Westfälische Wilhelms-Universität Münster

Direct Search for the Neutrino Mass and the KATRIN experiment

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Introduction

Direct Neutrino Mass determination

The Karlsruhe Tritium Neutrino expiirment KATRIN

Options for sterile neutrinos with KATRIN

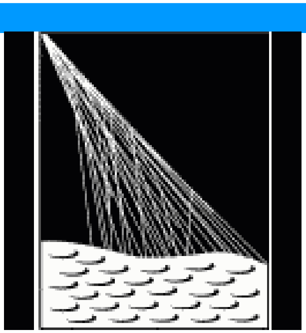
Outlook on other approaches: ECHo, HOLMes and Project 8

Conclusions

Photo: M. Zacher

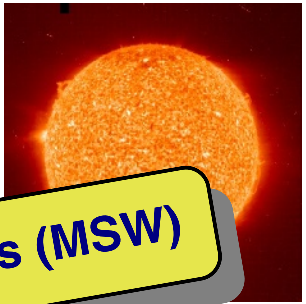
Positive results from ν oscillation experiments

atmospheric neutrinos
(Kamiokande,
Super-Kamiokande, ...)



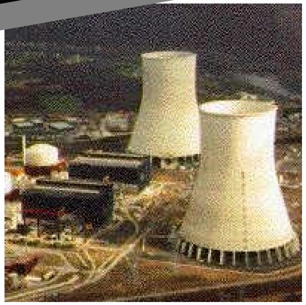
accelerator neutrinos
(K2K, T2K, MINOS,
OPERA, MiniBoone)

solar neutrinos
(Homestake, Gallex,
Sage, Super-Kamiokande,
SNO, Borexino)



Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ, Daya Bay,
DoubleCHOOZ, RENO, ...)



⇒ non-trivial ν-mixing

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

with:

$0.37 < \sin^2(\theta_{23}) < 0.63$ maximal!

$0.26 < \sin^2(\theta_{12}) < 0.36$ large !

$0.018 < \sin^2(\theta_{13}) < 0.030$ 8.9°

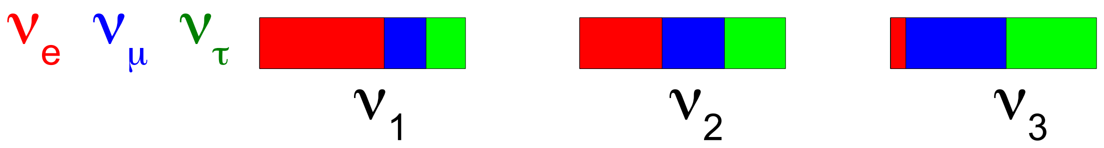
$7.0\ 10^{-5}\ \mathrm{eV}^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ \mathrm{eV}^2$

$2.2\ 10^{-3}\ \mathrm{eV}^2 < |\Delta m_{13}^2| < 2.6\ 10^{-3}\ \mathrm{eV}^2$

⇒ $m(\nu_j) \neq 0$, but unknown !

Need for the absolute ν mass determination

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Θ_{13}, Δm^2_{23}, Δm^2_{12}



degenerated masses

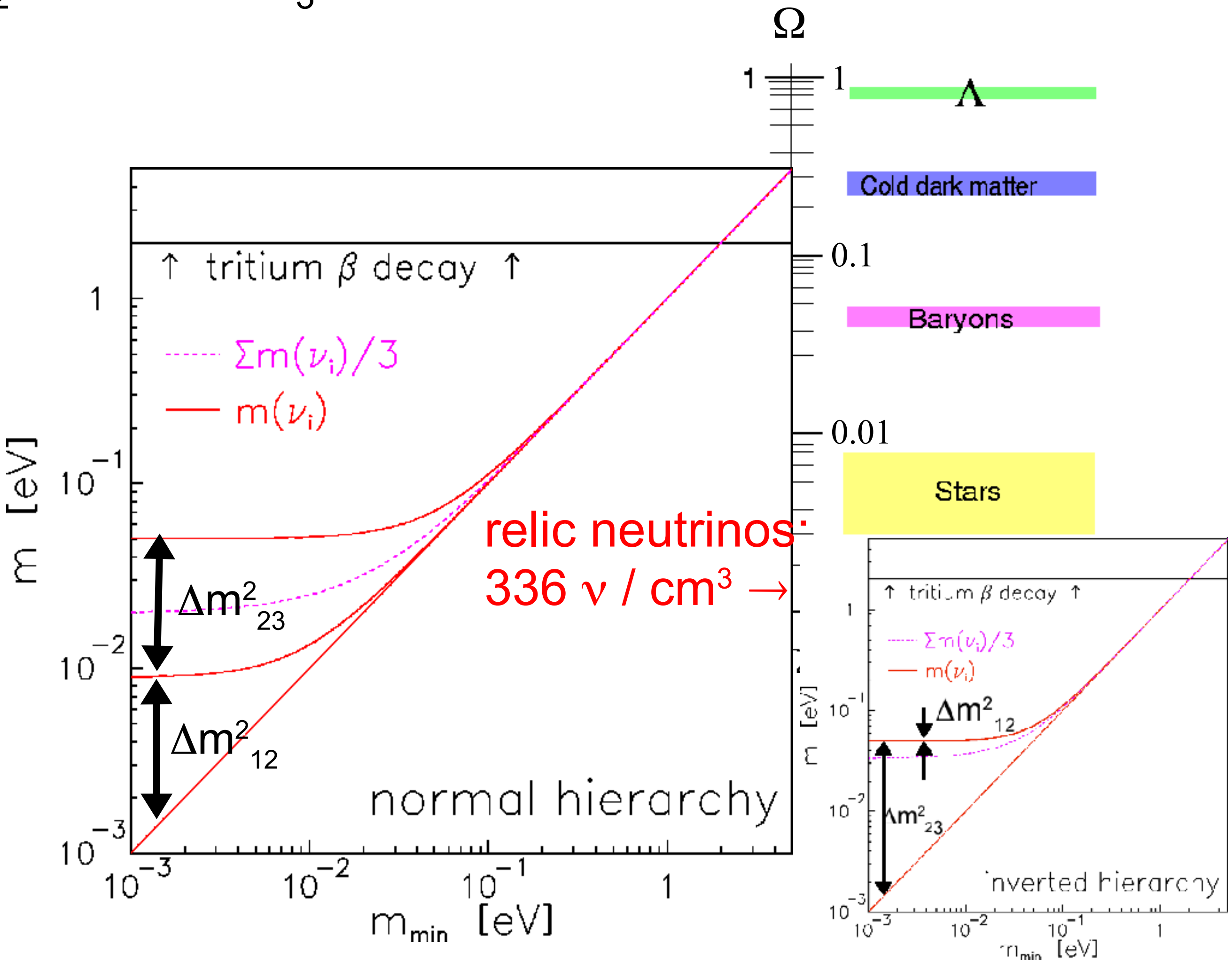
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

explains smallness of masses, but not large (maximal) mixing



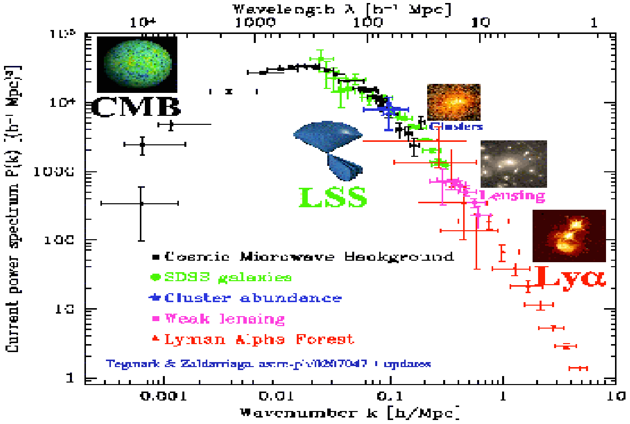
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

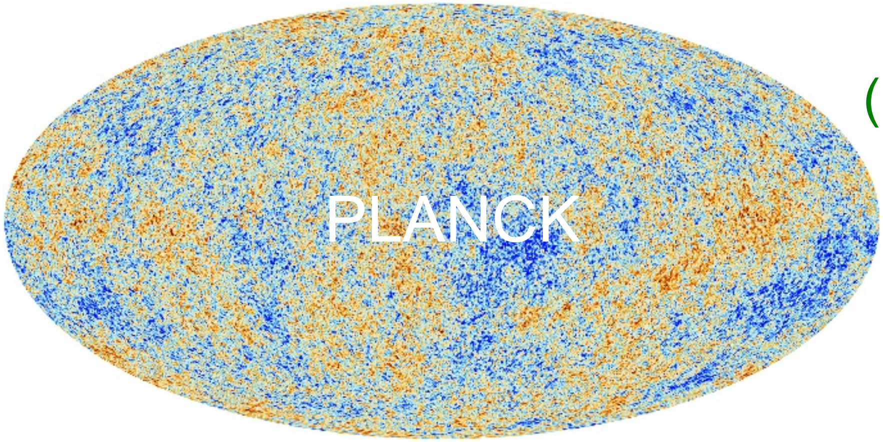
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV

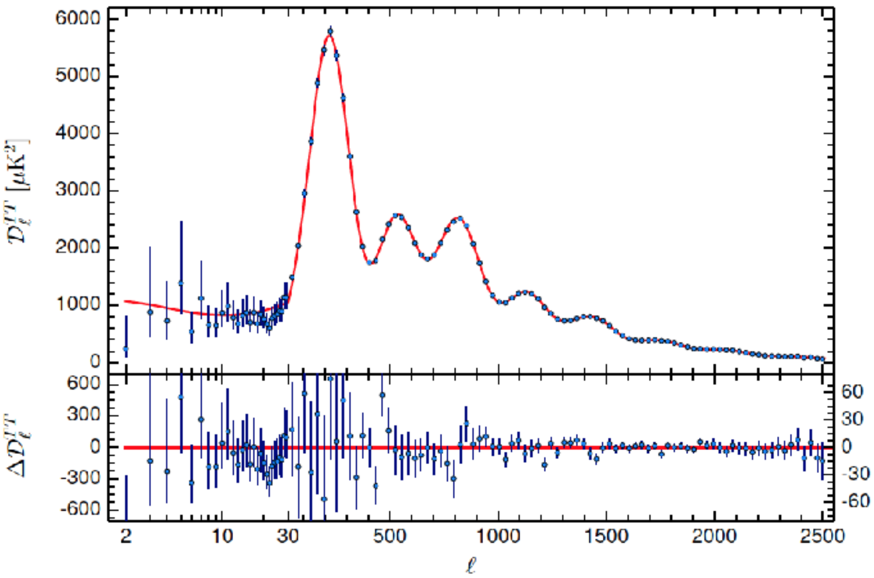


Neutrino mass from cosmology

measurement of CMBR

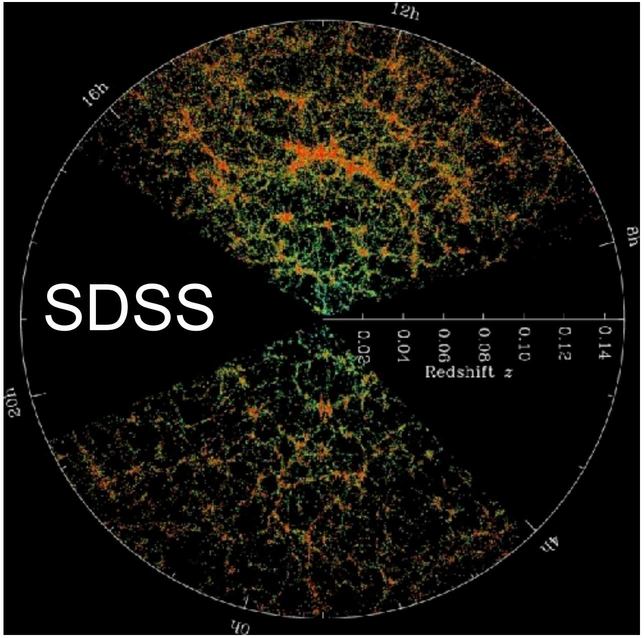
(Cosmic Microwave Background Radiation)



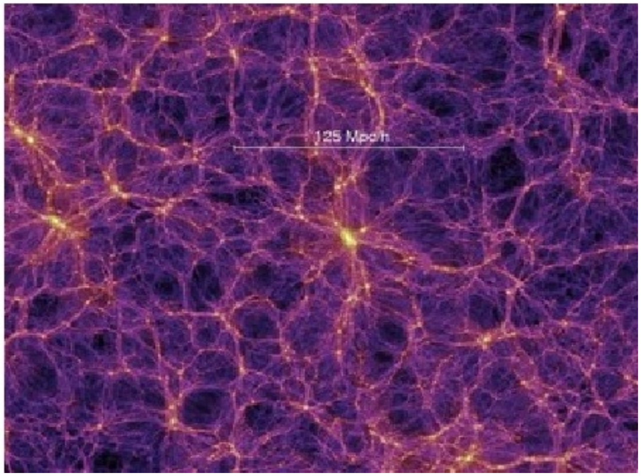


Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

measurement of
matter density
distribution LSS
(Large Scale Structure)
by 2dF, SDSS, ...



compare to
numeric. models
including relic
neutrino densitiy
of 336 cm^{-3}



Millenium simulation →
http://www.mpa-garching.mpg.de/galform/presse/

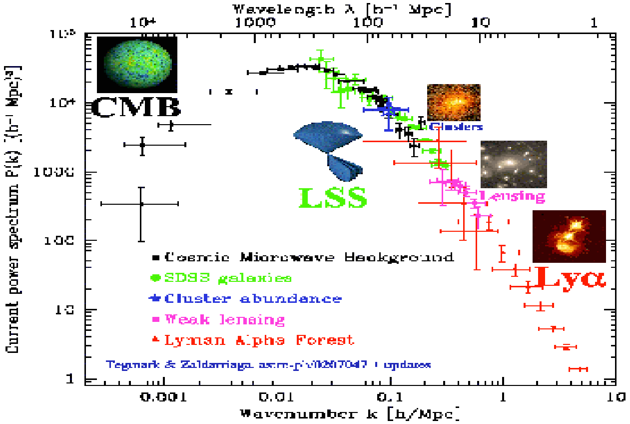
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

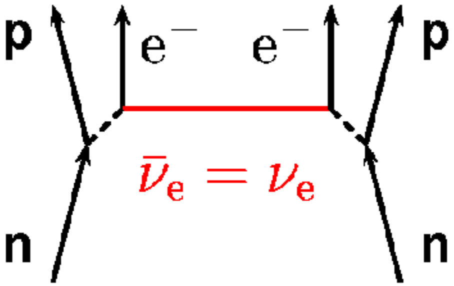
current sensitivity: $\Sigma m(\nu_i) \approx 0.5$ eV



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

Sensitive to Majorana neutrinos

First upper limits by EXO-200, KamLAND-Zen, GERDA



Three complementary ways to the absolute neutrino mass scale

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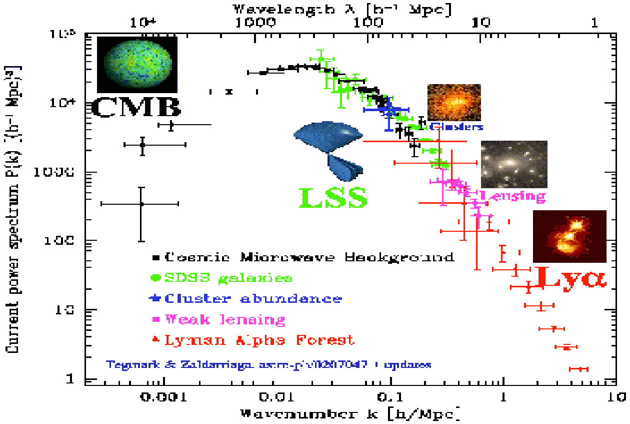

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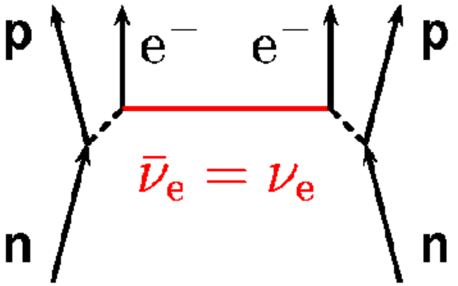
Sensitive to Majorana neutrinos

First upper limits by EXO-200, KamLAND-Zen, GERDA



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)

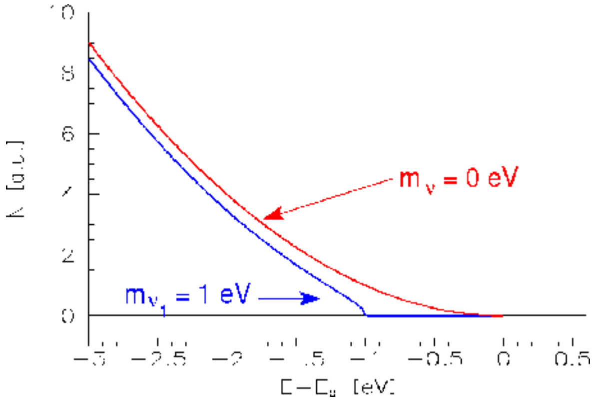
SN1987a (large Magellan cloud) ⇒ $m(\nu_e) < 5.7$ eV

Kinematics of weak decays / beta decays

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

β-decay searchs for $m(\nu_e)$ - tritium β spectrometers

- ^{187}Re, ^{163}Ho bolometers



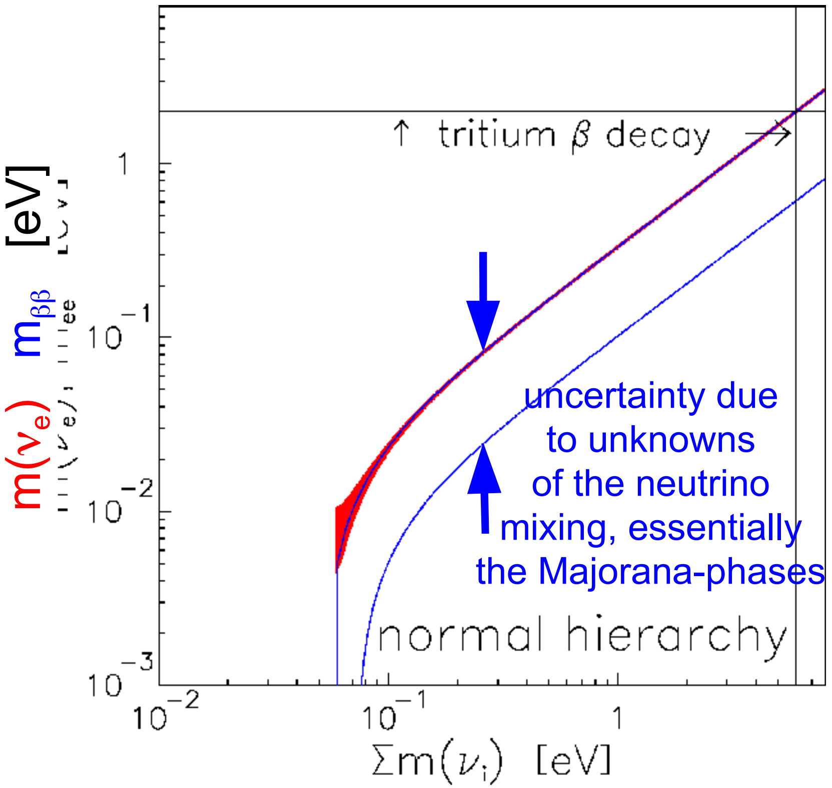
Comparison of the different approaches to the neutrino mass

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

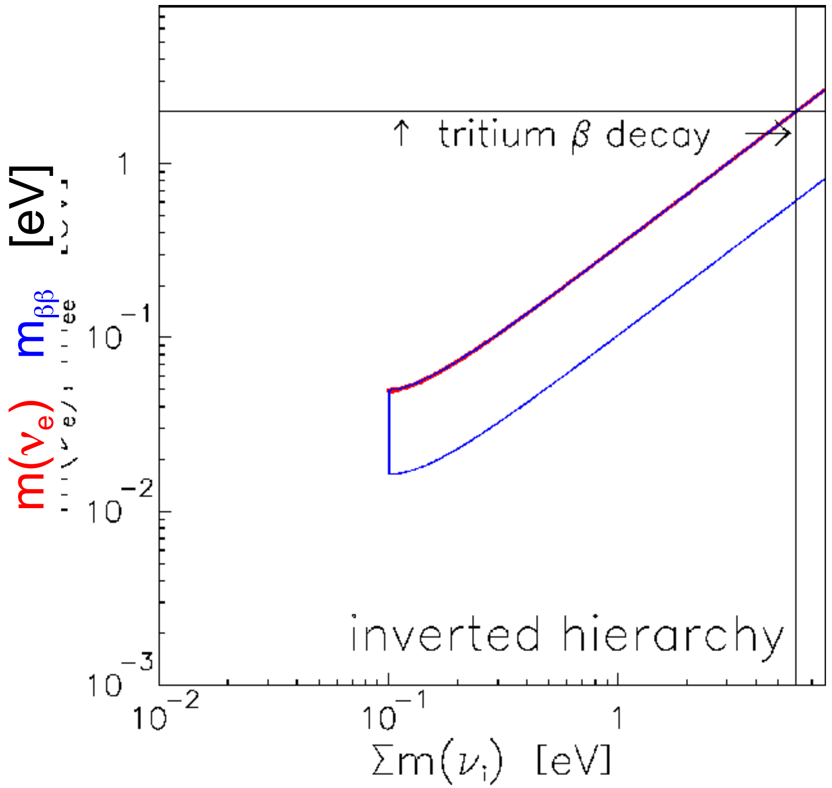
Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = |\, \Sigma |U_{ei}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$ (coherent)

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

problems with uncertainty of nuclear matrix elements



uncertainty due to unknowns of the neutrino mixing, essentially the Majorana-phases



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

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

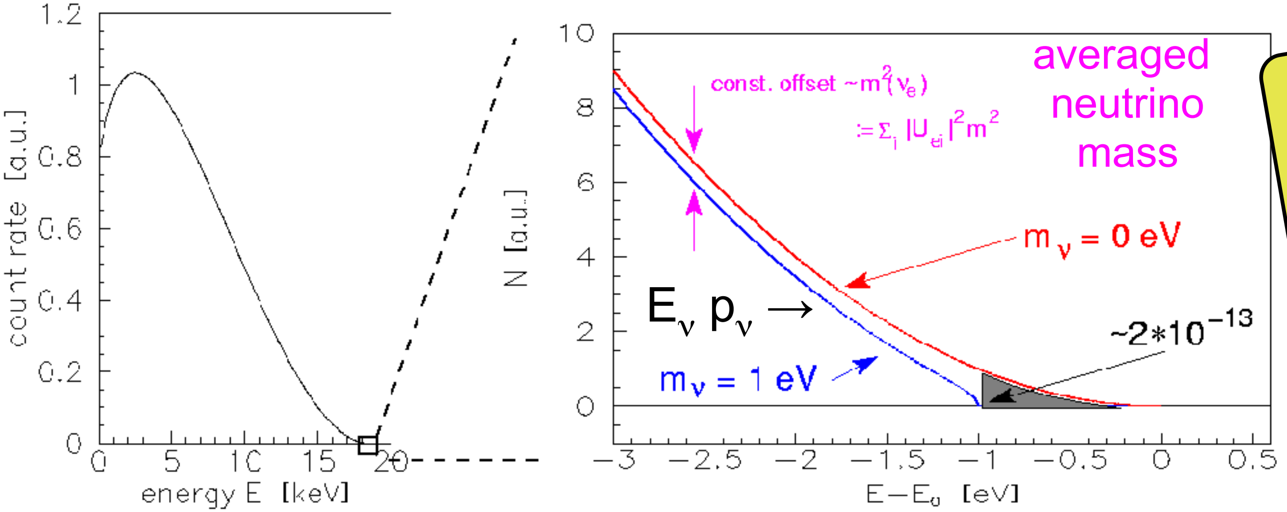
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + \boxed{e^-} + \bar{\nu}_e$

Complementary to $0\nu\beta\beta$ and cosmology

$$\beta\text{: } dN/dE = K\; F(E,Z)\; \underbrace{p}_{p_e}\; \underbrace{E_{tot}}_{E_e}\; \underbrace{(E_0-E_e)}_{E_\nu}\; \underbrace{\sqrt{(E_0-E_e)^2 - \text{"}m(\nu_e)\text{"}^2}}_{p_\nu}$$

phase space:

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



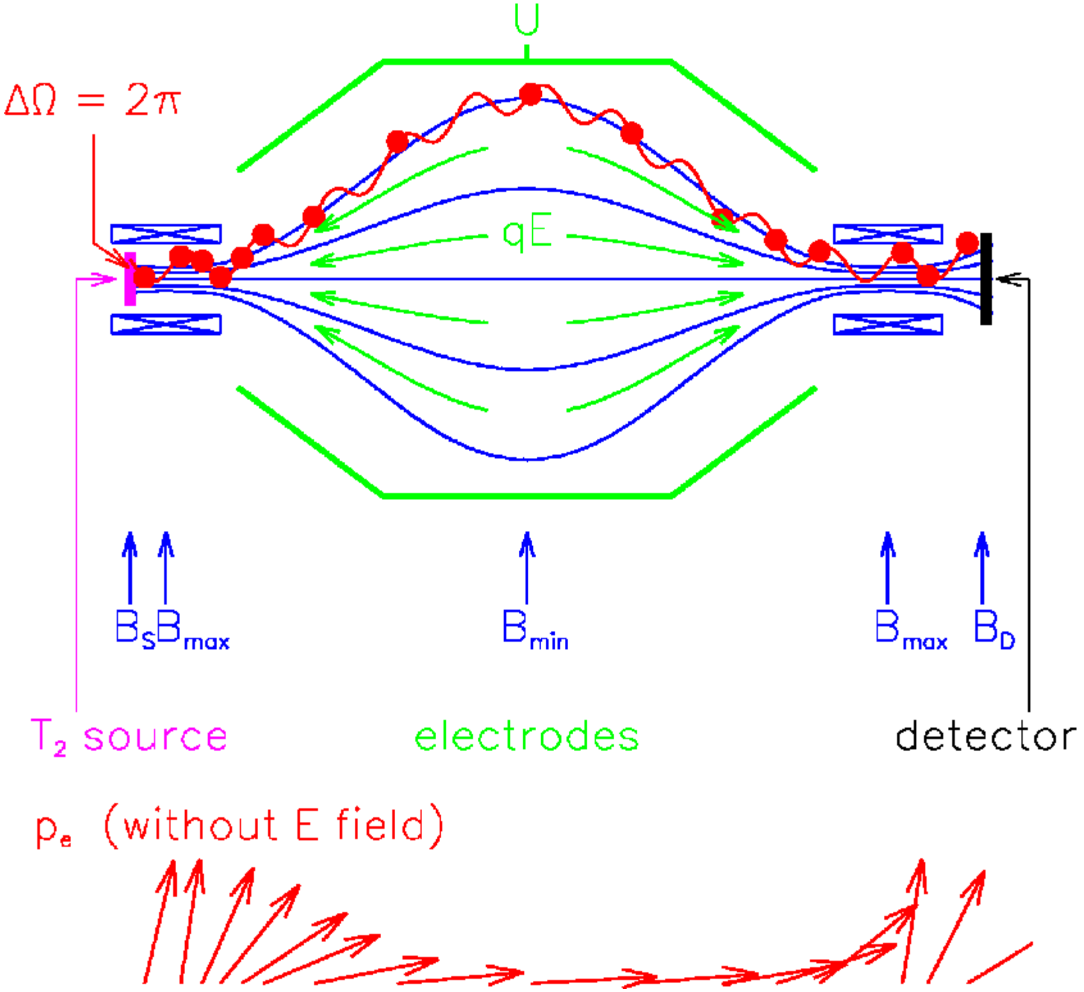
E.W. Otten & C. Weinheimer Rep. Prog. Phys. 71 (2008) 086201

