Neutrino masses from double-β decay and kinematics experiments

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Last decade: the age of ν physics

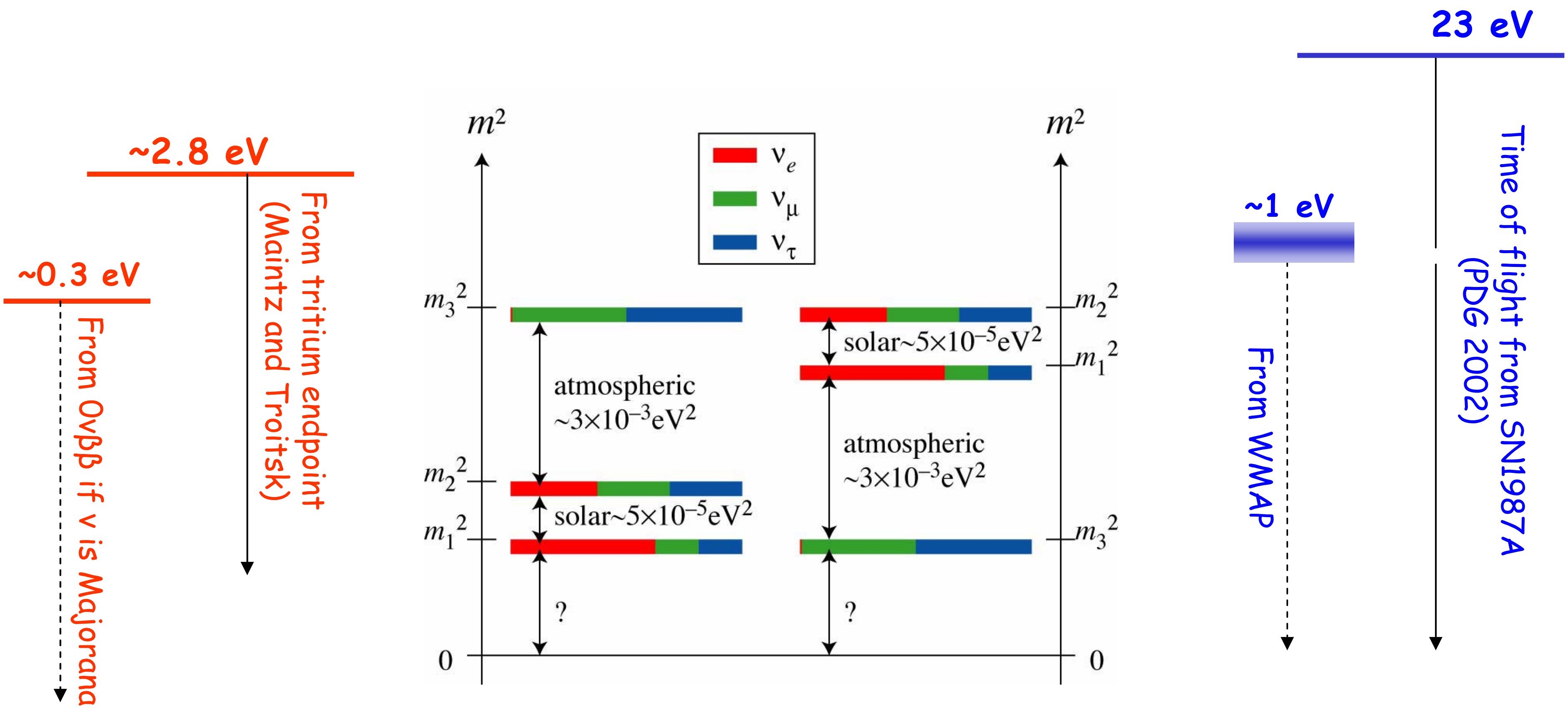
Discovery of ν flavor change

- *Solar neutrinos (MSW effect)*
- *Reactor neutrinos (vacuum oscillation)*
- *Atmospheric neutrinos (vacuum oscillation)*
- *K2K (vacuum oscillation)*
- *Lose ends: LSND/Karmen/miniBoone*

So, assuming miniBoone sees no oscillations,
we know that:

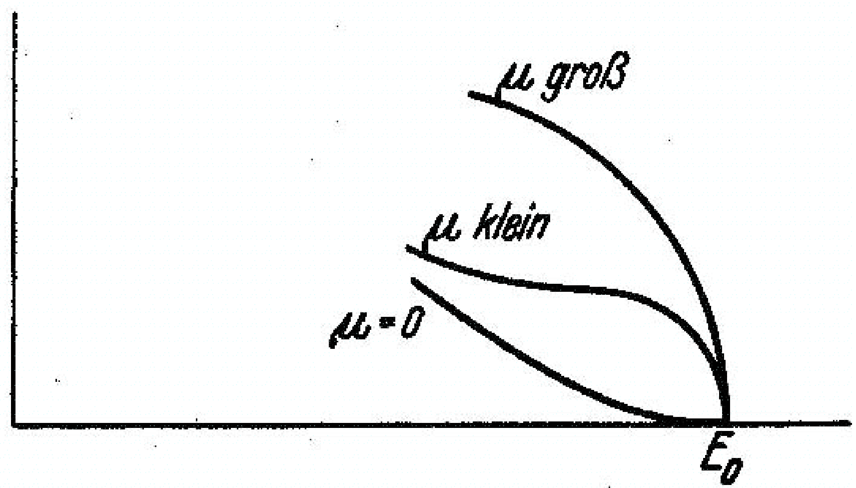
- ν masses are non-zero
- there are 2.981±0.008 ν (Z lineshape)
- 3 ν flavors were active in Big Bang Nucleosynthesis

Yet, we still do not know: - the neutrino mass scale
- the choice of mass hierarchy



These *experimental* problems take a central place in the future of Particle Physics

Endpoint mass measurements



Principle almost as old as neutrino itself:
E. Fermi, Z. Phys. 88 (1934) 161

Study the spectral shape near the endpoint of a β decay

(note that the end-point value is generally *not* known well enough to use its absolute position)

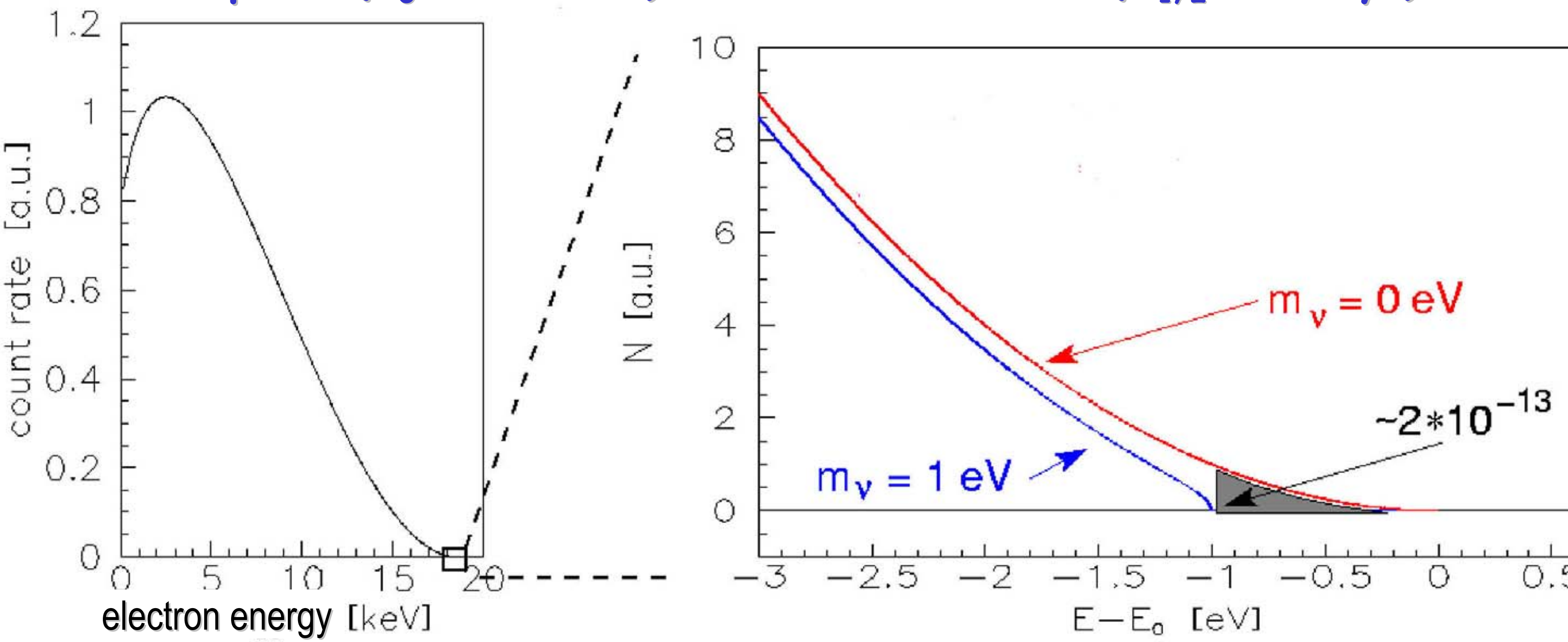
Measure the quantity:

$$m_{\nu_e}^{2\,(eff)} = \sum_i \left|U_{ei}\right|^2 m_i^2$$

If the experimental resolution is smaller than m_i^2-m_j^2 then one should see a separate kink in the spectrum for each of the states i and j

