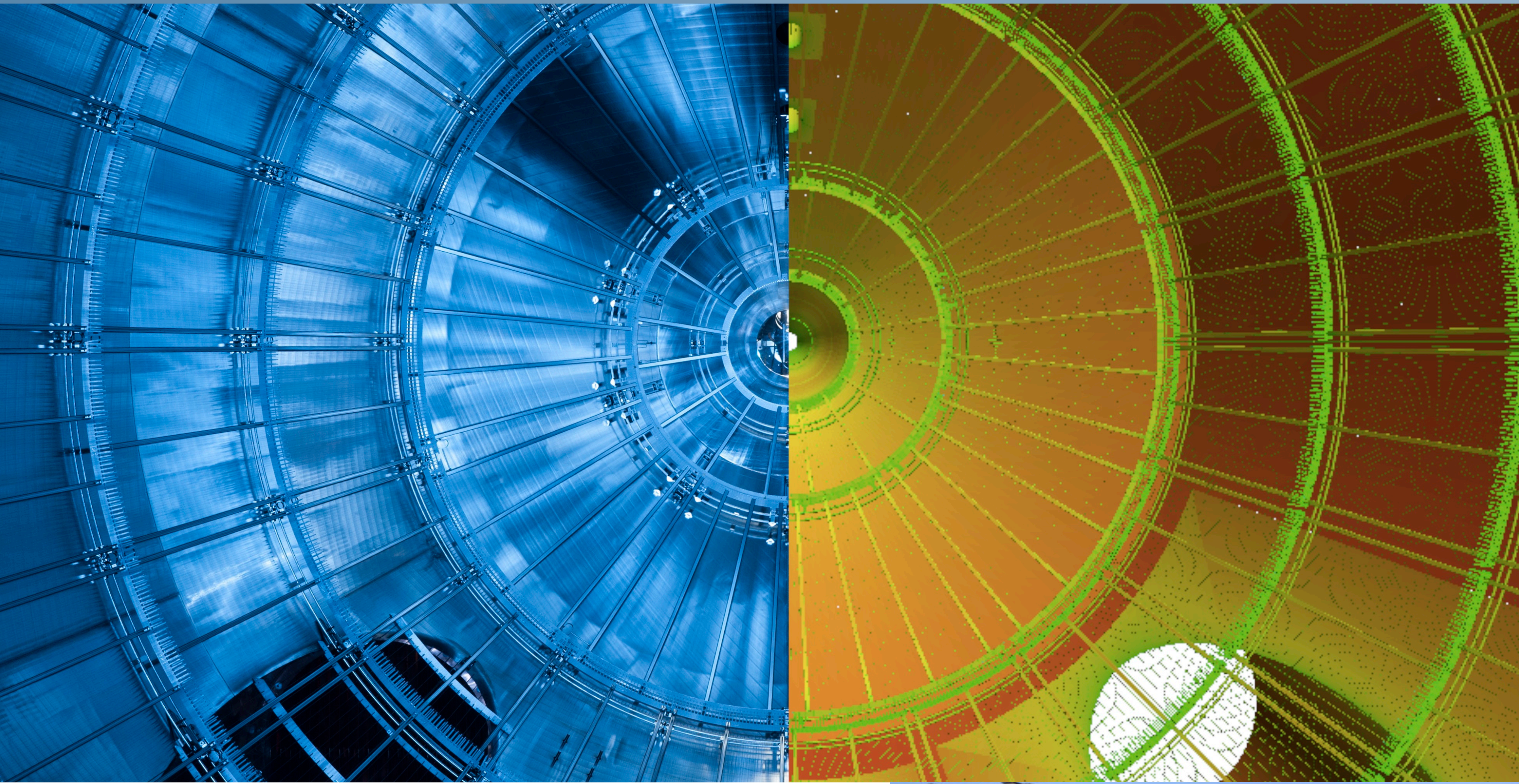
The KATRIN Neutrino Mass Experiment



J.F. Wilkerson

on behalf of the KATRIN Collaboration

COSMS INSTITUTE

THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

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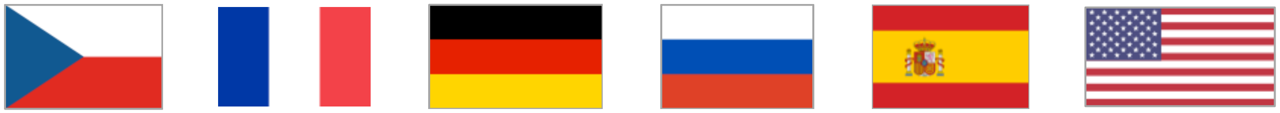
The KATRIN Collaboration



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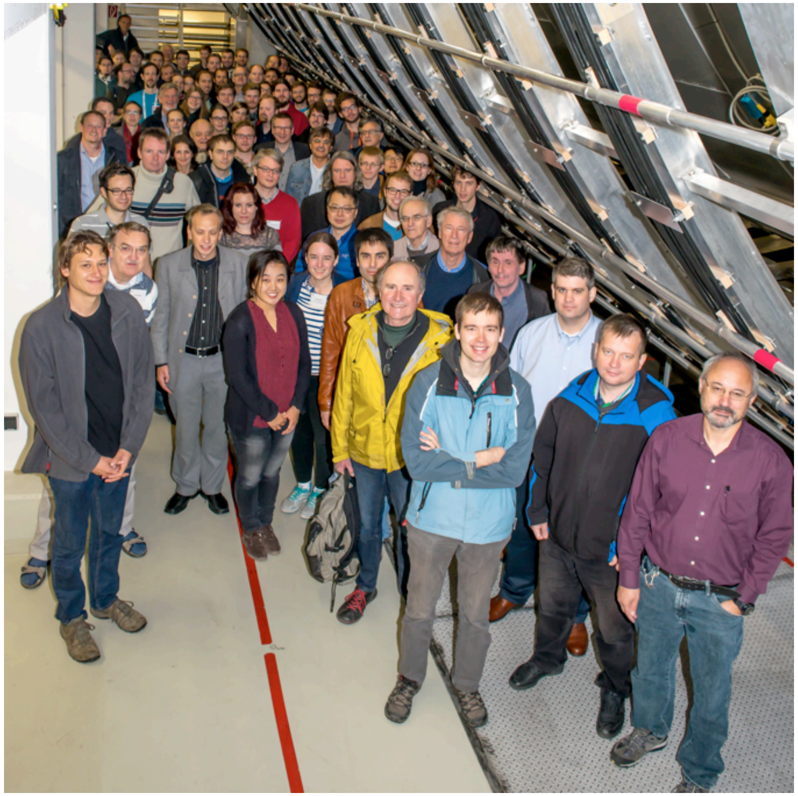

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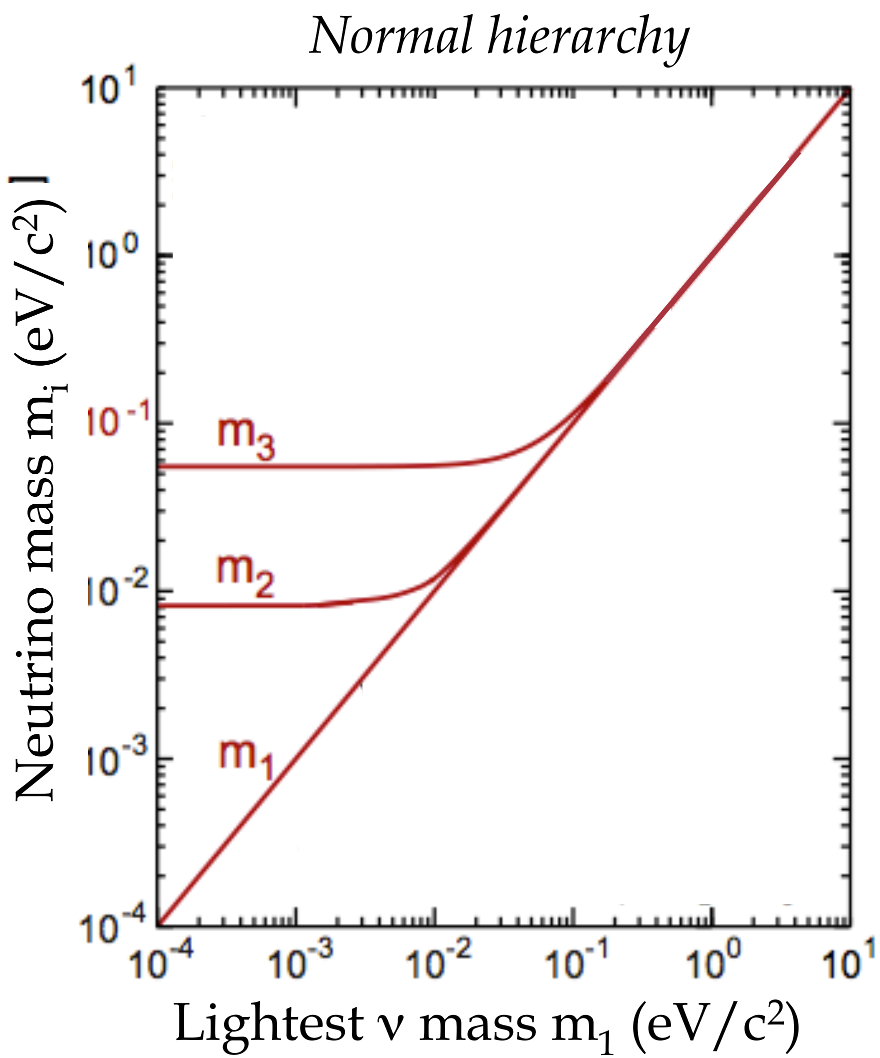
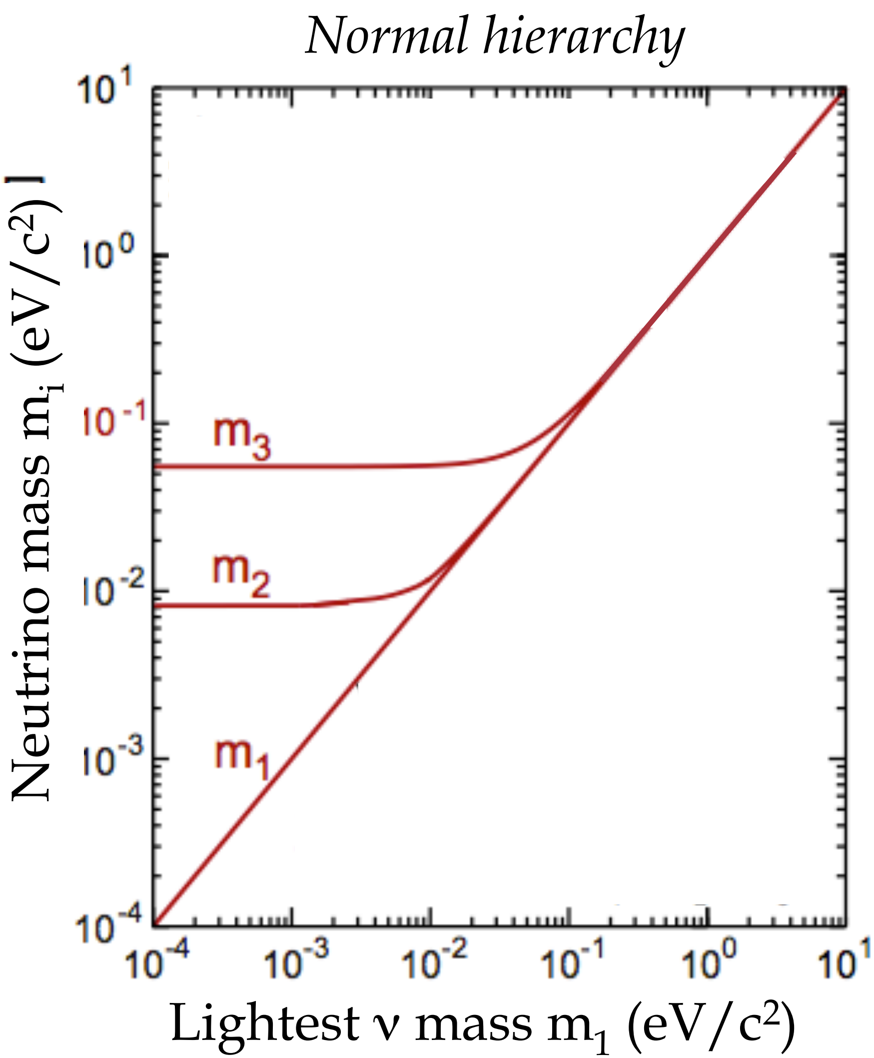
Special thanks from jfw to Diana Parno, Florian Fränkle, Christian Weinheimer, and Guido Drexlin.

The Neutrino Mass Scale



- Lower bound on m_2, m_3 from oscillation

The Neutrino Mass Scale



- Lower bound on m_2, m_3 from oscillation
- Upper bound from β decay

$$m_{\nu_\beta} = \sqrt{\sum_i^3 |U_{ei}|^2 m_i^2}$$

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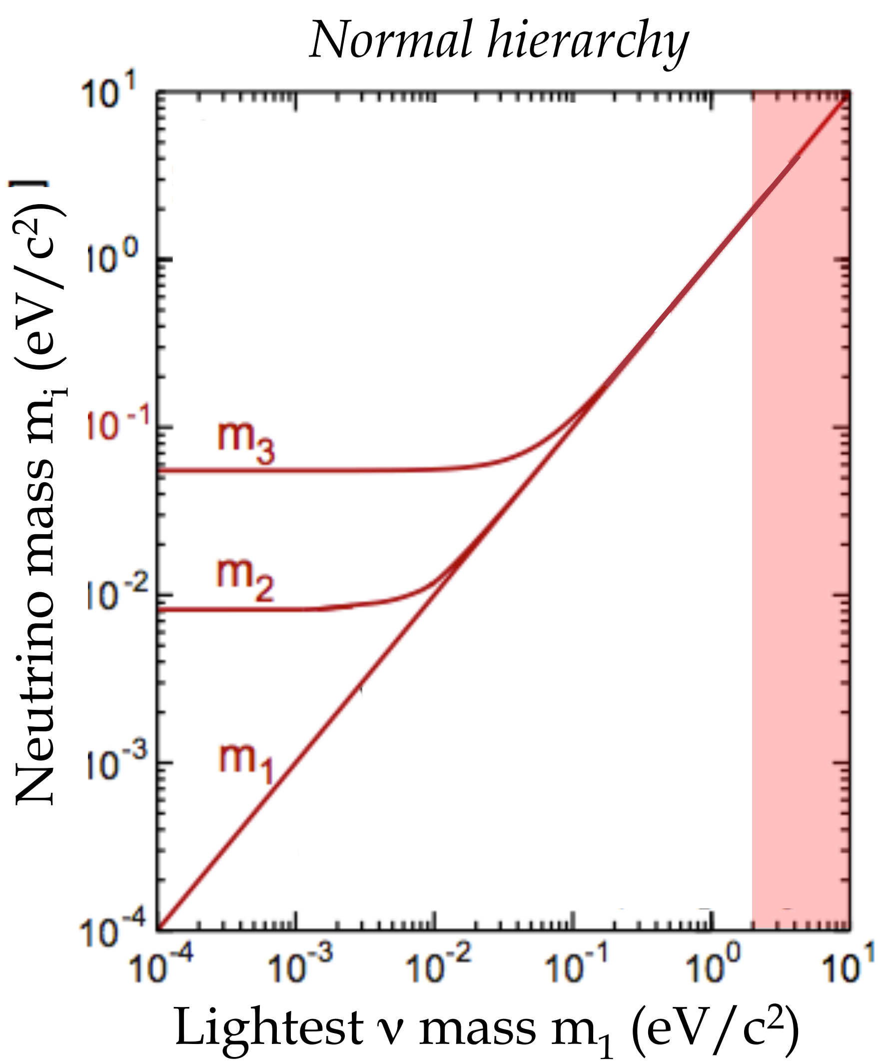

