Neutrino Physics

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Mexico

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Dirección General de Asuntos del Personal Académico

Algunas referencias

Algunos libros

Mohapatra R.n., Pal P.b. Massive Neutrinos In Physics And Astrophysics

Carlo Giunti and Chung W. Kim, Fundamentals of Neutrino Physics and Astrophysics

Kai Zube, Neutrino Physics

Jose Wagner Furtado Valle, Neutrinos in High Energy and Astroparticle Physics

Algunas lecture notes

Andre de Gouvea, 2004 TASI Lectures on Neutrino Physics,arXiv:hep-ph/0411274
Paul Langacker, Jens Erler, Eduardo Peinado Neutrino Physics arXiv:hep-ph/0506257
P. Hernandez Neutrino Physics arXiv:1708.01046 [hep-ph]

Muchas más referencias en:

http://www.nu.to.infn.it/

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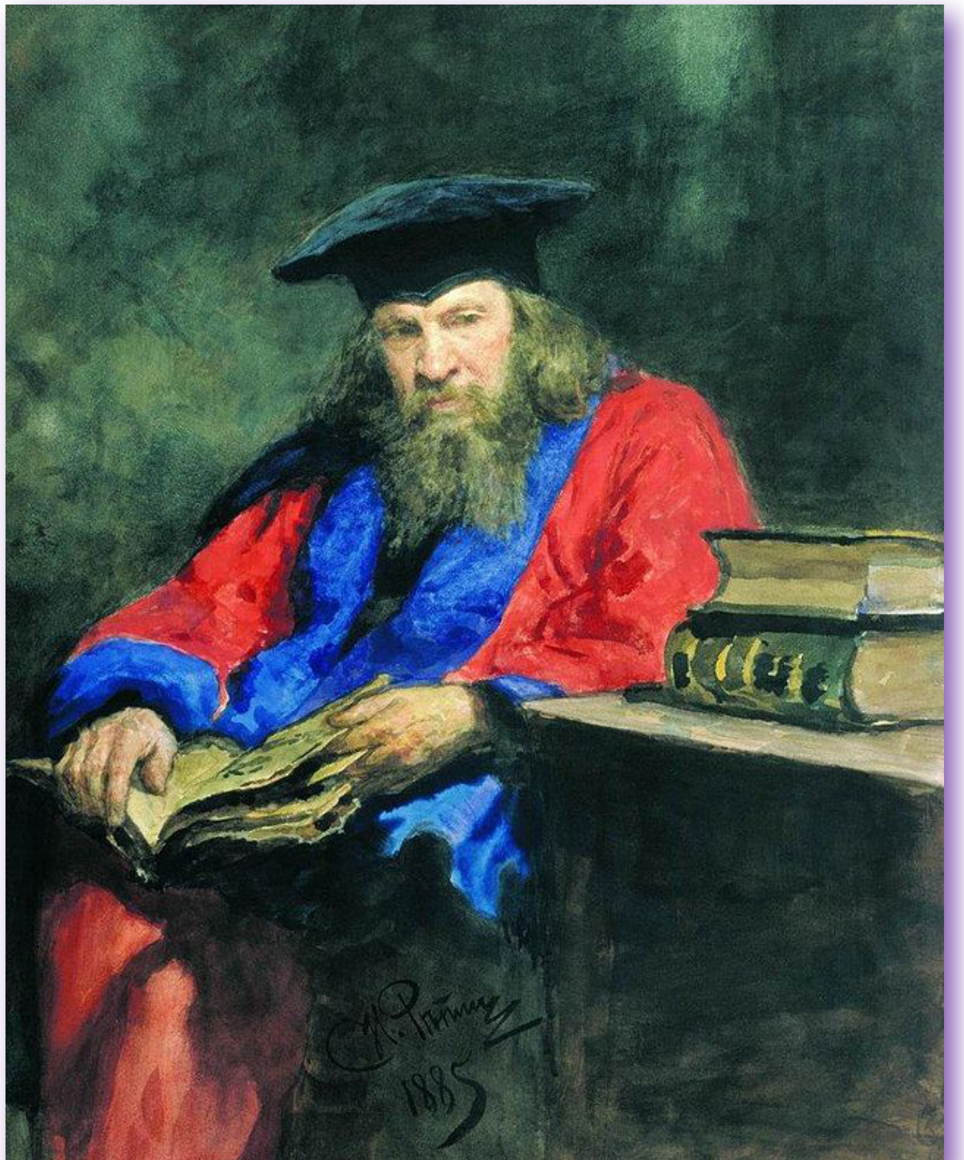
Clasificación periódica: Dalton

(1803)

- A principios del siglo XIX, John Dalton desarrolló una nueva concepción del atomismo, al que llegó gracias a sus estudios meteorológicos y de los gases de la atmósfera. Estableció como **unidad de referencia la masa de un átomo de hidrógeno** y refirió el resto de los valores a esta unidad, por lo que pudo construir un sistema de masas atómicas relativas.

Tabla Periódica



Mendeleev 1871

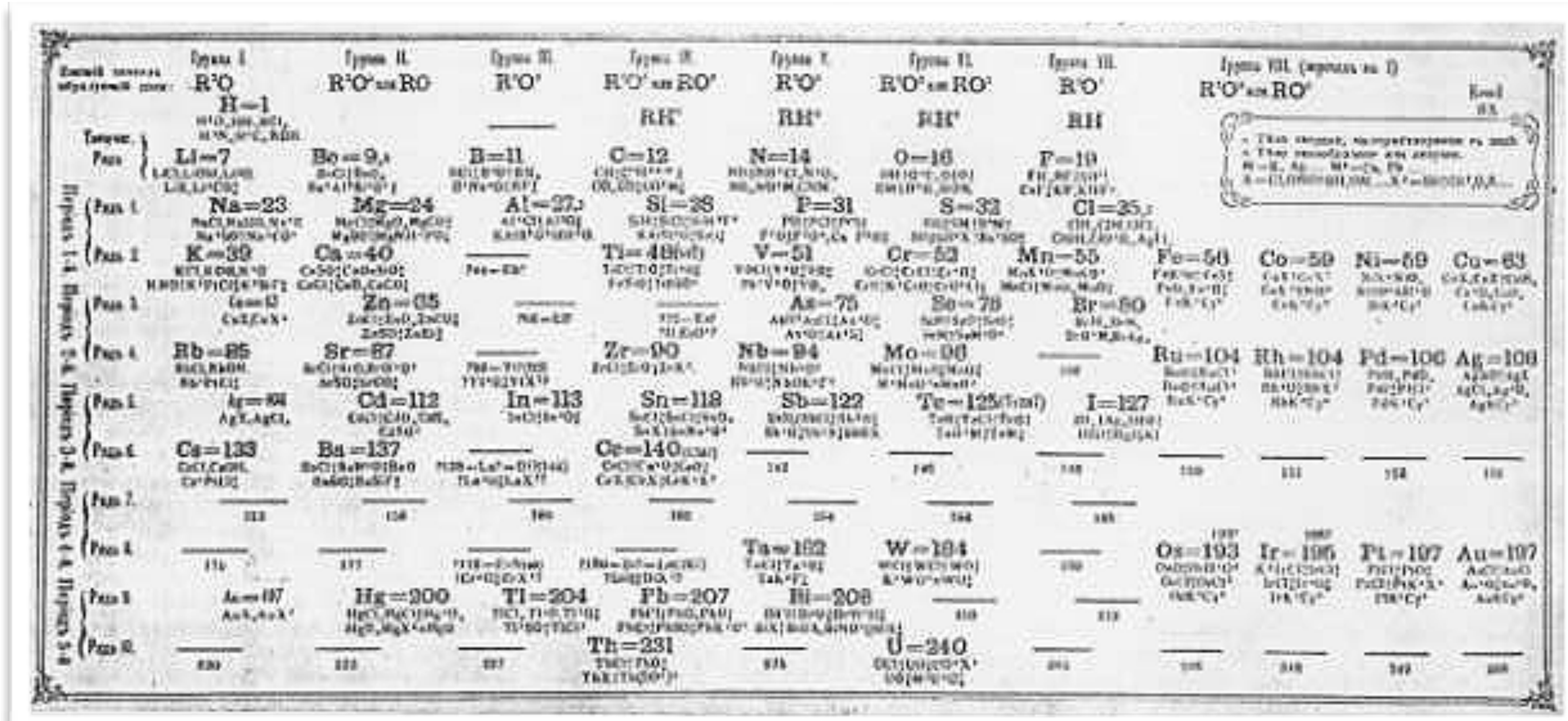
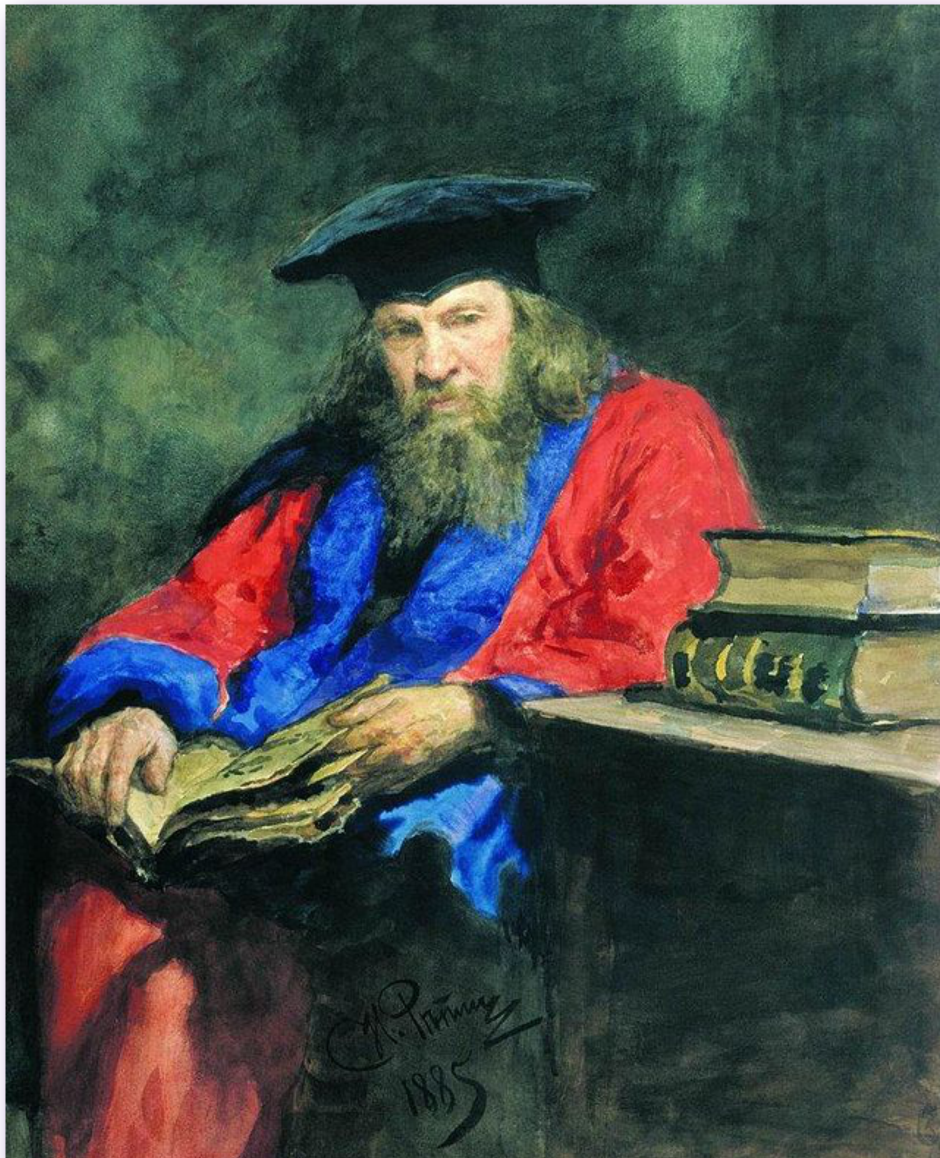
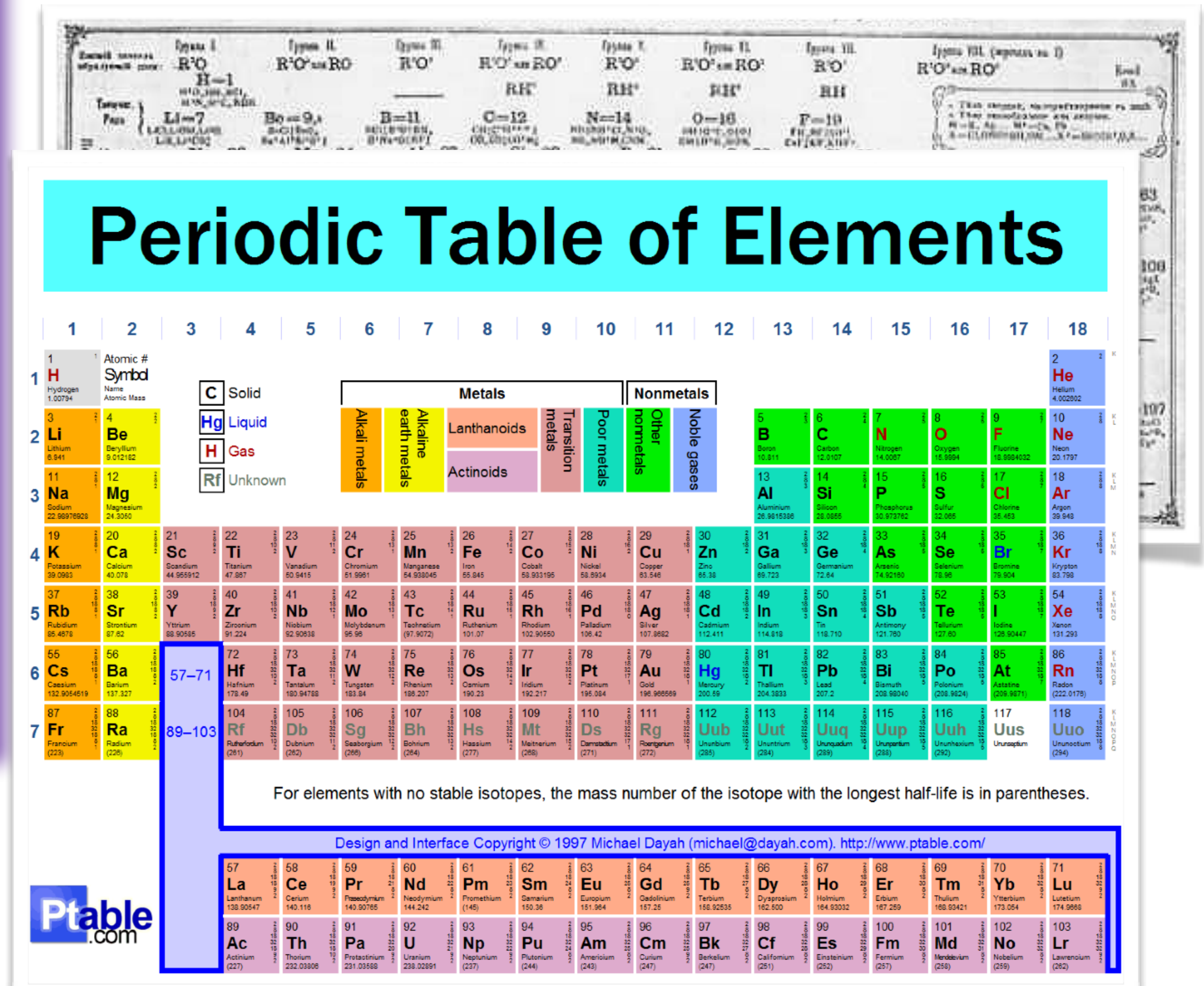


Tabla Periódica



Mendeleev 1871

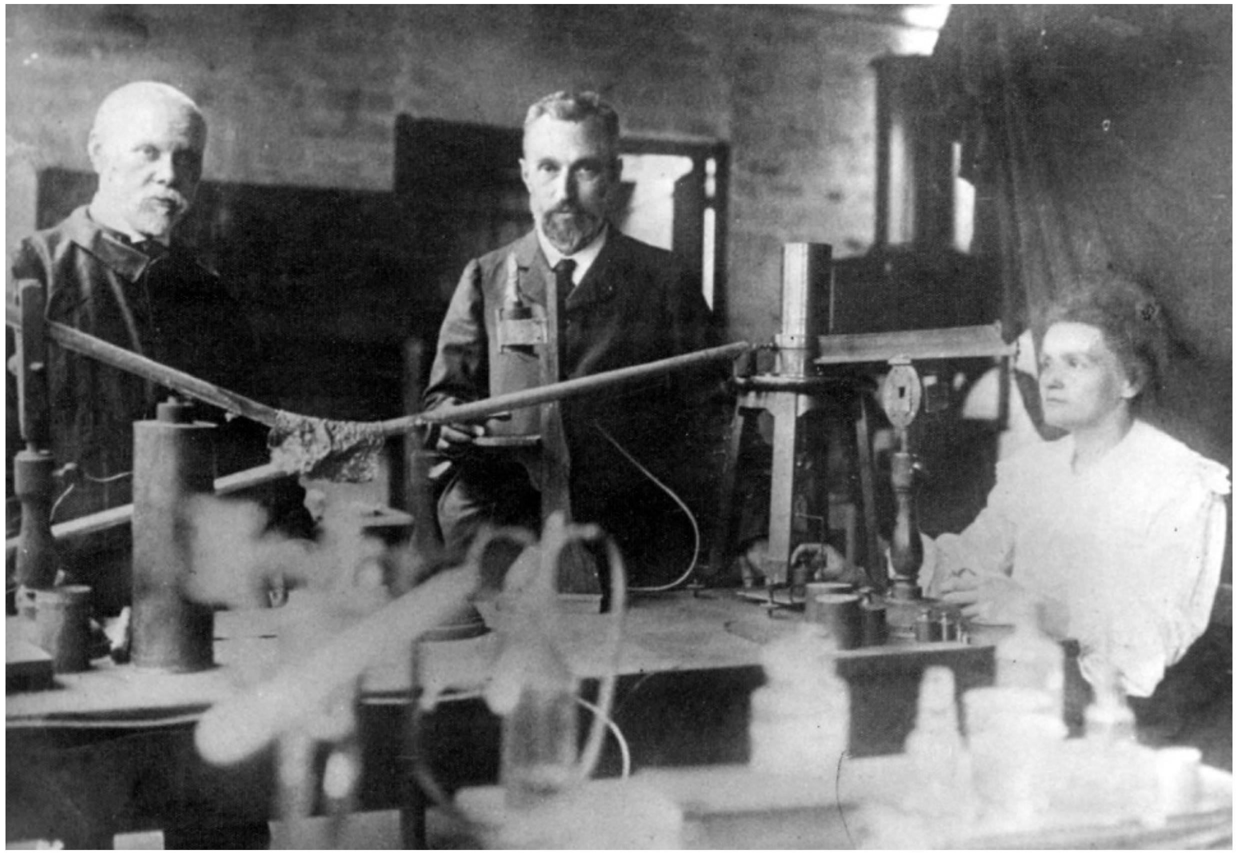


Breve historia de la radioactividad

- **1895 Roentgen** rayos catódicos descubre los rayos X (que no son defecados por campos magnéticos) (Radiografias)
- **1896 Becquerel** descubre la “radioactividad” cuando investigaba el efecto de los x-rays sobre películas fotográficas, que provenía de sales de uranio. (Por accidente?)
- **1898 Rutherford** estudia la radiación emitida por uranio y torio y observa que hay dos tipos de “radiación” α y β
- **1898 Marie Curie y Pierre Curie** estudian el uranio y torio y llama al proceso de decaimiento espontáneo “radioactividad”. Descubre también los elementos radioactivos polonio y el radio (de donde viene el nombre) (Aplicaciones de radioterapia)

Interacciones débiles

Henry Becquerel en 1896 descubre
por accidente la radioactividad en uranio



Pierre y Marie Curie estudian en otros materiales

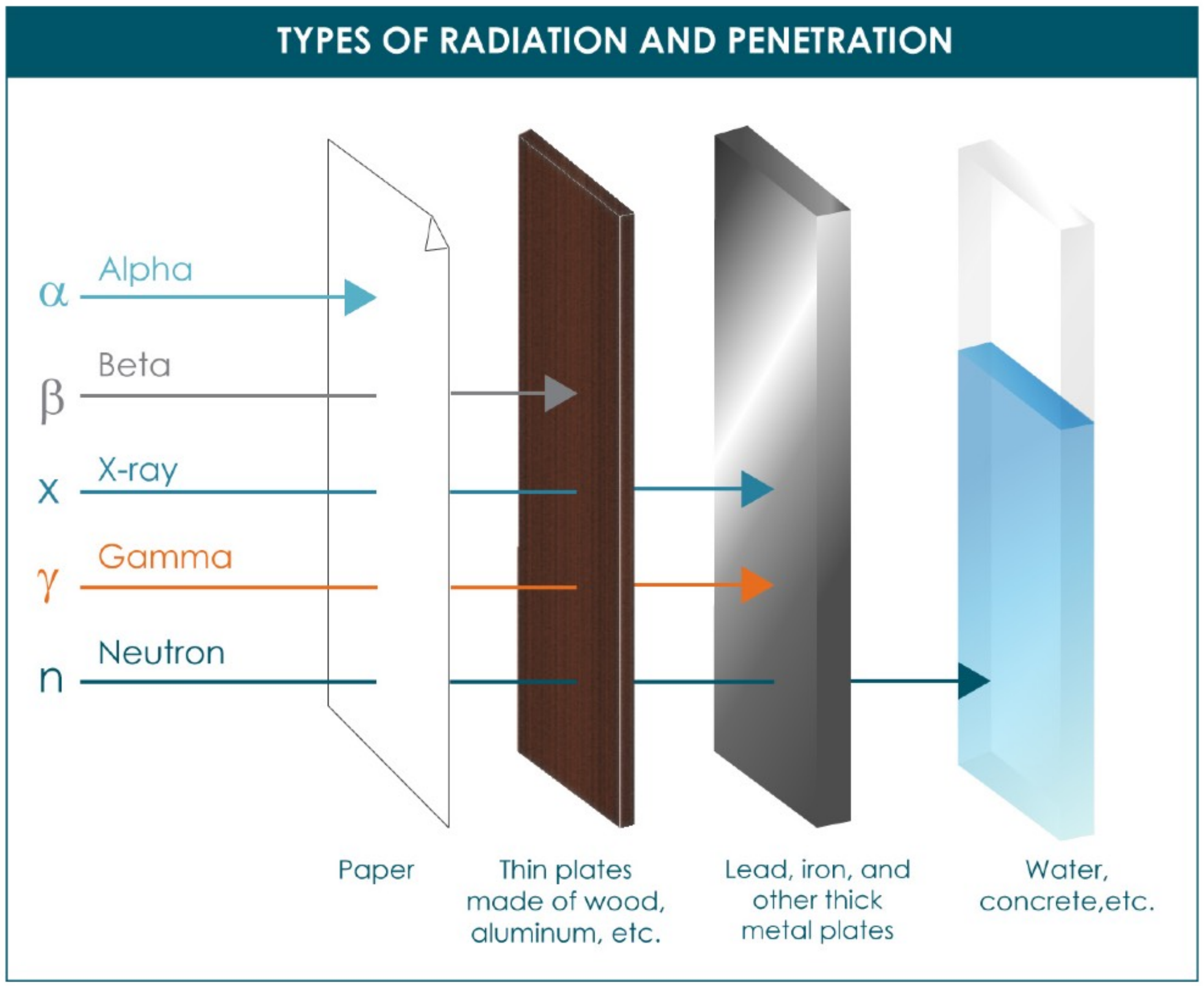
Premio Nobel de Física a los 3 en 1903

Mucha gente trabajó en esto, modelo atómico etc…

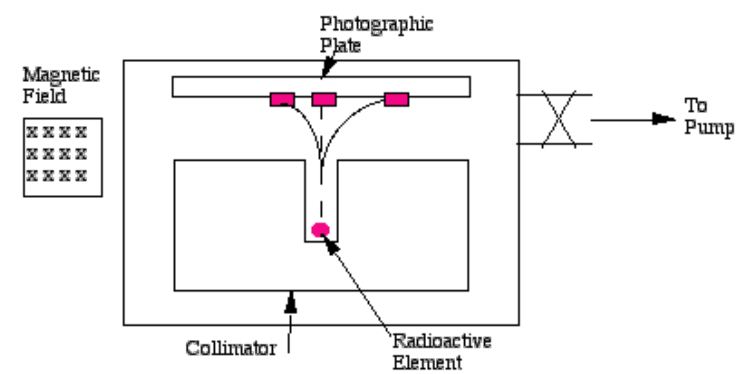
Antes de la MC

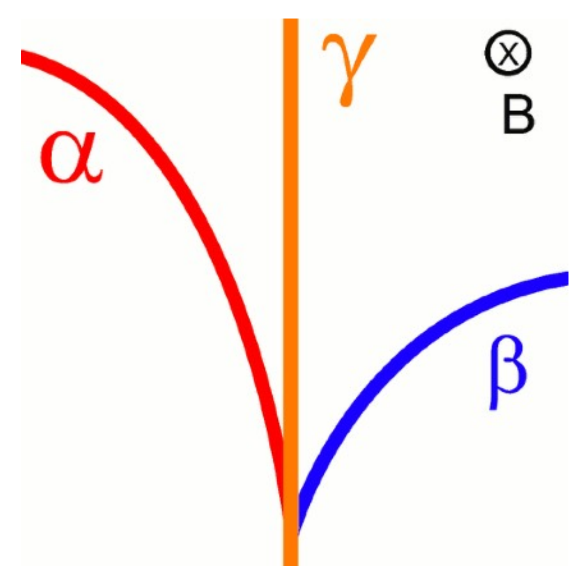
Radiación $\alpha, \ \beta, \ \gamma$

Los tipos de radiación



Rutherford clasificó los tipos de radiación



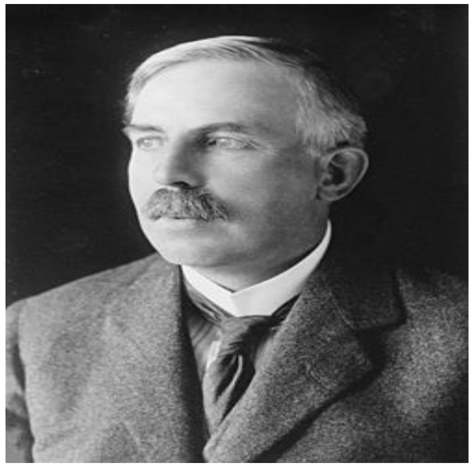


De que estamos hechos II

En 1897 J. J. Thompson

descubre el electrón

En 1886, el físico alemán E. **Goldstein** descubre el protón



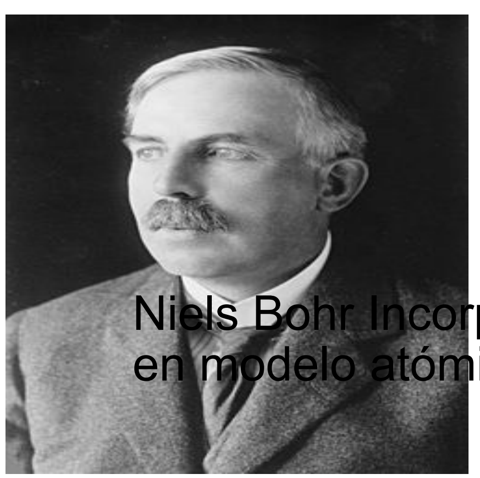
En 1911 modelo atómico de **Rutherford**

