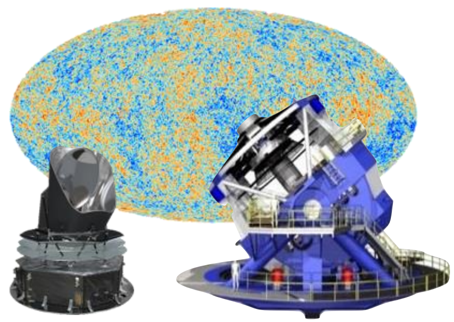
# Spectroscopy of the first electrons from the KATRIN tritium source

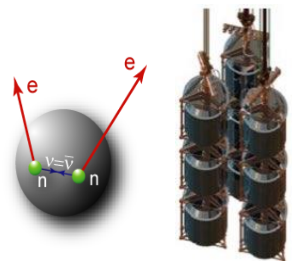
Magnus Schlösser for the KATRIN collaboration

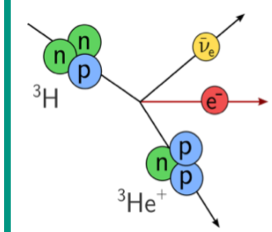
XXXIX International Conference on High Energy Physics, 7. July 2018, Seoul

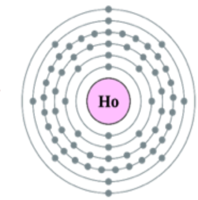
INSTITUTE OF TECHNICAL PHYSICS, TRITIUM LABORATORY KARLSRUHE

# Ways to access the neutrino mass





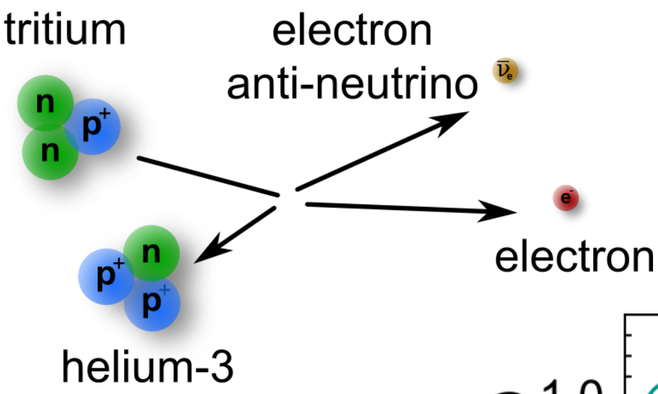

| | Cosmology | Search for 0νββ | β-decay & electron capture |
|---|---|---|---|
| **Observable** | $M_\nu = \sum_i m_i$ | $m_{\beta\beta}^2 = \left\lvert\sum_i U_{ei}^2\, m_i\right\rvert^2$ | $m_\beta^2 = \sum_i \lvert U_{ei}\rvert^2\, m_i^2$ |
| **Present upper limit** | 0.12 – 1 eV | 0.2 – 0.4 eV | 2 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 |

KATRIN → 200 meV



Tritium Laboratory Karlsruhe

# Tritium β-decay

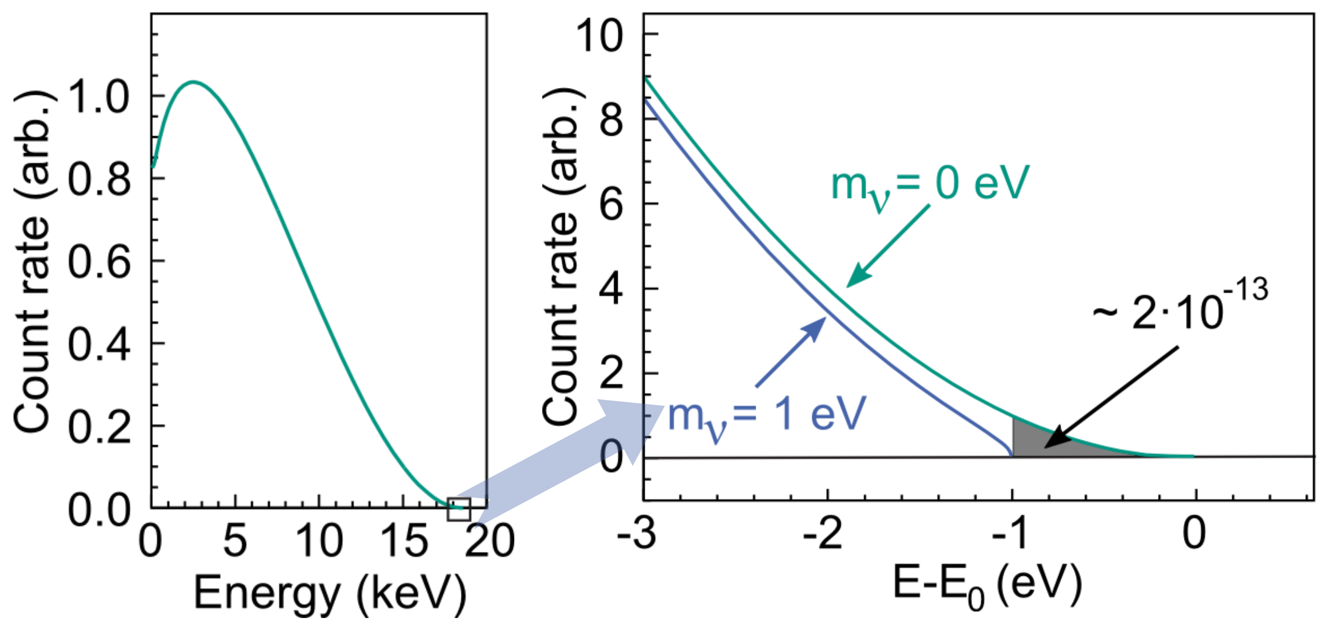



$E_0$ = 18.6 keV

$T_{1/2}$ = 12.3 y

## β -electron spectrum

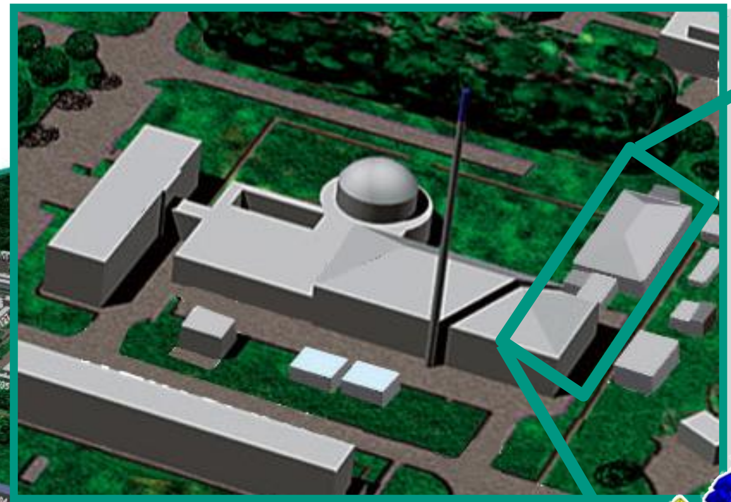
$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\nu_i}^2 c^4}$$

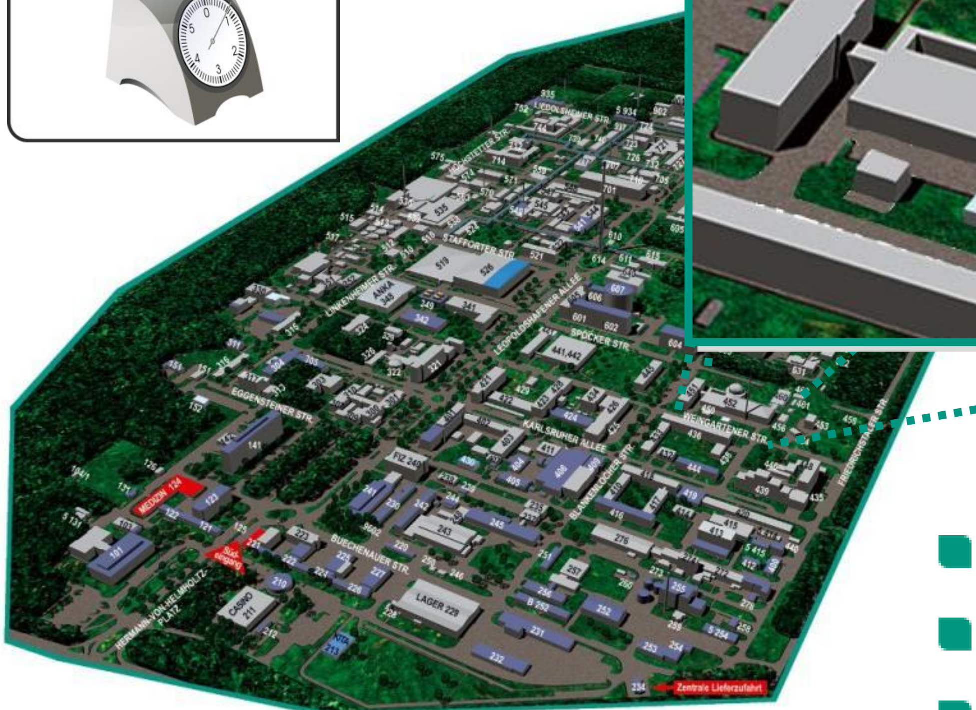


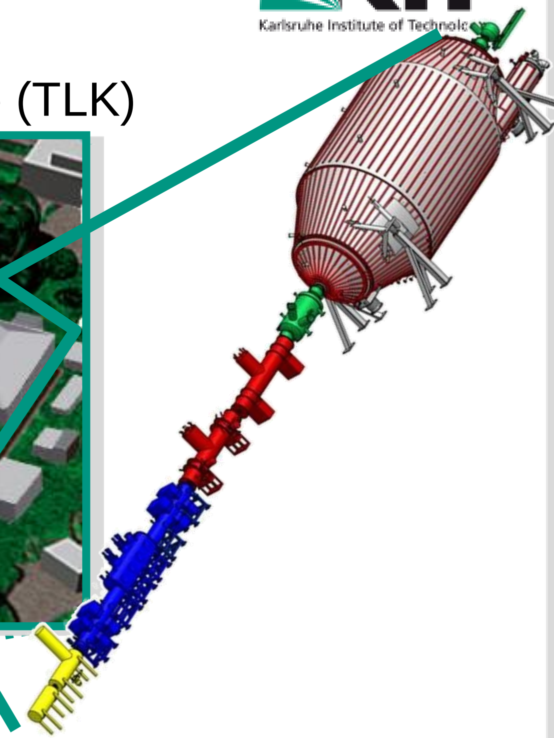

**KATRIN's aim: Measurement of $m_\nu$ with a sensitivity of 200 meV/c²**

# The Tritium Laboratory Karlsruhe

Tritium Laboratory Karlsruhe (TLK)





