“ETTORE MAJORANA” FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS
46th COURSE

The nature and the mass of neutrinos Majorana vs Dirac

A. Bettini
Università di Padova, Dipartimento di Fisica G. Galilei; INFN - Sezione di Padova
Laboratorio Subterráneo de Canfranc (Huesca) Spain

Mass eigenstates - Flavour eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&-s_{12}&0\\s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}1&0&0\\0&e^{i\phi_1}&0\\0&0&e^{i\phi_2}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

What we know @ 2σ level (95% c.l.)

G. Fogli et al. hep-ph/0805.2517

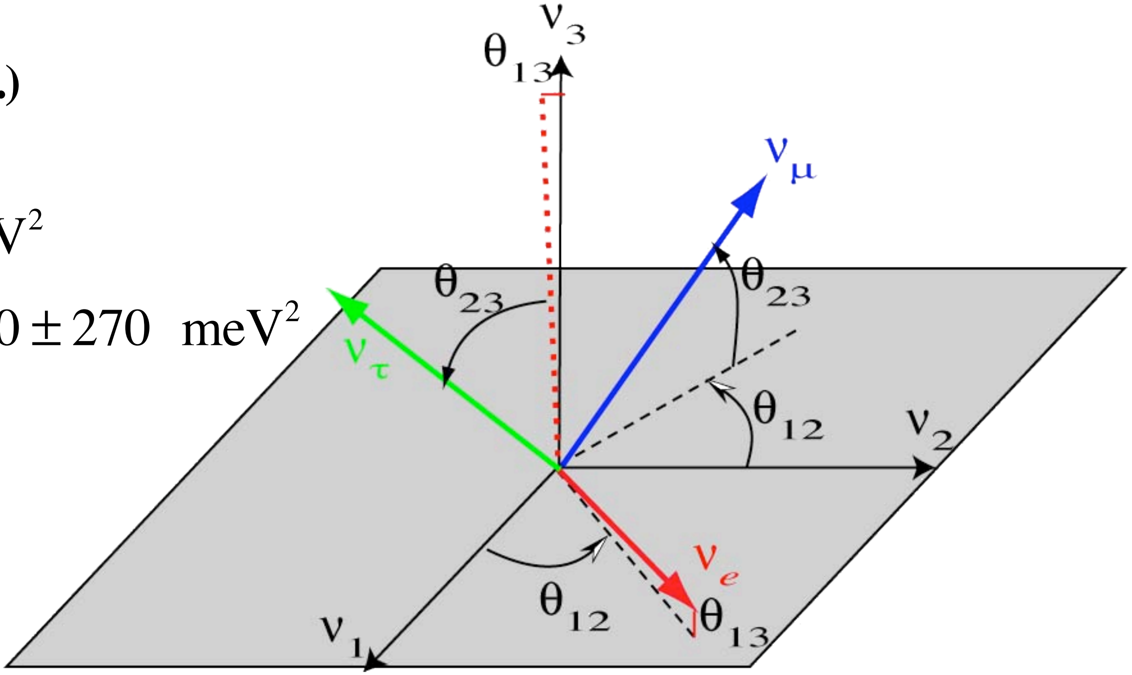
$$\delta m^2 \equiv m_2^2 - m_1^2 = 76.6 \pm 3.5 \ \ \mathrm{meV}^2$$

$$\left|\Delta m^2\right| \equiv m_3^2 - \left(m_2^2 + m_1^2\right)/2 = 2380 \pm 270 \ \ \mathrm{meV}^2$$

$$\sin^2\theta_{12} = 0.326^{+0.05}_{-0.04}$$

$$\sin^2\theta_{23} = 0.45^{+0.16}_{-0.09}$$

$$\sin^2\theta_{13} < 0.032$$



9 independent real parameters

- **3 masses m_1, m_2, m_3**
- **3 mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ $\theta_{ij} \in [0,\pi/2]$**
- **1 phase (δ ⇒CP violation if not δ≠0, δ≠ π)**
- **+2 phases (ϕ_2,ϕ_3), if neutrinos are Majorana ⇒irrelevant for oscillations**

What we know

ν_1, ν_2, ν_3 **defined in decreasing ν_e fraction** $\nu_1 \Rightarrow \approx 70\%\ \nu_e,\ \nu_2 \Rightarrow \approx 30\%\ \nu_e,\ \nu_3 \Rightarrow \approx 0\%\ \nu_e$

solar squared mass difference $\Rightarrow \delta m^2$ (>0 from solar neutrinos)

atmospheric squared mass difference $\Rightarrow \Delta m^2$

$$\delta m^2 = 76.6 \pm 3.5 \ \ \mathrm{meV}^2$$

$$\left|\Delta m^2\right| = 2380 \pm 270 \ \ \mathrm{meV}^2$$

$$\sin^2\theta_{12} = 0.326^{+0.05}_{-0.04}$$

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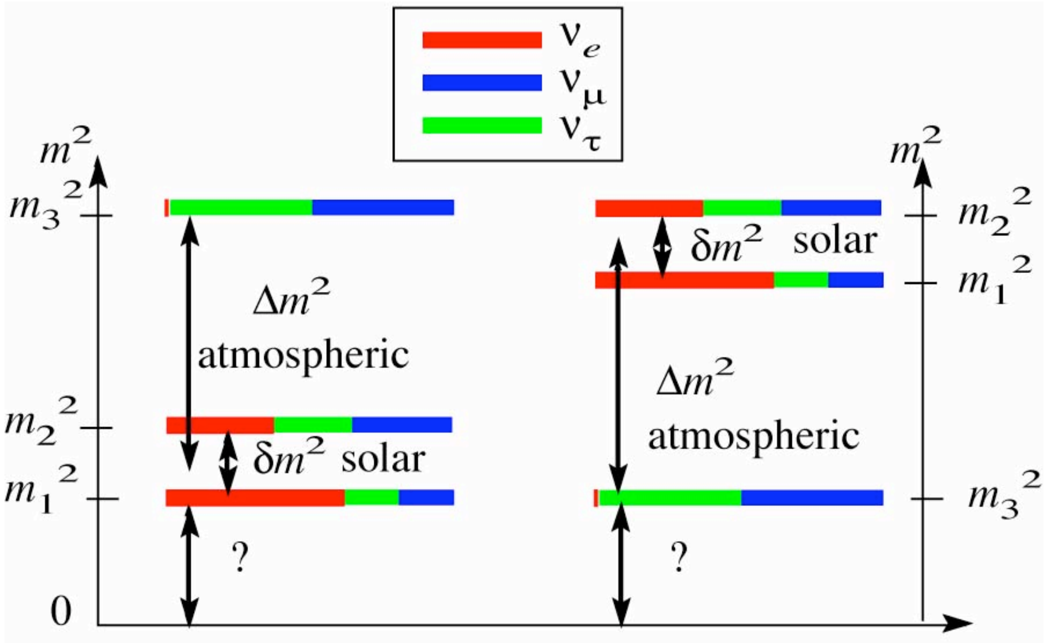


$m_3 > \sqrt{\Delta m^2} \approx 50 \ \ \mathrm{meV}$

$m_2 > \sqrt{\delta m^2} \approx 8.5 \ \ \mathrm{meV}$

$m_1, m_2 >\approx 50$ meV

$m_3 >\approx 8.5$ meV

We do not know

- **The absolute scale**
- **The sign of Δm^2**

Upper limits on the masses

1. β-decay. Electron spectrum near to its end point is affected by $m_i \neq 0$. Observable:

$$< m_{\nu e}^2 > = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \simeq$$

$$\simeq 0.7 m_1^2 + 0.3 m_2^2$$

Present limits **$<m_{\nu e}> < 2.2$ eV** from Mainz and Troitsk experiments

KATRIN (starts measurements in 2010) **$<m_{\nu e}> < 200$ meV**

2. 0ν2β-decay. If neutrinos are Majorana particles. Observable:

$$M_{ee} = |\sum_i U_{ei}^2 m_i| = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

3. Cosmology. Large Scale Structures spectrum is sensitive to neutrino mass, because neutrinos can escape from the structures during their formation, reducing the number of structures smaller than a scale depending on

$$\sum_i m_i$$

Limits are model dependent

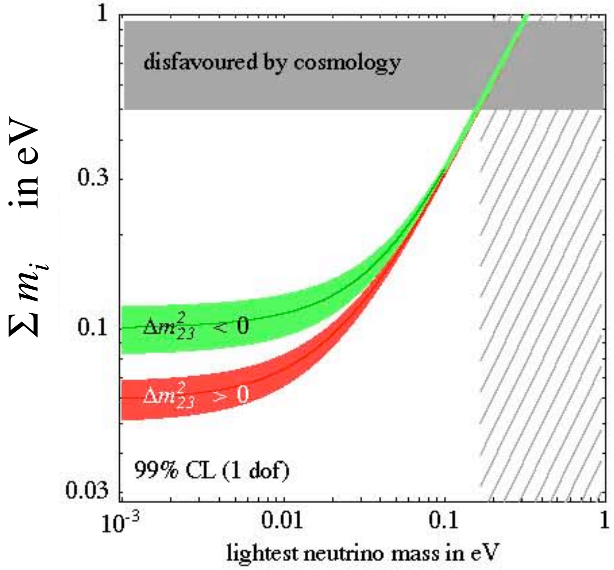
Conservative limit (CMB, BAO, LSS) **$\Sigma<600$ meV $\Rightarrow m_i<200$ meV**