De que estamos hechos II

En 1897 J. J. Thompson

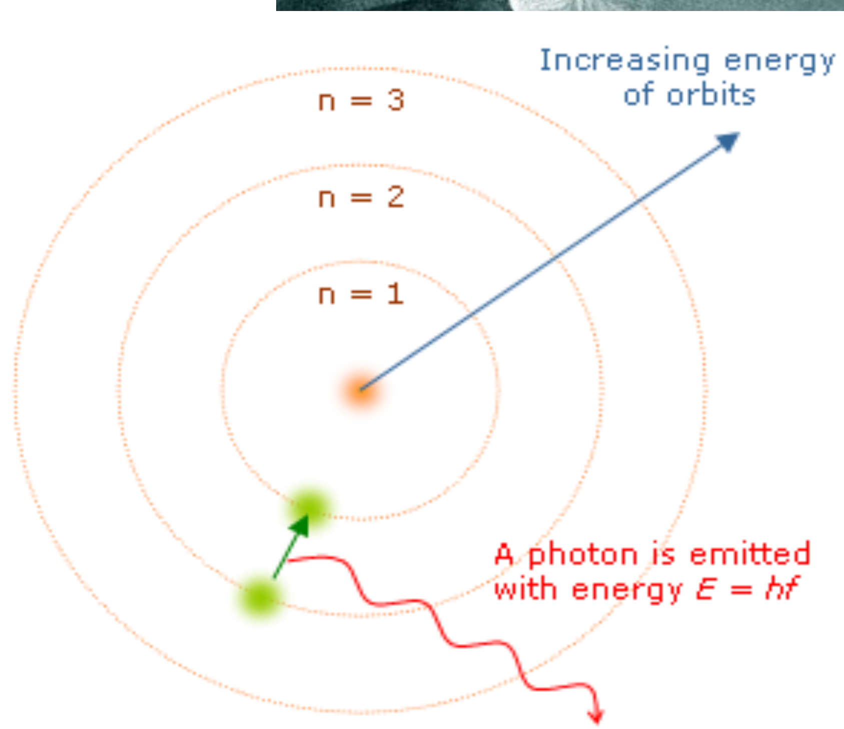
descubre el electrón

el físico
n descubı

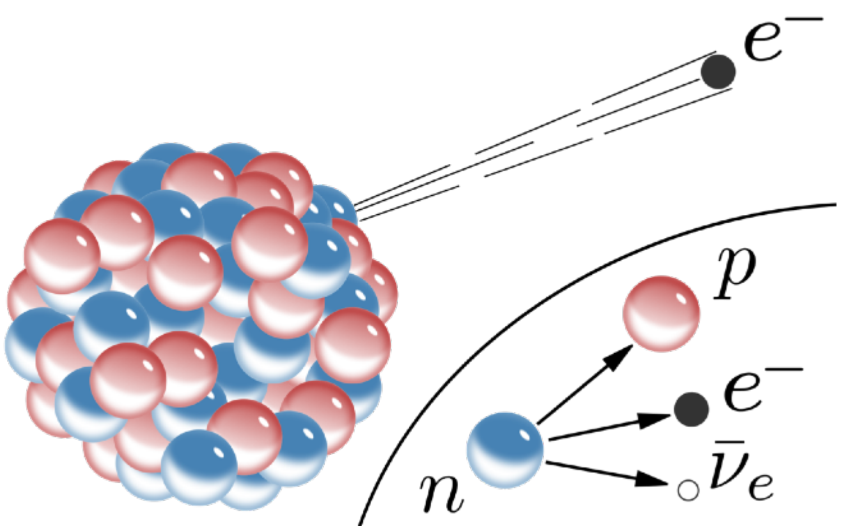


En 1911
de **Rutl**

Niels Bohr Incorpora la cuantización
en modelo atómico



Espectro de energía del electrón en β



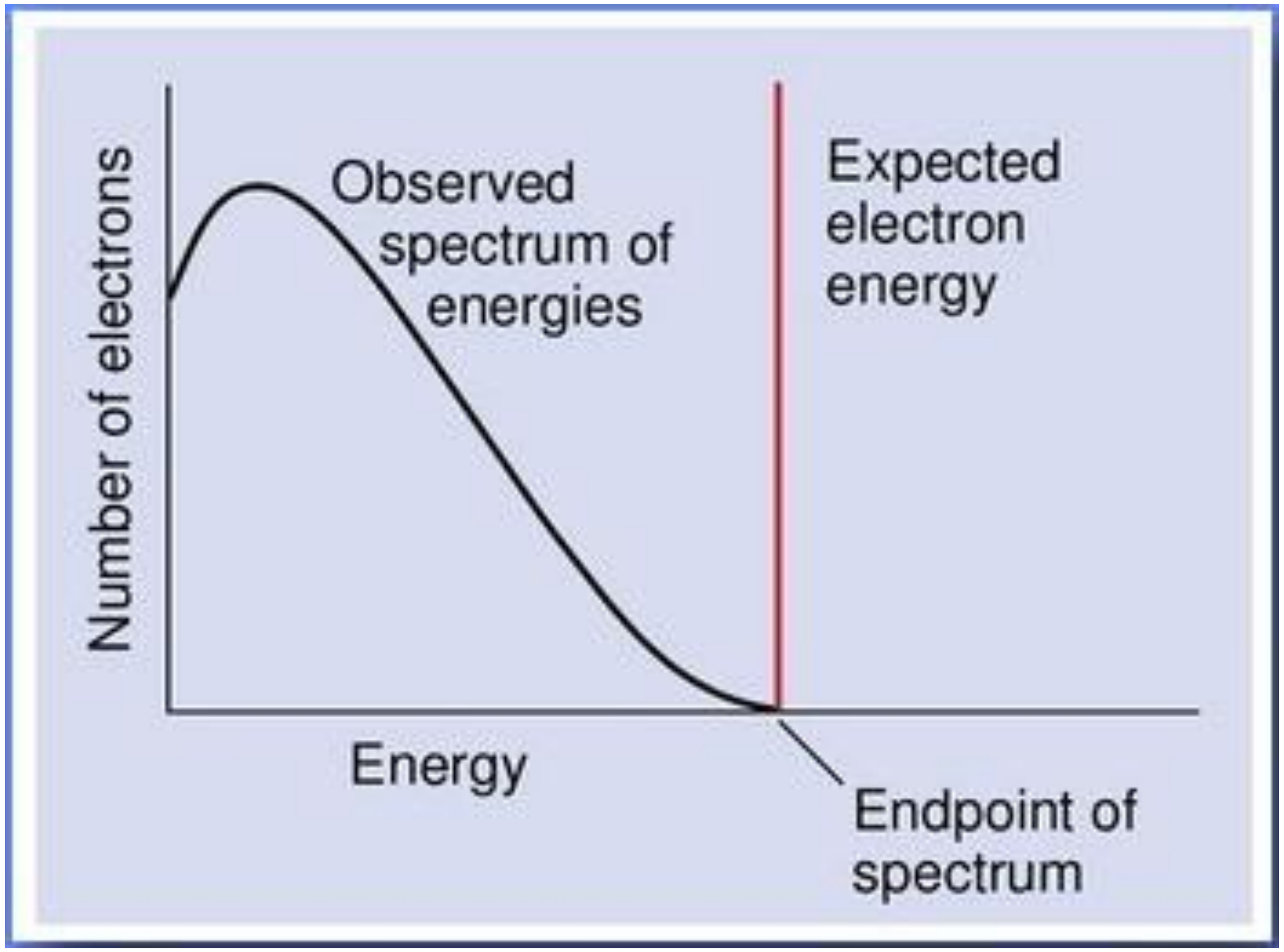
$$ {}^{A}_{Z}N \longrightarrow {}^{A}_{Z+1}N' + e^- $$

Conservación de la energía?

$$E_{\text{electrón}} \approx (M_N - M'_N)c^2$$

Lo que se espera en
2-body decay
Para el electrón

1911-1914



Lise Meitner, Otto Hahn in 1911

Nobel 1944

1914, Chadwick

Nobel 1935

Física nuclear en los 20´s

Un núcleo que tenia A protones y Z electrones
Con carga eléctrica A-Z

^4He Consistía de 4 protones y 2 electrones

^{14}N $$^{14}N = 14p + 7e^-$$

Se había observado que era
Un bosón

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Se había observado que era
Un bosón

Bohr's idea made it to the mainstream realm of textbooks: *"This would mean that the idea of energy and its conservation fails in dealing with processes involving the emission or capture of nuclear electrons. This does not sound improbable if we remember all that has been said about peculiar properties of electrons in the nucleus."*[4]

Wolfgang Pauli 1930

Nobel 1945

Dear Radioactive Ladies and Gentlemen,

I have come upon a desperate way out regarding the wrong statistics of the ^{14}N and ^{6}Li nuclei, as well as the continuous β-spectrum, in order to save the "alternation law" statistics and the energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call "neutrons," and satisfy the exclusion principle... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any case not larger than 0.01 times the proton mass. The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant...

For the time being I dare not publish anything about this idea and address myself to you, dear radioactive ones, with the question how it would be with experimental proof of such a neutron, if it were to have the penetrating power equal to about ten times larger than a γ-ray.

I admit that my way out may not seem very probable *a priori* since one would probably have seen the neutrons a long time ago if they exist. But only the one who dares wins, and the seriousness of the situation concerning the continuous β-spectrum is illuminated by my honored predecessor, Mr Debye who recently said to me in Brussels: "Oh, it is best not to think about this at all, as with new taxes." One must therefore discuss seriously every road to salvation. Thus, dear radioactive ones, examine and judge. Unfortunately, I cannot appear personally in Tübingen since a ball... in Zürich... makes my presence here indispensible....

Your most humble servant, W. Pauli

Adapted summary of an English Translation to Pauli's letter dated December 4, 1930, from Ref. 3.

Wolfgang Pauli 1930

Nobel 1945

$$^{14}\mathrm{N} = 14p + 7e^- + 7`\nu'$$

Bosón

Dear Radioactive Ladies and Gentlemen,
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1932, Chadwick

Nobel 1935

Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded

This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

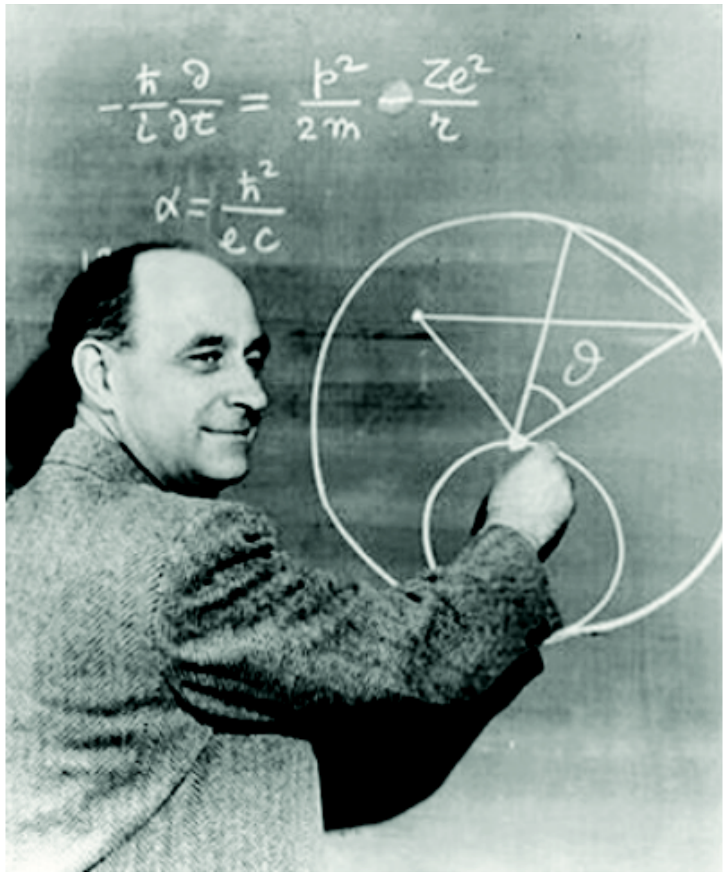
It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

The Oldoway Human Skeleton

A LETTER appeared in NATURE of Oct. 24, 1931, signed by Messrs. Leakey, Hopwood, and Reck, in which, among other conclusions, it is stated that "there is no possible doubt that the human skeleton came from Bed No. 2 and not from Bed No. 4". This must be taken to mean that the skeleton is to be considered as a natural deposit in Bed No. 2, which is overlaid by the later beds Nos. 3 and 4, and that all



Enrico Fermi

Nobel 1938

Nature did not publish his article: "contained speculations too remote from reality to be of interest to the reader…"

TENTATIVO DI UNA TEORIA DEI RAGGI β

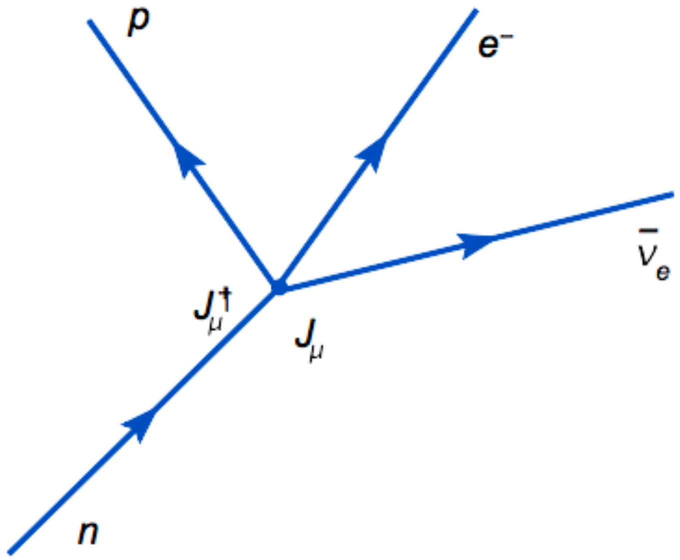
Nota [1] di Enrico Fermi

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.*

Ipotesi fondamentali della teoria.

§ 1. Nel tentativo di costruire una teoria degli elettroni nucleari e dell'emissione dei raggi β, si incontrano, come è noto, due difficoltà principali. La prima dipende dal fatto che i raggi β primari vengono emessi dai nuclei con una distribuzione continua di velocità. Se non si vuole abbandonare il principio della conservazione dell'energia, si deve ammettere perciò che una frazione dell'energia che si libera nel processo di disintegrazione β sfugga alle nostre attuali possibilità di osservazione. Secondo la proposta di Pauli si può p. es. ammettere l'esistenza di una nuova particella, il così detto « neutrino », avente carica elettrica nulla e massa dell'ordine di grandezza di quella dell'elettrone o minore. Si ammette poi che in ogni processo β vengano emessi simultaneamente un elettrone, che si osserva come raggio β, e un neutrino che sfugge all'osservazione portando seco una parte dell'energia. Nella presente teoria ci baseremo sopra l'ipotesi del neutrino.

$$\frac{G_F}{\sqrt{2}}\left(\bar{n}\Gamma_N p\right)\left(\bar{\nu}_e\Gamma_L e\right) + H.c.$$



$$1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}$$

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

$$n + \nu \to p + e^-$$

Diagram for β-decay in the Fermi theory

$$p + \bar{\nu} \to n + e^+$$

Bethe-Peierls (1934)

El camino libre medio en agua
Es de miles de años luz

The cross section σ for such processes for a neutrino of given energy may be estimated from the lifetime t of β-radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

$$\sigma = A/t$$

where A has the dimension cm.^{2} sec. The longest length and time which can possibly be involved are $\hbar/mc$ and $\hbar/mc^2$. Therefore

$$\sigma < \frac{\hbar^3}{m^3c^4t}$$

For an energy of $2{\cdot}3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.^{2} (corresponding to a penetrating power of 10^{16} km. in solid matter). It is

$$\frac{G_F}{\sqrt{2}}\left(\bar{n}\Gamma_N p\right)\left(\bar{\nu}_e\Gamma_L e\right)+H.c.$$

$$1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}$$

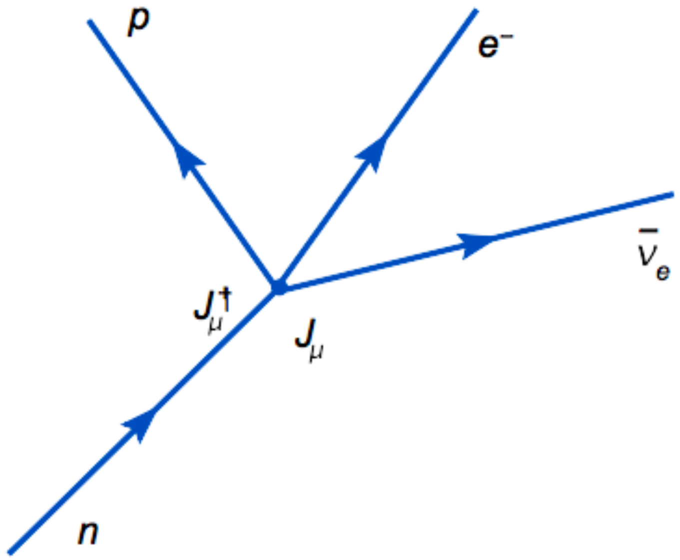


Diagram for β-decay in the Fermi theory

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$$n + \nu \rightarrow p + e^-$$

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

Bethe-Peierls (1934)

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El camino libre medio en agua
Es de miles de años luz

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

Como detectar neutrinos?

Bruno Pontecorvo 1946

$$\Phi_\nu \times \sigma \times \#blancos \times tiempo$$

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

Isótopo radioactivo que puede extraerse y contarse

Cowan y Reines (anti-neutrinos)

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

Primer propuesta
Peligrosa

Frederick Reines (left) and Clyde L. Cowan, Jr. with the control equipment used in their first tentative observations of the neutrino at Hanford, Washington, in 1953. Their definitive detection of the (anti) neutrino was performed at Savannah River, Georgia, three years later. (Courtesy General Electric Co.)

Reines Nobel 1995

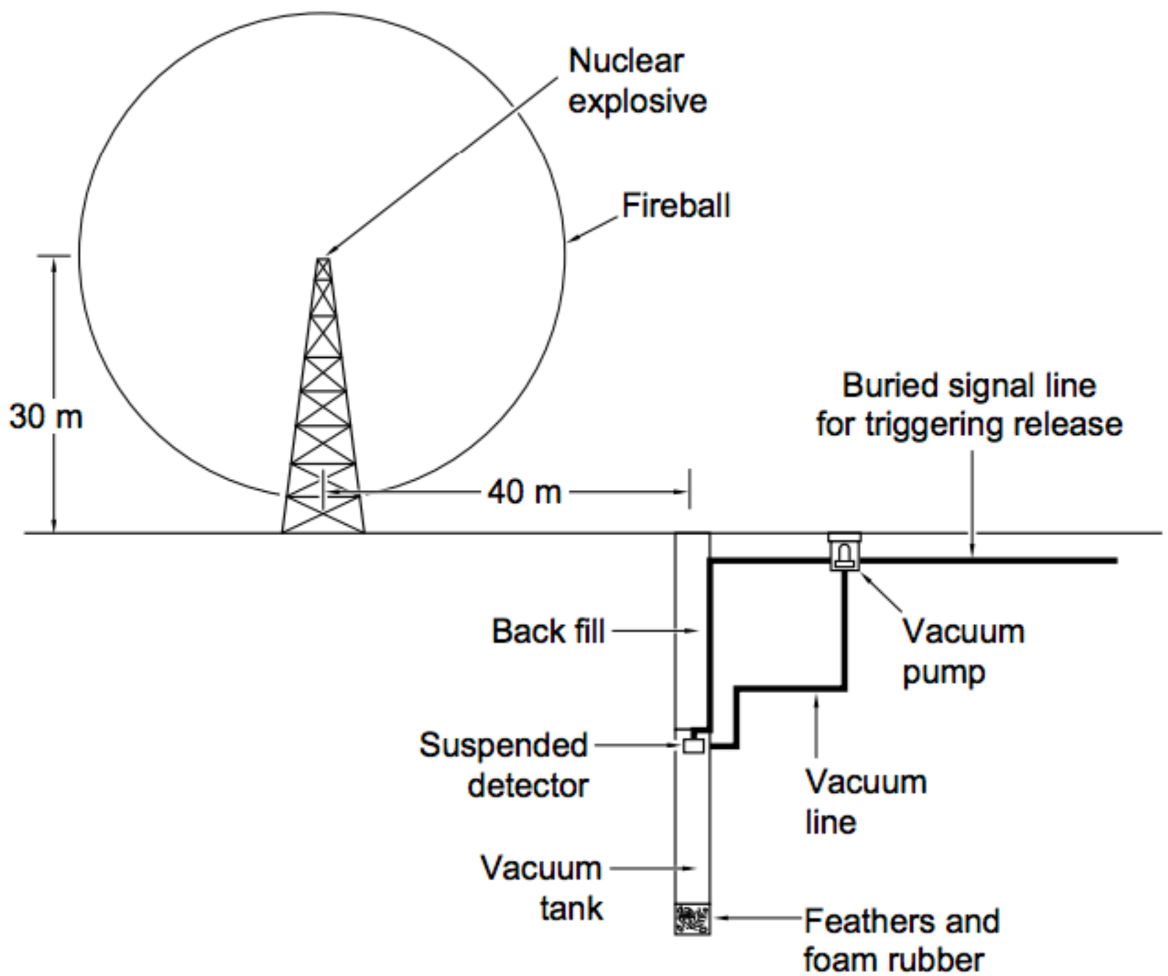
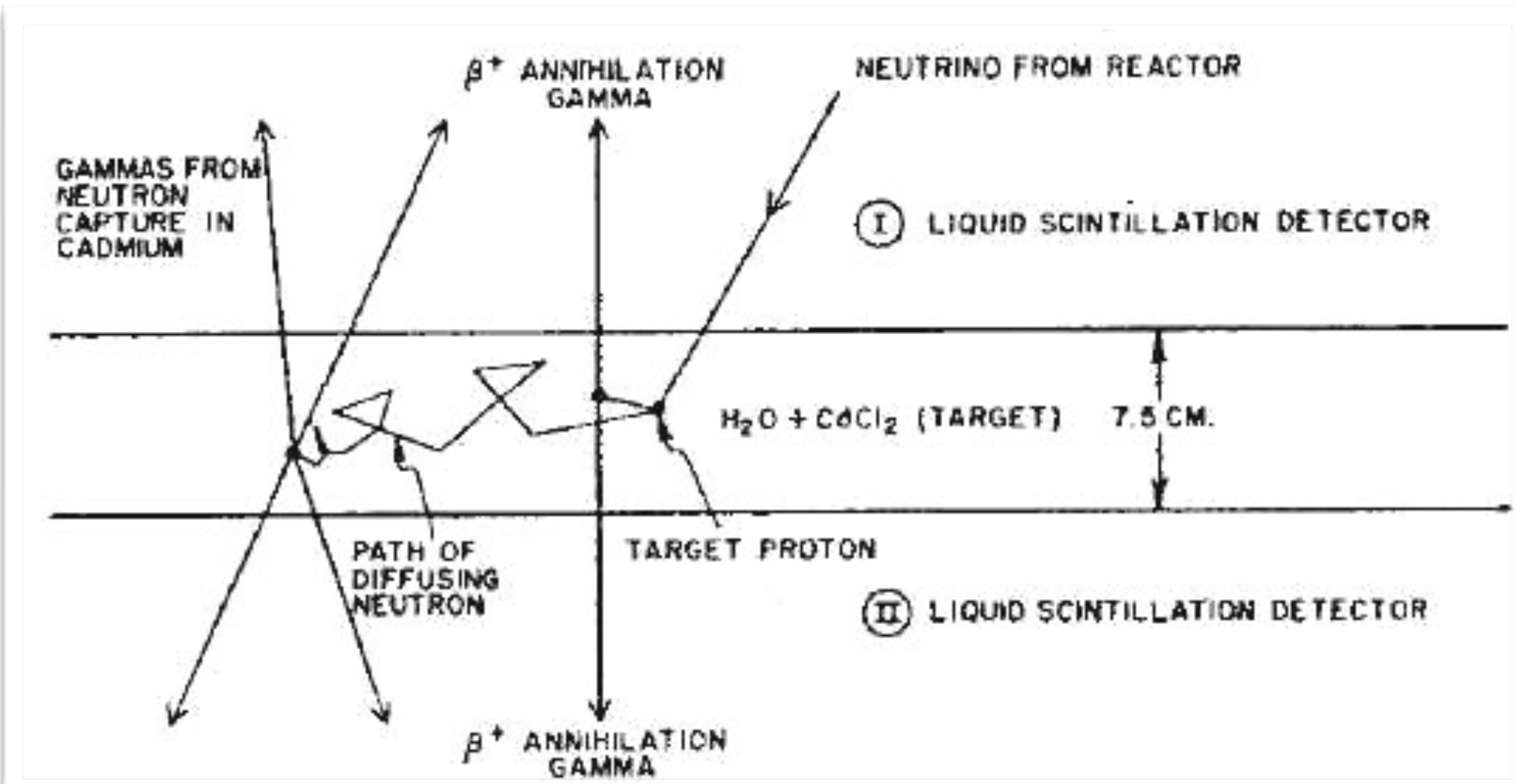


