Neutrino Physics

Graduate School 1504 „Mass, Spectra, Symmetry“
Automn Block Course, September 9-12, 2012, Berlin

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Neutrinos in the Standard Model of Particle Physics

Neutrino oscillations:
experiments with atmospheric,
solar, accelerator and reactor neutrinos

Neutrino masses:
- cosmology and astrophysics
- neutrinoless double β decay
- direct neutrino mass experiments

Neutrino telescopes

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Possible neutrino mass terms

Remark: each mass term has to be a scalar ($\overline{\psi}\psi$) and an isospin singulet

Fermion mass terms in the Standard Model by coupling to the Higgs:

$$\mathcal{L} = -f_e\,(\overline{\nu_e},\overline{e})_L \begin{pmatrix} \Phi^{+} \\ \Phi^0 \end{pmatrix} e_R = -\frac{f_e \cdot v}{\sqrt{2}} \cdot \overline{e_L}\, e_R =: -m_e \cdot \overline{e_L}\, e_R \qquad (\ldots + h.c.)$$

To obtain massive neutrinos also such "Dirac mass terms" are in principle possible by introducing right-handed neutrinos.

But it is very "unnatural" to have at least 6 orders smaller Yukawa-couplings to the Higgs !

lepton number violating ΔL=2

For neutral Majorana particles more terms are allowed:

$$\begin{aligned} -2\mathcal{L}_\nu &= m_D\left(\overline{\nu_L}\nu_R + \overline{(\nu_R)^c}(\nu_L)^c\right) + m_{LL}\overline{\nu_L}(\nu_L)^c + m_{RR}\overline{(\nu_R)^c}\nu_R \quad + h.c. \\ &= \left(\overline{\nu_L}\;\overline{(\nu_R)^c}\right)\begin{pmatrix} m_{LL} & m_D \\ m_D & m_{RR} \end{pmatrix}\begin{pmatrix} (\nu_L)^c) \\ \nu_R \end{pmatrix} \quad + h.c. \\ &= \left(\overline{\nu_L}\;\overline{(\nu_R)^c}\right)\mathcal{M}\begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix} \quad + h.c. \end{aligned}$$

The matrix $\mathcal{M}$ can be diagonilized

⇒ 2 Majorana neutrino mass states m_1, m_2

Seesaw mechanism

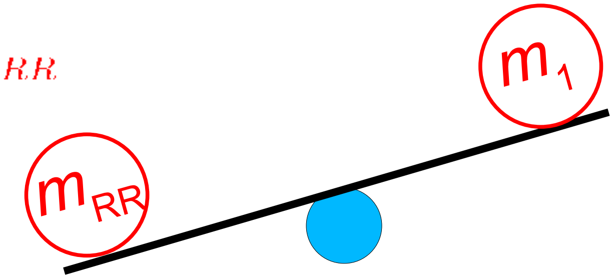
Assume $m_{LL} \approx 0$ (otherwise we will get a problem with e_L mass terms, since it appears within the $(\nu_e, e)_L$ isospin doublet)

and $m_{RR} \gg m_D$

$$-2\mathcal{L}_\nu = \left(\overline{\nu_L}\ \overline{(\nu_R)^c}\right) \begin{pmatrix} 0 & m_D \\ m_D & m_{RR} \end{pmatrix} \begin{pmatrix} (\nu_L)^c) \\ \nu_R \end{pmatrix} + h.c.$$

$$\Rightarrow m_1 \approx m_D^2/m_{RR} \qquad m_2 \approx m_{RR}$$

Seesaw effect: if m_{RR} gets big, then m_1 gets small



Is such a mass term realistic ?

Since $(\nu_L)^c \nu_L$ is a SU(2) triplet, the most simple possible form is:

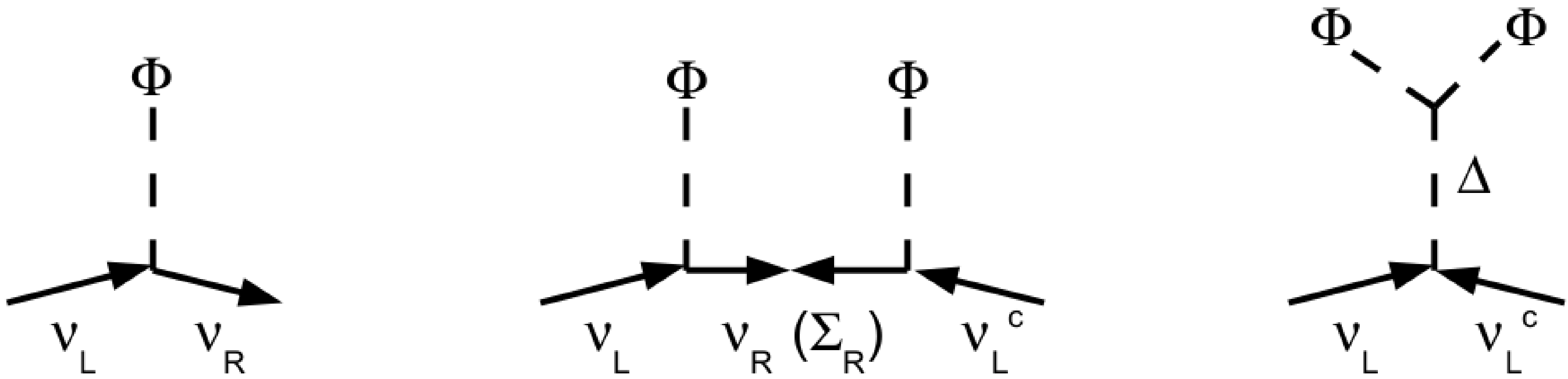
$$\mathcal{L}_{eff} = G/M \cdot \overline{\Phi^c} \Phi \overline{(\nu_L, e_L)^c} (\nu_L, e_L)$$

where M is an effektive mass of an effective field theory, in which the heavy neutrinos $N = \nu_R$ are integrated out.

Expect M on a very large scale, e.g. $M \approx M_{GUT}$

⇒ Seesaw mechanismus allows to address large scale M of new physics

Realisation of seesaw mechanisms



a) Realisation with Higgs doublet Φ like all other fermions
→ very small Yukawa couplings

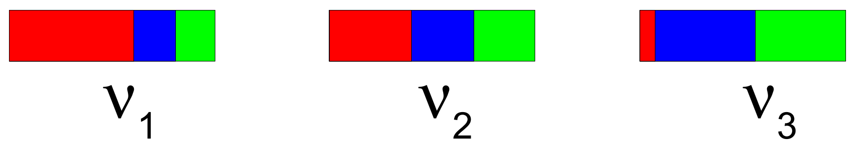
b) right-handed heavy Majorana neutrinos ν_R (seesaw I)
or right-handed fermionic triplett Σ_R (seesaw III)

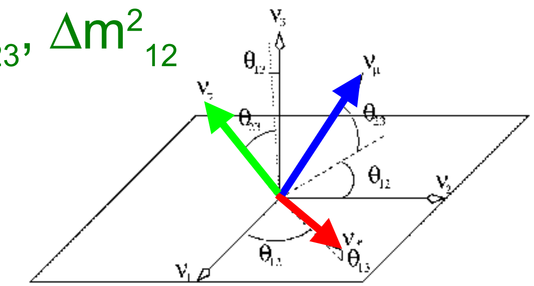
c) Higgs-triplet ξ (no -right-handed neutrinos needed !) (seesaw II)

Need for the absolute ν mass determination

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

ν_e ν_μ ν_τ





degenerated masses

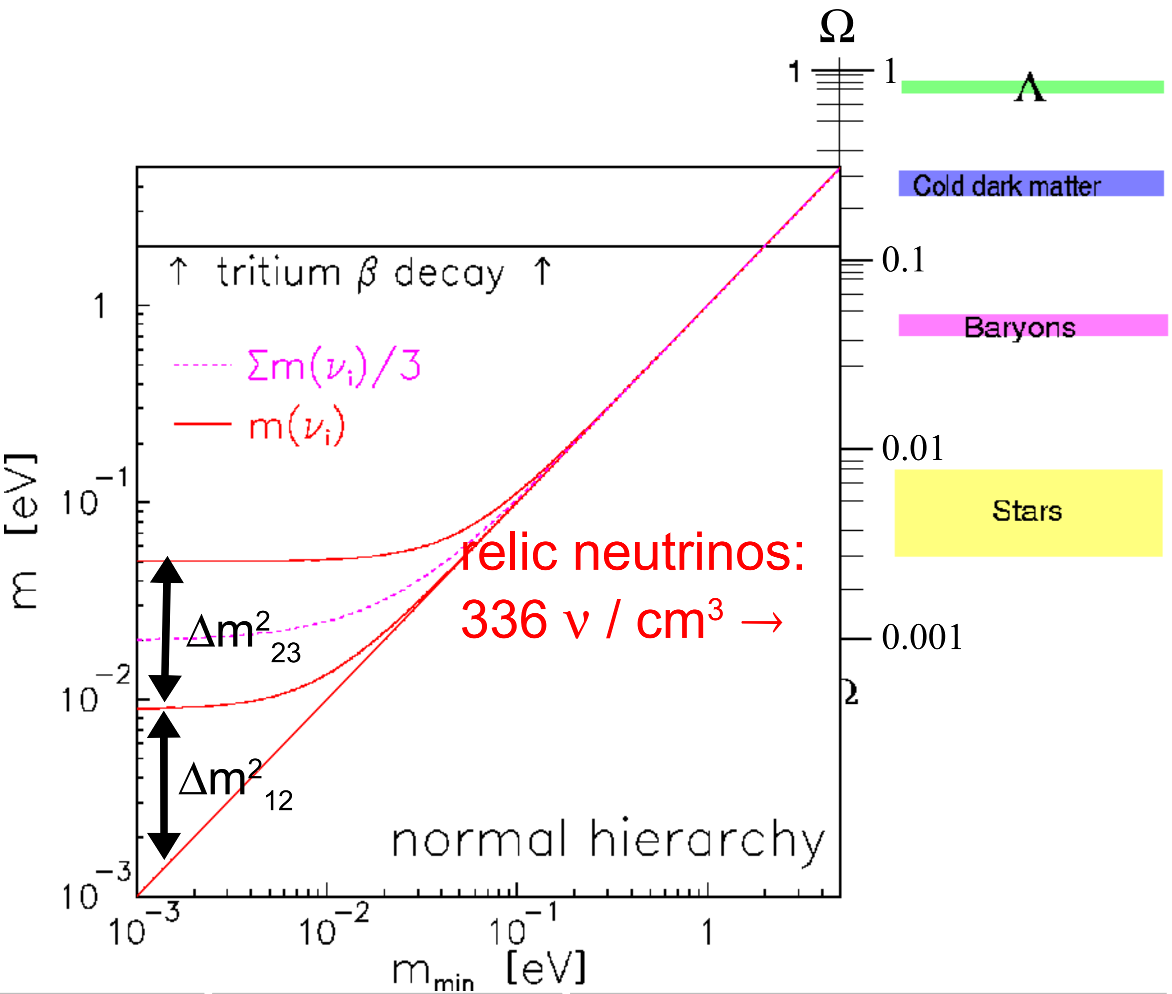
cosmological relevant

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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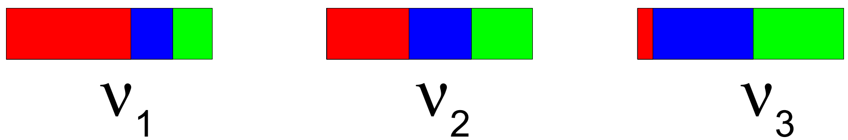

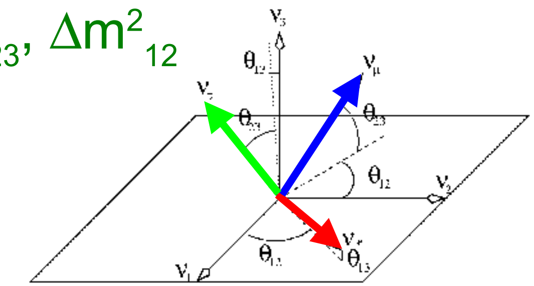

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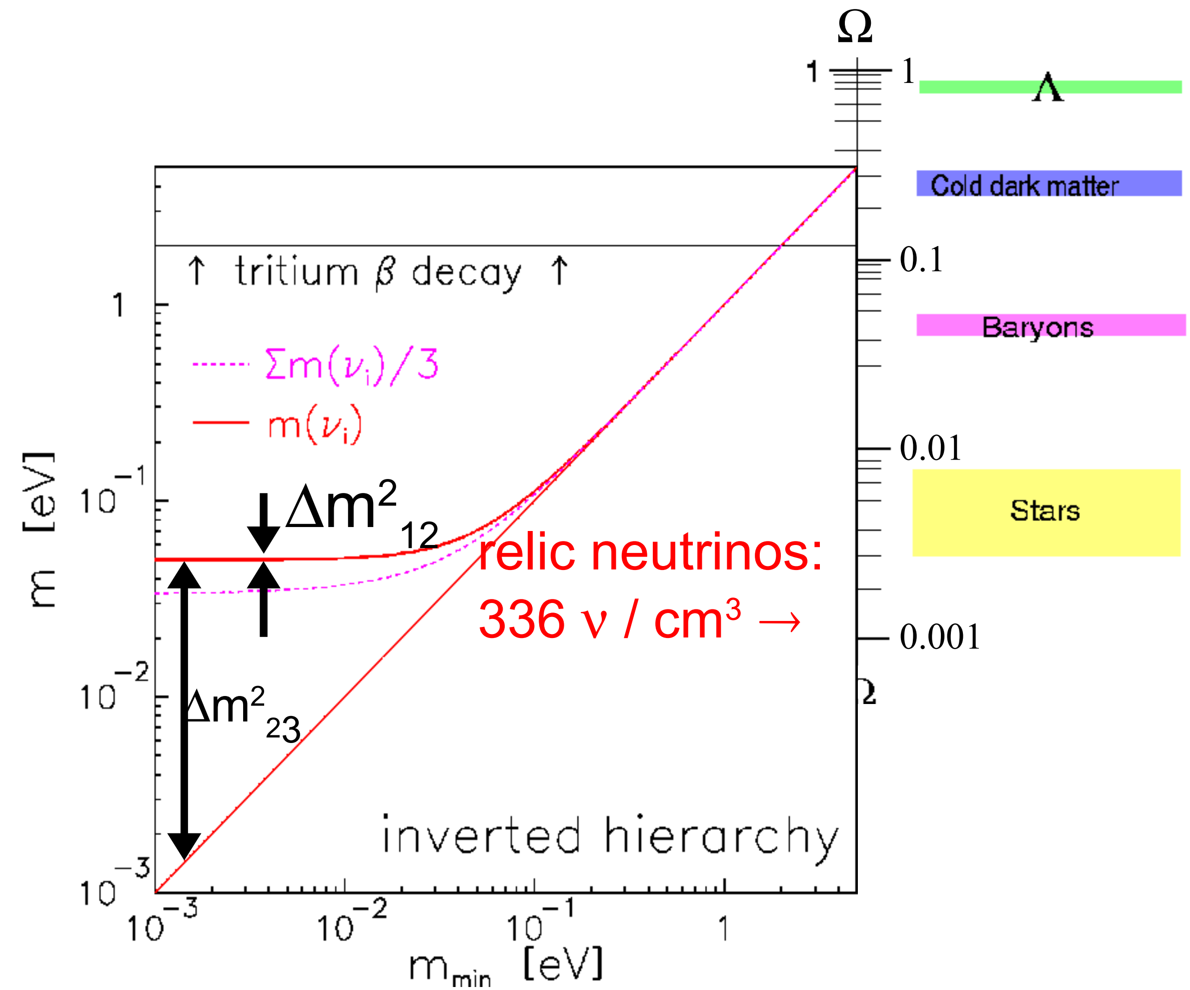

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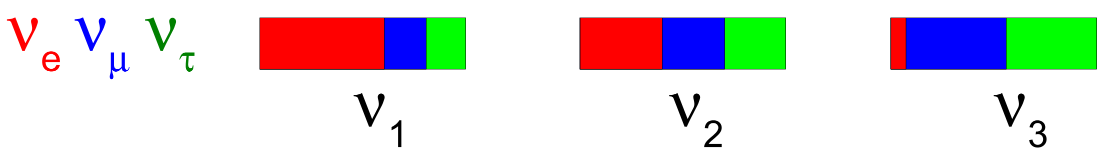

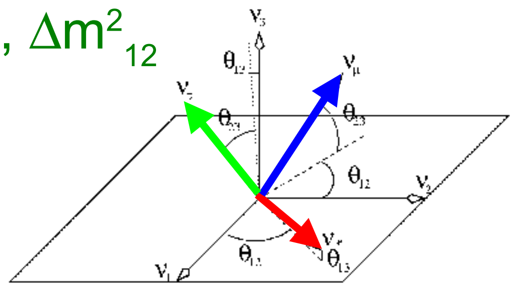

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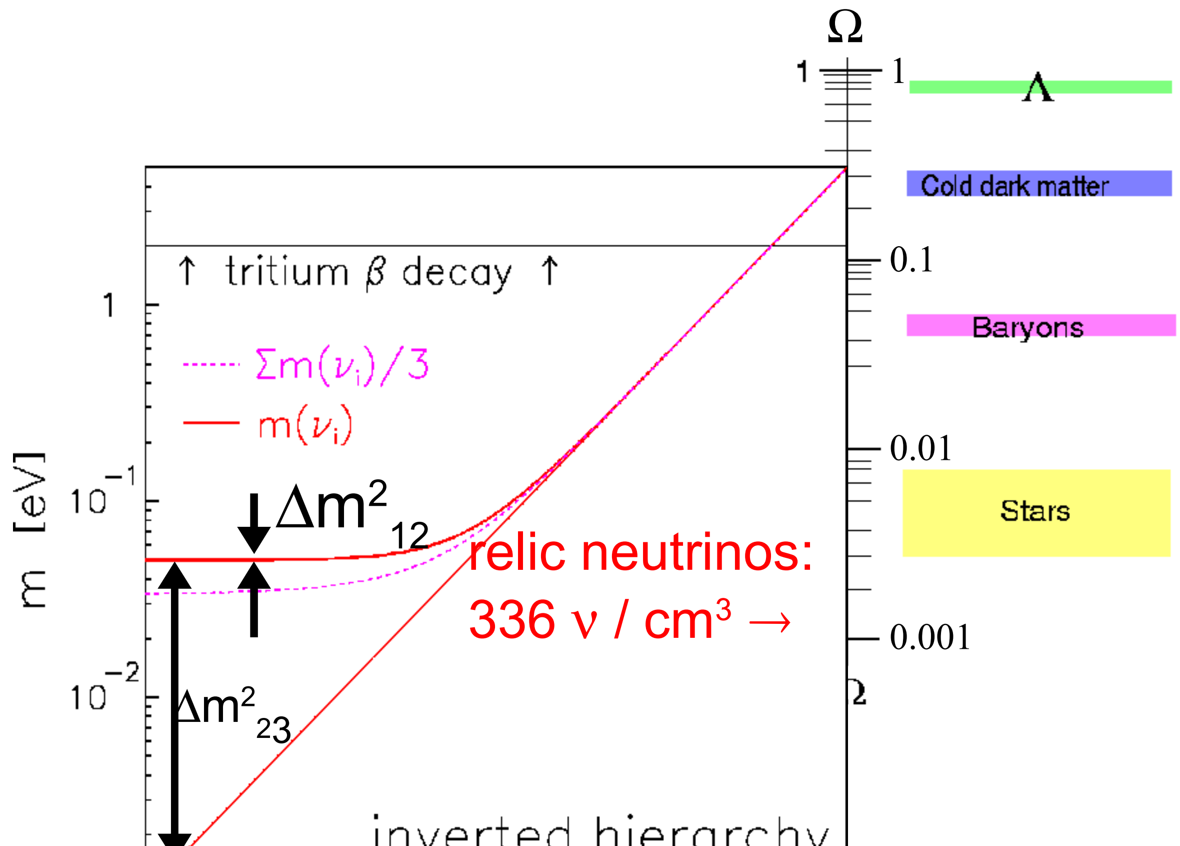


Need neutrino mass from non-oscillation method !

