Westfälische Wilhelms-Universität Münster

Non-oscillation probes of neutrino masses

Nufact09 workshop at Fermilab and Illinois Institute of Technology, Chicago, July 20-24, 2009

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- **Introduction**
- **Neutrino mass and cosmology**
- **Search for neutrinoless double beta decay**
- **Direct neutrino mass experiments**
  - **Rhenium β-decay and MARE**
  - **The Karlsruhe TRItium Neutrino experiment KATRIN**
- **Conclusion**

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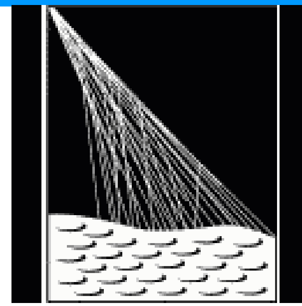
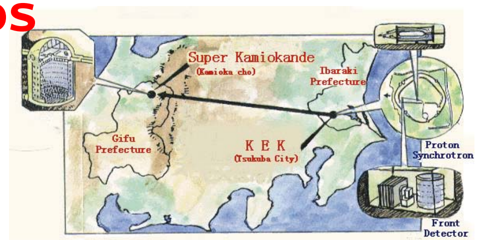
Positive results from ν oscillation experiments

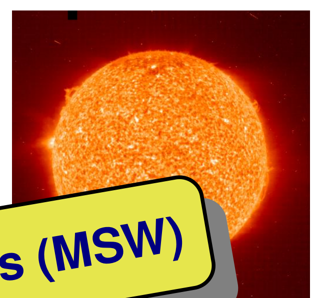
atmospheric neutrinos
(Kamiokande,
Super-Kamiokande, ...)



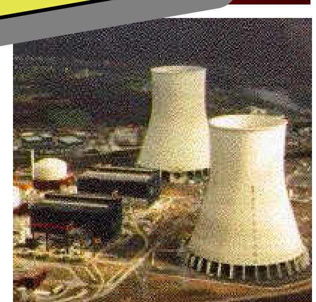
accelerator neutrinos
(K2K, MINOS, LSND,
MiniBoone)



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



Matter effects (MSW)



reactor neutrinos
(KamLAND, CHOOZ, ...)

⇒ 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:

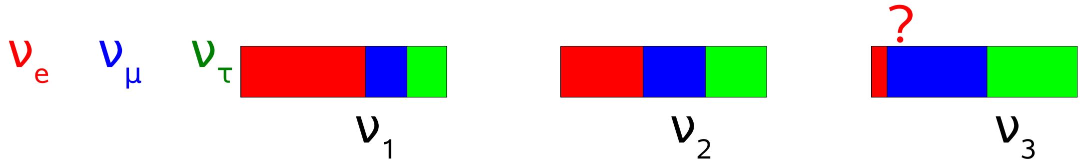
$0.79 < |U_{e1}| < 0.88$ maximal !
$0.47 < |U_{e2}| < 0.61$ large !
$|U_{e3}| < 0.20$ $\neq 0$?
$7.3 \cdot 10^{-5}\ eV^2 < \Delta m_{12}^2 < 9.3 \cdot 10^{-5}\ eV^2$
$1.6 \cdot 10^{-3}\ eV^2 < |\Delta m_{23}^2| < 3.6 \cdot 10^{-3}\ eV^2$

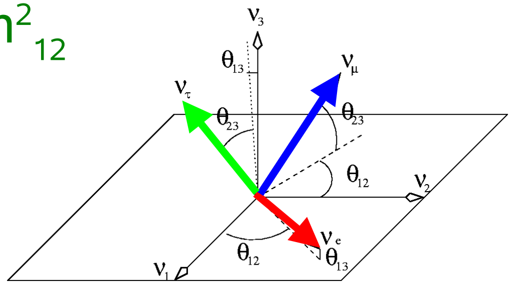
⇒ $m(\nu_j) \neq 0$, but unknown !

up to now: description by 2-flavour oscillation sufficient

Need for the absolute ν mass determination

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





degenerated masses

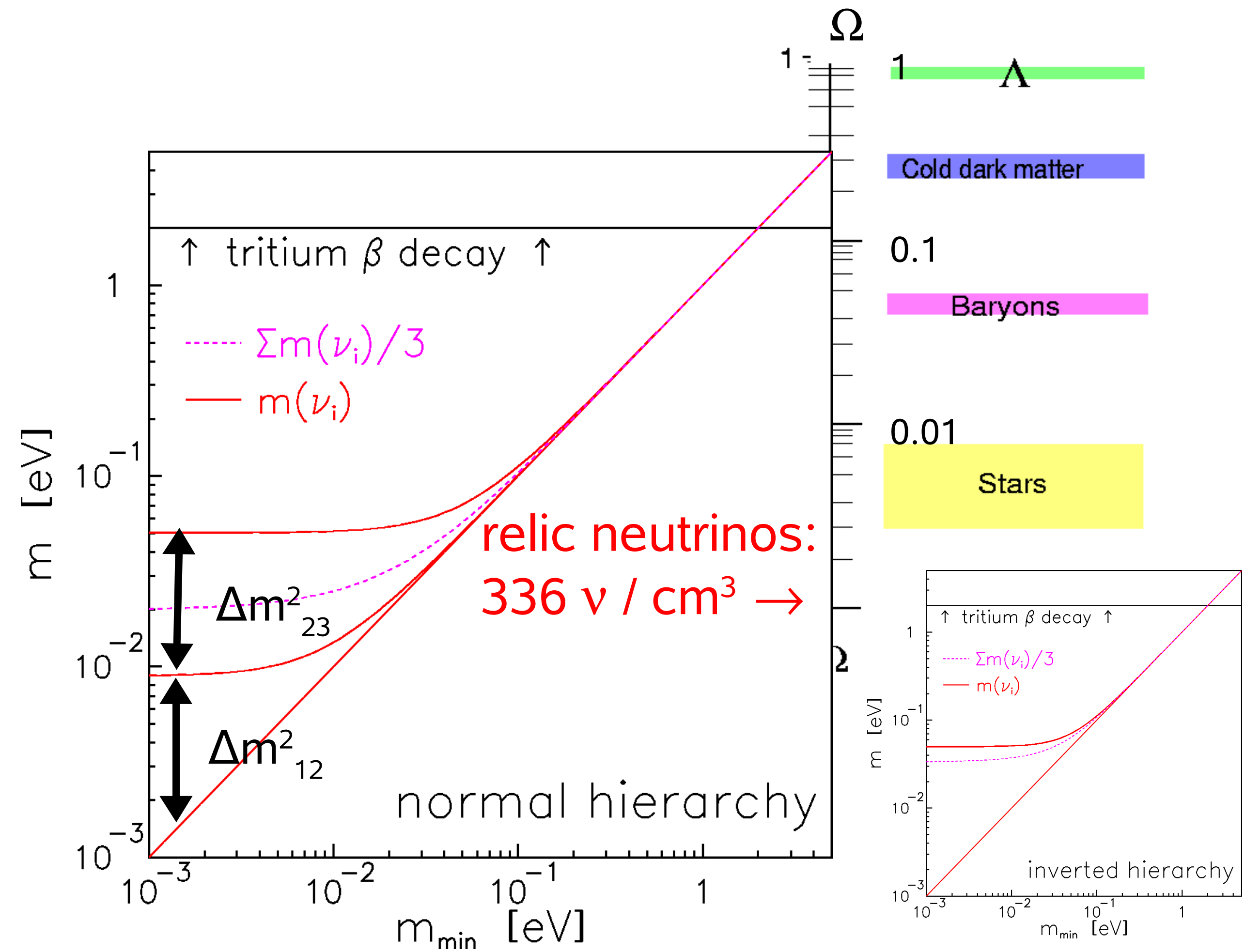
cosmological relevant

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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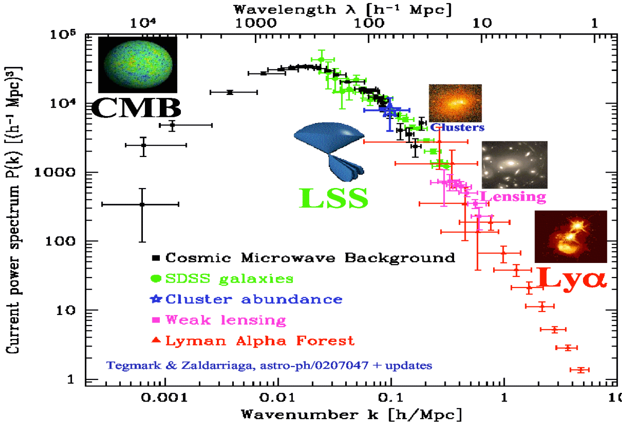
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

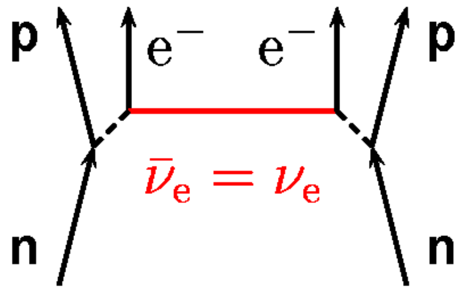
current sensitivity: $\Sigma m(\nu_i) \approx 0.4 - 1$ eV



2) Search for 0νββ

Sensitive to Majorana neutrinos

Evidence for $m_{ee}(\nu) \approx$ 0.4 eV (Klapdor-Kleingrothaus et al.)?

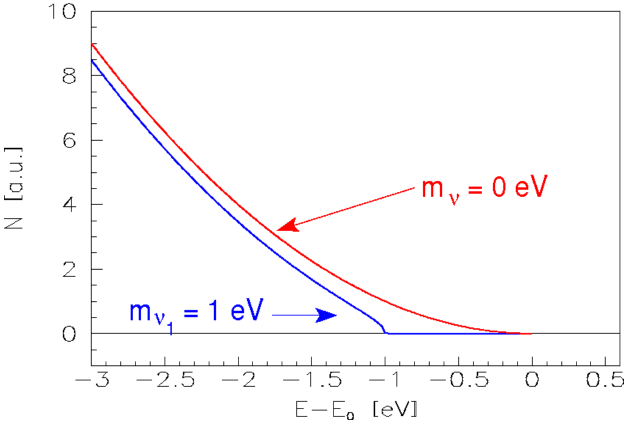


3) Direct neutrino mass determination:

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



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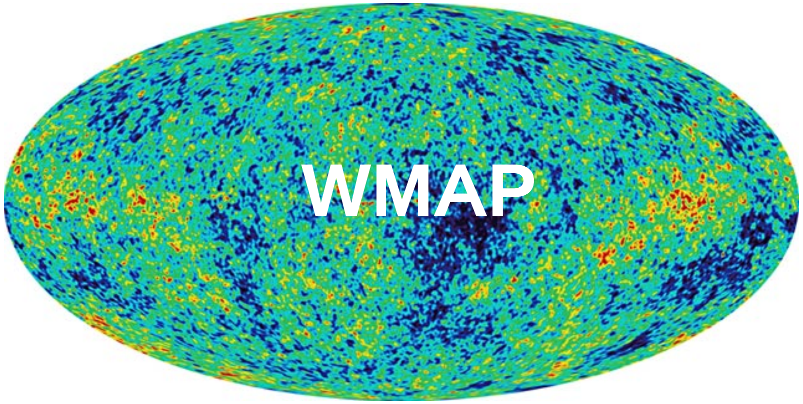
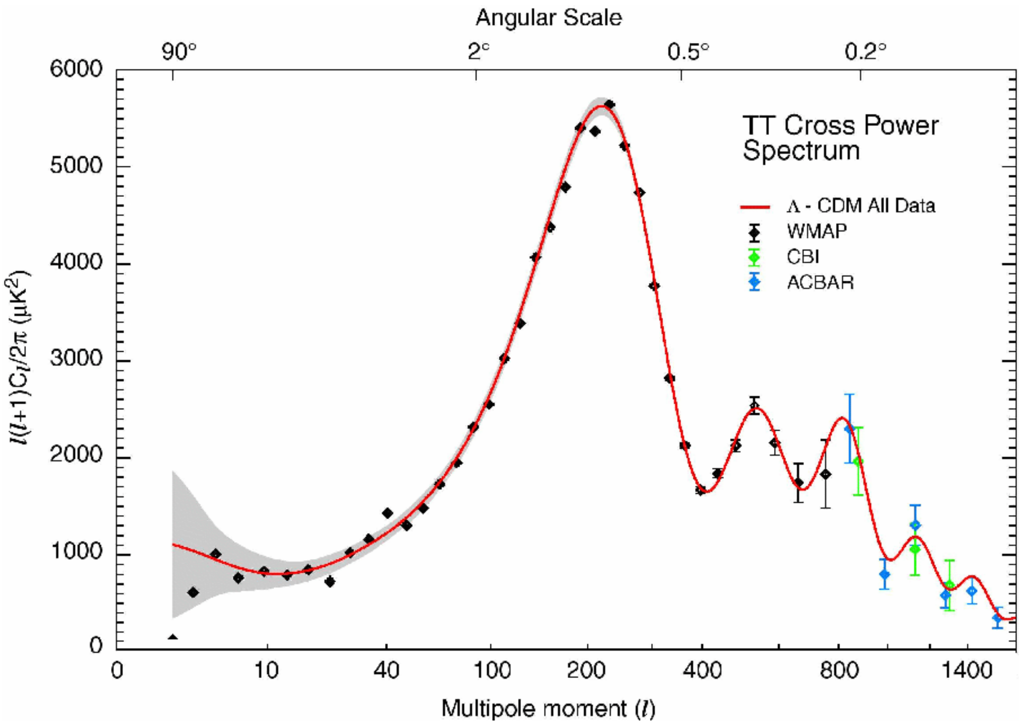
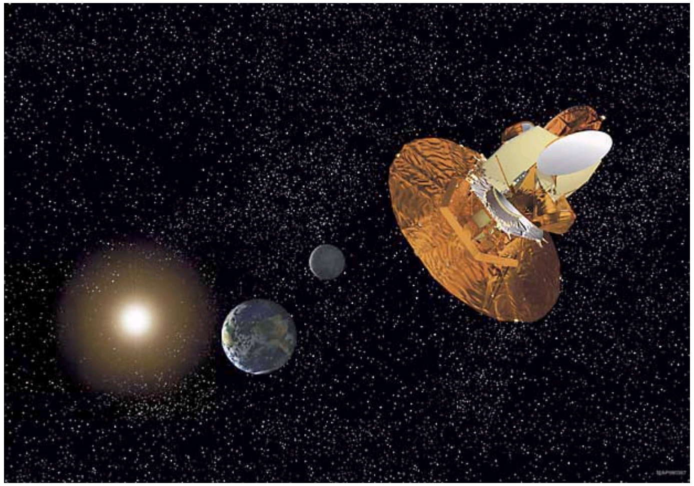
Neutrino mass from cosmology



measurement of CMBR

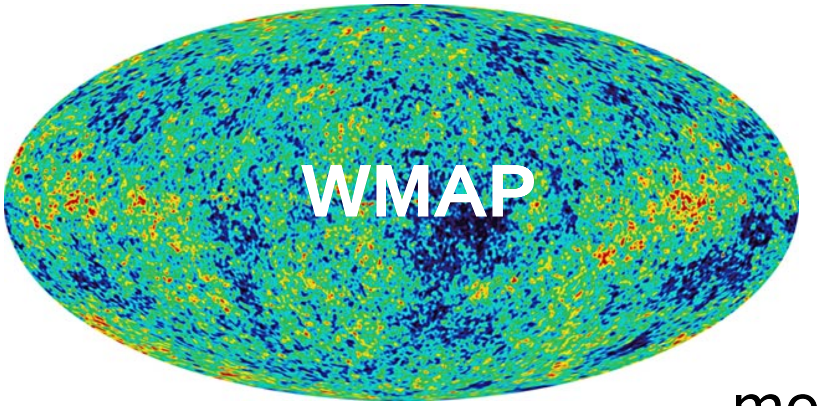
(Cosmic Microwave Background Radiation)





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

Neutrino mass from cosmology



measurement of CMBR

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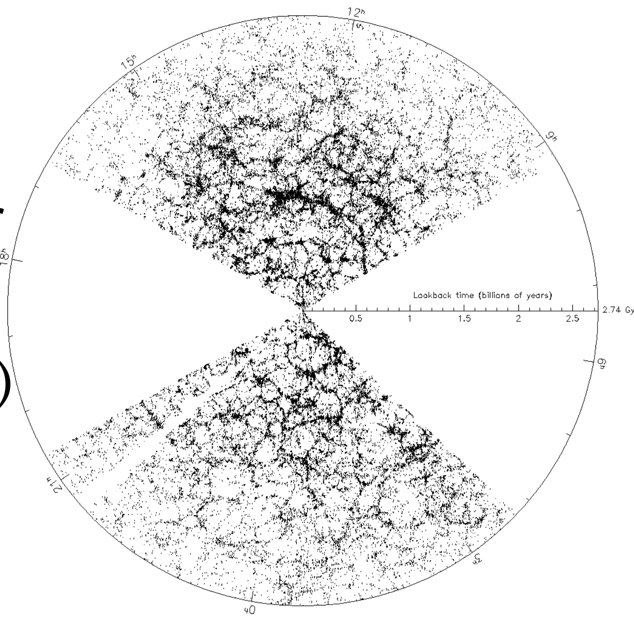
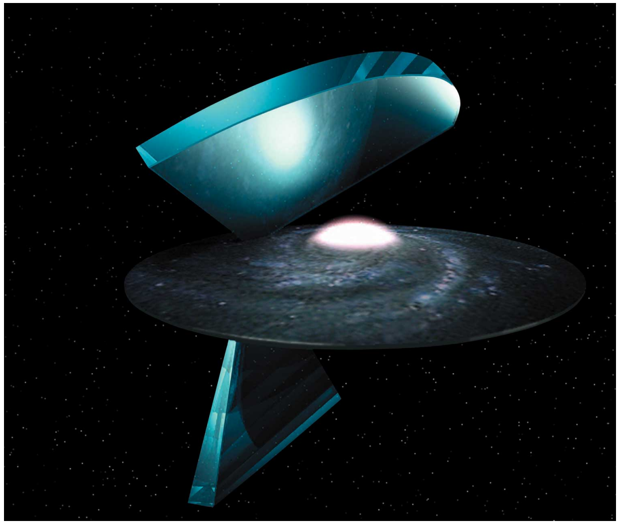


measurement of matter density distribution

LSS (Large Scale Structure)

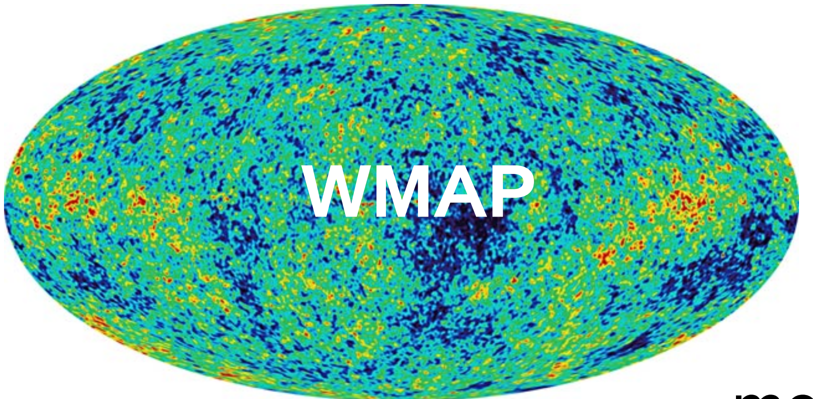
2dF, SDSS, ...



