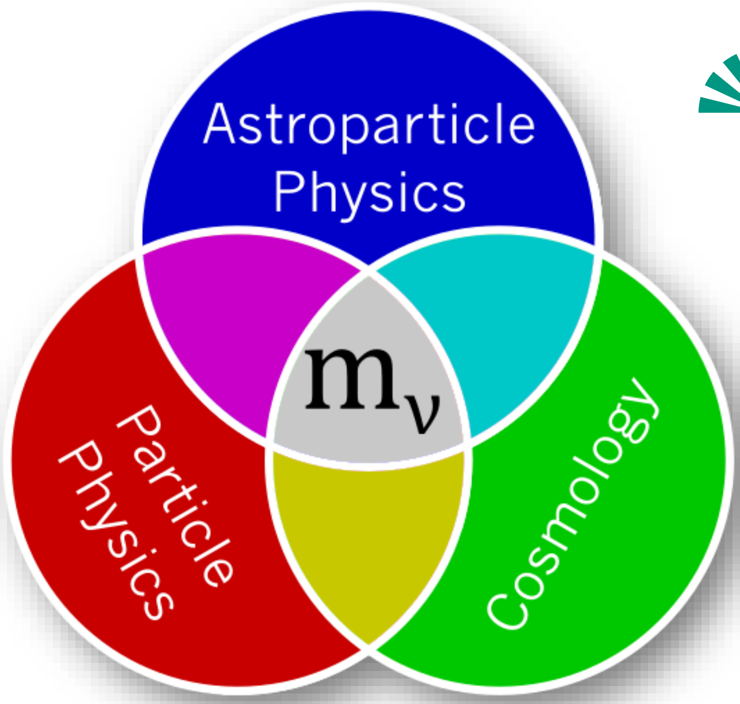
# Direct neutrino mass measurements

DPG Spring Meeting
Göttingen
T 42.1, Wed., 2nd April 2025



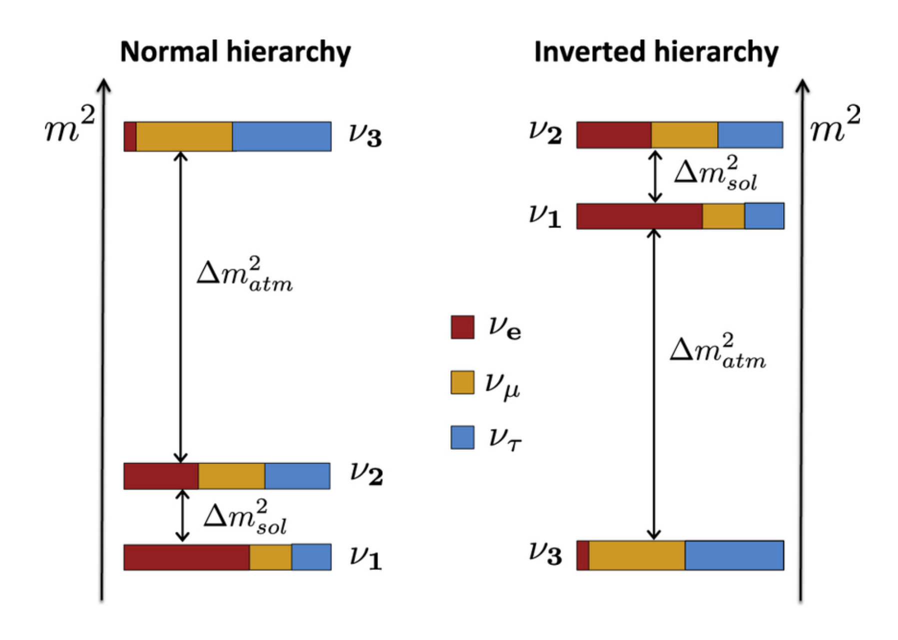

Magnus Schlösser
Karlsruhe Institute of Techology
Institute for Astroparticle Physics
Tritium Laboratory Karlsruhe

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

# Short motivation

## ~300 neutrinos per $cm^3$

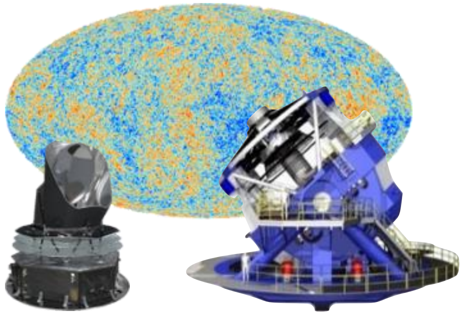
# $m_\nu$?

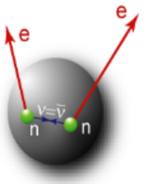


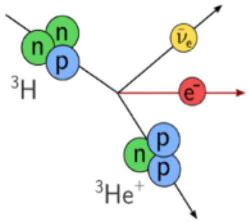

**Signal is „in reach“: Minimal mass scales exist!**
“$m(\nu_e)$“ > 10 meV (normal mass ordering)
“$m(\nu_e)$“ > 50 meV (inverted mass ordering)

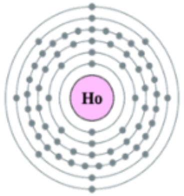
NASA’s Webb Delivers Deepest Infrared Image of Universe Yet, © NASA, ESA, CSA, and STScI

# Ways to access the neutrino mass






| | Cosmology | Search for 0νββ | β-decay & electron capture |
|---|---|---|---|
| **Observable** | $M_\nu = \sum_i m_i$ | $m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$ | $m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$ |
| **Present upper limit** | 0.12 eV (0.064 eV) | 0.156 eV | 0.45 eV |
| **Model dependence** | Multi-parameter cosmological model | - Majorana ν<br>- contributions other than m(ν)?<br>- nuclear matrix elements, $g_A$ | **Direct,** only kinematics; no cancellations in incoherent sum |

*T. Schwetz-Mangold, T 63.1, Thu. 11:00*
*D. Gruen, T 63.3, Thu. 12:00*

This talk

# Direct mass experiments

Direct, model-independent access to neutrino mass

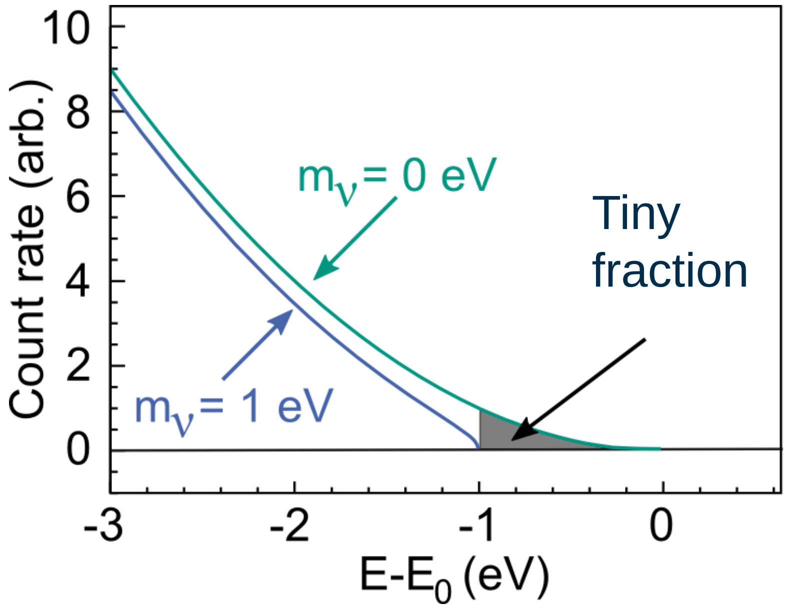
## $\beta^{(-)}$ decay

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

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

$$X \rightarrow Y + e^- + \bar{\nu}_e$$

Measurement of kinetic energy of electron




## Electron capture

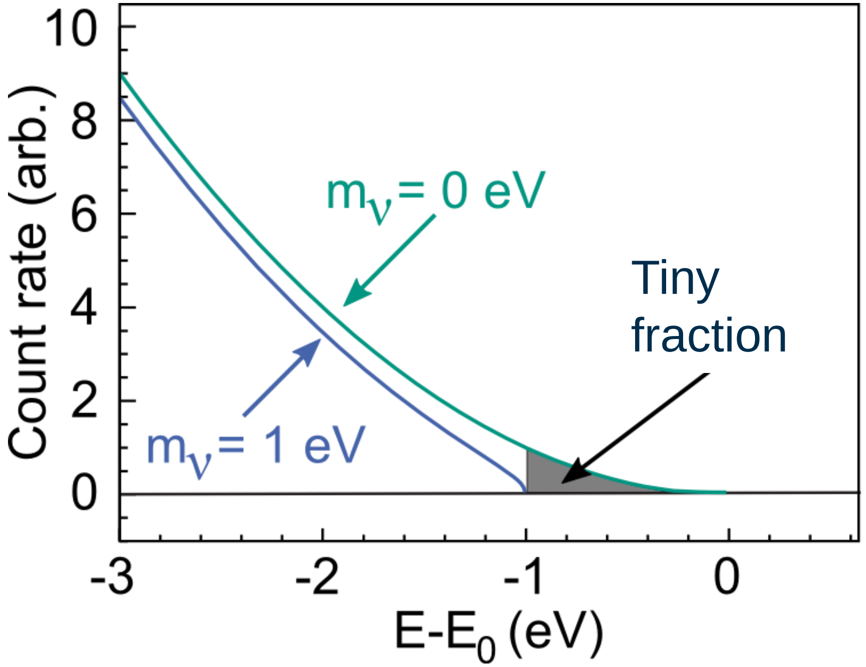
$$X + e^-(\text{shell}) \rightarrow Y^* + \nu_e \qquad Y^* \rightarrow Y + E_C$$

Measurement of internal excitation of daughter atom

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

# Challenges for achieving mass low sensitivity

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




**Low kinematic endpoint, high decay rate**

| | **$\beta$-decay** | **Electron capture** |
|---|---|---|
| Chosen isotope | $^3$H = T | $^{163}$Ho |
| Endpoint | 18.6 keV | 2.8 keV |
| Half life | 12.3 years | 4570 years |
| Typ. production | n-capture in $D_2O$ | n-irradiation of $^{162}$Er |

**High signal (→ statistics)**
**Low background (→ statistics)**

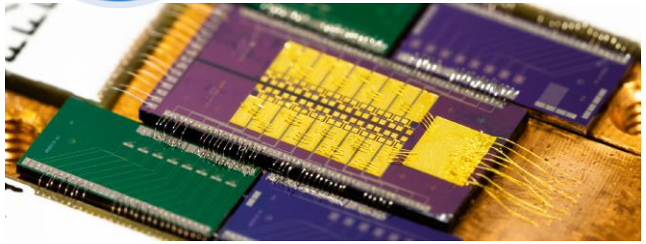
**High energy resolution (→ sensitivity)**
**Low and quantified systematic effects**

# Established measurement principles

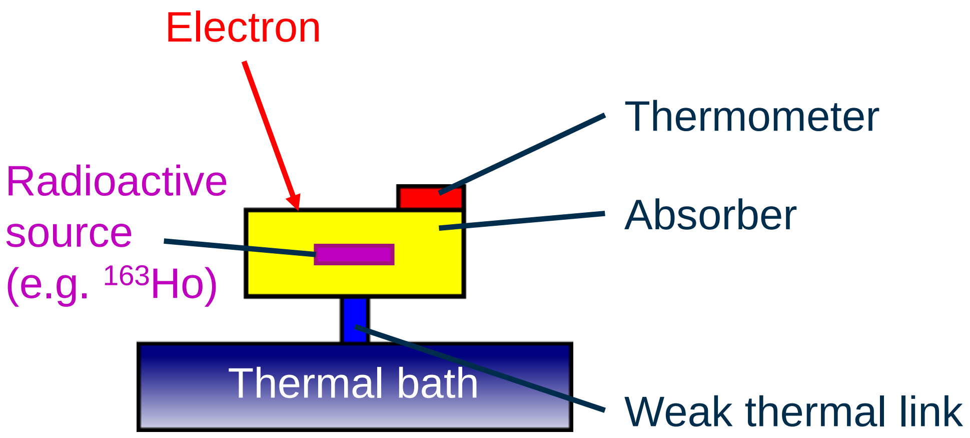
## Calorimeters

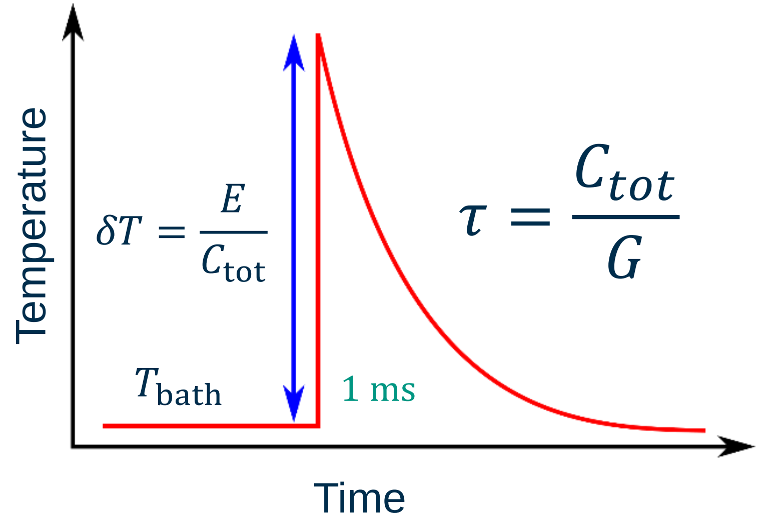
- Low-temperature micro calorimeters
- Measuring energy by **temperature change**

ECHo HOLMES



# Quantum sensors as high resolution differential detectors



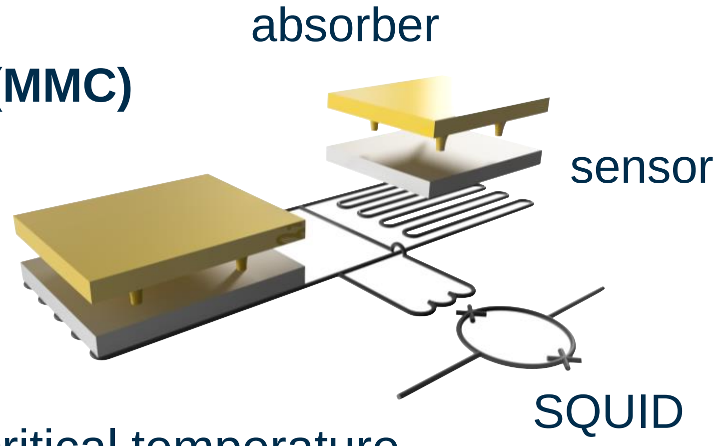

- **tiny heat capacity ($C_{tot}$) → strong temperature signal**
- **low temperature ($T_{bath}$) → low noise**
- **low activity (or rate) per pixel → no pile up**

## Advantages

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

## Metallic Magnetic Calorimeters (MMC)

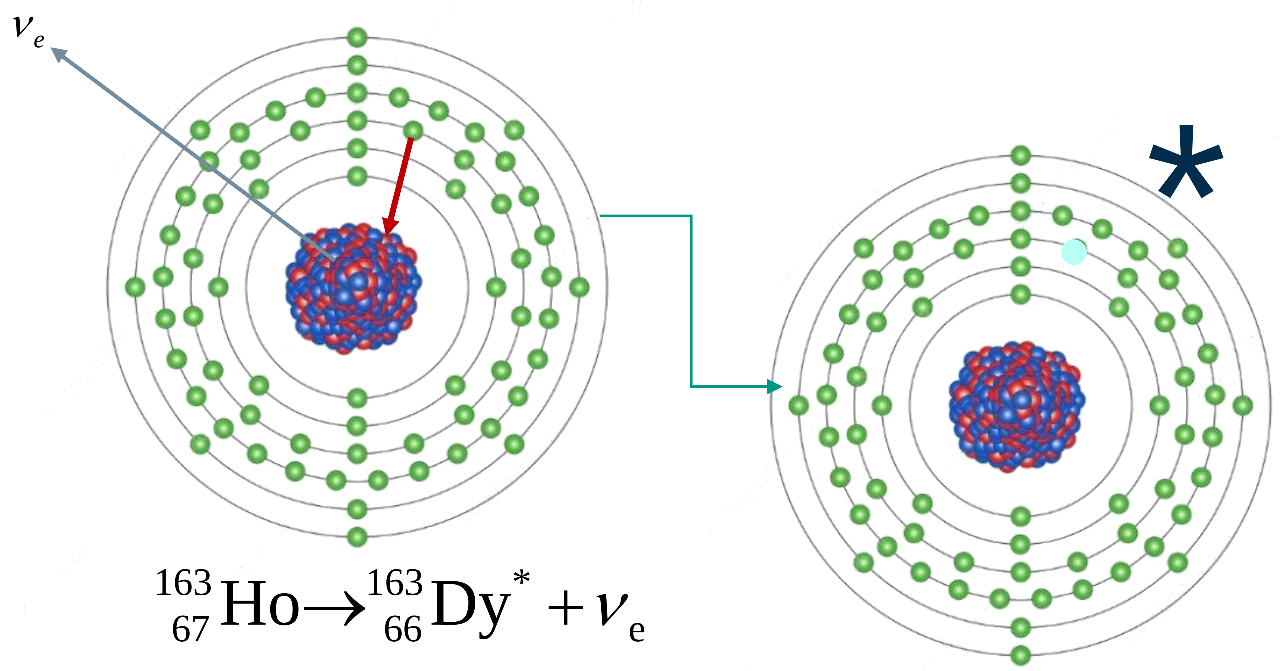
- Temperature-dependence in sensor magnetization




## Transition-Edge Sensor (TES)

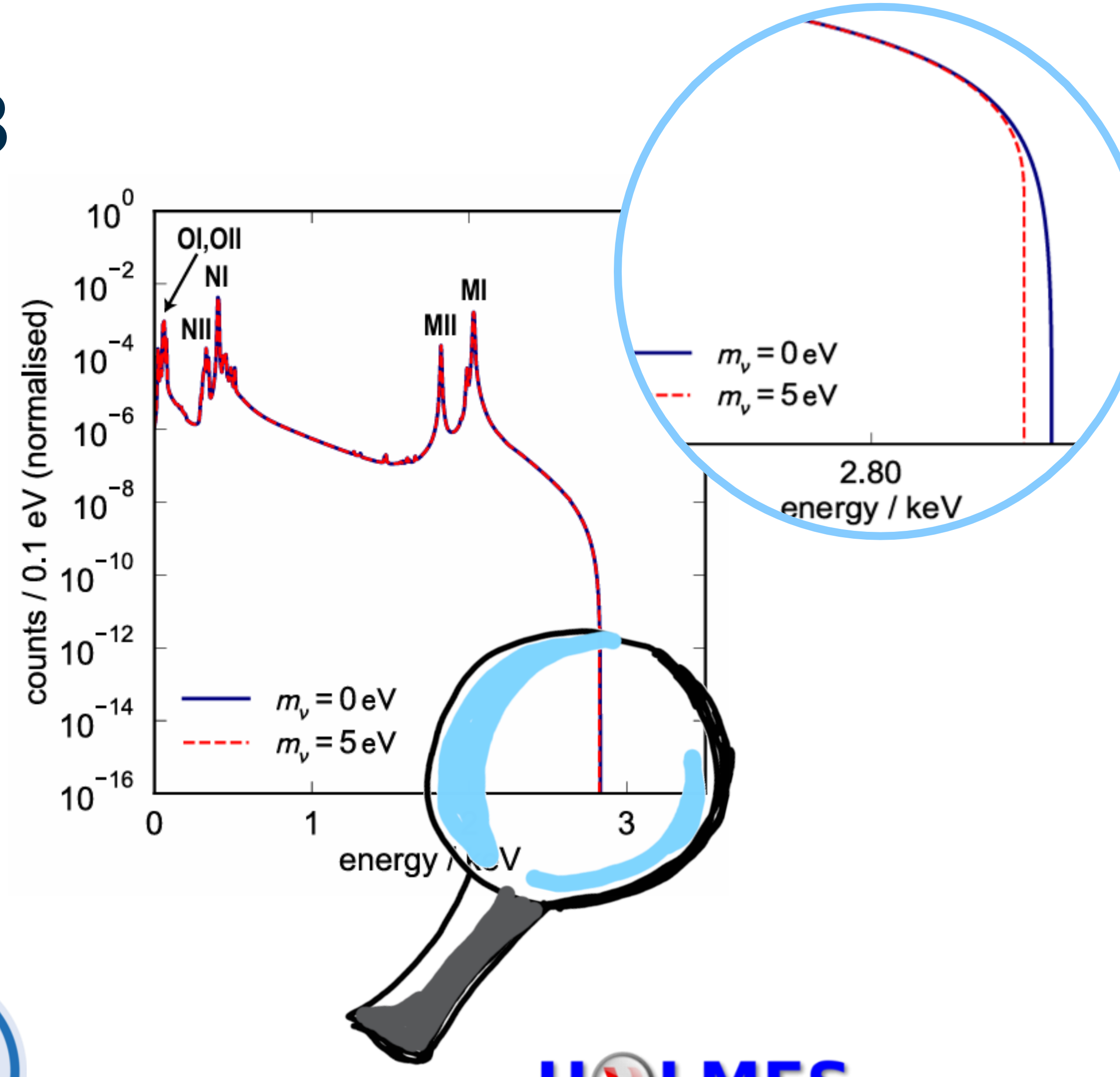
- Strong resistivity change near critical temperature of superconductor

# Electron capture in Holmium-163




$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$




- $\tau_{1/2}$ ≅ 4570 years (2*10[11] atoms for 1 Bq)
- $Q_{EC}$ = (2863.2 ± 0.6) eV

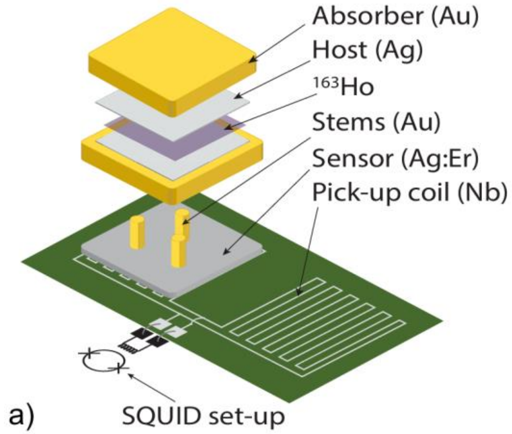
Ch. Schweiger et al.,
*Nat. Phys.* **20**, 921–927 (2024)

ECHo https://www.kip.uni-heidelberg.de/echo/

HOLMES https://holmes1.mib.infn.it/holmes/

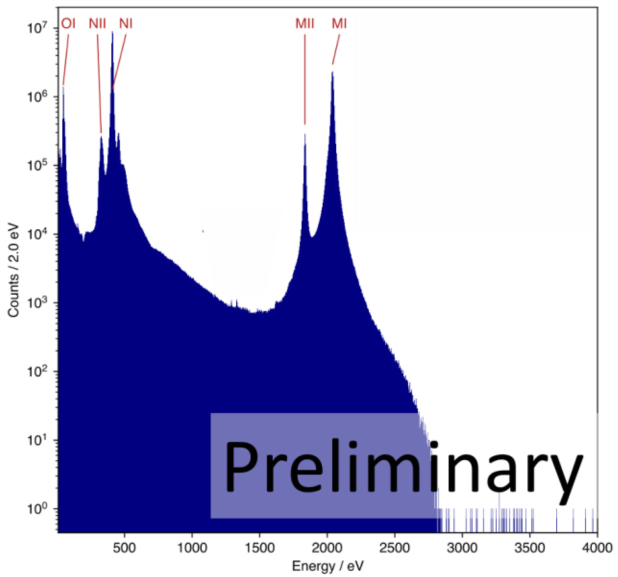
# Ongoing phases of holmium experiments

## Metallic Magnetic Calorimeters (MMC)



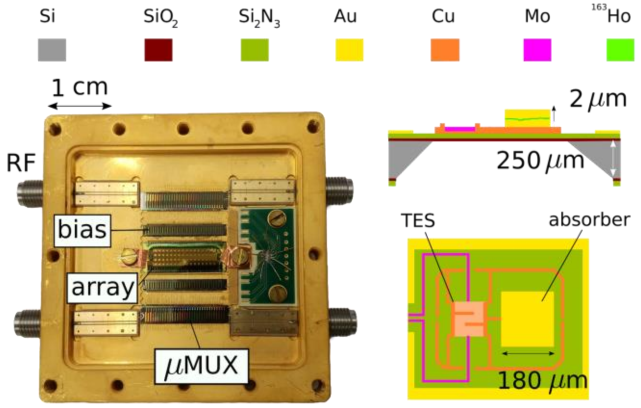

### ECHo-1K (2024)

- ~ 60 pixels
- ~ 1 Bq / pixel
- ~120x10$^6$ events
- 8.3 eV resolution
- Previous limit
  m < 150 eV
  Eur. Phys. J. C (2019) 79:1026



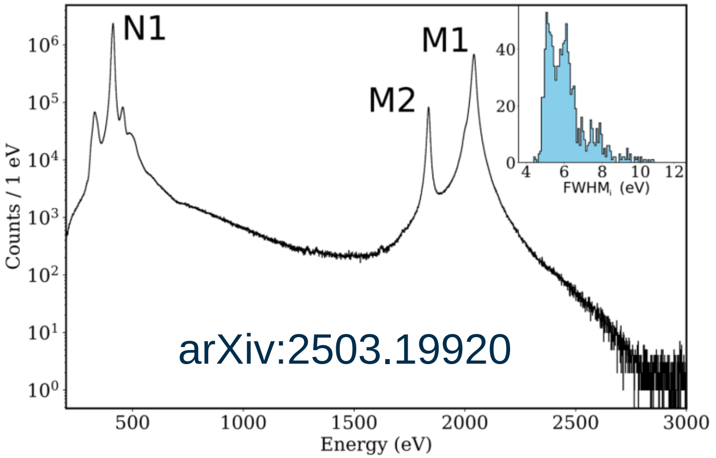

$m(\nu_e)$ < 19 eV 90% C.L.