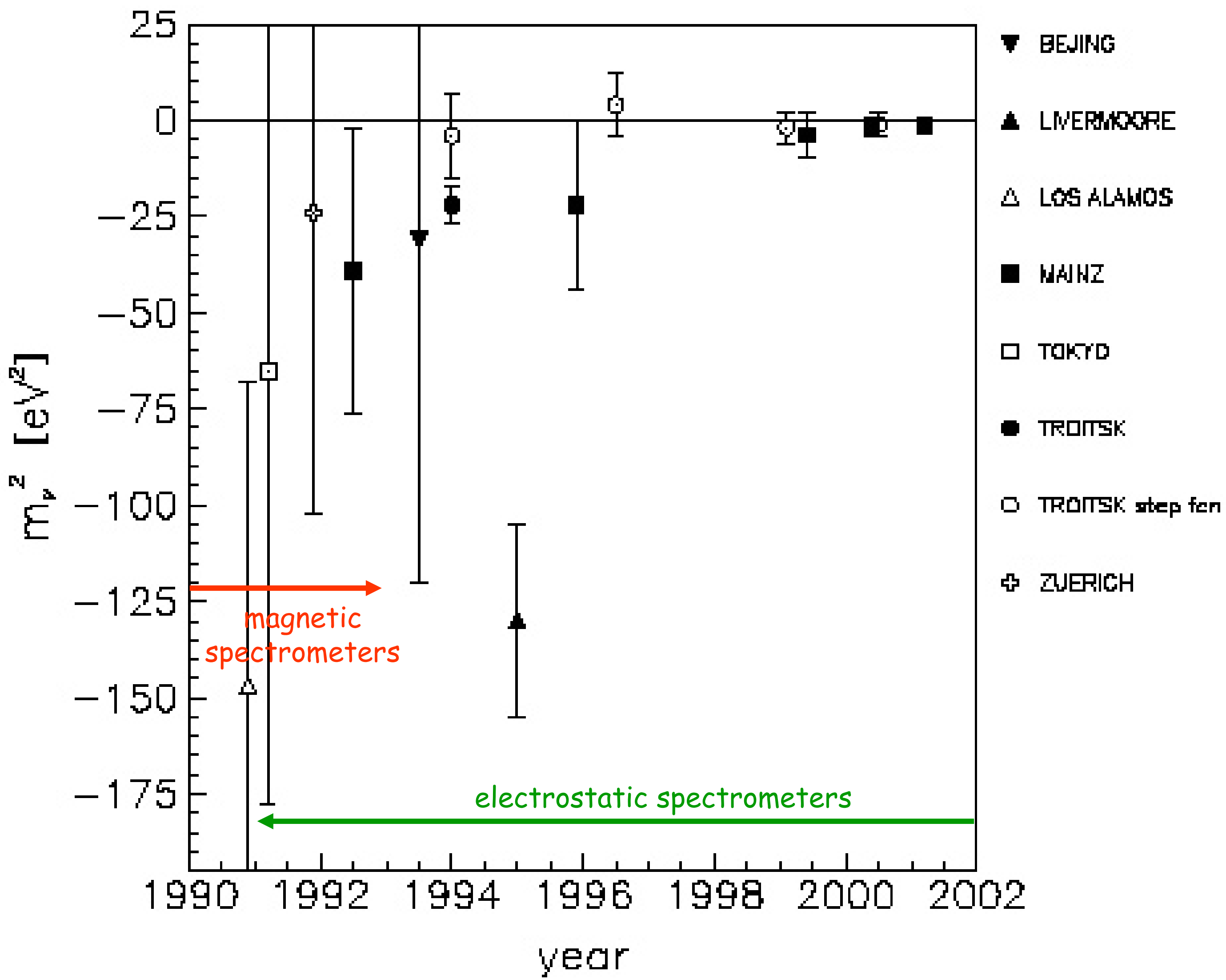
In modern experiments use mainly $^3_1T \rightarrow ^3_2He + e^- + \bar{\nu}_e$

a super-allowed transition with rather good combination of low end point (E_0=18.6 keV) and short half life ($T_{1/2}$=12.3 yr)

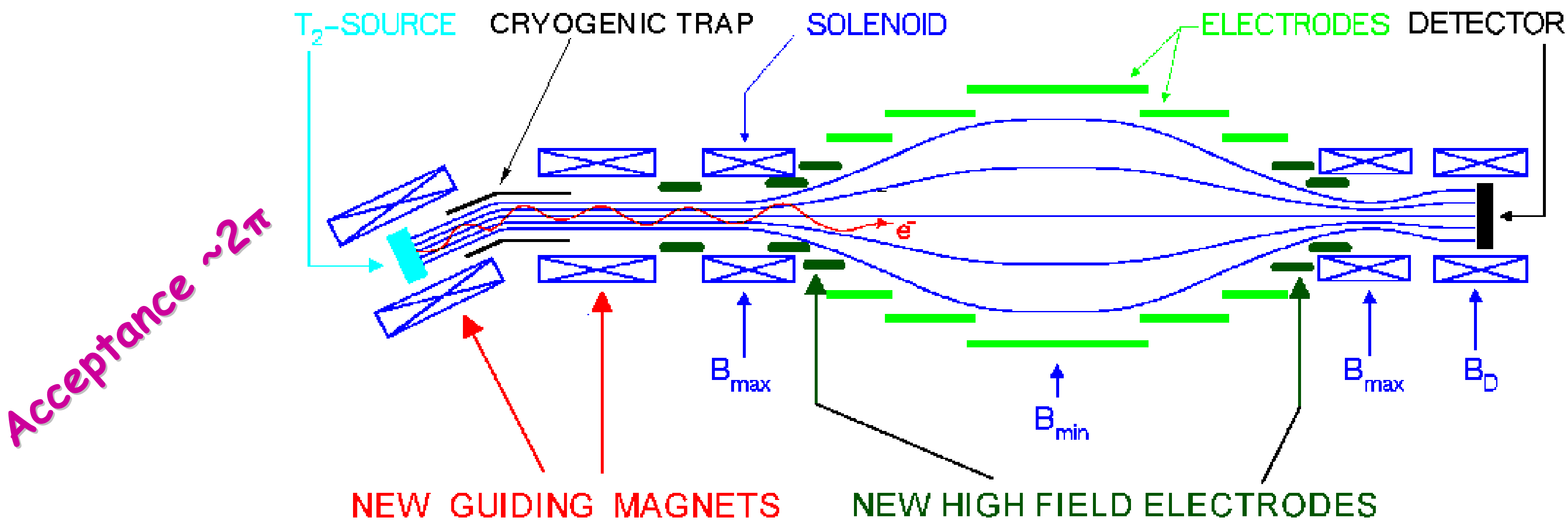


Spectrometer has to have
1) very high resolution
2) very high luminosity
(most of the statistics in the spectrum is not used…)

Long history of measurements that, for long time, have been plagued by negative central values for $m_\nu^{2\,(eff)}$

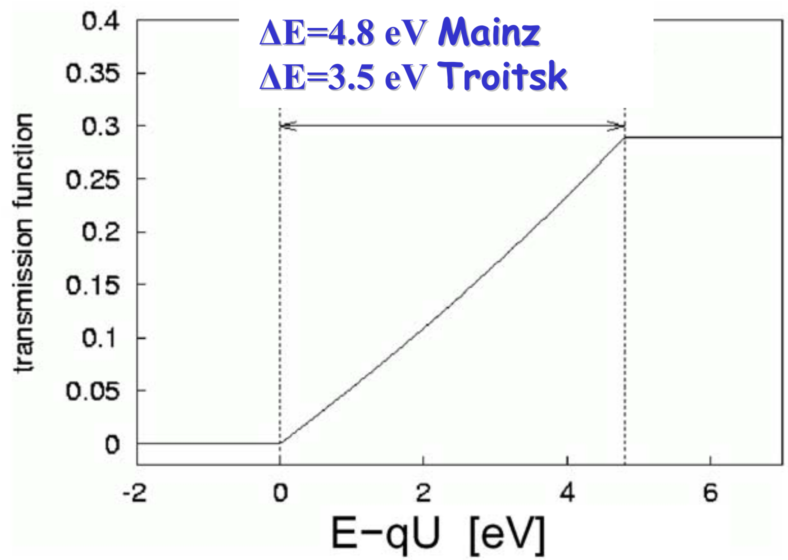


Recent experiments (Mainz and Troitsk) use Magnetic Adiabatic Collimation, Electrostatic Filter (MAC-E) integrating spectrometers



Sharp integrating transmission function with no tails

$$\Delta E/E = B_{min}/B_{max}$$



Low background (if vacuum good)

Main difference between exp:

- **Mainz: solid (frozen) source**
- **Troitsk: windowless gaseous source**

...still imperfect modeling of the energy loss in the source was the origin of the early negative m^2 effects in all experiments

Any broadening of the spectrometer resolution reduces the apparent value of m^2

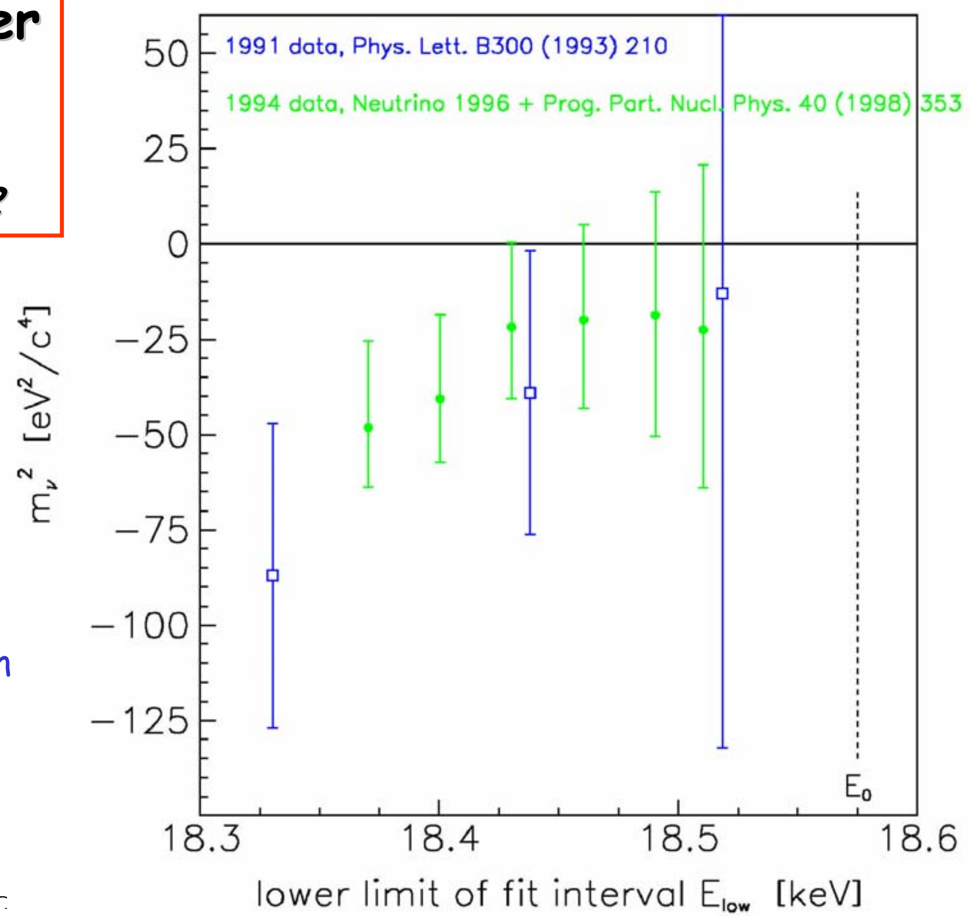
A.Saenz et al. Phys. Rev. Lett. 82 (2000) 242

