Direct measurements of neutrino mass

Pontecorvo100 – Symposium in honour of Bruno Pontecorvo for the centennial of the birth
Pisa/Italy, September 18-20, 2013

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Introduction

Direct neutrino mass determination

- Rhenium β decay and EC experiments

- Tritium β decay experiments

The Karlsruhe Tritium Neutrino expeirment KATRIN

- some first data from the main spectrometer and detector commissioning

Summary and Outlook

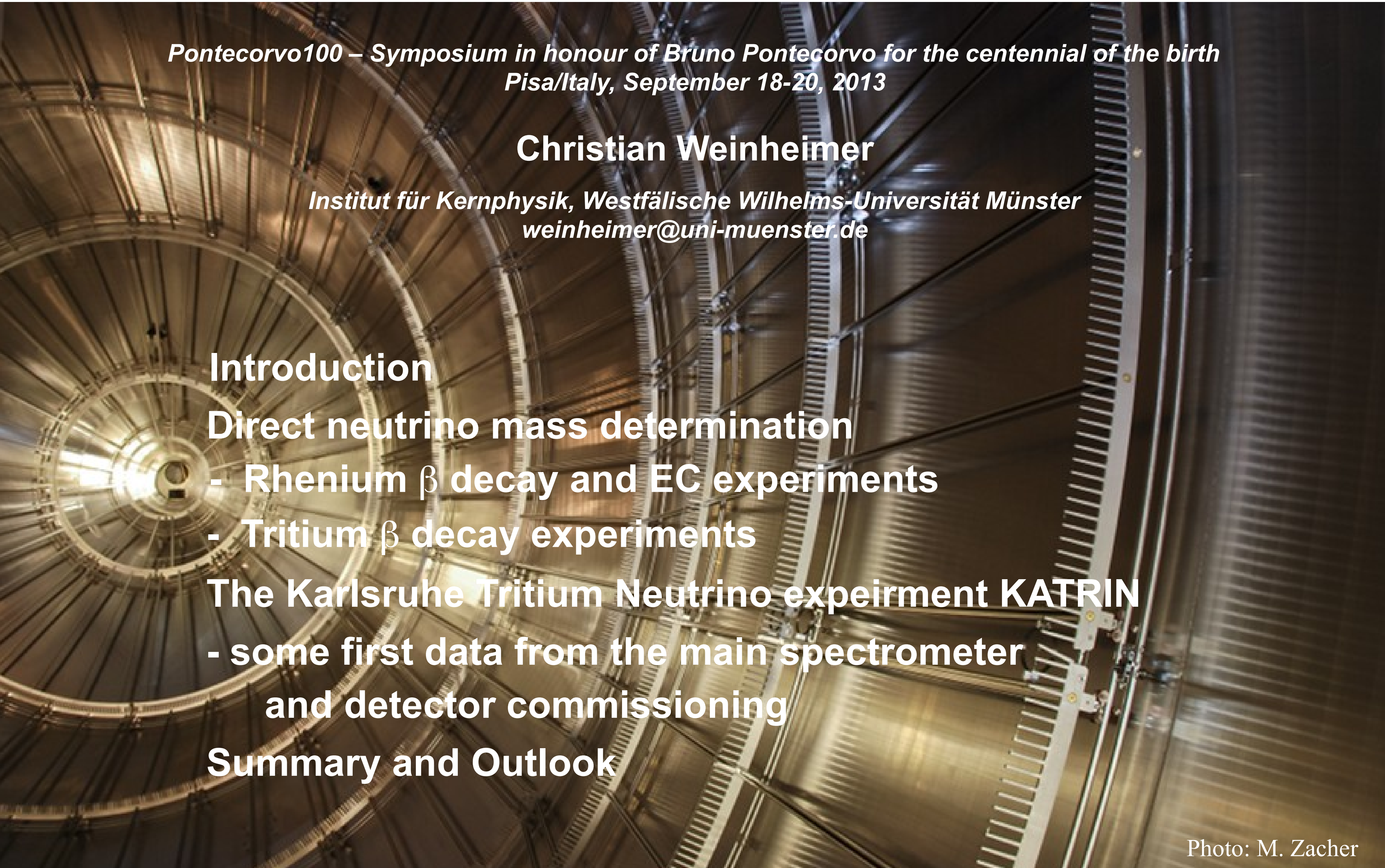


Photo: M. Zacher

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

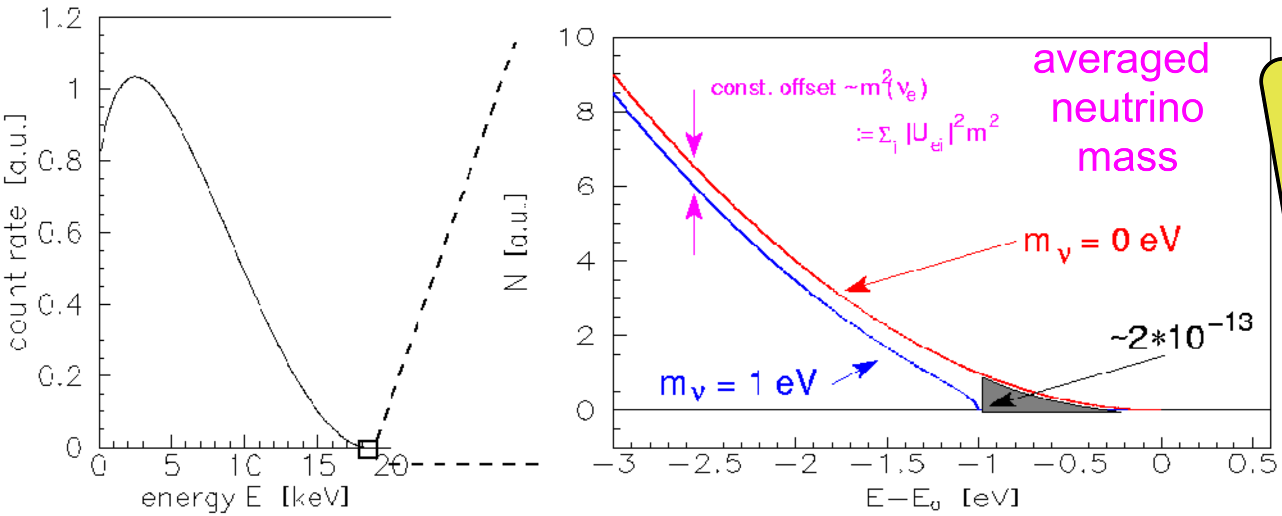
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

β electron energy spectrum:

Complementary to 0νββ and cosmology

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

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



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

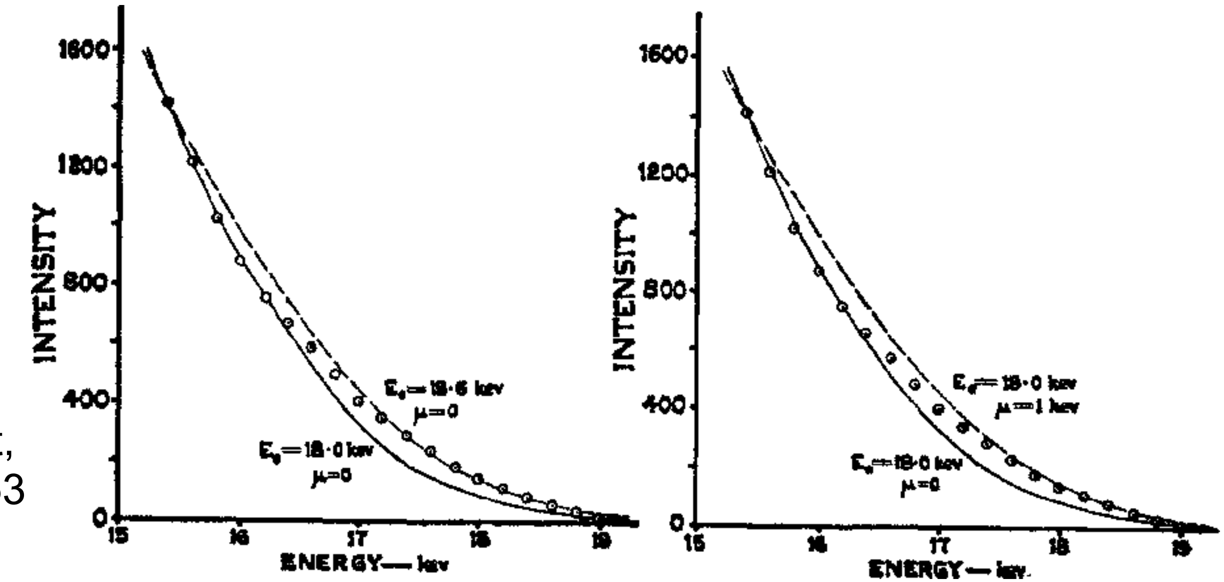
G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, Adv. High Energy Phys., 2013 (2013) 293986

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)**

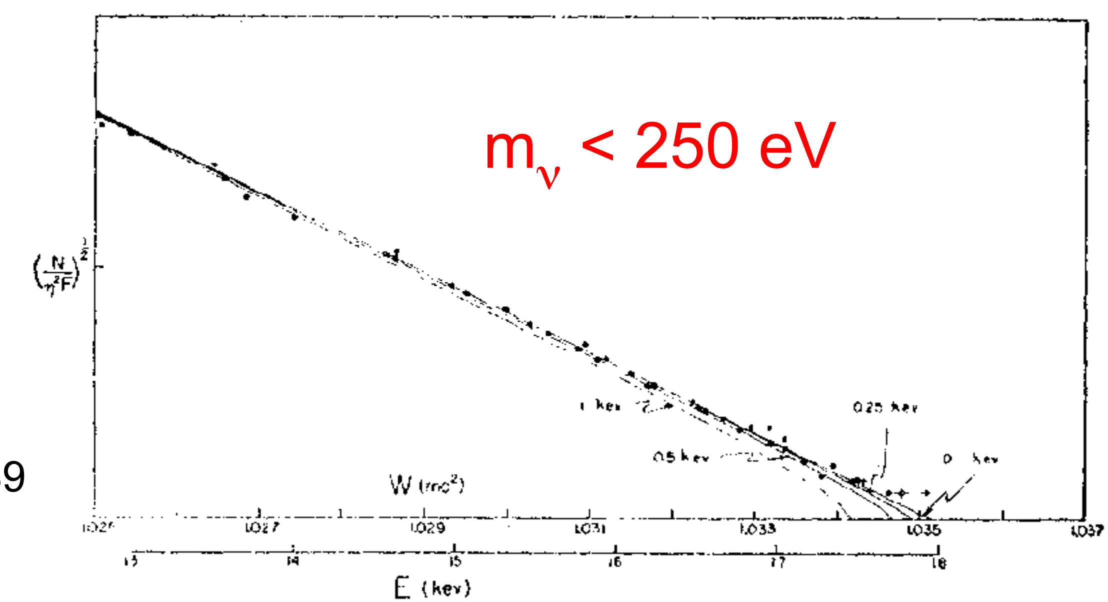
First measurements of the tritium β spectrum searching for the neutrino mass

Tritium β-spectrum measured with proportional counter:



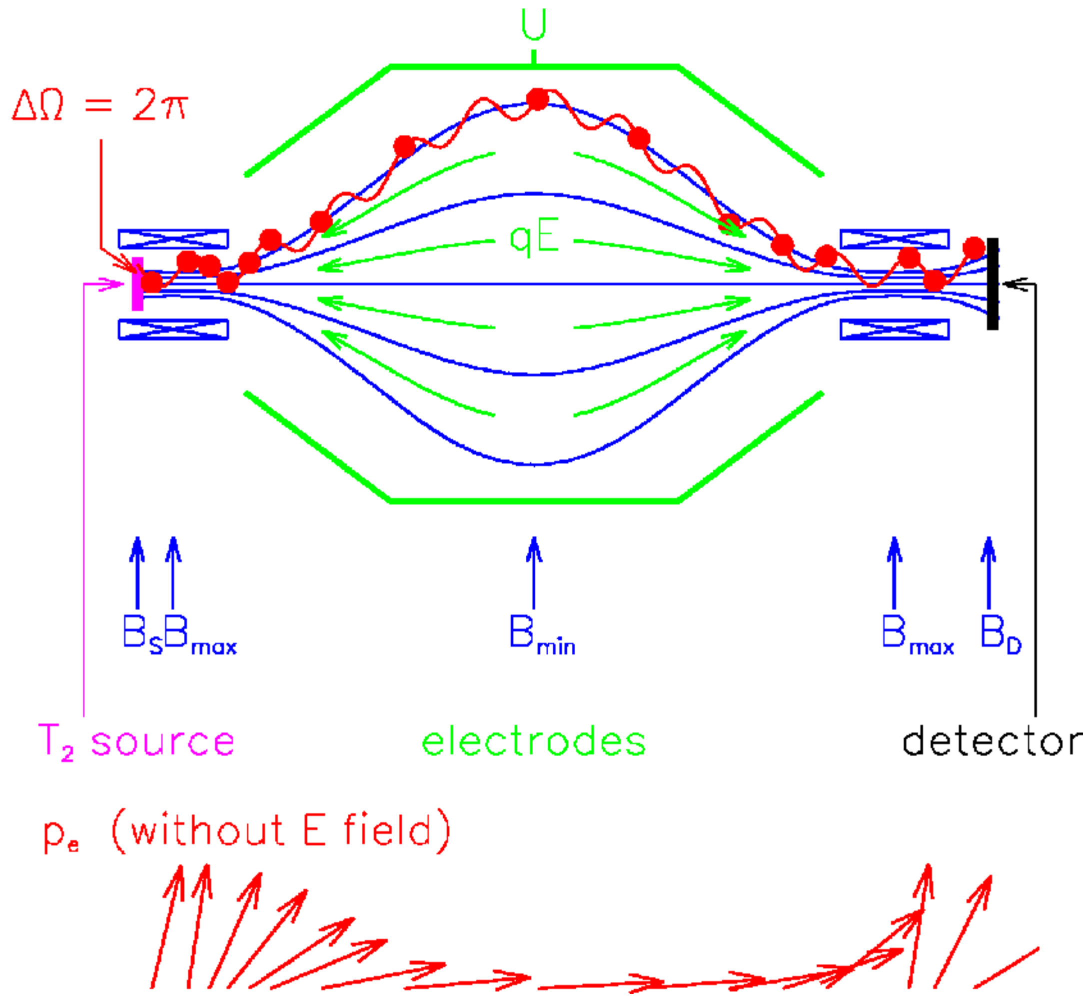
Curran, Angus, Cockroft, Phys. Rev. 76 (1949) 853

