Single Beta Decay and the neutrino mass

Int. School on NuclearPhysics 2013: Neutrino Physics – Present and Future
Erice/Italy, September 16-24, 2013

Christian Weinheimer

Institut für Kernphysik, Westfälische Wilhelms-Universität Münster
weinheimer@uni-muenster.de

Introduction

Direct Neutrino Mass determination
- **Rhenium β decay and EC experiments**
- **Tritium β decay experiments**

The Karlsruhe Tritium Neutrino expeirment KATRIN

Summary and Outlook

Photo: M. Zacher

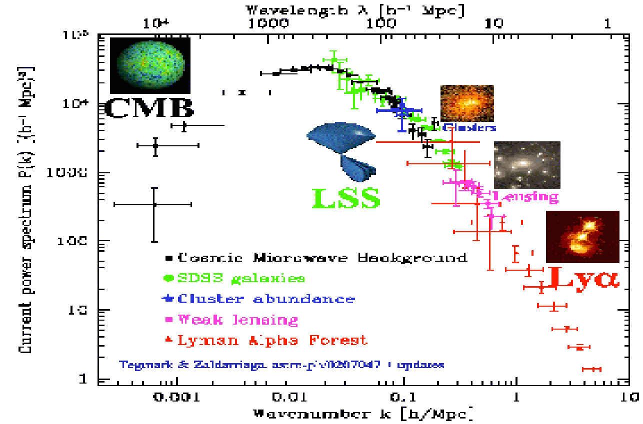
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

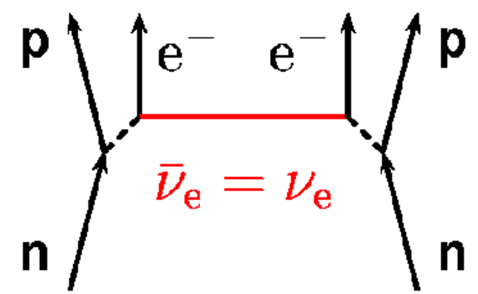
current sensitivity: $\Sigma m(\nu_i) \approx 0.5$ eV



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

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)

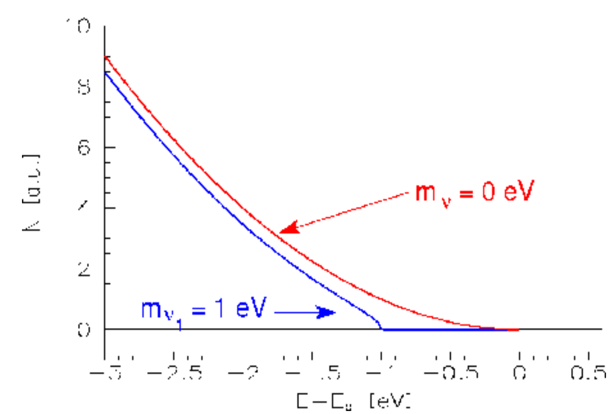
SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV

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



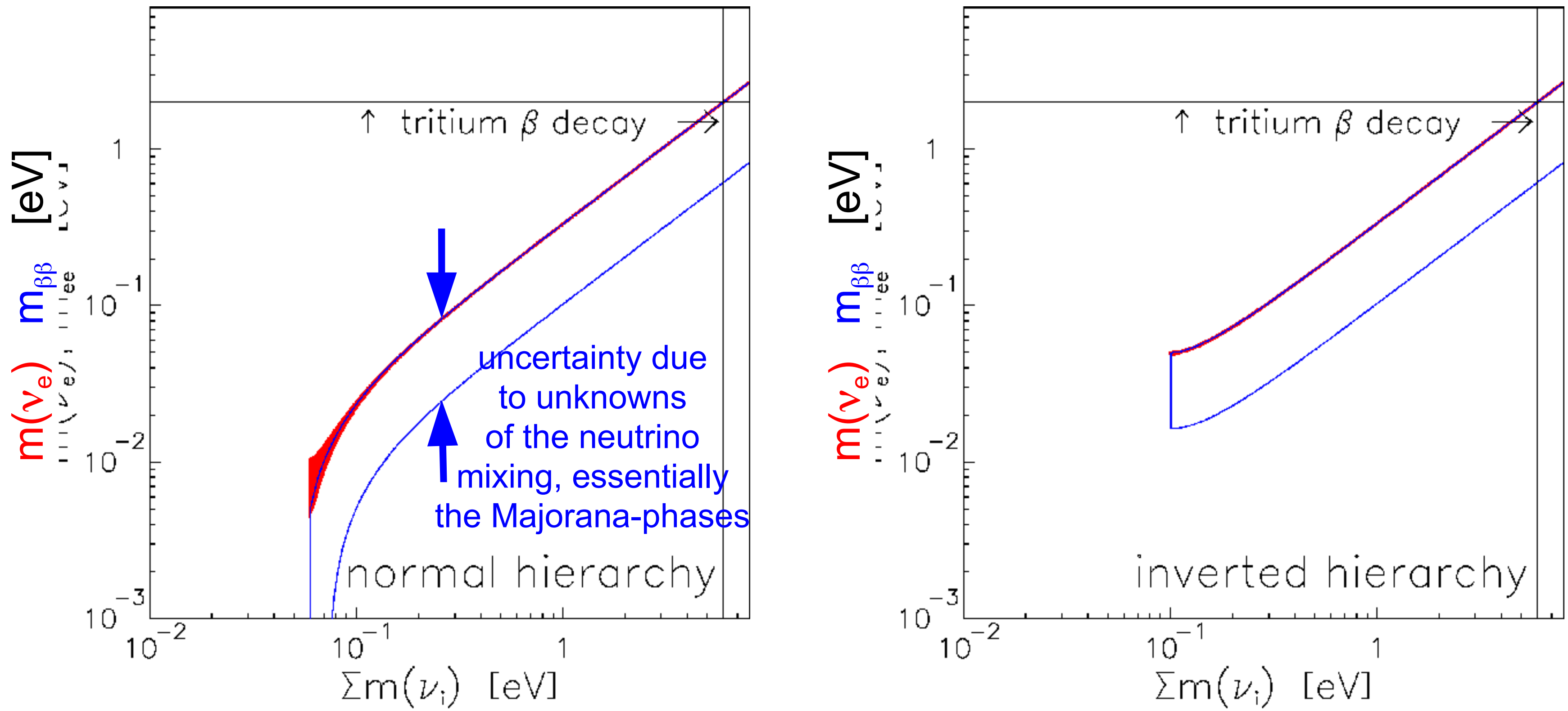
Comparison of the different approaches to the neutrino mass

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



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

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

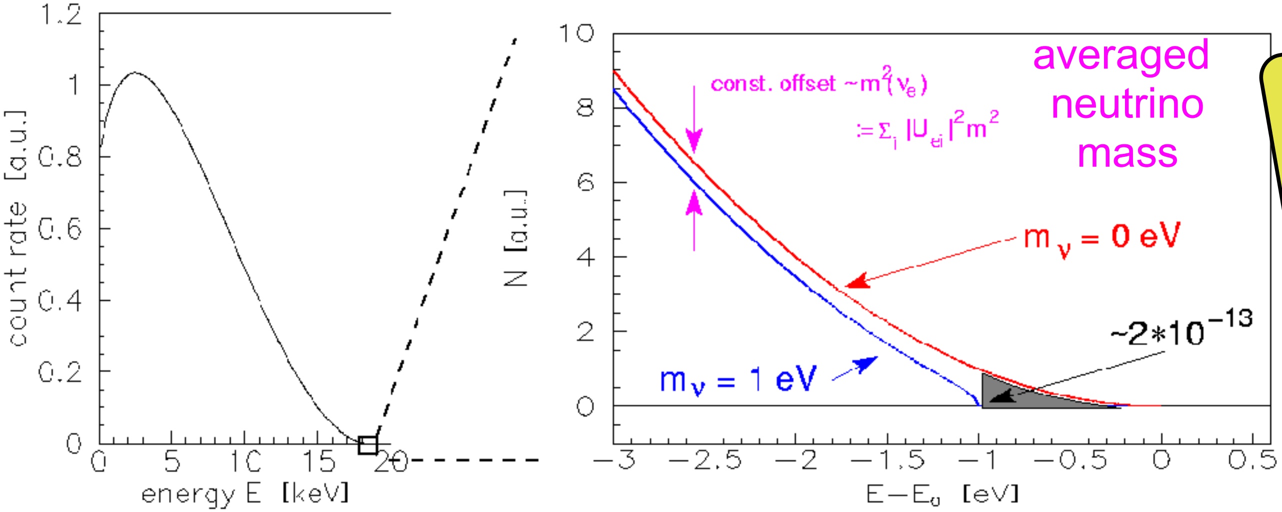
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

β electron energy spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \sqrt{(E_0-E_e)^2 - \text{"}m(\nu_e)\text{"}^2}$$

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

Complementary to 0νββ and cosmology



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 ^3H, (^{187}Re)**

very high energy resolution &
very high luminosity &
very low background
} ⇒ **MAC-E-Filter (or bolometer for ^{187}Re)**

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Summary: β-spectrum incl. electronic final states + ν mixing

Including electronic excited final states of excitation energy V_j with probability W_j

$$W_j = |\langle \Psi_0 | \Psi_{f,j} \rangle|^2$$

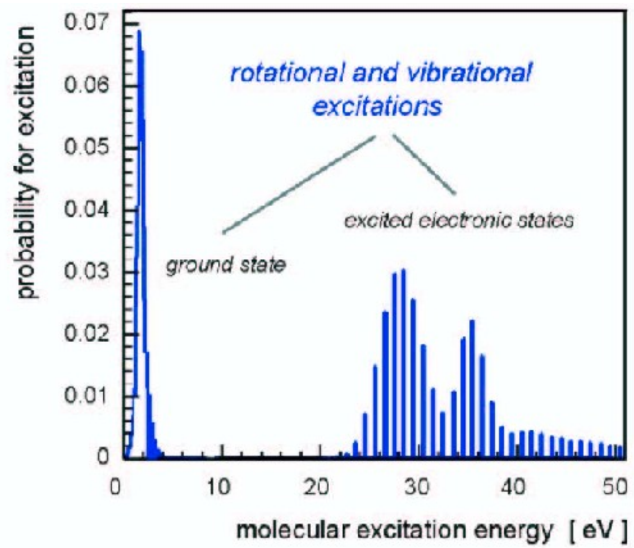
⇒ electronic final states are important

Using $\varepsilon_j = E_0 - V_j - E$

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j{}^2 - m^2(\nu_c)} \cdot \Theta(\varepsilon_j - m(\nu_c))$$

Final states of T_2 β-decay:

A. Saenz et al. Phys. Rev. Lett. 84 (2000) 242,
N. Doss et al., Phys. Rev. C73 (2006) 025502



Including neutrino mixing

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z+1) \cdot p \cdot (E+m)$$
$$\cdot \sum_j W_j \cdot \varepsilon_j \cdot \left(\sum_i |U_{ci}|^2 \sqrt{\varepsilon_j{}^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

⇒ "Electron neutrino mass"

$$m^2(\nu_c) := \sum_i |U_{ci}|^2 \cdot m^2(\nu_i)$$

⇒ the different $m(\nu_i)$ are not important at present precision

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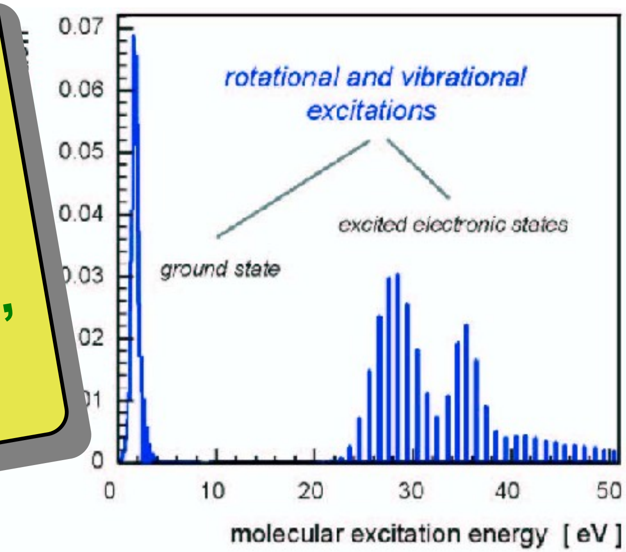
Final states c

A. Saenz et al. P

N. Doss et al., Ph

The electron spectrum coming out of a β-source is even more complicate due to inelastic scattering, backscattering. ...



Including neutrino mixing

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z +$$

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$$m^2(\nu_c) := \sum_i |U_{ci}|^2 \cdot m^2(\nu_i)$$

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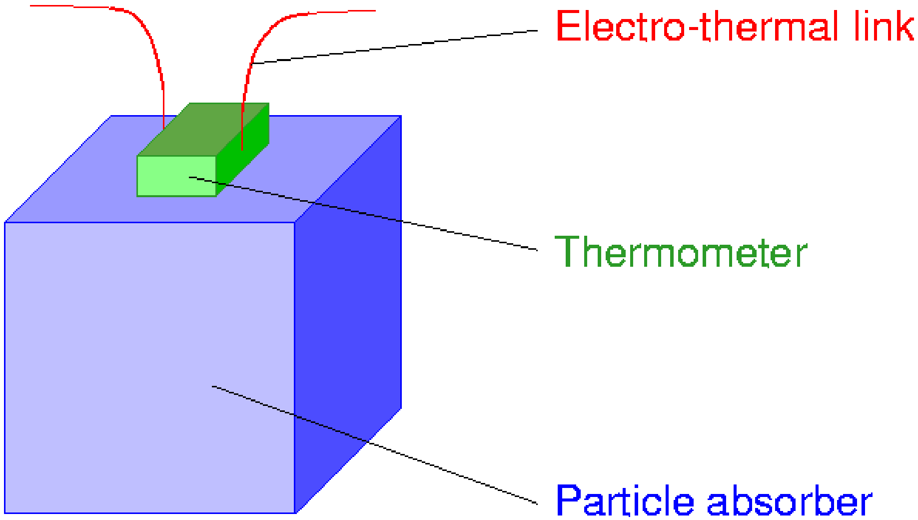
Cryogenic bolometers, e.g. with ^{187}Re



$\Delta T = \Delta E / C$

Debye:

$C \sim T^3$

Measures temperature rise by β-decay in an absorber

→ all energy except that of the neutrino is measured

→ „single final state experiment“, no problems with inelastic scattering, backscattering, …