## Multiplexed Transition Edge Sensors (TES)




### Run 7 / 9 (2024)

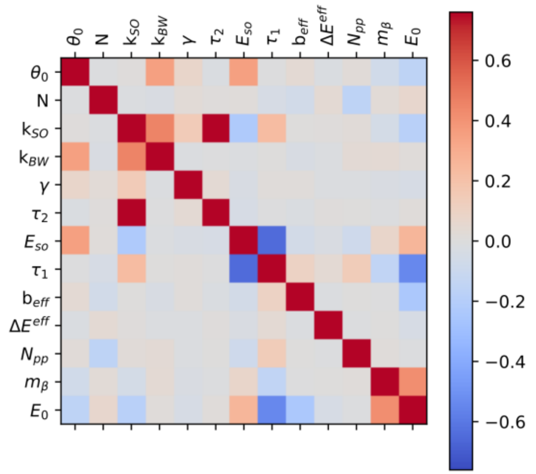
- 48 pixels multiplexed
- 15 Bq (tot)
- ~70x10$^6$ events
- 6 eV resolution



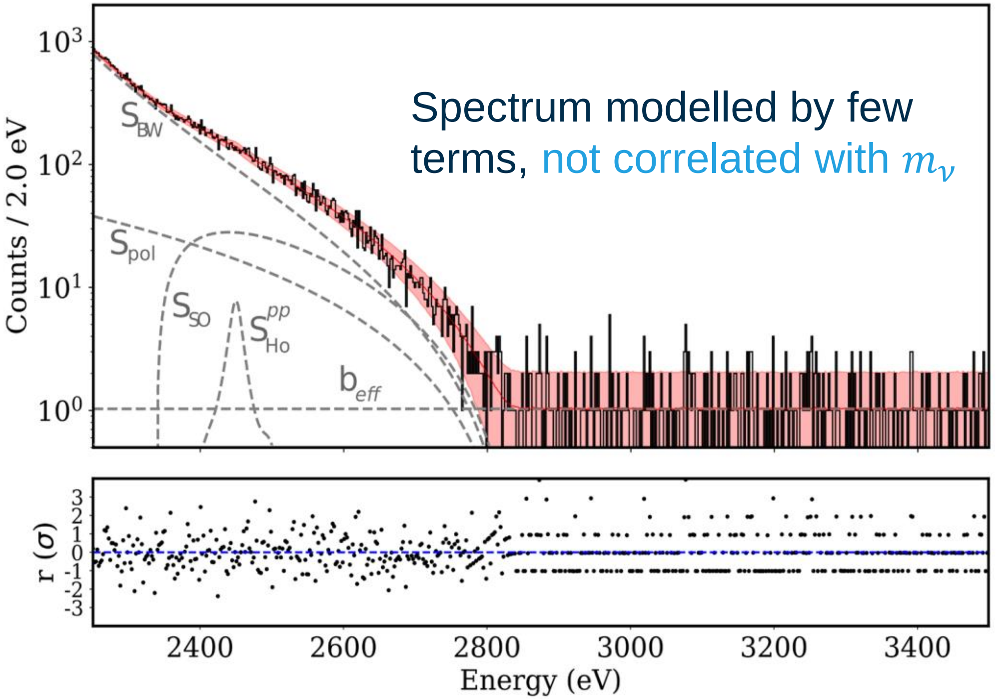
# New results and next steps

HOLMES

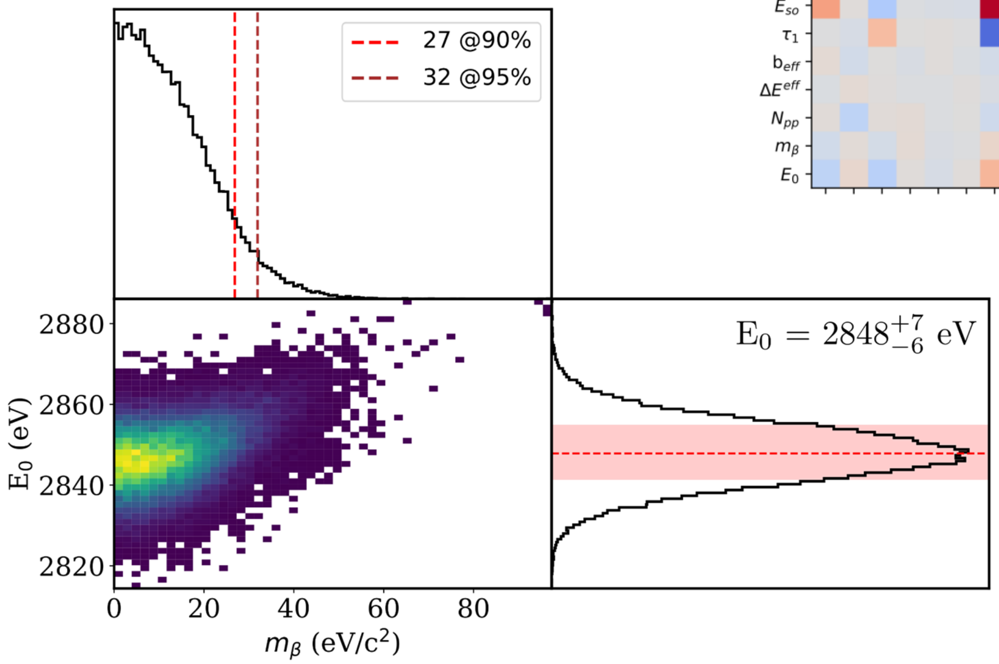
**Pearson correlation coefficients between parameters of the fit**




Combination of 1000 calibrated spectra




Spectrum modelled by few terms, not correlated with $m_\nu$



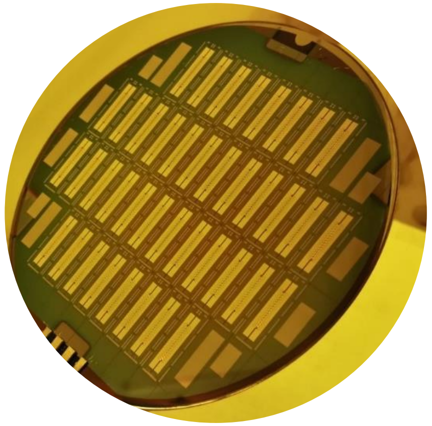

arXiv:2503.19920

- Bayesian 13 parameters analysis yields **$m_\nu < 27$ eV (90% C.L.)** and $E_0 = 2848 \pm 7$ eV
- Next: **prove** that a $m_\nu$ experiment for **sub 0.1 eV sensitivity is doable:**
  - Reduce cost per channel, increase multiplexing factor
  - Reducing the critical temperature of the TES → higher resolution



KIT

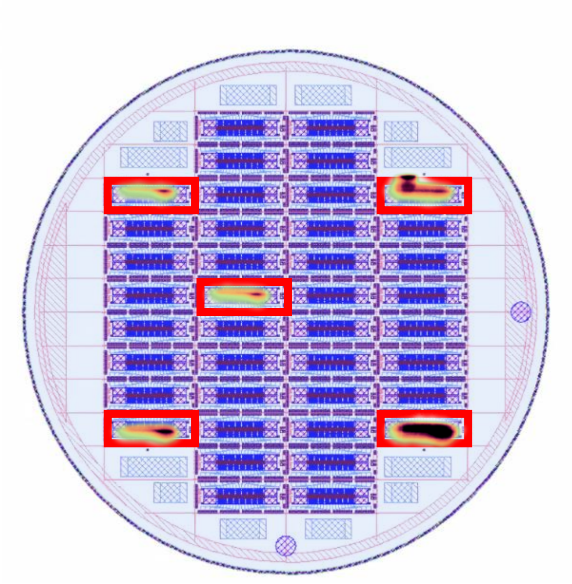
# Next steps



**ECHo-XX**

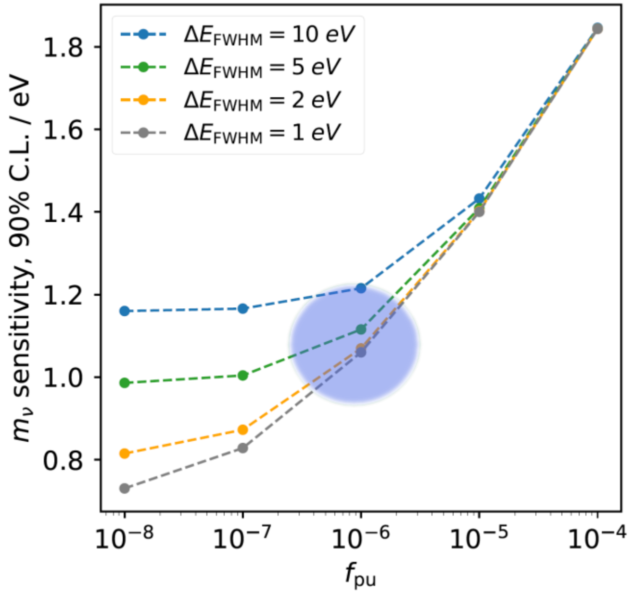
**Aim: $m(\nu_e) < 1$ eV 90% C.L.**

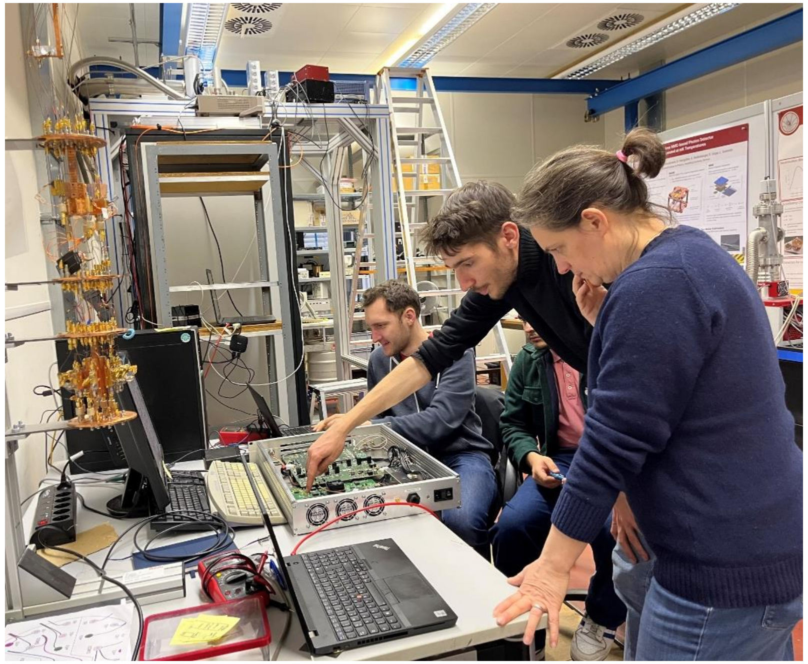
Activity per pixel: 10 Bq
Number of detectors: > 20000
Readout: microwave SQUID multiplexing



- Fabrication of 10x 3'' wafer with 40 chip each
- Implantation of 10 Bq/pixel on wafer scale
- optimization of the multiplexed readout of MMC arrays

number of events = $10^8 \rightarrow 10^{13}$

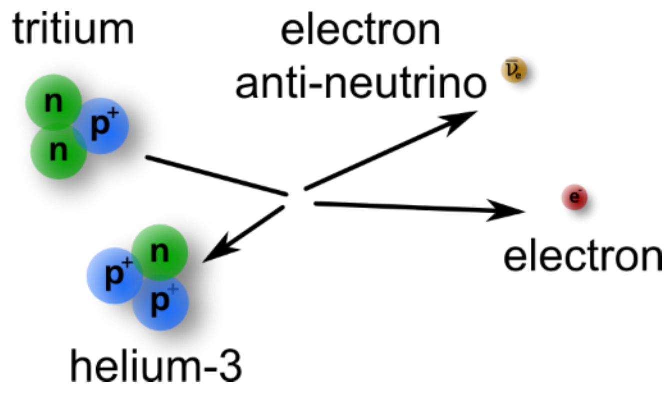


*F. Böhm, T 39.2, Tue 16:30*
*N. S. Buermann, T. 39.5, Tue 17:15*
*L. Calza, T 39.6, Tue 17:30*
*R. Pandey, T 101.5, Fri 10:00*
*R. Jeske, T 101.6, Fri 10:15*

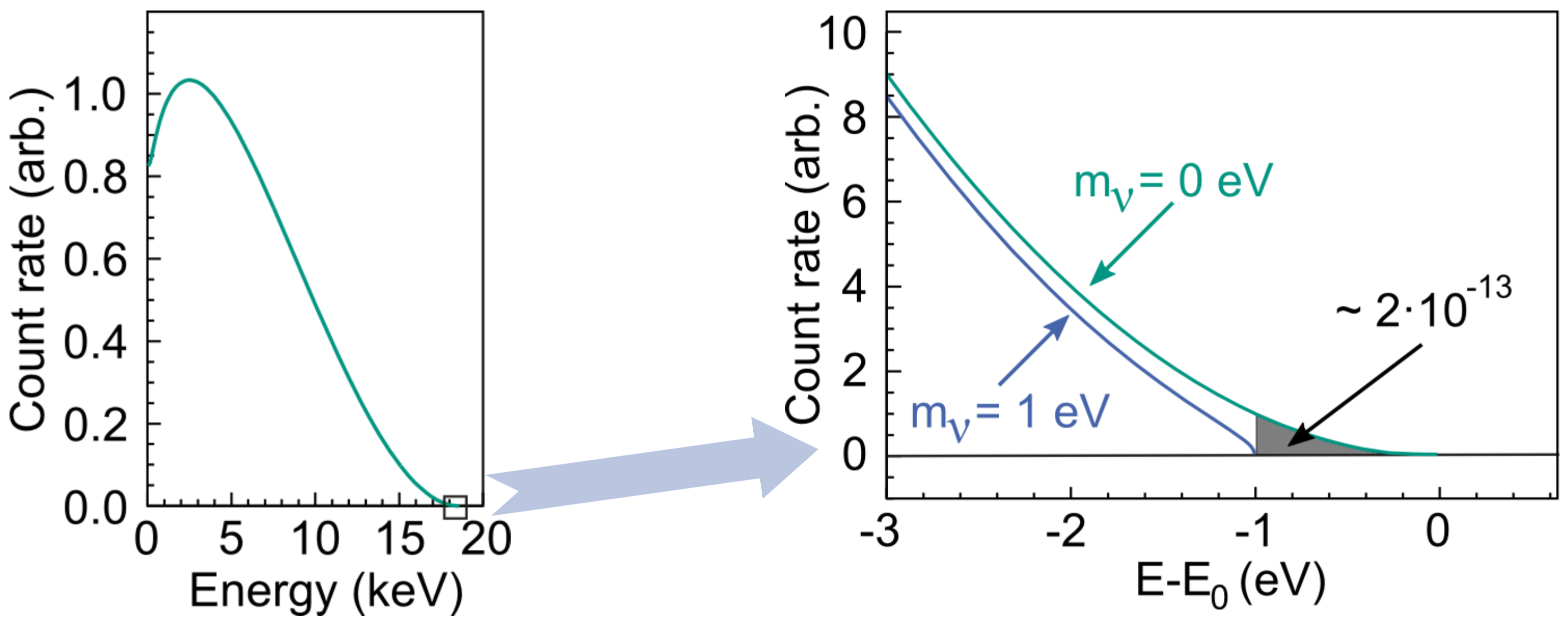
# Tritium beta decay experiments

Direct, model-independent access to neutrino mass




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

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

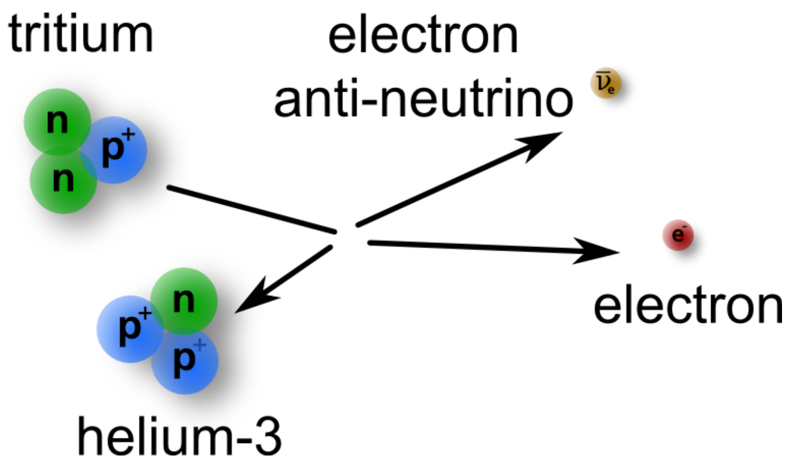



**$E_0$ = 18.6 keV**

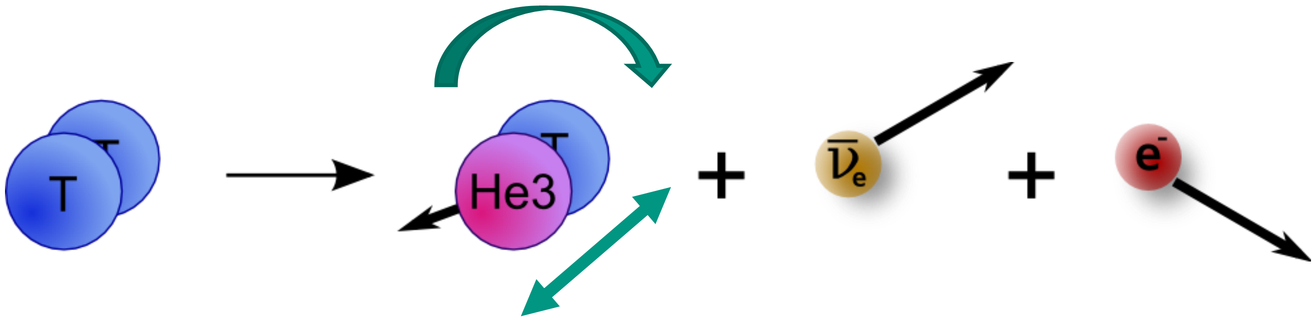
**$T_{1/2}$ = 12.3 y**

# Molecular decay

## Atomic decay

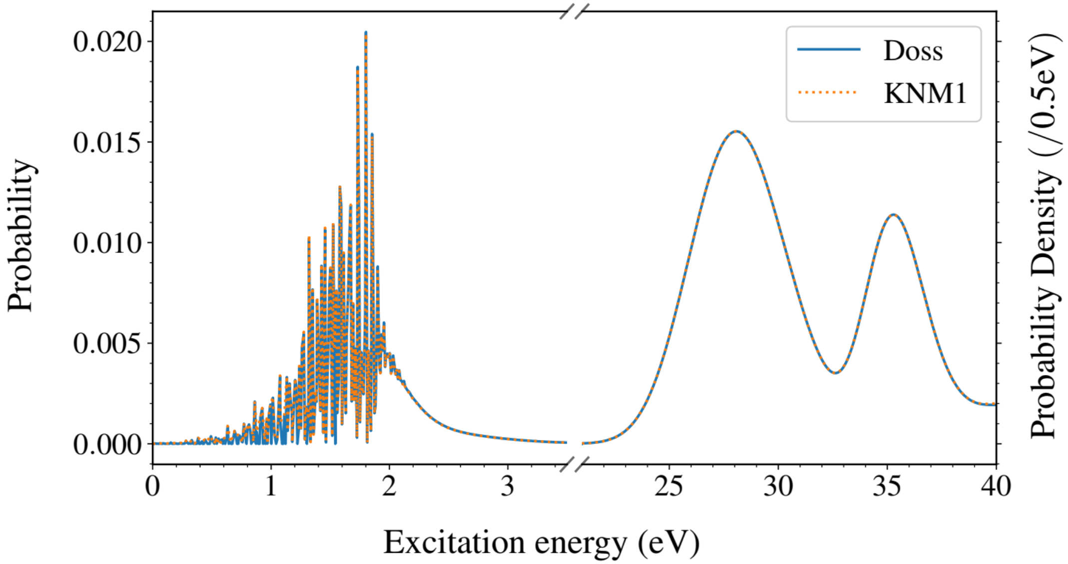



## Decay from a molecule




**+ further inner excitations (rotation / vibration)**

## Final-state distribution



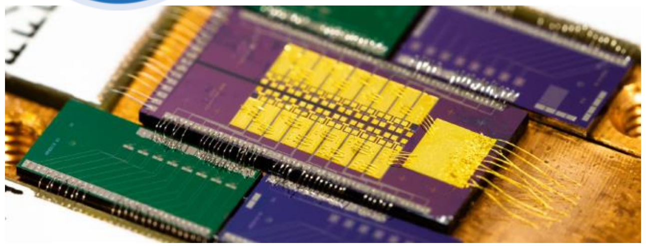

Molecular effects need to be taken into account in neutrino mass analysis

*„model-dependence“*

# Established measurement principles

## Calorimeters

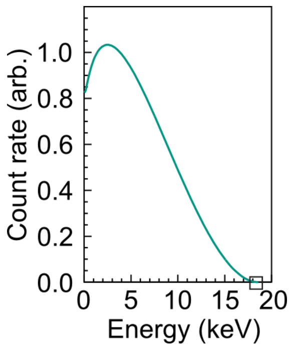
- Low-temperature micro calorimeters
- Measuring energy by **temperature change**

