a glimpse into...

Neutrino Physics

Sixth Lisbon mini-school on
Particle and Astroparticle Physics

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15 July 2021

FCT Fundação para a Ciência e a Tecnologia
DF Departamento de Física Técnico Lisboa
CFTP Centro de Física Teórica de Partículas
europa.eu European Union
QREN Quadro de Referência Estratégico Nacional
COMPETE Programa Operacional Factores de Competitividade

Neutrinos are...

Light

Fast

Shy

Three

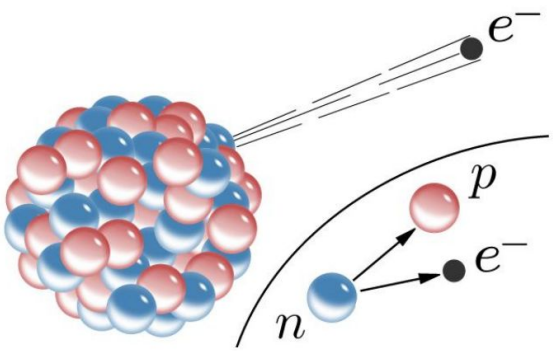
Abundant

Mysterious

Temperamental

Born out of desperation

Born out of desperation



beta-decay

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

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

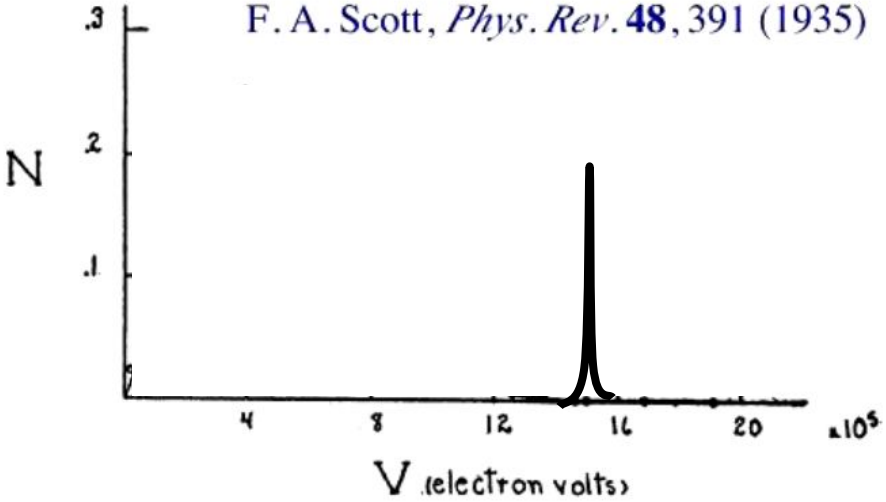
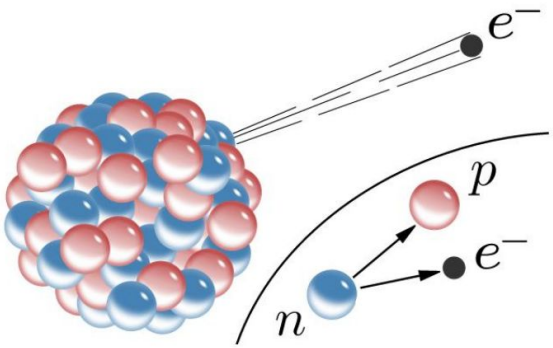


FIG. 5. Energy distribution curve of the beta-rays.

