

# Direct neutrino mass measurements

Seminar

L'Aquila

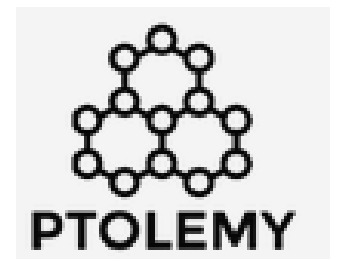
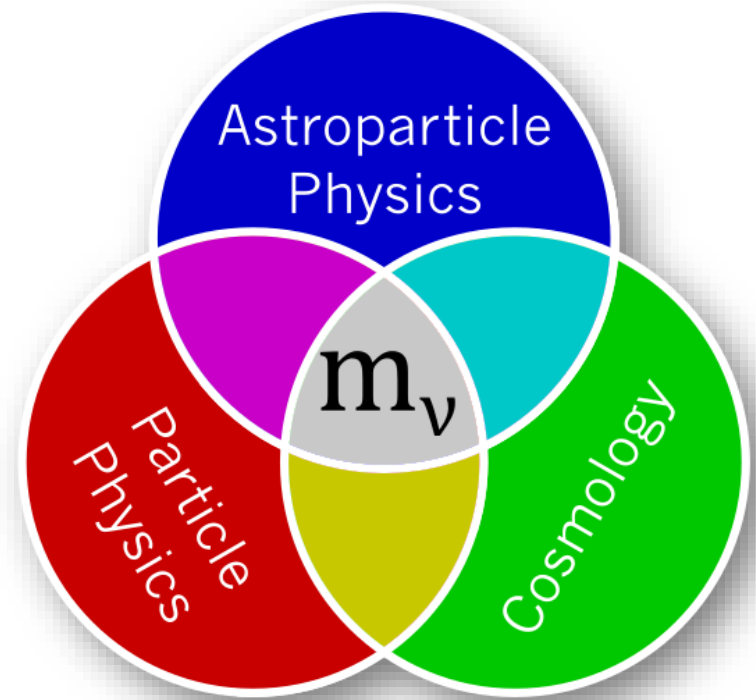
Wed., 25<sup>th</sup> March 2026

Magnus Schlösser

Karlsruhe Institute of Technology

Institute for Astroparticle Physics

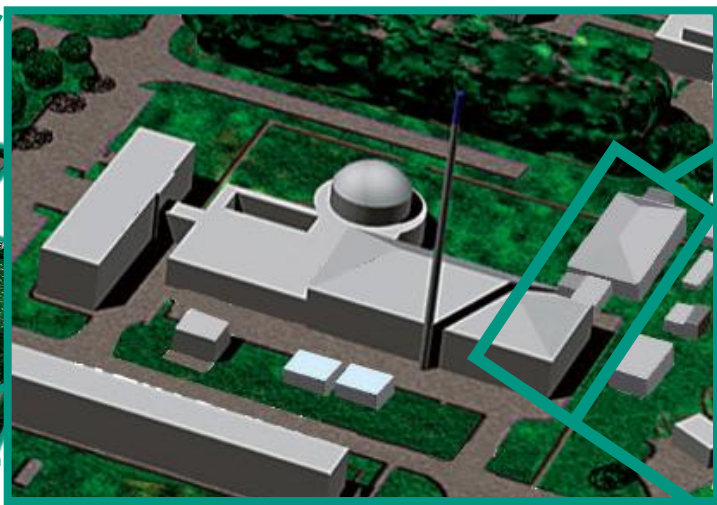
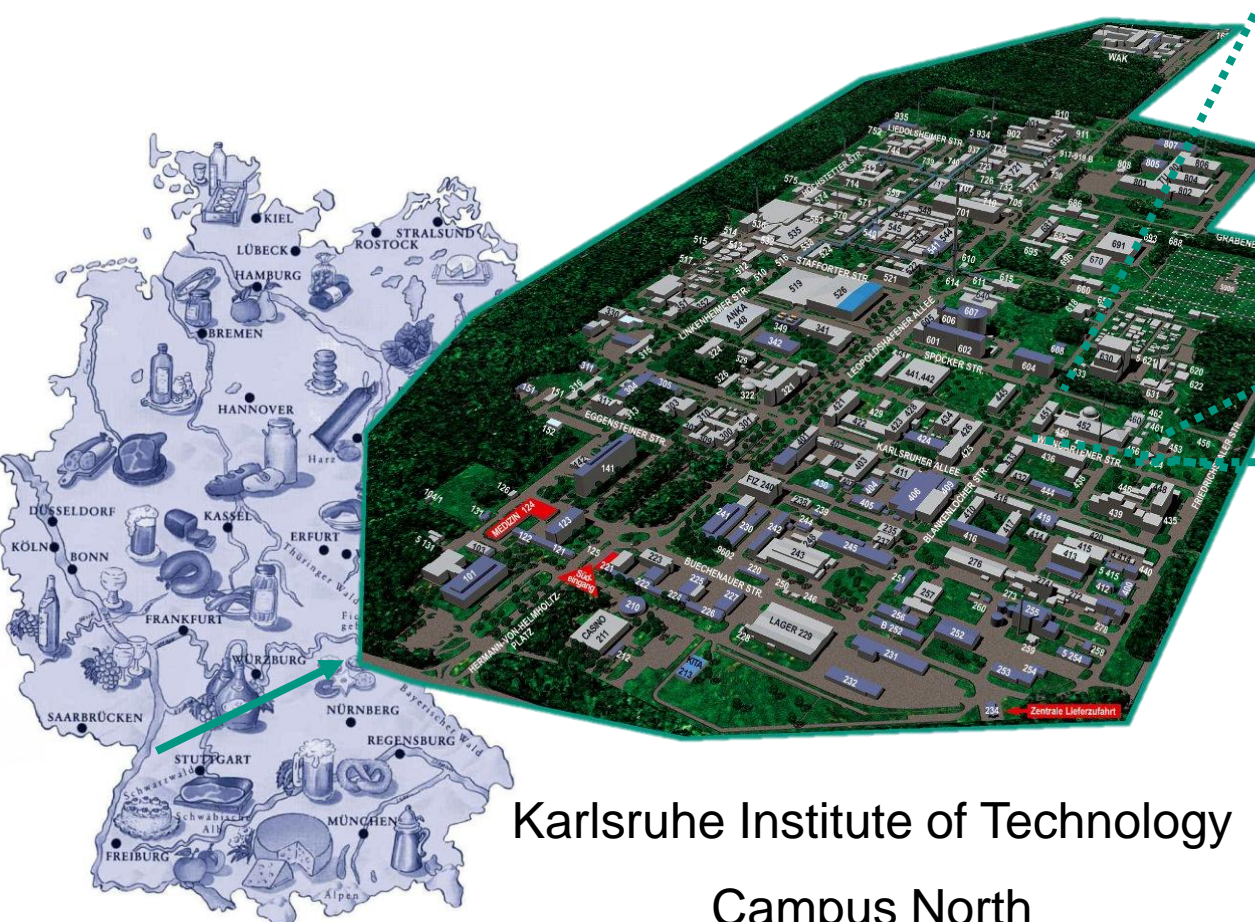
Tritium Laboratory Karlsruhe



With material from the KATRIN, ECHo, HOLMES, Project8, QTNM and PTOLEMY Collaborations

# The Tritium Laboratory Karlsruhe

## Tritium Laboratory Karlsruhe (TLK)



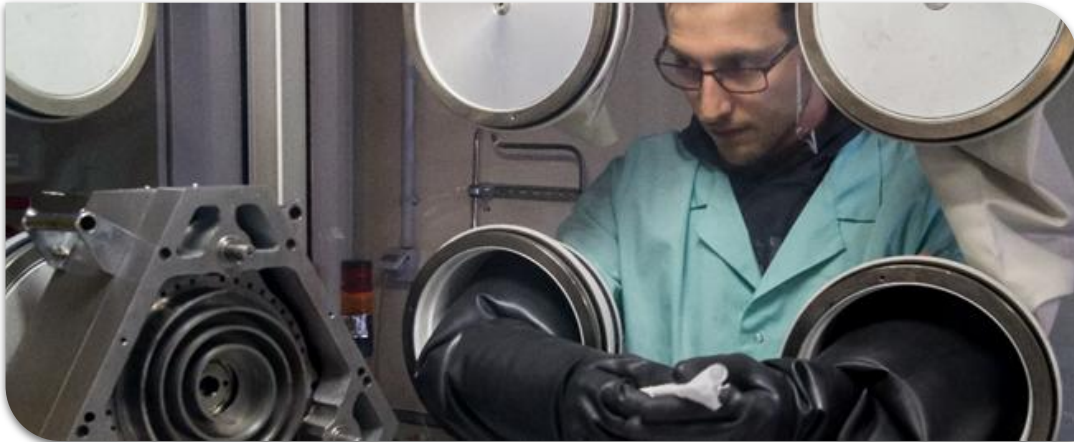
Karlsruhe Institute of Technology  
Campus North

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

# Tritium Laboratory Karlsruhe (TLK)

## A facility for high activity tritium experiments

- Two missions:
  - Fuel cycle for fusion reactors
  - **KATRIN Experiment**
- Licensed for 40 g Tritium ( $1.5 \cdot 10^{16}$  Bq)
- Closed tritium cycle for recycling and purifying tritium in gram amounts
- > 50 experienced scientists, engineers, technicians and students



We develop safe tritium technology and versatile tritium analytics since 1993



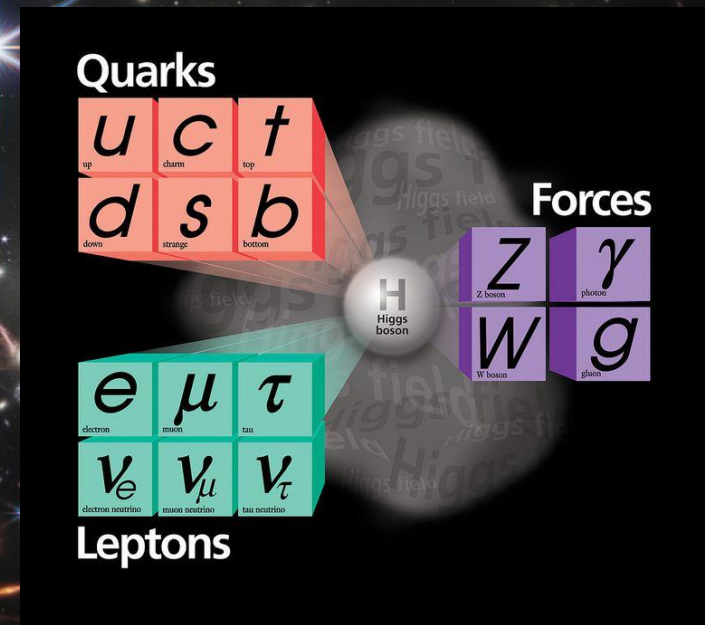
We are able to setup and operate a large variety of experiments with tritium

# direct neutrino mass measurement

# $m_\nu$ ?

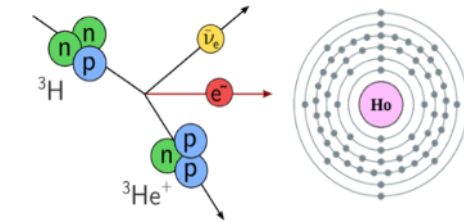
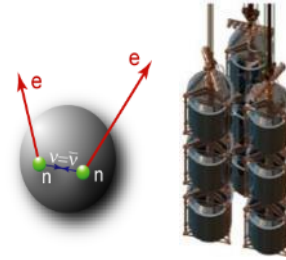
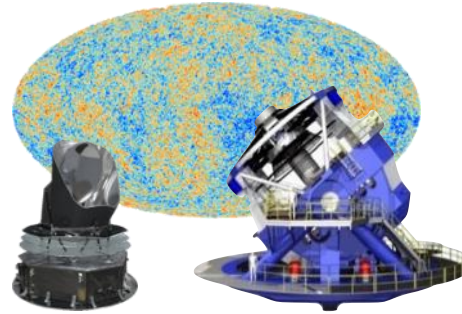
Determining the absolute neutrino mass

$\sim 300$  neutrinos  
per  $\text{cm}^3$



massless in  
standard model

# Ways to access the neutrino mass



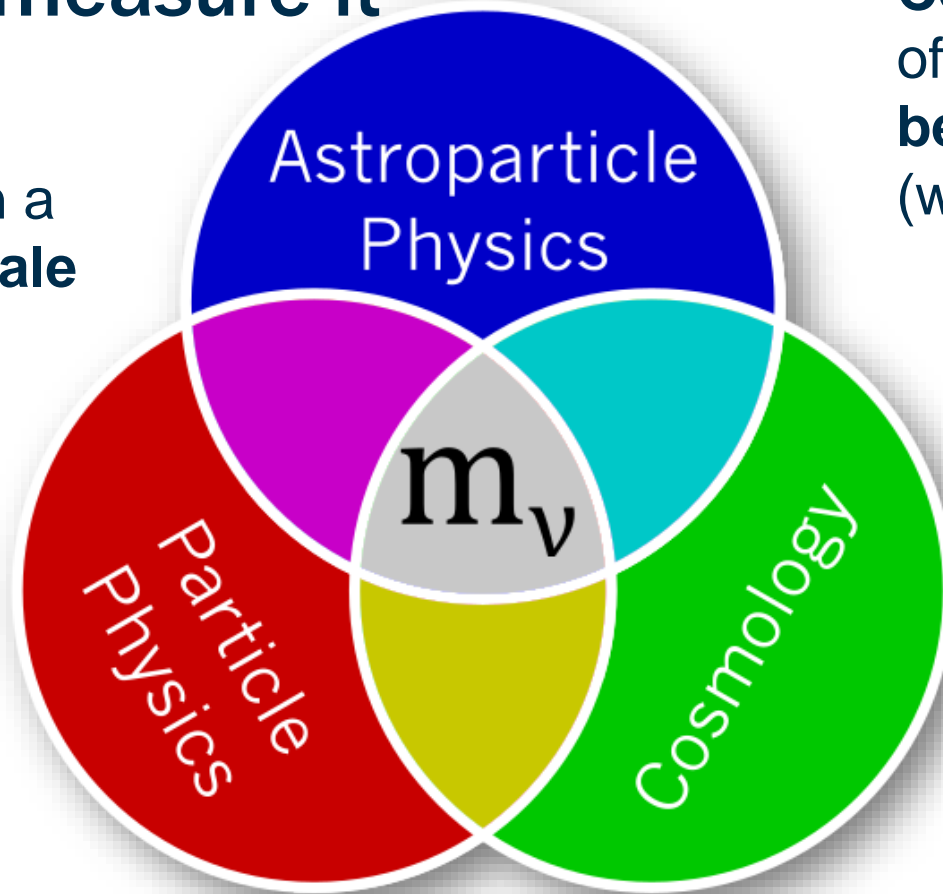
	Cosmology	Search for $0\nu\beta\beta$	$\beta$ -decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 =  \sum_i U_{ei}^2 m_i ^2$	$m_\beta^2 = \sum_i  U_{ei} ^2 m_i^2$
Present upper limit	0.12 eV (0.064 eV)	0.156 eV	0.45 eV
Model dependence	Multi-parameter cosmological model	<ul style="list-style-type: none"> <li>- Majorana <math>\nu</math></li> <li>- contributions other than <math>m(\nu)</math>?</li> <li>- nuclear matrix elements, <math>g_A</math></li> </ul>	<p><b>Direct</b>, only kinematics; no cancellations in incoherent sum</p>

This talk

# The role of massive neutrinos and motivations to measure it

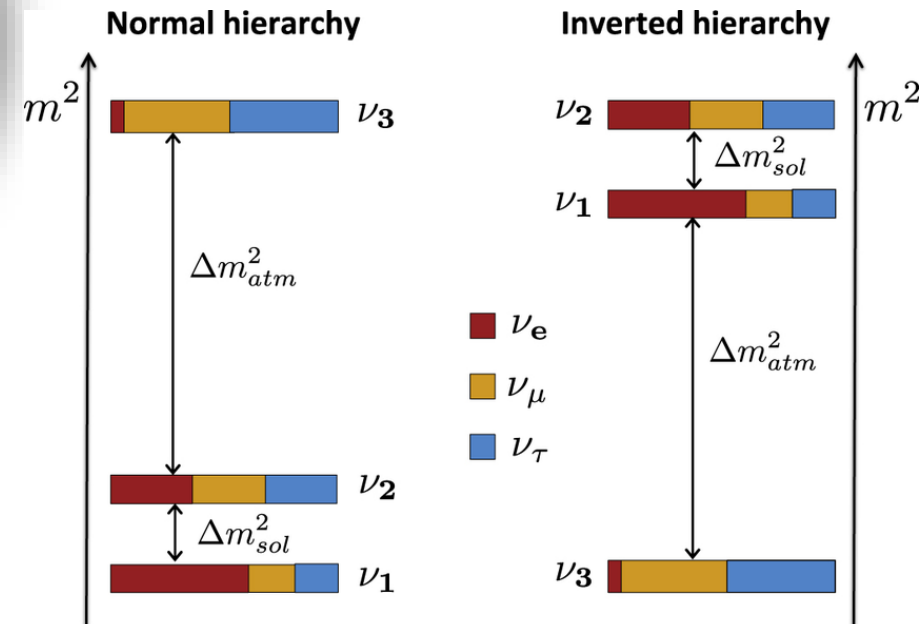
Neutrino masses bring in a **fundamental energy scale** (besides Higgs scale)

$0\nu\beta\beta$  observation **not necessarily** points to an neutrino mass



**Cosmology** and the role of neutrinos therein **may be more complex** (what is DE, ...?)

Model for mass generation needs: mixing matrix **AND mass scale**



**Signal is „in reach“: Minimal mass scales exist!**  
 “ $m(\nu_e)$ ” > 10 meV (normal mass ordering)  
 “ $m(\nu_e)$ ” > 50 meV (inverted mass ordering)

# Direct mass experiments

Direct, model-independent access to neutrino mass

## $\beta^{(-)}$ decay

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



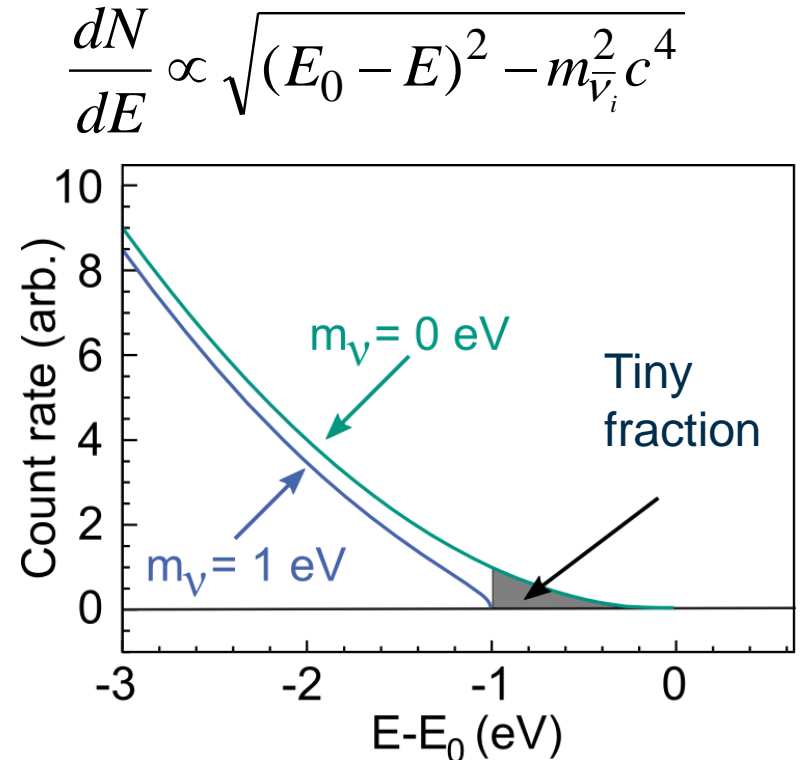
Measurement of kinetic energy of electron

## Electron capture



Measurement of internal excitation of daughter atom

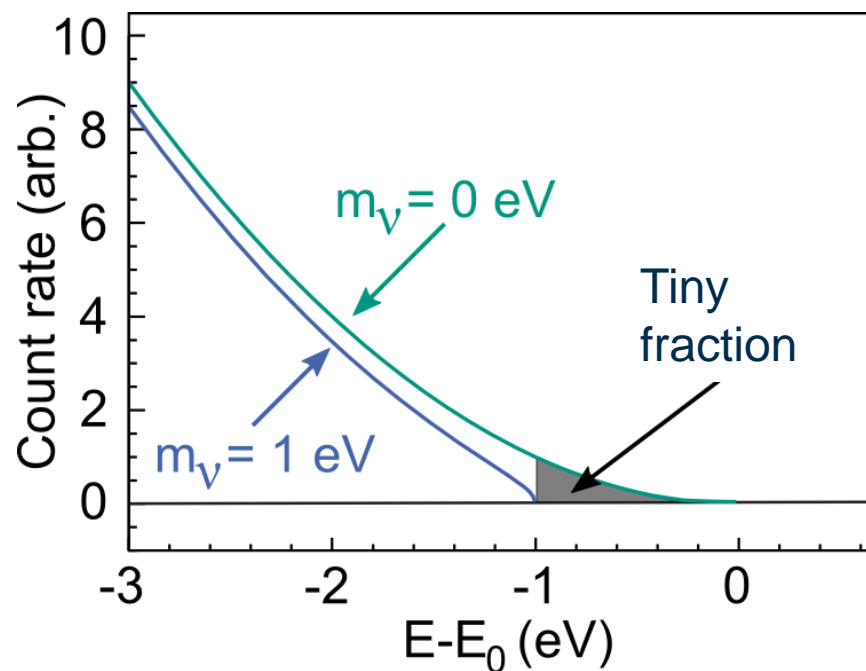
(Anti-) neutrino mass determined from shape distortion near kinematic endpoint



# Challenges for achieving mass low sensitivity

$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\nu_i}^2 c^4}$$

Low kinematic endpoint, high decay rate

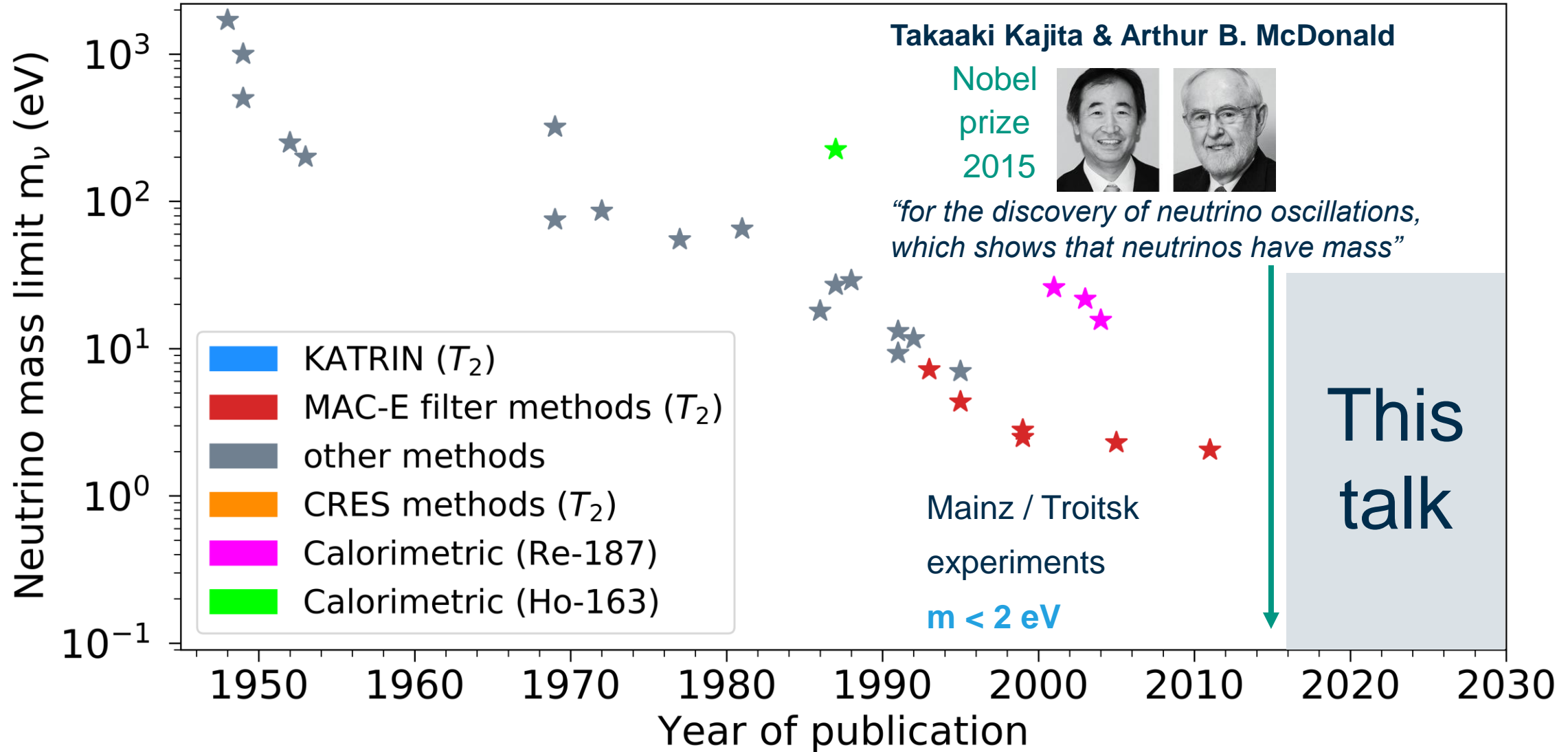


	$\beta$ -decay	Electron capture
Chosen isotope	${}^3\text{H} = \text{T}$	${}^{163}\text{Ho}$
Endpoint	18.6 keV	2.8 keV
Half life	12.3 years	4570 years
Typ. production	n-capture in $\text{D}_2\text{O}$	n-irradiation of ${}^{162}\text{Er}$