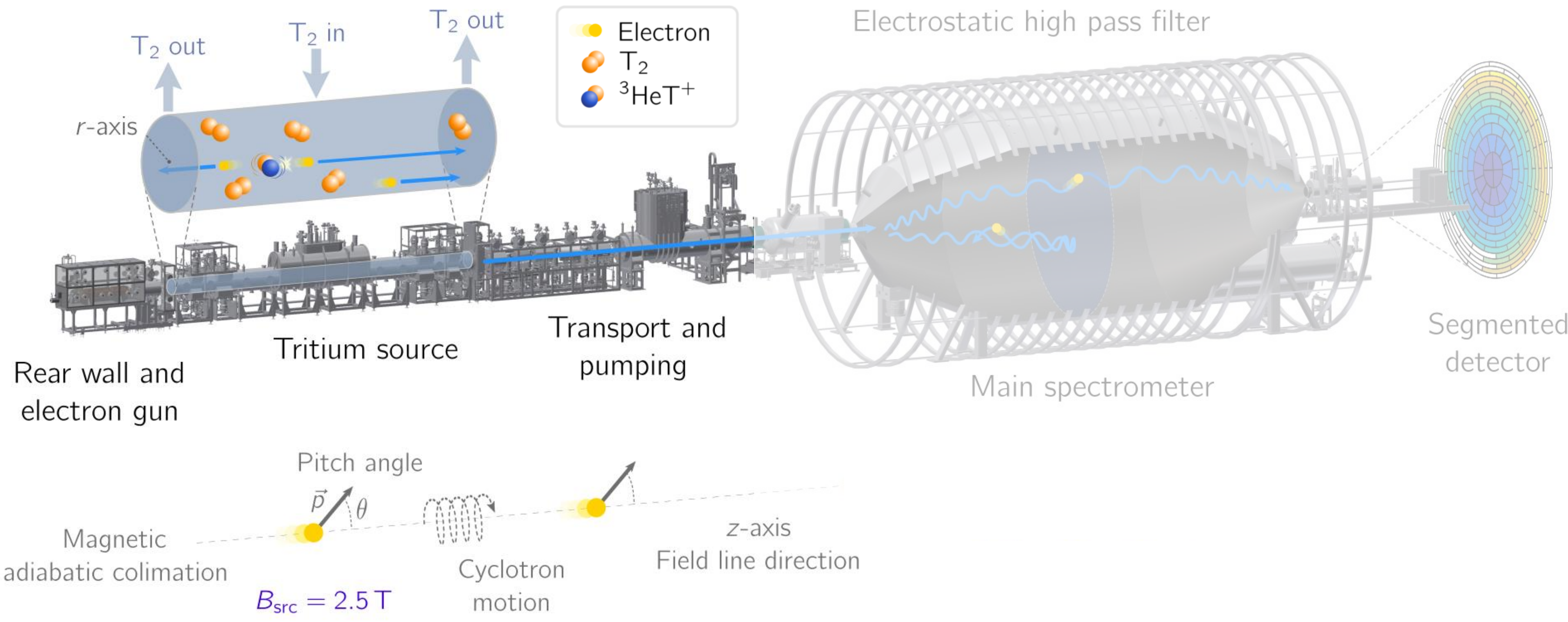


## MAC-E filter

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

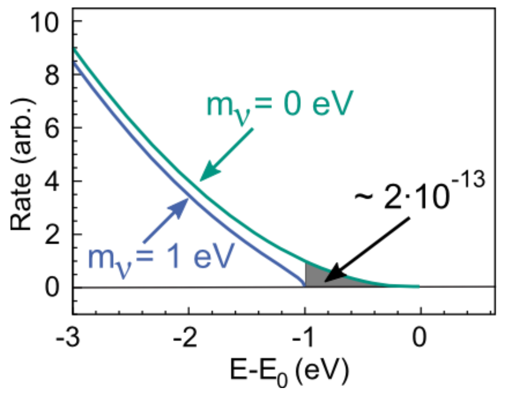
# Windowless gaseous source

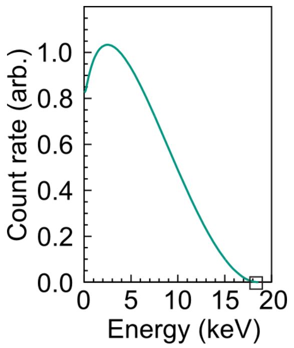


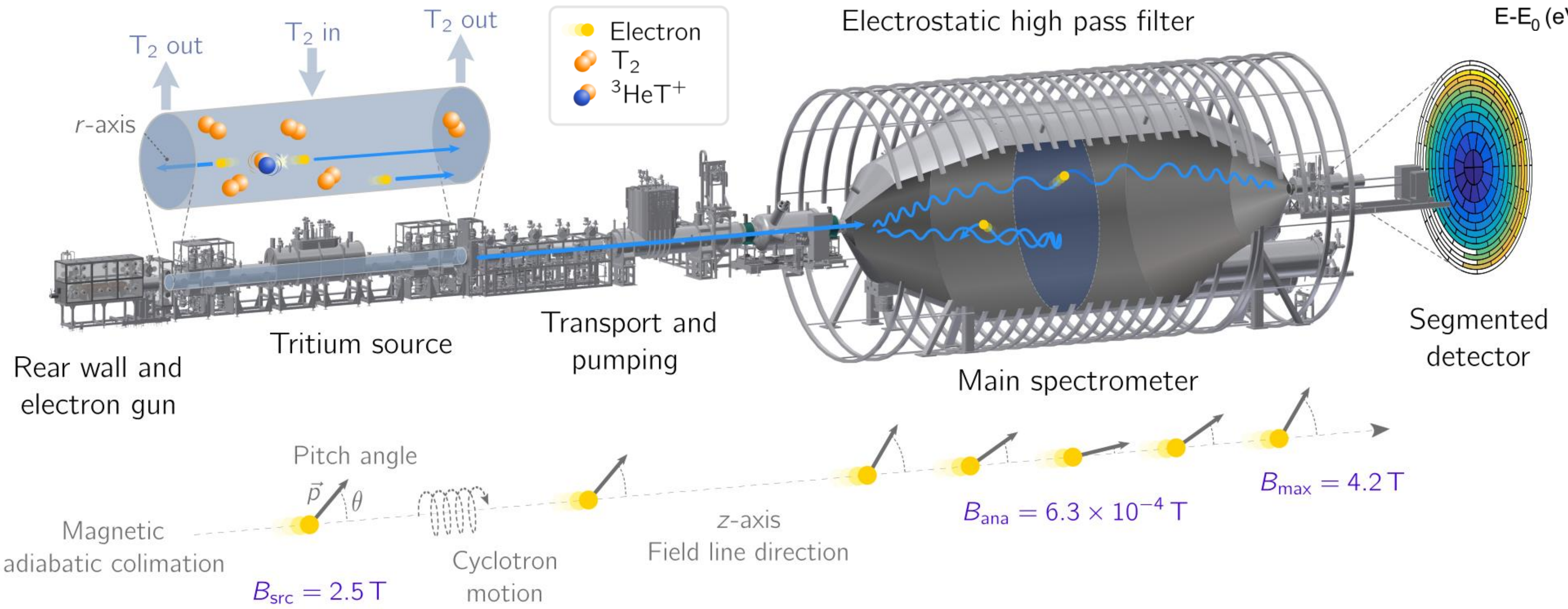



# MAC-E filter principle

Electron transmission
if above filter potential
(Integrating method)



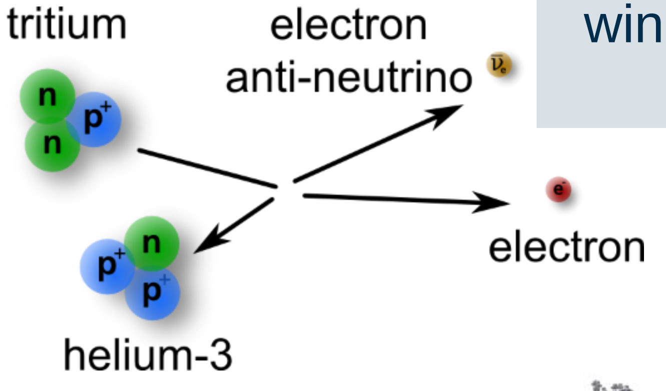




$$\frac{B_{\min}}{B_{\max}} = \frac{\Delta E}{E}$$ → **sharp filter transmission (resolution)**

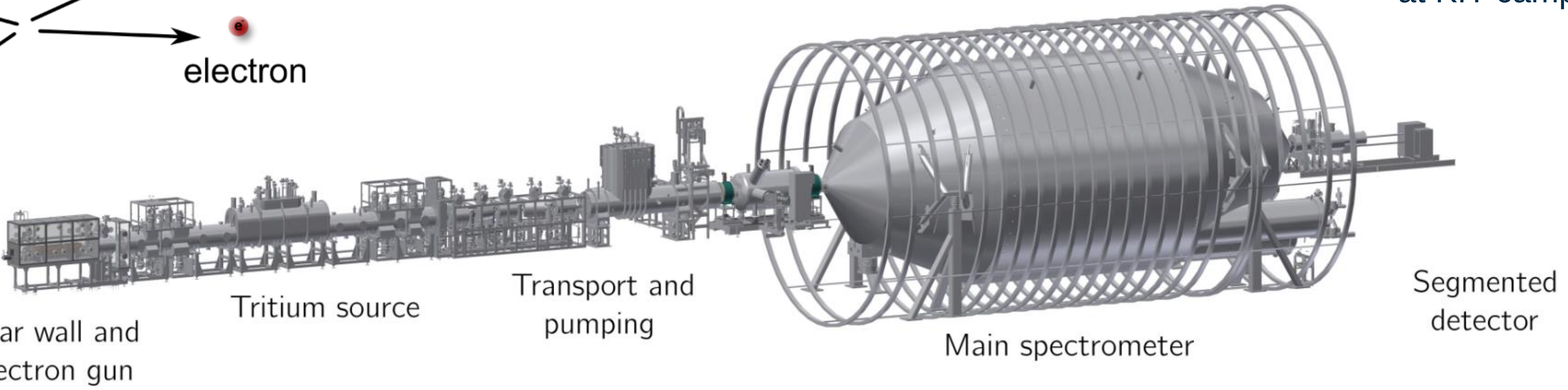
# Karlsruhe Tritium Neutrino Experiment (KATRIN)

https://www.katrin.kit.edu

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




70 m long setup
at KIT campus north




*JINST* **16** T08015 (2021)

high-resolution MAC-E filter with ~ eV energy resolution

**KATRIN's aim: Direct measurement of $m_\nu$ with a sensitivity of 0.3 eV/c²**

# 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
- Closed tritium cycle for recycling and purifying tritium in gram amounts
- > 50 experience scientists, engineers and technicians

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

# KATRIN data releases and neutrino mass results

**2019**: $m_\nu$ < 1.1 eV (90% CL)

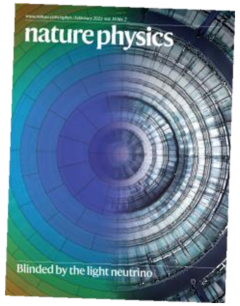
*PRL 123 (2019) 221802*

*PRD 104 (2021) 012005*


**2022**: $m_\nu$ < 0.8 eV (90% CL)

- ~6 x $10^6$ counts

*Nature Phys. 18 (2022) 160*

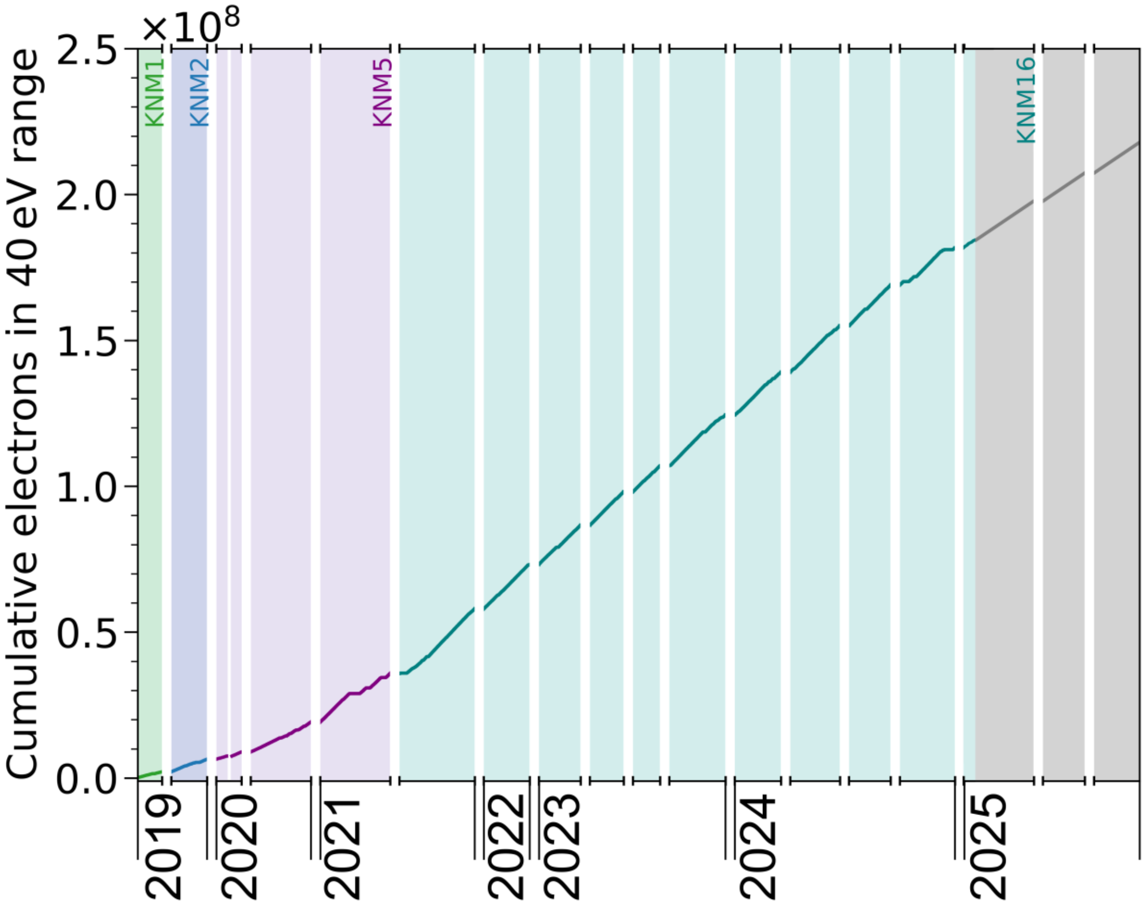



**2024: Data in latest analysis**

- 259 measurement days
- 1757 $\beta$-scans
- ~36 x $10^6$ counts
- Meticulous measurements to quantify and improve systematics

*L. Laschinger, T 81.2, Thu. 16:30*
*B. Bieringer, T 102.5, Fri. 10:00*
*J. Storek, T 102.6, Fri. 10:15*

## Reliable long-term data-taking of KATRIN & TLK

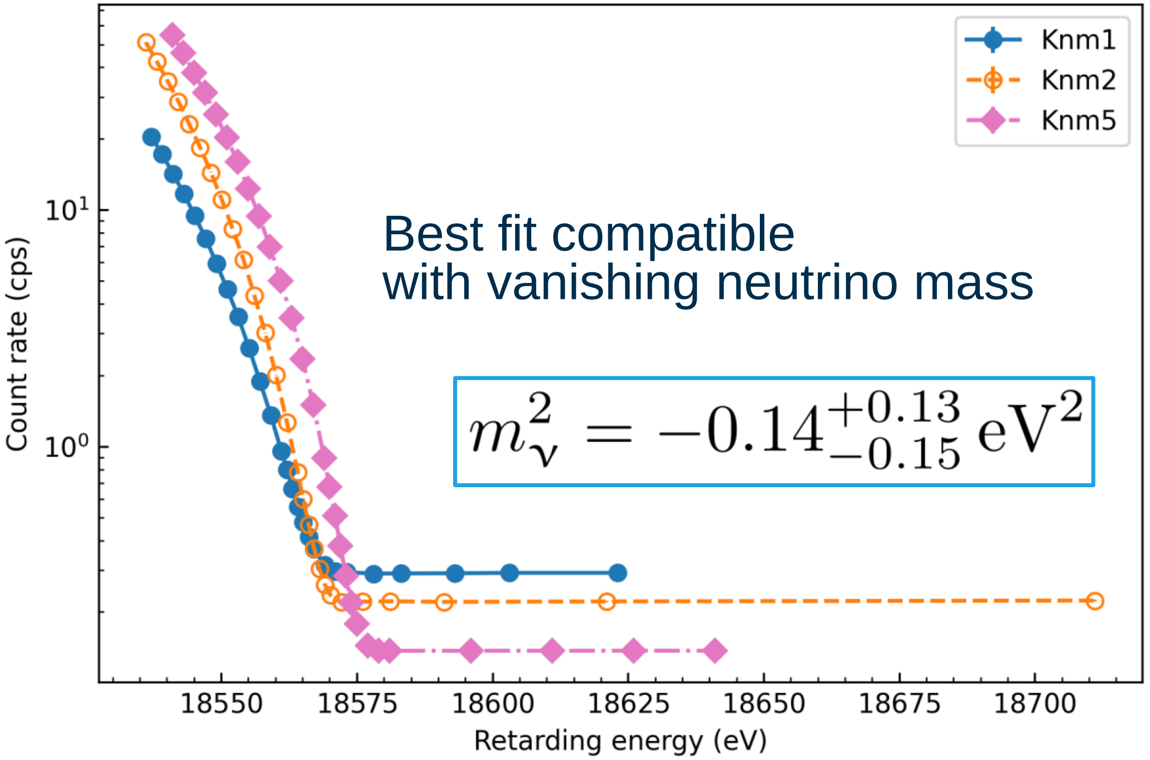


# Best fit and upper limit

*J. Plößner, T 39.1, Tue. 16:15*
*A. Schwemmer, T 101.3, Fri. 9:30*

*H. Henke, T 16.5, Mon. 17:45*
*Ch. Köhler, T 101.1, Fri. 9:00*
*J. Lauer, T 23.7, Tue. 17:45*

## Improvement of spectral quality




Best fit compatible with vanishing neutrino mass

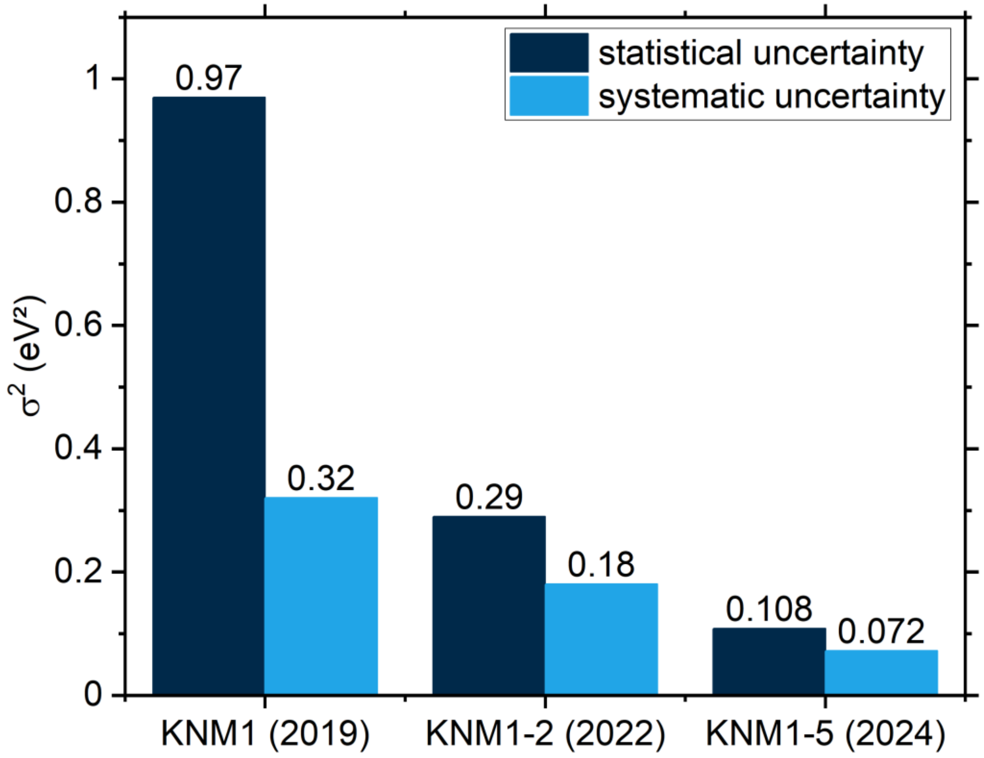
$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$$

Resulting in most stringent upper limit

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

*KATRIN 2024, arXiv:2406.13516 (accepted for publication)*

## Improvement of statistics and systematics




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

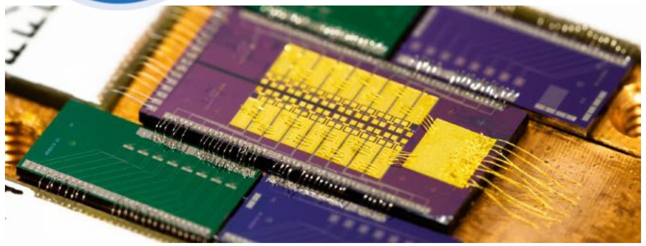
# Established measurement principles

## Calorimeters

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

ECHo

HOLMES



## MAC-E filter

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

KATRIN – Karlsruhe Tritium Neutrino Experiment

## CRES

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

PROJECT 8

QTNM – Quantum Technologies for Neutrino Mass

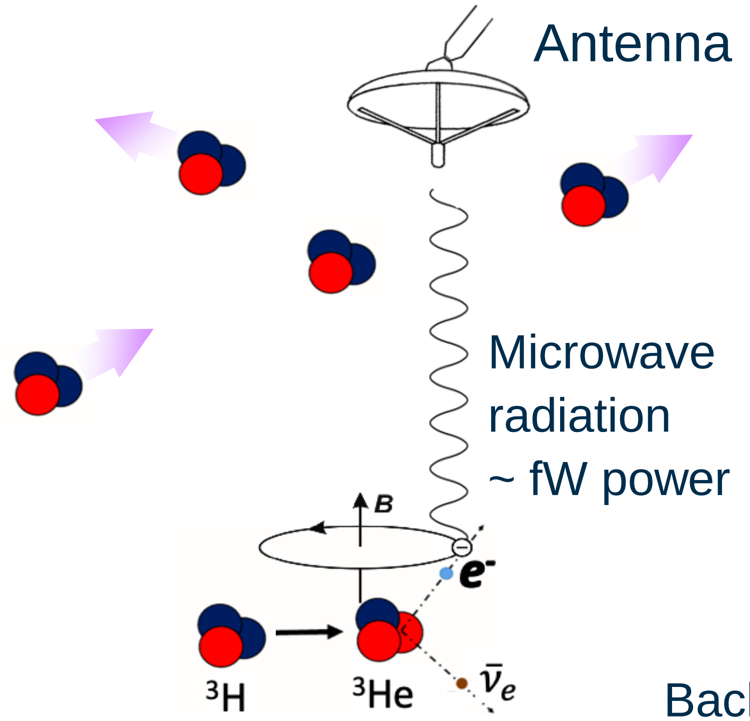
PTOLEMY



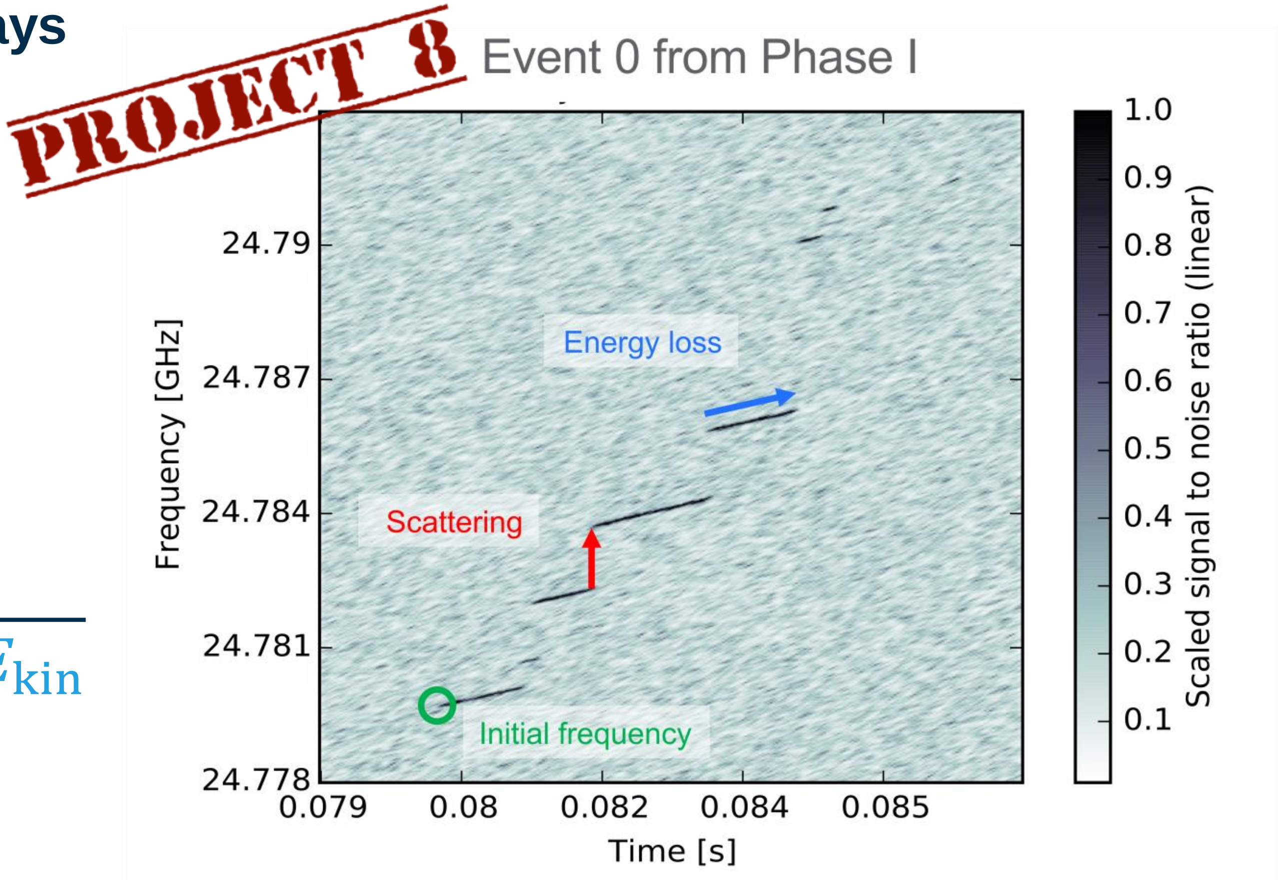
KIT

# Cyclotron Radiation Emission Spectroscopy

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




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




*PRL. 114, 162501 (2015)*

Background B-field determines the operational frequency

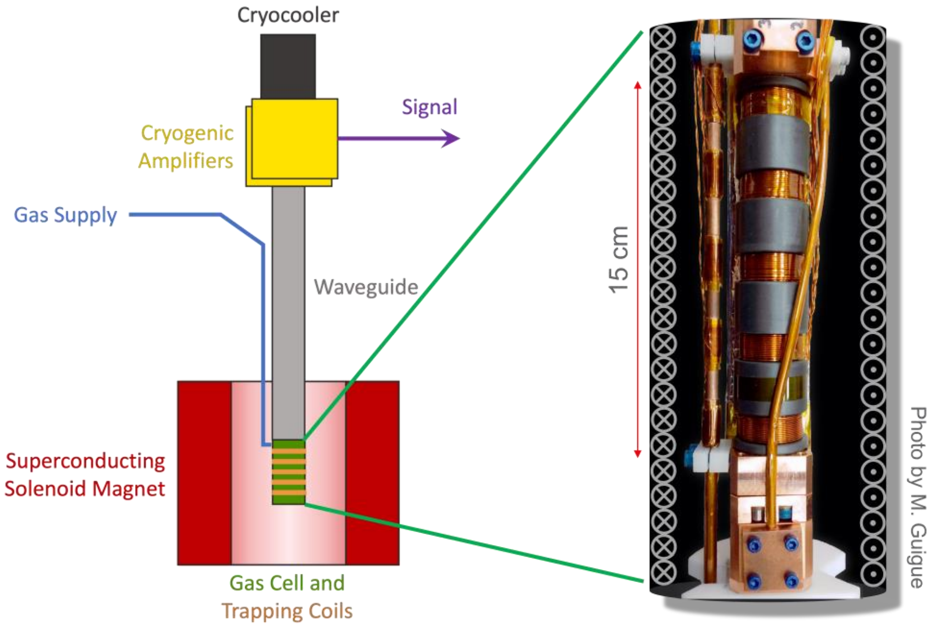
*B. Monreal and J. Formaggio, Phys. Rev D80 (2009) 051301*

