KATRIN-2017:
Background studies, sensitivity.

N.Titov, INR RAS
for the KATRIN Collaboration

International Session-Conference of SNP PSD RAS
"Physics of Fundamental Interactions"

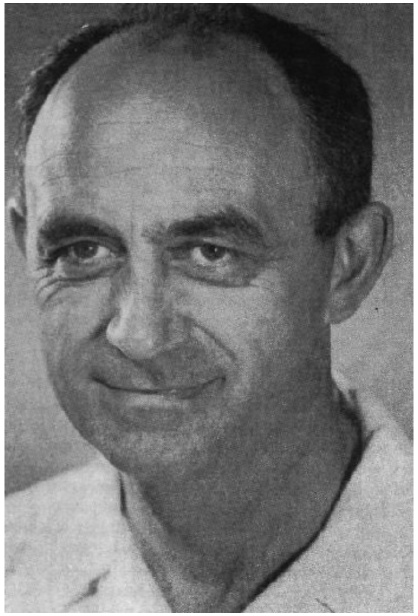
Dedicated to 50th anniversary of Baksan Neutrino Observatory

Kabardino-Balkarian State University. June 6, 2017. Nalchik

Outline:

1. The 83-year long search for neutrino mass.
   - Tritium β-decay spectrum analysis – best choice
   - Era of Electrostatic Spectrometer with Adiabatic Magnetic Collimation (MAC-E filter)
   - New challenge: Project KATRIN
2. October 14, 2016 - KATRIN ”First light”
3. KATRIN background studies, new players:
   - Radon
   - Rydberg states
4. KATRIN sensitivity
   - Final state spectrum – new calculations
   - Current expectations

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)

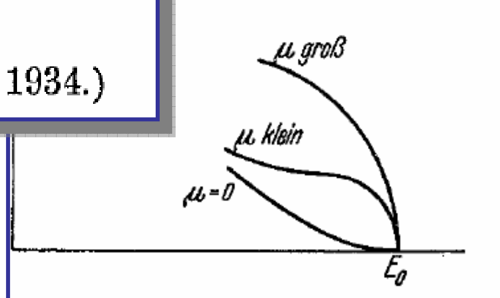
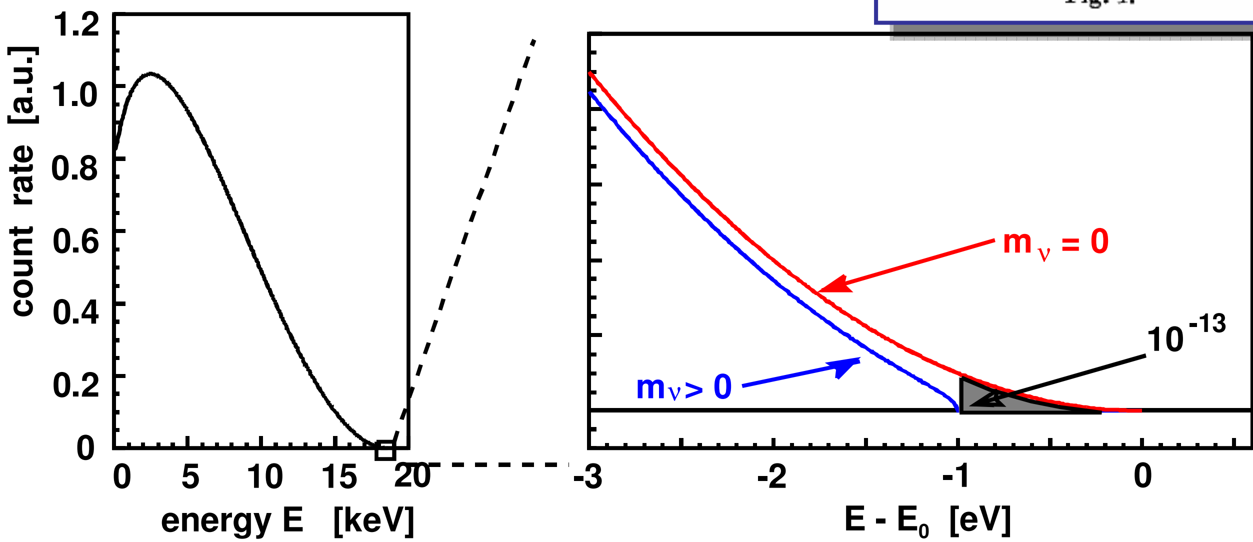


Fig. 1.



1948: First experiment with tritium

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

$m_{\nu} < 1$ кэВ/c^2

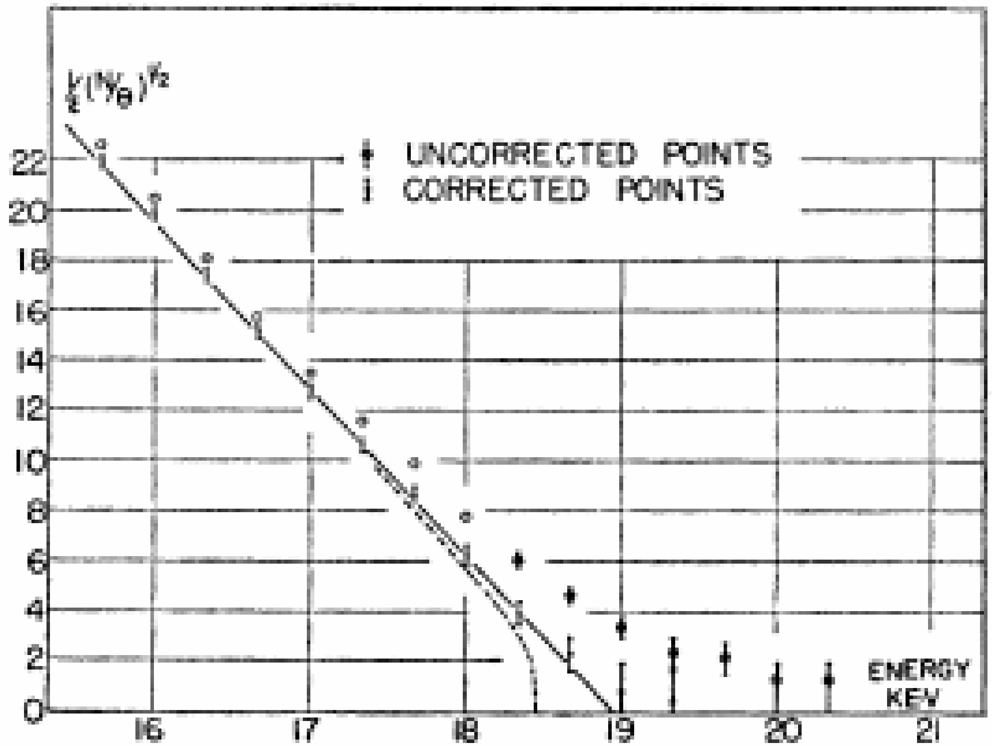


FIG. 2. "Kurie" plot of the end of the H³ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

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

1983: Electrostatic spectrometer with adiabatic magnetic collimation „Troitsk ν-mass” experiment

Petr Spivak
24.03.1911 - 30.03.1991

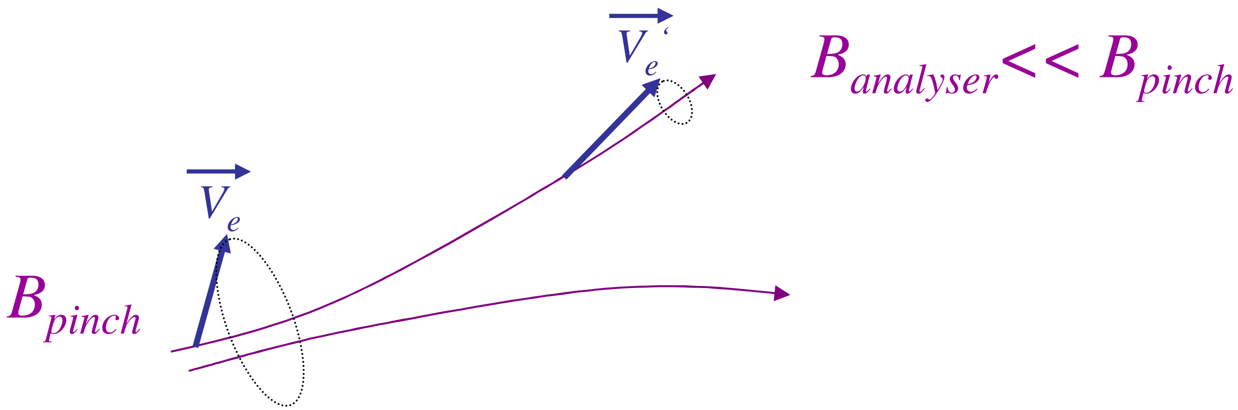
Vladimir Lobashev
29.07.1934 – 3.08.2011

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

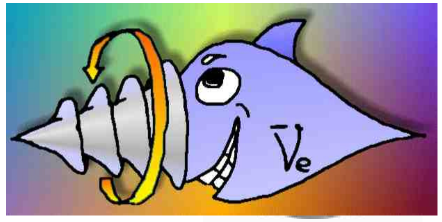
Electrostatic spectrometer with adiabatic magnetic collimation

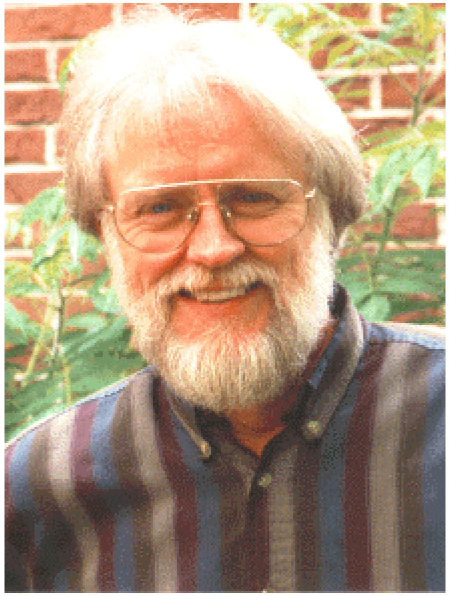
Charged particle in a slowly varying magnetic field moves *adiabatically*.