Tritium β-spectrums, measured with magnetic spectrometer

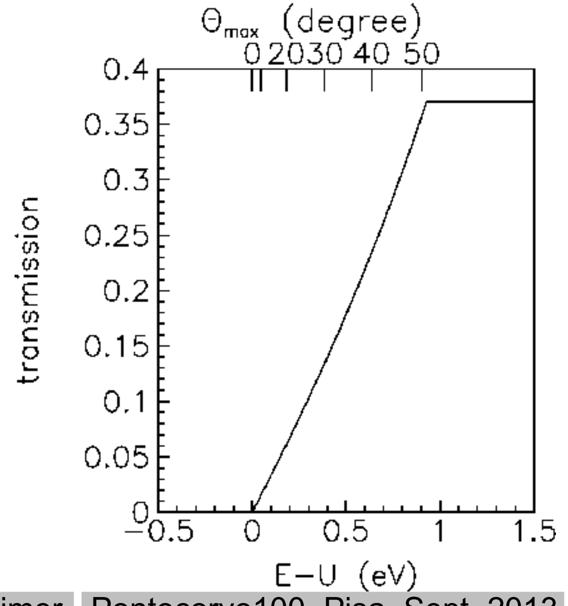


Langer, Moffat, Phys. Rev. 88 (1952) 689

Today's 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 Mainz Neutrino Mass Experiment
Phase 2: 1997-2001

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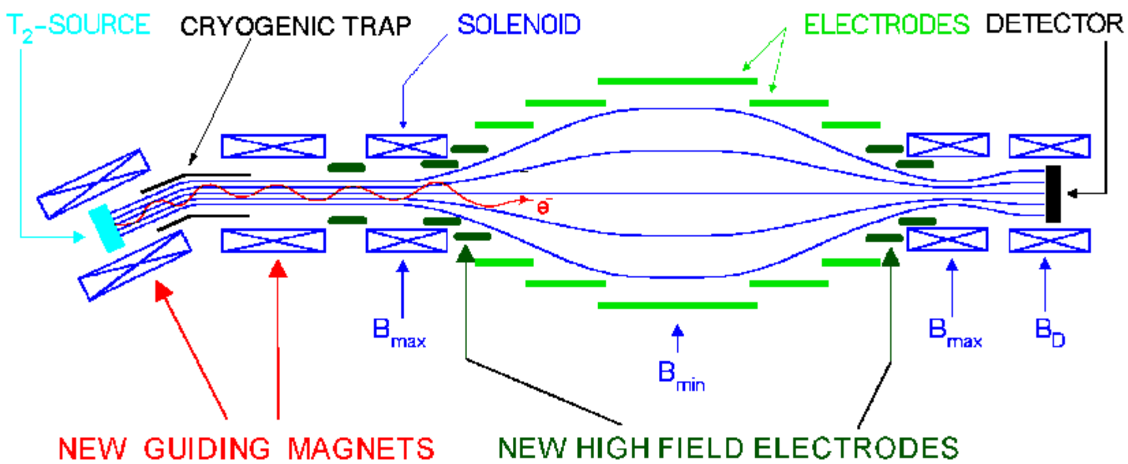

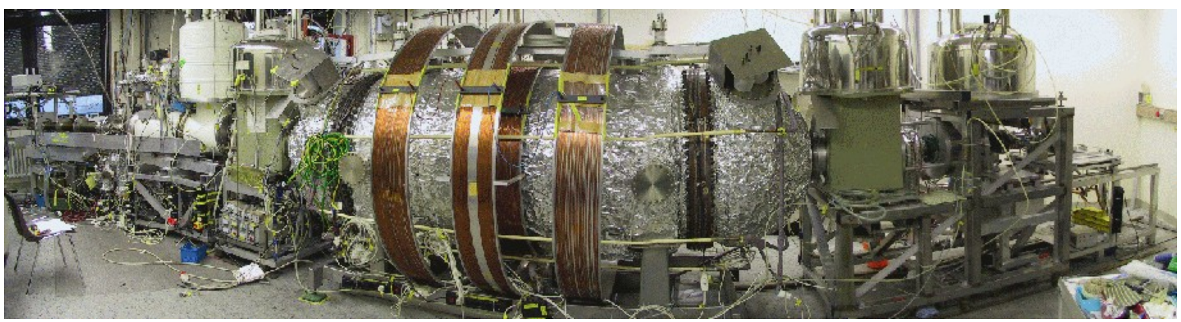

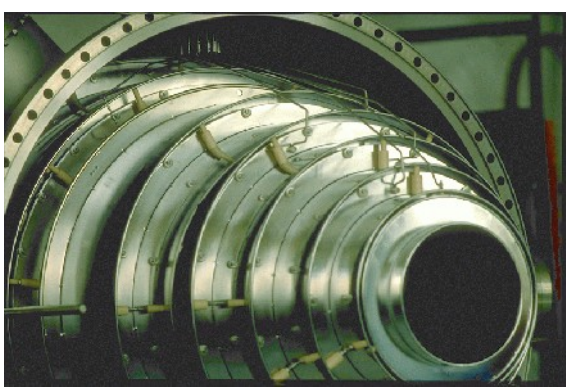

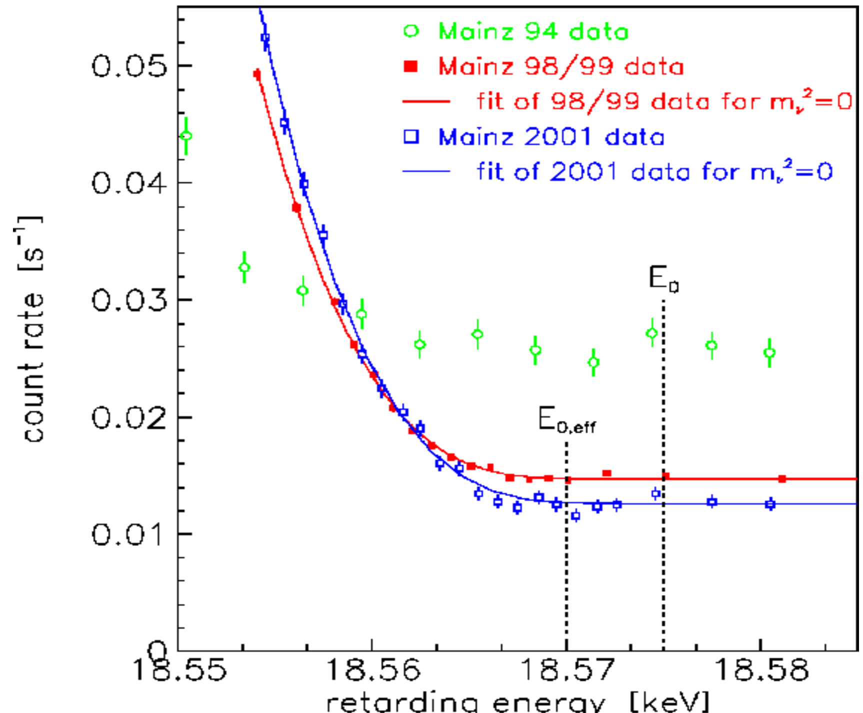

After all critical systematics measured by own experiment (atomic physics, surface and solid state physics:
inelastic scattering, self-charging, neighbour excitation):

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

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

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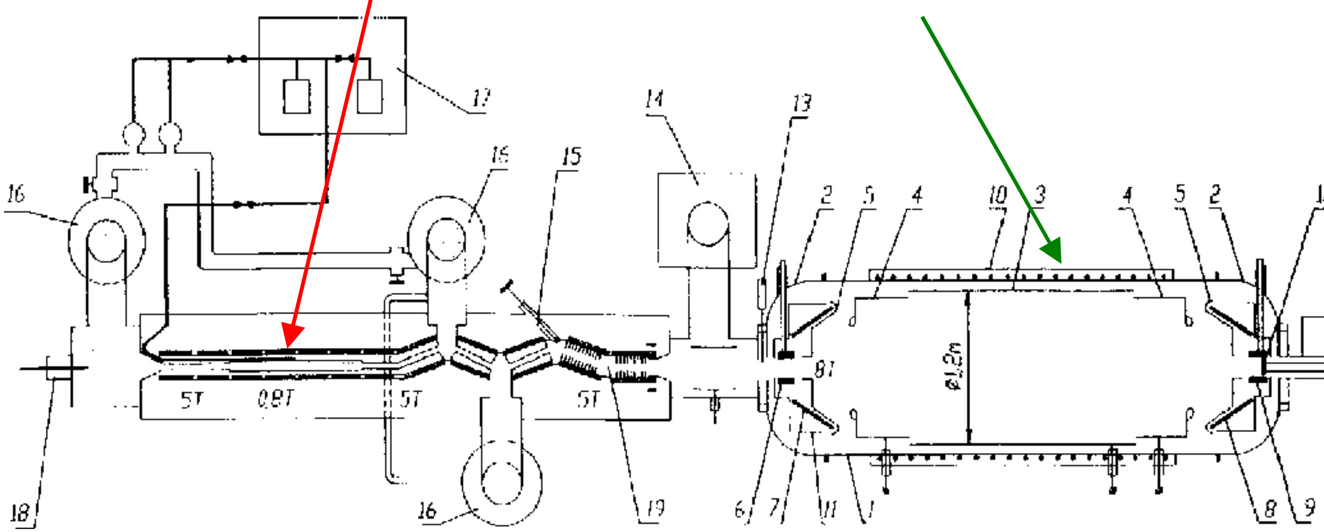
The Troitsk Neutrino Mass Experiment