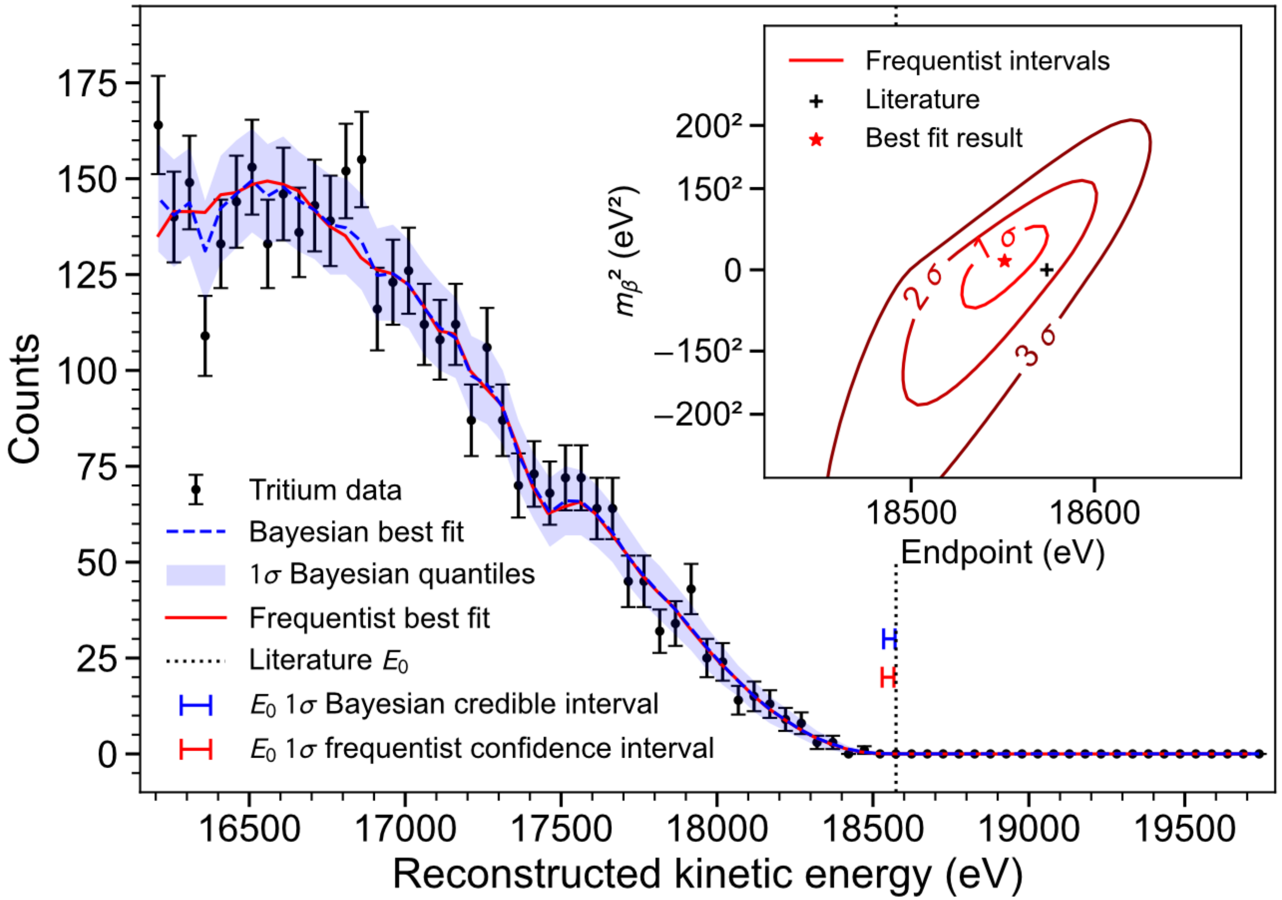
# Project 8 – Results



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

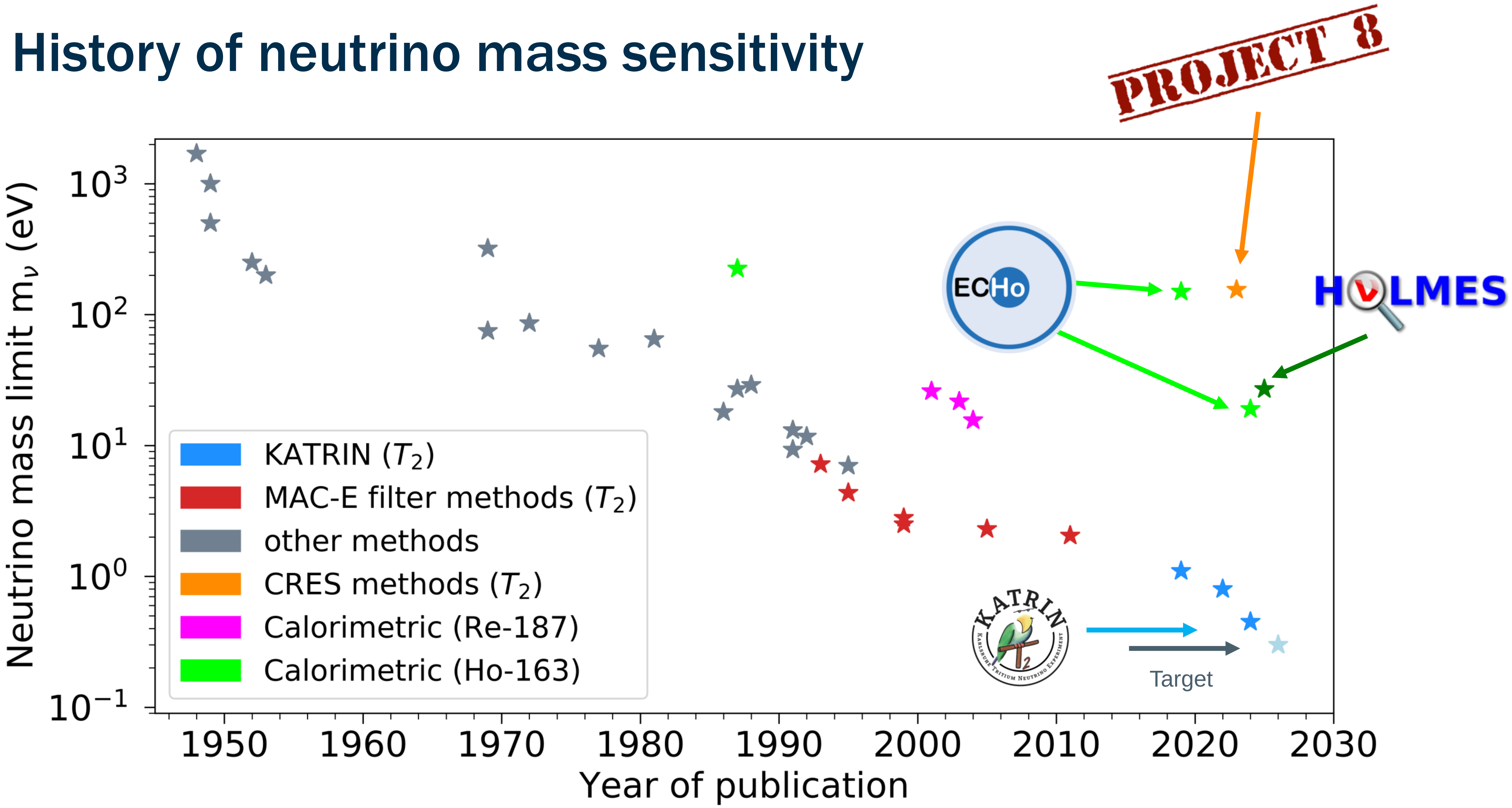
**Phase II:** First use of CRES for tritium beta decay electron spectroscopy
→ Neutrino mass limit ($m_\beta < 155$ eV)



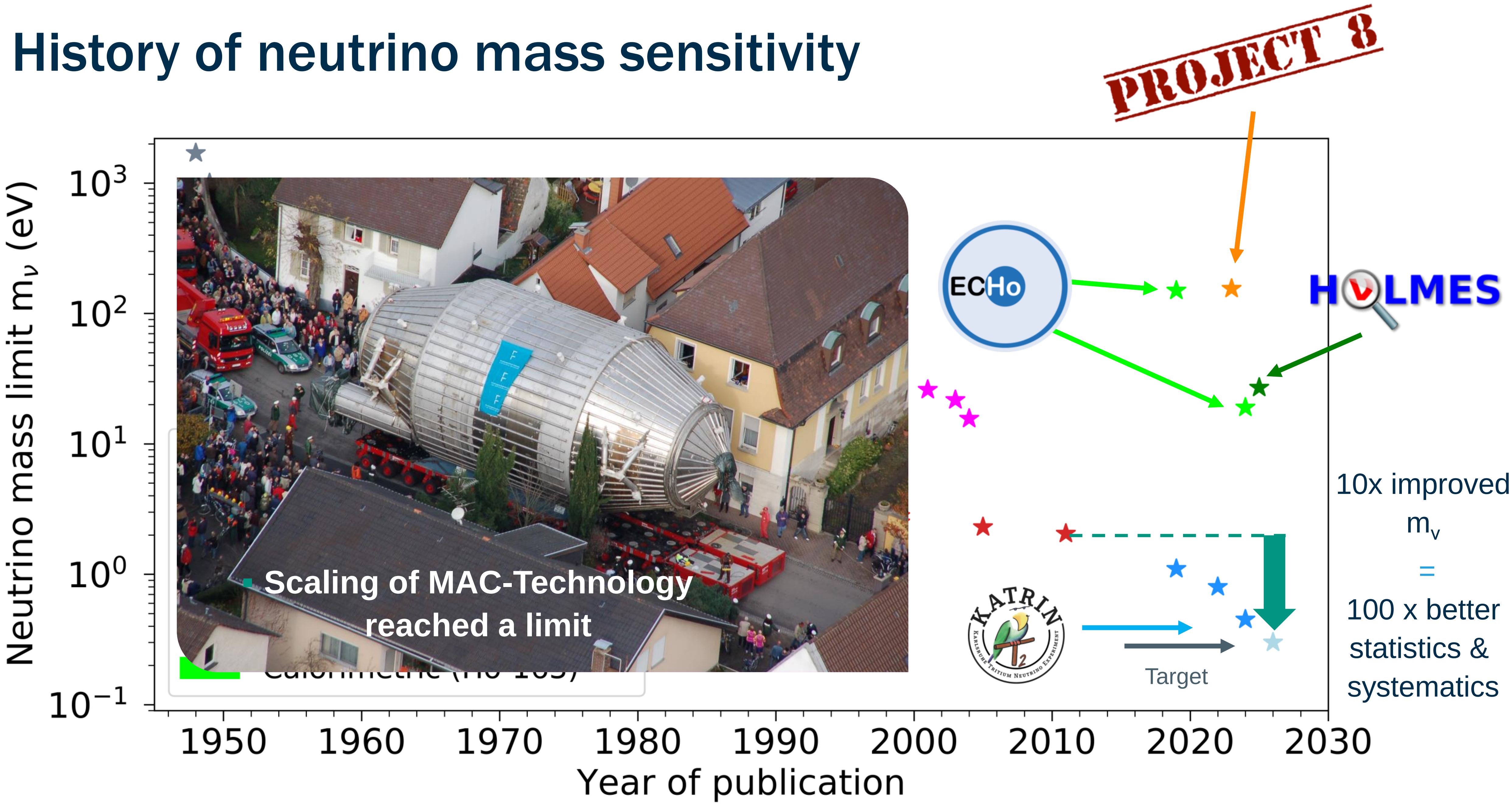




*PRL 131, 102502 (2023)*

# History of neutrino mass sensitivity

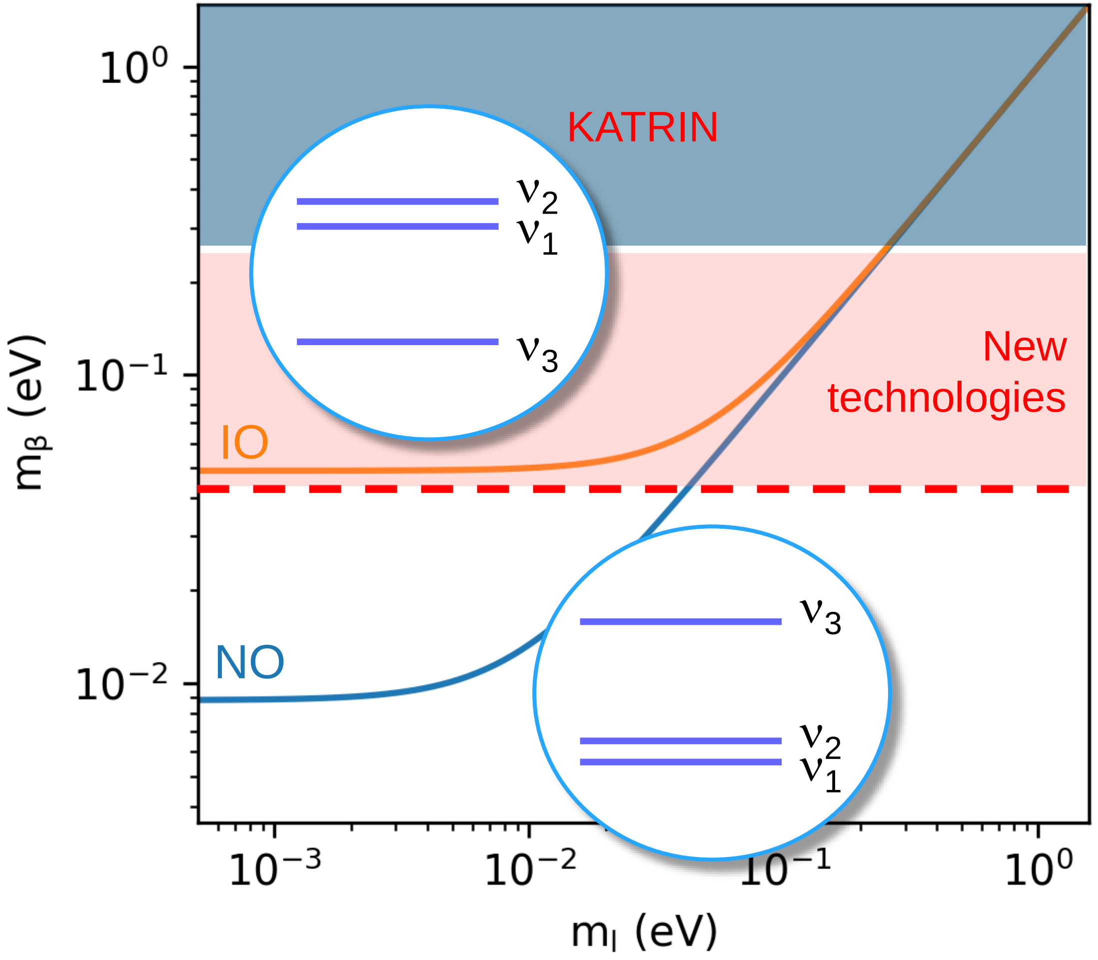


# History of neutrino mass sensitivity




10x improved $m_\nu$ = 100 x better statistics & systematics

# 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

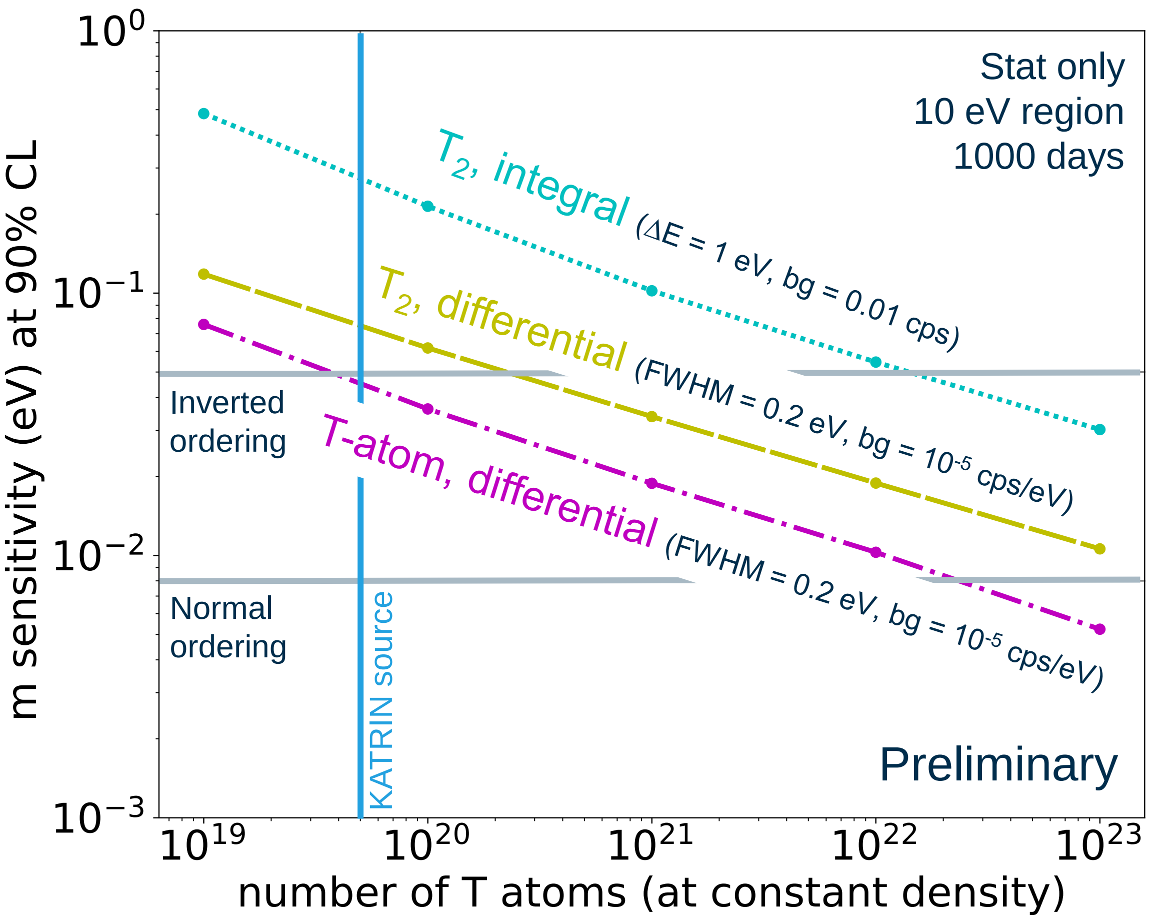
shared aim by

KATRIN PROJECT 8 PTOLEMY QTNM



KIT

# Improving neutrino mass sensitivity

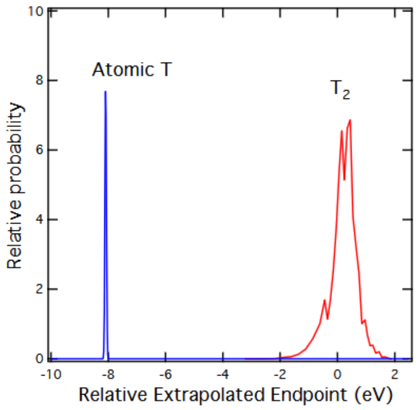



## Differential measurement (FWHM < 1 eV)

- Better use of statistics
- Lower background

## Atomic tritium

- Avoid broadening (~ 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 (~ 7 years)

*S. Heyns, T 101.4, Fri. 9:45*

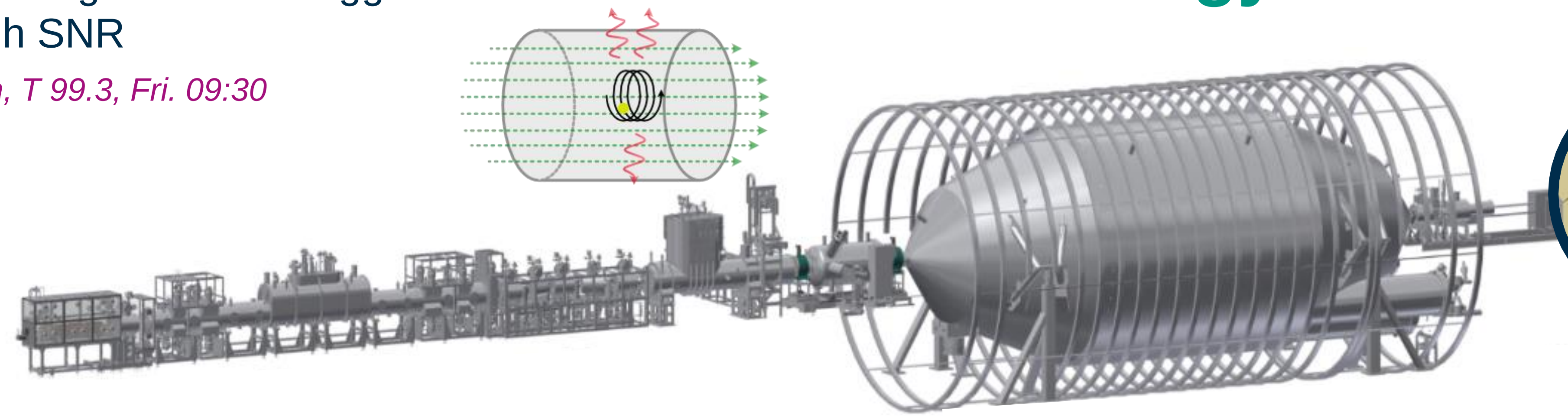
# KATRIN as R&D facility for differential detector

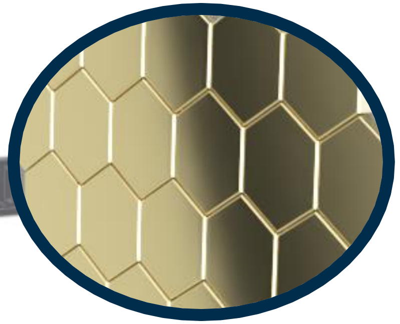
**Option 2**
**Time-of-flight via electron tagging**

- 1000 Hz single electron tagger with high SNR

*R. Salomon, T 99.3, Fri. 09:30*

**Differential detector technology**






- eV resolution for **differential** detection
- **immune to** MAC-E filter **backgrounds**

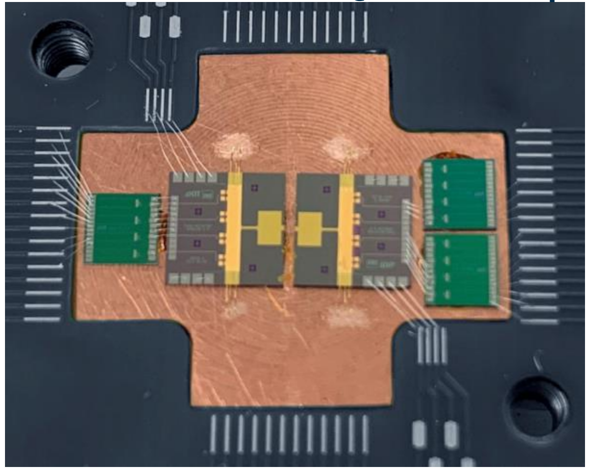
**Option 1**
**Micro-calorimeters / Quantum sensor**

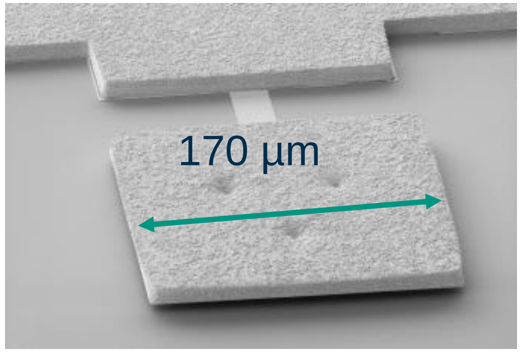
- Operation in **magnetic field (~20 mT)**
- Coupling of **mK cryo-platform** with RT spectrometer

