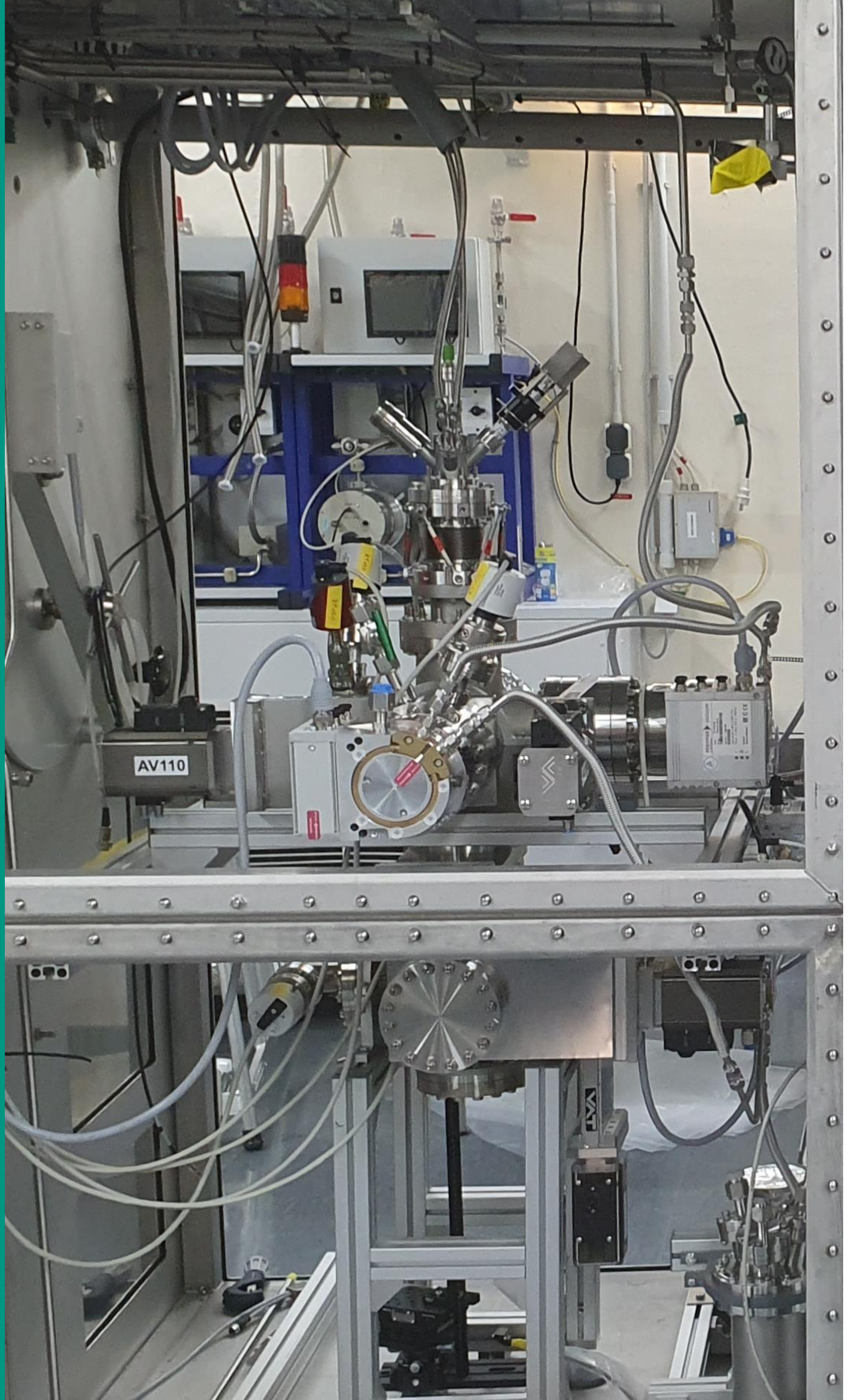
Research activities for a next generation neutrino mass measurement: KATRIN++

WIN 2025
Brighton, UK
Tue., 10th June 2025

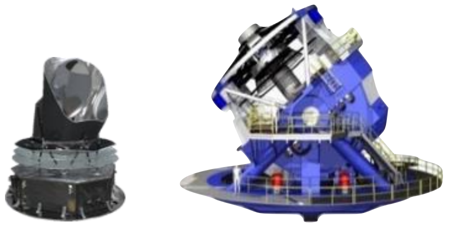
Alexander Marsteller for the KATRIN collaboration
Karlsruhe Institute of Technology
Institute for Astroparticle Physics
Tritium Laboratory Karlsruhe

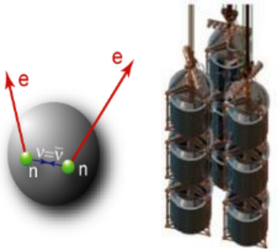


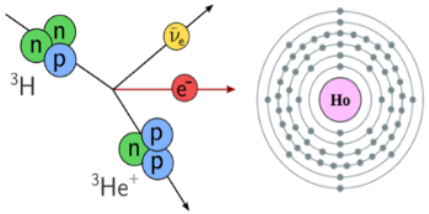
KIT

TLK
Tritiumlabor Karlsruhe

Access to the absolute neutrino mass scale







	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 - nuclear matrix elements, g_A	**Direct,** only kinematics; no cancellations in incoherent sum

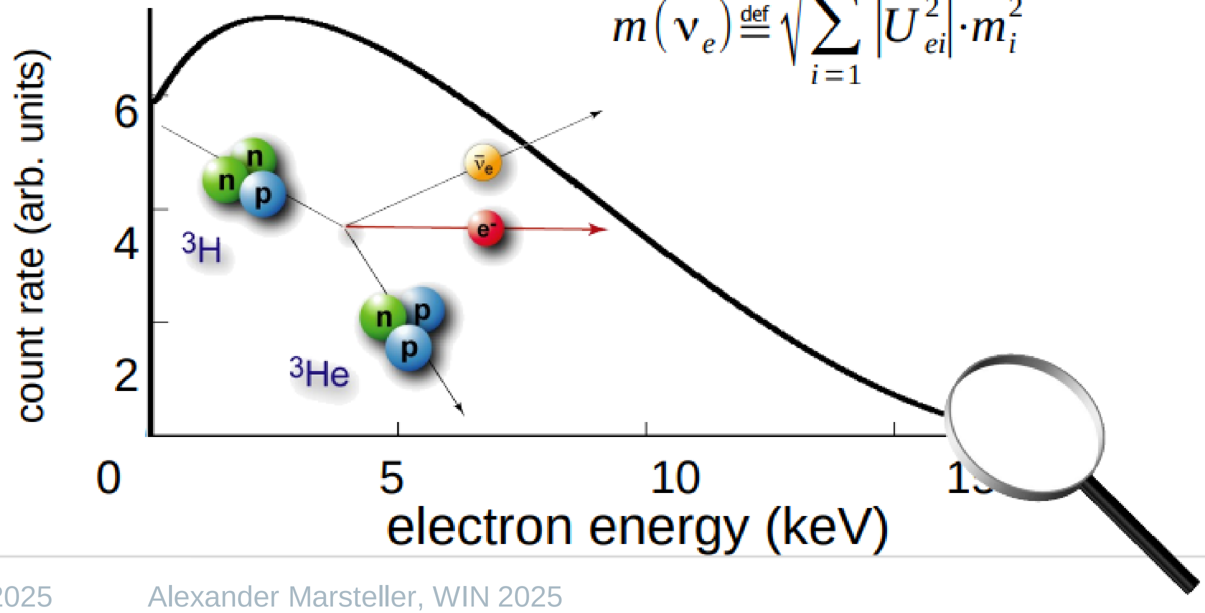
Tritium β-decay

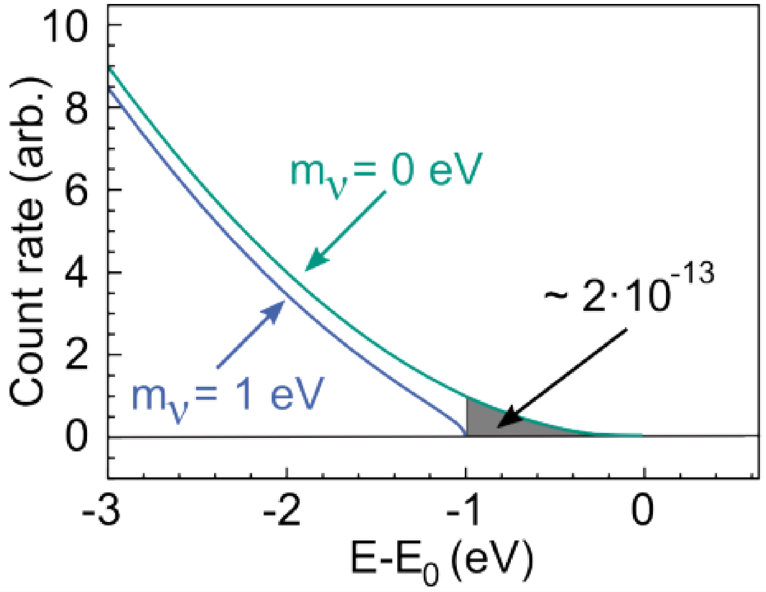
- Continuous β-decay spectrum described by Fermi‘s Golden Rule

