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Karlsruher Institut für Technologie

Beta decay and neutrino mass:

KATRIN and beyond

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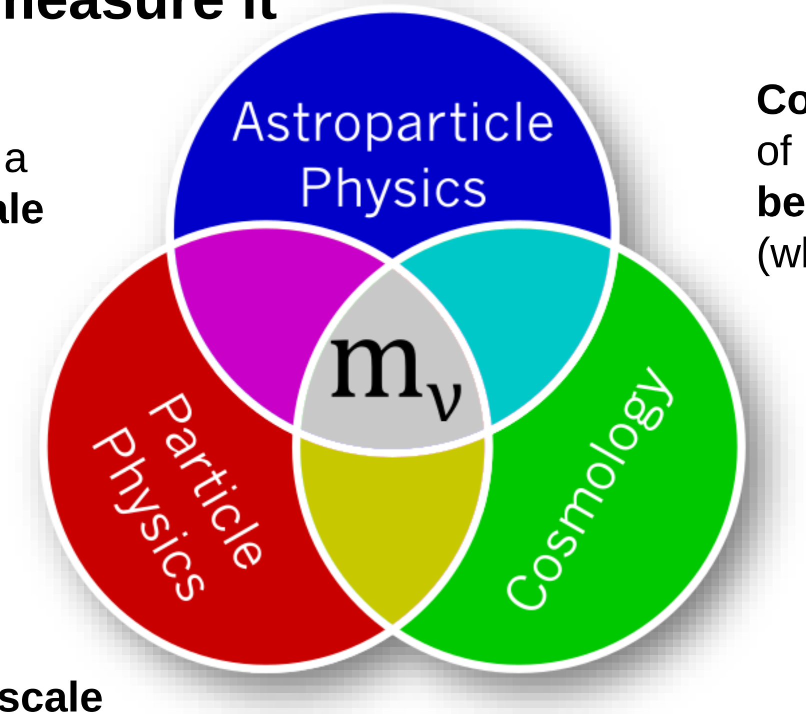
Institute for Astroparticle Physics
Tritium Laboratory Karlsruhe

Neutrino Oscillation Workshop
NOW 2024, Otranto, Italia

The role of massive neutrinos and motivations to measure it



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

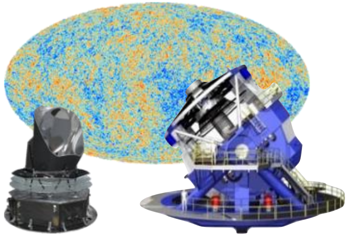
Model for mass generation needs: mixing matrix **AND mass scale**

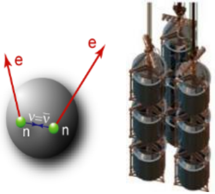
Cosmology and the role of neutrinos therein **may be more complex** (what is DE, …?)

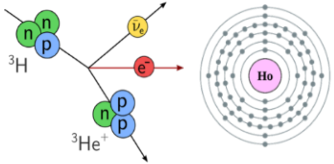
0νββ observation **not necessarily** points to an **neutrino mass**

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

Ways to access the neutrino mass





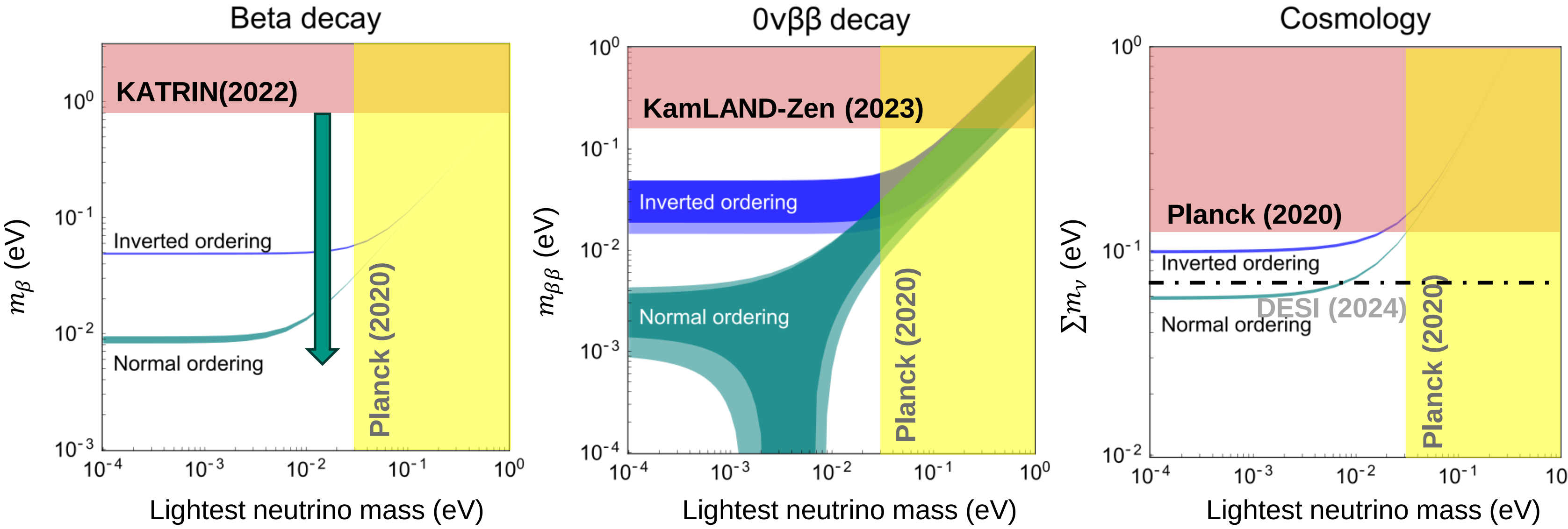


	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$	$m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Present upper limit	0.12 eV (0.072 eV)	0.156 eV	0.8 eV
Model dependence	Multi-parameter cosmological model	- Majorana ν - contributions other than m(ν)? - nuclear matrix elements, g_A	**Direct,** only kinematics; no cancellations in incoherent sum

This talk

Complementarity and need for direct mass measurements

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



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

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

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

Planck, Astron. Astrophys. **641** (2020) A6
DESI, 2406.14554

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

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

Direct mass experiments

- Direct, model-independent access to neutrino mass

$\beta^{(-)}$ decay

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

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

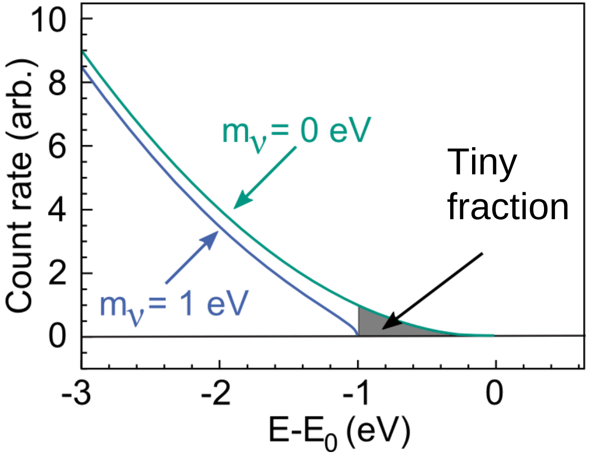
Measurement of kinetic energy of electron

Electron capture

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

Measurement of internal excitation of daughter atom

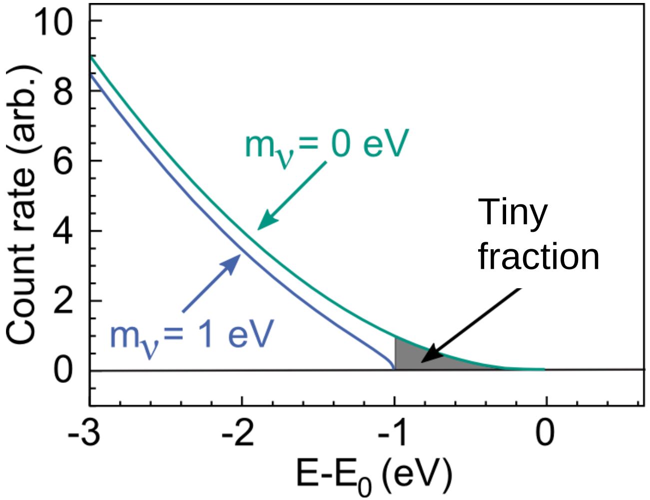
$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\bar{\nu}_i}^2 c^4}$$



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

Challenges for achieving mass low sensitivity

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



Low kinematic endpoint, high decay rate

	β-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

This talk

See Talk
06 Sep, 17:50

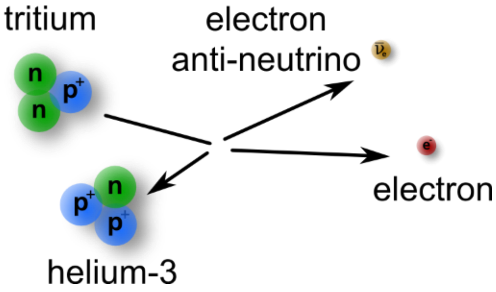
Elena Ferri

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

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

Tritium beta decay experiments

- Direct, model-independent access to neutrino mass

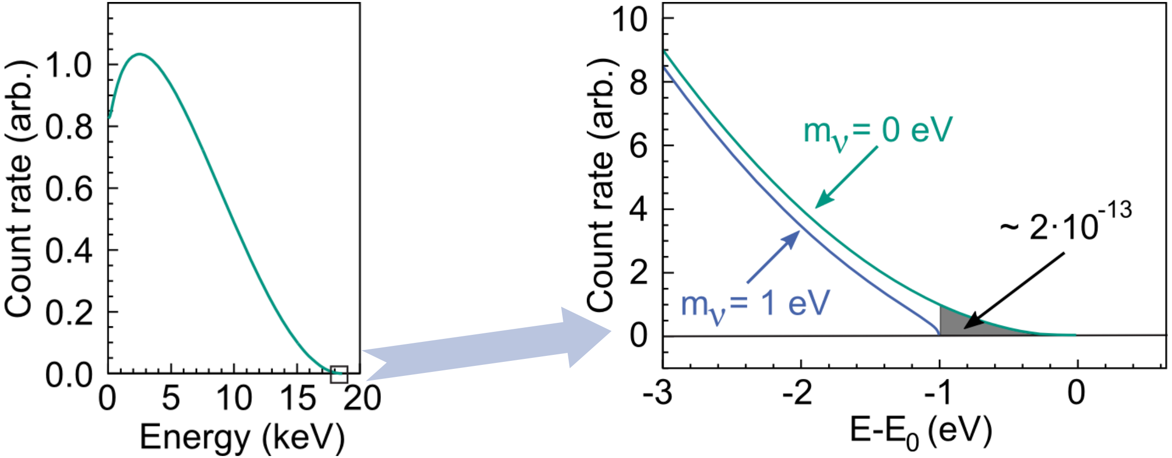


$$m_\beta^2 = \sum_i |U_{ei}|^2 \, m_i^2$$

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

E_0 = 18.6 keV

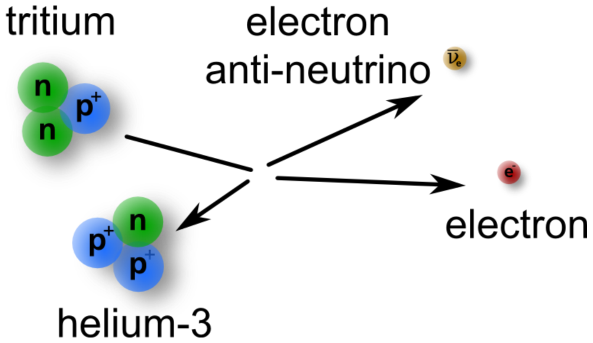
$T_{1/2}$ = 12.3 y



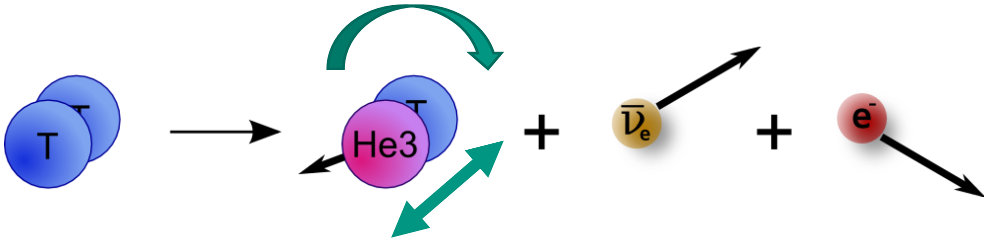
KATRIN’s aim: Measurement of m_ν with a sensitivity of 0.2 eV/c²

Molecular decay

Atomic decay

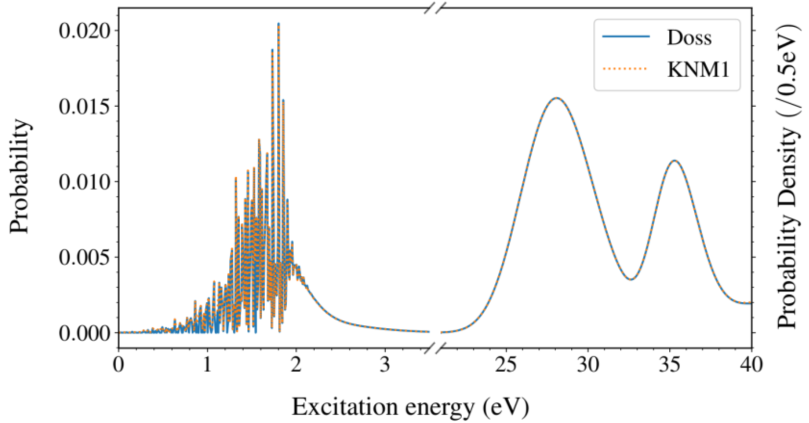


Decay from a molecule



+ 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

CRES

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

PROJECT 8

QTNM
Quantum Technologies for Neutrino Mass

MAC-E filter

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

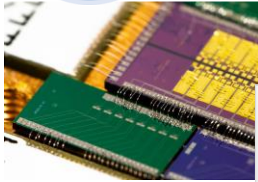
KATRIN
Karlsruhe Tritium Neutrino Experiment