*N. Kovač, T 102.4, Fri. 9:45*

# ELECTRON: e⁻ spectroscopy with quantum sensors

8 channel detector chips
& front-end SQUID chips

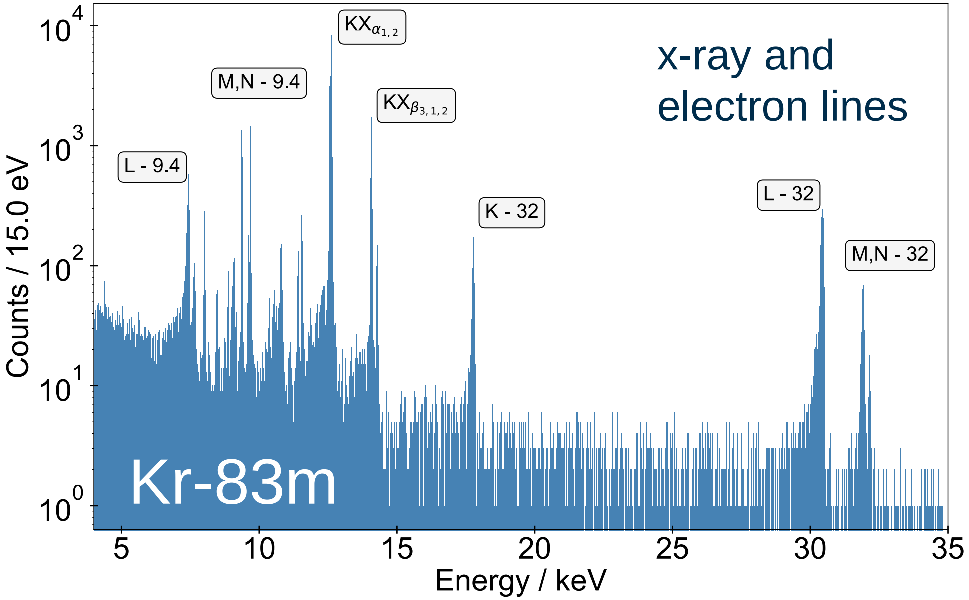





KIT-IMS (Kempf group)

## Metallic Magnetic Calorimeters (MMC)

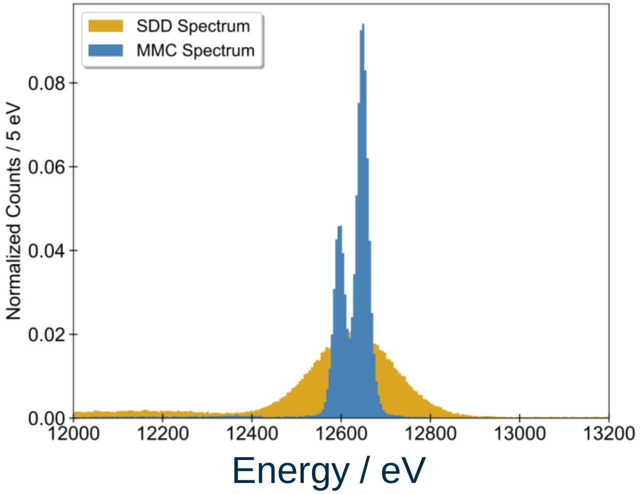
*Kovač et al. 2025, arXiv:2502.05975*

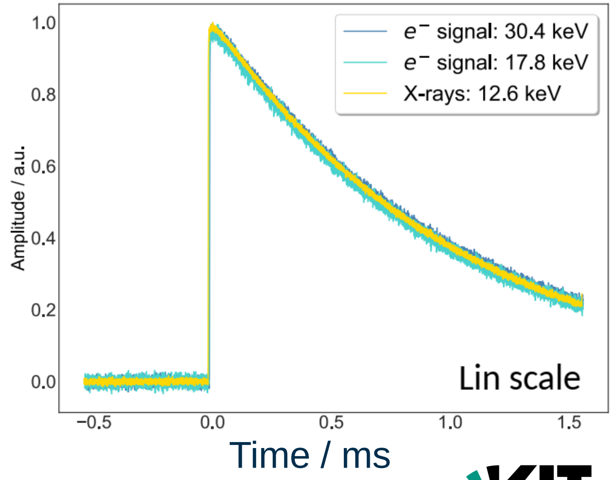



Calorim**. Kr-83m spectrum @ highest resolution**
Next: **tritium spectroscopy**

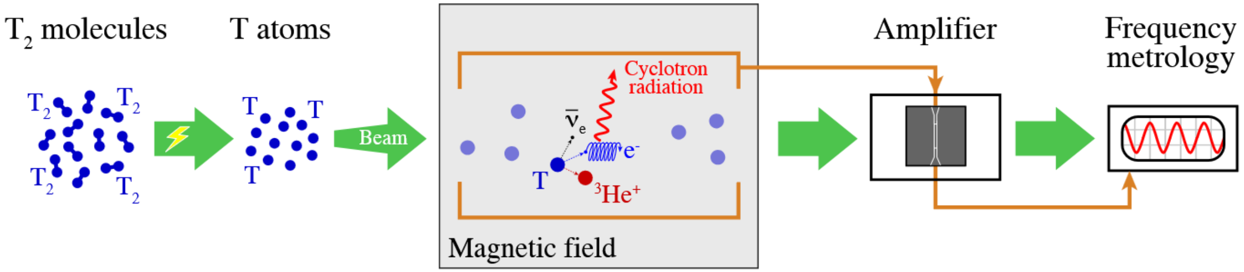
*N. Kovač, T 102.4, Fri. 9:45*

FWHM ~ 25 eV



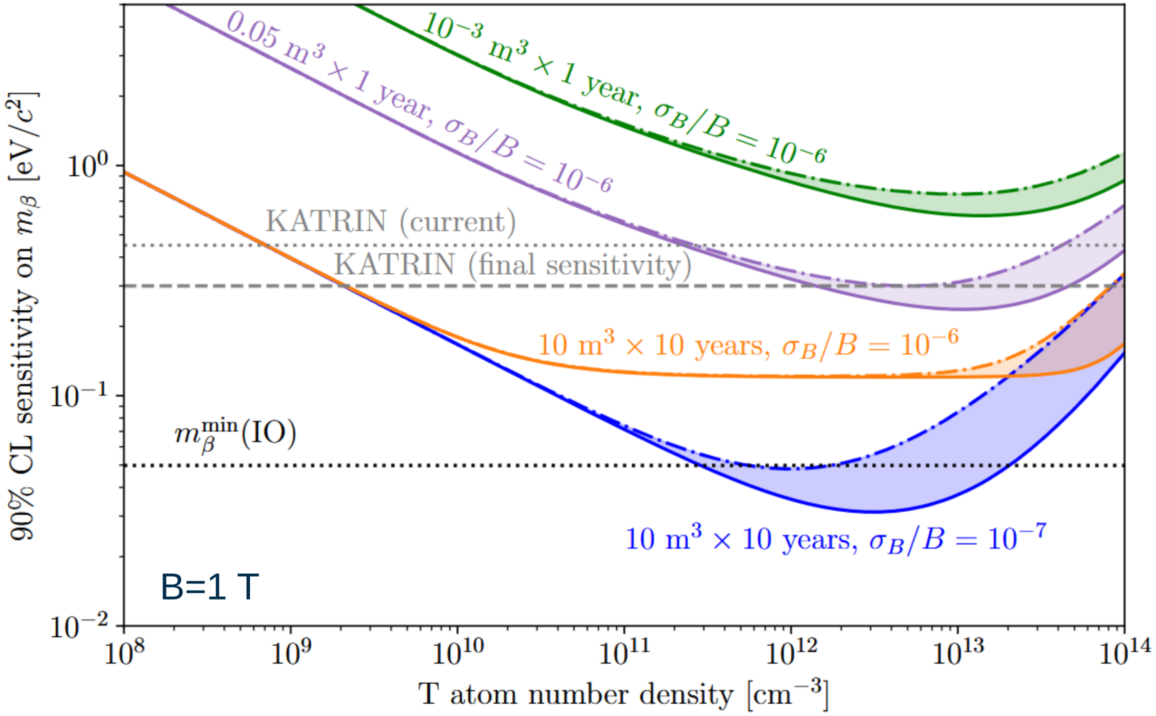



# CRES plans aiming at 40-50 meV sensitivity




https://www.hep.ucl.ac.uk/qtnm/

https://www.project8.org/




**Frequency measurement of electrons emitted inside of atomic tritium source**

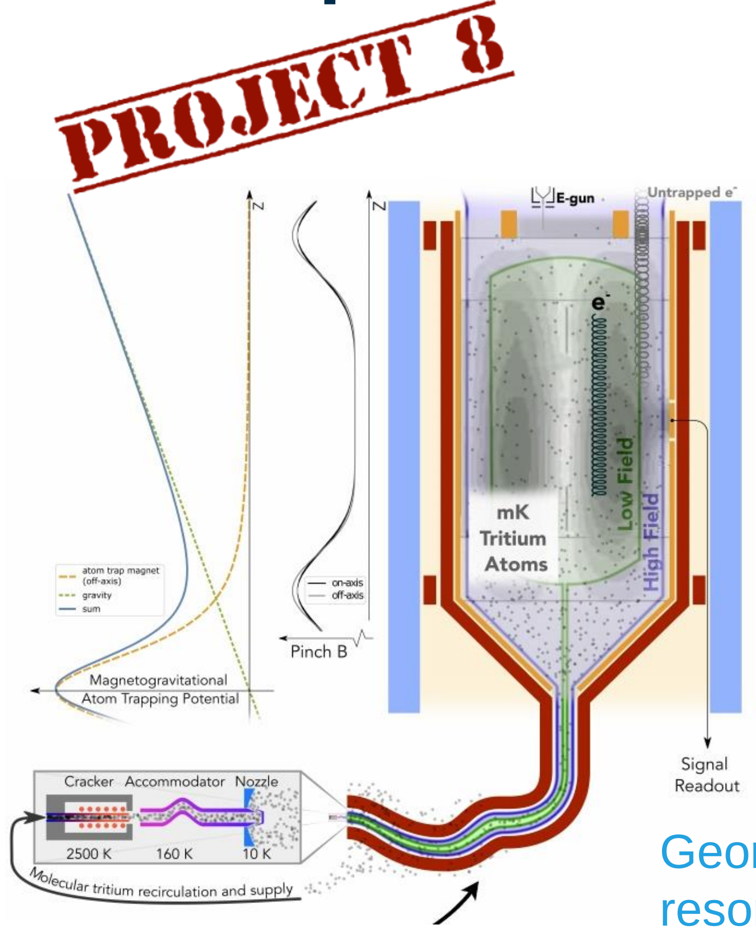
Limits by

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

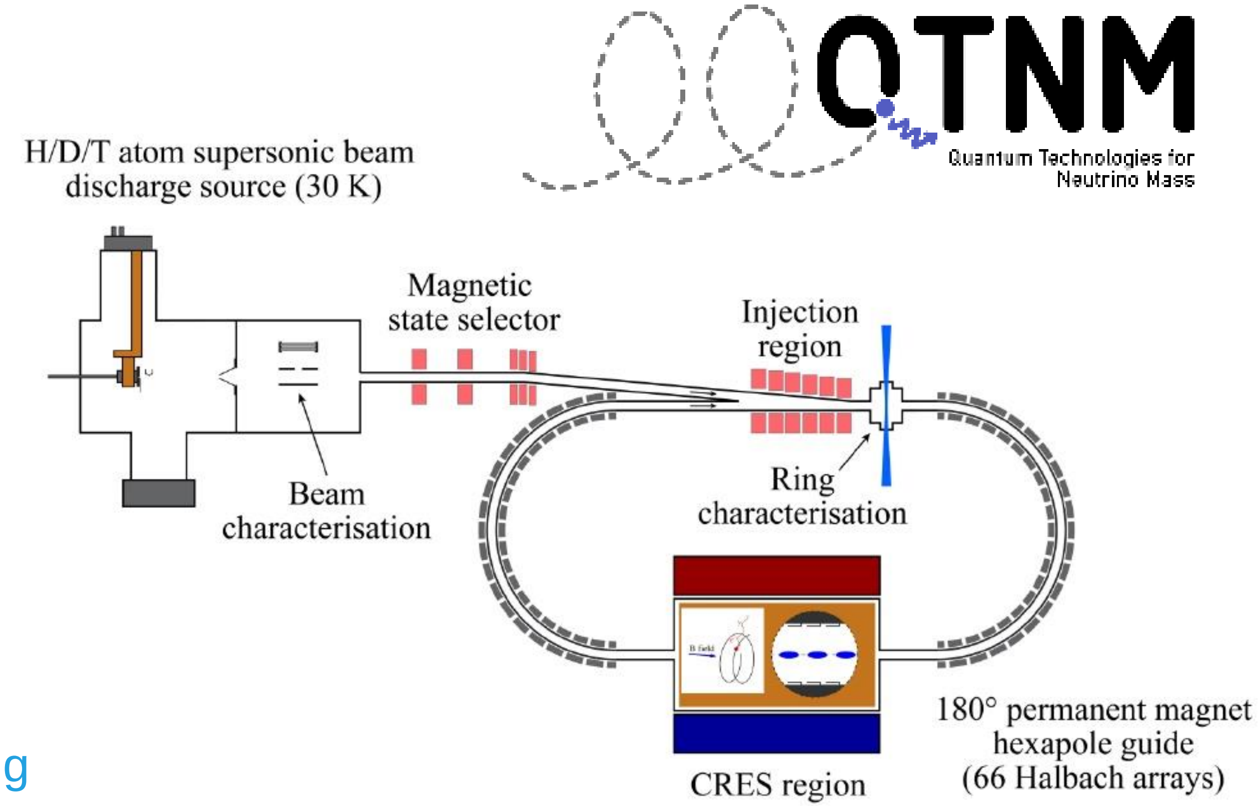
$$\mathrm{std}\left(\hat{\nu}_0\right) \gtrsim \frac{4\sigma_{\mathrm{noise}}}{\pi}\sqrt{\frac{3}{P_{\mathrm{sig}} t_{\mathrm{obs}}^3 f_s}}$$

*arXiv:2203.07349, arXiv:2412.06338, 10.1088/1367-2630/adc624*

# CRES plans aiming at 40-50 meV sensitivity




Geometry / B-field matching
resonant MW cavity



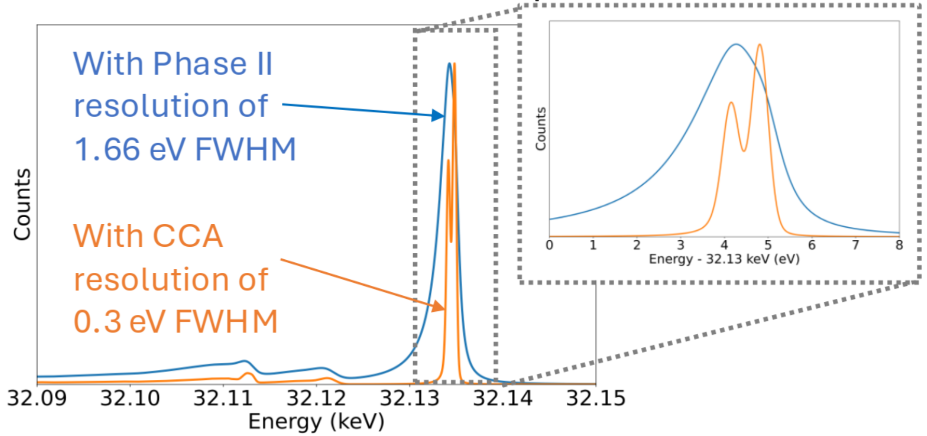

Concept: CRES readout
in **magneto-gravitational trap** for atomic tritium

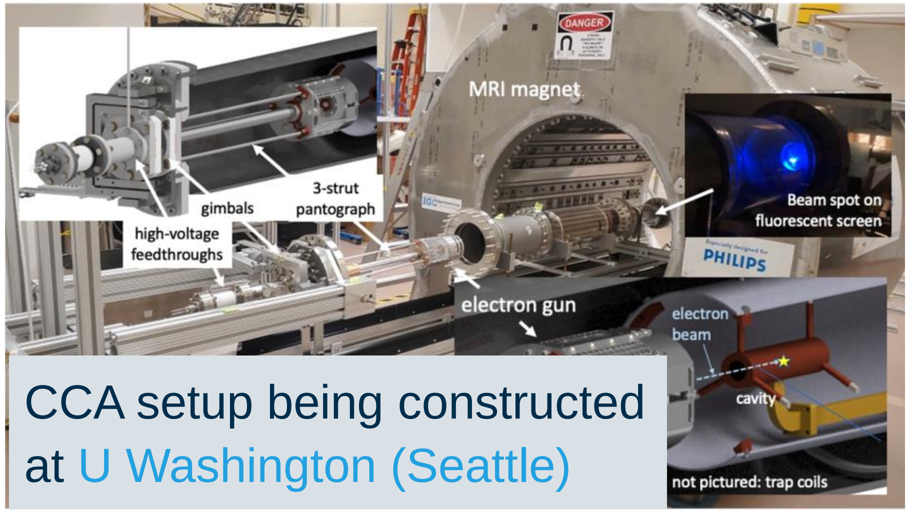
Concept: CRES readout
in **race-track** for atomic tritium

# Ongoing research at PROJECT 8

**Demonstrating of CRES in resonant cavity at 0.3 eV resolution**

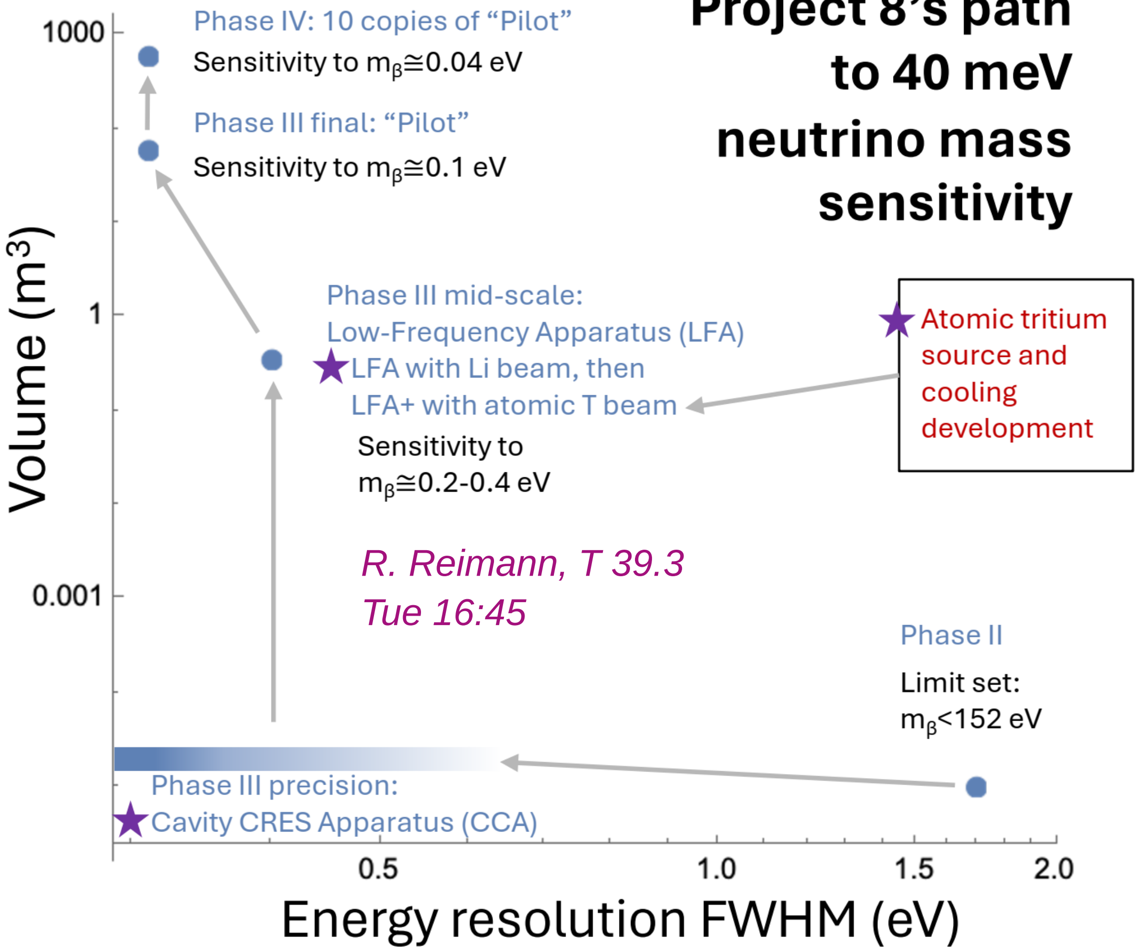
$^{83m}$Kr N-line spectra




CCA setup being constructed at U Washington (Seattle)

## Project 8's path to 40 meV neutrino mass sensitivity

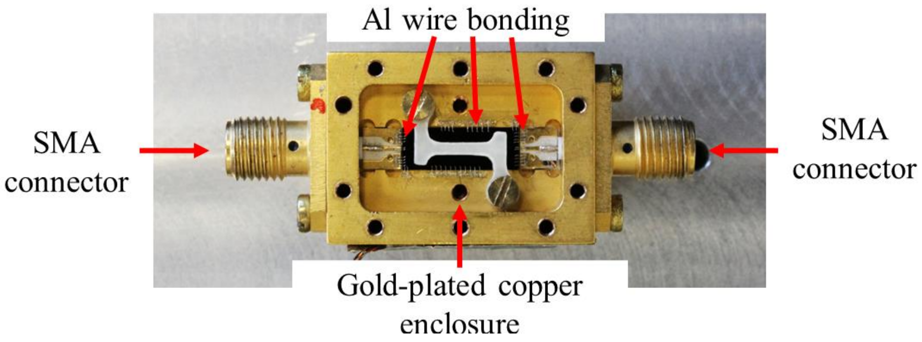



*R. Reimann, T 39.3*
*Tue 16:45*

# Ongoing research at QTNM

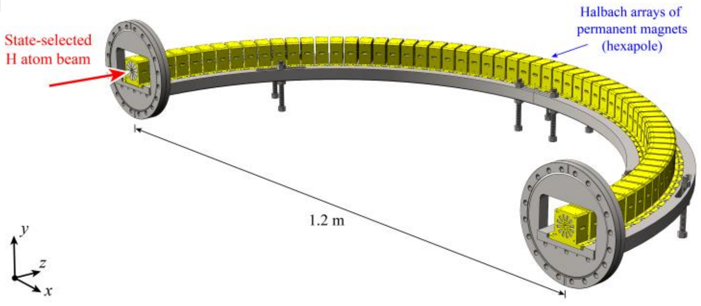
Quantum Technologies for Neutrino Mass

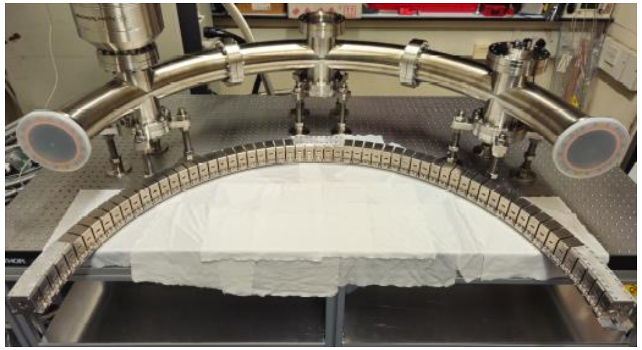
## Quantum noise limited superconducting amplifiers at 4 K and 18 GHz