G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, Adv. High Energy Phys., 2013 (2013) 293986

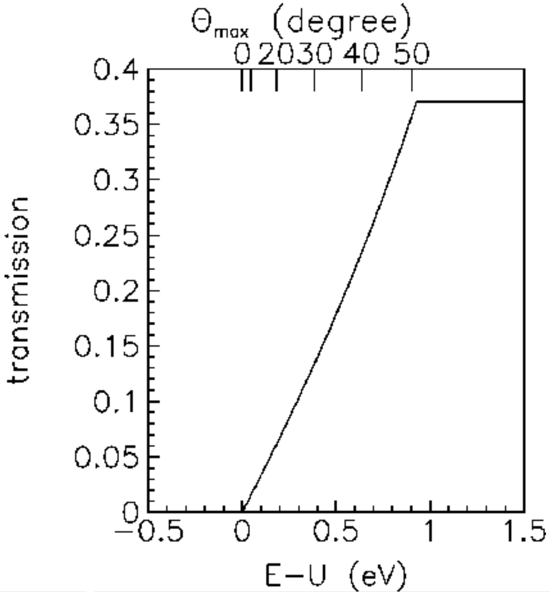
Need: **low endpoint energy** ⇒ **Tritium ^{3}H (^{187}Re, ^{163}Ho)**

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



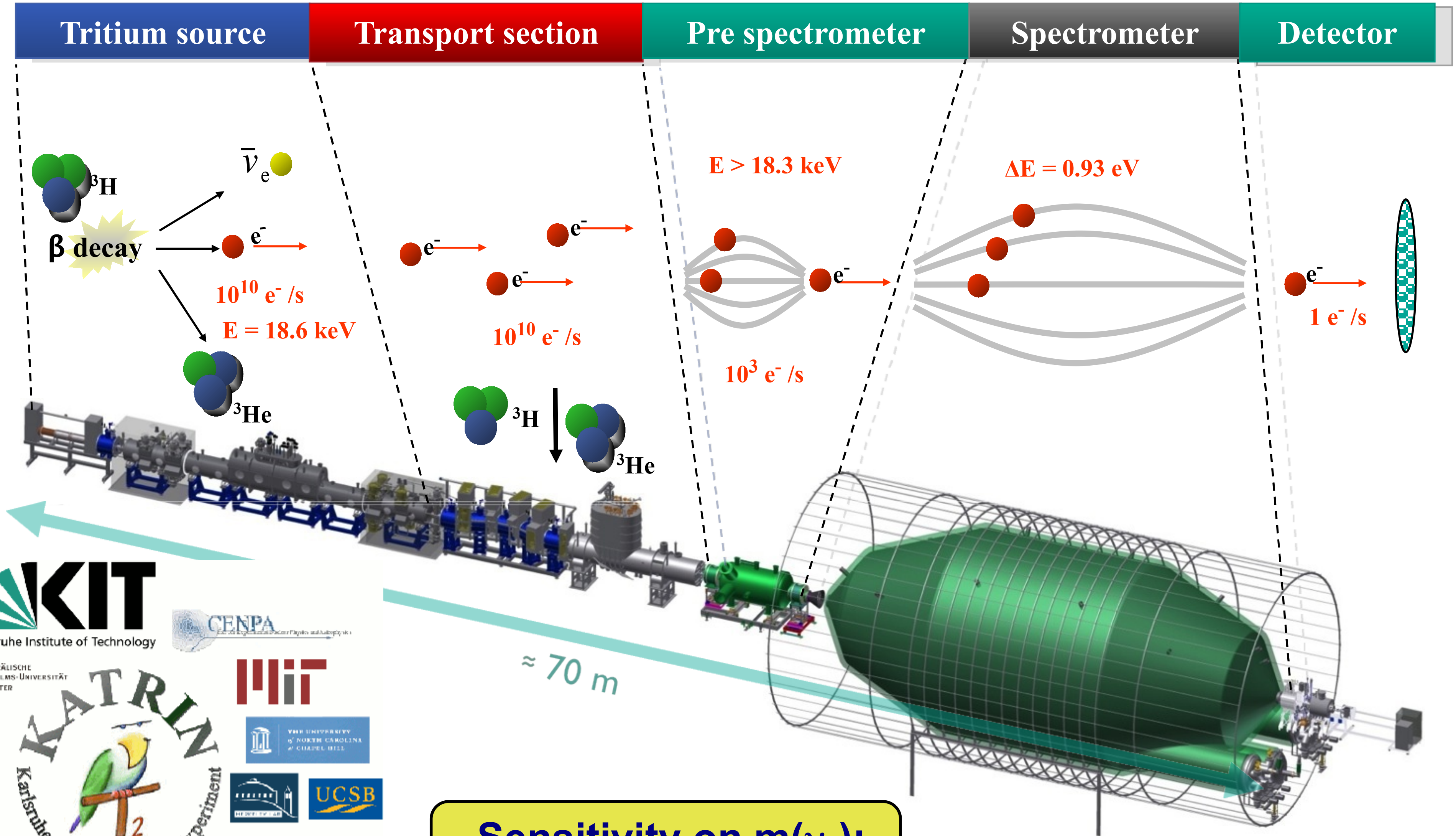
- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp / B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)



⇒ sharp integrating transmission function without tails →

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

The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview



Sensitivity on m(ν_e):

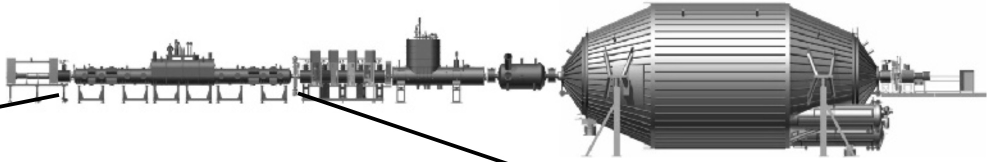
2 eV/c² → 200 meV/c²

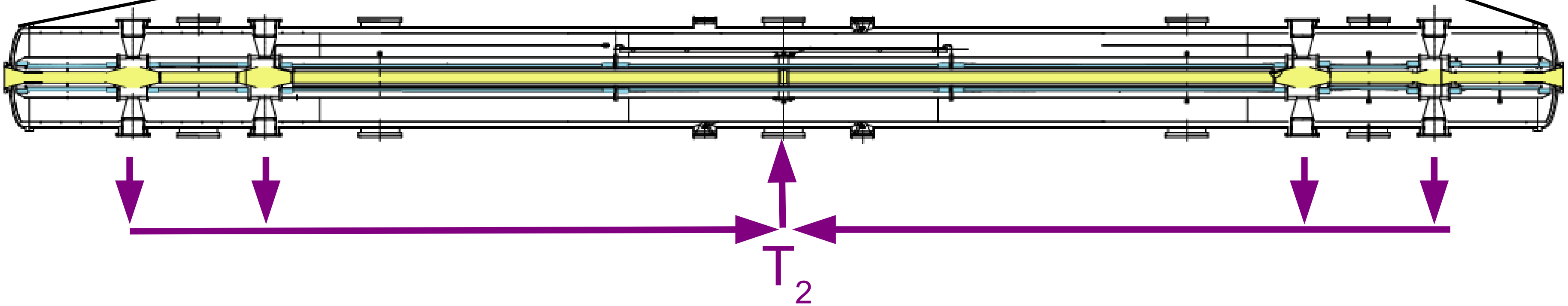
Molecular Windowless Gaseous Tritium Source WGTS

per mill stability source strength request:

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

tritium fraction f_T & ideal gas law

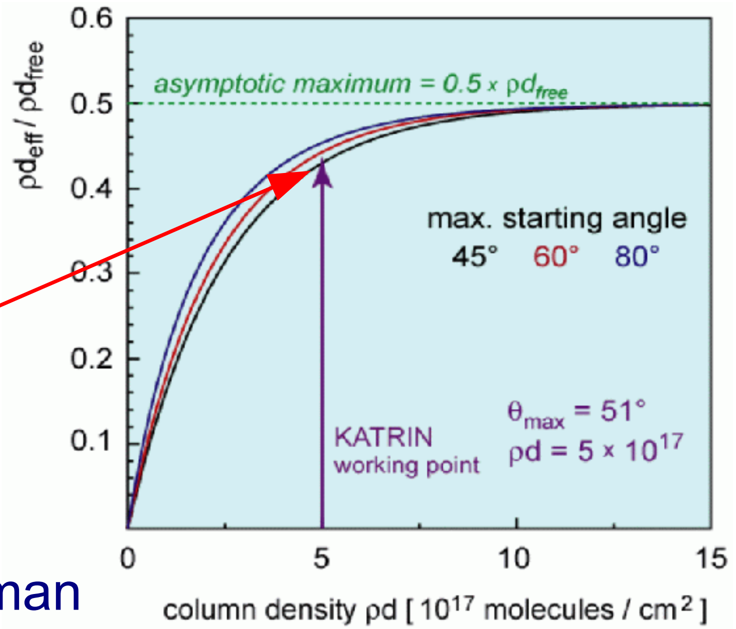




WGTS: tub in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

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

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



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

Status of Windowless Gaseous molecular Tritium Source WGTS

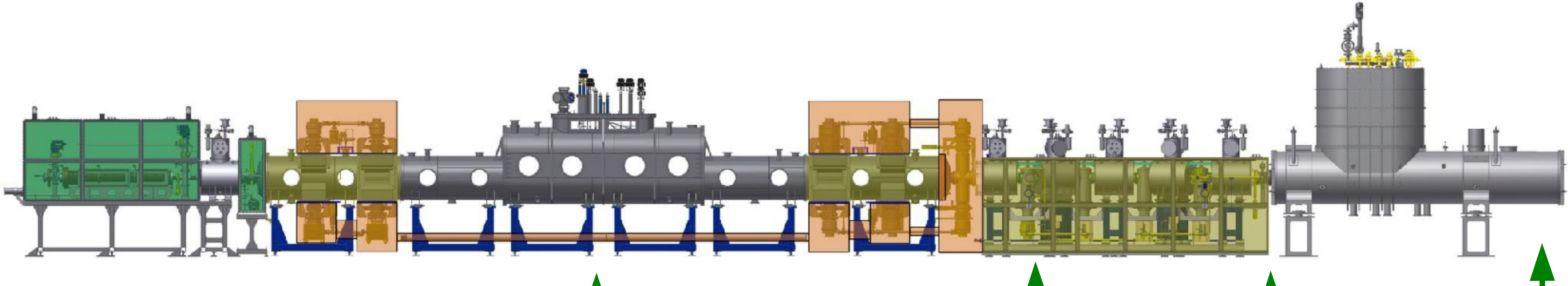
Assembly of beam tube, magnets and cryostat:

Temperature stability tests of „demonstrator“ very successful

Management now in the hand of KIT progress according schedule

Arrived at KIT on Sept 10, 2015 !

Transport and differential & cryo pumping sections



Monitoring & calibration system

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping
with Argon snow
at LHe temperatures

T_2-injection 1.8 mbar l/s (STP)
= $1.7 \cdot 10^{11}$ Bq/s = 40 g/d

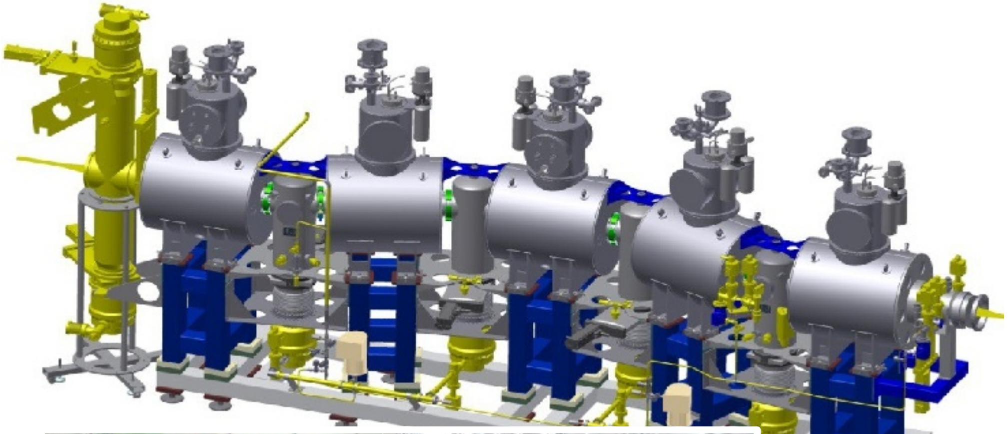
FT-ICR Penning traps to measure ions from WGTS

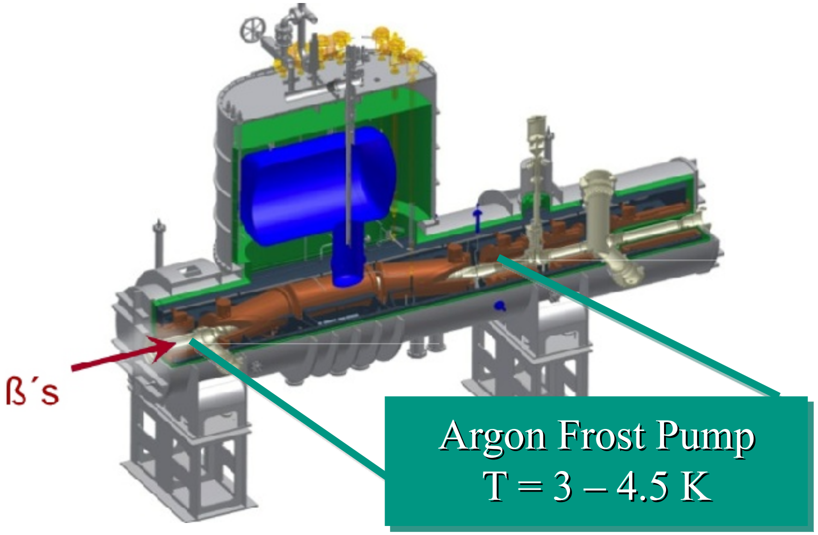
$\approx 10^{-7}$ mbar l/s

$< 2.5 \, 10^{-14}$ mbar l/s

⇒ adiabatic electron guiding & T_2 reduction factor of ~10^{14}

Differential and cryo pumping sections

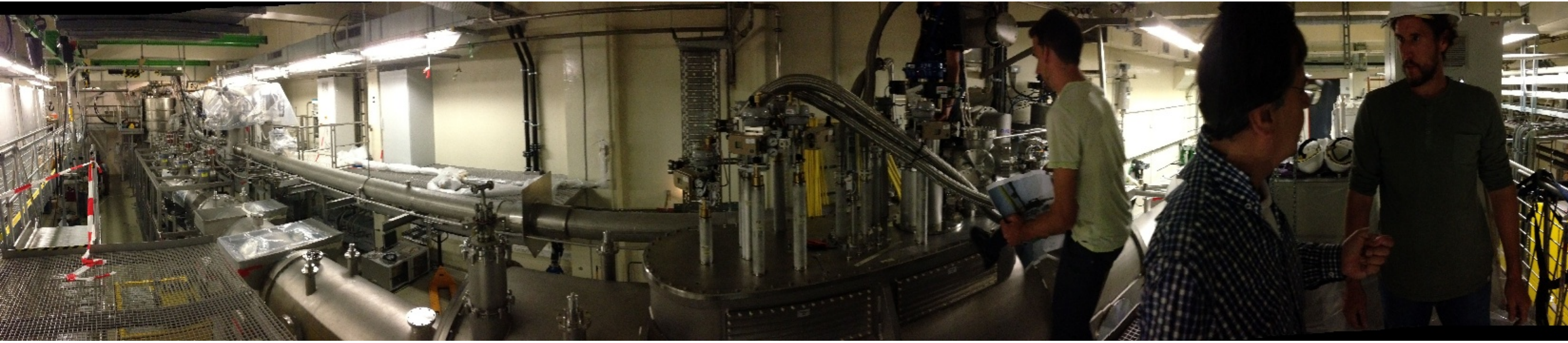


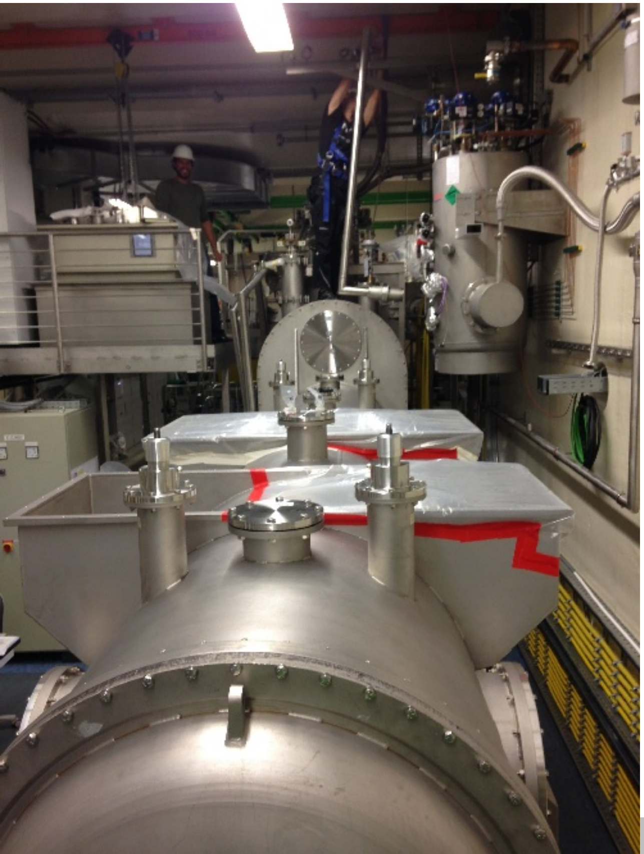


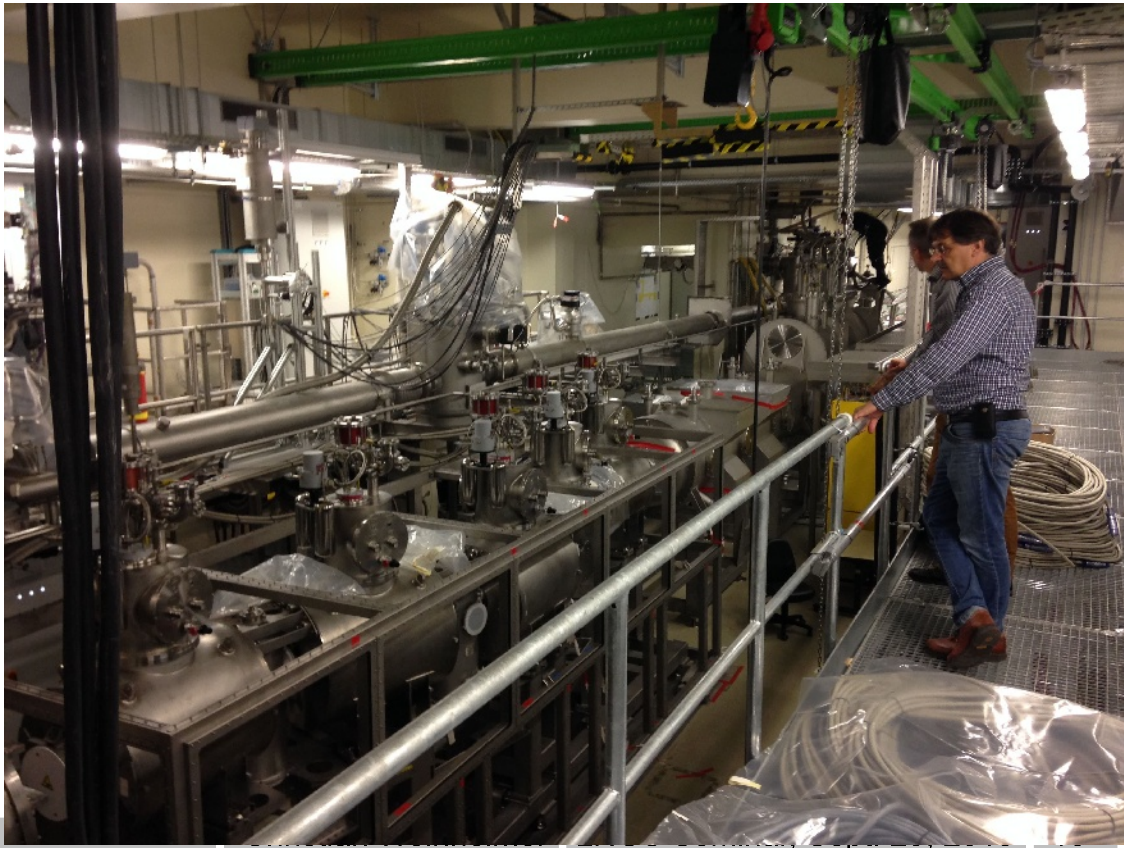
- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- **under commissioning**

- based on by cryo-sorption
- Tritium retention: >10^7
- magnetic field: 5.6 T
- **delivered to KIT: July 30, 2015**

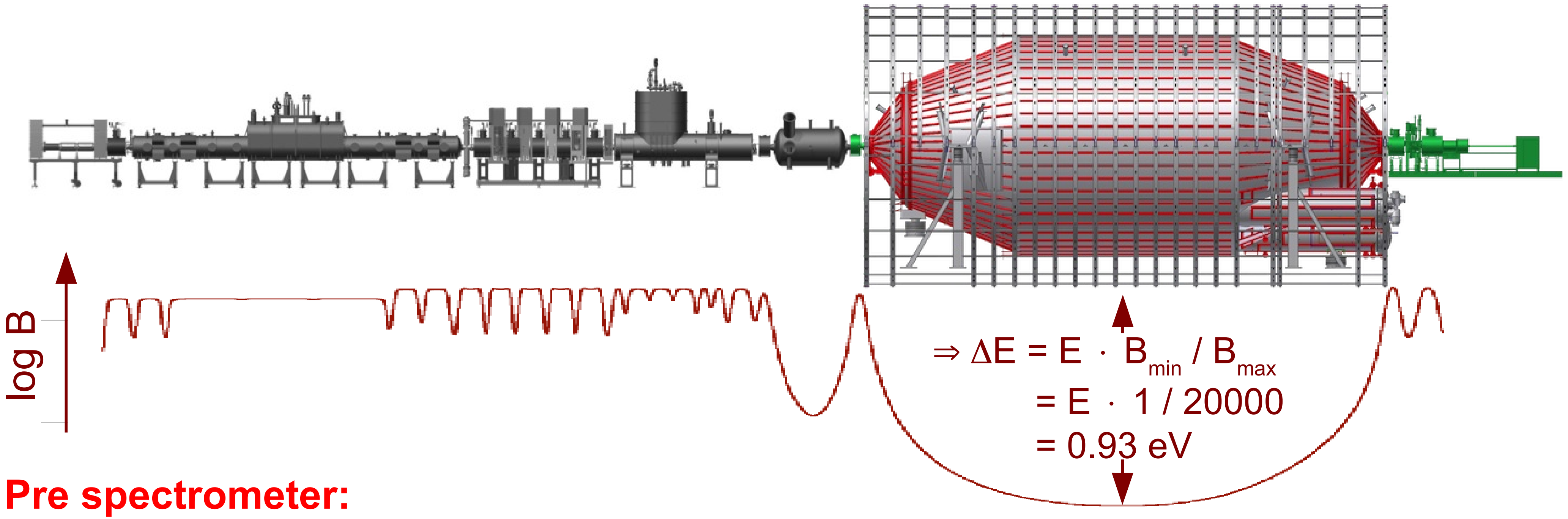
The source and transport section is really there !







