The KATRIN neutrino mass experiment - status update and first tritium measurements

V.M. Hannen for the KATRIN collaboration

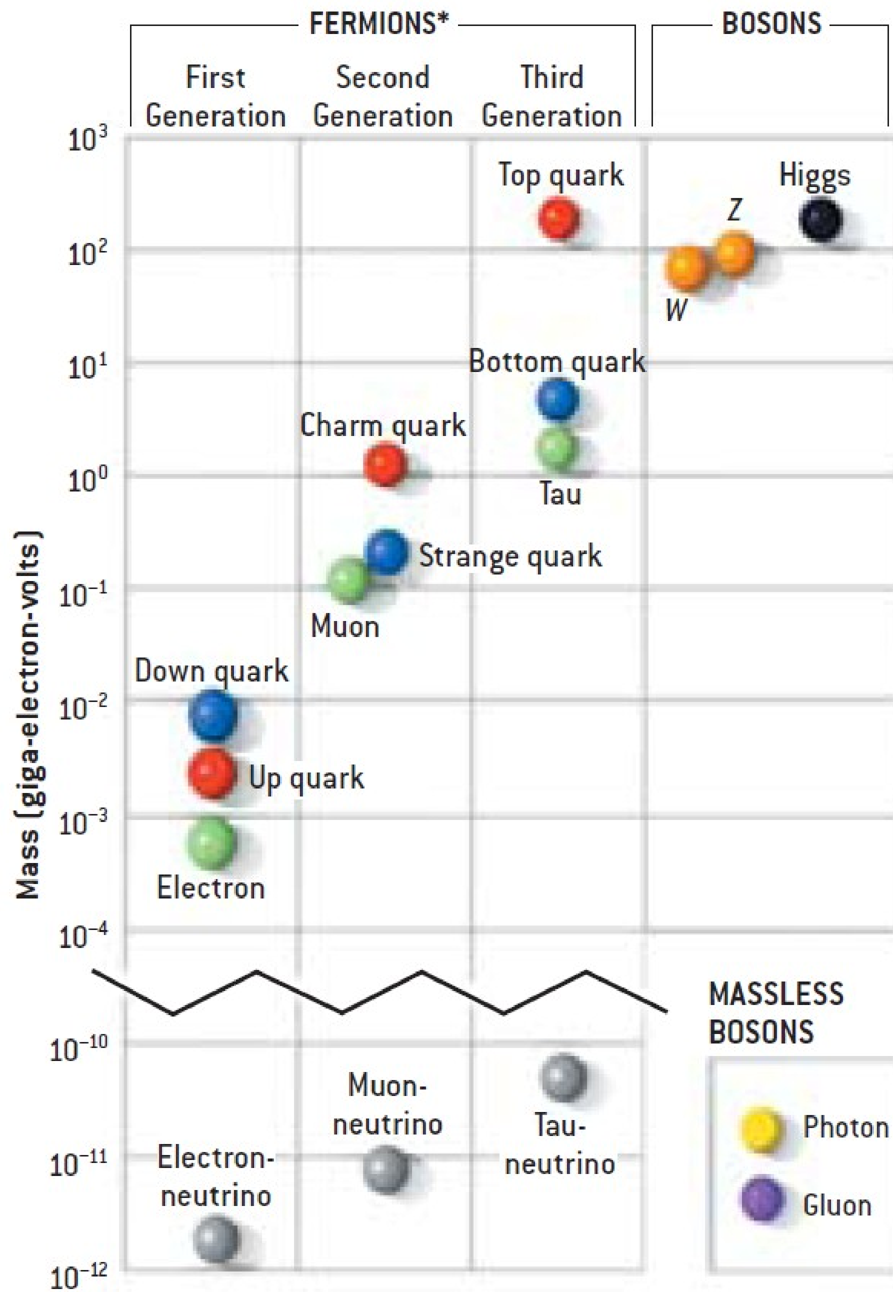
Institut für Kernphysik,
Westfälische Wilhelms-Universität Münster

Neutrino mass in particle physics

- Nature of the neutrino: Majorana or Dirac particle, i.e. is the neutrino it's own anti-particle ?

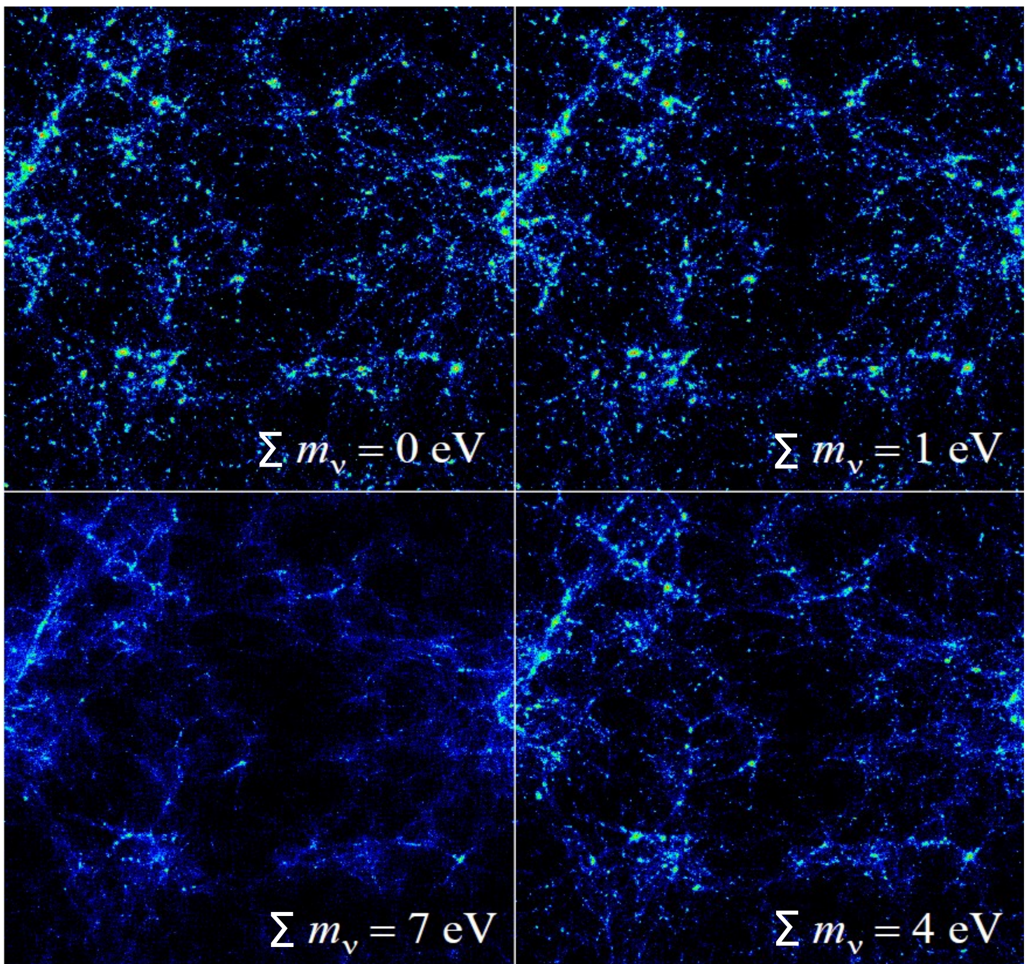
- How to explain the many orders of magnitude difference between neutrino mass limits and masses of the charged fermions of the standard model
  → sea-saw type I and type II mechanisms

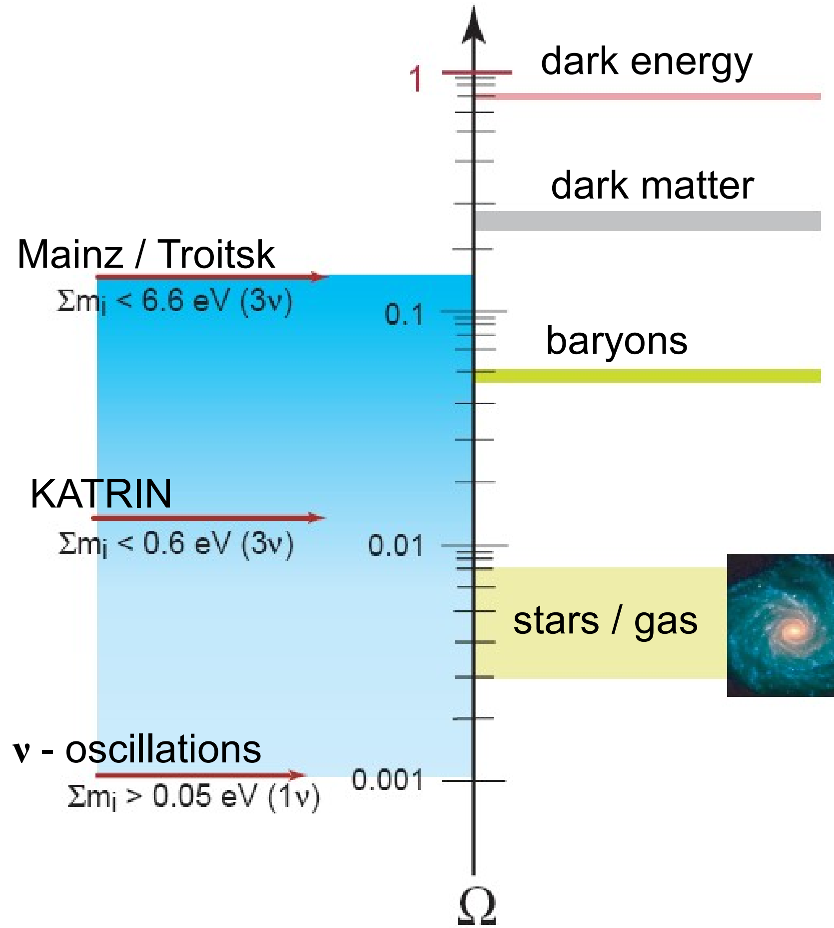
- Possible connection to the generation of the observed matter - antimatter asymmetry in the universe
  → leptogenesis



Neutrino mass in cosmology

- Neutrinos are (after γ's) the second most abundant particle species in the universe
- As part of the hot dark matter, neutrinos have a significant influence on structure formation





- For large Σm_ν values fine grained structures are washed out by the free streaming neutrinos

Chung-Pei Ma 1996

Search for neutrino mass

β-decay: absolute ν-mass

model independent, kinematics

status: $m_\nu < 2.3$ eV

potential: $m_\nu \approx 0.2$ eV

e.g.: KATRIN, Project-8, ECHO HOLMES, NuMECS

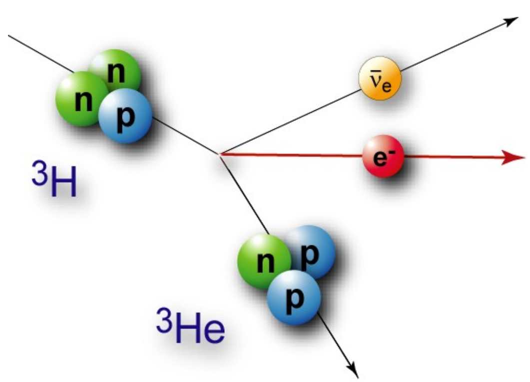
0νββ-decay: eff. Majorana mass

model-dependent (CP-phases)

status: $m_{\beta\beta} < 0.31$ eV

potential: $m_{\beta\beta} \approx 20\text{-}50$ meV

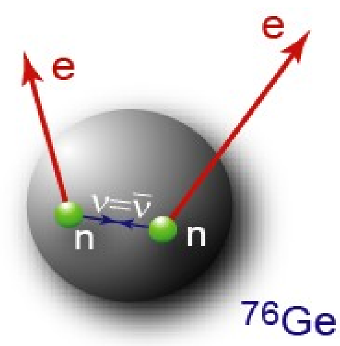
e.g.: GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA, KamLAND-Zen



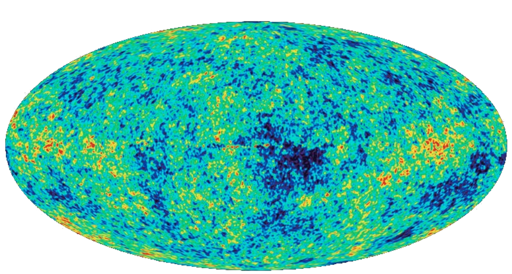
m_ν

neutrino mass measurements

$m_{\beta\beta}$



Σm_i



cosmology: ν hot dark matter Ω_ν

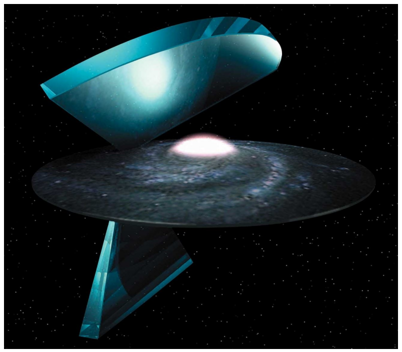
model dependent, analysis of CMB and structure formation data

status: $\Sigma m_\nu < 0.23$ eV

(*Planck Collaboration, A&A 594 (2016) A13*)

possible signal: $\Sigma m_\nu = 0.11 \pm 0.03$eV

(*Emami et al., arXiv:1711.05210*)