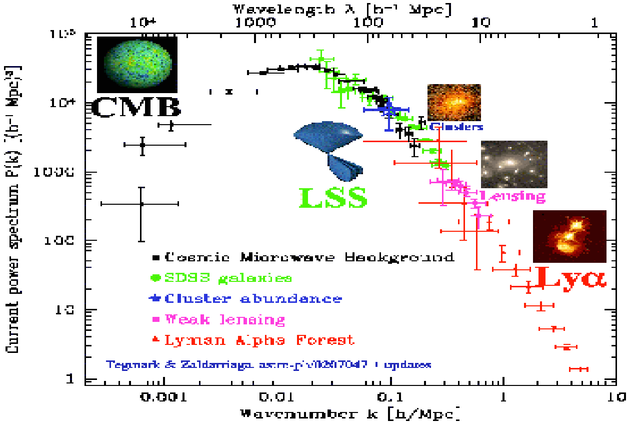
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

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

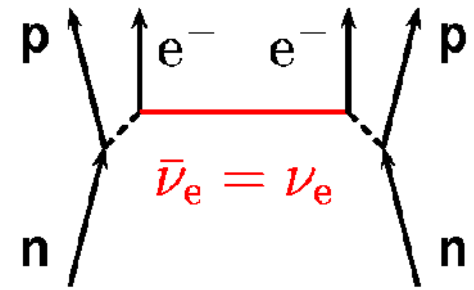


2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

Evidence for $m_{ee}(\nu) \approx 0.3$ eV (Klapdor-Kleingrothaus et al.)?

New upper limit by EXO-200, GERDA is running

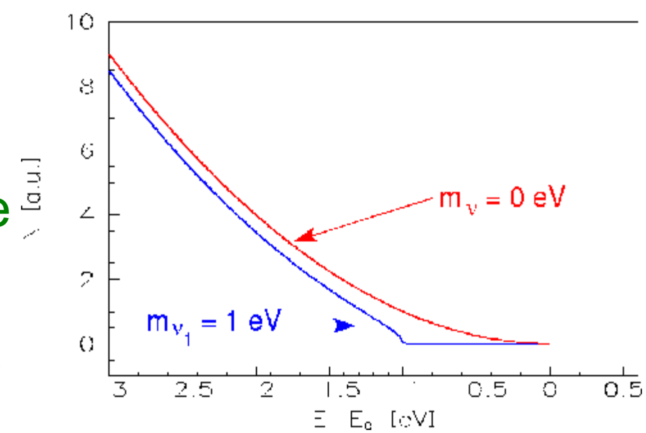


3) Direct neutrino mass determination:

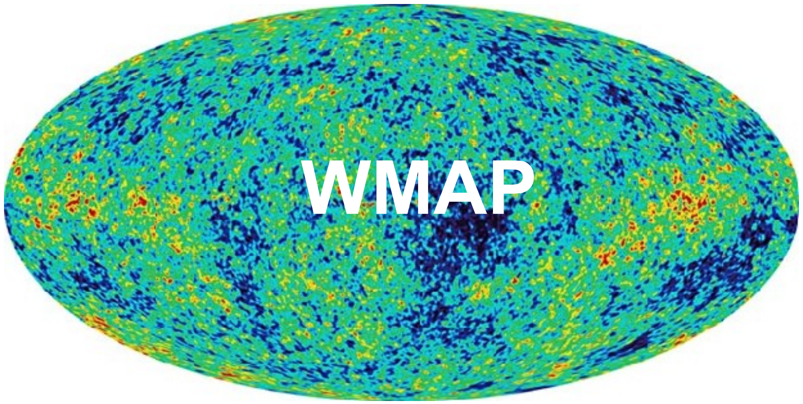
No further assumptions needed. no model dependence

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

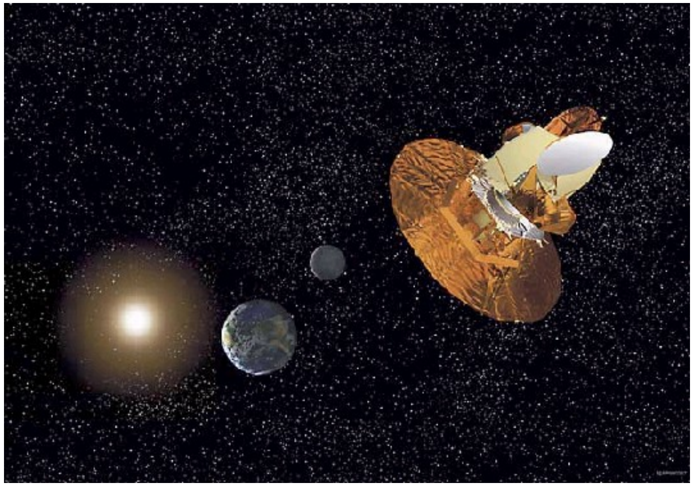
most sensitive methode: endpoint spectrum of β-decay

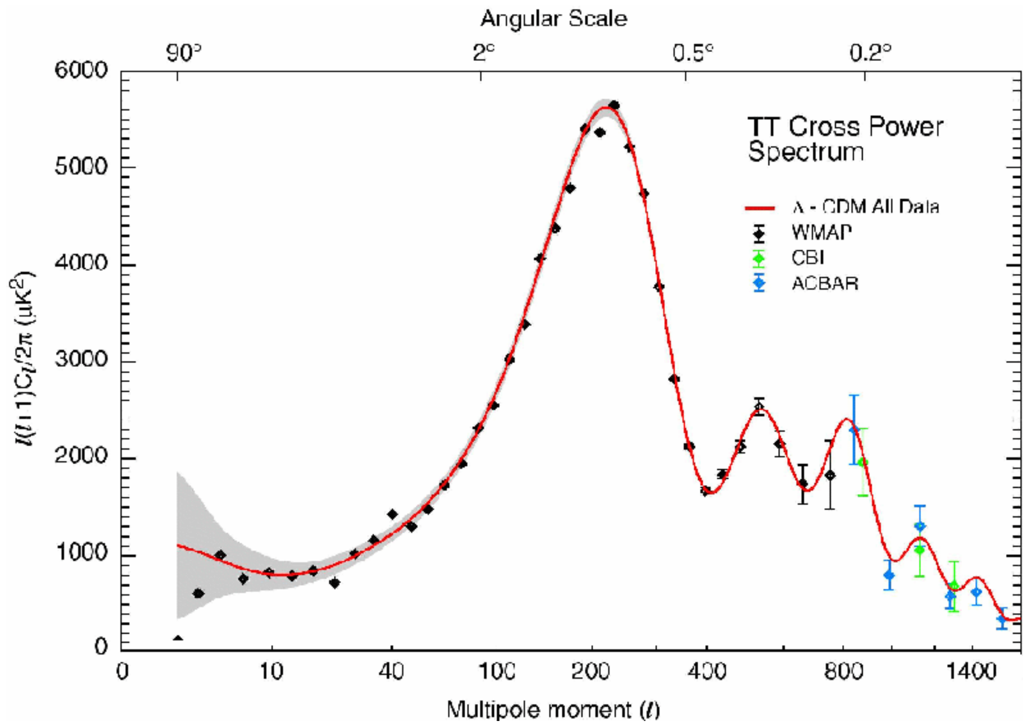


Neutrino mass from cosmology



measurement of CMBR
(Cosmic Microwave Background Radiation)





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

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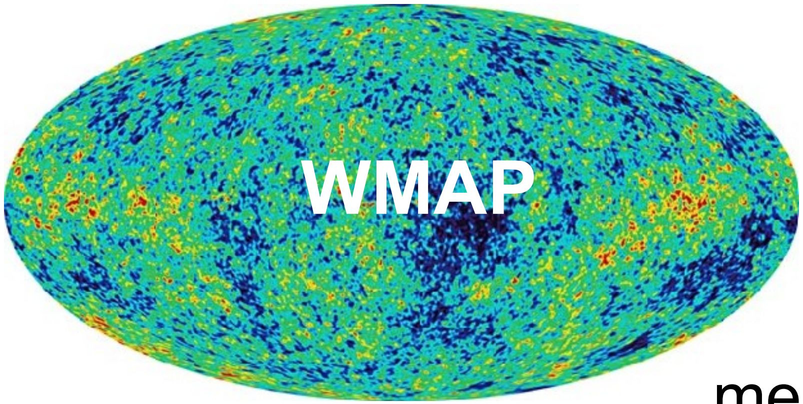

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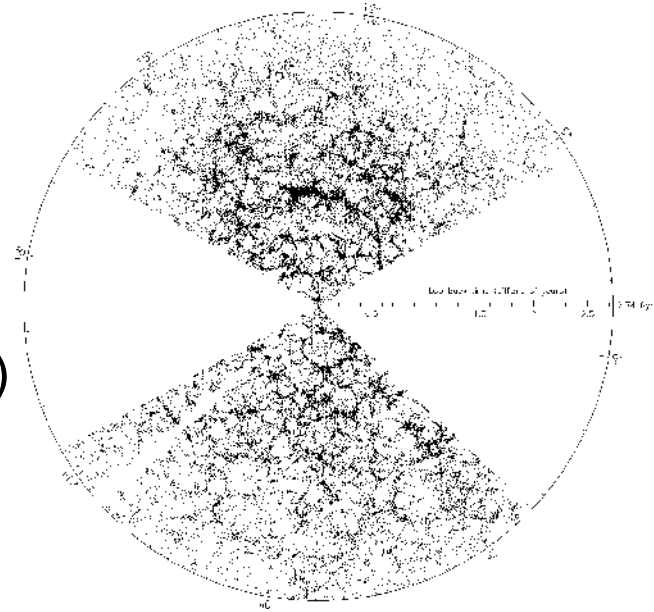
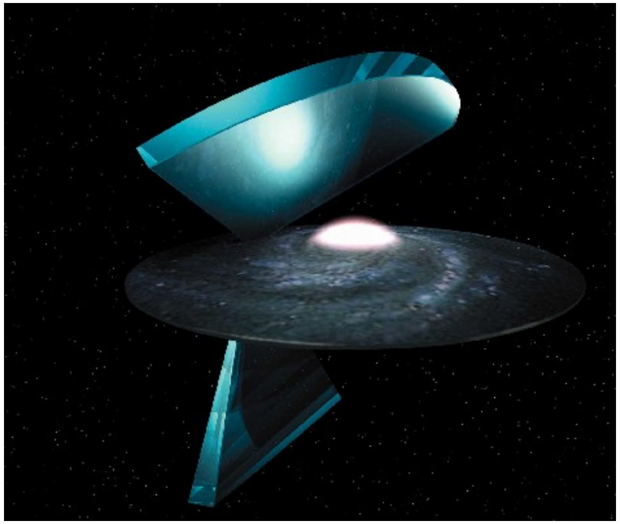


measurement of matter density distribution

LSS (Large Scale Structure)

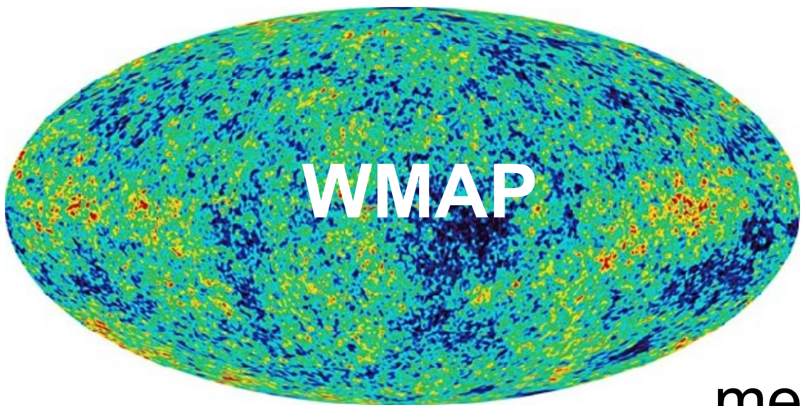
2dF, SDSS, ...



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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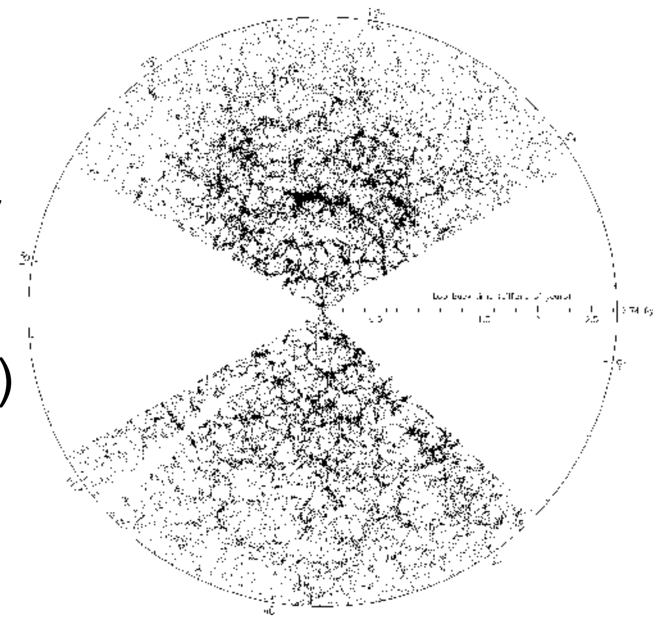

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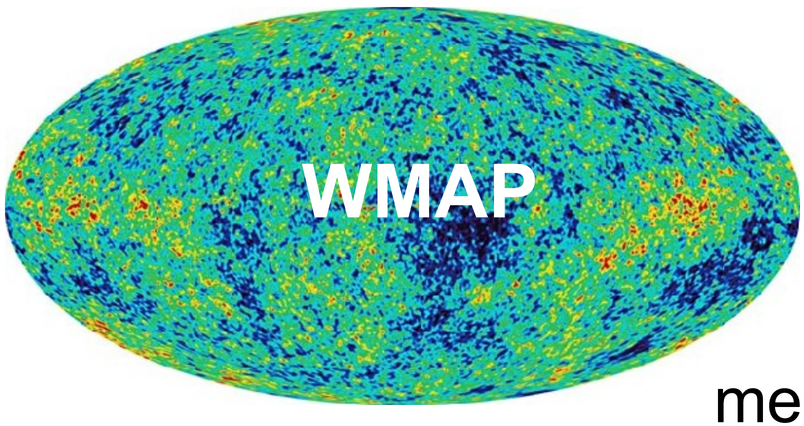
big bang theory:

neutrino density in universe

$n_\nu = 336 / cm^3$

Neutrino mass from cosmology



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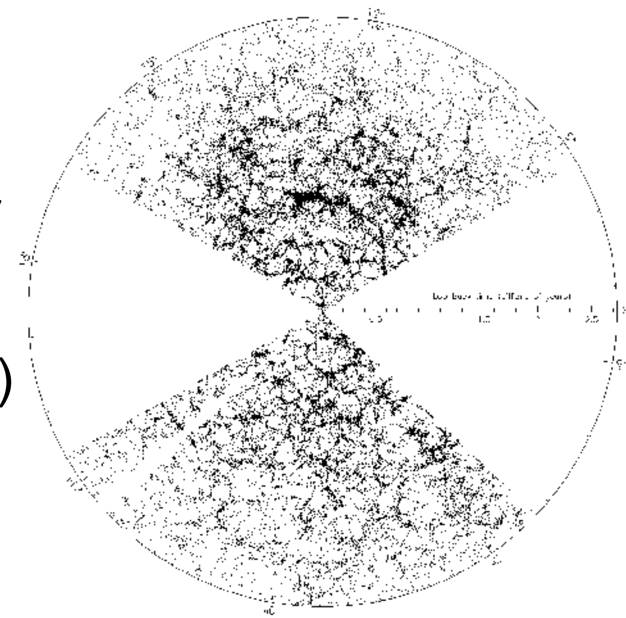

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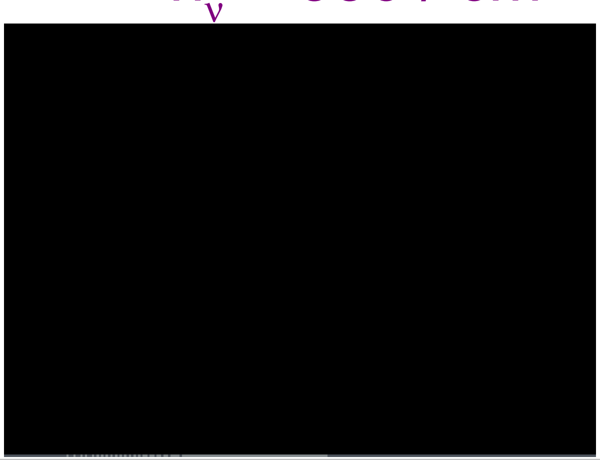
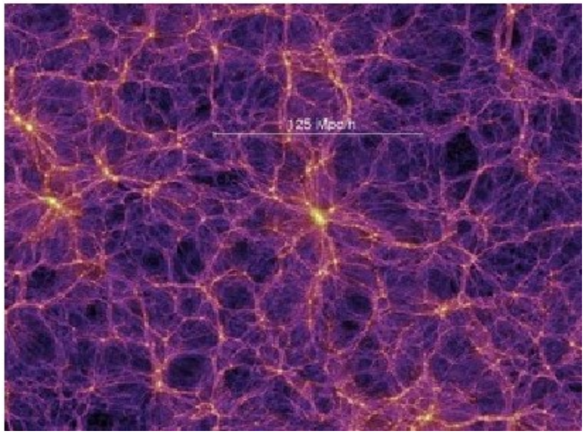


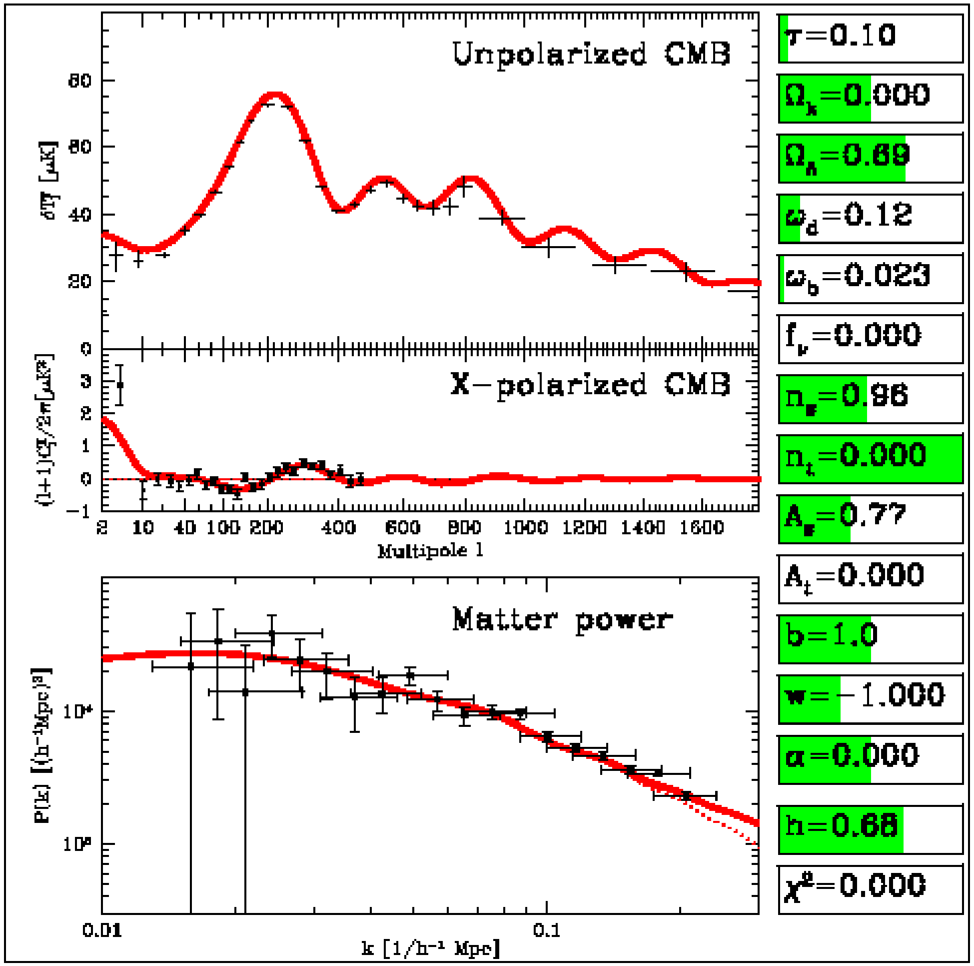
model development

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

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



Fraction of “hot” to “cold“ dark matter



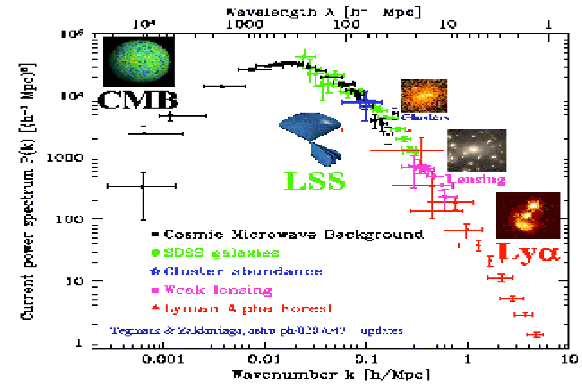
from http://space.mit.edu/home/tegmark/movies_60dpi/fn_movie.gif