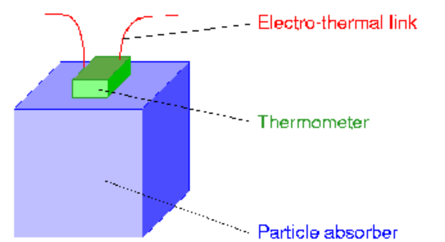
Disadvantage:

measure whole spectrum at once

→ pile-up problem

→ need many detector pixels

Cryogenic bolometers with ^{187}Re MIBETA (Milano/Como)



$\Delta T = \Delta E / C$
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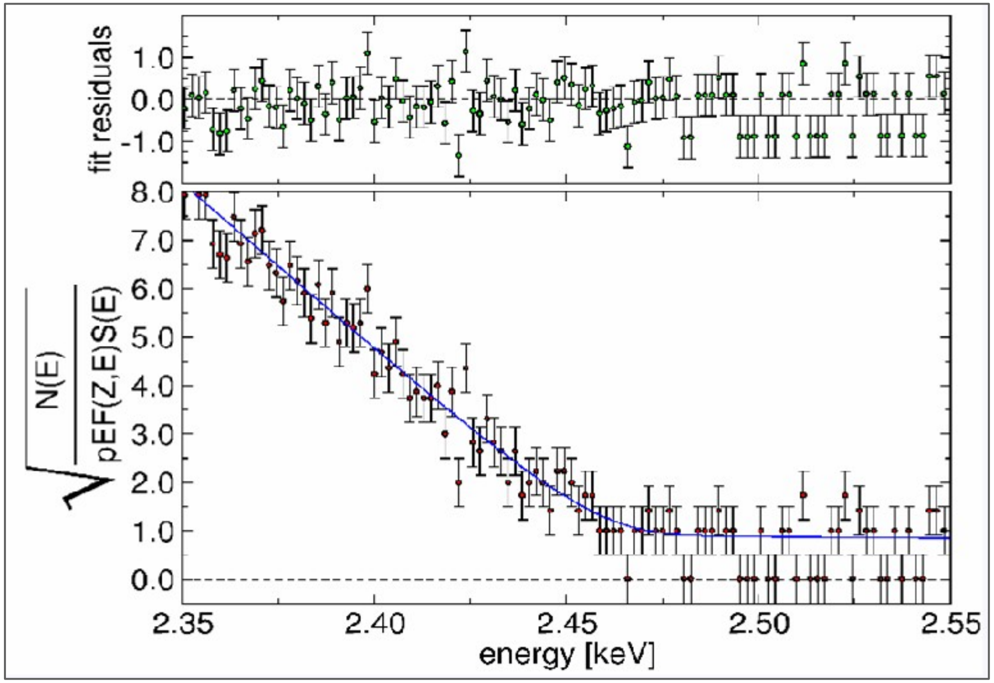

Measures all energy except that of the neutrino

detectors: 10 ($AgReO_4$)

rate each: 0.13 1/s

energy res.: $\Delta E = 28$ eV

pile-up frac.: $1.7\ 10^{-4}$

$M_\nu^2 = -141 \pm 211_{stat} \pm 90_{sys}\ eV^2$

$M_\nu < 15.6$ eV (90% c.l.)

(M. Sisti et al., NIMA520 (2004) 125)

MANU (Genova)

- Re metalic crystal (1.5 mg)
- BEFS observed (F.Gatti et al., Nature 397 (1999) 137)
- sensitivity: $m(\nu) < 26$ eV (F.Gatti, Nucl. Phys. B91 (2001) 293)

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MARE neutrino mass project: ^{187}Re beta decay with cryogenic bolometers

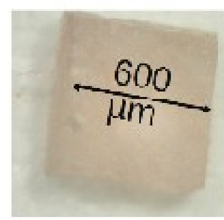
Advantages of cryogenic bolometers:
- measures all released energy except that of the neutrino
- no final atomic/molecular states
- no energy losses
- no back-scattering

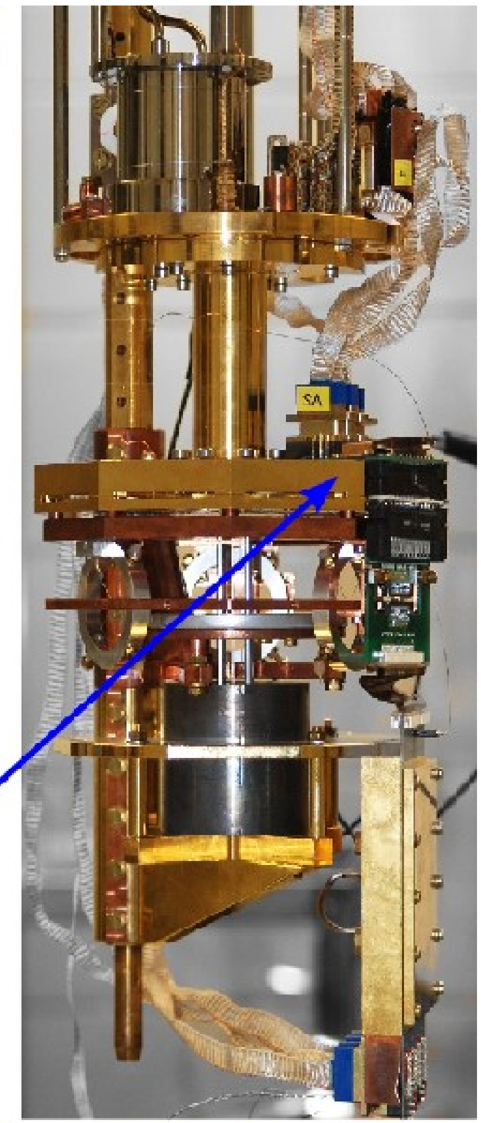
Challenges of cryogenic bolometers:
- measures the full spectrum (pile-up)
- need large arrays to get statistics
- understanding spectrum
- still energy losses or trapping possible
- beta environmental fine structure

MARE-2 aims for 10^4 to 10^5 detectors with much more advanced time & energy resolution

MARE-1 @ Milano-Bicocca

- 6x6 array of Si-implanted thermistors (NASA/GSFC)
- 0.5 mg $AgReO_4$ crystals
- $\Delta E \approx 30$ eV, $\tau_R \approx 250$ µs
- experimental setup for up to 8 arrays completed
- starting with 72 pixels in 2011
- up to 10^{10} events in 4 years → ~ 4 eV sensitivity





MARE-1 @ Genova

- R&D effort for Re single crystals on transition edge sensors (TES) → improve rise time to ~ µs and energy resolution to few eV
- large arrays (≈10^3 pixels) for 10^4-10^5 detector experiment
- high bandwidth, multiplexed SQUID readout
- also used with ^{163}Ho loaded absorbers

Angelo Nucciotti, Meudon 2011

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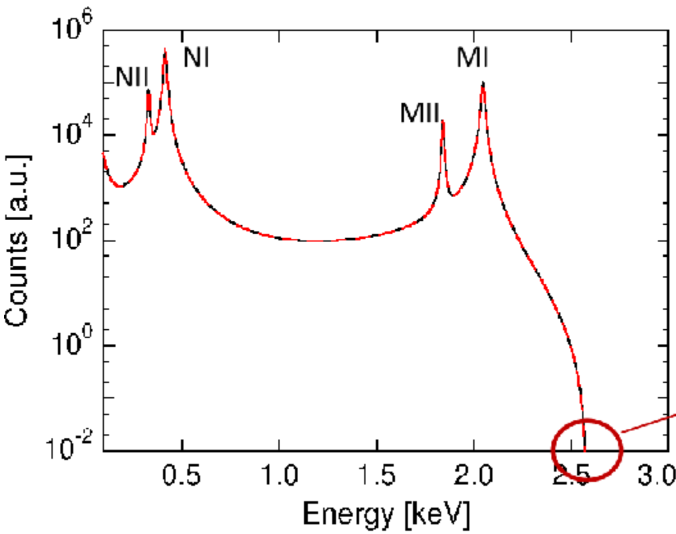
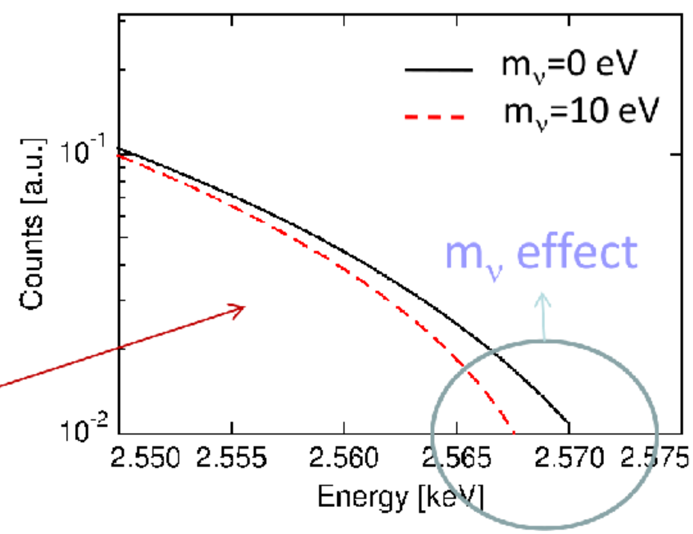
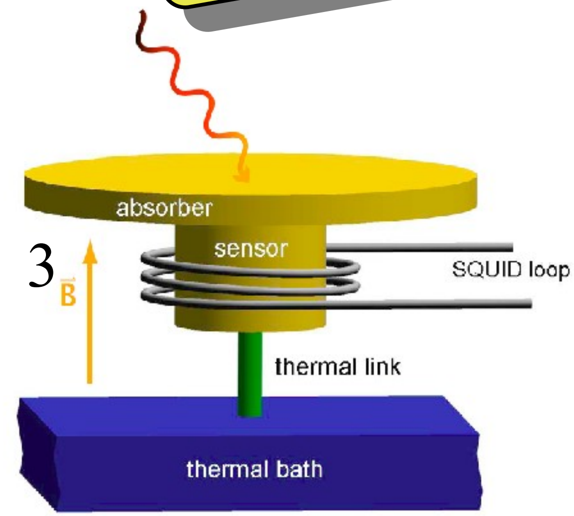
ECHO neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

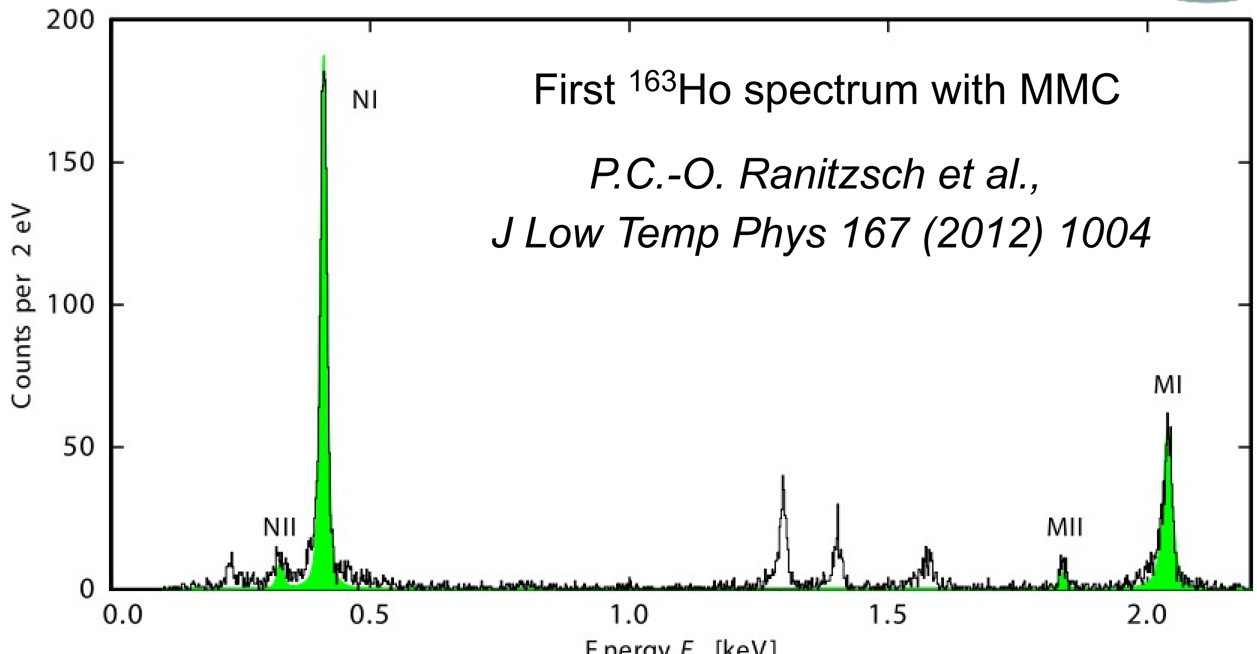
see talk by L. Gastaldo

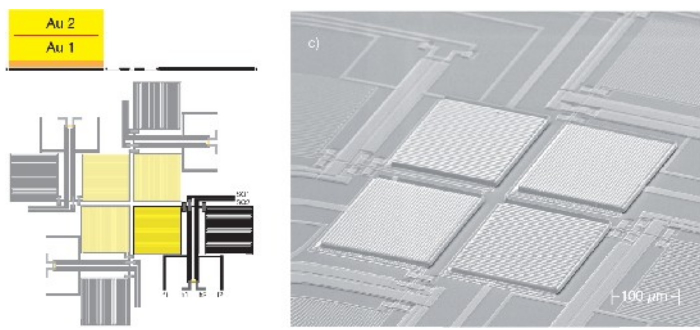
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$$





