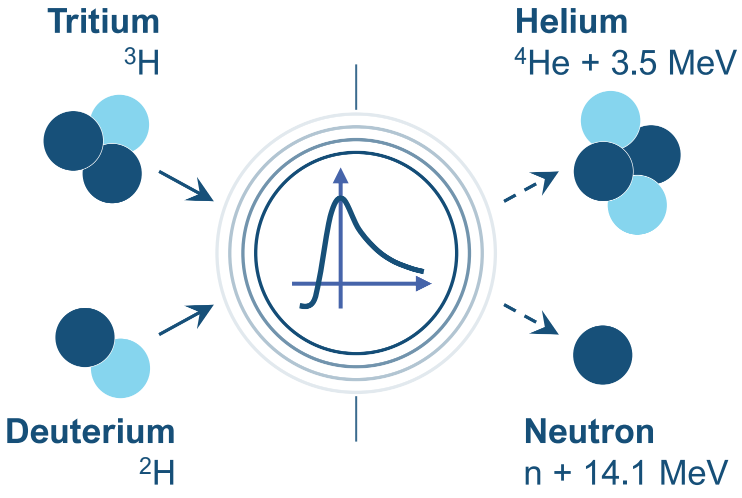
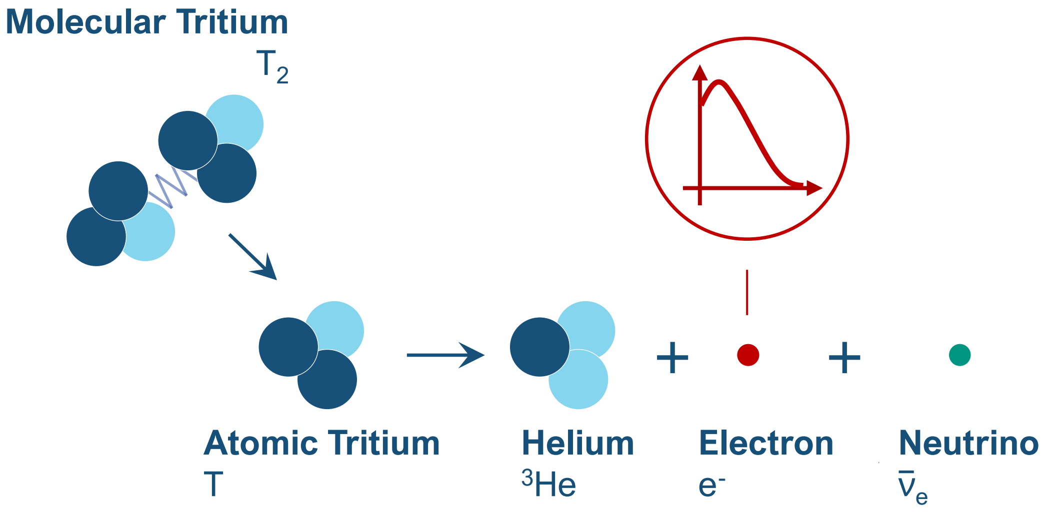
Karlsruher Institut für Technologie

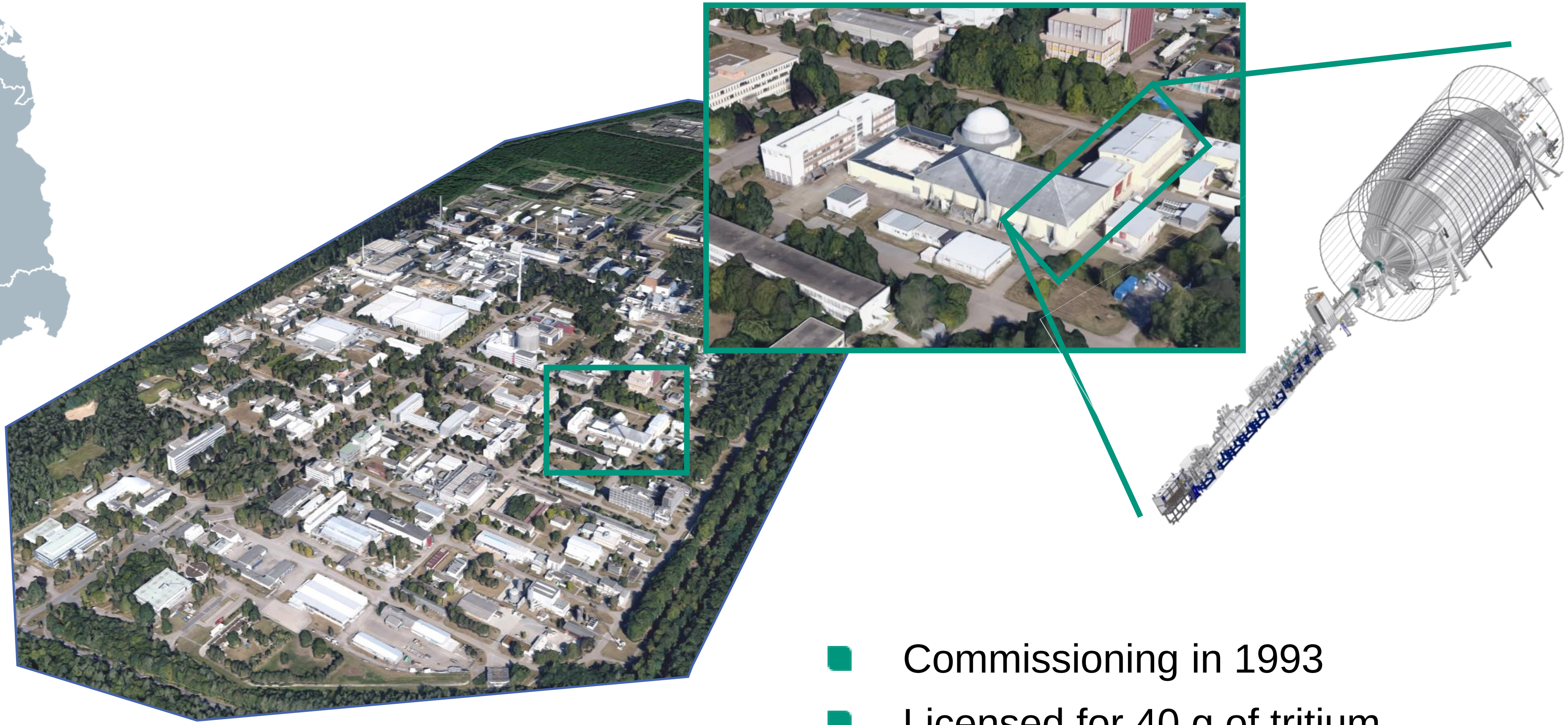
Technological Challenges in the Design and Operation of Tritium-Based Experiments

APPEC Tech Forum Maastricht, Marco Röllig





The Tritium Laboratory Karlsruhe (TLK)



Karlsruhe Institute of Technology
Campus North

- Commissioning in 1993
- Licensed for 40 g of tritium

The Tritium Laboratory Karlsruhe (TLK)

A facility for high-activity tritium research and experimentation

- Fuel cycle process demonstration on a semi-technical scale
- Analytics and accountancy tools development

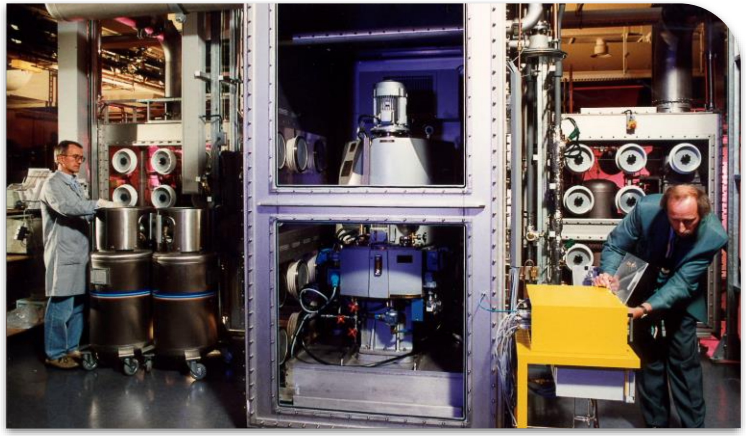
Fusion fuel cycle technology

- Large-scale neutrino physics with KATRIN
- 24/7 operation at 40 g/day throughput

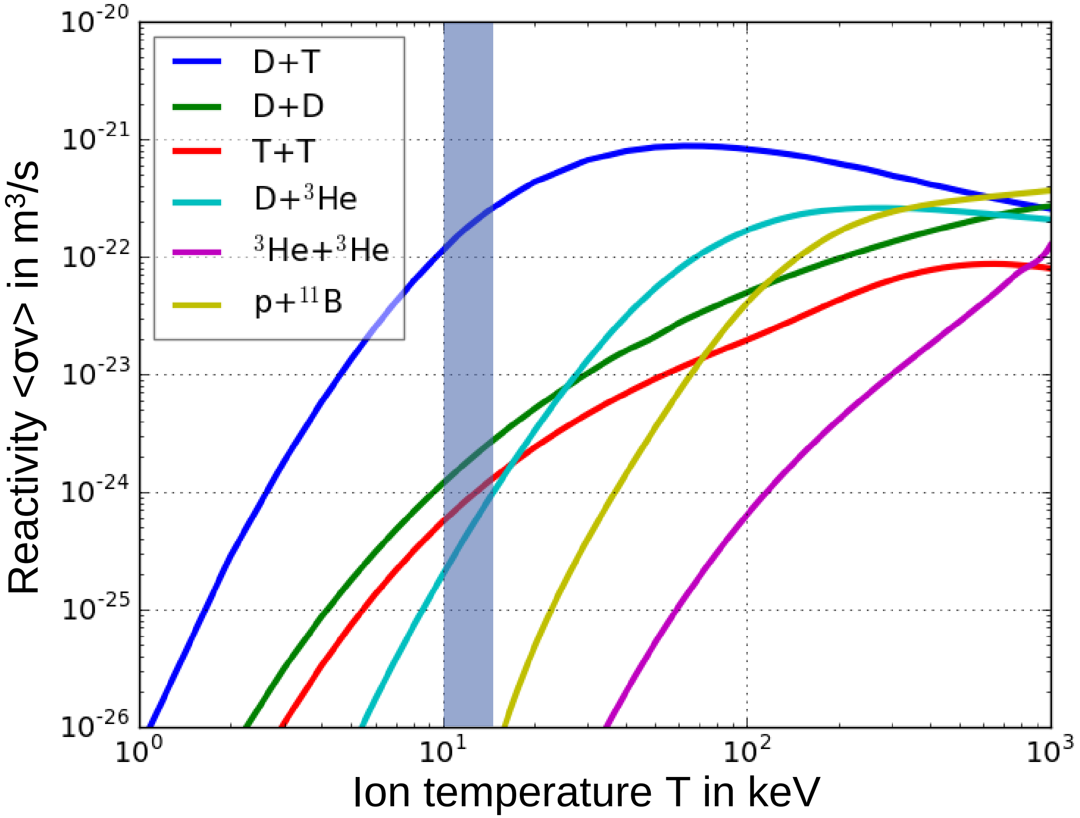
Astroparticle physics

The Tritium Laboratory Karlsruhe (TLK)
in a Nutshell

- **Closed tritium cycle** enabling efficient recycling and high-purity conditioning of tritiated process gases on the gram scale
- **1,600 m² of dedicated laboratory space** with more than 20 glove boxes for controlled tritium handling
- **Operational license for up to 40 g of tritium** (approx. $1.5 \cdot 10^{16}$ Bq)
- **Over 30 years of continuous operational experience** in high-activity tritium technologies
- **A team of 55+ staff**, including scientists, engineers, doctoral researchers, and students