Expected to improve

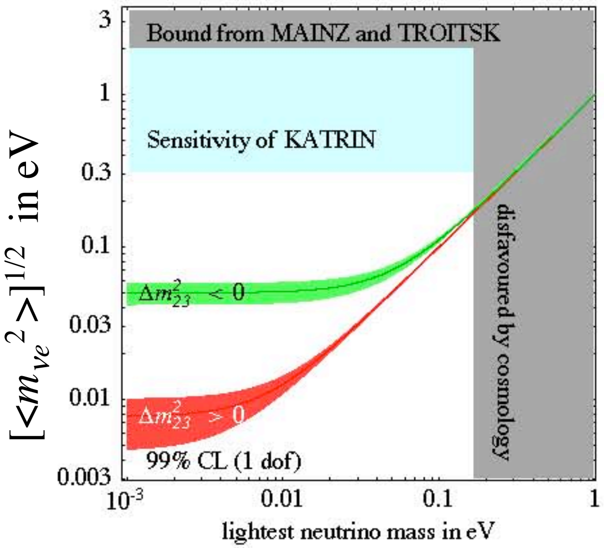
The three observables

A. Strumia and F. Vissani hep-ph/0606054

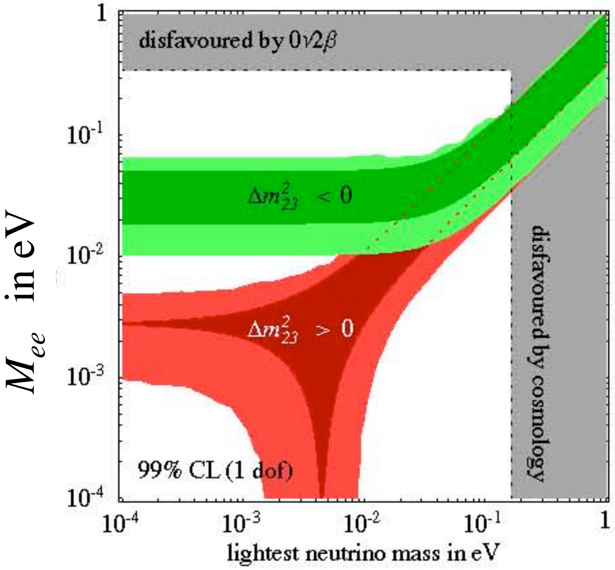
cosmology



β-decay

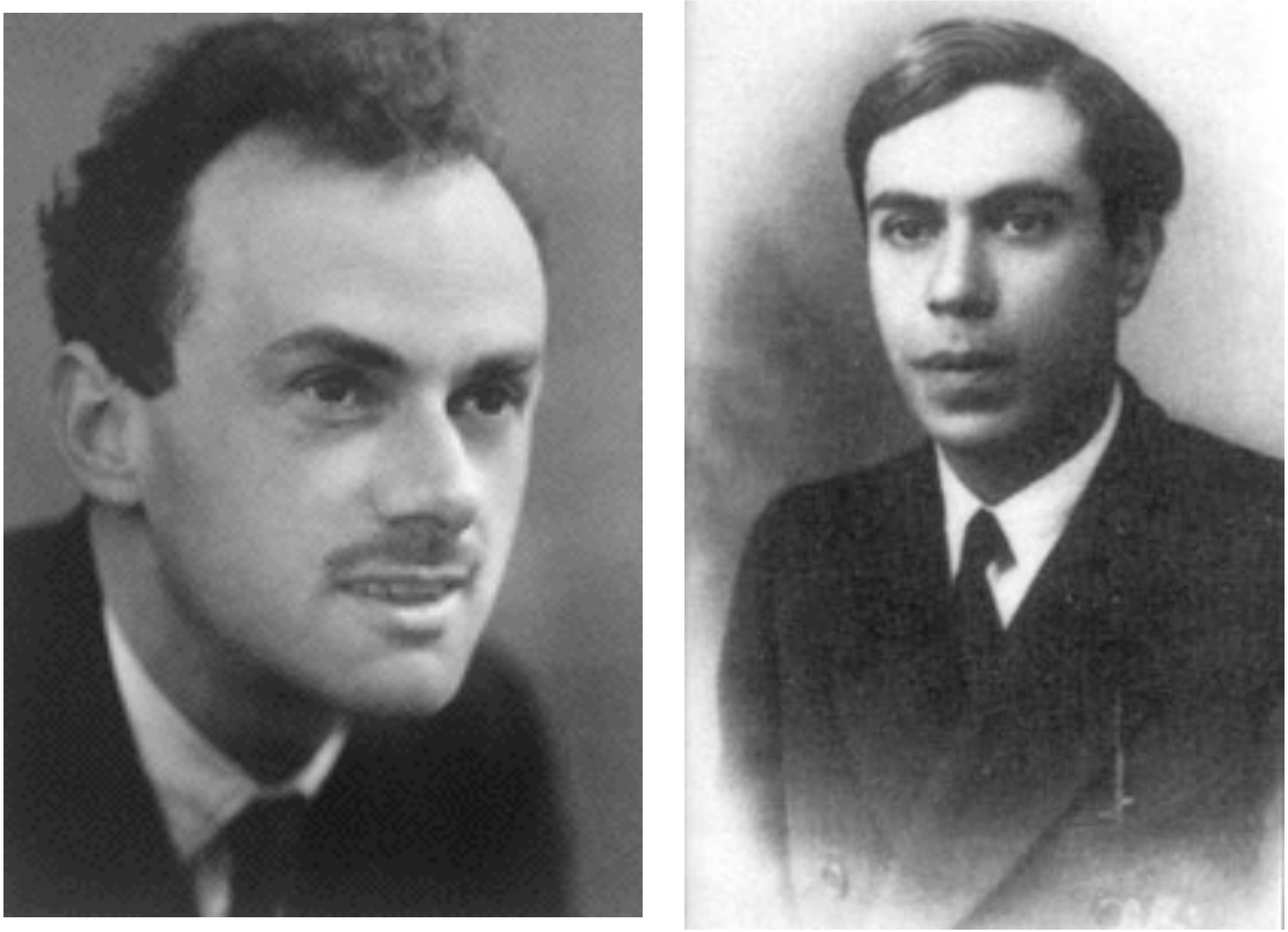


0ν2β-decay

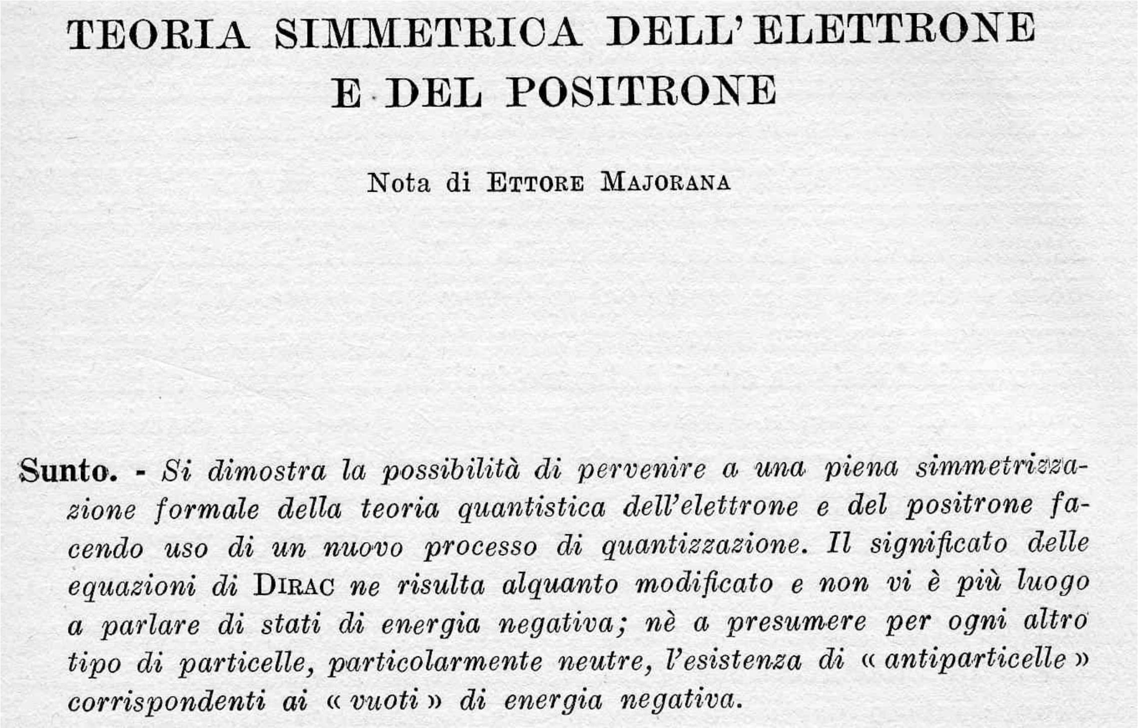


$$\frac{m_\nu}{m_t} < 10^{-12}$$

Dirac or Majorana?



Nuovo Cimento **14** (1937) 171-184



TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

We show that it is possible to achieve complete formal symmetrization in the electron and positron quantum theory by means of a new quantization process. The meaning of Dirac equations is somewhat modified and it is no more necessary to speak of negative-energy states; nor to assume, for any other type of particles, especially neutral ones, the existence of antiparticles, corresponding to the "holes" of negative energy.

An unpleasant asymmetry

“The interpretation of the so called “negative energy states” proposed by Dirac (in 1924) *leads, as it is well known, to a substantially symmetric description of electron and positrons”*

Majorana states not to be completely satisfied and to have tried another way leading directly to the goal

“*From this* (new way) *we can expect only a formal progress for electrons and positrons; but it looks to us important, in view of possible extensions, that the notion itself of negative energy state be abandoned. Indeed, we shall see that to be perfectly possible to build, in the most natural way, a **theory of the neutral elementary particles without negative states**.”*

The new approach allos to “*not only to give a symmetric form to the electron-positron theory, but also to build a substantially novel theory for the particles deprived of electric charge (neutrons and hypotetical neutrinos)”*

…….it is probably “*not yet possible to ask to the experience to decide between this new theory and the simple extension of the Dirac equations to the neutral particles*”

The neutrino had been introduced by W. Pauli in 1930, but it was not known to exist

Majorana observes that the new theory allows one to introduce “*in this poorly explored field the minimum possible number of new objects*”.

Namely, only two states, instead of the four states of the Dirac particles

The Dirac equation

The wave function of spin 1/2, free, elementary particles obeys Dirac equation.

$$\left(\gamma_\mu p^\mu - m\right)\psi = \left(E\gamma_0 - \vec{p}\cdot\vec{\gamma} - m\right)\psi = 0$$

$$x = (x_0, x_1, x_2, x_3)$$

$$\psi(x) = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix} = \begin{pmatrix} \varphi \\ \chi \end{pmatrix}; \quad \varphi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}; \quad \chi = \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

Ψ has 4 components (bispinor)

φ and χ have 2 components. They represent the **particle** and the **antiparticle**, each with **two** different states (s=1/2)

Helicity is a property of a <u>2-component</u> spinor, representing a particle with v≠0

It is the spin projection on the direction of velocity

The projection operator is

$$h = \frac{\vec{\sigma}\cdot\vec{p}}{|p|}$$

Chirality

Chirality is a property of the 4-component bispinor

Only negative chirality fields have CC weak interactions

The states of definite chirality are the eigenstates of γ_5, called *L* for the eigenvalue –1, *R* for +1

Obtained using the left and right projectors

$$\psi_L = \frac{1}{2}(1-\gamma_5)\psi, \qquad \gamma_5\psi_L = -\psi_L$$

$$\psi_R = \frac{1}{2}(1+\gamma_5)\psi, \qquad \gamma_5\psi_R = +\psi_R$$

The conjugate states $\quad \overline{\psi}_L = \overline{\psi}\frac{1}{2}(1+\gamma_5), \qquad \overline{\psi}_R = \overline{\psi}\frac{1}{2}(1-\gamma_5)$

γ_5 commutes with the Hamiltonian of free massless Dirac particles (not existing in Nature),

γ_5 does not commute with the mass term of the Dirac Hamiltonian

$$L_m = m(\overline{\psi}_R\psi_L + \overline{\psi}_L\psi_R)$$

Chirality is not an observable, we measure helicity instead

Chirality and helicity

In the representation in which γ_5 is diagonal $\gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & -\sigma^i \\ \sigma^i & 0 \end{pmatrix}, \quad \gamma^5 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$$\psi_L = \frac{1}{2}(1-\gamma_5)\psi = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} \varphi \\ \chi \end{pmatrix} = \begin{pmatrix} 0 \\ \chi \end{pmatrix} \qquad \psi_R = \frac{1}{2}(1+\gamma_5)\psi = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} \varphi \\ \chi \end{pmatrix} = \begin{pmatrix} \varphi \\ 0 \end{pmatrix}$$

Dirac equation
$$(E + \vec{p}\cdot\vec{\sigma})\chi - m\varphi = 0$$
$$(E - \vec{p}\cdot\vec{\sigma})\varphi - m\chi = 0$$

What is the helicity content of the (Left) spinor χ? Taking the z axis along the motion

$$\chi = \frac{1}{2}\left(\frac{E-p_z}{m}\right)\chi_L^{+1/2} + \frac{1}{2}\left(\frac{E+p_z}{m}\right)\chi_L^{-1/2} \approx \frac{m}{E}\chi_L^{+1/2} + \frac{1}{2}\left(\frac{E+p_z}{m}\right)\chi_L^{-1/2}$$

If the particle is ultrarelativistic, its negative chirality state contains a m/E “wrong” helicity component, very small if $E>>m$

Majorana equation

In the Dirac theory the two φ and χ spinor components of the bispinor have different transformation properties

Question: is it possible to find a spinor φ_c constructed with the components of φ only (and hence without further degrees of freedom), which transforms like a χ instead than a φ and that can consequently take its place inb the Dirac equation? And similarly for χ?

The answer, found by Majorana, is

$$\varphi_c = i\sigma_2\chi_M^* \qquad \chi_c = i\sigma_2\varphi_M^*$$

$$i\sigma_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Dirac equation

$$(E+\vec{p}\cdot\vec{\sigma})\chi - m\varphi = 0$$
$$(E-\vec{p}\cdot\vec{\sigma})\varphi - m\chi = 0$$

Majorana equation

$$(E+\vec{p}\cdot\vec{\sigma})\chi - im_a\sigma_2\chi^* = 0$$
$$(E-\vec{p}\cdot\vec{\sigma})\varphi - im_b\sigma_2\varphi^* = 0$$

If m=0, both the Dirac and the Majorana equations decouple one for φ and one for χ spinor
The positive chirality component does not interact and is unobservable
Nature has chosen $m \neq 0$, hence differences between the two theories exist

Dirac (4-component) bispinor field is equivalent to two degenerate (m_a=m_b) Majorana fields with

$$\varphi_D = i\sigma_2\chi_M^* \qquad \chi_D = i\sigma_2\varphi_M^*$$

I J R Aitchinson & A J G Hey Gauge theories in particle physics” Vol 2 Appendix P2 IoP 2004

Majorana bispinor

We can write the Majorana bispinor wave function as

$$\psi_D = \begin{pmatrix} \varphi \\ \chi \end{pmatrix} \quad \Longrightarrow \quad \psi_M = \begin{pmatrix} \varphi \\ i\sigma_2 \varphi^* \end{pmatrix}$$

The charge conjugated Majorana bispinor is

$$\psi_M^C = i\gamma_2 \psi_M = \begin{pmatrix} 0 & -i\sigma_2 \\ i\sigma_2 & 0 \end{pmatrix} \begin{pmatrix} \varphi \\ i\sigma_2 \varphi^* \end{pmatrix} = \begin{pmatrix} \varphi \\ i\sigma_2 \varphi^* \end{pmatrix} = \psi_M$$

Majorana neutrinos are their own antiparticles

Particle and antiparticle have all the “charges” with opposite values ⇒ **they are different particles**

Neutrinos and antineutrinos are possibly distinguished by a unique charge, the lepton number

Electric charge conservation corresponds to a local symmetry $U(1)$, which governs the dynamics

L conservation is a global symmetry, which does not govern the dynamics. Rather it is a consequence of the dynamic and of the field composition of the Standard Model

If lepton number is not conserved nothing distinguishes neutrino from antineutrino

Neutrino may be its own antiparticle

Being antiparticle its own antiparticle for a fermion

If ultrarelativistic ($m<<E$) ⇒ approximte distinction between Majorana “neutrinos” and “antineutrinos” possible

CC weak current $\overline{\nu_l}\gamma^{\mu}l_L$ creates

Dirac: ν

Majorana: $\left[\nu(h=-1)+\left(m/E\right)\,\nu(h=+1)\right]$

CC weak current $\overline{l_L}\gamma^{\mu}\nu_l$ creates

Dirac: $\bar{\nu}$

Majorana: $\left[\nu(h=+1)+\left(m/E\right)\,\nu(h=-1)\right]$

⇒ **Majorana neutrino ≡ negative helicity** (if $m/E<<1$ interacts almost as a Dirac neutrino)

Majorana antineutrino≡ positive helicity (if $m/E<<1$ interacts as almost a Dirac anti-ν)

