Project KATRIN:
First results and future plans.

N.Titov, INR RAS

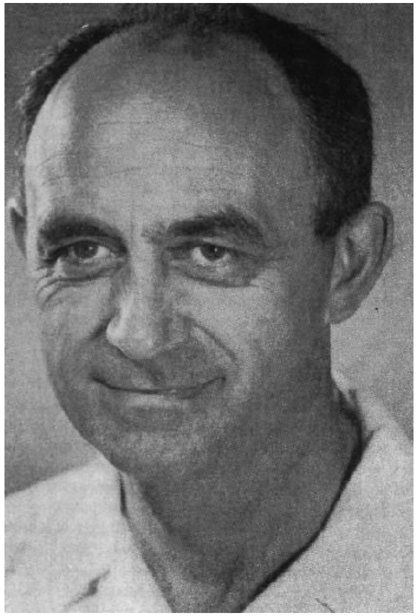
for the KATRIN Collaboration

IV International Conference on Particle Physics and Astrophysics, October 24, 2018 Moscow, Russia

Outline:

1. 84-year long history of the search for neutrino mass.
   - Enrico Fermi (1934) and Bruno Pontecorvo (1948)
   - 1983 – beginning of an era of Electrostatic Spectrometer with Adiabatic Magnetic Collimation (MAC-E filter)
   - New challenge: Project KATRIN
2. October 14, 2016 - KATRIN "First light"
3. June 11, 2018 "First tritium"
4. September – October, 2018 Extensive KATRIN set-up study
5. March 2019 start of data taking with Tritium

1934: Neutrino mass could be evaluated from nuclear β- decay spectrum



E. Fermi

Versuch einer Theorie der β-Strahlen. I[1]).

Von E. Fermi in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

E. Fermi, Z. Physik 88 (1934)

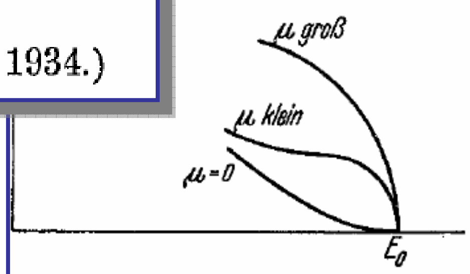
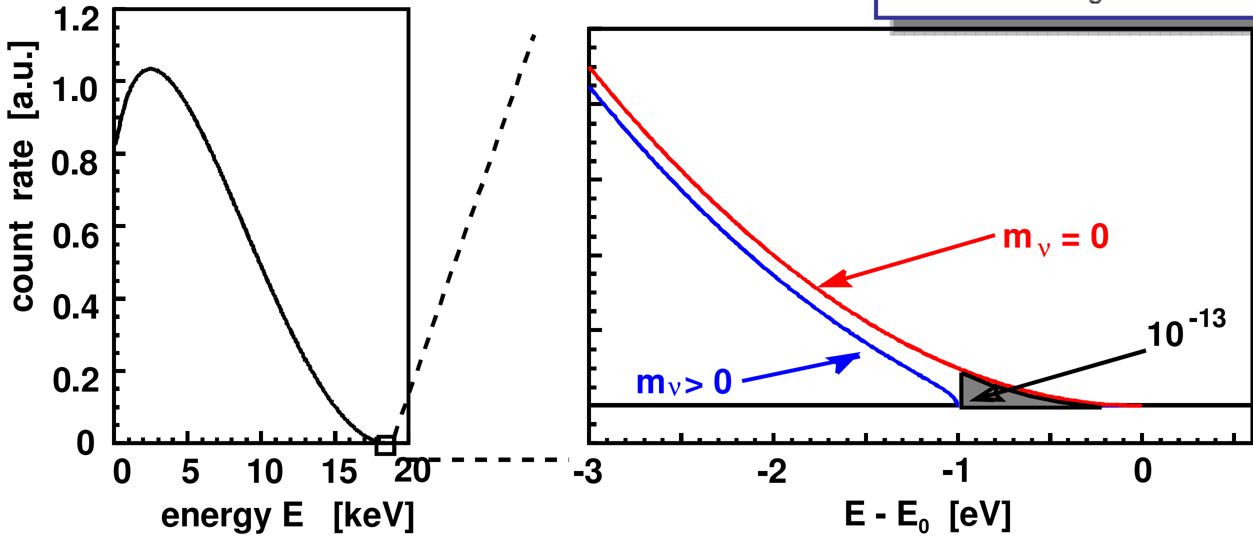
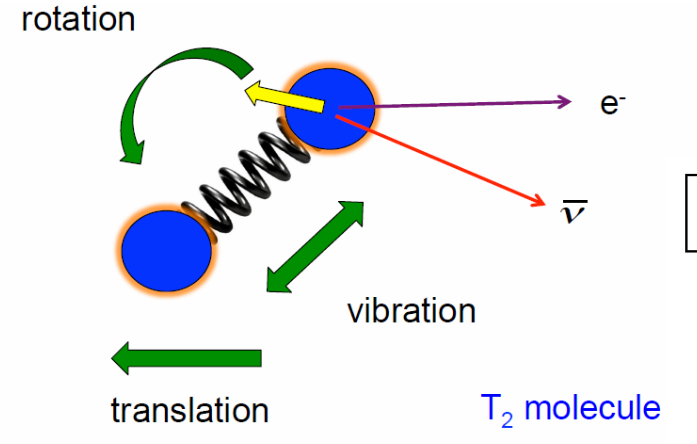
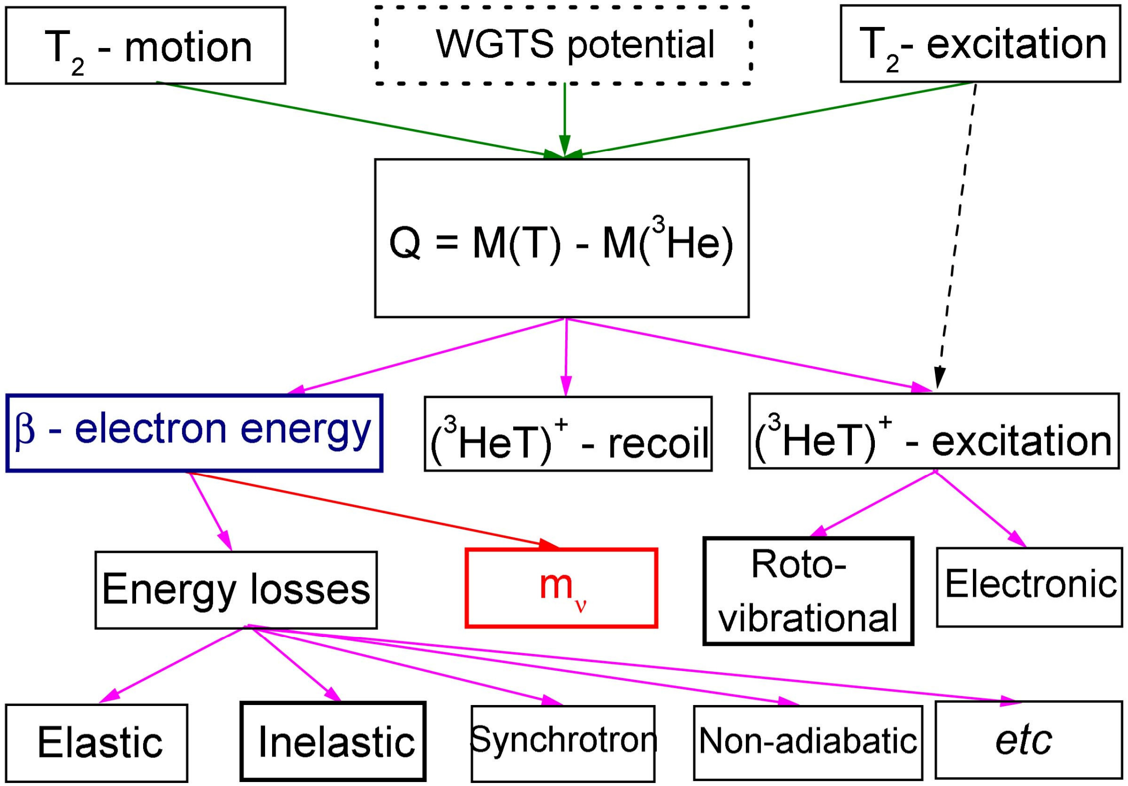


Fig. 1.



Kinematics experiment - basics





1948: First experiments with tritium
(proportional counter filled with Tritium)

$T \rightarrow {}^3He + e^- + \underline{18{,}6\ кэВ}$

$m_\nu < 1$ кэВ/c^2

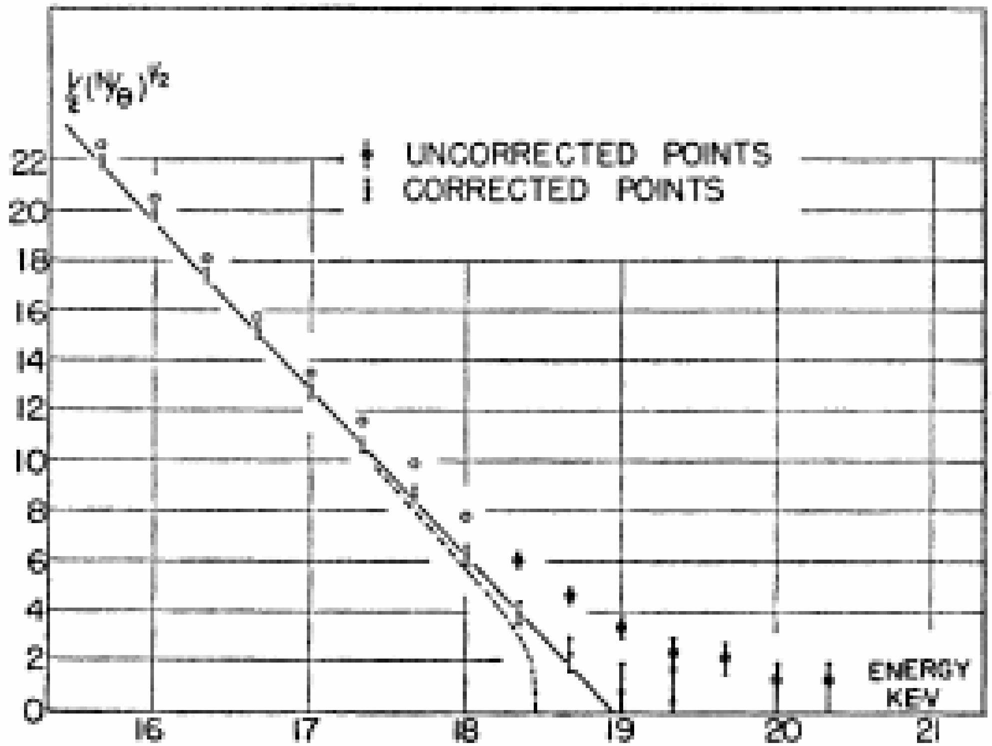
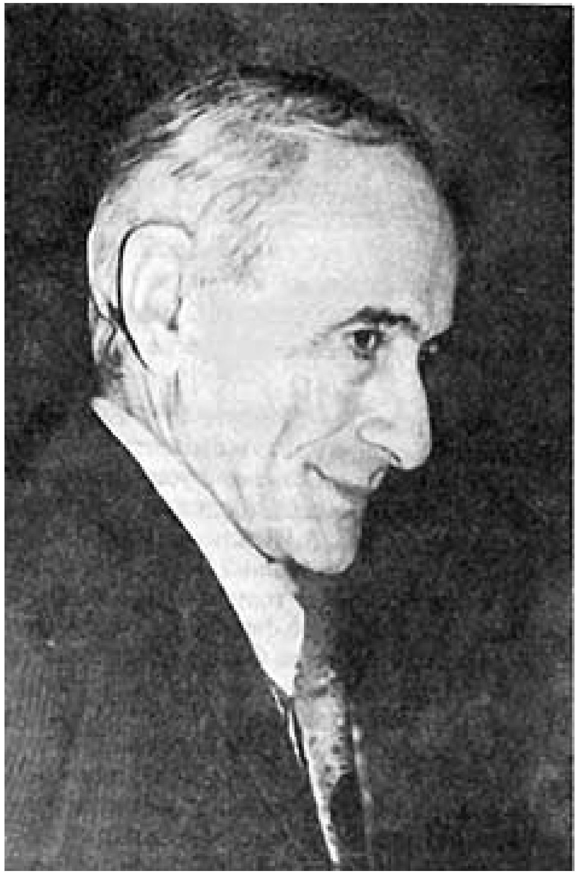


FIG. 2. "Kurie" plot of the end of the H³ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