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

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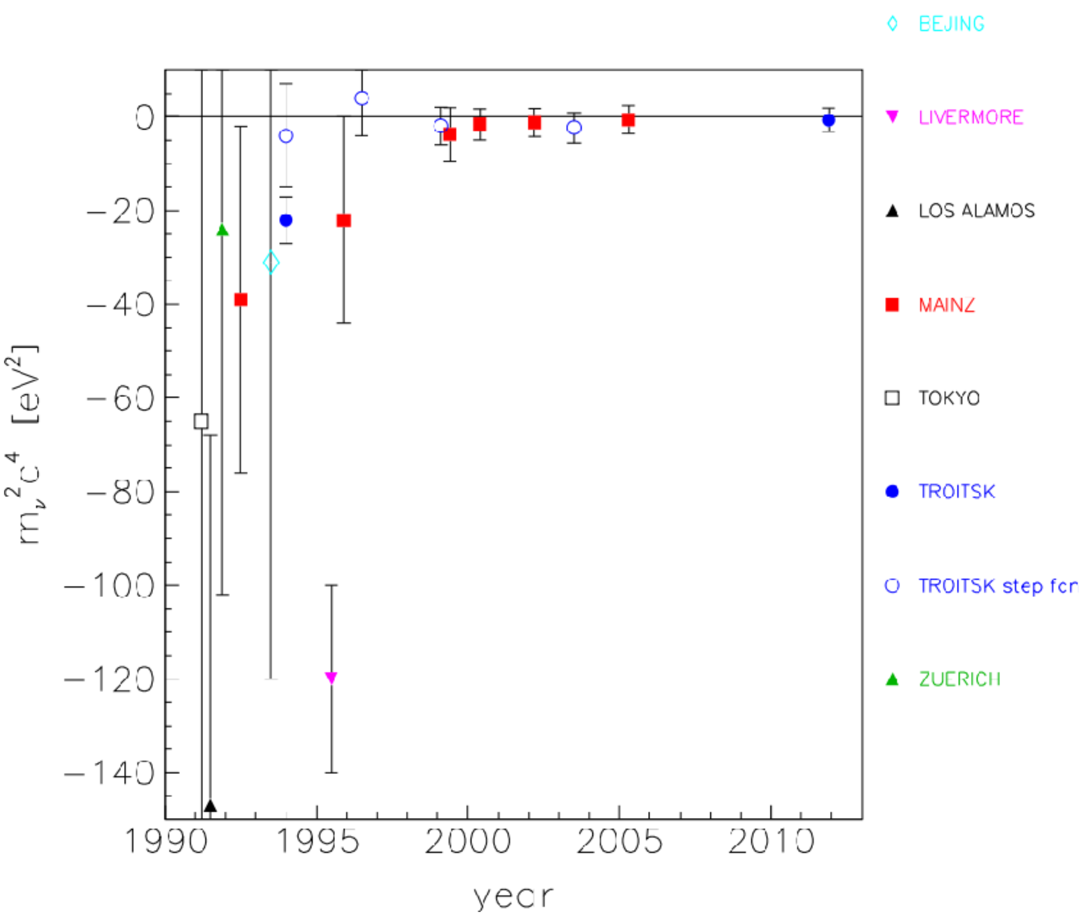
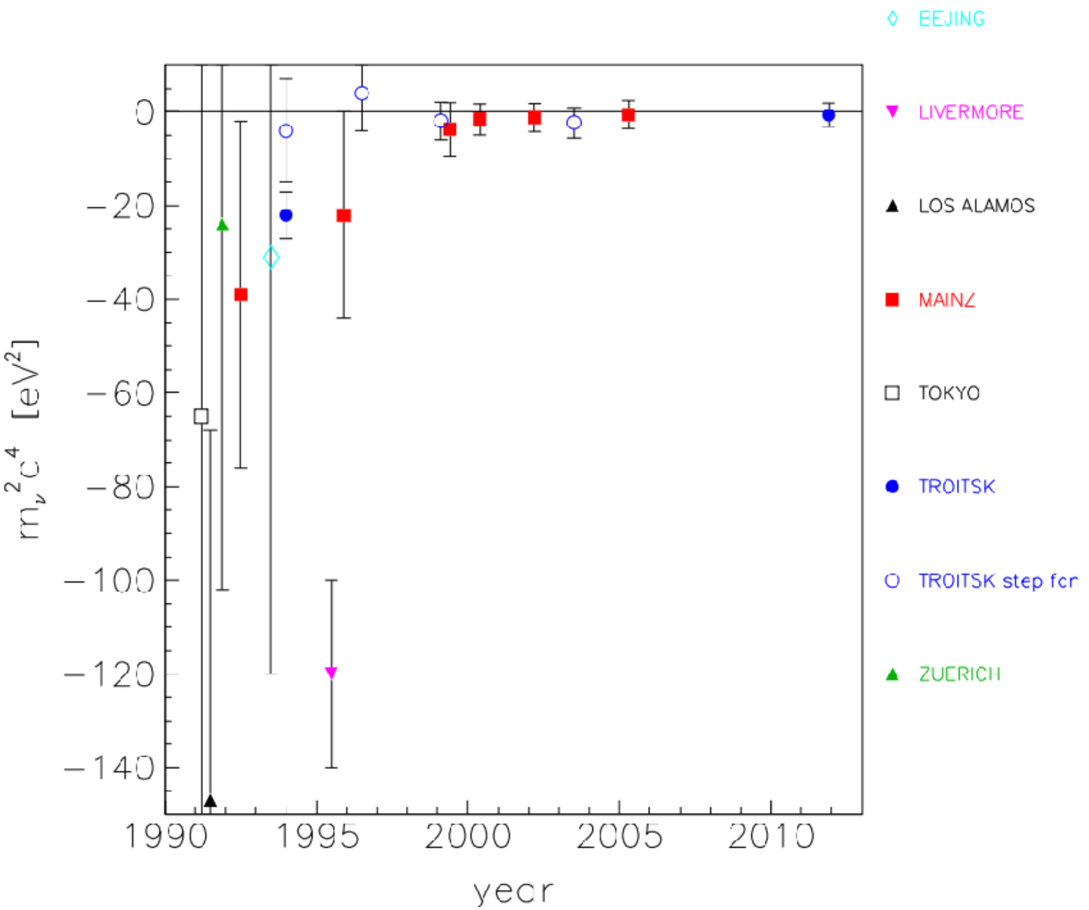
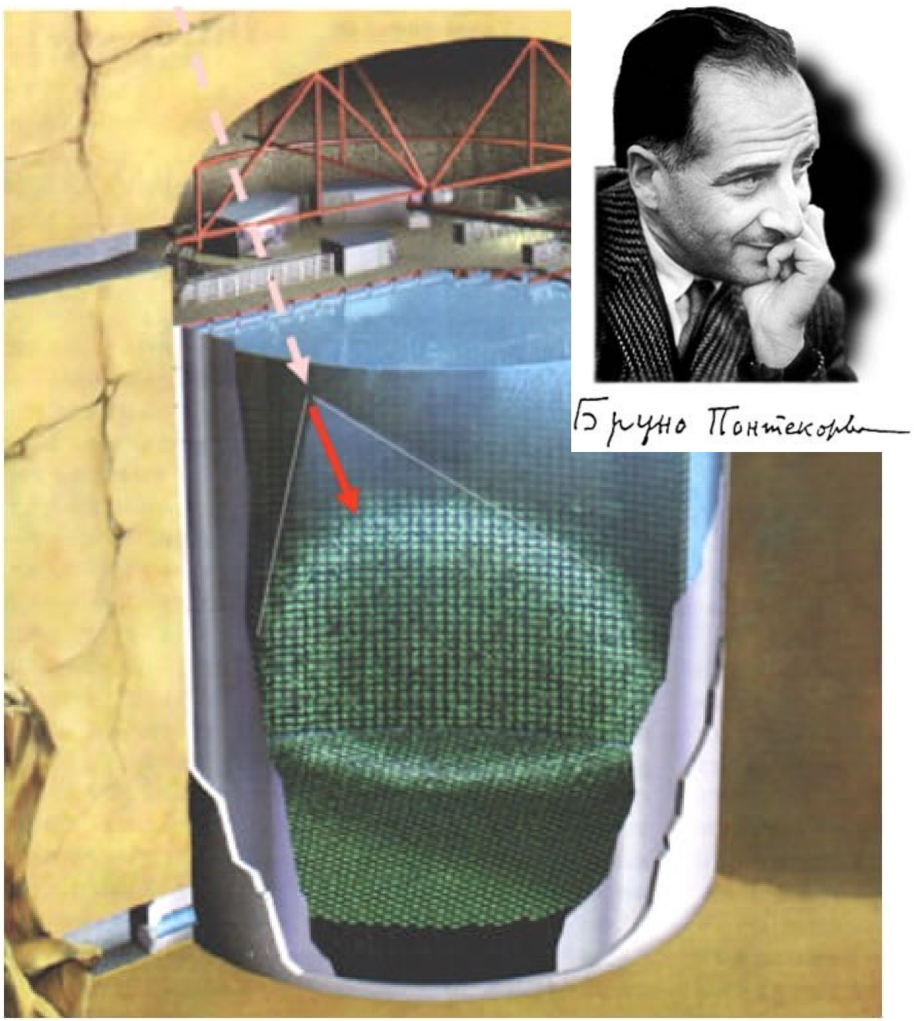
m(ν_e) from tritium β decay



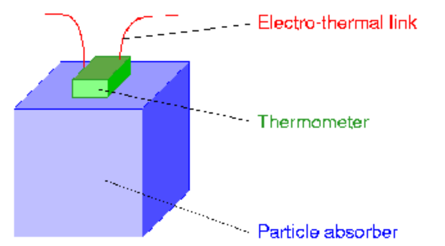
$m(\nu_e)$ from tritium β decay and discovery of neutrino oscillation



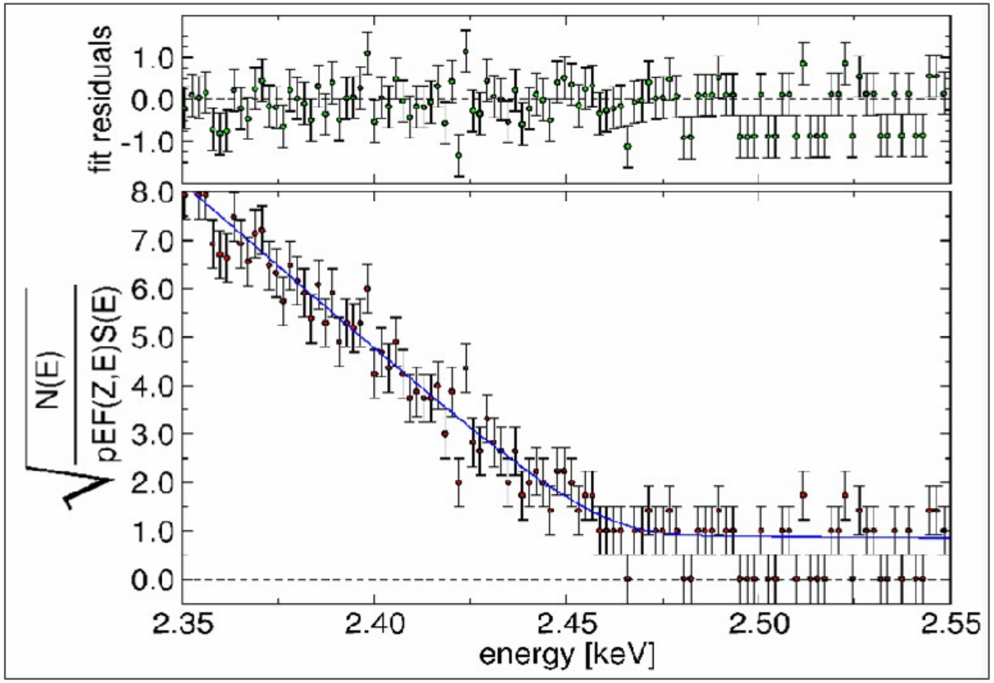


1998: Super Kamiokande detector
discovered oscillation of atmospheric neutrinos
$\rightarrow m(\nu) \neq 0$

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



$\Delta T = \Delta E / C$
Debye:
$C \sim T^3$



Measures all energy except that of the neutrino

detectors: 10 ($AgReO_4$)

rate each: 0.13 1/s

energy res.: ΔE = 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

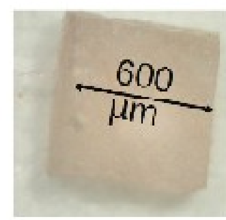
MARE-2 aims for 10^4 to 10^5 detectors with much more advanced time & energy resolution