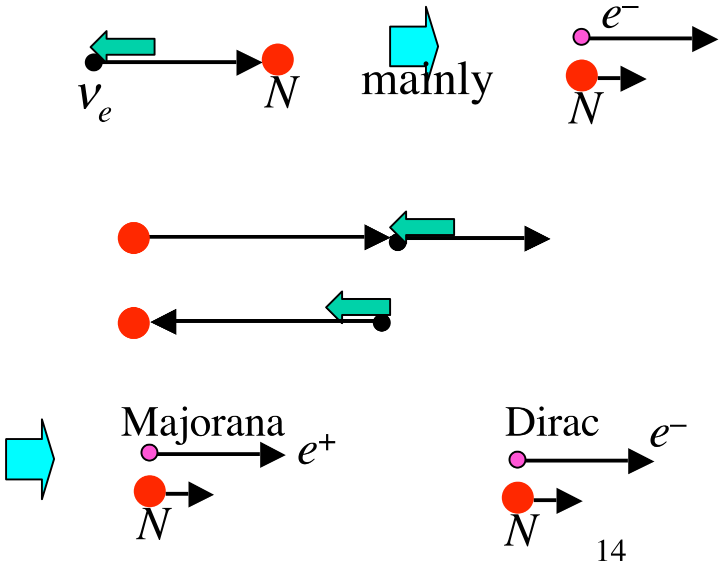
A meson can be its own antiparticle both if it is massive, π^0, and in massless, γ

A spin 1/2 particle needs to be massive

A Majorana ν_e with $E\approx+p_z>>m$ hitting a nucleus produces e^- and a fraction $(m/E)^2$ of e^+

[10^{-20} for E=1 GeV, m=100 meV] ⇒ $L_{\text{eff}}=+1$

The fraction of antineutrino in the amplitude (m/E) is not Lorentz-invariant. The same particle, in a frame in which $E\approx-p_z>>m$ is mainly antineutrino, with a fraction m/E of neutrino ⇒ $L_{\text{eff}}=-1$



Majorana Neutrinos $\nu_e^C = \nu_e$

Tow possible mass terms in the Hamiltonian:

Dirac: $m\bar{\psi}\psi$ and $m\bar{\psi}^C\psi^C$

Majorana: $\bar{\psi}\psi^C + \bar{\psi}^C\psi_l$

Dirac: invariant under global phase transformation $\psi \Rightarrow e^{i\varphi}\psi$, $\psi^C \Rightarrow e^{-i\varphi}\psi^C$ ⇒ Lepton number conservation

Majorana: not invariant ⇒ Lepton number violation

Matrix elements give observable physical processes $\Delta L=2$

Scattering processes, e.g. $M_{\mu e}^{M} \Rightarrow \mu^- + (Z,A) \rightarrow e^+ + (Z-2,A)$ Too small

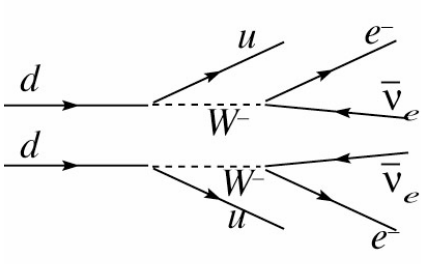
Decays $M_{ee}^{M} \Rightarrow (Z,A) \rightarrow 2e^- + (Z+2,A)$ $0\nu\beta\beta$

The neutrino less double beta decay is the only process in reach in the present years

N.B. $Q_{\beta\beta}$ are have been measured and are genrally known within a fraction of keV

Majorana vs. Dirac differences should be spectacular at milli-electronvolt neutrino energies

ββ2ν and ββ0ν Decay



2^{nd} order weak interaction
In nuclides stable against β decay

@ nucleon level

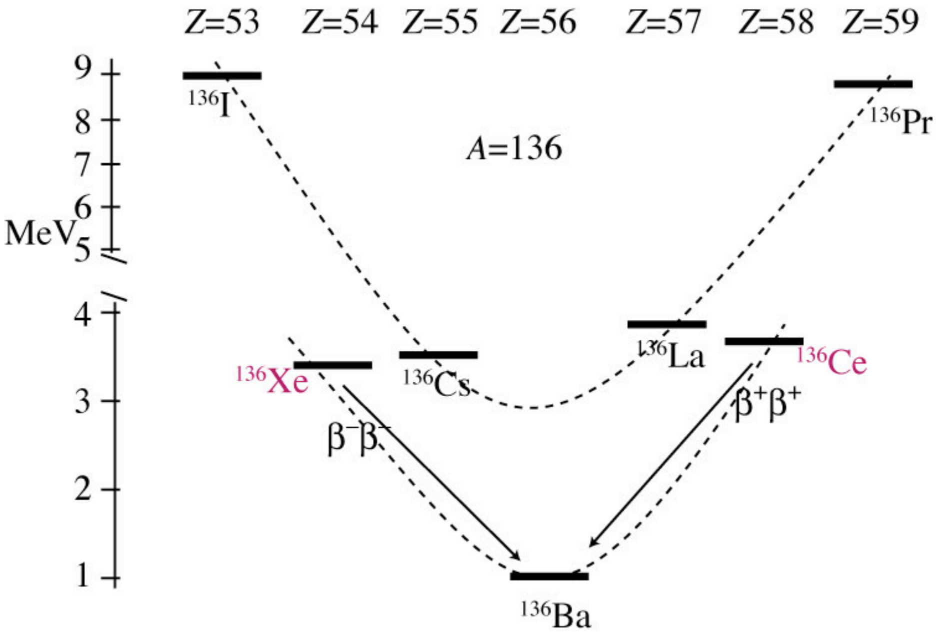
$$n+n \rightarrow p+p+e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

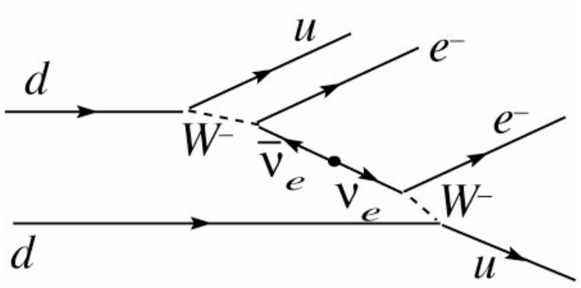
@ nuclear level

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

Lifetime measured for several isotopes (mainly by NEMO3)

Isotope	$T^{2\nu}_{1/2}(10^{19}$ yrs)
^{76}Ge	150±10
^{82}Se	9.2±0.7
^{100}Mo	0.71±0.04
^{130}Te	90±10
^{135}Xe	>81 (90% cl)





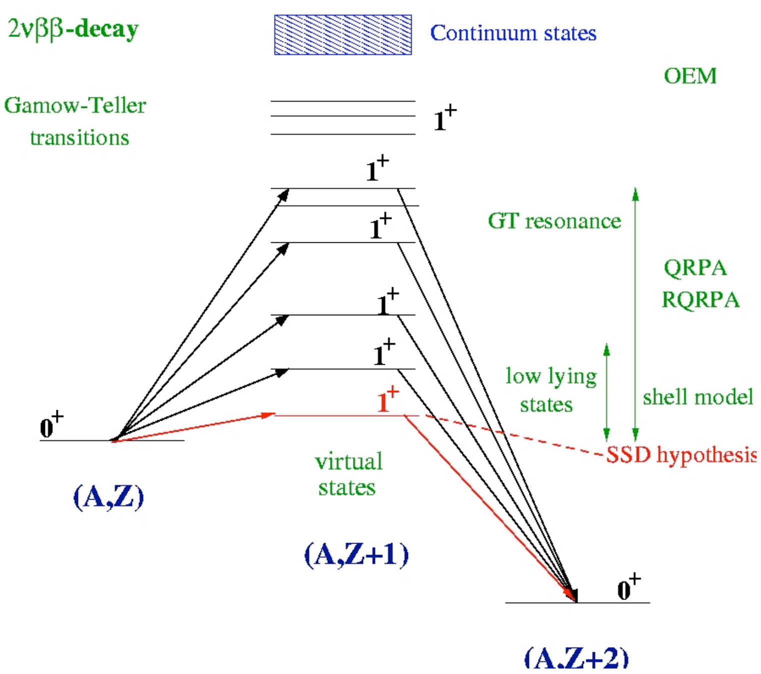
Forbidden in the Standard Model
If observed
- Lepton number is violated $\Delta L=2$
- Neutrinos are Majorana

The theoretical challenge

The $0\nu\beta\beta$ decay rate (reciprocal of the lifetime $\mathbf{1/\tau}$) depends on **phase space volume ($G \propto Q^5$)**, the **nuclear matrix element** and the **neutrino "mass" parameter M_{ee}**

$$1/\tau = G(Q,Z)\,|M^{0\nu}|^2\, M_{ee}^2$$

- Calculation of N.M.E $M^{0\nu}$ and $M^{2\nu}$ ⇒ evaluate ground state wave functions of both nuclei and construct complete set of states of intermediate nucleus
- Approximations and truncations needed. Main techniques: QRPA = Quasi Particle Random Phase Approximation & Shell Model
- "particle-particle" coupling g_{pp} **fixed by** comparing the calculated $M^{2\nu}$ with **$2\nu2\beta$ data**
- **Att.!** in $2\nu2\beta$ momentum transfer $q<$ few MeV (long distance); in $0\nu2\beta$ q=100-200 MeV (2-3 fm important)
- **Att.!** Cancellations between large terms (J=0 pairs vs. $J\neq0$ pairs)



Theoretical work has progressed considerably in the last years:

reasons for different results have been understood

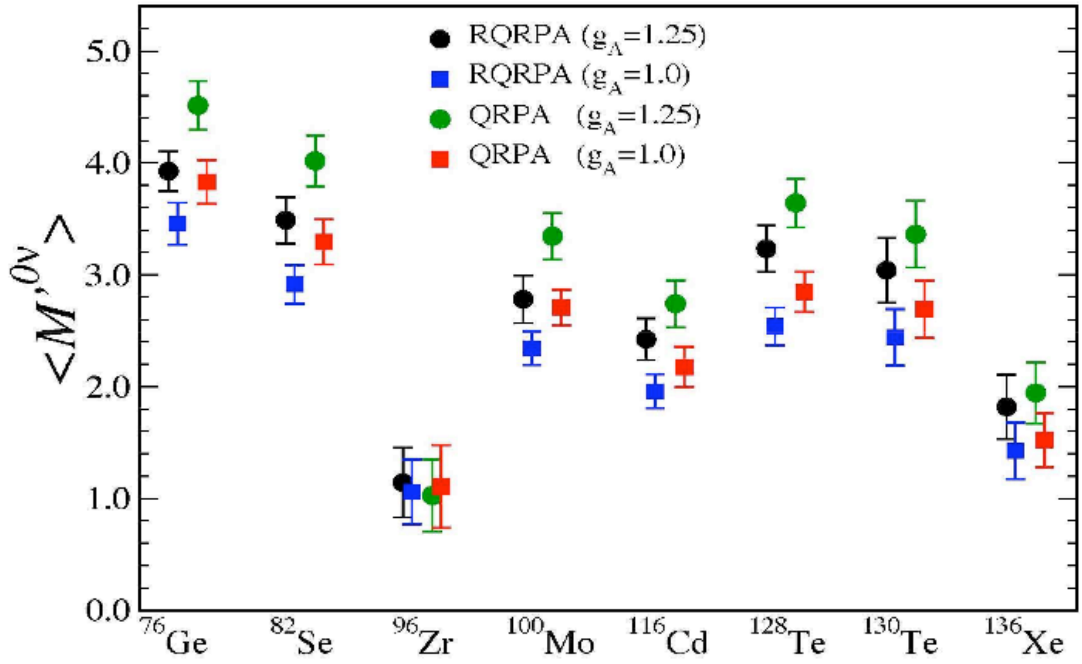
convergence and consensus increasing (depending on nucleus)

further progress needed, and possible

From the measured lifetime to M_{ee}

Rodin, Faessler, Simkovic, Vogel; Nucl. Phys. **A 766** (2006) 107; **A 793** (2007)

$$1/\tau = G(Q,Z)\,|M^{0\nu}|^2\,M_{ee}^2$$



Examples

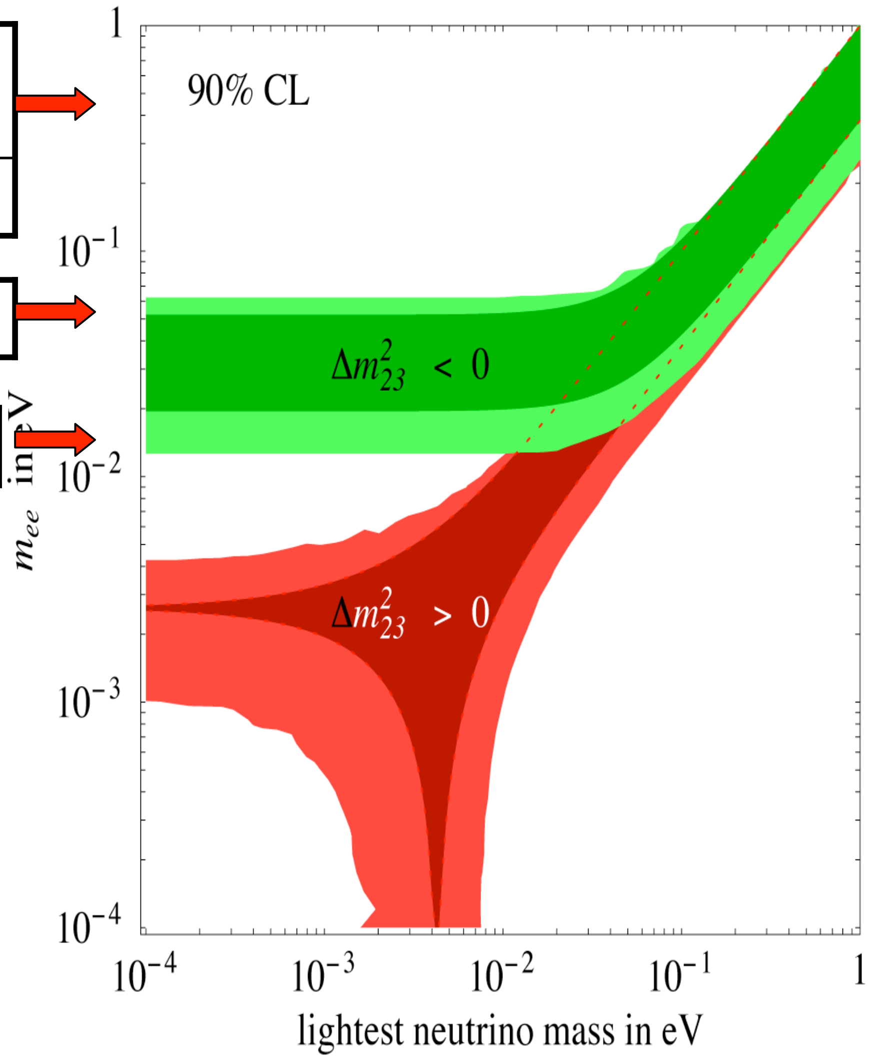
Nuclear transition	$M^{0\nu}$	$T^{0\nu}_{1/2}$ (years) ($m_{\beta\beta}$=50 meV)
$^{76}Ge \to {}^{76}Se$	3.92	8.6 10^{26}
$^{82}Se \to {}^{82}Kr$	3.49	2.4 10^{26}
$^{130}Te \to {}^{130}Xe$	2.95	2.2 10^{26}
$^{130}Xe \to {}^{130}Ba$	1.97	4.6 10^{26}