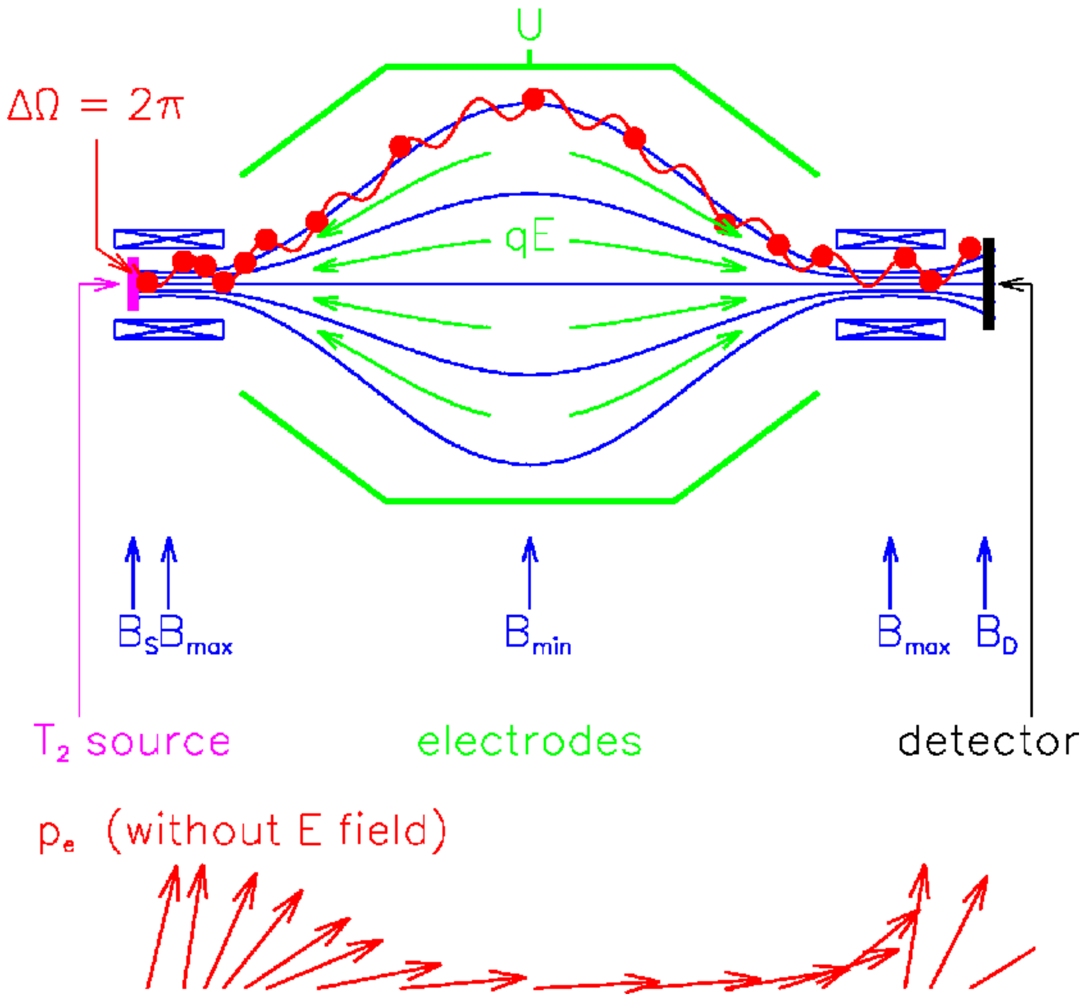




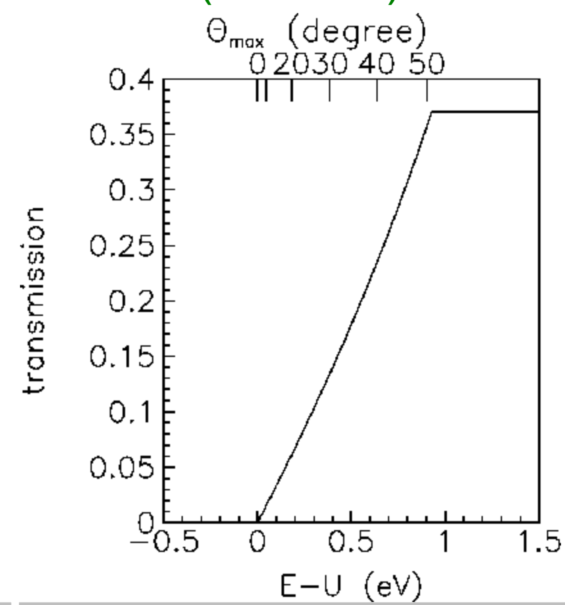


courtesy L. Gastaldo

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



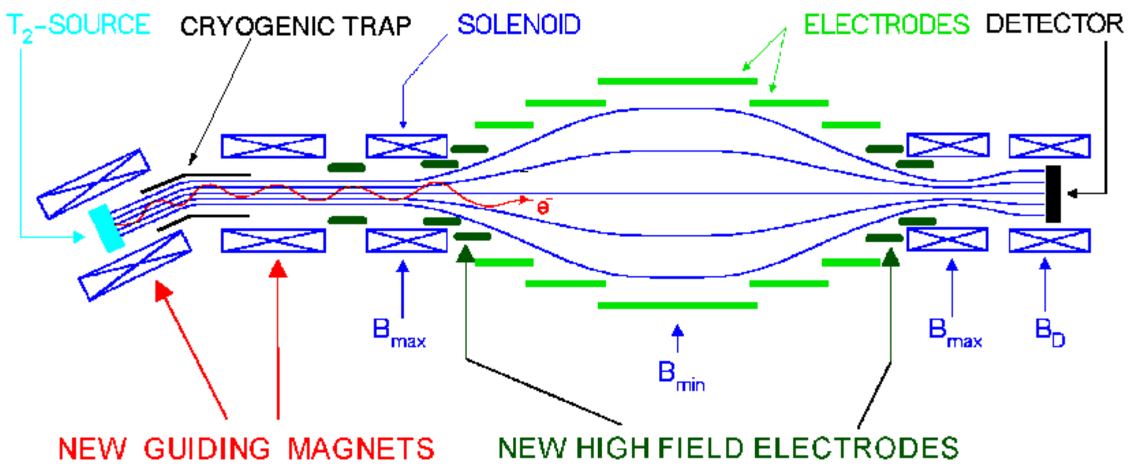
- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_{\perp} / B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)

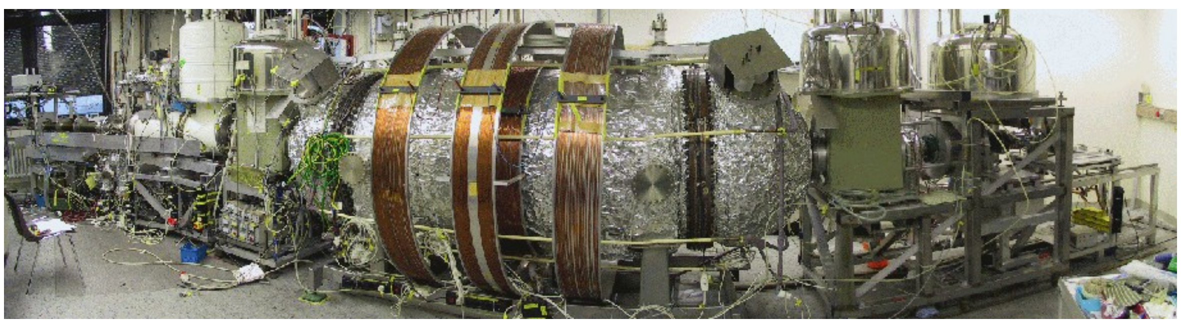


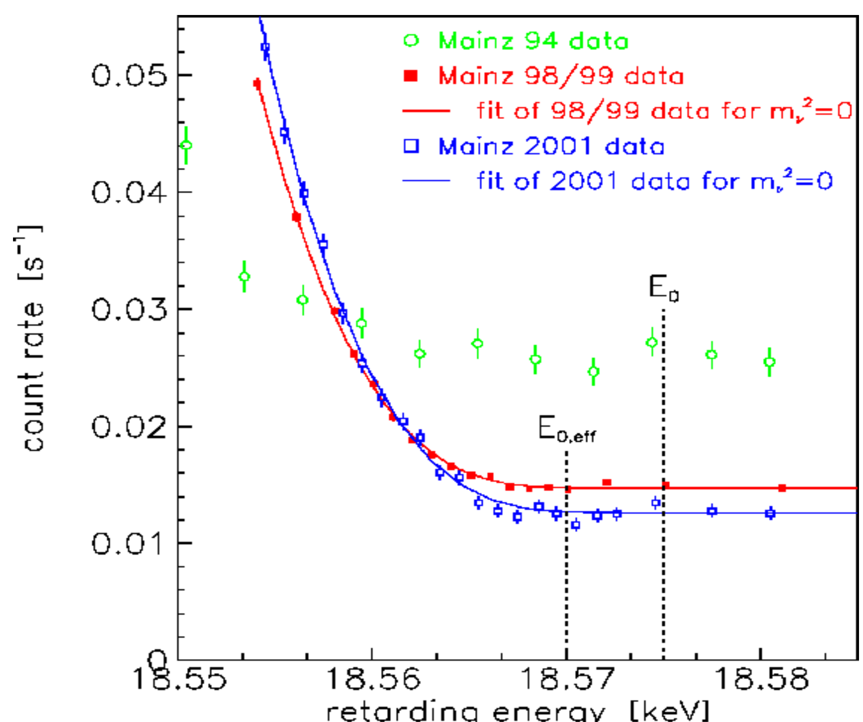
⇒ sharp integrating transmission function without tails →

<u>M</u>agnetic <u>A</u>diabatic <u>C</u>ollimation + <u>E</u>lectrostatic <u>Filter</u>
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

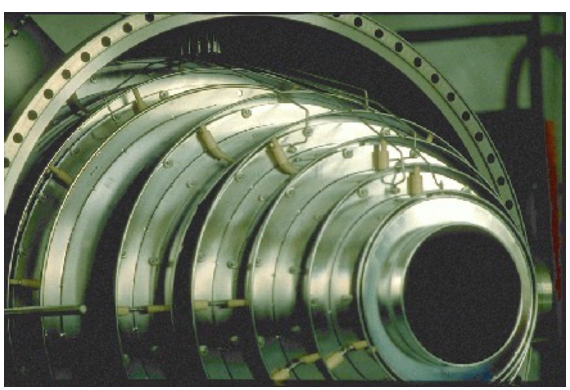
The Mainz Neutrino Mass Experiment Phase 2: 1997-2001







⇓



After all critical systematics measured by own experiment (atomic physics, surface and solid state physics:
inelastic scattering, self-charging, neighbour excitation):

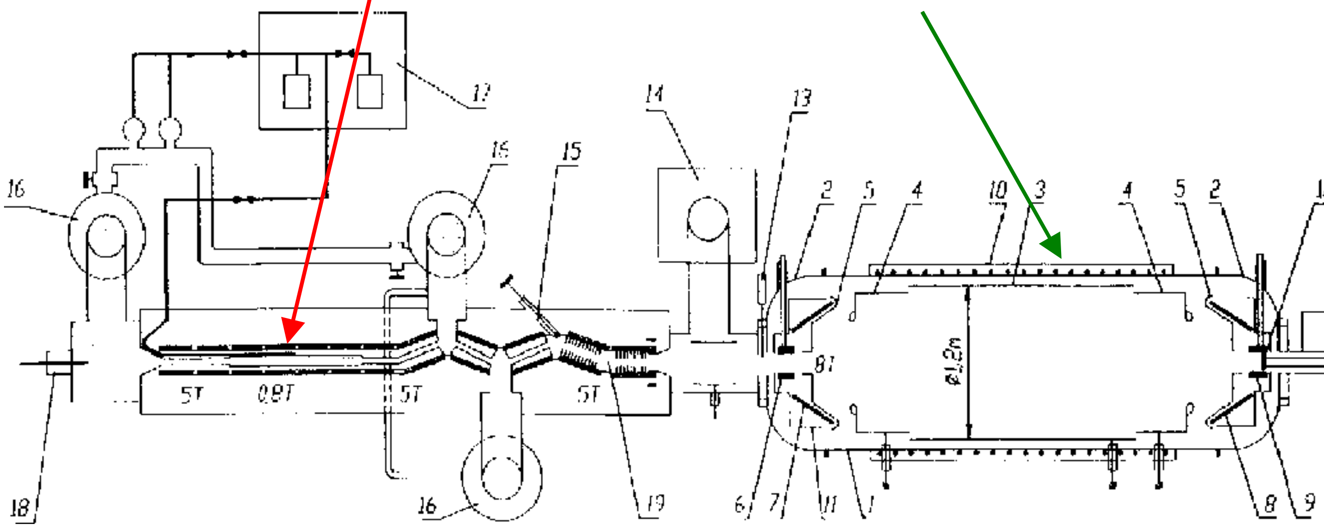
$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1$ eV^2 ⇒ $m(\nu) < 2.3$ eV (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

The Troitsk Neutrino Mass Experiment

windowless gaseous T_2 source, similar to LANL

MAC-E-Filter, similar to Mainz



Re-analysis of data
(better source thickness, better run selection)
Aseev et al, Phys. Rev. D 84, 112003 (2011)
m_β < 2.05 eV, 95% CL

Luminosity: L = 0.6cm²
($L = \Delta\Omega/2\pi * A_{source}$)

Energy resolution: ΔE = 3.5eV
3 electrode system in 1.5m diameter UHV vessel ($p<10^{-9}$ mbar)

upgraded setup at Troitsk for KATRIN systematics and sterile keV neutrino search

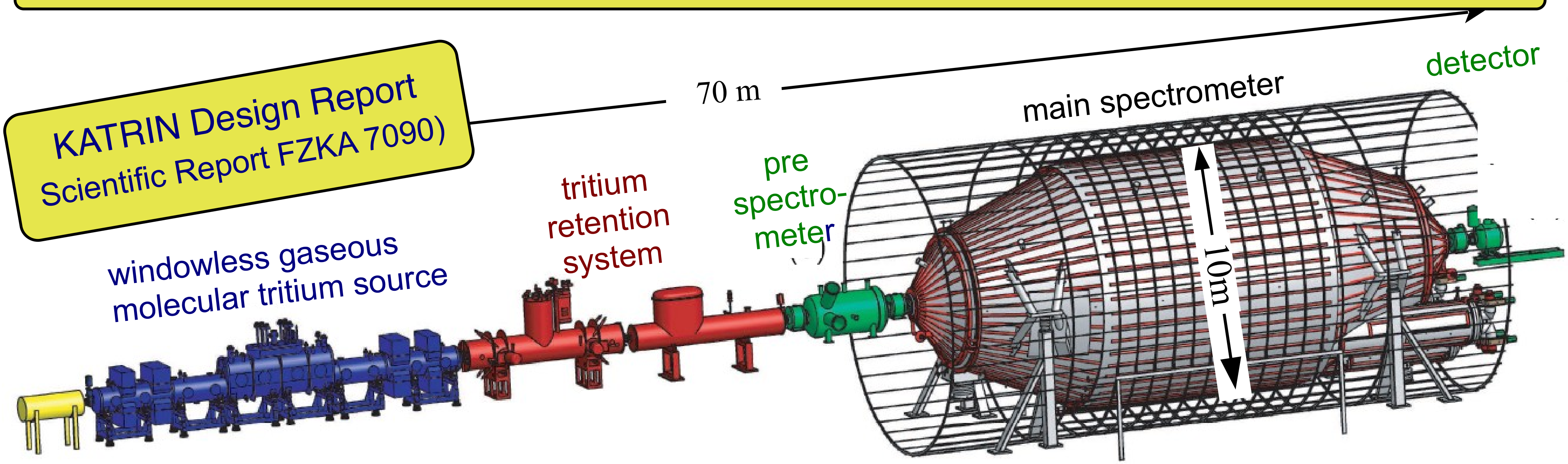
The KATRIN experiment at KIT

Aim: $m(\nu_e)$ sensitivity of 200 meV (currently 2 eV)