- Simple structure allows accurate theoretical modelling

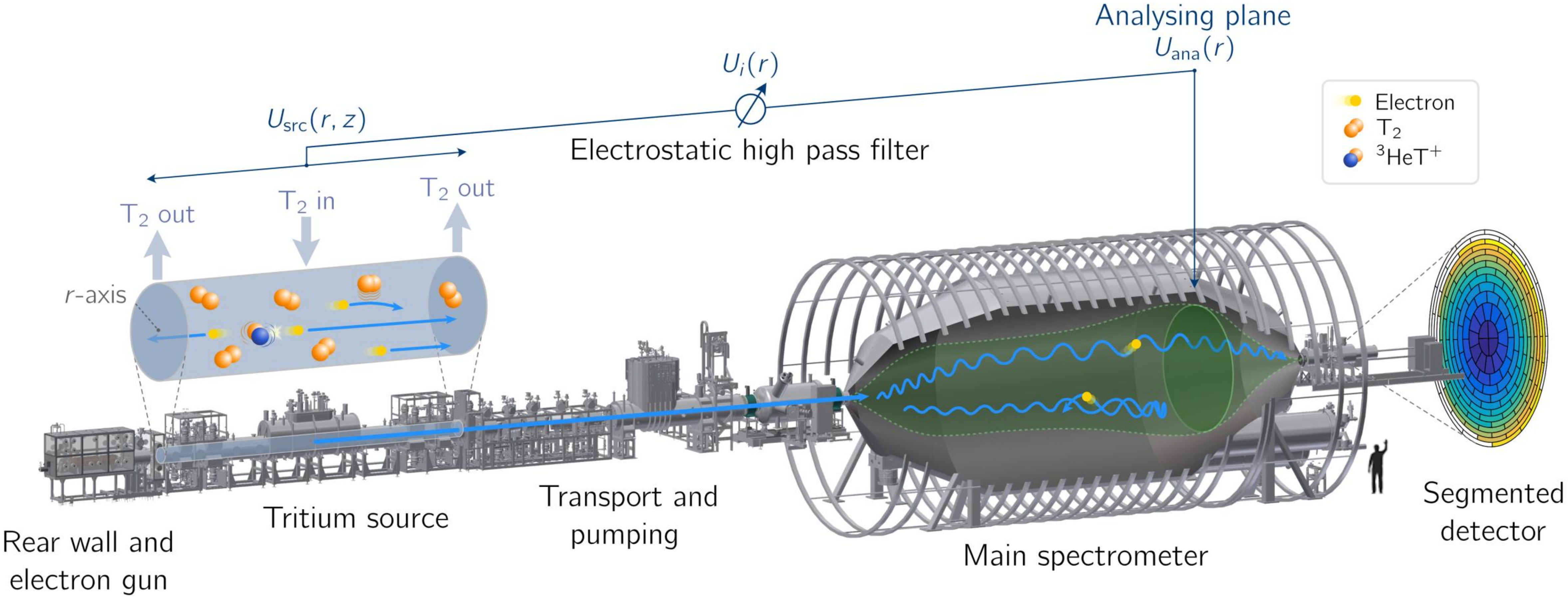
$$\frac{d\Gamma}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot \sqrt{(E_0 - E)^2 - m_{\nu_i}^2} \cdot F(E, Z) \cdot \theta(E_0 - E - m_{\nu_i}^2)$$

$$m(\nu_e) \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$





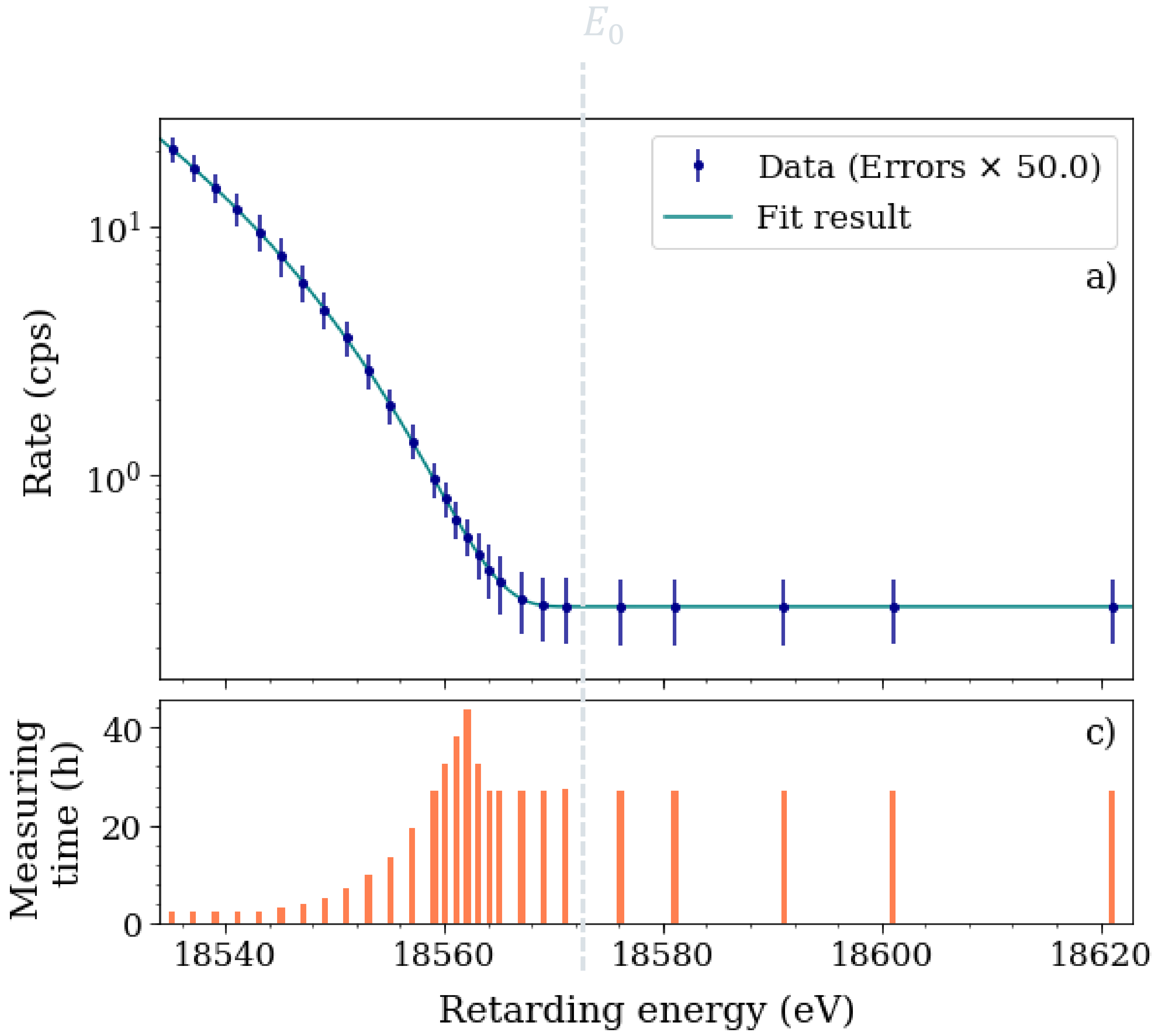
The KATRIN experiment



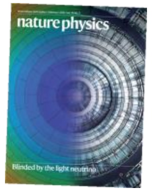
KATRIN measurement principle

Scan through spectrum integrated by highpass M

- ~30 steps with varying duration
- From $[E_0 - 300\text{ eV}, E_0 + 135\text{ eV}]$
- ~3 h measurement time per scan
- O(500) scans per year