Hanna G.C. and Pontecorvo B., Phys. Rev. 75 (1949) 983

KATRIN - Founders



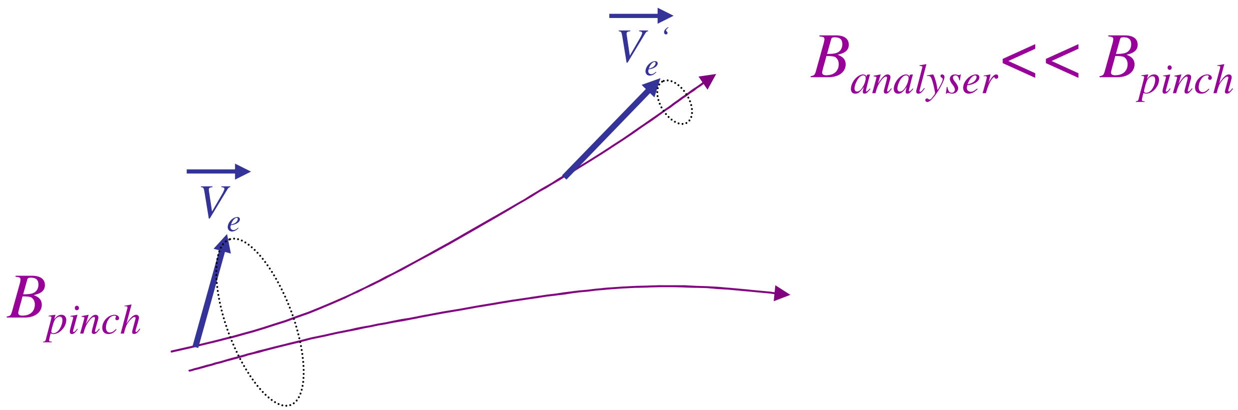
Peter Spivak
24.03.1911 - 30.03.1991

Vladimir Lobashev
29.07.1934 – 3.08.2011

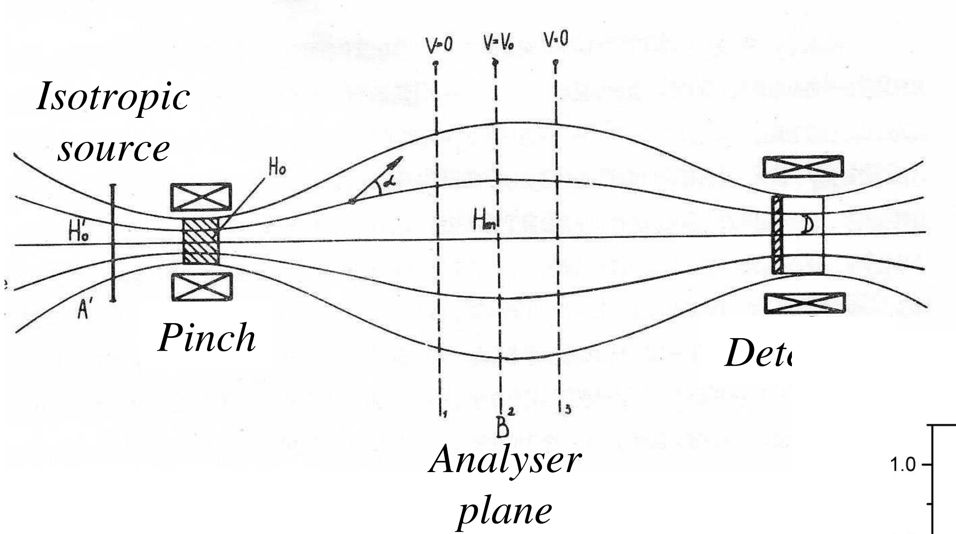
Electrostatic spectrometer with adiabatic magnetic collimation

Charged particle in a slowly varying magnetic field moves *adiabatically*.

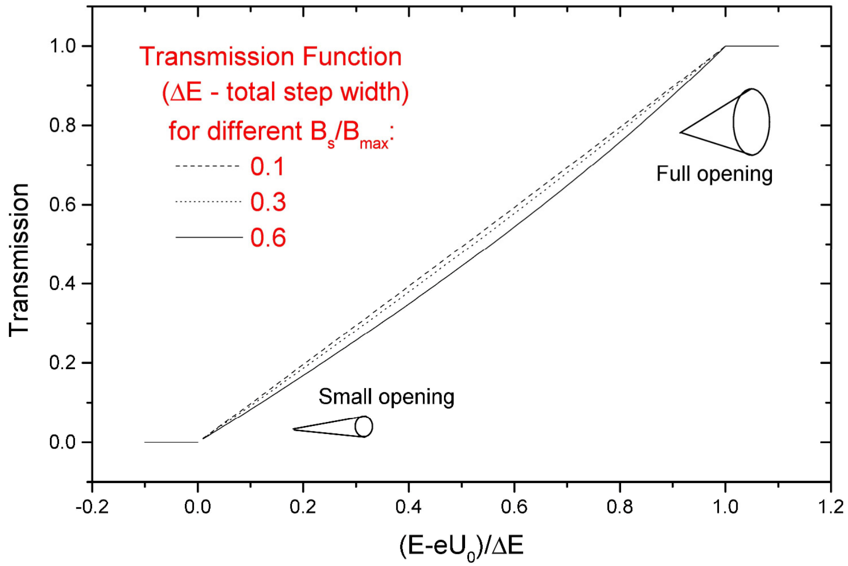
- During transition into weaker magnetic field velocity vectors are aligned along the magnetic field – electrostatic analysis is applicable
- **Spectrometer resolution is decoupled from the source dimensions**
- Electrons from decay on the walls can't reach detector



Electrostatic spectrometer with adiabatic magnetic collimation Principle of operation



$$\Delta E = |eU_0| \frac{B_{analyser}}{B_{pinch}}$$



High
spectrometer resolution
does not depend
on the size of the source

V.M. Lobasev, P.E, Spivak Nucl. Instr. Meth. A240 (1885) 305

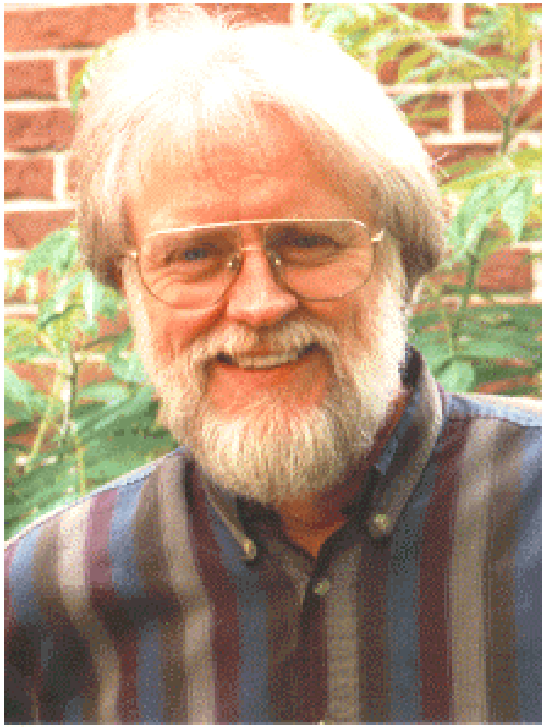
KATRIN - Founders

"Great minds think alike"

Jochen Bonn
7.04.1944 – 27.08.2012

Ernst Otten

Physics Institute
Johannes Gutenberg University
Mainz, Germany



Robert B. Moore

Physics Department,
McGill University
Montreal, Canada

KATRIN - Founders
Windowless gaseous Tritium source for LANL experiment

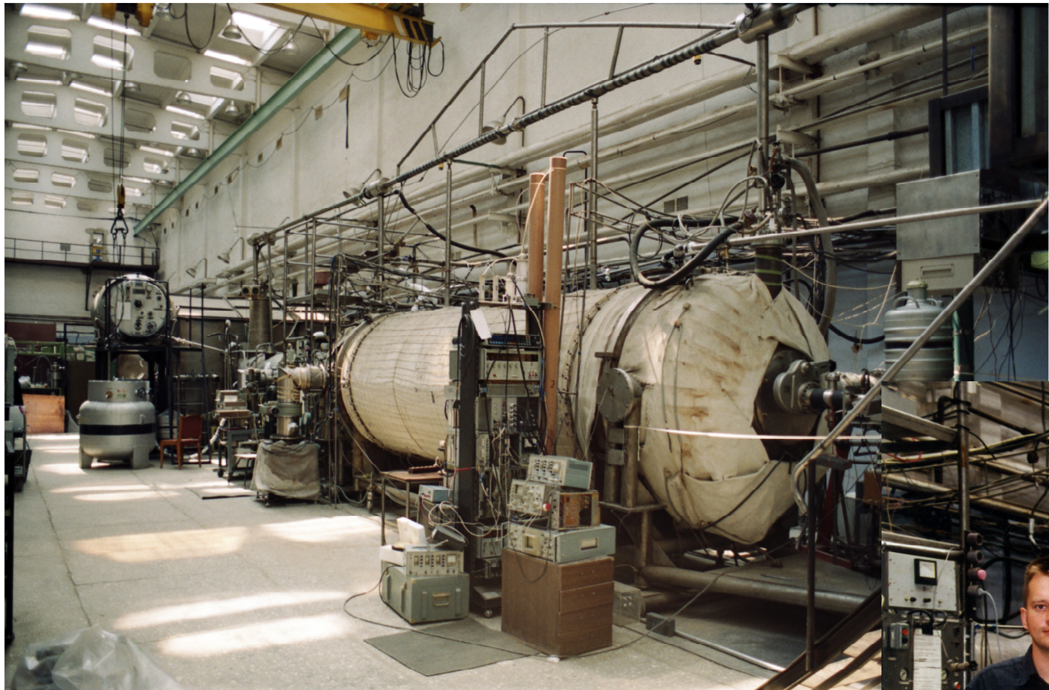
(the lowest systematic up to now)

Hamish Robertson
Center for Experimental Nuclear Physics and Astrophysics,CENPA
University of Washington, Seattle, WA, USA

John Wilkerson
Department of Physics and Astronomy
University of North Carolina, NC, USA

Troitsk ν-mass experiment

Spectrometer:
Length 6,5 м
Electrode dia. 1,2 м
Resolution 3,7 eV
Source dia. 20 мм
Column density $1\cdot10^{17}$ mol/см^2,
Instant activity 0.6 GBk (15 mCi)



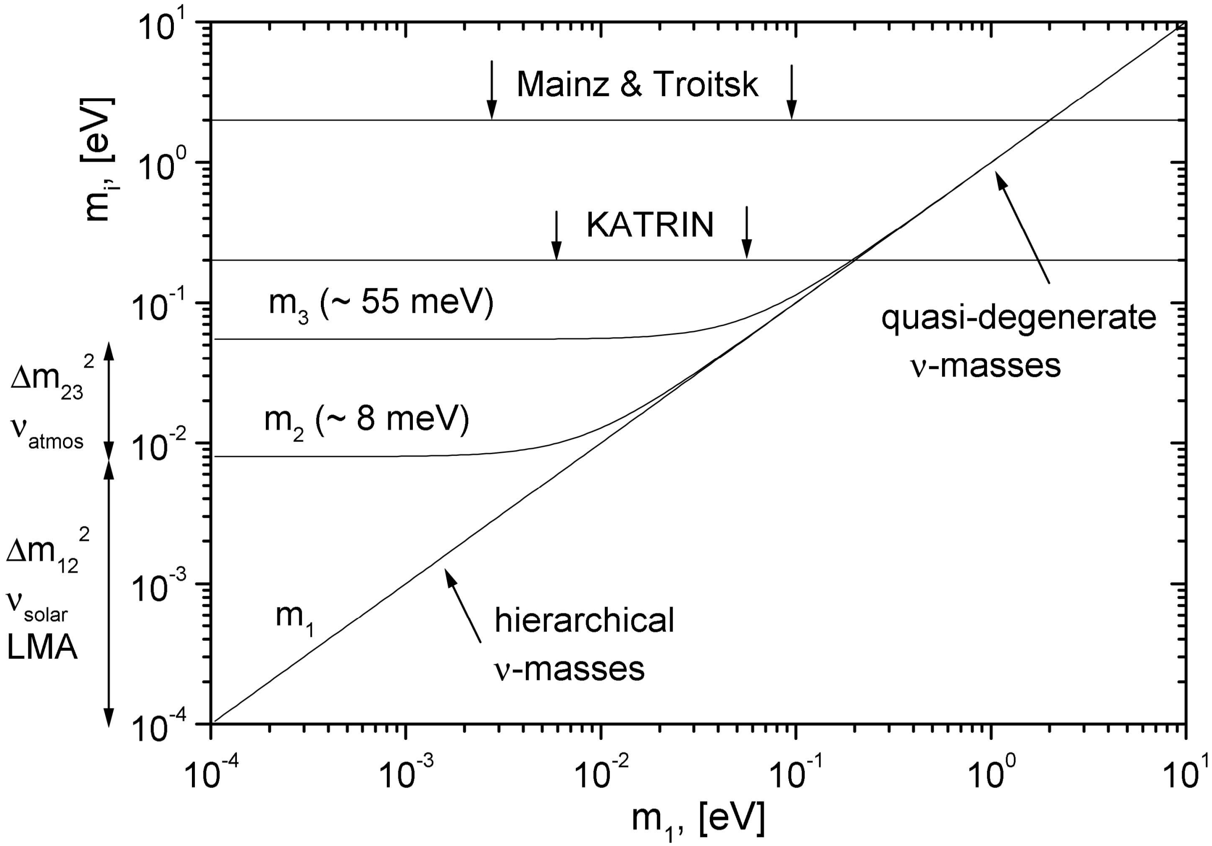
First data were published in 1994

Paper presented at XXVII Int. Conf. on High Energy Physics. Glasgow, UK, 20–27 July 1994

