«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS

53rd Course: The Future of our Physics including new Frontiers

Neutrinos

Measuring the unexpected

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INFN

Neutrinos in the SM and in Nature

Standard Model	**Experiment**
States of definite flavour are stationary, i.e. have definite mass	**False**
Neutrino masses are = 0	**False**
Neutrinos and antineutrinos are distinguished by lepton number	**Not proven**
Neutrinos have definite helicity <0, antineutrinos >0	**False**
There are three neutrinos	**True within the uncertainties** LEP $N_\nu = 2.984 \pm 0.008$ Cosmo $N_{\nu-eff} = 3.30^{+0.54}_{-0.51}$

Development of neutrino physics

Neutrino properties are difficult to study, due to their small cross section
The use of different sources has contributed

Natural

Cosmic rays collisions in atmosphere (ν_e and ν_μ at production)

Sun (ν_e at production)

Supernovae (ν_e, ν_μ and ν_τ at production)

Artificial

Proton accelerators (mainly ν_μ at production)

Nuclear reactors (anti ν_e at production)

Progress due to theoretical genius and experimental arts

1928-9. One ante-fact

1920s. Nucleus is made of the known particles: (A,Z) = A protons + (A–Z) electrons

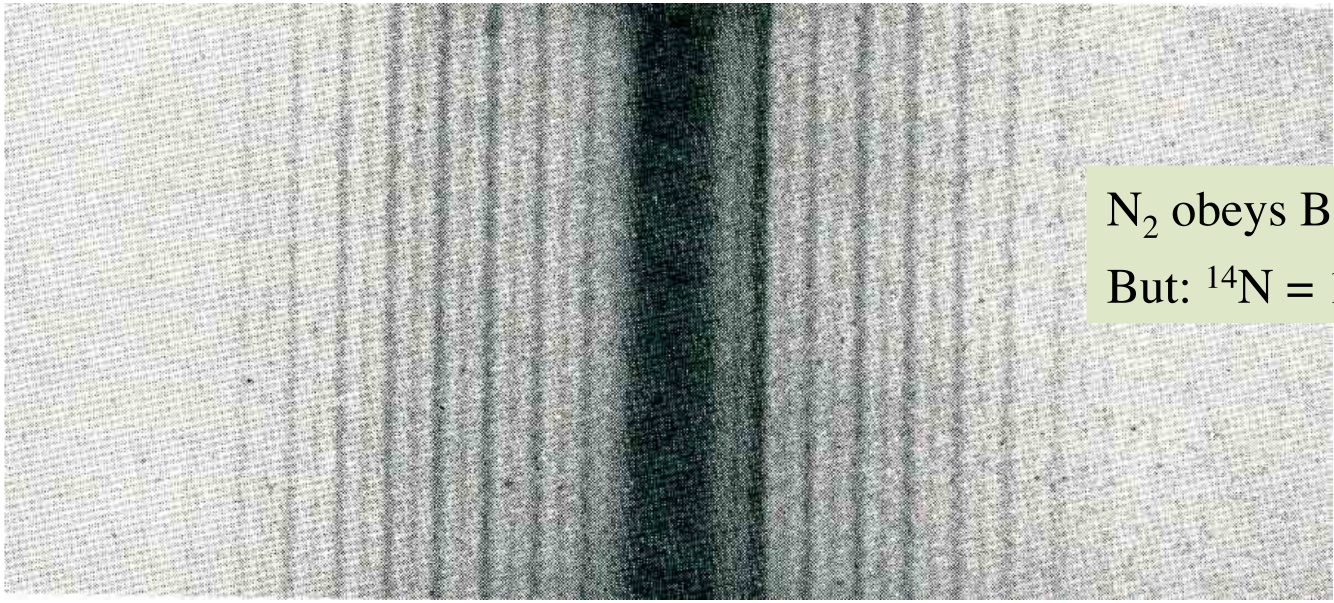
1928-29. **Rasetti measures Raman spectra in gases of diatomic molecules**.

Homo-nuclear molecules, H_2, N_2 and O_2 show alternation of strong and weak lines

space symmetric and space anti-symmetric

If Bose, N. of symmetric lines)/N. anti-symmetric lines= $(I+1)/I$

If Fermi, N. of symmetric lines)/N. anti-symmetric lines= $I/(I+1)/I$



N_2 obeys Bose statistics

But: ^{14}N = 14 p + 7 e. Half integer spin

F. Rasetti. *Nuovo Cimento* 6 (1929) 356
F. Rasetti. *Phys*. *Rev*. 34 (1929) 367
F. Rasetti. *Z. Physik* 61 (1930) 598
E. Fermi Molecules Crystals and Quantum Statistics

The beginning

4 December 1930

"*Dear radioactive Ladies and Gentlemen…*
unfortunately I cannot appear in Tübingen since I am indispensable here in Zurich because of a ball on the night of 6-7 December

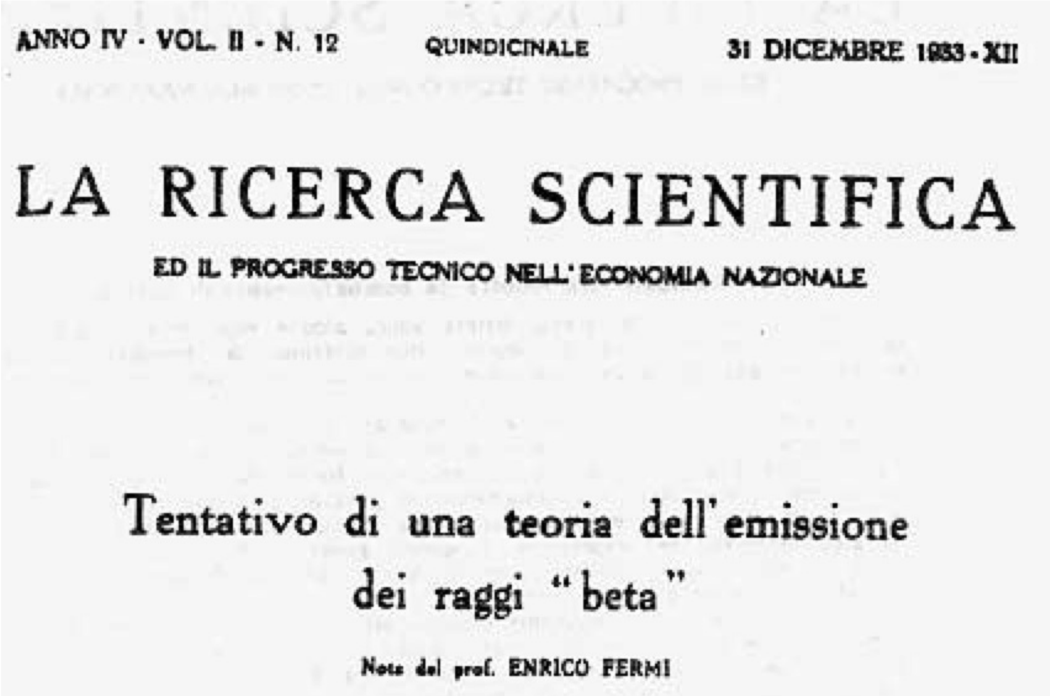
Considering the 'wrong' statistics of ^{14}*N and* ^{6}*Li nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem*

One more type of particle in the nucleon = neutron
neutral, small mass <0.01 proton mass
Emitted with the electron in the beta decay

1932. Chadwick discovers the neutron. Nucleus is made of *p* and *n* with similar masses. No electrons needed in the nucleus.

J. Chadwick, F. R. S. *The existence of the neutron*.
Proc. Roial Soc. of London A 136 (1932) 692, *Nature* 192 (1932) 312

1933. A new fundamental force


ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Theory of β rays emission of radioactive substances, built on the hypothesis that the electron emitted by the nuclei 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. Comparison of theory and experiment

More completely *Nuovo Cimento* 11 (1934) 1
English transl. Fred L. Wilson Am. J. Phys. 36 (1968) 1150

Two questions

Does neutrino exist?

Answer, in **1956**: **YES**

Are neutrinos and antineutrinos different particles?

Answer, in **2015**: **WE DO NOT KNOW**

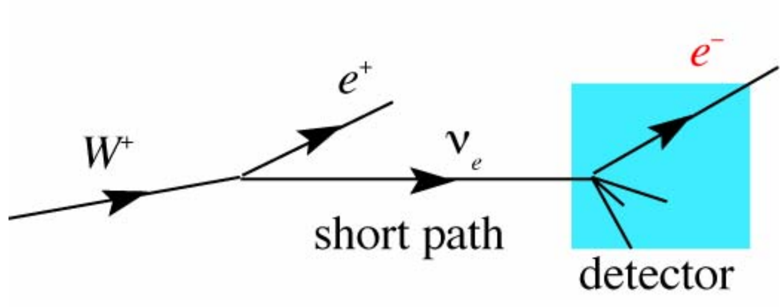
DEFINITION

neutrino (ν_e) $\equiv$ the neutral particle produced in β^+ decay

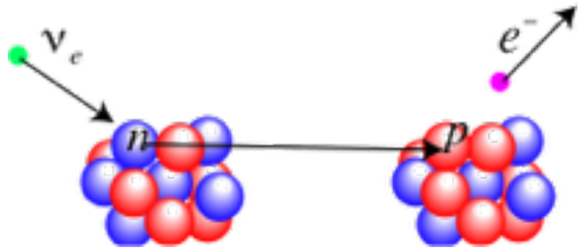
antineutrino $(\bar{\nu}_e)$ $\equiv$ the neutral particle produced in β^- decay

Neutrinos cannot be directly detected. The charged lepton produced by the neutrino interaction in the detector identifies by definition the neutrino flavour

(Similarly will be for the other flavours)



The inverse beta decay



$$\nu + {}^{Z}_{A}N \rightarrow e^- + {}^{Z+1}_{A}N$$

1934. Bethe and Peirls. If neutrinos are produced in beta decay, the inverse process **must** happen B&P estimate the cross section < 10^{-44} cm^2 ➔ one interaction every 10^{16} km in solid matter (1000 light years)

"it is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations"

Pauli. *I did a horrible thing, I postulated a particle that cannot be detected*

Too pessimistic. Avogadro can help us. In addition we need high flux, 1 GW reactor OK

$$R = N\sigma\Phi = 6\times10^{23}\times10^{-48}\left(\mathrm{m}^2\right)10^{17}\left(\mathrm{m}^{-2}\mathrm{s}^{-1}\right) = 6\times10^{-8}\,\mathrm{mol}^{-1}\mathrm{s}^{-1}$$

e.g. with 1 t detector and A=100, the expected rate is R=2/h. But be aware of backgrounds

H. Bethe & R. Peierls, Nature 133, 532 (1934)
H. Bethe & R. Becher, Rev. Mod. Phys. 8, 82 (1936)

Pauli quote is of Reines, in the preface to *Spaceship Neutrino* by C. Sutton (1992), p. XI]

1939. H. Crane. The salt bag experiment

Radiochemical method.

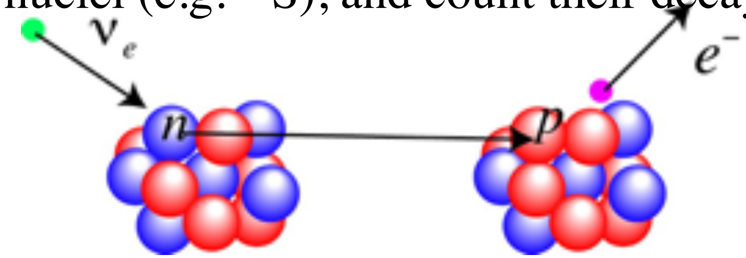
Since Marie Curie times: expose the target to neutrons for several weeks and measure induced radioactivity

Do similarly with neutrinos

Classical chemistry to separate the few produced nuclei, which are in a different atomic species

Consider radioactive final nuclei (e.g. ^{35}S), and count their decay after exposure

$$\bar{\nu} + {}^{35}\mathrm{Cl} \rightarrow {}^{35}\mathrm{S} + e^{+}$$



Crane used a 1 mC capsule of radioactive material in a three-pound bag of common salt (NaCl)

90 days exposure

Chemical extraction of S and counting in a ionization counter.

No activity detected ➔ $\sigma < 10^{-30}$ cm^2

Problem. Cross section is much smaller: $\boldsymbol{\sigma} \sim 10^{-44}$ cm^2

Separation at 1/10^{30} needed! Impossible for S

H.R. Crane Phys. Rev. **55** (1934) 501

H.R. Crane Rev. Mod. Phys. **20** (1948) 278

1945. Pontecorvo Cl-Ar

A Chalk River (Canada). UK nuclear programme "Tube alloy"

Two classified reports

1945. PD-141. classified up to 1964

Pontecorvo. **The detection via inverse beta is not out of question**

J. Guèron: use as a target Cl in C Cl4

Radiochemical method, similar to Crane

$$\nu + {}^{35}\mathrm{Cl} \rightarrow {}^{35}\mathrm{S} + e^{+}$$

1946. PD-205. classified up to 1948

The Cl-Ar reaction

Ar is an inert gas, might be separable at $1/10^{30}$

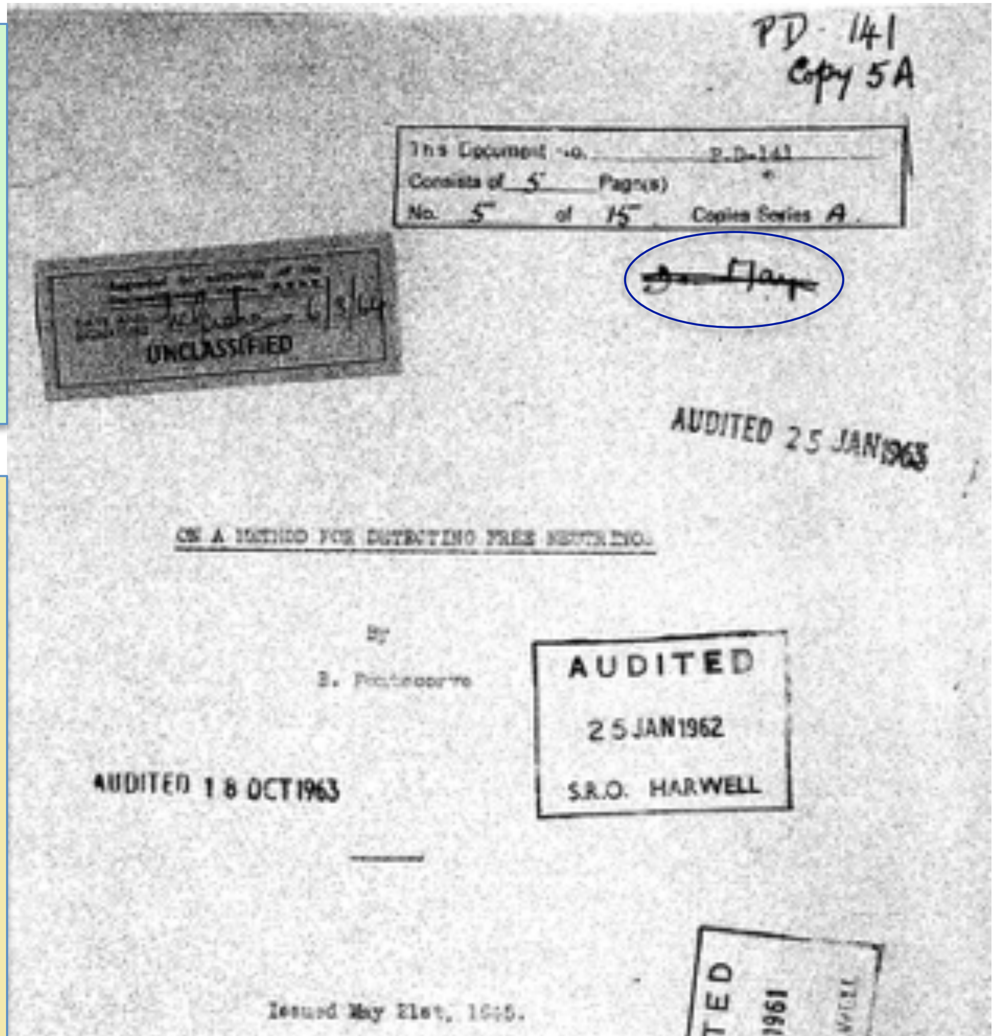
Source. Nuclear reactor (flux $\approx 10^{16}\ \mathrm{m^{-2}\ s^{-1}}$)

(works if neutrino=antineutrino)

BP cross section estimation is over-evaluated by two orders of magnitude

BP discusses only superficially the background issue

$$\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^{-}$$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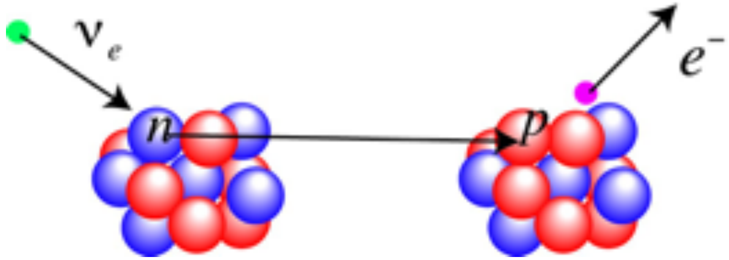
This Document No. P.D-141
Consists of 5 Page(s)
No. 5 of 15 Copies Series A.
UNCLASSIFIED
AUDITED 25 JAN 1963
ON A METHOD FOR DETECTING FREE NEUTRINO.
By
B. Pontecorvo
AUDITED
25 JAN 1962
S.R.O. HARWELL
AUDITED 18 OCT 1963
Issued May 21st, 1945.