Figure 1. Detecting Neutrinos from a Nuclear Explosion

Detección del anti-neutrino

Planta nuclear Savannah River

Reines and Cowan 1956



Detección de fotones, positrón y captura de neutrón

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

Yukawa

Yukawa en 1935
Predice la existencia de Mesones

Nobel 1949

En 1936 se descubre el muón

En 1947 se descubren los piones

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

Casi siempre

Se creía que el **μ** era un estado excitado del e, y que decairía como

$$\mu \to e + \gamma$$

hipótesis de los dos neutrinos

$$\mu \to e + \gamma$$

Experimentalmente se observaba que

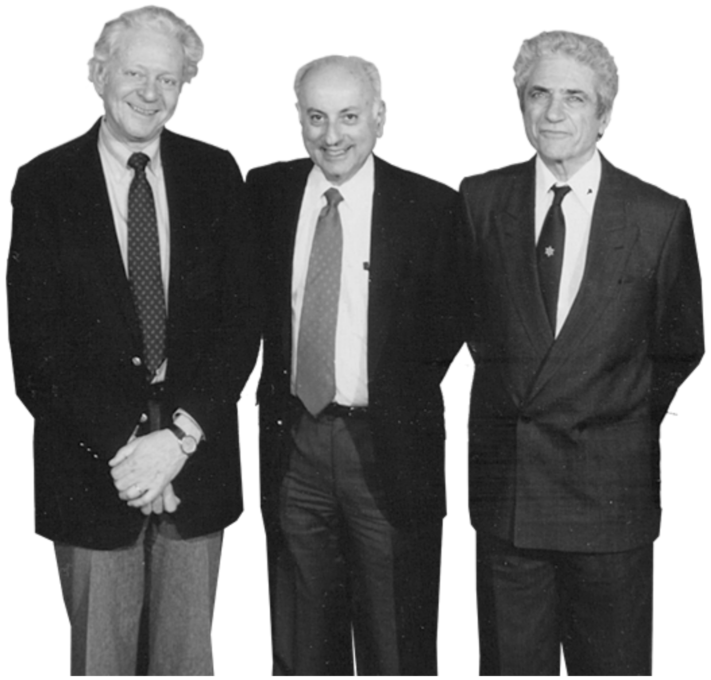
$$\mu \to e + \nu + \bar{\nu}$$

A un loop

$$\mu \to e + \gamma$$

número muónico se conserva y los neutrinos Son diferentes

El sabor de los neutrinos



Leon Lederman, Melvin Schwartz and Jack Steinberger en 1962

Nobel 1988

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

Son diferentes

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

Neutrinos Solares

Raymond Davis (junto a John Bahcall)
en 1969 Homestake detecta
los neutrinosdel sol

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

Neutrino, recordemos que en el beta decay
Es un anti-neutrino

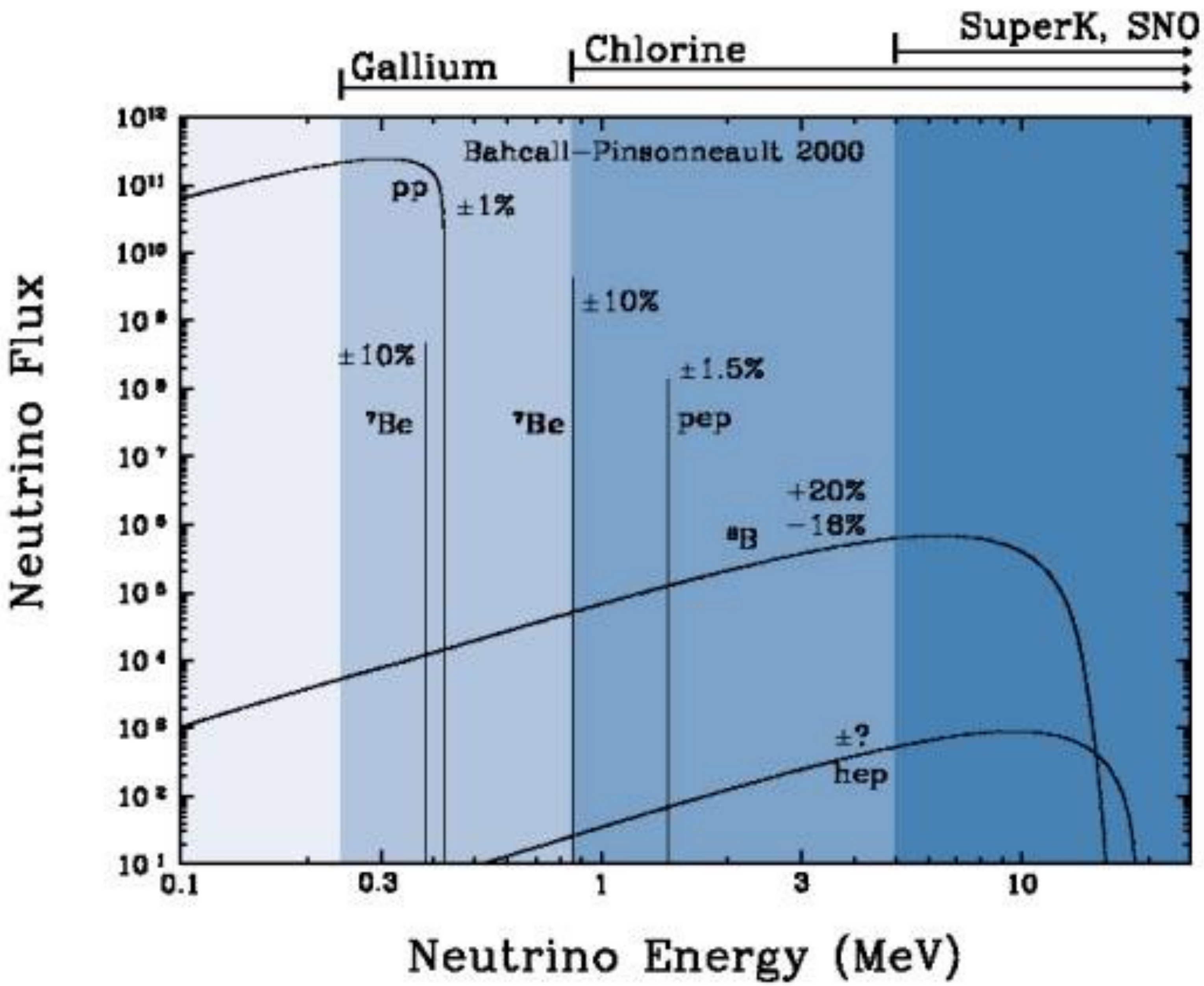
$$E_\nu > 0.814\ MeV$$

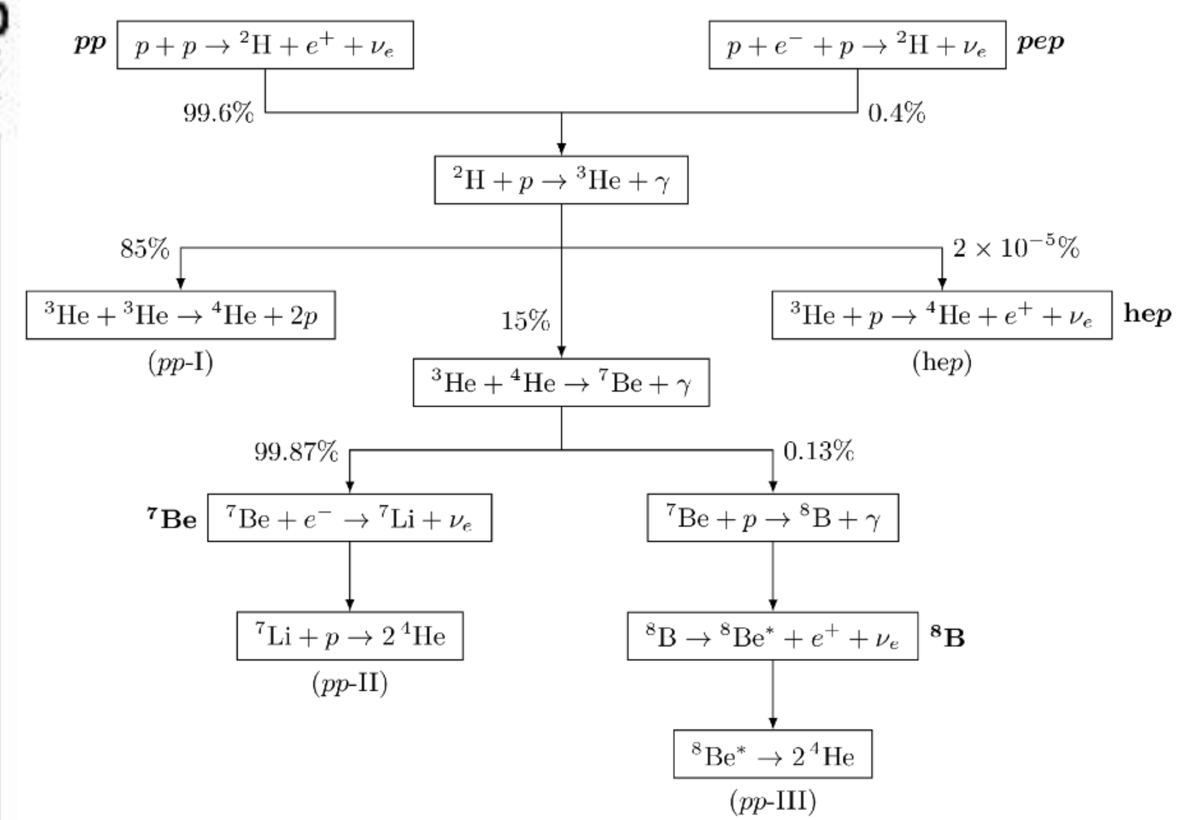
Contaban el argón a las pocas semanas
Vieron menos neutrinos de los esperados

Nobel 2002

"Solar neutrino problem"

Bahcall y el Modelo Estándar del Sol



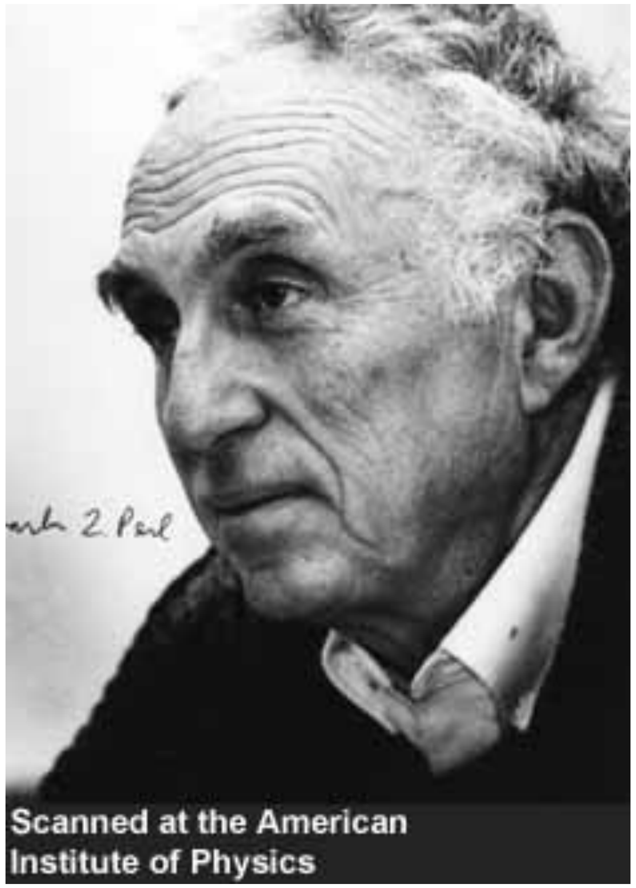


Leptón tau

Martin Lewis Perl descubre el τ en 1976
slac

$$e^{+} + e^{-} \rightarrow \tau^{+} + \tau^{-}$$

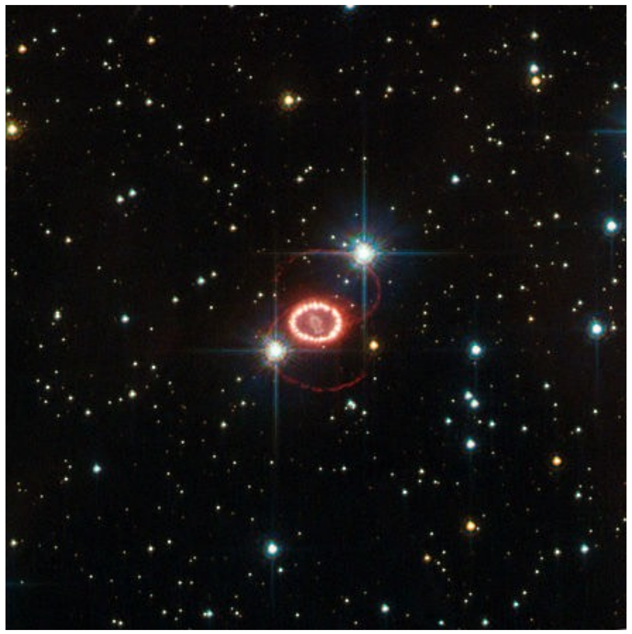
Se descubre el tercer leptón cargado y se
Intuye que existe un tercer neutrino debido a la
Energía y momento perdido en su decaimiento



Nobel 1995

Se descubre el neutrino del tau en 1997
Donut experiment

KamiokaNDE y SN 1987A



Kamioka Nucleon Decay Experiment
Buscaba el decaimiento del protón

12 neutrinos, inicia “neutrino astronomy”

Masatoshi Koshiba

Nobel 2002

“I have done a terrible thing. I have postulated a particle that cannot be detected”
W. Pauli

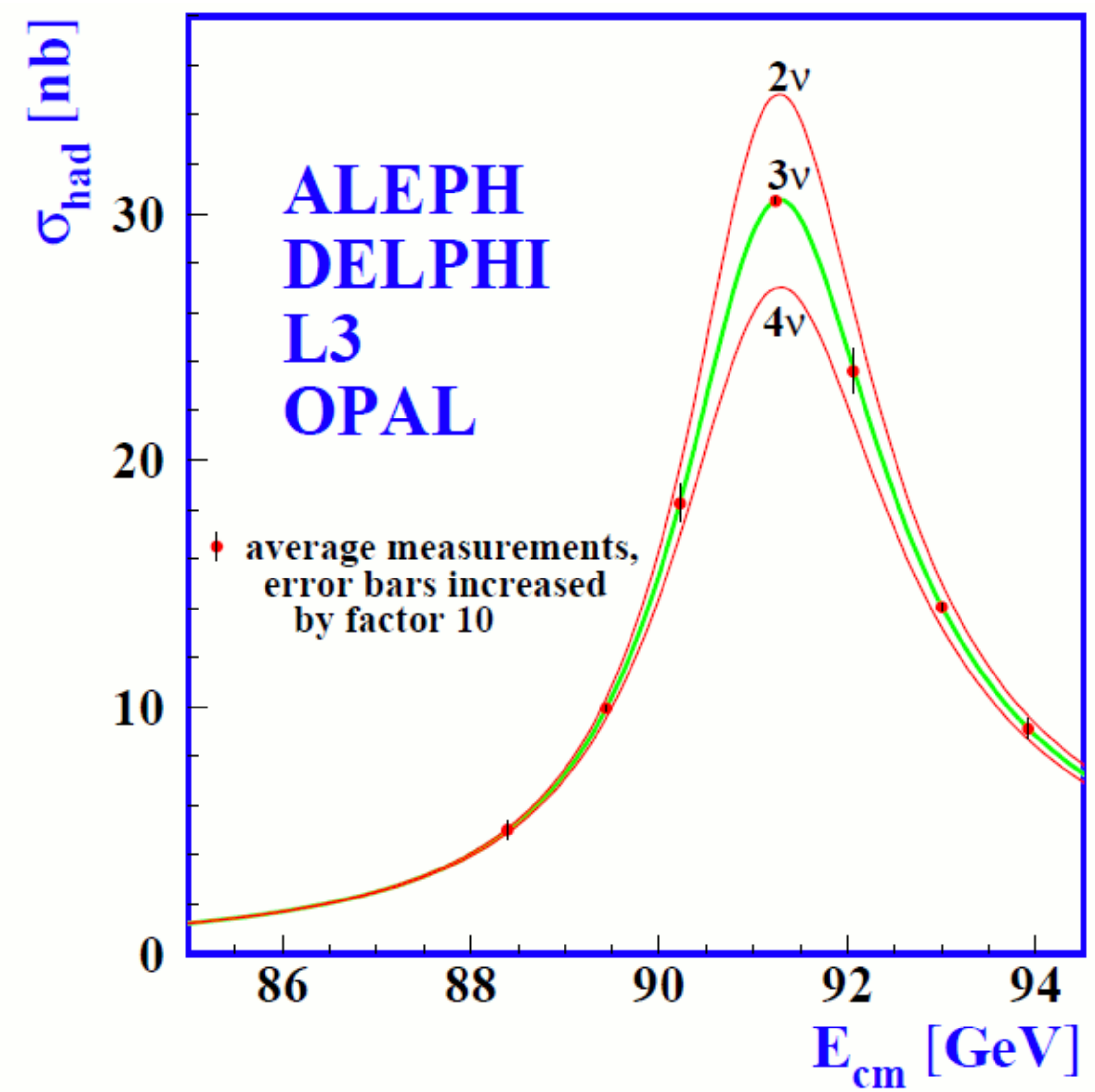
Número de neutrinos

De la distribución de energía
De la resonancia del Z
LEP y SLAC

3 neutrinos ligeros

$$\boxed{m_\nu < \frac{1}{2} M_Z}$$

$$e^+e^- \to Z^0 \to f\bar{f}$$



1947-1960's

Número leptónico,
número muónico y número electrónico

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

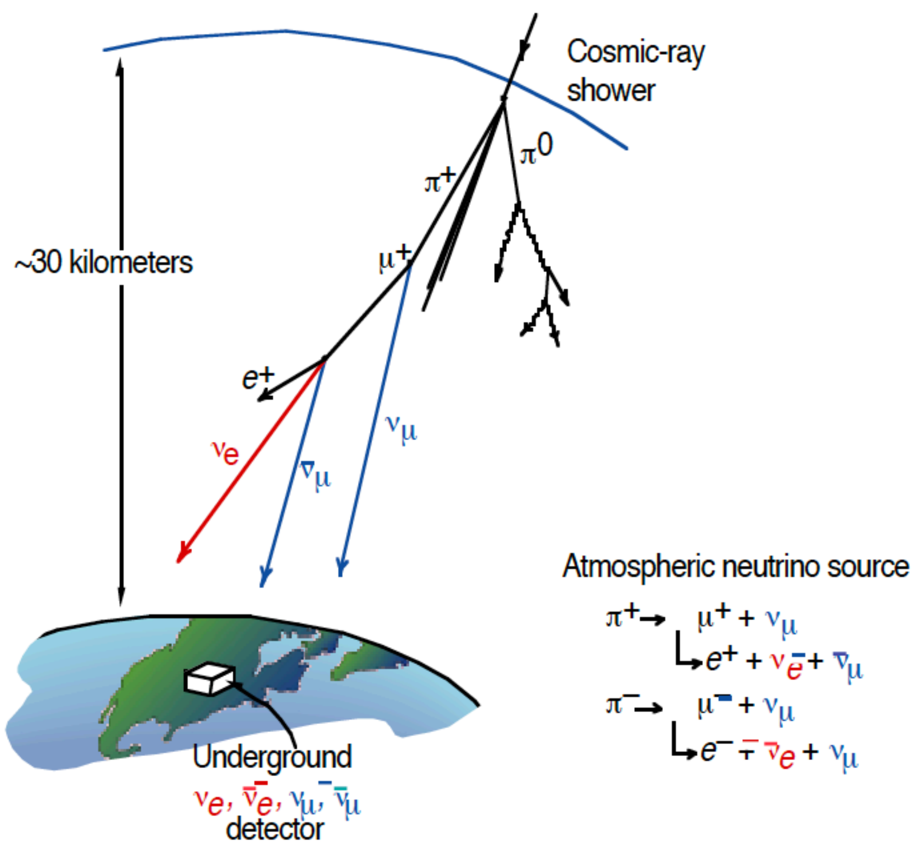
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

L	e	μ
1	0	1

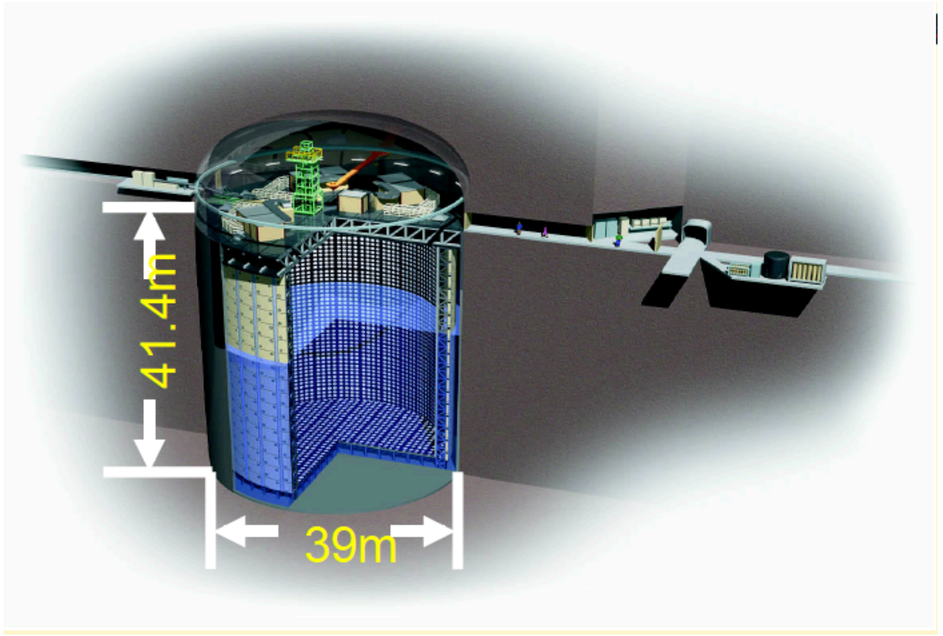
1947 – 1960

Lepto	L	e	μ
e^-	1	1	0
ν_e	1	1	0
μ^-	1	0	1
ν_μ	1	0	1
anti			
e^+	-1	-1	0
$\bar{\nu}_e$	-1	-1	0
μ^+	-1	0	-1
ν_μ	-1	0	-1

Atmosfericos y SK



1 Km bajo tierra
50 KTon



Observó un deficit en neutrinos del muón

$$\nu_\mu \to \nu_\tau$$

Neutrinos solares

Despues de 25 años de Homestake
2200 atomos de Argon
El flujo era el 30% del esperado

Otros experimentos
GNO, GALLEX y SAGE

GALLEX (GALLIUM Experiment)

