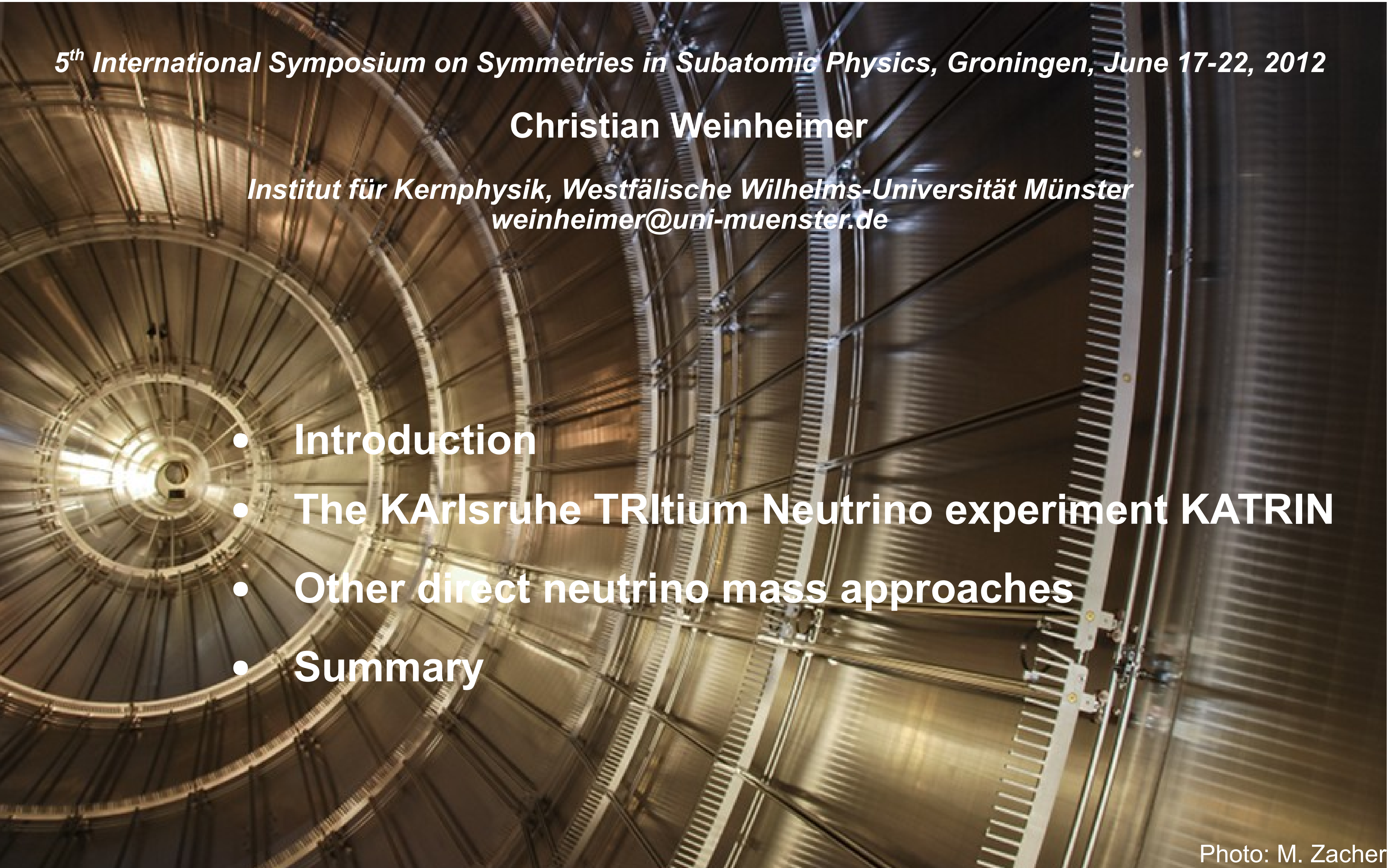
Westfälische
Wilhelms-Universität
Münster

Direct Neutrino Mass Measurements



5^{th} International Symposium on Symmetries in Subatomic Physics, Groningen, June 17-22, 2012

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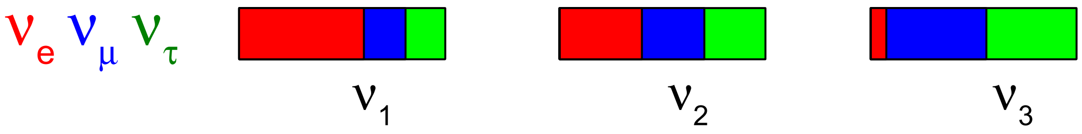
- **Introduction**
- **The KArlsruhe TRItium Neutrino experiment KATRIN**
- **Other direct neutrino mass approaches**
- **Summary**

Photo: M. Zacher

Hot Dark Matter: neutrinos
Their contribution depends on m_ν

Results of recent oscillation experiments: $\Theta_{23}, \Theta_{12}, \Theta_{13}, \Delta m^2_{23}, \Delta m^2_{12}$



Relics from the hot plasma after the big bang (like CMB): 336 ν / cm³

degenerated masses

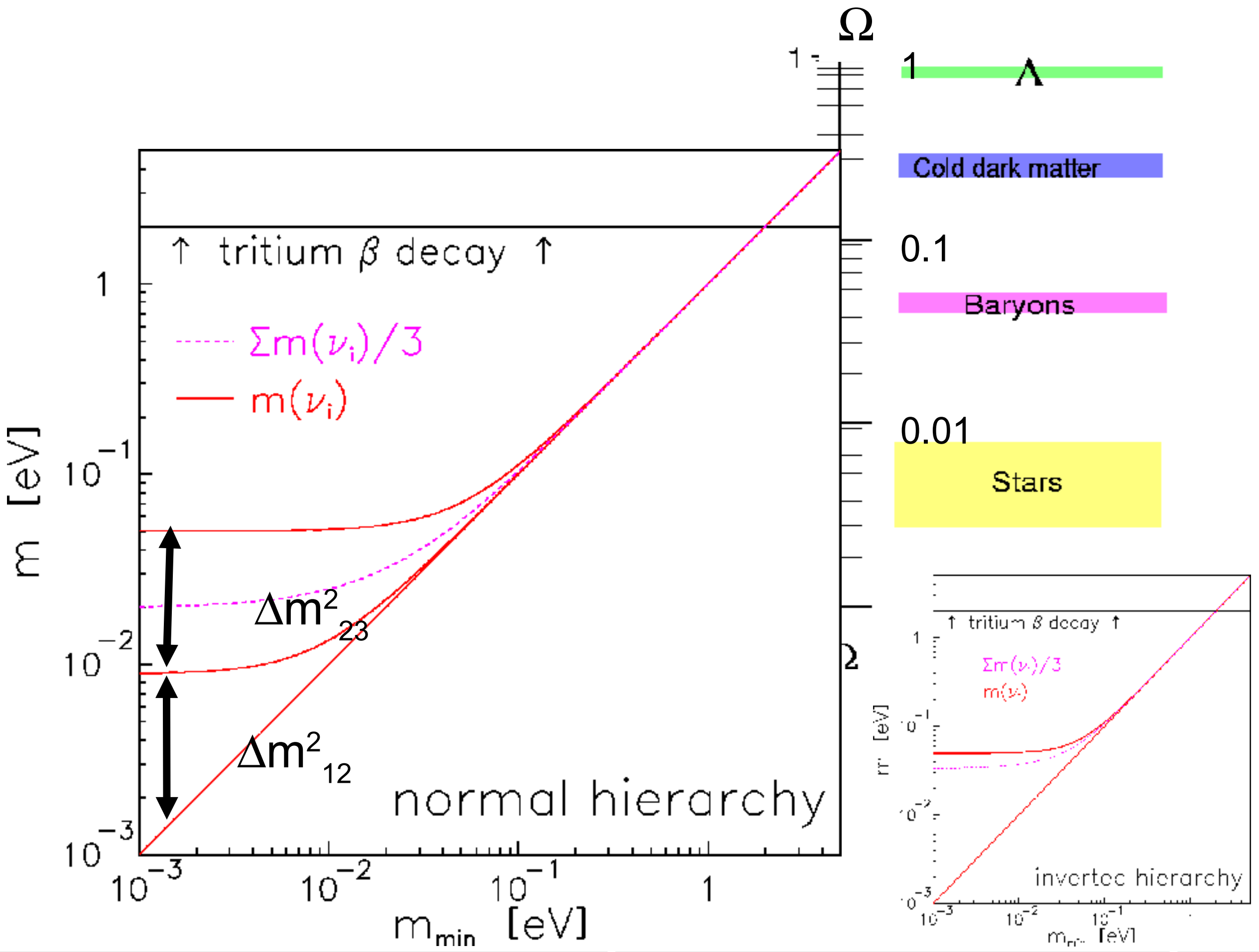
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

explains smallness of masses,
but not mixing



Three complementary ways to the absolute neutrino mass scale

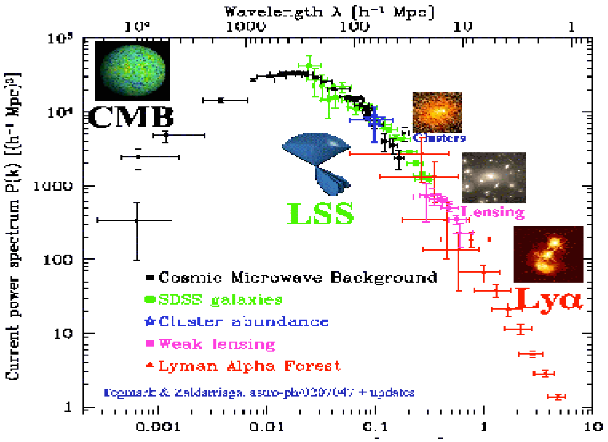
1) Cosmology

very sensitive, but model dependent

compares power at different scales

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

e.g. S. Hannestad, Prog. Part. Nucl. Phys. 65 (2010) 185



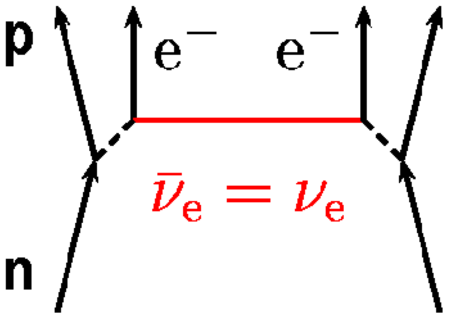
2) Search for 0νββ

Sensitive to Majorana neutrinos

Evidence for $m_{ee}(\nu) \approx 0.3$ eV ?

GERDA is running, EXO delivered 1st limit !

$$m_{\beta\beta}(\nu) = |\, \Sigma\, |U_{ei}{}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$$



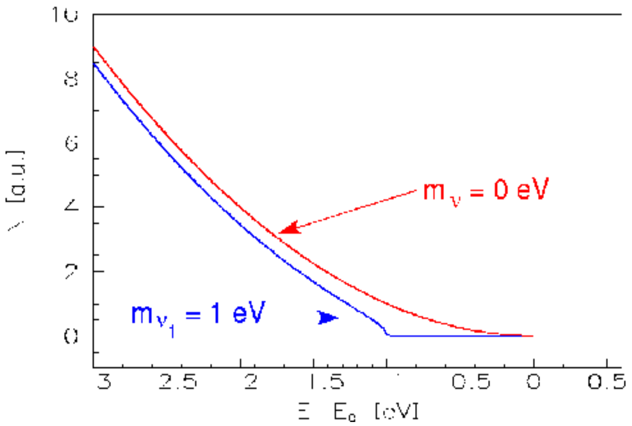
3) Direct neutrino mass determination:

No further assumptions needed. no model dependence

use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly

most sensitive methode: endpoint spectrum of β-decay

$$m^2(\nu_e) = \Sigma |U_{ei}{}^2|\, m^2(\nu_i)$$



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

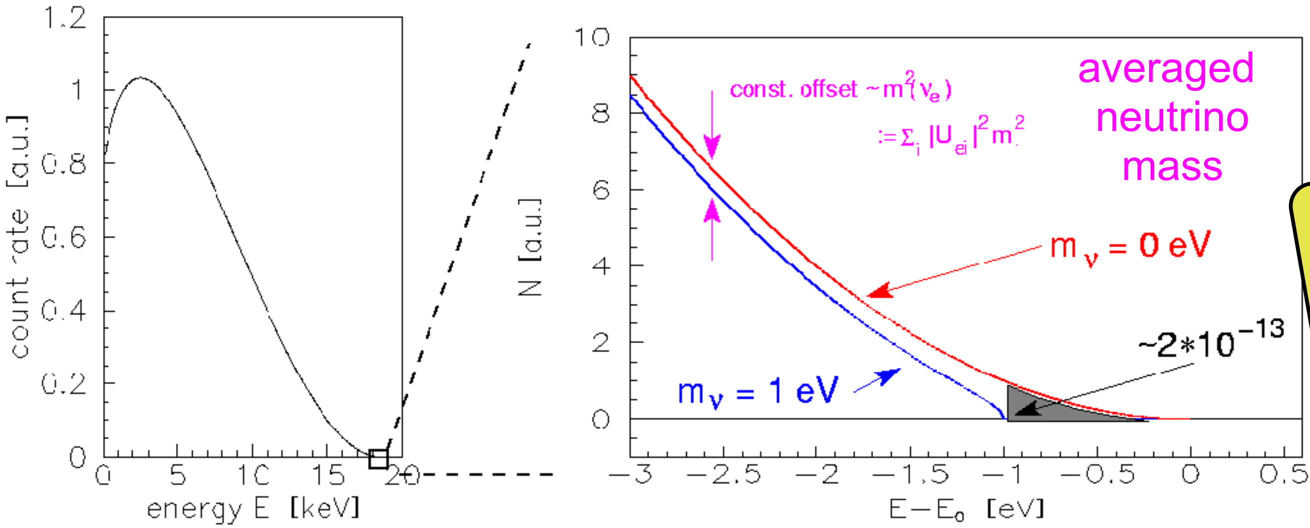
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