KATRIN spectrometers



$\Rightarrow \Delta E = E \cdot B_{min} / B_{max}$
$= E \cdot 1 / 20000$
$= 0.93$ eV

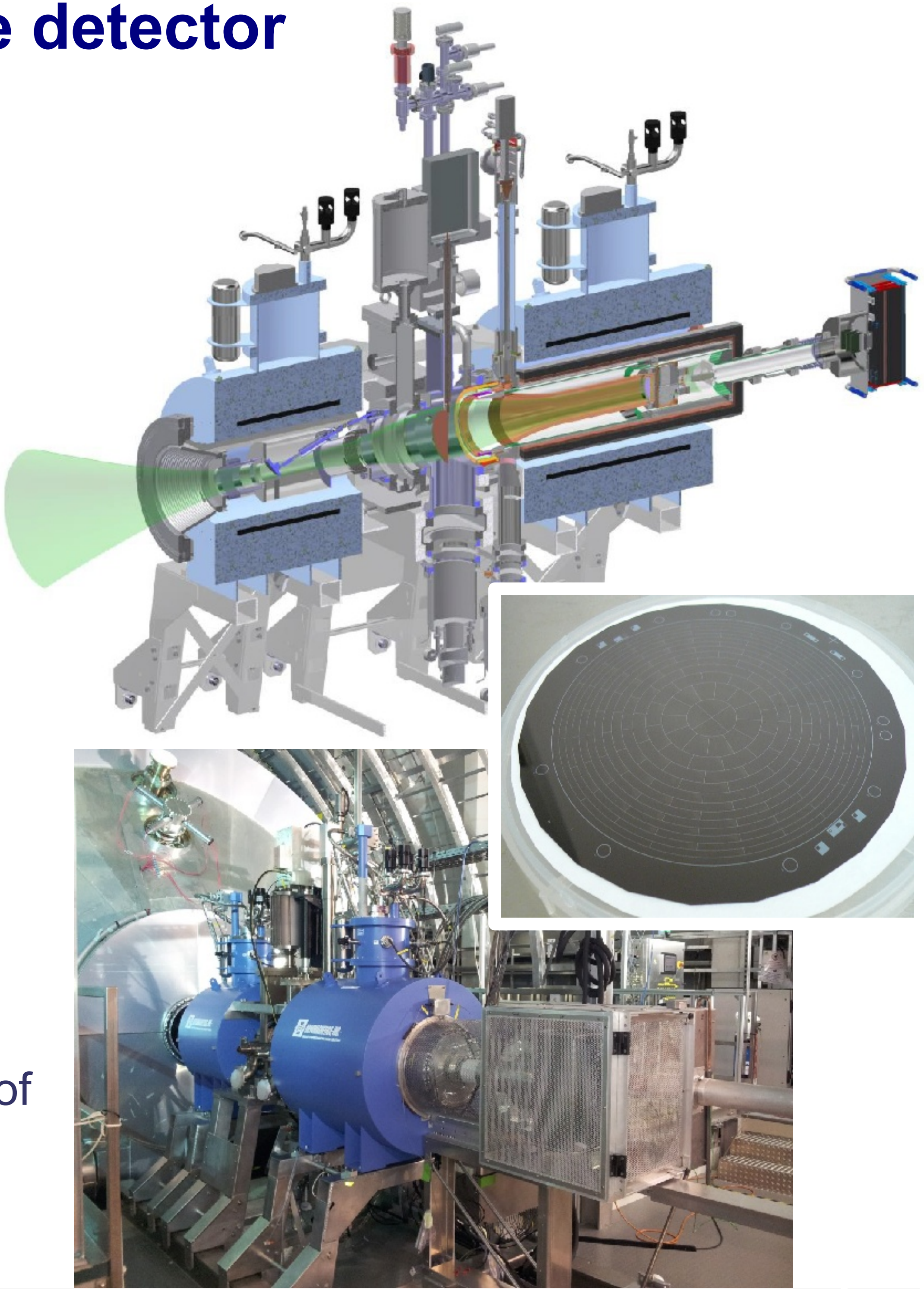
Pre spectrometer:

- 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: ΔE = 0.93eV
- vacuum vessel on precise high voltage (ppm precision)

The detector



Requirements

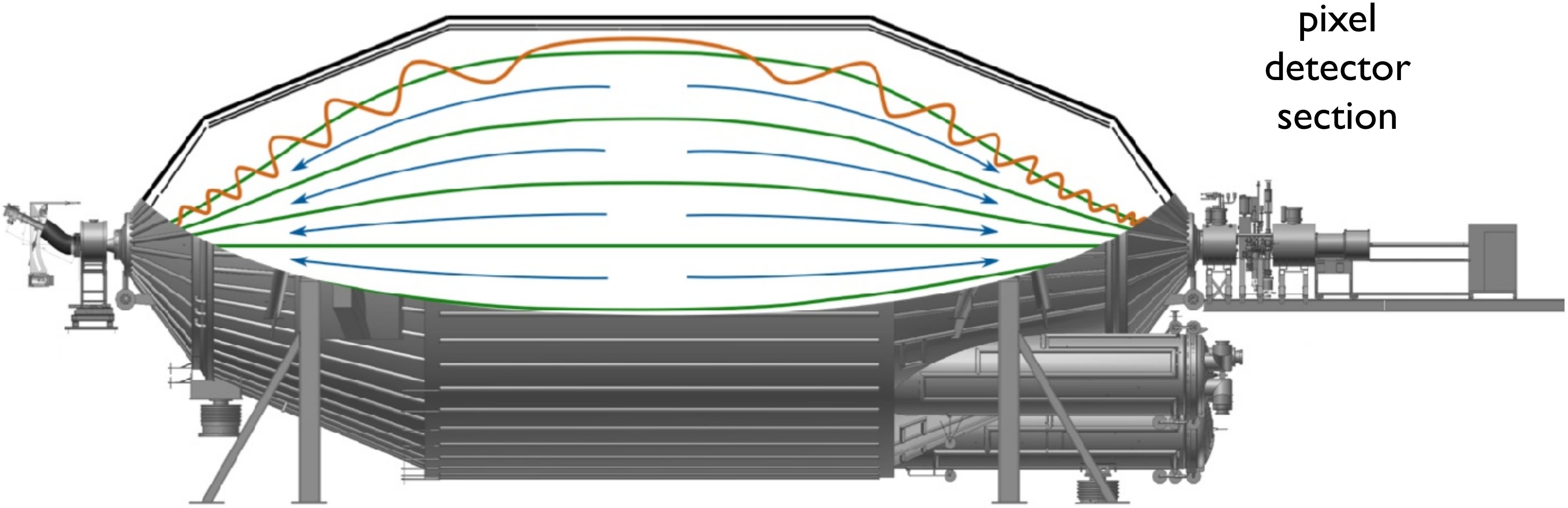
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  (passive and active shielding)
- good energy resolution (< 1 keV)

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

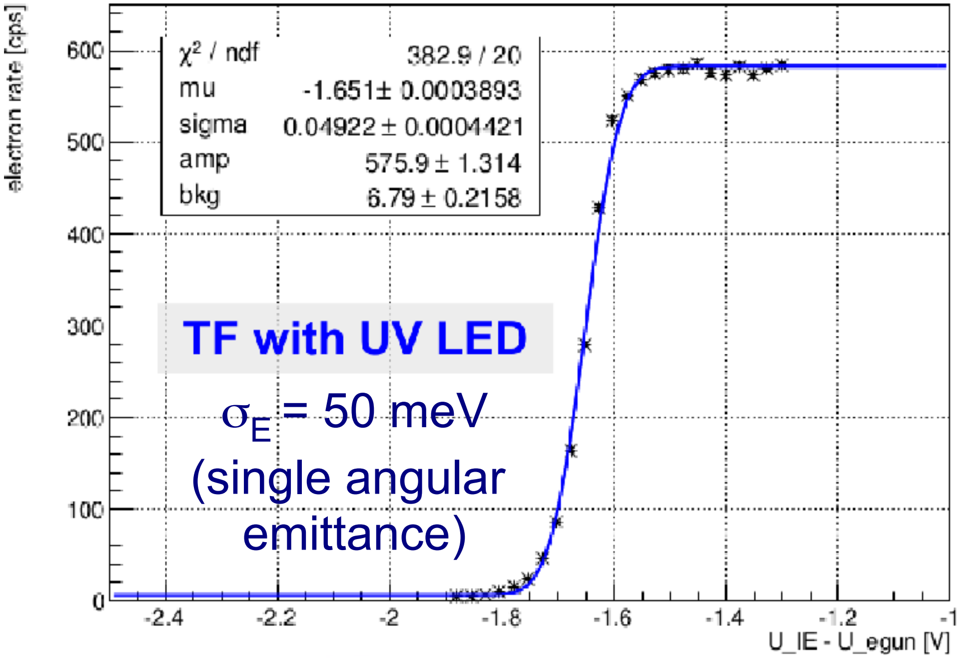
Main spectrometer and detector commissioning – objectives



Primary objectives:

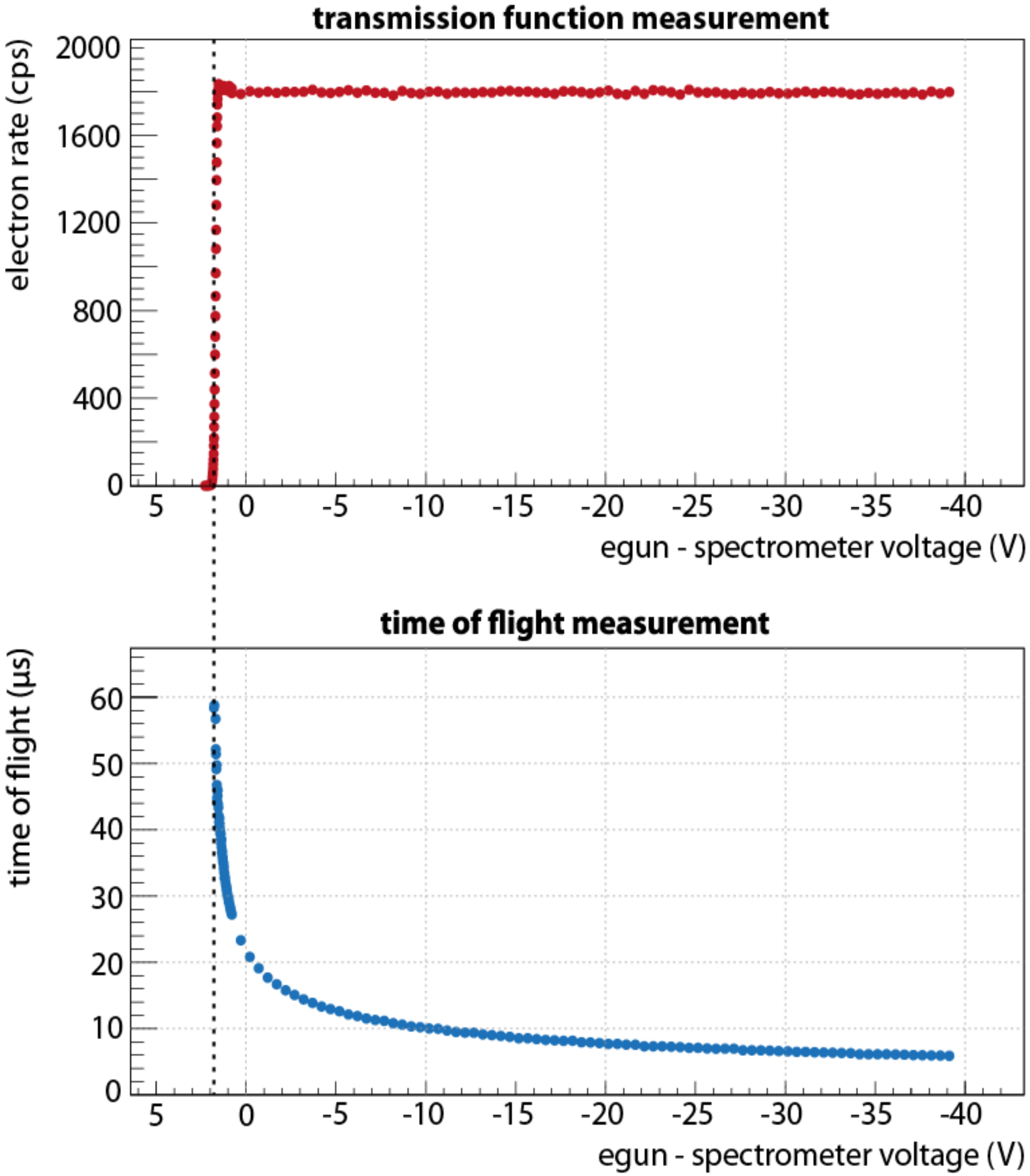
- test of individual hardware, software and slow control components
- provide ultra high vacuum conditions at the $p \approx 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter ($E = 18.6$ keV with $\Delta E = 0.93$ eV resolution) and compare to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes

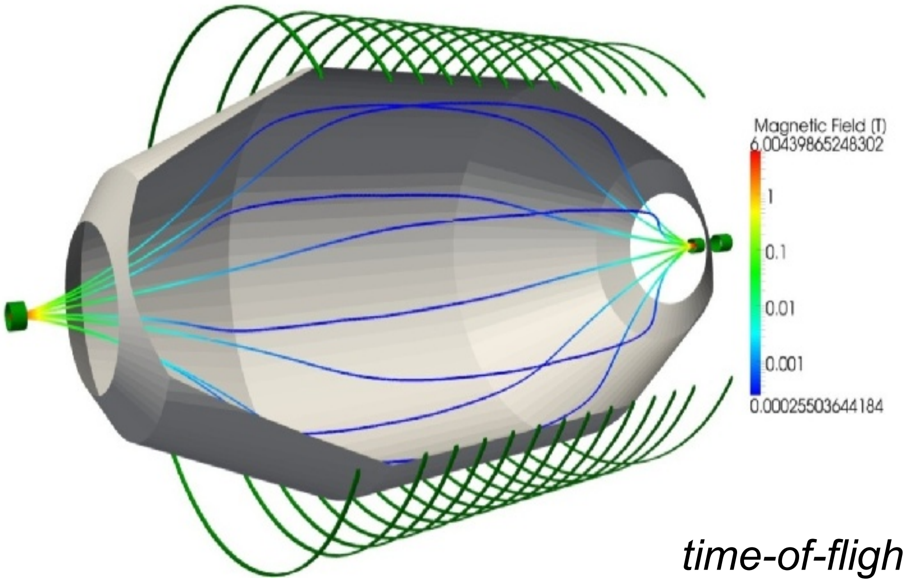
Commissioning of main spectrometer and detector



TF with UV LED

σ_E = 50 meV (single angular emittance)





time-of-flight, see also N. Steinbrink et al., NJP 15 (2013) 113020

Suppress secondary electron background from walls on high potential

Secondary electrons from wall/electrode

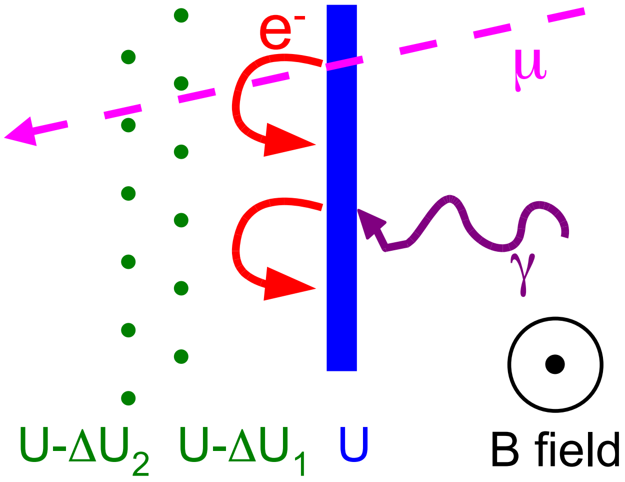
by cosmic rays, environmental radioactivity, ...

Excellent magnetic shielding by nearly perfect axial sym.

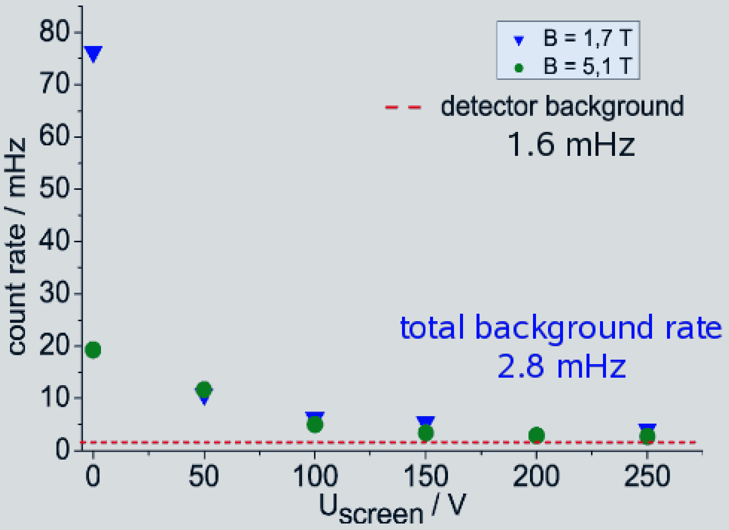
Additionally double layer wire electrode

on slightly more negative potential

(ca. 23,000 wires, 200 μm precision, UHV compatible)



Background suppression successfully tested at the Mainz MAC-E filter:



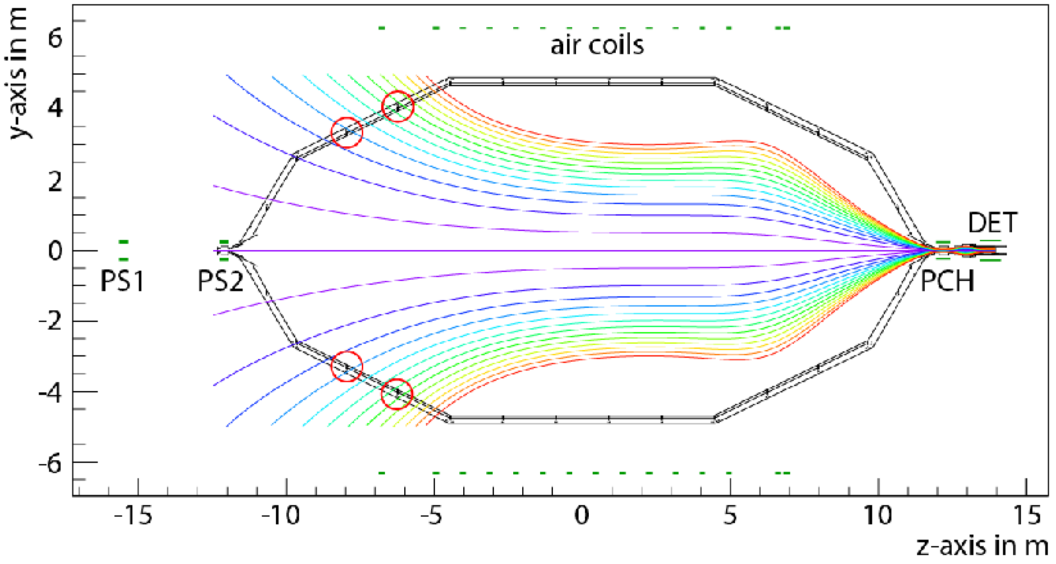
Dipl. thesis B. Ostrick (U Mainz, 2002),
PhD thesis B. Flatt (U Mainz, 2004)

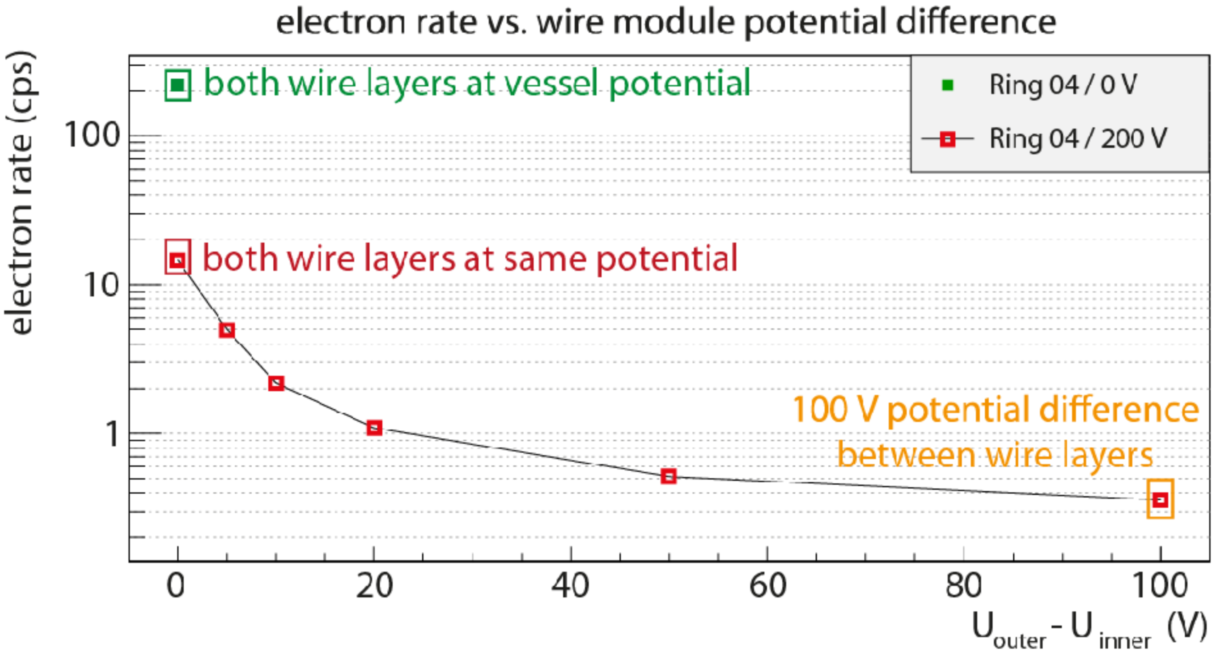
Background suppression by wire electrode

Investigating secondary electrons from the walls by directly looking to the wall and applying an asymmetric magnetic field

→ there are many secondary electrons from the walls, which are shielded by the wire electrode

→ but there is a very efficient magnetic shielding as well





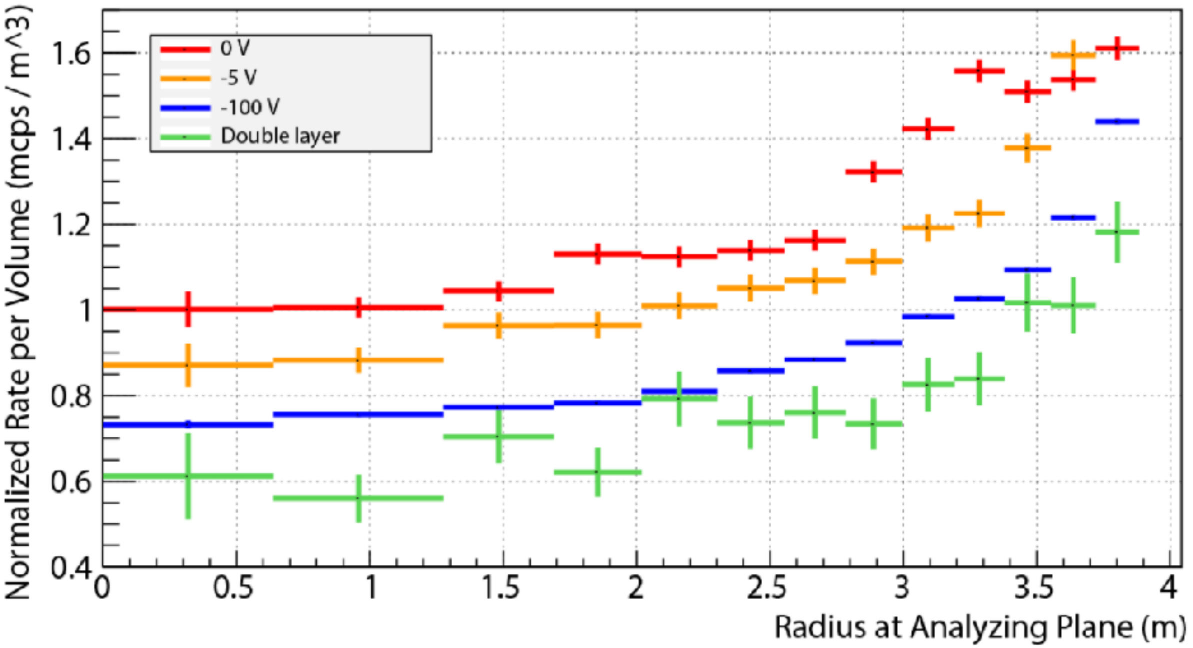
Background suppression by wire electrode

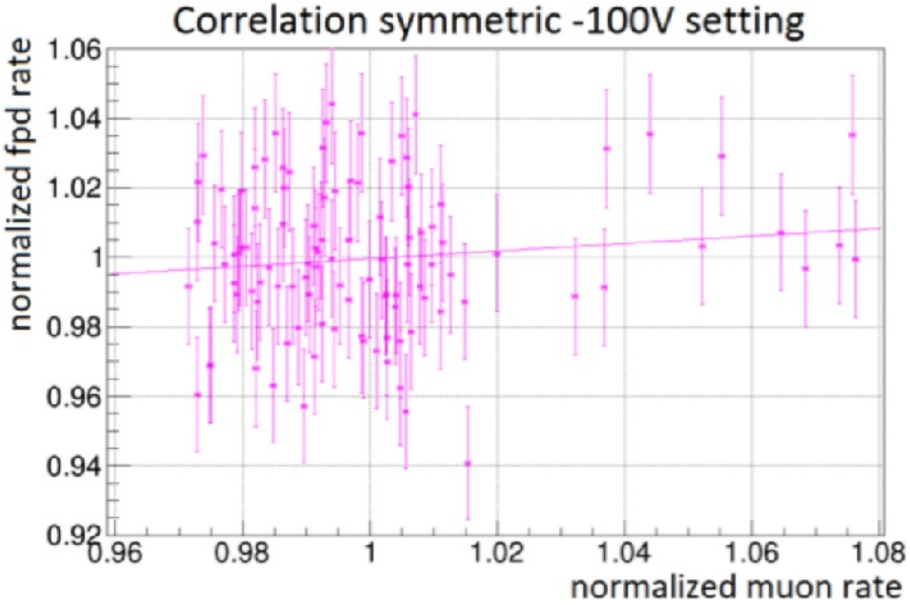
Significant background reduction by single & dual layer wire electrode

(some electric shorts prohibit full dual layer operation)

but the remaining background does not seem to originate from cosmic muons or other charged particles,

but from neutrals ...





slope a: 0.11 ± 0.07
correlation factor: 0.11 ± 0.09

Radon background in the pre spectrometer from the non-evaporable getter (NEG) pumps

Getter strips (SAES ST707) adsorbing residual gas (H_2) are essential to reach 10^{-11} mbar, composition:

70 % Zirconium: contains ^{227}Ac

25 % Vanadium

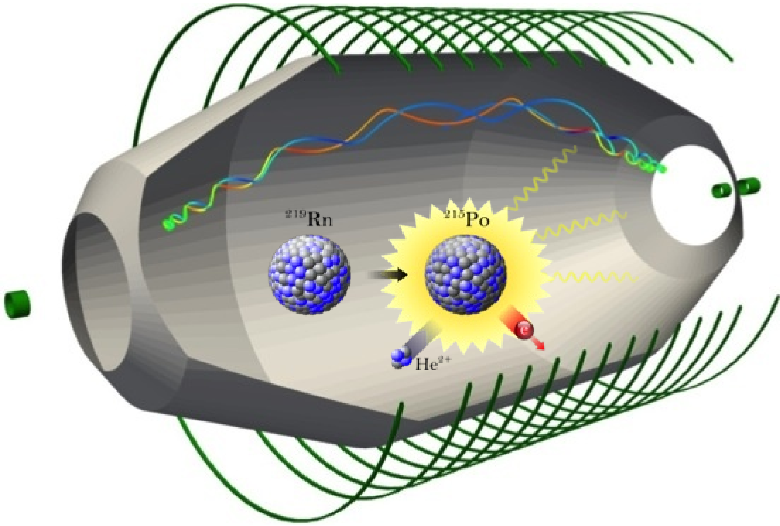
5 % Iron

$$^{235}\mathrm{U} \xrightarrow{} \cdots \xrightarrow{} {}^{227}\mathrm{Ac} \xrightarrow{\alpha} {}^{223}\mathrm{Fr} \xrightarrow{\beta} {}^{223}\mathrm{Ra} \xrightarrow{} \boxed{{}^{219}\mathrm{Rn} \xrightarrow{\alpha\ (4s)} {}^{215}\mathrm{Po} \xrightarrow{\alpha\ (2ms)}} {}^{211}\mathrm{Pb}$$

^{219}Ra is gaseous → spectrometer → ionizations → **background**

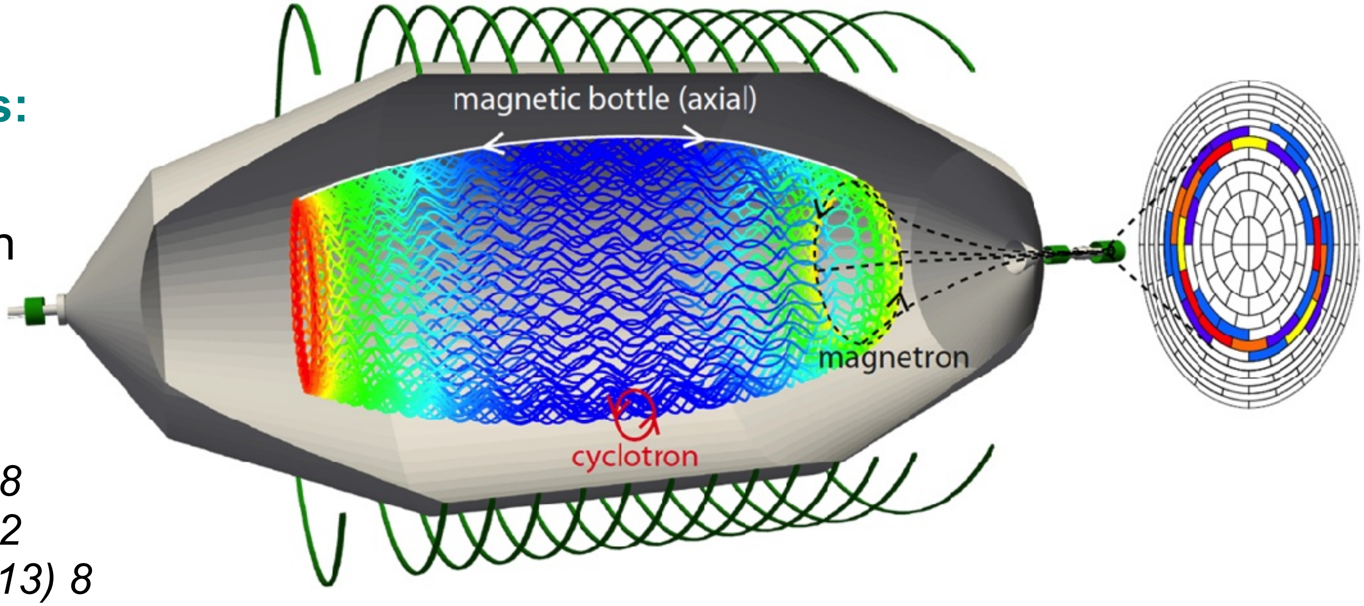
Secondary electron background from radon decays in the volume