Example: Mainz

source produced as a thin, smooth layer

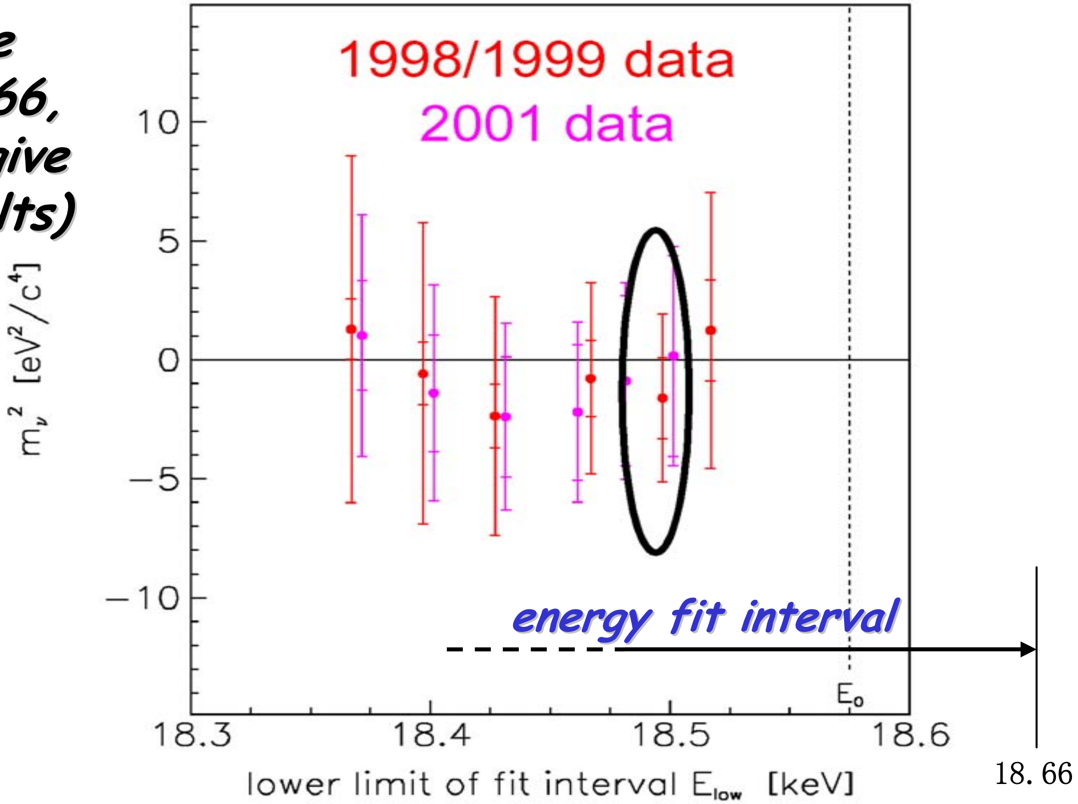
"roughening" transition occurs at finite temperature →change of energy loss function

At 2K the transition has a time constant of ~10yrs



Mainz results:

Use fit range 18.500 – 18.666, (other ranges give consistent results)



1998-99 runs

$$m_\nu^{2(eff)} = -1.6 \pm 2.5 \pm 2.1 \; eV^2/c^4$$

2001 runs

$$m_\nu^{2(eff)} = +0.1 \pm 4.2 \pm 2.0 \; eV^2/c^4$$

Together

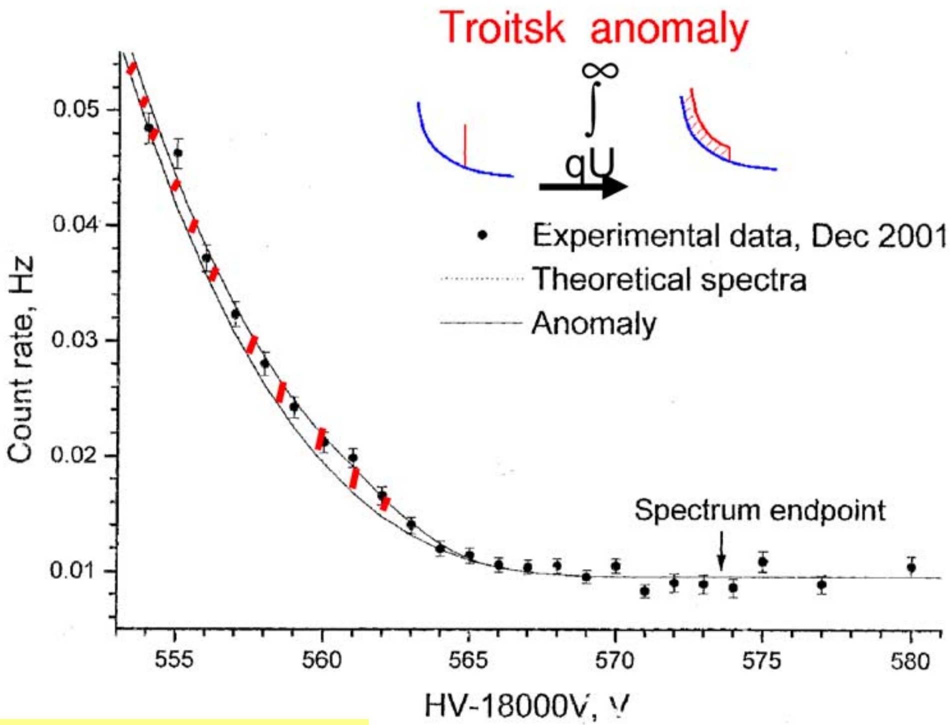
$$m_\nu^{2(eff)} = -1.2 \pm 2.2 \pm 2.1 \; eV^2/c^4$$

$$m_\nu^{(eff)} < 2.2 \; eV/c^2 \quad (95\% \; CL)$$

Ch.Kraus et al. Nucl.Phys. B 118 (2003) 482
Ch.Weinheimer Nucl.Phys. B 118 (2003) 279

A step in the integral spectrum is found. → this would imply that there is a line in the energy spectrum of tritium decay !

Position of the "line" seems to change from 0.5 eV to 15 eV with a 6 month period



Not well understood

If one ignores the issue and adds a phenomenological peak to the fit (leaving the position free from period to period)

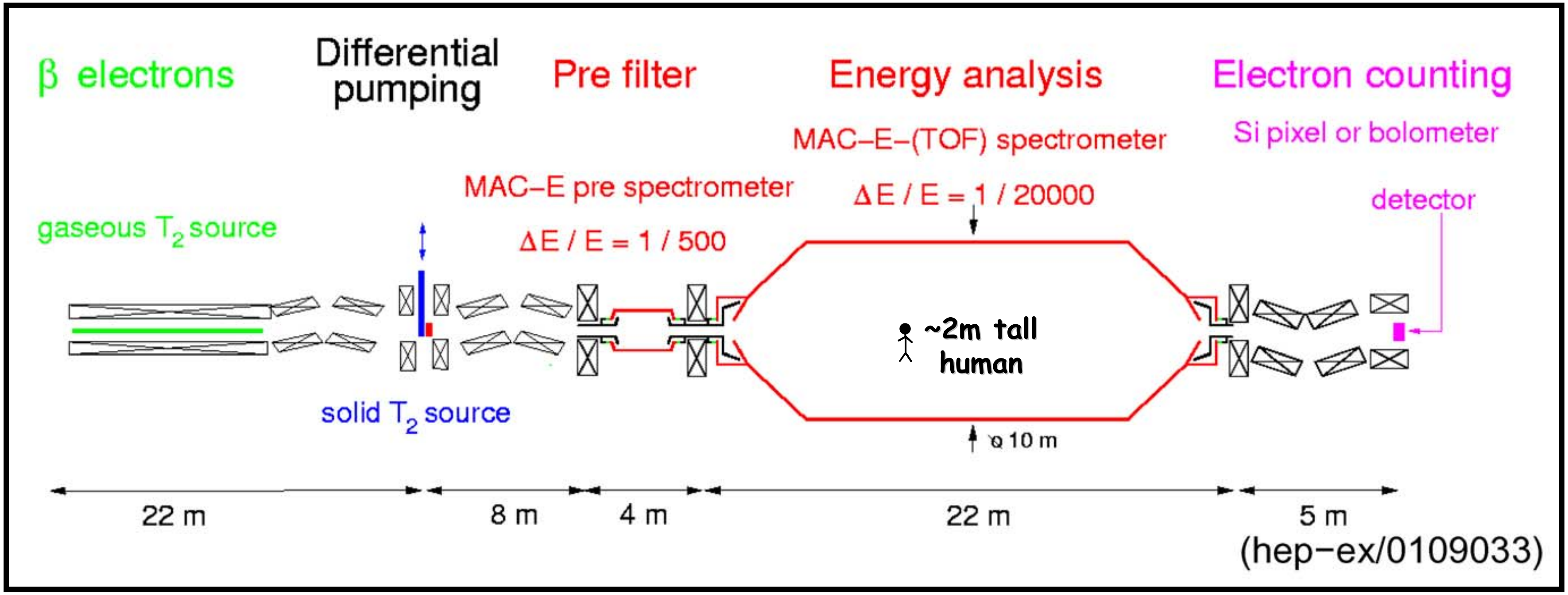
$$m_\nu^{2(eff)} = -2.3 \pm 2.5 \pm 2.0\ eV^2/c^4$$

$$m_\nu^{(eff)} < 2.05\ eV/c^2 \quad (95\%\ CL)$$

V.M.Lobashev et al.Nucl.Phys.B91 (2000) 280
V.M.Lobashev Proc.Eur.Conf.Nucl.Phys.in Astrophys. NPDC17 Sept/Oct 2002, Debrecen, Hungary

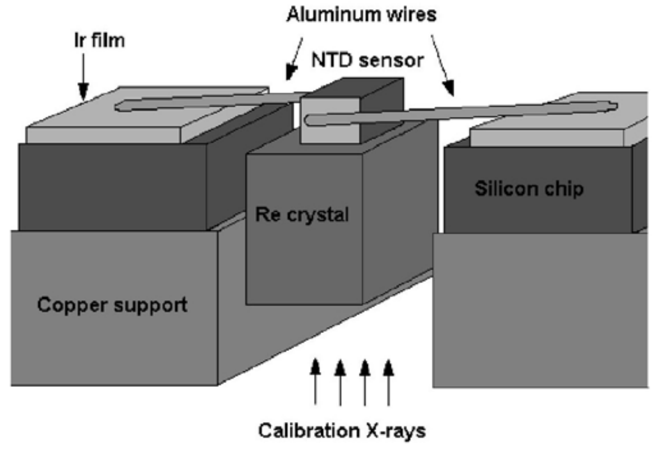
New, very large spectrometer being built in Karlsruhe for a better measurement with tritium: "KATRIN"