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

β electron energy spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma\, |U_{ei}|^2\ \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$$

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

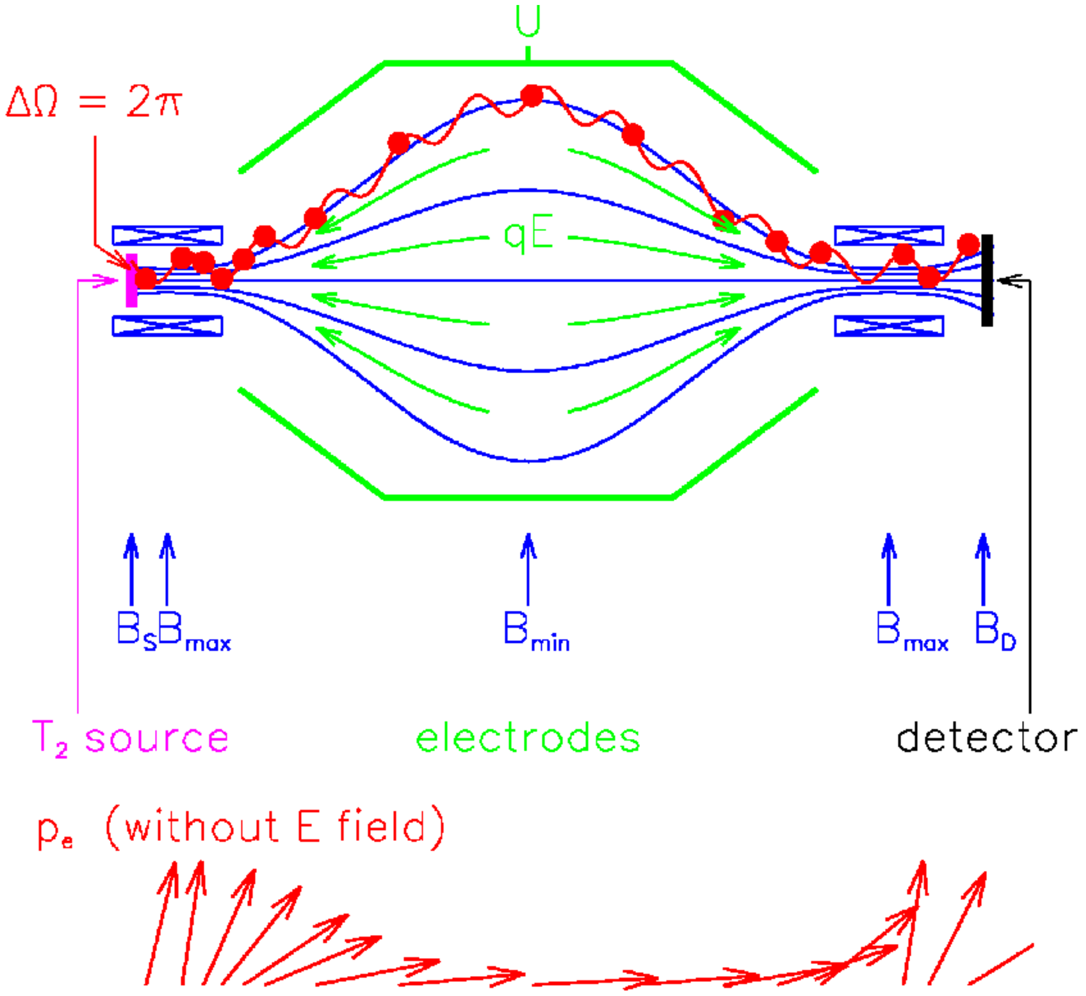


Review:
E.W. Otten & C. Weinheimer
Rep. Prog. Phys., 71 (2008) 086201

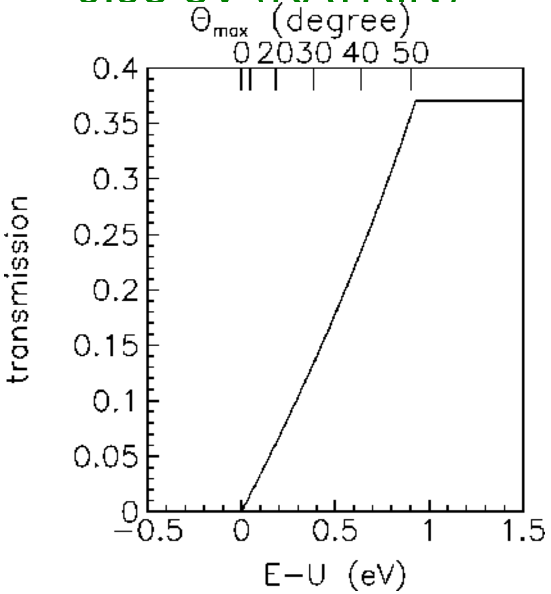
Need: low endpoint energy ⇒ Tritium ^{3}H, (^{187}Re)

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

Tritium experiments: source ≠ spectrometer
MAC-E-Filter



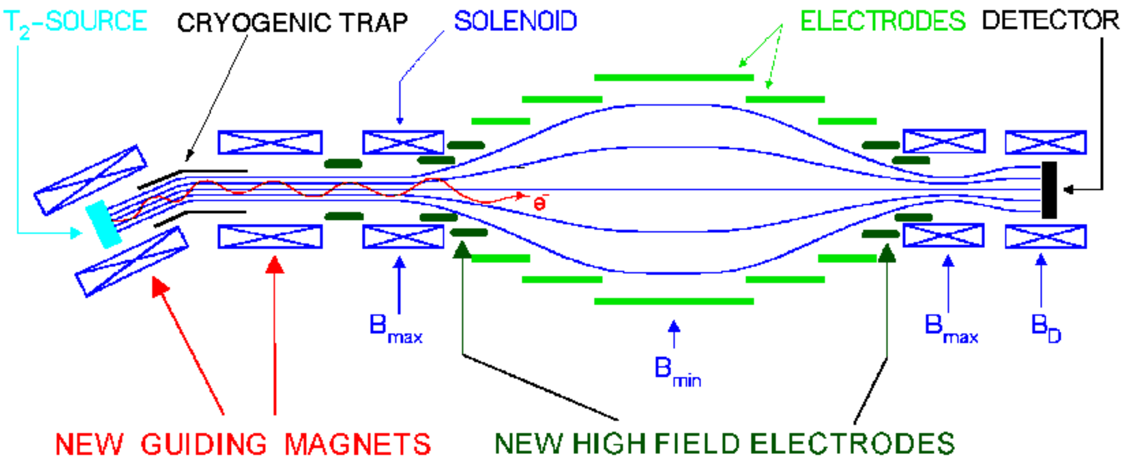
- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E/B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = EB_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)

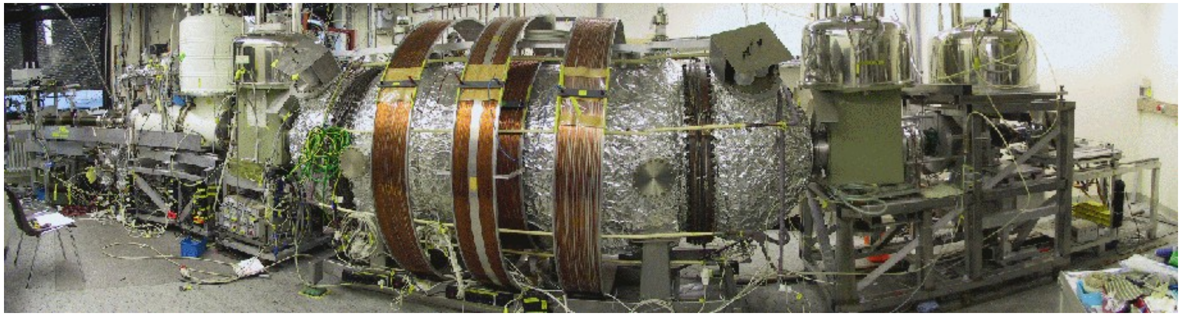


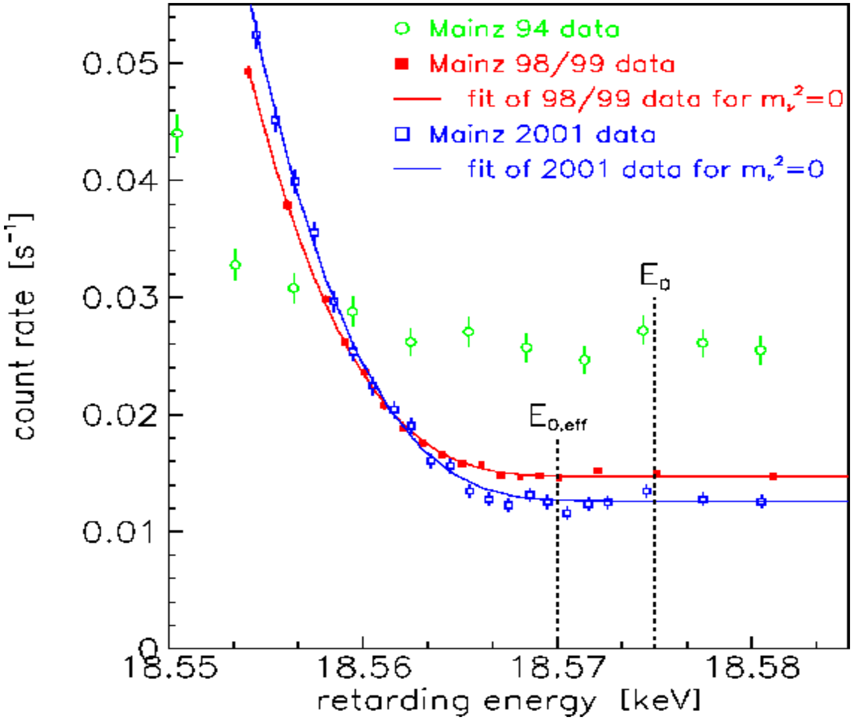
⇒ sharp integrating transmission function without tails →

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

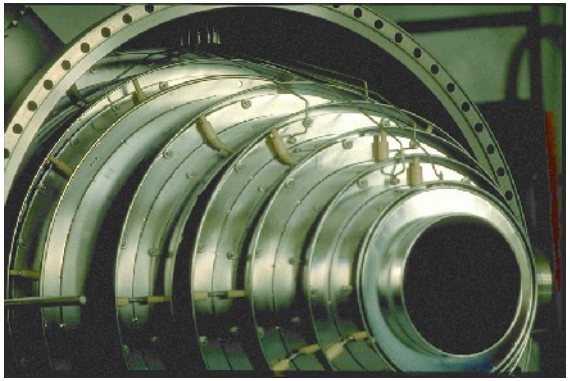
The Mainz Neutrino Mass Experiment
Phase 2: 1997-2001







⇓



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

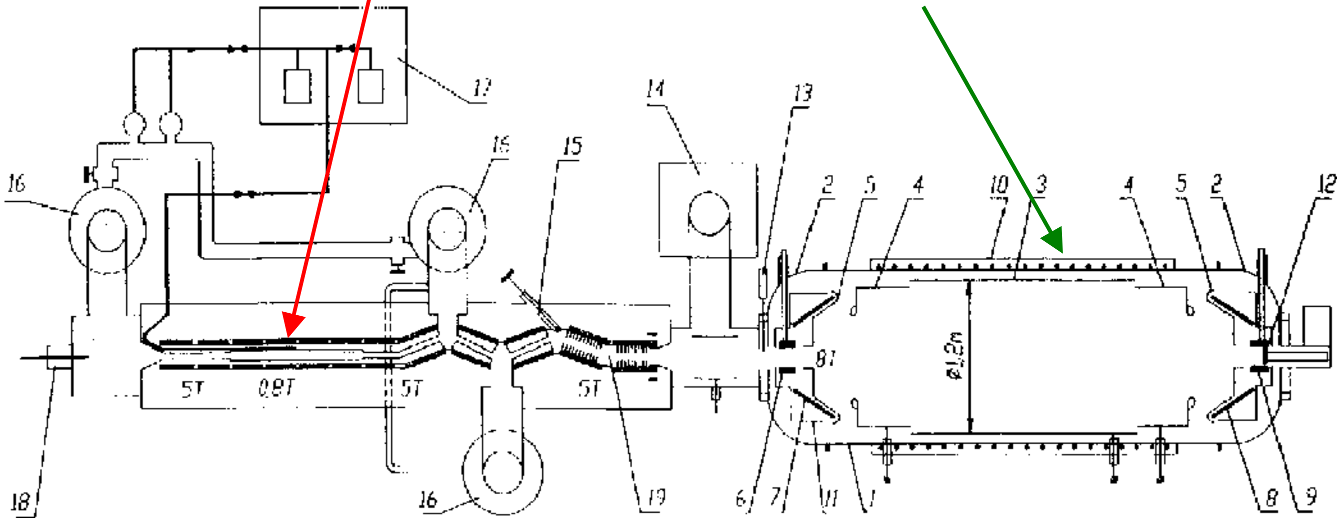
$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ \text{eV}^2 \Rightarrow m(\nu) < 2.3\ \text{eV}$ (95% C.L.)