- ^{219,220}**Rn emanation** mainly from SAES getter pumps (zirconium vanadium iron alloy)
  conversion, Auger, shake-off electrons can get stored
  my magnetic mirror effect



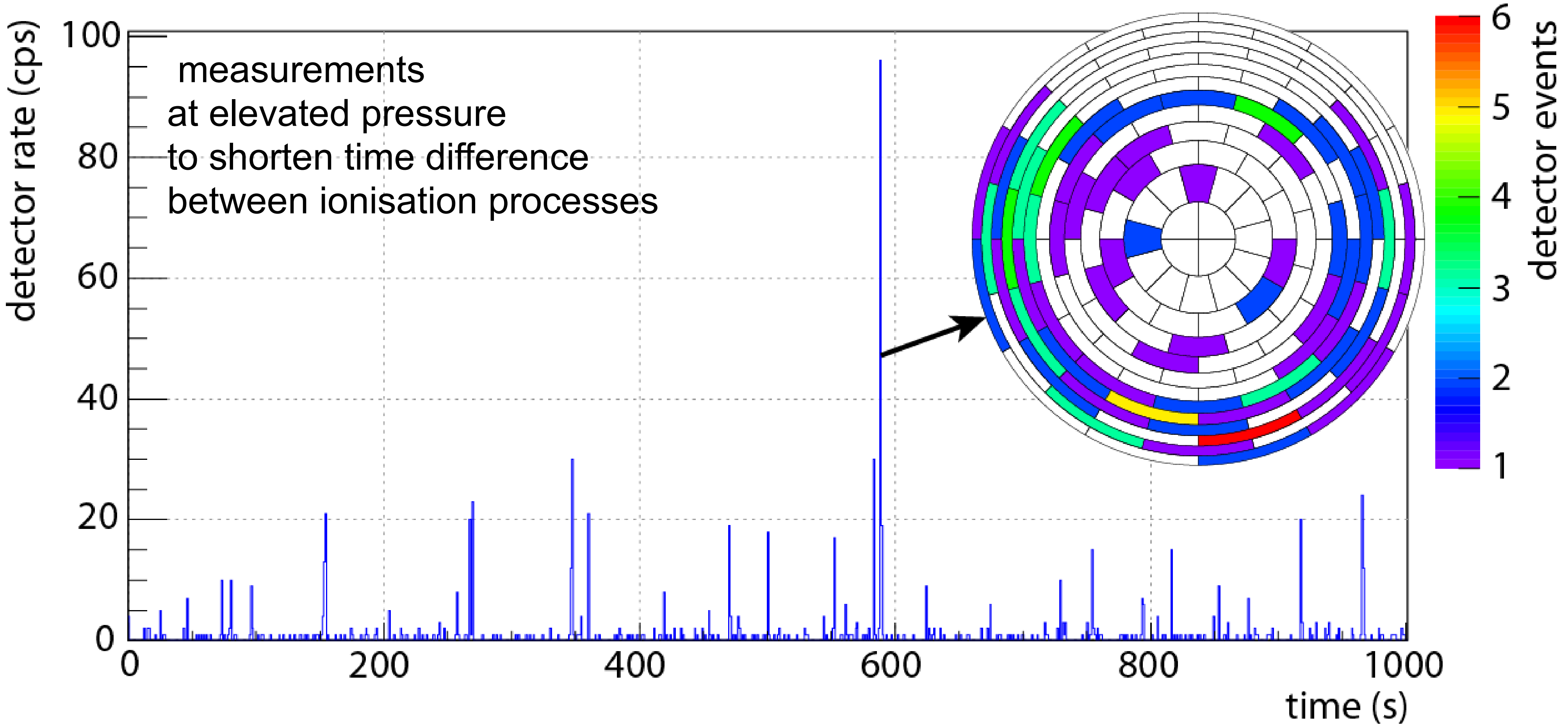
- **background process continues:**
  - ionization of residual gas → secondary electrons
  - primary electron energies: 100 eV < E < 500 keV
  - up to 5000 secondary electrons per stored primary
  - significant background increase for hours

- **stored multi-keV electrons:**
  rapid cyclotron motion
  intermediate axial oscillation
  slow magnetron drift



F. Fränkle et al., APP 35 (2011) 128
S. Mertens et al., APP 41 (2012) 52
N. Wandkowsky et al., NJP 15 (2013) 8

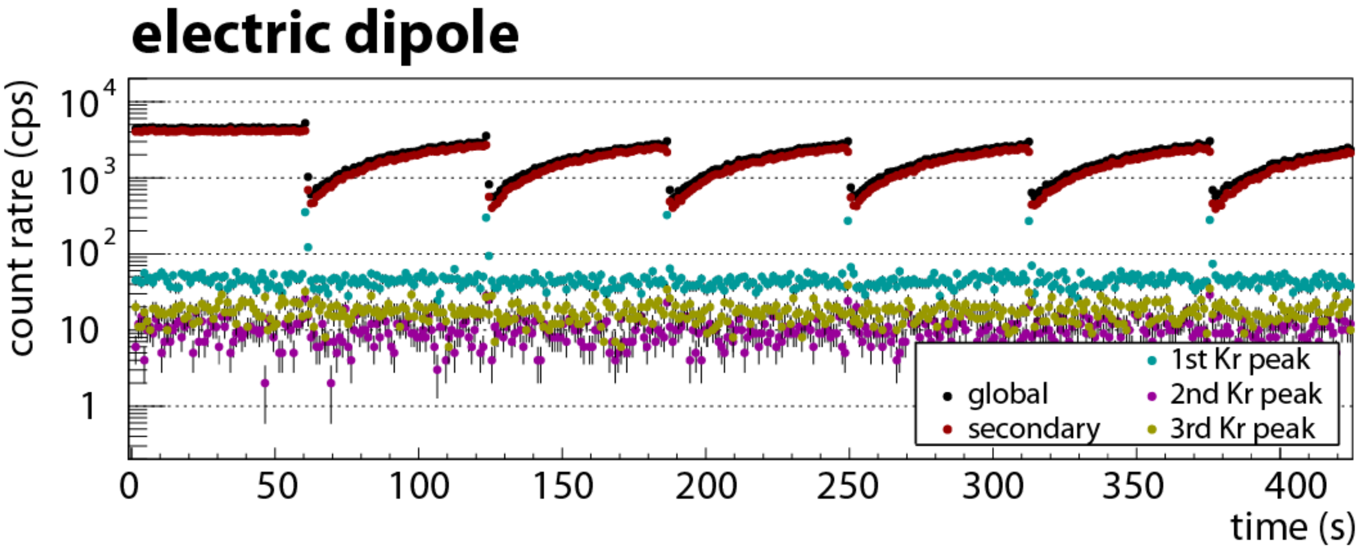
Understanding the background: Radon and other background sources

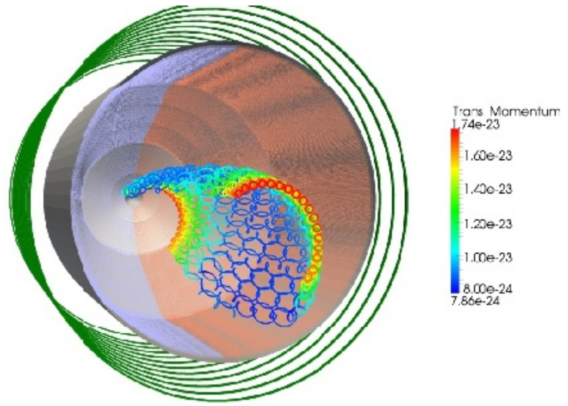


measurements at elevated pressure to shorten time difference between ionisation processes

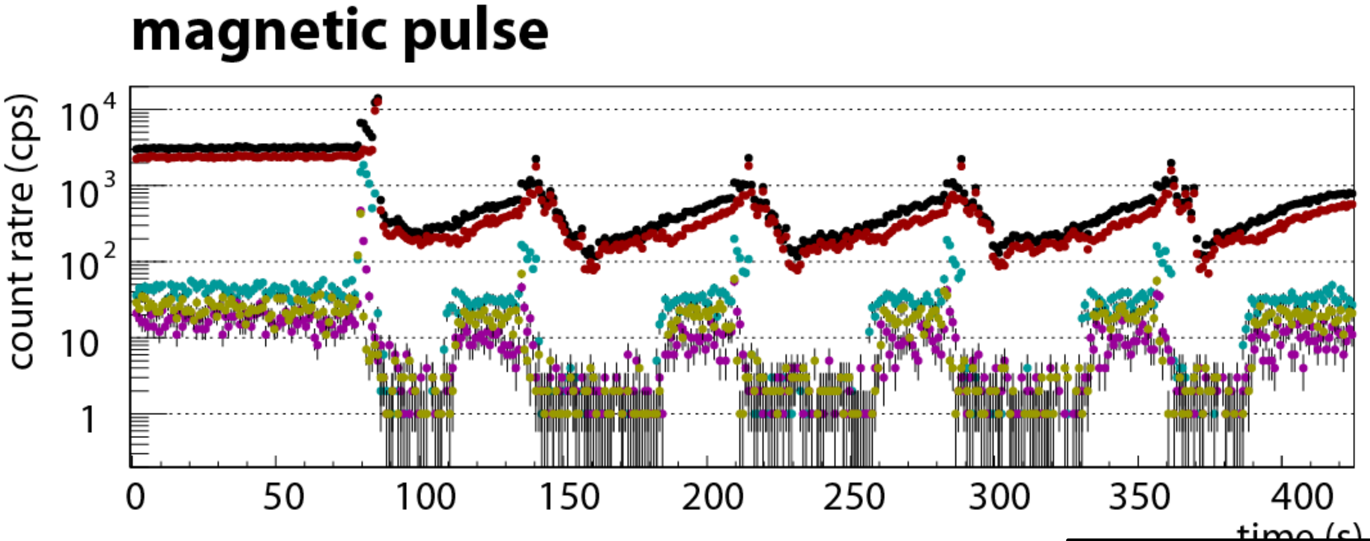
High energy electrons from radon decays:
→ multiple, spike-like events
with a ring pattern at the detector (magnetron motion)

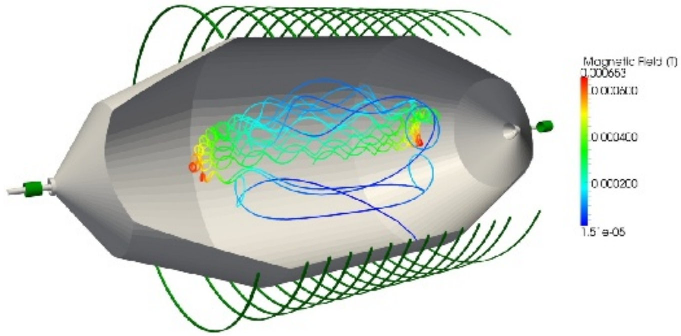
Active stored particle removal by electric dipole and magnetic zeroing





$\boldsymbol{v}_D = \mathbf{E} \times \mathbf{B} / B^2$



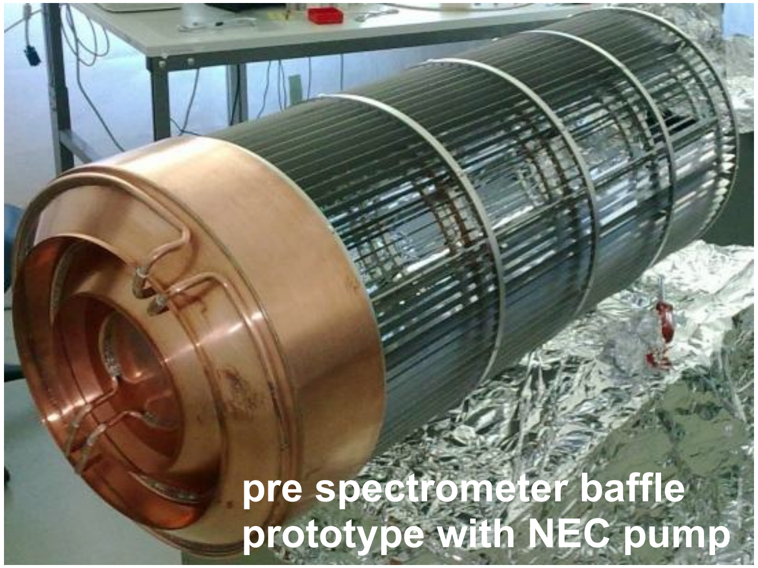


loss of magnetic guidance

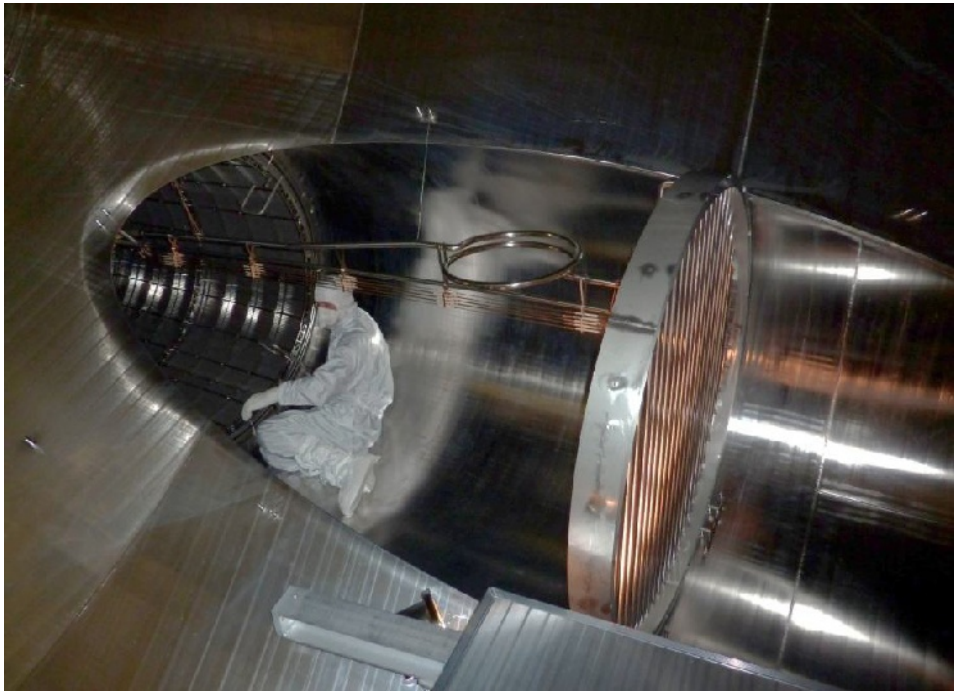
^{83m}Kr injected
to enhance number of stored particles

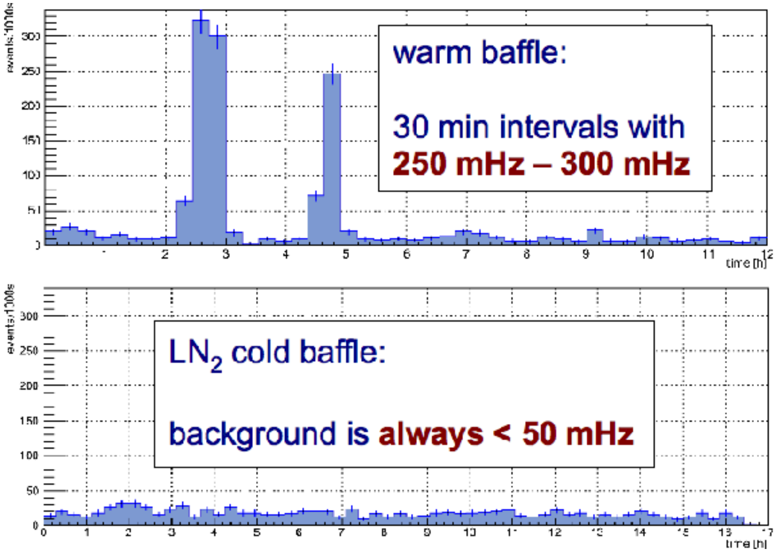
2014: all 14 axial air coils are instrumented
with fast magnet puls switches in SDS II
(compared to 1 switch in SDS I in 2013)

Radon elimination by LN_2-cooled baffles in the pre & main spectrometer



pre spectrometer baffle prototype with NEC pump



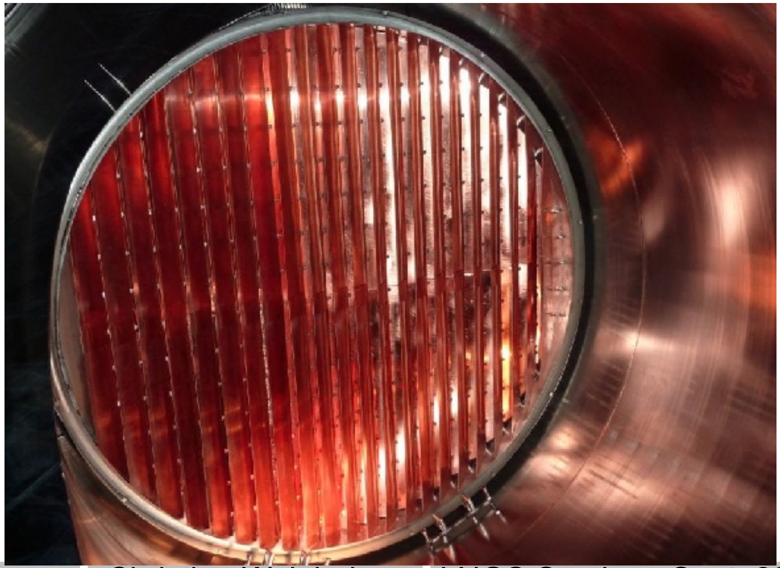


warm baffle:

30 min intervals with **250 mHz – 300 mHz**

LN_2 cold baffle:

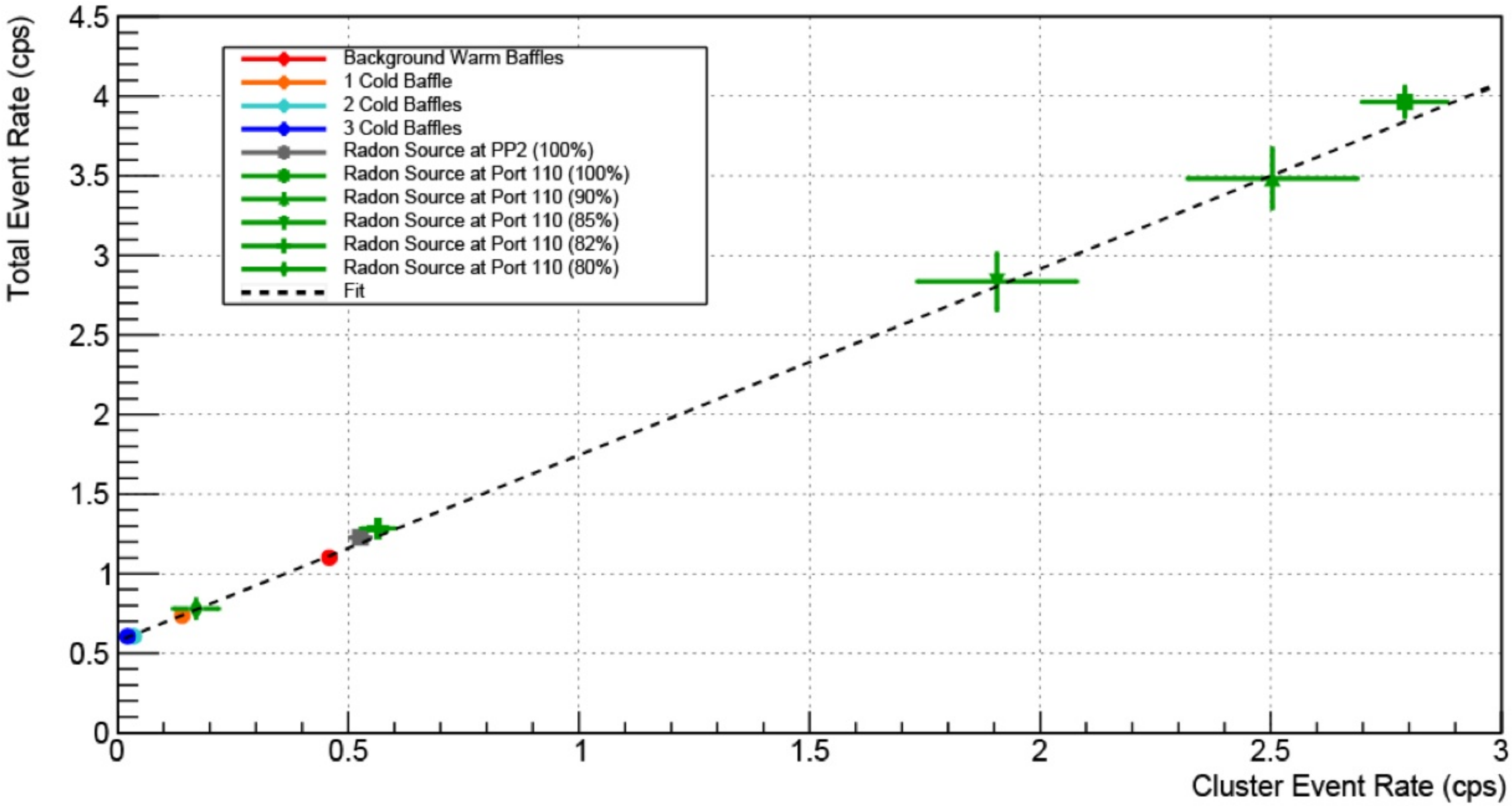
background is **always < 50 mHz**



successful application at pre spectrometer

Radon induced background

^{219}Rn from getter and artefical ^{220}Rn source



→ radon-induced background is very efficiently eliminated by LN$_2$ baffles

→ residual non-radon background of about 600 mcps

→ optimal magnetic field settings: 477 mcps = reference background rate (SDS2)

SDS2b after baking to reach better understanding of residual background:
bg < 300 mcps reached (July 2015, preliminary)

Systematic uncertainties

As smaller m(ν) as smaller the region of interest below endpoint E_0

→ quantum mechanical thresholds help a lot !

A few contributions with $\Delta m_\nu^2 \leq$ 0.007 eV² each:

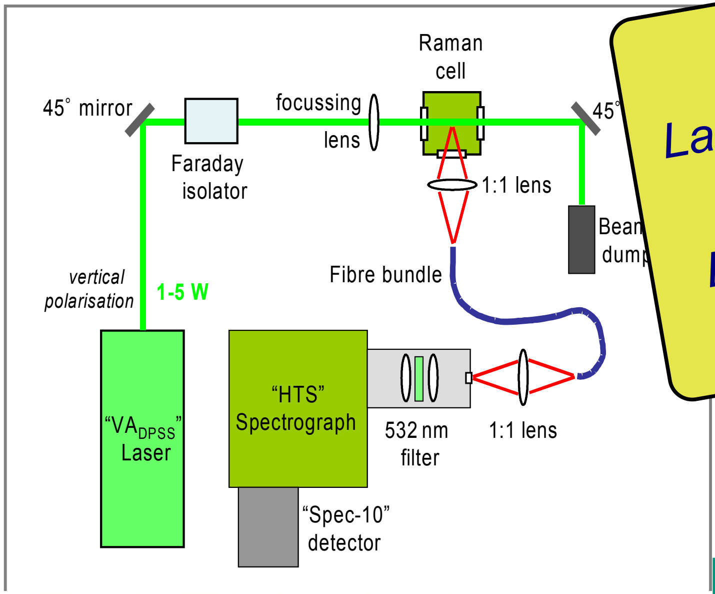
1. inelastic scatterings of β´s inside WGTS
   - **dedicated e-gun measurements**, unfolding of response fct.
2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, **e-gun measurements**
3. WGTS charging due to remaining ions (MC: φ < 20mV)
   - **monocrystaline rear plate short-cuts potential differences**
4. final state distribution
   - **reliable quantum chem. calculations**

tritium source

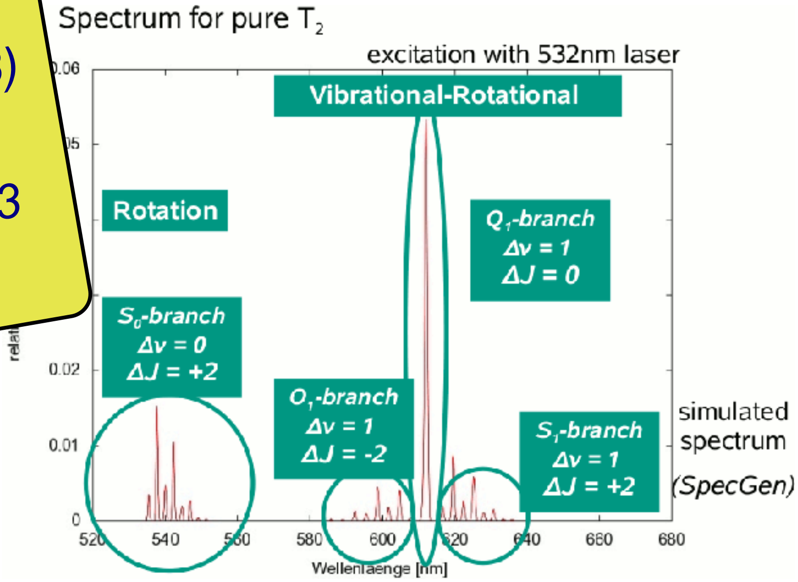
5. transmission function
   - detailed simulations, **angular-selective e-gun measurements**
6. HV stability of retarding potential on ~3ppm level required
   - **precision HV divider (with PTB)**, **monitor spectrometer beamline**

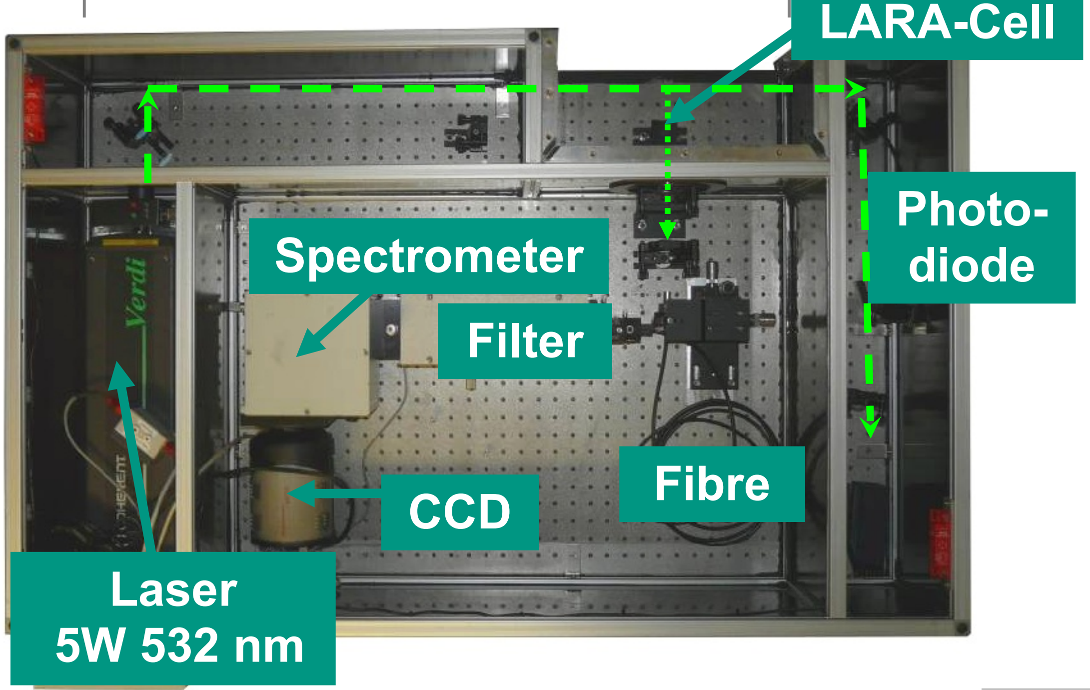
spectrometer

Measurement of tritium concentration by laser Raman spectroscopy

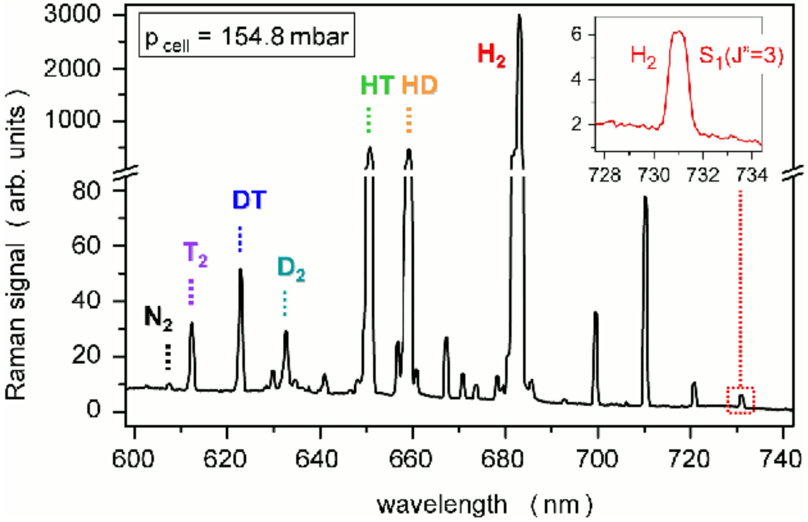


R.J. Lewis et al.,
Las. Phys. Lett.1-10 (2008)
M.Sturm et al,
Las. Phys. 20 (2010) 493
& many more ...