KATRIN data releases and neutrino mass results

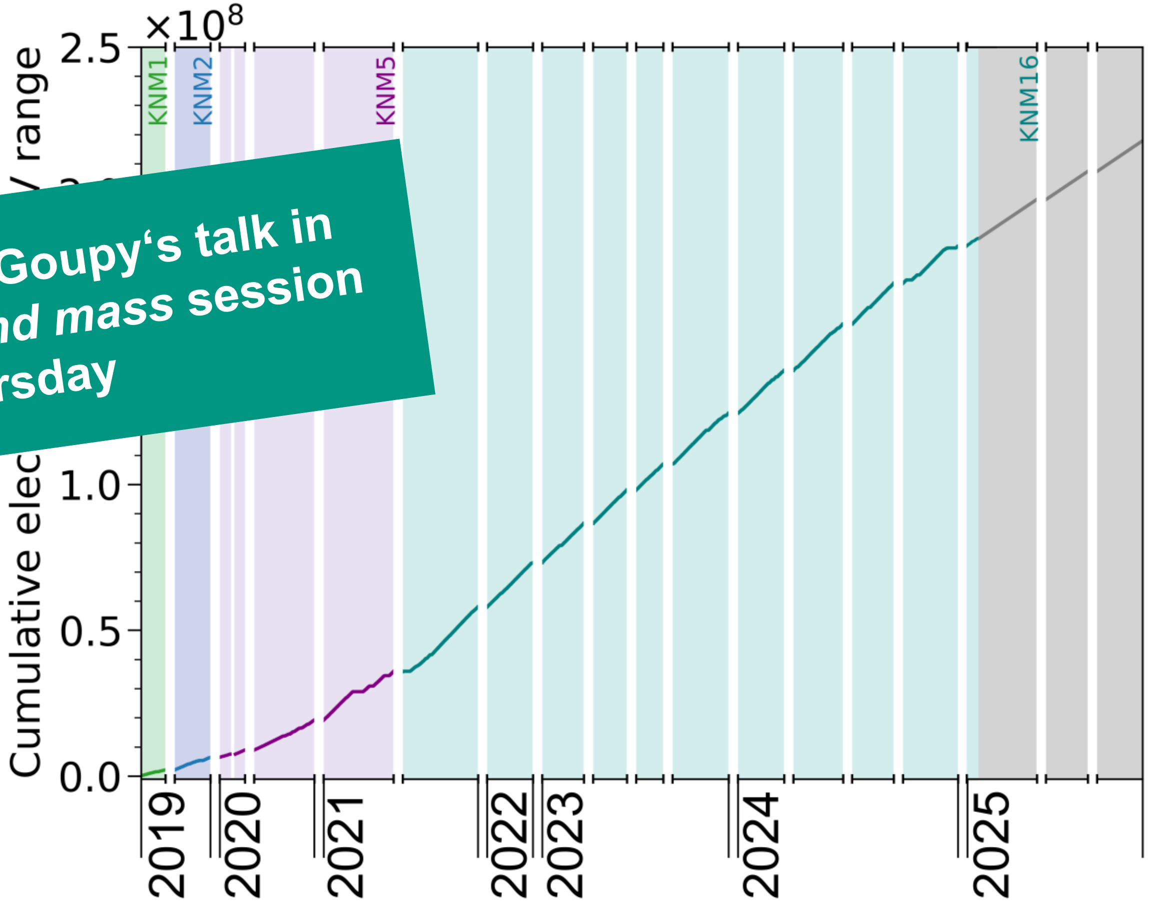


2019: $\boldsymbol{m_\nu}$ < 1.1 eV (90% CL)
PRL 123 (2019) 221802
PRD 104 (2021) 012005

2022: $\boldsymbol{m_\nu}$ < 0.8 eV (90% CL)
Nature Phys. 18 (2022) 160

2024: $\boldsymbol{m_\nu}$ < 0.45 eV (90% CL
KATRIN, Science 388 (2025) 6743

Reliable long-term data-taking of KATRIN & TLK

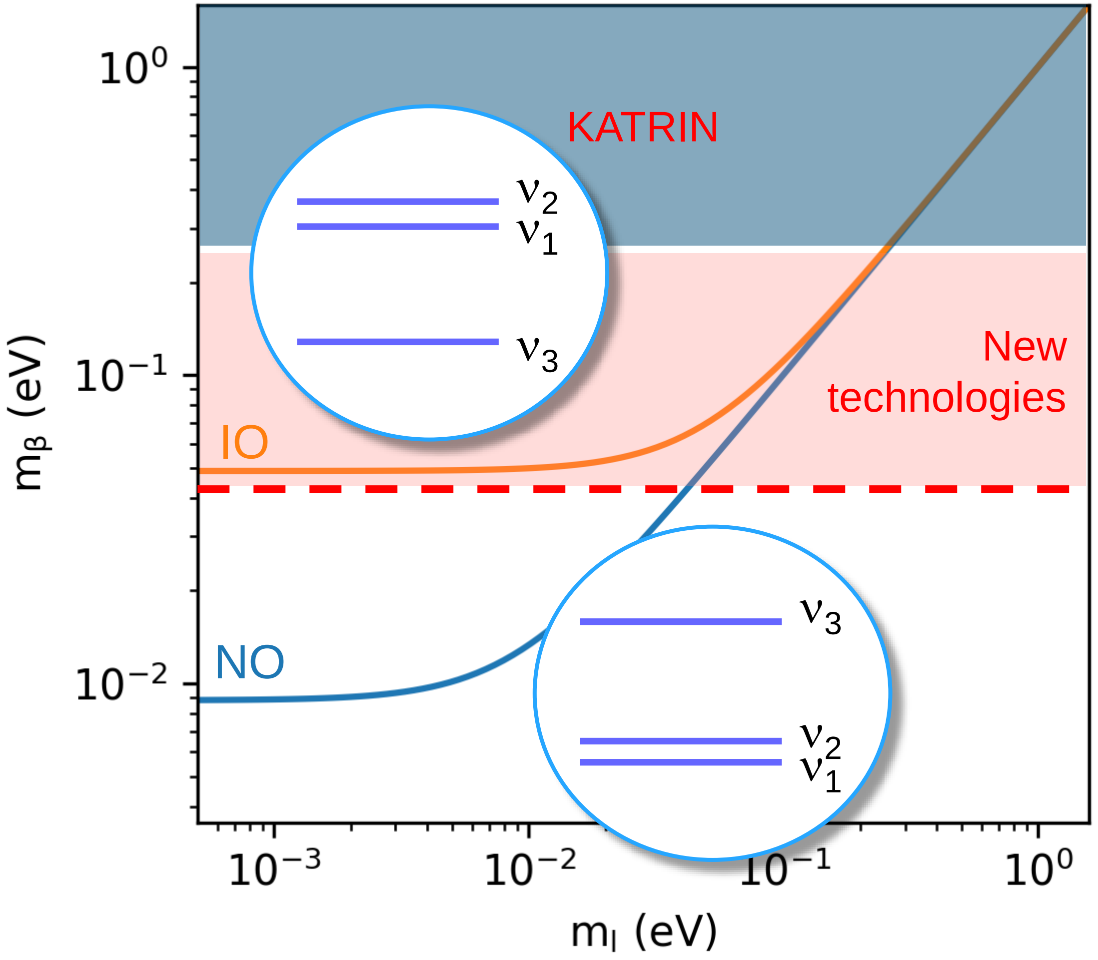


More details in C. Goupy's talk in *Neutrinos: $0\nu\beta\beta$ and mass session* on Thursday

- KATRIN projected to conclude neutrino mass data ta **end of 2025**
- KATRIN final sensitivity after 1000 measurement day be below 0.3 eV