Born out of desperation



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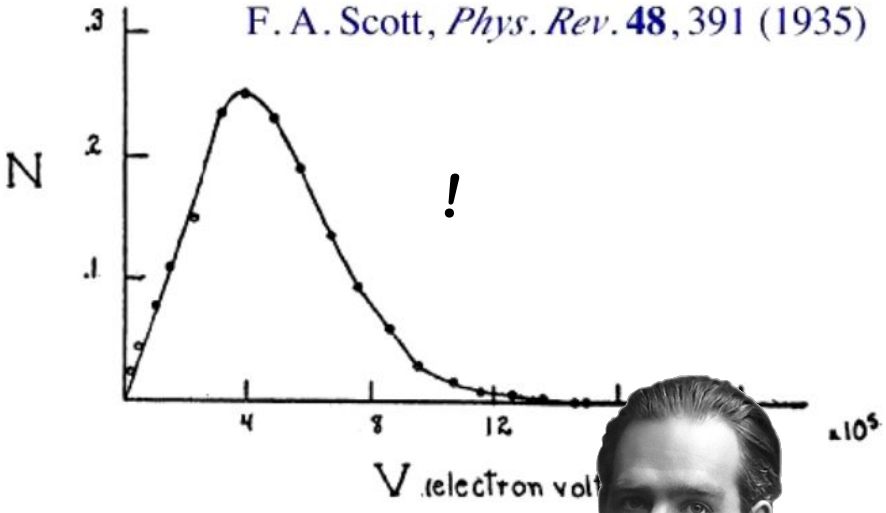
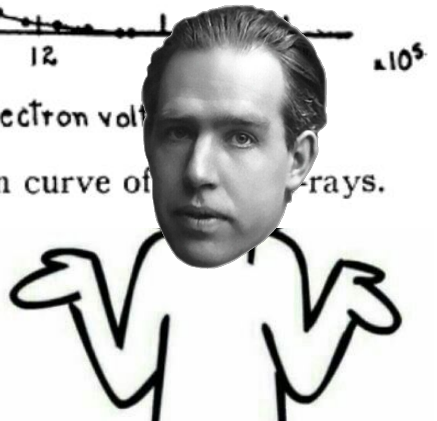
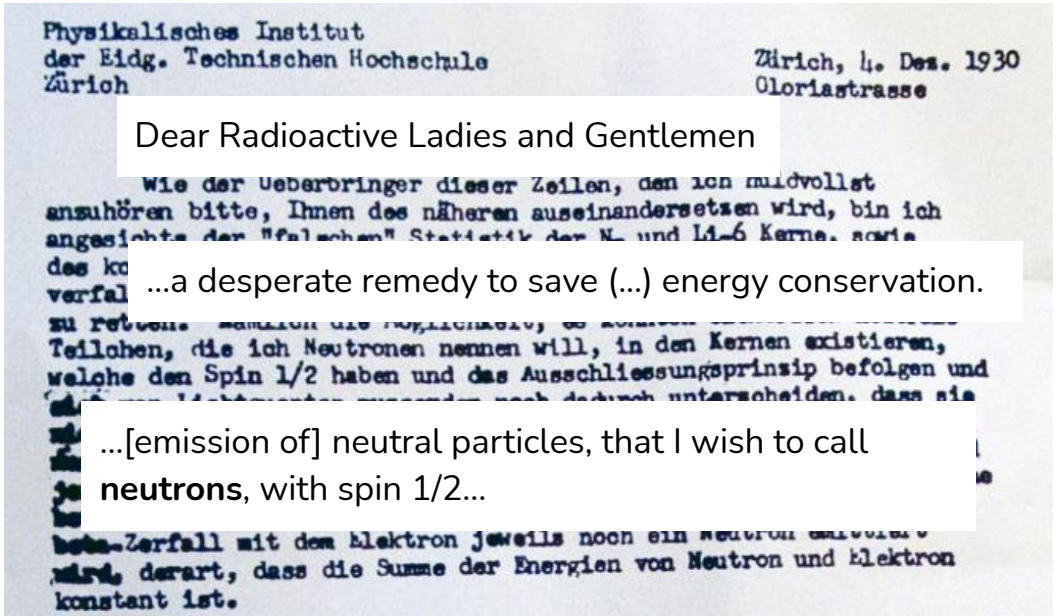




Born out of desperation



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen

Wie der Ueberbringer dieser Zeilen, den ich mildvollst
ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kc
verfal

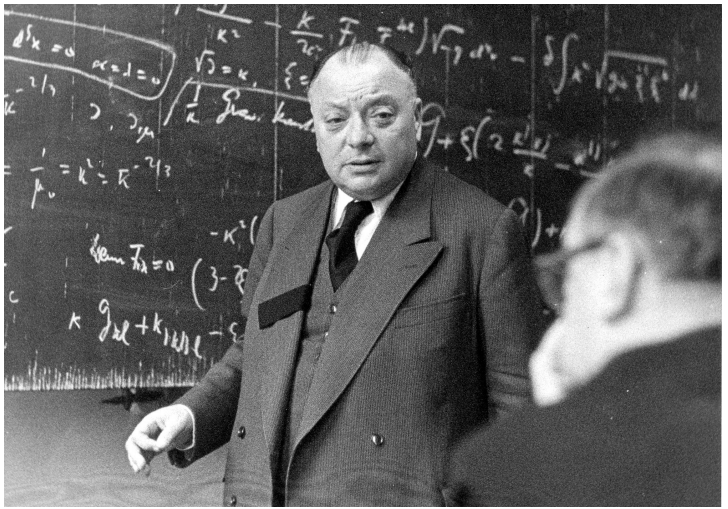
...a desperate remedy to save (...) energy conservation.

zu retten
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und

...[emission of] neutral particles, that I wish to call **neutrons**, with spin 1/2...

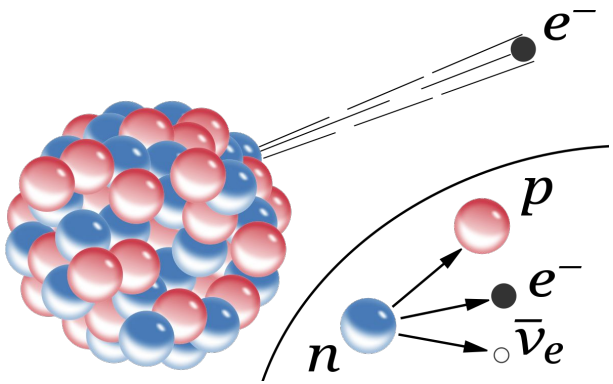
Beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, derart, dass die Summe der Energien von Neutron und Elektron
konstant ist.

(...indispensable here in Zurich due to a ball)