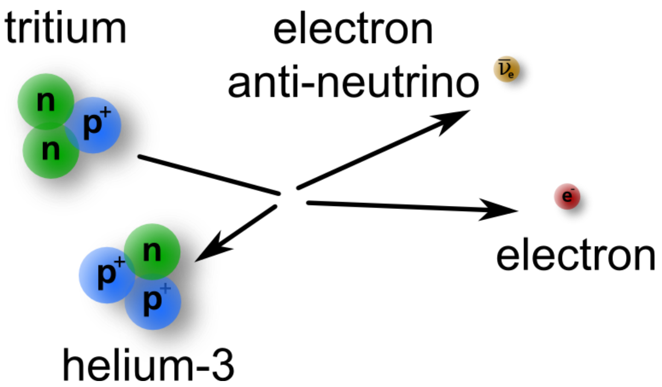


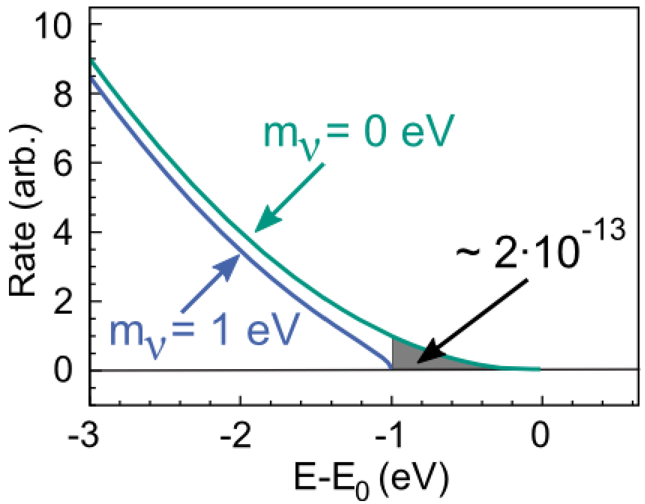
Karlsruhe Institute of Technology

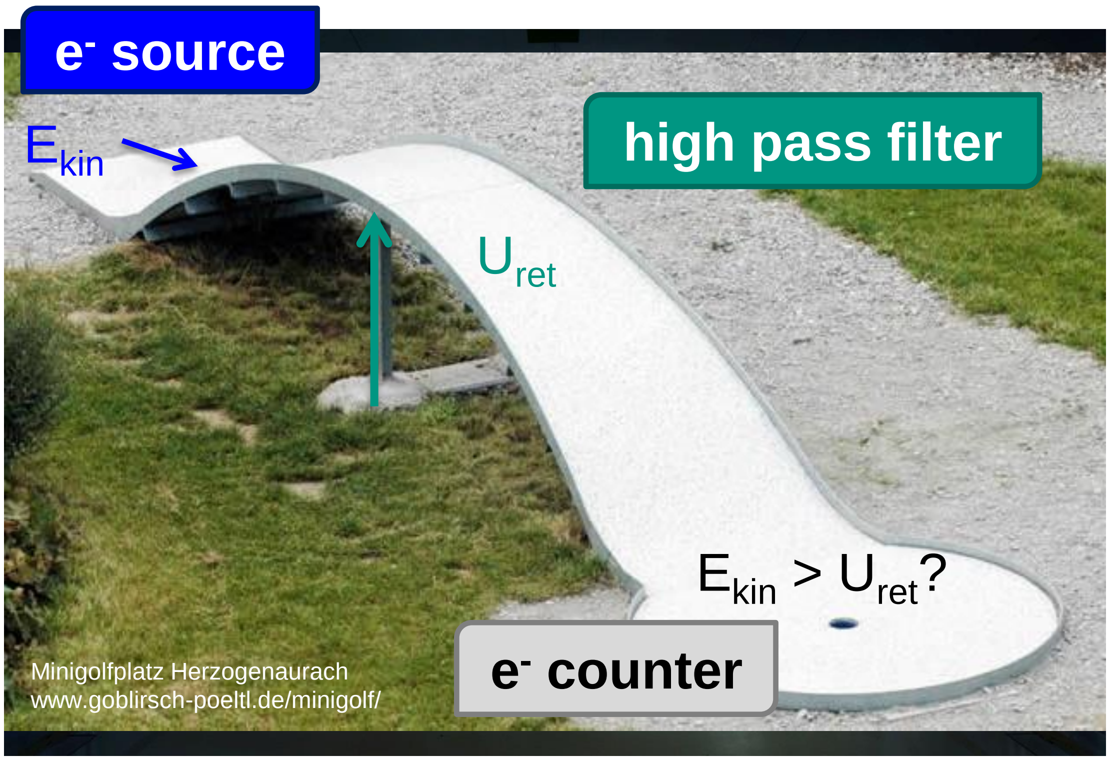
Campus North

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

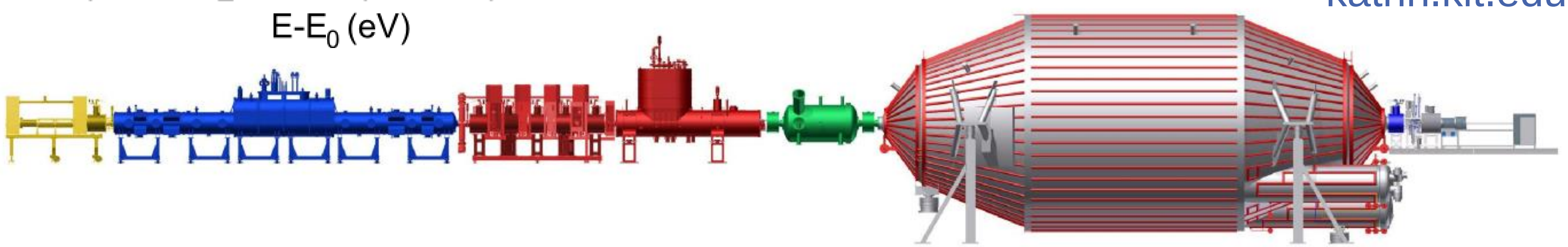
# The Karlsruhe Tritium Neutrino Experiment



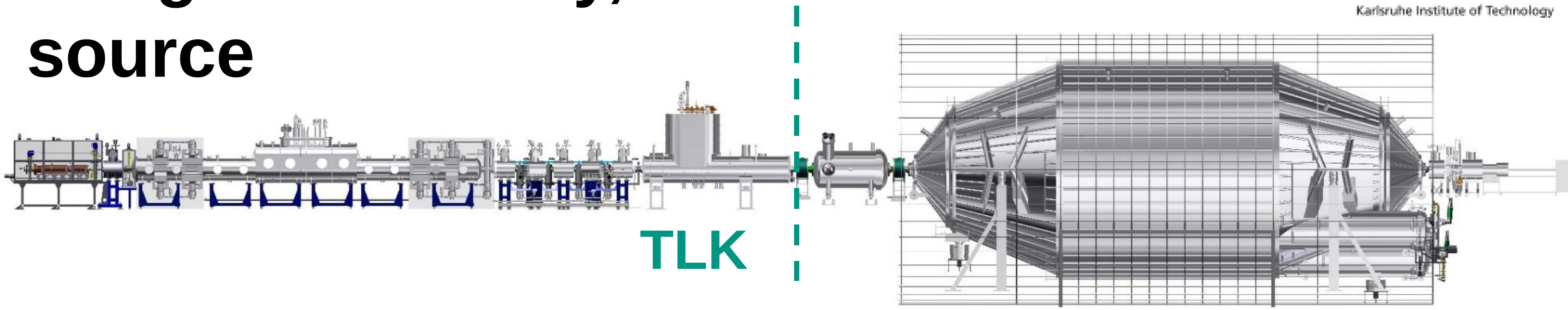



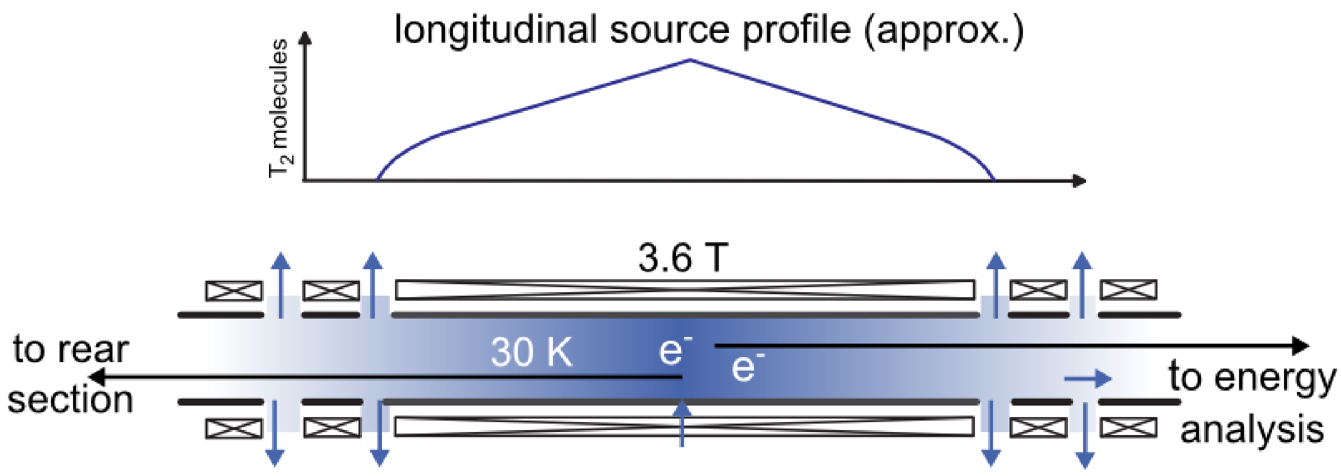




katrin.kit.edu



# A high-luminosity, ultra-stable tritium source

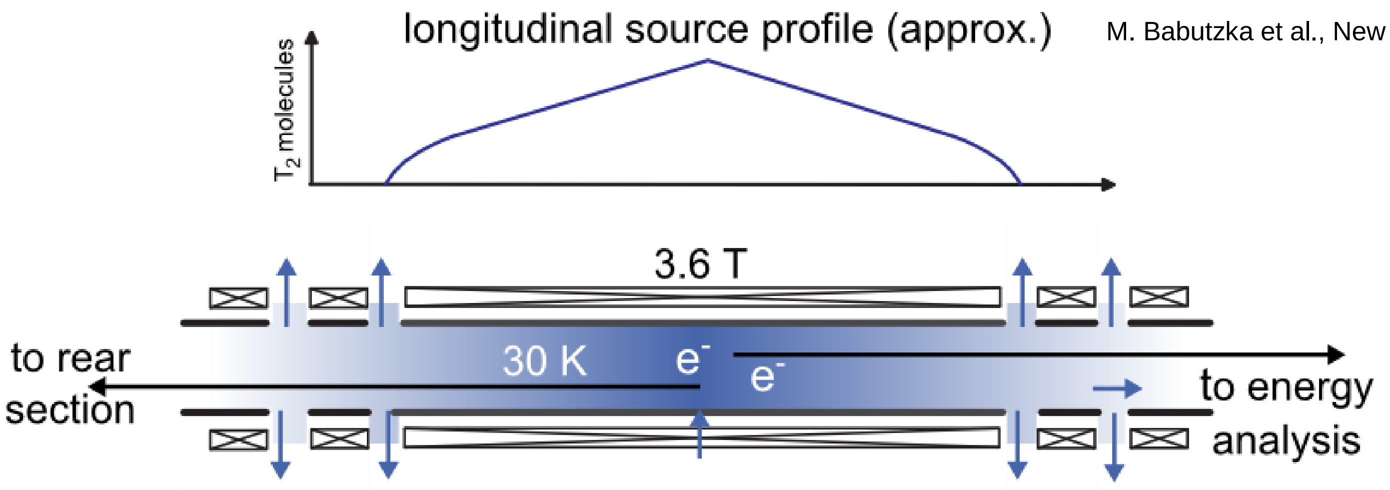



- $T_2$ purity > 95%
- $T_2$ retention before spectrometers >$10^{14}$
- Source profile stable to $10^{-3}$ level
- Source activity $10^{11}$ Bq
- $T_2$ throughput ~ 40 g/day
- Operation 24/7, 60 days/run
- Necessary inventory >15 g

# The stable tritium source

M. Babutzka et al., New J. Phys. **14** (2012) 103046



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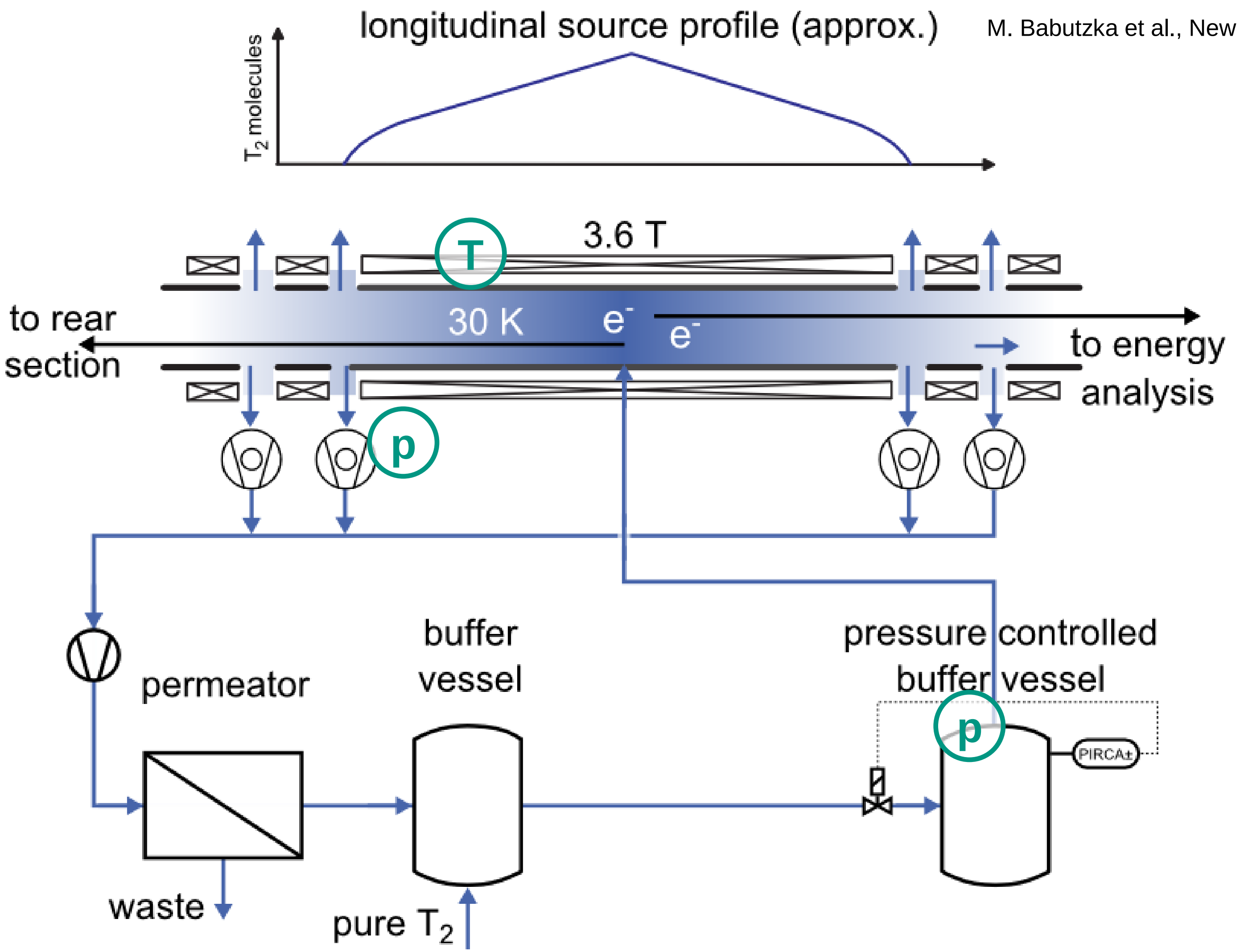