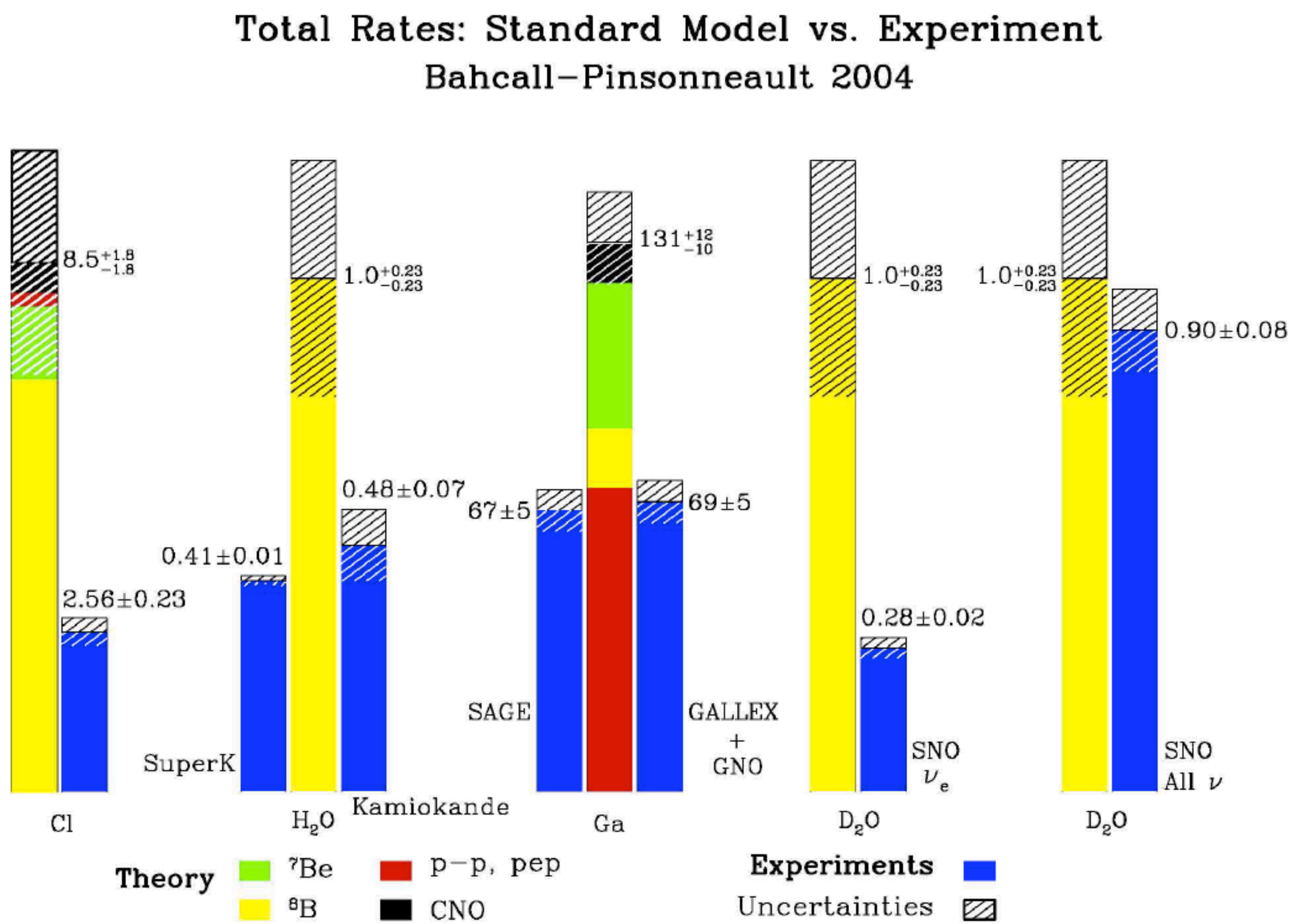
30 Tons Gran Sasso

GNO(Gallium Neutrino Obs)

100 Tons Gran Sasso

SAGE (Soviet American Gallium Exp)

50 Tons Baksan Underground Lab

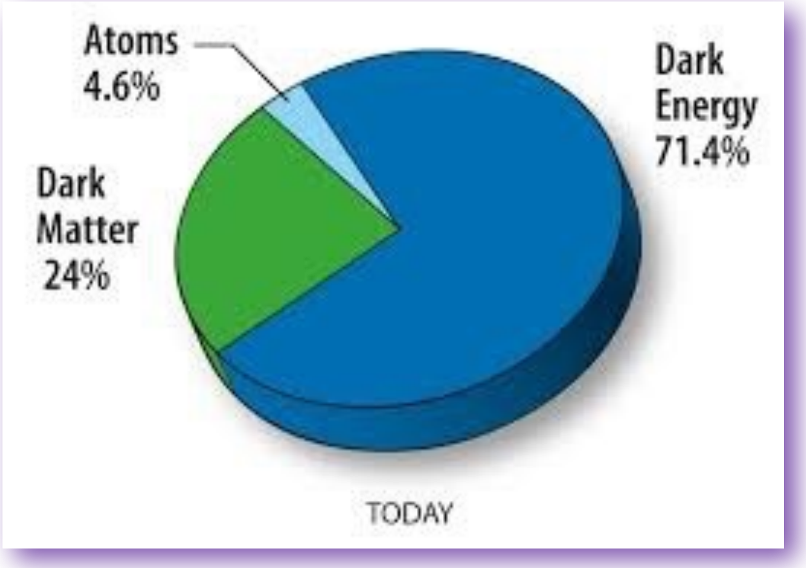

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2004
$8.5^{+1.8}_{-1.8}$
2.56 ± 0.23
Cl
$1.0^{+0.23}_{-0.23}$
0.48 ± 0.07
0.41 ± 0.01
SuperK
Kamiokande
H_2O
131^{+12}_{-10}
67 ± 5
69 ± 5
SAGE
GALLEX
+
GNO
Ga
$1.0^{+0.23}_{-0.23}$
0.28 ± 0.02
SNO
ν_e
D_2O
$1.0^{+0.23}_{-0.23}$
0.90 ± 0.08
SNO
All ν
D_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

Más allá del Modelo Estándar

La evidencia

- Los neutrinos tienen masa y oscilan
- La asimetría bariónica en el Universo
  Por que está hecho de materia y no vemos grandes cantidades de antimateria
- La materia Oscura (el 85% de la materia en el universo se desconoce que es)
- La energía Oscura en el Universo.

  El universo está dominado por la Energía Oscura, ésta hace que este en expansión acelerada



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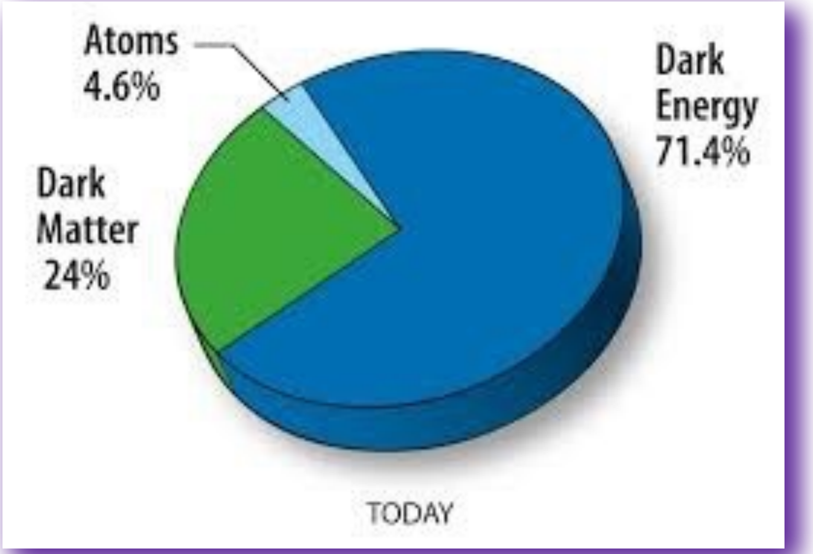
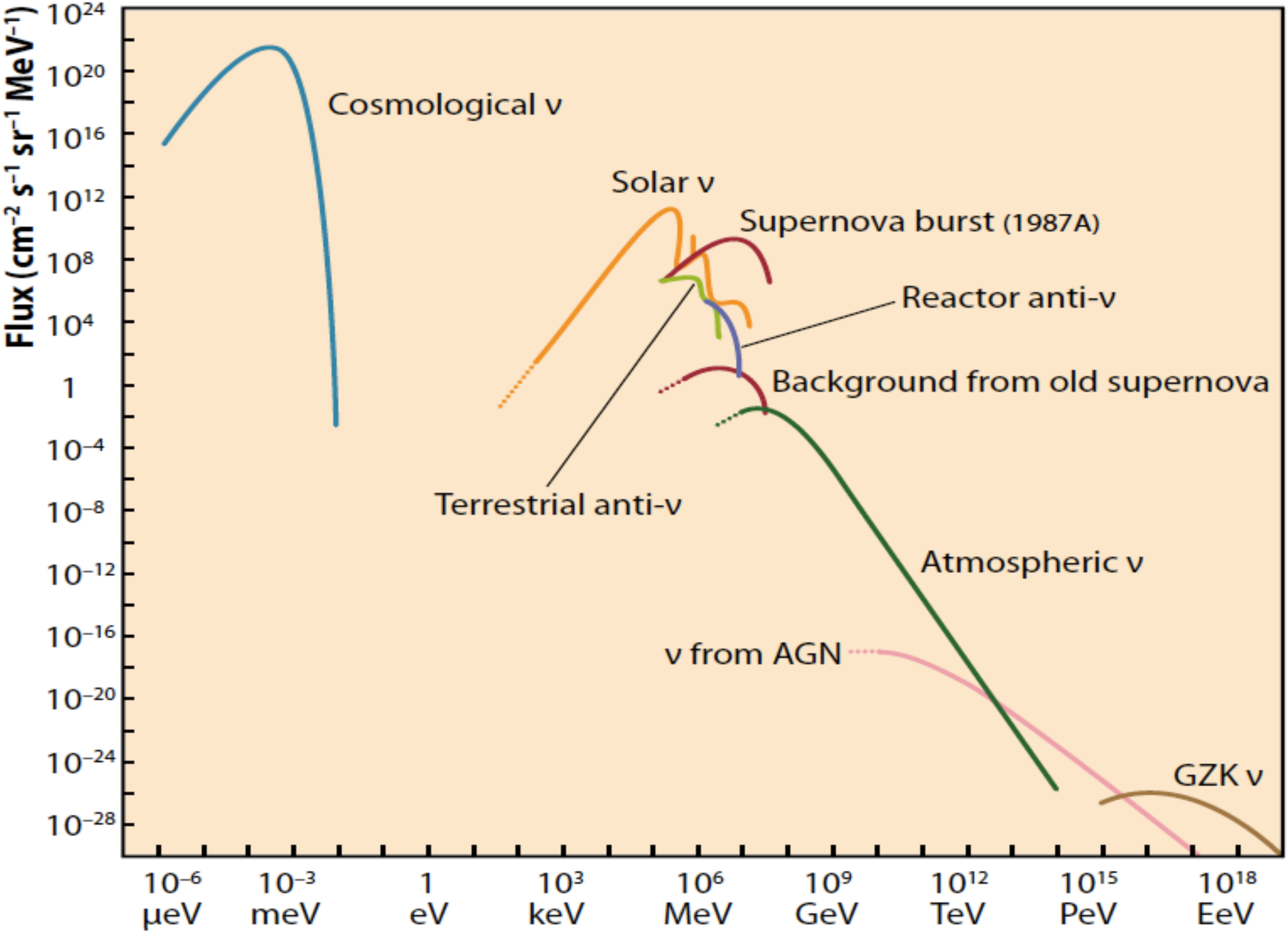
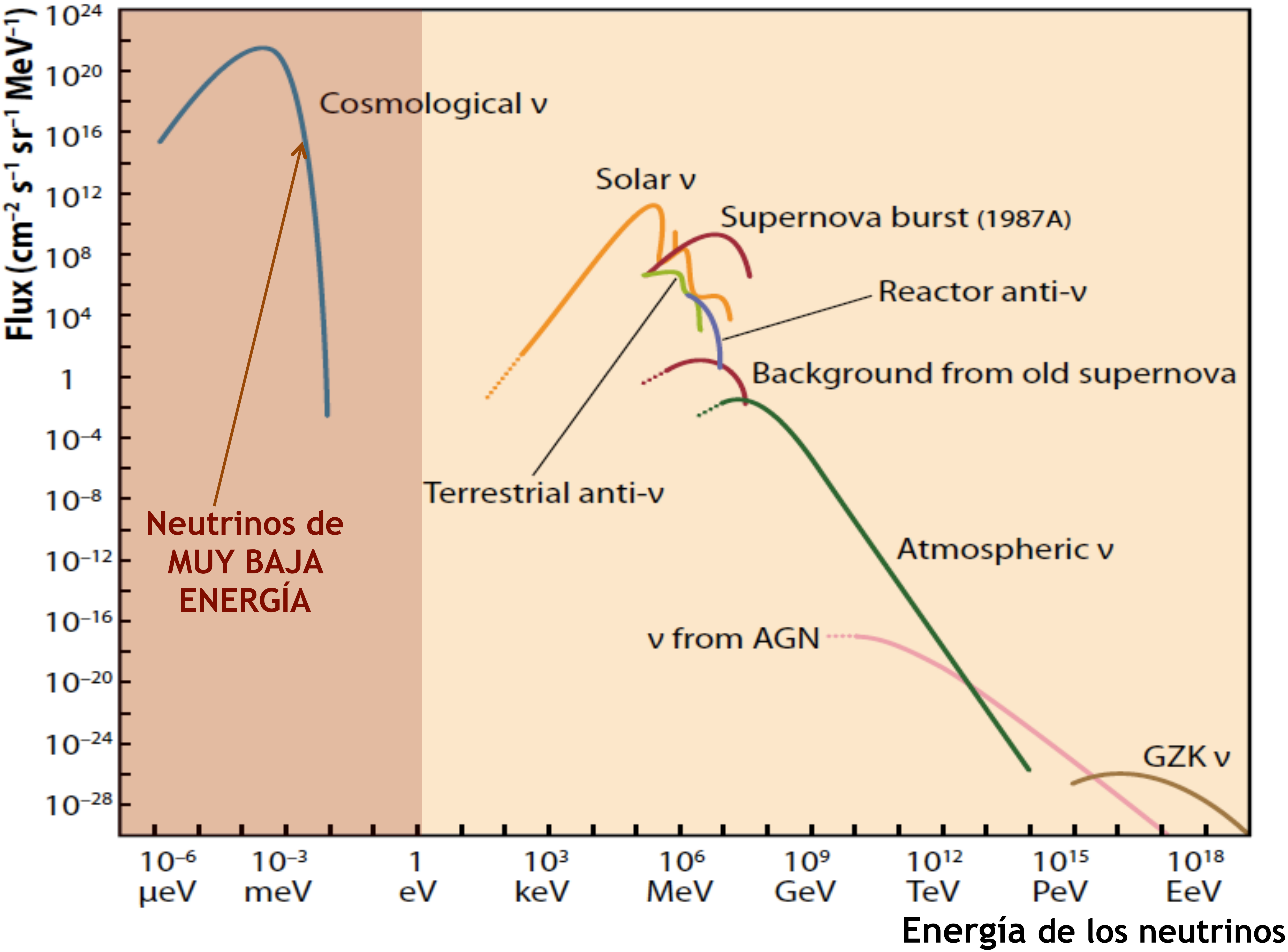
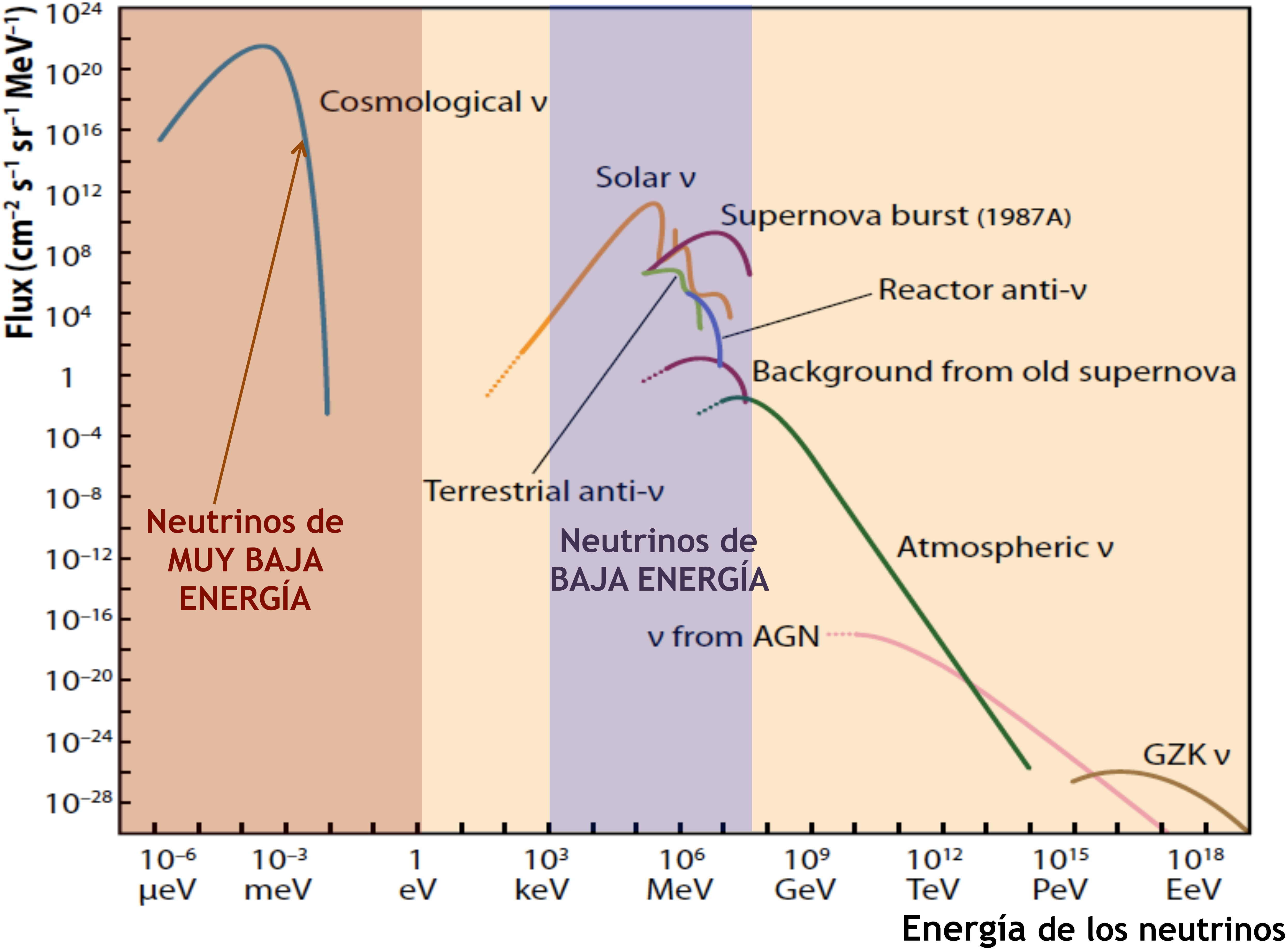




Energía de los neutrinos



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
Neutrinos de MUY BAJA ENERGÍA
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Energía de los neutrinos



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
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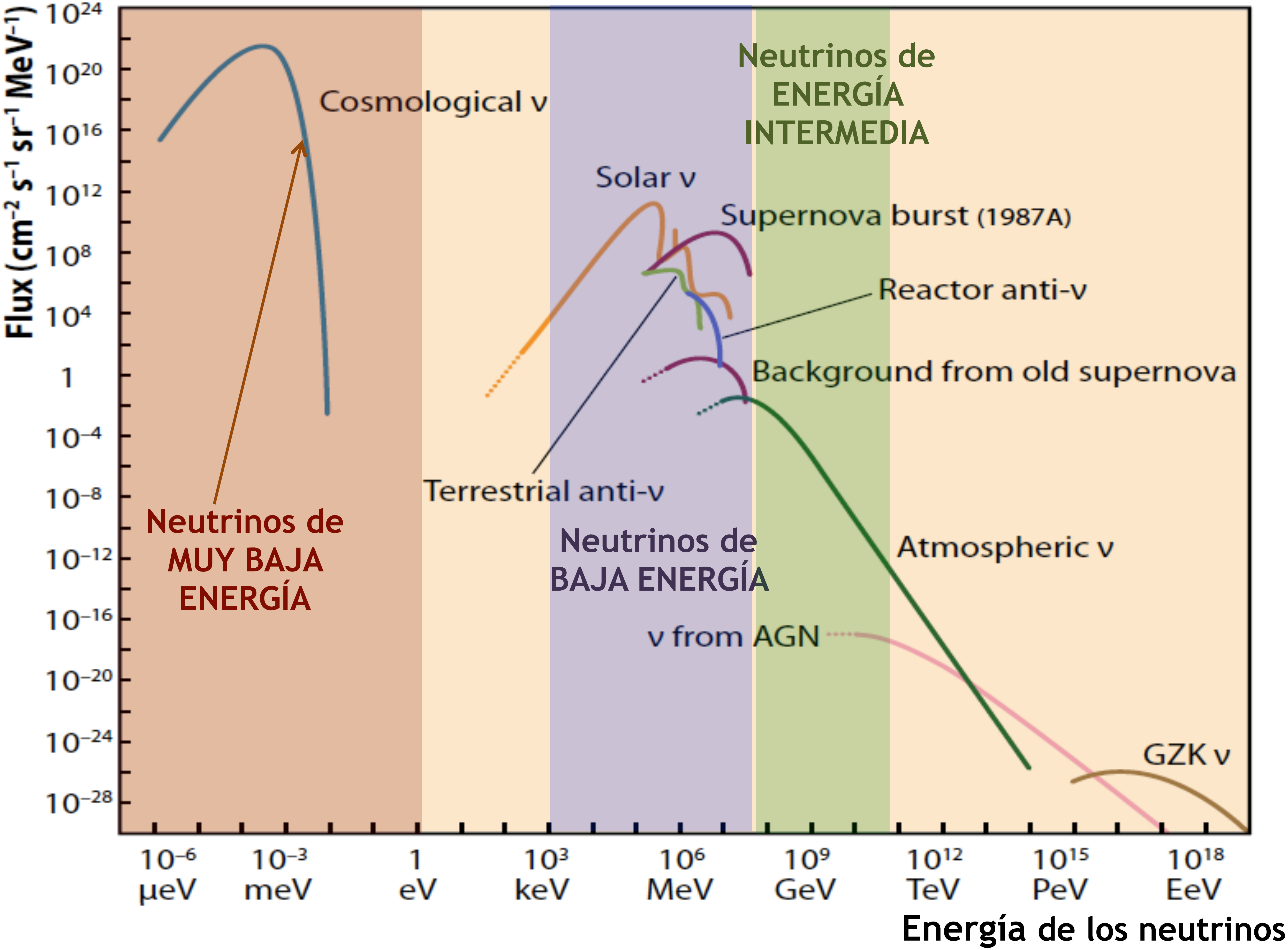
Atmospheric ν
ν from AGN
GZK ν
Neutrinos de MUY BAJA ENERGÍA
Neutrinos de BAJA ENERGÍA
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Energía de los neutrinos



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Neutrinos de ENERGÍA INTERMEDIA
Solar ν
Supernova burst (1987A)
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eV
keV
MeV
GeV
TeV
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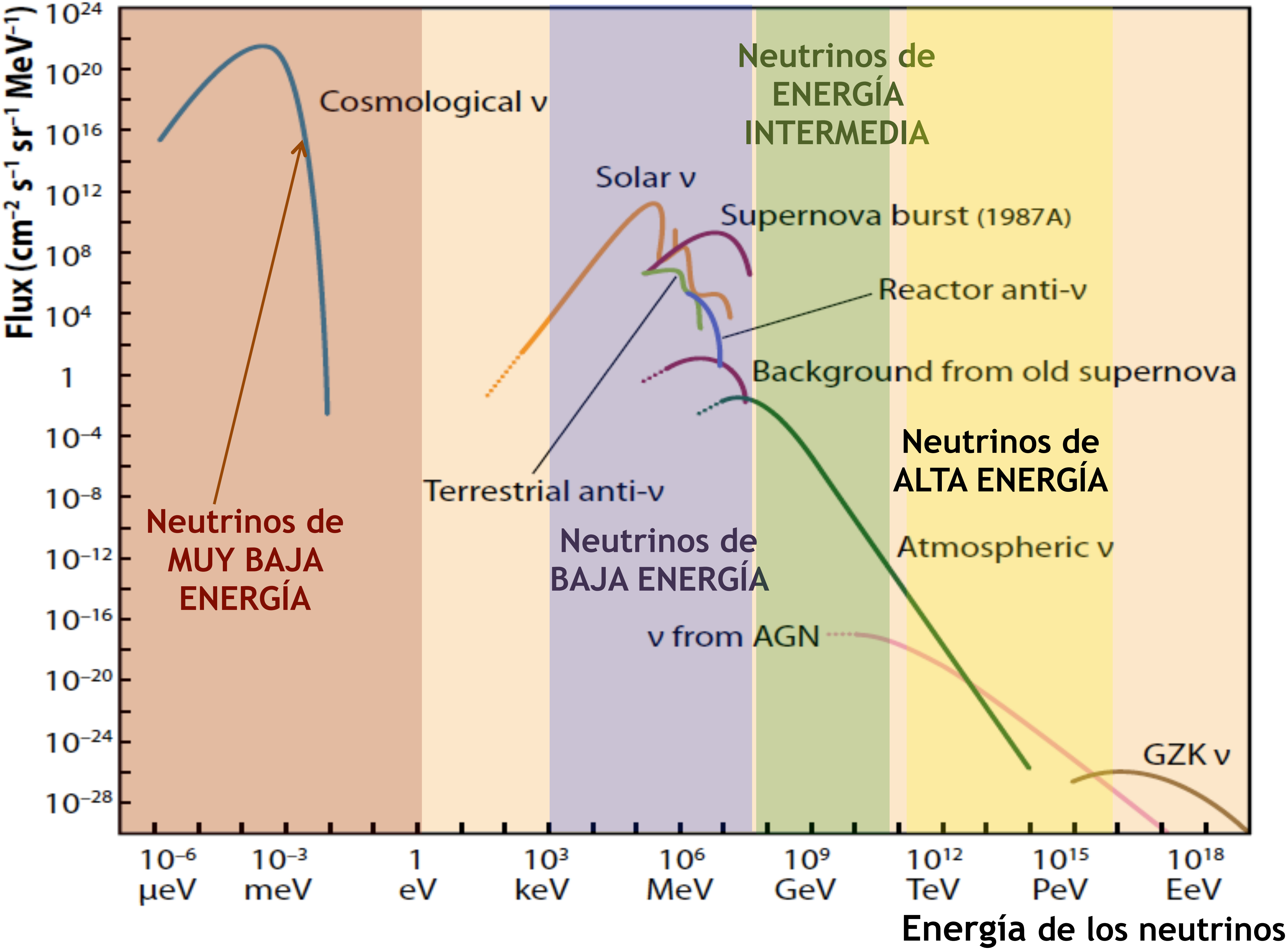

Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Neutrinos de
MUY BAJA
ENERGÍA
Solar ν
Supernova burst (1987A)
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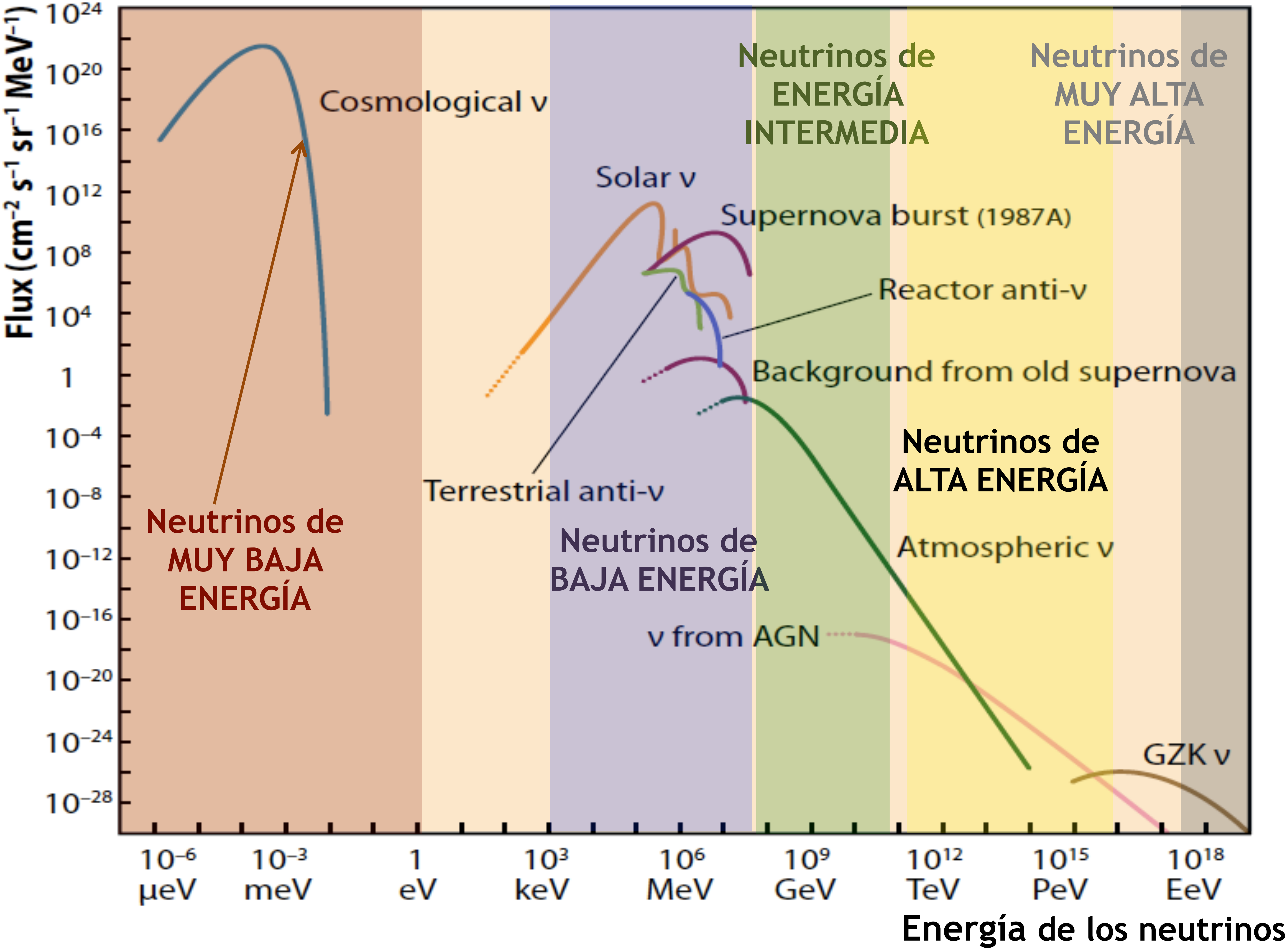

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10²⁴
10²⁰
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1
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10⁻⁸
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10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Neutrinos de ENERGÍA INTERMEDIA
Neutrinos de MUY ALTA ENERGÍA
Solar ν
Supernova burst (1987A)
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Background from old supernova
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1 eV
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10⁶ MeV
10⁹ GeV
10¹² TeV
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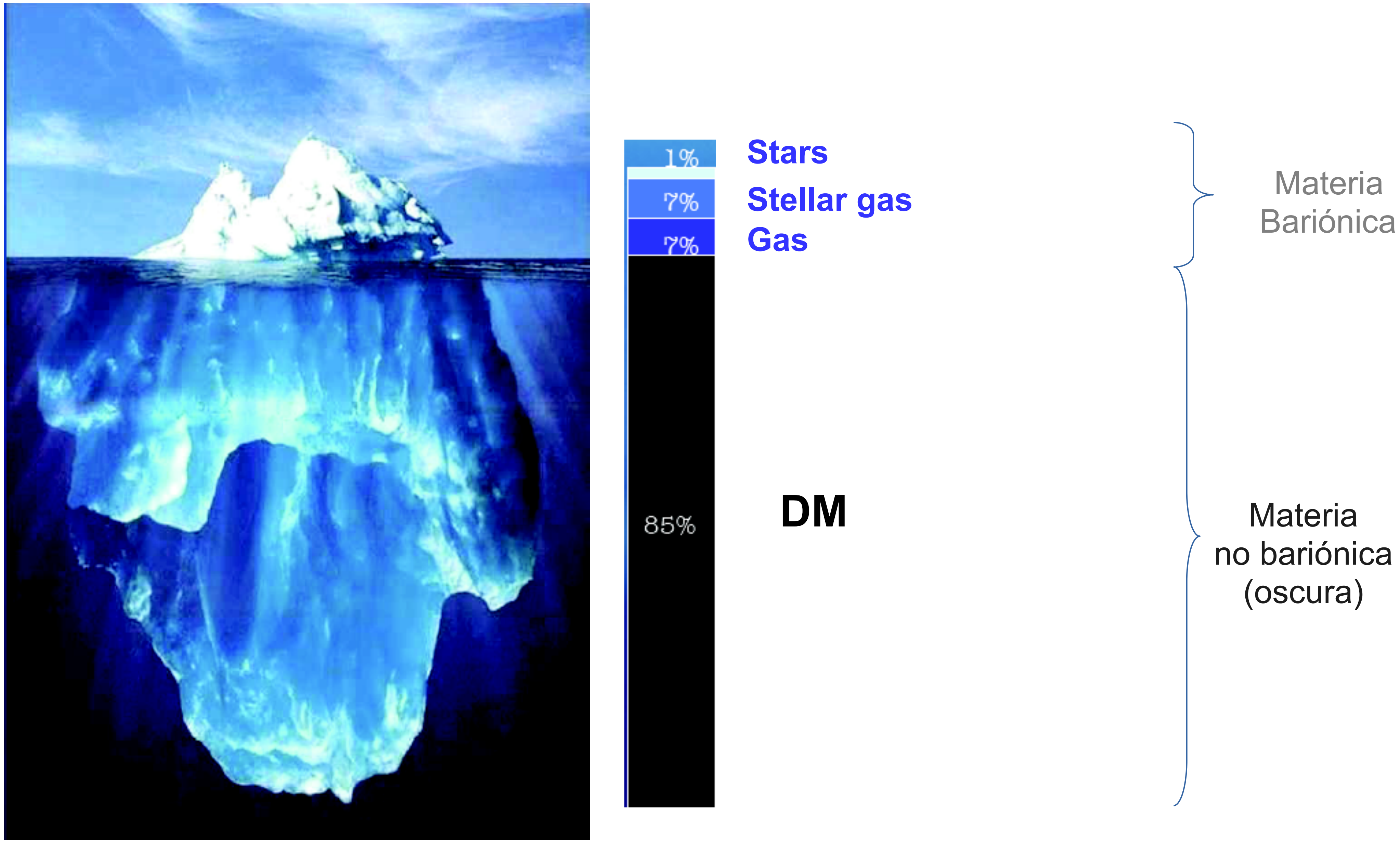
10¹⁸ EeV
Energía de los neutrinos

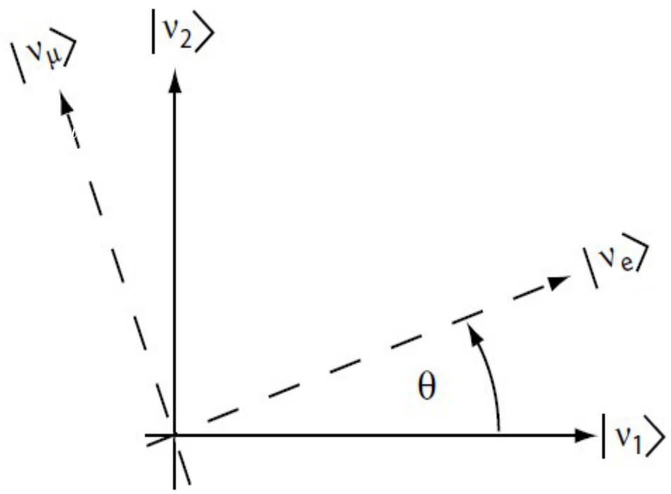
Inventario de la materia en el Universo



Volveremos a esto mas tarde

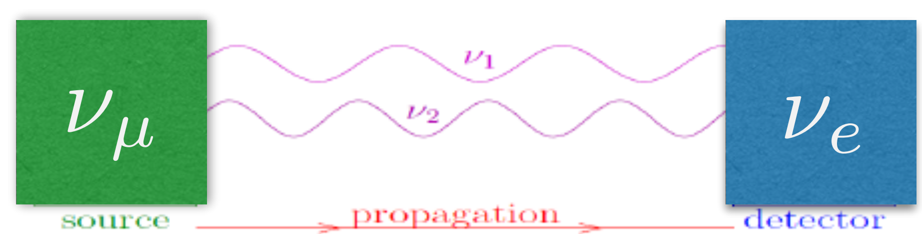
Neutrino oscillation

Neutrino oscillations 2 flavors



weak eigenstates mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$\boxed{P(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)}$$

3 mixing angles and 2 squared mass differences

¿Conversiones de sabor de los neutrinos?

Se observa en ciertos experimentos que **los neutrinos cambian su naturaleza (sabor)** durante su propagación

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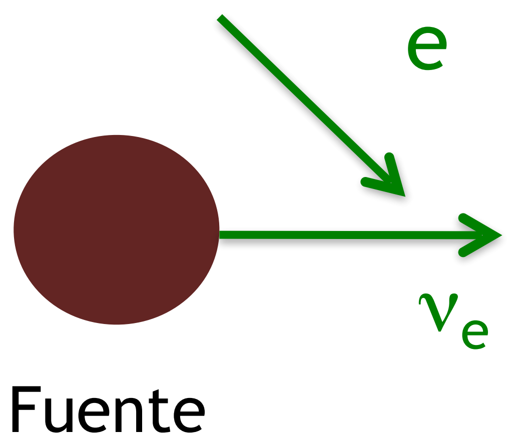

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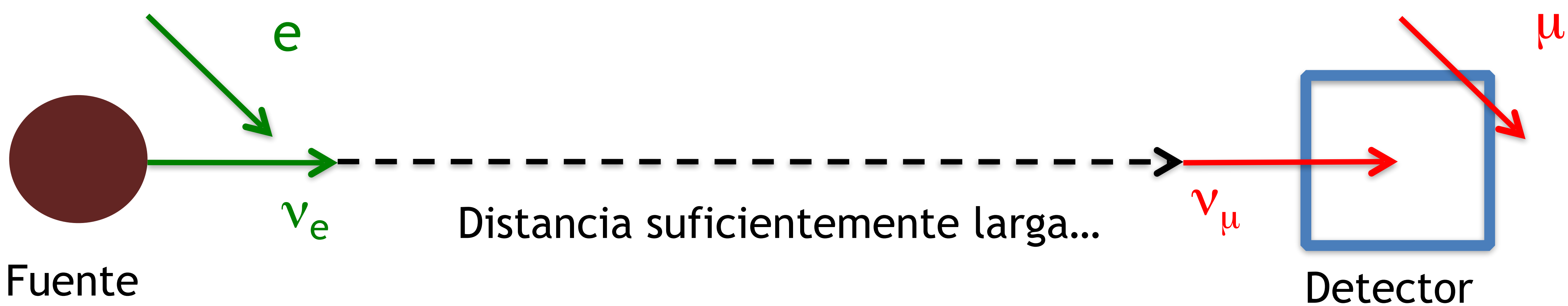

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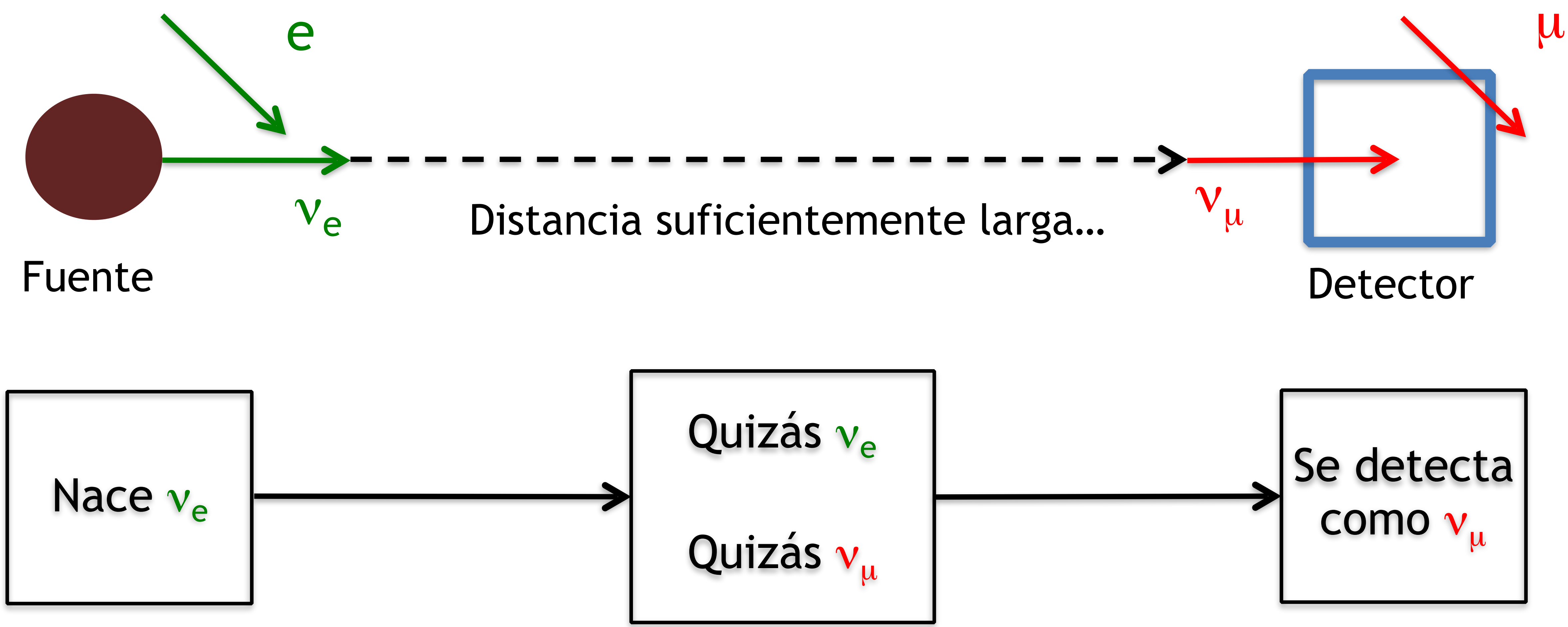

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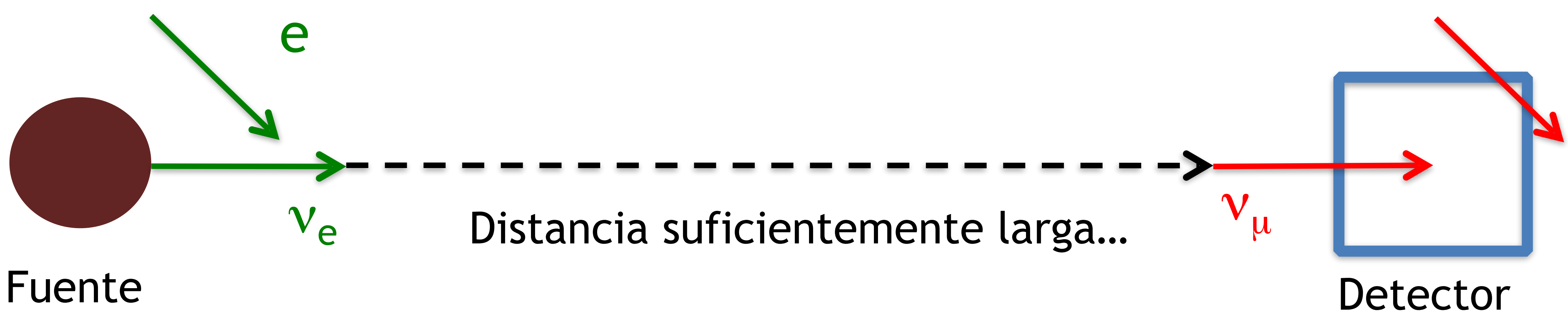
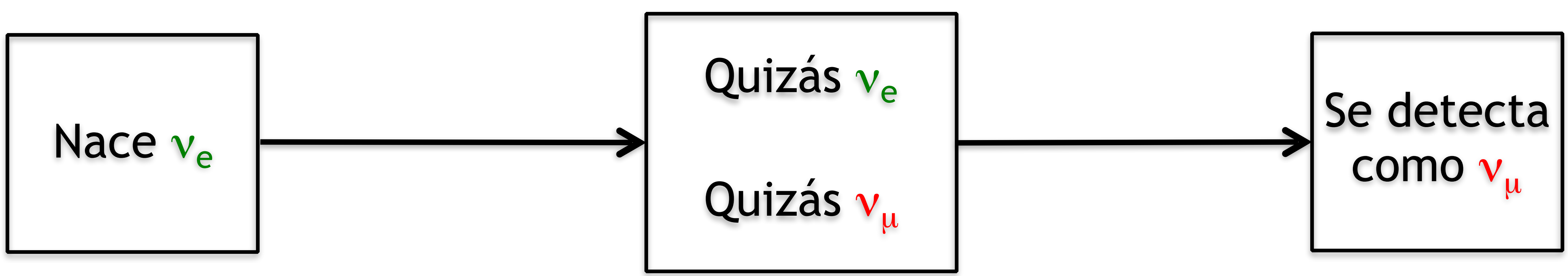
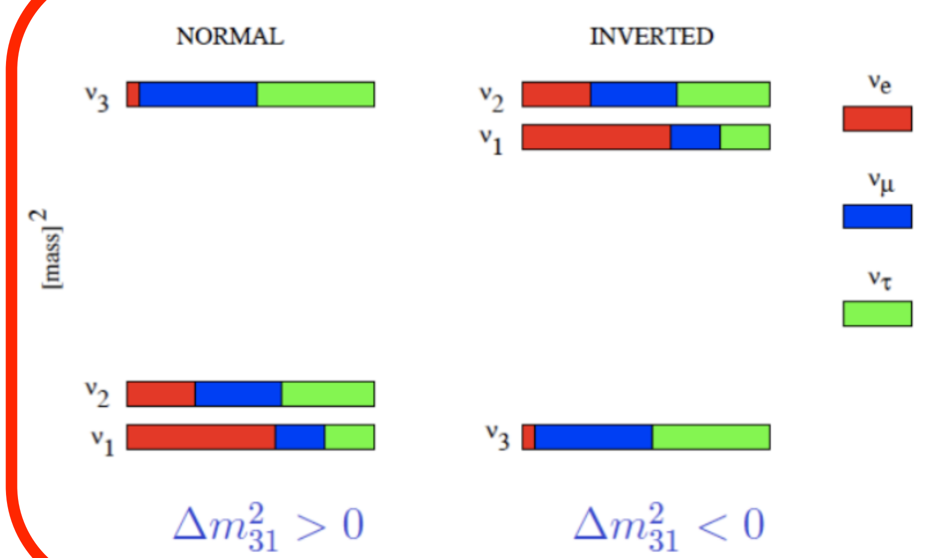




Se producen y detectan los **neutrinos de sabor**, pero se propagan otros estados: los estados de masa (ν_1, ν_2)

What do we know?

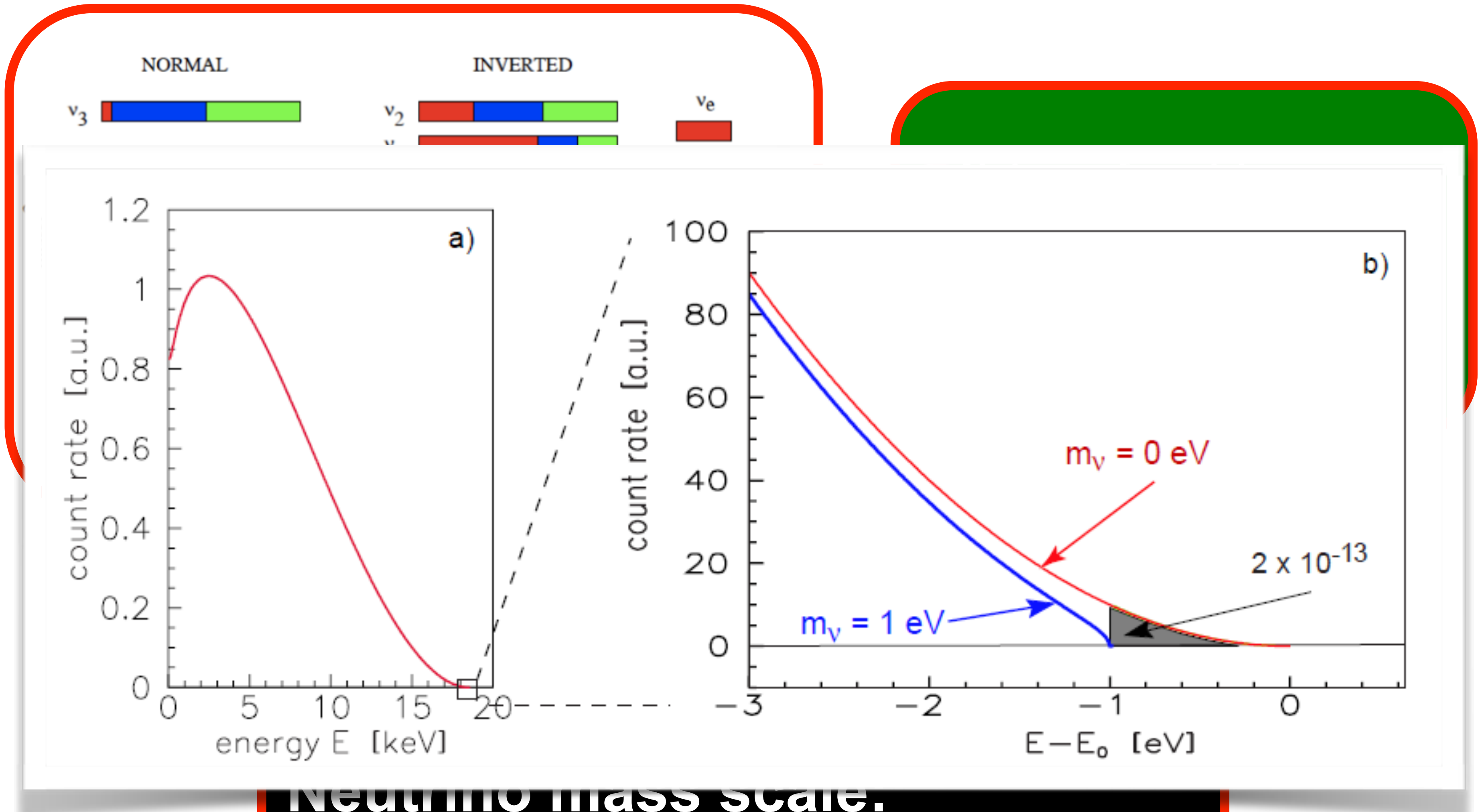


- Nature of neutrinos
- Absolute mass scale
- Mass ordering
- CP phases
- Precision in mixing angles

Neutrino mass scale:

Mainz current limit	Σ mν < 2 eV
Katrin future sensitivity	~ 0.2 eV
PLANK+BAO	Σ mν <0.23 eV

What do we know?



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Neutrino nature

Dirac?

Majorana?