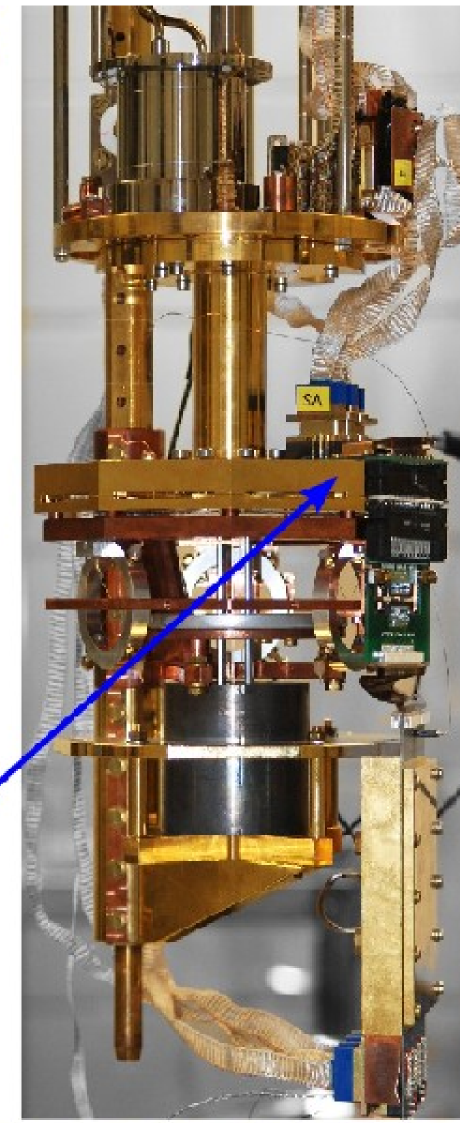
MARE-1 @ Genova

- 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

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



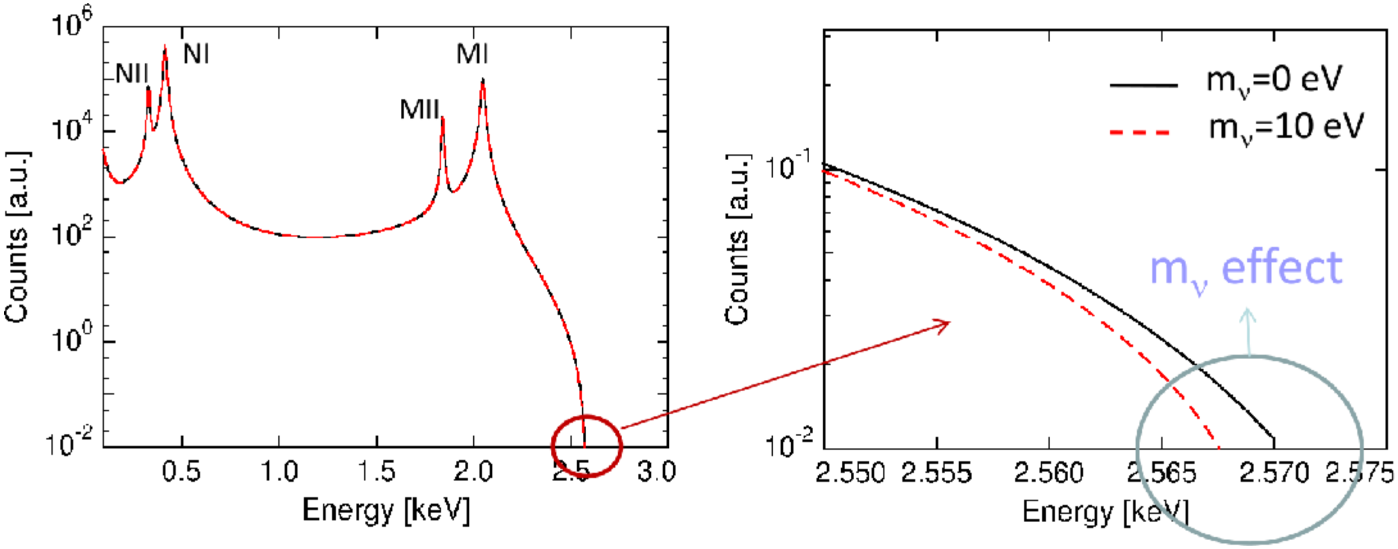


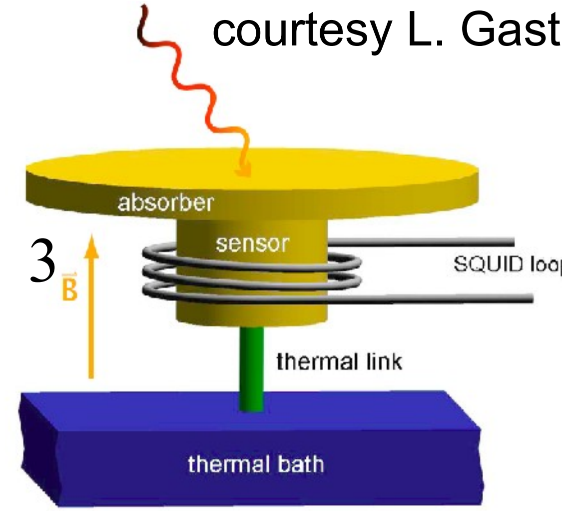
Angelo Nucciotti, Meudon 2011

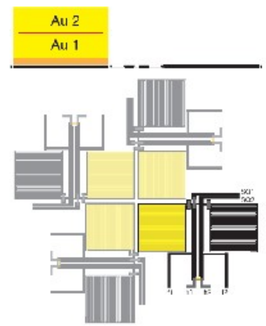
ECHO neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

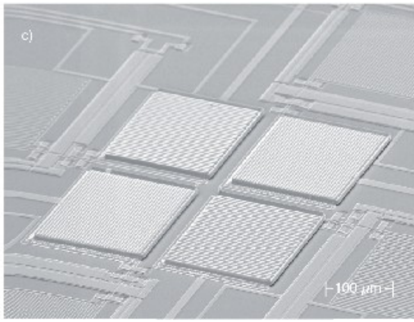
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$$

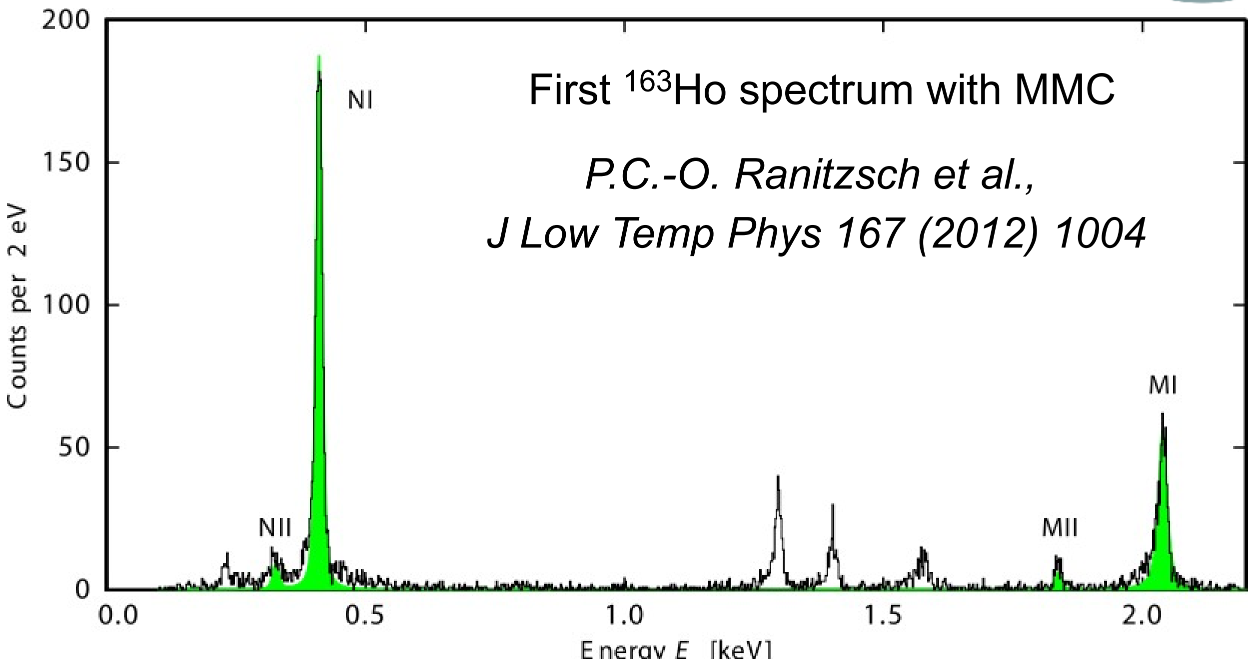
courtesy L. Gastaldo











other cryo-bolometer projects with EC(^{163}Ho) as well: MARE, Holmes, ...

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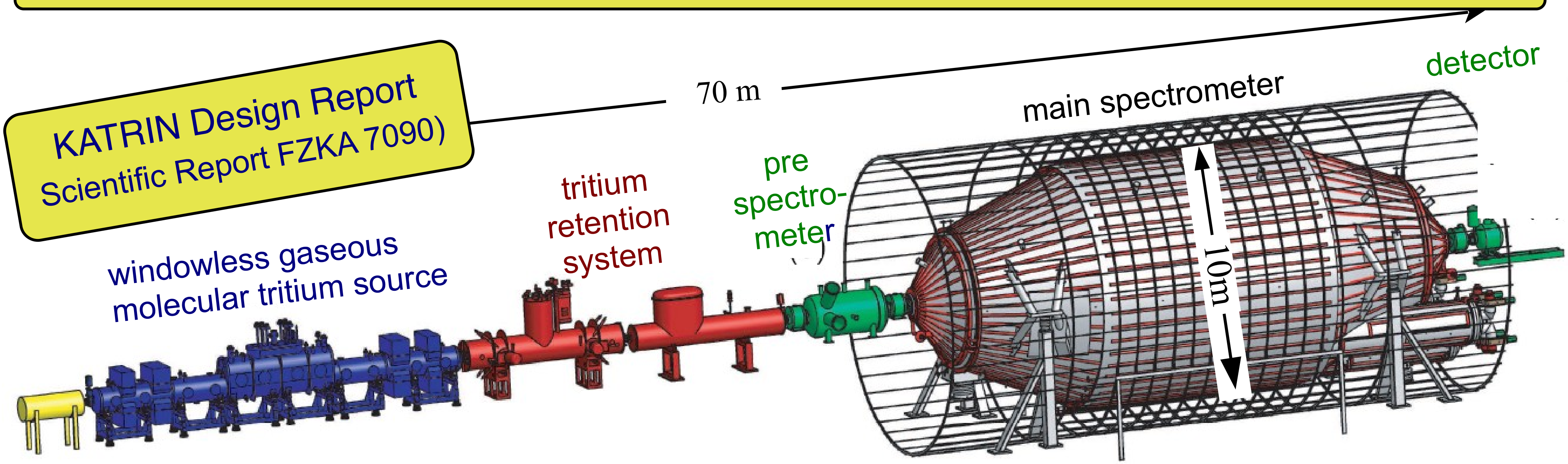
The KATRIN experiment at KIT

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) ⇒ source ≠ spectrometer concept
- strong, opaque source ⇒ $dN/dt \sim A_{source}$
- magnetic flux conservation (Liouville) ⇒ 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

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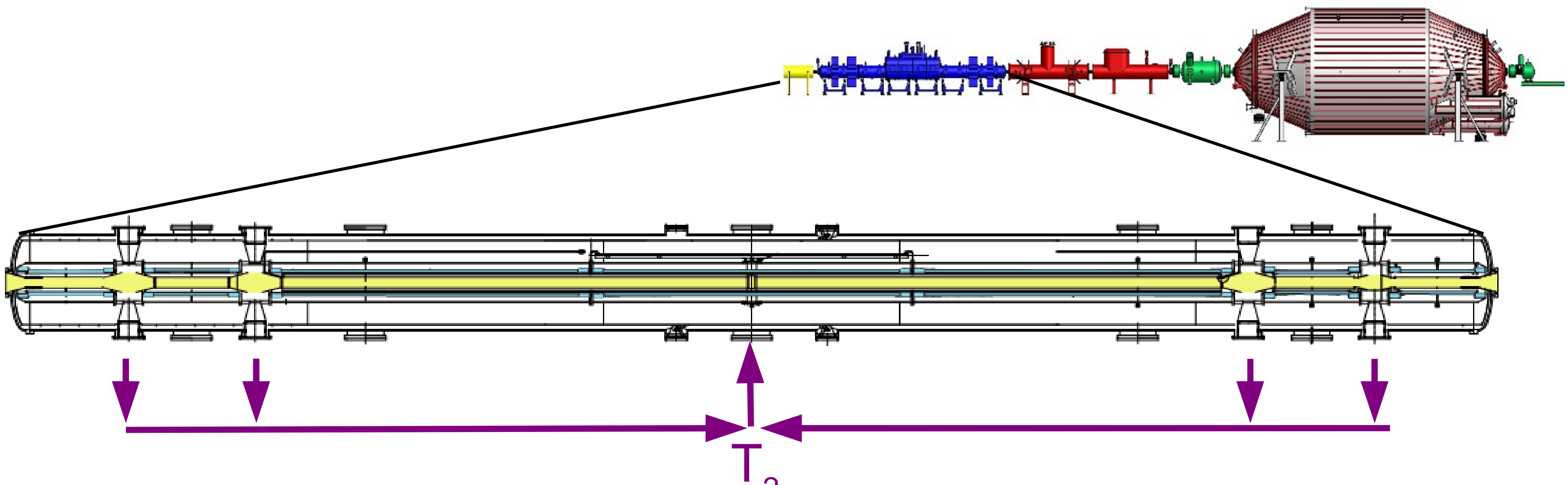
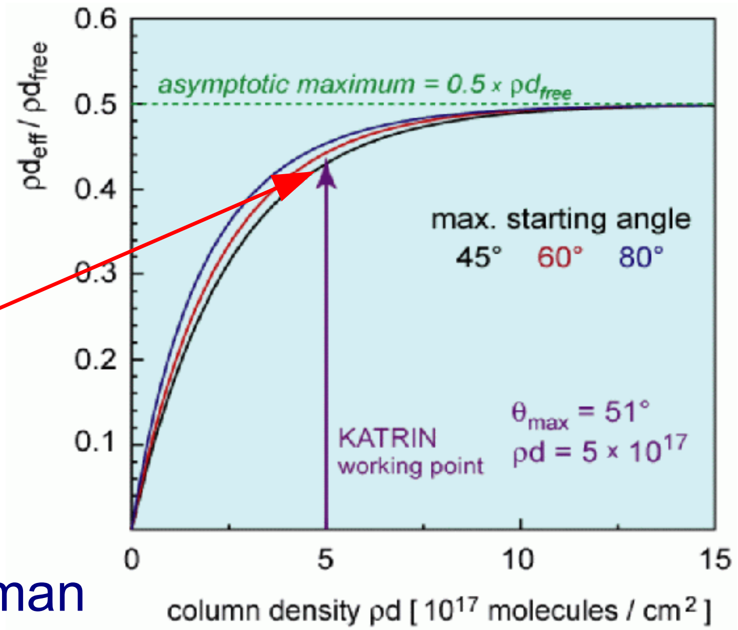


