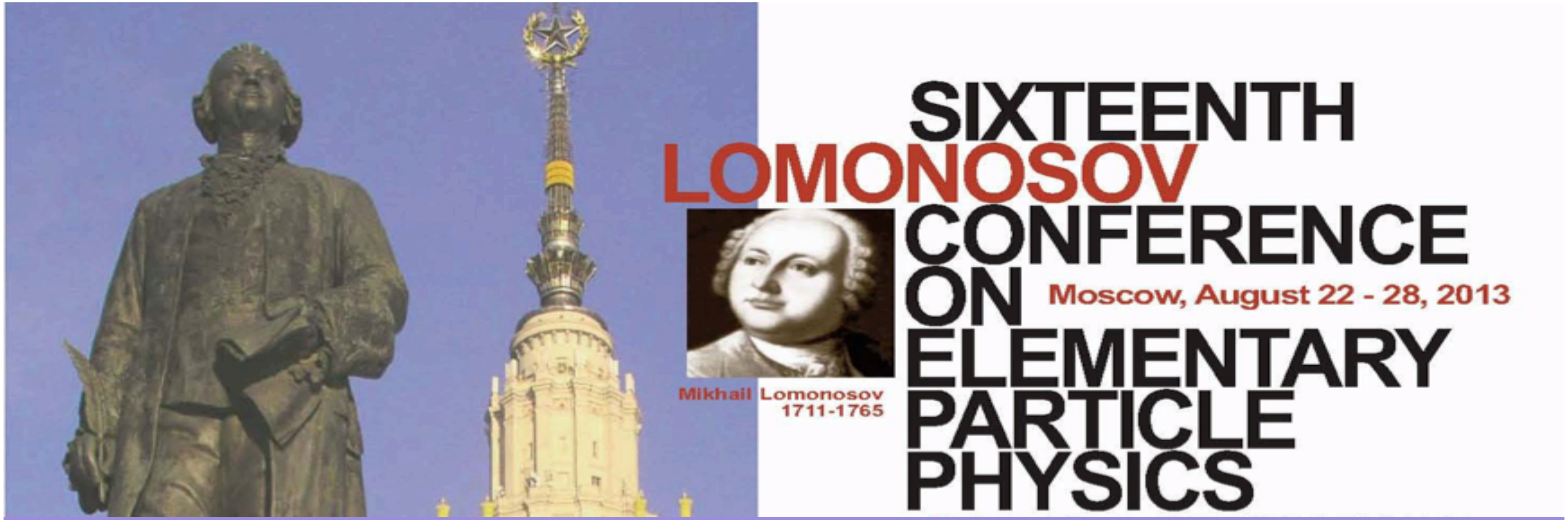


Are neutrinos completely neutral?

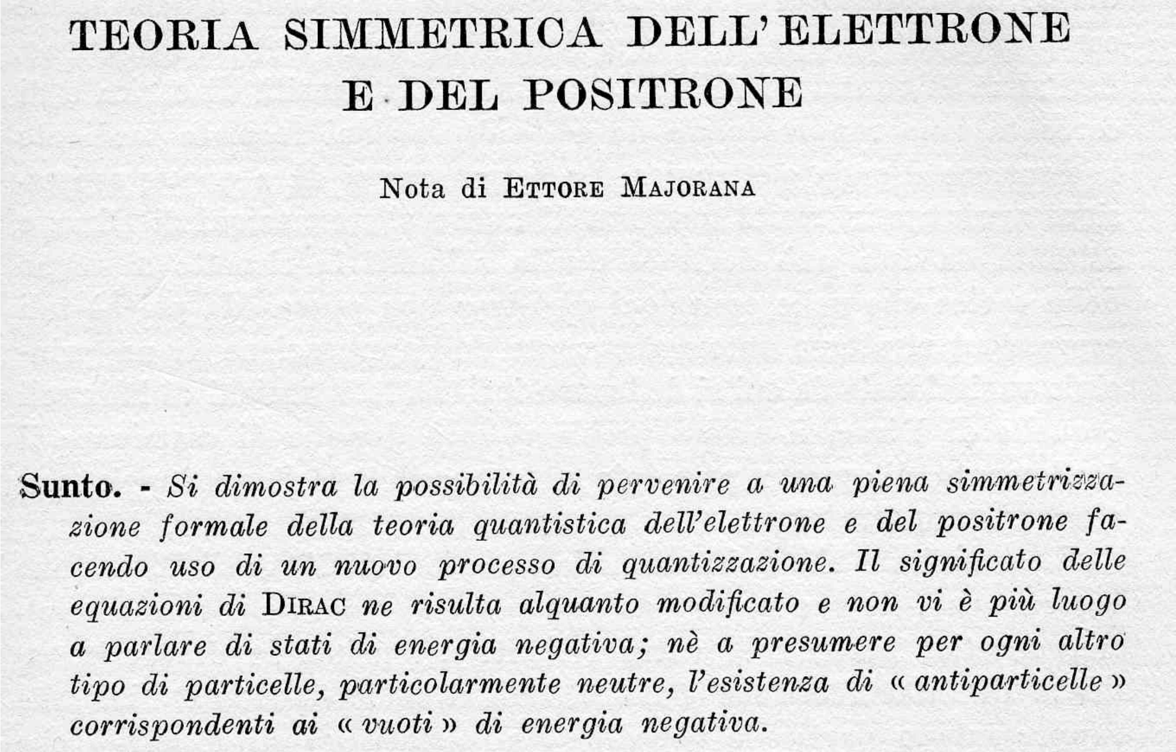
A. Bettini

Canfranc Underground Laboratory. Spain

G. Galilei Physics Dept. Padua University. Italy

INFN

1937 *Nuovo Cimento* 14 171-184



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 symmetrisation 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 new approach allows 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 hypothetical 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*"

B. M. Pontecorvo. The infancy and youth of neutrino physics: some recollections. Journ. de Phys. **12** (1982) vol. 43, p. c8-221

"*For the benefit of the young reader who from the beginning of his activity has been used to hear not only of electric charge but also of other types of "charge" (baryon, lepton,…) I would like to underline that in 1937 only electric charge was known. Now Majorana,* ***first,*** *invented explicitly truly neutral fermions or Majorana particles, that is fermions which are identical to their own antiparticles*."

Completely neutral particles

Definition
neutrino = neutral particle produced in β^+ decay
anti-neutrino = neutral particle produced in β^- decay

Completely neutral: antiparticle = particle

All "charges" (electric, colour, lepton number, baryon number) **= 0**

Bosons

can be mass-less: γ

or massive: Z^0, H, π^0, η,….

Fermions

must be massive: ν? neutralino?

Majorana equation

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

In the Dirac theory the φ and χ components have different transformation properties

Question: is it possible to find a spinor X 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 in the Dirac equation? And similarly a spinor Φ transforming like a φ?

The answer, found by Majorana, is

$$\Phi = i\sigma_2\chi_M^*$$
$$\mathrm{X} = i\sigma_2\varphi_M^*$$

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

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

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

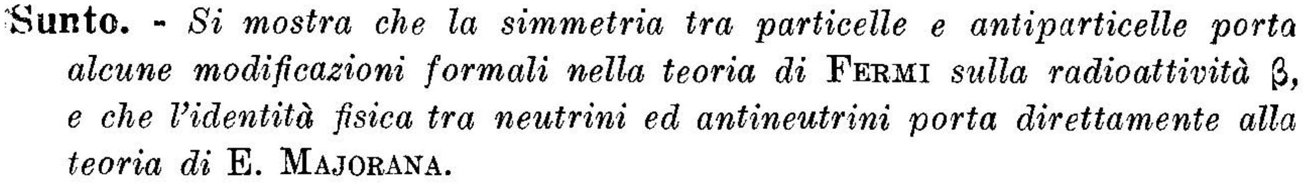
- **Majorana equations are decoupled, one for φ and one for χ spinor** (possibly two masses)
- **If m=0, Dirac equation = Majorana equation**
- **Nature has chosen m≠0, hence differences between the two theories exist**

1937 *Nuovo Cimento* **14** 323

SULLA SIMMETRIA TRA PARTICELLE
E ANTIPARTICELLE

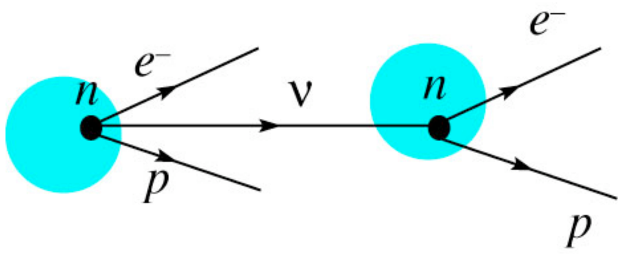
Nota di GIULIO RACAH

We show that the symmetry between particles and antiparticles leads to some formal modifications of the Fermi theory of the β radioactivity and that the physical identity between neutrinos and antineutrinos leads directly to Majorana theory.



Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* FERMI *sulla radioattività β, e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. MAJORANA.