Kinematic determination of $m(\nu_e)$

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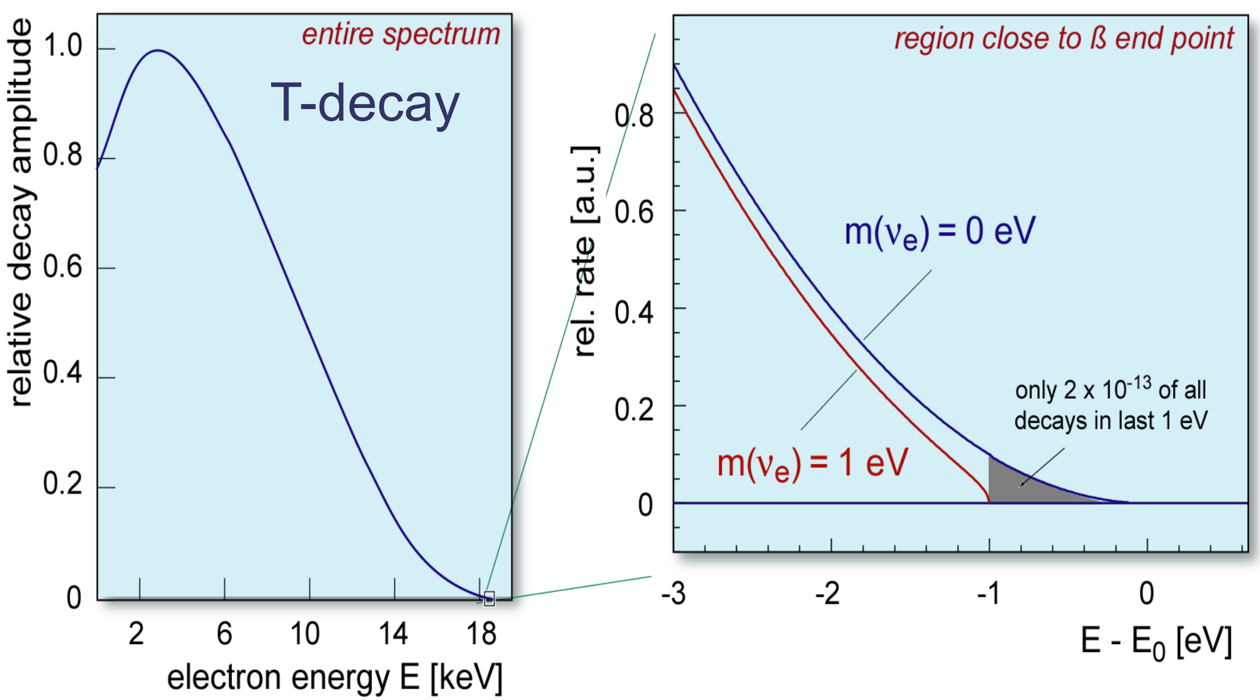
$$\frac{d\Gamma}{dE} = C\, p\,(E+m_e)(E_0-E)\sqrt{(E_o-E)^2-m_{\nu_e}^2}\,F(Z+1,E)\,\Theta(E_0-E-m_{\nu_e})\,S(E)$$

$$C = \frac{G_F^2}{2\pi^3}\cos^2\theta_C\,|M|^2$$

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3}|U_{ei}|^2 m_i^2}$$

(modified by final state distribution, recoil corrections, radiative corrections, ...)



Tritium

- E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a
- S(E) = 1 (super-allowed)

Detector requirements:

- large solid angle or source=detector approach
- high energy resolution
- low background
- low dead time / no pile up

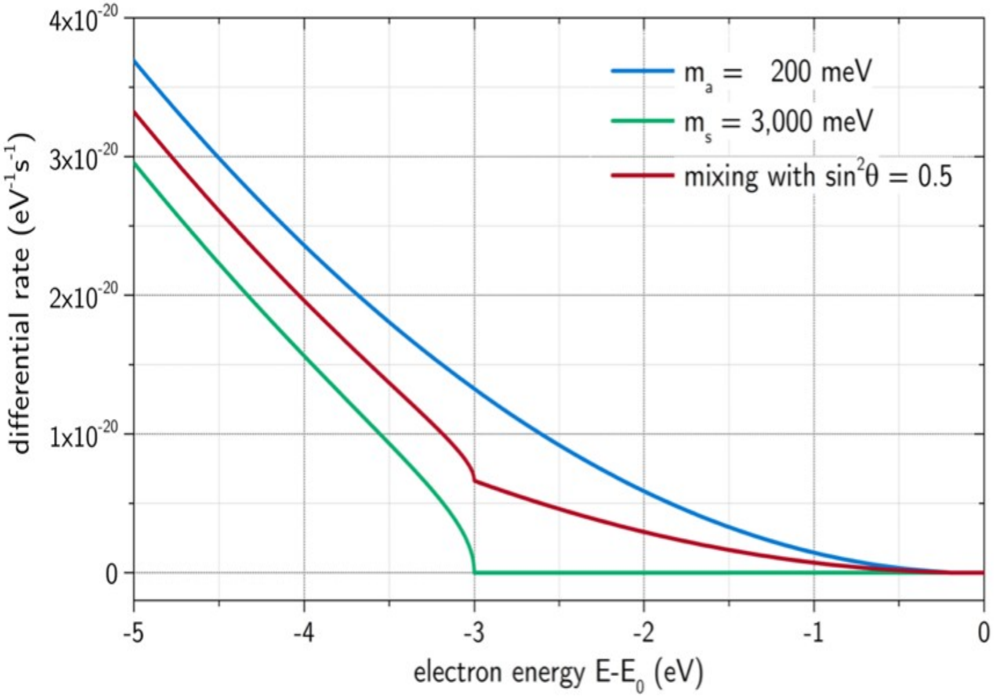
Signature of sterile neutrinos

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

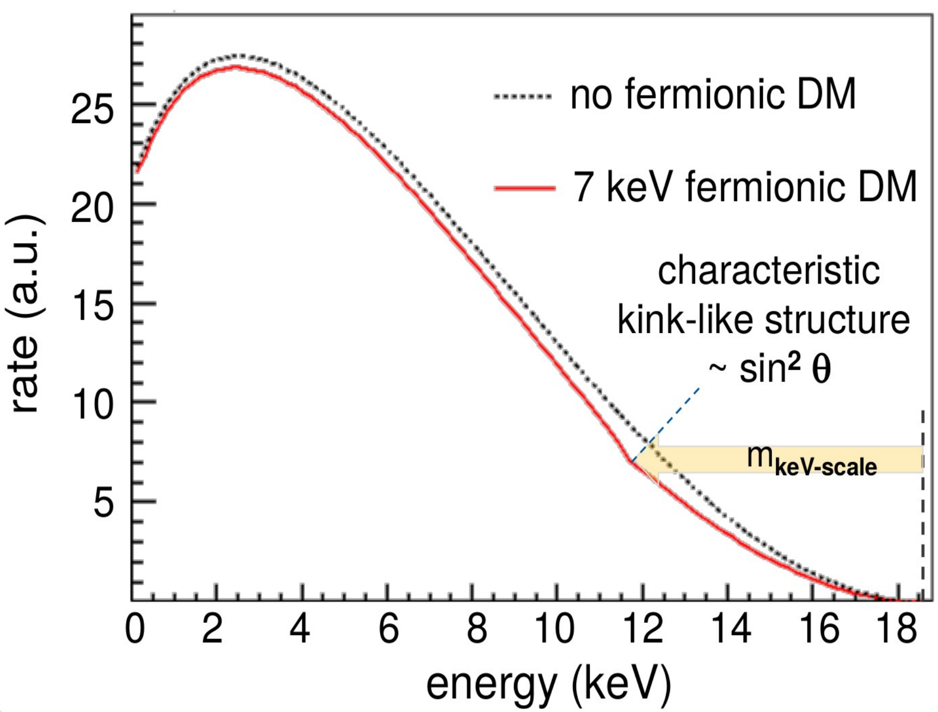
$$\frac{d\Gamma}{dE} = \cos^2(\theta_s)\frac{d\Gamma}{dE}(m_a^2) + \sin^2(\theta_s)\frac{d\Gamma}{dE}(m_s^2)$$

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

light sterile ν, ms = 3 eV



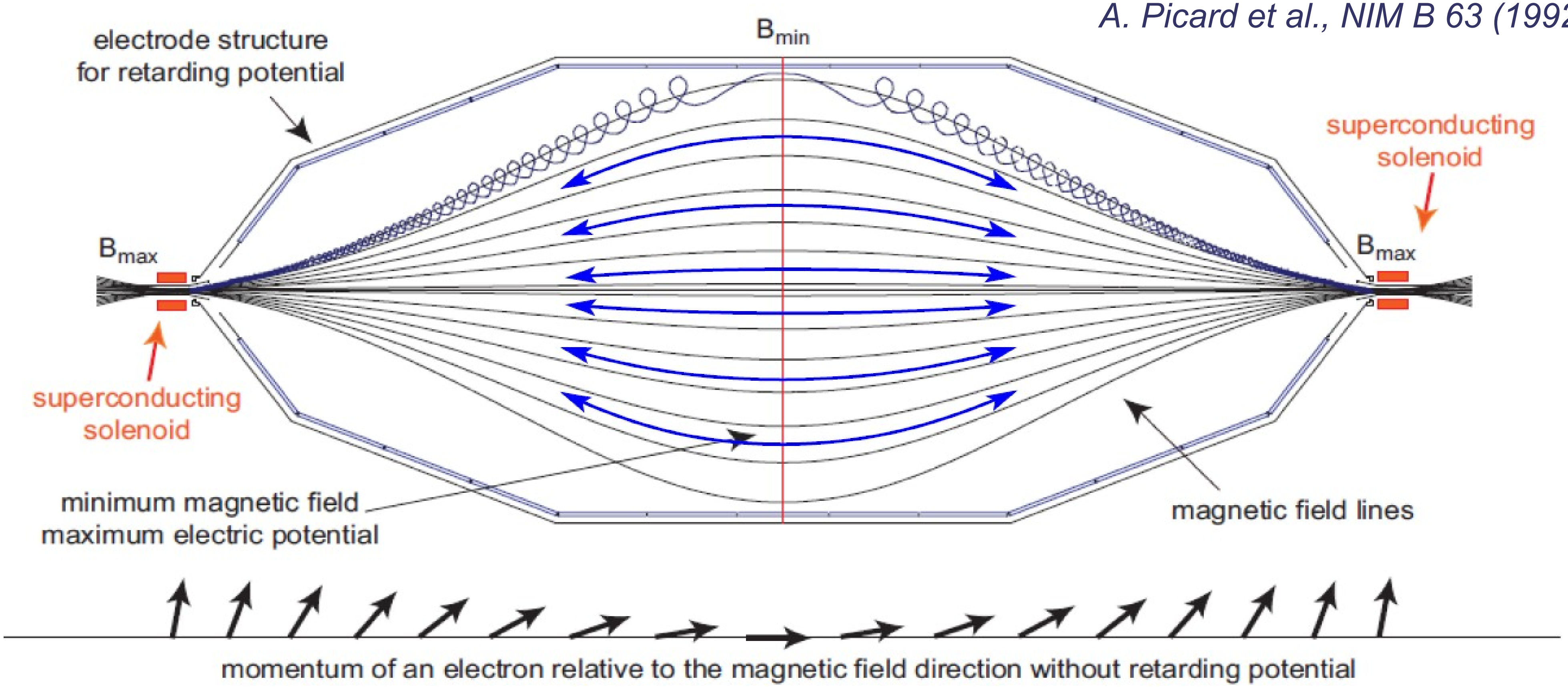
keV sterile ν, ms = 7 keV



MAC-E filter concept

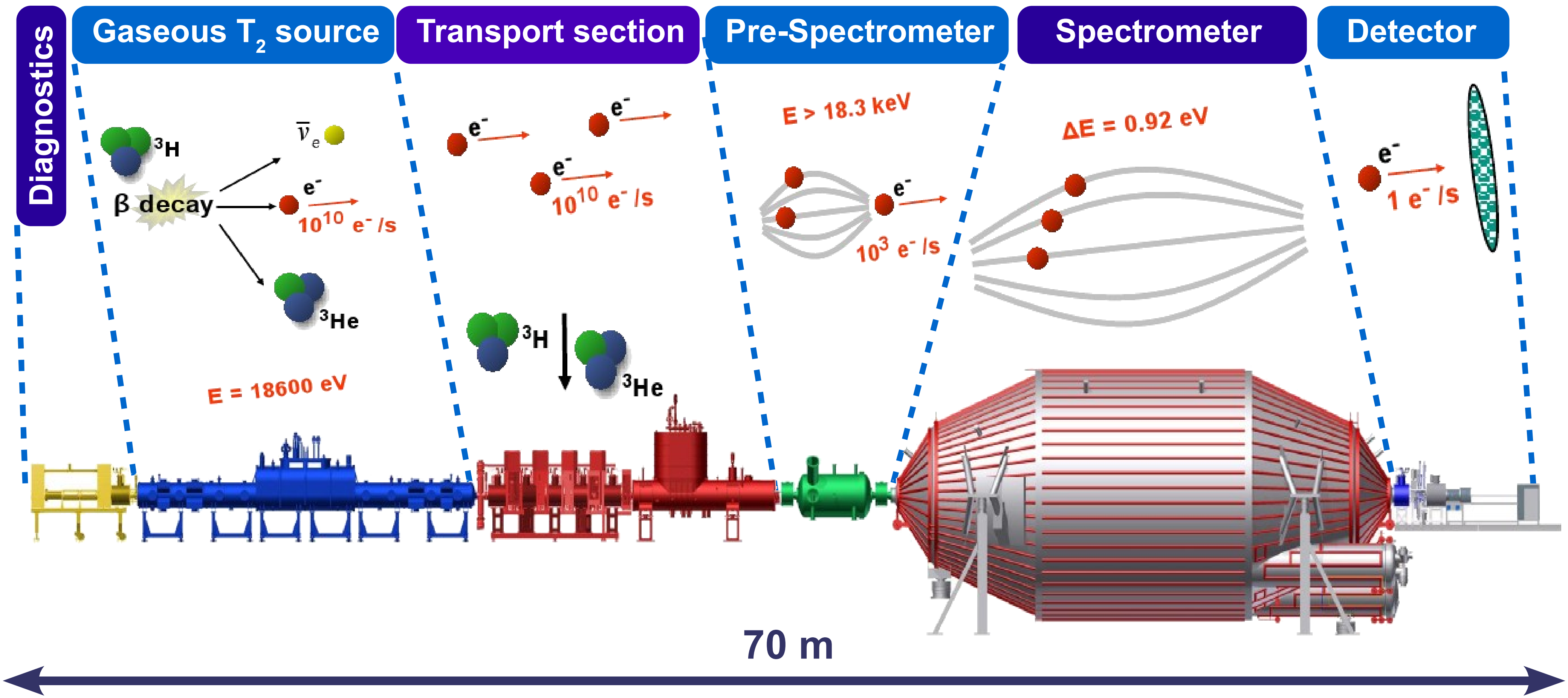
Magnetic Adiabatic Collimation with Electrostatic Filter