Forschungzentrum Karlsruhe (FZK), Universitat Mainz, INR (Troitsk), University of Washington (Seattle), University of Wales (Swansea), Nuclear Physics Institute (Rez/Prague), Fachhochschule Fulda, Universitat Karlsruhe, Universitat Bonn, JUNR (Dubna)



Expected sensitivity 0.20 - 0.25 eV

(assuming systematics are understood)



Metallic Re detector in Genova

Calorimetric measurements:

Technique less mature and resolution worse but freedom to select β emitter:

1) calorimeter should be less sensitive to condensed matter effects
2) thin source (large specific activity or short ½ life) not required

$^{187}Re \rightarrow {}^{187}Os + e^- + \nu$

E_0 = 2.5 keV lowest end-point

$T_{1/2} = 4.1 \cdot 10^{10}$ yr

Genova

1.6 mg metallic Re crystal (1.1Bq)

$m_\nu^{(eff)} < 26$ eV 95% CL

F.Gatti proceedings Neutrino 2000, p293

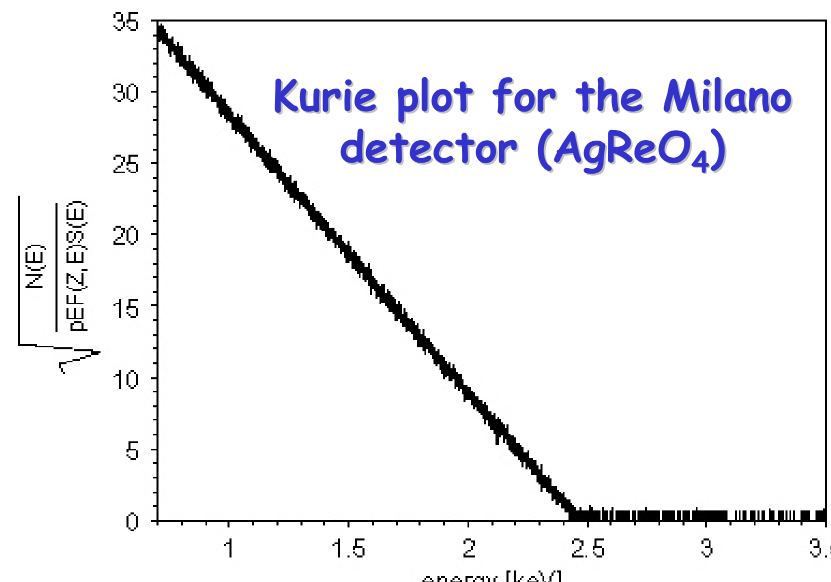
Milano

~10·30μg $AgReO_4$ crystal

resolution 28 eV FWHM

$m_\nu^{(eff)} < 21.7$ eV 90% CL

C.Arnaboldi et al. hep-ex/0302006



Kinematics mass measurements at "high energy"

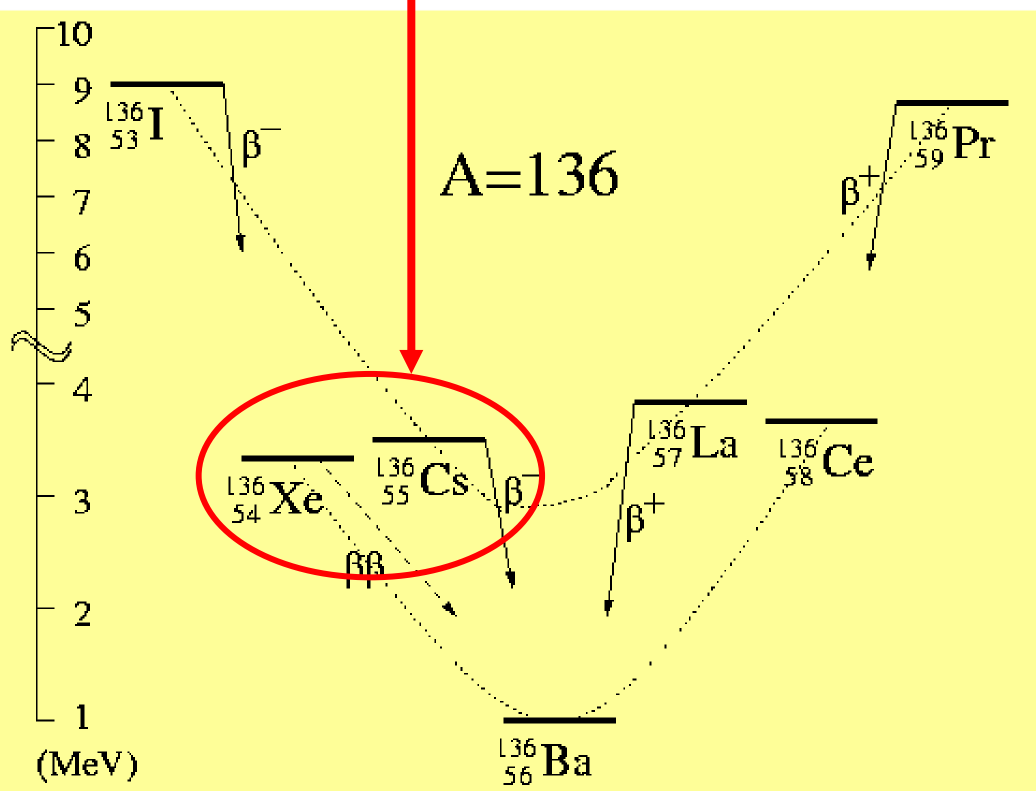
- $M(\nu_\mu)<$ 0.19 MeV/c^2 90% CL
  from $\pi^+ \rightarrow \mu^+ \nu$ decays at rest
  (K.Assamagan et al. PRD 53 (1996) 6065 + PDG 2002)
  BNL E952 proposal expects ~ 8keV sensitivity

- $M(\nu_\tau)<$ 18.2 MeV/c^2 95% CL from τ decays
  in ALEPH (R. Barate et al. EPJ C2 (1998) 395)
  M■♦< 15.5 MeV/c^2 95% CL from combined fit to Υ(4s) and Z^0 data
  (J.M. Roney, Neutrino 2000, Sudbury)
  ~3 MeV seems the asymptotic sensitivity of B factories

Unlikely to reach the "interesting" region below 1 eV

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



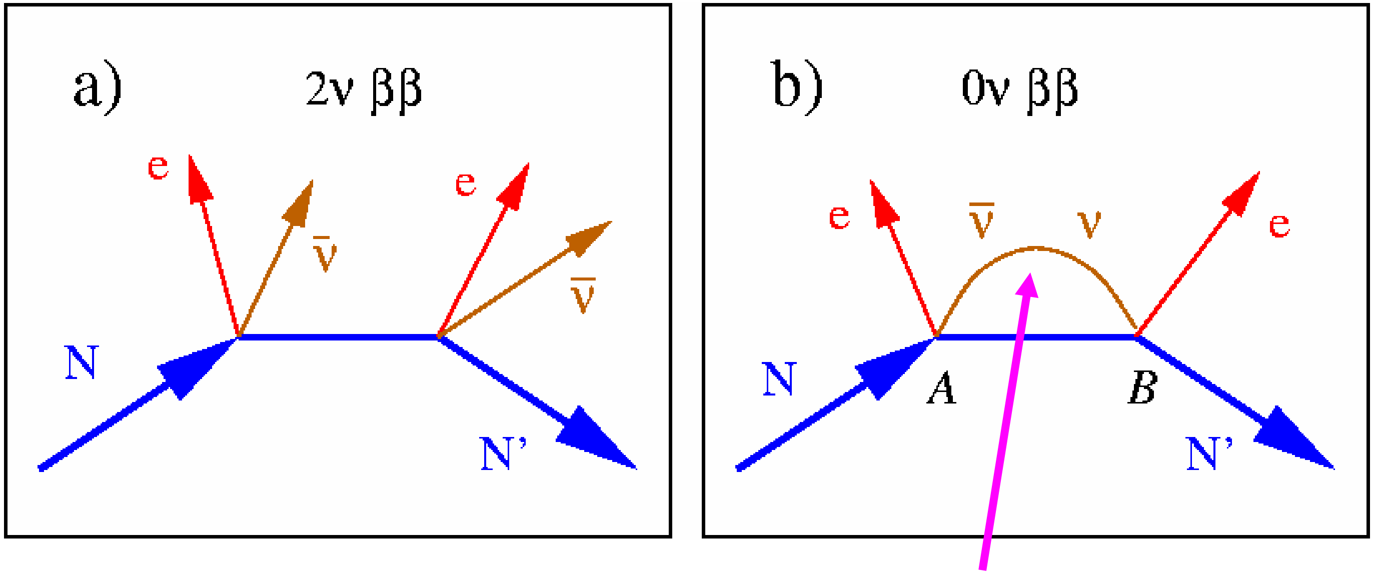
Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