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$$\approx m_\nu \textit{ (quasidegenerate regime)}$$

$$\leq 2\ \mathrm{eV} \textit{ (Mainz, Troitsk)}$$

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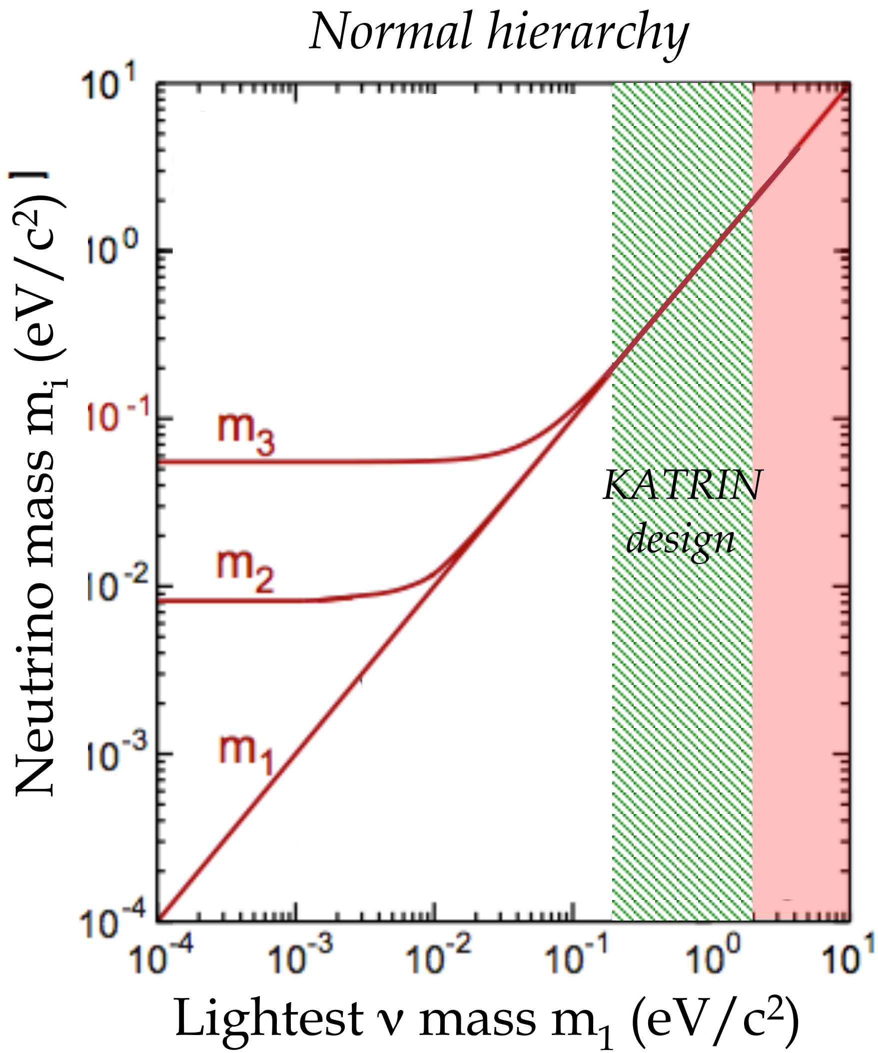

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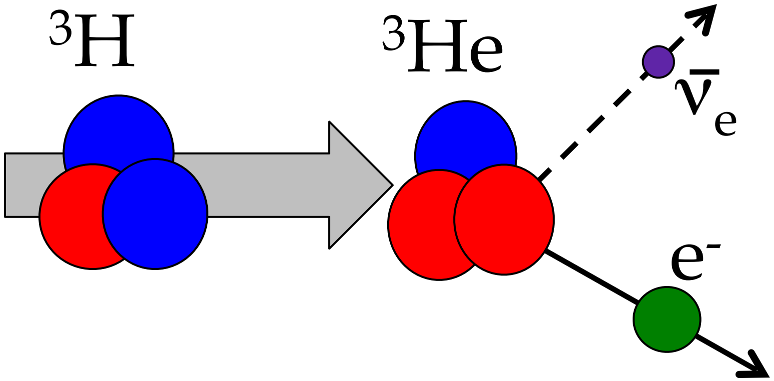
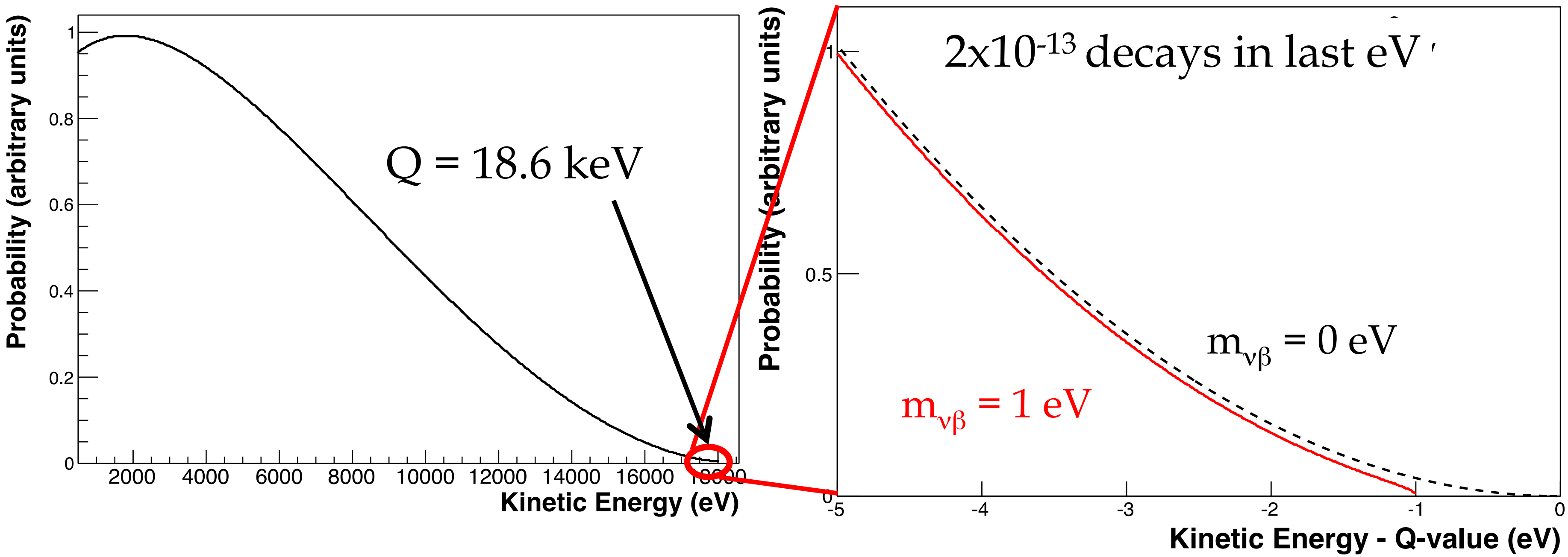
From T_2 to $m_{\nu\beta}$

- Extract $m^2_{\nu\beta}$ from fit to spectral shape near endpoint
- Almost model-independent

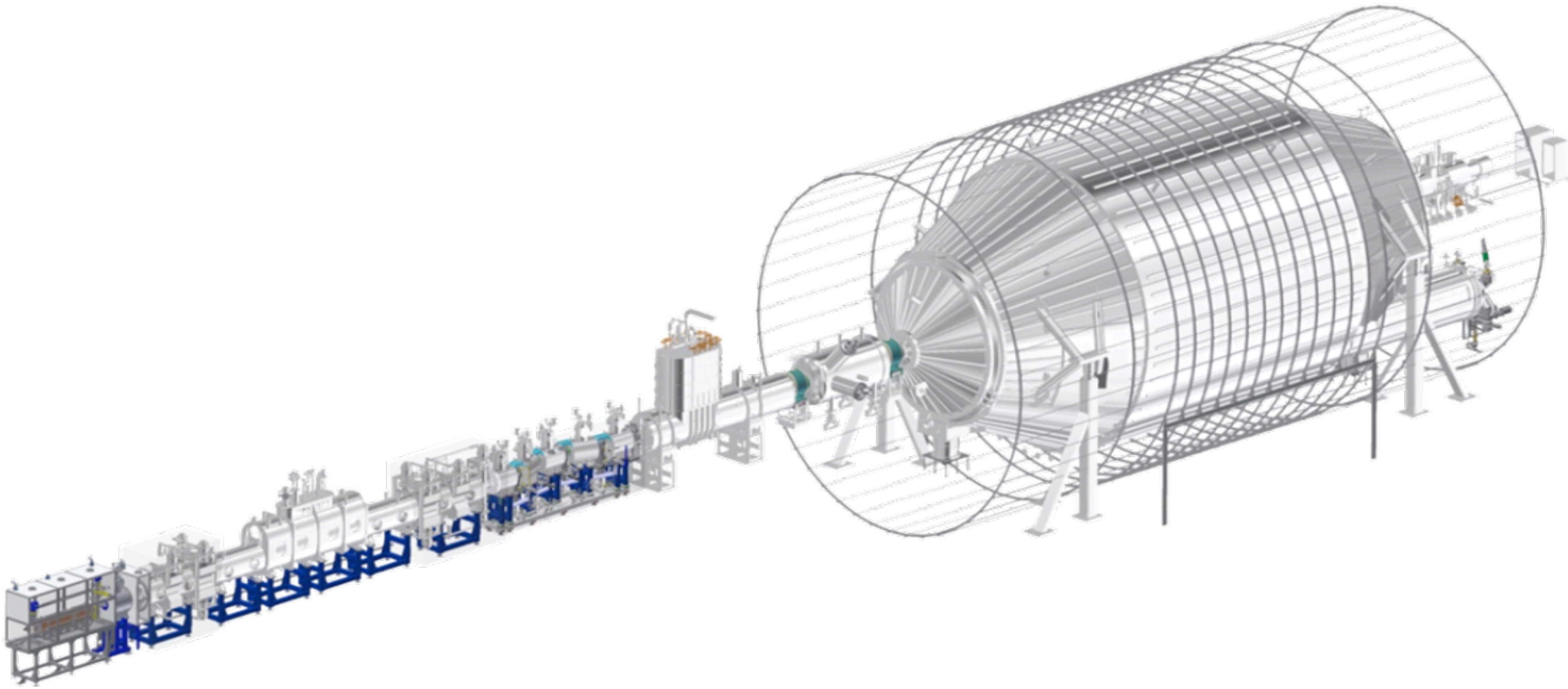




KArlsruhe TRItium Neutrino

- Intense T_2 source (10^{11} decays/second)
- Spectrum analysis with electromagnetic filter
- Design resolution 0.93 eV
- Design $m_{\nu\beta}$ sensitivity: **0.2 eV/c² at 90% confidence level**

KATRIN - Overview



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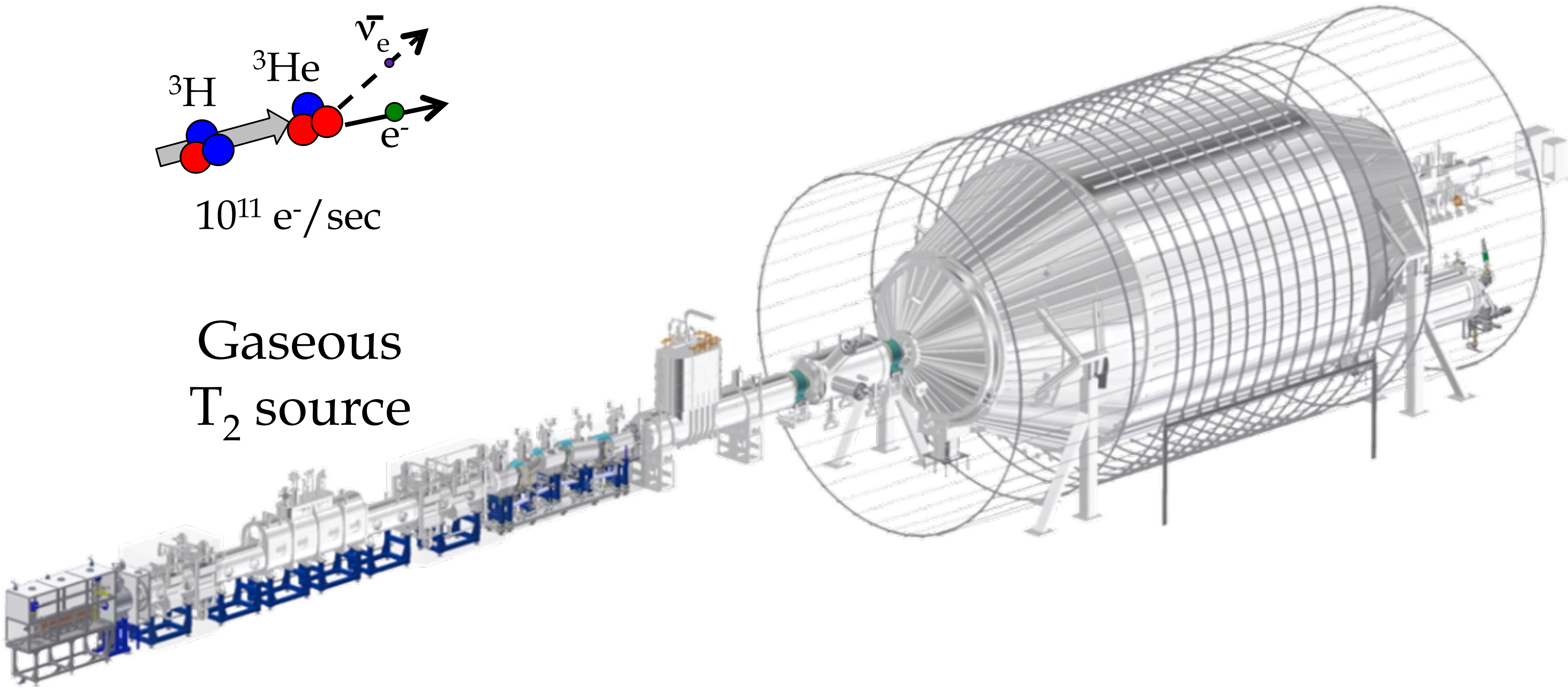