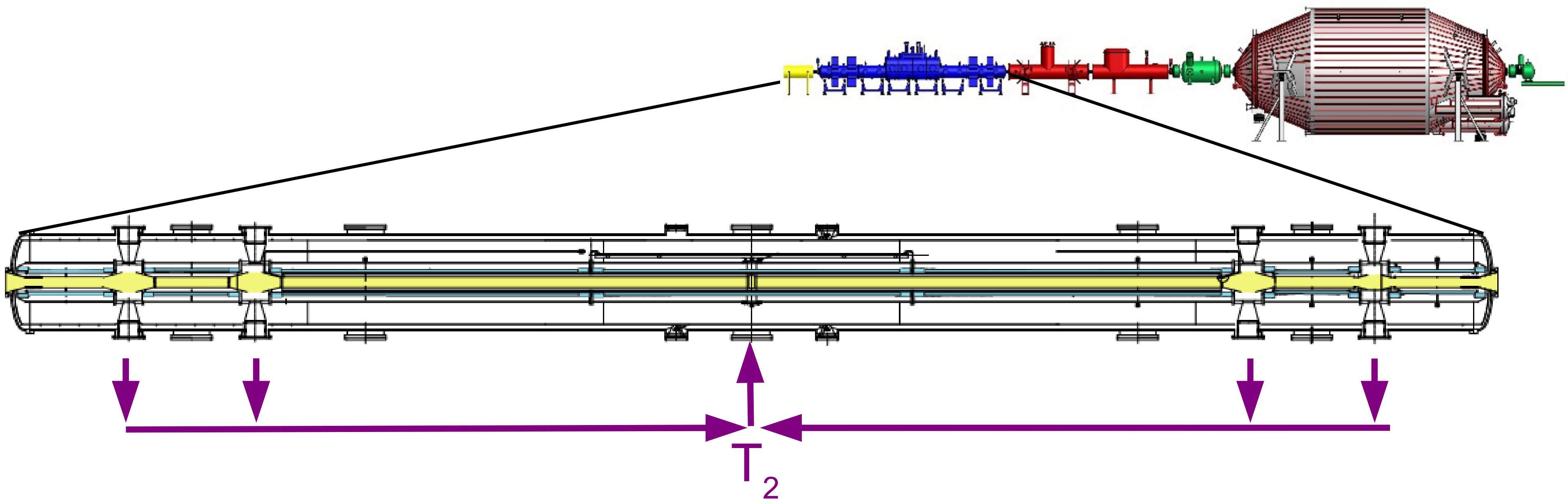
- very high energy resolution ($\Delta E \leq$ 1eV, i.e. σ = 0.3 eV) $\Rightarrow$ source $\neq$ spectrometer concept
- strong, opaque source $\Rightarrow$ $dN/dt \sim A_{source}$
- magnetic flux conservation (Liouville) $\Rightarrow$ scaling law:

$$A_{spectrometer} / A_{source} = B_{source} / B_{spectrometer} = E / \Delta E = 20000 / 1$$

KATRIN Design Report
Scientific Report FZKA 7090)



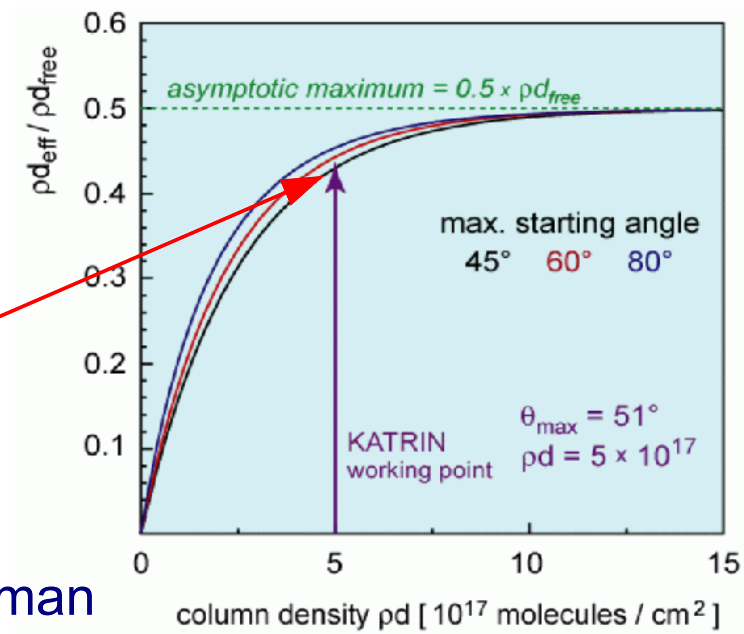
Molecular Windowless Gaseous Tritium Source WGTS



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
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics



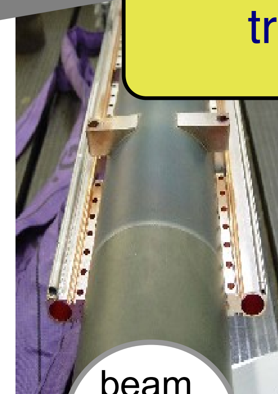
check column density by e-gun, T_2 purity by laser Raman

Very successful cool-down and stability tests of the WGTS demonstrator

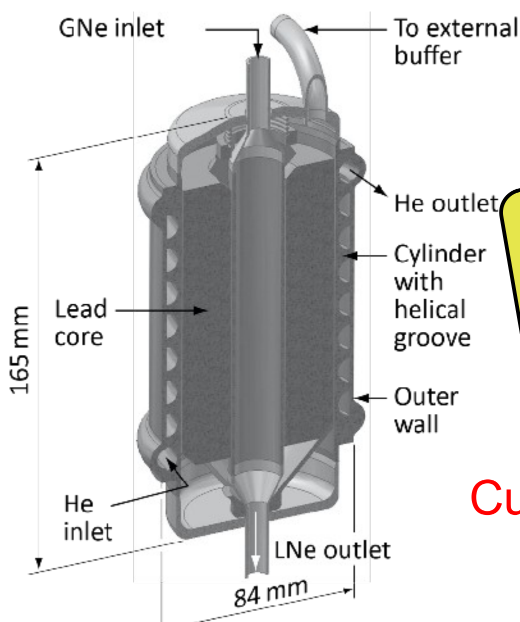

arrival of WGTS demonstrator at KIT: April 2010

see talk by S. Fischer

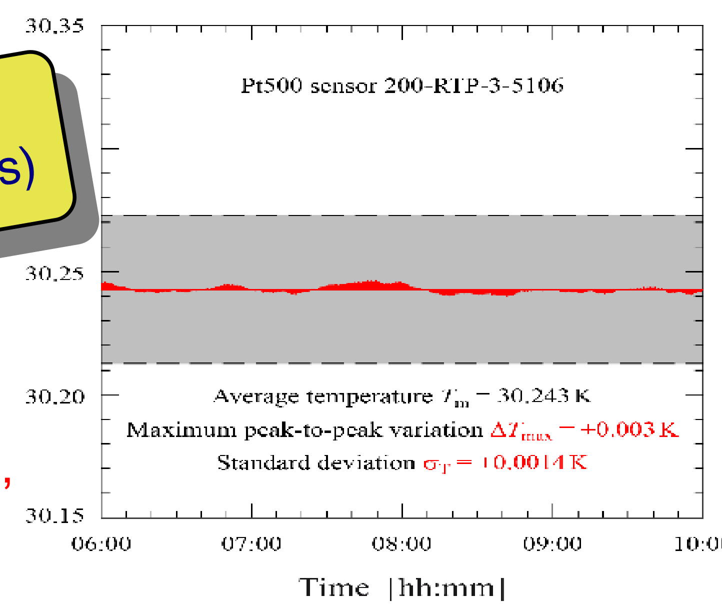
per mill stability source strength request:
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p\, V / R\, T$
tritium fraction f_T & ideal gas law


beam tube Ø=90mm


cooling concept of WGTS:
pressurized 2-phase Ne



S. Grohmann et al., Cryogenics, (2013, in press)



Currently: tests of sc magnets, constructing of WGTS out of demonstrator

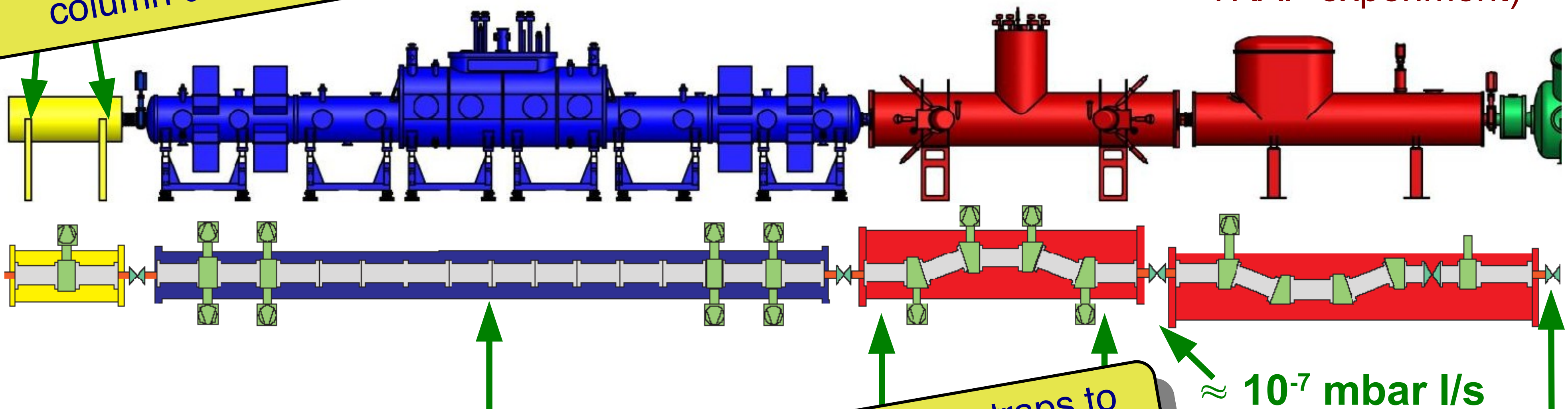
Transport and differential & cryo pumping sections

Molecular windowless gaseous tritium source

Differential pumping new set-up

Cryogenic pumping with Argon snow at LHe temperatures (successfully tested with the TRAP experiment)

Rear wall to stabilize WGTS potential
Egun to measure column density



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

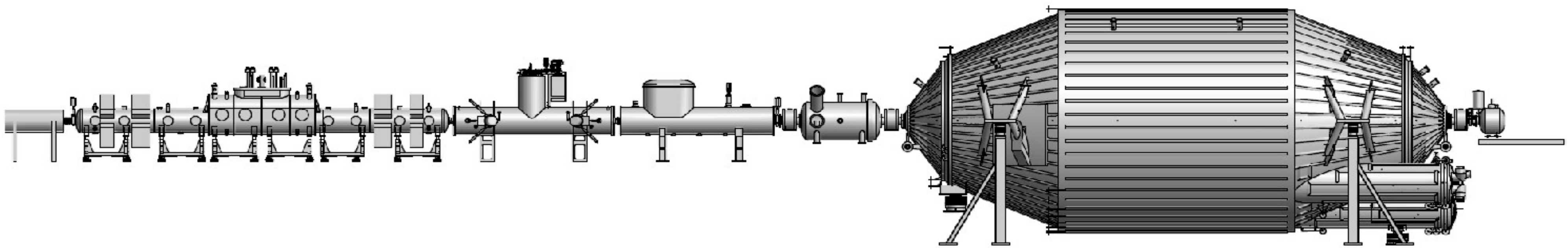
FT-ICR Penning traps to measure ions from WGTS