Last data were taken in 2003

≈1998: New challenge:

Mainz and Troitsk reached their limits but it was desirable to improve neutrino mass limit at least by another order of magnitude



Confirm or excludes quasi-degenerate mass regime

Test cosmological neutrino mass limit

Karlsruhe Institute for technology
(former Forschungszentrum Karlsruhe)

Tritium laboratory with license for 40g (0.4 MCi) of Tritium

KATRIN

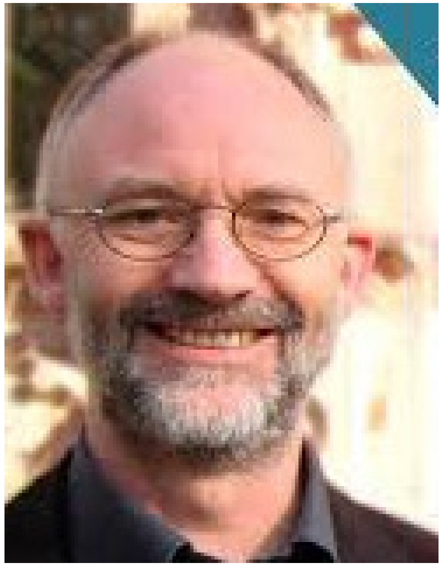
Main design parameters:
Total installation length 70 m
40 superconducting solenoids
Spectrometer diameter 10 m
Inner source diameter 90 mm
Source column density $5 \cdot 10^{17}$ mol/cм^2
Total source activity ≈ 100 GBk (3Ci)
Resolution $\Delta E = 0.9$ eV at 18 keV
Neutrino mass sensitivity (after 3 years of data taking): $m_\nu < 0.2$ eV/c^2

Project started at 2001

First Tritium in the set-up - 2018

2001: Project KATRIN

Co-spokeperson
Prof. Dr. Guido Drexlin
Karlsruhe Institute of Technology
Institut für Experimentelle Kernphysik

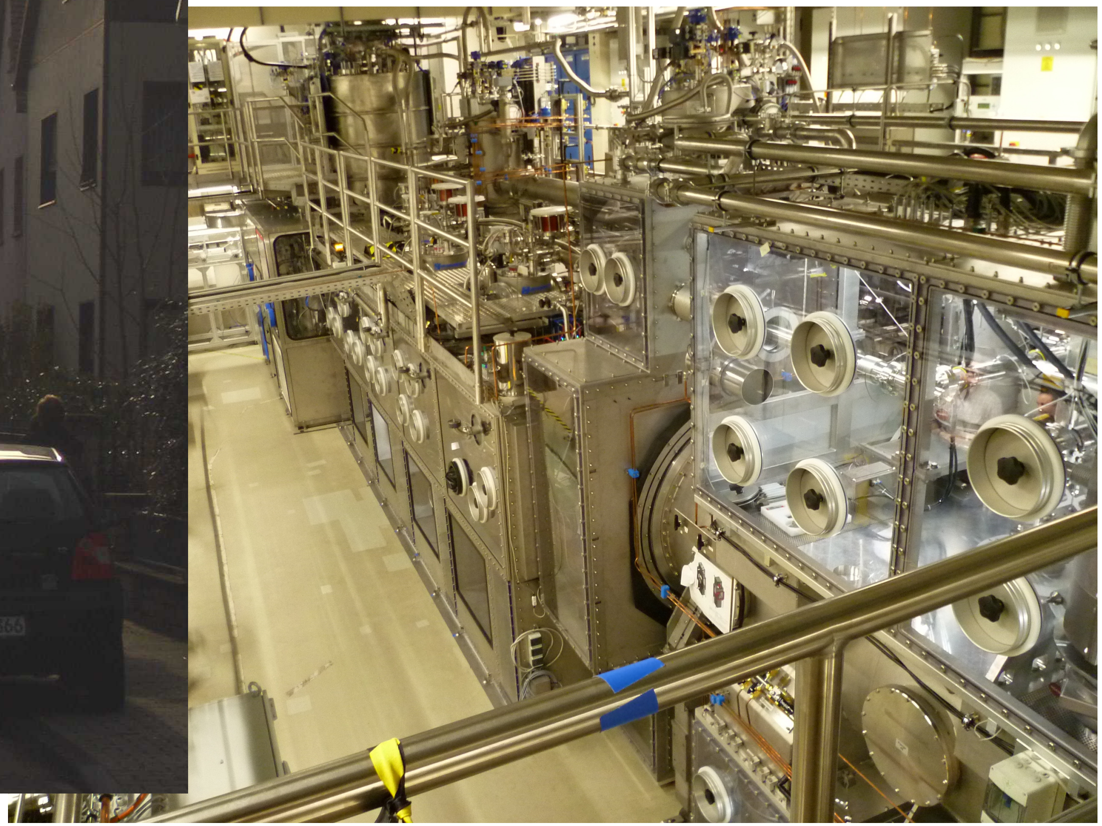


First Head of collaboration board
Prof. Dr. Johannes Blümer
Former Director of the Institute for Nuclear Physics
Karlsruhe Institute of Technology

Co-spokeperson
Prof. Dr. Christian Weinheimer
Universität Münster
Institut für Kernphysik

KATRIN Spectrometer and WGTS
(Windowless Gaseous molecular Tritium Sources)

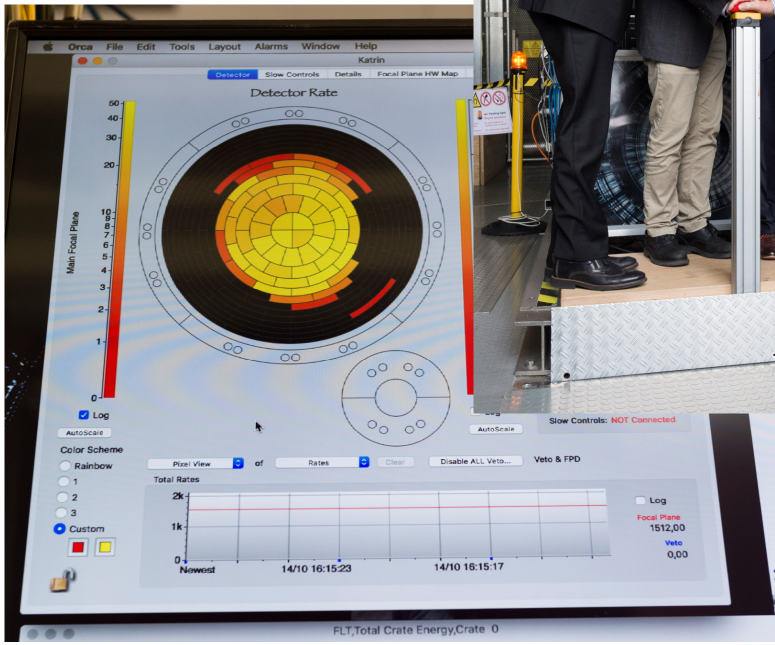
Spectrometer diameter 10 m
Instant source activity
≈ 100 GBk (3Ci)



KATRIN – 2016

14.10.2016 - “First light”

Electrons with 100 eV energy uniformly emitted from “Rear Wall” were detected by focal plane multipixel detector placed at the opposite end of installation at 70 m distance

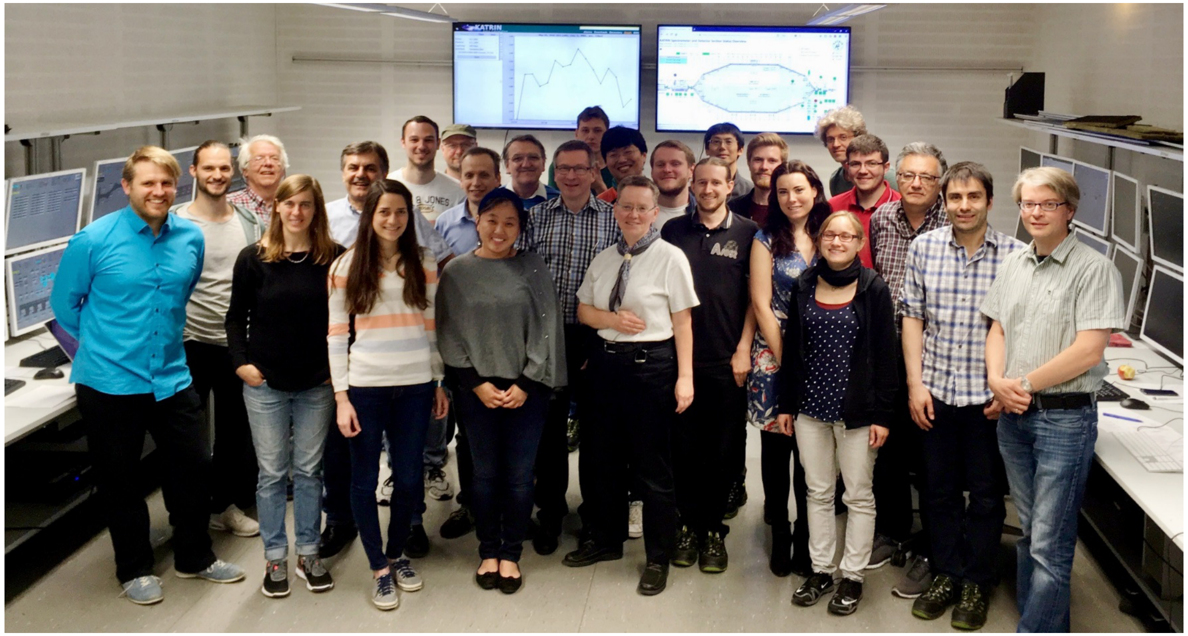


June 11, 2018
KATRIN
“First Tritium”

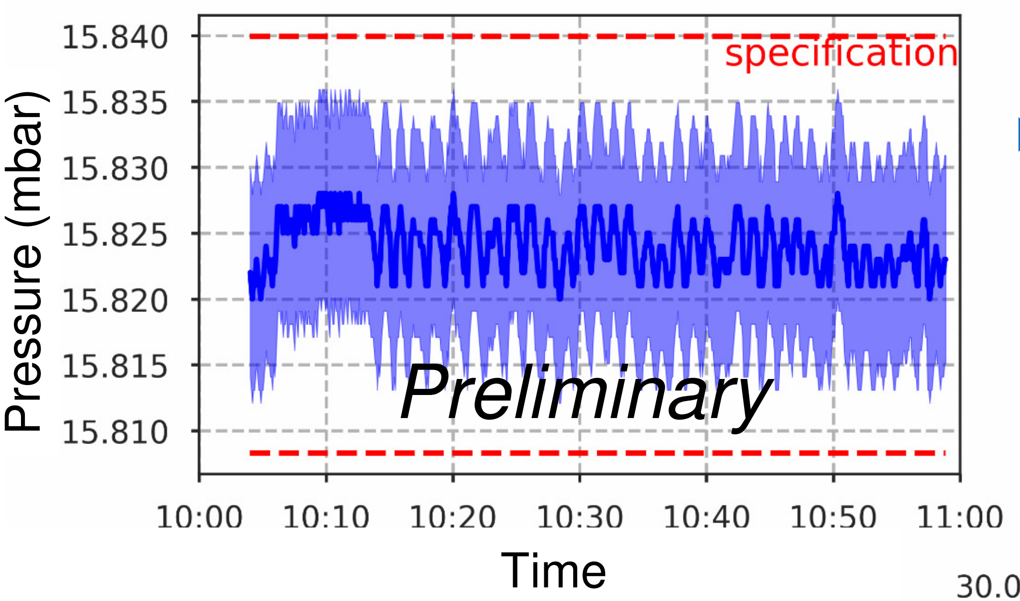
“First Tritium”

Inject known gas mix from prepared sample cylinders (4 doses): 0.5% T atoms in D2 gas (90% nominal column density) mainly as DT.