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

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

Neutrino mass from cosmology



measurement of CMBR

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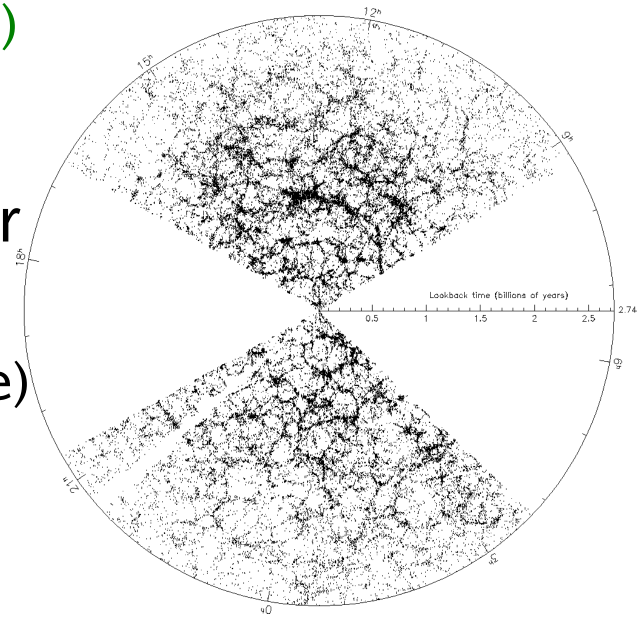


measurement of matter density distribution

LSS (Large Scale Structure)

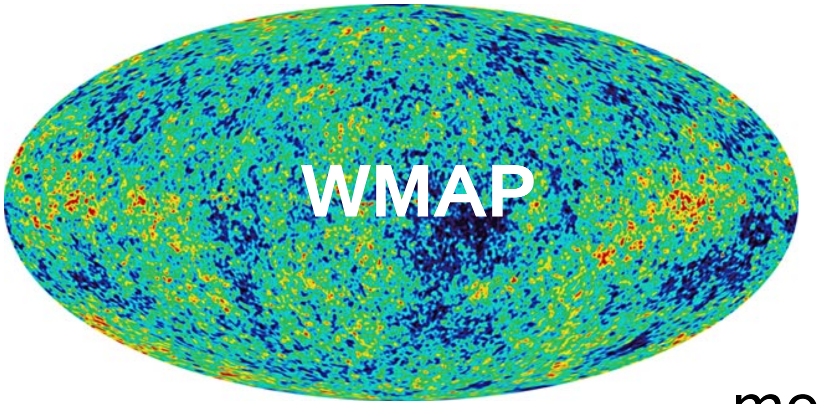
2dF, SDSS, ...

big bang theory:

neutrino density in universe

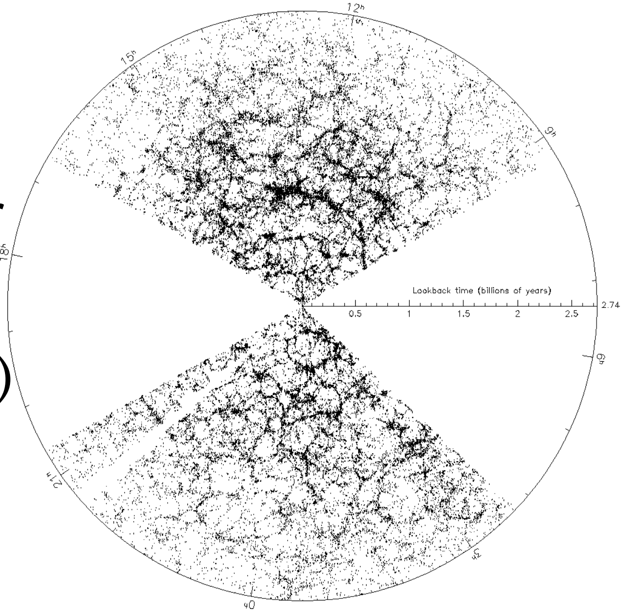
n_ν = 336 / cm³

Neutrino mass from cosmology



measurement of CMBR

(Cosmic Microwave Background Radiation)



measurement of matter density distribution

LSS (Large Scale Structure)

2dF, SDSS, ...

big bang theory:

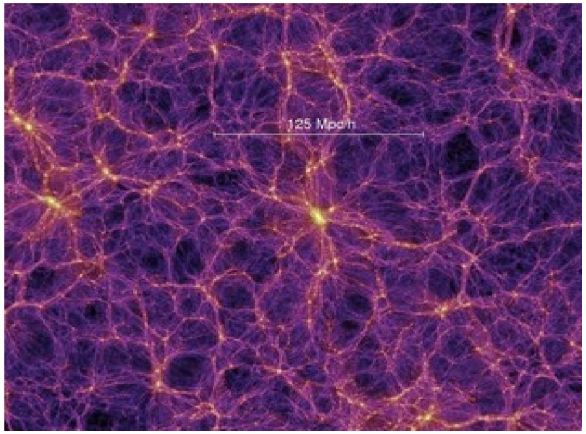
neutrino density in universe

$n_\nu = 336 / cm^3$

model development

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

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

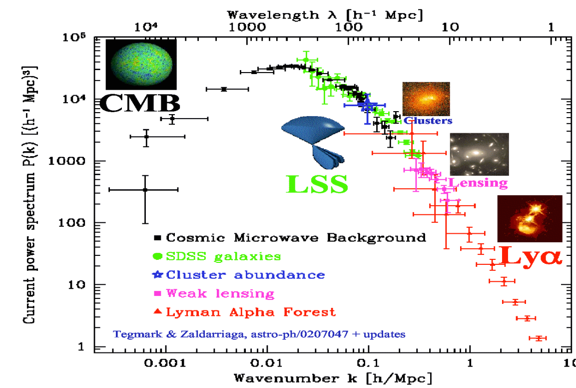


Neutrino mass from cosmology

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

$$\Sigma m(\nu_i) < 0.67 \text{ eV}$$

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



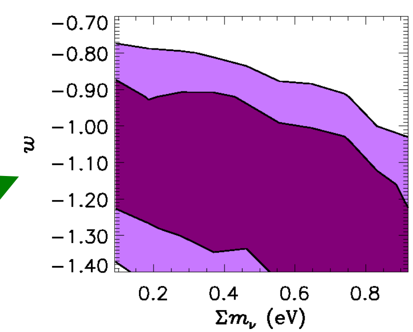
GOOBAR, HANNESTAD, MÖRTSELL (astro-ph/0602155)

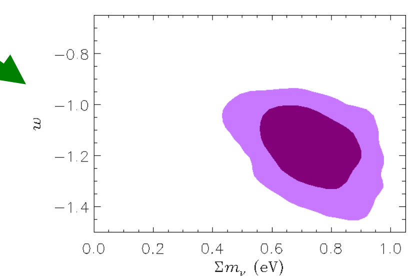
$$\Sigma m(\nu_i) < 0.62 \text{ eV}$$

WMAP+SDSS, no Lyman α, but making use of baryon accoustic peaks free equation of state w for dark energy

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

$\Rightarrow$ neutrino mass determination can help dark energy (arXiv0710.1952)



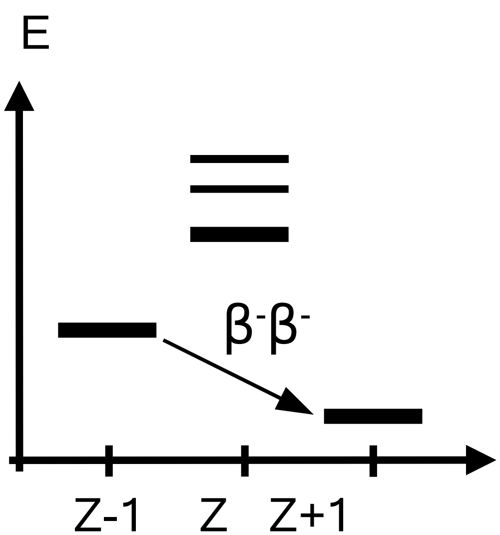


Ch. Wetterich et al. (e.g. arXiv:0905.0715): avoids bound on $\Sigma m(\nu_i)$

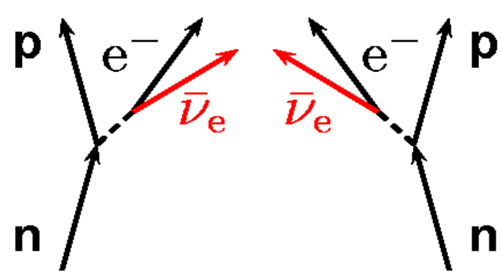
ν coupling to cosmon (quintessence model for dark energy) leads to growing neutrino mass

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

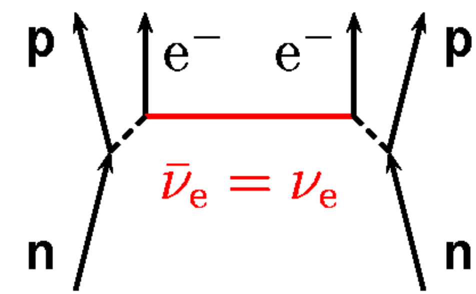
Double β-decay



normal (2νββ)



neutrinoless (0νββ)



0νββ requires: a) $\bar{\nu} = \nu$ (Majorana)

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

or other new physics

⇒ sensitive to coherent sum:

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

In contrast to direct mass measurement (single β decay, incoherent sum):

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

Signal: line at Q-value

Current and future double β decay experiments

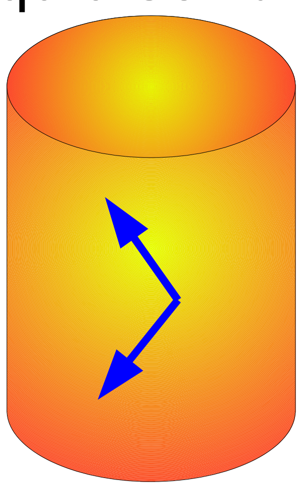
$m_{ee} \sim (1/\text{enrichment})^{1/2} \cdot (\mathit{\Delta E} \cdot \mathit{bg/M} \cdot t)^{1/4}$

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

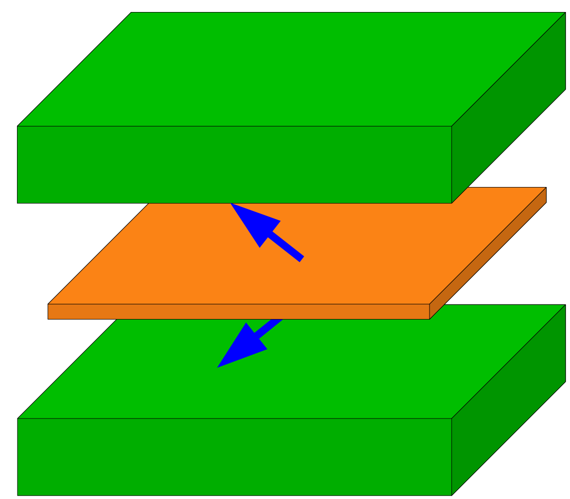
2 ways to measure both β-electrons:

semiconductor,
cryogenic bolometer
liquid scintillator

source
=
detector



tracking calorimeter



detector

source

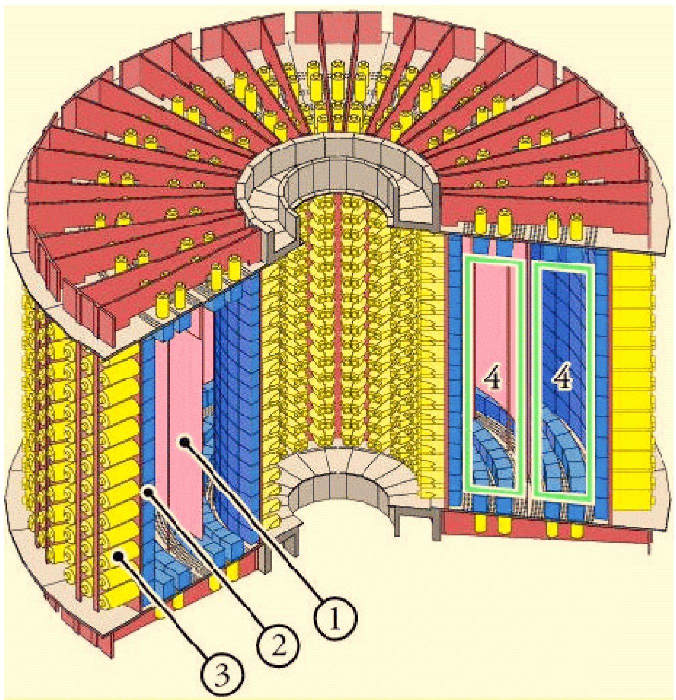
detector

running: CUORICINO
setting up: GERDA, CUORE, EXO-200
planned: Majorana, EXO, COBRA, SNO+ ..

running: NEMO-3
setting up: SuperNEMO
planned: MOON

Searching for $0\nu\beta\beta$: NEMO3, CUORICINO

NEMO3: tracking calorimeter
(⟶ SuperNEMO with enr. ^{82}Se)

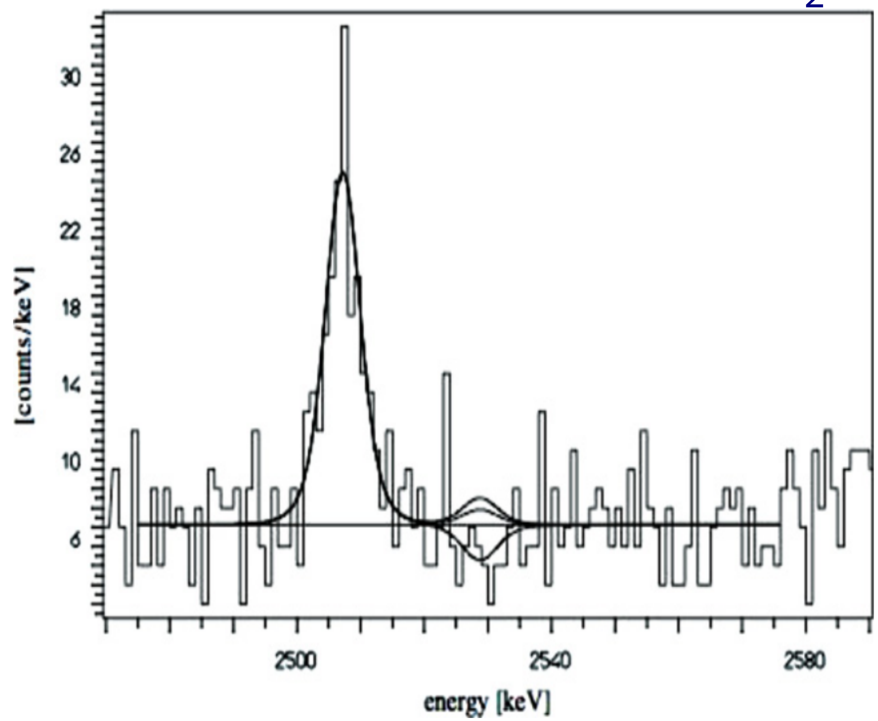


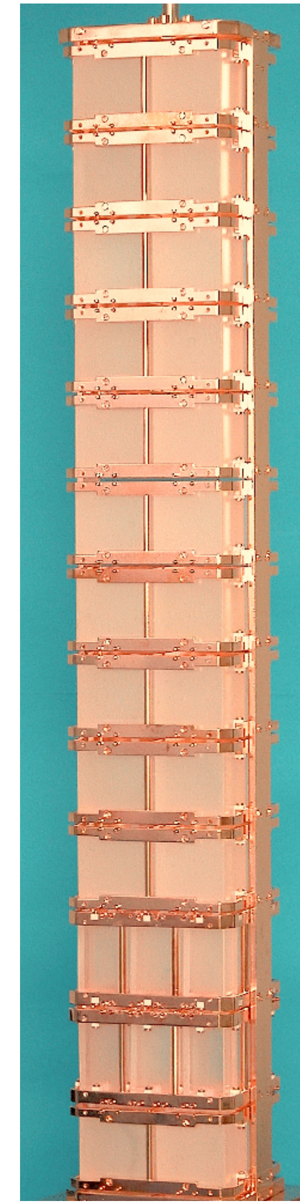
^{100}Mo: $T_{1/2}$ $(0\nu\beta\beta) > 1.1 \times 10^{24}$ y

$\Rightarrow m_{ee} < (0.45 – 0.93)$ eV

F Mauger, TAUP09

CUORICINO:
Te cryo bolometer)
(⟶ CUORE: 741 kg TeO_2)



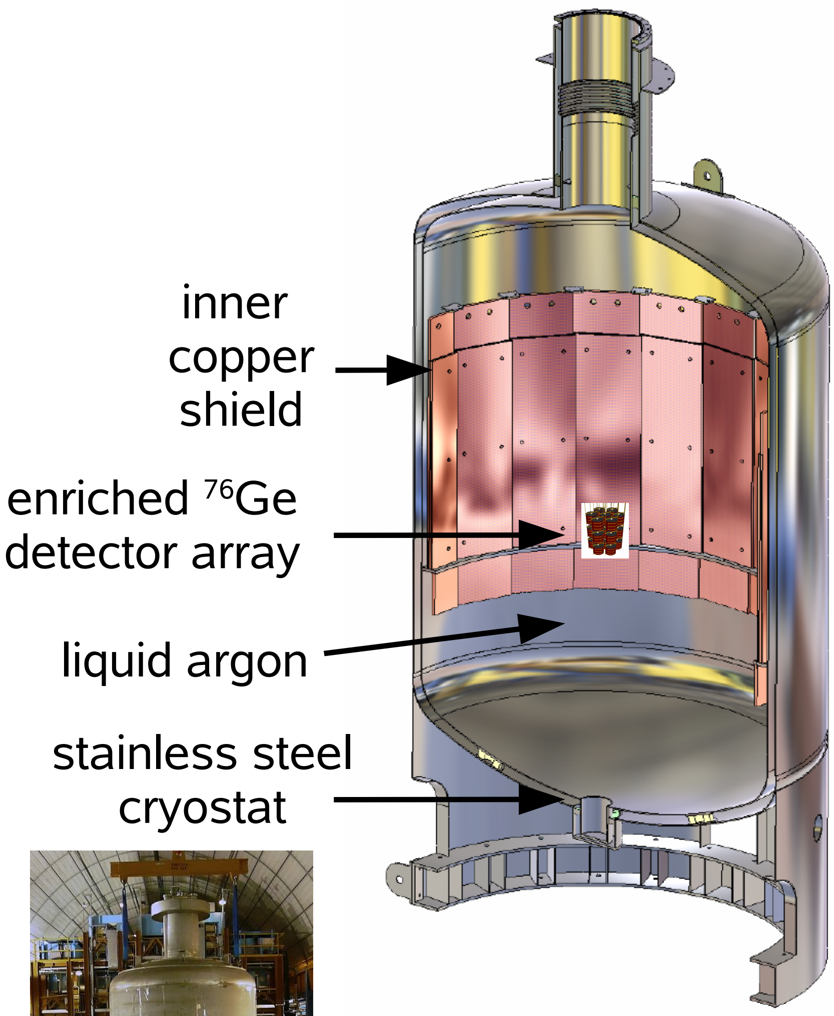


^{130}Te: $T_{1/2} > 3 \cdot 10^{24}$ y

$\Rightarrow m_{ee} < 0.19 – 0.68$ eV

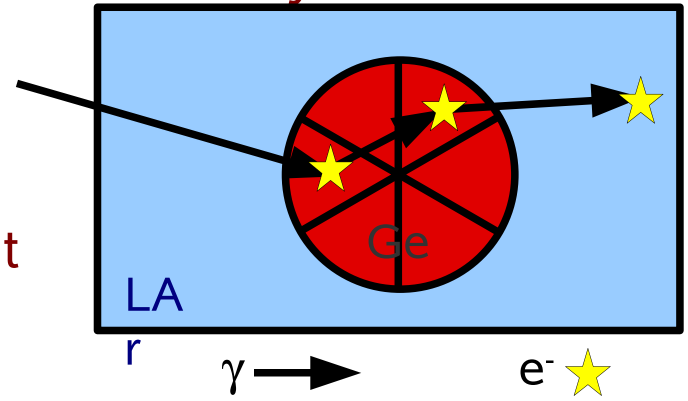
PRC 78 (2008) 35502

Coming soon: The GERDA experiment



New background reduction methods:

- naked Germanium detectors in noble liquid
- segmented detectors to identify multi-side events
- identify escaping Compton photons by scintillation light in LAr



3 Phases of GERDA

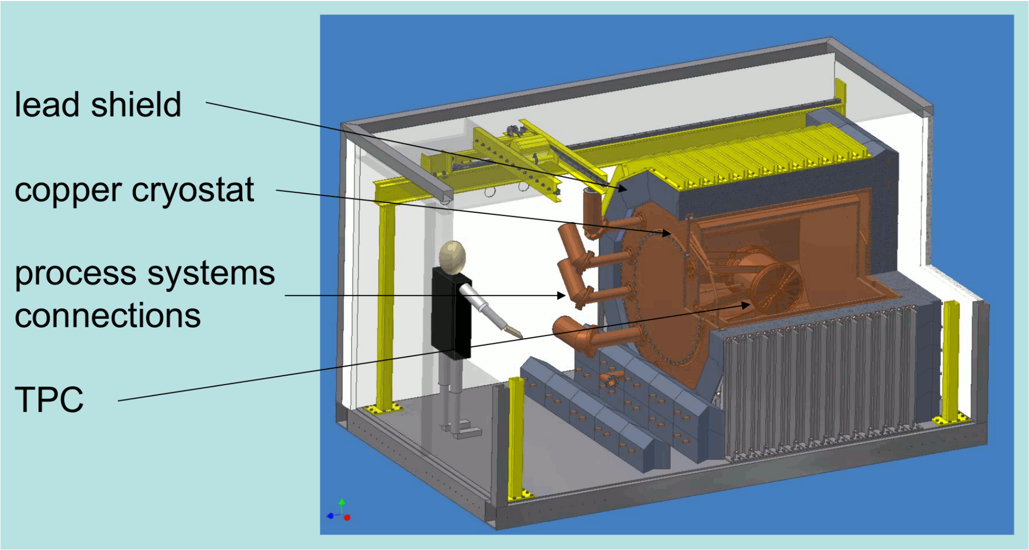
Phase 1: reuse old detectors of Hd-Moscow and IGEX

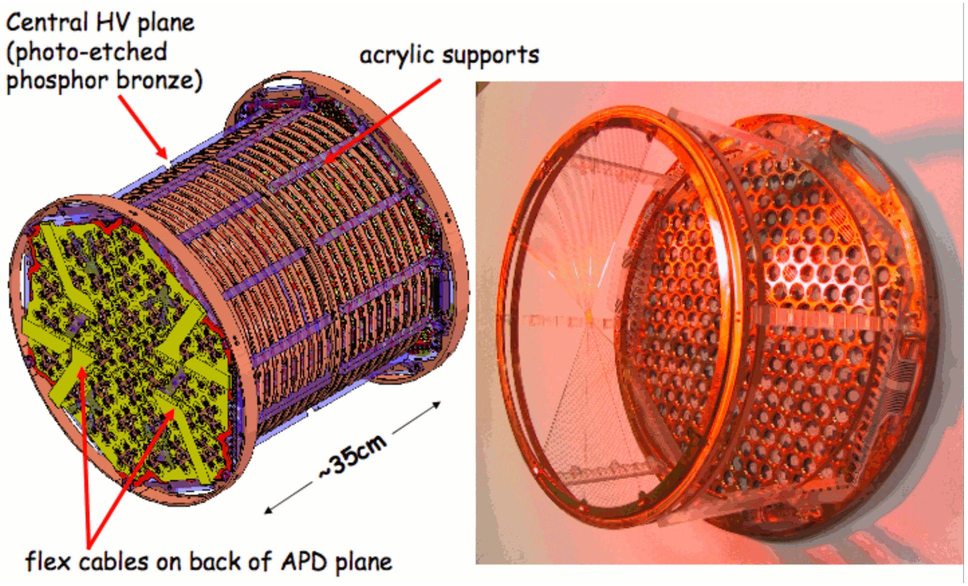
start commissioning in 2009

Phase 2: new segmented detectors (40 kg)

Phase 3: (with Majorana) many more detectors (500 kg)

Coming soon: EXO 200





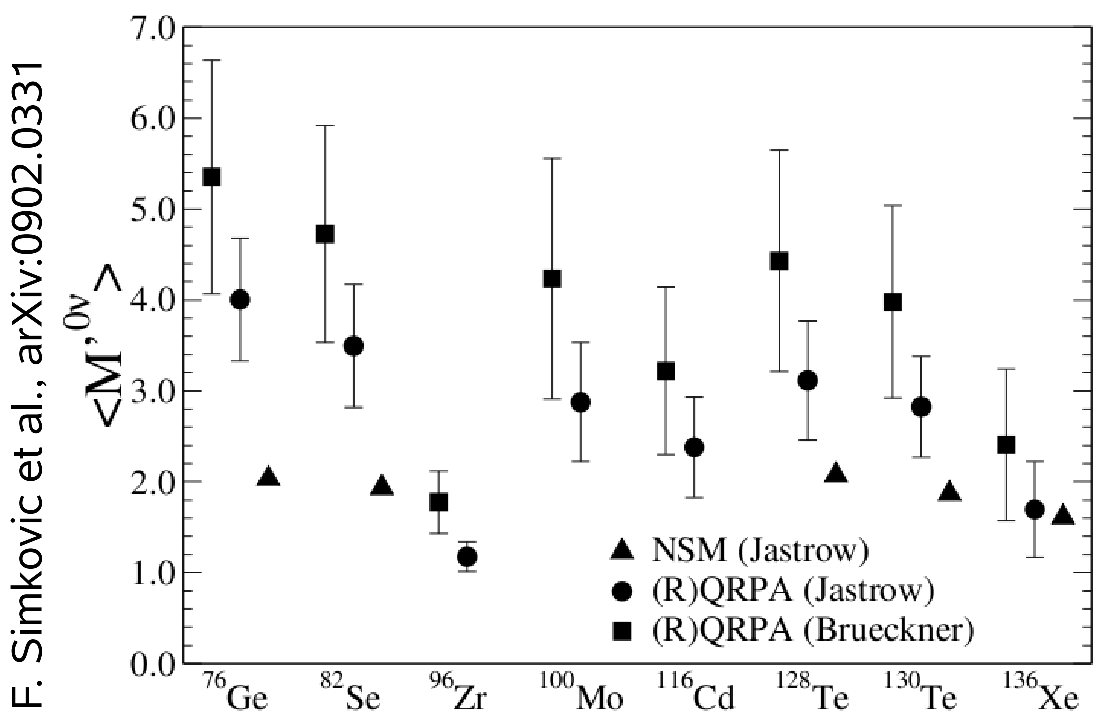
figures: K. Graham, CAP09

EXO200: 200 kg enriched ^{136}Xe at WIPP/New Mexico
commissioning will start end of 2009

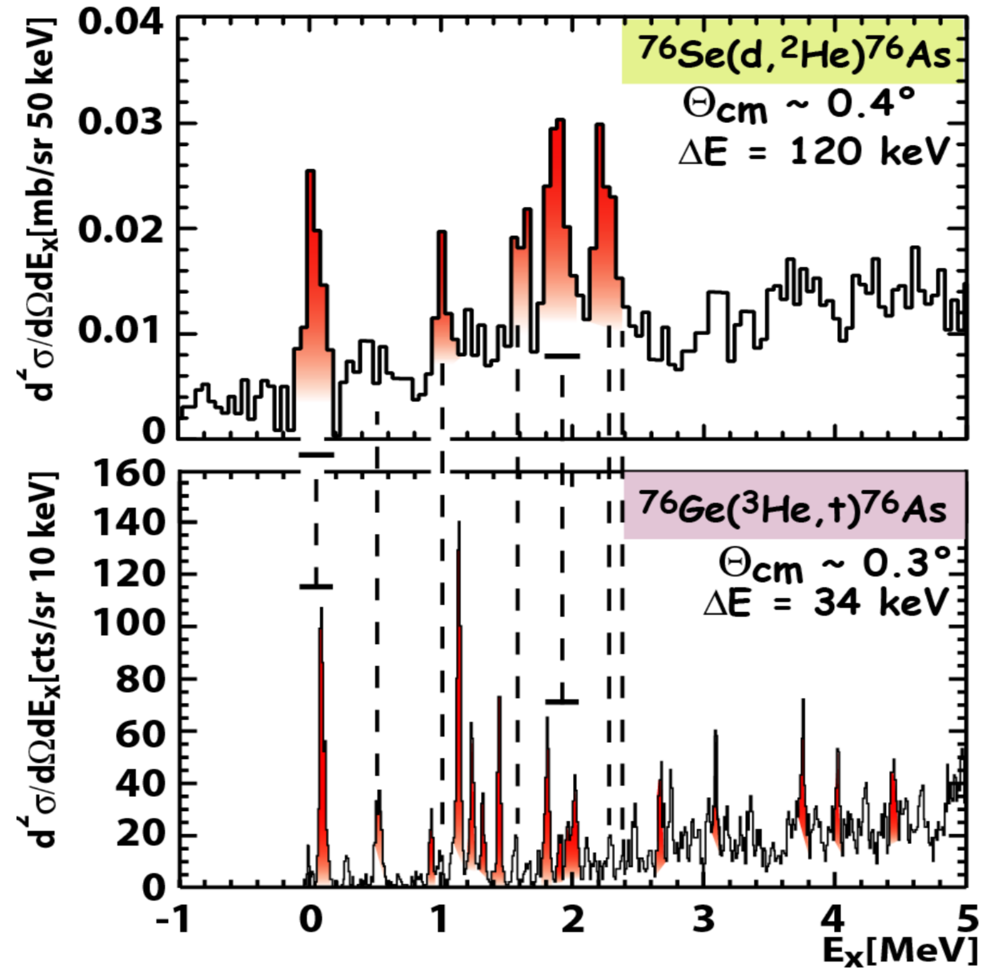
R&D: Majorana, SNO++, Cobra

$0\nu\beta\beta$ nuclear matrix elements

short range correlations are important:



experimental tests are important:



Frekers, Schleching 2009

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

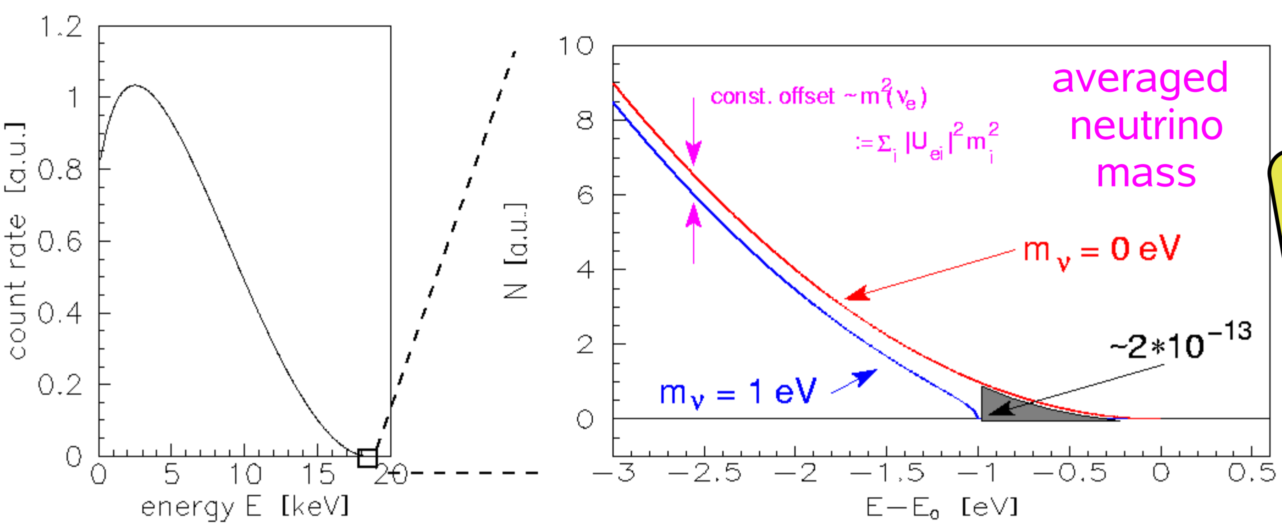
no time to discuss up-coming new ideas, e.g. talk by C. Orme, WG1 Friday

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

β electron energy spectrum:

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

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



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

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

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

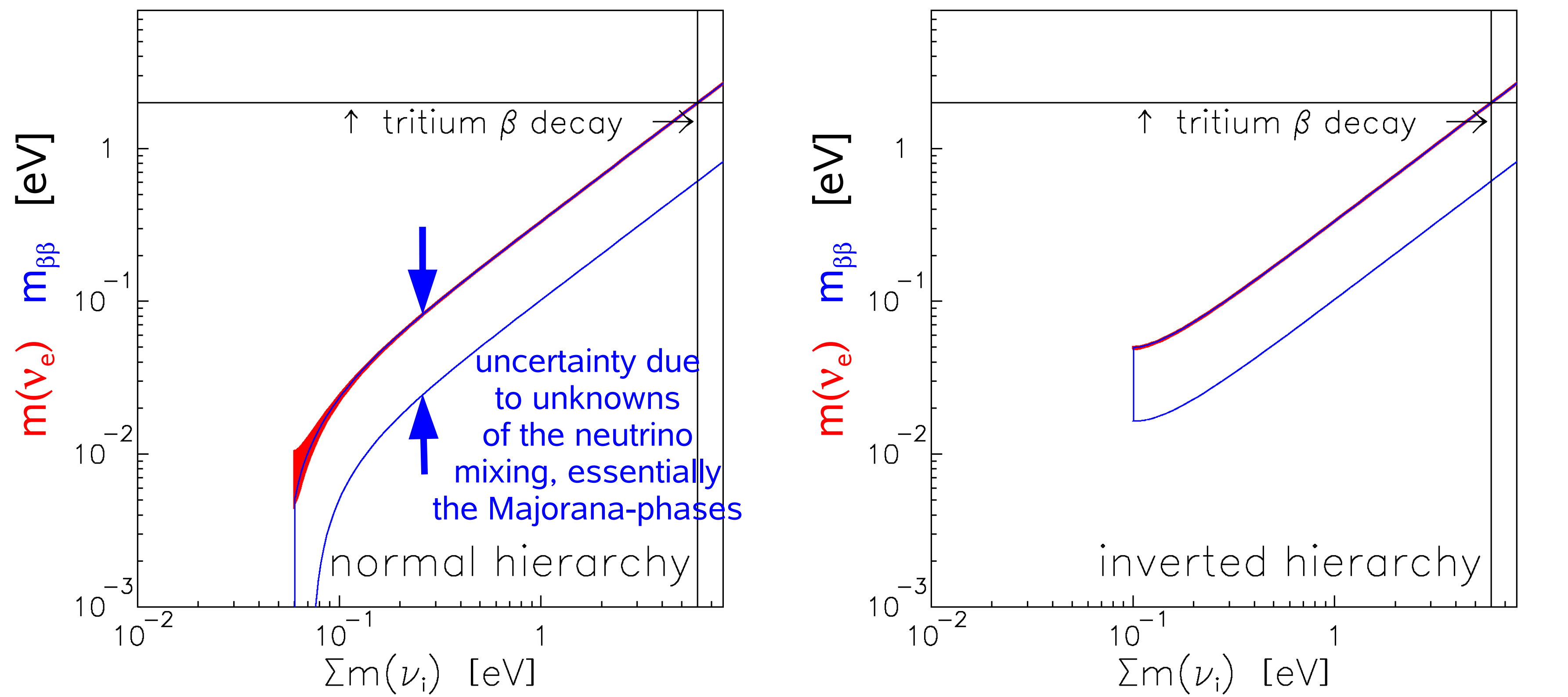
Comparison of the different approaches to the neutrino mass

Westfälische Wilhelms-Universität Münster

Direct kinematic measurement: $m^2(\nu_e) = \Sigma\ |U_{ei}{}^2|\ m^2(\nu_i)$ (incoherent)

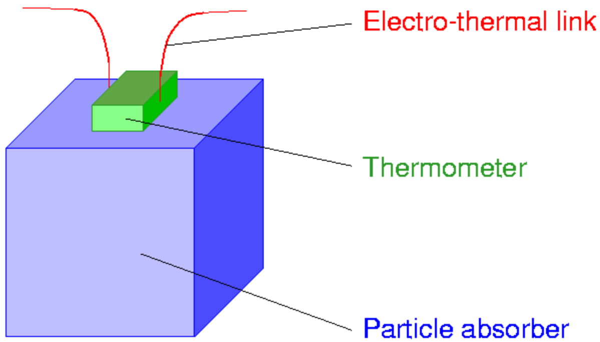
Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = |\ \Sigma\ |U_{ei}{}^2|\ e^{i\alpha(i)}\ m(\nu_i)|$ (coherent)