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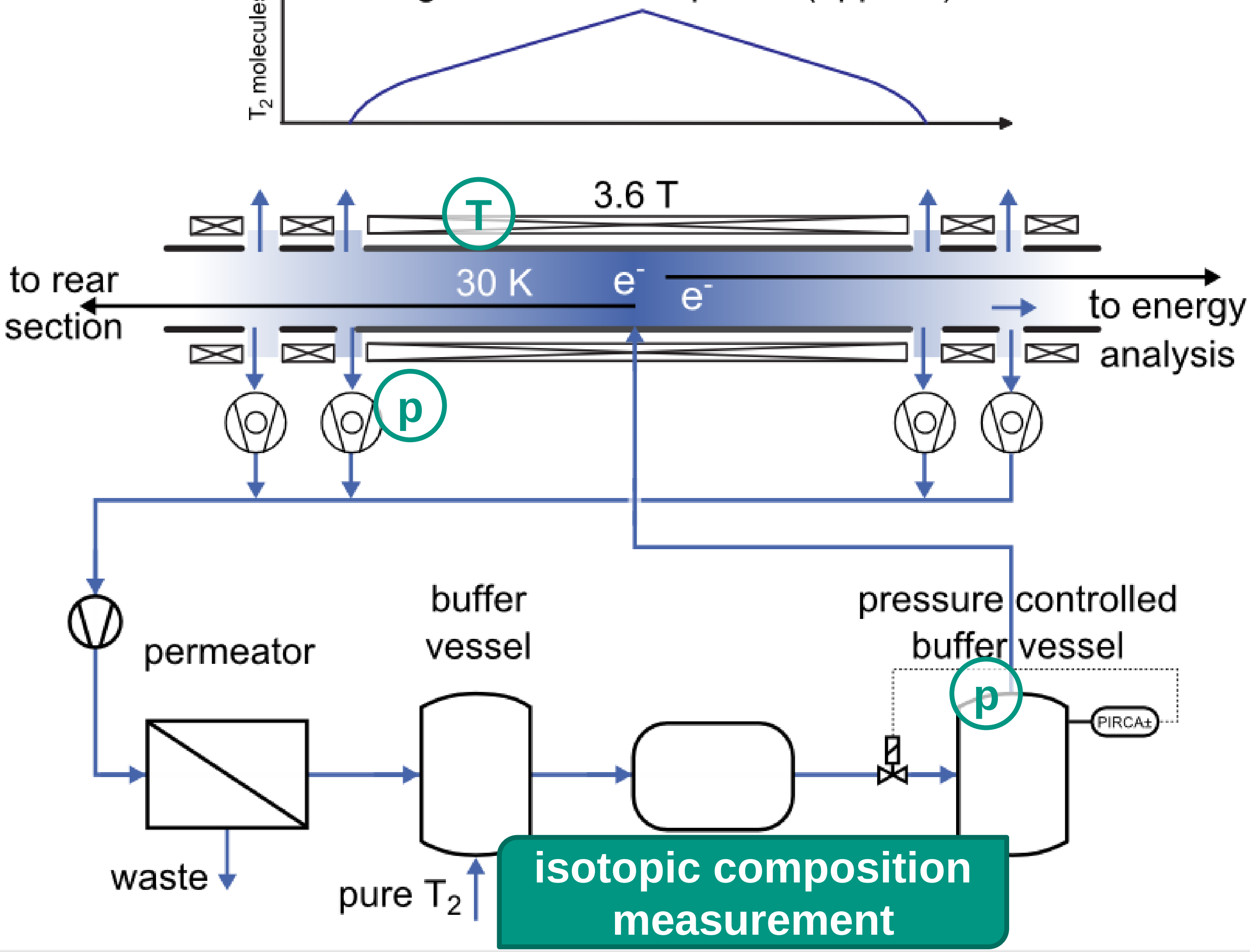
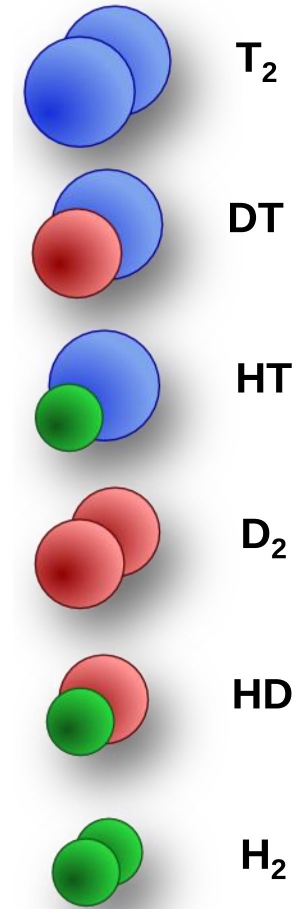



**Hydrogen isotopologues**



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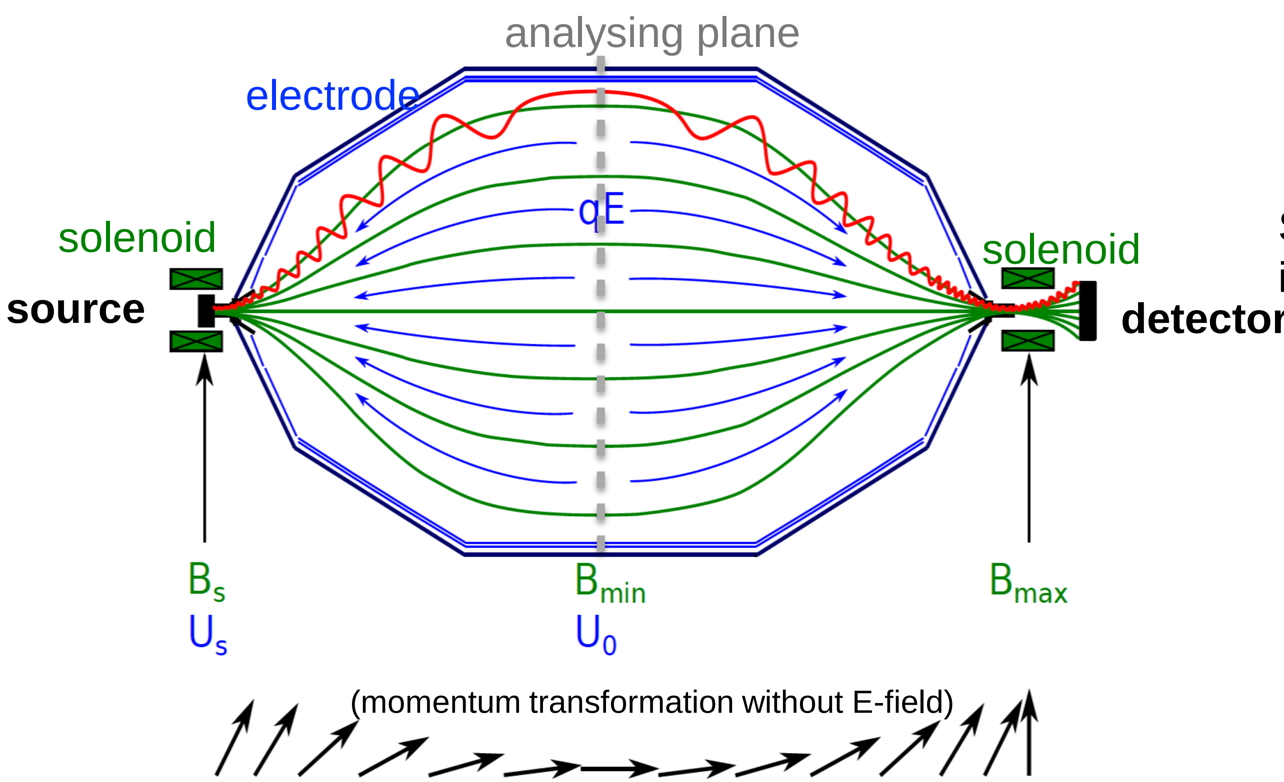
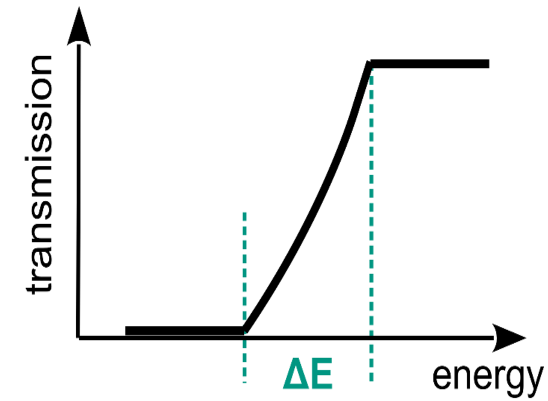
# High-resolution spectrometer: MAC-E filter

## Magnetic Adiabatic Collimation & Electrostatic Filter:

- **integrating electrostatic filter ($E_{kin} > eU_0$)**
- **“clean” (analytic) response function**




Sharp high pass filter:



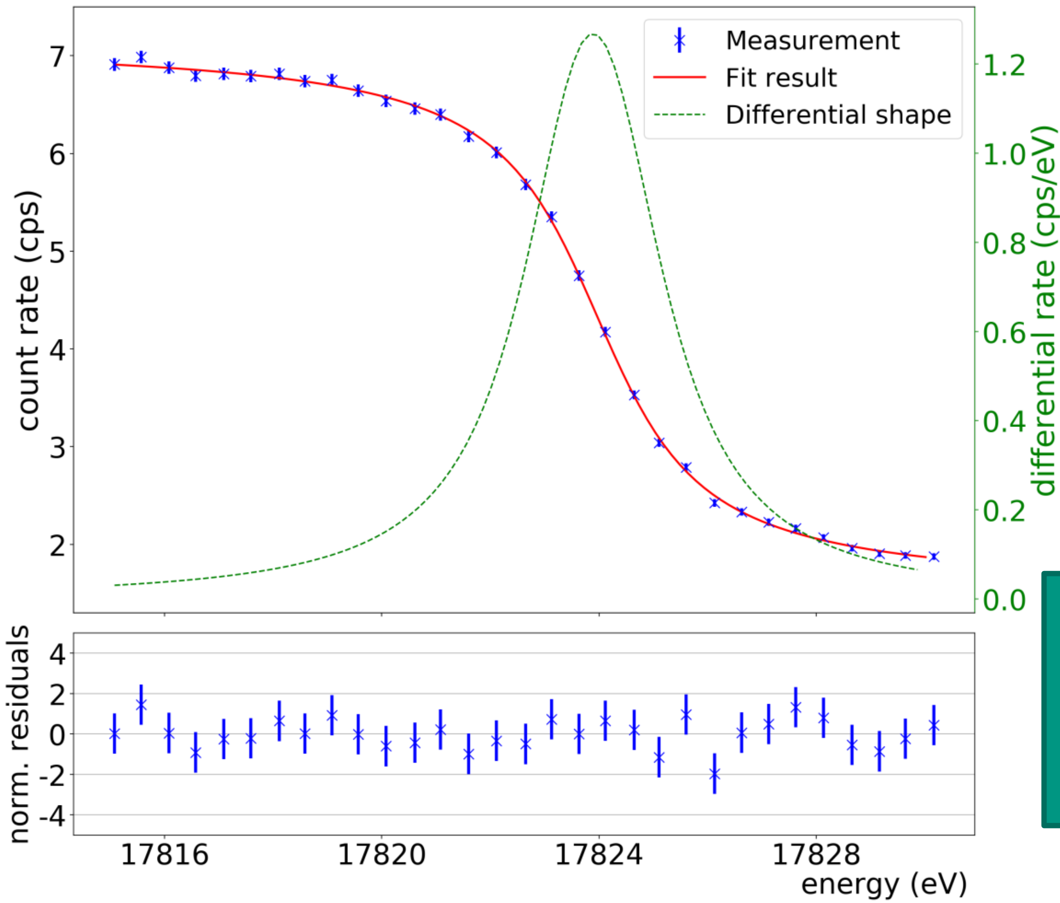

Steps of filter potential → integrated β spectrum

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

→ **$\Delta E$ < 1 eV** at 18.6 keV

# Spectroscopy of electrons from $^{83m}Kr$

**K-32** line (17.8 keV, Γ ~2.8 eV)




- **Gaseous $^{83m}Kr$ provides isotropic electrons for commissioning (summer 2017)**
- **Energy scale calibration and stability validated**

