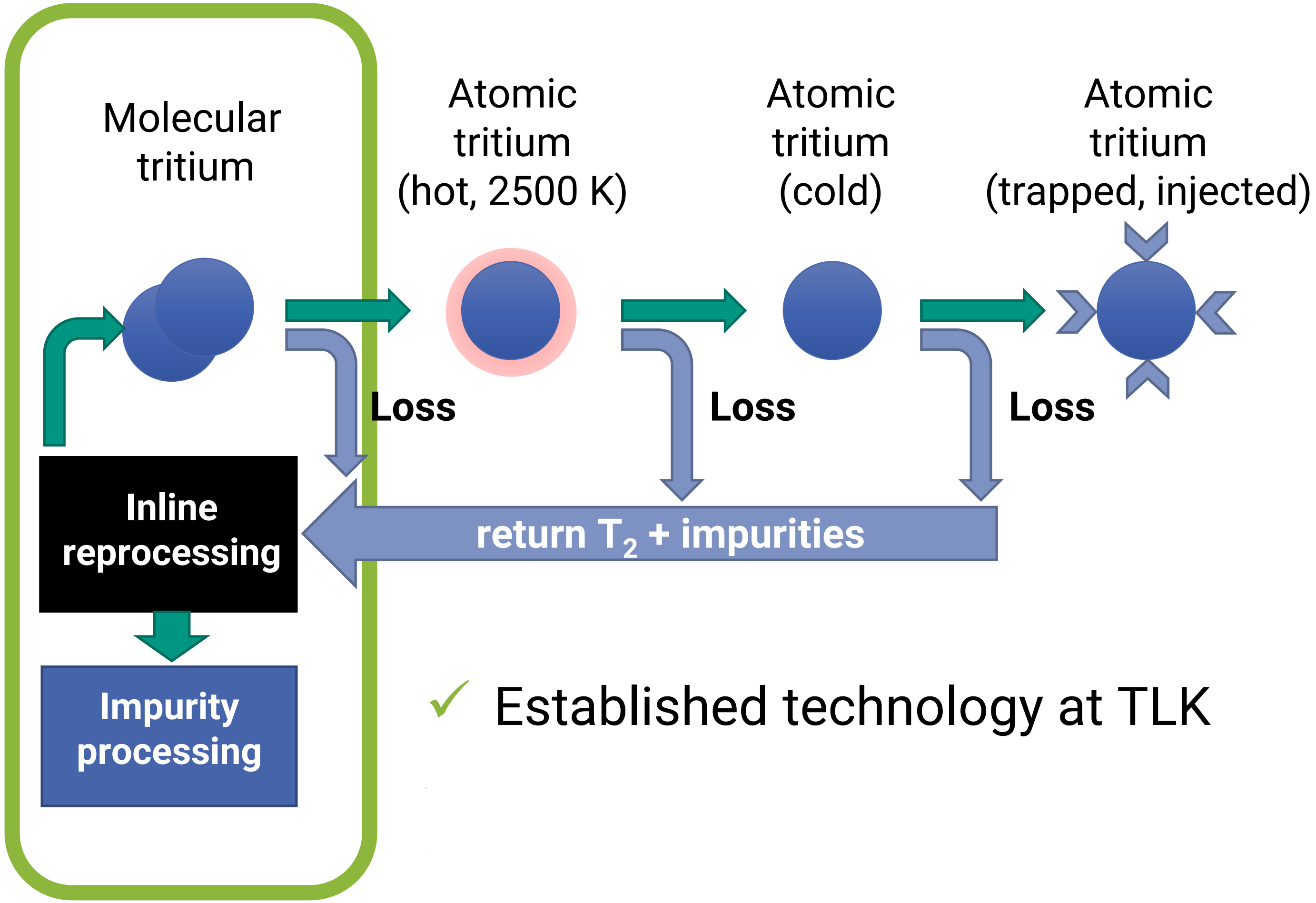
Molecular tritium: 57 %
Atomic tritium: **70 %**
of decays to electronic ground state

Steps towards an atomic tritium source



- **Aim:** Generate source of mK-cold tritium atoms with high activity (ultimately $> 10^{11}$Bq $\approx$ KATRIN)
- Efficiency of each processing step needs to be optimized to achieve a high total efficiency

Steps towards an atomic tritium source



✓ Established technology at TLK

- **Aim:** Generate source of mK-cold tritium atoms with high activity (ultimately $> 10^{11}$Bq $\approx$ KATRIN)
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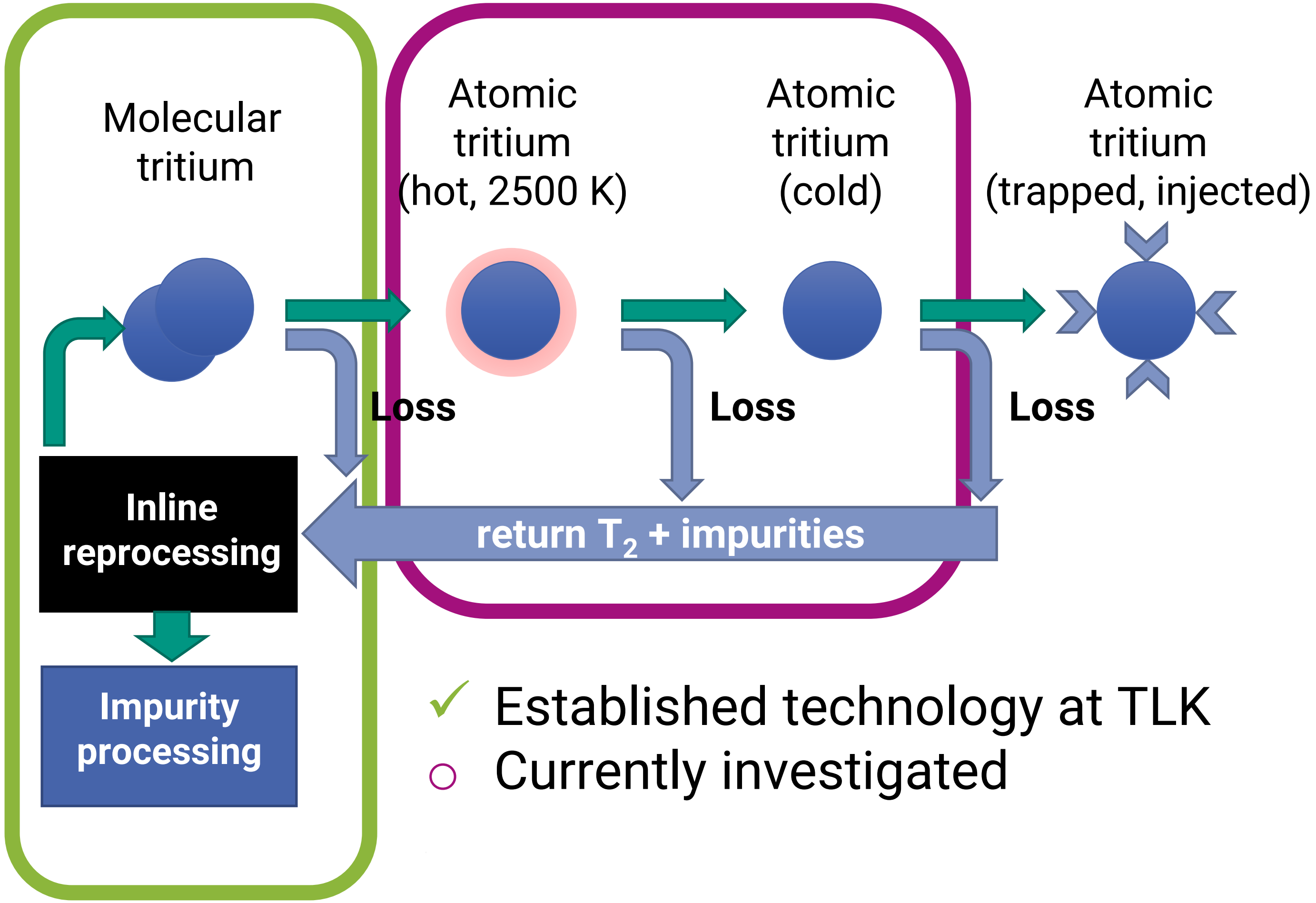

- ✓ Established technology at TLK
- ○ Currently investigated

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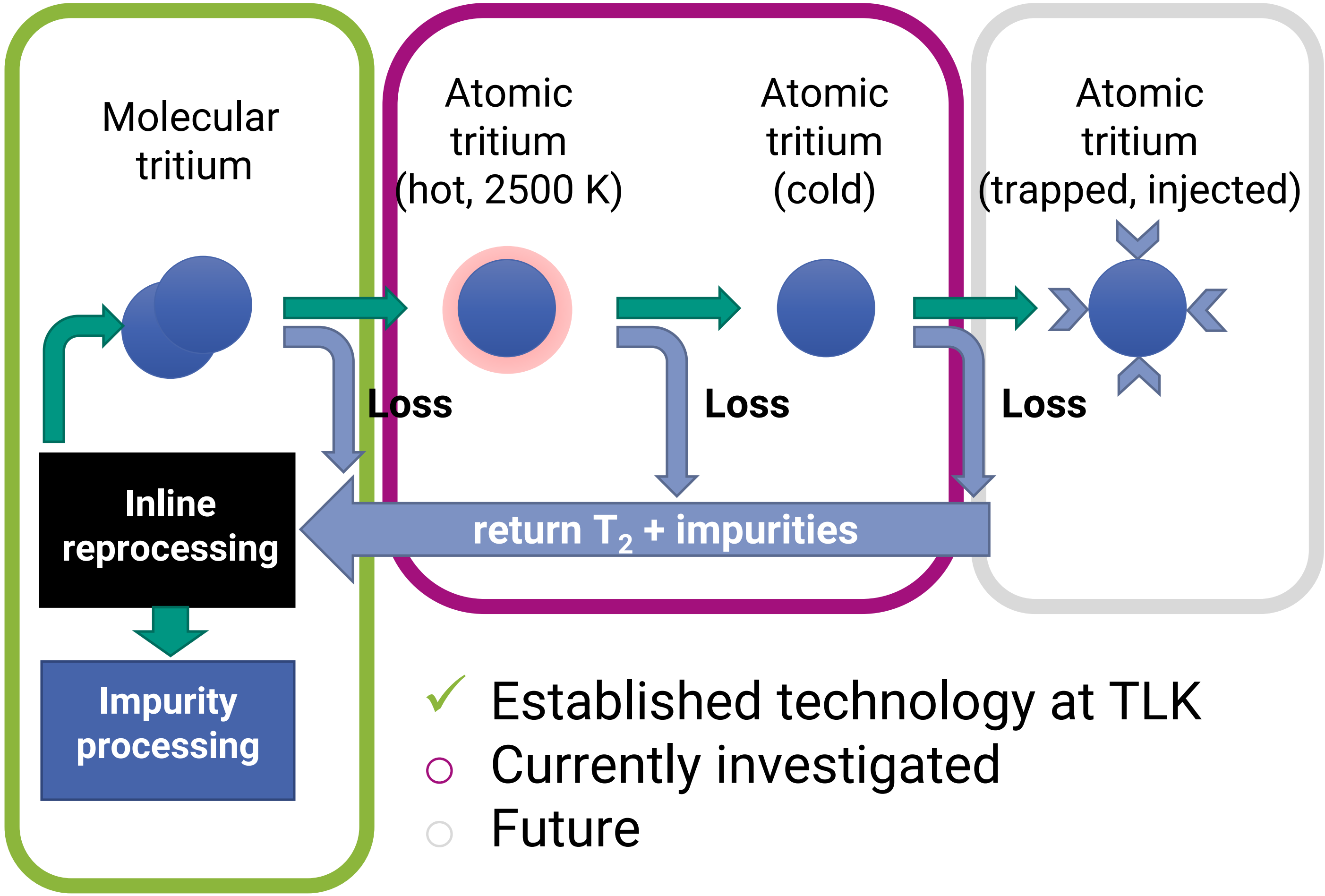

- ✓ Established technology at TLK
- ○ Currently investigated
- ○ Future

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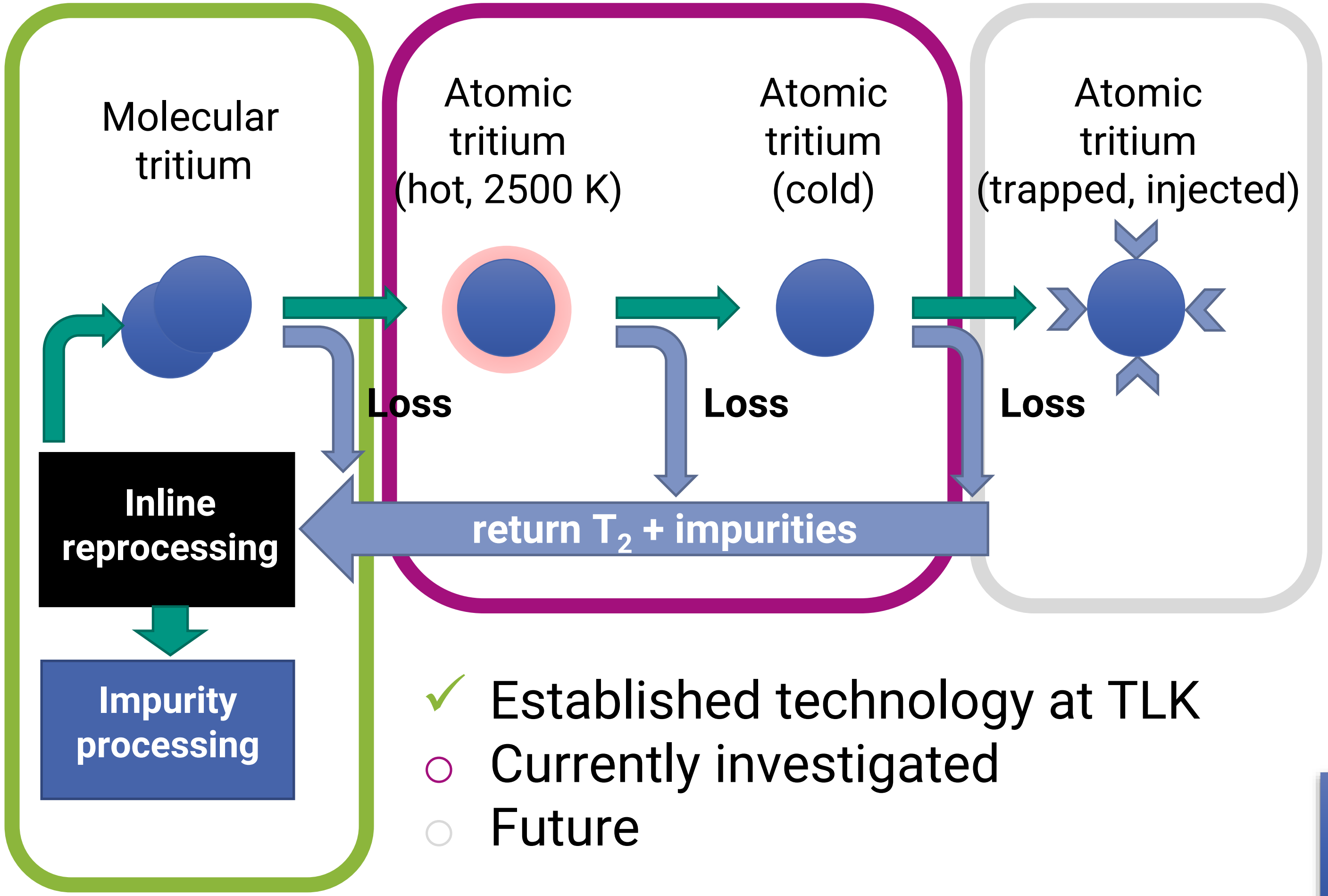
Steps towards an atomic tritium source



- ✓ Established technology at TLK
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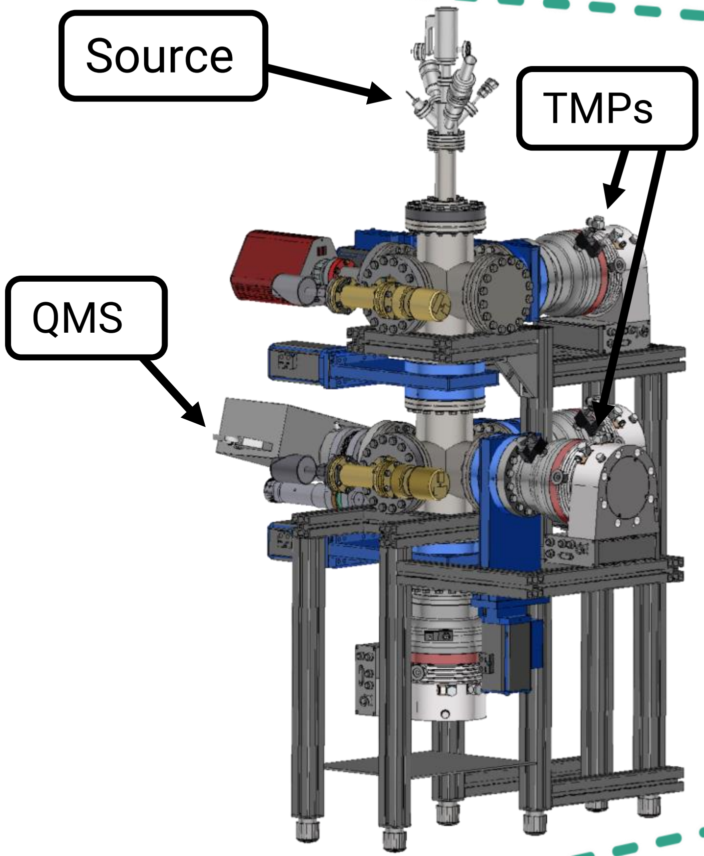
- ○ Future