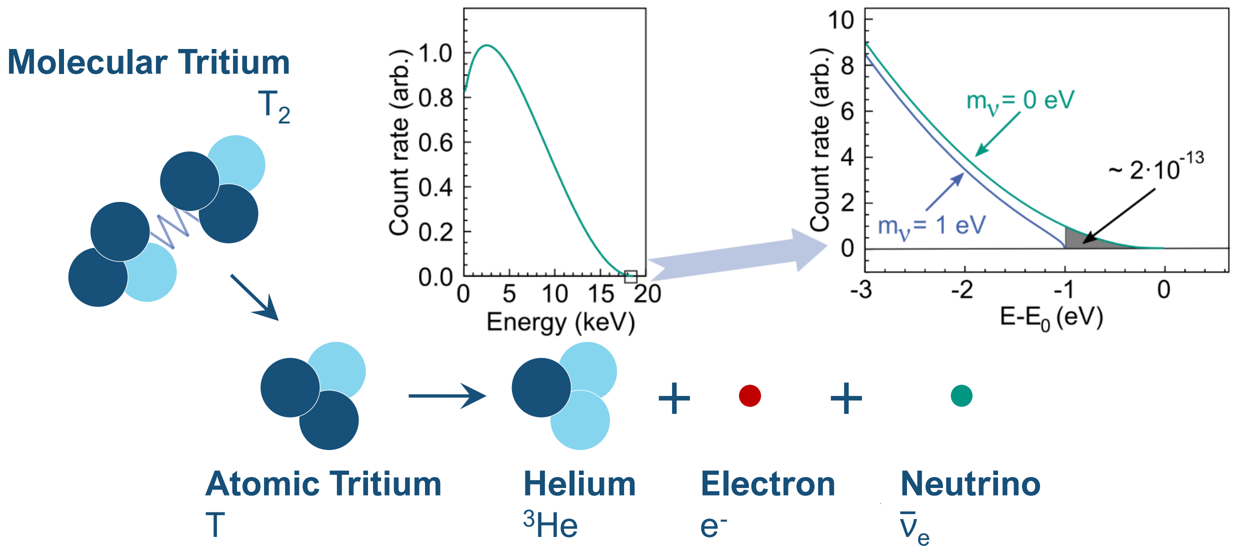


Why Tritium?



- **D+T Fusion** has high reactivity at comparatively “low temperature” and good energy output

  D + T → He(3.52 MeV) + n(**14.06 MeV**)

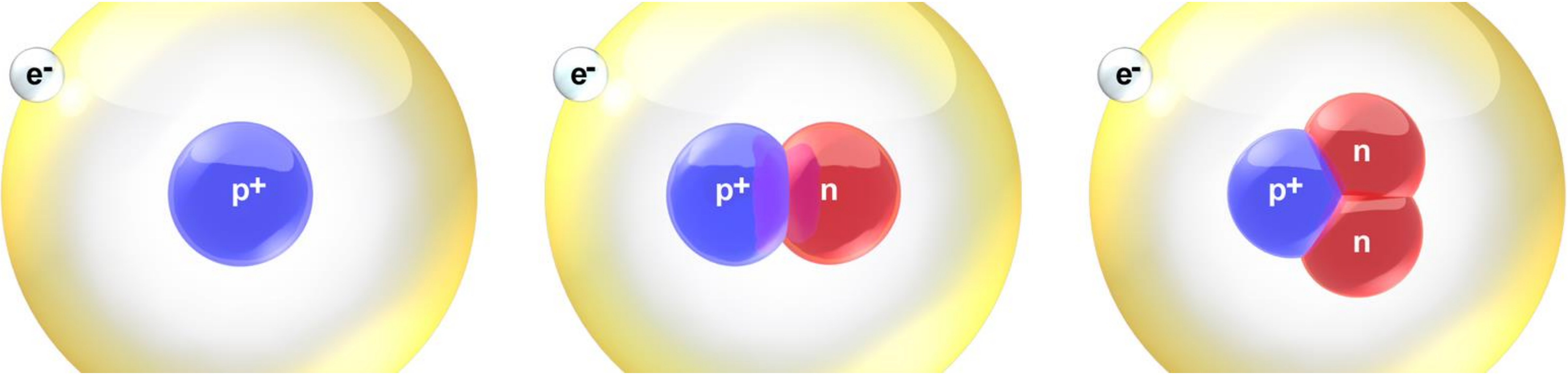


Direct, model independent access to neutrino mass

Tritium has

- a comparatively **simple structure**,
- **low endpoint energy** of 18.6 keV,
- **high specific activity** of 3.57×10^{14} Bq/g.

Why Tritium?



Large relative mass differences between the hydrogen isotopes, combined with simple electronic structure, make them powerful systems for precision spectroscopy.

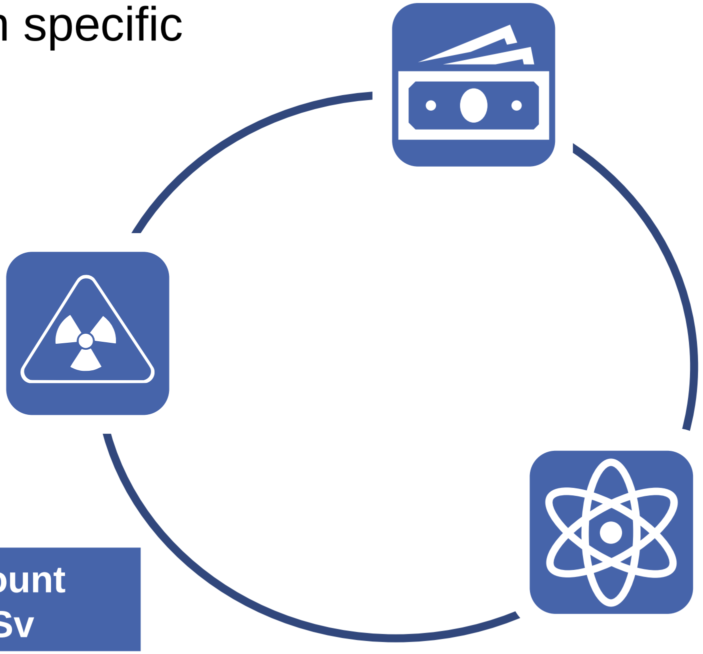
Isotope-shifts in atomic energy levels provide sensitive probes of fundamental nuclear properties.

Why Tritium Technology Is Fundamentally Different - Key Challenges Beyond Hydrogen and Deuterium

Radiological hazard

- β-emitter (18.6 keV) with high specific activity
- Multi-barrier confinement, continuous monitoring and accountancy
- LD_{50} depends on biological pathway

Form	T-amount for 20 mSv	T-amount for 8 Sv
Gas	≈31 mg	≈12 g
Water vapour	≈3.1 µg	≈1.2 mg
Aerosol bound	≈0.22 µg	$\boxed{≈86 µg}$



Limited & valuable resource

- Globally produced only in gram-scale quantities (Inventory: global 25-35 kg, natural ~3.5 kg)
- Requires a **closed tritium cycle**: recovery, purification, retention → no routine
- Losses translate directly into scientific, licensing, and financial penalties (5.5 %/year decay losses)

Increased radiochemical reactivity

- Tritium shows enhanced isotope exchange rates and faster impurity generation
- Radiolysis effects, generate reactive radicals, increase corrosion, change gas composition and material properties

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Radiological hazard

- β-emitter (18.6 keV) with hi
- LD_{50} depends on biological
- Demands multi-barrier conf continuous monitoring and accountancy
- $LD_{50/60}$ is approx. 4 Sv (dose at which only 50% of humans will survive at least 60 days)

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Gas	≈31 mg	≈12 g
Water vapour	≈3.1 µg	≈1.2 mg
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These three aspects dictate nearly all engineering decisions:

confinement architecture, material selection, gas-handling systems, purification technology, analytics and maintenance concept.

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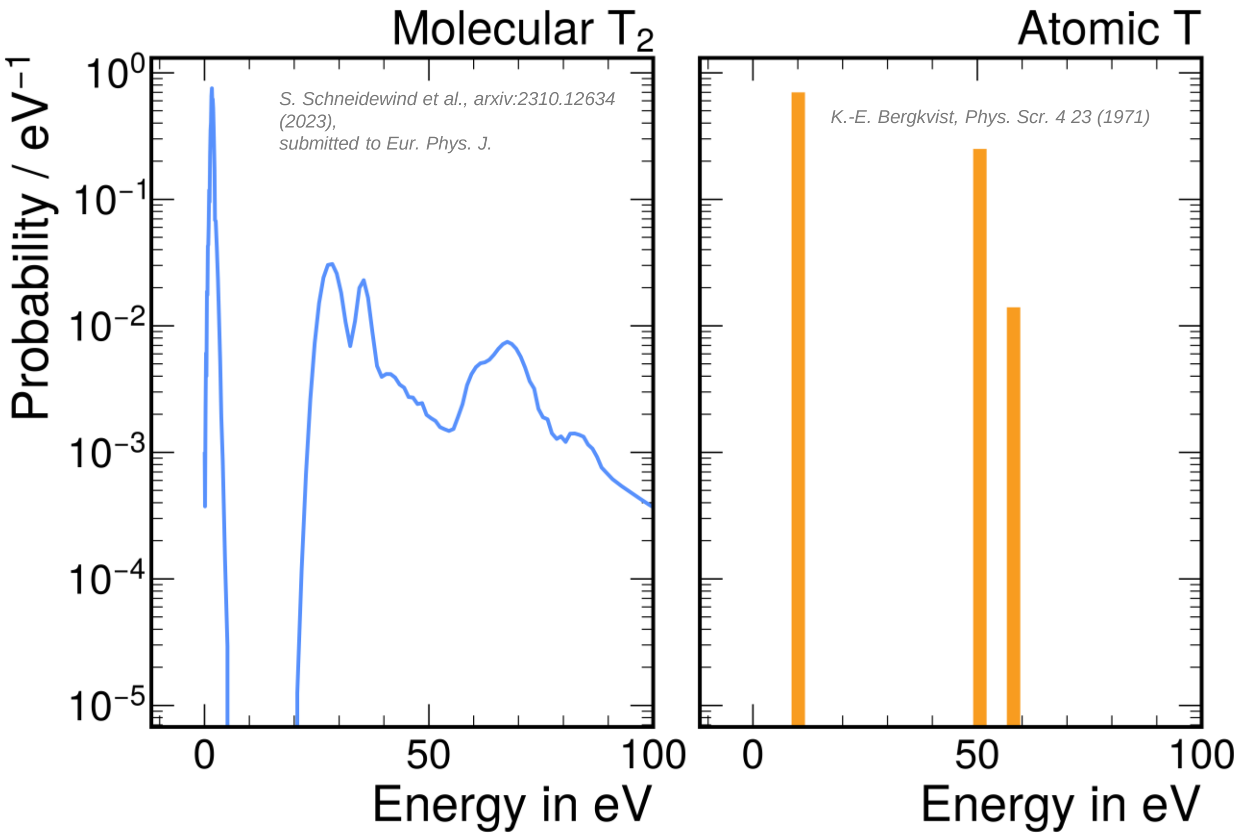
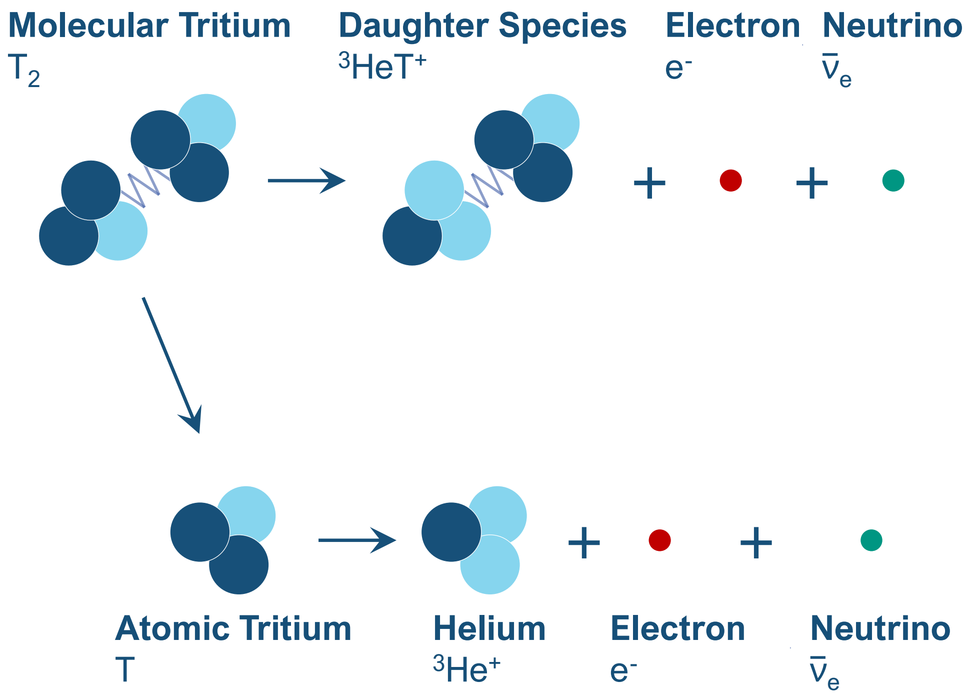
An Atomic Tritium Source for Neutrino Mass Experiments