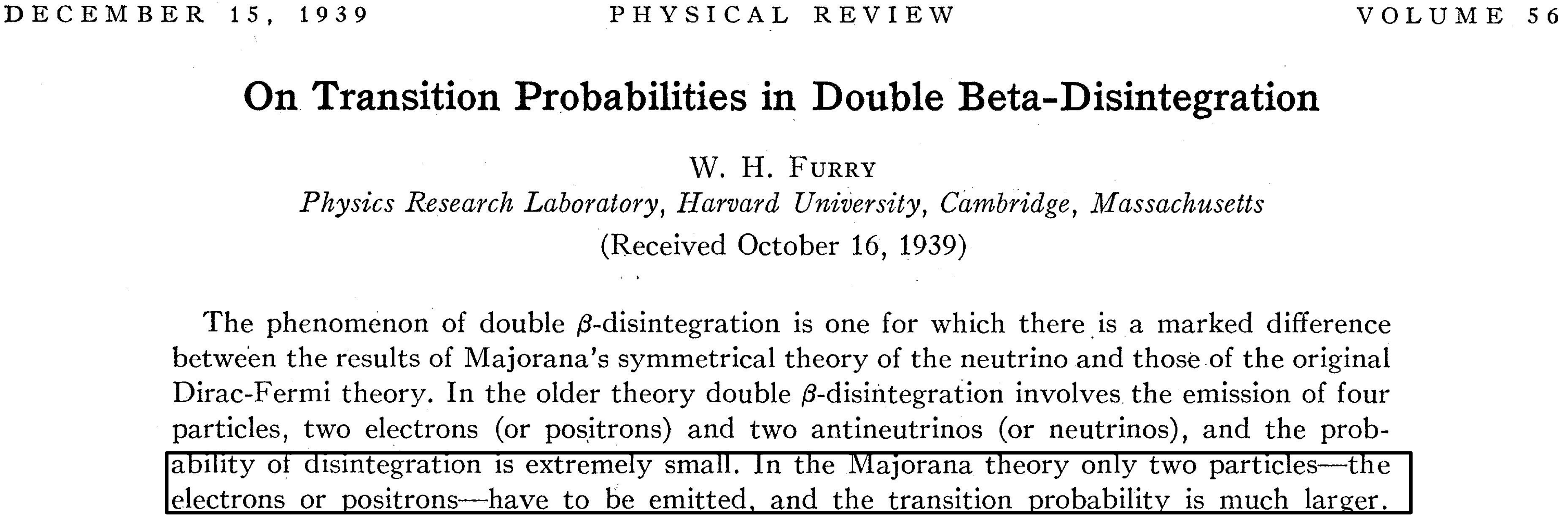
If neutrinos obey Dirac equation, neutrinos emitted in a β^- decay can induce only a β^+ process and vice versa
If they obey Majorana equation, any neutrino can produce both electrons and positrons



Neutrons cannot obey Majorana equation for two reasons

1. Neutron has a magnetic moment
2. Neutrons would decay β^- into protons and β^+ into antiprotons with equal probabilities

1939 *Physical Review* 56 1184



DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

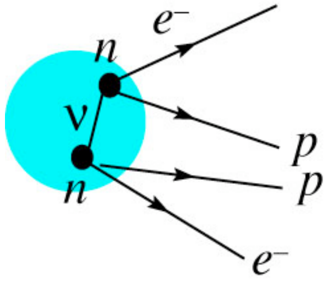
On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger.

The Racah proposal to distinguish between Dirac and Majorana neutrinos cannot be realized in practice

The Furry proposal can be followed, but unfortunately "the transition probability" is not "much larger", but rather **much smaller**



For two elements unknown to Furry:

- **CC weak current is V-A**
- **neutrino masses are very small**

1946 *Report PD-205, Chalk River, Canada.*

W. Pauli: *"I have done a terrible thing. I have postulated a particle that cannot be detected."*

B. Pontecorvo. Try with

$$\nu + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar}^{*} + e^{-}$$

Use low background proportional counter to detect X ray from Ar* de-excitation

Report was classified.
Method might be used to detect nuclear submarines

Neutrino or antineutrino?

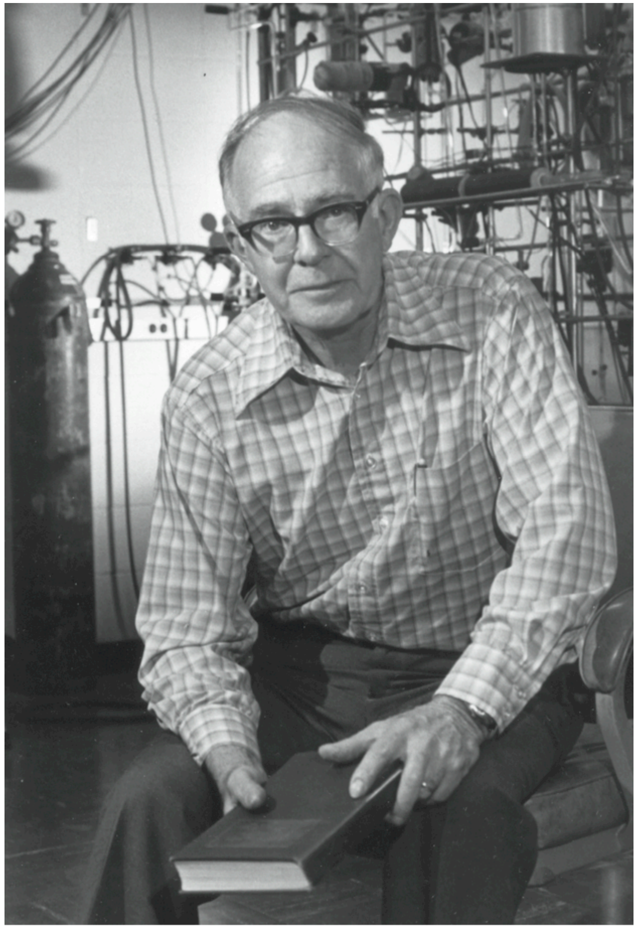
1958. R. Davis. Neutrino≠antineutrino?

Several improvements of the Cl Ar method proposed by L. Alvarez in 1949
Use C_2Cl_4, He-sweep for extraction, LN2 cooling of the trap, etc.

R. Davis. *Attempt to detect antineutrinos from a nuclear reactor by the* $^{37}Cl(\nu,e^-)^{37}Ar$ *reaction*. Phys. Rev. **97** (1955) 766. @ the Brookhaven reactor

No signal, but due to the insufficient sensitivity: flux too low + background too high

Theory: $2\ 10^{-44}$ cm^2/atom; limit $<2\ 10^{-42}$ cm^2/atom



R. Davis. *An attempt to observe the capture of reactor neutrinos in Chlorine-37*. Unesco Conference **1958**. Paris. Vol. 1 p. 728
At Savannah River the sensitive was enough (factor 5)

Neutral particles from a reactor do not induce Pontecorvo reaction

$$\cancel{\bar{\nu}_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\ \mathrm{Ar}^* + e^-}$$

Neutrino has different reactions than antinutrino

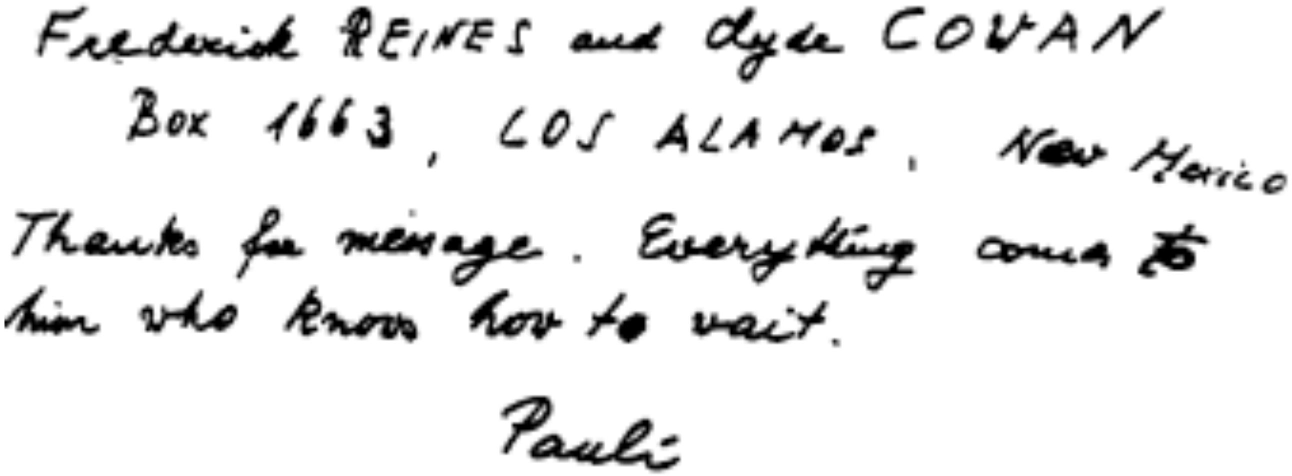
The conclusion: neutrino and antineutrino are different particles, made in the SM, is premature

Alvarez L. Univ. Calif. Lab. Rep. 328 (1949)

1956 *Science* 124 103

Detection of the Free Neutrino: a Confirmation

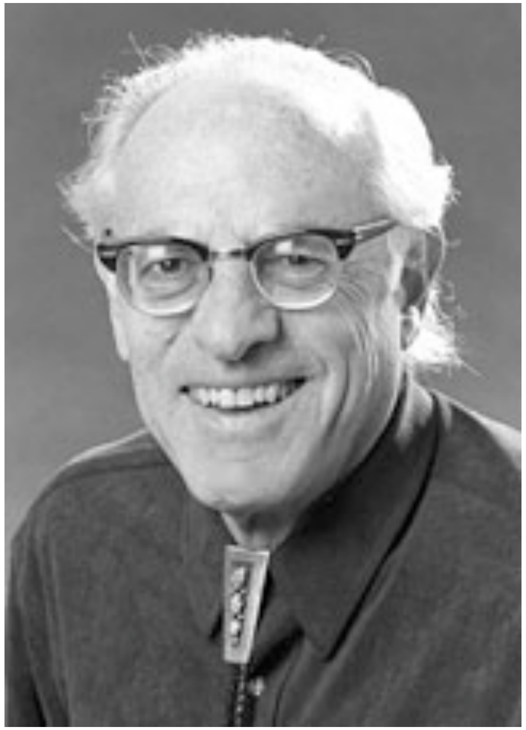
C. L. Cowan, Jr., F. Reines, F. B. Harrison,
H. W. Kruse, A. D. McGuire



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli



NB “**Free** ?? neutrinos”. But Fermi 1933: electrons do not exist before the decay “*On the contrary they are created together with a **neutrino**, similarly to the creation of a light quantum that goes with a quantum jump of an atom*

1957 JINR Preprint P-95

B. Pontecorvo "Fifty years of neutrino physics: a few recollections" Neutrino 1980 Conf.

Now at the time I was told in a wrong way about such experiment. A delegation came to Moscow and someone (I do not remember who) told me that R. Davis got a positive signal in his experiment (interpreted by Davis as bakground from cosmogenic ^{37}Cl(p,n)^{37}Ar). *Such result at the time seemed to me fantastic (and rightly so!). Wrong rumours sometimes are useful. I tried to find a way out and invented neutrino oscillations of the type*