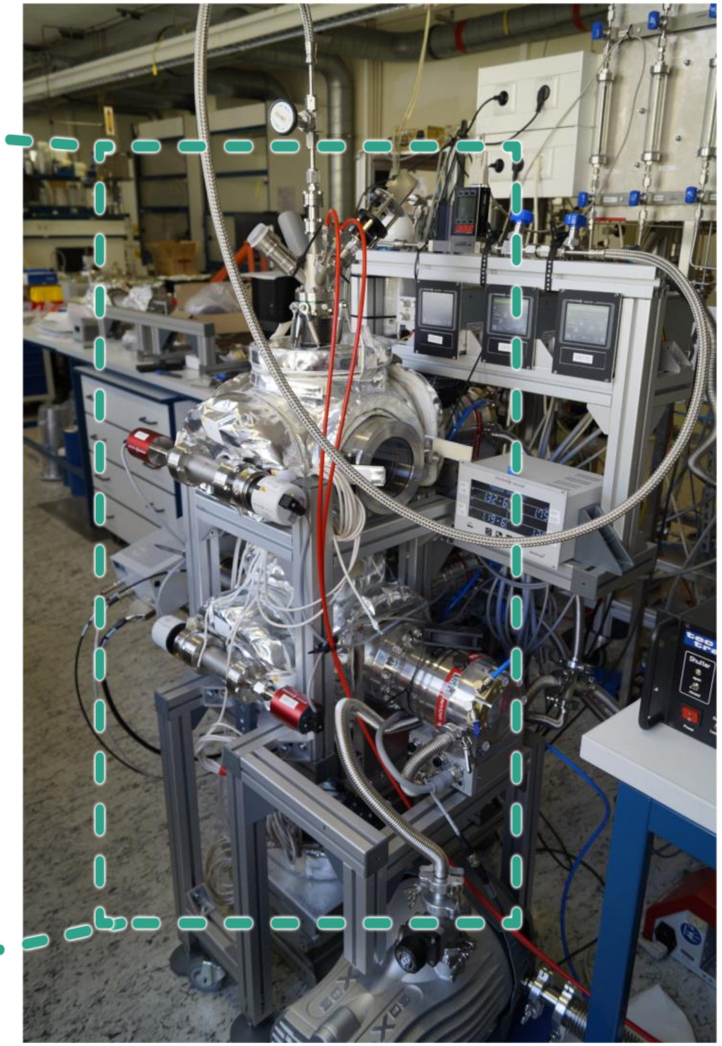
- **Aim:** Generate source of mK-cold tritium atoms with high activity (ultimately $> 10^{11}\mathrm{Bq} \approx$ KATRIN)
- Efficiency of each processing step needs to be optimized to achieve a high total efficiency

TLK has a unique infrastructure for atomic source development with **partners**

Towards first tritium atoms

- **Goal:** Demonstrate tritium operation in simple setup.
- Built setup with standard vacuum parts
- Use setup for investigating:
  - Tritium compatibility
  - Tritium recovery
  - Isotopic effects
- Determine atomic fraction by quadrupole mass spectrometer (QMS)
- Reduce detection of scattered particles with skimmers



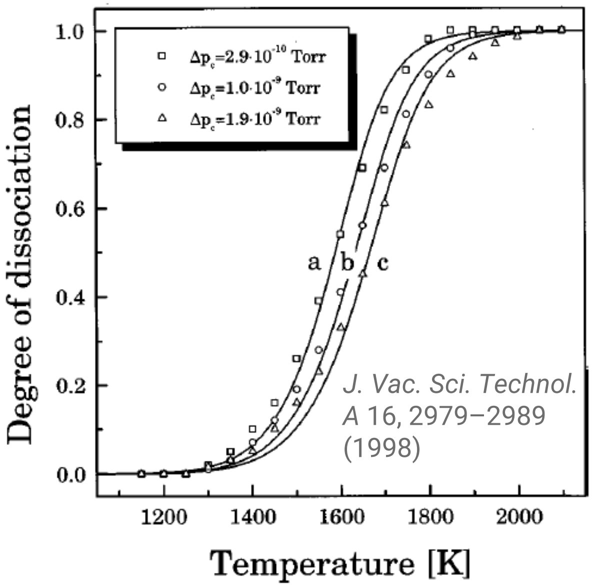


Different types of atomic sources

Thermal dissociation

Currently in use

- Heat tungsten capillary with electron bombardment
- Atoms with temperatures of > 2000 K



J. Vac. Sci. Technol. A 16, 2979–2989 (1998)

Tectra h-flux

RF-discharge

Soon under investigation

- Dissociation in RF plasma
- Succesfully used with hydrogen
  J. Slevin, W. Stirling, Rev. Sci. Instrum. 52, 1780–1782 (1981)
- Experience in Los Alamos showed decrease of dissociation rate over time
  Formaggio et al. Phys. Rep. 914 1–54 (2021)

SVT RF 4.5

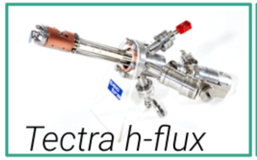
KArlsruhe MAinz Tritium Experiment

Join knowledge and experience gathered at Mainz (group by S. Böser) and TLK to develop an atomic tritium source.

Tritium Laboratory Karlsruhe

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

KAMATE 0.5:
Identify best source at MATS with inactive hydrogen: thermal dissociation vs. RF-discharge



KAMATE 1.0:
Operate KAMATE 0.5 setup at TLK with tritium

KAMATE 2.0:
Add accomodator as first stage cooling

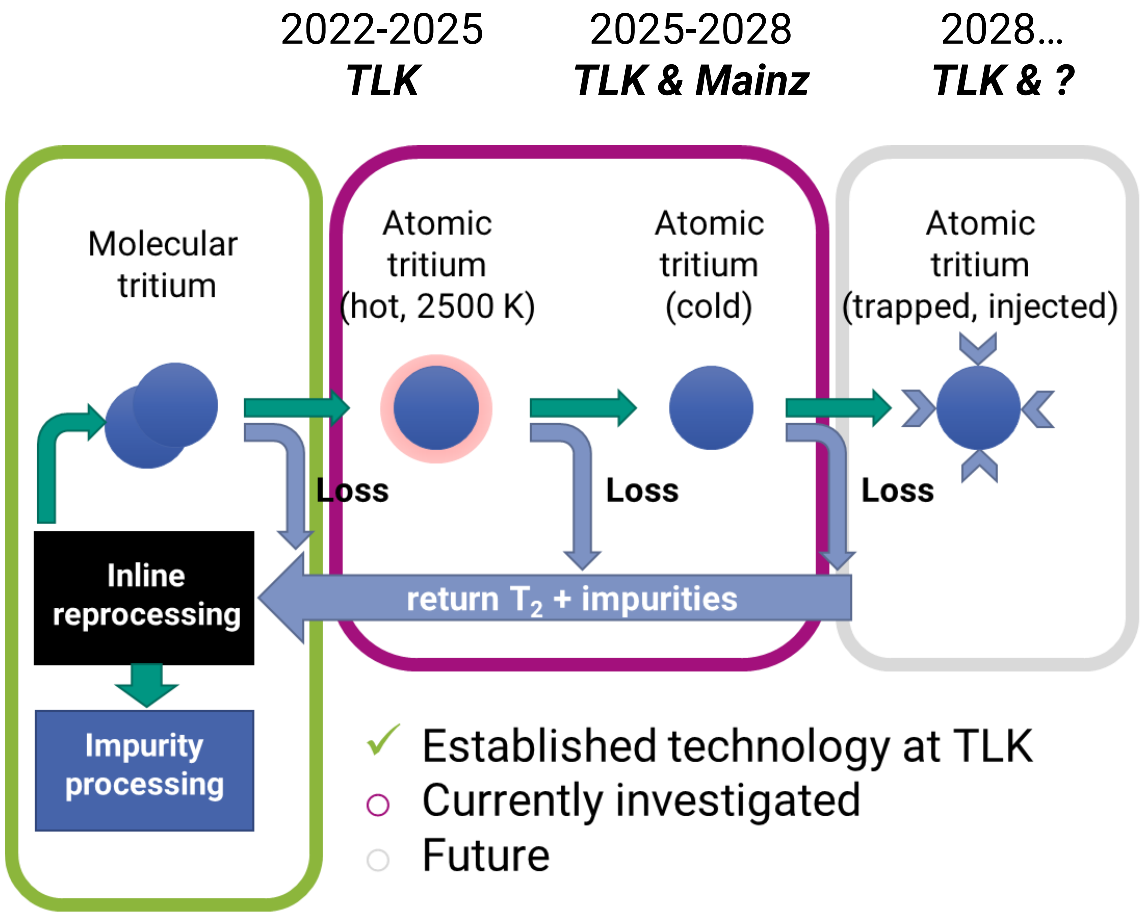
KAMATE 3.0:
Add nozzle for second stage cooling and beam temperature meas. setup (time of flight)

KAMATE

KARLSRUHE MAINZ TRITIUM EXPERIMENT

Atomic tritium source for future neutrino experiments such as KATRIN++ and Project 8

Atomic tritium demonstrator at TLK



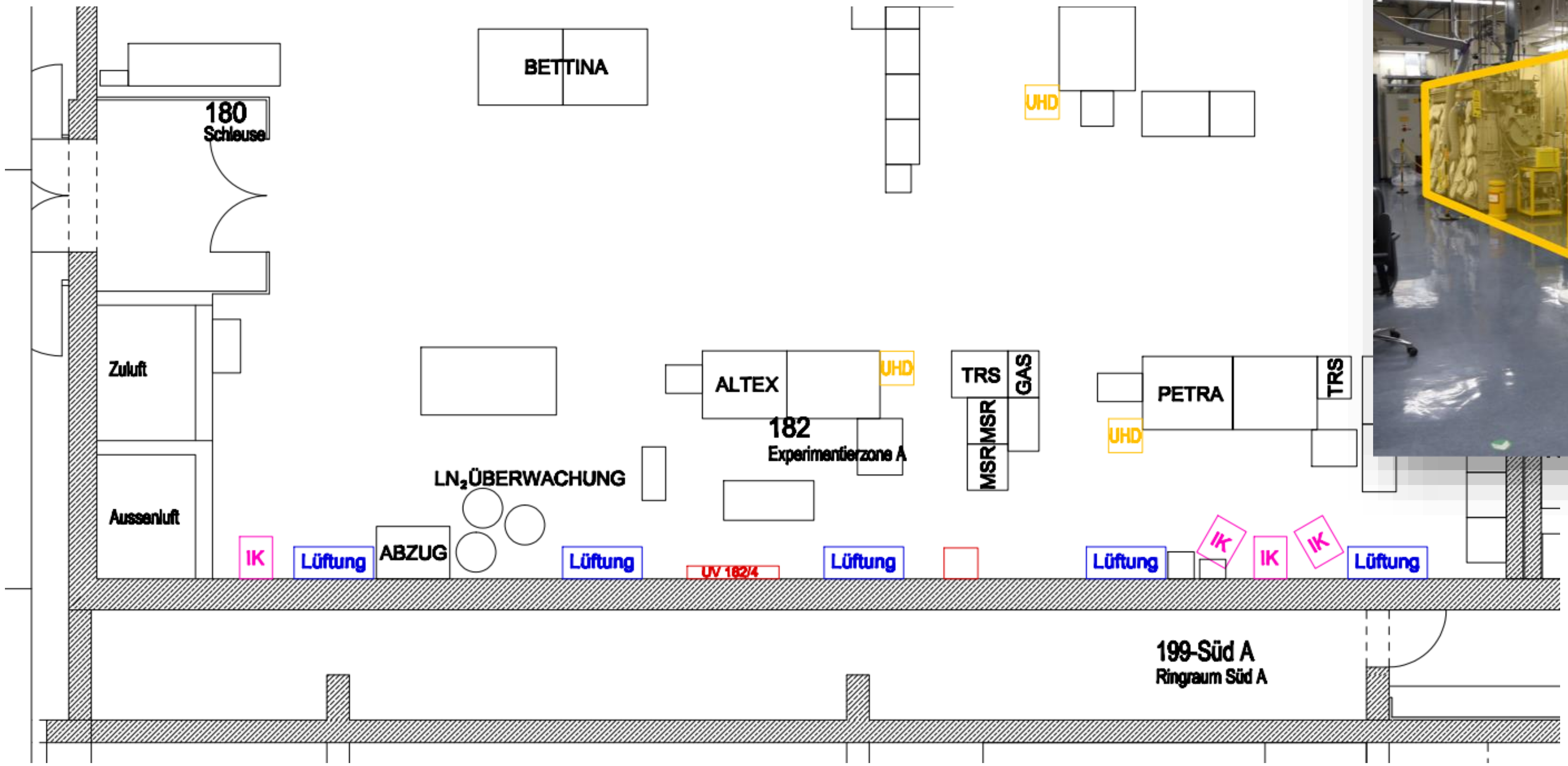
✓ Established technology at TLK
○ Currently investigated
○ Future

Purpose of the demonstrator

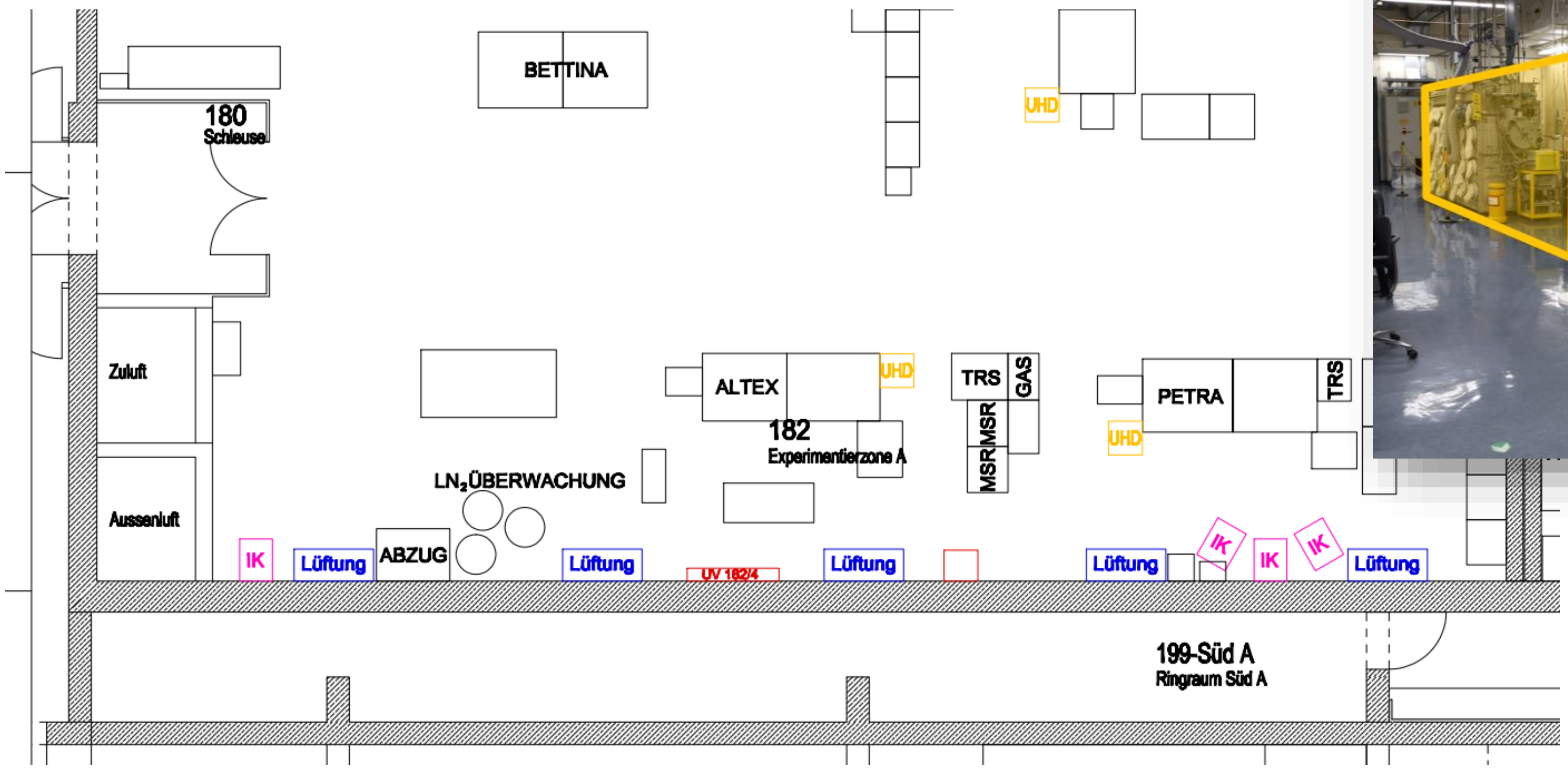
- Develop cooling (≈ 10 mK) mechanism for atoms
- Atom throughput on the order of 10 g / day (c.f. KATRIN: 40 g/day)
- Investigate trapping times and maximal atom densities
- Investigate interplay of beta-driven plasma (meV−eV) and ultra-cold trapped atoms (neV)

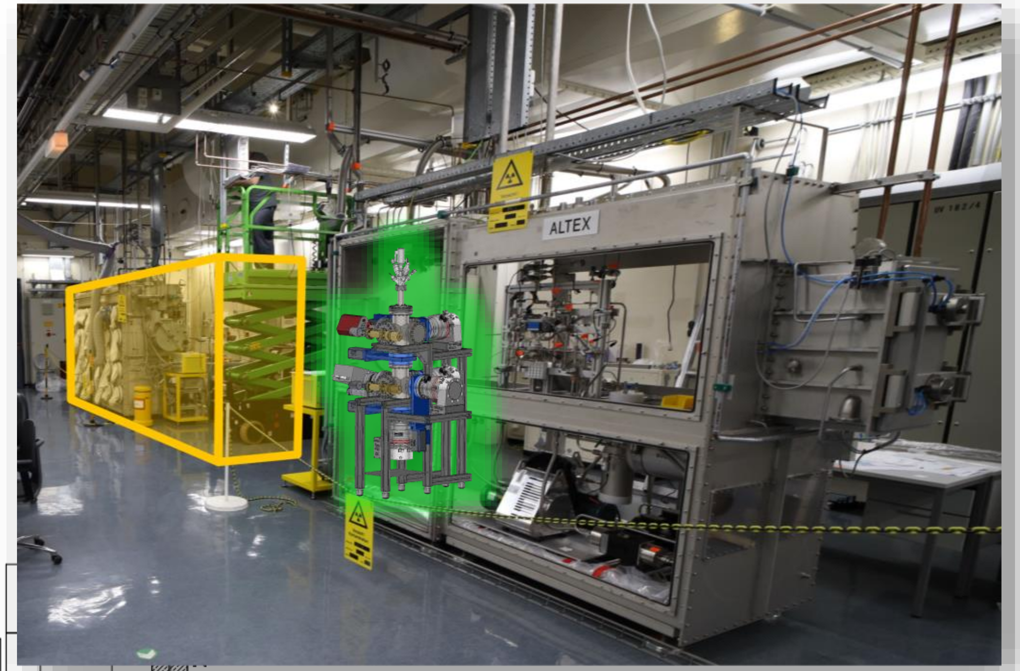
Demonstrator is essential for next generation neutrino mass experiments!