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



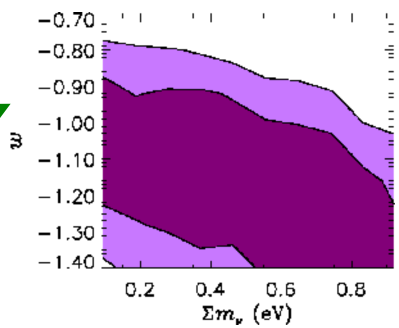
S. Hannestad, Prog. Part. Nucl. Phys. 65 (2010) 185

$$\Sigma m(\nu_i) < 0.5 \text{ eV}$$

using baryon accoustic peaks

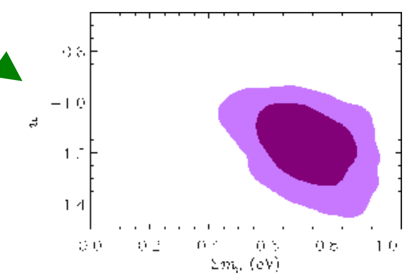
Remark: w is correlated to $\Sigma m(\nu_i)$ (arXiv:0709.4152, 0505.551)

$\Rightarrow$ 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

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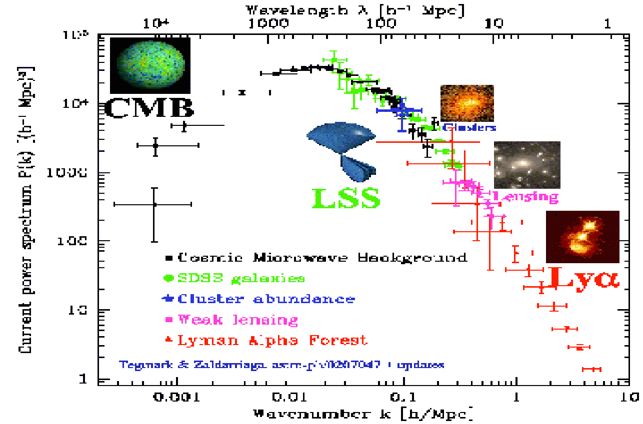
current sensitivity: $\Sigma m(\nu_i) \approx 0.4 - 1$ eV



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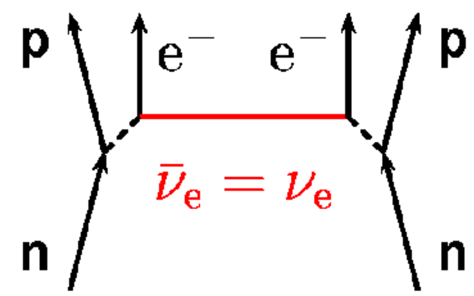

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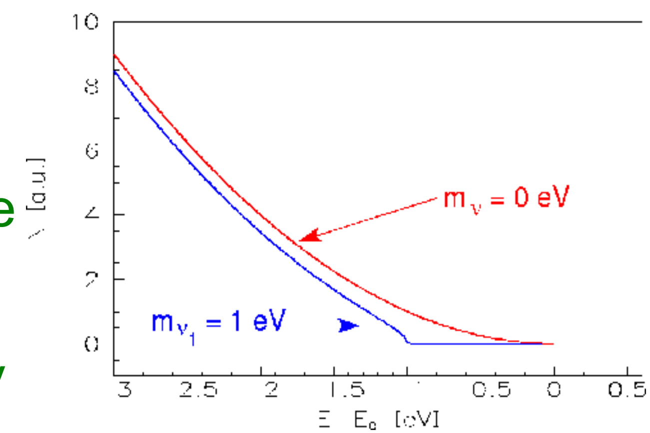
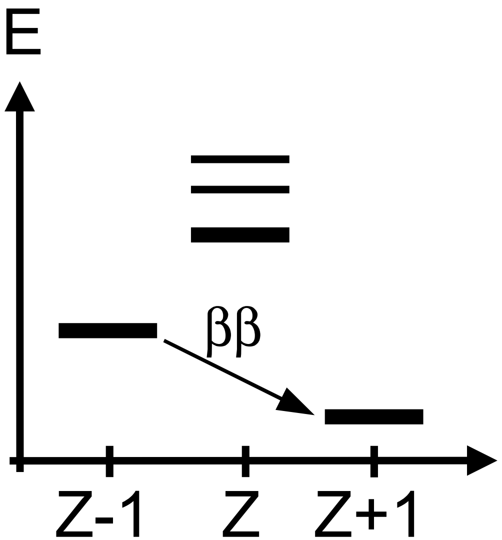
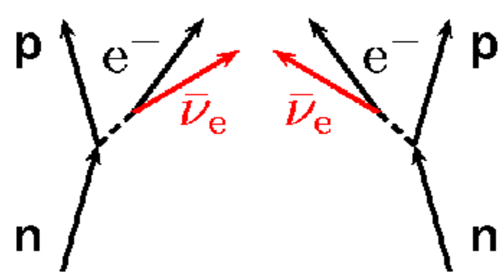
most sensitive methode: endpoint spectrum of β-decay



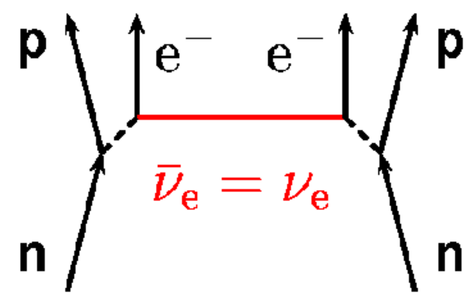
Double β decay



normal (2νββ)



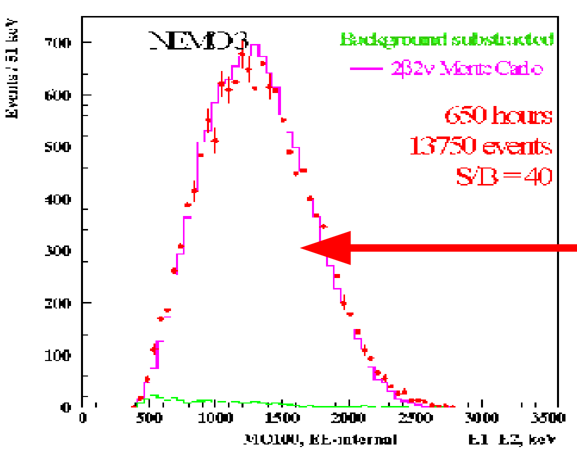
neutrinoless (0νββ)

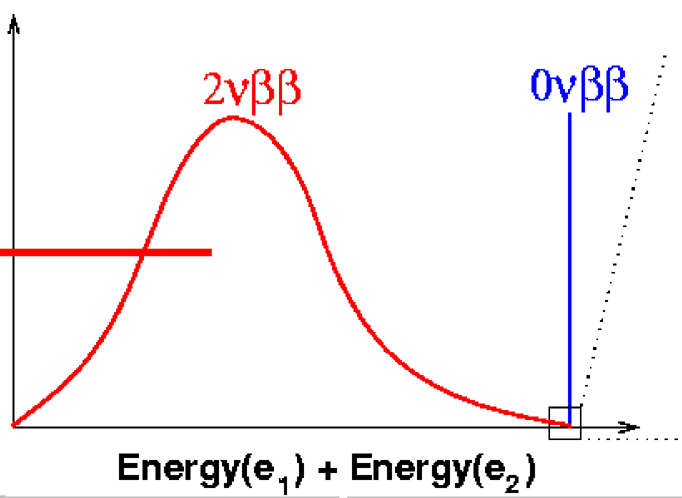


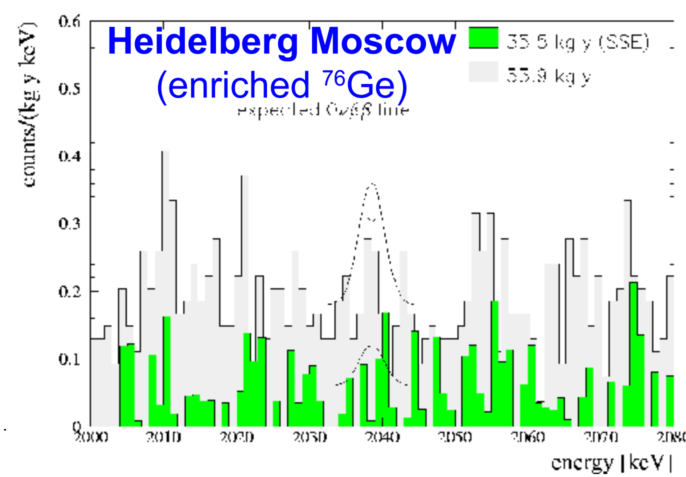
needed: a) $\bar{\nu} = \nu$ (Majorana)

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

or other new physics



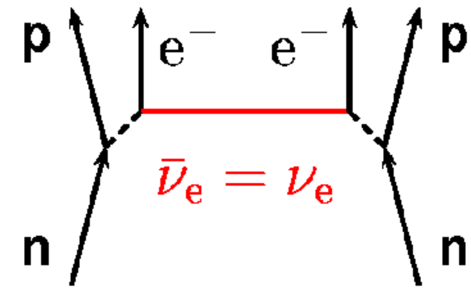




Neutrinoless double β decay: 0νββ

Weak interaction: left-handed fermions $\Psi_L = (1-\gamma_5)/2\ \Psi$ couple to charge current

0νββ: decay rate is proportional to fraction of positive helicity state within Ψ_L



$$
\begin{aligned}
\Gamma \sim u_2^{+} u_L &= W'(\mathcal{H}=+1) \\
&= \frac{1}{2}(1-\beta_\nu) \\
&= \frac{1}{2}\left(1-\frac{p_\nu c}{E_\nu}\right) = \frac{1}{2}\left(\frac{E_\nu - p_\nu c}{E_\nu}\right) \\
&= \frac{1}{2}\,\frac{\sqrt{p_\nu^2 c^2 + m_\nu^2 c^4} - p_\nu c}{E_\nu} \\
&= \underbrace{\frac{p_\nu c}{2E_\nu}}_{\approx \frac{1}{2}}\left(\sqrt{1+\frac{m_\nu^2 c^2}{p_\nu^2}} - 1\right) \\
&= \frac{1}{2}\left(1 + \frac{m_\nu^2 c^2}{2 p_\nu^2} - 1\right) \sim m_\nu^2
\end{aligned}
$$

more complete

decay rate $\propto m^2_{ee}(\nu)$:

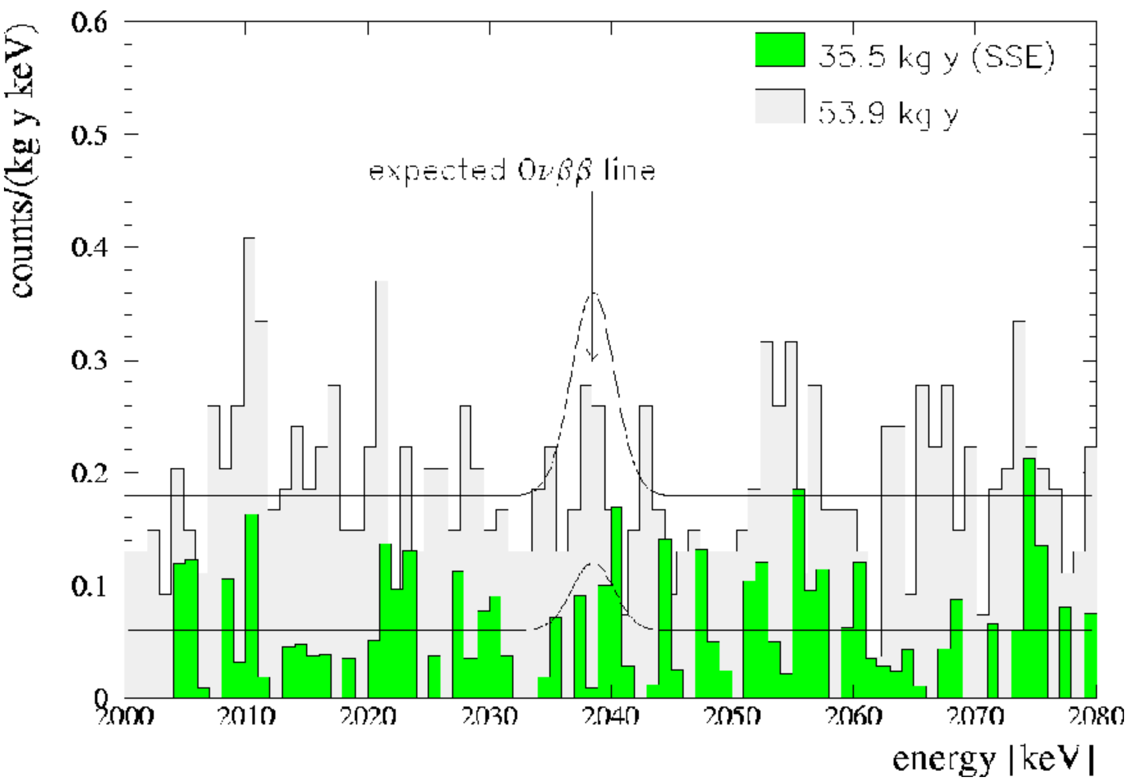
$m_{ee}(\nu) = |\,\Sigma\, |U_{ei}{}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$

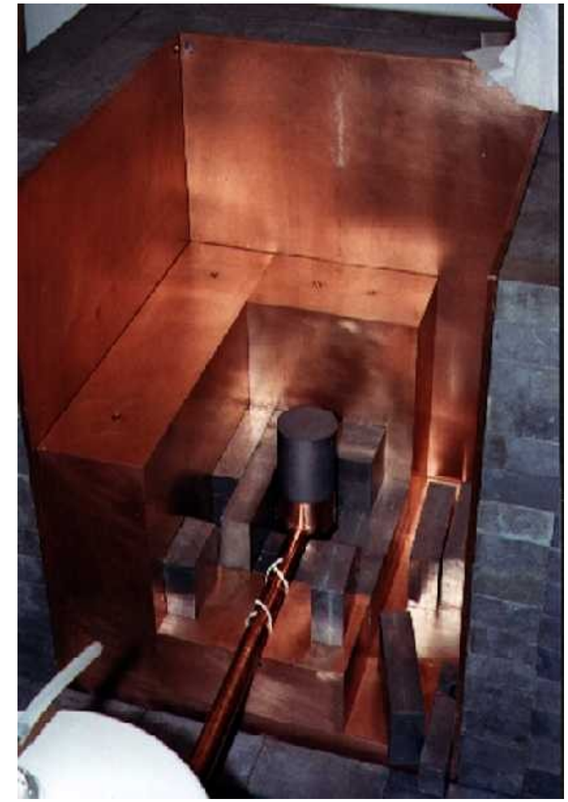
(coherent sum over all neutrino mass eigenstates contributing to the electron neutrino)

⇒ partial cancelation possible

Heidelberg Moscow experiment

- 5 Ge detectors, 10.9 kg total mass
- enrichted ^{76}Ge (86%)
- in the Gran Sasso underground laboratory/italy
- digital puls shape analysis: reduction of background by a factor of 5





up to 2001: 0νββ not observed

$T_{1/2} > 1.9\ 10^{25}$ a

$\Rightarrow m_{ee} < 0.35$ eV (90% C.L.)

H.V. KLapdor-Kleingrothaus et al., Eur. Phys. J. A12 (2001) 147

Evidence for $0\nu\beta\beta$ at Heidelberg Moscow Exp.?

New, data up to 2003: 72 kgy,

with new data selection, new calibration,

new analysis:

assume peaks in [2000,2060] keV,

some of them are known as ^{214}Bi lines

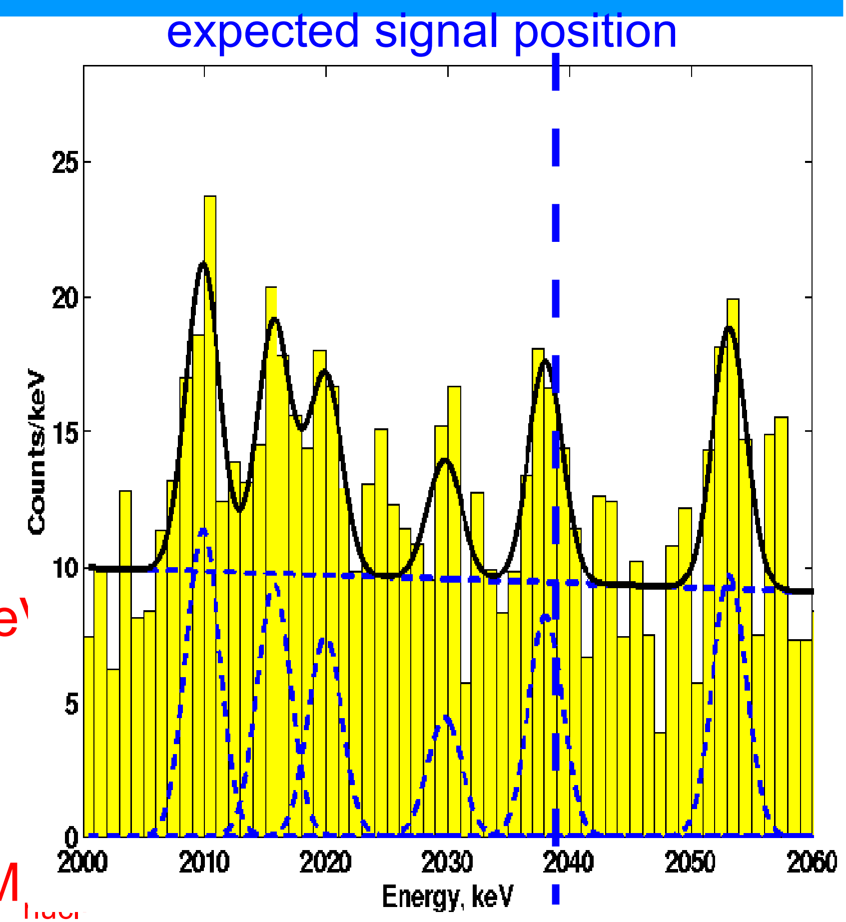
Klapdor-Kleingrothaus et al., PL B586 (2004) 198

⇒ 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

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



⇒ Need to be checked by other experiments: NEMO, CUORICINO (CUORE), EXO, GERDA

⇒ Nuclear matrix elements need to be worked on

Westfälische Wilhelms-Universität Münster

Current and future double β decay experiments

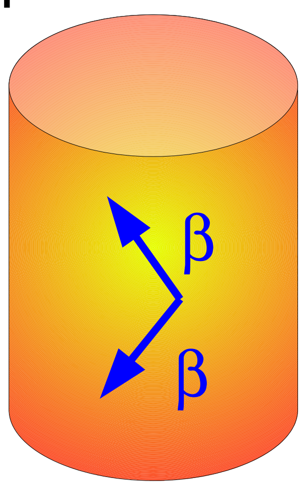
$m_{ee} \sim (1/\text{enrichment})^{1/2} \cdot (\Delta E \cdot bg/M \cdot t)^{1/4}$