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



Vladimir
Mikhailovich
Lobashev
1934-2011

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

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

Re-analysis of Troitsk data

(better source thickness, better run selection)

Aseev et al, Phys. Rev. D 84, 112003 (2011)

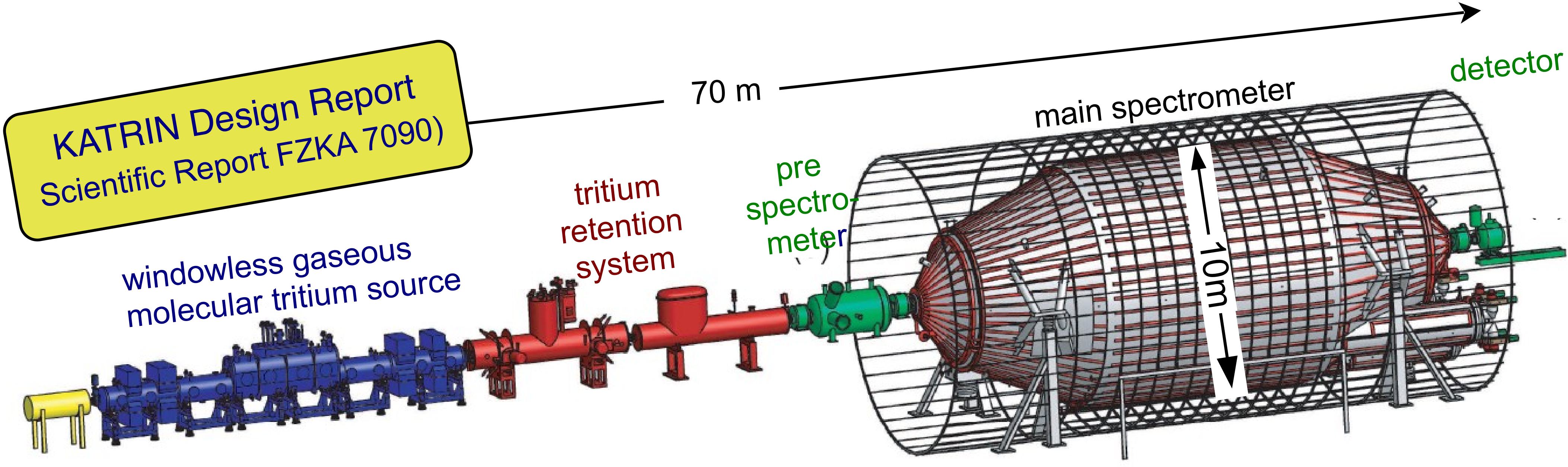
m_β < 2.2 eV, 95% CL

The KATRIN experiment at KIT

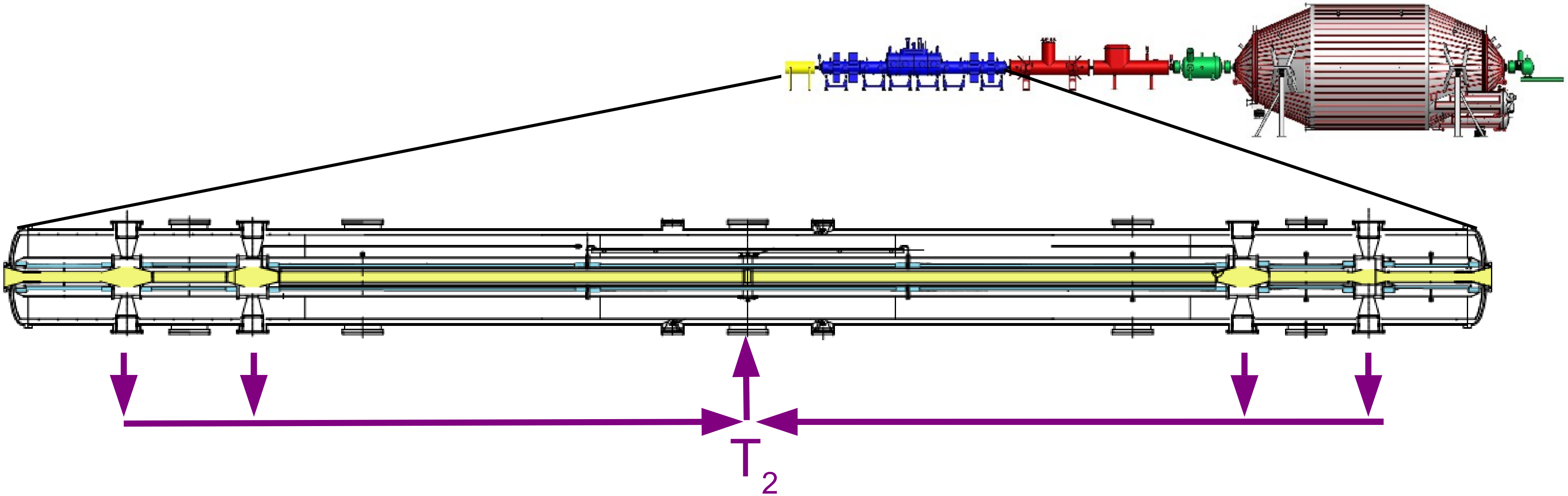
Aim: $m(\nu_e)$ sensitivity of 200 meV (currently 2 eV)

- **very high energy resolution ($\Delta E \leq 1$eV, i.e. $\sigma = 0.3$ 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)

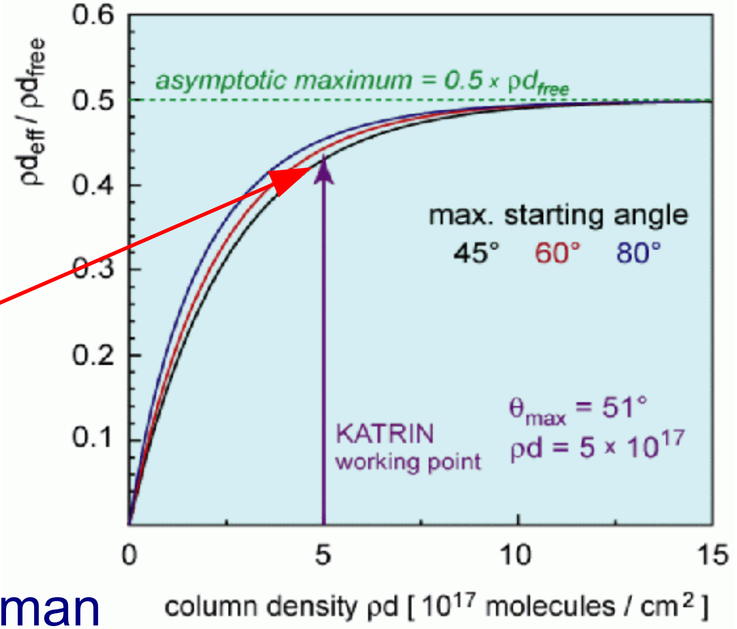
Molecular Windowless Gaseous Tritium Source WGTS



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

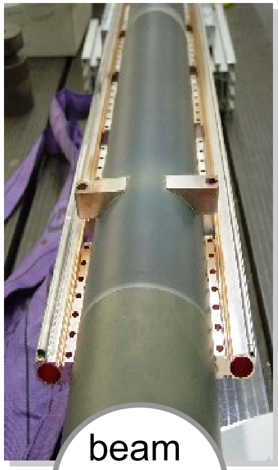
allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/\text{cm}^2$
with small systematics



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

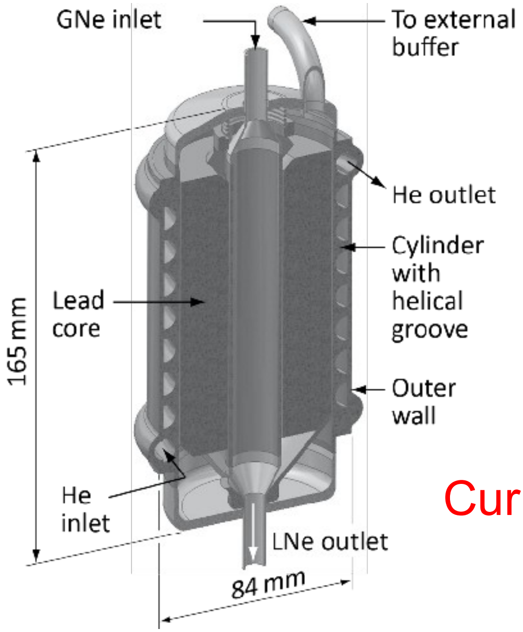
Very successful cool-down and stability tests of the WGTS demonstrator

arrival of WGTS demonstrator at KIT: April 2010

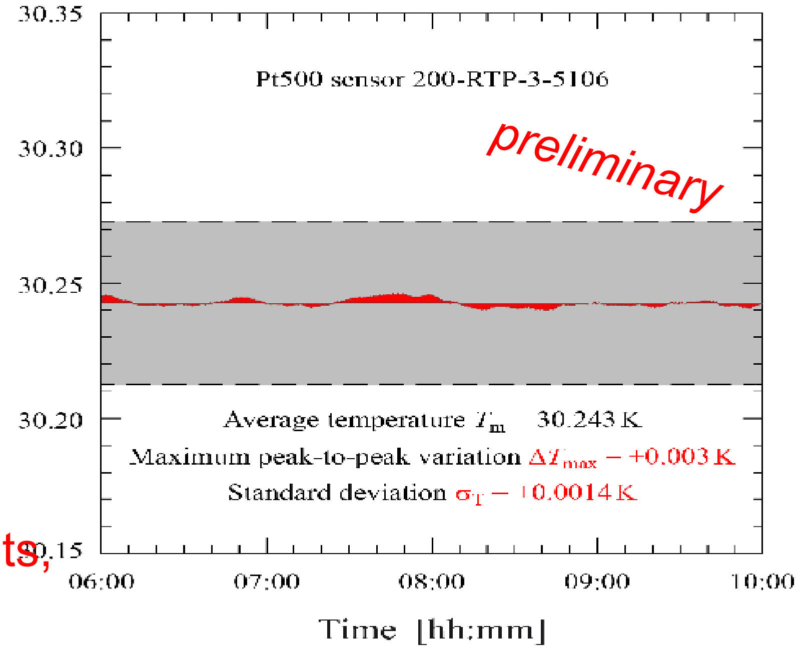


beam tube
Ø=90mm

cooling concept of WGTS:
pressurized 2-phase Ne



S. Grohmann,
Cryogenics 49,
No. 8 (2009) 413



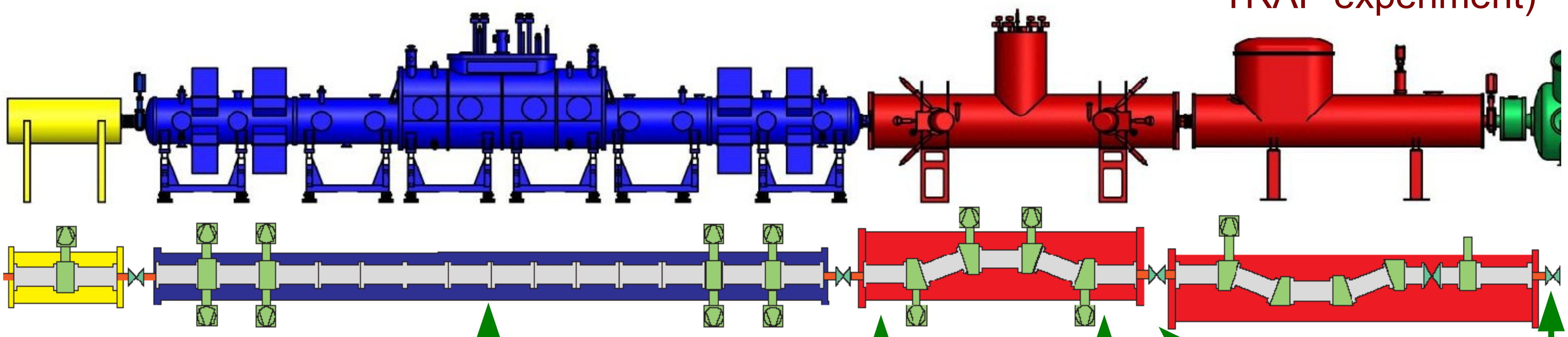
Currently: tests of sc magnets,
constructing of WGTS
out of demonstrator