1949. Luis Alvarez



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

1949. L. Alvarez Report UCRL-238. Not classified
Fireman claims to have found evidence for the 0ν2β decay ➔ neutrino=antineutrino.
It was not true, but LA thought that Cl,Ar reaction might work at a reactor
Evaluation of the cross section: 2 10^{-45} cm^2 **correct**
Detector mass= 40 t of CCl_4
In depth discussion on the separation issue, based on the authors experience
Main problem: backgrounds. Other process can transform Cl into Ar,
(p,n) reactions cosmic ray induced background too high on surface
➔ go **underground** under the reactor

Separation papers
F. G. P. Seidel and S. P. Harris. Rev. Sci. Instr **18** (1937) 897
L. Alvarez. Phys. Rev. (1949)

1949-50. Liquid scintillator

Simple, fundamental detector for neutrinos

Long attenuation lengths. We can build **very large detectors**

Tonnes to kilotonnes

Mixture of two or three components

Photomultipliers available since 1934

Almost contemporary discovered by

Roma ISS. M. Ageno et al.

New York. H. Kallmann

Princeton. G. I. Reynolds, F.B. Harrison, G. Salvini

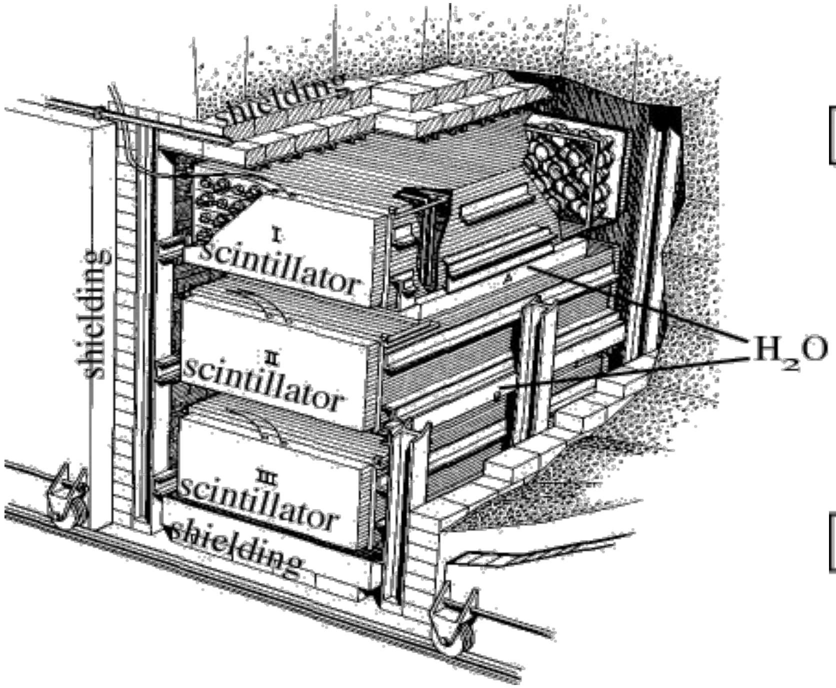
M. Ageno et al. Atti Acc. Naz. Lincei **6** (1949) 626; Phys Rev **79** (1950) 720

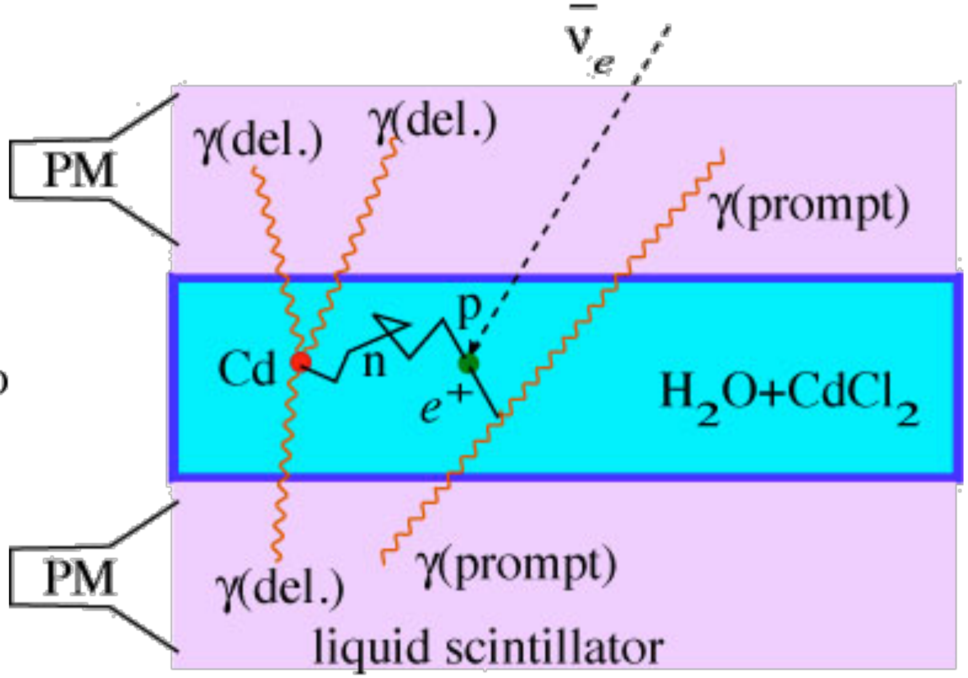
H. Kallmann Phys. Rev. **78** (1950) 621

G. I. Reynolds, F.B. Harrison, G. Salvini Phys Rev. **78** (1950) 488

1956. Neutrino detected, finally

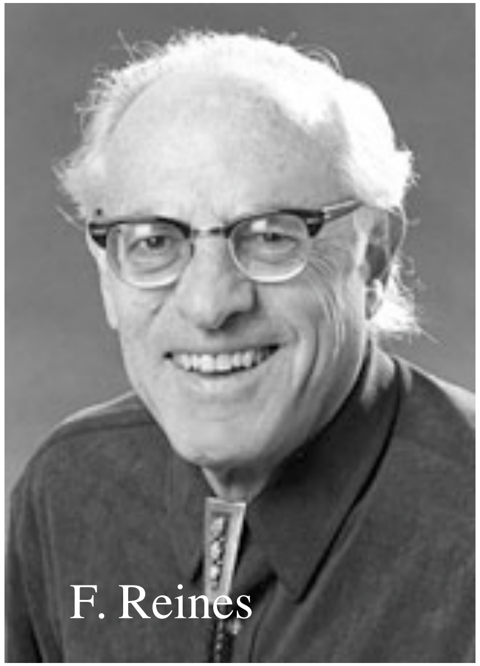
$$\bar{\nu}_e + p \rightarrow n + e^+$$



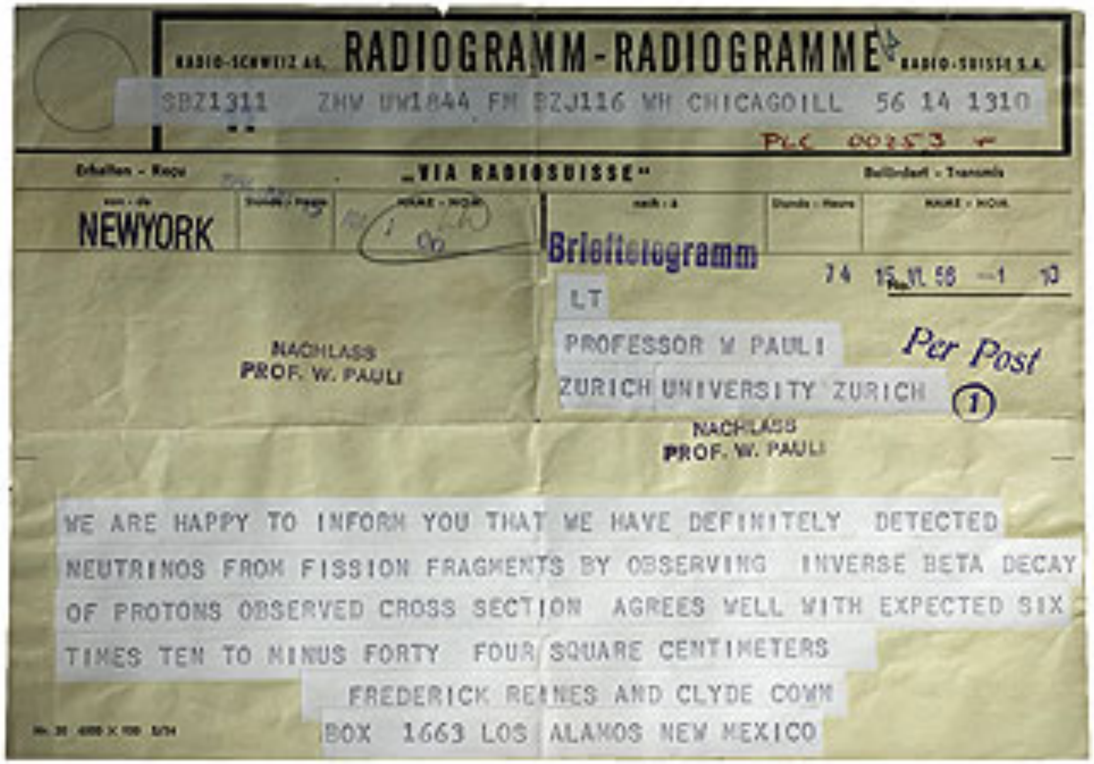


1956. Neutrino detected, finally

C. L. Cowan Jr



F. Reines



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

"VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

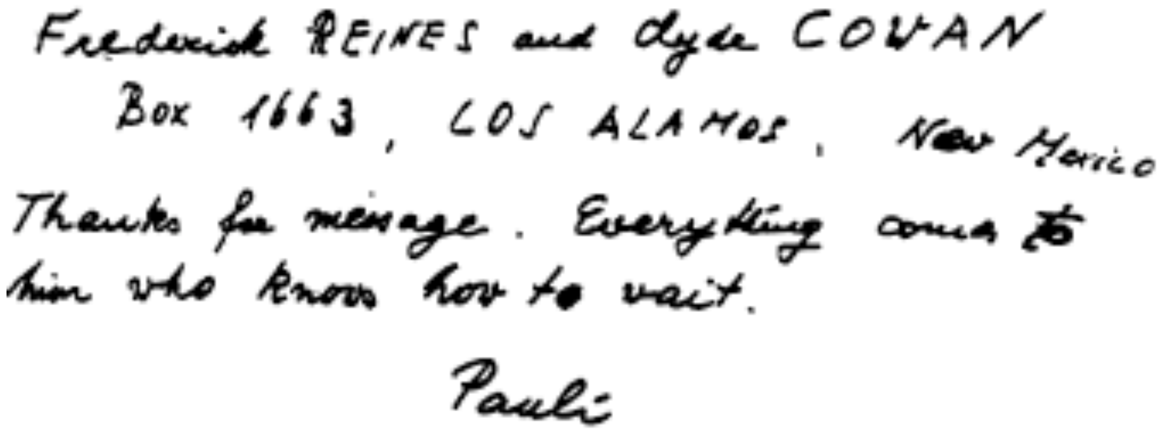
Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO



Frederick REINES and Clyde COWAN

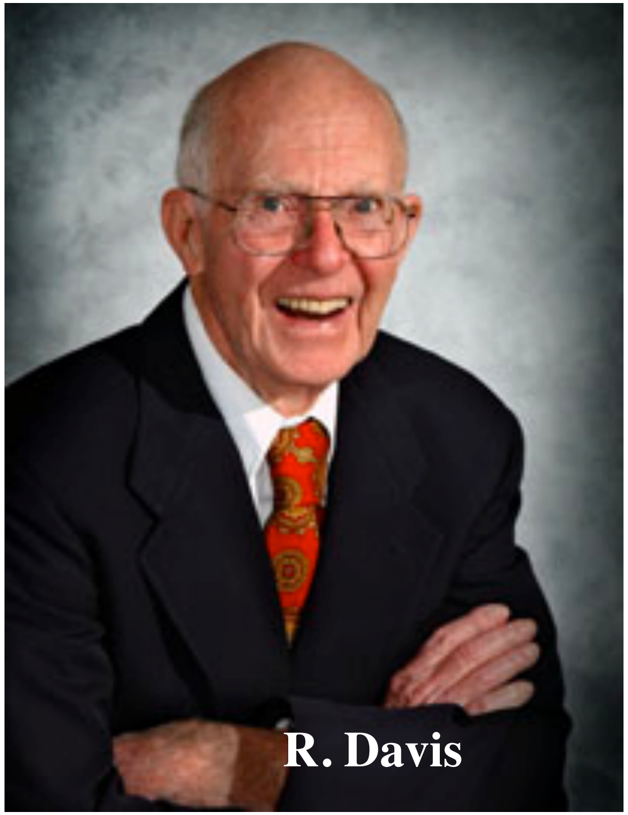
Box 1663, LOS ALAMOS, New Mexico

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

Pauli

Science **124** (1956) 104

1954-58. Neutrino ≠ antineutrino?



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

1958.
The most powerful reactor becomes operational at Savannah River (0.8 GW)
Target: 11 400 l (18.5 t) of C_2Cl_4
Sufficient sensitivity : 20 > theoretical if neutrino = antineutrino
No detected event
The neutral particle produced in β^+ decay do not induce the Cl-Ar reaction

Neutrino and antinutrino are different particles

The conclusion, assumed in the Standard Model, is premature
The Cl-Ar does not happen for other reasons
(V–A and smallness of neutrino masses)

R. Davis, Unesco Conference 1958. Paris. Vol. 1 p. 728

The Cl-Ar reaction. Solar neutrinos

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

1964. J. Bahcall and R. Davis: two face to face articles, on the solar model predicting neutrino flux and spectrum and on the proposal of an experiment to detect them, using the Cl-Ar reaction
Flux much smaller than at a reactor ➔ Cosmic ray background much more relevant ➔ go deep underground: Homestake gold mine in SD. 1480 m deep. Cosmic flux ~ 4 μ/(d m^2)
Detector. 380 m^3 of perchlorethylene (C_2Cl_4), containing 133 t di ^{37}Cl

ν_e flux about 1/3 of the prediction
The solar neutrino puzzle
Will be solved with neutrino oscillations, first physics beyond the standard model

John N. Bahcall; *Phys. Rev. Lett.* **12** (1964) 300
Raymond Davis Jr. *Phys. Rev. Lett.* **12** (1964) 303

The 2nd question: antiν≠ν?
1937 Ettore Majorana

Nuovo Cimento **14** (1937) 171

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.*

The 2nd question: antiν≠ν?
1937 Ettore Majorana

Nuovo Cimento **14** (1937) 171
E. Majorana "Teoria simmetrica dell'elettrone e del positrone"

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.