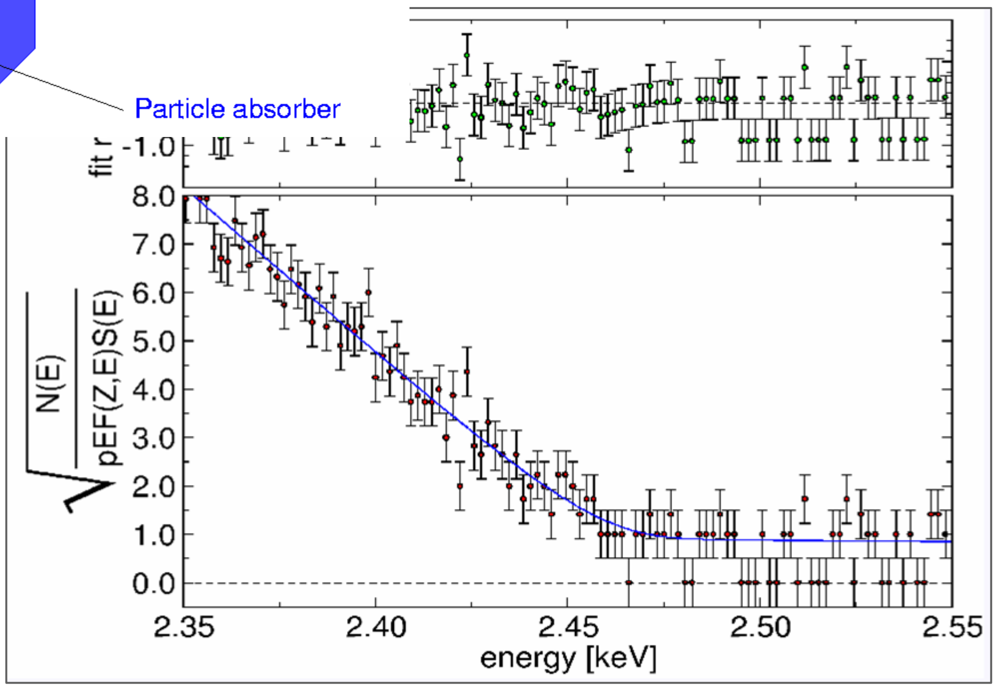
- if no other particle is exchanged (e.g. R-violating SUSY)
- problems with uncertainty of nuclear matrix elements



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

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





Parameters

detectors: 10 ($AgReO_4$)

rate each: 0.13 1/s

energy res.: ΔE = 28 eV

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

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

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

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

MANU (Genova)

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

Proposal: Microcalorimeter Arrays for a Rhenium Experiment (MARE)

Collaboration: Genova, Goddard Space Fligth Center/NASA, Heidelberg, Como, Milano, Trento, U Wisconson

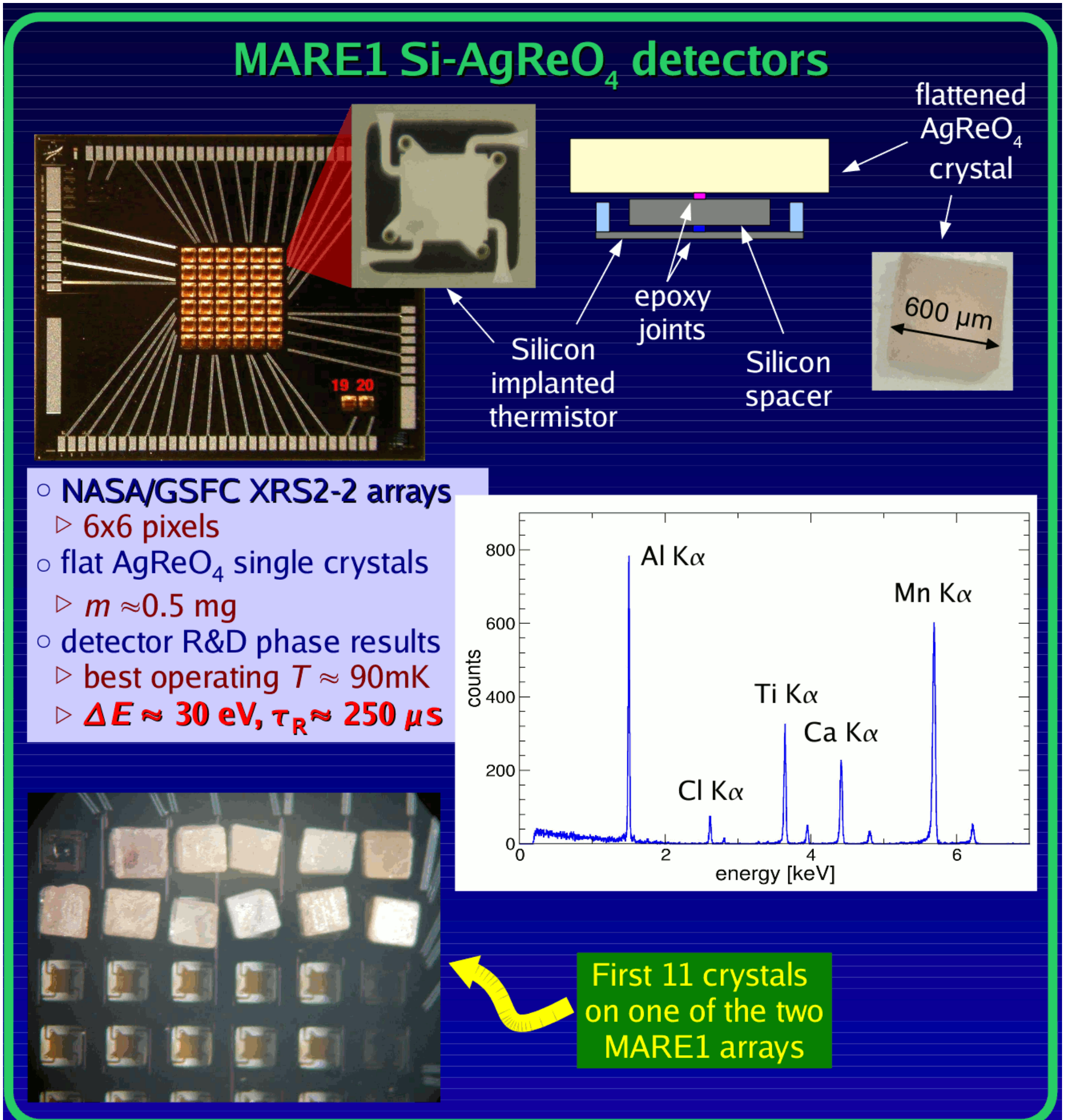
Idea: 2nd and 3rd generation rhenium β decay experiment

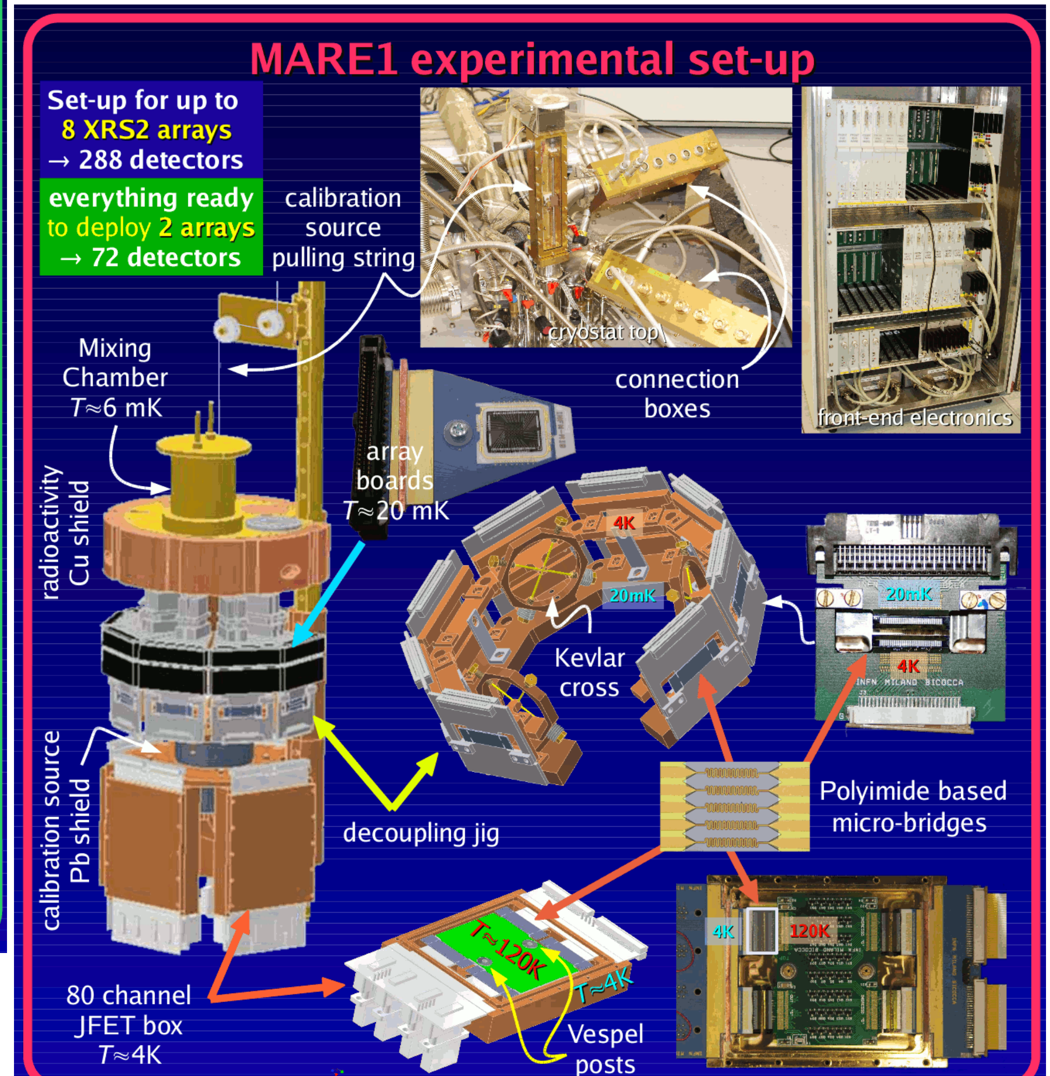
MARE I:
300 detectors (MIBETA: 10)
ΔE = 10 eV (MIBETA: 28 eV)
$\tau = 10^{-4}$ s (MIBETA: 10^{-3} s)
with semiconductor sensors (like MIBETA/MANU)

a

expected sensitivity on $m(\nu_e)$: 2-3 eV

Status of MARE 1 at Milano





pictures from A. Nucciotti/Milano

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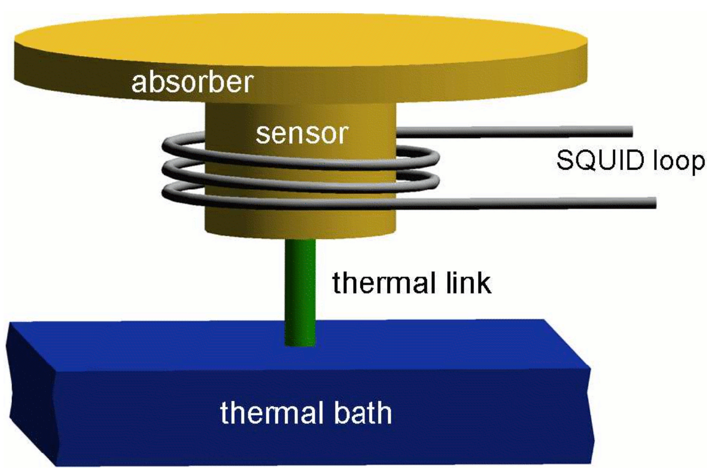
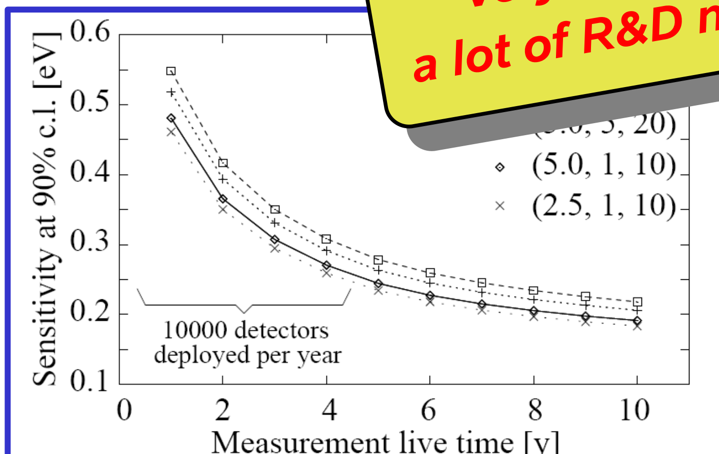
Idea: 2nd and 3rd generation rhenium β decay experiment

MARE II:
5000 – 50000 detectors (MIBETA: 10)
ΔE = 2.5 - 5 eV (MIBETA: 28 eV)
τ = a few 10^{-6} s (MIBETA: 10^{-3} s)
with superconducting transition edge sensors (TES) or
with metallic magnetic temperature sensors (MMC) or
with multiplexed kinetic inductance detectors (MKID)

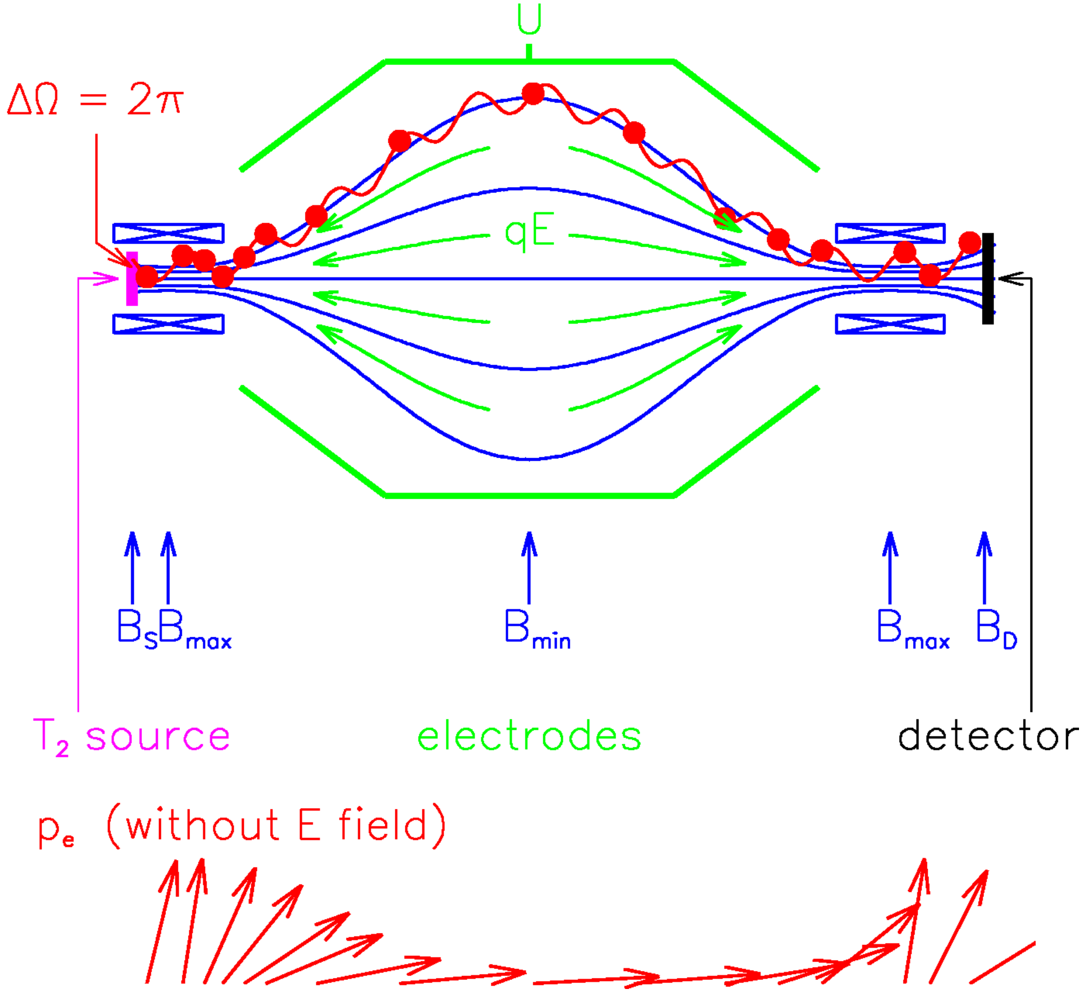
expected sensitivity on $m(\nu_e)$: 0.2 eV

very challenging,
a lot of R&D necessary

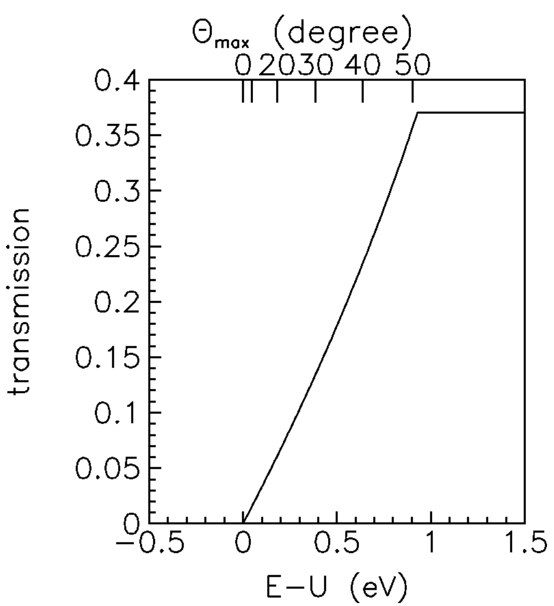




Tritium experiments: source ≠ spectrometer MAC-E-Filter



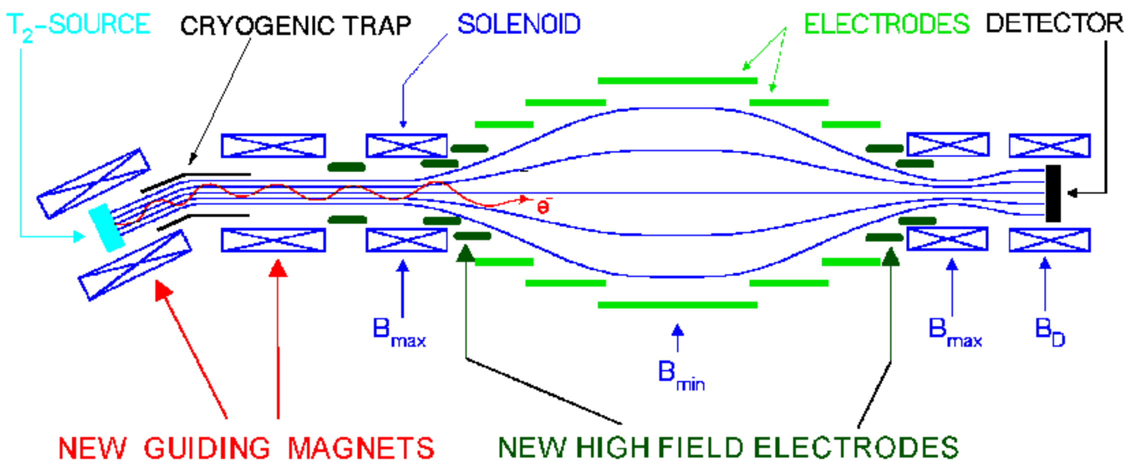
- Two supercond. solenoids compose magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp / B = \text{const.}$
  ⇒ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)