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

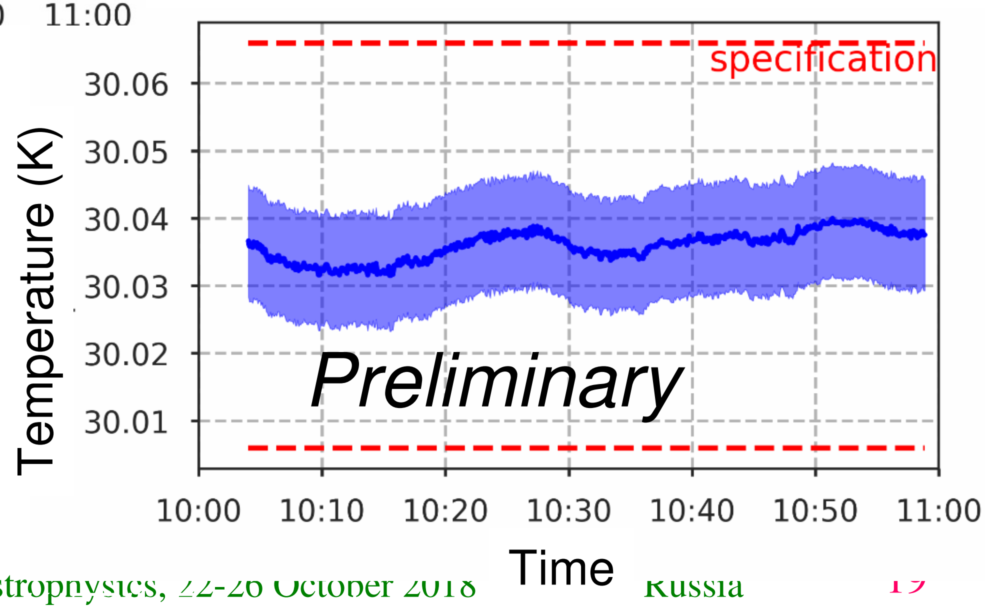


"First Tritium"
WGTS stability



- Pressure in buffer vessel
  - Standard deviation less than 0.2% over 60 min

- WGTS beam-tube temperature
  - Standard deviation less than 0.1% over 60 min

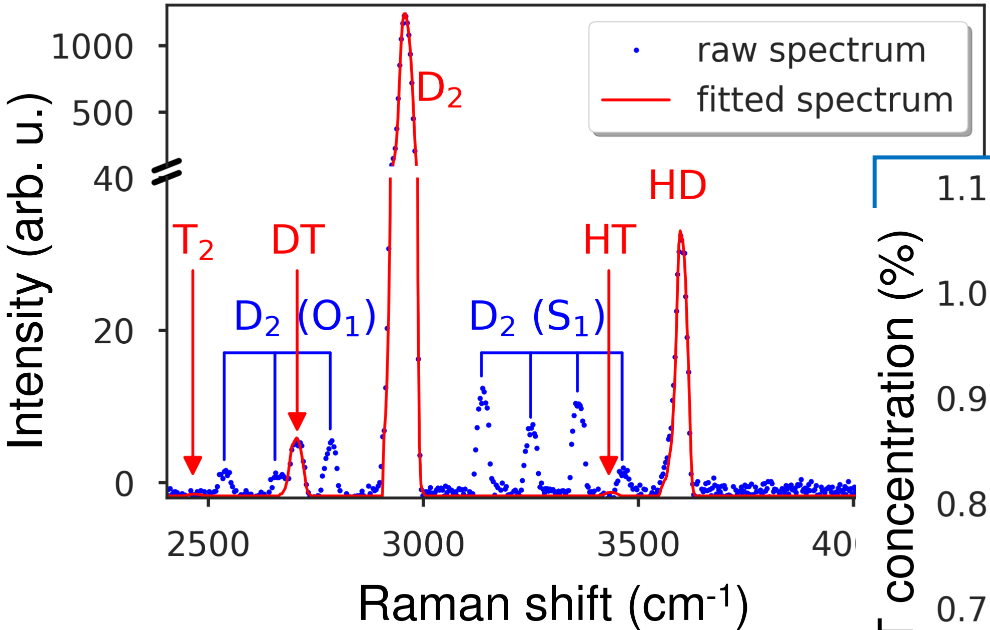


“First Tritium”

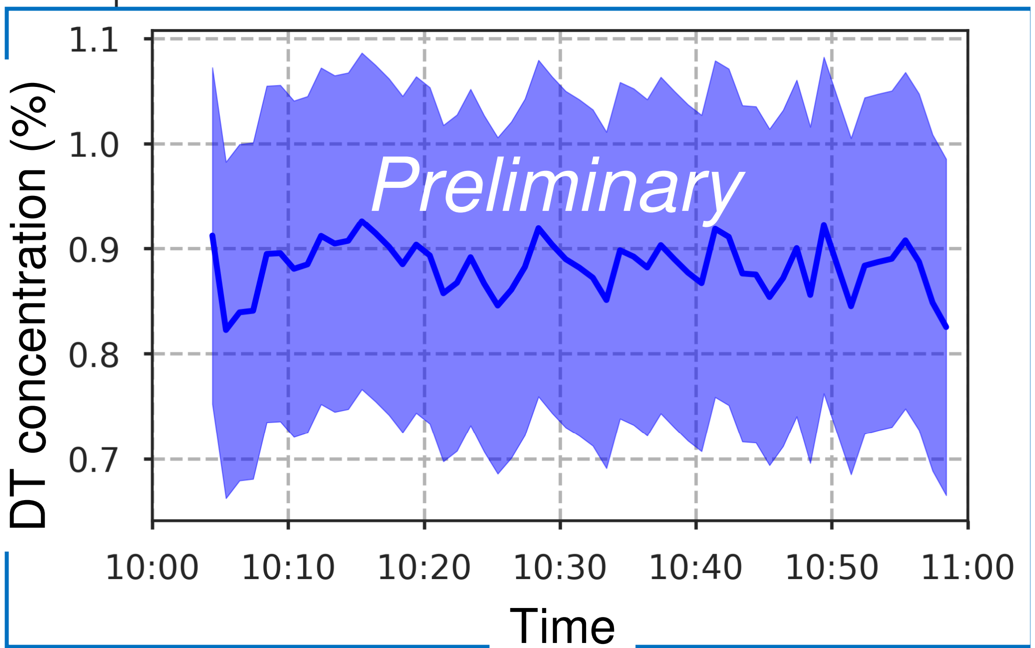
Tritium Concentration stability

Measurement of tritium concentration (mostly bound in DT) with laser Raman spectroscopy

LARA system: Schlösser et al., J. Mol. Spect. ***1044*** *61 (2013)*

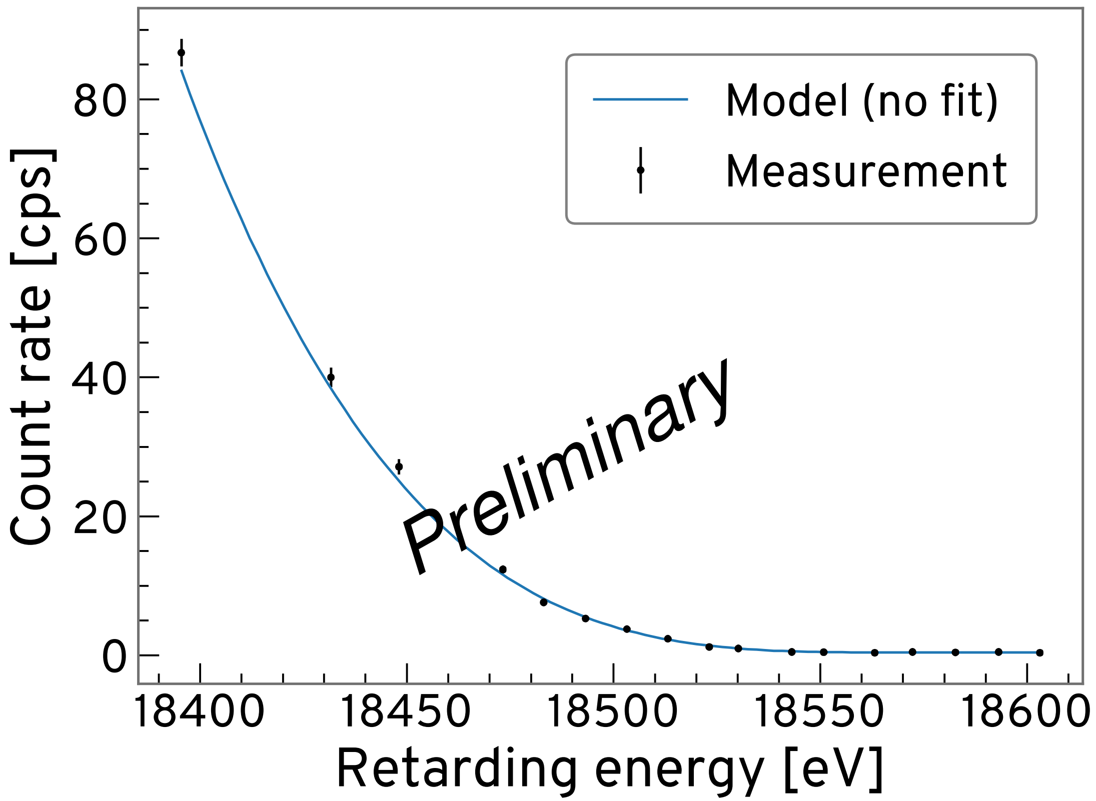


DT conc.: 0.9% (3% variation over scan)



"First Tritium"

First tritium scan – Immediate comparison of data to model



Model initialized with system parameters from slow controls

Very good agreement "out of the box"

2018: September – October measurement phase

with WGTS loops fully operational (ended October 22)

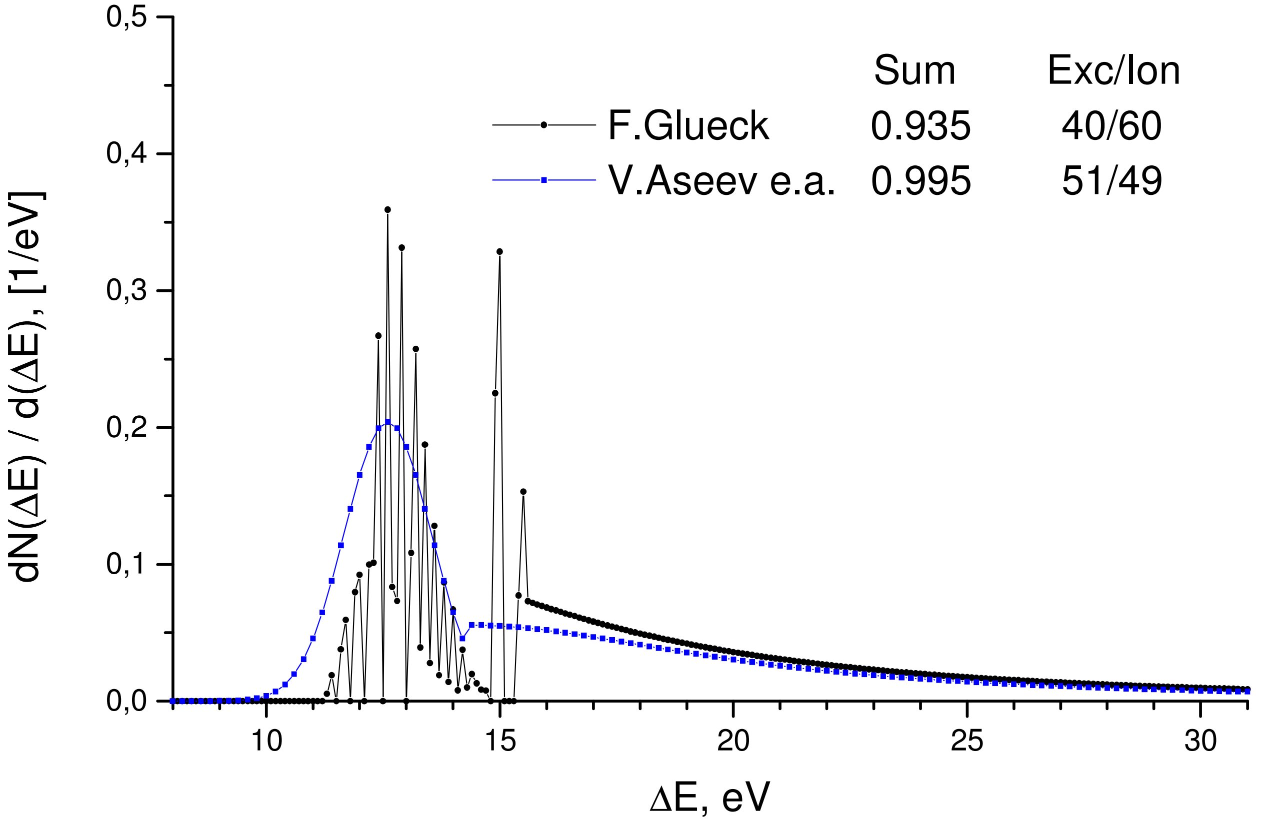
Testing:

- rear system with e-gun
- - e-gun
- - rear wall
- scanning of beam volume with RW e-gun
- Forward Beam Monitor scans and positioning
- column density precise measurement and stability

Studying:

- plasma properties
- transmission functions measurement stability
- Fowler measurements of work functions
- gaseous Kr-83m spectrum shape in vacuum and in gaseous D_2
- background caused by the Rn-222 and it product Pb-210 by injection of an artifical Ra-223 source
- inelastic energy loss spectrum in electron scattering from gaseous D_2
- ....