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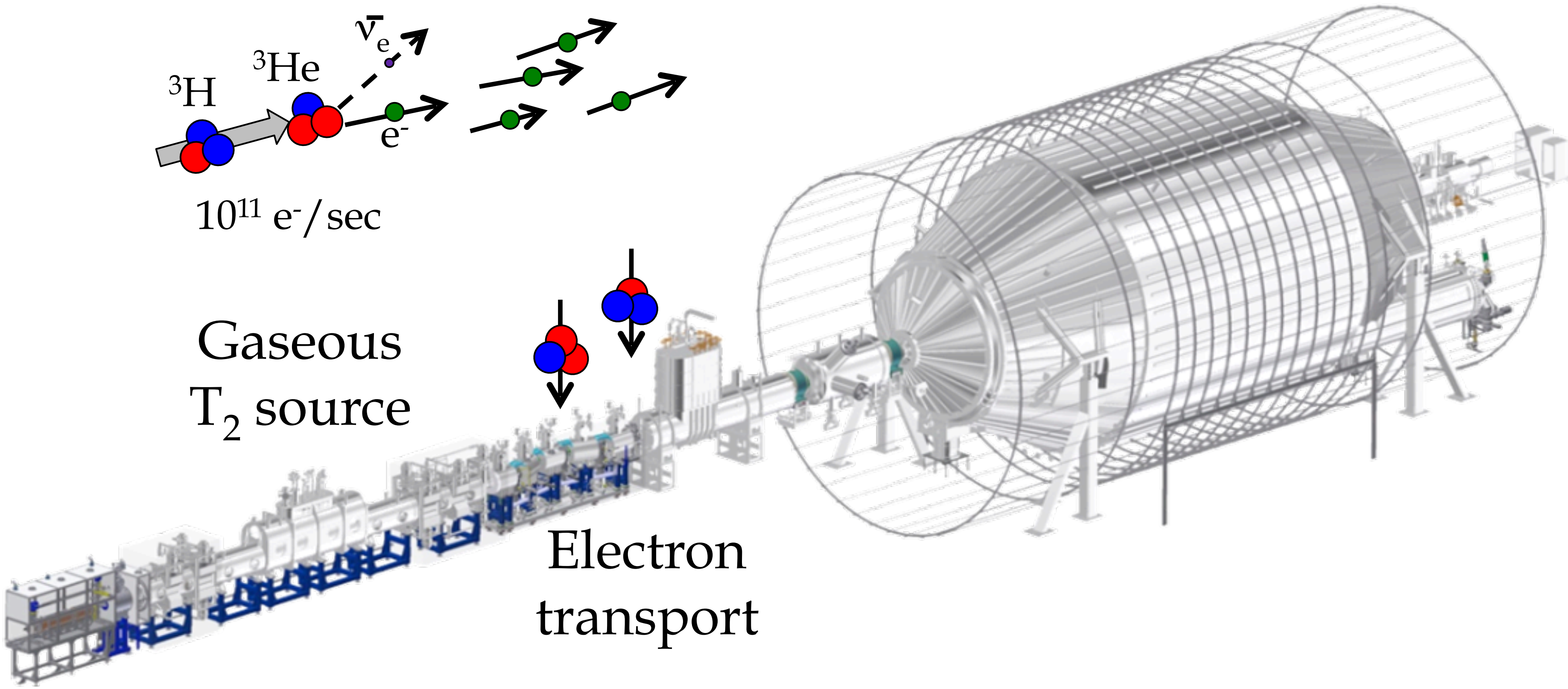

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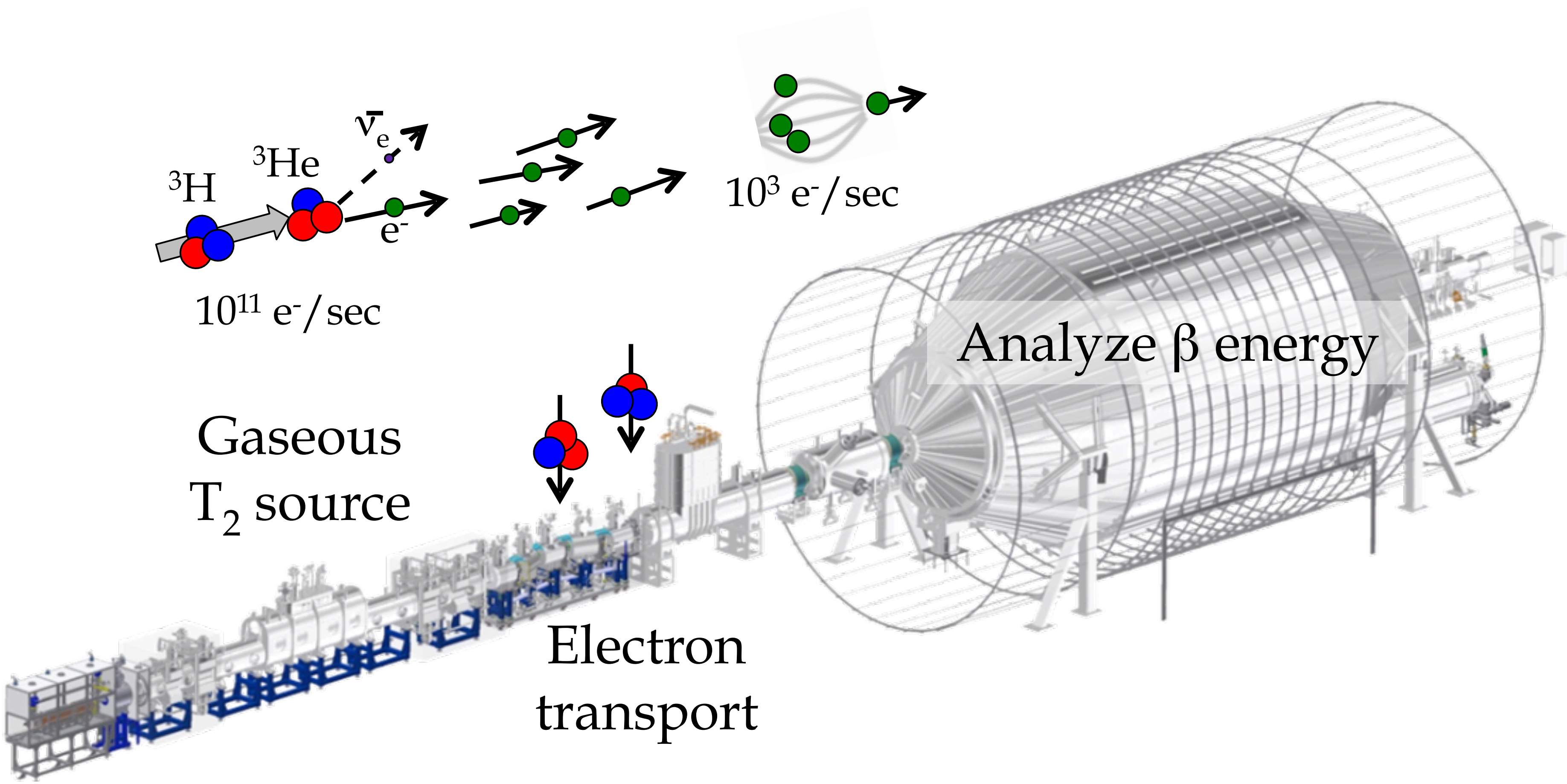

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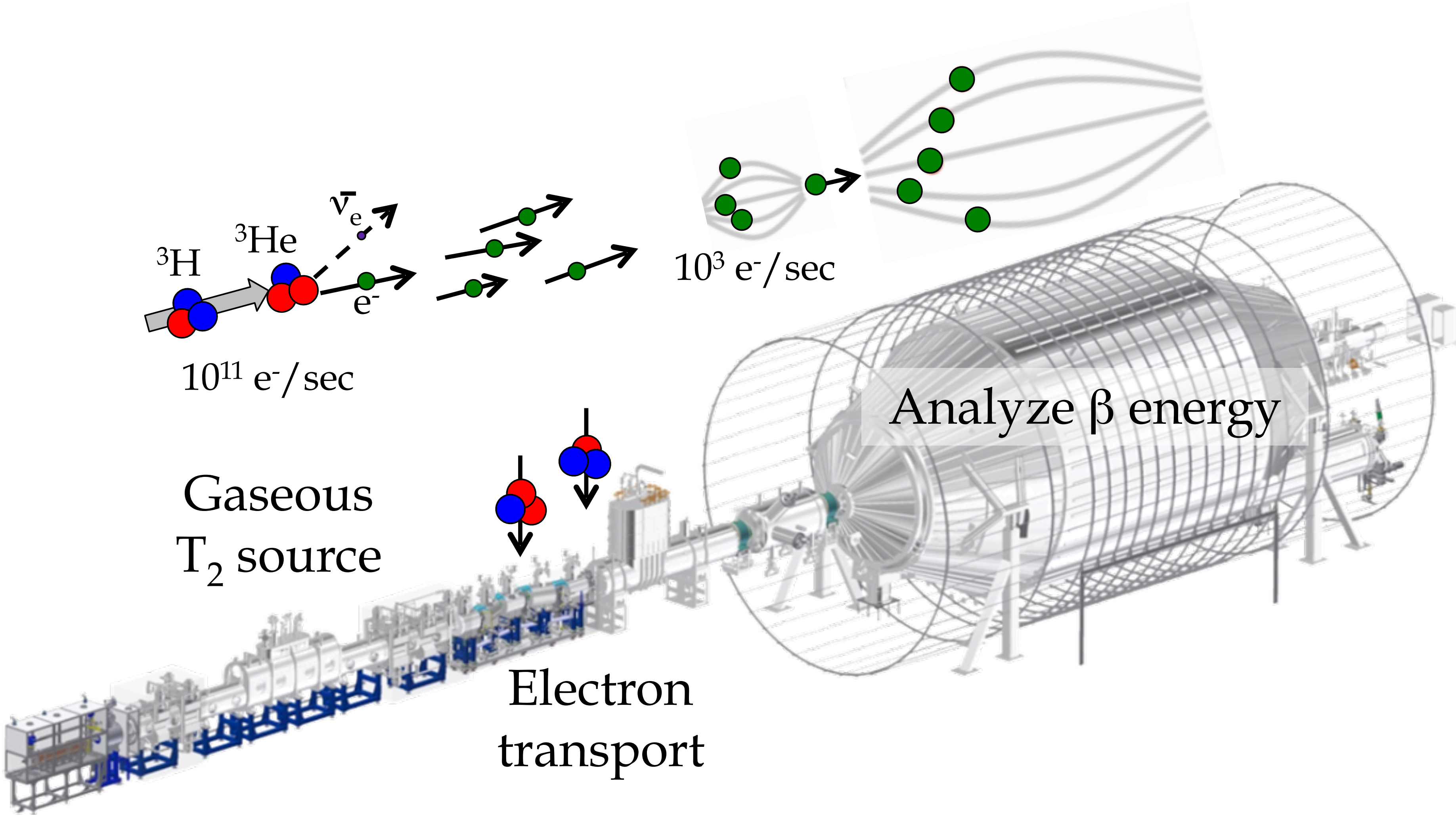

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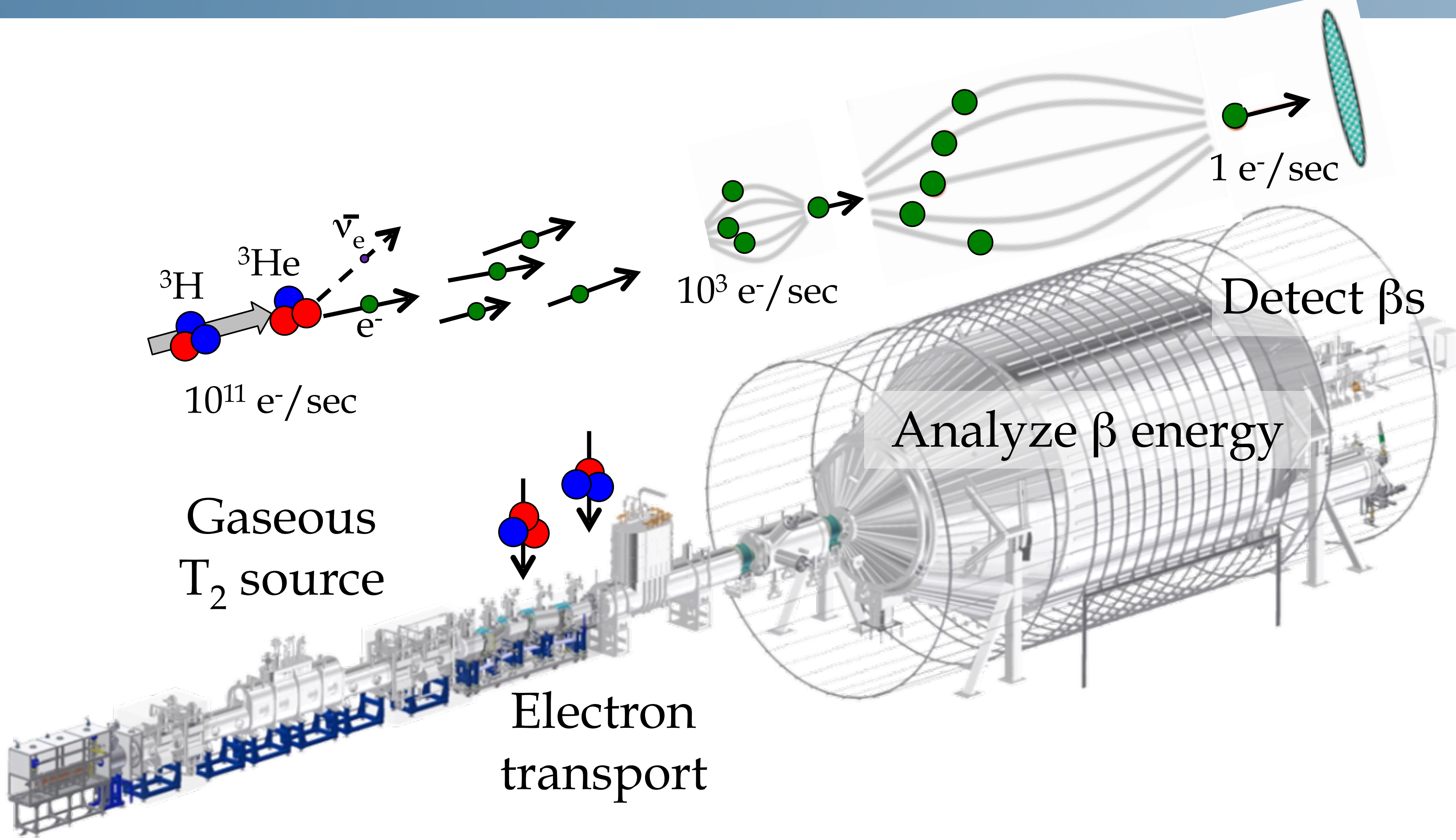

