Neutrino Mass Measurements in Laboratory Experiments

Thomas Thümmler for the KATRIN collaboration
International Workshop on Double Beta Decay and Neutrinos, Osaka, Japan, 2011

KIT Center Elementary Particle and Astroparticle Physics (KCETA)
Institute for Nuclear Physics (IK)

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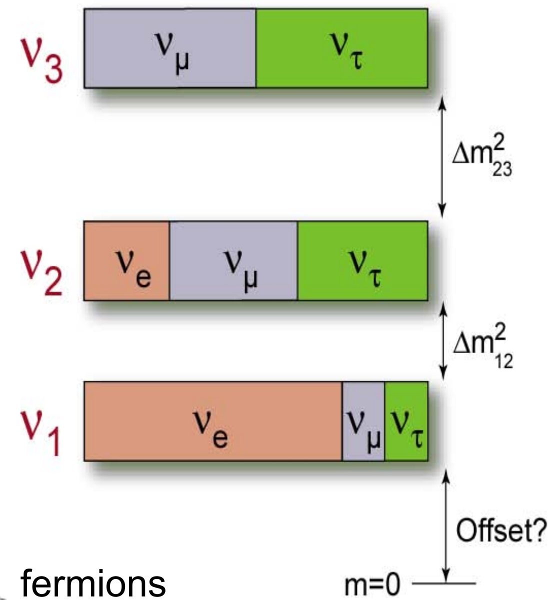
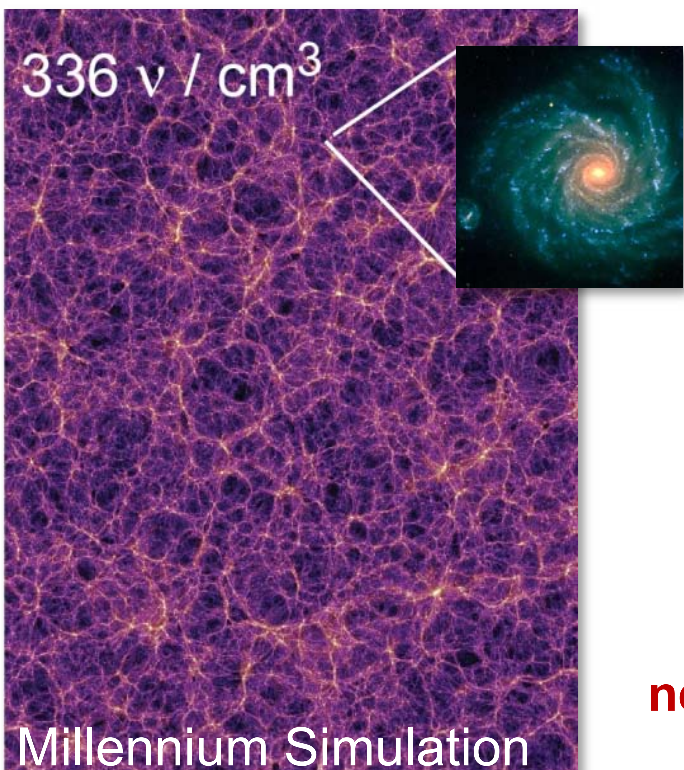
- Motivation of ν-mass determination
- Direct methods
- Present and future experiments
- KATRIN overview
- KATRIN status
- Summary and Outlook

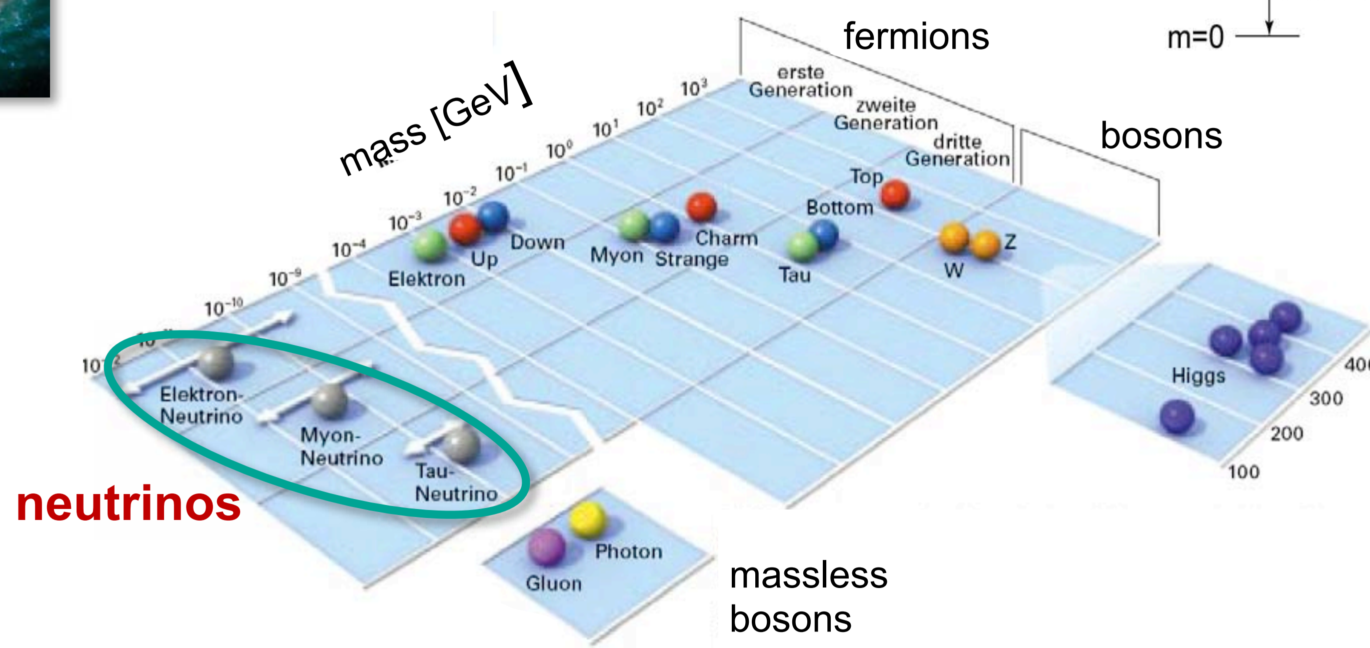
Motivation: ν´s in Astroparticle Physics

cosmology: role of ν´s as hot (warm?) dark matter?
particle physics: origin and hierarchy of the ν-mass?



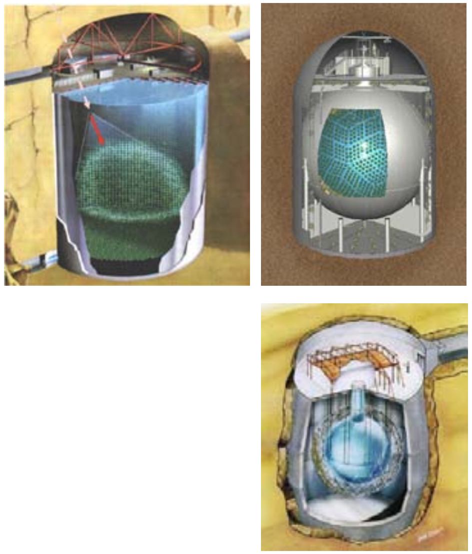
cosmology ⇔ **particle physics**





Neutrinos mass: status and perspectives

Experiments on Neutrino Oscillations:

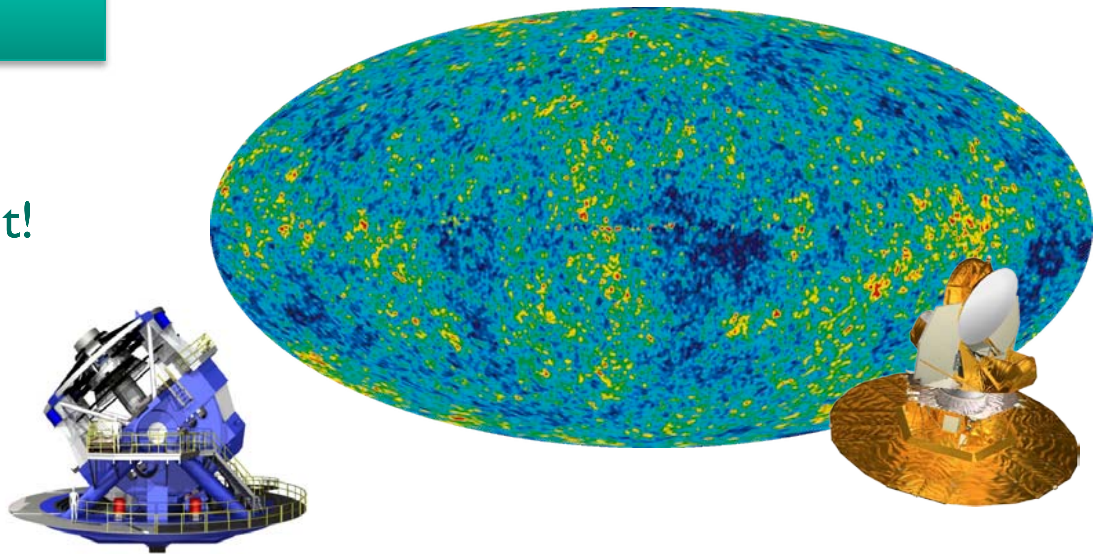


- Clear evidence for neutrino flavour oscillations:
  - Atmospheric neutrinos: $(\Delta m_{32})^2 \cong 2.4 \times 10^{-3}\ eV^2/c^4$
  - Solar neutrinos: $(\Delta m_{21})^2 \cong 7.6 \times 10^{-5}\ eV^2/c^4$

➔ Well established fact: $m_\nu \neq 0$

Input from Cosmology:

- measures Σm_i and HDM Ω_ν
- very sensitive, but model dependent!
- WMAP 7yr: $\Sigma m_i < 1.2$ eV
  (Hannestad et al., arXiv:1004.0695)
- potential: Σm_i = 20-50 meV
  (Planck, LSST, weak lensing)



Neutrinos mass: status and perspectives

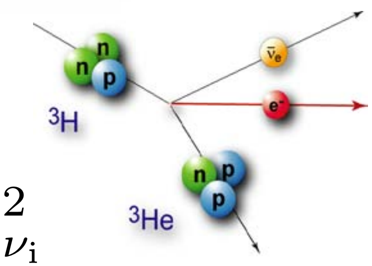
status and potential of neutrino masses in lab experiments

kinematics of ß-decay
absolute ν_e-mass: m_ν

search for 0νßß
eff. Majorana mass $m_{ßß}$

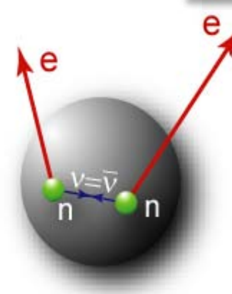
model-independent

squared neutrino mass:



$$m^2_{\nu_e} = \sum_i |U_{ei}|^2 \cdot m^2_{\nu_i}$$

- direct, from kinematics
- status: $m_\nu < 2.3$ eV
- potential: $m_\nu = 200$ meV
- MARE, Project 8, KATRIN



model-dependent (CP-phases)

effective Majorana mass:

$$m_{\beta\beta} = \left| \sum_i U^2_{ei} \cdot m_{\nu_i} \right|$$

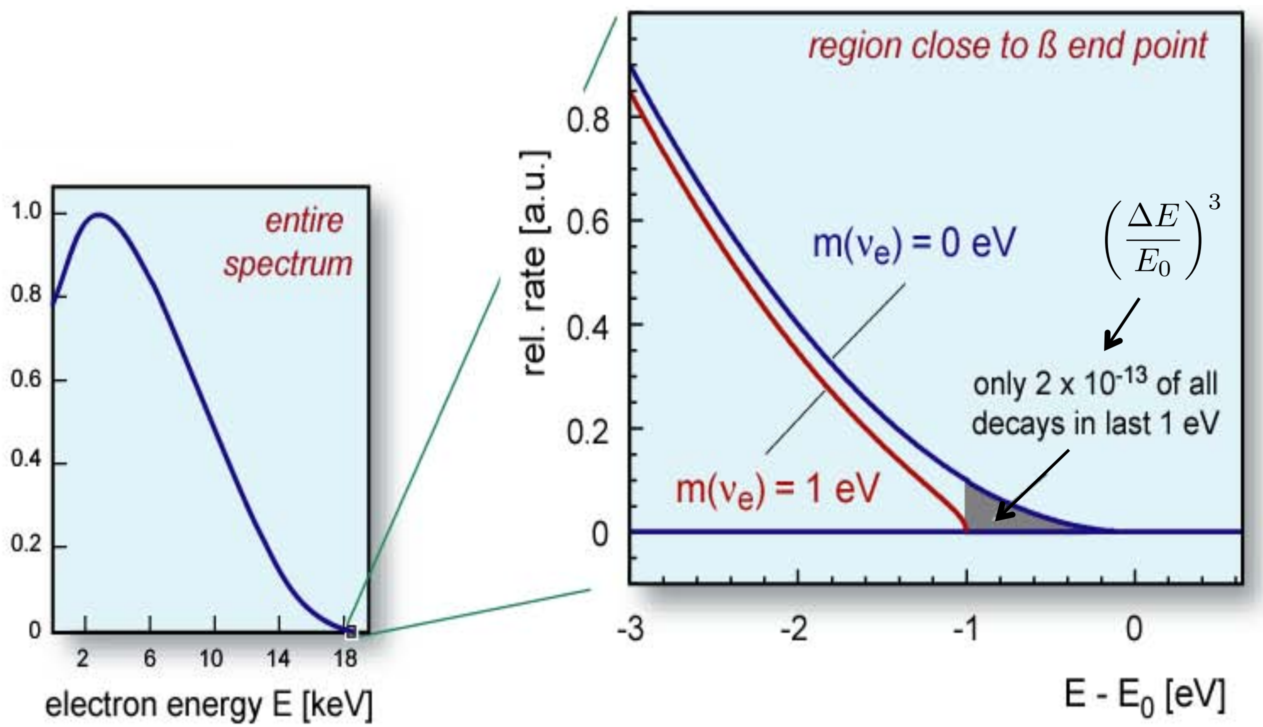
- probe ν as Majorana particle: $\nu = \bar{\nu}$?
- status: $m_{ßß} < 0.35$ eV, evidence?
- potential: $m_{ßß} = 20\text{-}50$ meV
- GERDA, EXO, SNO+, MAJORANA, Cuore, KamLAND-Zen, ...