Transport and differential & cryo pumping sections

Molecular windowless gaseous tritium source

Differential pumping

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



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

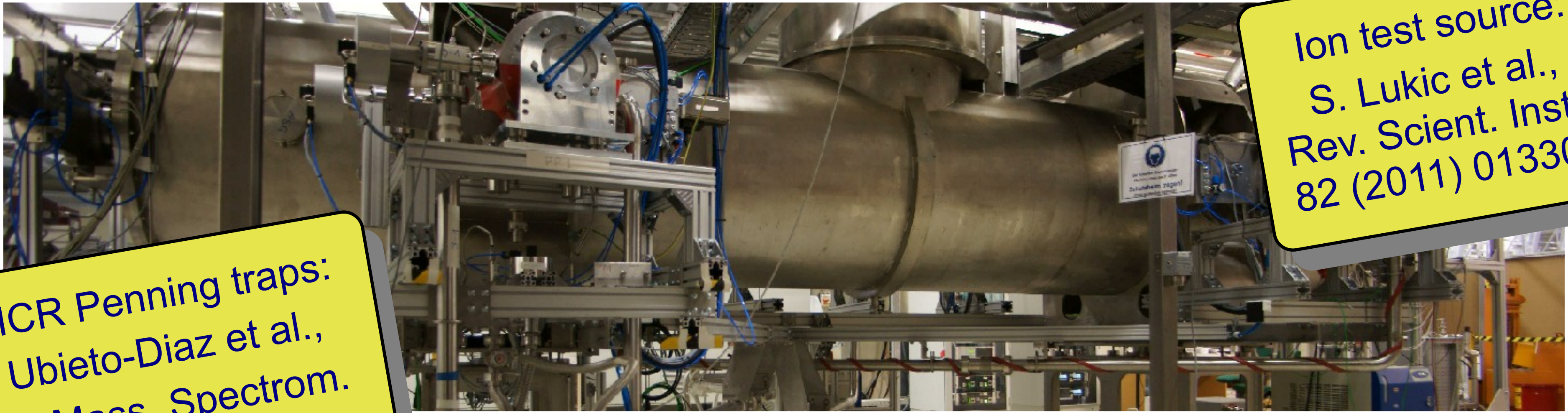
FT-ICR Penning traps to measure ions from WGTS

≈ 10^{-7} mbar l/s

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

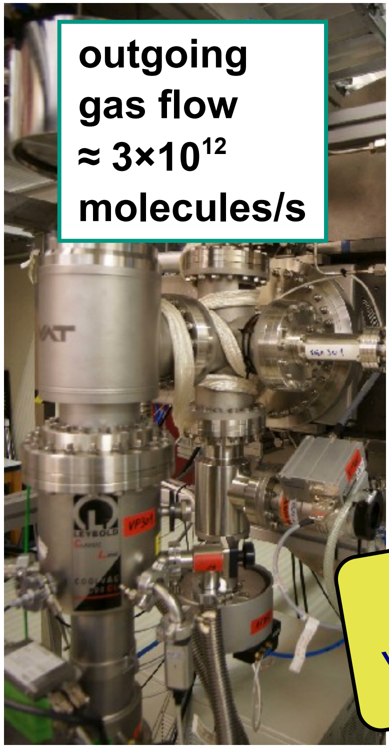
⇒ adiabatic electron guiding & T_2 reduction factor of ~10^{14}

Commissioning of DPS2-F



FT-ICR Penning traps:
M. Ubieto-Diaz et al.,
Int. J. Mass. Spectrom.
288 (2009) 1-5

Ion test source:
S. Lukic et al.,
Rev. Scient. Instr.
82 (2011) 013303



outgoing gas flow $\approx 3\times10^{12}$ molecules/s

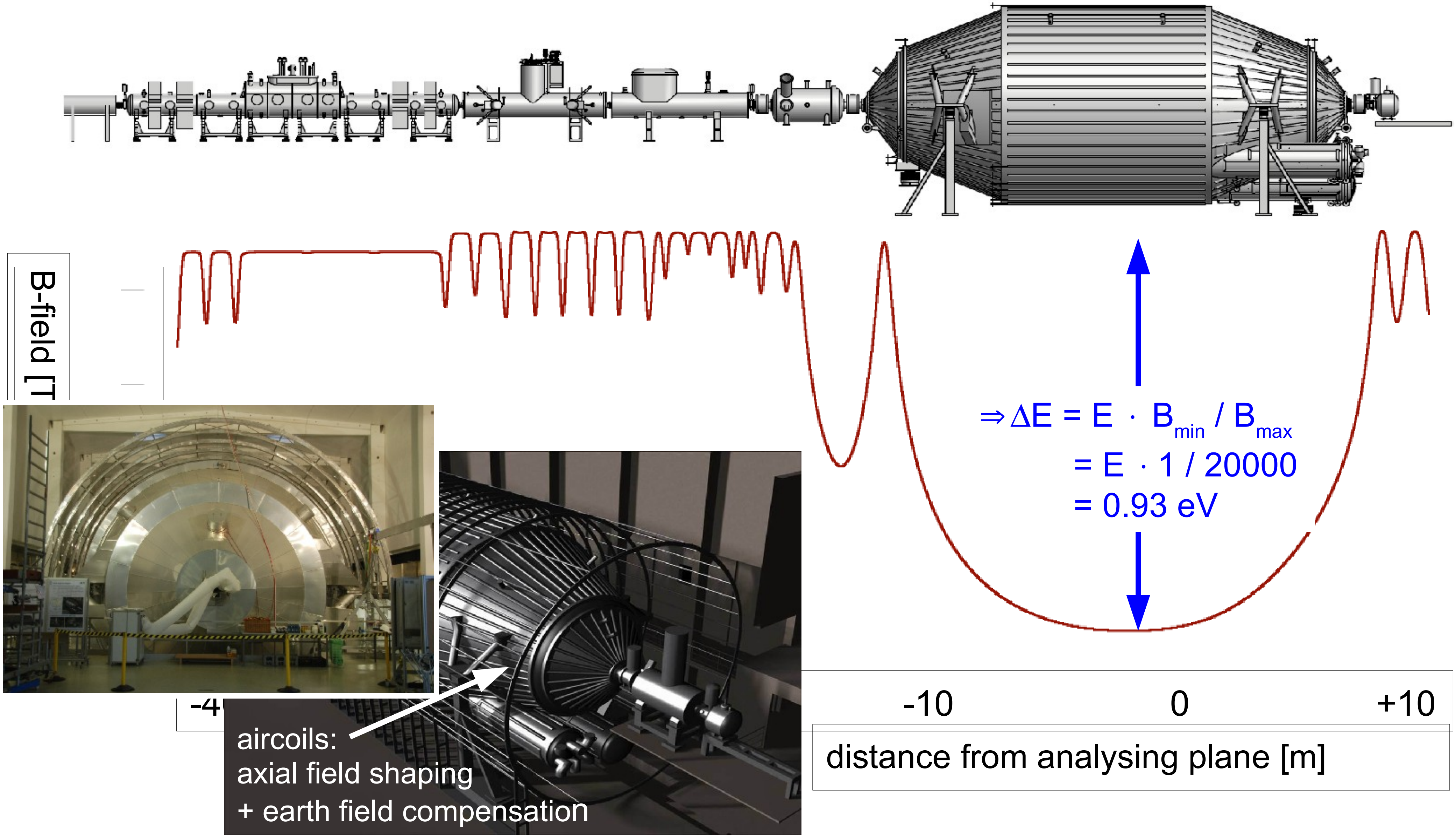
First gas
flow reduction
measurements
with Ar

gas inlet $\approx 3\times10^{17}$ molecules/s

S. Lukic et al.,
Vacuum 86 (2012) 1126

Currently:
Problem of a broken diode
from the safety system
of a superconducting coil

Electromagnetic design: magnetic fields



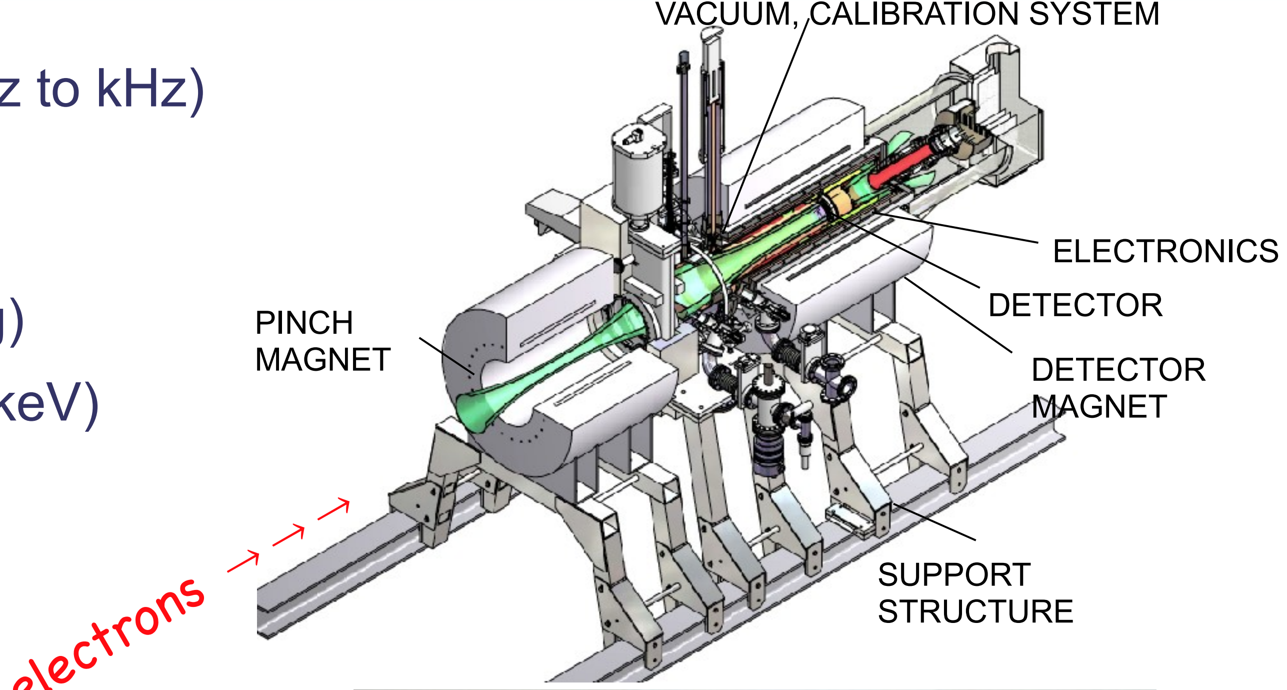
$$\Rightarrow \Delta E = E \cdot B_{min} / B_{max}$$
$$= E \cdot 1 / 20000$$
$$= 0.93 \text{ eV}$$