A. Picard et al., NIM B 63 (1992)



- adiabatic transport → $\mu = E_{\perp} / B = const.$
- B drops by $2 \cdot 10^4$ from solenoid to analyzing plane → $E_{\perp} \rightarrow E_{||}$
- only electrons with $E_{||} > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\perp,max,\,start} \cdot B_{min} / B_{max} < 1$ eV

KATRIN experiment at KIT



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CENPA
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
Max-Planck-Institut für Kernphysik
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BERGISCHE UNIVERSITÄT WUPPERTAL
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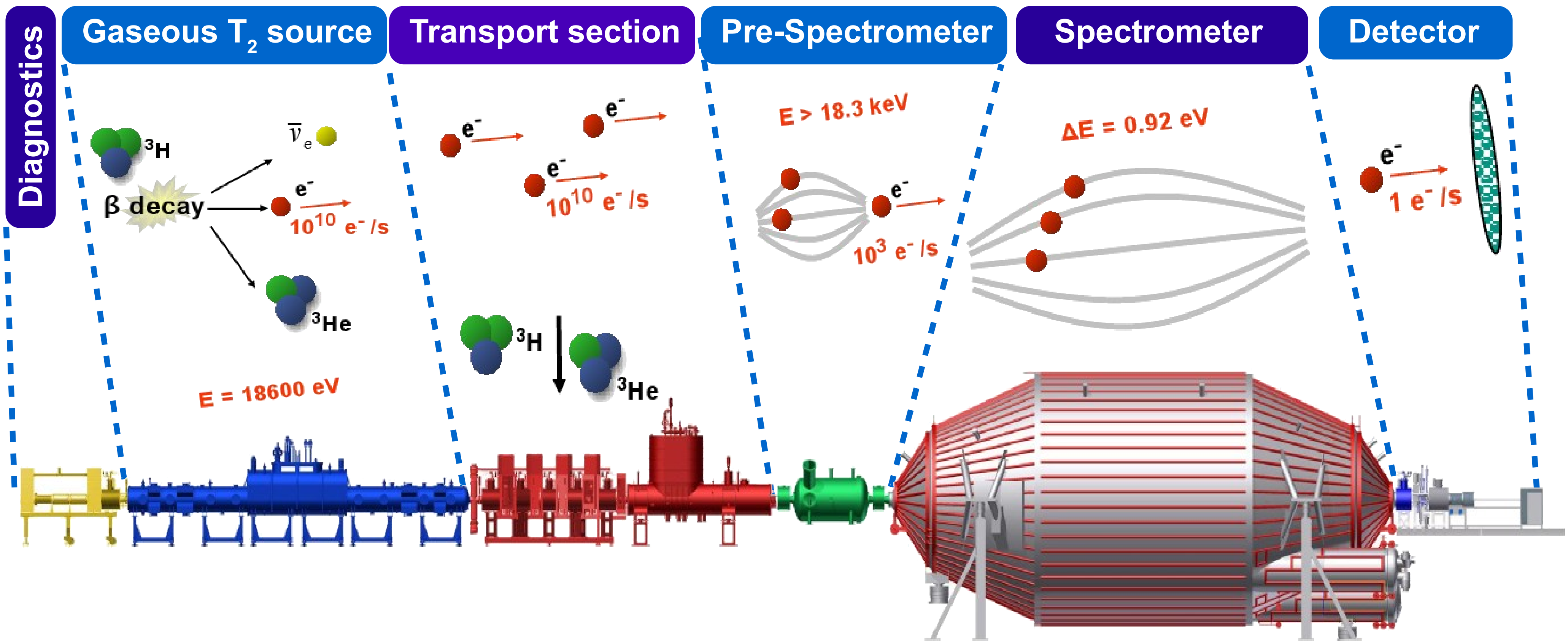
KATRIN Karlsruhe Tritium Neutrino Experiment

KATRIN experiment at KIT



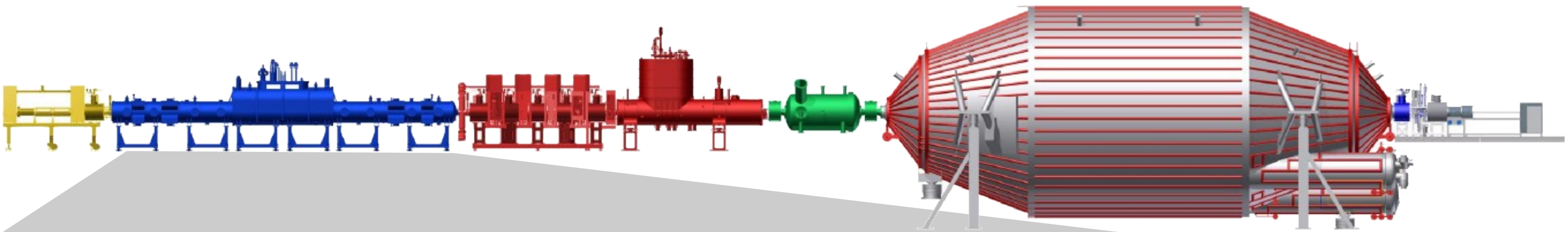
KATRIN sensitivity:
5 year measurement
(eff. 3 y of data)

statistical uncertainty σ_{stat} **≈ 0.018 eV²**

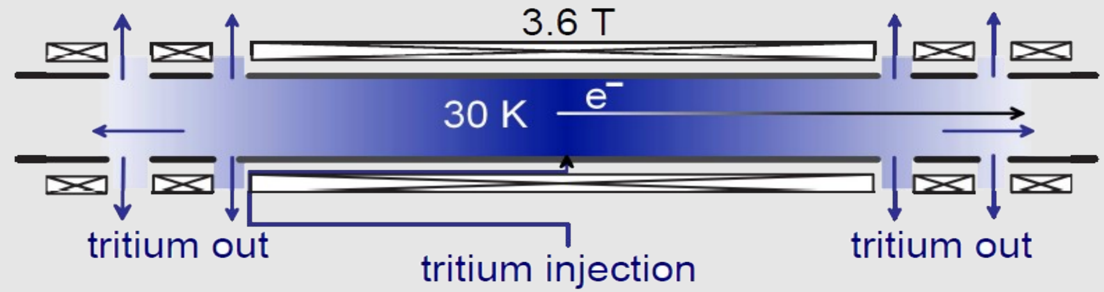
systematic uncertainty $\sigma_{sys,tot}$ **≈ 0.017 eV²**

→ sensitivity for upper limit: **0.2 eV/c²** (90% C.L.)
$m(\nu_e)$ = 0.35 eV observable with 5σ

Windowless Gaseous Tritium Source



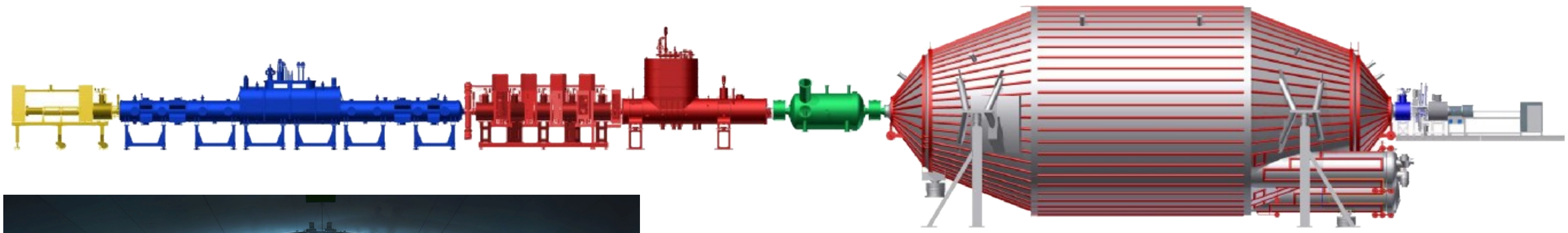
• beam tube	Ø = 9 cm , L = 10 m
• guiding field	3.6 T
• temperature	T = 30 K ± 30 mK,
• T_2 flow rate	$5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)
• T_2 purity	95% ± 0.1 %
• T_2 inlet pressure	10^{-3} mbar ± 0.1 %



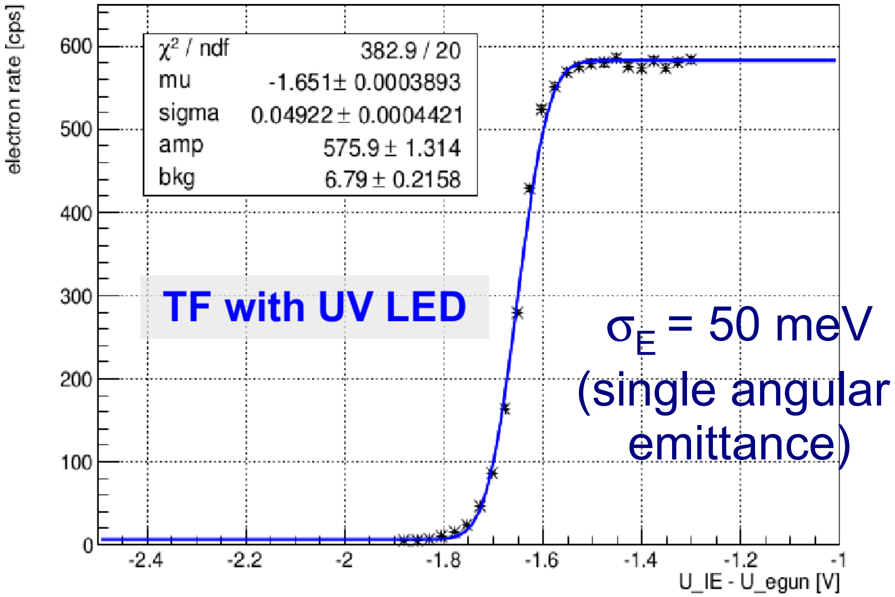
• column density	$5 \cdot 10^{17}$ T_2/cm^2
• luminosity	$1.7 \cdot 10^{11}$ Bq


