Searching for the absolute neutrino mass scale

Seesaw25, Paris, 11.06.04

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Search for the neutrino mass scale

Cosmological bounds

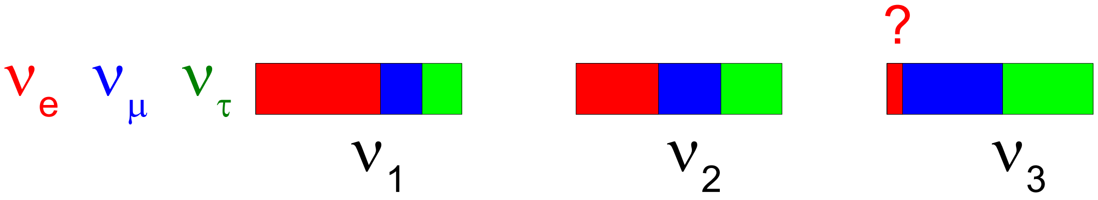
Neutrinoless double β decay

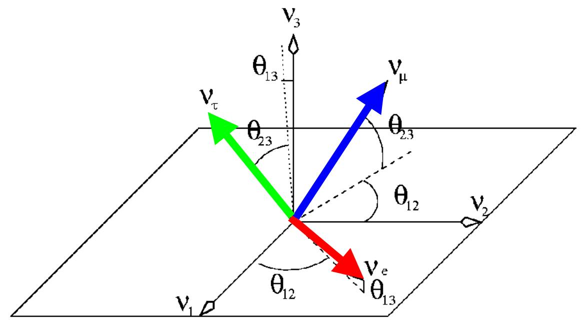
Direct neutrino mass determination

Summary

Absolute ν mass determination

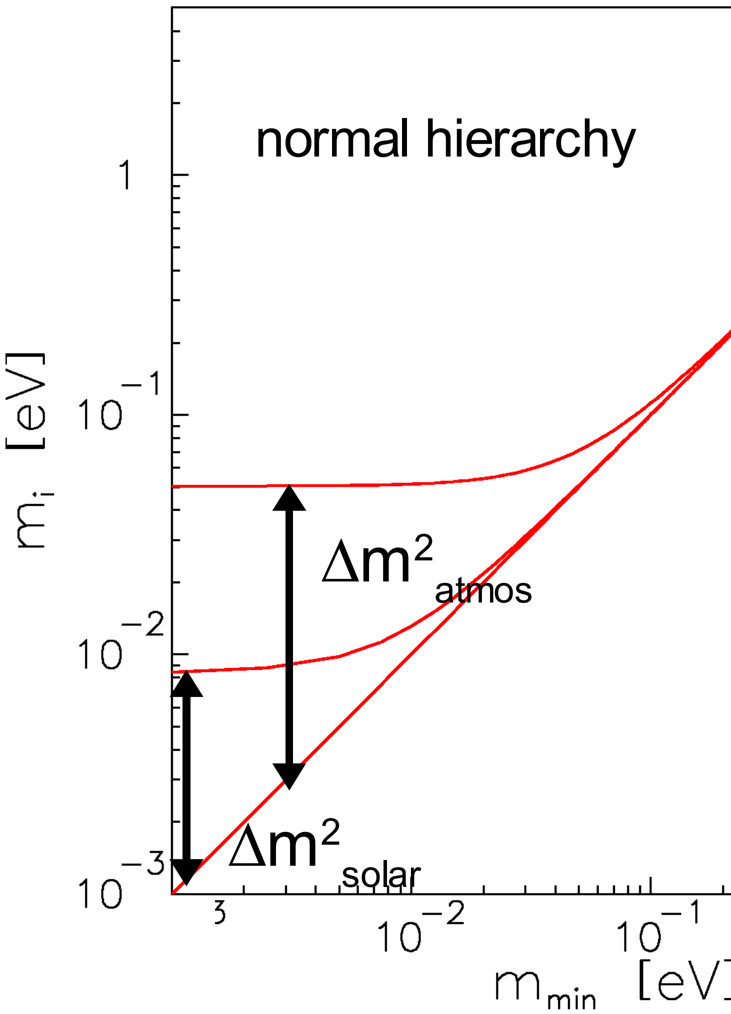
Results of recent experiments: Θ_{23}, Θ_{12}, Δm^2_{23}, Δm^2_{12}

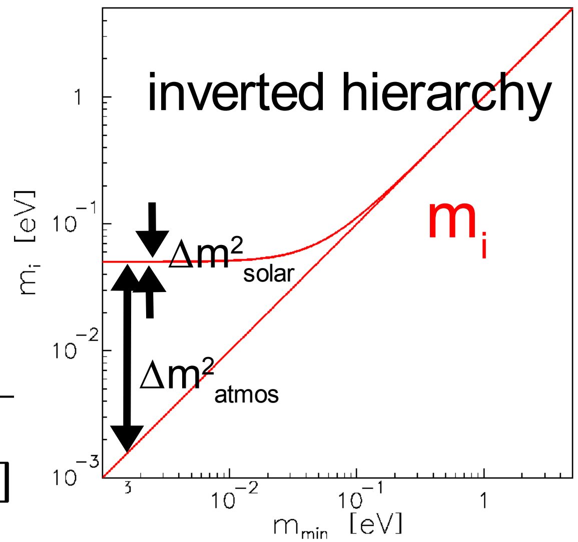




Motivation:

1) distinquish hierarchical and degenerate masses
2) check cosmological relevance (ν hot Dark Matter)





Absolute ν mass determination

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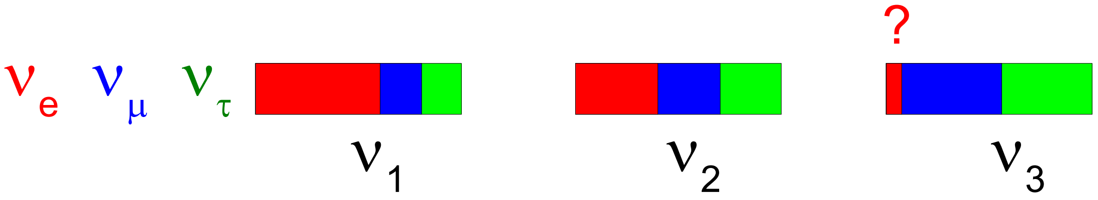

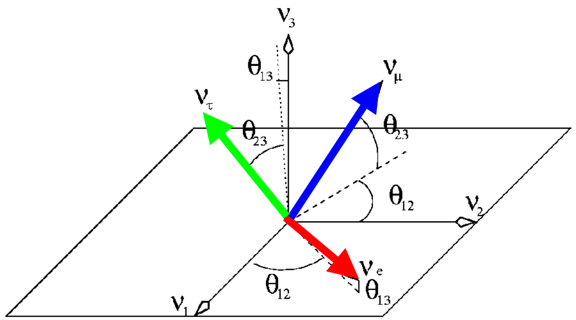

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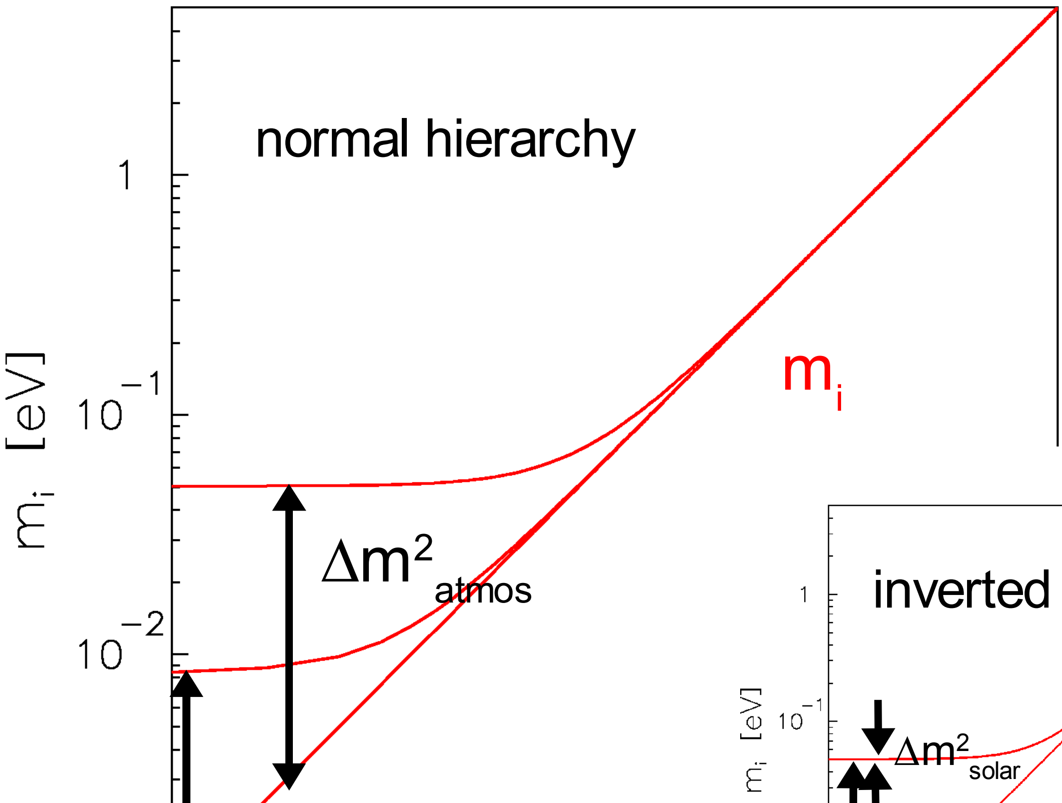
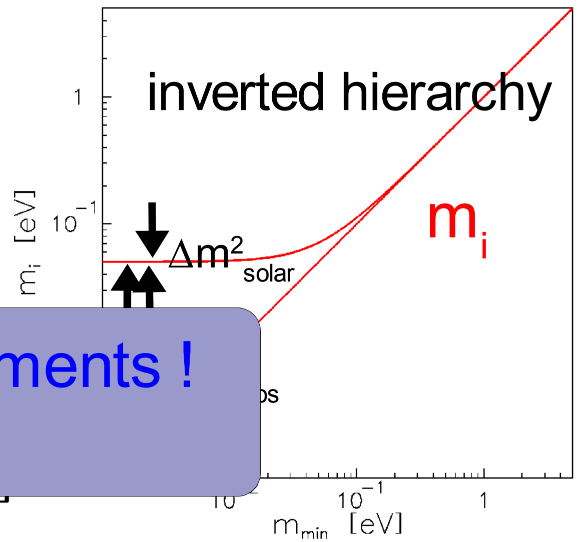


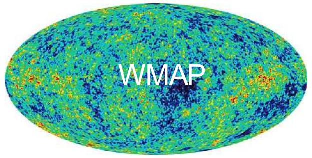


⇒ Cannot be resolved by oscillation experiments !
need absolute neutrino mass scale !

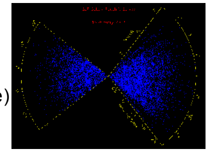
Search for the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent

Neutrino mass from cosmology



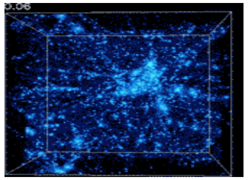
Messung der CMBR
(Cosmic Microwave Background Radiation)

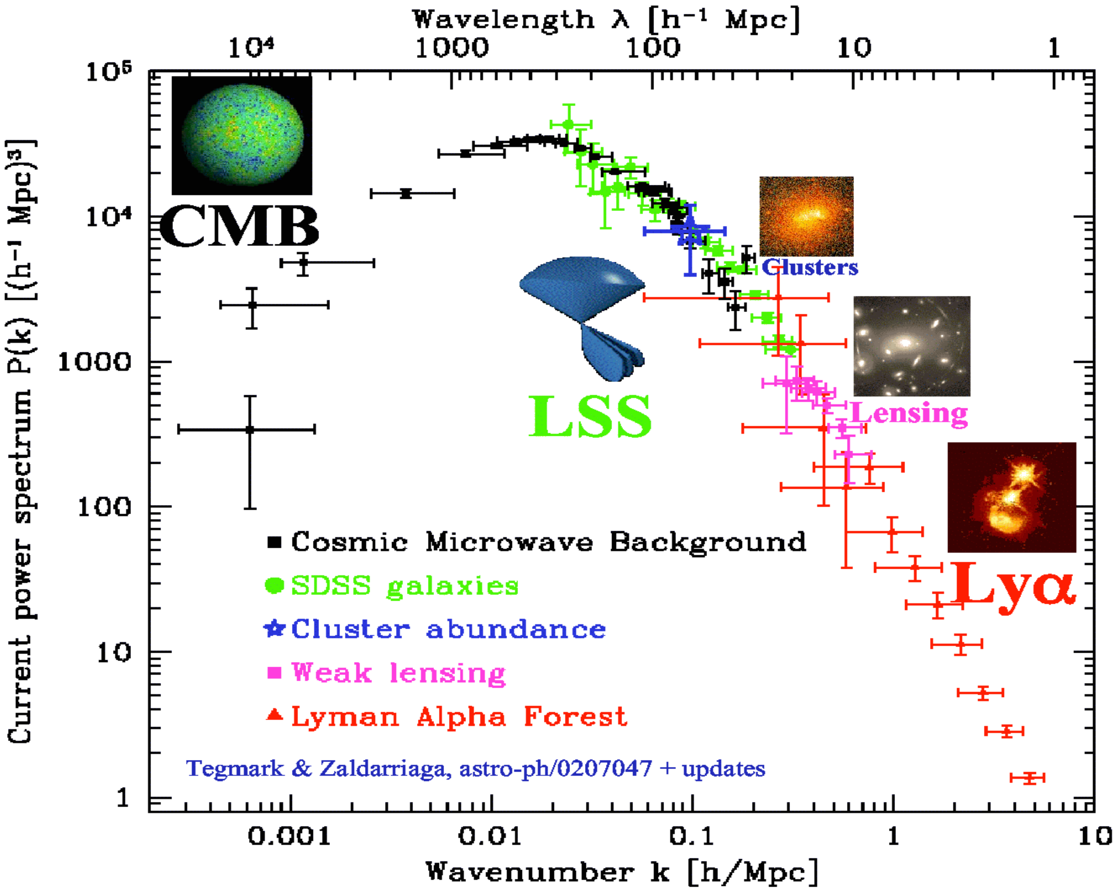


Messung der Materie-
Dichteverteilung
LSS (Large Scale Structure)
2dF, SDSS, ...