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 (… 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*"

The Majorana equation

Dirac equation $\left(i\gamma^{\mu}\partial_{\mu}-m\right)\psi(x)=0$ The ψ bi-spinor has 4 complex components

The 4 degrees of freedom correspond to the two helicity states of electron and positron

Only the anticommutators of the γ matrices are defined (Clifford algebra)
Majorana question: can γ matrices be chosen such as to have ψ real? $\left\{\gamma_{\mu},\gamma_{\nu}\right\}=2\eta_{\mu\nu}$
Answer: the following obey Clifford algebra and are imaginary

$$\tilde{\gamma}_0=\sigma_2\otimes\sigma_1,\quad \tilde{\gamma}_1=i\sigma_1\otimes 1,\quad \tilde{\gamma}_2=i\sigma_3\otimes 1,\quad \tilde{\gamma}_3=i\sigma_2\otimes\sigma_2$$

$\left(i\tilde{\gamma}^{\mu}\partial_{\mu}-m\right)\tilde{\psi}(x)=0$ all the $i\tilde{\gamma}_{\mu}$ beam real, it can govern a $\tilde{\psi}$ with all real components

Only 2 independent components, the two helicity states. Particle=antiparticle

Majorana particles are **completely neutral spin 1/2 particles** (like γ, *Z, H* etc. for bosons)
Neutrinos?
Gluinos (imaginary parity)**, neutralinos, gravitinos?**

No Majorana particles found yet, however quasi-particles found in superconductors: "*parti-holes* = spin 1/2, zero energy modes, superpositions of electrons and holes in equal parts

F. Wilczek *"Majorana returns"* Nature Phys. **5** (2009) 614
S. Nadi-Perge et al. *Observation of Majorana fermions in…..* Science **31** (2014) 346 no. 6209 pp. 602-607

G. Racah. The first proposal

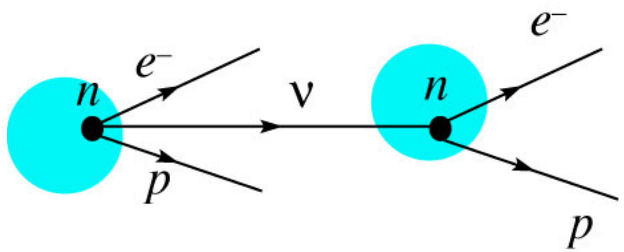
SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Nota di GIULIO RACAH

Nuovo Cimento **14** 323

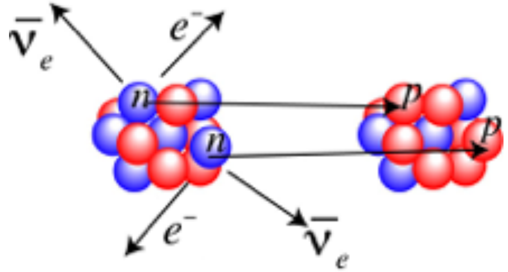
Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* FERMI *sulla radioattività* β, *e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. MAJORANA.

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



1939. Furry: look for 0ν2β

2ν2β



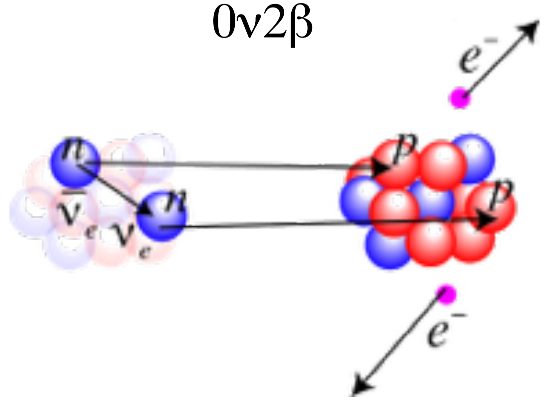
1935. M. Goeppert-Mayer "Double beta disintegration"

Phys. Rev. **48**

1939. W. H. Furry "On the transition probabilities in double beta-decay" Phys Rev **56** 1184

"*In the older theory double-β disintegration involves emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability is extremely small. In the Majorana theory only two particles – the electrons or positrons – have to be emitted, and transition probability is much larger*"

0ν2β



He did not know that

- **Charged current weak interactions are *V–A***
- **Neutrino masses are very small *m<< E***

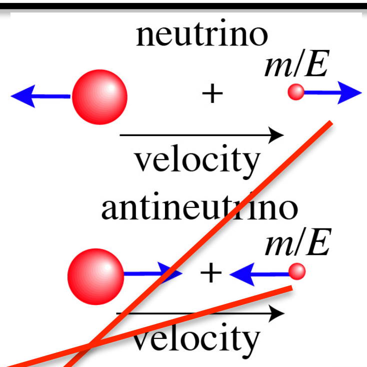
➔ "the transition probability" is not "much larger", but unfortunately rather **much smaller**

Neutrino and antineutrino

V–A only left-handed neutrinos (eigenstates of γ_5 with eigenvalue –1)

ν_e = neutral particle produced with e^+.
Dominant negative helicity + m/E positive helicity

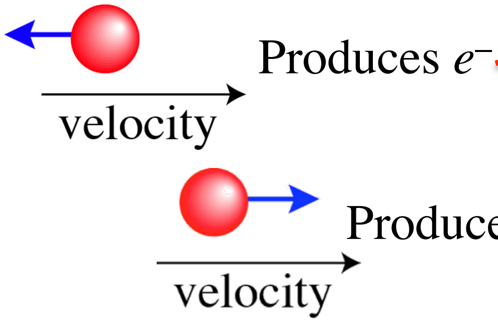
Anti ν_e = neutral particle produced with e^-
Dominant positive helicity + m/E negaitive helicity



Dirac
Produces e^-

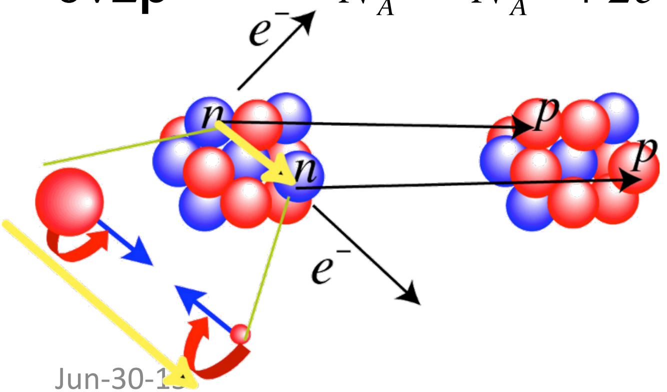
Produces e^+

Majorana



Only the extremely small m/E component distinguishes between Dirac and Majorana
E_ν=10 MeV, m= 100 meV
➔ $(m/E_\nu)^2 = 10^{-14}$

0ν2β $N_A^Z \rightarrow N_A^{Z+2} + 2e^-$



Best present limits
^{76}Ge GERDA Ph1
^{36}Xe EXO-200 and KL-ZEN
$T_{1/2}$> 2 10^{25} yr
Sensitivity of experiments in preparation: 10^{26} yr.

The second family. Neutrino and neutretto?

1947-50. Question (Bernardini, Hincks, Pontecorvo, Puppi, Steinberger,…)
Are the neutral particles produced in the *μ* decay and in β different or equal?

1960. Lee and Yang show to be essentially impossible to avoid the decay $\mu^{\pm} \rightarrow e^{\pm} + \gamma$ if the two neutrinos are equal

B. Pontecorvo *The infancy and youth of neutrino physics*. *Some recollections*. Jour. De Phys. 1982. n. 12, Vol 43, p C8-221

In the URSS

1957-58. Docho Fakirov, a student of M. A. Markov. Thesis: "**On the Possibility to Investigate the Interaction of High Energy Neutrinos with Matter at Accelerators**"
Calculates a neutrino beam from pions decays **in flight** produced by protons from 6 to 100 GeV

1959. Pontecorvo suggests looking at $\boldsymbol{e^+}$ in interactions of neutrinos from decays of pions **at rest**
π^- are captured by nuclei and do not decay. If $\nu_\mu \neq \nu_e$, the decay chain of π^+ is

$$\pi^+ \to \mu^+ + \nu_\mu; \;\; \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad \text{there is no } \bar{\nu}_e$$

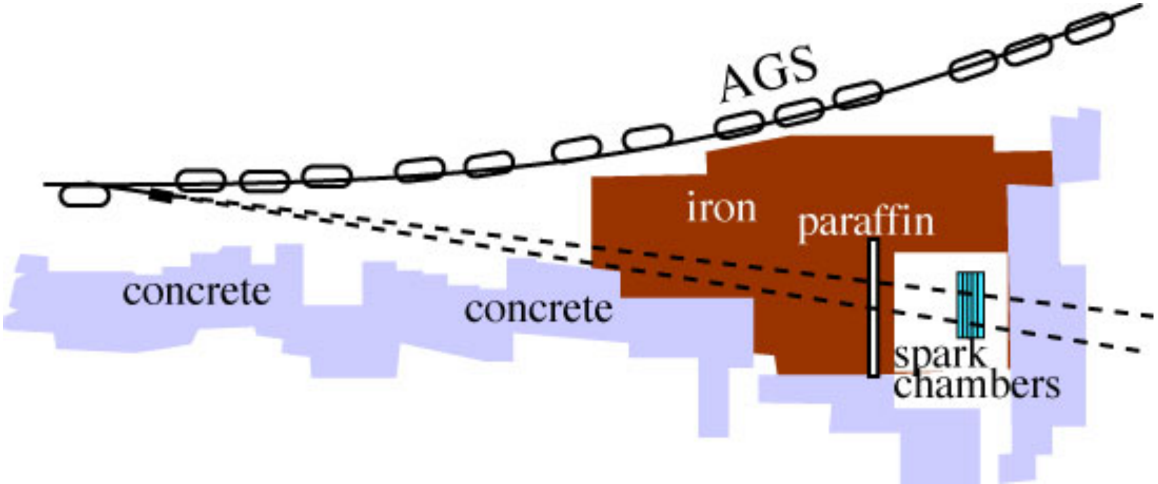
If I observe positrons, $\nu_\mu = \nu_e$
Notice that muon neutrinos are "sterile" because their energy is below the threshold for

$$\nu_\mu + N \to \mu + N'$$

Hence, if $\nu_\mu \neq \nu_e$, nothing is observed.
But a null observation does not prove anything
Moreover, neutrinos from pions (kaons) at rest go in all direction. **Only a very small fraction would be collected at the detector**, several metres far.
Such an experiment could not succeed

Pontecorvo, B. 1960. Electron and Muon neutrinos. Sov. J. Phys. JETP 10: 1236-1240

1962. The BNL experiment



1962. Experiment by Schwartz, Lederman, Steinberger et al.

Pions produced on an internal target

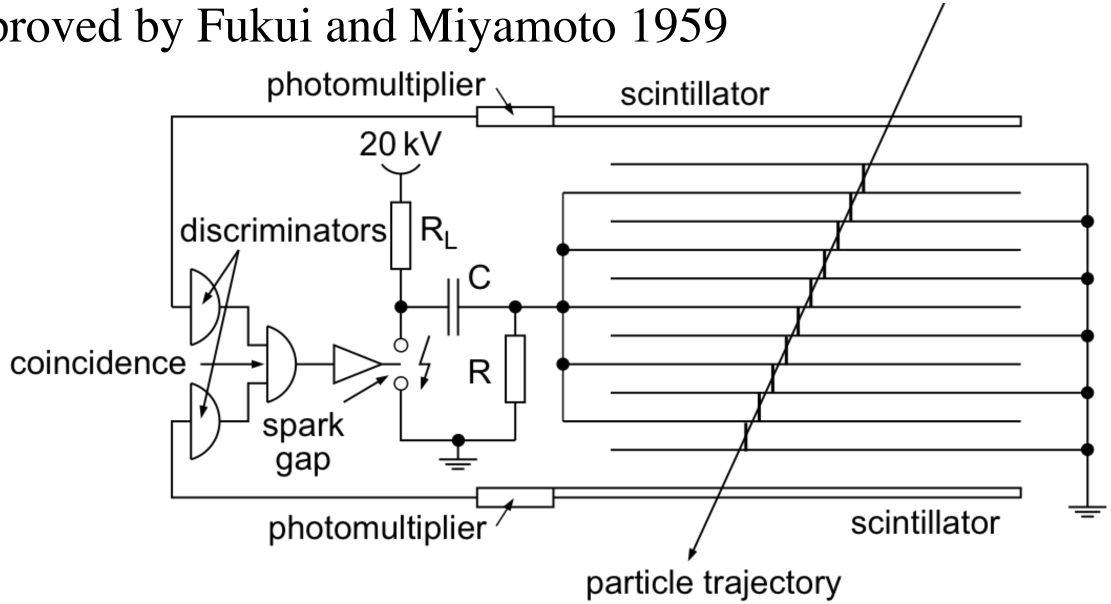
Iron shield absorbs hadrons and muons

Detector must be massive and tracking: use spark chamber

The spark chamber

Spark chamber (target and detector): Conversi and Gozzini 1955

Improved by Fukui and Miyamoto 1959



A number of parallel plates are mounted in a gas filled volume

Plates are alternatively connected to ground and to a high voltage supply

The high-voltage pulse is triggered when has to become sensitive

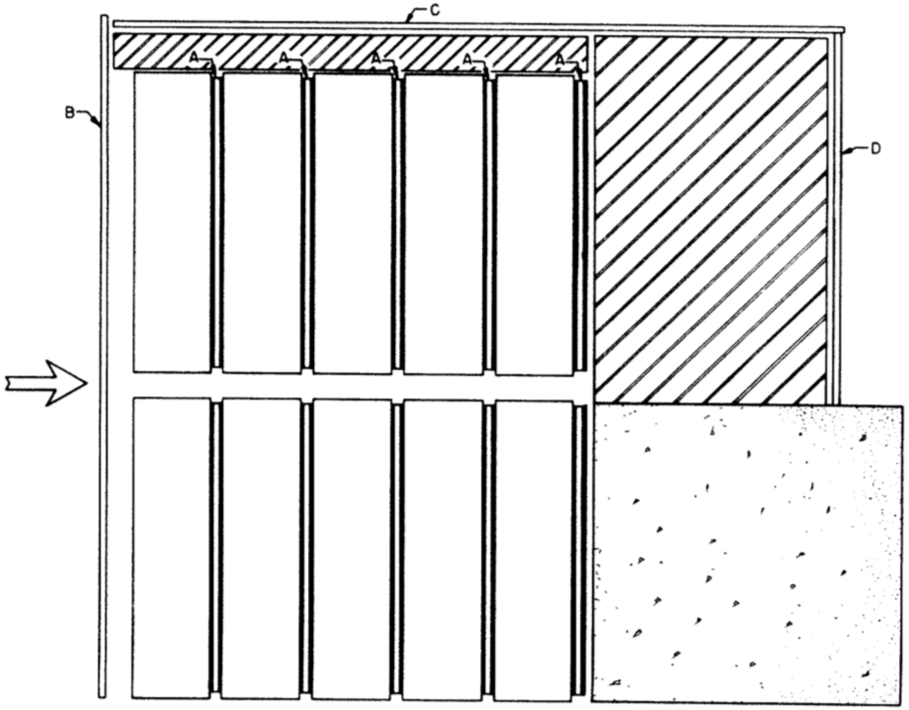
Spark discharge along the trajectory of the particle.