WGTS: tub in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

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

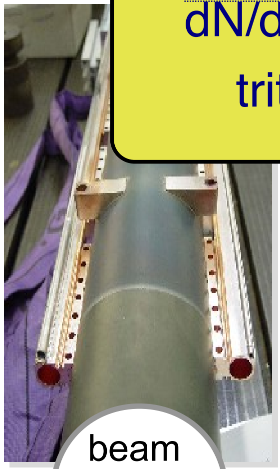
allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics



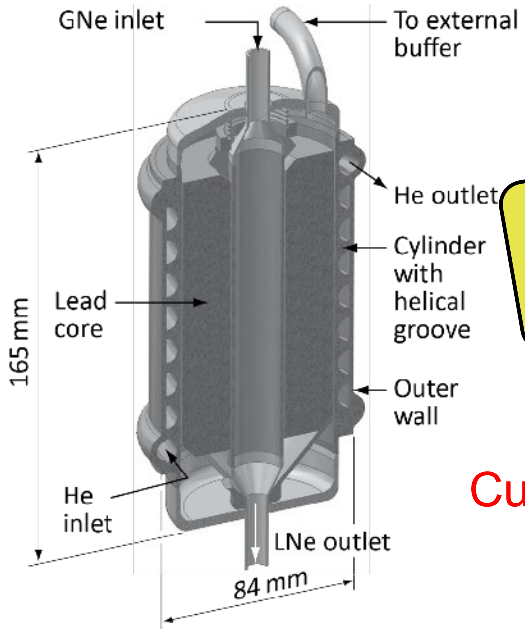
check column density by e-gun, T_2 purity by laser Raman

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

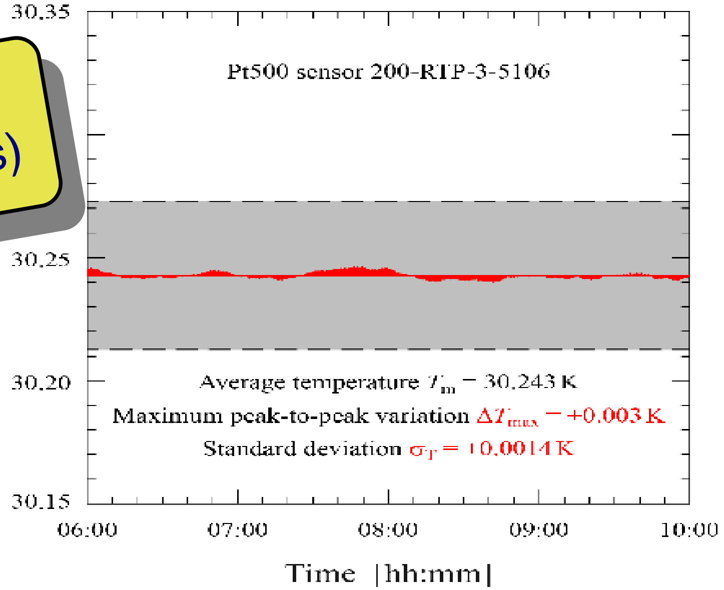
per mill stability source strength request:
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \, V / R \, T$
tritium fraction f_T & ideal gas law



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

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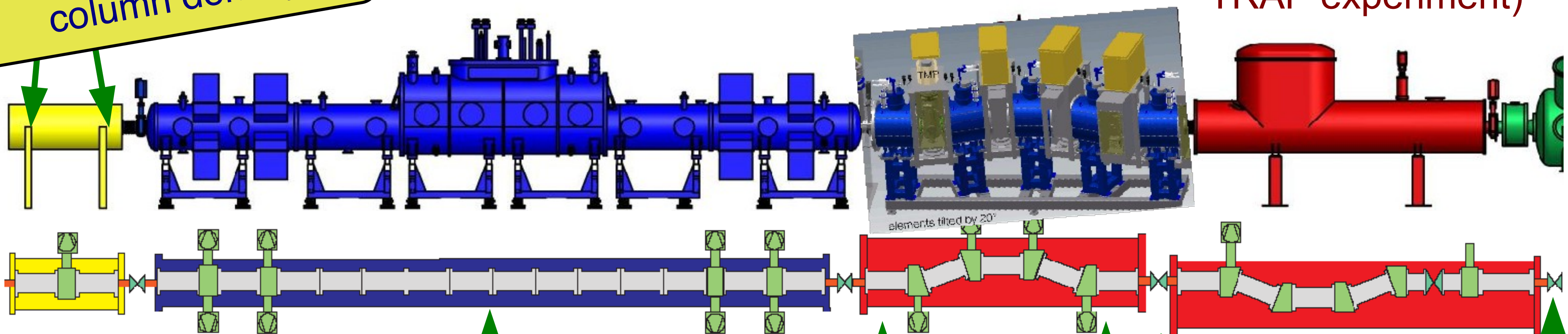
Transport and differential & cryo pumping sections

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*10^{11} Bq/s = 40 g/d

FT-ICR Penning traps to measure ions from WGTS

≈ 10^{-7} mbar l/s

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

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

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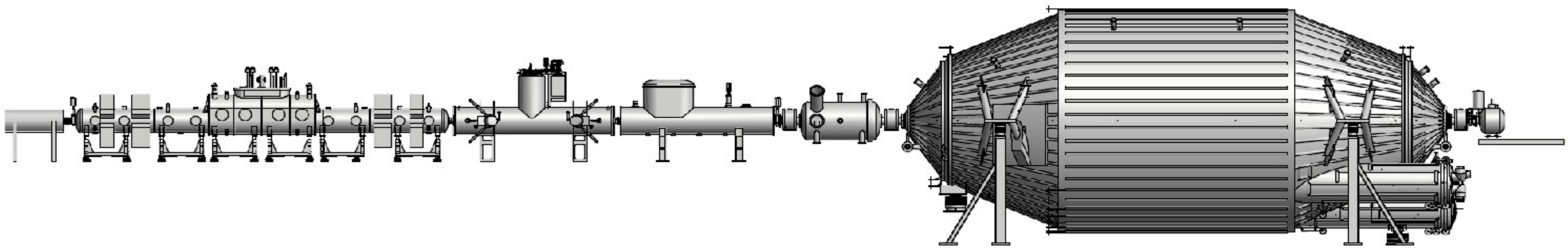
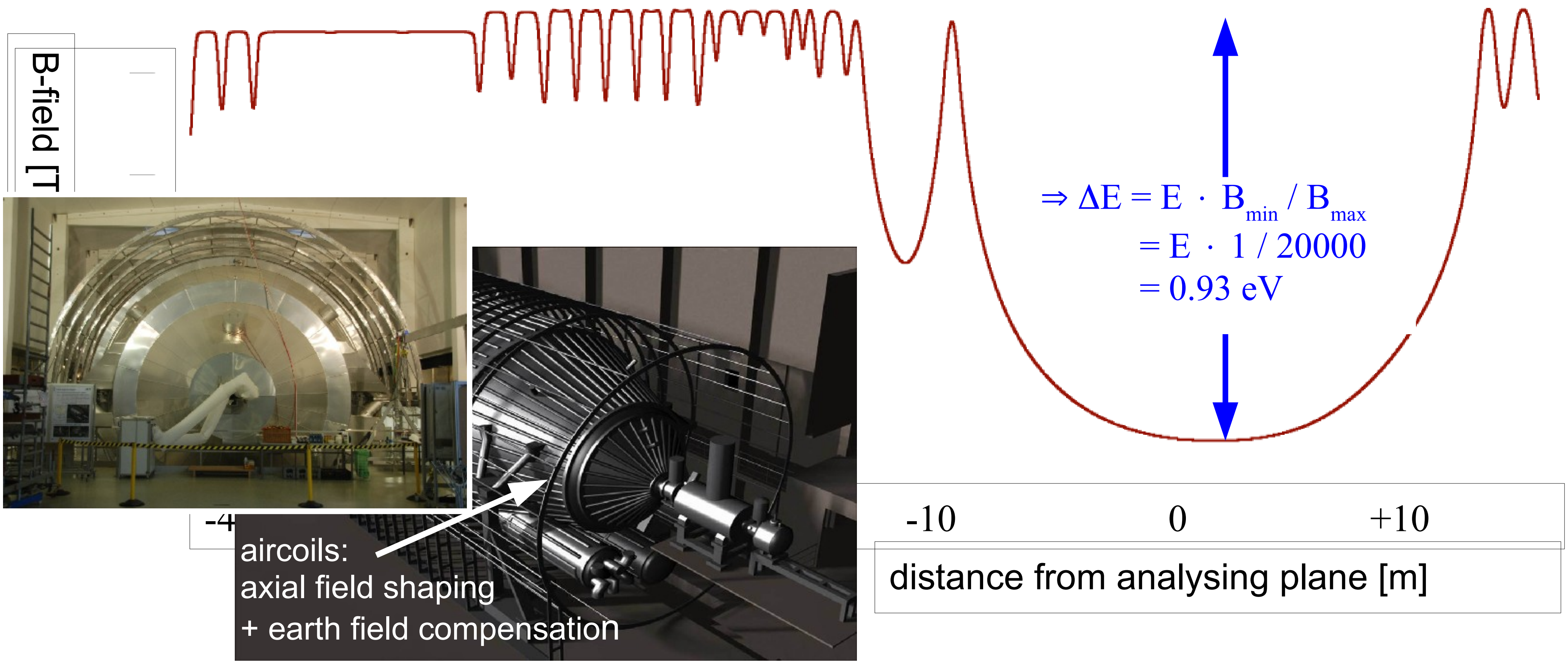
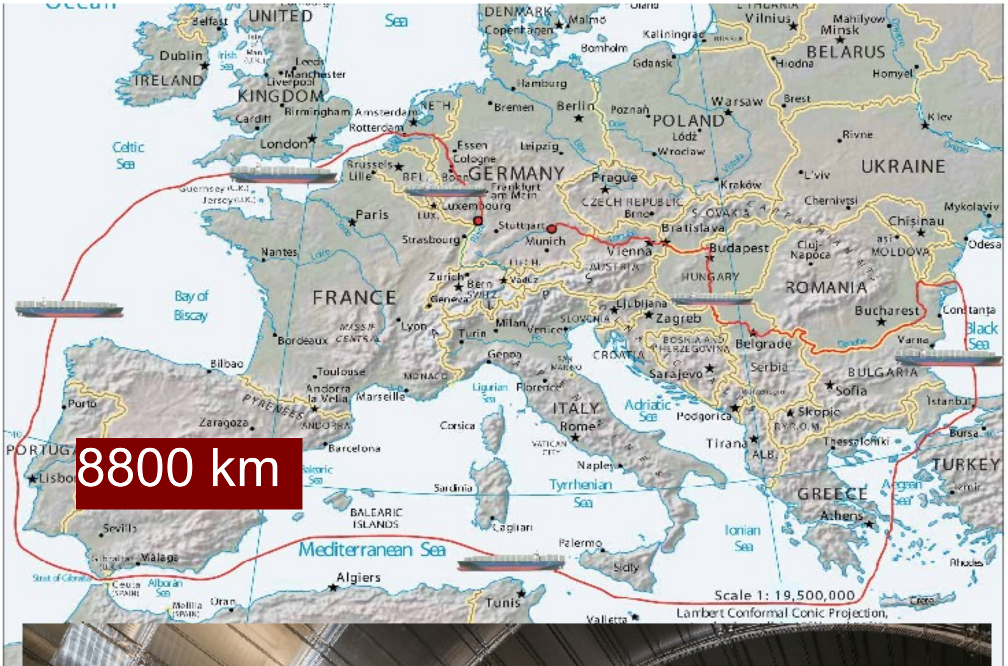
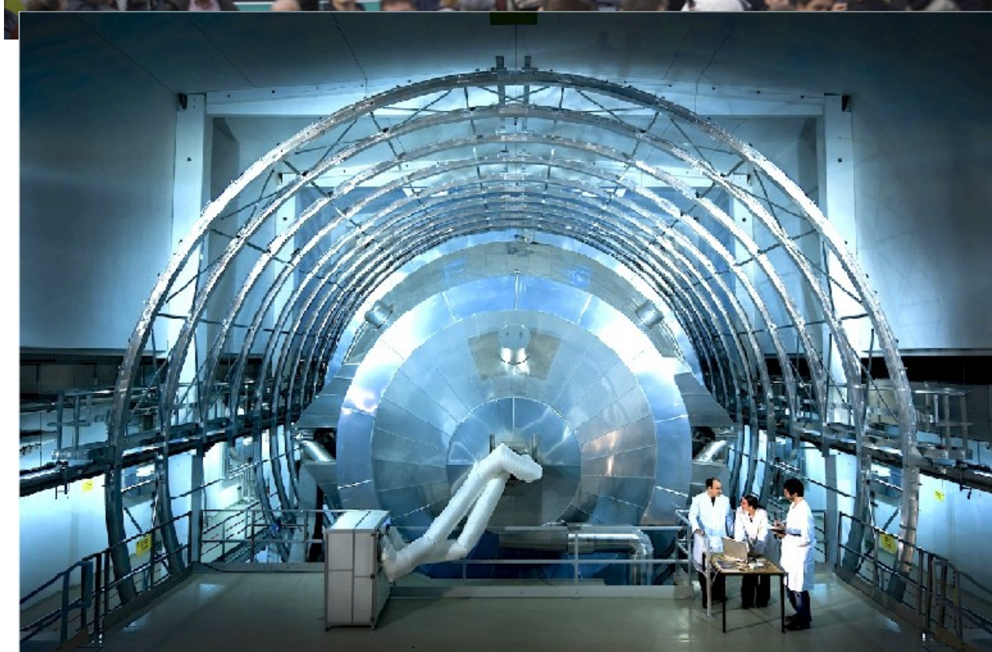
Electromagnetic design: magnetic fields