Inelastic energy loss spectrum puzzle

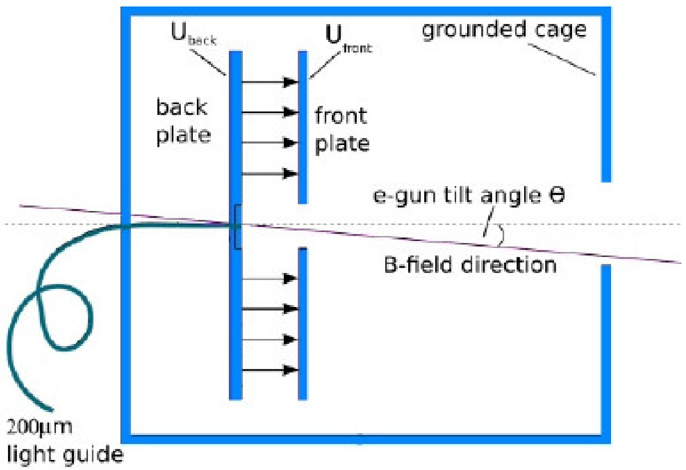


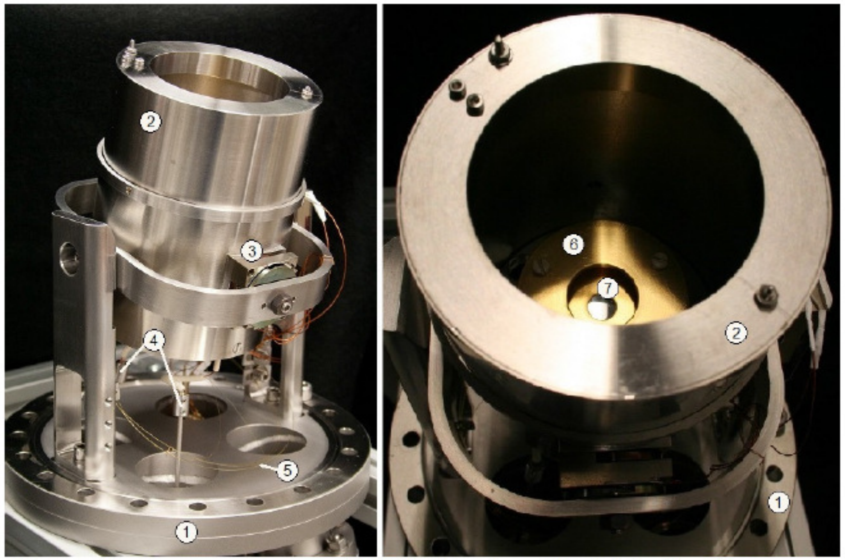
Experiment: V.N. Aseev , Energy loss of 18 kev electrons in gaseous T_2 and quench condensed D_2 films, Eur. Phys. J. D 10 (2000) 39–52 .
Theory: F. Glück, Computer code *Scatter*, unpublished, 2008.

Inelastic energy loss spectrum
eD_2 loss spectrum was measured

Experimental data V.N. Aseev e.a. (Eur. Phys. J. D 10 (2000) 39–52) were taken with resolution 3.7 eV.

New measurement utilizes different approach with new type e-gun (J. Behrens *et al.* Eur.Phys.J. C77 (2017) no.6, 410) that provides resolution ≈ 0.4 eV





(1) vacuum flange
(2) enclosure
(3) attocube motor for position readout
(4) HV feedthrough
(5) optical fibre
(6) front plate
(7) back plate with gold layer

Thank you for your attention !

Back up slides

Электростатический спектрометр с магнитной адиабатической коллимацией Фундаментальные основы

Критерий адибатичности ε:

$$\varepsilon = \frac{|gradB|}{B} r_H << 1 \quad \text{или} \quad \varepsilon = \frac{1}{\omega_H} \cdot |\frac{\dot{B}}{B}| << 1$$

где r_H, ω_H – радиус и частота Ларморовской прецессии

Адиабатический инвариант сохраняется экспоненциально:

$$\frac{\Delta\mu}{\mu} \sim e^{-\frac{1}{\varepsilon}}$$

Л.А. Арцимович, Р.А. Сагдеев Физика плазмы для физиков. Атомиздат, 1979

При соблюдении критерия адиабатичности разрешение спектрометра не зависит от радиуса и кривизны траектории!

2003: завершение сбора данных по массе электронного антинейтрино.

ELSEVIER

Nuclear Physics A719 (2003) 153c–160c

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

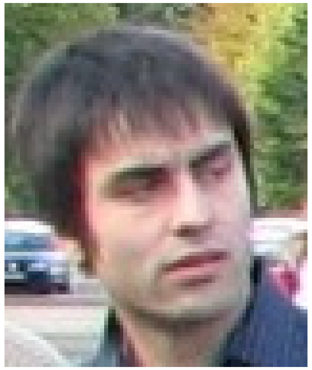
The search for the neutrino mass by direct method in the tritium beta-decay and perspectives of study it in the project KATRIN

V.M. Lobashev[a]

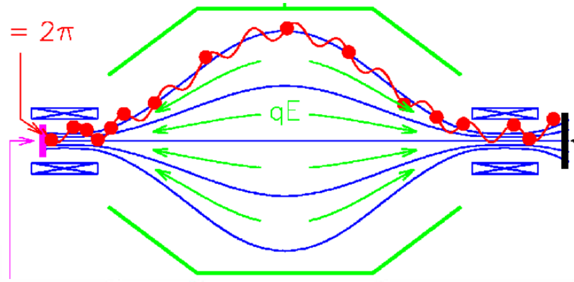
[a]Institute for Nuclear Research of the Russian Academy of Sciences 60th October Anniv. prospect 7a, 117312 Moscow, Russia

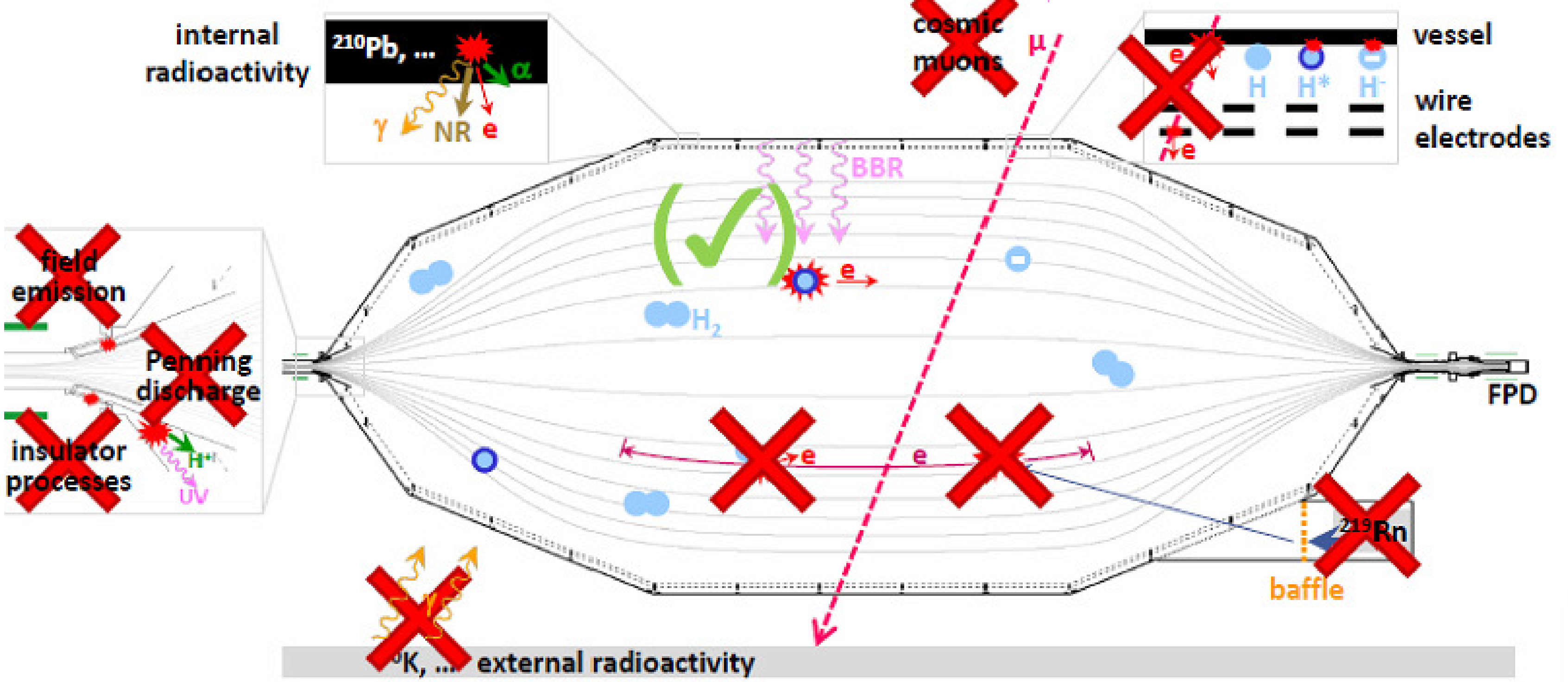
The updated results of the search for neutrino mass in the tritium beta-decay on the Troitsk nu-mass and Neutrino Mainz set-ups are presented. Both groups give an upper limit for the neutrino mass at 95% $m_\nu < 2.05\ eV/c^2$ in Troitsk and $m_\nu < 2.2\ eV/c^2$ in Mainz. Further improvement is limited both by statistic and systematic errors. In order to enter in the cosmologically important sub-electronvolt area the collaboration of groups from Karlsruhe Forschungszentrum, Mainz, Troitsk et al. proposed a new advanced project KATRIN. The status of the project is presented.

KATRIN – since 2013
Main spectrometer own background studies



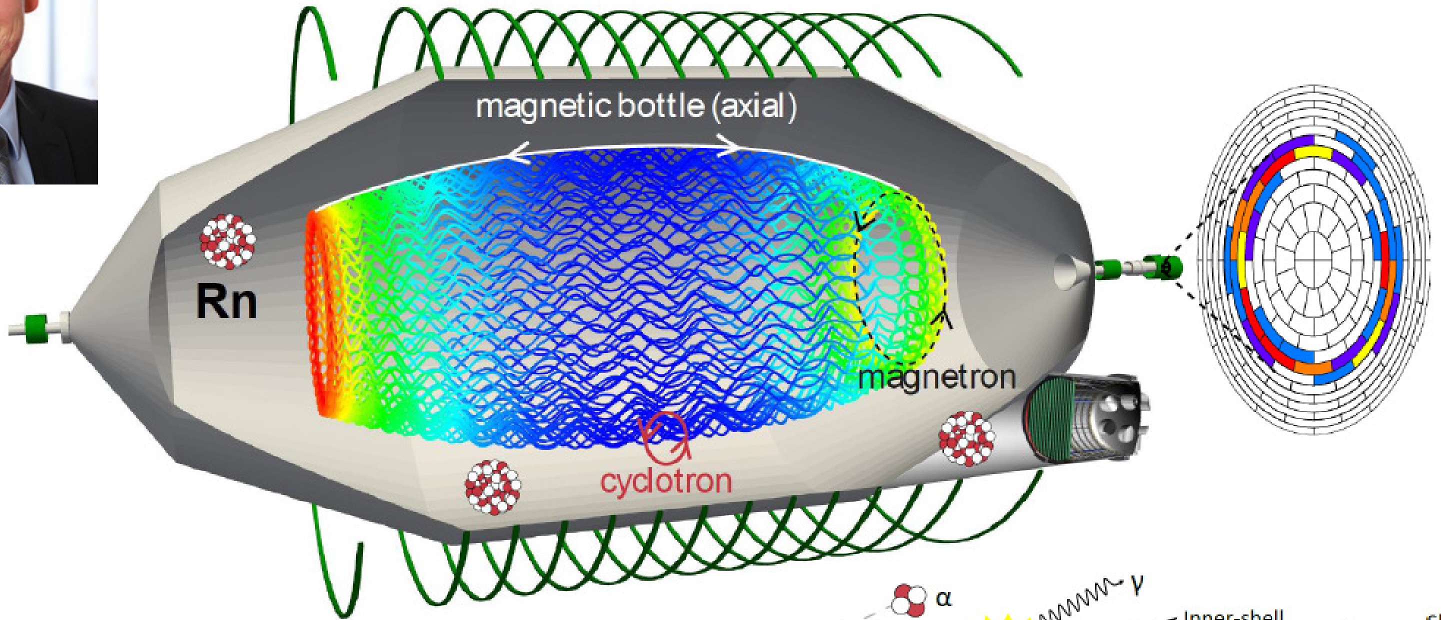
Background studies summary
(F.Fraenkle talk at CM 09.03.2016)
will be published soon



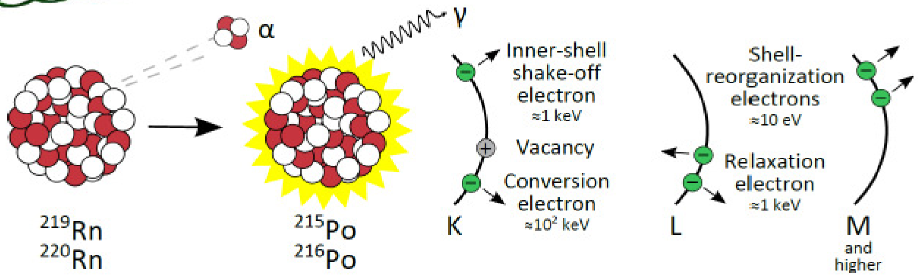


Radon induced background (≈ 400 mHz)

Fabian Harms talk at KATRIN CM, March 2017,
will be published soon



KATRIN Main Spectrometer has about 100% detection efficiency for Rn decay when it happens in the volume