Validation of high (<1 eV) spectroscopic resolution of KATRIN spectrometer

*KATRIN collab., JINST **13** P04020 (2018), KATRIN collab., EPJ C **78** 368 (2018)*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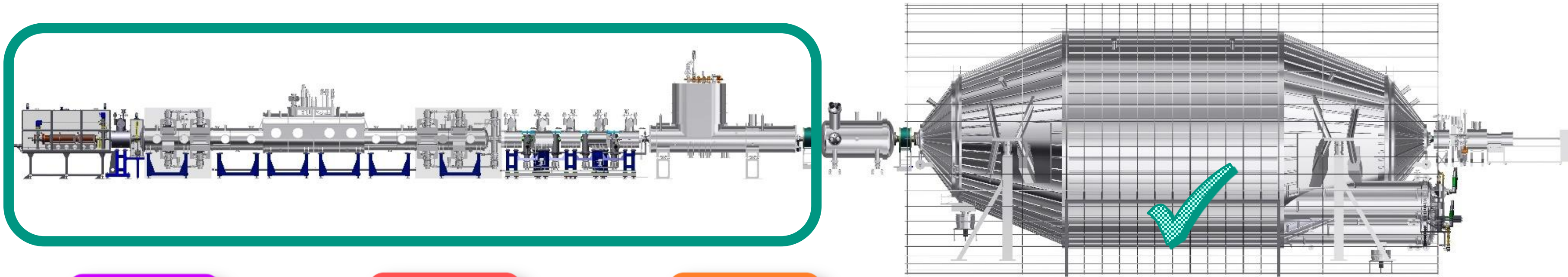
# Unique Selling Points of KATRIN

- KATRIN will measure the neutrino mass with 200 meV/c² sensitivity by employing
  - an ultra-stable high-luminosity windowless gaseous tritium source
  - and a high-resolution MAC-E filter with < 1 eV energy resolution.



**Inner loop buffer vessel pressure**

*Priester et al. Vacuum 116 (2015) 42*

**WGTS Temperature**

*Grohmann et al. Cryogenics 51,8 (2011) 438*

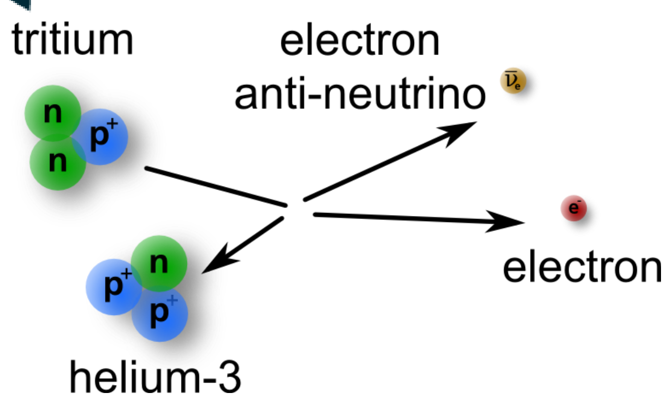
**Gas composition**

*Schlösser et al. J. Mol. Struct. 1044, 24 (2013) 61*

**Source activity**

Not yet demonstrated


# First tritium with KATRIN in May / June 2018





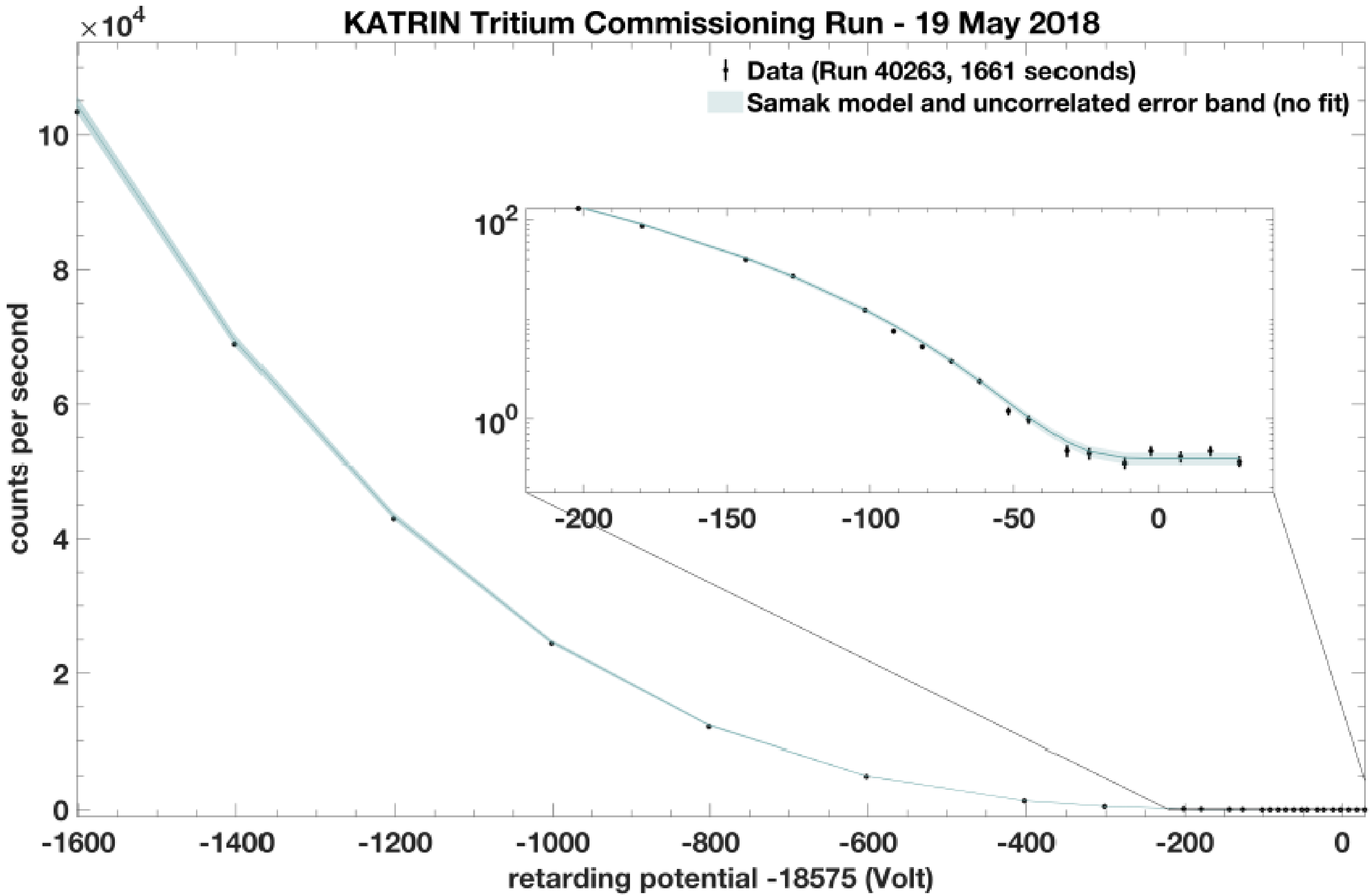
Karlsruhe Institute of Technology
Tritium Laboratory Karlsruhe

# First tritium campaign May / June 2018

- **Motivation:**
  - **Commissioning of system with tritium (1% of nominal activity)**
  - **Demonstrate 0.1% global system stability**
  - **Investigate ion generation and retention**
  - **Study beta spectrum for systematic effects and test analysis strategies**

First tritium injection:
Friday 18 May
7:48 am UTC

# The very first tritium spectrum




- **Input parameters for model directly taken from experimental "slow control" data**
- **No tuning!!!**

Very good agreement of model with data
(shape and absolute rate!)



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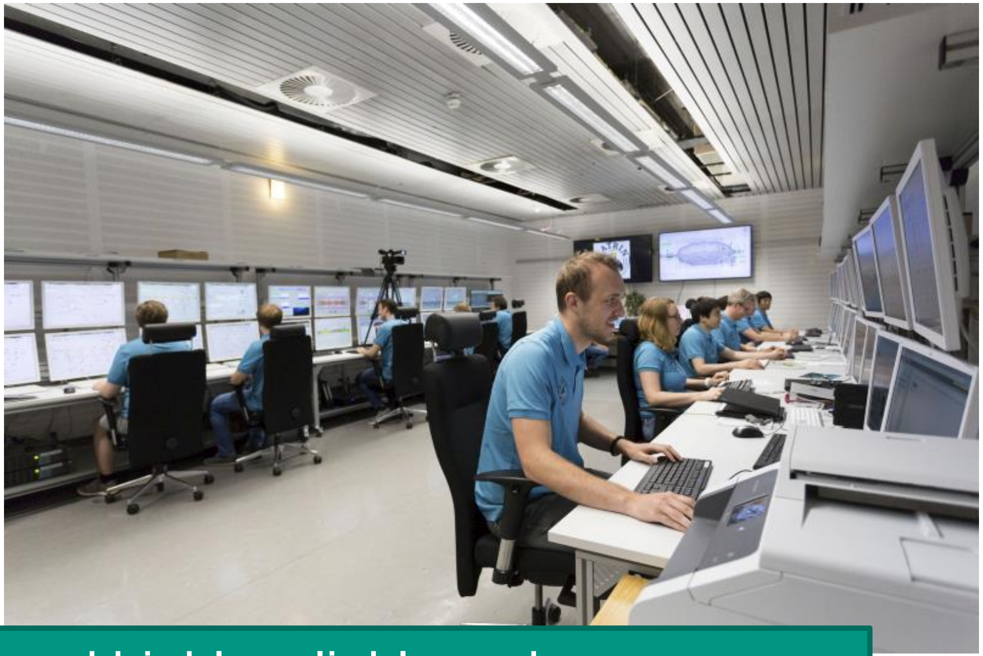
# First tritium campaign

- Two week operation
  - Tritium-loop was started 5th June and stopped 18th June (without interruption)
  - During day - Special investigations
    - ion studies
    - column density effect on scattering
    - sterile neutrino scans
    - high rate investigations
    - or beta spectrum scan
  - During night and weekend
    - beta spectrum scan
    - stability measurements



KATRIN system behaved highly reliably and all investigations could be performed successfully