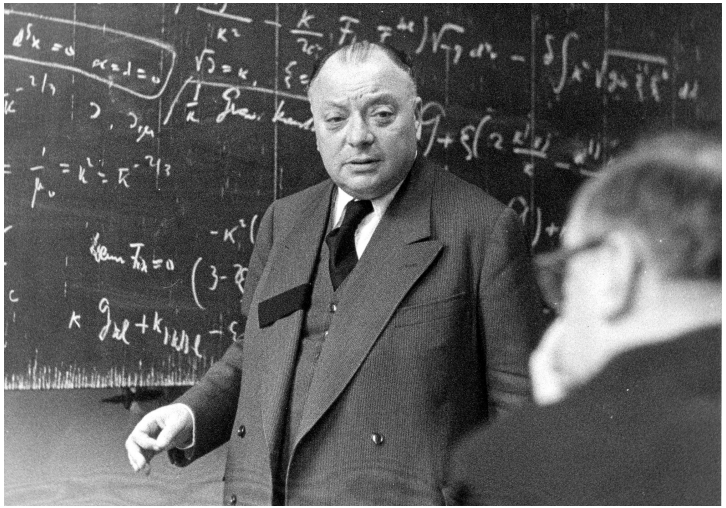
Wolfgang Pauli

Born out of desperation



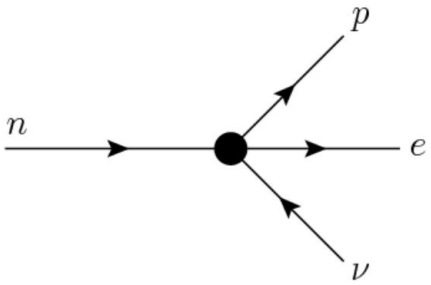
$$n \rightarrow p + e^- + \overline{\nu}_e$$

Neutrino must be **very light**
(could be massless!)

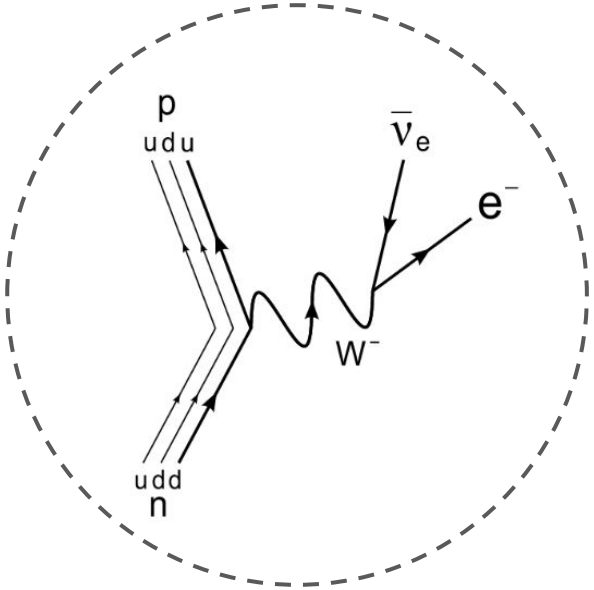


"I have done a terrible thing, I have postulated a particle that cannot be detected."

Shy (ghost-like)



Fermi interaction



$$\mathcal{L} = G_F(\psi_\nu^\dagger \gamma^\mu \psi_e)(\psi_p^\dagger \gamma_\mu \psi_n)$$

$$G_F \simeq 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

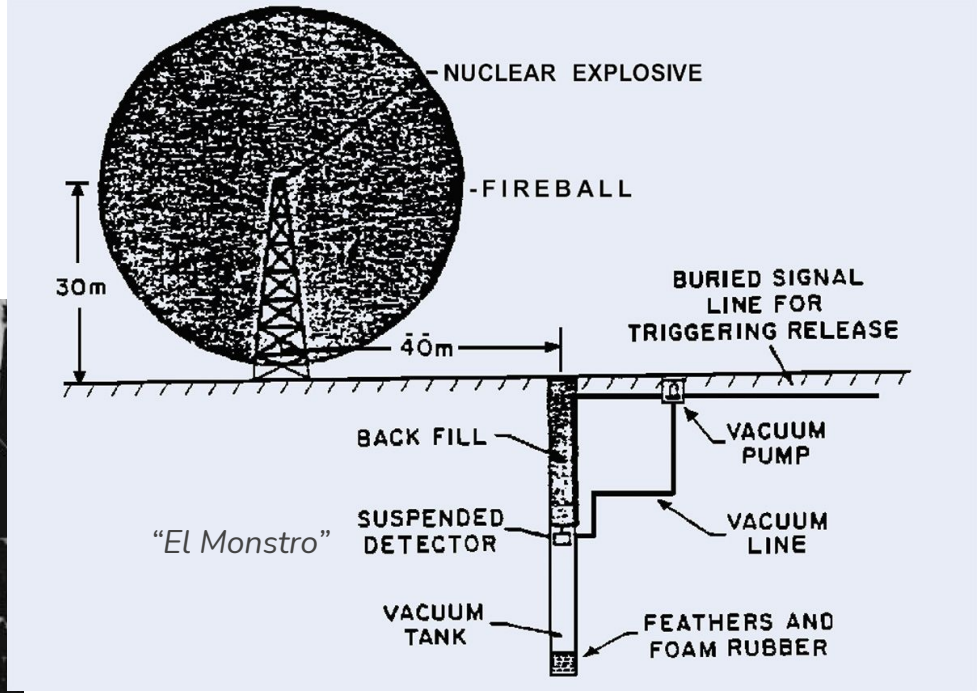
(Fermi constant)

The interaction is mediated by a W boson

Neutrinos only interact **weakly** and **gravitationally**

Shy (ghost-like)

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



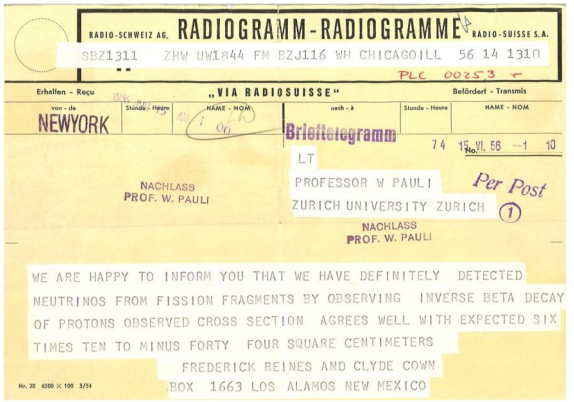
"El Monstro"

Approved by the Director of the Los Alamos Laboratory!
Then they realized a nuclear reactor would work better...