2ν mode: a conventional 2nd order process in nuclear physics

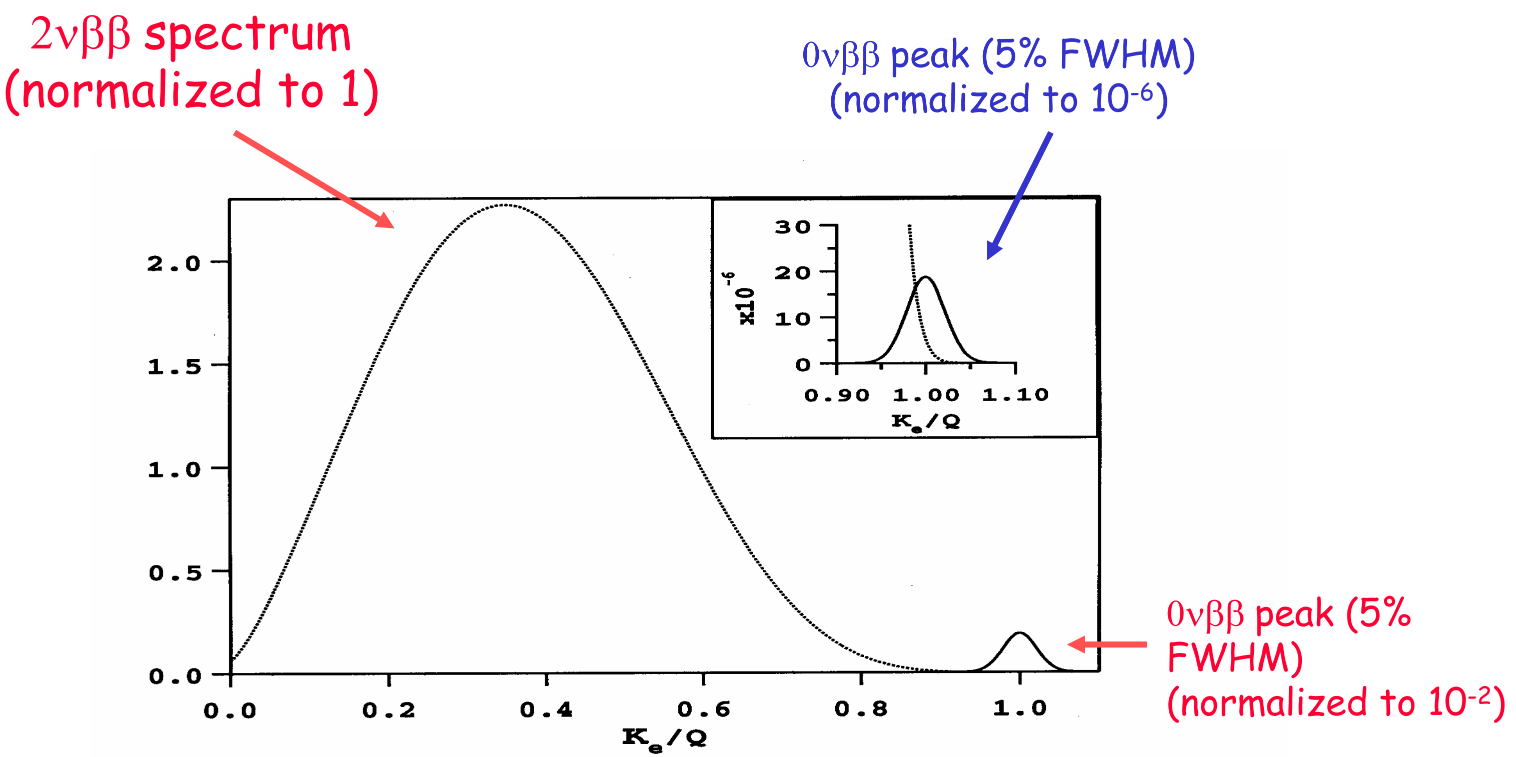
0ν mode: a hypothetical process can happen only if:
- $M_\nu \neq 0$ — Since helicity has to "flip"
- $\nu = \bar{\nu}$



Several new particles can take the place of the virtual ν

But 0νββ decay always implies new physics

Background due to the Standard Model $2\nu\beta\beta$ decay



Summed electron energy in units of the kinematic endpoint (Q)

from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.

<u>The only effective tool here is energy resolution</u>

$\beta\beta$ decay experiments are at the leading edge of "low background" techniques

- Final state ID: 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
  - + Very specific signature
  - + Large live times (particularly for 1)
  - + Large masses
  - - Possible only for a few isotopes (in the case of 1)
  - - No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source≠detector
  - + Energy/some tracking available (can distinguish modes)
  - + In principle universal (b)
  - - Many γ backgrounds can fake signature
  - - Exposure is limited by human patience

Real time is needed to discover ν masses, final state ID would be a nice complement !

Isotope	$T_{1/2}^{2\nu}$ (yr)
^{48}Ca	$(4.3\pm2.2)\cdot10^{19}$
^{76}Ge	$(1.77\pm0.12)\cdot10^{21}$
^{82}Se	$(8.3\pm1.2)\cdot10^{19}$
$^{96}Zr^{\dagger}$	$(9.4\pm3.2)\cdot10^{18}$ § $(2.1\pm0.6)\cdot10^{19}$ $(3.9\pm0.9)\cdot10^{19}$ §
^{100}Mo	$(9.5\pm1.0)\cdot10^{18}$
^{116}Cd	$(2.6\pm0.6)\cdot10^{19}$
^{128}Te	$(7.2\pm0.4)\cdot10^{24}$ §
$^{130}Te^{\dagger}$	$(2.7\pm0.1)\cdot10^{21}$ § $(7.9\pm1.0)\cdot10^{20}$ § $(6.1\pm3.5)\cdot10^{20}$
$^{136}Xe^{\$}$	$>1.1\cdot10^{22}$ 90% CL
^{150}Nd	$(6.7+0.8)\cdot10^{18}$
^{238}U	$(2.0\pm0.6)\cdot10^{21}$ *

The Standard Model $2\nu\beta\beta$ decay has been observed in many isotopes

Table arbitrarily simplified from PDG 2003

† Results not in good agreement
§ Geochemical experiment
* Radiochemical experiment
$ Decay NOT observed, lower limit reported

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phasespace factor

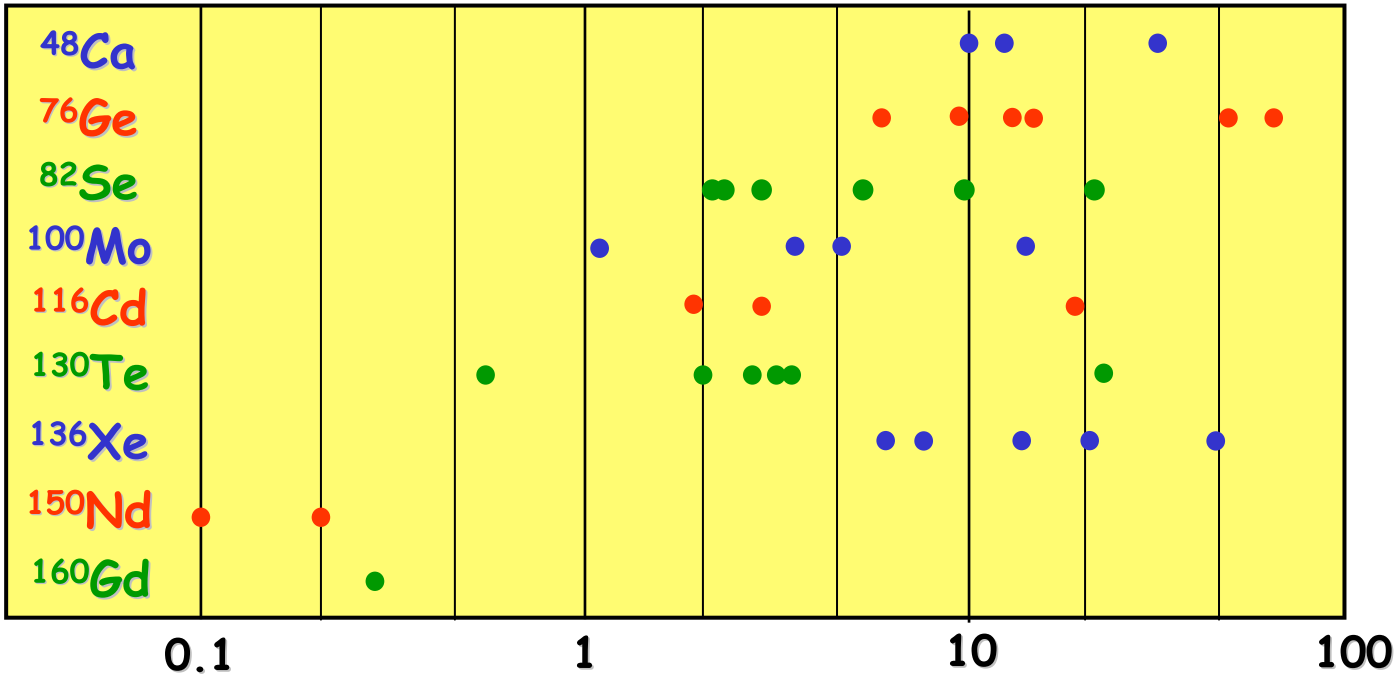
$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{e,i}^2 m_i \; \varepsilon_i \right|$$

effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Cancellations are possible…

$0\nu\beta\beta$ decay half lives in 10^{26} yr units for $\langle m_\nu \rangle$ = 50 meV according to different nuclear matrix element calculations



[adapted from S.R.Elliott & P.Vogel Ann. Rev. Nucl. Part. Sci. 52 (2002) 115]

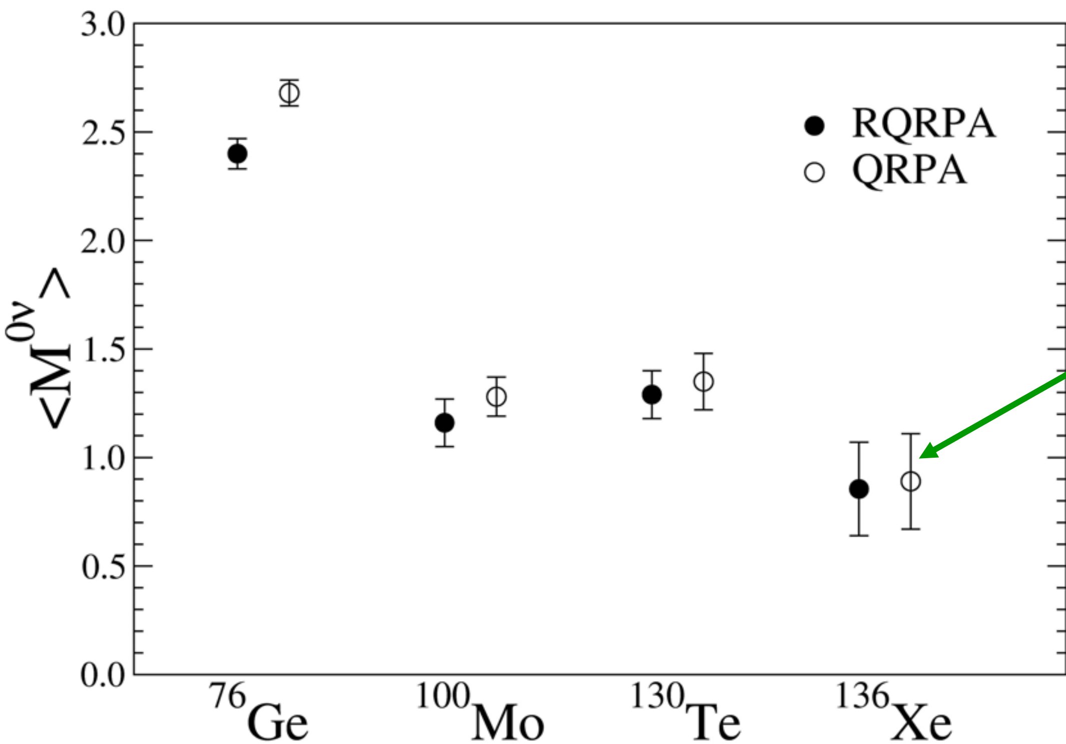
Unfortunately it is not trivial to use the 2ν matrix element to normalize the 0ν one:

- **$|M_{2\nu}|$ - has stronger dependence on intermediate states**
- **$|M_{0\nu}|$ - all multipoles contribute**
  - ν propagator results in long range potential

However it was recently found that main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface. This should be the same for $0\nu\beta\beta$ and for $2\nu\beta\beta$.