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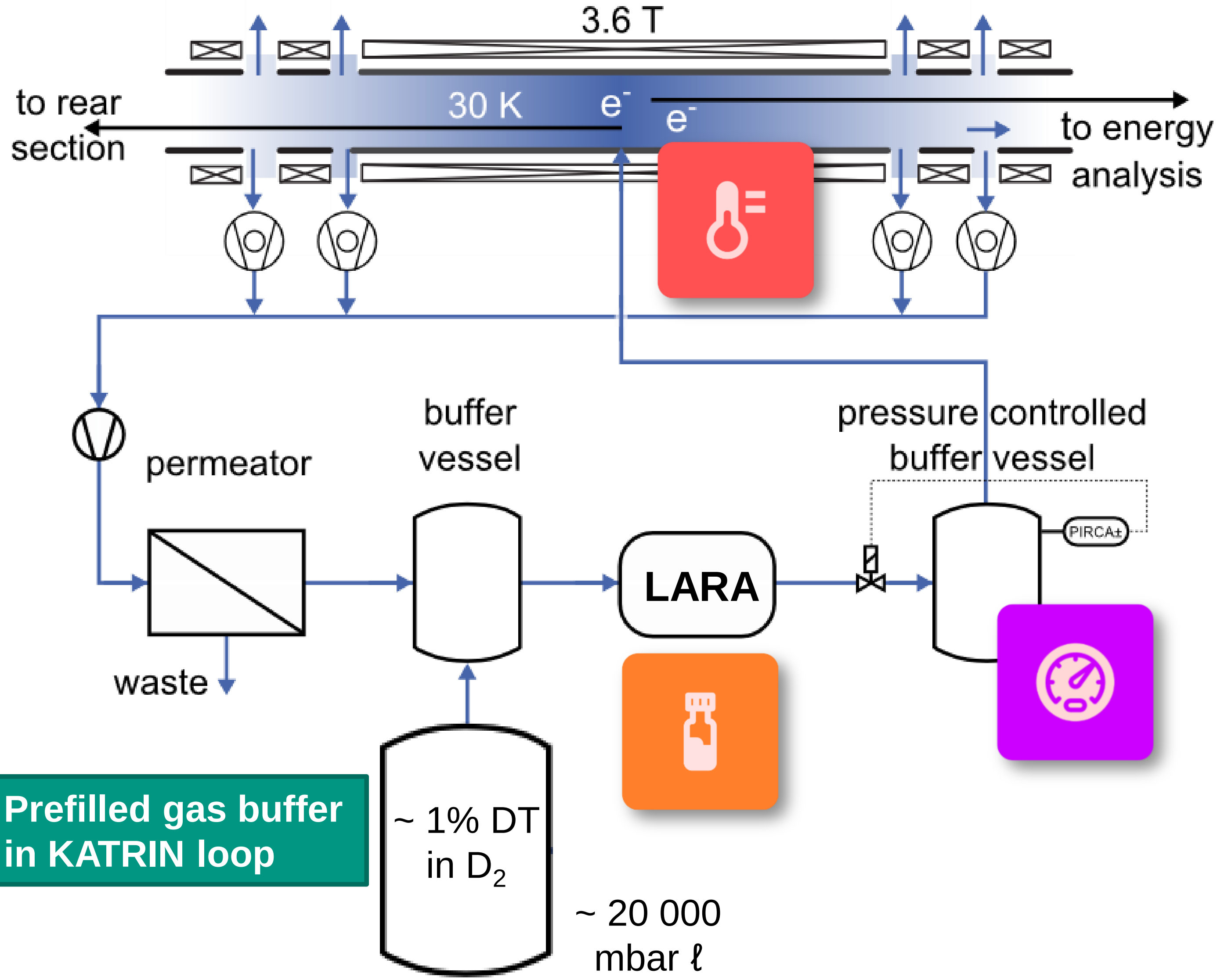
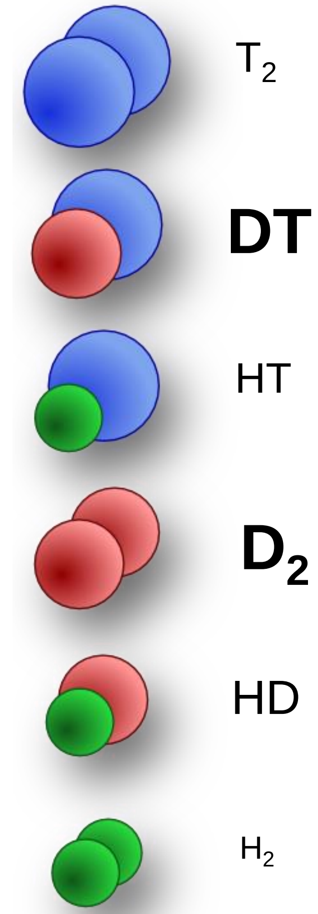
# Stability during First Tritium

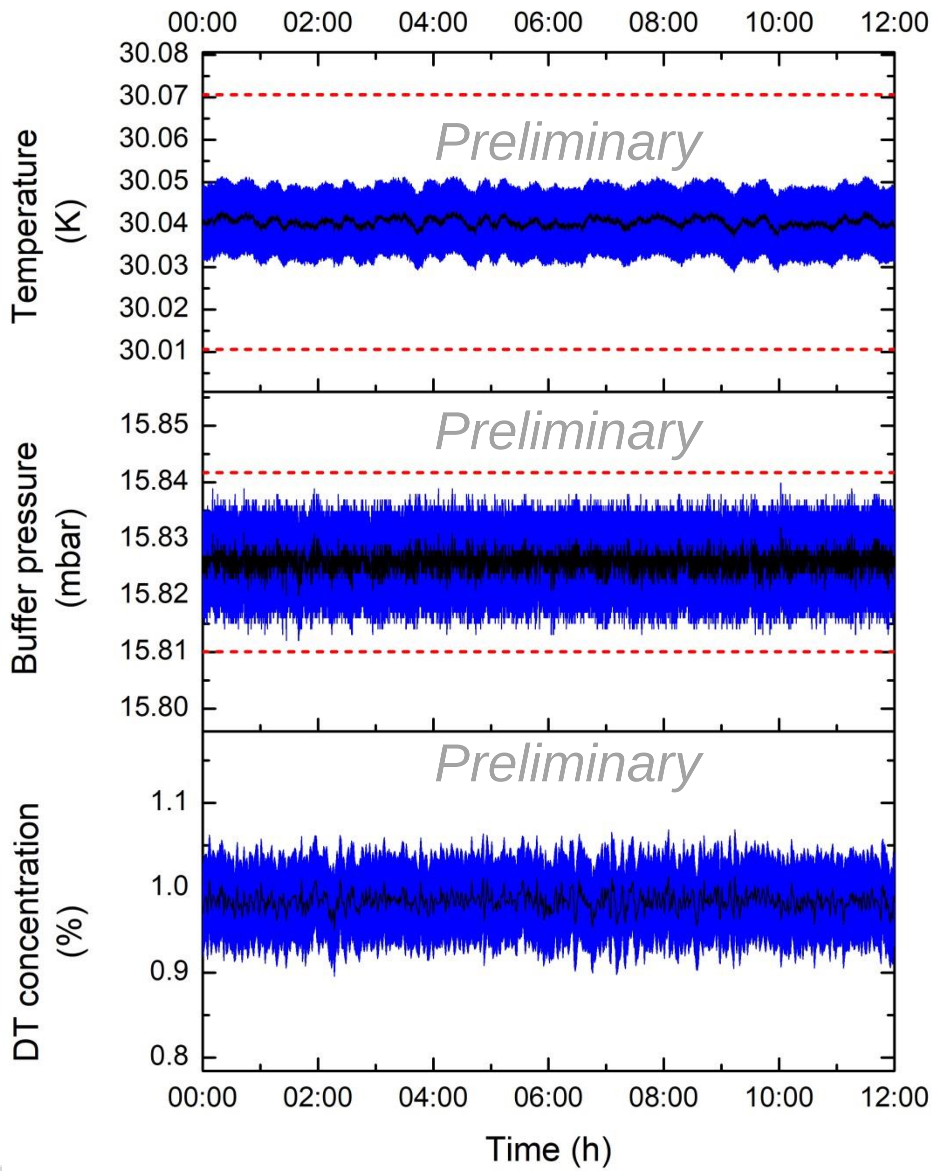



Prefilled gas buffer in KATRIN loop

## Hydrogen isotopologues



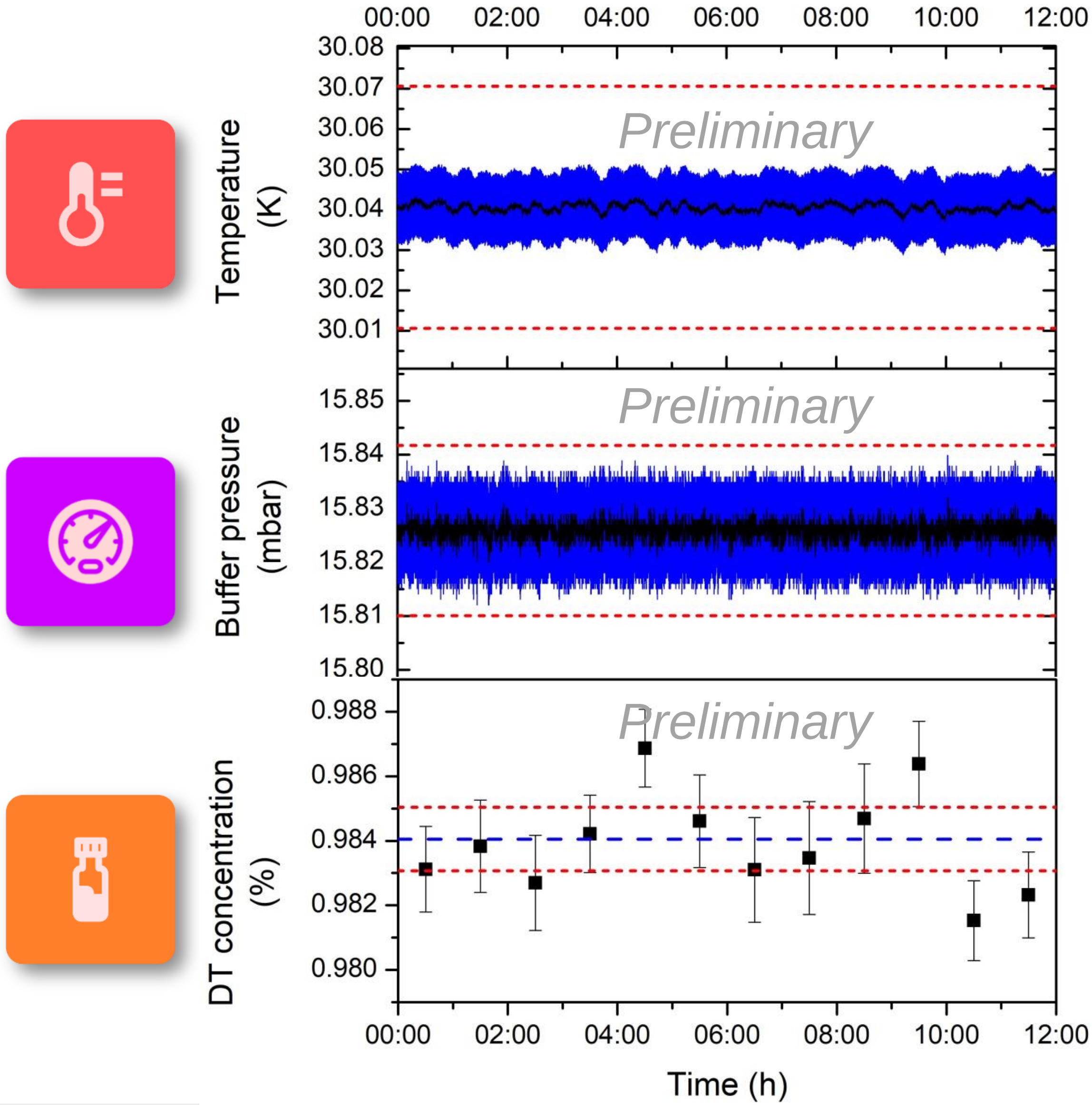
# Stability of source parameters during 12 h