KIT

Going beyond KATRIN



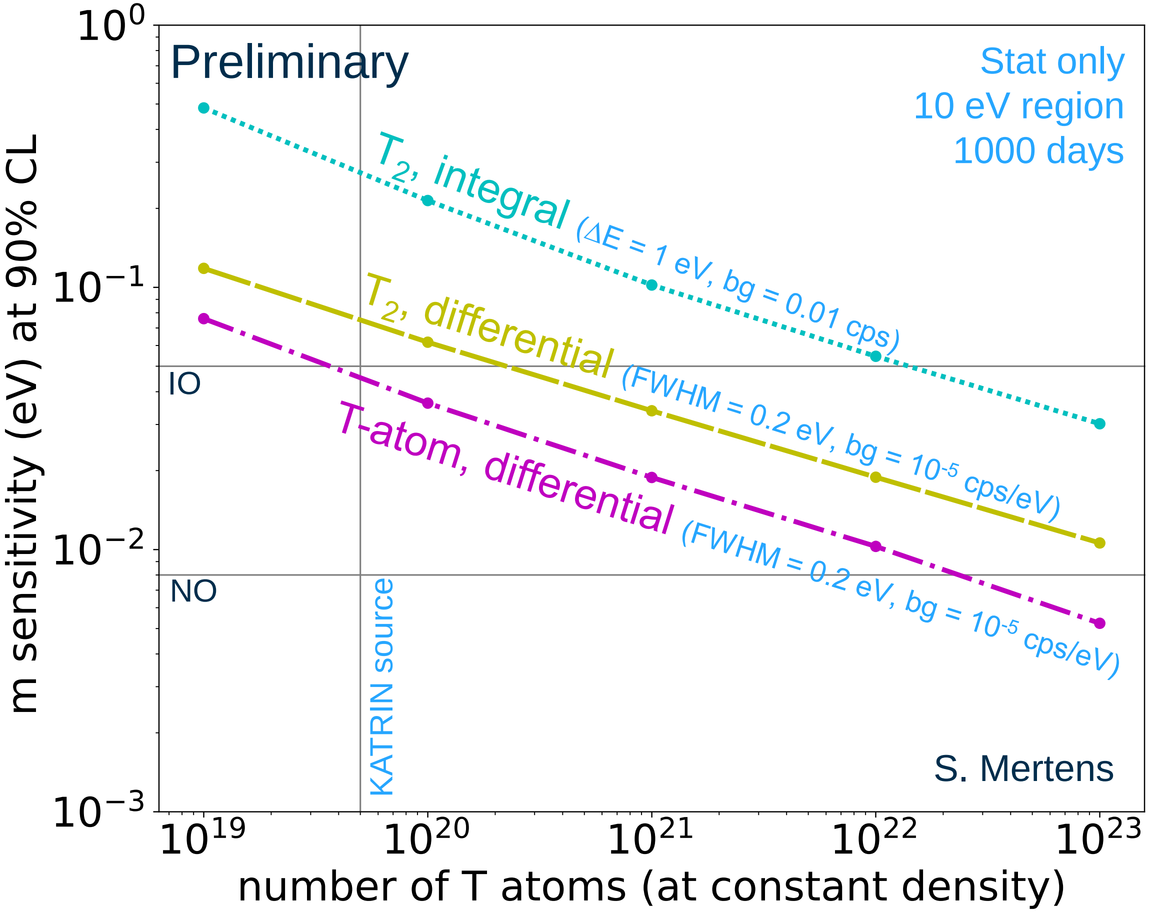
KATRIN final: < 0.3 eV (90% CL)
Distinguish between **degenerate** and **hierarchical** scenario

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)

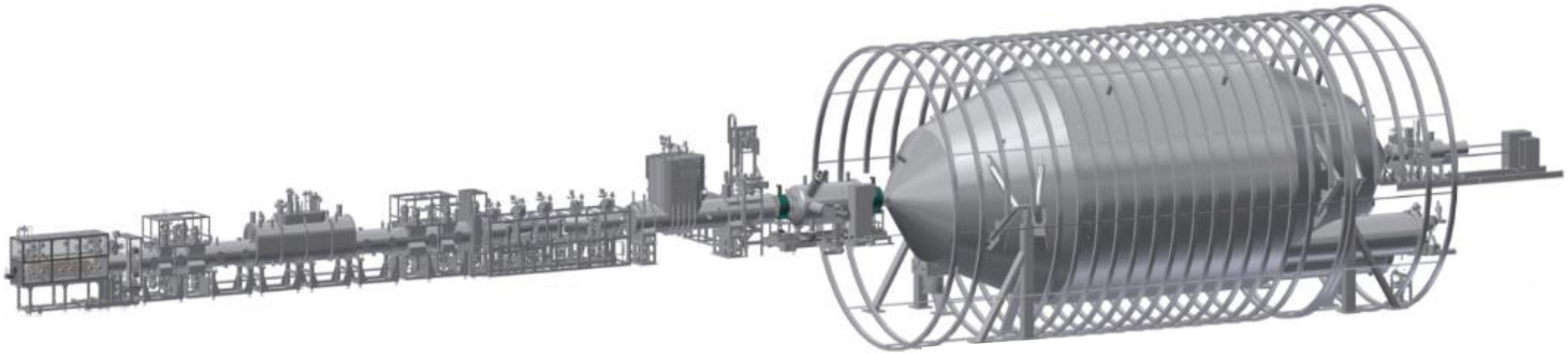
- Better use of statistics
- Lower background

