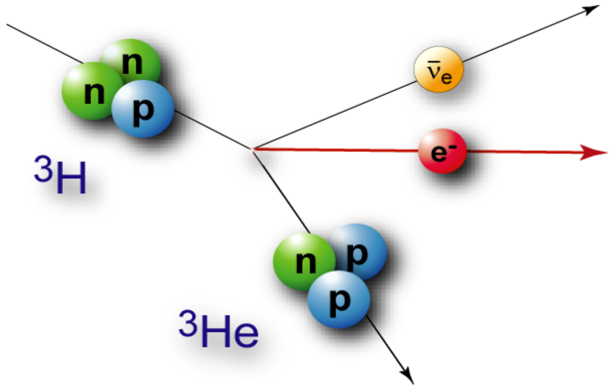
measurement and reduction of low-level radon background in the KATRIN experiment

Florian M. Fränkle
for the KATRIN Collaboration

outline

- the KATRIN experiment
- pre-spectrometer background measurement
- radon emanation
- background mitigation techniques
- summary & outlook

tritium β-decay



$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

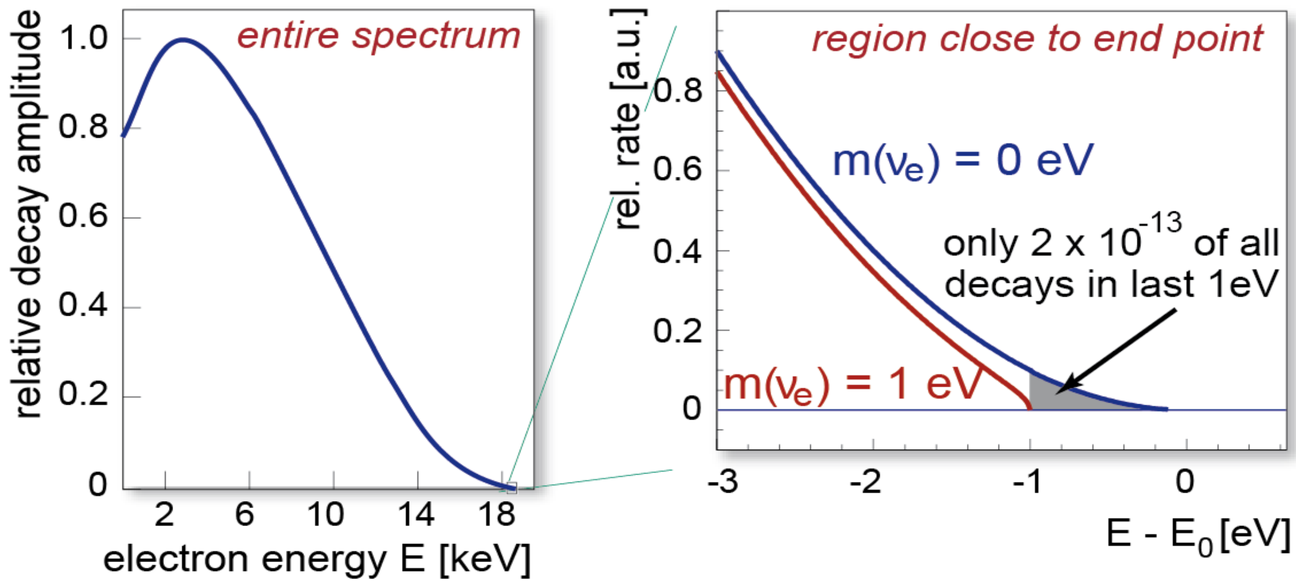
Fermi theory of β-decay:

$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p(E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

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

tritium as β emitter:

- high specific activity (half-life: 12.3 years)
- low endpoint energy E_0 (18.57 keV)
- super-allowed

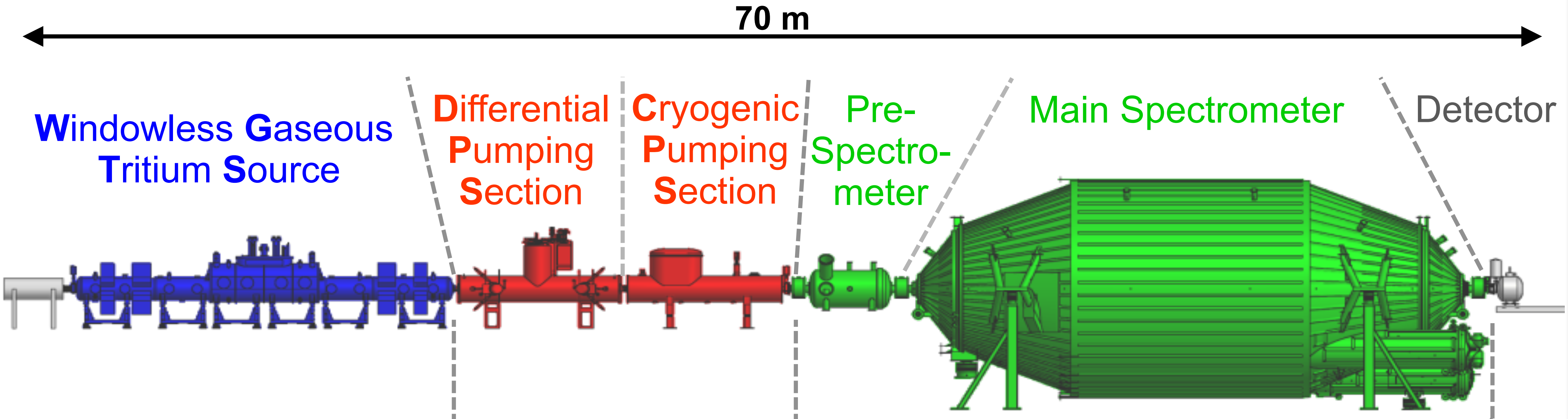


→ model independent measurement of neutrino mass

KATRIN experiment

(**KA**rlsruhe **TRI**tium **N**eutrino experiment, location: Karlsruhe Institute of Technology)

sensitivity on electron anti-neutrino mass: **200 meV/c²**



Windowless Gaseous Tritium Source

- tritium β-decay
- decay rate 10^{11} 1/s
- T_2 pressure 10^{-3} to 10^{-6} mbar

Differential / Cryogenic Pumping Section

- β-electron transport
- tritium retention (factor $>10^{12}$)