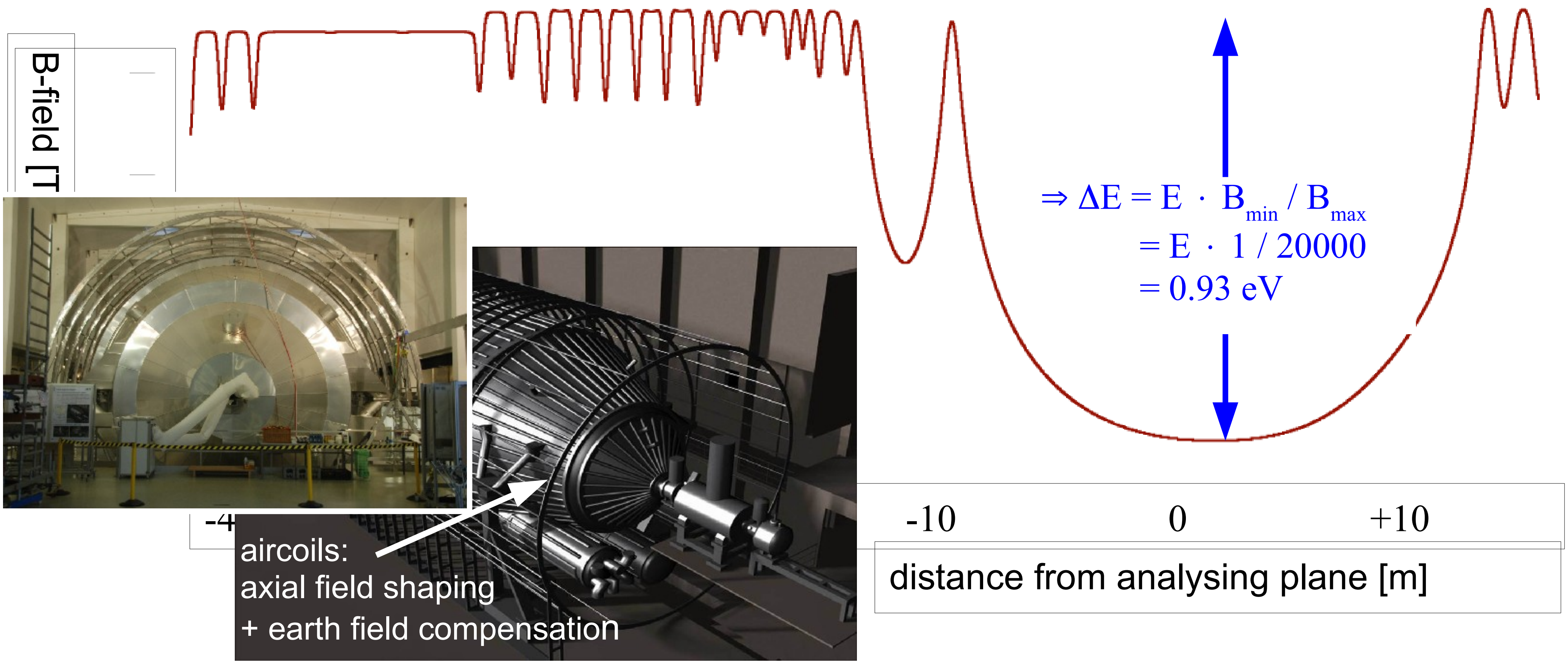
$\approx 10^{-7}$ mbar l/s

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

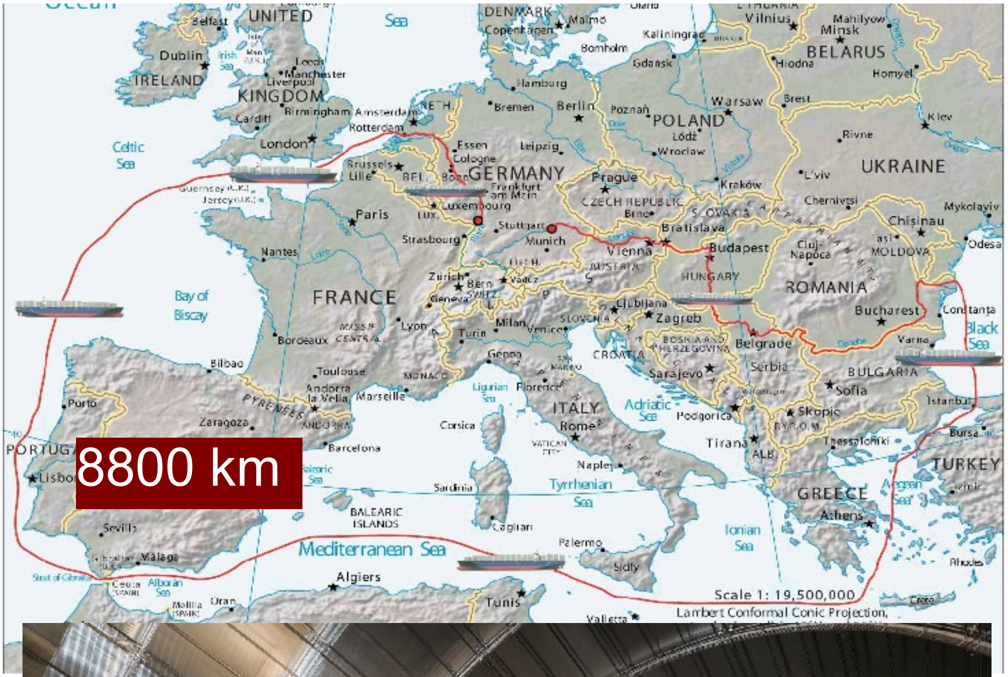
⇒ adiabatic electron guiding & T_2 reduction factor of $\sim 10^{14}$

Electromagnetic design: magnetic fields





Main Spectrometer



Suppress secondary electron background from walls on high potential

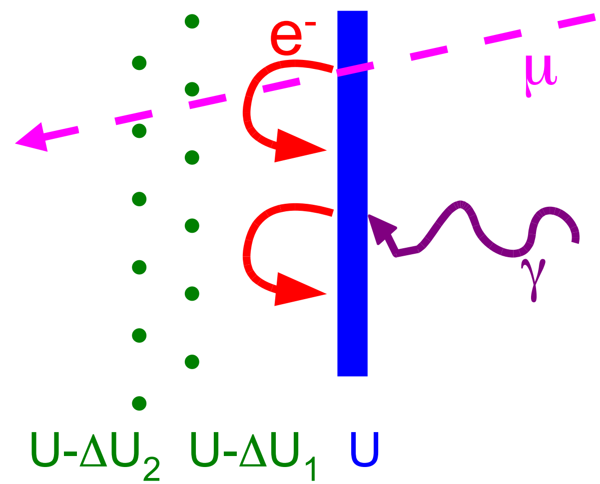
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

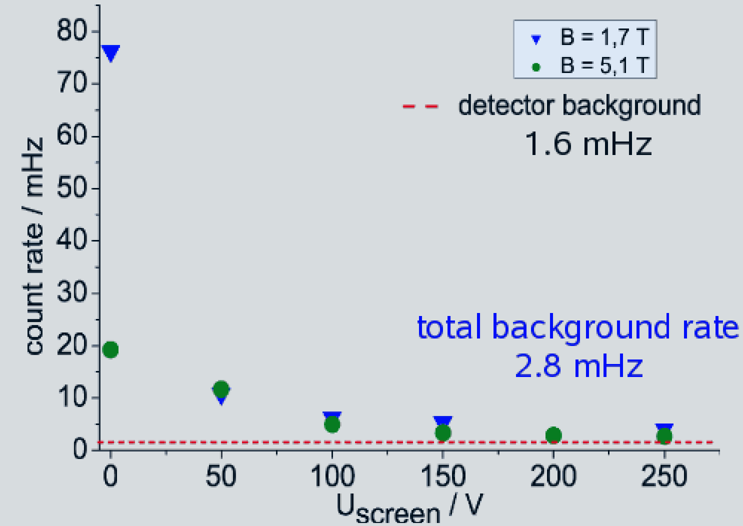
New: double layer wire electrode

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 from stored electrons: methods to avoid or to eliminate them

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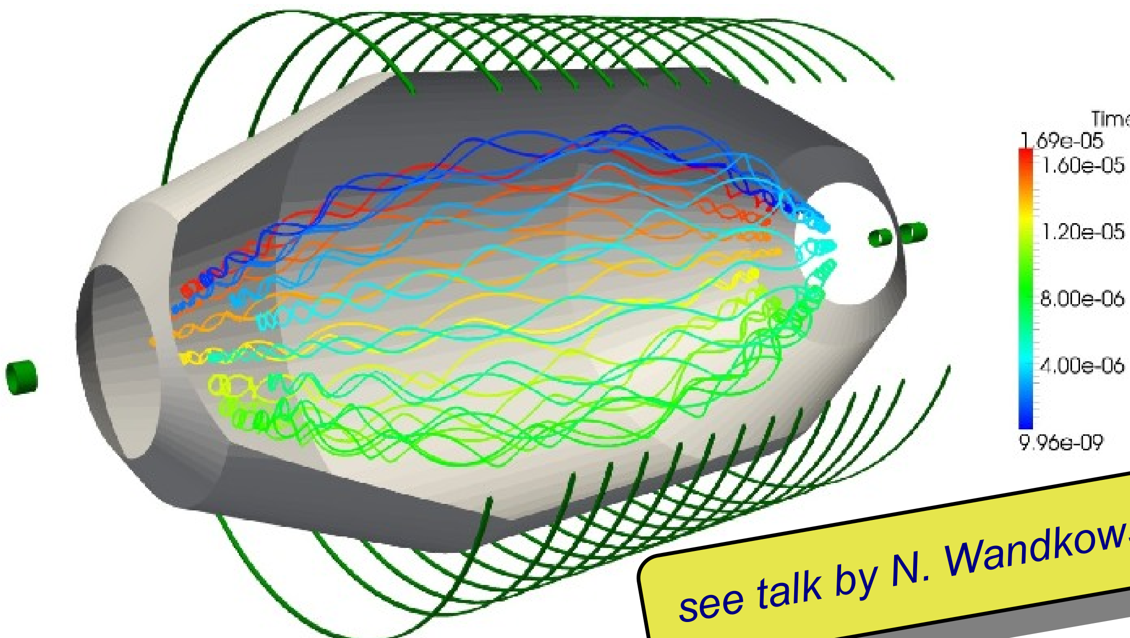
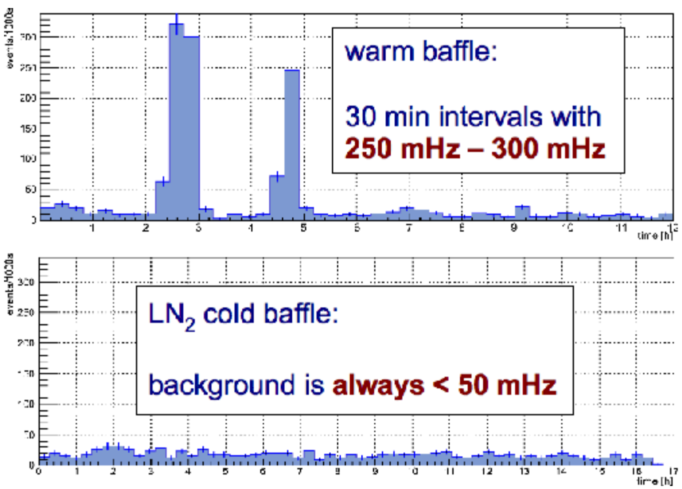
Stored electron by magnetic mirrors

F. Fränkle et al., Astropart. Phys. 35 (2011) 128



Radon suppression by LN_2 cooled baffle

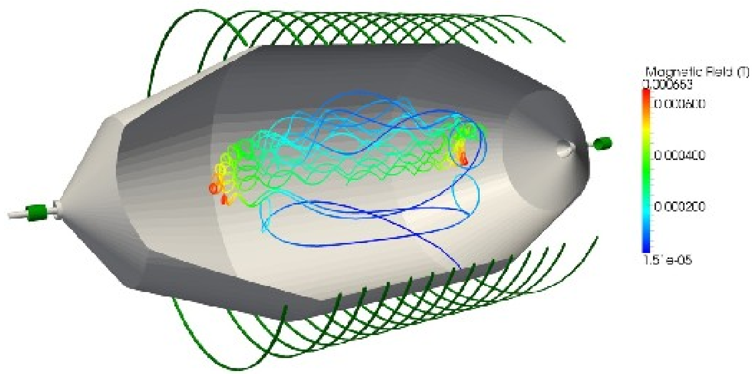
S. Görhardt, diploma thesis, KIT



see talk by N. Wandkowsky

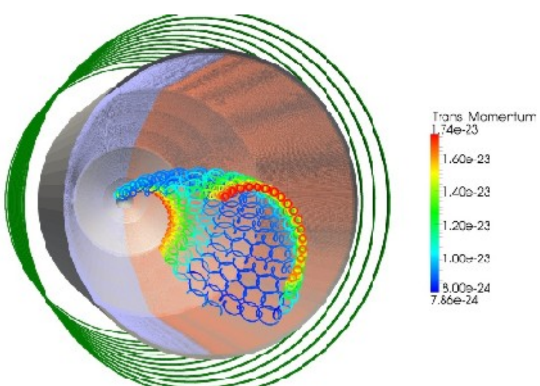
Nulling magnetic field by magn. pulse

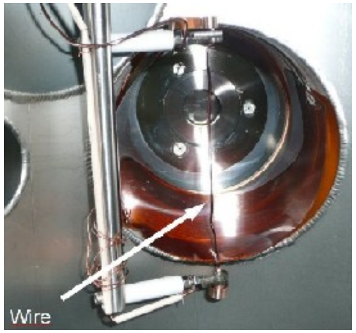
B. Hillen, PhD thesis, Münster



radial E x B drift due to electric dipole pulse

G. Drexlin et al., arXiv:1205.3729





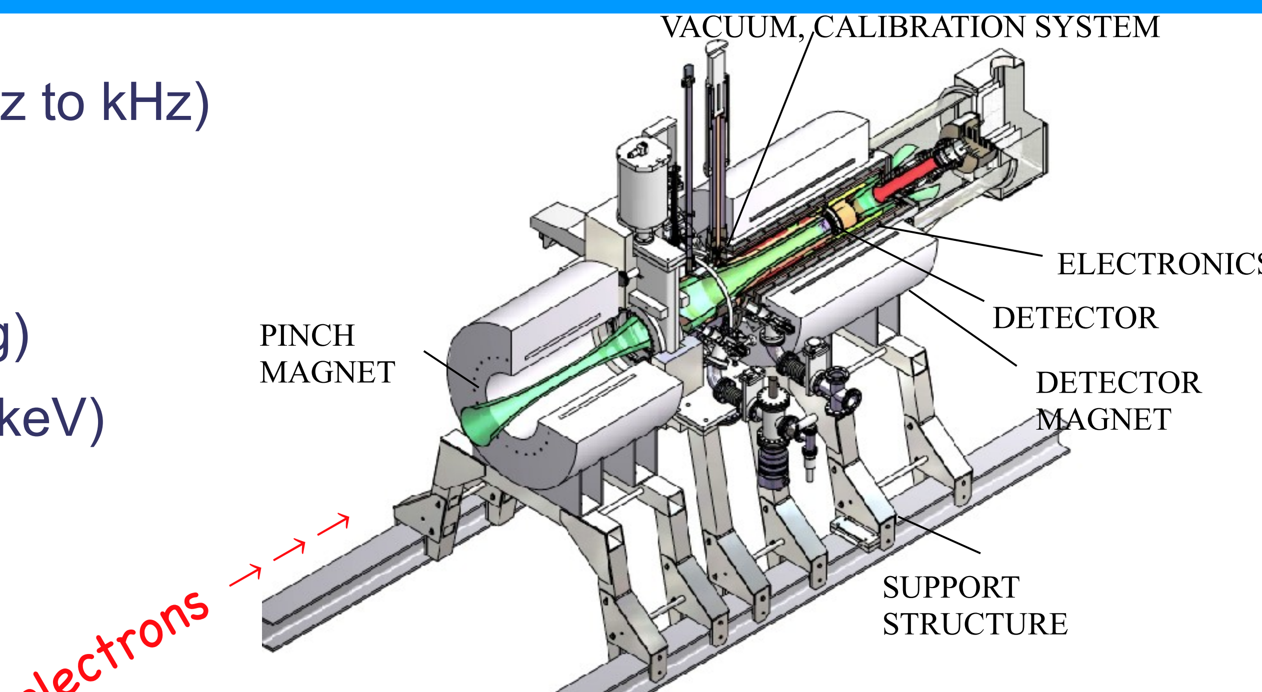
Mechanical eliminating stored particles:

M. Beck et al, Eur. Phys. J. A44 (2010) 499

The detector

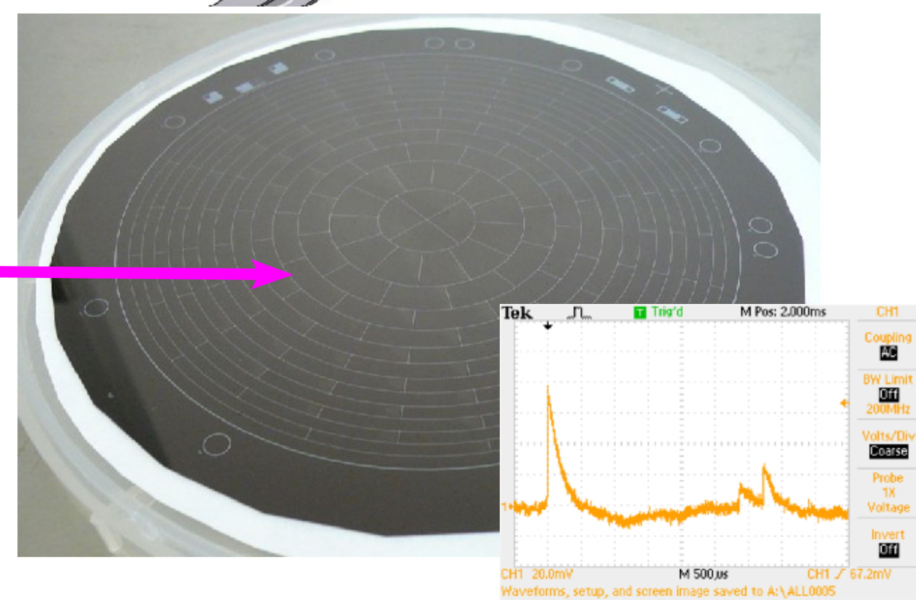
Requirements

- 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



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

Systematic uncertainties

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

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

1. inelastic scatterings of β´s inside WGTS
   - **dedicated e-gun measurements**, unfolding o

2. fluctuations of WGTS column density (required < 0.)
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, **e-gun measurements**

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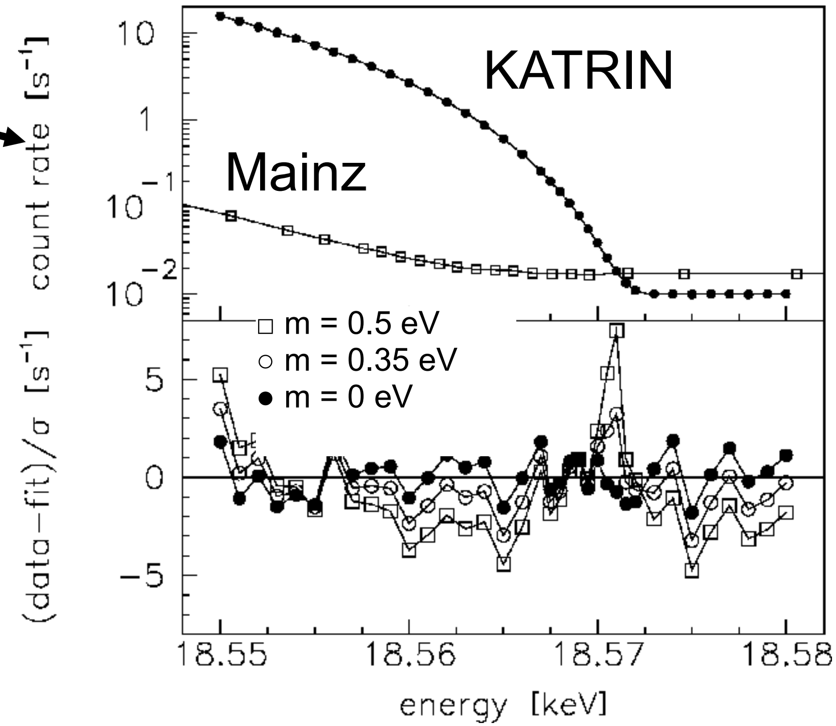
} spectrometer

KATRIN´s sensitivity

Example of KATRIN simulation & fit
(last 25eV below endpoint, reference):



sensitivity:

m_ν < 0.2eV (90%CL)

discovery potential:

m_ν = 0.3eV (3σ)

m_ν = 0.35eV (5σ)

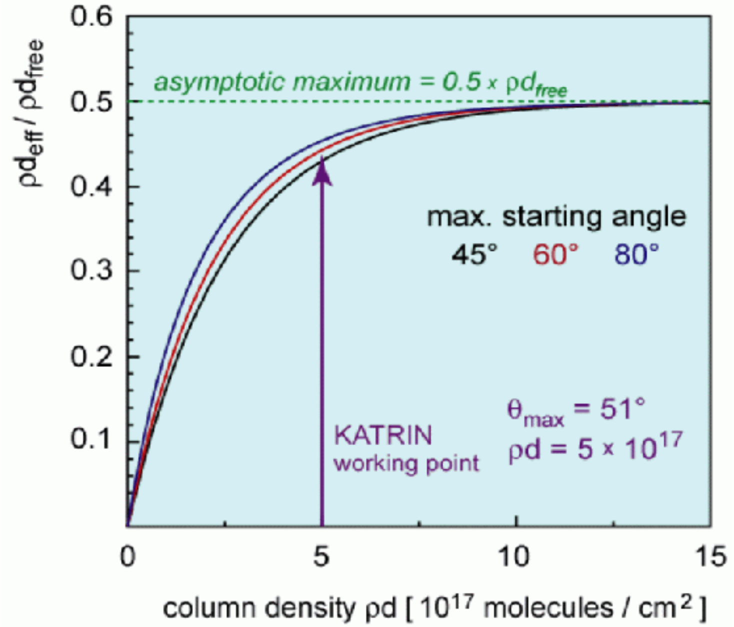
Expectation for 3 full data taking years: $\sigma_{syst} \sim \sigma_{stat}$

⇒ **KATRIN will improve the sensitivity by 1 order of magnitude**
will check the whole cosmological relevant mass range
will detect degenerate neutrinos (if they are degen.)

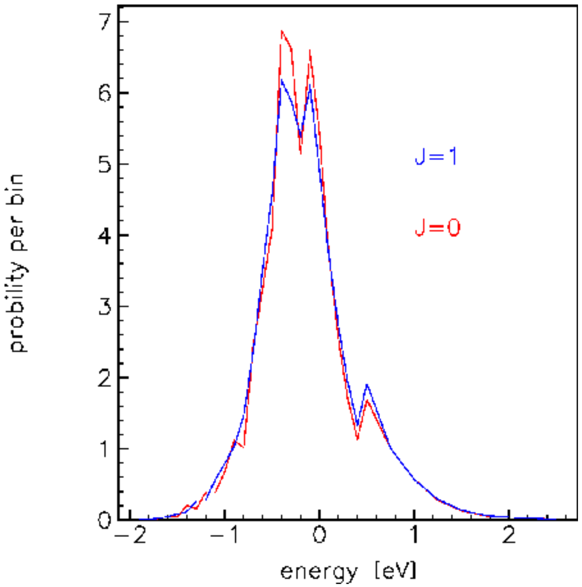
Can KATRIN be largely improved ?

Problems

1) The source is already opaque
   → need to increase size transversally
   but a Ø100m spectrometer is not feasible



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



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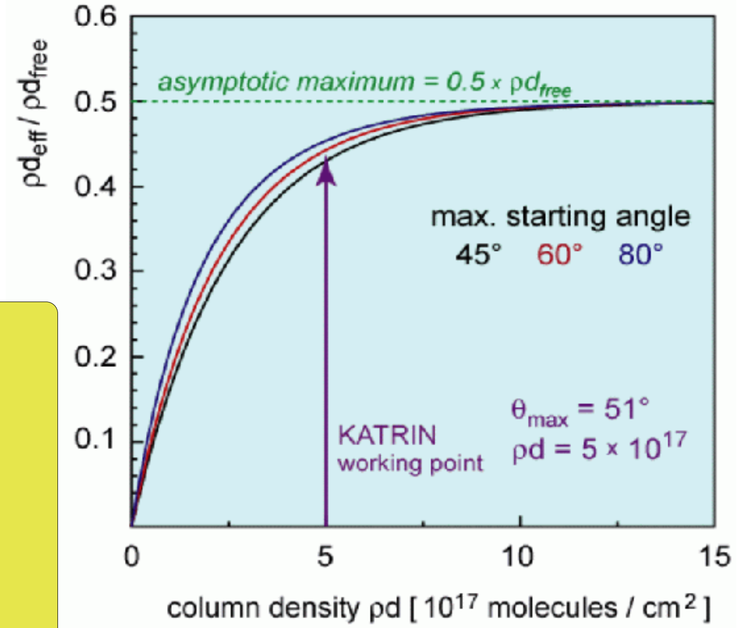
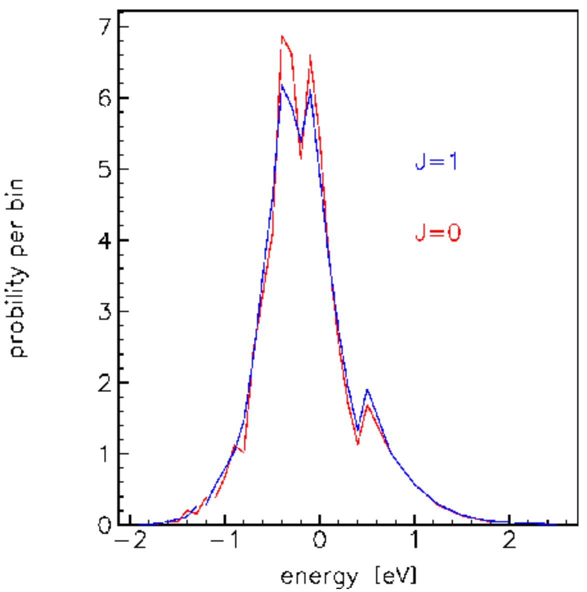


Two possible ways out:

a) source inside detector
using cryogenic bolometers (MARE, ECHO)

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

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

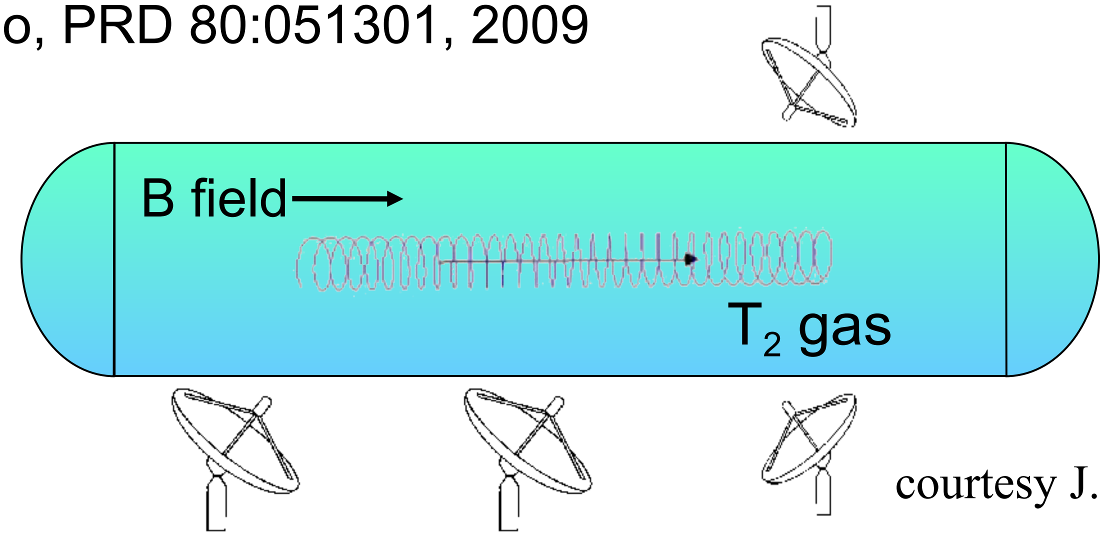


Not really realistic yet:

c) atomic tritium source
Unfortunately, it is technically really a challenge

Outlook - Project 8: Measure coherent cyclotron radiation of tritium β electrons

B. Monreal and J. Formaggio, PRD 80:051301, 2009



courtesy J. Formaggio

General idea:

- Source = KATRIN tritium source technology :
  uniform B field
  low pressure T_2 gas

β electron radiates coherent cyclotron radiation

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

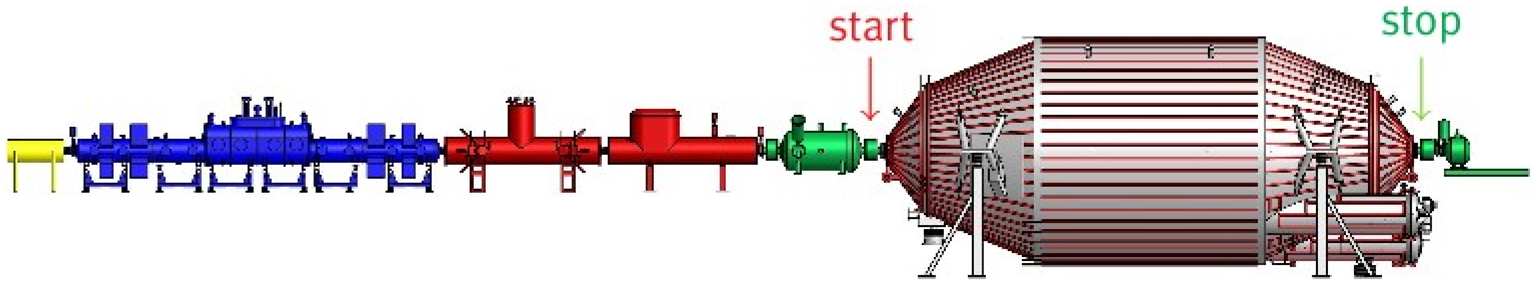
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and
  carries the information of the β-electron energy

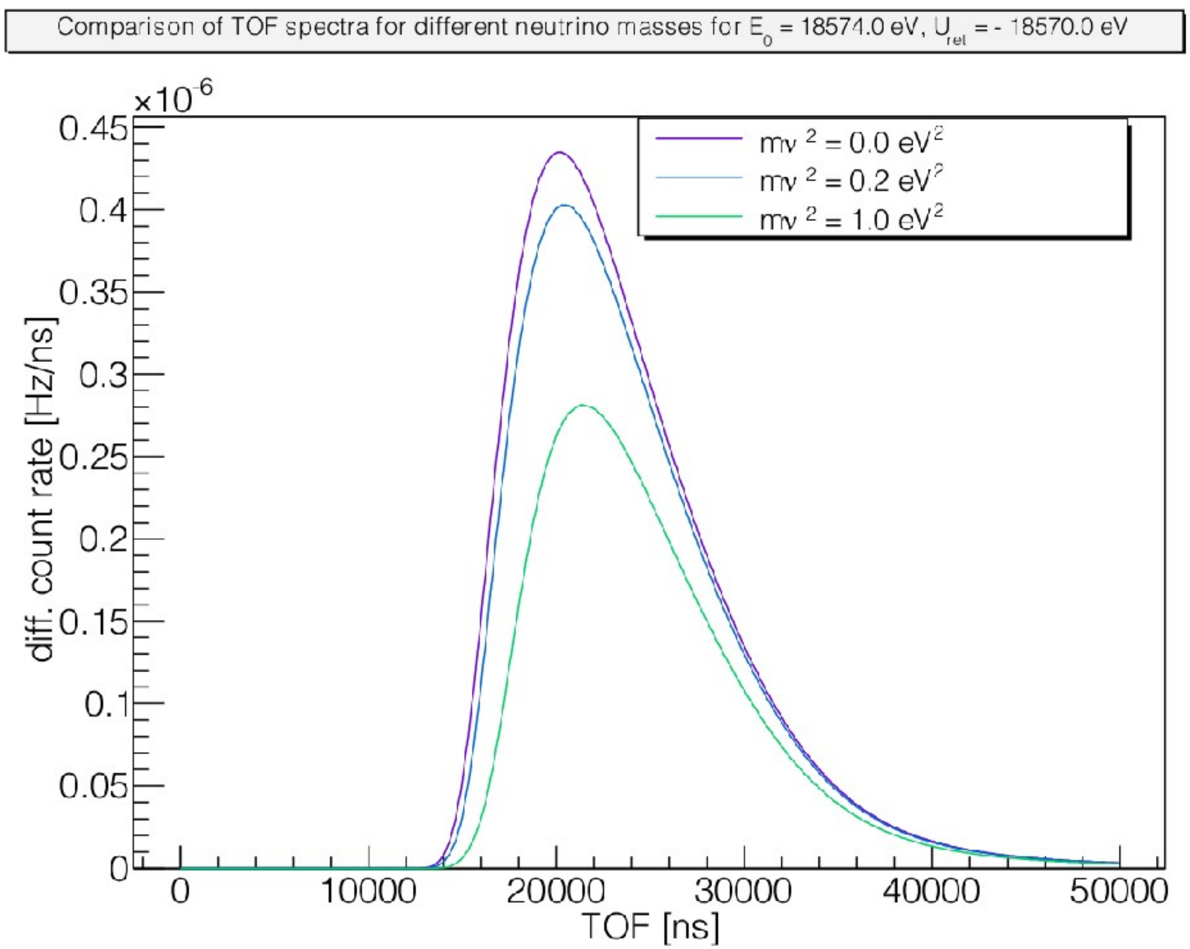
A lot of R&D necessary and has started
- Is it really possible ?
- What are the systematic uncertainties ?