Calorimeters

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

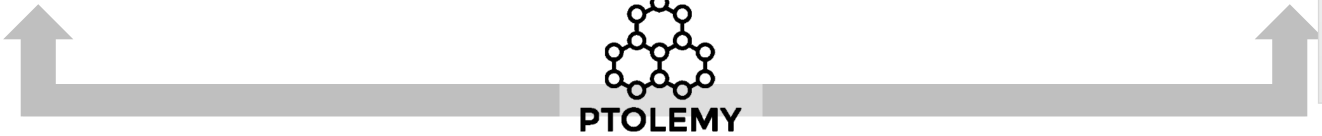
ECHo

HOLMES

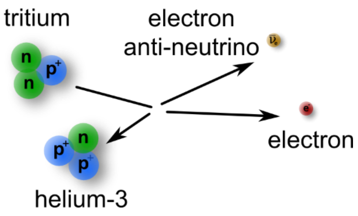


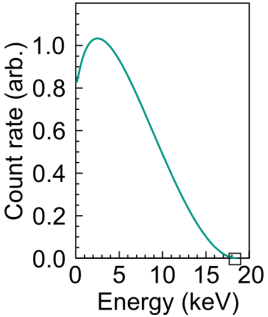
See Talk
06 Sep, 17:50

Elena Ferri

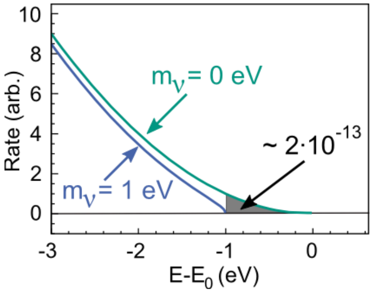


Basic principle of KATRIN-like experiment



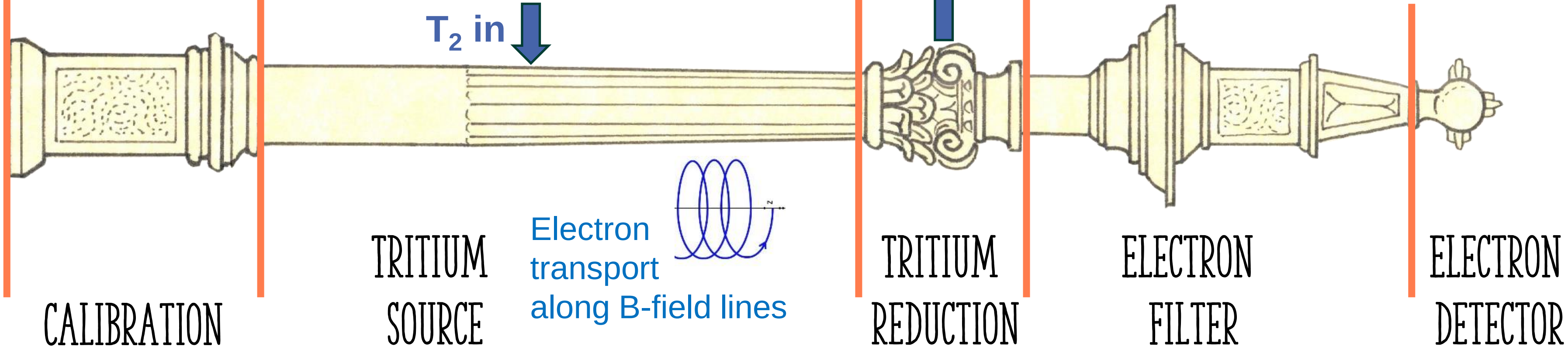


Electron transmission if above filter potential



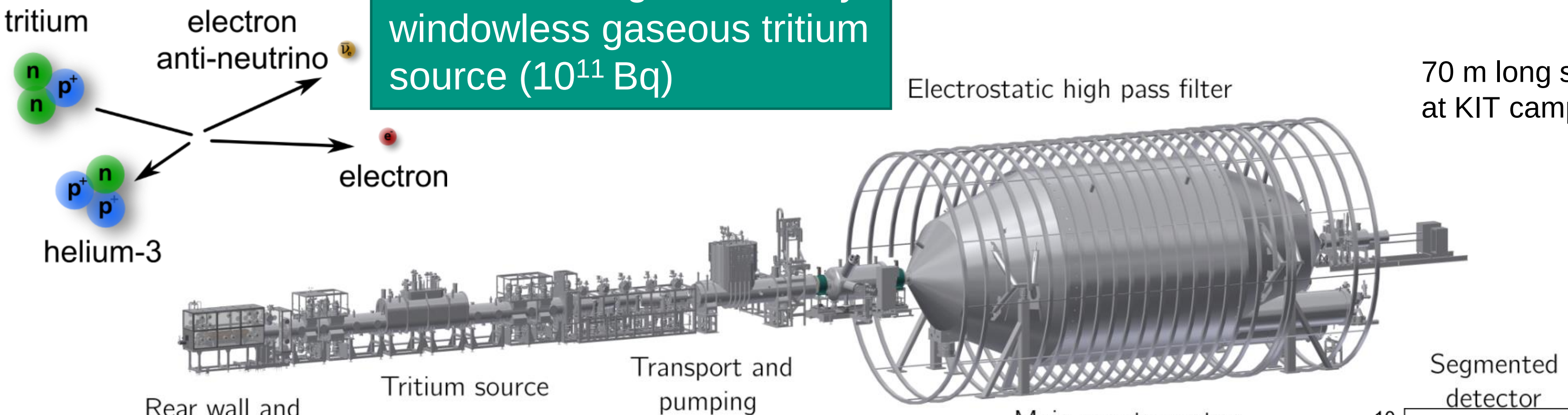
T_2 out

T_2 in



Electron transport along B-field lines

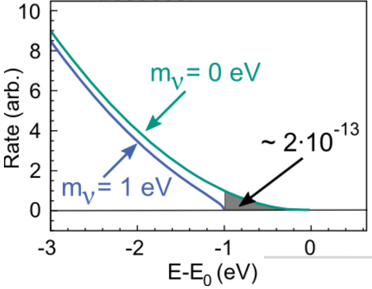
Karlsruhe Tritium Neutrino Experiment (KATRIN)



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

70 m long setup
at KIT campus north

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



JINST **16** T08015 (2021)

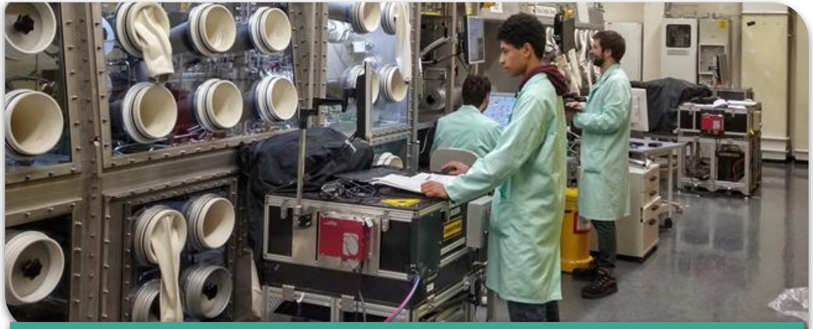
KATRIN's aim: Direct measurement of m_ν with a sensitivity of 0.2 eV/c²

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 timeline

2019-2025	2026-2027	2028-2034	Scientific goal
Phase 1 (Integral) Neutrino mass	Phase 2 (Differential) keV sterile ν	**R&D Phase for KATRIN++** Atomic Tritium Demonstrator Differential detection demonstrators	Neutrino mass

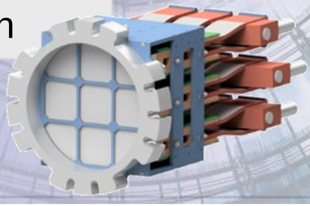
See Talk
06 Sep, 18:10

Richard Salomon
Details of the latest KATRIN data analysis

This talk

See Talk
04 Sep, 18:50

Andrea Nava
KATRIN: keV sterile neutrino search



TRISTAN detector

This talk

KATRIN data releases and neutrino mass results

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

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

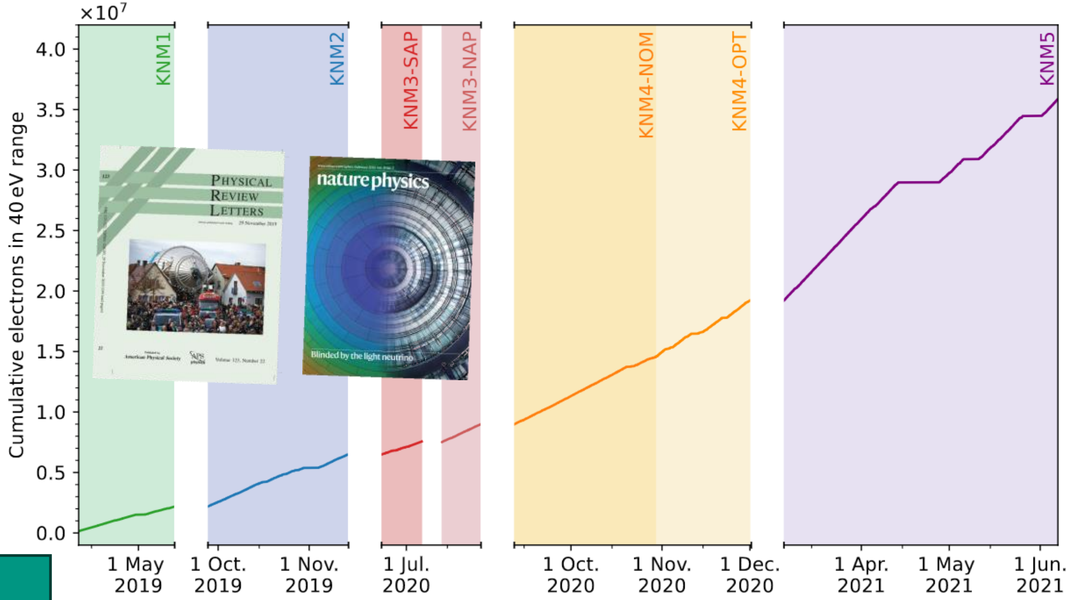
- ~**6** Mio counts

Current data set

- **259** measurement days
- **1757** β-scans
- ~**36** Mio counts

Expected sensitivity < 0.5 eV

First 5 campaigns:
taking data while finding optimal operation conditions

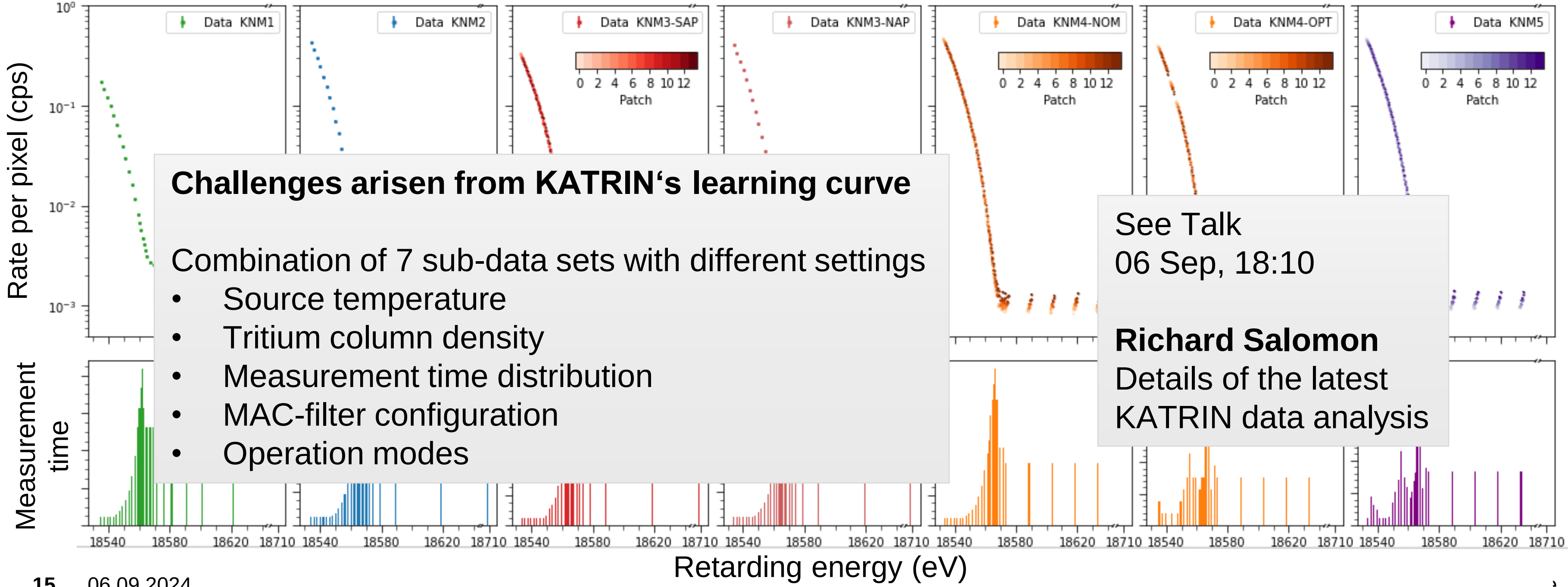


PRL 123 (2019) 221802
PRD 104 (2021) 012005

Nature Phys. 18 (2022) 160

Data combination challenges

59 stacked spectra with
27 + **28** + **14 x 28** + **28** + **14 x 28** + **14 x 25** + **14 x 28** =
1609 data points