Shy (ghost-like)

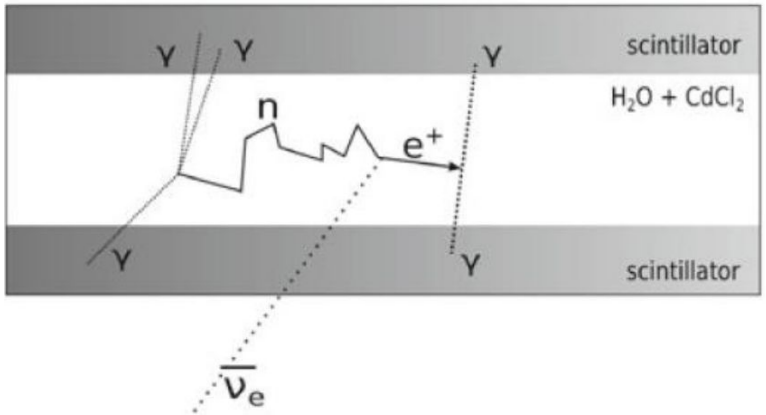
Direct detection of a neutrino
Cowan-Reines experiment (1956)

(1995)



"Everything comes to him who knows how to wait."

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

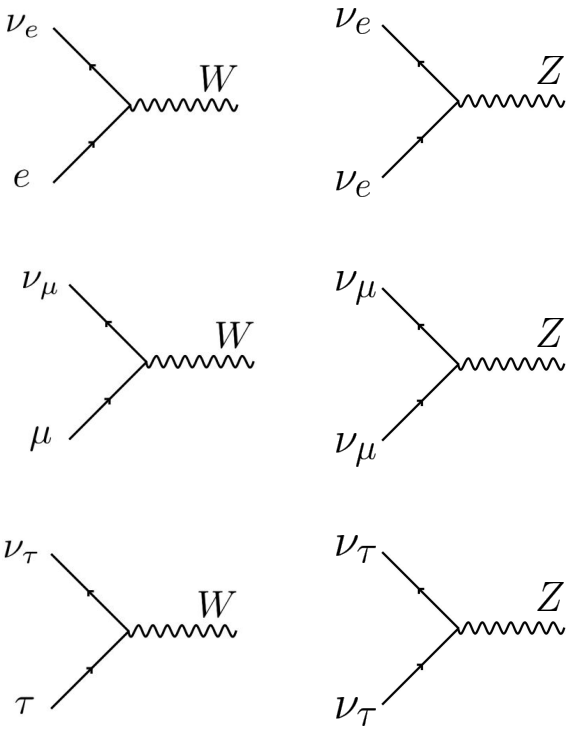


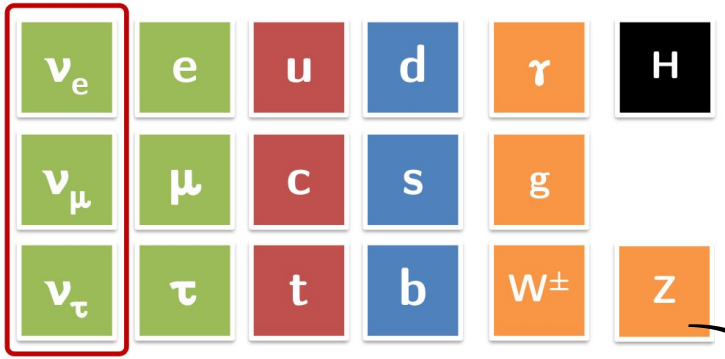
$$\sigma \sim 6 \times 10^{-44}\ \mathrm{cm}^2$$

mean free path of a
few-MeV neutrino in lead?

~1 light-year!

Three

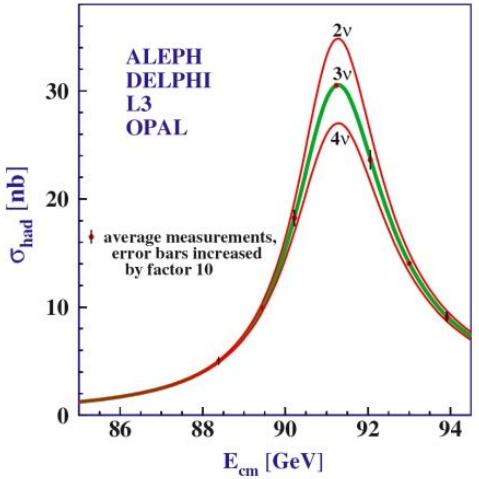




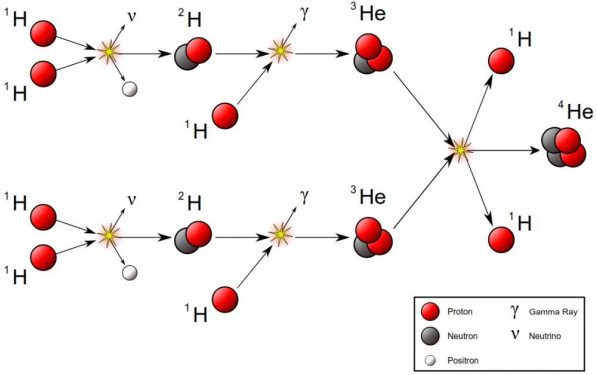
(1988)