Pre-Spectrometer / Main Spectrometer

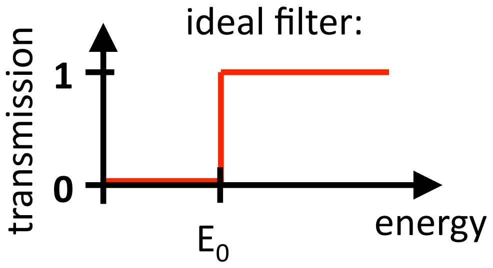
- energy analysis of β-electrons
- resolution 0.93 eV @ 18.6 keV
- pressure < 10^{-10} mbar

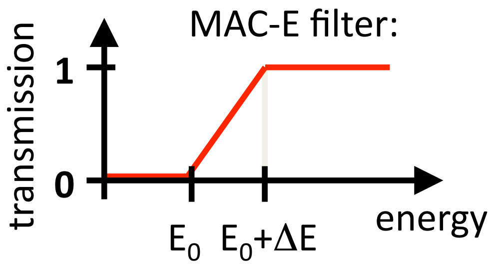
Detector

- counting of transmitted β-electrons

MAC-E filter

Magnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter



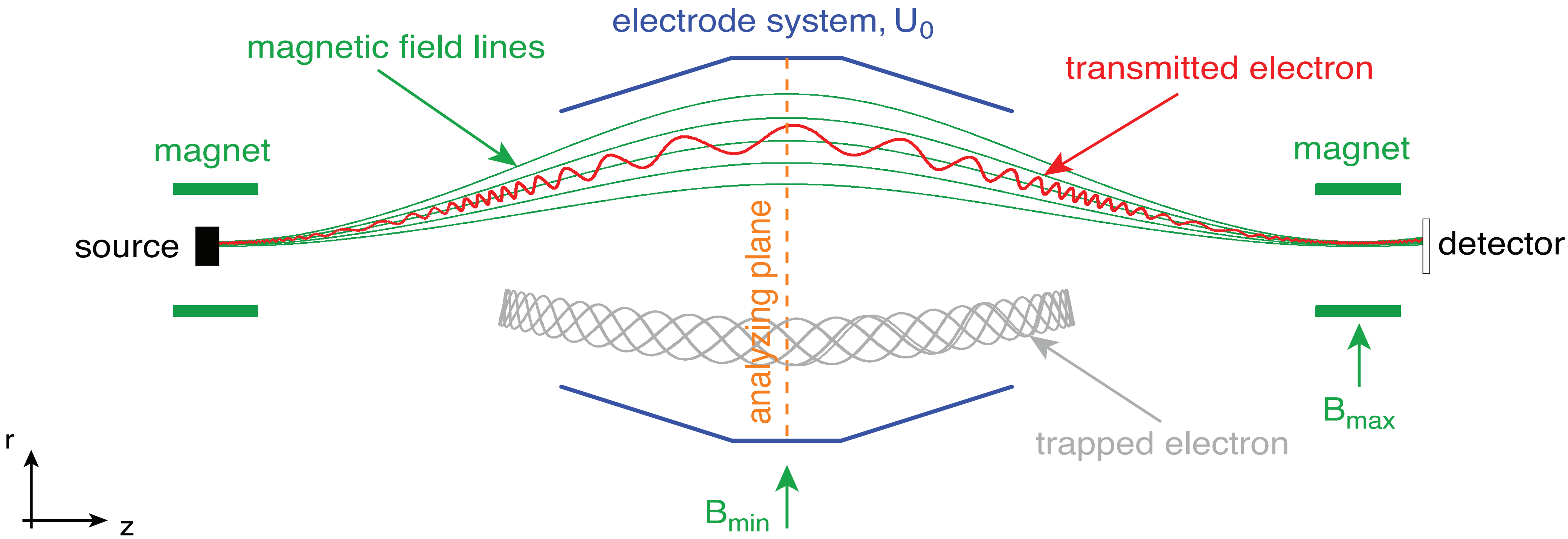


magnetic moment:

$$\mu = \frac{E_t}{B} = const$$

energy resolution:

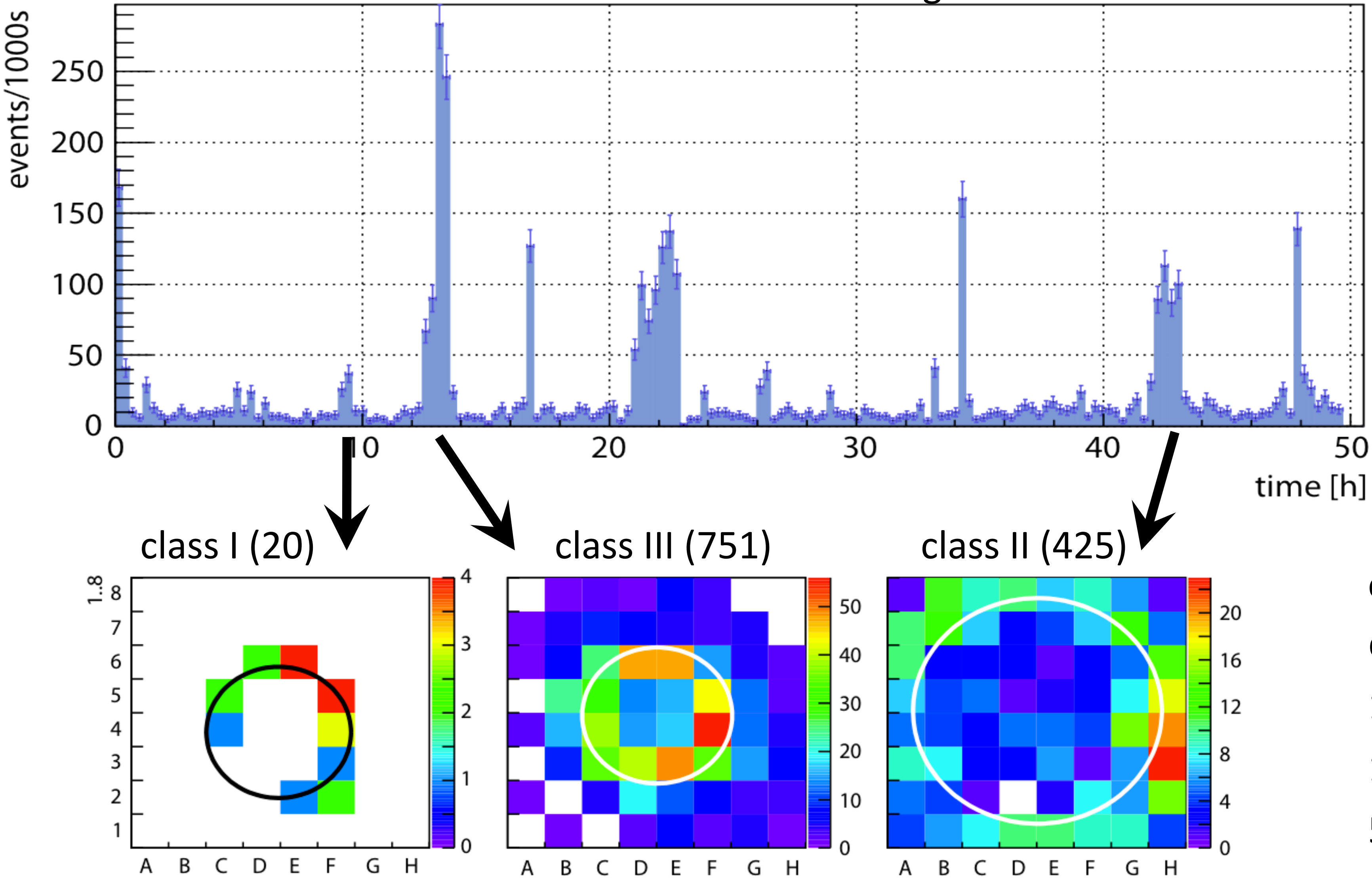
$$\Delta E = \frac{B_A}{B_{max}} E_t$$



- combines high luminosity with high energy resolution
- intrinsic protection against background via magnetic shielding

pre-spectrometer background

count rate at the detector for a 50h background measurement

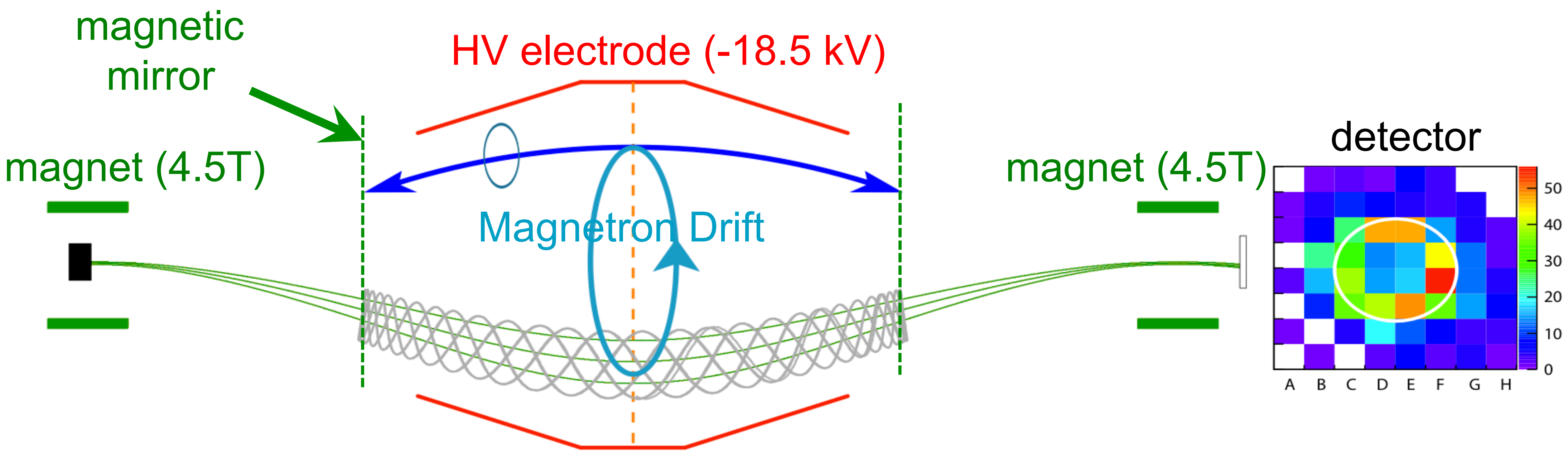


event classes:

detector hits	class
1 .. 9	0
10 .. 50	I
51 .. 500	II
501 .. 5000	III

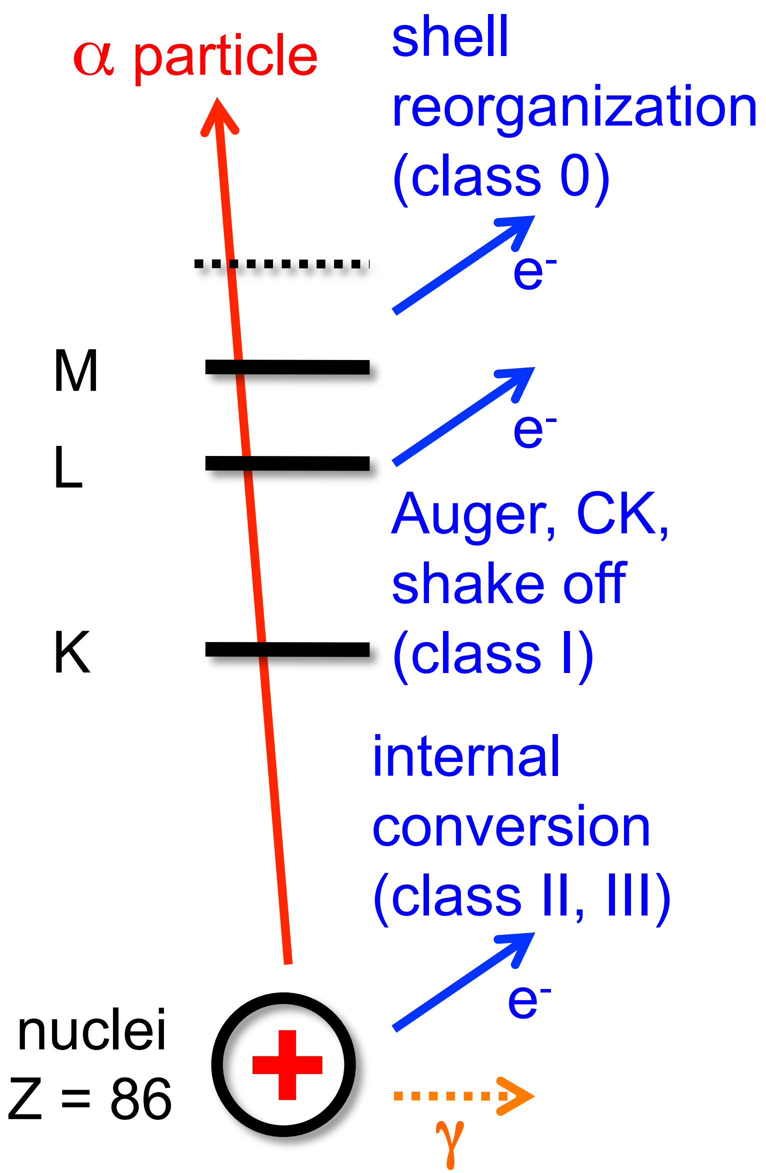
- time dependent background (average rate 23.3 ± 0.4 * 10^{-3} cps)