Challenges arisen from KATRIN‘s learning curve

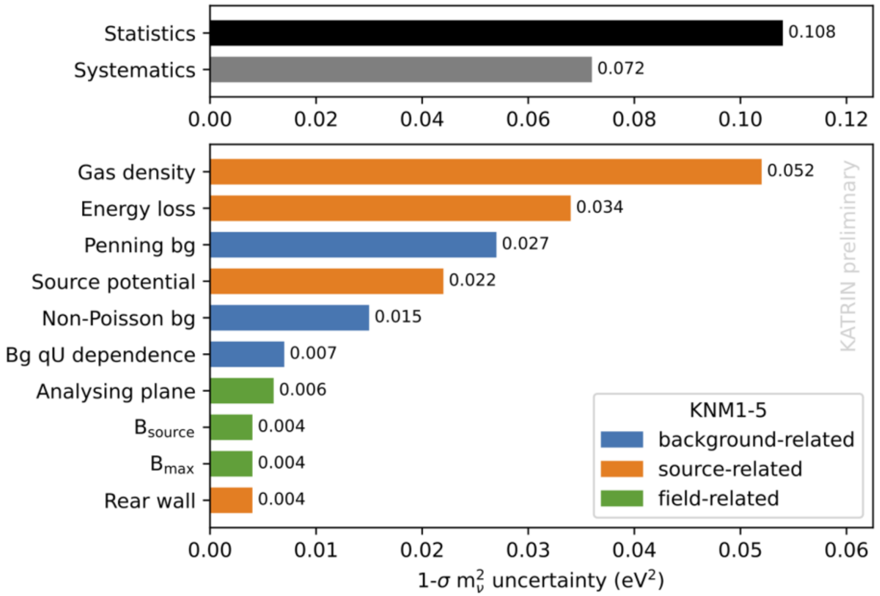
Combination of 7 sub-data sets with different settings

- Source temperature
- Tritium column density
- Measurement time distribution
- MAC-filter configuration
- Operation modes

See Talk
06 Sep, 18:10

Richard Salomon
Details of the latest KATRIN data analysis

Systematic uncertainties



- Statistical uncertainties dominate
- Significant reduction of the background-related systematics
- Better control over source scattering
- Increased conservative uncertainties in this release
  - Reduced uncertainties in current data
  - Reduction of the molecular final-states uncertainties

Forecast: individual systematics in final KATRIN analysis (post 2025) expected to be > 0.01 eV^2 range

New best fit and upper limit

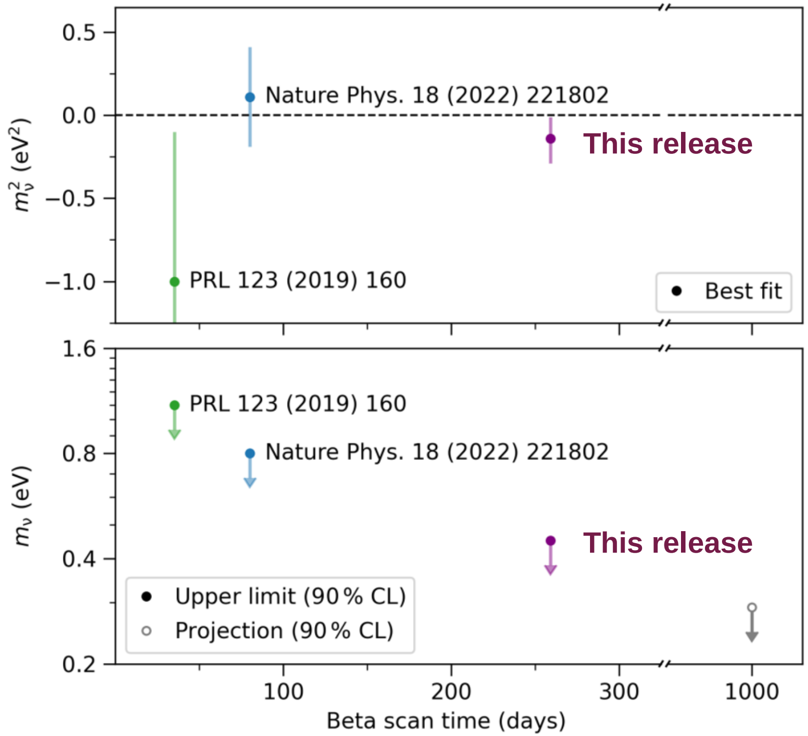
New best fit compatible with vanishing neutrino mass

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

Resulting in an new upper limit

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

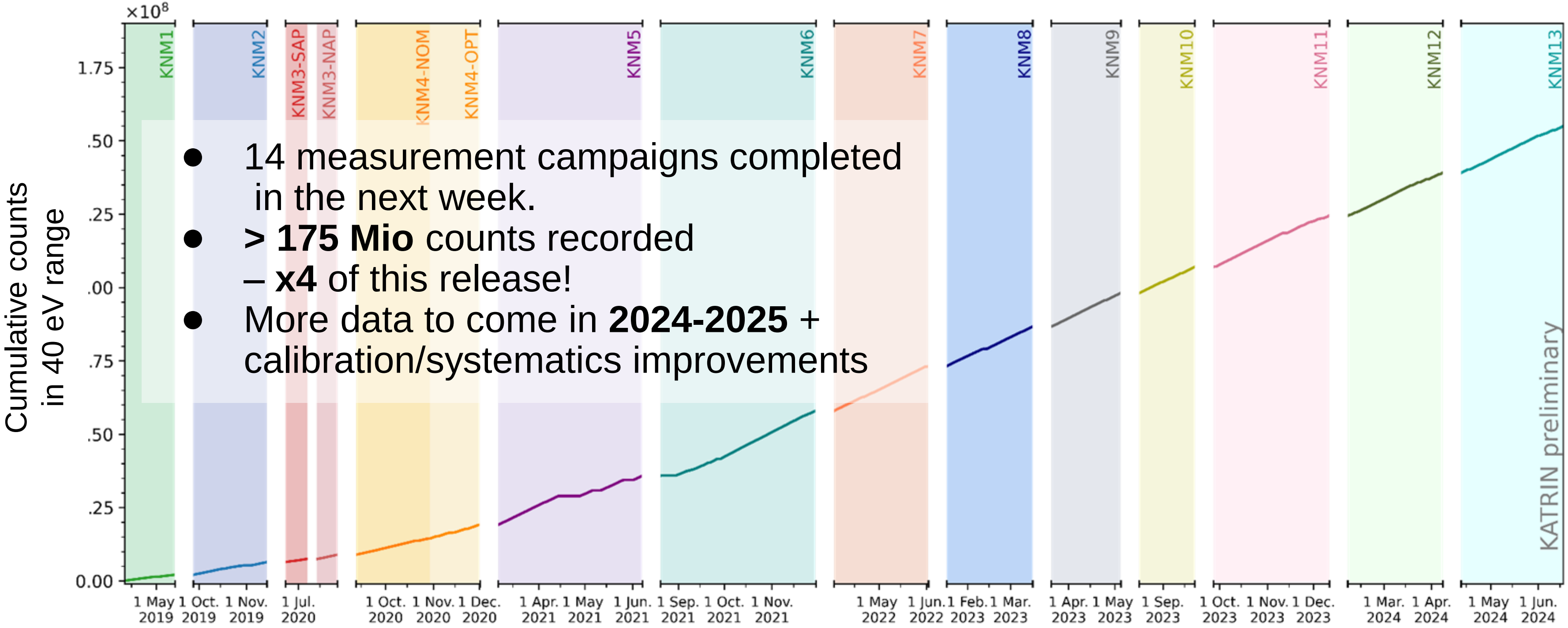
New KATRIN release improves
direct neutrino-mass bound by a factor of 2



https://arxiv.org/abs/2406.13516

KATRIN data taking continues

Ongoing data taking through **2025 → Σ 1000 days** ➔ **target sensitivity below 0.3 eV**



- 14 measurement campaigns completed in the next week.
- **> 175 Mio** counts recorded – **x4** of this release!
- More data to come in **2024-2025** + calibration/systematics improvements

Established measurement principles

CRES

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

PROJECT 8

QTNM
Quantum Technologies for Neutrino Mass

MAC-E filter

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KATRIN
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- Low-temperature micro calorimeters
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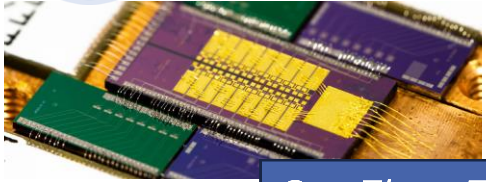
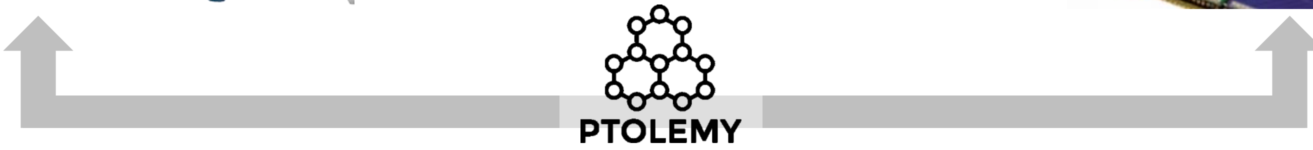
ECHo

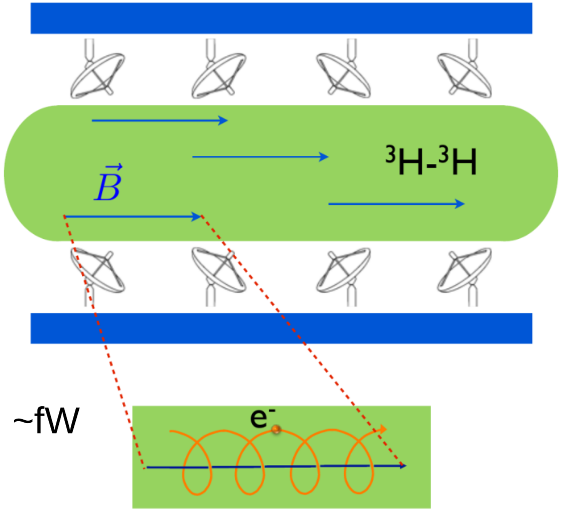
HOLMES



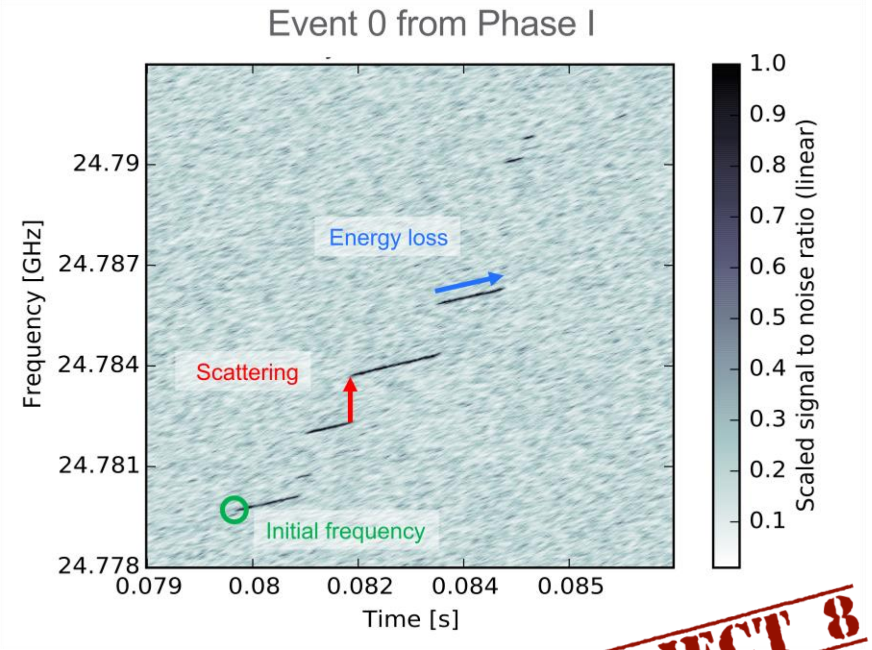
See Elena Ferri



Cyclotron Radiation Emission Spectroscopy



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



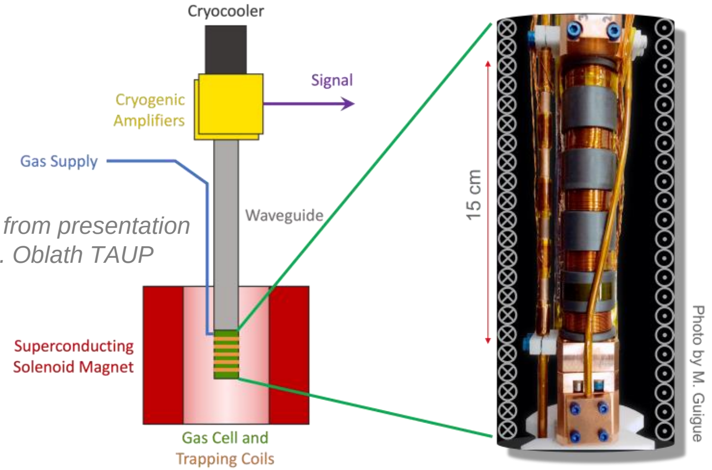
PROJECT 8

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

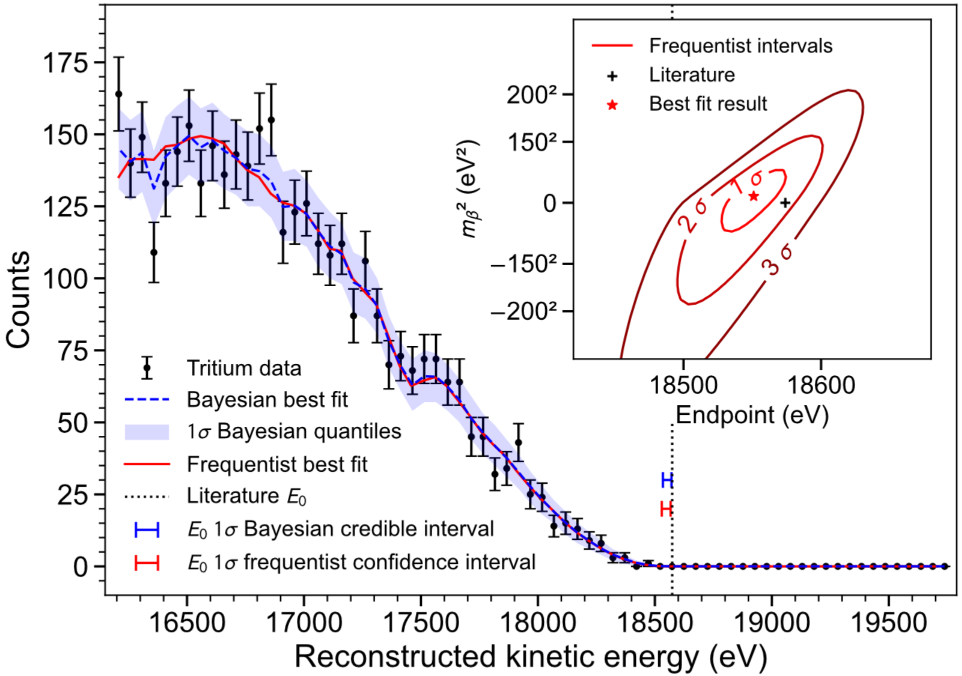
→ Frequency measurement

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)