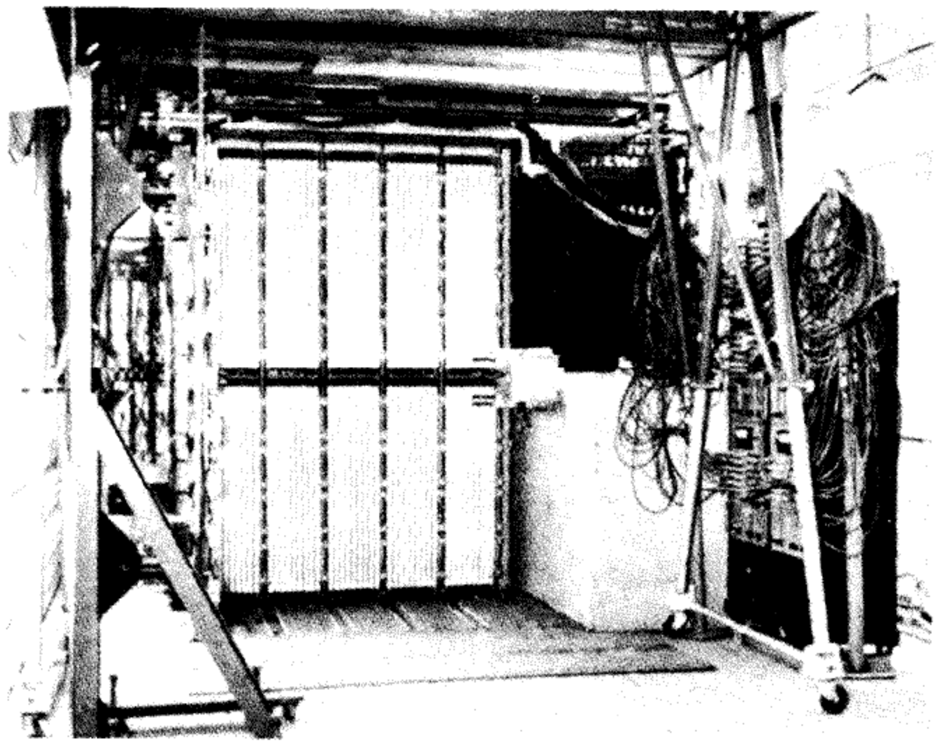
The detector

Calculations showed that target/detector mass should be about 10 t. Bubble chambers (then) too small

Built: 10 modules of 9 optical spark chambers each

Al plates 1.1 x 1.1 m^2, thickness: 2.5 cm. Total mass. = 10 t





Second neutrino discovered

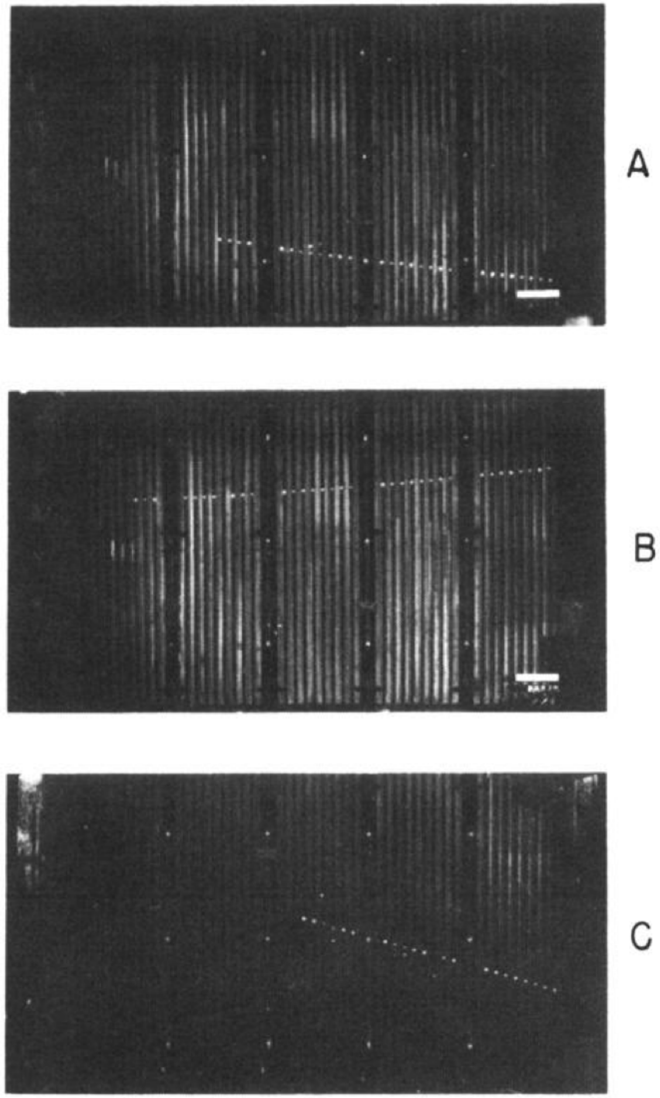


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

34 "single muon" events observed

additional 8 events compatible with background

No electron observed

Conclusion: the neutrino that is born together with a μ in the π decay when interacts produce a μ, not e.

Two different conserved quantities exist, lepton flavours: n_e and n_μ

Check how electrons look like

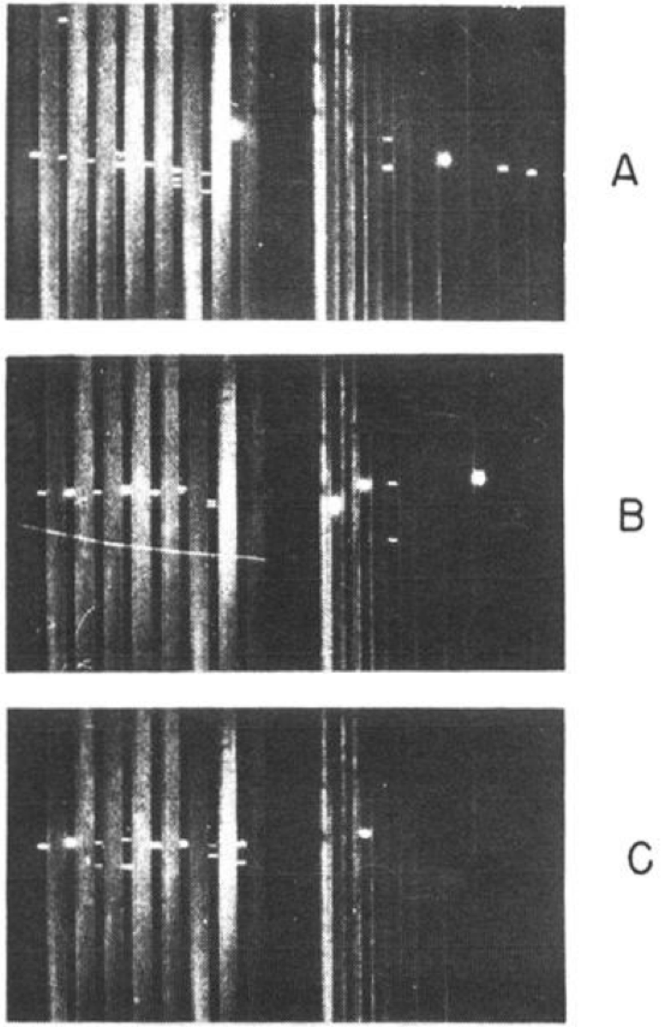


FIG. 8. 400-MeV electrons from the Cosmotron.

Exposure of the chambers at the 400 MeV electron beam at Cosmotron

Electrons always produce a shower

A third lepton family?

1963. Zichichi started the search for **the 3rd sequential lepton family**, a replica of the first two, he "Heavy Lepton and its neutrino" at CERN
Searching for **acoplanar lepton pairs of opposite charges**

$$\begin{pmatrix} \nu_{HL} \\ HL \end{pmatrix}$$

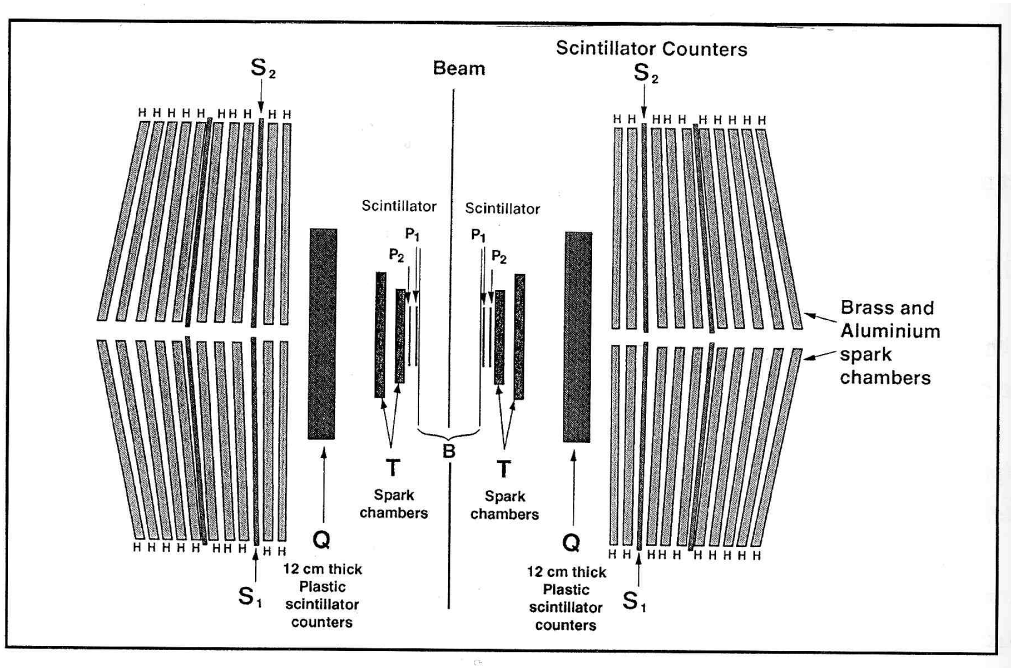
$$pp \rightarrow HL^{+} + HL^{-}$$

$$HL^{+} \rightarrow e^{+}\,\nu_e\,\bar{\nu}_{HL} \qquad HL^{-} \rightarrow e^{-}\,\bar{\nu}_e\,\nu_{HL}$$

$$HL^{+} \rightarrow \mu^{+}\,\nu_\mu\,\bar{\nu}_{HL} \qquad HL^{-} \rightarrow \mu^{-}\,\bar{\nu}_\mu\,\nu_{HL}$$

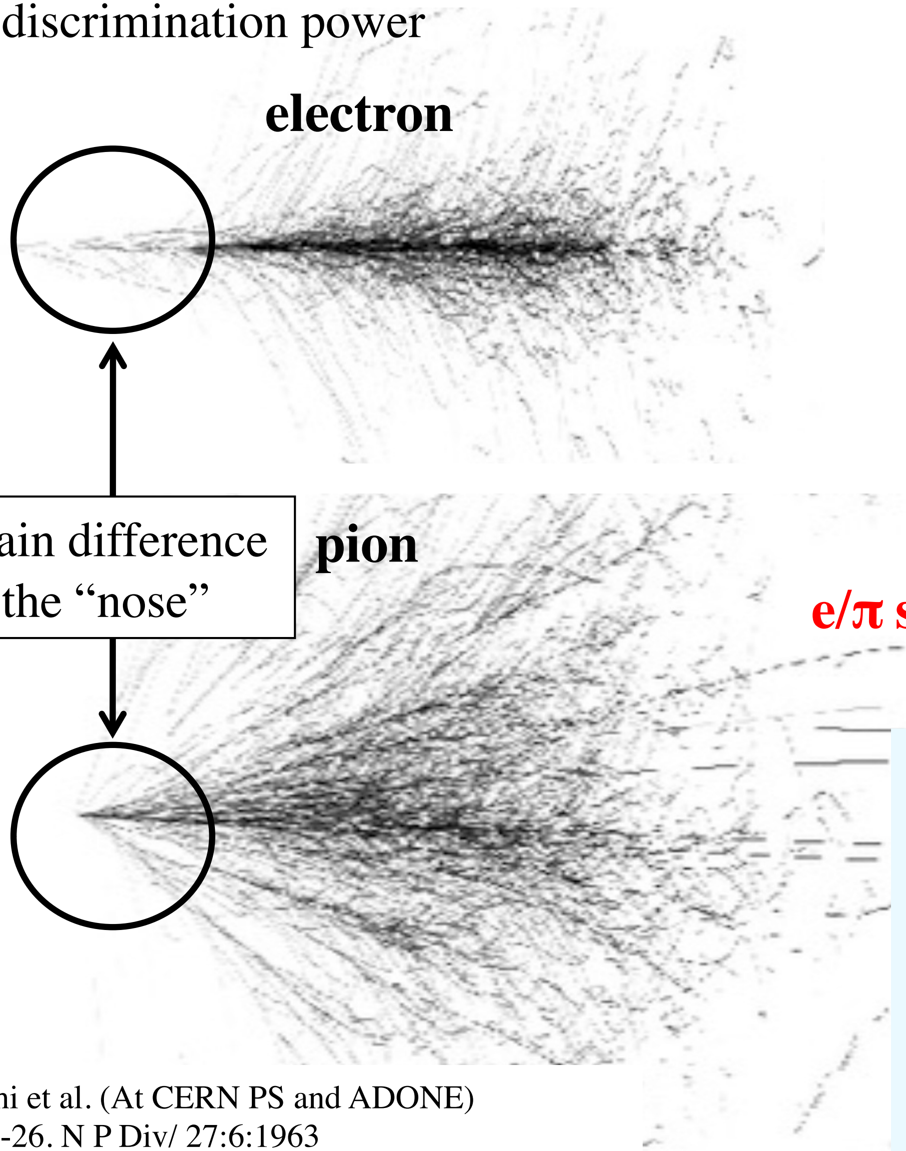
1967. and later at the ADONE $e^{+}e^{-}$ collider at Frascati
But maximum energy (3 GeV) was too small
It was found at SLAC with the same method

M. Bernardini et al. INFN/AE-67/3, 20 March 1967



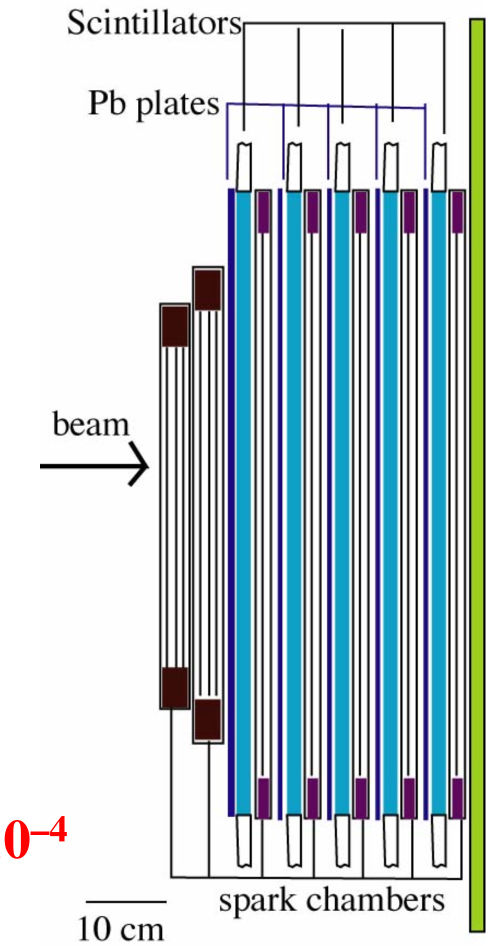
Identify electrons

Hadrons are produced much more frequently than leptons.
Need discrimination power