trapped electron



- nuclear decays can create electrons in the volume of the spectrometer
- electrons with sufficient initial energy (>100 eV) can be magnetically trapped in the spectrometer
- trapped electrons ionize residual gas molecules and thus produce secondary electrons
- the secondary electrons can leave the spectrometer and are detected at the detector
- the magnetron drift of the primary electron causes the ring-shape event distribution

radon decay



Rn α-decay is accompanied by different processes:

^{219}Rn, ^{220}Rn, ^{222}Rn:

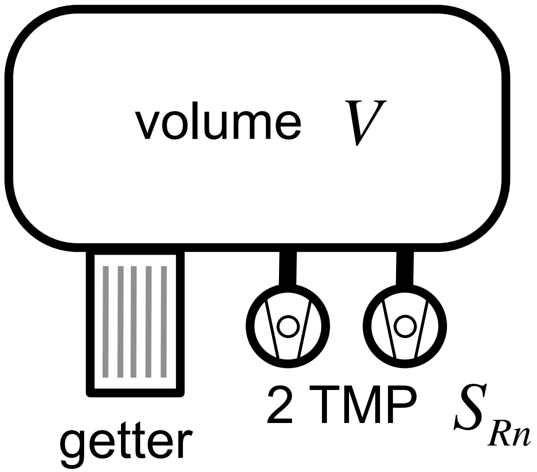
- α particle (~ 6 MeV)
- "shell reorganization" electrons (~ 10 eV)
- inner shell shake off electrons (~ 1 keV)
- Auger and Coster-Kronig electrons (~ 1 keV)

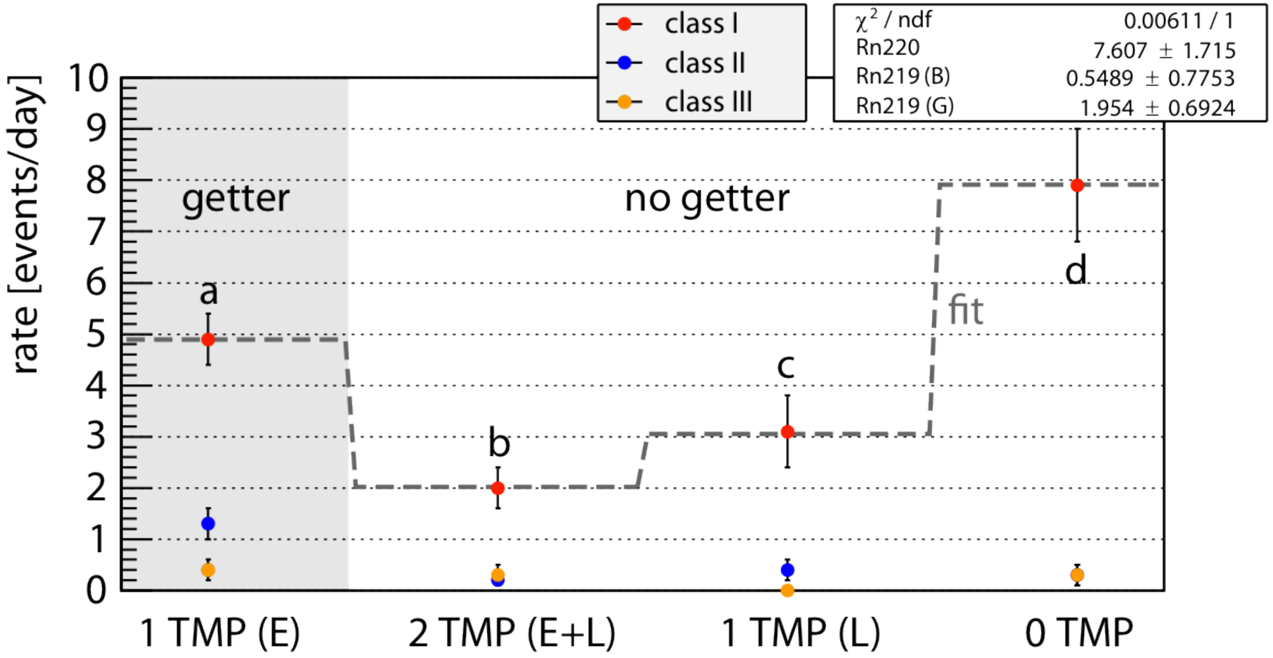
^{219}Rn only:

- γ ray (~ 100 keV)
- "conversion" electrons (~ 100 keV)

determination of radon activity

pre-spectrometer





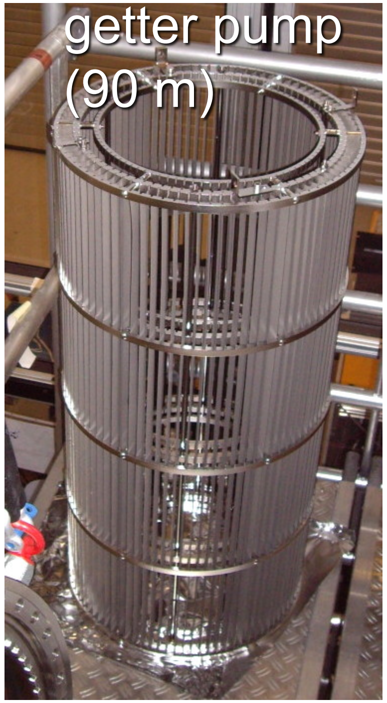
radon decay probability inside volume: $p = \dfrac{1}{1 + \dfrac{\tau_{Rn} S_{Rn}}{V}}$

allow three possible contributions: $^{219}Rn_G$ (getter), $^{219}Rn_B$, $^{220}Rn_B$ (else)