B.M.P. considers an analogy with the $K^0\bar{K}^0$ system $\nu_e \rightleftarrows \bar{\nu}_e$

…neutrino and antineutrino are…. symmetrical and antisymmerical combinations of two truly neutral Majorana particles ν₁ and ν₂.

$$\nu_1 = \frac{1}{\sqrt{2}}\left(\nu + \bar{\nu}\right)$$

$$\nu_2 = \frac{1}{\sqrt{2}}\left(\nu - \bar{\nu}\right)$$

It follows that neutrinos in vacuum can transform themselves in antineutrinos and viceversa….So, a beam of neutral leptons from a reactor which first consists mainly of antineutrinos will change in composition and at a certain distance…will be composed of neutrinos and antineutrinos in equal quantities

Бруно Понтекорво

Neutrino flavour mixing

1956 Sakata model. Fundamental particles are p, n and Λ

1957-8 Parity violation. V–A structure

1959 Gamba, Marshak and Okubo **baryon-lepton fundamental symmetry** (ν, e, μ) - (p, n, Λ)

1960 Maki et al. **Nagoya model**. "Ur" matter B^+ and $p = \nu B^+$ $n = e^- B^+$ $\Lambda = \mu^- B^+$

1962 Second neutrino, lepton-baryon symmetry lost

Try to recover: **Katayama et al**. and **Maki et al.** advanced two hypothesis

1. are not the "true" neutrinos, but linear mixtures, of them

$$\nu_1 = \nu_e \cos\delta + \nu_\mu \sin\delta \qquad \nu_2 = \nu_e \cos\delta - \nu_\mu \sin\delta$$ **The true ones**

2. only ν_2, for not explained reasons, couples to the B^+

Maki et al. mentioned also the possibility of "transmutation" between neutrino flavours

Katayama et al. advanced the hypothesis that a 4th "Sakaton" might exist

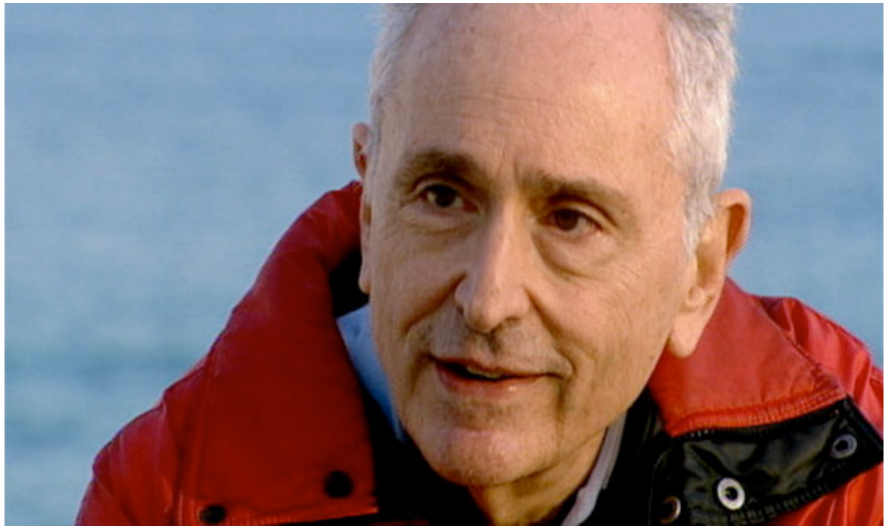
N.B. If it were true neutrino and quark (Cabibbo) mixing angles would have to be equal

1962 Lipkin et al. notice that the observation of $\bar{p}p \to K_L^0 K_S^0$ at rest falsifies Sakata model

Neutrino oscillations
50 years of BSM physics

1963.

John Bahcall starts building the Solar Standard Model



Bahcall and Davis at Homestake

11 August 1967. R. Davis writes to Fowler "*Dear Willy, I do have a preliminary result from our first good run. The sample was taken June 22nd and counting has continued until today. I am now removing the sample and will rerun background. So we do have a result and during the last few weeks I have told a few people that are interested.*".

Neutrino oscillations

9 June 1967 (two months before the letter of Davis to Fowler) B. Pontecorvo sends a paper to *Zhurnal Eksperim. noi i Teoreticheskoi Fiziki*.

Considers $\nu_e \rightleftarrows \bar{\nu}_e, \quad \nu_\mu \rightleftarrows \bar{\nu}_\mu, \nu_e \rightleftarrows \nu_\mu$ assuming eigenstates to be Majorana

From an observational point of view the ideal object is the sun. If the oscillation length is smaller than the radius of the sun effectively producing neutrinos (let us say, one tenth of the solar radius…for the ^{8}*B neutrinos)….the only effect on the earth surface must be two times smaller than the total flux*

B.M.P. was almost but not quite right. Boron neutrinos do not change flavour by oscillations but by adiabatic transition in matter (MSW effect).

L. Wolfenstein (1978) **Oscillations in matter**

S. P. Mikheyev, A. Yu. Smirnov (1985) **Adiabatic transition in matter**

Chirality and Helicity

States of definite chirality are the eigenstates of γ_5 , L for the eigenvalue –1, R for +1

Neutrino field has negative chirality. Neutrinos and antineutrinos are left

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

γ_5 does not commute with the mass term of the Hamiltonian

Chirality is not an observable, we measure helicity instead

Both neutrinos and anti have **positive (+) and negative (–) helicity** components. For *E*>>*m*

$$\varphi = \nu \approx \frac{m}{E}\nu_L^+ + \nu_L^- \qquad \chi = \overline{\nu} \approx \nu_L^+ + \frac{m}{E}\nu_L^-$$

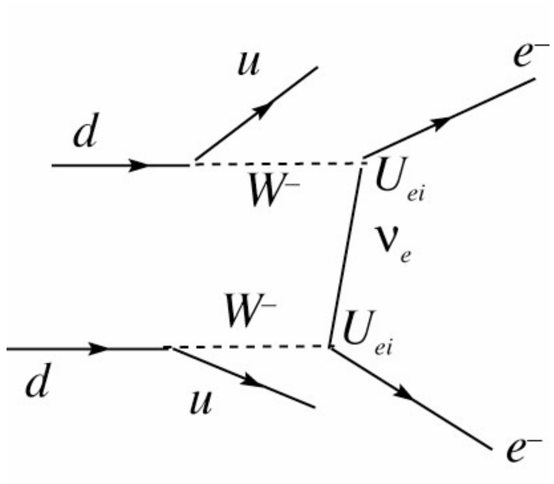
If *m*=0 neutrinos are pure *h*=– states, antineutrinos pure *h*=+ states

If **Majorana**, **“neutrino”** is the state with ***h*=–1**; **“antineutrino”** is the state with ***h*=+1**

$0\nu\beta\beta$ Decay

Majorana neutrino couples to *W* exactly as Dirac neutrino

The SM violation is in the propagator



The status created at one vertex has definite flavour, hence is a superposition of mass eigenstates

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

Mass eigenstates do not have definite helicity, are superpositions of Majorana neutrinos and antineutrinos

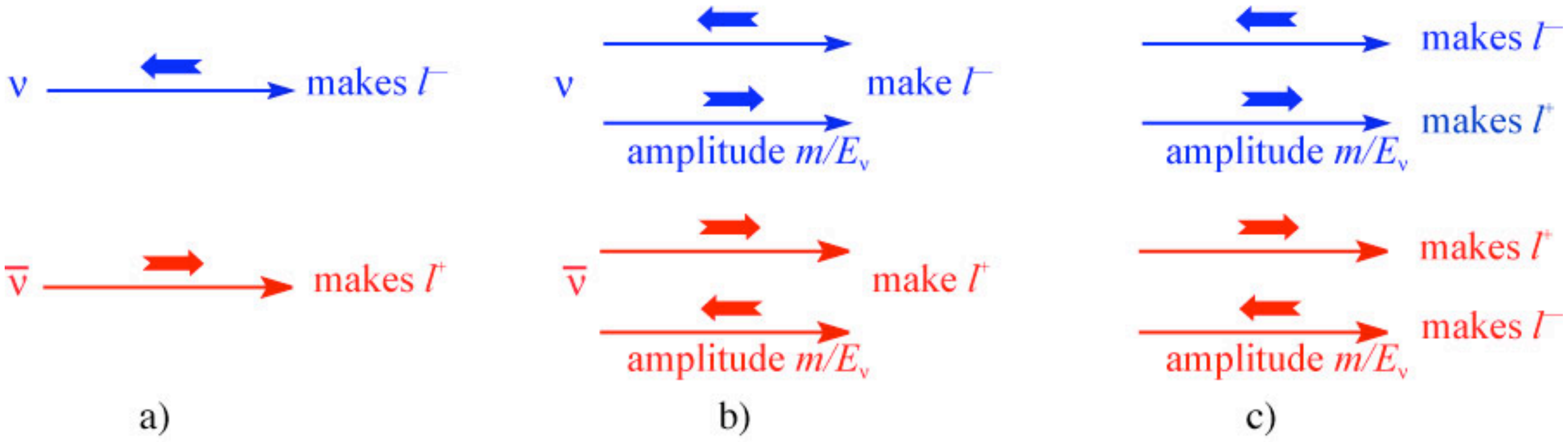
$$\nu_i \approx \frac{m_i}{E}\nu_{iL}^+ + \nu_{iL}^-$$

At one vertex the antineutrino component matters, the neutrino component at the other vertex

$$M_{ee} = \left| \sum_i U_{ei}^2 m_i \right| \approx \left| 0.67 m_1 + 0.30 m_2 e^{i2\alpha} + 0.03 m_3 e^{i2(\beta-\delta)} \right|$$

Majorana vs Dirac at relativistic energies

$m/E_\nu<10^{-10}$



The V–A structure of the charged weak currents + smallness of neutrino mass are sufficient to explain experimental observations

No need to invoke lepton number conservation

No need to have neutrino different from antineutrino

The experimental challenge

$$\left(T_{1/2}^{0\nu 2}\right)^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{M_{ee}}{m_e}\right|^2$$