Copied from presentation by N. S. Oblath TAUP 2023



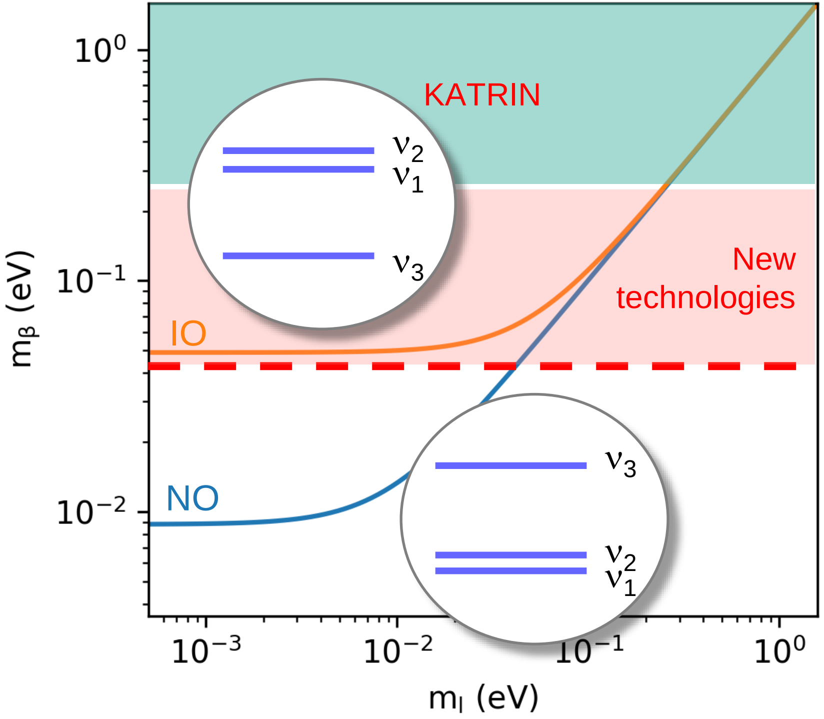
A. Ashtari Esfahani et al.Phys. Rev. Lett. 131, 102502 (2023)

Outline

2019-2025	2026-2027	2028-2034	Scientific goal
Phase 1 (Integral) Neutrino mass	Phase 2 (Differential) keV sterile ν	**R&D Phase for KATRIN ++** Atomic Tritium Demonstrator Differential detection demonstrators	Neutrino mass

- **KATRIN** on way to achieve 1000 d measurement time **(final sensitivity m_β < 0.3 eV).**
  Next m_β result : ~ **0.5 eV sensitivity**
- We will be ready for **TRISTAN**-Operation at the end of 2025 (**Search for keV sterile neutrinos)**

Going beyond KATRIN

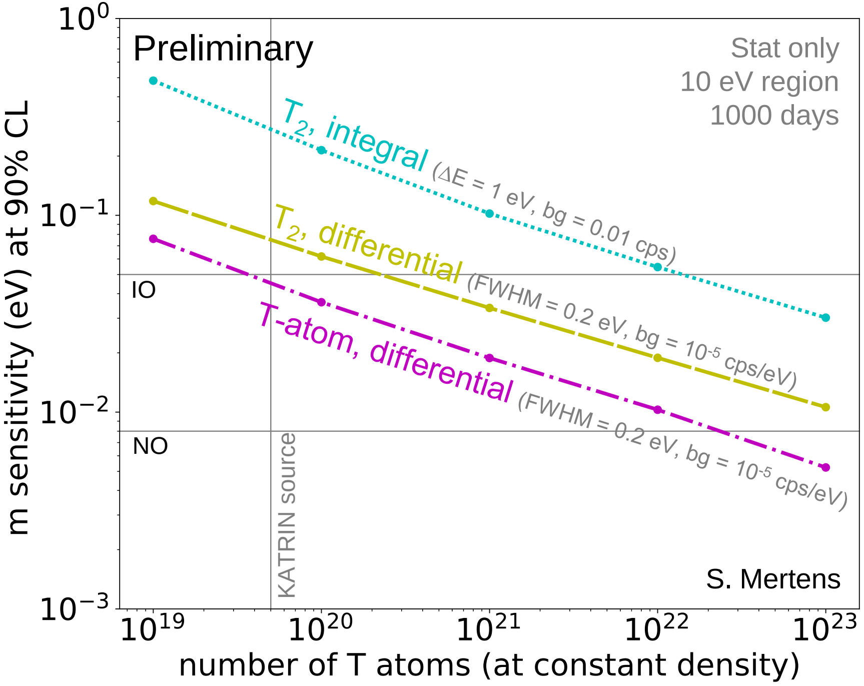


- KATRIN final: < 0.3 eV (90% CL)
  Distinguish between **degenerate** and **hierarchical** scenario
- New technologies: < **0.05 eV**
  Cover **inverted** ordering

KATRIN++ mission

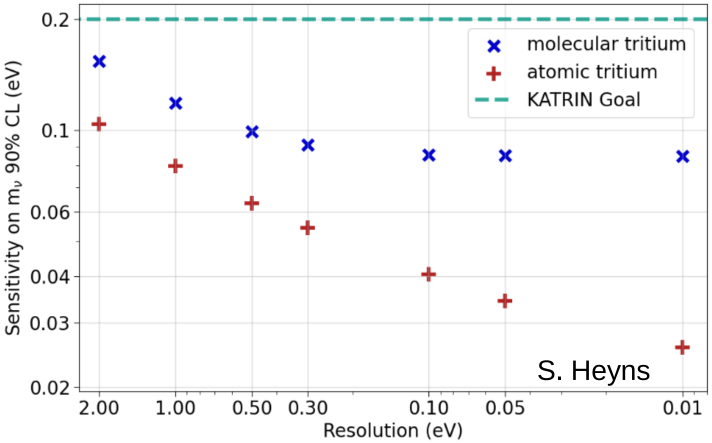
- Next generation m_ν experiment
- Identify and develop scalable technology
- Use KATRIN/TLK infrastructure
  for R&D phase (~ 7 years)

Going beyond KATRIN



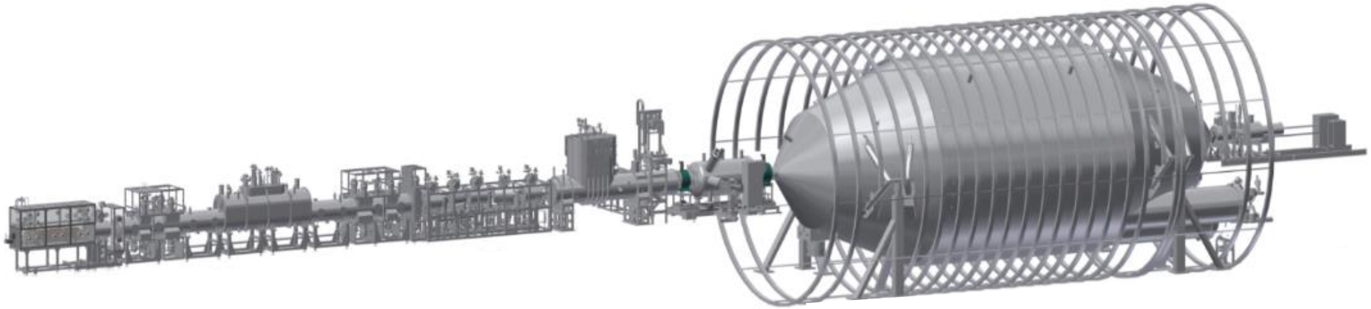
Current KATRIN performance (integral, ΔE = 2.7 eV, bg = 0.1 cps)

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



KATRIN and TLK as ideal R&D facilities

Differential detector technology



Atomic source technology

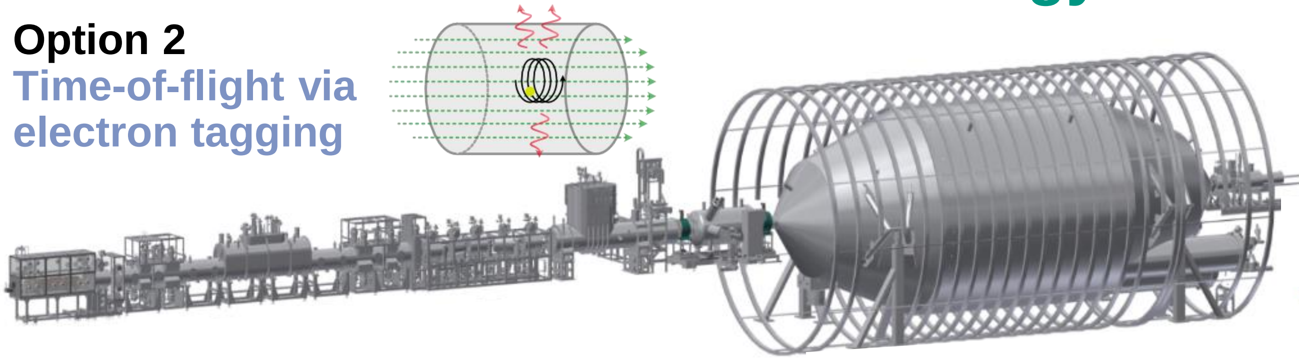
KATRIN and TLK as ideal R&D facilities

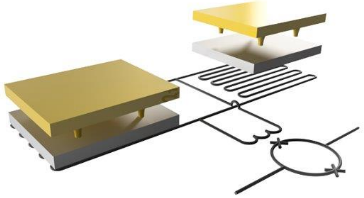
Further options?

Technologies by community?

Differential detector technology

Option 2
Time-of-flight via electron tagging

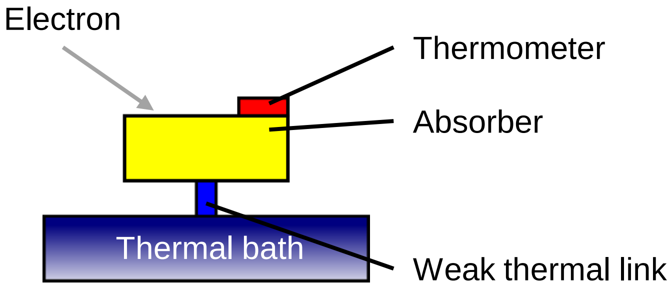


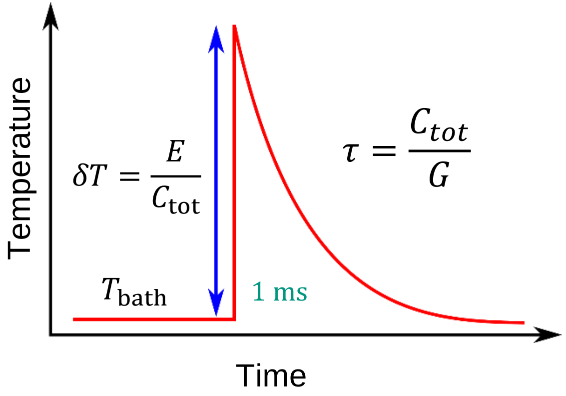


- eV resolution for **differential** detection
- **immune to** Rydberg-like **backgrounds**

Option 1
Micro-calorimeters / Quantum sensor

Quantum sensors as high resolution differential detectors



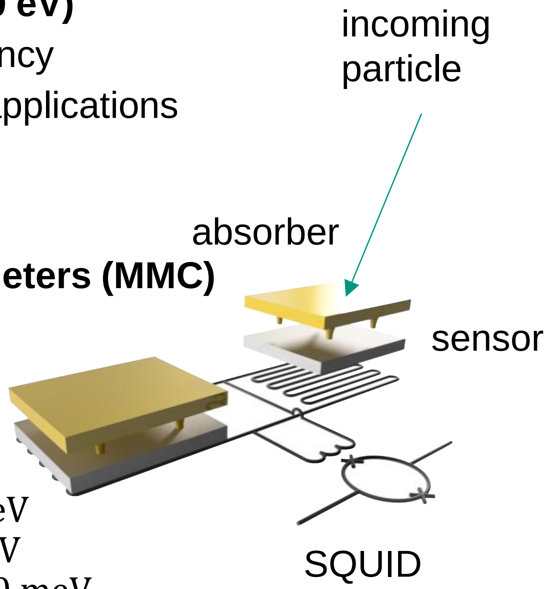


Advantages

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

e.g. Metallic Magnetic Calorimeters (MMC)

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

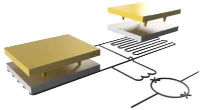


Not yet tested with external electrons

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

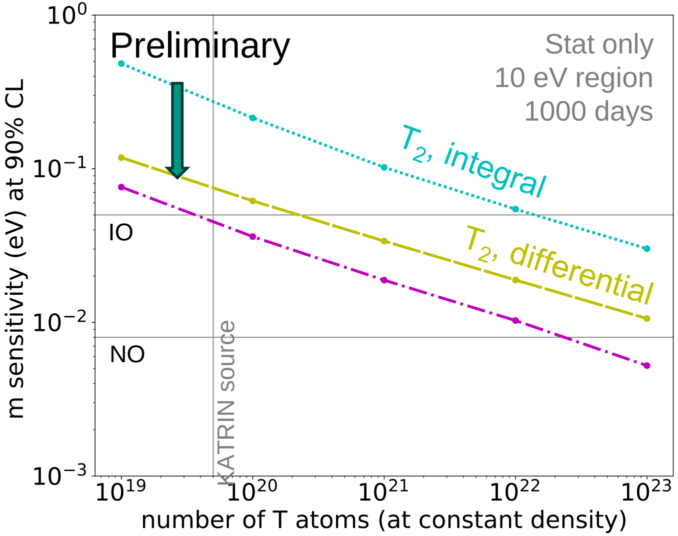
Use existing / well-characterised beamline