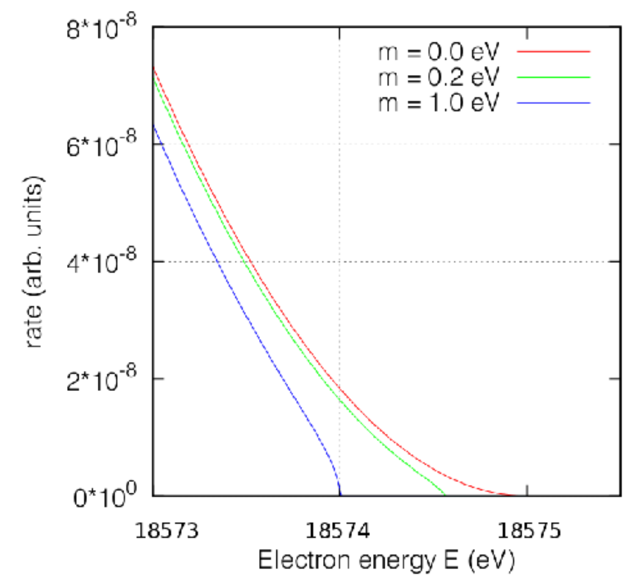
Can KATRIN be improved a bit ?

?

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





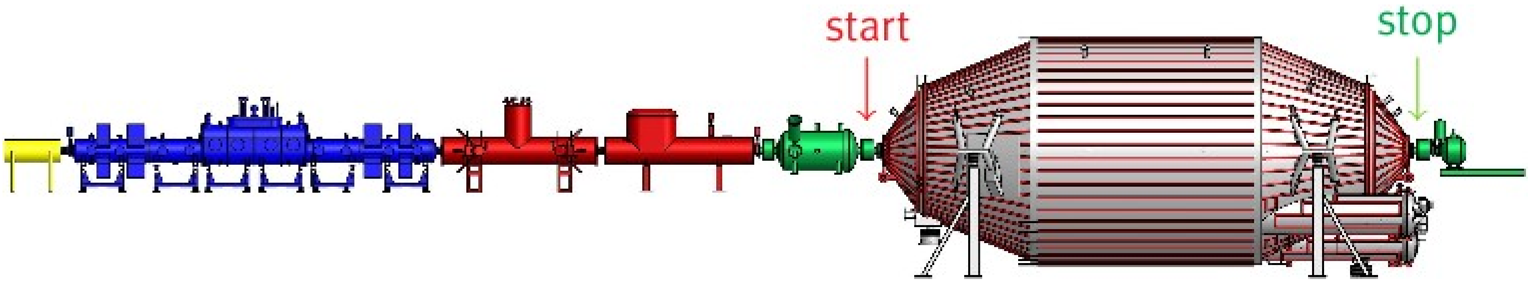


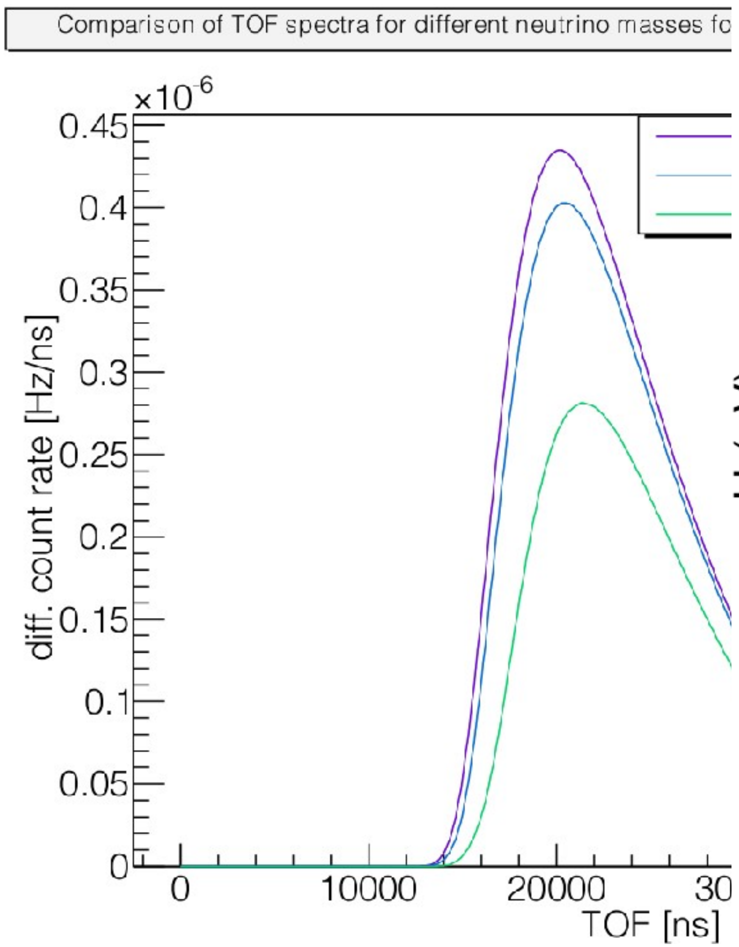
Time-of-flight spectrum is sensitive to the neutrino mass

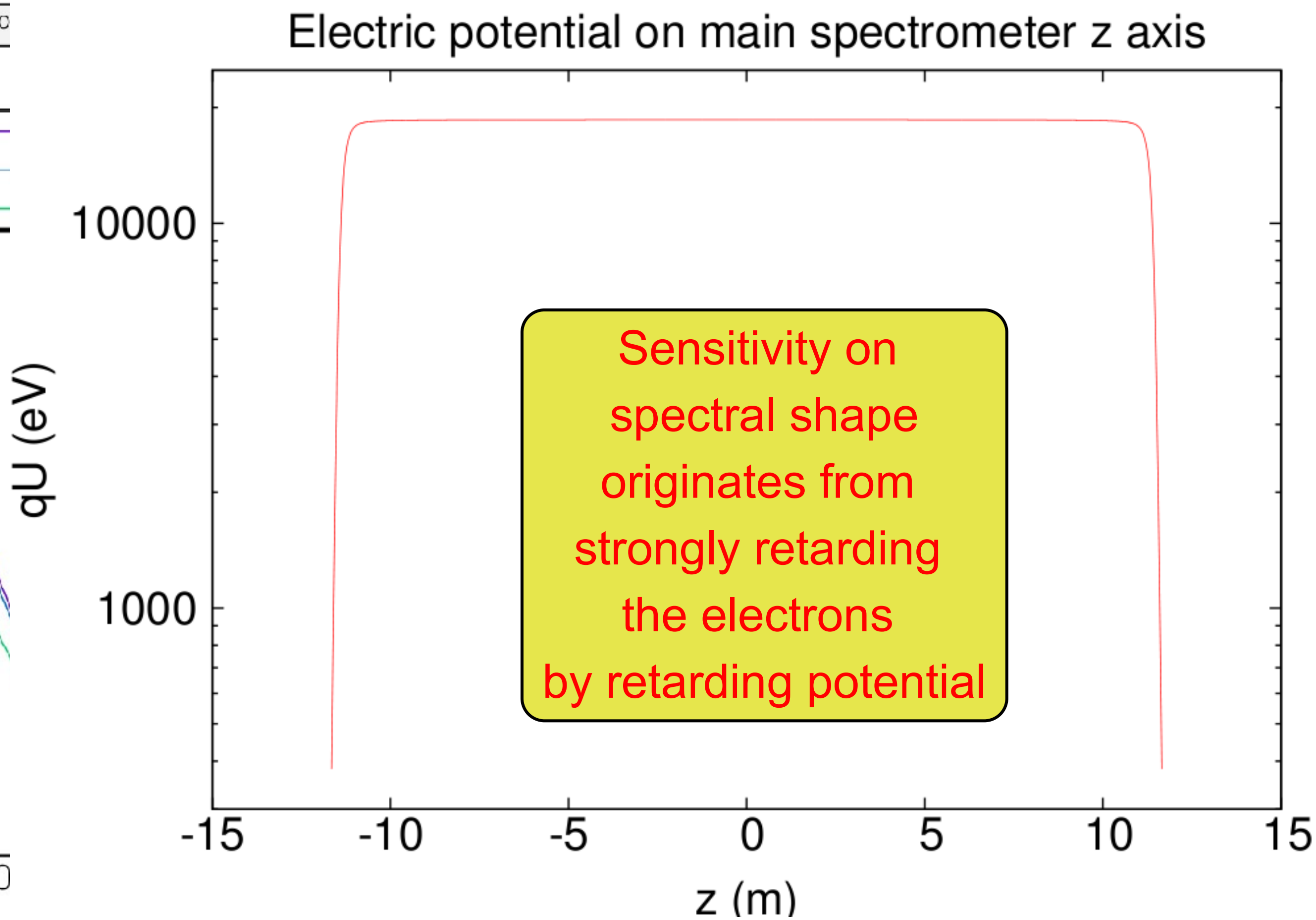
require one retardation potential only

not integral but differential β-spectrum

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





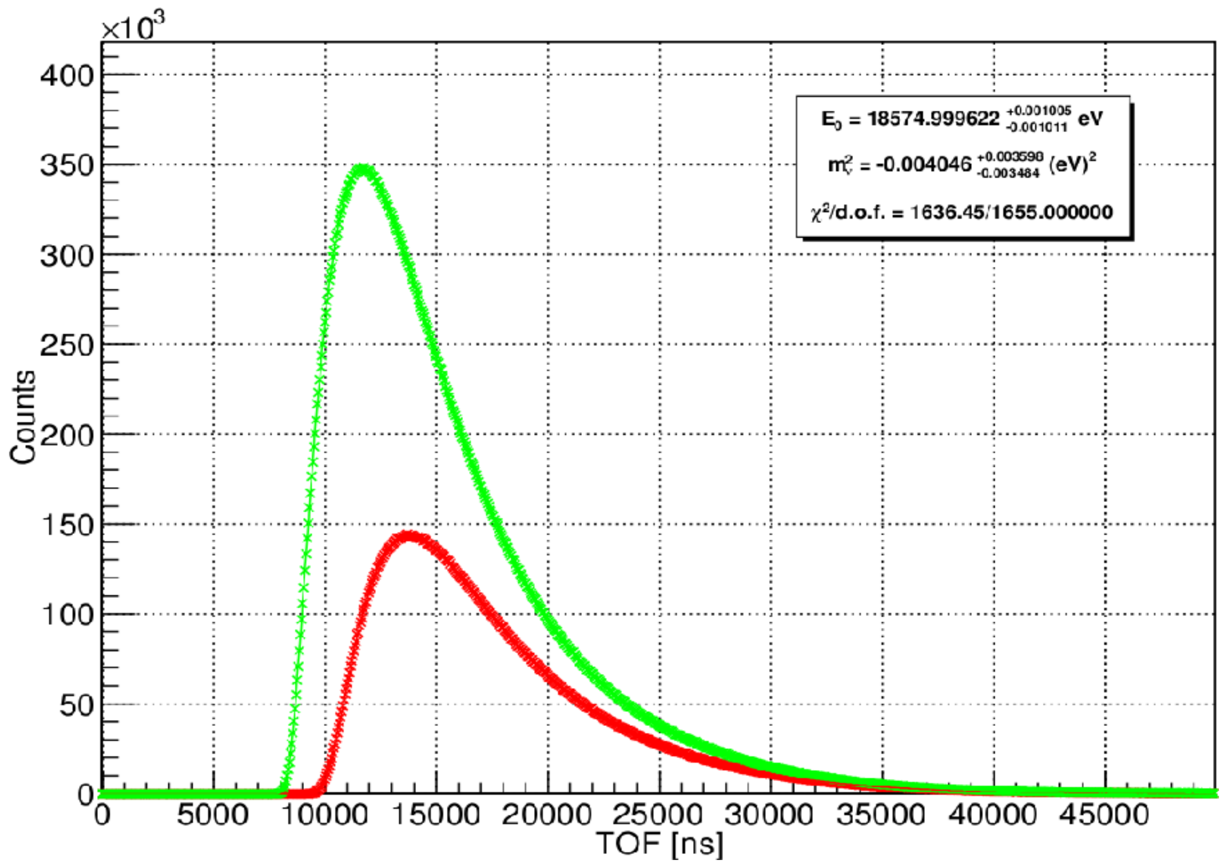


Sensitvity improvement on $m^2(\nu_e)$ by ideal TOF determination

Measure at 2 (instead of ≈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_n^2 w.r.t. standard KATRIN, but ideal case !