aircoils:
axial field shaping
+ earth field compensation

The detector

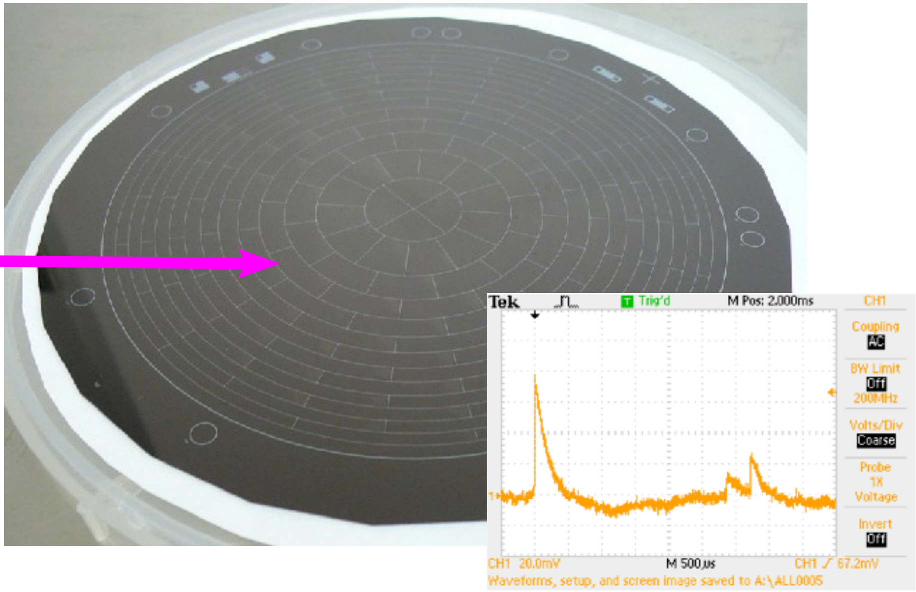
Requirements

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

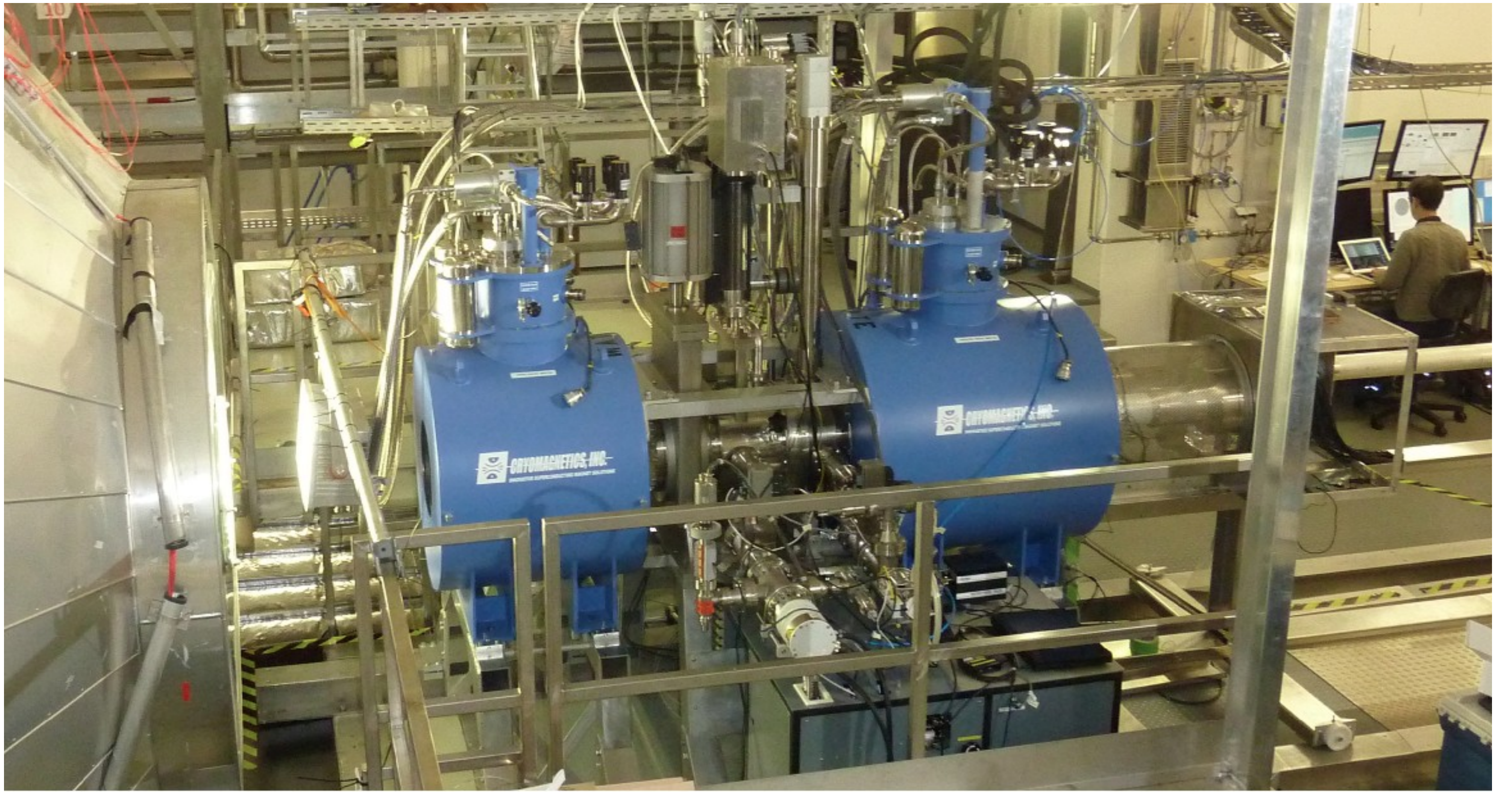


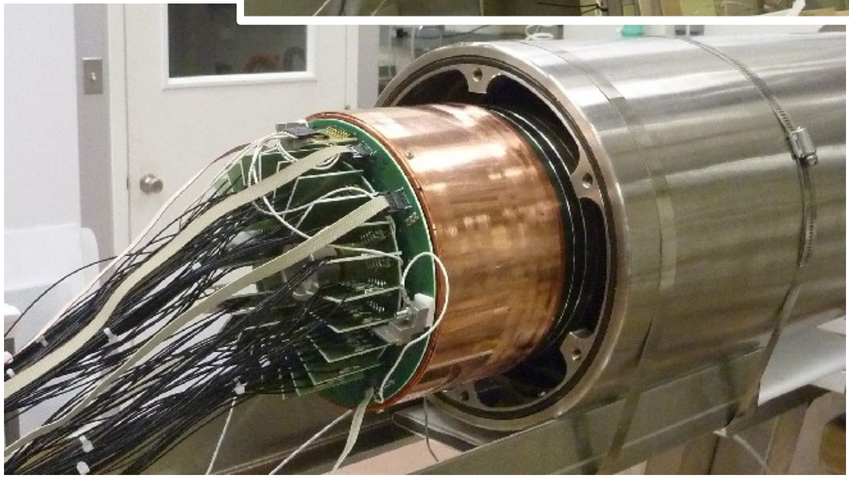
Properties

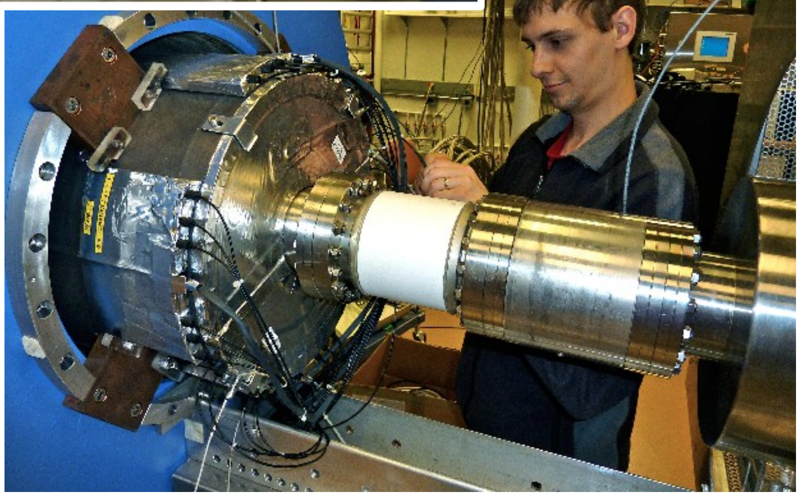
- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV)
  (to lower background in signal region)
- segmented wafer (145 pixels)
  - → record azimuthal and radial profile of the flux tube
  - → investigate systematic effects
  - → compensate field inhomogeneities



KATRIN detector is being commissioned at KIT







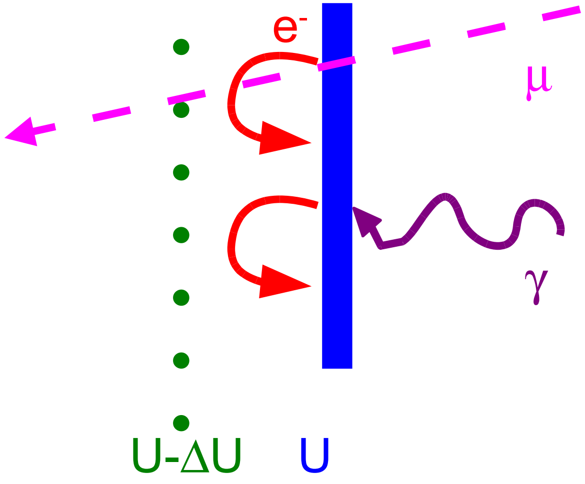
Main Spectrometer – Transport to Karlsruhe Institute of Technology

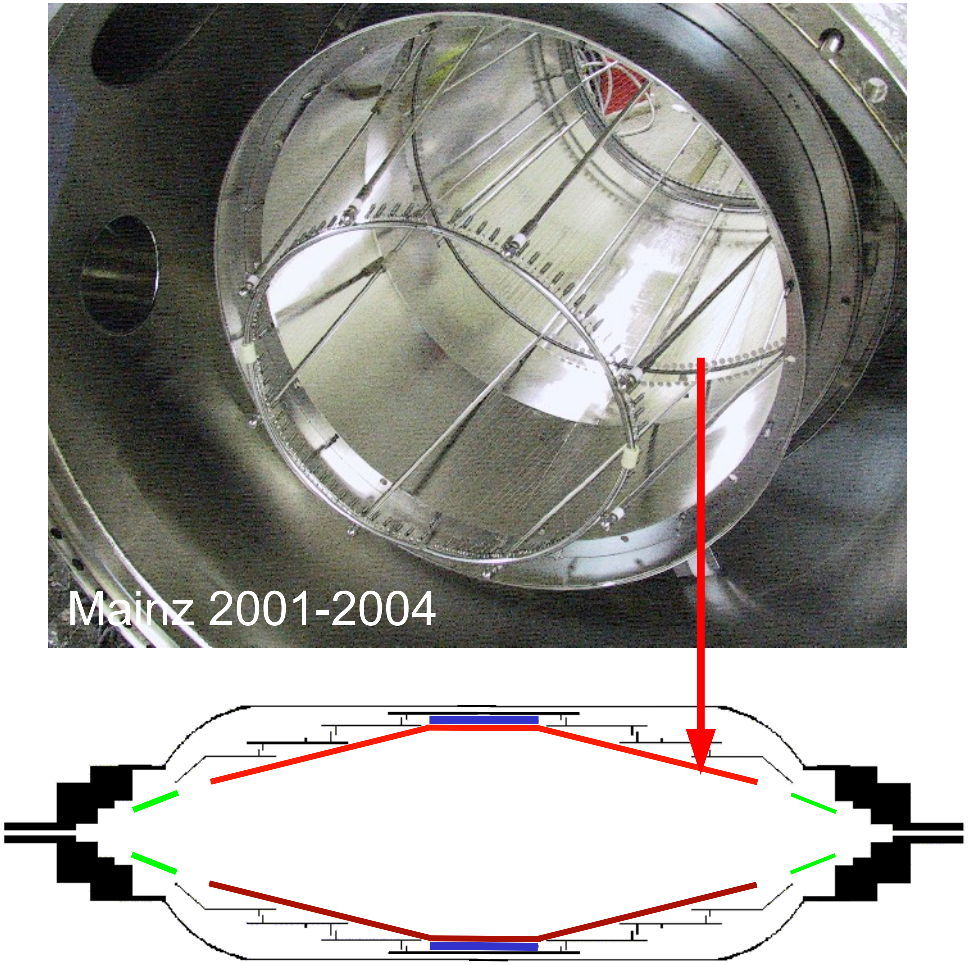
KATRIN has a 100-times larger surface, but requests same bg → something new

Secondary electrons from wall/electrode

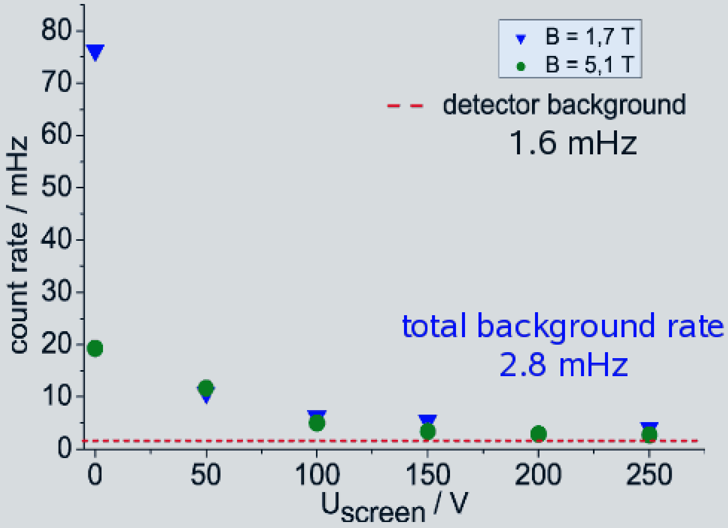
by cosmic rays, environmental radioactivity, ...