$m(\nu_e)$ from β decay: model-independent, based on kinematics and energy conservation

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

(ν– mass)^2



$m_\nu \neq 0$ influence:

- shift of E_0
- changed shape
- shape to be analysed!

key requirements:

- low endpoint β source
- high count rate
- high energy resolution
- extremely low background

Two complementary approaches with different systematics:

	calorimeter	spectrometer
source	^{187}Re (metallic or dielectric) • source = detector	T_2 (gaseous or condensed) • external β source
endpoint	2.47 keV	18.6 keV
$t_{1/2}$	4.3×10^{10} y	12.3 y
activity	low: $< 10^5$ β/s, ≈ 1 Bq / mg Re	high: $\approx 10^{11}$ β/s, 4.7 Ci/s injection
technique	single crystal bolometer	electrostatic spectrometer
response	entire β decay energy	kinetic energy of β decay electrons
interval	entire spectrum	narrow interval close to endpoint
method	differential energy spectrum	integrated energy spectrum
set-up	modular size, scalable	integral design, size limits
resolution	$\Delta E_{expected} \approx 5 - 10$ eV (FWHM)	$\Delta E_{expected} \approx 0.93$ eV (100 %)

→ MARE

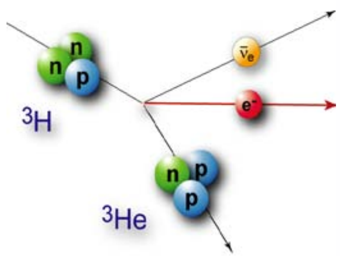
→ KATRIN

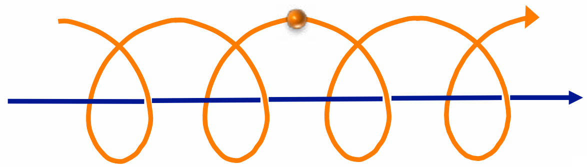
Measuring the Neutrino Mass

3rd approach, proposed recently:

PROJECT 8

Radio-frequency spectroscopy of coherent cyclotron radiation of β decay electrons.

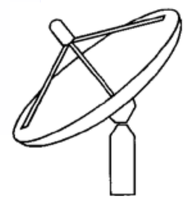




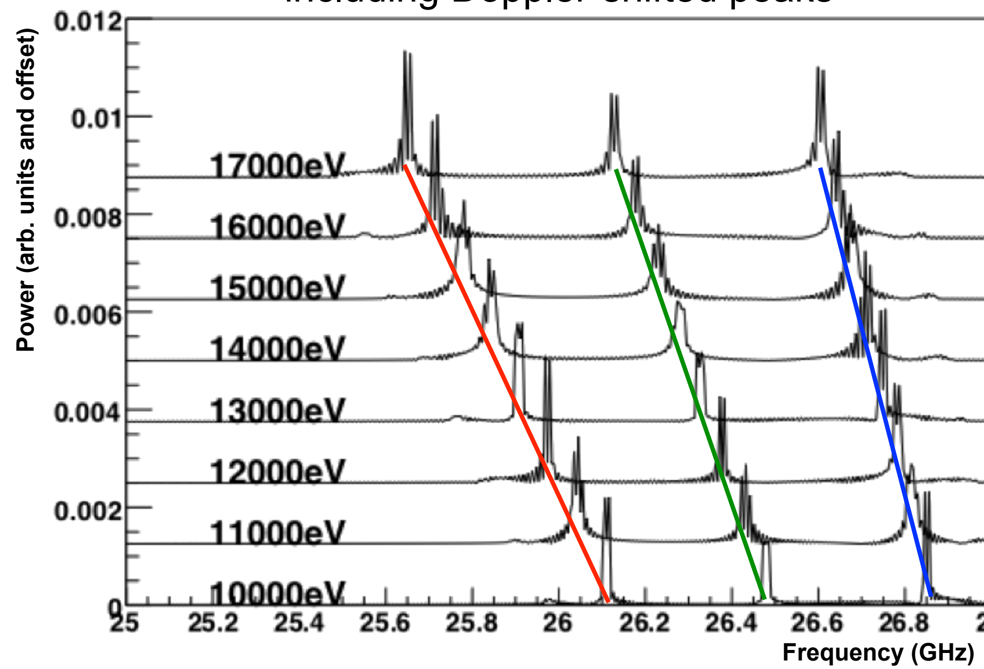
Electron motion in a uniform magnetic field

Cyclotron Frequency

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



Signal power for different electron energies, including Doppler-shifted peaks



Experimental Parameter:

- B = 1 T
- ω(γ) = 27 GHz
- ΔE = 1 eV
- P_s = 1×10^{-15} W
- P_N = 5×10^{-17} W
- T = 77 K

Projected sensitivity on m_ν: 0.1 eV

3rd approach, proposed recently:

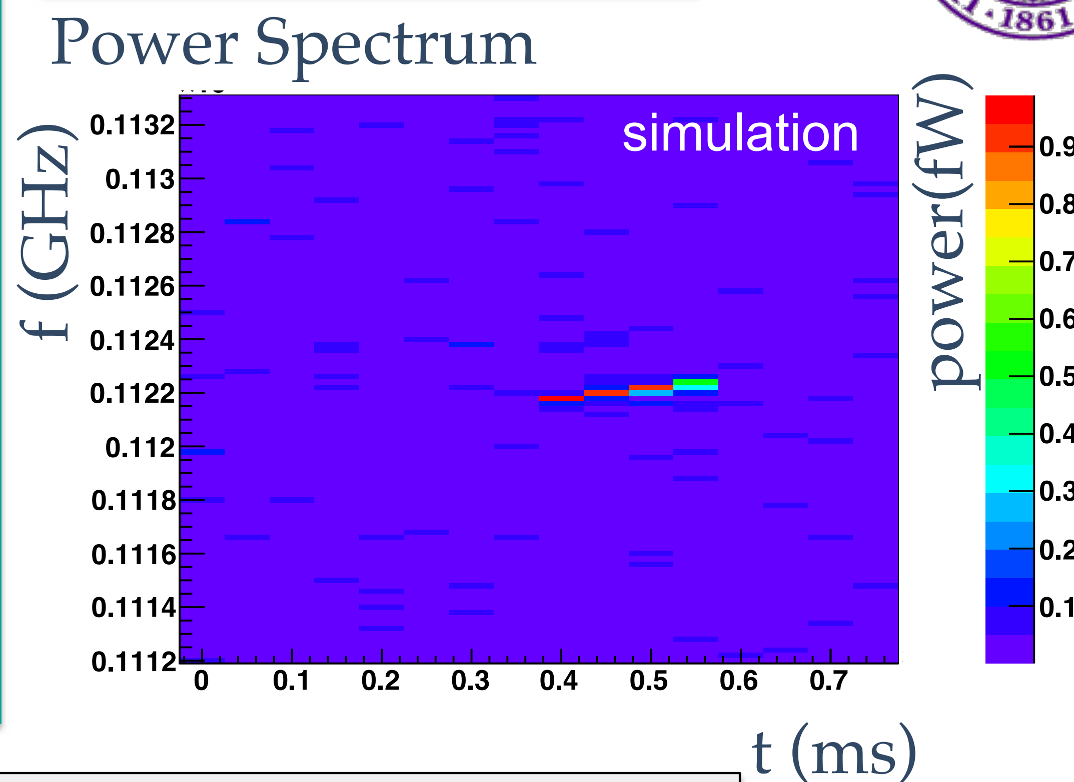
Present Status:

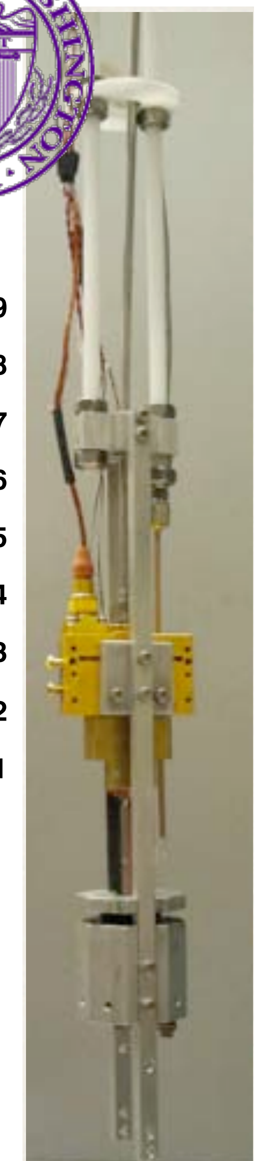
- Prototype running
- ^{83m}Kr in magn. bottle
- Investigate antenna, receiver and DAQ
- Watch for electron signals

Complications:

- sidebands
- Doppler shifts
- reflections
- B-field variations

Electron signal expected:





B. Monreal, J. Formaggio, Phys. Rev. D 80, 051301(R) (2009)
Relativistic cyclotron radiation detection of tritium decay electrons as a new technique for measuring the neutrino mass

MARE

Measuring the Neutrino Mass

MARE: Microcalorimeter Arrays for a Rhenium Experiment

- ^{187}Re as β-emitter: isotropic abundance of 62.6 %
- $5/2^+$ to $1/2^-$ first order unique forbidden transition

$$^{187}_{85}\mathrm{Re} \longrightarrow {}^{187}_{86}\mathrm{Os} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

MARE Phase-I:

ΔE = 15 eV
Δt = 50 μs
3 years

- based on MANU and MIBETA (result: $m_\nu < 15$ eV / 6×10^6 β's)
- improve sensitivity for m_ν by factor 10
- increase statistics to 10^{10} β decays
- scrutinize tritium-based MAINZ and TROITZK result

→ $m_\nu \approx 2$ eV

- Genova: metallic Re, superconducting at T = 1.6 K, 1 mg absorber
- Milano: new $AgReO_4$ crystals, 500 μg absorber at T ≈ 85 mK, 6x6 pixel arrays, energy resolution ΔE = 34 eV at 2.5 keV

MARE Phase-II:

ΔE = 5 eV
Δt = 1 μs
> 5 years

- improve sensitivity for m_ν by another factor 10
- increase statistics to 10^{14} β decays
- scrutinize KATRIN in future

→ $m_\nu \approx 0.2$ eV

- R&D program for new detectors
- magnetic micro-calorimeters (MMC) + paramagnetic sensor + SQUID
- projected sensitivity requires ≈50000 bolometers and t > 5 years

Measuring the Neutrino Mass

MARE: Microcalorimeter Arrays for a Rhenium Experiment

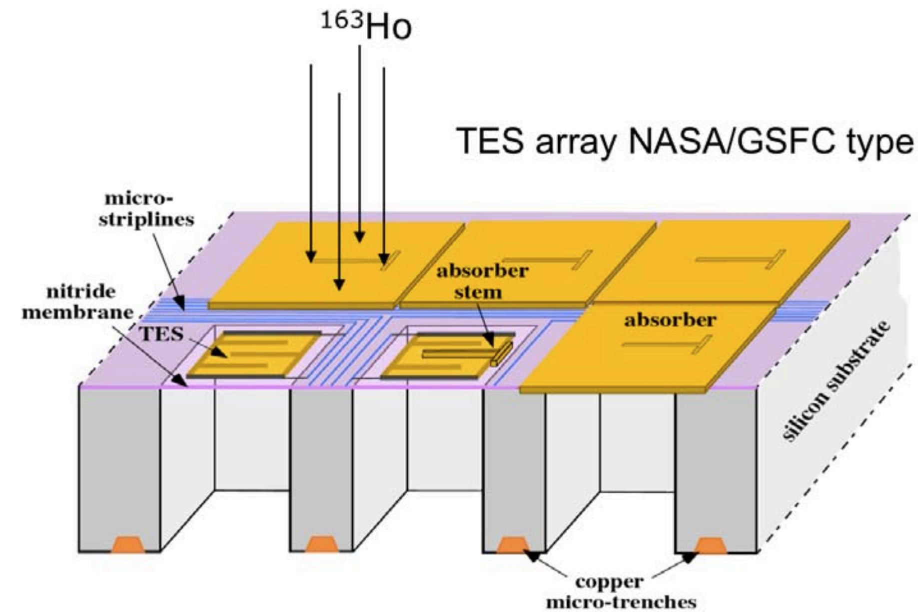
moving towards ^{163}Ho isotope

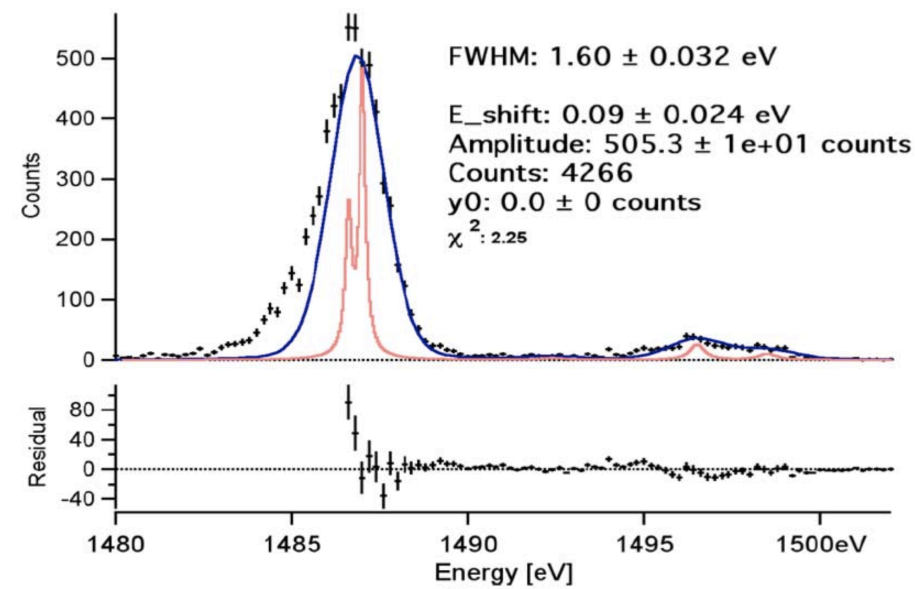
- EC decay of Holmium to Dysprosium:

$$^{163}_{67}\mathrm{Ho} \rightarrow\, ^{163}_{66}\mathrm{Dy}^* + \nu_\mathrm{e}$$

- $Q_{EC} \approx 2.5$ keV, $t_{1/2} = 4570$ y
- Use TES arrays with 32x32 pixels
- Resolution 1 – 2 eV FWHM
- Need 5 TES arrays for 0.2 eV/c^2 sensitivity
  - Makes **5000 pixels** (vs. 50000 for Re)

- ^{163}Ho production has been demonstrated
- Embedding process is under investigation
- Readout developed and tested as prototype
- Next: TDR for funding