WGTS at Tritium Laboratory Karlsruhe

Main-Spectrometer



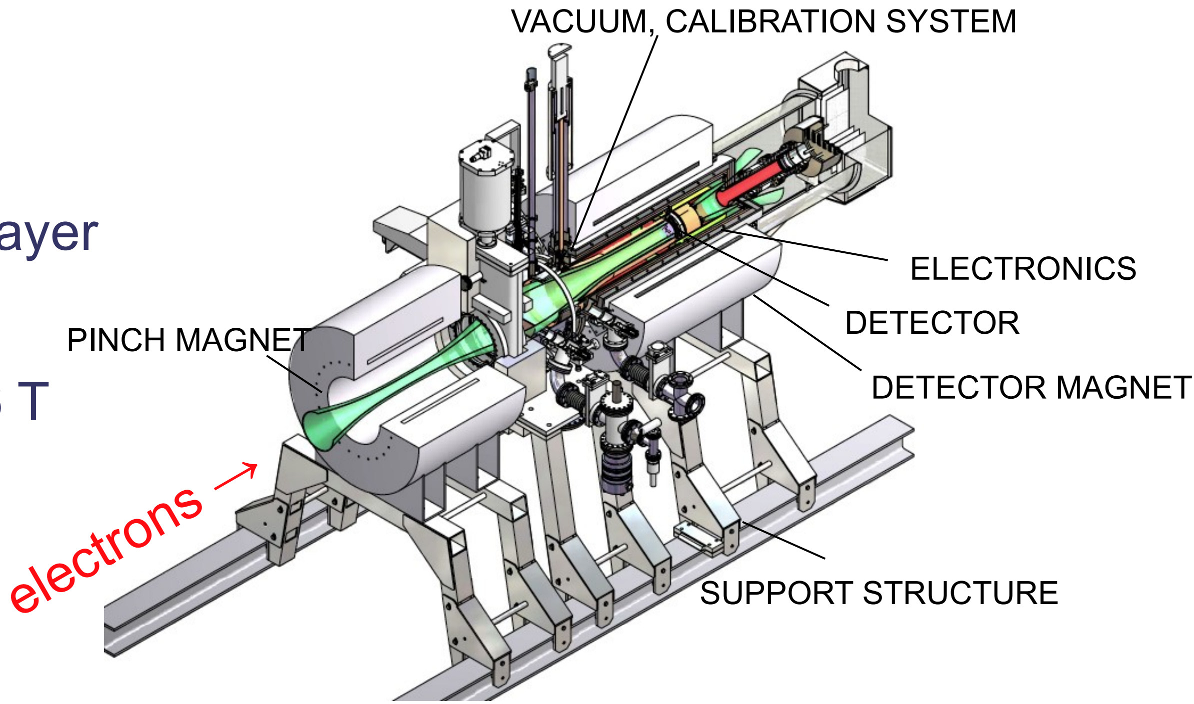
- 18.6 kV retardation voltage, σ < 60 meV
- 0.93 eV resolution
- pressure < 10^{-11} mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping



Focal Plane Detector

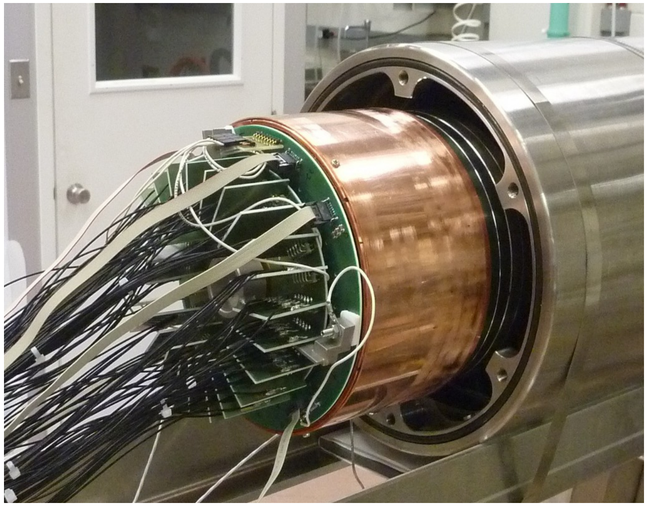
Focal plane detection system

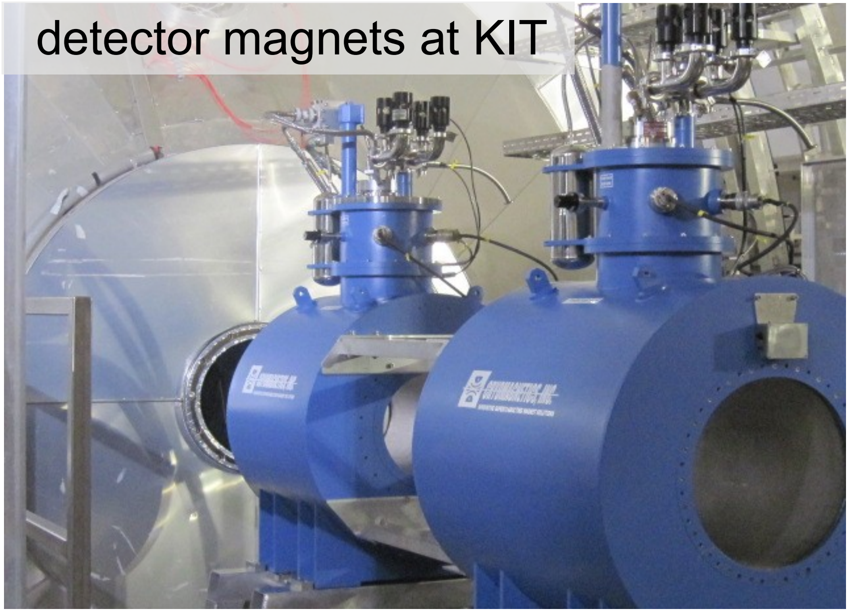
- segmented Si PIN diode:
  90 mm Ø, 148 pixels, 50 nm dead layer
- energy resolution ≈ 1 keV
- pinch and detector magnets up to 6 T
- post acceleration (10kV)
- active veto shield



segmented Si-PIN wafer

pre-amplifier wheel





Project milestones: first light 2016

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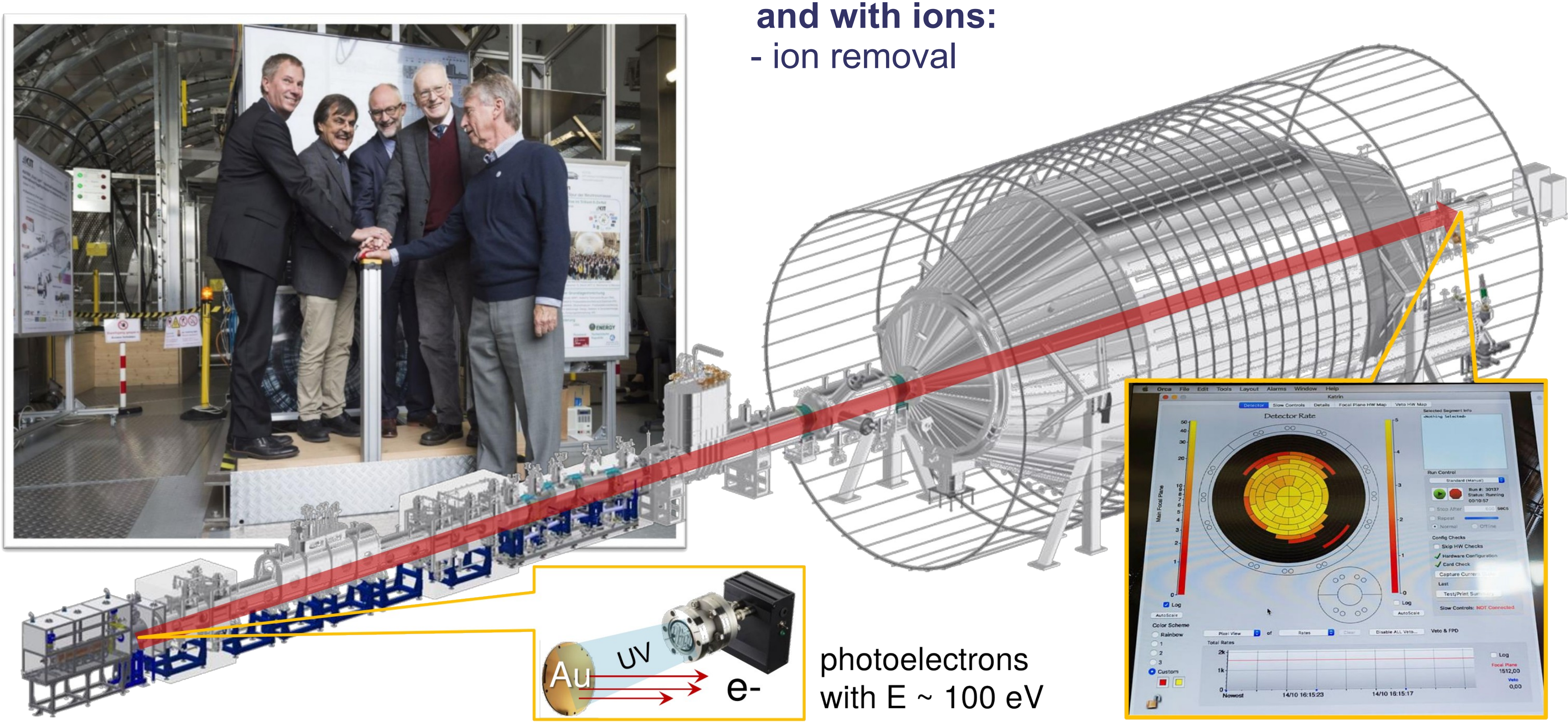
Technical inauguration of KATRIN, October 2016

Testing complete 70m long beamline with electrons:
- alignment
- magn. stearing of pencil beam

and with ions:
- ion removal

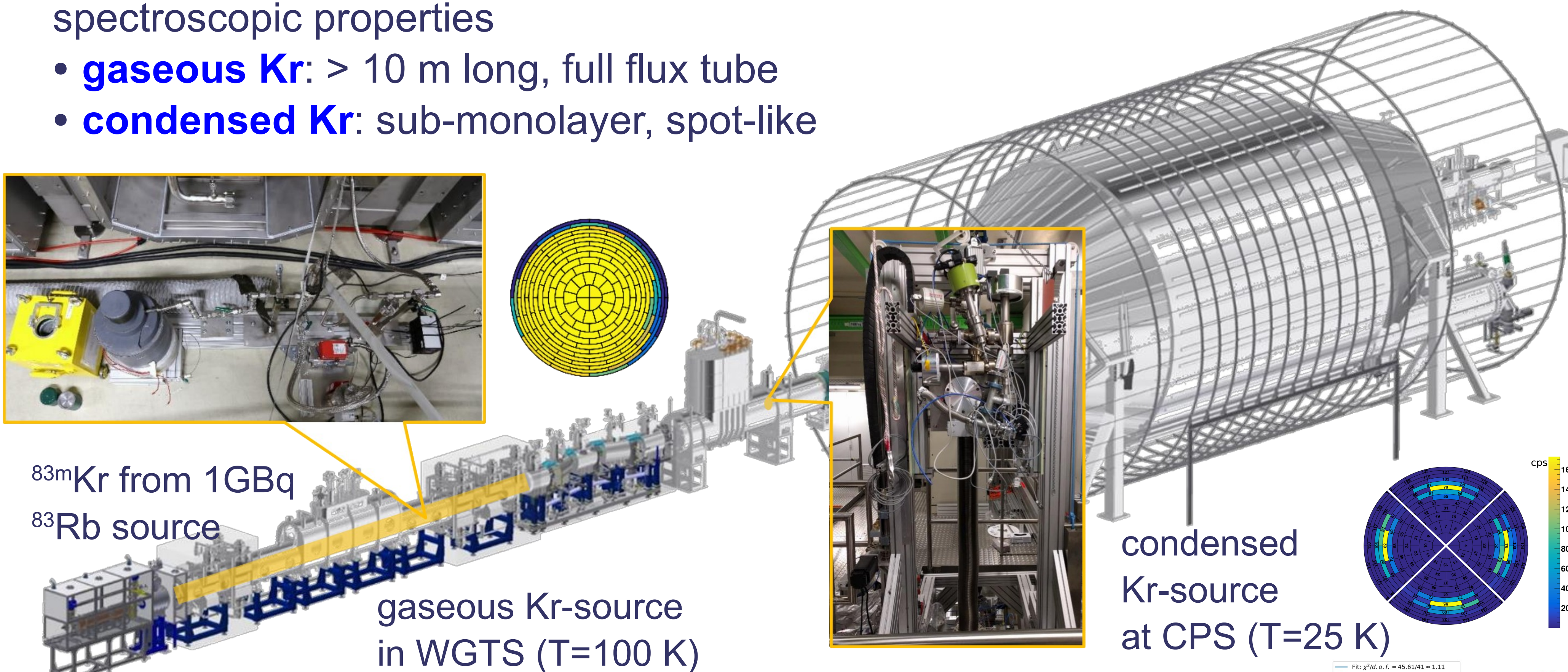


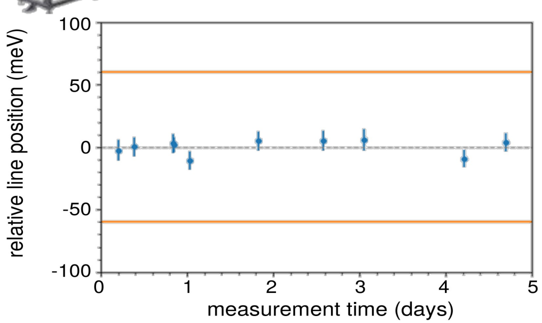
2017: scientific campaign with ^{83m}Kr

KATRIN collab., JINST 13 P04020 (2018)

Use of **monoenergetic conversion electrons from ^{83m}Kr** sources to investigate stability and MAC-E filter spectroscopic properties

- **gaseous Kr**: > 10 m long, full flux tube
- **condensed Kr**: sub-monolayer, spot-like

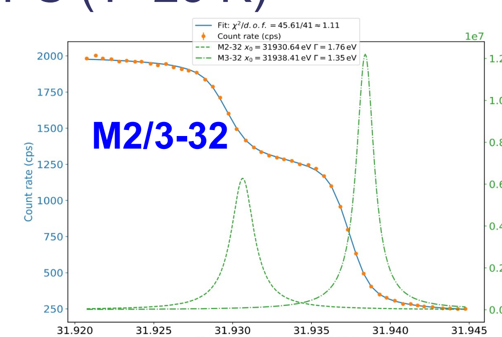




repeated scans of L3-32 line over a week:
required ± 60 meV
GKrS measured
→ excellent long term stability