Use the measured $2\nu\beta\beta$ experimental $T_{1/2}$ to make a correction.

V.A.Rodin et al. nucl-th/0305005



Lower bound on $T_{1/2}$ used for ^{136}Xe

Can one get agreement from Nuclear Shell Models ?

Still, if/once $0\nu\beta\beta$ decay is discovered, the $T_{1/2}$ in more than one nucleus will be needed to pin down neutrino masses

Present Limits for 0ν double beta decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>9.5*10^{21}$ (76%CL)	
^{76}Ge	Ge diode	~30	$>1.9*10^{25}$ (90%CL)	$<0.39^{+0.17}_{-0.28}$
^{82}Se			$>9.5*10^{21}$ (90%CL)	
^{100}Mo			$>5.5*10^{22}$ (90%CL)	
^{116}Cd			$>7.0*10^{22}$ (90%CL)	
^{128}Te	TeO_2 cryo	~3	$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~3	$>2.1*10^{23}$ (90%CL)	<1.1 - 2.6
^{136}Xe	Xe scint	~10	$>1.2*10^{24}$ (90%CL)	<2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

Adapted from the Particle Data Group 2003

Has 0νββ decay been already discovered ??

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

H.V. KLAPDOR-KLEINGROTHAUS[1,3],
A. DIETZ[1], H.L. HARNEY[1], I.V. KRIVOSHEINA[1,2]
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[2] *Radiophysical-Research Institute, Nishnii-Novgorod, Russia*
[3] *Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,*

(Part of the Heidelberg-Moscow collaboration)

Mod. Phys Lett. A27 (2001) 2409

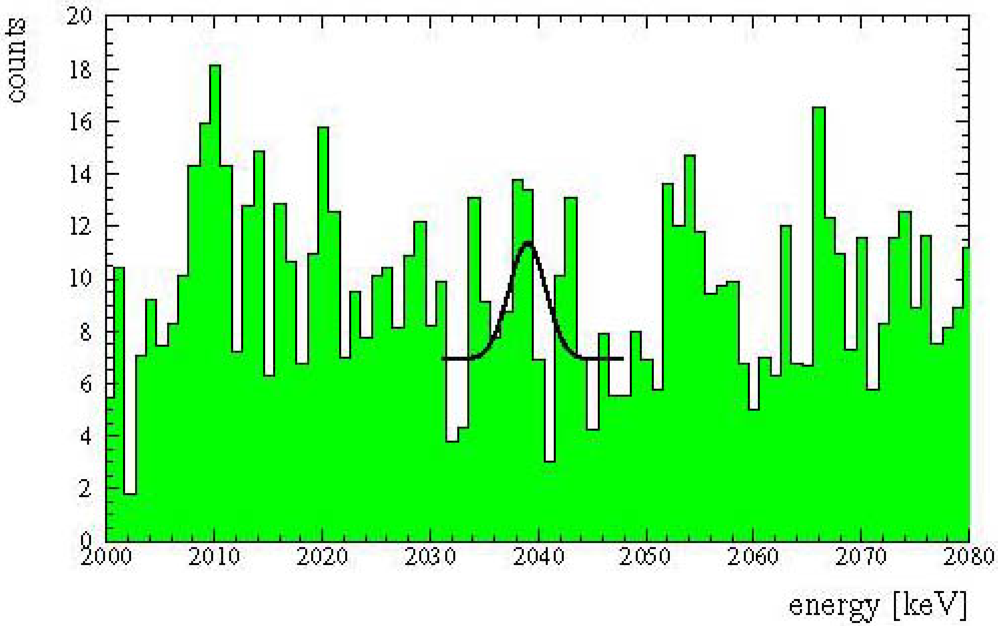
…most likely not

…see details in

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345-377
Addendum-ibid. B659 (2003) 359-362
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
H.V.Klapdor-Kleingrouthaus hep-ph/0205228
A.M.Bakalyarov et al. ("Moscow" of Heidelberg-Moscow) to appear in proceedings of NANP 2003, June 2003, Dubna, Russia

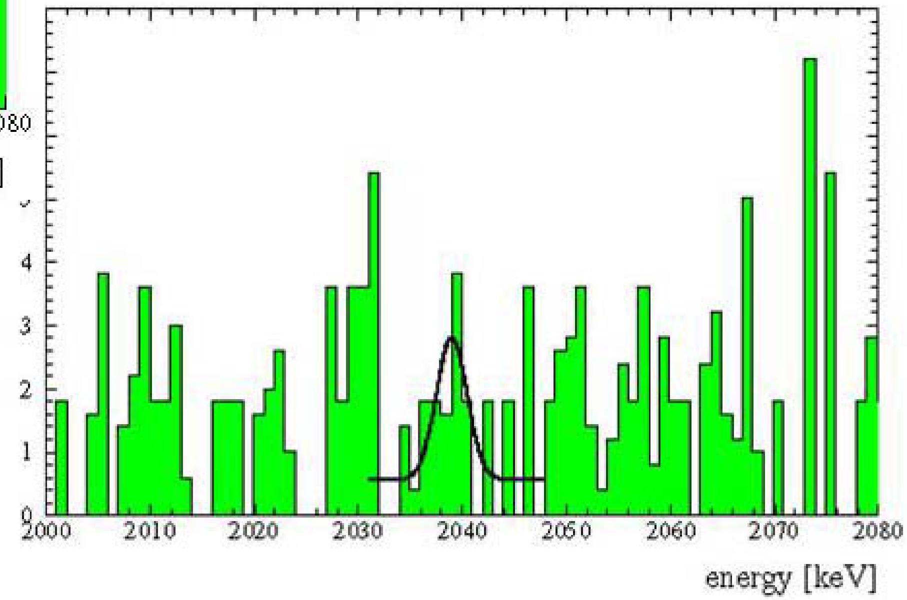
Paper's bottom line is $T_{1/2}$ = [0.8 – 18.3] · 10^{25} yr at 95% CL
best value is $T_{1/2}$ = 1.5 · 10^{25} yr corresponding to 0.39 eV

Allegedly this is a 2 to 3 sigma effect depending on the analysis



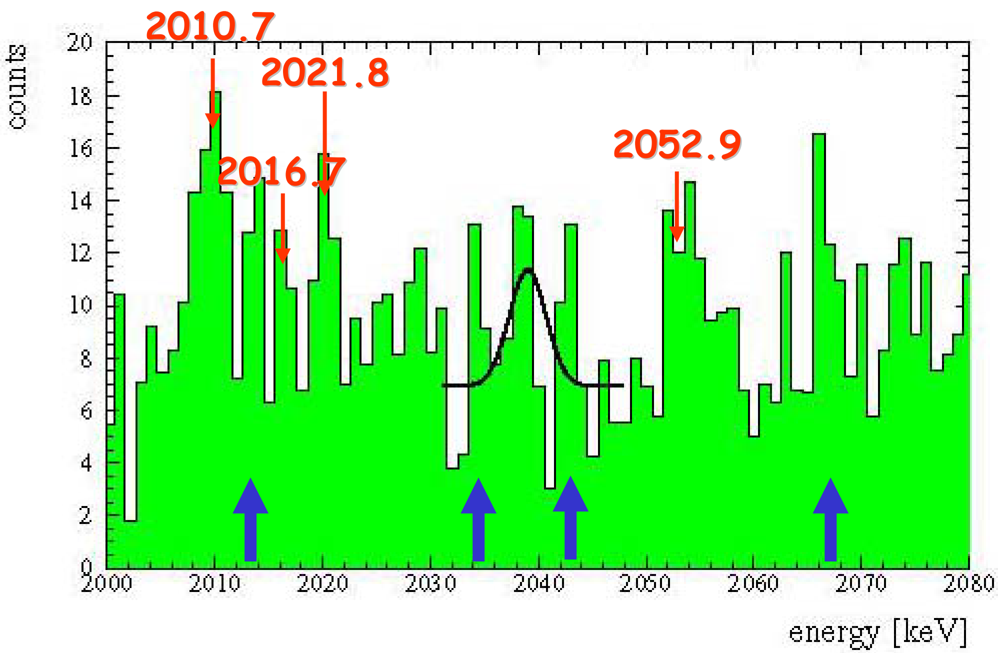
"Evidence" from the search of a peak in the energy spectrum observed in a set of low activity Ge detectors inside the Gran Sasso Lab.

Spectrum can be somewhat cleaned-up by applying pulseshape discrimination to remove γ ray events ...still lots of peaks besides the 2039 keV



The fit to the "signal" peak at 2039.006 keV is done *AFTER* the subtraction of 4 peaks that are claimed to be *UNDERSTOOD* background from *IDENTIFIED* lines of ^{214}Bi

Without this subtraction the significance of the 2039 peak is even less than 2 sigma, as it is evident by just staring at the spectrum



But then, what about the other peaks ! There are more that are not understood !

Note that the data used is the same that was earlier interpreted as an upper limit $T_{1/2} > 1.9 \cdot 10^{25}$ eV at 90% CL

"The claim of discovery…is considered critically and firm conclusion about, at least, prematurely of such claim is derived on the basis of simple statistical analysis…"

Yu.Zdesenko et al. Phys Lett B546 (2002) 206

The latest 2 experiments to start operation:

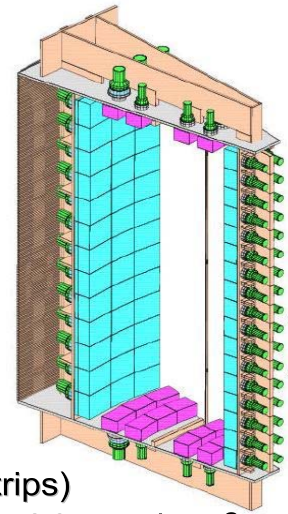
NEMO III

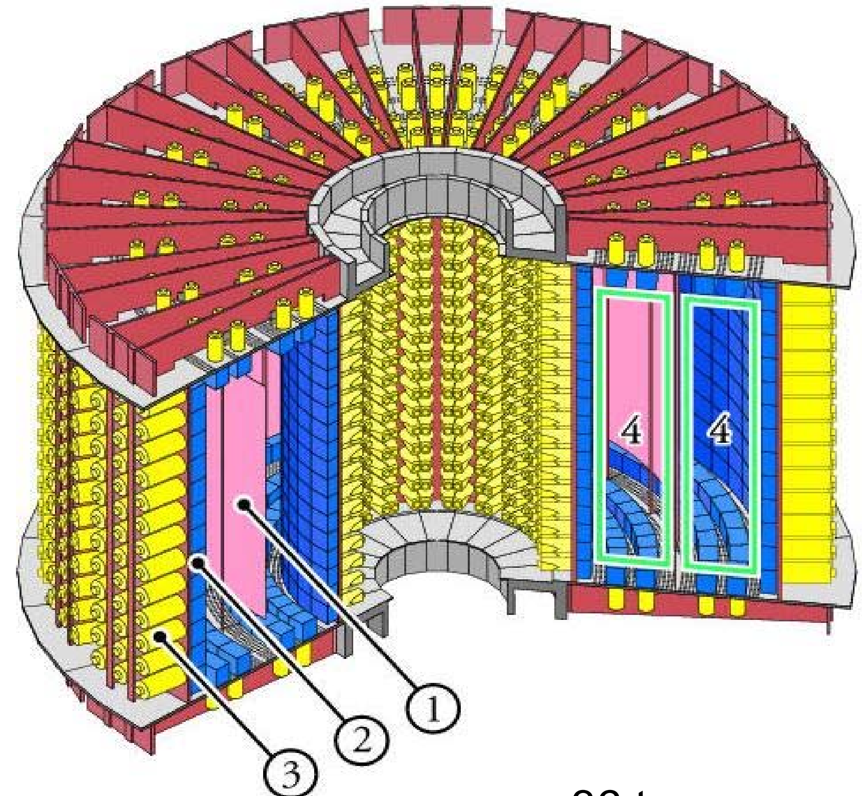
Neutrinoless Experiment with MOlibdenum III
or Neutrino Ettore Majorana Observatory