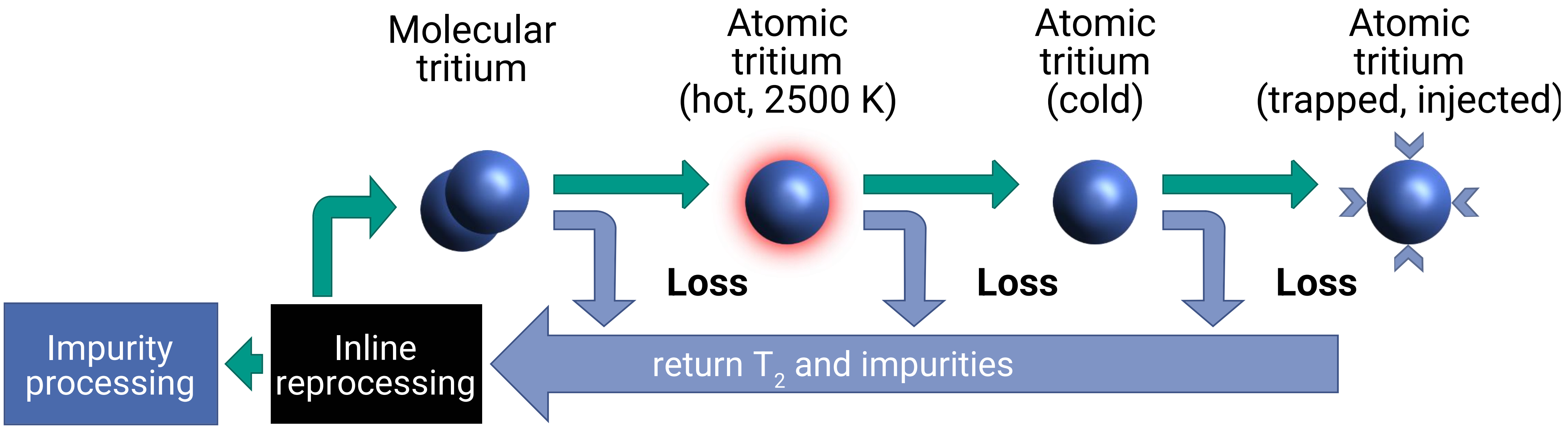
Final State Distribution of Molecular and Atomic Tritium

Excitations of the decay daughter lead to a characteristic **final-state distribution (FSD)**.This FSD broadens (“smears”) the observed β-electron spectrum and directly contributes to the **neutrino-mass uncertainty**.





Technology Needed for an Atomic Source



Beam diagnostic: atomic fraction, beam temperature, beam profile

- Atomic source: high throughput and high atomic fraction
- Beam/Particle multi-stage cooling: 2500 K to ≈10 mK
- R&D required on each step

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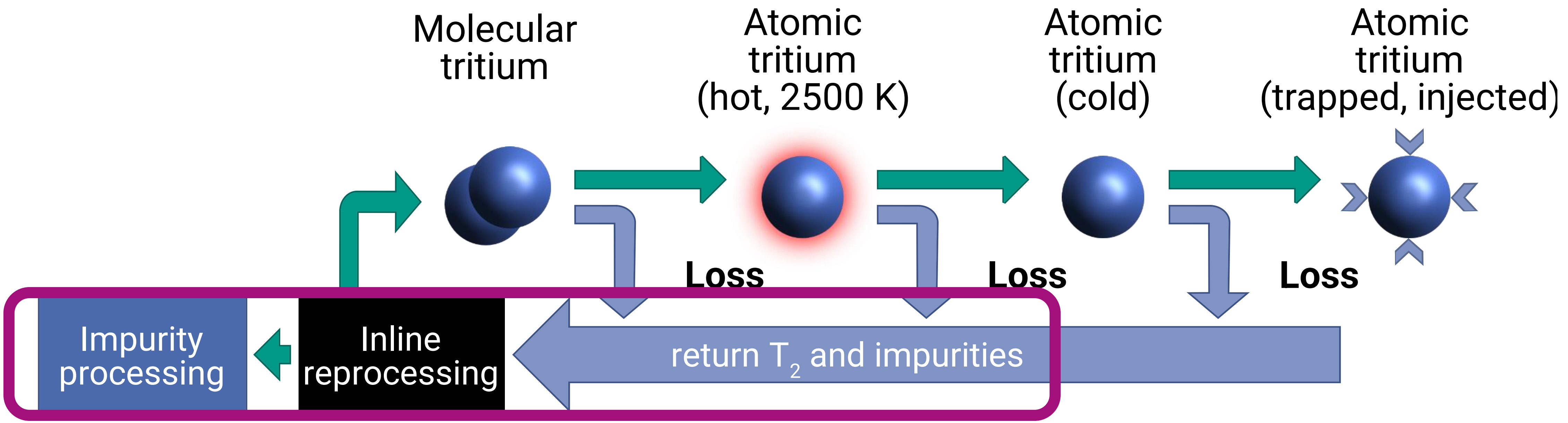

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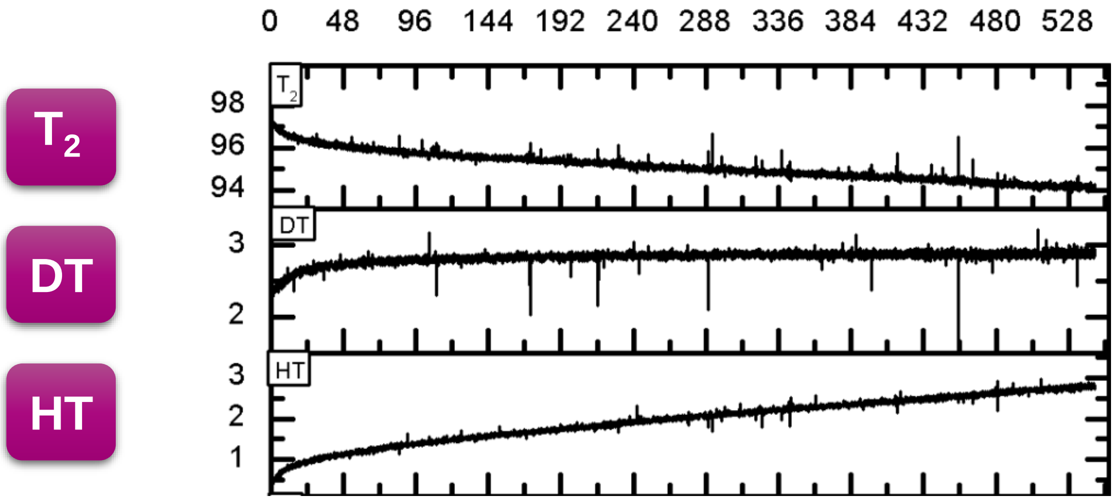
Radiochemical Reactions in Tritium Systems
A Selection

Isotope Exchange Reaction

- Tritium efficiently exchanges with protium/deuterium in metals and alloys, adsorbates, and water layers.
- Dominant processes: Surface-mediated T/H exchange (sorption/desorption cycles).
- Bulk metal hydride formation and equilibration.

Shift of isotopic composition over time ($T_2 \leftrightarrow HT \leftrightarrow H_2$). Relevant for **accountancy**, **purification** systems, and experimental goals. Furthermore, leads to **tritium surface contamination** and **bulk accumulation.**

Time evolution of gas composition in %
Start: >98% T_2, approx. 550 hours



→ **Contaminated equipment stays within the supervised area. No external repair of pumps or other equipment.**

Radiochemical Reactions in Tritium Systems
A Selection

Methane & CO generation

- Generation of tritiated methanes and CO in tritium systems observed - depends on materials, cleaning procedures, tritium amount
- Typical products: CH_4, CT_4, mixed isotopologues, CO/CO_2

$C + 2Q_2 \leftrightarrow CQ_4$
$CQ_4 + Q_2O \leftrightarrow CO + 3Q_2$
$CO + Q_2O \leftrightarrow CO_2 + Q_2$ Q=H, D, T

Shift of gas composition over time ($T_2 \leftrightarrow CQ_4$). Relevant for **accountancy**, **gas-purification systems**, and experimental goals. Accumulation of methane species can lead to partial **blockage in cryogenic systems**.