New: wire electrode on slightly more negative potential



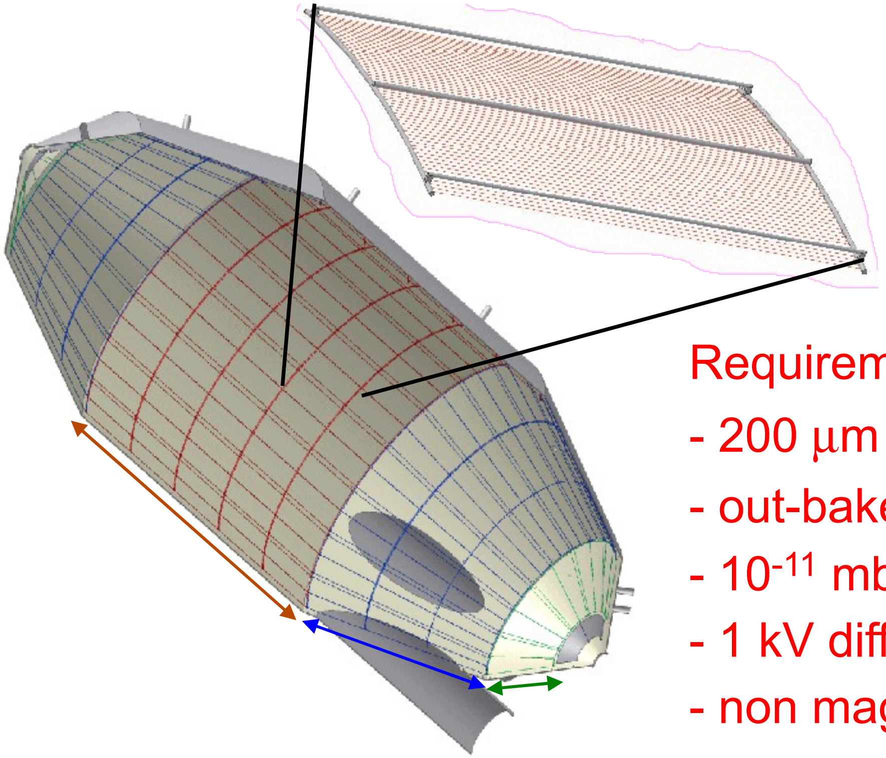


Background suppression successfully tested at the Mainz MAC-E filter:



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

Design, construction and mounting of the 690m^2 2-layer wire electrode system

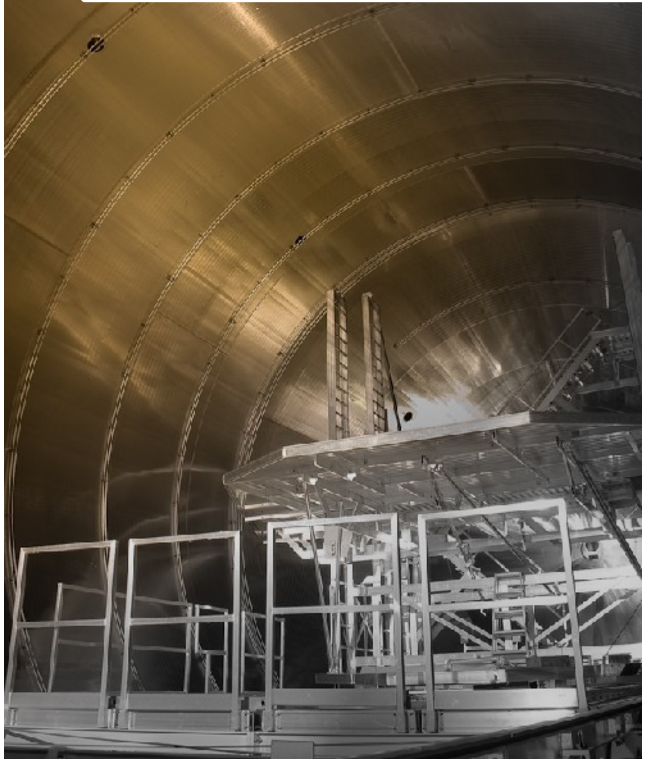


Requirements:

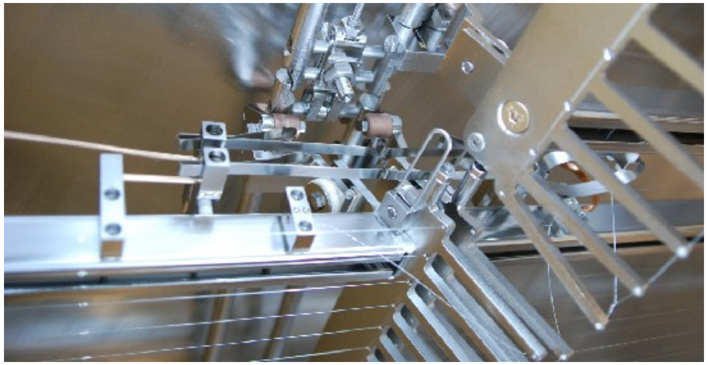
- 200 μm precision
- out-bakeable 350 °C
- 10^{-11} mbar compatiible
- 1 kV difference voltage
- non magnetic
- ...

Foto: Peter Lessmann

Two-layer wire electrode modules installation inside main spectrometer

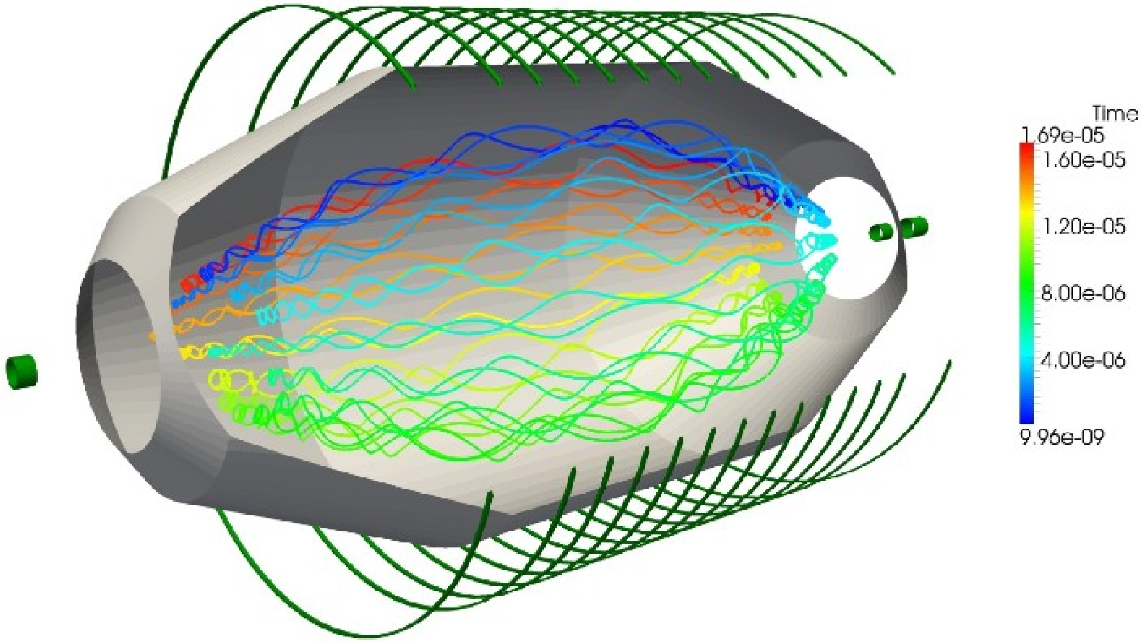


All 248 modules are installed, January 31, 2012

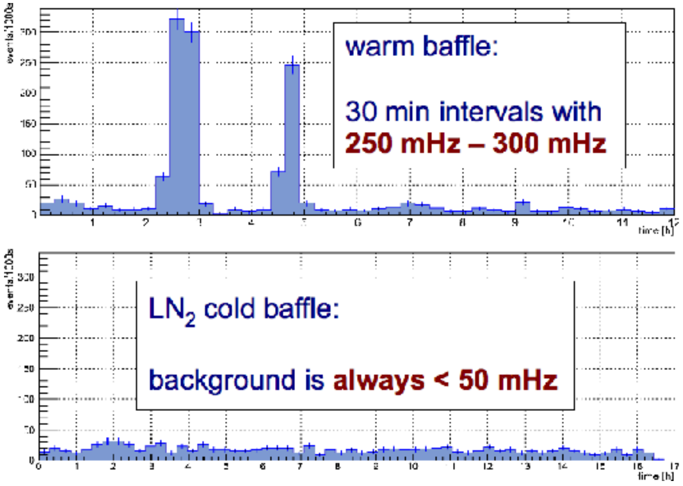


Background from stored electrons: methods to avoid or to eliminate them

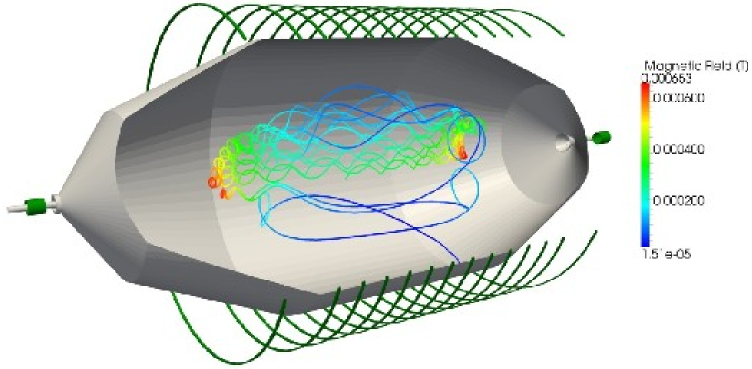
Stored electron by magnetic mirrors
F. Fränkle et al., Astropart. Phys. 35 (2011) 128



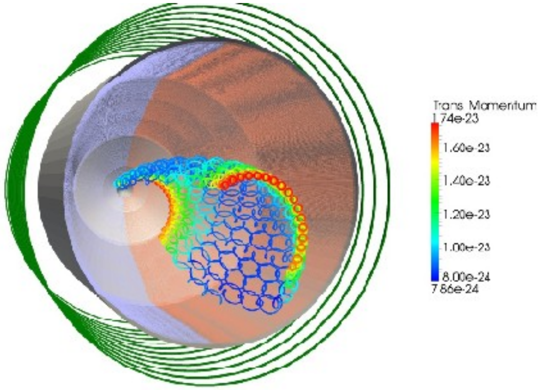
Radon suppression by LN_2 cooled baffle

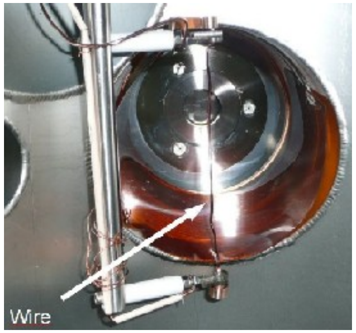


Nulling magnetic field by magn. pulse



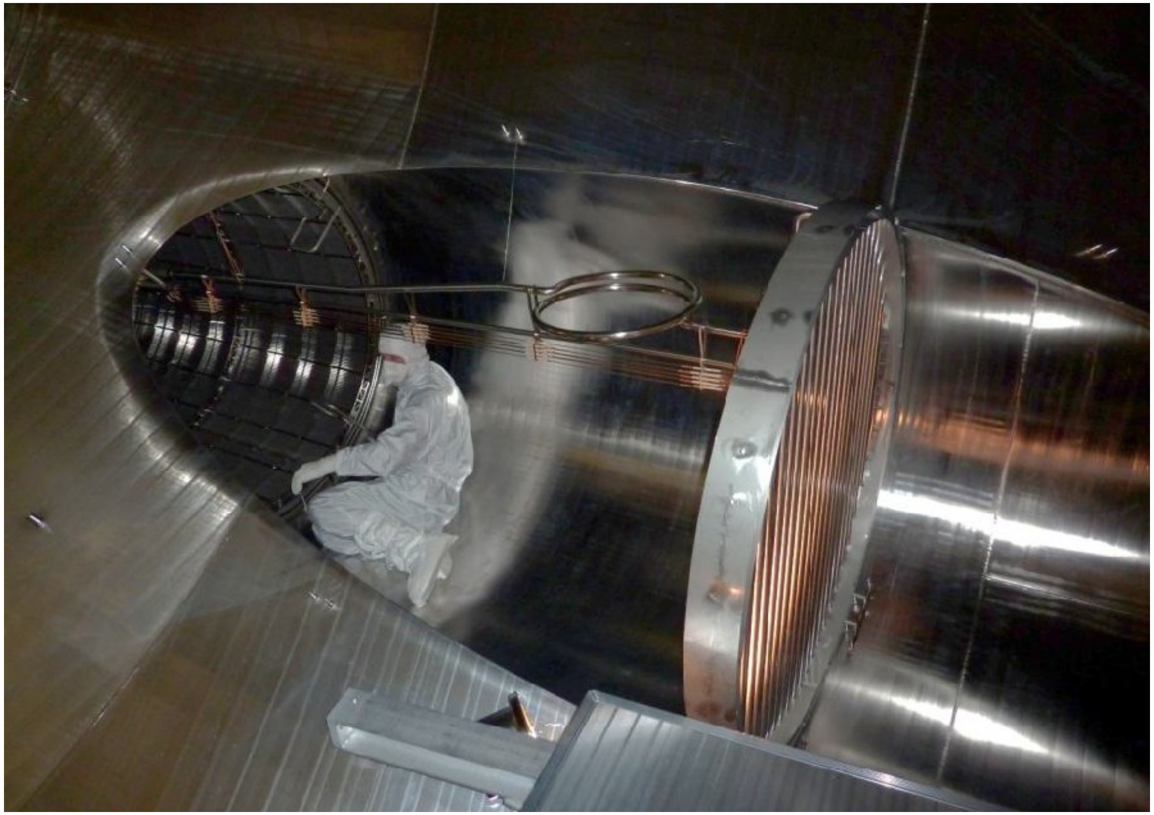
radial E x B drift
due to electric
dipole pulse