Urknalltheorie:
Neutrinodichte im Universum
$n_\nu = 336 / cm^3$

Modell-Entwicklung





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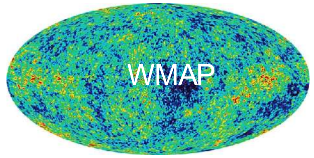

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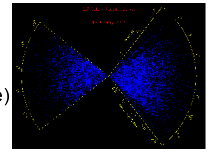

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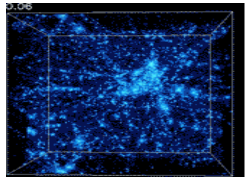
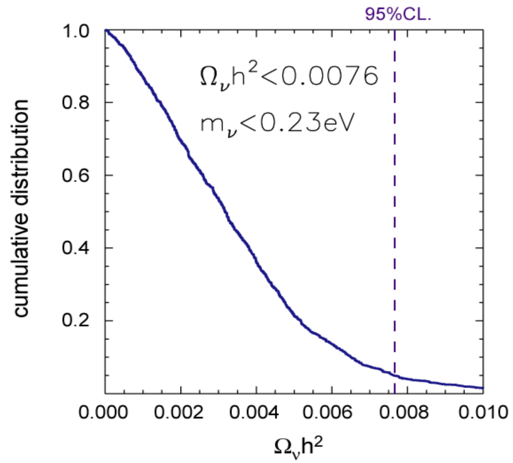


D.N. Spargel et al. (WMAP)

(astro-ph/0302209)

WMAP+ACBAR+CBI+2dFGRS +Lyα Daten

$\Sigma m(\nu_i) < 0.7$ eV →



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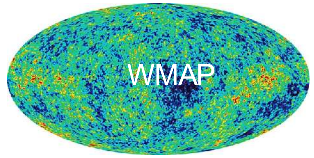

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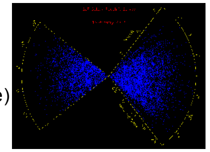

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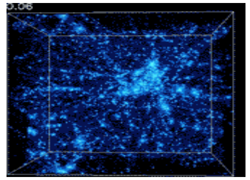

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same data, more conservative asumptions

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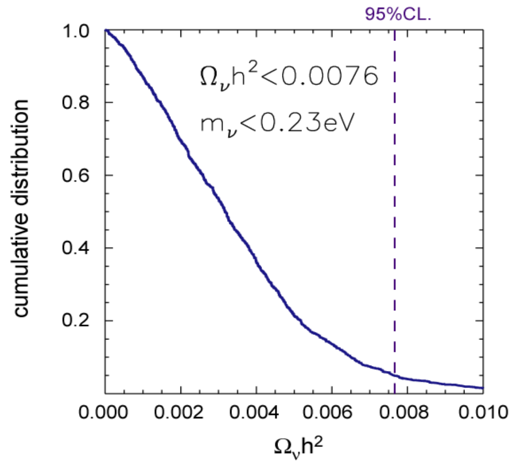

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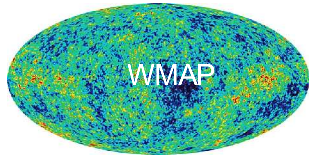

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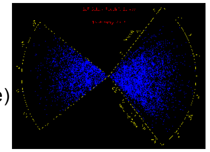

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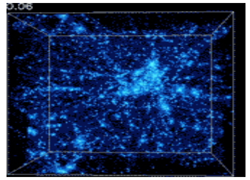

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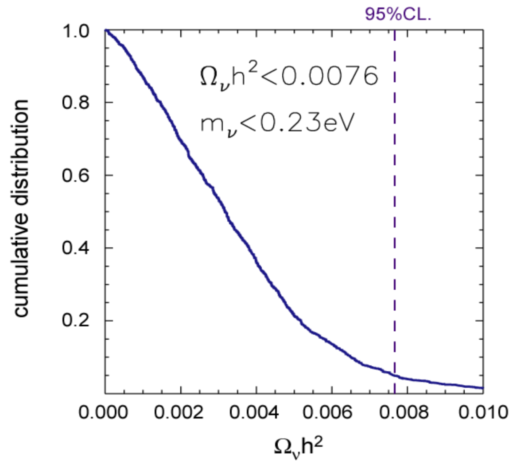

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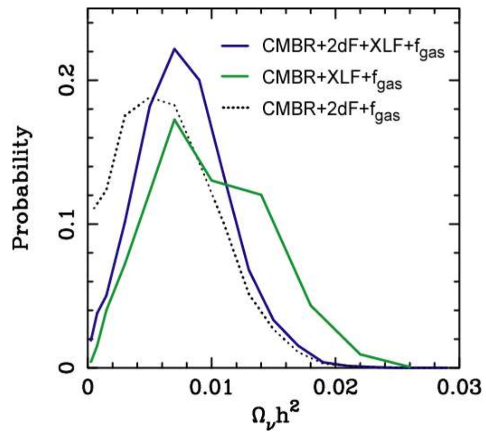
WMAP+2dFGRS

+f_{gas}+XLF (x-ray cluster data) data



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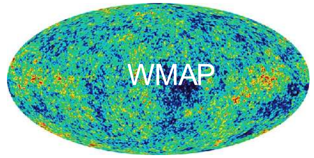

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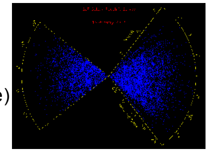

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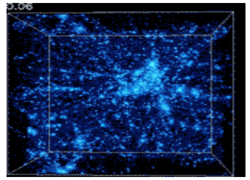

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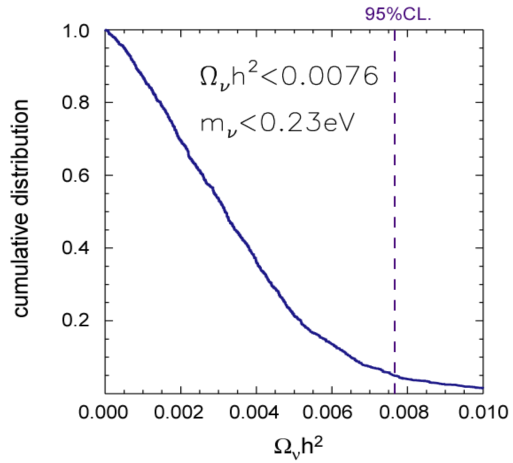

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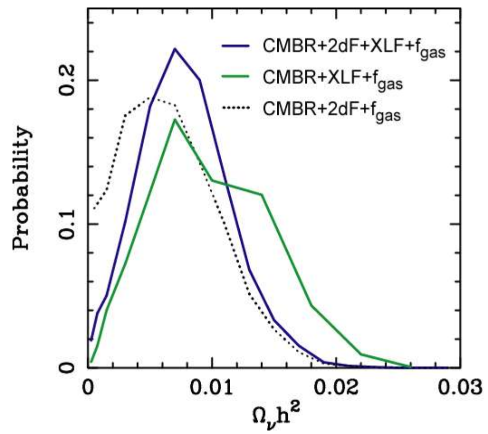
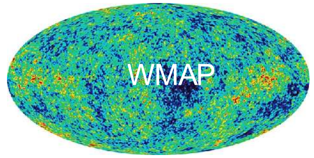


J. Beacom et al. astro-ph/0404585: no upper limit on $\Sigma m(\nu_i)$ from cosmology

neutrino annihilate into light or massless scalars

Neutrino mass from cosmology



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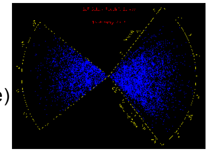
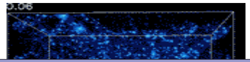
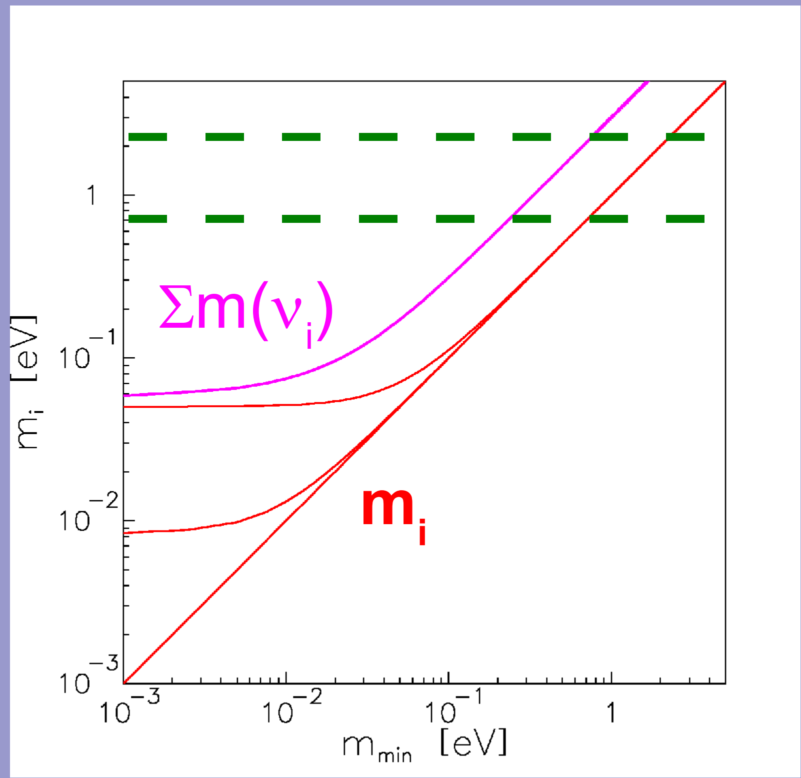


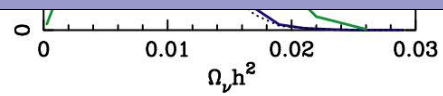


Conclusions:

- neutrinos: hot Dark Matter
- important for
  - evolution of universe
  - intepretation of LSS + CMB
    (correlations with other cosmol. pararameters)
- important quantity: $\Sigma m(\nu_i)$
- model dependent limits:
  $\Sigma m(\nu_i) < 0.7 - 2.2$ eV or
  $\Sigma m(\nu_i) > 0$



need laboatory experiment on absolute neutrino mass



Search for the absolute neutrino mass scale

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very sensitive, but model dependent

Search for the absolute neutrino mass scale

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very sensitive, but model dependent

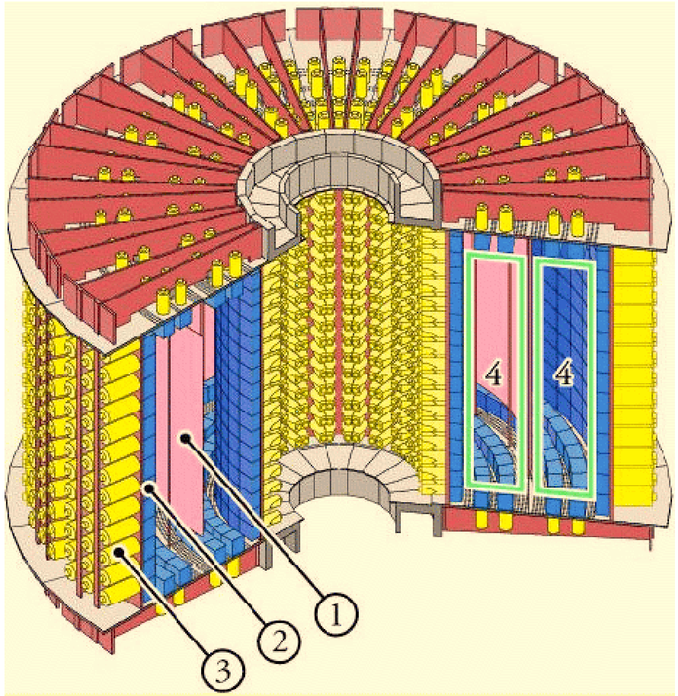
2) Search for $0\nu\beta\beta$

very sensitive, but needs ν to be of Majorana-type

sensitive to coherent sum: $m_{ee}(\nu) = | \Sigma |U_{ei}{}^2| e^{i\alpha(i)} m(\nu_i)|$

