Direct Search for the Neutrino Mass and the KATRIN experiment

Westfälische Wilhelms-Universität Münster

Seminar at the Centre de Physique des Particules de Marseille, May 12, 2014

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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

Summary and Outlook

Photo: M. Zacher

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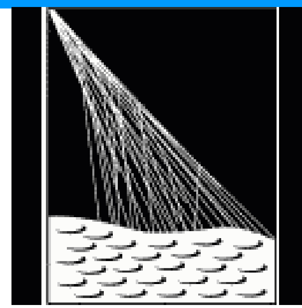
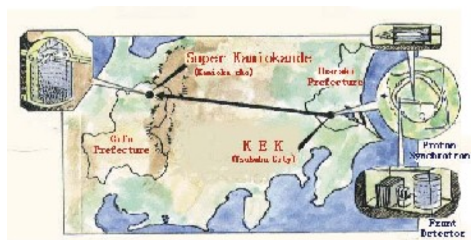
Positive results from ν oscillation experiments

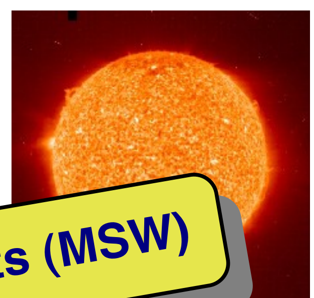
atmospheric neutrinos
(Kamiokande, Super-Kamiokande, ...)



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

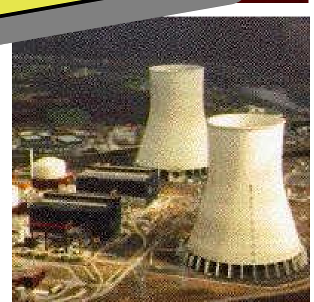


solar neutrinos
(Homestake, Gallex, Sage, Super-Kamiokande, SNO, Borexino)



Matter effects (MSW)

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



⇒ non-trivial ν-mixing

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

with:

$0.34 < \sin^2(\theta_{23}) < 0.64$ maximal!

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

$\sin^2(\theta_{13}) = 0.089 \pm 0.010 \pm 0.005$

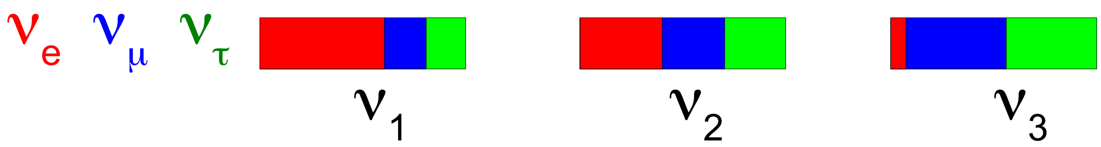
$7.0\ 10^{-5}\ eV^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ eV^2$

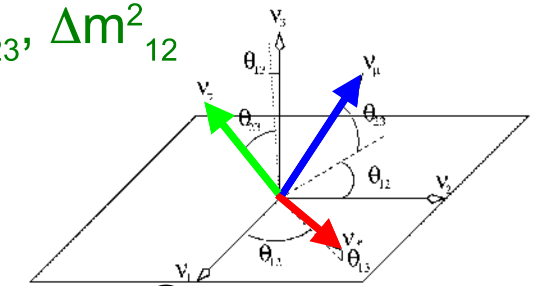
$2.1\ 10^{-3}\ eV^2 < |\Delta m_{13}^2| < 2.7\ 10^{-3}\ eV^2$

⇒ $m(\nu_j) \neq 0$, but unknown !

Need for the absolute ν mass determination

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





degenerated masses

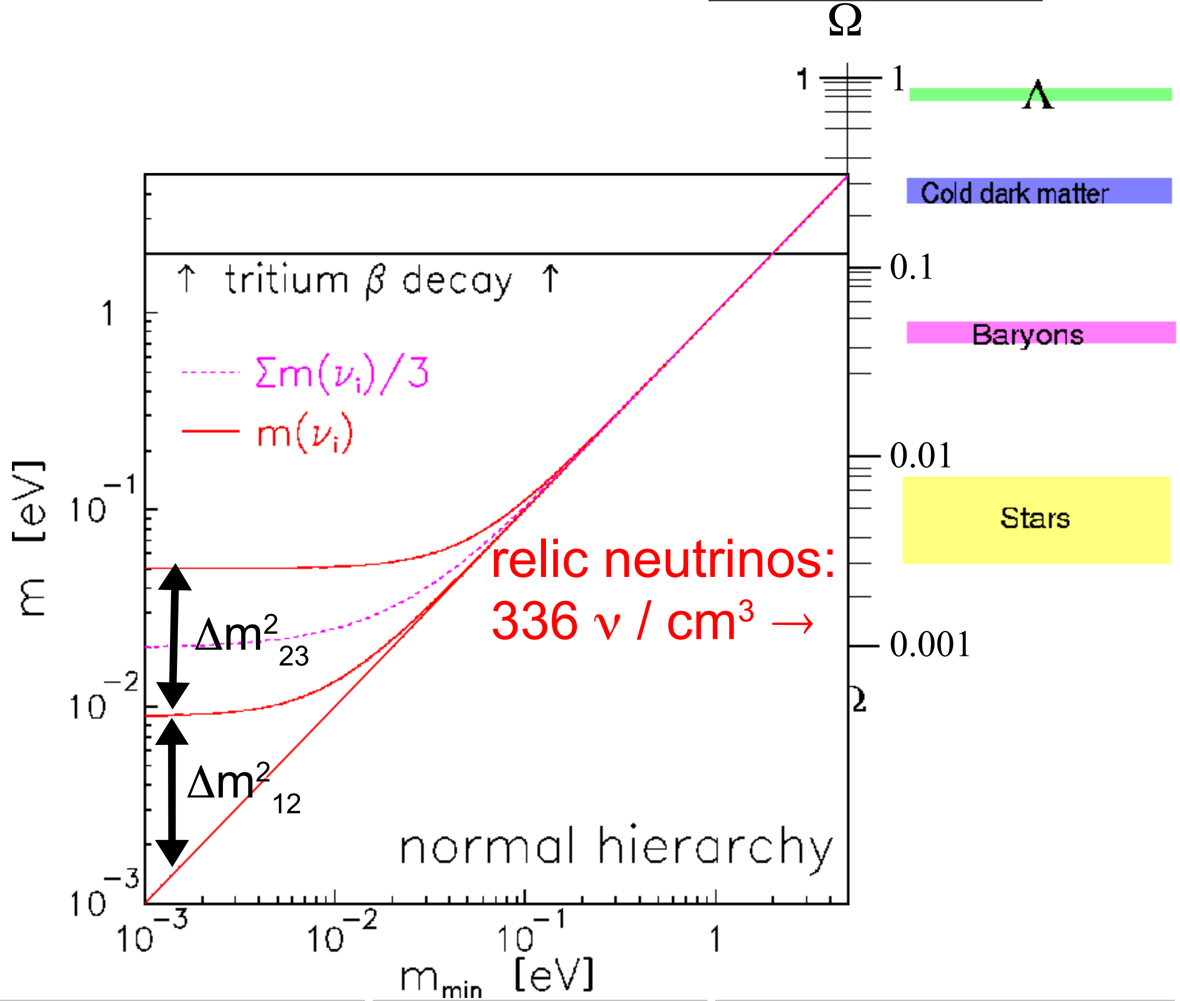
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

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



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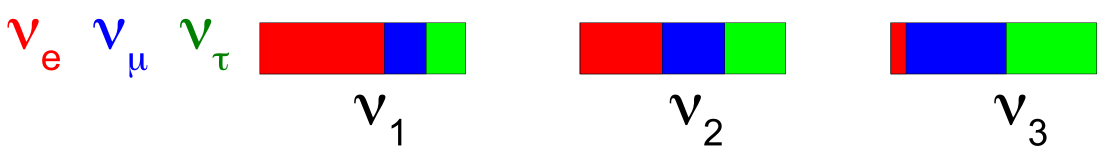

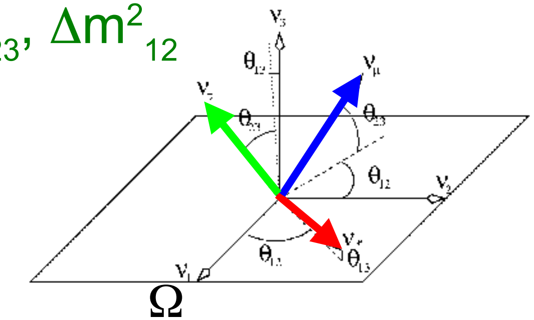

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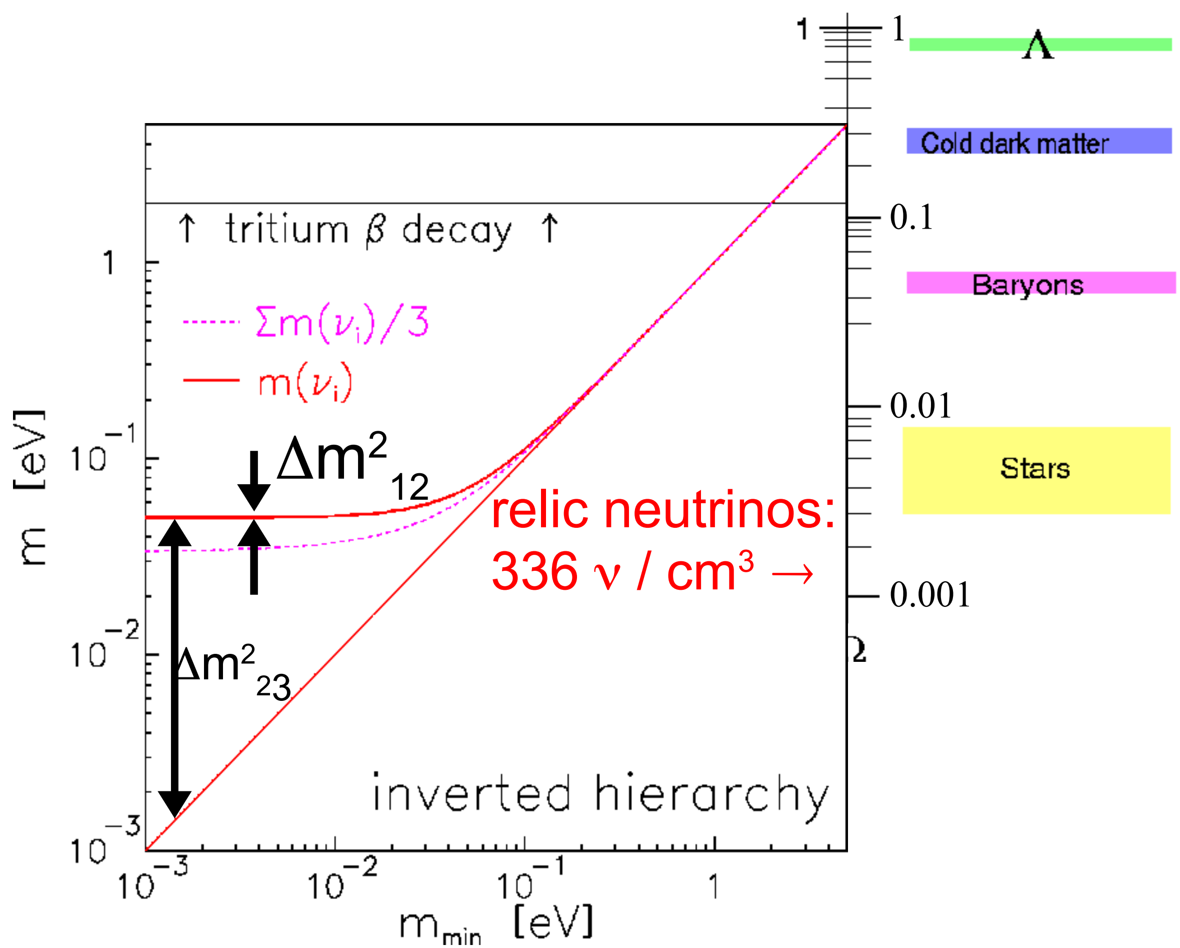

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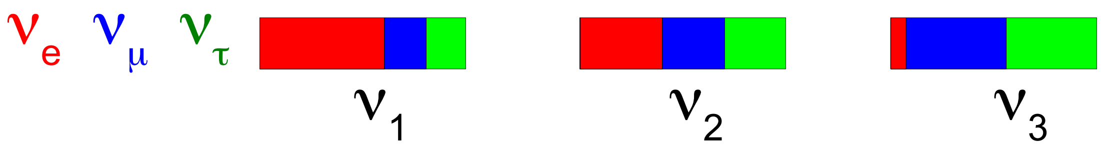

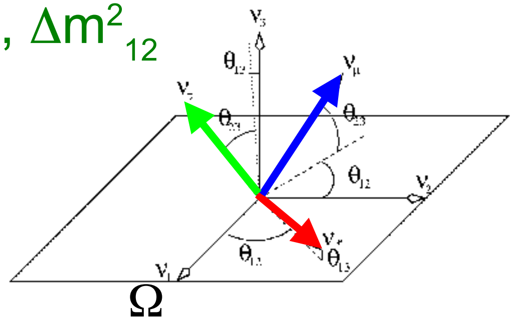

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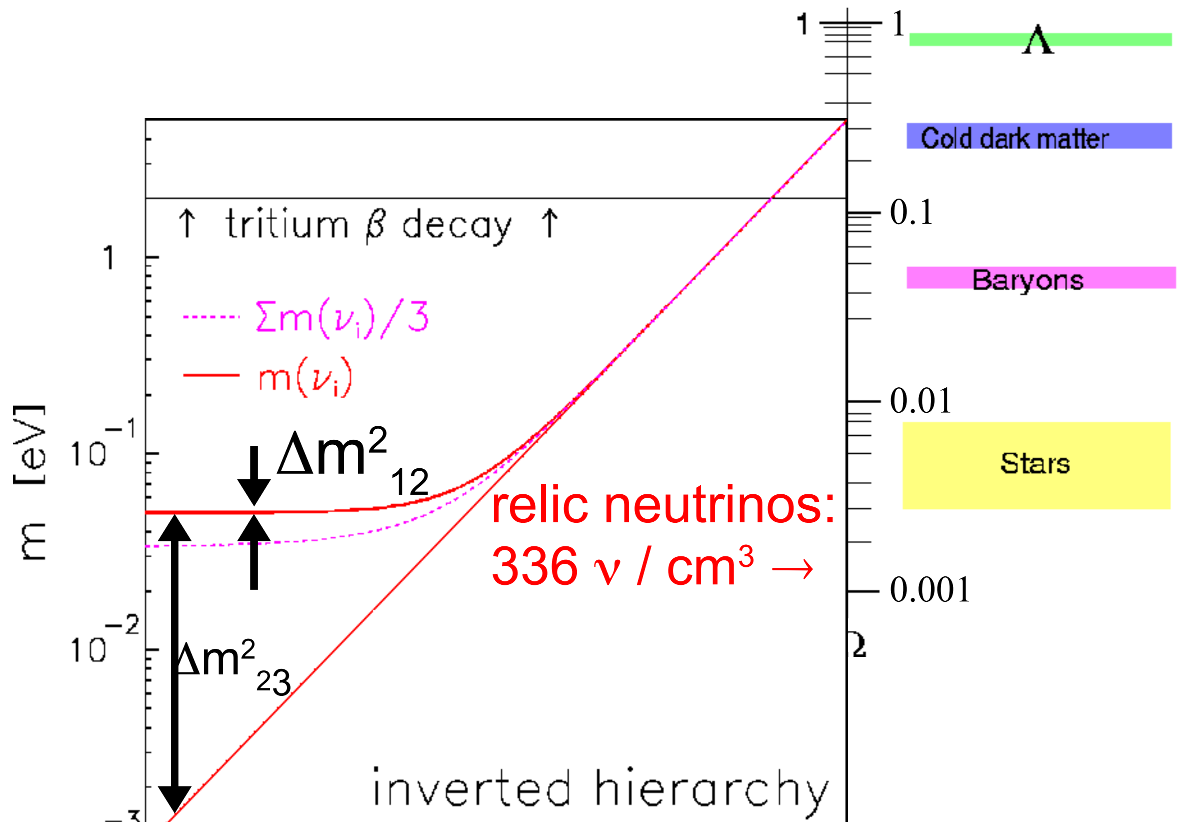
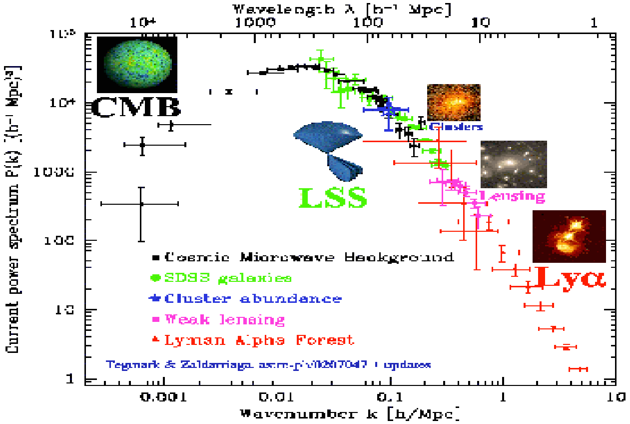


Need neutrino mass from non-oscillation method !

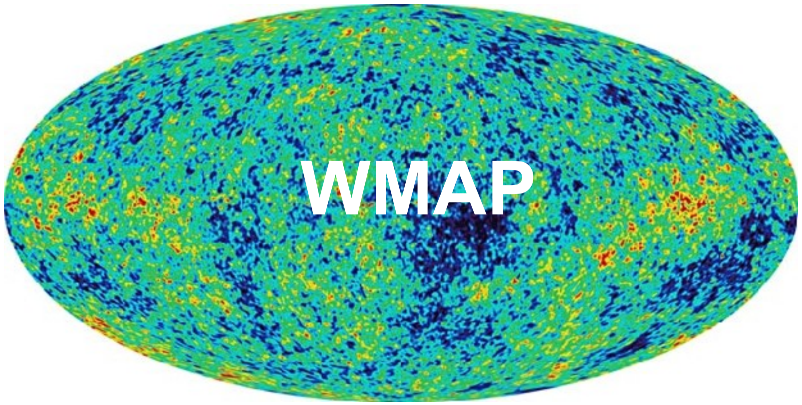
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

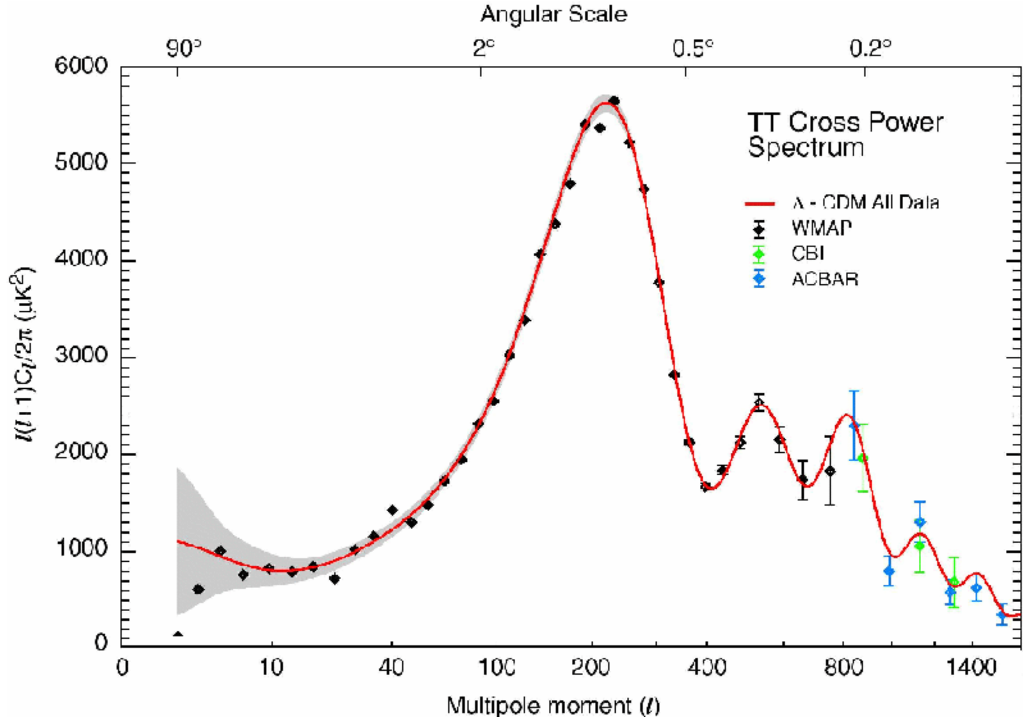
- very sensitive, but model dependent
- compares power at different scales
- current sensitivity: $\Sigma m(\nu_i) \approx 0.5$ eV

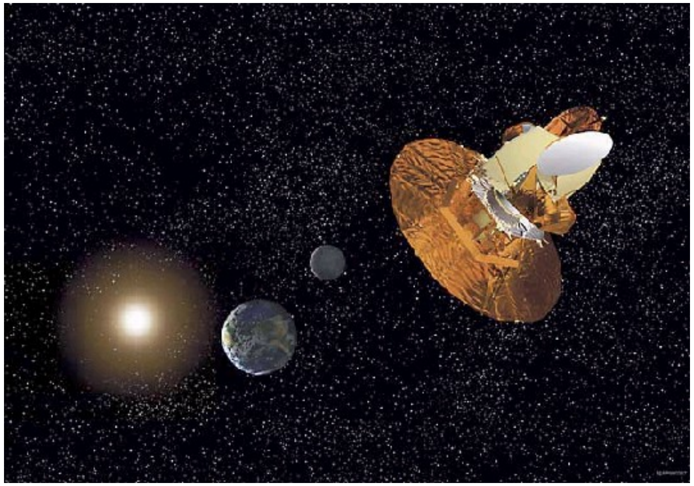


Neutrino mass from cosmology



measurement of CMBR
(Cosmic Microwave Background Radiation)





D.N. Spergel et al., astro-ph/0302209

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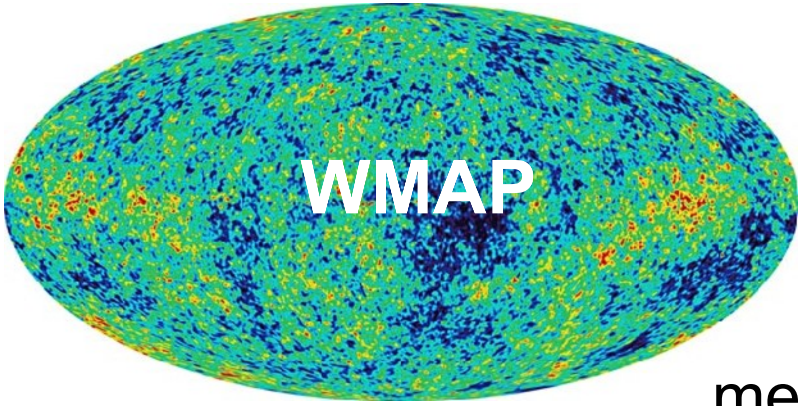

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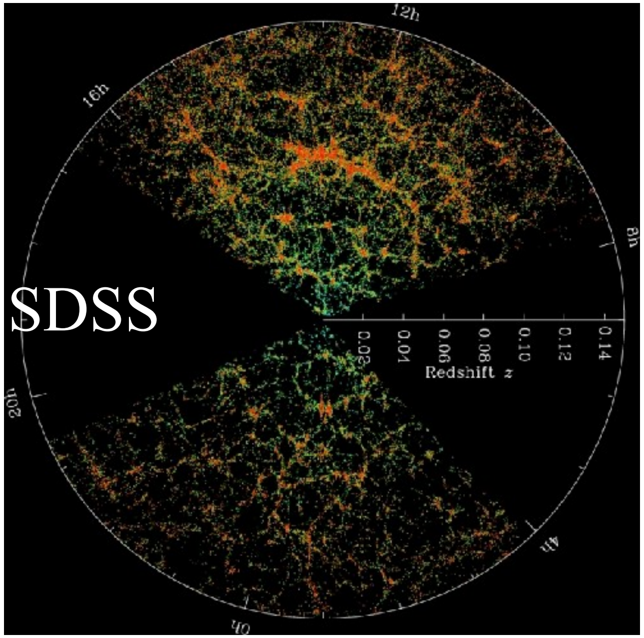
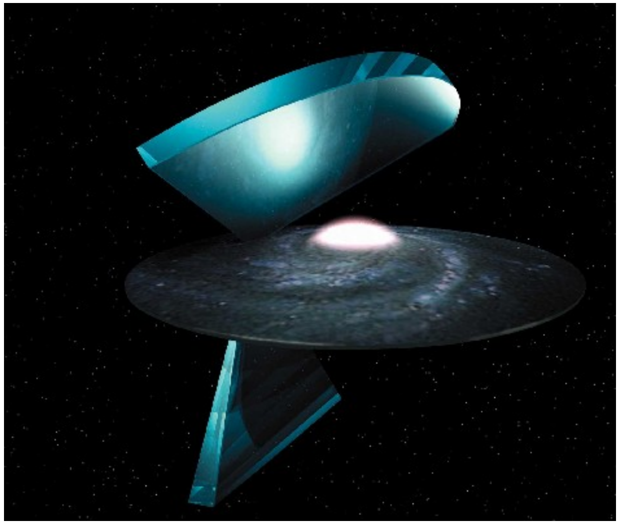


measurement of matter density distribution

LSS (Large Scale Structure)

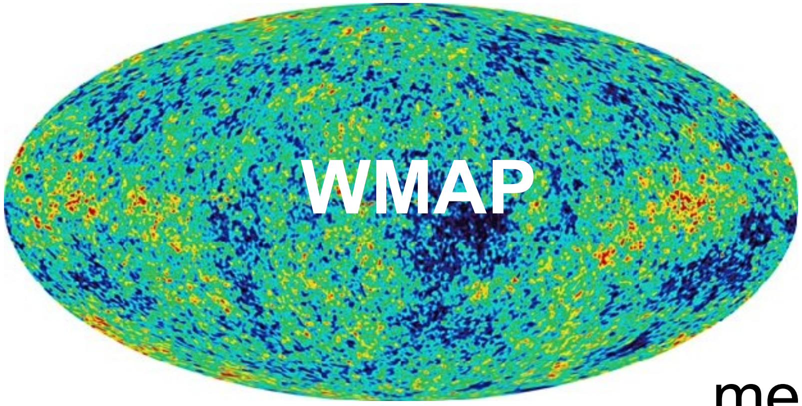
2dF, SDSS, ...