+ *10^6 x*



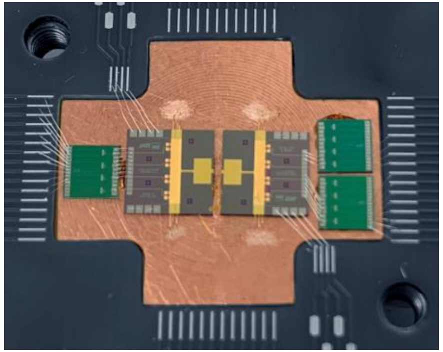
with Milano‘s cryo expertise

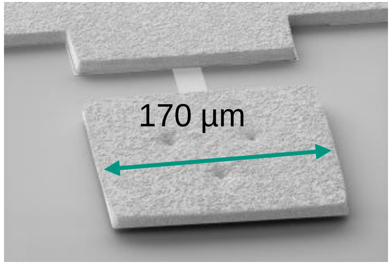
- Challenges of coupling **quantum sensor detector array to KATRIN infrastructure**
  - **Type** of quantum sensor
  - Operation in **magnetic field (~10 mT)**
  - Coupling of **mK cryo-platform** with RT spectrometer
  - Large area detector and **multiplexing of ~1e6 channels**
  - **Limits to energy resolution**



ELECTRON: *e*⁻ spectroscopy with quantum sensors

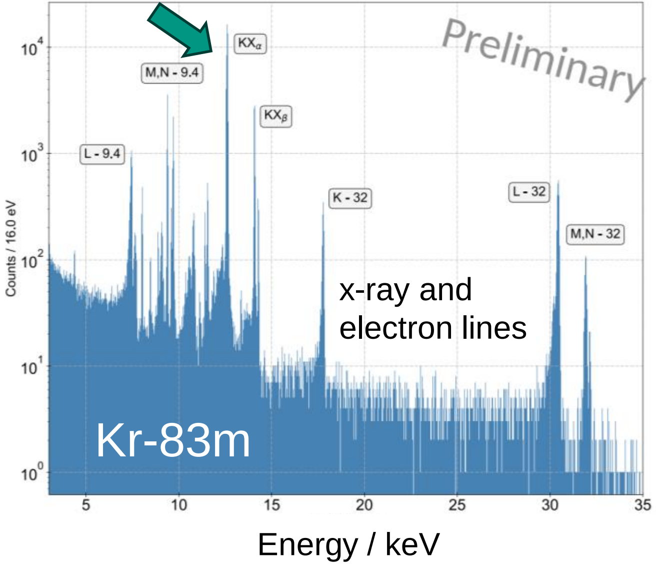
8 channel detector chips
& front-end SQUID chips





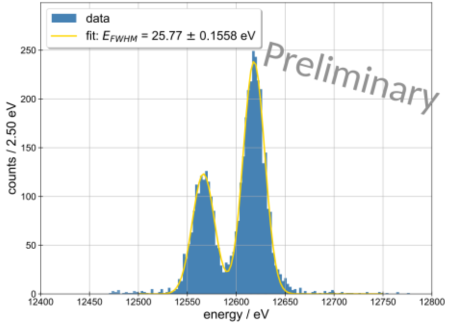
KIT-IMS (Kempf group)

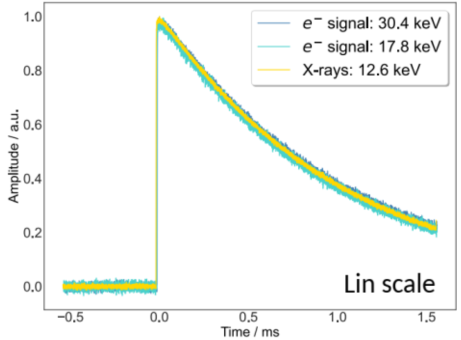
Metallic Magnetic Calorimeters (MMC)



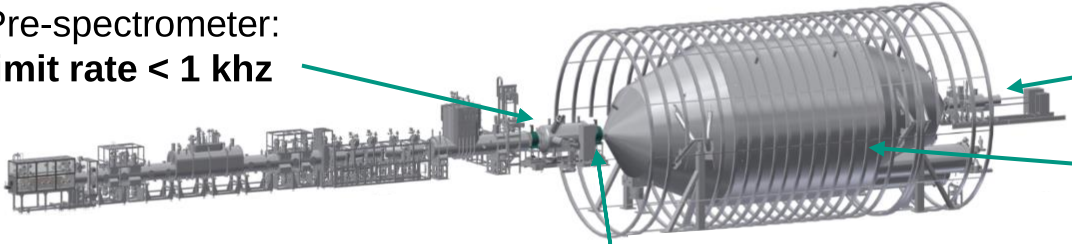
Calorim. Kr-83m spectrum @ highest resolution
Next: tritium spectroscopy

FWHM ~ 25 eV





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



Pre-spectrometer:
limit rate < 1 khz

Fast detector: **stop**

Main spectrometer:
delay line due to retardation pot.

KATRIN Source:
10^{11} Bq

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

Single electron tagging is challenging

Cyclotron radiation emission detection (CRES)

Coreless cryogenic current comparator

Tiny signals vs. minimal noise floor

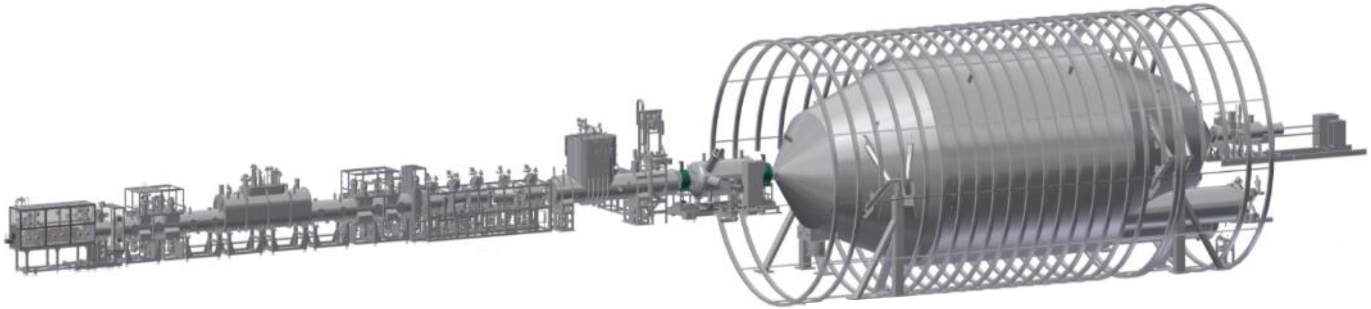
R&D ongoing at U North Carolina

Strategy

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

KATRIN and TLK as ideal R&D facilities

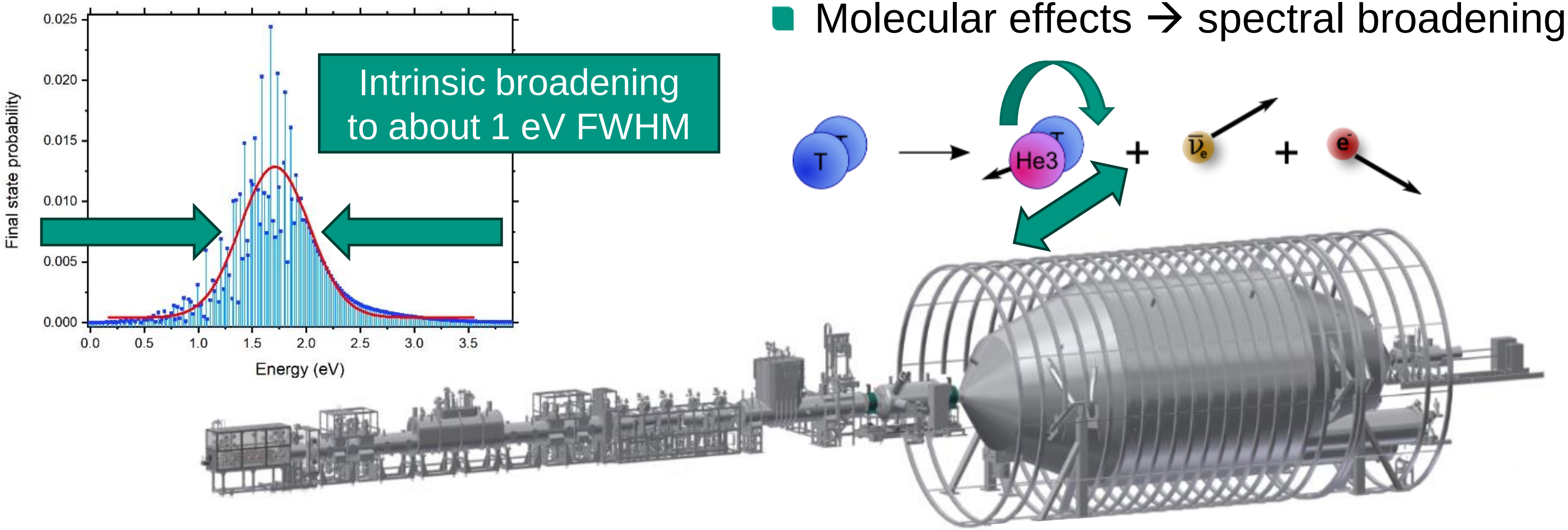
Differential detector technology



Atomic source technology

KATRIN and TLK as ideal R&D facilities

- Molecular effects → spectral broadening



Intrinsic broadening to about 1 eV FWHM

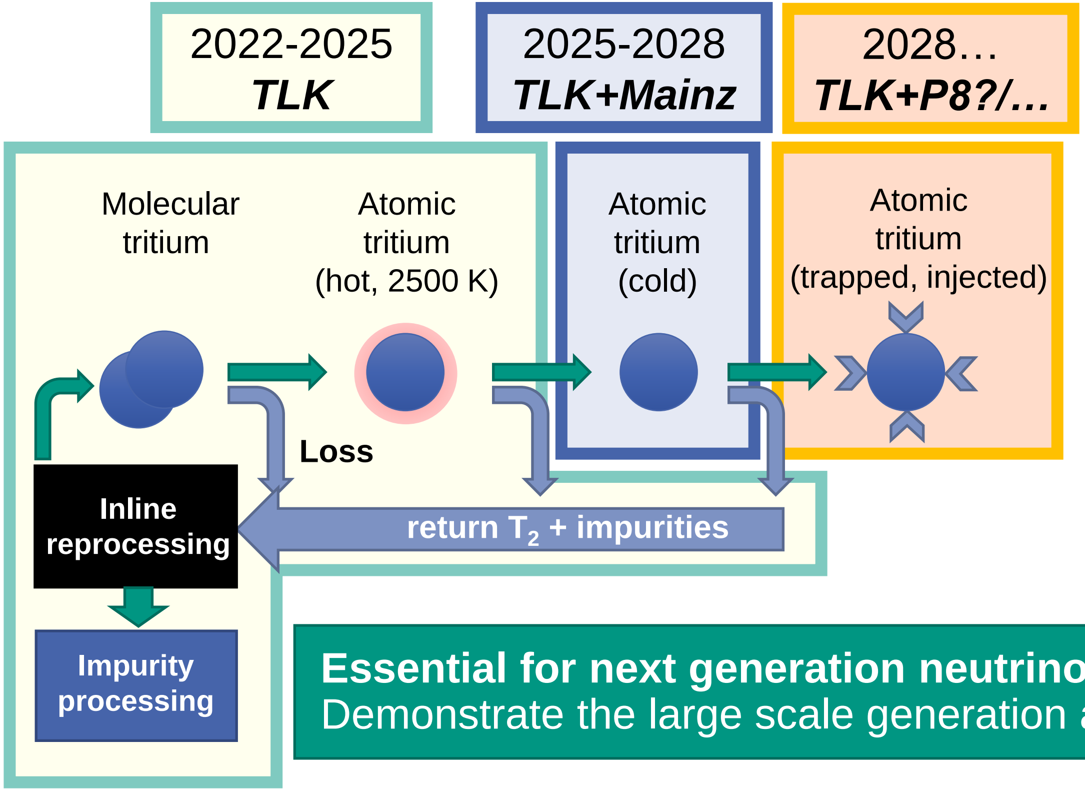
Atomic source technology

- Atomic source cannot be adapted to existing KATRIN beamline

QTNM Quantum Technologies for Neutrino Mass

PROJECT 8

Atomic Tritium Demonstrator at TLK

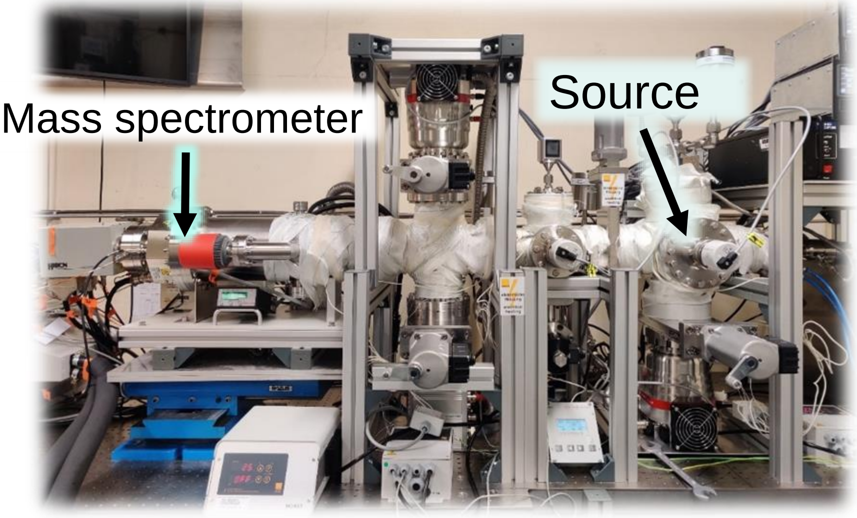


- **Aim for investigation**
  - Develop atom cooling mechanism
  - Trapping times / max. densities
  - Interplay of beta-driven plasma (meV−eV) and ultra-cold trapped atoms (neV)