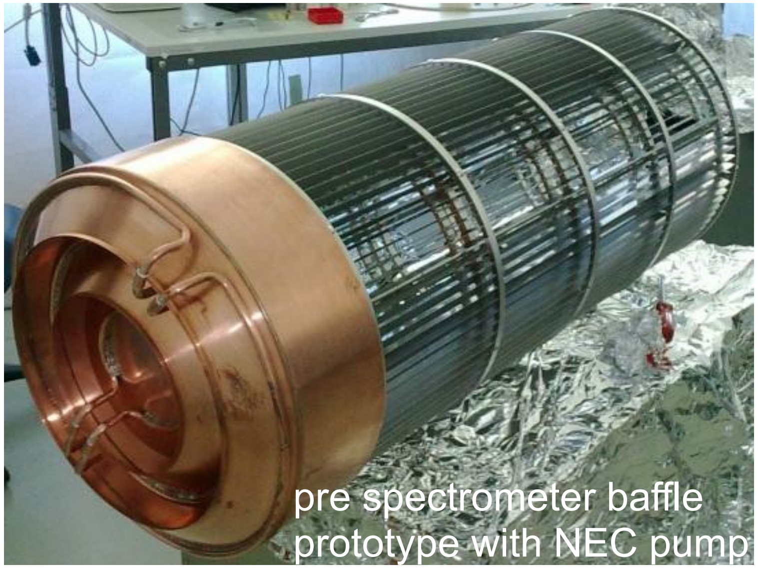




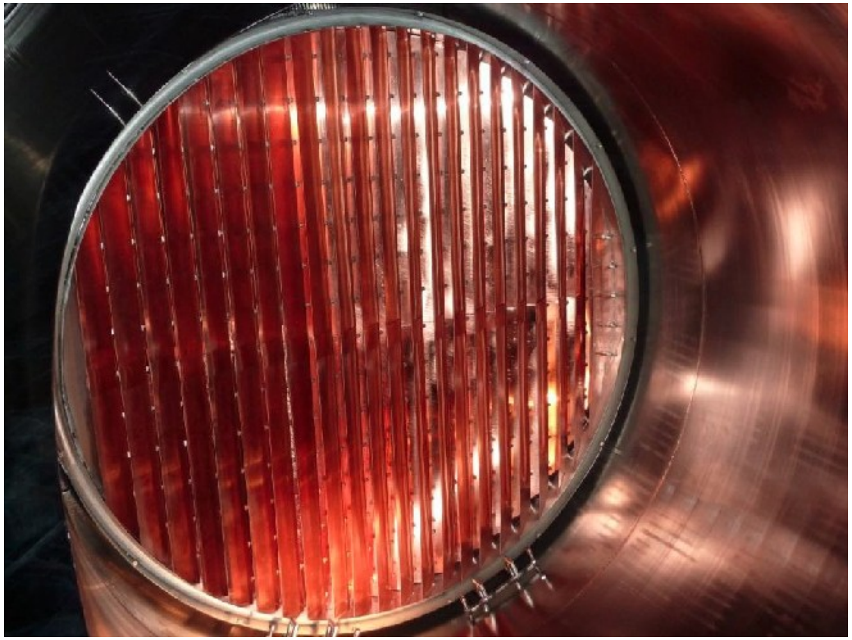
Mechanical eliminating stored particles:
M. Beck et al, Eur. Phys. J. A44 (2010) 499

Radon elimination by LN2-cooled baffles in the main spectrometer





pre spectrometer baffle
prototype with NEC pump



Main spectrometer vessel is closed
Commissioning of main spectrometer with detector
and e-gun ist starting in fall 2012

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 $\Delta m_\nu^2 \leq 0.007\ eV^2$ 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

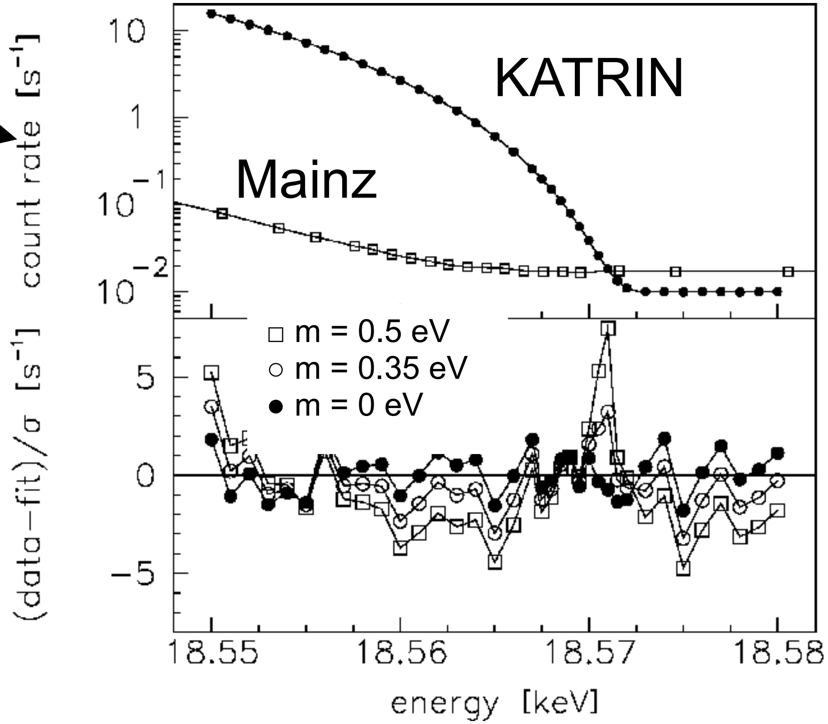
tritium source

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

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)

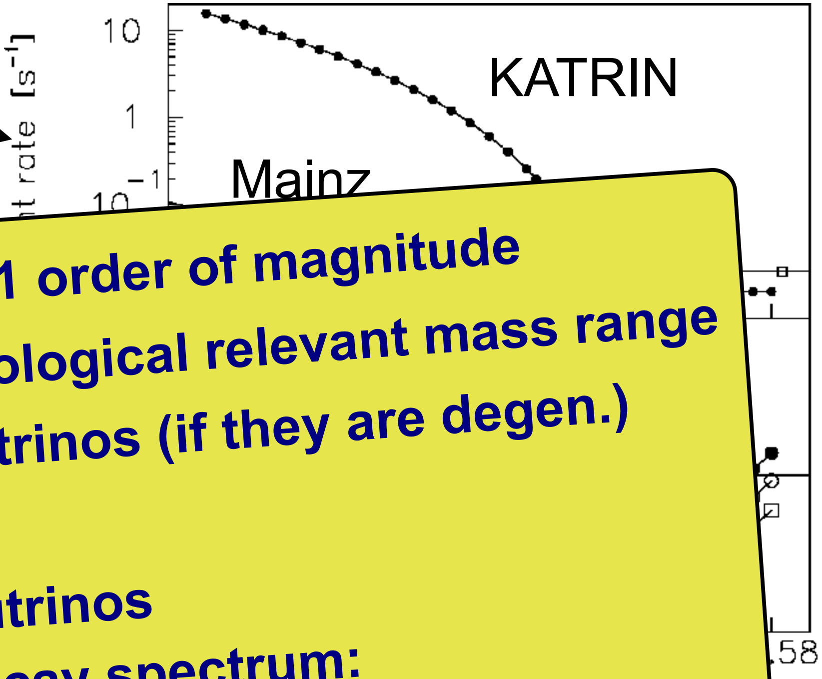
Expectation for 3 full data taking years: $\sigma_{syst} \sim \sigma_{stat}$

Sensitivity is still statistically limited,
because with more statistics would go closer to the endpoint,
where most systematics nearly vanish

Sensitivity still has to proven, but there might be even some more improvements

KATRIN´s sensitivity

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



sensitivity:

⇒ **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.)

KATRIN can also searching sterile neutrinos
by looking for a kink in the decay spectrum:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e) \sum_{i=1}^{n_{active}+n_{sterile}} |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - \mathbf{m(\nu_i)^2}}$$

eV scale (reactor anomaly):
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

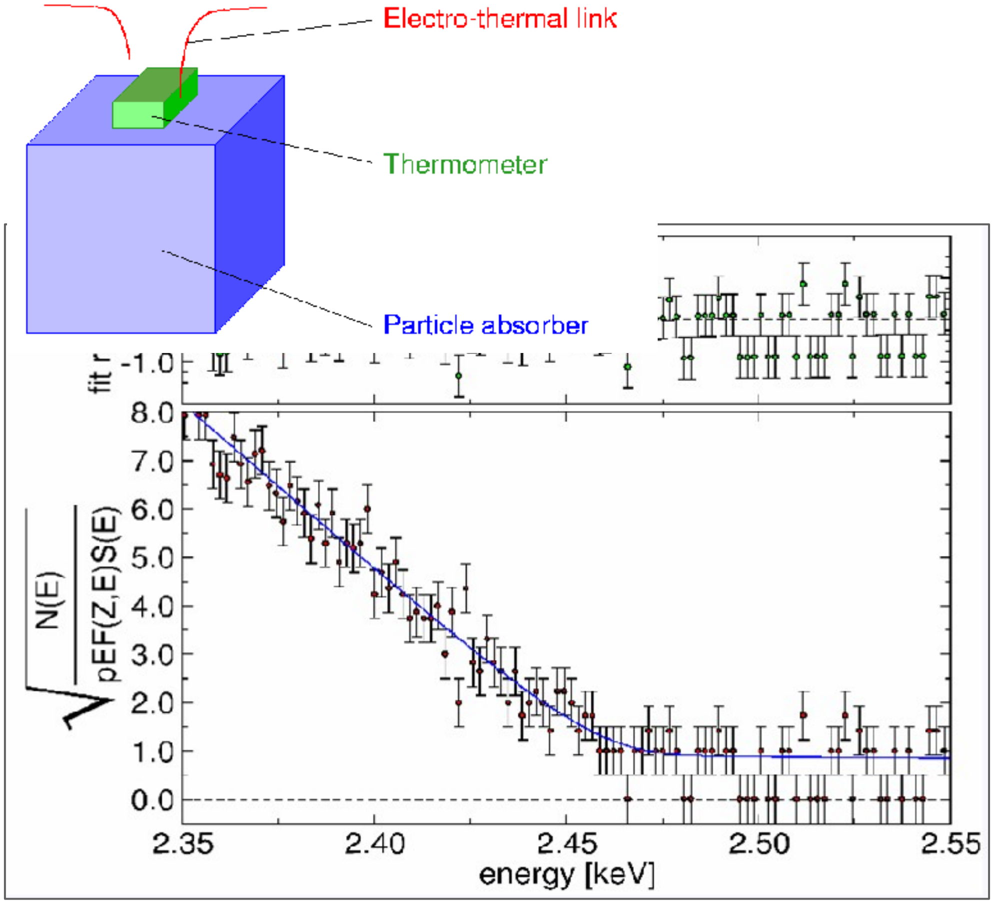
keV scale (dark matter): under study

Ex

Se

Sen might be even some more improvements

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



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.: $1.7\ 10^{-4}$

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

$M_\nu < 15.6$ 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)

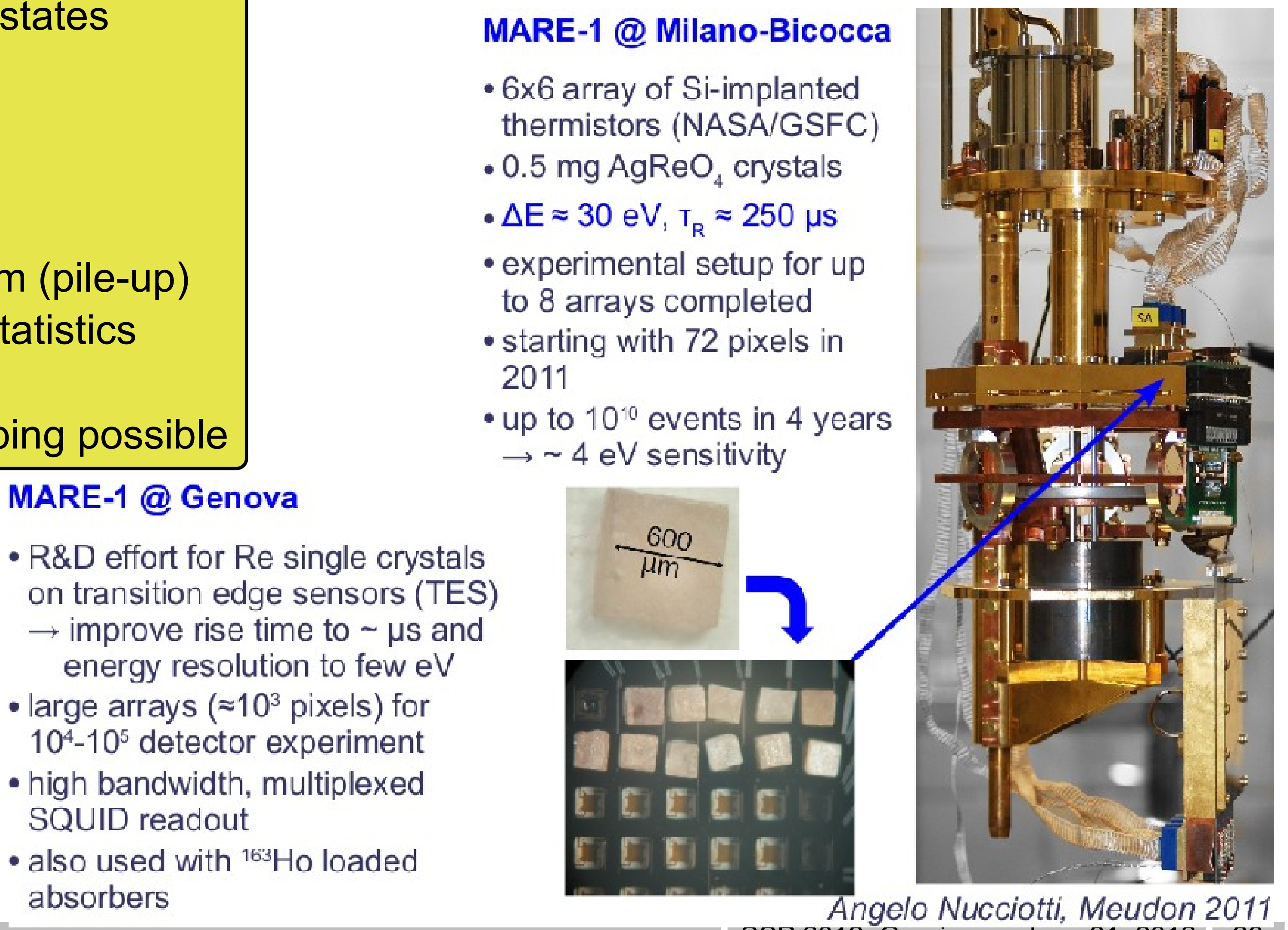
MARE neutrino mass project: ^{187}Re beta decay with cryogenic bolometers