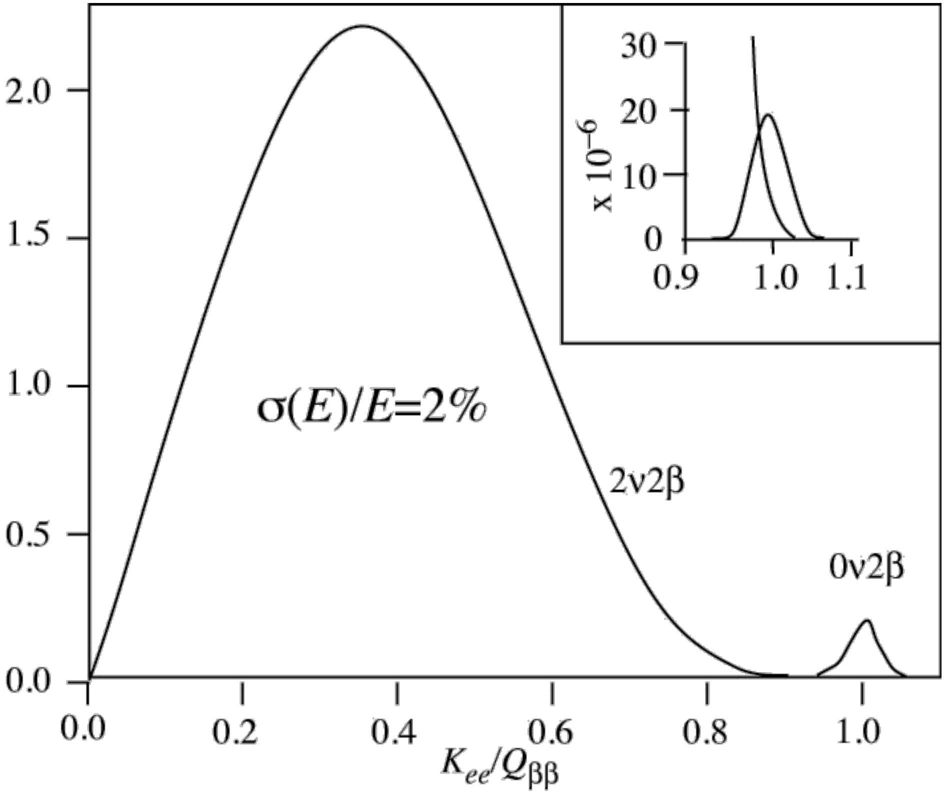
g_A=0.6-1.25

Barea J, Kotila J and Iachello F 2012 Phys. Rev. Lett. 109 042501

Experiments measure the sum energy of the two electrons

If background index *b*, sensitive mass *M*, live time *T* and energy resolution Δ*E*

sensitivity to $\frac{1}{M_{ee}} \propto F_M = \left(\varepsilon \frac{i.a.}{A}\right)^{1/2} \left(\frac{MT}{b\Delta E}\right)^{1/4}$

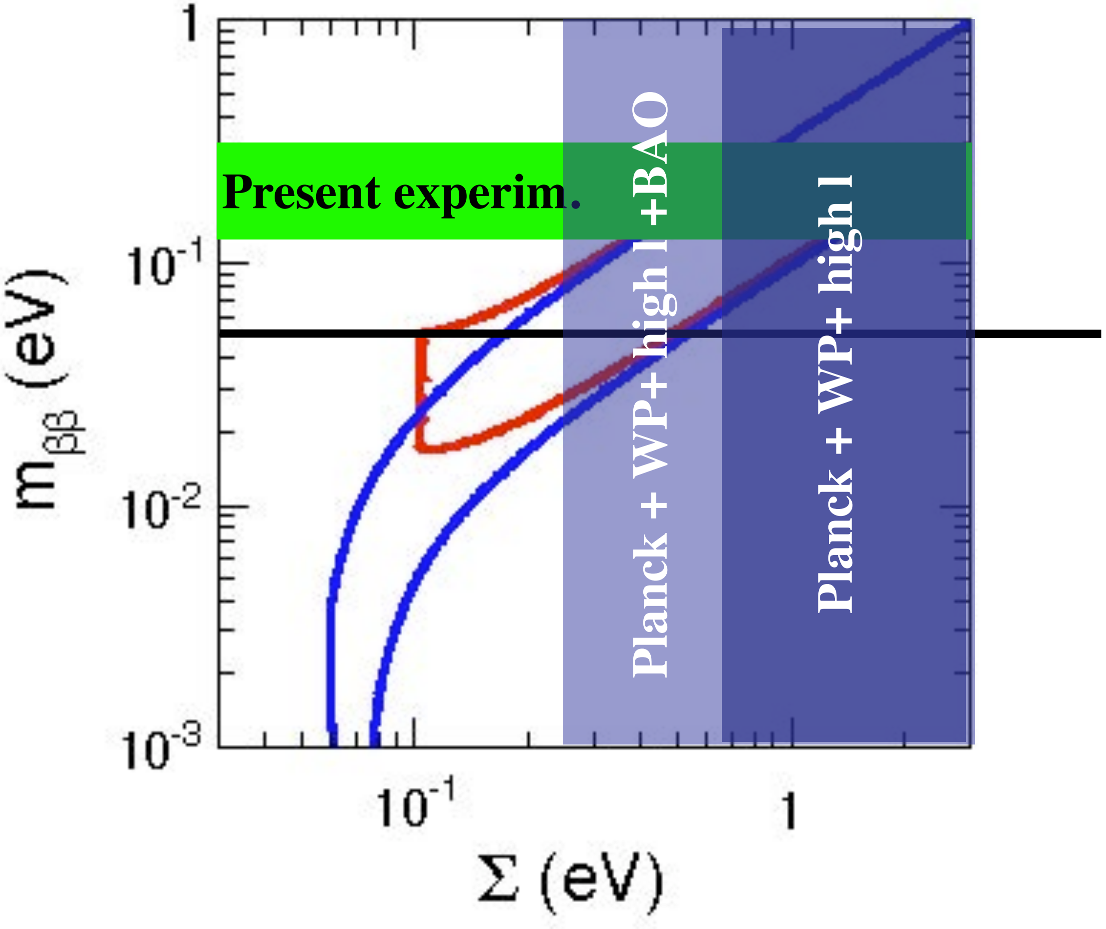


If *b*=0 during *T*, in an energy window of about *ΔE* sensitivity to M_{ee}

$$F_M \propto \varepsilon \frac{i.a.}{A} \sqrt[2]{MT}$$

Energy resolution and almost zero background are the key factors

The landscape



Running experiments

$T_{1/2}$ several 10^{25} yr

M_{ee} = 200-300 meV

If the limits from cosmology on neutrino mass are taken seriously, we need to reach

M_{ee} = 50 meV
$T_{1/2}$ several 10^{26} yr
1 kmol = 6×10^{26} nuclei

Is it possible?

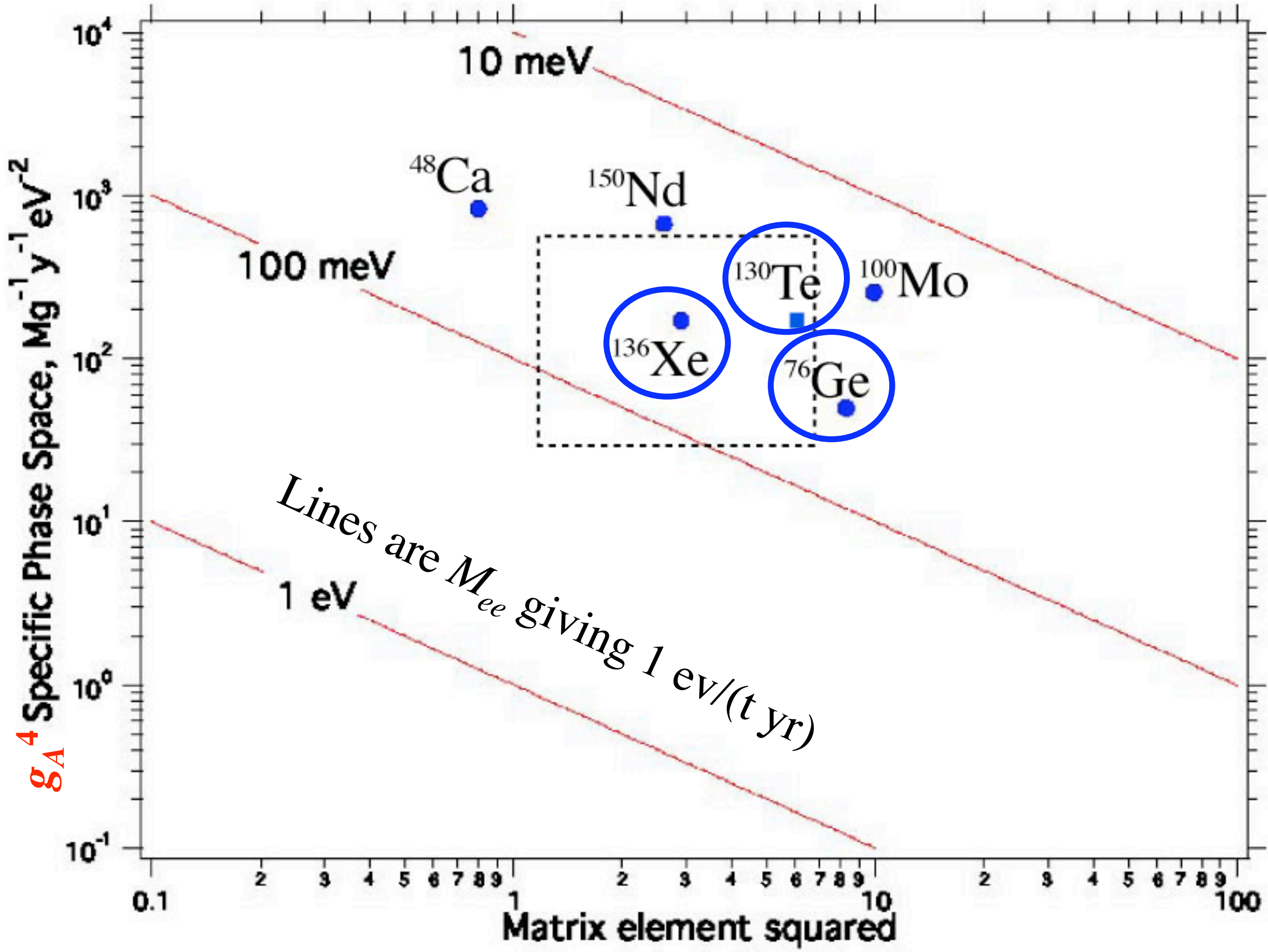
Need
M>1 t isotope
FWHM energy resolution < 1%
BI≈10^{-4}/(keV kg yr)

Adapted from R.G. H. Robertson.
arXiv: 1301.1323

Which isotope?