Muon neutrino (1962)
Lederman, Schwartz, Steinberger

Tau neutrino (2000)
DONUT collaboration

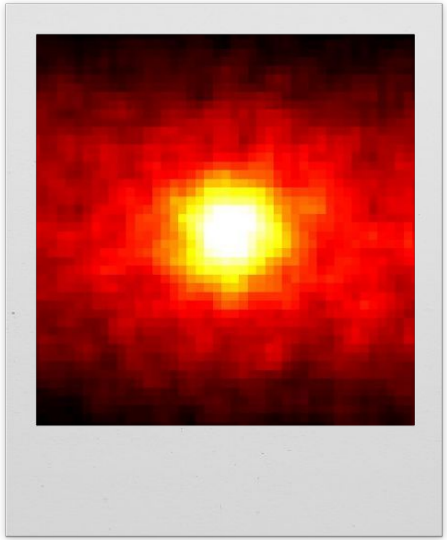


Abundant

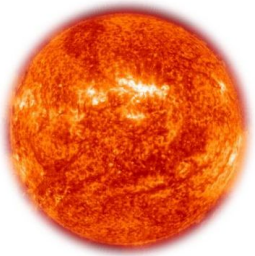


The Sun **shines via neutrinos**!

The Sun shines at night and underground!



The Sun as seen by an underground neutrino detector (Super-Kamiokande)



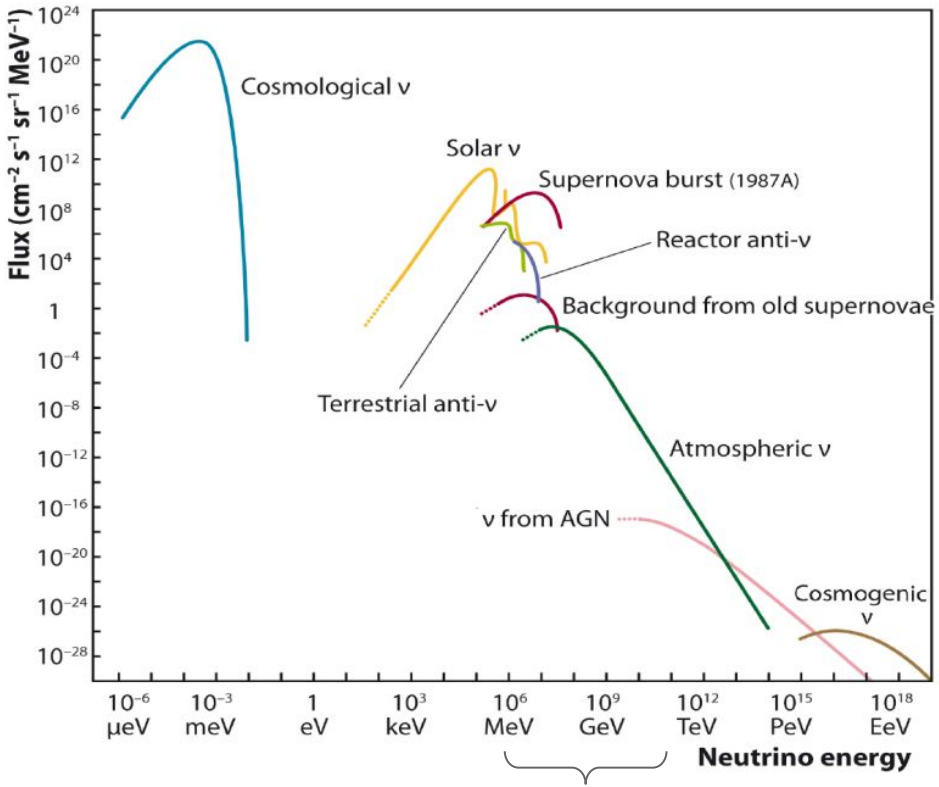
$$\sim 7 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

(thankfully, they are shy)

50 000 tonnes of ultra-pure water

Abundant (and Fast)

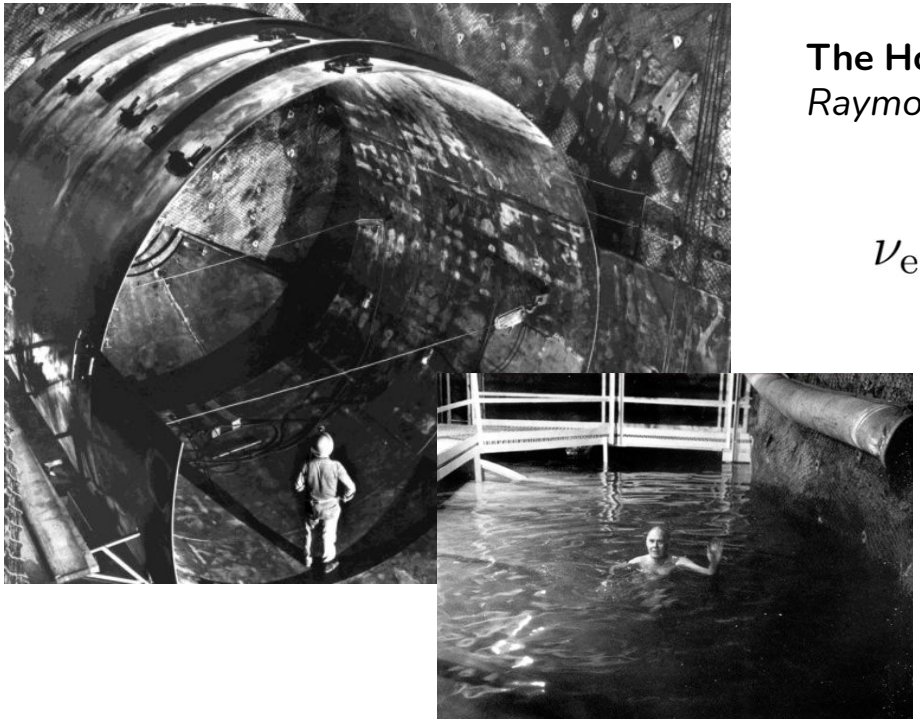
A plethora of neutrino sources!