Preparing TLK for the atomic tritium demonstrator



Preparing TLK for the atomic tritium demonstrator





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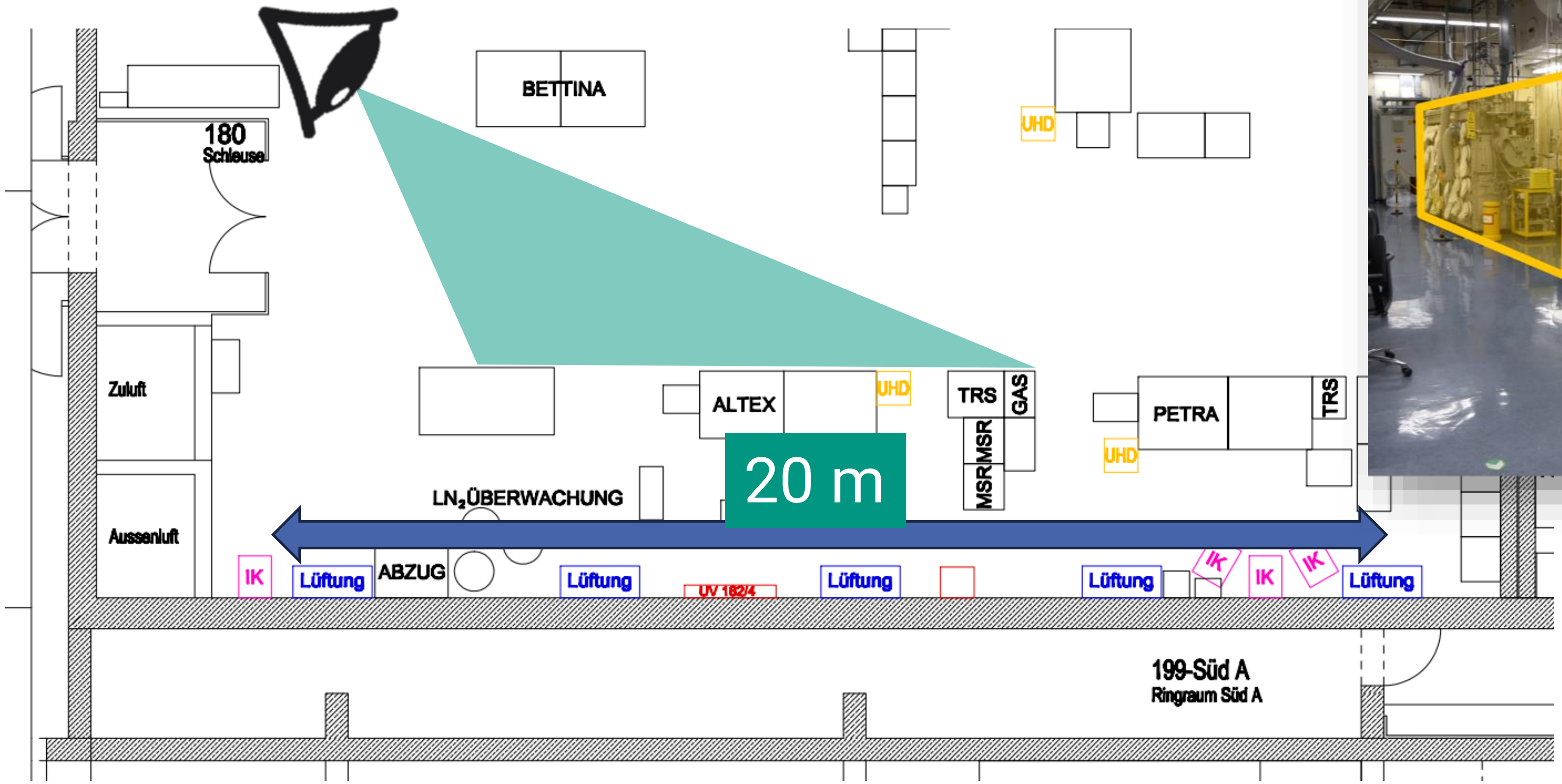
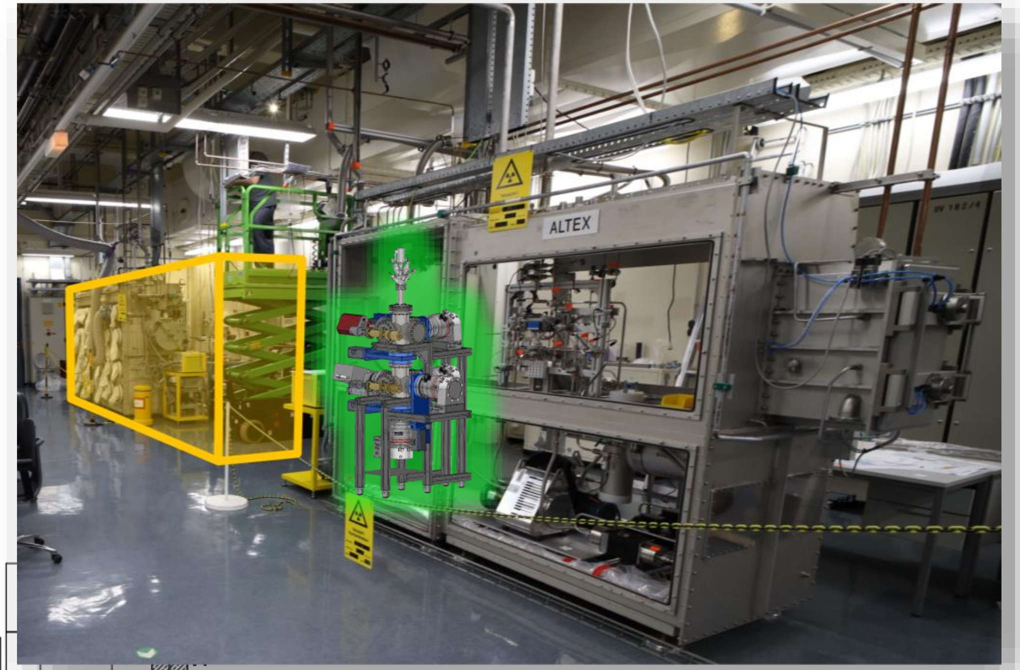
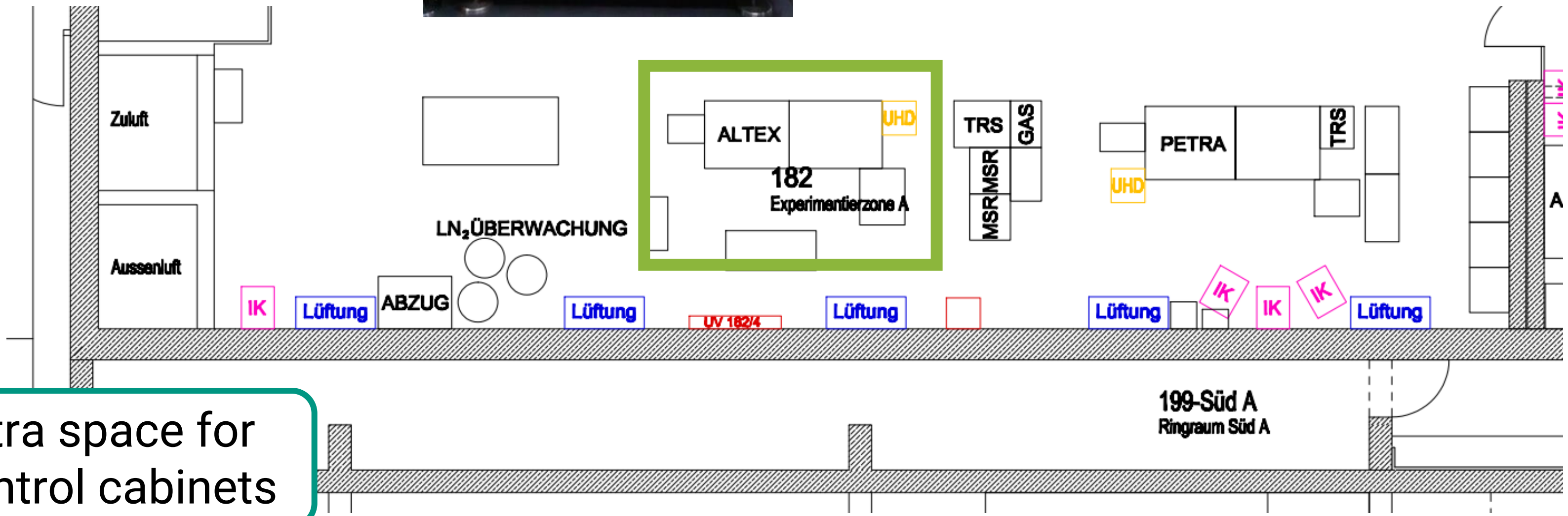




Preparing of TLK for Atomic Tritium Demonstrator

ALTEX Box

- Decontamination completed
- Installation ongoing



Extra space for control cabinets

Preparing of TLK for Atomic Tritium Demonstrator

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PETRA box

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

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Other systems

e.g. tritium retention system, gas bottles, control cabinets, …
→ Are being relocated

Extra space for control cabinets

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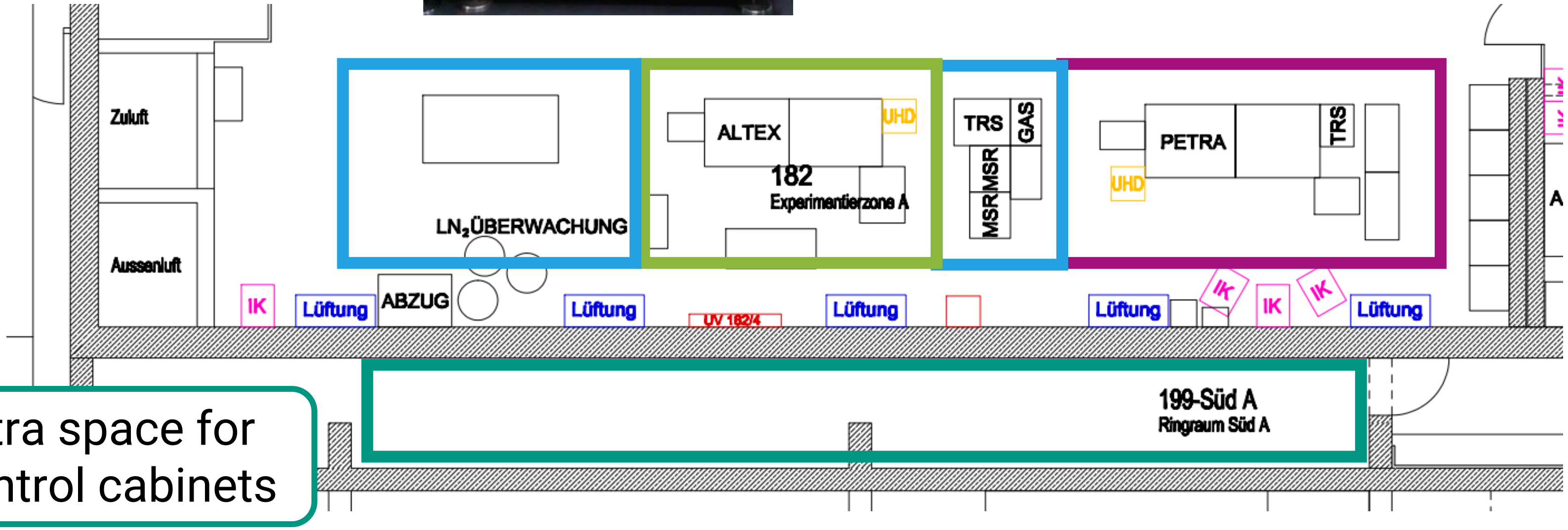

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A wall is in principle not the limit …

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Other systems

e.g. tritium retention system, gas bottles, control cabinets, …
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Extra space for control cabinets

A wall is in principle not the limit …

Overview on KATRIN & TLK

Karlsruhe Institute of Technology

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		Quantum sensor demonstrator	
Atomic tritium R&D		Atomic tritium demonstrator	

- Future neutrino mass experiment (sensitivity on m_β < 0.05 eV) requires: differential detector principle and an atomic tritium source
- Use established MAC-E filter technology to characterize new detector technologies
- Use expertise and technical capabilities of existing TLK to develop atomic tritium source
- First atomic tritium source underway and first tritium atoms expected in 2024

KATRIN invites research groups to tackle challenges together

Credits – R&D phase KATRIN++

Karlsruhe Institute of Technology

Atomic Tritium Source

Hassan Abdulahi Ali
Albert Braun
Beate Bornschein
Robin Größle
Leonard Hasselmann
Florian Hanß
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
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

Thank you! Questions?

Backup

The atomic tritium source team at TLK

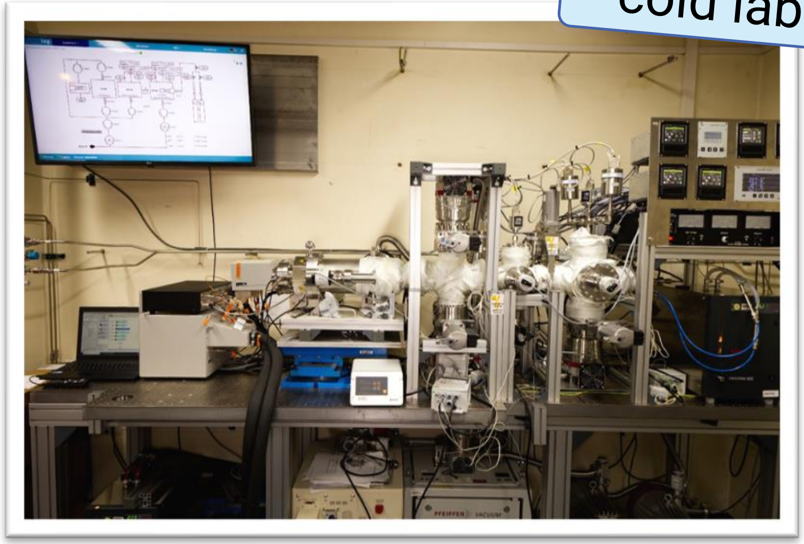
Tritium Laboratory Karlsruhe

Karlsruhe Institute of Technology

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

Two experimental setups at TLK

“cold lab”



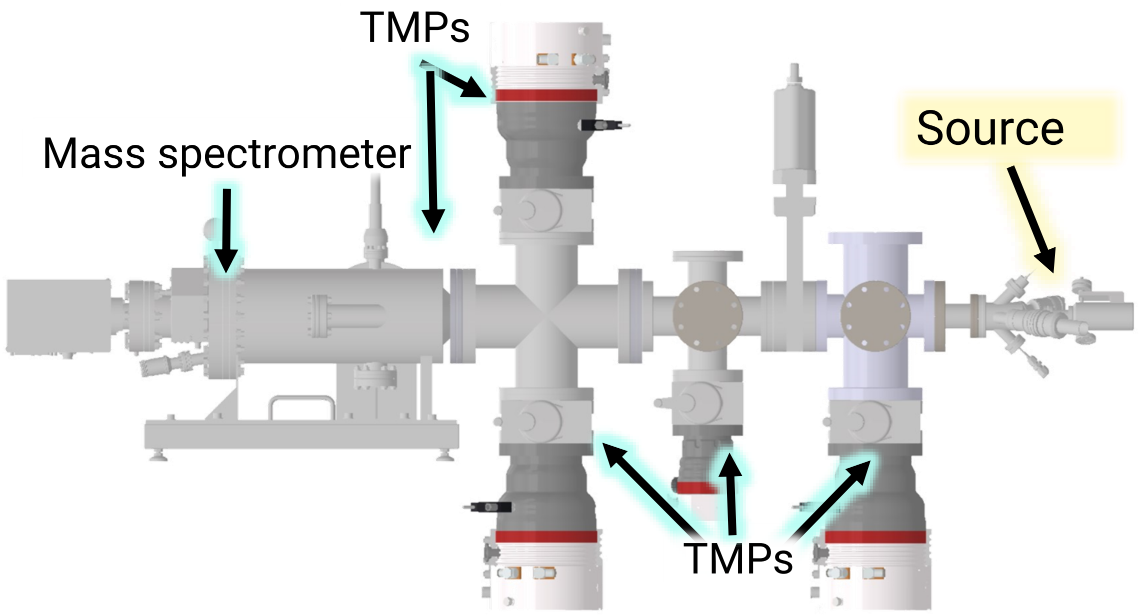
“hot lab”

- R&D of new designs using inactive hydrogen isotopologs, for example:
  - Beam diagnostics: mass spec. meas.
  - Beam shaping: skimmer development
  - Beam cooling: cooling nozzle

- **First goal:** Demonstrate tritium operation in a simple setup
- Build atomic tritium source based on experience gathered at TLK and Mainz (KAMATE collaboration)

Current setup in the cold lab – AHS 1.5

- *Beam analytics* with high-resolution mass spectrometer (Hiden DLS 20)
- *Vacuum setup:* five turbomolecular pumps: 3x HiPace 300, 1x HiPace 80, 1x Edwards STP301 and multiple pressure sensors



Atomic hydrogen source
Tectra h-flux

Current setup in the cold lab – AHS 1.5

Karlsruhe Institute of Technology

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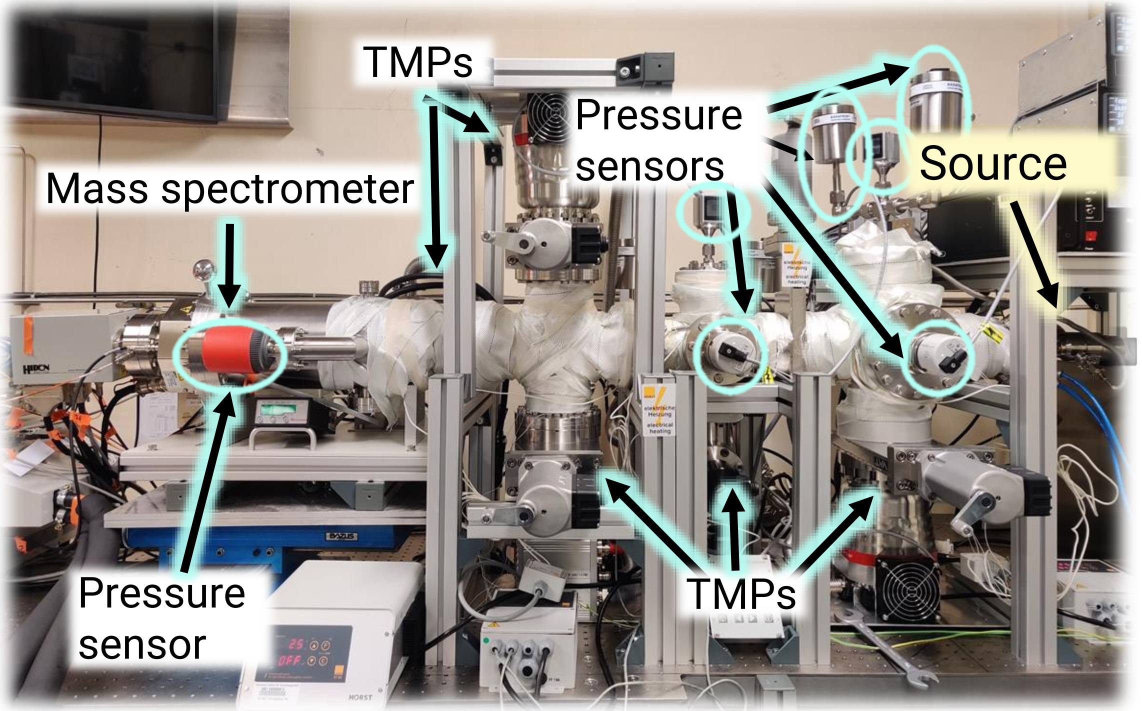