250 kg of ^{76}Ge enriched @ 86%
⇒ 1 event/yr @ 100% efficiency

The experimental challenge

Events per ton per year

	Ge enrich. (85%)	TeO_2 natural	Xe enrich. (85%)
M_{ee}=500 meV	400	250	430
M_{ee}=50 meV	4	2.5	4.3
M_{ee}=15 meV	0.4	0.2	0.4

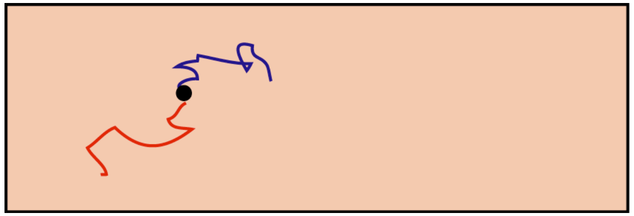


Within a factor ≈ 2

Two main approaches

Present generation of experiments aims at 100 meV scale ⇒ $b<10^{-3}$/(keV kg yr)

two orders of magnitude better than now



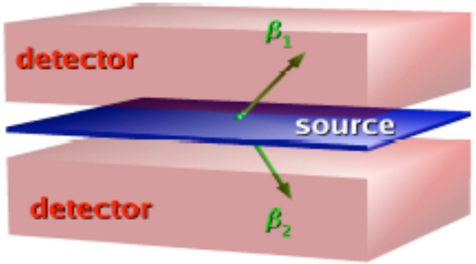
Source=detector

Measure total two electron energy K_{ee} (calorimetry)

Ge diodes, bolometers

+ very clean materials
+ very large sensitive masses
  several 100 kg:
  - CUORICINO/CUORE, bolometers
  - GERDA, MAJORANA Ge diodes
+ ΔE_{FWHM} Ge≈3 keV @ 2 MeV (0.16%)
  ΔE_{FWHM} Bolometrs ≈6 keV @ 2 MeV (0.3%)

+ FINAL STATE TAGGING under R&D



Source ≠ detector

Tracking in TPC (gas or liquid), drift chambers or scintillators

Possible **B** field for charge sign

Possible calorimetry

downstream tracking

+ bckgnd suppression via event reconstruction
– **limited energy resolution**
  (NEMO3 ΔE_{FWHM}≈400 keV @ 3 MeV, 13%)
– large surface/volume⇒ sensitivity to surface bckg.
– "dilute" detectors, need large space
+ several nuclides possible
  NEMO3: tracking, calorimetry, **B**-field
  ⇒Future: SuperNEMO

ββ2ν decay, the ultimate background

ββ2ν spectrum in the Primakoff Rosen approximation

$$\frac{dN}{dK_{ee}} \simeq K_{ee}\left(Q_{\beta\beta}-K_{ee}\right)^5\left(1+2K_{ee}+\frac{4}{3}K_{ee}^2+\frac{1}{3}K_{ee}^3+\frac{1}{30}K_{ee}^4\right)$$

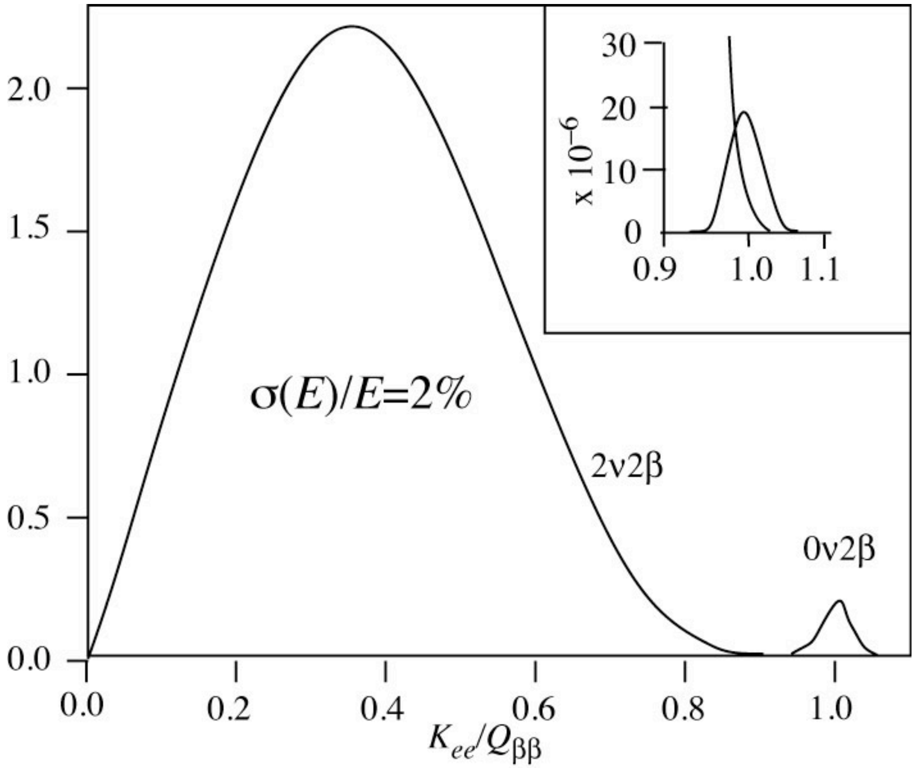
Near the end point $\frac{dN}{dK_{ee}} \propto \left(Q_{\beta\beta}-K_{ee}\right)^5$

The fraction of ββ2ν events in ΔE near end point is

$$F \simeq \frac{7\left(\Delta E\right)^6}{m_e Q_{\beta\beta}^5}$$

And the signal/background

$$\frac{S}{B} \simeq \frac{m_e Q_{\beta\beta}^5}{7\left(\Delta E\right)^6}\frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$



Extreme importance of energy resolution

Nuclides with large $Q_{\beta\beta}$ and long ββ2ν look "easier"

Sensitivity of the 2β0ν experiments

Sensitivity to τ in presence of background b ct/(keV kg yr)
ε efficiency

$$F_\tau \propto \underset{\text{Isotopic abundance}}{a}\,\varepsilon\left(\frac{\overset{\text{Detector mass}}{M}\,\overset{\text{Exposure time}}{T}}{b\,\underset{\text{Energy resolution}}{\Delta E}}\right)^{1/2}$$

sensitivity to $\frac{1}{M_{ee}^{M}} \propto F_M = \left(\frac{MT}{b\Delta E}\right)^{1/4}$

If b=0 during T, in a energy window of a few ΔE with (a few keV for Ge and bolometers) sensitivity on $M_{ee} \propto$ **2nd root** of the exposure

$$F_M \propto \sqrt[2]{MT}$$

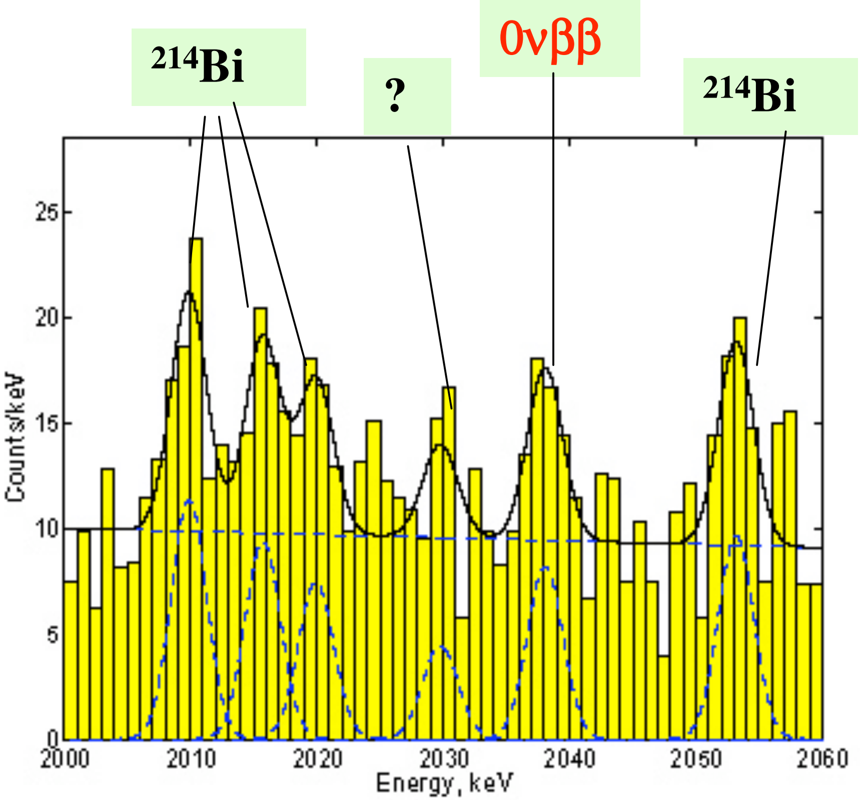
Background reduction and energy resolution are the key features

Evidence from Heidelberg-Moscow @ LNGS

MT = 71.7 kg y (86% ^{76}Ge)

b = 0.11 ev/(kg keV yr) before PSA

Resolution on 8 years ΔE = 3.27 keV



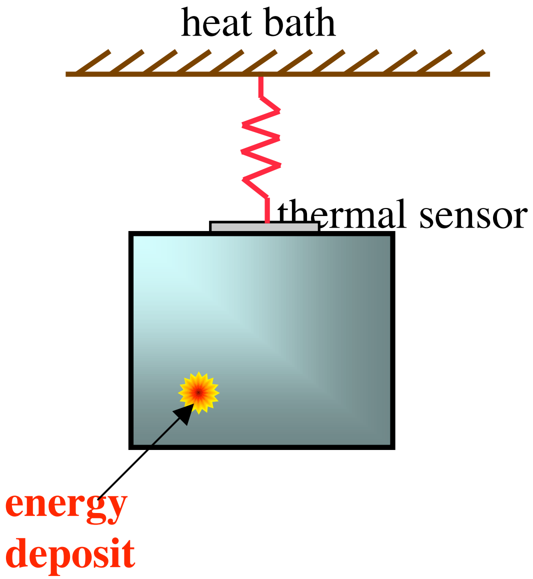
Claimed evidence of 0νββ @ 4σ
$T_{1/2}$= 2.2 $_{-0.31}^{+0.44}$ 10^{25} y
M_{ee}= 150 - 520 meV
(as quoted by Fogli et al. hep-ph/0805.2517)

Expected position of 0νββ line well known
$Q_{\beta\beta}$=2039.006±0.05 keV
found @ $Q_{\beta\beta}$=2038.7±0.44 (+2.1 σ)

IGEX @ LSC, the other experiment with Ge diodes and similar sensitivity, gives an upper limit $T_{1/2}$> 1.6 10^{25} y

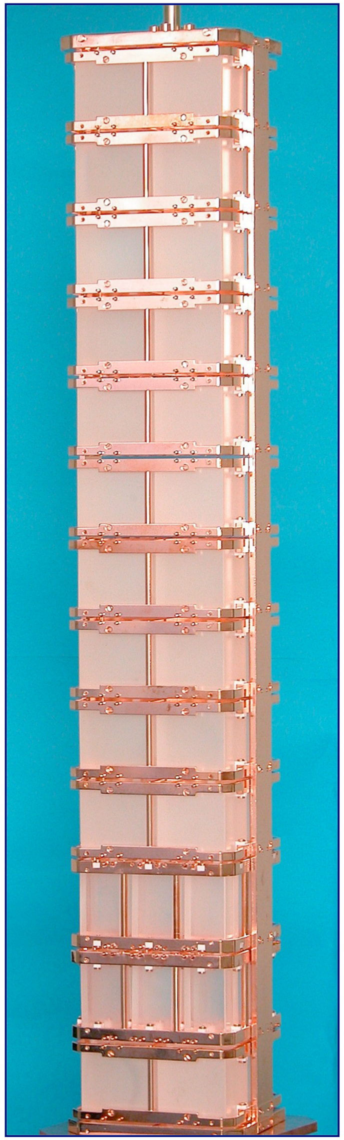
CUORICINO@LNGS

Bolometric technique ⇒ detect energy deposit as ΔT @ a few mK; ^{130}Te (Q=2529 keV)