- 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



"Great minds think alike"
Mainz Neutrino Mass Experiment





Robert B. Moore
Physics Department,
McGill University
Montreal, Canada

Ernst Otten

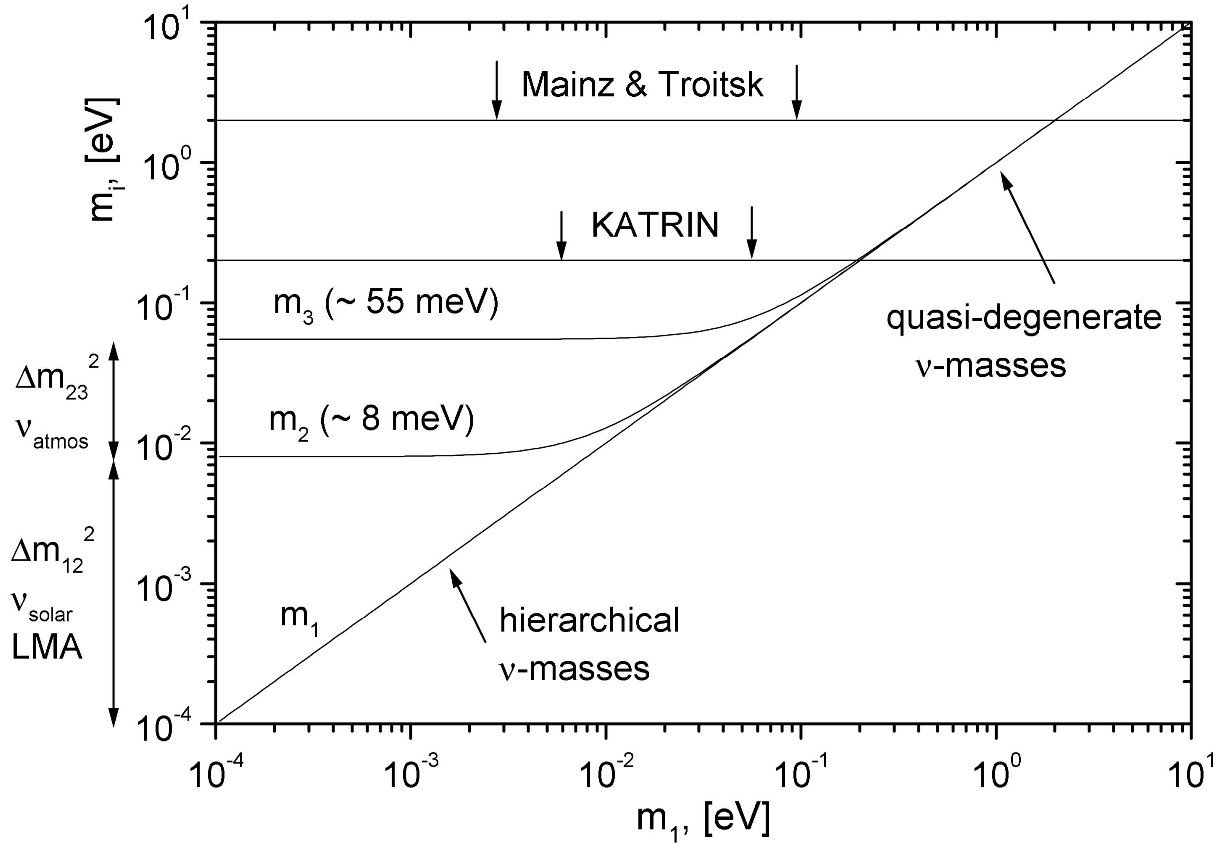
Jochen Bonn
7.04.1944 – 27.08.2012

Physics Institute
Johannes Gutenberg University
Mainz, Germany

A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345

≈1998: New challenge:

Mainz and Troitsk reached their limits but it is possible to improve neutrino mass limit by another order of magnitude



Confirm or excludes quasi-degenerate mass regime

Test cosmological neutrino mass limit

Forschungszentrum Karlsruhe

Tritium laboratory with license for 40g of Tritium

2001: Workshop at Bad Liebenzell

5 groups from 4 countries:
- Karlsruhe
- Mainz
- Troitsk
- Seattle
- NPI Rezz near Prague

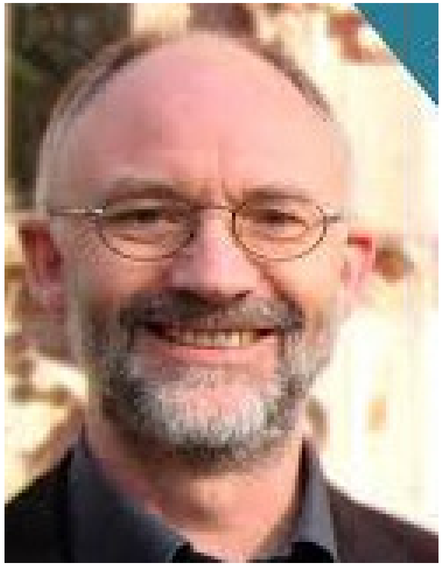
Letter of Intent

KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass

A. Osipowicz[a], H. Blümer[b,f], G. Drexlin[b], K. Eitel[b], G. Meisel[b], P. Plischke[b], F. Schwamm[b], M. Steidl[b], H. Gemmeke[c], C. Day[d], R. Gehring[d], R. Heller[d], K.-P. Jüngst[d], P. Komarek[d], W. Lehmann[d], A. Mack[d], H. Neumann[d], M. Noe[d], T. Schneider[d], L. Dörr[e], M. Glugla[e], R. Lässer[e], T. Kepcija[f], J. Wolf[f], J. Bonn[g], B. Bornschein[g], L. Bornschein[g], B. Flatt[g], C. Kraus[g], B. Müller[g], E.W. Otten[g], J.-P. Schall[g], T. Thümmler[g], C. Weinheimer[g], V. Aseev[h], A. Belesev[h], A. Berlev[h], E. Geraskin[h], A. Golubev[h], O. Kazachenko[h], V. Lobashev[h], N. Titov[h], V. Usanov[h], S. Zadoroghny[h], O. Dragoun[i], A. Kovalík[i], M. Ryšavý[i], A. Špalek[i], P.J. Doe[j], S.R. Elliott[j], R.G.H. Robertson[j], J.F. Wilkerson[j]

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
Director of the Institute for
Nuclear Physics
Karlsruhe Institute of Technology

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

Among KATRIN senior fellows

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

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

VOLUME 67, NUMBER 8 PHYSICAL REVIEW LETTERS 19 AUGUST 1991

Limit on $\bar{\nu}_e$ Mass from Observation of the β Decay of Molecular Tritium

R. G. H. Robertson, T. J. Bowles, G. J. Stephenson, Jr., D. L. Wark,[a] and J. F. Wilkerson
Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

D. A. Knapp
Physics Division, Lawrence Livermore National Laboratory, Livermore, California 94550
(Received 6 May 1991)

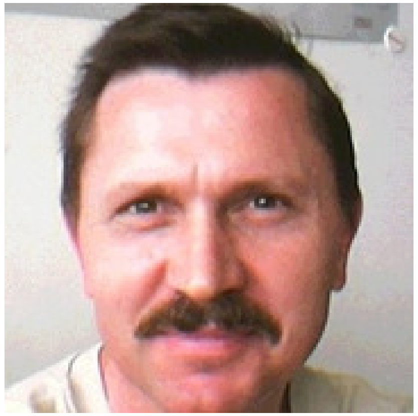
$m_\nu < 9.3$ eV (95% c.l.)

Among KATRIN senior fellows

Nuclear Physics Institute, Acad. Sci. Czech Rep.
Rezz near Prague, Czech Republic

Drahoslav Vénos

Otokar Dragoun



Alojz Kovalík

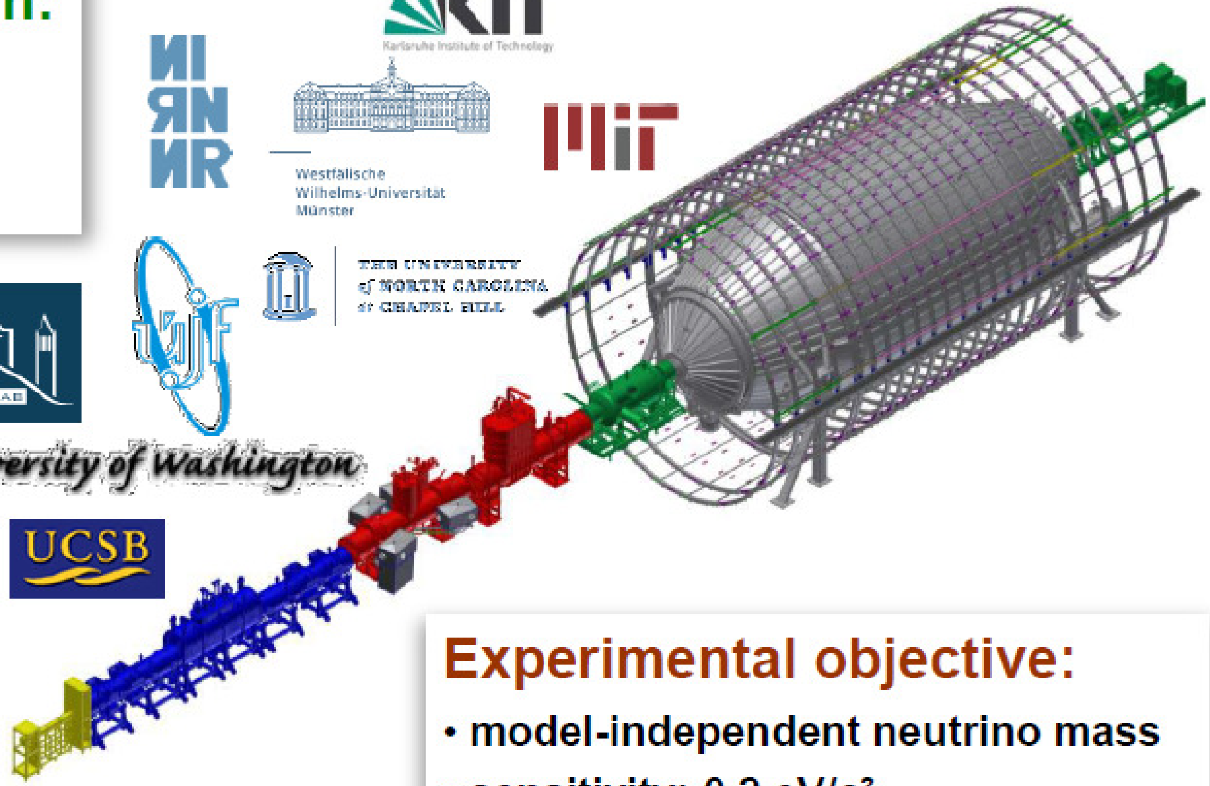
Miloš Ryšavý

Antonin Špalek

KATRIN collaboration at 2015

Collaboration:

- 130 scientists
- 5 countries
- 14 institutions



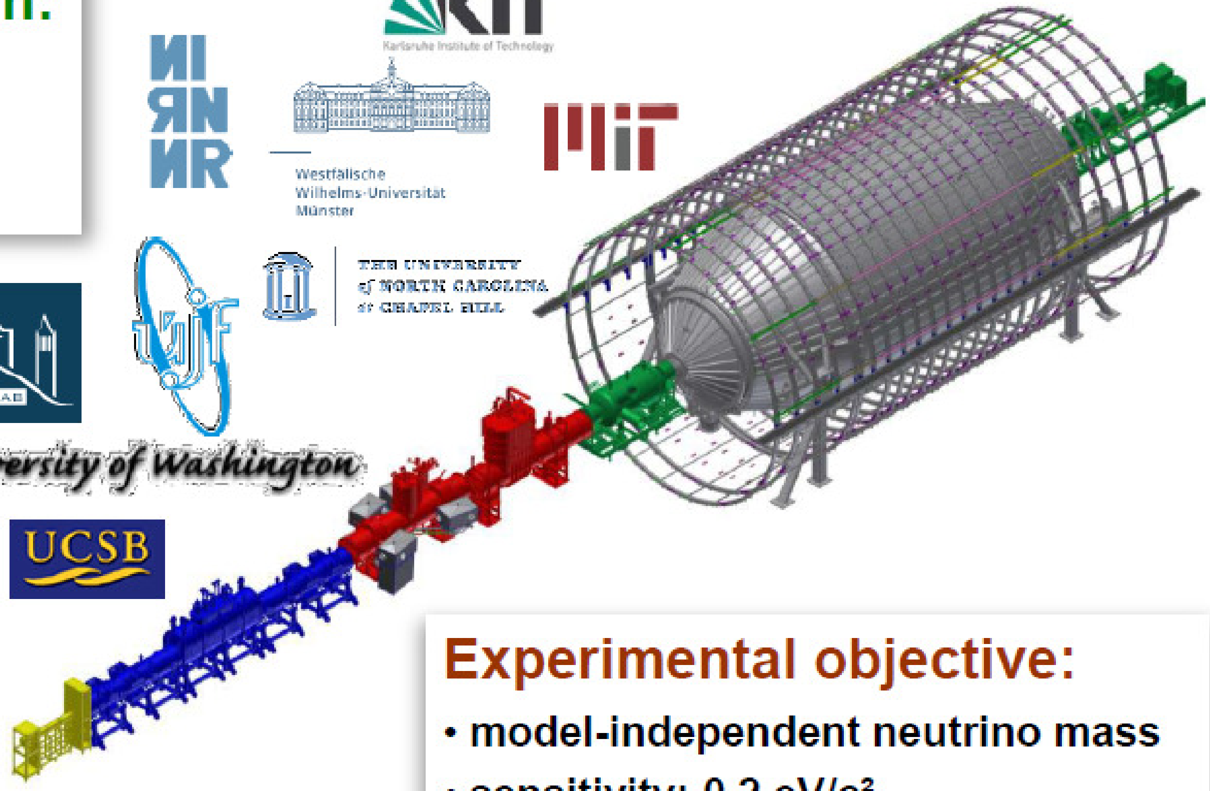
Experimental objective:

- model-independent neutrino mass
- sensitivity: 0.2 eV/c²
- source: gaseous tritium (ß-decay)

KATRIN collaboration at 2017

Collaboration:

- 130 scientists
- 6 ~~5~~ countries
- 17 ~~14~~ institutions



Experimental objective:

- model-independent neutrino mass
- sensitivity: 0.2 eV/c²
- source: gaseous tritium (ß-decay)

KATRIN project

Main 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/см^2

Total source activity ≈ 100 GBk (3Ci)

Resolution $\Delta E = 0.9$ eV at 18 keV

Neutrino mass sensitivity

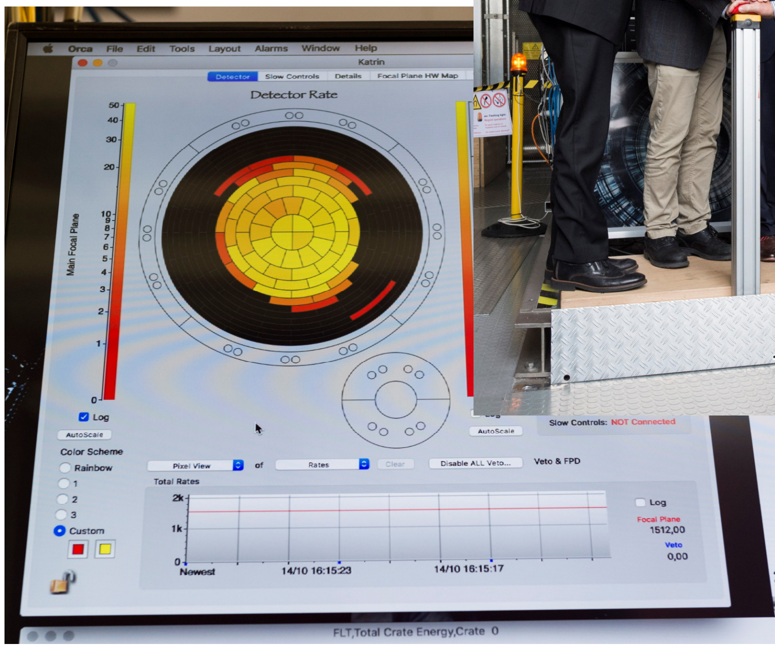
(after 3 years of data taking):

$$m_\nu < 0.2 \text{ eV}/c^2$$

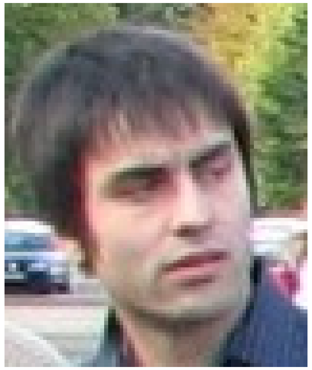
KATRIN – 2016

14.10.2016 - “First light”

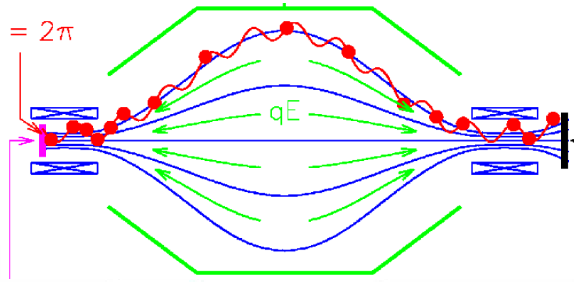
Electrons with 100 eV energy uniformly emitted from “Rear Wall” were detected by focal plane multipixel detector placed at the opposite end of installation at 70 m distance