High signal ( $\rightarrow$  statistics)  
Low background ( $\rightarrow$  statistics)

High energy resolution ( $\rightarrow$  sensitivity)  
Low and quantified systematic effects

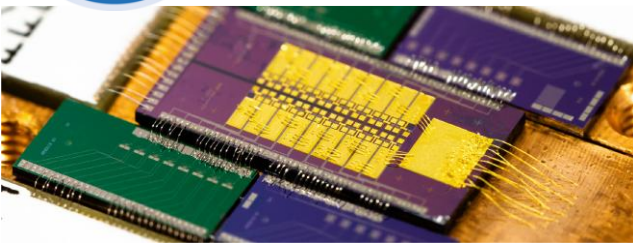
# History of neutrino mass sensitivity (“pre-KATRIN”)



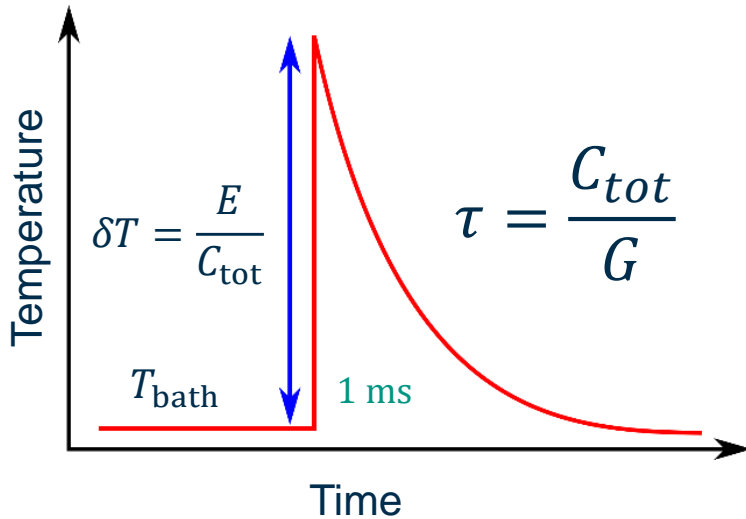
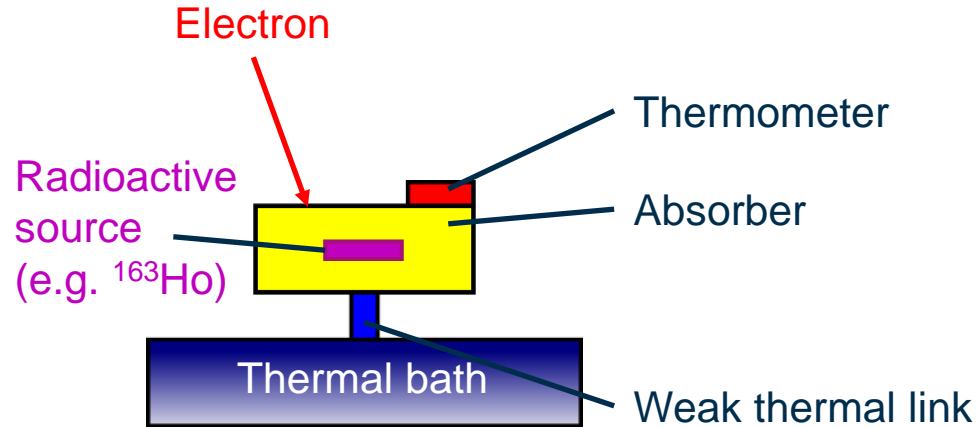
# Established measurement principles

## Calorimeters

- Low-temperature micro calorimeters
- Measuring energy by **temperature change**



# Quantum sensors as high resolution differential detectors



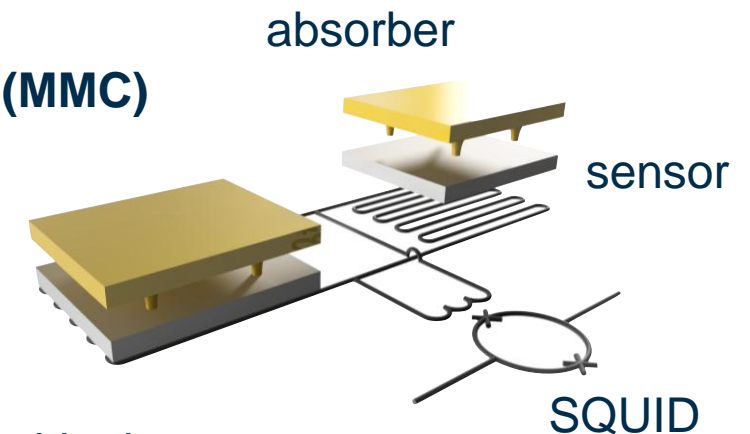
- tiny heat capacity ( $C_{tot}$ ) → strong temperature signal
- low temperature ( $T_{bath}$ ) → low noise
- low activity (or rate) per pixel → no pile up

## Advantages

- Energy resolution  $O(eV)$  compared to conventional detectors  $O(100 eV)$
- Nearly 100% quantum efficiency

## Metallic Magnetic Calorimeters (MMC)

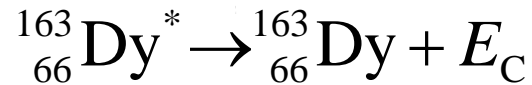
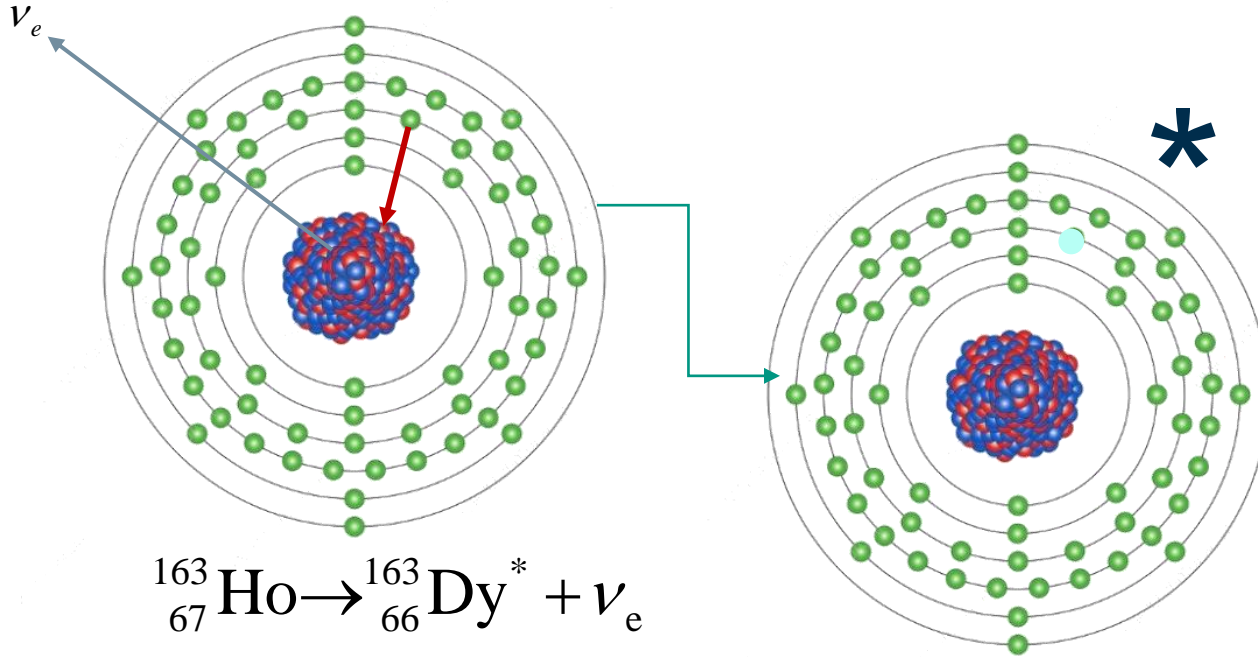
- Temperature-dependence in sensor magnetization



## Transition-Edge Sensor (TES)

- Strong resistivity change near critical temperature of superconductor

# Electron capture in Holmium-163

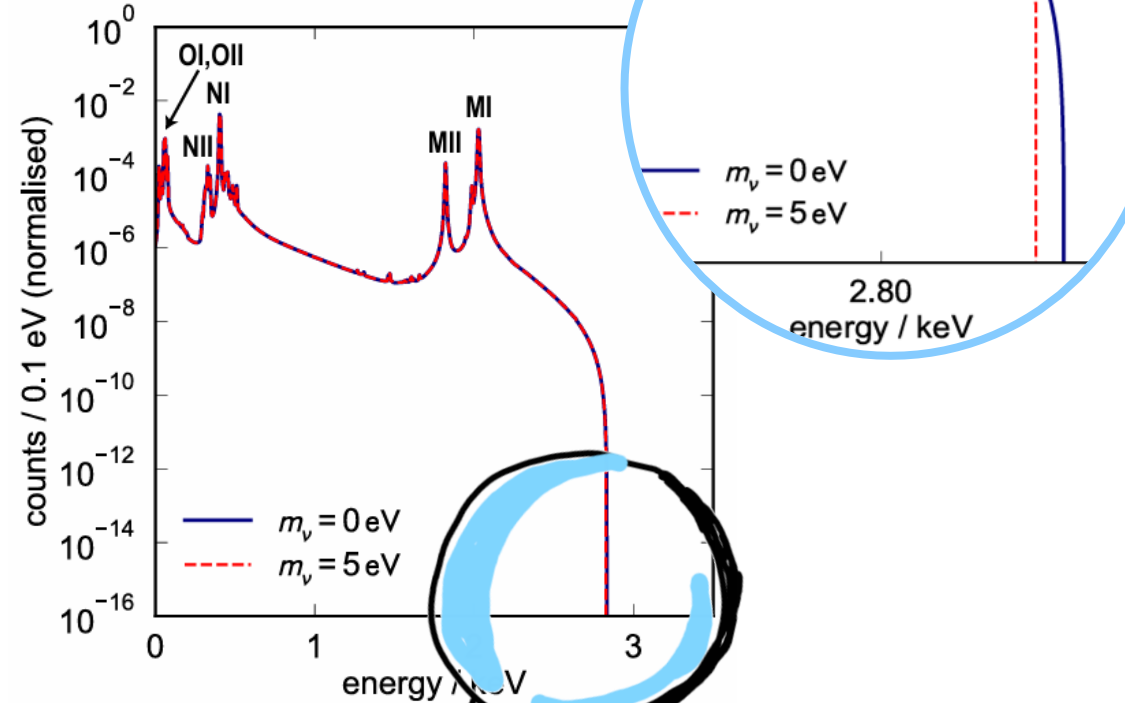


Ch. Schweiger et al.,  
*Nat. Phys.* **20**, 921–927 (2024)

- $\tau_{1/2} \cong 4570$  years ( $2 \cdot 10^{11}$  atoms for 1 Bq)
- $Q_{\text{EC}} = (2863.2 \pm 0.6)$  eV



<https://www.kip.uni-heidelberg.de/echo/>



<https://holmes1.mib.infn.it/holmes/>

# ECHo: results and outlook



UNIVERSITÄT  
HEIDELBERG  
ZUKUNFT  
SEIT 1386



EBERHARD KARLS  
UNIVERSITÄT  
TÜBINGEN



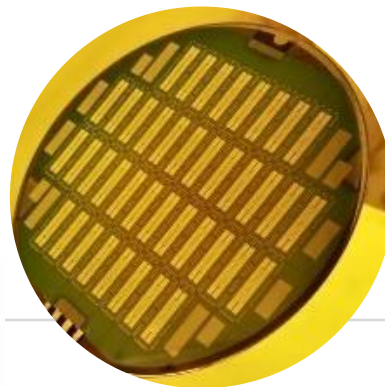
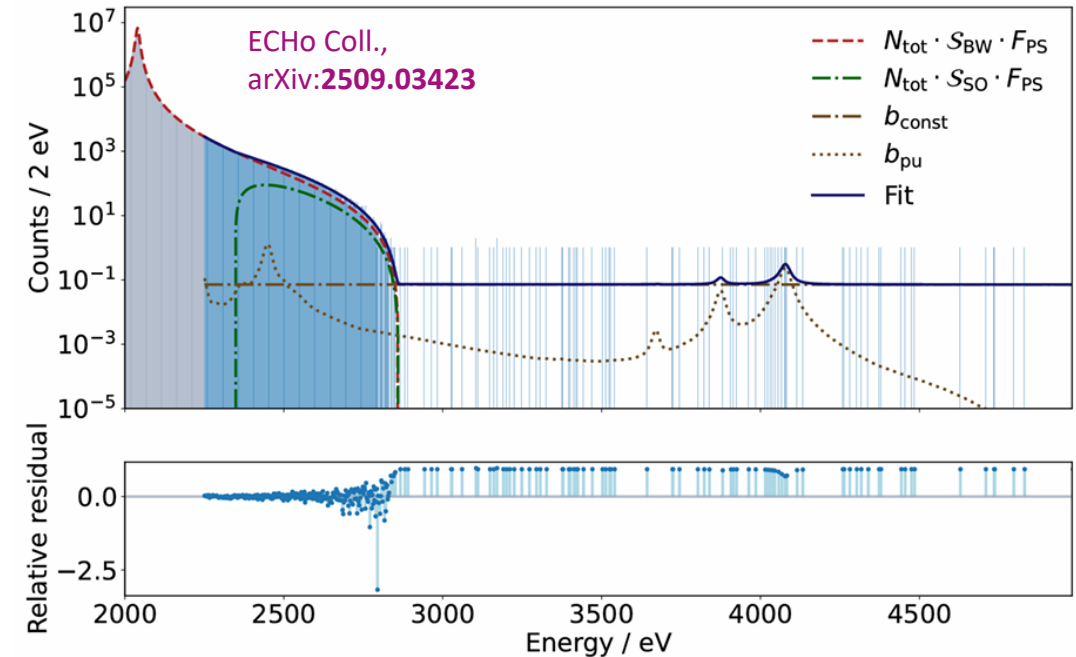
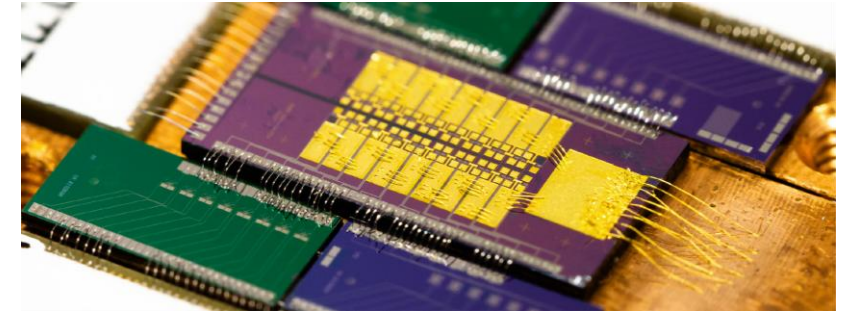
MMC with ion-implanted  $^{163}\text{Ho}$ , SQUID readout

Mantegazzini et al., *NIM A* **1030** (2022) 166406

- **ECHo-0**: 4 pixels loaded with  $\sim 0.2$  Bq  $^{163}\text{Ho}$ , 4 days  
 $m(\nu_e) < 150$  eV (95% C.L.) and  $Q_{\text{EC}} = (2838 \pm 14)$  eV  
Velte et al., *EPJ C* **79** (2019) 1026

- **ECHo-1k**: ca. 200 mio. events from  $\sim 60$  pixels  
(ca. 45 Bq total)  
 $m(\nu_e) < 15$  eV (90% C.L.) and  $Q_{\text{EC}} = 2862(4)$  eV

- **ECHo-LE (2026-2030)**: target **sub-eV sensitivity**  
20k channels - fabrication ongoing  
microwave SQUID-multiplexing  
> improve energy resolution  
> better spectrum model



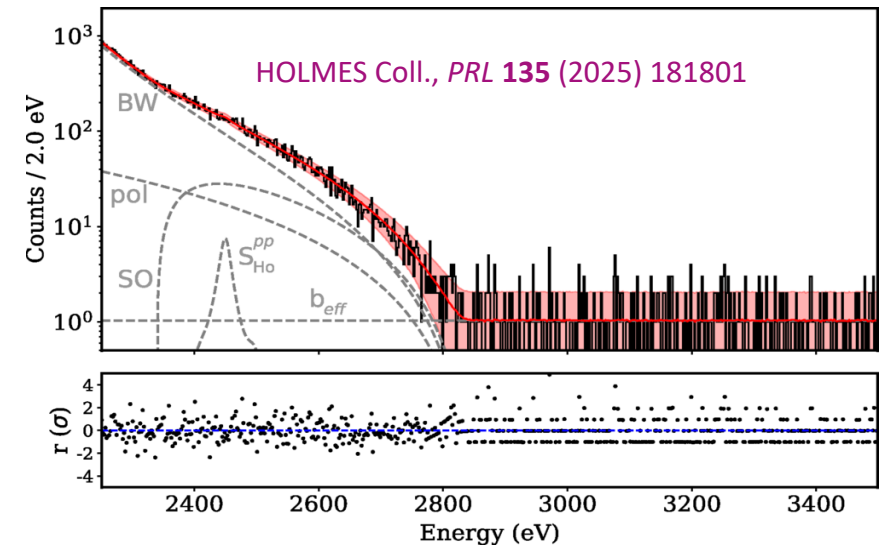
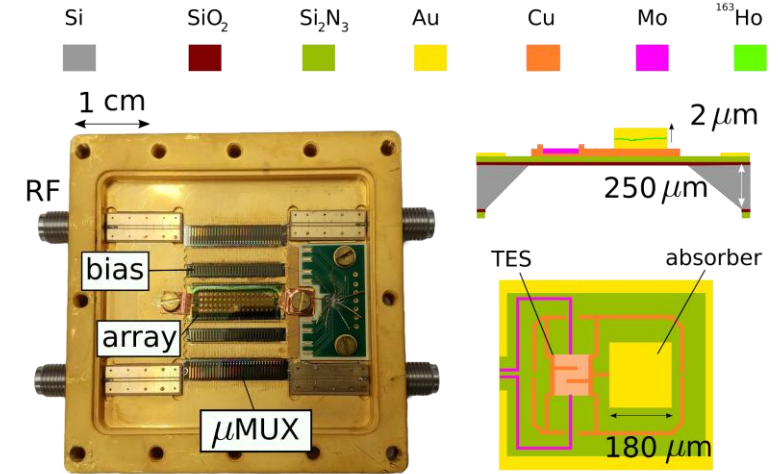
# HOLMES: results and outlook



## TES with ion-implanted $^{163}\text{Ho}$ , multiplexing readout

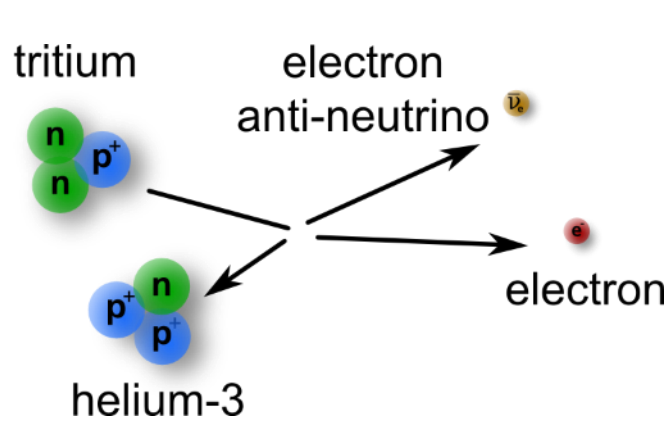
Alpert *et al.*, *EPJ C* **79** (2019) 304

- **HOLMES**: ~70 mio. events from ~50 pixels (ca. 15 Bq total)  
 $m(\nu_e) < 27 \text{ eV}$  (99% C.I.) and  $Q_{\text{EC}} = 2848(7) \text{ eV}$
- Data-driven model of  $^{163}\text{Ho}$  spectrum  
 Ahrens *et al.*, arXiv:2507.09240, subm. to JHEP
- **HOLMES+ (2024-2027)**:  
 define building blocks for “almost table-top sized”  $\nu$ -mass experiment with **sensitivity < 100 meV**  
 > improve multiplexing ( $\mu\text{mux} \rightarrow$  kinetic inductance current sensors), production in 2026  
 > developed low- $T_c$  TES prototypes (2025), fabrication & testing of 4x4 array in 2026



# Tritium beta decay experiments

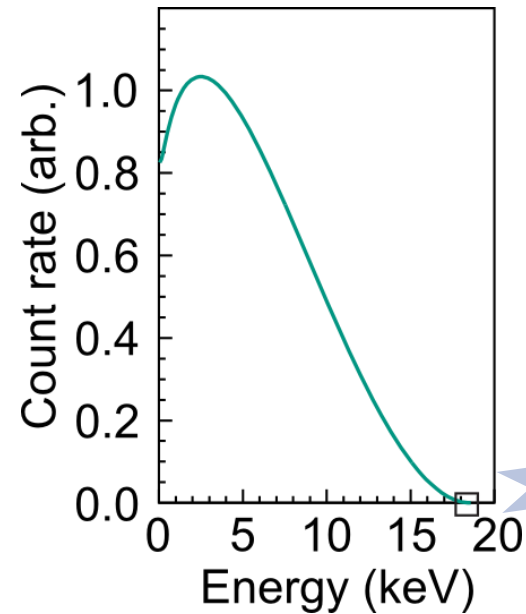
Direct, model-independent access to neutrino mass