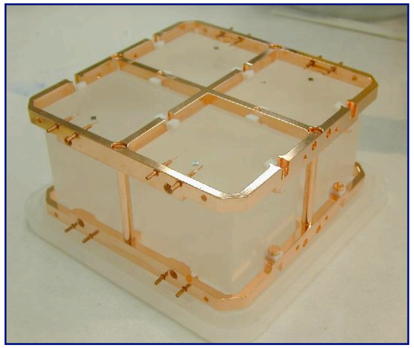


$$C_V \propto \left(\frac{T}{T_D}\right)^3$$

ΔE~ keV @ 2 MeV
~10 mk ~ 1 kg



One tower of TeO_2 crystals (11.7 kg **^{130}Te**)
Running April 2003 - July 2008
ΔE≈8 keV; ***b*=0.18±0.01** ev/(kg keV yr)



11 modules
4 detector each,
crystal size 5x5x5 cm^3
crystal mass 790 g
34.76 kg of TeO_2

2 modules
9 detector each,
crystal size 3x3x6 cm^3
crystal mass 330 g
5.94 kg of TeO_2

CUORICINO limit

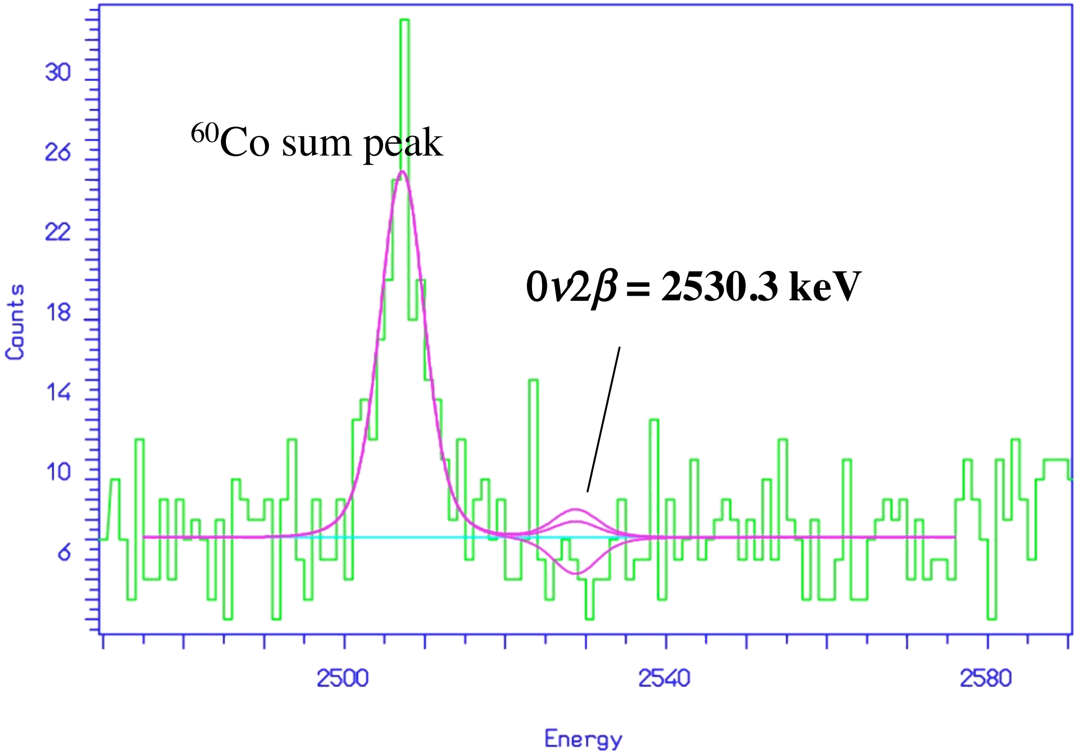
Exposure **15.53 kg yr**

$T_{1/2}$> 3.1 10^{24} y @90% c.l.

M_{ee}< 380-460 meV

With Rodin et al. ME (nucl-th/0706.4304)

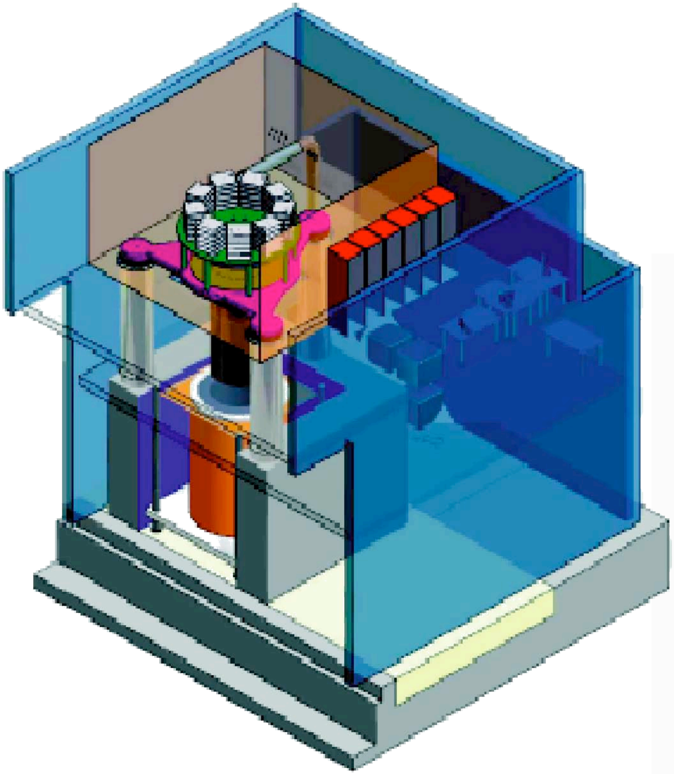
as quoted by C. Arnaboldi et al. (CUORICINO) 0802.3439

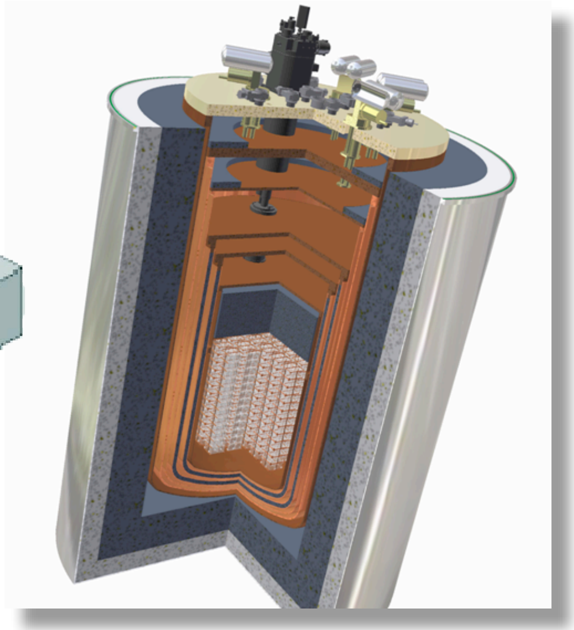


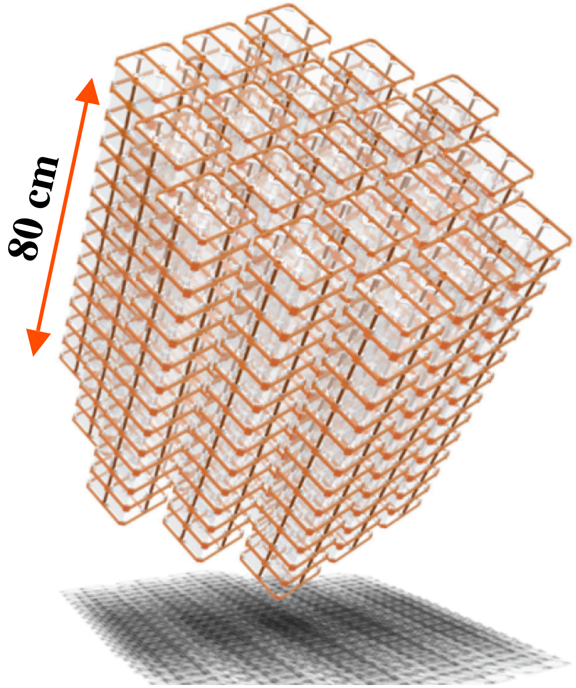
Curves show
- •Best fit (negative)
- •68% limit
- •90% limit

CUORE=Cryogenic Underground Observatory of Rare Events

CUORE =988 detectors in towers $M(^{130}\mathrm{Te}) = 203$ kg
Work on bckg ⇒ $b=10^{-2}$/(kg keV yr) or better, **$\Delta E=5$ keV**
Sensitivity in 5 yr ⇒ $M_{ee} < 50$ meV







19 towers with
13 planes of
4 crystals each

CUORE background model

Adapted from A. Giuliani

Monte Carlo model developed on the basis of the CUORICINO background model, experimentally tested, the CUORE structure, specific measurements in the test facility @ LNGS

Component	b (10^{-3} keV^{-1} kg^{-1} y^{-1})
Environmental γ	<1
Apparatus γ	<1
Crystal, bulk	<0.1
Crystal, surfaces	<3
Inert materials, bulk	<1
Inert materials, surface	**20-40**
Neutrons	0.01
Muons	0.001

Explained as due to ^{238}U and ^{210}Pb on the Cu surface facing the detectors

100 pg/g on 10 μm depth

Strategies to control surface backgrounds being developed

- Passive: Mechanical polishing, Electropolishing, Chemical etching, Sputtering in UHV, LASER cleaning, Plasma cleaning
- Active
    - surface sensitive bolometers (surface events are faster)
    - measure heat and light

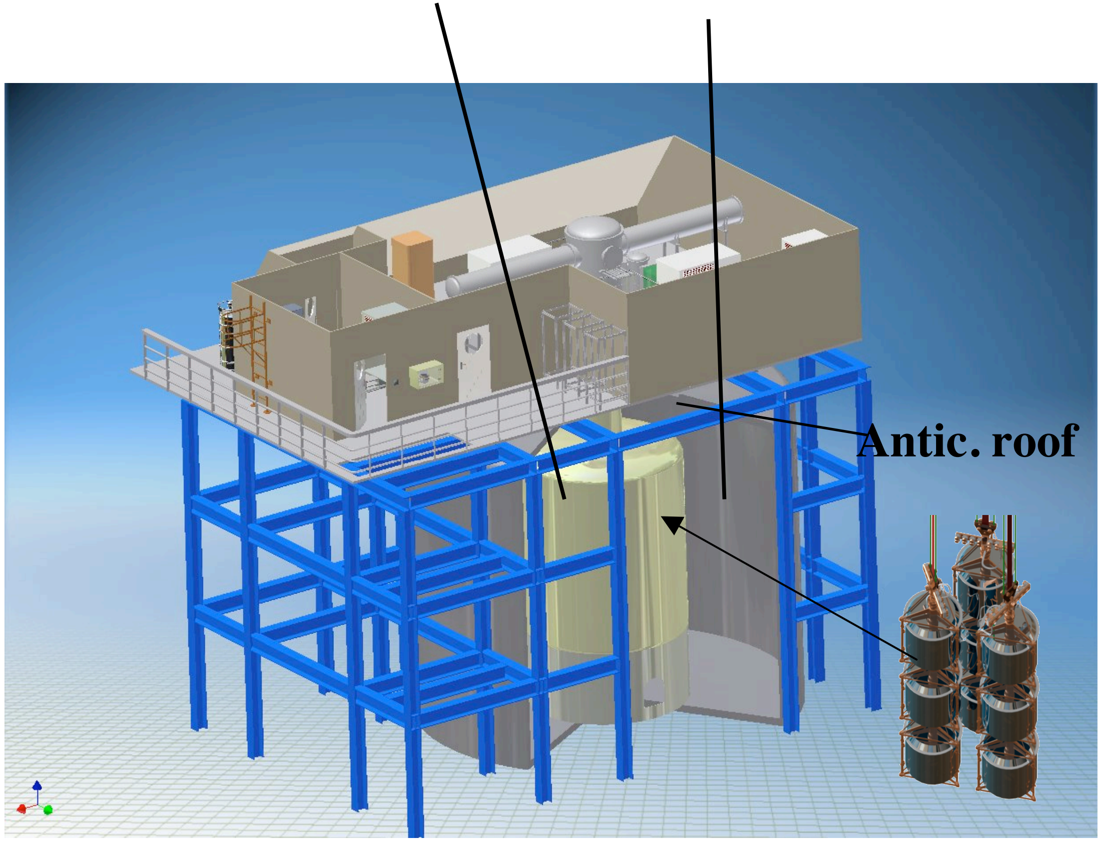
Diagnostic problem: measure U & Th contaminations of the order of ng/g ⇒ ICPMS