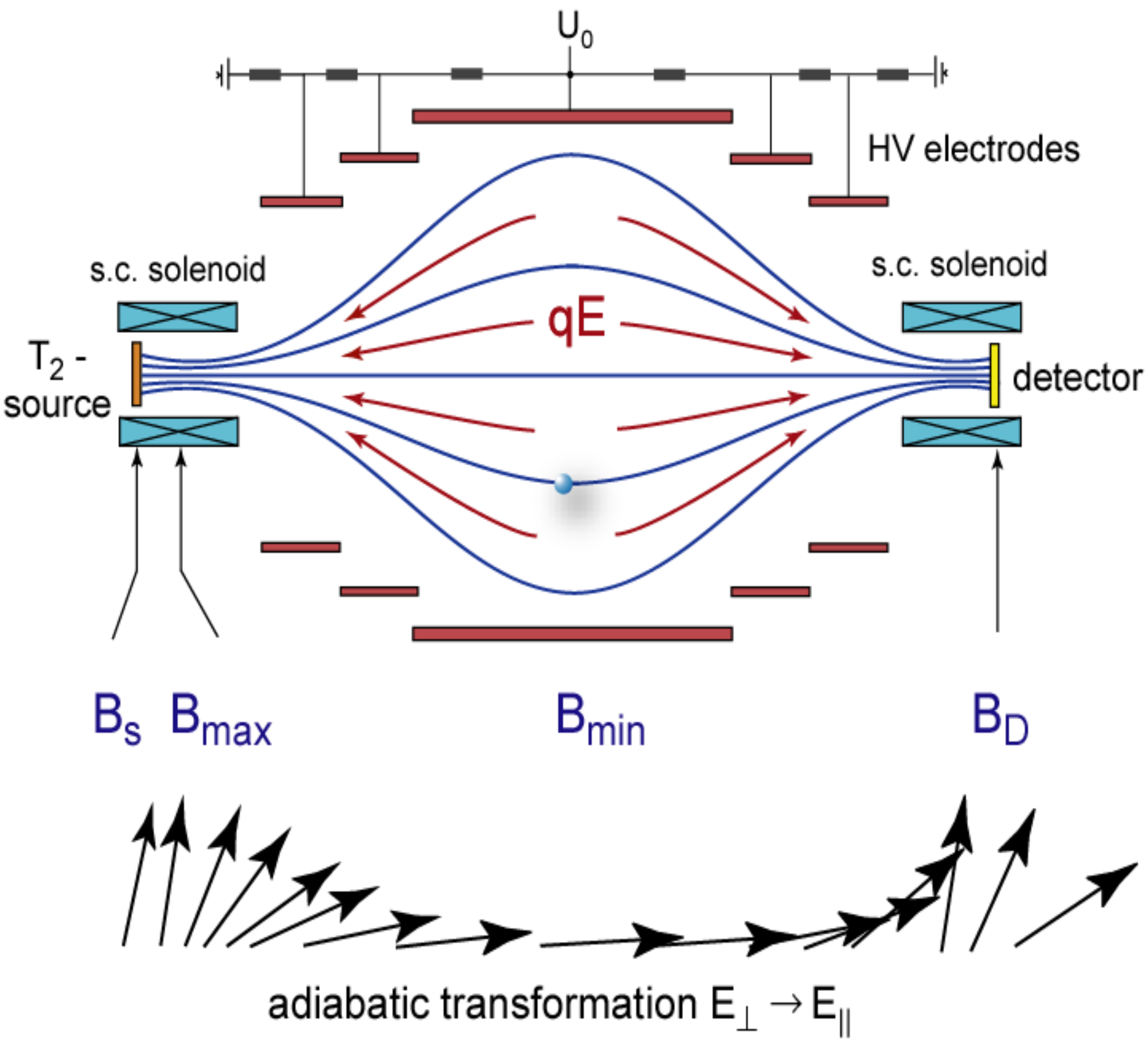
according to F. Gatti, ISAPP 2011 and J Low Temp Phys (2008) 151

KATRIN

The MAC-E Filter

Magnetic Adiabatic Collimation with Electrostatic Filter

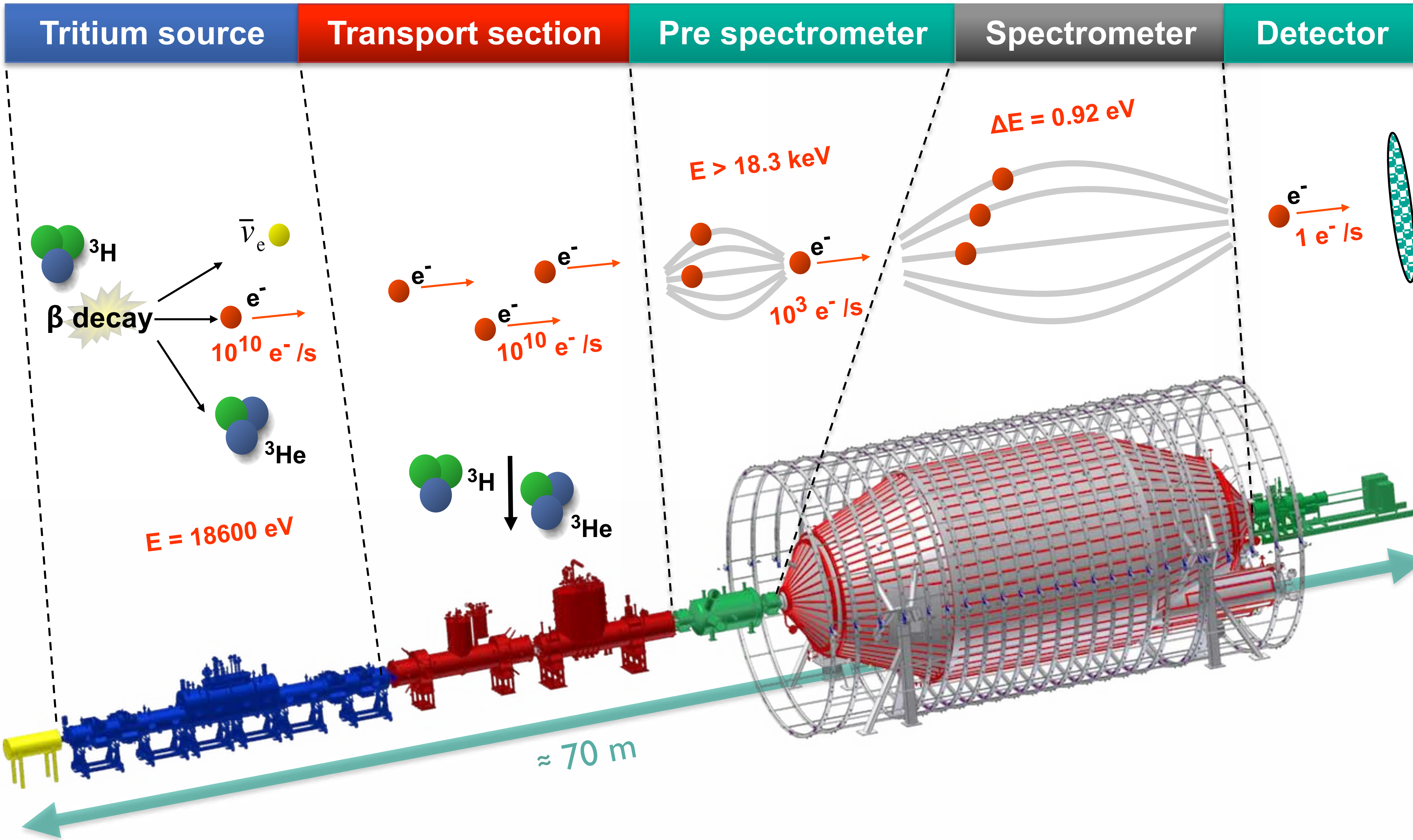
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)



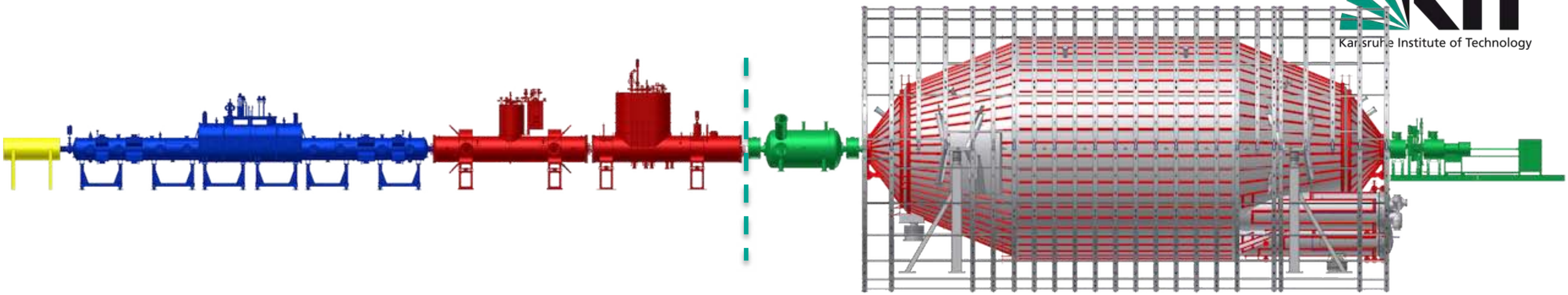
- inhom. magn. guiding field:
  → gradient force:
  adiab. transformation $\mathbf{E_\perp \to E_{||}}$
  due to $\boldsymbol{\mu} = \mathbf{E_\perp/B} =$ ***const.***
- momentum of e^- || magnetic field
  → el. retarding potential
  → energy analysis

  → **high-pass filter** with a sharp transmission function, no tails!
- high resolution:
  $\mathbf{\Delta E = E \cdot B_{min} / B_{max}}$
- magn. adiab. collimation
  → large solid angle (2π)

The KATRIN Setup



The KATRIN Setup

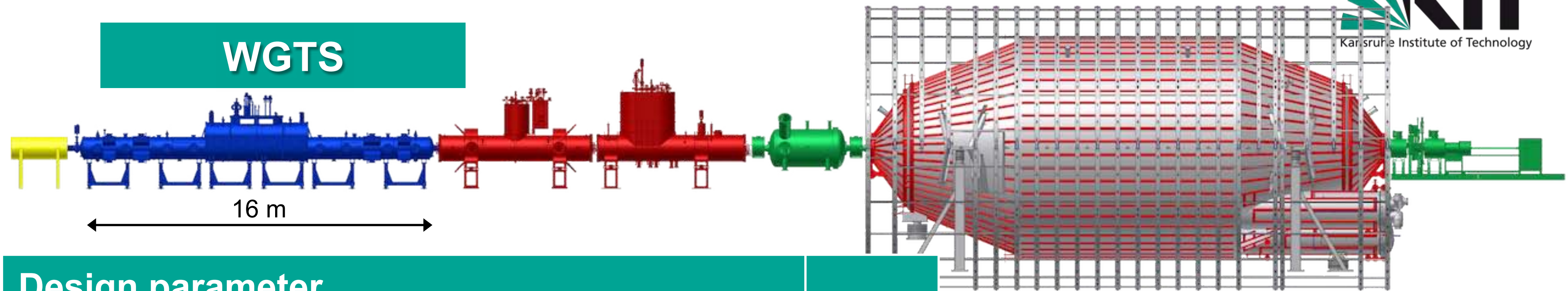


tritium-bearing components → **10^{11} electrons/s tritium source**

electrostatic spectrometers & detector → **$<10^{-2}$ cps total background**

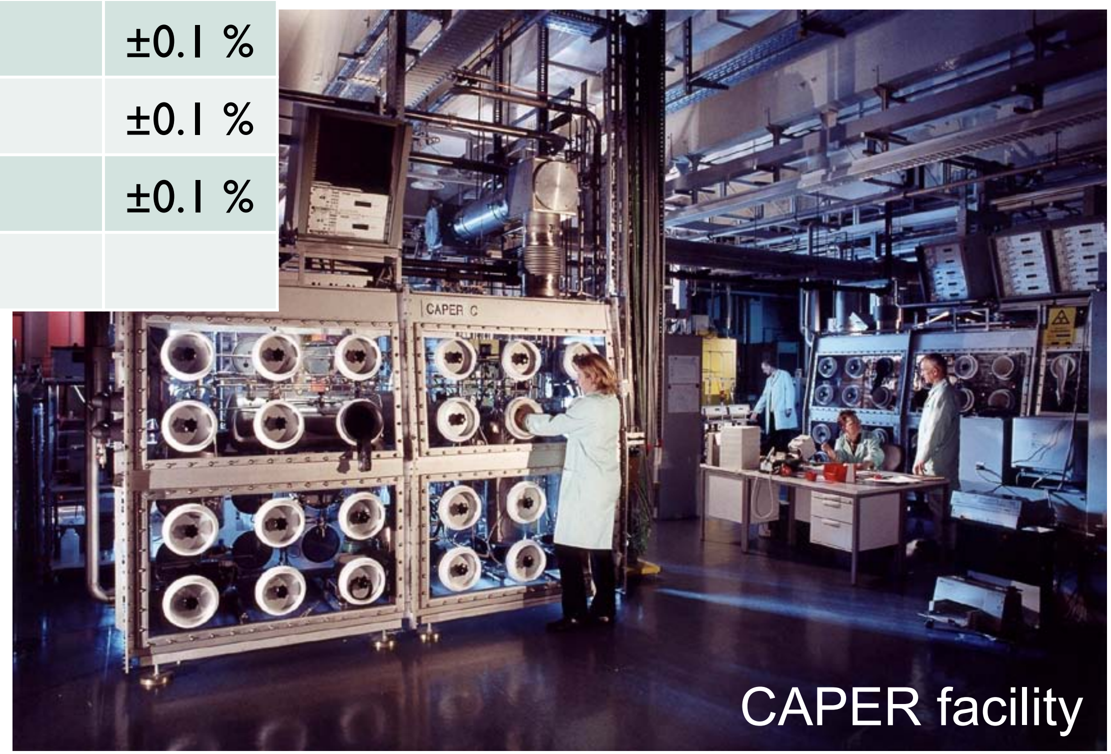
- 10^{-3} stability of tritium source column density ρd
- retention factor for molecular tritium $R = 10^{14}$
- effective removal of ions
- fully adiabatic (meV scale) transport of electrons over > 50 m
- avoid particle storage in Penning-like traps
- avoid contermination by Rn in the volume

Windowless Gaseous Tritium Source WGTS



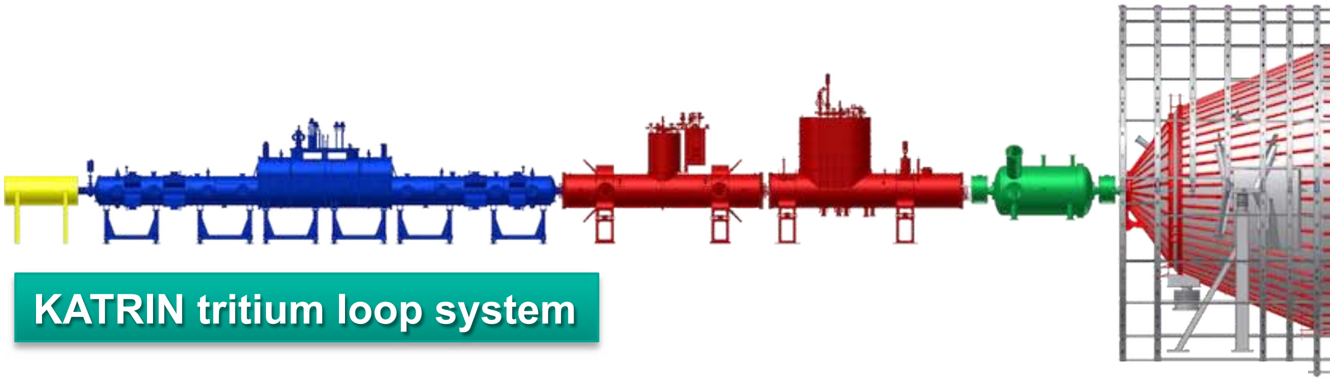
Design parameter		
luminosity	1.7×10^{11} Bq	
injection rate	5×10^{19} T_2/s ≈ 40 g/day ≈ 10 kg/y	
Tritium purity	> 95%	±0.1 %
temperature	T = 27 K ± 30 mK	±0.1 %
pressure	$p_{inj} \approx 10^{-3}$ mbar	±0.1 %
magnetic guiding	B = 3.6 T	