Non-relic neutrinos are relativistic (v ~ c)

Temperamental

The Sun shines in a cave in South Dakota, but not as much as expected...



The Homestake Experiment (1970-1994)
Raymond Davis, John Bahcall

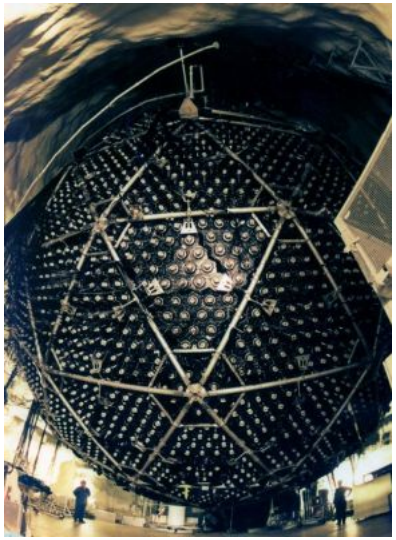
(2002)

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

extracted from the tank and counted

Only ~1/3 of the neutrino flux predicted by Bahcall's solar model!

Temperamental

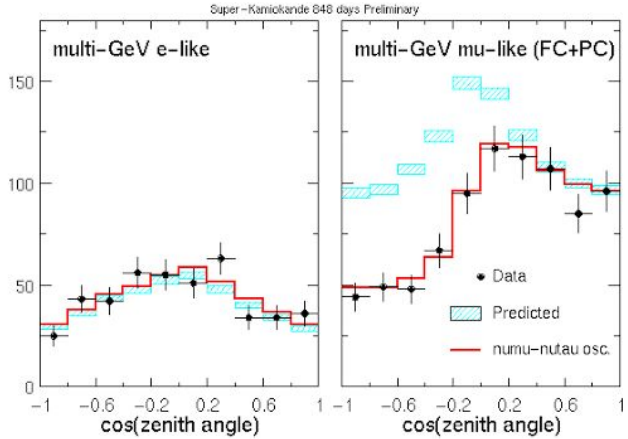


The Sudbury Neutrino Observatory (SNO, 2001)
~1000 tonnes of ultra-pure heavy water
Can detect all 3 flavours of neutrinos

The expected solar neutrino flux was there,
they had just ***changed flavour!***

(2015)

Super-Kamiokande (1998)
Up-going muon neutrinos are
transforming into tau neutrinos



Neutrino oscillation: neutrinos can change flavour as they propagate!

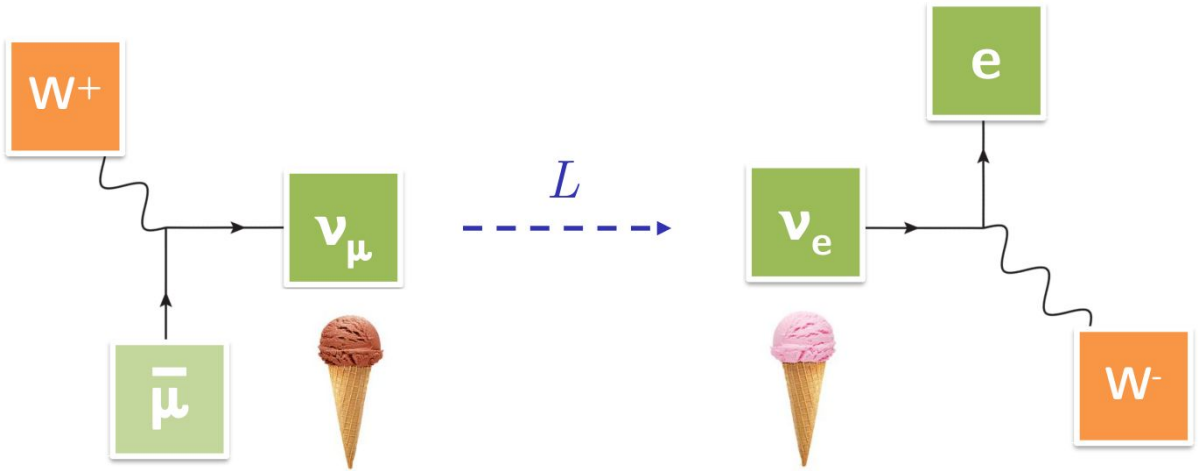
Temperamental

(aka **neutrino oscillation**)

Mixing matrix elements

$$|\nu_e\rangle = U^*_{e1}|\nu_1\rangle + U^*_{e2}|\nu_2\rangle + U^*_{e3}|\nu_3\rangle$$
$$|\nu_\mu\rangle = U^*_{\mu 1}|\nu_1\rangle + U^*_{\mu 2}|\nu_2\rangle + U^*_{\mu 3}|\nu_3\rangle$$
$$|\nu_\tau\rangle = U^*_{\tau 1}|\nu_1\rangle + U^*_{\tau 2}|\nu_2\rangle + U^*_{\tau 3}|\nu_3\rangle$$