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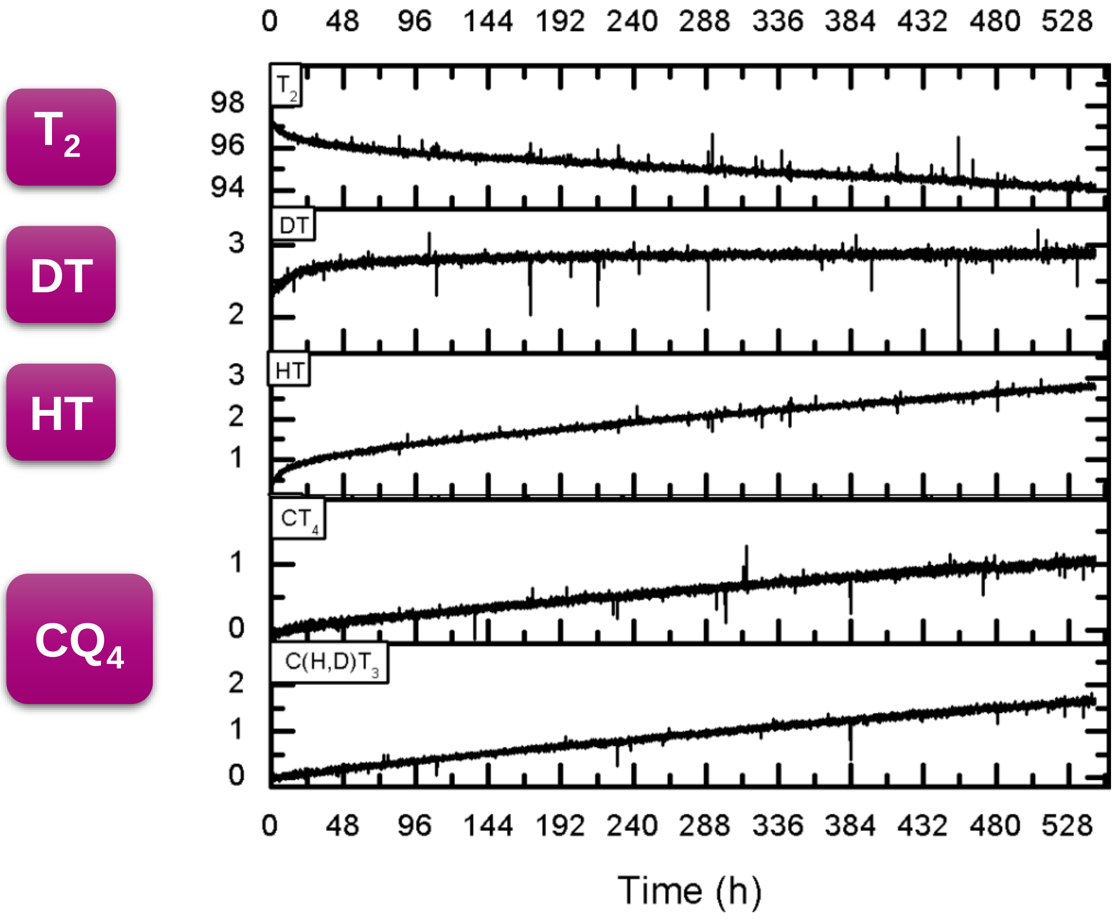

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Karlsruher Institut für Technologie

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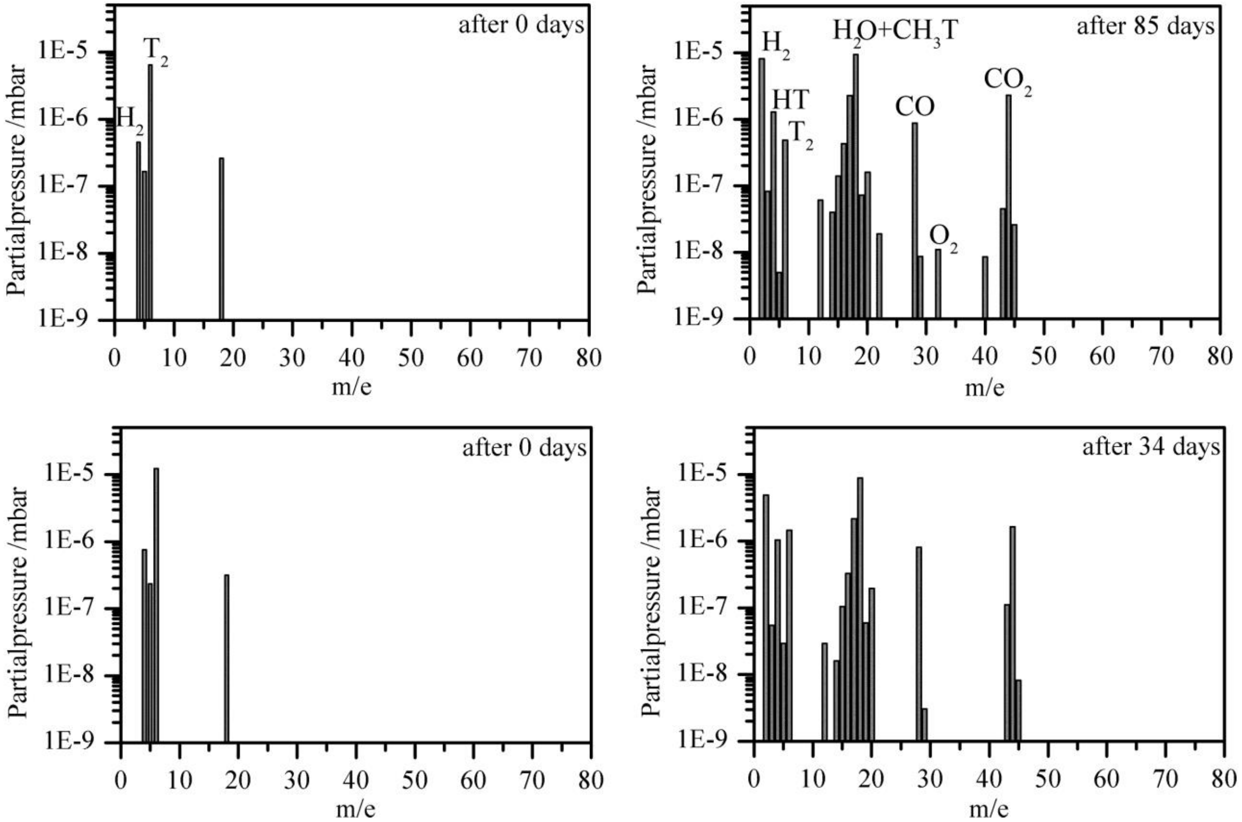
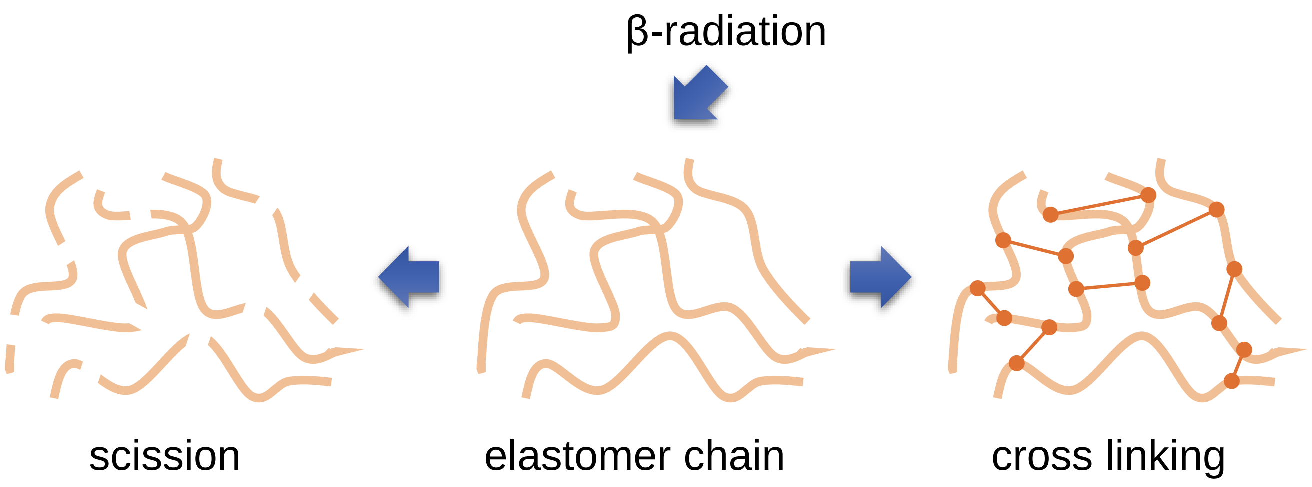


Radiochemical Reactions in Tritium Systems
A Selection

Radiolysis of complex molecules

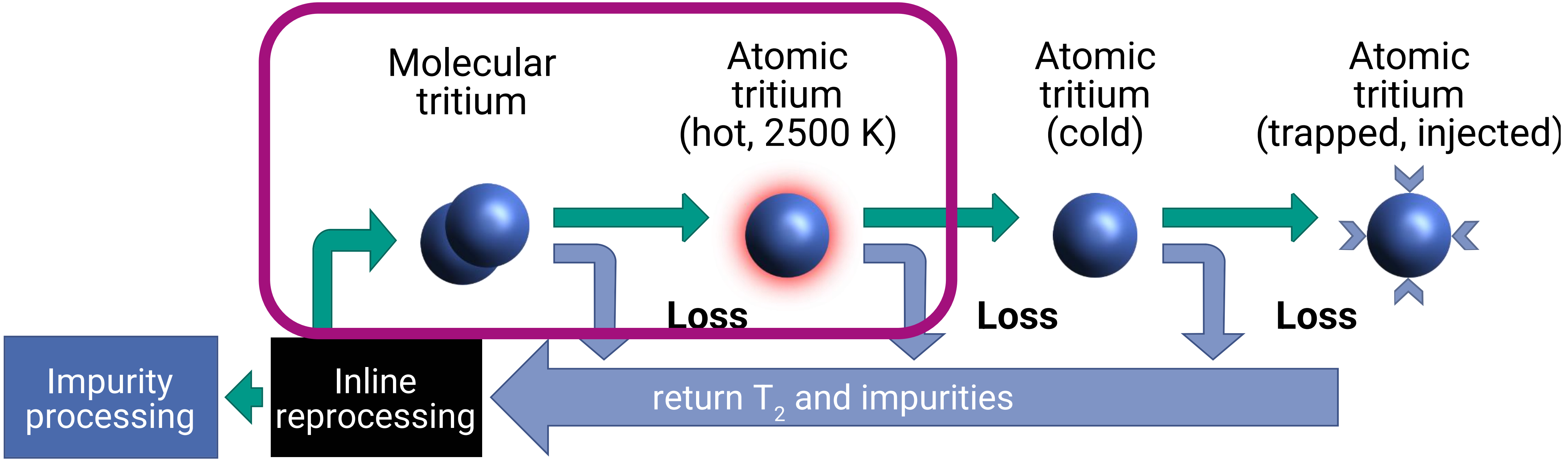
- β-particles generate ionization tracks causing bond cleavage, radicals, and secondary electrons.
- Leads to degradation of non-metallic sealings, due to scission or cross linking of elastomer chains.
- Increased impurity generation and holdup.