The preshower

e/π separation 4 x 10^{-4}



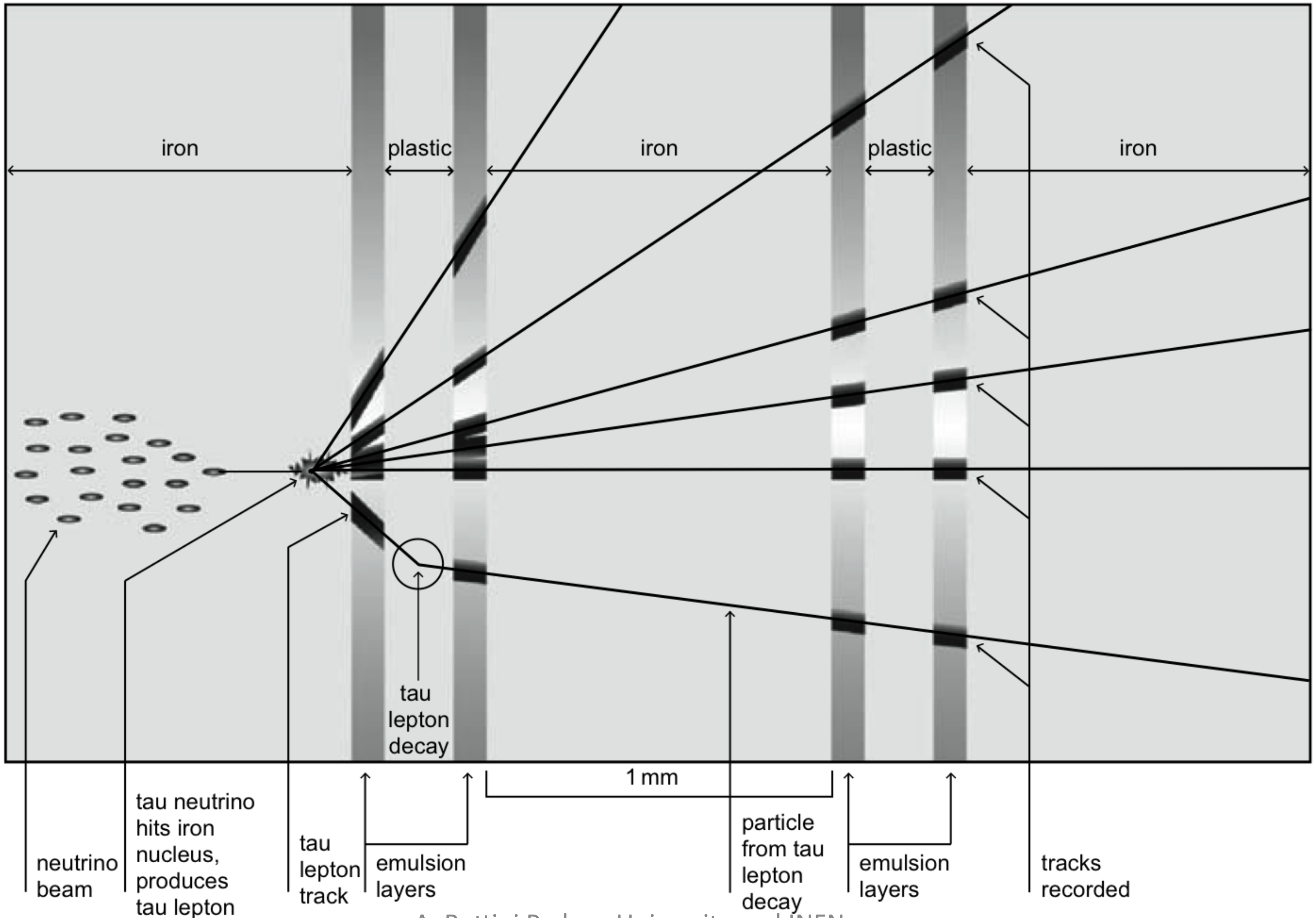
Control early shower development with Z and thicknesses of detector elements
Combine visual and non-visual approaches (each 10^{-2} rejection)
Tracking with thin plate spark chambers
Energy sampling with Pb-scintillator sandwiches

A. Zichichi et al. (At CERN PS and ADONE)
CERN-63-26. N P Div/ 27:6:1963
T. Massam, Th. Muller, M. Schneegans and A. Zichichi
Nuovo Cimento **39** (1965) 464

ν_{HL}/ν_{τ} *discovered*

HL/τ lifetime is short, 0.29 ps → O(100 μm) length

Nagoya **Emulsion Cloud Chamber**



Mass eigenstates - Flavour eigenstates

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

if Majorana

9 quantities to be measured: 3 masses, 3 angles, 3 phases

4 known + 1 in absolute value

Two mechanisms observed changing neutrino flavour

•oscillation in vacuum (kinetic)

•transformation in matter (**dynamical:** interaction of neutrinos with electrons)

$$\alpha \equiv \frac{|\delta m^2|}{|\Delta m^2|} \simeq 0.03$$

$$\theta_{13}^2 \simeq 0.024$$

These two quantities being small short and long period oscillations & matter transformations decouple at 1st order

$$P(\nu_x \to \nu_y, L) = A(\nu_x \to \nu_y)\sin^2\left(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

$$P(\nu_x \to \nu_y, L) = A(\nu_x \to \nu_y)\sin^2\left(1.27\delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Amplitudes *A* are functions of the mixing angles, different for different ν_x and ν_y pairs

PDG review (Fig. 14.9) severely misleading

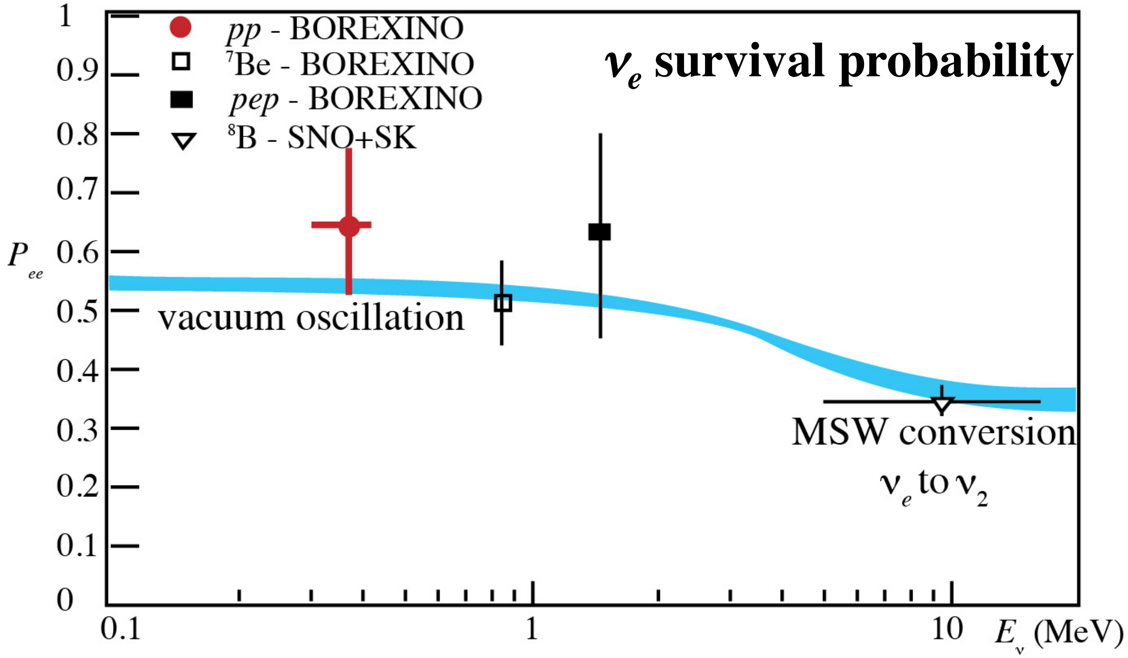
Leading order amplitudes

Vacuum oscillation probabilities **do not** depend at 1st order on **sign of Δm^2** and **sign of ($\theta-\pi/4$)**
MSW depends on signs
Neutrino oscillations were searched at proton accelerators for decennia, but not found
Square mass differences are very small ➔ much longer distances between source an detector needed
Natural sources + Underground laboratories

$\delta m^2 \simeq 75\ \text{meV}^2$ $\quad L_{max}(E=1\ \text{GeV}) \approx 16000\ \text{km}$ Discovered with solar neutrinos

$\left|\Delta m^2\right| \simeq 2430\ \text{meV}^2$ $\quad L_{max}(E=1\ \text{GeV}) \approx 500\ \text{km}$ Discovered with atmospheric neutrinos

Neutrinos are produced as ν_e in the core of the Sun
If E is large enough meet MSW resonance
If E is smaller behave as in vacuum
Different components neasured by BOREXINO @ LNGS



BOREXINO.Nature, **512** (2014) 383

What we know and what we do not

$\sin^2\theta_{12} = 0.307 \pm 0.017 \qquad \theta_{12} \simeq 33^\circ$

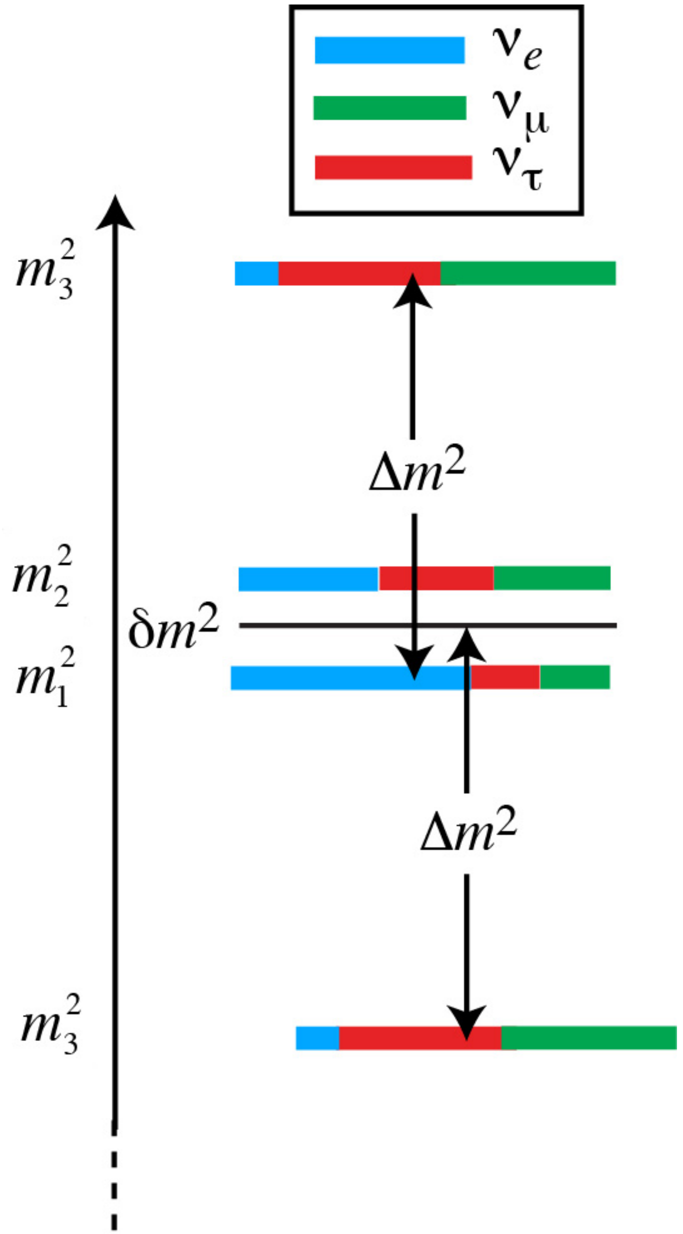
$\sin^2\theta_{23} = 0.390 \pm 0.033 \qquad \theta_{12} \simeq 40^\circ\text{–}50^\circ$

$\sin^2\theta_{13} = 0.0242 \pm 0.0026 \qquad \theta_{12} \simeq 9^\circ.$

$\delta m^2 = 75.4 \pm^{2.6}_{2.2}\ \text{meV}^2 \qquad 2.6\%$

$\left|\Delta m^2\right| = 2430^{+70}_{-90}\ \text{meV}^2 \qquad 3.5\%$

Indirect upper limits from cosmology
$m_i < 100\text{-}150$ meV



We do not know
The sign of the larger mass difference
The absolute values of the masses
The three phases (one if Dirac, the other two do not appear in oscillations or MSW)

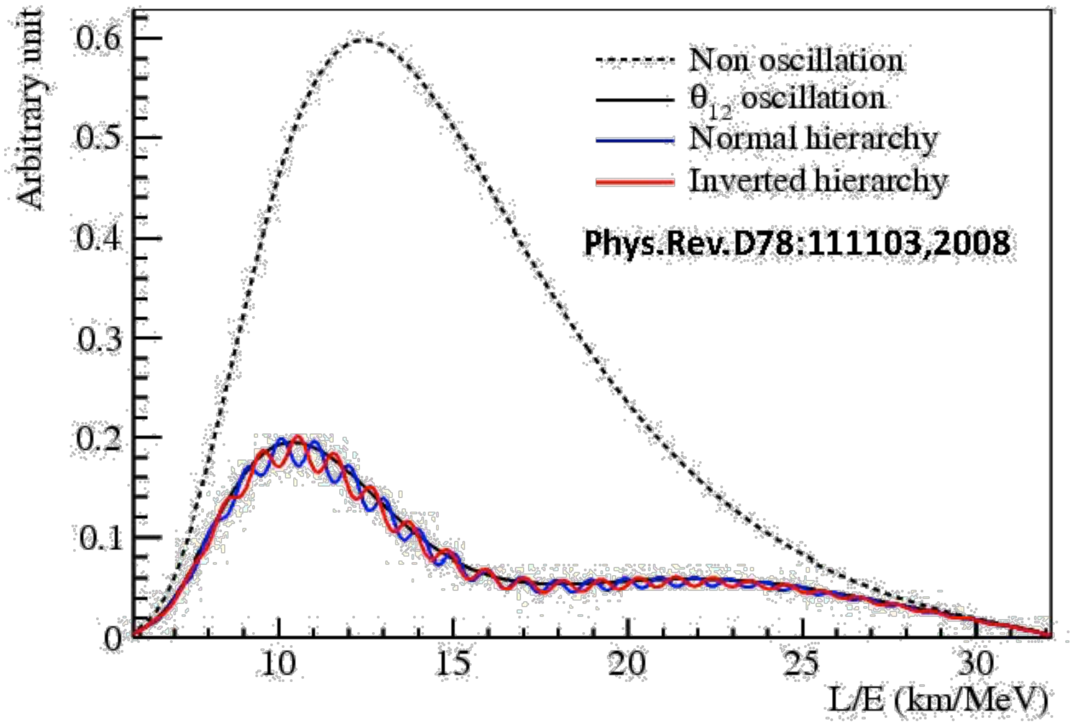
G. L. Fogli et al. 1205.5254

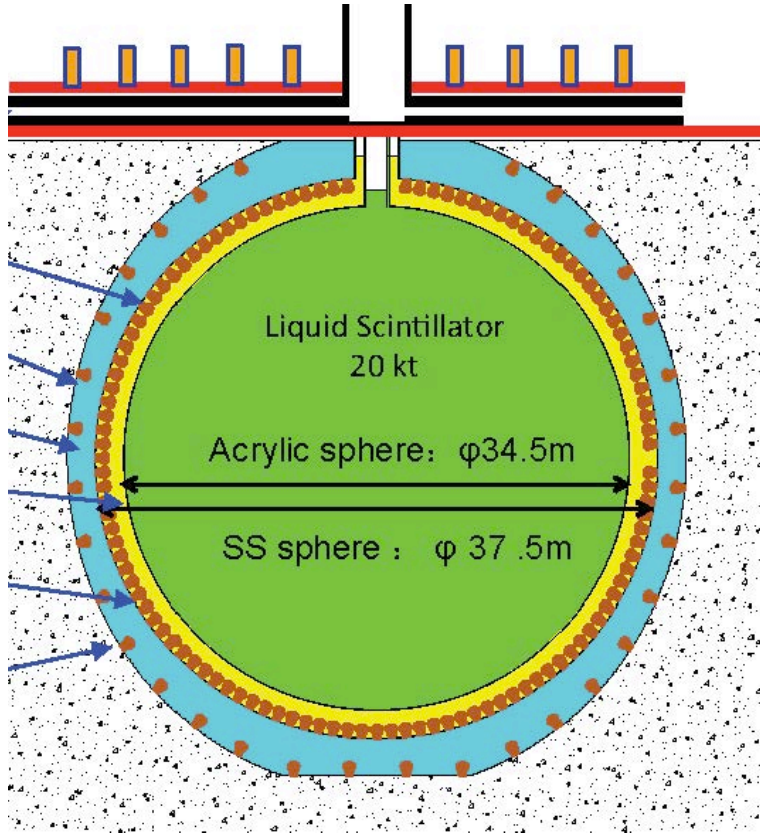
Sign Δm^2 JUNO. 50 kt - Liquid Scintillator

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21} - 4\theta_{13}^2 \cos^2 \theta_{12} \sin^2 \Delta_{31} - 4\theta_{13}^2 \sin^2 \theta_{12} \sin^2 \Delta_{32}$$

$\Delta \equiv 1.27 \Delta m^2 \frac{L}{E}$ NH $|\Delta_{31}^2| = |\Delta_{32}^2| + |\Delta_{21}^2|$ IH $|\Delta_{31}^2| = |\Delta_{32}^2| - |\Delta_{21}^2|$