2dF: M. Colless et al., MNRAS 328 (2001) 1039

SDSS: M. Tegmark et al., Astrophys.J. 606 (2004) 702-740

Neutrino mass from cosmology



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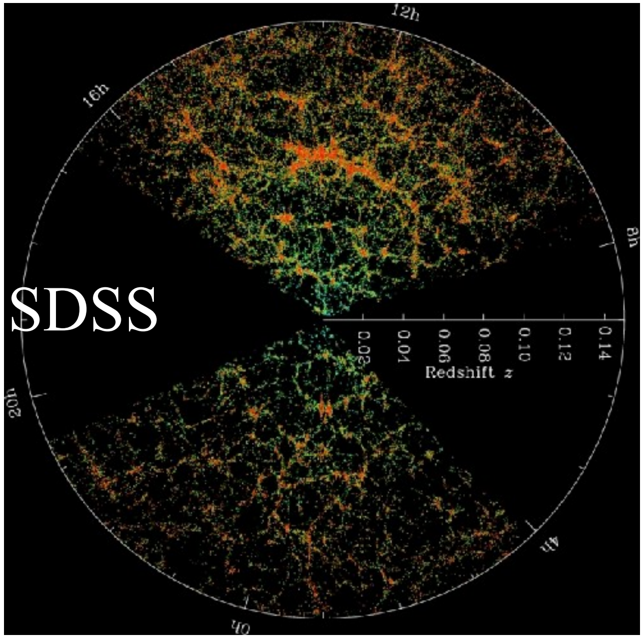
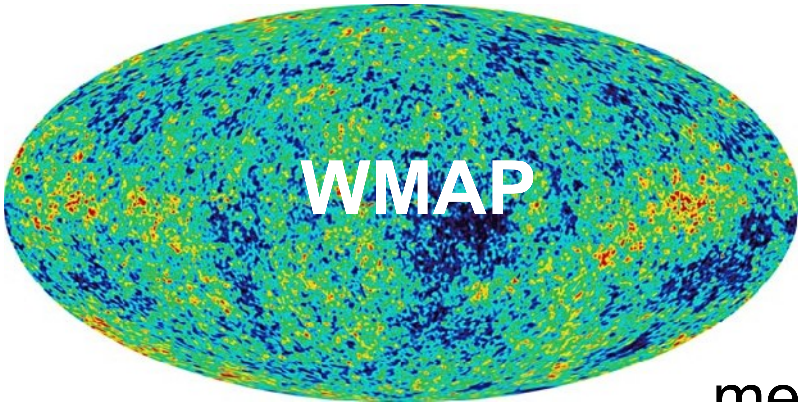


measurement of matter density distribution
LSS (Large Scale Structure)
2dF, SDSS, ...

big bang theory:
neutrino density in universe
$n_\nu = 336 / cm^3$

Neutrino mass from cosmology



measurement of CMBR

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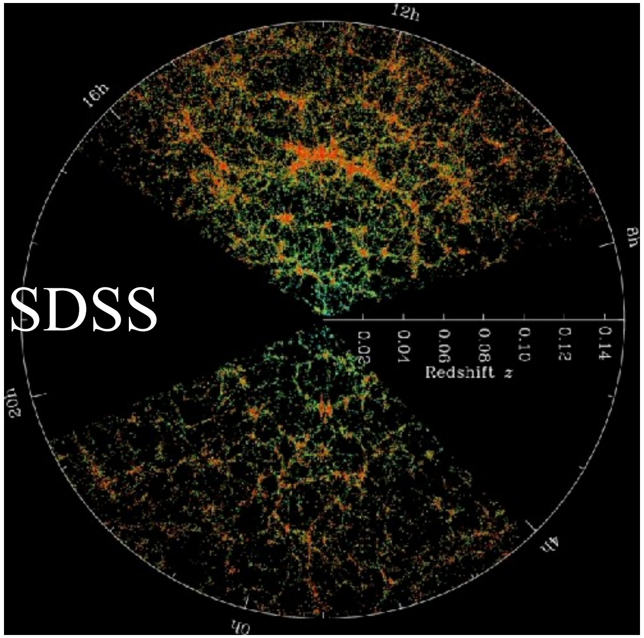

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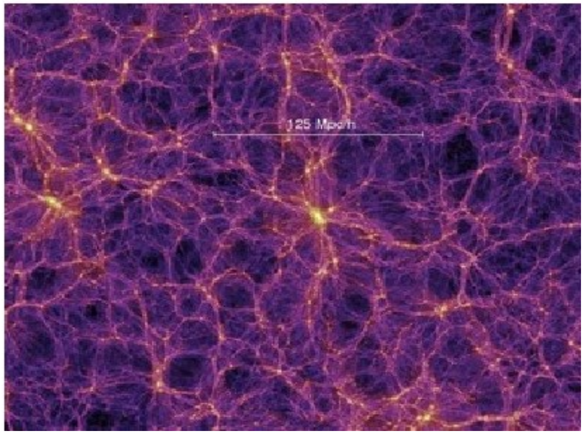
model development

← National Center for SuperComputer Simulations, http://cosmicweb.uchicago.edu/sims.html

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



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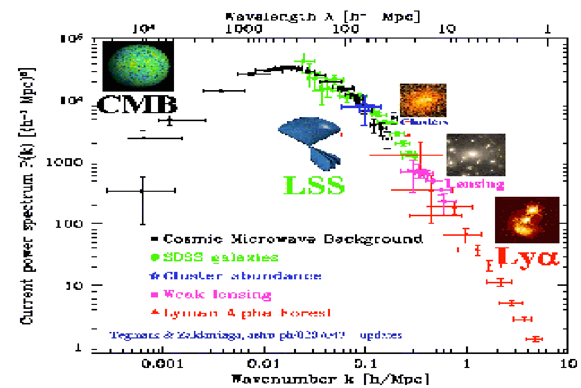
Neutrino mass from cosmology

E. Komatsu et al. (WMAP, 5 years, arXiv:0803.0547)

$\Sigma m(\nu_i) < 0.67$ eV

CMB, LSS, SN data, always assuming the cosmological concordance model with cosmological constant Λ = const., no quintessence



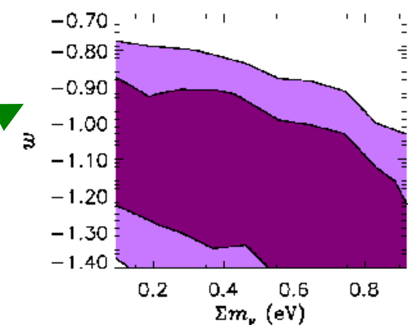
S. Hannestad, Prog. Part. Nucl. Phys. 65 (2010) 185

$\Sigma m(\nu_i) < 0.5$ eV

using baryon accoustic peaks

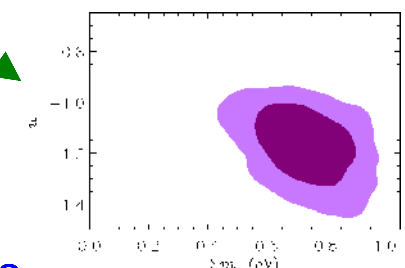
Remark: w is correlated to $\Sigma m(\nu_i)$ (arXiv:0709.4152, 0505.551)

⇒ neutrino mass determination can help dark energy (arXiv0710.1952)



Ch. Wetterich et al. (e.g. arXiv:0905.0715): avoids bound on $\Sigma m(\nu_i)$

ν coupling to cosmon (quintessence model for dark energy) leads to growing neutrino mass



O.E. Bjaelde et al. (astro-ph/0705.2018): ν coupling to scalar field leads to time-varying neutrino mass and connection to dark energy

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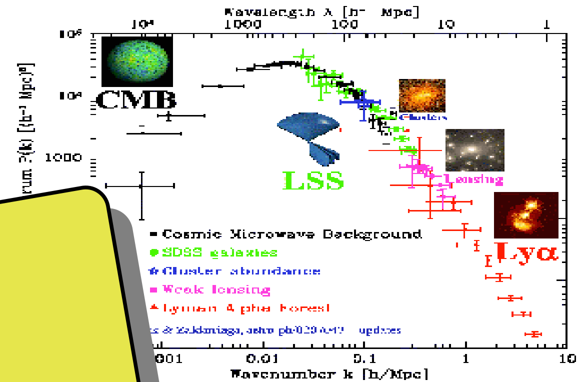

S. Hannestad, Prog. Part. N

$\Sigma m($

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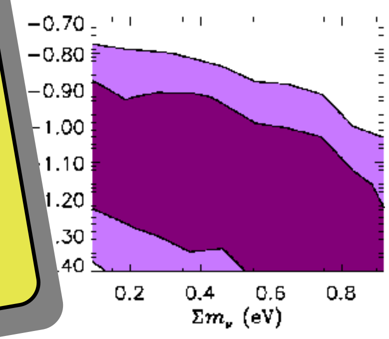
⇒ neutrino mass det



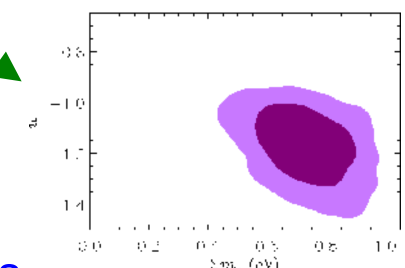
More stringent limits from new PLANCK data and better other cosmology data (WMAP, WMAP-pol, BAO, high-l CMB):

$\Sigma m(\nu_i) < 0.23$ eV

Ch. Wetterich et al. (e.g. … $m(\nu_i)$

ν coupling to cosmon (quin … energy)

leads to growing neutrino m



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Three complementary ways to the absolute neutrino mass scale

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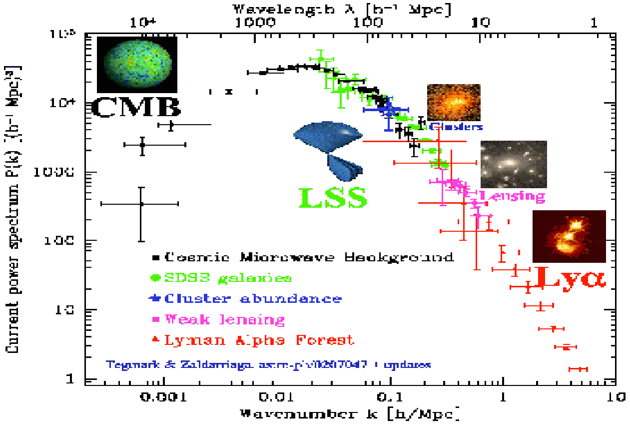
very sensitive, but model dependent

compares power at different scales

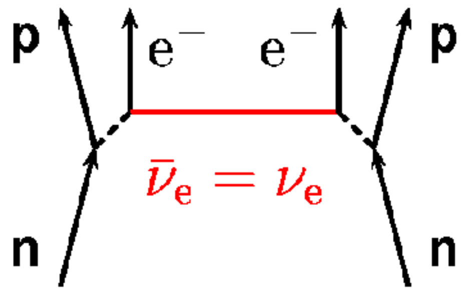
current sensitivity: $\Sigma m(\nu_i) \approx 0.5$ eV



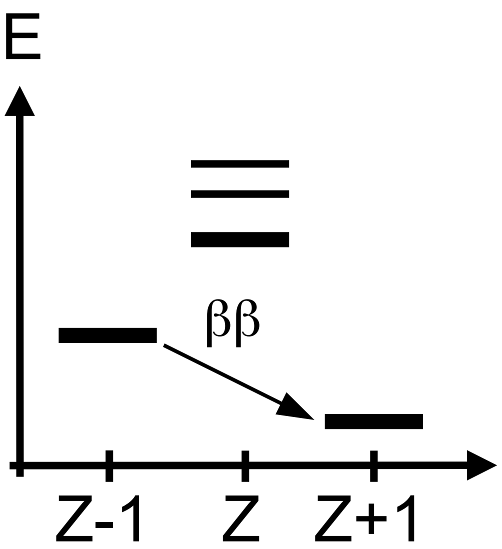
2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

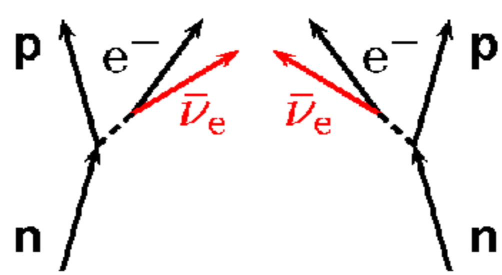
First upper limits by EXO-200, KamLAND-Zen, GERDA



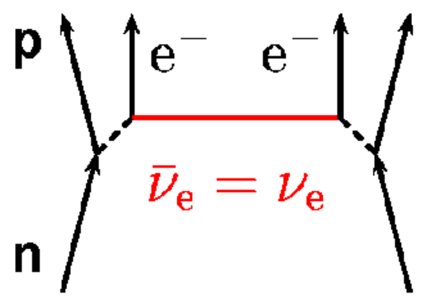
Double β decay



normal ($2\nu\beta\beta$)



neutrinoless ($0\nu\beta\beta$)

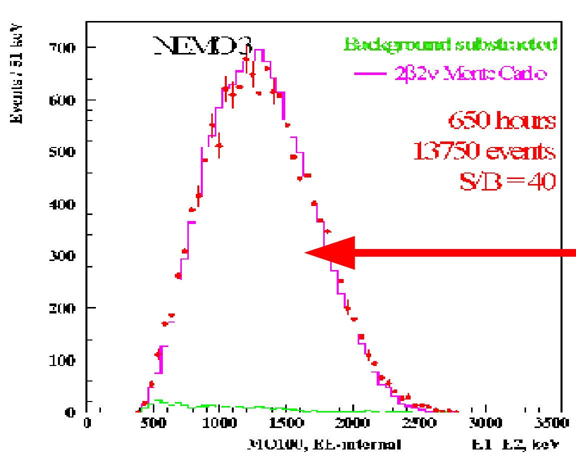


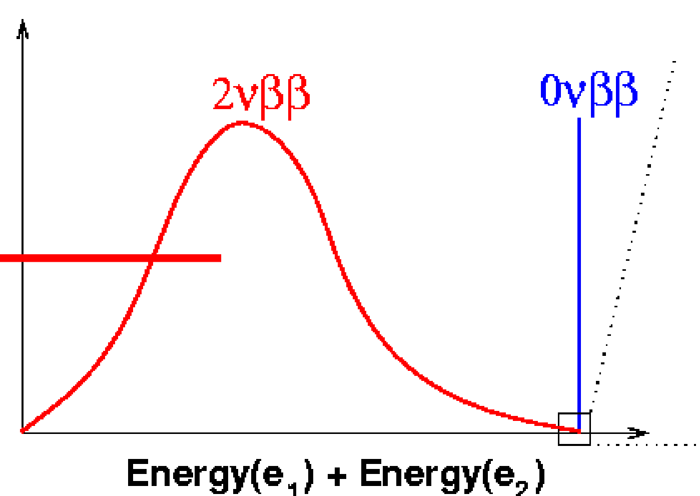
needed: a) $\overline{\nu} = \nu$ (Majorana)

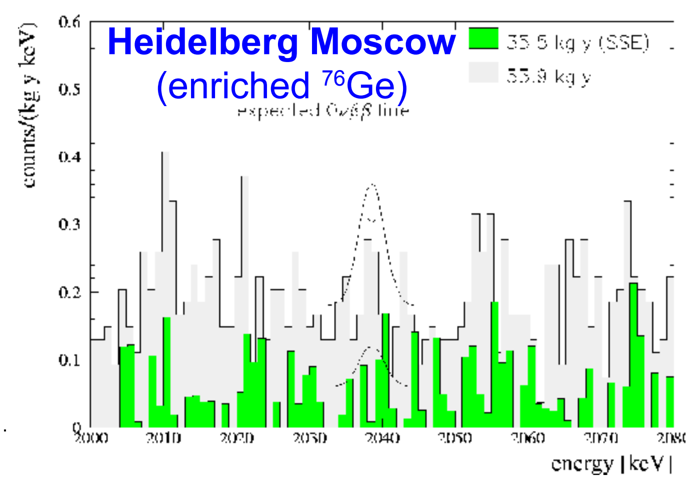
b) helicity flip: $m(\nu) \neq 0$

or other new physics

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







Current and future double β decay experiments

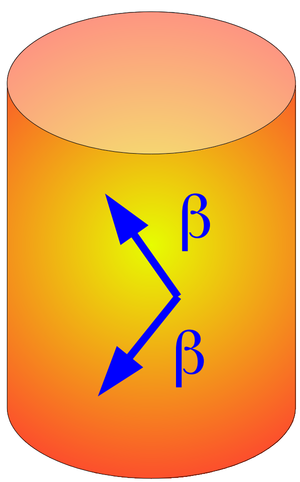
$m_{ee} \sim (1/\text{enrichment})^{1/2} \cdot (\Delta E \cdot bg/M \cdot t)^{1/4}$

⇒ mass → 1t, high enrichment, very low background *bg*

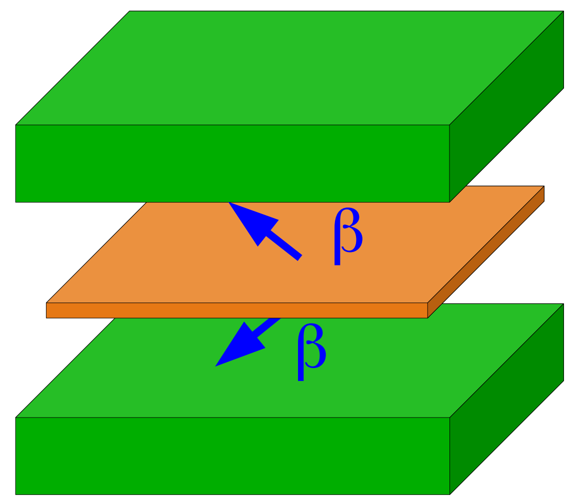
2 ways to measure both β-electrons:

semiconductor,
cryogenic bolometer
liquid scintillator

source
=
detector



tracking calorimeter



detector
source
detector

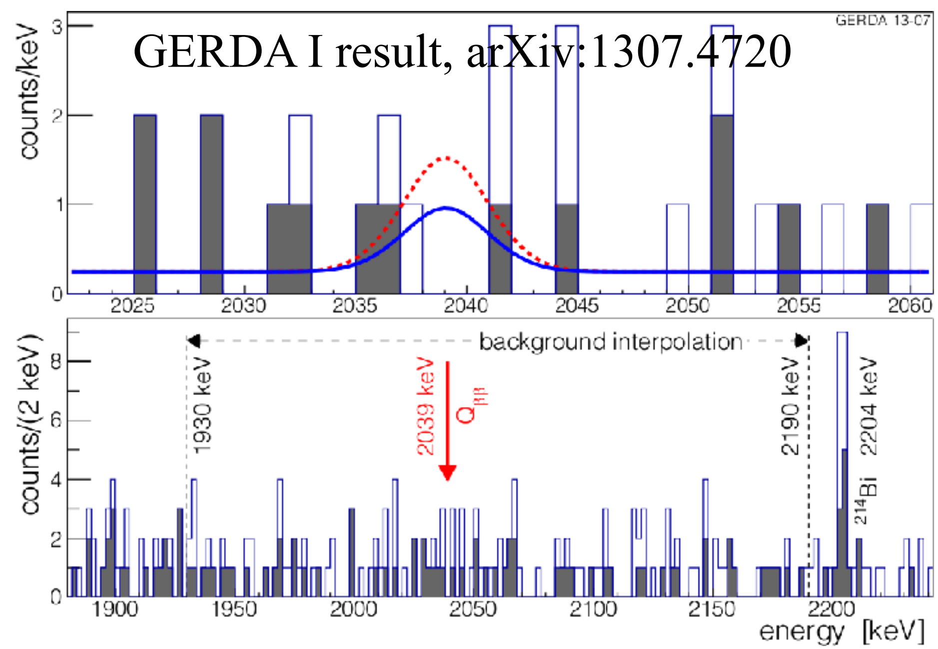
running:	GERDA, EXO-200, KamLAND-Zen
setting up:	CUORE, SNO+, Majorana
planned:	COBRA, Luzifer, AMORE, ...

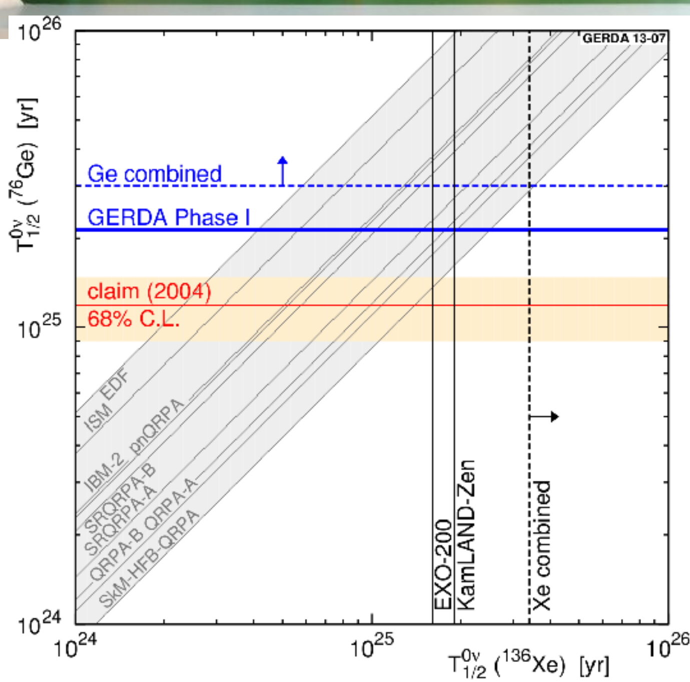
finished (Jan 11):	NEMO-3
setting up:	SuperNEMO
planned:	MOON

First results from GERDA phase 1

New background reduction methods:

- phase 1: 18 kg enriched Ge detectors in LAr
- phase 2: point contact detectors p-type (BEGe)
  to identify multi-side events and
  use scintillation of LAr shield as veto





$T_{1/2} > 2.1\ 10^{25}$ yr (90% C.L.)

$T_{1/2} > 3.0\ 10^{25}$ yr (90% C.L.) (using all ^{76}Ge experiments)

$m_{\beta\beta} < 0.2 – 0.4$ eV (using all ^{76}Ge experiments)

Three complementary ways to the absolute neutrino mass scale

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very sensitive, but model dependent

compares power at different scales

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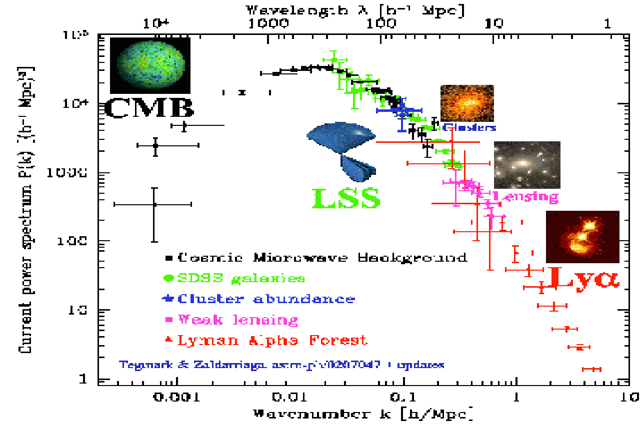

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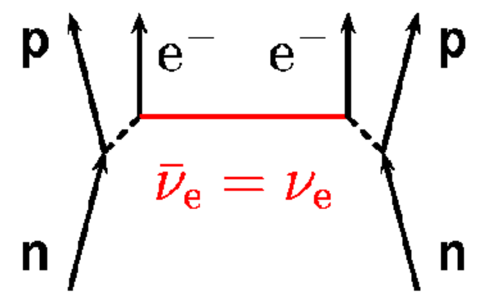


3) Direct neutrino mass determination:

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)

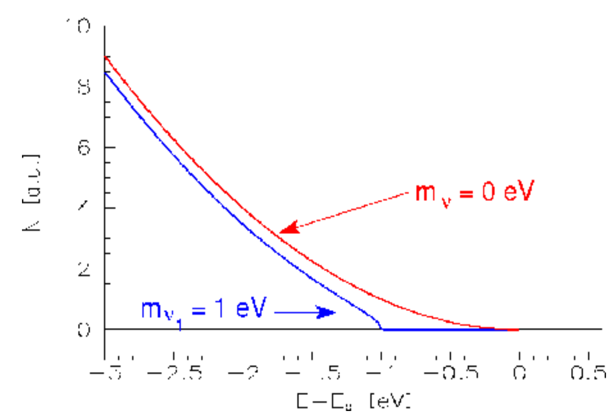
SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV

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

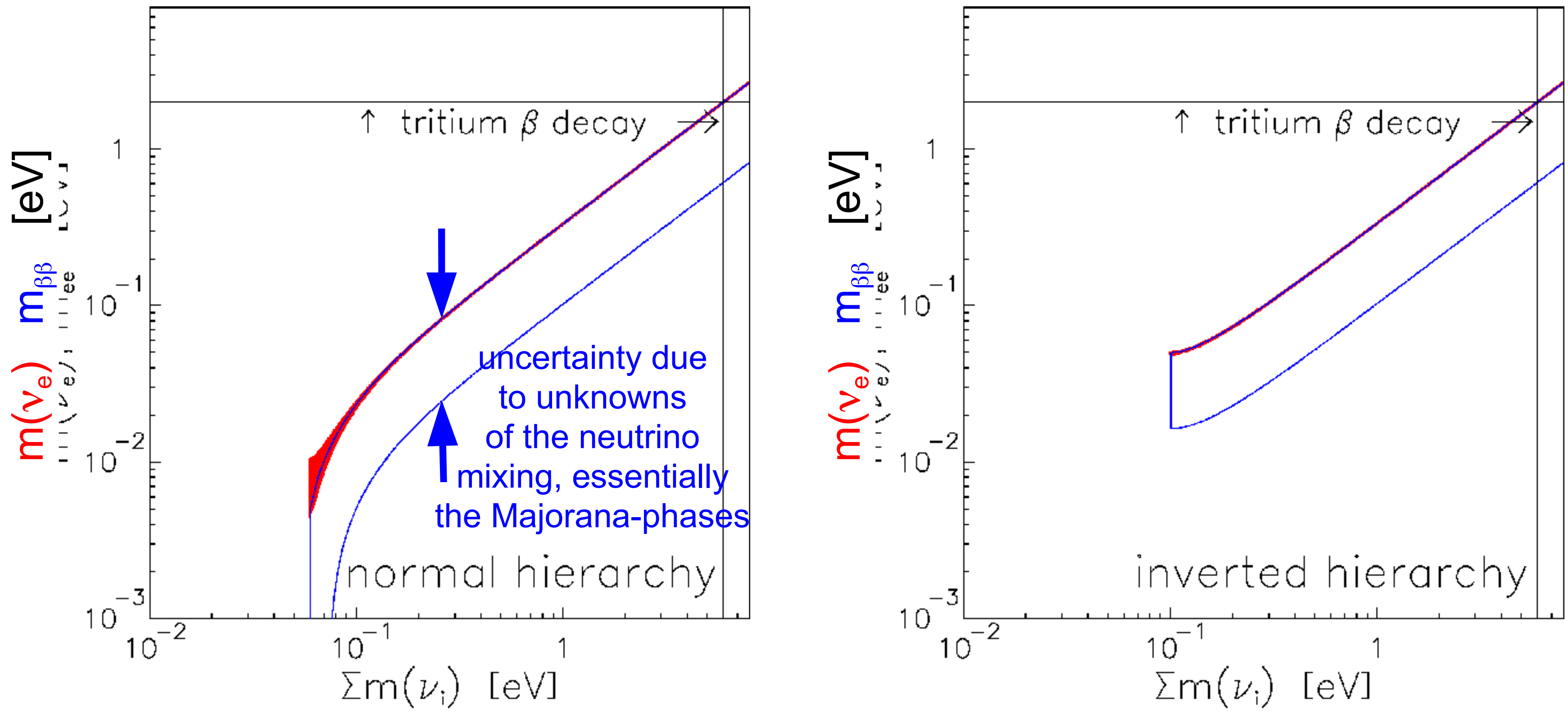


Comparison of the different approaches to the neutrino mass

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

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

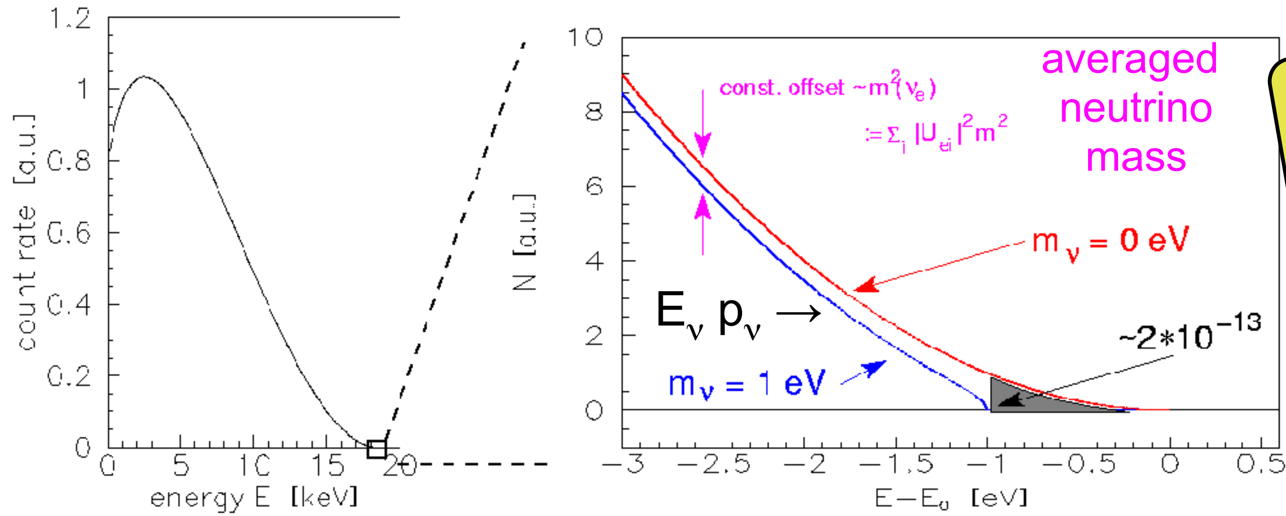
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

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

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

phase space: p_e E_e E_ν p_ν

(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** $\Rightarrow$ **Tritium ^3H, (^{187}Re)**

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

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

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

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

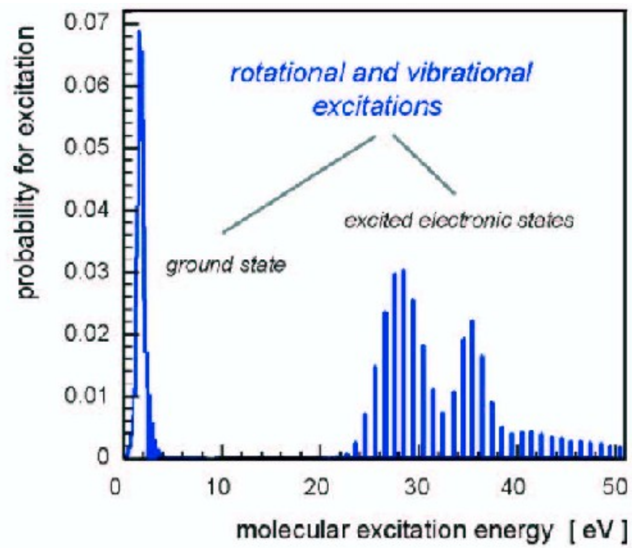
⇒ **electronic final states are important**

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

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

⇒ "Electron neutrino mass"

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

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

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

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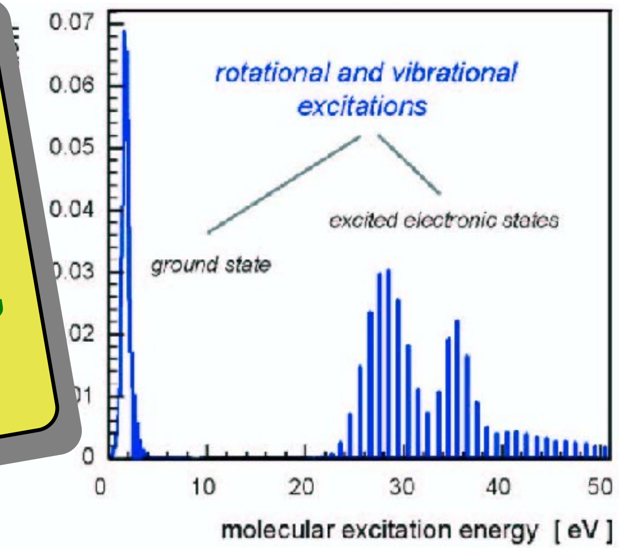
Final states c

A. Saenz et al. P

N. Doss et al., Pl

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



Including neutrino mixing

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

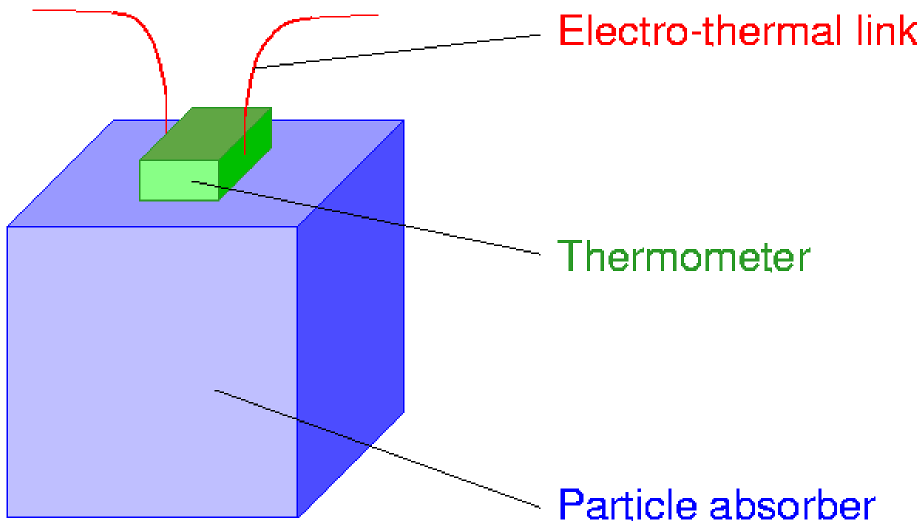
$$\cdot \sum_j W_j \cdot \varepsilon_j \cdot \left(\sum_i |U_{ci}|^2 \sqrt{\varepsilon_j^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

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

⇒ "Electron neutrino mass"

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

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



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, …

$\Delta T = \Delta E / C$

Debye:

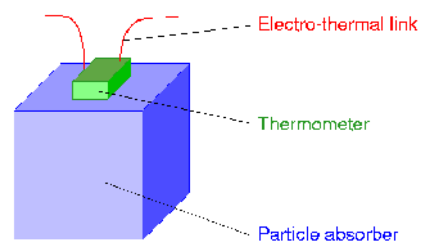
$C \sim T^3$

Disadvantage:
measure whole spectrum at once

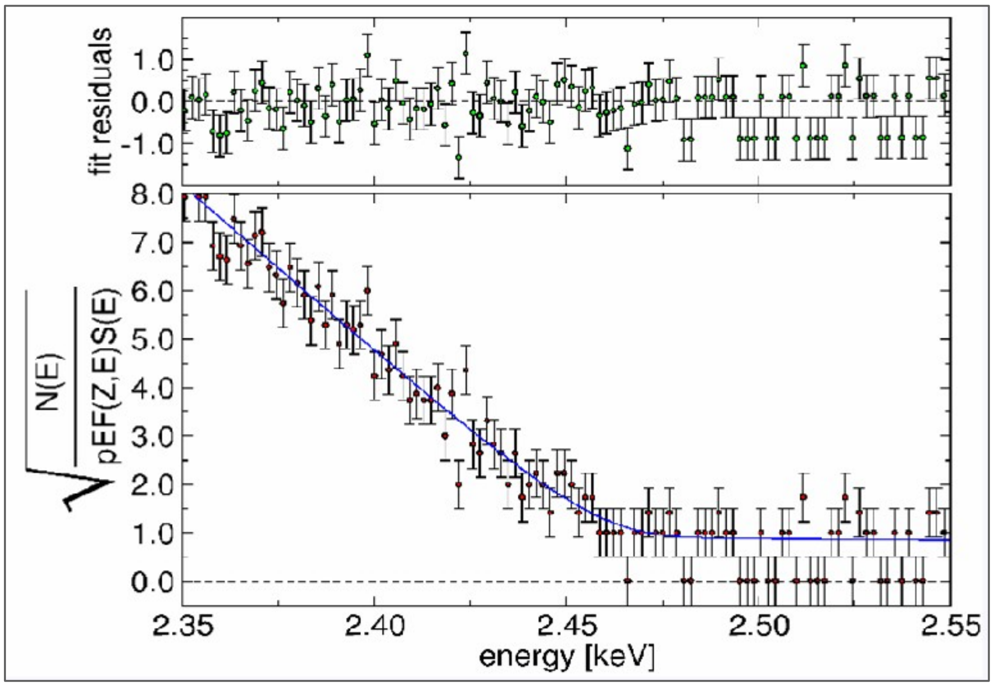
→ pile-up problem

→ need many detector pixels

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



$\Delta T = \Delta E / C$
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(ν) < 26 eV (F.Gatti, Nucl. Phys. B91 (2001) 293)

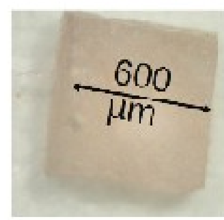
MARE neutrino mass project: ^{187}Re β-decay with cryogenic bolometers

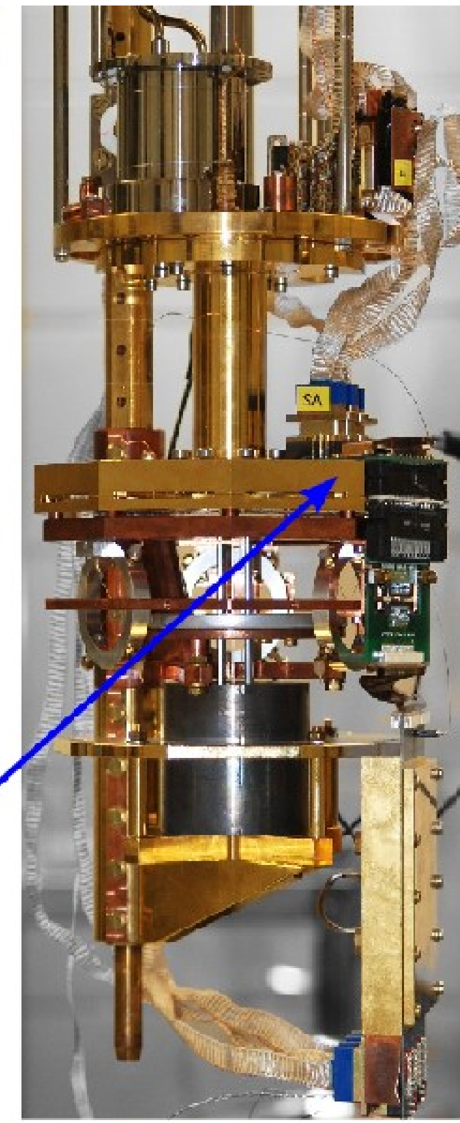
Advantages of cryogenic bolometers:
- measures all released energy except that of the neutrino
- no final atomic/molecular states
- no energy losses
- no back-scattering

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-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

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

Angelo Nucciotti, Meudon 2011

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

Advantages of cryogenic bolometers:
- measures all released energy except that of the neutrino
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Challenges of cryog
- measures the full s
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- understanding spe
- still energy losses
- beta environmenta

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)

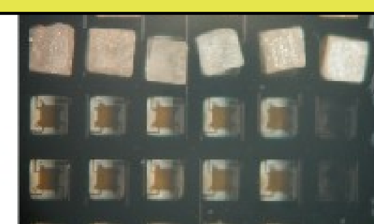
MARE is not anymore proceeded due to severe problems

a) to build high-resolution and fast cryo-bolometers with Rhenium absorbers

b) there is a better idea: electron capture of ^{163}Ho

→ experiments: ECHo, HOLMES

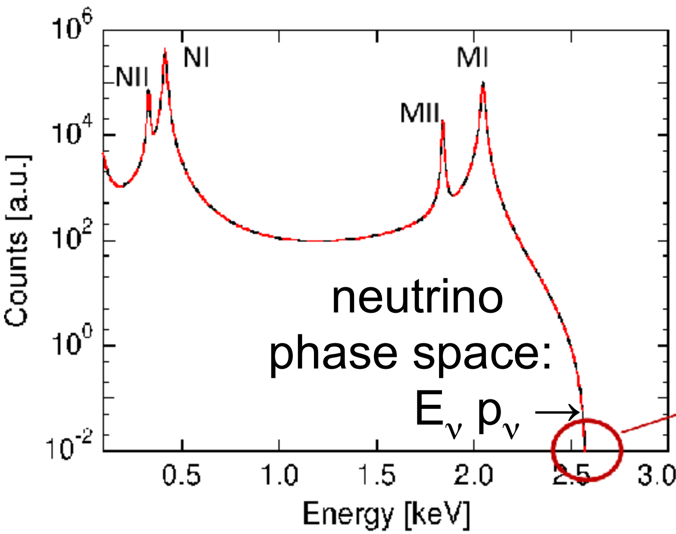
10^4-10^5 detector experiment
- high bandwidth, multiplexed SQUID readout
- also used with ^{163}Ho loaded absorbers

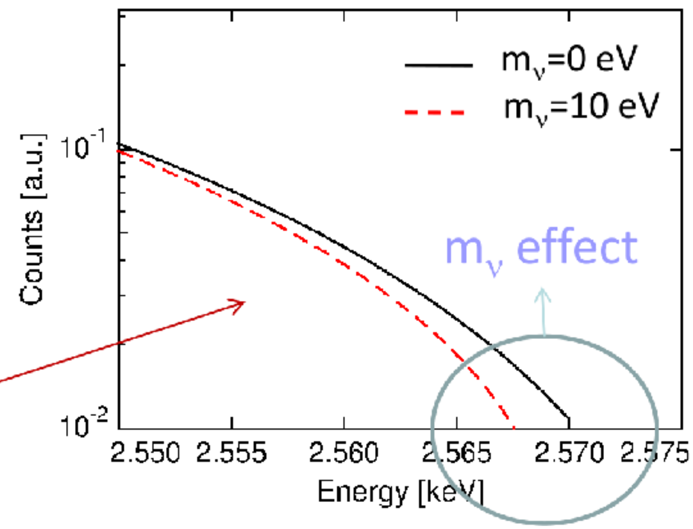


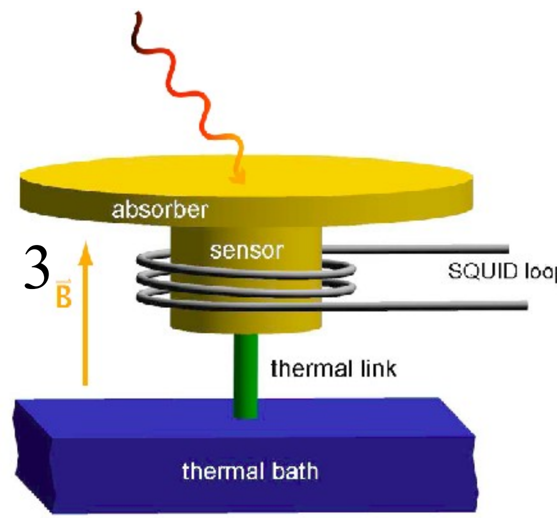
Angelo Nucciotti, Meudon 2011

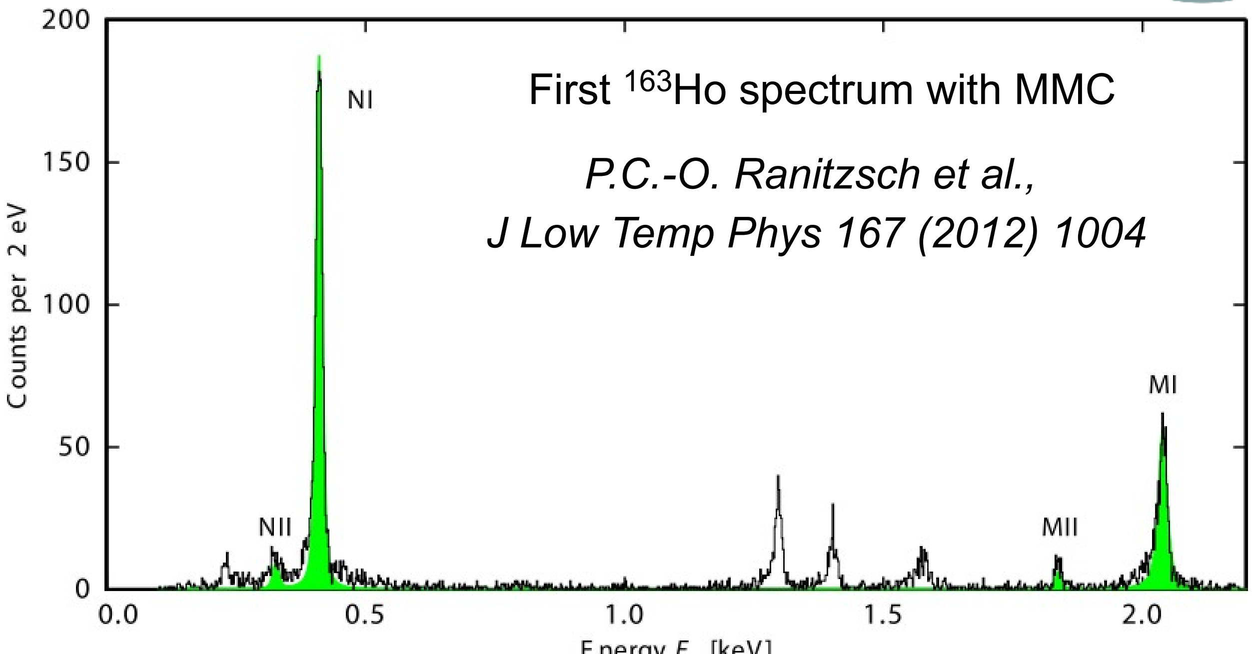
ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

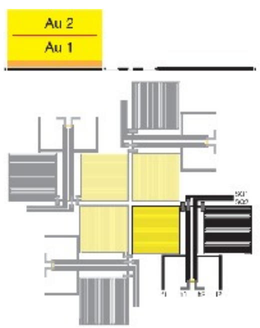
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$$

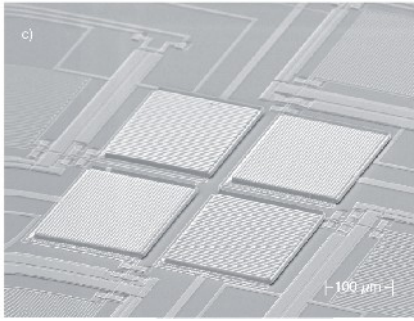








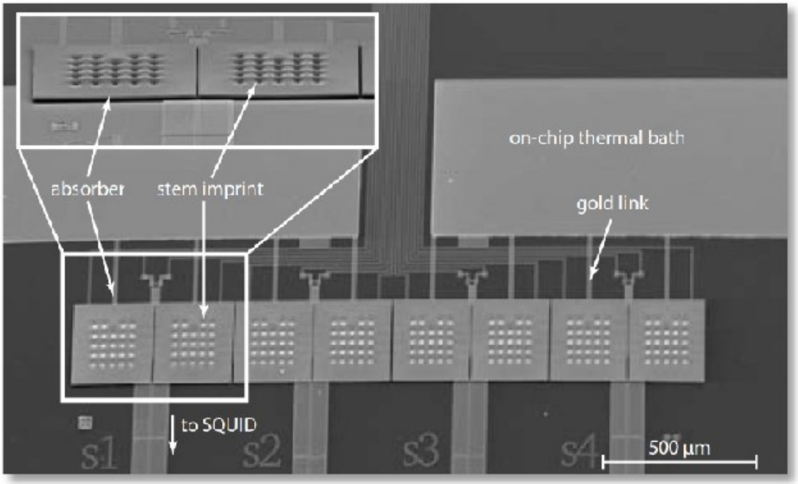


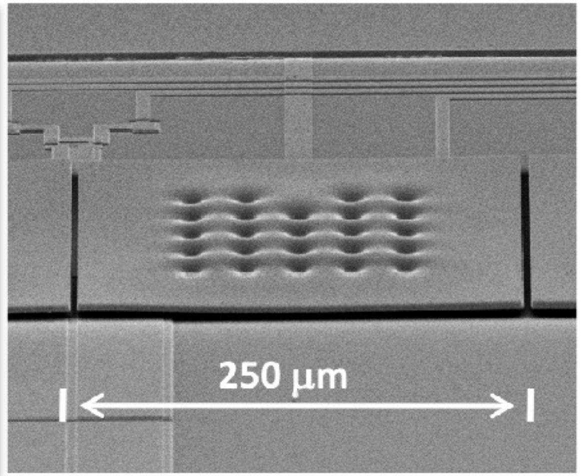


courtesy L. Gastaldo

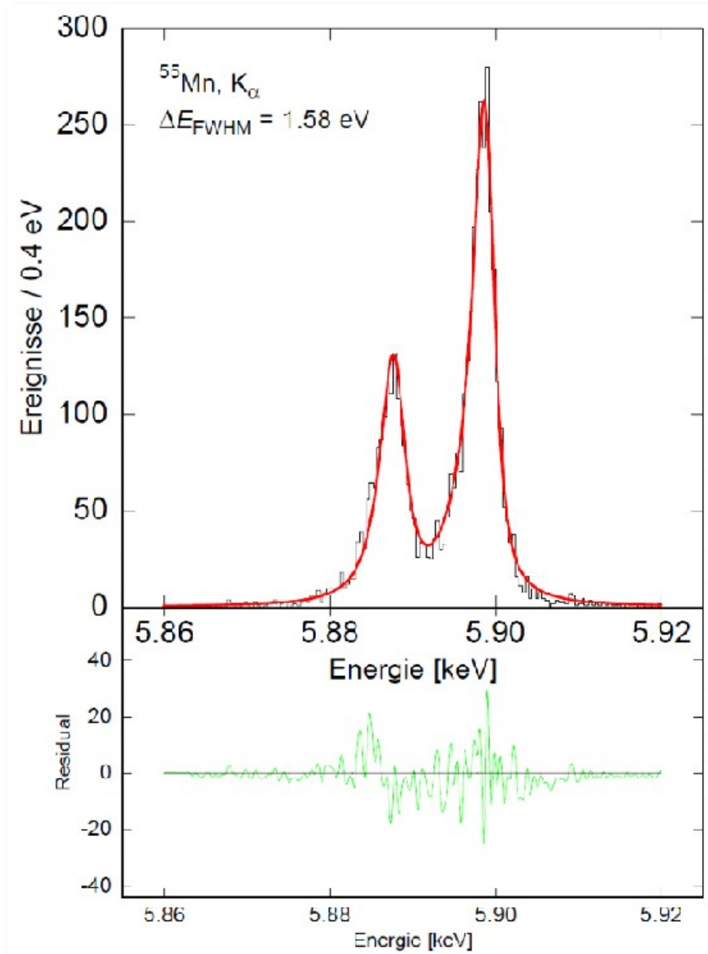
Westfälische Wilhelms-Universität Münster

MMCs: 1d array for soft X-rays (T=20mK) by the Heidelberg ECHo group

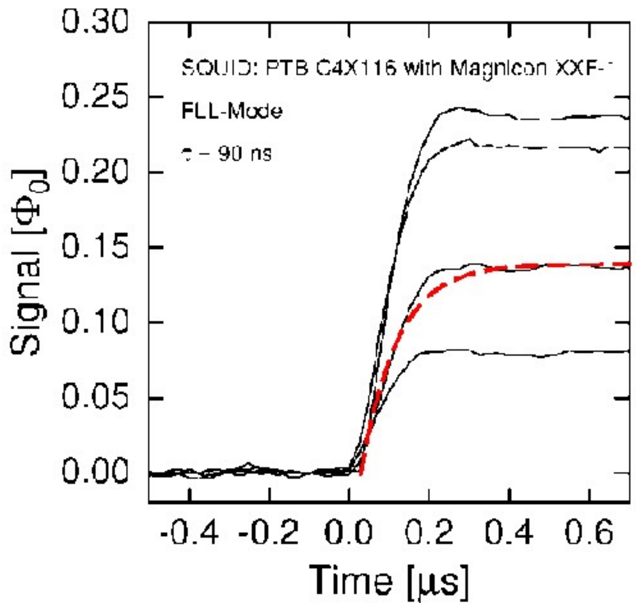




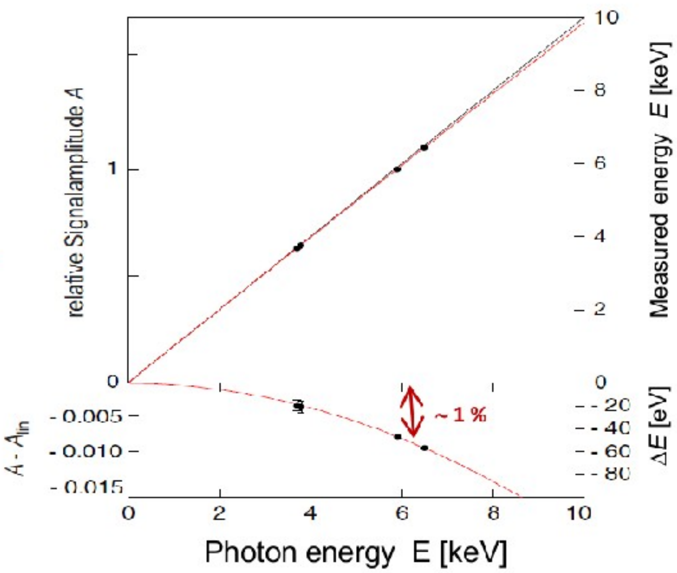
ΔE_{FWHM} = 1.6 eV @ 6 keV



Rise Time: 90 ns



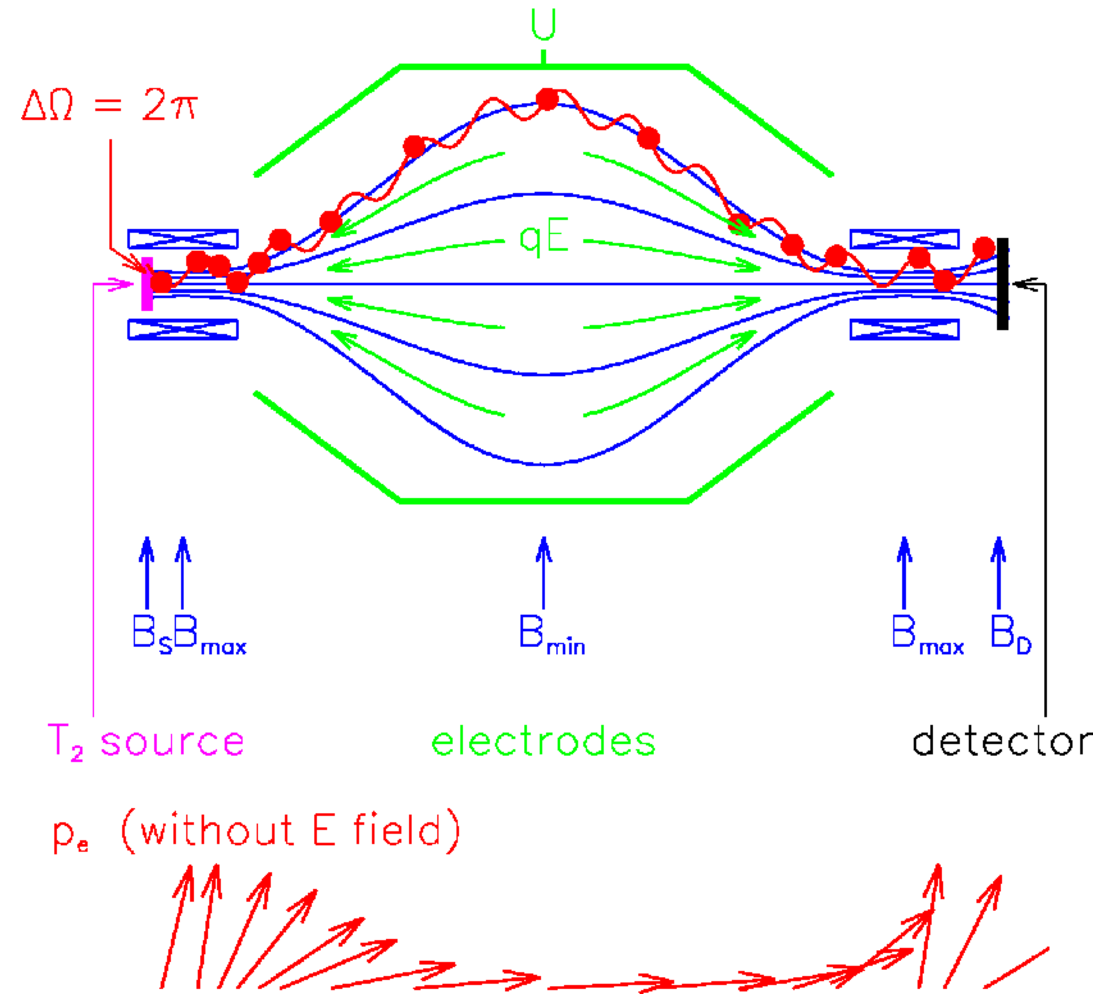
Non-Linearity < 1% @6keV



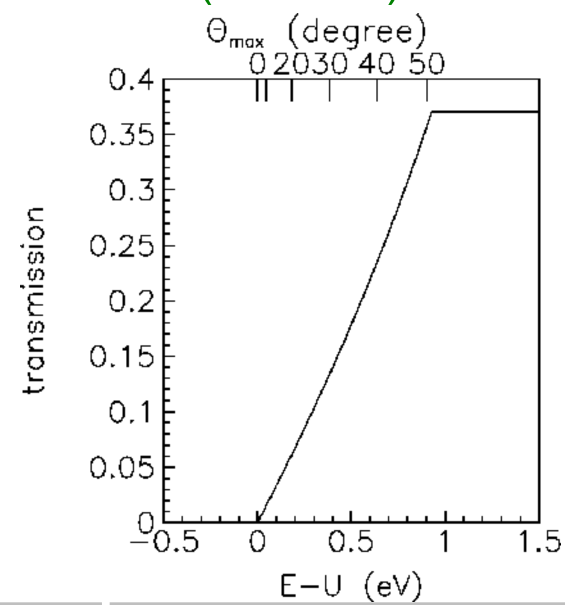
L. Gastaldo, WE Heraeus Seminar „Massive Neutrinos“, April 2014

The classical way:

Tritium β-spectroscopy with a MAC-E-Filter



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

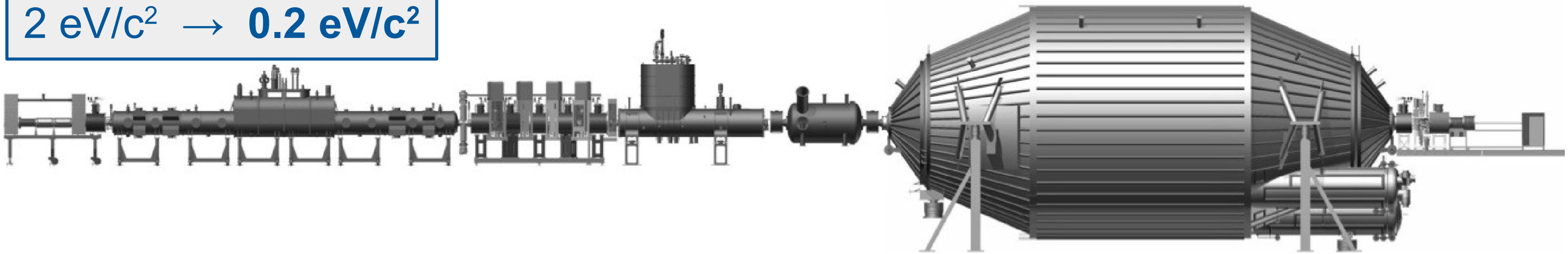


⇒ sharp integrating transmission function without tails →

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

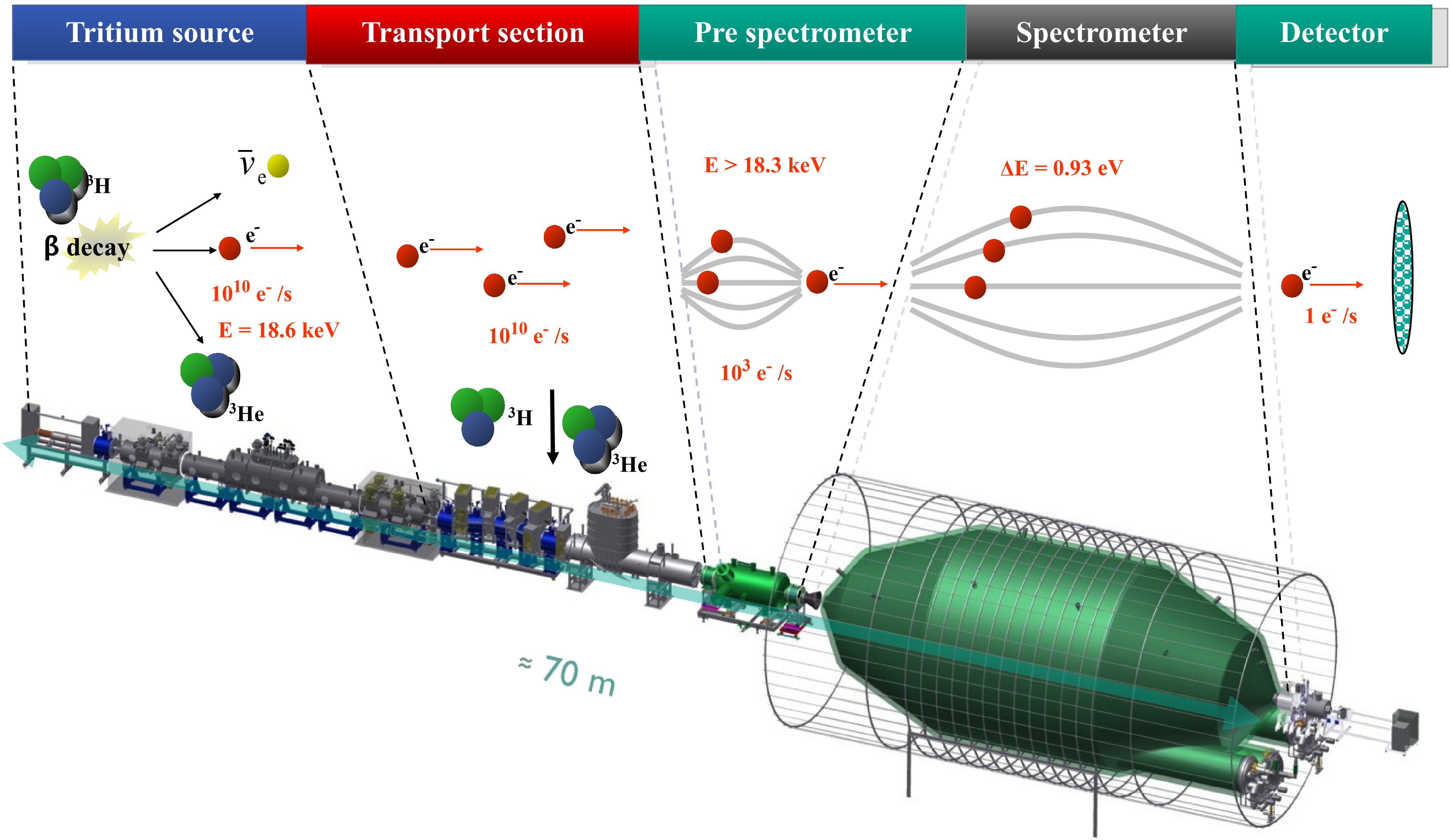
The Karlsruhe Tritium Neutrino Experiment KATRIN

Sensitivity on $m(\nu_e)$:
$2\ eV/c^2 \rightarrow$ **$0.2\ eV/c^2$**



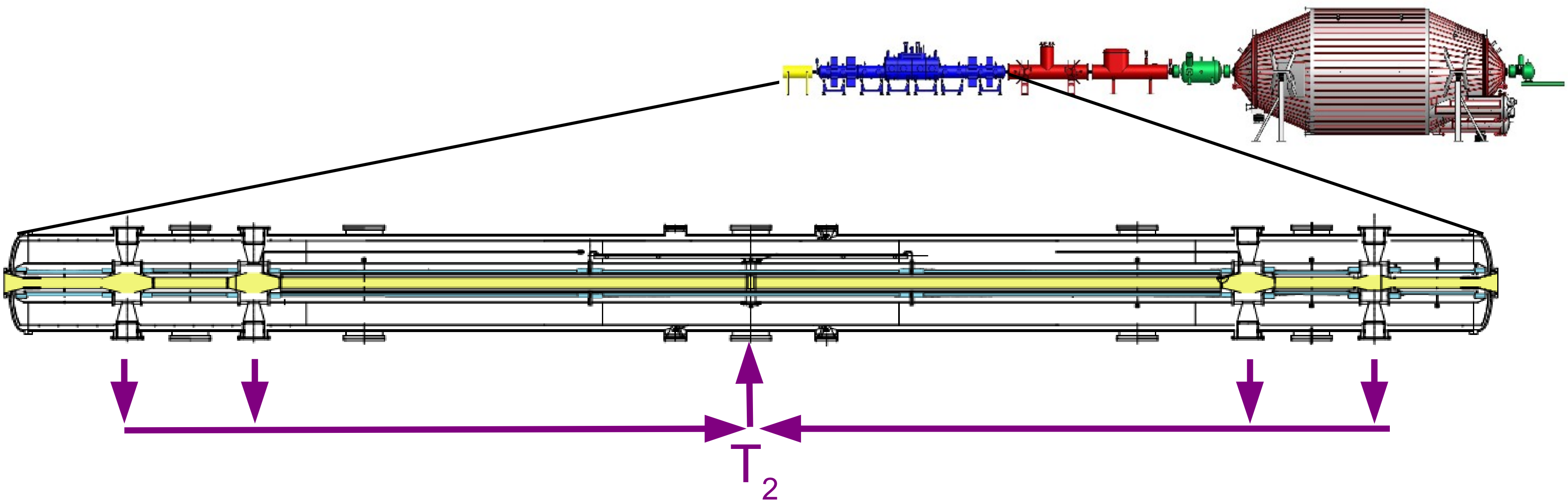
- The KATRIN collaboration is based on strong international (US, CZ, RUS, UK) & national partners with unique expertise in many key technological areas
- Uniting the world-wide expertise in tritium β-decay