Shift of gas composition over time. Relevant for **accountancy**, **purification** systems, and experimental goals. Furthermore, leads to increased **tritium contamination.**



→ **Degradation of non-metallic vacuum components e.g. pumps, valves, flow controller.**

Technology Needed for an Atomic Source



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Atomic Tritium Source Setup at TLK

- Test of tritium operation of thermal/plasma sources
    - Tritium accumulation
    - Impurity generation
- Up to 0.5 sccm throughput
- Isotopic effects (H_2, D_2, T_2)

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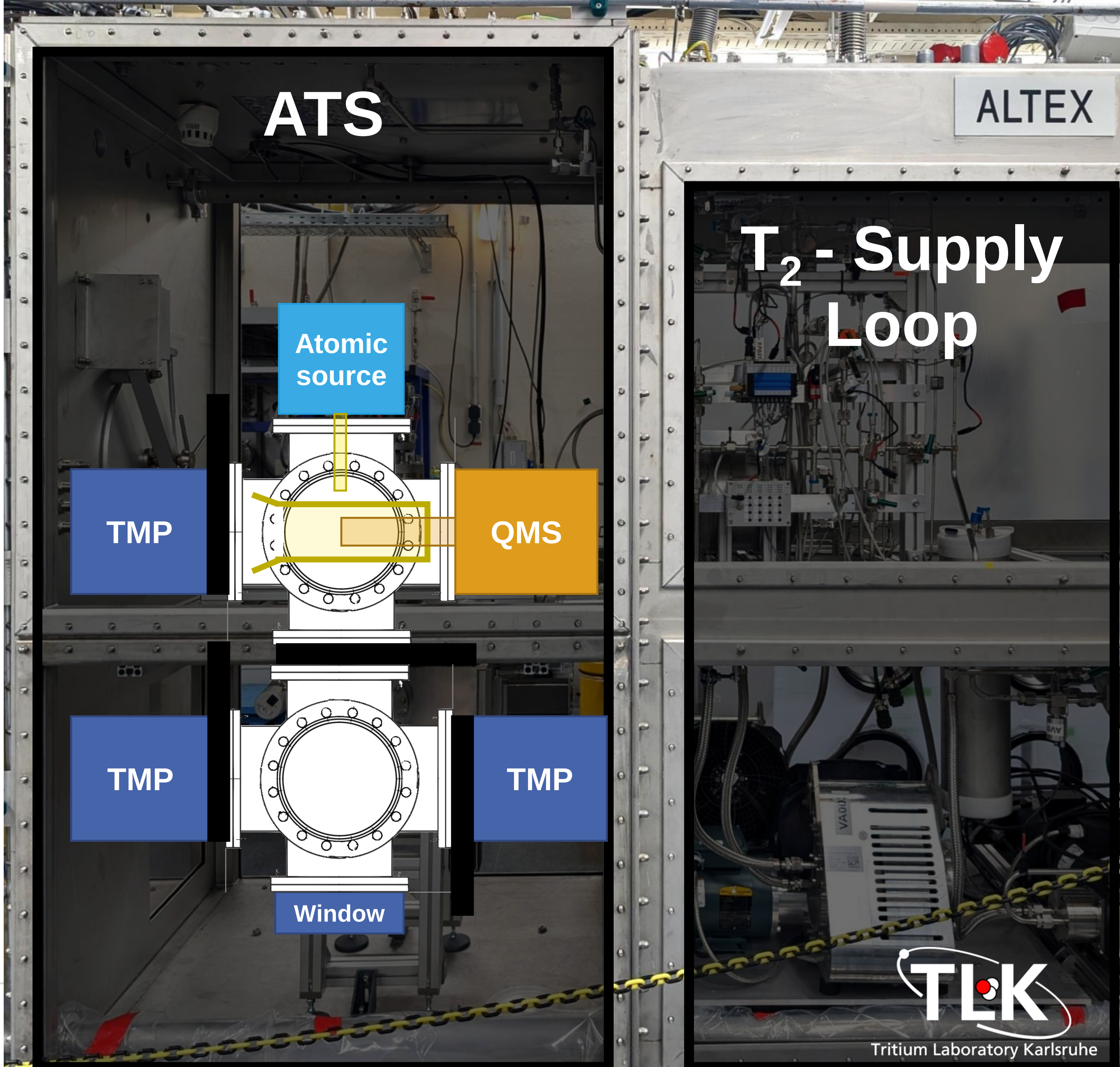
Testbed for commercial atomic hydrogen sources.

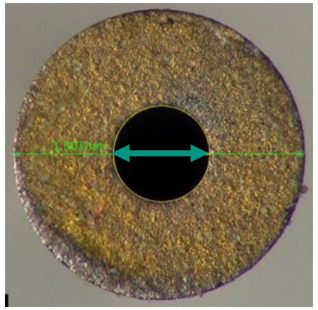


Atomic Beam Characterization

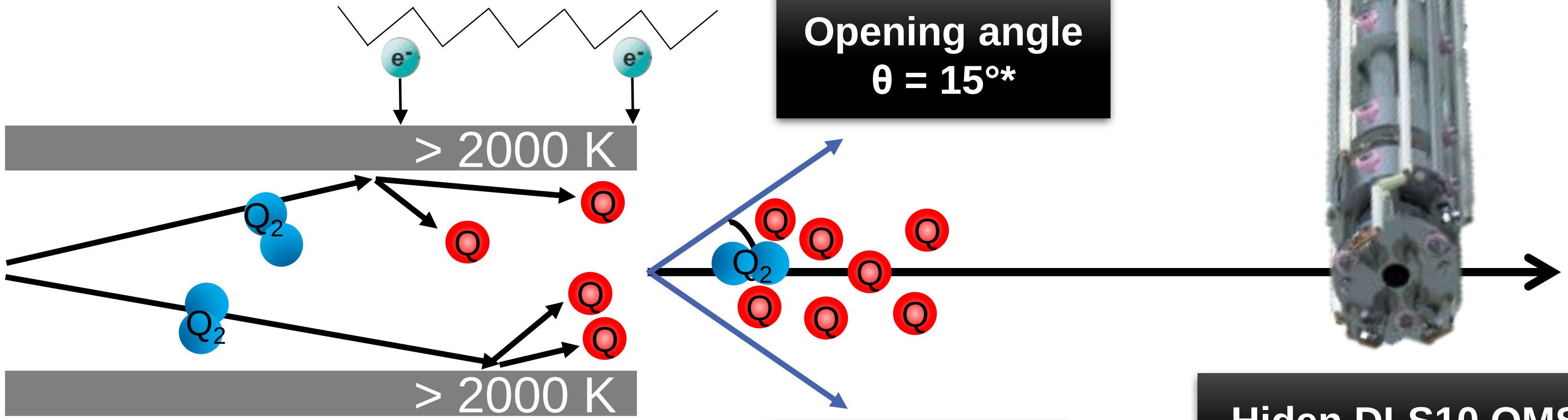
- Heating of a tungsten capillary (Ø 0.5 mm) via electron bombardment
- Use quadrupole mass spectrometer (QMS) with cross beam ion source for beam analytics

Tectra h-flux

0.5 mm

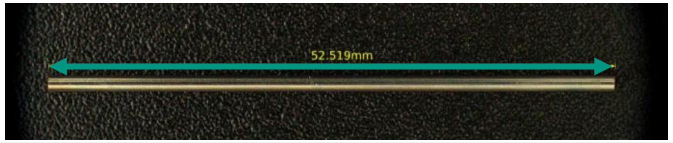


Heating on the last 3 mm



Opening angle θ = 15°*

52.52 mm



Up to 99% dissociation possible*

Hiden DLS10 QMS Cross-Ion

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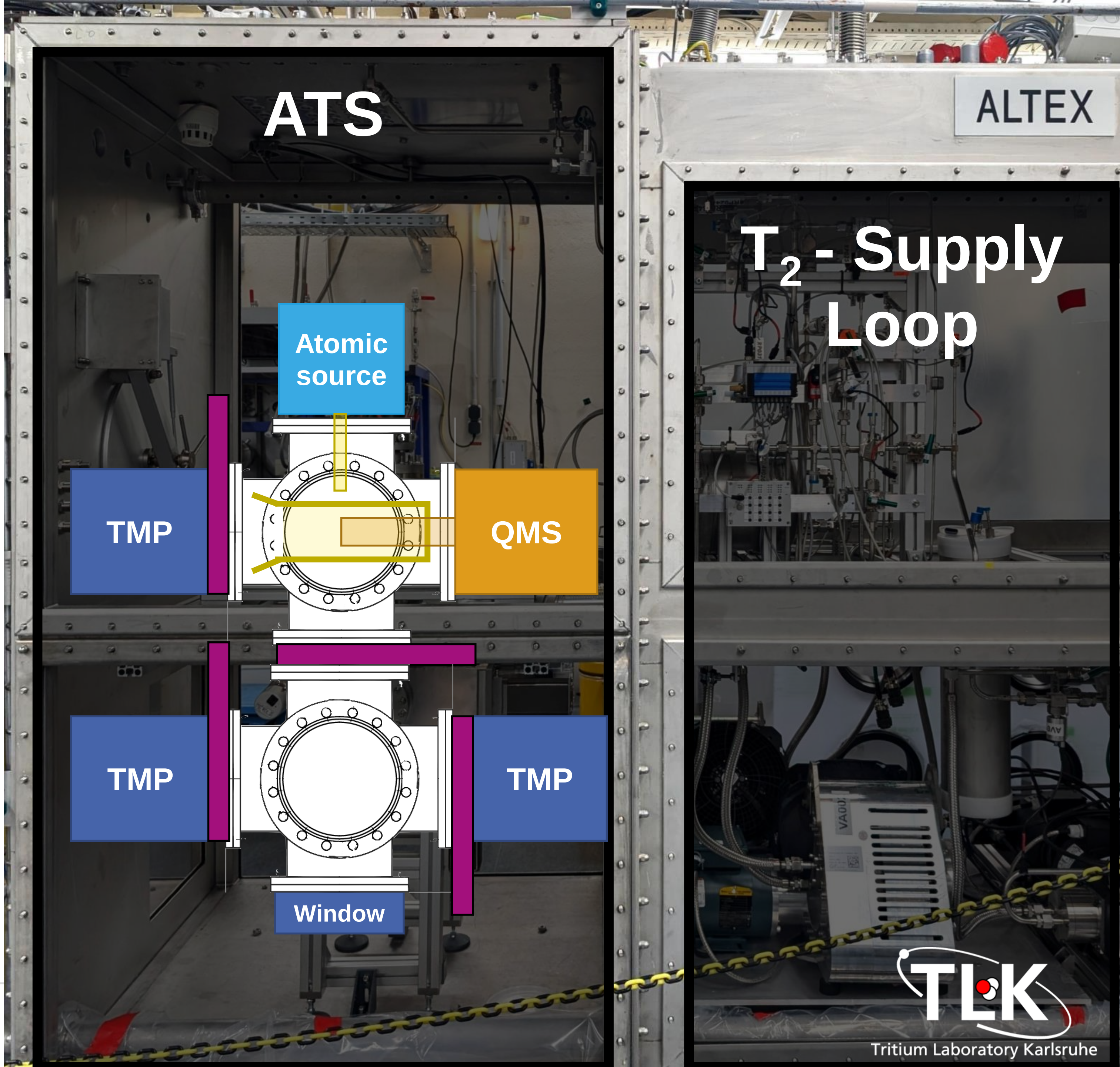
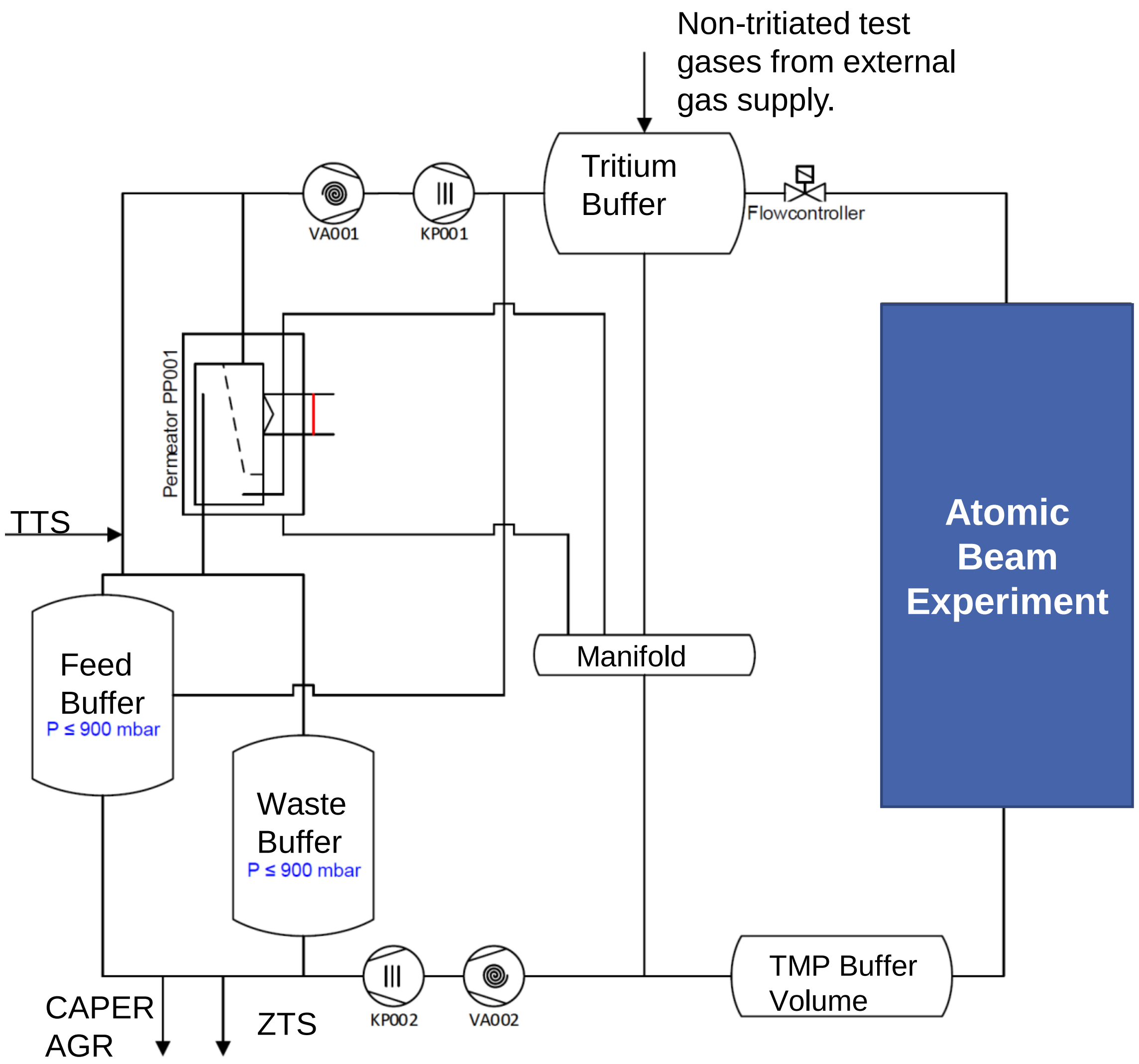