Blue area:
systematic uncertainty

Red dashed line:
± 0.1 % stability
required for neutrino
mass taking

# Stability of source parameters during 12 h




Blue area:
systematic uncertainty

Red dashed line:
± 0.1 % stability
required for neutrino
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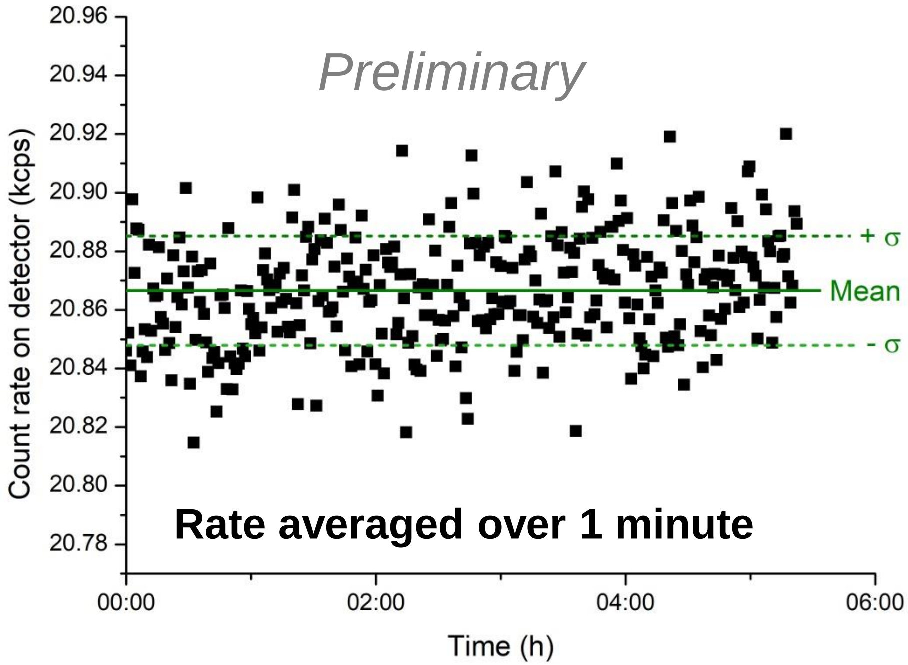
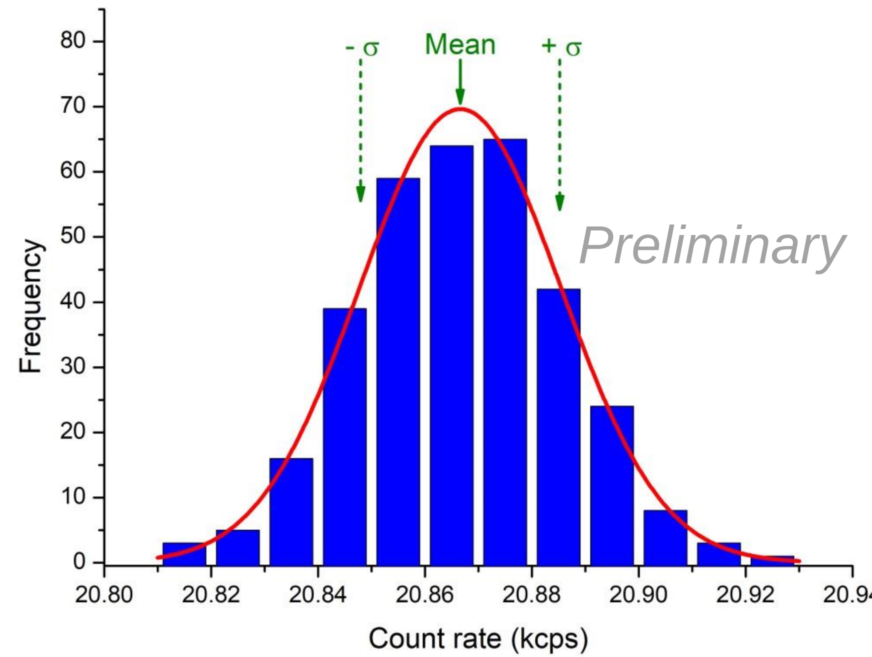
Source parameters are stable and within the specifications

# Integral rate stability for more than 5 h

- **Set spectrometer high-voltage to 1000 V below kinematic endpoint**
  **➔ Constant rate expected**



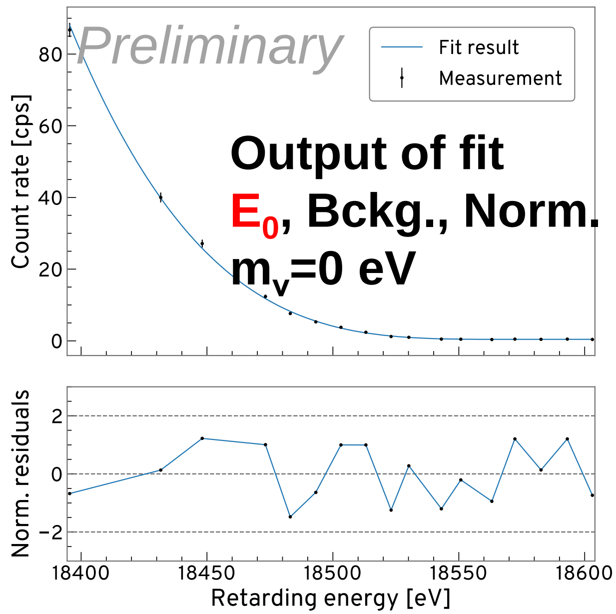




- **Expected 0.1 % precision at this rate (1 min base)** **$\sqrt{N}$=18.65 cps .**
  **Measured precision** **σ= 18.85 cps.**

Precision requirement achieved on minute base over 5 h!
Integral KATRIN stability on 0.1% level!

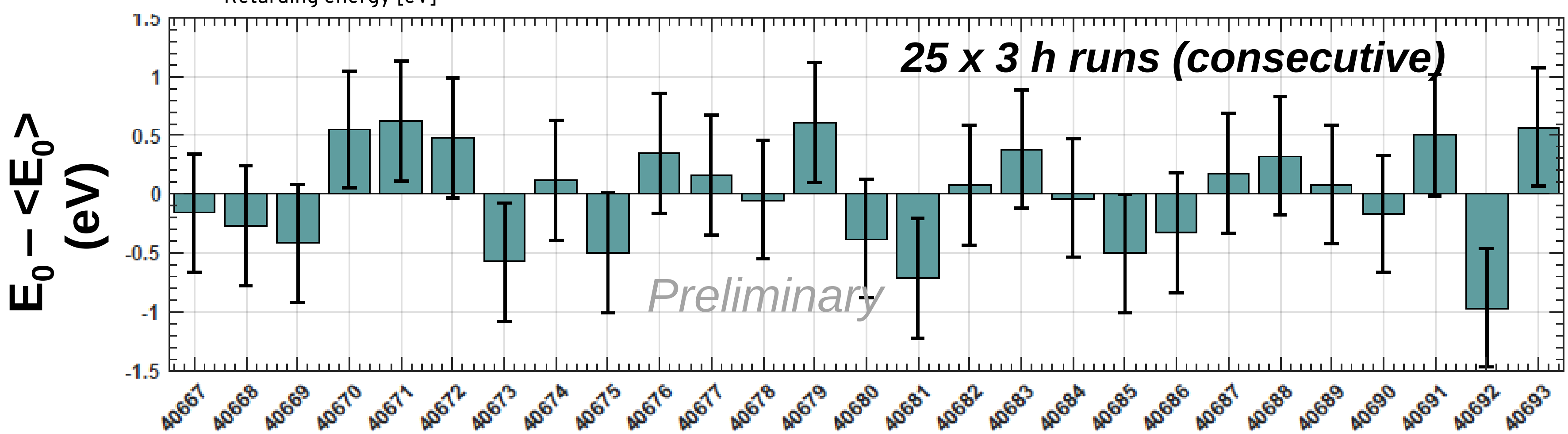
# Endpoint stability



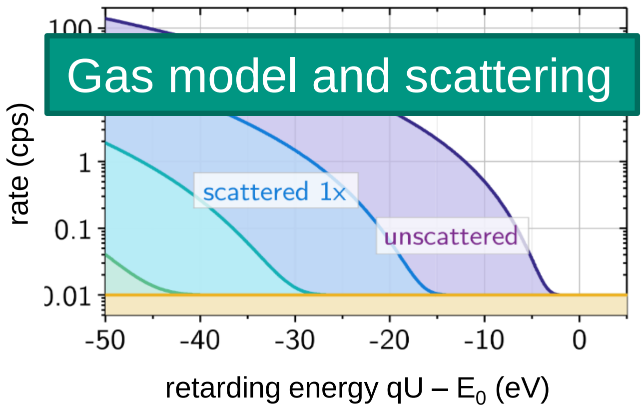



**Endpoint fit parameter can be reproduced from scans with <1 eV**

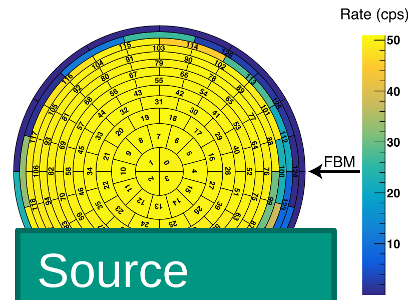
**Agrees with expectation (only statistics here)**



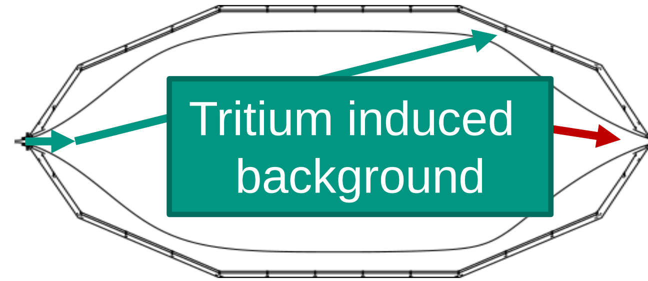
# Ongoing analysis



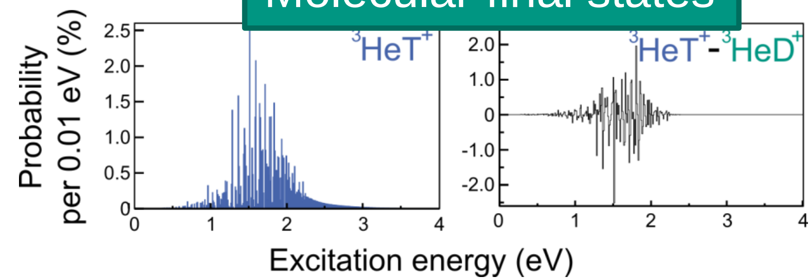

Gas model and scattering



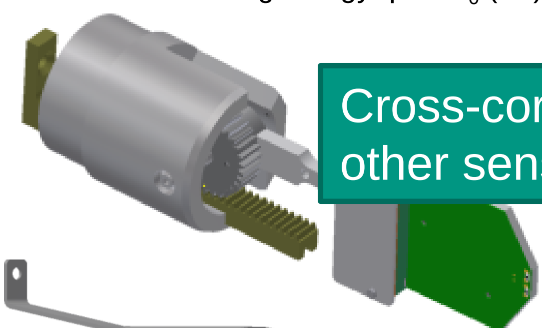

Source homogeneity



Tritium induced background




Molecular final states



Cross-correlation against other sensors

Ion retention


Time correlated measurements


Method testing for sterile neutrinos search



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# Conclusion

Karlsruhe Institute of Technology

- **First tritium campaign very successful**

Very smooth operation

0.1 % stability demonstrated

Beta spectrum nicely fitable

Systematic studies ongoing

- **Currently ongoing  measurements**

E-gun and krypton source for gas density determination

**KATRIN is active and has been successfully commissioned with tritium**



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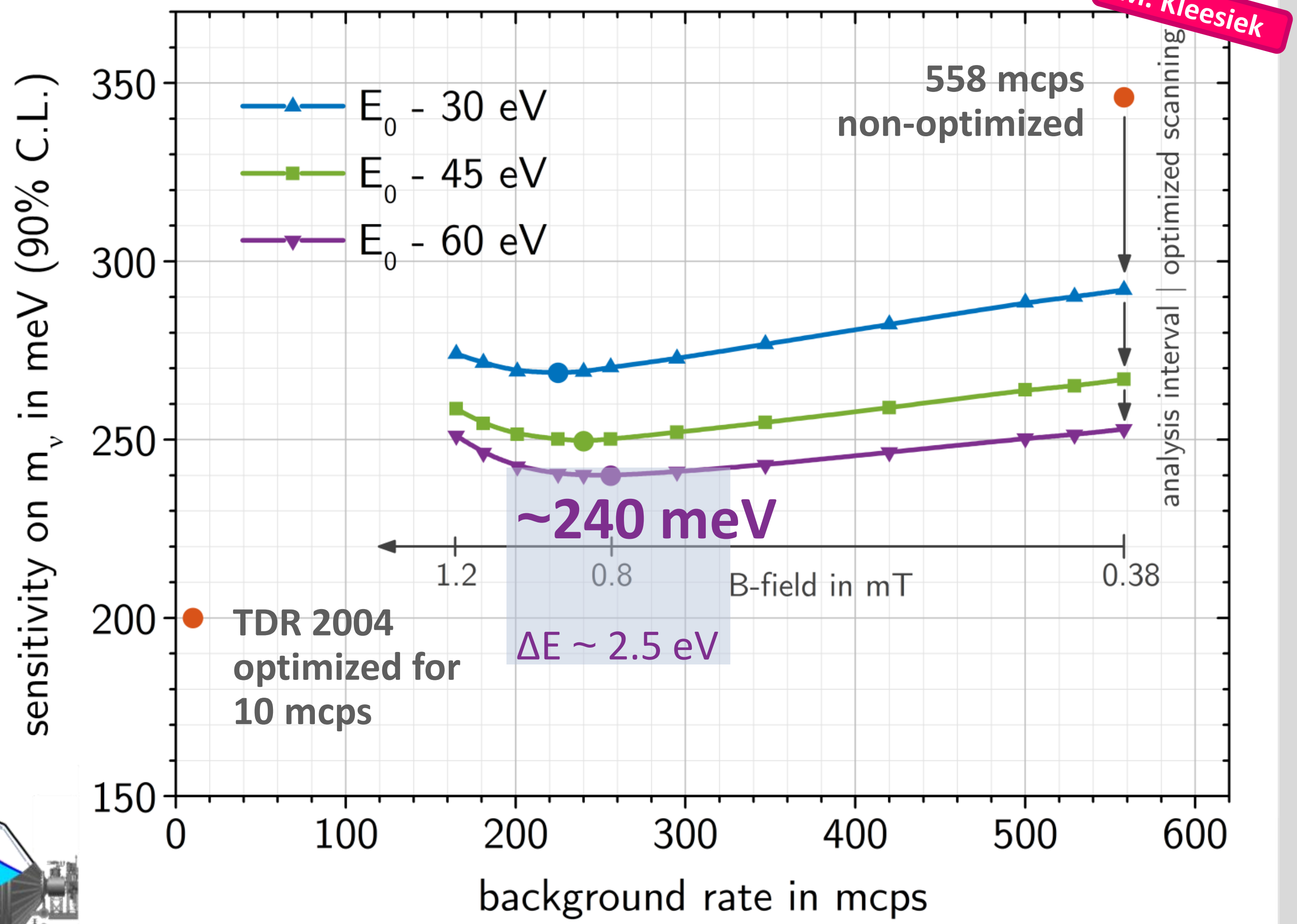
# The KATRIN collaboration