$\Rightarrow$ partial cancelation possible

NEMO3 in the Frejus tunnel



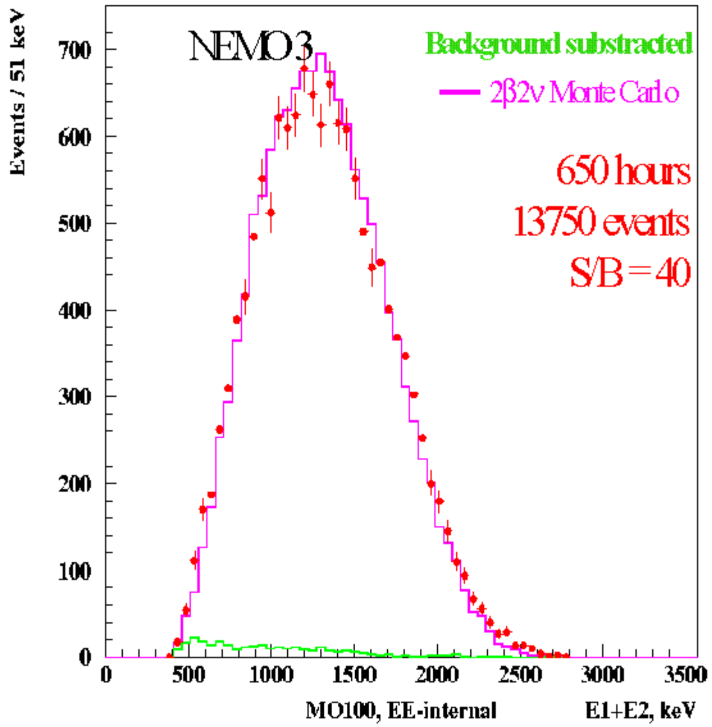
Start of data taking: February 2003

① 20 sectors: foils with ββ emitters
^{100}Mo (7.2kg), ^{82}Se (1kg), ^{116}Cd (0.4kg), ^{130}Te (0.6kg)

② tracking in magnetic field
6180 Geiger cells

③ calorimeter: plastic scintillators

First results on 2νββ of ^{100}Mo →

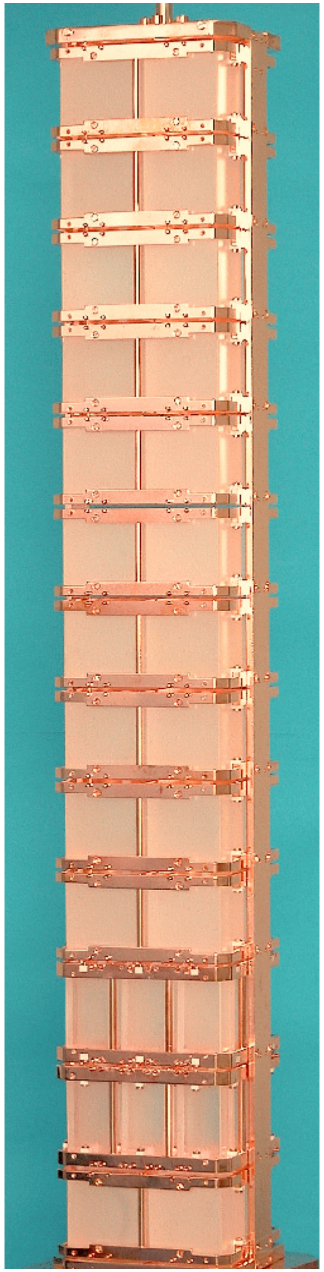


Erpected sensitivity on 0νββ:

^{100}Mo: m_{ee} < 0.1 -0.4 eV

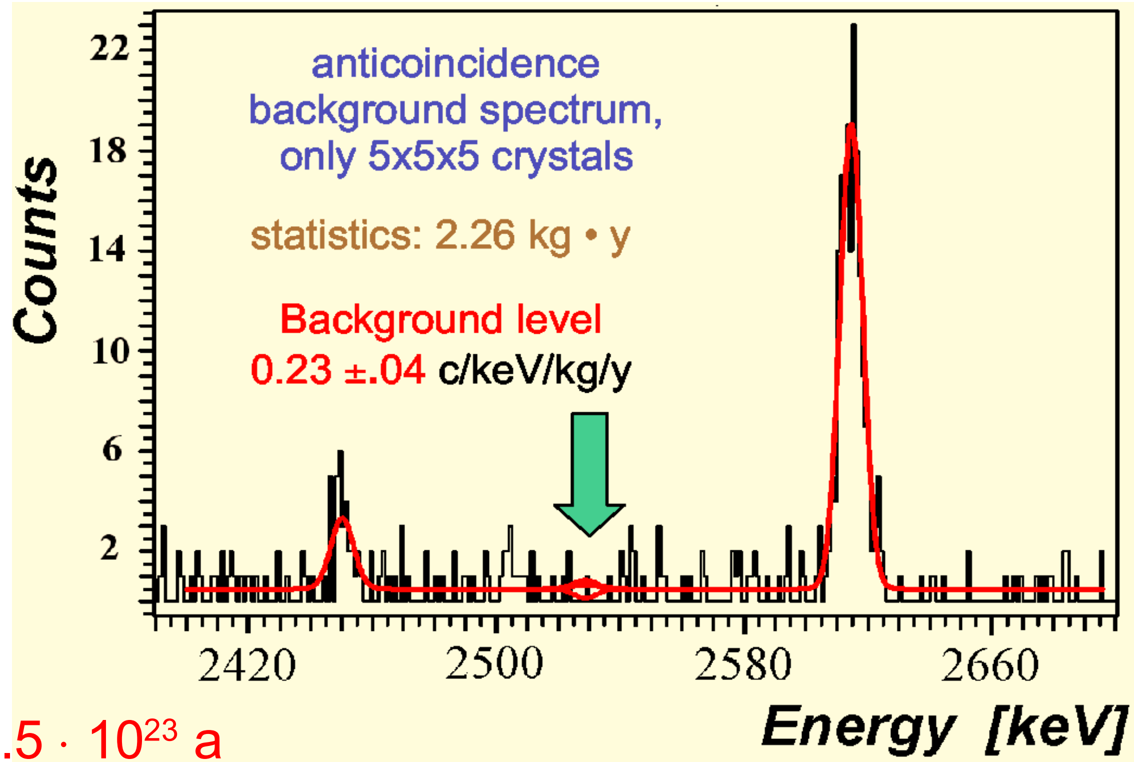
^{82}Se: m_{ee} < 0.6 -1.2 eV

Cuoricino in Gran Sasso



41 kg TeO_2 cryo detectors

data taking since April 2003



$T_{1/2} > 5.5 \cdot 10^{23}$ a

$\Rightarrow$ $m_{ee} < 0.37 - 1.9$ eV (90% C.L.) (PLB584 (2004) 584)

expected in 3 years: $m_{ee} < 0.25 - 0.60$ eV

Evidence for 0νββ at Heidelberg Moscow Exp.?

Klapdor-Kleingrothaus et al., MPLA 37 (2001) 2409
(s.also comments: hep-ex/0202018, hep-ph/0205228, hep-ph/0205293)

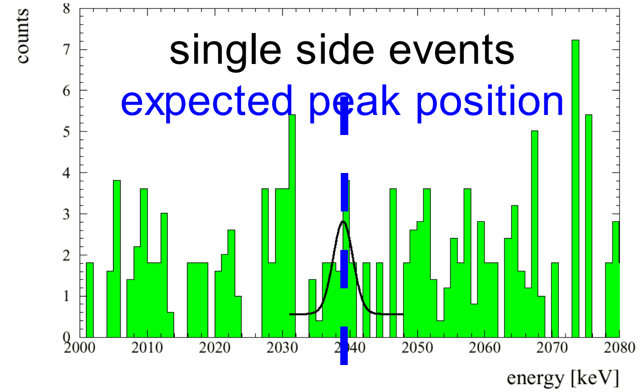
Nearly same data as earlier (54kgy: 8/1990 - 5/2000)

but now asumptions of peaks in [2000,2080] keV:

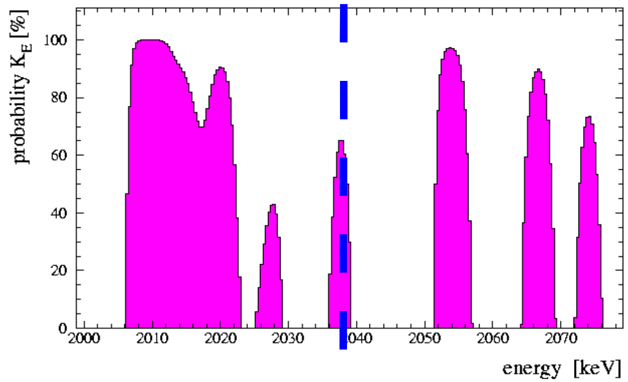
⇒ background level is lower

fit only [2032,2046] keV with background and peak

⇒ peak at 0νββ signal position (2039 keV)



Peak search
Hd Moscow



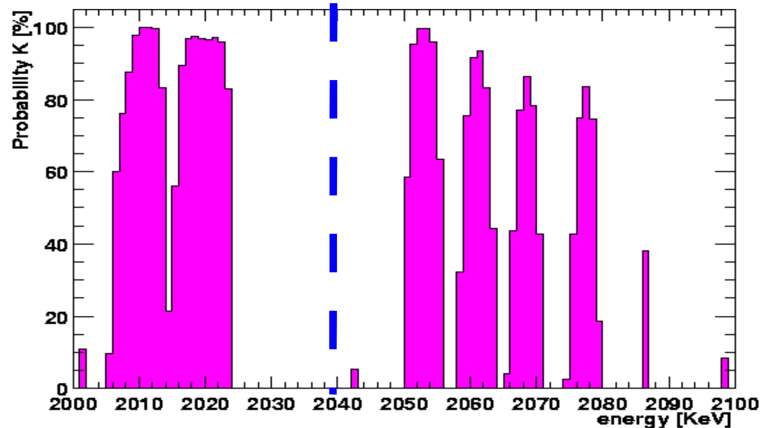
⇒ $T_{1/2}^{0\nu}$ = (0.8 -18.3) 10^{25} y

⇒ m_{ee} = (0.11 - 0.56) eV

⇒ $m(\nu_e)$ = (0.05 - 3.4) eV

⇒ (fast) degenerierte ν ?
(jeweils 95 % C.L.)

Peak search
UCBS
(non-enriched Ge)
all peaks except
signal?



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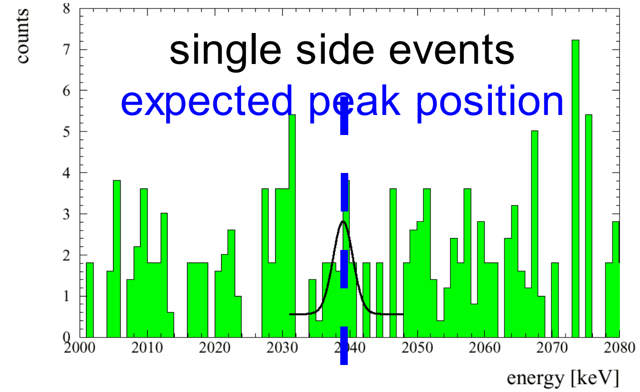
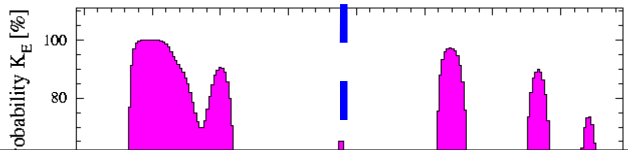


Peak search



New, data up to 2003: 72 kgy,

with new data selection, new calibration

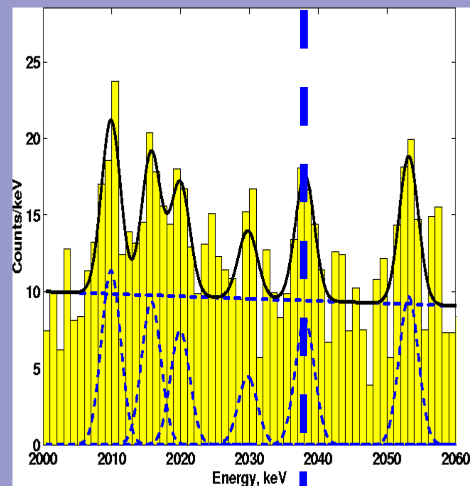
Klapdor-Kleingrothaus et al., PL B586 (2004) 198

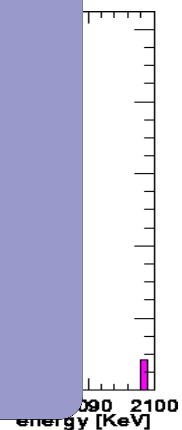
$\Rightarrow$ Peak at 2038.1(5) keV (expected: 2039.006(50) keV)