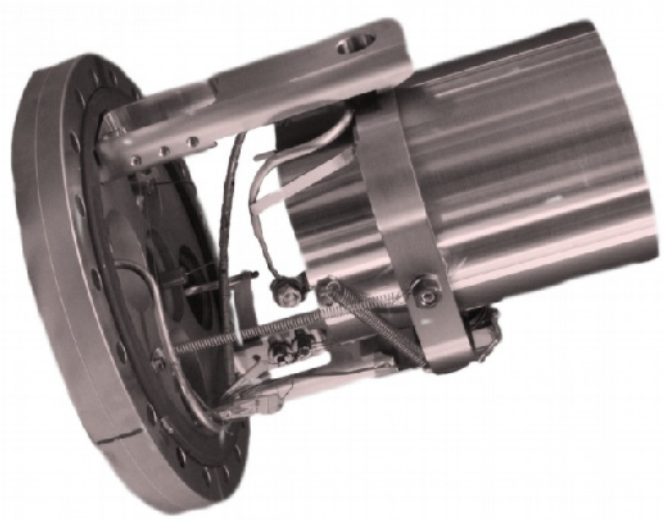




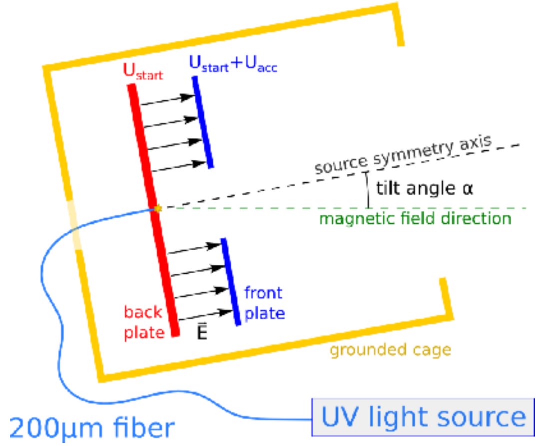
H_2 / HD / T_2 / DT / HT
= 0.820 / 0.083 / 0.003 / 0.005 / 0.085



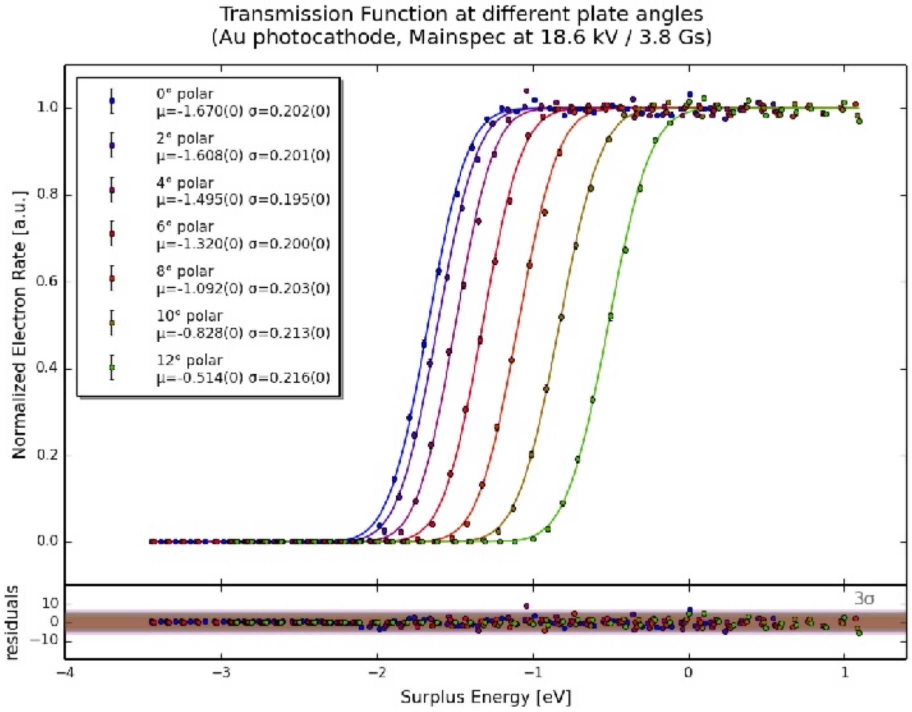
An angular-selective, pulsed UV photoelectron e-gun



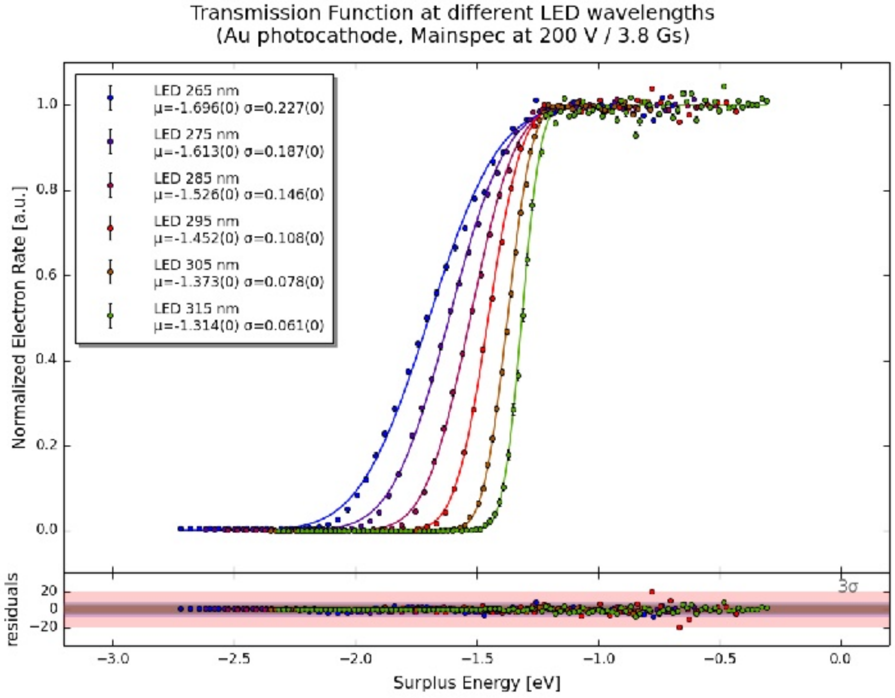
see poster by Jan Behrens



Different tilding angles of egun


Transmission Function at different plate angles
(Au photocathode, Mainspec at 18.6 kV / 3.8 Gs)

Different UV wavelengths


Transmission Function at different LED wavelengths
(Au photocathode, Mainspec at 200 V / 3.8 Gs)

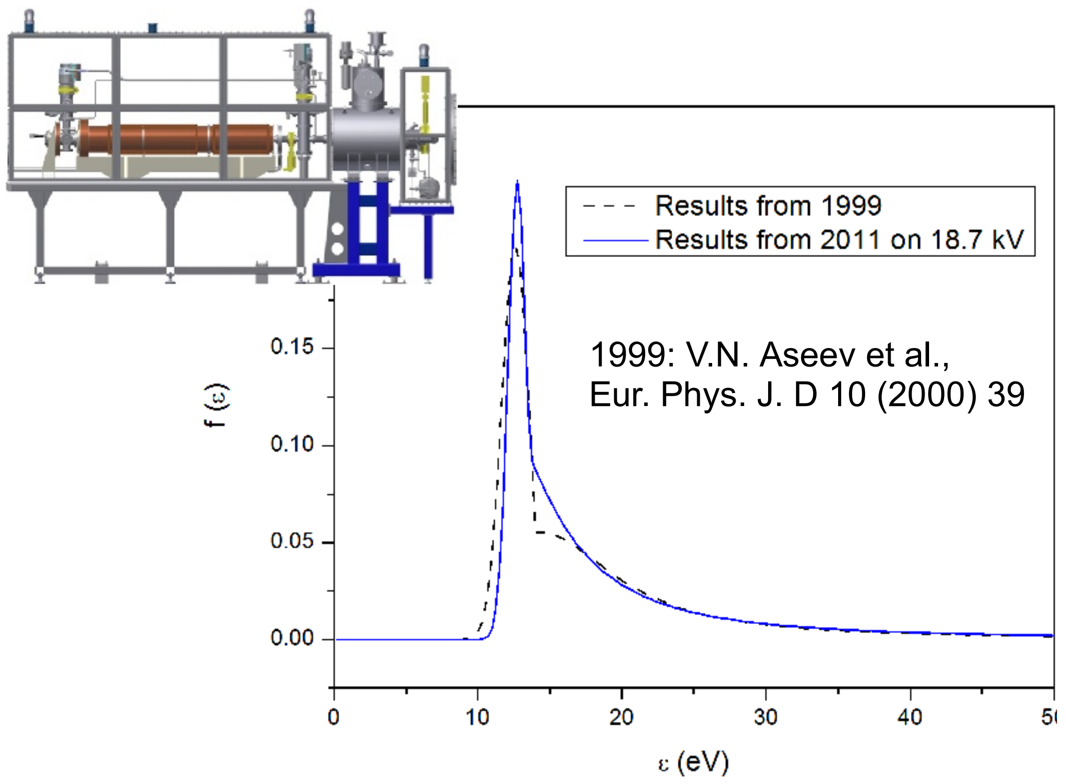
Recently achieved results at Troitsk

Measurement of electron scattering on H_2 at 14, 18, and 25 keV. New data on excitation and ionization spectra obtained with spectrometer resolution of about 1 eV.

e- from monoenergetic e-gun

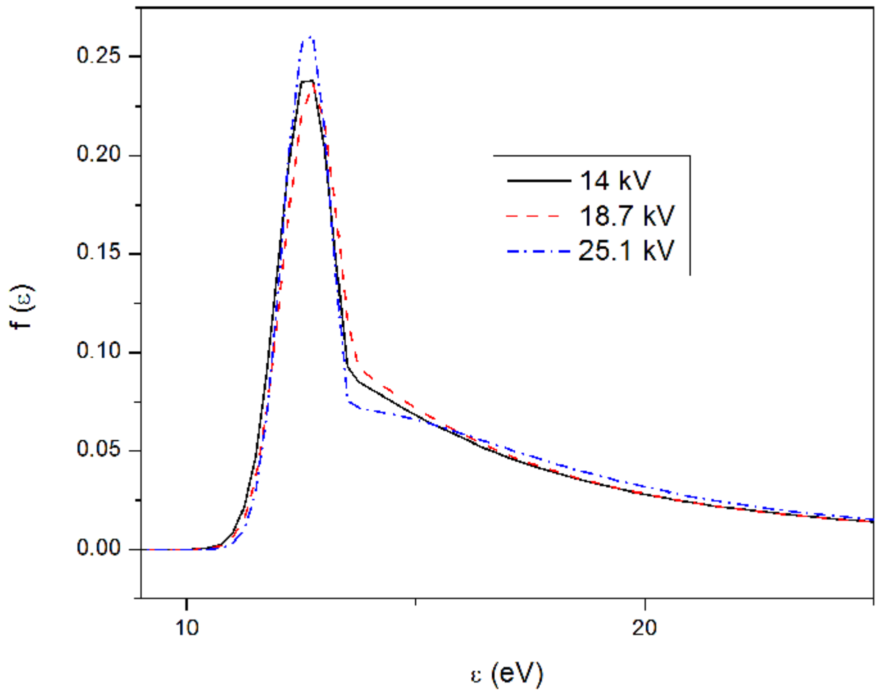
moleclar windowless gaseous tritium source

towards the spectrometer



1999: V.N. Aseev et al., Eur. Phys. J. D 10 (2000) 39

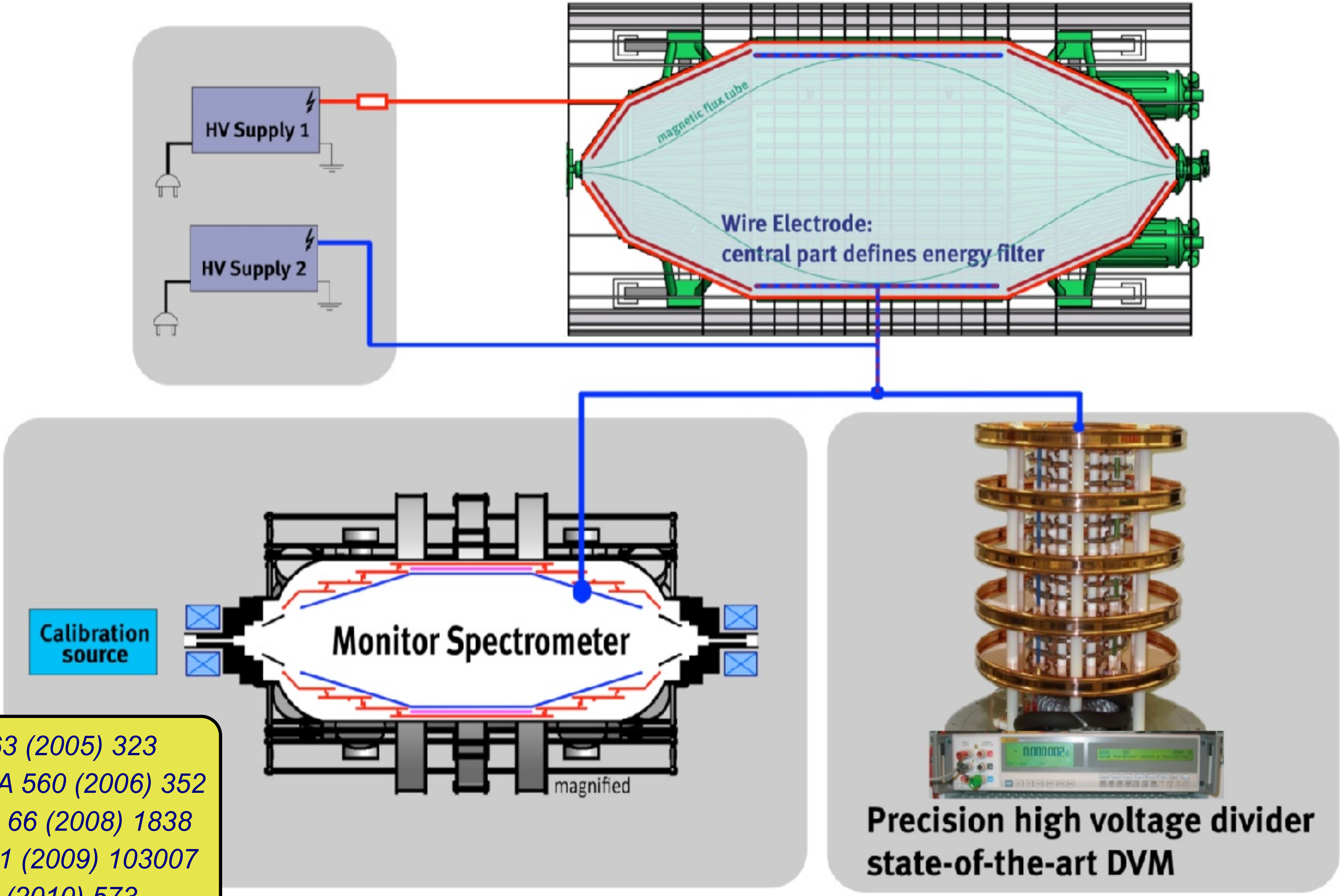
Electron energy losses by scattering in H_2

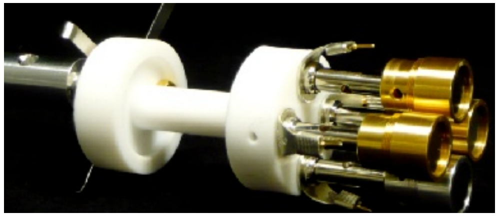


The same, at different energies

V. Pantuev, Dubna, Dec. 2012

KATRIN's high voltage concept: stability and monitoring: ppm at -18.6 kV

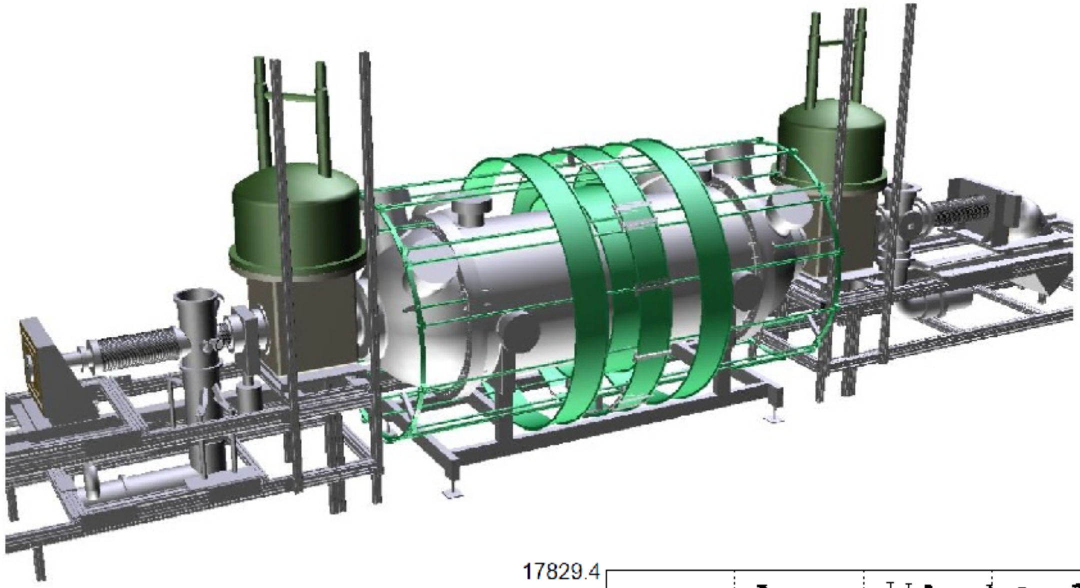


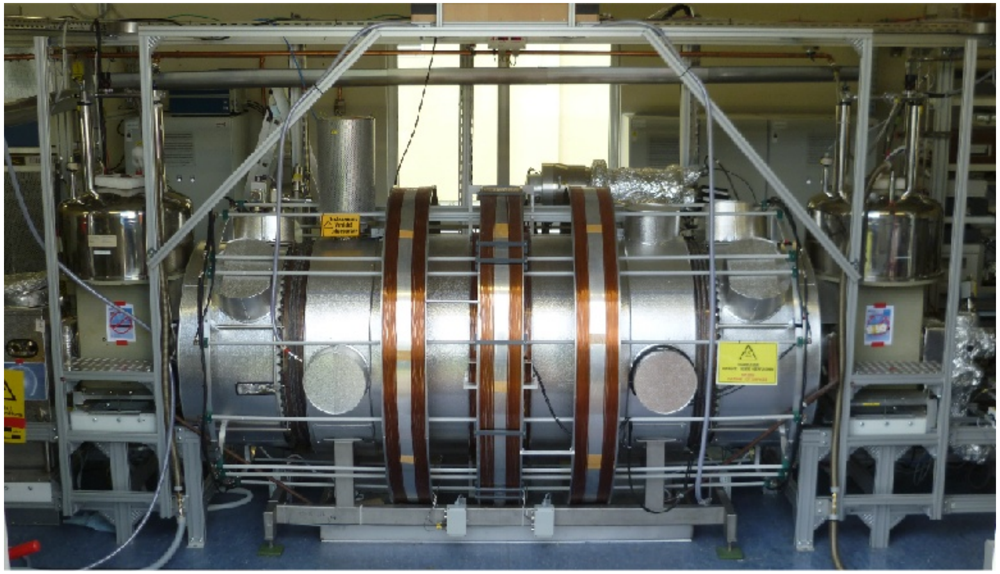


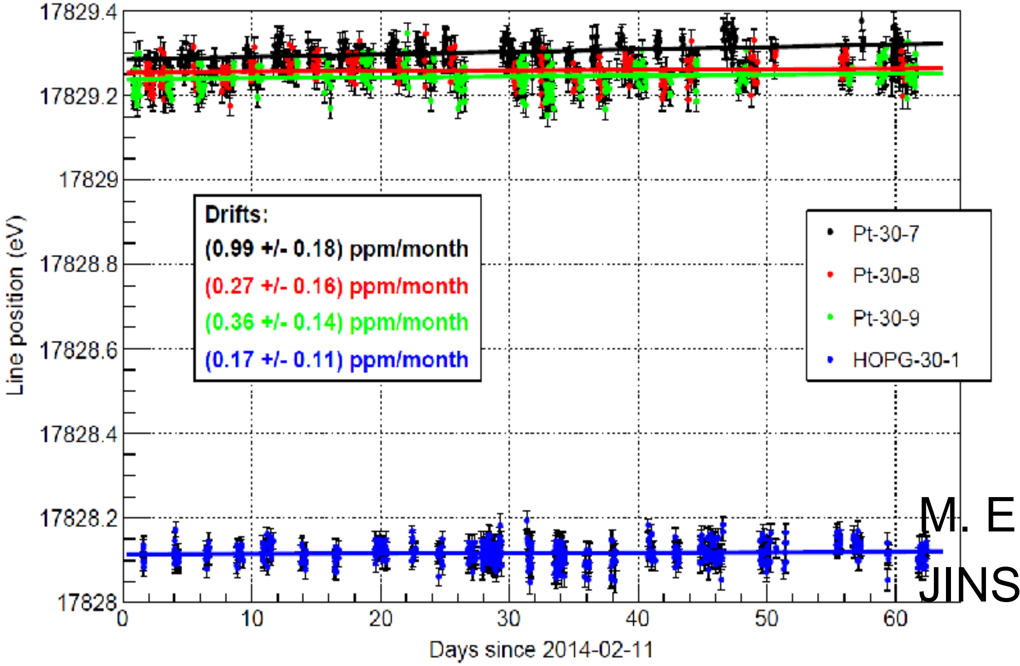
D. Venos et al., Appl. Rad. Iso. 63 (2005) 323
D. Venos et al, Nucl. Instrum. Meth. A 560 (2006) 352
M. Rasulbaev et al., Appl. Rad. Iso. 66 (2008) 1838
Th. Thümmler et al., New J. Phys. 11 (2009) 103007
D. Venos et al., Meas.Tech. 53 (2010) 573
M. Slezák et al., EPJ A48 (2012) 12
M. Zboril et al., JINST 8 (2013) P03009
J. Bauer et al., JINST 8 (2013) P10026
M. Slezak et al., JINST 8 (2013) T12002
M. Erhard et al., JINST 9 (2014) P06022

courtesy: S. Bauer

The former Mainz Spectrometer still contributes as monitor spectrometer for ppm HV precision







M. Erhard et al.,
JINST 9 (2014) P06022

Systematic uncertainties

As smaller m(ν) as smaller the region of interest below endpoint E_0

→ quantum mechanical thresholds help a lot !

A few contributions with $\Delta m_\nu^2 \leq$ 0.007 eV²

**Measuring the last 25 or 30 eV only
KATRIN becomes nearly
a „single final state“ experiment
as cryo-bolometers**

1. inelastic scatterings of β´s inside WGTS
   - **dedicated e-gun measurements**, unfoldin
2. fluctuations of WGTS column density (required <
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, **e-gun measurements**
3. WGTS charging due to r
   - **monocrystaline rea**
4. final state distribution
   - **reliable quantum c**
5. transmission function
   - detailed simulations **s**
6. HV stability of retarding
   - **precision HV divider (line**

tritium source

spectrometer

sensitivity:

m_ν < 0.2eV (90%CL)

discovery potential:

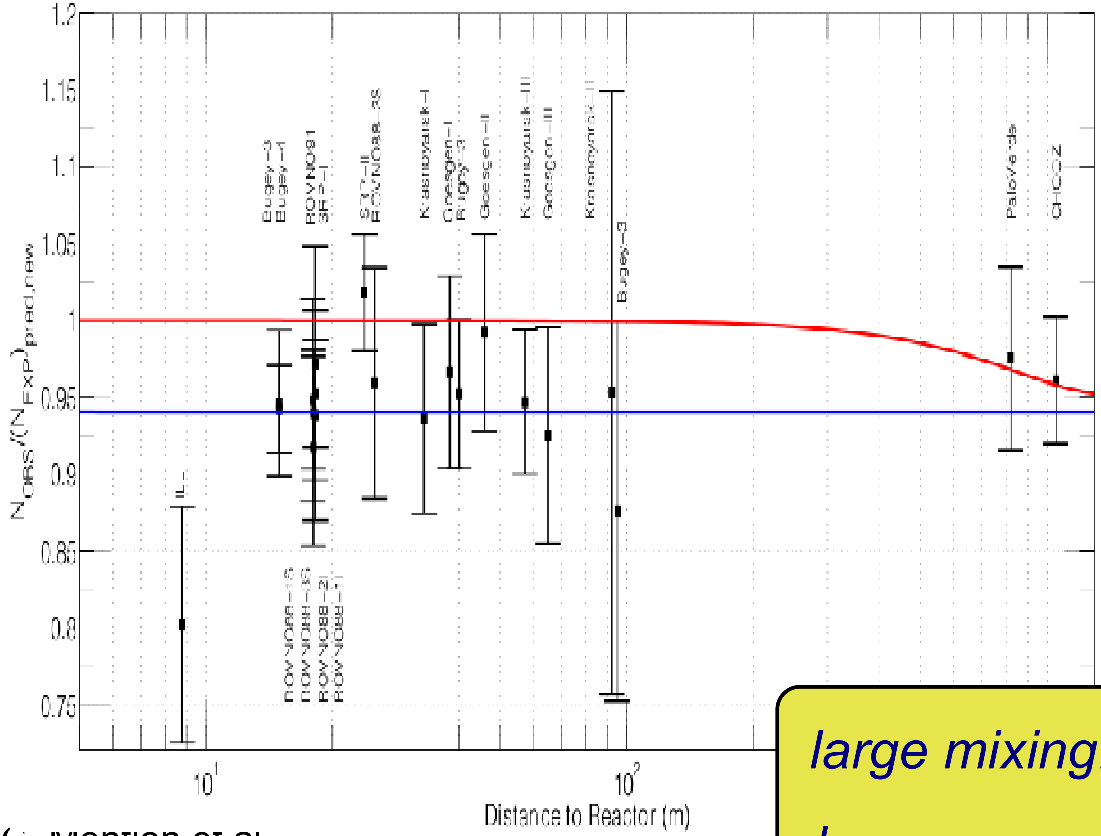
m_ν = 0.3eV (3σ)

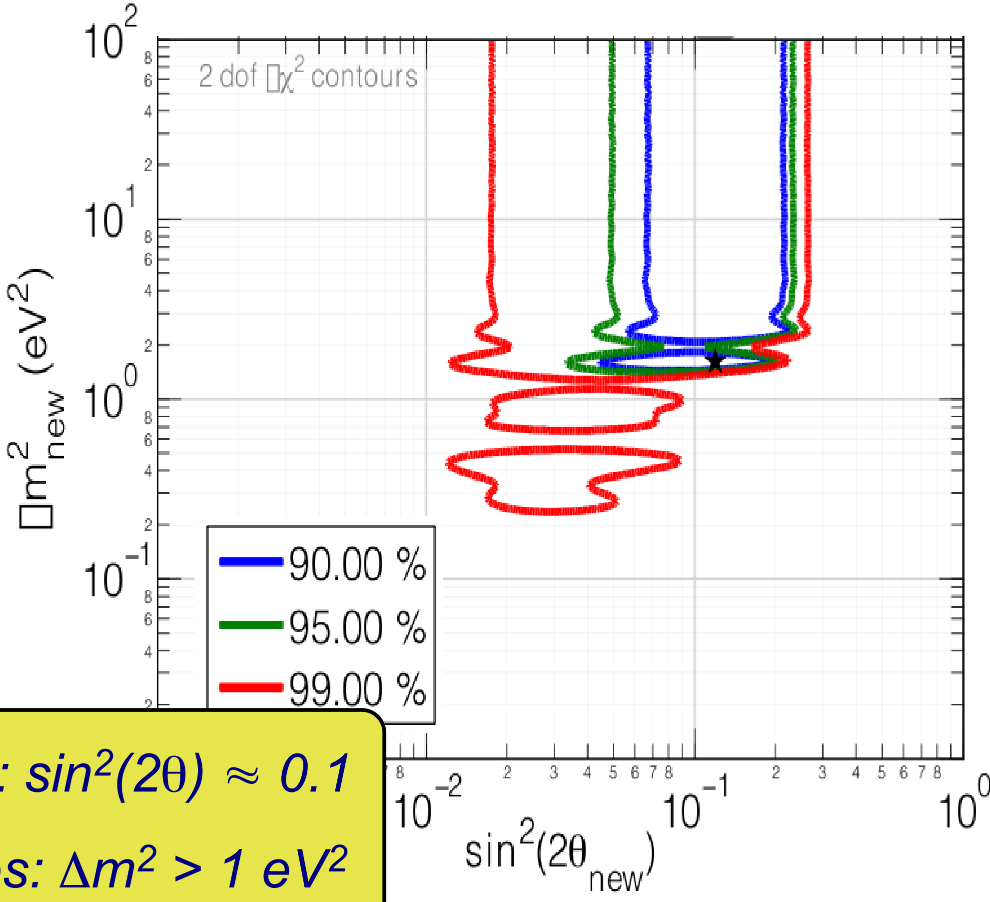
m_ν = 0.35eV (5σ)

Is there a fourth sterile neutrino state ?