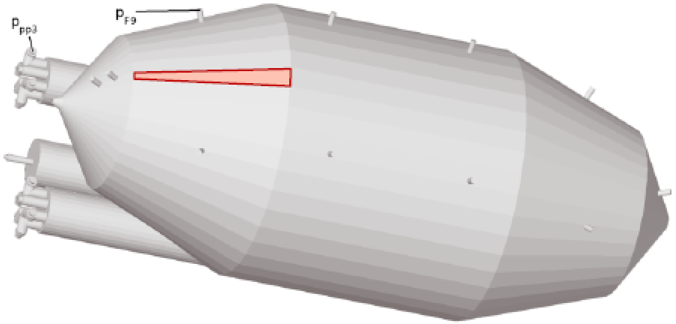


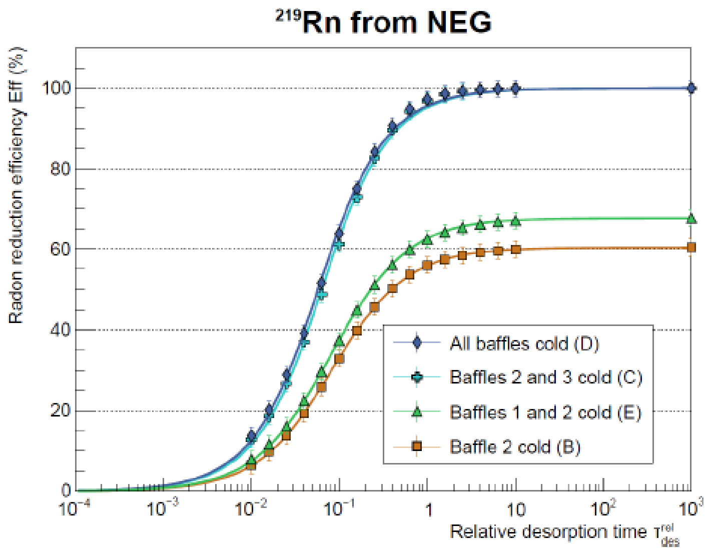
^{219}Rn vs ^{220}Rn

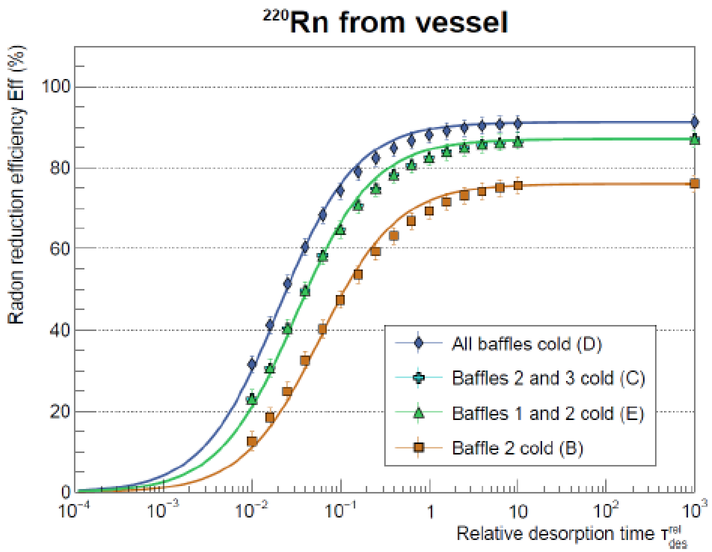
Baffle efficiency

MolFlow+ simulations

G. Drexlin et al., Vacuum, Volume 138, Pages 165 – 172, 2017







Radon background was reduced by 97% after baffles at nitrogen temperature were installed in pumping ports

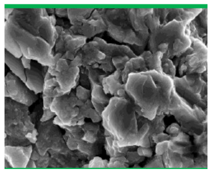
Two known sources of Rn:

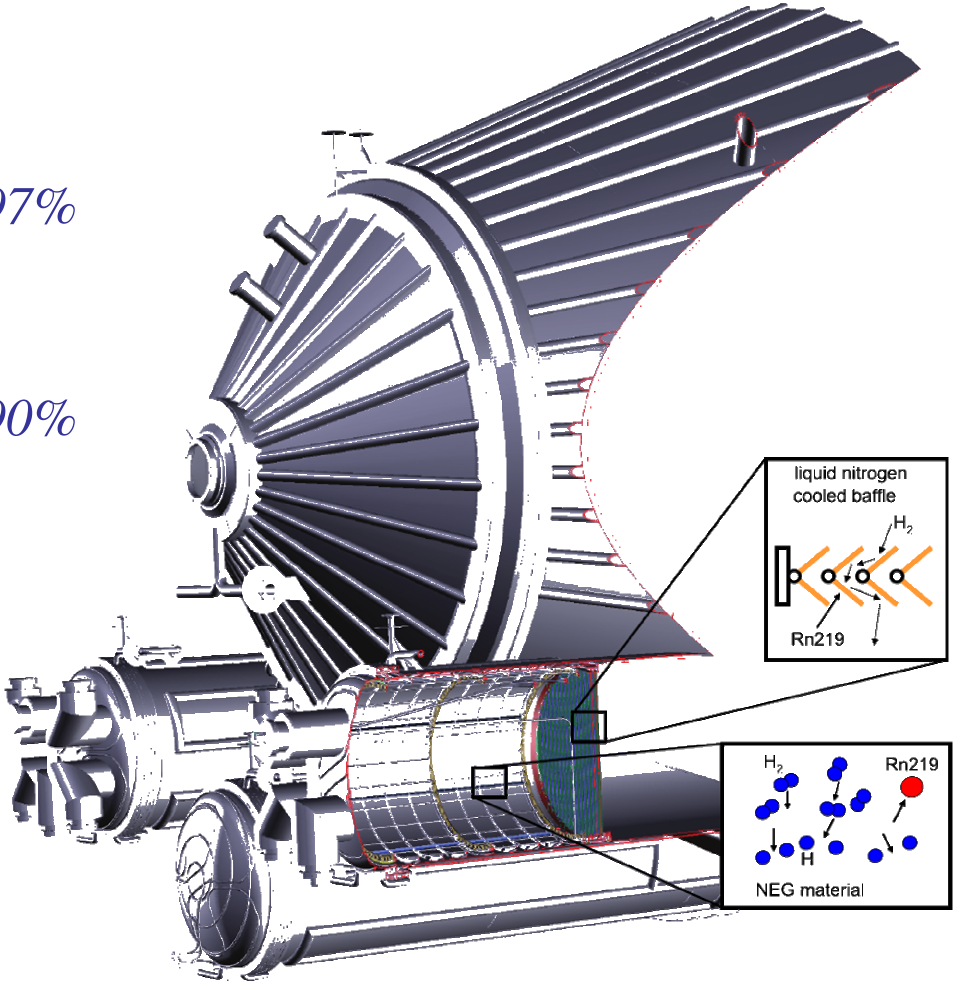
^{219}Rn from NEG getter pump

Interception efficiency by cold baffles 97%

^{220}Rn from welding → *excluded*

~~*Interception efficiency by cold baffles 90%*~~





KATRIN – 2016

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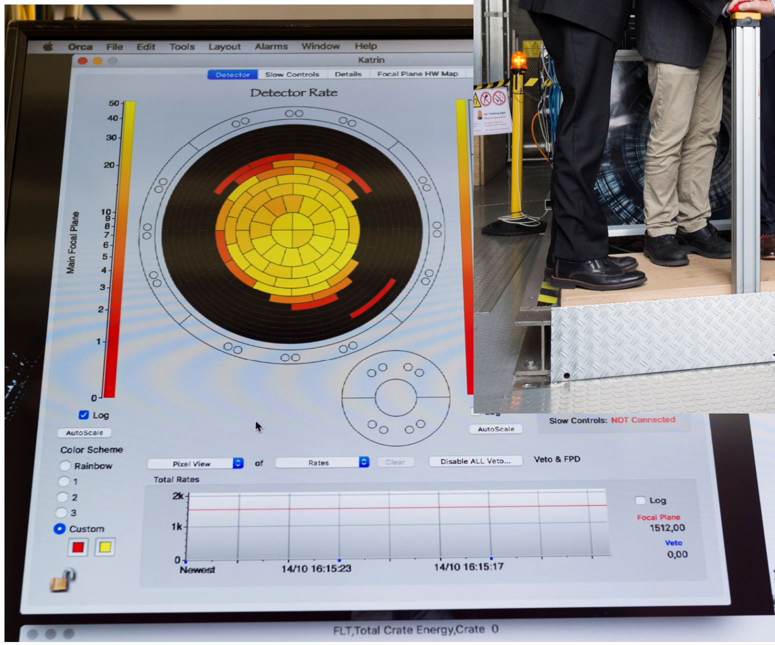


New type of background was observed

Observations:

1. Background is generated uniformly in spectr. volume.
2. Background rate is independent on vacuum level.

Long term puzzle:

A background exists that is generated by low energy (below 1 keV) electrons that appear in the center of spectrometer vessel. It was theoretically and experimentally proven that because of magnetic collimation electrons with such a low energy couldn’t be emitted from the vessel wall or any solid electrode.

^{206}Pb-induced H*-Rydbergs – a coherent spectrometer background model

G.Drexlin at KATRIN CM, March 2016

will be published soon

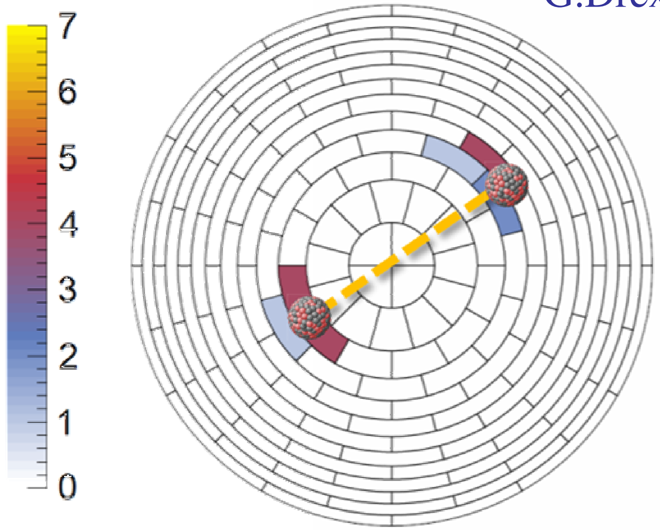
Rydberg states act as **long-lived neutral messengers** from **surface** processes

KATRIN spectrometer surface is about 100 larger than in Mainz/Troitsk cases

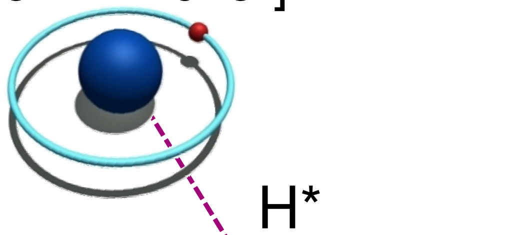
A **Rydberg atom** is an excited atom with one or more electrons that have a very high principal quantum number n, and $r \sim n^2$, $E_{ion} \sim 1/n^3$ Thus Rydberg atom is extremely large with loosely bound valence electrons, easily perturbed or ionized by collisions or external fields (Wikipedia).

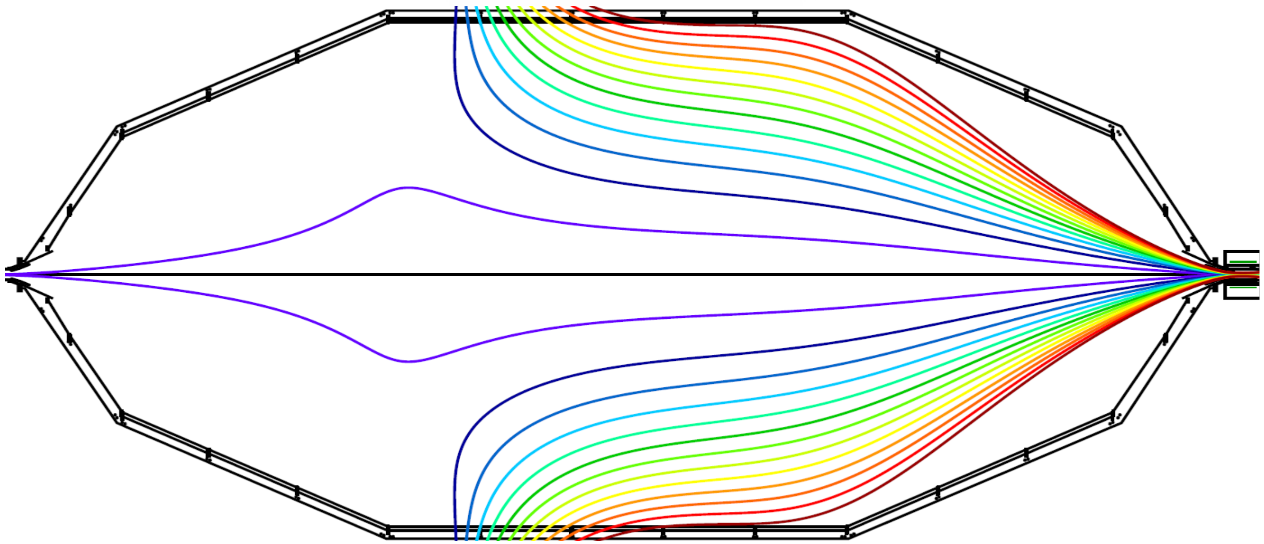
New obeservation method - a surface microscope by asymmetric B fields