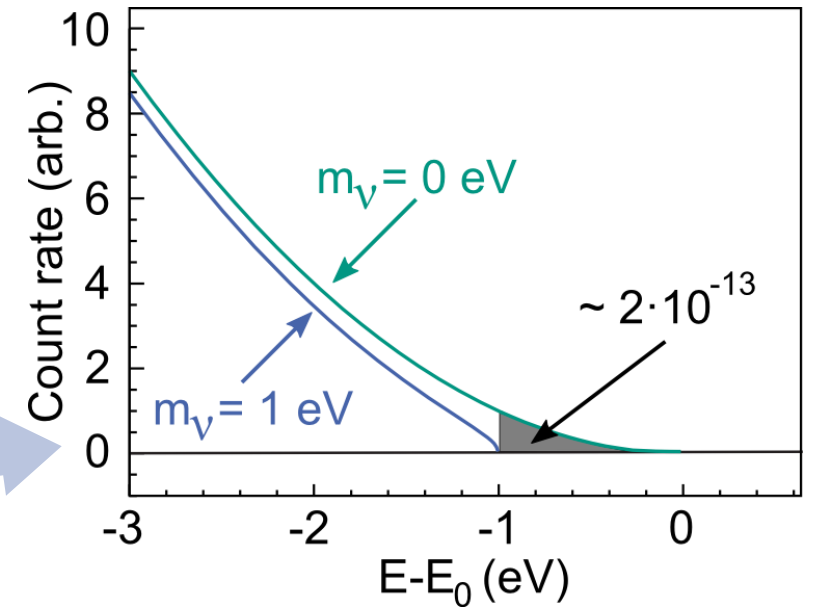
$$E_0 = 18.6 \text{ keV}$$

$$T_{1/2} = 12.3 \text{ y}$$

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

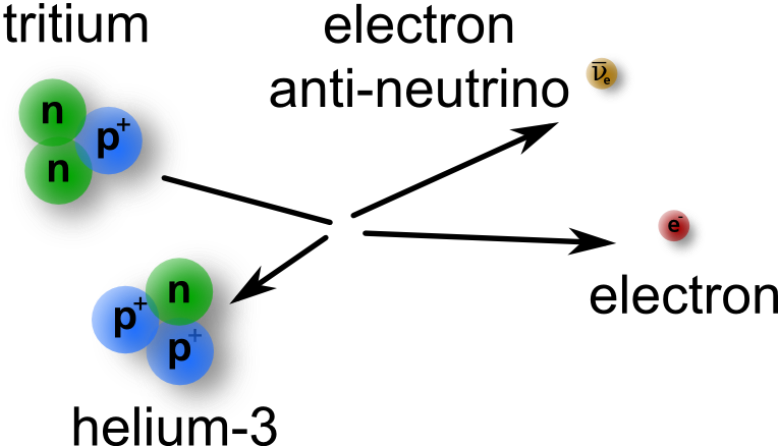


$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\nu_i}^2 c^4}$$

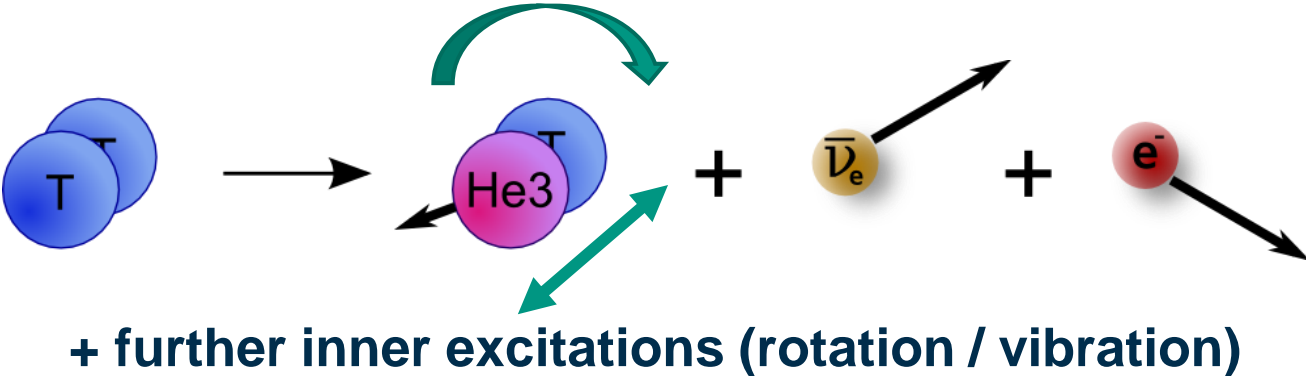


# Molecular decay

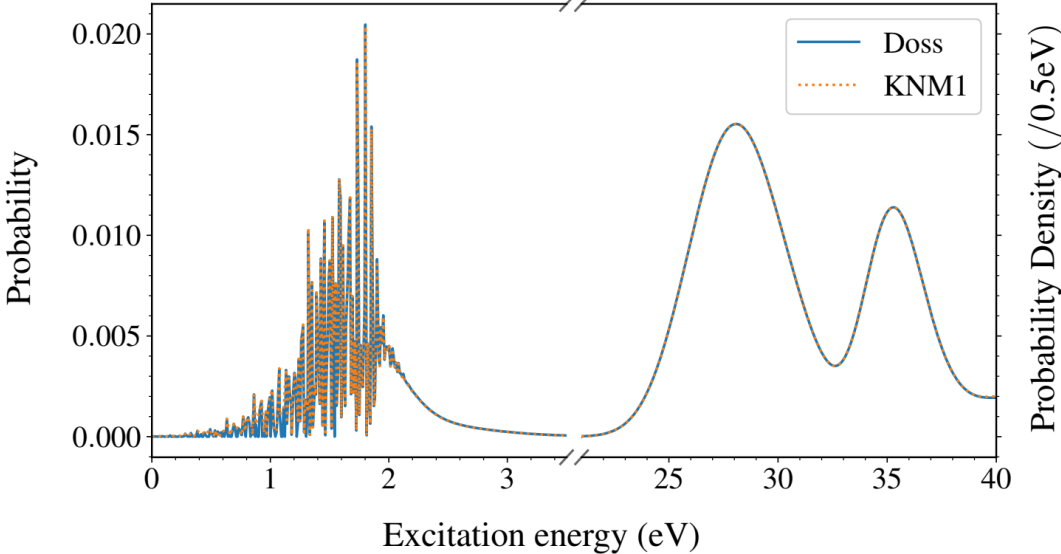
## Atomic decay



## Decay from a molecule



## Final-state distribution



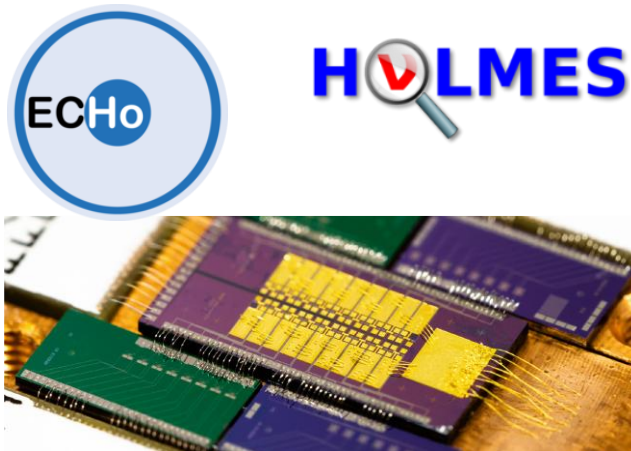
Molecular effects need to be taken into account in neutrino mass analysis

„model-dependence“

# Established measurement principles

## Calorimeters

- Low-temperature micro calorimeters
- Measuring energy by **temperature change**

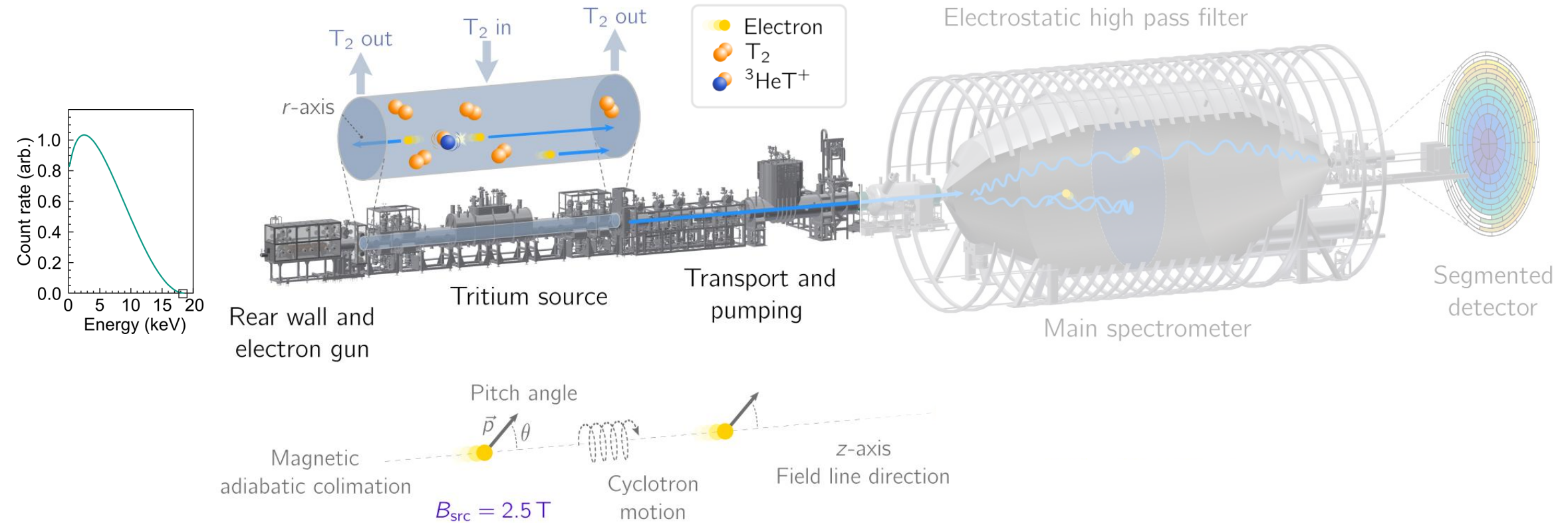


## MAC-E filter

- Magnetic Adiabatic Collimation with an Electrostatic Filter
- Measuring energy by applying a **high-pass filter**



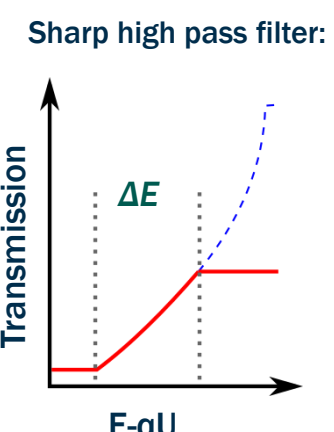
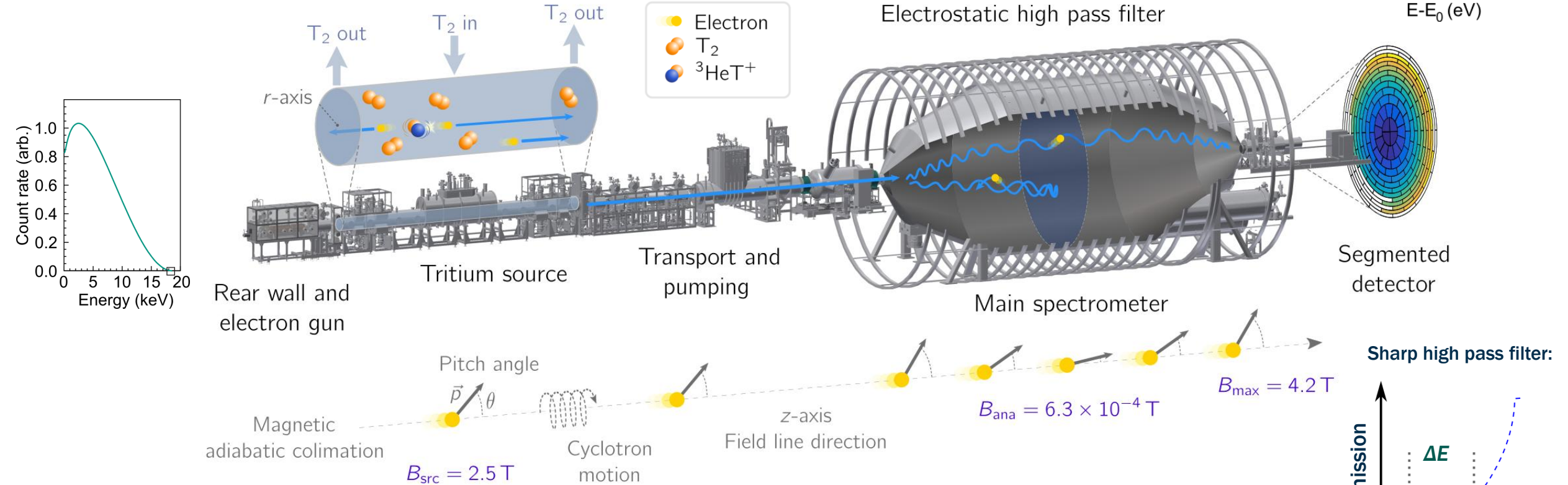
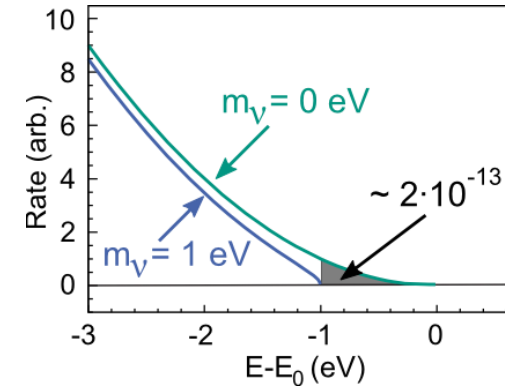
# Windowless gaseous source



# MAC-E filter principle

**M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter

Electron transmission if above filter potential (Integrating method)



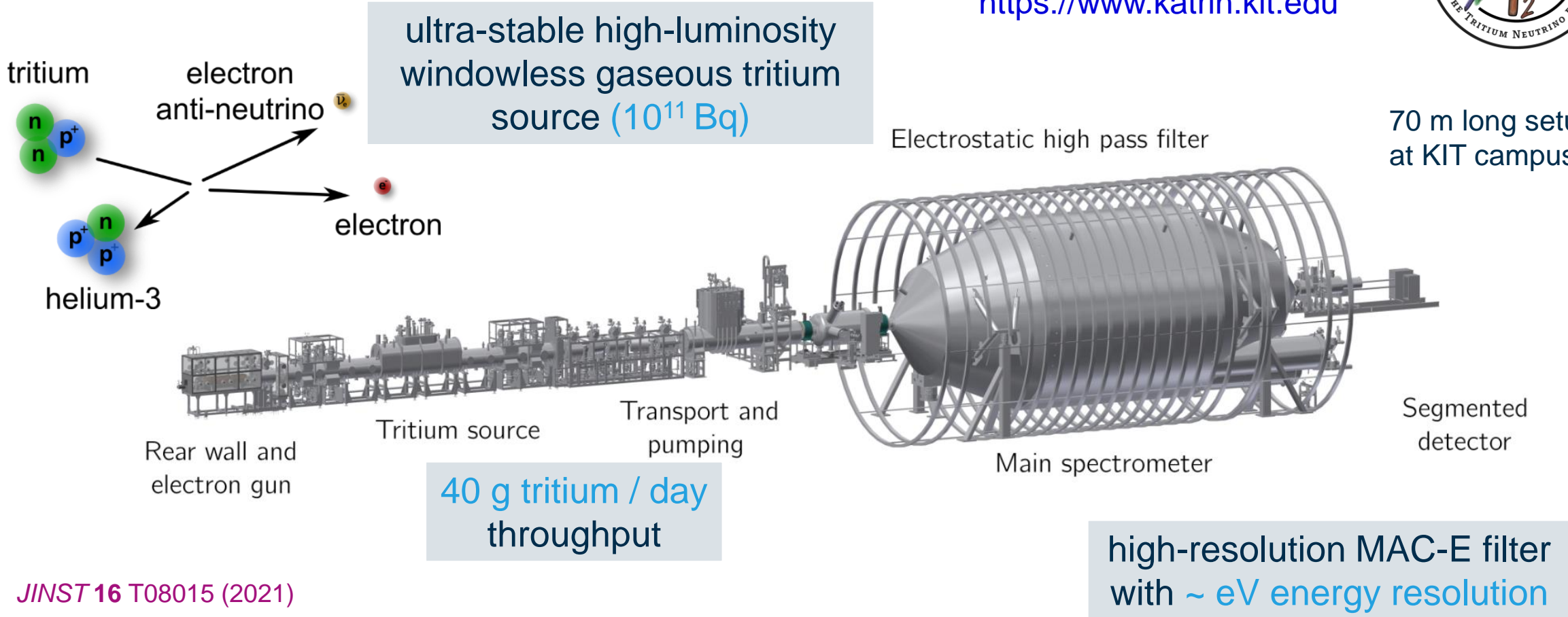
$$\frac{B_{\min}}{B_{\max}} = \frac{\Delta E}{E} \rightarrow \text{sharp filter transmission (resolution)}$$

# Karlsruhe Tritium Neutrino Experiment (KATRIN)

<https://www.katrin.kit.edu>



70 m long setup at KIT campus north



JINST 16 T08015 (2021)

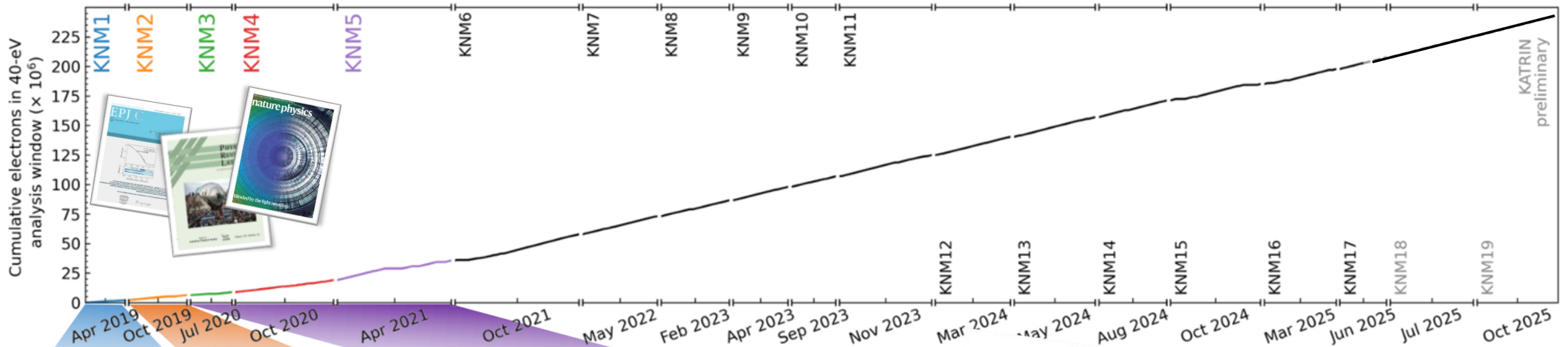
**KATRIN's aim: Direct measurement of  $m_\nu$  with a sensitivity of  $0.3 \text{ eV}/c^2$**

# KATRIN Data-taking: Mission completed

Final KATRIN analysis will lead to **0.3 eV sensitivity**



**20 October 2025**  
1000 days of data taking



- 1<sup>st</sup>  $m_\nu$  campaign
- $m_\nu < 1.1$  eV

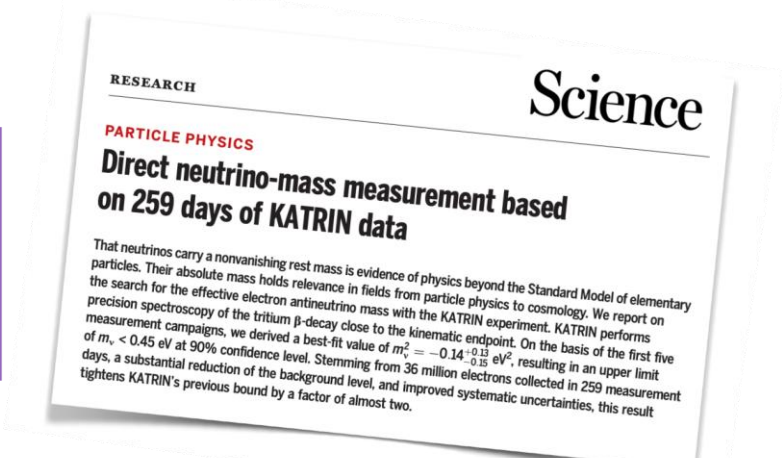
PRL 123, 221802 (2019)  
Phys. Rev. D 104, 012005 (2021)

- 2<sup>nd</sup>  $m_\nu$  campaign
- $m_\nu < 0.8$  eV

Nat. Phys. 18, 160–166 (2022)

- 1<sup>st</sup> - 5<sup>th</sup>  $m_\nu$  campaign
- $m_\nu < 0.45$  eV

Science 388 (2025) 180-185



# Systematic and statistical uncertainties

- Statistical uncertainty dominates
- Reduced background
- Meticulous measurements to quantify and improve systematics

**Removal of the penning trap**

*EPJ C 80 (2020) 821*

**Shifted analyzing plane**

*EPJ C 82 (2022) 258*

*EPJ C 84 (2024) 1258*

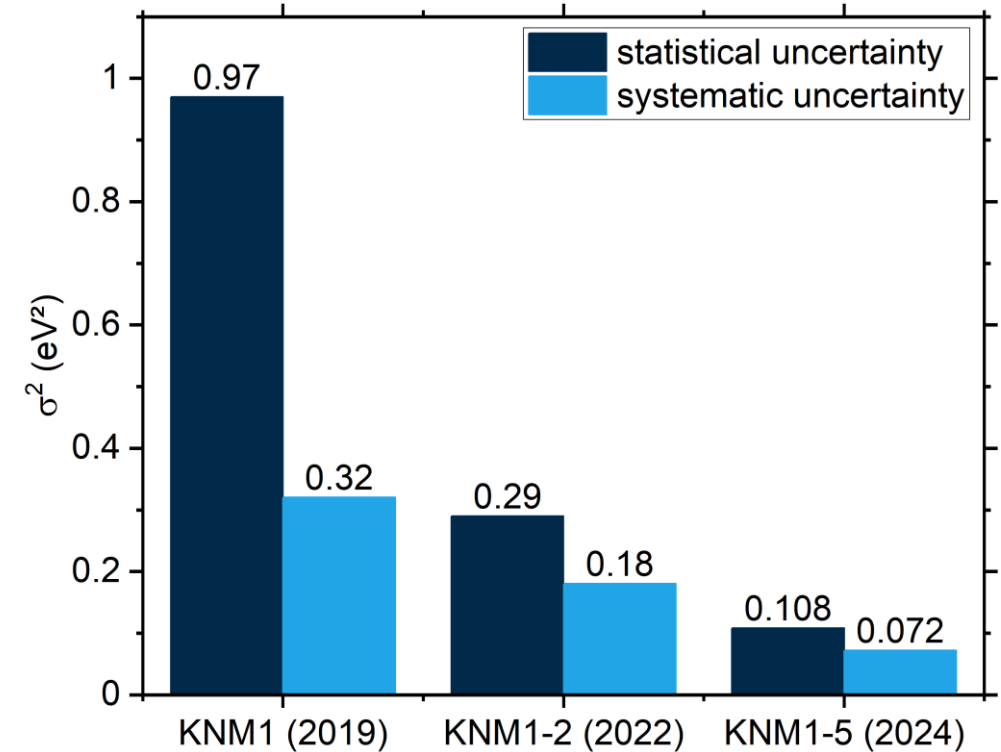
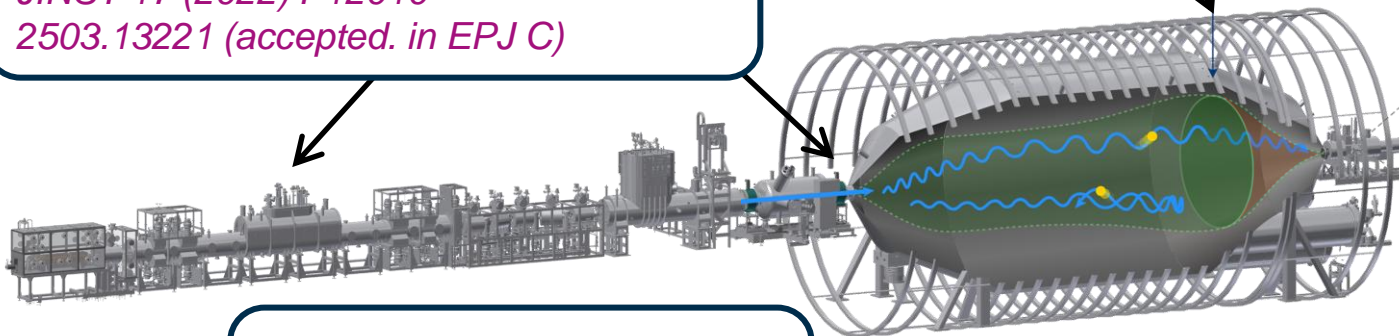
**High-statistics krypton-83m calibration**