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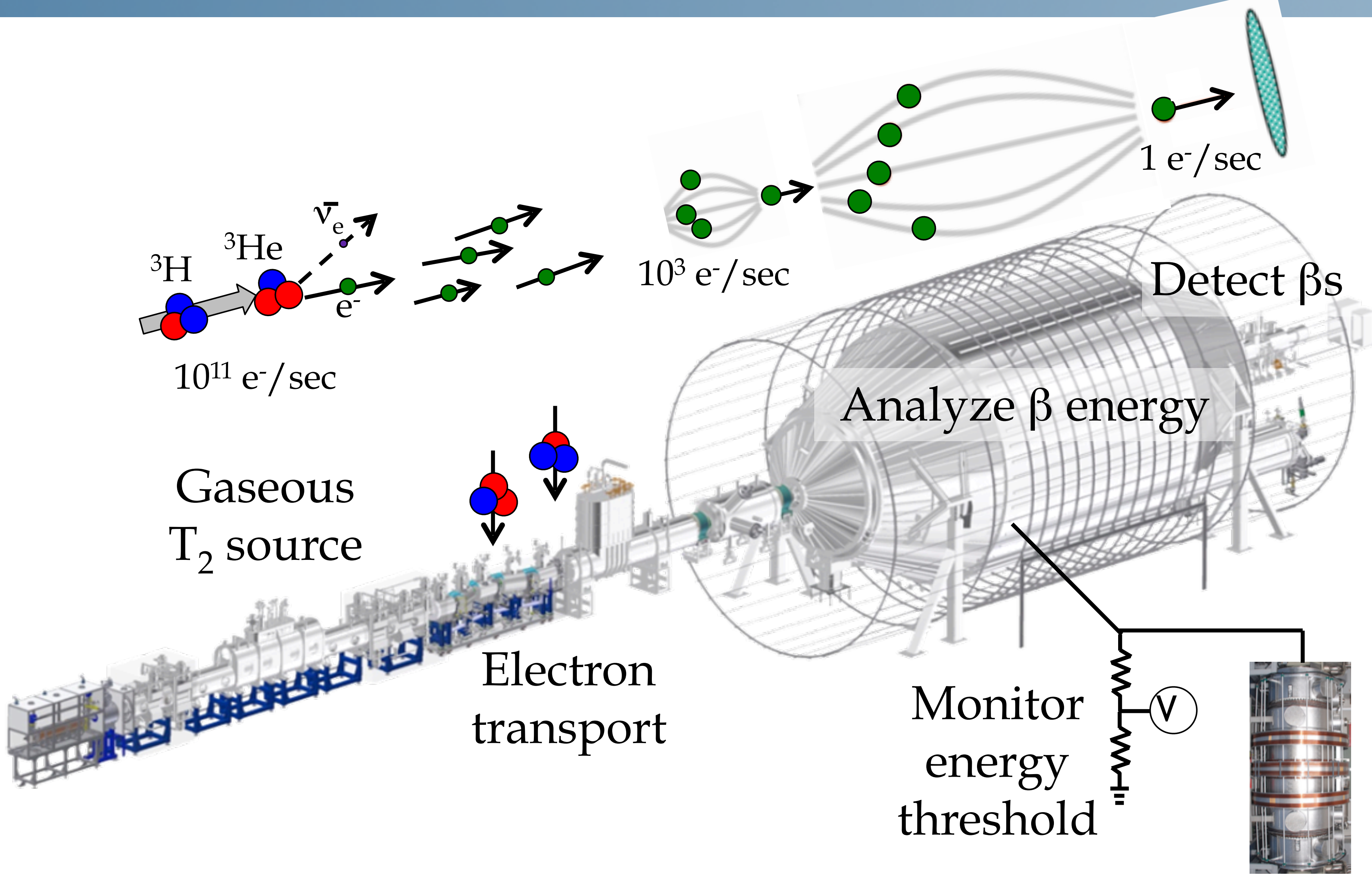
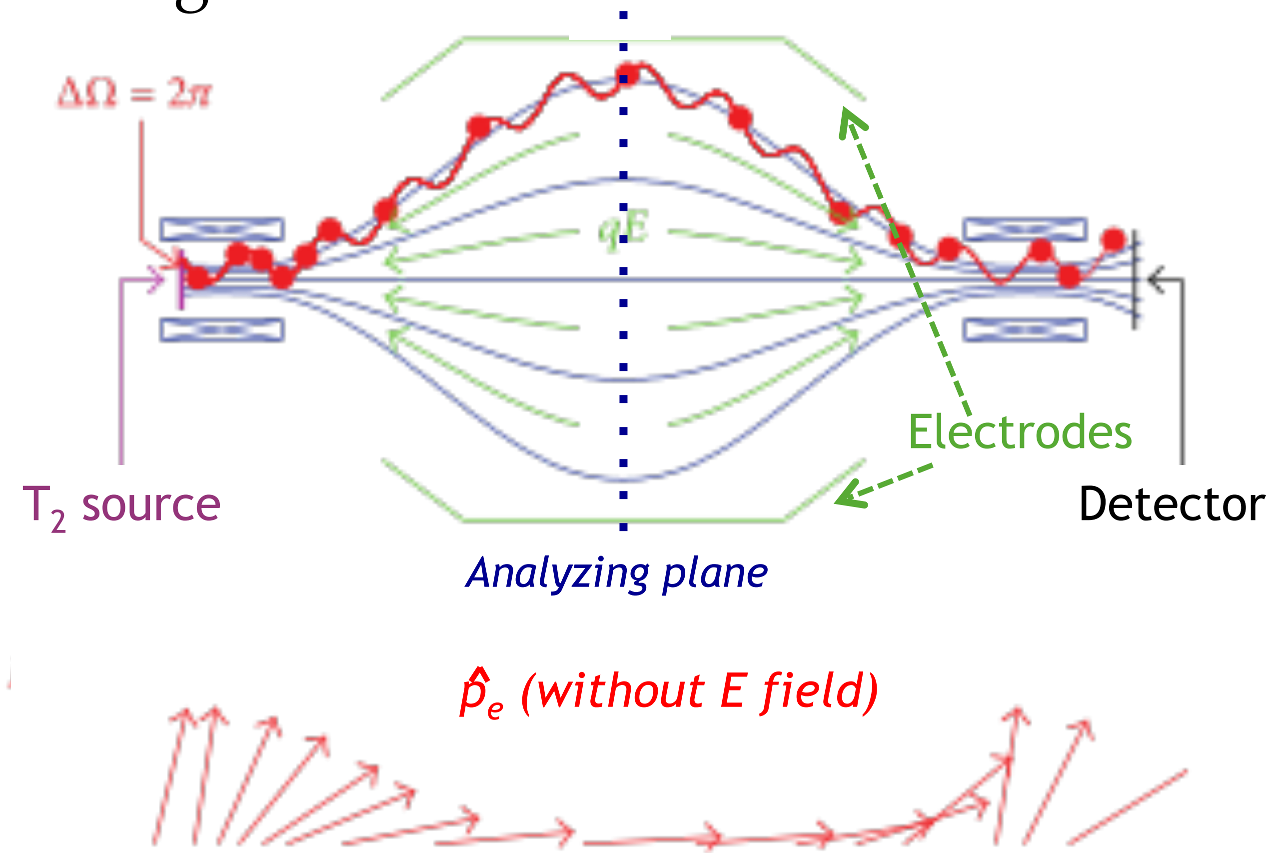


T_2 Spectroscopy: MAC-E Filter

- Measure integral spectrum with moving threshold
- **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter



- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation: $\mu = E_{\perp} / B = \text{const.}$ $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field $\Delta E = E \cdot B_{min}/B_{max} = 0.93$ eV (KATRIN)

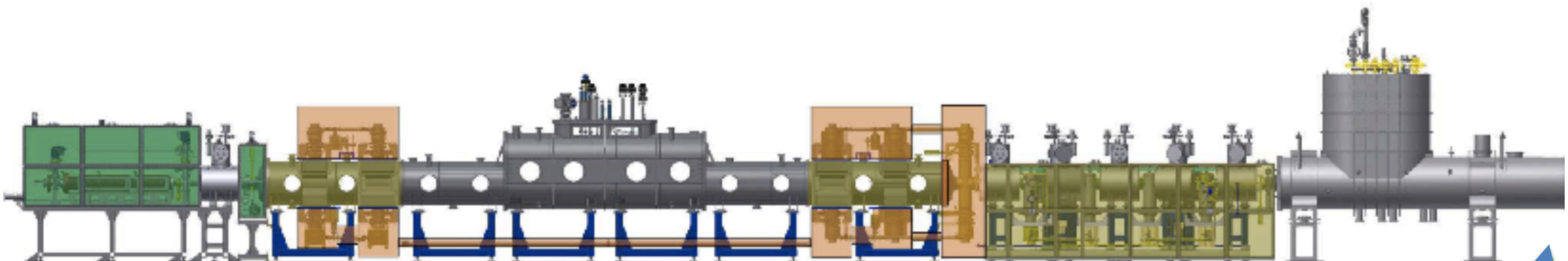
Source, Transport & Pumping

Monitoring & calibration system

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping
with Argon snow at LHe temperatures



T_2-injection 1.8 mbar l/s (STP)
= $1.7*10^{11}$ Bq/s = 40 g/d

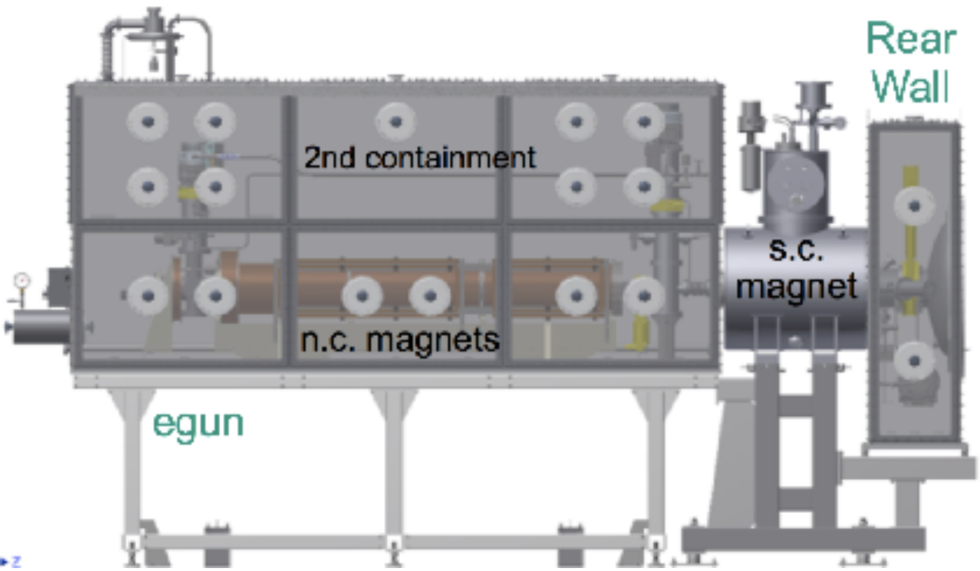
4 10^{-7} mbar l/s

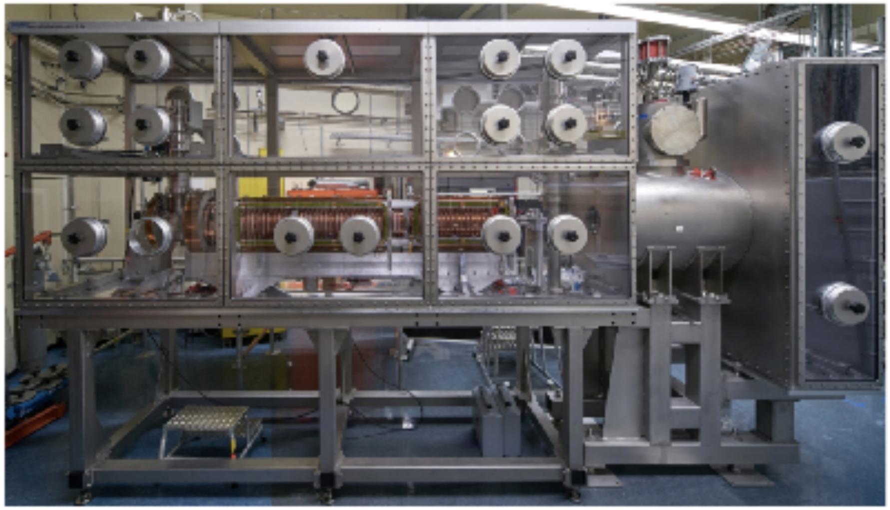
< 2.5 10^{-14} mbar l/s

8 adiabatic electron guiding & T_2 reduction factor of ~10^{14}

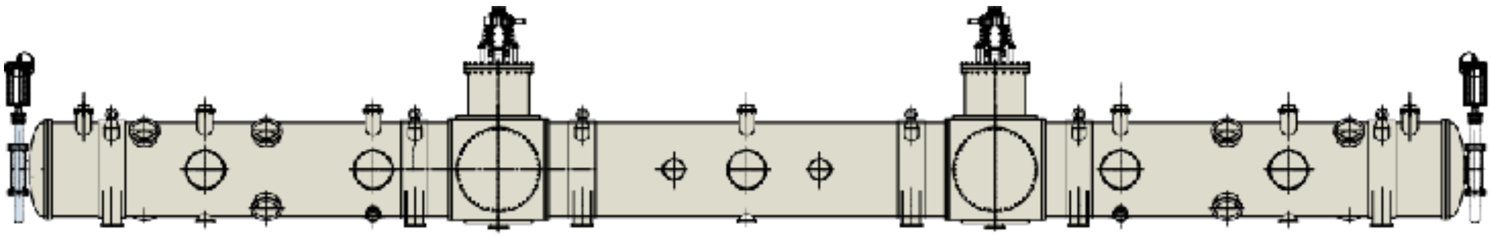
Rear section - Calibration & Monitoring

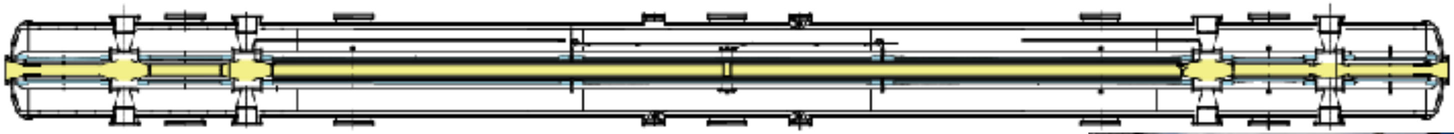
Essential for diagnostics of tritium source & spectrometer transmission
- photoelectron gun: spectrometer transmission & energy losses in source
- rear wall: definition of source potential, neutralization of tritium plasma
- X-ray detectors: online monitoring of tritium ß-decay activity via X-rays (BIXS)