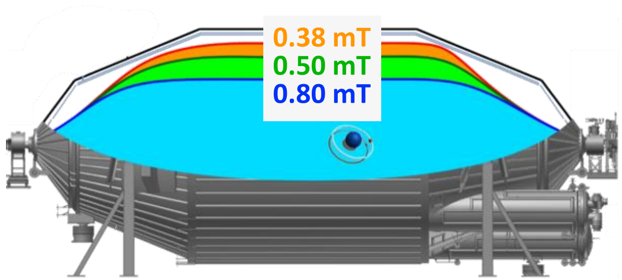
Funding and support from: **Helmholtz Association** (HGF), **Ministry for Education and Research BMBF** (05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), **Helmholtz Alliance for Astroparticle Physics** (HAP), and **Helmholtz Young Investigator Group** (VH-NG-1055) in Germany; **Ministry of Education, Youth and Sport** (CANAM-LM2011019), cooperation with the **JINR Dubna** (3+3 grants) 2017–2019 in the Czech Republic; and the **Department of Energy** through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, and DE-SC0011091 in the US.

# BACKUP SLIDES

# KATRIN background & sensitivity

- Further background reduction measures under investigation
- In addition: several mitigation strategies
  - optimized scanning
  - energy range of spectral analysis
  - flux tube compression by increasing B



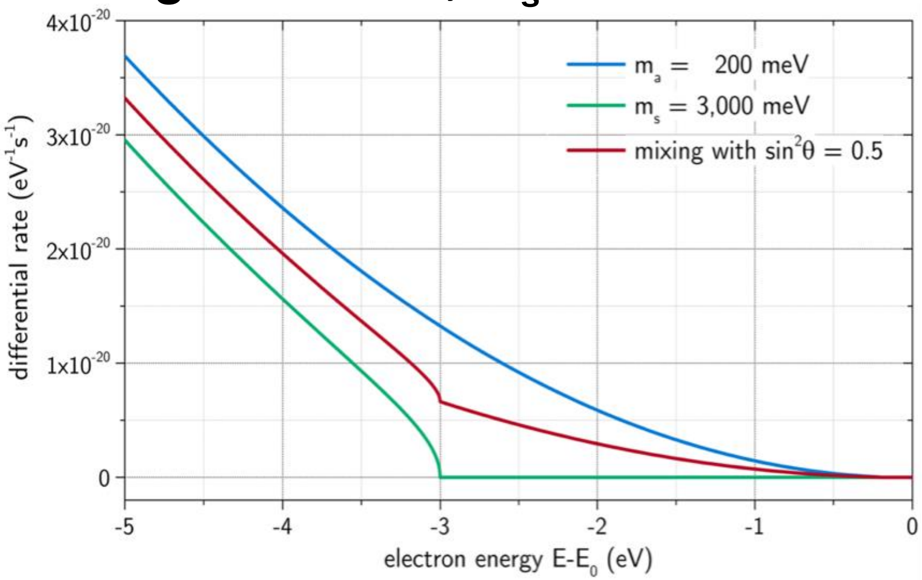
# Imprint of sterile neutrinos on β spectrum

Shape modification below $E_0$ by active $(m_a)^2$ and sterile $(m_s)^2$ neutrinos:

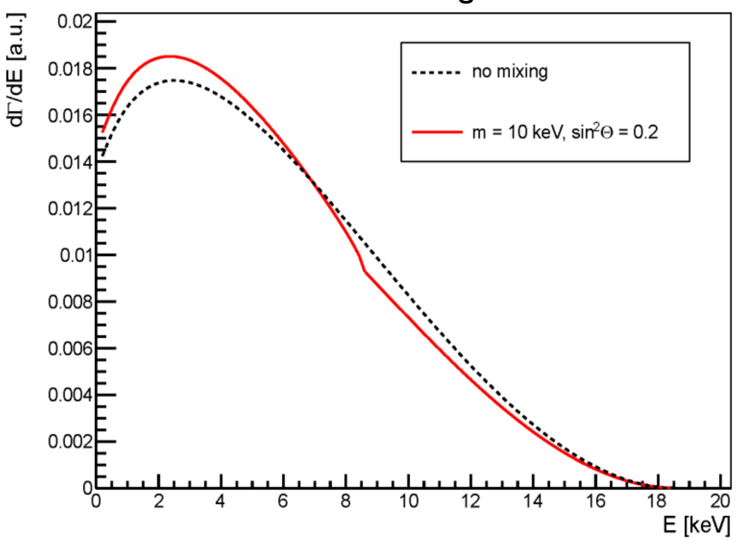
$$\frac{dN}{dE} = \cos^2\theta_s \frac{dN}{dE}(m_a^2) + \sin^2\theta_s \frac{dN}{dE}(m_s^2)$$

⇨ additional kink in β spectrum at $E = E_0 - m_s$

**light sterile ν, $m_s$ = 3 eV**



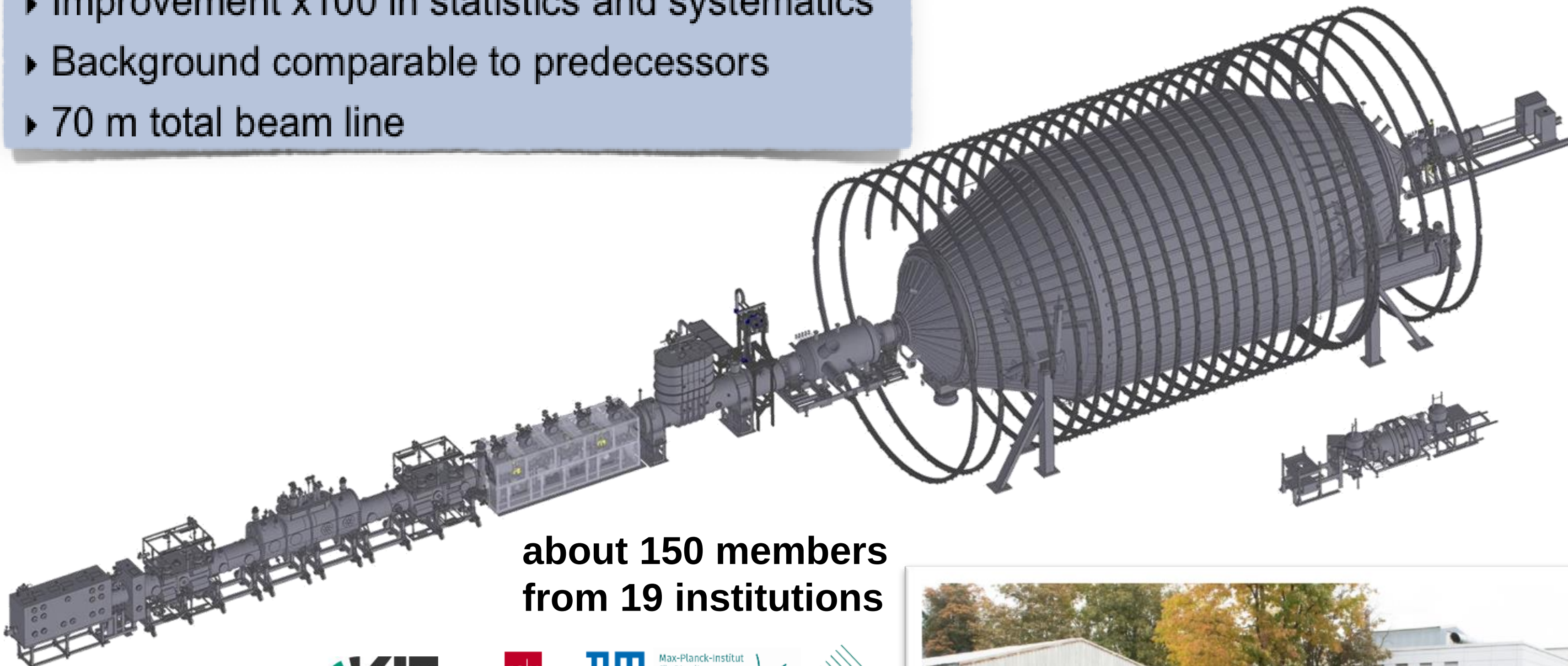

**keV sterile ν, $m_s$ = 10 keV**



# The Karlsruhe Tritium Neutrino Experiment

**Sensitivity: 2 eV ➜ 0.2 eV**

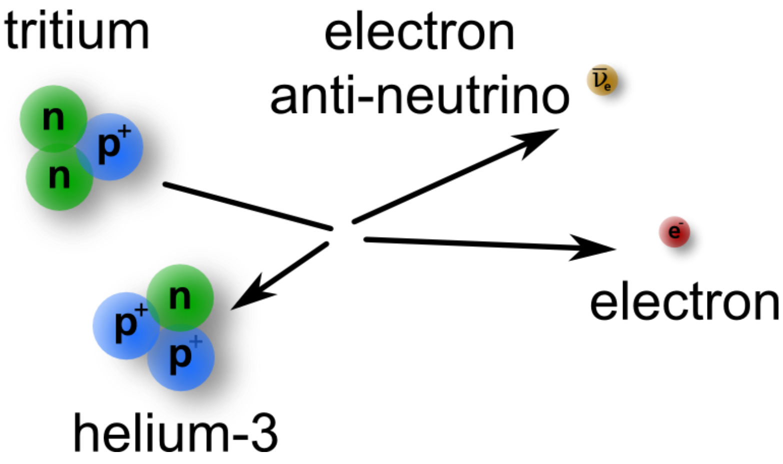
- Improvement x100 in statistics and systematics
- Background comparable to predecessors
- 70 m total beam line



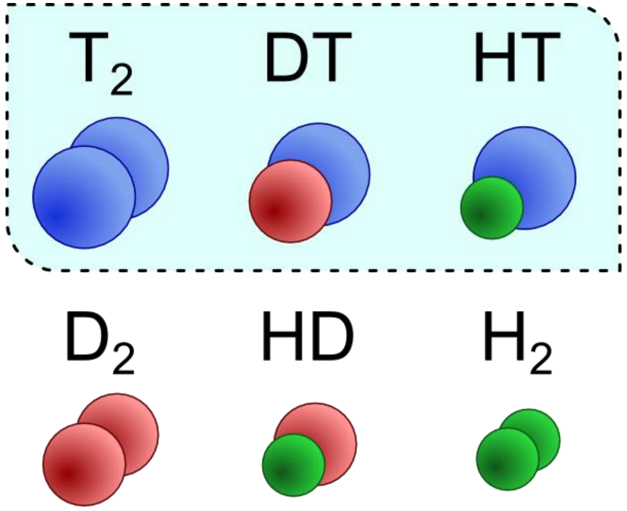
**about 150 members from 19 institutions**