*JINST 17 (2022) P12010*

*2503.13221 (accepted. in EPJ C)*

**Improved evaluation of theoretical uncertainties**

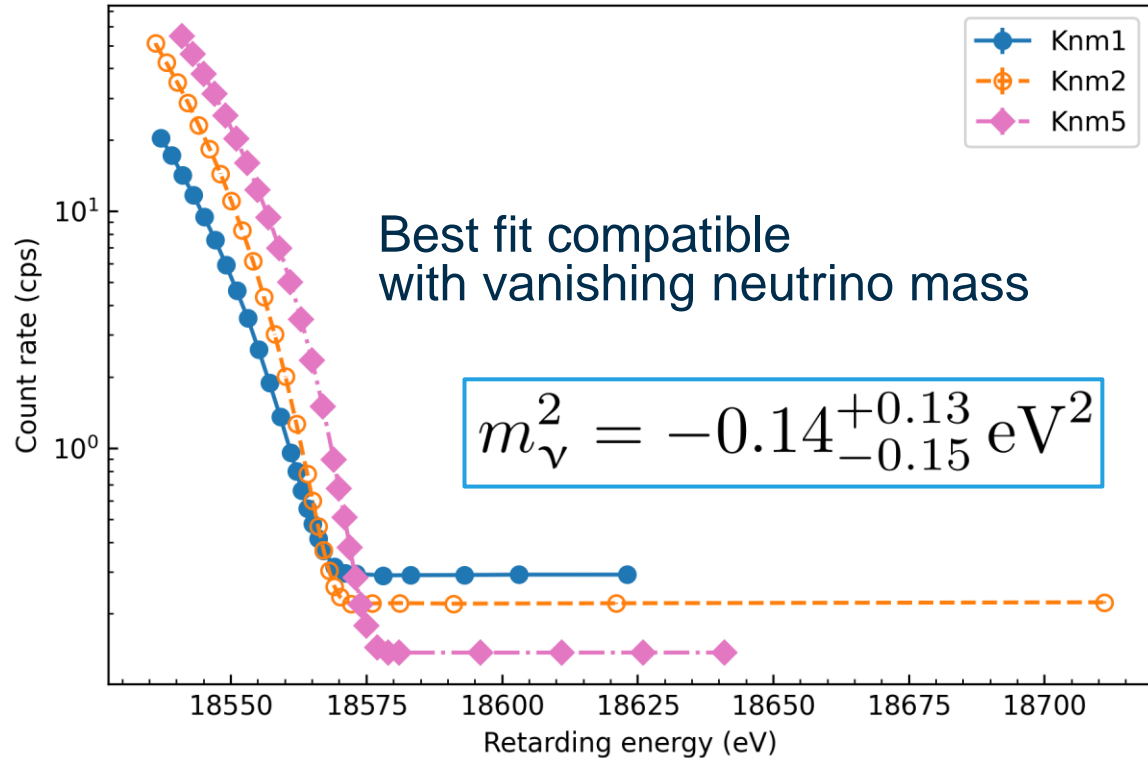
*EPJ C 84 (2024) 494*



Final KATRIN analysis  
(post 2025 after 1000 d)  
Systematics and statistics will  
lead to **0.3 eV sensitivity**

# Best fit and upper limit

Improvement of spectral quality

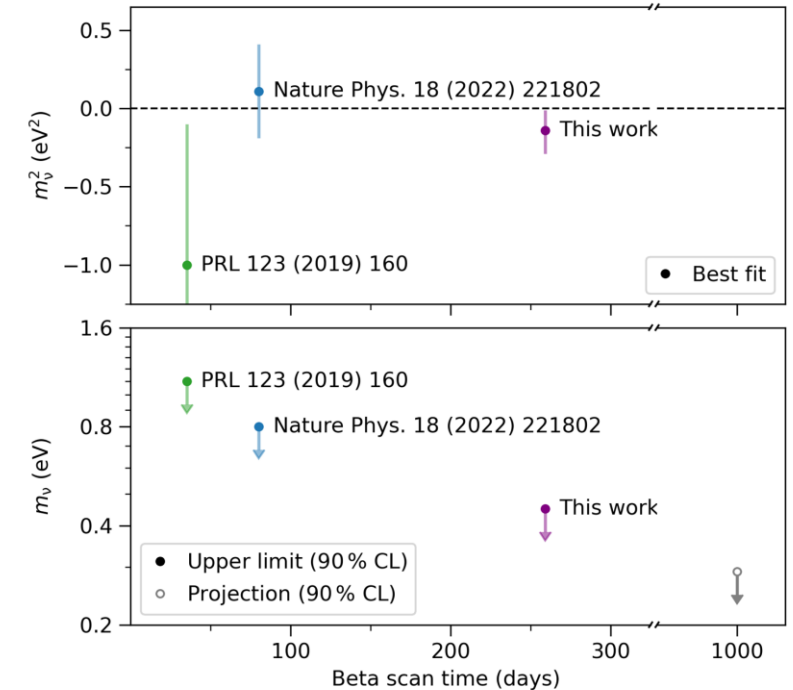


Resulting in most stringent upper limit

$$m_{\nu} < 0.45 \text{ eV (90 \% CL)}$$

*KATRIN, Science 388 (2025) 6743*

Improvement of upper limit



Final KATRIN analysis  
(post 2025 after 1000 d)  
Systematics and statistics will  
lead to **0.3 eV sensitivity**

# Physics analyses beyond the neutrino mass

## Neutrino mass analysis

*PRL 123 (2019) 221802*  
*Nat. Phys. 18 (2022) 160,*  
*Science 388 (2025) 6743*

## Light sterile neutrinos

*PRL 126 (2021) 091803*  
*PRD 105 (2022) 072004*  
*Nature 648 (2025), 70*

## Relic neutrinos

*PRL 129 (2022) 011806*

## Lorentz Violation

*PRD 107 (2023) 082005*

## General Neutrino interaction

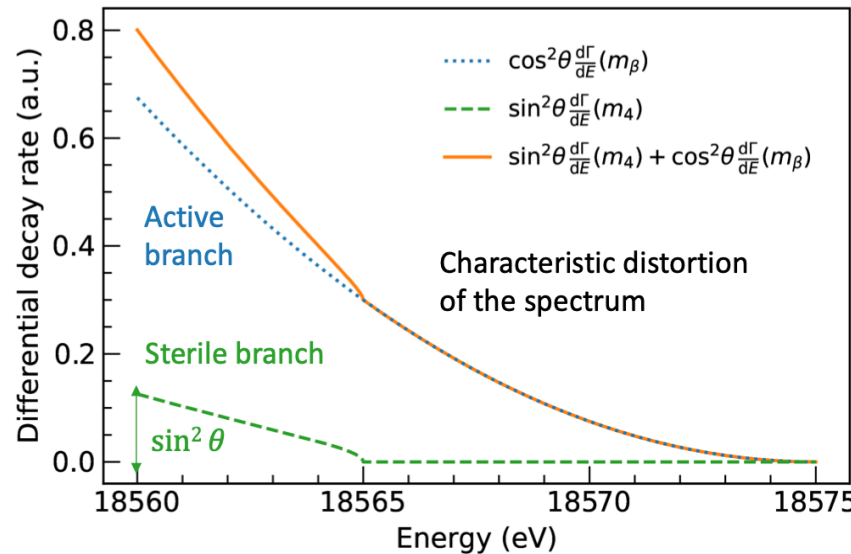
*PRL 134 (2025) 251801*

## Dark MSW

Ongoing analysis

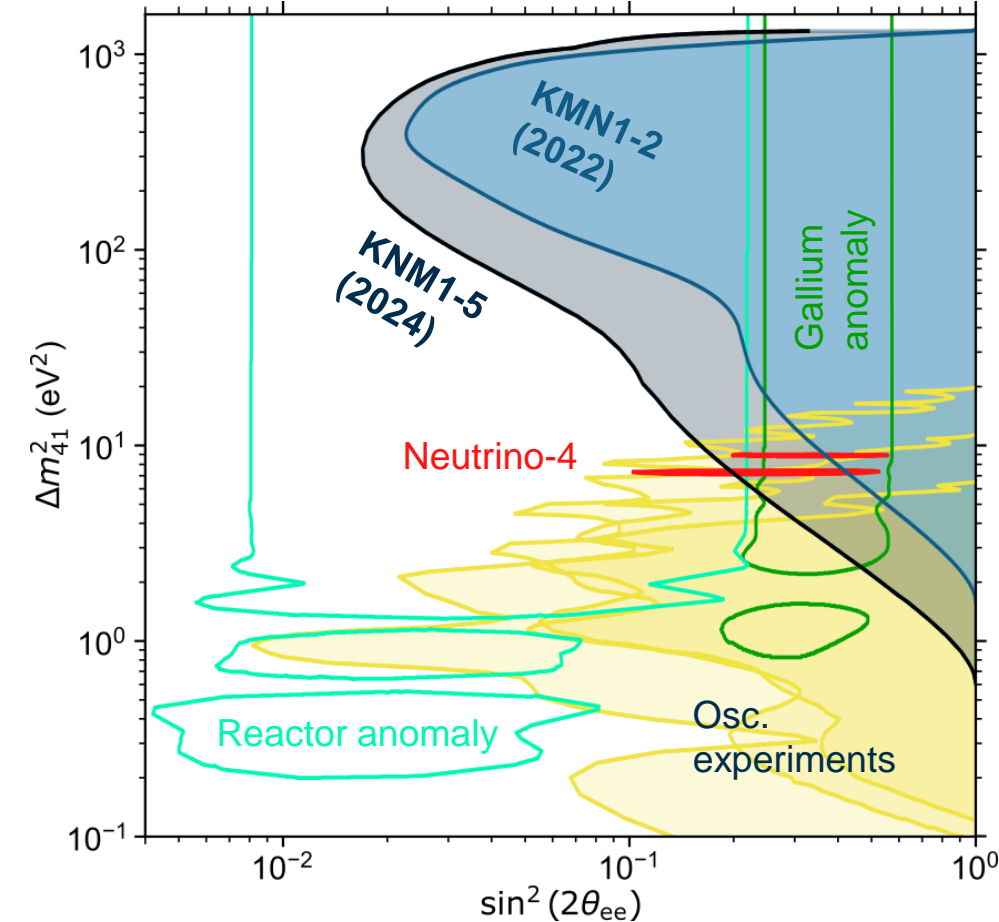
## Light Bosons

Ongoing analysis



$$\frac{d\Gamma}{dE} = \underbrace{(1 - |U_{e4}|^2) \frac{d\Gamma}{dE}(m_\beta^2)}_{\text{Active neutrinos}} + \underbrace{|U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)}_{\text{Sterile neutrino}}$$

*KATRIN, Nature 648 (2025), 70 (simplified)*



Exclusion of sterile neutrinos - complementary to short-baseline oscillation experiments

# Established measurement principles

## Calorimeters

- Low-temperature micro calorimeters
- Measuring energy by **temperature change**



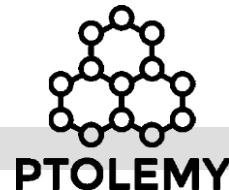
## MAC-E filter

- Magnetic Adiabatic Collimation with an Electrostatic Filter
- Measuring energy by applying a **high-pass filter**



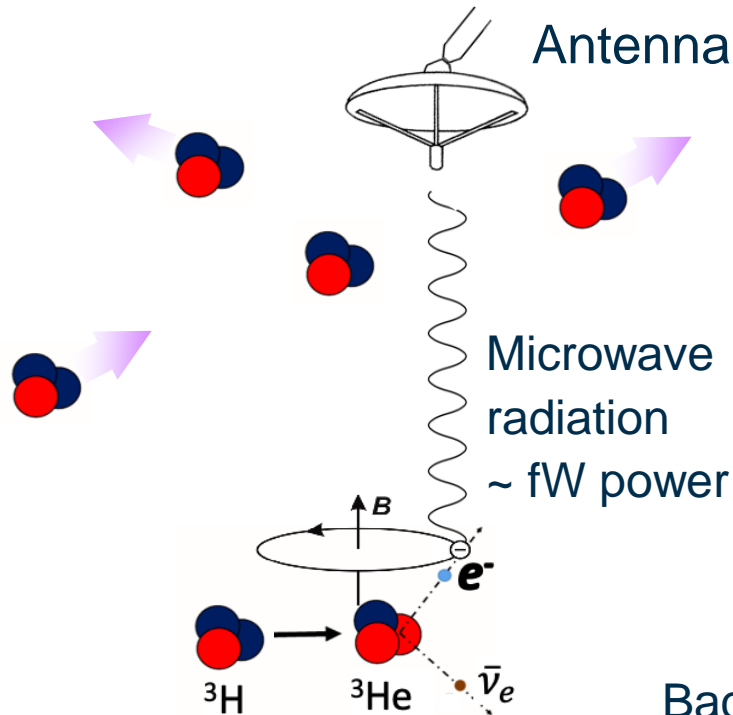
## CRES

- Cyclotron Radiation Emission Spectroscopy
- Measuring energy via **frequency**



# Cyclotron Radiation Emission Spectroscopy

Differential measurement with antenna arrays  
around a (atomic) tritium source  
→ Frequency measurement

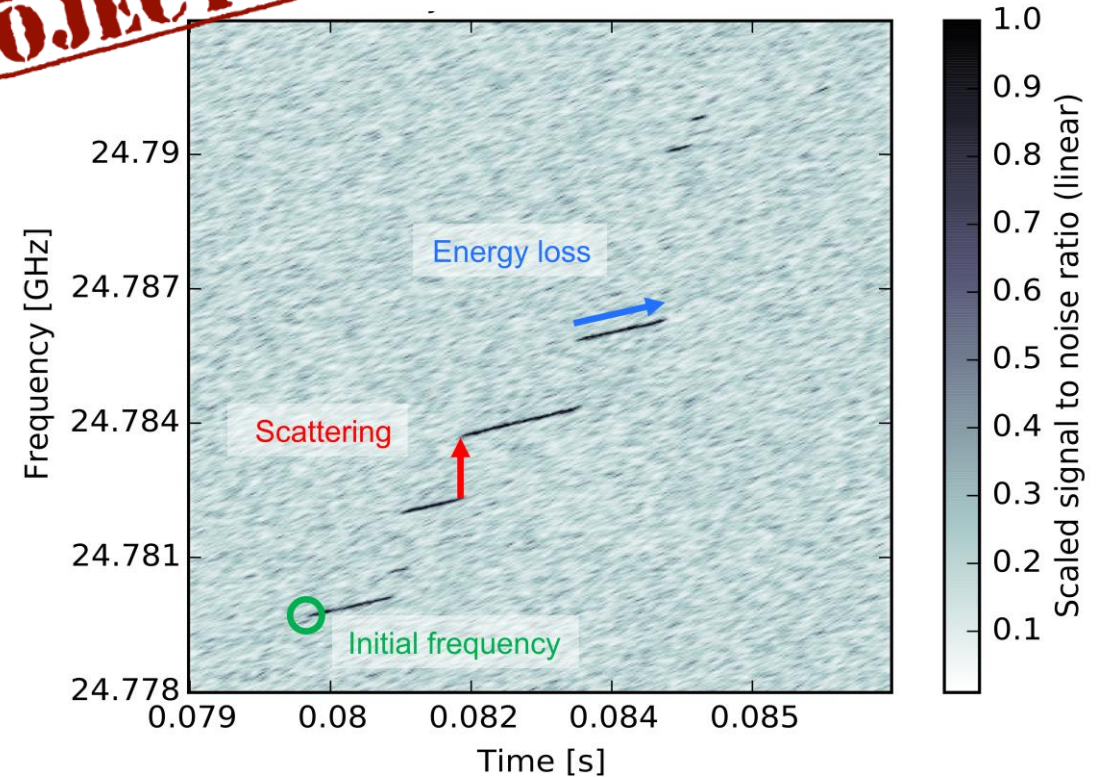


$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi m_e + E_{kin}} eB$$

Background **B-field** determines the operational frequency

**PROJECT 8**

Event 0 from Phase I



*PRL. 114, 162501 (2015)*

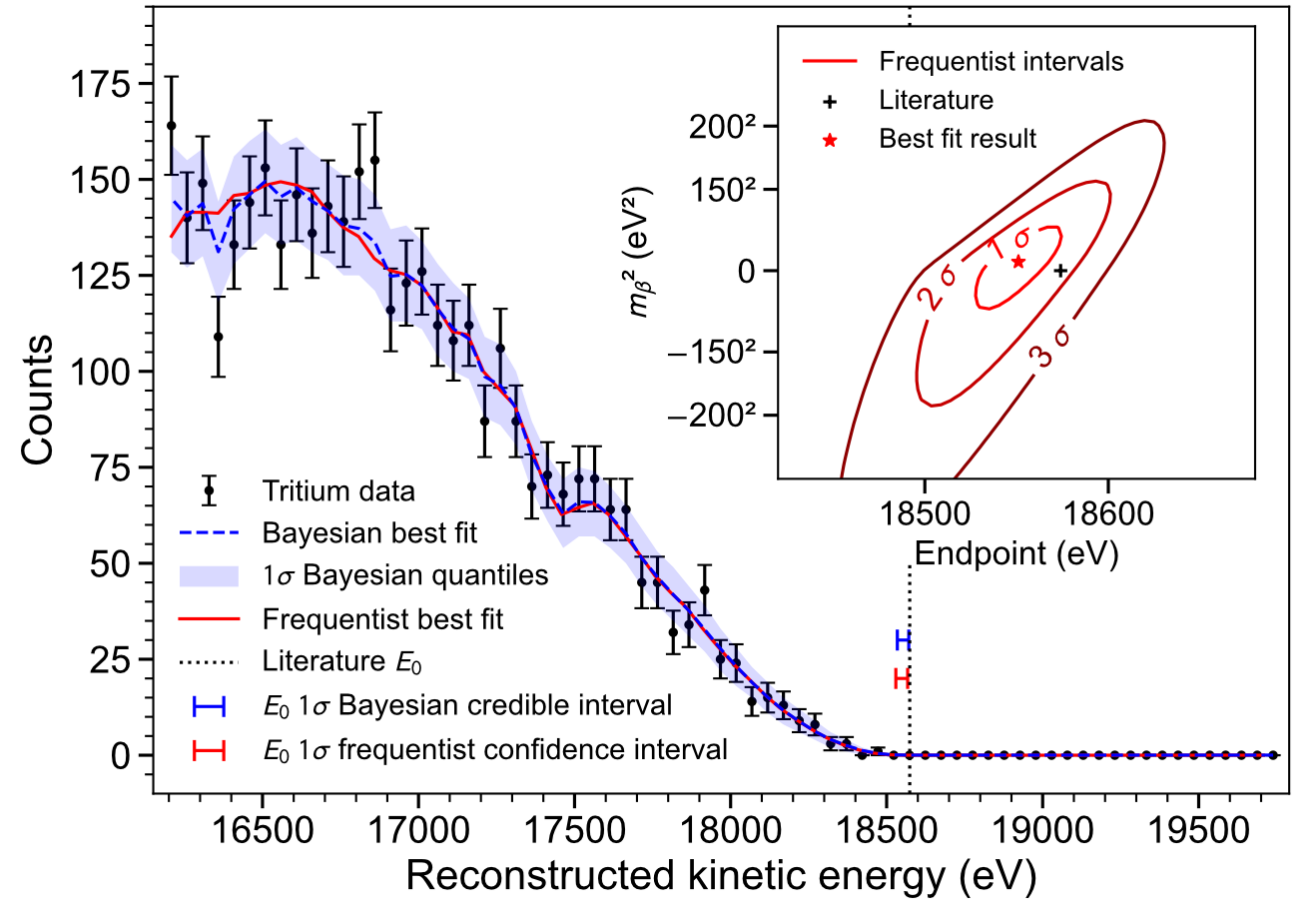
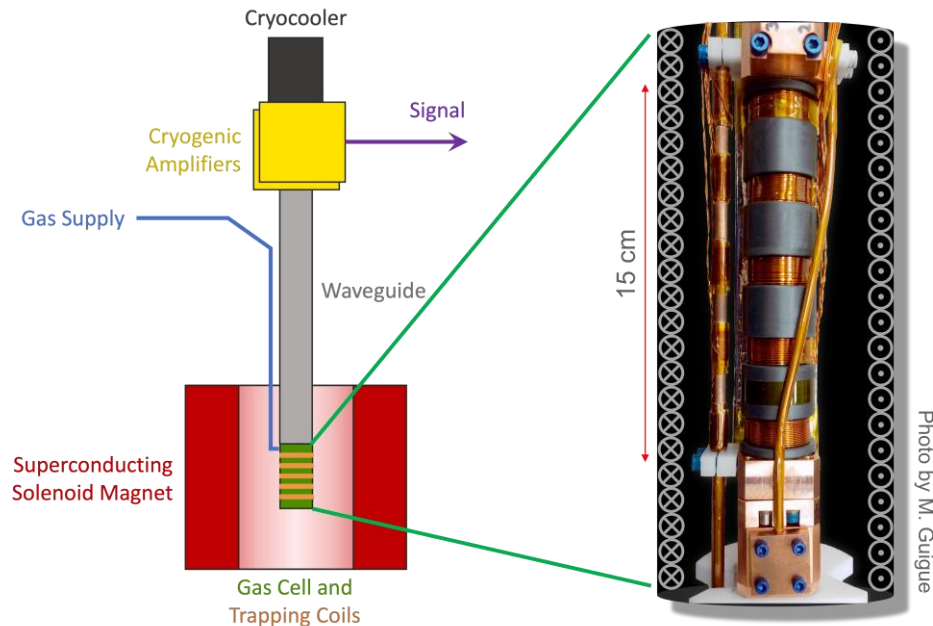
*B. Monreal and J. Formaggio, Phys. Rev D80 (2009) 051301*

# Project 8 – Results

**PROJECT 8**

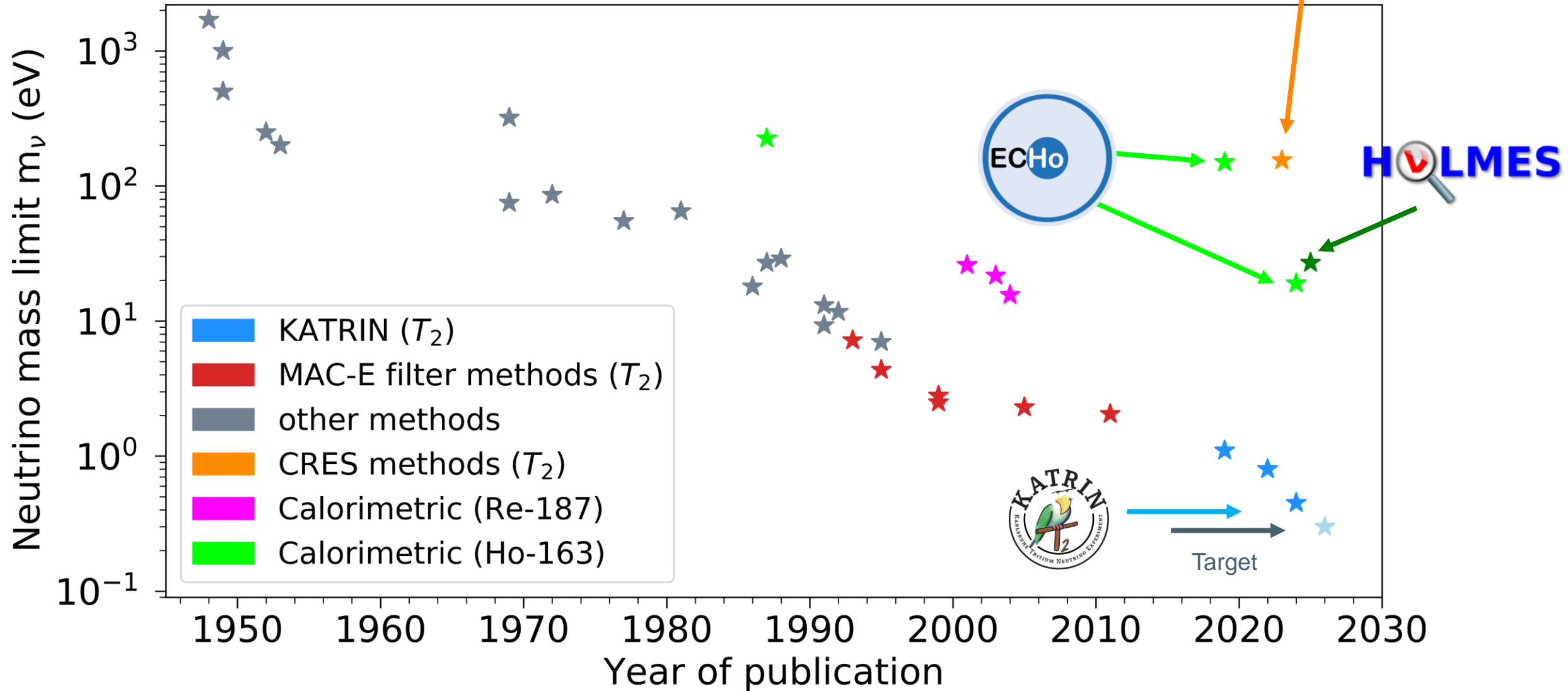
**Phase I:** First use of CRES for electron spectroscopy ( $^{83\text{m}}\text{Kr}$ )