See Barabash for full review

Phase space factor is smaller for low mass, low *Q* isotopes
Matrix element tend to decrease with increasing *A*
Uncertainties much larger than overall differences



Lines are M_{ee} giving 1 ev/(t yr)

No indication for preference
Choices on **practical** grounds
- **"Easy" enrichment**
- **Energy resolution**
- **"No" surfaces**
- **Scalability**
- **Cost**

Only three isotopes have shown to work at 100 kg yr scale

- **Cost of 1 ton of enriched**
  - **^{76}Ge O(100 M$)**
  - **^{136}Xe O(10 M$)**

NME (IBM-2): J. Barea and F. Iachello, Phys. Rev. C79 , 04430 (2009)
Nucl Phys B (Proc. Suppl.) 217 (2011) 5

$$M_{ee} = 50 \text{ meV}$$

$$^{76}\text{Ge}: \quad \Leftrightarrow \quad 10^{27} \text{ yr}$$

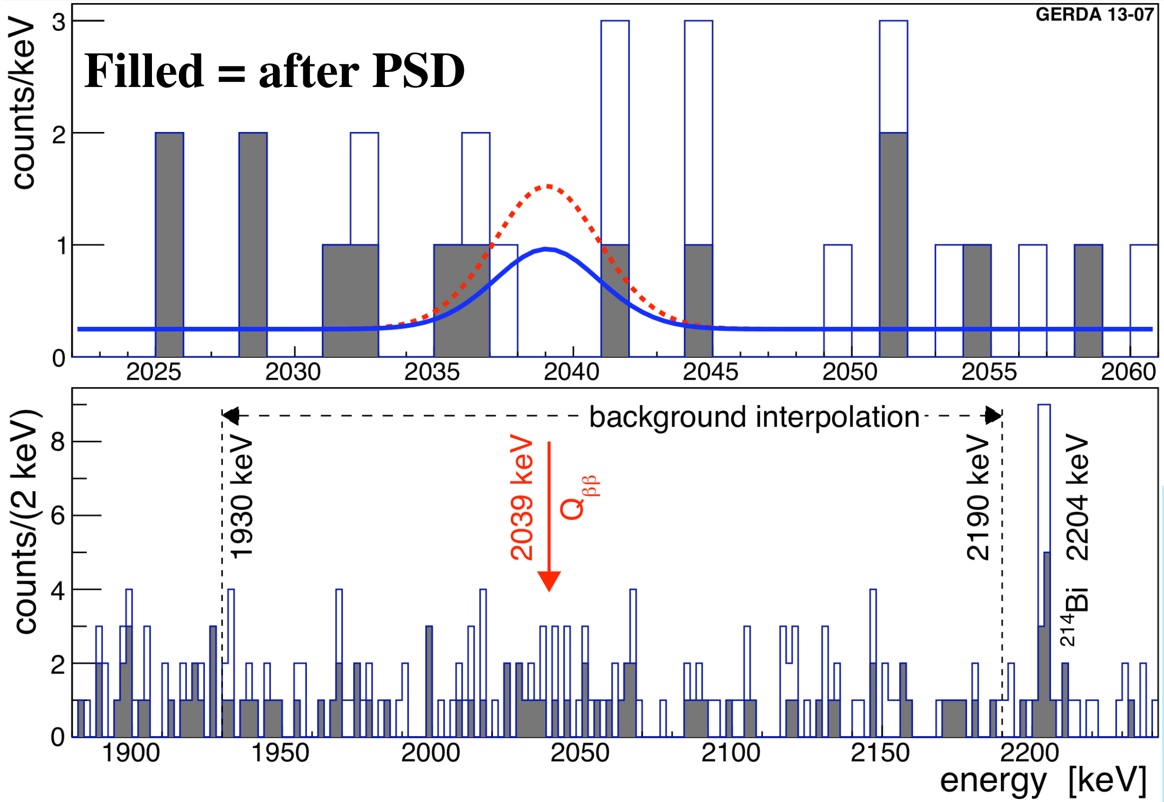
$$^{136}Xe: \quad \Leftrightarrow \quad 4.4 \cdot 10^{26} \text{ yr}$$

$$^{130}Te: \quad \Leftrightarrow \quad 3.1 \cdot 10^{26} \text{ yr}$$

GERDA (and MAJORANA)
GE diodes

see Bezrukov

GERDA (and MAJORANA)



Phase 1 completed (see Bezrukov)
a ≈ 86%
ε a f_{act} = 66%
$M_{Ge} \approx$ 20 kg
Mt = 21.6 kg yr
ΔE= 4 keV
BI= 10^{-2}/(keV kg yr)
$T_{1/2}$>2.1 10^{25} yr

Phase 2 expected (2013-2015)
$M \approx$ 40 kg
Mt = 100 kg yr
BI= 10^{-3}/(keV kg yr)
$T_{1/2}$> 1.5 10^{26} yr

Exposure needed for S/N = 4 at M_{ee}=50 meV
Assume BI can be to **BI= 3 10^{-4}/(keV kg yr)**

$$N_{ee} = \varepsilon \log 2 \frac{N_A \cdot Mt}{A \cdot T_{1/2}}$$

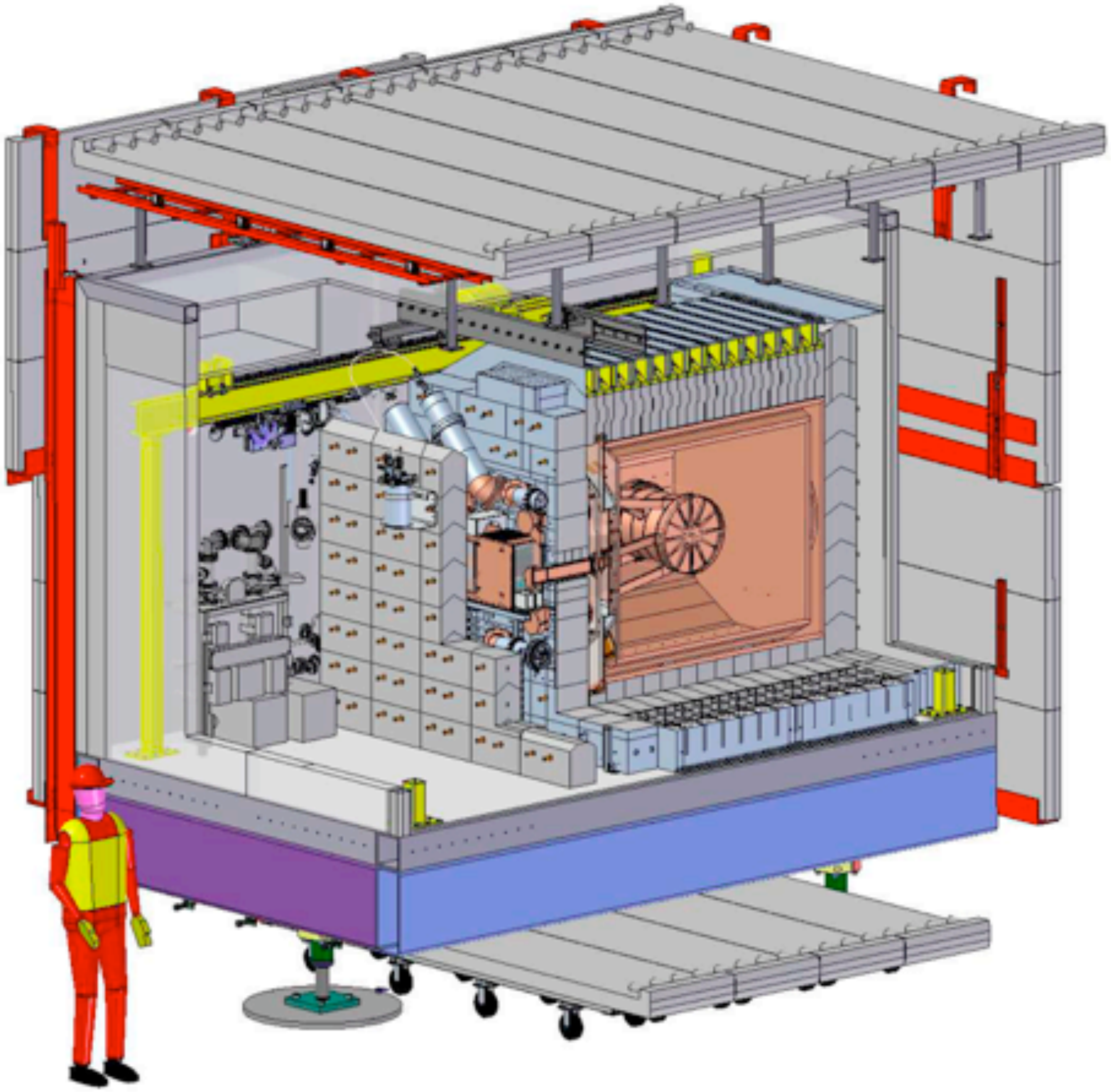
$$N_{ee}\left(10^{27}\right) = \varepsilon \cdot a \cdot f_{act} \cdot 5.5 \cdot M_{Ge}t\left(\text{t yr}\right) = 3.6 \cdot M_{Ge}t\left(\text{t yr}\right)$$

$$N_b = \Delta E \cdot BI \cdot M_{Ge}t = 4 \cdot 3 \cdot 10^{-4} \cdot 10^{3} \cdot M_{Ge}t = 1.2 \cdot M_{Ge}t$$