Atomic tritium

- Avoid broadening (~ 1 eV)
- Avoid limiting systematics of T_2

Current R&D of KATRIN++

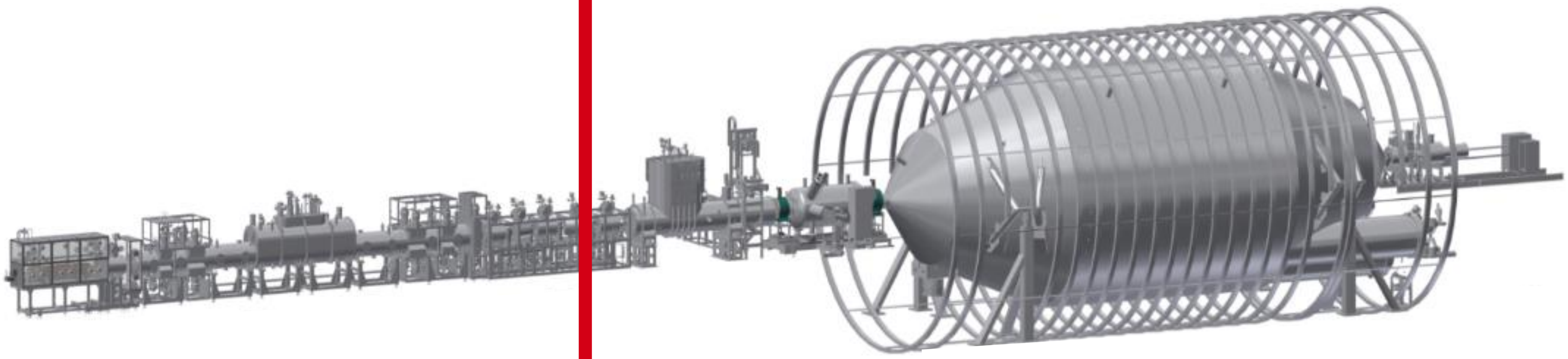
Differential detector technology



Atomic source technology

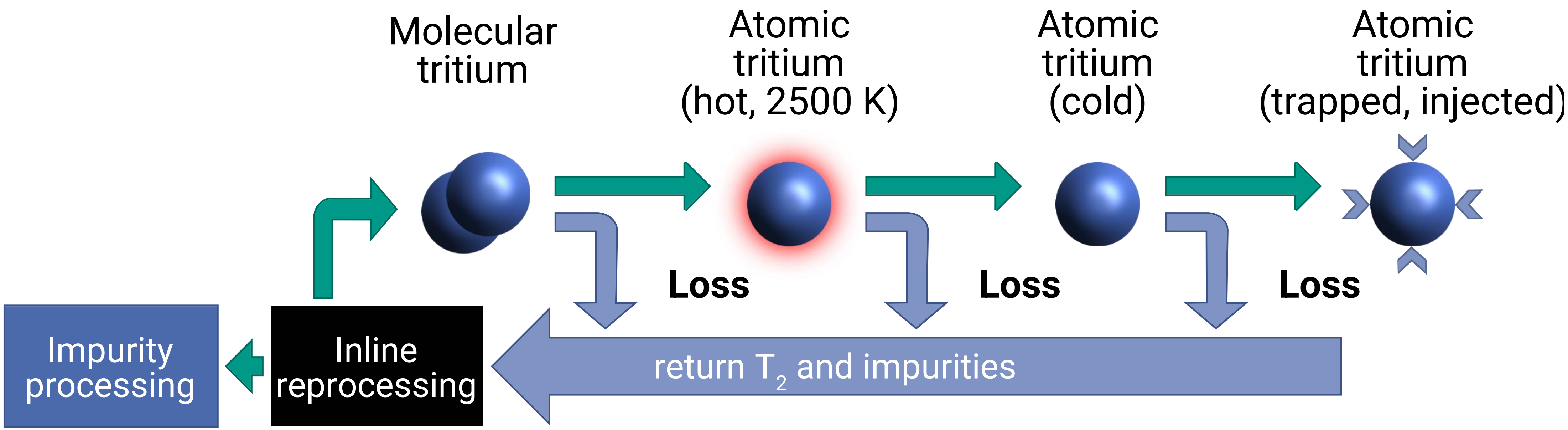
Current R&D of KATRIN++

Differential detector technology



Atomic source technology

Technology Development for an Atomic Tritium Source

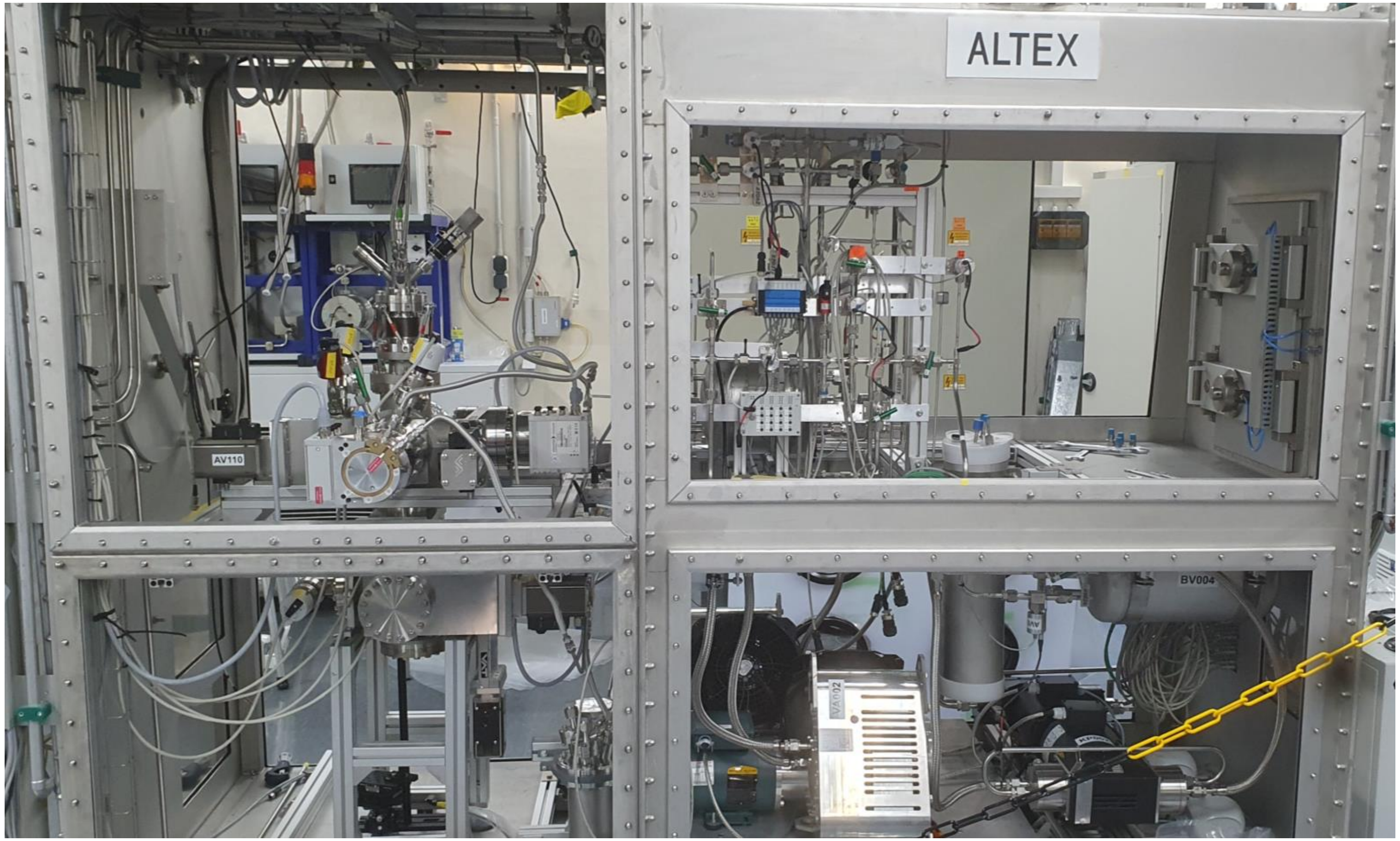


Additionally: Beam diagnostic atomic fraction, velocity distribution, beam profile

- Atomic source: high throughput and atomic fraction
- Beam/Particle multi-stage cooling: 2500K to ≈10mK
- Trapping
- KATRIN-like T_2 throughput (or above)
- R&D required on each step

Atomic tritium source test stand

- Investigate source performance with tritium
  - Tritium accumulation
  - Impurity generation
  - Isotopic effects (H_2, D_2, T_2)
- Planned capabilites
  - Up to 20 sccm tritium throughput
  - Detection of atomic hydrogen/deuterium/tritium
  - Long term operation



Commissioning will start soon

Test of different atomic sources

Thermal dissociation

- Thermal dissociation in a tungsten capillary
- Atoms with temperatures of ~2500 K

Plasma

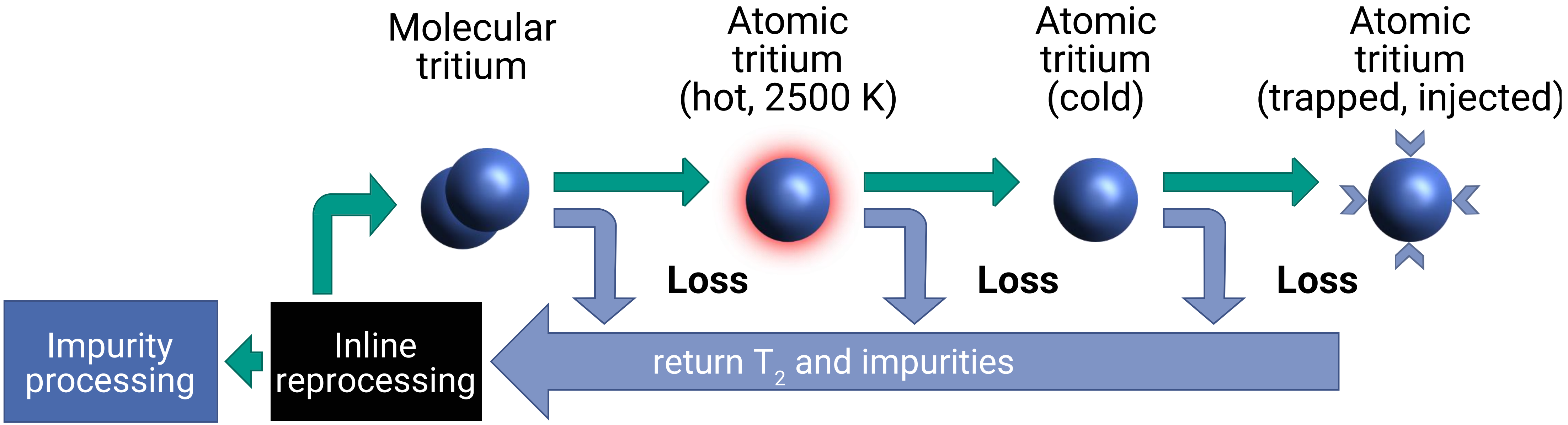
- Dissociation in RF plasma
- Succesfully used with hydrogen
  J. Slevin, W. Stirling, Rev. Sci. Instrum. 52, 1780–1782 (1981)
- Experience in Los Alamos showed decrease of dissociation rate over time
  Formaggio et al. Phys. Rep. 914 1–54 (2021)