Tritium Laboratory Karlsruhe
- a unique research facility in Europe

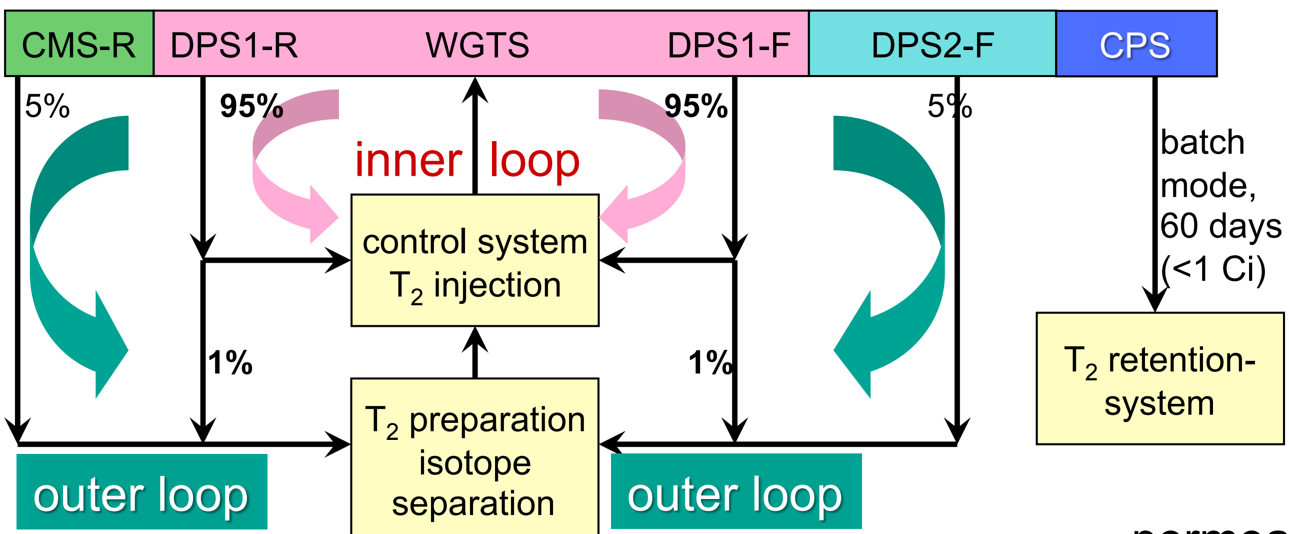


CAPER facility

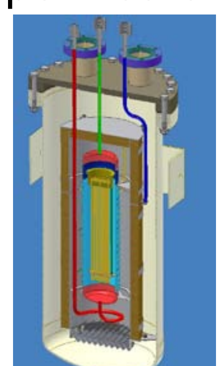
Windowless Gaseous Tritium Source WGTS

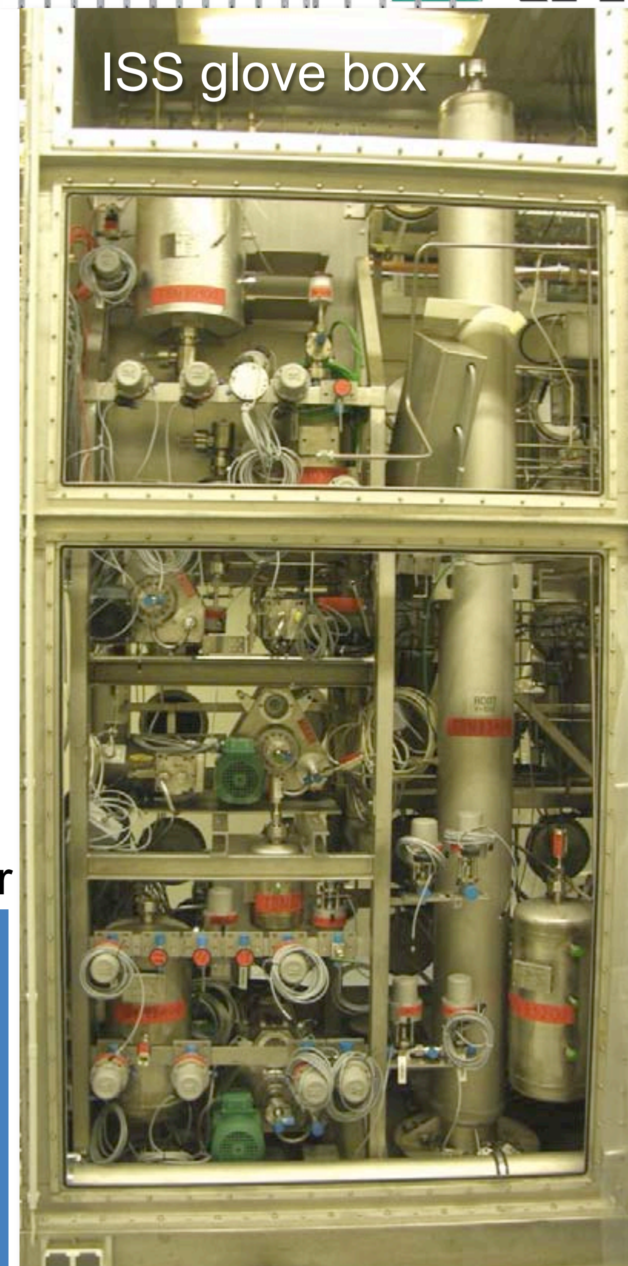


KATRIN tritium loop system



permeator



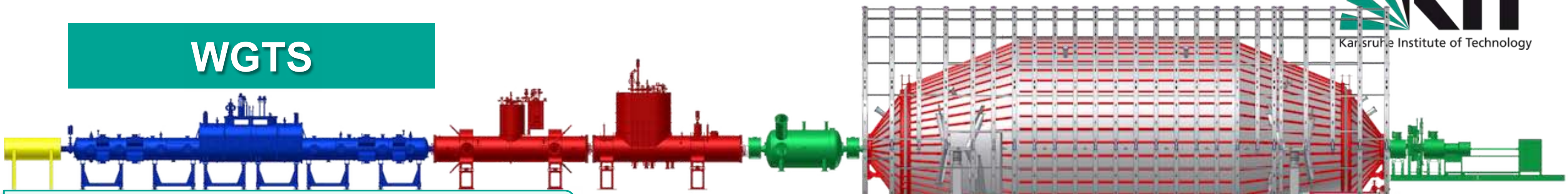


Up and running **extremely** stable!

- **designed for a stability at 10^{-3} level**
- **achieved: 2×10^{-4} over 4 months**

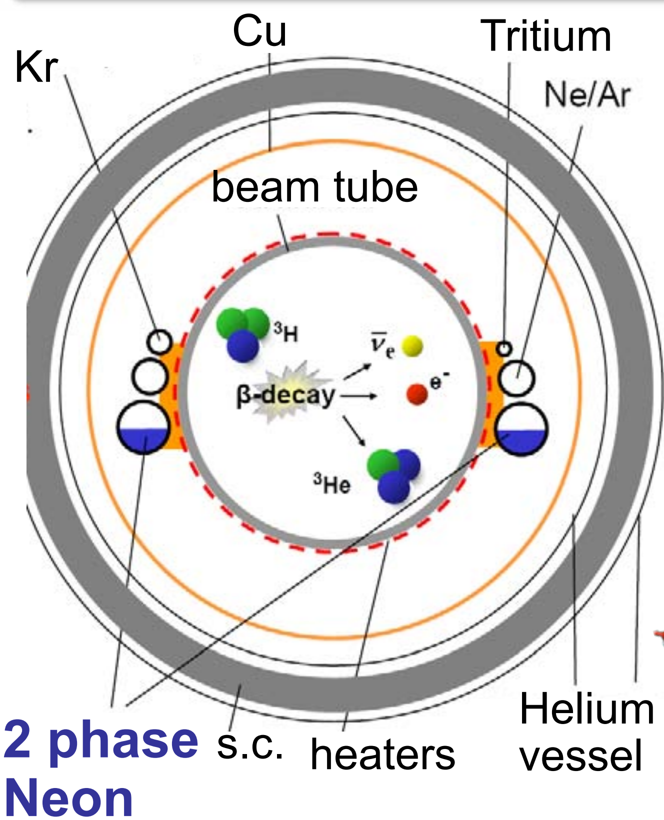
Windowless Gaseous Tritium Source WGTS

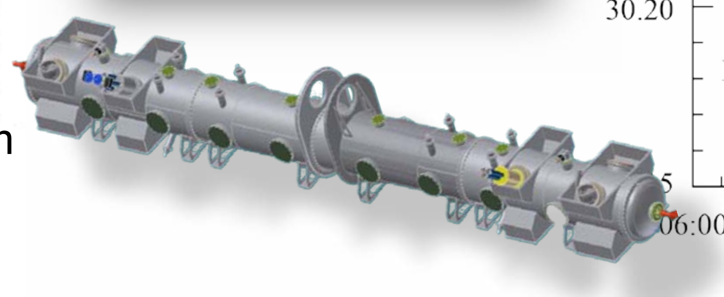
WGTS



KATRIN requirement:

T = 27 K with ΔT < 30 mK

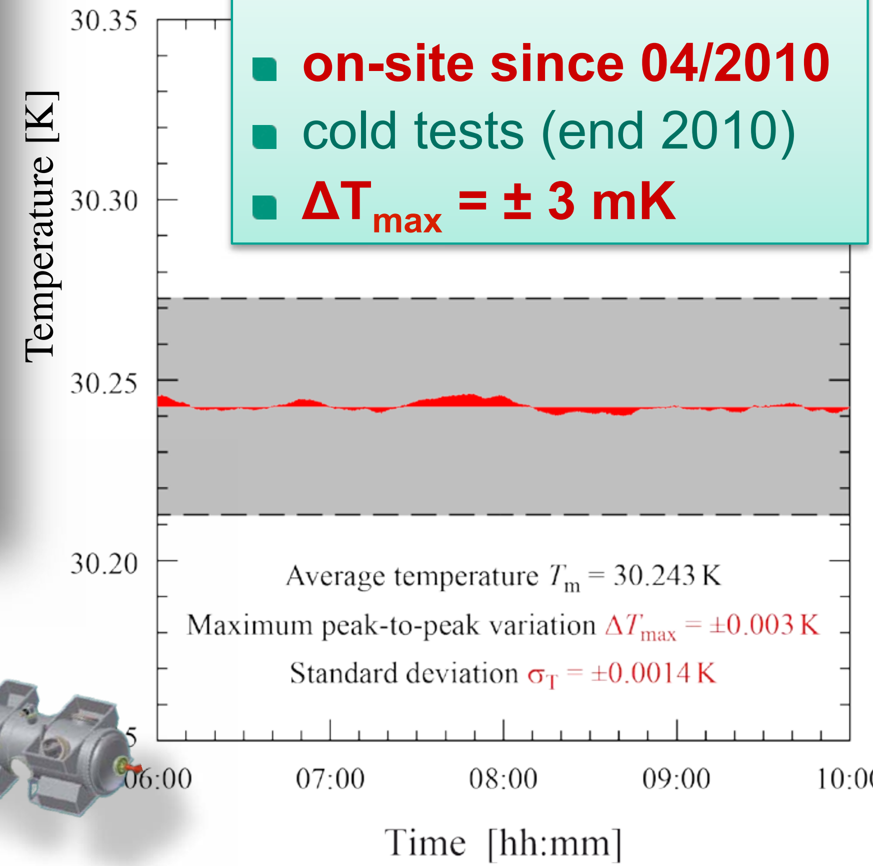




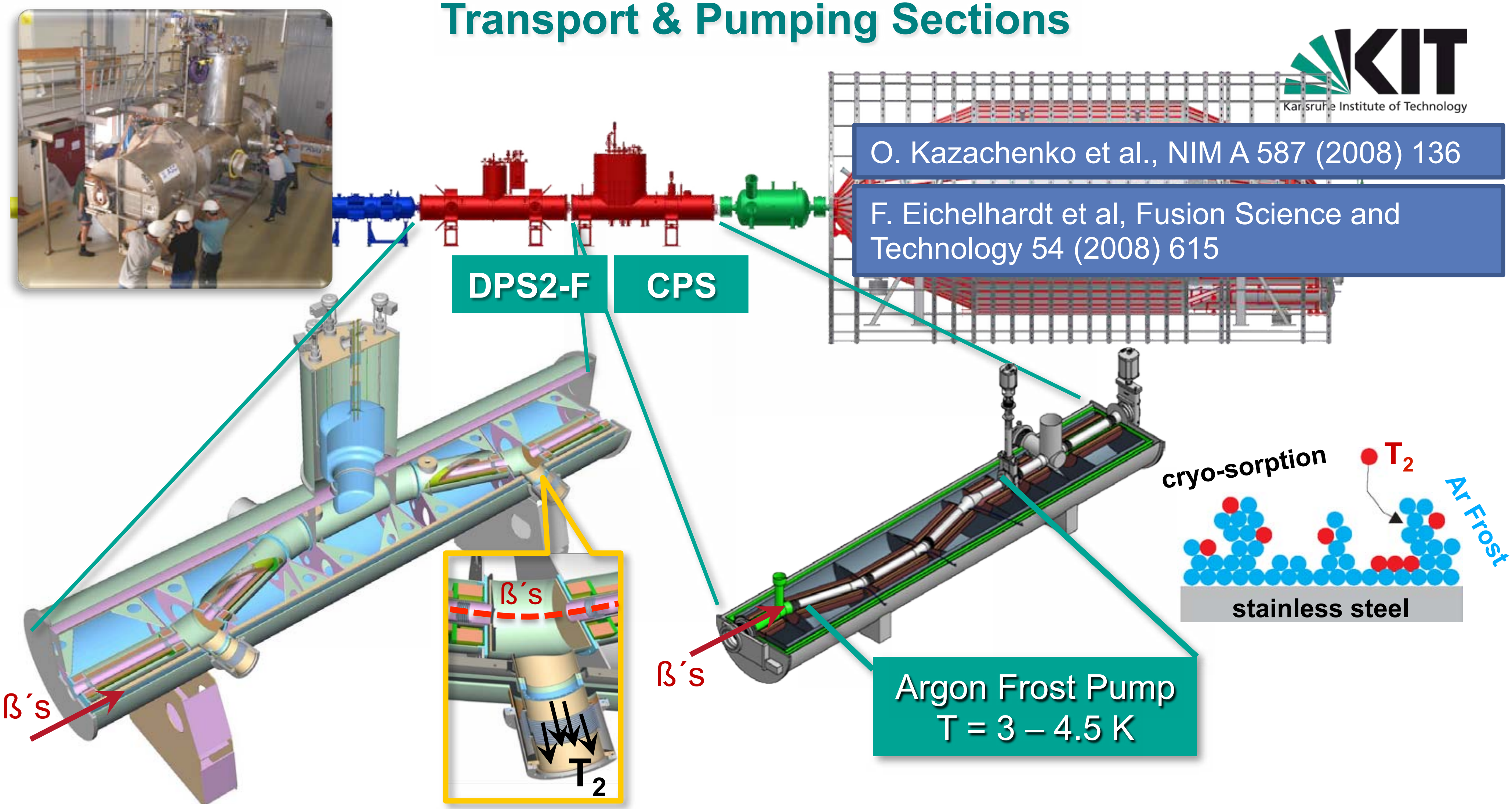
S. Grohmann et al., Cryogenics, Volume 51, Issue 8, August 2011

WGTS Demonstrator:

- **on-site since 04/2010**
- cold tests (end 2010)
- **ΔT_{max} = ± 3 mK**



Transport & Pumping Sections



- active pumping, 4 TMPs
- Tritium retention 10^5
- magnetic field: 5.6 T
- on-site since 08/2009, under commissioning