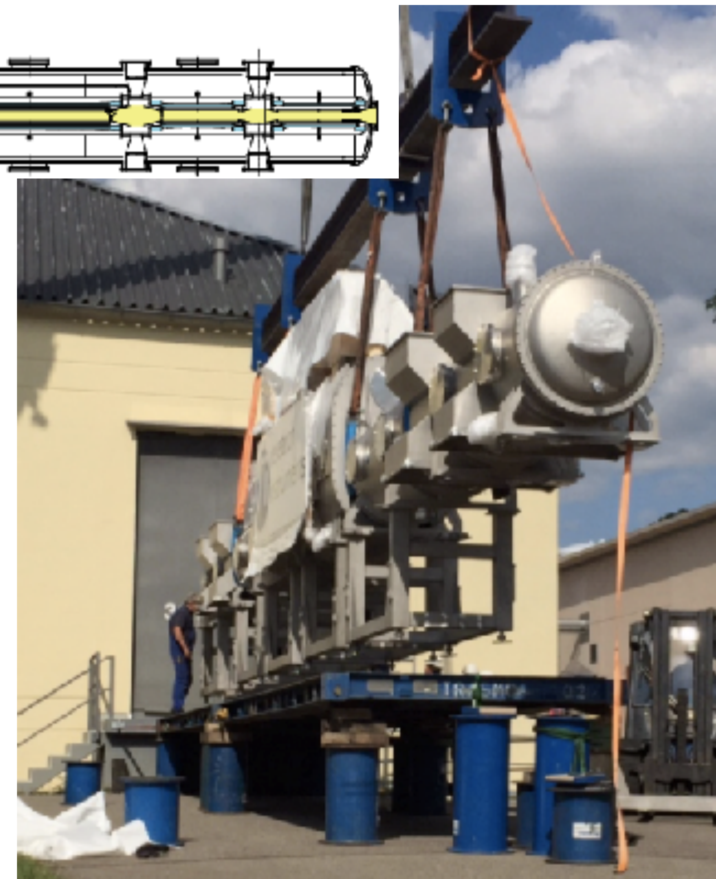


Windowless Gaseous molecular Tritium Source WGTS

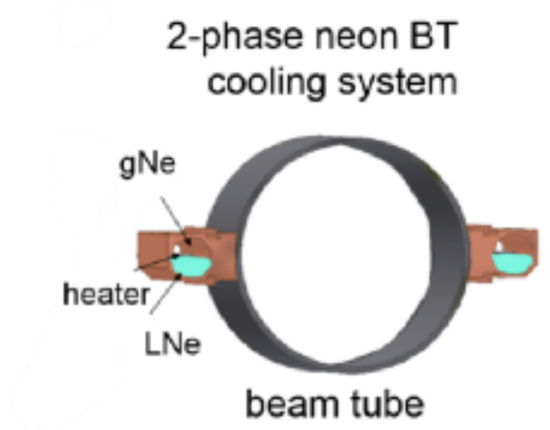


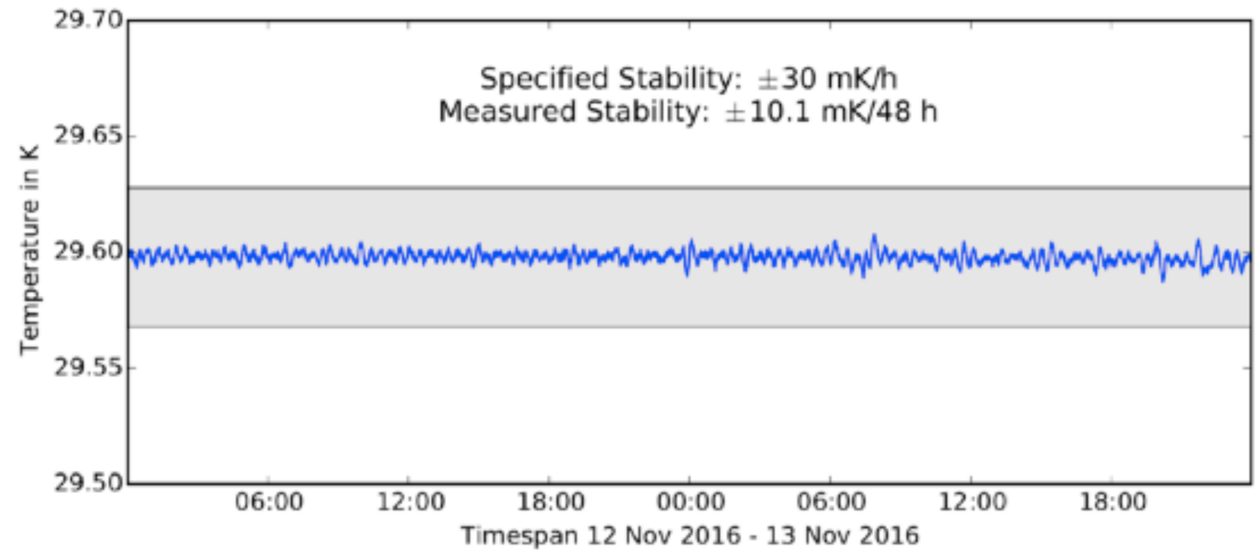


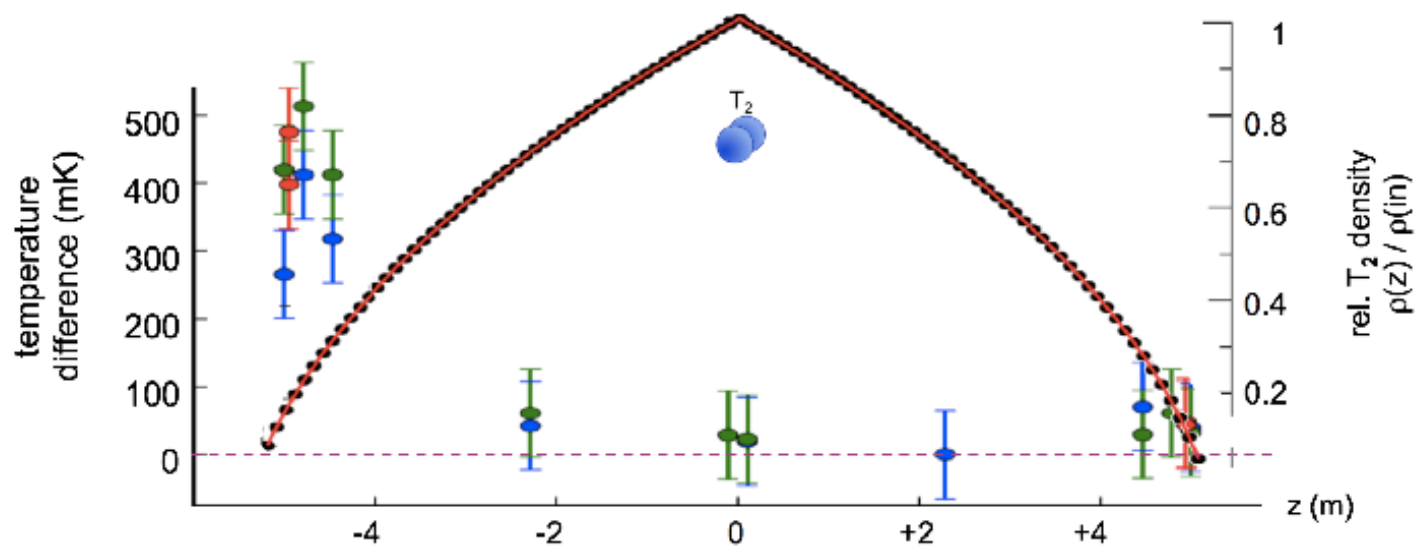
tube in long superconducting solenoids
5 9cm, length: 10m, T = 30 K



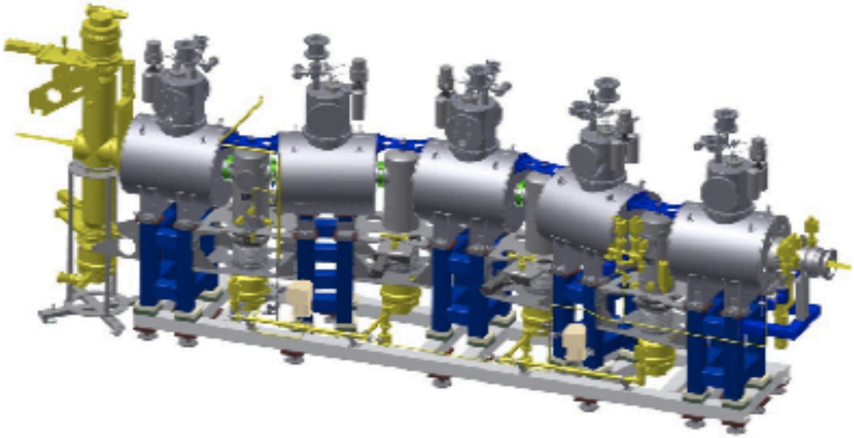
WGTS: Temperature stability and density

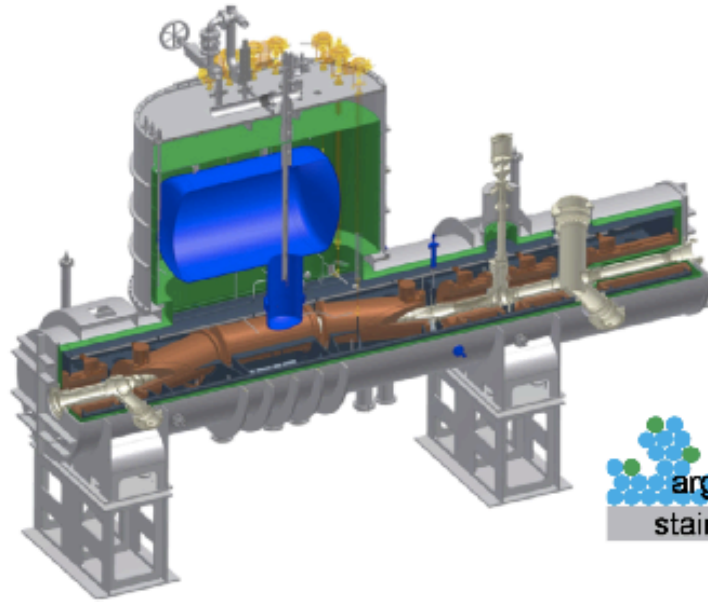


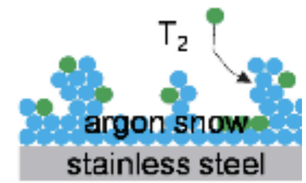


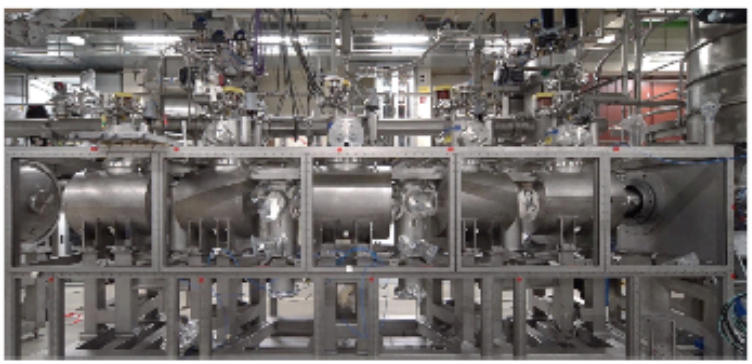


Differential and Cryo Pumping









- based on by cryo-sorption at Ar snow at 3-4 K
- Tritium retention: >10^7
- magnetic field: 5.6 T

- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- **Ion monitoring by FTICR and ion manipulation by dipole and monopole electrodes inside**

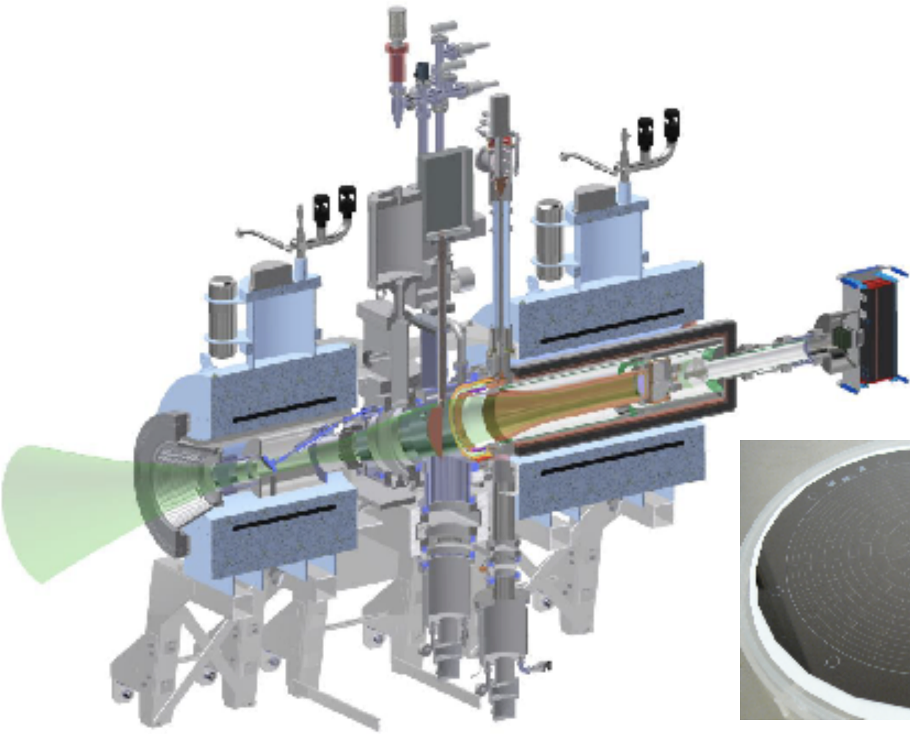
Detector

Requirements

- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
- (passive and active shielding)
- good energy resolution (< 1 keV)

Properties

- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- segmented wafer (148 pixels)
  - record azimuthal and radial profile of the flux tube
  - investigate systematic effects
  - compensate field inhomogeneities
- detector magnet 3 - 6 T
- post acceleration (30kV)