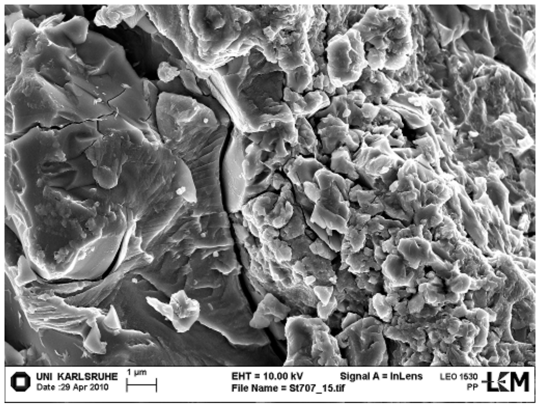
$$rate_{I,m} = \sum_{i=1}^{3} Rn_i \cdot p_{i,m} \cdot \varepsilon_i$$

ε_i probability for creating M shell vacancy (3.7%)

pre-spectrometer radon sources



~ 20 µm



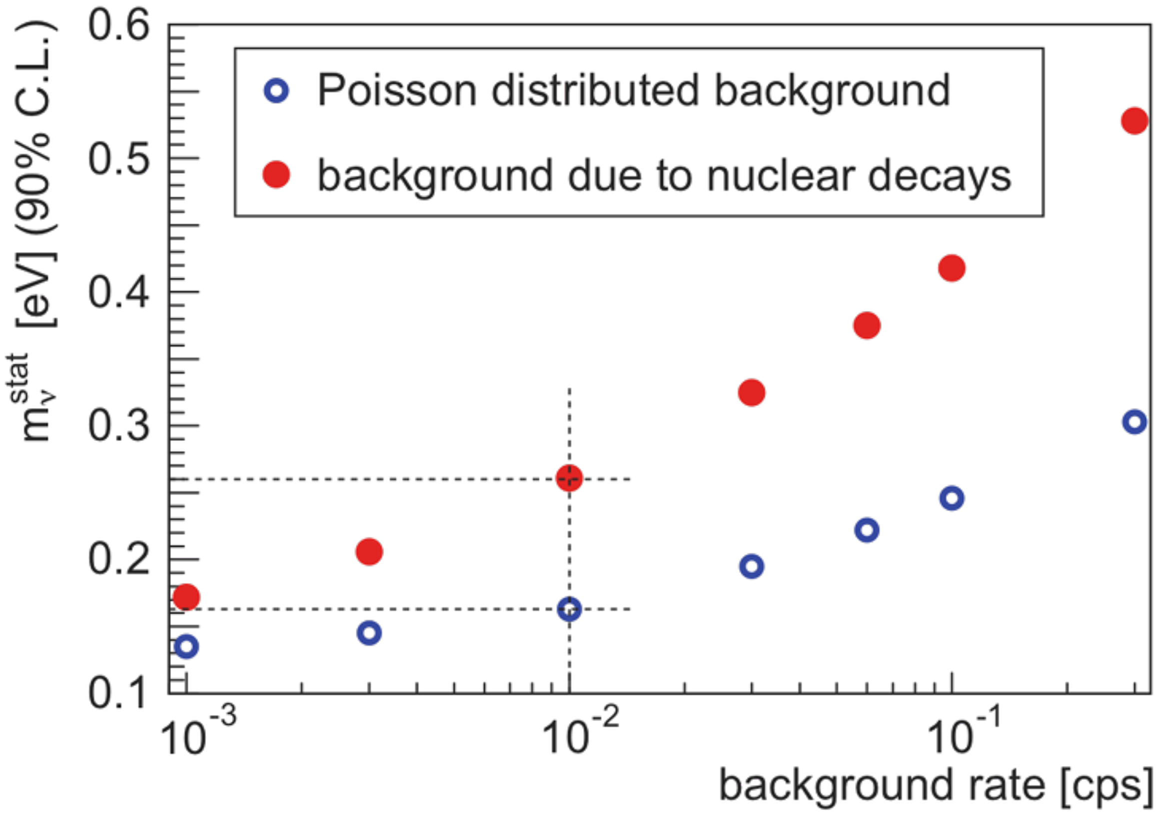
Isotope:	released activity	average rate
$^{219}Rn_G$:	7.5 ± 1.8 mBq	19 ± 4 *10^{-3} cps
$^{219}Rn_B$:	2.4 ± 2.0 mBq	6 ± 4 *10^{-3} cps
$^{220}Rn_B$:	33 ± 9 mBq	2.1 ± 0.4 *10^{-3} cps

SAES St707 NEG pump (70% Zr, 25% V, 5% Fe):

- pre-spectrometer: 90m (1.8kg, 270 m^2), 27000 l/s (H_2)
- ^{219}Rn activity material (“gamma”): ~ 90 mBq/m
- ^{219}Rn emanation (“ring count”): ~ 0.13 mBq/m
- ^{219}Rn emanation (“SNO lab”): ~ 0.23 mBq/m

measurements after removing auxiliary devices from the pre-spectrometer identified a thermocouple as dominant ^{220}Rn source

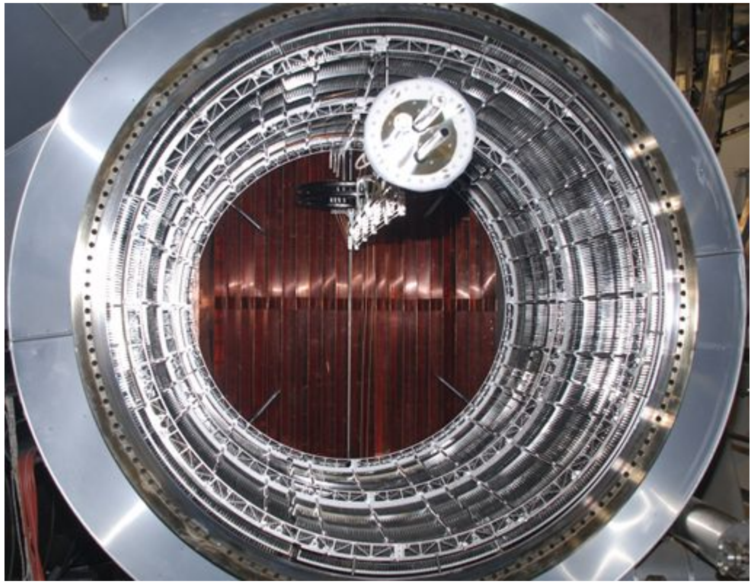
radon background vs sensitivity



- 3 km getter material installed in the main spectrometer
- estimated released activity ~120 mBq ~1 cps average background rate)
- non Poisson background reduces sensitivity on neutrino mass
- counter measures to reduce radon induced background needed