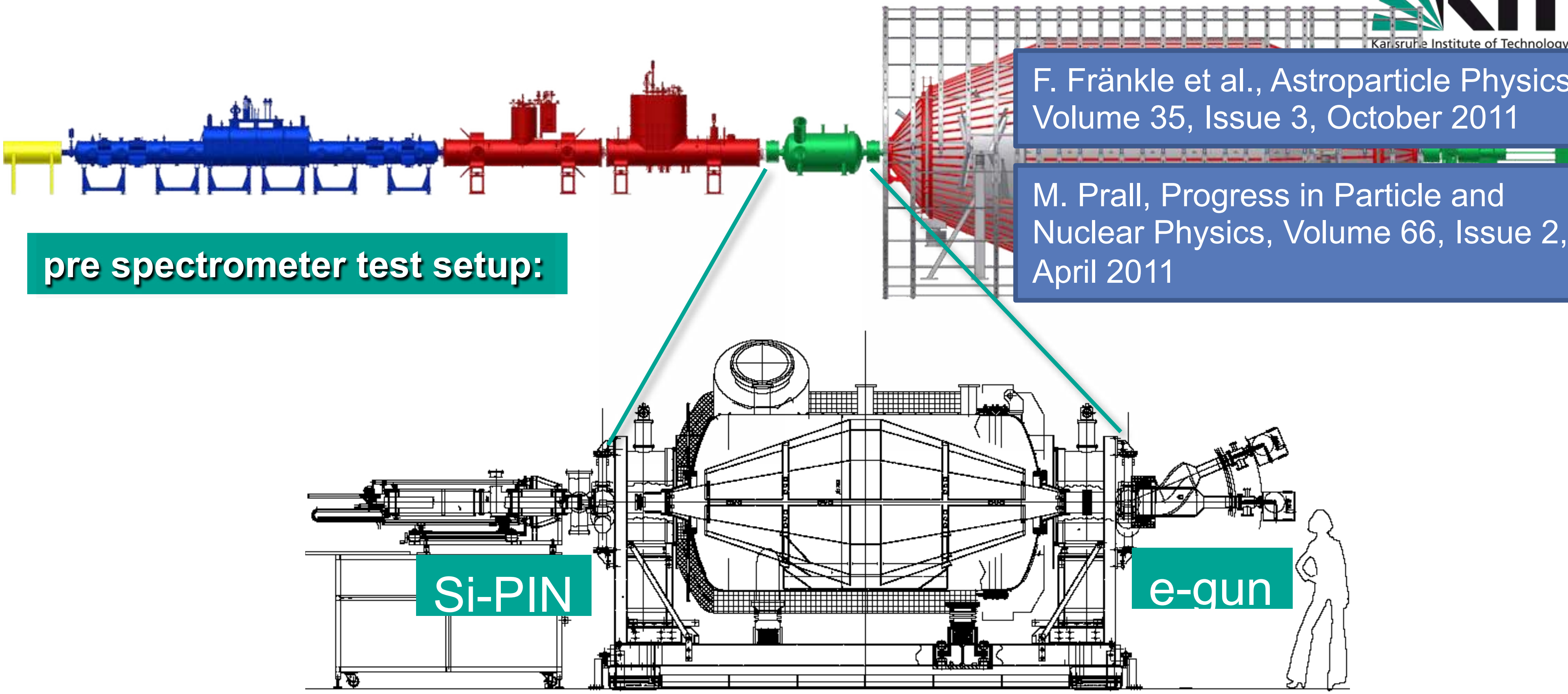
- pumping by cryo-sorption
- Tritium retention $>10^7$
- magnetic field: 5.6 T
- delivery postponed to 2012

Pre Spectrometer

F. Fränkle et al., Astroparticle Physics, Volume 35, Issue 3, October 2011

M. Prall, Progress in Particle and Nuclear Physics, Volume 66, Issue 2, April 2011

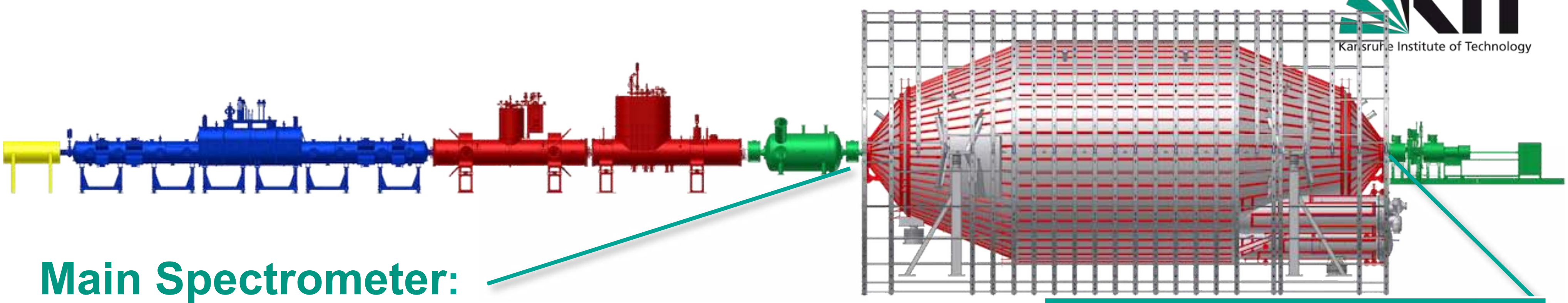
pre spectrometer test setup:



- Tested all major technologies for the Main Spectrometer
  - Vacuum, electro-magnetic and transmission properties, detector
- Achieved quasi background free operation by
  - Avoiding Rn and electron trapping conditions in the volume

Tests have been finished, vessel moved to final position in beam-line

Main Spectrometer



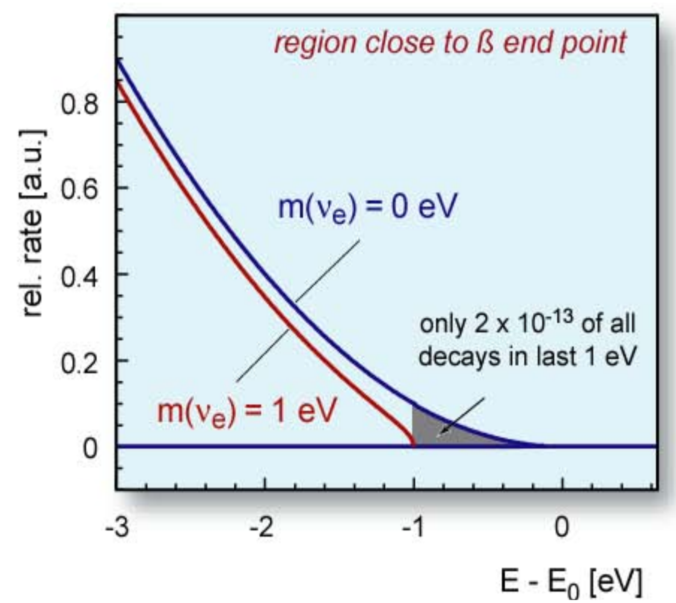
Main Spectrometer:

- MAC-E Filter principle → precise energy analysis
- Vacuum vessel on retarding potential
- high resolution: **ΔE = 0.93 eV**

$$\Delta E/E_0 = B_{min}/B_{max} = 1/20000$$

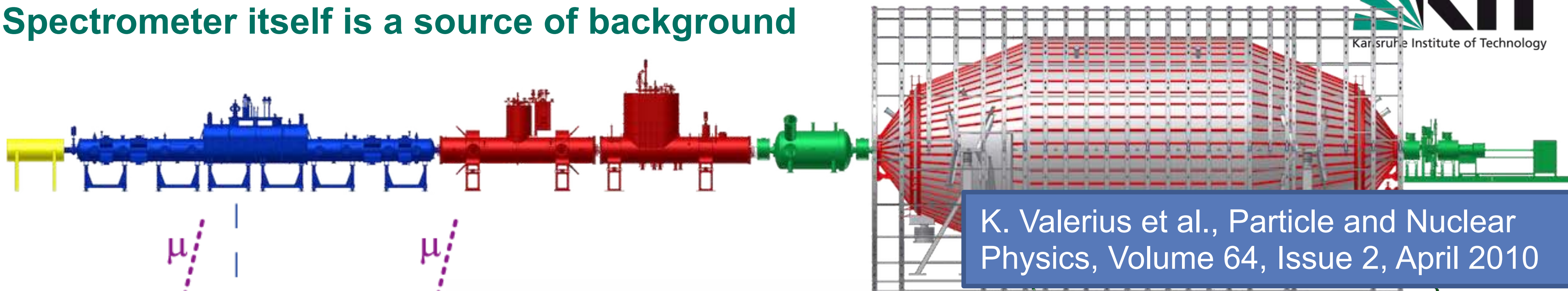
- ∅ 10 m, length 23 m
  - volume: 1240 m³
  - inner surface: 690 m²
- **Reduce background rate:**
  - **ultra high vacuum (UHV): $p < 10^{-11}$ mbar**
  - **induced by cosmic ray muons:**
    → background increase
    → counter measure: wire electrode

Precision Energy Filter:
variable retardation
U_0 = -18.4 … -18.6 kV
ΔE ~ 0.93 eV

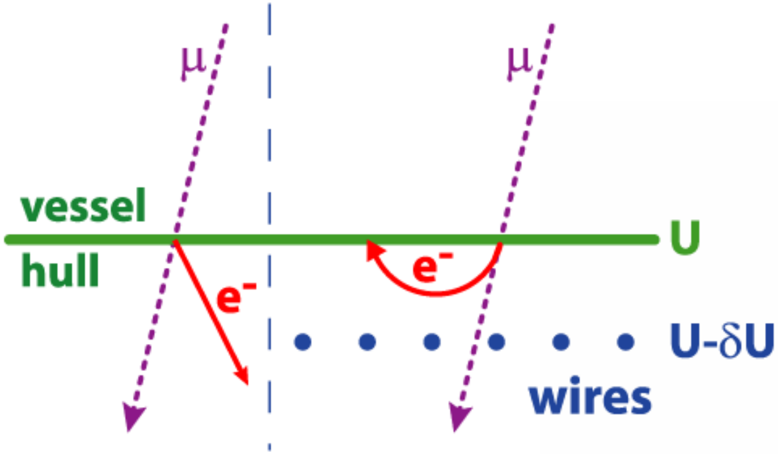


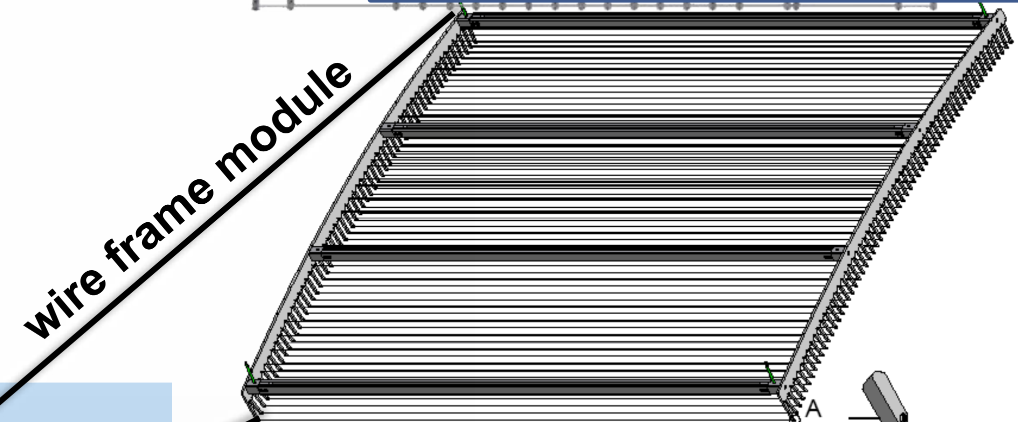
Main Spectrometer

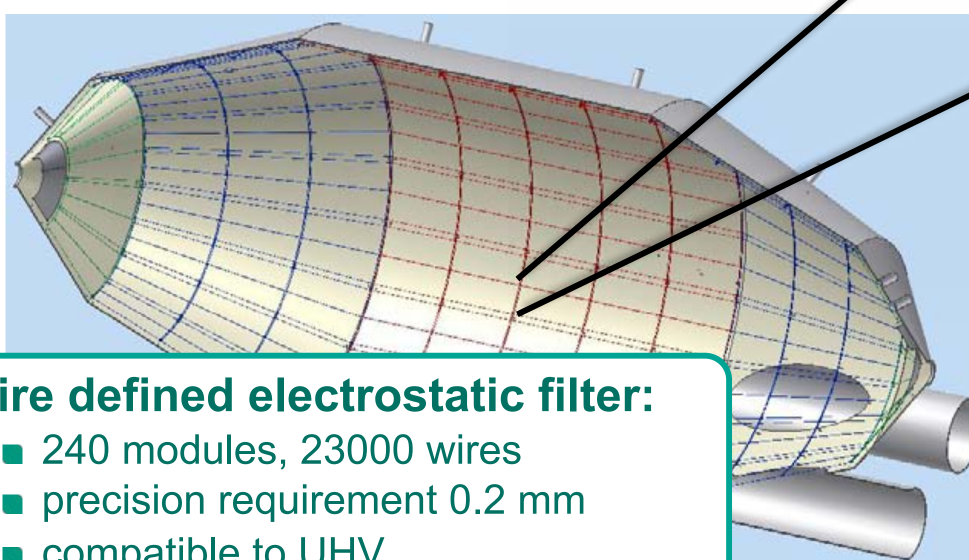
Spectrometer itself is a source of background