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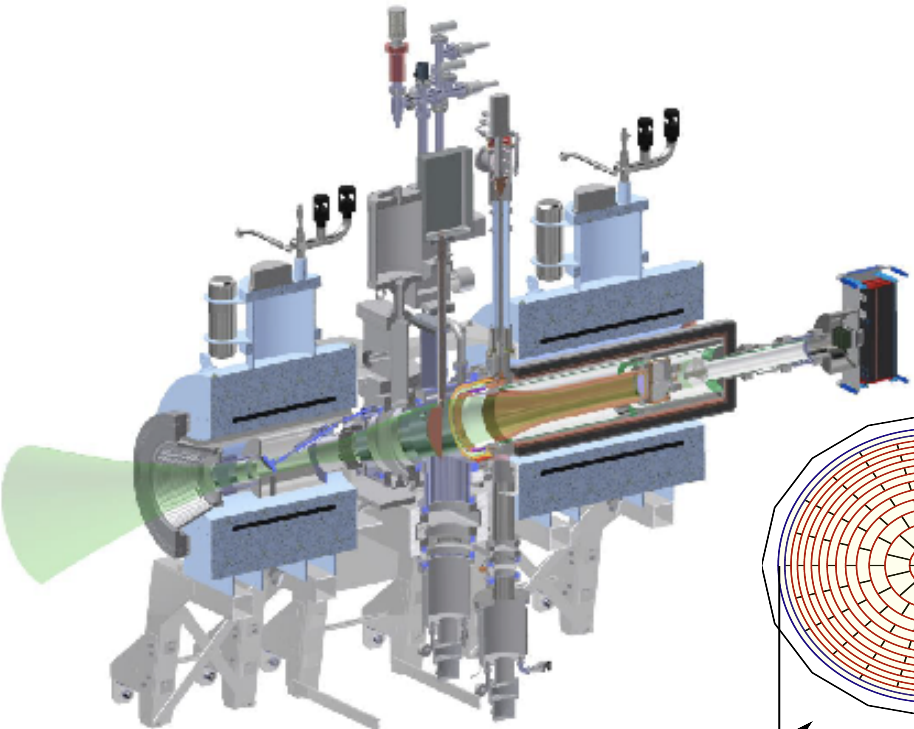
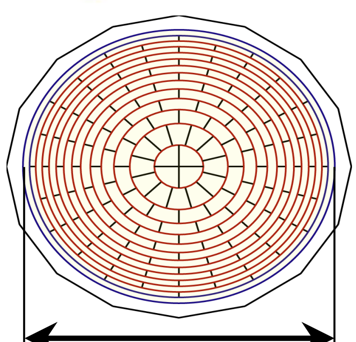
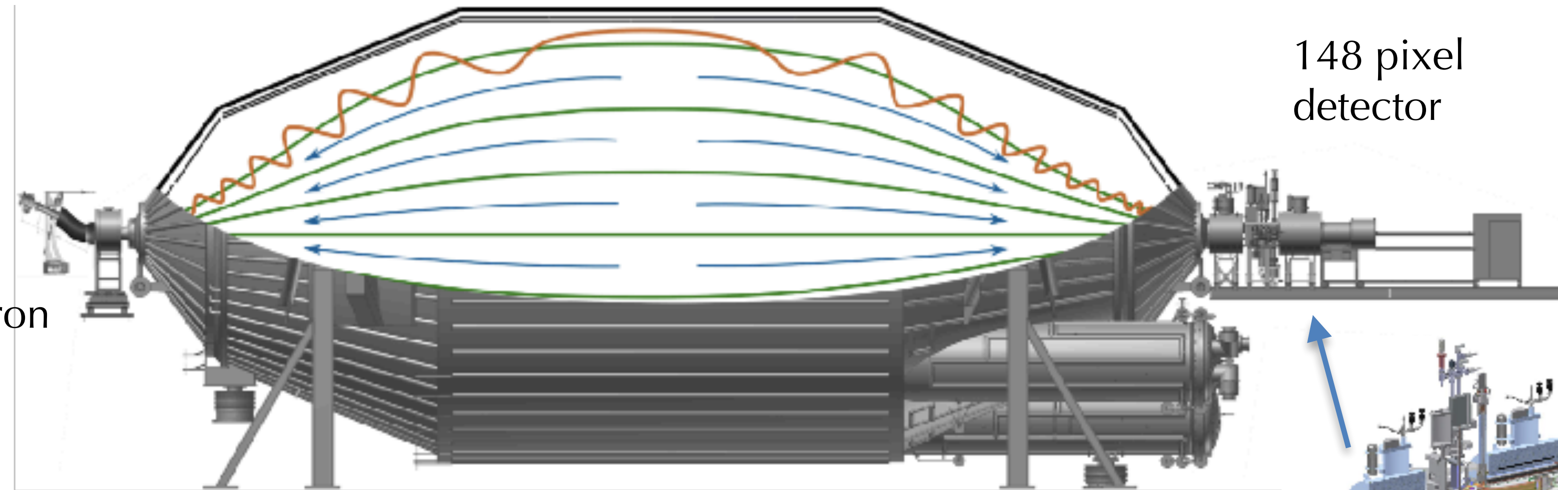


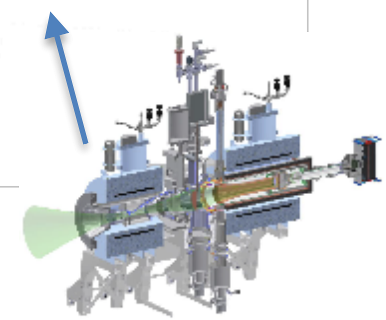


Main spectrometer and detector commissioning objectives

angular selective pulsed photoelectron source



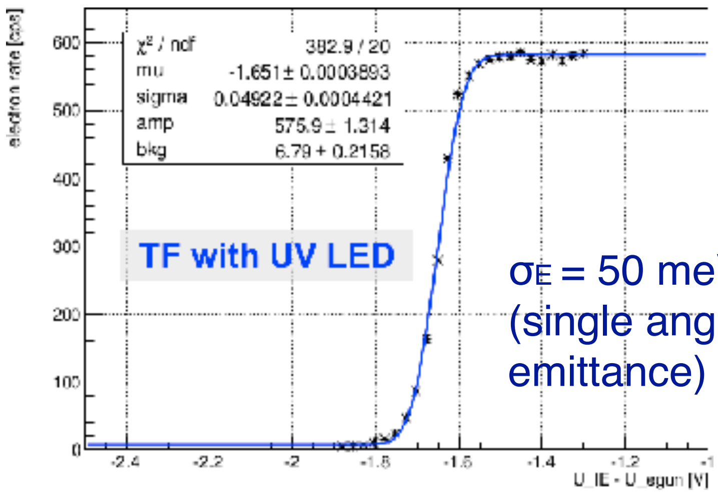
148 pixel detector



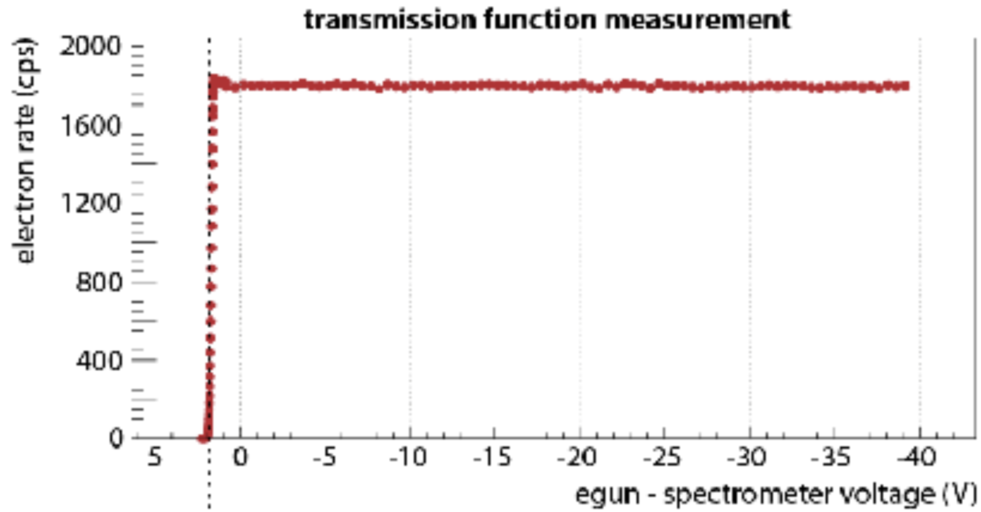
Primary objectives:

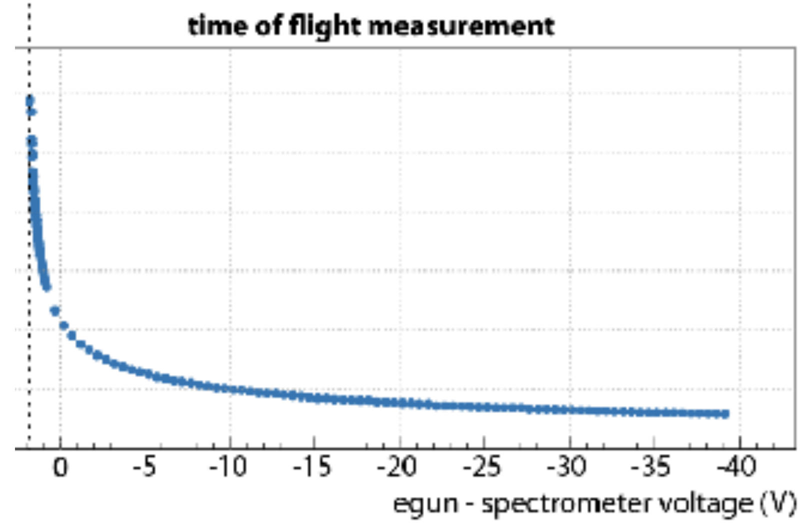
- test of hardware, software and slow control components
- provide ultra high vacuum conditions at the p 4 10^{-11} mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter (E = 18.6 keV with ΔE = 0.93 eV resolution) compared to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes

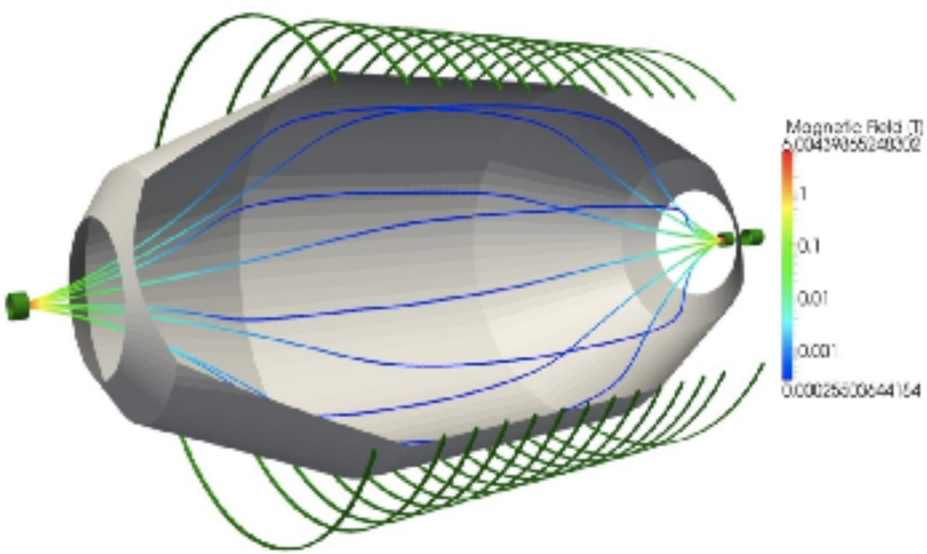
Main spectrometer and detector commissioning results



σ_E = 50 meV (single angular emittance)



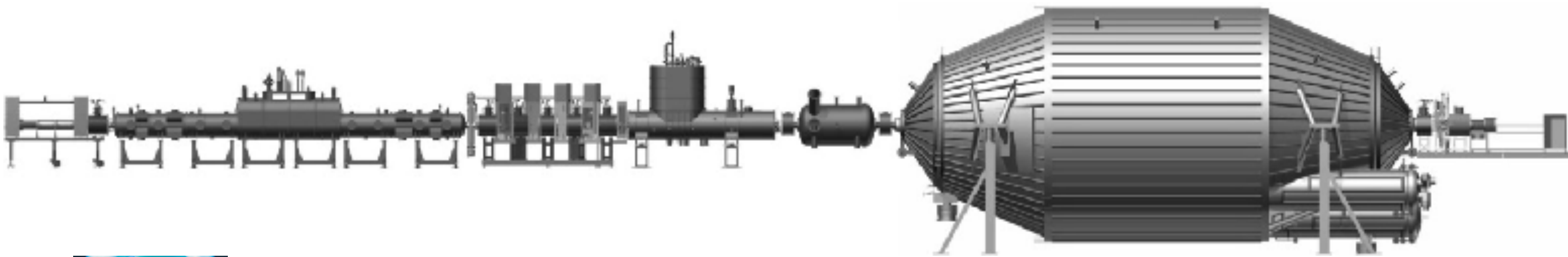


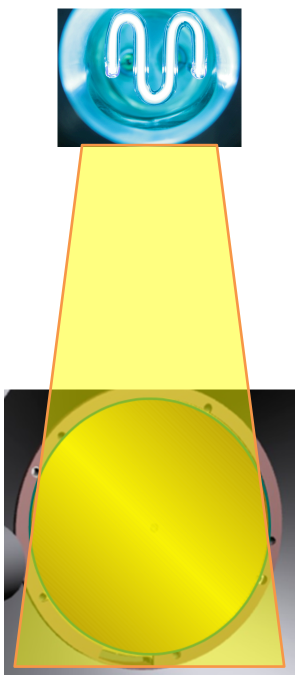


First Light

14 October 2016

Major Milestone: Photo electrons transported over full 70m apparatus.





- Illuminate rear wall
- Magnetically guide photoelectrons along beamline
- First all-KATRIN commissioning

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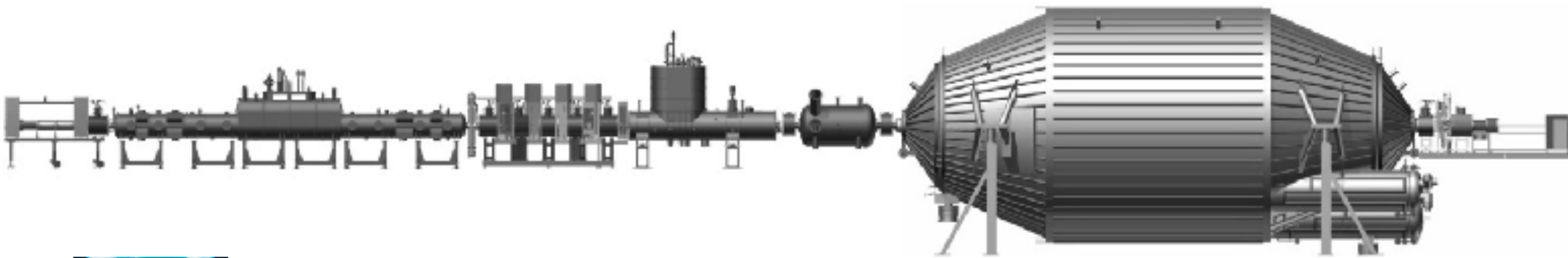

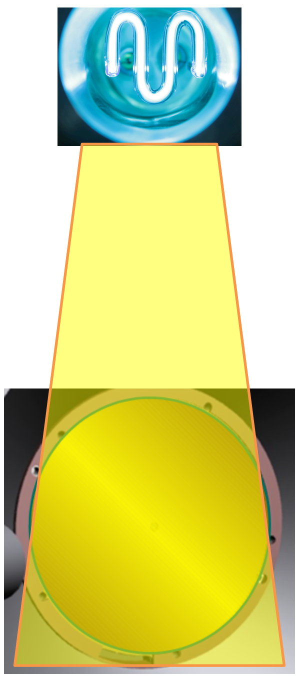

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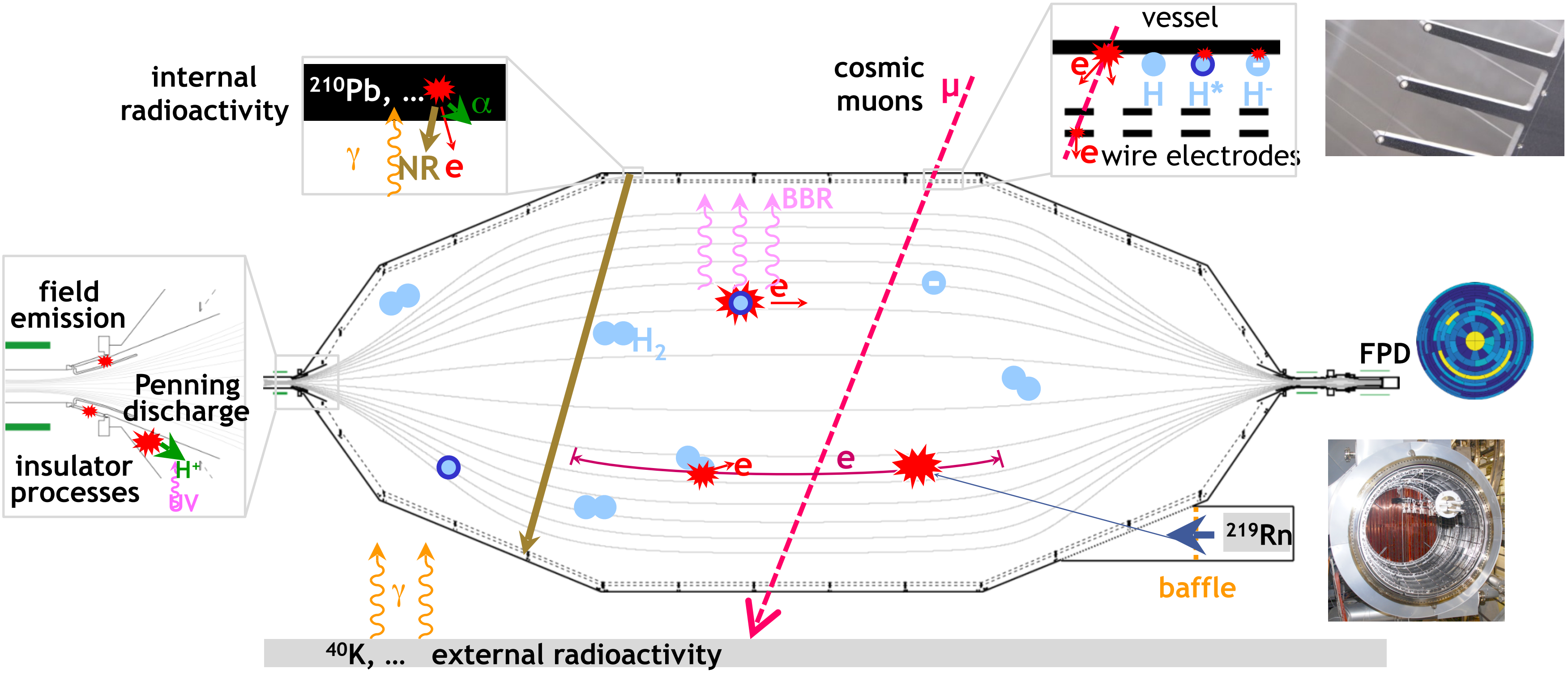
- Magnetically guide photoelectrons along beamline
- First all-KATRIN commissioning