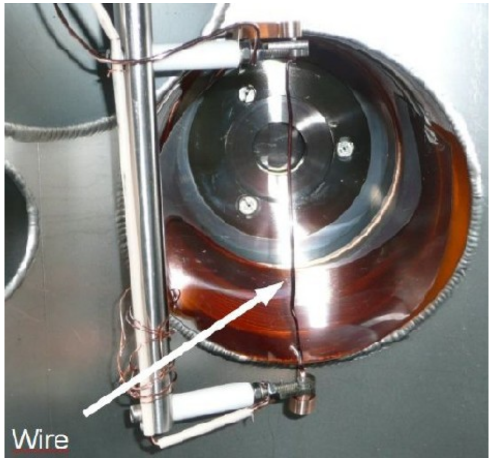
➔ Benjamin Leiber, "*Simulation of low-level tritium and radon background in the KATRIN main spectrometer*"

passive counter methods



LN2 cooled baffle

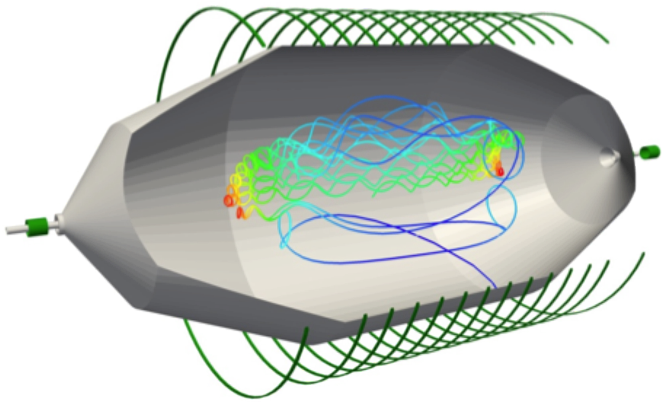
- installed between getter pump and sensitive spectrometer volume
- concept successfully tested at pre-spectrometer
- baffle system installed at the main spectrometer



mechanical pin

- removes trapped primary electrons
- successfully tested at pre-spectrometer and Mainz spectrometer

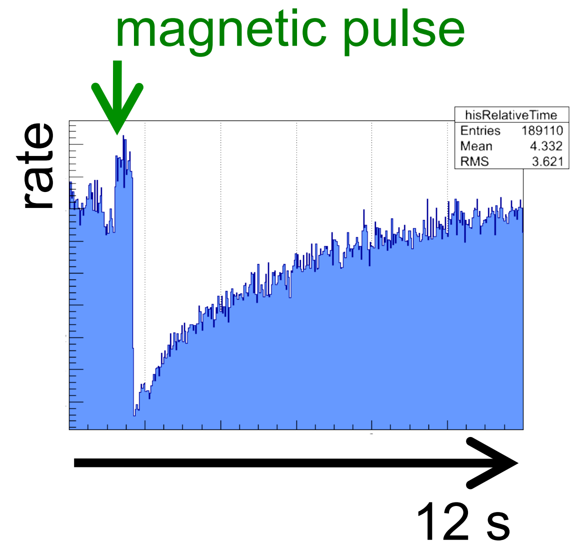
active counter methods

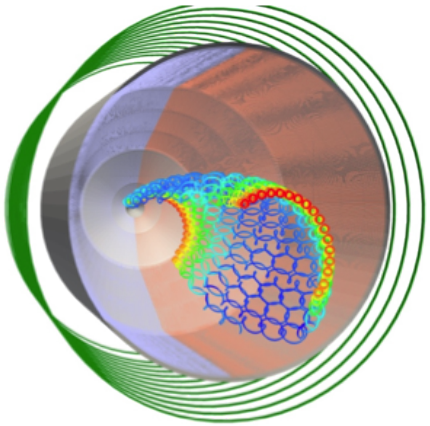


simulation
main spectrometer

magnetic pulse

- weaken or reverse magnetic field in the centre of the spectrometer
- “proof of principle” measurements at monitor spectrometer successful