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

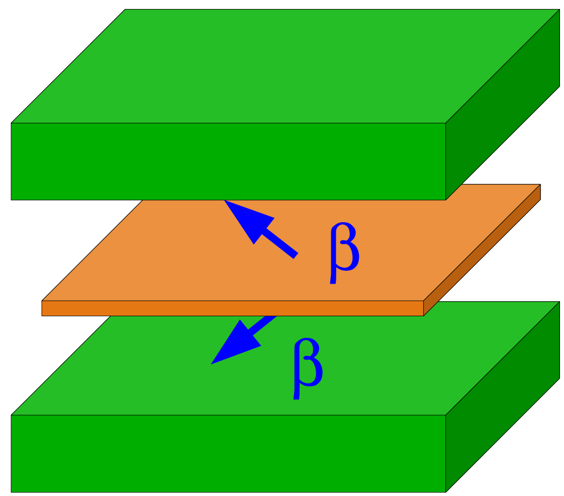
2 ways to measure both β-electrons:

semiconductor,
cryogenic bolometer
liquid scintillator

source
=
detector



tracking calorimeter



detector

source

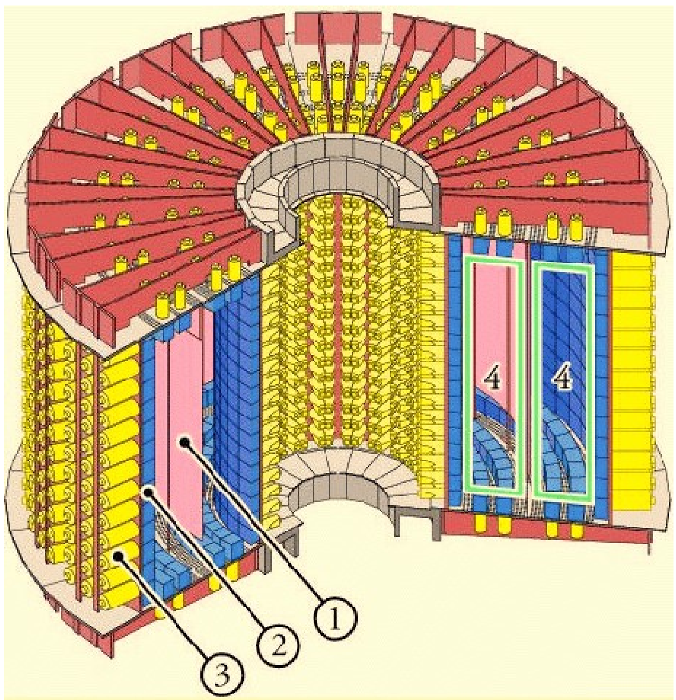
detector

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

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

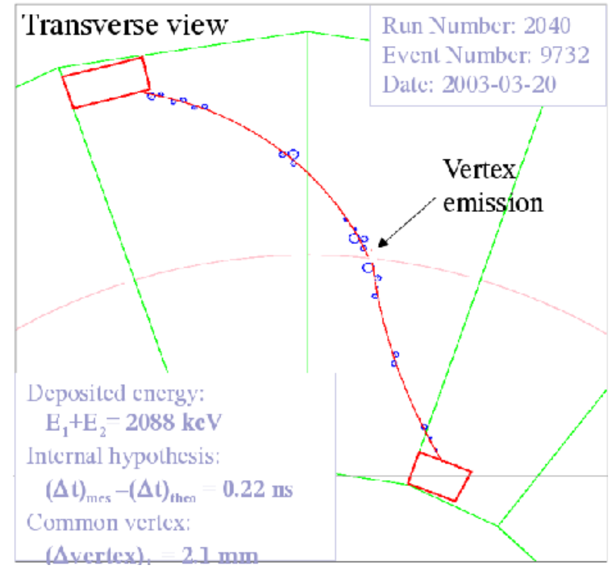
Searching for $0\nu\beta\beta$: NEMO3

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

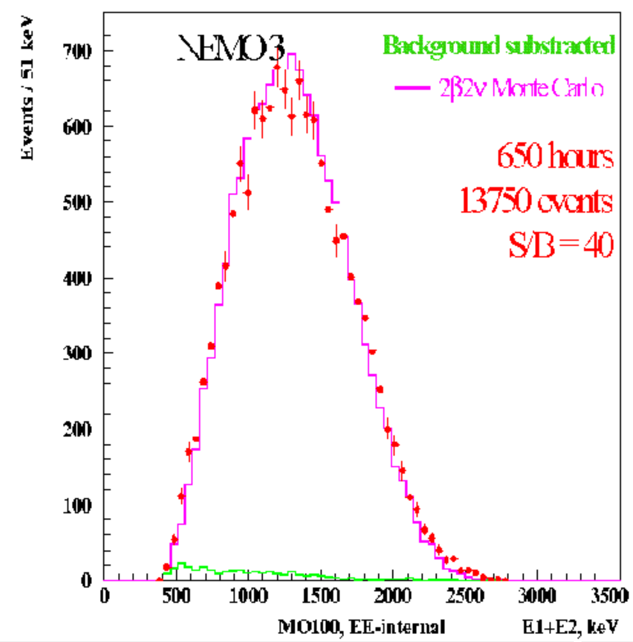


F Mauger, TAUP09

$2\nu\beta\beta$ of ^{100}Mo



from Ruben Saakyan, DBD06



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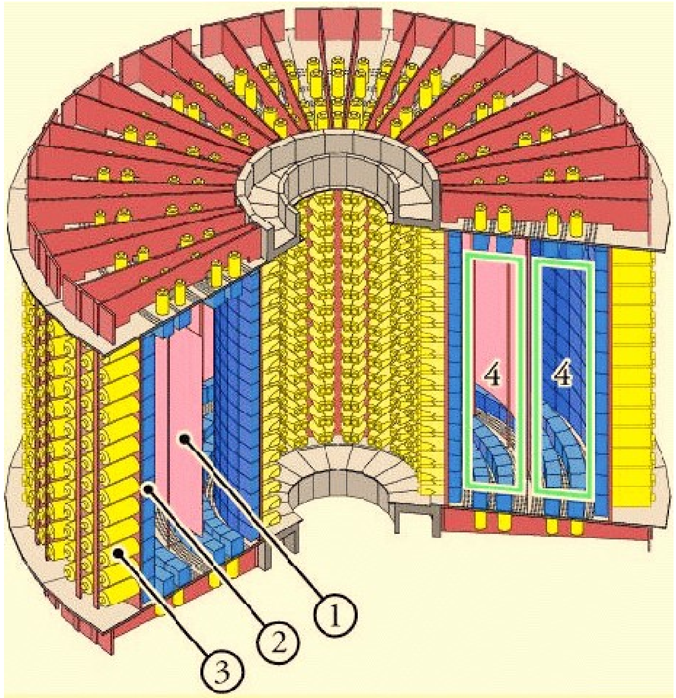
Searching for $0\nu\beta\beta$: NEMO3 → SuperNEMO

NEMO3: tracking calorimeter with several isotopes (finished Jan 2011)

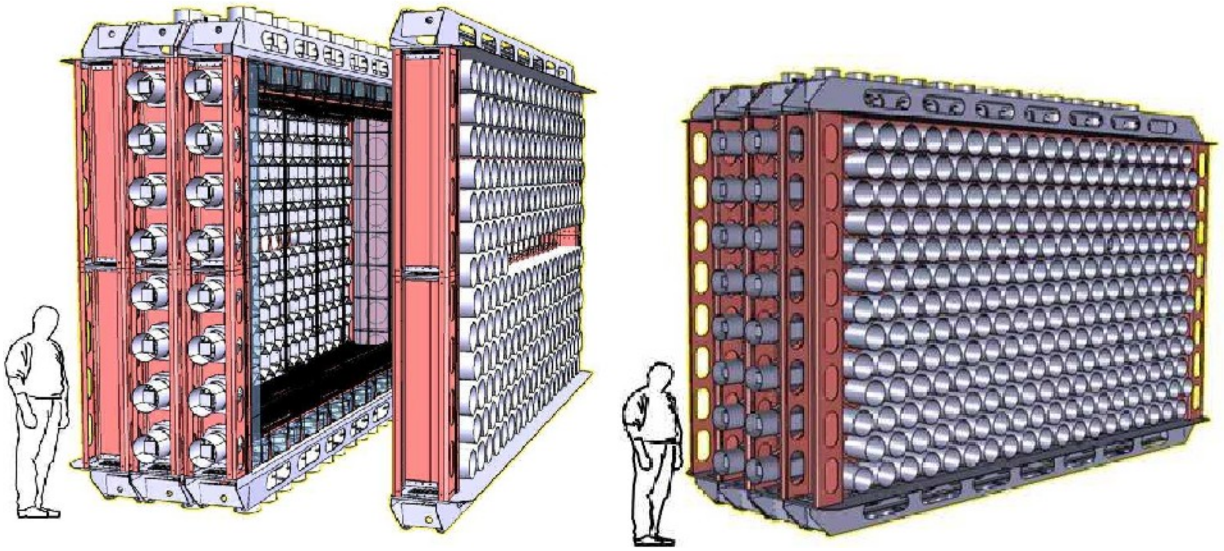


^{100}Mo: $T_{1/2}$ $(0\nu\beta\beta) > 1.1 \times 10^{24}$ y

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

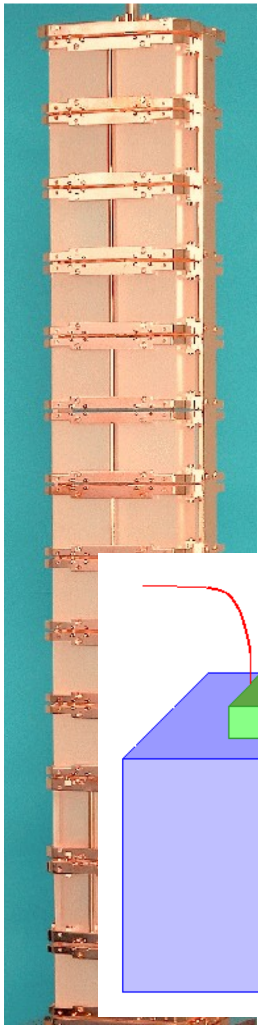
F Mauger, TAUP09

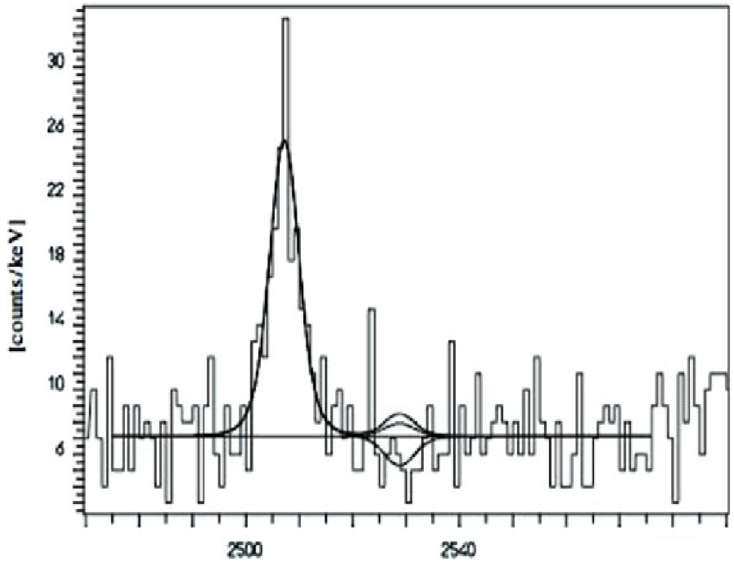
SuperNEMO: tracking calorimeter modules enriched ^{82}Se, ^{150}Nd



expect sensitivity: $T_{1/2}$ $(0\nu\beta\beta) > 10^{26}$

Searching for $0\nu\beta\beta$: TeO_2 cryobolometers: CUORICINO → CUORE



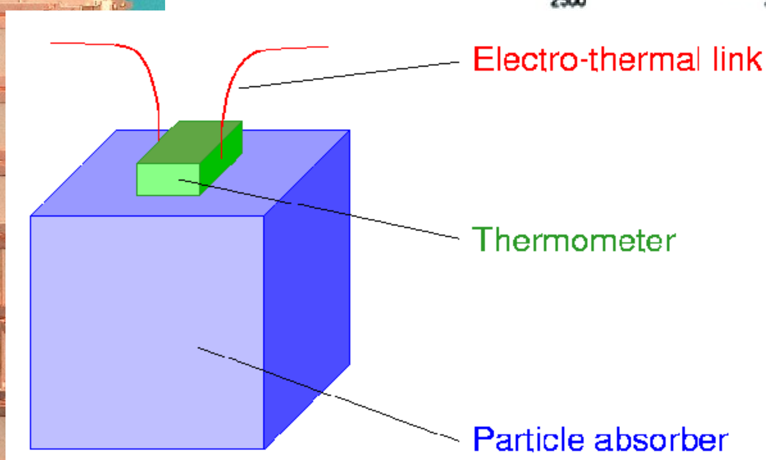


CUORICINO:

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

$\Rightarrow m_{ee} < 0.19 – 0.68$ eV

PRC 78 (2008) 35502



In 5 years of live running time

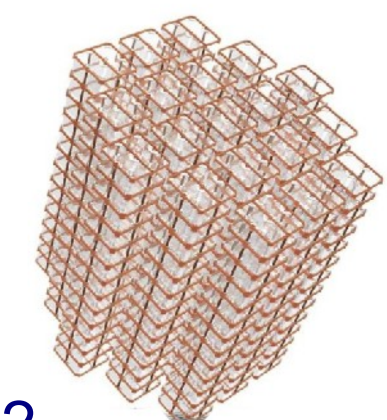
Background [c/keV/kg/y]	ΔE_{FWHM} [keV]	$\tau_{1/2}^{0\nu}$ [y] @ 68%C.L.	m_{ee} [meV] R(QRPA)[1]	pn(QRPA)[2]	ISM[3]	IBM-2[4]
0.01	5	**2.1×10^{26}**	35÷66	41÷67	65÷82	41
0.001	5	**6.5×10^{26}**	20÷38	23÷38	37÷47	23

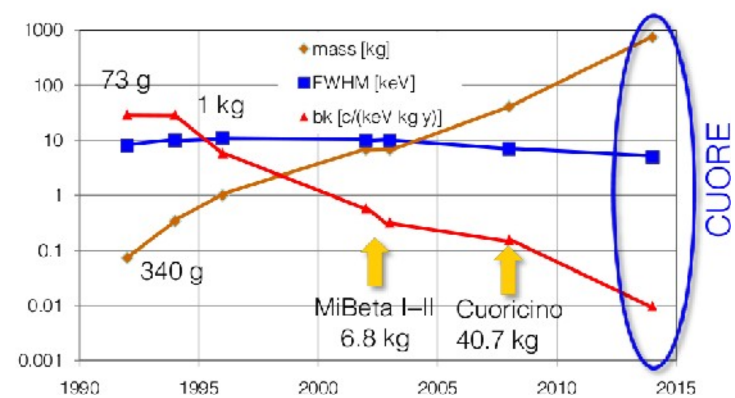
1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

starting:

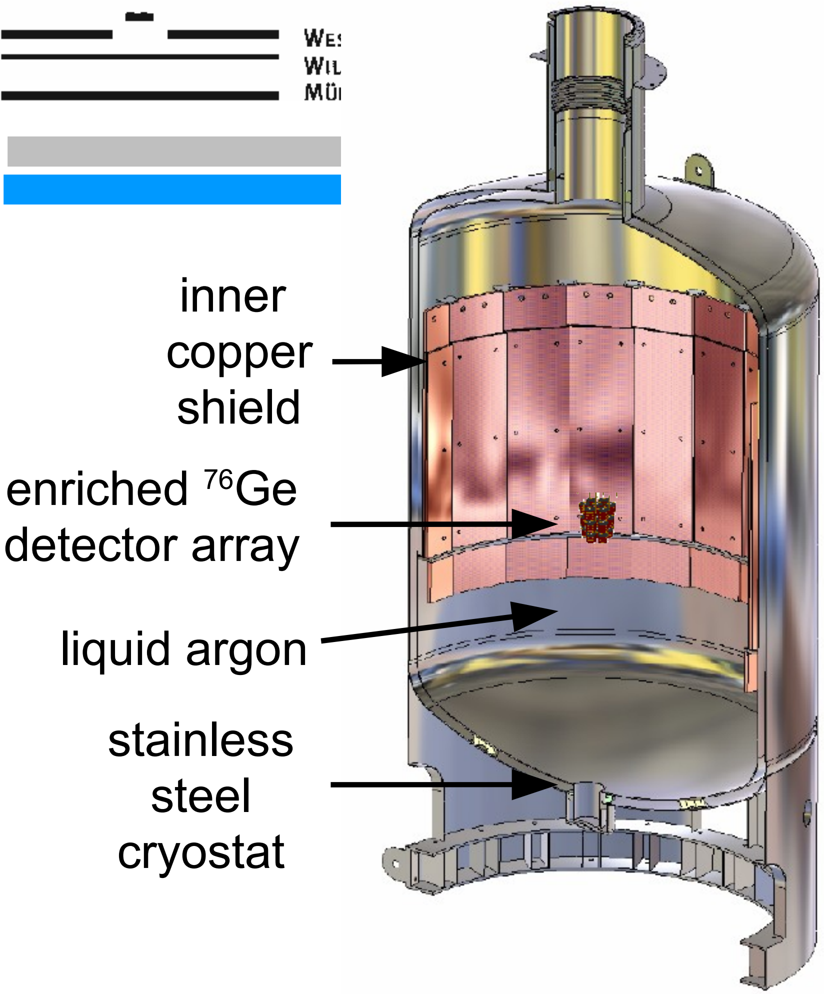
CUORE: 741 kg TeO_2

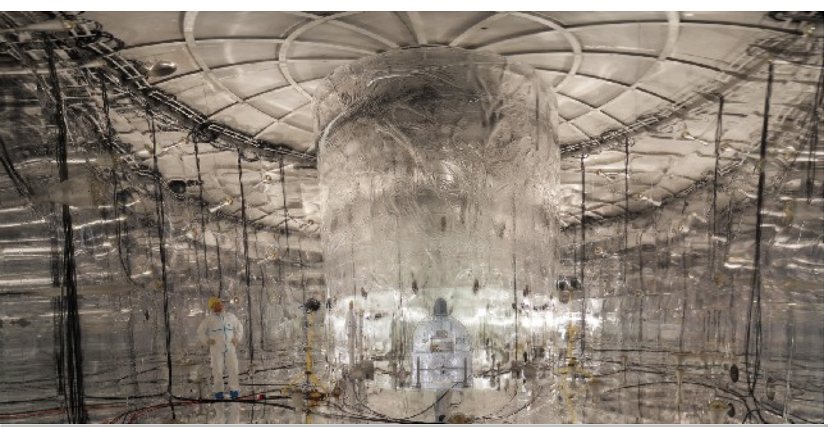
CUORE-0 will start in 2012





The GERDA experiment





New background reduction methods:

- naked Germanium detectors in noble liquid
- phase 2: point contact detectors p-type (BEGe) to identify multi-side events
- maybe use scintillation of LAr shield as veto

Phases of GERDA:

Phase 1: reuse old det. (Hd-Moscow, IGEX (18 kg)

1st test string with 3 non-enriched detectors
problem $^{42}Ar \rightarrow {}^{42}K \rightarrow {}^{42}Ca$, seems to be solved

since Oct 2011: 8 enriched detectors (14.6 kg)
3 natural detectors (7.6 kg)

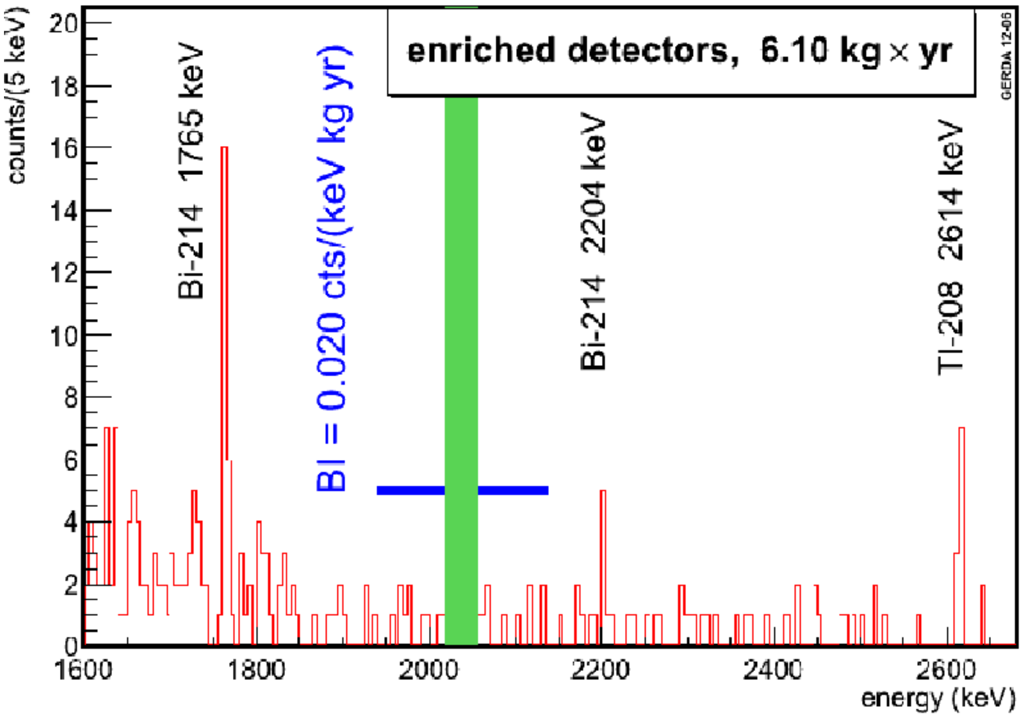
Phase 2: new enriched BEGe detectors (+18 kg)
expect start installing 1st BEGes in 2012