Main Spectrometer





Suppress secondary electron background from walls on high potential

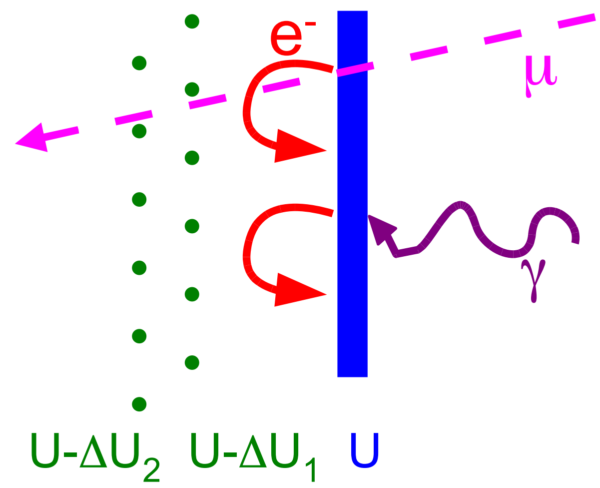
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

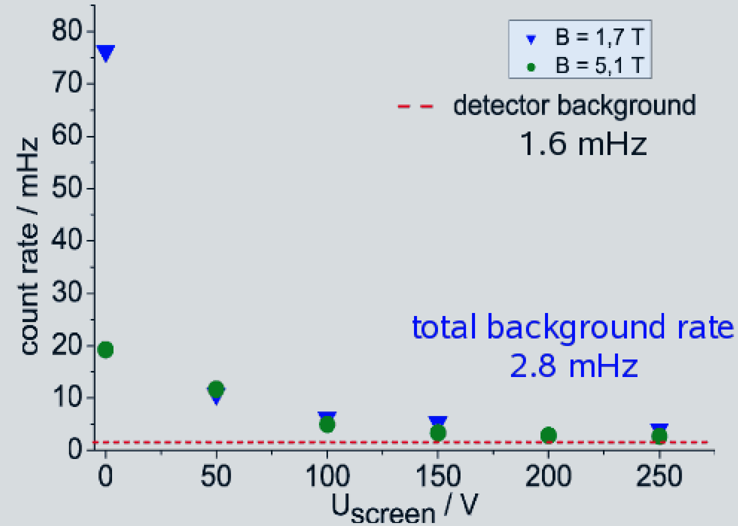
New: double layer wire electrode

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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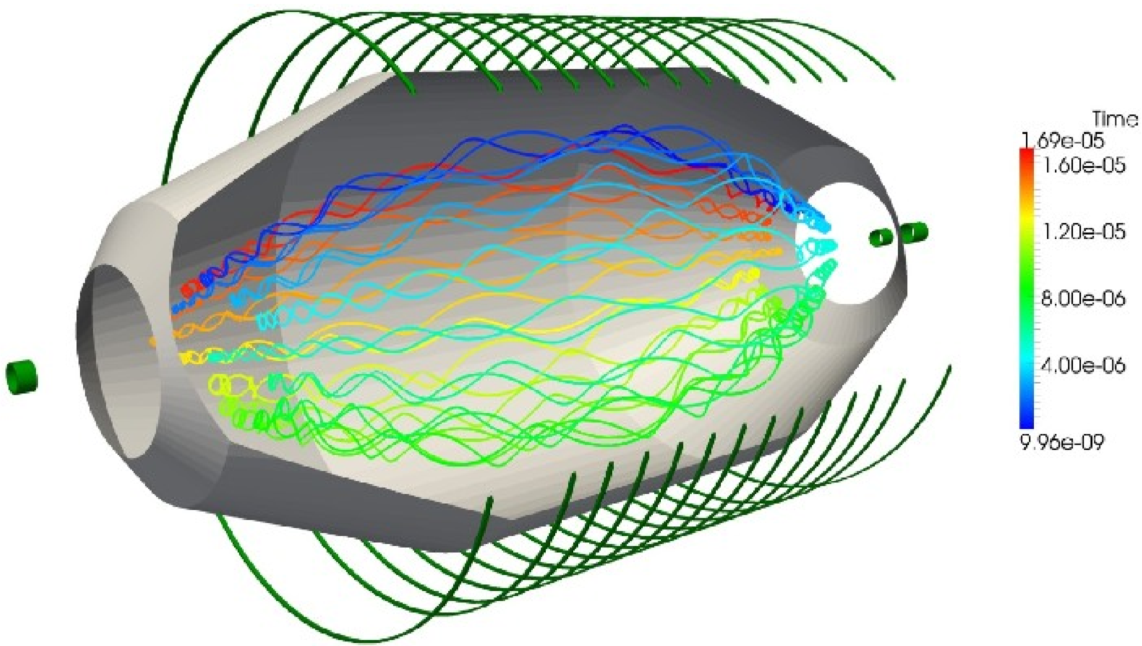
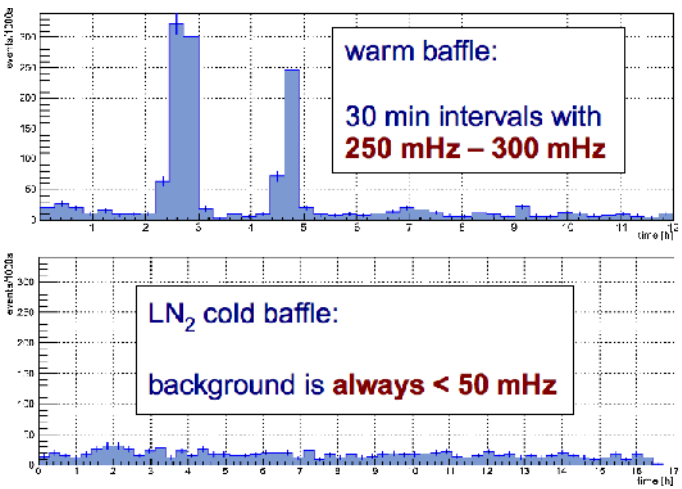
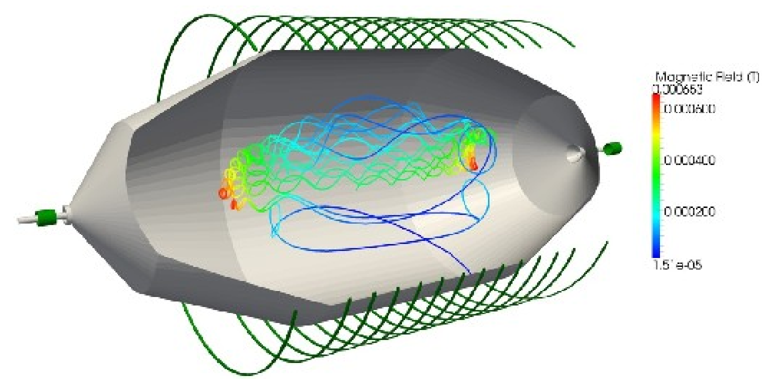
Stored electron by magnetic mirrors
F. Fränkle et al., Astropart. Phys. 35 (2011) 128



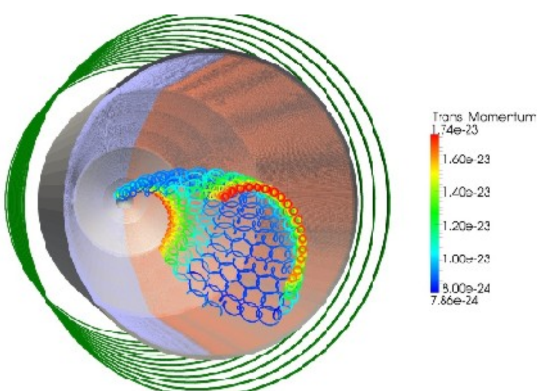
Radon suppression by LN_2 cooled baffle
S. Görhardt, diploma thesis, KIT

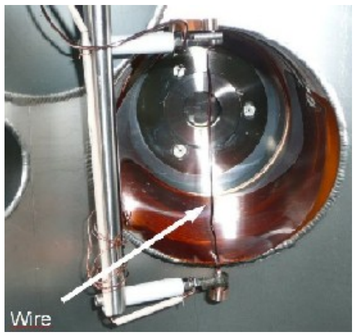


Nulling magnetic field by magn. pulse
B. Hillen, PhD thesis, Münster



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

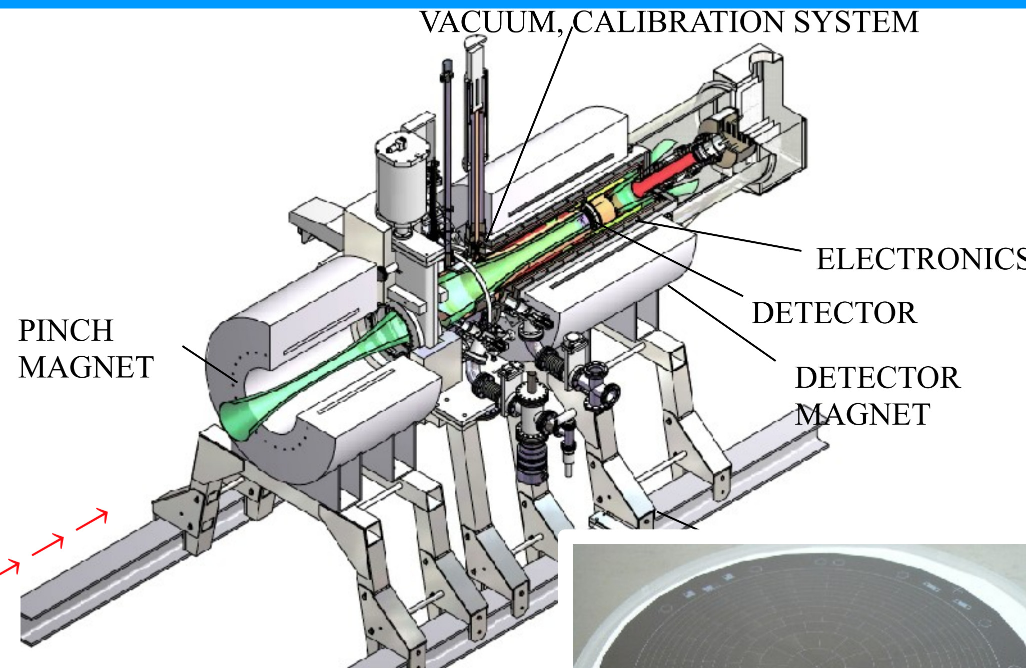
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  (passive and active shielding)
- good energy resolution (< 1 keV)