The KATRIN experiment - overview



Westfälische Wilhelms-Universität Münster

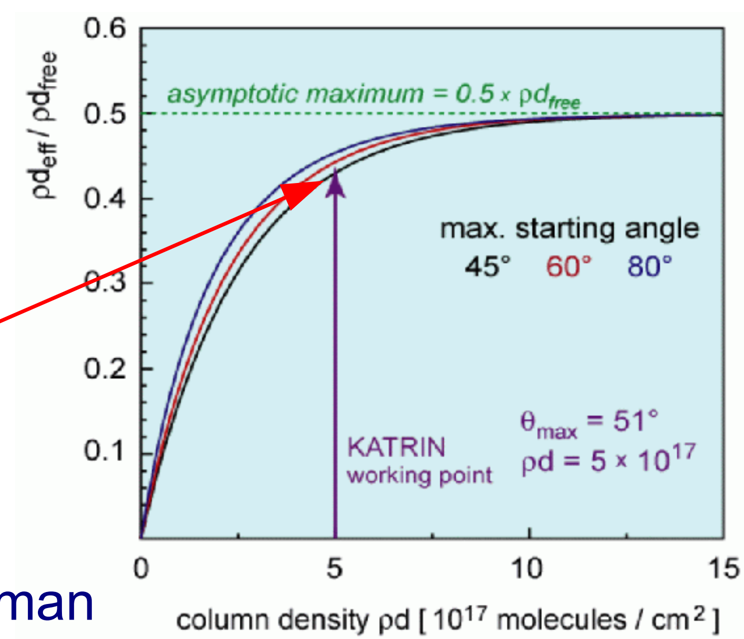
Molecular Windowless Gaseous Tritium Source WGTS



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

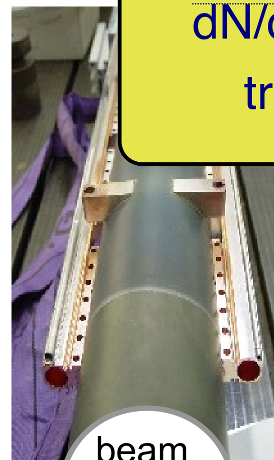
Very successful cool-down and stability tests of the WGTS demonstrator

arrival of WGTS demonstrator at KIT: April 2010

per mill stability source strength request:

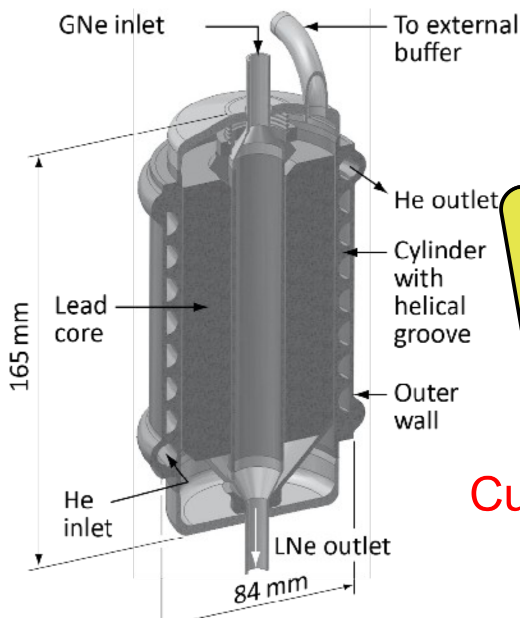
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p\, V / R\, T$

tritium fraction f_T & ideal gas law

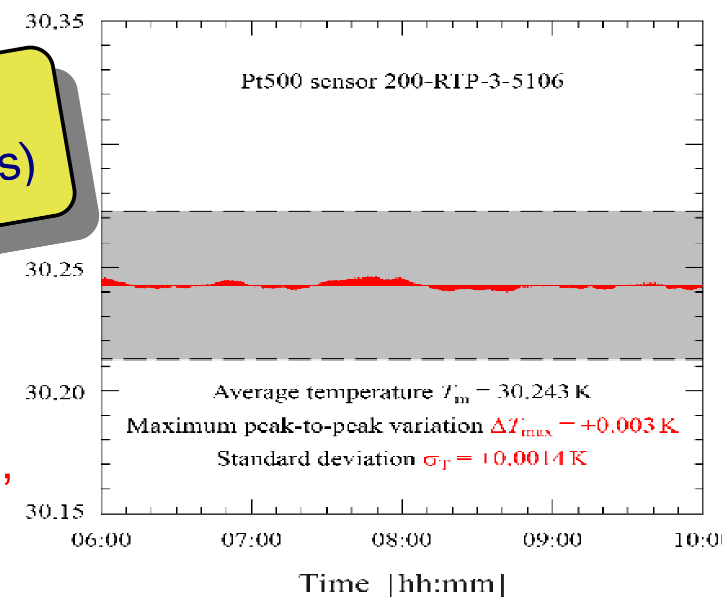


beam tube Ø=90mm

cooling concept of WGTS: pressurized 2-phase Ne



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



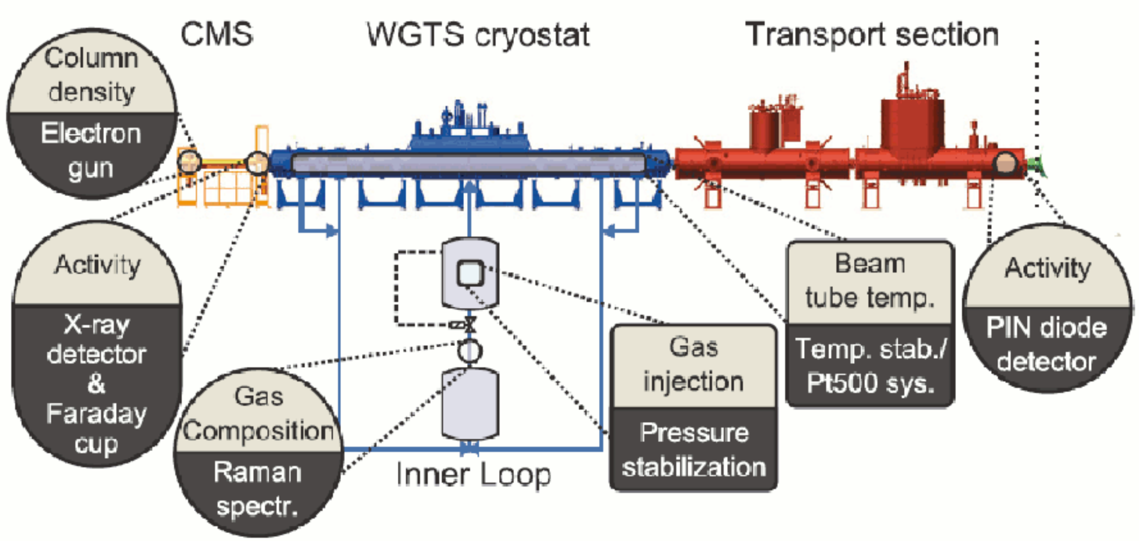
Currently: tests of sc magnets, constructing of WGTS out of demonstrator

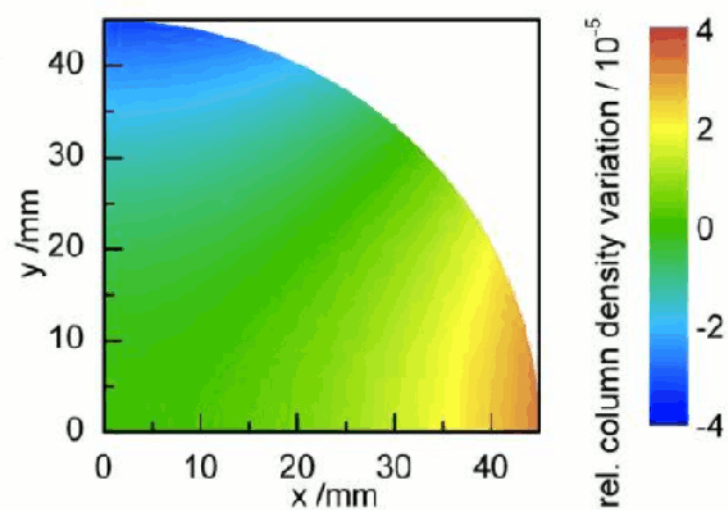
Tritium source systematics

tritium source systematics – a review

Karlsruhe Institute of Technology

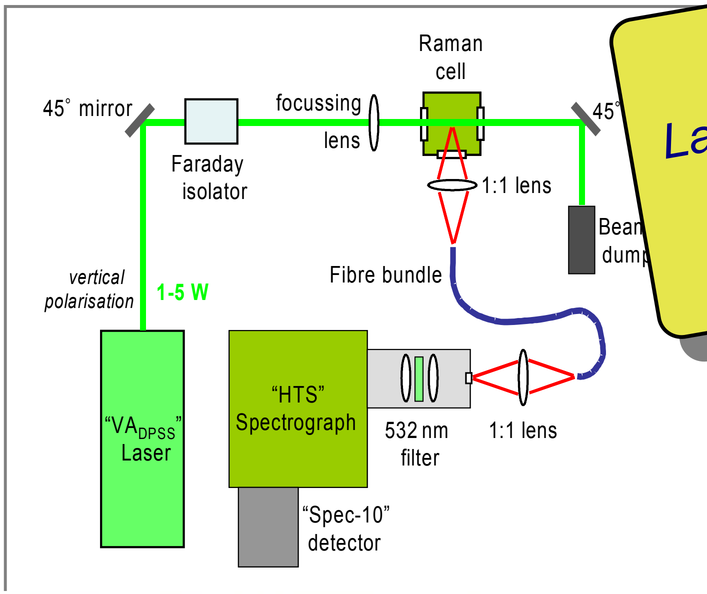
- near-time monitoring tools & quasi 3-D source model
  - extensive sensor instrumentation & control/monitoring systems ☑
  - successful large-scale test experiments (WGTS demo, LARA, loops) ☑
  - improved source modelling: quasi-3D model of gas flow ☑



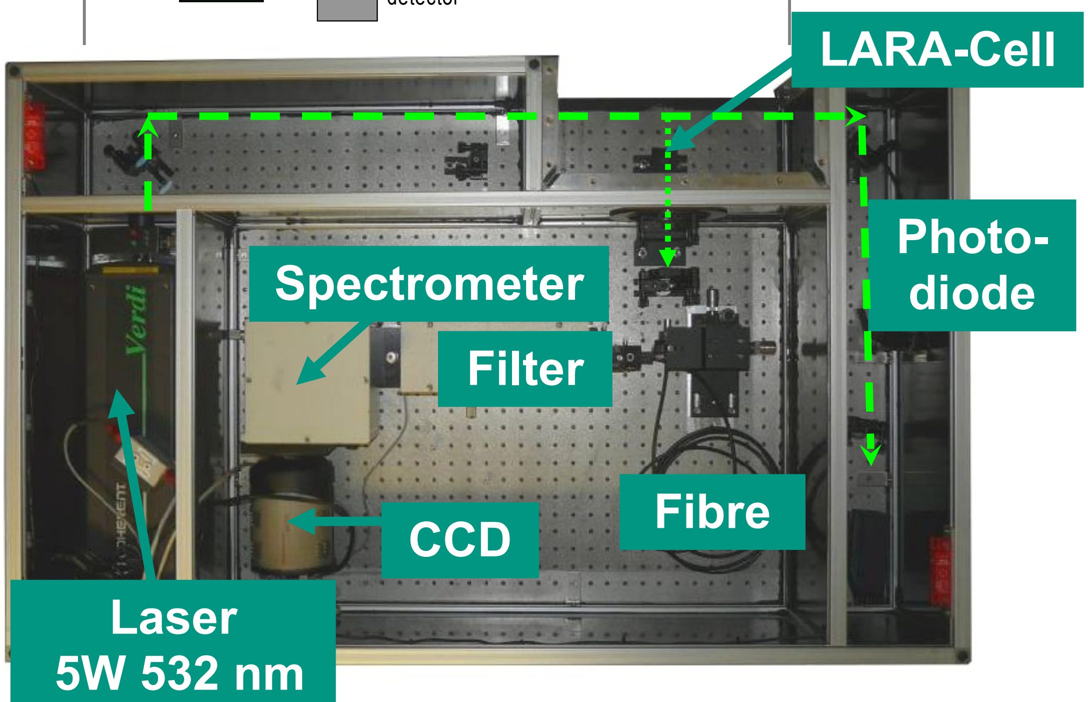


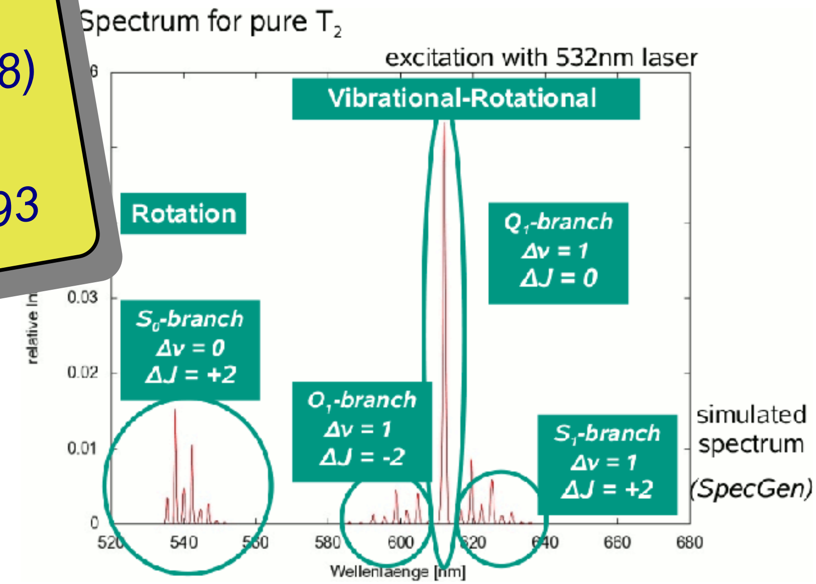
M. Babutzka et al.,
Monitoring of the operating parameters of the KATRIN Windowless Gaseous Tritium Source
New Journal of Physics 14 (2012) 103046
M. Hötzel et al.,
Accurate computation of the integrated tritium β-spectrum near the endpoint energy for KATRIN
to be subm. to New J. of Phys.

Measurement of tritium concentration by laser Raman spectroscopy

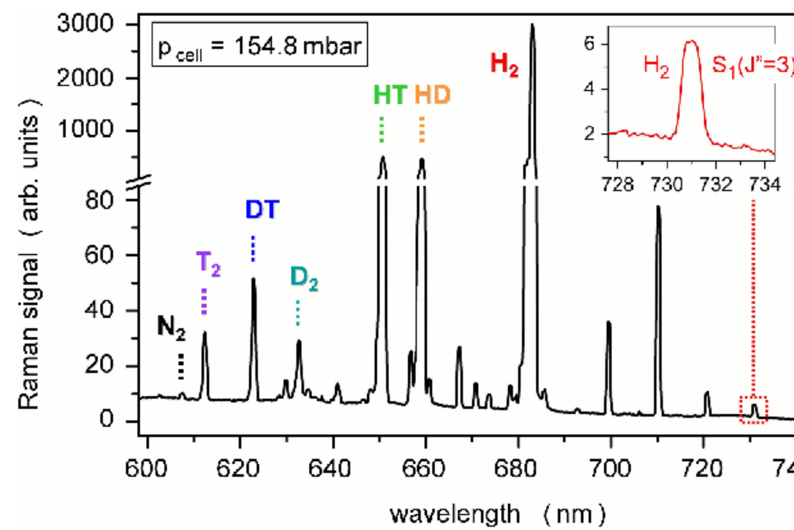


R.J. Lewis et al., Las. Phys. Lett.1-10 (2008)
M.Sturm et al, Las. Phys. 20 (2010) 493



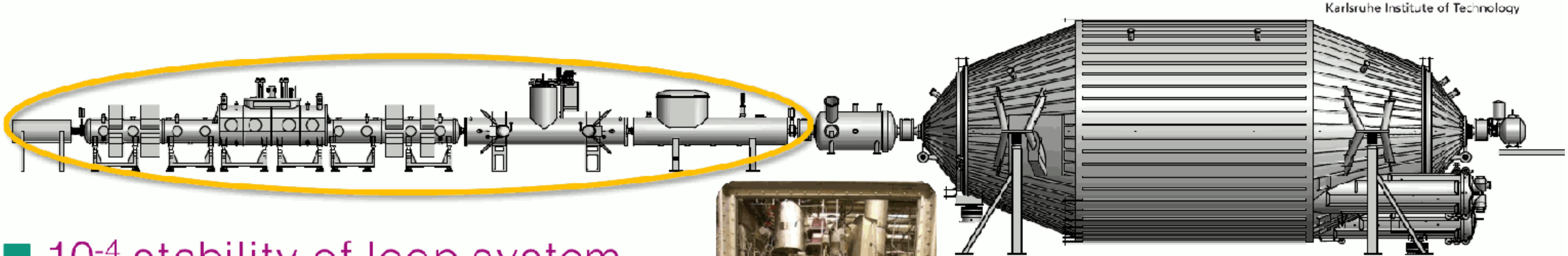


H_2 / HD / T_2 / DT / HT
= 0.820 / 0.083 / 0.003 / 0.005 / 0.085

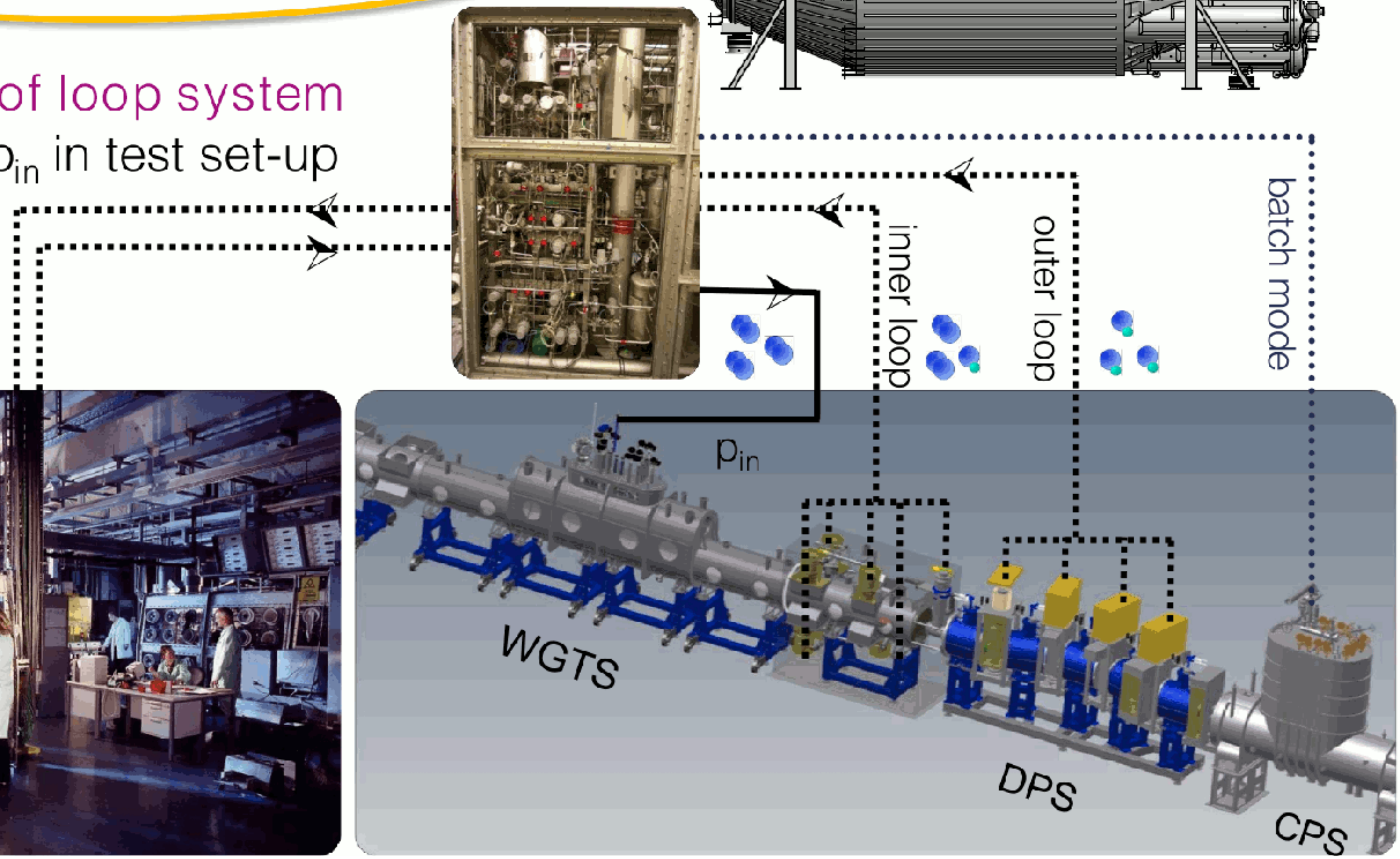


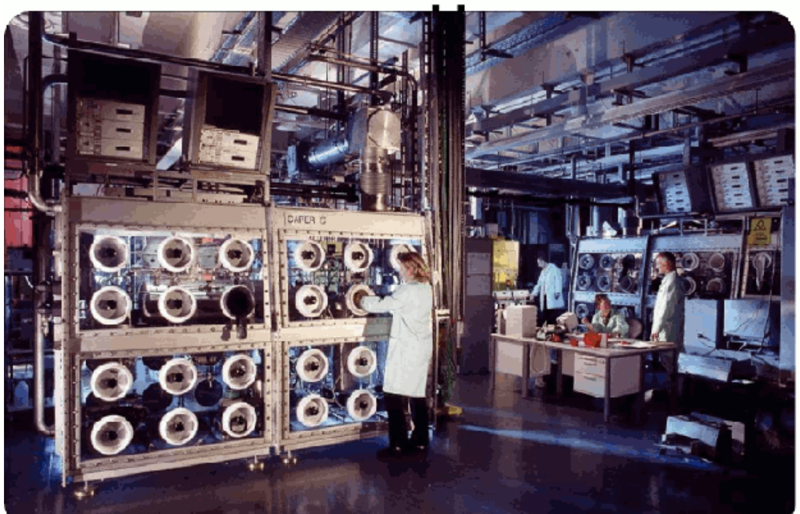
Tritium loops at Tritium Laboratory Karlsruhe

tritium source: loop system

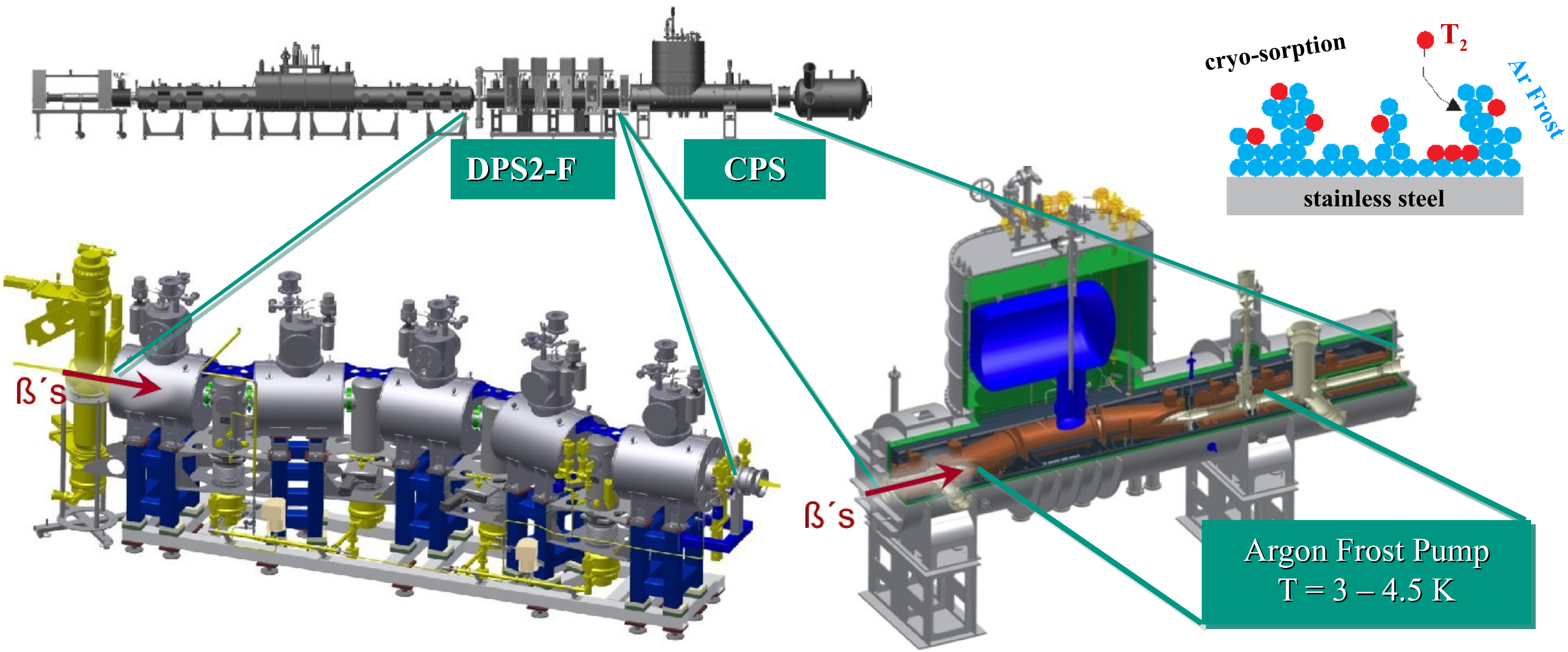


- 10^{-4} stability of loop system achieved for p_{in} in test set-up





Transport and differential & cryo pumping sections



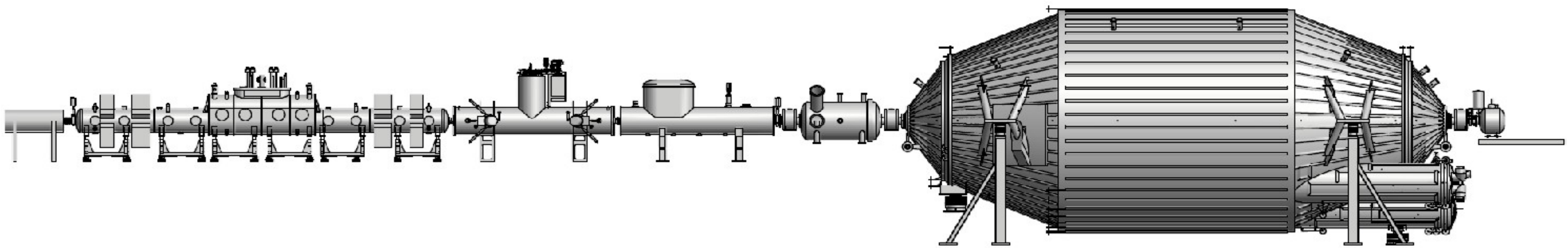
- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- under construction, to be installed mid 2014

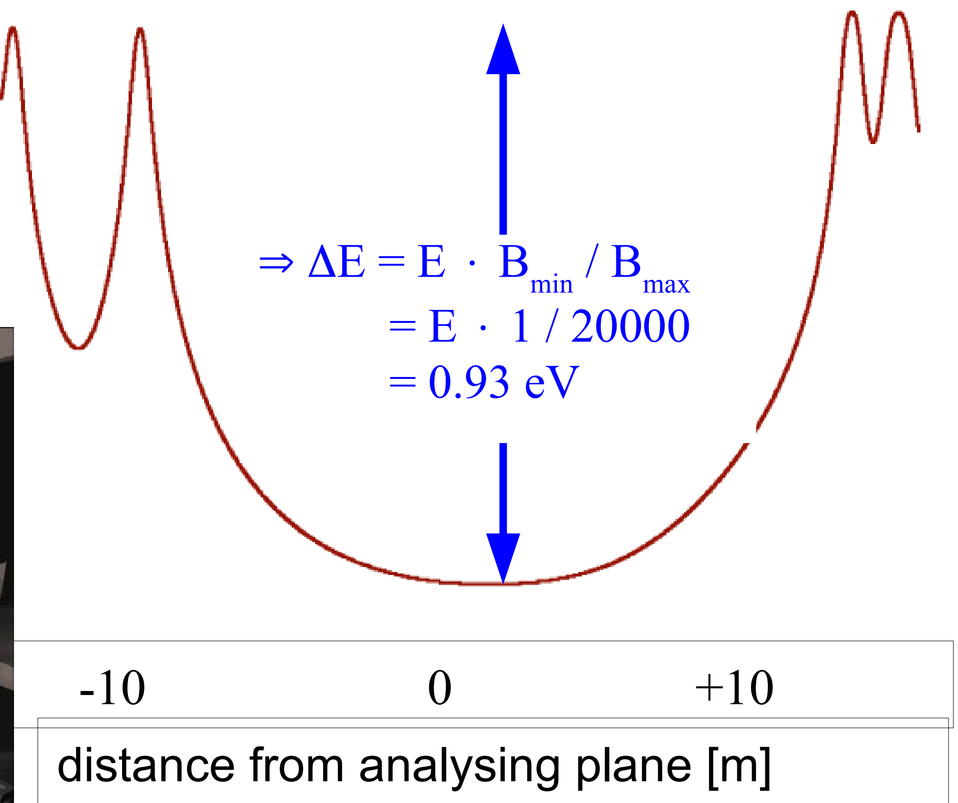
- based on by cryo-sorption
- Tritium retention: $>10^7$
- magnetic field: 5.6 T
- delivery Fall 2014

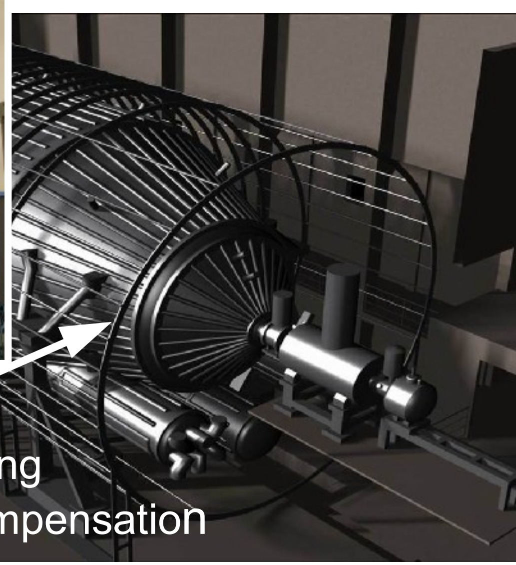
F. Eichelhardt et al, Fusion Science and Technology 54 (2008) 615