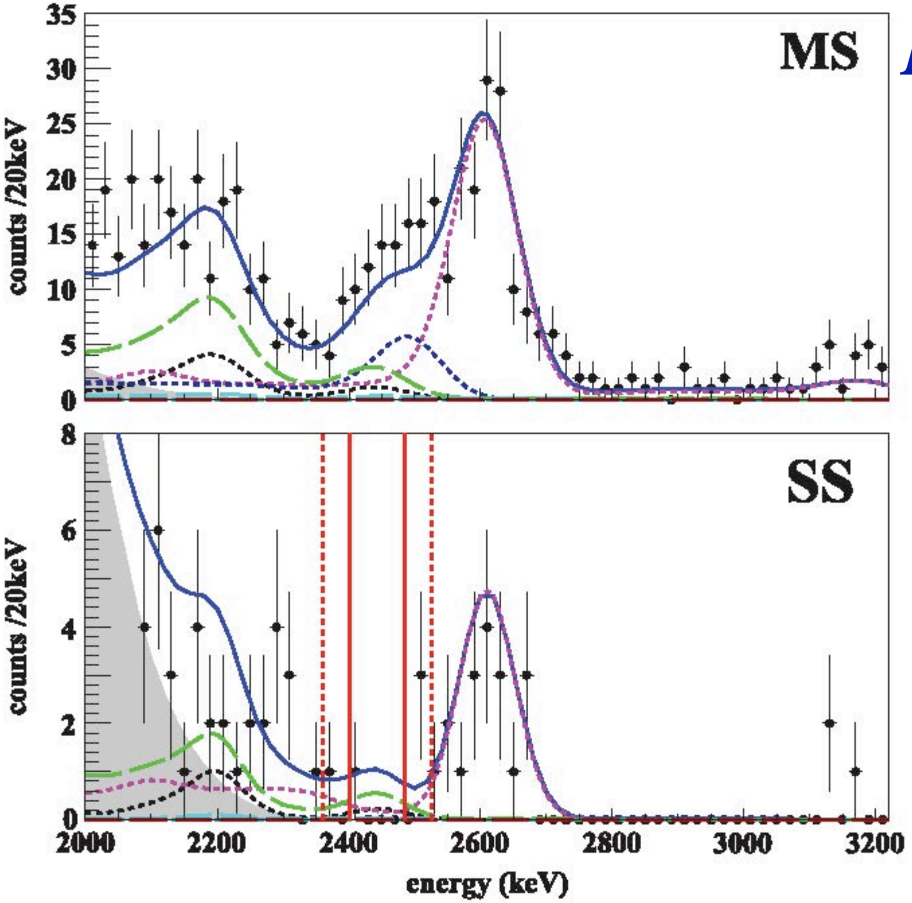
$$S/N = \frac{3.6}{\sqrt{1.2}}\sqrt{M_{Ge}t} = 3.3\sqrt{M_{Ge}t} \qquad M_{Ge}t = \left(\frac{4}{3.6}\right)^{2} = 1.2 \text{ t yr}$$

EXO-200 Liquid Xe TPC

see Belov



A. Bettini. LSC and Padova



EXO-200

a =0. 806
f_{act} = 0.49
ε a f_{act} = 0.33
$M_{Xe} \approx 200$ kg
$M_{act}\, t = 32.5$ kg yr
$\Delta E = 97$ keV
BI= 1.5 10^{-3}/(keV kg yr)
$T_{1/2} > 1.6\ 10^{25}$ yr

$$M_{Xe}t = \frac{M_{act}t}{f_{act}} = \frac{6.3}{0.49} = 12.6 \text{ t yr}$$

Exposure needed for S/N = 4 at M_{ee}=50 meV

Assume BI close to the 2ν2β contribution: **BI= 10^{-4}/(keV kg yr**

Assume (?) energy resolution improvement **ΔE=90 keV**

$$N_{ee}\left(4.4\cdot 10^{26}\right) = \varepsilon\cdot a\cdot 7\cdot M_{act}t\left(\text{t yr}\right) = 0.67\cdot 7\cdot M_{act}t\left(\text{t yr}\right) = 4.7\cdot M_{act}t\left(\text{t yr}\right)$$

$$N_b = \Delta E\cdot BI\cdot M_{act}t = 90\cdot 10^{-4}\cdot 10^{3}\cdot M_{act}t = 9\cdot M_{act}t$$

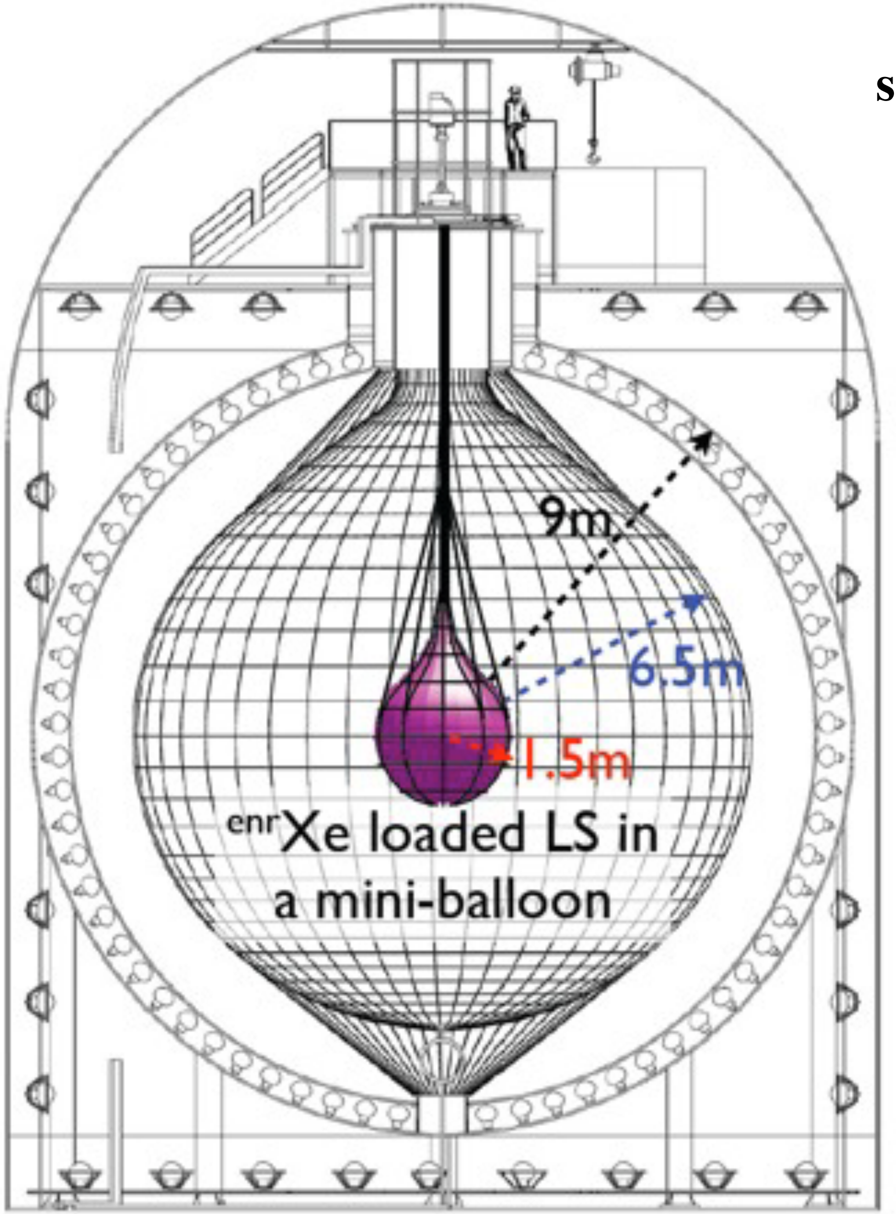
$$S/N = \frac{4.7}{\sqrt{9}}\sqrt{Mt} = 1.6\sqrt{Mt} \qquad M_{act}t\left(4.4\cdot 10^{26}\right) = \left(\frac{4}{1.8}\right)^2 = 6.3 \text{ t yr}$$