20 kt liquid scintillator
$\Delta E/E < 3\%$ crucial and challenging

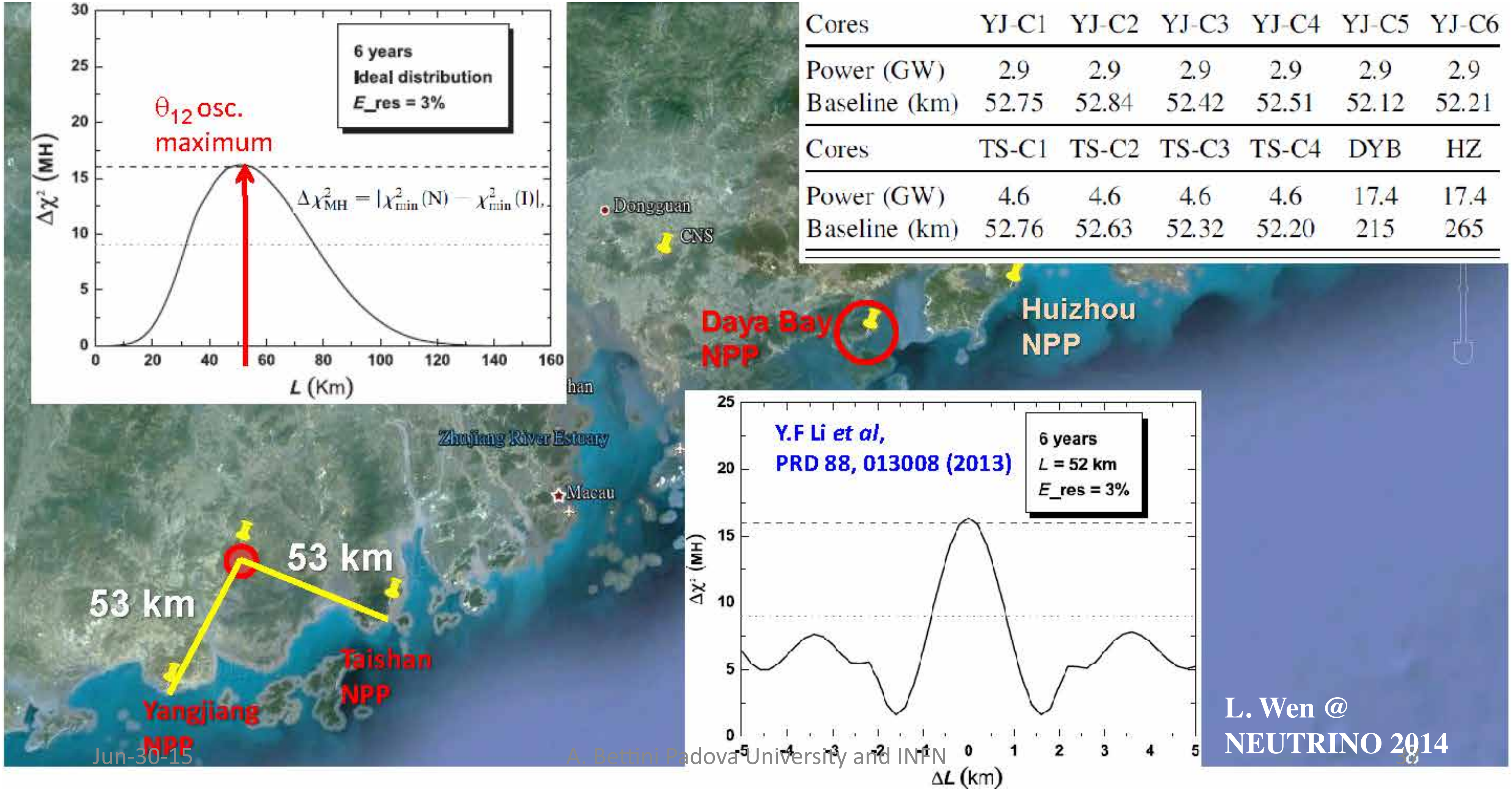




S.T. Petcov et al., PLB533(2002)94; S.Choubey et al., PRD68(2003)113006; J. . Learned et al., hep-ex/0612022
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008 PRD79:073007, 2009

JUNO-Location & sensitivity

Optimum distance at the oscillation maximum for θ_{12}
Distances from the sources must be equal within 500 m
Civil engineering started
Planned start of operation 2020



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Sign Δm^2 Atmospheric μ neutrinos

Mass= 50 kt; B=1.3

RPC tracking

Time resolution important

Momentum resolution crucial

Originally proposed by MONOLITH (LNGS P26/2000)

$$P\left(\nu_\mu \to \nu_\mu\right) \neq P\left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right)$$

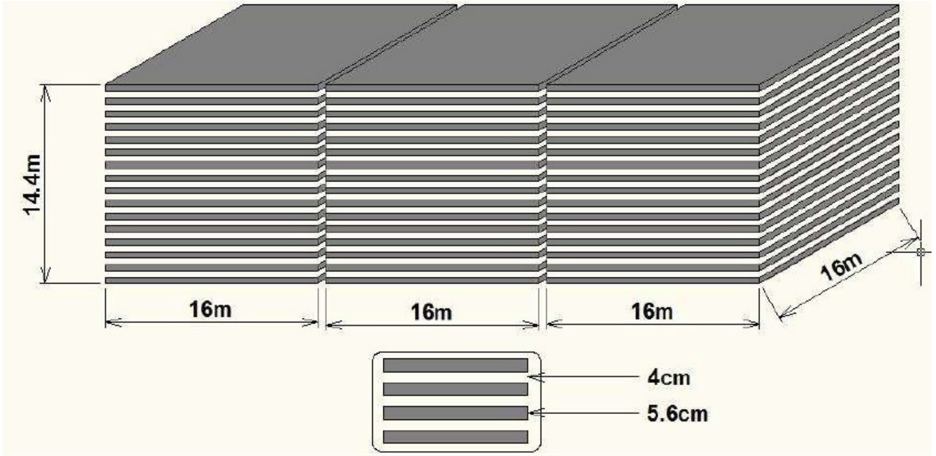
The surviving probabilities differ due to opposite matter potential (subdominat effect)

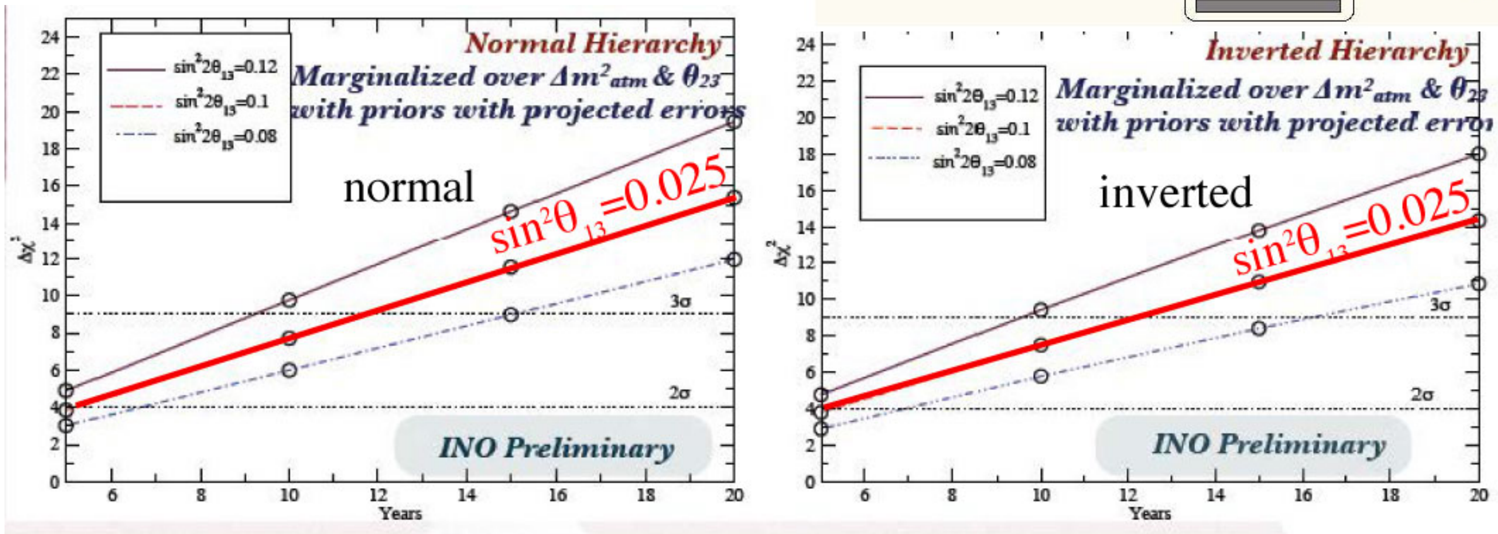
Effect depends on sign of Δm^2

Effect most important at MSW resonance

Magnetized Fe tracking calorimeter

Compare Down/Up vs. Zenith angle

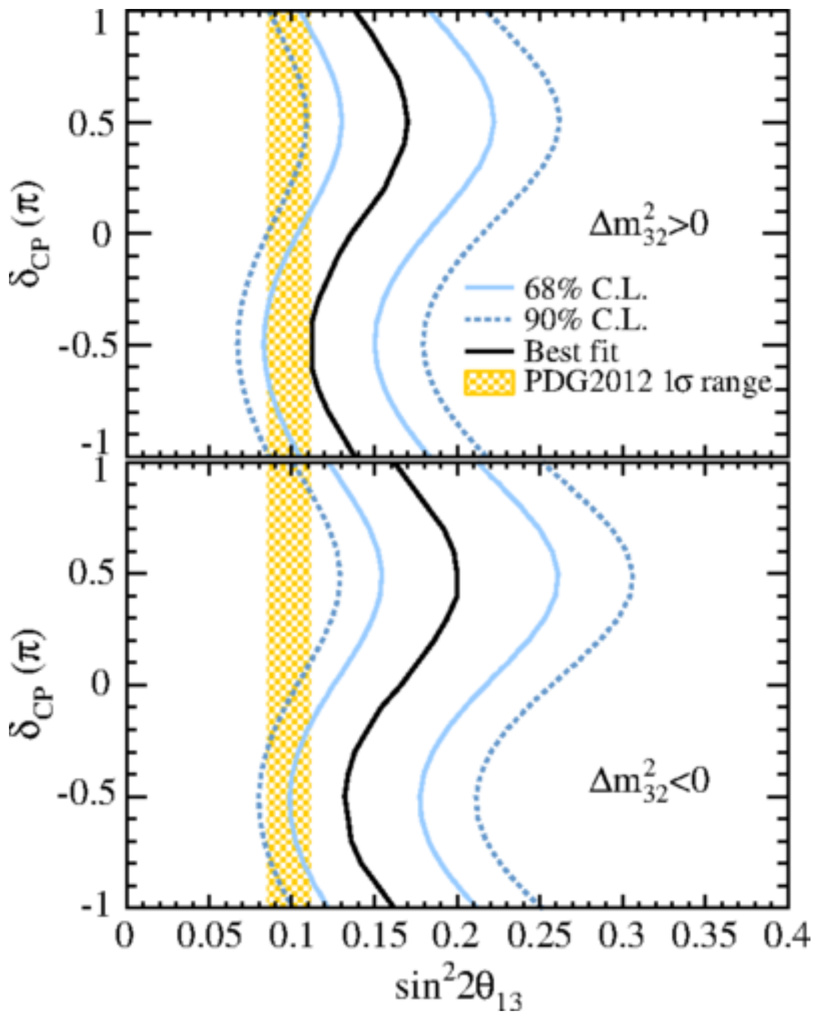




Sensitivity to MH: 2 s in 5 yr, 2.7 σ in 10 years (or doubling the mass, about 130 M€)

CP phase

T2K **appearance** PRL 112, 061802 (2014)



Anti-nue **disappearance (reactor**) experiments (yellow band) do not depend on δ_{CP}

Liquid scintillator experiments

DayaBay, RENO, DChooz

ν_μ to ν_e **appearance** depend on θ_{13} **and** δ_{CP}

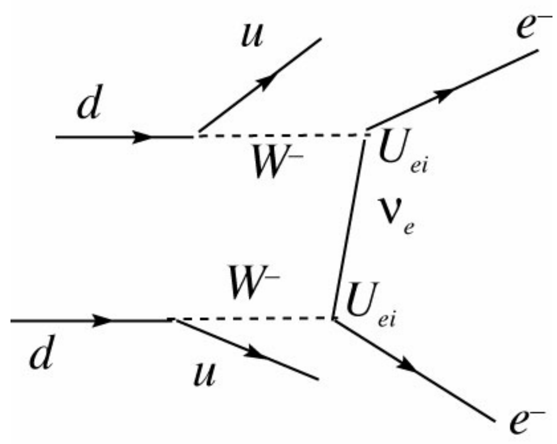
T2K is taking data in antineutrino mode

NOνA will give complementary information soon

We shall learn a lot in the coming years!

$2\beta 0\nu$ 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

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

M_{ee} vs lightest

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

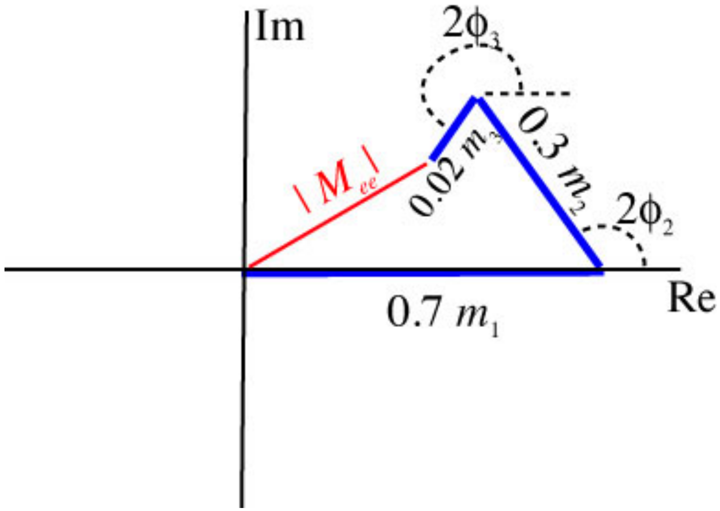
$$\approx \left|0.83 m_1 + 0.55 m_2 e^{i\phi_2} + 0.15 m_3 e^{i\phi_3}\right|$$

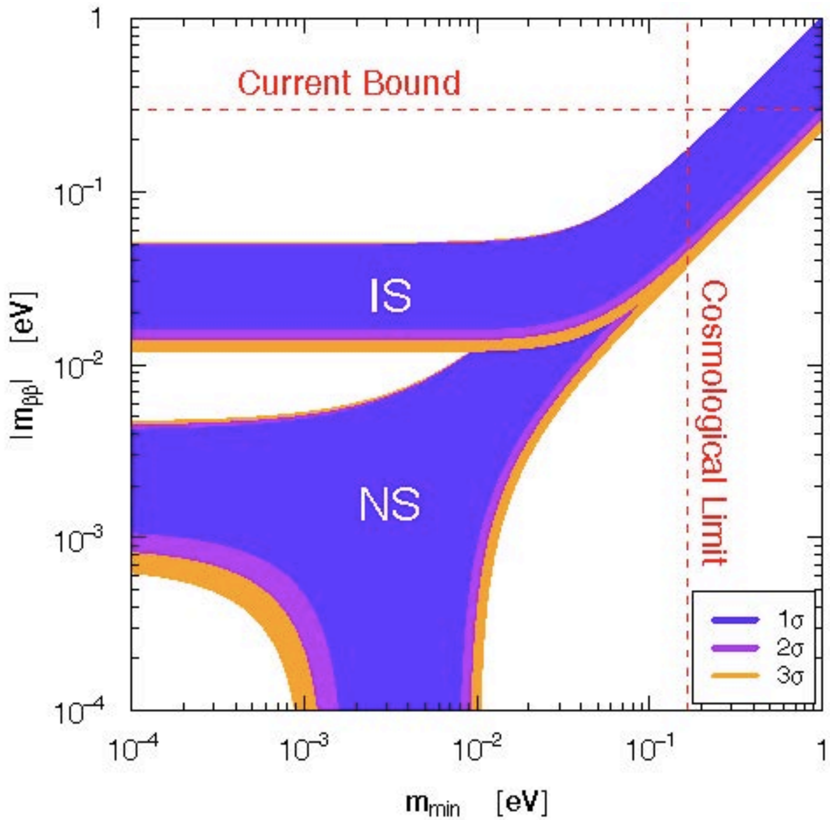
N. M. E.