Re-evaluation of reactor neutrinos fluxes and use of GALLEX/SAGE calibration measurements:

“reactor antineutrino anomaly”: $P_{ee} = 0.943 \pm 0.023$





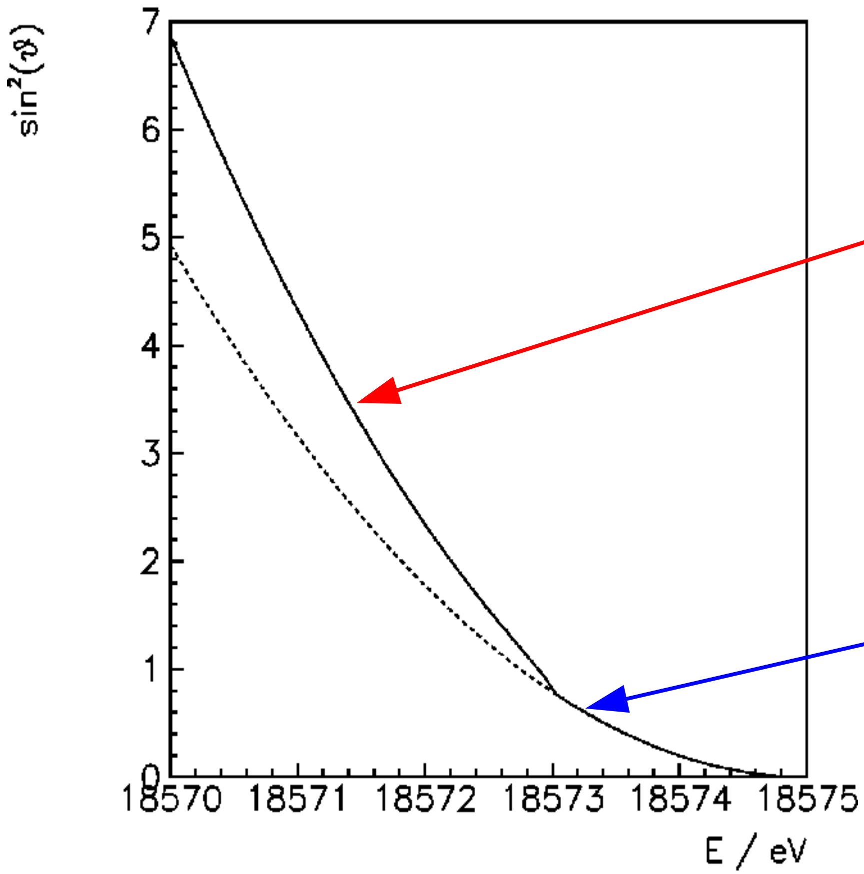
G. Mention et al.,
Phys. Rev. D 83 (2011) 073006

large mixing: $\sin^2(2\theta) \approx 0.1$

large masses: $\Delta m^2 > 1$ eV^2

Influence of a 4th sterile neutrino near the endpoint E_0

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



e.g.

$m(\nu_4) = 2$ eV

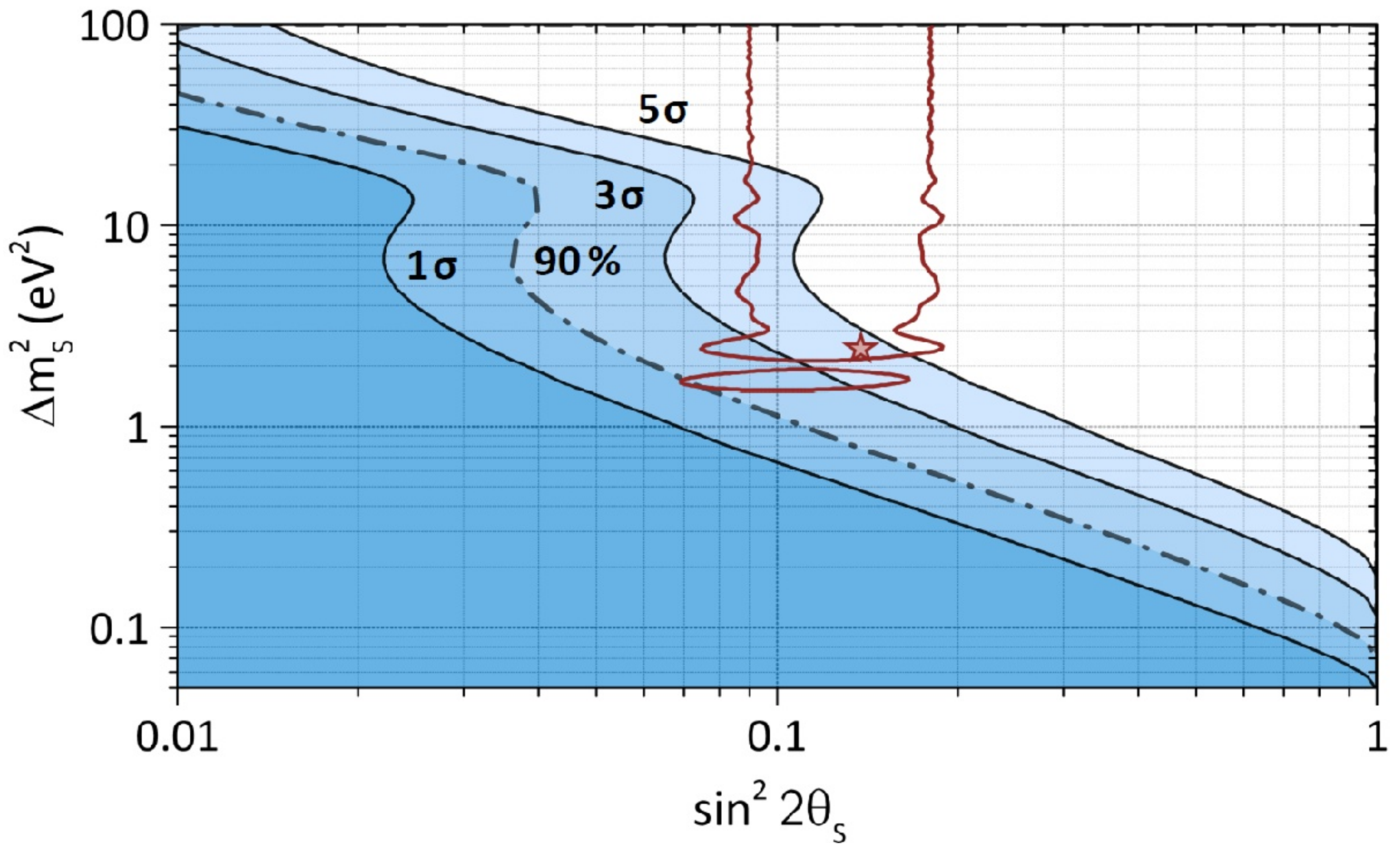
$\sin^2(\theta) = 0.3$

e.g.

$m(\nu_{1,2,3}) \approx 0$ eV

$\cos^2(\theta) = 0.7$

Sensivity on sterile eV neutrinos



M.Kleesiek,
PhD thesis,
KIT (2014)

see also:

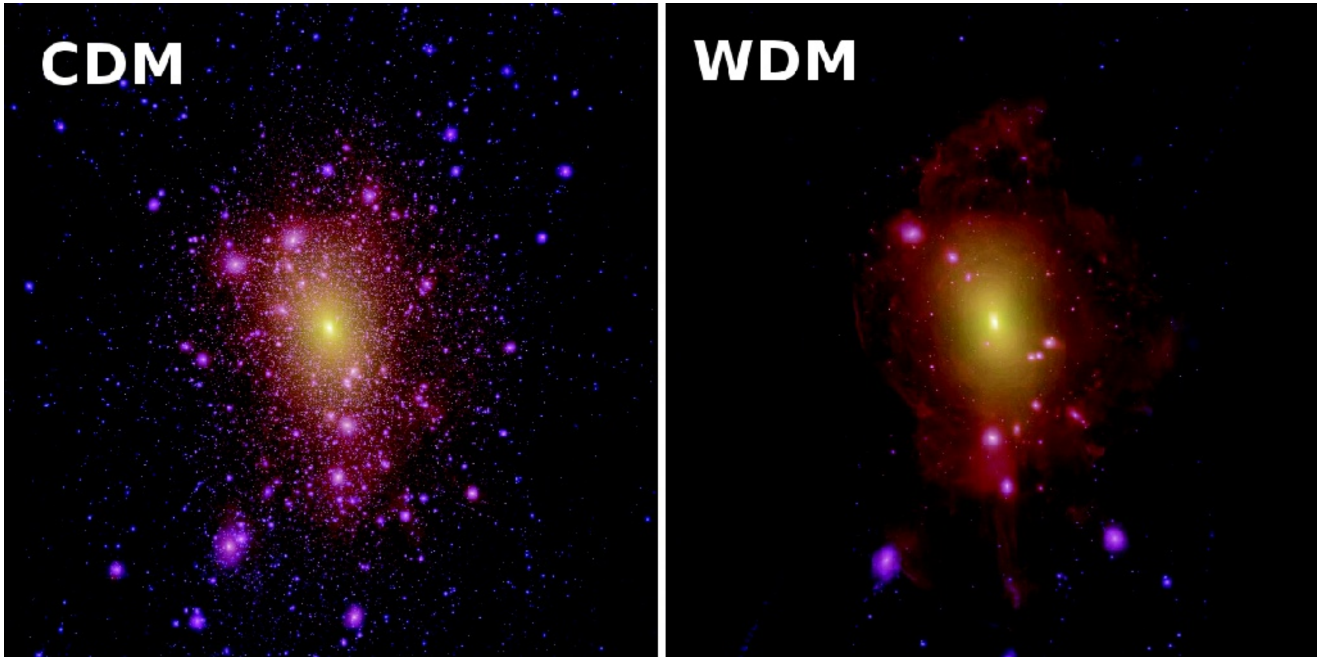
J. A. Formaggio, J. Barret, PLB 706 (2011) 68

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

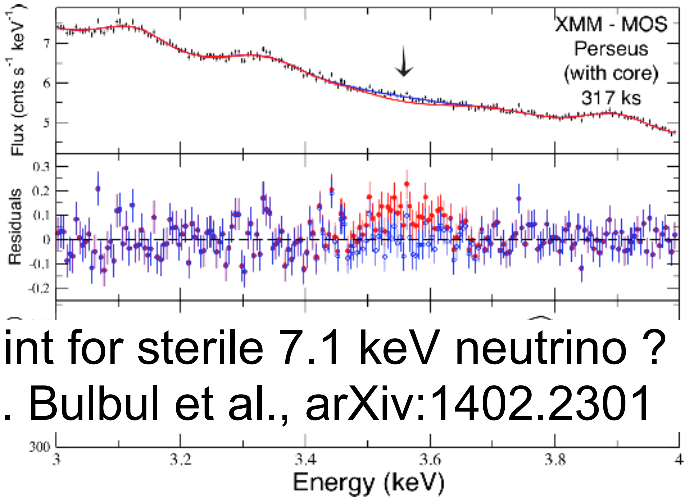
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

Hints for a 2nd sterile neutrino: Warm Dark Matter in the universe

ΛCDM (Cold Dark Matter with cosmological constant) models (masses of about 100 GeV) predict to much structure at galactic scales (too many satellite galaxies)

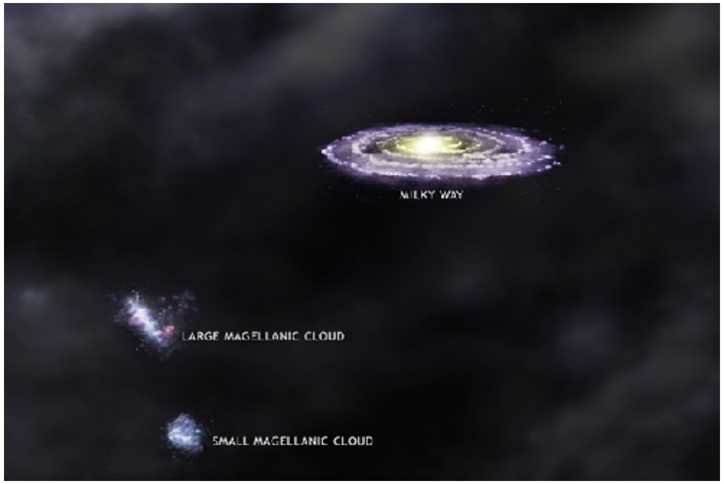


(e.g. Lovell et al. at Meudon Workshop 2012)



Hint for sterile 7.1 keV neutrino ?
E. Bulbul et al., arXiv:1402.2301

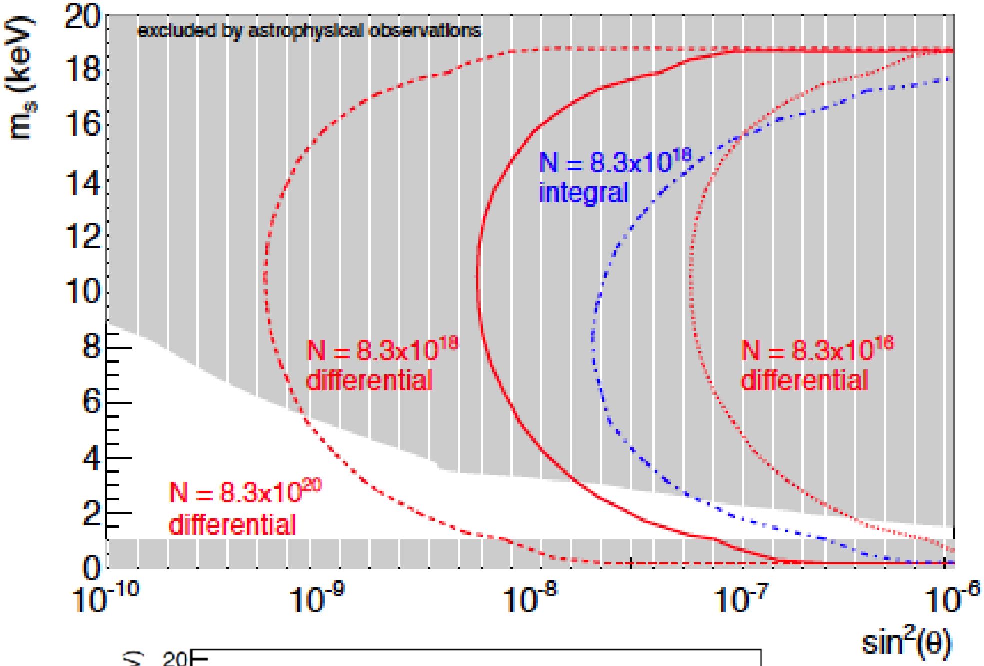
In contrast to observations ! (here only artist view on the right)

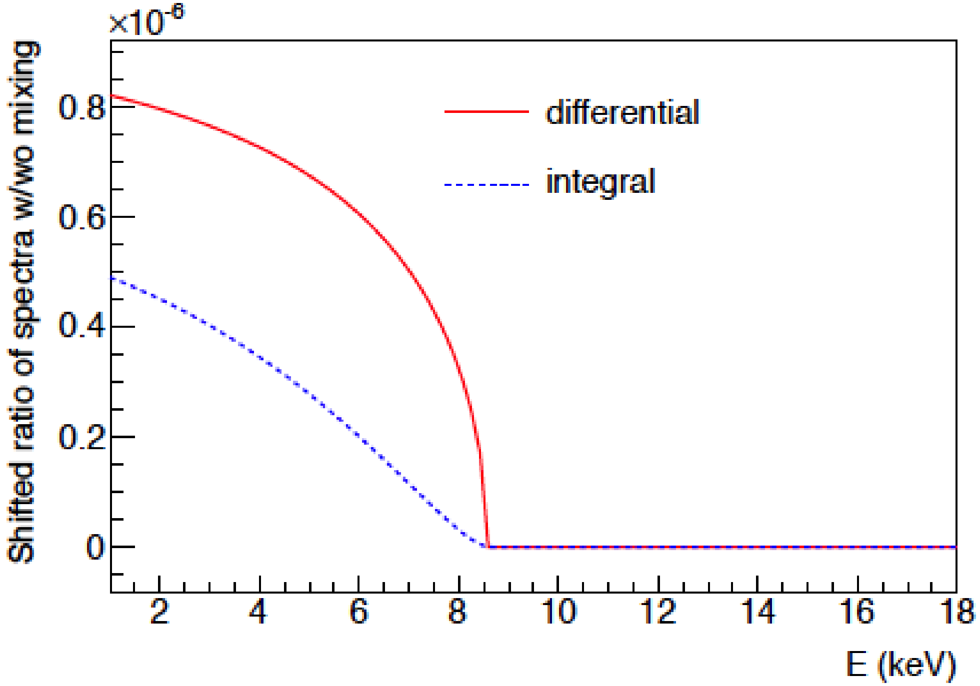


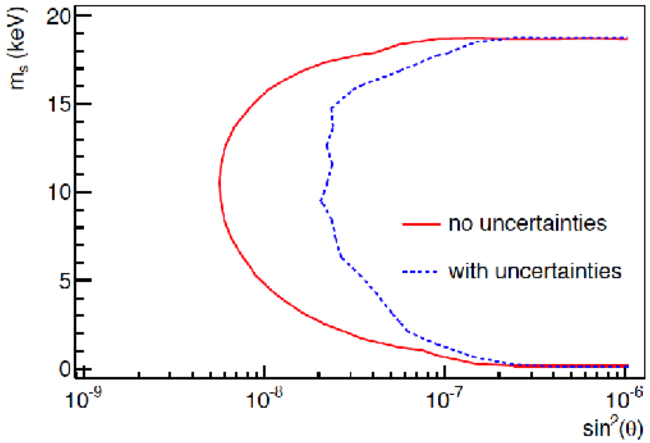
Warm Dark Matter (masses of a few keV, e.g. sterile neutrinos) would smear out these structures

http://chandra.harvard.edu/graphics/resources/illustrations/milkyWay/milkyway_magellanic_clouds.jpg

Statistical sensitivity for integral and differential measurement





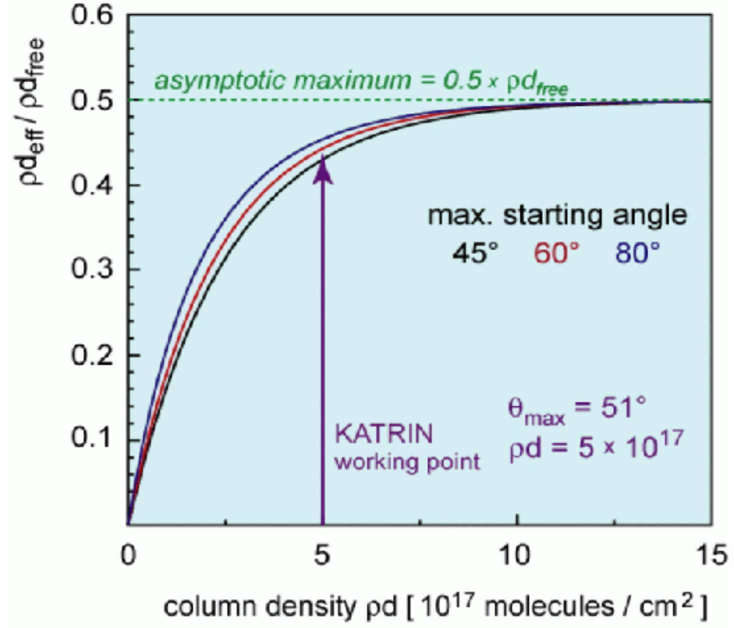


→ **statistical uncertainty is not a problem for 10^{-7} even including systematics (1st investigation)!**

S. Mertens et al., JCAP 02 (2015) 020
„Sensitivity of Next Generation Tritium β-Decay Experiments for keV-Scale Sterile Neutrinos“

Can KATRIN be largely improved ?
Problems to be solved

1) The source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible



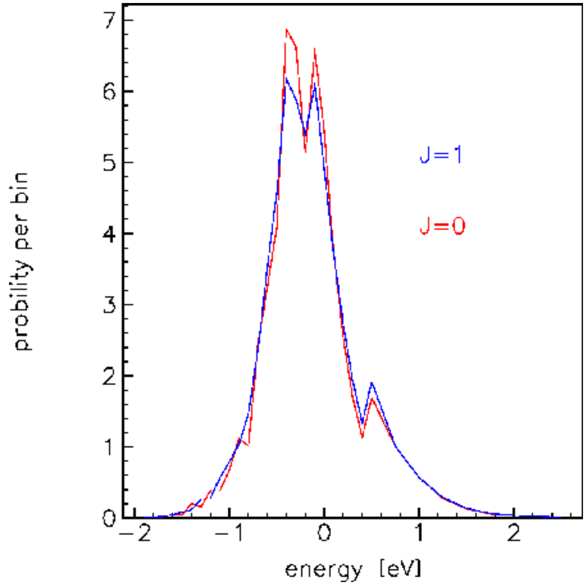
Three possible ways out:

a) source inside detector
using cryogenic bolometers (ECHo, HOLMES)

b) hand-over energy information of β electron
to other particle (radio photon),
which can escape tritium source (Project 8)

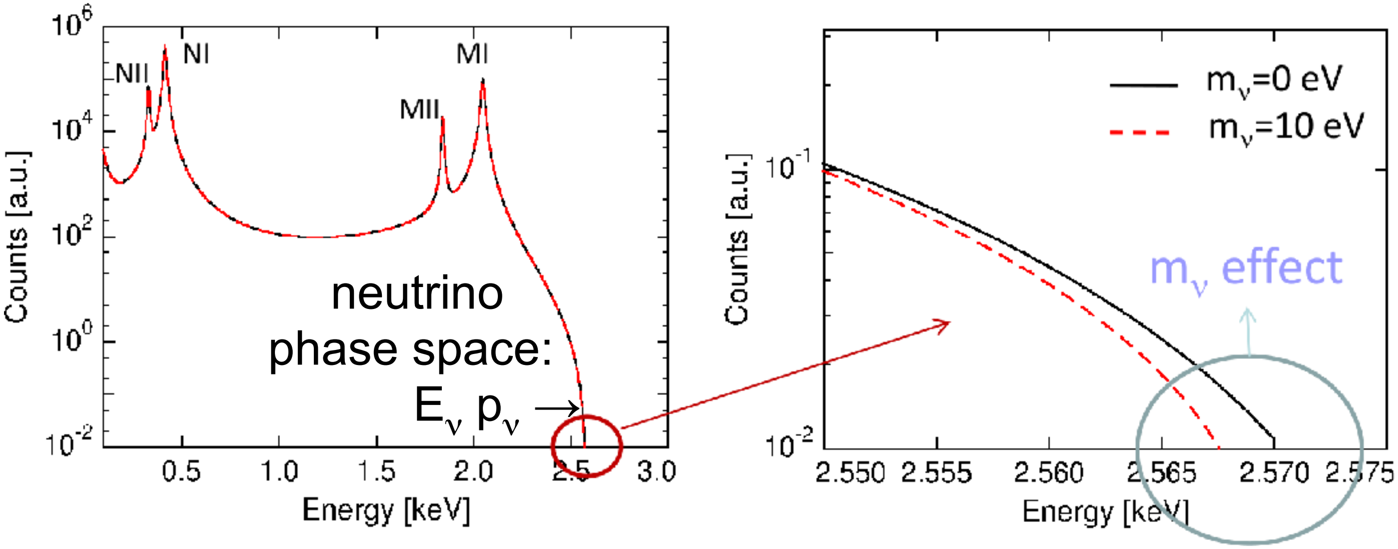
c) make better use of the electrons
→ time-of-flight spectroscopy

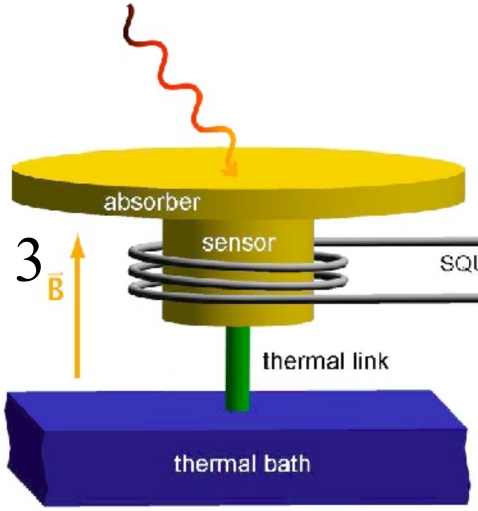
2) Resolution is limited to σ = 0.34 eV
when using molecular tritium by the
excitation of ro-vibrational states in the final state

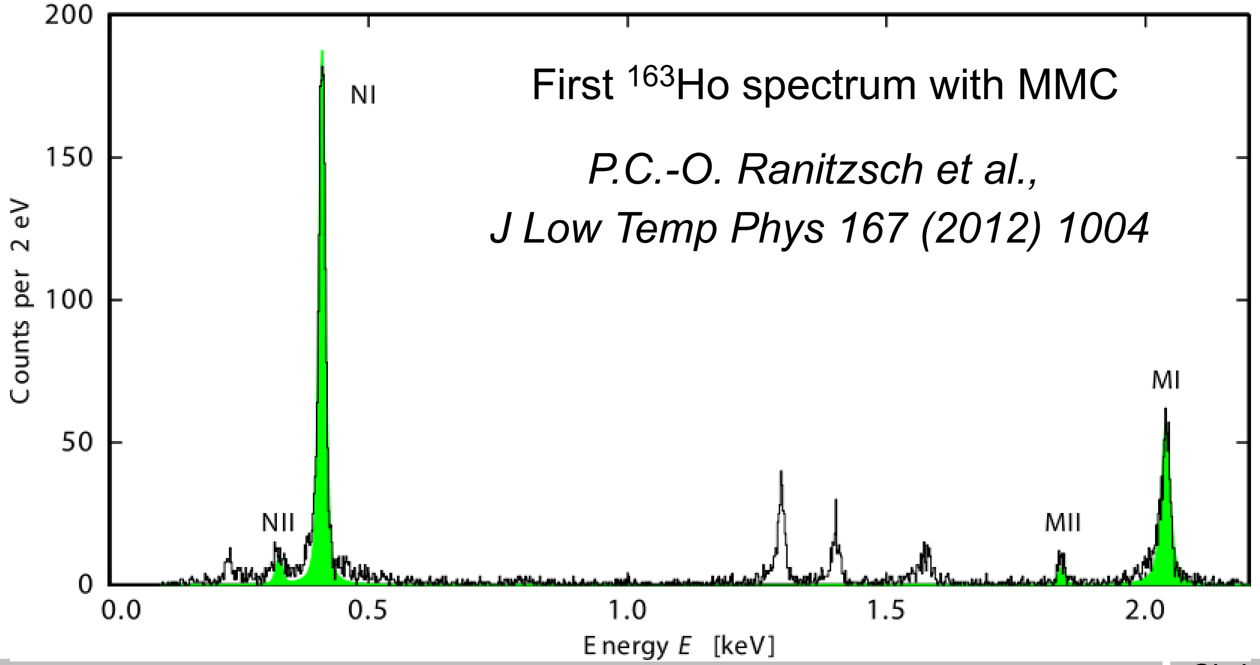


ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$$

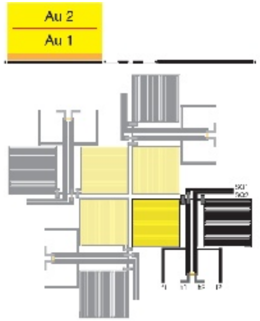


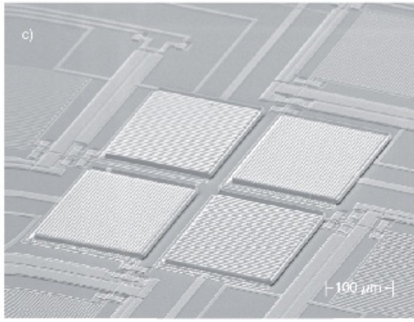




First ^{163}Ho spectrum with MMC

P.C.-O. Ranitzsch et al., J Low Temp Phys 167 (2012) 1004





courtesy L. Gastaldo

ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

Recent achievements by ECHo:

- new Q-value: 2.8 keV (independently by MMC & Penning trap, was 2.5 keV before!)