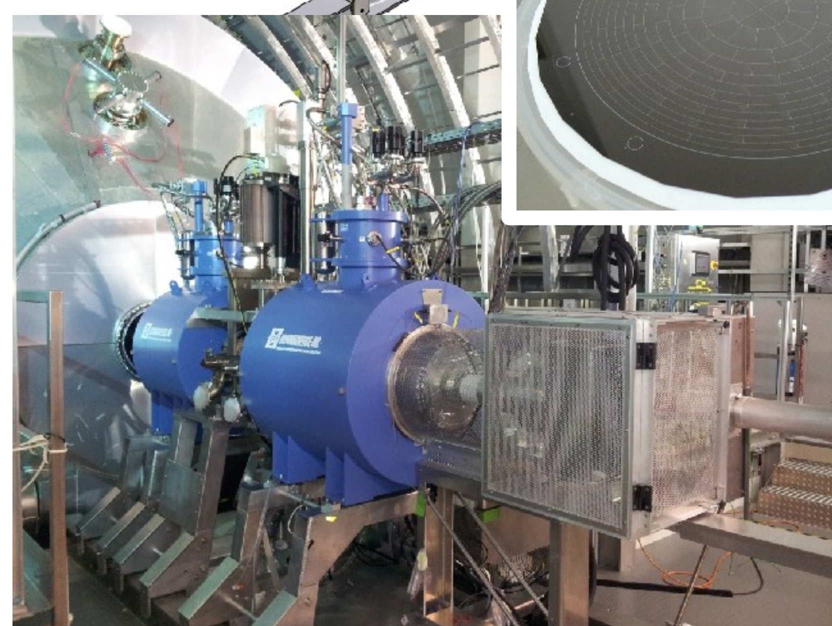
Properties

- 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

electrons → → →





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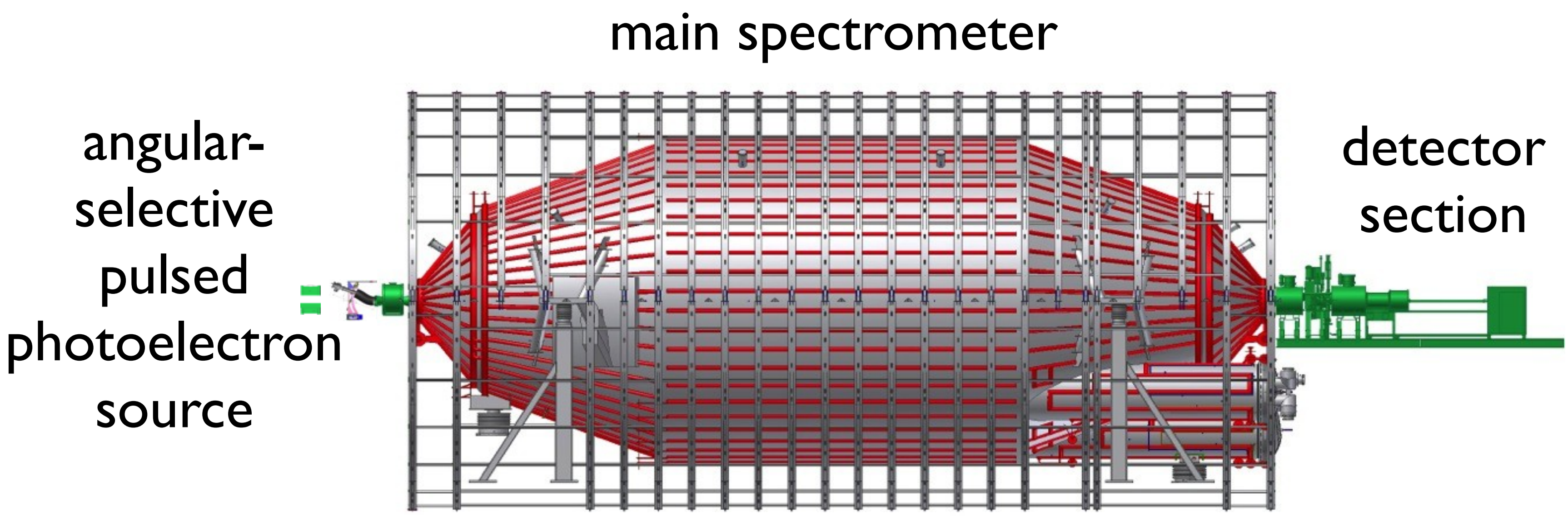
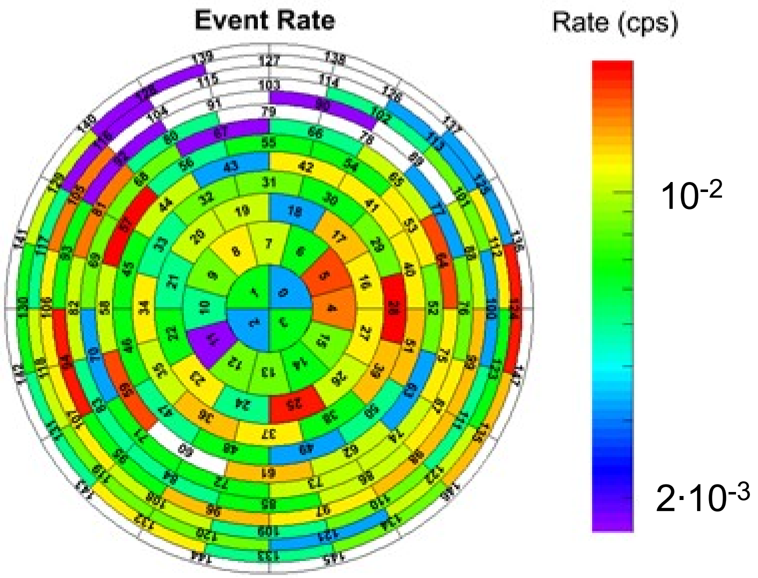
SDS commissioning - objectives

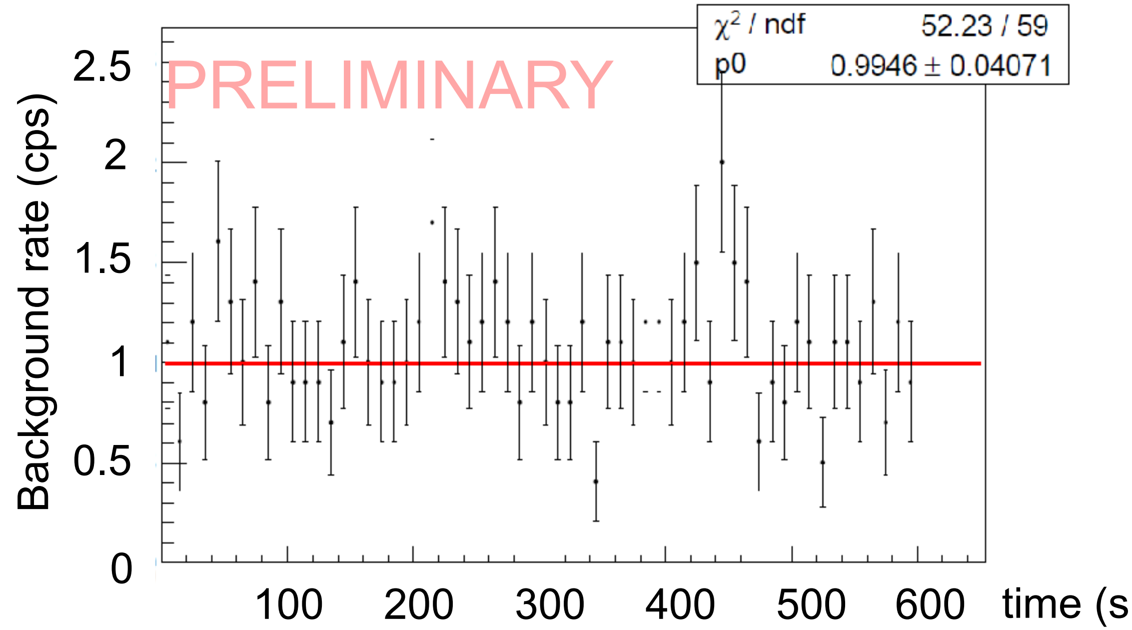


Primary objectives:

- 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 ΔE = 0.93 eV resolution) and compare to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes

First switch on with full high voltage on August 13/14, 2013





Could switch on main spectrometer without large background rate

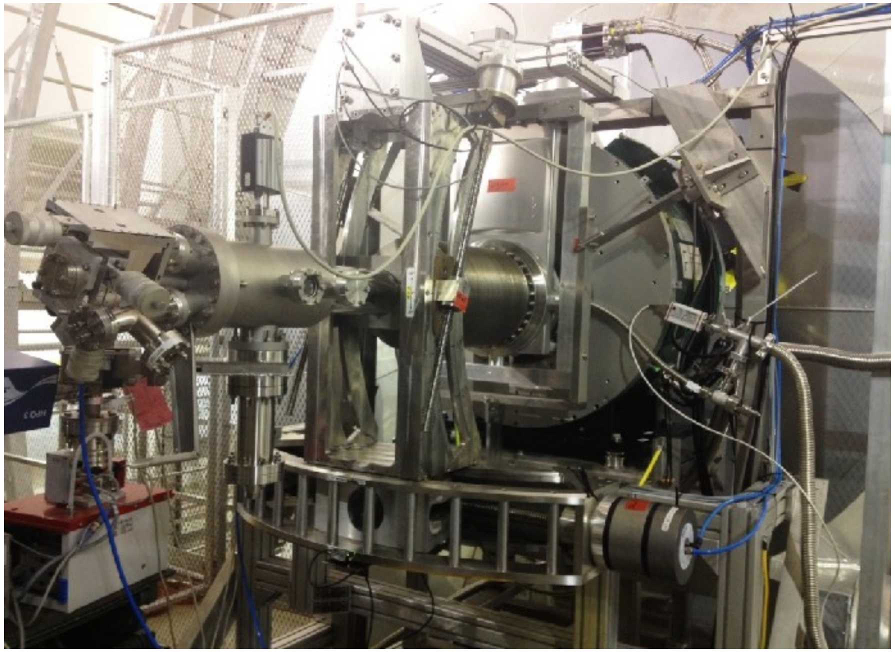
all other MAC-E-Filters (Troitsk, Mainz, KATRIN pre spectrometer) exhibited rates > 10^5 cps when switched on for the first time

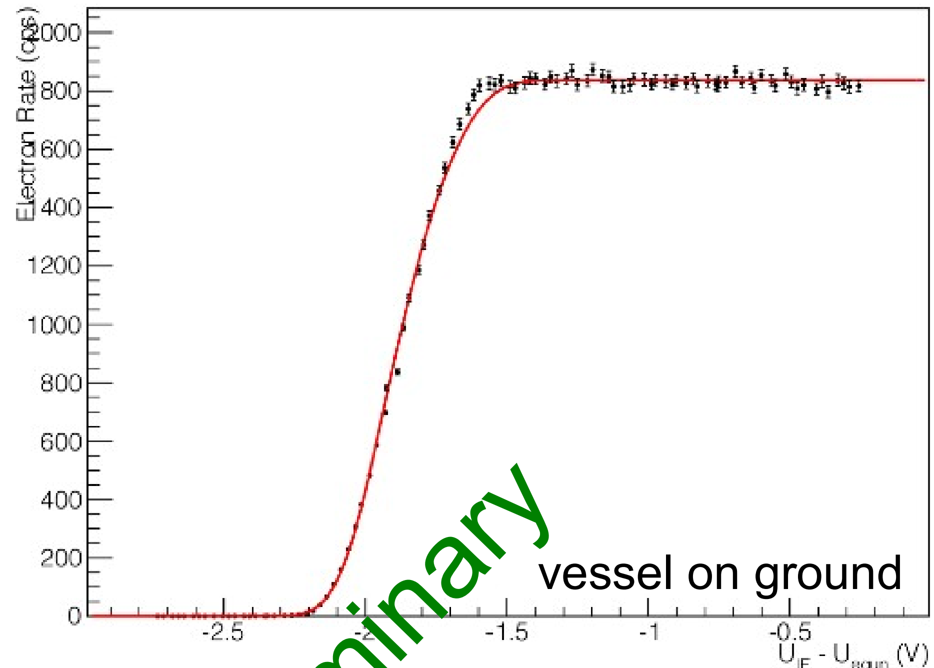
→ **No large Penning traps (advanced KATRIN design works)**

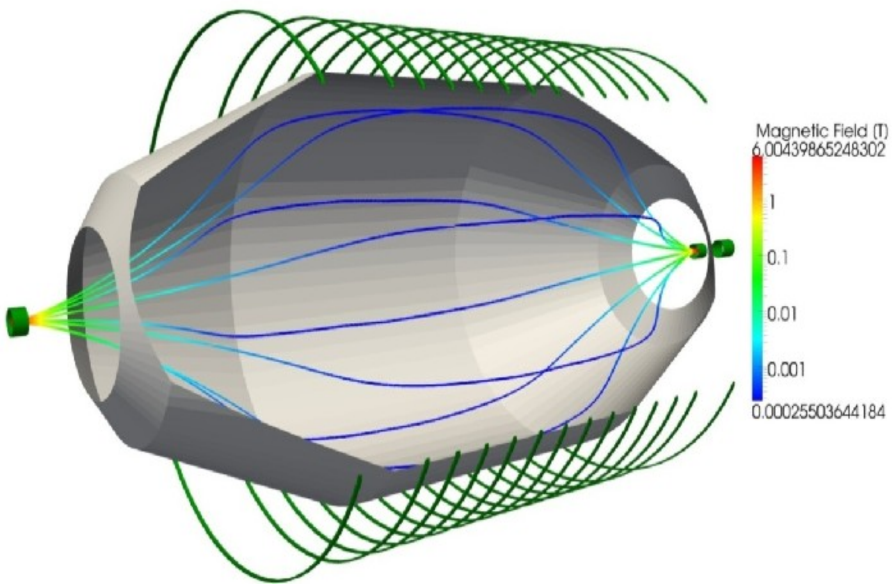
This first measurement without wire electrode on screening potential, LN_2 baffles cold and active counter measures against stored electrons