Atomic hydrogen source
Tectra h-flux

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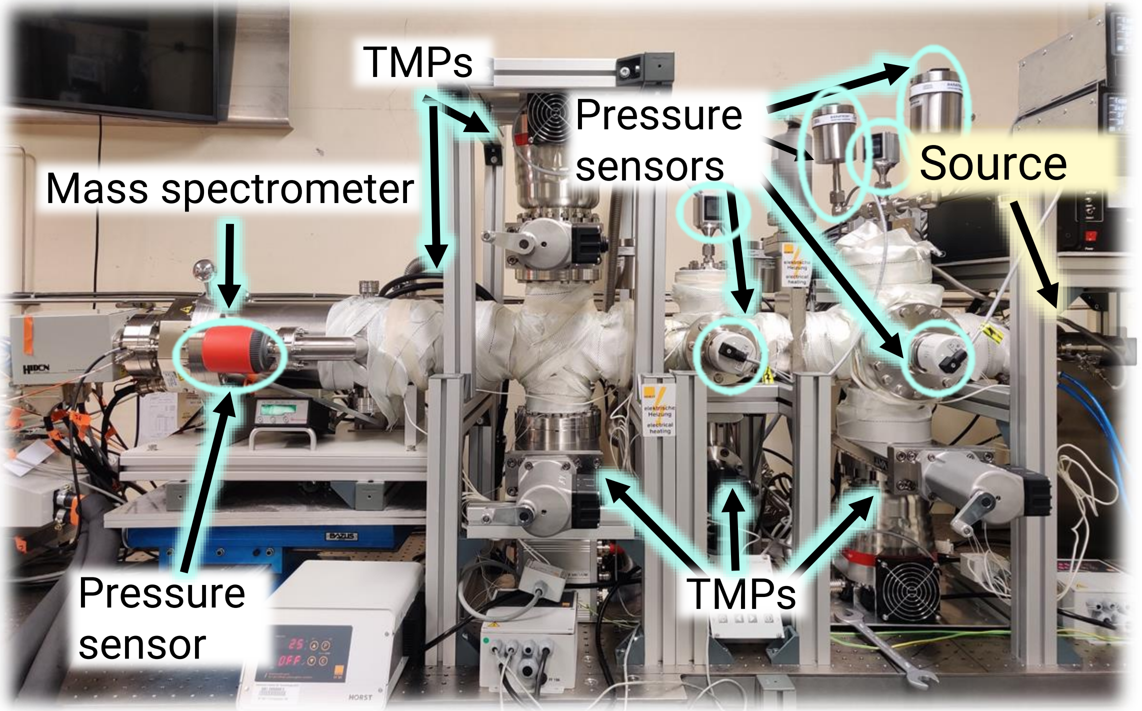
- *Beam analytics* with high-resolution mass spectrometer (Hiden DLS 20)
- *Vacuum setup:* five turbomolecular pumps: 3x HiPace 300, 1x HiPace 80, 1x Edwards STP301 and multiple pressure sensors
- Work of bachelor students at the setup:

Marc Thiel	Tim Sandmann	Elias Lütkenhorst
Building & characterization of setup AHS 1.0	Improvement & characterization of setup AHS 1.0	Building setup AHS 1.5 & first characterization

- Master's thesis (ongoing):

Daniel Kurz
Skimmer development at AHS 1.5



Atomic hydrogen source
Tectra h-flux

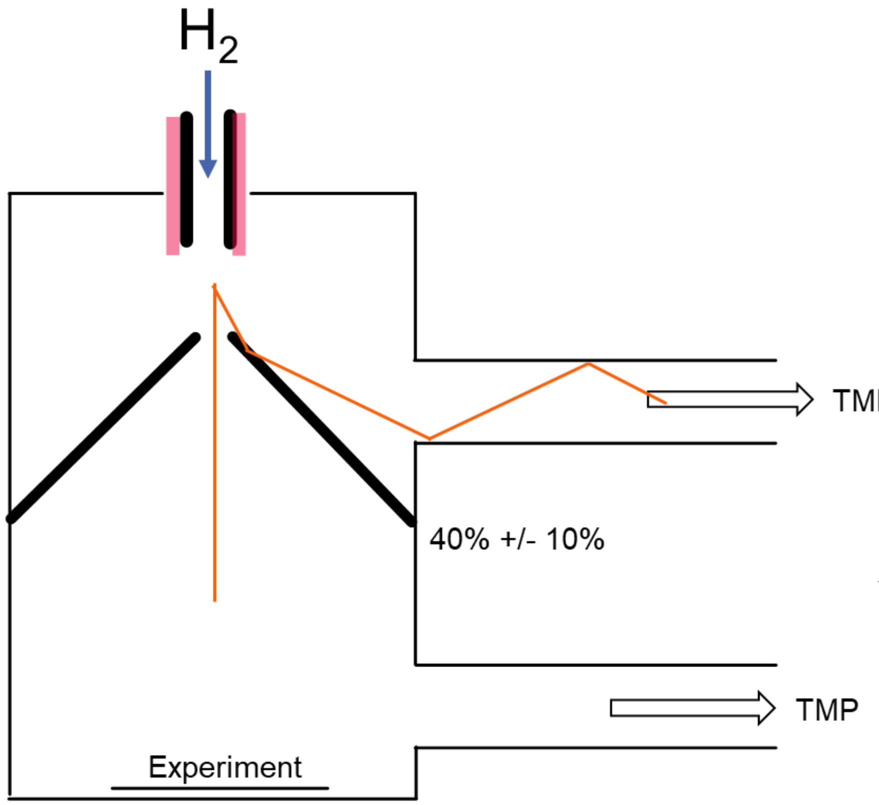
Simulations for different skimmer designs

- **Goal:** Reduce recombination rate in system by implementing skimmers
- Investigate different skimmer geometries with simulations
- Molflow simulations by J. Wörner for AHS 1.5 setup
  - Test of different skimmer geometries with different radii and length

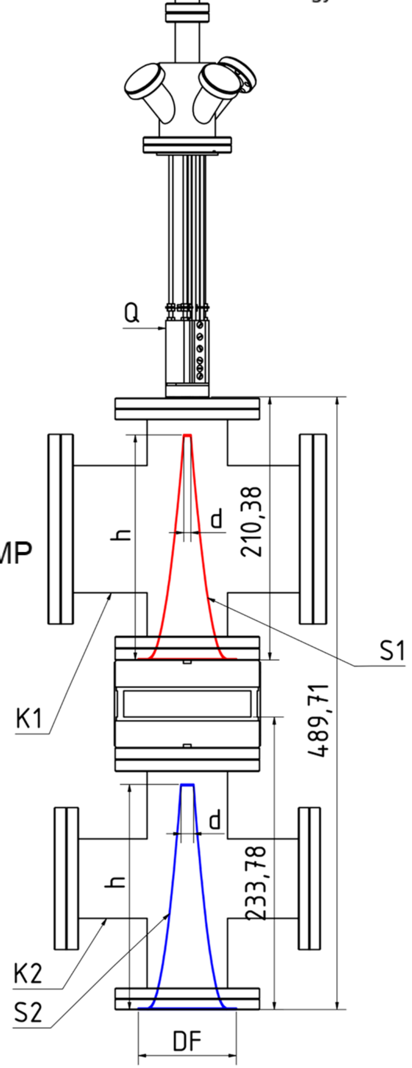
  - Parabola-shaped skimmer gives best results

Ongoing: Test of skimmers

Master's thesis D. Kurz (2024, ongoing)

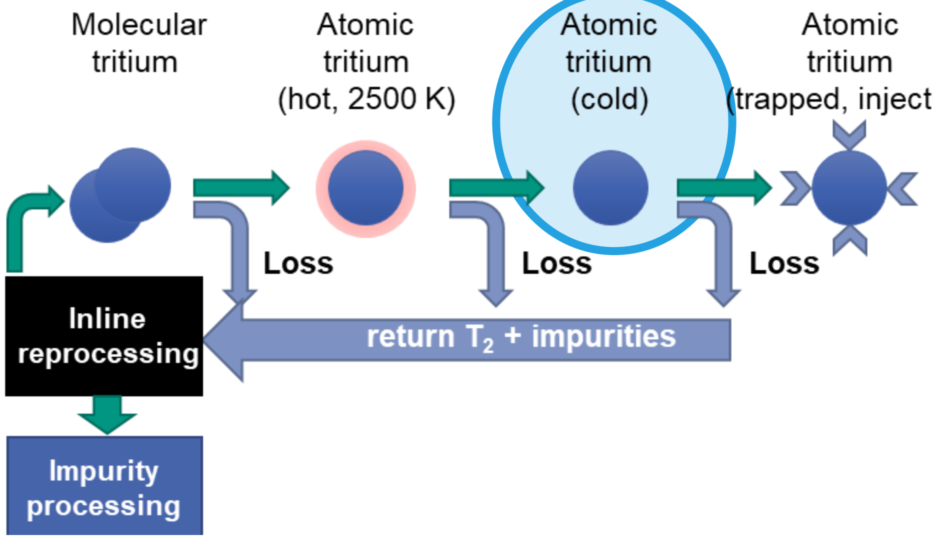


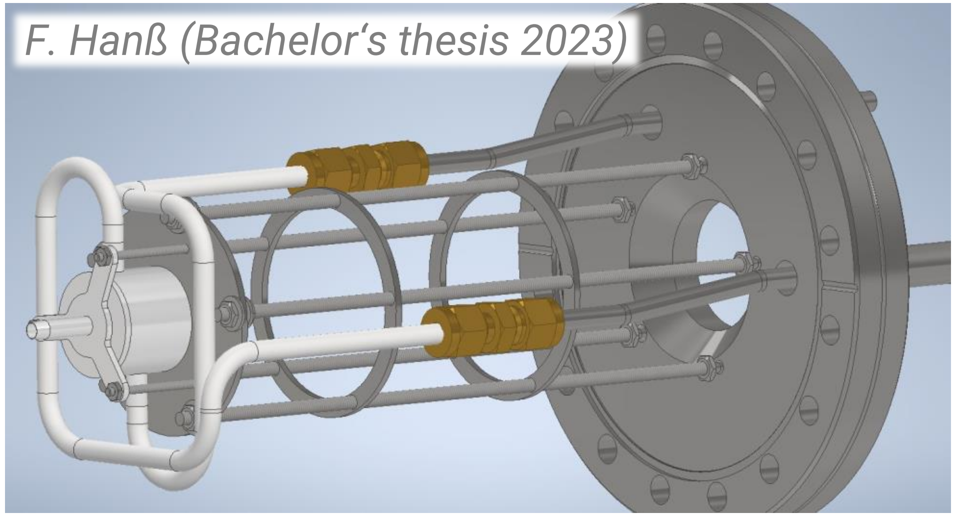
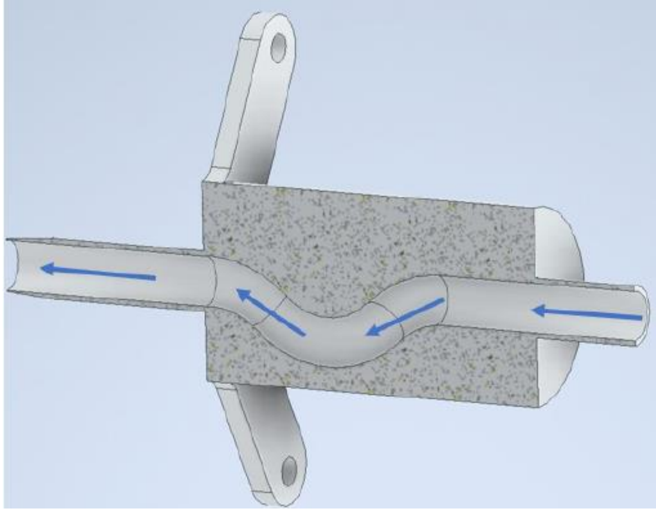
J. Wörner (Bachelor's thesis 2023)



Design of beam cooler

- Design of cold gas cooling system to cool beam down to at least 120 K
  - System currently in production at workshop
  - Further improvements to achieve tritium compatibility planned



F. Hanß (Bachelor's thesis 2023)

Working principle
- Beam cooling by collision of atoms with cold walls
- Using aluminum as wall to achieve low recombination rates and tritium compatibility

Design of beam cooler

- Design of cold gas cooling system to cool beam down to at least 120 K
  - System currently in production at workshop
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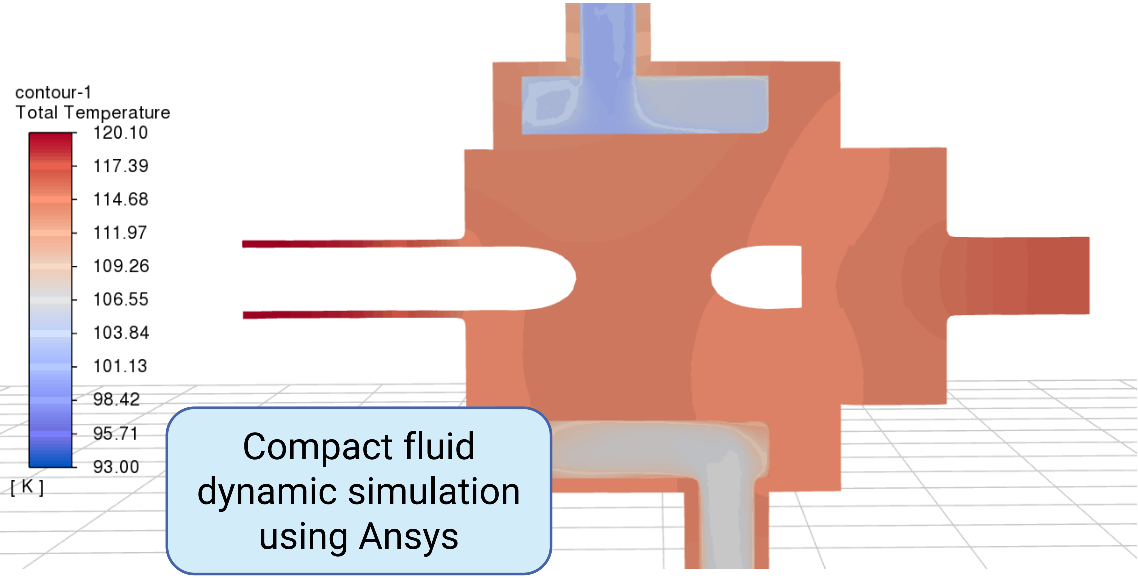
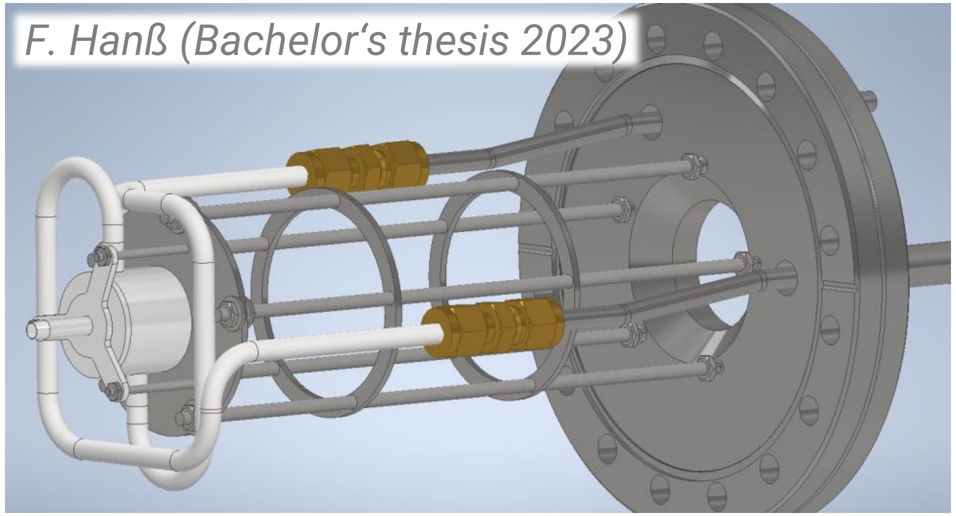
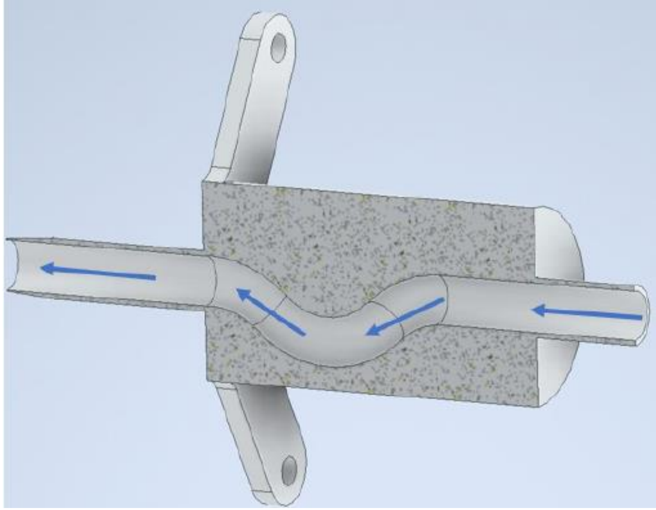


Compact fluid dynamic simulation using Ansys

F. Hanß (Bachelor's thesis 2023)





Working principle
- Beam cooling by collision of atoms with cold walls
- Using aluminum as wall to achieve low recombination rates and tritium compatibility