Large Collaboration: 13 groups from Europe, USA and Japan

Passive source - Spectroscopic approach

$0\nu2\beta$ sensitivity:
T ~ 10^{24} y
$<m\nu>$ ~ 0.1 eV





Detector structure: 20 sectors

1 Source:
up to 10 kg of $\beta\beta$ isotopes
(metal film or powder glued to mylar strips)
cylindrical surface: 20 m^2 x 40-60 mg/cm^2

2 Tracking volume:
open octagonal drift cells (6180)
operated in Geiger mode
(σ_r=0.5 mm, σ_z=1 cm)

3 Calorimeter:
1940 plastic scintillators coupled to low activity PMs:
FWHM(1 MeV) ~ 11-14.5 %

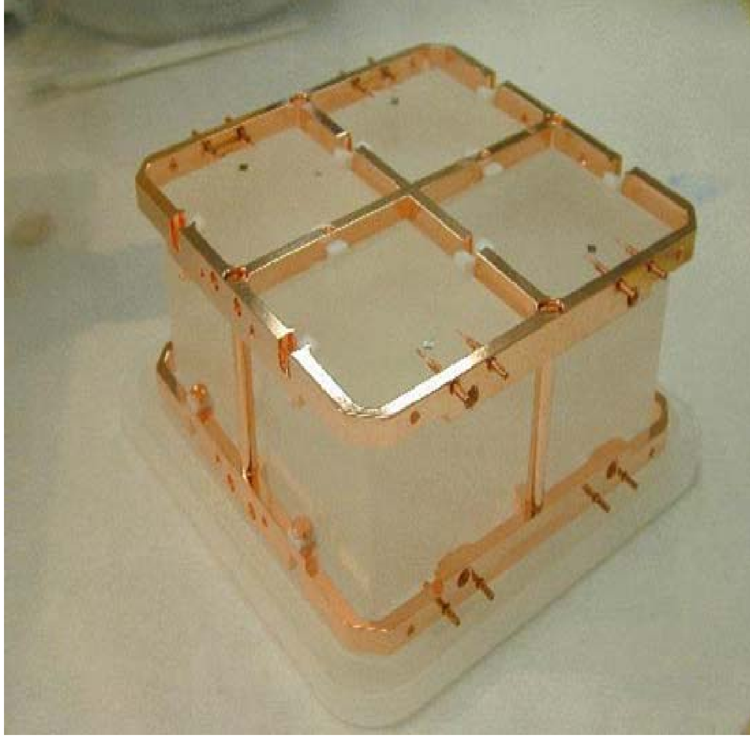
m_{tot} ~ 36 tons
Low activity materials

Magnetic Field (30 G) + Iron Shield (20 cm) + Neutron Shield (30 cm H_2O)

"Cuoricino" (small CUORE)

Mostly natural TeO_2
44 (5*5*5) cm^3 crystals (44*780g)
18 (3*3*6) cm^3 crystals (18*340g)
Total ~40 kg
Tower structure prototype for much larger CUORE

Running at Gran Sasso in a dilution refrigerator at ~10 mK



NTD thermistor readout:
1 MeV = ΔT = 300 μV

$0\nu\beta\beta$ sensitivity
$T_{1/2} \sim 4 \times 10^{23}$ yr
$\langle m_\nu \rangle \sim 0.7 - 1.6$ eV

A (probably incomplete) list of the different ideas discussed by various groups

Experiment	Nucleus	Detector	$T^{0\nu}$ (y)	< m_ν > eV
CUORE	^{130}Te	.77 t of TeO_2 bolometers (nat)	7×10^{26}	.014-.091
EXO	^{136}Xe	10 t Xe TPC + Ba tagging	1×10^{28}	.013-.037
GENIUS	^{76}Ge	1 t Ge diodes in LN	1×10^{28}	.013-.050
Majorana	^{76}Ge	1 t Ge diodes	4×10^{27}	.021-.070
MOON	^{100}Mo	34 t nat.Mo sheets/plastic sc.	1×10^{27}	.014-.057
DCBA	^{150}Nd	20 kg Nd-tracking	2×10^{25}	.035-.055
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator	> 10^{26}	.053-.24
COBRA	^{116}Cd, ^{130}Te	10 kg of CdTe semiconductors	1×10^{24}	.5-2.
Candles	^{48}Ca	Tons of CaF_2 in liq. scint.	1×10^{26}	.15-.26
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scint in liq scint	2×10^{26}	.038-.172
Xmass	^{136}Xe	1 t of liquid Xe	3×10^{26}	.086-.252

Note that the sensitivity numbers are somewhat arbitrary, as they depend on the author's guesstimate of the background levels they will achieve

Alabama, Caltech, Colorado State,
Irvine, ITEP, Neuchatel, Stanford collaboration

An exotic approach to deal with the main experimental problems

1. To reach $\langle m_\nu \rangle$ ~ 10 meV very large fiducial mass (tons)
   (except for Te) need massive isotopic enrichment
2. Reduce and control backgrounds in qualitatively new ways
   bkgnd for Ge ~0.3 ev/kg yr FWHM

For no bkgnd $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$$

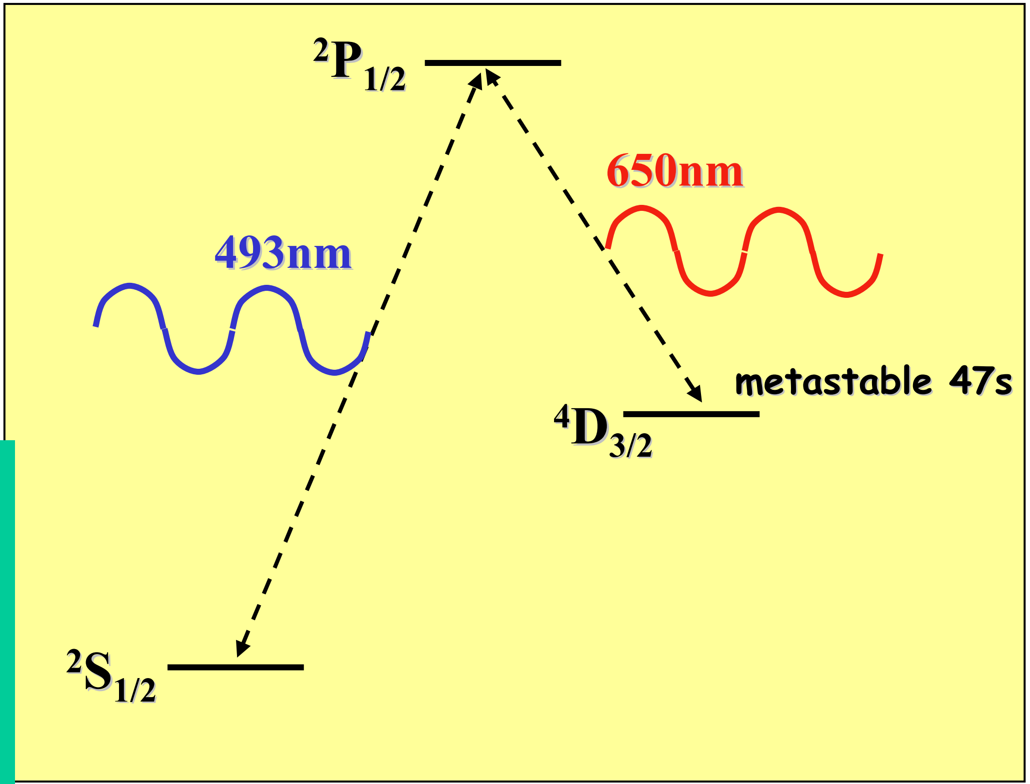
Scaling with bkgd goes like *Nt* $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$$

In addition would like a multi-parameter experiment,
→ possible discovery can be backed-up by cross checks with more than one single variable

Xe offers a qualitatively new tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^- e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

Ba^+ system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
Very specific signature "shelving"
Single ions can be detected from a photon rate of 10^7/s

- Important additional constraint
- Huge background reduction



The Ba-tagging, added to a conventional Xe TPC rejection power provides the tools to develop a background-free next-generation ββ experiment