Fermion masses

$$
\begin{aligned}
\mathcal{L} = & \, i\overline{L'_{\alpha L}}\not{D}L'_{\alpha L} + i\,\overline{Q'_{\alpha L}}\not{D}Q'_{\alpha L} + i\overline{l'_{\alpha R}}\not{D}l'_{\alpha R} \\
& + i\overline{q'^{D}_{\alpha R}}\not{D}q'^{D}_{\alpha R} + i\overline{q'^{U}_{\alpha R}}\not{D}q'^{U}_{\alpha R} - \frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& + (D_\rho\Phi)^\dagger(D^\rho\Phi) + \mu^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2 \\
& \left.\begin{aligned}
& - \left(Y'^{l}_{\alpha\beta}\,\overline{L'_{\alpha L}}\,\Phi\,l'_{\beta R} + Y'^{l*}_{\alpha\beta}\,\overline{l'_{\beta R}}\,\Phi^\dagger\,L'_{\alpha L}\right) \\
& - \left(Y'^{D}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,\Phi\,q'^{D}_{\beta R} + Y'^{D*}_{\alpha\beta}\,\overline{q'^{D}_{\beta R}}\,\Phi^\dagger\,Q'_{\alpha L}\right) \\
& - \left(Y'^{U}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,(i\sigma_2\Phi^*)\,q'^{U}_{\beta R} + Y'^{U*}_{\alpha\beta}\,\overline{q'^{U}_{\beta R}}\,(-i\Phi^T\sigma_2)\,Q'_{\alpha L}\right)
\end{aligned}\right\} \text{Yukawa Lagrangiana}
\end{aligned}
$$

Fermion masses:

m_e	$.5\ MeV$
m_d	$4.8\ MeV$
m_u	$2.3\ MeV$
m_μ	$105\ MeV$
m_s	$95\ MeV$
m_c	$1.275\ GeV$
m_τ	$1.776\ GeV$
m_b	$4.18\ GeV$
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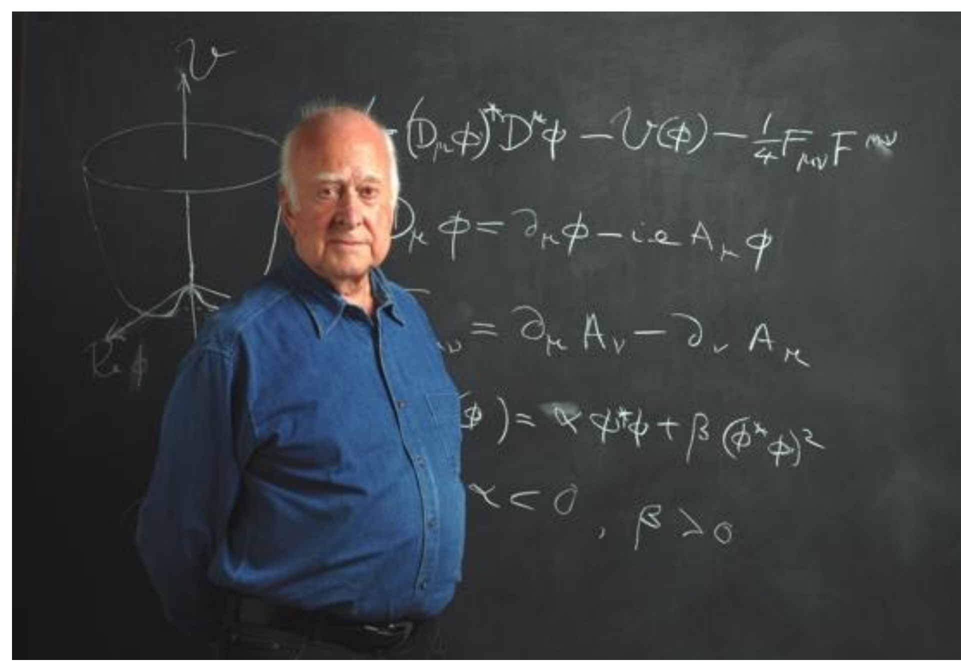

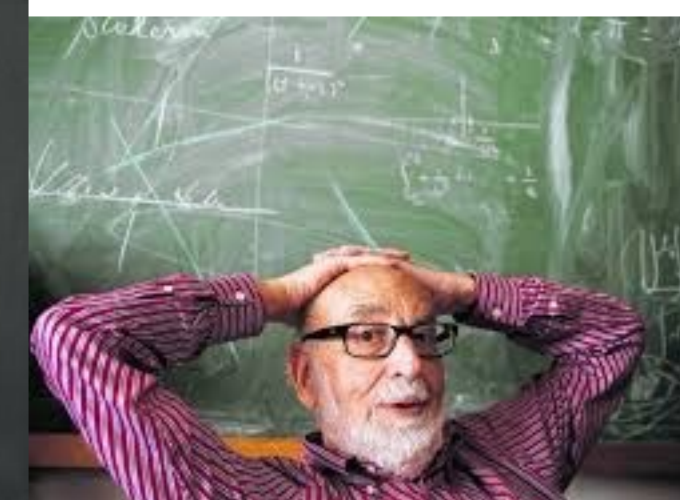

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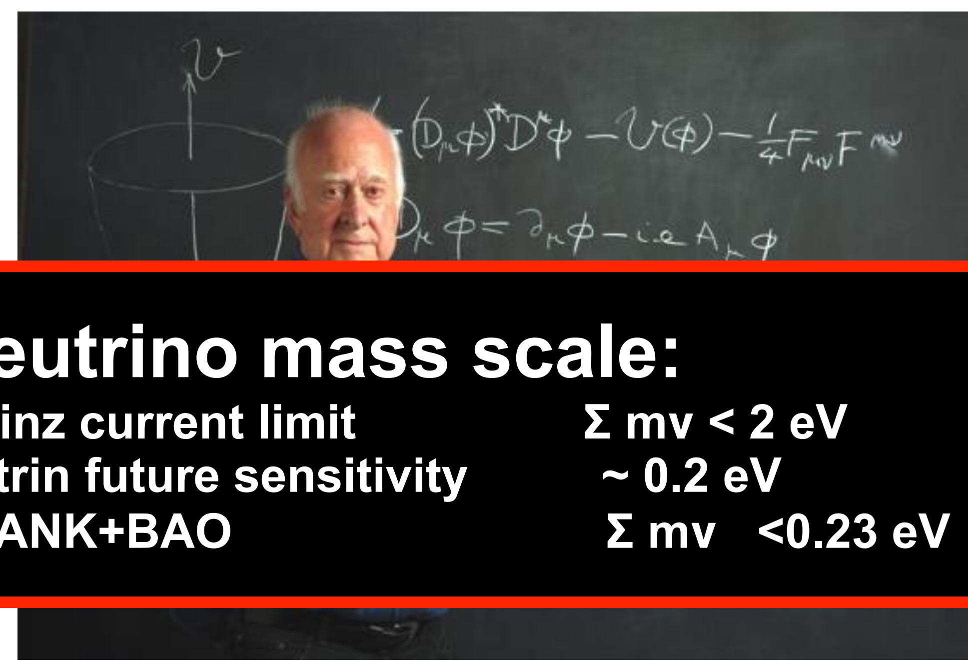

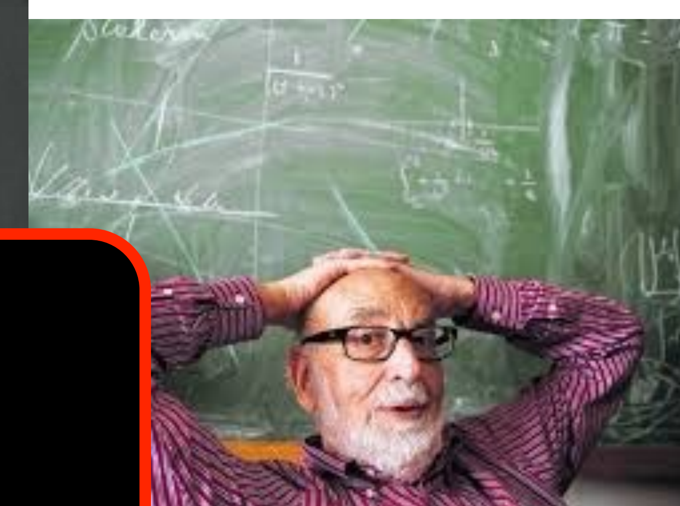

Neutrino mass scale:

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Neutrino masses

how can we give mass to the neutrinos?

- Neutrinos are neutral particles
- If we add a Right-Handed neutrino (singlet of SM) then we have the Yukawa coupling with the Higgs (like quarks and leptons)

$$\lambda_{\alpha i} \bar{L_\alpha} \epsilon H^\star N_i$$

- But there is no symmetry that forbids also this term

$$M_i \bar{N}_i N_i$$

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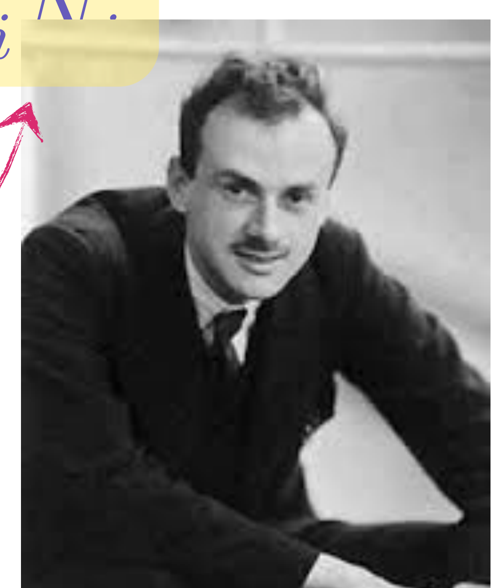
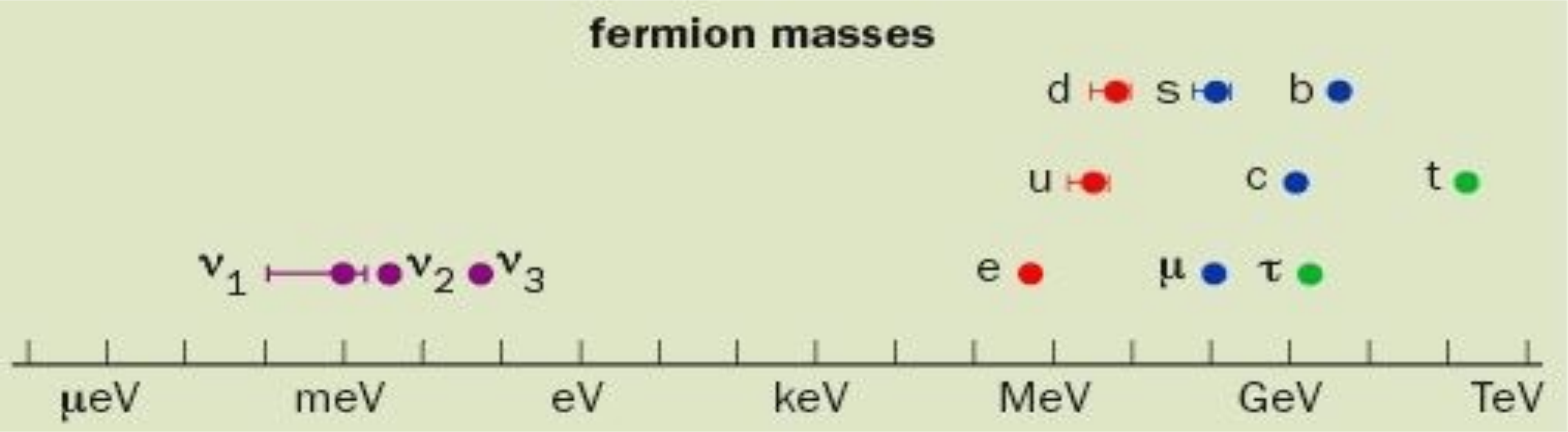


Vs.

Dirac neutrino masses

- **If we impose Lepton number then the neutrinos are Dirac particles just like quarks and charged leptons**



- **many orders of magnitude**

m_ν	$< 1\ eV$
m_e	$.5\ MeV$
m_t	$174\ GeV$

$$m_\nu << m_e << m_t$$

The Yukawa couplings are very different

$$Y_{\nu_e} : Y_e : Y_t$$

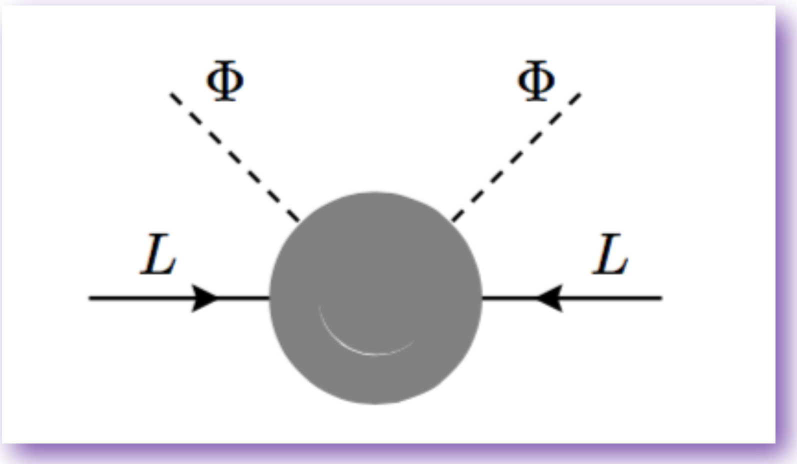
$$< 10^{-11} : 10^{-}6 : 1$$

Majorana neutrinos

If we allow L to be violated?

- **The simplest effective source of Majorana neutrino masses dim 5 Weinberg operator**

Valle's talk



Weinberg, S. (1980)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5$$

$$\mathcal{L}_5 = LL\Phi\Phi \qquad \Delta L = 2$$

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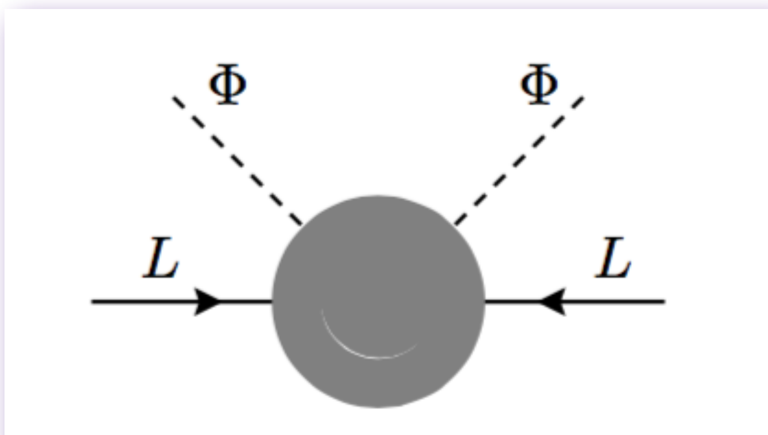

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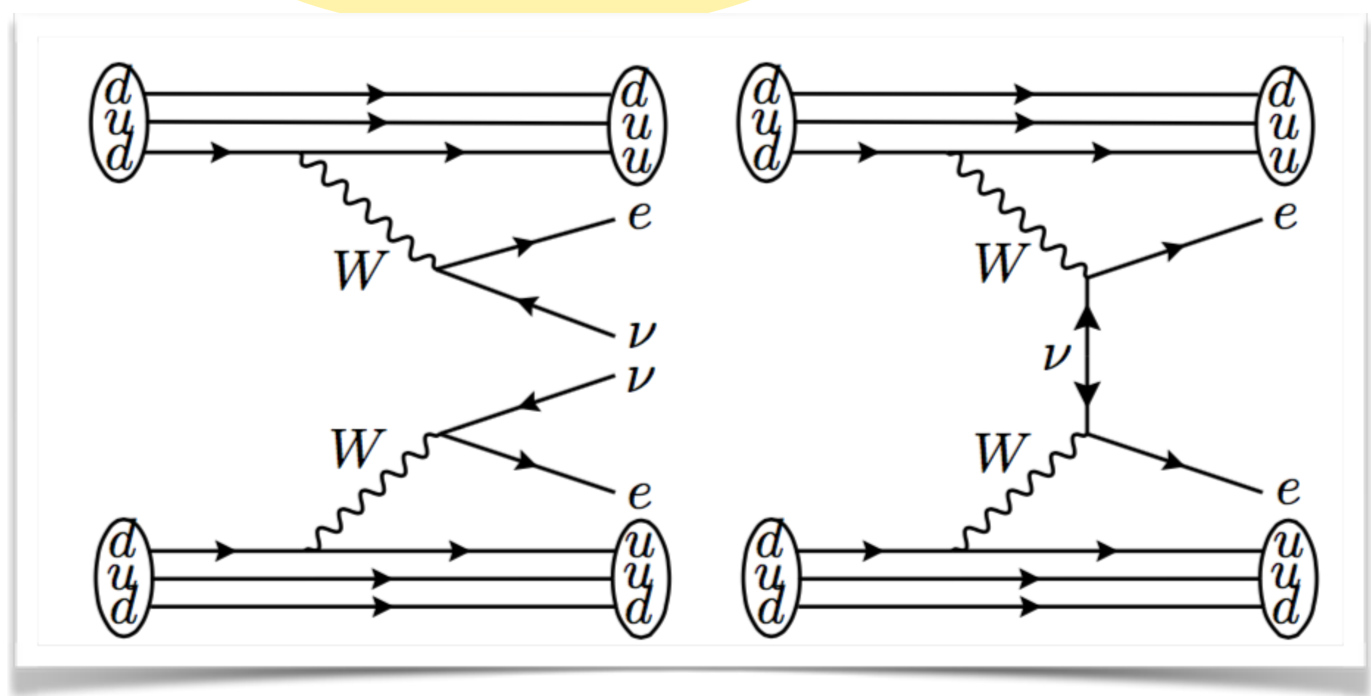
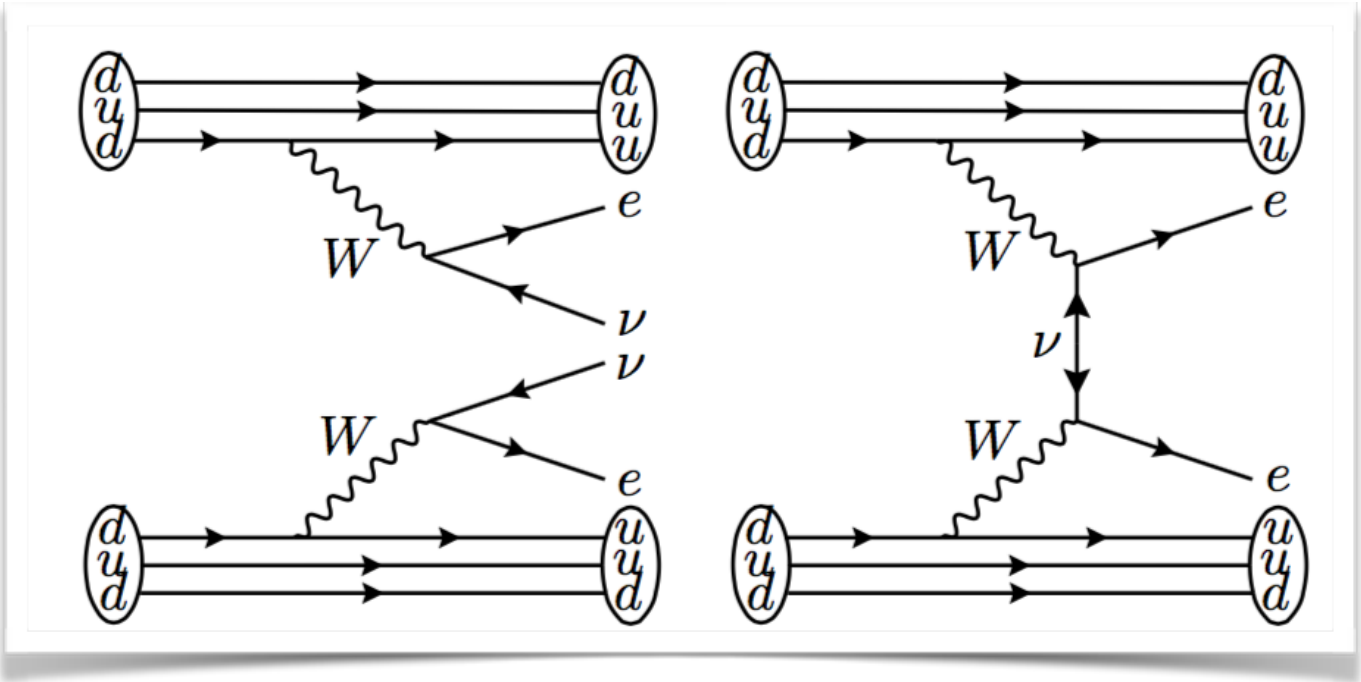
- **Implications?**

$0\nu\beta\beta$



Neutrinoless double beta decay



$$0\nu\beta\beta$$

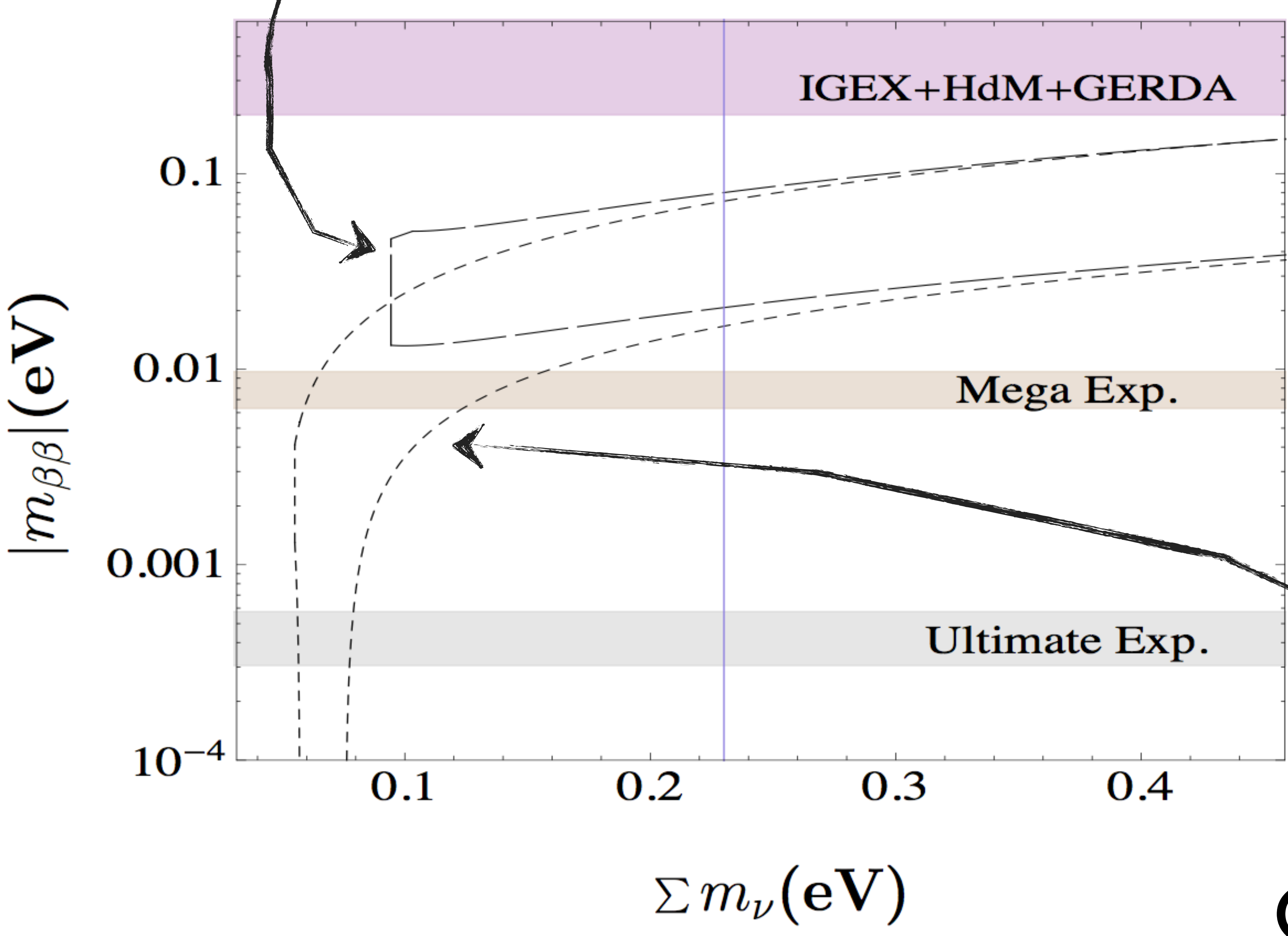
$$m_{2\beta} = \sum_{k=1}^{3} U_{ek}^2 \, m_k \, .$$

$$m_{2\beta} = c_{12}^2 \, c_{13}^2 \, m_1 + e^{2i\lambda_2} \, s_{12}^2 \, c_{13}^2 \, m_2 + e^{2i(\lambda_3 - \delta_{13})} \, s_{13}^2 \, m_3$$

Neutrinoless double beta decay

IH

If Majorana



In the case of 3 active Majorana neutrinos

NH

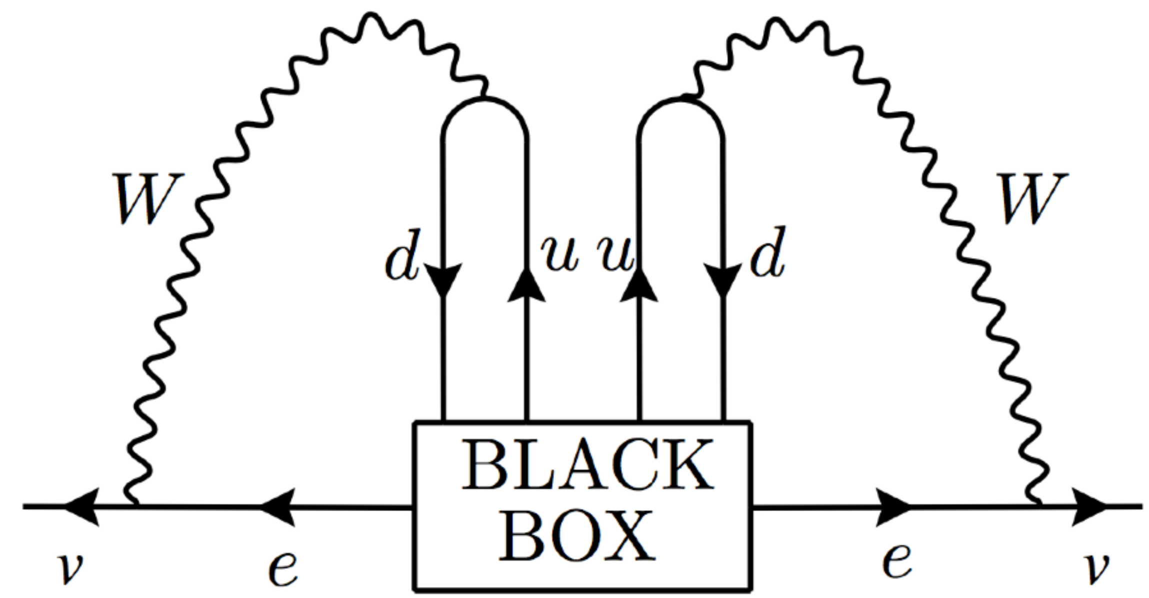
Can also be zero

Neutrinoless double beta decay

If Majorana

Black Box Theorem

If the neutrinoless double beta decay is observed that will imply a Majorana nature of the neutrinos

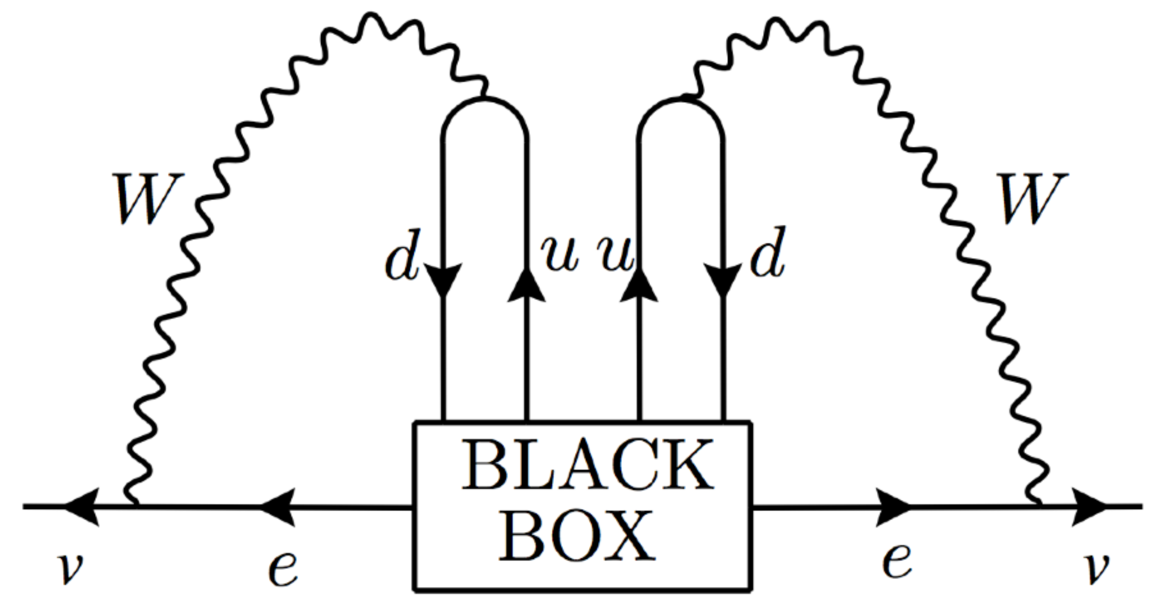


Schechter, J. and Valle, J.W.F. (1982)

Vs.