O. Kazachenko et al., NIM A 587 (2008) 136

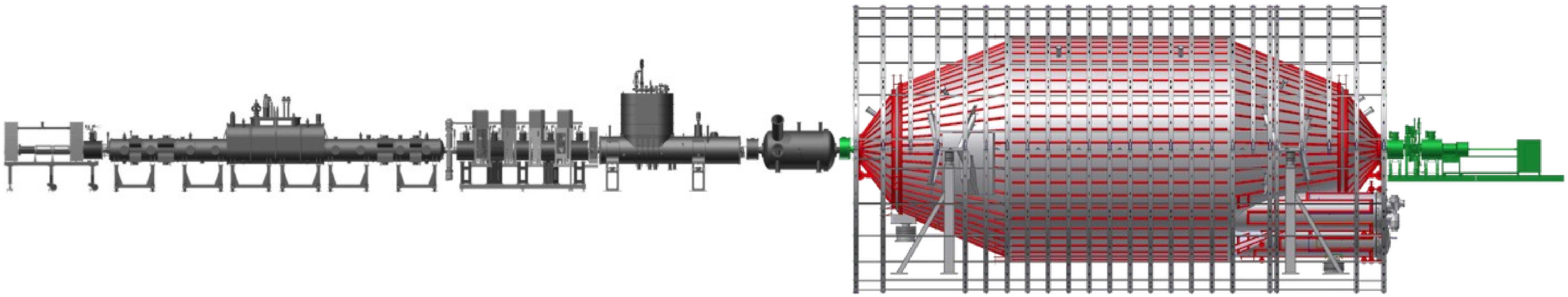
Electromagnetic design: magnetic fields







KATRIN main spectrometer



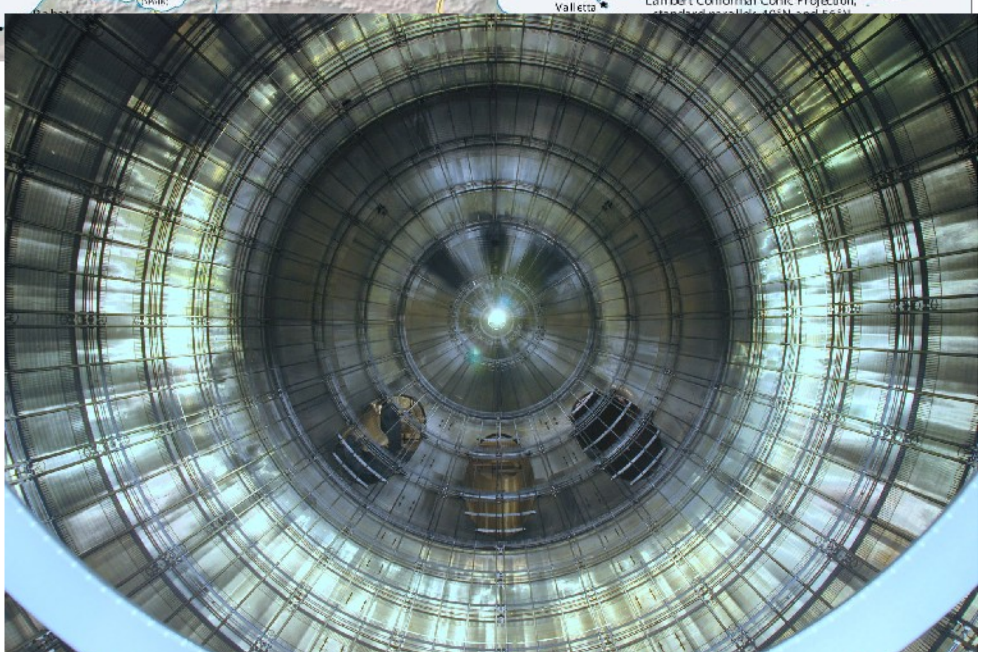
Spectrometer:

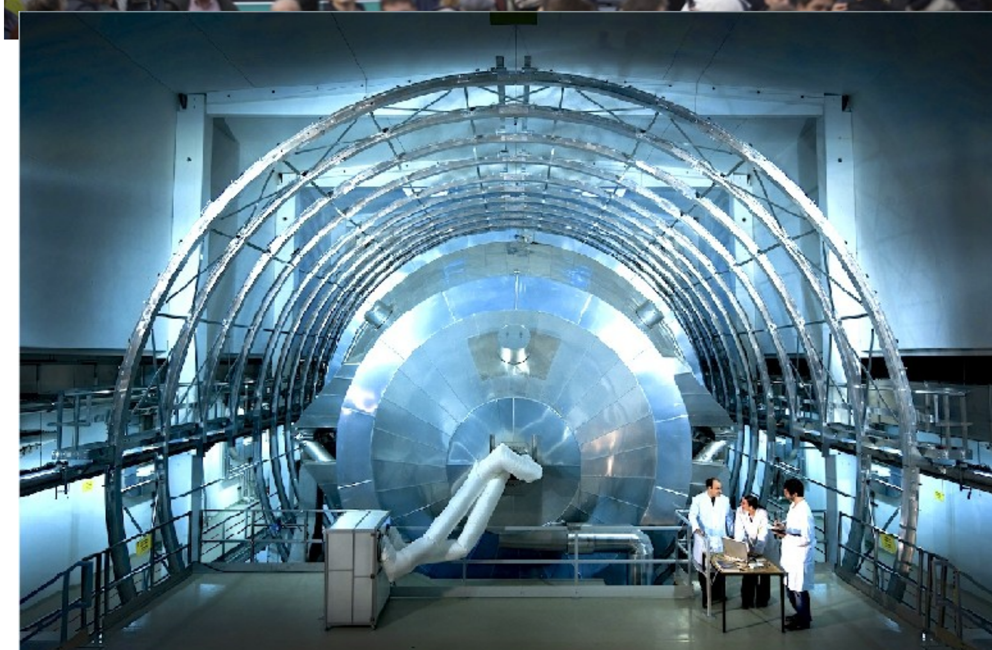
- huge size: 10m diameter, 24m length
  1240 m^3 volume, 690 m^2 inner surface
- ultra-high energy resolution: ΔE = 0.93eV
- vacuum vessel on precise high voltage

Background reduction:

- ultra-high vacuum: p = O(10^{-11} mbar)
- reduce cosmic ray induced bg by wire electrode
- reduce radon induced bg by cryo baffles
- eject stored electrons by active measures

Main spectrometer history





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The detector

Requirements

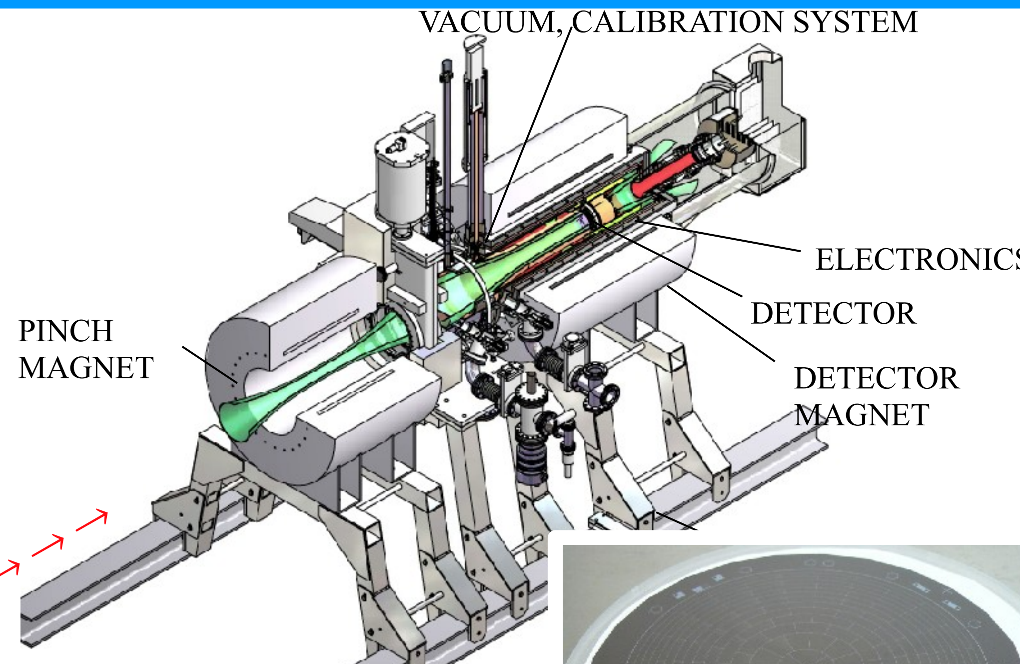
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  (passive and active shielding)
- good energy resolution (< 1 keV)

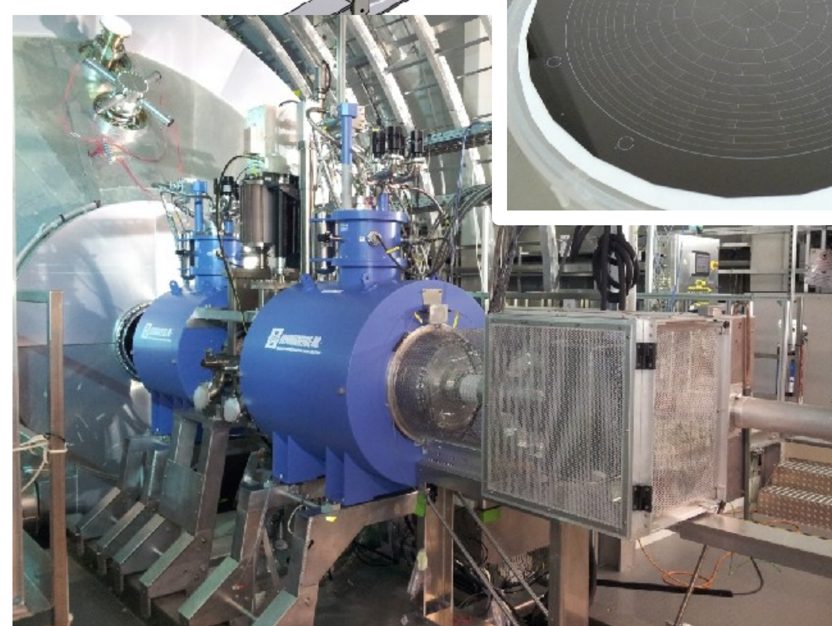
Properties

- 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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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

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

→ quantum mechanical thresholds help a lot !

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

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

1. inelastic scatterings of β´s inside WGTS
   - **dedicated e-gun measurements**, unfolding …
2. fluctuations of WGTS column density (required < …
   - 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**

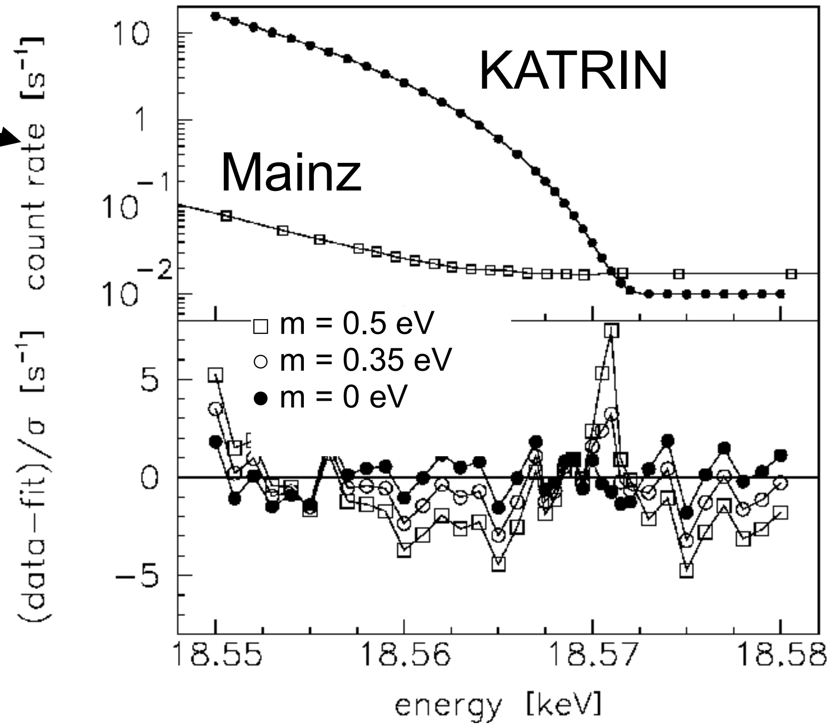
tritium source

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: $\sigma_{syst} \sim \sigma_{stat}$

⇒ 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.)

Suppress secondary electron background from walls on high potential

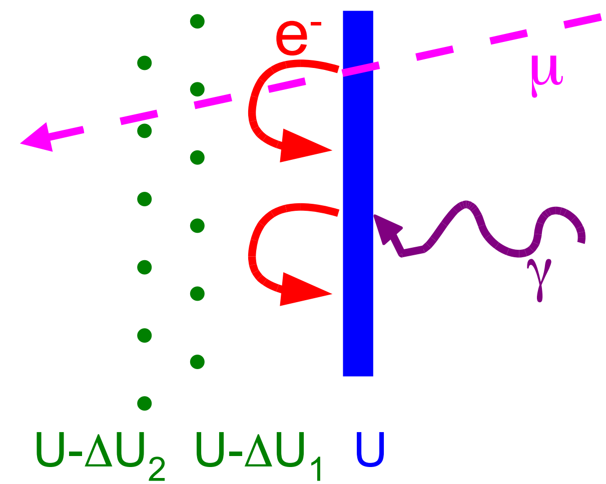
Secondary electrons from wall/electrode

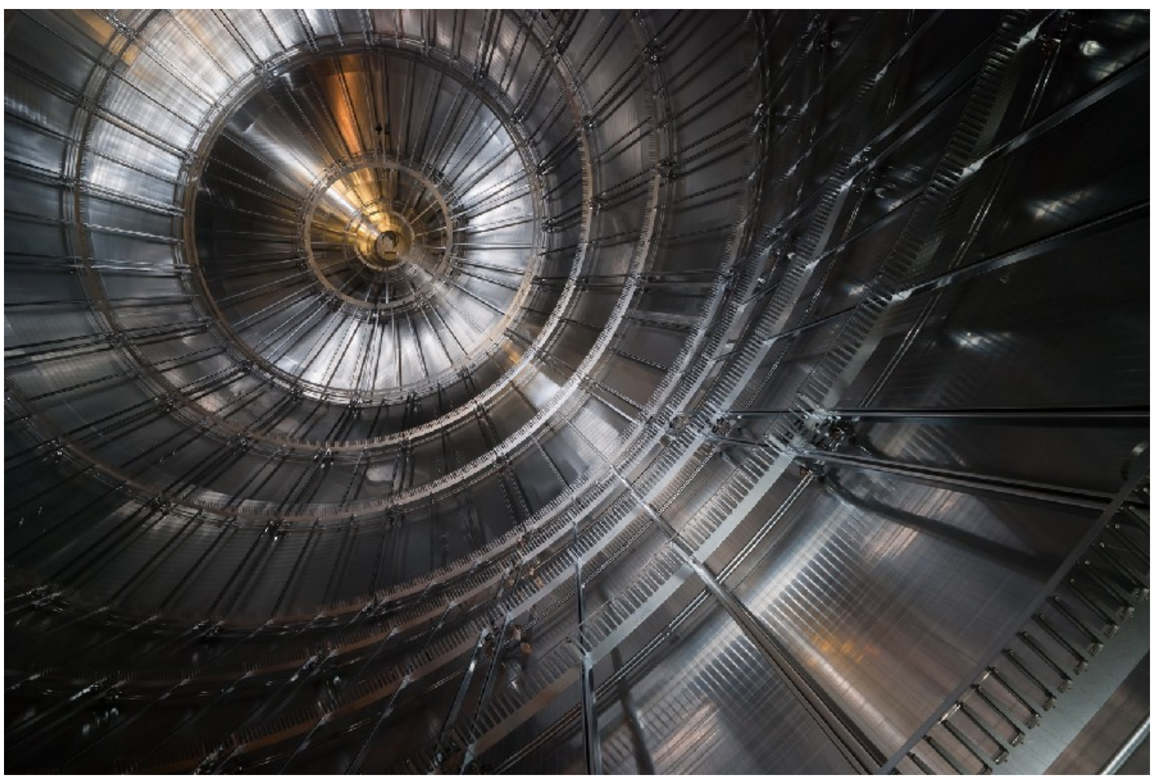
by cosmic rays, environmental radioactivity, ...

New: double layer wire electrode

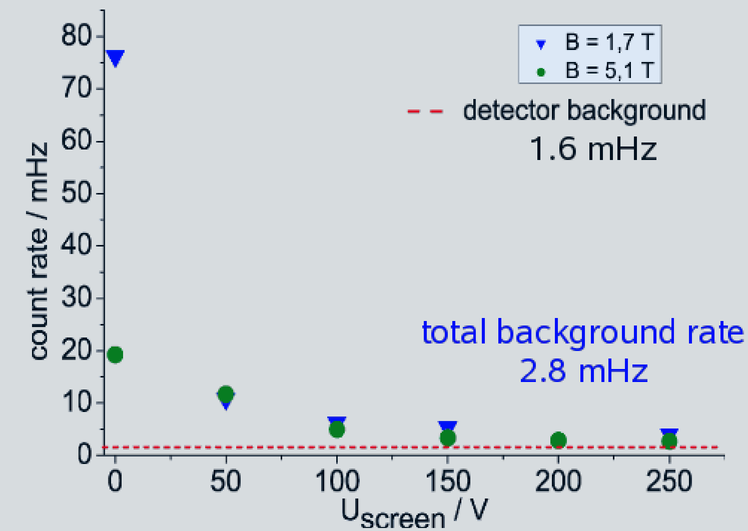
on slightly more negative potential

(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)

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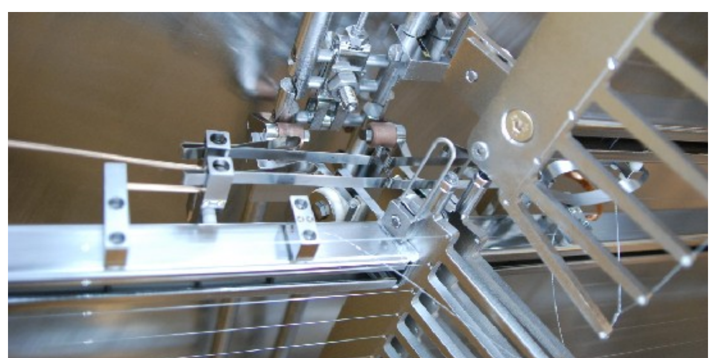
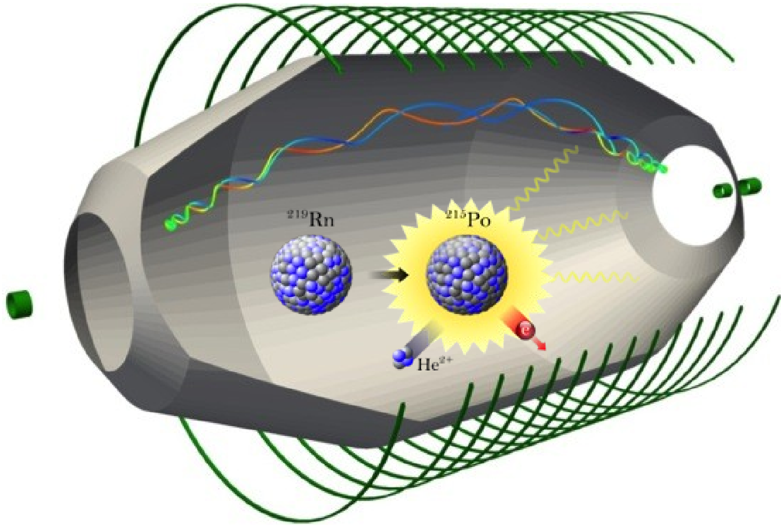
Two-layer wire electrode modules installation inside main spectrometer



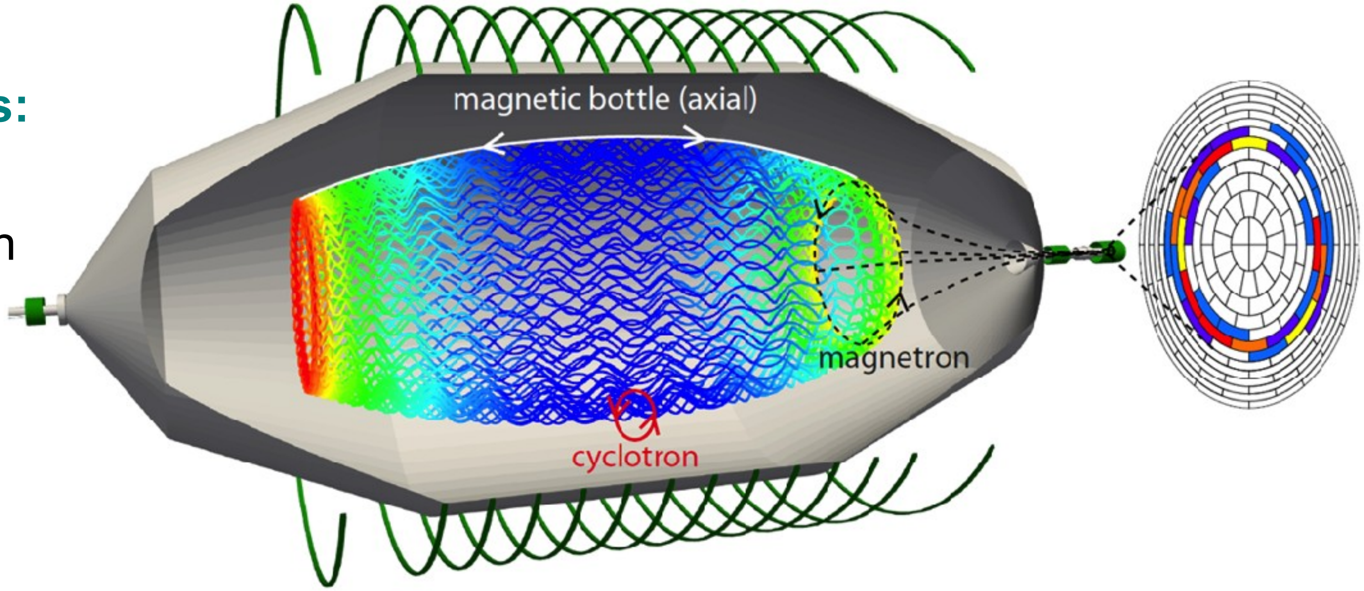
Secondary electron background from radon decays from getter pumps

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



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

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



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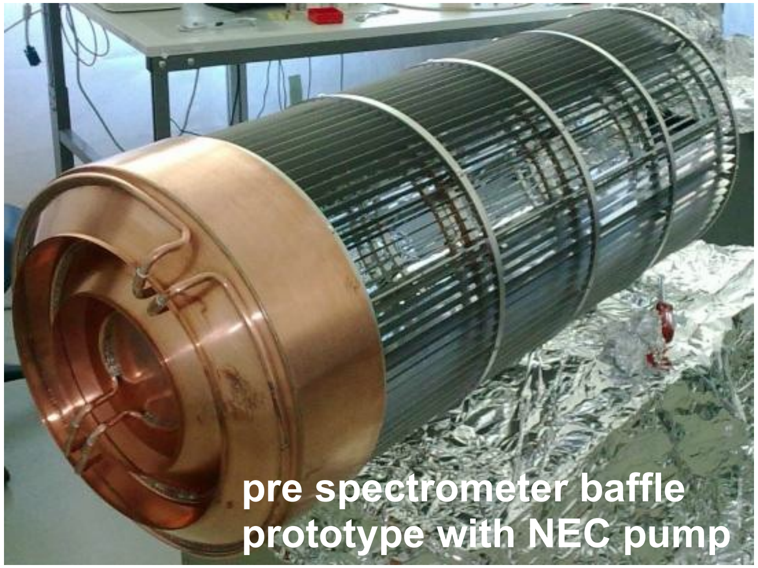
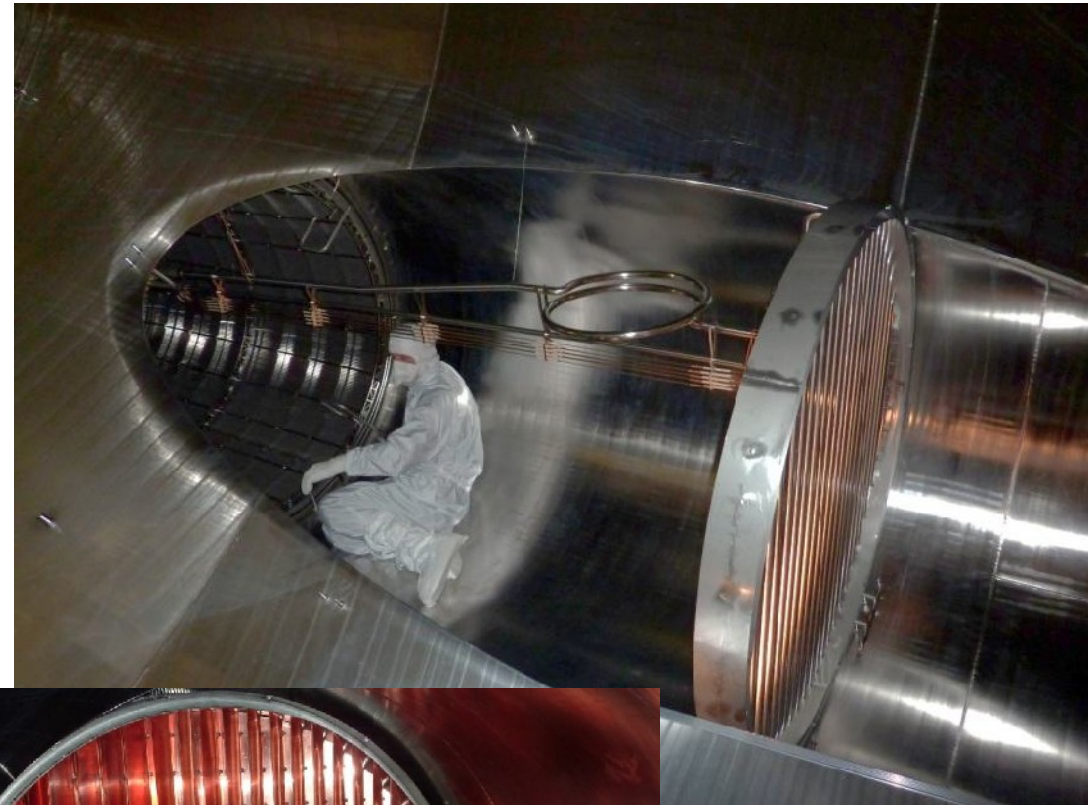
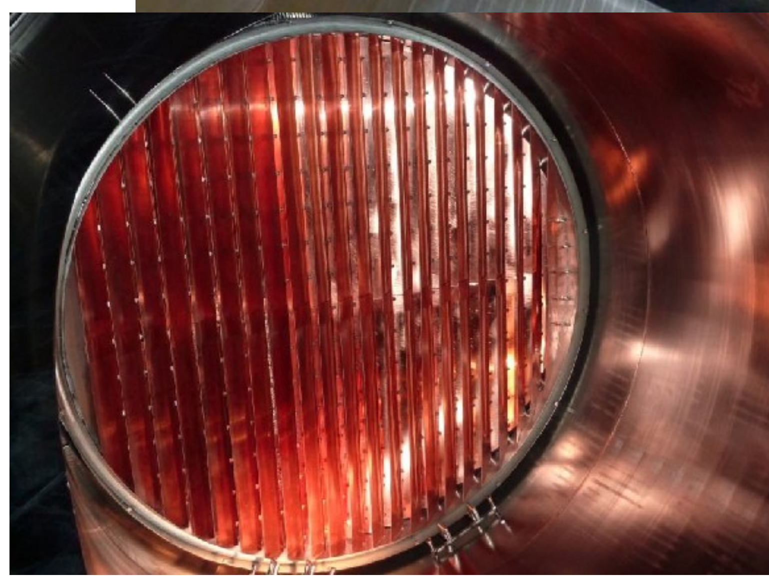
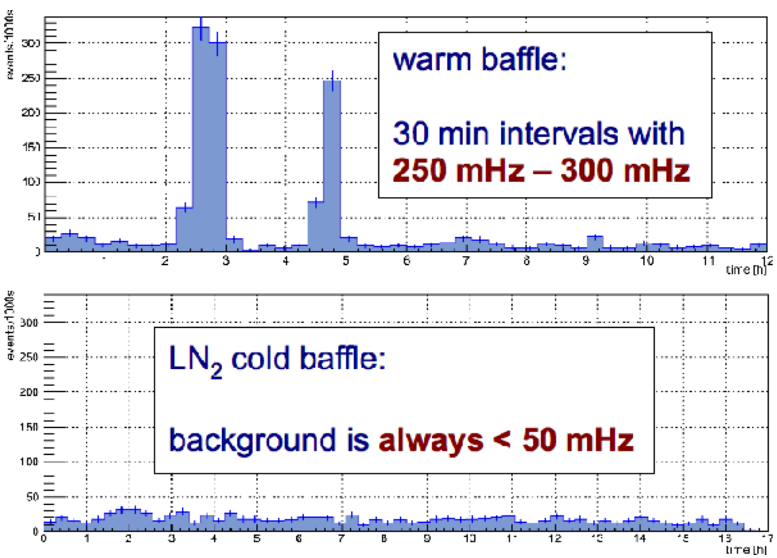
Radon elimination by LN_2-cooled baffles in the main spectrometer