**Phase II:** First use of CRES for tritium beta decay electron spectroscopy  
→ Neutrino mass limit ( $m_\beta < 155 \text{ eV}$ )

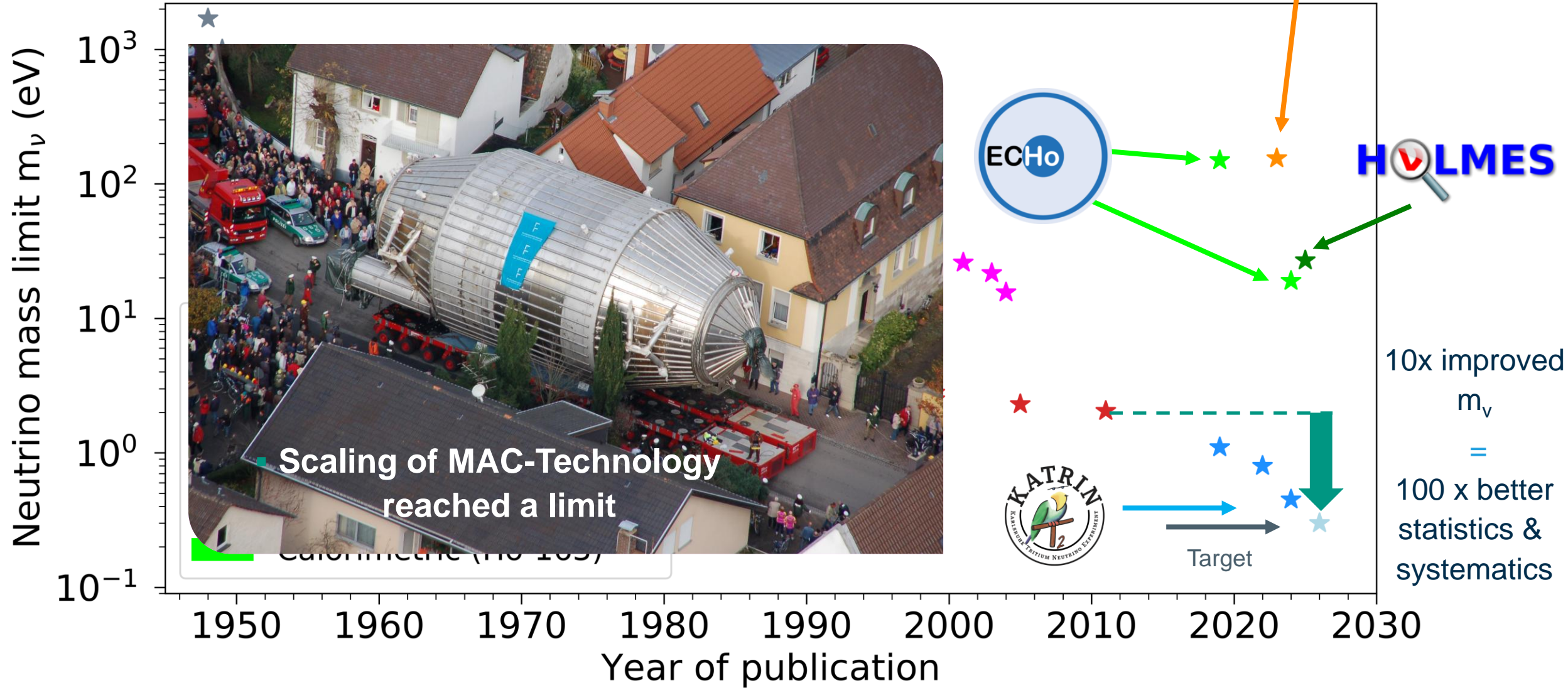


*PRL 131, 102502 (2023)*

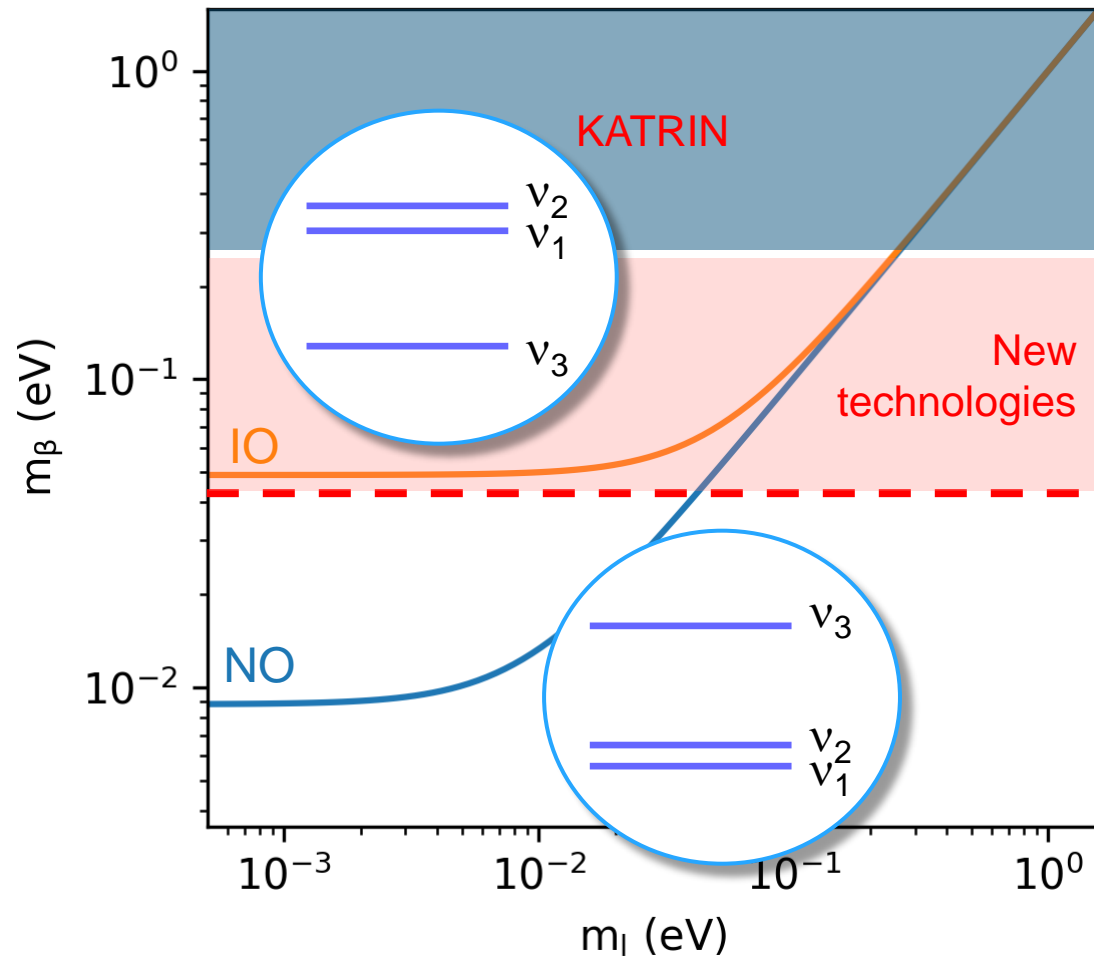
# History of neutrino mass sensitivity



# History of neutrino mass sensitivity



# Going beyond KATRIN



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

New technologies:  $< 0.05$  eV  
 cover **inverted** ordering and below

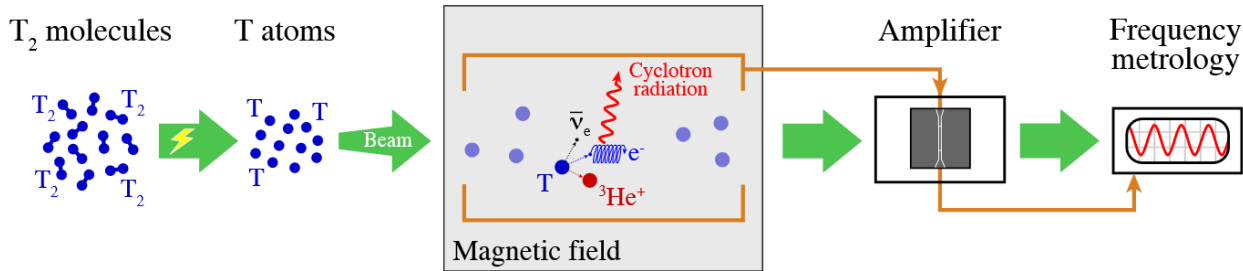
shared aim by



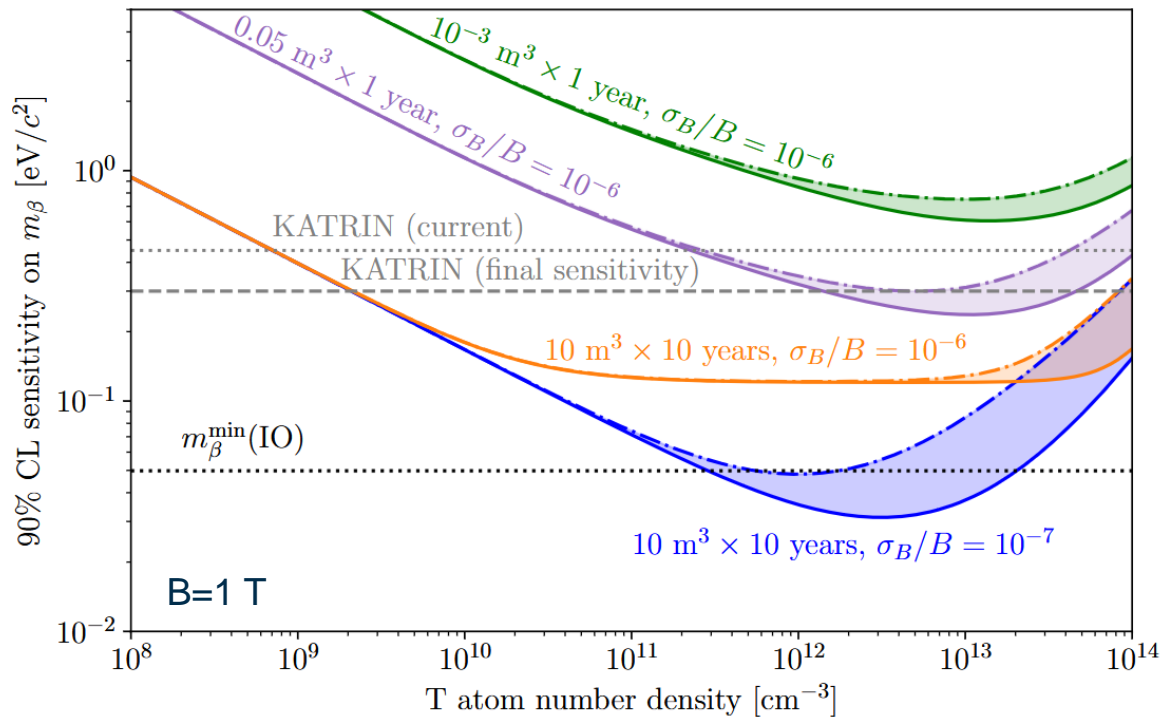
**PROJECT 8**



# CRES plans aiming at 40-50 meV sensitivity



<https://www.project8.org/>



Frequency measurement of electrons emitted inside of atomic tritium source

Limits by

- B-field accuracy
- Electron observation time (limits max. T density)

$$\text{std}(\hat{\nu}_0) \gtrsim \frac{4\sigma_{\text{noise}}}{\pi} \sqrt{\frac{3}{P_{\text{sig}} t_{\text{obs}}^3 f_s}}$$

# The Project 8 experiment

Target: 0.04 eV sensitivity — **Phase IV**

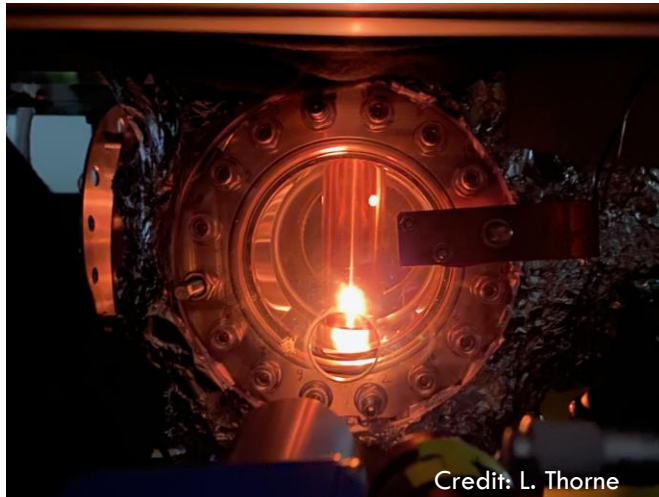
- Large-volume (~10 m<sup>3</sup> scale) **cavity** for CRES detection  
→ resonance enhancement of low-power electron signal
- High-intensity source of **cold atomic tritium**
- Magneto-gravitational **trap** for tritium atoms  
→ complex magnetic system

Next up: **Phase III**

- 1.5 m<sup>3</sup> cavity operating at *low frequency* (natural scaling to large volume)
- m(v) sensitivity of **0.3-0.7 eV** in one year
- Integrated field design with trap ready for atomic tritium

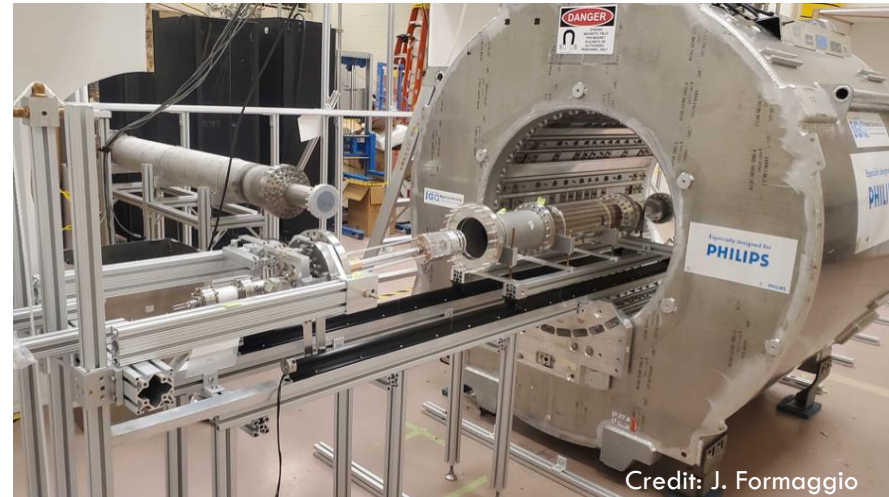


Phase II:  
~mm<sup>3</sup>-scale  
effective volume



Credit: L. Thorne

Mainz Atomic Test Stand (MATS)



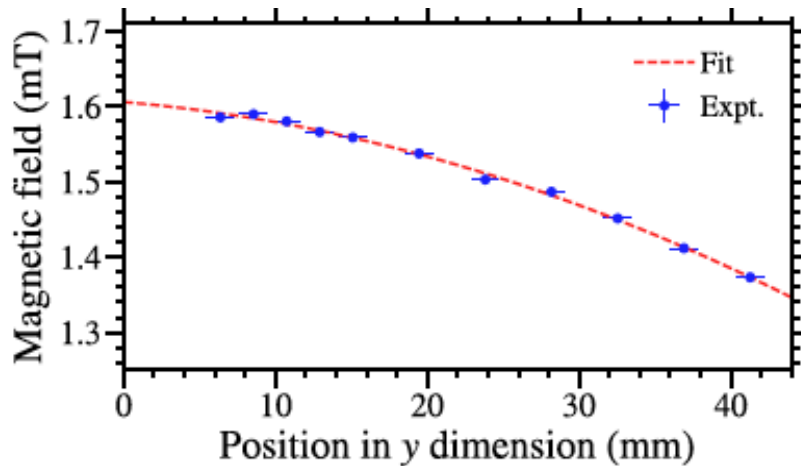
Credit: J. Formaggio

Cavity prototype and electron source (MIT)

Funded as part of the *Quantum Technologies for Fundamental Physics* programme, leverages QT to address **key challenges of CRES**:

## Extreme precision of B- & E-fields

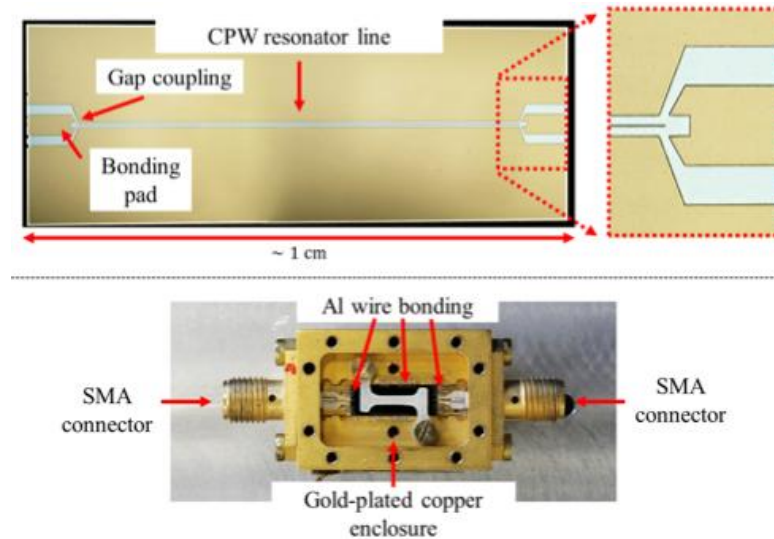
3D field mapping w. Rydberg atoms,  
< 1  $\mu\text{T}$  precision, < 1 mm resolution



Zou & Hogan, *Phys. Rev.* **A107** (2023) 062820

## Tiny radiated powers, $\sim fW$

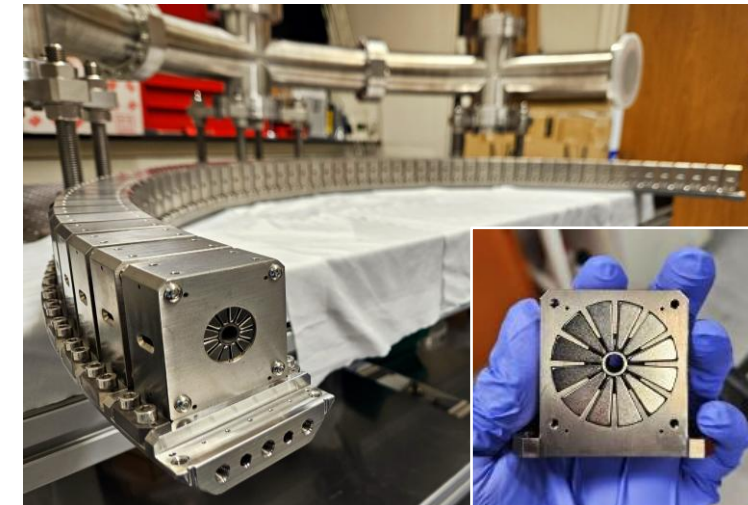
Quantum-noise-limited superconducting amplifiers



Zhao et al., *SC Sci. Tech.* **36** (2023) 105010  
& [arXiv:2406.02455](https://arxiv.org/abs/2406.02455)

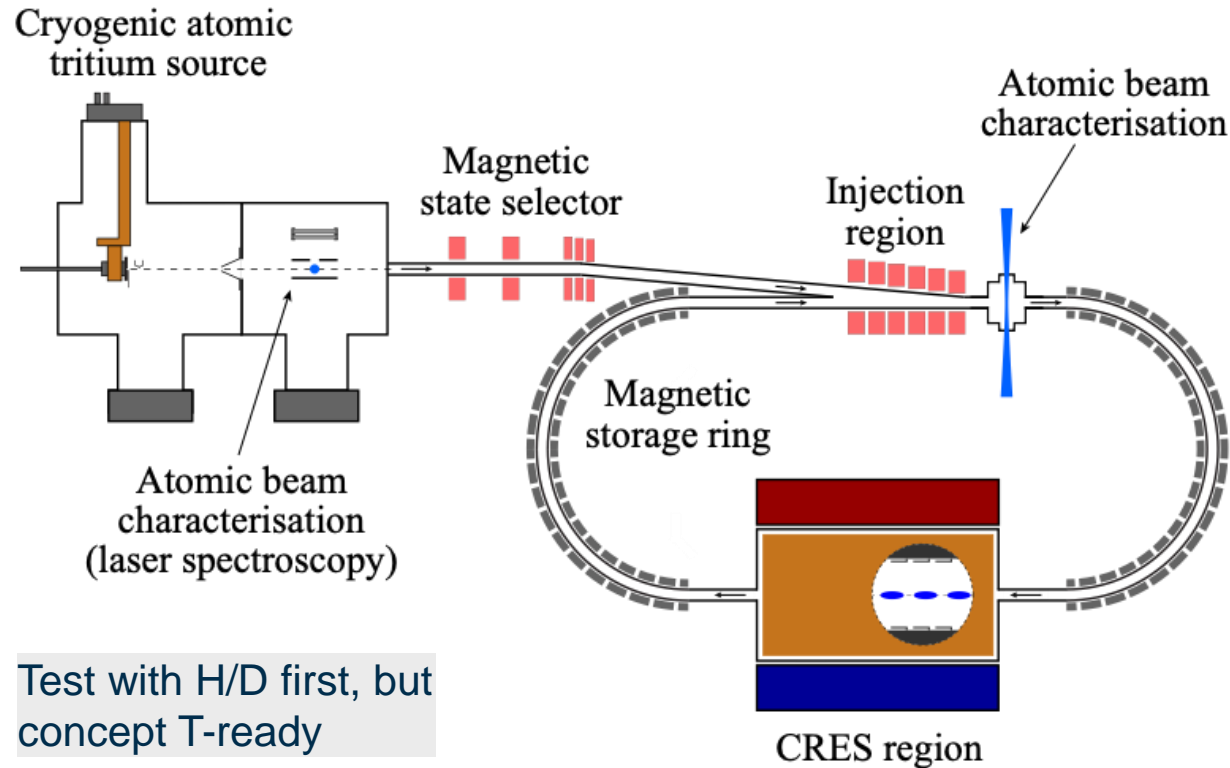
## Observe $\sim 10^{20}$ tritium atoms for $O(1-10)$ yr

Storage ring to avoid trap-loading losses, multiple CRES modules



# : plans & outlook

CRES Demonstrator Apparatus (**CRESDA**), employing phased approach:



Test with H/D first, but concept T-ready

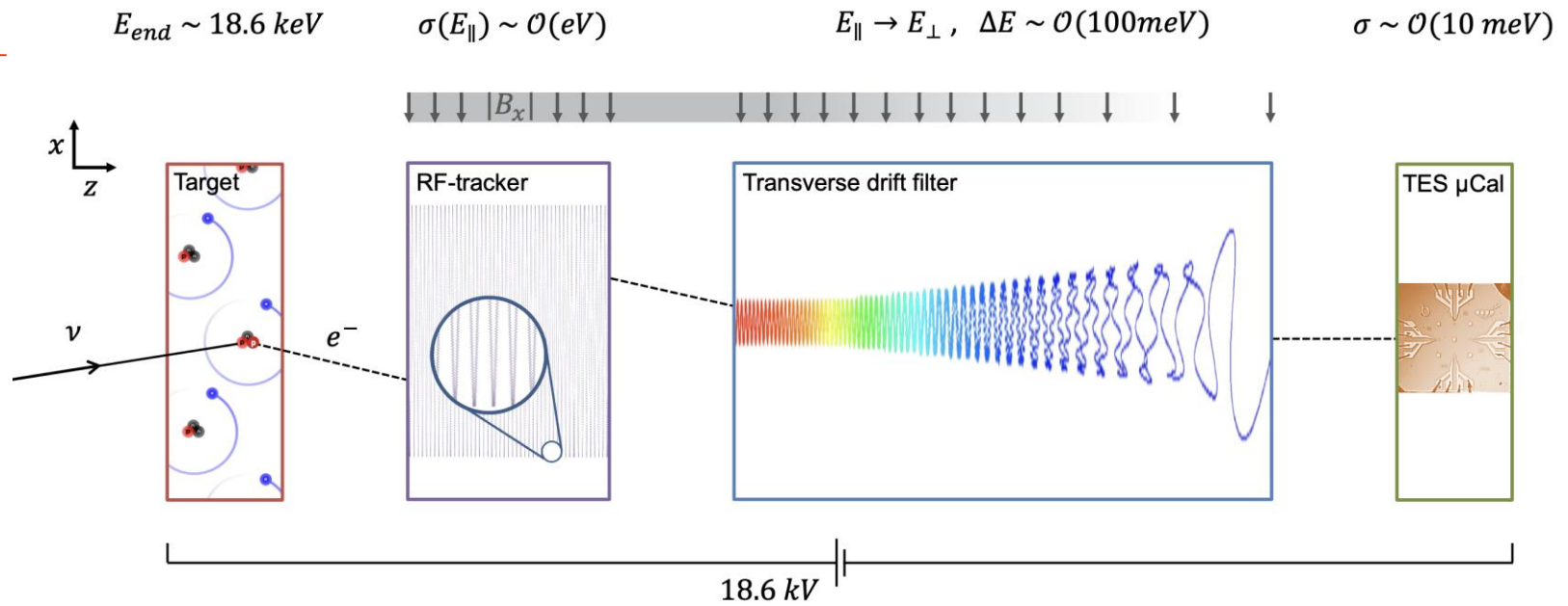
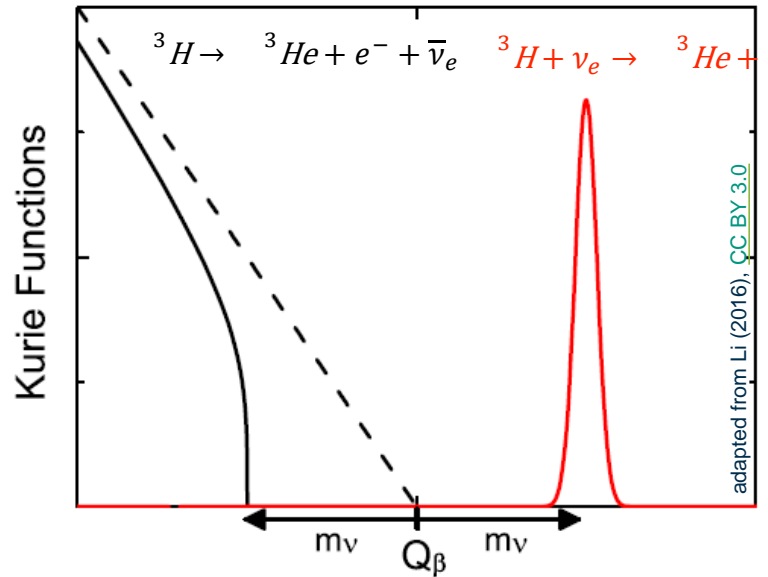
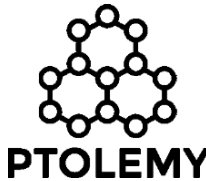
Amad *et al.*, *New J. Phys.* **27** (2025) [105006](#)

- **2021-2025 (CRESDA-0):**  
Basic technology demonstration
- **2026-2030 (CRESDA Tritium):**  
System demonstration, scaling, tritium readiness
- **Next decade:** Neutrino mass experiment  
→ 100 meV → 50 meV → O(10 meV)  
(at Culham/UK or similar facility, international collaboration)



# The PTOLEMY project

**Goal:** develop technologies for direct **detection of cosmic neutrino background** through capture on  $^3\text{H}$ . (Weinberg Phys. Rev. 1962; Cocco, Mangano & Messina JCAP 2007; Betti *et al.* JCAP 2019)



$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

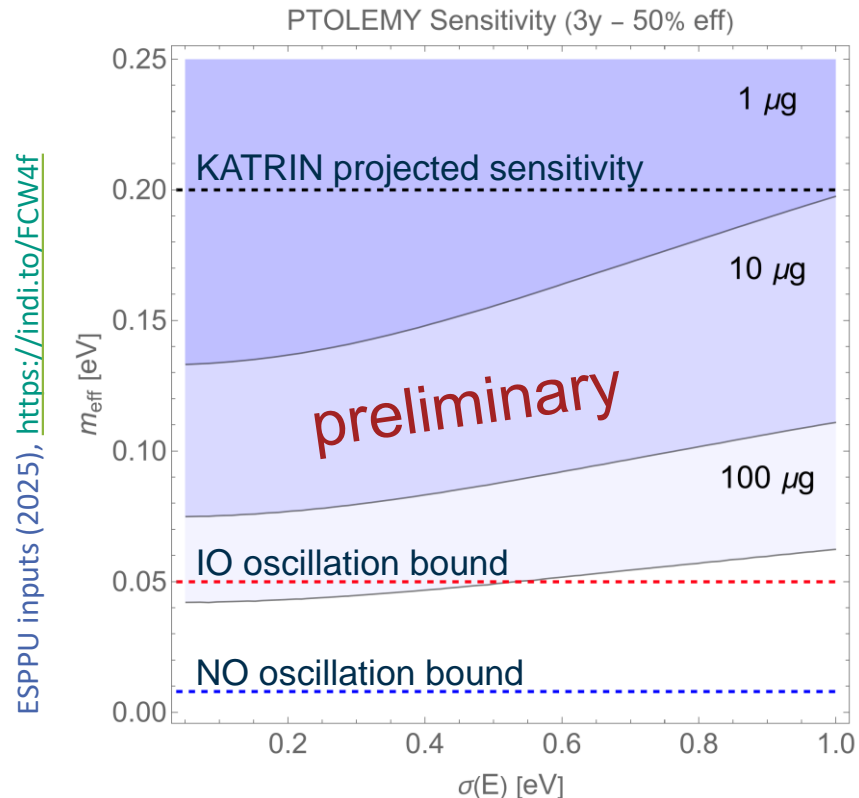
**Working principle** combines strong (gram-level) atomic tritium source on carbon nanostructure, CRES-type electron tracker, dynamic ExB drift filter, and high-resolution calorimetry.

ESPPU inputs (2025), <https://indi.to/FCW4f>

# The PTOLEMY project

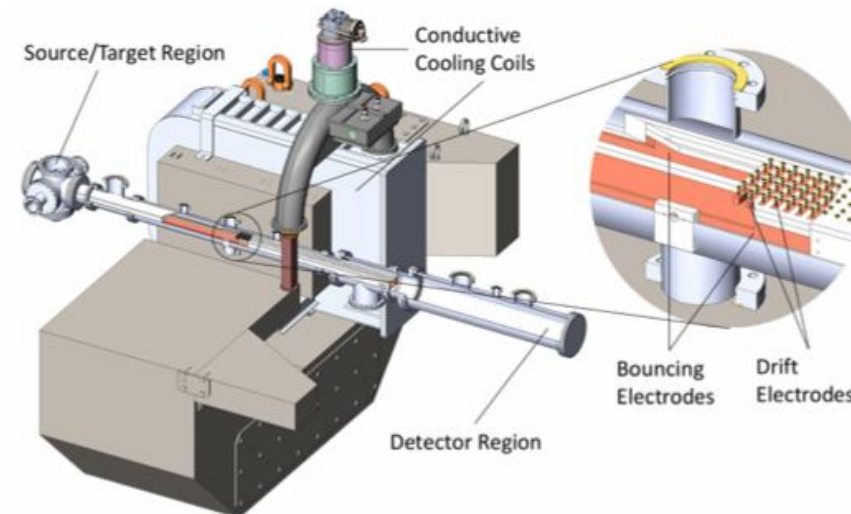
## Intermediate goal: $\nu$ -mass measurement

(e.g., 150 meV sensitivity with  $O(10) \mu\text{g}$   $^3\text{H}$  mass, target resolution  $\sigma(E) \sim 50$  meV over few tens of eV)



## Experimental challenges:

- Final states of tritium-graphene bound system → modeling (cf. PRD 106 (2025) [053002](#) & [2504.13259](#))
- High levels (1-100  $\mu\text{g}$ ) of tritium implantation needed → collab. with Culham/UK established
- Demonstration of complex end-to-end measurement chain (e.g. dynamic filter, CRES tagging)



### PTOLEMY Demonstrator:

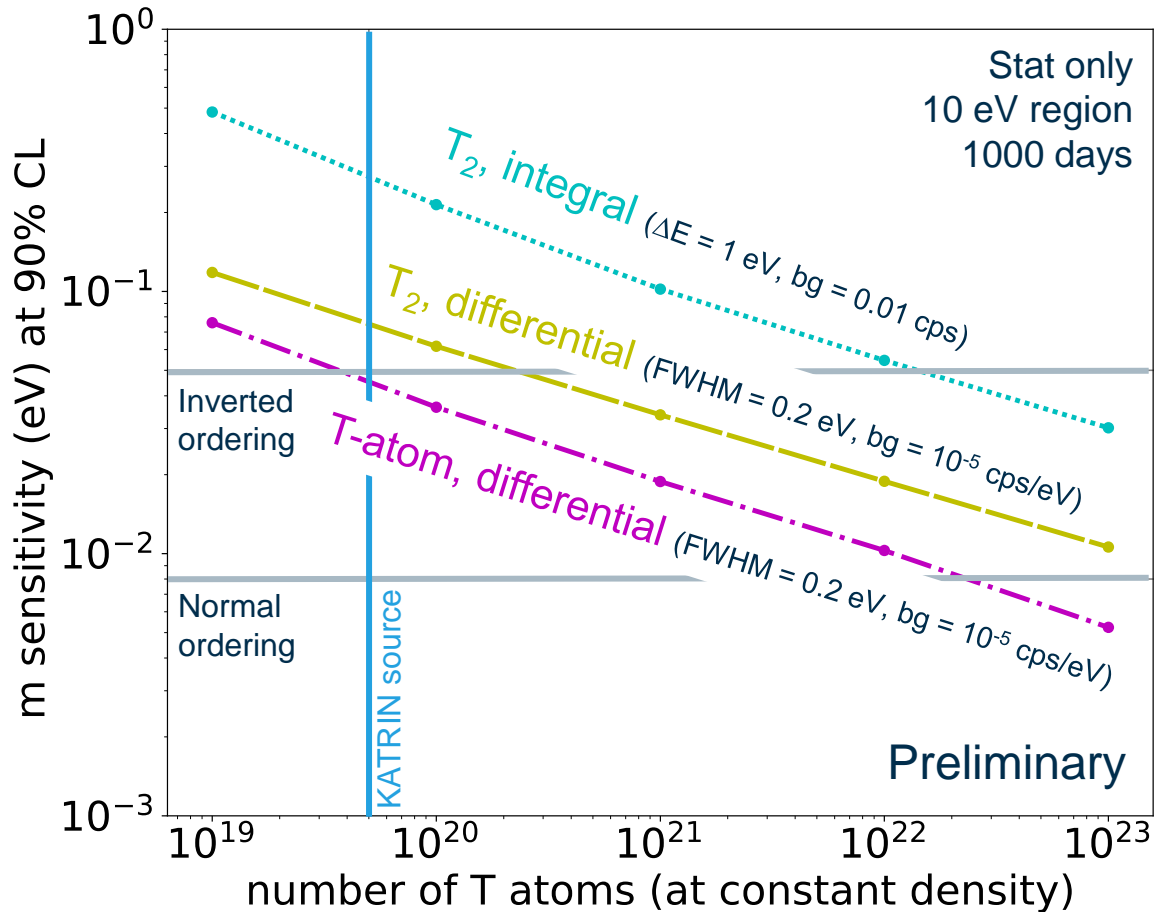
- Custom s.c. magnet expected at LNGS in 2026
- First test of filtering concept (grad. E-field tuned to a grad. B-field to select endpoint)

> [Apponi et al., JINST 2022](#)

> [Farino et al., JINST 2025](#)

> [Amendola et al., 2512.19437](#)

# Improving neutrino mass sensitivity

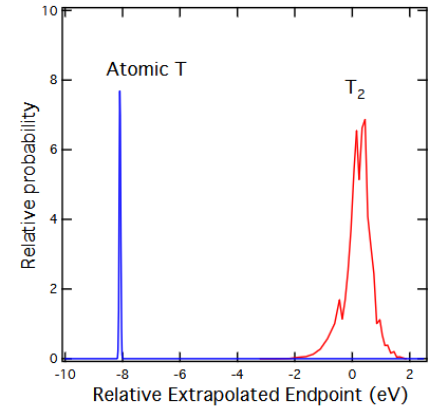


## Differential measurement (FWHM < 1 eV)

- Better use of statistics
- Lower background

## Atomic tritium

- Avoid broadening ( $\sim 1$  eV)
- Avoid limiting systematics of  $T_2$



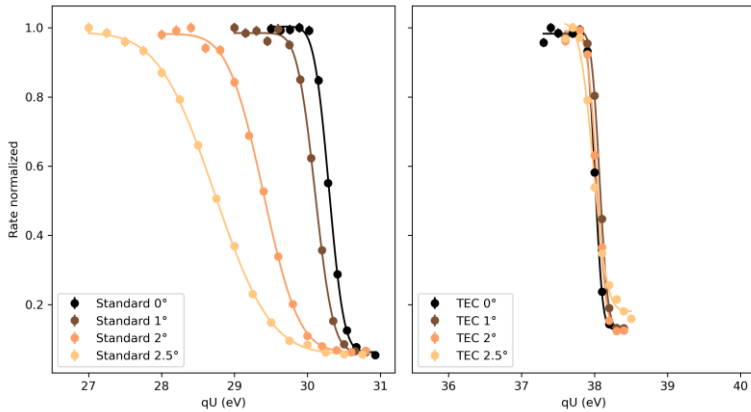
## KATRIN++ mission

- Next generation  $m_\nu$  experiment
- Identify and develop scalable technology
- Use KATRIN/TLK infrastructure for R&D phase ( $\sim 7$  years)

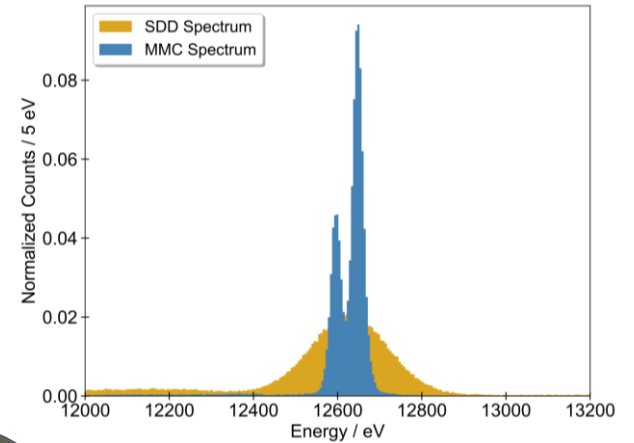
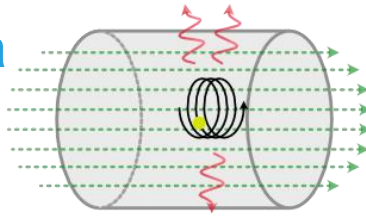
# KATRIN as R&D facility for differential detector

**Goal #1:** Sub-eV resolution for **differential** energy measurement.  
**Added benefit:** Immune to MAC-E filter backgrounds!

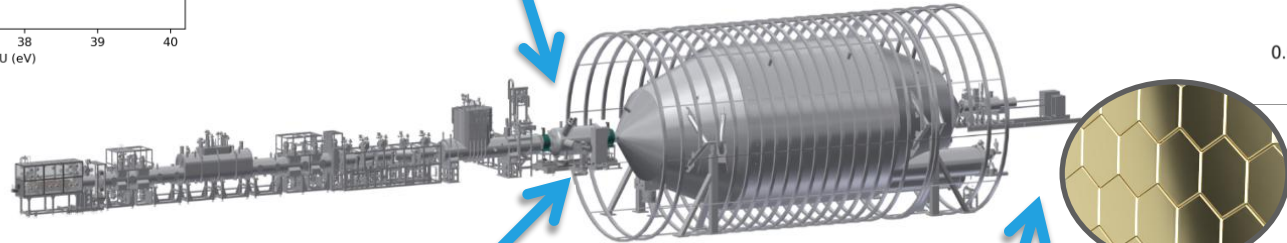
Several promising technology options



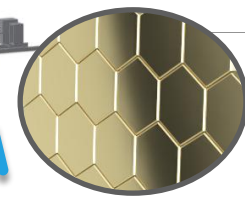
Time-of-flight via electron tagging (e.g. CRES-type)



**TEC test stand (U Münster)**  
 Demonstrated improvement of MAC-E resolution by factor  $\sim 10$   
 Salomon, Weinheimer *et al.*, in prep.



**Transverse Energy Compensator (TEC)**  
 fast-ramping drift tube



$\times 10^5 \dots 10^6$

**Quantum sensor array**  
 (MMC or TES)

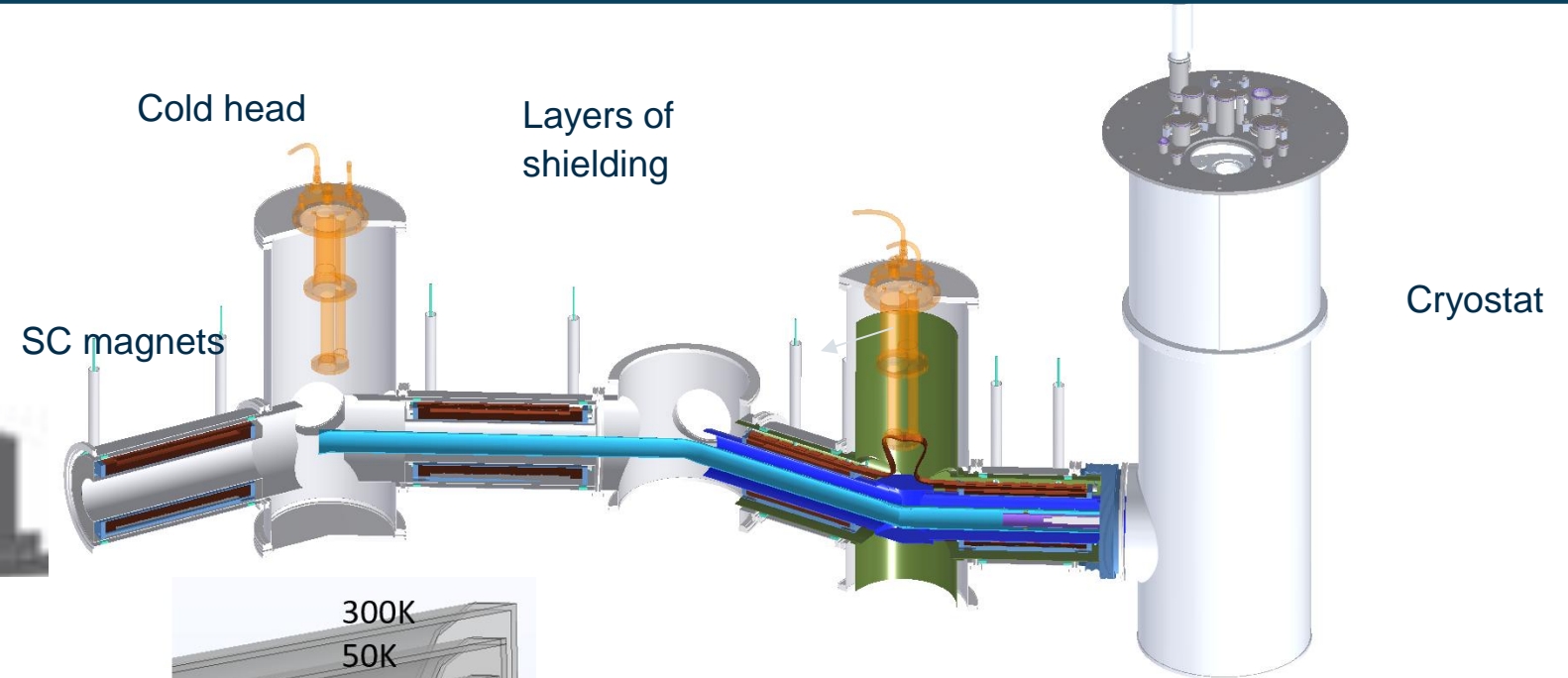
**Electron spectroscopy with external source on MMCs**  
 Kovac *et al.*, [NIM A, 2025](#)  
 Next: demonstrator for magnetic guidance and thermal coupling

# Attaching a warm spectrometer to a mK detector

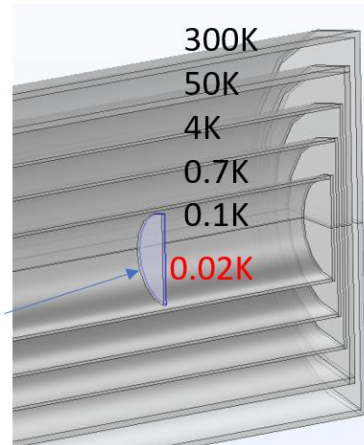
Quantum sensor demonstrator at KATRIN beamline

Main spectrometer exit  
(300 K)

Current  
silicon-based detector

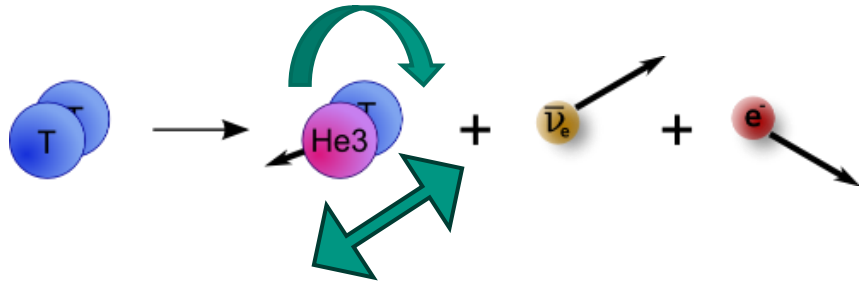


QSA:  
D=30mm

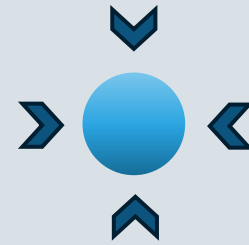


sub-eV  $m_\nu$ -sensitivity possible for  
4cm<sup>2</sup> MMC-detector with  $\Delta E_{\text{FWHM}} < 1\text{eV}$  in 30days of measurement

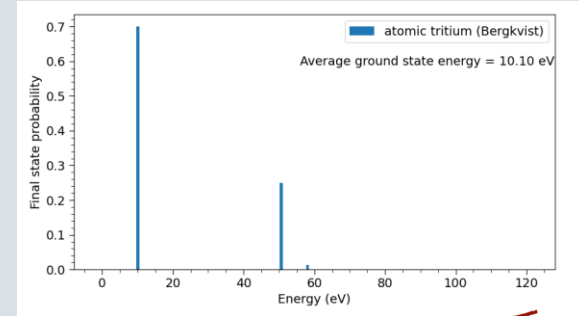
# Overcoming molecular effects and spectral broadening