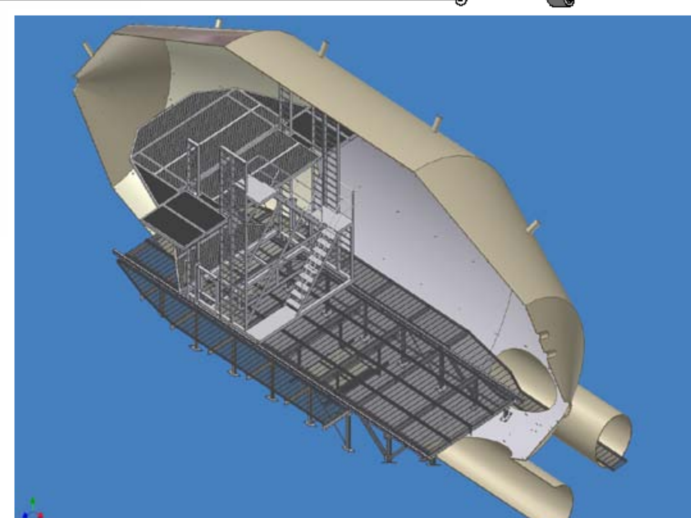


K. Valerius et al., Particle and Nuclear Physics, Volume 64, Issue 2, April 2010







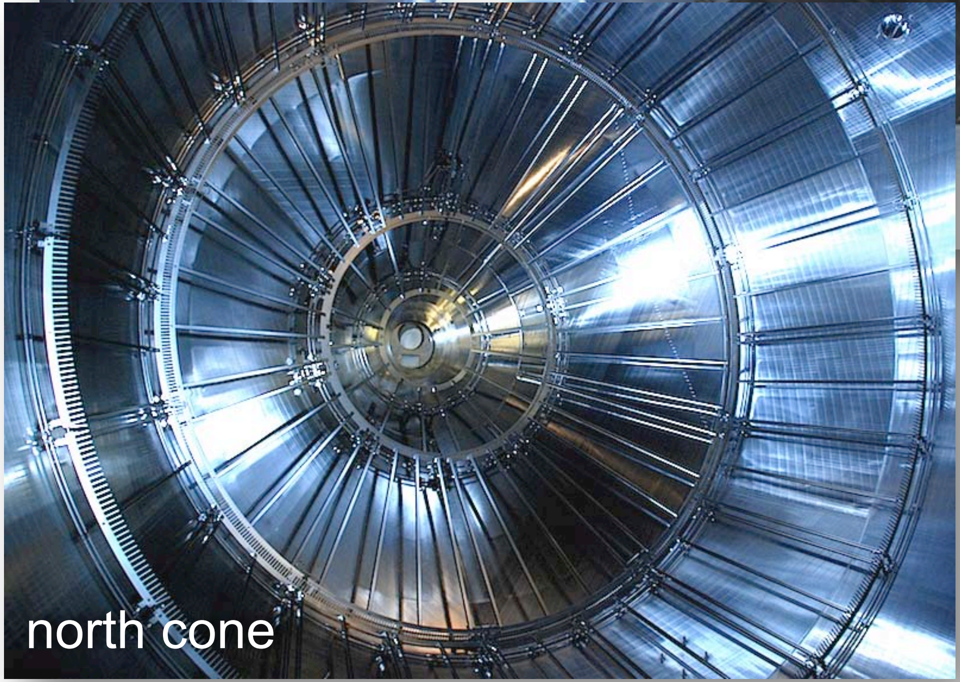


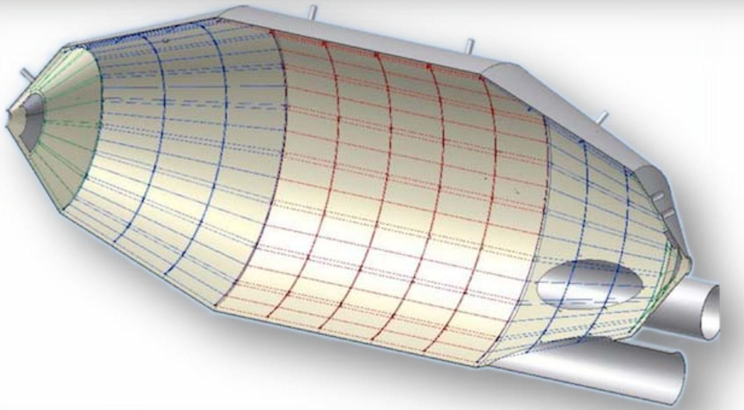
Wire defined electrostatic filter:

- 240 modules, 23000 wires
- precision requirement 0.2 mm
- compatible to UHV

Wire Electrode System - Mounting

Installation ongoing → finished until end of 2011





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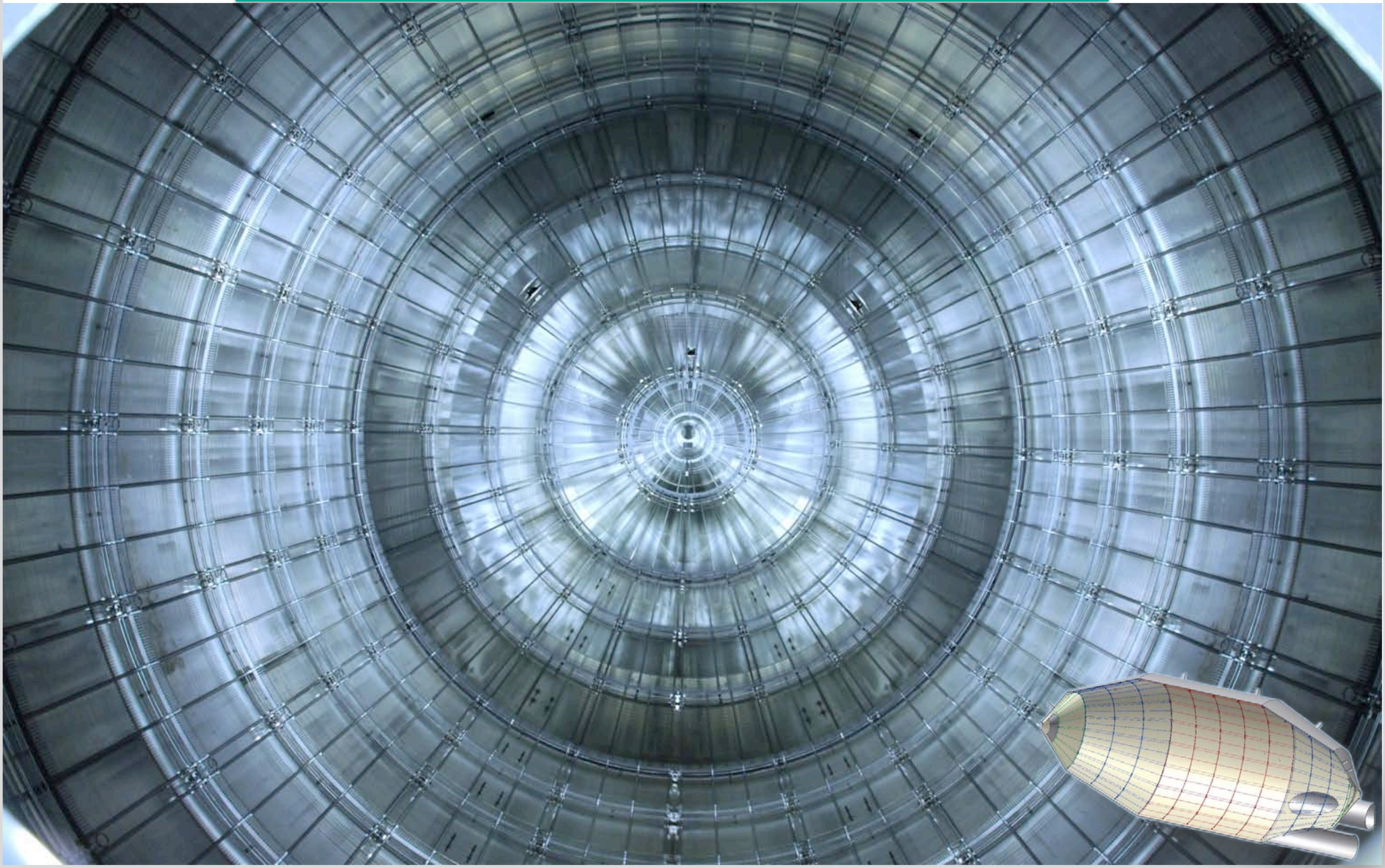
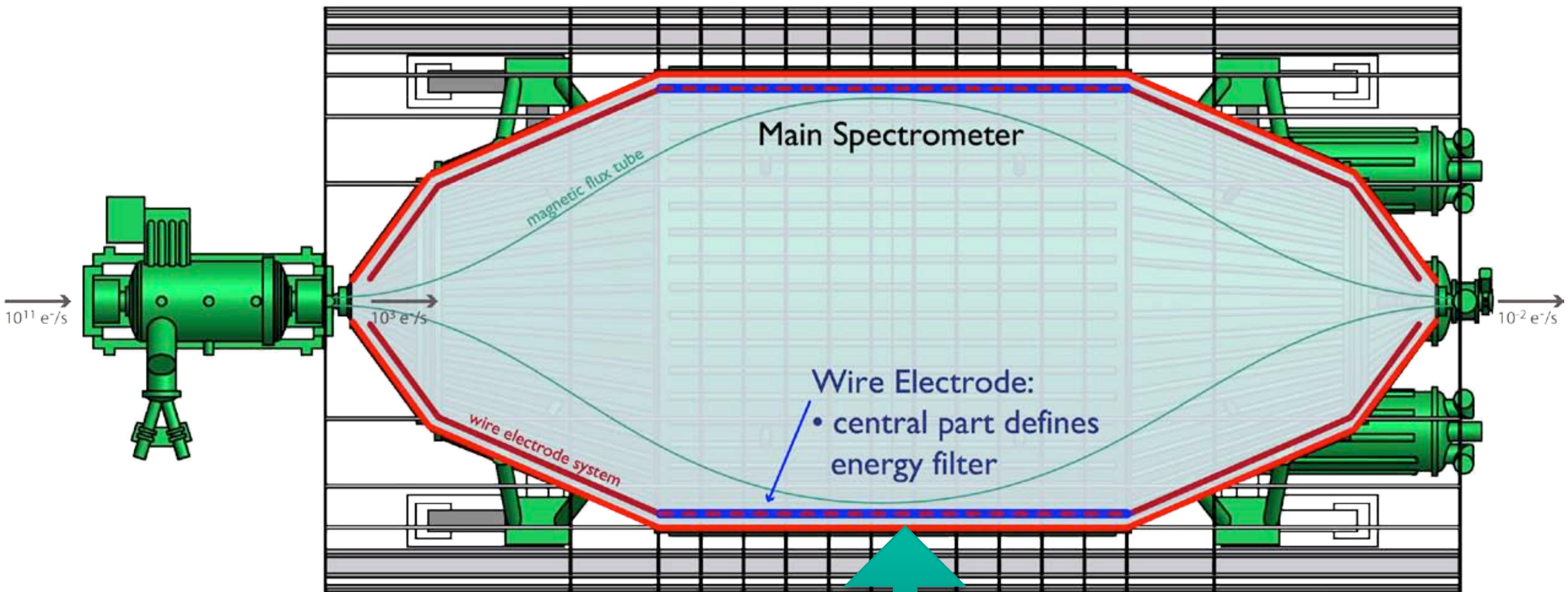
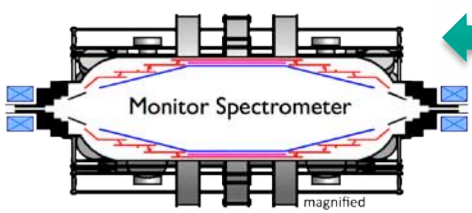


HV Monitoring of Main Spectrometer Energy Filter

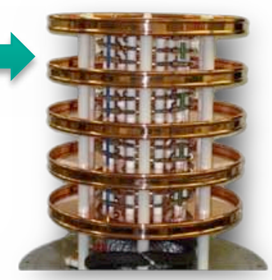
- **KATRIN sensitivity goal requires: 60 mV (3×10^{-6}) at 18.6 kV**
- non-trivial, not state-of-the-art and of serious importance for KATRIN



refurbished Mainz ν-mass spectrometer for monitoring



HV



Top level precision high voltage dividers

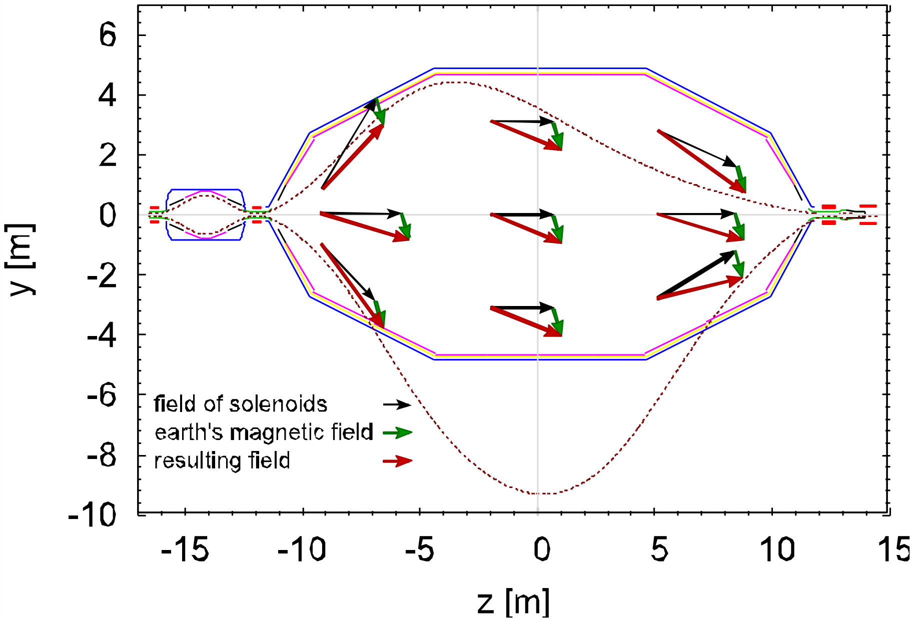
Th Thümmler et al
New J. Phys. 11 103007 (2009)

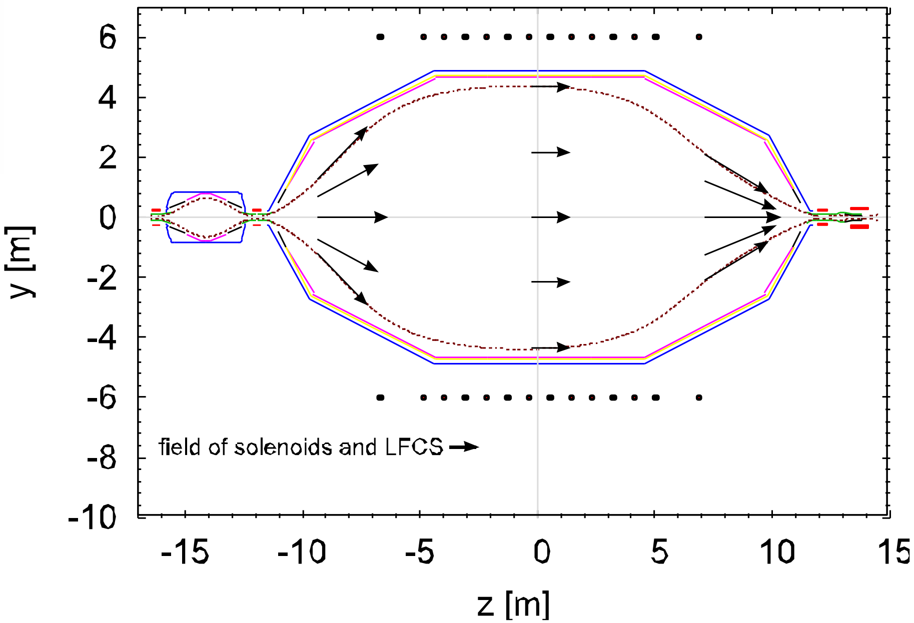
Monitoring of the analyzing potential in the main spectrometer:

- verification with ^{83m}Kr reference source at monitor spectrometer
- online monitoring with precision HV divider

Air Coil System

- Earth magnetic field compensation & low field correction





- earth magnetic/environmental fields distort magn. flux tube in low field region (0.3 mT)
- needs to be compensated!
- low field correction:
  - optimize flux tube
  - fine tune transmission and resolution.