GERDA

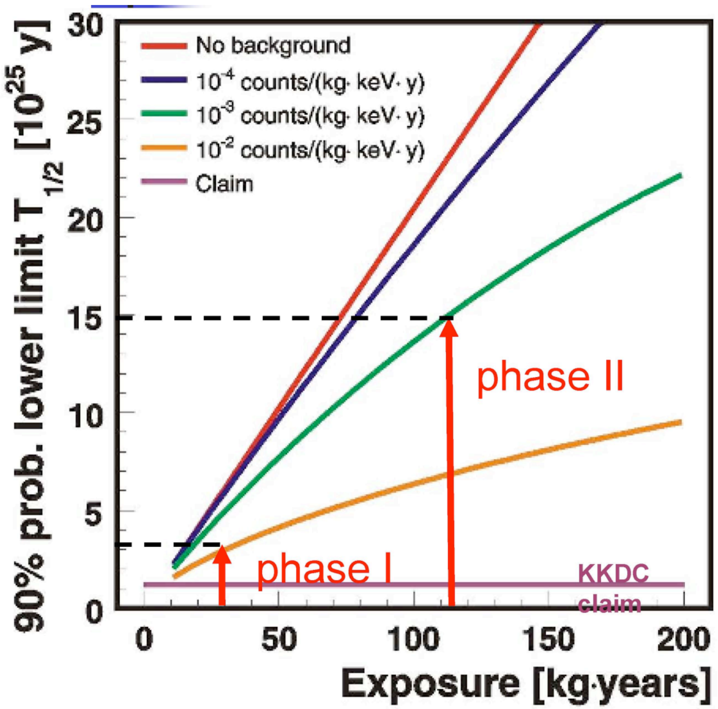
Source & detector = HP enriched Ge crystals

Shields=ultra-pure liquids

LAr + <u>Active</u> H_2O



Rodin et al. NP **A766** (2006) 106; erratum nucl-ex/0706.4304



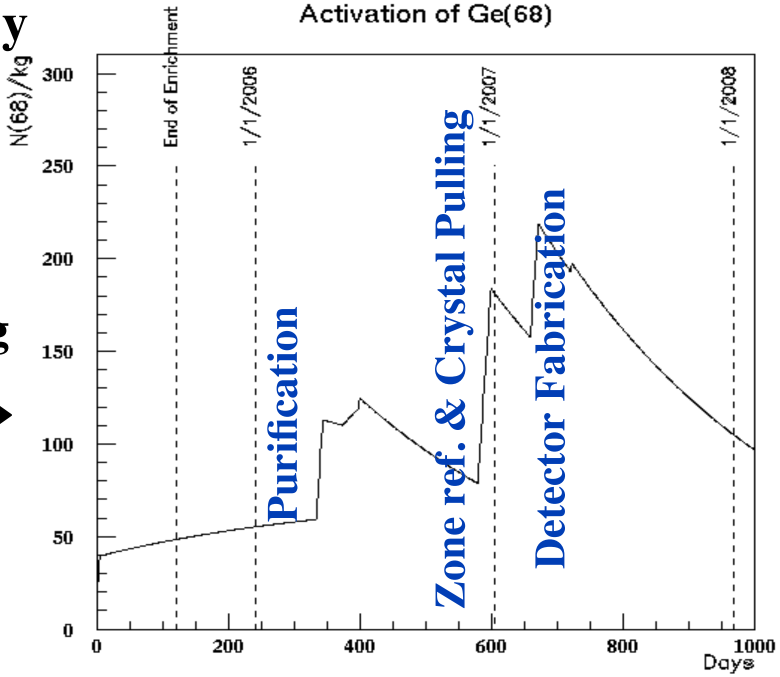
Phase 1; existing HM+IGEX detectors
Exposure 15 kg y
$b = 10^{-2}$ ev/(kg keV yr)
Sensitivity **$T_{1/2}=2\times10^{25}$ y: $M_{ee}\approx$ 400 meV**

Phase 2: Additional 20 kg of enriched segmented detectors
Exposure 100 kg y
$b = 10^{-3}$ ev/(kg keV yr)
Sensit. **$T_{1/2}=13\times10^{25}$ y; M_{ee}= 140 meV**

Background Evaluation and Materials Screening

Detailed evaluation of background sources by

- **Analytical calculations**
  - **Example: Cosmogenic activation of ^{68}Ge during detector production**



- **Monte Carlo simulations: MAGE = frame (GEANT4) and database developed in co-operation with Majorana**

- **Screening of the materials and components in different sites, depending on the issue**
  - **γ spectroscopy @LNGS, Baksan, MPIK, GEEL**
  - **ICP-MS** (Inductively Coupled Plasma Mass Spectroscopy) **@ LNGS** and **Frankfurt U.**

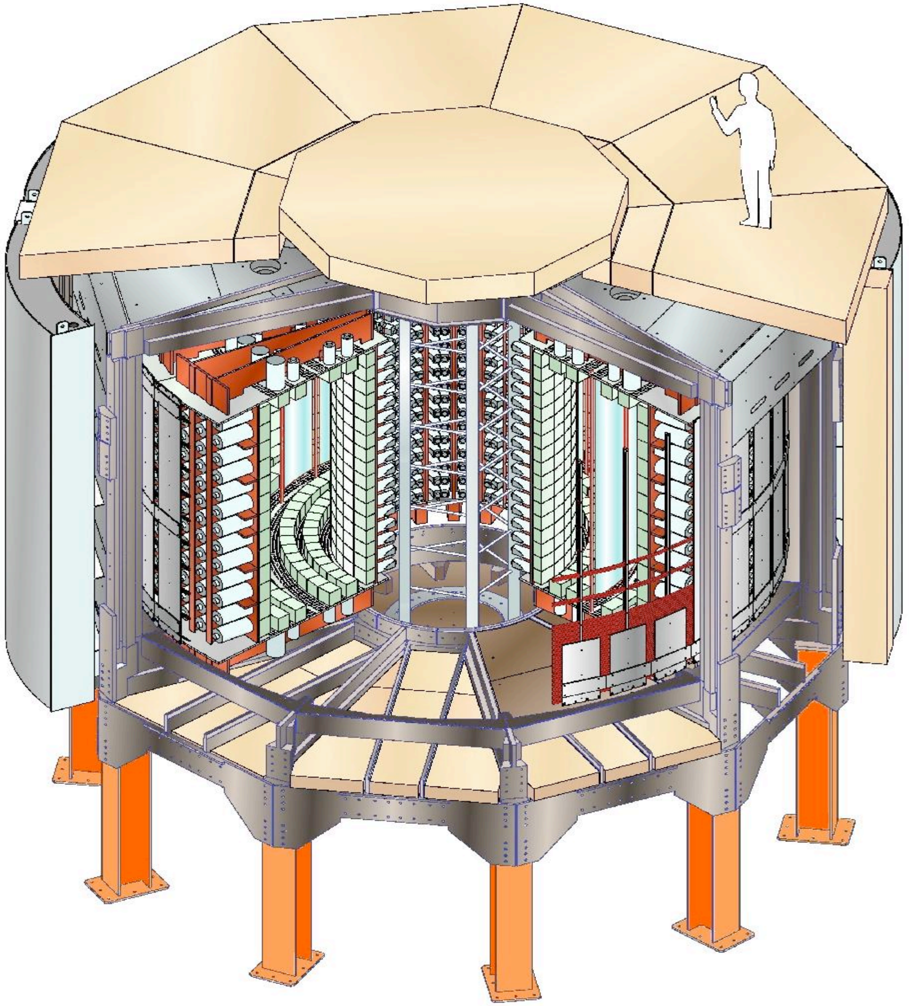
Background Evaluation & Reduction

Source	Actions
γ's from external environment ^{208}Tl, ^{214}Bi,…	•Shield with hyperpure liquids (3m H_2O+ 2m Lar) $\Rightarrow 3\times10^{-5}$ kg^{-1} y^{-1} keV^{-1}
^{228}Th (<10 mBq/kg) in Cryostat (SS)	•HP Cu shield (25 μBq/kg; 10-15 cm thick)+**active** LAr
μ induced prompt signals	•1400 m rock overburden •Anticoincidence between crystals&segments •μ-vetos: top (plastic scint.) +Water Cherenkov $\Rightarrow 10^{-4}$ kg^{-1} y^{-1} keV^{-1}
μ induced delayed signals $n+{}^{76}Ge \rightarrow {}^{77m}Ge \Rightarrow {}^{77}As$ ($t_{1/2}$= 53 s)	•Low-Z shields •Tag γ's from ^{77m}Ge decay$\Rightarrow 10^{-4}$ kg^{-1} y^{-1} keV^{-1}
Internal to crystals Cosmogenic ^{60}Co ($t_{1/2}$= 5.27 y (crystal production)	•Minimize time above ground after crystal growing •Anticoincidence between segments, PSA $\Rightarrow 3.5\times10^{-5}$ kg^{-1} y^{-1} keV^{-1}
Internal to crystals Cosmogenic ^{68}Ge ($t_{1/2}$= 270 d) (crystal and detector productions)	•Minimize time above ground after enrichment; shielded transport container. After 2 years underground $\Rightarrow$ **5×10^{-4}** kg^{-1} y^{-1} keV^{-1} Reduce by segmentation and PSA
Front-end electronics, cables, supports	•Material minimisation (grams), screening by activity measurements $\Rightarrow$ **5×10^{-4}** kg^{-1} y^{-1} keV^{-1} •Still nder R&D

Adapted from Sarazin @ Neutrino 2004

NEMO 3

Data taking at Frejus Underground Laboratory since February 2004



Sources:

- 6.9 kg of ^{100}Mo ($Q_{\beta\beta}$ =3034 keV)
- 0.9 kg of ^{82}Se ($Q_{\beta\beta}$ =2995 keV)
- +several grams of ^{116}Cd, ^{96}Zr, ^{150}Nd, ^{48}Ca

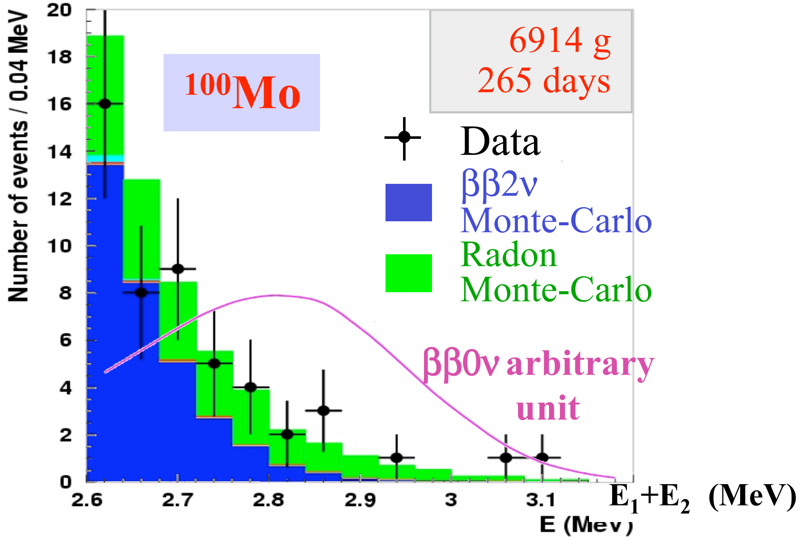
Tracking detector:

- drift chamber operating in Geiger mode

Calorimeter:

plastic scintillators

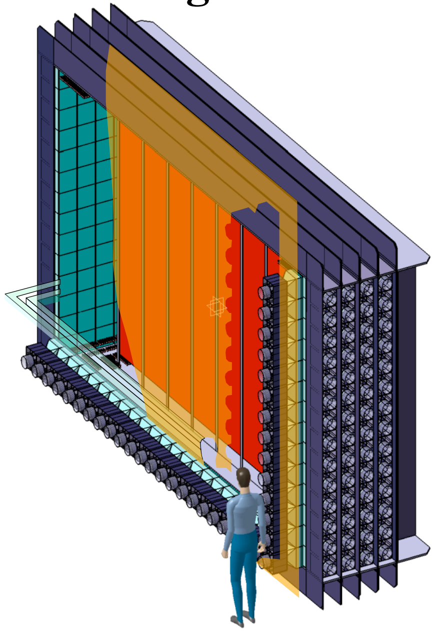
- Energy res. FWHM @ 1MeV = 14-17%



SuperNEMO R&D

20 such modules = 100 kg

Enclosed
in a
water
shield



5 kg source foil (40 mg/cm^2): enriched ^{82}Se (^{150}Nd if enrichment possible)

Calorimeters: scintillator

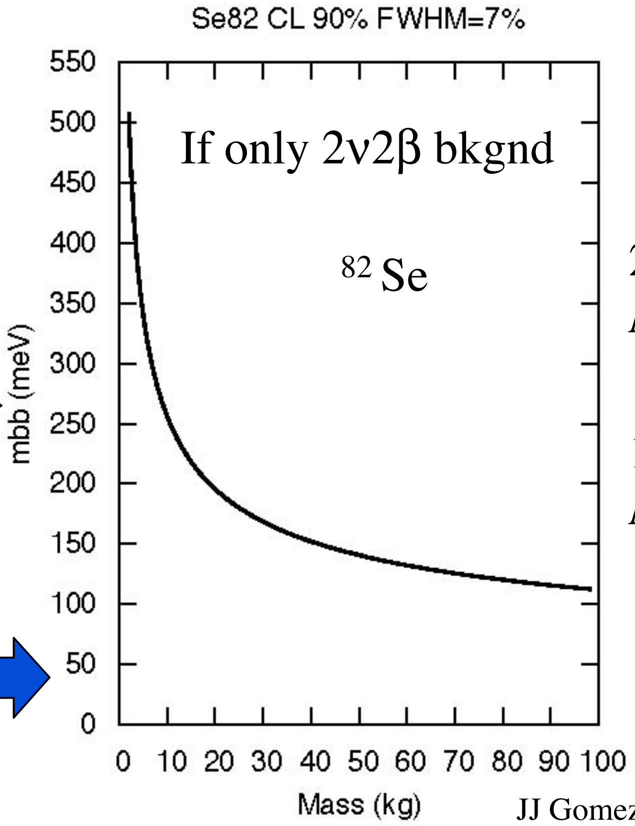
Tracking: Drift chambers (Geiger)