G.Drexlin at KATRIN CM, March 2016



Large number of 2-hit cluster (20-50 electrons per event) [master A. Müller]



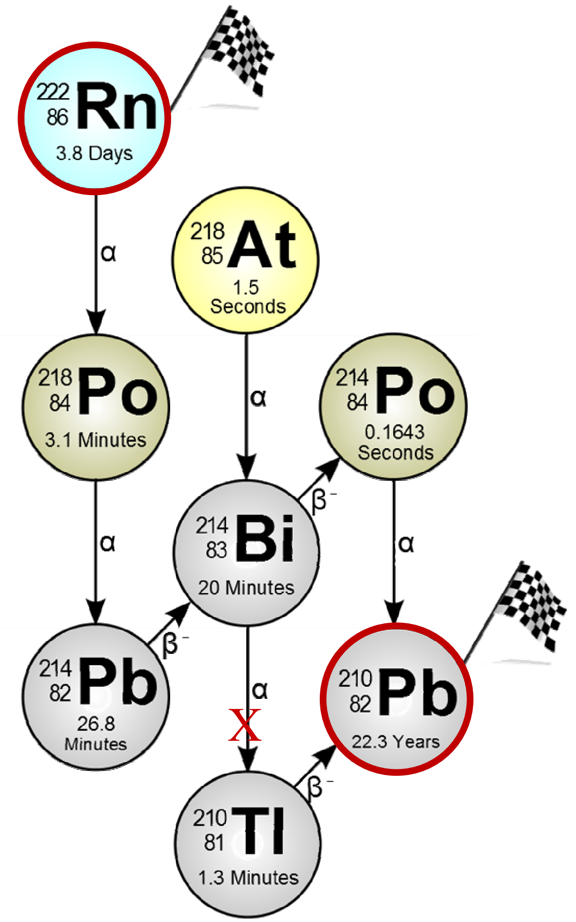


generation of Rydberg states H*

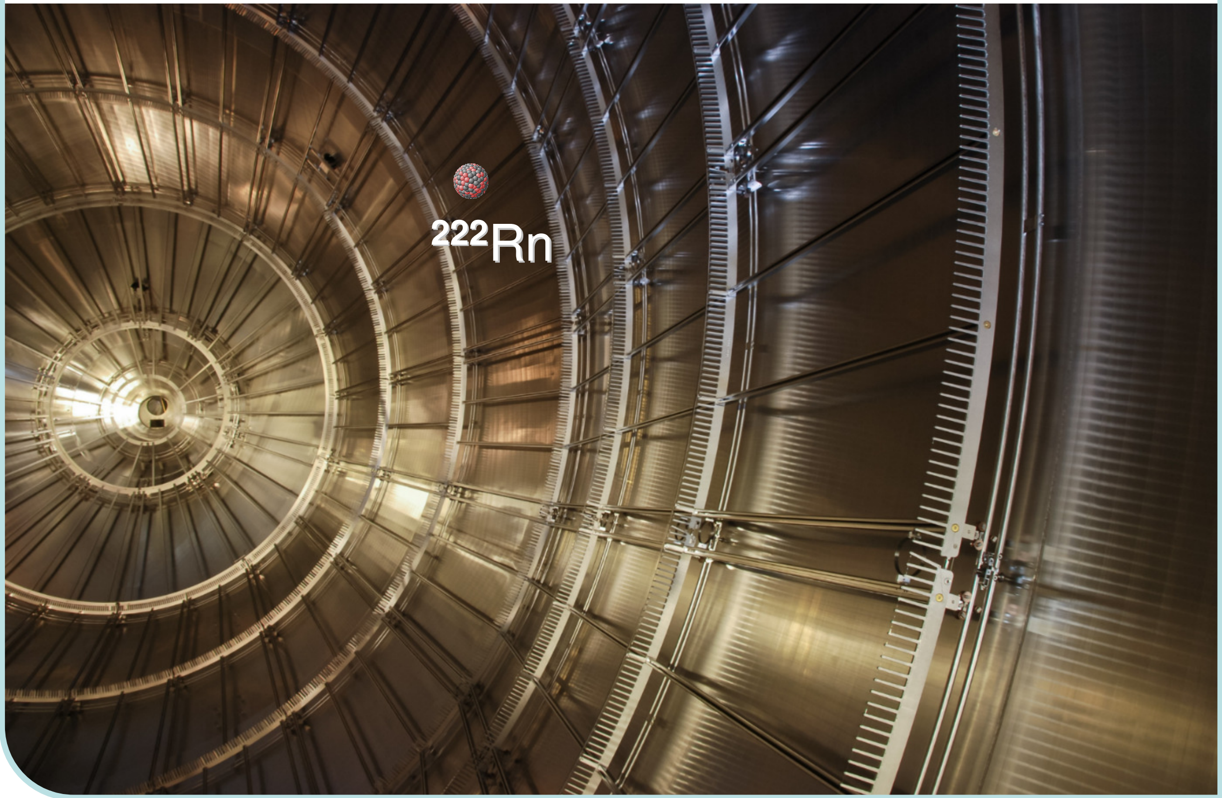
Rn-222 from forced spectrometer venting

G.Drexlin at KATRIN CM, March 2016

- Rn-222 decays in inner volume
  - short-lived progenies decay to Pb-210
  - complex transport (aerosols, electrostat. fields)



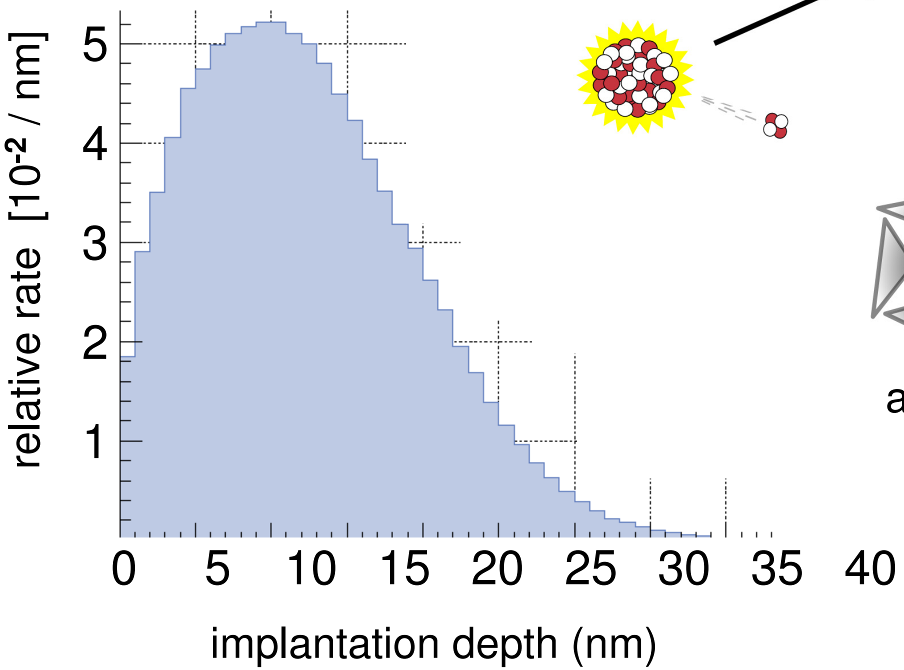
U-238 decay chain

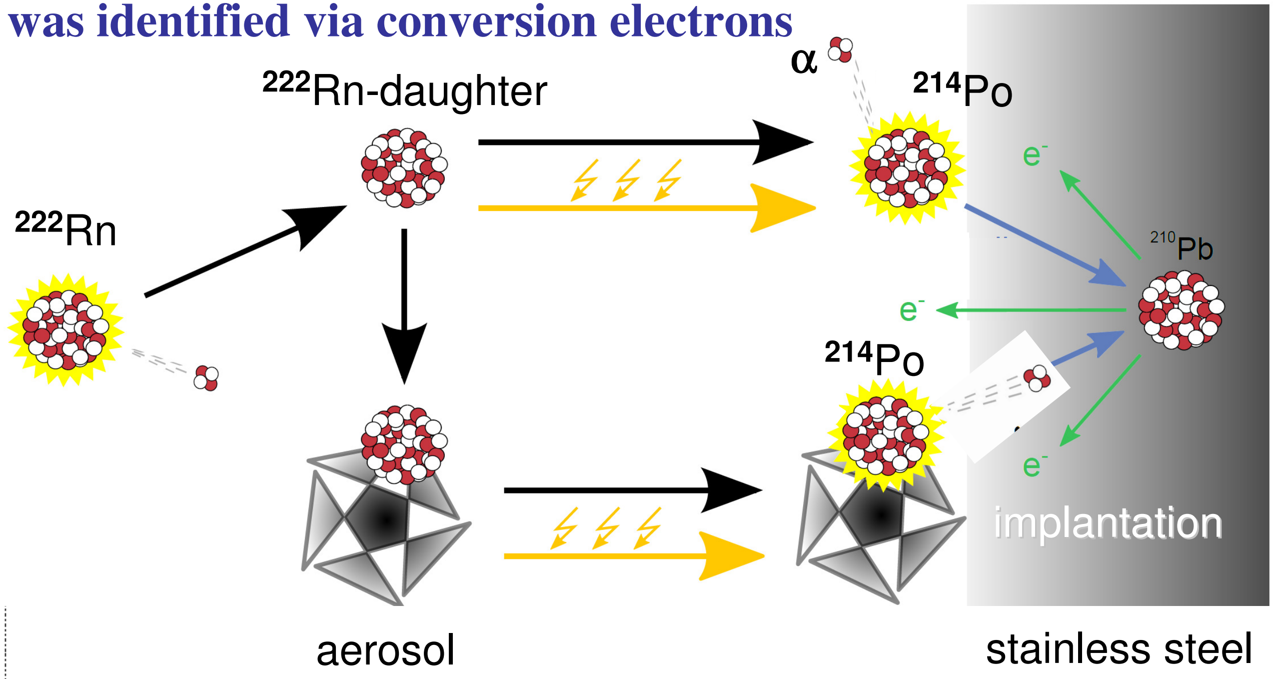


Rb-210 deposition on inner surface

G.Drexlin at KATRIN CM, March 2016

- implantation: maximum depth of Pb-210 d < 40 nm [PhD F. Harms]
  incorporation into aerosols: sticking to inner surface
- **^{210}Pb-decay on the wall was identified via conversion electrons**