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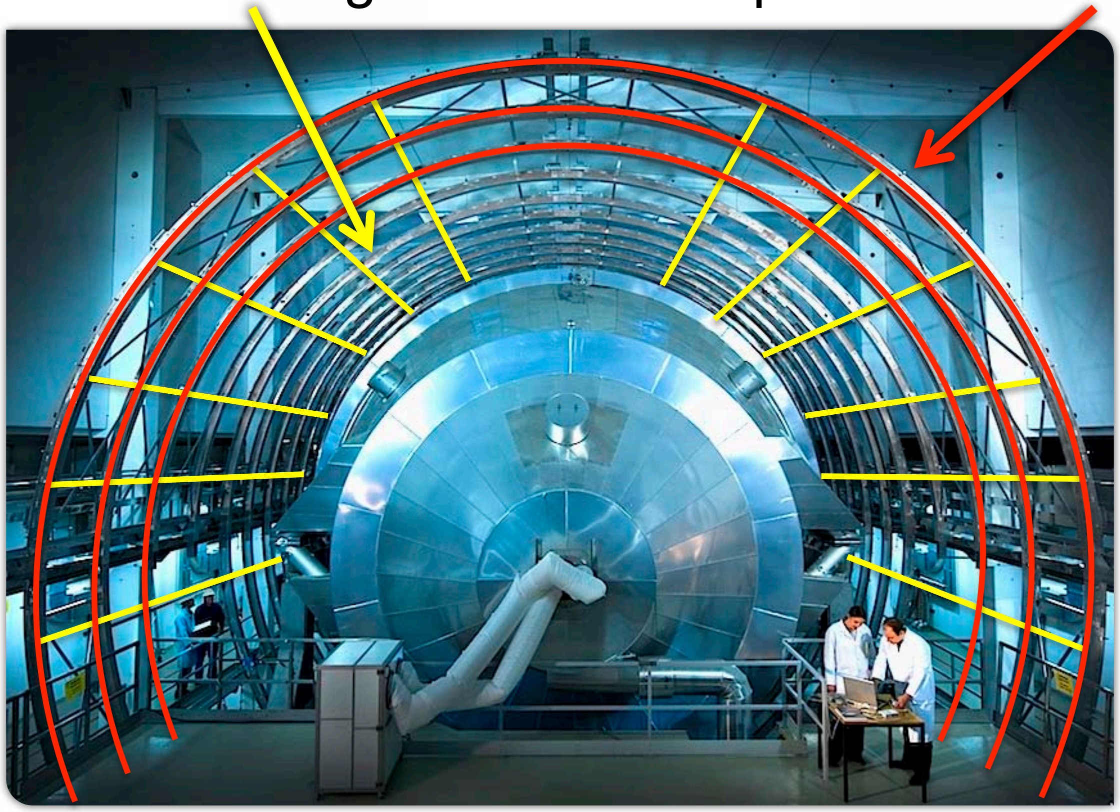

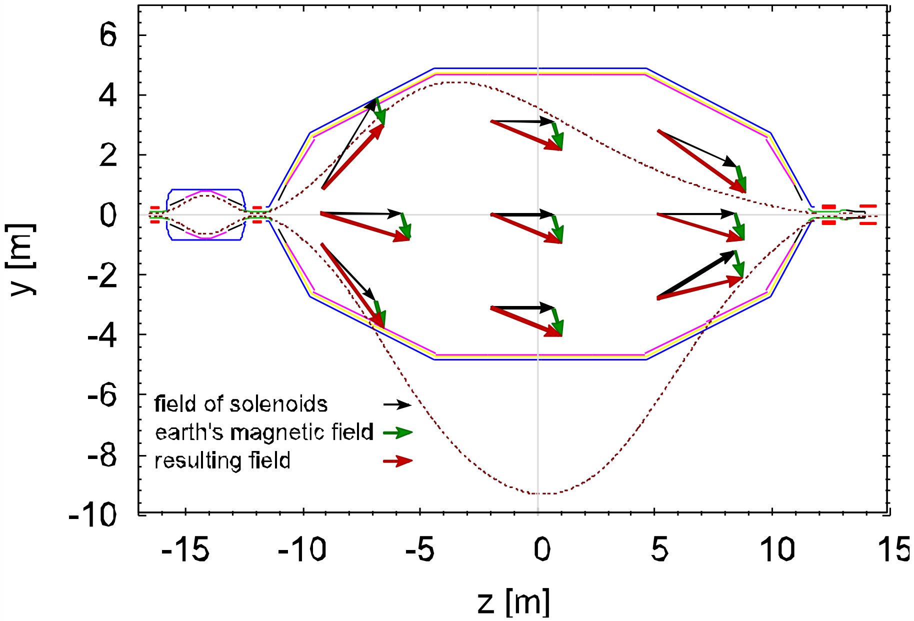

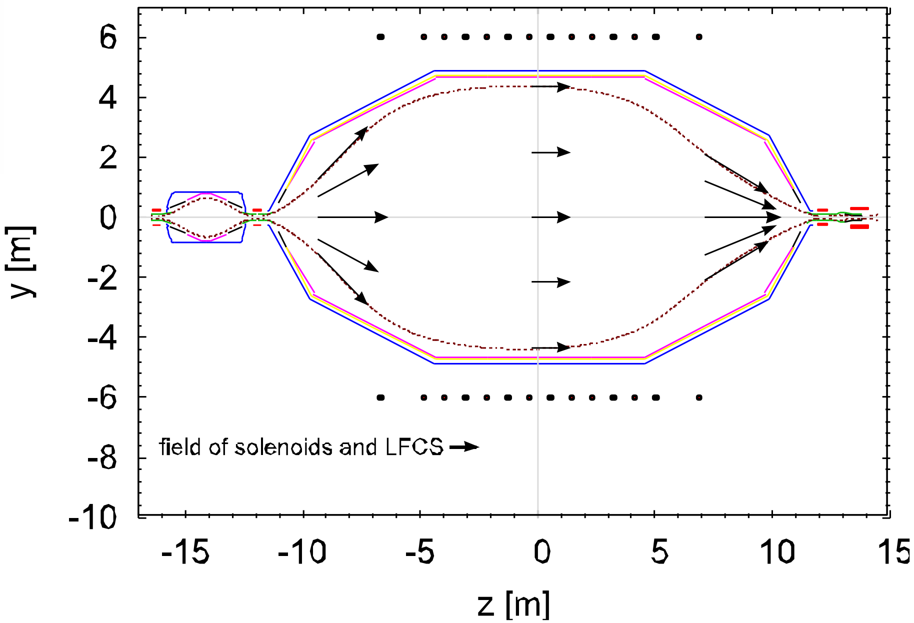

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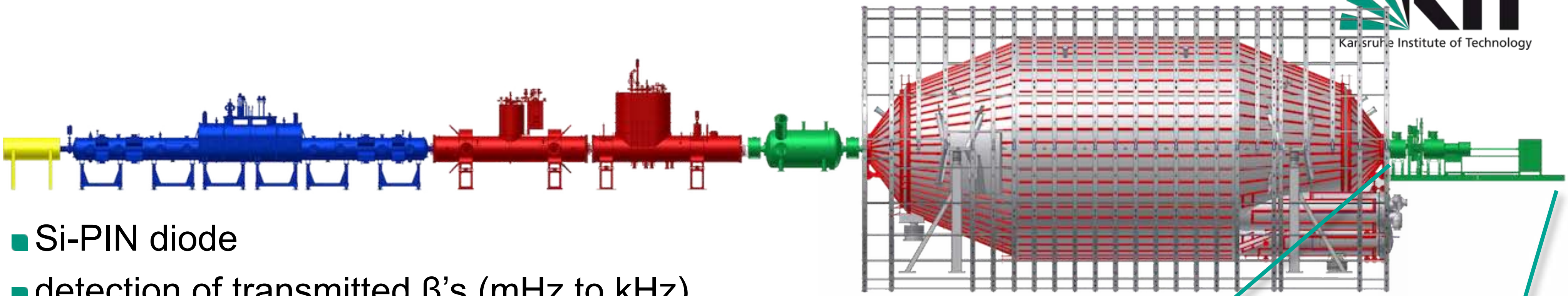
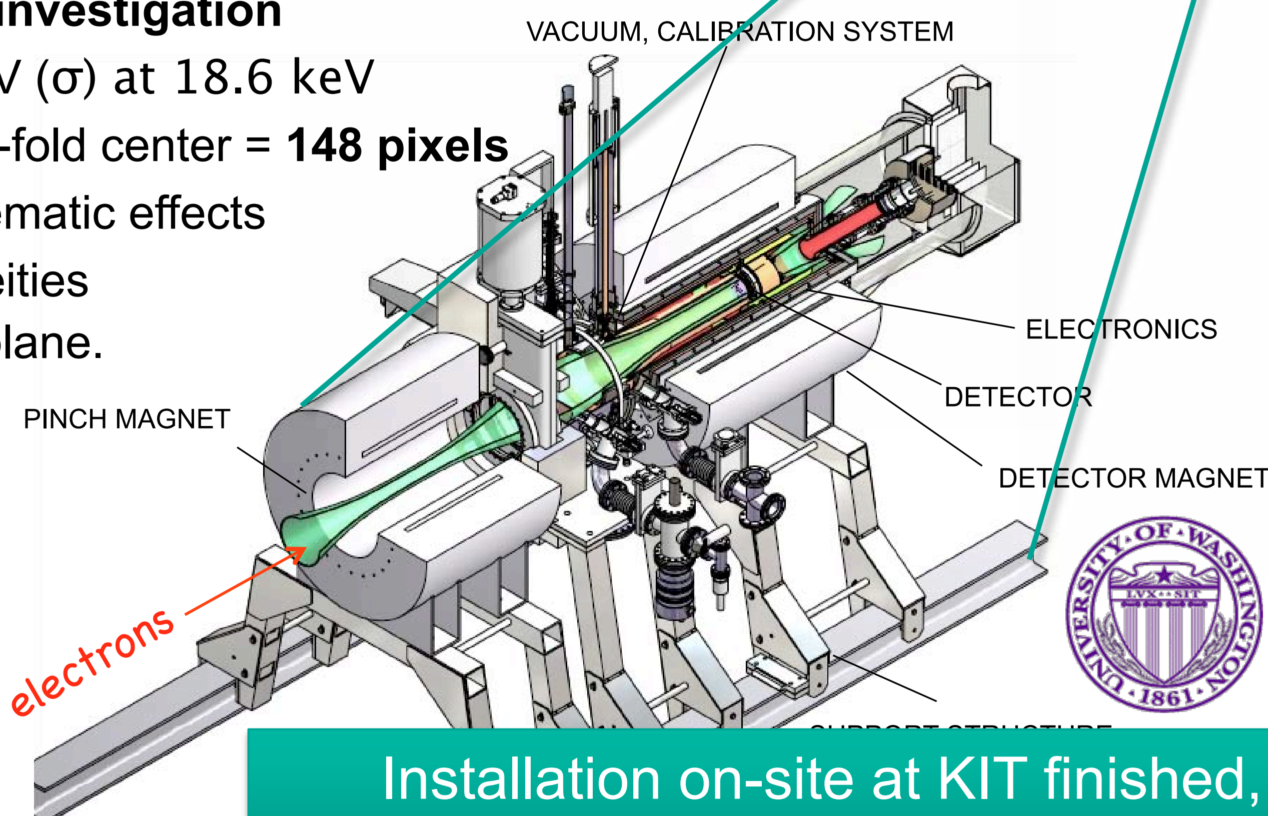
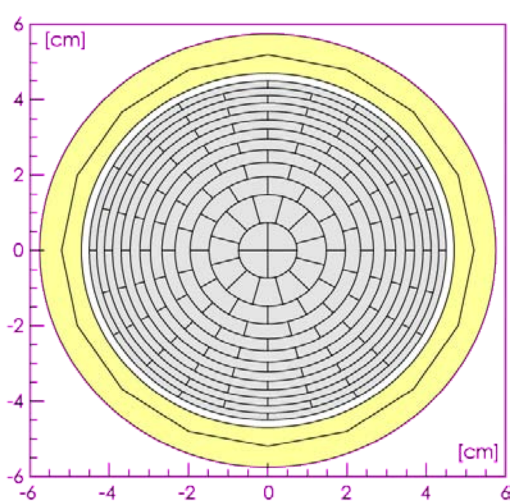
Main Detector



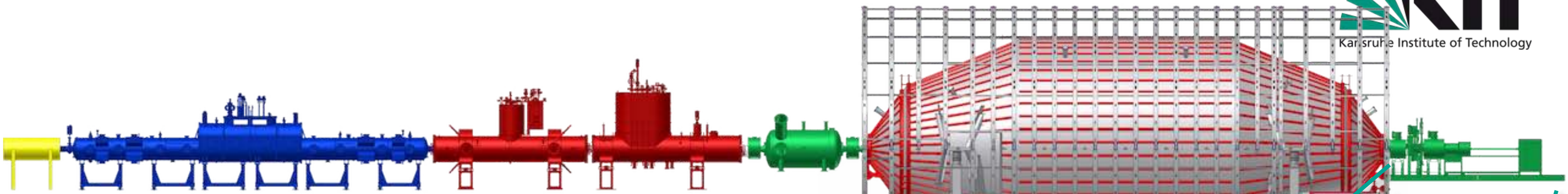
- Si-PIN diode
- detection of transmitted β's (mHz to kHz)
- **low background for T_2 endpoint investigation**
- high energy resolution ΔE = 0.7 keV (σ) at 18.6 keV
- 12 rings with 30° segmentation + 4-fold center = **148 pixels**
  - minimize bg, investigate systematic effects
  - compensate field inhomogeneities of spectrometer's analyzing plane.