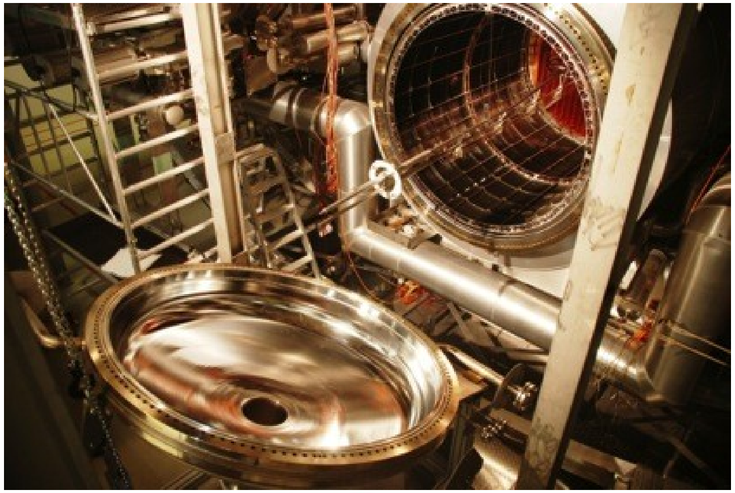


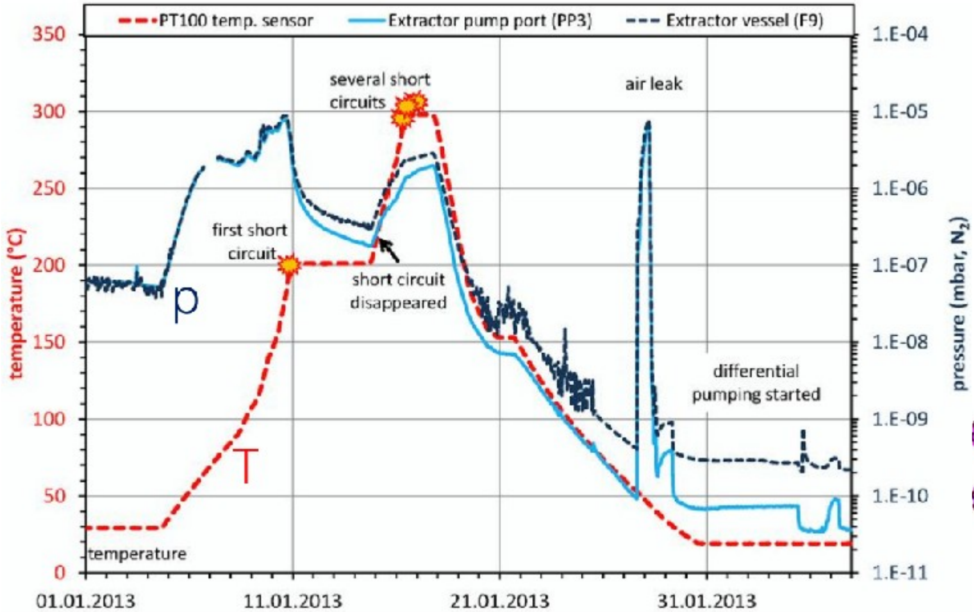


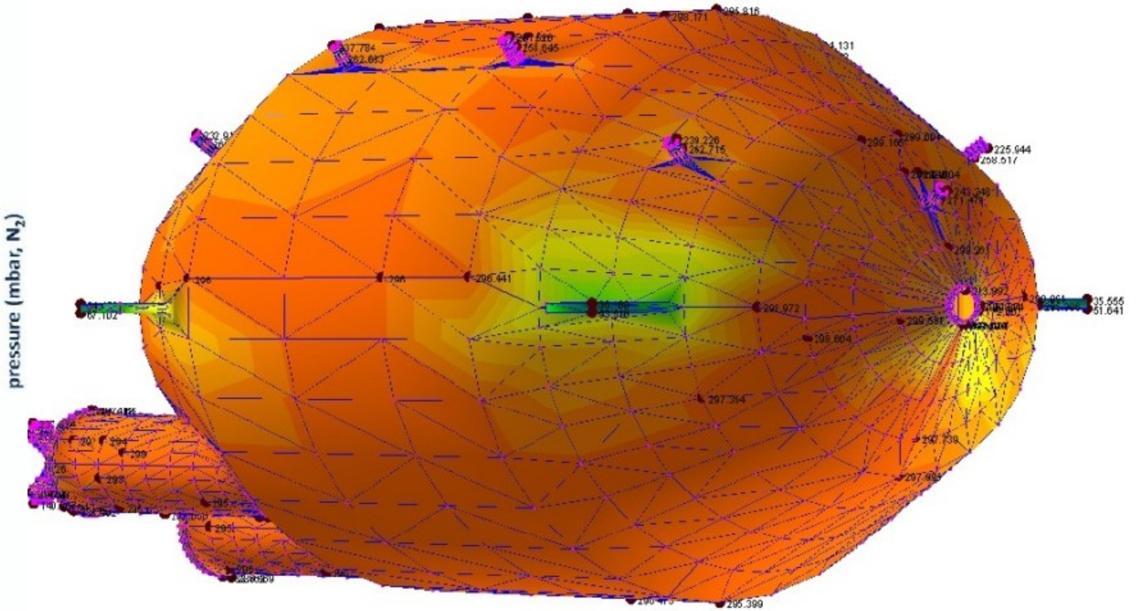
Prepare for spectrometer and detector commissioning: out-baking

Vacuum conditioning for the commissioning measurements

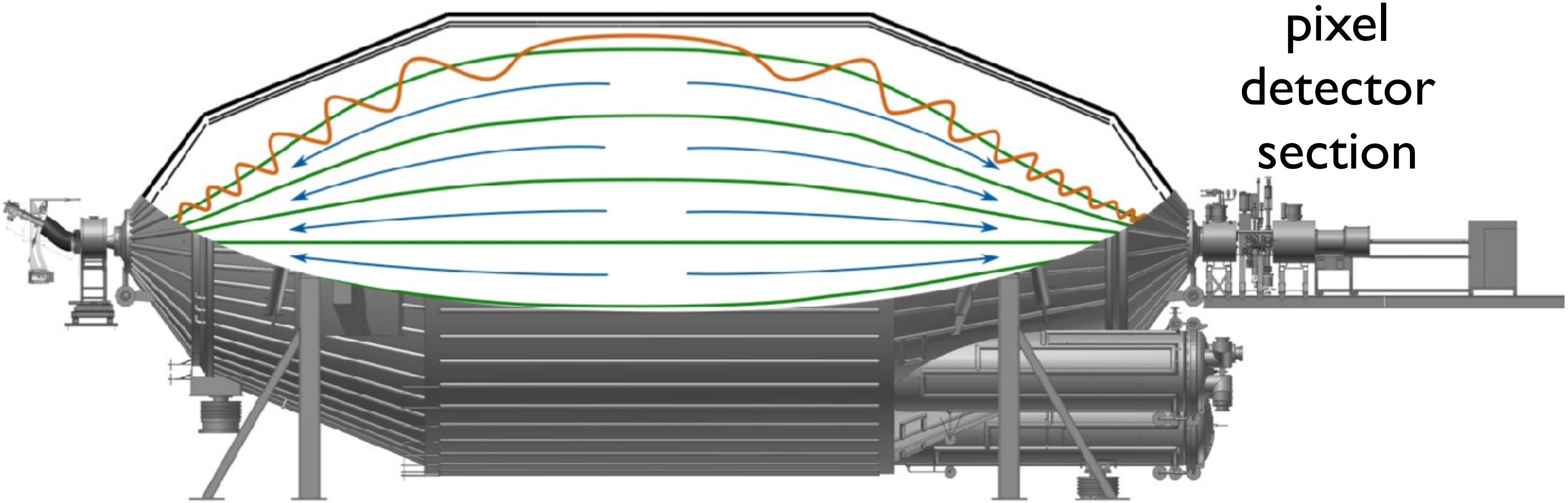
- aim: UHV in huge spectrometer: p ≈ 10^{-11} mbar
- to do: spectrometer bake-out at T = 300 °C
  also to activate SAES getter pumps
  → 1000 000 l/s pumping speed
- achieved in January 2013 ✔







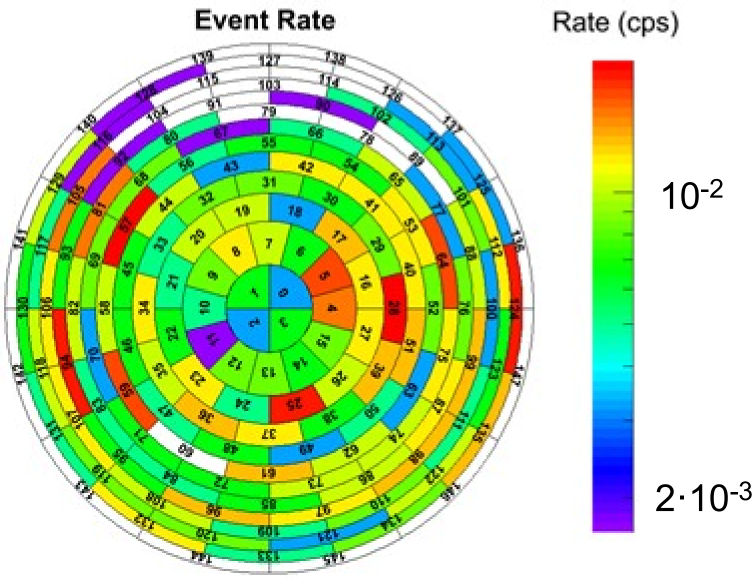
Spectrometer and detector commissioning: objectives

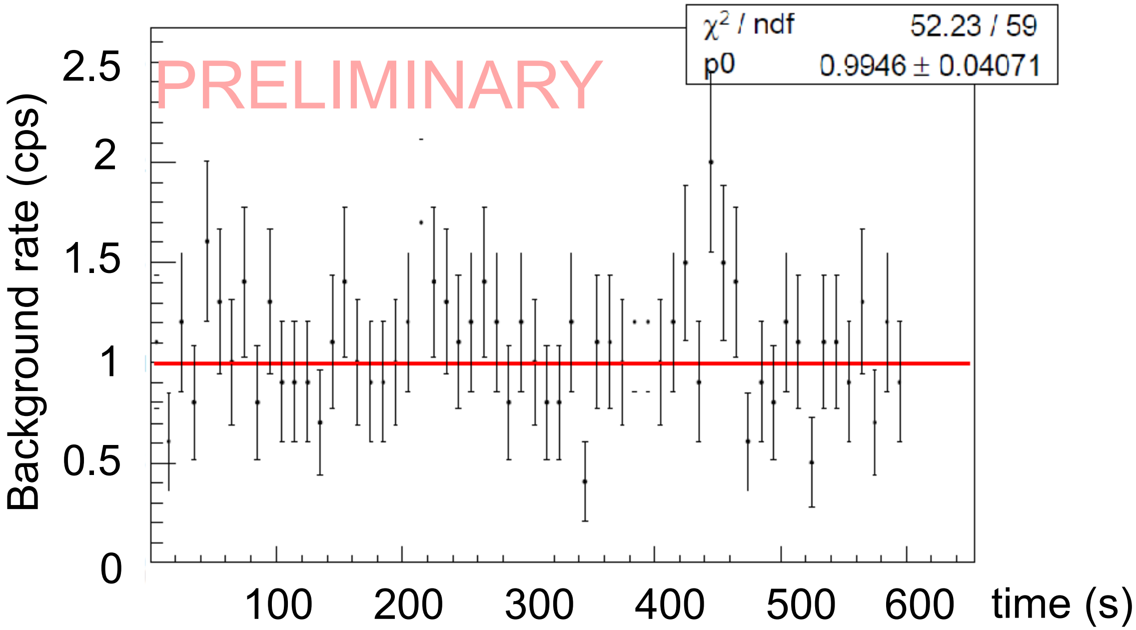


Primary objectives:

- test of individual hardware, software and slow control components
- provide ultra high vacuum conditions at the p $\approx 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter (E = 18.6 keV with 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)**

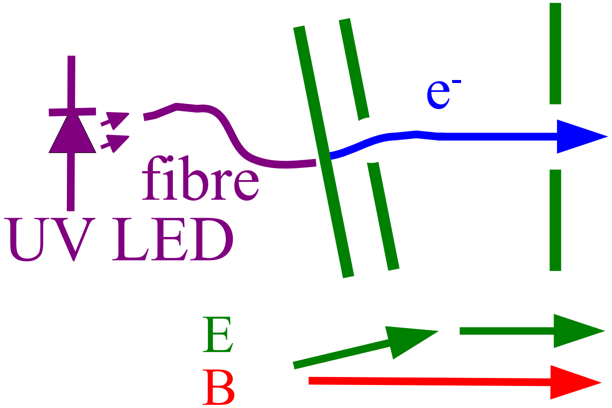
This first measurement without wire electrode on screening potential, LN_2 baffles cold and active counter measures against stored electrons

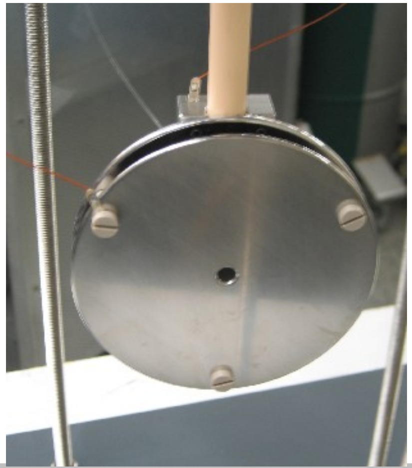
But still KATRIN requires a background rate of **10^{-2} cps**

A new pulsed angular-defined UV LED photoelectron source

K. Valerius et al., NJP 11 (2009) 063018
K. Valerius et al., JINST 6 (2011) P01002
K. Hugenberg, Prog. Part. Nucl. Phys. 64 (2010) 288

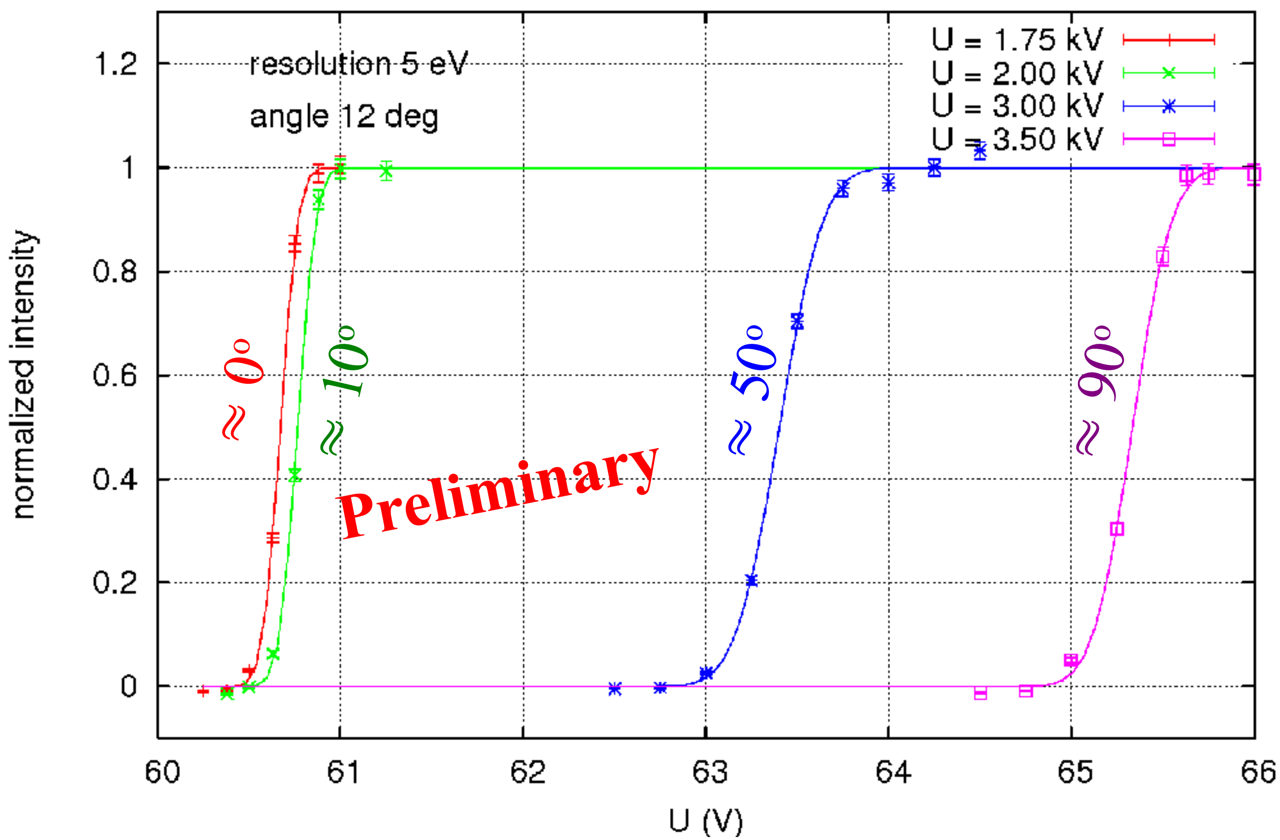
Idea:
fast non-adiabatic acceleration with adjustable non-parallel E and B fields



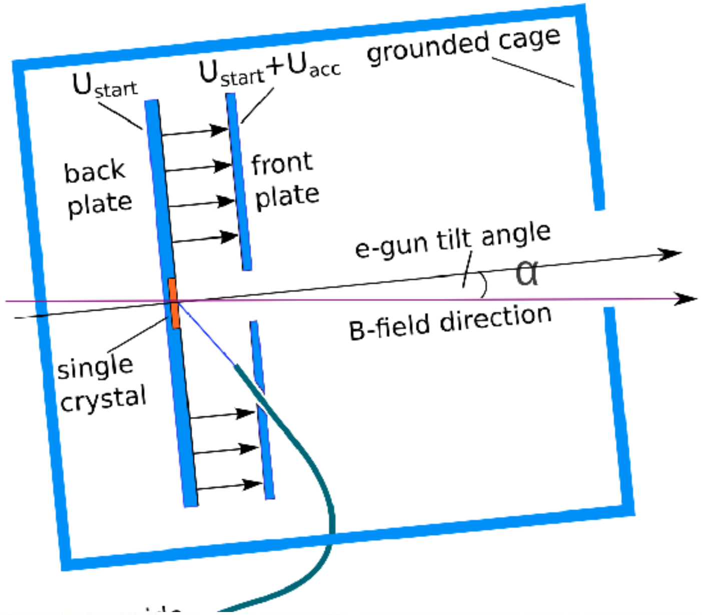


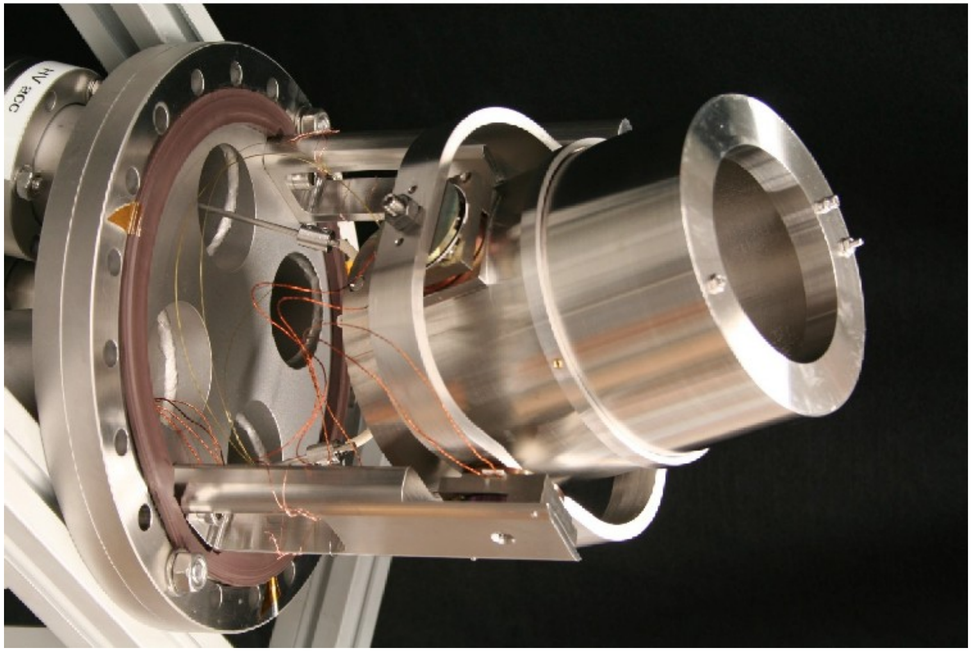
Angle at

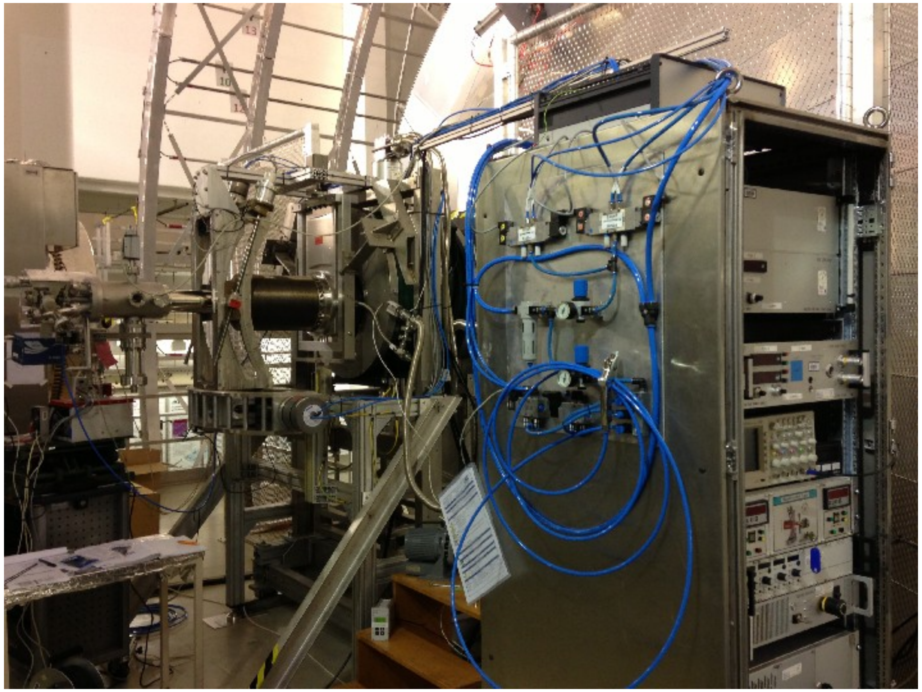
electron source: 0° ... 3.3°
pinch magnet: 0° ... 90°