Time-of-flight temperature measurements

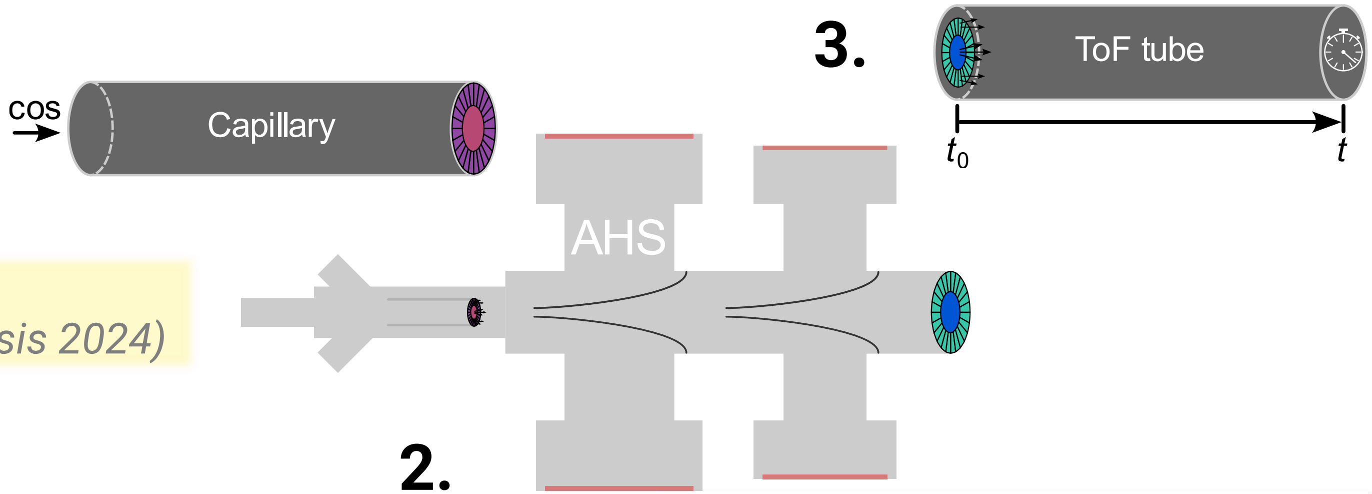
- **Goal:** Design of a time-of-flight setup to determine the beam temperature
- First step, use simulations to develop possible setup

S. Koch (master's thesis 2024)

- Parameters of the simulation:
  - Beam shape (using the Tschersich model)
  - Shape of rotary shutter
  - Shape of ToF tube
- **Next step:** Build setup ☺

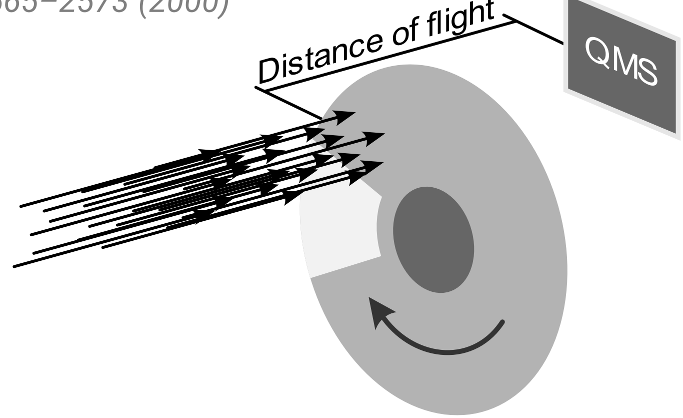
K. G. Tschersich, J. Appl. Phys. 87, 2565–2573 (2000)

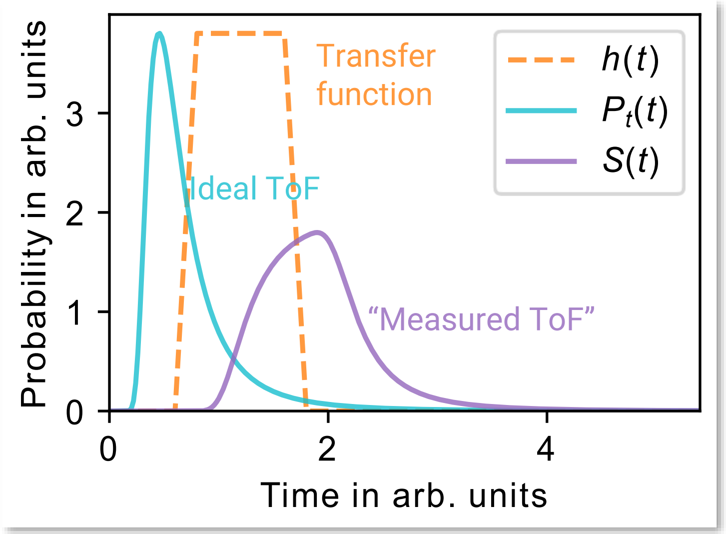
1.



3.

2.





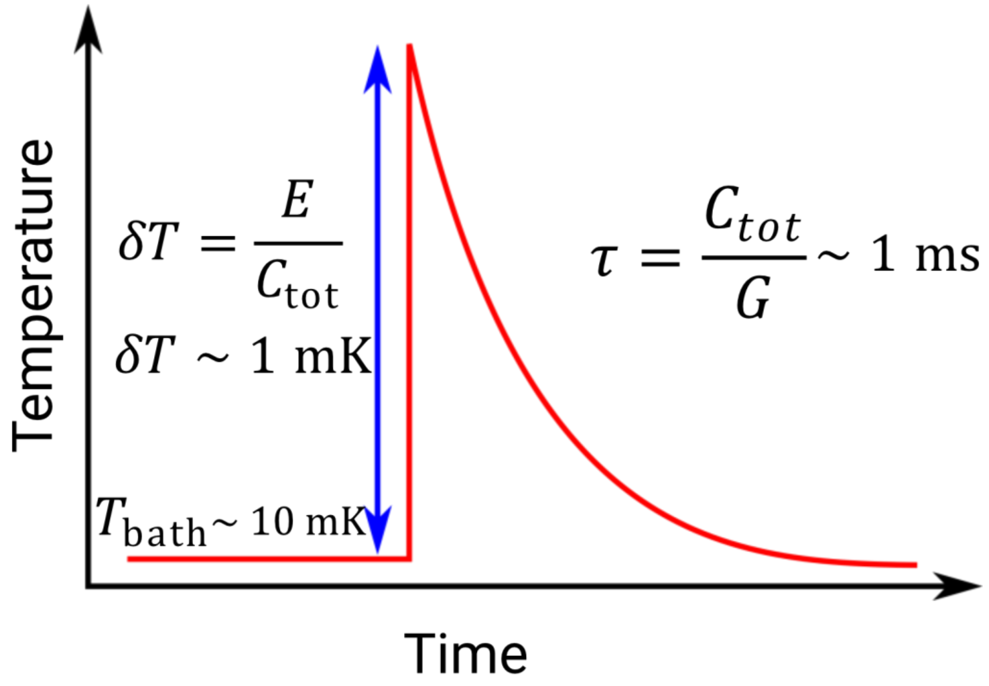
Metallic magnetic calorimeters as differential detectors

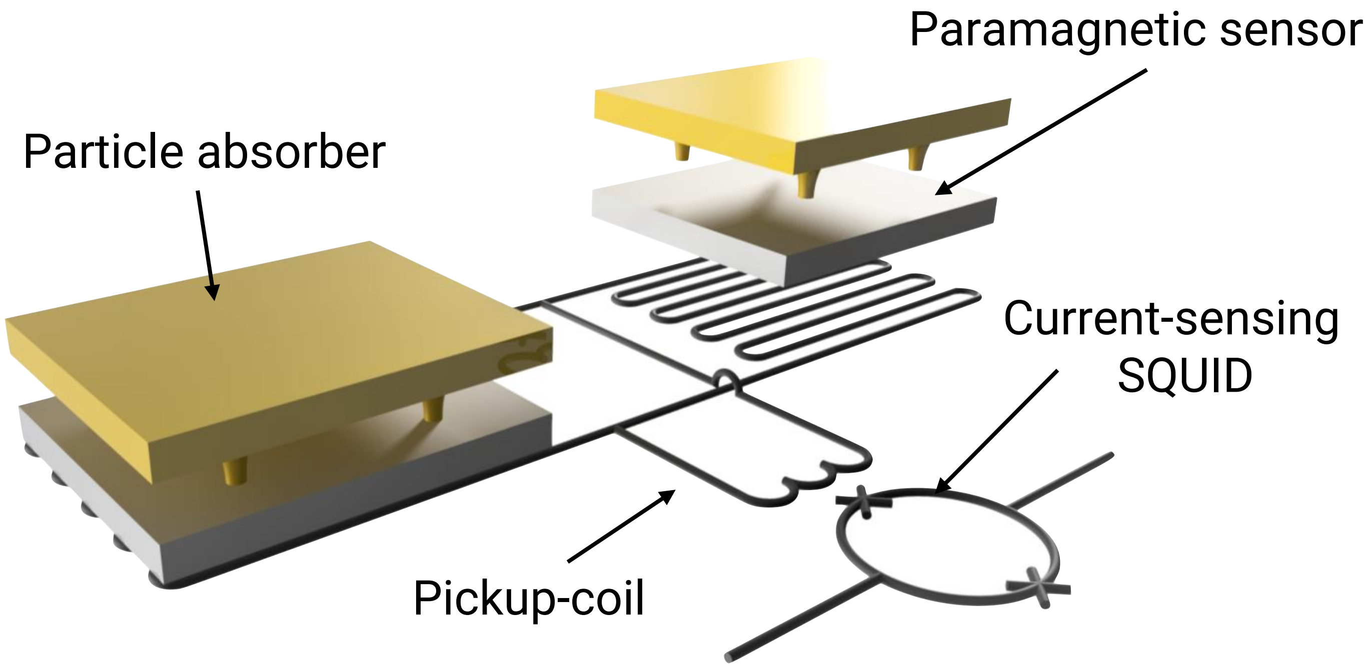
- Cryogenic micro-calorimeters, $T_{opt} \approx 10$ mK
- Working principle based on magnetization response of paramagnetic sensor

World leading energy resolution (photons)

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

M. Krantz et al., arXiv:2310.08698





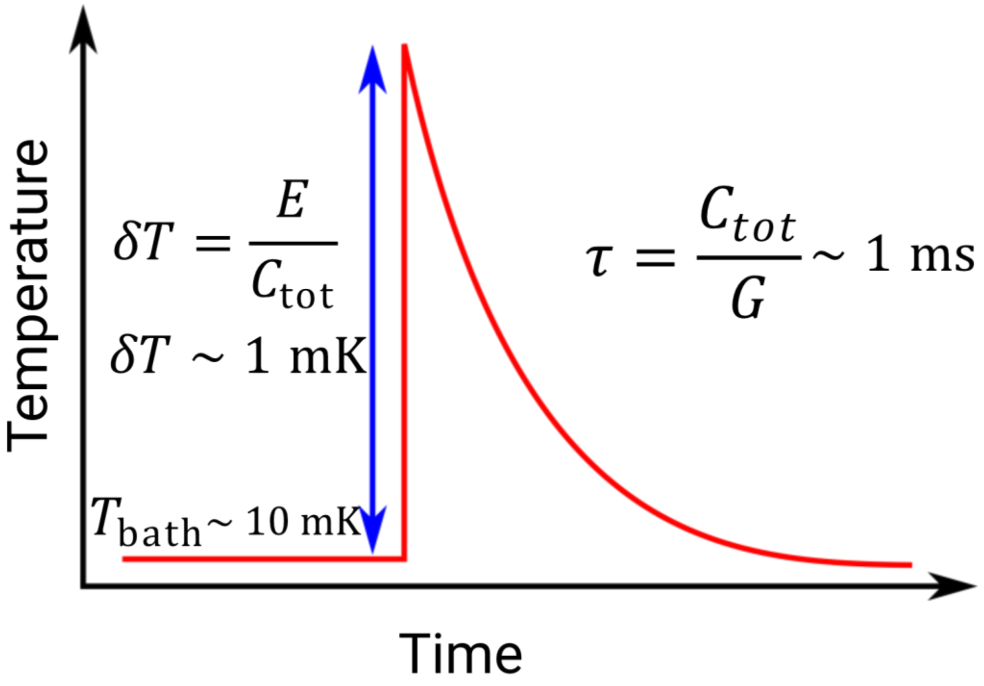
Metallic magnetic calorimeters as differential detectors

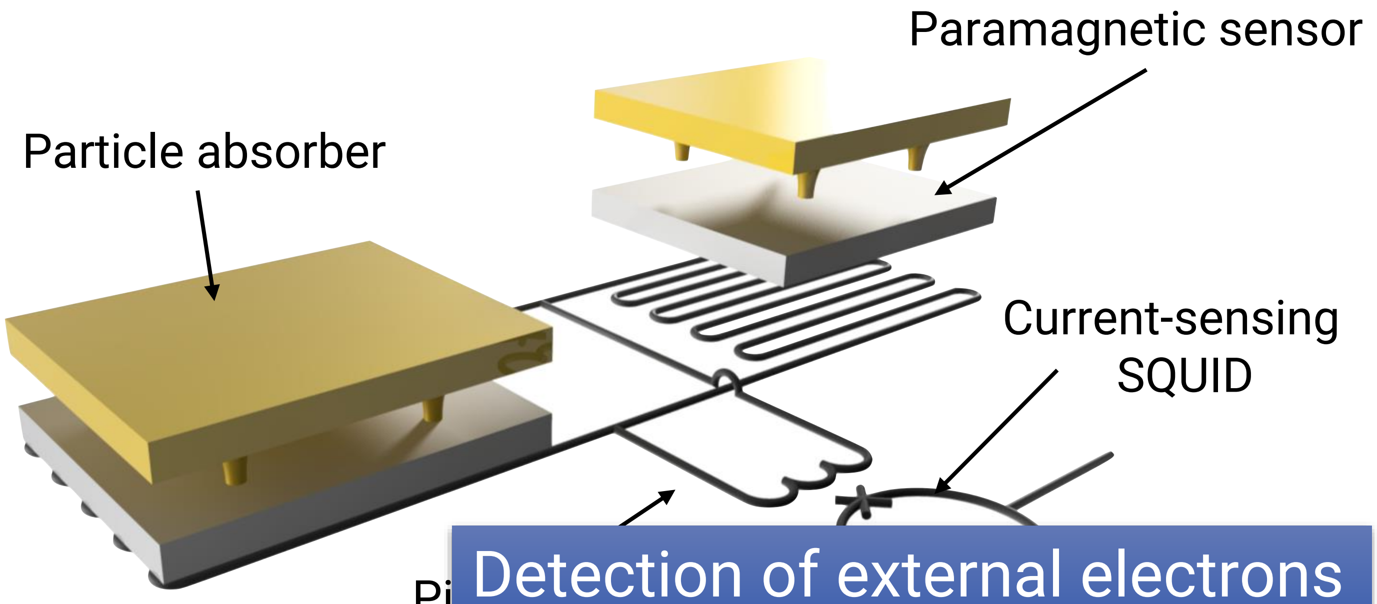
- Cryogenic micro-calorimeters, $T_{\mathrm{opt}} \approx 10\ \mathrm{mK}$
- Working principle based on magnetization response of paramagnetic sensor

World leading energy resolution (photons)

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

M. Krantz et al., arXiv:2310.08698

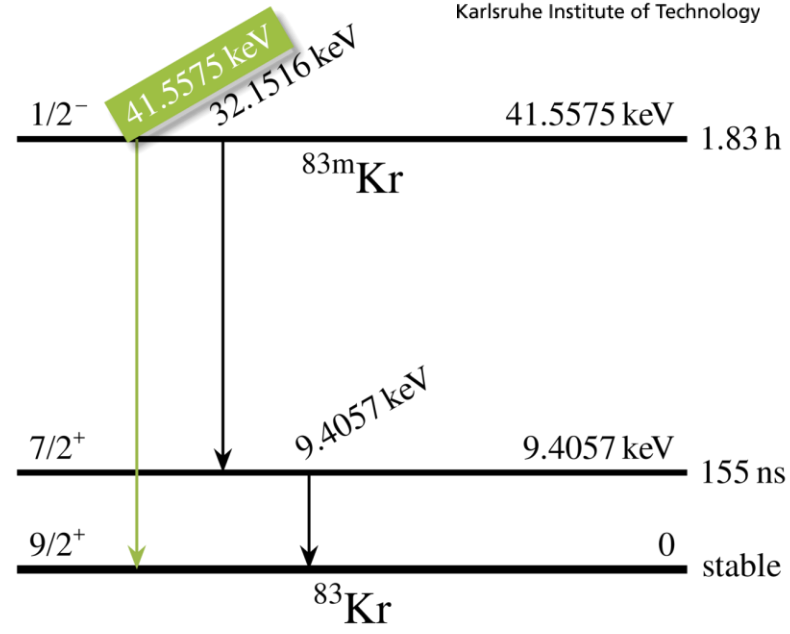




Detection of external electrons to be demonstrated!