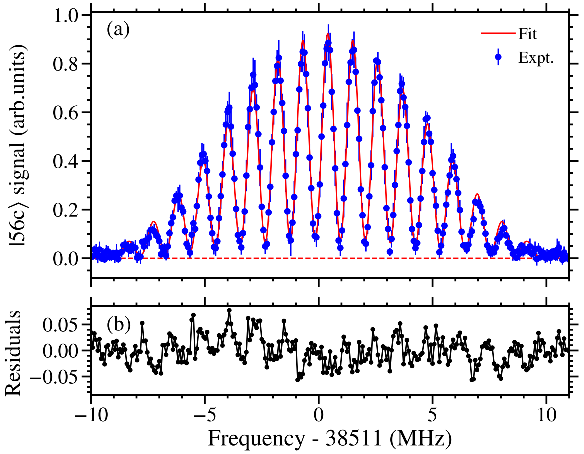

Supercond. Sci. Technol. 36 105010 (2023)
arXiv:2406.02455v2

## H/D/T-atoms confinement with storage ring



## Precise B-field mapping using H-atoms as quantum sensors – Rydberg Magnetometry with µT accuracy




Phys. Rev. A **107**, 062820



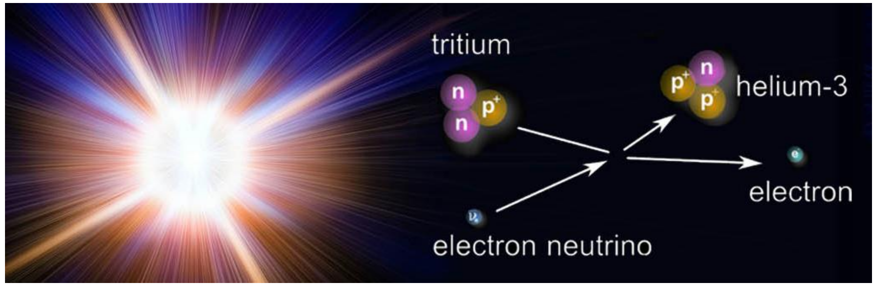
KIT

# PonTecorvo / PrinceTon Observatory for Light Early-universe Massive-neutrino Yield

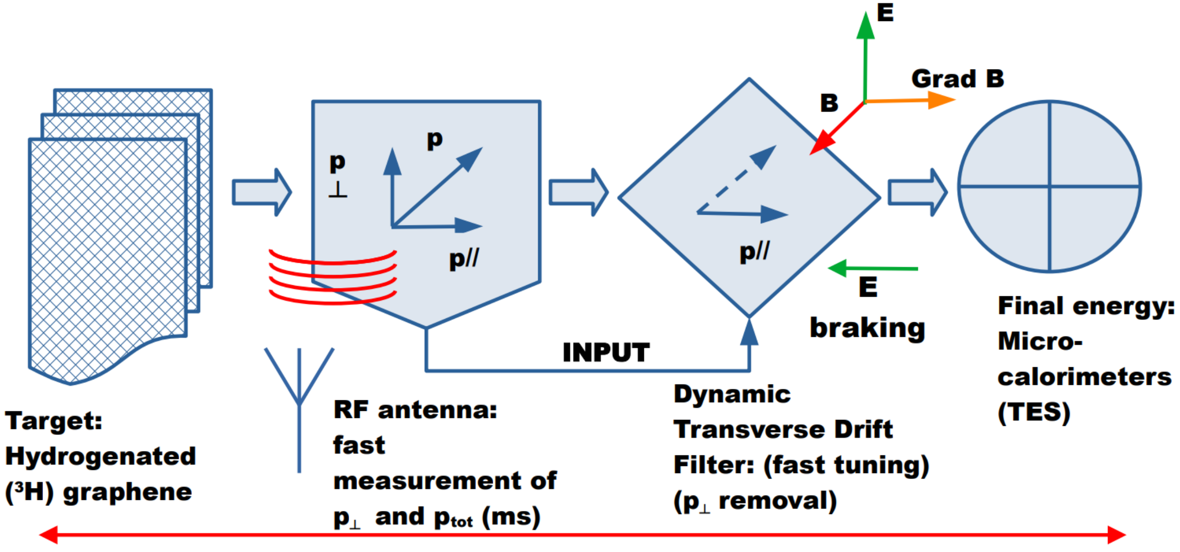
PTOLEMY

Aim: direct detection of big-bang neutrinos;
determination of neutrino mass is „by-product“

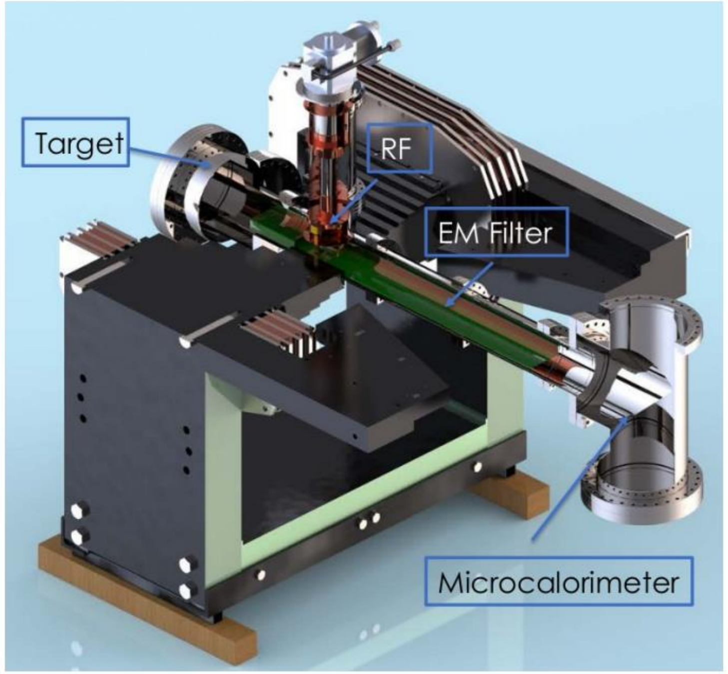
*M.G. Betti et al JCAP07(2019)047*




https://ptolemy.lngs.infn.it/




*Content from „Nicola Rossi, EPS-HEP July 2023 Hamburg“*




Combine technologies (TES, CRES, novel drift filter) with large scale O(100g) tritiated graphene target

Start of technology demonstrator @LNGS soon



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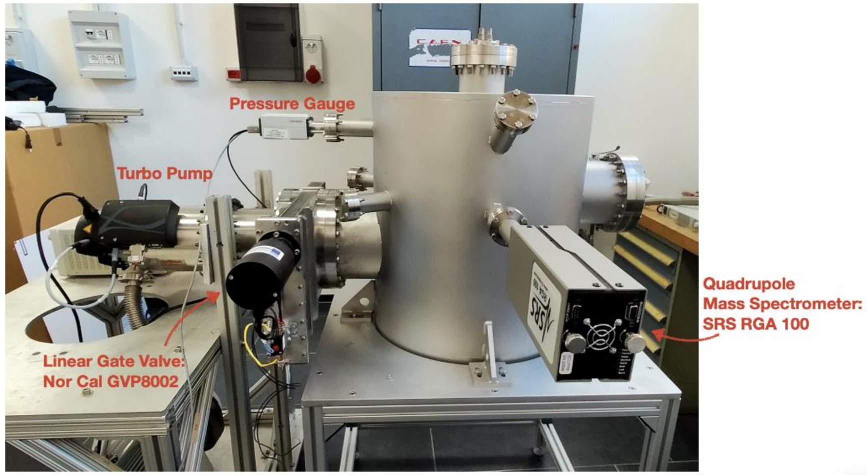
# Recent, selected R&D results from PTOLEMY

Graphene loading chamber

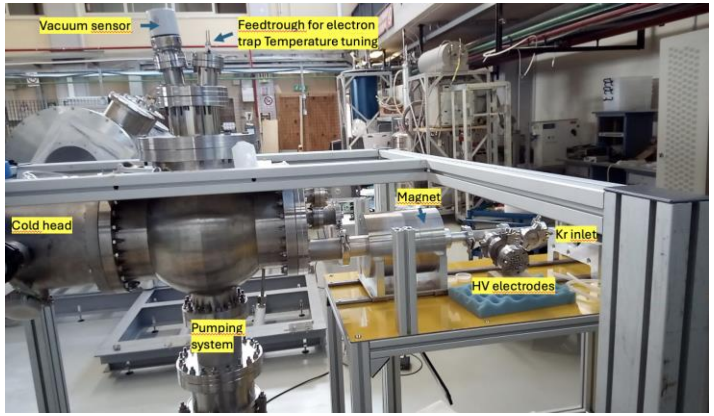


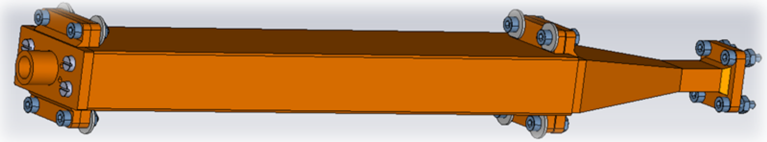

Betti et all, Nano Lett. **22**, 2971 (2022)

Loading with H up to 90%

Next step: work on with UKAEA on tritium design

RF detection test stand

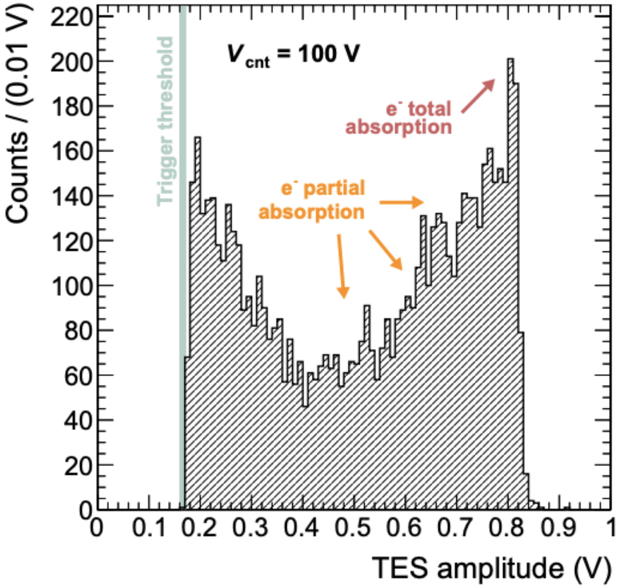


Kr inlet

RF detection

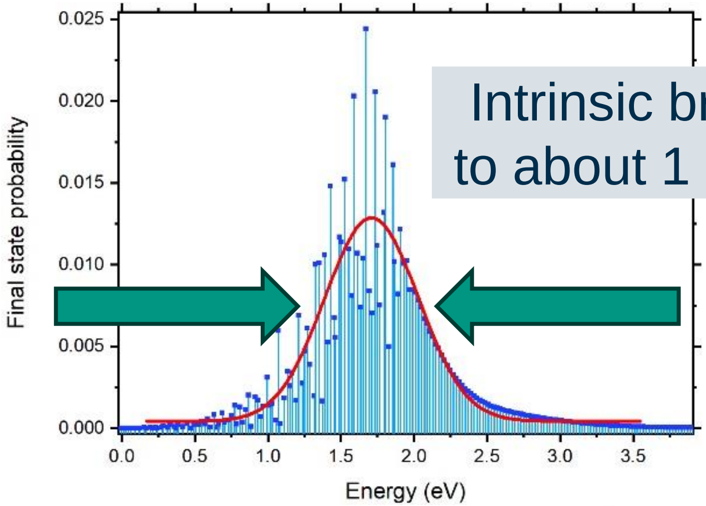
Electron detection with TES




Phys.Rev.Applied 22 (2024) 4, L041007

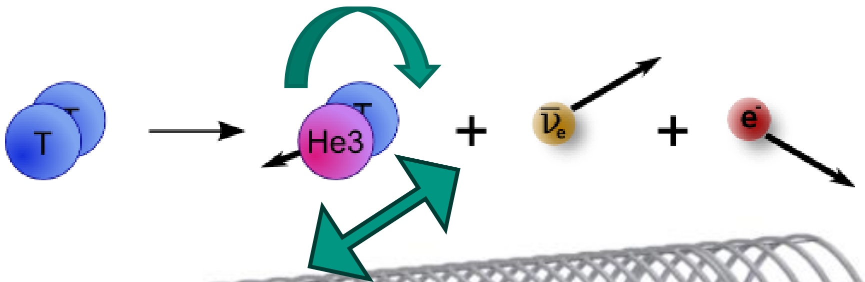
First measurement of 100 eV electrons with ~1-1.5 eV resolution

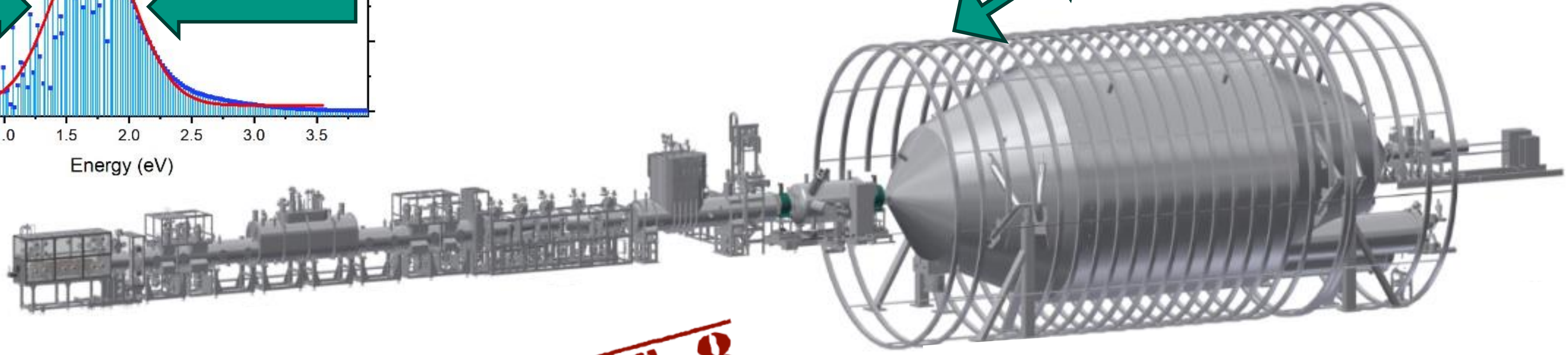
# TLK as R&D facility for Atomic source technology




Intrinsic broadening to about 1 eV FWHM

- Molecular effects → spectral broadening

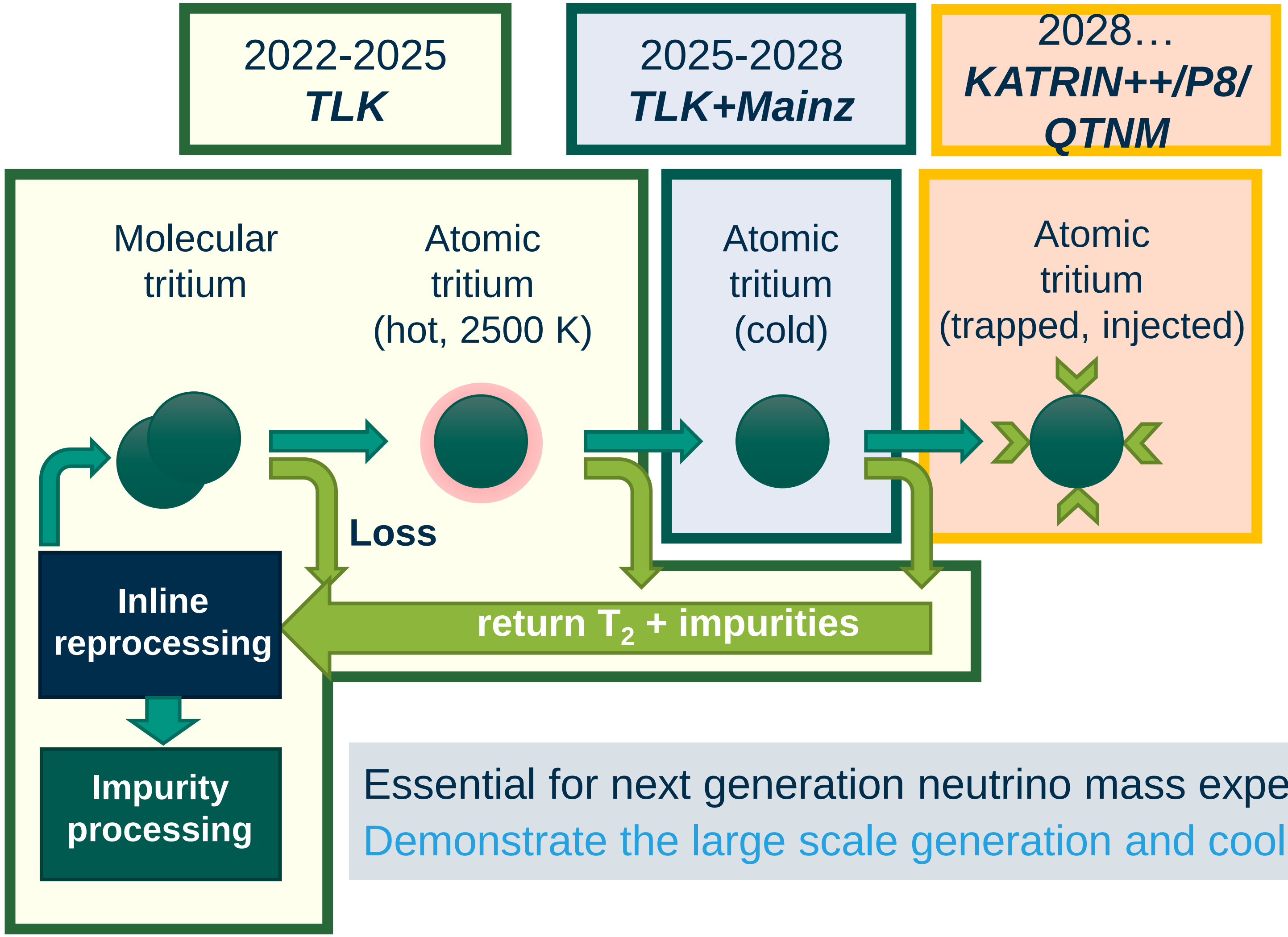


KATRIN++

**Atomic tritium trap** is key independently of detection techniques

# Atomic Tritium Demonstrator at TLK




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

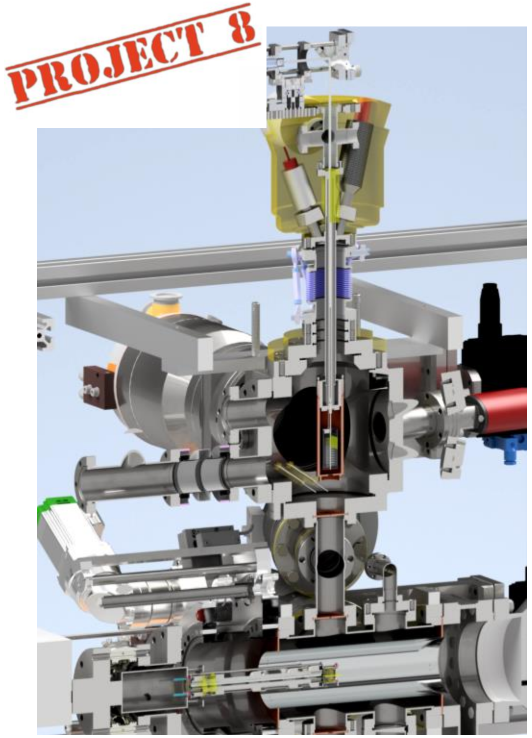
Tritium atom throughput on the order of 10 g/day (c.f. KATRIN: 40 g/day)

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

# Atomic source R&D progress

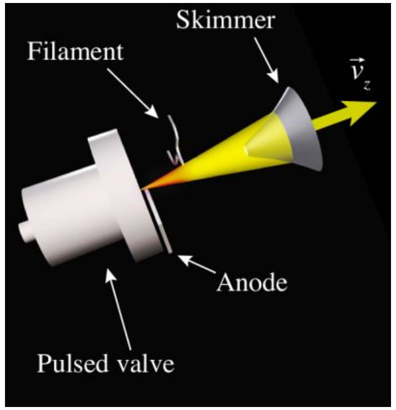

Installation of first ever atomic **tritium** source at TLK ongoing

*D. Frese, P 19.4, Thu. 12:00*
*L. Hasselmann, T 99.1, Fri. 09:00*
*D. Kurz, T 99.2, Fri. 09:15*

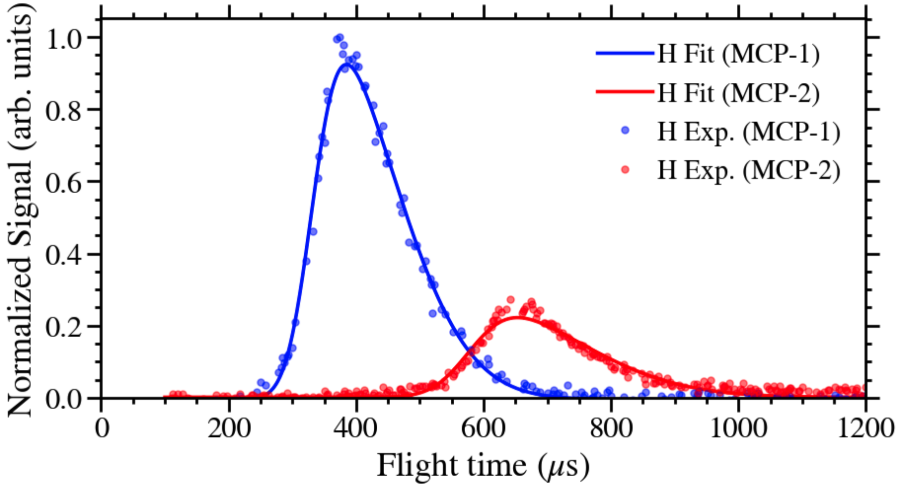



H/D - dissociator characterization test stand at Mainz

*A. El Boustani, T 39.4, Tue 17:00*



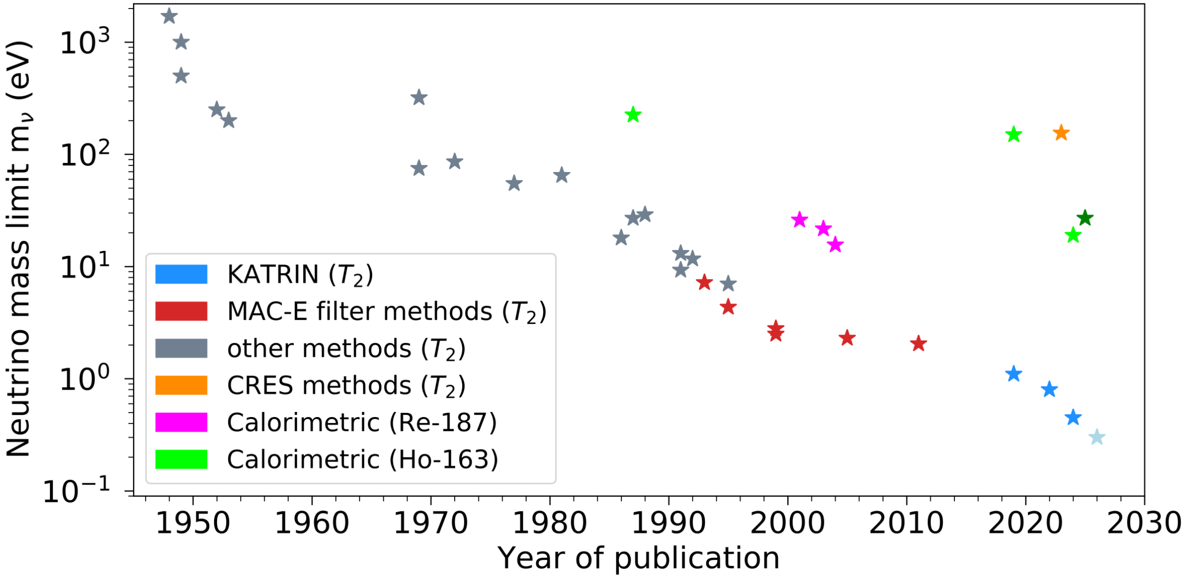

Measurement of temperature profiles of H/D atoms in super sonic beam

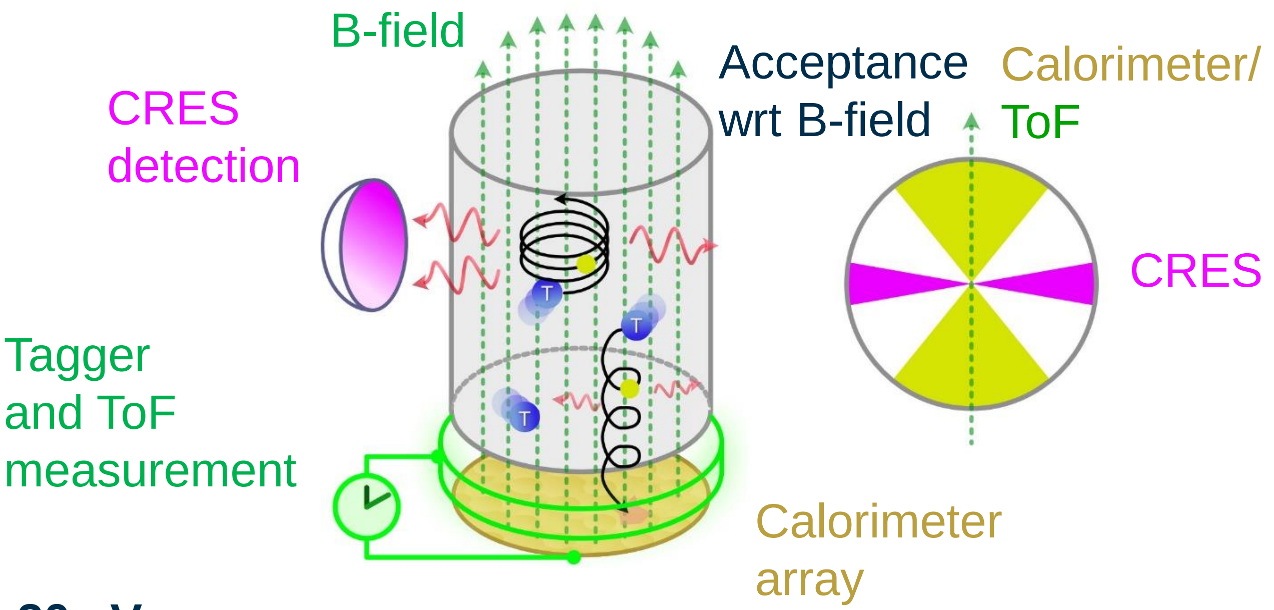



**Joint Atomic Tritium Pathfinder**
Demonstration of prototype trap loading and storage with cool T atoms

→ **TLK as ideal location**

# Status and outlook of direct neutrino mass experiments




- Limits by cryogenic Ho-163 experiments around **$m_\nu$ < ~20 eV**
- Most stringent limits by KATRIN : **$m_\nu$ < 0.45 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 (~10 meV)**
- Mid term: inverted ordering (~50 meV)