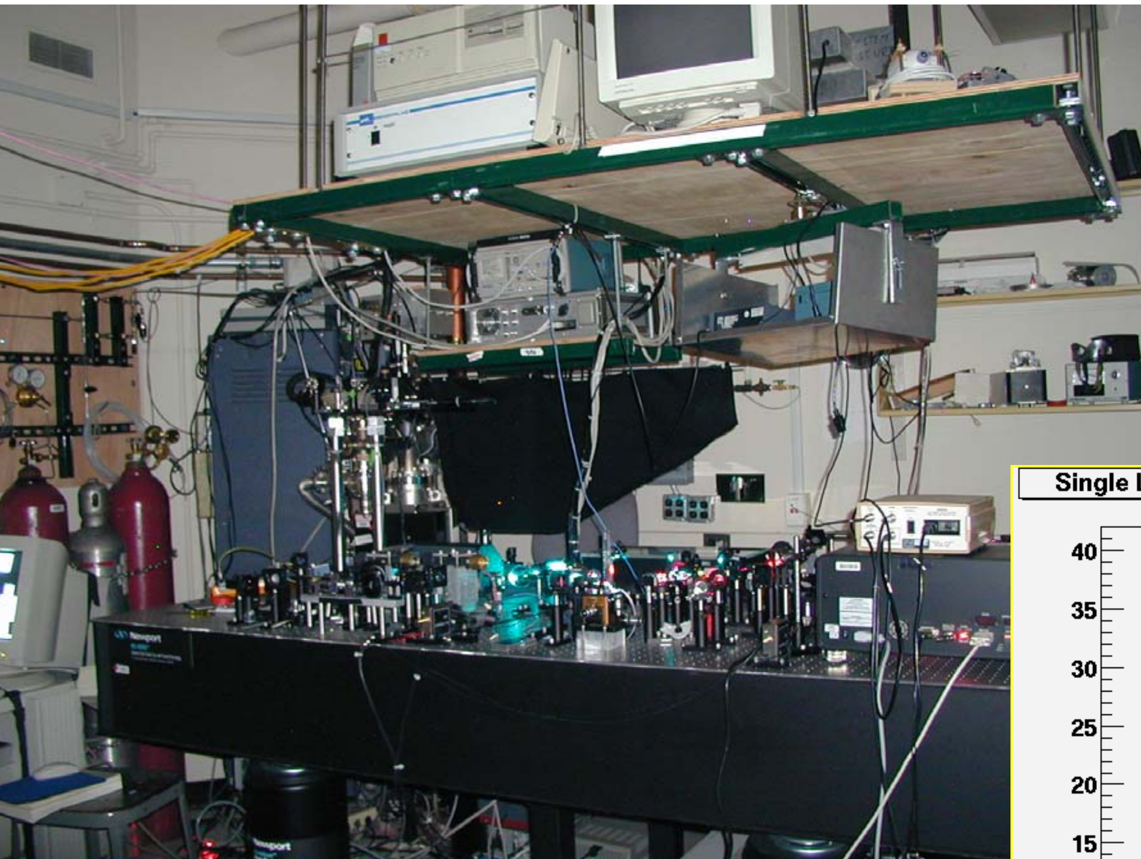
Assume an "asymptotic" fiducial mass of 10 tons of ^{136}Xe at 80%

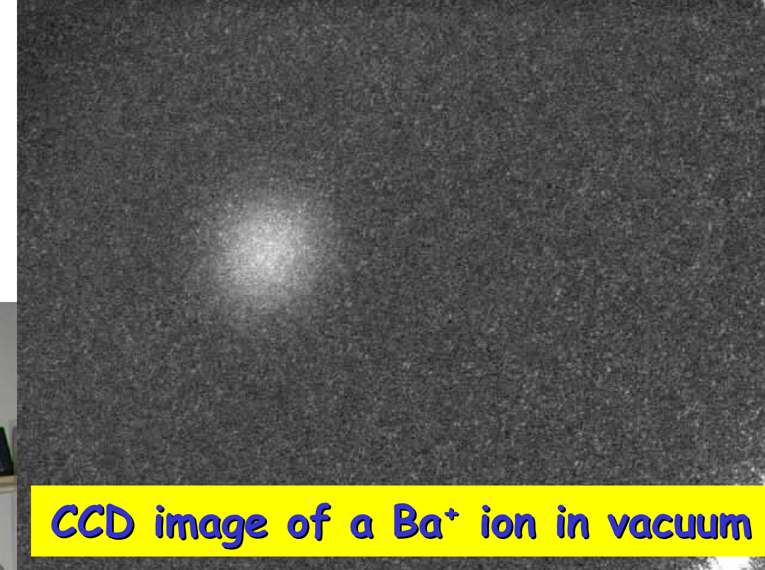
R&D program focused on:

- Single Ba^+ tagging in Xe background
- Energy resolution in xenon (liquid and gas)
- Transfer of single Ba ions out of LXe
- 200kg prototype detector construction (no Ba tagging yet) to study detector performance, backgrounds and measure 2νββ mode
- Isotopic enrichment of large quantities of 136Xe

Already have in hand 200kg of enriched Xe (80% 136 isotope) → the largest stockpile of highly enriched isotope ever produced for pure science !

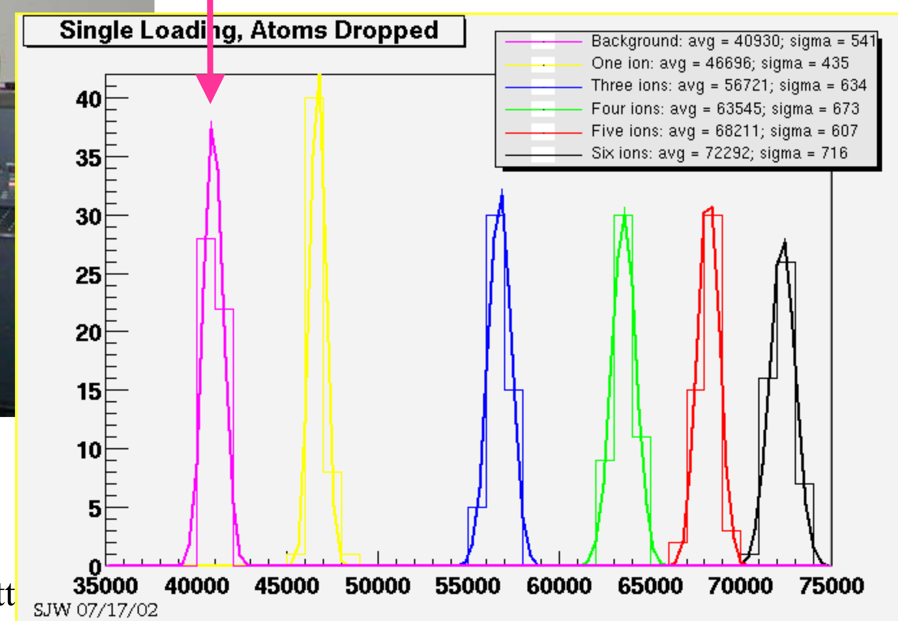
Laser spectroscopy R&D



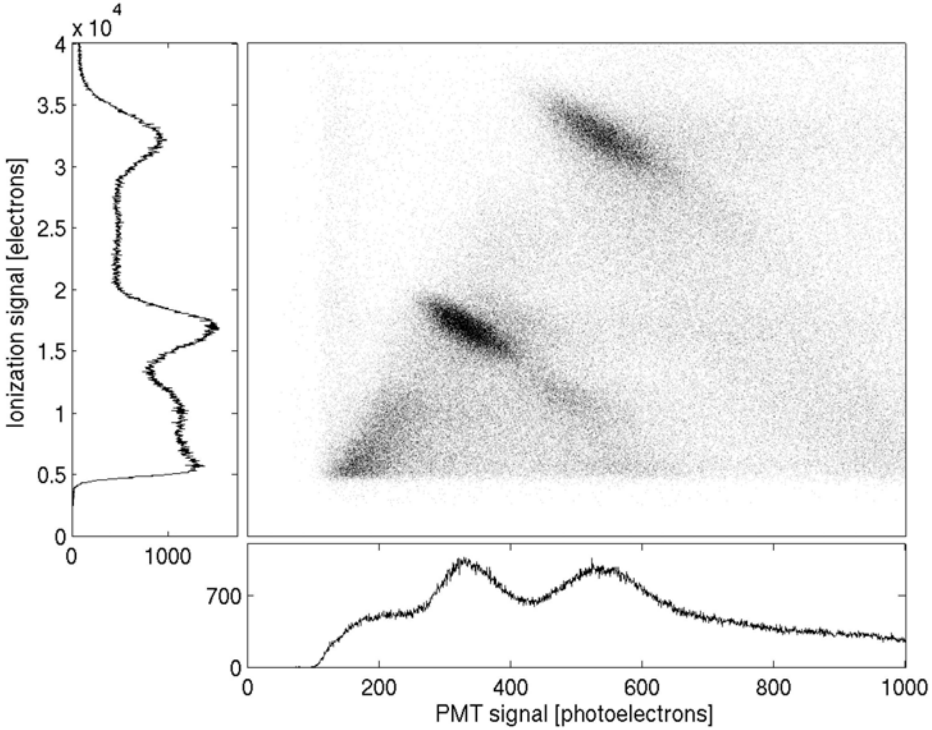


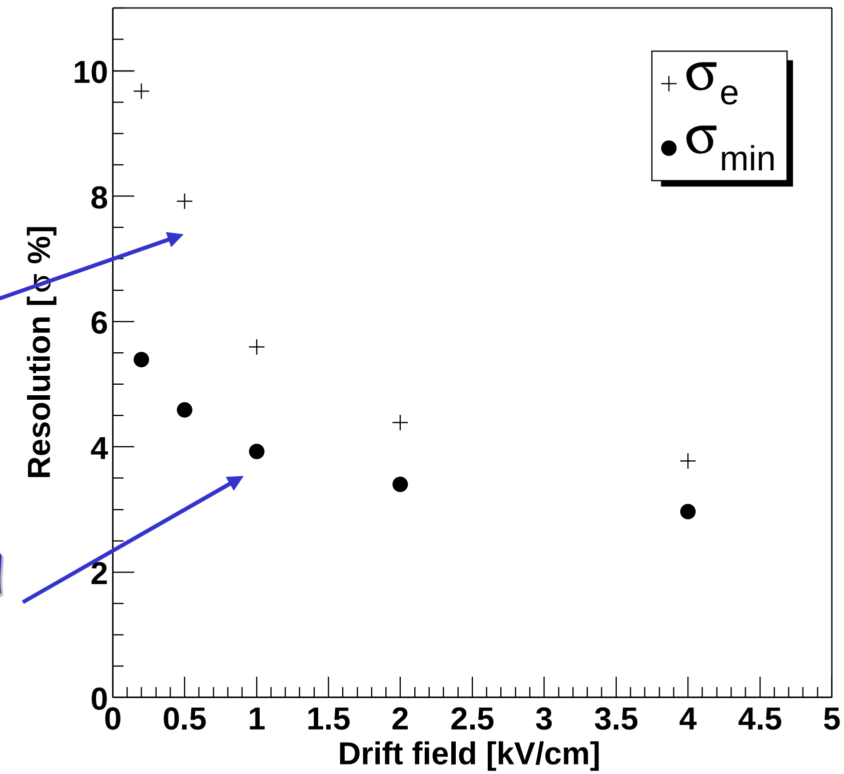
CCD image of a Ba^{+} ion in vacuum

Zero ion background



Sufficient improvement in energy resolution already demonstrated using anti-correlation between scintillation and ionization (σ=2% @ 2.5 MeV)





Ionization only

Ionization combined with scintillation

E.Conti et al Phys. Rev. B 68 (2003) 054201

Conclusions

- Welcome to the era of massive neutrinos !
- After 75 years of neutrinos we now know that neutrinos are massive
- For the first time there is a good chance that the mass scale and the Dirac/Majorana structure of the neutrino sector will be measured in the lab
- Lots of fun physics and interesting techniques !