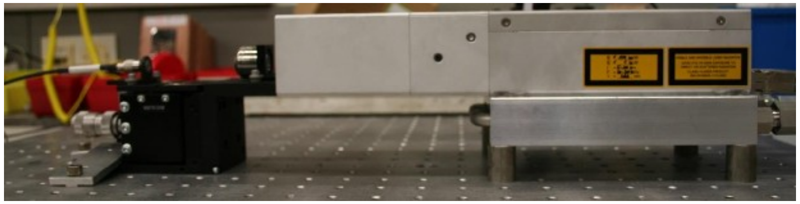


UV LED photoelectron source for the main spectrometer

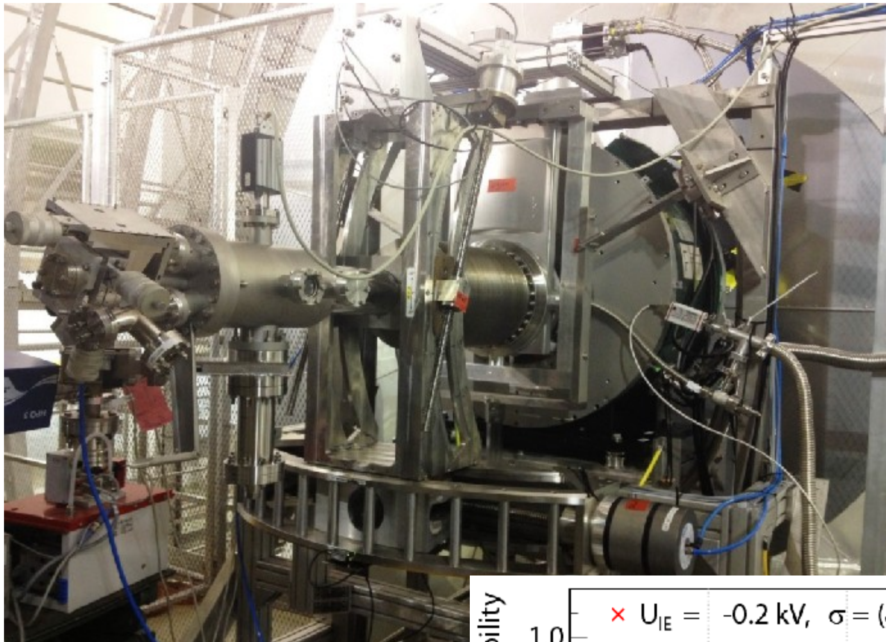


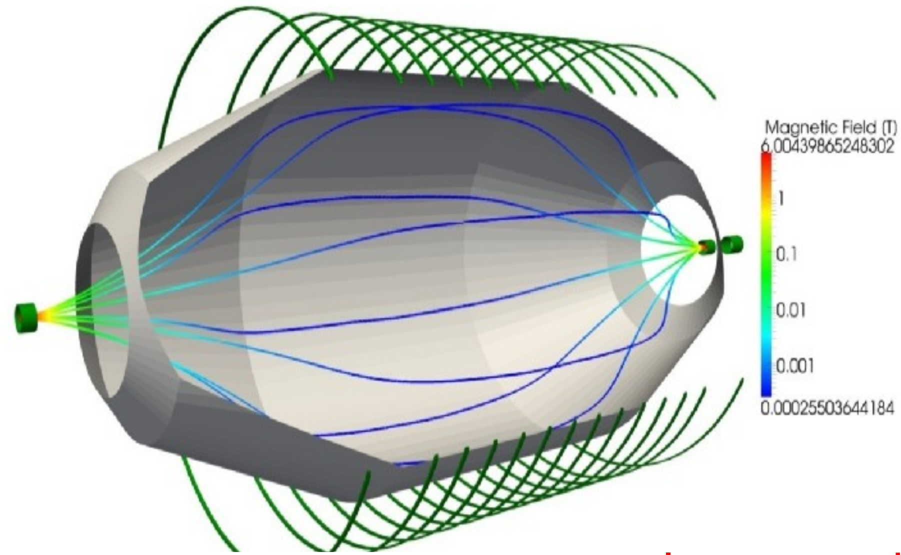


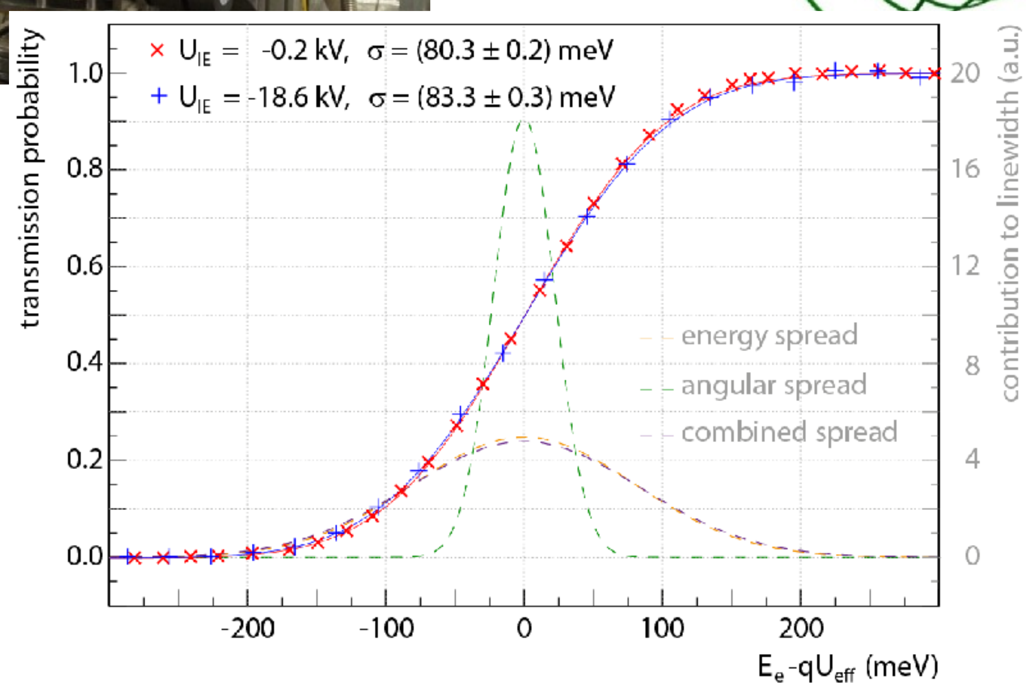




Test of transmission function



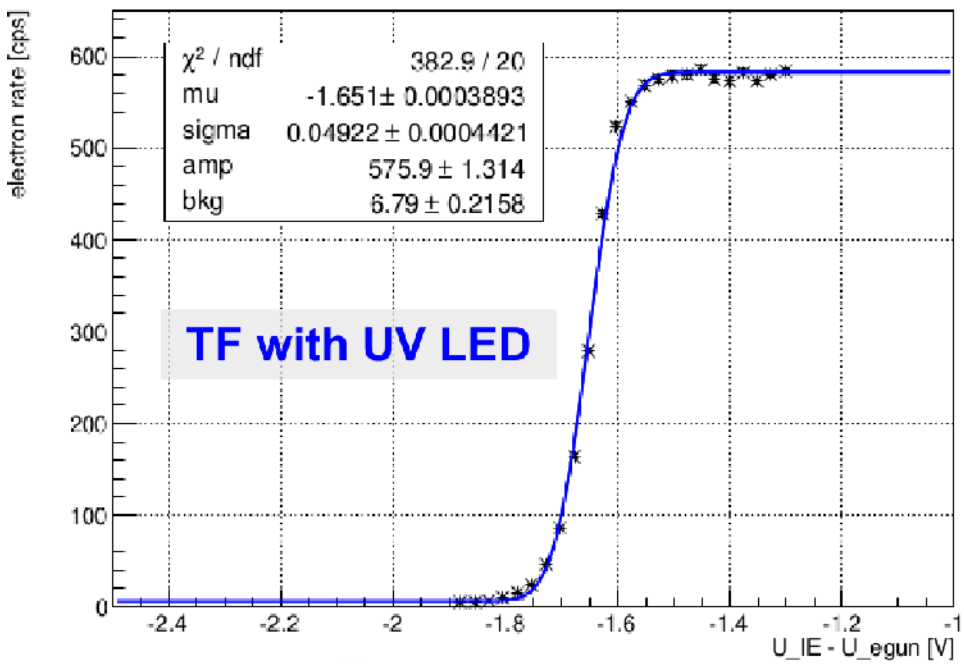


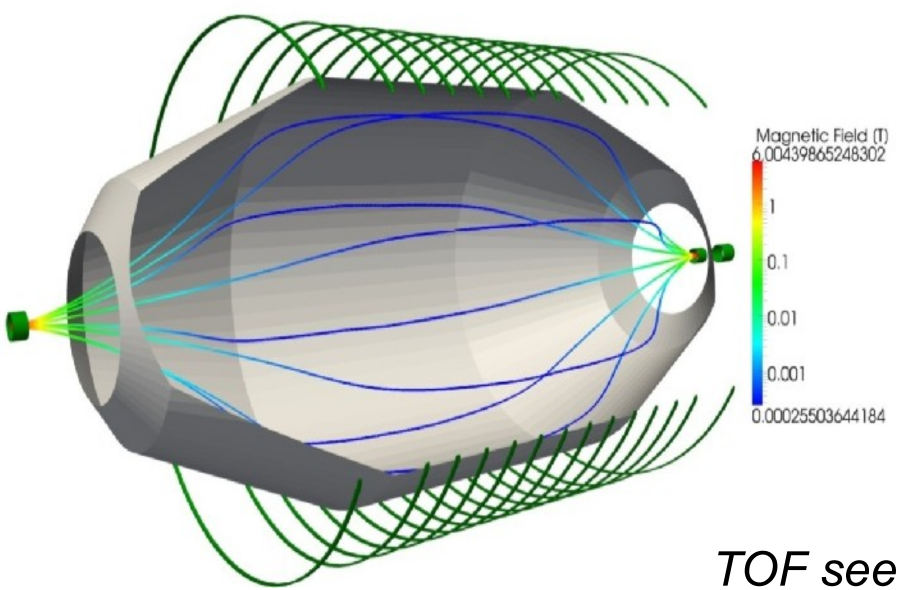


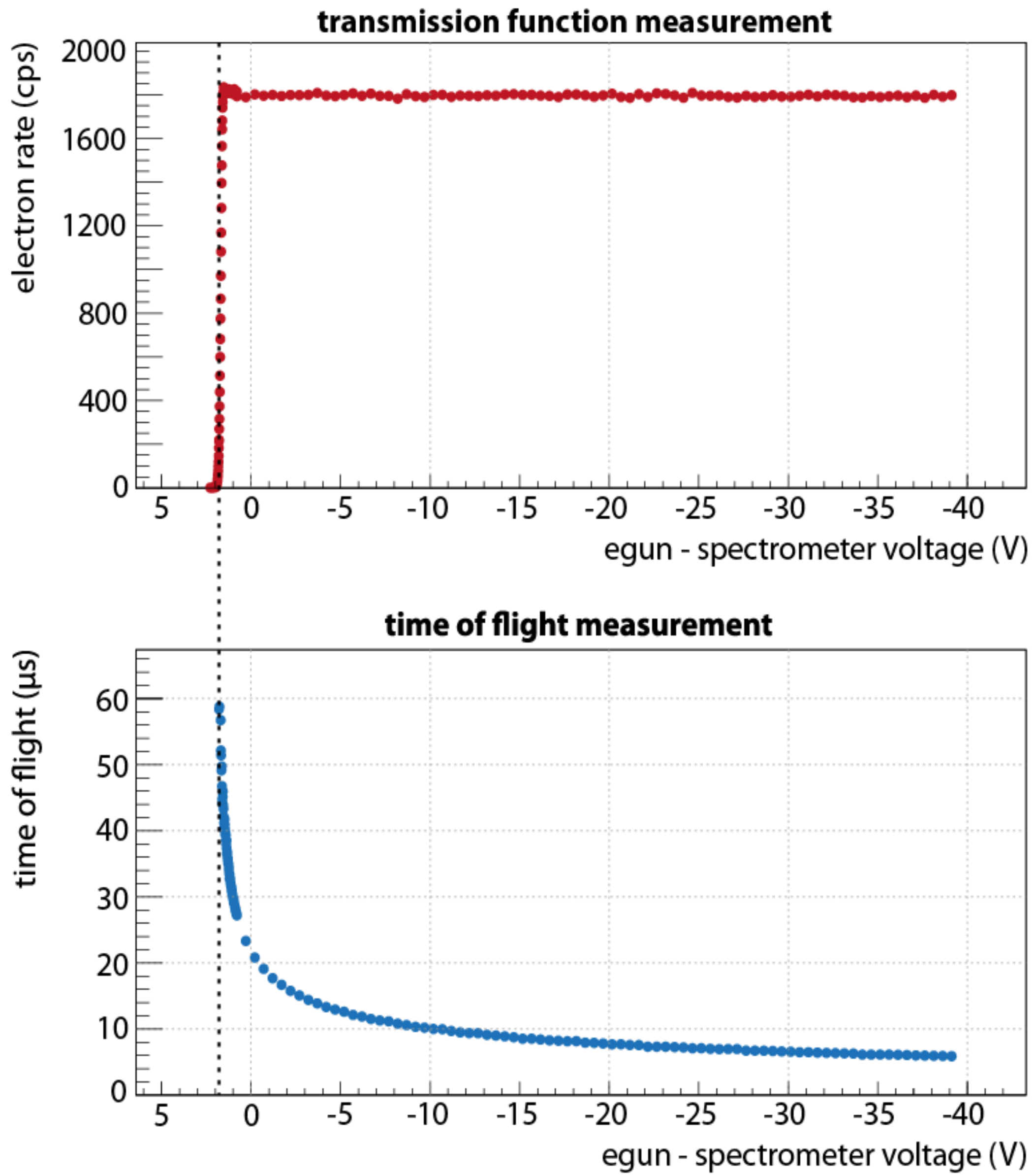
vessel on ground

vessel on high voltage

Commissioning of main spectrometer and detector







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

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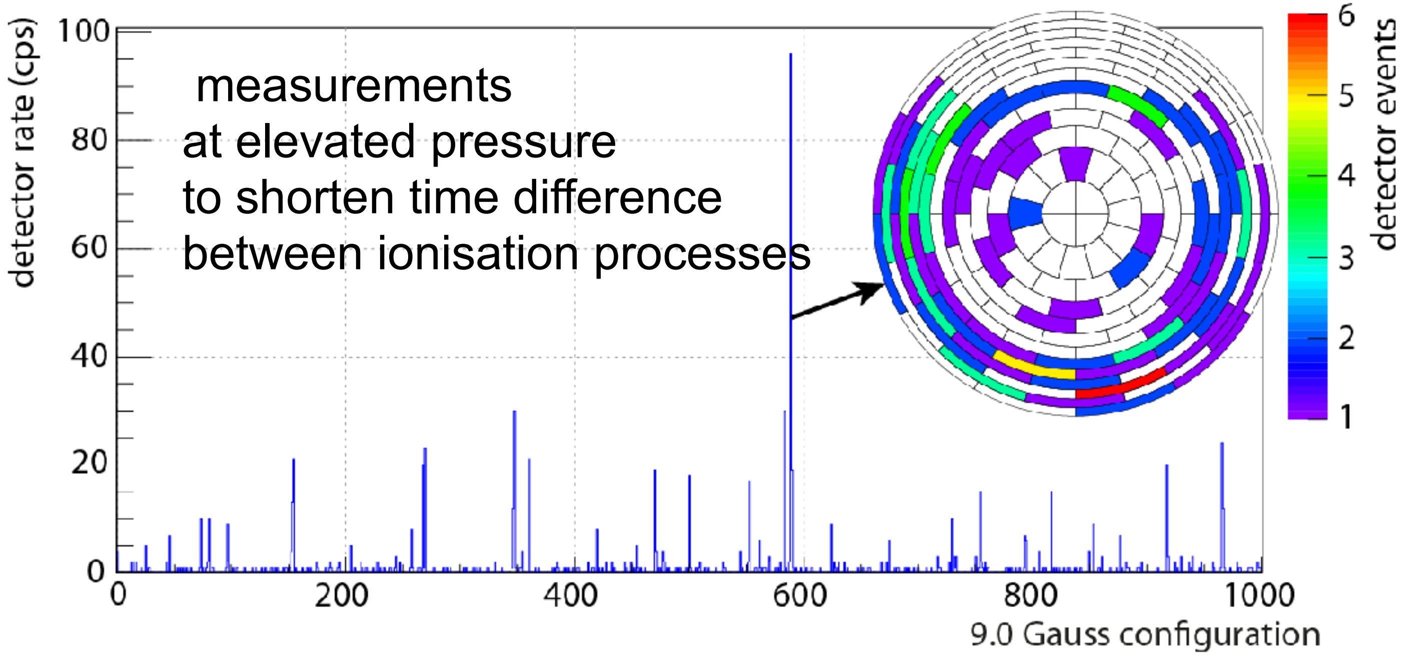
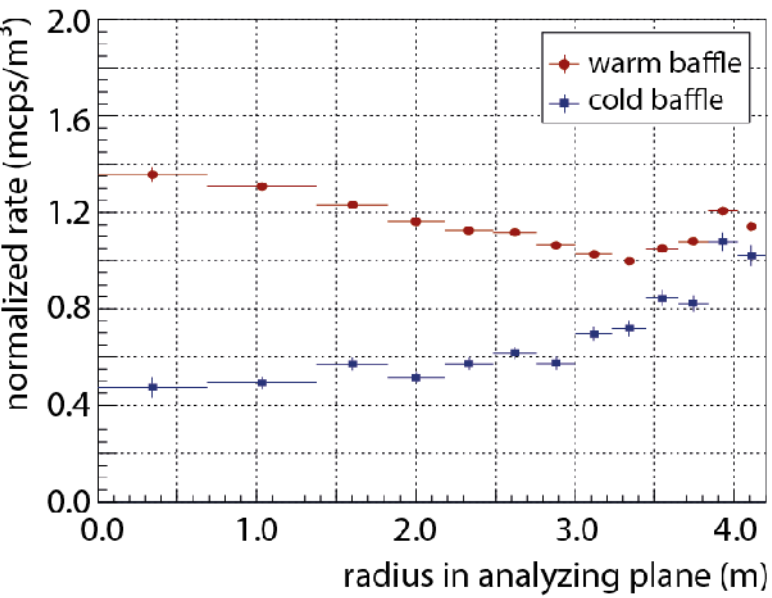
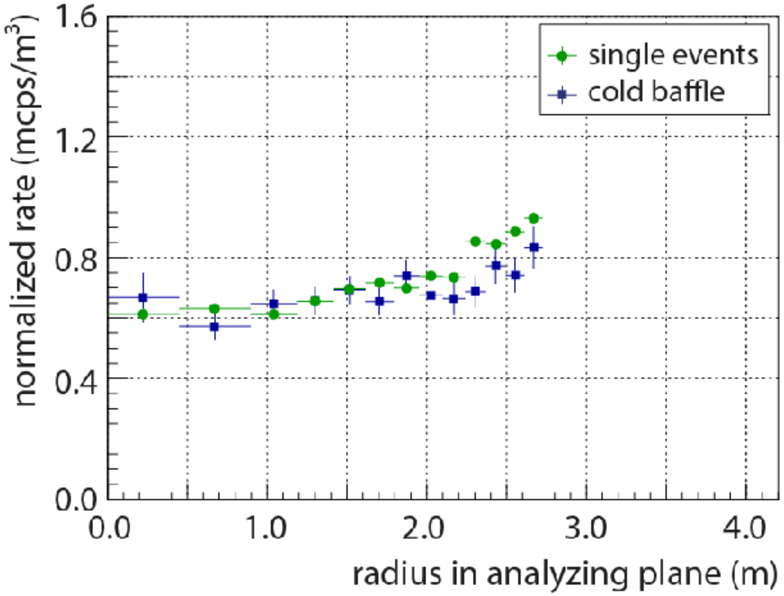
Understanding the background: Radon and other background sources





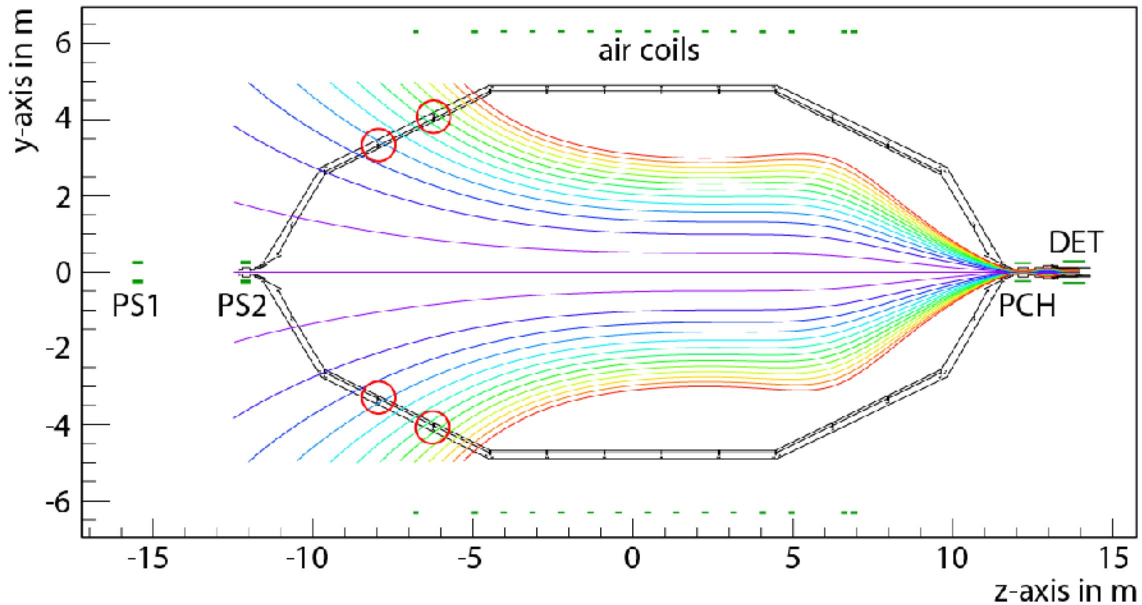


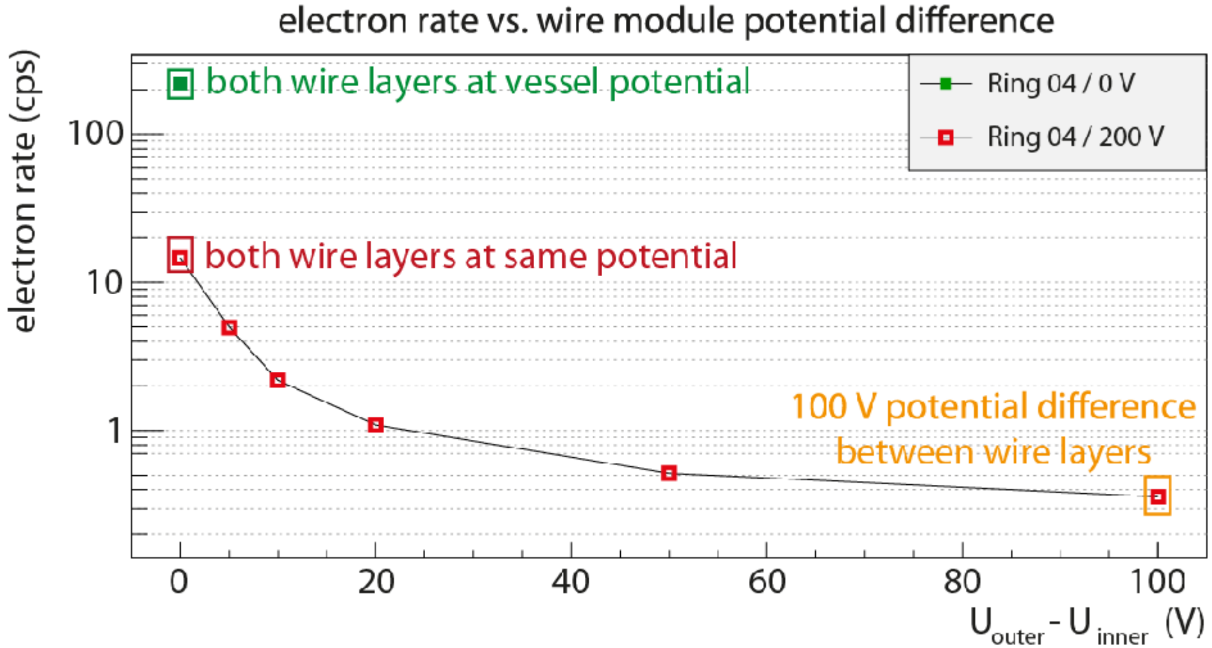
Very good background understanding:

spike pulses can also be removed by LN2 baffle

→ indeed stored electrons by radon decays

Background suppression by dual layer wire electrode





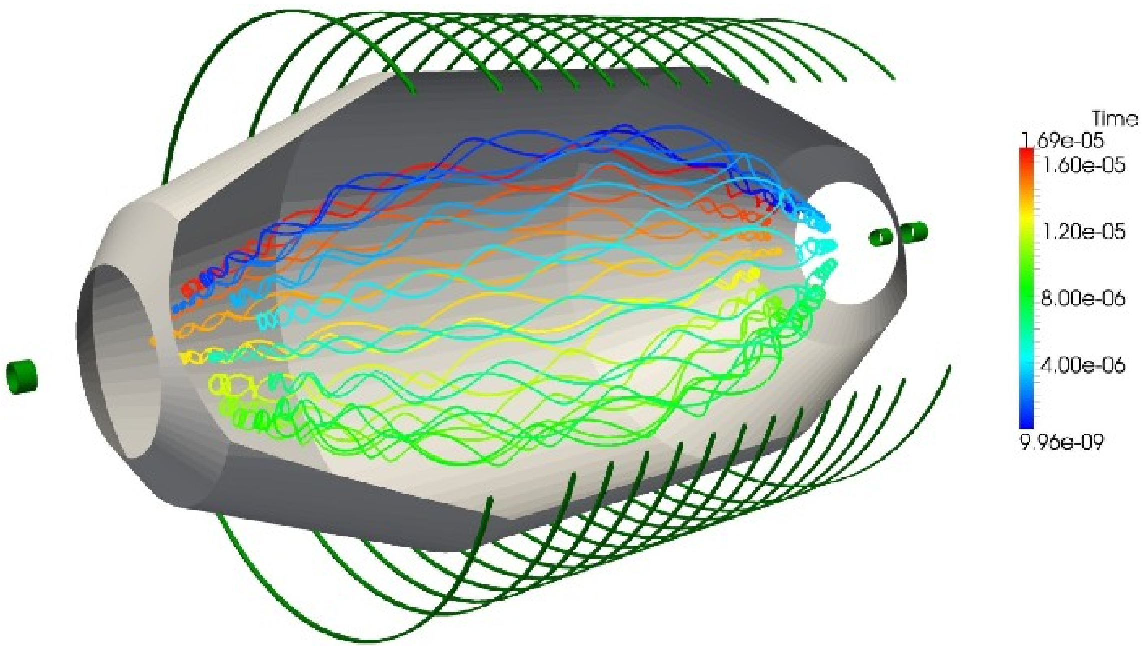
April 2014:

Problems of electric shorts in central spectrometer parts resolved !

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

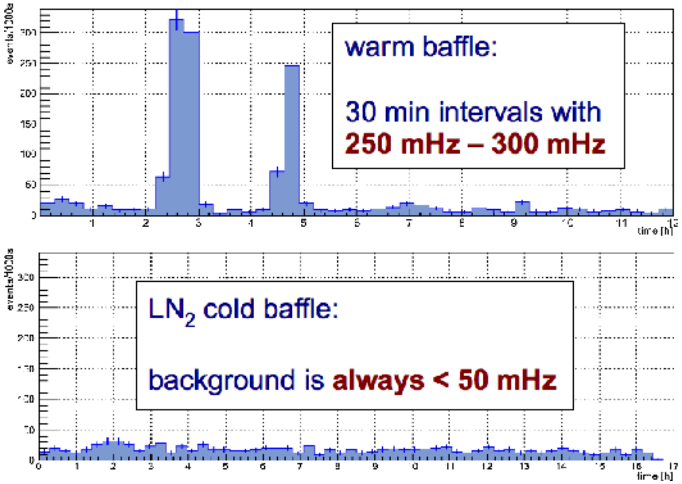
Stored electron by magnetic mirrors

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



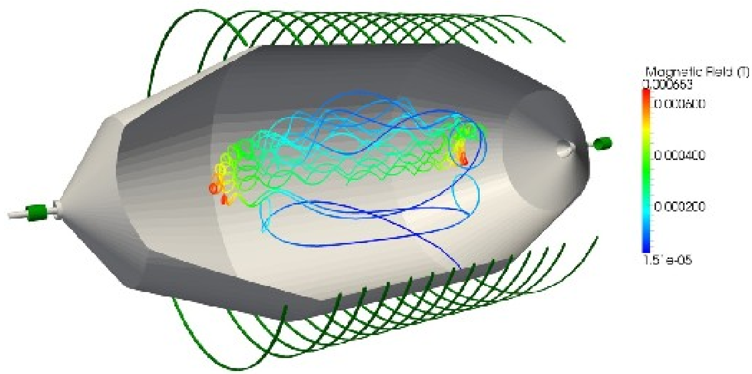
Radon suppression by LN_2 cooled baffle

S. Görhardt, diploma thesis, KIT



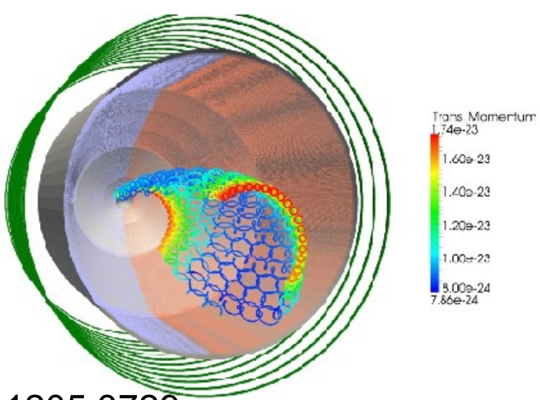
Nulling magnetic field by magn. pulse

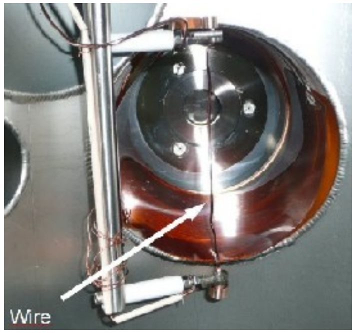
B. Hillen, PhD thesis, Münster



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

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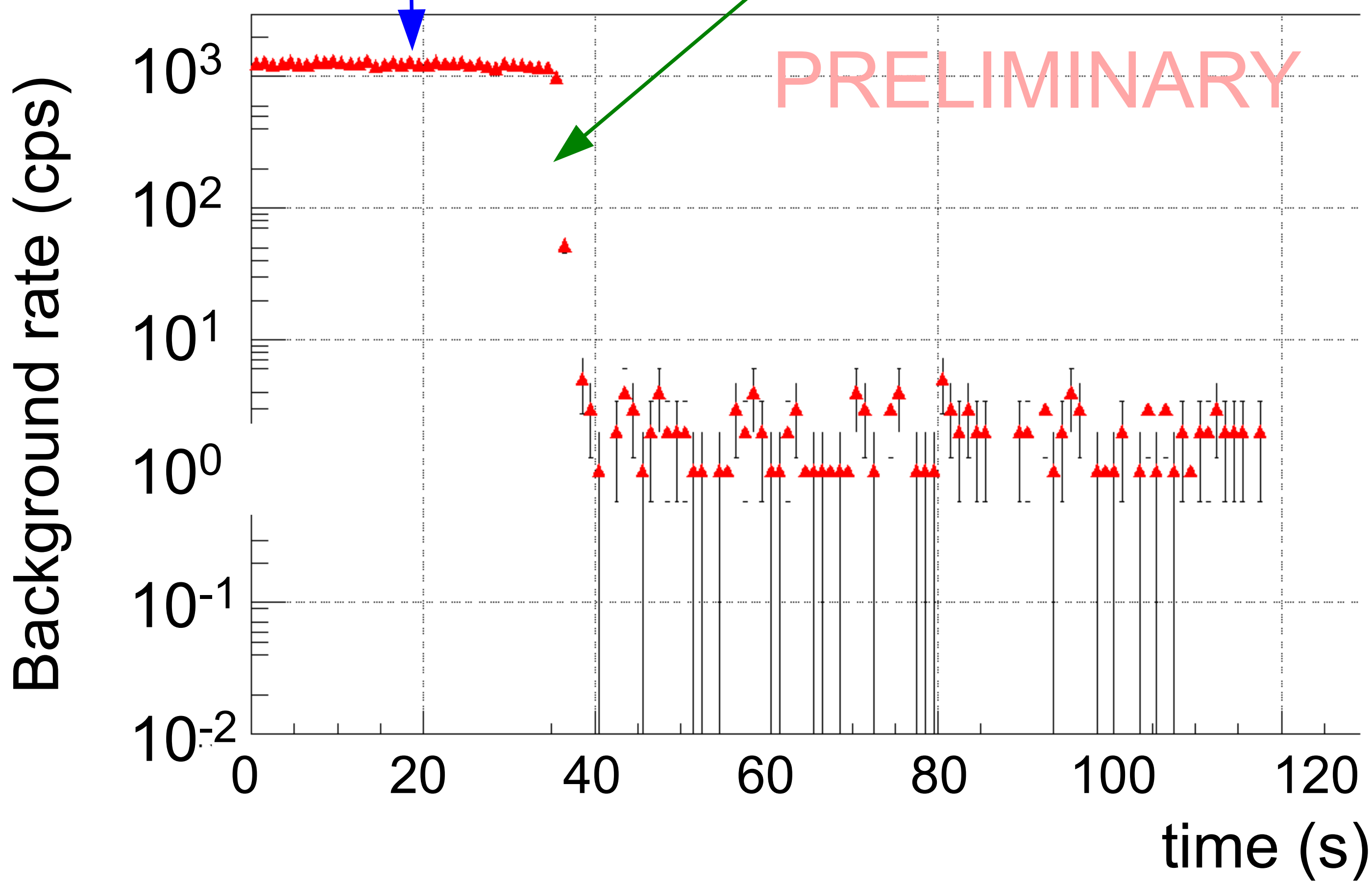
First tests of active background removal by E x B drift

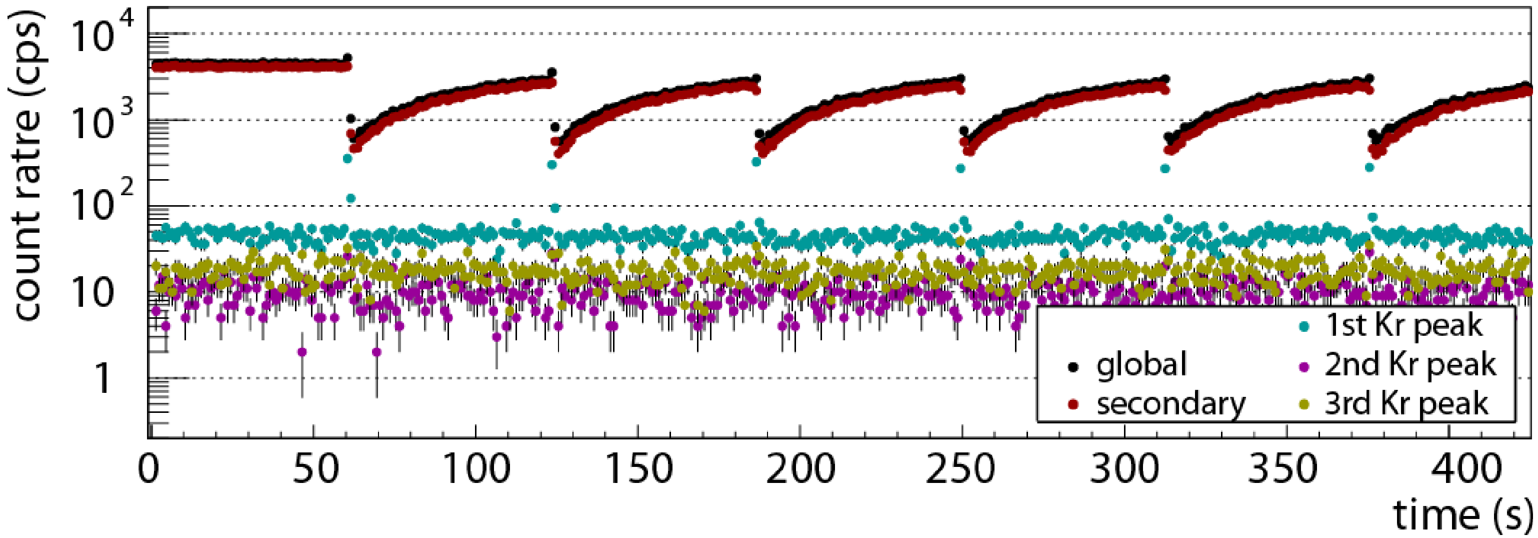
enhanced bg rate
by igniting Penning trap
between egun & spec

applying dipole voltage of 10 V
between east and west half of
wire electrode system
→ E x B drift

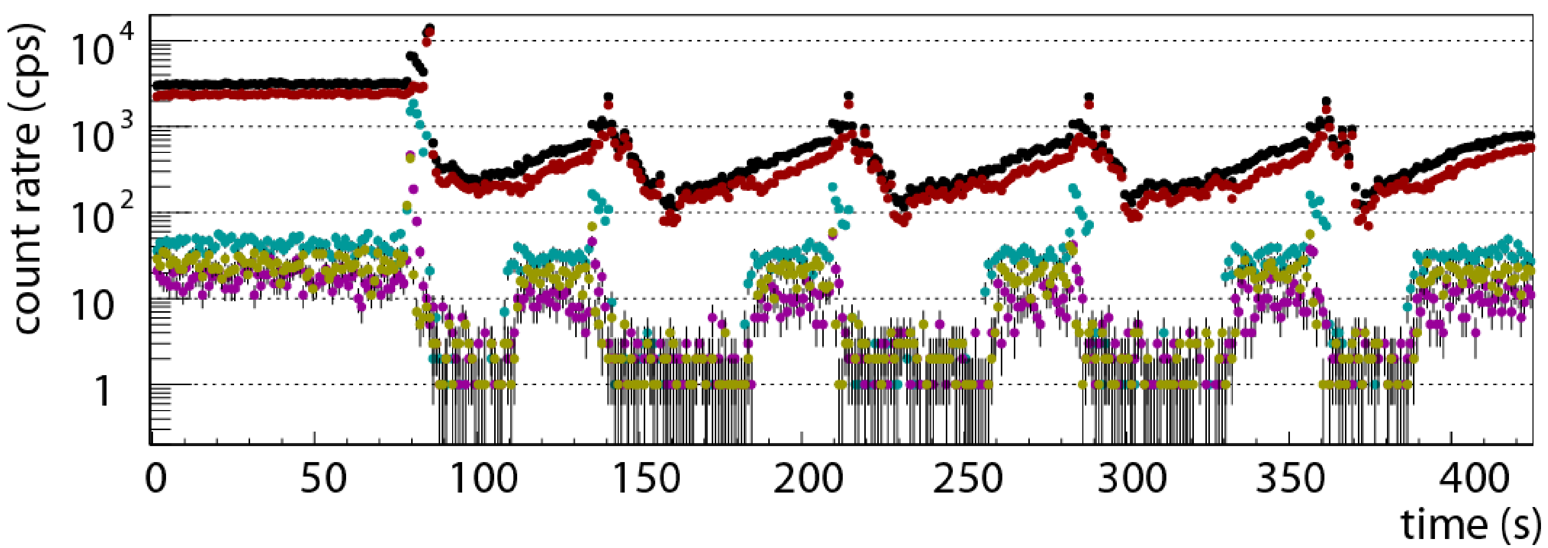


Active stored particle removal by electric dipole and magnetic zeroing

electric dipole

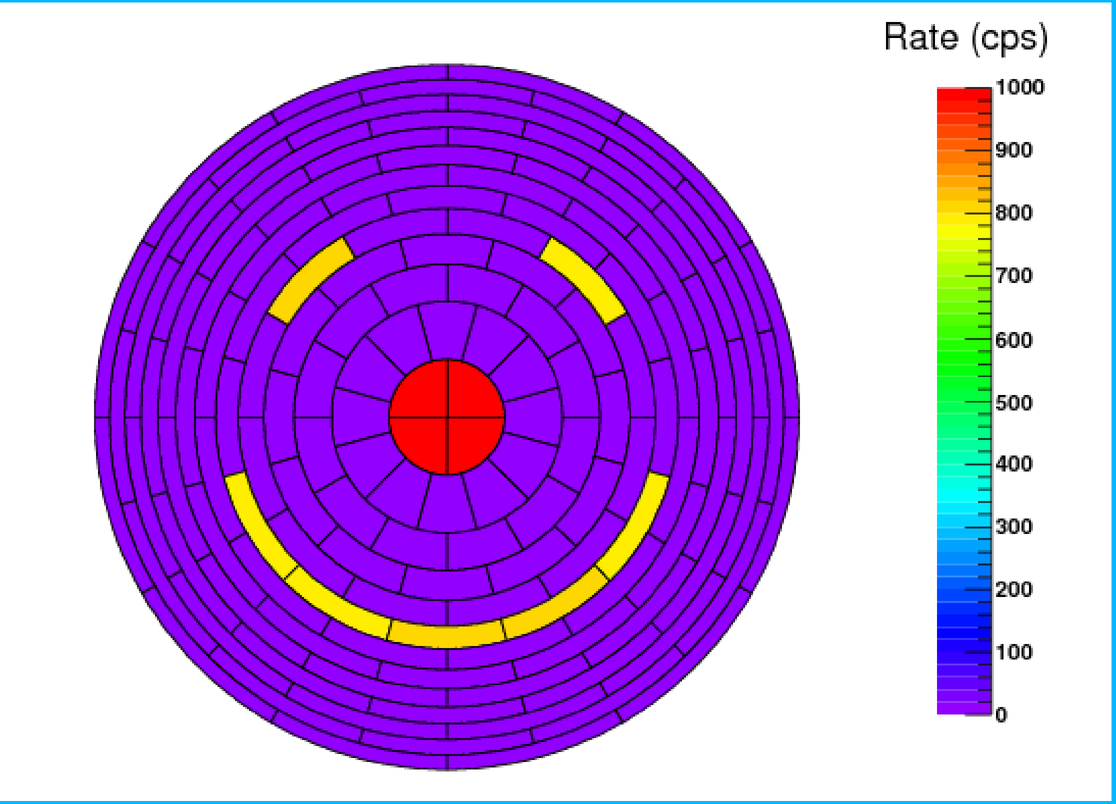


magnetic pulse



And finally ...