$1/T_{1/2} = G(Q,Z)\, |M_{nucl}|^2\, M_{ee}^2$

Phase Space

"Effective" Majorana mass





Bilenki & Giunti arXiv 1203.5250

Experimental challenges

Experiments measure the sum energy of the two electrons

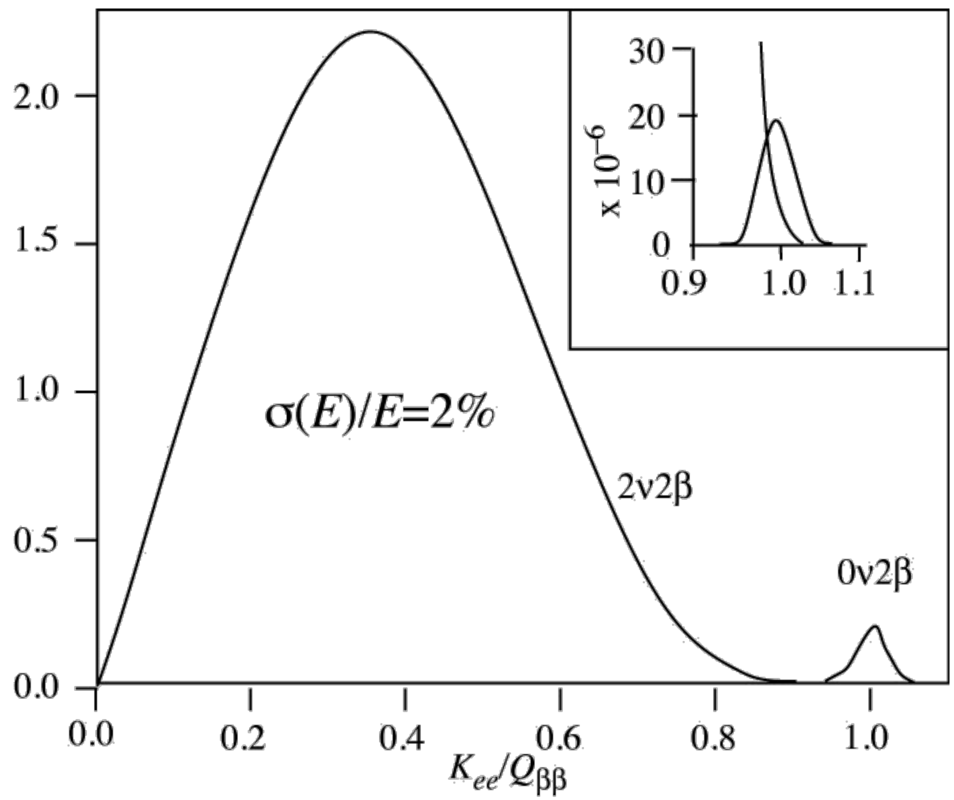
If background index b, sensitive mass M, live time T and energy resolution ΔE

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

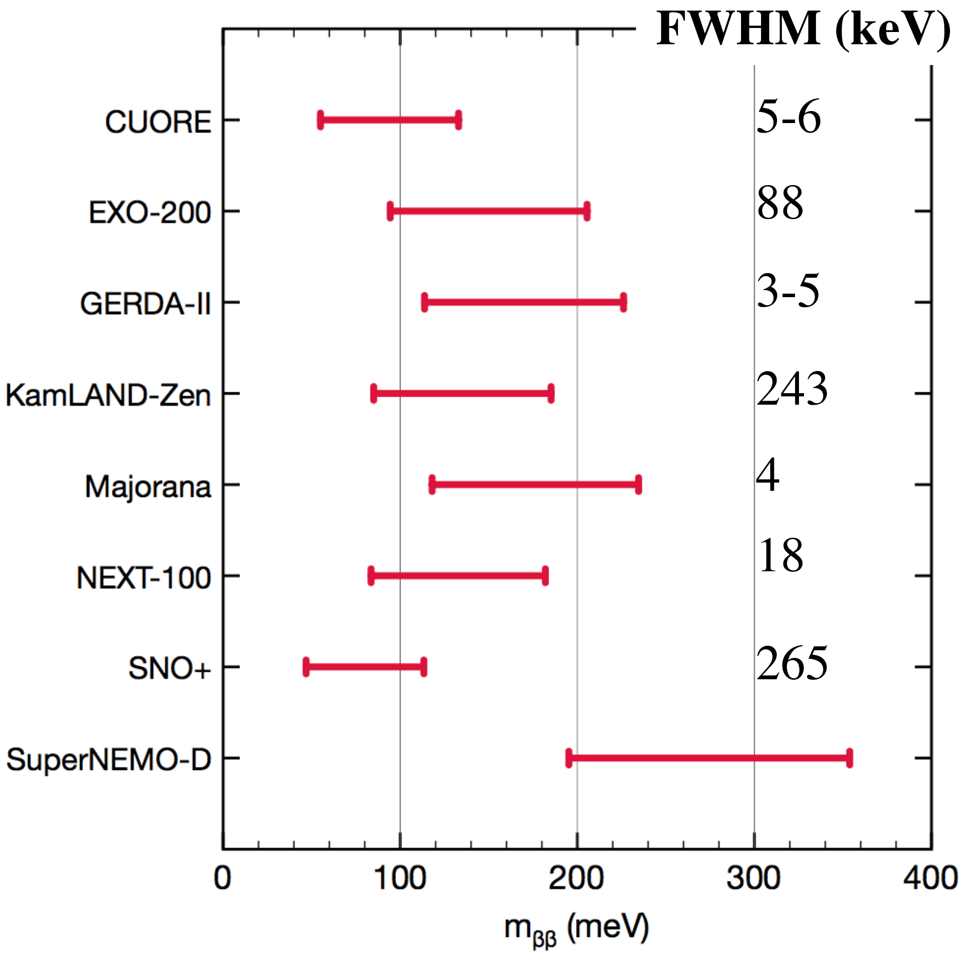
If b=0 during T, in an energy window of about ΔE sensitivity to M_{ee}

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

Aim at
Energy resolution < 1% FWHM
Background index ≅ 0
Scalability at ton scale



Sensitivity of the present experiments

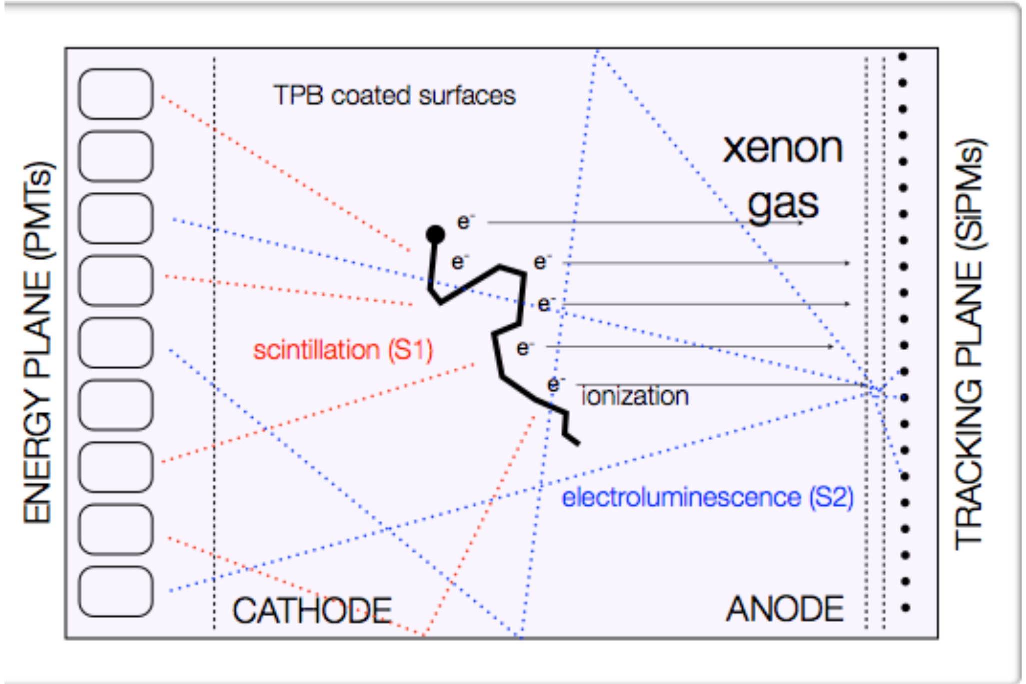


Effective Majorana neutrino mass sensitivity ranges (depending on different NME calculations) for a 3-year run of the present $0\nu2\beta$ decay experiments
From J. Martin-Albo PhD thesis

NEXT at LSC

A light TPC

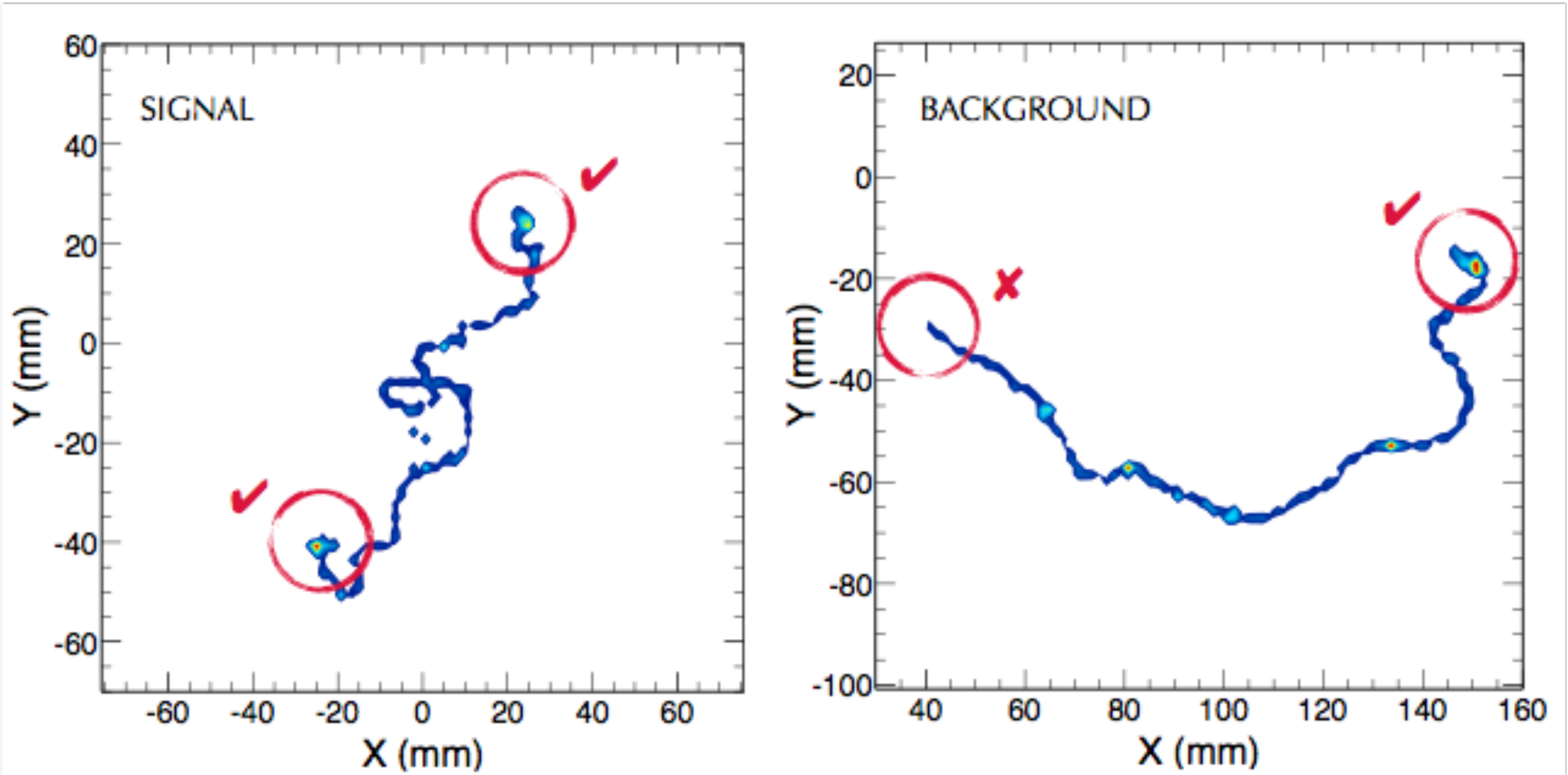
A new way to the ton scale?



EL mode is essential to get lineal gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

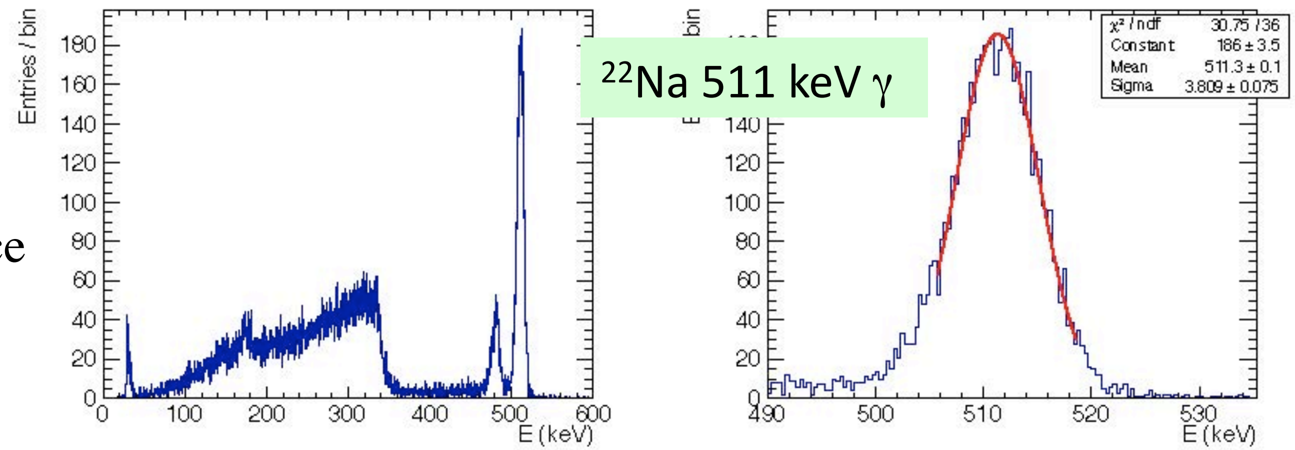
- It is a High Pressure Xenon (HPXe) TPC operating in EL mode.
- It is filled with 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).