Characteristics of krypton-83m NEW

- Short-lived daughter nucleus krypton-83m **usually decays** via two-step process to ground state
- Strongly suppressed direct transition also possible!
  - Hints in KATRIN's detector spectrum since 2017
  - Pronounced background for precision measurements
    with high-luminosity 10 G[illegible]ource in 2021
    (source available from NP[illegible]



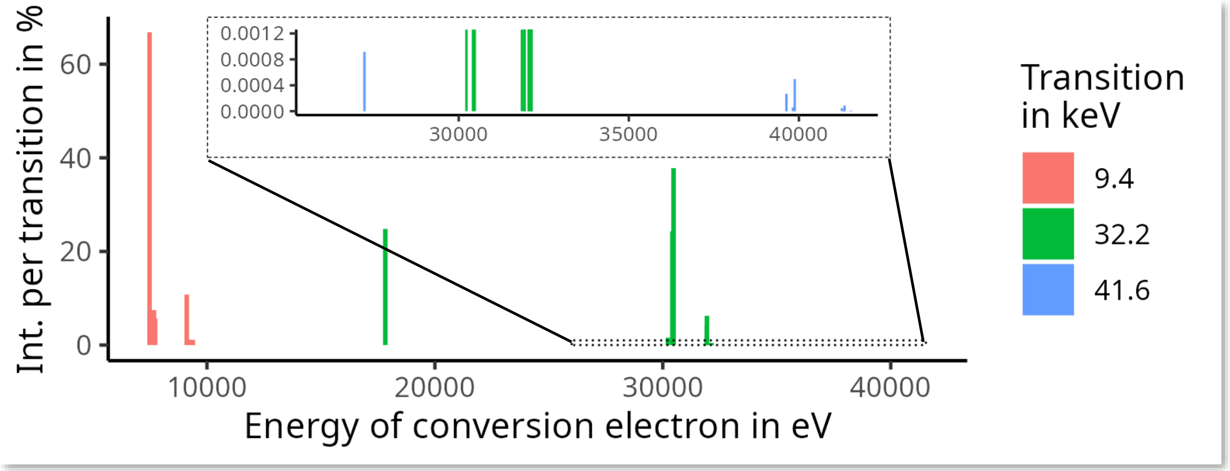
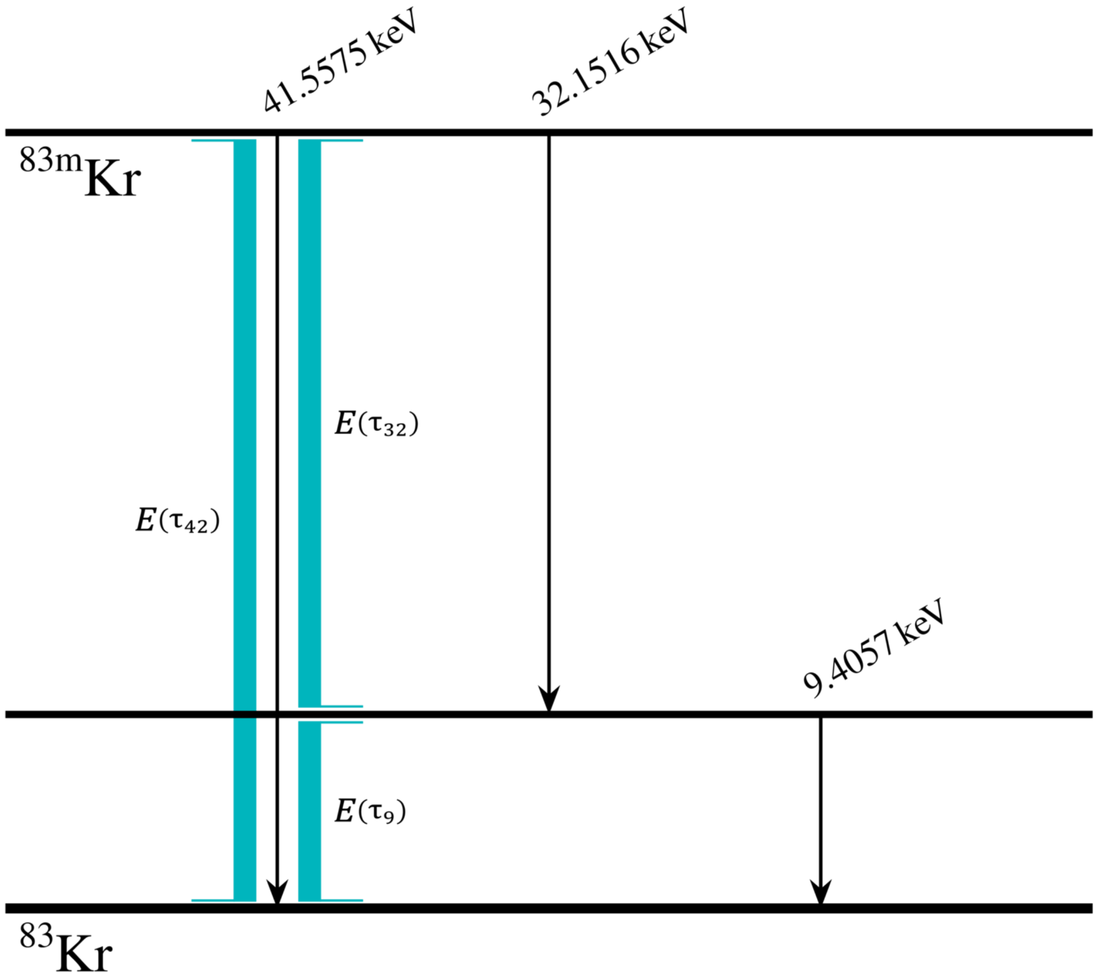


Illustration using theoretical predictions from
D. Vénos et al., J. Instrum. 13 T02012 (2018)

A new method using the direct transition

- The direct transition connects the two single transitions (9 keV, 32 keV)
- Equivalence allows the determination of effective shift $\Delta\Phi'$
  - Only possible due to excellent linearity of spectrometer
- **Three steps:**
  1. Determine the effective shift $\Delta\Phi'$ by measurement of three lines, each from one transition
  2. Determining transition energies now possible with high accuracy, since $\Delta\Phi'$ is known
  3. Use newly measured transition energies as a reference for usual calibration procedure

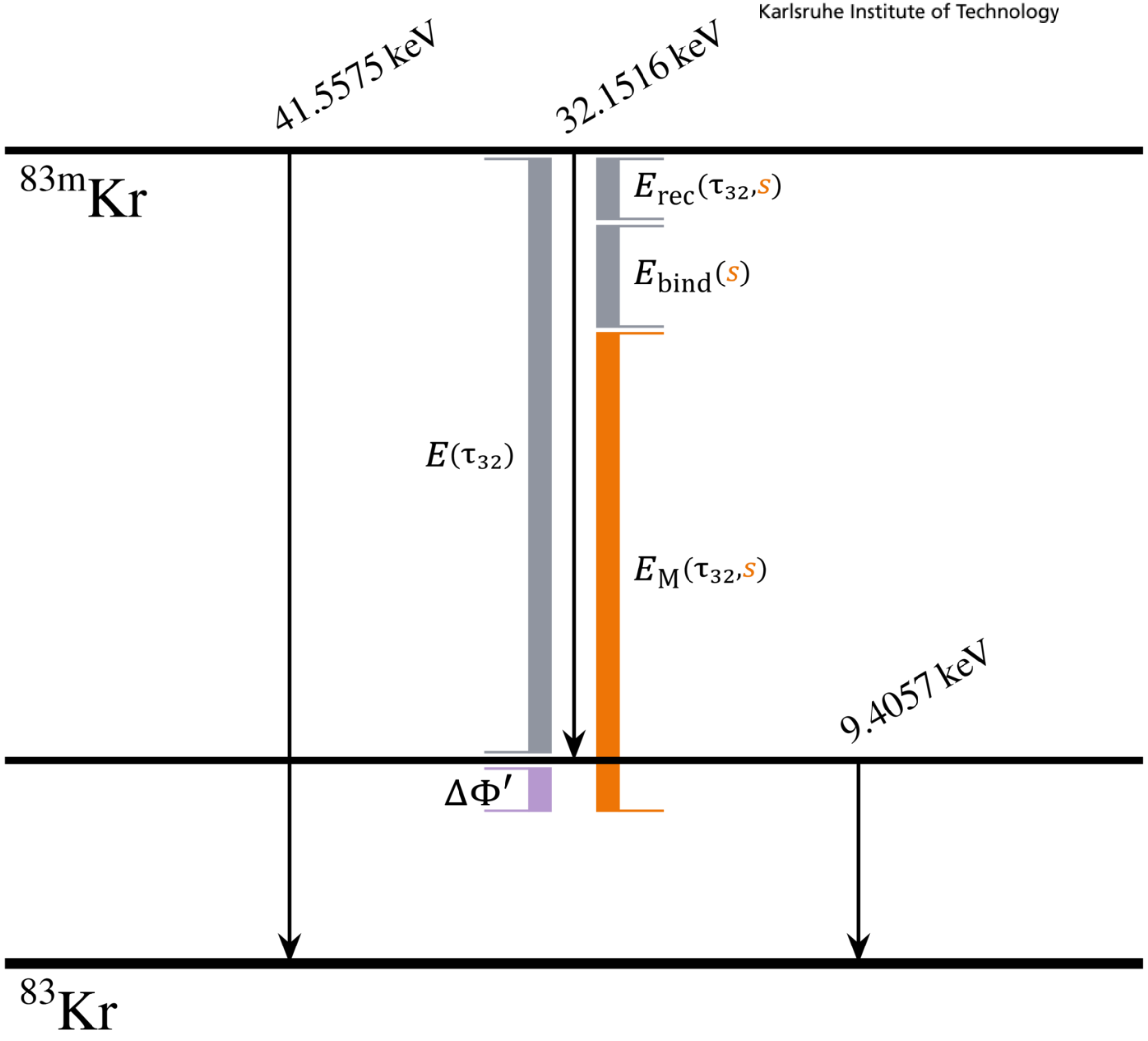


Determining the effective shift

- Line position in general terms:

$$E_{\mathrm{M}}(g,s) = E(g) - E_{\mathrm{bind}}(s) - E_{\mathrm{rec}}(g,s) + \Delta\Phi'$$

where g is a transition and s is an electron subshell



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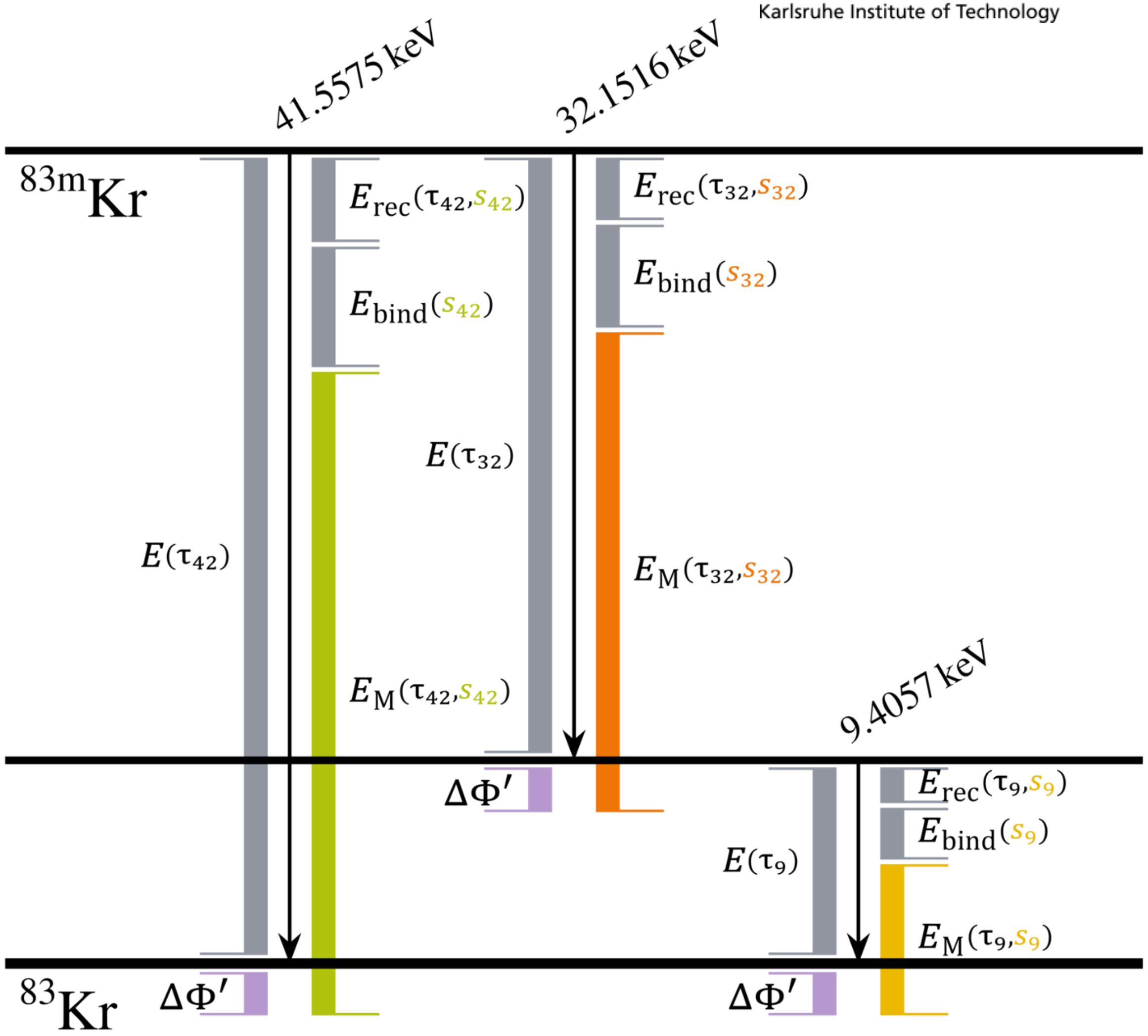

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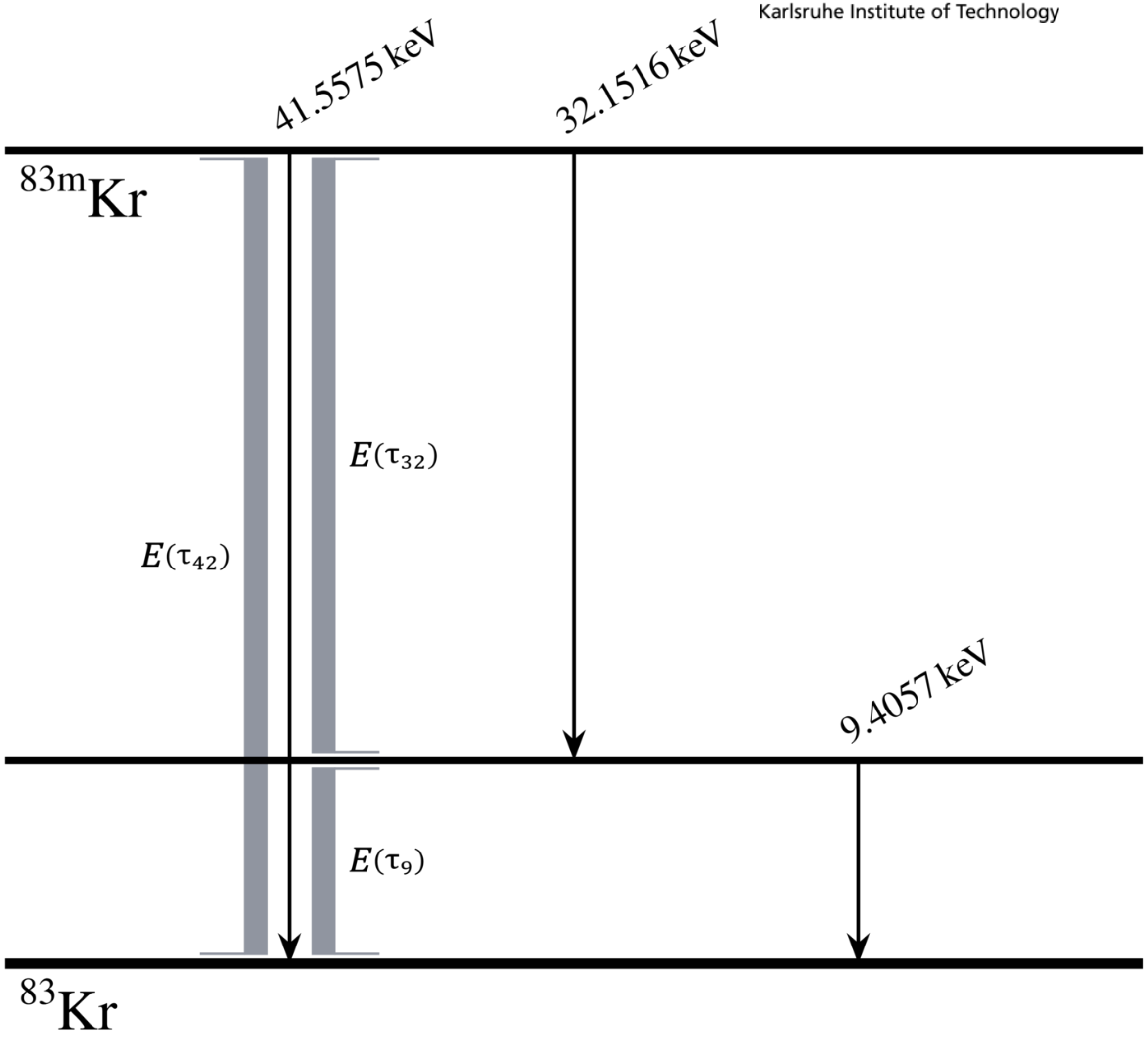
  $$E_{\mathrm{M}}(g,s) = E(g) - E_{\mathrm{bind}}(s) - E_{\mathrm{rec}}(g,s) + \Delta\Phi'$$
  where g is a transition and s is an electron subshell
- Transition energies related via:
  $$E(\tau_{42}) = E(\tau_{32}) + E(\tau_9)$$



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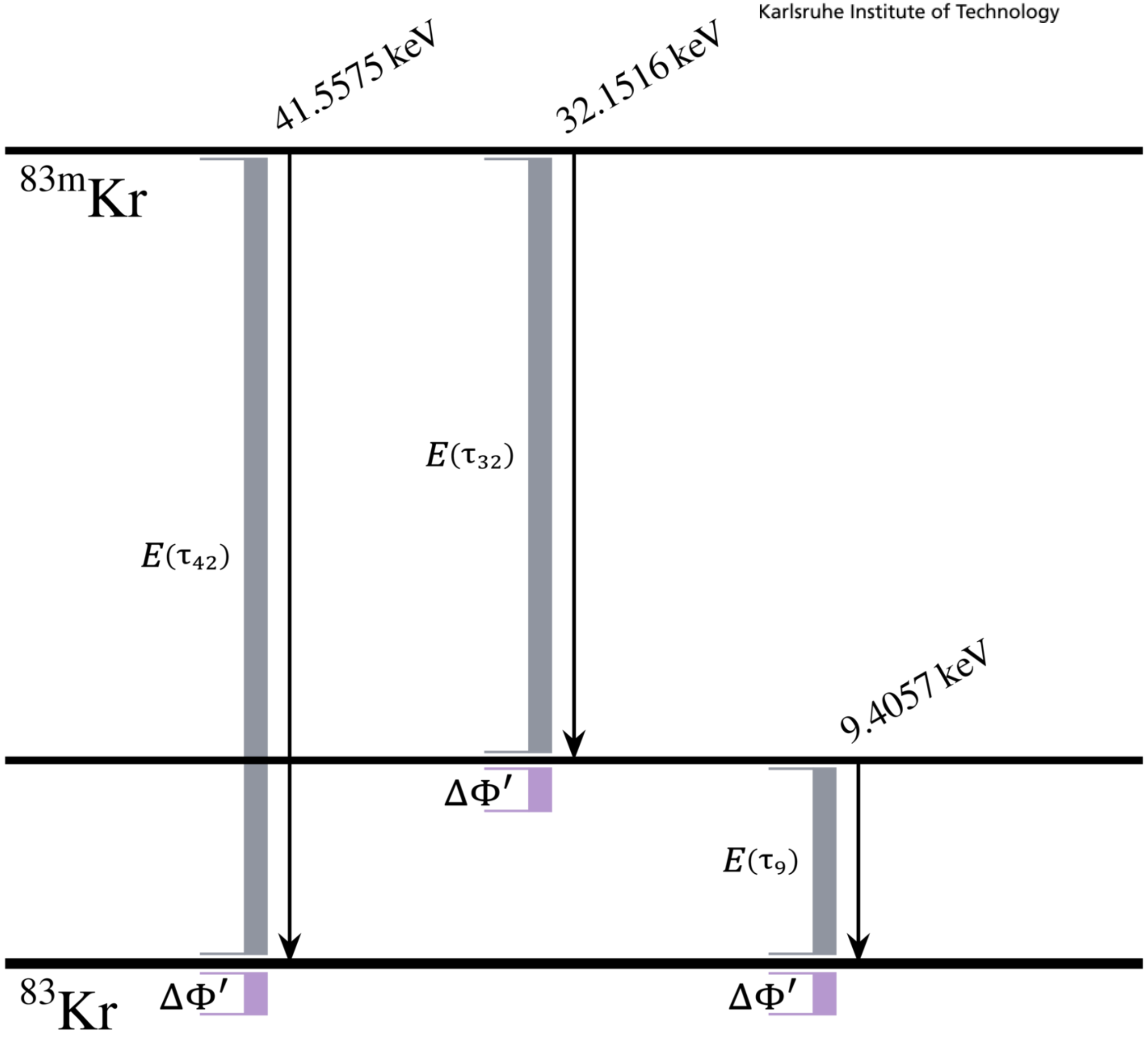