Black Box Theorem

If the neutrinoless double beta decay is observed that will imply a Majorana nature of the neutrinos



Schechter, J. and Valle, J.W.F. (1982)

see-saw tipo I

$$
\begin{aligned}
\mathcal{L} = & \, i\overline{L'_{\alpha L}} \not{D} L'_{\alpha L} + i\, \overline{Q'_{\alpha L}} \not{D} Q'_{\alpha L} + i\overline{l'_{\alpha R}} \not{D} l'_{\alpha R} \\
& + i\overline{q'^{D}_{\alpha R}} \not{D} q'^{D}_{\alpha R} + i\overline{q'^{U}_{\alpha R}} \not{D} q'^{U}_{\alpha R} - \frac{1}{4}\vec{F}_{\mu\nu} \cdot \vec{F}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
& + \left(D_\rho \Phi\right)^\dagger \left(D^\rho \Phi\right) + \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2 \\
& - \left(Y'^{l}_{\alpha\beta}\, \overline{L'_{\alpha L}}\, \Phi\, l'_{\beta R} + Y'^{l*}_{\alpha\beta}\, \overline{l'_{\beta R}}\, \Phi^\dagger\, L'_{\alpha L}\right) \\
& - \left(Y'^{D}_{\alpha\beta}\, \overline{Q'_{\alpha L}}\, \Phi\, q'^{D}_{\beta R} + Y'^{D*}_{\alpha\beta}\, \overline{q'^{D}_{\beta R}}\, \Phi^\dagger\, Q'_{\alpha L}\right) \\
& - \left(Y'^{U}_{\alpha\beta}\, \overline{Q'_{\alpha L}}\, (i\sigma_2 \Phi^*)\, q'^{U}_{\beta R} + Y'^{U*}_{\alpha\beta}\, \overline{q'^{U}_{\beta R}}\, (-i\Phi^T \sigma_2)\, Q'_{\alpha L}\right)
\end{aligned}
$$

$$\Delta\mathcal{L} = y_D \bar{\ell}_L \sigma_2 \Phi^* \nu_R + \frac{M_R}{2} \nu_R^T C \nu_R + h.c.$$

$$
\begin{aligned}
\nu & \equiv \nu_L + C\bar{\nu}_L^T \\
N & \equiv \nu_R + C\bar{\nu}_R^T
\end{aligned}
$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

UV-completion dim 5 operator

seesaw

- **We have several possibilities SU(2) doublets L**

$$2 \otimes 2 = 1 + 3$$

type I seesaw

$LHN \qquad 2 \otimes 2 \otimes 1$

type II seesaw

$L\Delta L \qquad 2 \otimes 3 \otimes 2$

type III seesaw

$LH\Sigma \qquad 2 \otimes 3 \otimes 2$

UV-completion dim 5 operator

seesaw

- **We have several possibilities SU(2) doublets L**

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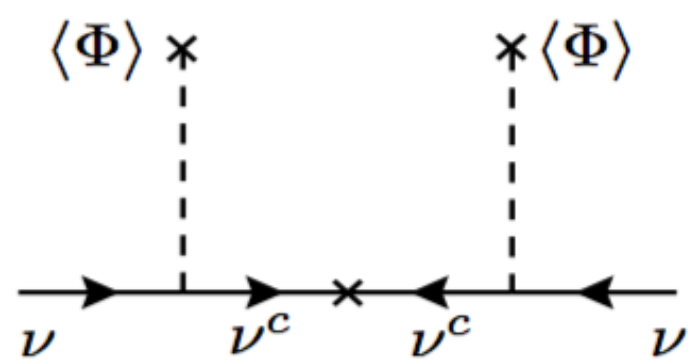
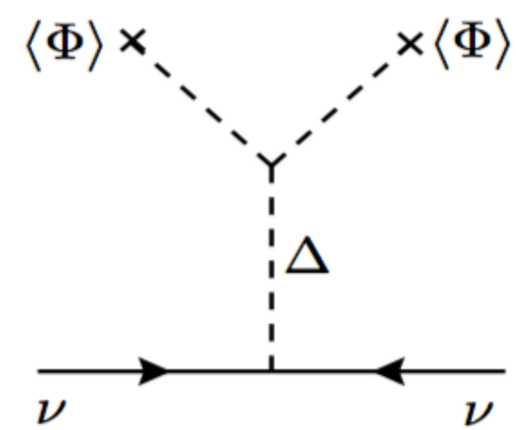


type I seesaw

$$LHN \qquad 2 \otimes 2 \otimes 1$$



type II seesaw

$$L\Delta L \qquad 2 \otimes 3 \otimes 2$$

type III seesaw

$$LH\Sigma \qquad 2 \otimes 3 \otimes 2$$

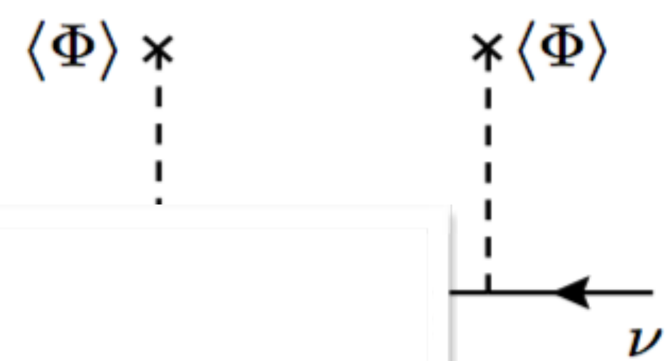
Type III

UV-completion dim 5 operator

seesaw

- We have several possibilities SU(2) doublets L

$$2 \otimes 2 = 1 + 3$$



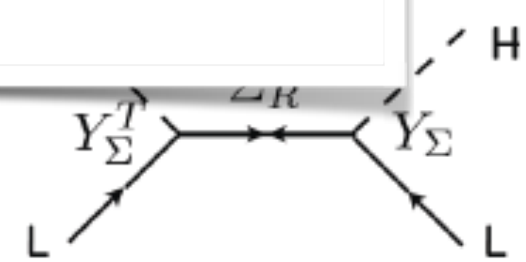
type I

type I

$$\mathcal{M}_\nu = \begin{bmatrix} \boxed{M_1} & M_D \\ M_D^T & \boxed{M_2} \end{bmatrix}$$

type II

$LH\Sigma$ $\quad$ $2 \otimes 3 \otimes 2$



Type III

Other scenarios

Inverse see-saw

- New features emerge when the seesaw is realized with non-minimal lepton content (Isosinglets) SU(2) singlets: (ν_i^c, S_i) transforming as

$field$	L
ν_i	$+1$
N	-1
S_i	$+1$

Other scenarios

Inverse see-saw

- New features emerge when the seesaw is realized with non-minimal lepton content (Isosinglets) SU(2) singlets: (ν_i^c, S_i) transforming as

$field$	L
ν_i	$+1$
N	-1
S_i	$+1$

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_\nu^T \langle \Phi \rangle & 0 \\ Y_\nu \langle \Phi \rangle & 0 & M^T \\ 0 & M & \mu \end{bmatrix}$$

Other scenarios

Inverse see-saw

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violates L in 2 units

$\mu_{ij} S_i S_j$ mass terms

smallness of neutrino mass is related to the smallness of the parameter mu "natural" in the sense of 't Hooft

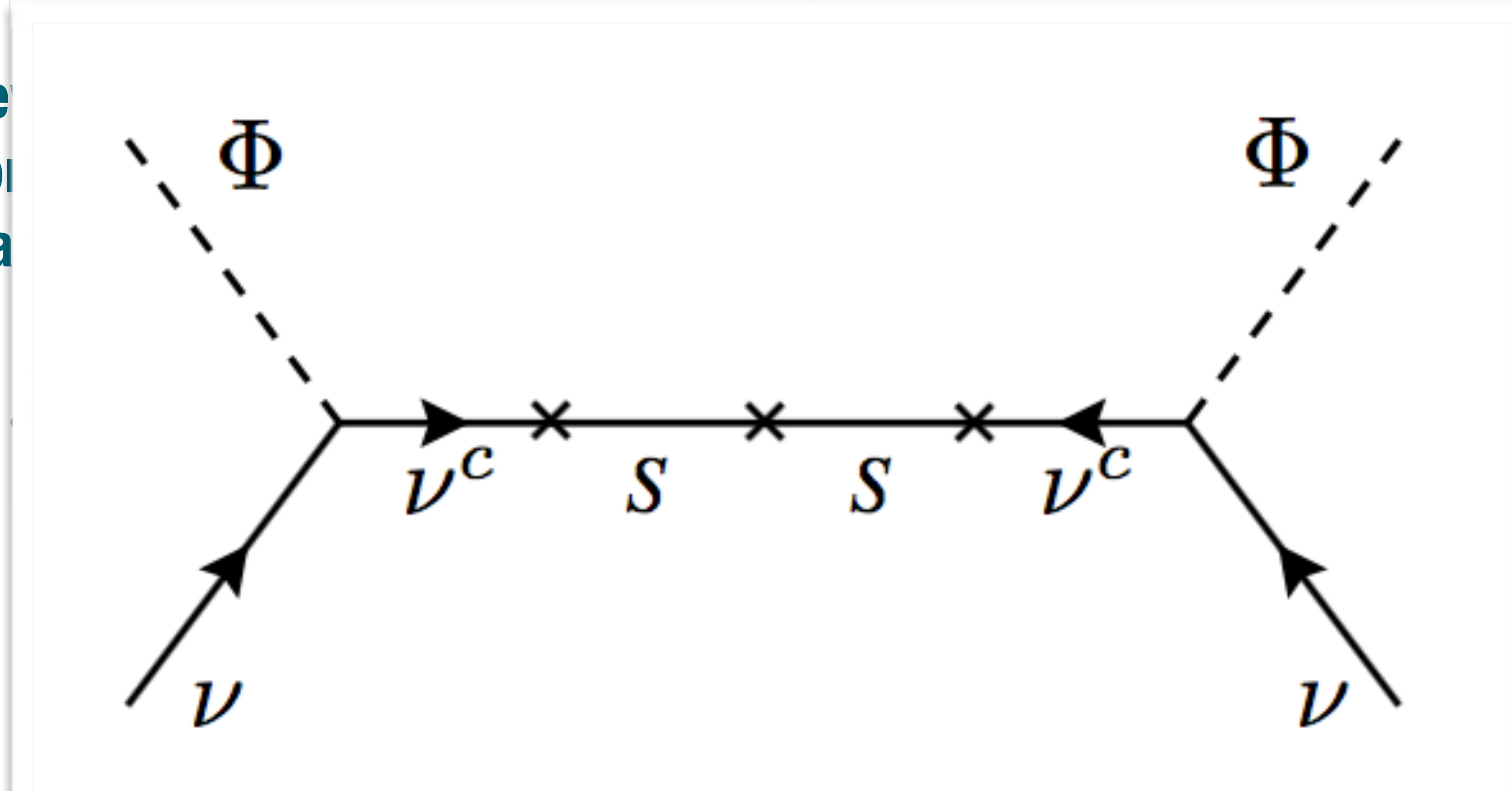
$$m_\nu \to 0 \quad \text{as} \quad \mu \to 0$$

t'Hooft, G. (1982)

Other scenarios

Inverse see-saw

Ne… mal lepton
co…
tra…



0
M^T
μ

violates L in 2 units

$$m_\nu{}^{\text{inverse}} = M_D M^{T^{-1}} \mu M^{-1} M_D^T.$$

m_ν

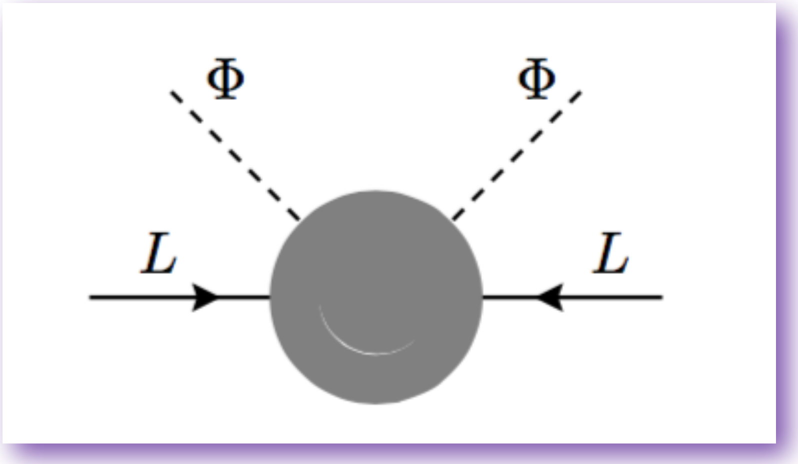
… is related to the
… mu "natural" in
…Hooft

t'Hooft, G. (1982)

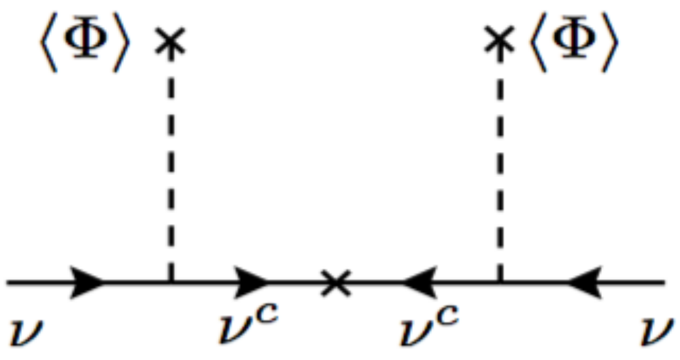
in the limit as $\mu \to 0$ the lepton number symmetry is restored.

Seesaw

type I seesaw

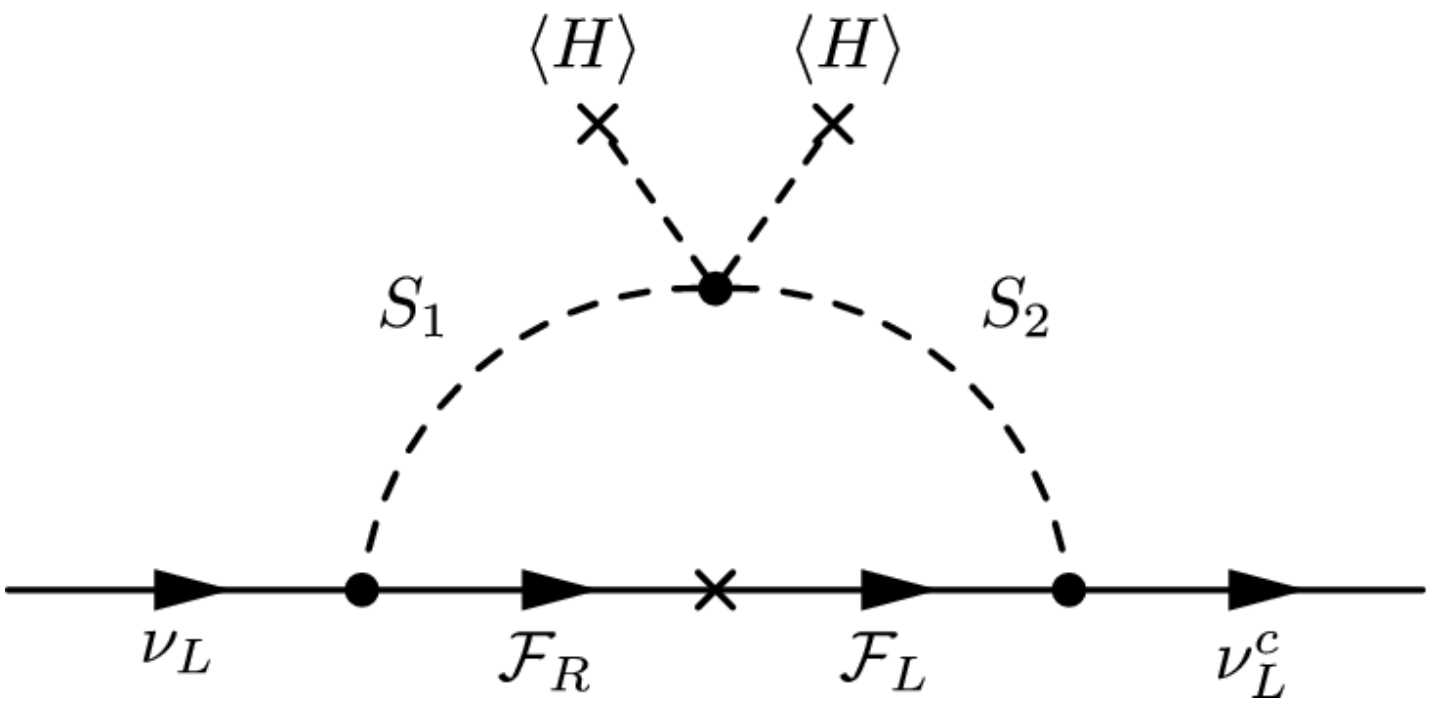


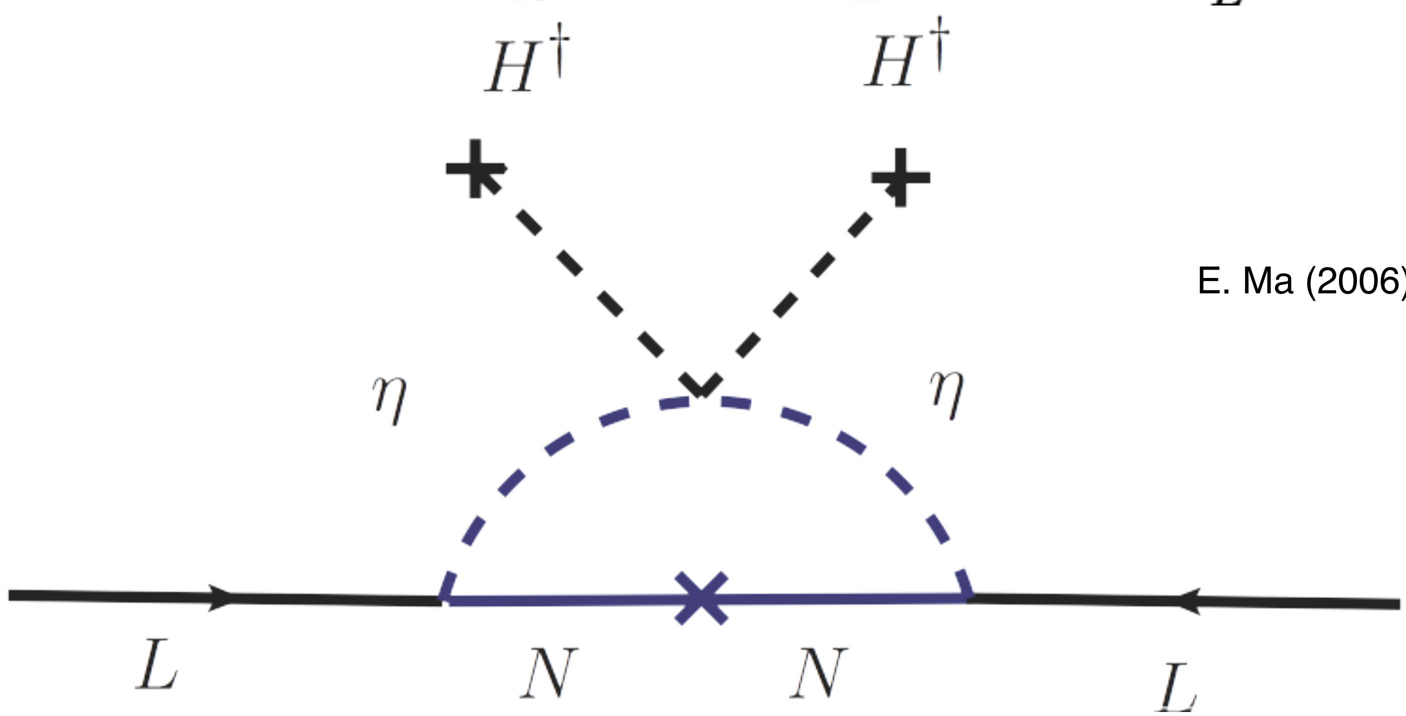
Weinberg, S. (1980)



See-saw radiativo

A. Zee (1980)





E. Ma (2006)

Parámetros de Oscilación

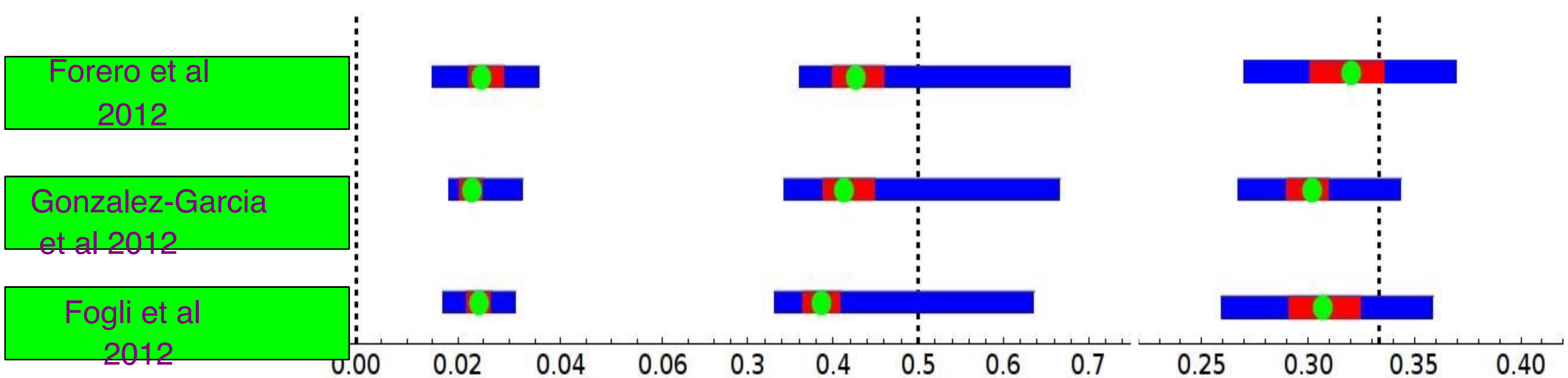
tri-maximal

bi-maximal

Harriso, Perkin, Scott

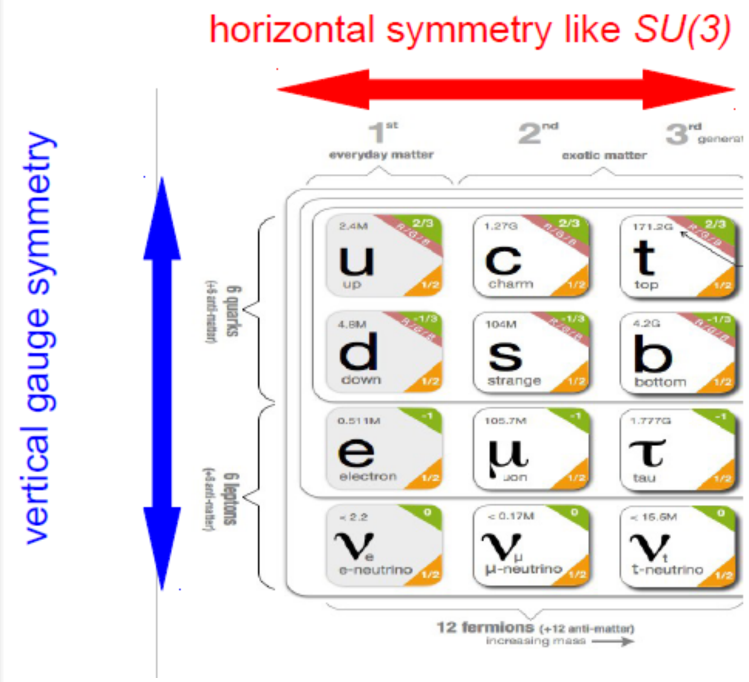
$$U_{\mathrm{HPS}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$$\sin^2\theta_{23} = 0.5 \qquad \sin^2\theta_{12} = 1/3 \qquad \sin^2\theta_{13} = 0$$



Frampton and Kephart, PRD64 (01)

order	groups
6	$S_3 \equiv D_3$
8	$D_4, Q = Q_4$
10	D_5
12	$D_6, Q_6, T \equiv A_4$
14	D_7
16	$D_8, Q_8, Z_2 \times D_4, Z_2 \times Q$
18	$D_9, Z_3 \times D_3$
20	D_{10}, Q_{10}
22	D_{11}
24	$D_{12}, Q_{12}, Z_2 \times D_6, Z_2 \times Q_6, Z_2 \times T, Z_3 \times D_4, Z_3 \times Q, Z_4 \times D_3, S_4$
26	D_{13}
28	D_{14}, Q_{14}
30	$D_{15}, D_5 \times Z_3, D_3 \times Z_5$



Abelian, non-abelian
continuous, discrete,
global, local

Poder predictivo
se reduce el número de
parámetros libres

Simetrias del Sabor (Horizontales)

Flavour symmetries

Simetrías del sabor reducen
de acoplamientos de Yukawa

Correlación entre observables
Masas, mezclas y CP

Algunos casos predicciones
como la mezcla tribimáxima

An example: A4

Ma and Rajasekaran 2001
Babu, Ma, Valle 2003
Altarelli, Feruglio 2005
...