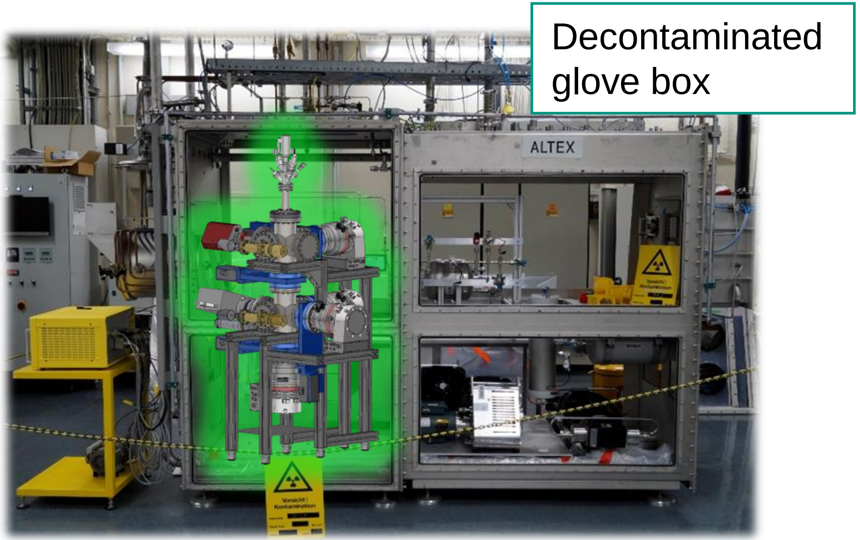
Tritium atom throughput on the order of 10 g/day (c.f. KATRIN: 40 g/day)

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

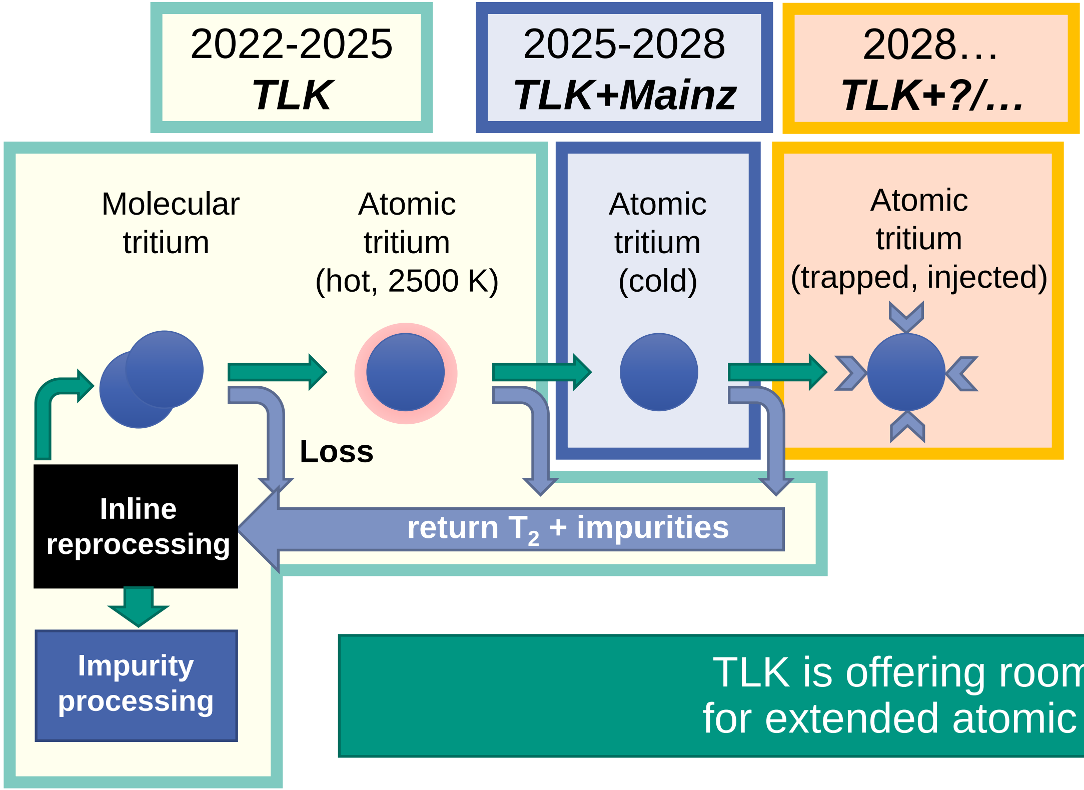


- Non-tritium hydrogen cracker being operated
- **Characterization measurements for tritium beamline ongoing**



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

Atomic Tritium Demonstrator at TLK



2022-2025
TLK

2025-2028
TLK+Mainz

2028…
TLK+?/…

Molecular tritium

Atomic tritium (hot, 2500 K)

Atomic tritium (cold)

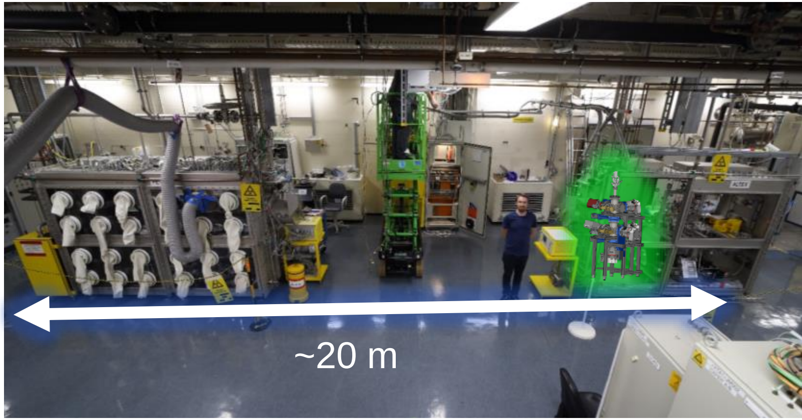
Atomic tritium (trapped, injected)

Loss

return T_2 + impurities

Inline reprocessing

Impurity processing



TLK is offering room and infrastructure
for extended atomic tritium experiments

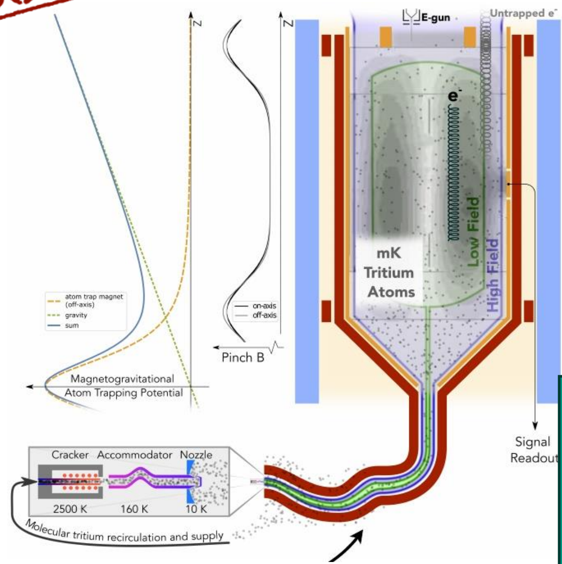
CRES plans aiming at 40-50 meV sensitivity

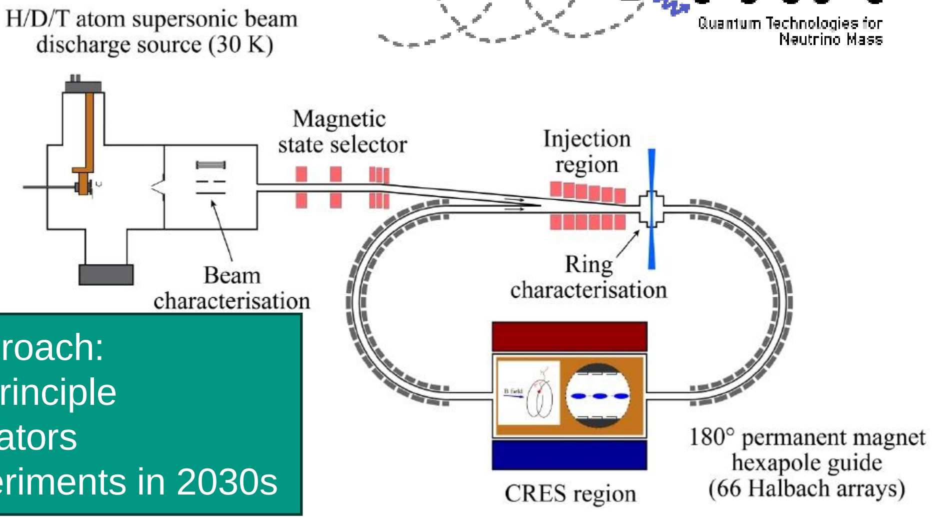
PROJECT 8

https://www.project8.org/

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

QTNM
Quantum Technologies for Neutrino Mass



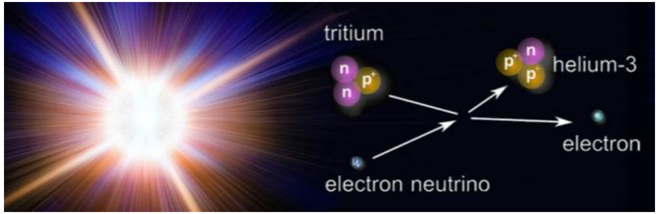


Staged approach:
- Proof-of-principle
- Demonstrators
- Final experiments in 2030s

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

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

Future of direct neutrino mass detection

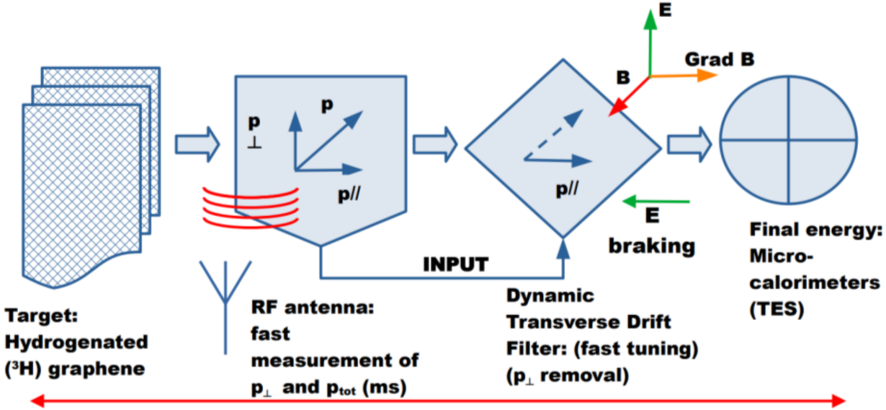


PTOLEMY

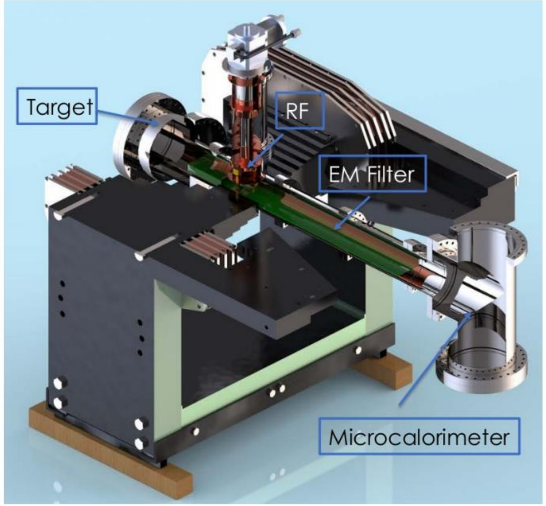
- Aim: direct detection of big-bang neutrinos; determination of neutrino mass is „by-product“

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

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



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

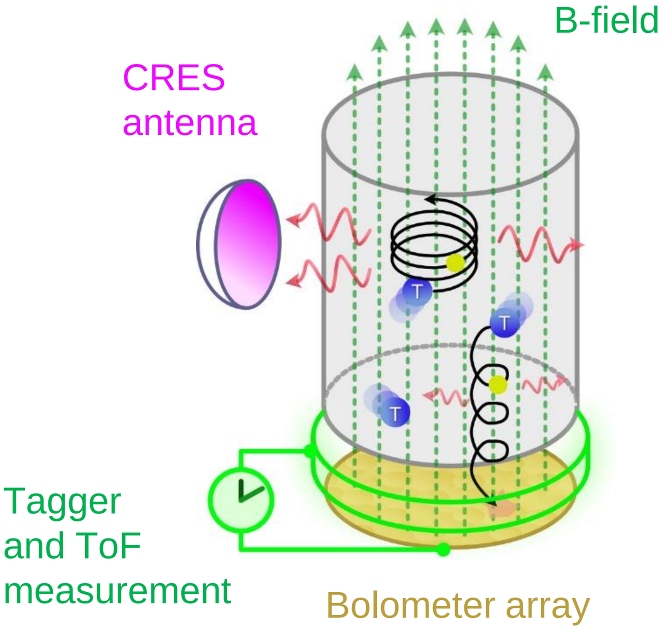


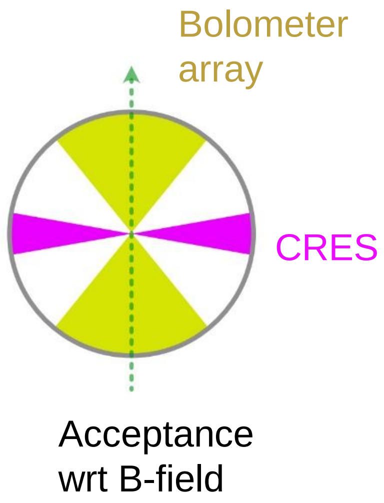
Combine technologies (TES, CRES, novel drift filter) with large scale *O*(100g) tritiated graphene target