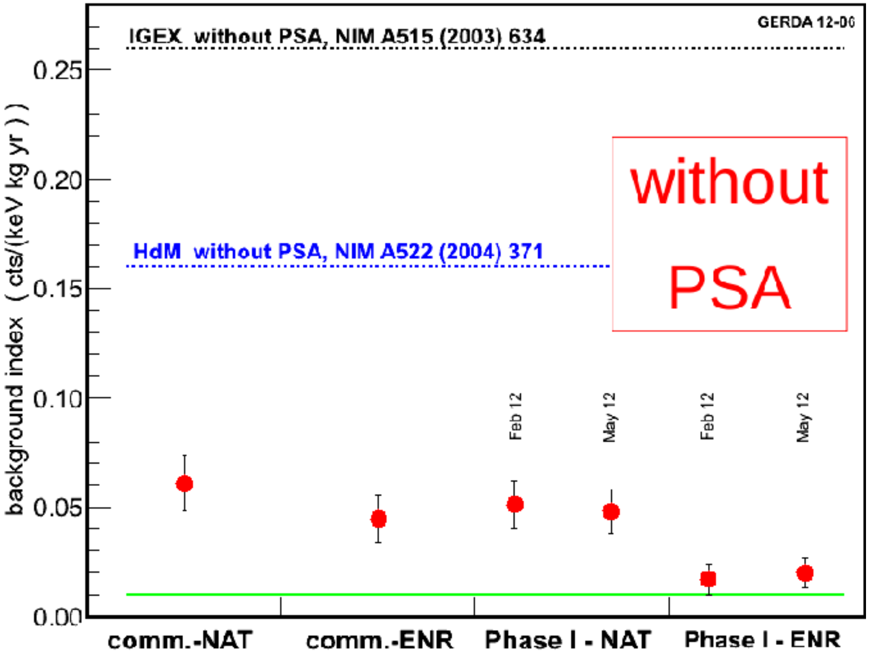
Opt. phase: many detectors (with MAJORANA, 500 kg)

The GERDA experiment

The GERDA background index (BI)

from P. Grabmayr's talk at Neutrino 2012





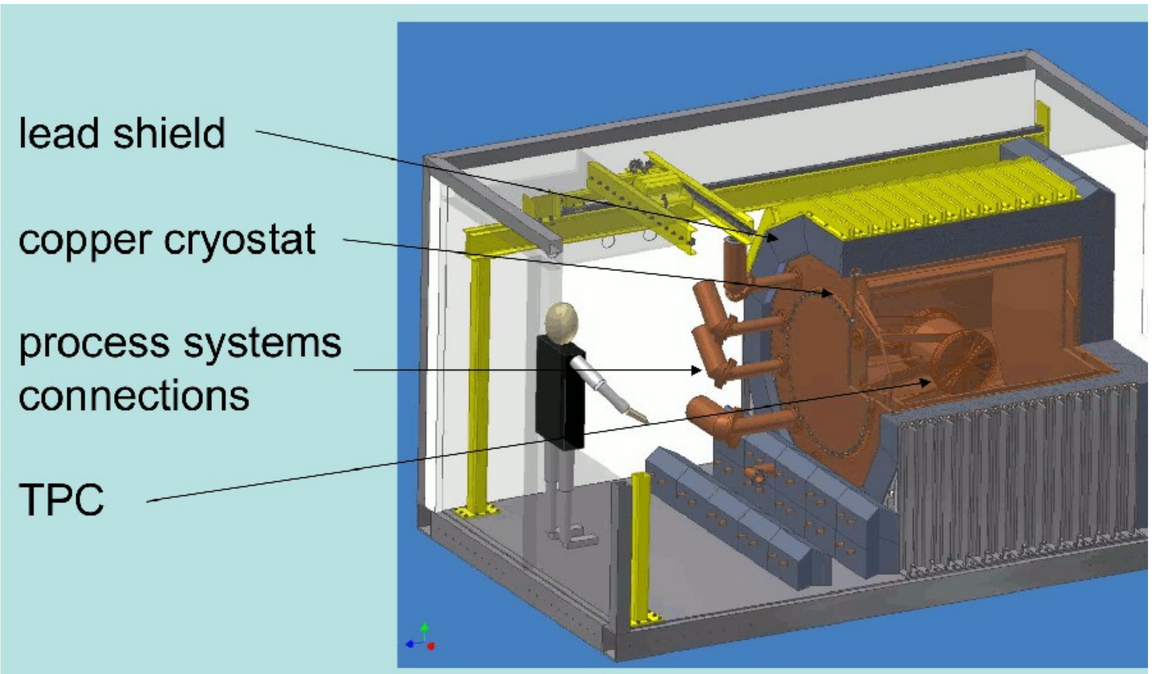
window: 200 – 40 = 160 keV

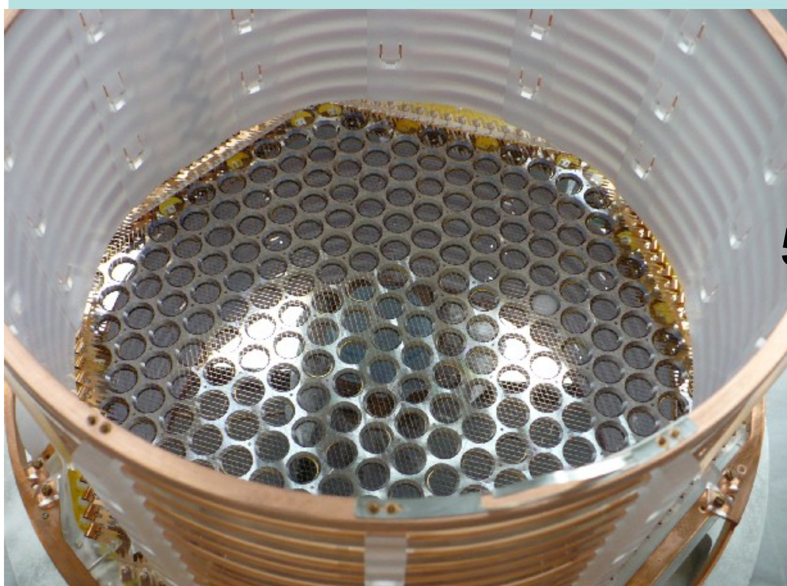
BI = 0.020 +0.006 -0.004 cts/ (keV kg yr) [68% coverage]

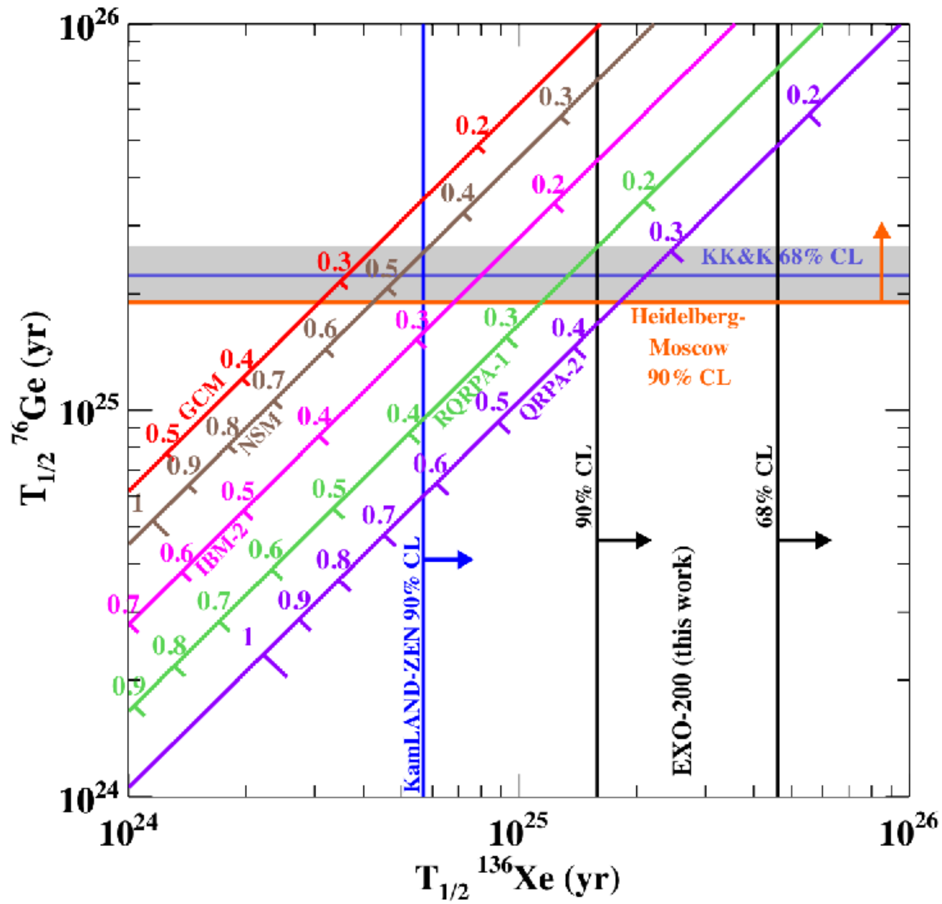
duty factor: usually 95% ;
one run not used for physics analysis because of temperature instabilities (overall duty cycle 80%)

Running since 2011: EXO 200

200 kg enriched ^{136}Xe at WIPP/New Mexico







5 events observed, 7.5 background events expected

$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

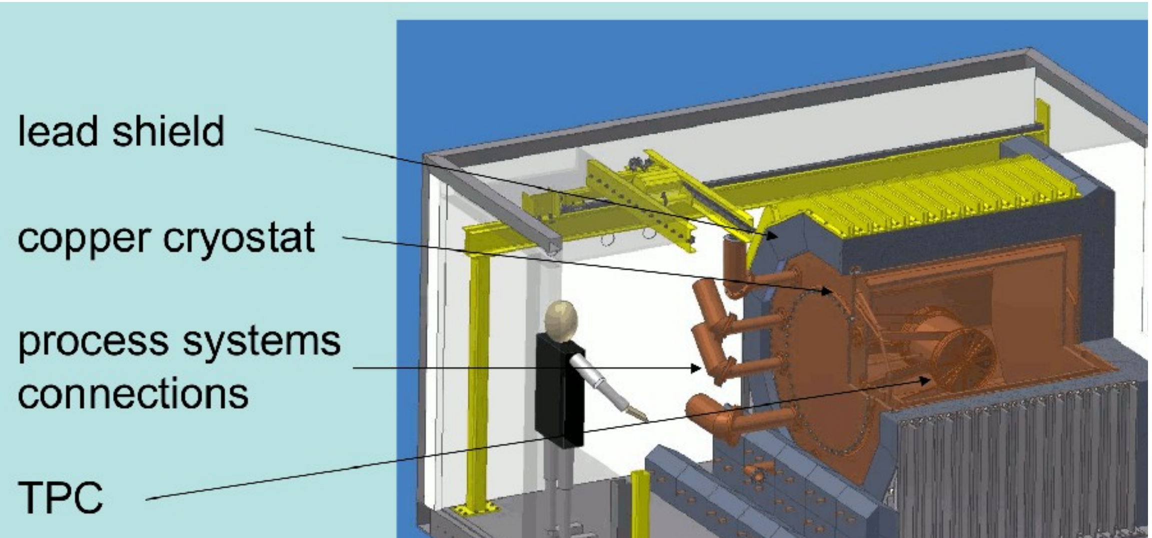
$\langle m_{\beta\beta} \rangle < 140\text{–}380$ meV

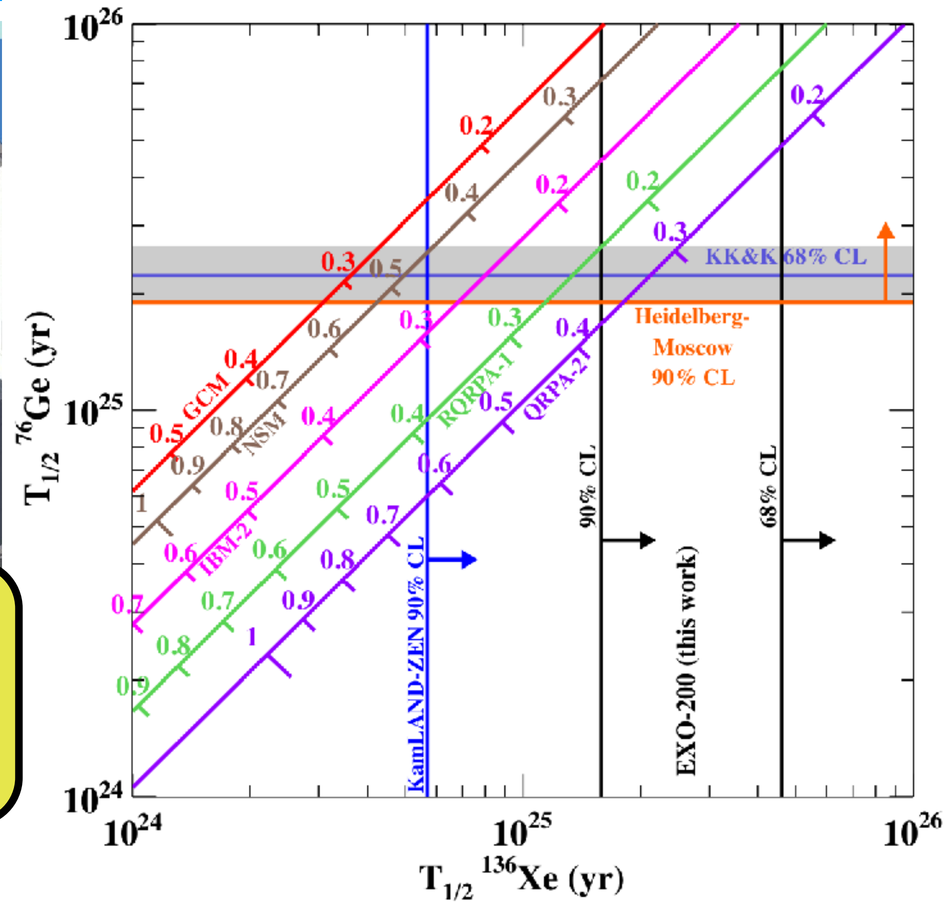
(90% C.L.)

arXiv:1205.5608 – Subm. to PRL

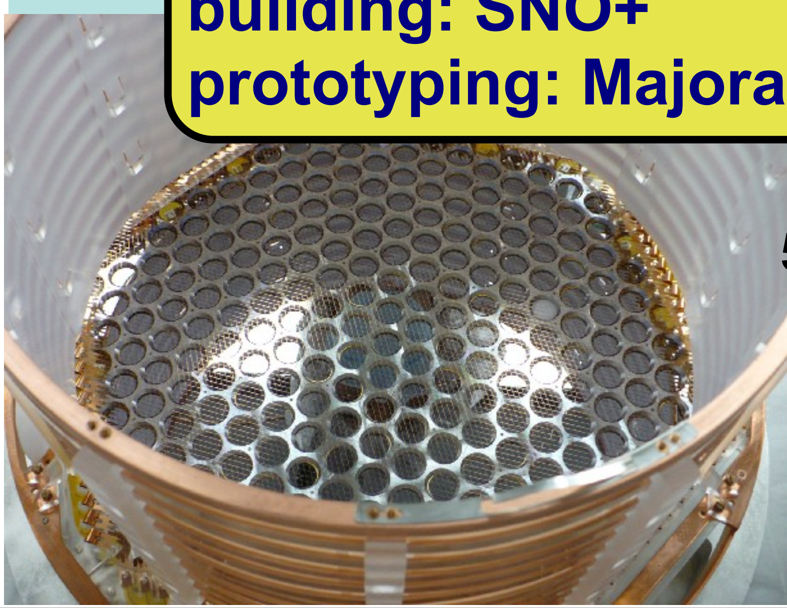
Running since 2011: EXO 200

200 kg enriched ^{136}Xe at WIPP/New Mexico





running: KamLAND-Zen
building: SNO+
prototyping: Majorana, Cobra, ..



5 events observed, 7.5 background events expected

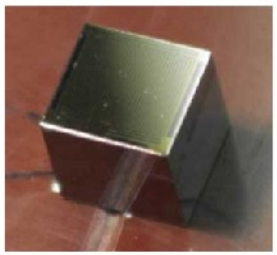
$$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}\ \text{yr}$$

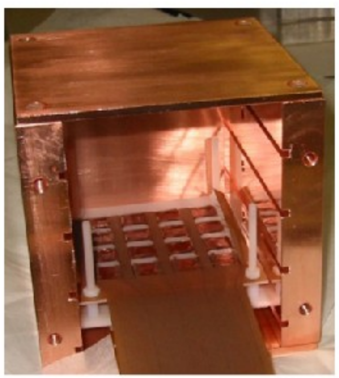
$$\langle m_{\beta\beta} \rangle < 140\text{–}380\ \text{meV}$$

(90% C.L.)

arXiv:1205.5608 – Subm. to PRL

R&D study: COBRA
CnZnTe detectors at room temperature





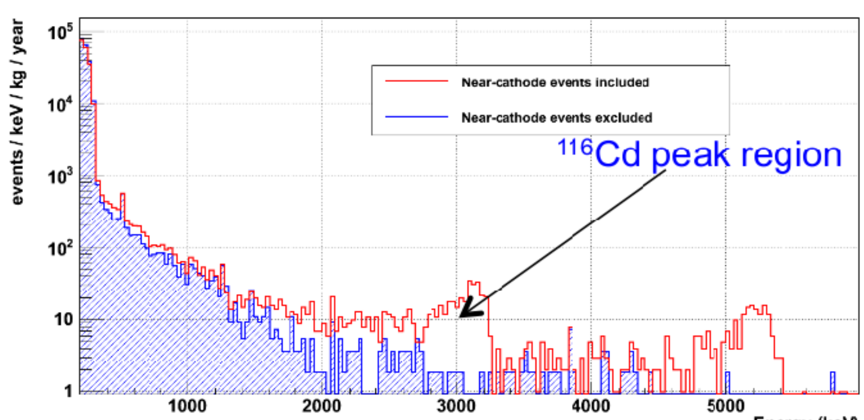
- Source = detector
- Focus on 116Cd
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Tracking/Pixelisation („Solid state TPC“)

K. Zuber, Phys. Lett. B 519,1 (2001)

Current spectrum (black), **12.73 kg*days**

Background at 2813 keV about 1 ct/keV/kg/yr

PSA very successful



from F. Piquemal, talk given at Neutrino 2012

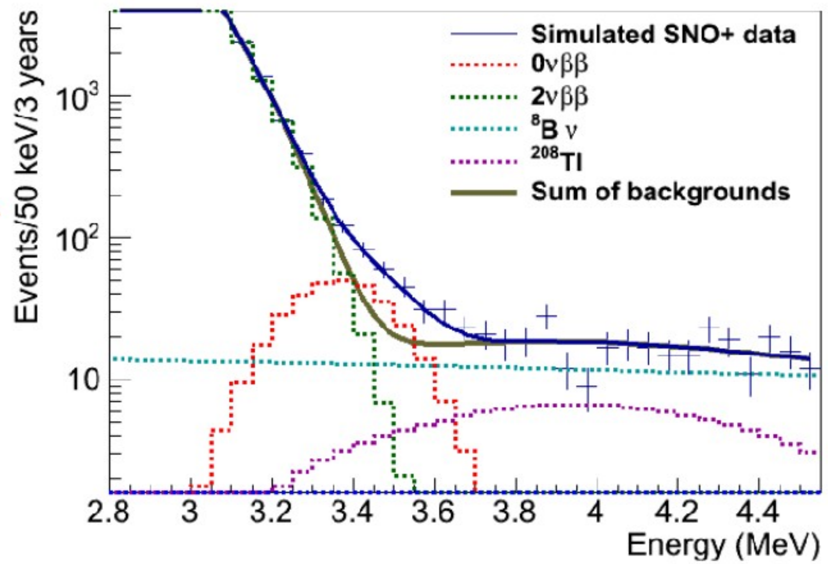
WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

SNO+

^{nat}Nd salt dissolved in liquid scintillator

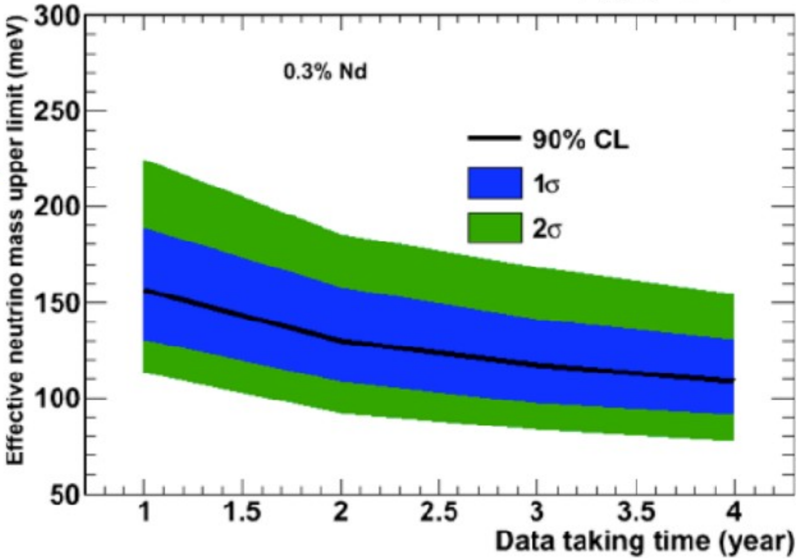
ββ-decay signal for 0.3% Nd-loaded scintillator