Magnetic field B = 2.5 mT (sign)

Expected efficiency for ββ0ν =20%

$\Delta E_{FWHM}/E$ @ 1MeV
NEMO3 =14-17%
Best prototype so far = 8%
Design figure = 4% @3 MeV

Contamination of the (large) source foil
BiPo detectors for requested sensitivity
^{208}Tl < 20 μBq/kg ⇒ <2 μBq/kg
^{214}Bi < 300 μBq/kg ⇒ <10 μBq/kg



25 kg ⇒ M_{ee}<120 meV

100 kg ⇒ M_{ee}<80 meV

JJ Gomez-Cadenas et al. 2008

EXO200. LXe TPC

TPC of enriched (80%) ^{136}Xe

Phased programme up to 1-10 t

200 kg under construction @ WIPP

ΔE_{FWHM}=3.3 %

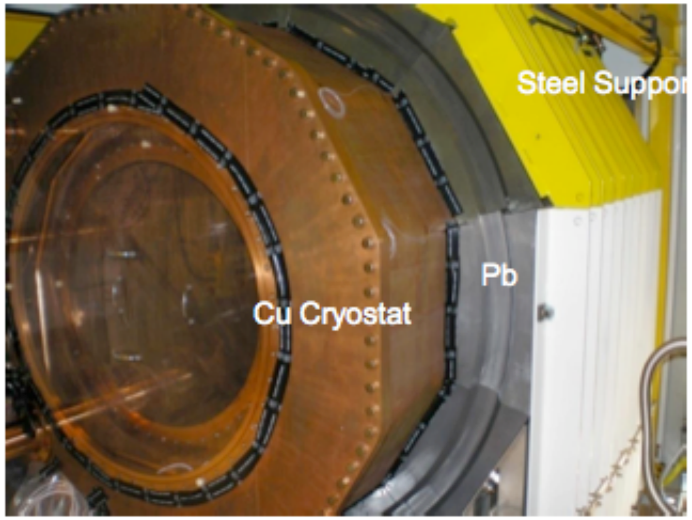
Achieved by measuring ionisation & light

Engineering run in 2009

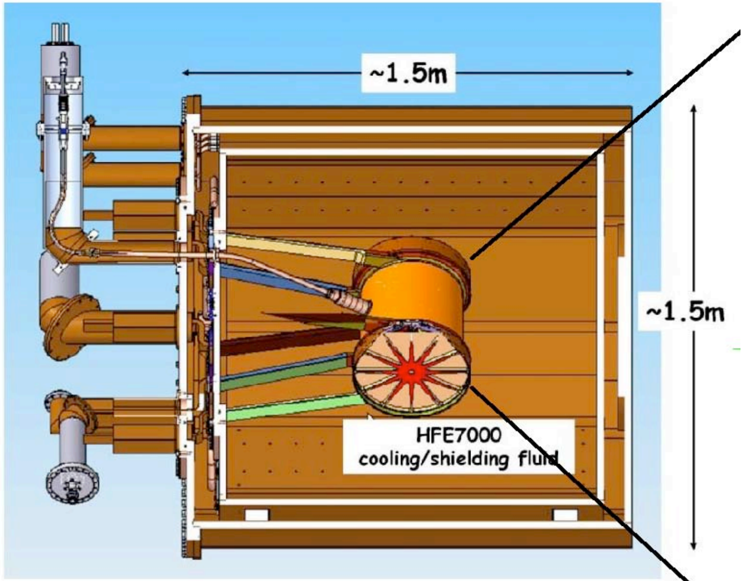
2 y run time with 70% detection efficiency

Expected background = 40 events

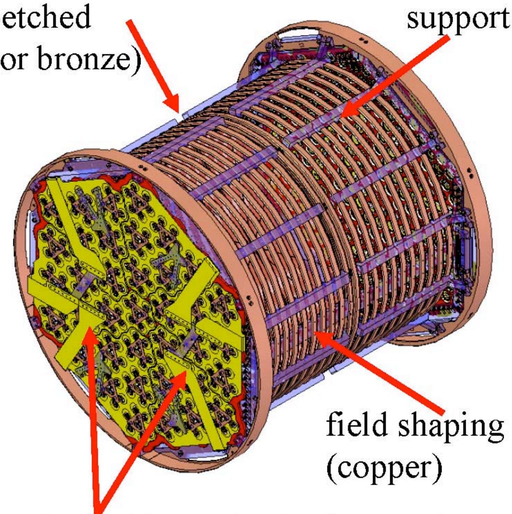
M_{ee}> 133 meV (Rodin et al. ME)



Pb shielding outside of the copper cryostat



Detector inside the cryostat



Central HV plane (photo-etched phosphor bronze)

acrylic supports

field shaping rings (copper)

flex cables on back of APD plane (copper on kapton, no glue)

All parts tested for U, Th content within stringent limits

EXO 1000-10000. LXe TPC

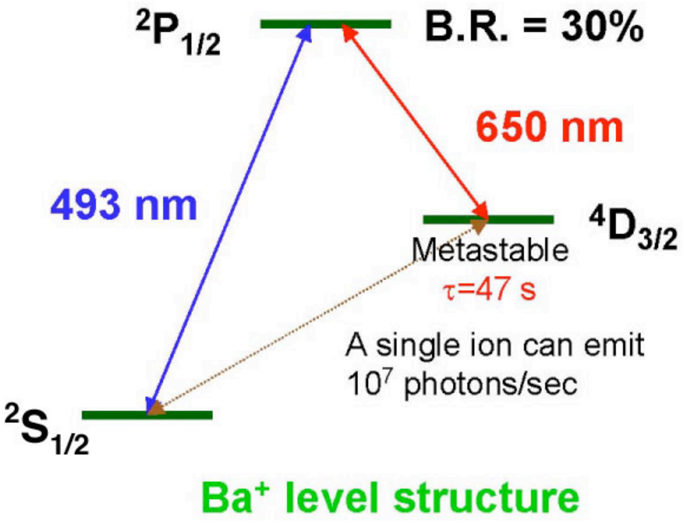
EXO is a phased programme up to 1-10 t

R&D for grabbing & **tagging Ba^+ daughter**

$^{136}Xe \rightarrow {}^{136}Ba^{++} + e^- + e^- (+2\nu)$ $^{136}Ba^{++} + e^- \rightarrow {}^{136}Ba^+$ in the liquid

Extract Ba^+ into gas phase

pump optically in resonance



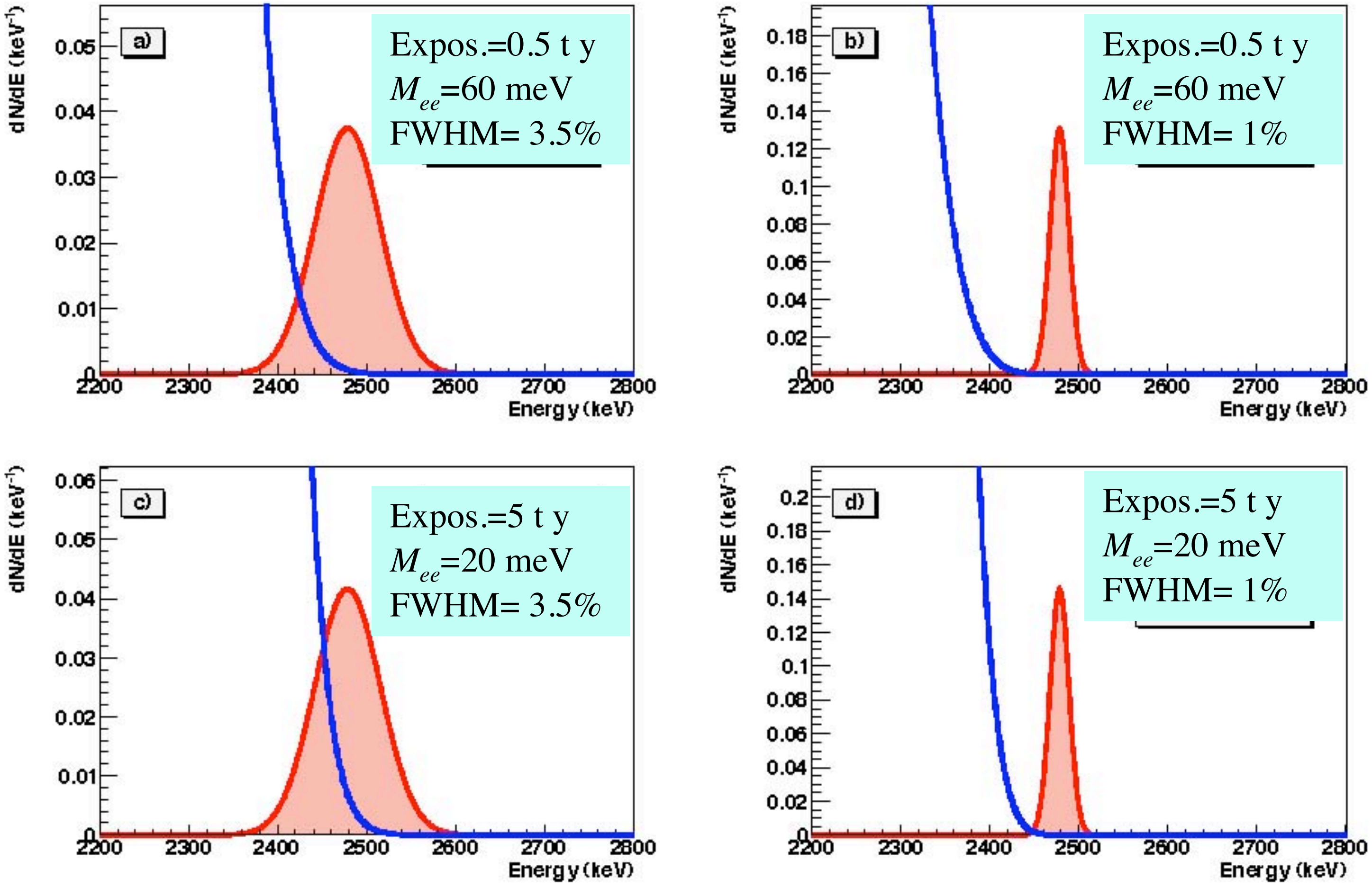
If it works, ultimate limit will be given by $2\beta 2\nu$ background

Only weapon= energy resolution

The ultimate background: 2β2ν

Case of ^{136}Xe assuming $T_{1/2}(2\nu2\beta)\approx10^{21}$ (measured lower limit)

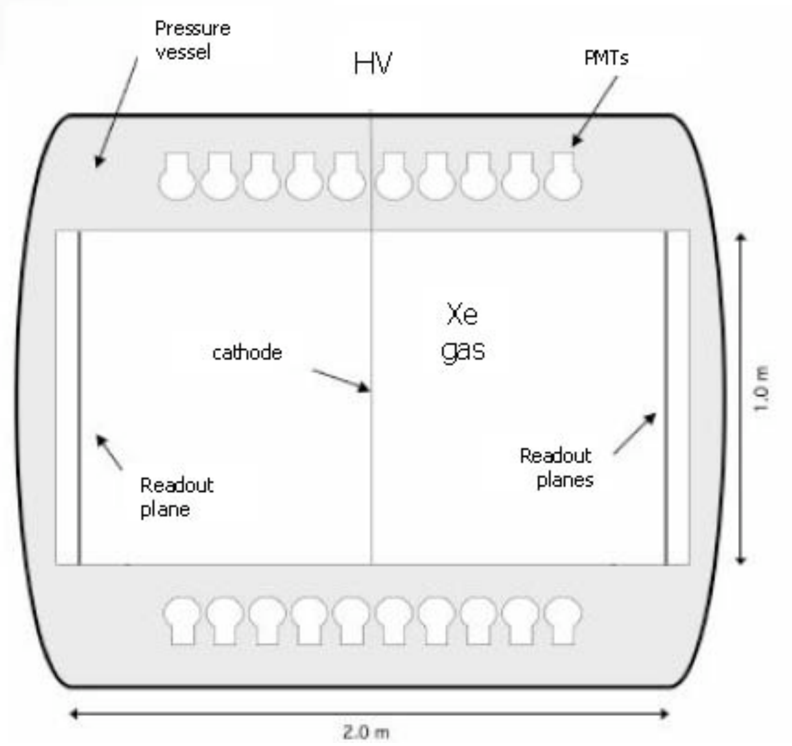
$$\frac{S}{B}\simeq\frac{m_e Q_{\beta\beta}^5}{7(\Delta E)^6}\frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$



EXO achieved

High pressure TPC with Micromegas read out. Aim

NEXT Neutrino Experiment with Xe Gas TPC

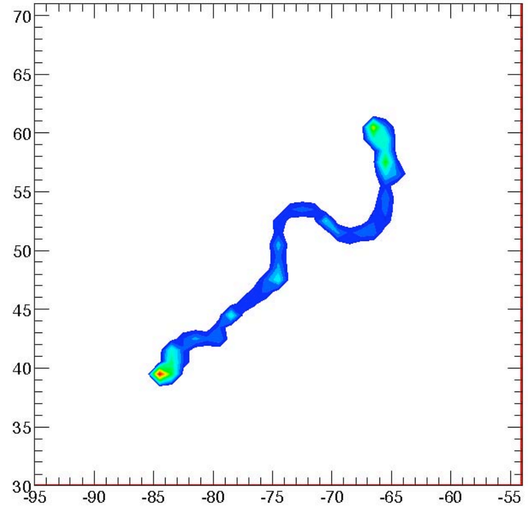


High pressure gas TPC with enriched Xe

Complementary to EXO

Status. Initial R&D phases. Approved by LSC

- Avoid charged background from surfaces by eliminating surfaces, based on 100% active, completely closed **virtual** fiducial surface
- Obtain fine topological information (unlike EXO)
  - Tag signal by topology: 2 balls at the end of the spaghetti
    - Expected reduction of (dominant) gamma background > 100
- FWHM resolution *O*(1%) appears feasible with latest TPC R/O techniques
  - Electroluminescence measurement (Nygren)
  - Montecarlo evaluation of the tolerable radioactive contaminant in the materials and screening starting now
- Monolithic structures easier to scale (and cheaper) than modular ones



Another way to neutrino spectroscopy?