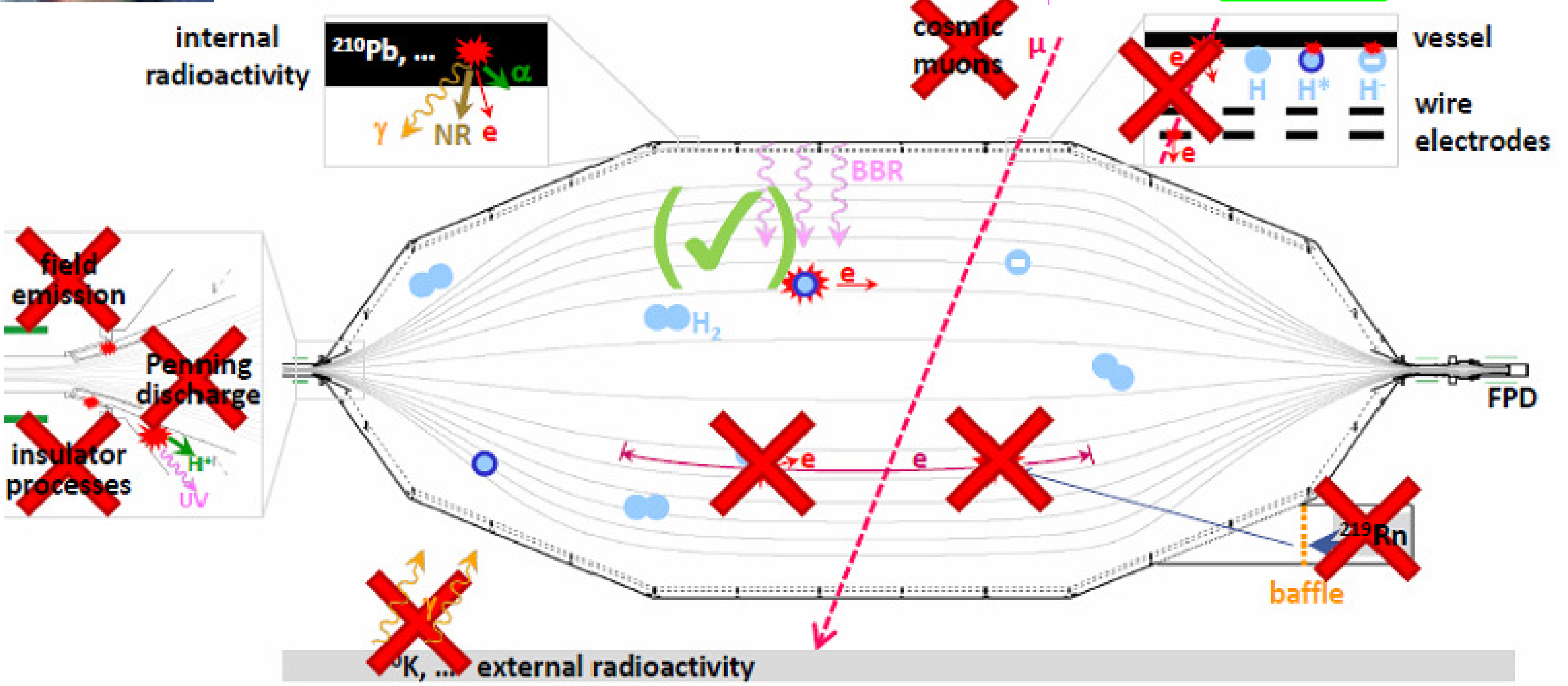


KATRIN – since 2013
Main spectrometer own background studies



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

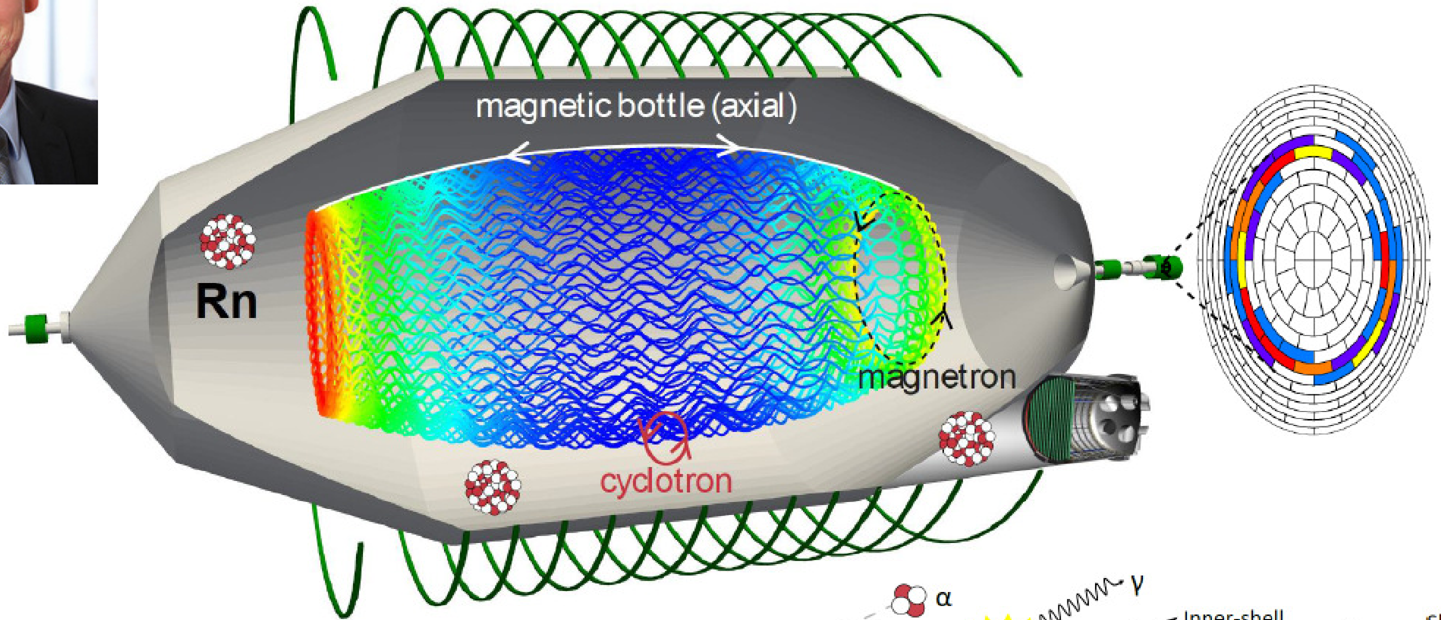


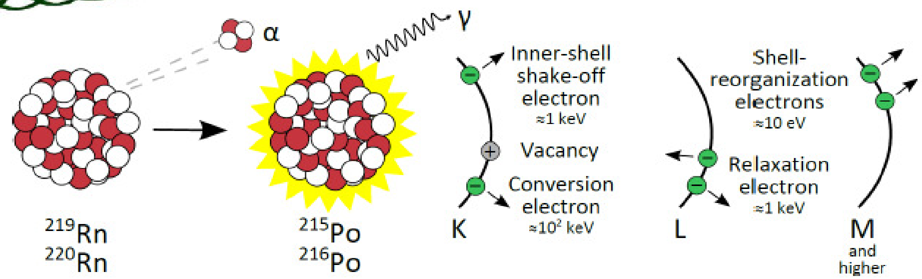


 International Session-Conference of SNP PSD RAS "Physics of Fundamental Interactions". June 6-8, 2017. Nalchik

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

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

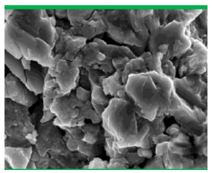
Two known sources of Rn:

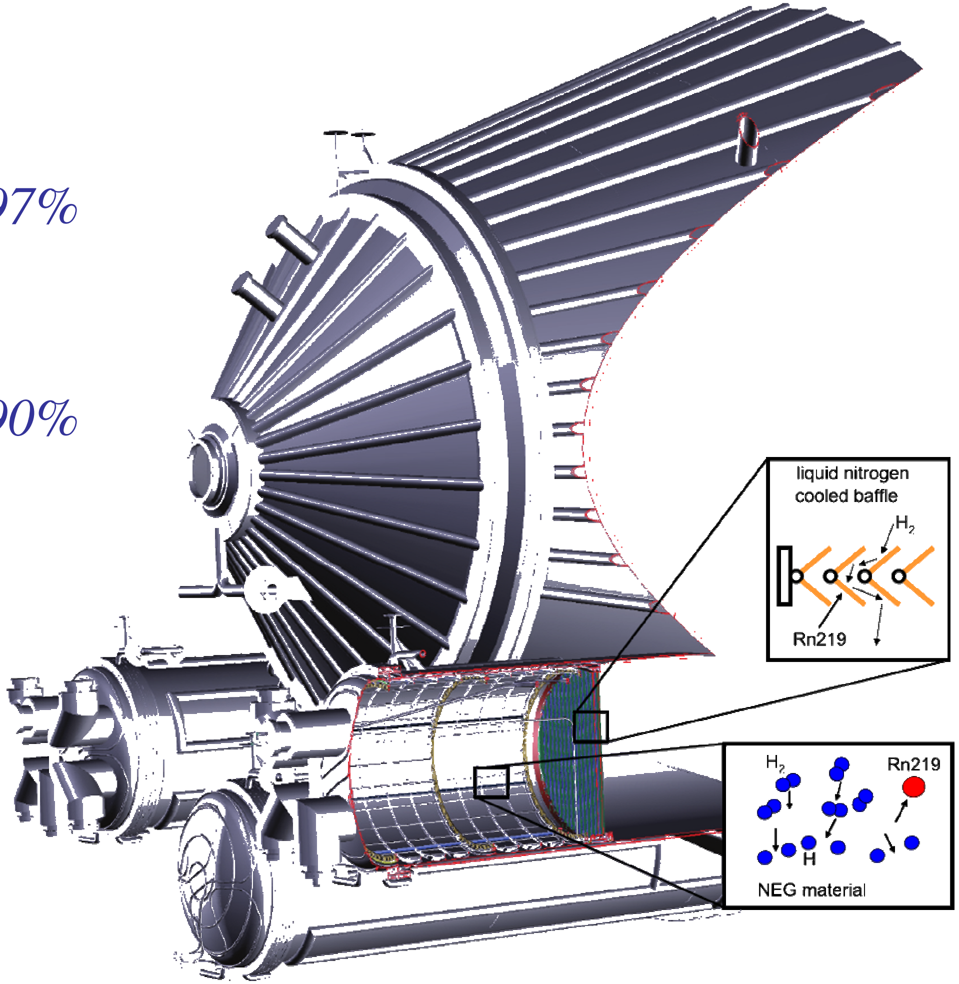
^{219}Rn from NEG getter pump

Interception efficiency by cold baffles 97%

^{220}Rn from welding → *excluded*

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





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

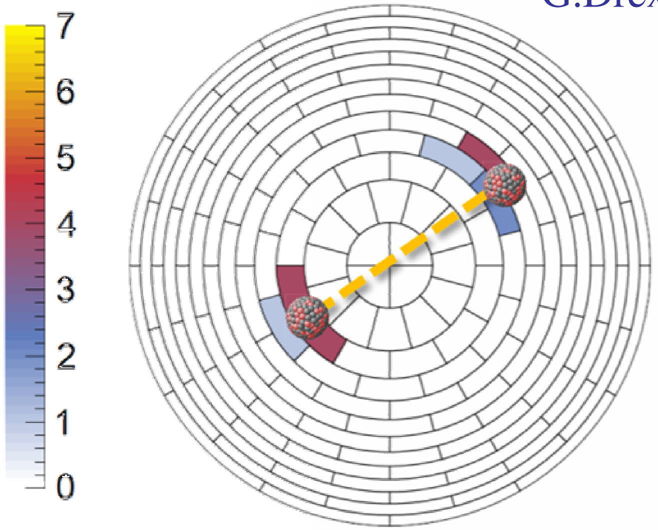
G.Drexlin at KATRIN CM, March 2016
will be published soon

Rydberg states act as **long-lived neutral messengers** from **surface** processes
KATRIN spectrometer surface is about 100 larger than in Mainz/Troitsk cases

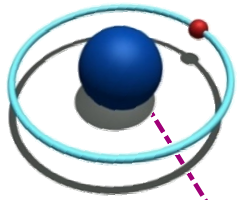
A **Rydberg atom** is an excited atom with one or more electrons that have a very high principal quantum number *n*, and $r \sim n^2$, $E_{ion} \sim 1/n^3$
Thus Rydberg atom is extremely large with loosely bound valence electrons, easily perturbed or ionized by collisions or external fields (Wikipedia).