Multi-Gauss. Fit: 4.2σ significance for 0$\nu\beta\beta$,

$T_{1/2}^{0\nu}$ = (0.34-20.3) 10^{25} y

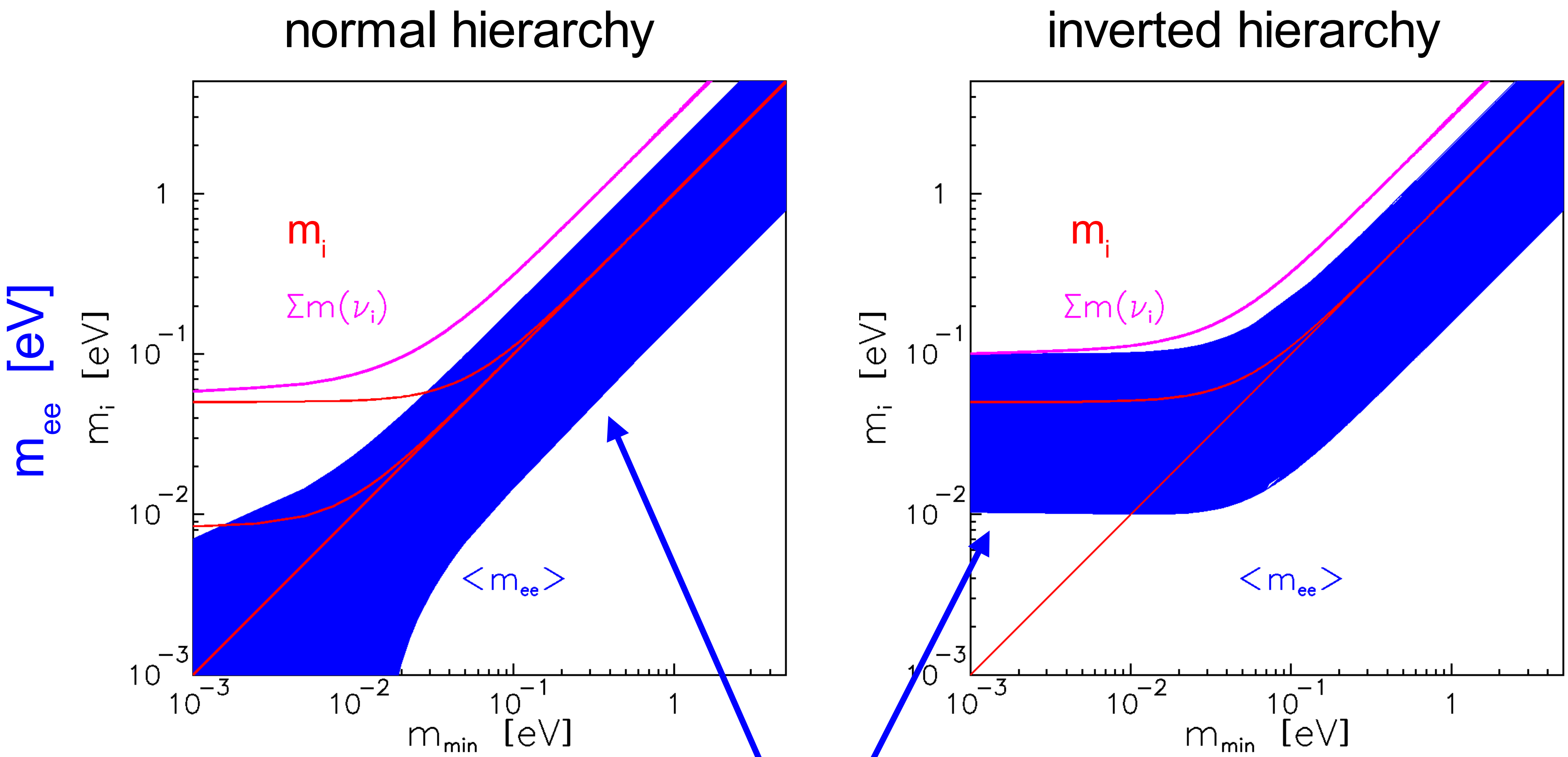
$\Rightarrow m_{ee}$ = 0.1-0.9 eV (99.7% C.L., incl. uncertainty of M_{nucl})





Neutrinoless double β decay and m_ν

Observable: $\langle m_\nu \rangle = \langle m_{ee} \rangle = | \Sigma |U_{ei}{}^2| e^{i\phi(i)} m(\nu_i)|$



Uncertainty: phases $e^{i\phi(i)} = \pm 1$, mixing U ($\Theta_{13} < 13^o$), matrix element $\Delta M_{Kern} / M_{Kern} = \pm 2$

$\Rightarrow$ factor of 10 uncertainty for $\Sigma m(\nu_i)$

plots following F.Feruglio et al., Nucl. Phys. B637 (2002) 345

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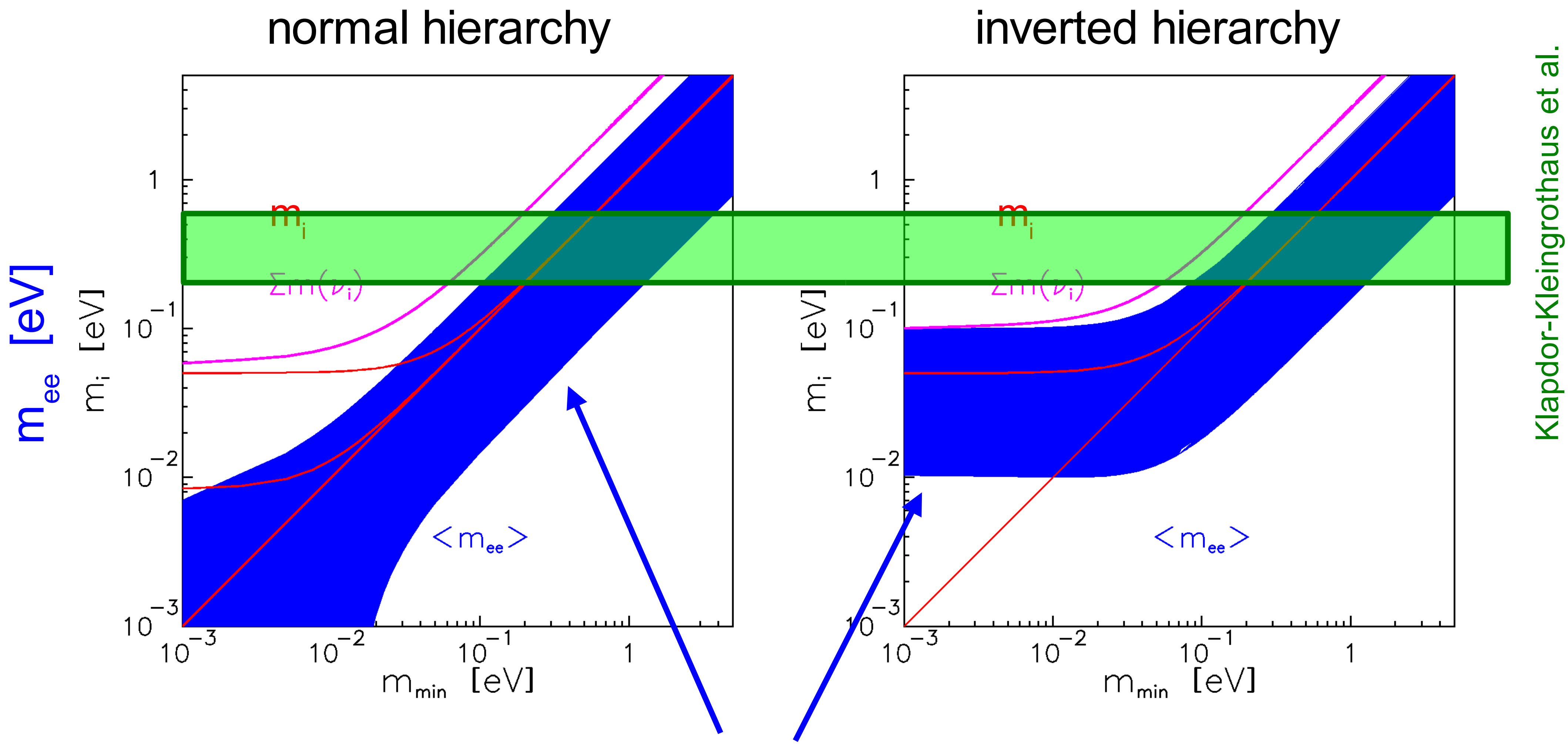

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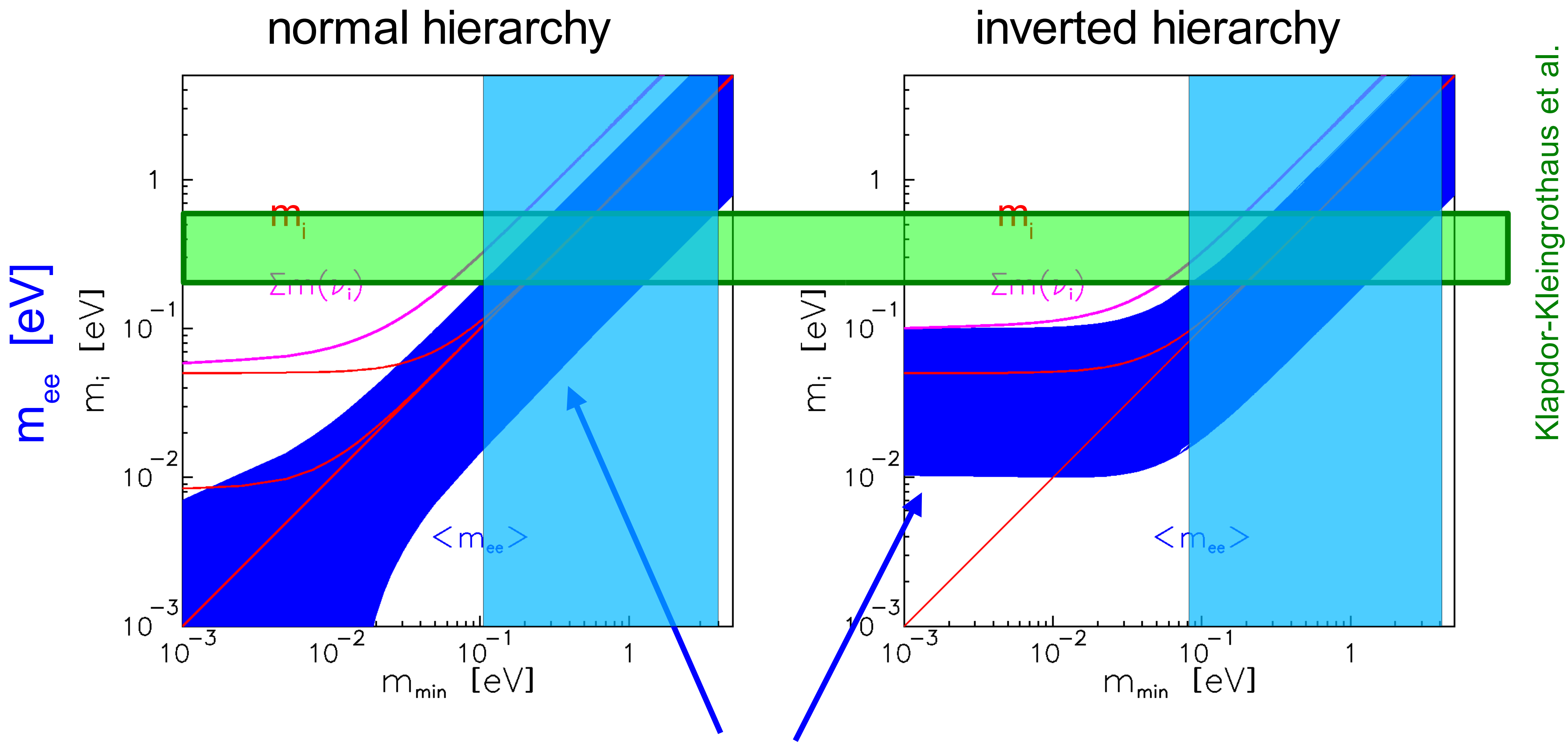

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Future 0νββ projects

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

⇒ mass ≈ 1t, high enrichment, very low background

- GENIUS/New ^{86}Ge ββ exp. at Gran Sasso
  ^{76}Ge, 1t, 86% enriched
  cryo liquid active shielding, GTF started
- Majorana
  ^{76}Ge, 0.5t, 86% enriched
  segmented HPGe diodes with PSA
  prototype under development
- MOON (Japan, USA, Rußland)
  ^{100}Mo, 3.3t, 85% enriched
  foils between tracking detectors and calorimeters
- EXO
  ^{136}Xe, 10t, 75% enriched
  TPC, optical detection of barium ions
- CUORE
  ^{130}Te, 760 kg, 34% natural or enriched
  TeO_2 cryo detectors
- many more proposals
  e.g. Cobra

These experiment expect large background improvements

expected sensitivity on m_{ee}: 10 - 100 meV

Search for the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent

2) Search for $0\nu\beta\beta$
   very sensitive, but needs ν to be of Majorana-type
   sensitive to coherent sum: $m_{ee}(\nu) = | \Sigma |U_{ei}{}^2| e^{i\alpha(i)} m(\nu_i)|$
   $\Rightarrow$ partial cancelation possible