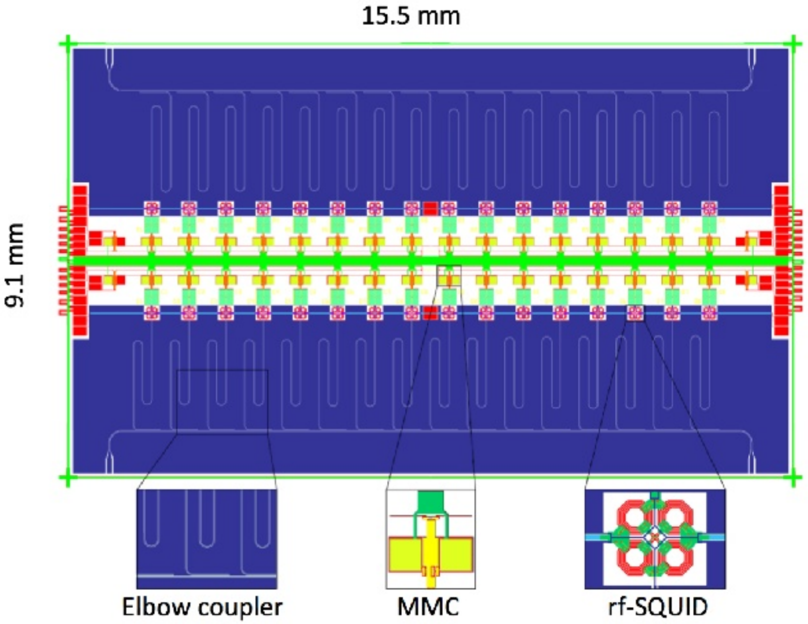
- new source production: chemical purification + mass separation → no ^{144}Pm or ^{166m}Ho

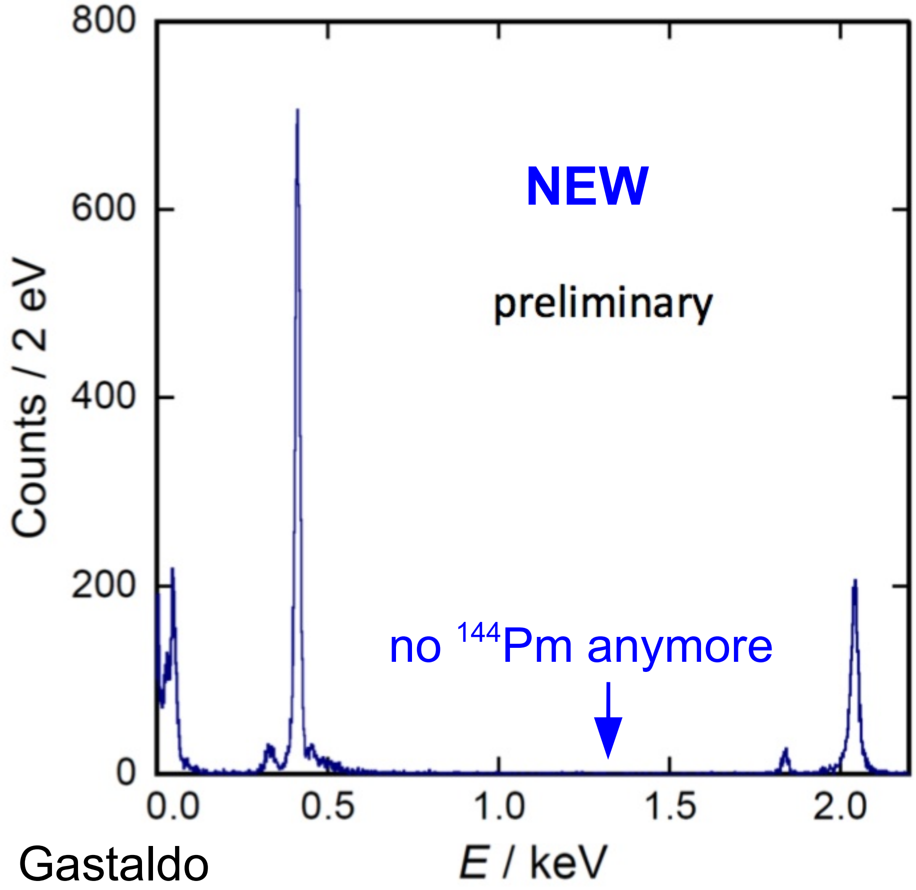
- very good energy resolution of this technology (ΔE = 1.6 eV at 6 keV)

- ultra-short response (pile-up!): risetime 90 ns

- 128 pixels: microwave SQUID multiplexing

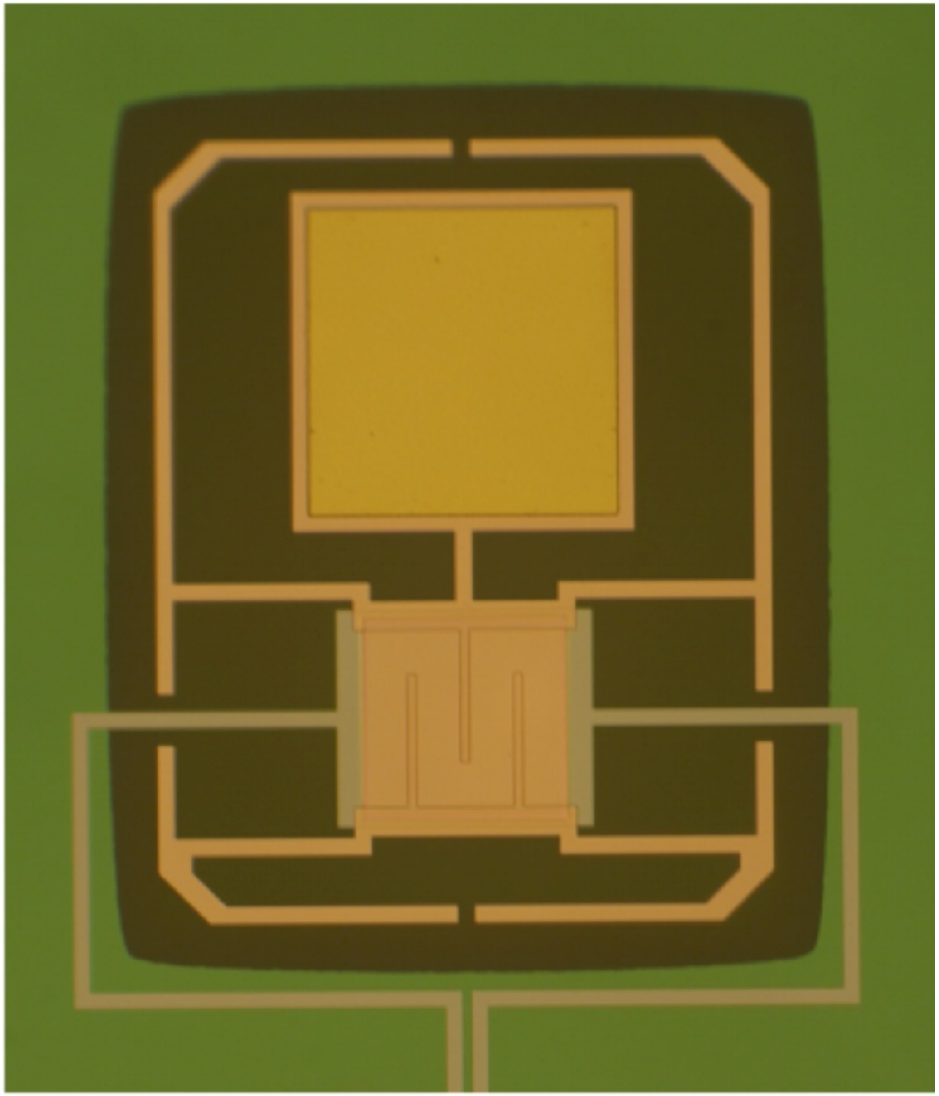
- fu





courtesy L. Gastaldo

HOLMES: cryogenic calorimeter with transition edge sensor (TES) read-out



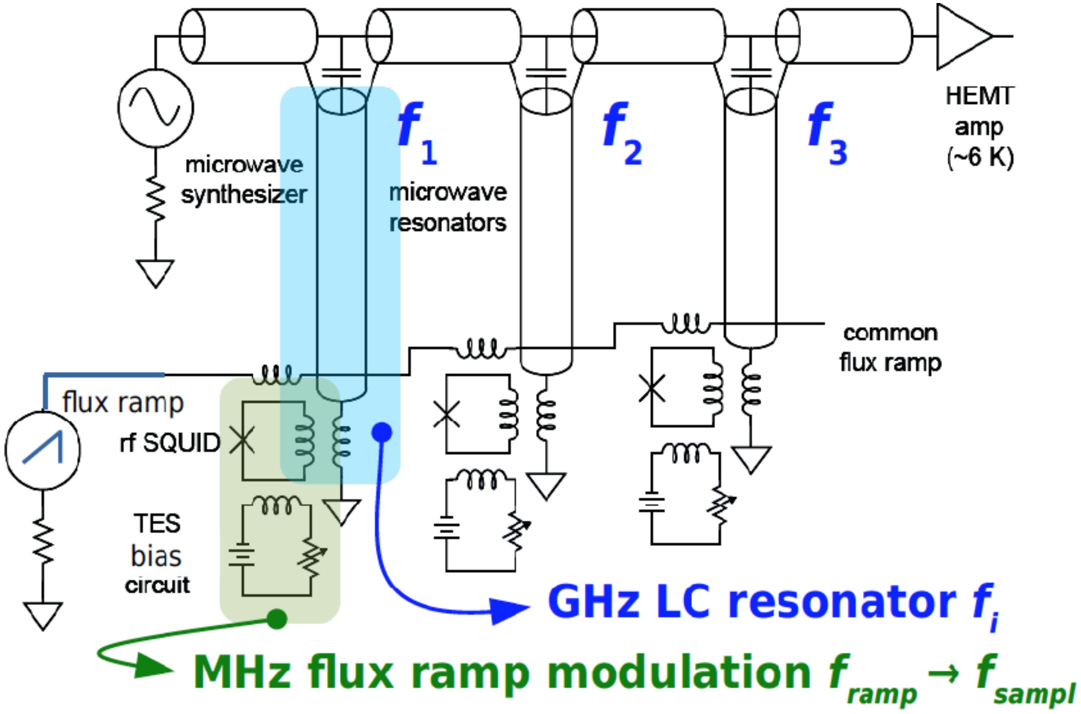
funding by ERC grant

courtesy A. Nucciotti

Prediction from test measurements:

$\Delta E_{FWHM} \approx 3$ eV, $\tau_{rise} \approx 6$ μs, $\tau_{decay} \approx 130$ μs

radiofrequency SQUID multiplexing

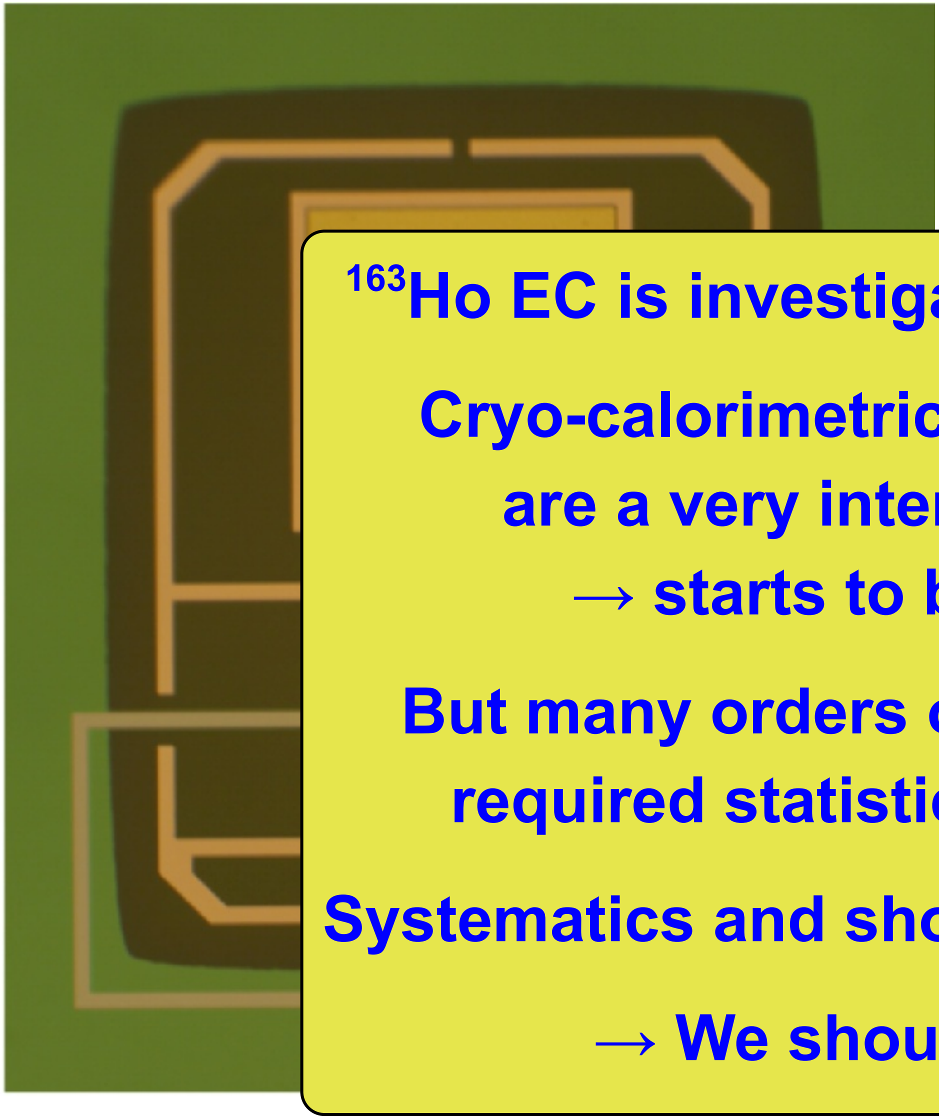


Westfälische
Wilhelms-Universität
Münster

HOLMES: cryogenic calorimeter with transition edge sensor (TES) read-out

Prediction from test measurements:

$\Delta E_{FWHM} \approx 3$ eV, $\tau_{rise} \approx 6$ µs, $\tau_{decay} \approx 130$ µs



^{163}Ho EC is investigated by 3 collaborations

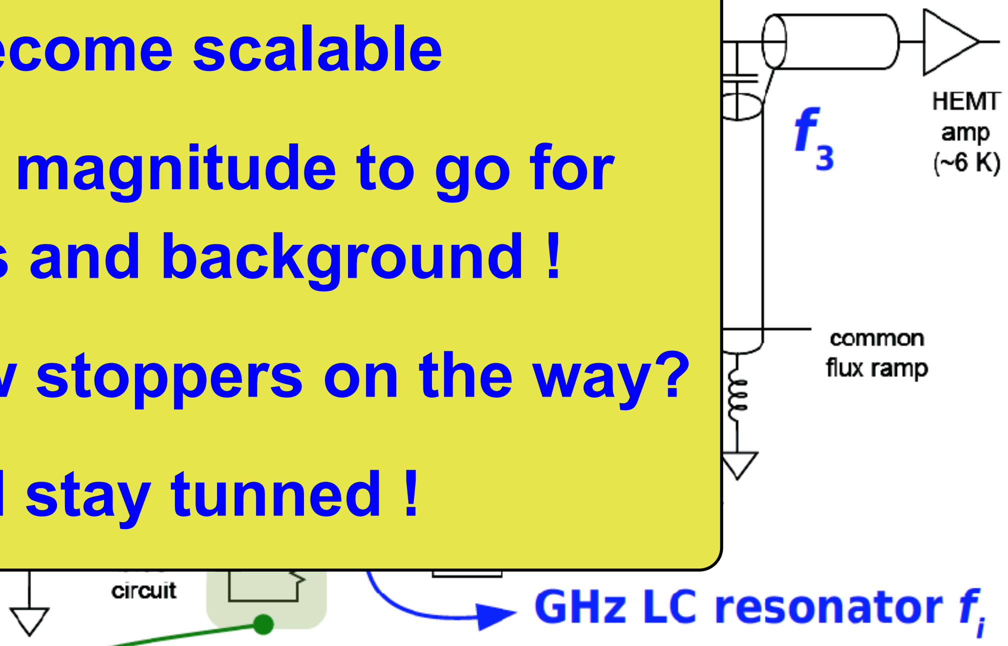
Cryo-calorimetric multipixel detectors
are a very interesting technology
→ starts to become scalable

But many orders of magnitude to go for
required statistics and background !

Systematics and show stoppers on the way?

→ We should stay tuned !

xing



GHz LC resonator f_i

MHz flux ramp modulation $f_{ramp} \rightarrow f_{sampl}$

funding by ERC grant

courtesy A. Nucciotti

Project 8's goal: Measure coherent cyclotron radiation of tritium β electrons

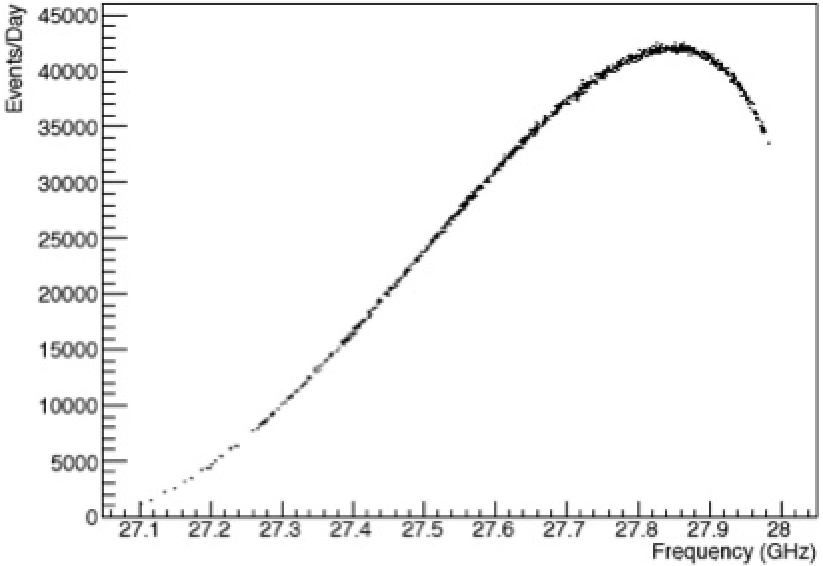
General idea: *B. Monreal and J. Formaggio, PRD 80 (2009) 051301*

- Source = KATRIN tritium source technology :

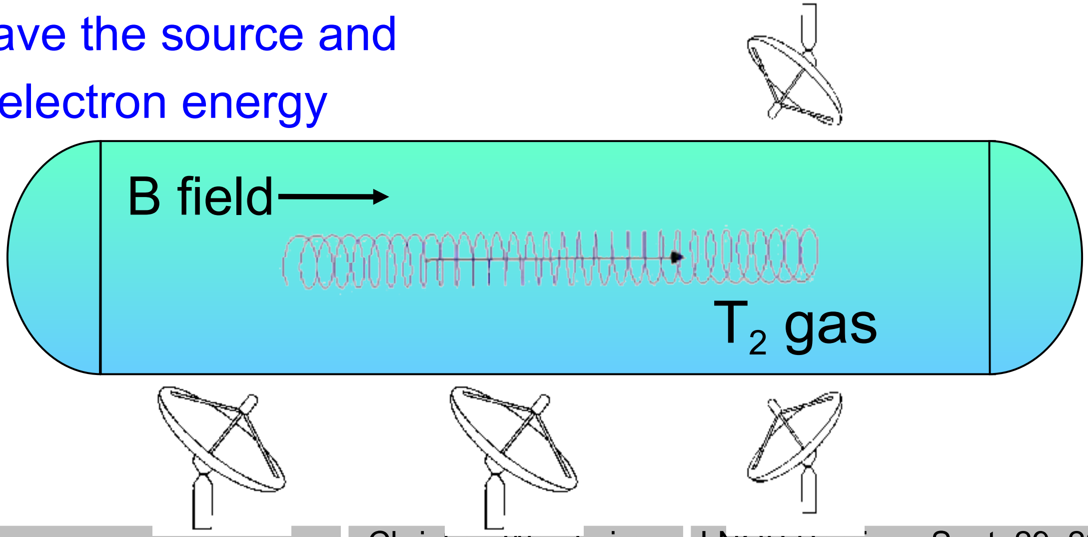
uniform B field + low pressure T_2 gas

β electron radiates coherent cyclotron radiation

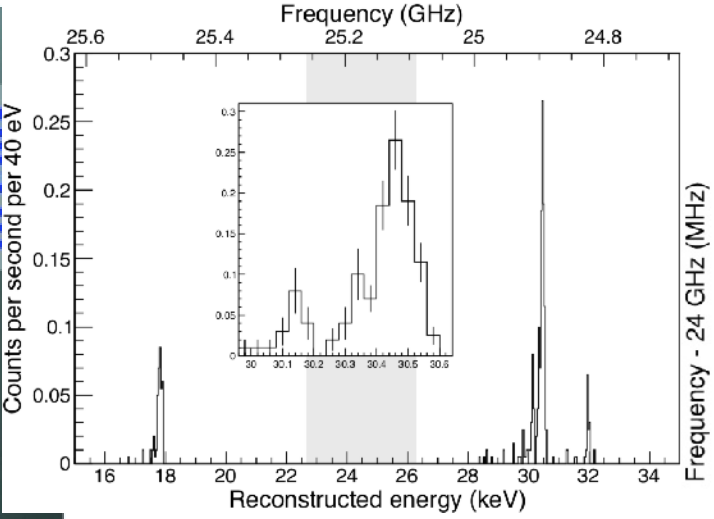
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



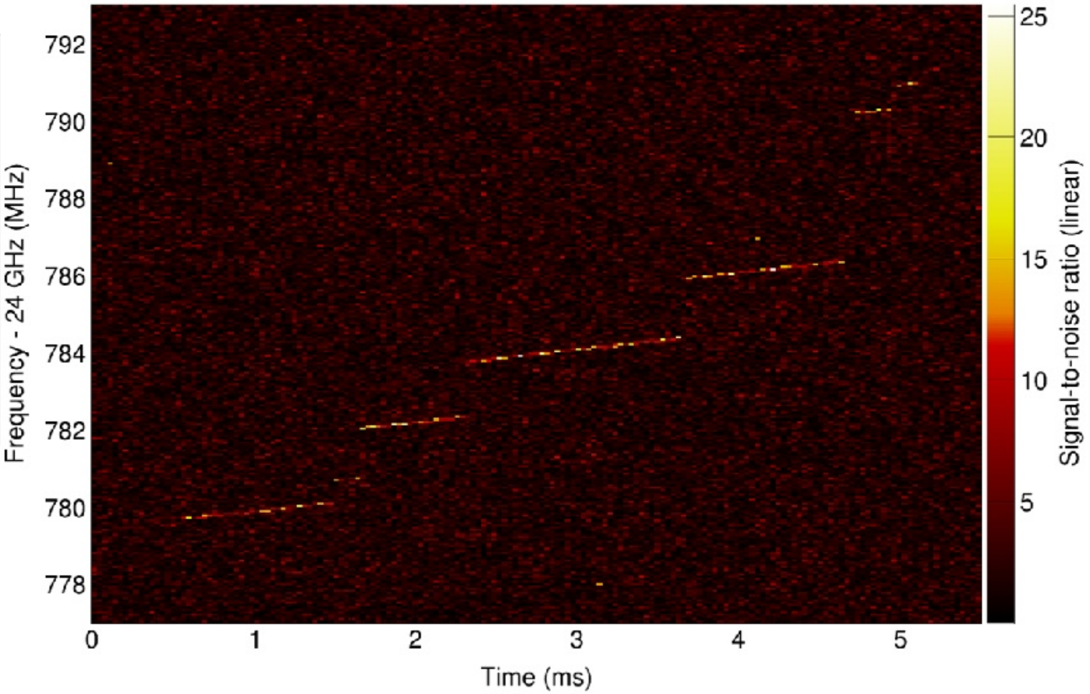
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and
  carries the information of the β-electron energy