However, reduction of the BI may require reduction of f_{act}

Self shielding is expensive, being done of enriched Xe

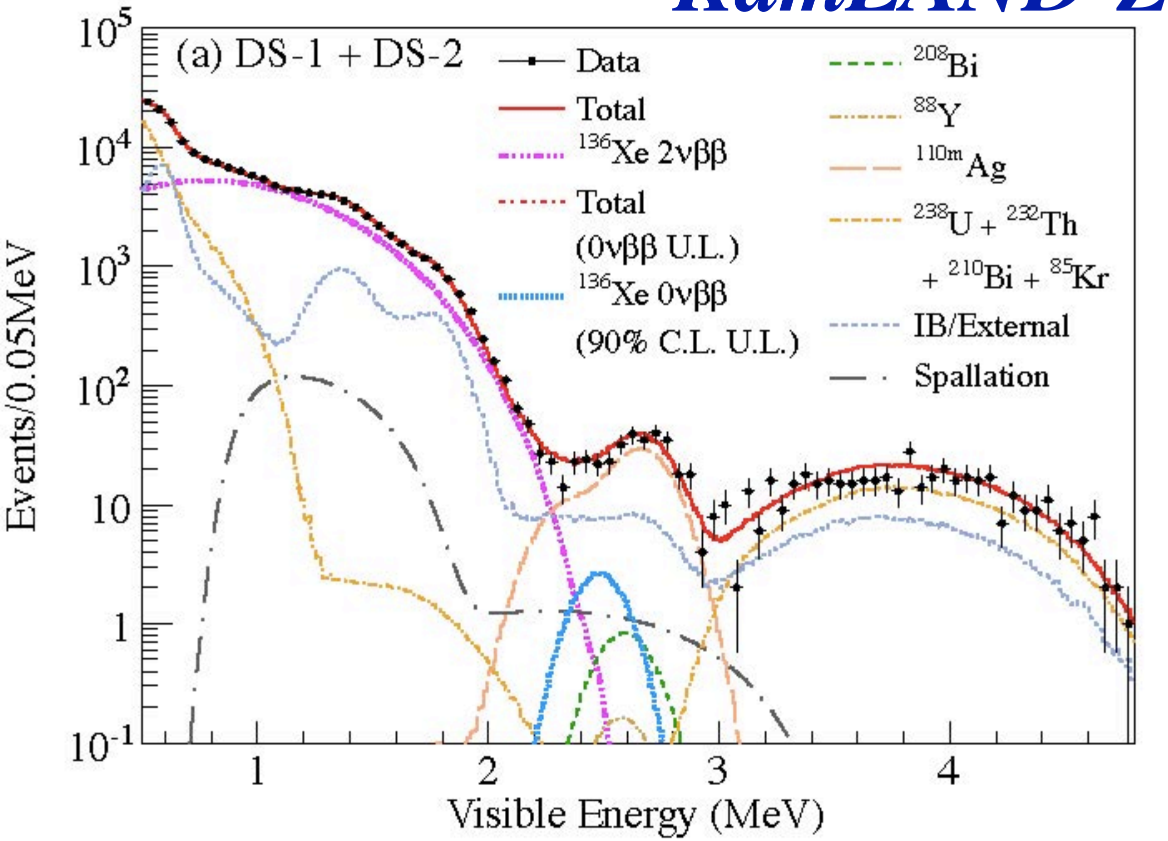
24

KamLAND-ZEN. Xe dissolved in LScintillator



see Shirai

KamLAND-ZEN



$a \approx 0.91$
$f_{act}=0.62$
$\varepsilon\ a\ f_{act} = 0.46$
$M_{Xe} \approx 300$ kg
$M_{act} = 186$ kg
$M_{act}\ t = 89.5$ kg yr
$\Delta E = 175$ keV
BI= 5 10^{-3}/(keV kg yr)
$T_{1/2} > 1.9\ 10^{25}$ yr
NB. 2ν2β contribution to BI =0.7 10^{-4}/(keV kg yr)

Exposure needed for S/N = 4 at M_{ee}=50 meV

Assume BI close to the 2ν2β contribution: **BI= 10^{-4}/(keV kg yr)**

$$N_{ee}\left(4.4\cdot10^{26}\right)=\varepsilon\cdot a\cdot 7\cdot M_{act}t\left(\text{t yr}\right)=5.2\cdot M_{act}t\left(\text{t yr}\right)$$

$$N_b=\Delta E\cdot BI\cdot M_{act}t=175\cdot10^{-4}\cdot10^{3}\cdot M_{act}t=17.5\cdot M_{act}t$$

$$S/N=\frac{5.2}{\sqrt{17.5}}\sqrt{M_{act}t}=1.2\sqrt{M_{act}t}\quad M_{act}t\left(4.4\cdot10^{26}\right)=\left(\frac{4}{1.2}\right)^2=11\text{ t yr}$$

$$M_{Xe}t=\frac{M_{act}t}{f_{act}}=\frac{11}{0.62}=18\text{ t yr}$$

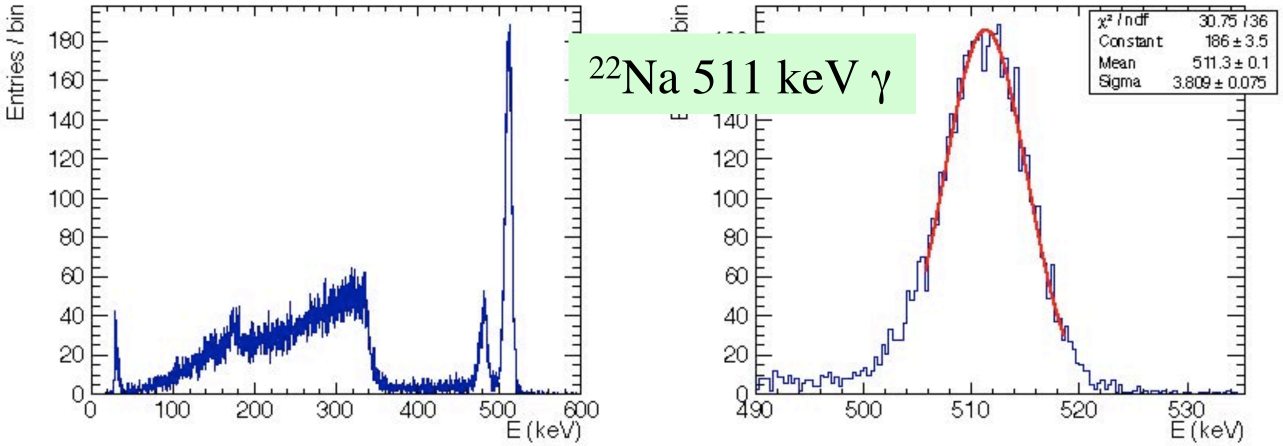
However, reduction of the BI may require reduction of f_{act}

Self shielding is expensive, being done of enriched Xe

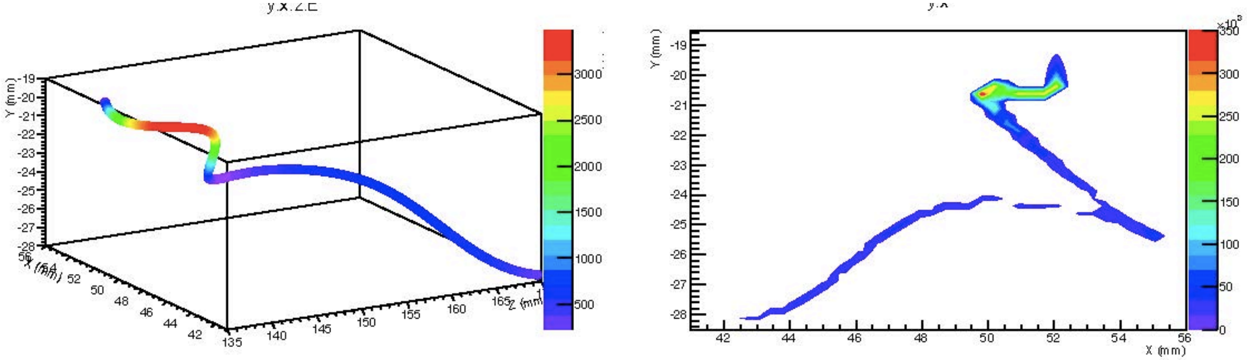
NEXT. High pressure Xe TPC

Data from prototpes

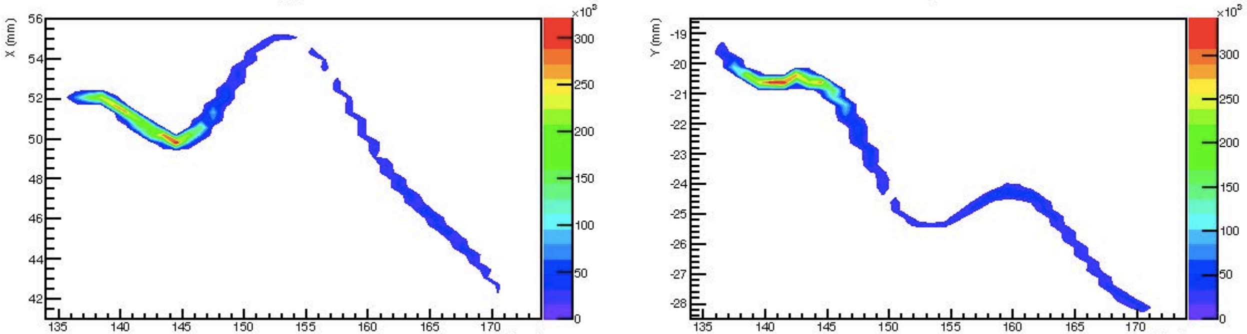
Energy resolution
FWHM = 0.75% @ Q_{bb}
measured in prototypes



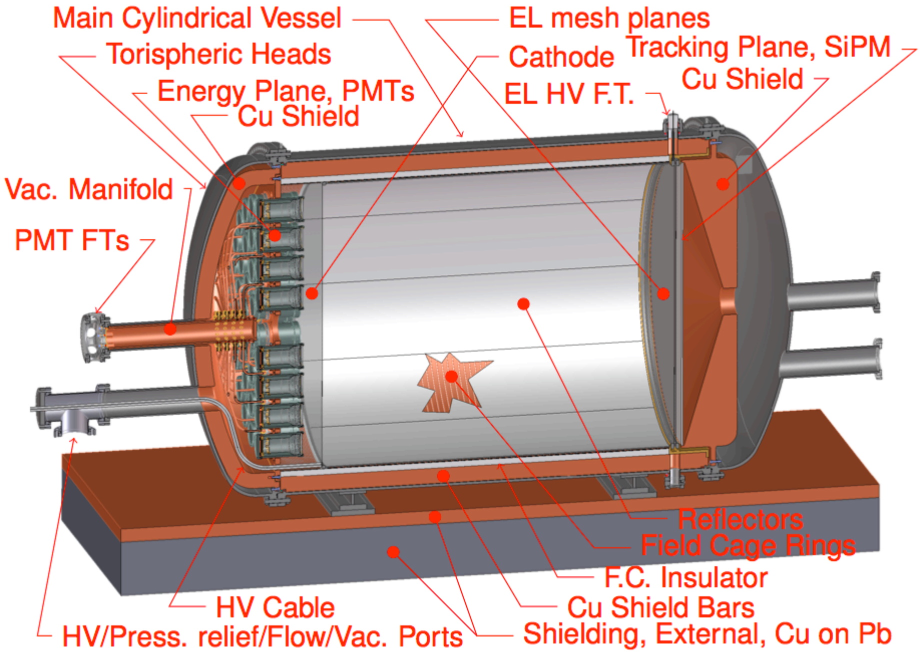
^{22}Na 511 keV γ



Electron track 600 keV γ source



NEXT



Present MonteCarlo + screening gives BI= 5 10^{-4}. Assume **BI= 10^{-4}/(keV kg yr)**