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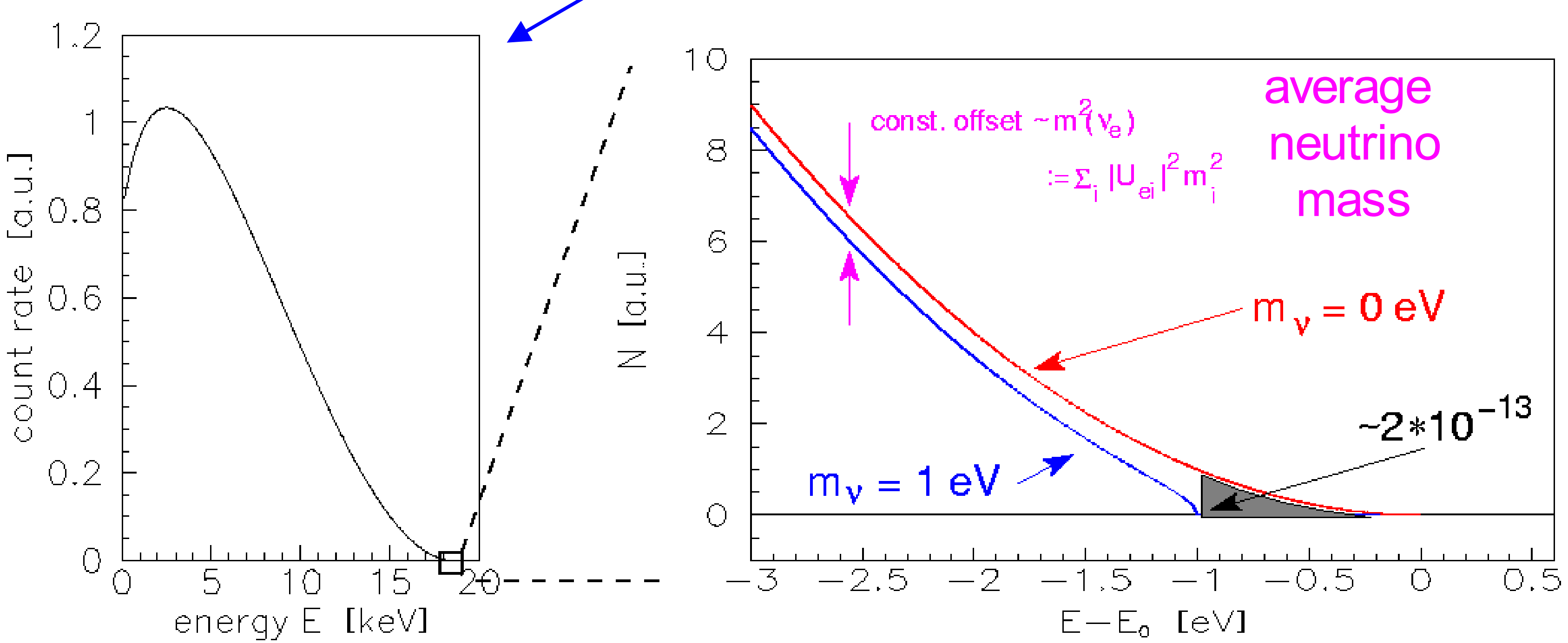
3) Direct neutrino mass determination:
No further assumptions needed
use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly

- **Time-of-flight measurements** (ν from supernova)
  SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 23$ eV (PDG 2002)
- **Kinematics of weak decays**
  measure charged decay products, use energy/momentum conservation $\Rightarrow m^2(\nu)$
  β-decay searchs for $m(\nu_e)$ - tritium β decay spectrometers
  - ^{187}Re bolometers

Direct Determination of $m(\nu_e)$

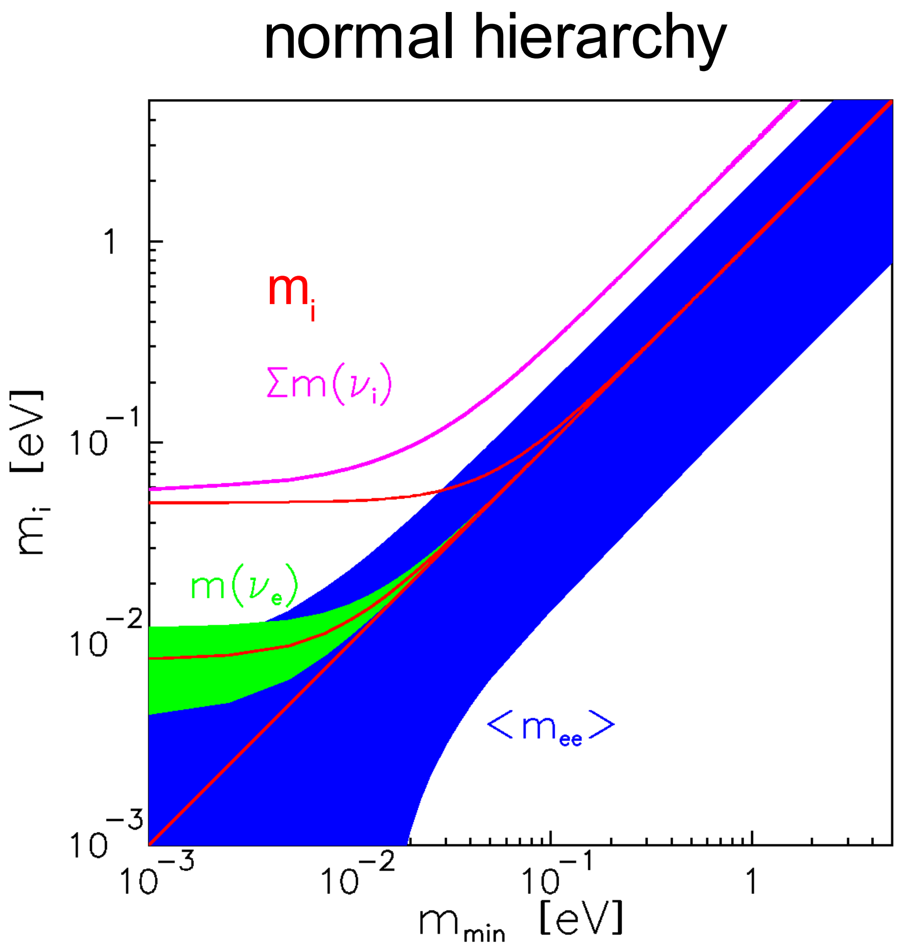
tritium β decay: $^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

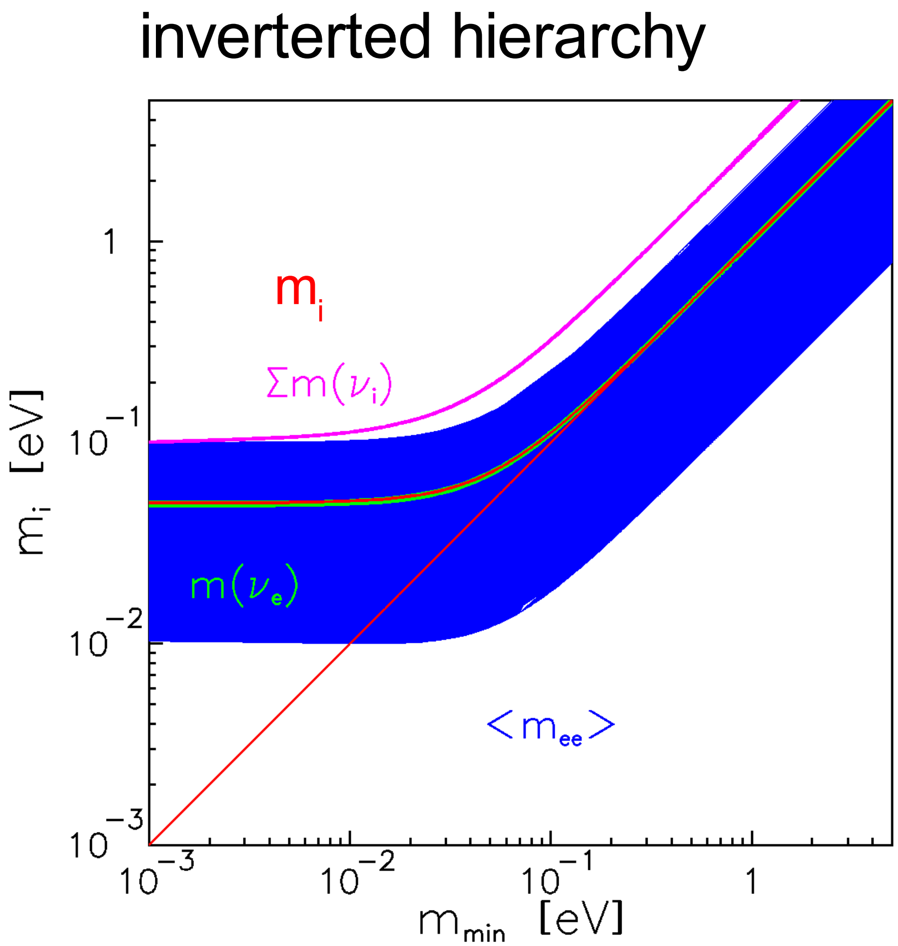
super allowed
$E_0 = 18.6$ keV
$t_{1/2} = 12.3$ a



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

β decay compared to 0νββ





- β decay yields:
  $m^2(\nu_e) := \Sigma|U_{ei}{}^2|\cdot m^2(\nu_i)$, which determines very precisely $\Sigma m(\nu_i)$
- 0νββ experiments might be more sensitive, but they cannot determine $\Sigma m(\nu_i)$ so well
- $m(\nu_e)$ and m_{ee} are complementary observables

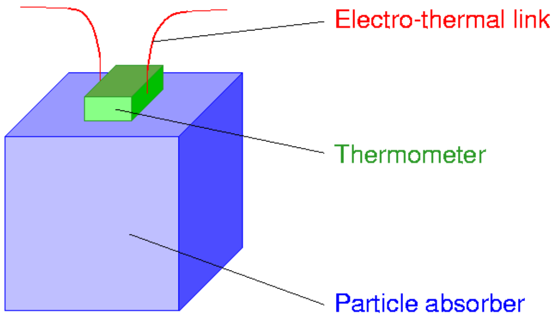
Cryo bolometer experiments with ^{187}Re

Multiple purpose, scalable new detector technology

basic idea: β emitting crystal = cryodetector

⇒ single final state: detection of total energy except ν

Choice of β emitter: ^{187}Re: E_0 = 2.5 keV ($t_{1/2}$ = 5 10^{10}y)



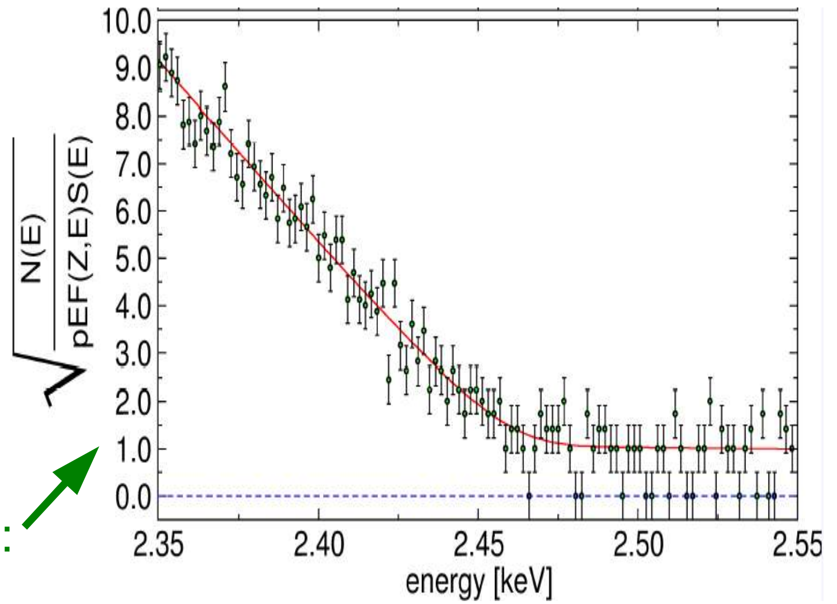
MANU2 (F. Gatti et al., Genua)

- Re metalic crystal (1.5 mg)
- BEFS observed (F.Gatti et al., Nature 397 (1999) 137)
- sensitivity:

  now: m(ν) < 26 eV (.F.Gatti, Nucl. Phys. B91 (2001) 293)

  future: eV resolution by s.c. transition sensors.