Installation on-site at KIT finished, now commissioning

Main Detector



- Si-PIN diode
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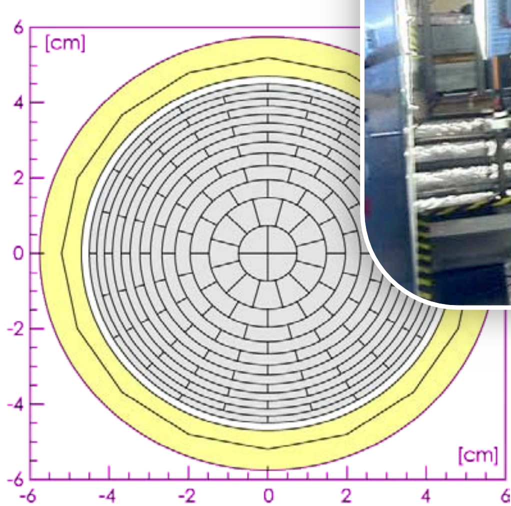
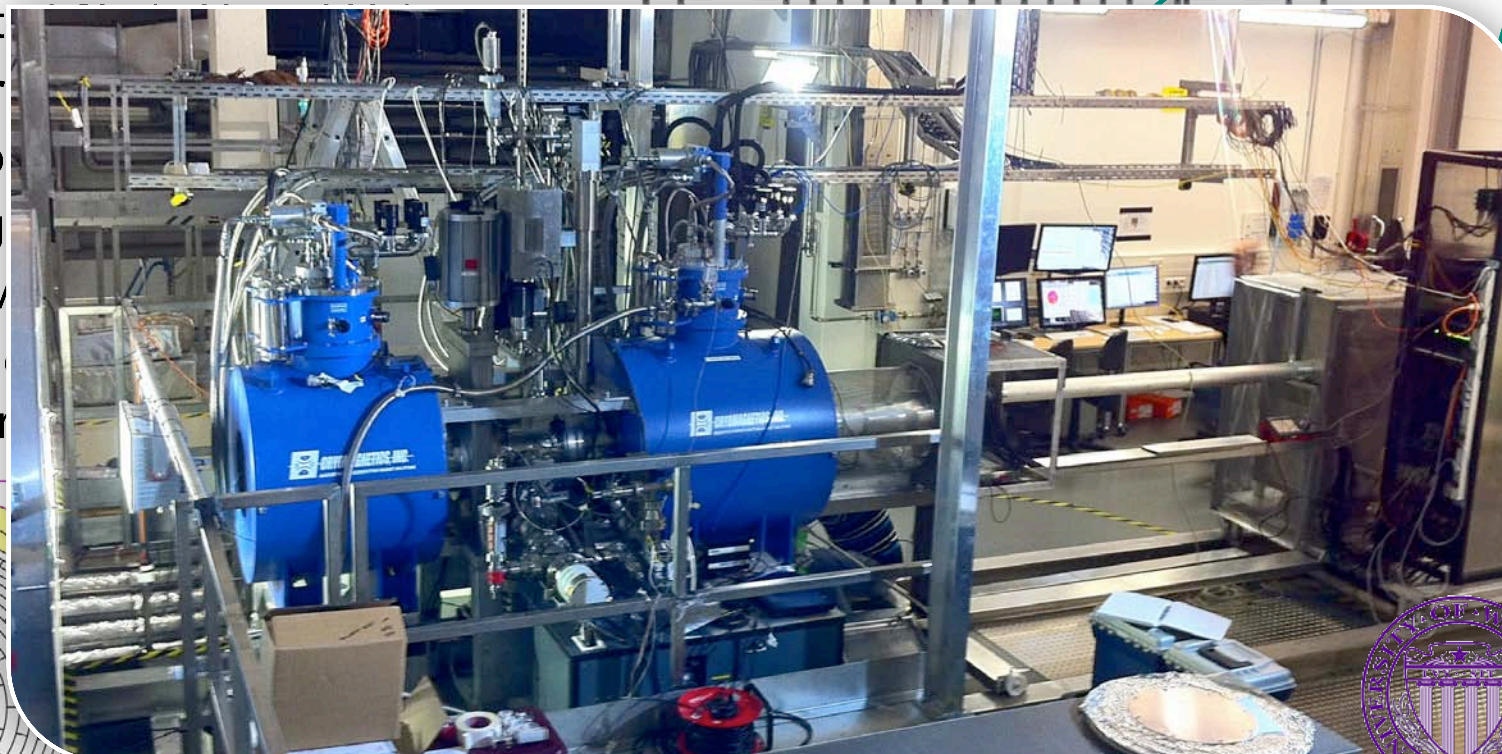
    of spectrometer





Installation on-site at KIT finished,
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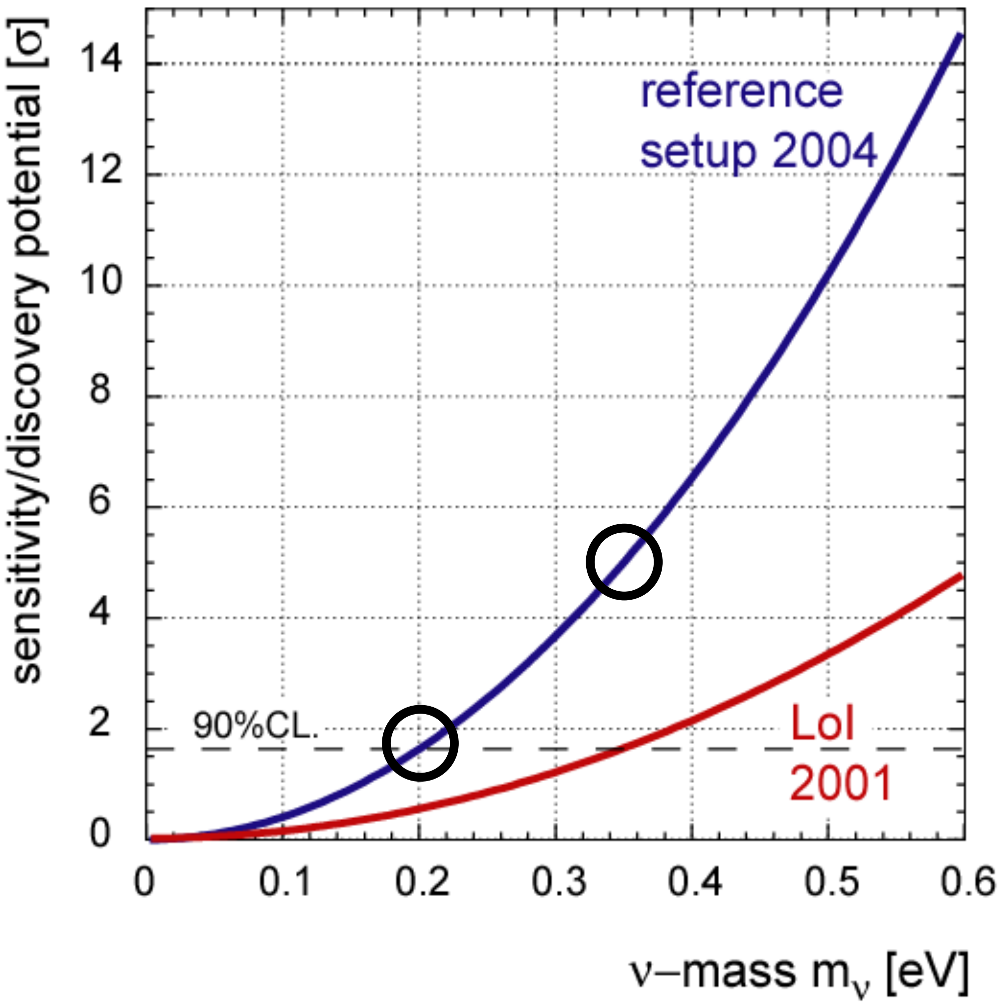
KATRIN Sensitivity



After 3 years data (5y realtime):

discovery potential
$m(\nu) = 0.35$ eV (5σ)

sensitivity (90% CL)
$m(\nu) < 0.2$ eV

$\Delta m_{tot}^2 = (\Delta m_{stat}^4 + \Delta m_{sys,tot}^4)^{1/2}$

$\Delta m_{tot}^2 \approx 0.025\ eV^2/c^4$

and

$\Delta m_{stat} = \Delta m_{sys,tot}$

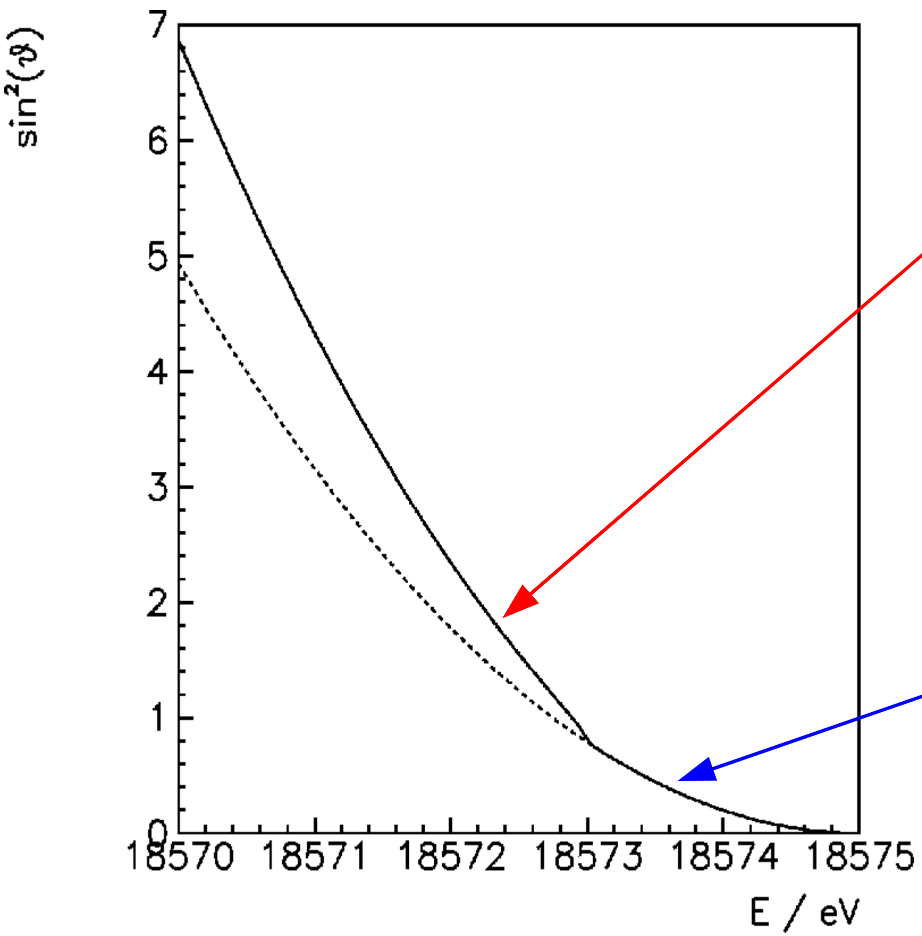
$\Delta m_{stat}^2 = 0.018\ eV^2/c^4$

$\Delta m_{sys,tot}^2 \leq 0.017\ eV^2/c^4$

What about sterile Neutrinos in KATRIN?

Influence on β decay near the endpoint:

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m_{1,2,3}^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m_{sterile}^2} \right)$$



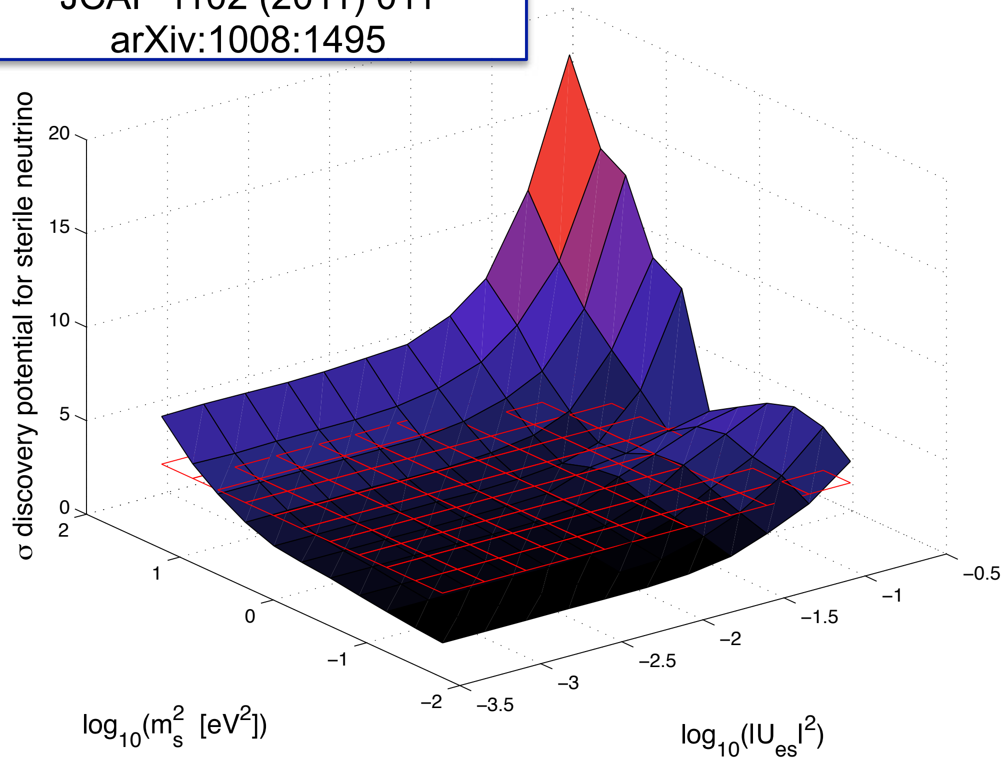
- $m_{sterile}$ = 2 eV
- $\sin^2(\theta)$ = 0.3

- $m_{1,2,3} \approx 0$ eV
- $\cos^2(\theta)$ = 0.7

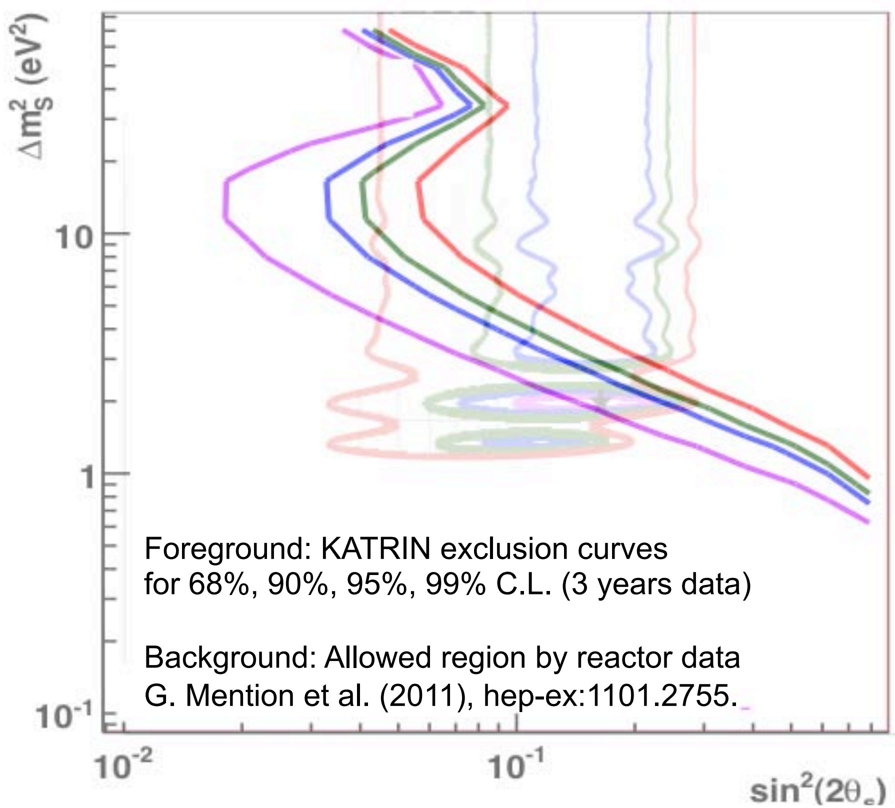
taken from C. Weinheimer, 2011

What about sterile Neutrinos in KATRIN?

A. Sejersen Riis & S. Hannestad, JCAP 1102 (2011) 011 arXiv:1008:1495



J. A. Formaggio, J. Barret, arXiv:1105.1326



- Single β decay experiments (MARE, Project8, KATRIN) can detect a sterile neutrinos signature.
- KATRIN: for $m_{sterile} > 3.2$ eV a 3σ detection could be made for any mixing angle.
- Single β decay offers a complementary input, independent of CP phases.

Summary and Outlook

- motivation for neutrino mass meas. from particle and astroparticle physics
- β decay offers a model-independent method to determine m_ν
- Project 8 investigates a new detection method for future experiments
- Re-based MARE is moving to a new isotope ^{163}Ho in order to reach a sensitivity, which is comparable to KATRIN in future.

- T_2-based KATRIN is designed to reach a sensitivity of 0.2 eV on m_ν
- KATRIN construction continuing:
  - Main Spectrometer – Detector commissioning starts spring 2012
  - complete system integration and start of data taking not before 2014