CKrS line stability with pre-plating

≈ 1meV/h



2018: First tritium campaign

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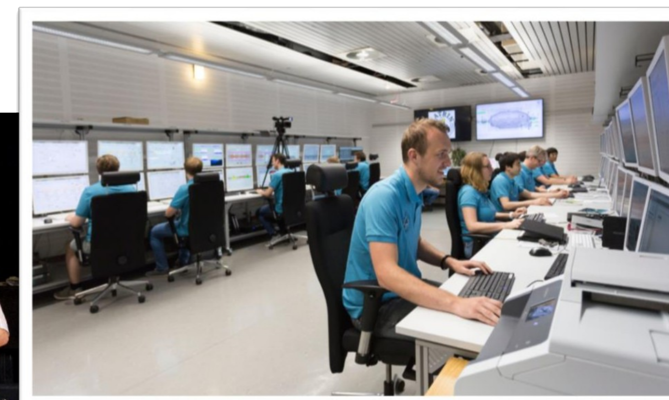
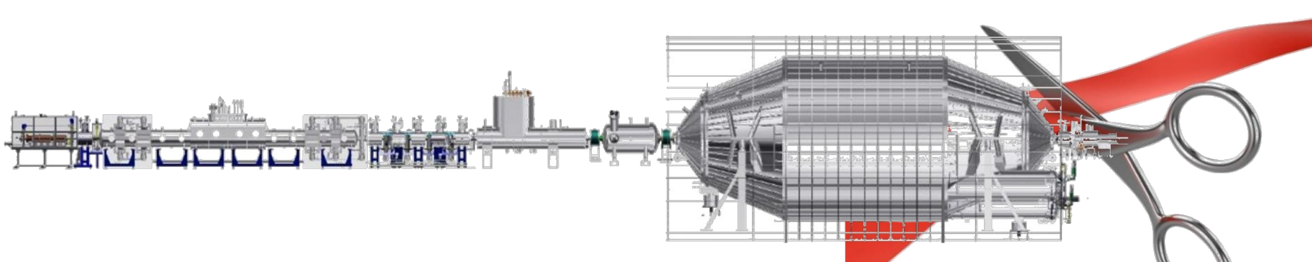
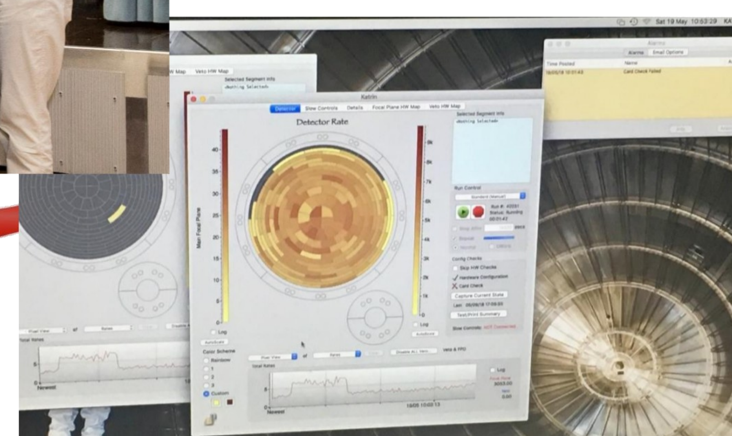
Official KATRIN inauguration: first tritium campaign (engineering run)

Motivation:

- method: inject known gas mix from prepared cylinders (80% of nominal ρd, ~1% DT and ~99% D2 corresponds to <1% of nominal activity ≈ 500 Mbq)
- verify functionality of all system components and demonstrate 0.1% global stability
- study beta spectrum for systematic effects and test analysis strategies

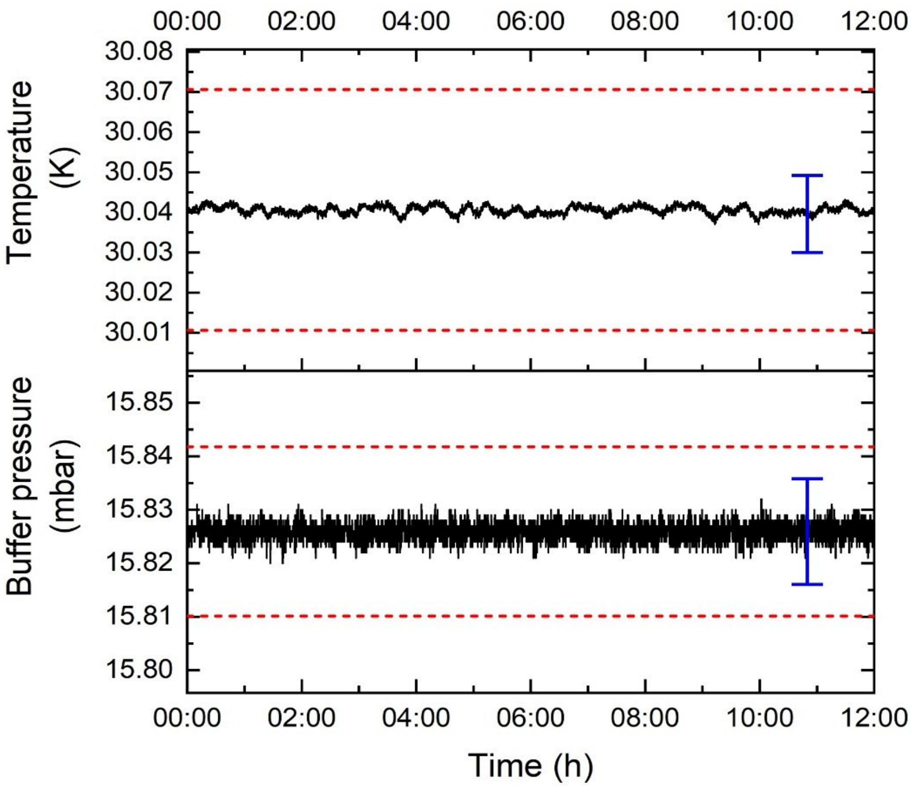


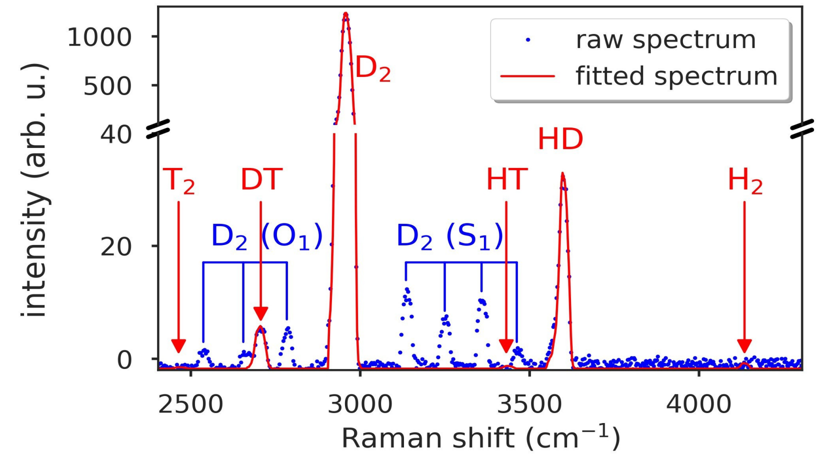


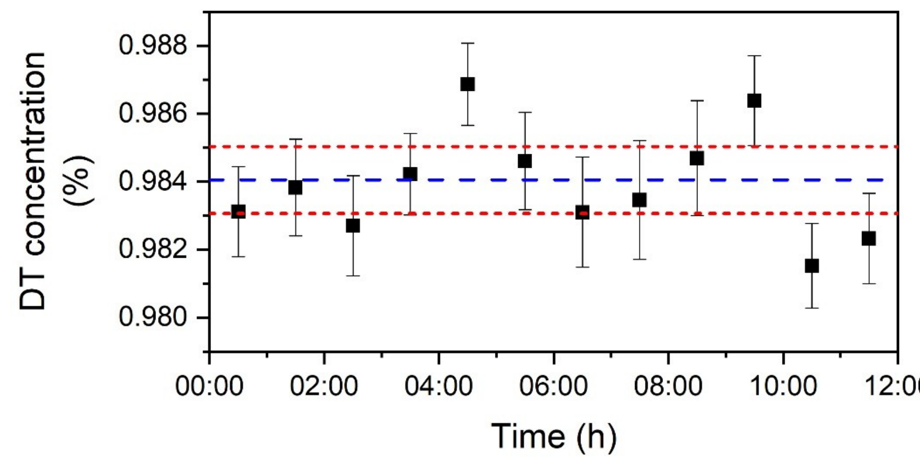


Stability of experimental parameters

Source stability over 12h period







Blue arrow: systematic uncertainty
Red dashed line: ± 0.1 % stability required for neutrino mass taking

Source parameters are stable and within the specifications

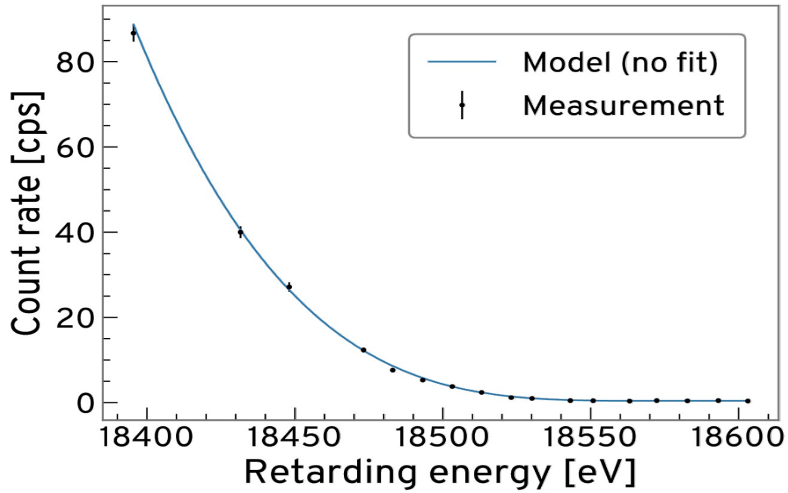
DT concentration measured by laser Raman spectroscopy

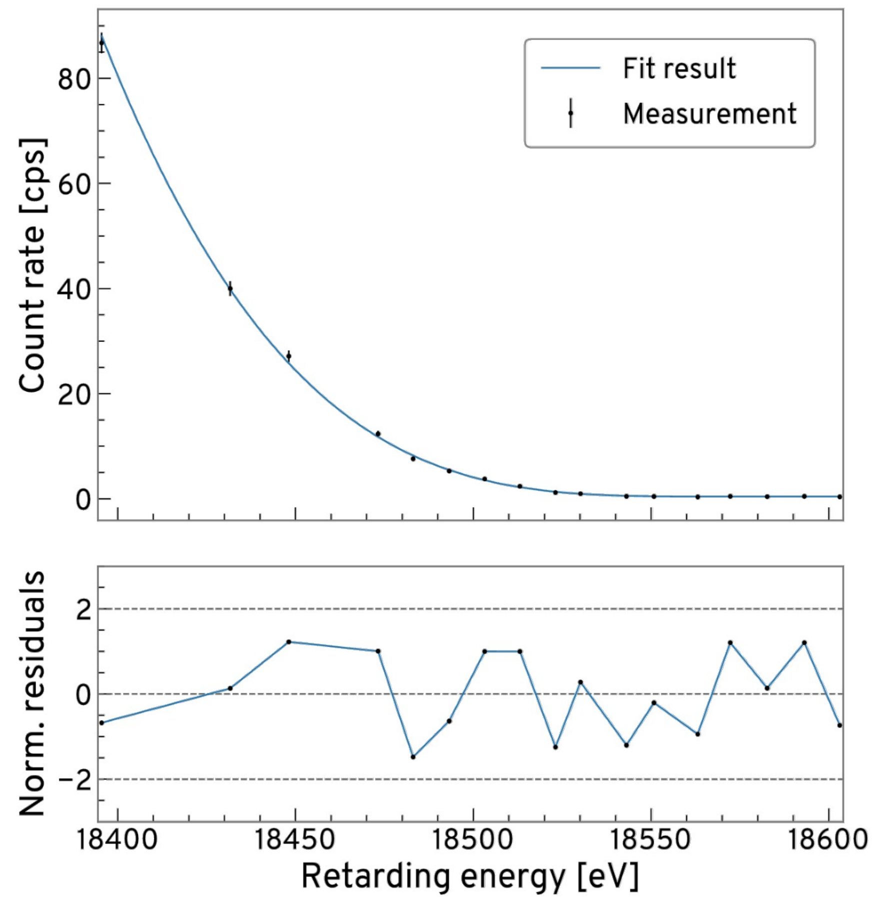
Schlösser et al.,
J. Mol. Spect. 1044 61 (2013)