  (now typically: ΔE = 30 eV)



MiBeta (E. Fiorini et al., Mailand,Como)

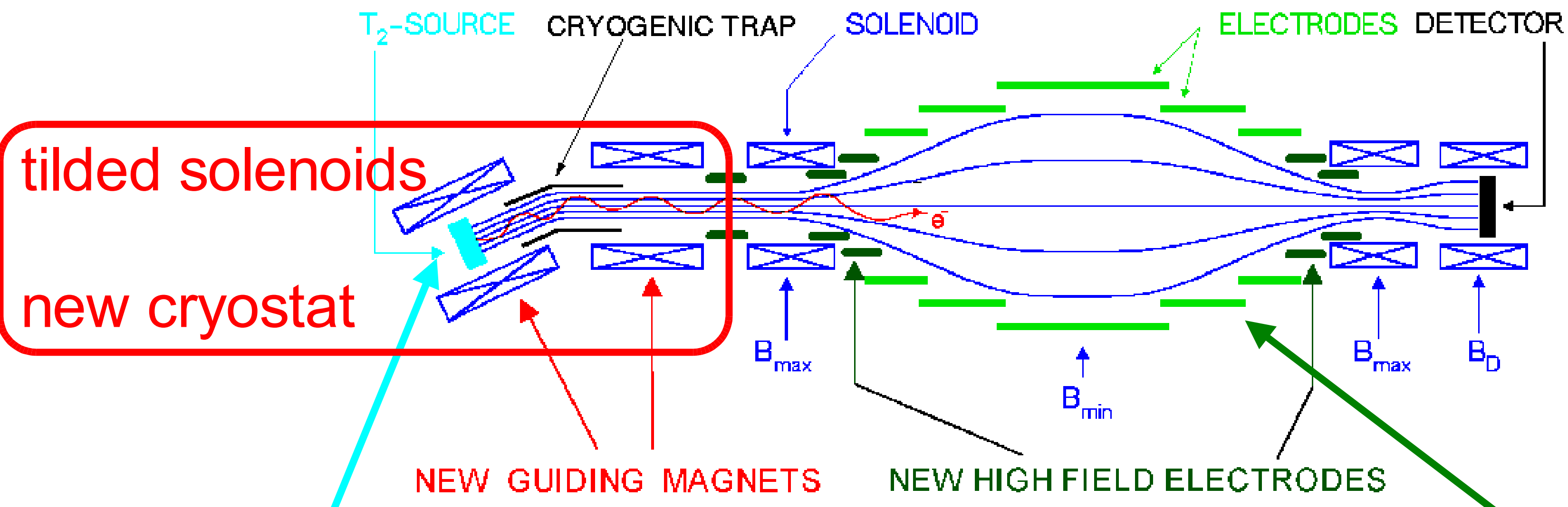
- $AgReO_4$ (10 * 250 -350 mg)
- Final result of Mibeta after 1 year data taking with 10 detectors : (M. Sisti et al., NIMA520 (2004) 125)

  $m_\nu^2 = -112 \pm 207 \pm 90$ eV^2 ⇒ **m_ν < 15 eV (90%CL)**

  β environmental fine structure (BEFS) seen

Future: sensitivity 1 - 10 eV expected need: better resolution + large arrays

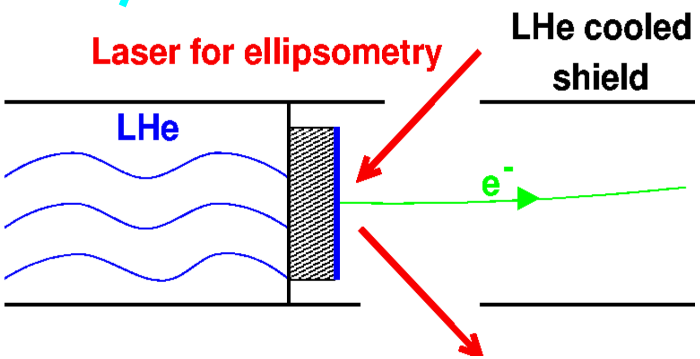
The Mainz Neutrino Mass Experiment 1997-2001

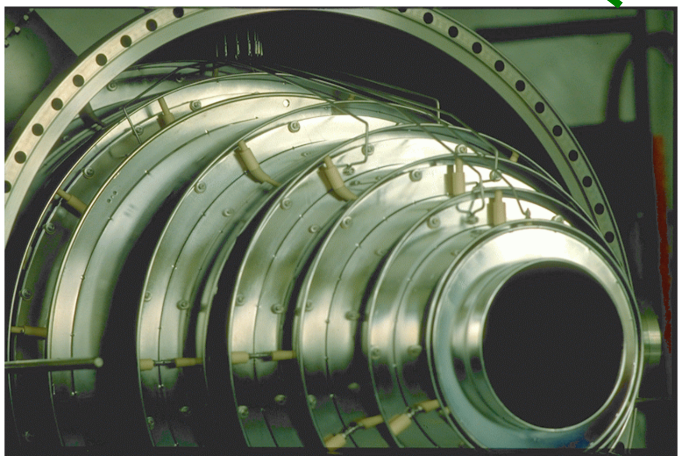


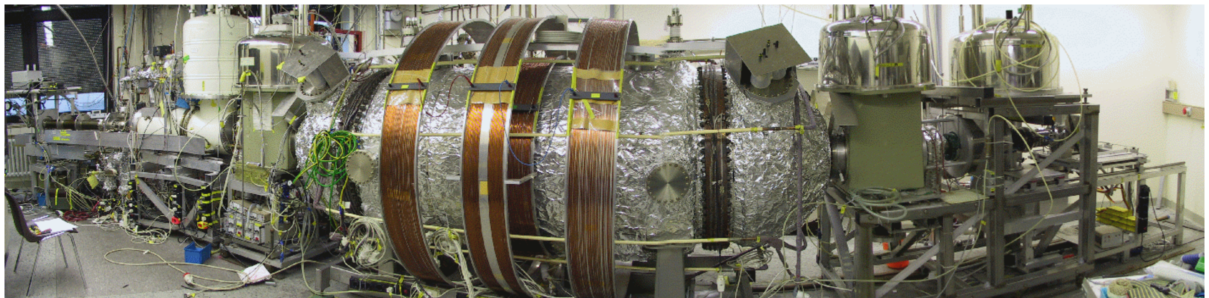
Mainzer
ν-Gruppe
2001:

J. Bonn
B. Bornschein*
L. Bornschein*
B. Flatt
Ch. Kraus
B. Müller**
E.W. Otten
J.P.Schall
Th. Thümmler**
Ch. Weinheimer**

* $\rightarrow$ FZ Karlsruhe
** $\rightarrow$ Univ. Bonn

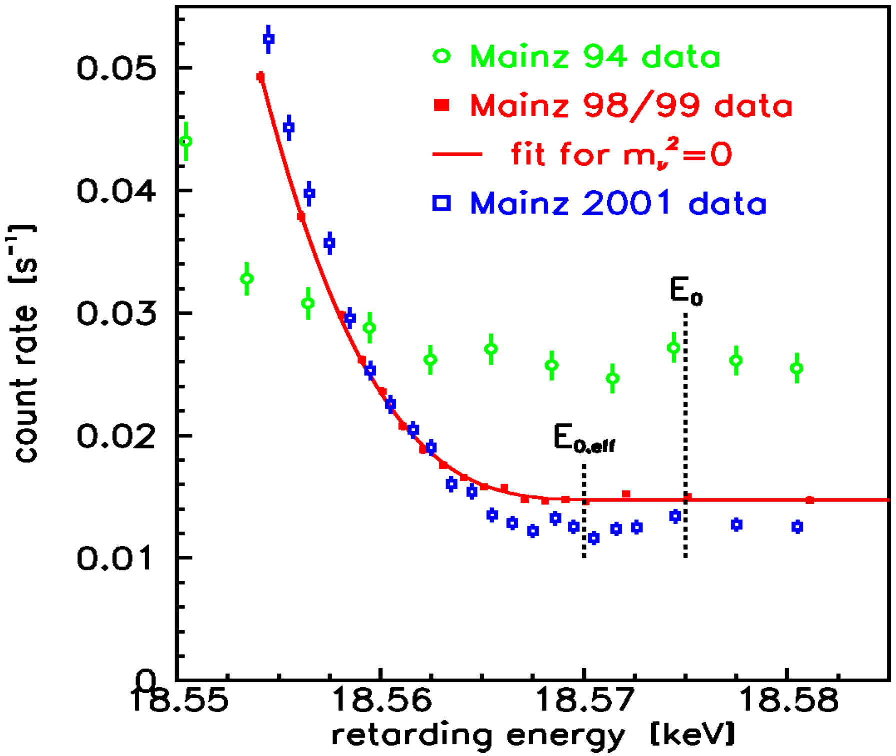






- T_2 film at 1.86 K
- quench-condensed on graphite (HOPG)
- 45 nm thick (≈130ML), area 2cm²
- thickness determination by ellipsometry

Final Mainz result



Improvement of S/Bg by factor 10

Longterm measurements in 1998,1999,2001
(analysed: Σt = 20 weeks)

Stable background: HF pulses on electrode
inbetween single measurements of 20s

Using neighbour excitation from calculation (Kolos et al., Phys. Rev. A37 (1988) 2297)

$m^2(\nu) = -1.2 \pm 2.2 \pm 2.1$ eV^2 $\Rightarrow$ $m(\nu) < 2.2$ eV (95% C.L.)

Ch. Weinheimer, Nucl. Phys. B (Proc. Suppl.) 118 (2003) 279, C. Kraus et al., Nucl. Phys. B (Proc. Suppl.) 118 (2003) 482

Neighbour excitation amplitude from own tritium β spectrum

$m^2(\nu) = -0.7 \pm 2.2 \pm 2.1$ eV^2 $\Rightarrow$ $m(\nu) < 2.3$ eV (95% C.L.)

C. Kraus, EPS HEP03, Aachen, July 2003

final publication will come soon:C. Kraus et al.

The Karlsruhe Tritium Neutrino experiment KATRIN

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

(Letter of Intent: hep-ex/0109033)

KATRIN
Karlsruhe Tritium Neutrino Experiment

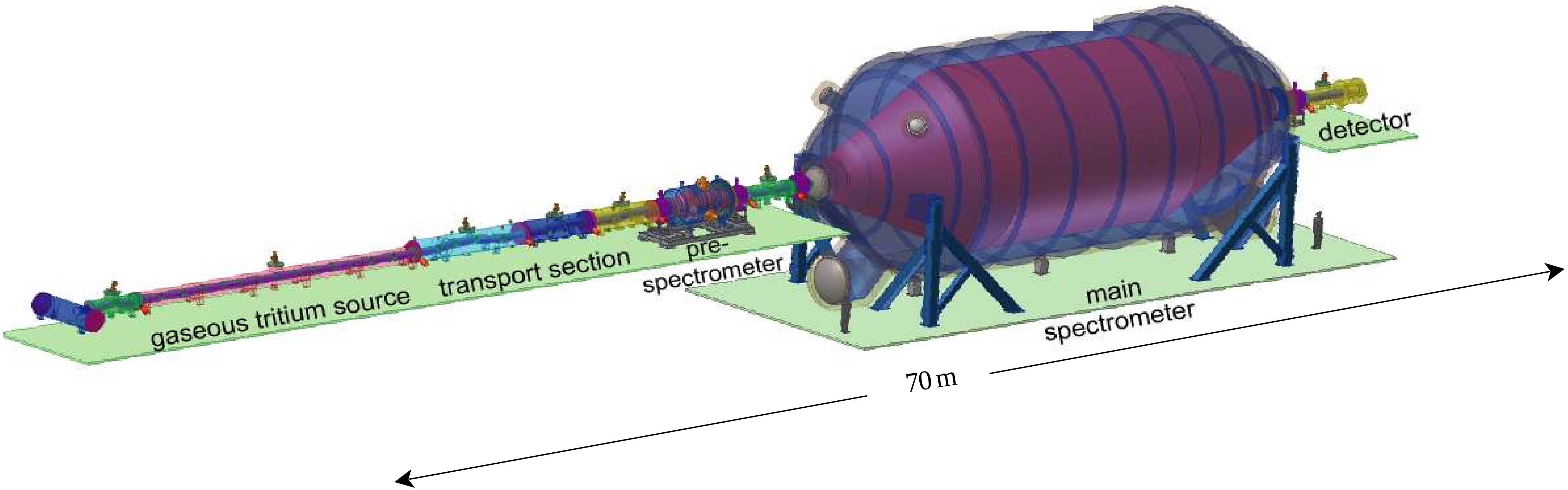
Physics Aim:

Sensitivity on neutrino mass scale: $m(\nu) << 1\,\text{eV}$

new, since 12/2002

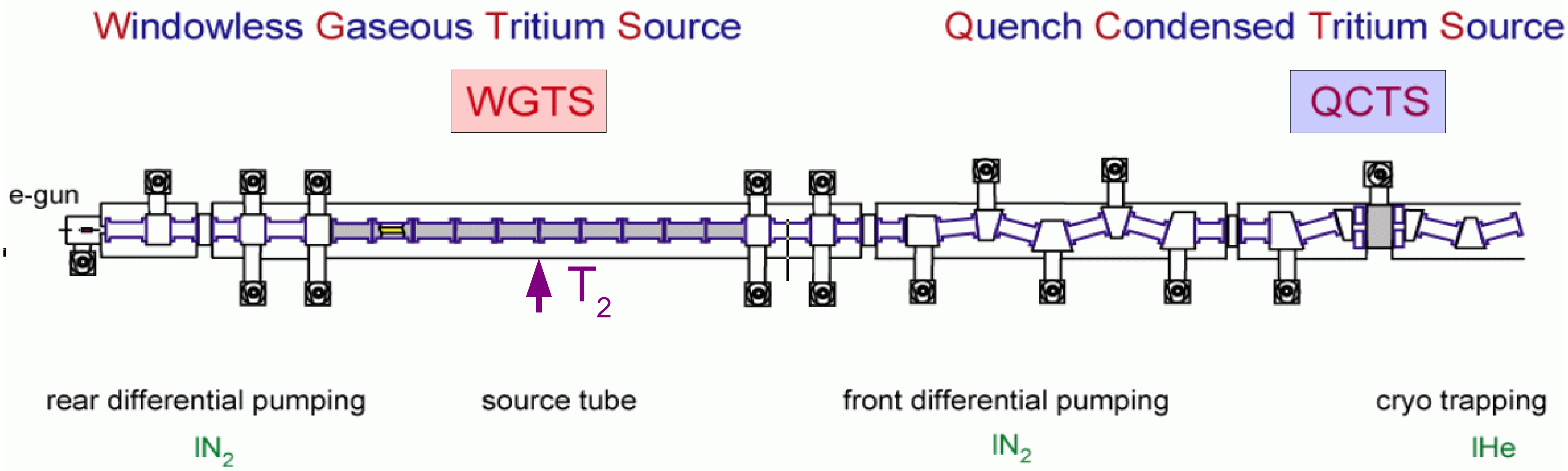
- higher energy resolution: $\Delta E \approx 1\,\text{eV}$
  since $E/\Delta E \sim A_{\text{spectrometer}}$ $\Rightarrow$ larger spectrometer
- relevant region below endpoint becomes smaller
  even less count rate $dN/dt \sim A_{\text{spectrometer}}$ $\Rightarrow$ larger spectrometer

