The elusive neutrino

03 June 2021

Neutrino University summer lectures Fermilab - online

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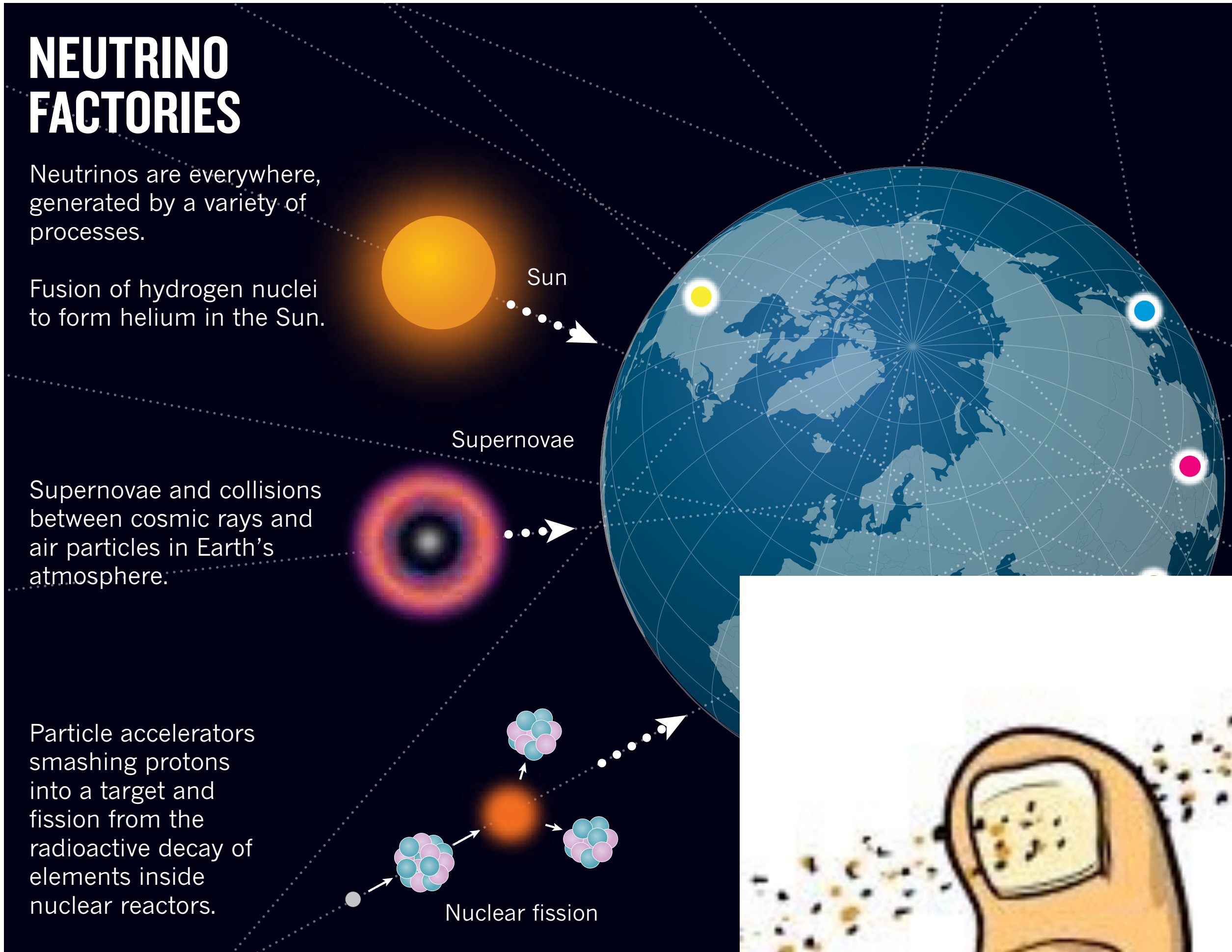
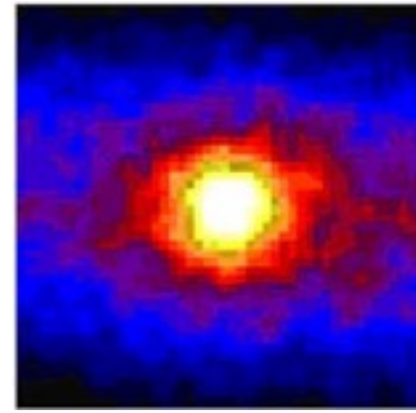
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos
Horizon2020
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
Durham University
IP3

Neutrinos are all around and through us.



@Nature, 2015



@Super-Kamiokande

Neutrinoscope

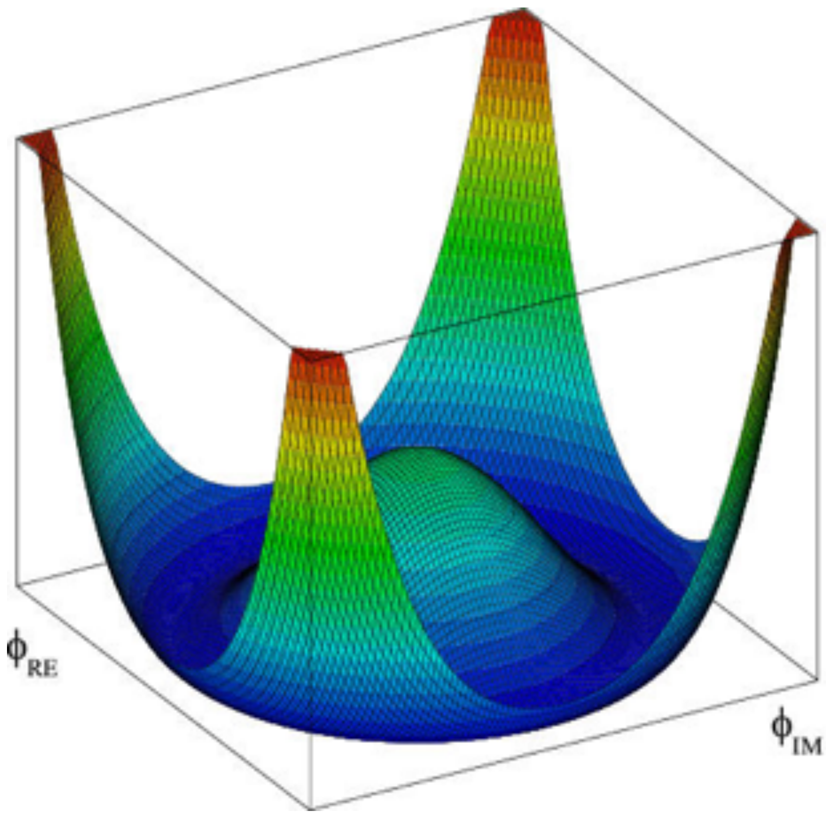
Neutrinoscope is a free App for iPhone and iPad developed by Cambridge Consultants and Durham University. It allows to visualise the neutrinos as they are around us.

Neutrinos in the SM

SM is a gauge theory

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

SSB breaking and the Higgs mechanism

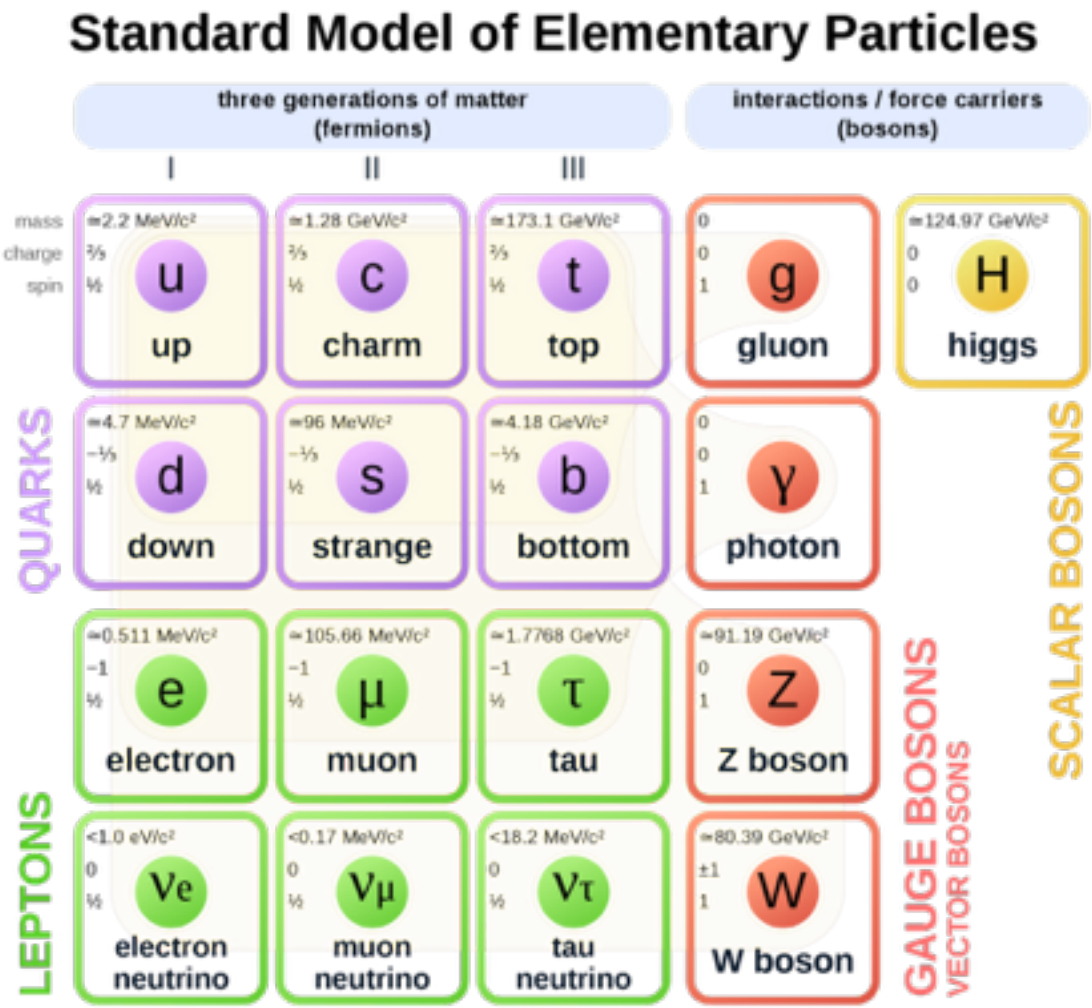


Yukawa interactions of fermions with the Higgs, after SSB, lead to mass terms for the quarks and charged leptons:

$$y_e \bar{e}_R L \cdot H \xrightarrow{\langle H^0 \rangle = v_H/\sqrt{2}} m_e \bar{e}_R e_L$$

Note: Commonly one uses natural units: c=1, hbar=1, G=1.

Neutrinos are the lightest and most elusive of all the known elementary particles.

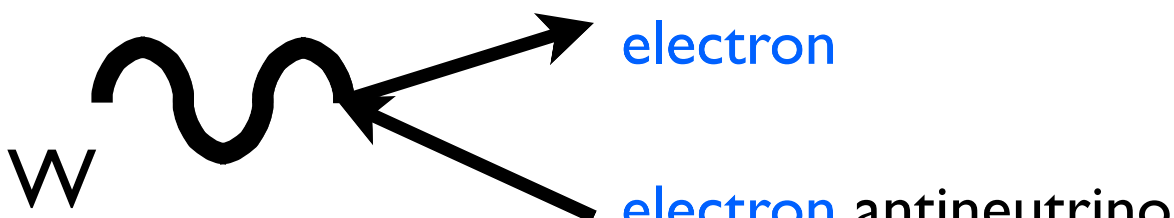


- Neutrinos in the SM are described by Weyl spinors with left chirality ($P_L = 1 - \gamma_5/2$).

- The theory is chiral (L and R do not behave the same). For instance nuR is not included.

- Neutrinos come in 3 flavours, corresponding to each of the charged leptons.