Tectra h-flux

MBE HABS

SVT RF 4.5

Technology Development for an Atomic Tritium Source



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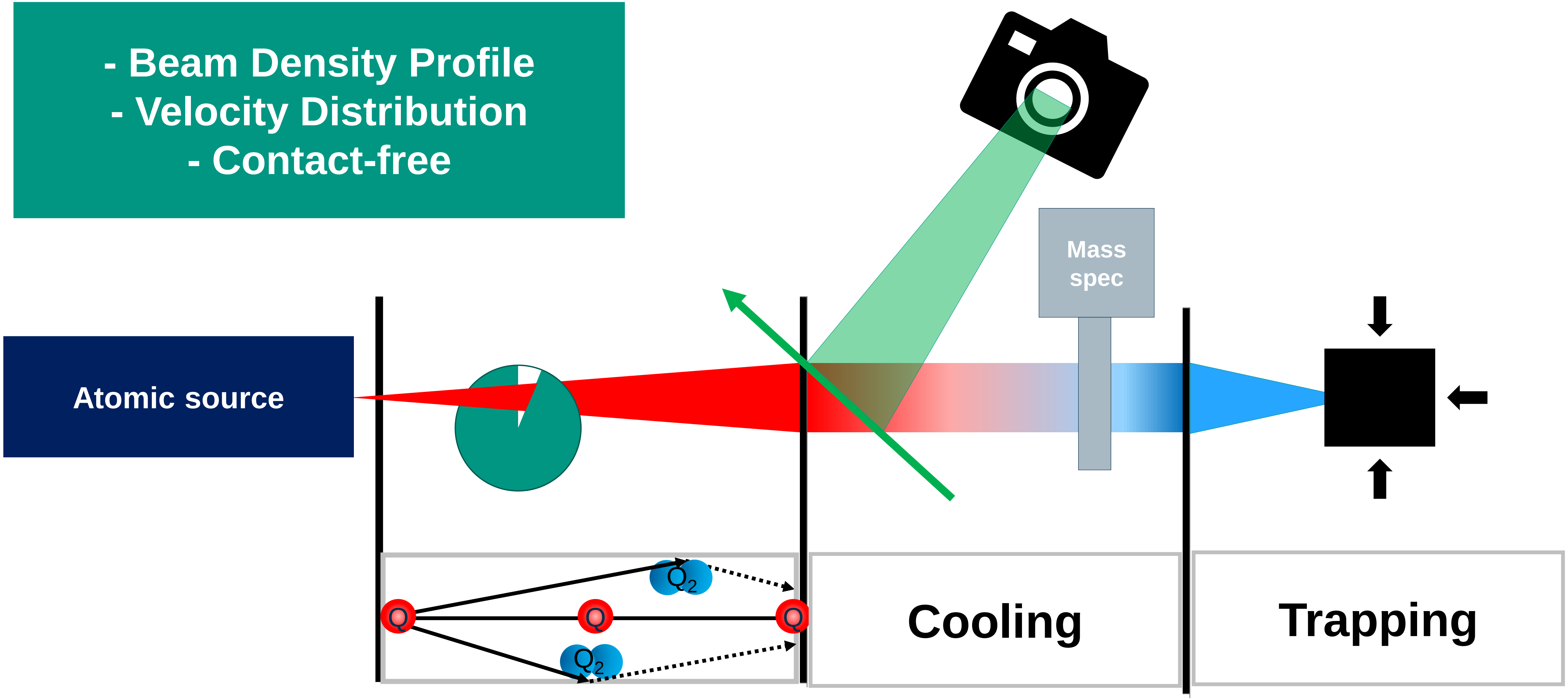
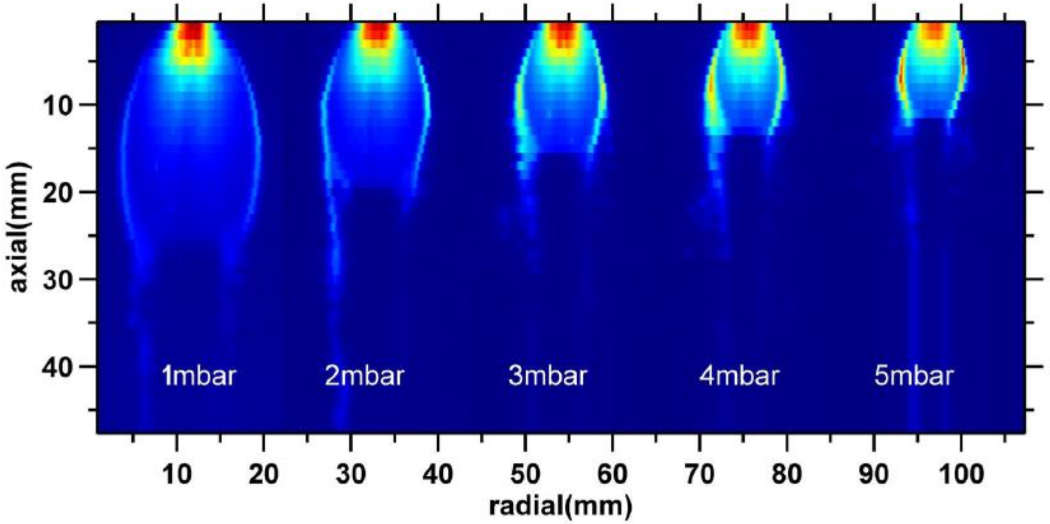
Beam Analysis Requirements

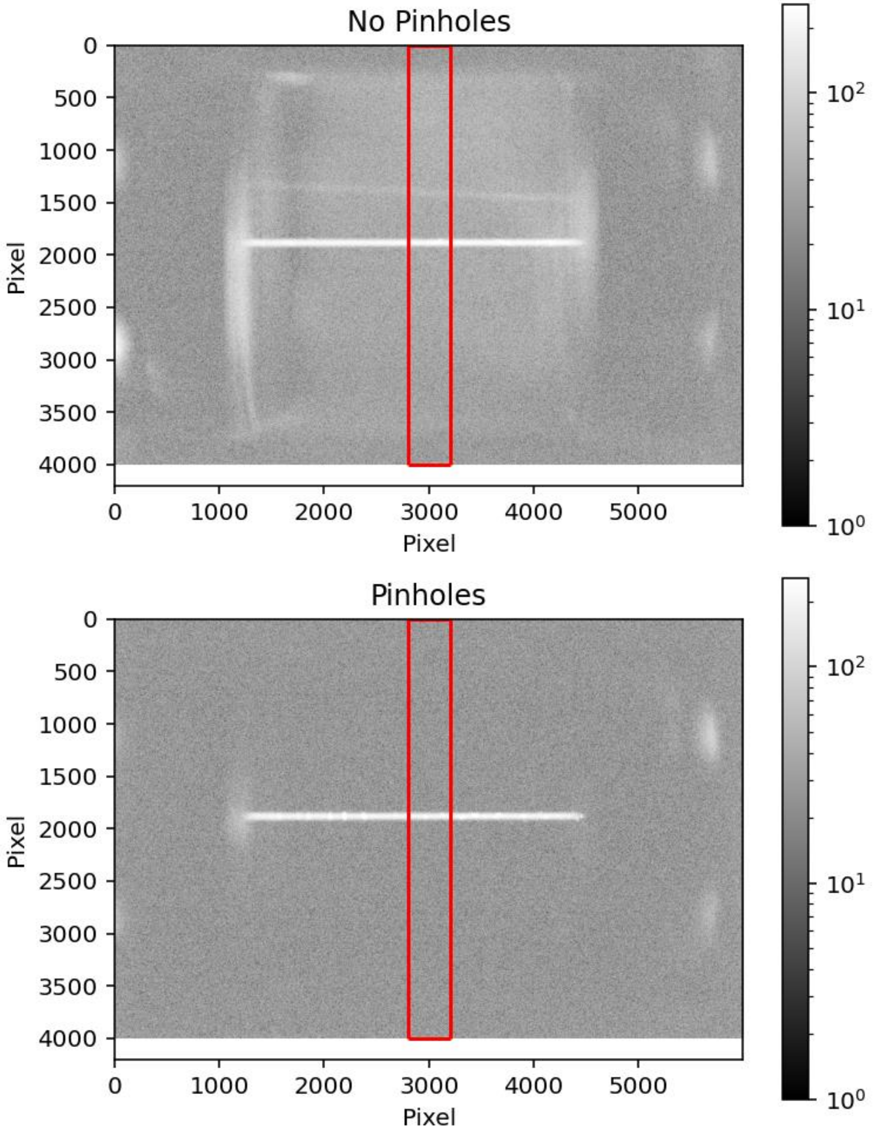
- Beam Density Profile
- Velocity Distribution
- Contact-free