New obeservation method - a surface microscope by asymmetric B fields

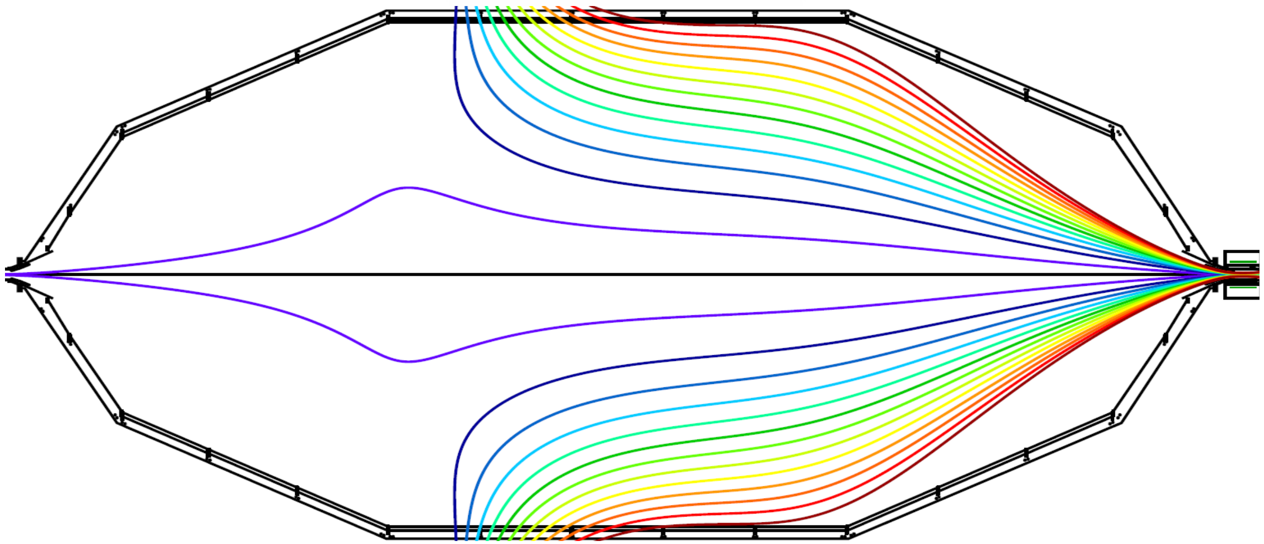
G.Drexlin at KATRIN CM, March 2016



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



H*



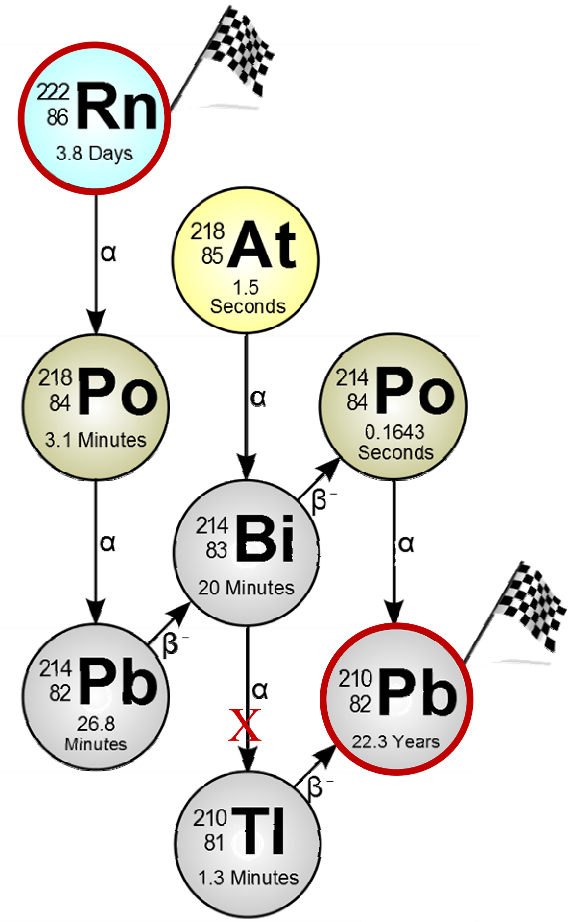
generation of Rydberg states H*

G. Drexlin – KATRIN

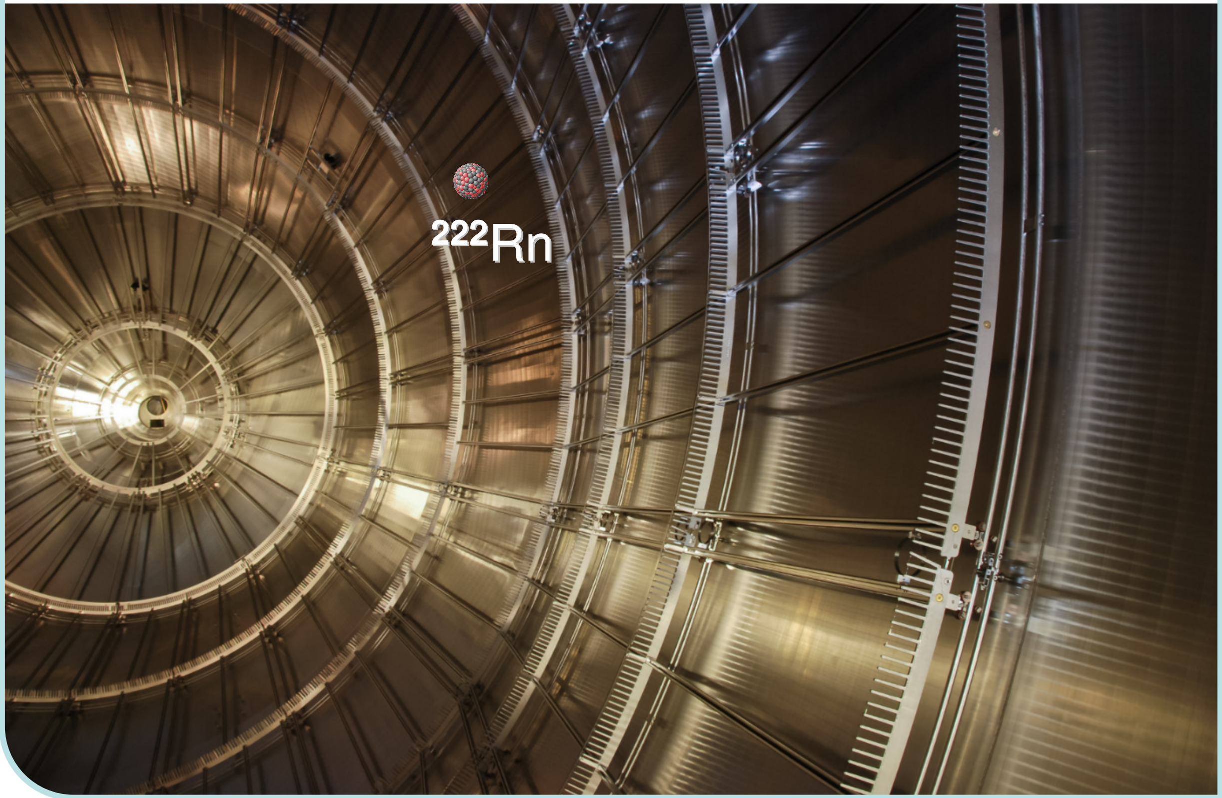
Rn-222 from forced spectrometer venting

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

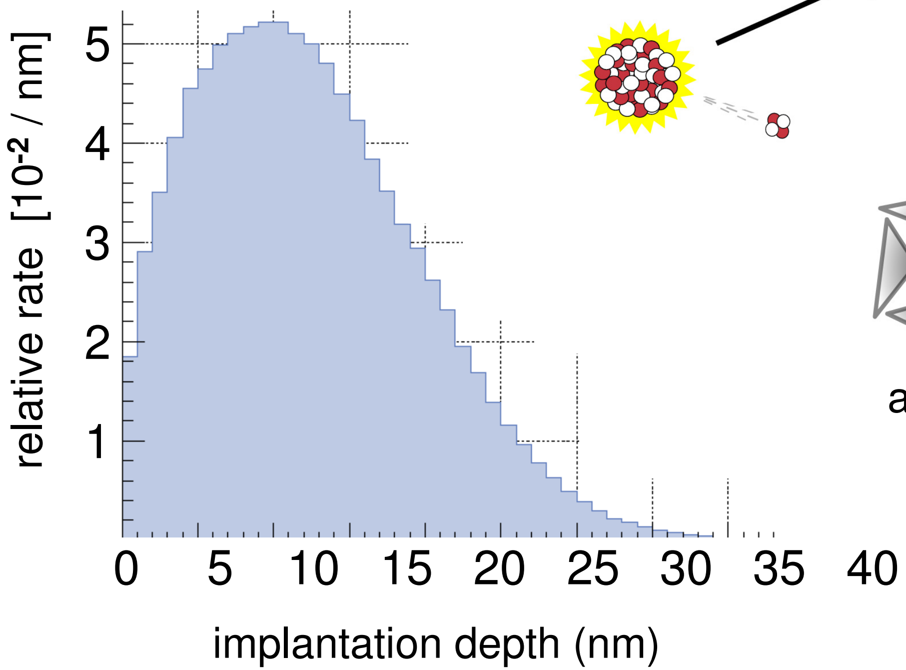


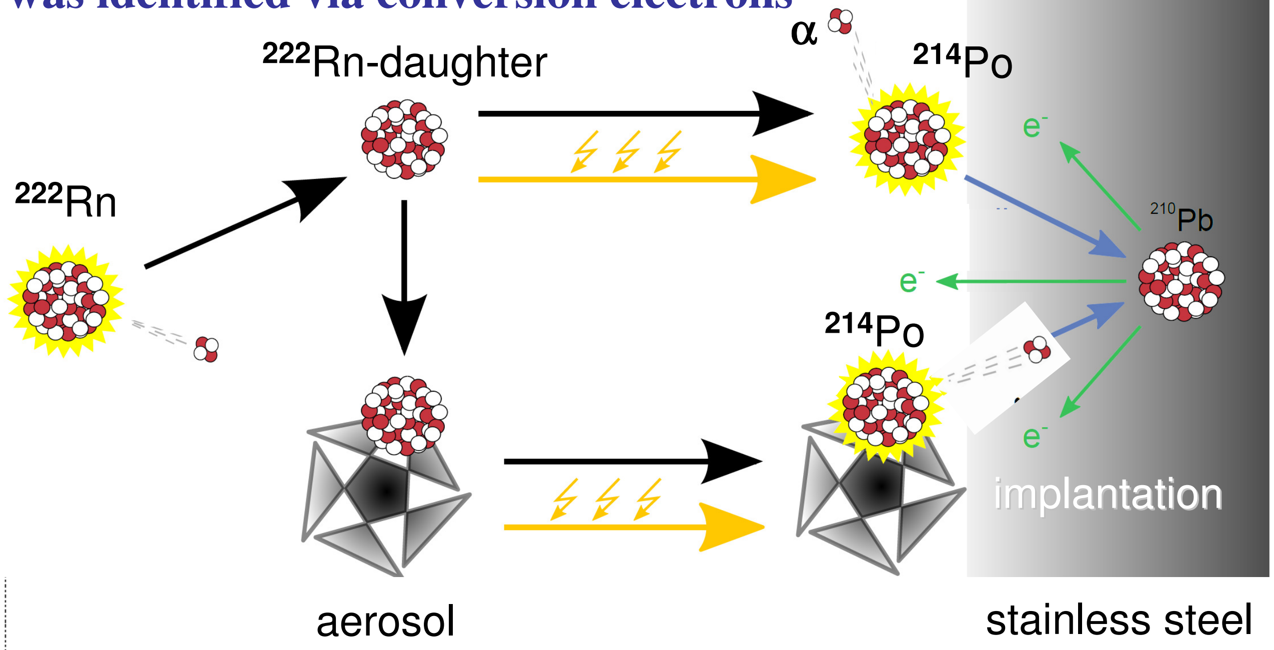
G. Drexlin – KATRIN