T_2 Supply Loop – Critical Components

- Significant tritium flow or purity requirements require **closed-loop operation** to enable continuous or batch-wise purification and to maintain stable process conditions.



T_2 Supply Loop – Critical Components

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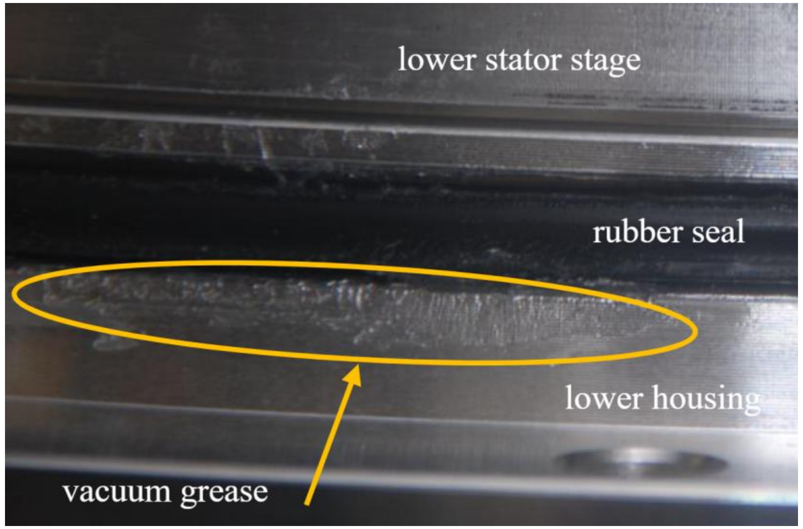
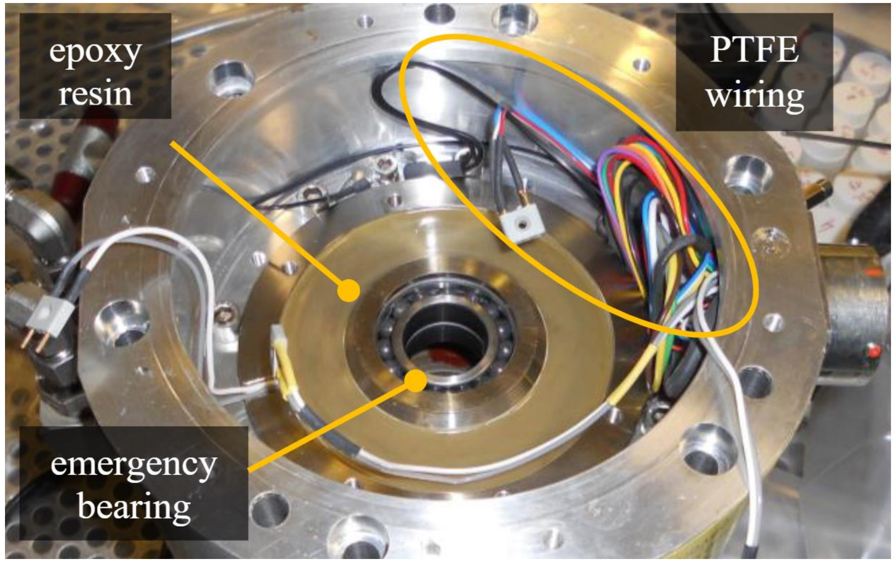
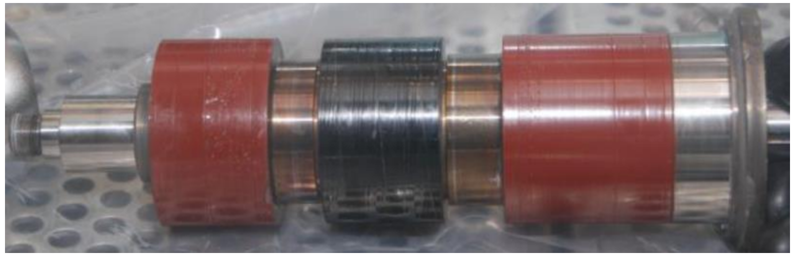
- **Turbo-molecular pumps**
  Non-metallic internal components (e.g., magnetic bearings, seals) and inherent leakage rates (typically ~1×10^{-7} mbar l/s per TMP) contribute to impurity generation and tritium hold-up within the pumping system.