- signal at the level of Klapdor [Phys. Lett. B 586 (2004) 198]
- 2.4 live-years data simulated
- ^{214}Bi tagged and removed with ^{214}Bi-Po
- ^{208}Tl constrained with ^{212}Bi-Po delayed coincidence
- $t_{1/2}$ 3 min alpha tag of ^{208}Tl rejects 90%



Neutrino mass sensitivity for 0.3% Nd loading (44 kg of ^{150}Nd)

- IBM-2 [Phys. Rev. C 79 (2009) 044301] NME values were used (includes deformation)
- radioactivity backgrounds at the levels achieved by Borexino



from F. Piquemal, talk given at Neutrino 2012

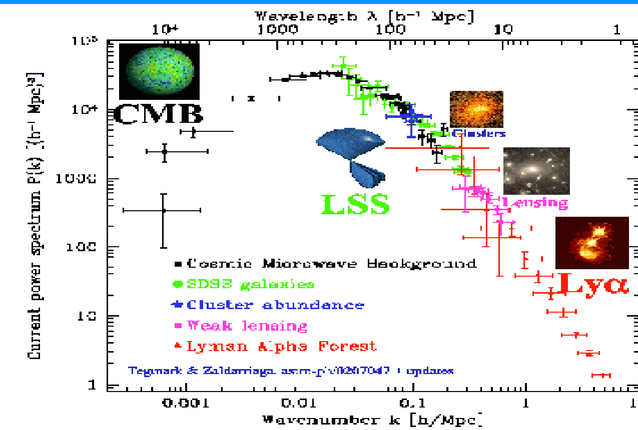
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

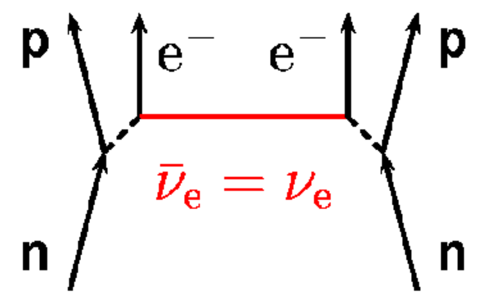
current sensitivity: $\Sigma m(\nu_i) \approx 0.4 – 1$ eV



2) Search for 0νββ

Sensitive to Majorana neutrinos

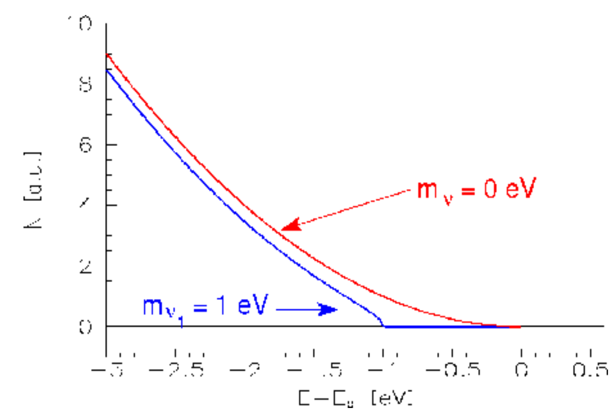
Evidence for $m_{ee}(\nu) \approx 0.4$ eV (Klapdor-Kleingrothaus et al.)?



3) Direct neutrino mass determination:

No further assumptions needed, 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**
  measure charged decay prod., E-, p-conservation
  β-decay searchs for $m(\nu_e)$ - tritium β spectrometers
  - ^{187}Re bolometers



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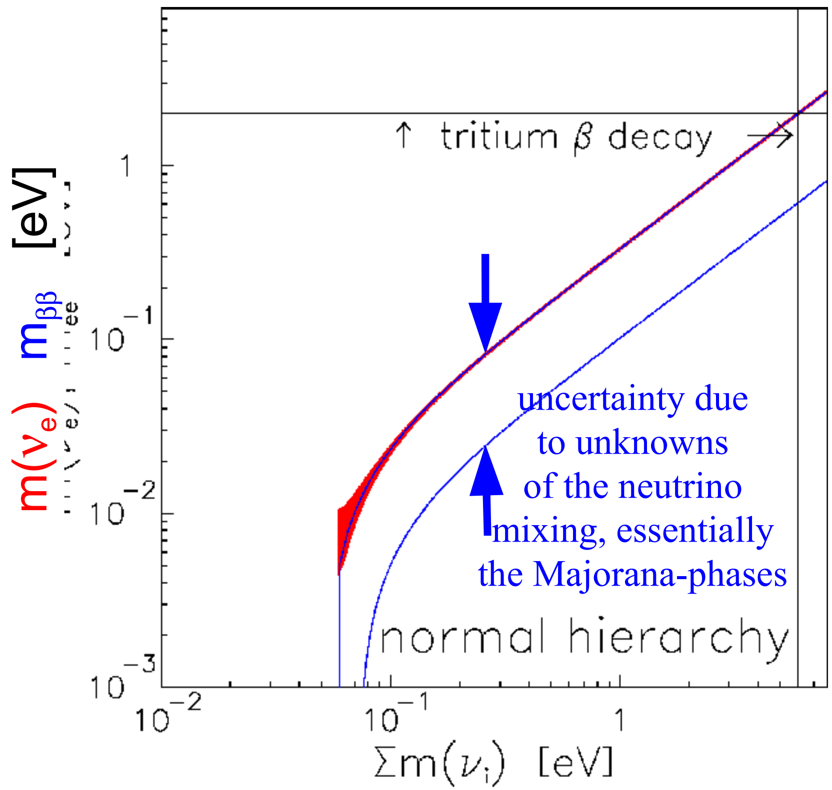
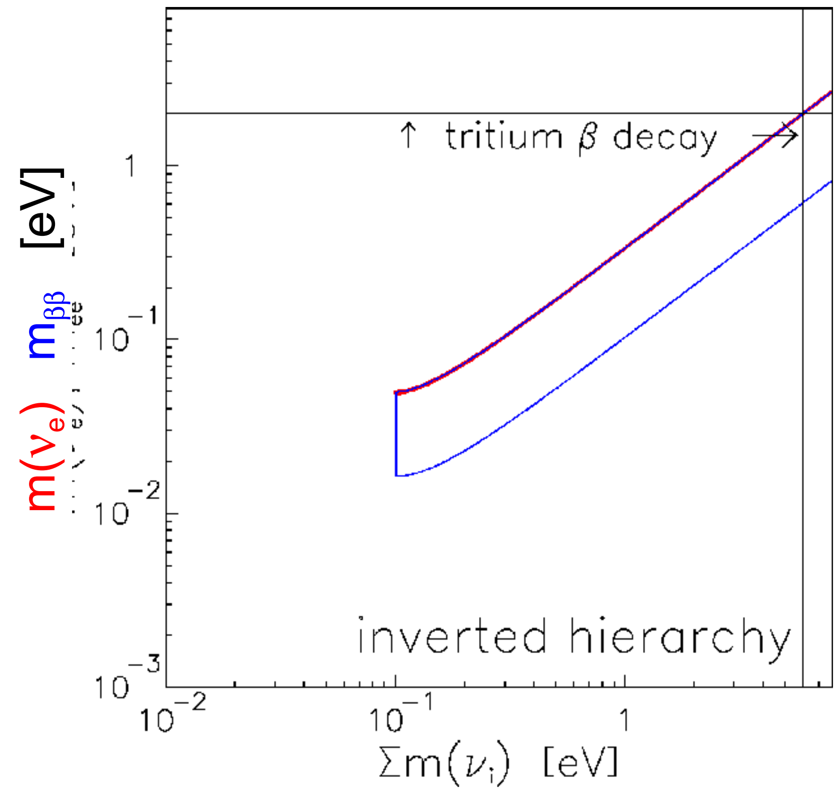
Comparison of the different approaches to the neutrino mass

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

Neutrino mass from supernovae (time-of-flight)

Only one SN detected in ν`s: SN1987a

Simple dependence for sharp ν emission in time:

$$\Delta t = \frac{L}{c} - \frac{L}{\beta_\nu} = L - \frac{L}{1-\frac{m_\nu^2}{2E_\nu^2}}$$

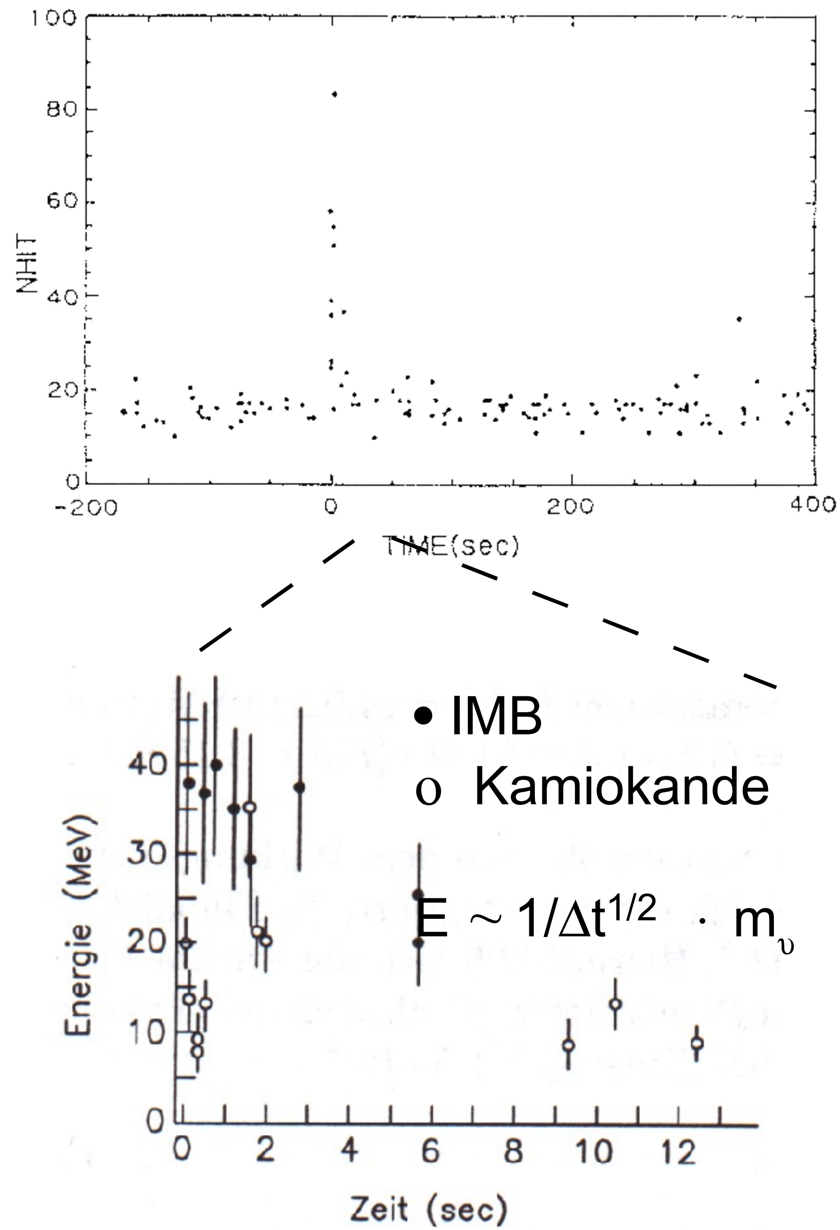
$$\approx L - L\cdot\left(1+\frac{m_\nu^2}{2E_\nu^2}\right) = -L\cdot\frac{m_\nu^2}{2E_\nu^2}$$

with:

$$m^2 = E^2 - p^2 = E^2(1-\beta^2)$$

$$= E^2(1+\beta)(1-\beta) \approx 2E^2(1-\beta)$$

$$\Rightarrow \beta = 1 - \frac{m^2}{2E^2}$$



Neutrino mass from supernovae (time-of-flight)

Only one SN detected in ν`s: SN1987a

No energy versus time dependence visible

→ only upper limit on neutrino mass

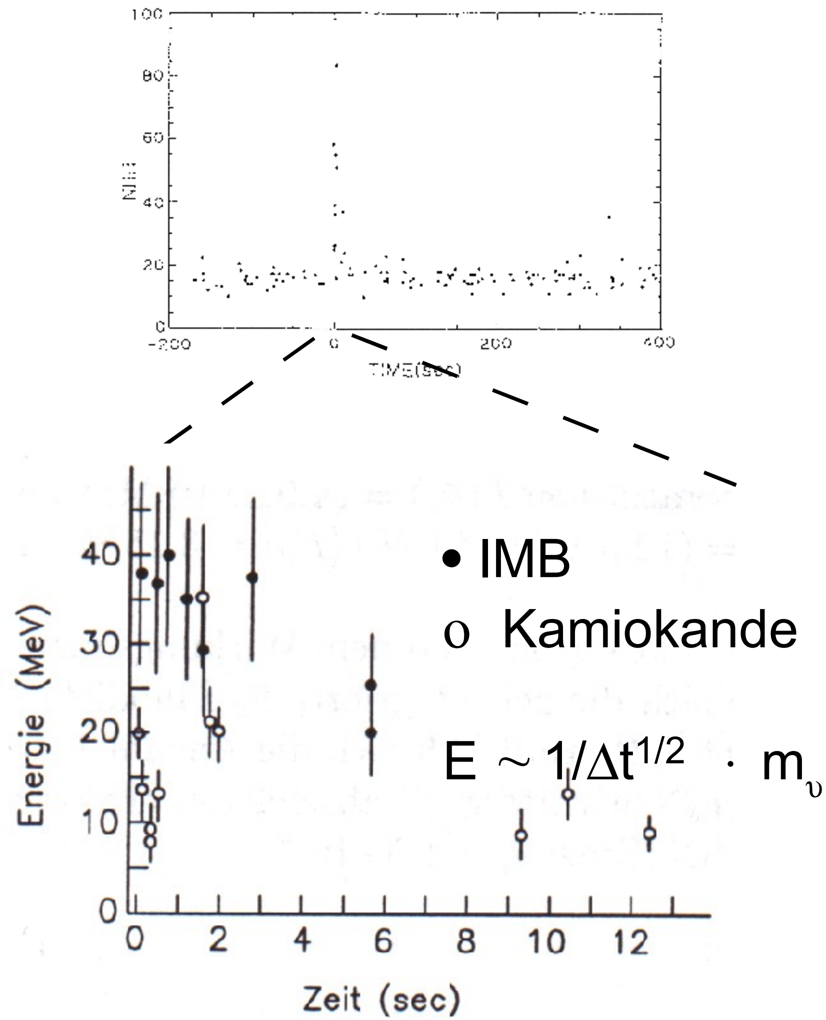
Results depends on underlying SN model, e.g.:

$m(\nu_e) < 5.7$ eV

T.J. Loredo et al., PRD65 (2002) 063002

$m(\nu_e) < 5.8$ eV

G. Pagliarolia, F. Rossi-Torresa and F. Vissani, Astropart. Phys. 33 (2010) 287

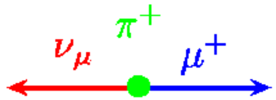


BUT
- galactic SN only about every 40 years
- not sensitive below 1eV (uncertainty of neutrino emission time spectrum)

Determination of „m(ν_μ)“ what does m(ν_μ) mean ?

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ (Two body decay)

Decay at rest:



$|\vec{p}_\nu| = |\vec{p}_\mu|$

$m_\pi = E_\nu + E_\mu$

$\rightarrow m_\nu^2 = m_\pi^2 + m_\mu^2 - 2 \cdot m_\pi \cdot \sqrt{m_\mu^2 + p_\mu^2}$

3 different Experiments:

Values from PDG2000

Pionic atoms: $m_\pi = 139.570180(350)$ MeV

Myonium: $m_\mu = 105.658357(5)$ MeV

Magnetic spektrometer (PSI): $p_\mu = 29.791998(110)$ MeV

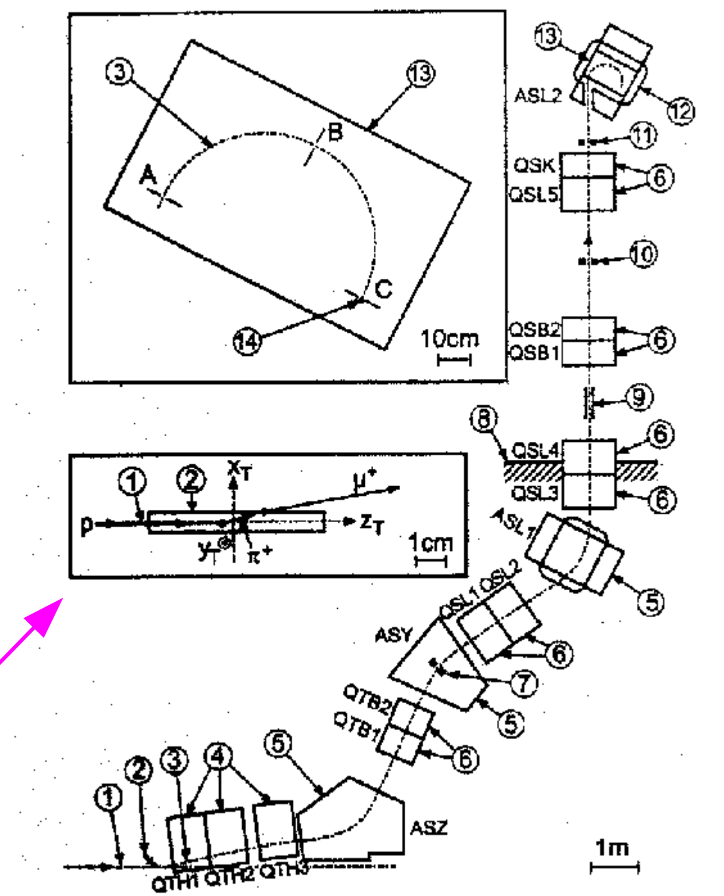


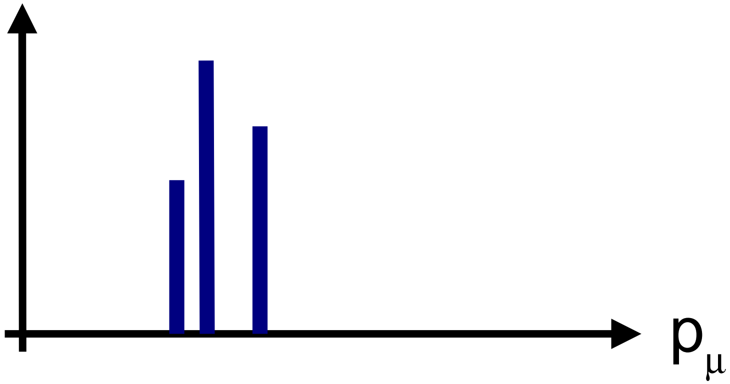
FIG. 1. Experimental setup. (1) Central trajectory of 590 MeV proton beam; (2) graphite target; (3) central trajectory of muon beam; (4) half-quadrupole magnets; (5) dipole magnets; (6) quadrupole magnets; (7) collimator defining the beam momentum acceptance; (8) concrete shielding of proton channel; (9) crossed-field particle separator; (10) lead collimator; (11) remotely movable collimator system (normally open); (12) magnetic spectrometer; (13) pole of spectrometer; (14) muon detectors (silicon microstrip and single surface-barrier detectors); A, B, C: copper collimators.

$\rightarrow m(\nu_\mu) < 170 \mathrm{keV/c^2}$ (95% c.l.) (K. Assamagan *et al.*, Phys. Rev. D53 (1996) 6065)

PDG2000: $m(\nu_\mu) < 190 \mathrm{keV/c^2}$ (95% c.l.)