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**





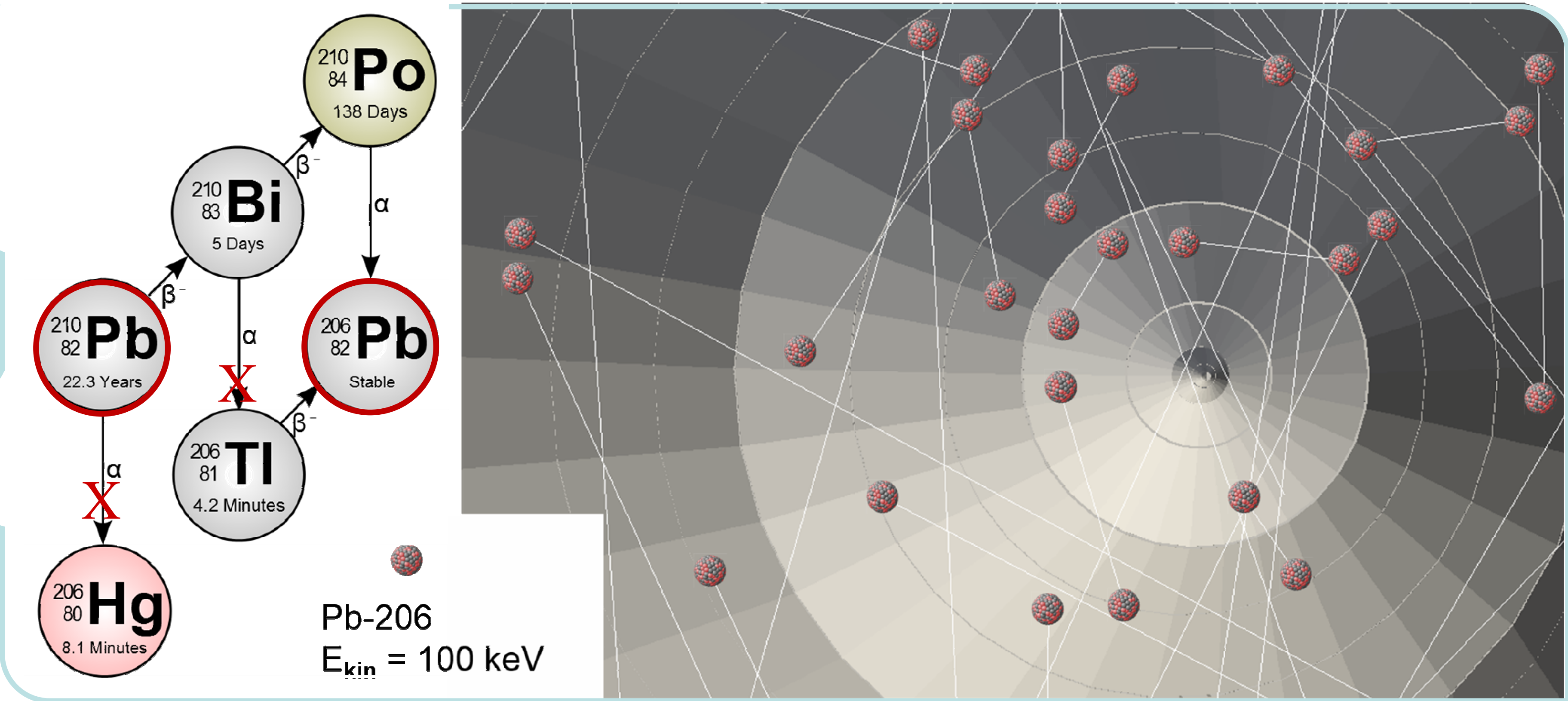
- Pb-210 implanted in stainless steel
- Pb-210 incorporated in aerosols

G. Drexlin – KATRIN

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

G.Drexlin at KATRIN CM, March 2016

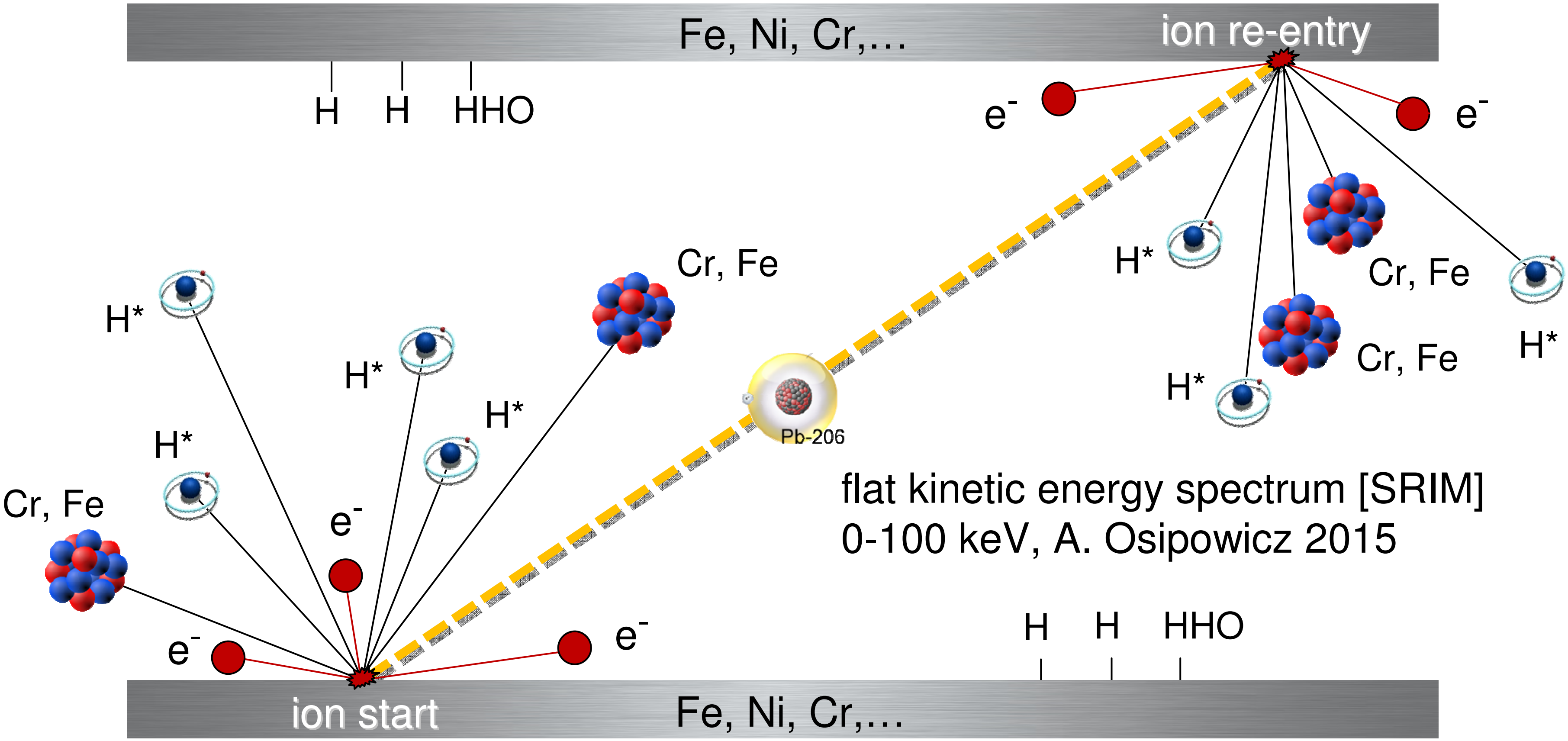
- measured rate (in 2π) ~ $A_{Pb\text{-}210}$ ~ $(900 \pm 100)\ s^{-1}$ [PhD F. Harms, 2015]
- $A_{Pb\text{-}210}$ upper limit for $A_{Pb\text{-}206}$: **^{206}Pb recoil ions with E_{kin} < 100 keV**