ε=0.35

ΔE=10 keV

Exposure needed for S/N = 4 at M_{ee}=50 meV

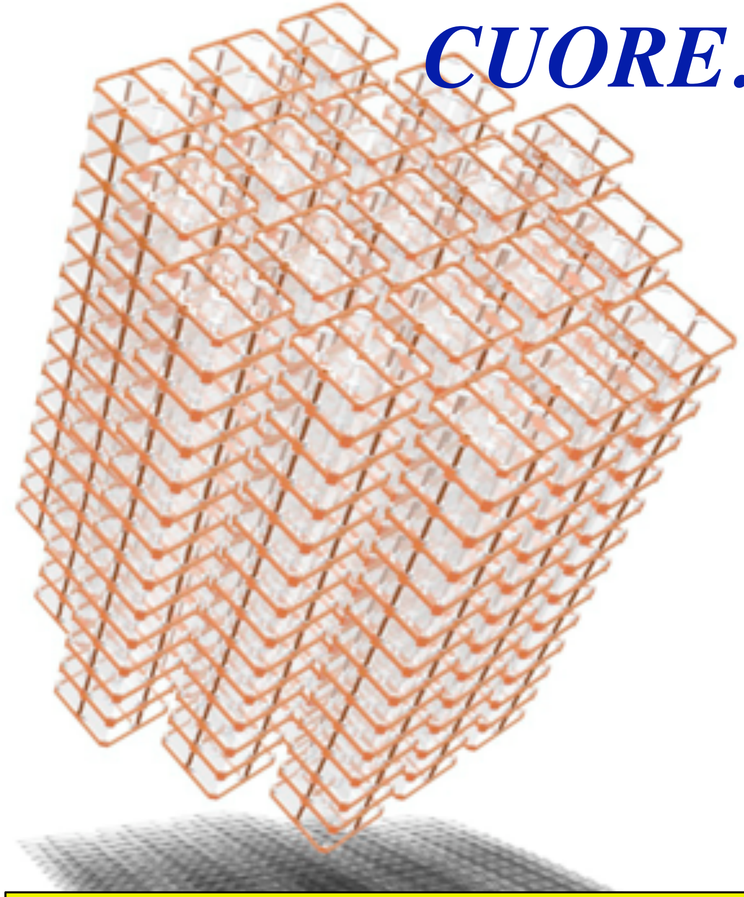
$$N_{ee}\left(4.4\cdot 10^{26}\right)=\varepsilon\cdot 7\cdot Mt\left(\text{t yr}\right)=2.5\cdot Mt\left(\text{t yr}\right)$$

$$S/N=\frac{1}{\sqrt{1}}\sqrt{Mt}=1\sqrt{Mt}$$

$$N_b=\Delta E\cdot BI\cdot Mt=10\cdot 10^{-4}\cdot 10^{3}\cdot Mt=1\cdot Mt$$

$$Mt\left(4.4\cdot 10^{26}\right)=\left(\frac{4}{2.5}\right)^2=2.6\ \text{t yr}$$

CUORE. Te O2 bolometers



a = 0.27
ε = 0.9 ?
$M_{130} \approx 203$ kg
ΔE=6 keV
BI= 10 10^{-3}/(keV kg yr)
= 37 10^{-3}/(keV kg_{130} yr)

Surfaces are the main sources of background
Need active discrimination (LUCIFER)
If not, BI can be improved using enriched Te (1/3?)

Exposure needed for S/N = 4 at M_{ee}=50 meV

Assume **BI= 3 10^{-3}/(keV kg yr); ε $f_{230}\, f_{act}$=0.7**

$$N_{ee}\left(3\cdot 10^{26}\right)=\varepsilon\cdot 10\cdot M_{130}t\,(\text{t yr})=7\cdot M_{130}t\,(\text{t yr})$$

$$N_b=\Delta E\cdot BI\cdot M_{130}t=6\cdot 12\cdot 10^{-3}\cdot 10^3\cdot M_{130}t=72\cdot M_{130}t$$

$$S/N=\frac{7}{\sqrt{72}}\sqrt{M_{130}t}=0.82\sqrt{M_{130}t}$$

$$M_{130}t\left(3\cdot 10^{26}\right)=\left(\frac{4}{0.82}\right)^2=24\ \text{t yr}$$

Conclusions

- **Is it now "***possible to ask to the experience to decide between this new theory and the simple extension of the Dirac equations to the neutral particles***"?**
- **Enormous progress has been done, both in the theory and in the experiments. It is now possible to ask, but no answer yet**
- **Theory (+experiment) should clarify the g_A issue, and more**
- **Experiments taking data or close to do so will reach 150-100 meV sensitivity in this decennium**
- **Reaching 50 meV discovery will need**
  - **Ton scale isotope mass**
  - **Energy resolution FWHM <1%**
  - **a major effort to achieve BI of 10^{-4} / (keV kg yr)**
  - **Tags of the final state (SS vs MS, track images,….)**
  - **Other ideas, not discussed here, are being pursued at R&D level**
- **Nature may be kind with us, once more (LMA, θ_{13}), choosing a not too small Majorana mass**

THANKS

Sakata forbidden

$p\bar{p} \to K_L^0 K_S^0$

The decay can happen only from negative parity states

Argument for pedestrians. In the Sakata model the neutral kaons are made of neutrons and Λ's and their antiparticles and contain no protons nor antiprotons. The charged pions and kaons all contain a proton or antiproton. Thus a proton-antiproton system can become two charged pions or kaons by creating a single additional neutron- antineutron or Λ-anti-Λ pair which combines with the initial proton and antiproton to form the two final mesons. This cannot occur for the neutral kaon pair final state

SU3 based argument $\Lambda\bar{\Lambda} \to \pi^+\pi^-$ forbidden for odd parity

$I(\pi\pi) = I(\Lambda\bar{\Lambda}) = 0$ $\pi\pi$ space wave function must be symmetric, even parity

In the Sakata model there is an SU(3) transformation $p \Leftrightarrow \Lambda$

$$\pi^-(\bar{p}n) \Rightarrow K^0(\bar{\Lambda}n)$$

$$\pi^+(p\bar{n}) \Rightarrow \bar{K}^0(\Lambda\bar{n})$$

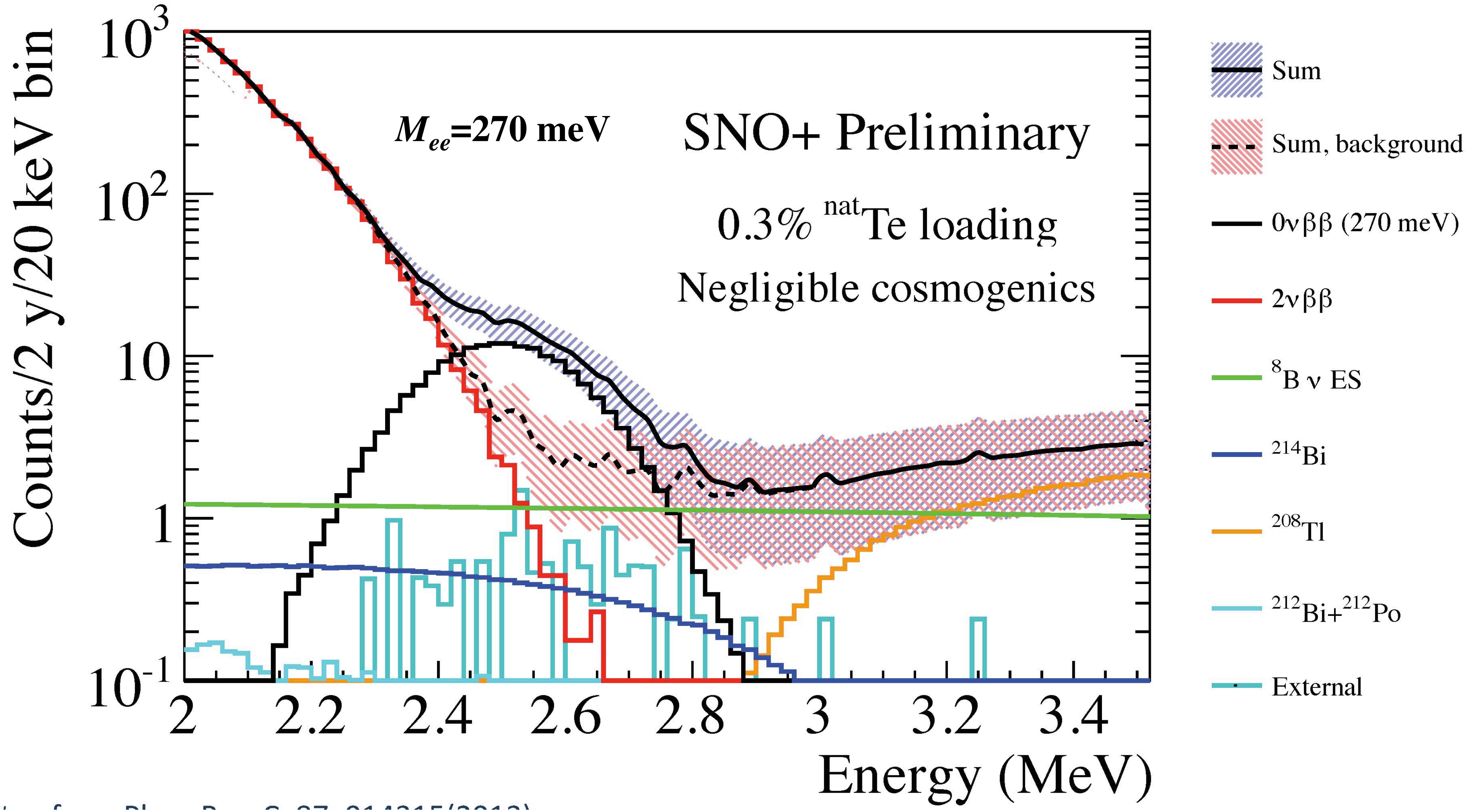
and the selection rule becomes $p\bar{p} \to K^0\bar{K}^0$ forbidden for odd parity

In the quark model $u \Leftrightarrow s$ $\Lambda \Leftrightarrow \Sigma$

Lipkin Prog.Theor.Phys.Suppl.167:155-162,2007

SNO+

Planning to dissolve natural
Te in liquid scintillator



M. Mottran @ EPS HEP 2013