## Magnetically-trapped cold tritium atoms

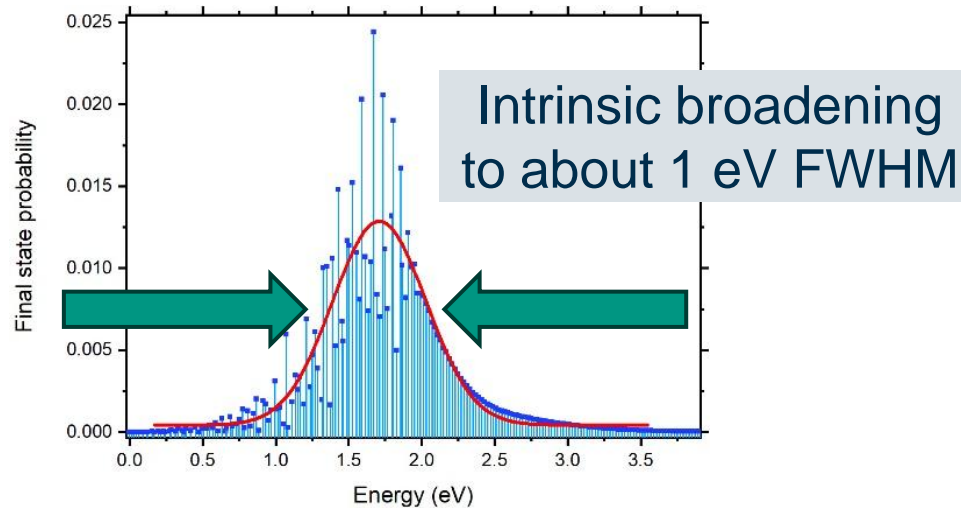


- + no molecular effects
- + experience with cold H-atoms
- cooling and trapping challenges

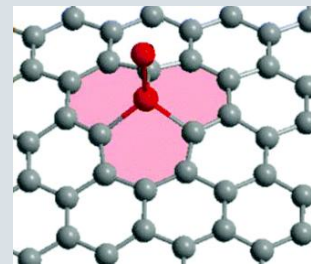


KATRIN++

**PROJECT 8**



## Tritium atoms bound to graphene



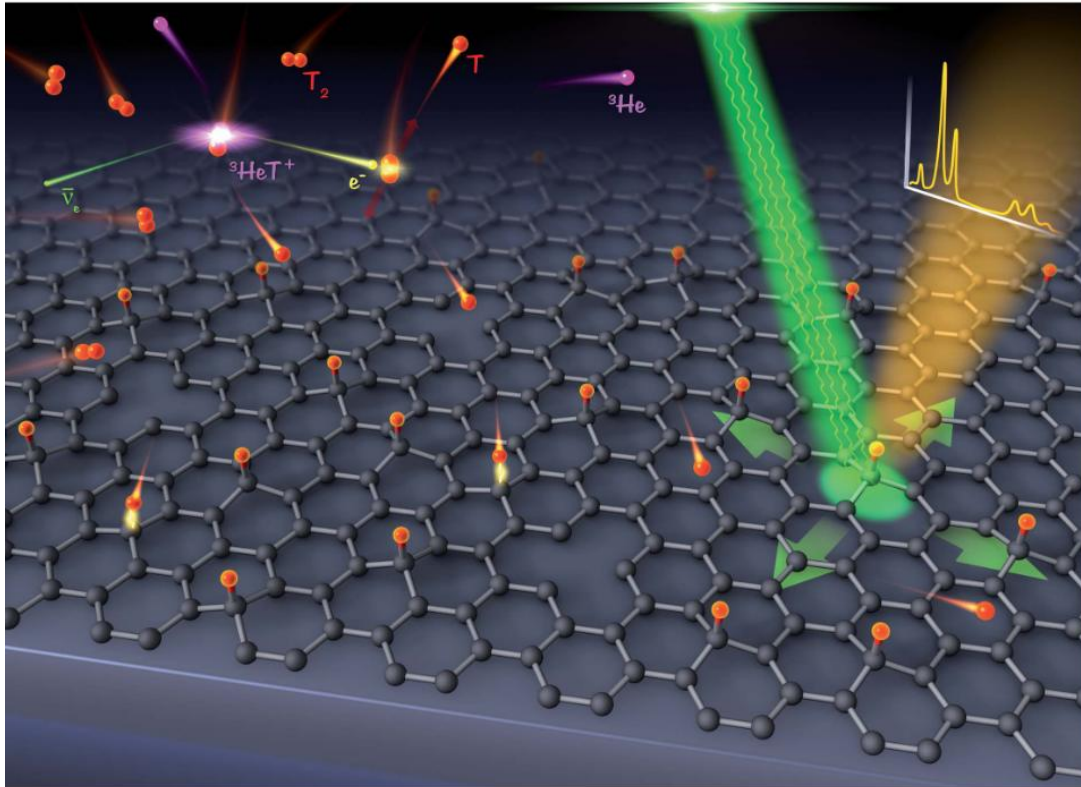
- + high-density
- + recoil against bulk reduces molecular effects? (Mössbauer-like)



**NO, because of uncertainty principle:**  
localized atoms → momentum broadening  
Cheipesh et al., Phys. Rev. D **104** (2021) 116004  
Nussinov & Nussinov, Phys. Rev. D **105** (2022) 043502

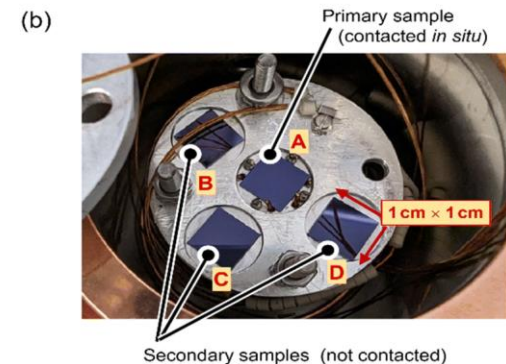
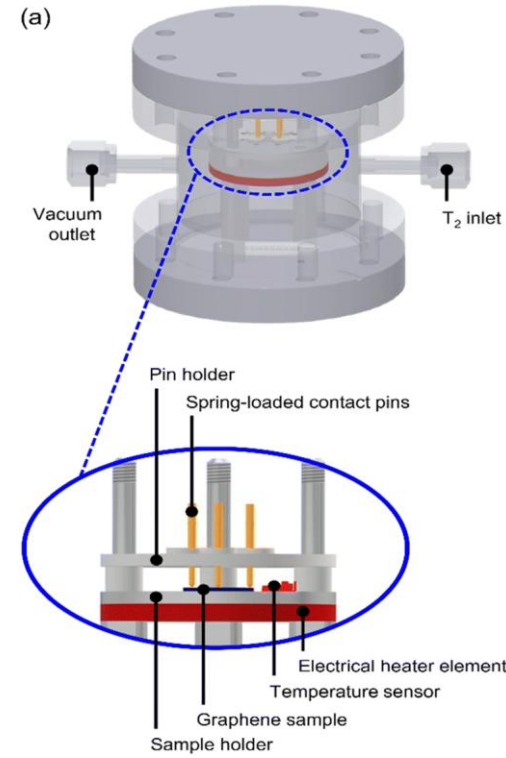
# Demonstration of tritium adsorption on graphene

## Tritium atom / ion formation via beta decay

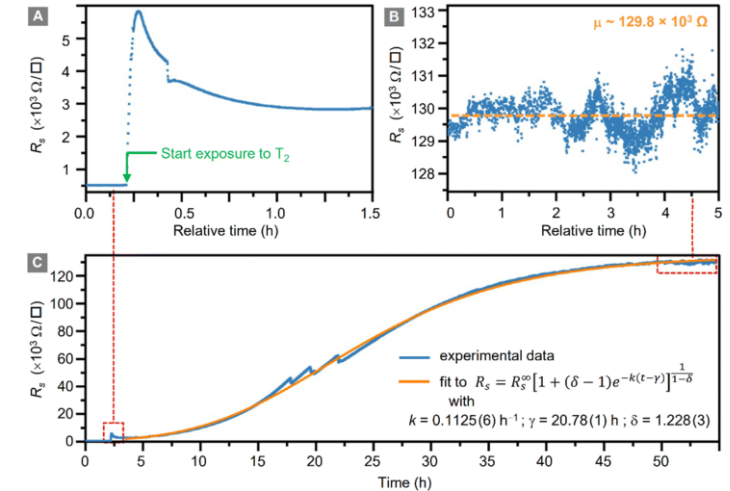


## Raman microscopy to measure graphene modifications

G. Zeller, et al, Nanoscale Adv. 6 (2024) 2838



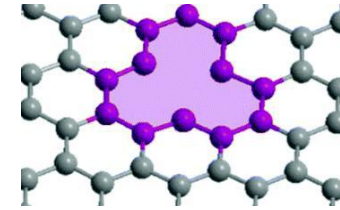
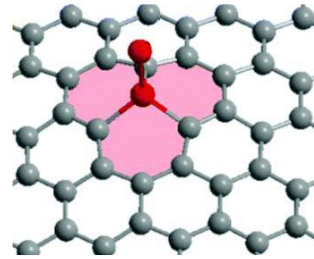
- 4x mono-layer graphene on Si/SiO<sub>2</sub>-substrate
- ~400 mbar T<sub>2</sub> ( $7,6 \times 10^{12}$  Bq)
- 55 h exposure time



Resistivity increase →  
loss of free charge carriers

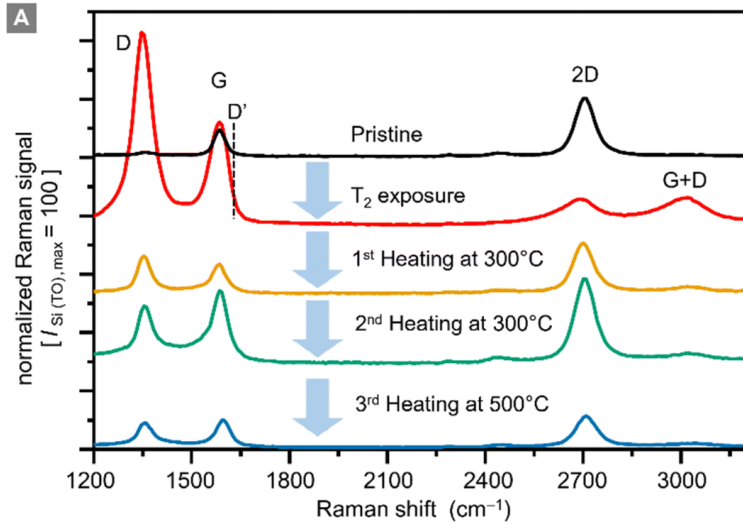
# Raman microscopy studies on tritiated graphene

Wanted: adsorption ( $sp^3$ )



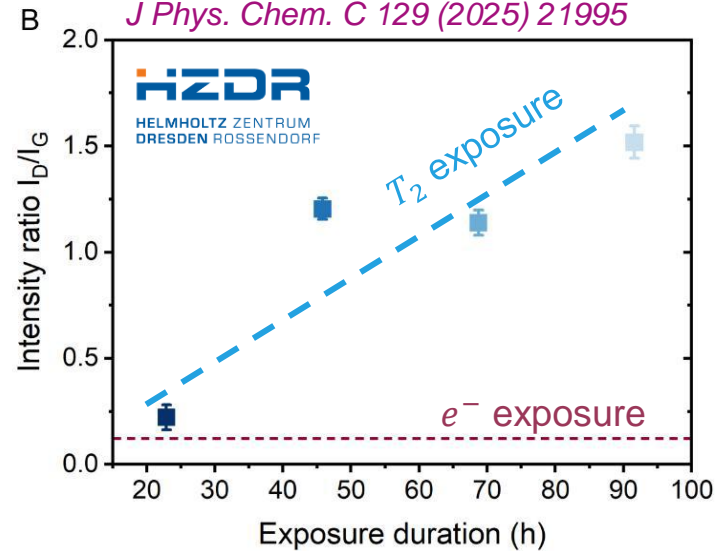
Unwanted: vacancy defects

G. Zeller, et al, *Nanoscale Adv.* 6 (2024) 2838



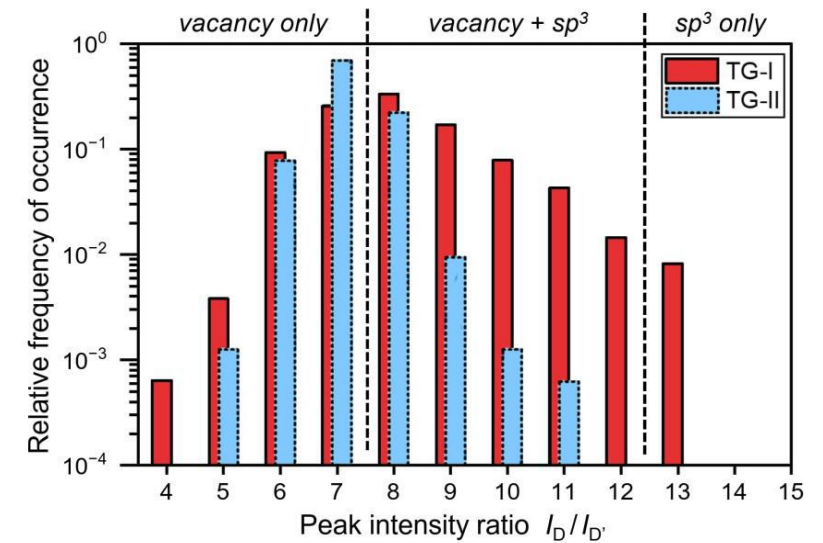
Spectrum partly recovered by heating  
→ mix of  $sp^3$  and vacancies

A. Becker, et al,  
*J Phys. Chem. C* 129 (2025) 21995



Defects increase with T-exposure,  
but not with electron exposure

G. Zeller, HHT, MS, *Nanoscale Adv.* 8(4) (2026) 1291

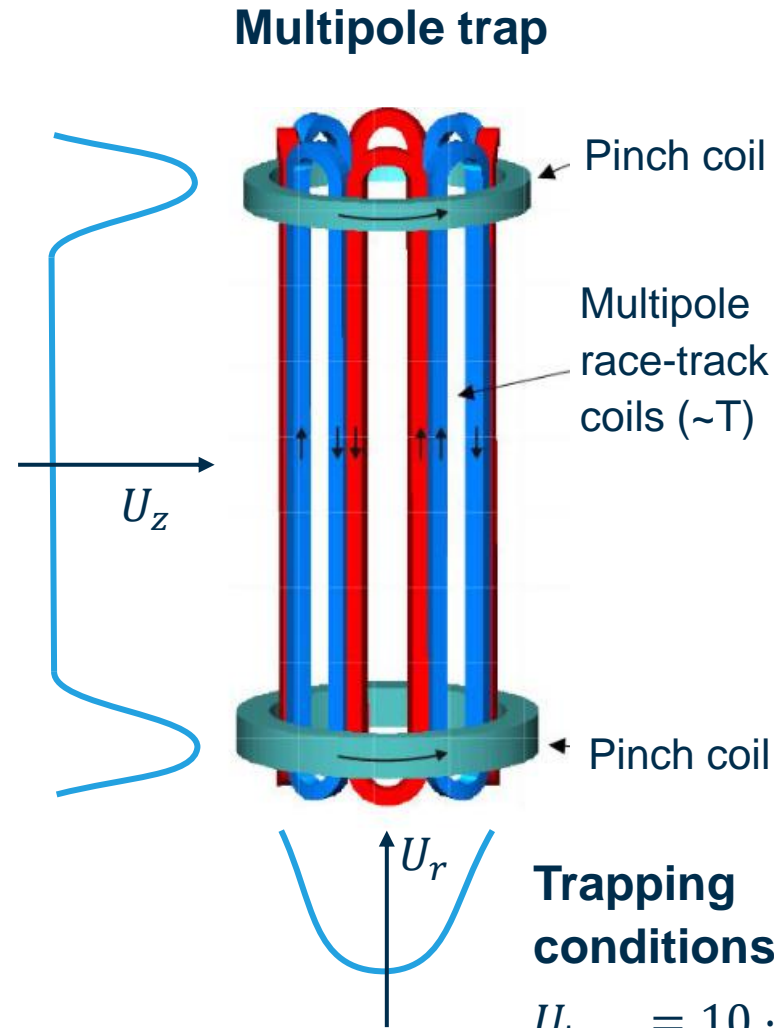
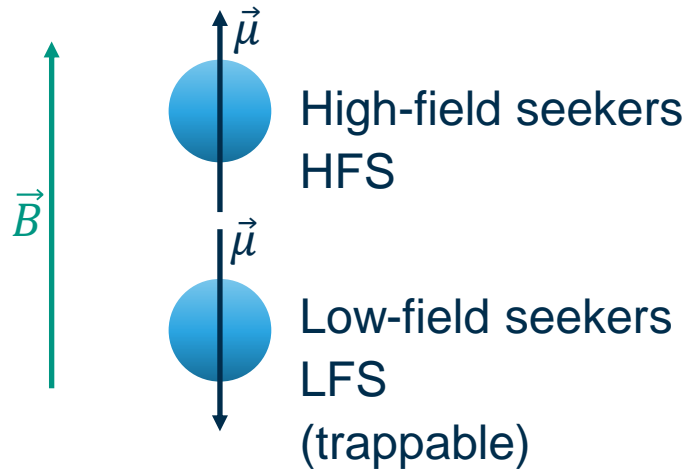


Remeasured T-graphene after  
1 year: adsorbed T vanishes

Usability of T-graphene for neutrino mass measurement questionable → still very useful tool

# Magnetically-trapped cold tritium atoms

$$U = -\vec{\mu} \cdot \vec{B}$$



## Trapping conditions

$$U_{\text{trap}} = 10 \cdot k_B T$$

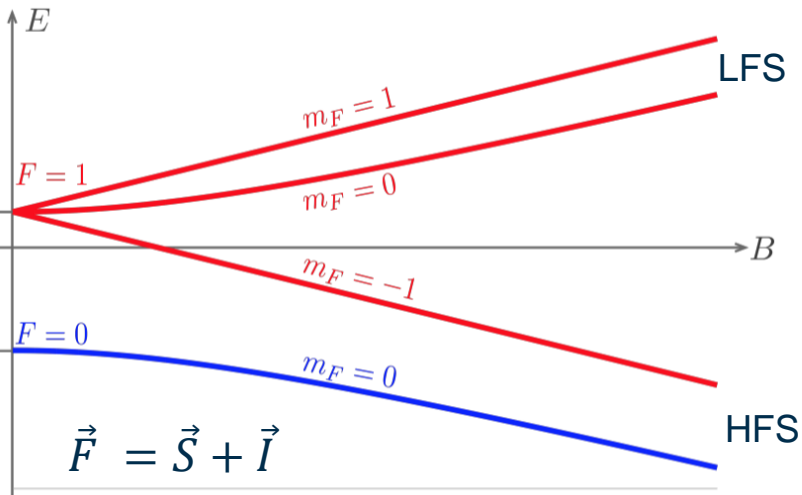
For  $B = 1 \text{ T}$   
 $T \leq 70 \text{ mK}$

## Losses

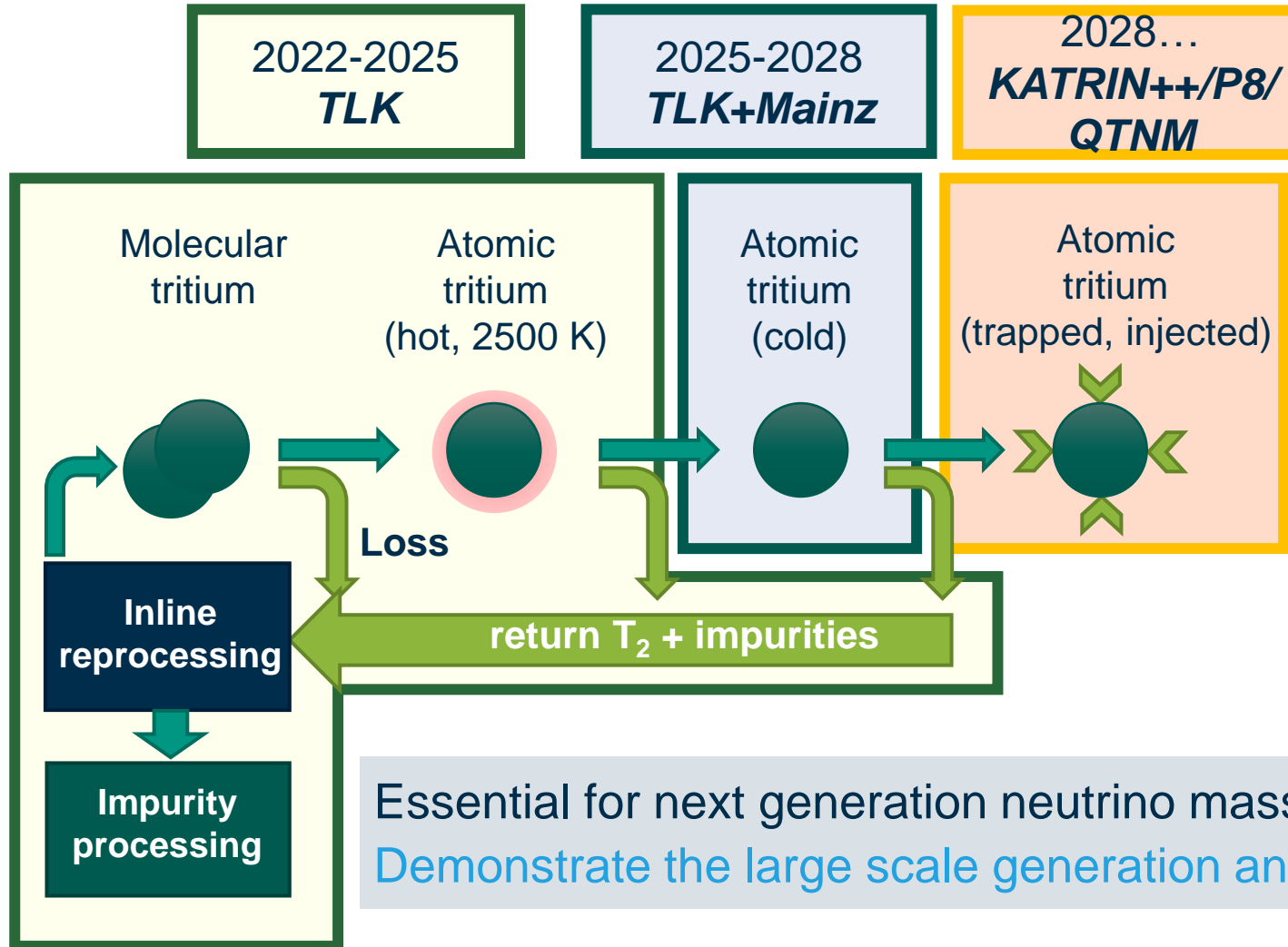
- **Majorana-losses**  
( $T^\downarrow$  loses polarization in low B)
- **Dipolar spin flip in scattering**  
(e.g. high-field seekers  $\rightarrow$  low-field seeker)
- **Recombination to  $T_2$**
- **Heating by  $\beta$ -decay**
- ...