The generators are :

S and T $\qquad S^2 = T^3 = (ST)^3 = \mathcal{I}.$

$1,\ 1',\ 1''$ and 3

1	$S=1$	$T=1$
$1'$	$S=1$	$T=e^{i4\pi/3}\equiv\omega^2$
$1''$	$S=1$	$T=e^{i2\pi/3}\equiv\omega$

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \qquad T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

A4 and TBM

$$\langle \phi \rangle = (1,1,1) \qquad \langle \phi' \rangle = (1,0,0)$$

$$Z_3 \qquad Z_2$$

Altarelli Feruglio (2005)

$$M_l \qquad M_\nu$$

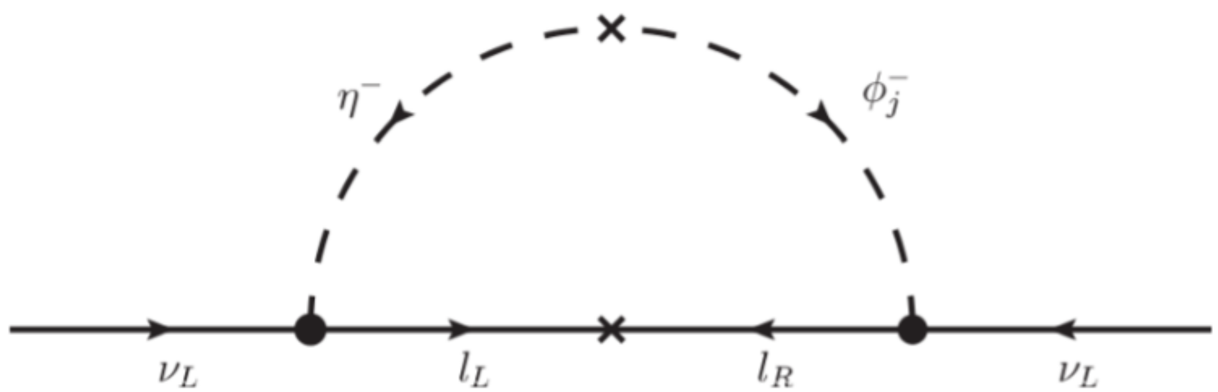
$$m = \begin{pmatrix} x & y & y \\ y & x+v & y-v \\ y & y-v & x+v \end{pmatrix}$$

A4 completely broken

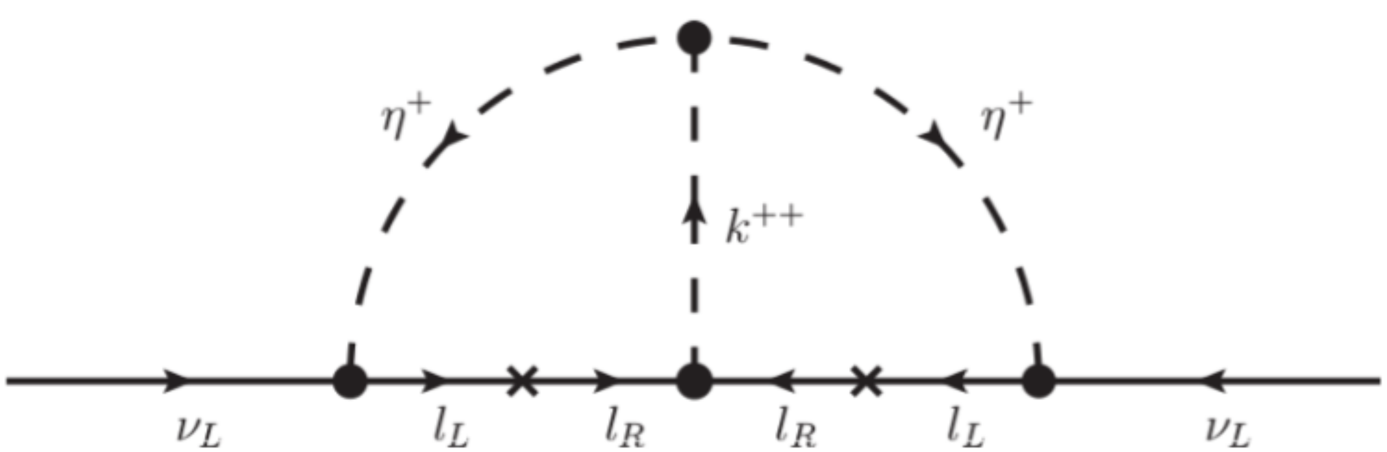
$$V_{lep} = U_l^+ U_\nu = TBM$$

Large neutrino mixing ⟺ $\phi \neq \phi'$ **Misalignment**

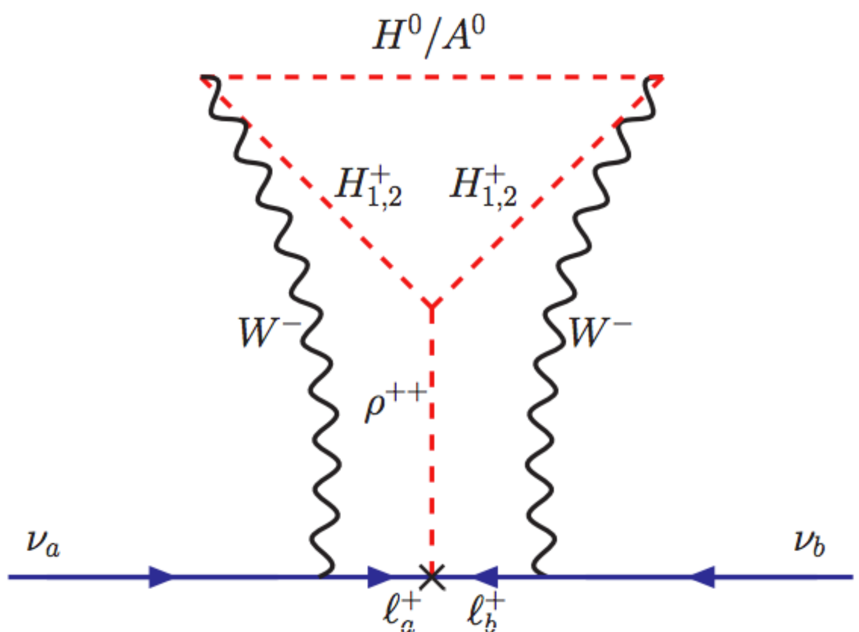
Radiative neutrino masses



Zee model



Zee Babu



Gustafsson, No and Rivera

Dirac Neutrinos

If **L** is conserved ☞ Dirac Neutrinos

☞ Imposed or accidental (like B in the SM)

Flavour symmetries

Z_N $\quad$ NN $\quad$ $\Delta(27)$

Aranda et. al. 2014

Heck, Rodejohann. 2013
Centelles, Ma, Srivastava, Valle 2016

small
Yukawa
Couplings

Dirac Neutrinos

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Z_N

$\cancel{NN}$

$\Delta(27)$

Aranda et. al. 2014

small
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Couplings

Heck, Rodejohann. 2013
Centelles, Ma, Srivastava, Valle 2016

Muchas Gracias

How to use it to stabilise DM

Instead of **breaking A4** in two different directions

$$\langle \phi \rangle = (1, 0, 0)$$

Preserves "S" (Z_2)

$$\langle \phi \rangle = (1, 1, 1)$$

Preserves "T" (Z_3)

How to use it to stabilise DM

Instead of **breaking A4** in two different directions

$$\langle \phi \rangle = (1,0,0)$$

Preserves "S" (Z_2)

$$\cancel{\langle \phi \rangle = (1,1,1)}$$

~~Preserves "T" (Z_3)~~

No TBM, but Z2

How to use it to stabilise DM

Instead of **breaking A4** in two different directions

$$\langle\phi\rangle = (1,0,0)$$

Preserves "S" (Z_2)

$$\cancel{\langle\phi\rangle = (1,1,1)}$$

~~Preserves "T" (Z_3)~~

No TBM, but Z2

$\longrightarrow$

DM Stability

Generación de θ_{13}

Acoplamos un campo escalar a los Neutrinos derechos

M. Lamprea and E. Peinado, Phys.Rev. D94 (2016) no.5, 055007

Generación de θ_{13}

Acoplamos un campo escalar a los Neutrinos derechos

Este campo rompe la FS a la escala del see-saw

M. Lamprea and E. Peinado, Phys.Rev. D94 (2016) no.5, 055007

Generación de θ_{13}

Acoplamos un campo escalar a los Neutrinos derechos

Este campo rompe la FS a la escala del see-saw

A la escala EW se tiene una Z_2 (como en el caso inerte)

M. Lamprea and E. Peinado, Phys.Rev. D94 (2016) no.5, 055007

The model(s)

M. Lamprea and E. Peinado, e-Print: arXiv:1603.02190

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	N_5	H	η	ϕ
SU(2)	2	2	2	1	1	1	1	1	1	2	2	1
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	$1'$	1	3	3

$$\langle\phi\rangle = (1,0,0)$$

$$A_4 \longrightarrow Z_2$$

Para preservar la simetría Z_2, solamente η_1 adquiere vev

$$\begin{aligned}\mathcal{L}_{\mathrm{Y}}^{(\mathrm{A})} &= y_e L_e l_e^c H + y_\mu L_\mu l_\mu^c H + y_\tau L_\tau l_\tau^c H \\ &+ y_1^\nu L_e [N_T\,\eta]_1 + y_2^\nu L_\mu [N_T\,\eta]_{1''} + y_3^\nu L_\tau [N_T\,\eta]_{1'} + y_4^\nu L_e\, N_4\, H + y_5^\nu L_\tau\, N_5\, H \\ &+ M_1\, N_T N_T + M_2\, N_4 N_4 + y_1^N [N_T\,\phi]_{3_i} N_T + y_2^N [N_T\,\phi]_1 N_4 + y_3^N [N_T\,\phi]_{1''} N_5\end{aligned}$$

M. Lamprea and E. Peinado, Phys.Rev. D94 (2016) no.5, 055007

Neutrino masses

$$m_{\mathrm{D}}^{(\mathrm{A})} = \begin{pmatrix} y_1^\nu v_\eta & 0 & 0 & y_4^\nu v_h & 0 \\ y_2^\nu v_\eta & 0 & 0 & 0 & 0 \\ y_3^\nu v_\eta & 0 & 0 & 0 & y_5^\nu v_h \end{pmatrix}$$

$$M_{\mathrm{R}} = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Neutrino masses

$$m_{\rm D}^{({\rm A})} = \begin{pmatrix} y_1^\nu v_\eta & 0 & 0 & y_4^\nu v_h & 0 \\ y_2^\nu v_\eta & 0 & 0 & 0 & 0 \\ y_3^\nu v_\eta & 0 & 0 & 0 & y_5^\nu v_h \end{pmatrix}$$

$$M_{\rm R} = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Solamente 3 RHN participan en el see-saw

Neutrino masses

$$m_{\rm D}^{(\rm A)} = \begin{pmatrix} y_1^\nu v_\eta & 0 & 0 & y_4^\nu v_h & 0 \\ y_2^\nu v_\eta & 0 & 0 & 0 & 0 \\ y_3^\nu v_\eta & 0 & 0 & 0 & y_5^\nu v_h \end{pmatrix}$$

$$M_{\rm R} = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Solamente 3 RHN participan en el see-saw

$$m_\nu^{(\rm A)} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

Texturas de dos ceros

Frampton, Glashow ,Marfatia
Merle, Rodejohan
Xing, Fritsch
Ludl, Morisi, Peinado
Meroni, Meloni, Peinado
…

Neutrino masses

$$m_D^{(A)} = \begin{pmatrix} y_1^\nu v_\eta & 0 & 0 & y_4^\nu v_h & 0 \\ y_2^\nu v_\eta & 0 & 0 & 0 & 0 \\ y_3^\nu v_\eta & 0 & 0 & 0 & y_5^\nu v_h \end{pmatrix}$$

$$M_R = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Solamente 3 RHN participan en el see-saw

$$m_\nu^{(A)} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

e d

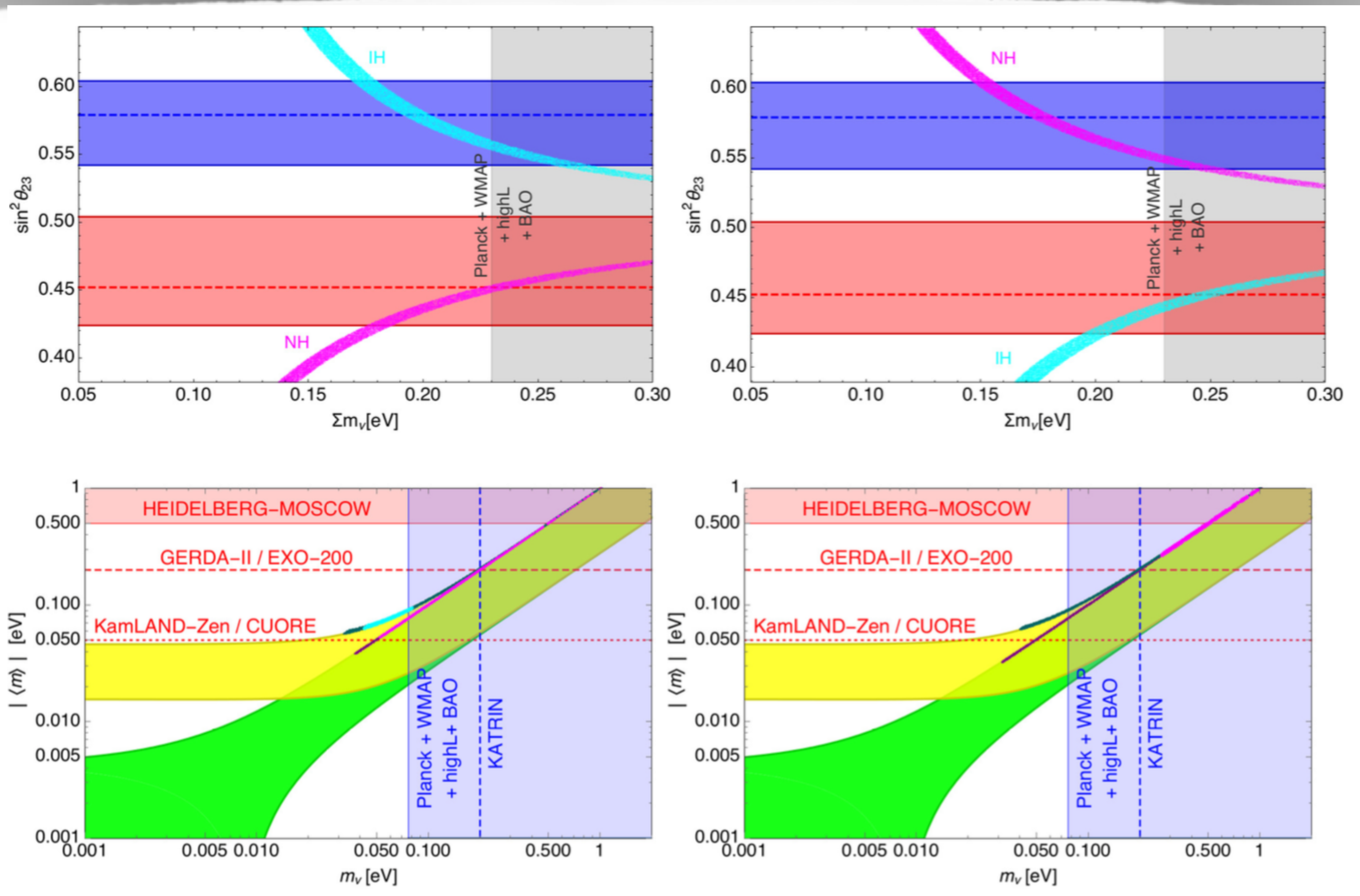
Si N5 es 1''

Ludl, Morisi, Peinado
Meroni, Meloni, Peinado
…

$$m_\nu^{(B)} \equiv \begin{pmatrix} a & b & 0 \\ b & d & c \\ 0 & c & 0 \end{pmatrix}$$

Neutrino Phenomenology

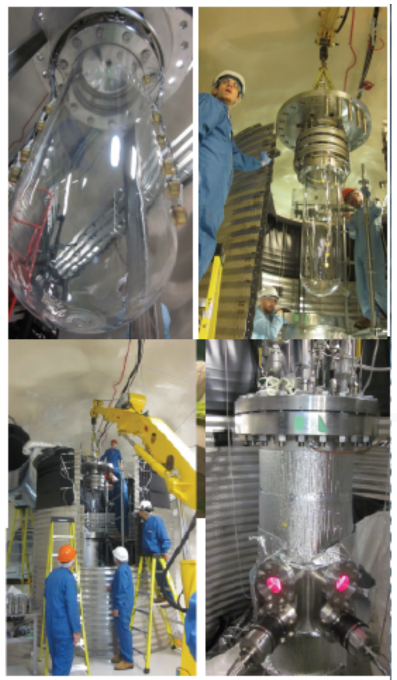
Fits de M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, arXiv:1512.06856 [hep-ph]

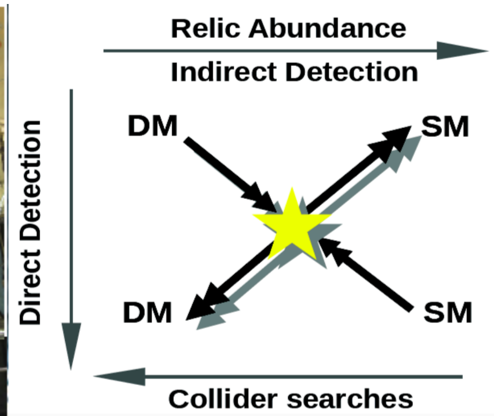


Conclusiones

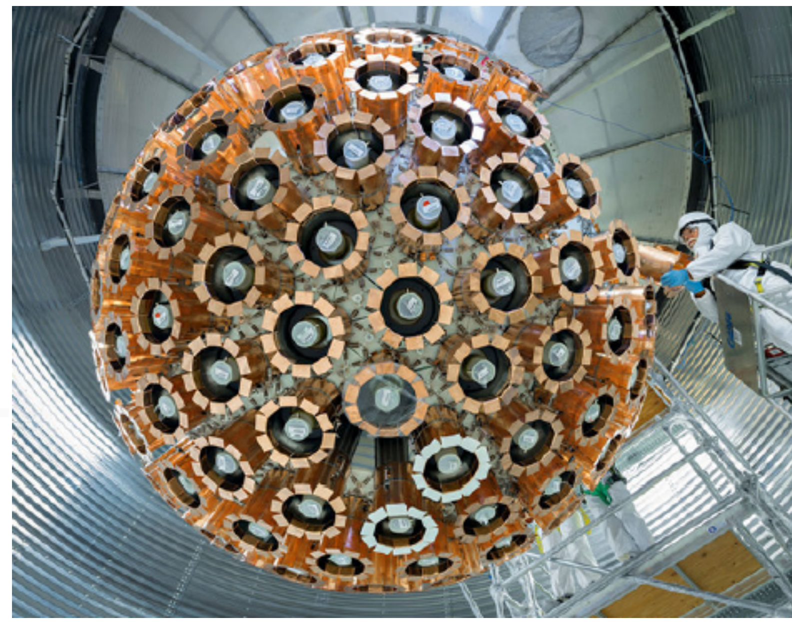
- We have evidence of “physics beyond the SM”
- It is interesting to find scenarios where some of them have a common explanation
- neutrino physics is a nice “portal to PBSM”
- DM stability and neutrino physics can be related
- Neutrino and BAU also related
- why not neutrinos - DM - BAU

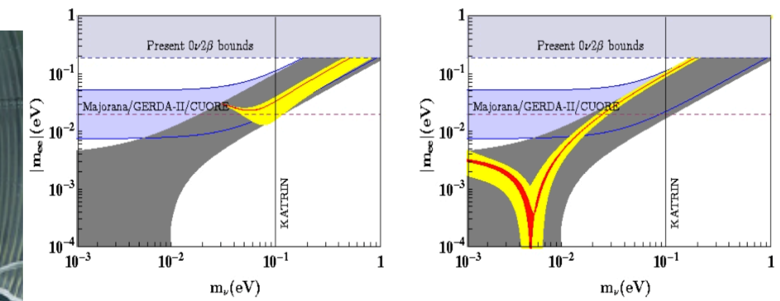
``Neutrinos y materia oscura''





SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

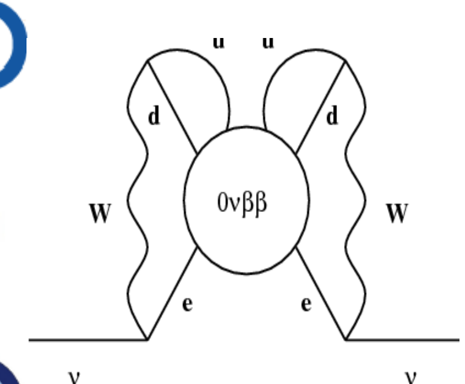


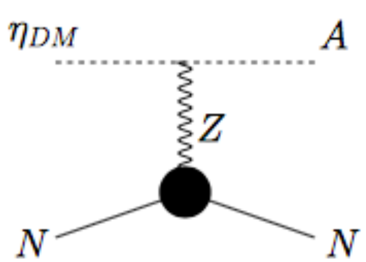


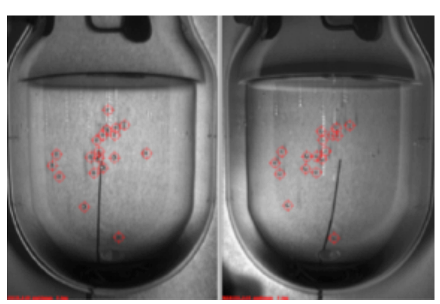
Trabajo de investigación teórico y experimental
Física de Astropartículas en un laboratorio 2 km bajo la superficie
Experimental: Eric Vázquez Jáuregui (ericvj@fisica.unam.mx)
Teórico: Eduardo Peinado Rodríguez (peinado@fisica.unam.mx)

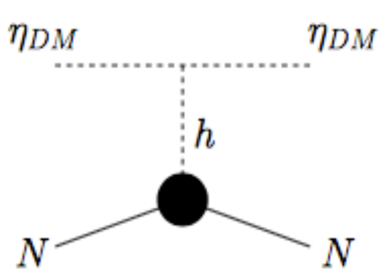
PICO

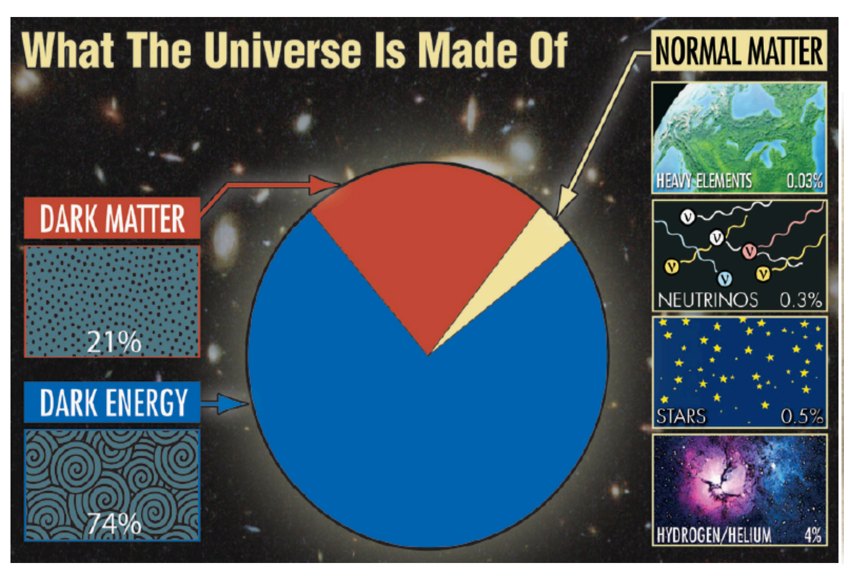
DEAP 3600











SNO+