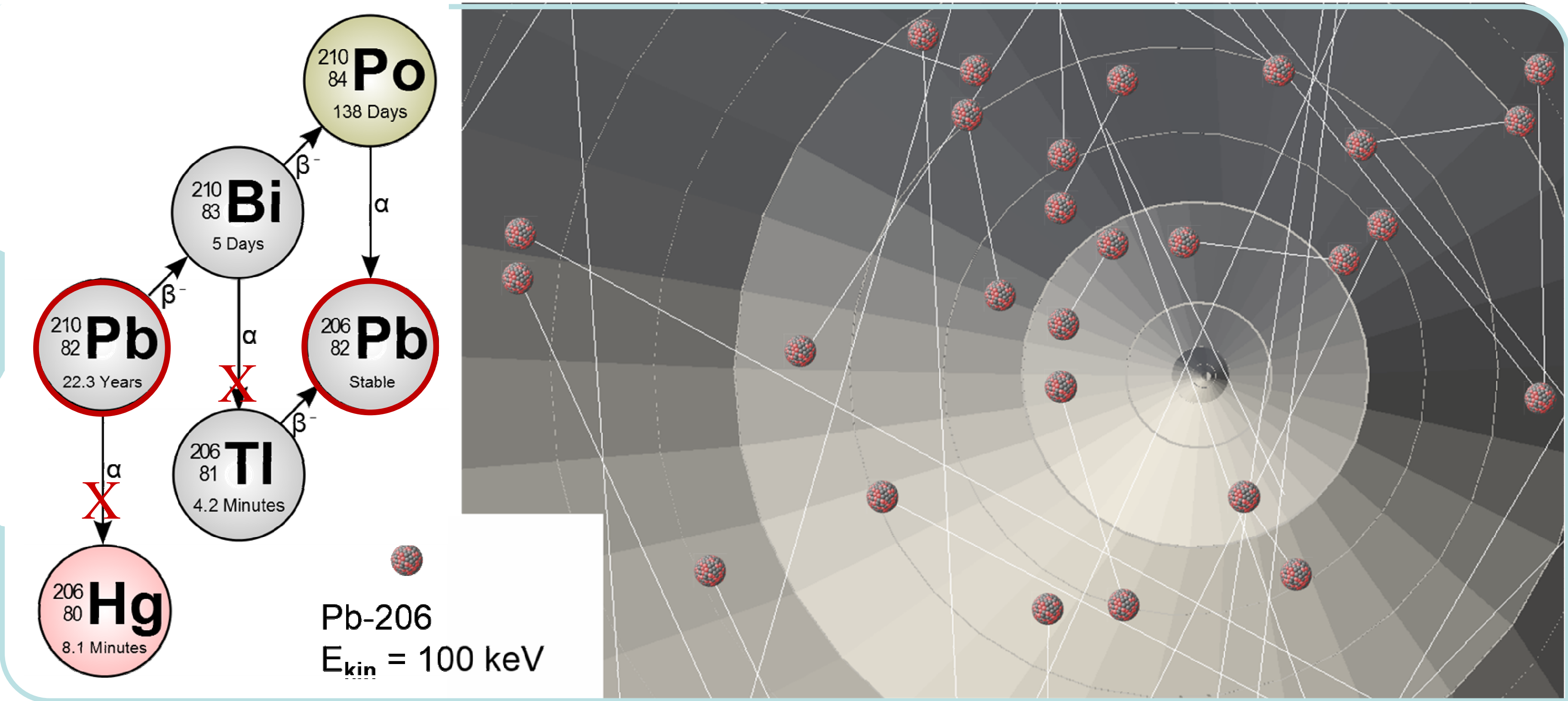


- Pb-210 implanted in stainless steel
- Pb-210 incorporated in aerosols

^{206}Pb ions from ^{210}Pb chain

G.Drexlin at KATRIN CM, March 2016

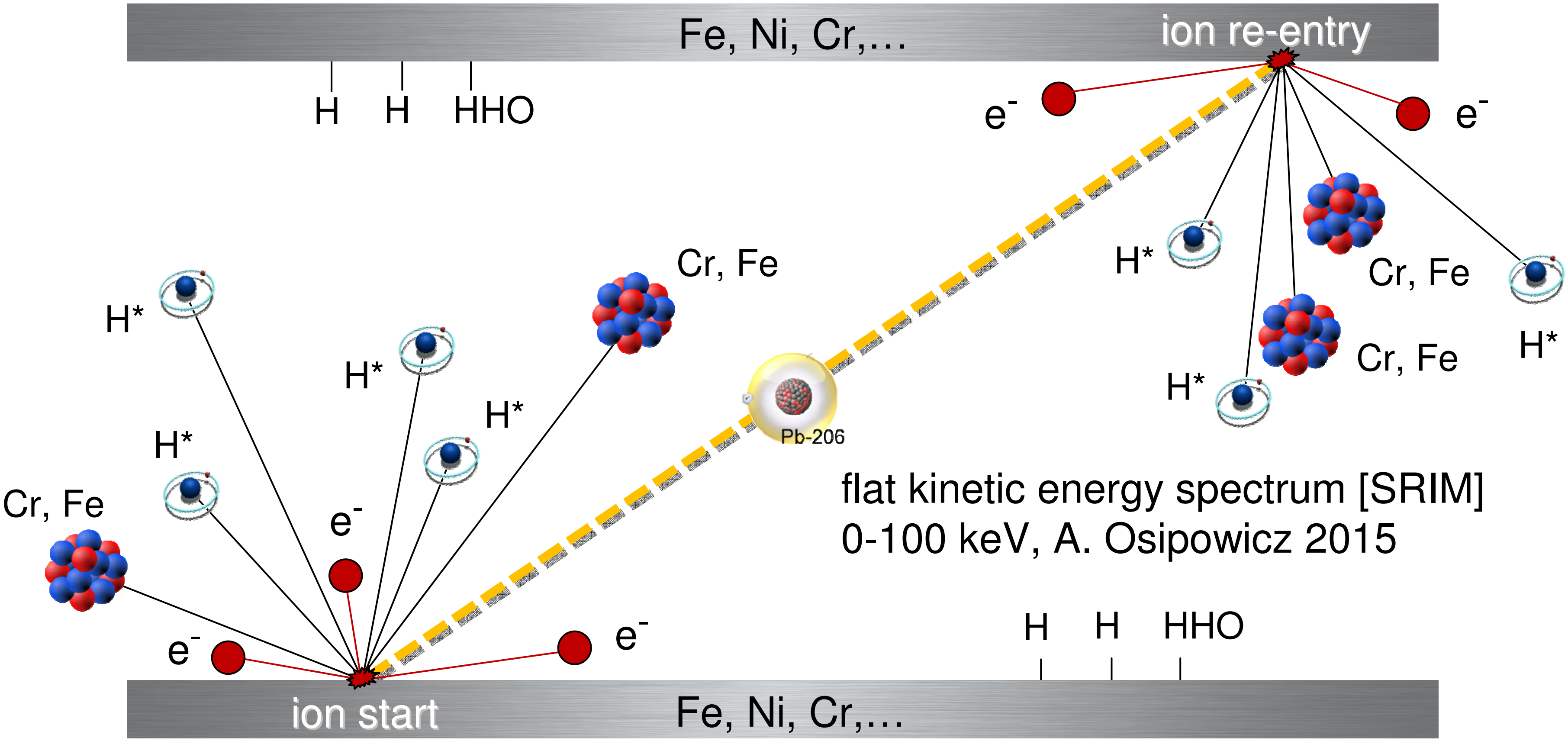
- measured rate (in 2π) ~ $A_{Pb\text{-}210}$ ~ (900 ± 100) s^{-1} [PhD F. Harms, 2015]
- $A_{Pb\text{-}210}$ upper limit for $A_{Pb\text{-}206}$: **^{206}Pb recoil ions with E_{kin} < 100 keV**



^{206}Pb ions as source of H* & electrons

G.Drexlin at KATRIN CM, March 2016

- ^{206}Pb-ions are proposed to generate:
  - low-energy electrons (E<1eV) with exponential multiplicity distribution
  - large number of Rydberg H*-atoms (~100) & Fe, Ni, Cr, O atoms (~20)



flat kinetic energy spectrum [SRIM]
0-100 keV, A. Osipowicz 2015

New Final States
Spectrum calculations

Alejandro Saenz, Institute of Physics Humboldt-University of Berlin

Talk at KATRIN CM, March 2017

Will be published soon

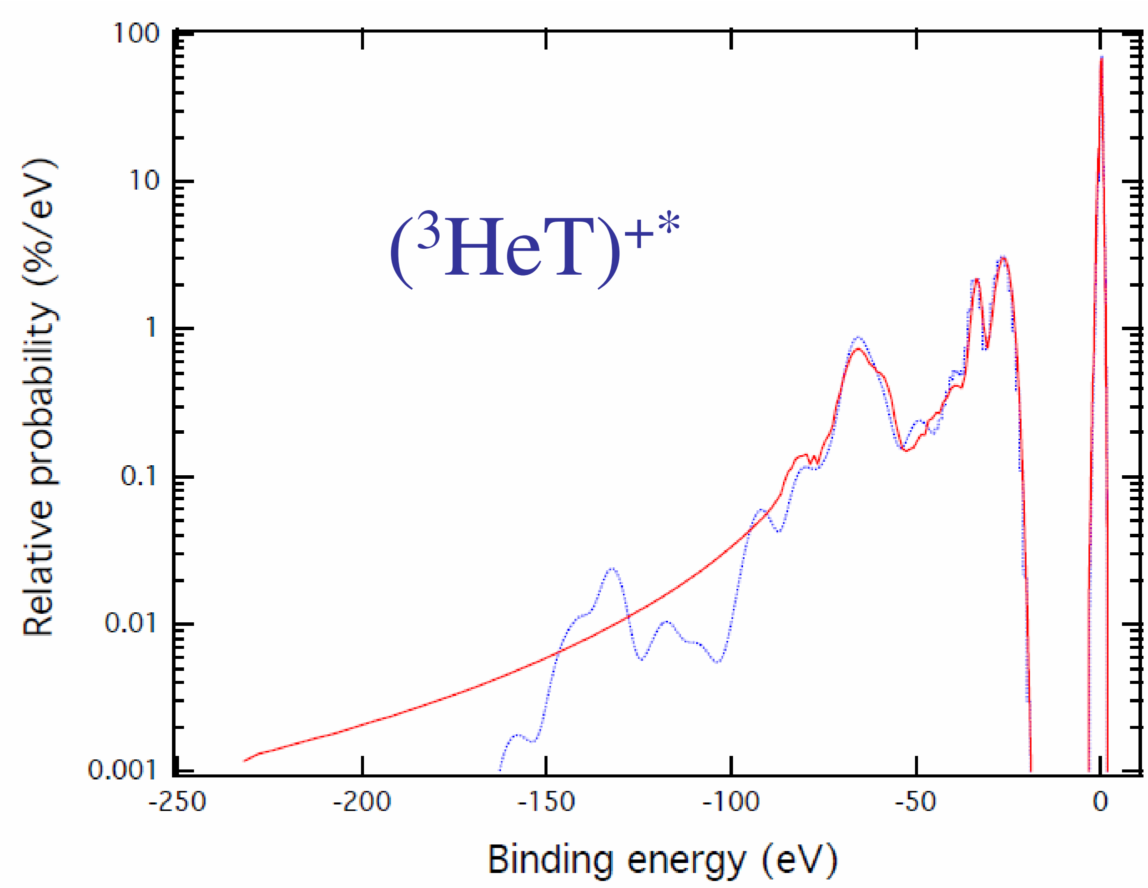
Summary and outlook

- Cross-check of the old calculation using a completely new approach for both electronic and nuclear part.
- Automatized set-up for arbitrary isotope mixtures, temperatures, and fit ranges.

Outlook:

- Continue convergence studies $\longrightarrow$ error estimate.
- Inclusion of non-adiabatic corrections for all states.
- Analysis of final molecular products/fragments (for TRIMS experiment).
- Energy loss (electron scattering).
- Consider non-Σ states (non-adiabatic effects, recoil effect, corrections to sudden approximation).

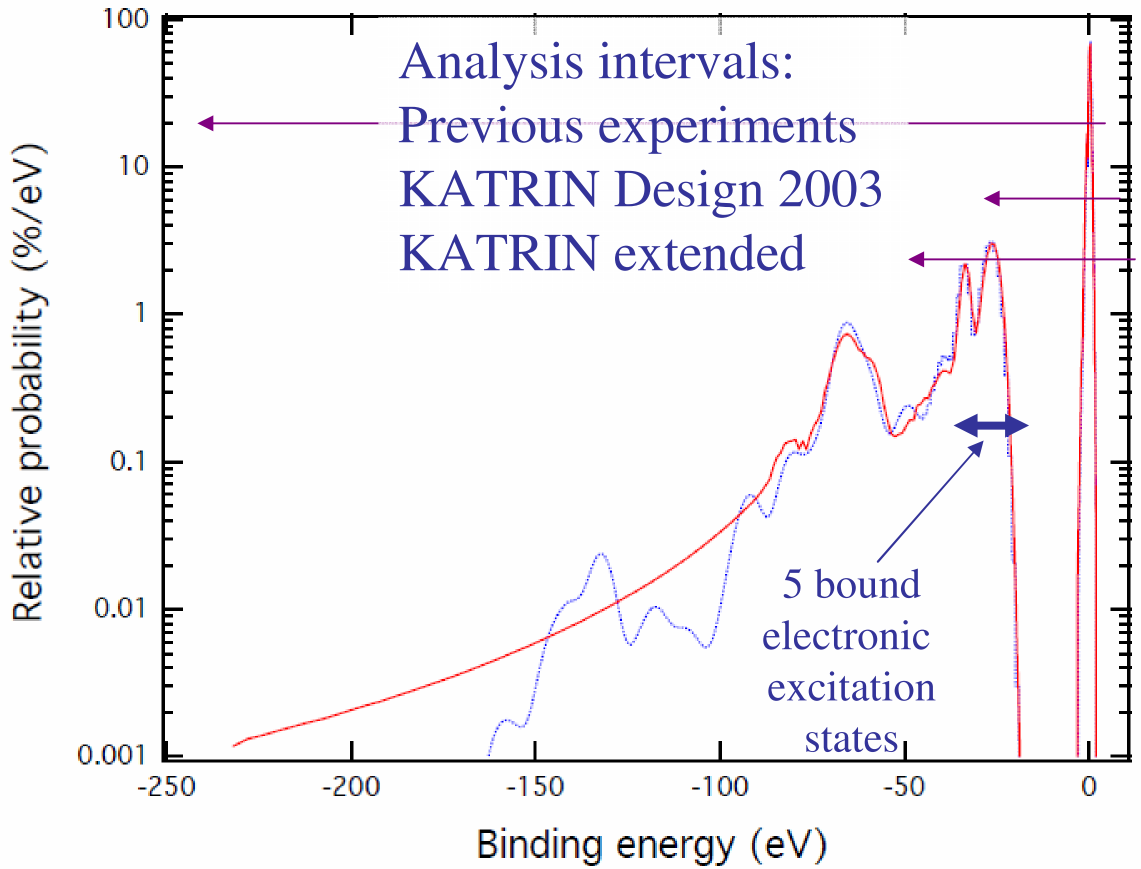
Electronic part of the Final States Spectrum



Picture from
L. I. Bodine, D. S. Parno, and R. G. H. Robertson
Phys. Rev. C 91, 035505

Calculations by
Saenz, S. Jonsell, and P. Froelich, Phys. Rev. Lett. 84, 242 (2000).
– red
O. Fackler, B. Jeziorski, W. Kolos, H. J. Monkhorst, and K.Szalewicz, Phys. Rev. Lett. 55, 1388 (1985).
– blue

Electronic part of the Final States Spectrum



Provided that calculation of Final States Spectrum electronic part is robust data analysis interval could be extended.

KATRIN sensitivity with increased background 240 meV (90% c.l.) after 3 years

(K.Valerius at "Neutrino – 2016")

Background reduction measures were studied

- optimized scanning strategy
- increased range of spectral analysis
- flux tube compression by increasing $B_{analysis}$