Advantages:

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

Challenges:

- measures the full spectrum (pile-up)
- need large arrays to get statistics
- understanding spectrum
- still energy losses or trapping possible



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

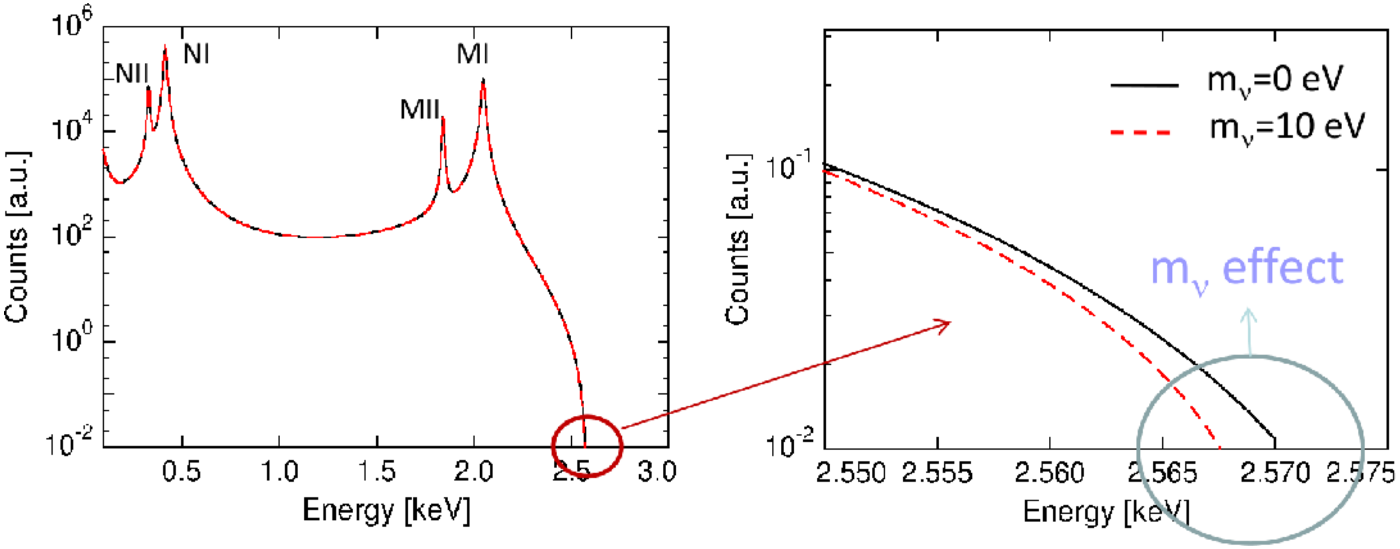
MARE-1 @ Genova

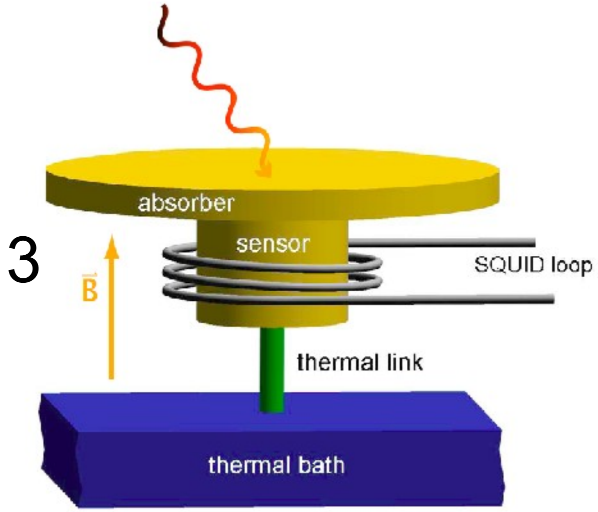
- R&D effort for Re single crystals on transition edge sensors (TES) → improve rise time to ~ µs and energy resolution to few eV
- large arrays (≈10^3 pixels) for 10^4-10^5 detector experiment
- high bandwidth, multiplexed SQUID readout
- also used with ^{163}Ho loaded absorbers

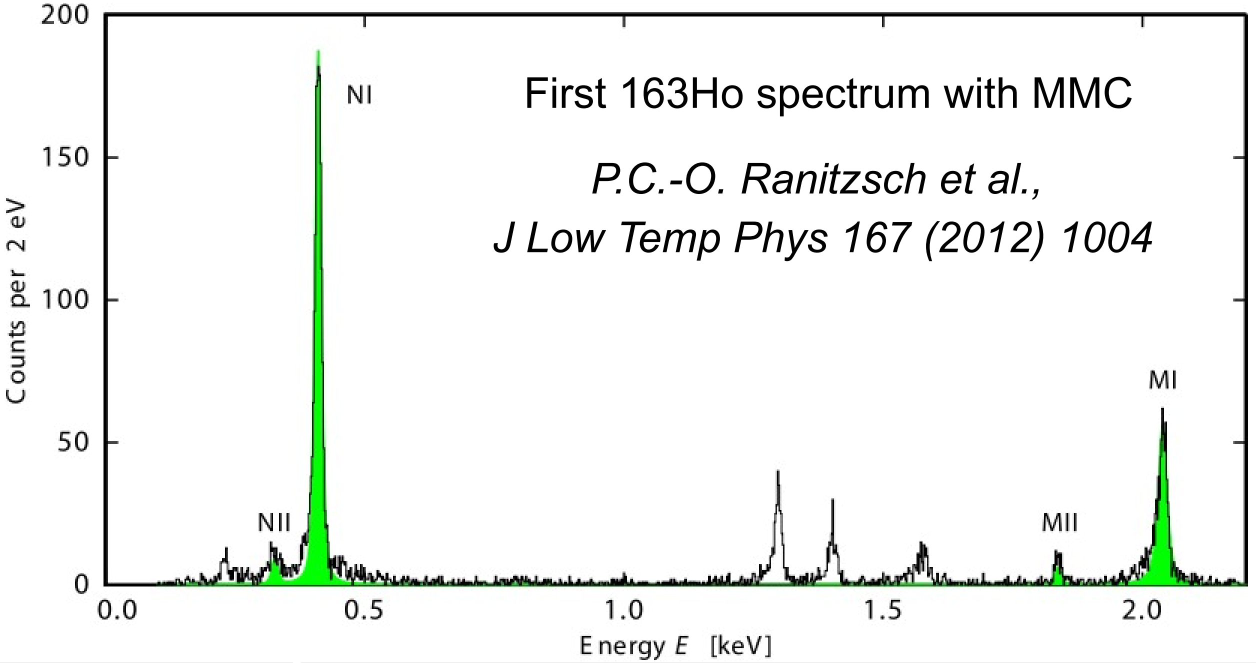
Angelo Nucciotti, Meudon 2011

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

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

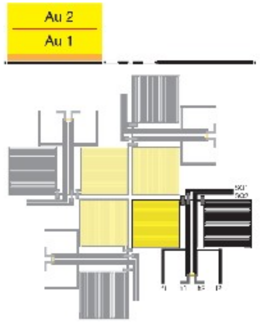


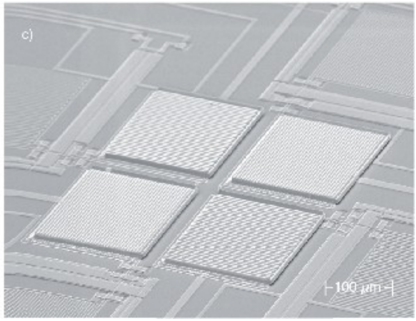




First 163Ho spectrum with MMC

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

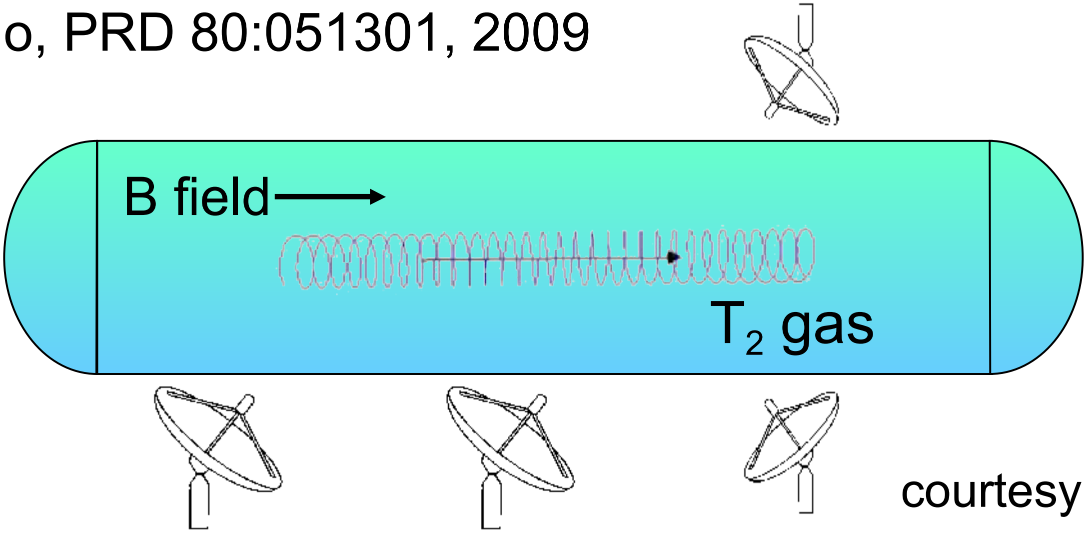




courtesy L. Gastaldo

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 just started
- Is it really possible ?
- What are the systematic uncertainties ?

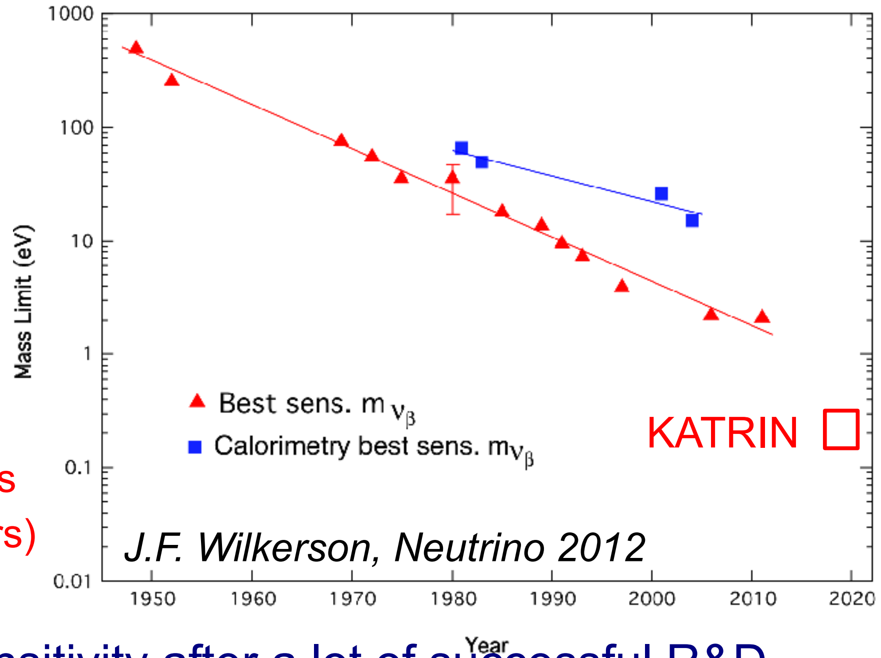
Summary & Outlook

Neutrinos do oscillate → non-zero neutrino mass which is very important
for nuclear & particle physics (which model beyond the Standard Model ?)
for cosmology & astrophysics (evolution of the universe)

3 complementary approaches to the neutrino mass:
cosmology, 0νββ, direct (no further assumptions)

KATRIN is the next generation
direct neutrino mass experiment
with 0.2 eV sensitivity

2012-2013: commissioning of spectrometer & detector
2011-2015: commissioning of tritium source & elimination lines
2015 (?): regular data taking for 5-6 years (3 full-beam-years)



J.F. Wilkerson, Neutrino 2012

MARE, ECHO: cryo-bolometers may achieve similar sensitivity after a lot of successful R&D

Quite different attempts: Project 8, ...