Topological signature

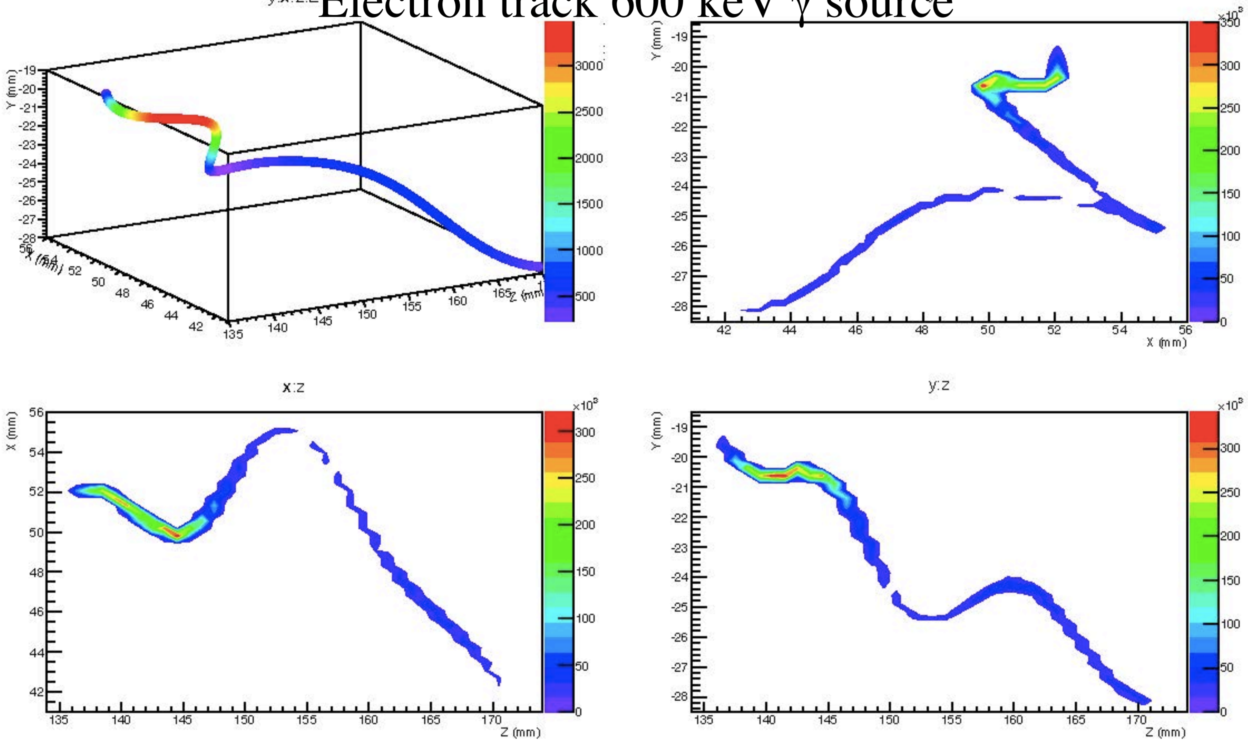


NEXT. Data from prototypes

NEXT is a ^{136}Xe high pressure TPC
Energy resolution
Exploit electroluminescence to avoid fluctuations in the charge amplification
FWHM = 0.75% @ $Q_{\beta\beta}$
measured in prototypes



Electron track 600 keV γ source



BI 5x10^{-4}/(keV kg yr)
Exploit
topological signature

If successful it might be a way to the tonne scale

Go to low energy. RENP

Consider working at energies not too larger than neutrino masses. **Atomic systems?**

⇒**RENP** = Radiative Emission of Neutrino Pairs. Proposed by Yoshimura and coll.

The cell wit the atoms is irradiated by two counter-propagating trigger LASERs tuned on 1/2 ε_{eg}

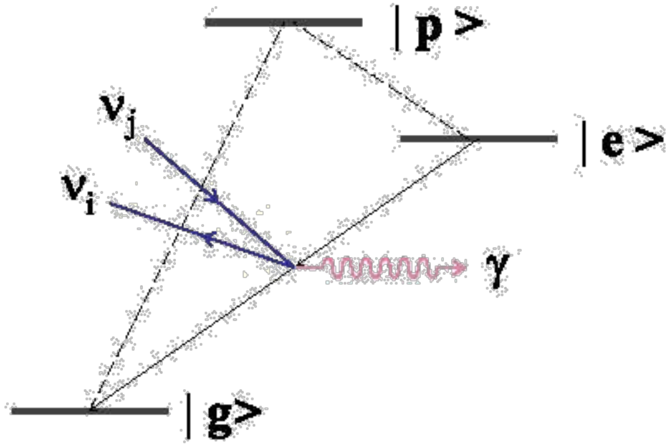
e to *g* transition is dipole forbidden;

Trigger field induces macroscopic **coherent** polarisation of the atoms. Rate proportional to n^2

Decay occurs via E1 x M1 coupling to |p>

Calculations show that detectable rates might be obtained with $n \approx O(N_A)$ and volumes of $O(10^2\ \text{cm}^3)$

$$|e\rangle \to |g\rangle + \gamma + \nu_i + \nu_j$$



Six thresholds corresponding to six different possible neutrino pairs
➔ redundant information on the absolute values of neutrino masses
Spectrum shape near thresholds ➔ sign of Δm^2 and mixing angles
$\varepsilon_{eg} \approx 2$ eV looks adequate

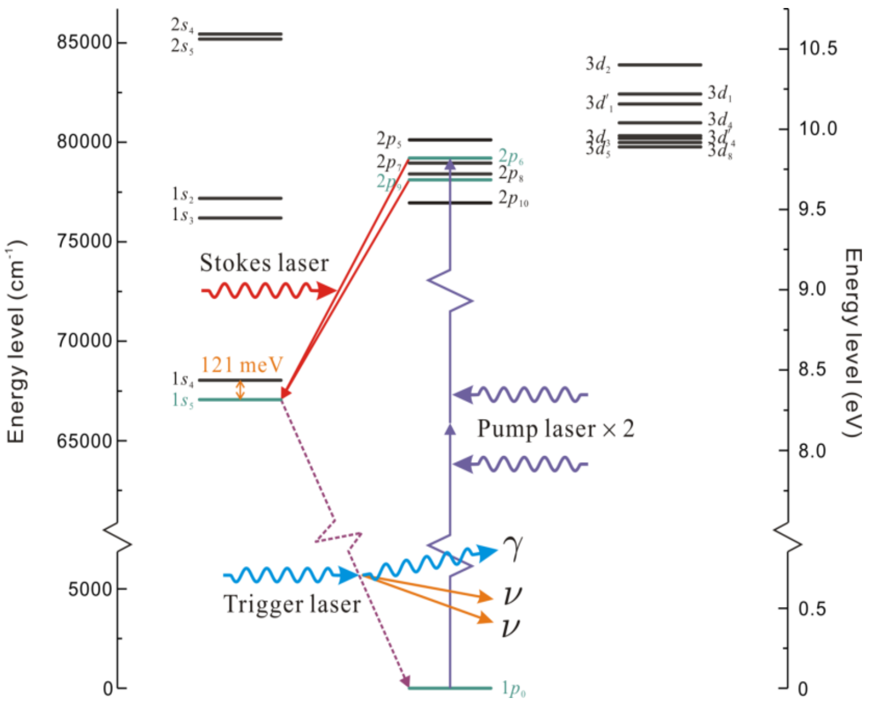
$$\omega_{ij} = \frac{\varepsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\varepsilon_{eg}}$$

Info Majorana vs Dirac and Majorana phases in (small) interference terms $m_i m_j B^M_{ij}$
$\varepsilon_{eg} \cong$ O(100 meV) needed

$$B^M_{12} \propto \cos 2\alpha$$
$$B^M_{13} \propto \cos 2\beta$$
$$B^M_{23} \propto \cos 2(\alpha - \beta)$$

Y. Yoshimura, Phys Rev. **D** 75 (2007) 113007
D. N. Dinh et al. Phys Lett B **719** (2013) 154

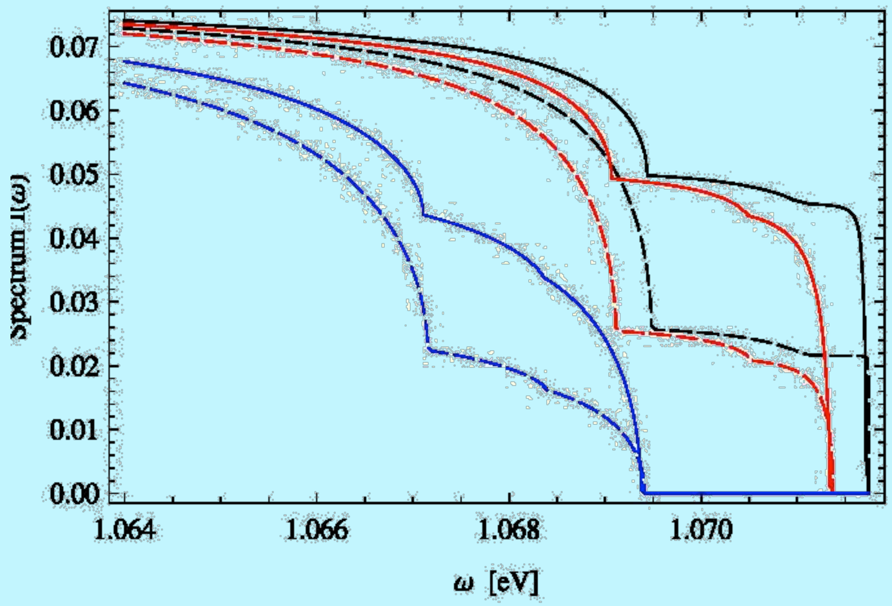
Photon energy spectrum



Xe

$Yb \quad {}^3P_0 \rightarrow {}^1S_0 \qquad \varepsilon_{eg} = 2.14$ eV

Near thresholds spectra



Solid lines $\Delta m^2 > 0$
Dashed lines $\Delta m^2 < 0$
Black $m_{\text{lightest}} = 2$ meV
Red $m_{\text{lightest}} = 20$ meV
Blu $m_{\text{lightest}} = 50$ meV

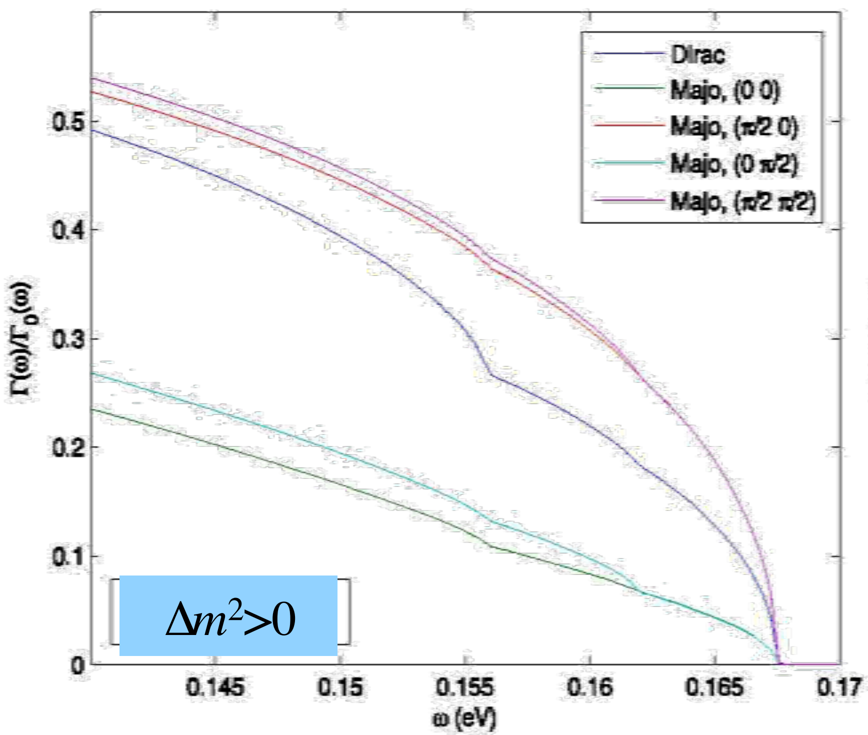
Dirac and Majorana almost identical

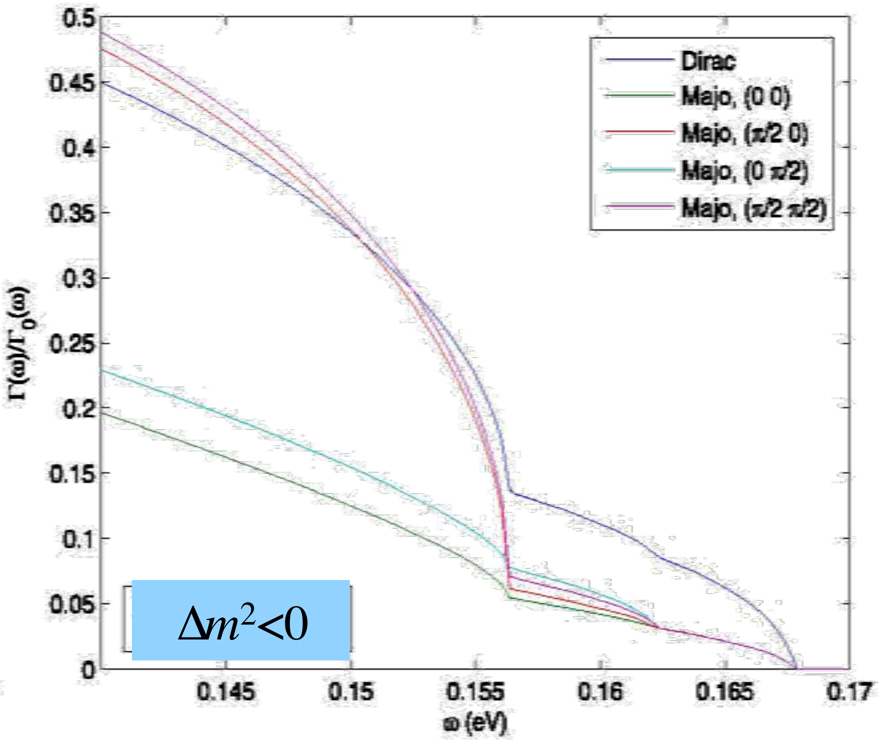
Y. Yoshimura, Neumass 2013

Majorana phases

We need to go to smaller transition energies to distinguish Majorana vs Dirac and for Majorana phases

E_{eg}= 0.429 eV; E_{pg}= 0.446 eV; m_{lightest}= 100 meV





Y. Yoshimura, Phys Rev. **D** 75 (2007) 113007
D. N. Dinh et al. Phys Lett B **719** (2013) 154

Conclusions

- **Neutrino history gave many surprises, Nature behaves often differently from what we think**
- **Neutrinos are showing us physics beyond the standard model**
  - since when the standard model building started (late 1960s)
- **Progress has been due mainly to novel detector technologies and use of**
  - underground laboratories (discoveries)
  - reactor experiments
  - accelerator experiments
- **Neutrino masses are 7 orders of magnitude smaller than the lightest charged particle (*e*)**
  - **theoretically:** pointing to physics at very high energy (close to the grand unification scale)
  - **experimentally:** progress will require development of detectors exploiting eV and sub-eV (atomic and molecular) physics
    - needed for axion search too
- **Several experiments that are starting or being built now will give answers to the open problems in the next few years**
  - the sign of Δm^2 from natural sources
  - the Dirac phase δ_{CP}, if we are lucky, with running experiments at accelerators
  - the absolute mass scale, indirectly, from cosmology
- **and, presumably, more surprises**
- **More progress will require novel thinking and creativity in the experimental art**


THANK YOU

What next

- Sign of Δm^2 (mass hierarchy=MH, problem)
  - **Long base line (O 50 km) reactor. JUNO, RENO50** (start 2020)
  - **Atmospheric neutrinos**
  - Very long (O 1000 km) base line from accelerator
    - HyperK in Japan, LBNF in USA (start > 2025)
  - **Supernova, with luck**
- CP violation in mixing Dirac matrix
  - Beam from accelerator
    - **Energy and baseline can be small** (electron appearance)
- Absolute neutrino mass scale
  - **Beta decays or electron capture**
  - **Cosmology**
  - **Neutrino-less double beta**
- Nature of neutrinos
  - **Neutrino-less double beta**

Homo-nuclear molecules

Wave function = $u(\text{spin})\ \Phi(\mathbf{r})$

For spin I there are $(2I+1)^2$ independent functions of the spin coordinates
Under the exchange of the two nuclei
$I(2I+1)$ anti-symmetric
$(I+1)(2I+1)$ symmetric

$$\frac{\text{number of symmetric spin states}}{\text{number of antisymmetric spin states}} \equiv \rho = \frac{I+1}{I}$$

If I is integer, Bose, then ***u*** **Sym and** ***Φ*** **Sym** or ***u*** **Anti and** ***Φ*** **Anti**
If I is semi-integer, Fermi, then ***u*** **Anti and** ***Φ*** **Sym** or ***u*** **Sym and** ***Φ*** **Anti**

Transitions only between states of the same spatial symmetry can take place:
symmetric lines (between to spatially symmetric states)
antisymmetric lines (between two spatially antisymmetric states)

^{14}N has $I=1$ ➔ $\rho=2$
Bose statistics

$$\frac{\text{number of symmetric lines}}{\text{number of antisymmetric lines}} = \text{intensity ratio} = \rho = 2$$