} $\varnothing$10m



Molecular tritium sources

Standard source: Alternative Source:



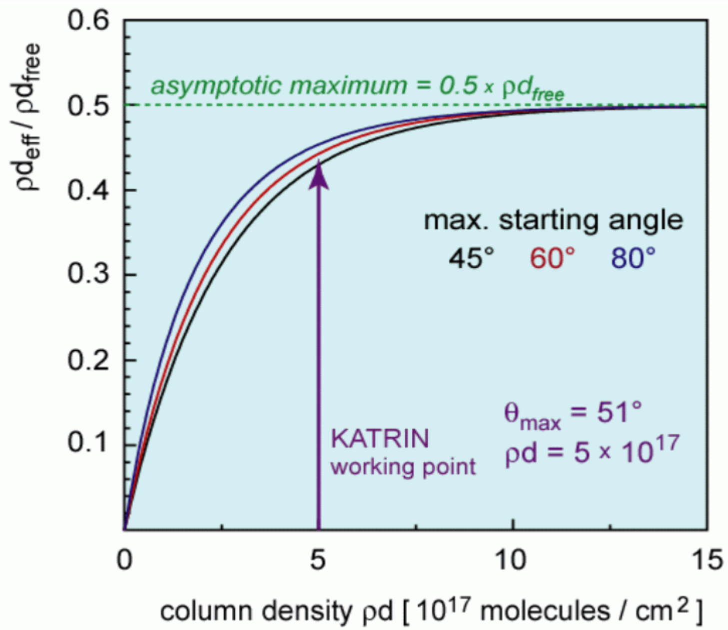
WGTS: ∅ 9cm, length: 10m, T = 30 K

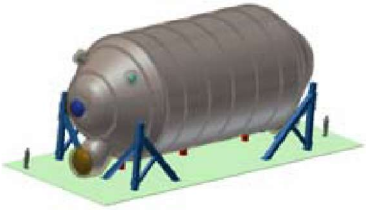
allows to measure with near to maximum count rate using $\rho d = 5 \cdot 10^{17}/cm^2$

with small systematics

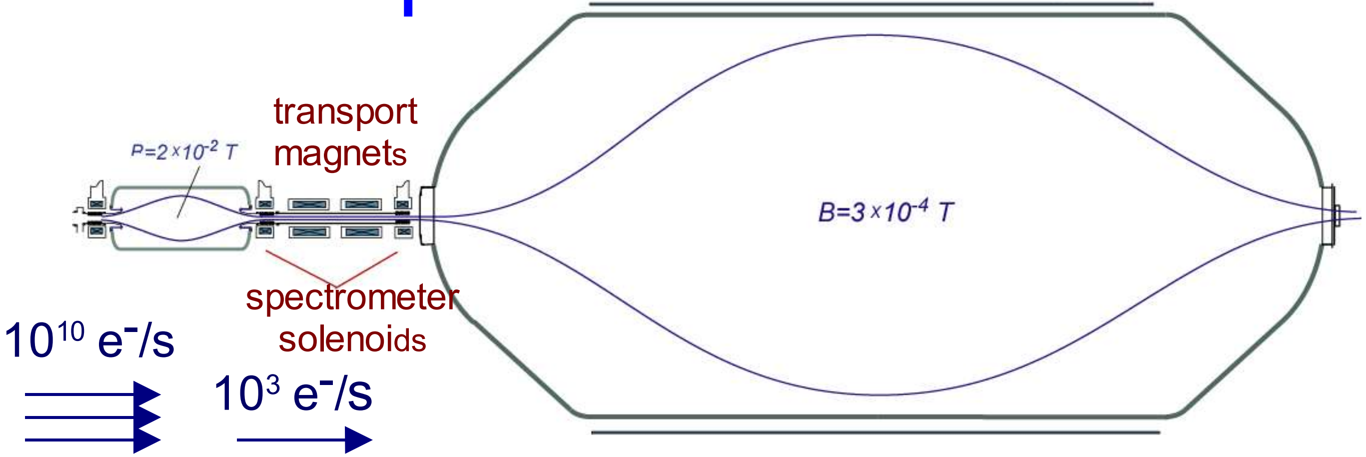
QCTS: ∅ 8cm, T=1.6 K, d = 35 nm

presently limited by self-charging





Pre and main spectrometer



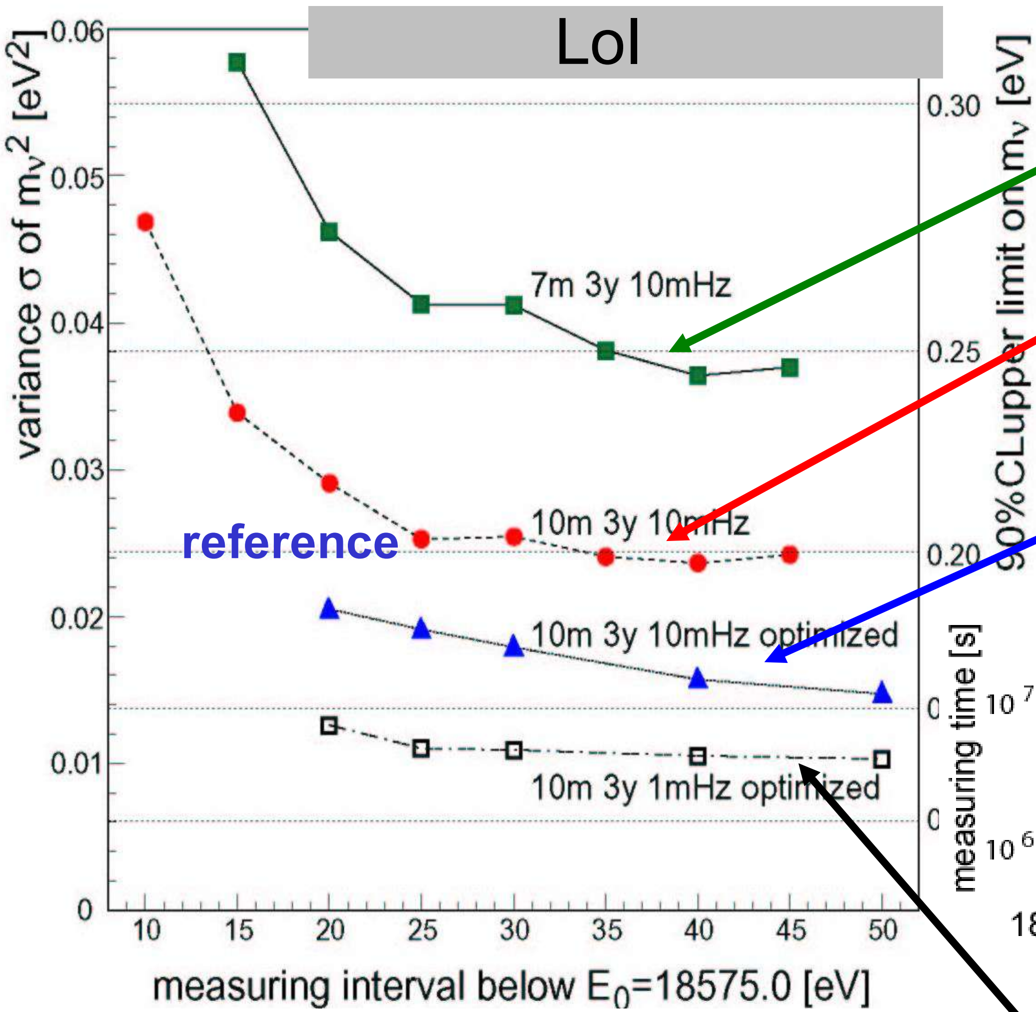
Main spectrometer

- 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
- „simple“ construction: vacuum vessel at HV = electrode + „massless“ screening electrode
- industry study

Pre spectrometer:

- Transmission of electron with highest energy only
  (10^{-7} part in last 100 eV)
  $\Rightarrow$ Reduction of scattering probaility in main spectrometer
  $\Rightarrow$ Reduction of background
- only moderate energy resolution required:
  $\Delta E = 50$ eV
- Test of new ideas (XHV, shape of electrodes, avoid and remove of trapped particles, ...)

Statistical uncertainty

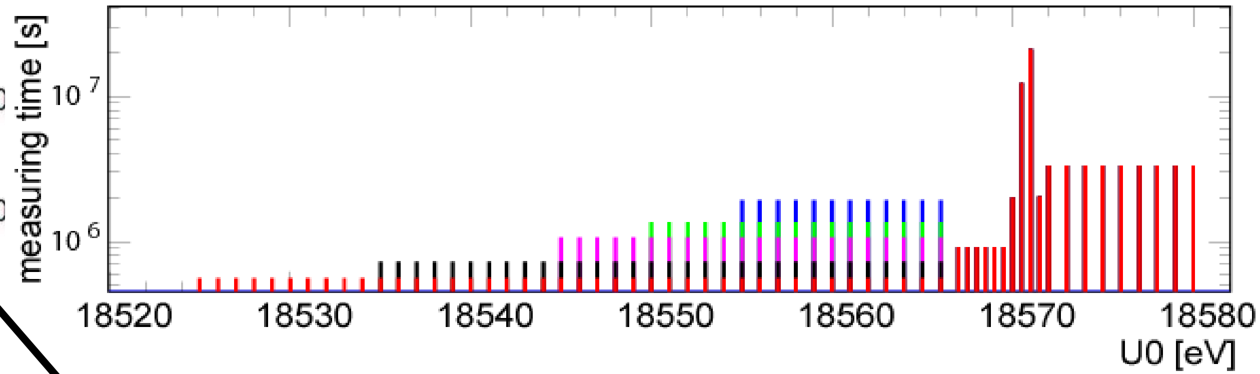


design optimisation ´01 -´03

- tritium purity by tritium laboratory (>95%)

2× stronger gaseous source (Ø=75mm → Ø=90mm) requires Ø=10m spectrometer)

optimised measuring point distribution (~5 eV below E_0)



- active background reduction by inner electrode system, low background detector (needs further detailed tests)

Systematic uncertainties

As smaller m(ν)

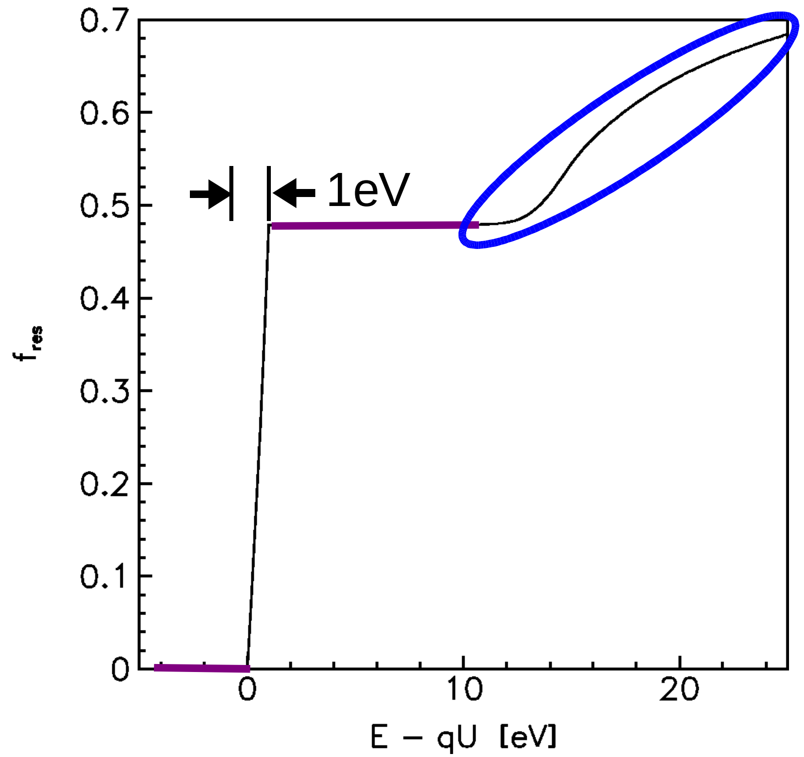
as smaller the region of interest below endpoint E_0

⇒ Excited electronic final states does not play a role (ΔE_{exc} > 27 eV)

⇒ Inelastic scattering in T_2 is small ($\Delta E_{inel.}$ > 12eV ⇒ largest interval 25eV: 2%)

⇒ One well-defined final state (similiar to cryo detectors)

Is only true, since MAC-E-Filter response function has no tails



Still systematic uncertainties:

- inelastic scattering, column density
- retarding high voltage
- tritium purity
- potential in windowless gaseous tritium source
- ......

Systematic uncertainties

as

⇒ Excited elec
a role (ΔE_{exc}

⇒ Inelastic sca
($\Delta E_{inel.}$ > 12

⇒ One well-de
(similiar to c

Is only true, sir
has no tails

Still systematic
inelastic sca
retarding hi
tritium purity
potential in windowless gaseous tritium source
......