N. Steinbrink et al.
arXiv:1308.0532

Westfälische Wilhelms-Universität Münster

How to measure time-of-flight at KATRIN ? → gated-filter

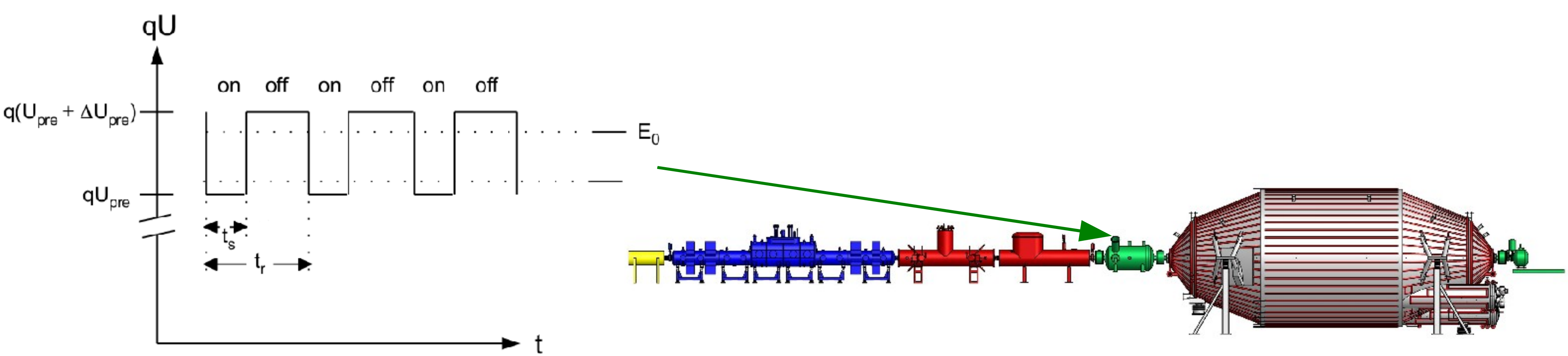
1) Can measure time-of-arrival with KATRIN detector with $\Delta t = 50$ ns → ok

2) Need to determine time-of-passing-by of beta electron before main spectrometer
without disturbing energy and momentum by more than 10 meV !
→ Need „detector“ with 10 meV threshold
This seems not to be prohibited in principle but it is unrealistic for the near future !

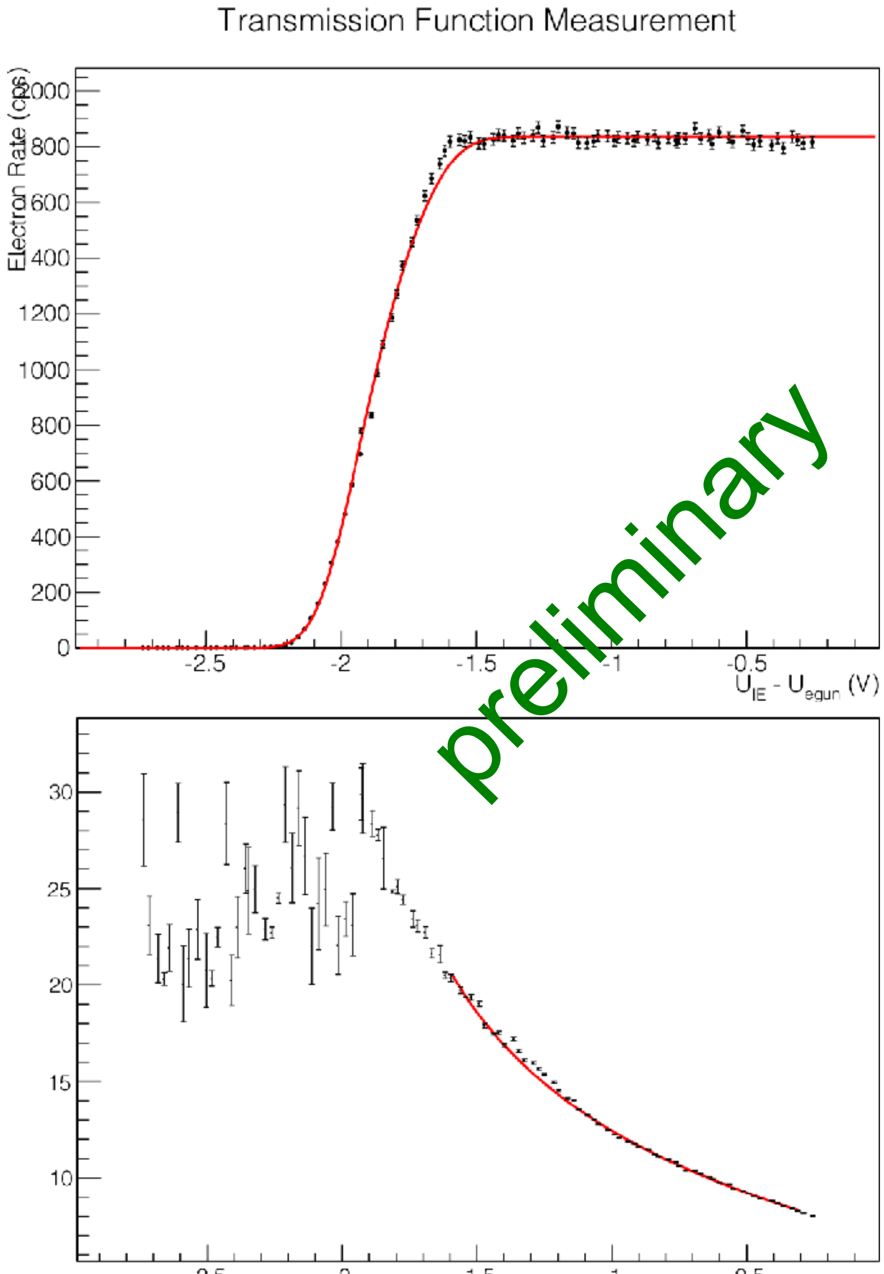
2') Use pre spectrometer as a „gated-filter“ by switching fast the retarding voltage

MAC-E-TOF demonstrated: *J. Bonn et al., Nucl. Instr. Meth. A421 (1999) 256*
no problem with transmission properties: *M. Prall et al., NJP 14 (2012) 073054*

About as sensitive on the neutrino mass as standard KATRIN:
N. Steinbrink et al., arXiv:1308.0532



Test of TOF method at main spectrometer during SDS commissioning with pulsed egun

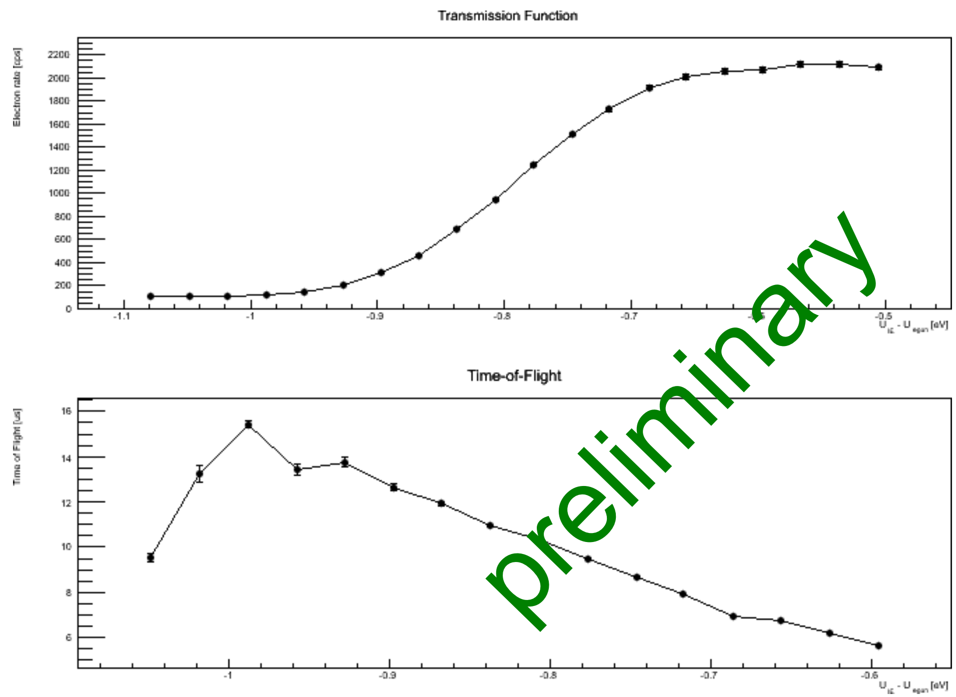


Integral transmission function at -200 V

measured TOF agrees with calculated TOF by N. Steinbrink

from electrical potential

and magnetic field maps



Integral & TOF transmission function at -18600 V

Summary

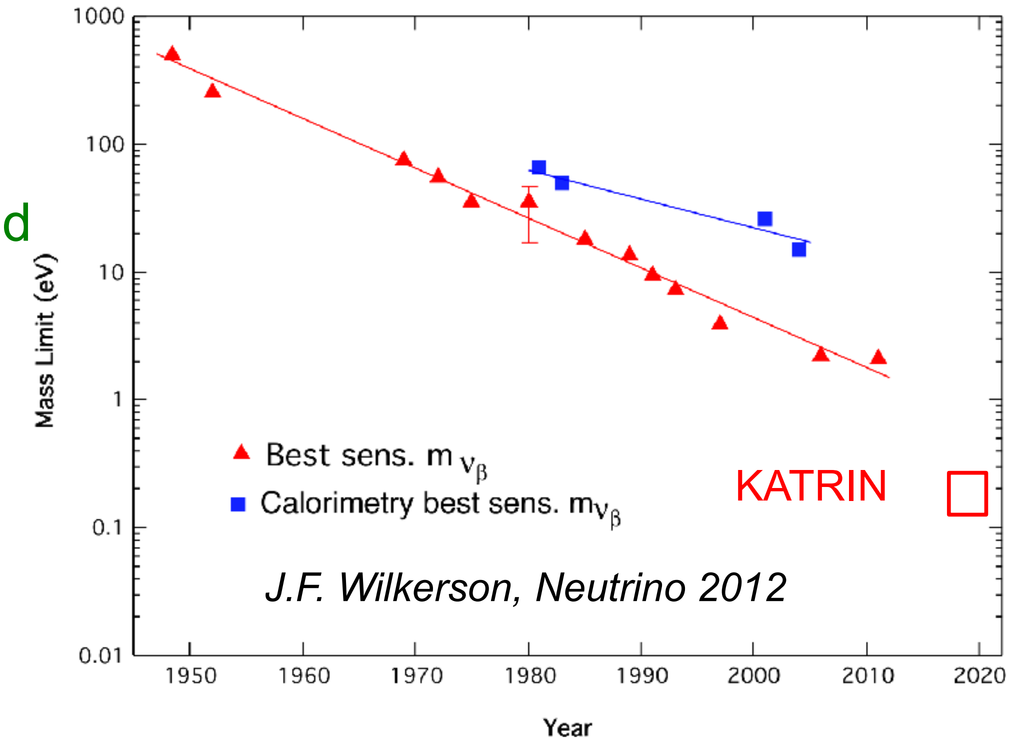
Different ways for a direct neutrino mass measurement from β-decay

- cryogenic bolometers investigating ^{187}Re β-decay (→ MARE)
- cryogenic bolometers investigating ^{163}Ho EC (→ MARE, ECHO)
- tritium β-decay using MAC-E-Filter (→ KATRIN)
- detection of synchrotron radiation (→ Projekt 8)
- …

KATRIN is using a complex
but established method:
→ sensitivity: 2 eV → 200 meV
main spectrometer is being commissioned

Cryobolometers seem to have
a large potential
but need large arrays → multiplexing
what are the systematics ?

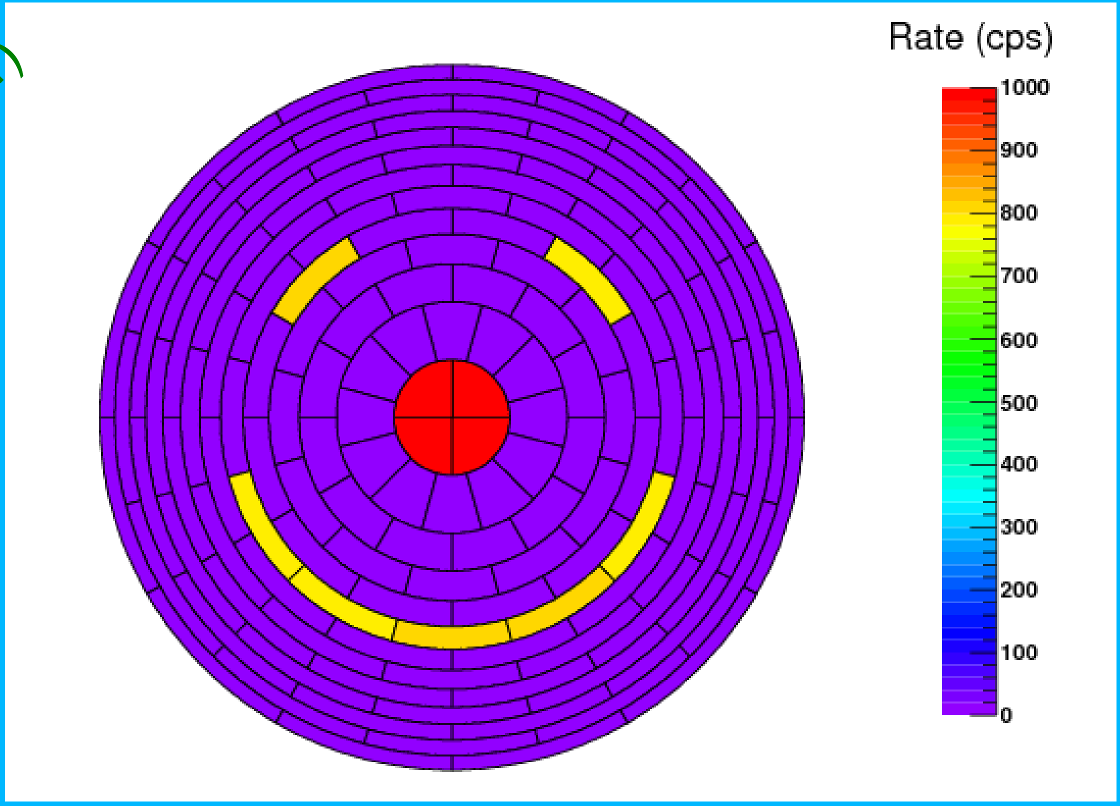
Are alternative methods feasible ?



And finally ...

real data from the KATRIN experiment
(scannable egun + main spectromter + detector)

The KATRIN 148-pixel detector is smiling



when being hit by electrons
from 11 subsequent positions
of the scanning photoelectron source