Start of technology demonstrator @LNGS soon

KATRIN++ and other next generation projects

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



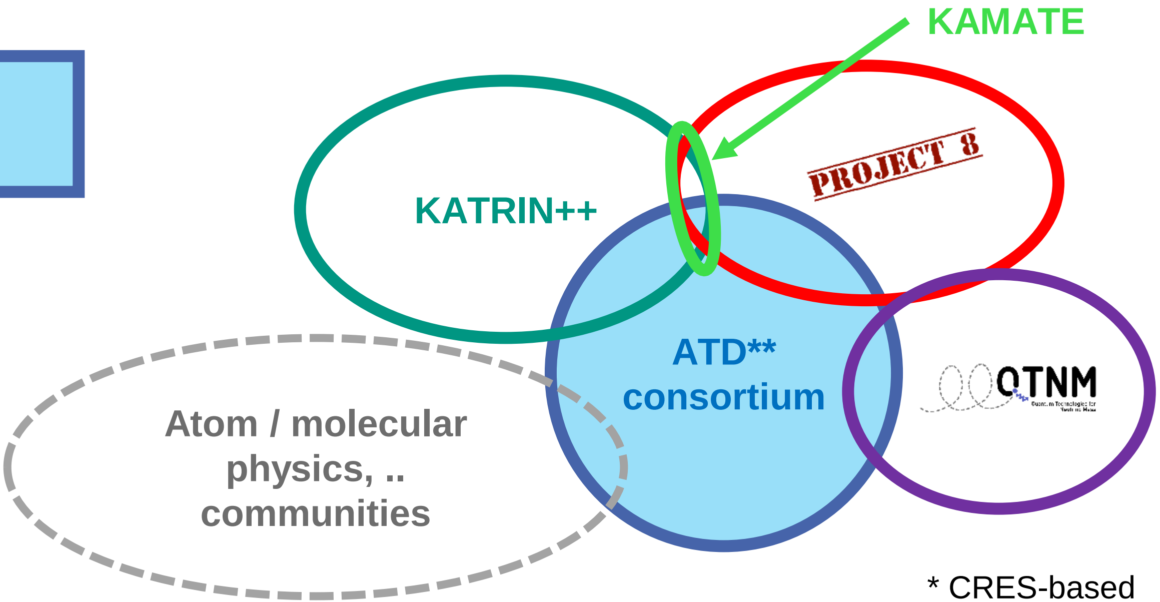


Atomic source research

Atomic tritium trap is key independently of detection techniques

Mission: Realize (global) Atomic Tritium Demonstrator (at TLK)

Form joint working group
(kick-off meeting in September)


KAMATE

KATRIN++

ATD**
consortium

Atom / molecular
physics, ..
communities

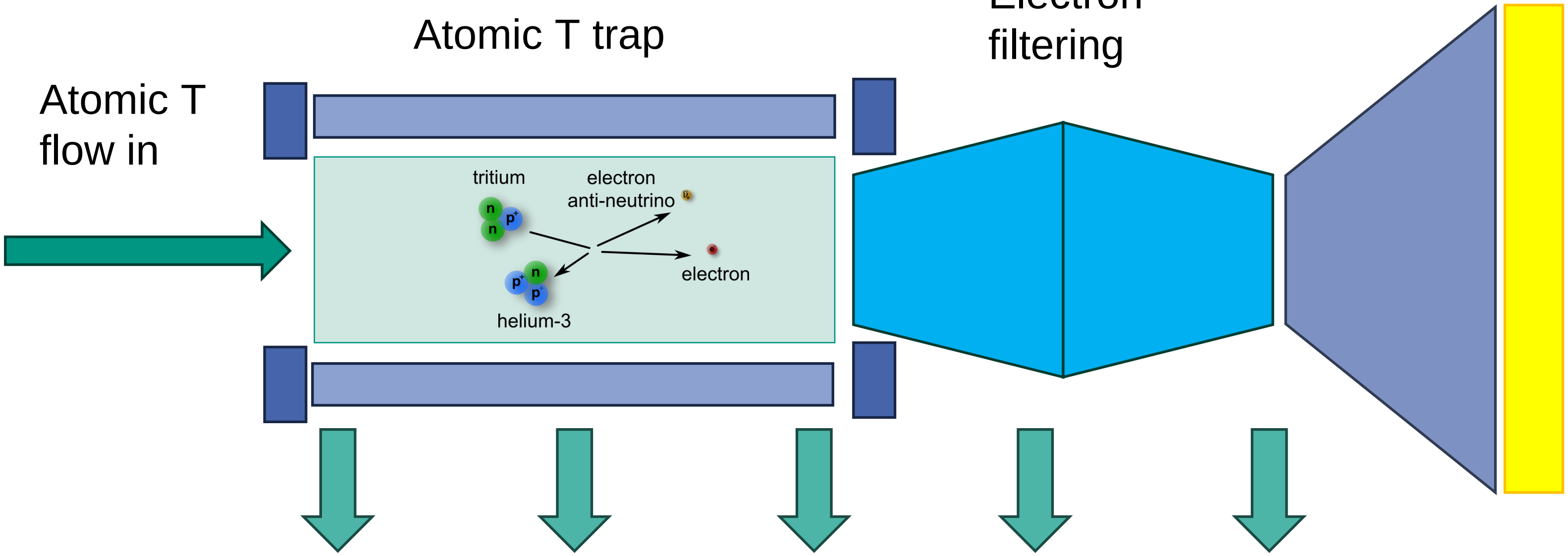
* CRES-based

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

**placeholder name

Final R&D goal
Atomic tritium with Quantum sensor array

Conceptual idea

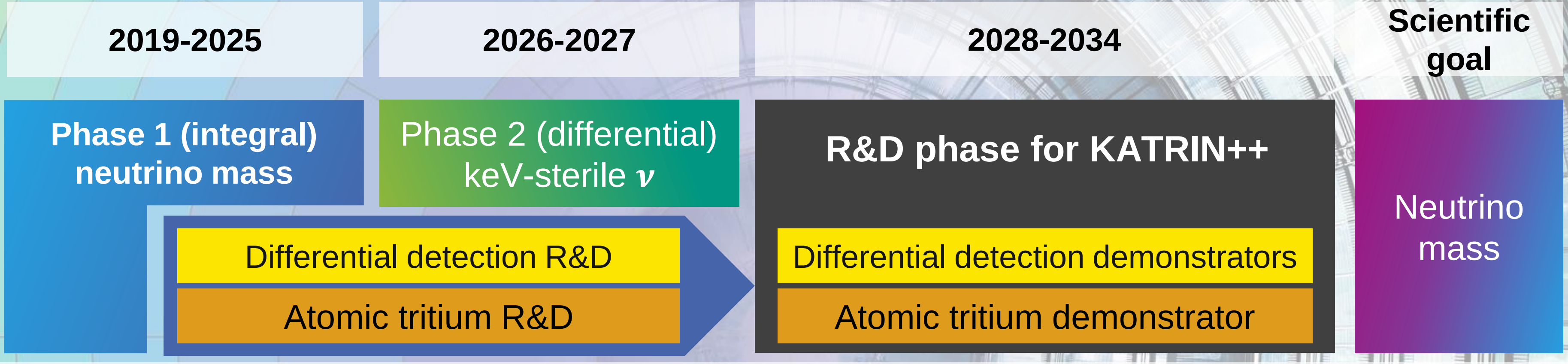


Sensor array

Flow out

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 ν

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

KATRIN collaboration

Collaboration meeting, March 2024, TUM

https://www.linkedin.com/company/tritiumlab/

Karlsruher Institut für Technologie

BERKELEY LAB

Nuclear Physics Institute

BERGISCHE UNIVERSITÄT WUPPERTAL

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Max-Planck-Institut für Physik

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Carnegie Mellon University

Universität Münster

UAM Universidad Autónoma de Madrid

UNIVERSITÄT BONN

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN

POLITECNICO MILANO 1863

Chula Chulalongkorn University

Bundesministerium für Bildung und Forschung

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DFG

MAX PLANCK GESELLSCHAFT

U.S. DEPARTMENT OF ENERGY | Office of Science

Czech Republic: MŠMT MINISTRY OF EDUCATION, YOUTH AND SPORTS

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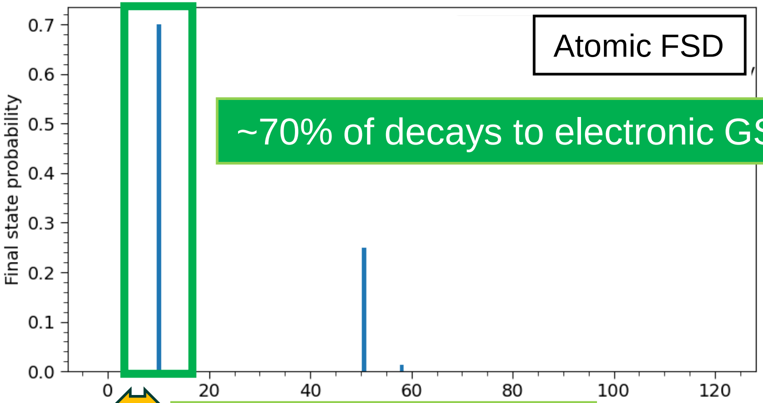
INFN