KATRIN's sensitivity (since June 2003):

- higher T2 purity
- larger statistics
- optimized measurement point distribution
- smaller systematic uncertainties

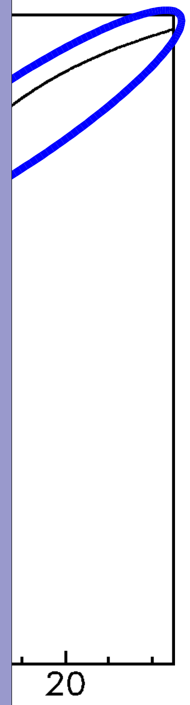
⇒ sensitivity on $m(\nu_e)$

≈ 0.20 eV/c^2

(about equal contribution from stat. and syst. uncertainties)
(90% C.L. upper limit for $m(\nu_e) = 0$)

$m(\nu_e) = 0.30$eV observable with 3σ

$m(\nu_e) = 0.35$eV observable with 5σ



Status and schedule of Katrin

2001 Presentation at Bad Liebenzell Workshop
Foundation of KATRIN collaboration
Letter of Intent (hep-ex/0109033)
First, but significant funds by BMBF, FZ Karlsruhe

2002 Very positive report of International Review Panel

2003 Background investigations at Mainz
Setup of pre spectrometer at FZK

2004 Reviewing, design report

2004 - 2008 Setup of major KATRIN components:
WGTS, transport system, main spectrometer, detector

2008 Commissioning at start of data taking

Status of hardware components

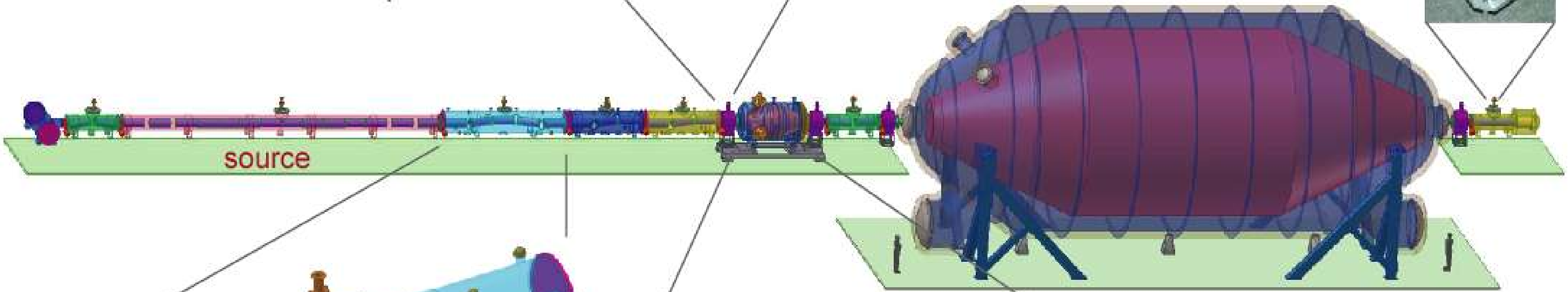
October/November 2003

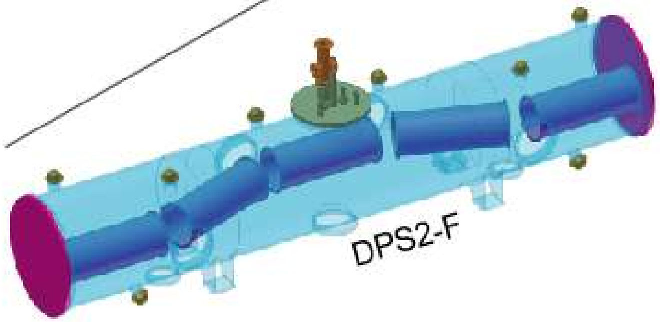
status s.c. magnets:

10/03: 2 'cryogenfree'magnets
11/03: quench tests

status main spectrometer:

04/03 : X-VAT Workshop
11/03 : industrial study





differential pumping section:

07/03: specification
until 10/03: tender
11/03: order
} DPS2-F
11/03: test T_2 extinction @ 4K (TLK)

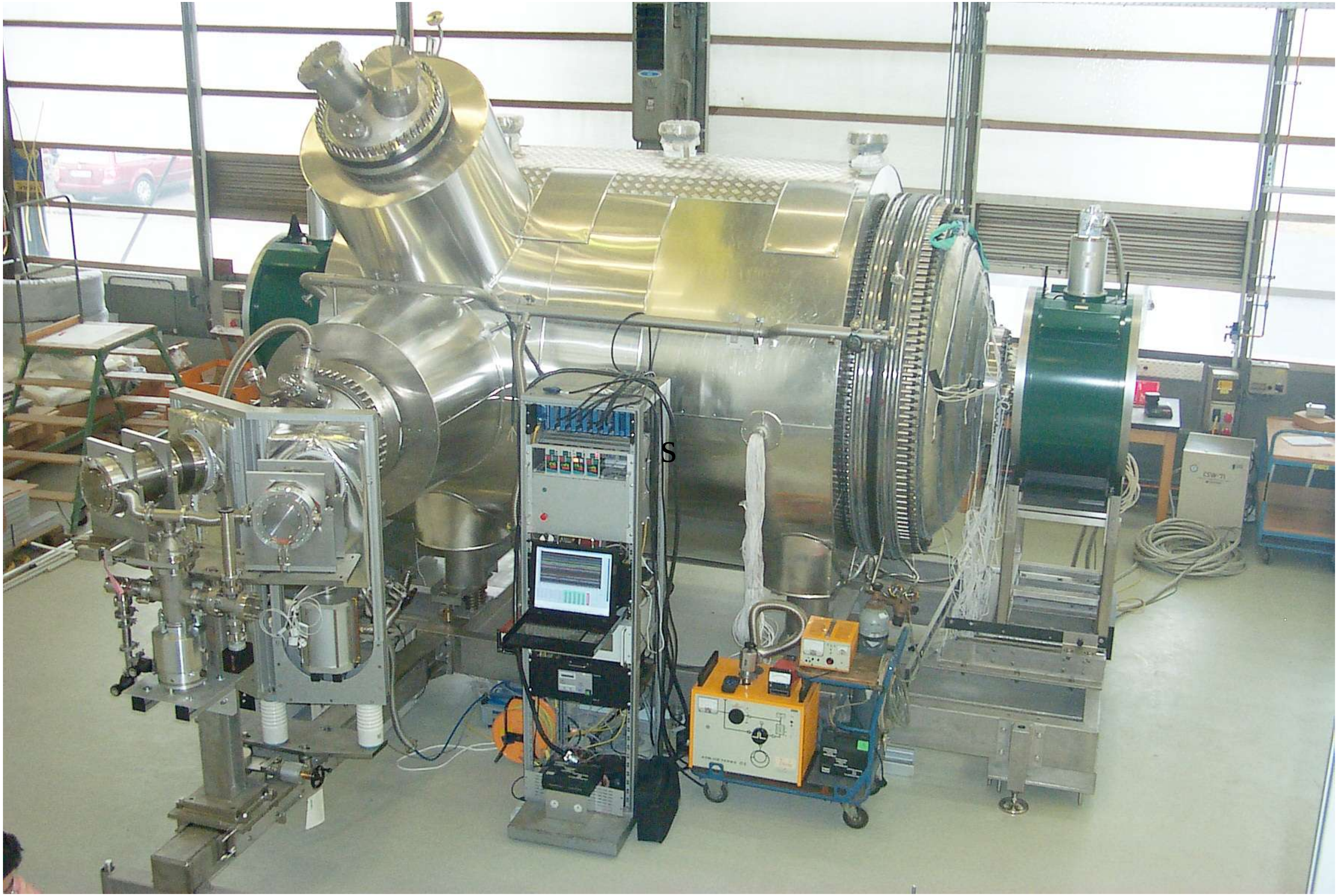
status detector:

10/03: 8x8 Si-PIN diode array prototype tests

status pre-spectrometer:

1.10.03: delivery on-site
10/03-05/04 vacuum tests
06/04-12/04 electromagnet. tests, background studies

Setup of pre spectrometer at FZ Karlsruhe

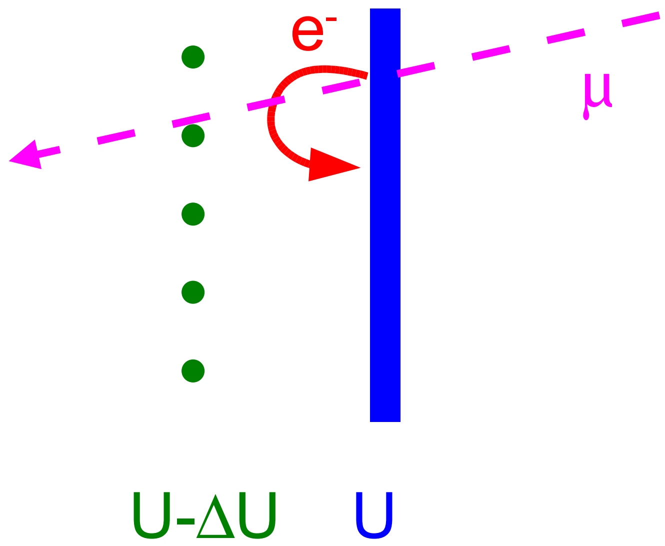


Electric screening by „massless“ wire electrode

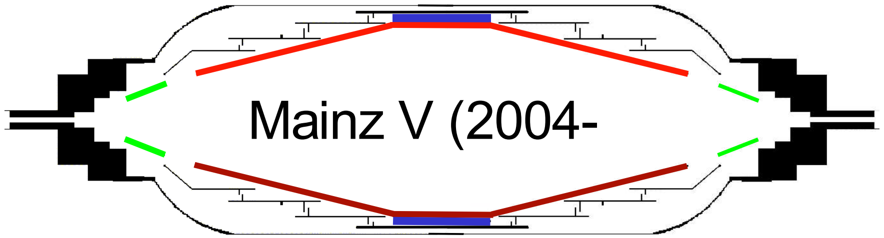
Secondary electrons from wall/electrode

by cosmic rays, environmental radioactivity, ...

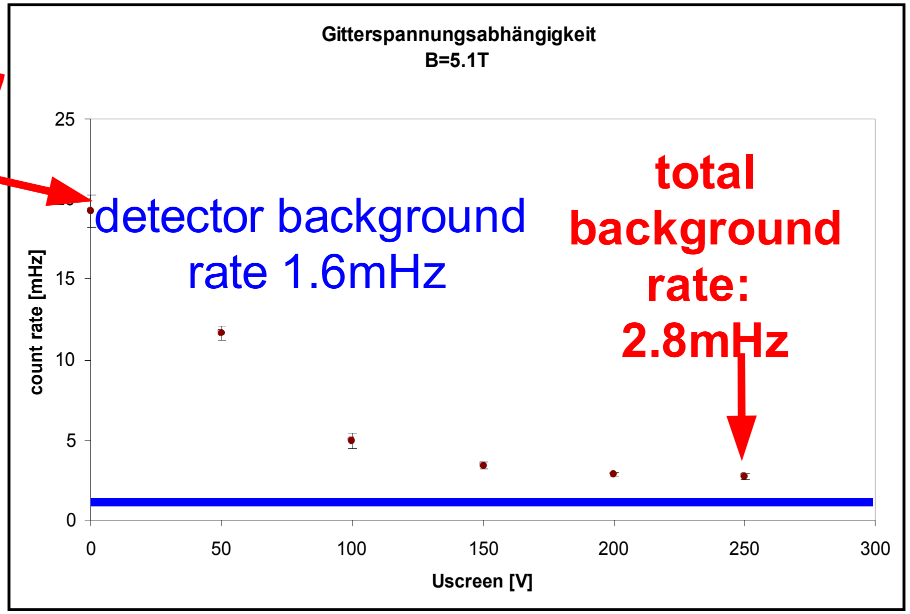
wire electrode on slightly more negative potential



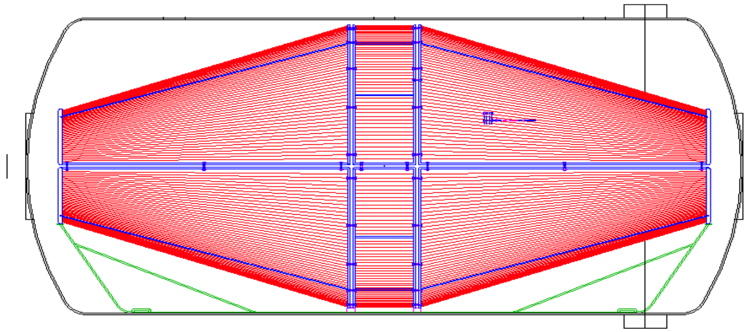
First realisation:
Mainz III



New record !
April 04



PhD thesis: B. Flatt/Mz



KATRIN pre spectrometer

Summary

Neutrino masses from astrophysics and cosmology:

- now: $\Sigma m(\nu_i) < 0.7$ -2.2 eV oder $\Sigma m(\nu_i) > 0$ (WMAP, 2dF/SDDS, ...)
- in 5-10 years: $\Delta\Sigma m(\nu_i) \approx 0.1$ eV ? (Planck, SDSS)
- but always model-dependent

complementary, need both

$0\nu\beta\beta$:

- very sensitive, but dependent on phases, mixing, M_{nucl}
- Nemo3, Cuoricino started, signal from Hd-Moscow at $m_{ee} = 0.4$ eV ?

β endpoint spectrum: only model independent method:

- Cryogenic detectors with Rhenium: fascinating new approach, how far do they go?
- Mainz finished: $m(\nu_e) < 2.3$ eV (95% C.L.)
- KATRIN: A large tritium β neutrino mass experiment with sub-eV sensitivity
  $m(\nu_e) < 0.2$ eV or $m(\nu_e) > 0$ eV (for $m(\nu_e) \geq 0.30$ eV @ 3σ)
  $\Rightarrow$ key experiment w.r.t. absolute neutrino mass scale