First tritium: model fits

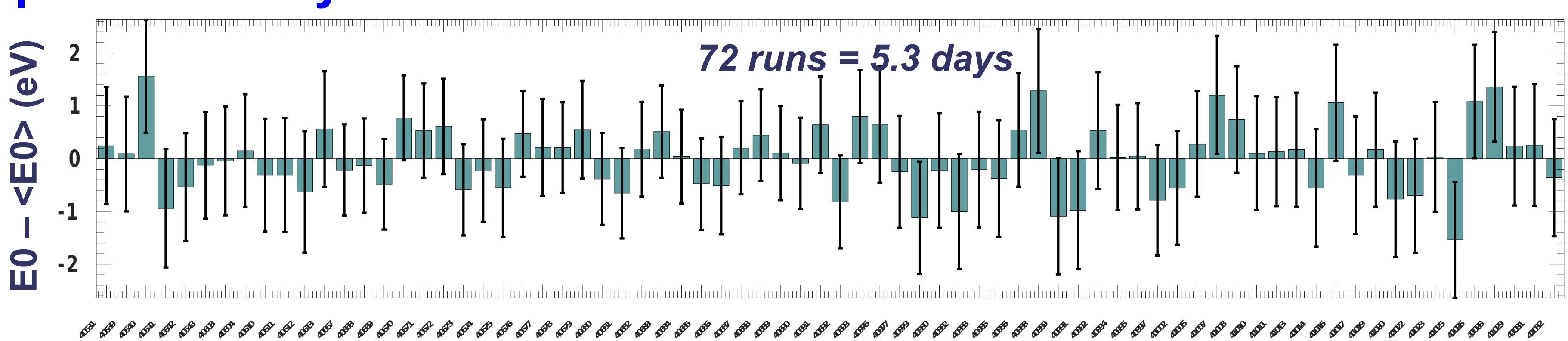
Analysis of first tritium scan (200 eV):

- model gives very good understanding of both rate and shape (even up to 2 keV!!)
- fit (E_0, bckg., Amp.) results agree with expectations





Endpoint stability



KATRIN physics programme

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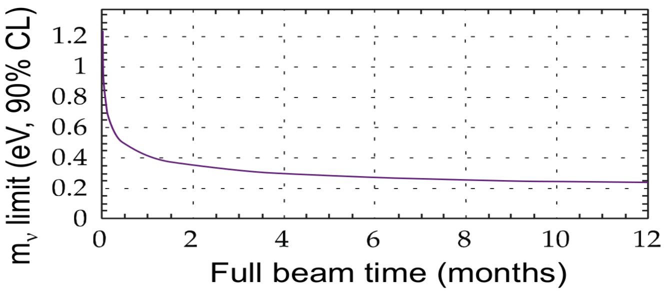
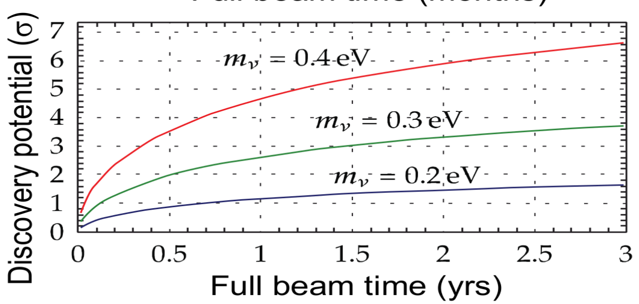
KATRIN physics channels:

- model-independent electron (anti-)neutrino mass: $m(\nu_e)$, sensitivity 0.2 eV @ 90% CL
- search for sterile neutrinos in the eV to keV range
- constrain local relic-ν density, search for Lorentz violations, exotic currents, BSM physics ...

KATRIN $m(\nu_e)$ sensitivity

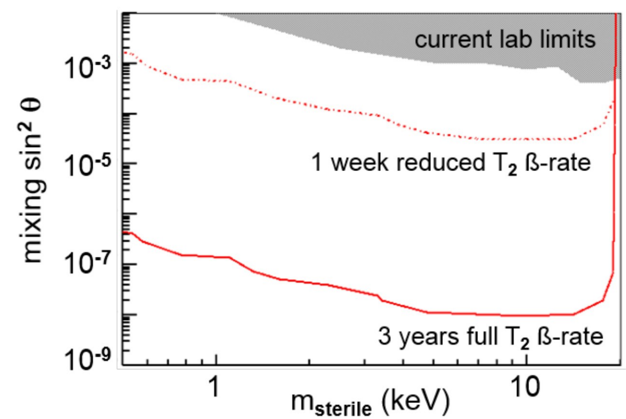




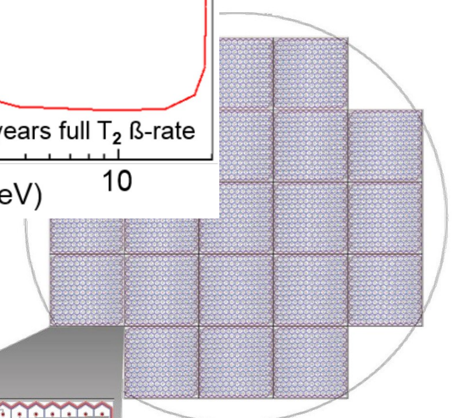
observed increased spectrometer background can largely be mitigated by optimized measure-ment procedure
→ 0.24 eV sensitivity
not the final word ...

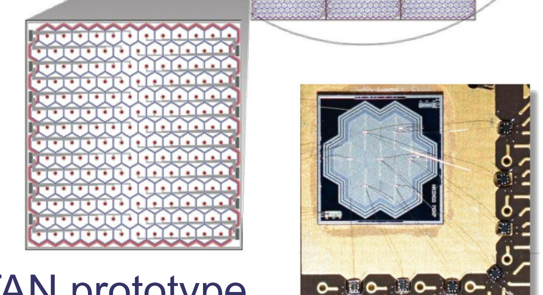
G. Drexlin et al., Adv. High Energy Phys. 2013 (2013) 293986

projected sensitivity to keV scale neutrinos



A. Boyarsky et al., arXiv:1807.07938



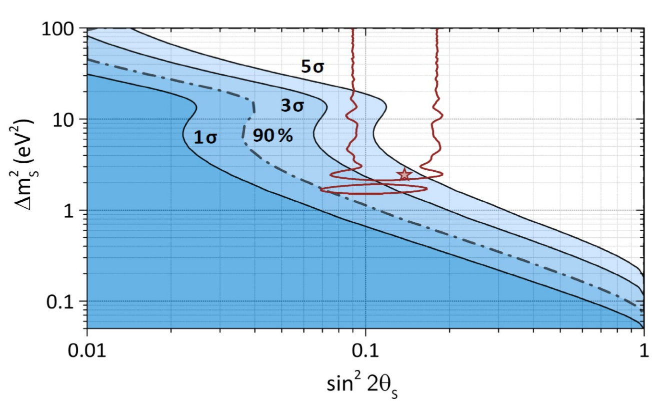


TRISTAN prototype

sensitivity to eV scale neutrinos

Formaggio & Barrett, PL B706 (2011) 68

Riis & Hannestad, JCAP 02 (2011) 011



Summary

- Studies of β-decay kinematics offer a model-independent way to determine the neutrino mass, complementary to cosmology and 0νββ searches
- KATRIN will probe the neutrino mass range down to 0.2 eV
- By default, KATRIN is also sensitive to eV scale sterile neutrinos and, with a future detector upgrade, able to probe for keV sterile neutrinos
- First tritium measurements with reduced activity in June 2018
- Tritium data taking with full source strength beginning 2019

KATRIN Karlsruhe Tritium Neutrino Experiment

supported by Bundesministerium für Bildung und Forschung

Thank you for your attention !


LN2 baffle installed in main spectrometer pump port

Systematic effects and error budget

1. Inelastic scattering of ß´s in the source (WGTS)
   - calibration measurements with e-gun necessary
   - deconvolution of electron energy loss function

2. Fluctuations of WGTS column density (required < 0.1%)
   - rear wall detector, Laser - Raman spectroscopy, T=30K stabilization, e-gun measurements

3. Transmission function
   - spatially resolved e-gun measurements

4. WGTS charging due to decay ions (MC: ϕ < 20mV)
   - Injection of low energy (meV) electrons from the rear end, diagnostic tools available

5. Final state distribution
   - reliable quantum chem. calculations

6. HV stability of retarding potential on 3ppm level required
   - precise HV-Divider (PTB), monitor spectrometer, calibration sources

fluctuations σ^2 lead to a downward shift in m_ν^2

$$\Delta m_\nu^2 = -2\sigma^2$$

allow only few contributions with $\Delta m_\nu^2 \leq 0.007\ eV^2$

$\Leftrightarrow$ $\sigma < 60$ meV

$$\frac{\Delta U}{U} = \frac{0.06}{18575} \approx 3 \cdot 10^{-6}$$

$\Rightarrow$ 3 ppm long term stability

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KATRIN sensitivity:
5 year measurement
(eff. 3 y of data)

statistical uncertainty σ_{stat} **≈ 0.018 eV²**

systematic uncertainty $\sigma_{sys,tot}$ **≈ 0.017 eV²**

→ sensitivity for upper limit: **0.2 eV/c²** (90% C.L.)
$m(\nu_e)$ = 0.35 eV observable with 5σ

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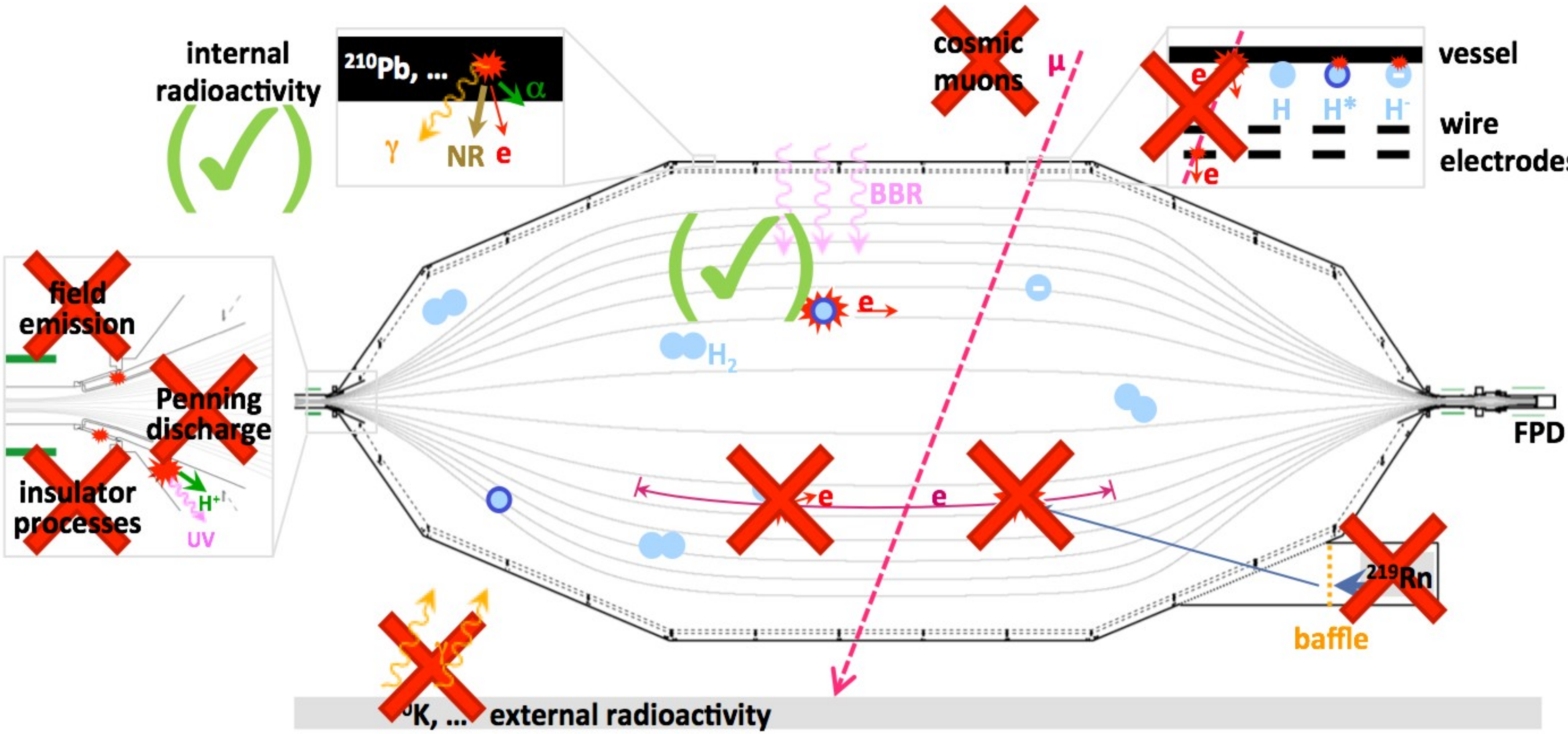
⇒ 3 ppm long term stability

KATRIN background studies



- **8 sources of background investigated and understood**
- **7 out of 8 avoided or actively eliminated by**
  - fine-shaping of special electrodes
  - symmetric magnetic fields
  - LN_2-cooled baffles (cold traps)
  - wire electrode grids

- **1 out of 8 remaining:** caused by ^{210}Pb on spectrometer walls (neutral H* atoms ionised by black-body radiation in spectrometer)

H* Rydberg atoms:

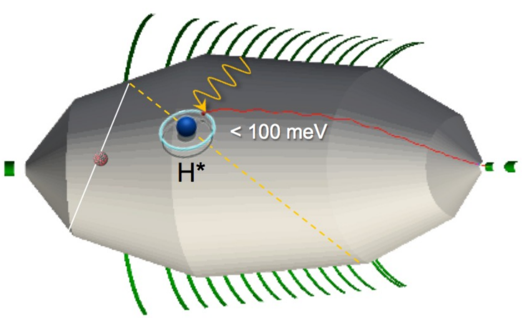
- desorbed from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- non-trapped electrons on meV-scale
- bg-rate: ~0.5 cps

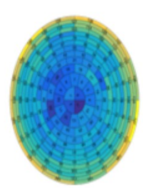
counter measures:

- reduce H-atom surface coverage:
  a) extended bake-out phase: done
  b) strong UV illumination source

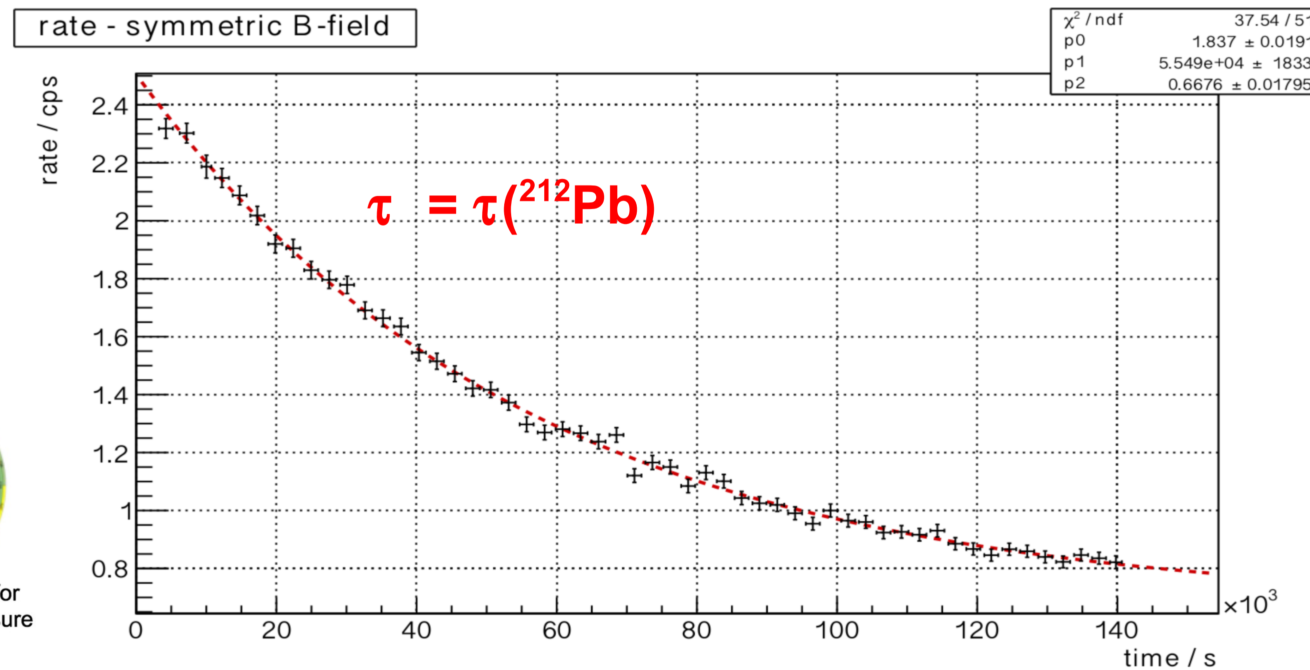
Testing this hypothesis:

artifically contaminating the spectrometer with implanted short-living daughters of ^{220}Rn





isotropic bg for longer exposure



Mitigation strategies for higher (Rydberg) background rate:

use larger data range (E_0-60 eV), an optimized magnetic field setting (lower energy resolution, but smaller flux-tube volume) and a different measurement time distribution

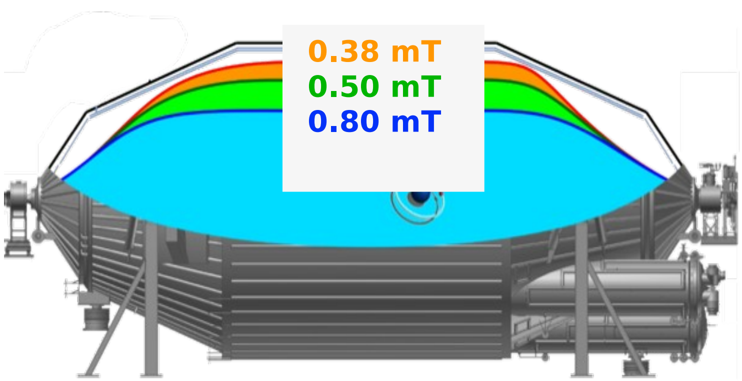
→ 240 meV (without further background reduction)

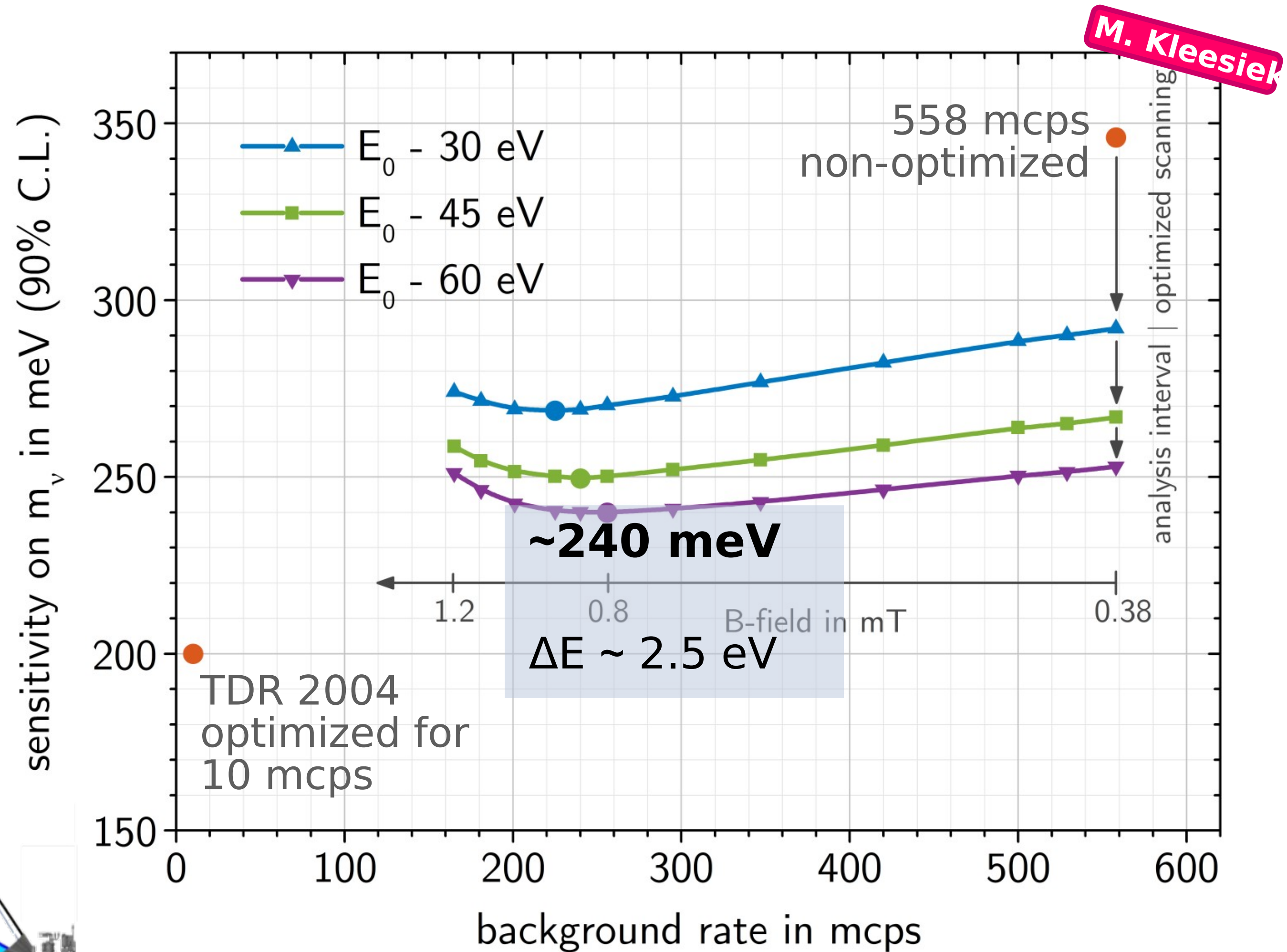
KATRIN background & sensitivity

Problem: current background level much higher than design value

Mitigation strategy:

- optimized measurement time distribution
- enlarged energy range of spectral analysis
- flux tube compression by increasing B_{min}





What about sterile neutrinos ?

WWU MÜNSTER

- Reactor anomaly: ca. 6% deficit in observed neutrino flux measured close to nearly 20 nuclear power stations *(Mention et al., Phys.Rev.D83:073006,2011)*
  → could be a hint to the existence of so-called **sterile** neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e\ \mathrm{sterile}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu\ \mathrm{sterile}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau\ \mathrm{sterile}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_{\mathrm{sterile}} \end{pmatrix}$$

- Sterile neutrinos: only interact gravitationally, produced by mixing with standard (active) neutrino species
- 3+1 scenario: consider only one large mass splitting between lower (L) and upper (U) mass regime: $\Delta m^2_S \approx \bar{m}^2_U - \bar{m}^2_L$
  → best fit from combined data of reactor flux measurements, GALLEX and SAGE calibration data and MiniBooNE:

$$|\Delta m^2_S| > 1.5\ \mathrm{eV}^2, \quad \sin^2(2\theta_S) = 0.14 \pm 0.08$$

Sterile neutrinos as warm dark matter

- ΛCDM (Cold Dark Matter with cosmological constant) models predict too much structure at galactic scales (too many satellite galaxies)

CDM (100 GeV)

non-thermal WDM (1keV)

thermal WDM (1keV)

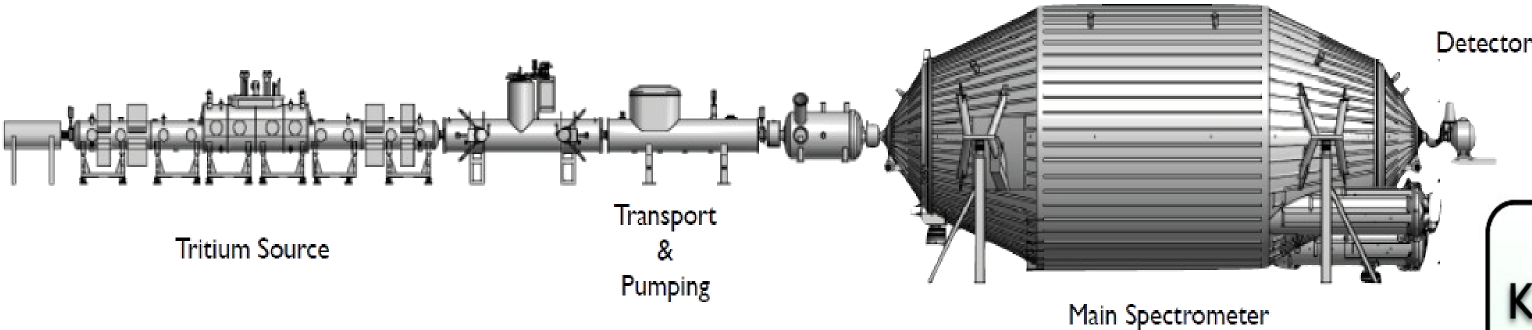
(e.g. A. Kamada at Meudon Workshop 2011)

→ Warm Dark Matter (e.g. keV sterile neutrinos) could resolve this problem

- In KATRIN: look for a kink a few keV below the endpoint of the β - spectrum
- **But:** Systematic uncertainties due to
  - ○ Electronic excitation of daughter molecules
  - ○ Inelastic scattering of decay electrons in the source

→ careful investigation required to see if we have a chance for detection

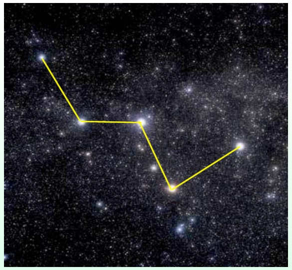
Monte Carlo framework KASSIOPEIA



Particle Generation (KPAGE, SSC)	Transport (KTRACK)	Field Calculation (KAFCA, KEMField, KNAXS)	Detection (KESS, KDES)

- KATRIN requires precise numerical simulations of all experiment components to minimize systematic uncertainties
- many software packages have been written for the individual subsystems
  → need a coherent framework to unify these efforts
  → development of a global simulation package: **KASSIOPEIA**
- tailored to the special needs of the KATRIN experiment:
  - ultra high precision
  - calculation of electromagnetic fields
  - particle generation / tracking / scattering
  - inclusion of a realistic geometrical model of the experiment
  - compatibility with KATRIN database and DAQ

Kassiopeia::