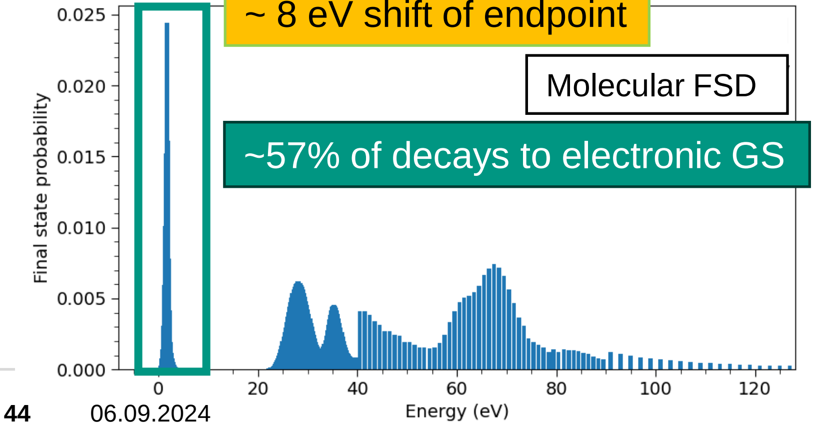
Atomic vs molecular tritium



Atomic FSD

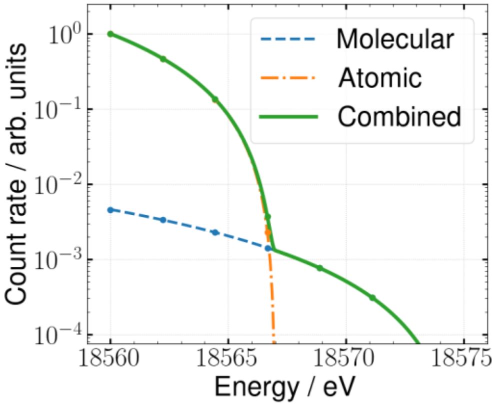
~70% of decays to electronic GS

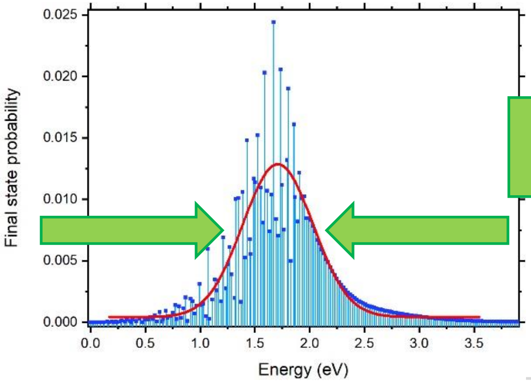
~ 8 eV shift of endpoint



Molecular FSD

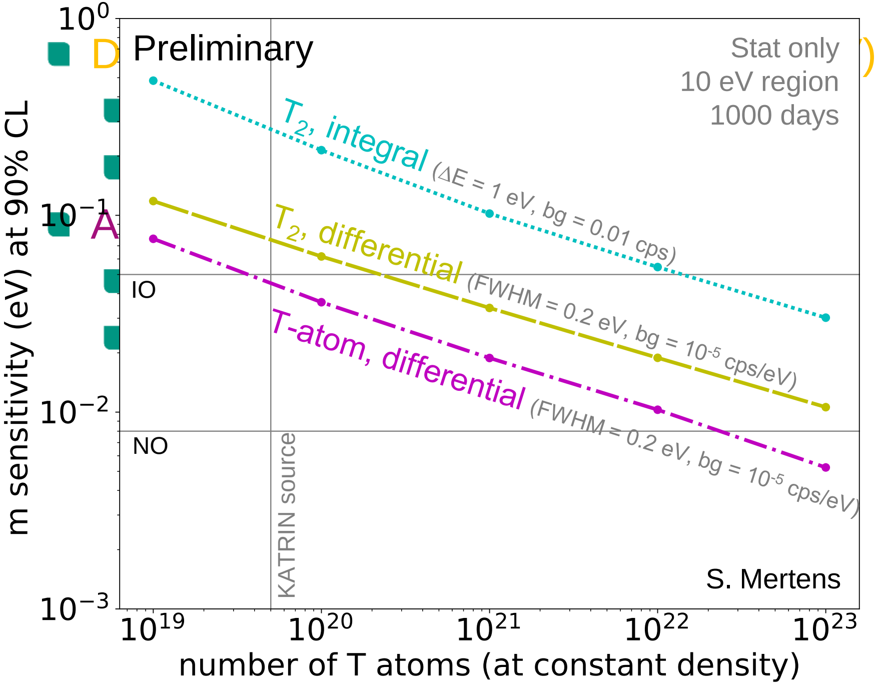
~57% of decays to electronic GS

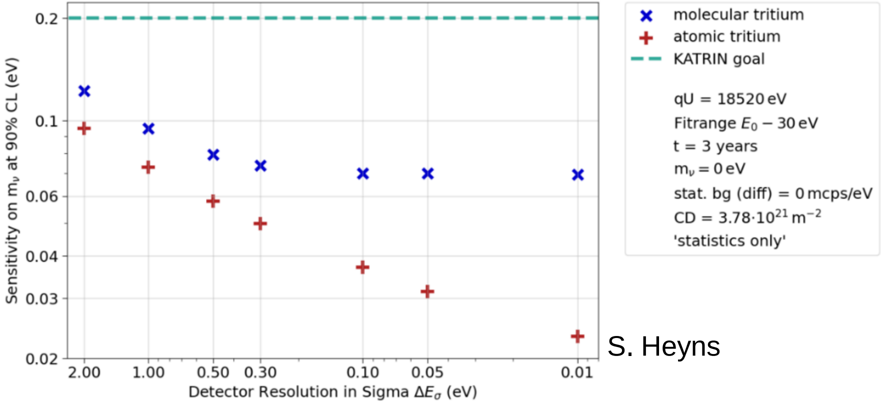




Intrinsic broadening to about 1 eV FWHM

Going beyond KATRIN



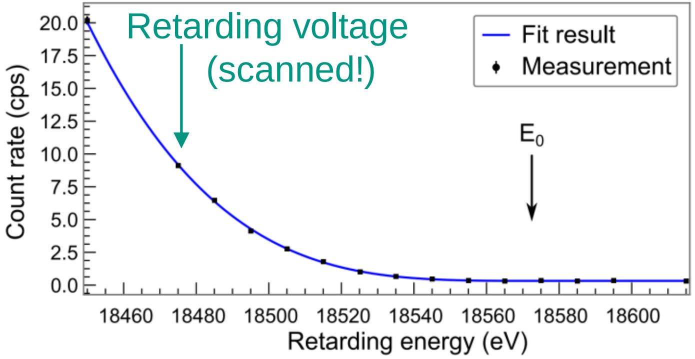


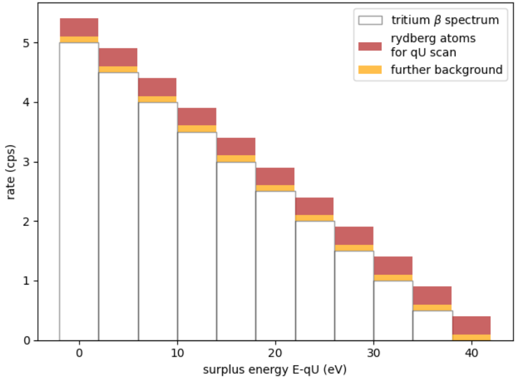
S. Heyns

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

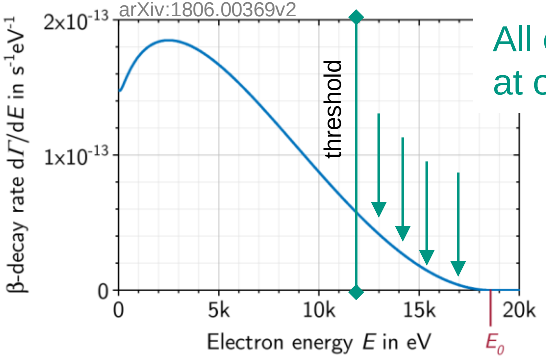
Improved measurement principle

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

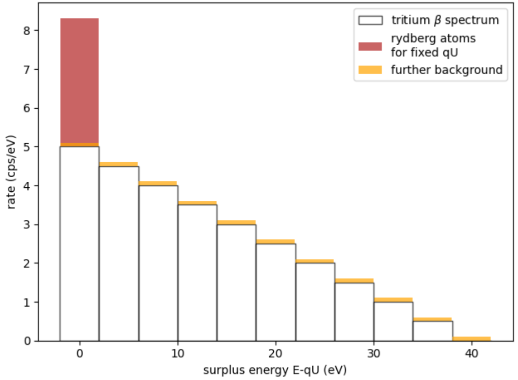




Differential measurement
- Energy resolution determined by
  - **A) detector**
  - or
  - **B) time of flight**



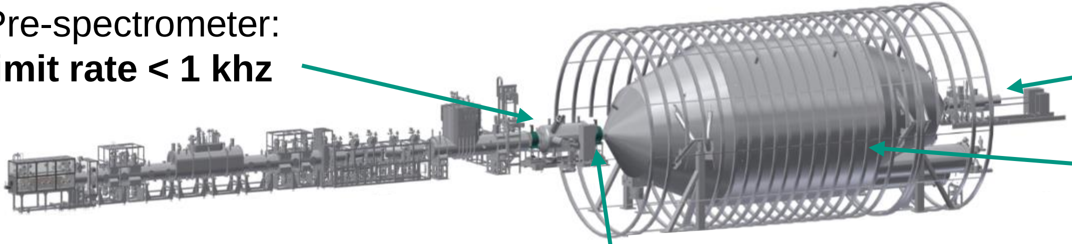
All energies at onces



More signal

Less background

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



Pre-spectrometer:
limit rate < 1 khz

Fast detector: **stop**

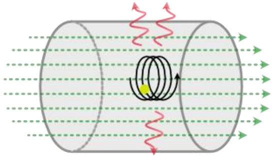
Main spectrometer:
delay line due to retardation pot.

KATRIN Source:
10^{11} Bq

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

Single electron tagging is challenging

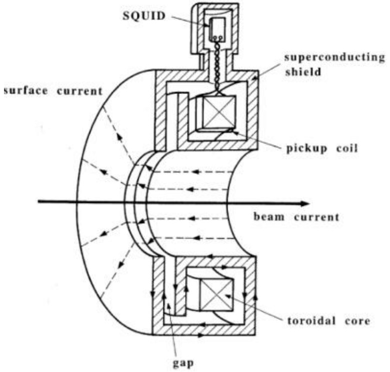
Cyclotron radiation emission detection (CRES)



See Project 8

Coreless cryogenic current comparator

Tiny signals vs minimal noise floor



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

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)

R&D ongoing at U North Carolina

KAMATE – Karlsruhe Mainz Atomic Tritium experiment

A. Lindman

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

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

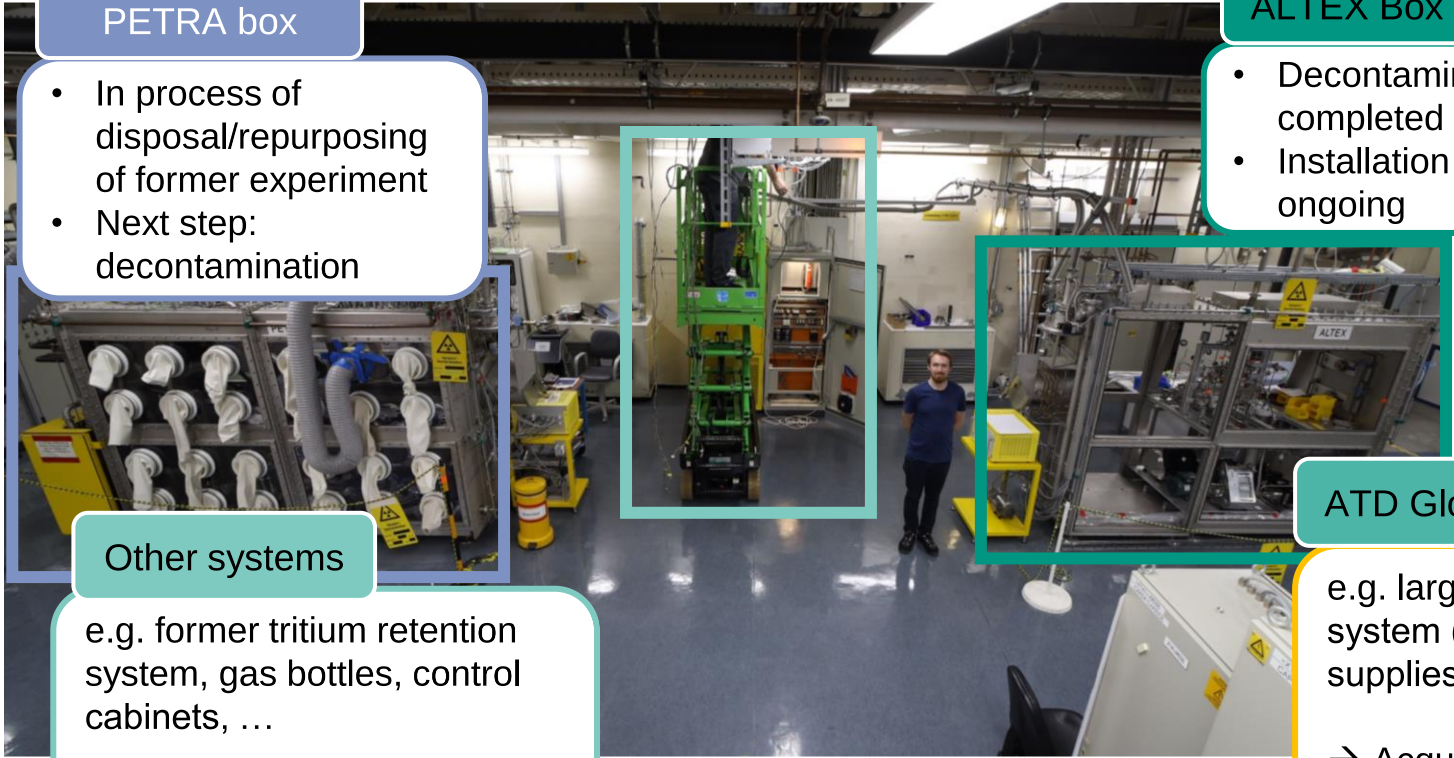
KAMATE 3.0 (at TLK)
Add nozzle for second stage cooling and beam temperature measurement setup (time of flight).
T(Beam) ~ 4 K

2028

Karlsruhe

Mainz

Preparing TLK for Atomic Tritium Demonstrator (ATD)



PETRA box

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

ALTEX Box

- Decontamination completed
- Installation ongoing

Other systems

e.g. former tritium retention system, gas bottles, control cabinets, …

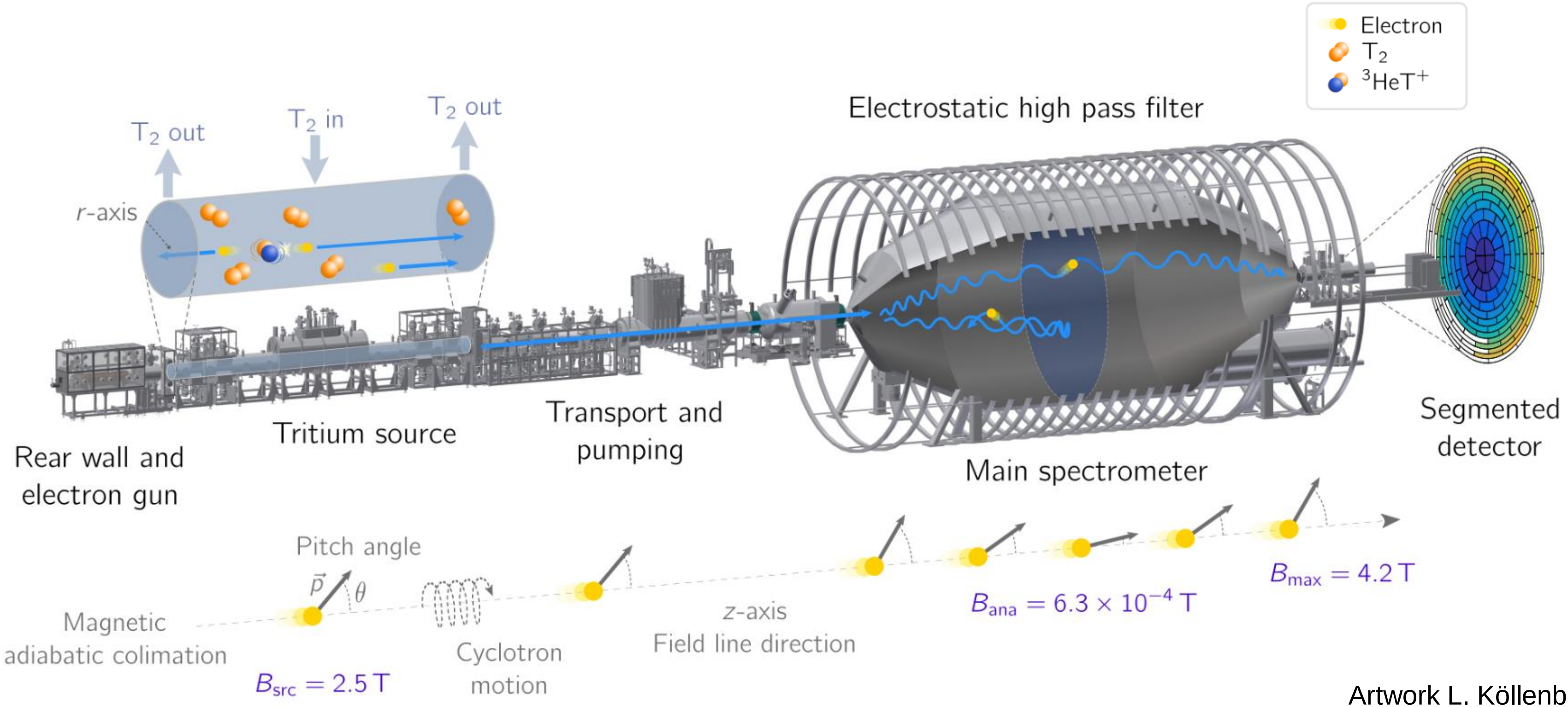
→ Relocation in progress

ATD Glove box infrastructure

e.g. large tritium retention system (~500k€), tritium supplies, …

→ Acquisition on-going

Working principle of KATRIN



Artwork L. Köllenberger