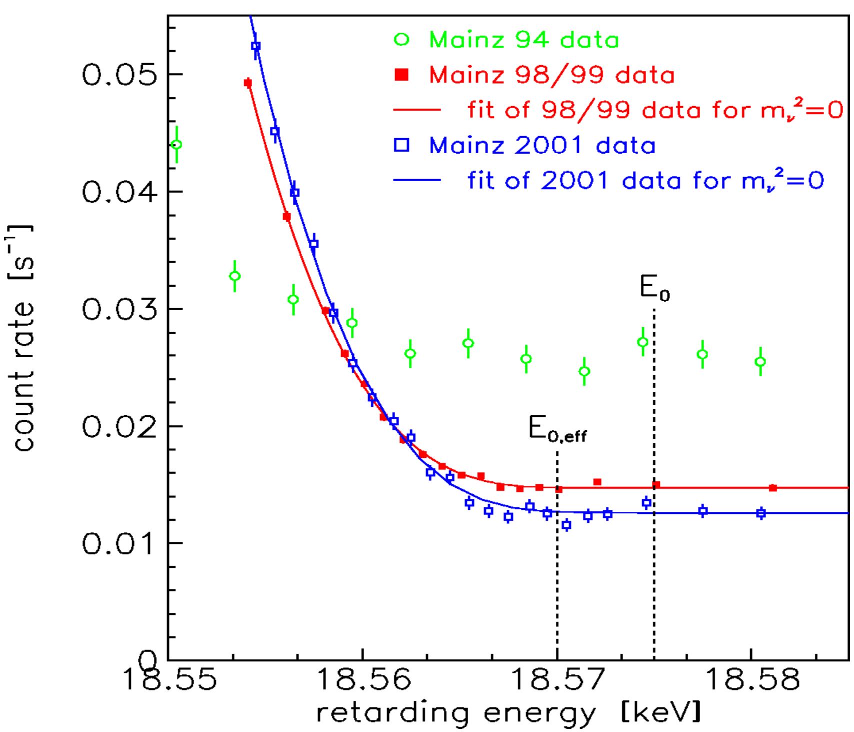


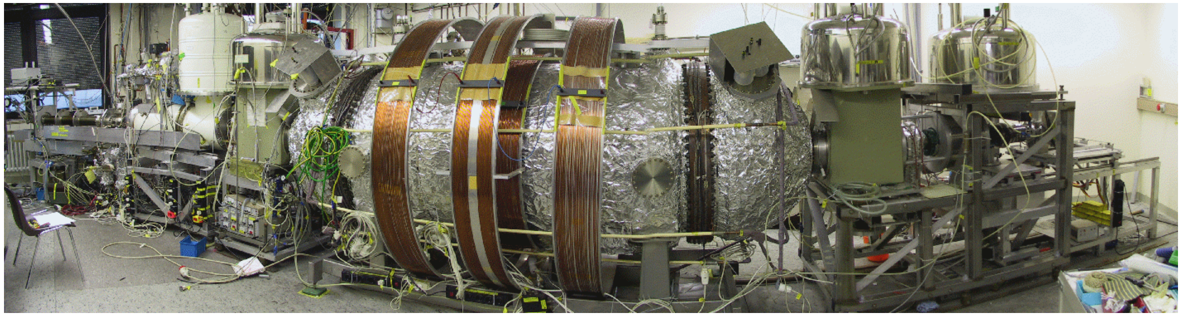
⇒ sharp integrating transmission function without tails →

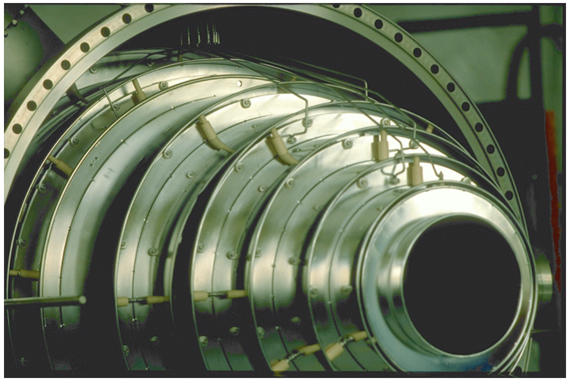
Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

The Mainz Neutrino Mass Experiment Phase 2: 1997-2001









After all critical systematics measured by own experiment (inelastic scattering, self-charging, neighbor excitation):

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

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447
E.W. Otten & C. Weinheimer, Rep. Prog. Phys. 71 (2008) 086201

The Karlsruhe Tritium Neutrino experiment KATRIN

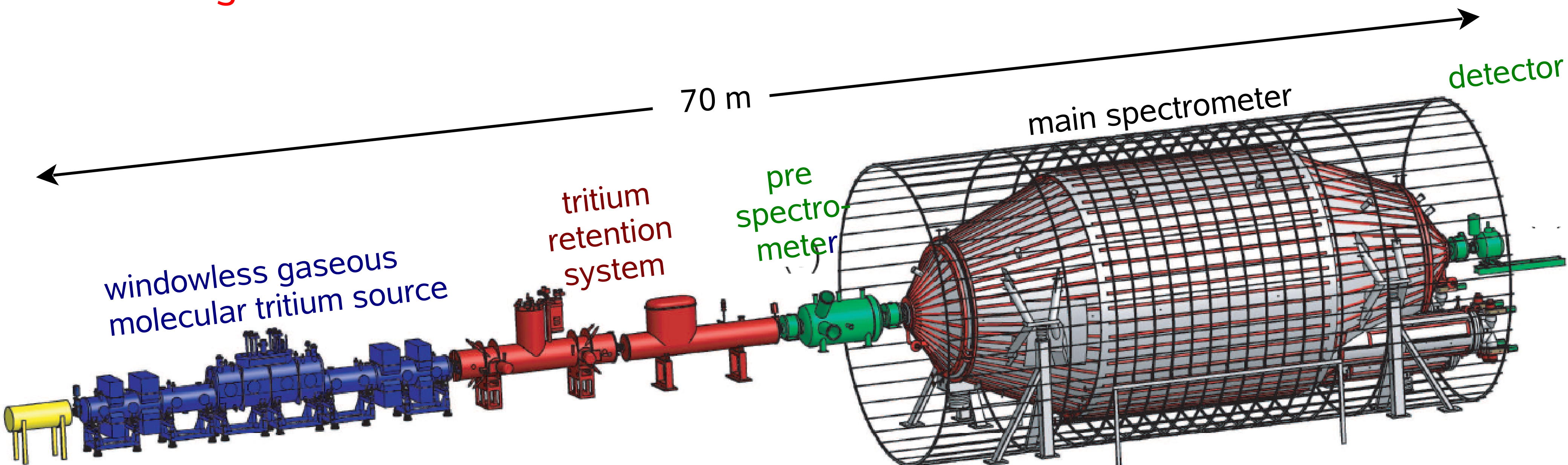
is being set up at the Forschungszentrum Karlsruhe

Physics Aim: $m(\nu_e)$ sensitivity of 0.2 eV

- higher energy resolution: $\Delta E \approx 1$eV
  since $E/\Delta E \sim A_{spectrometer}$ ⇒ larger spectrometer
- relevant region below endpoint becomes smaller
  even less rate $dN/dt \sim A_{source} \sim A_{spectrometer}$ ⇒ larger spectrometer

$\Big\}$ ⌀10m

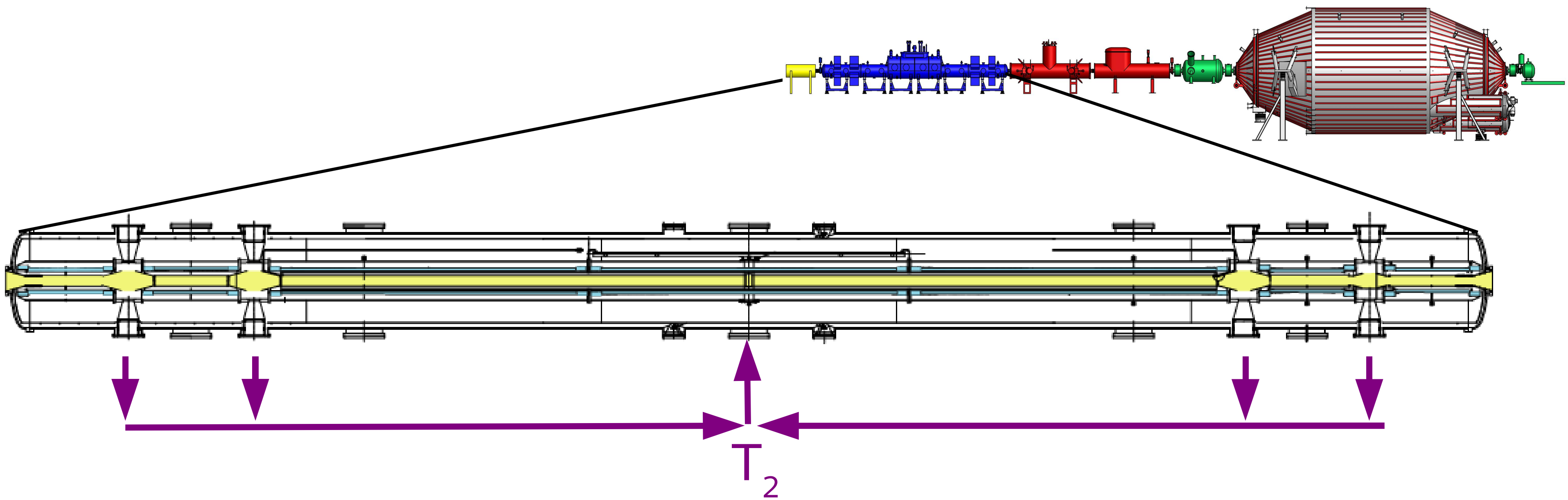
- small systematics ⇒ windowless gaseous tritium source
- much longer measurement time: 100 d → 1000 d



(Scientific Report FZKA 7090)

Molecular Windowless Gaseous Tritium Source WGTS

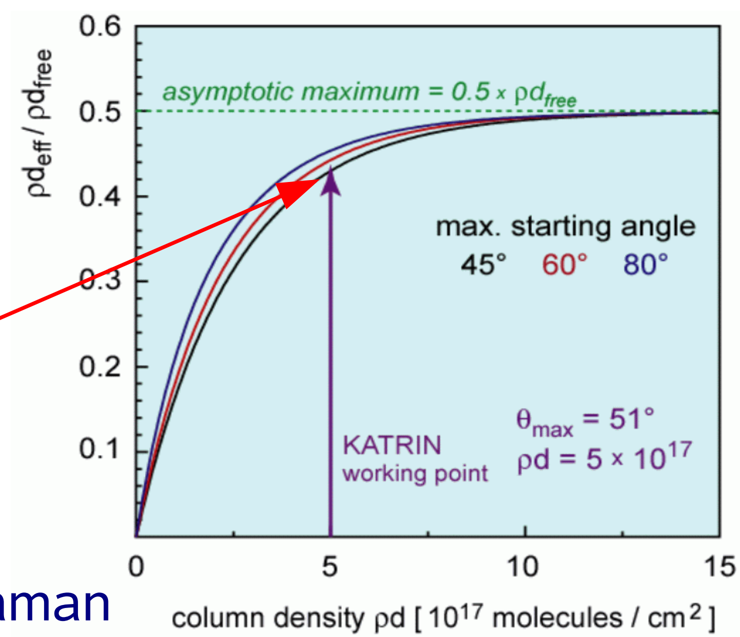
Westfälische Wilhelms-Universität Münster



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

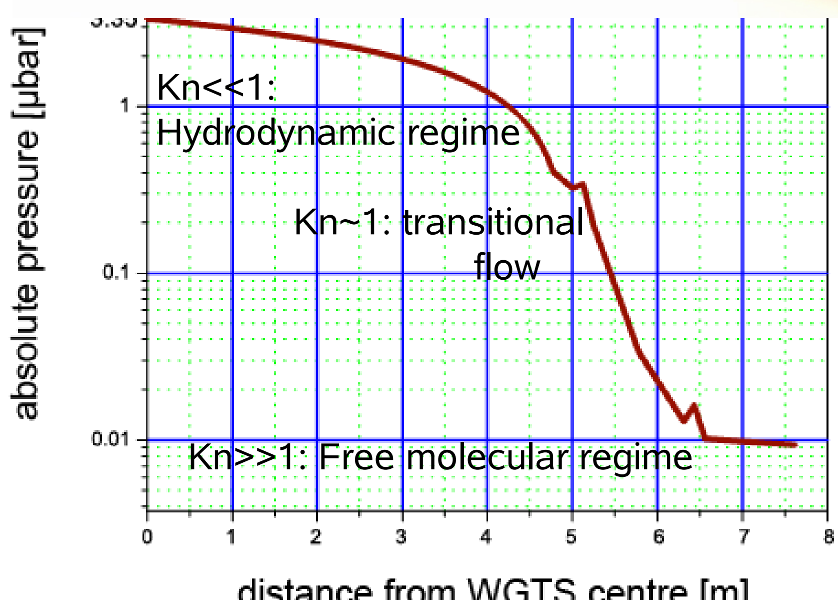
Molecular Windowless Gaseous Tritium Source WGTS

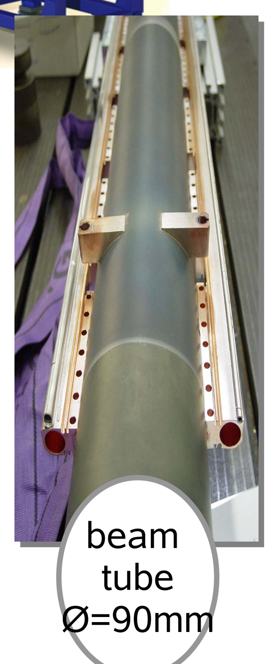
WGTS-demonatrator will arrive early 2010

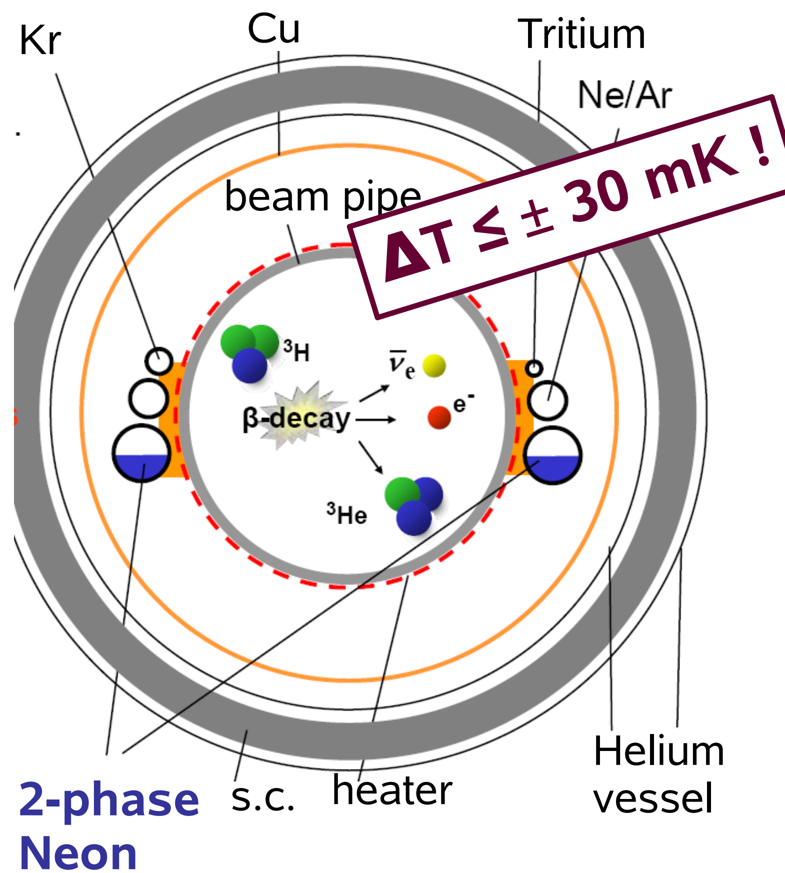
Conceptional design

2 phase Neon cooling with operating temperature: 27–28 K

- **spatial** (homogeneity): ± **0.1%**
- **time** (stability/hour): ± **0.1%**







WGTS under construction

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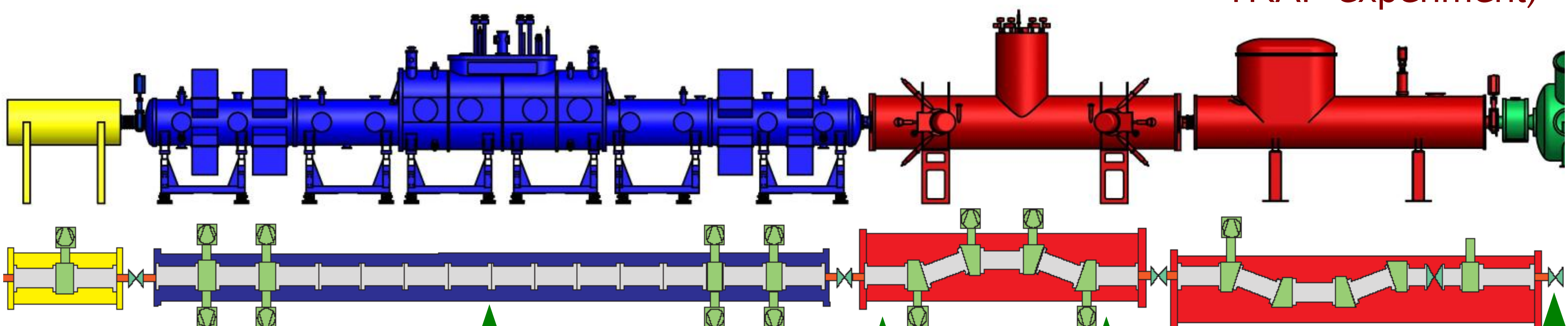
Transport and differential & cryo pumping sections