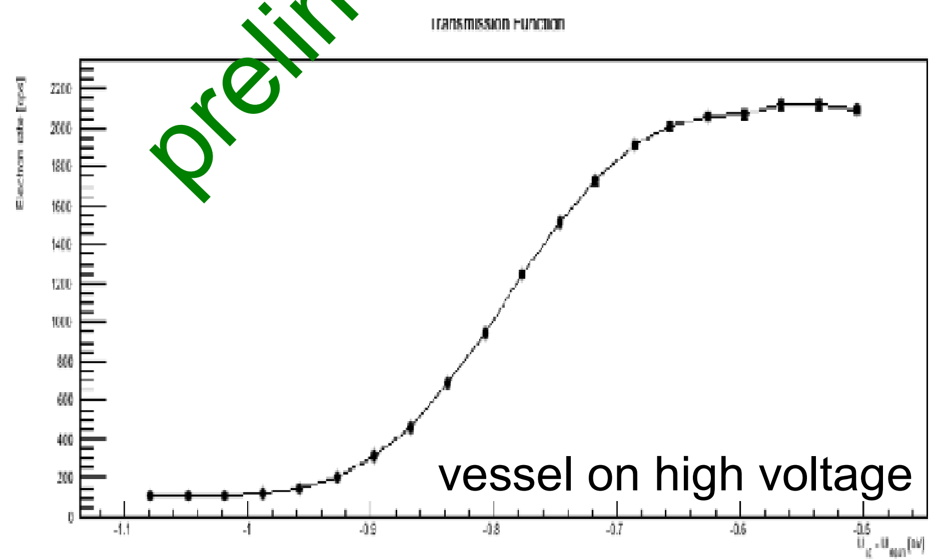
But still KATRIN requires a background rate of **10^{-2} cps**

Test of transmission function

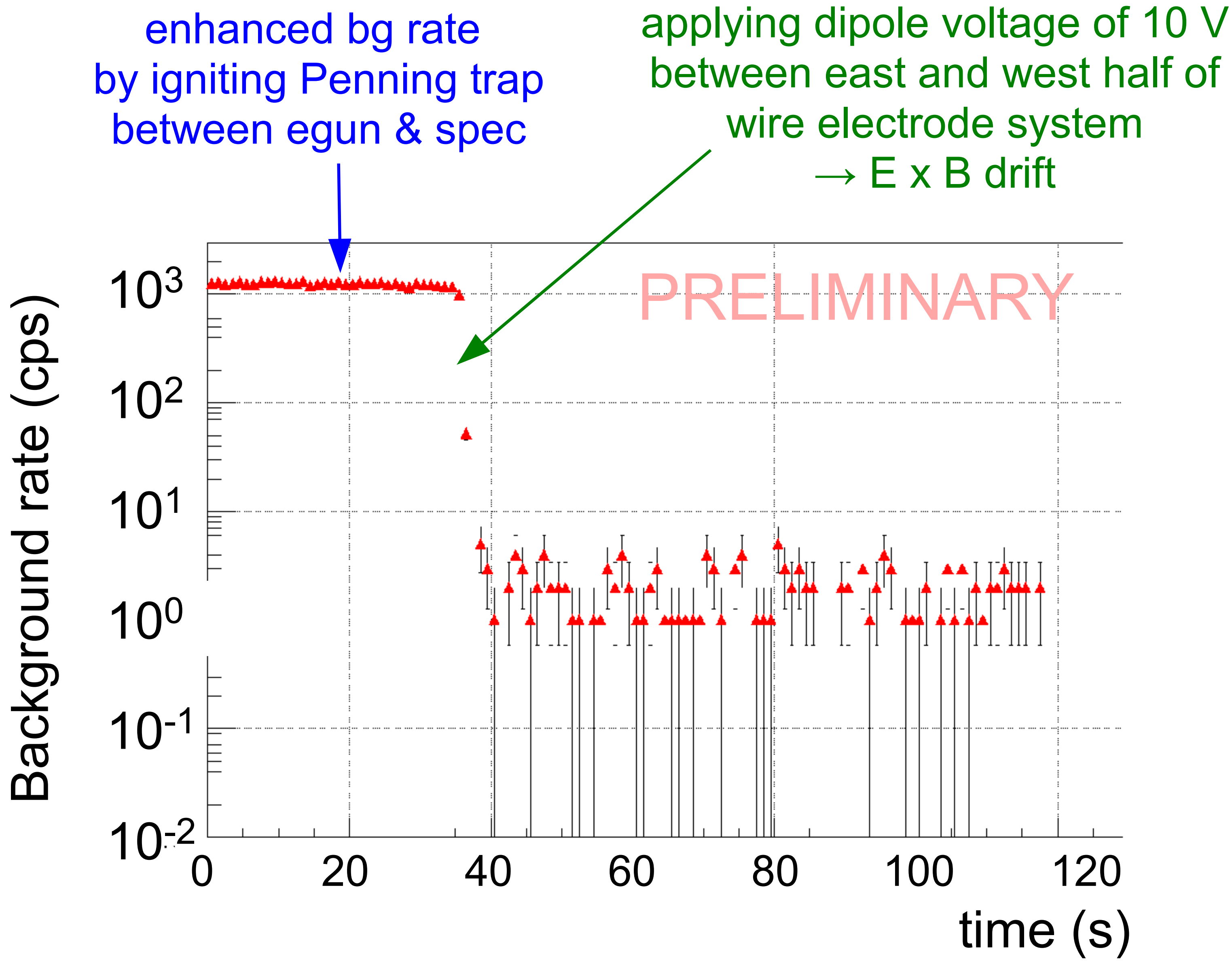






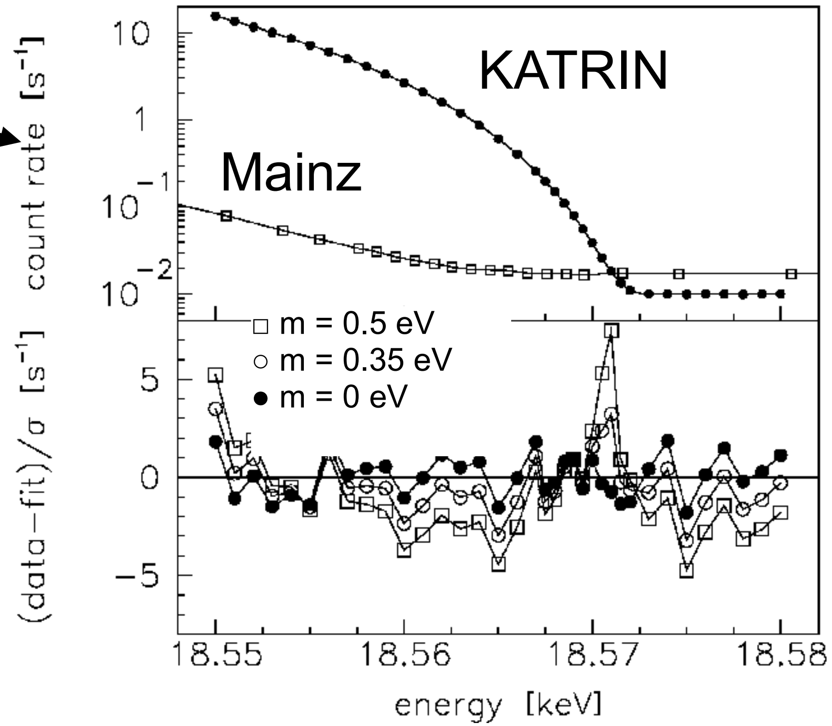


First tests of active background removal by E x B drift



KATRIN´s sensitivity

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



sensitivity:

$m_\nu < 0.2$eV (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.)

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, Holmes (new), ECHO)
- tritium β-decay using MAC-E-Filter (→ KATRIN)
- …

KATRIN is using a complex but established method:

→ sensitivity: 2 eV → 200 meV

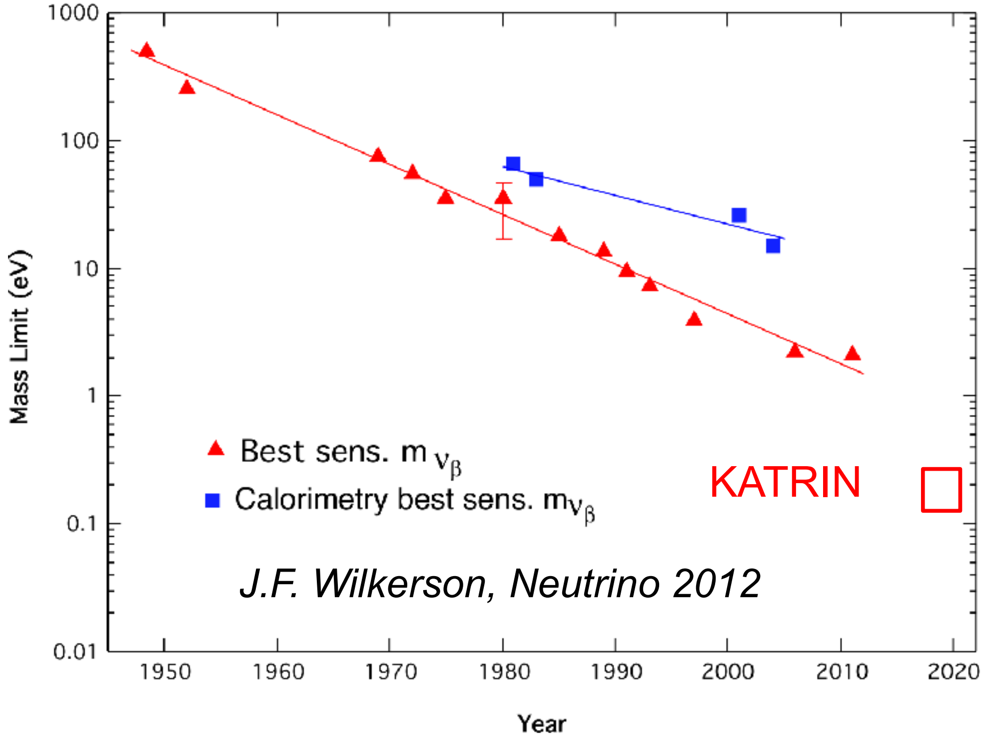
main spectrometer & detector are being commissioned looking quited promising

expect start of tritium data taking in 2015

Cryo-microcalorimeters have a large potential

but need large arrays → multiplexing

what are the systematics ?

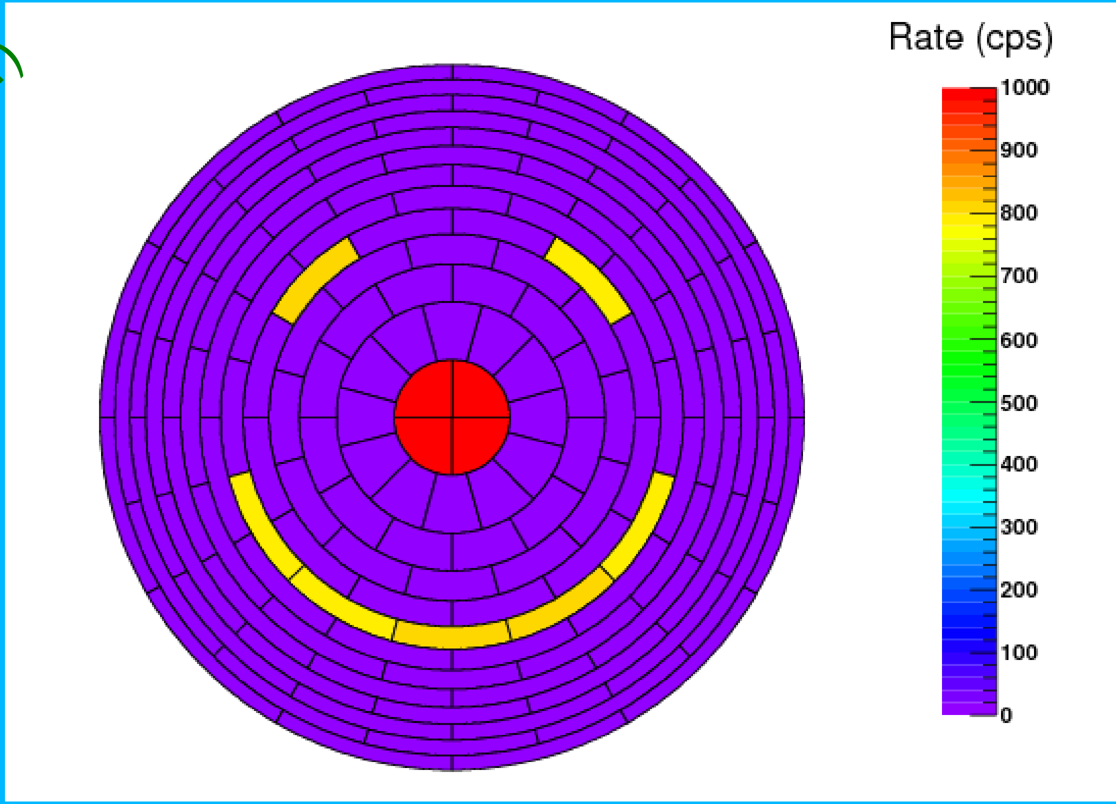


Westfälische Wilhelms-Universität Münster

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