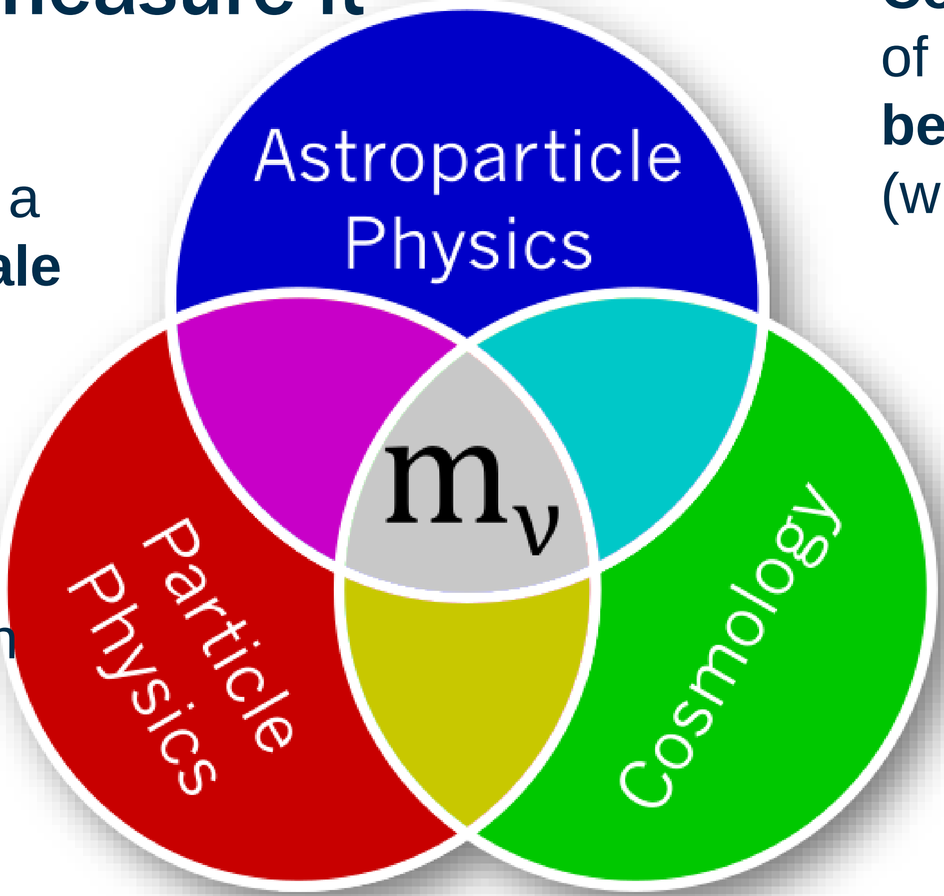
- **Complementary detector technolgies:** Calorimeters, CRES, ToF, …
- **Joint effort:** Atomic source

# Backup

# The role of massive neutrinos and motivations to measure it

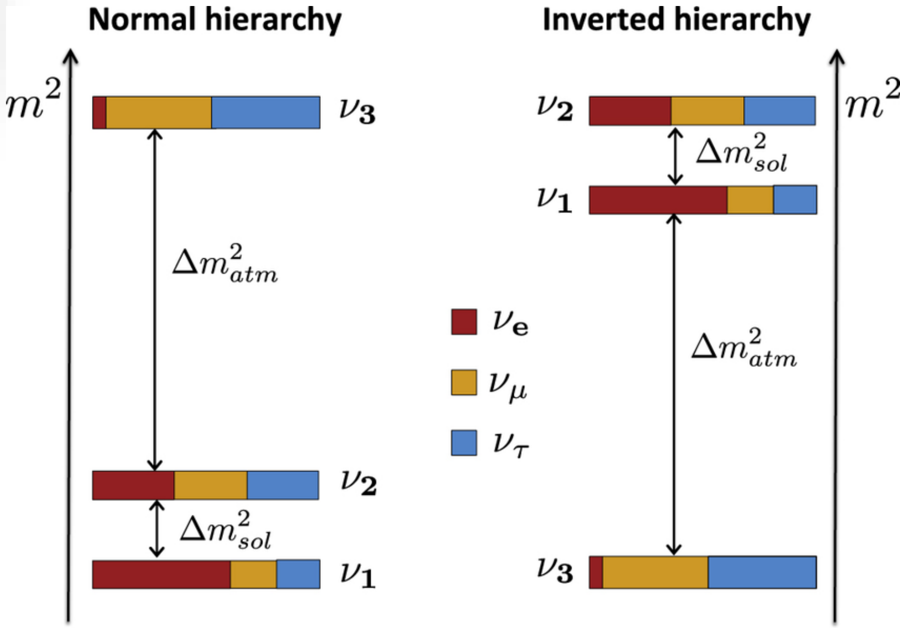
Neutrino masses bring in a **fundamental energy scale** (besides Higgs scale)

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




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

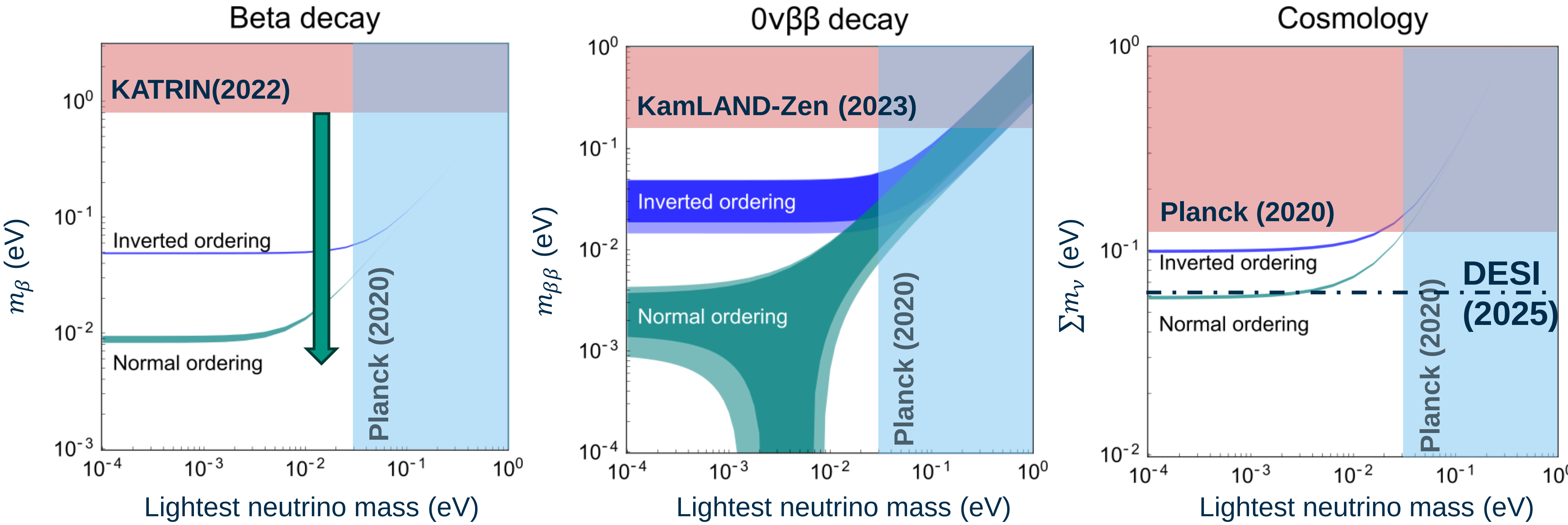
Model for mass generation needs: mixing matrix **AND mass scale**




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

# Complementarity and need for direct mass measurements

*Standard neutrino picture:* ***observations have to be found in colored regions***




*KATRIN, Nat. Phys.* ***18*** *(2022) 160*

*KamLAND-Zen, PRL* **130,** 051801 (2023)

*Planck, Astron. Astrophys.* **641** (2020) A6
*DESI, 2503.14738*

*T. Schwetz-Mangold, T 63.1, Thu. 11:00*

*D. Gruen, T 63.3, Thu. 12:00*

*NuFit, J. High Energ. Phys.* 2020, 178 (2020).

Inspired by IUPAP neutrino panel white paper, www.iupapneutrinopanel.org

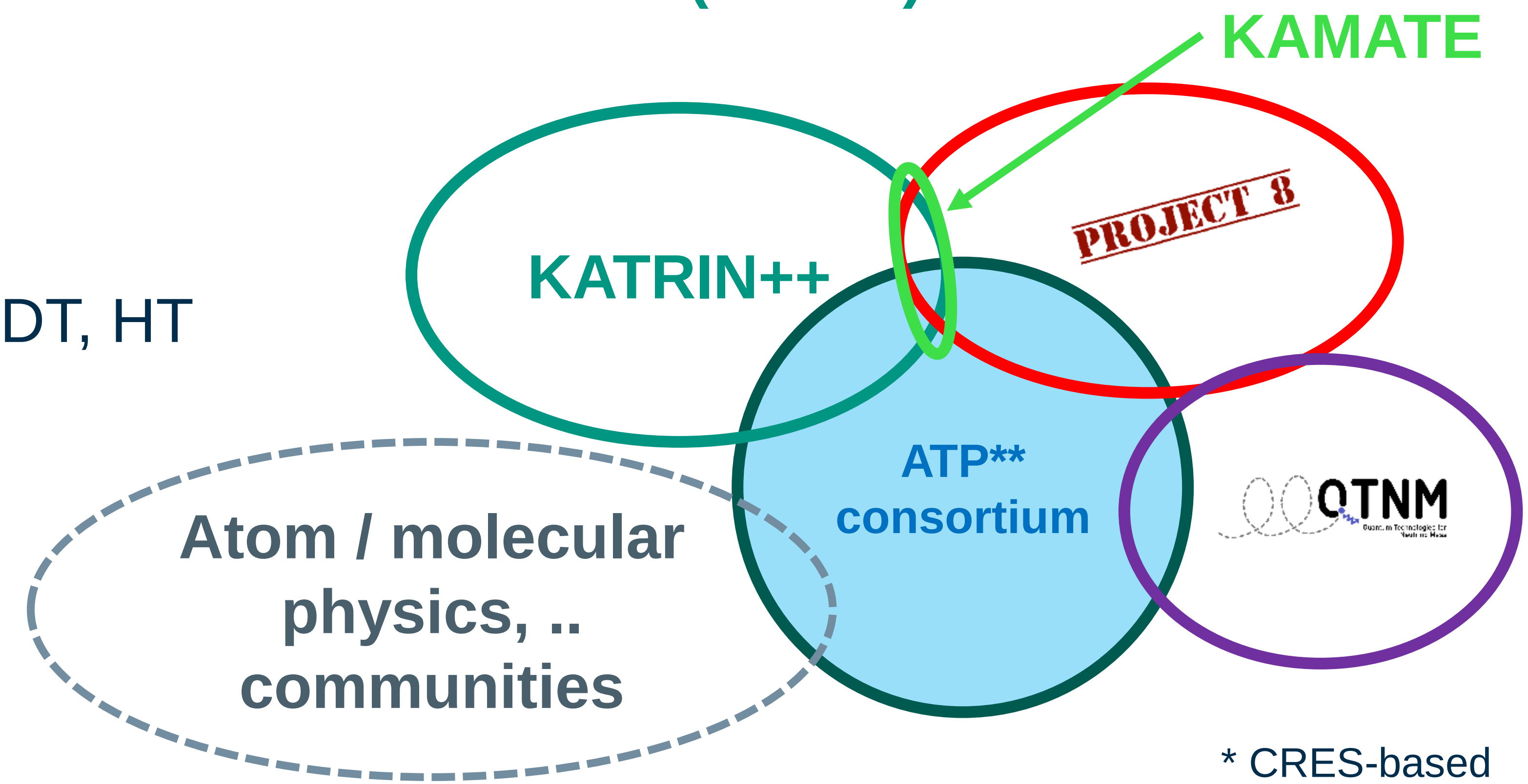
**Tie-breaker needed to exclude exotic models in neutrino nature or cosmology**

# Atomic source research

**Atomic tritium trap** is key independently of detection techniques

**Mission: Realize (global) Atomic Tritium Pathfinder (at TLK)**

**Possible partners:**
Ubachs (VU Amsterdam), $T_2$, DT, HT
Schiller (U Düsseldorf) $HT^+$
Pohl (U Mainz) T
….




**placeholder name

* CRES-based

# Physics analyses beyond the neutrino mass

## Neutrino mass analysis
*PRL 123 (2019) 221802*
*Nat. Phys. 18 (2022) 160,*
*KATRIN 2024, arXiv:2406.13516*

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## Light sterile neutrinos
*PRD 126 (2021) 091803*
*PRD 105 (2022) 072004*
*New data set in unblinding*

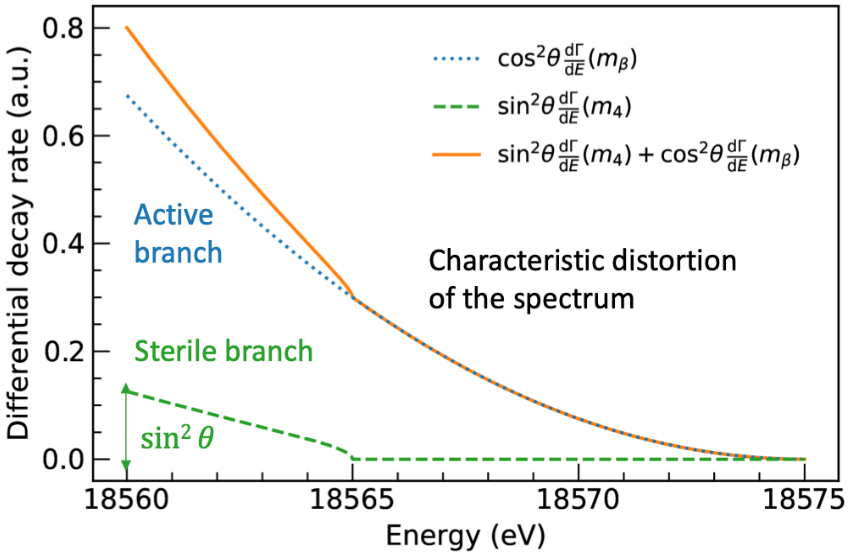
## Relic neutrinos
*PRL 129 (2022) 011806*

## Lorentz Violation
*PRD 107 (2023) 082005*

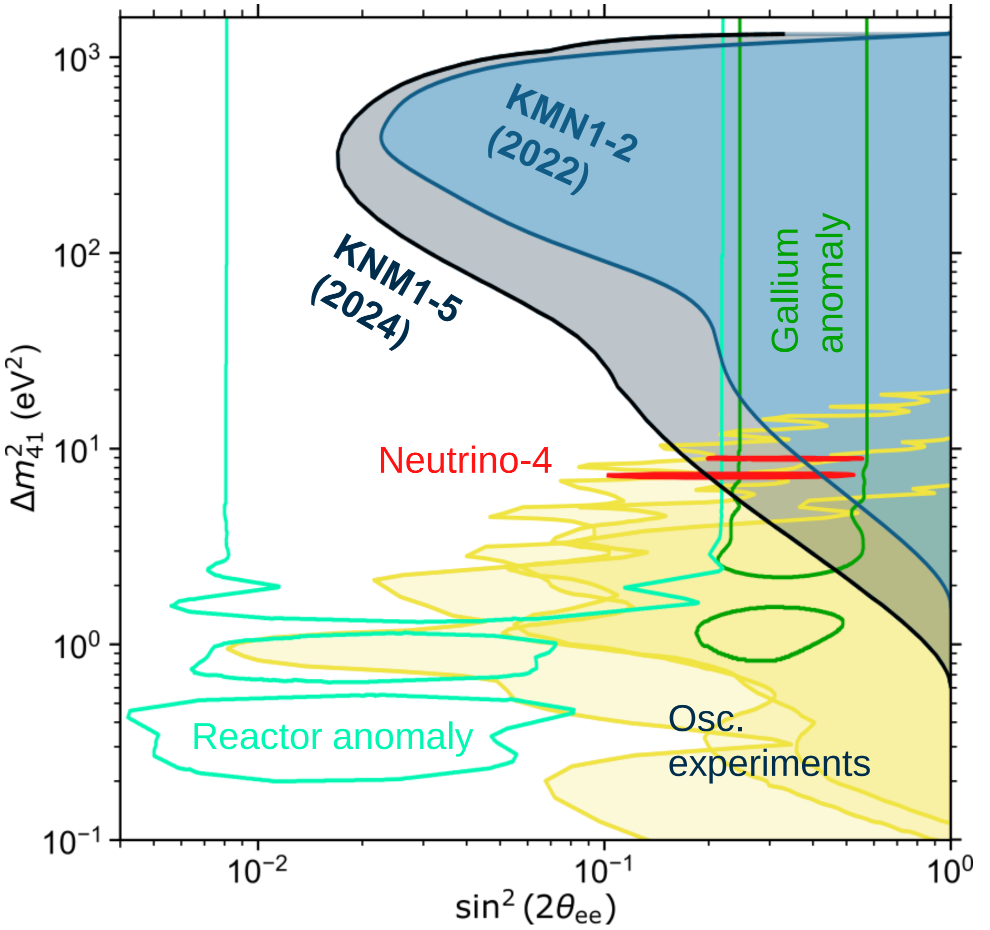
## General Neutrino interaction
*KATRIN 2024, arXiv:2410.13895*

## Dark MSW
Ongoing analysis

## Light Bosons
Ongoing analysis



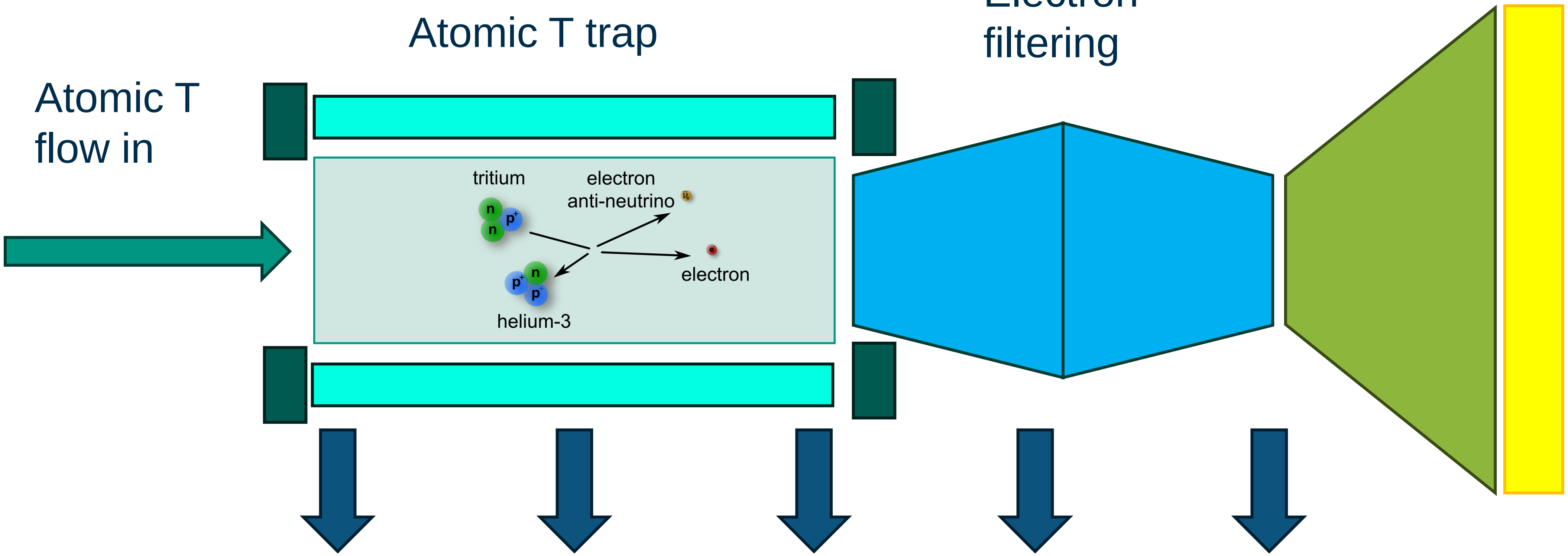

$$\frac{d\Gamma}{dE} = \underbrace{\left(1 - |U_{e4}|^2\right) \frac{d\Gamma}{dE}(m_\beta^2)}_{\text{Active neutrinos}} + \underbrace{|U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)}_{\text{Sterile neutrino}}$$




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

# *Final R&D goal*
# Atomic tritium with Quantum sensor array

*Conceptual idea*




**Work started**
- concept
- sensitivities
- R&D

# Beta decay and neutrino mass: KATRIN and beyond

| 2019-2025 | 2026-2027 | 2028-2034 | Scientific goal |
| --- | --- | --- | --- |
| **Phase 1 (integral) neutrino mass** | Phase 2 (differential) keV-sterile $\nu$ | **R&D phase for KATRIN++** | Neutrino mass |

Differential detection R&D

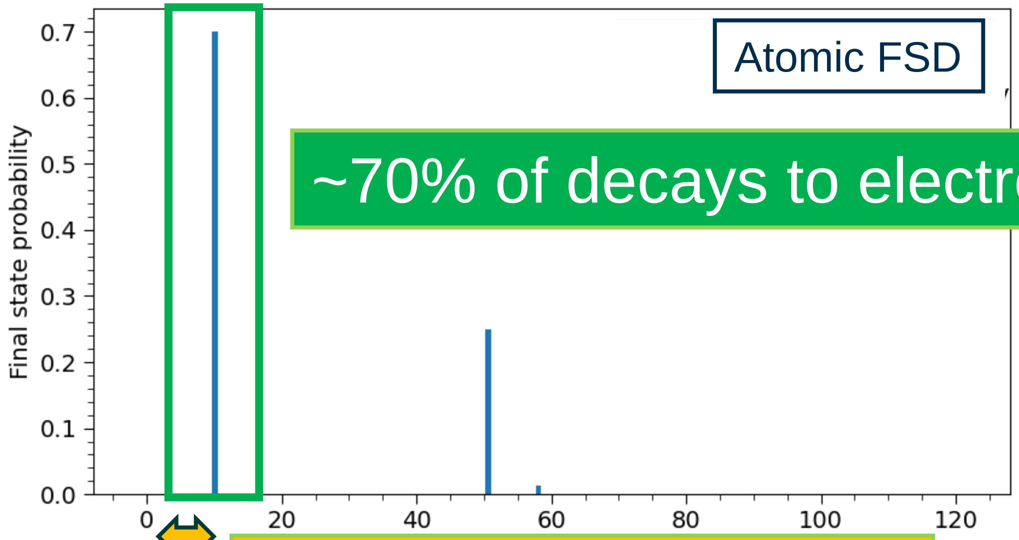
Atomic tritium R&D

Differential detection demonstrators

Atomic tritium demonstrator

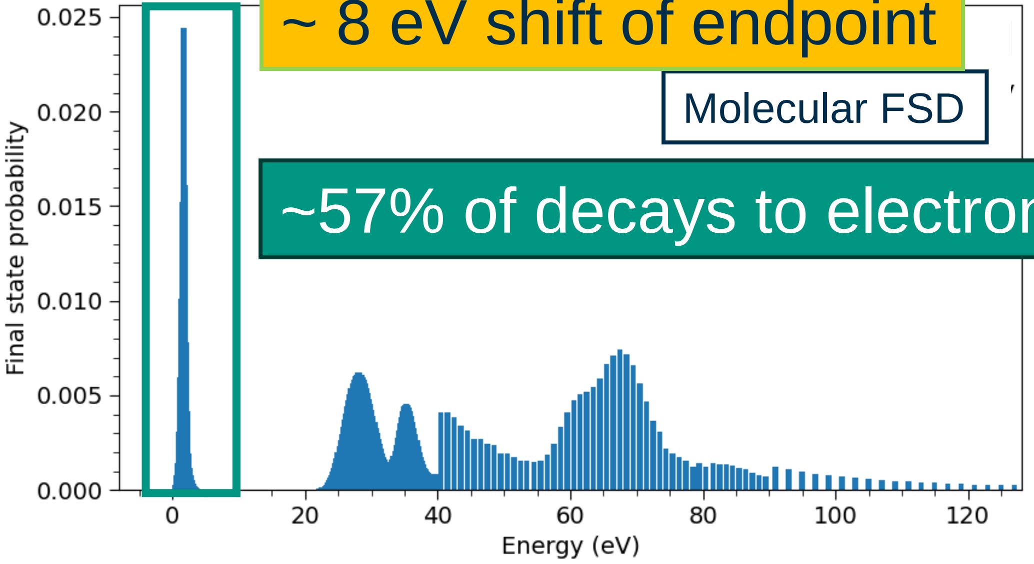
- **KATRIN** on way to achieve 1000 d measurement time **(final sensitivity $m_\beta$ < 0.3 eV).** Next $m_\beta$ result : ~ **0.5 eV sensitivity**
- We will be ready for **TRISTAN**-Operation at the end of 2025 (**Search for keV sterile neutrinos)**
- Ultimate neutrino mass experiment (Normal Ordering**;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