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

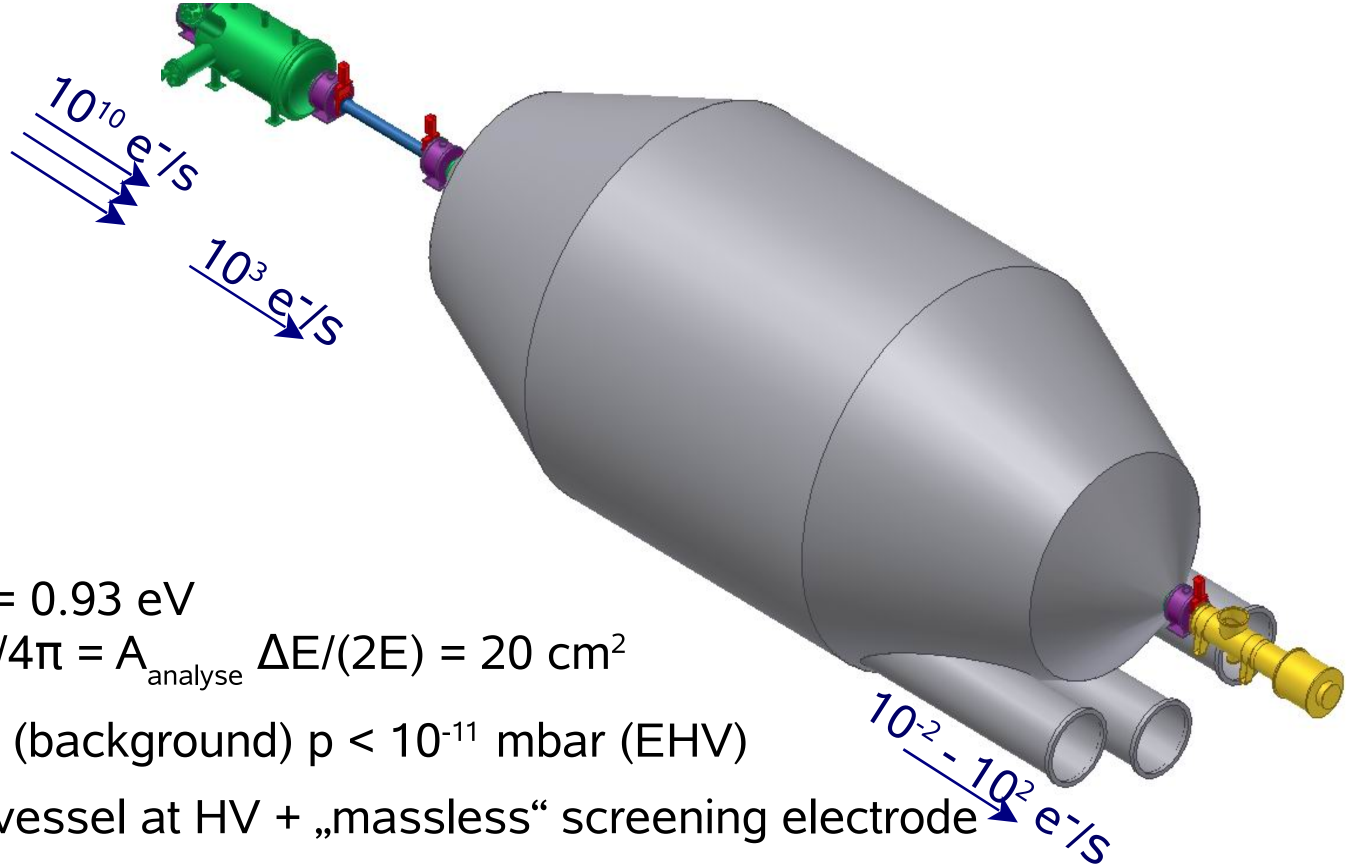
≈ 10^{-7} mbar l/s

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

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

Arrival of DPS2-F at FZ Karlsruhe: July 15, 2009

Pre and main spectrometer



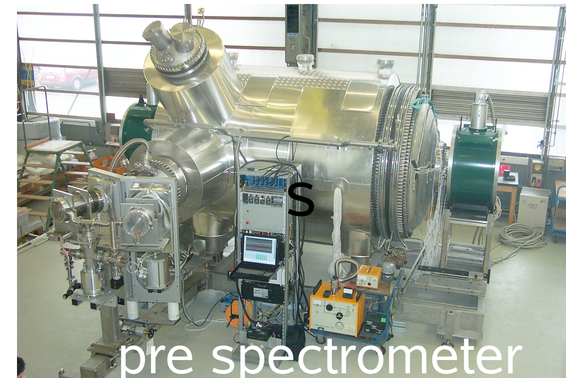
Main spectrometer:

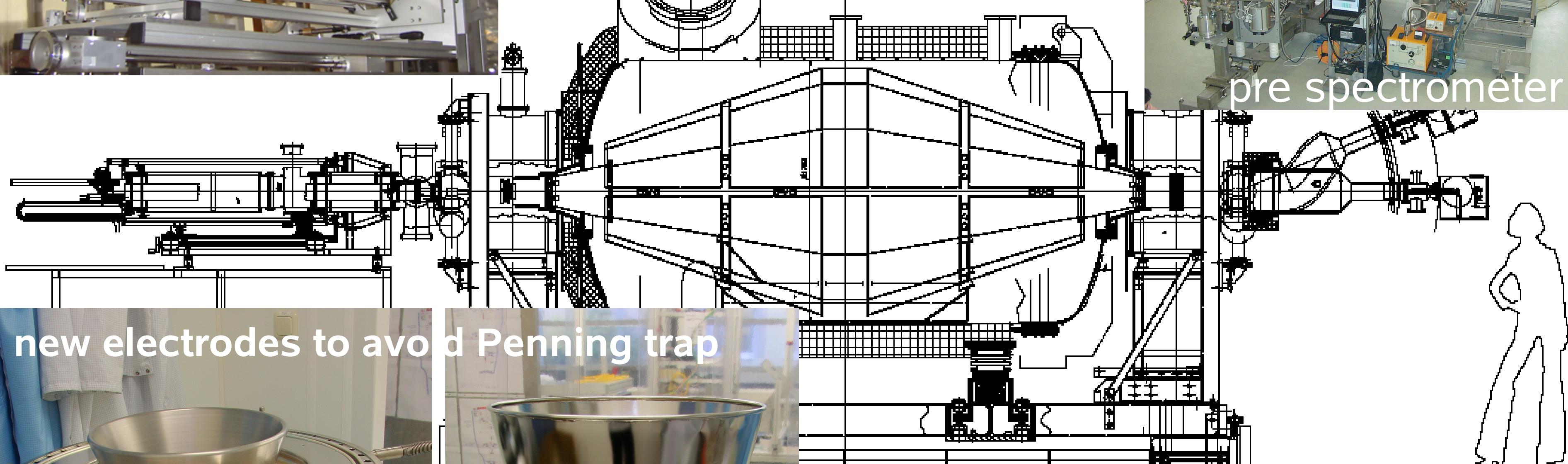
- ⌀10m, length 24m
  ⇒ large energy resolution: $\Delta E = 0.93$ eV
  ⇒ high luminosity: $L = A_{Seff}\ \Delta\Omega/4\pi = A_{analyse}\ \Delta E/(2E) = 20\ cm^2$
- ultrahigh vacuum requirements (background) $p < 10^{-11}$ mbar (EHV)
- „simple“ construction: vacuum vessel at HV + „massless“ screening electrode

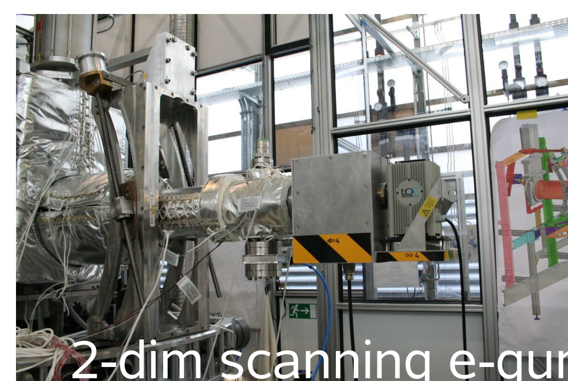
Pre spectrometer

- Transmission of electron with highest energy only
  (10^{-7} part in last 100 eV)
  ⇒ Reduction of scattering probaility in main spectrometer
  ⇒ Reduction of background
- only moderate energy resolution required: $\Delta E = 80$ eV
- test of new ideas (EHV, shape of electrodes, avoid and remove of trapped particles, ...)

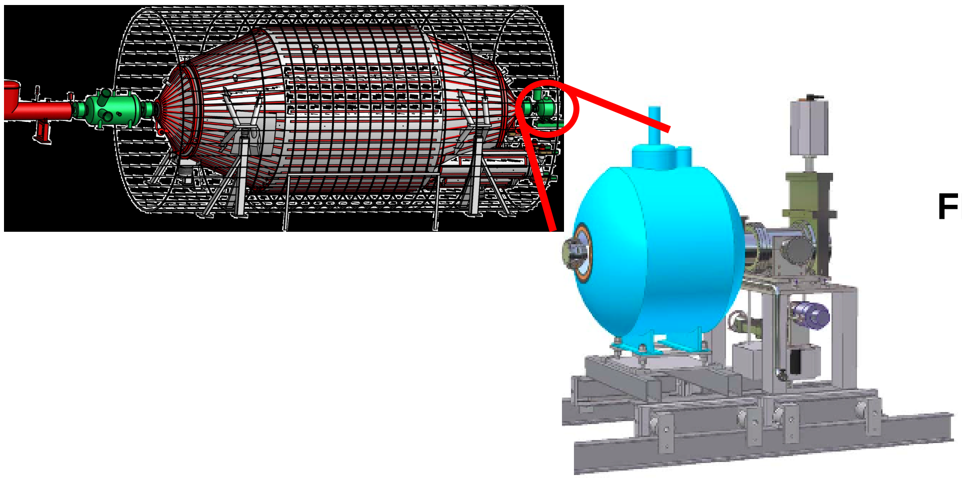
Electromagnetic design tests at the pre spectrometer

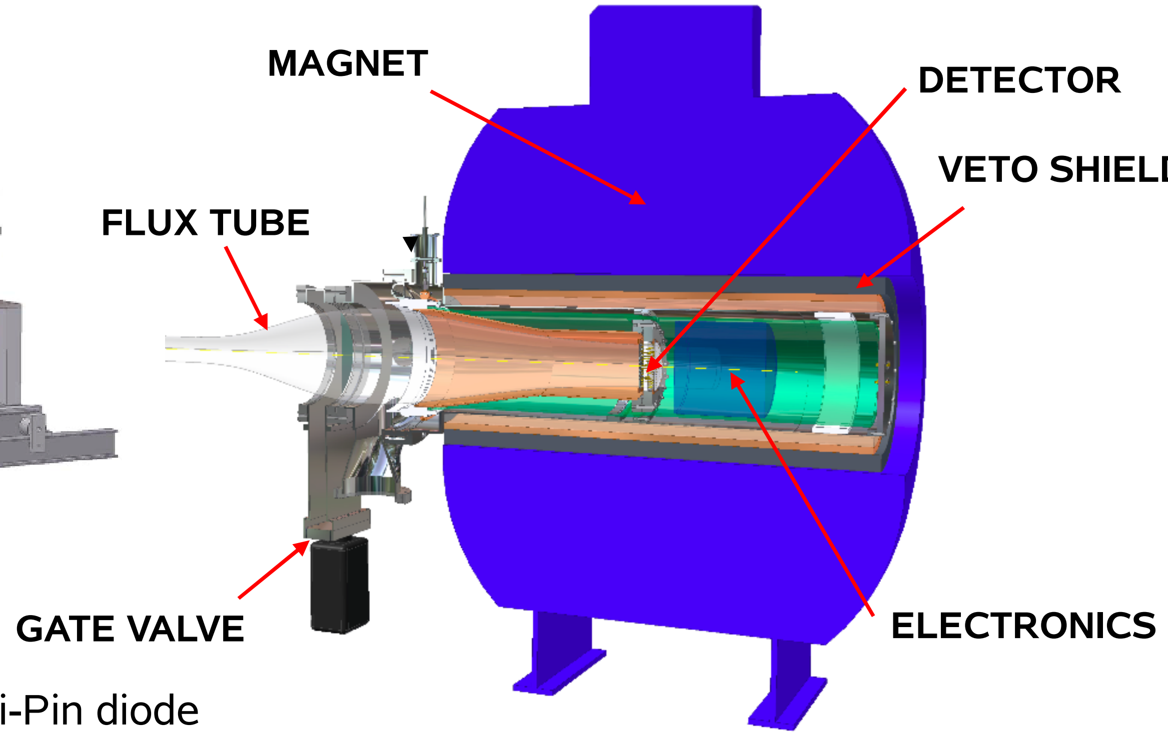


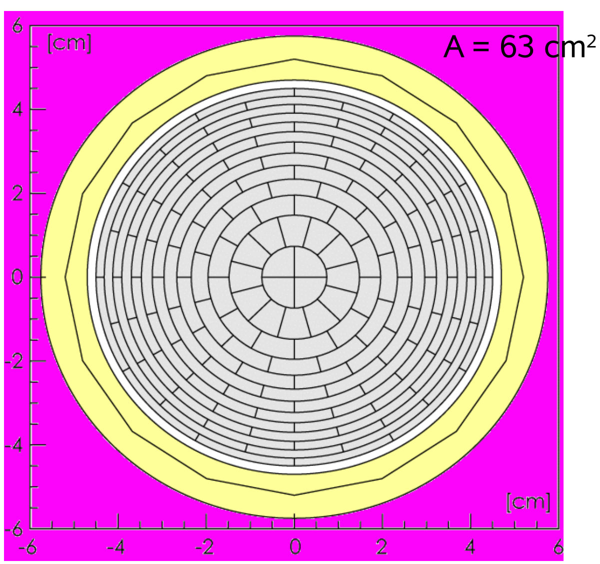




Detector Setup



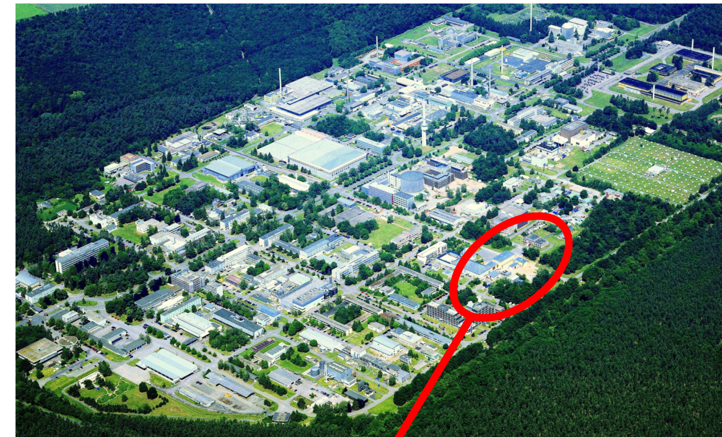


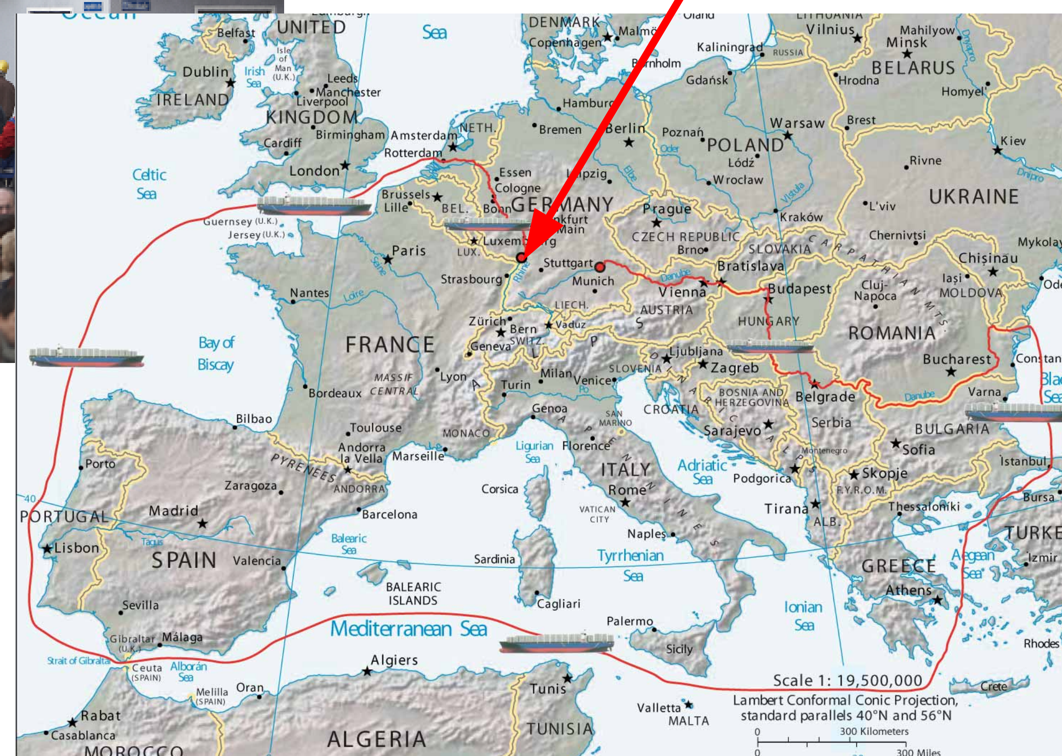


- Si-Pin diode
- Detection of transmitted β-decay electrons (mHz to kHz)
- **Low background for endpoint investigation**
- High energy resolution ΔE < 1 keV
- 12 rings with 30° segmentation + 4 fold center = **148 pixels**
  - record azimuthal and radial profile of flux tube
    - minimize background
    - investigate systematic effects
    - compensate field inhomogeneity in analyzing plane

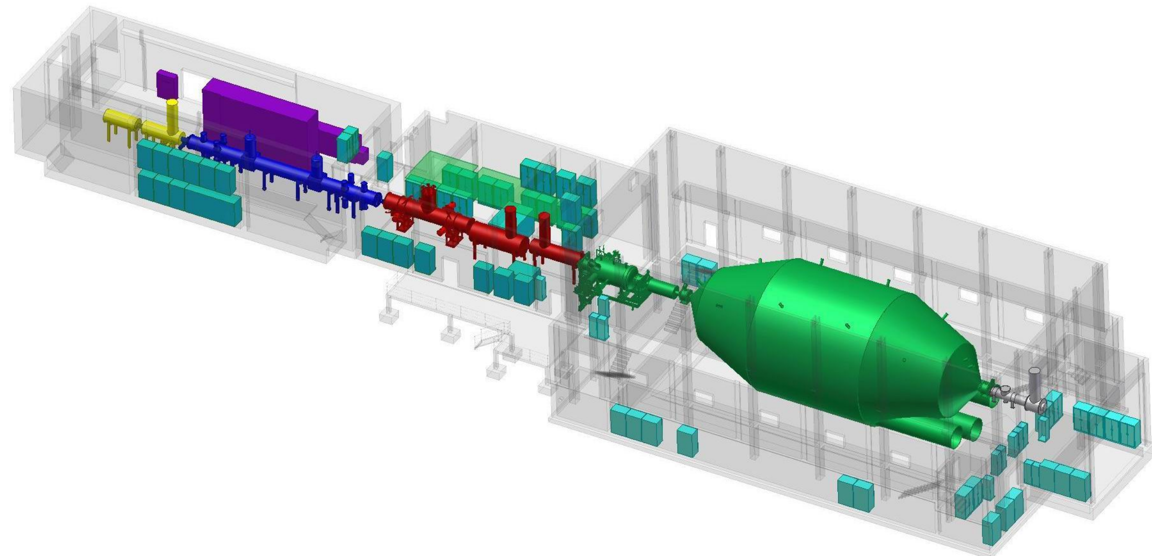
(magn. field of 3 - 6 T, active veto shield, post-accel. mode)