Bruno Pontecorvo



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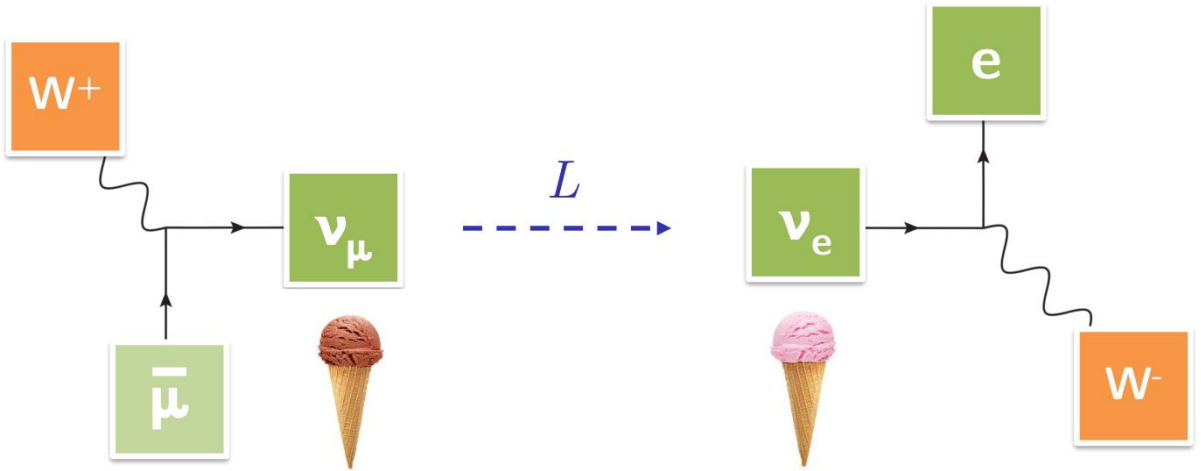
Бруно Понтекорво



Neutrino oscillation: neutrinos can change flavour as they propagate!

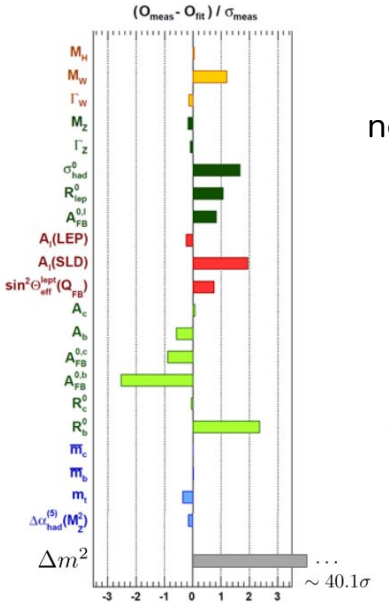
Light (but not massless)

...a 40σ deviation from the Standard Model!?

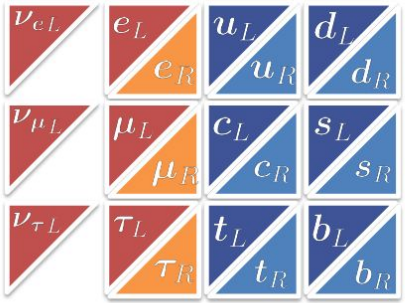
In a *2-neutrino approximation*,

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \ \ \sin^2\left(\frac{\Delta m^2 \, L}{4E}\right)$$

depends on the $U_{\alpha i}$



In the Standard Model, neutrinos cannot get a mass (by construction)

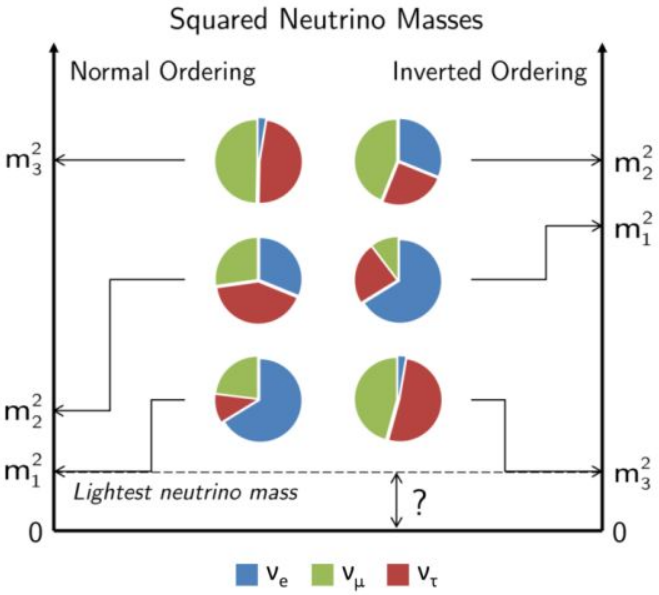


Neutrino oscillations are observed!

difference of squares of neutrino masses m_i

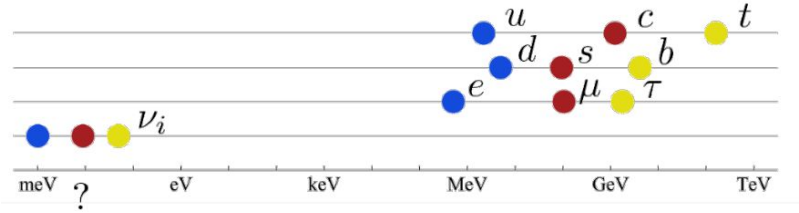
$$\Delta m^2 \neq 0$$

(massively) Mysterious



Other unknowns: octant of θ_{23}, δ_{CP}

Bound on the mass scale?