The KATRIN 148-pixel detector is smiling



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

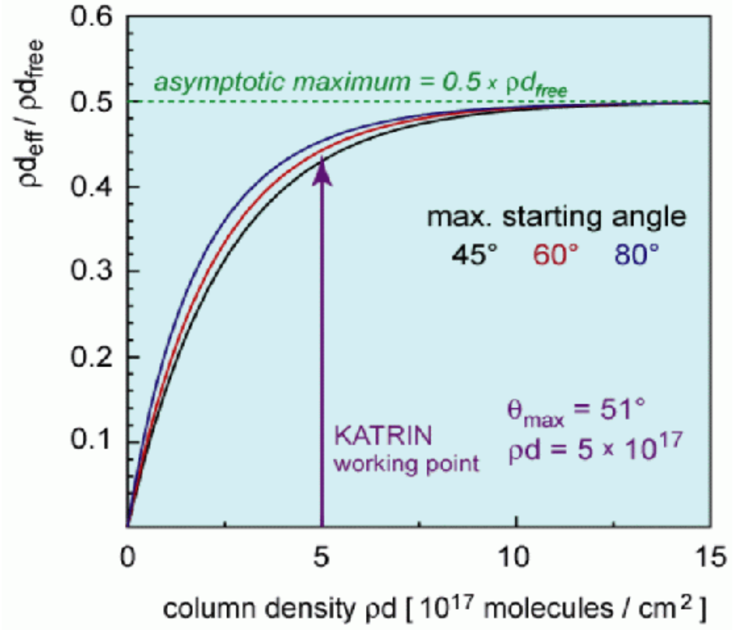
Waiting for commissioning measurements phase 2 in sommer/automn 2014 with

- **dual layer wire electrode (in central part at least)**
- **better egun**
- **better alignment**
- **better high voltage settings**
- **full magnetic zeroing**
- **full operational LN2 baffles**

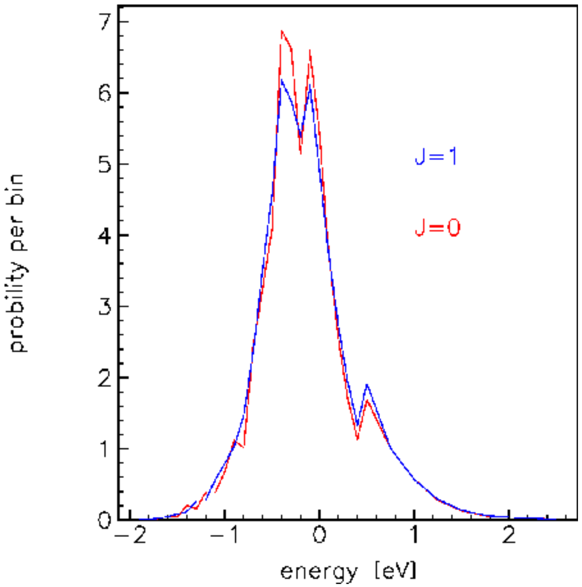
Can KATRIN be largely improved ?

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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Can KATRIN be largely improved ?

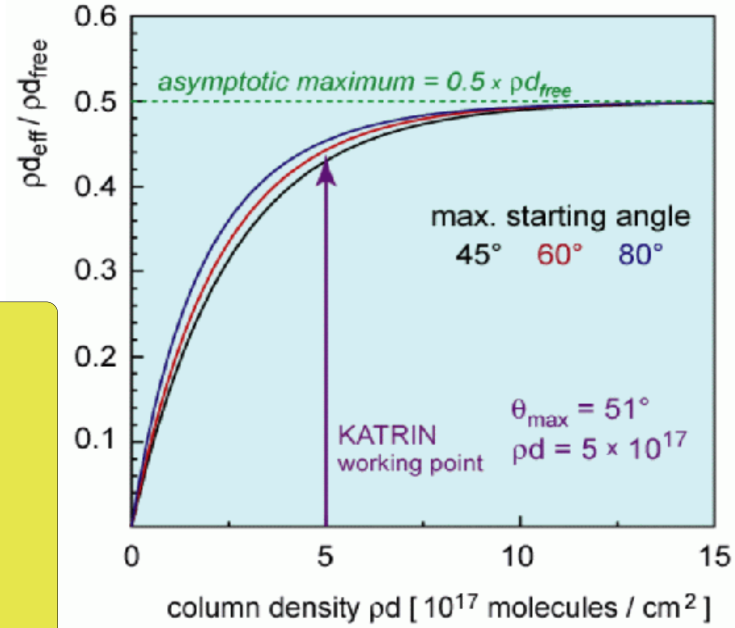
Problems

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

Two possible ways out:

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

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



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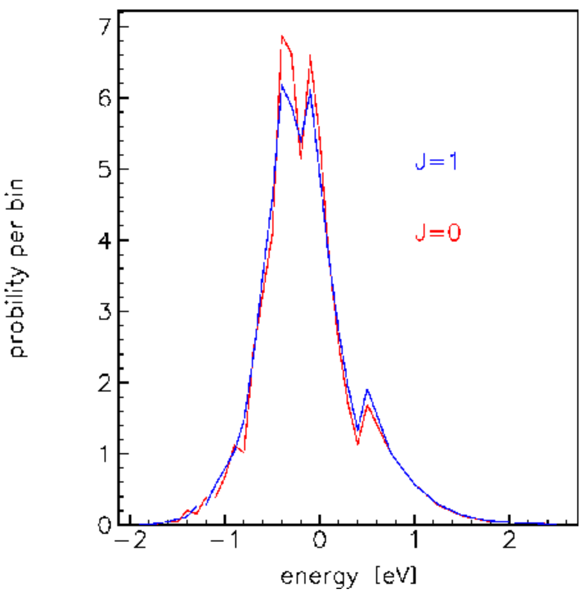
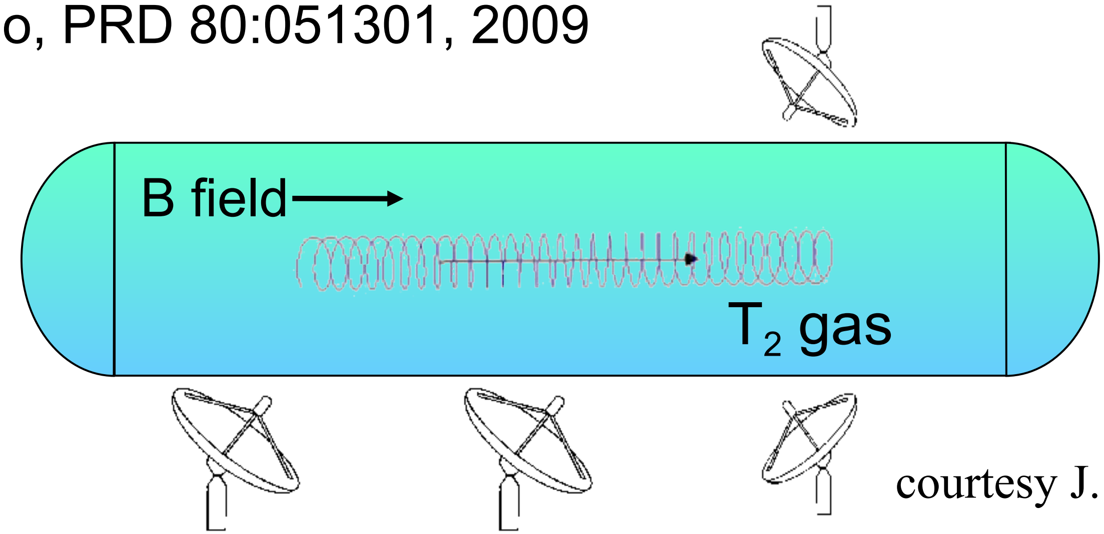


Not really realistic yet:

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

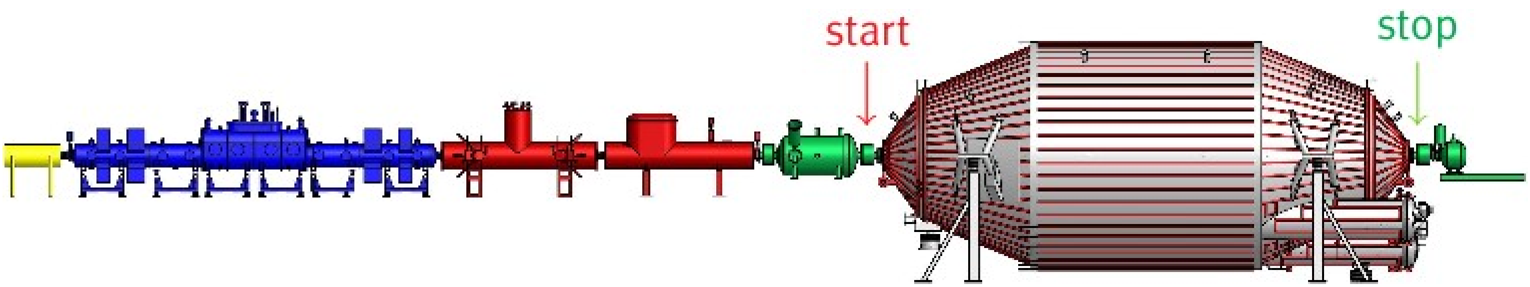
A lot of R&D necessary and has started
- Is it really possible ?
- What are the systematic uncertainties ?

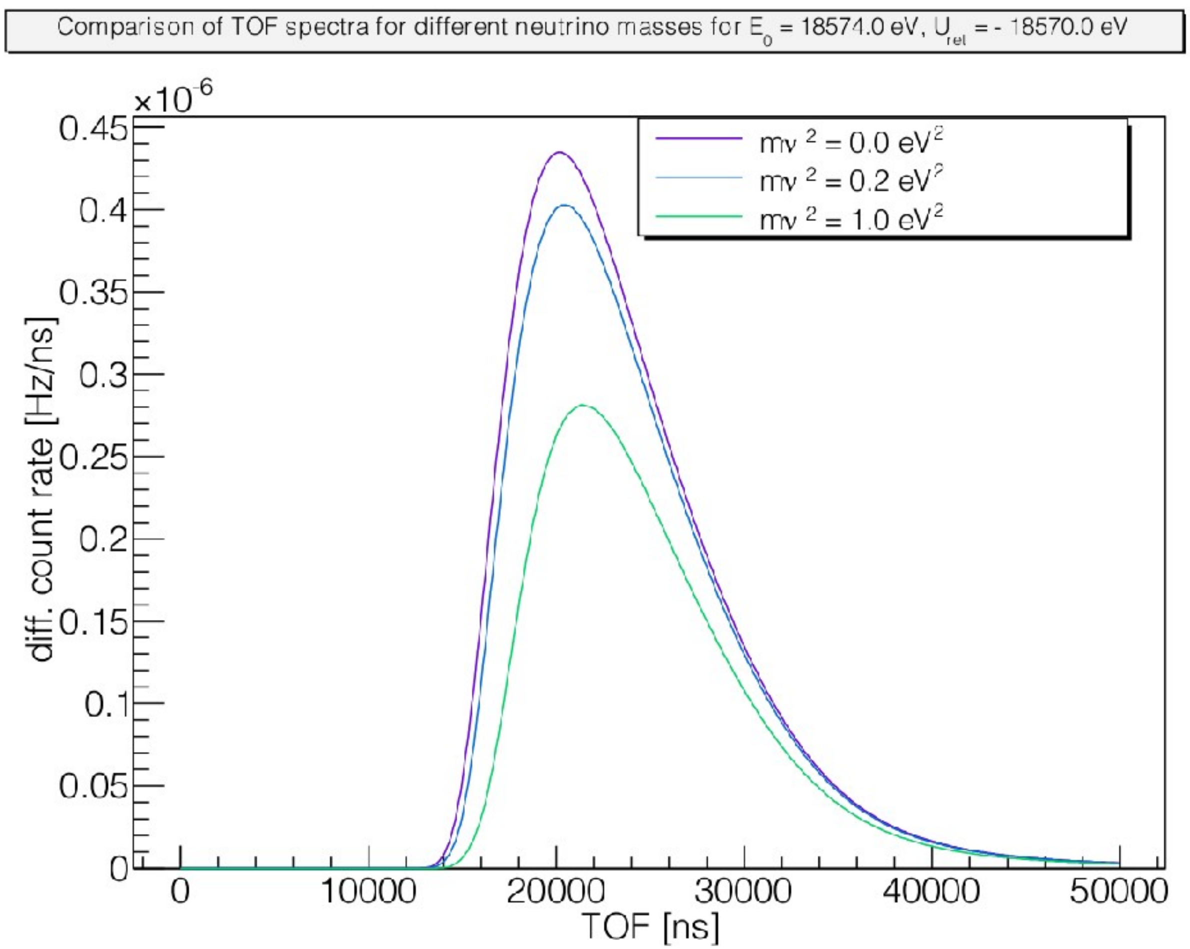
Can KATRIN be improved a bit ?

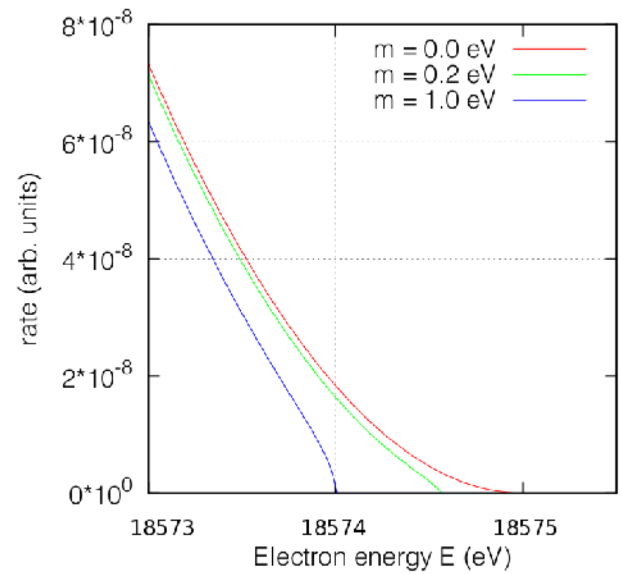
?

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

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER







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

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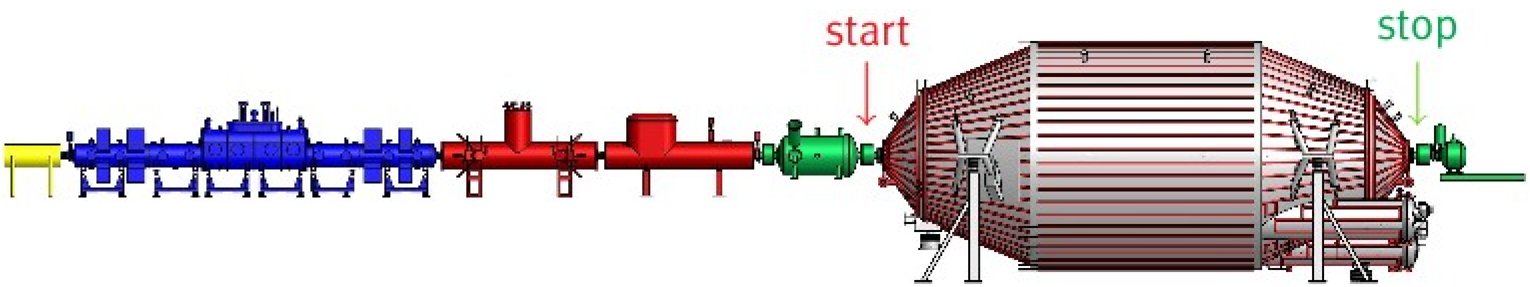
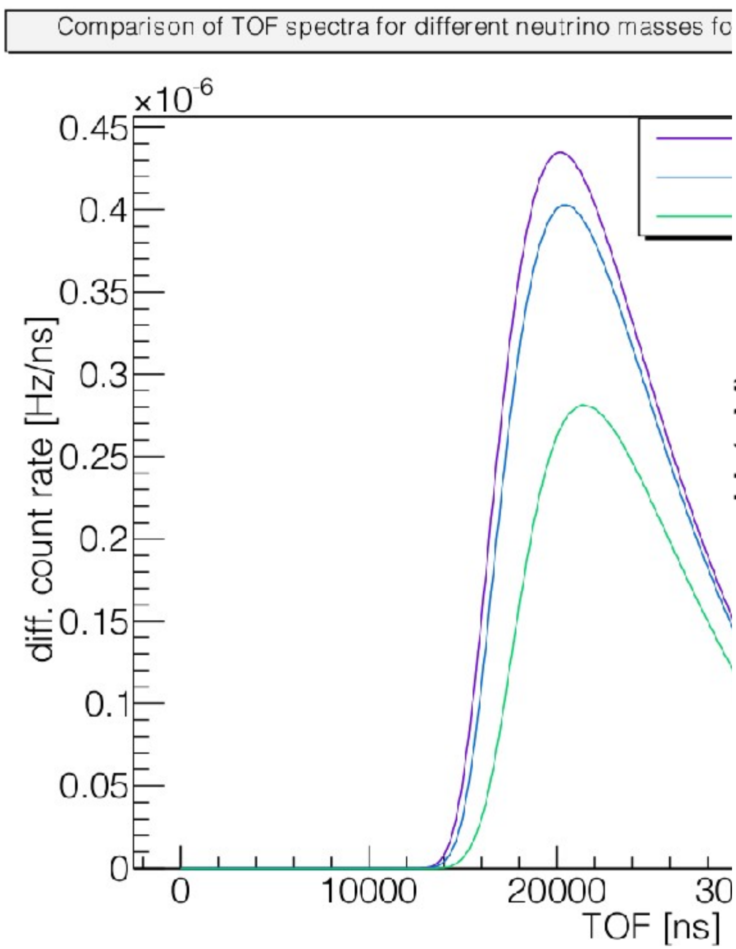
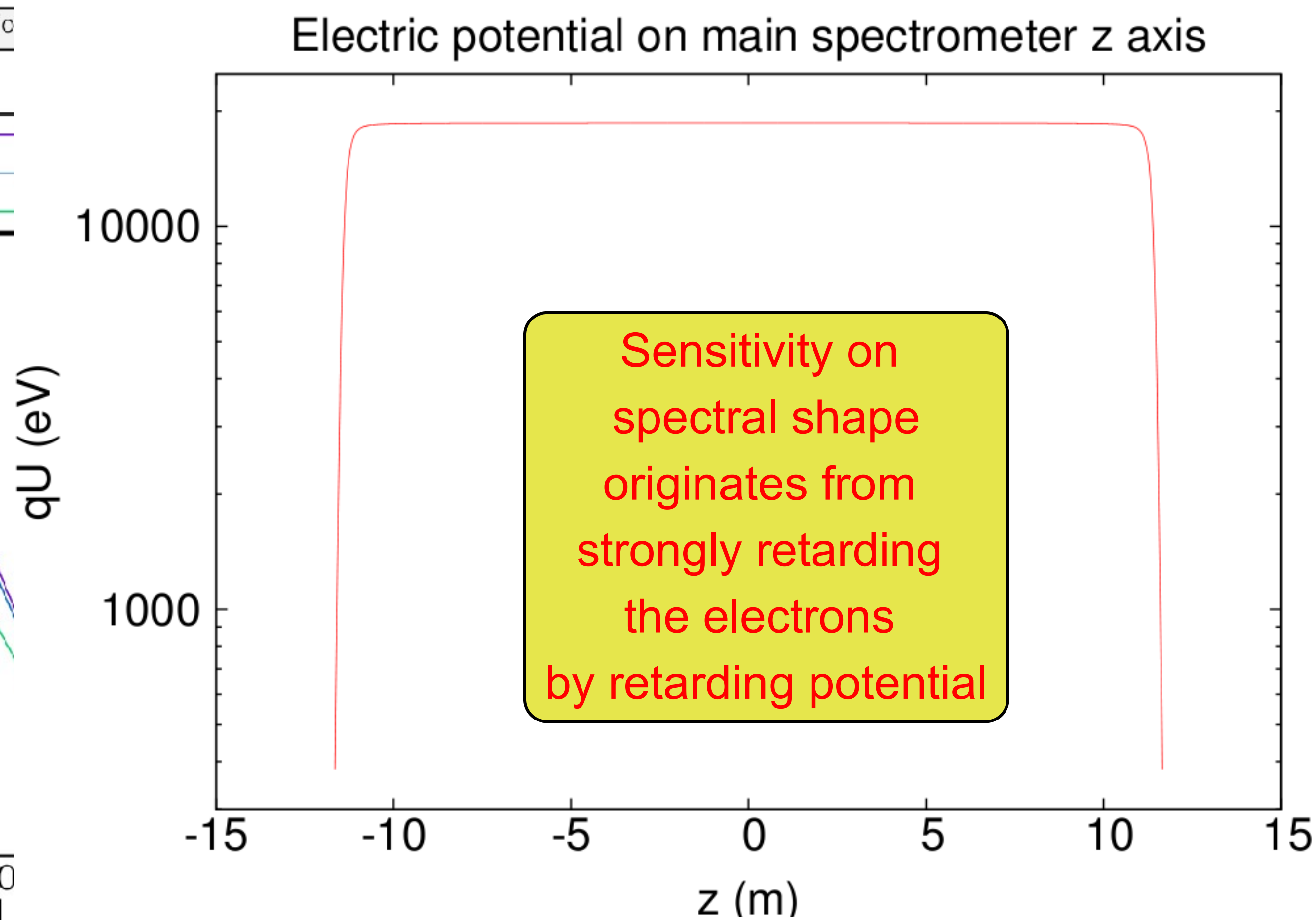




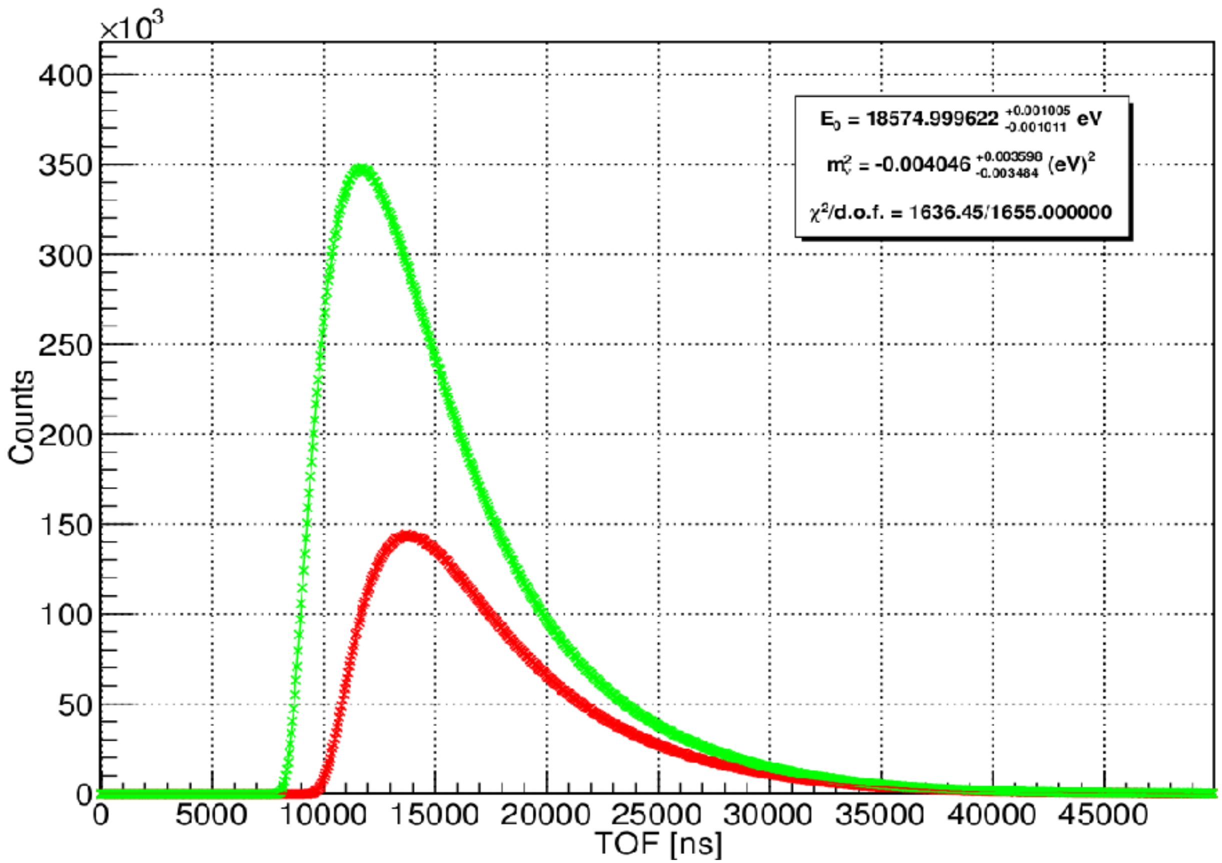


Sensitvity improvement on $m^2(\nu_e)$ by ideal TOF determination

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_ν^2 w.r.t. standard KATRIN, but ideal case !



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

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

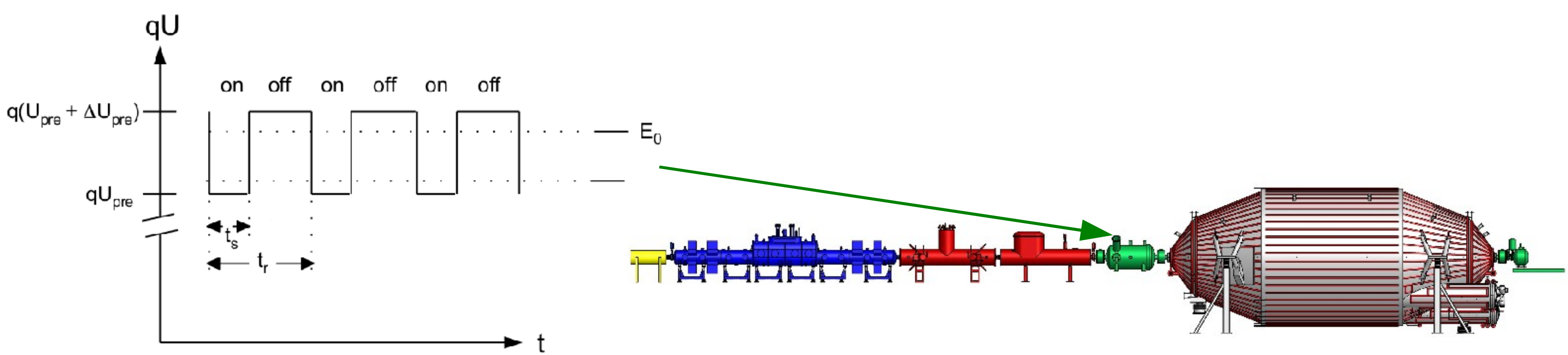
1) Can measure time-of-arrival with KATRIN detector with $\Delta t = 50$ ns → ok

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., NJP 15 (2013) 113020



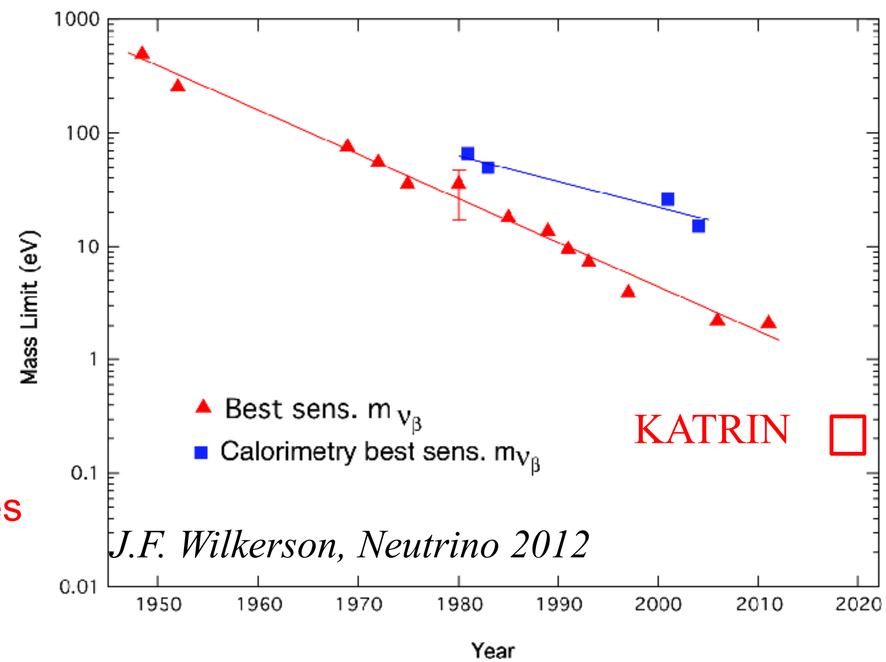
Summary & Outlook

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, $0\nu\beta\beta$, direct (no further assumptions)

KATRIN is the next generation
direct neutrino mass experiment
with 0.2 eV sensitivity
and to sterile eV and keV neutrinos ...

2013-2014: commissioning of spectrometer & detector
2014-2016: commissioning of tritium source & elimination lines
2016- : regular data taking for 5-6 years (3 full-beam-years)



ECHo, HOLMES: cryo-bolometers measuring ^{163}Ho EC
Can they archieve similar sensitivites to KATRIN? Still a long way to go

Quite different attempts: Project 8, ...