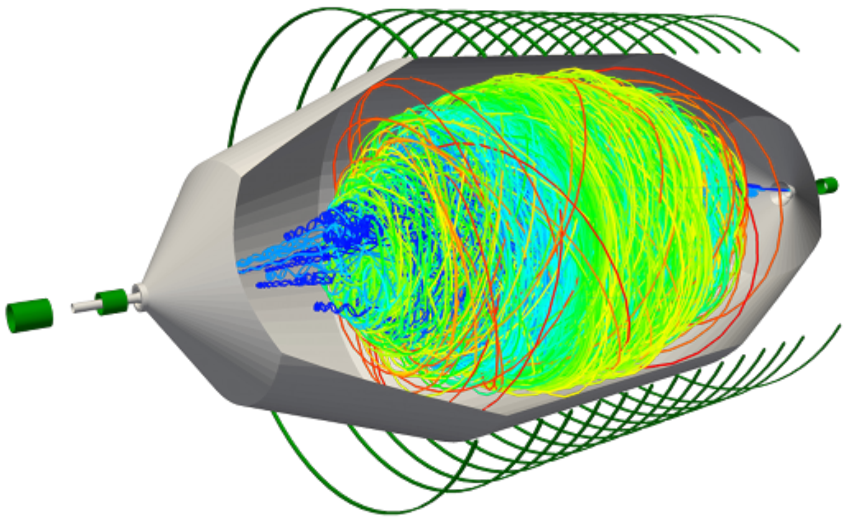


electric dipole

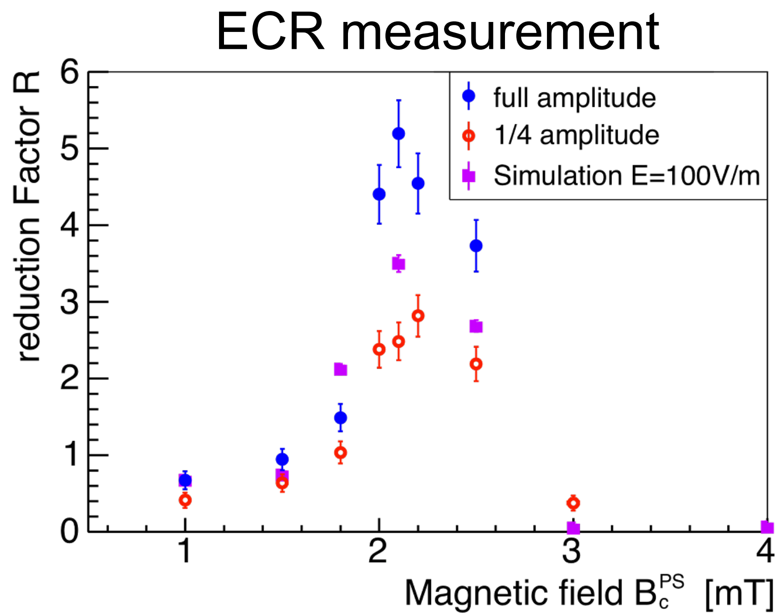
- electric dipole (< 100 V/m) field can be applied between main spectrometer halves
- E x B drift causes electrons to move out of spectrometer volume
- only effective for removing trapped electrons with energies < 1keV

active counter methods

electron cyclotron resonance (ECR)



simulation main spectrometer



- stochastic heating of trapped electrons via ECR
- cyclotron radius of trapped particle increases until it hits the spectrometer wall
- “proof of principle” measurements at the pre-spectrometer successful, background reduction factor of 5 achieved

summary & outlook

summary:

- KATRIN will measure the mass of the electron anti-neutrino, sensitivity: 200 meV/c^2
- measurements at the pre-spectrometer showed that ^{219}Rn is a major background concern for the experiment
- the SAES St707 getter strips could be identified as dominant ^{219}Rn source
- passive and active counter measures against radon induced backgrounds have been tested successfully and are implemented at the main spectrometer

outlook:

- first commissioning measurements at the main spectrometer start this year
- commissioning of the complete KATRIN beam line will start 2014/2015
- start of neutrino mass measurements 2015

KATRIN collaboration

Karlsruhe Institute of Technology

Westfälische Wilhelms-Universität Münster

University of Washington

Hochschule Fulda University of Applied Sciences

Swansea University Prifysgol Abertawe

Johannes Gutenberg Universität Mainz

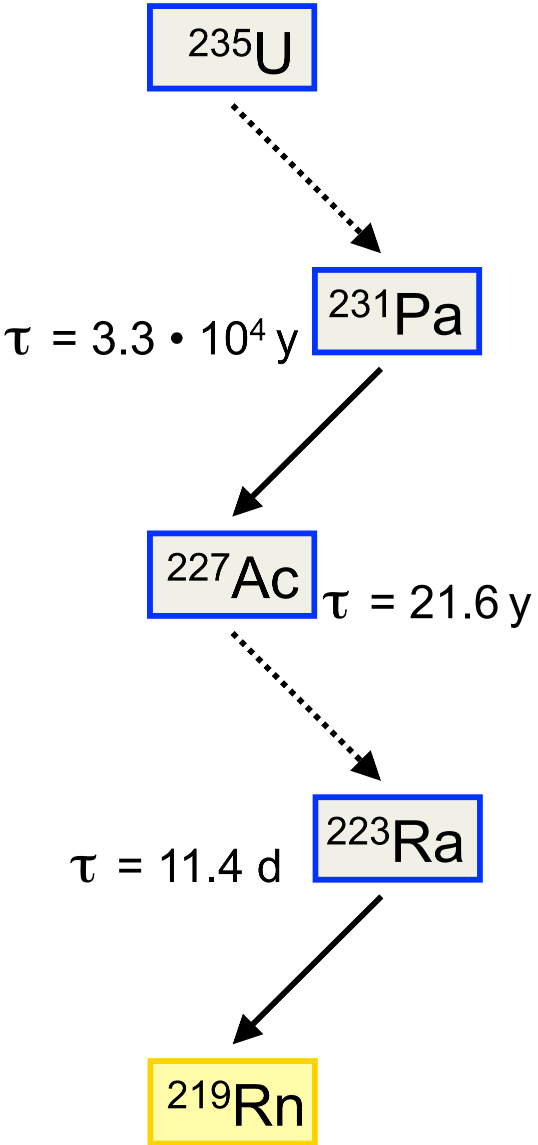
The University of North Carolina at Chapel Hill