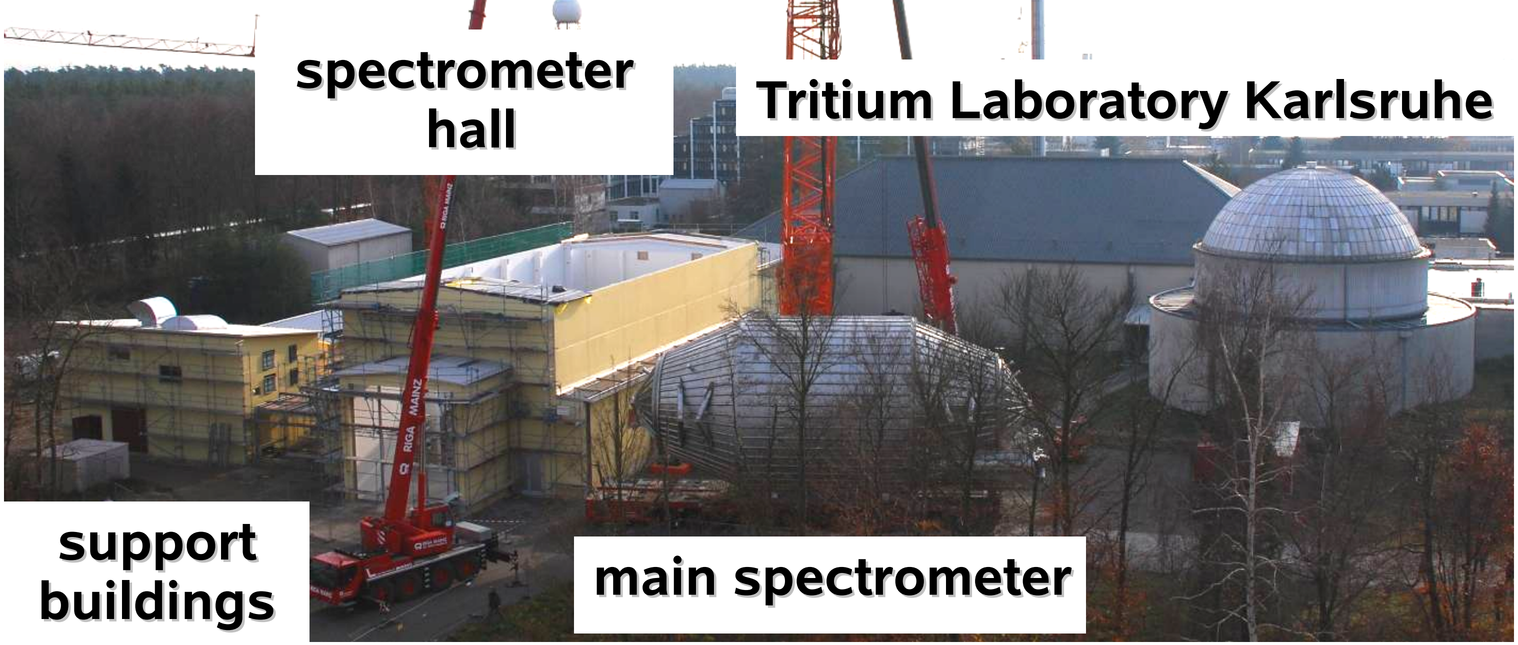
Main Spectrometer – Transport to Forschungszentrum Karlsruhe





KATRIN`s location at Forschungszentrum Karlsruhe





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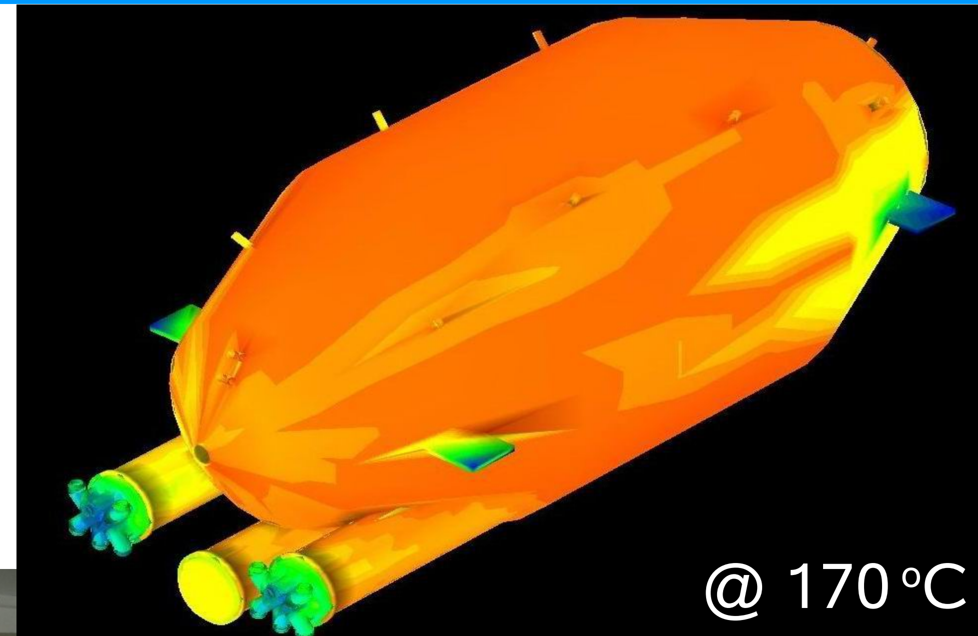
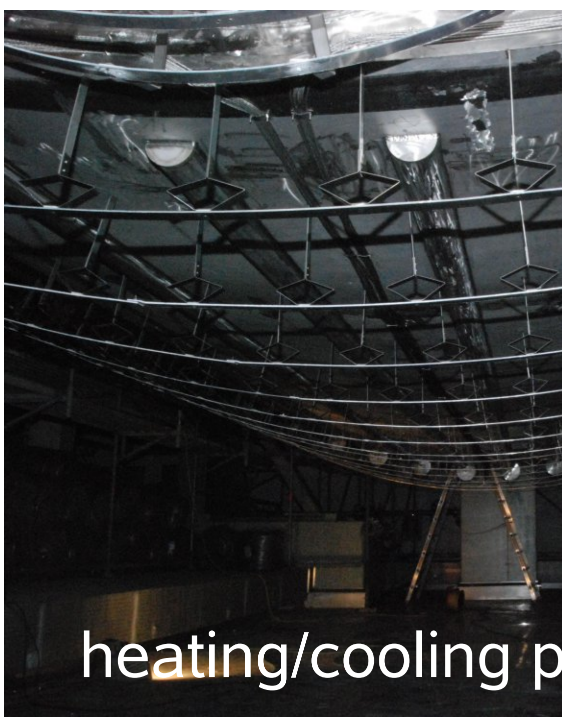
Installation of heating/cooling system and first out-baking at 350 °C

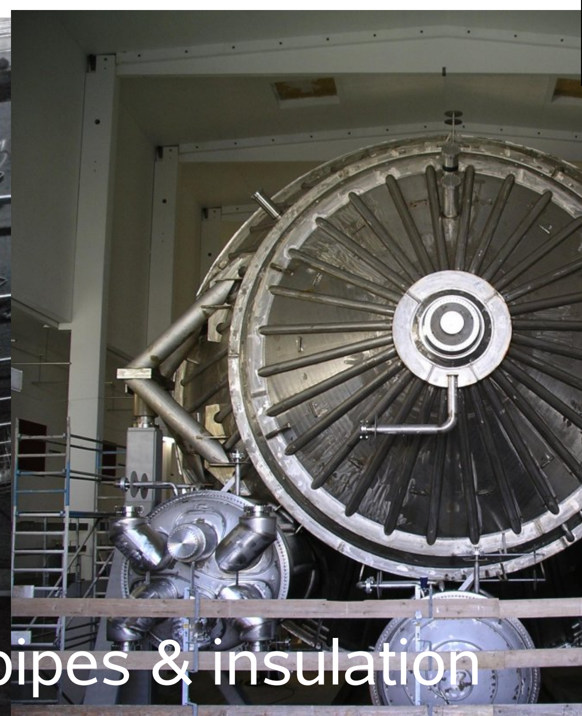
After out-baking (with only 6 TMPs):

a) $p = 5 * 10^{-10}$ mbar,
(but pumping speed will still be increased by 2 orders of magnitude by NEGs)

b) out-gasing rate is about KATRIN´s design value of
$q<10^{-12}$ mbar l/s cm^2







Sensitivity requirements

1) Huge statistics: optimized source &
large spectrometer

2) Low background: Mainz experiment:
most background from spectrometer
but KATRIN spectrometer is much bigger!
⇒ need something new !

3) Systematic uncertainties:
need to be very small !

Background reduction: shielding by „massless“ wire electrode

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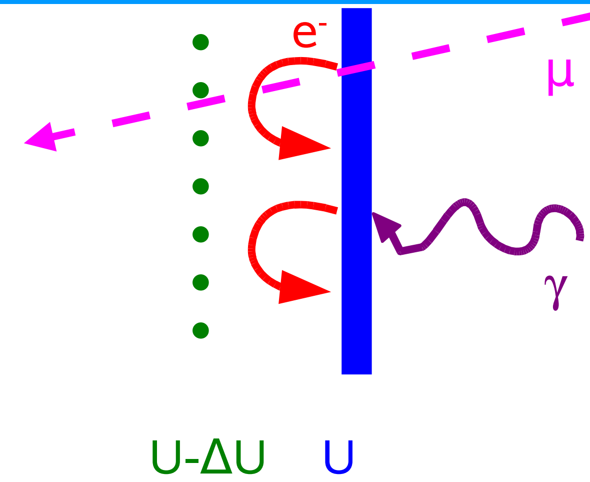
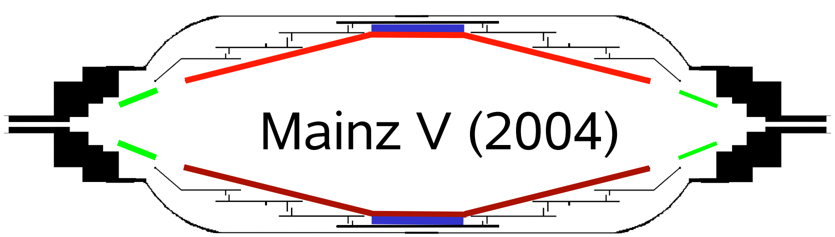
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

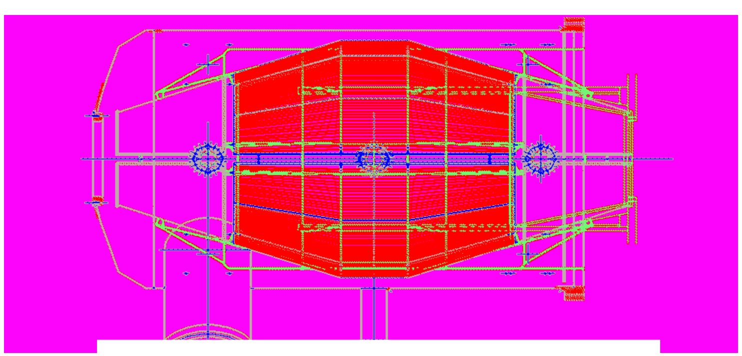
wire electrode on slightly more negative potential



First realisation:
Mainz III



New record !
April 04

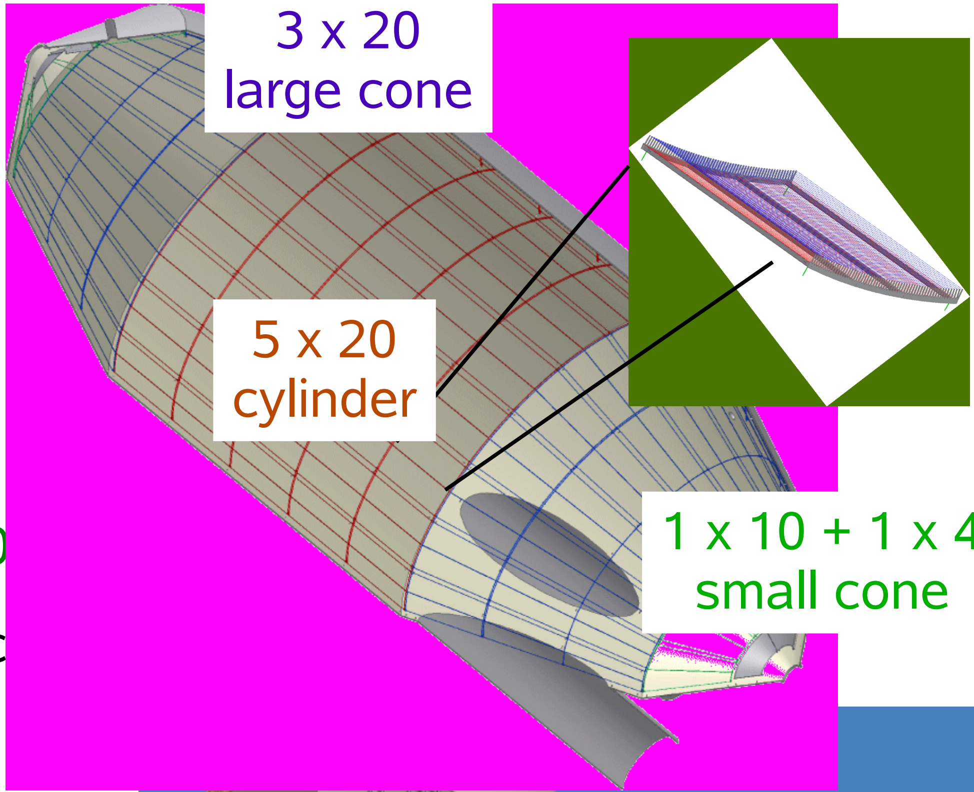


KATRIN pre spectrometer

Concept for KATRIN:
690 m² surface: 2-layer wire modules

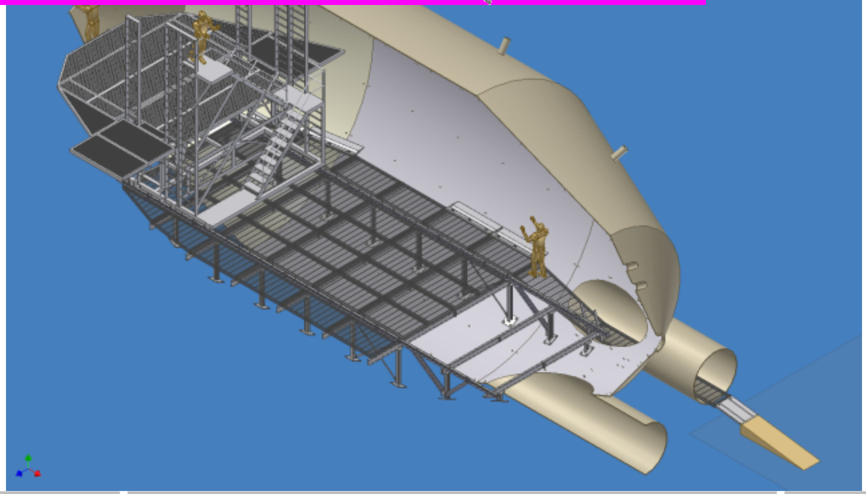
Two layers:

- to increase background shielding
- to increase electrical shielding
- to allow mechanical precision



Wire electrode system of KATRIN main spectrometer (A=690 m², V=1240

248 modules, 23120 wires, 46240 ceramic



Technical requirements:

- modules have to withstand bake-out at 350°C
- module design needs to be compatible with UHV requirements (10^{-11} mbar)
- exact relative wire position (Δx = 200 μm)
- non-magnetic, non-radioactive, ...

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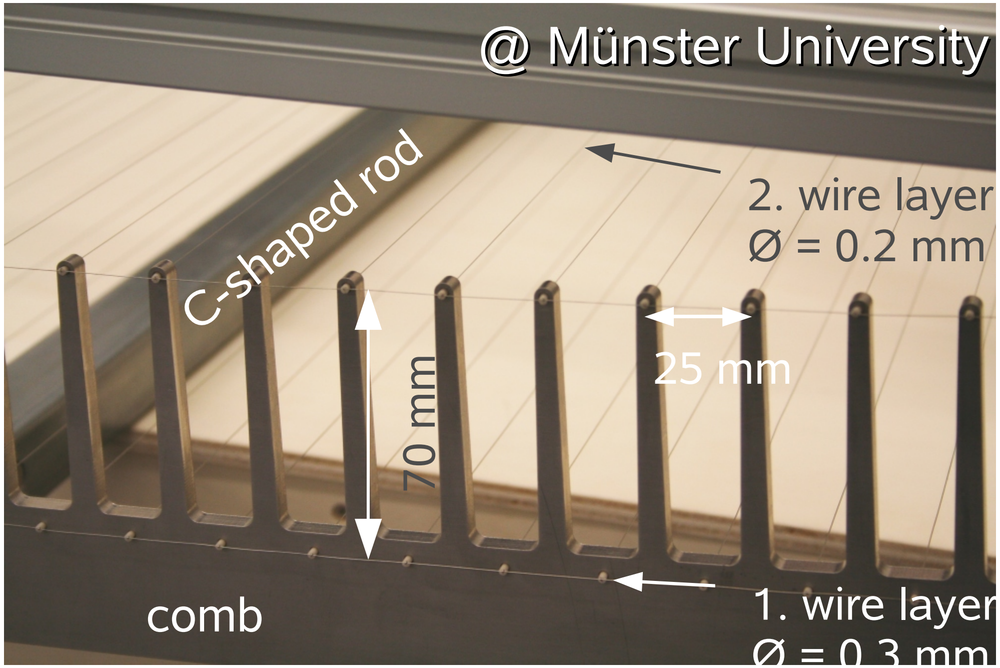
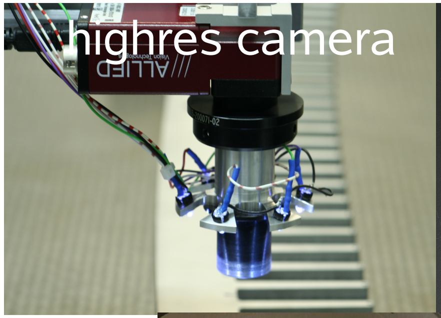
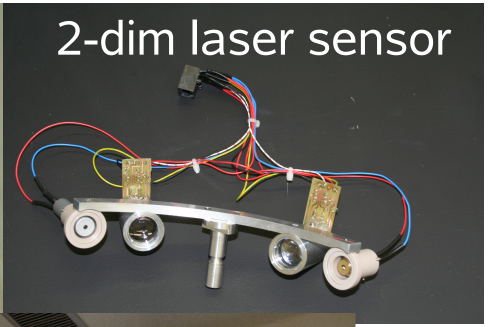
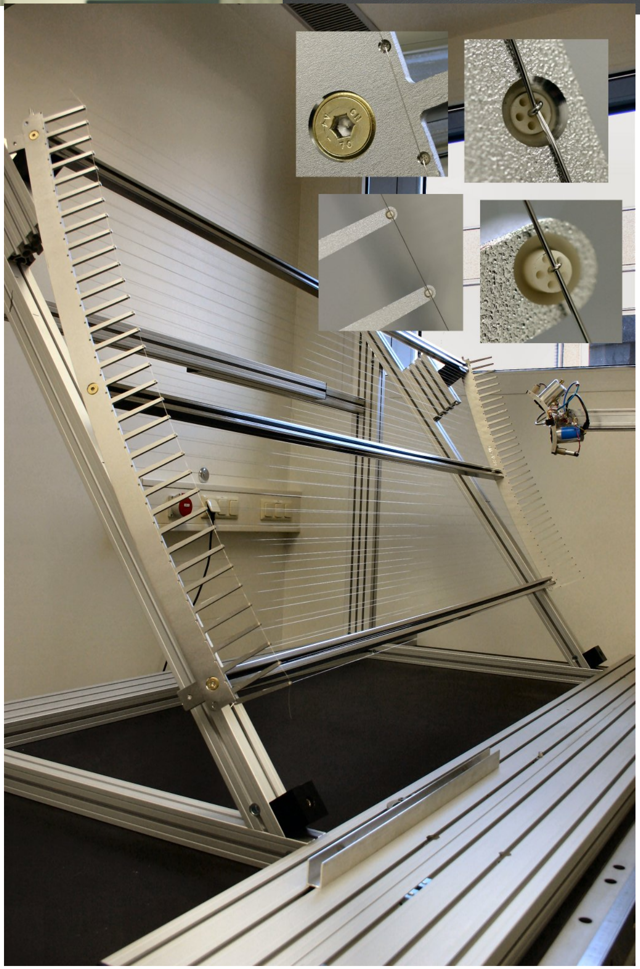
Wire electrode mass production and quality assurance