- Beta-decay endpoint (KATRIN, 90% CL)

$$\sqrt{\sum_i m_i^2 |U_{ei}|^2} < 1.1 \text{ eV}$$

- Cosmology (Planck 2018, 95% CL)

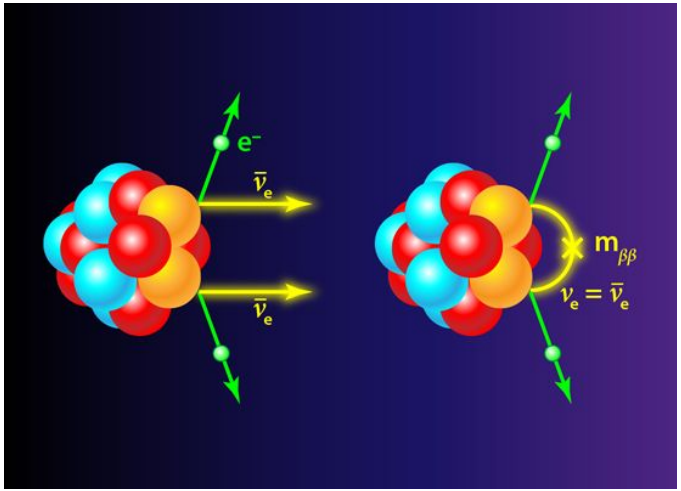
$$\sum_i m_i < 0.1 - 0.5 \text{ eV}$$

(massively) Mysterious

Unlike the other elementary fermions (which have **Dirac** masses),
neutrinos could have **Majorana** masses and **be their own anti-particles**

Chi l'ha visto ?

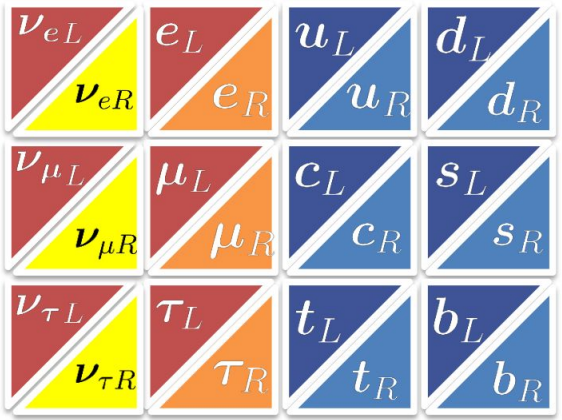
Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Mariannecci, Viale Regina Margherita 66 - Roma.



Neutrinoless double beta decay: a process which can only occur if neutrinos are Majorana particles

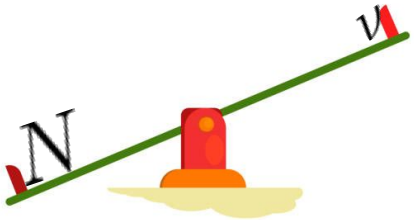
Messengers from Beyond the Standard Model

Most direct SM extension?



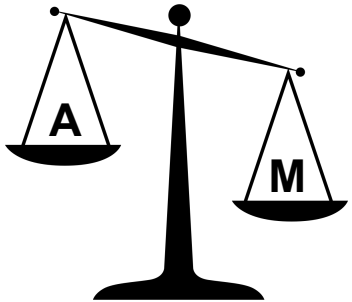
Leads naturally to small Majorana masses for the neutrinos

(**Seesaw** mechanism)



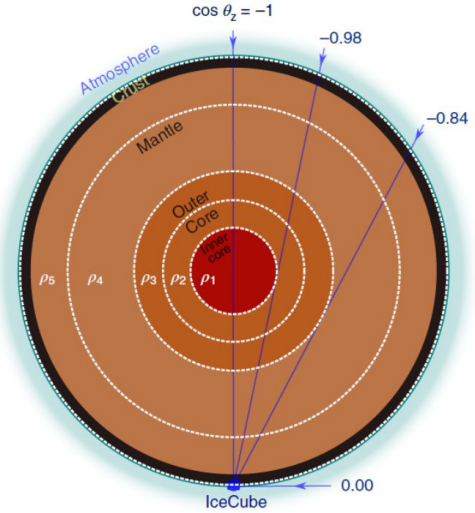
New, heavy neutrinos also appear in the theory. Their decays in the early Universe could explain why matter dominates over anti-matter

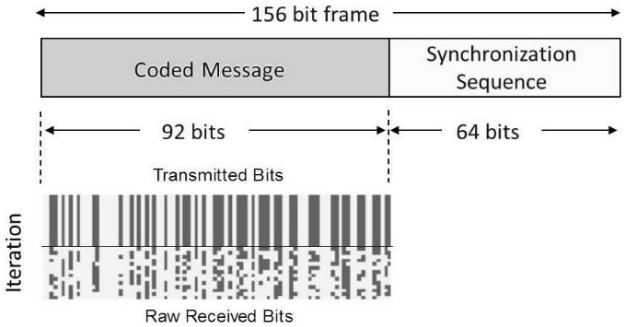
(**Leptogenesis**)



(Useful?)

- See inside the Earth (tomography) and measure its mass
  Donini et al., Nature Phys. 15 (2019) 1, 37
- Communicate (proof of concept)
  MINERvA collab., Mod.Phys.Lett.A 27 (2012) 1250077
- Neutrino detectors as tools for nuclear security





Neutrinos are

Light, Fast, Abundant, Shy, Three, Mysterious, Temperamental, Born out of desperation...

...and potential Messengers from Beyond the Standard Model