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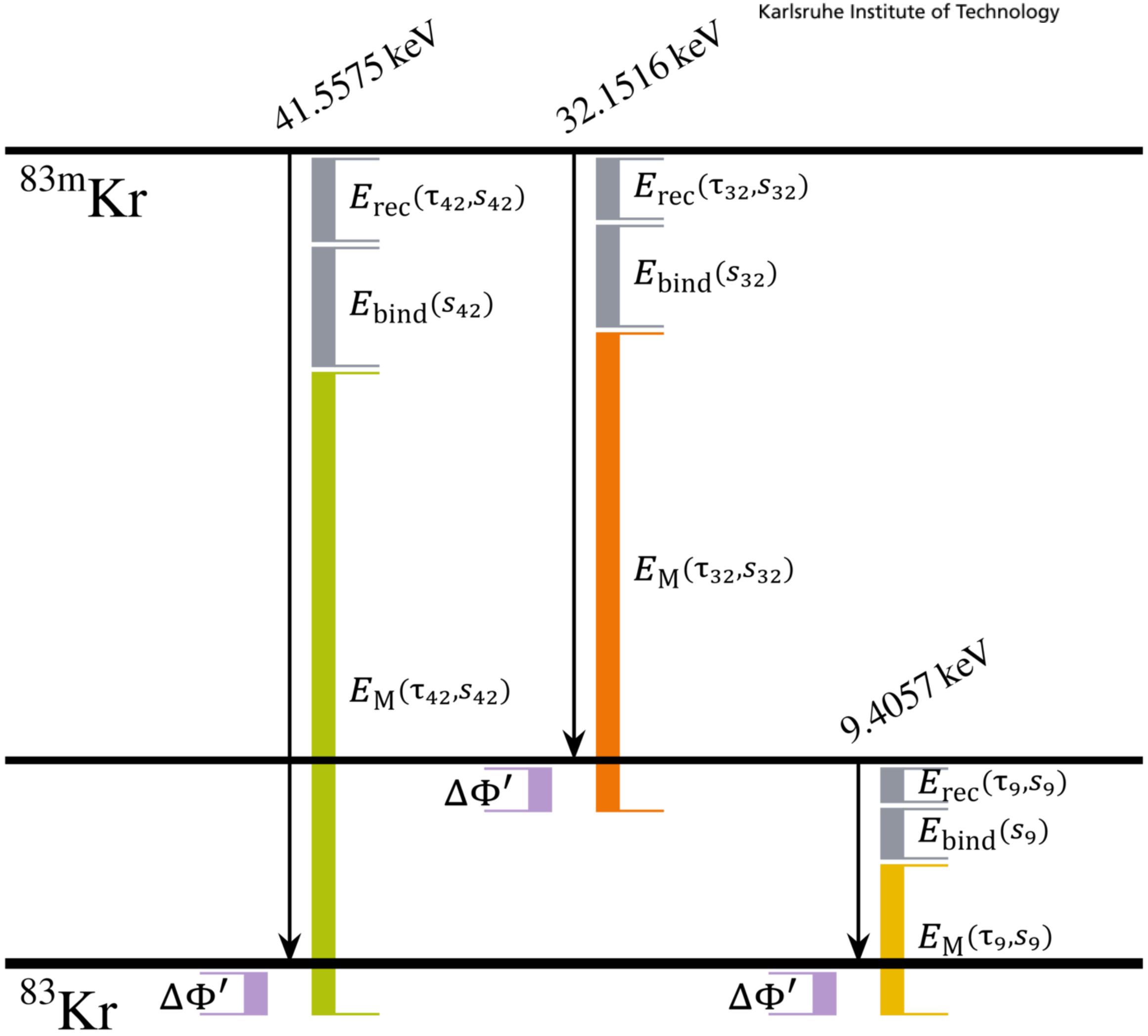
where g is a transition and s is an electron subshell

- Transition energies related via:

$$E(\tau_{42}) = E(\tau_{32}) + E(\tau_9)$$

- Shift can be determined from three lines:

$$\begin{aligned}\Delta\Phi' = &- E_{\mathrm{M}}(\tau_{42},s_{42}) - E_{\mathrm{bind}}(s_{42}) - E_{\mathrm{rec}}(\tau_{42},s_{42}) \\ &+ E_{\mathrm{M}}(\tau_{32},s_{32}) + E_{\mathrm{bind}}(s_{32}) + E_{\mathrm{rec}}(\tau_{32},s_{32}) \\ &+ E_{\mathrm{M}}(\tau_9,s_9) + E_{\mathrm{bind}}(s_9) + E_{\mathrm{rec}}(\tau_9,s_9)\end{aligned}$$



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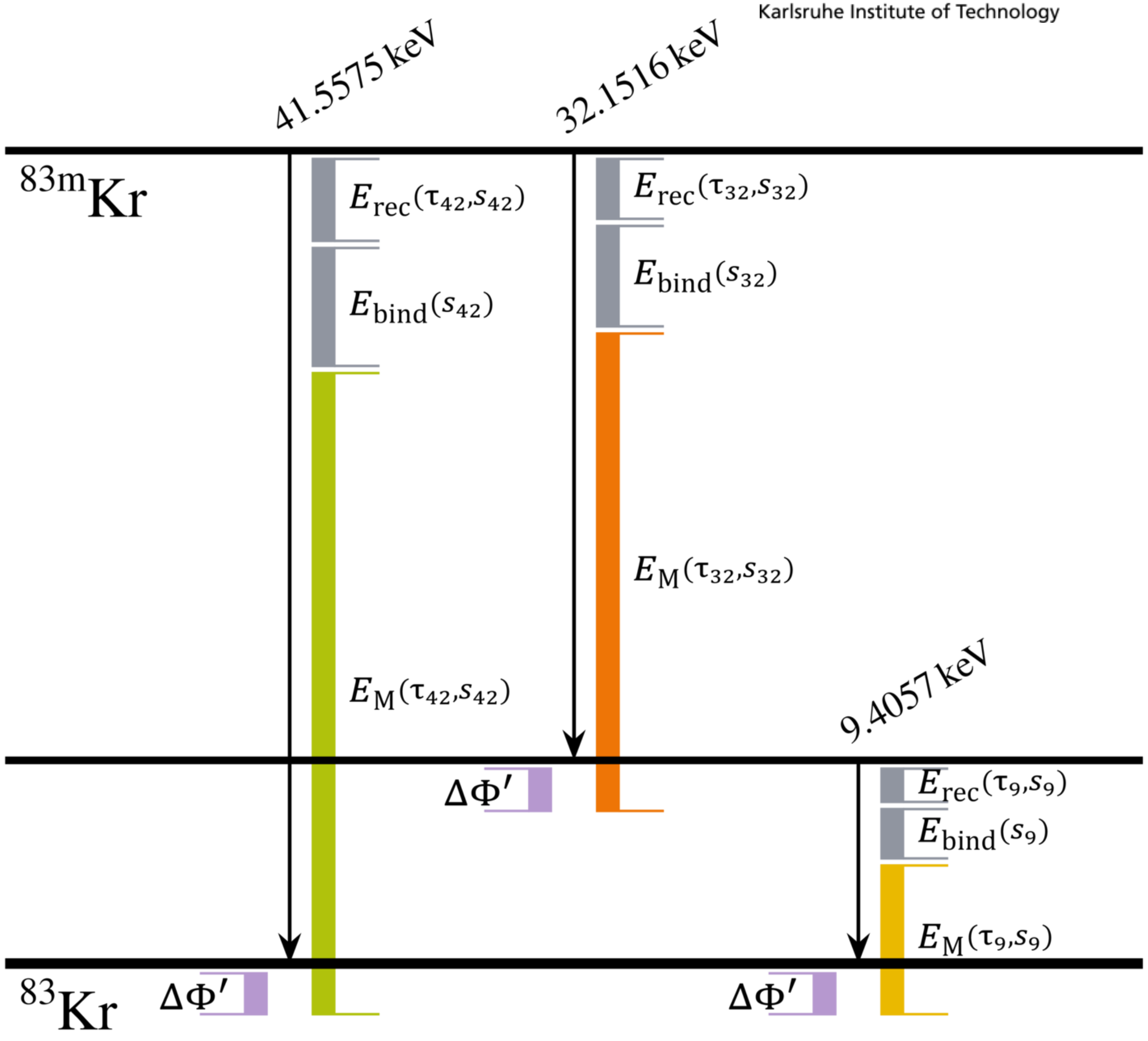
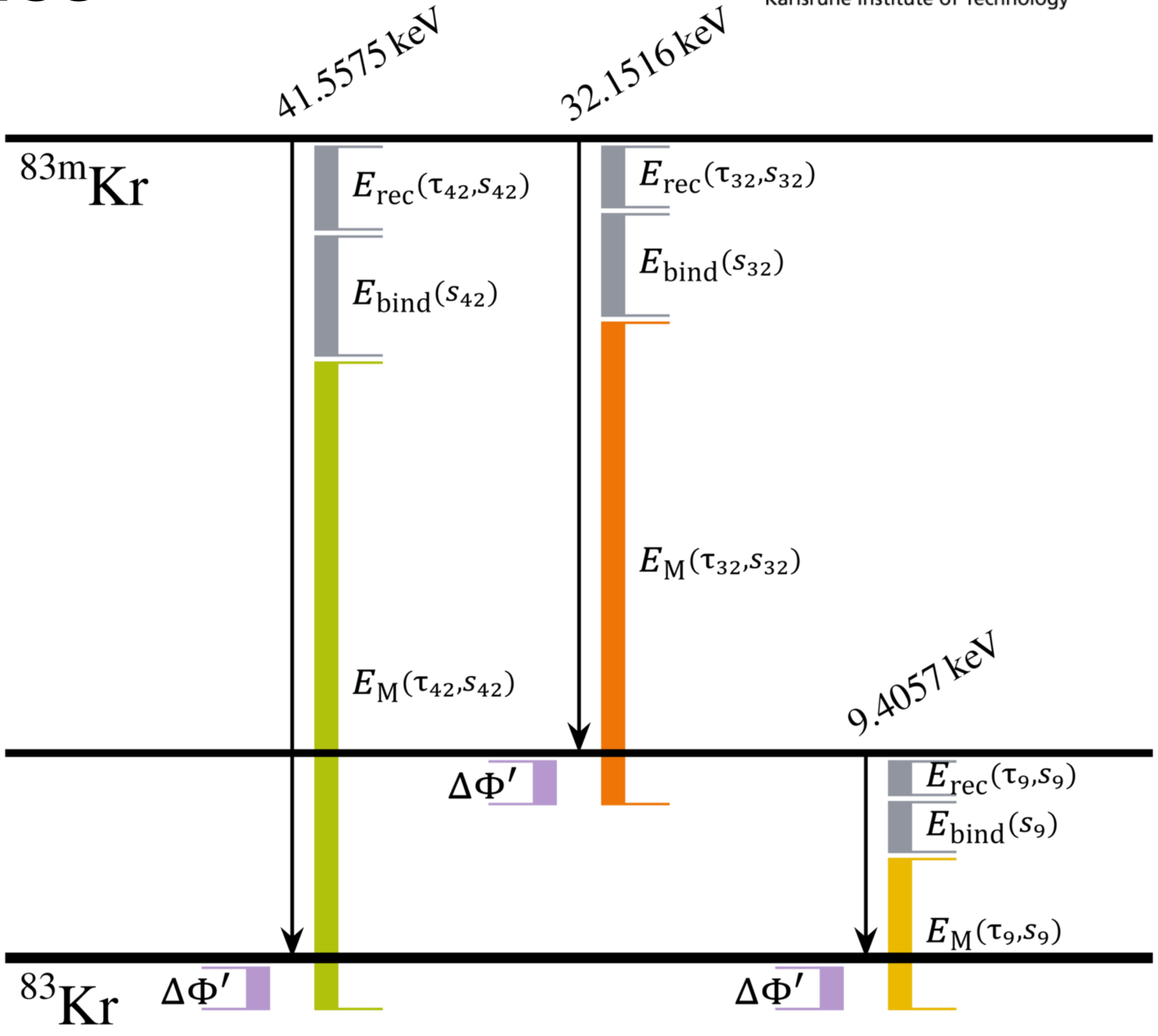
This way of determining $\Delta\Phi'$ **does not require reference values** from gamma decay!



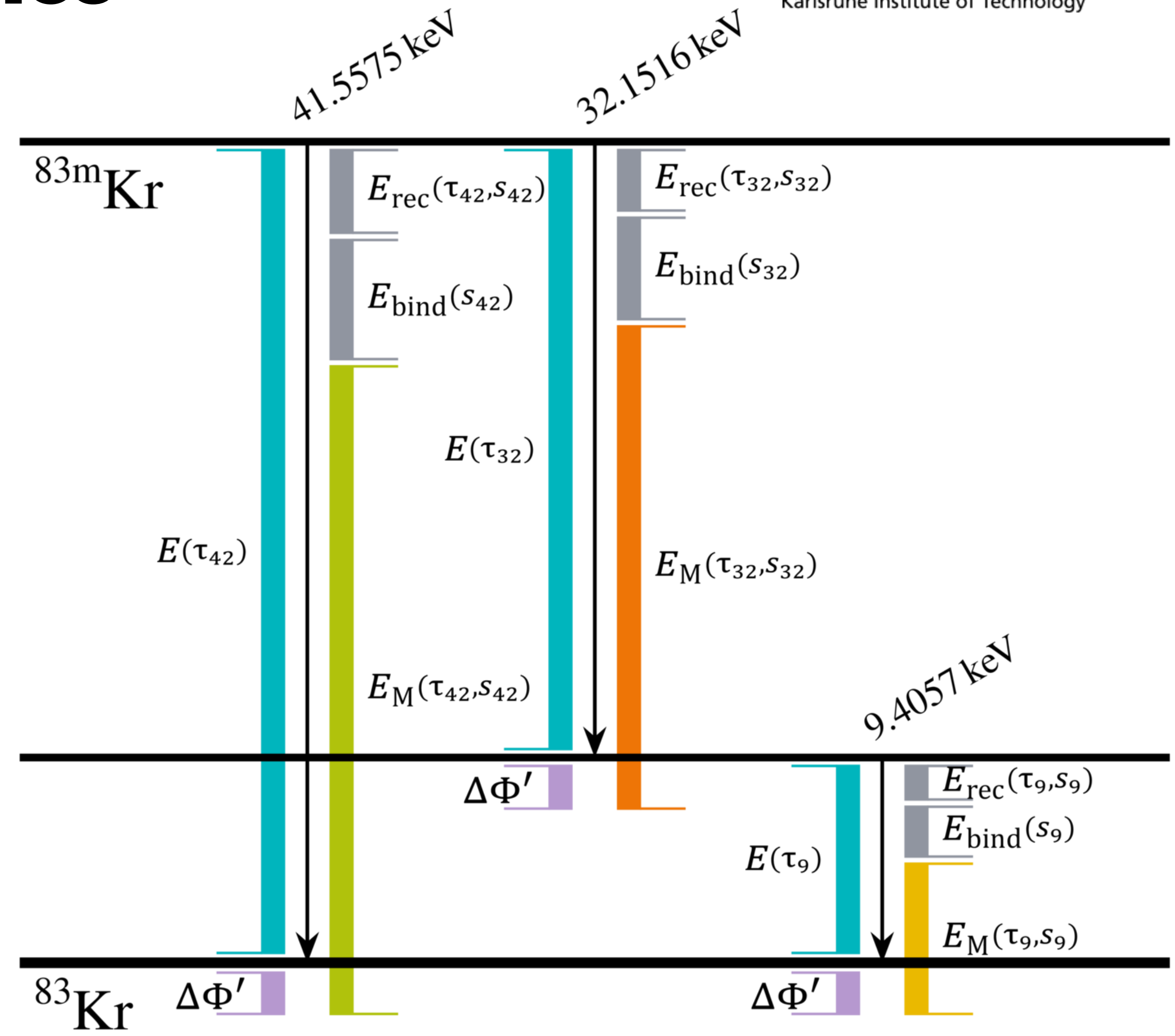
Determining the transition energies



Determining the transition energies

- The transition energies are determined as:

$$E(g) = E_{\mathrm{M}}(g,s) + E_{\mathrm{bind}}(s) + E_{\mathrm{rec}}(g,s) - \Delta\Phi'$$
$$= E_{\mathrm{M}}(g,s) + E_{\mathrm{bind}}(s) + E_{\mathrm{rec}}(g,s)$$
$$\boxed{\begin{aligned} &+ E_{\mathrm{M}}(\tau_{42}, s_{42}) + E_{\mathrm{bind}}(s_{42}) + E_{\mathrm{rec}}(\tau_{42}, s_{42}) \\ &- E_{\mathrm{M}}(\tau_{32}, s_{32}) - E_{\mathrm{bind}}(s_{32}) - E_{\mathrm{rec}}(\tau_{32}, s_{32}) \\ &- E_{\mathrm{M}}(\tau_{9}, s_{9}) - E_{\mathrm{bind}}(s_{9}) - E_{\mathrm{rec}}(\tau_{9}, s_{9}) \end{aligned}}$$