- Core
- PhysicsSim:
  - --KPAGE
  - --KTRACK
  - --KESS
  - --SSC
- --FieldSim
  - --KNAXS
  - --KEMField
  - --KAFCA
- --DAQSim
  - --KDES
- --Geometry
- --Utility
- --User
- -- Verification

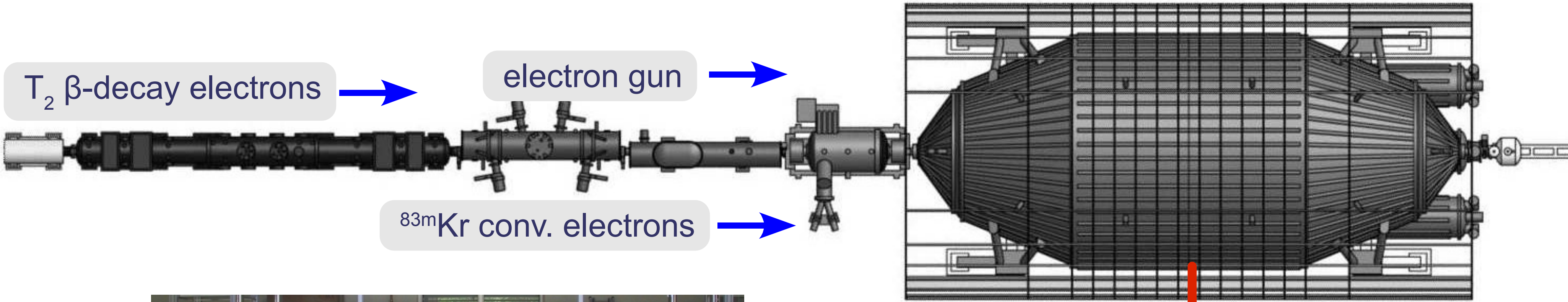
Spectrometer calibration and monitoring

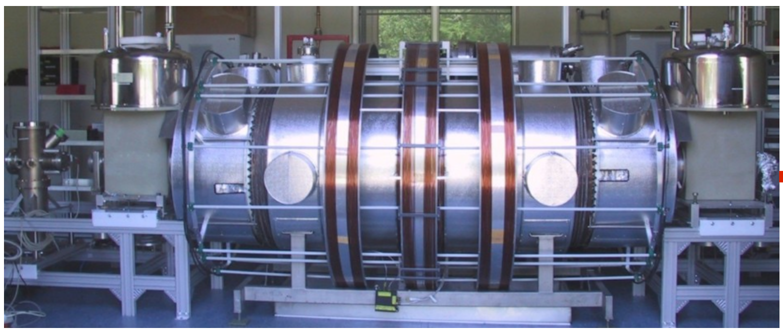
WWU MÜNSTER

T_2 β-decay electrons

electron gun

^{83m}Kr conv. electrons



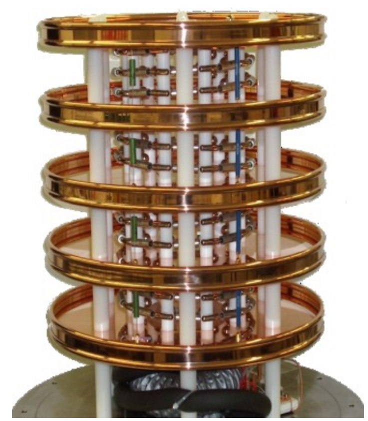


monitor spectrometer

HV-supplies
- up to 35 kV
- 5 ppm/8h

^{83m}Kr conversion electrons
natural standard via 17.8 keV conversion electrons from ^{83m}Kr

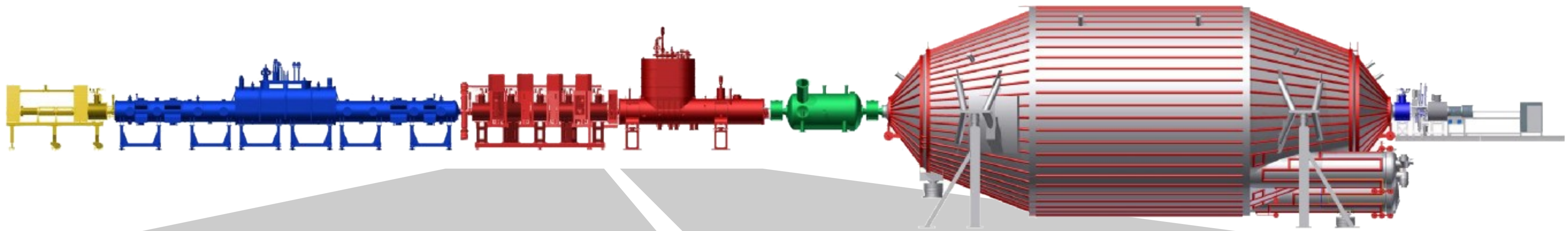
D. Venos, arXiv 0902.0291;
M. Rasulbaev et al.,
Appl. Rad. Iso., 66 (2008) 1838



T. Thümmler et al., New Jour. Phys. 11, 103007 (2009)

precision HV dividers (with PTB)
error budget: $\Delta m^2_U < 0.0075$ eV²/c⁴ → $\sigma_U < 60$ mV @ 18.6 kV

Pumping sections

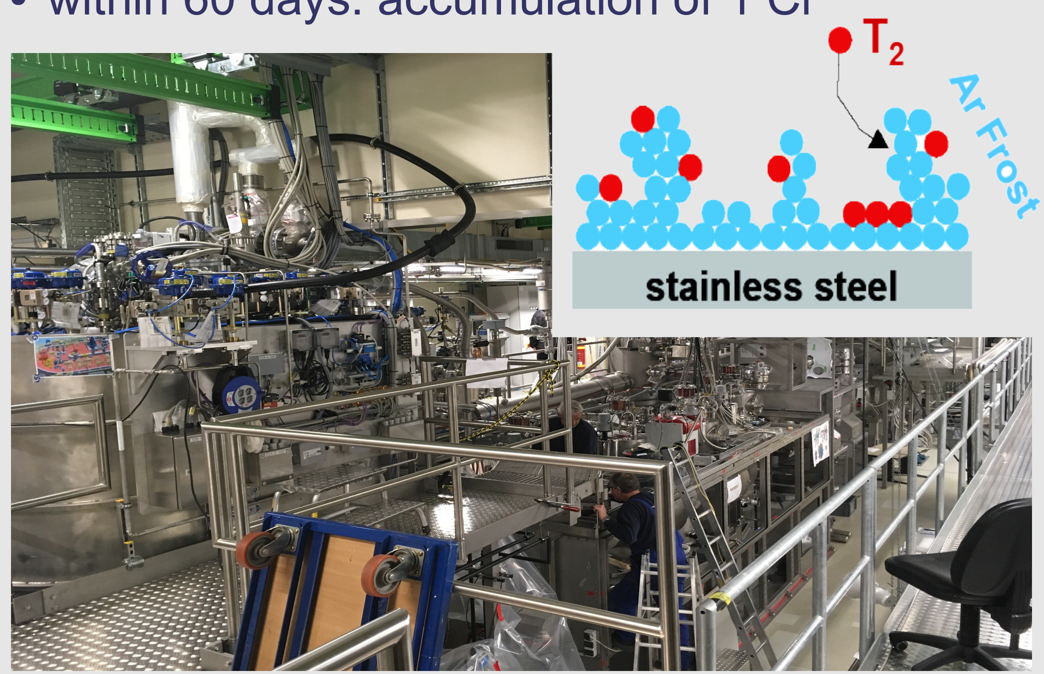


Differential Pumping Section (DPS2-F)

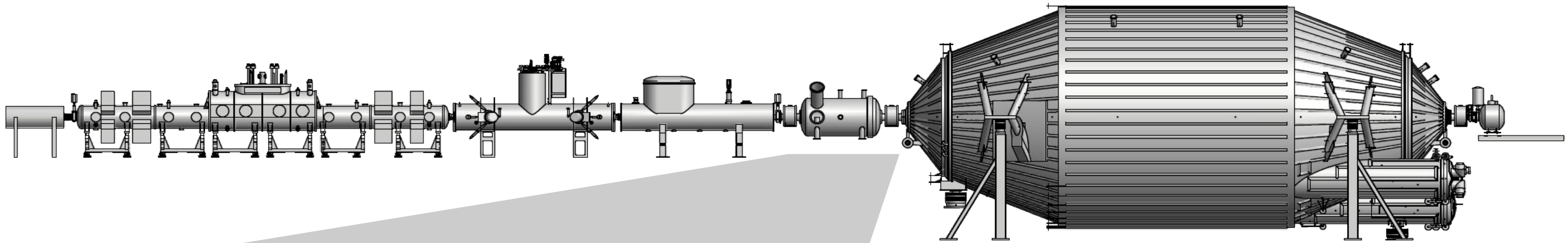
- magnetic guiding field B = 5.6 T
- differential pumping using 2000 l/s TMPs
  → tritium reduction factor: **$1\cdot10^5$**
- ion monitoring by FTICR
- ion manipulation by electrodes

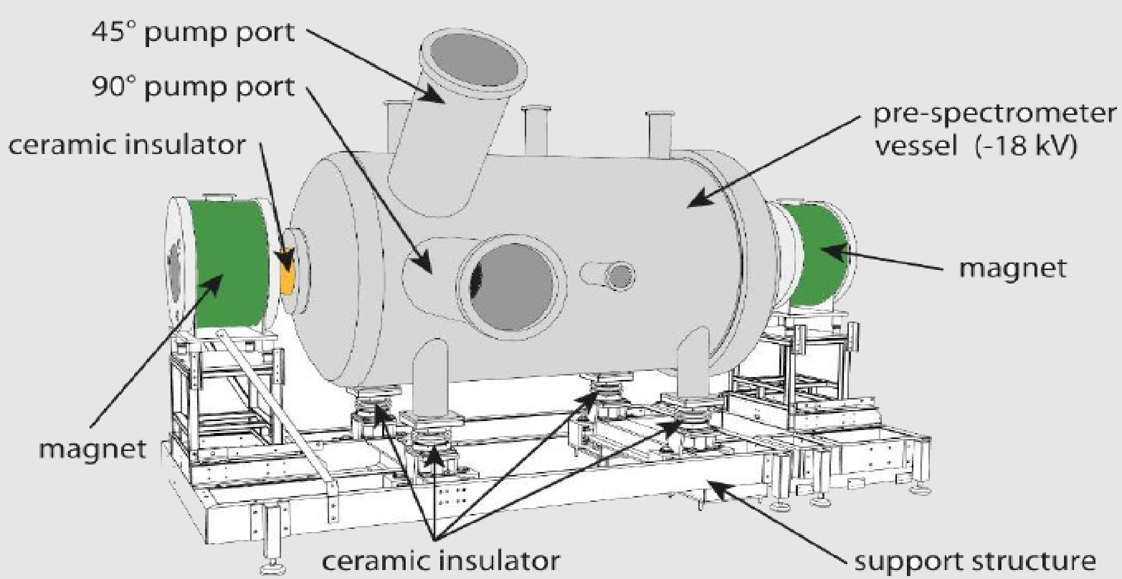
Cryogenic Pumping Section (CPS)

- magnetic guiding field B = 5.6 T
- cryosorption of T_2 on Ar frost at ≈ 3 K
  → tritium reduction factor **$1\cdot10^7$**
- within 60 days: accumulation of 1 Ci



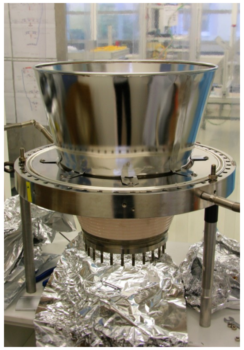
Pre-Spectrometer



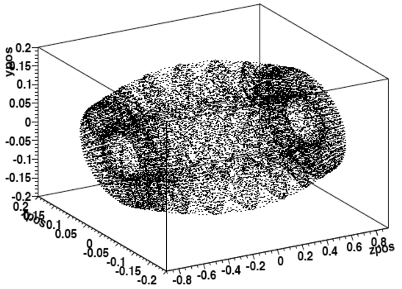


- Pre-filter with a fixed potential: E = 18.3 keV
- Transmission of high energy electrons only
  → reduction from 10^{10} to 10^3 e^-/s
  → reduction of background due to scattering in the main spectrometer

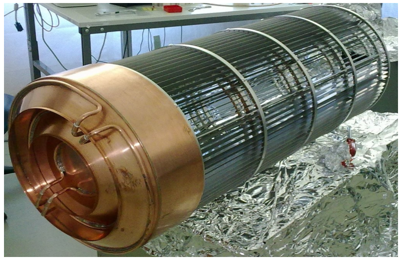
Testing ground for many systematical effects and background sources, e.g.:



- Removal of Penning traps (special electrode shapes)
- Compensation of high frequency HV noise (triode shunt circuit)



- Removal of trapped particles (dipole mode, HF excitation)



- Removal of Radon induced background (LN2 baffle)
- Remaining background ≈ **20 mHz**

Current knowlegde and open questions

What we know (from ν oscillations):

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm^2 values known (with varying accuracies)

What we don't know :

- Normal or inverted hierachy ?
- Dirac or Majorana particle ?
- CP violating phases in mixing matrix ?
- **No information about absolute mass scale !** (only upper limits)
- Existence of sterile neutrinos ?