## Challenges

- **Generate substantial amount of T to compensate losses**
- **Atom cooling to mK**



# Atomic Tritium Pathfinder 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

# Possible tritium sources

Hot dissociation requires cooling afterwards

Thermal dissociation source:  
*MBE Komponenten HABS*



Thermal dissociation source:  
*Tectra h-flux*



RF-discharge plasma source  
*SVTA RF 4.5*



- D<sub>2</sub>-test experiments outside of TLK concluded
- Installation completed mid Nov 2025
- Ongoing commissioning operation before T-operation

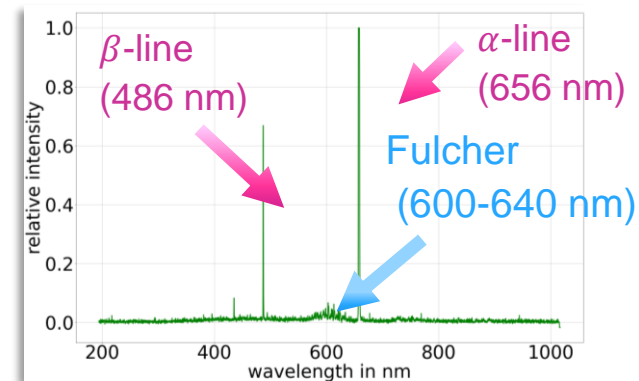
- Plasma source commissioned with H
- Optical emission → plasma parameters
- Beam-profile from Raman-maps of H-loaded-graphene

Atomic source installed Tritium circulation loop (1:5 KATRIN-flow)

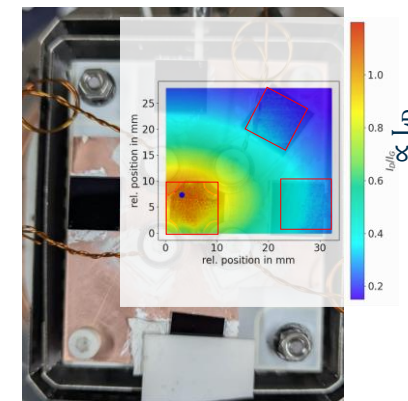


L. Hasselmann, PhD-Thesis, 2026

Optical emission spectrum of H



Graphene-sheets



# KAMATE – Karlsruhe Mainz Atomic Tritium experiment



A. Lindman

2024

## **KAMATE 0.5** (at Mainz)

Identify best source at MATS with H/D

## **KAMATE 1.0** (at TLK)

Operate KAMATE 0.5 setup with T.  
T(Beam) ~ 2500 K

## **KAMATE 2.0** (at TLK)

Add accommodator as first stage cooling.  
T(Beam) ~ 150 K

## **KAMATE 3.0** (at TLK)

Add nozzle for second stage cooling and beam  
temperature measurement setup (time of flight).  
T(Beam) ~ 4 K

2028

KAMATE stages

Karlsruhe



Tritium Laboratory Karlsruhe

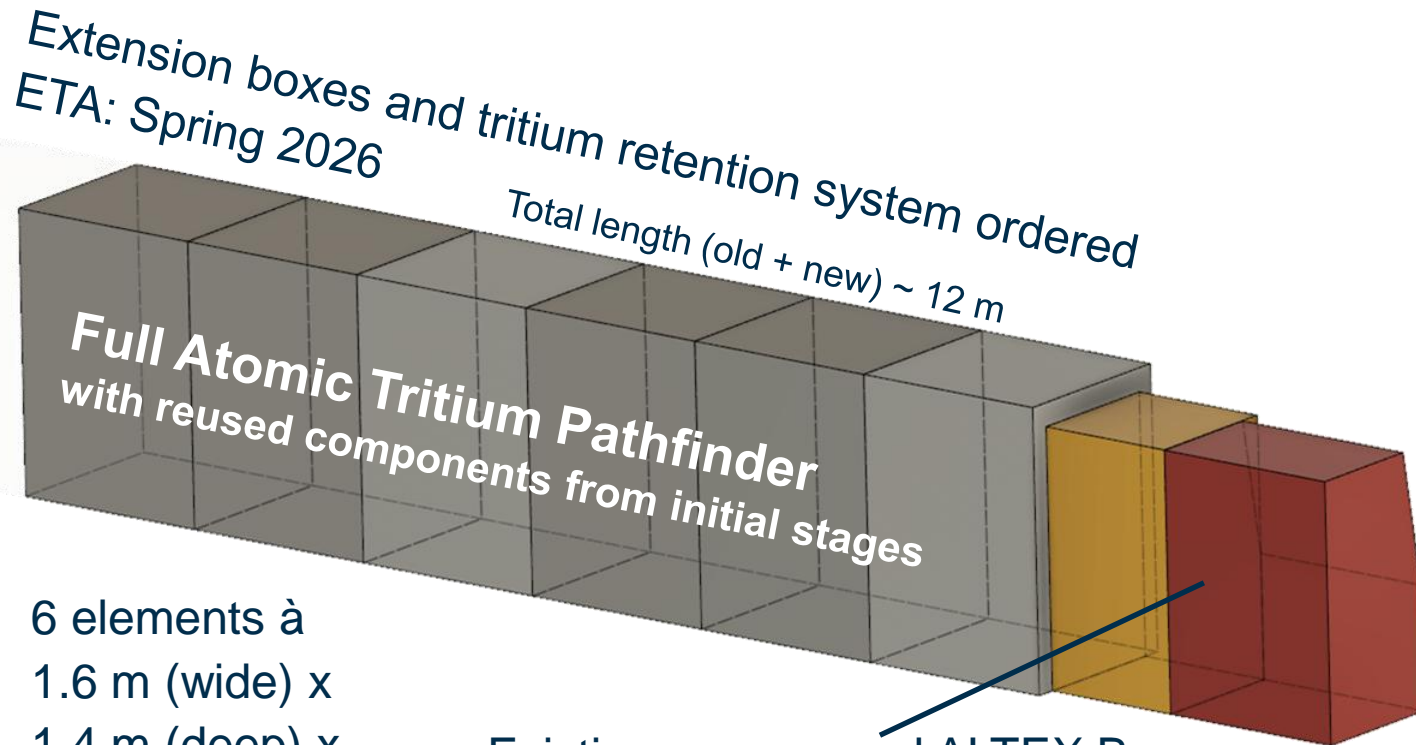
Mainz

**PROJECT 8**



JOHANNES GUTENBERG  
UNIVERSITÄT MAINZ

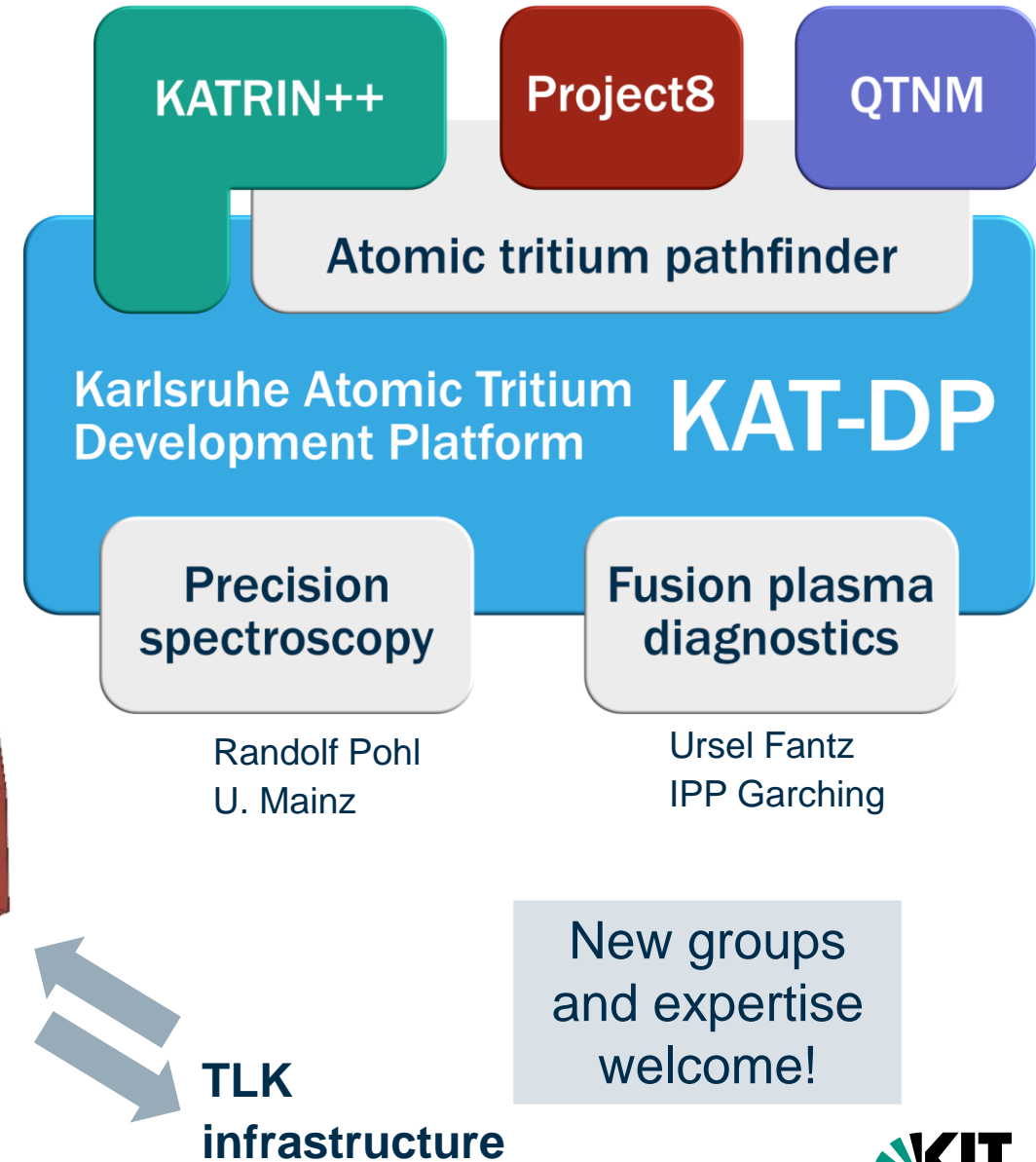
# Karlsruhe Atomic Tritium Development Platform (KAT-DP)



6 elements à  
1.6 m (wide) x  
1.4 m (deep) x  
2.2 m (high)

Existing, repurposed ALTEX Box  
Simple dissociator + tritium supply loop  
already installed

Currently connected  
via KAMATE



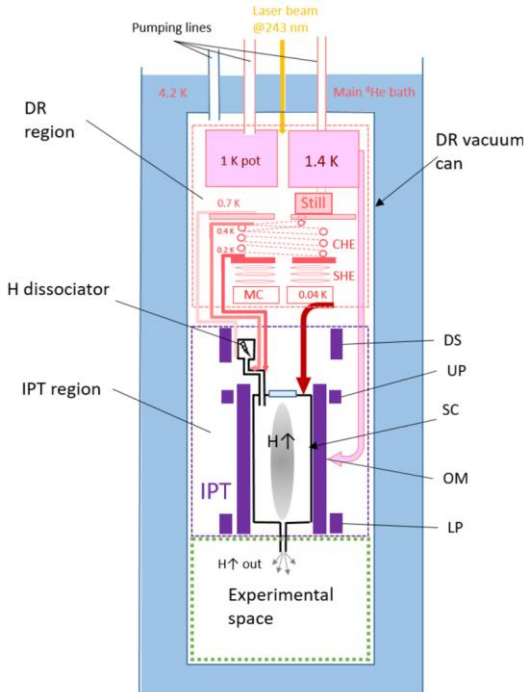
# New approaches

Atomic hydrogen at



UNIVERSITY OF TURKU

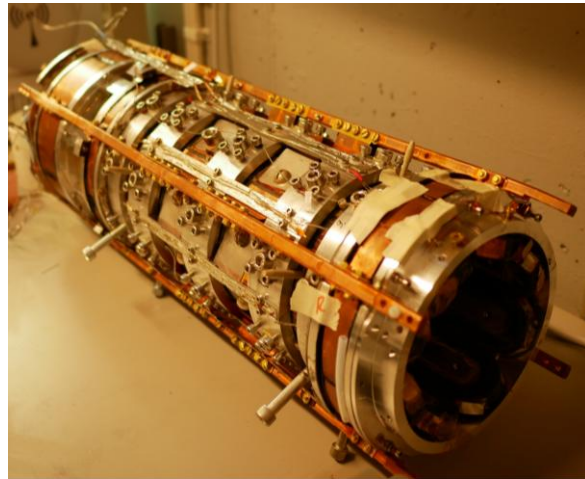
“Cold source of atomic hydrogen for loading large magnetic traps”



A. Semakin et al.,  
*Eur. Phys. J. D* **79**:23 (2025)

$7 \times 10^{13}$  H / s  
130 - 200 mK

“A large octupole magnetic trap for research with atomic hydrogen”

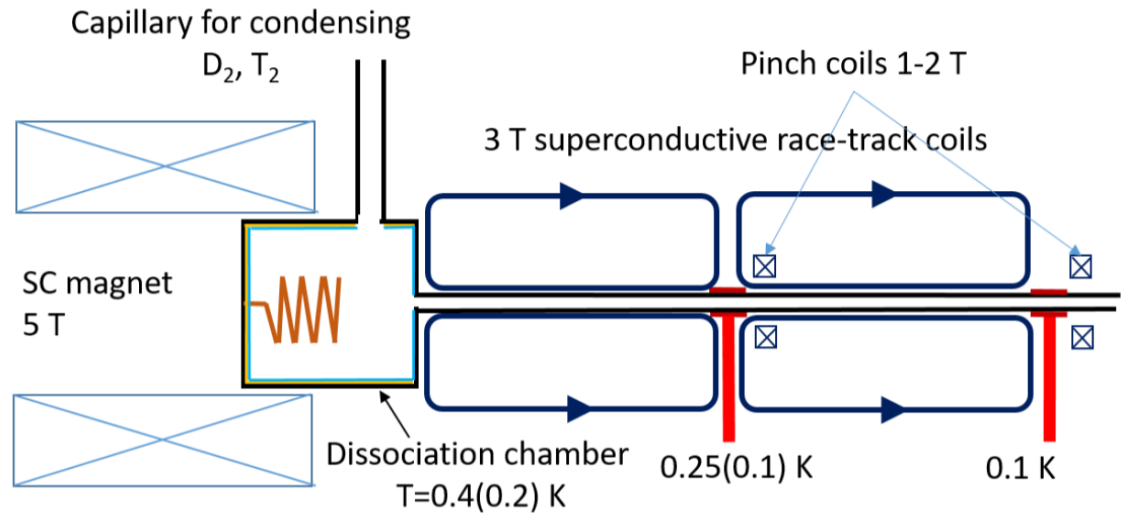


J. Ahokas et al.,  
*Rev. Sci. Instrum.* **93** (2022) 023201

$10^{11}$  H / cm<sup>3</sup>  
 $\sim 10^3$  s

## Cryogenic source of atomic tritium

A. Semakin, et al, arXiv:2511.08313, submitted to PRR

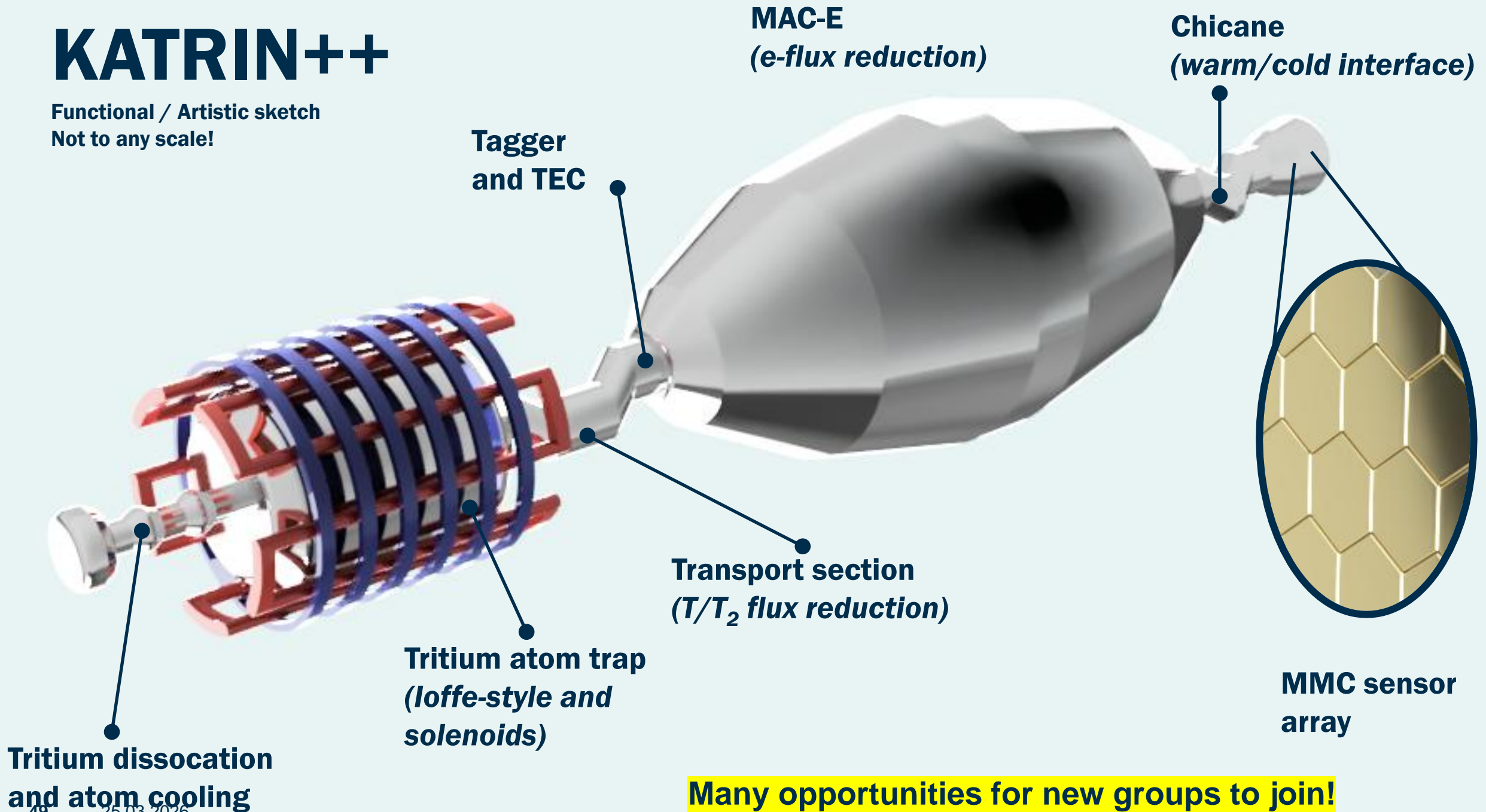


- Condense T<sub>2</sub> films at < 1K
- Cryogenic discharge generates T atoms
- Strong B-field pushes atoms out into multipole guide
- Residual pressure above super-fluid helium finally buffer-gas-cools down to ~100 mK

Very promising for large atomic tritium flows at almost trappable temperatures!

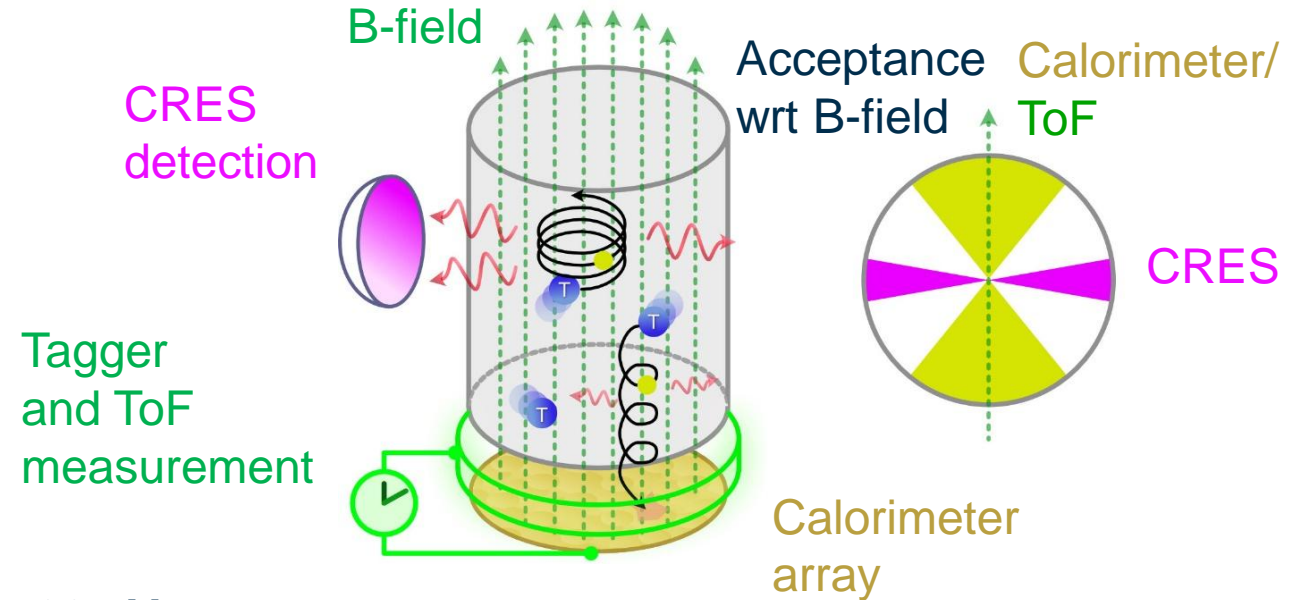
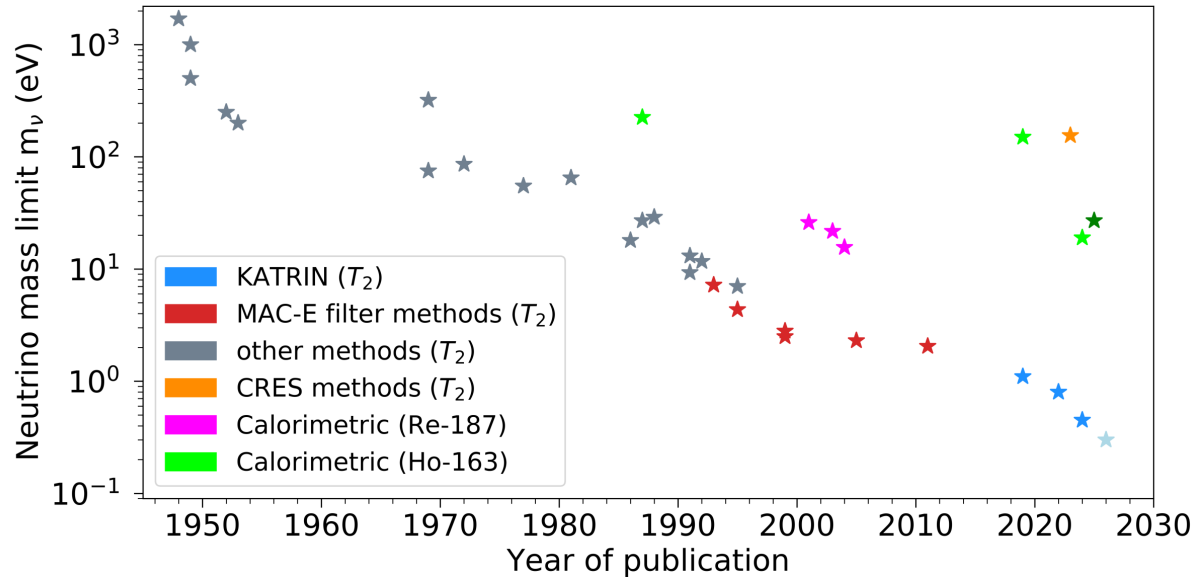
# KATRIN++

Functional / Artistic sketch  
Not to any scale!



**Many opportunities for new groups to join!**

# Status and outlook of direct neutrino mass experiments



- Limits by cryogenic Ho-163 experiments around  $m_\nu < \sim 20 \text{ eV}$
- Most stringent limits by KATRIN :  $m_\nu < 0.45 \text{ eV}$  (0.3 eV after 2025)
- R&D for **beyond MAC-E filter technology** picked up by community →
- Long term: **Definitive neutrino detector @ normal ordering ( $\sim 10 \text{ meV}$ )**
- Mid term: **inverted ordering ( $\sim 50 \text{ meV}$ )**

- **Complementary detector technologies:** Calorimeters, CRES, ToF, ...
- **Joint effort:** Atomic source



# DETERMINATION of the ABSOLUTE ELECTRON (ANTI-)NEUTRINO MASS



Data analysis  
Holmium / EC source  
Background & Systematic  
RF-Based methods  
Calibration methods  
Wild card / new ideas

Atomic T source  
Tritiated Graphene  
Quantum sensors  
Front end electronics  
Strategy and synergies

Photo: Tim Huegls, Poster: Beatrix von Pukemeyer

13.-16. April in  
Karlsruhe

Registration open until  
31.03!!!!