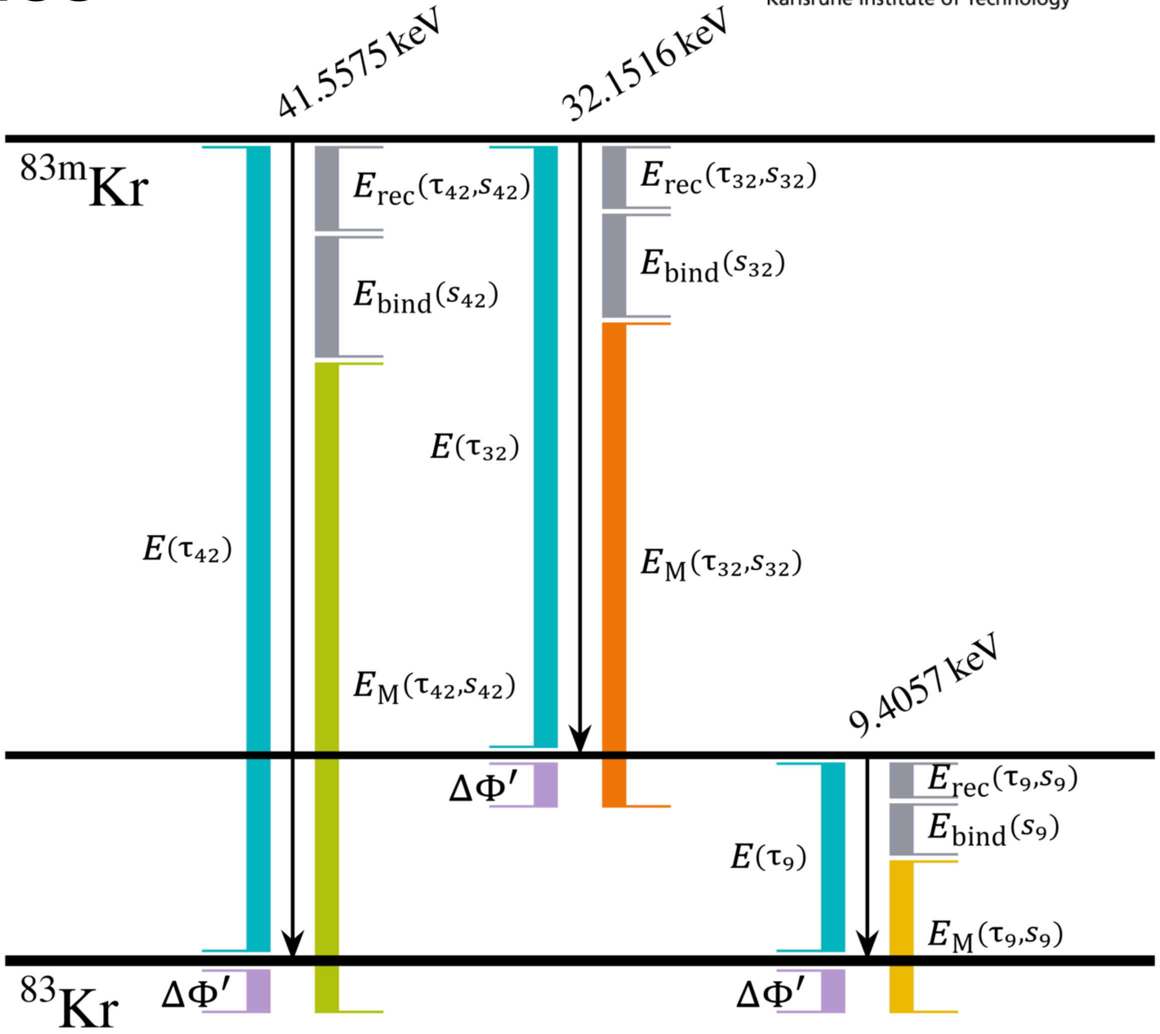


Determining the transition energies

- The transition energies are determined as:

$$
\begin{aligned}
E(g) &= E_{\mathrm{M}}(g,s) + E_{\mathrm{bind}}(s) + E_{\mathrm{rec}}(g,s) - \Delta\Phi' \\
&= E_{\mathrm{M}}(g,s) + \cancel{E_{\mathrm{bind}}(s)} + E_{\mathrm{rec}}(g,s) \\
&\quad + E_{\mathrm{M}}(\tau_{42},s_{42}) + \cancel{E_{\mathrm{bind}}(s_{42})} + E_{\mathrm{rec}}(\tau_{42},s_{42}) \\
&\quad - E_{\mathrm{M}}(\tau_{32},s_{32}) - \cancel{E_{\mathrm{bind}}(s_{32})} - E_{\mathrm{rec}}(\tau_{32},s_{32}) \\
&\quad - E_{\mathrm{M}}(\tau_{9},s_{9}) - \cancel{E_{\mathrm{bind}}(s_{9})} - E_{\mathrm{rec}}(\tau_{9},s_{9})
\end{aligned}
$$

same subshells:
$s_{32} = s_9 = s_{42}$



Determining the transition energies – uncertainty estimation

- Using L_3 subshell in each of the three measurements: $s_{32} = s_9 = s_{42} = \mathrm{L}_3$
- Uncertainty of L_3-32 line position in measurement of 2017: **25 meV** (3 meV stat.) [1]
- Assumption: L_3-9.4 and L_3-42 are measured with comparable uncertainty

Transition	Literature [2]	Expectation (KATRIN)
9 keV	600 meV	35 meV
32 keV	500 meV	35 meV
42 keV	700 meV	50 meV

negligible

25 meV

$$E(g) = E_{\mathrm{M}}(g,s) + E_{\mathrm{rec}}(g,s)$$
$$+ E_{\mathrm{M}}(\tau_{42}, s_{42}) + E_{\mathrm{rec}}(\tau_{42}, s_{42})$$
$$- E_{M}(\tau_{32}, s_{32}) - E_{\mathrm{rec}}(\tau_{32}, s_{32})$$
$$- E_{M}(\tau_{9}, s_{9}) \quad - E_{\mathrm{rec}}(\tau_{9}, s_{9})$$

[1] KATRIN collaboration, J. Phys. G: Nucl. Part. Phys. 47 065002 (2020)
[2] E. McCutchan, Nucl. Data Sheets 125 pp. 201–394 (2015)

Energy scale calibration – improved

- Use transition energy as reference

$$\Delta\Phi' = E_{\mathrm{M}} - E + E_{\mathrm{bind}} + E_{\mathrm{rec}}$$

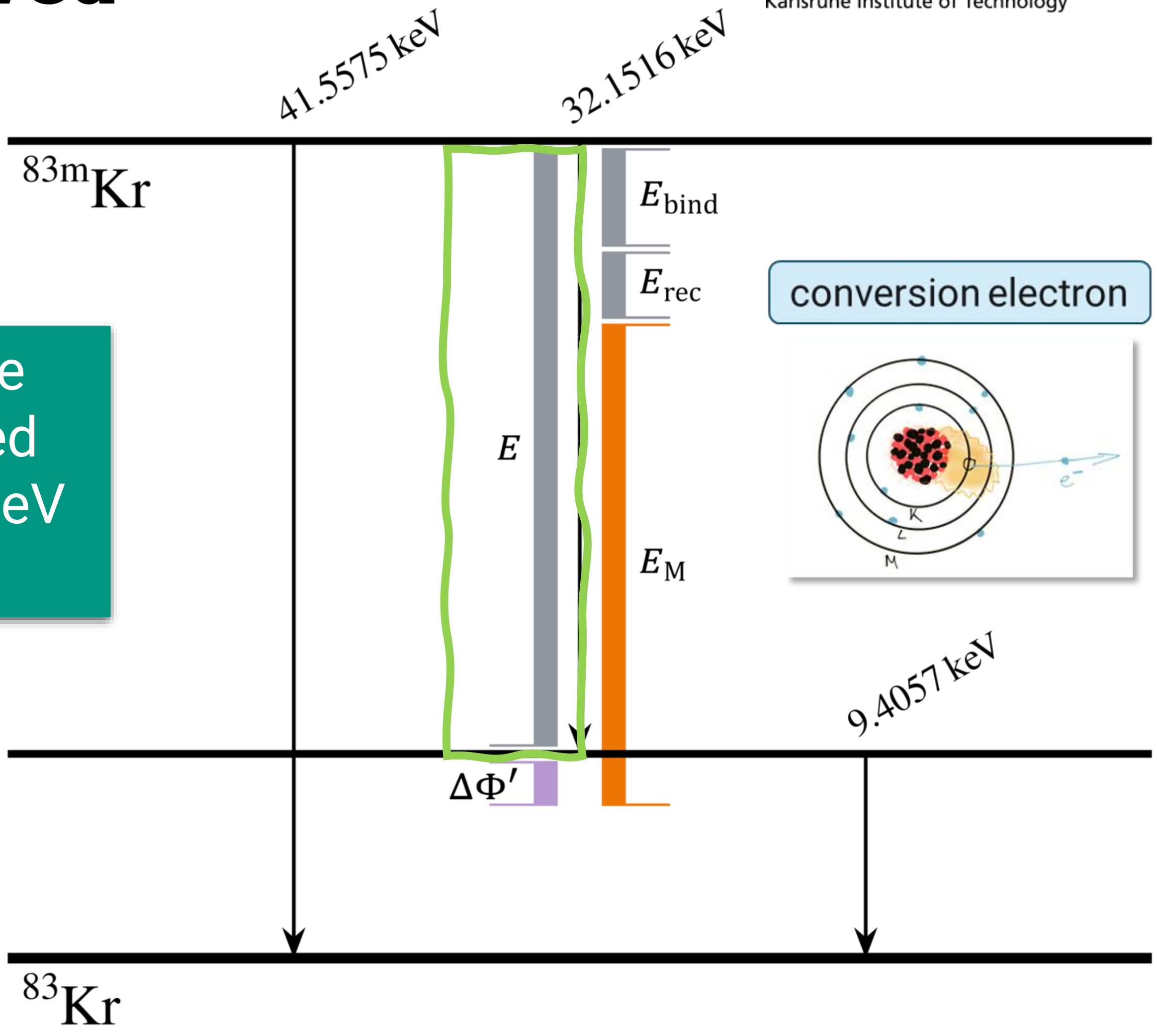
- Expected uncertainties:

E 35 meV (before 500 meV)

E_{bind} ~ 50 meV

E_{M} 25 meV

Δϕ′ can be determined with 66 meV accuracy!



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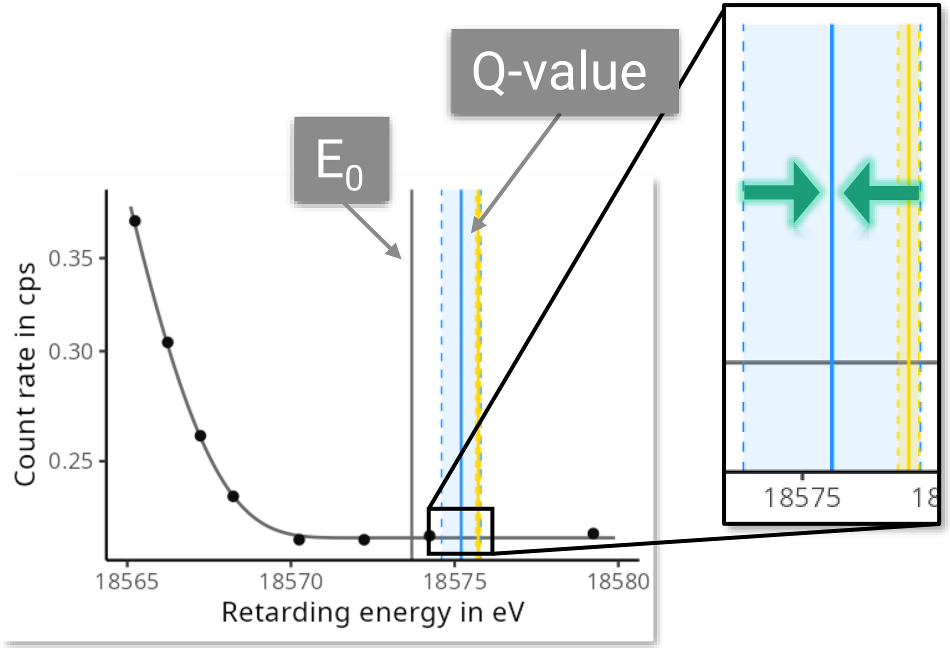


KATRIN

New uncertainty:
0.066 eV
(previously 0.6 eV)

External measurement

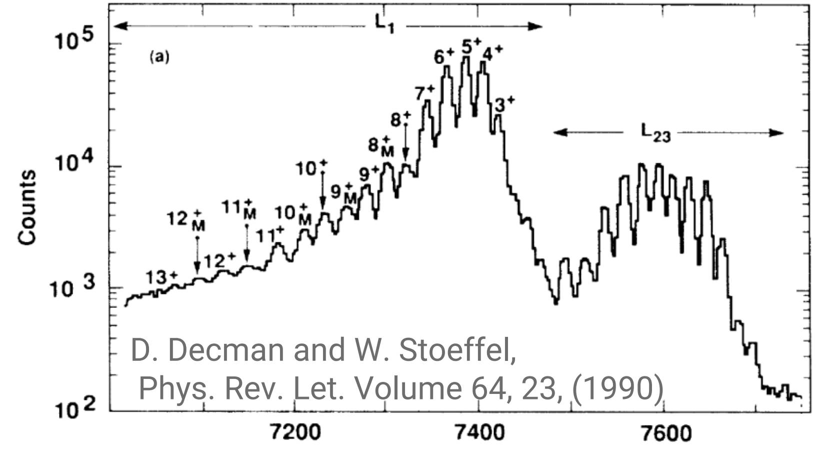
Q-value from ^{3}He-^{3}H mass difference measurement

18575.72 ± **0.07** eV

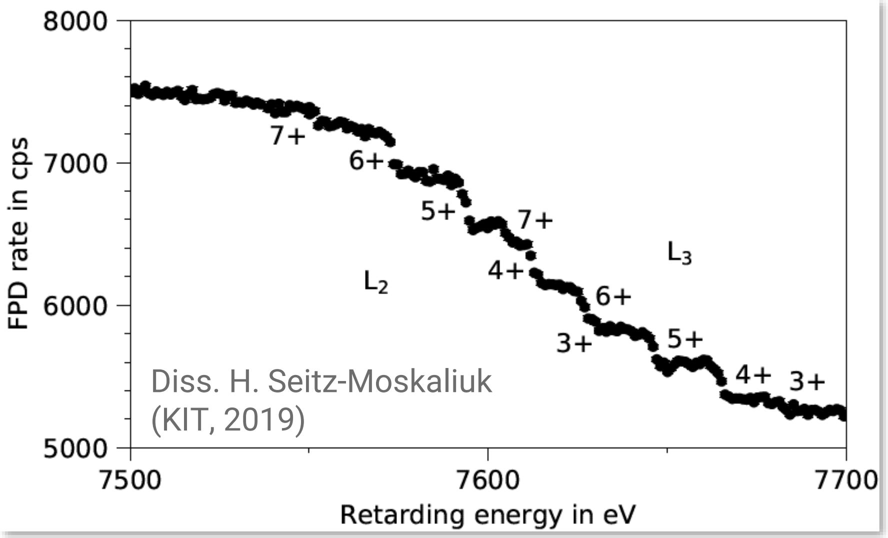
Comparison with external Q-value becomes actually useful! ☺

Challenges – Measurement of the 9-keV line

- 32-keV transition leaves the atom in a multiply-ionized state.
- 9-keV transition follows the 32-keV transition within a half-life of 155 ns.
- GKrS:
  - Low krypton density inside WGTS
    → Neutralization times longer than half-life
- CKrS:
  - Neutralization times shorter than half-life
    → Single (“normal”) krypton line



D. Decman and W. Stoeffel,
Phys. Rev. Let. Volume 64, 23, (1990)

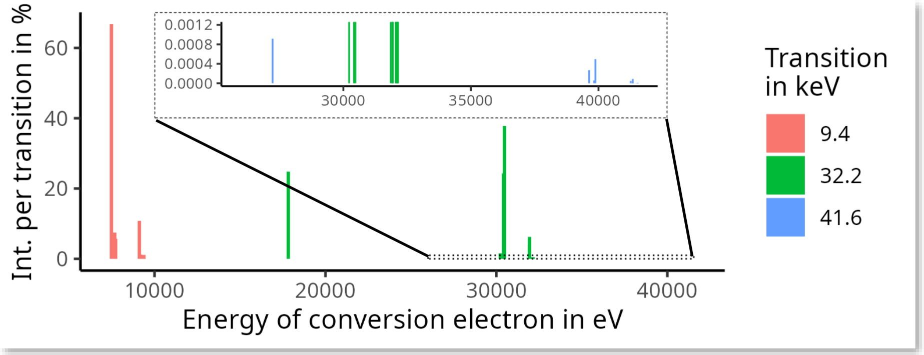


Diss. H. Seitz-Moskaliuk
(KIT, 2019)

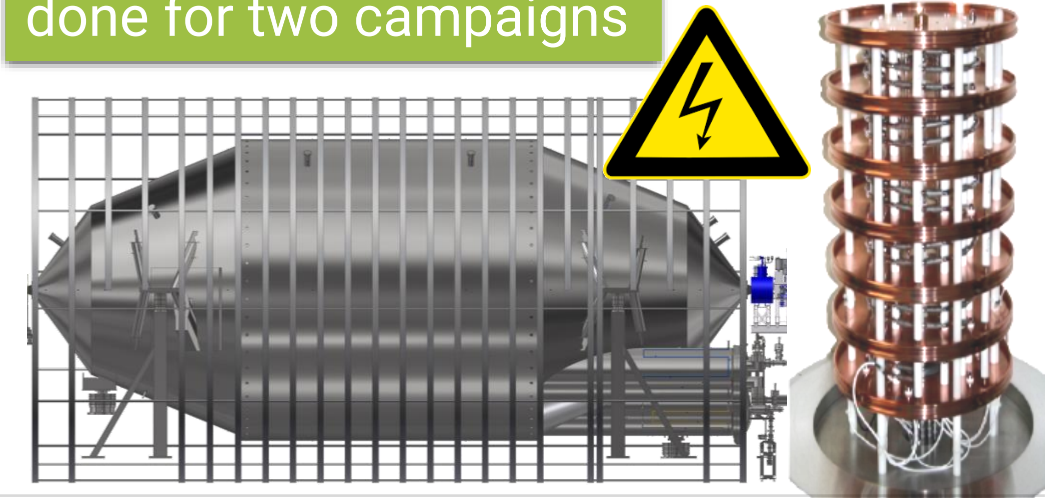
New data taken in 2022, 2023. Analysis ongoing. (M. Boettcher and B. Bieringer, Uni. Münster)

Challenges – Measurement of the 42-keV line

- Highly suppressed transition:
  - Expected intensity of L3-42 line is ~13 ppm of the L3-32 line, ~0.16 % of the N3-32 line
    → Use high-luminosity source
    (10-GBq source available from NPI)
- Measurements of L3-42 need -39.8 kV at main spectrometer
  - Achievable with several feasible hardware changes
  - High-precision divider K65 is usable up to 65 kV
- Measurements of K-42 line at -27.2 kV
  - Background due to higher lines!
    (adjust adiabaticity conditions)
  - Not possible with CKrS
    (same subshell needed, no K-9 line)



Already successfully done for two campaigns



Current measurement status

Karlsruhe Institute of Technology

- Successfully applied -40 kV at KATRIN's main spectrometer!
- Measurements performed with GKrS and CKrS
- First preliminary results with CKrS and analysis of GKrS is ongoing
- CKrS shows some self-charging effects
- The L_3-42 line measurement is the first direct detection at the KATRIN experiment!

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L_3-42 line with CKrS

Measurements and plot by B. Bieringer, M. Boettcher (PhD students, Uni. Münster)