Project 8's phase 1: detection single electrons from ^{83m}Kr



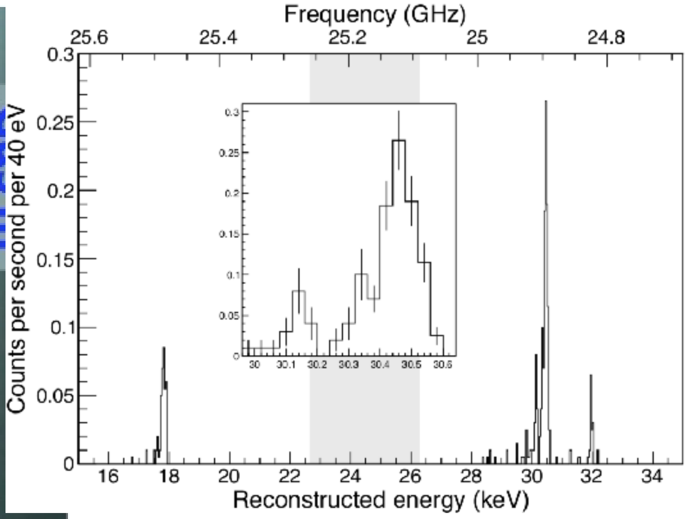
D. M. Asner et al., Phys. Rev. Lett. 114, 162501

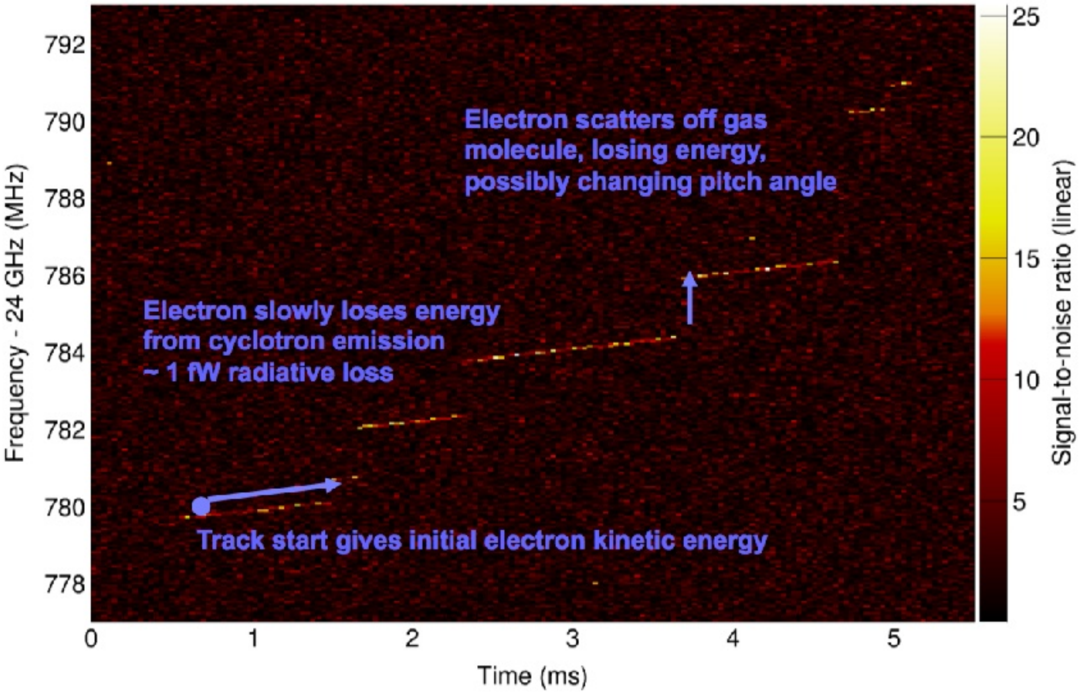


courtesy J. Formaggio, RGH Robertson

Project 8's phase 1: Detection single electrons from ^{83m}Kr

D. M. Asner et al., Phys. Rev. Lett. 114, 162501

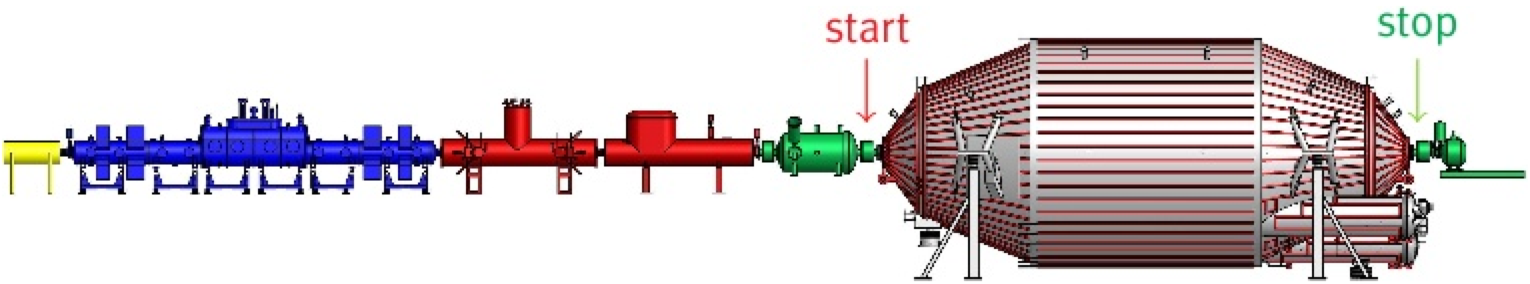


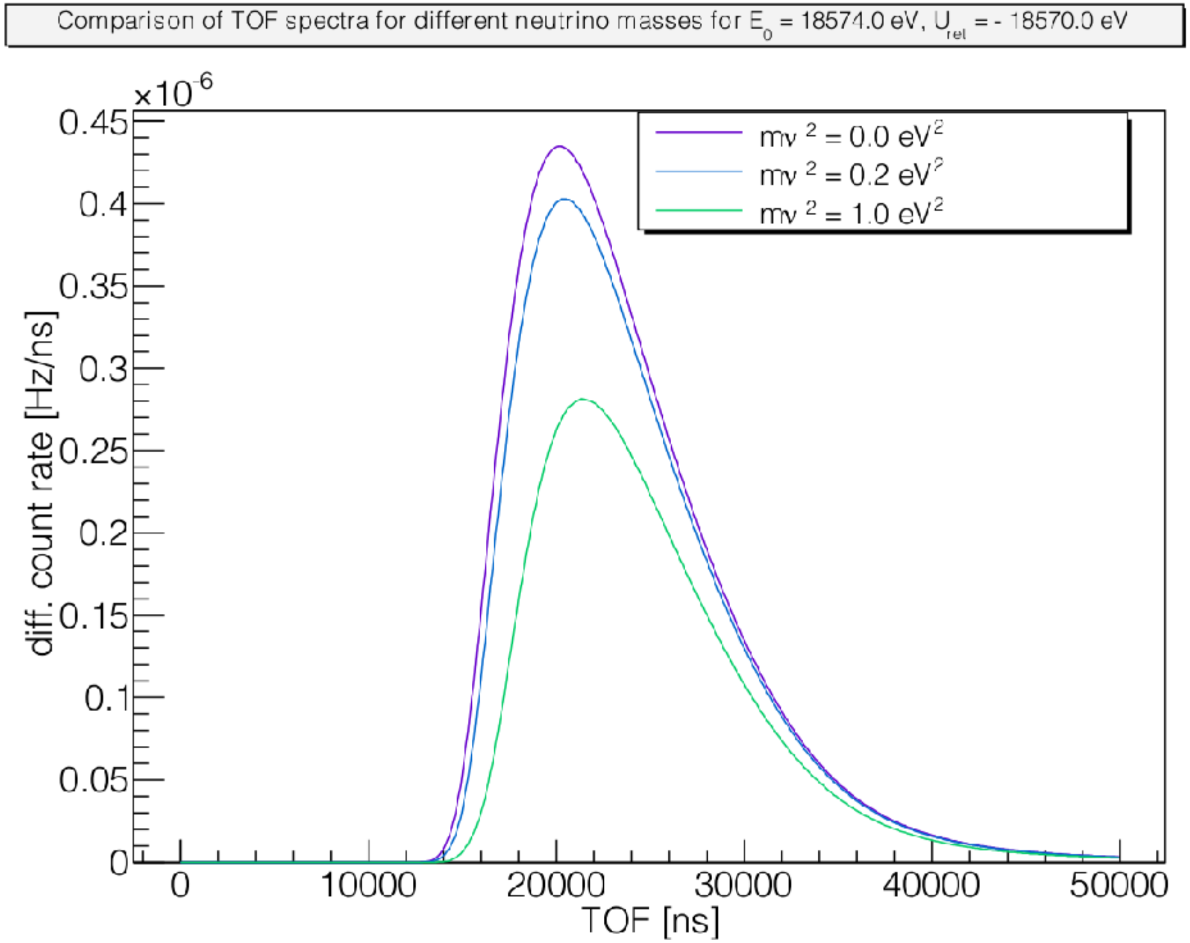


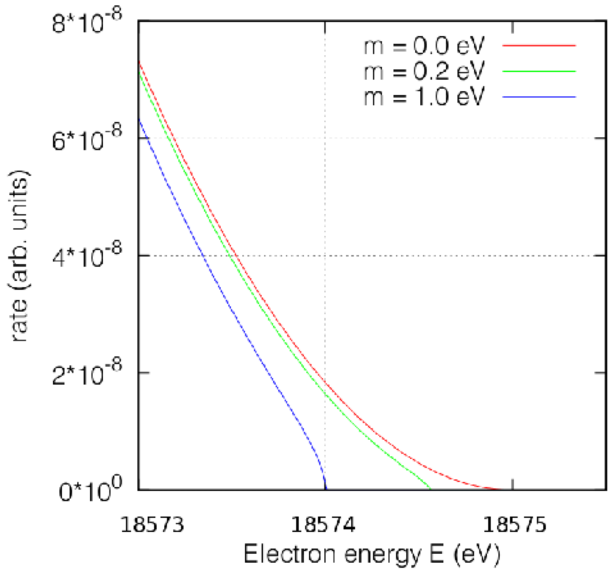
First detection of single electrons successfull but still a lot of R&D necessary
- **Is a large scale experiment possible ?**
- **What are the systematic uncertainties & other limitations?**

courtesy J. Formaggio, RGH Robertson

Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer





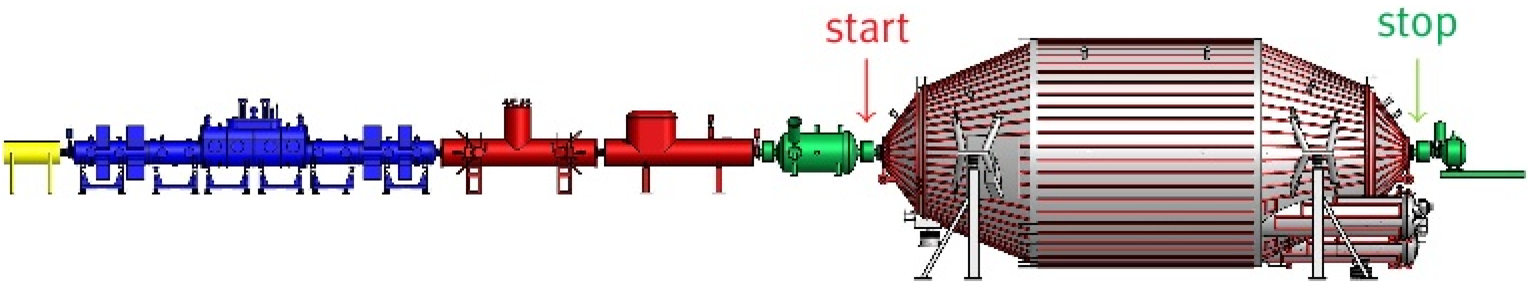


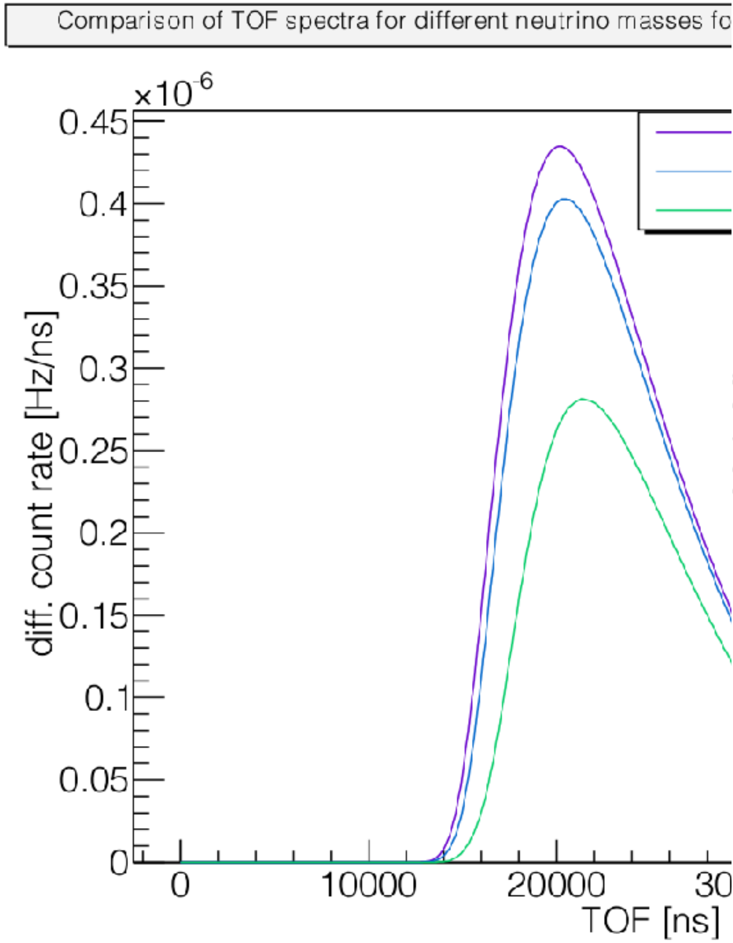
Time-of-flight spectrum is sensitive to the neutrino mass

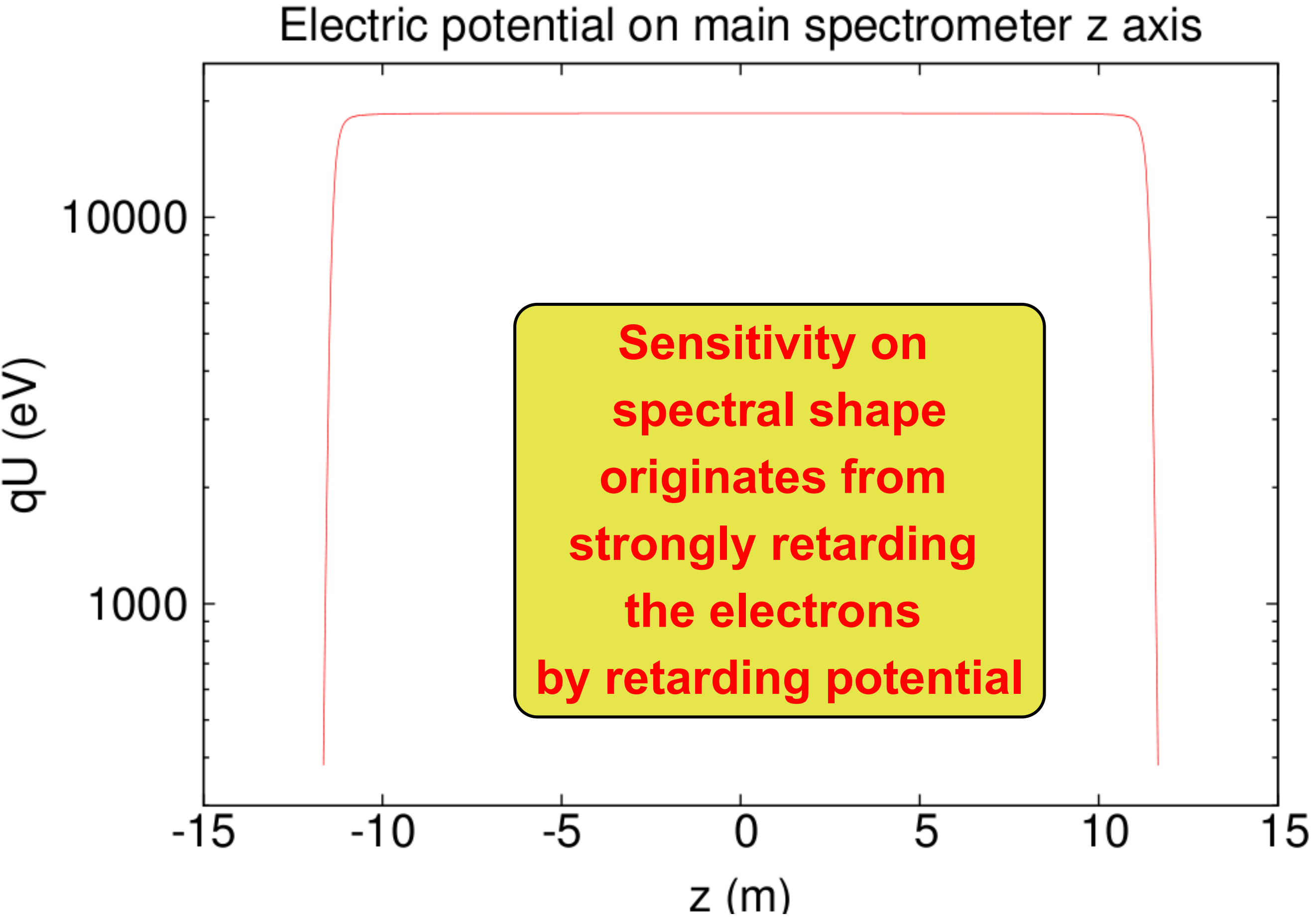
requires one retardation potential only

not integral but differential β-spectrum

Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer







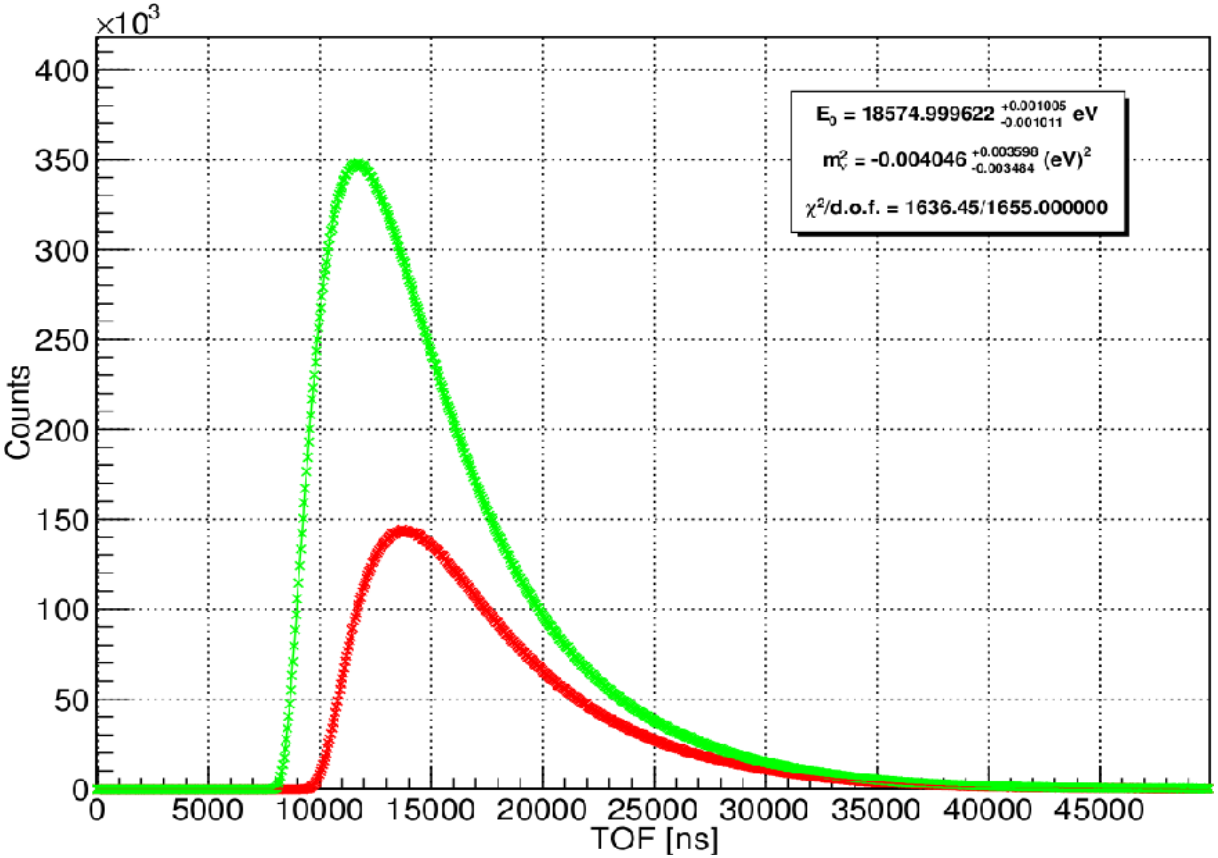
Sensitivity on spectral shape originates from strongly retarding the electrons by retarding potential

Sensitvity improvement on $m^2(\nu_e)$ by ideal TOF determination

Measure at 2 (instead of $\approx$30) different retarding potentials
since TOF spectra contain all the information

Coincidence request between start and stop signal → nice background suppression

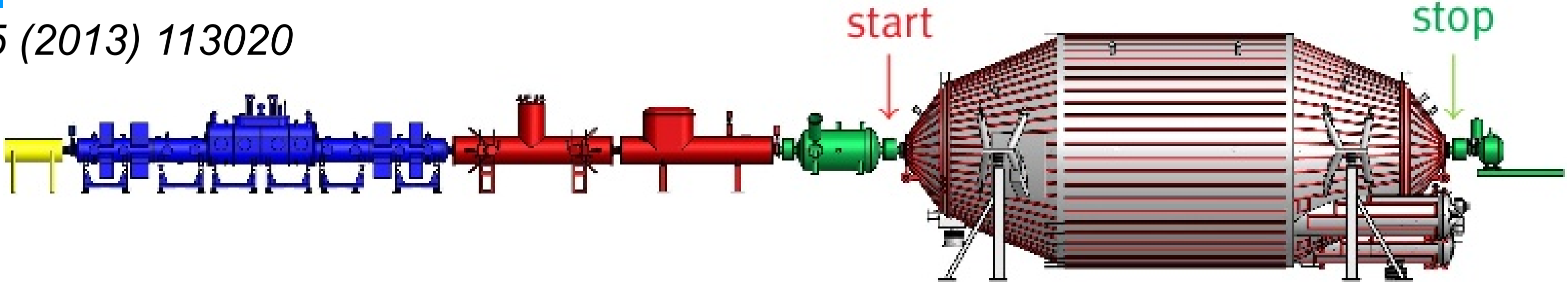
→ Factor 5 improvement in $m_\nu{}^2$ w.r.t. standard KATRIN, but ideal case !



N. Steinbrink et al.
NJP 15 (2013) 113020

Alternative spectroscopy: measure time-of-flight through KATRIN spectrometer

N. Steinbrink et al., NJP 15 (2013) 113020



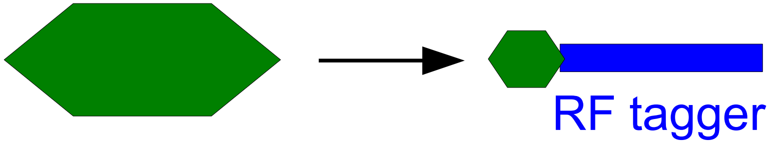
Advantage: measure full β-spectrum by time-of-flight at one (a few) retarding potential

Stop: Can measure time-of-arrival with KATRIN detector with $\Delta t = 50$ ns → ok

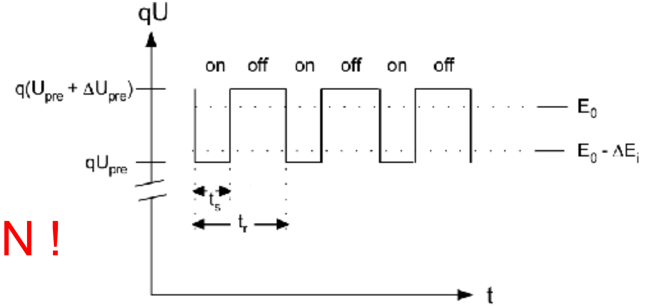
Start: e^--tagger: Need to determine time-of-passing-by of e^- before main spectrometer
without disturbing energy and momentum by more than 10 meV:
→ Need „detector“ with 10 meV threshold
seems not to be forbidden but very difficult for the near future !
Added value: significant background reduction by coincidence !

→ factor 5 in $\Delta m(\nu)^2_{stat}$ under ideal cond.

An implementation: reduce pre spectrometer and add a Project 8-type tagger within a long solenoid



or: Use pre spectrometer as a „gated-filter“
by switching fast the retarding voltage
→ As sensitive on the neutrino mass as standard KATRIN !



Conclusions

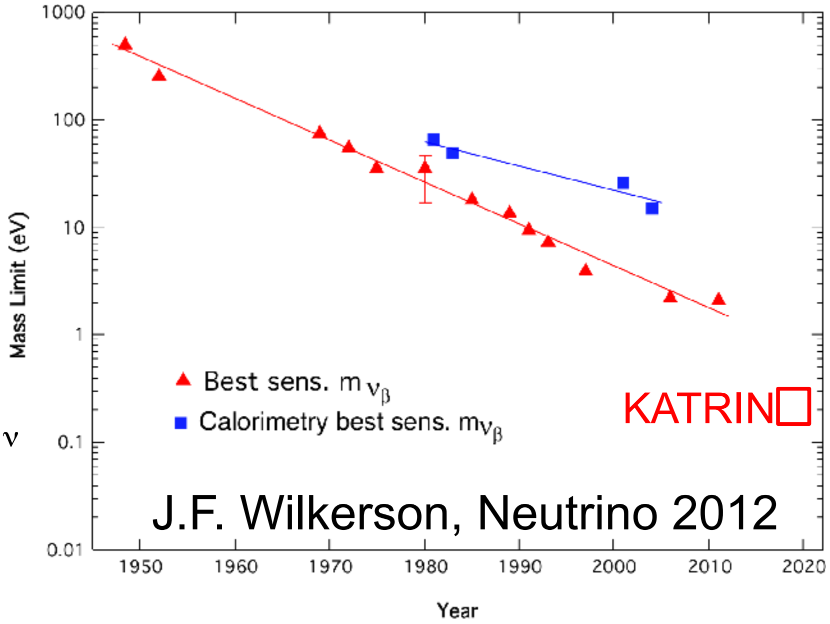
KATRIN is the direct neutrino mass experiment complementary
to cosmological analyses and 0νββ searches

KATRIN can also look for sterile neutrinos (eV, keV)

KATRIN is close to start direct neutrino mass measurements

- Commissioning of spectrometer & detector SDS IIb
  finished in August 2015
- Commissioning of tritium source & transport section:
  up to summer 2016
- Tritium data taking: start in 2016
  with small column density
- early 2017 operate with normal column density → m_ν

KATRIN's sensitivity: 200 meV



J.F. Wilkerson, Neutrino 2012

significant R&D on ^{163}Ho micro calorimeters (ECHo, HOLMES, ...)
new ideas like Project 8, ...

THANK YOU FOR YOUR ATTENTION !