Beam Profile Measurement: Laser based



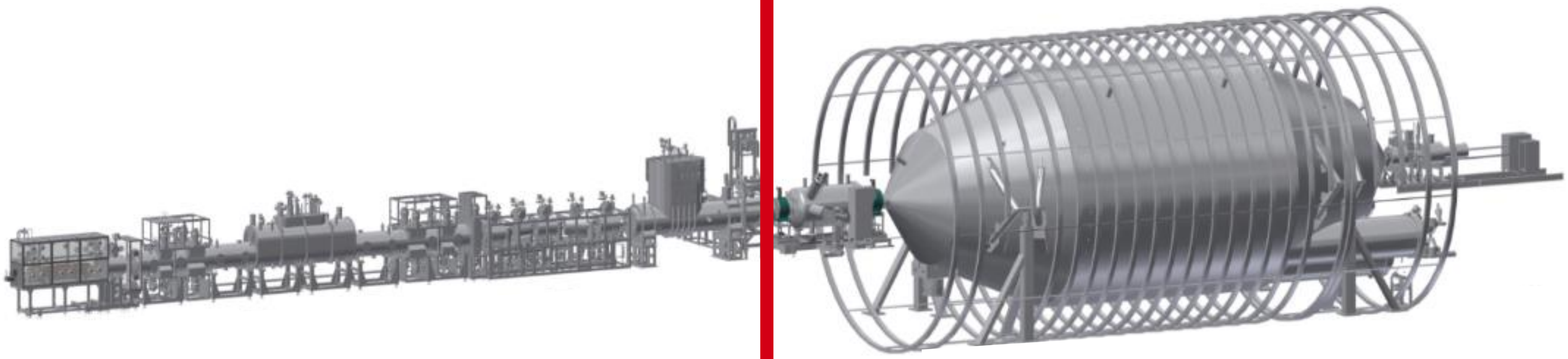
Spatial mapping of low pressure cluster jets using RayleighScattering; M. Patel, .R. Geethika, J. Thomas, H. Joshi; 2023; Nature