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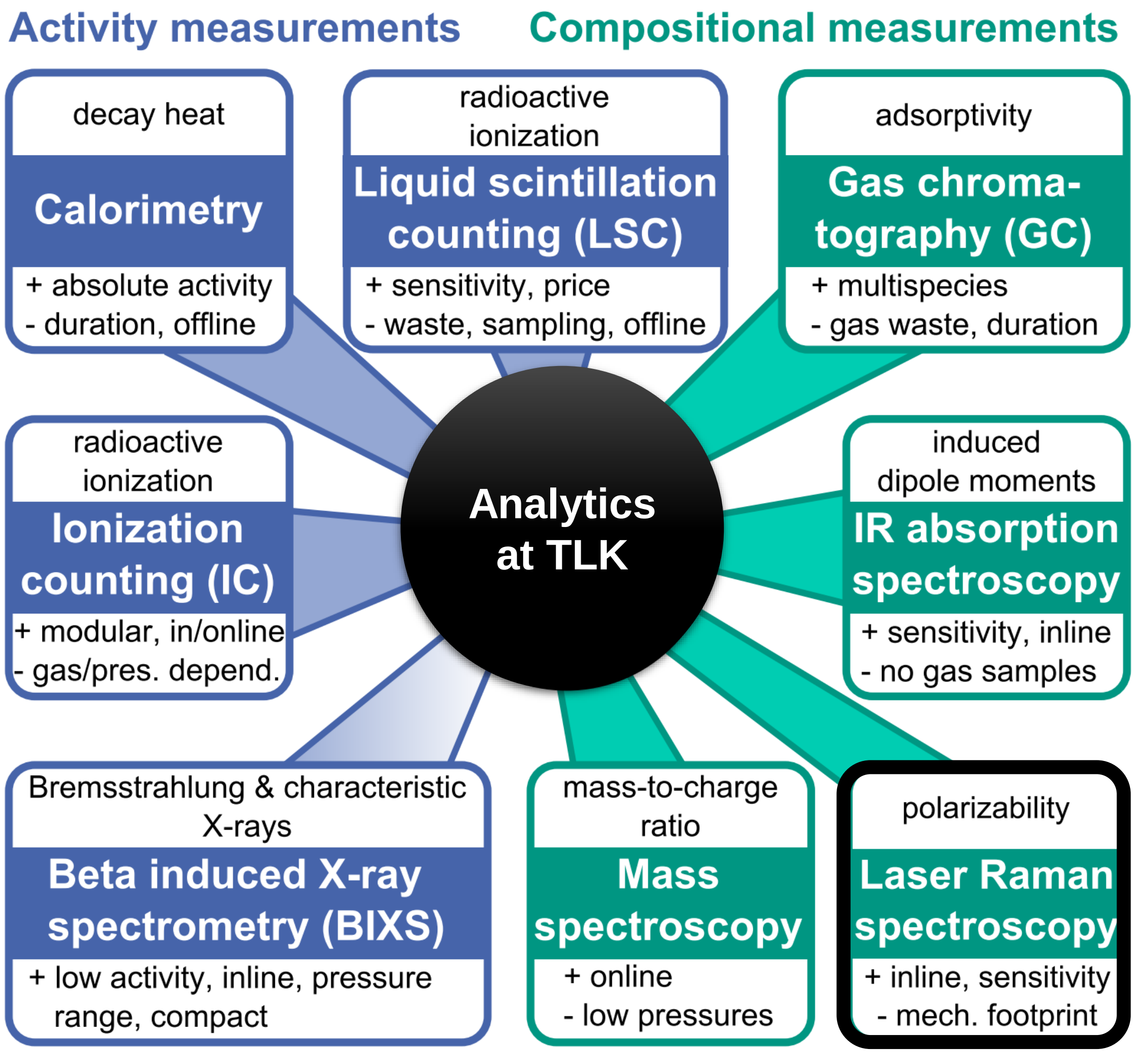
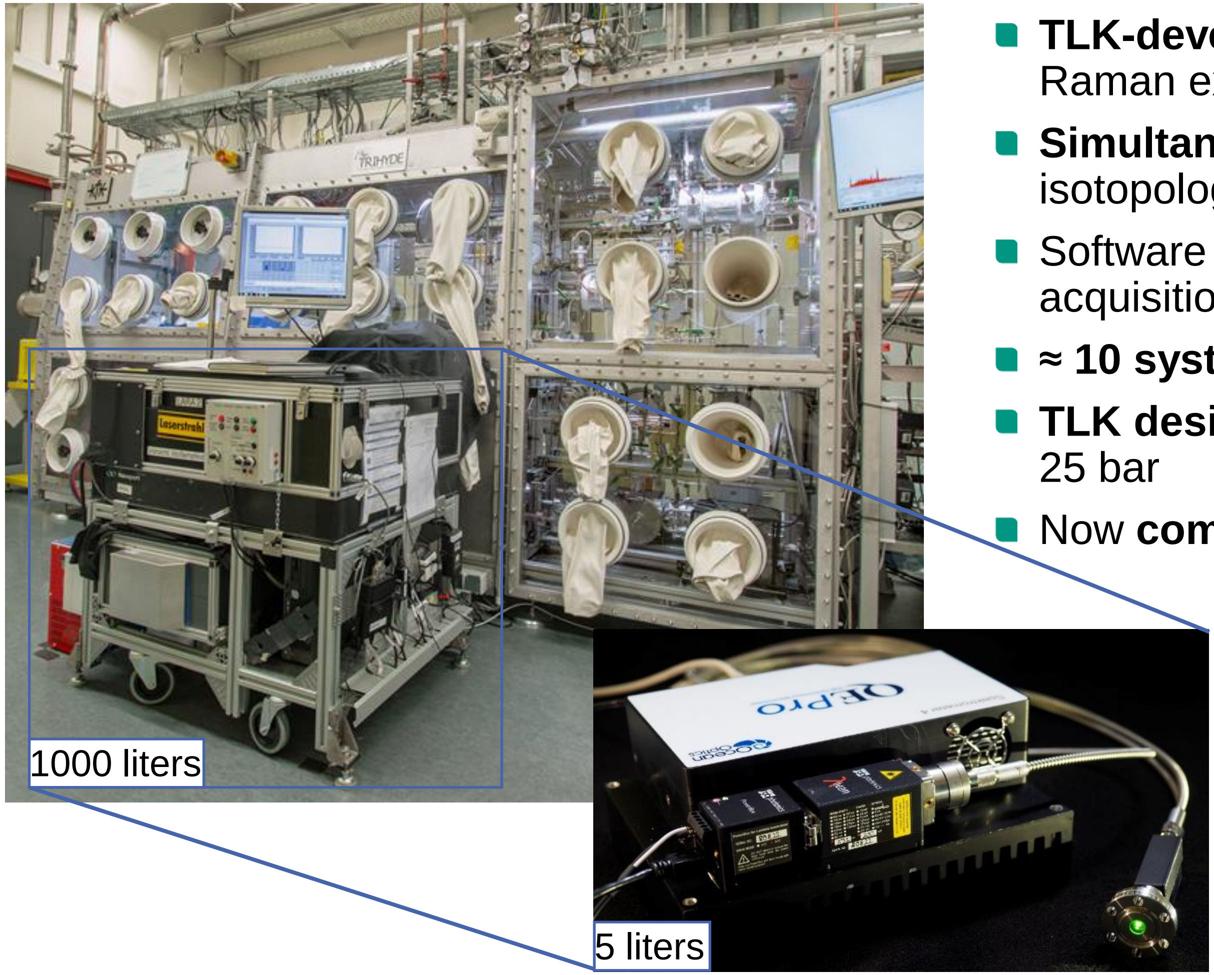
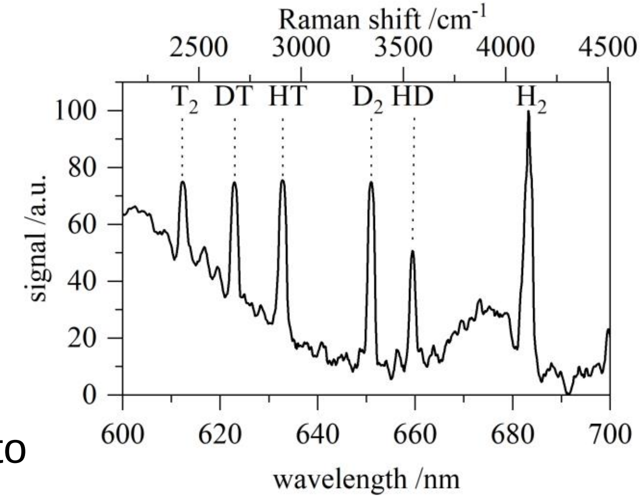
- **In-line analytics**
  Often based on in-house developments. Proper calibration generally requires dedicated on-site calibration facilities.



Inline Raman Spectroscopy – with µRa



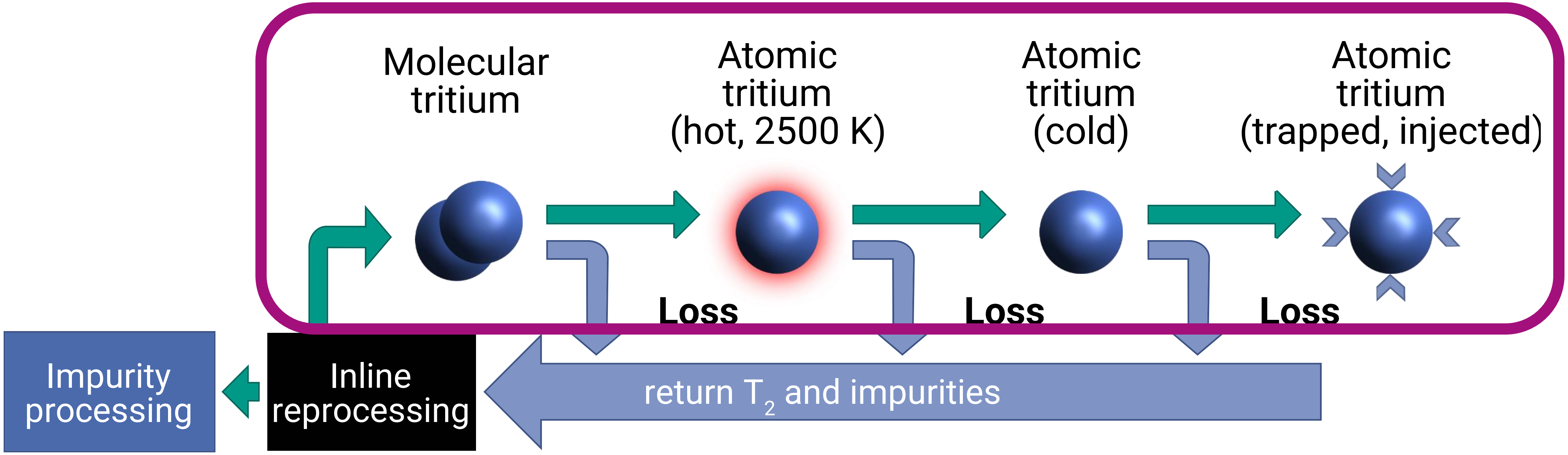
- **TLK-developed** based on decade long Raman experience for KATRIN
- **Simultaneous** detection of all six isotopologues plus N_2, O_2, H_2O
- Software **tailored** for every-day use for acquisition and analysis
- ≈ **10 system** in use at TLK
- **TLK designed** viewport for operation up to 25 bar
- Now **commercially available** from *Smolsys*



µRa micro Raman system

Niemes et al., *Accurate Reference Gas Mixtures Containing Tritiated Molecules: Their Production and Raman-Based Analysis* (2021).
Priester et al., *µRA—A New Compact Easy-to-Use Raman System for All Hydrogen Isotopologues* (2022).

Technology Needed for an Atomic Source



Beam diagnostic: atomic fraction, beam temperature, beam profile

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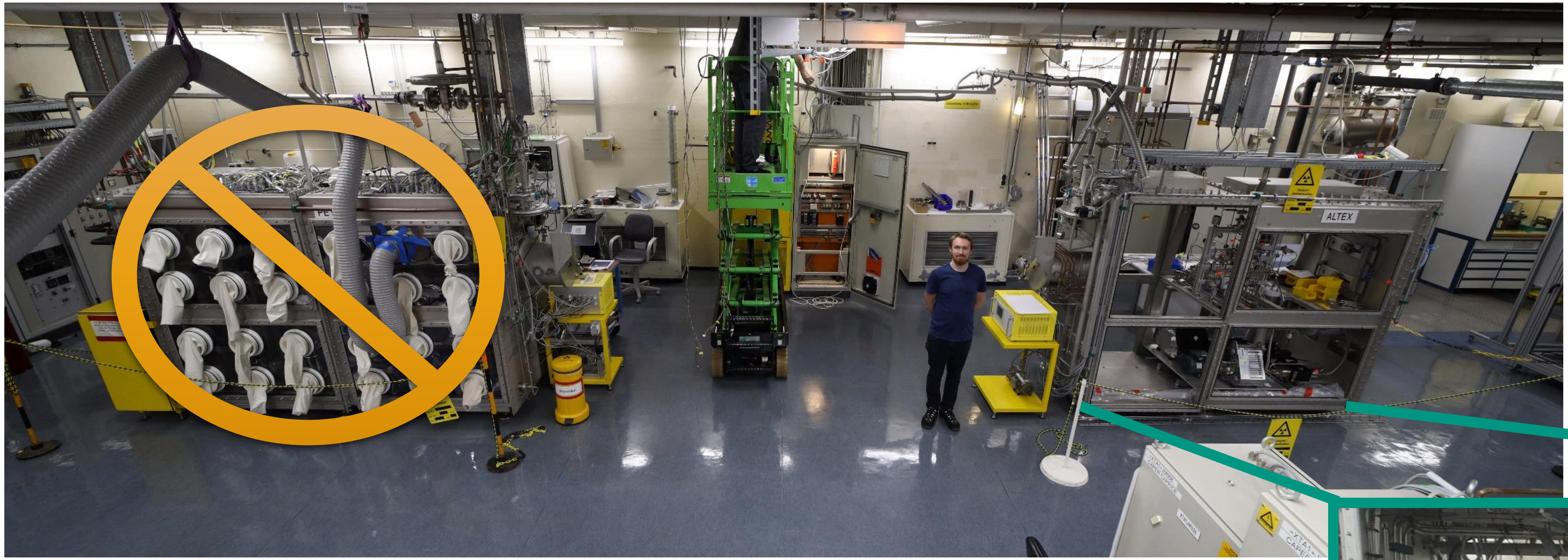
Karlsruhe Atomic Tritium Development Platform