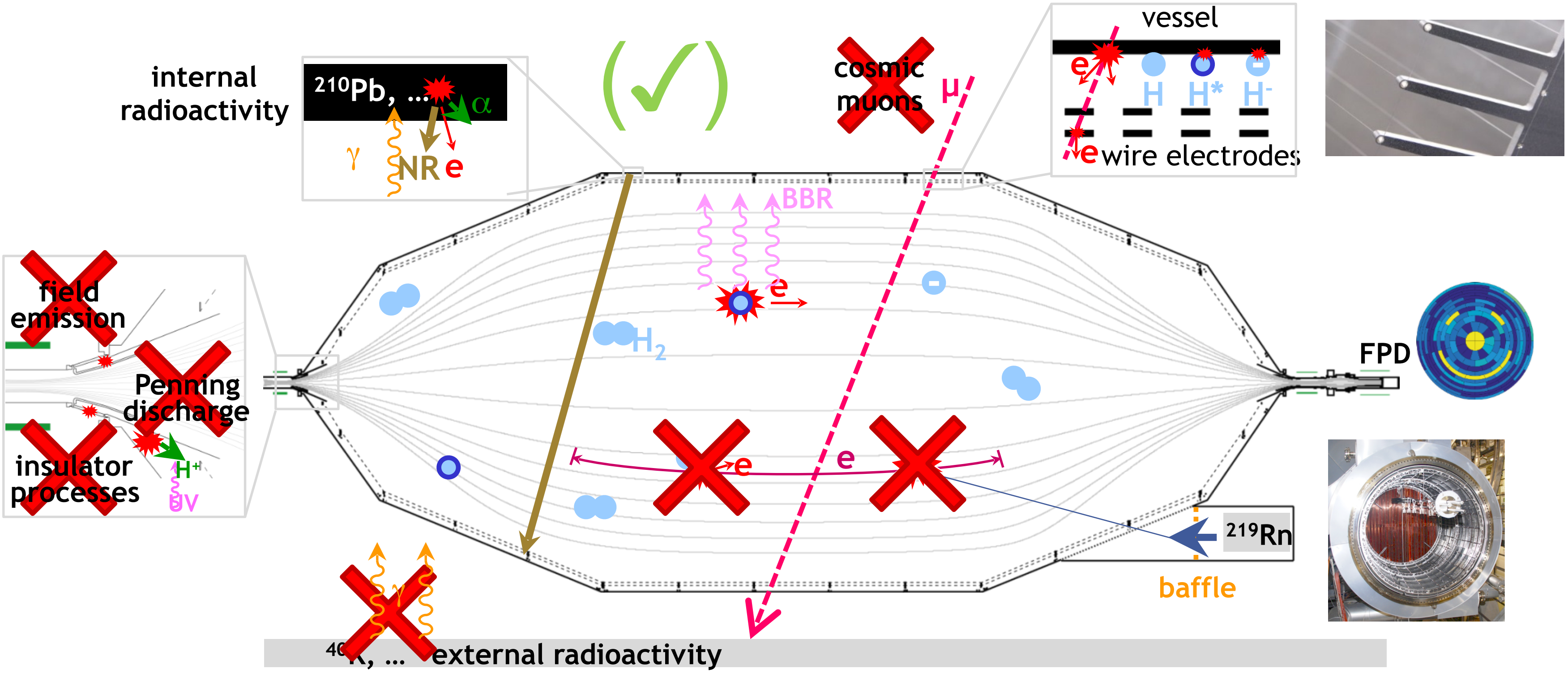
Last beamline valve opens

KATRIN main spectrometer backgrounds



- Various processes can contribute to the spectrometer background
- Spectrometer backgrounds were investigated in detail during two measurement phases (SDS1 & SDS2)

KATRIN main spectrometer backgrounds



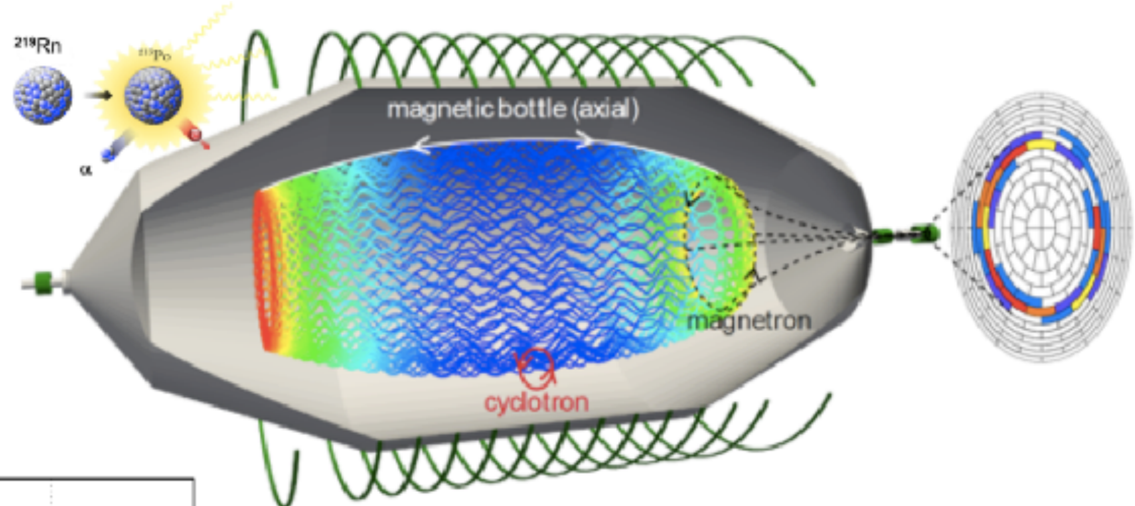
- All previously known background processes are efficiently suppressed
- Background rate about 50 times larger then design value (10 mcps), presumably due to ionization of Rydberg atoms by black body radiation

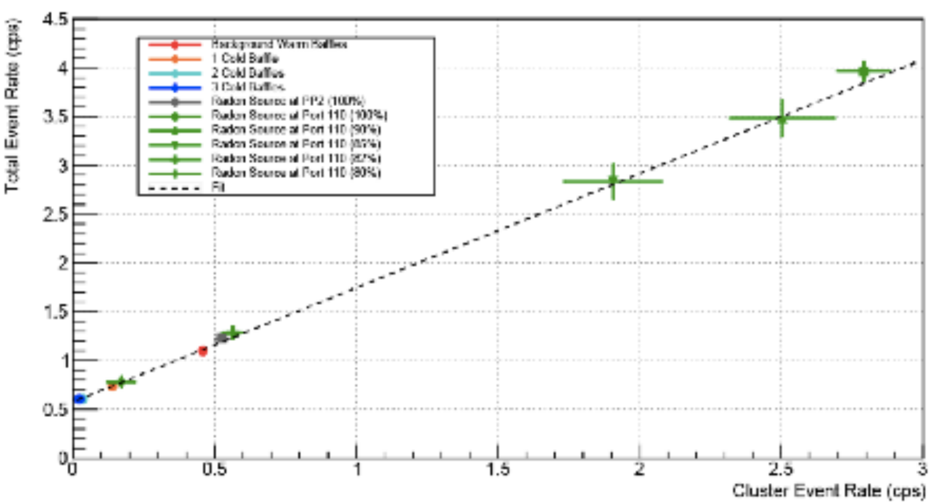
Decays of neutral particles

^{219}Rn from getter (and artificial ^{220}Rn source)

^{219}Rn atoms:

- ^{219}Rn emanates from NEG
- stored electrons eV…keV
- bg-rate: ~500 mcps

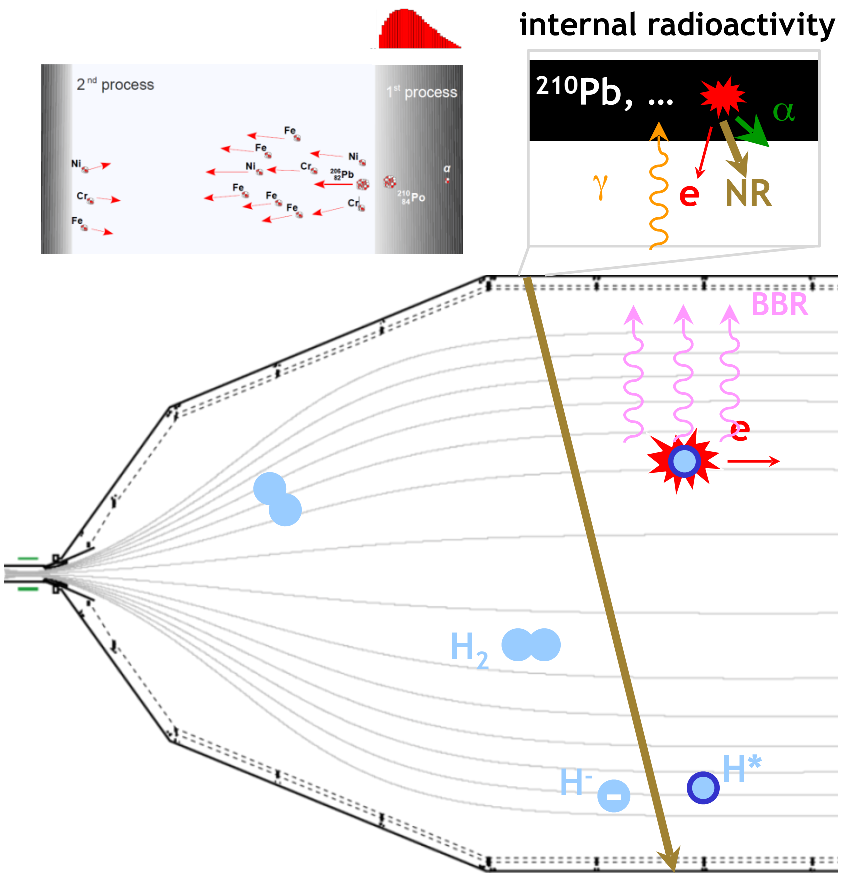




countermeasure (passive):

- cryotraps in front of NEG
- 3 LN_2-cooled Cu-baffles eliminate ~97% of emanated ^{219}Rn atoms

Rydberg model



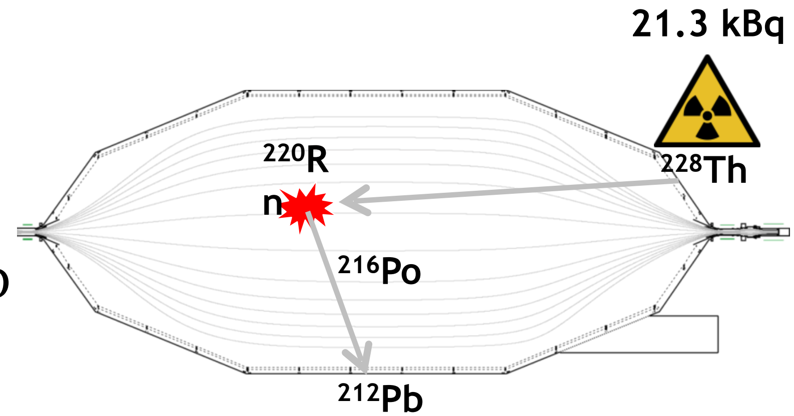
- Remaining spectrometer background independent of magnetic field
- Approximately constant “background density” -> volume effect
- No cluster events at elevated pressure -> background not due to radioactive decays in spectrometer volume
- No effect of active methods
  -> no trapped particles

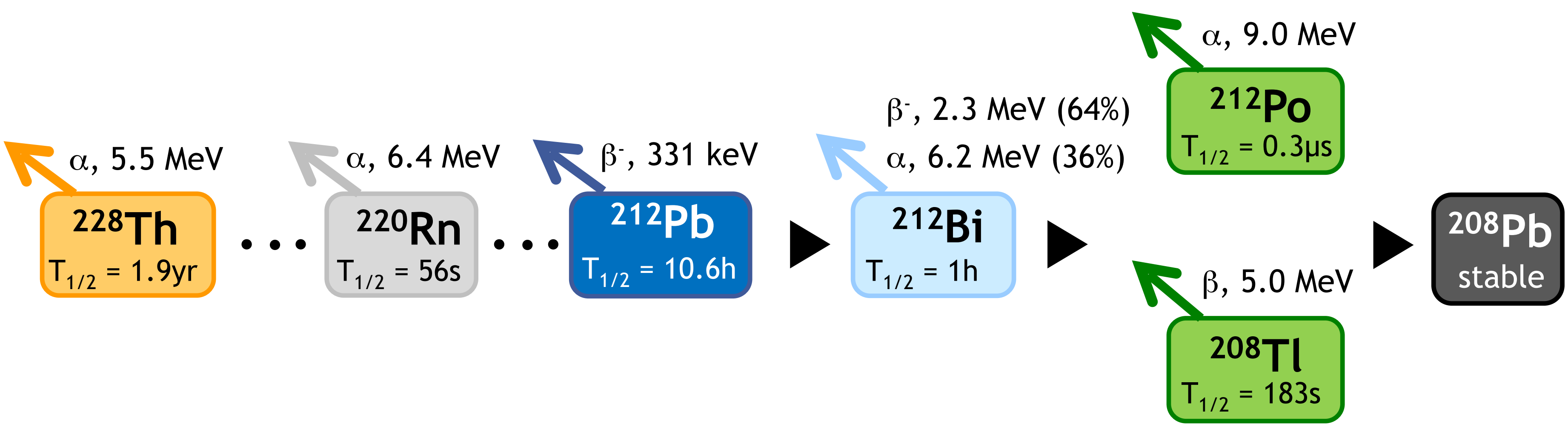
Rydberg model:

- Rydberg atoms created in the decay of ^{210}Pb and accompanying processes, enter the spectrometer volume where they are ionized by thermal radiation, thus creating low-energy electrons

Rydberg model ^{228}Th test

- attach ^{228}Th source to main spectrometer
- “contaminate” inner surface with ^{212}Pb
- close valve to ^{228}Th source and check for exponentially decaying background rate

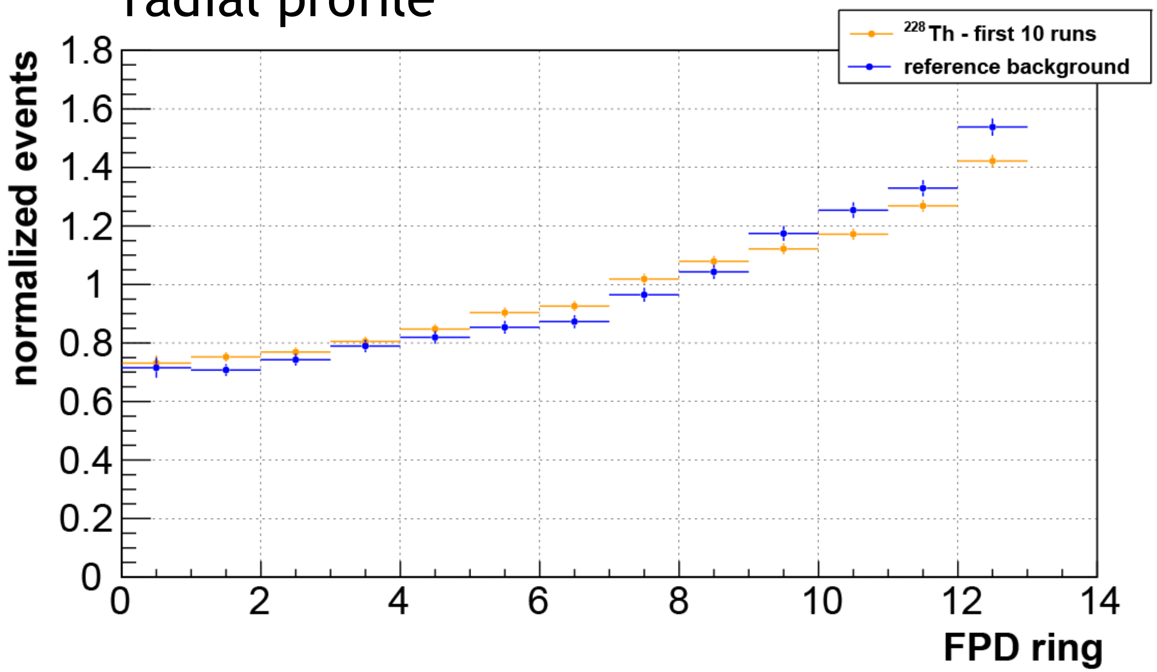




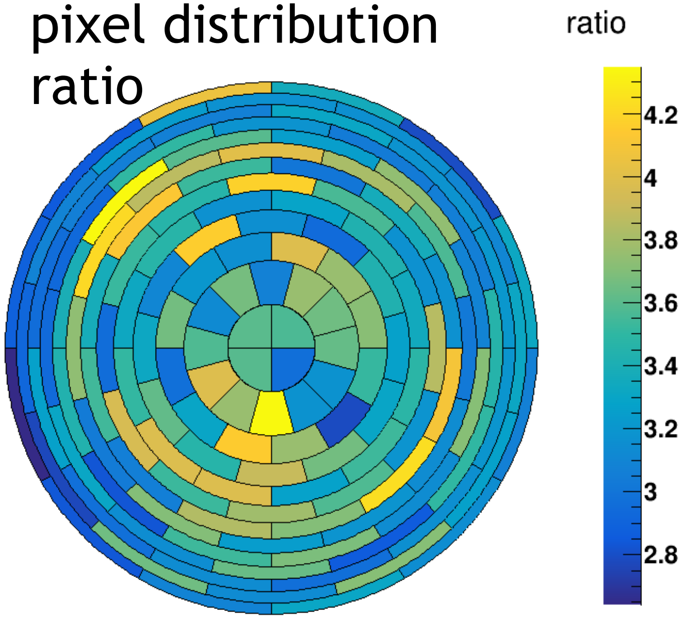
Florian Fränkle, “SDS3 measurements - status and outlook”
KATRIN CM32, Karlsruhe, Germany

Background signature comparison

radial profile



pixel distribution ratio

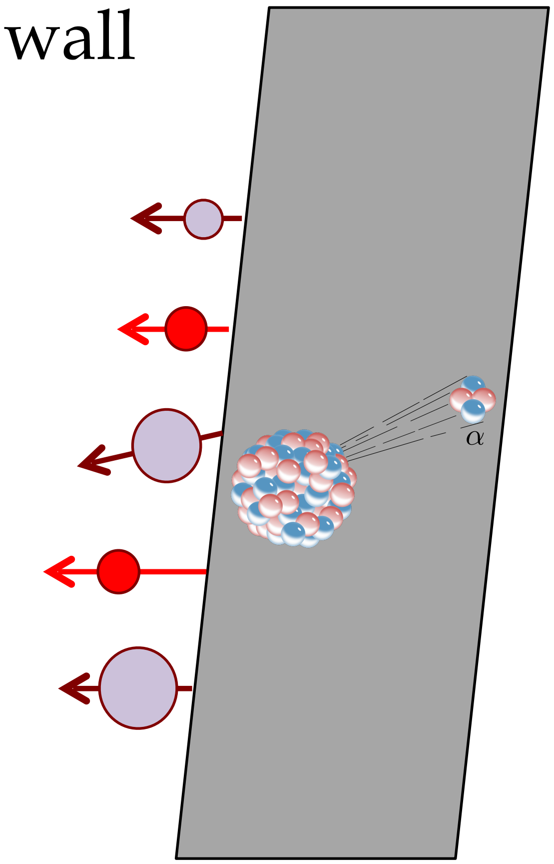


- induced background has the same behavior as existing background

→ main spectrometer ^{210}Pb contamination is root cause of background

Spectrometer Background

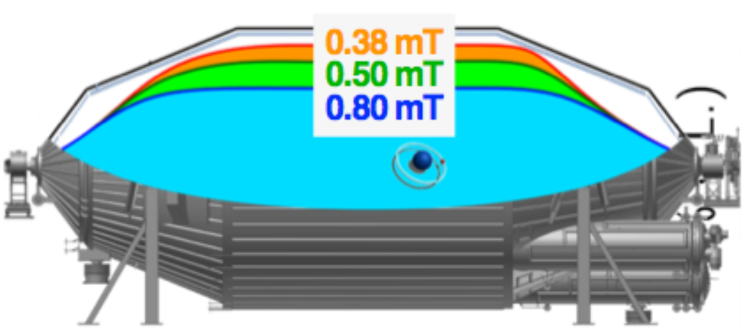
- 2015 commissioning revealed high backgrounds
  - ~50x higher than design value (10 mcps)
- Primary mechanism: ^{210}Po decay in/on wall
  - Secondary particles via sputtering
  - Rydberg atoms (H*) enter flux tube
  - H* ionized via blackbody radiation
  - *Low-energy e⁻ created in flux tube!*
- Countermeasures
  - reduce H-atom surface coverage:
    - extended bake-out phase
    - strong UV source illumination
  - revise data taking strategy

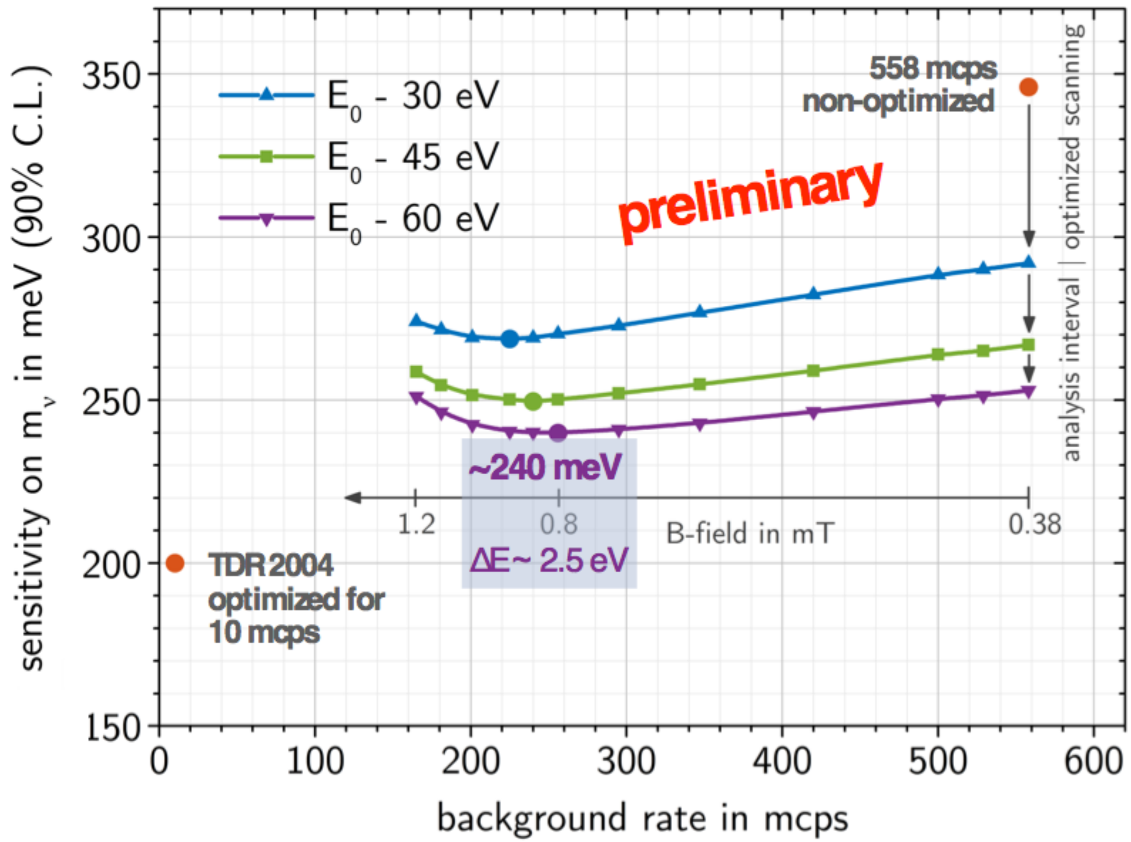


Mitigating High Backgrounds

Ideas and early plan

- Optimize scanning
- Enlarge analysis window
- Increase B_{min}





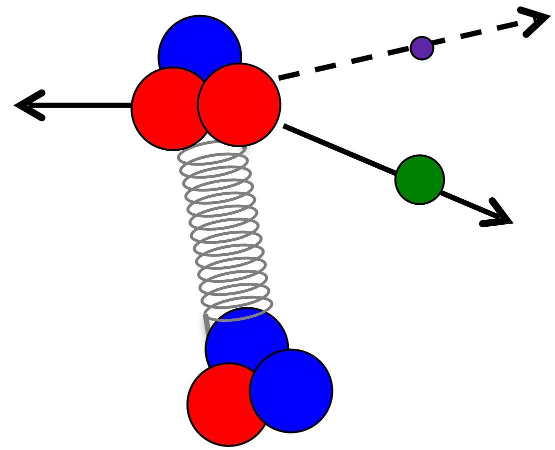
KATRIN 2017-2018

- *Right now:*
  - Analysis of commissioning data (up to late 2016)
  - Final work on tritium related hardware loops
  - Continued work on monitoring systems
  - Maintenance, upgrades, software work preparing for:
- *Summer/Fall 2017*: System commissioning with ^{83m}Kr, H_2, and D_2
- *Early 2018:* First tritium data
- *And beyond:*
  - Early mass results (final sensitivity: 3 beam yrs)
  - Sterile neutrino searches
  - Searches for physics beyond the Standard Model

Backup slides

Molecular Final-State Distribution

- Electronic excitations in T atoms
- Excitations in T_2 gas
  - Electronic: 20 eV
  - Vibrational: ~0.1 eV
  - Rotational: ~0.01 eV
- Beta spectrum depends on excitation energies V_k **and** probabilities P_k



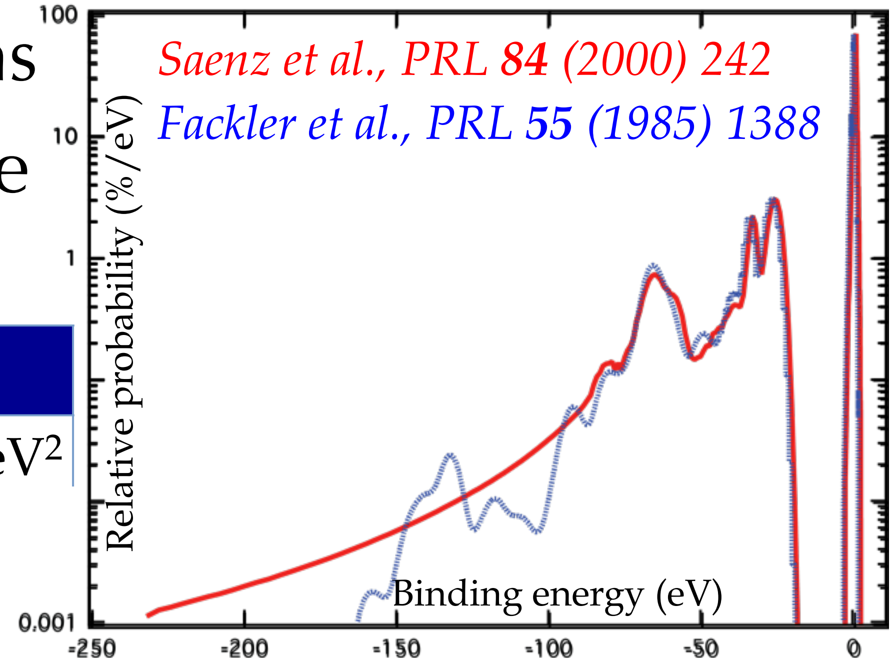
$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\mathrm{nuc}}|^2 F(Z,E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\max} - E_e - V_k)$$
$$\times \sqrt{(E_{\max} - E_e - V_k)^2 - m_{\nu i}^2} \times \Theta(E_{\max} - E_e - V_k - m_{\nu i})$$

Describing T_2 Final States

- Precise ab initio calculations
- Uncertainty hard to estimate
- Enters directly into analysis

Calculation	LANL m_ν^2	LLNL m_ν^2
1985	-147(79) eV^2	-130(25) eV^2

Bodine, DSP, Robertson, PRC ***91****, 035505 (2015)*



- KATRIN needs σ_{FSD} to 1%
  - New calculations
  - Initial-state source characterization
- TRIMS experiment to resolve historical discrepancy