Biggest limiting factor: Stray light

Research to improve sensitivity and stray light suppression ongoing

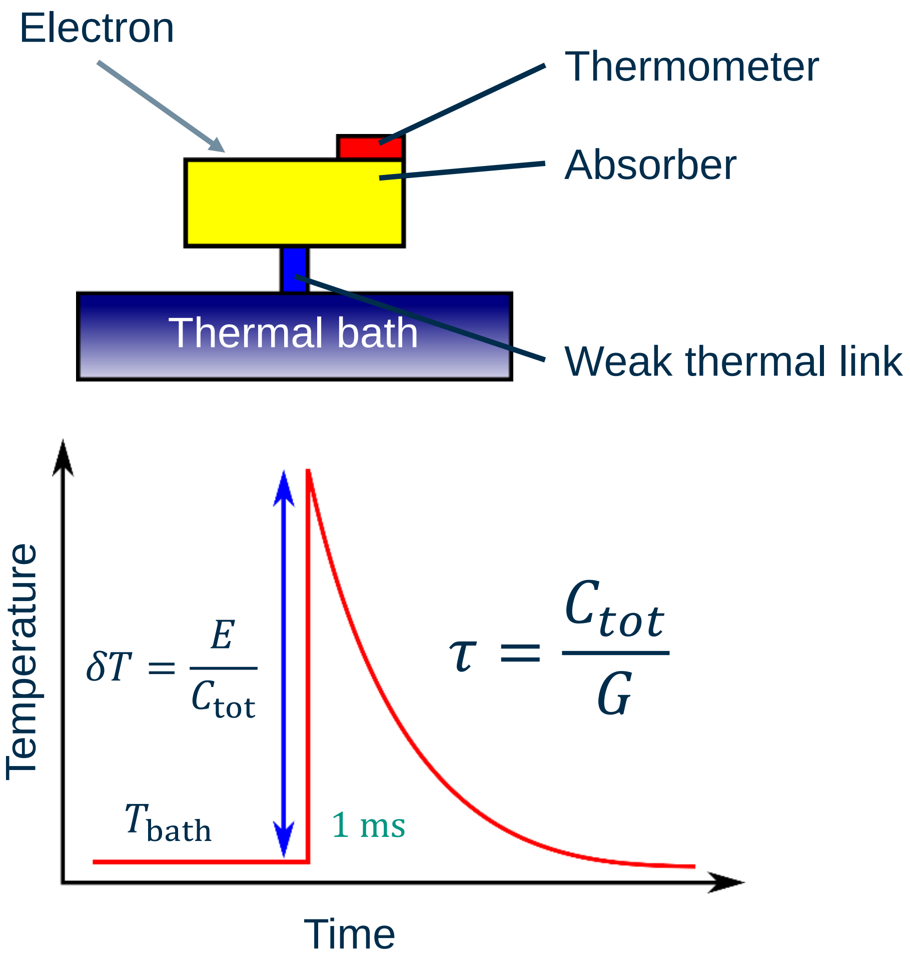
Current R&D of KATRIN++



Differential detector technology

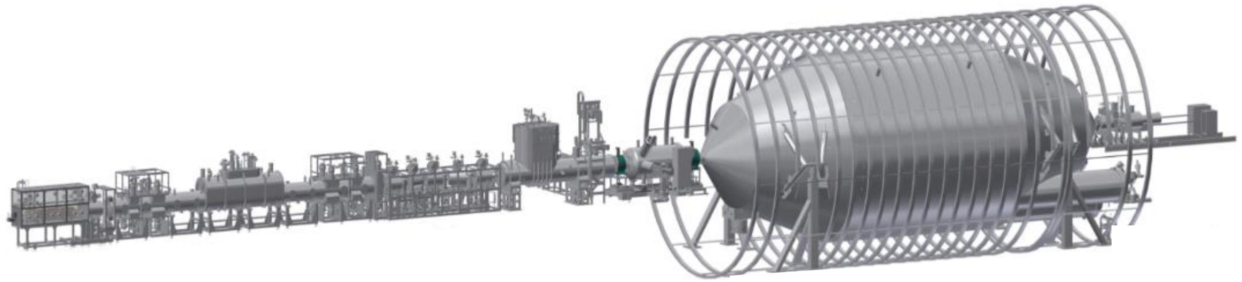
Atomic source technology

Differential electron energy detection using Metallic Magnetic Calorimeters



Advantages

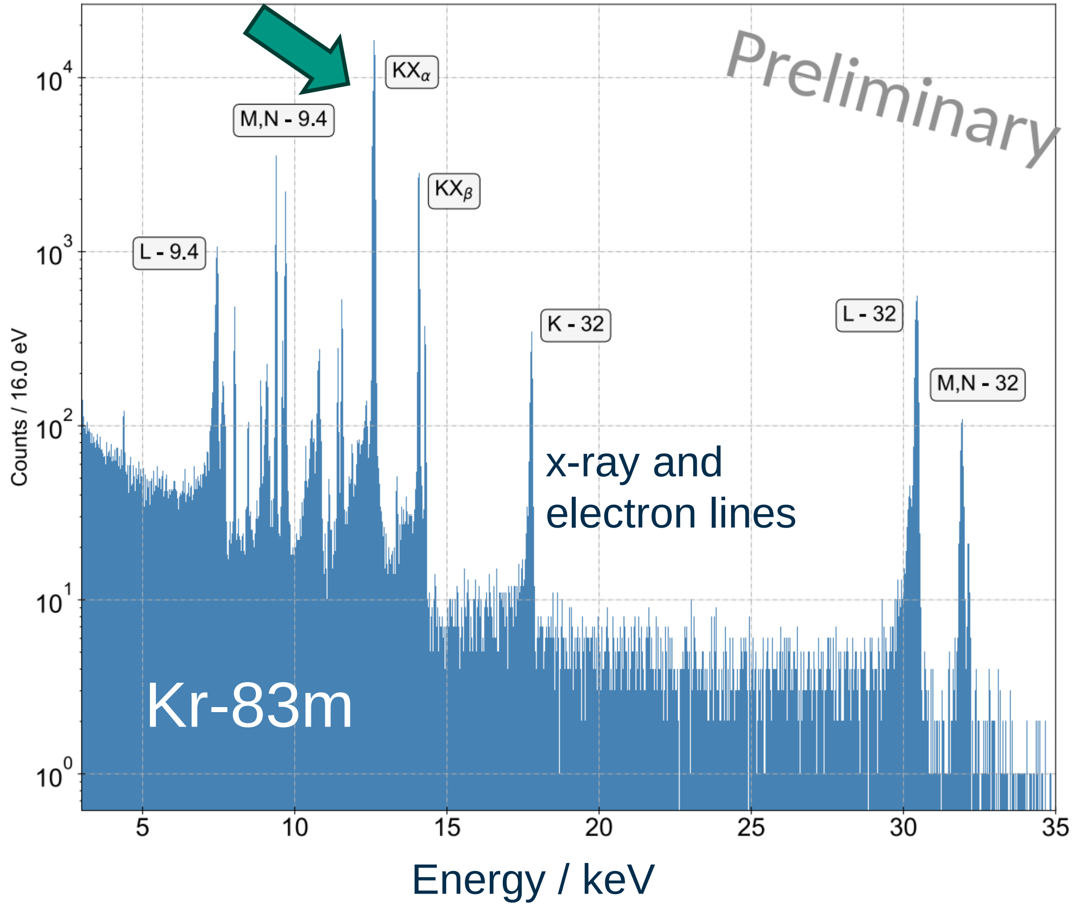
- Energy resolution *O*(eV)
- Nearly 100% quantum efficiency
- Broad spectrum of possible applications



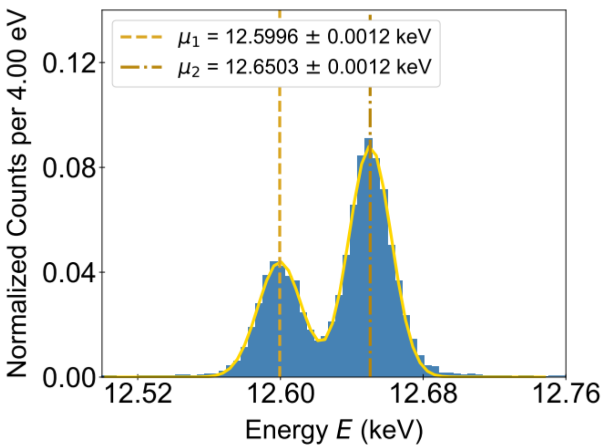
Challenges of coupling quantum sensor detector array to KATRIN infrastructure

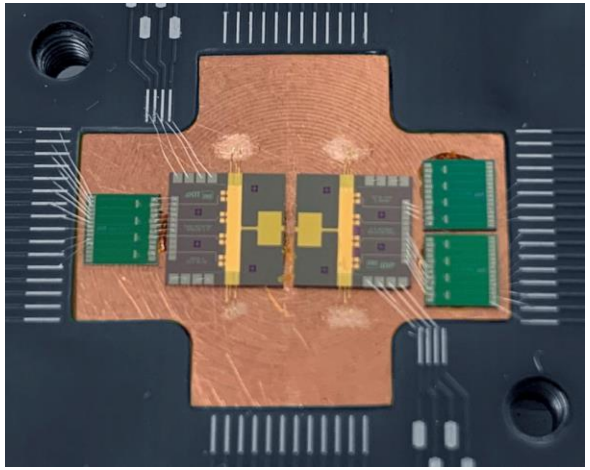
- Operation in magnetic field (~10 mT)
- Coupling of mK cryo-platform with RT spectrometer
- Large area detector and multiplexing of ~1e6 channels
- Limits to energy resolution

ELECTRON: e^- spectroscopy with quantum sensors



FWHM ~ 25 eV





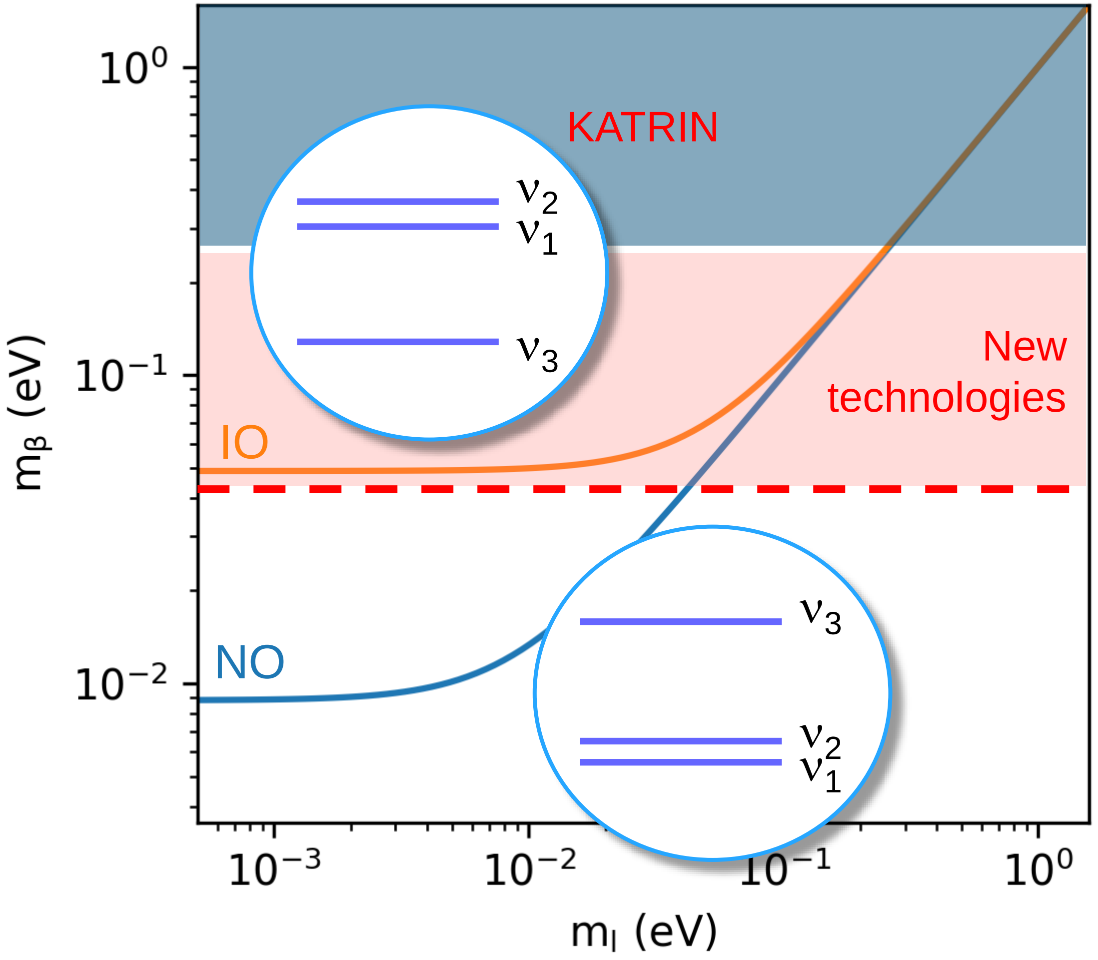
Novac et al., Nucl. Instrum. Meth. A 1080 (2025) 170662

Highest resolution differential ^{83m}Kr electron spectrum

Potential sub-eV differential detector for tritium experiments

KIT-IMS (Kempf group)

Conclusion



- KATRIN
  - Finish data taking in 2025
  - Reach < 0.3 eV (90% CL) sensitivity
  - Will be able to distinguish between degenerate and hierarchical scenario
- New technologies are necessary to reach the inverted mass ordering scale
  - Atomic tritium
  - Differential electron energy detection
- R&D framework KATRIN++ as long term research effort to develop these technologies

KATRIN collaboration

Collaboration meeting, March 2025, Münster University

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