Why neutrino mass spectroscopy is so difficult?

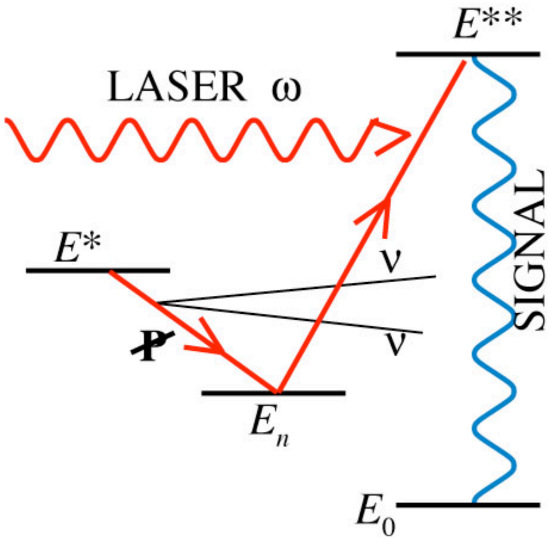
Why establishing Majorana vs. Dirac neutrino nature is so demanding? Difference appears in non-relativistic region

The price to pay at neutrino energies $E >> m_i$

Consider atomic physics ⇒ ΔE in eV range

⇒ LASER Irradiated Neutrino Pair Decay proposed by M. Yoshimura hep-ph/0611362

Metastable, $\tau \approx 1$ s
Initially populated



$$\gamma_{LASER} + I^* \rightarrow I^{**} + \nu_i + \nu_j$$

Spontaneous weak rate

$$\Gamma_{\nu\nu} \propto \frac{G_F^2 (\Delta E)^5}{15\pi^3} \sim 3.3 \times 10^{-34} \ \mathrm{s}^{-1} [\Delta E / \mathrm{eV}]^5$$

Enhance by imposing intense field @ resonance frequency $E^* \Rightarrow E^{**}$

$$\Gamma_{I^* I^{**}} = \Gamma_{\nu\nu} \times \frac{\omega}{\Delta\omega} \times \tau \times \omega P \times \sigma$$

LASER bandwidth

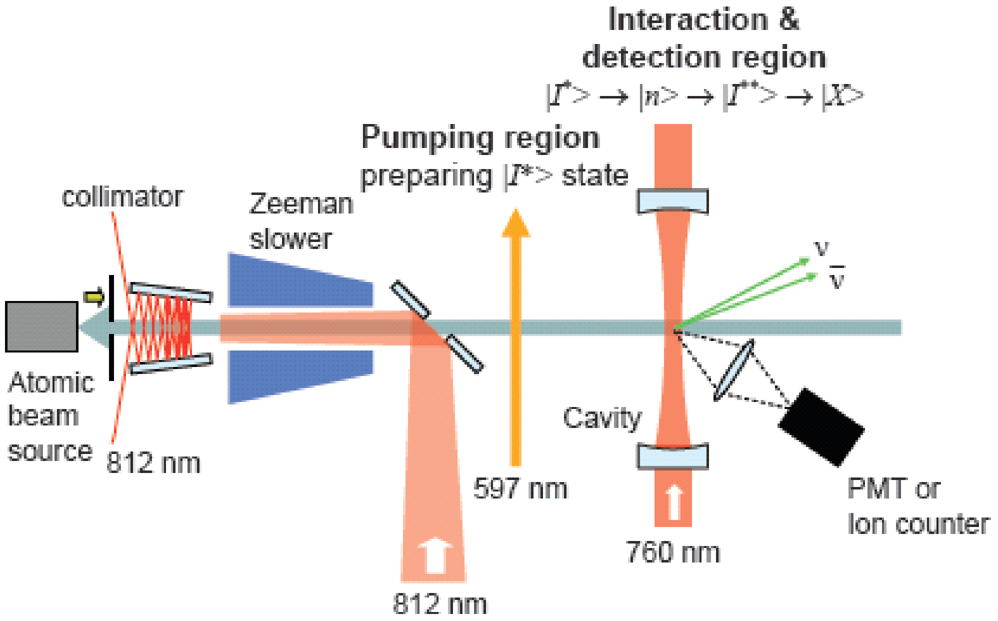
LASER power

Absorption cross-sect.

LASER Irradiated Neiutrino Pair Decay

With P=1 W mm^{-2}, $\Delta\omega/\omega$=10^{-9}, ω = 1eV, τ = 1s

$\Rightarrow \Gamma_{I^{**}I^{*}} \approx 10^{-21}\ \mathrm{s}^{-1} \Rightarrow$ 1 ev/day (x 10^3-10^4 with resonant cavity)



Neutrino mass spectroscopy

Gradually increase ω through energy thresholds, for each neutrino pair (11,12, 22, 13, 23, 33)

$$\omega_{th} = E^{**} - E^{*} + m_i + m_j$$

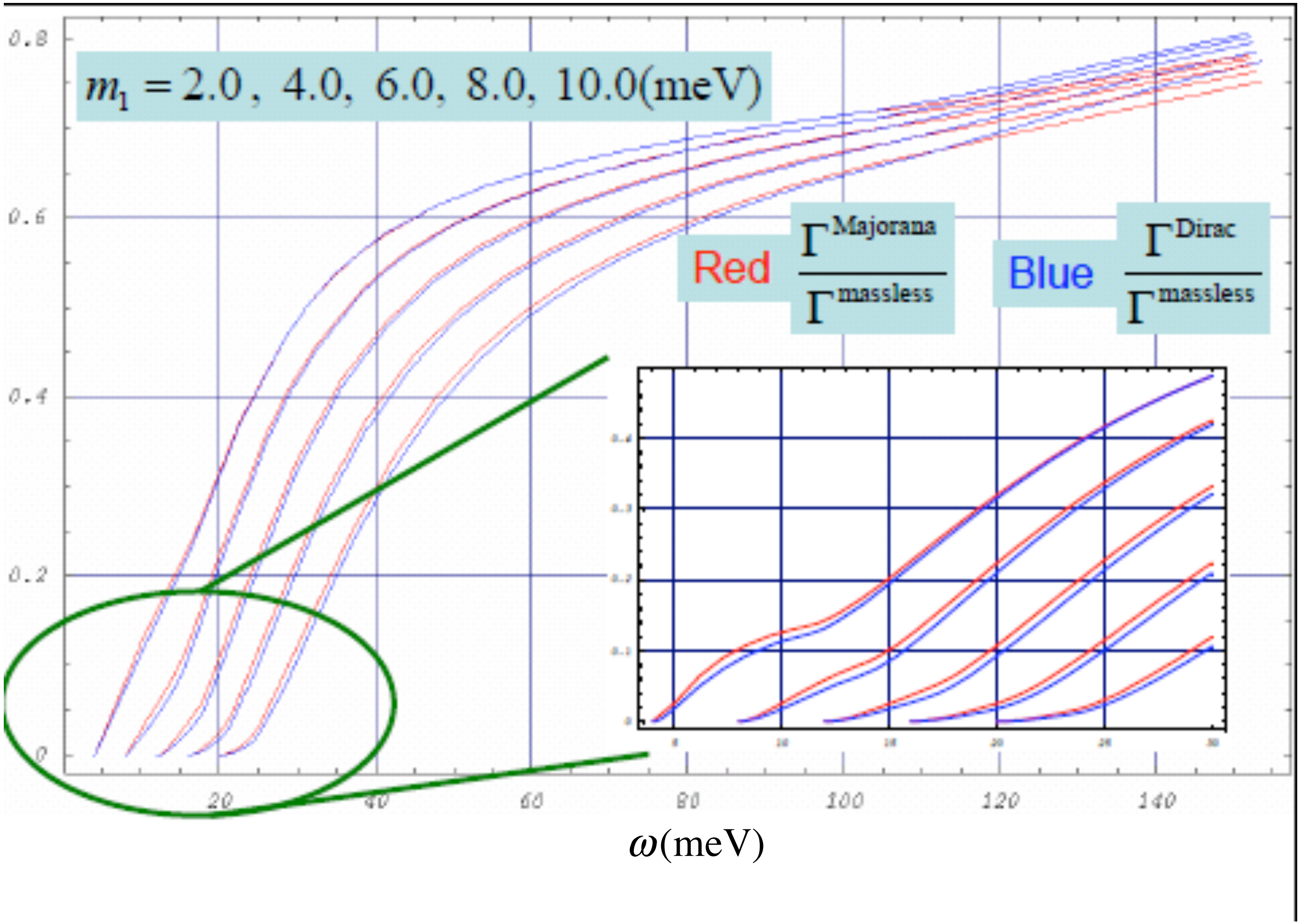
Majorana vs Dirac

Dirac: different particles

Majorana: equal particles ⇒ antysimmetry of wave function

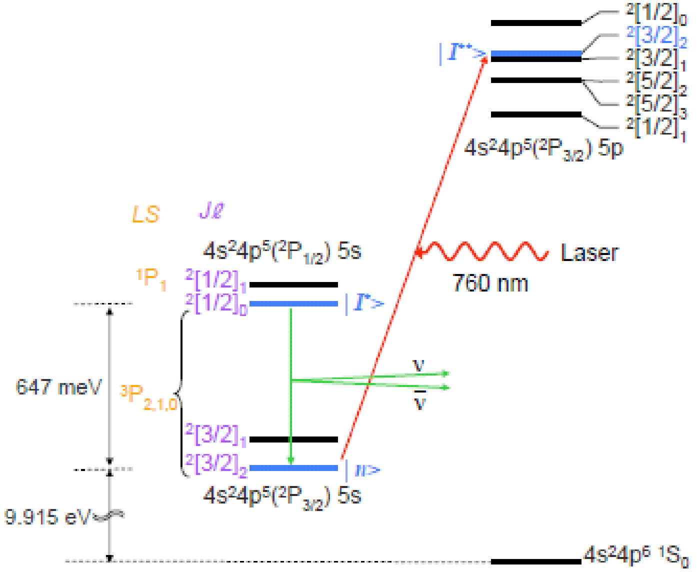
Difference ∝ $(m_1 m_2)/(E_1 E_2)$

Rate/Rate if massless

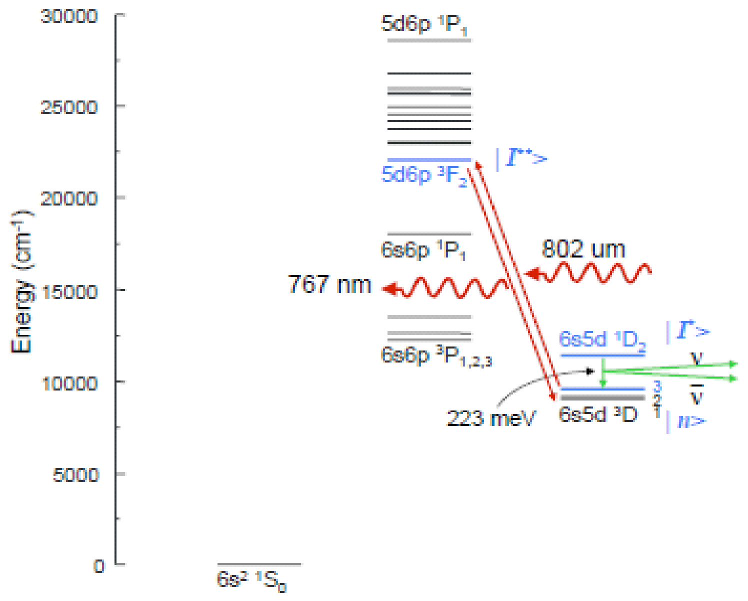


Two interesting possibilities

Level Scheme of Atomic Krypton



Level Scheme of Atomic Barium



Conclusions and outlook

- **Answering to the Majorana question: *"is neutrino its own antiparticle?"* is critical for understanding the origin of mass**
- Other related questions:
  - ***"Why matter dominates on antimatter in the Universe?" [Leptogenesis?]***
  - ***"Why neutrino masses are so small?" [Connection to the unification scale]***
  - ***"Is the lepton number violated?" [Connection to the unification scale]***
- $0\nu2\beta$ is the **only presently** available means to answer
- **Several experiments** are under development & construction (we discussed some)
- **Theoretical techniques** for reliable calculations of nuclear matrix elements are being developed at increasing pace
- Progress is rapid in developing **material purification technologies and assay techniques** (direct $\gamma-$rays counting underground and ICPMS=inductively coupled plasma mass spectroscopy)
- **Much more effort and fun needed to reach the target of 1 ton detector**
- **The atomic physics option must be sutdied and understood**

THANK YOU