^{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

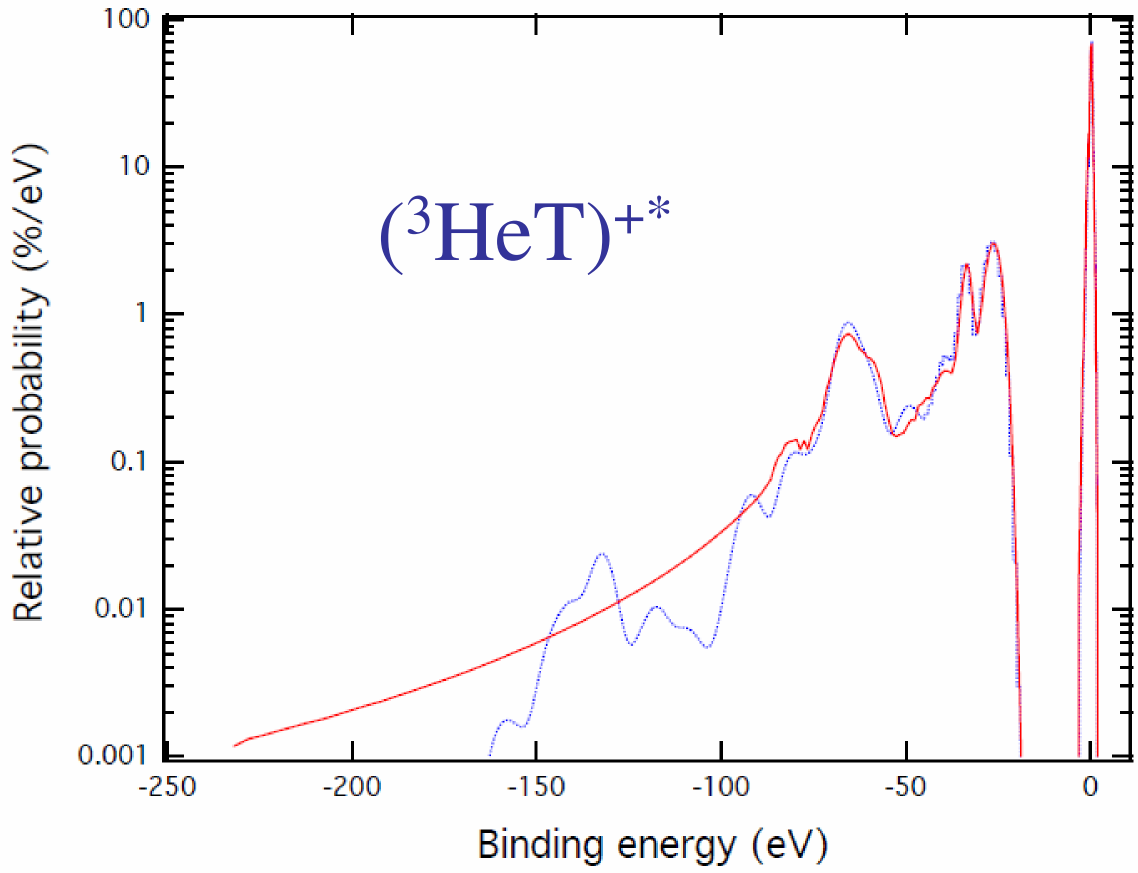
Summary and outlook

- 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).

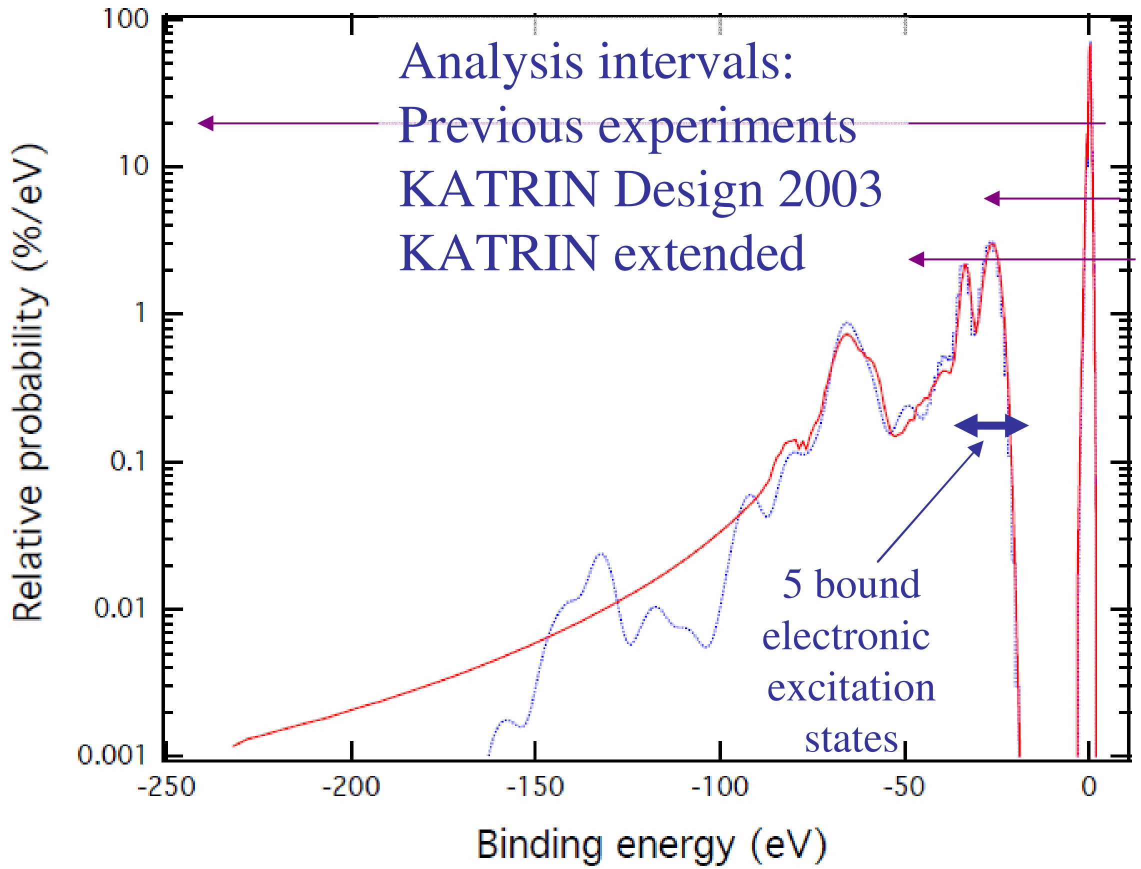
Electronic part of the Final States Spectrum



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



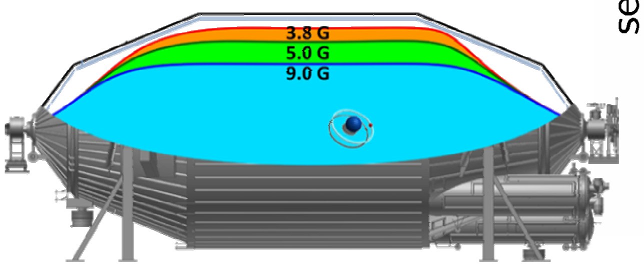
Provided that calculation of Final States Spectrum electronic part is robust data analysis interval could be extended.

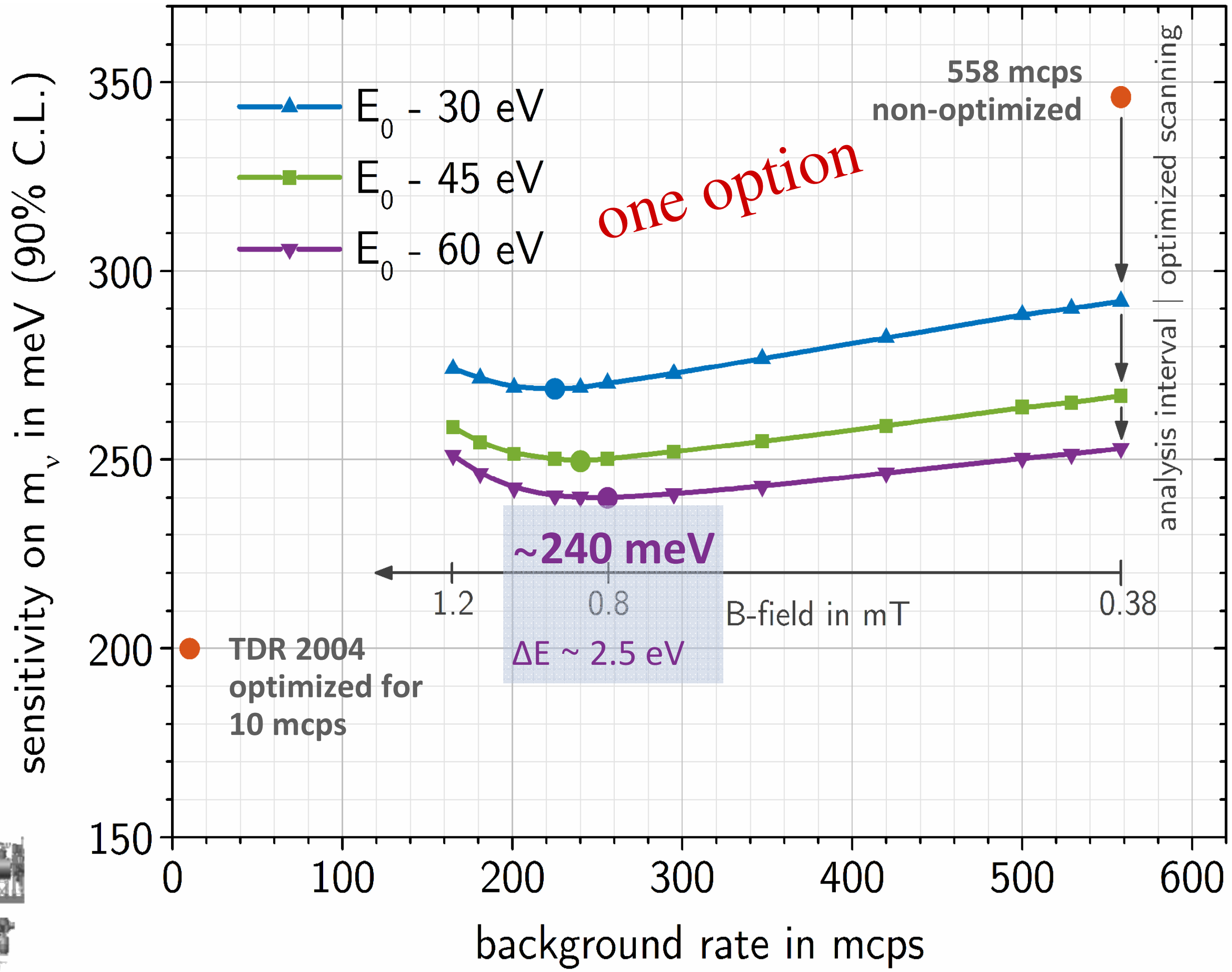
KATRIN sensitivity with increased background 240 meV (90% c.l.) after 3 years

(K.Valerius at "Neutrino – 2016")

Background reduction measures were studied

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





Thank you for your attention !