- Ongoing preparation for glove box extension
- Tritium supply loop with ~ 10 gT_2/day ~20 sccm (1/5 of KATRIN)
- Connection to TLK infrastructure for gas processing
- 2024/2025 preparations. Removal and re-siting of infrastructure almost completed

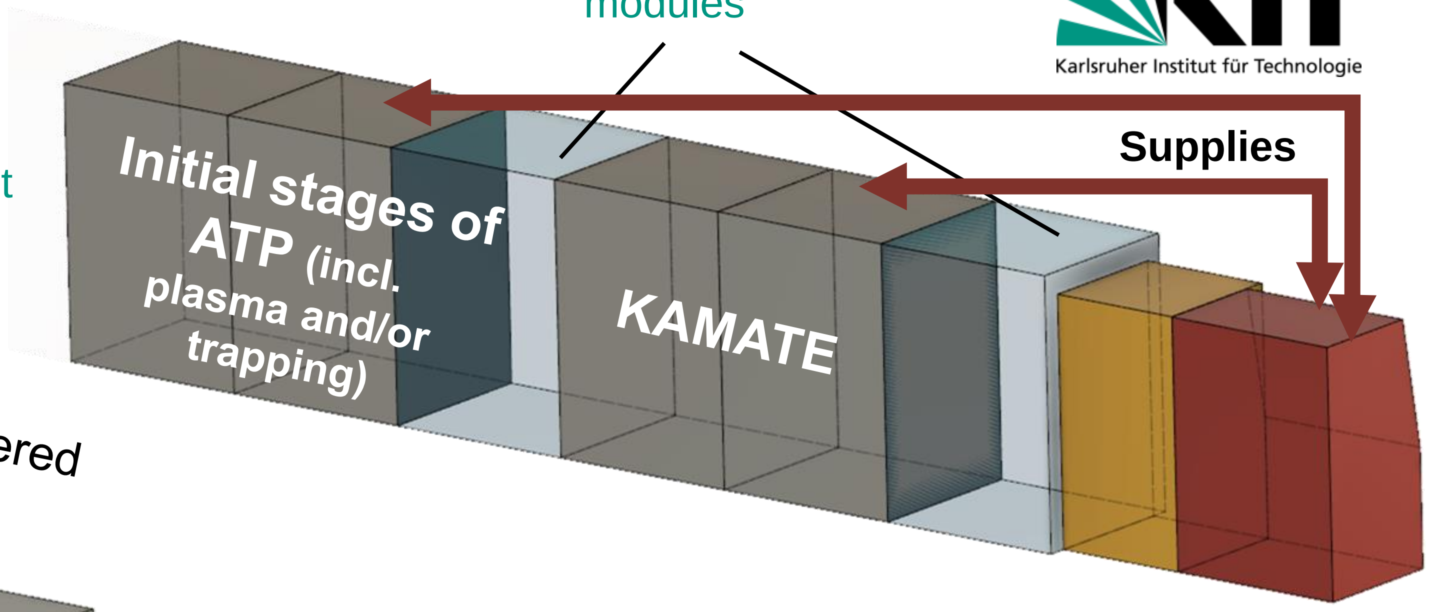
KAT-DP concept

Initial configuration (2026++)

Initially missing modules

In parallel: setting up of experiment with or w/o tritium

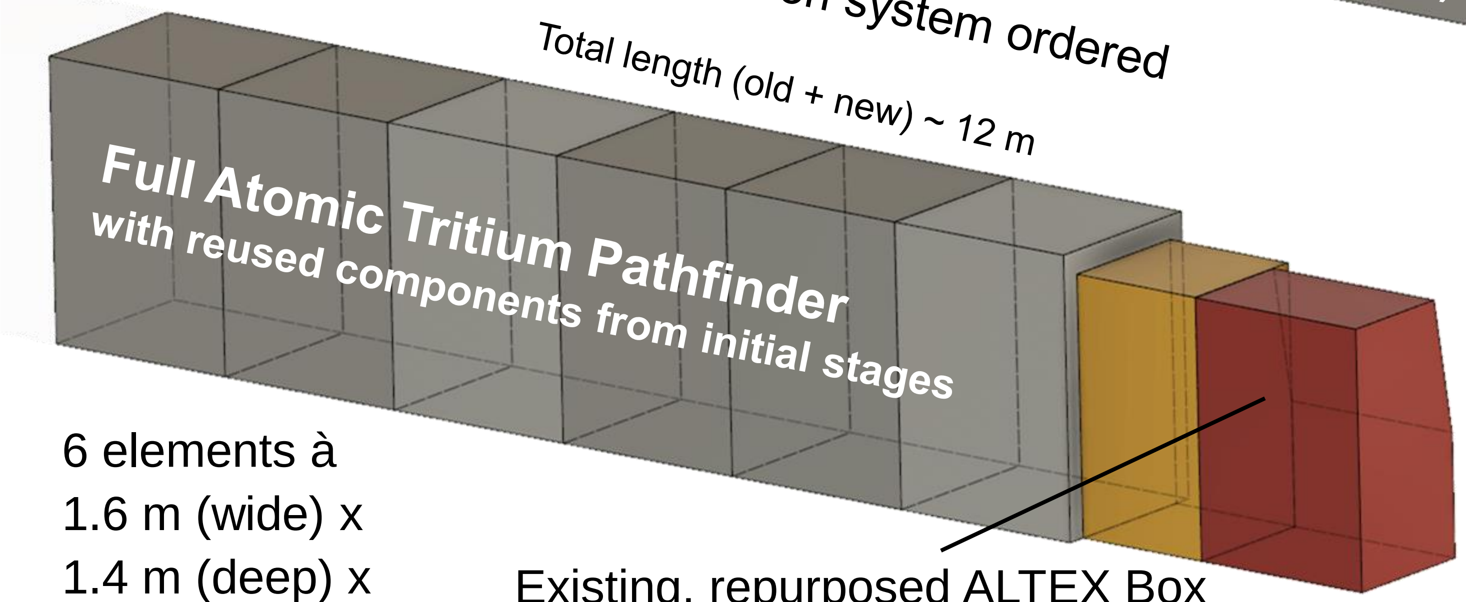
Supplies



Final configuration

Extension boxes and tritium retention system ordered
ETA: Spring 2026

Total length (old + new) ~ 12 m



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

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

Thank you for your attention

Backup Slides

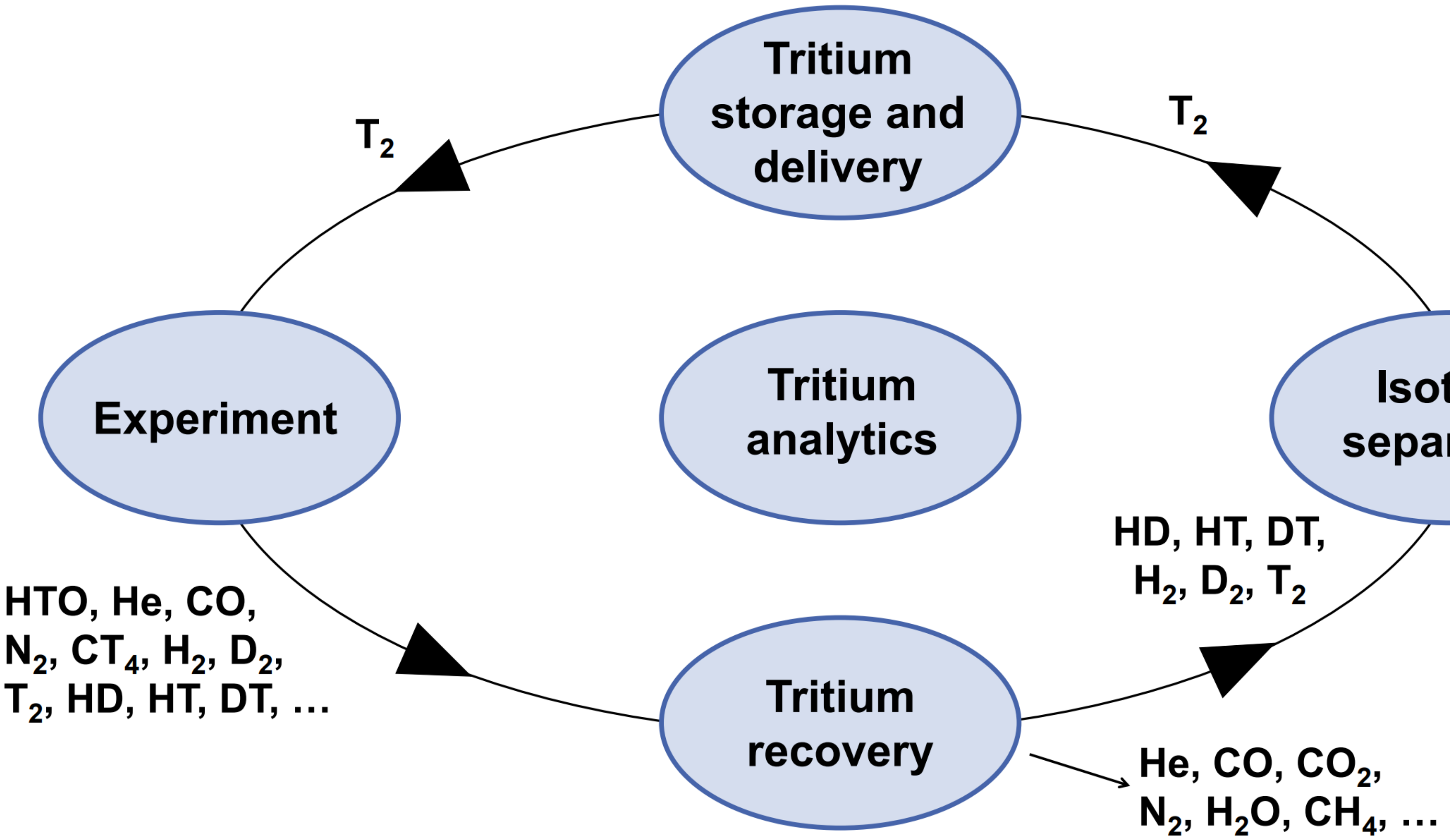
Timeline KATRIN++

2019-2025	2026-2027	2028-2034 (PoF-V)	Scientific goal
Phase 1 (integral) neutrino mass	**Phase 2 (differential) keV-sterile ν**	**R&D phase KATRIN ++**	**Neutrino mass**
	Quantum sensor R&D	Quantum sensor demonstrator	
	Atomic tritium R&D	Atomic tritium demonstrator	

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 is extending with specialised groups for **tackling challenges together**

Leveraging research infrastructures **(KATRIN beamline for detector demonstration; KAT-DP for atomic source development)**


Tritium storage and delivery
T_2
T_2
H_2, D_2
Experiment
Tritium analytics
Isotope separation
HD, HT, DT,
H_2, D_2, T_2
HTO, He, CO,
N_2, CT_4, H_2, D_2,
T_2, HD, HT, DT, …
Tritium recovery
He, CO, CO_2,
N_2, H_2O, CH_4, …