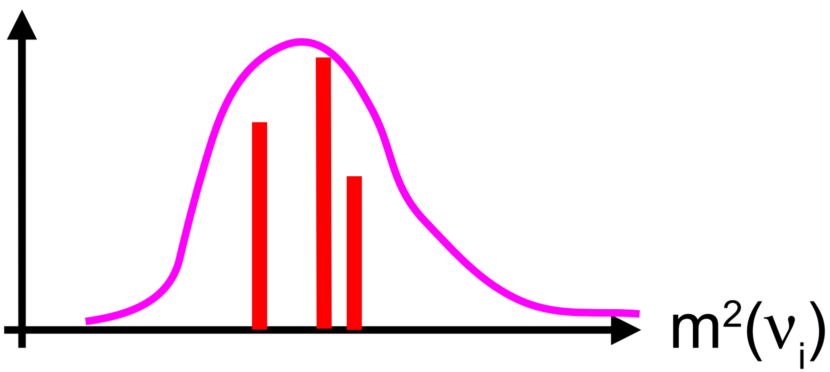
Different neutrino mass states ν_i

⇒ Measure different muon momenta p_μ with probability $|U_{\mu i}^2|$



$$m_\nu^2 = m_\mu^2 + m_\pi^2 - 2m_\pi (m_\mu^2 + p_\mu^2)^{1/2}$$

⇒ 3 different neutrino masses $m^2(\nu_i)$ with probability $|U_{\mu i}^2|$



if different mass states can experimentally not be resolved:
⇒ $m^2(\nu_\mu) := \Sigma_i \cdot |U_{\mu i}^2| \cdot m^2(\nu_i)$

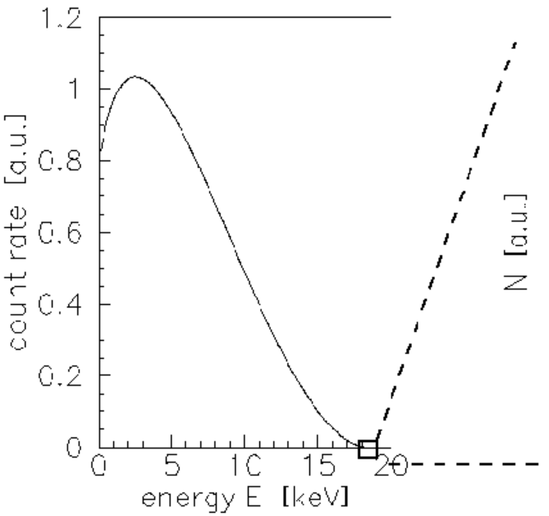
Direct determination of $m(\nu_e)$ from β decay

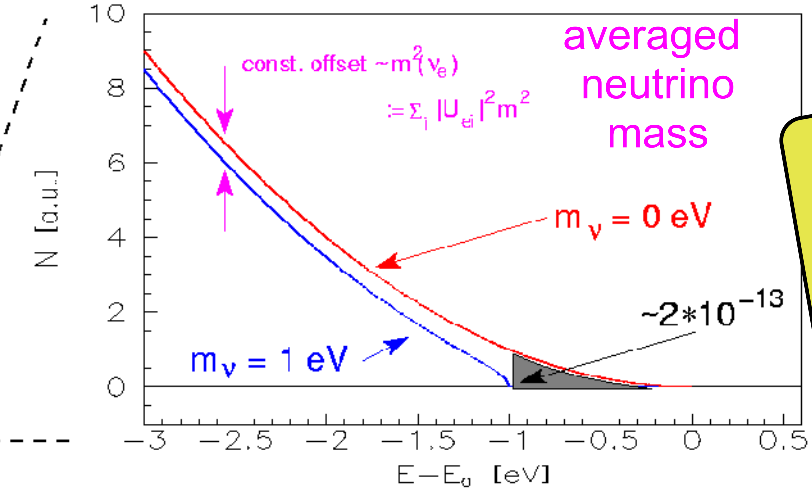
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

β electron energy spectrum:

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

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





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)

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

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

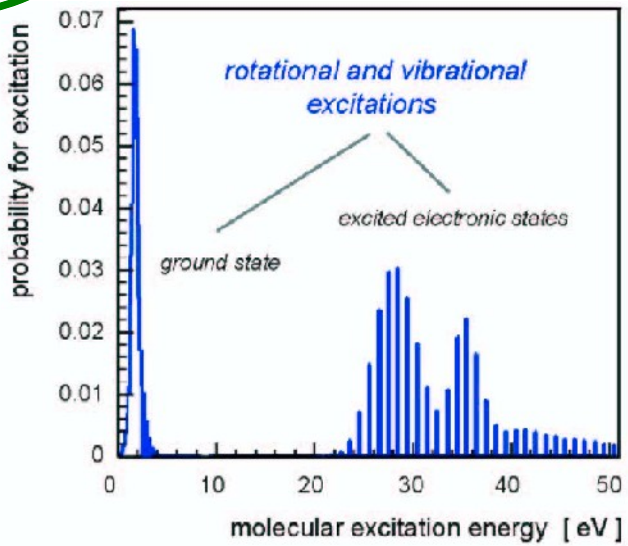
$$W_j = |\langle\Psi_0|\Psi_{f,j}\rangle|^2$$

⇒ look at endpoint region

Using $\varepsilon_j = E_0 - V_j - E$

$$\frac{d^2N}{dt\,dE} = A \cdot F(E,Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \sqrt{\varepsilon_j^2 - m^2(\nu_c)} \cdot \Theta(\varepsilon_j - m(\nu_c))$$

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)



⇒ electronic final states are very important

Including neutrino mixing

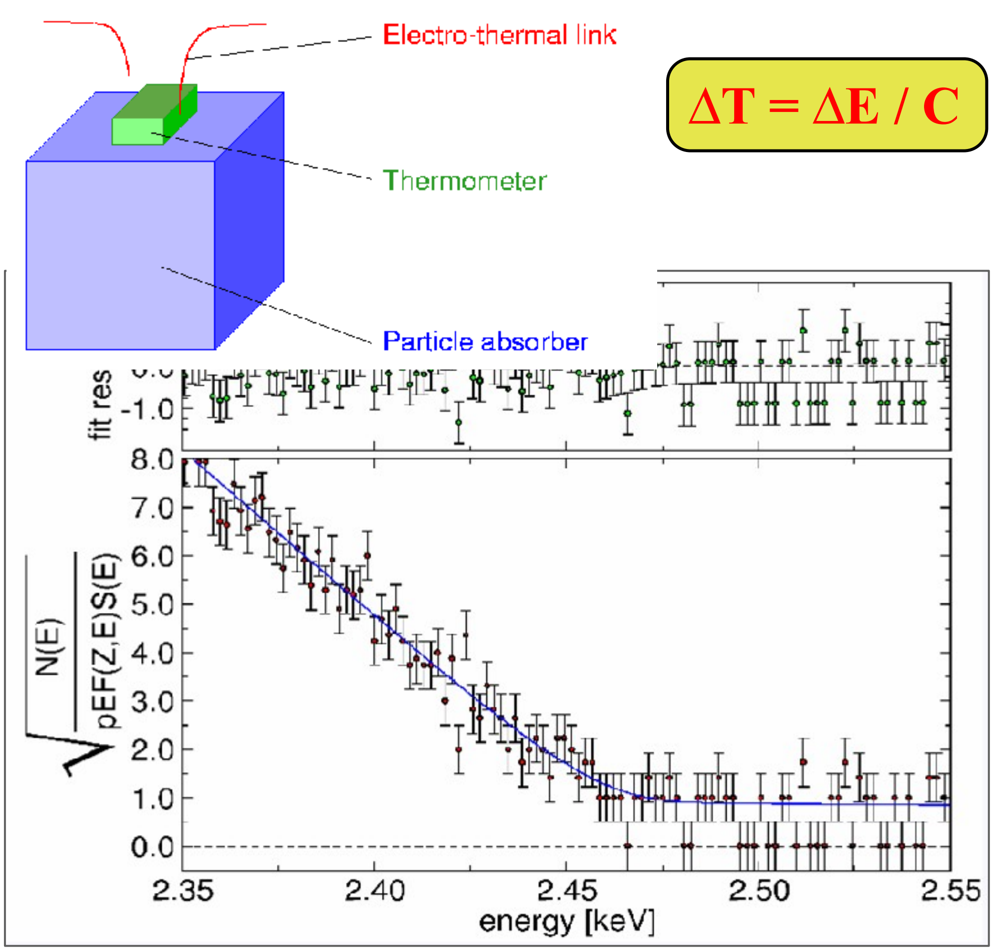
$$\frac{d^2N}{dt\,dE} = A \cdot F(E,Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \left(\sum_i |U_{ci}|^2 \sqrt{\varepsilon_j^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i))\right)$$

⇒ "Electron neutrino mass"

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

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

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



$\Delta T = \Delta E / C$

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 beta 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

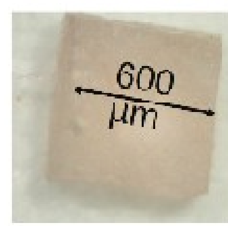
Challenges of cryogenic bolometers:
- measures the full spectrum (pile-up)
- need large arrays to get statistics
- understanding spectrum
- still energy losses or trapping possible

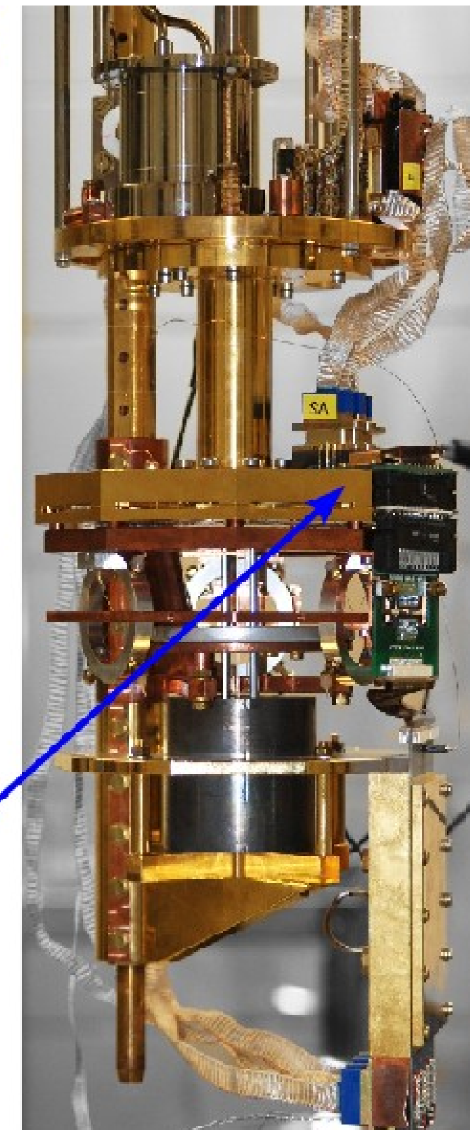
MARE-1 @ Milano-Bicocca

- 6x6 array of Si-implanted thermistors (NASA/GSFC)
- 0.5 mg $AgReO_4$ crystals
- $\Delta E \approx 30$ eV, $\tau_R \approx 250$ μs
- experimental setup for up to 8 arrays completed
- starting with 72 pixels in 2011
- up to 10^{10} events in 4 years → ~ 4 eV sensitivity

MARE-1 @ Genova

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



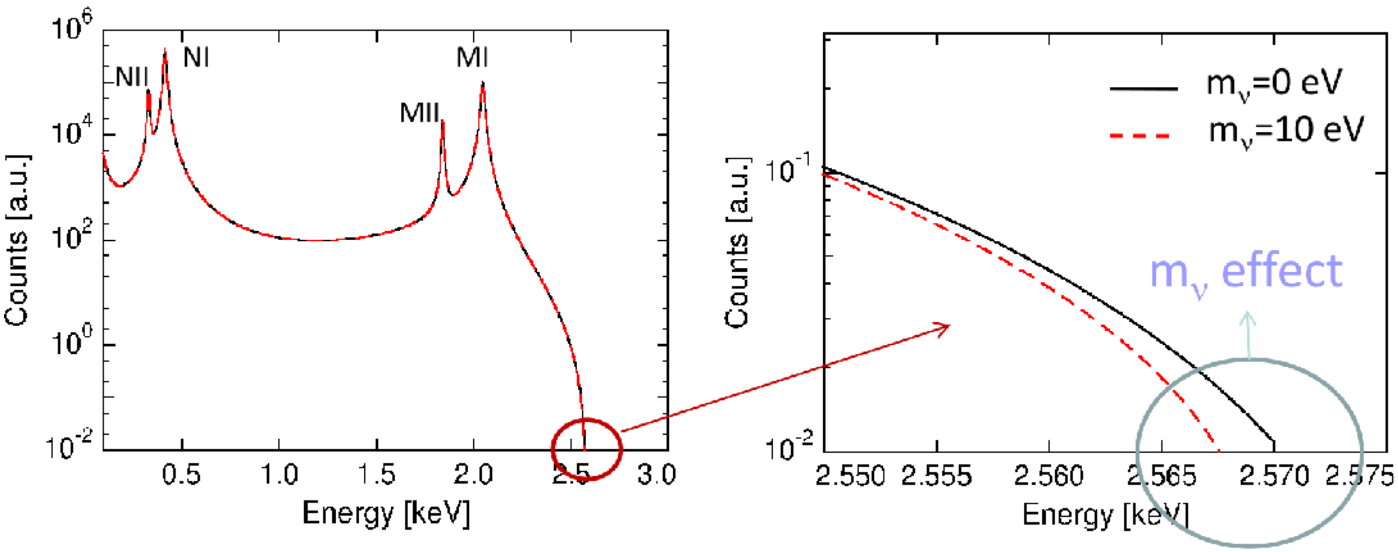


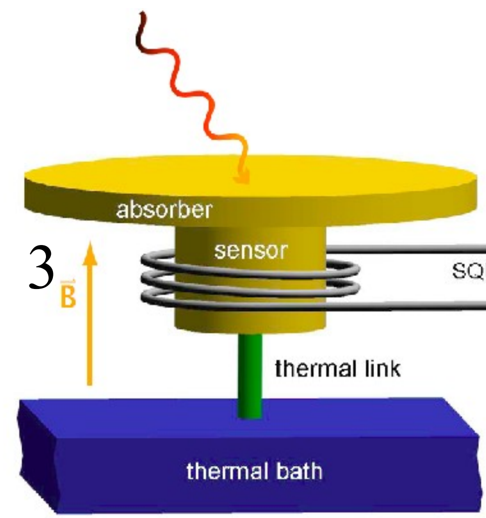
Angelo Nucciotti, Meudon 2011

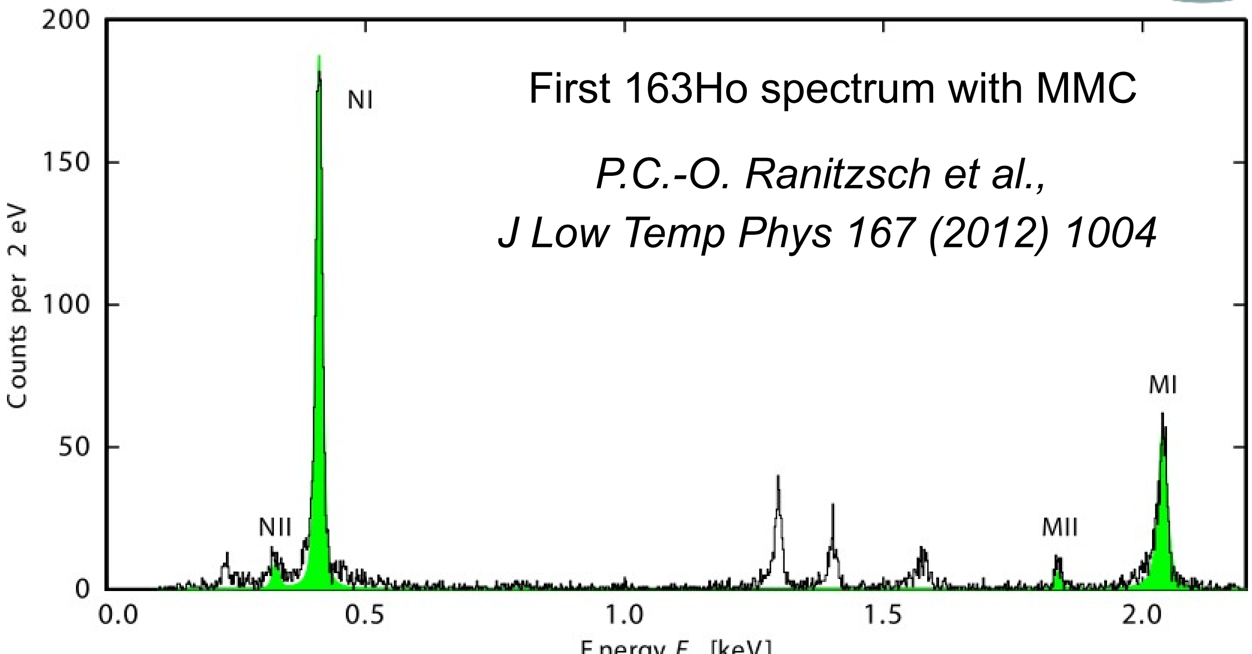
ECHO neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

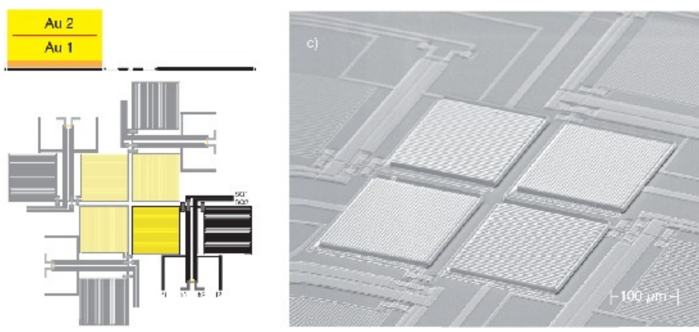
Westfälische Wilhelms-Universität Münster

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









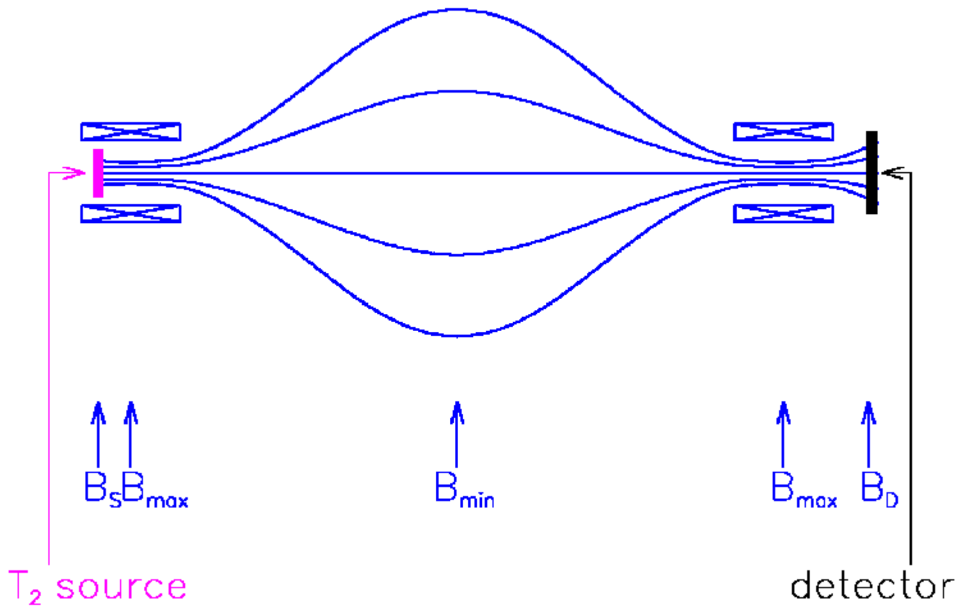
courtesy L. Gastaldo

Principle of the MAC-E-Filter

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

- Two supercond. solenoids compose magnetic guiding field

- Electron source (T_2) in left solenoid



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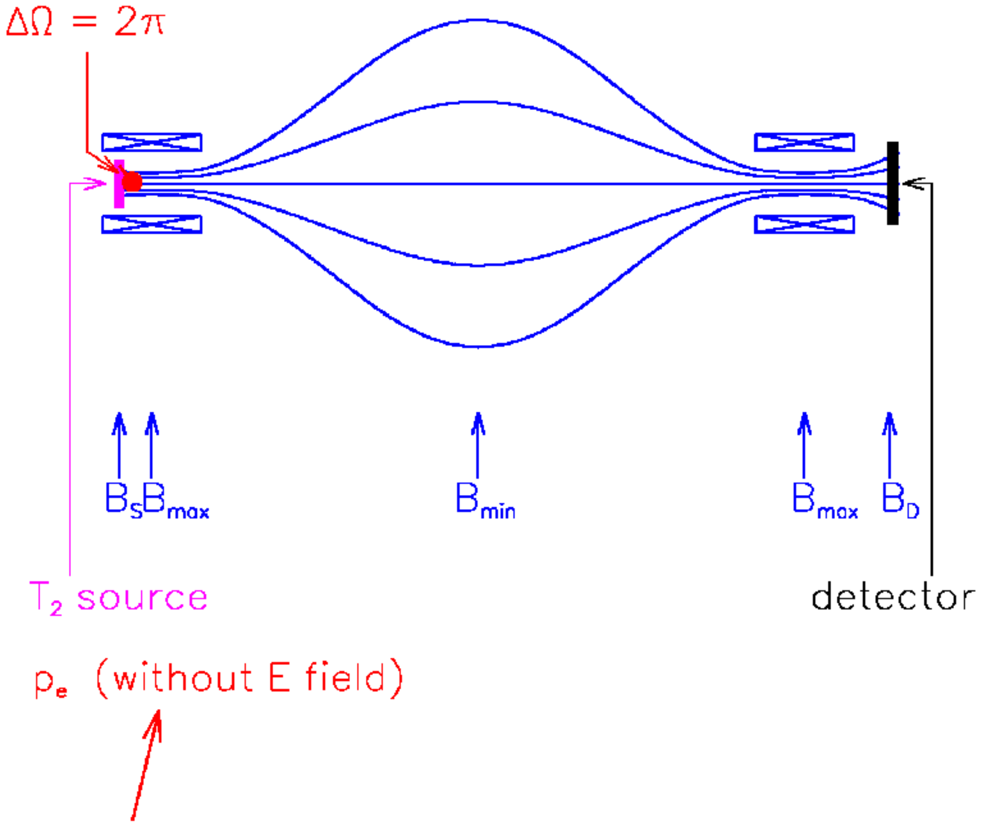
- adiabatic transformation: $\mu = E/B = \text{const.}$
  $\Rightarrow$ parallel e^- beam