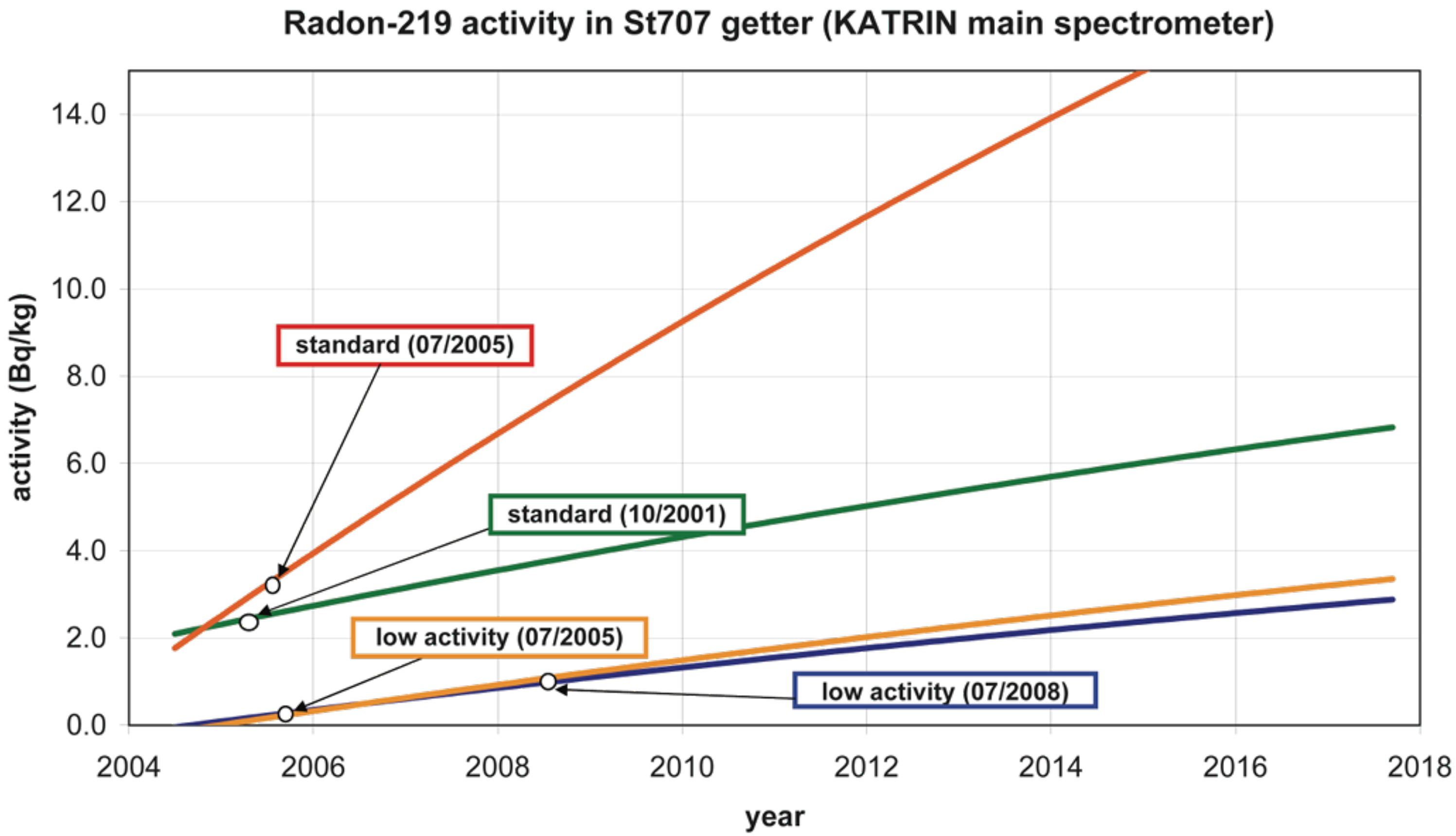
UCL

Berkeley Lab

backup slides

getter pump

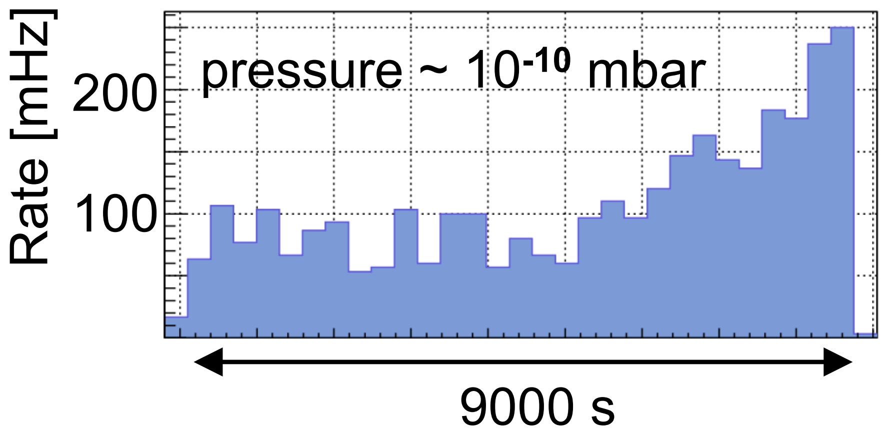


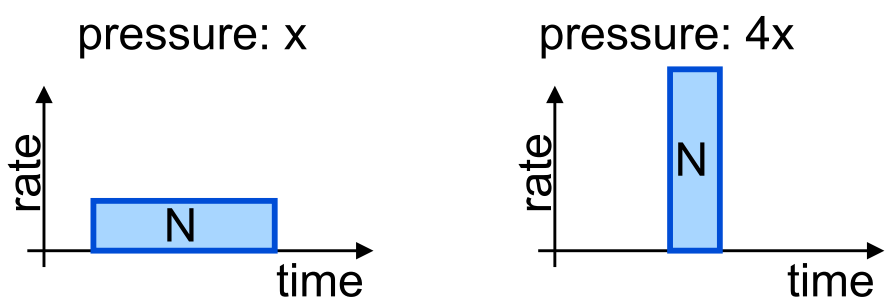


^{219}Rn activity in pre-spectrometer ≈ 8 Bq

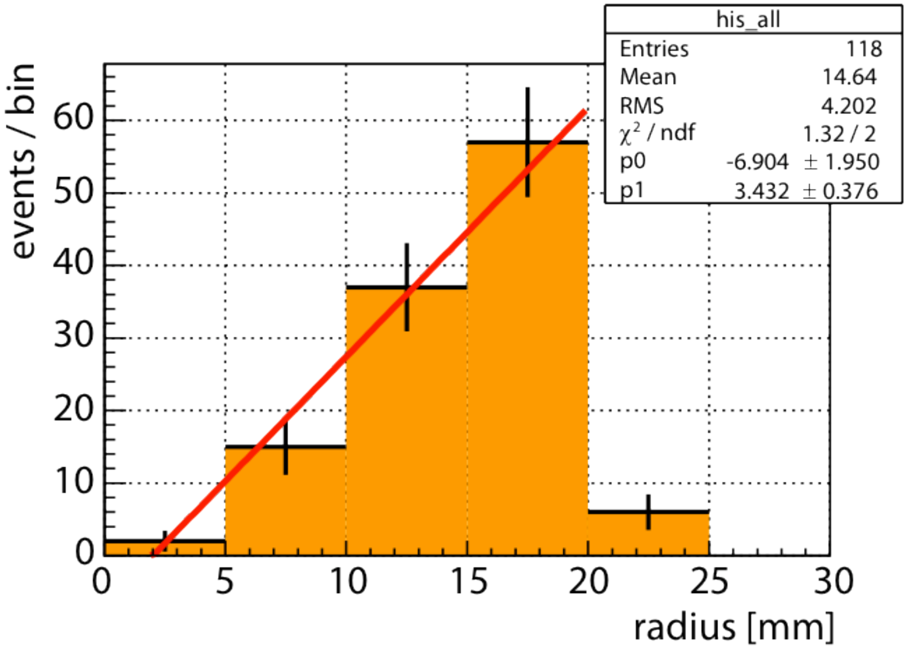
measurement results

time series class III event





ring radii distribution



- events are distributed homogenous (V ~ r dr)

➔ class I to III events can be explained with the storage of high energetic trapped electrons (energies up to ~100 keV)

➔ electrons are produced inside the pre-spectrometer volume