# Molecular decay

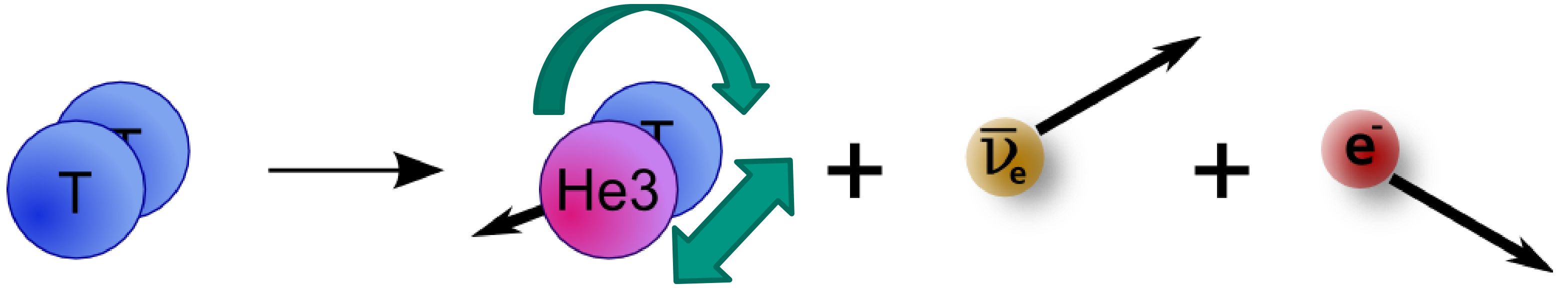
## Atomic decay




## Hydrogen isotopologues

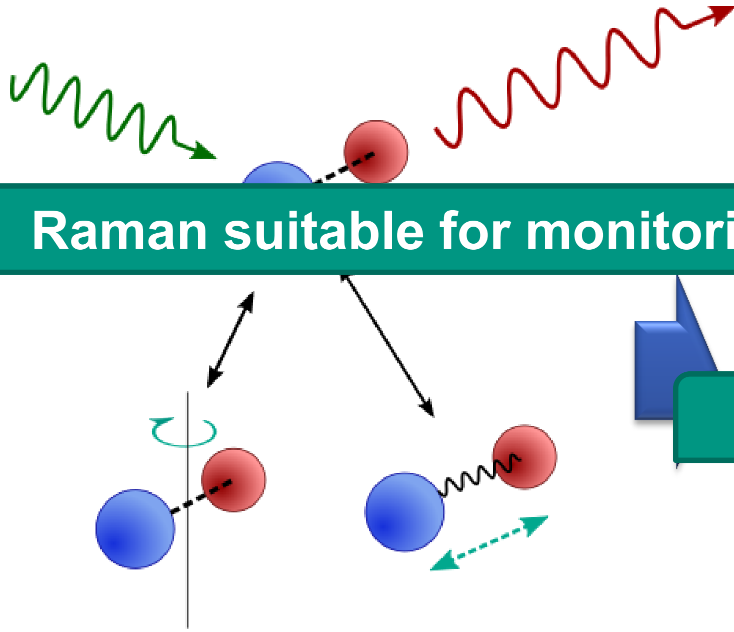


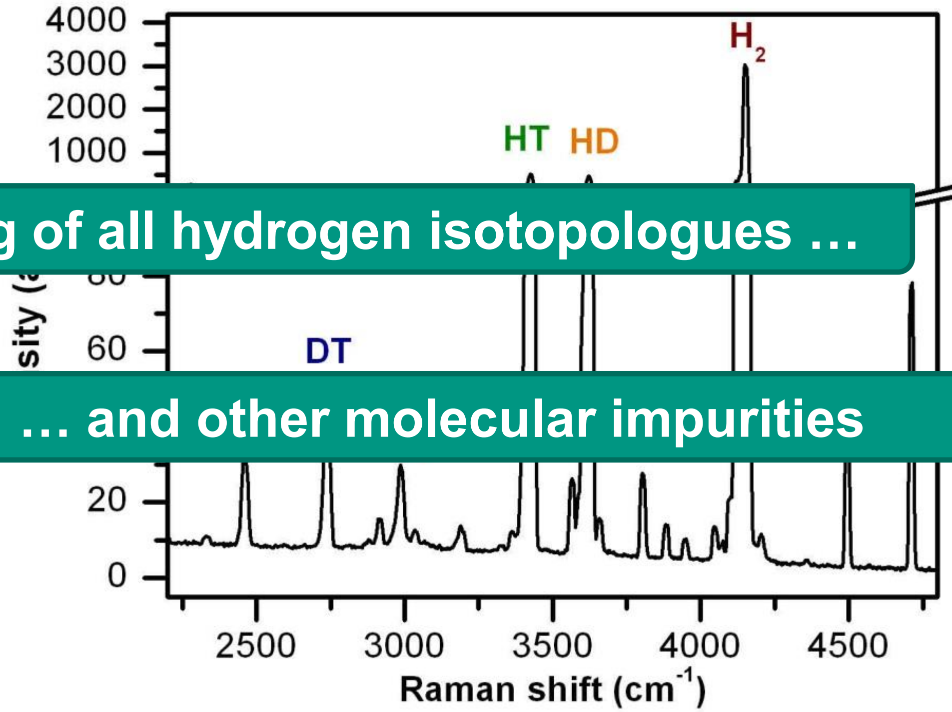

## Decay from a molecule




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

# Raman for KATRIN




**Raman suitable for monitoring of all hydrogen isotopologues …**

**… and other molecular impurities**

- Simultaneous detection of multiple species
- Contact-free, inline gas analysis
- Automated, non-stop measurements possible



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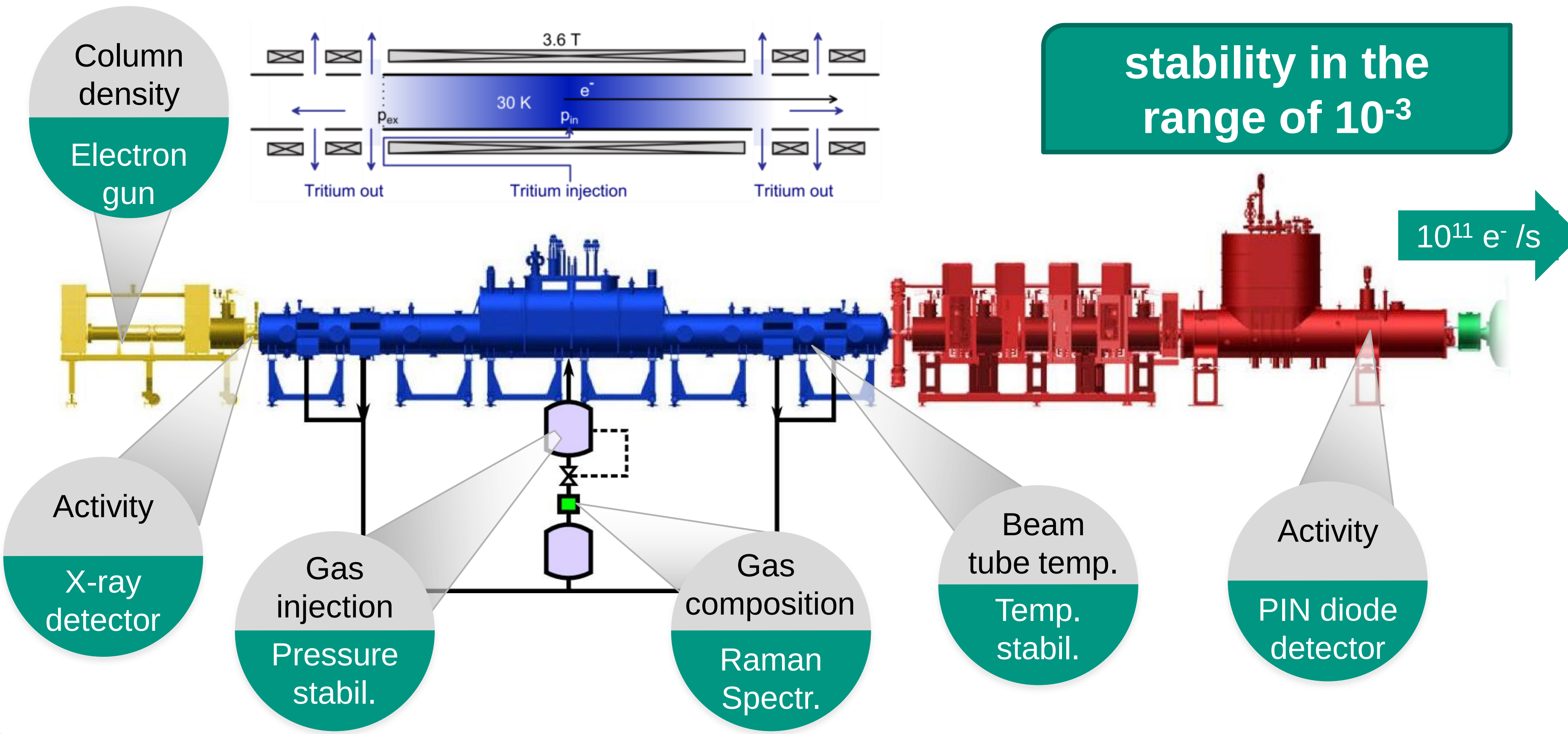
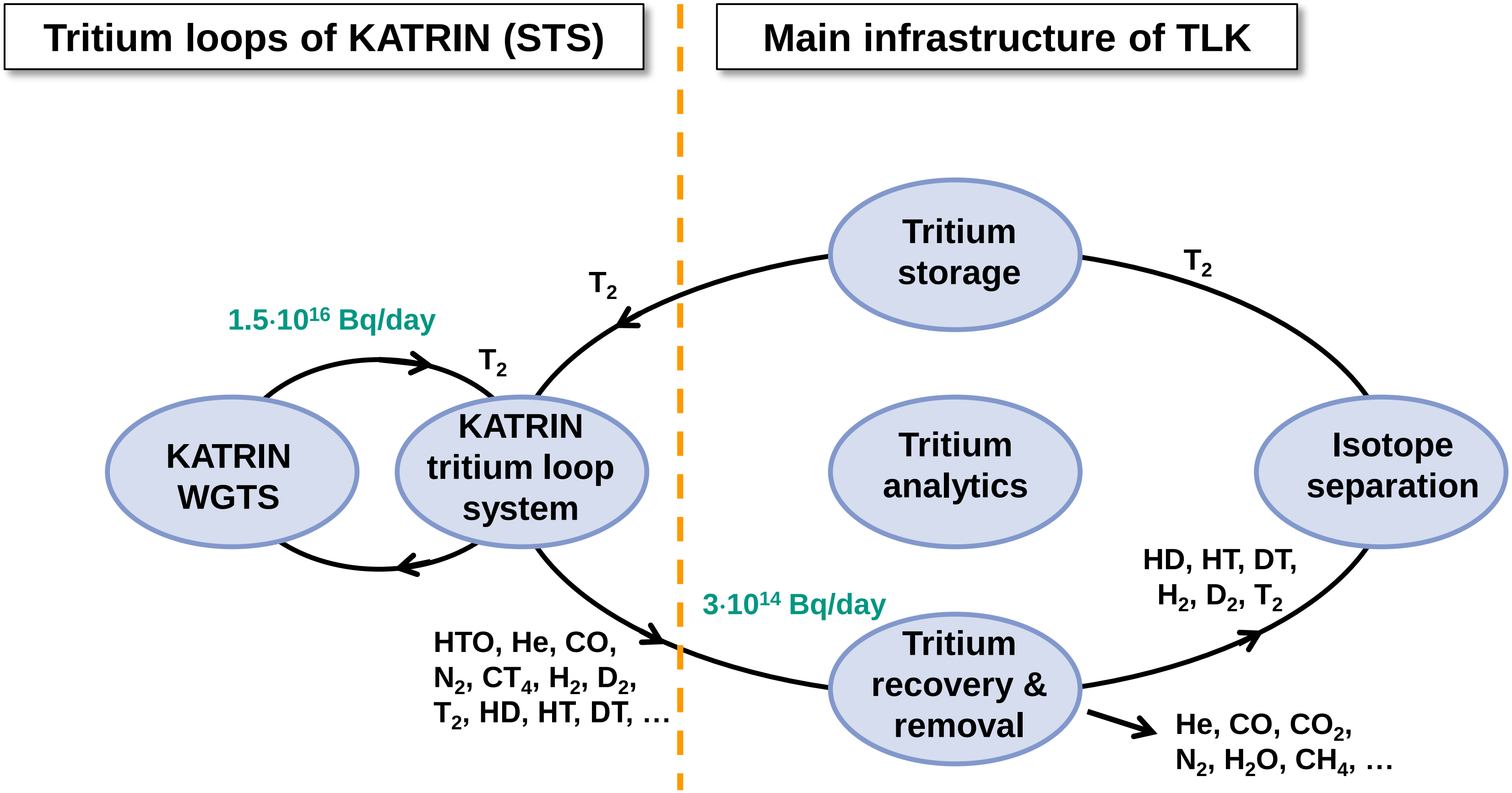
# Systematics of tritium source

- **Previous experiments: m ~ 2 eV** **KATRIN aim: m ~ 0.2 eV**

**Aim: 100 x better systematics**



# The closed tritium loop of KATRIN and the TLK




**Closed tritium processing needed to provide the high activity and isotopic tritium purity for KATRIN**