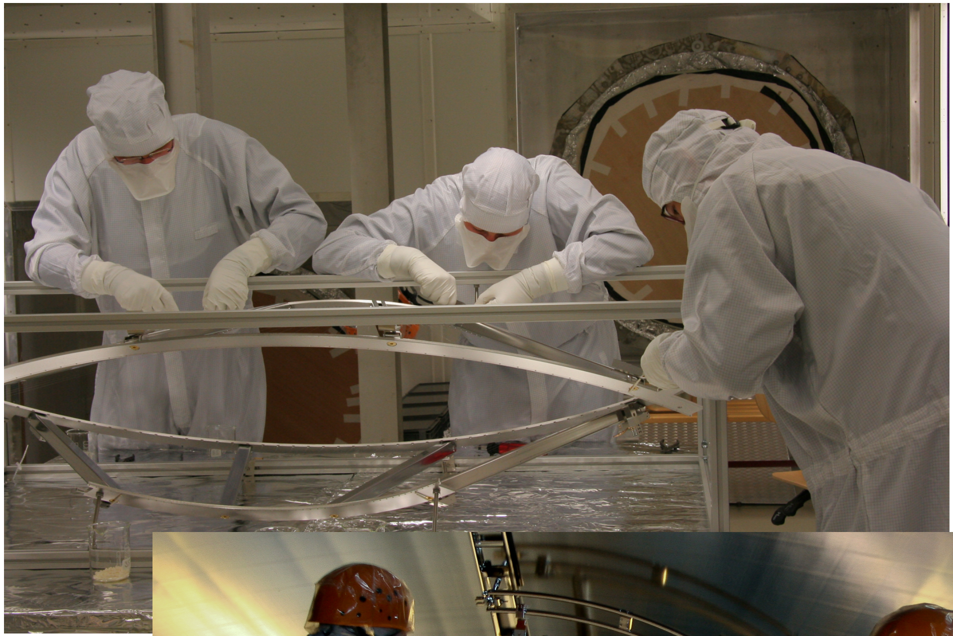


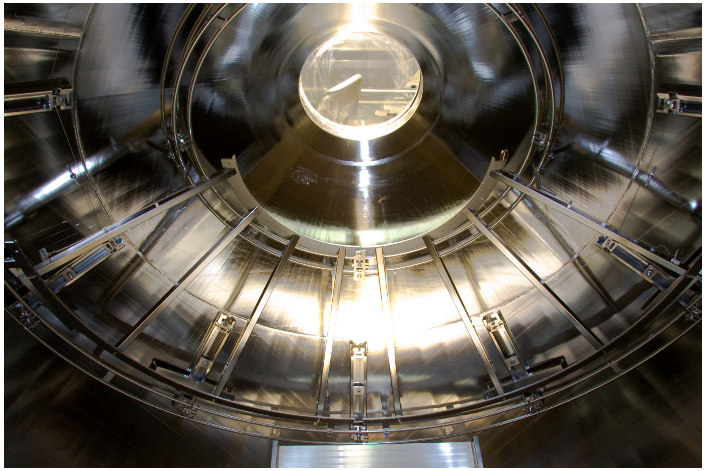






Electrode module installation at the main spectrometer has started





Systematic uncertainties

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

B) Any unaccounted variance σ^2 leads to negative shift of m_ν^2: $\Delta m_\nu^2 = -2\sigma^2$

1. inelastic scatterings of ß´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. transmission function
   - **spatial resolved e-gun measurements**

4. WGTS charging due to remaining ions (MC: ϕ < 20mV)
   - inject low energy meV electrons from rear side, diagnostic tools available

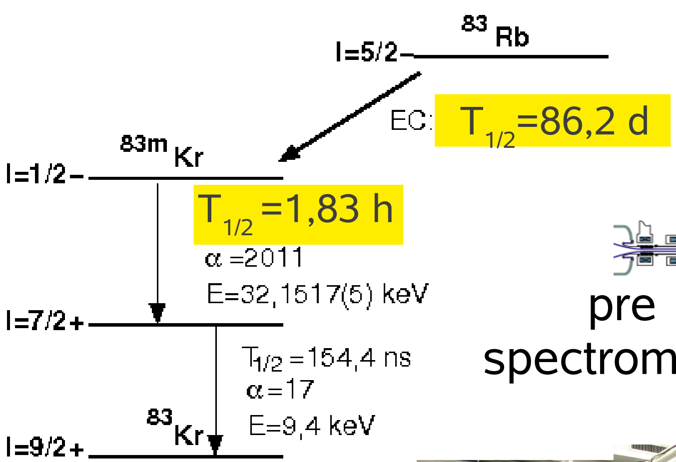
5. final state distribution
   - reliable quantum chem. calculations

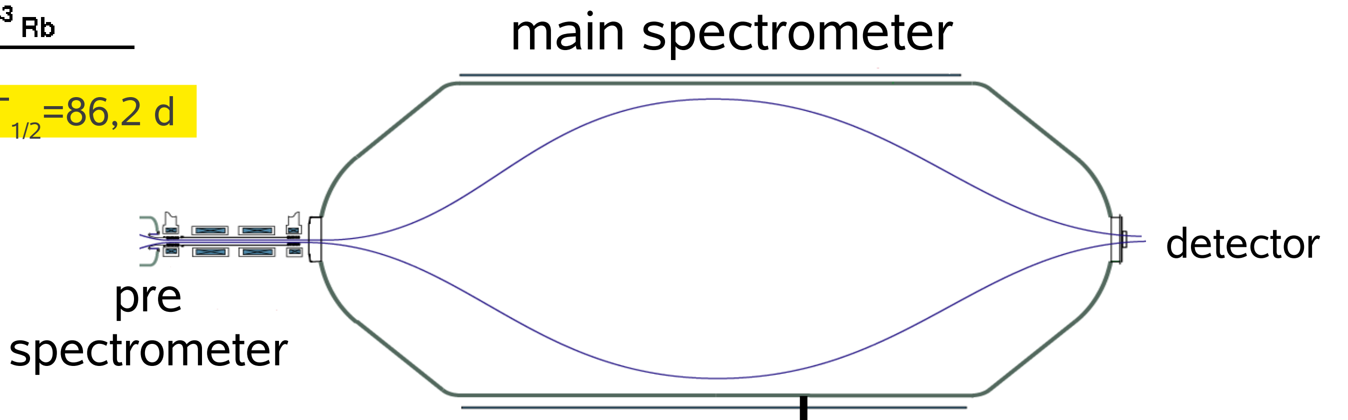
6. HV stability of retarding potential on ~3ppm level required
   - **precision HV divider (PTB), monitor spectrometer beamline**

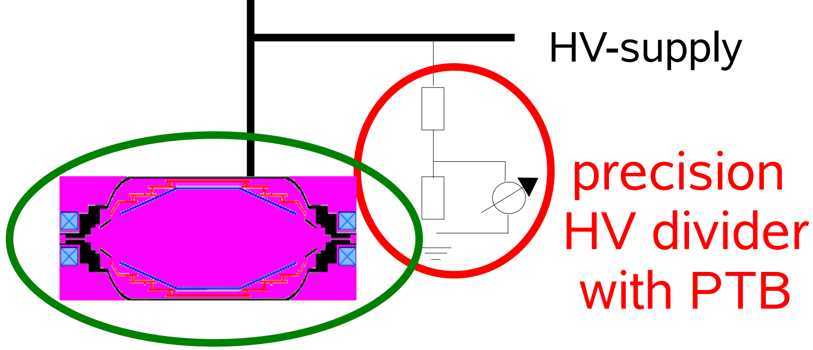
$\Big\}$ a few contributions with $\Delta m_\nu^2 \leq$ 0.007 eV^2 each

Stability of retarding potential / energy calibration: ppm precision at 18.6 kV

- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined electron line with monitor spectrometer

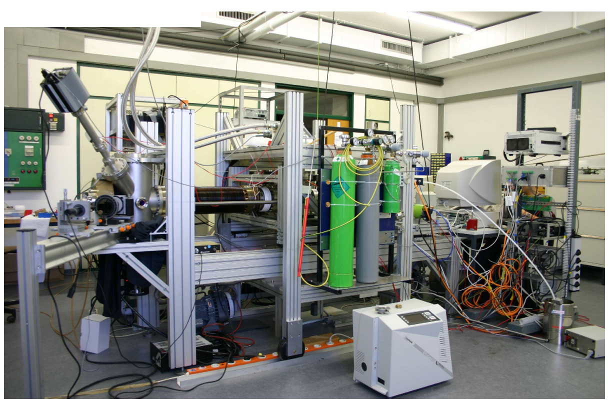




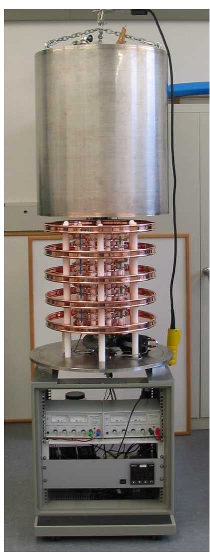


^{83m}Kr conversion electron sources:

- condensed ^{83m}Kr: Münster/Mainz
- ^{83}Rb/^{83m}Kr: Rez/Mainz/Münster/Karlsruhe
- ^{83}Rb production: Bonn, Rez

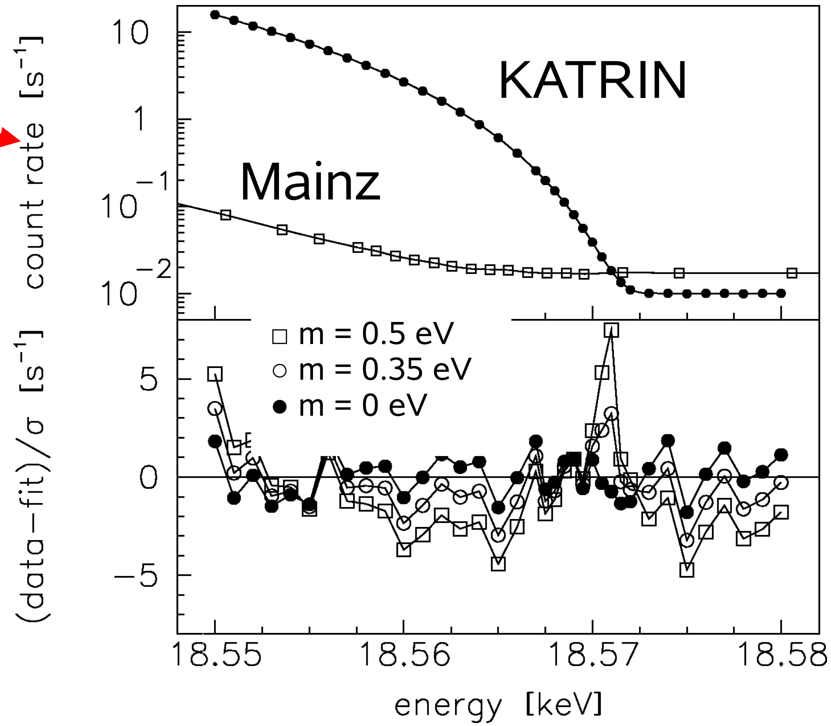


monitor spectrometer = modified Mainz spec.: ΔE=5eV → 1 eV

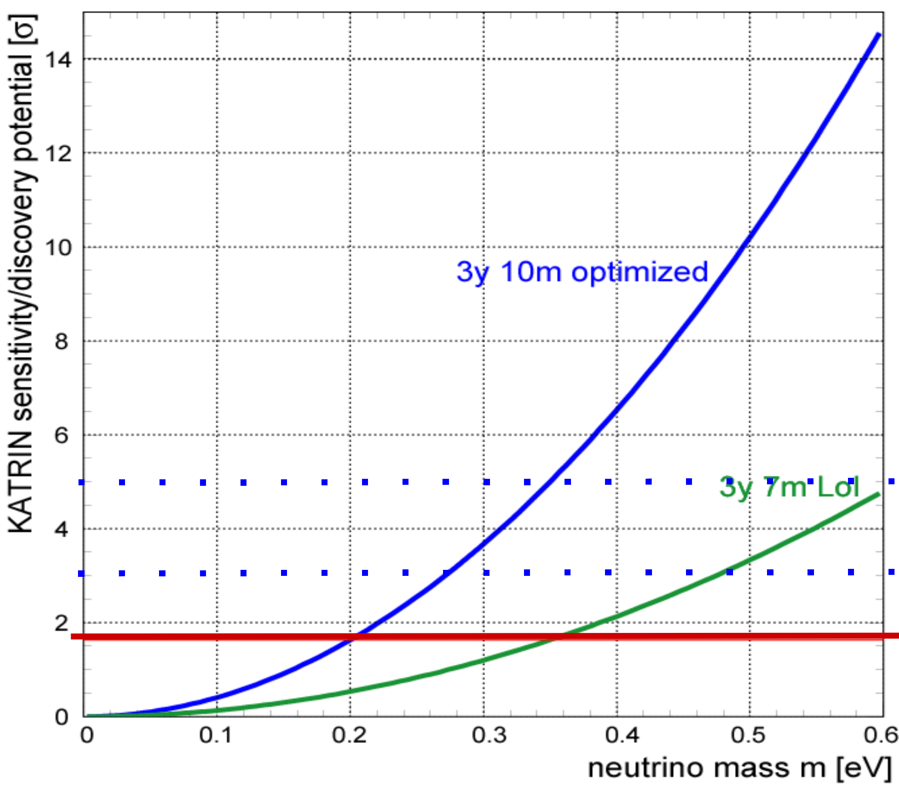


KATRIN´s sensitivity

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



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



discovery potential:

m_ν = 0.35eV (5σ)

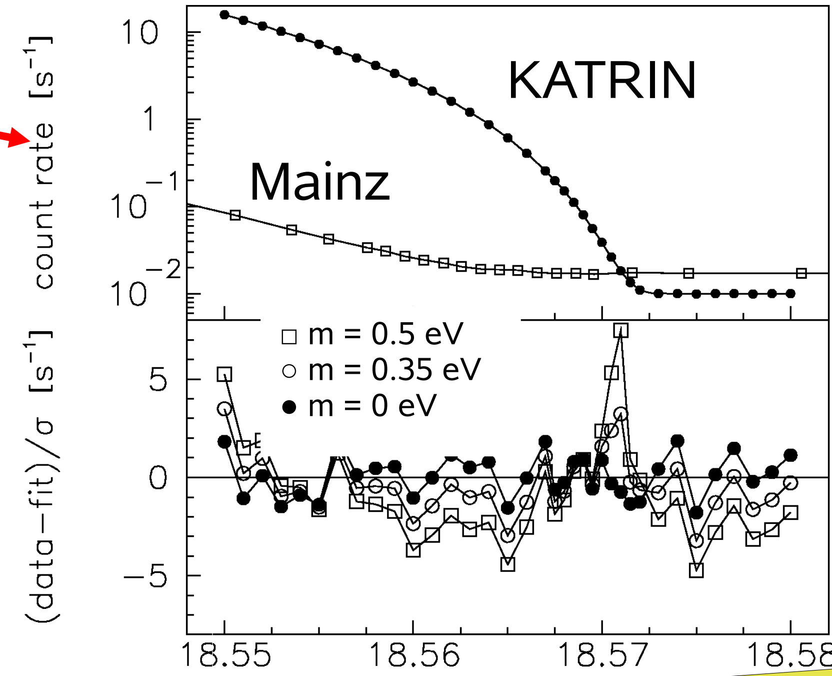
m_ν = 0.3eV (3σ)

sensitivity:

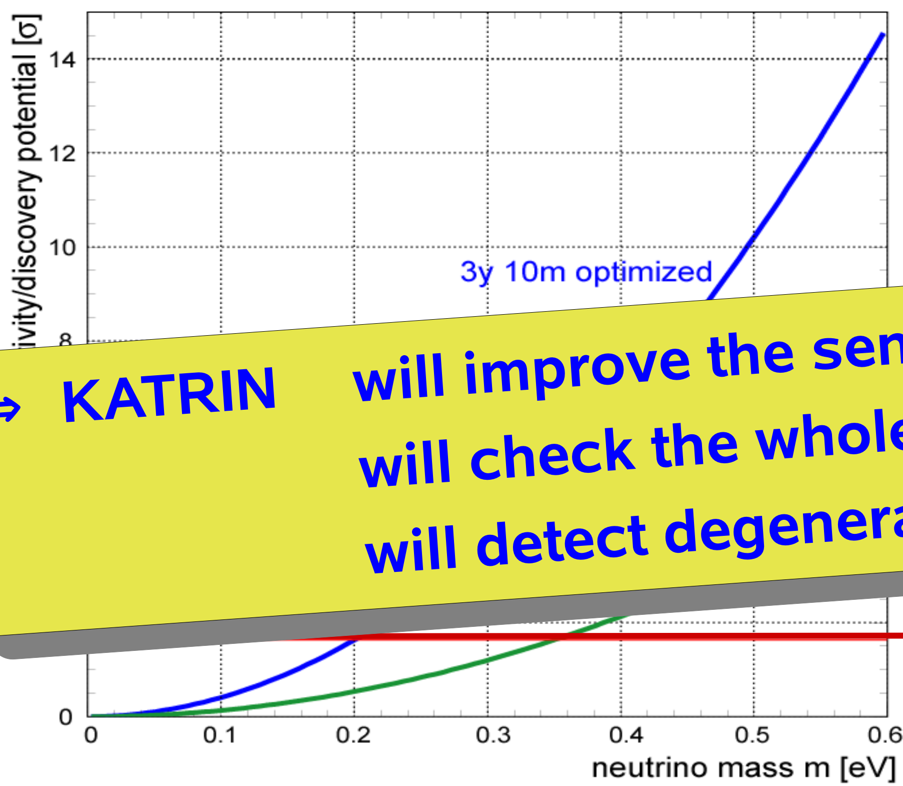
m_ν < 0.2eV (90%CL)

KATRIN´s statistical uncertainty

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



Expectation for 3 full beam 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.)

m_ν = 0.3eV (3σ)

sensitivity:
m_ν < 0.2eV (90%CL)

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Conclusion

3 complementary probes of the neutrino mass:

comosology: very sensitve, but model-dependent

$0\nu\beta\beta$: sensitive to Majorana neutrinos

Majorana phases and nuclear matrix elements

searches for lepton number violation

direct neutrino mass determination:

no other assumptions, kinematics of β-decay at endpoint

KATRIN: 0.2 eV sensitivity:

2009-11 commissioning of main spectrometer and detector

2009-12 commissioning of tritium source and tritium elimination lines

2012- regular data taking for 5-6 years (3 full-beam-years)


KATRIN collaboration of 2009

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung