The direct neutrino mass search with KATRIN

Conference on Neutrino and Nuclear Physics CNNP 2017, October 2017, Catania/Italy

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- Introduction
- The KArlsruhe TRIitium Neutrino experiment KATRIN
- Commissioning data
- Neutrino mass sensitivity
- Conclusions

Photo: M. Zacher

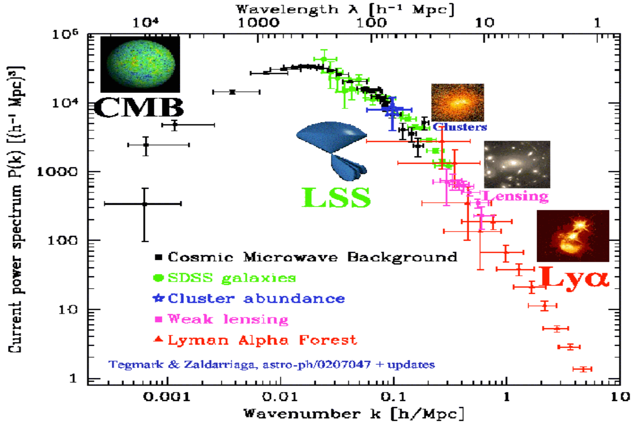
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

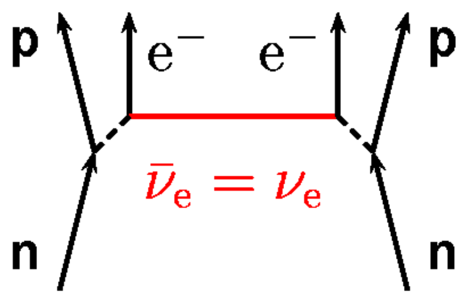
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV



2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

Upper limits by EXO-200, KamLAND-Zen, GERDA, CUORE



3) Direct neutrino mass determination:

No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly

Time-of-flight measurements (ν from supernova)

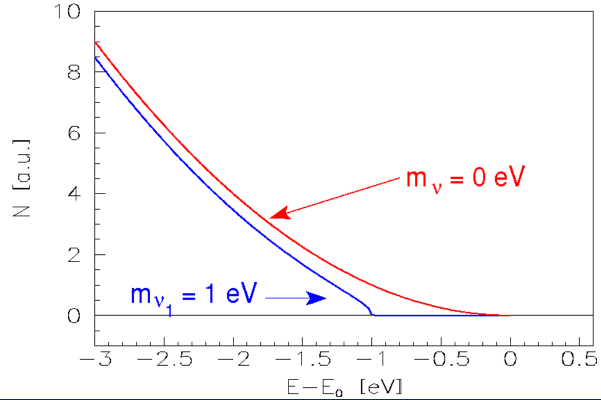
SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV

Kinematics of weak decays / beta decays

measure charged decay prod., E-, p-conservation

β-decay searches for $m(\nu_e)$ - tritium, ^{187}Re β-spectrum

- ^{163}Ho electron capture (EC)



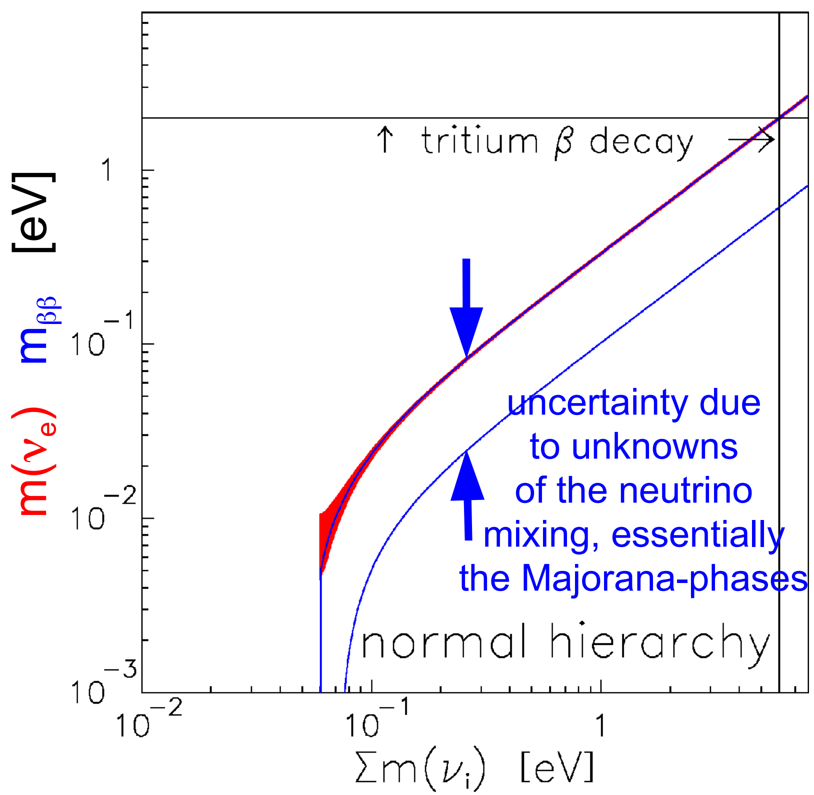
Comparison of the different approaches to the neutrino mass

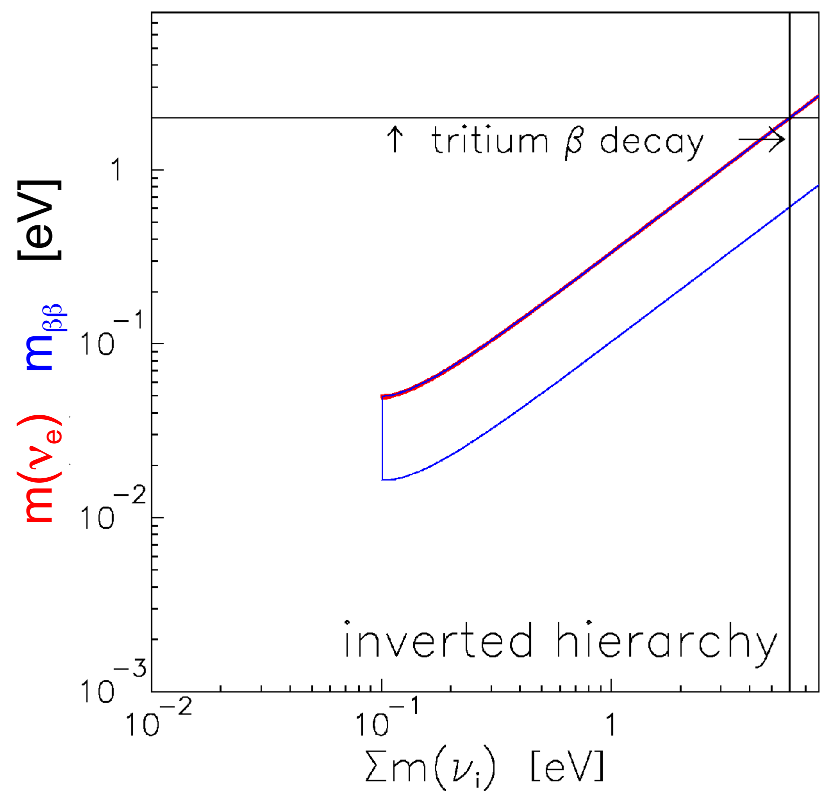
Direct kinematic measurement: $m^2(\nu_e) = \Sigma |U_{ei}{}^2| \, m^2(\nu_i)$ (incoherent)

Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = | \Sigma |U_{ei}{}^2| \, e^{i\alpha(i)} \, m(\nu_i)|$ (coherent)

if no other particle is exchanged (e.g. R-violating SUSY)

without additional uncertainties of nuclear matrix elements M and quenching factor g_A





⇒ absolute scale/cosmological relevant neutrino mass in the lab by single β decay

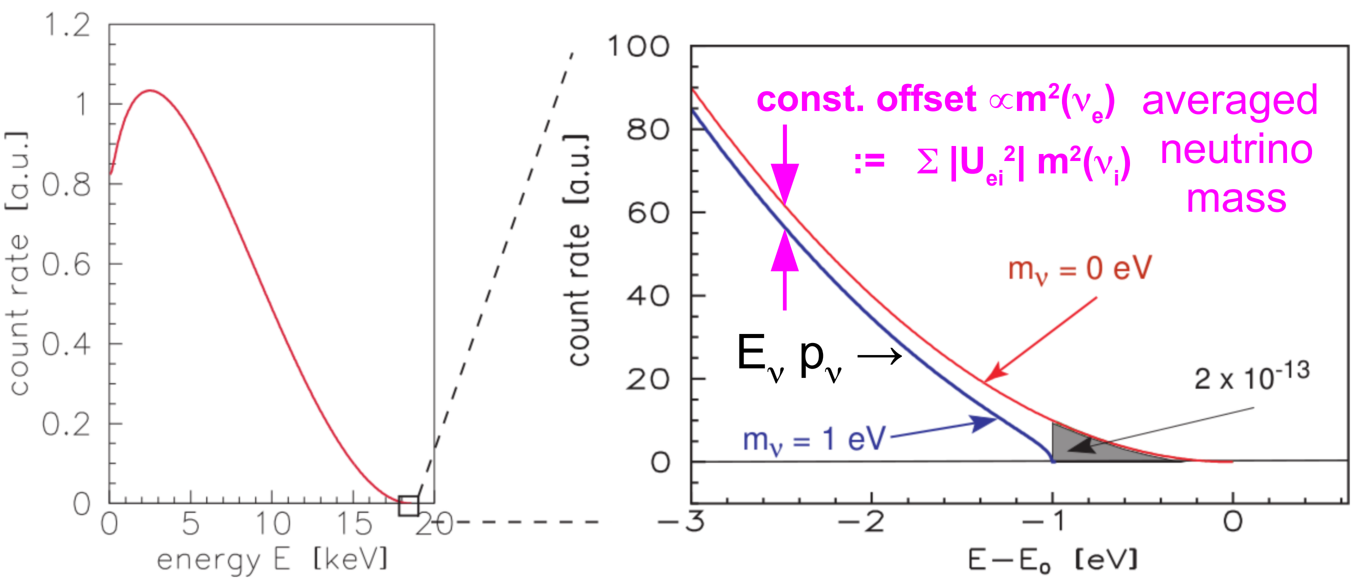
Direct determination of $m(\nu_e)$ from β-decay (and EC)

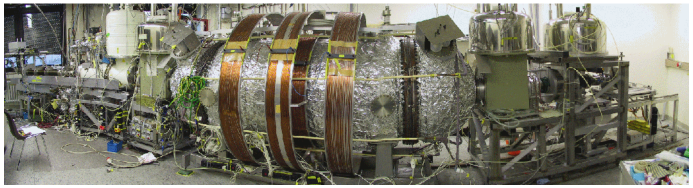
β: $dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0 - E_e)\ \Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$

essentially phase space: p_e (p), E_e (E_{tot}), E_ν (E_0-E_e), p_ν ($\Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$)

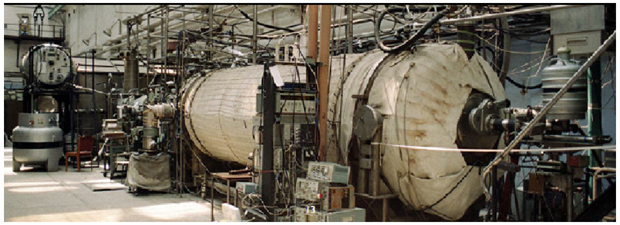
with "electron neutrino mass": $m(\nu_e)^2 := \Sigma |U_{ei}|^2\ m(\nu_i)^2$, complementary to 0νββ & cosmology

(modified by electronic final states, recoil corrections, radiative corrections)



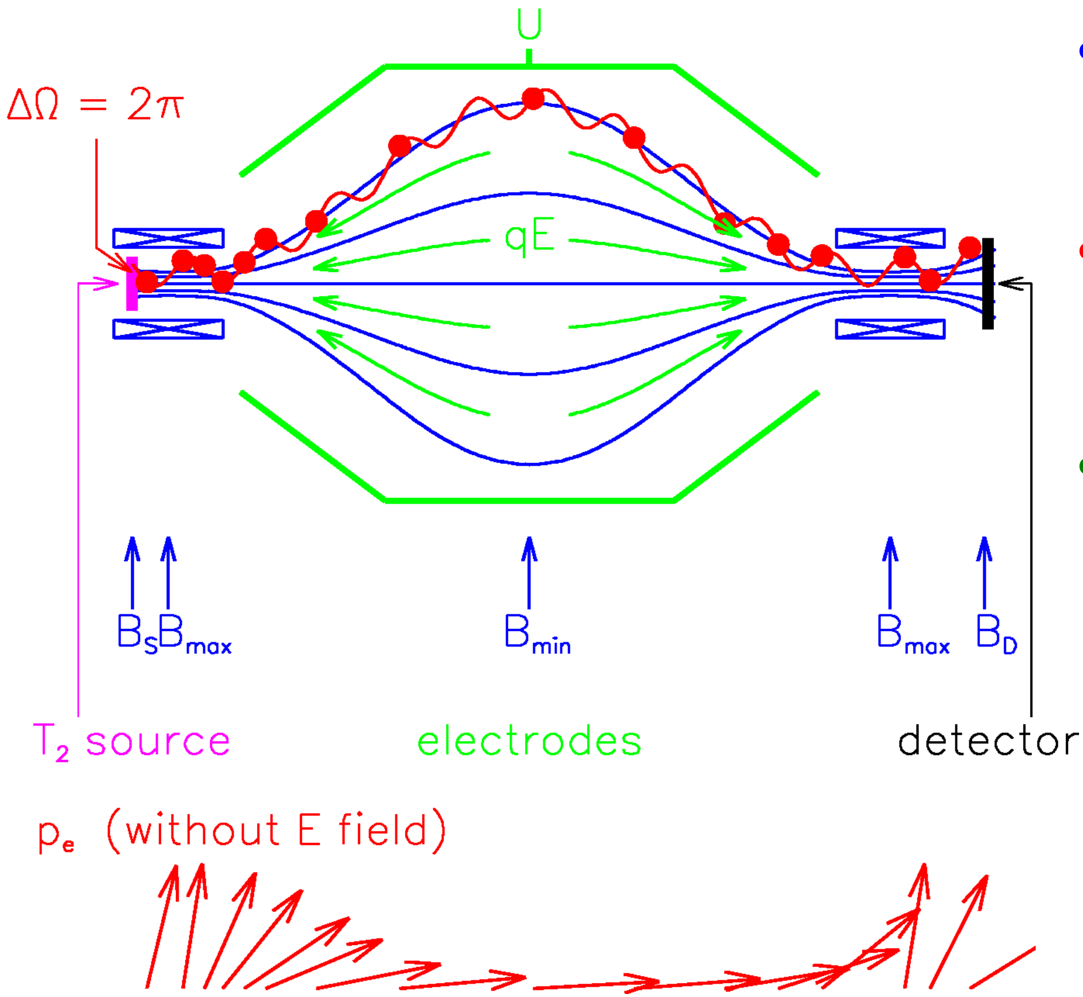


$m(\nu)$ < 2 eV (Mainz, Troitsk)
ν do not solve DM problem

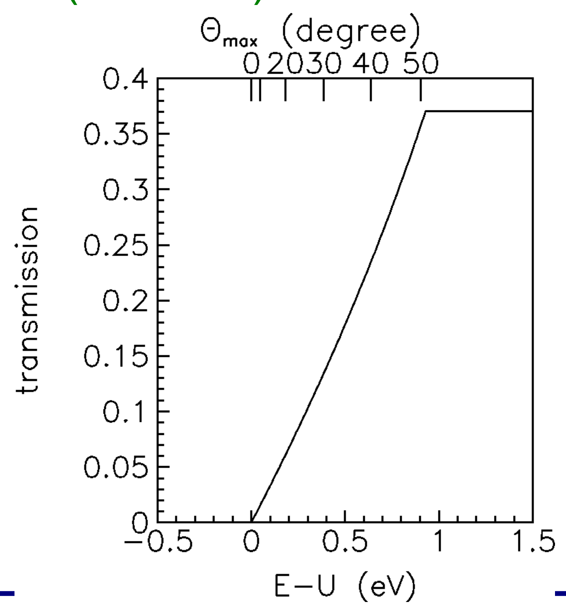


Need:
- low endpoint energy ⇒ Tritium ^3H (^{187}Re, ^{163}Ho)
- very high energy resolution & very high luminosity & very low background ⇒ MAC-E-Filter (or bolometer for ^{187}Re, ^{163}Ho)

The classical way: Tritium β-spectroscopy with a MAC-E-Filter



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



⇒ sharp integrating transmission function without tails →

Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

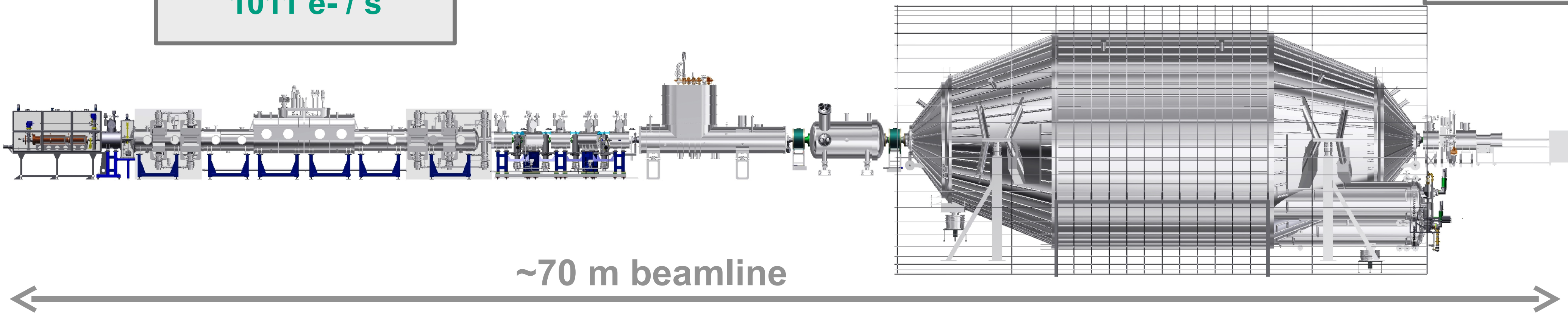
The KATRIN experiment

windowless gaseous T2 source
1011 e- / s

tritium pumping & e- transport

MAC-E type spectrometer
10 m diameter, 24 m length

electron detector
< 1 e- / s



Sensitivity on $m(\nu_e)$:
2 eV → 200 meV

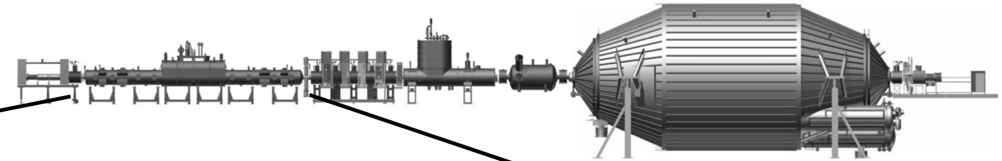
KATRIN at Karlsruhe Institute for Technology
Int. Collaboration: 20 institutions from 6 countries

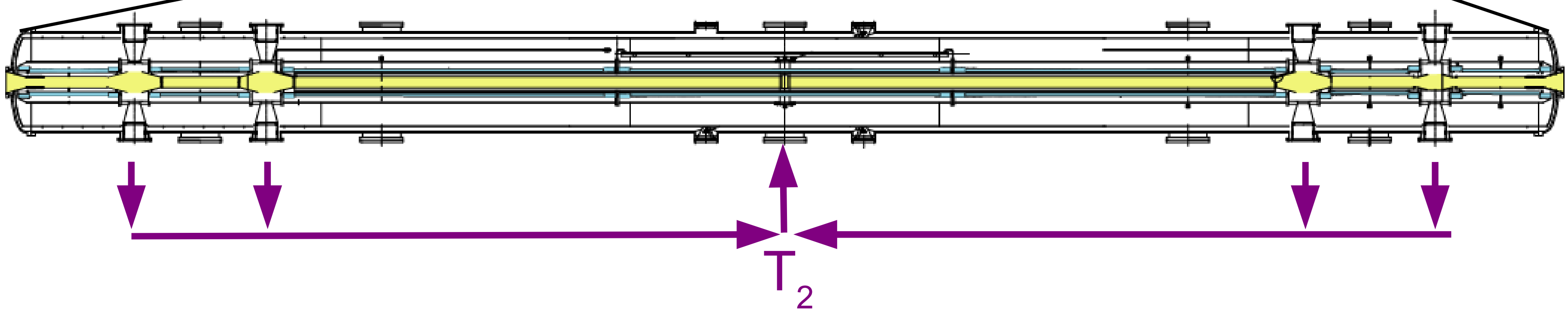
Molecular Windowless Gaseous Tritium Source WGTS

per mill stability source strength request:

$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \, V / R \, T$

tritium fraction f_T & ideal gas law

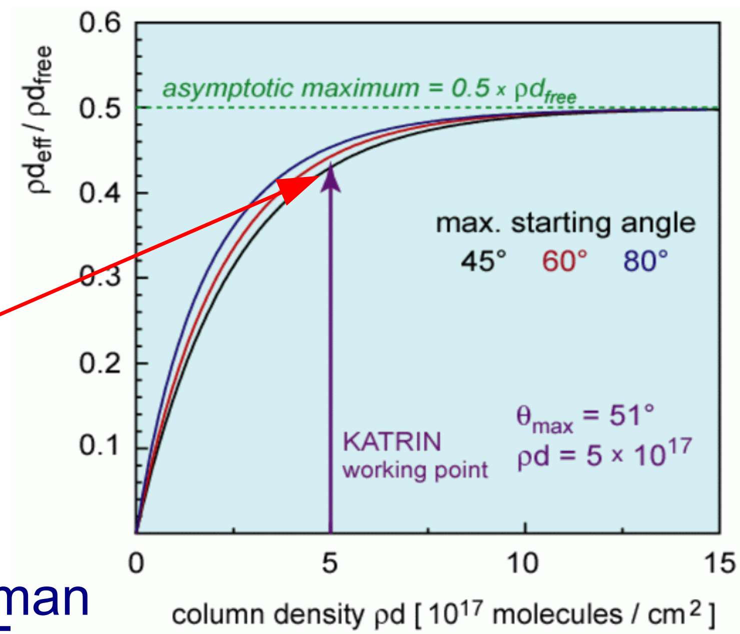




WGTS: tube in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

Tritium recirculation (and purification)
p_{inj} = 0.003 mbar, q_{inj} = 4.7Ci/s

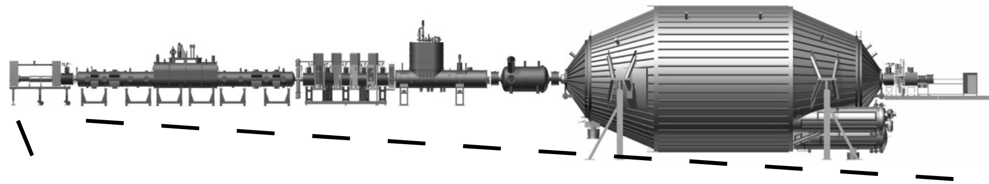
allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics



check column density by e-gun, T_2 purity by laser Raman

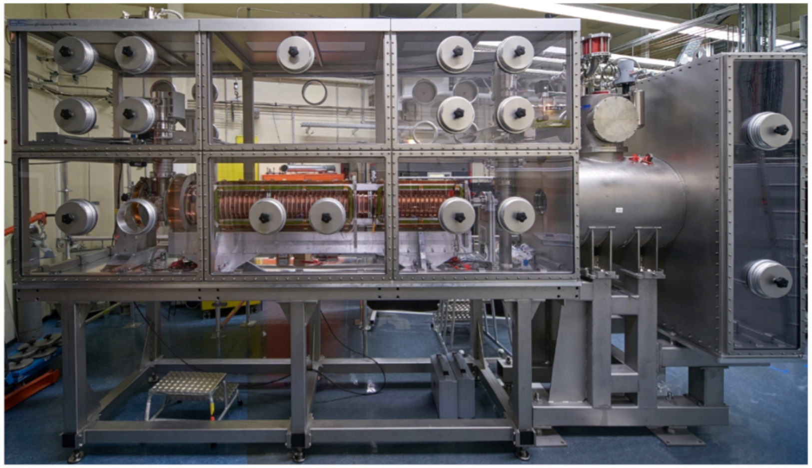
Molecular Windowless Gaseous Tritium Source WGTS

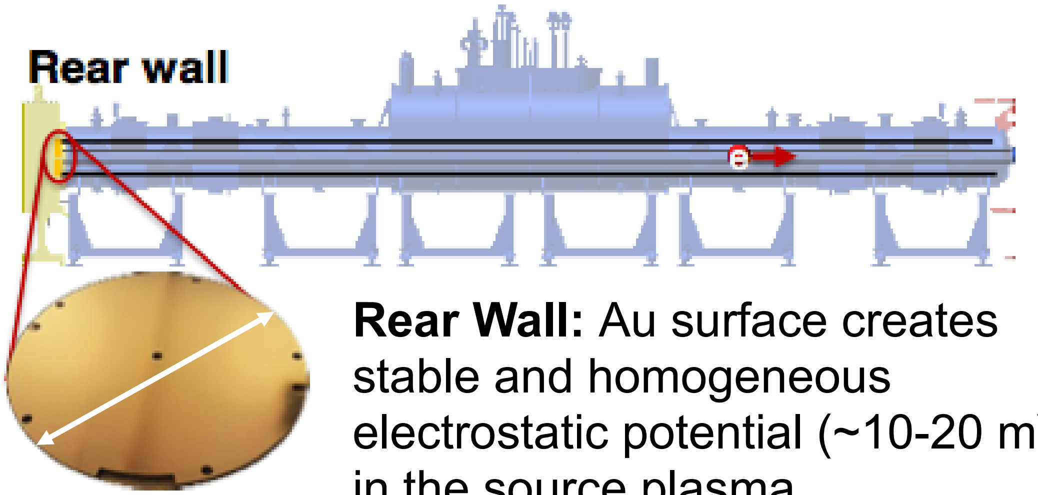
Calibration and monitoring rear system: controling and studying systematics



Essential for diagnostics of tritium source & spectrometer transmission

- **photo-electron gun**:
  spectrometer transmission
  column density & energy losses in source
- **rear wall**: definition of source potential,
  neutralization of tritium plasma



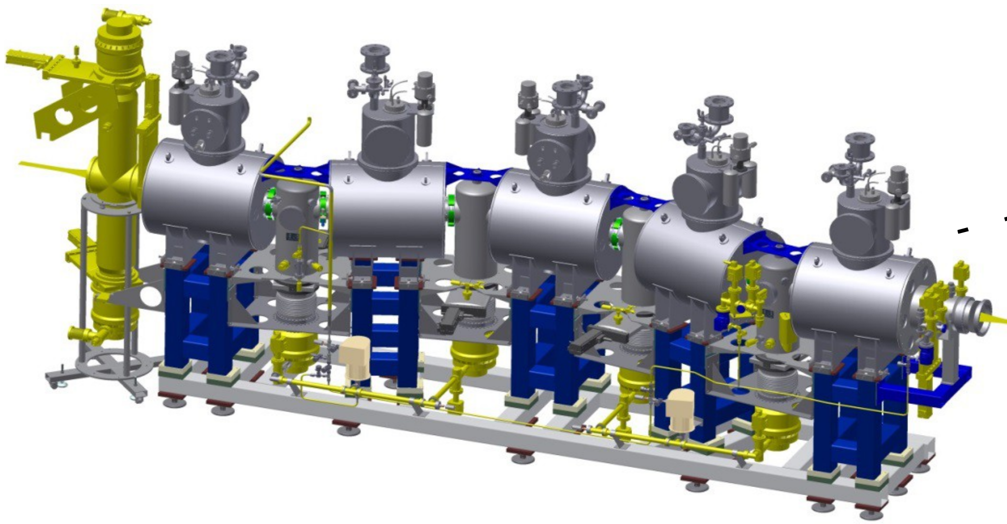


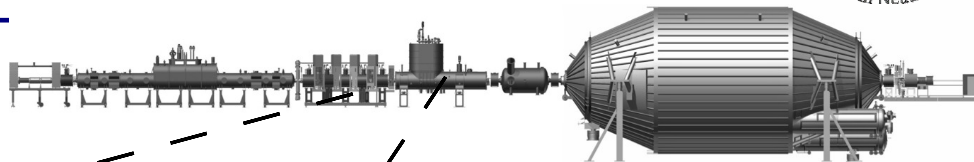
∅ 150 mm

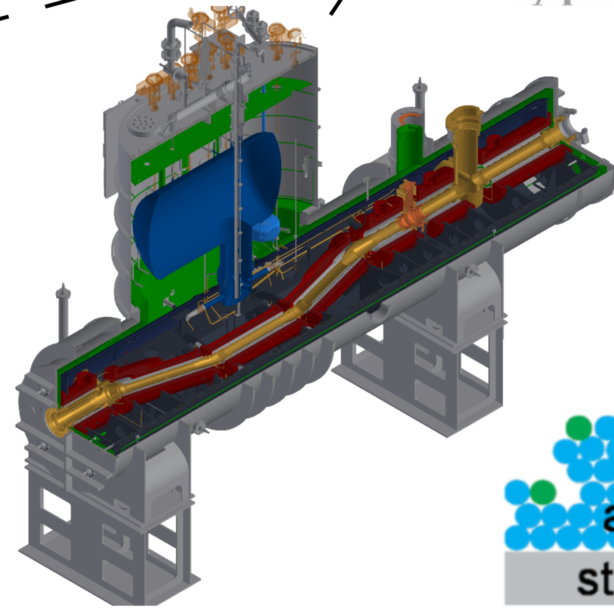
Rear Wall: Au surface creates stable and homogeneous electrostatic potential (~10-20 mV) in the source plasma

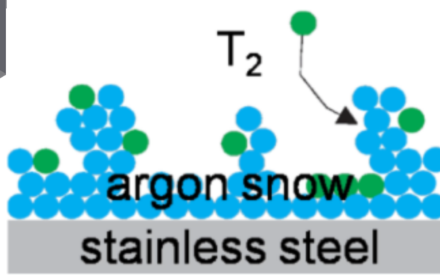
- **X-ray detectors:**
  online monitoring of tritium
  ß-decay activity via X-rays (BIXS)

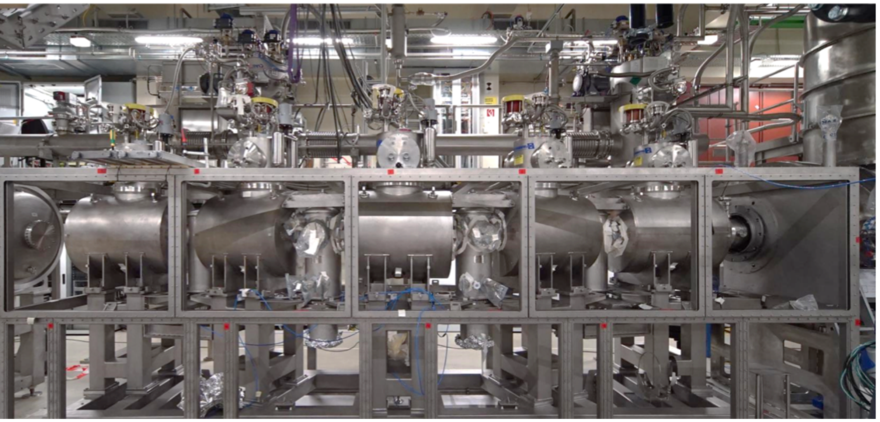
Differential and cryo pumping sections: supression of T_2 by 10^{14} (incl. WGTS)







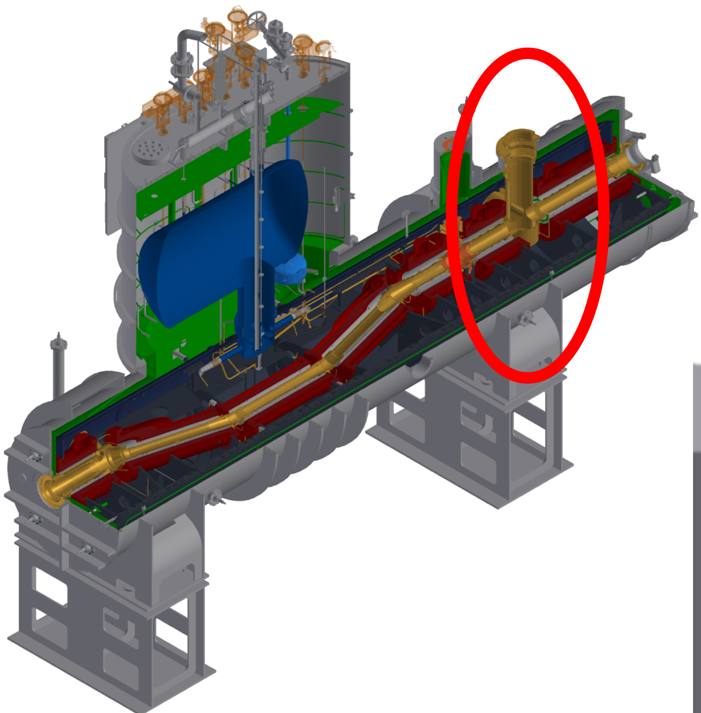




- based on by cryo-sorption at Ar snow at 3-4 K
- Tritium retention: $>10^7$
- magnetic field: 5.6 T

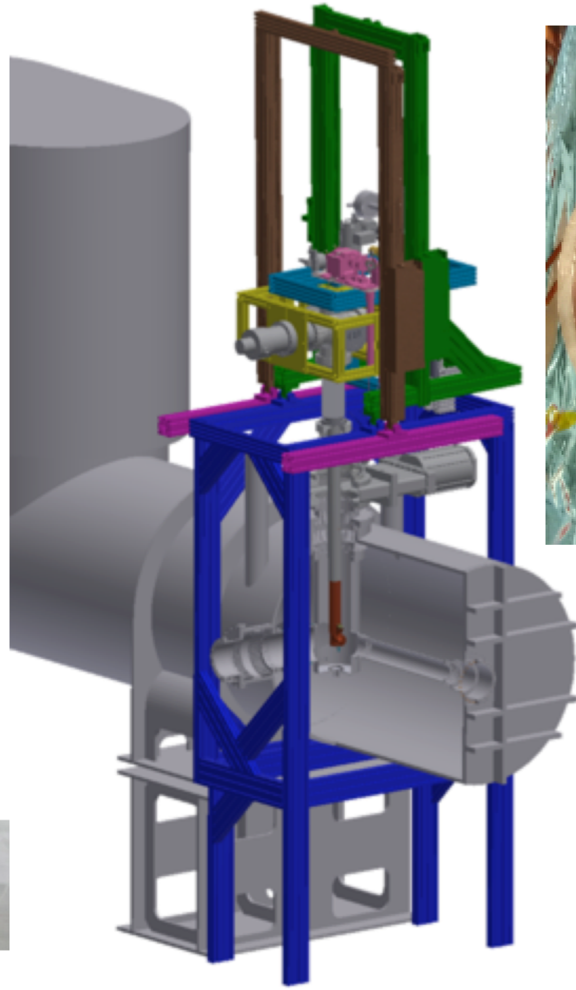
- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- **Ion monitoring by FTICR and ion manipulation by dipole and monopole electrodes inside**

Monitoring and calibration instrumentation of the CPS



Condensed ^{83m}Kr conversion electron source

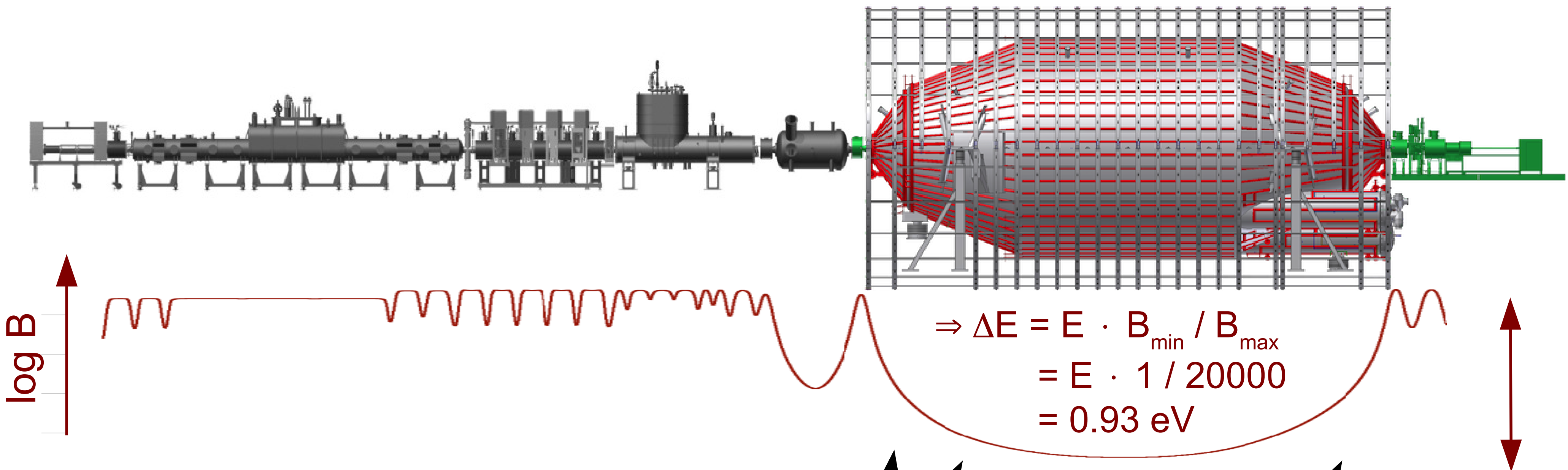
for energy calibration and studies of transmission properties
HOPG @T=25K, UHV, on HV, can scan full flux tube
surface control: heating & laser ablation, laser ellipsometry



Electron rate monitor

scanning small SD or PIN diode

KATRIN spectrometers of MAC-E-Filter type



Pre spectrometer:

- successful tests & developments of new concepts

Main spectrometer:

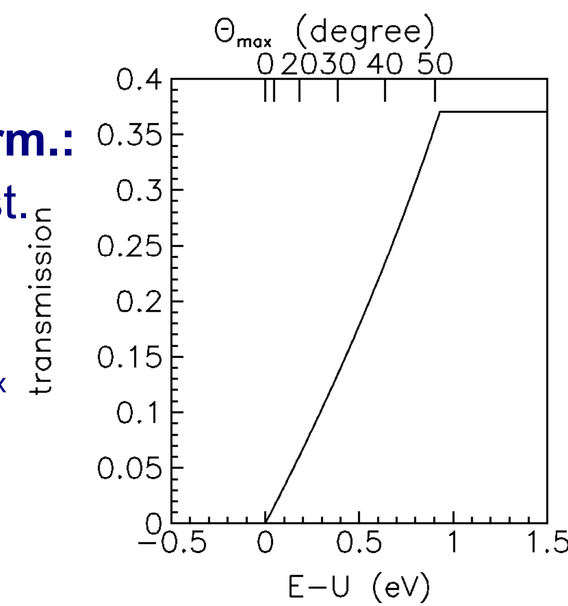
- huge size: 10m diameter, 24m length
  1240 m^3 volume, 690 m^2 inner surface
- ultra-high vacuum: $p = O(10^{-11}$ mbar)
- ultra-high energy resolution: $\Delta E = 0.93$eV
- vacuum vessel on precise high voltage (ppm precision)

adiabatic transform.:

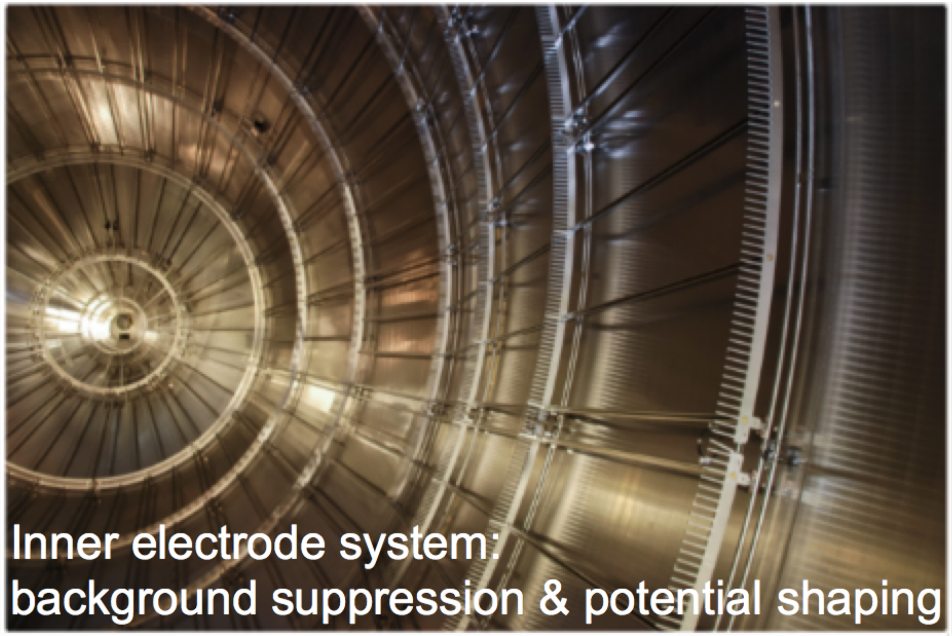
$\mu = E_\perp / B = \text{const.}$

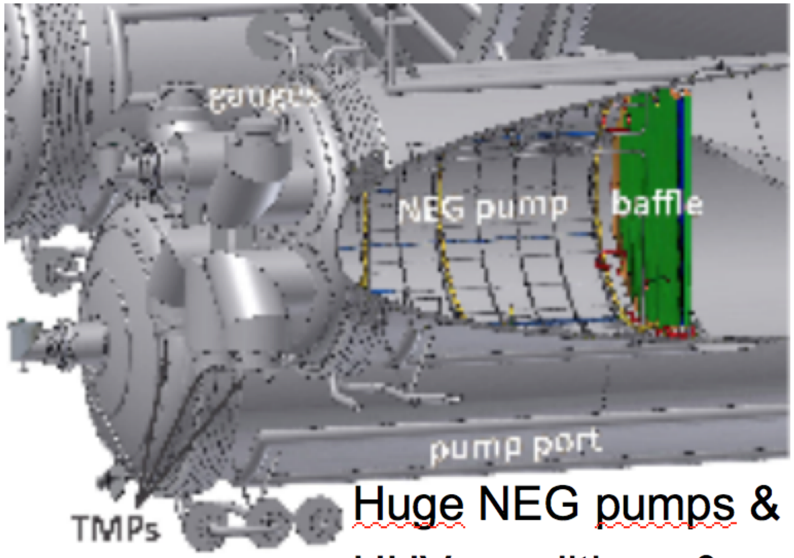
$\Rightarrow$ parallel e^- beam

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

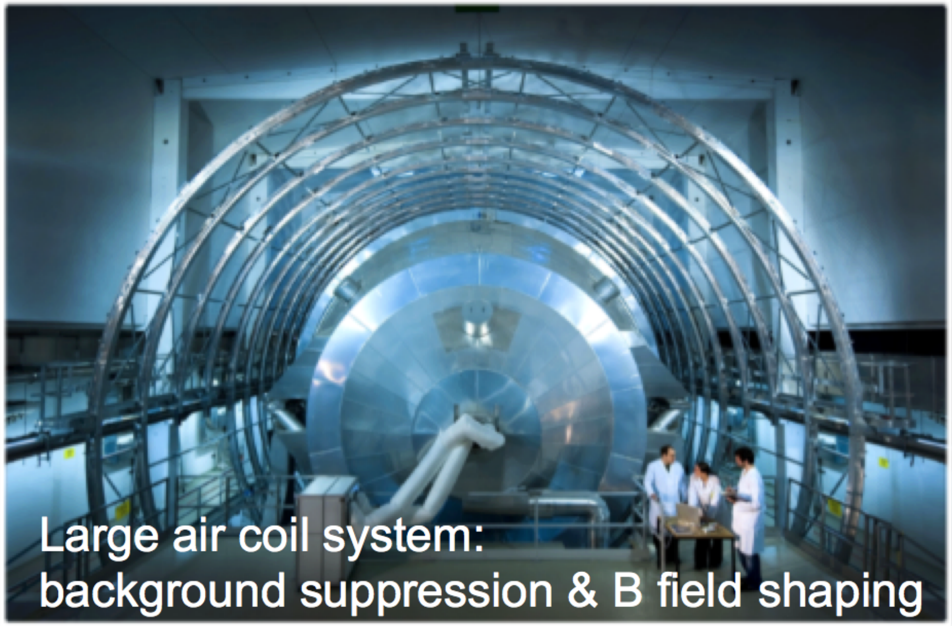


KATRIN main spectrometer





Huge NEG pumps & LN_2 baffles:
UHV conditions & radon trapping



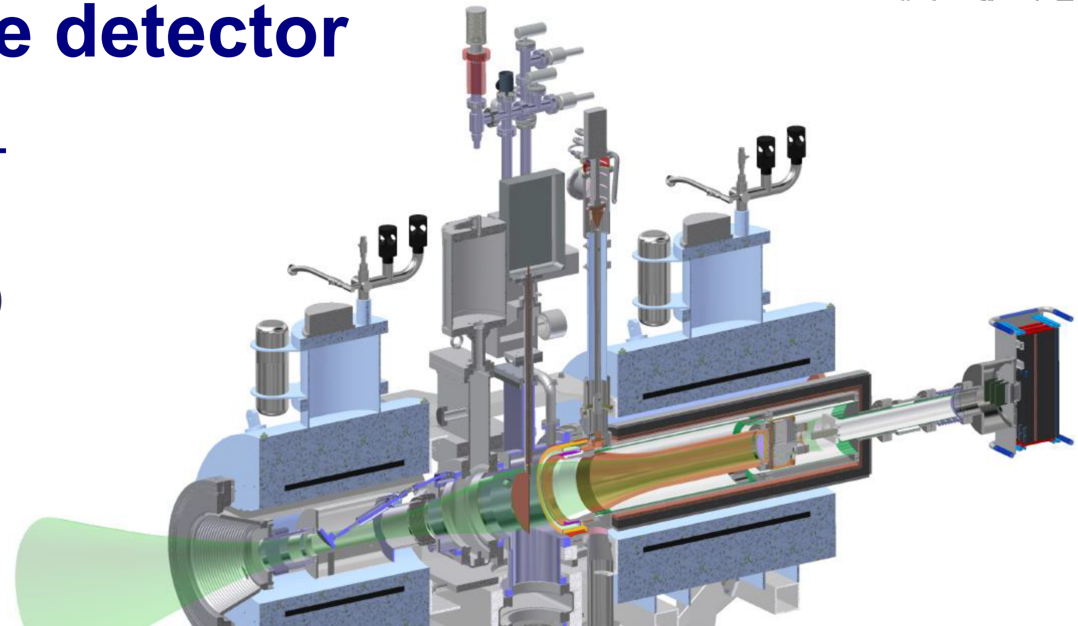
The detector

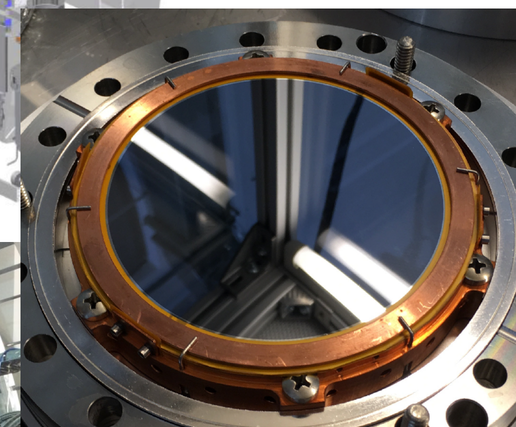
Requirements

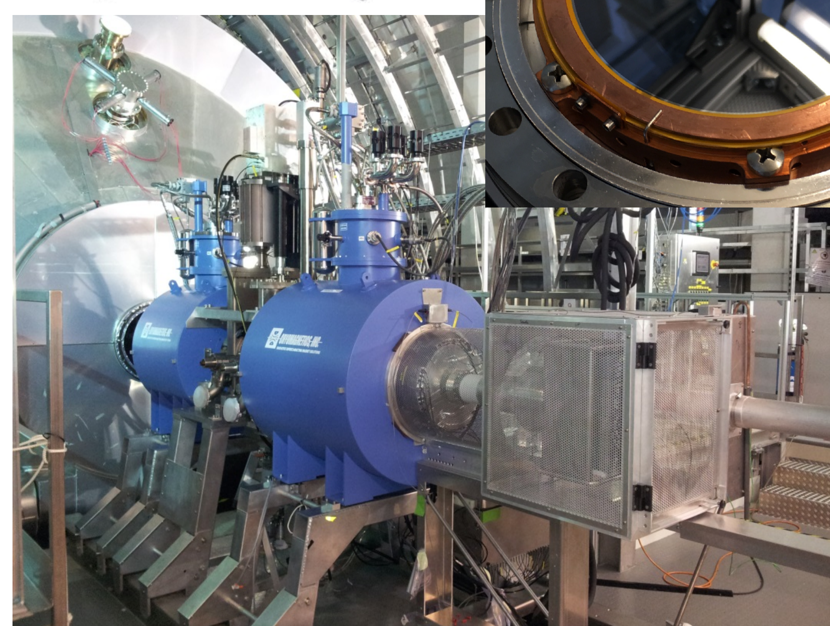
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  (passive and active shielding)
- good energy resolution (< 1 keV)

Properties

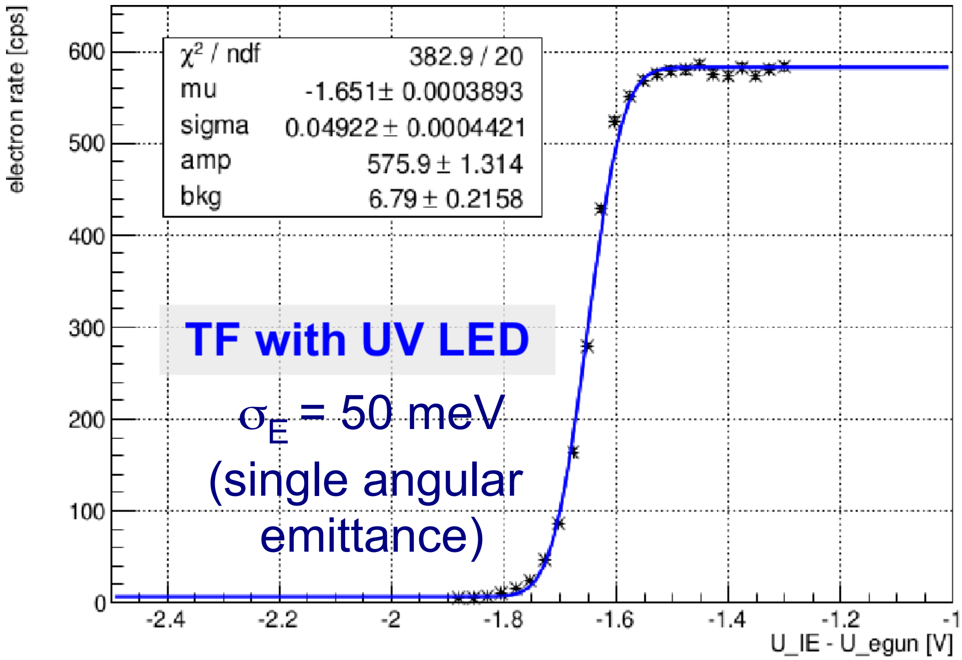
- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV)
  (to lower background in signal region)
- segmented wafer (148 pixels)
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities

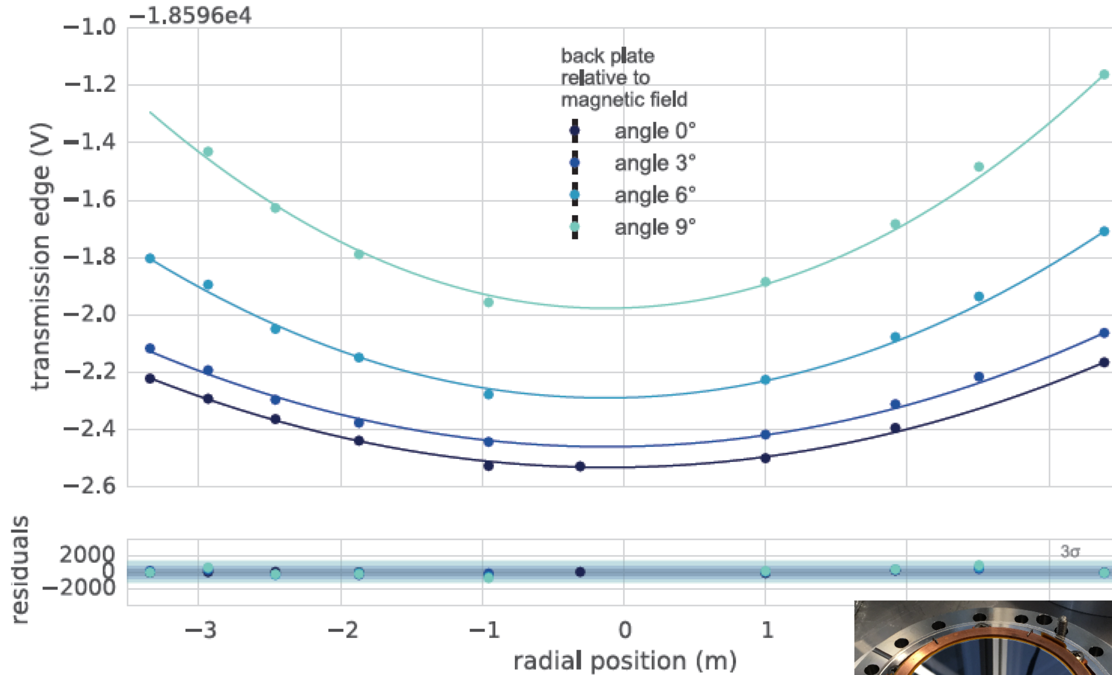




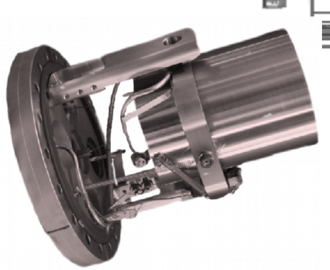


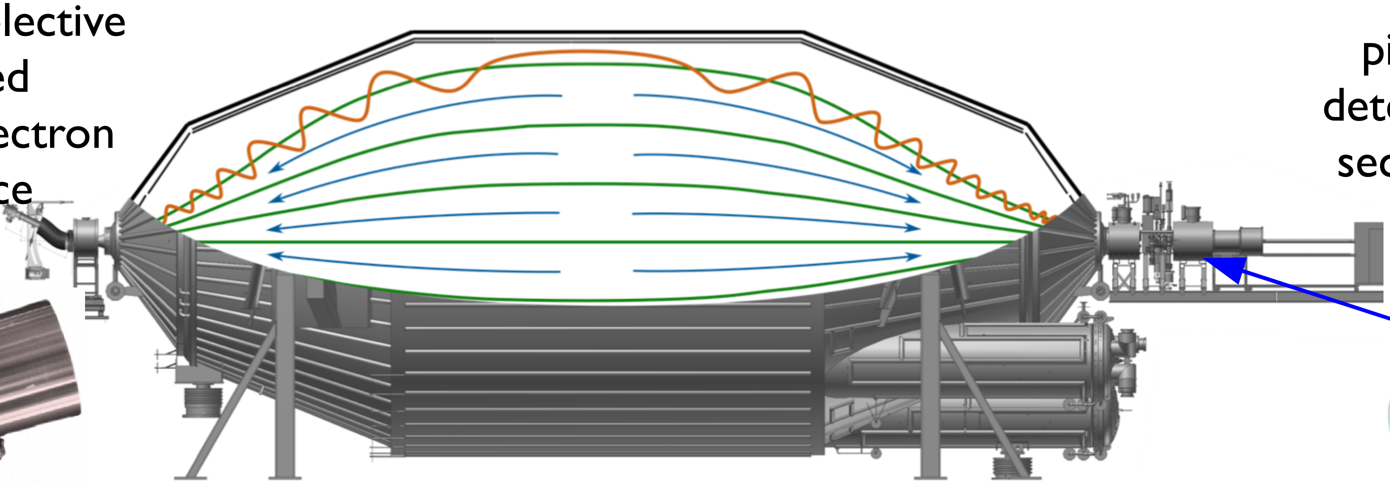
Commissioning of main spectrometer (ΔE = 0.93 eV) and detector



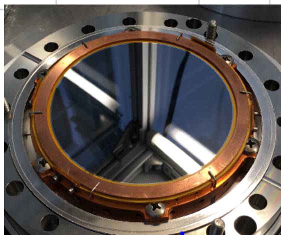


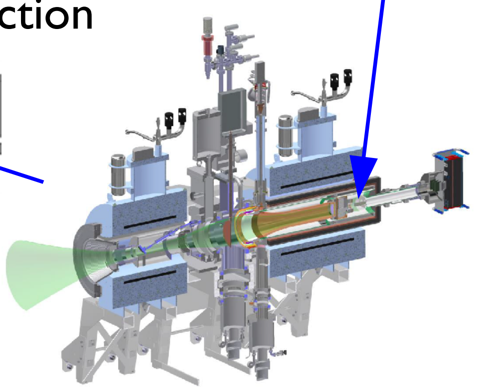
angular-selective pulsed photo-electron source



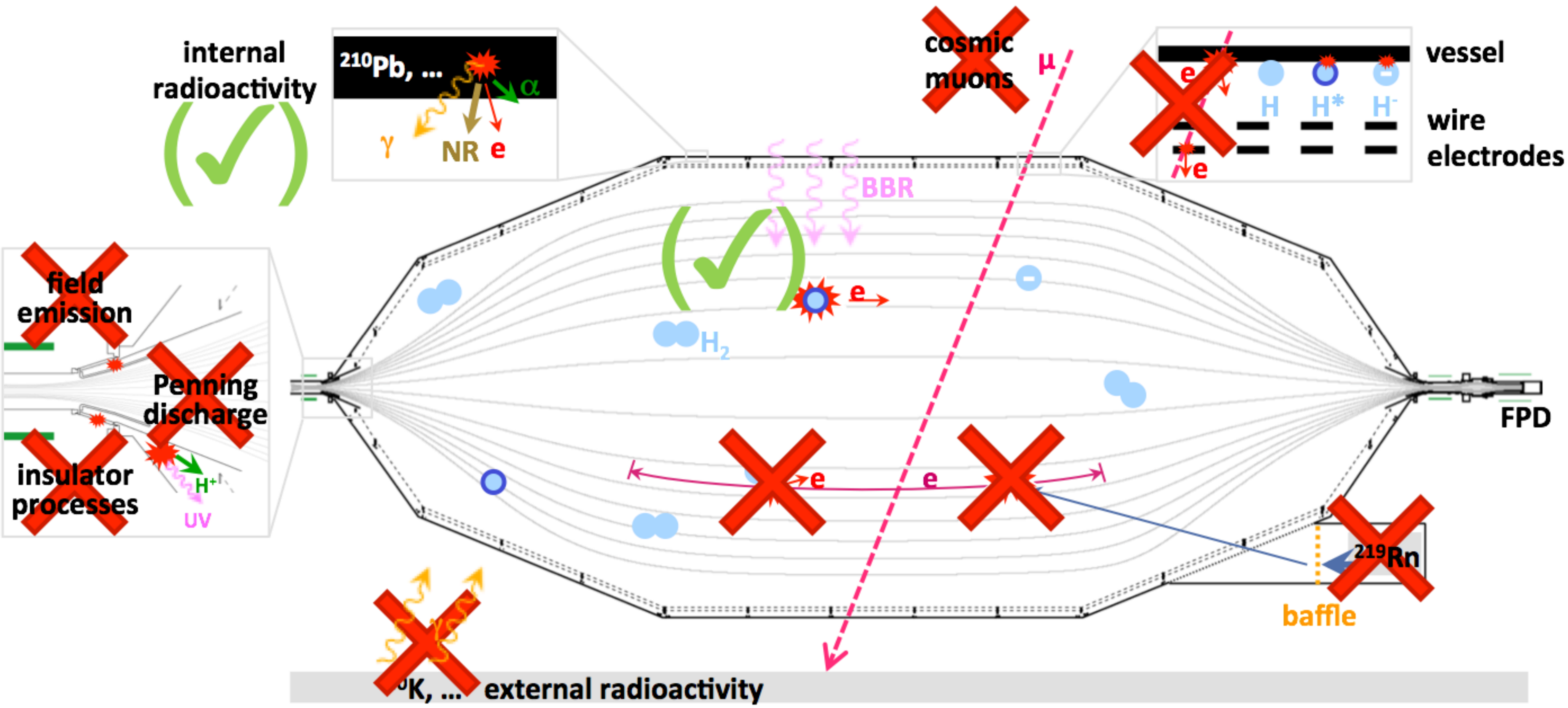


pixel detector section





Background sources at KATRIN: detailed understanding, but ...



- **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)

Background due to ionization of Rydberg atoms sputtered off by α decays

H* Rydberg atoms:

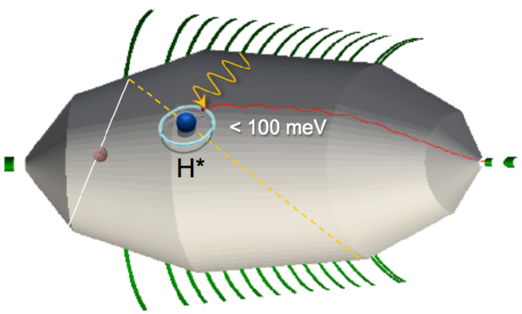
- desorbed from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- non-trapped electrons on meV-scale
- bg-rate: ~0.5 cps

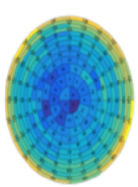
counter measures:

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

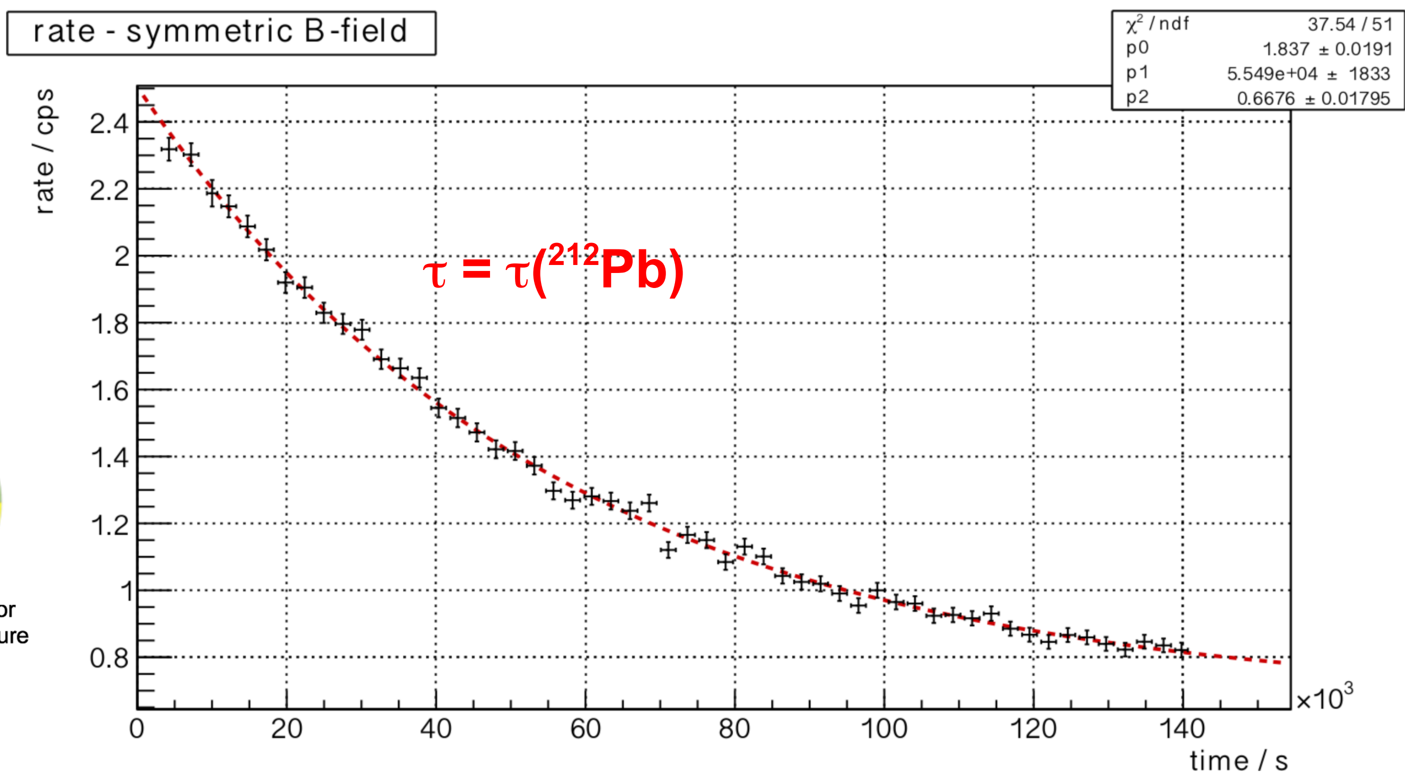
Testing this hypothesis:

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

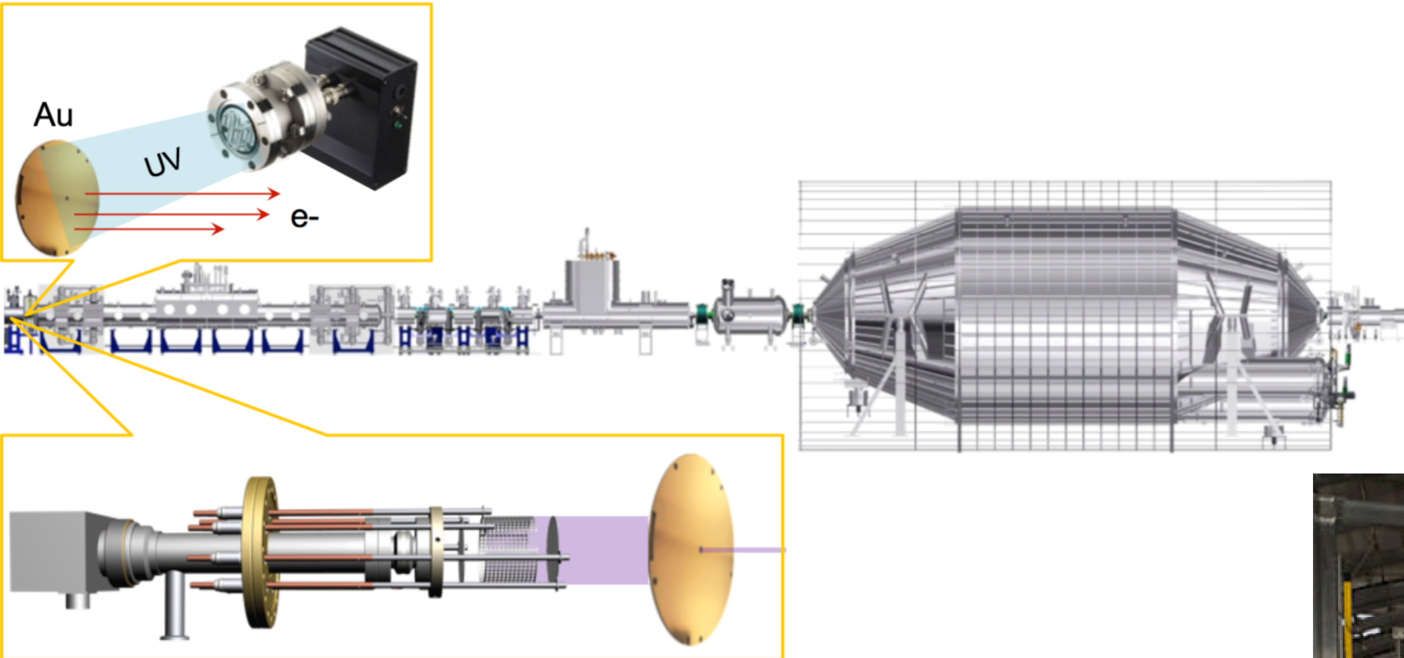




isotropic bg for longer exposure



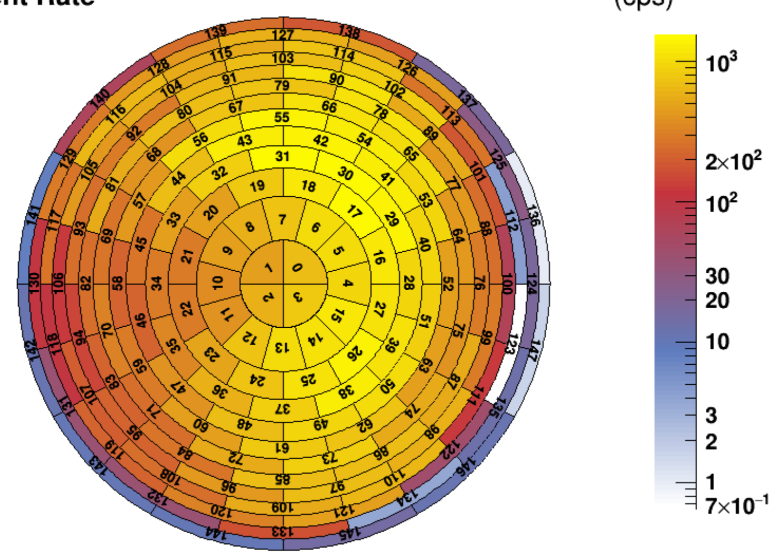
Technical start of KATRIN: „1st light“, photo-electrons from rear wall & and ions



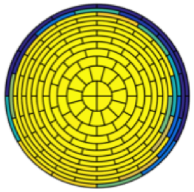
Testing whole 70m long beamline with electrons:
- alignment
- magn. stearing of pencil beam

With ions:
- ion removal

no tritium yet

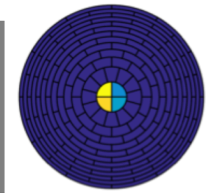


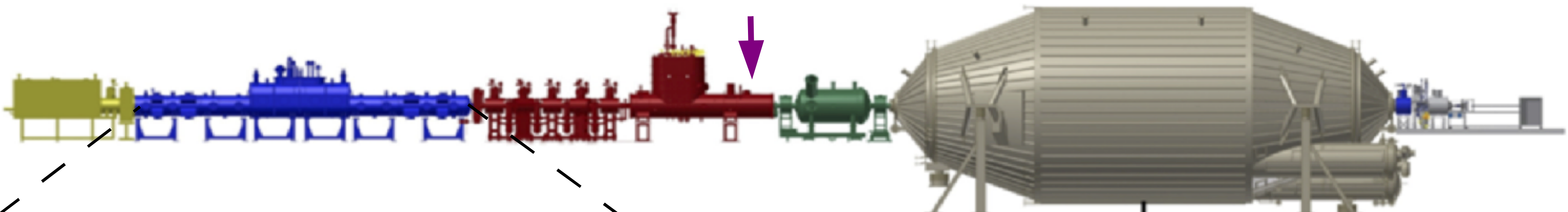
July 2017: calibration and comissioning campaign with all 3 ^{83m}Kr sources

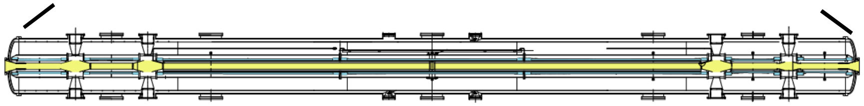


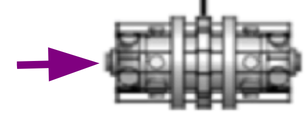
gaseous ^{83m}Kr source
decaying ^{83m}Kr atoms fill whole WGTS (at 100 K)

condensed ^{83m}Kr source
point-like source
full flux tube scanable



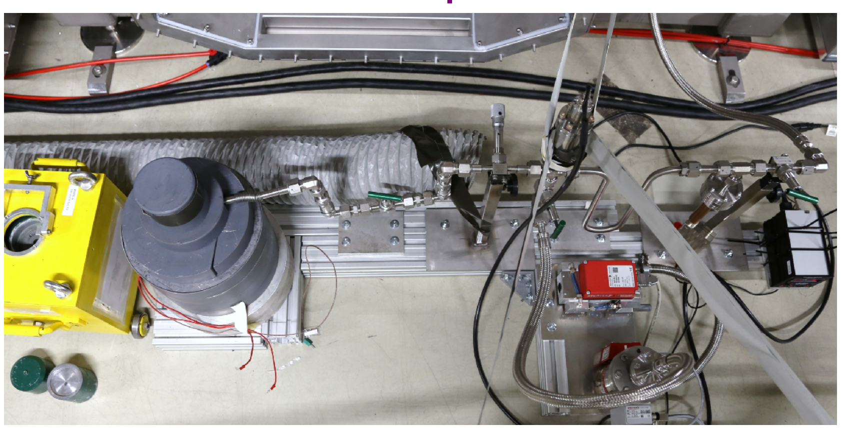


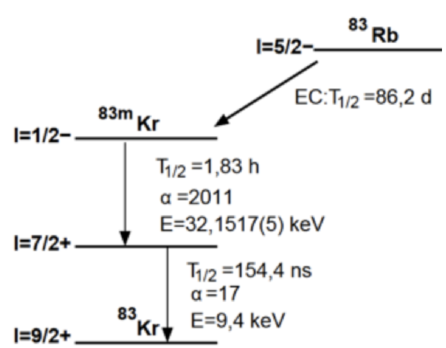


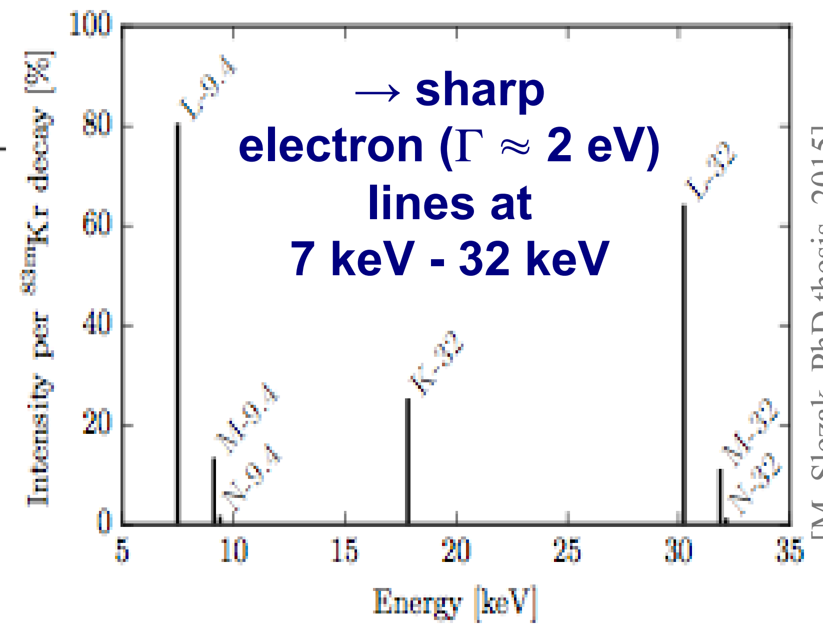


implanted ^{83}Rb/^{83m}Kr source

^{83m}Kr
from 1 GBq ^{83}Rb source



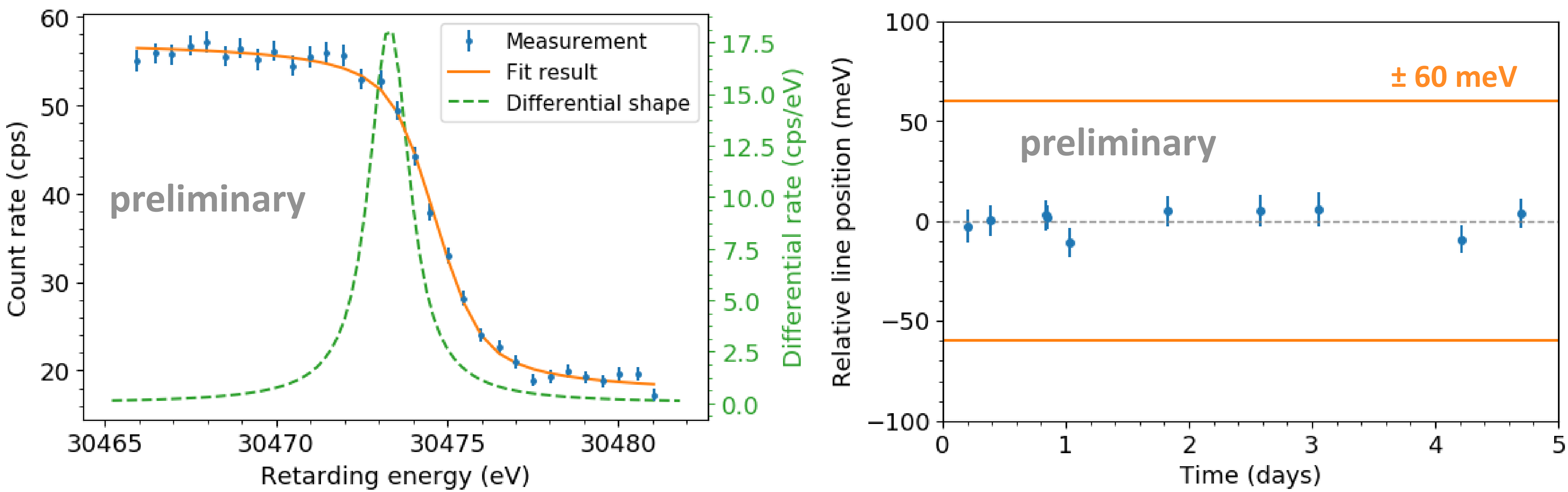




→ sharp electron ($\Gamma \approx$ 2 eV) lines at 7 keV - 32 keV

Line scan & stability (gaseous Kr source GKrS)

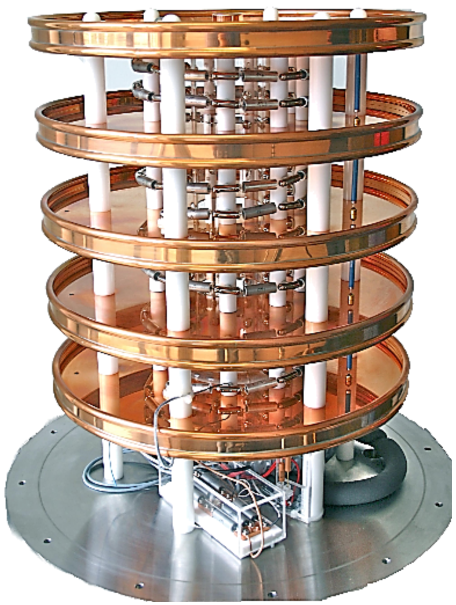
L3-32 line (30.47 keV, Γ ~1.4 eV)



- Just one example (one out of many line scans)
- Only central detector ring shown (x30 more statistics available)
- High-resolution scans of narrow N2,3-32 doublet (670 meV hyperfine splitting, sub-eV natural widths, background-free at 32 keV) currently being analyzed

Absolute energy scale calibration by difference of electron conversion lines

Measure retarding voltage with ultra-high precision HV divider:

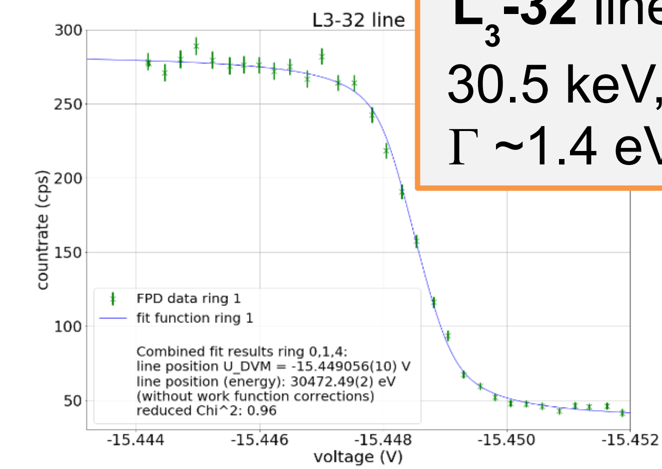


In cooperation with German national metrology institute PTB

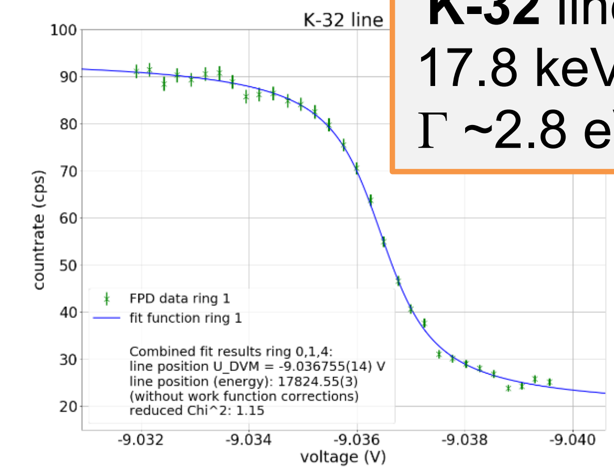
Last calibration at PTB in 2013:

M = 1972.4531(20)

Determine difference of conversion electron line positions:



L_3-32 line: 30.5 keV, Γ ~1.4 eV



K-32 line: 17.8 keV, Γ ~2.8 eV

Energy of electrons:

$$E_{kin} = E_\gamma - E_{binding} + E_\gamma^{rec} - E_{ion}^{rec}$$

Energy of γ –transition | Binding energy | Recoil energies

Transmission condition:

$$E_{kin} = -\Delta\Phi - q\Delta U + qU_{spec}$$

Work function difference source - spectrometer | Potential decrease in analyzing plane (≈2V)

→ systematic effects ($\Delta\Phi$, E_γ) cancel out

$$q(U_{spec}^{L3-32} - U_{spec}^{K-32}) - q(\Delta U_{L3-32} - \Delta U_{K-32}) = E_{binding}^{K-32} - E_{binding}^{L3-32} + E_{rec}^{K-32} - E_{rec}^{L3-32}$$

$$M \cdot (U_{DVM}^{L3-32} - U_{DVM}^{K-32})$$

→ GKrS 2017:

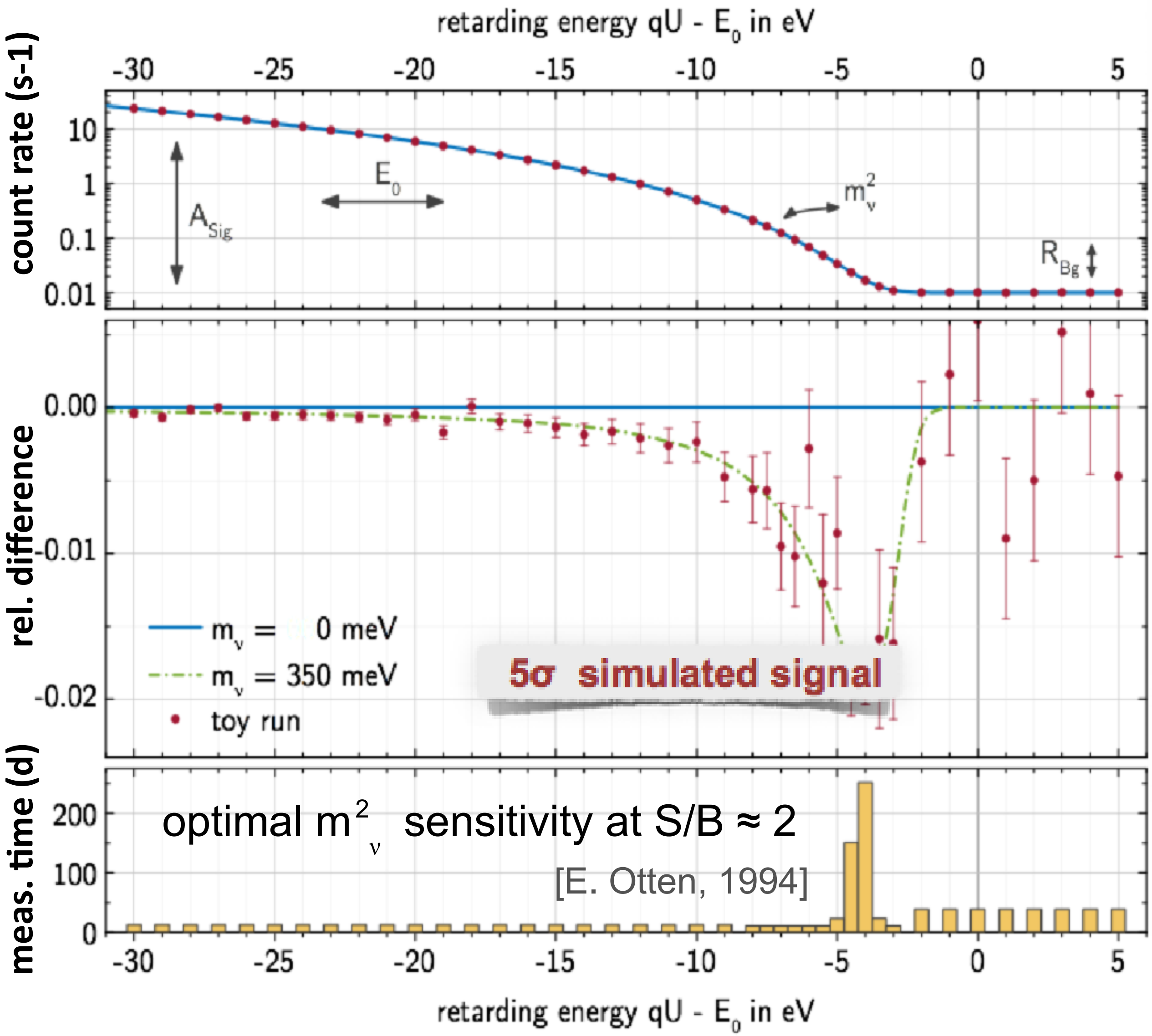
M = 1972.453(10)

K-32 line
$E(ce)$ = 17824.23(50) eV
$E_{binding}(ce)$ = 14327.26(4) eV
$E_{recoil}(ce)$ = 0.120 eV

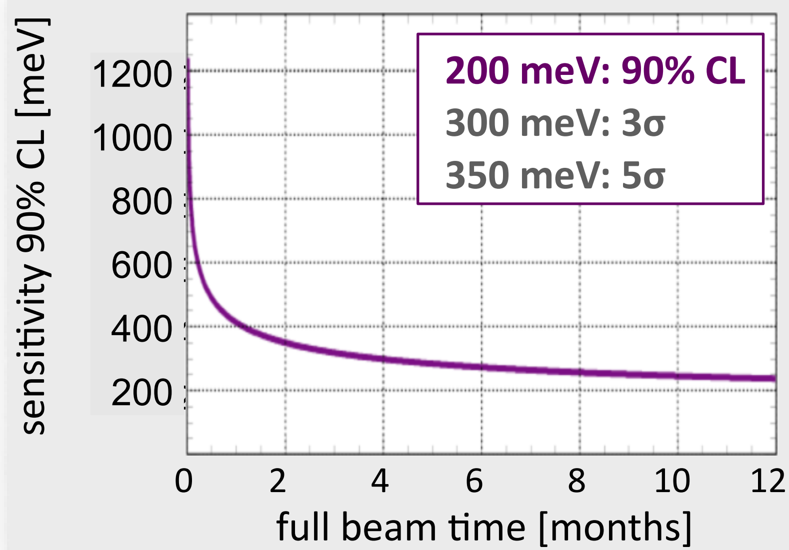
L3-32 line
$E(ce)$ = 30472.19(50) eV
$E_{binding}(ce)$ = 1679.21(3) eV
$E_{recoil}(ce)$ = 0.207 eV

→ both values agree perfectly !

HV divider scale factor stays constant over 4 years (5 ppm uncertainty)



- Relative **shape** measurement of **integrated β spectrum**
- 4 fit parameters: $m^2(\nu)$, E_0 , amp , bg

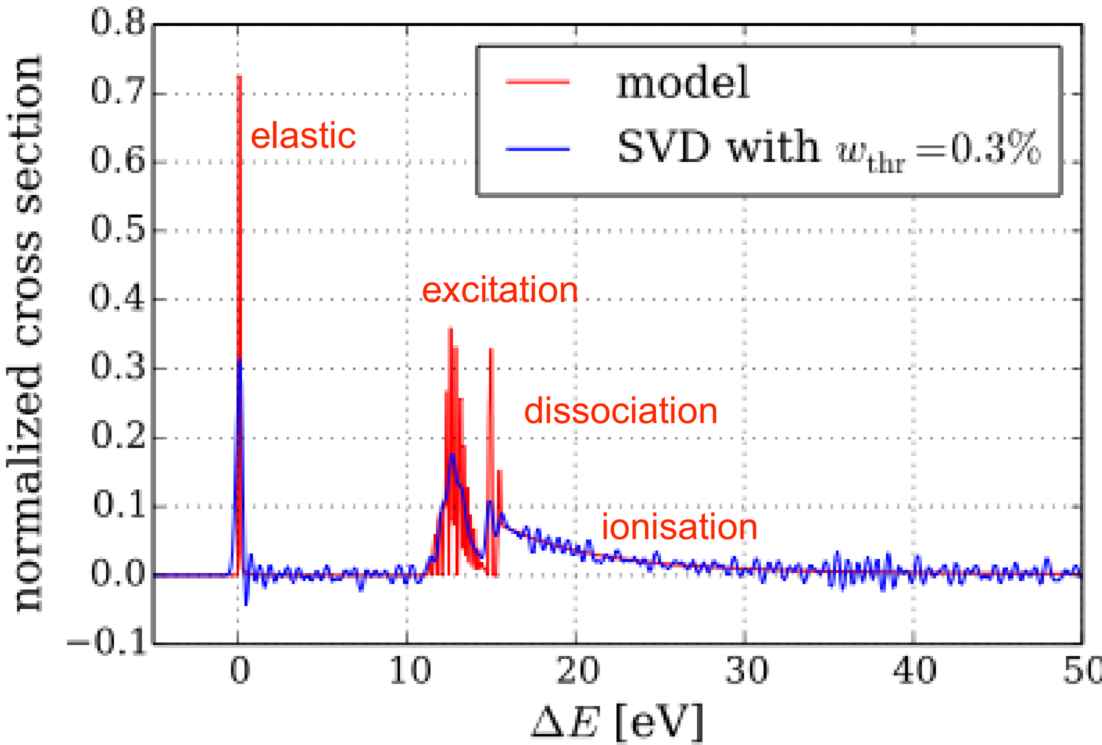


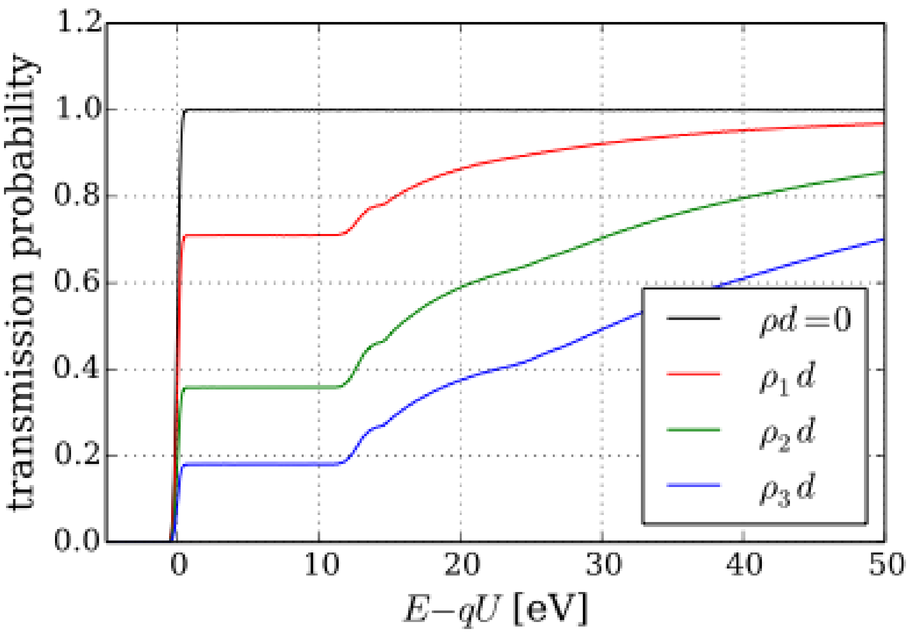
Determining the energy loss function

Measurement of electron transmission at different gas column densities

→ determine energy loss function through deconvolution

(here: singular value decomposition, SVD)

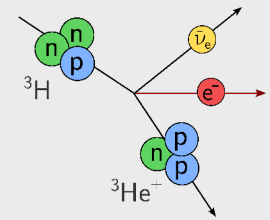




V. Hannen *et al.*, Astropart. Phys. 89 (2017) 30

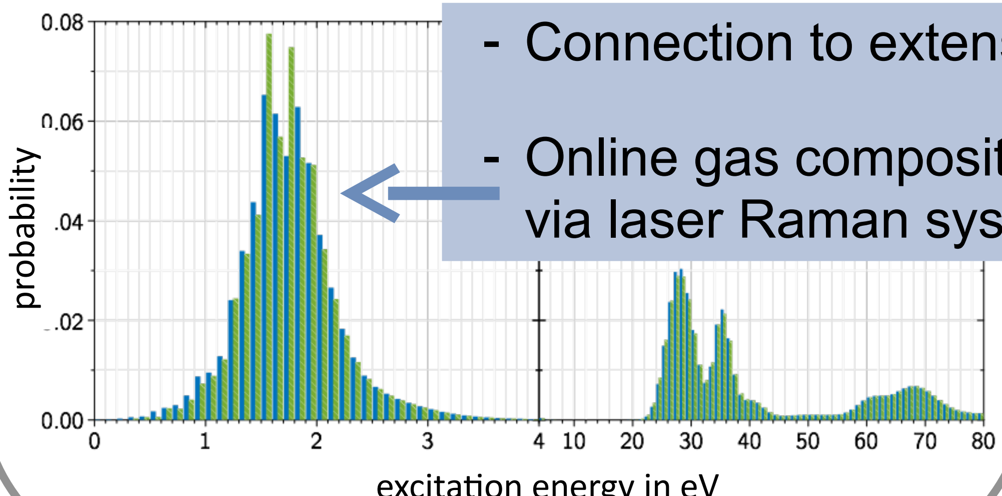
Modelling of the β spectrum

Reference spectrum generator



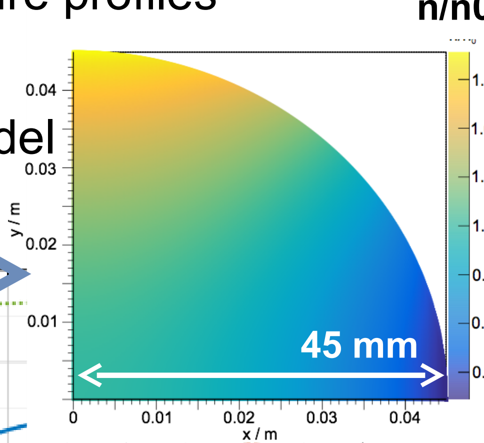
State-of-the-art nuclear & molecular theory

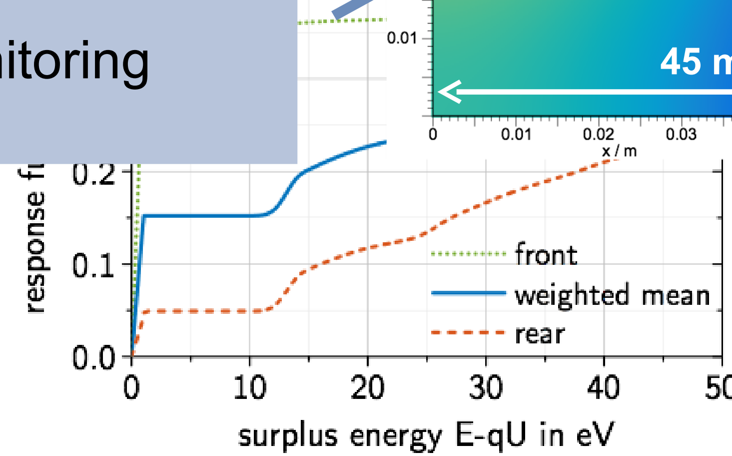
- electronic final states, radiative corrections, Doppler effect
- minor: relativistic Fermi function & recoil, screening, finite nuclear extension, …



3d gas-dynamics modelling

- longitudinal and radial pressure, density, temperature profiles
- plasma potential
- magnetic field model

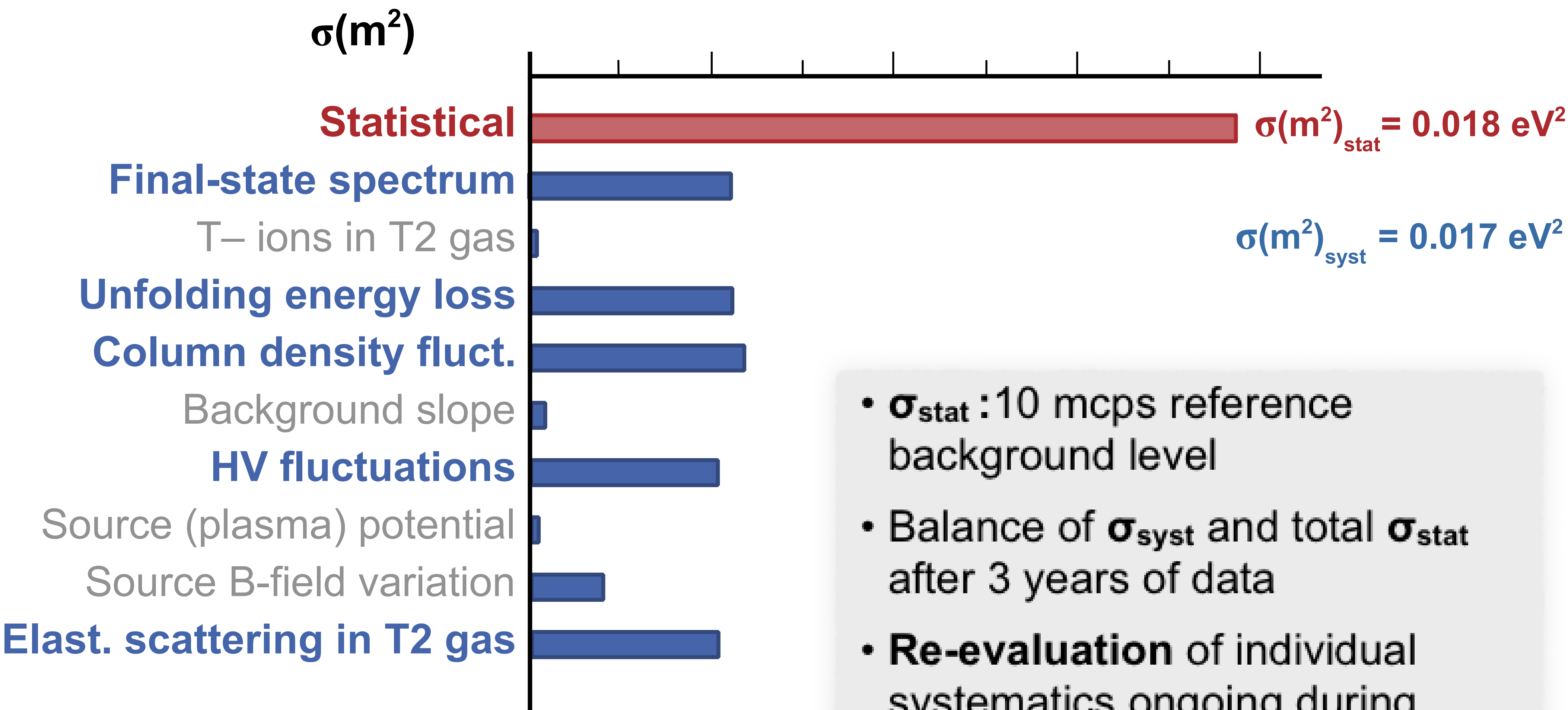




- Connection to extensive sensor network
- Online gas composition monitoring via laser Raman system

Statistical & systematic uncertainties

KATRIN's uncertainty budget (design sensitivity, ~2004):



- σ_{stat} : 10 mcps reference background level
- Balance of σ_{syst} and total σ_{stat} after 3 years of data
- **Re-evaluation** of individual systematics ongoing during system characterisation

Statistical & systematic uncertainties

KATRIN's uncertainty budget (design sensitivity, ~2004):

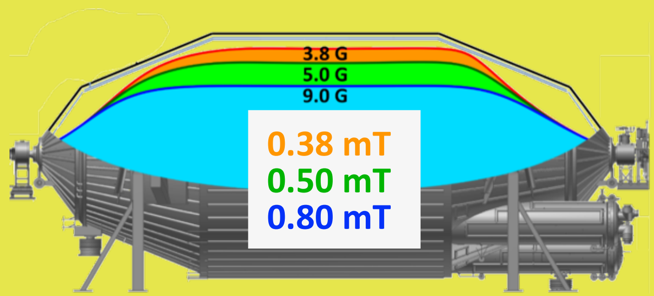
3 yr of data taking

sensitivity on the neutrino mass (stat.+sys. uncertainties):

→ 200 meV (design value)

Higher (Rydberg) background rate

→ using larger data range (E_0-60 eV) and a bit less energy res.:



→ 240 meV (without further mitigation of the Rydberg background)

eV²

eV²

S

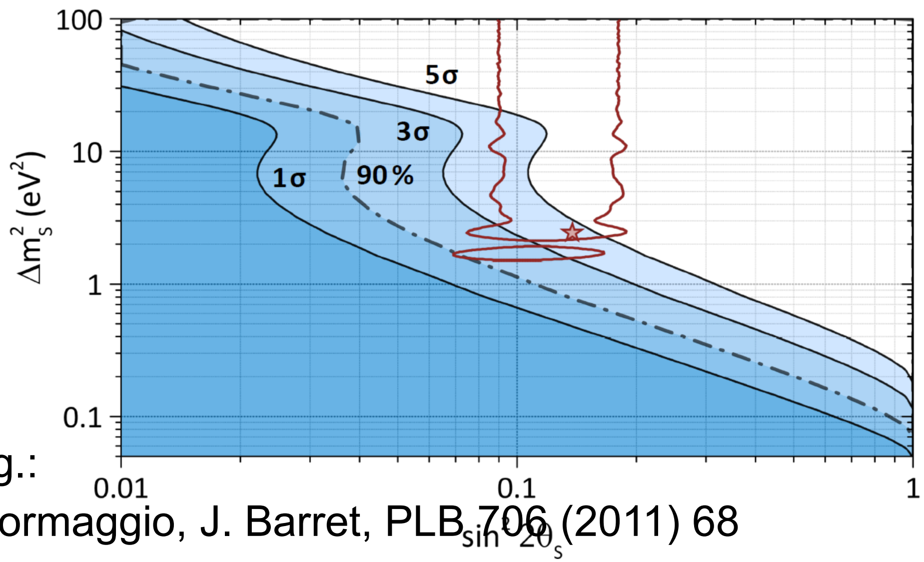
Ela

system characterisation

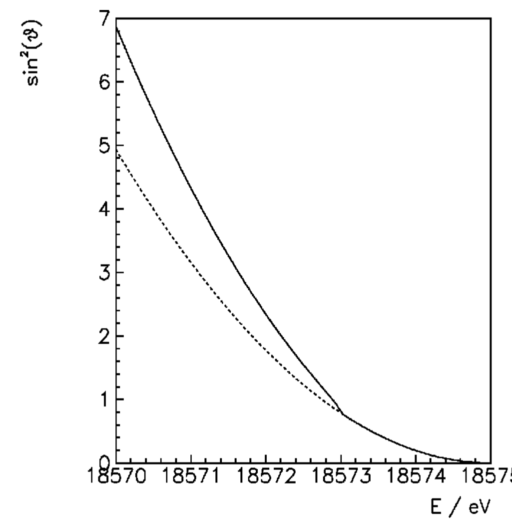
Sterile neutrinos

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2}\right)$$

eV ν:



M.Kleesiek, PhD thesis, KIT (2014)



see e.g.:

J. A. Formaggio, J. Barret, PLB 706 (2011) 68

A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011

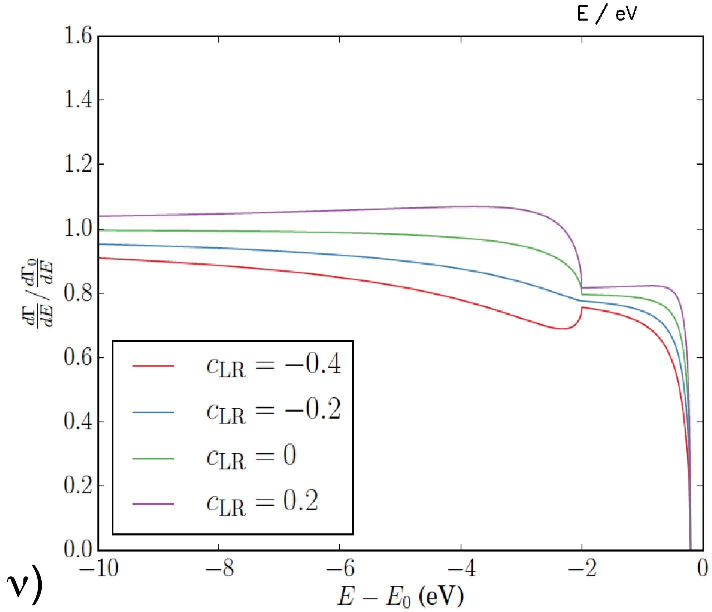
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV ν:

see e.g.

S. Mertens et al., JCAP 02 (2015) 020

M. Drewes et al. JCAP 01 (2017) 025



non SM currents, ...

see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν)

Conclusions

Direct neutrino mass experiments:

complementary to cosmological analyses and 0νββ

can look also for sterile neutrinos (eV, keV) and other BSM

KATRIN: the direct neutrino mass experiment with 200 meV sensitivity

System is complete (except tritium loops and rear wall and calibration system):

- 1^{st} light in October 2016
- ^{83m}Kr calibration measurements in July 2017 successful

- **tritium data taking will start in 2018**

KATRIN inauguration ceremony: June 11, 2018

(after Neutrino 2018 at Heidelberg)

Thank you for your attention !