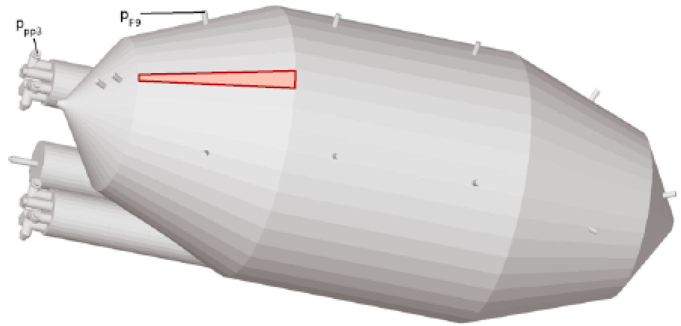
Back up slides

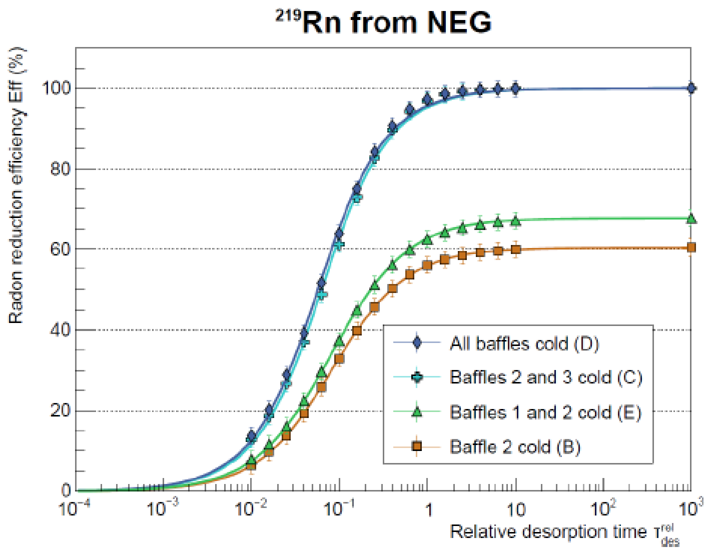
^{219}Rn vs ^{220}Rn

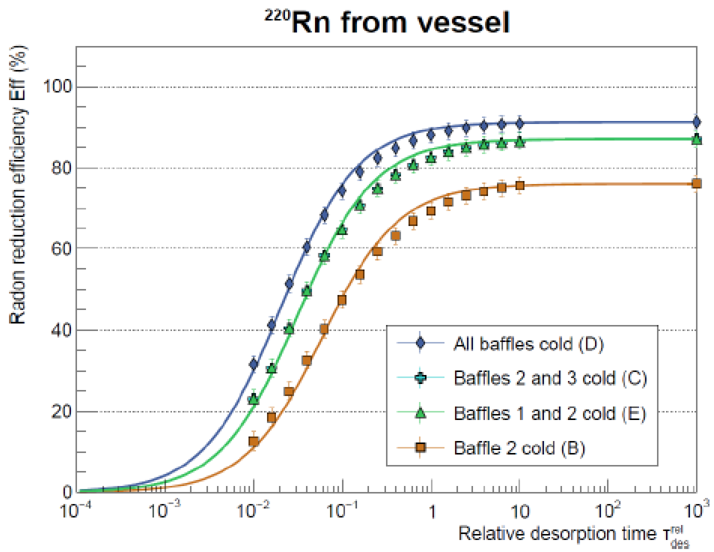
Baffle efficiency

MolFlow+ simulations

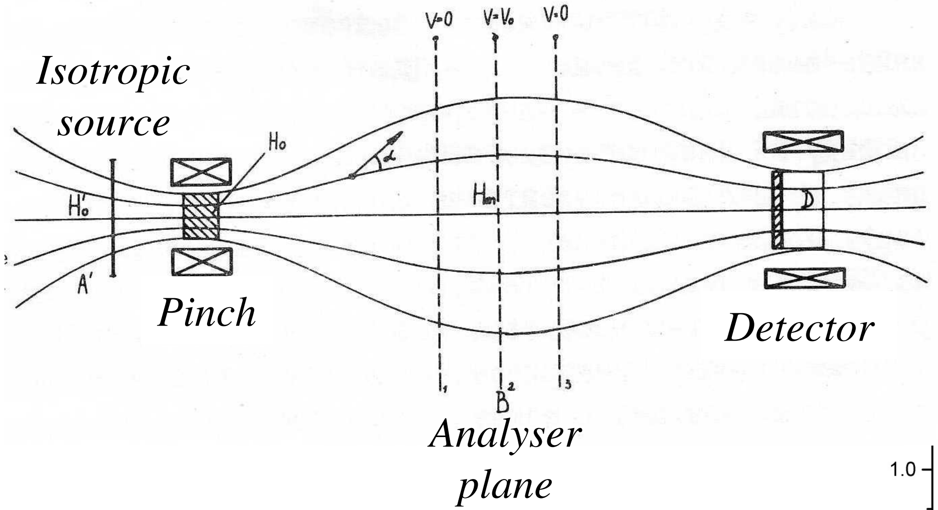
G. Drexlin et al., Vacuum, Volume 138, Pages 165 – 172, 2017



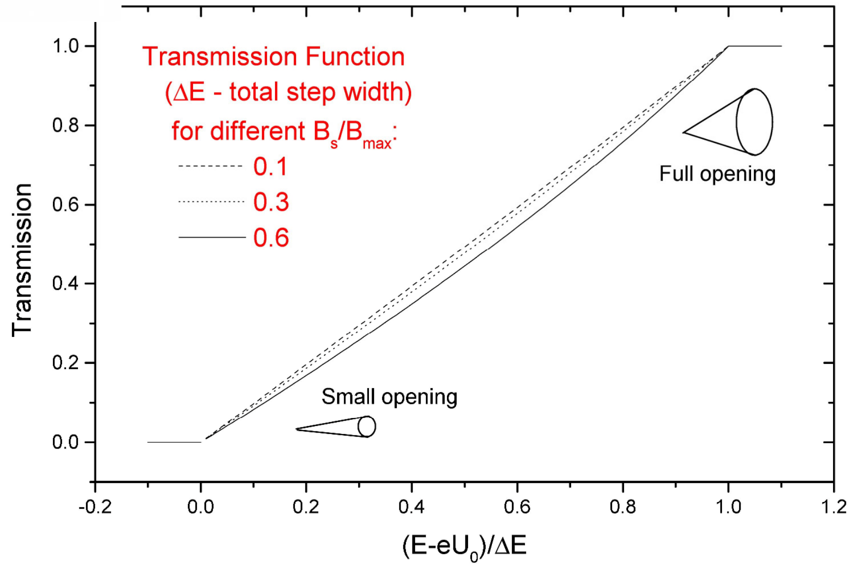




Электростатический спектрометр с адиабатической магнитной коллимацией
Принцип работы



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



Высокое
разрешение спектрометра
не зависит
от размера источника

Электростатический спектрометр с магнитной адиабатической коллимацией
Фундаментальные основы

Критерий адибатичности ε:

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

где r_H, ω_H – радиус и частота Ларморовской прецессии

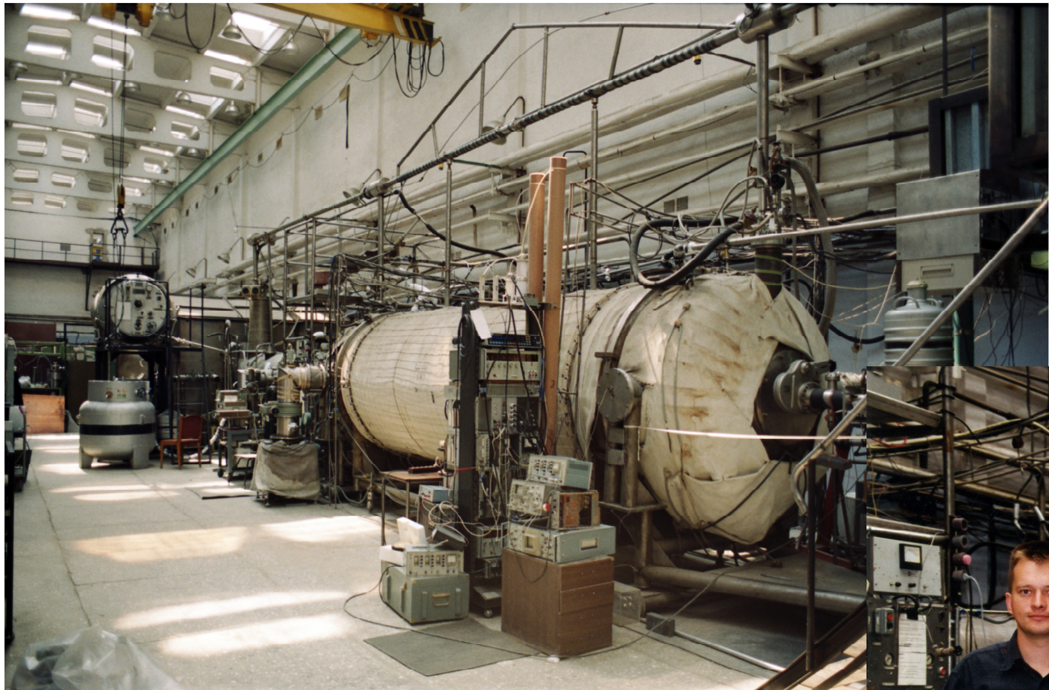
Адиабатический инвариант сохраняется экспоненциально:

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

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!

Установка «Троицк ню-масс



Спектрометр
длина 6,5 м
диаметр электрода 1,2 м
разрешение 3,7 эВ
Диаметр источника 20 мм
толщина $1 \cdot 10^{17}$ мол/см2

Первые данные
опубликованы в 1994г:

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

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.