# Atomic vs molecular tritium

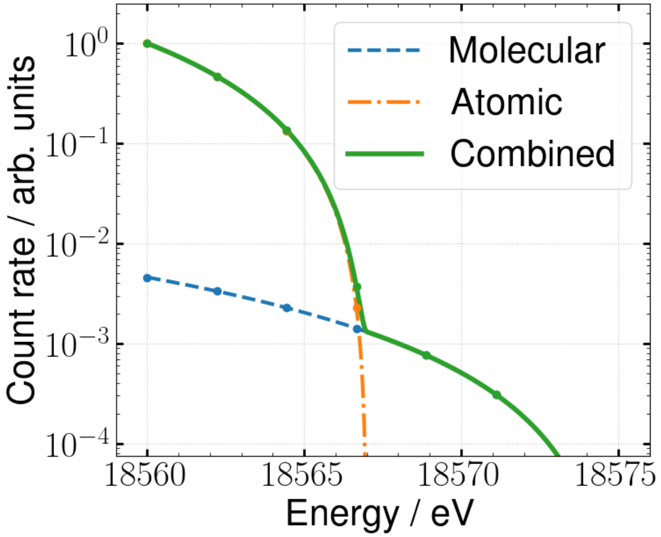


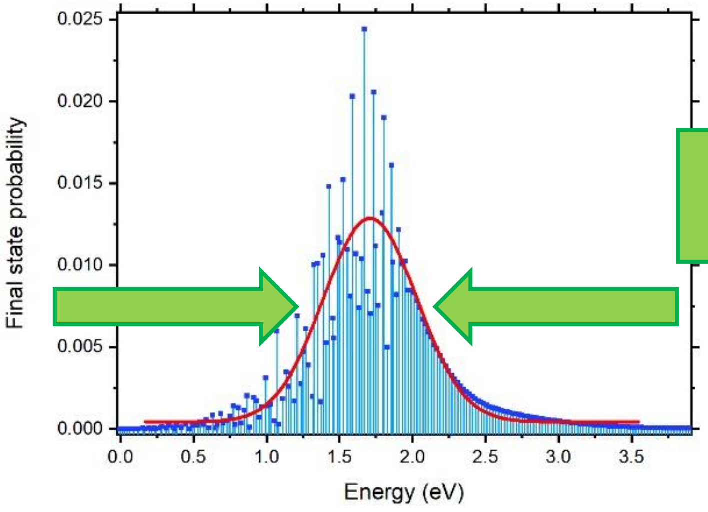

~70% of decays to electronic GS

~ 8 eV shift of endpoint



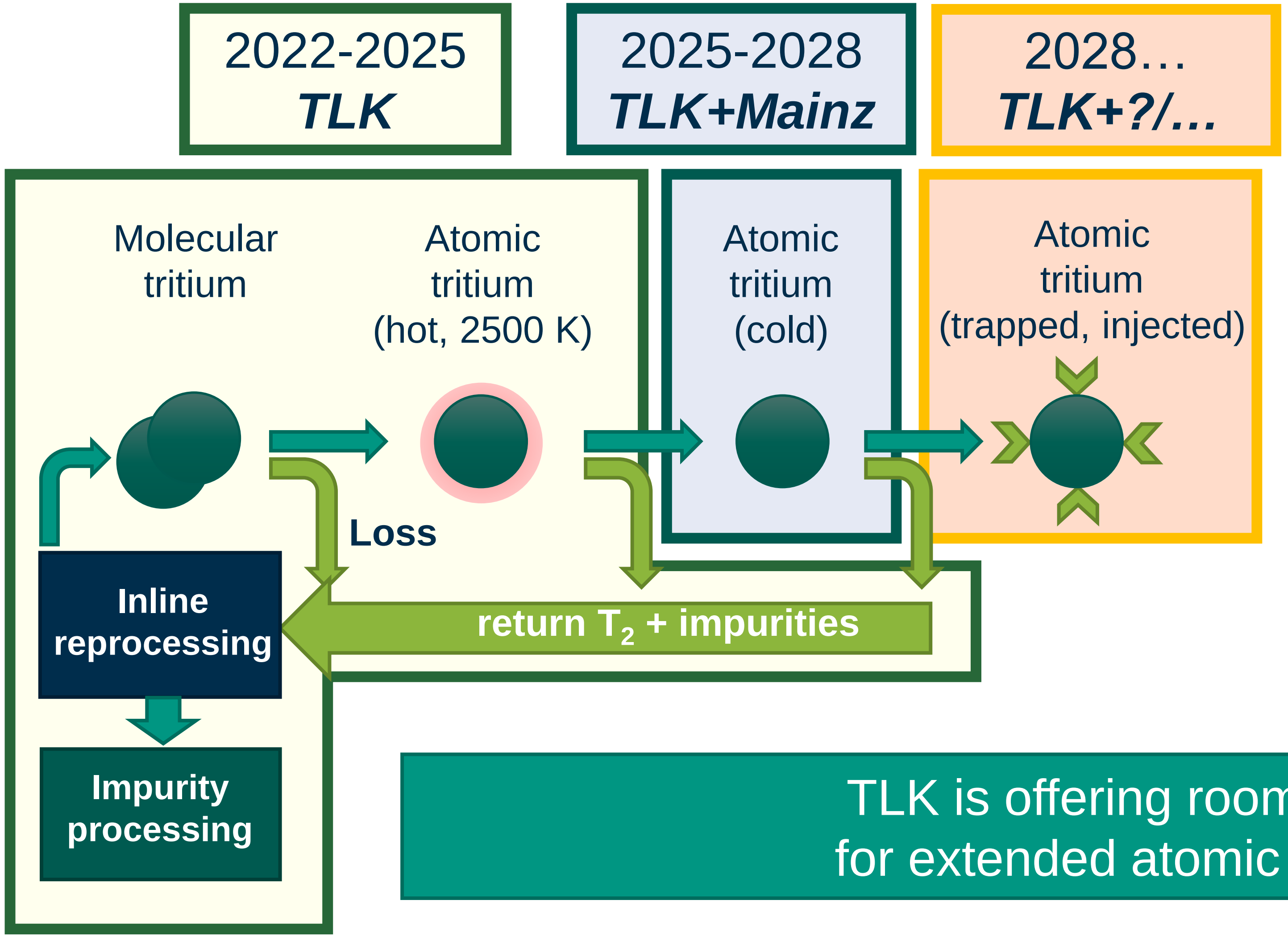

~57% of decays to electronic G

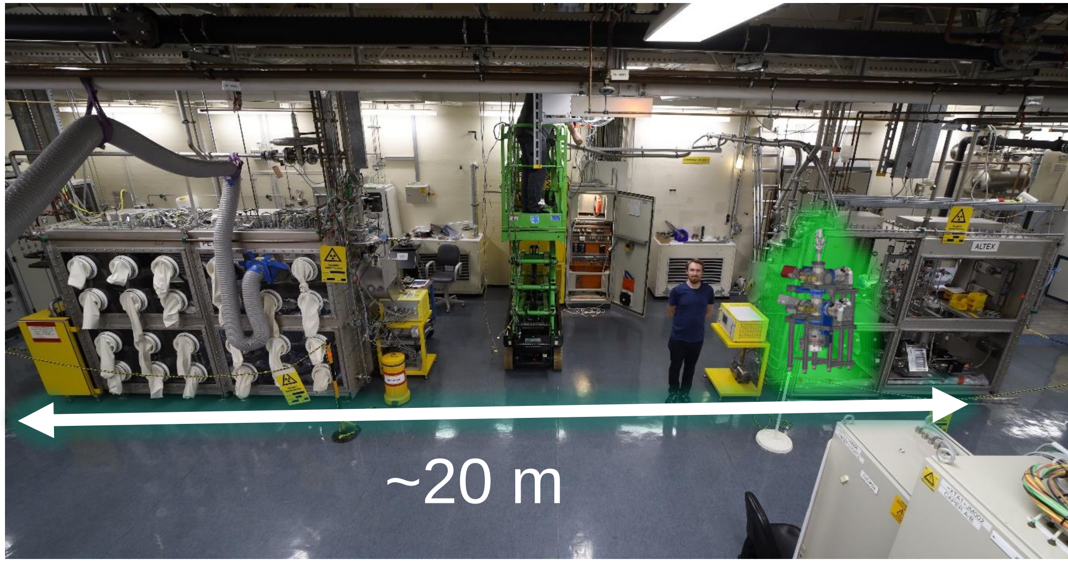



broadening to about 1 eV

# Atomic Tritium Demonstrator at TLK



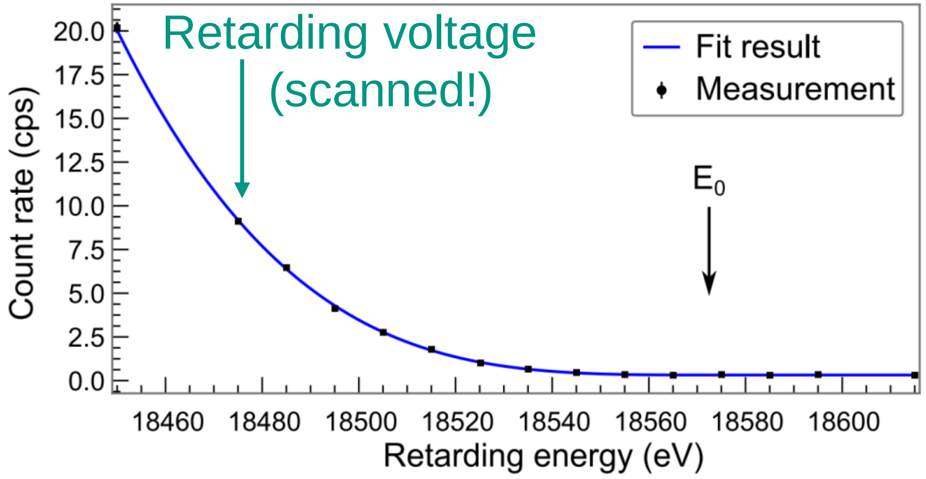



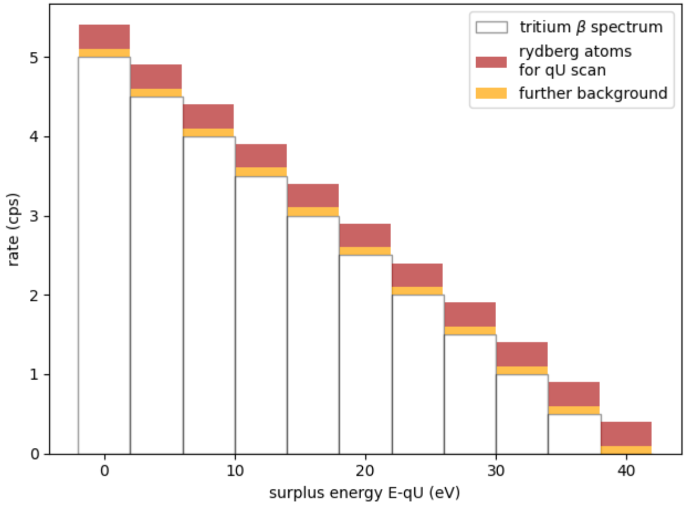

TLK is offering room and infrastructure
for extended atomic tritium experiments

# Improved measurement principle

**Integral measurement (high pass filter)**

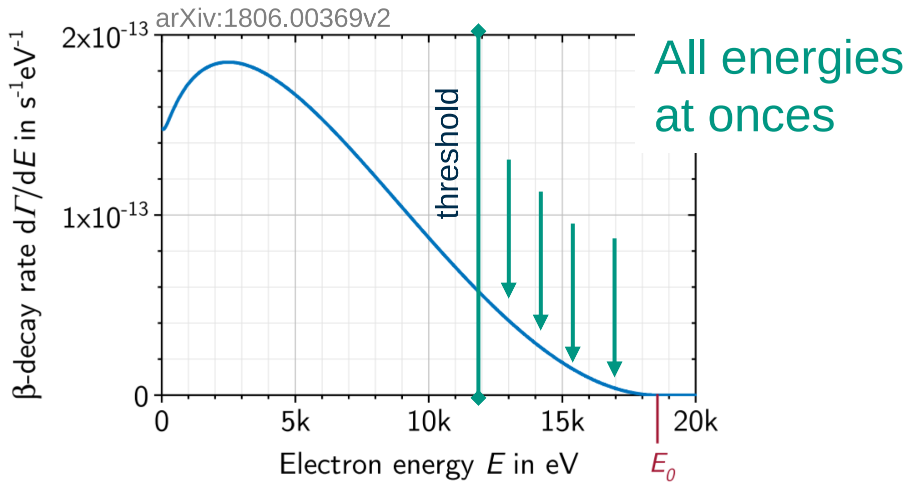
- Energy resolution determined by filter
- Detector „only“ counts
- Reduced statistics

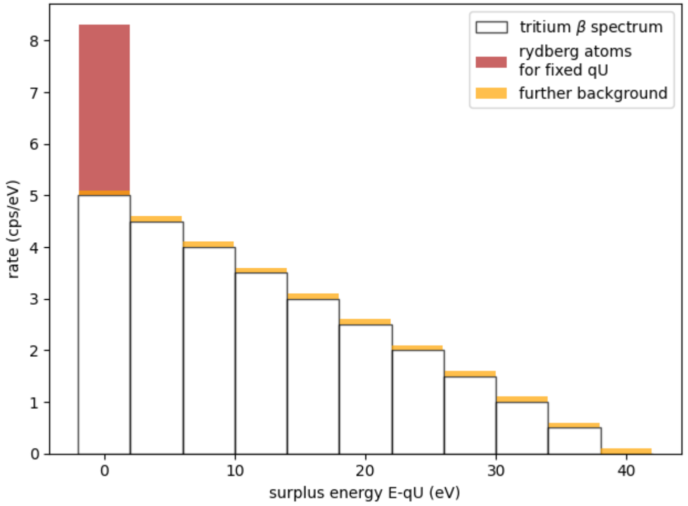



**Differential measurement**

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



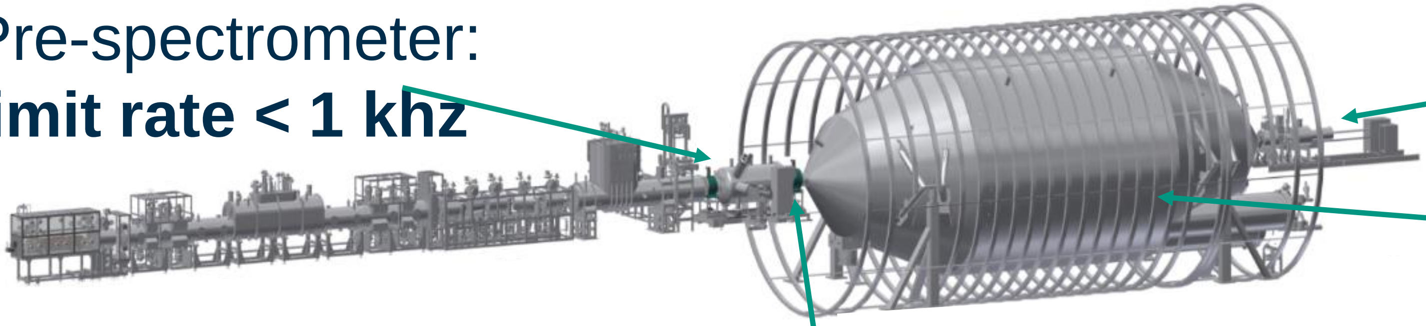




**More signal**

**Less background**

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

Pre-spectrometer:
**limit rate < 1 khz**



Fast detector: **stop**

Main spectrometer:
**delay line due to retardation**

KATRIN Source:
**$10^{11}$ Bq**

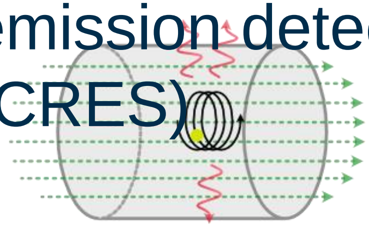
Tagger: **start** (~1000 Hz)

**Strategy**

- „Single channel“ detector → less complex than quantum sensor array (QSA)
- Differential measurement with ToF before QSA is ready
- Work on techniques to improve ToF resolution (U Münster)

**Single electron tagging is challenging**

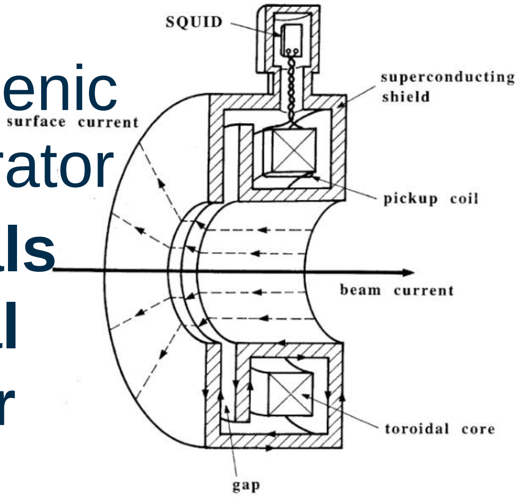
Cyclotron radiation emission detection (CRES)



See Project 8

Coreless cryogenic current comparator

**Tiny signals vs minimal noise floor**




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

R&D ongoing at U North Carolina

# KAMATE –
# Karlsruhe Mainz Atomic Tritium experiment


## Scientific / technical goals

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

Karlsruhe

Mainz

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

# KAMATE –
# Karlsruhe Mainz Atomic Tritium experiment

A. Lindman

2024

KAMATE stages

2028

**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

**Karlsruhe**

KATRIN Karlsruhe Tritium Neutrino Experiment

TLK Tritium Laboratory Karlsruhe

**Mainz**

PROJECT 8

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ



KIT

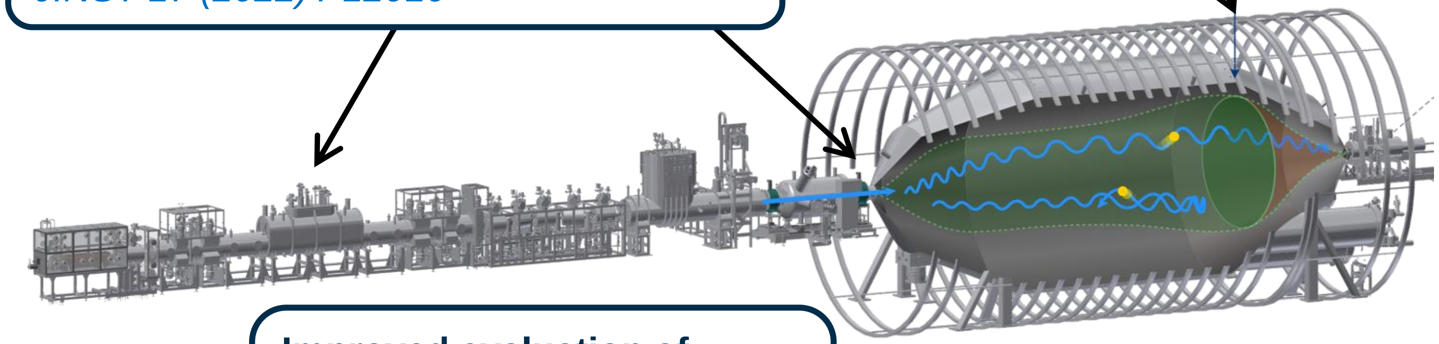
# Systematic and statistical uncertainties

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

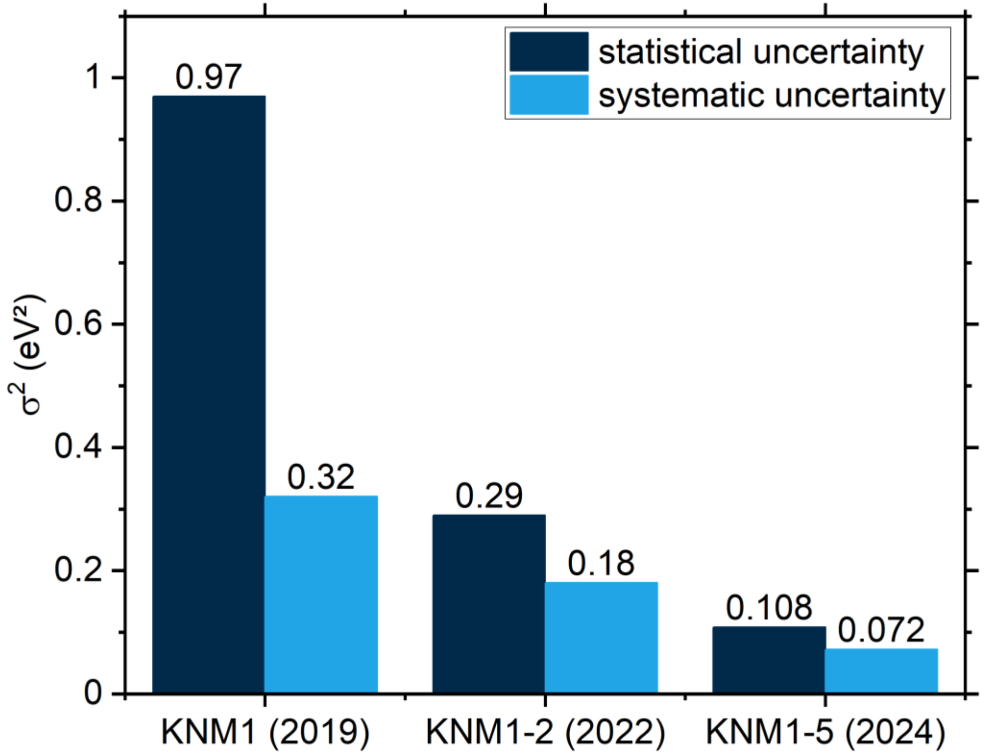
**Removal of the penning trap**
*EPJ C 80 (2020) 821*

**Shifted analyzing plane**
*EPJ C 82 (2022) 258*
*EPJ C 84 (2024) 1258*

**High-statistics krypton-83m calibration**
*JINST 17 (2022) P12010*



**Improved evaluation of theoretical uncertainties**
*EPJ C 84 (2024) 494*




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

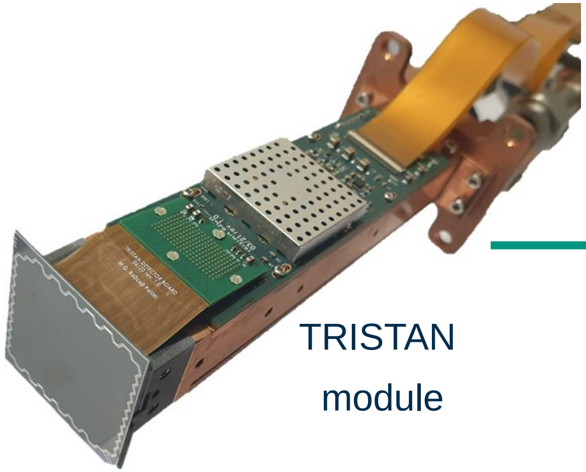
# KATRIN with TRISTAN detectors

## New challenges

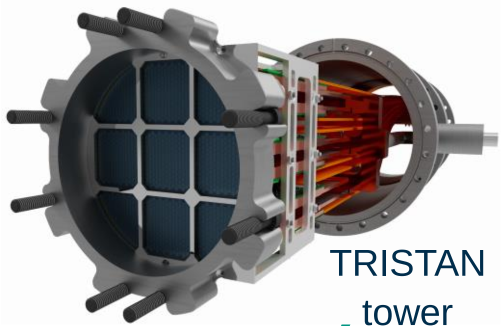
- Differential measurement → new systematics
- Rate increase (from cps to Mcps)

  → **new detector technology**

  **(Silicon Drift Detectors)**




9x




## Status of preparations

- Detailed sensitivity studies identify key systematics
- Wafer processing finished – First modules under tests
- On schedule to start installation in January 2026


**KATRIN ready to open new physics program in 2026**