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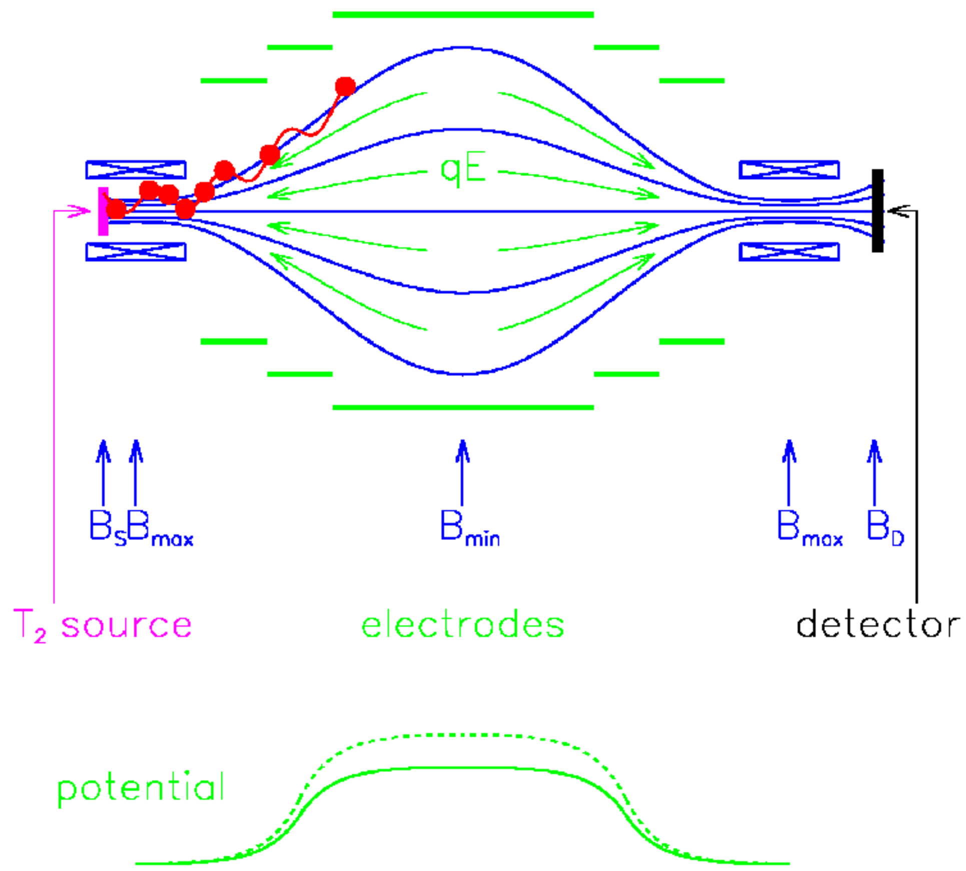
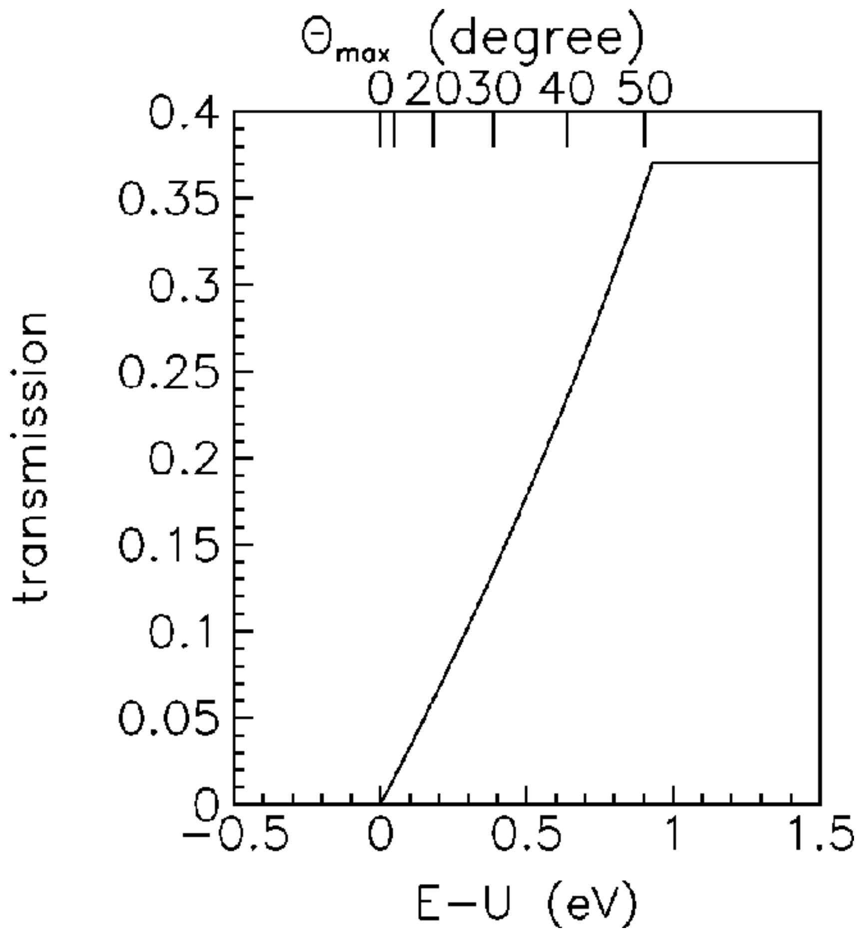
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E/B = \text{const.}$
  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E B_{min}/B_{max} = E A_{s,eff}/A_{analyse}$ $\approx$ 4.8 eV (Mainz) = 0.93 eV (KATRIN)



Principle of the MAC-E-Filter

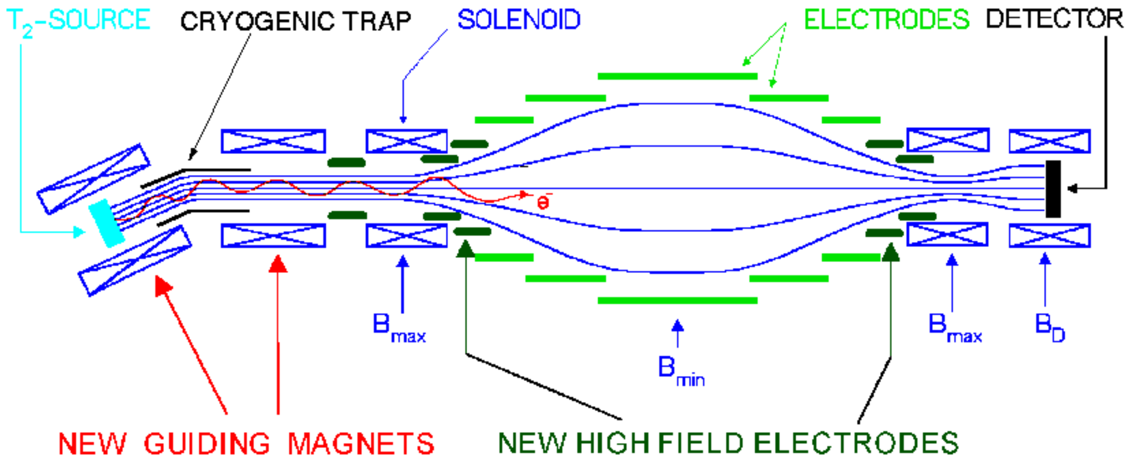
Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

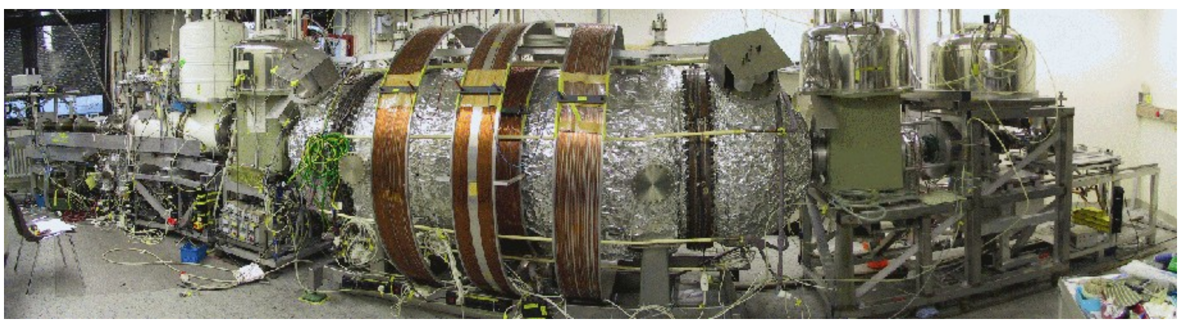
⇒ sharp integrating transmission function without tails:

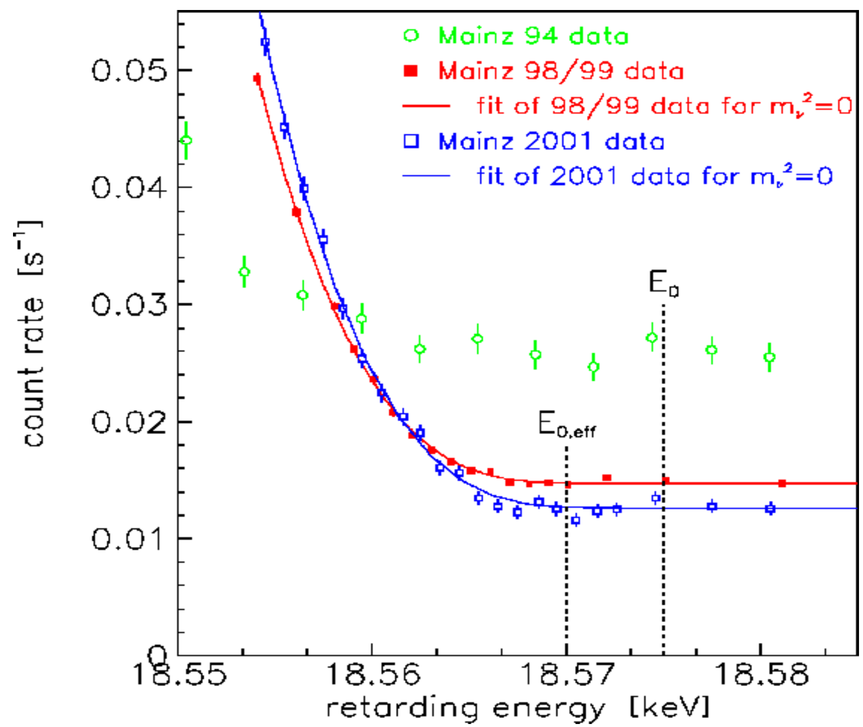


$\Delta E = E\,B_{min}/B_{max} = E\,A_{s,eff}/A_{analyse}$ ≈ 4.8 eV (Mainz) = 0.93 eV (KATRIN)

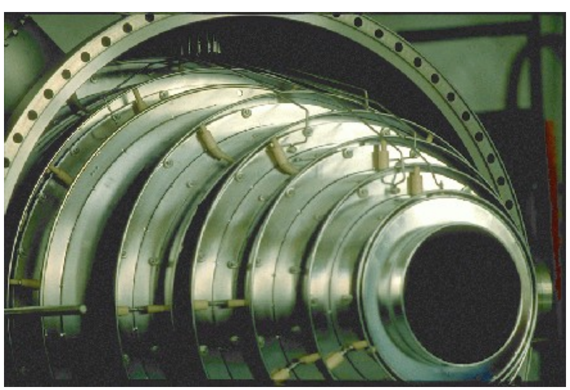
The Mainz Neutrino Mass Experiment Phase 2: 1997-2001







⇓

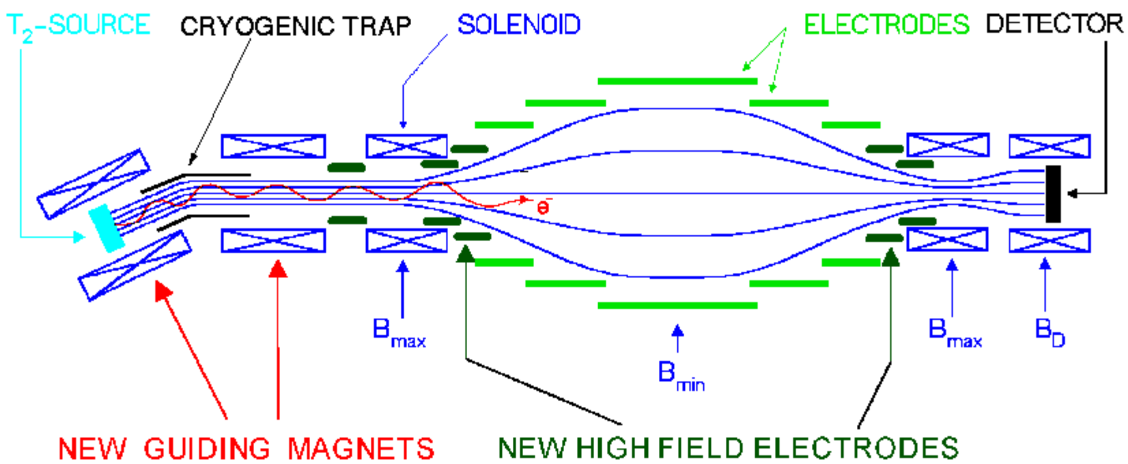


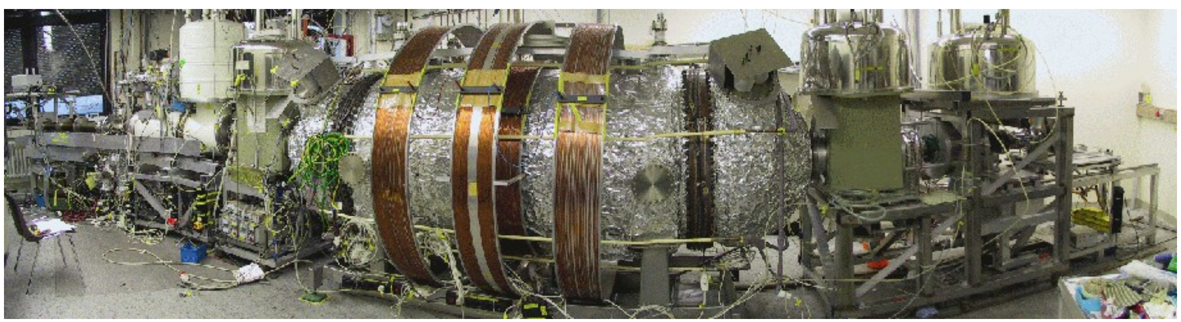
After all critical systematics measured by own experiment (atomic physics, surface and solid state physics:
inelastic scattering, self-charging, neighbour excitation):

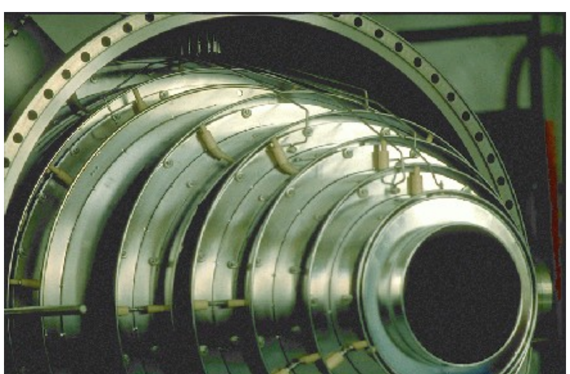
$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1\ eV^2 \quad \Rightarrow m(\nu) < 2.3\ eV$ (95% C.L.)

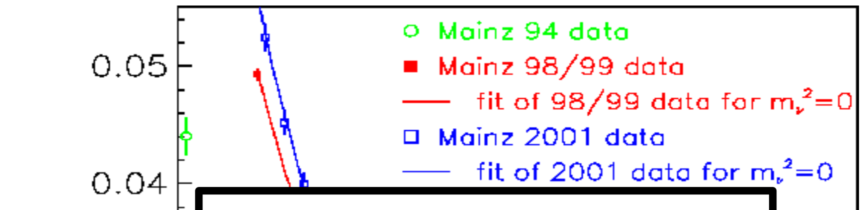
C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

The Mainz Neutrino Mass Experiment Phase 2: 1997-2001









Dr. Jochen Bonn

* 7.4.44

+ 27.8.12

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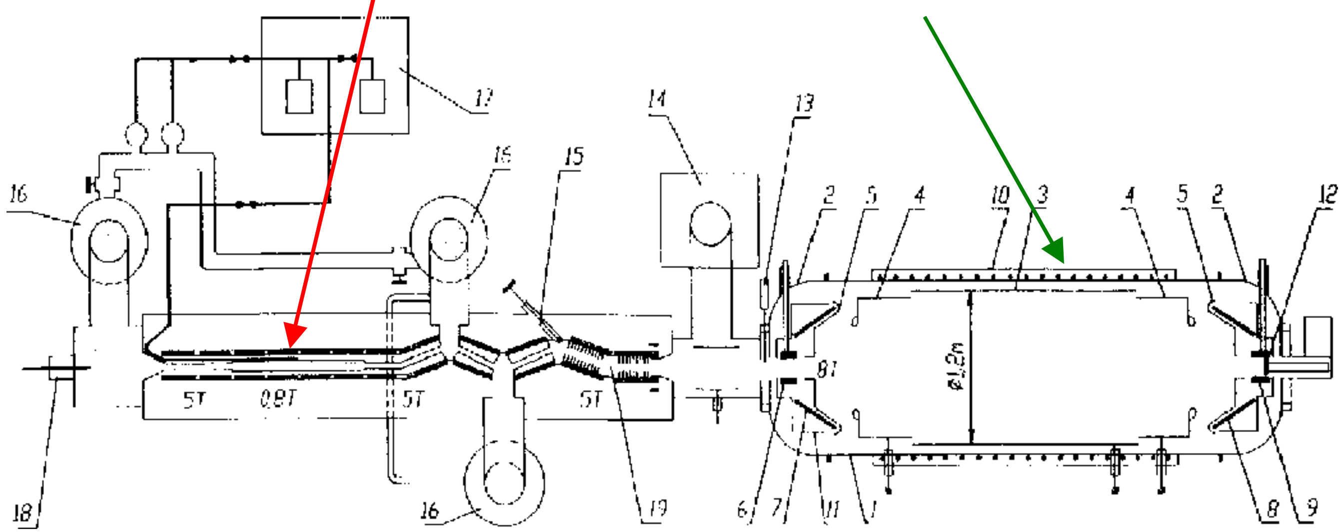
C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

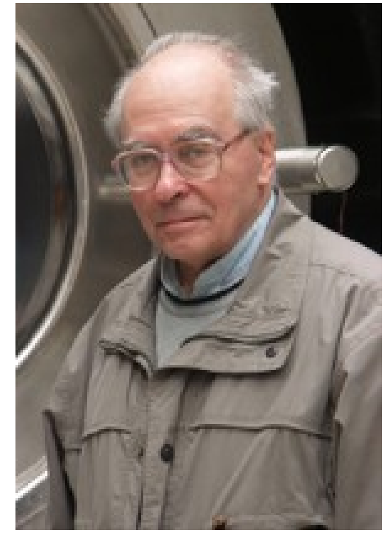
Westfälische Wilhelms-Universität Münster

The Troitsk Neutrino Mass Experiment

windowless gaseous T_2 source, similar to LANL

MAC-E-Filter, similar to Mainz





Vladimir Mikhailovich Lobashev 1934-2011

Luminosity: L = 0.6cm²

(L = ΔΩ/2π * A_{source})

Energy resolution: ΔE = 3.5eV

3 electrode system in 1.5m diameter UHV vessel ($p<10^{-9}$ mbar)

Re-analysis of Troitsk data

(better source thickness, better run selection)

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

m_β < 2.2 eV, 95% CL