Particles	$SU(3)$	$SU(2)_L$	$U(1)_Y$
Leptons			
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L, \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L, \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	**1**	**2**	$-1/2$
$e_R\,, \quad \mu_R\,, \quad \tau_R$	**1**	**1**	-1
Quarks			
$\begin{pmatrix}u\\ d\end{pmatrix}_L, \quad \begin{pmatrix}c\\ s\end{pmatrix}_L, \quad \begin{pmatrix}t\\ b\end{pmatrix}_L$	**3**	**2**	$1/6$
$u_R\,, \quad c_R\,, \quad t_R$	**3**	**1**	$2/3$
$d_R\,, \quad s_R\,, \quad b_R$	**3**	**1**	$-1/3$



- They carry lepton number, $U(1)_{\text{lepton}}$

$$\ell \xrightarrow{U(1)_{\text{lepton}}} e^{i\alpha}\ell \qquad \nu_L \xrightarrow{U(1)_{\text{lepton}}} e^{i\alpha}\nu_L$$

They have charge current (CC) and neutral current (NC) interactions

$$\mathcal{L}_{\rm SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \overline{\nu}_{\alpha L} \gamma^\mu \ell_{\alpha L} W_\mu - \frac{g}{2\cos\theta_W} \sum_{\alpha=e,\mu,\tau} \overline{\nu}_{\alpha L} \gamma^\mu \nu_{\alpha L} Z_\mu + \mathrm{h.c.}$$

Number of active neutrinos

The invisible width of the Z (measured precisely at LEP) restricts the number of active neutrinos to

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\bar{\nu}\nu}} = 2.984 \pm 0.008$$

Note: Additional neutrinos can be present but they cannot partake of the SM interactions and are called sterile neutrinos.

Neutrino cross sections

Neutrino/electron scattering

For $E_\nu \ll m_e$ $\qquad \sigma \sim G_F^2 E_\nu^2$

$E_\nu \gg m_e$ $\qquad \sigma \sim G_F^2 m_e E_\nu$

$$\sigma(\nu_e e) \simeq 0.93 \times 10^{-44}\mathrm{cm}^2 \frac{E_\nu}{\mathrm{MeV}} \qquad \sigma(\nu_{\mu,\tau} e) \simeq 0.16 \times 10^{-44}\mathrm{cm}^2 \frac{E_\nu}{\mathrm{MeV}}$$

Neutrino/nucleons scattering

For $E_\nu \ll m_p$ $\qquad \sigma \sim G_F^2 E_\nu^2$

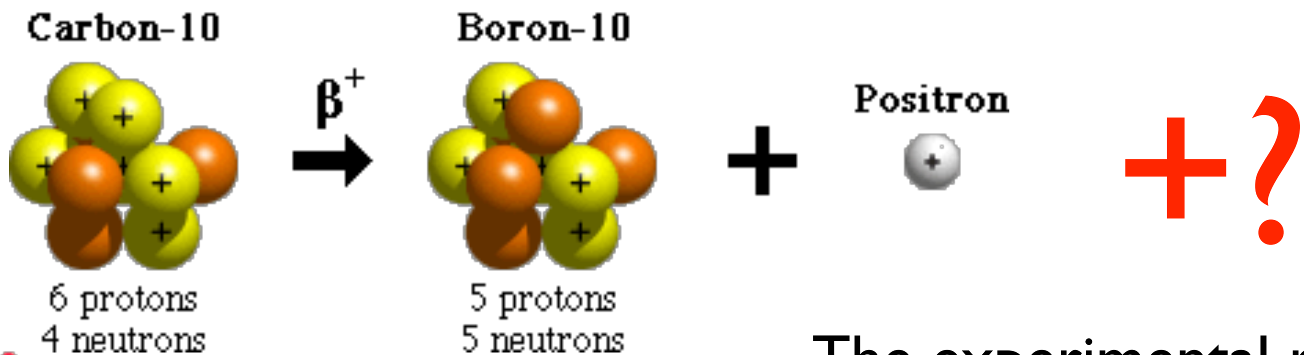
$E_\nu \gg m_p$ $\qquad \sigma \sim G_F^2 m_p E_\nu$

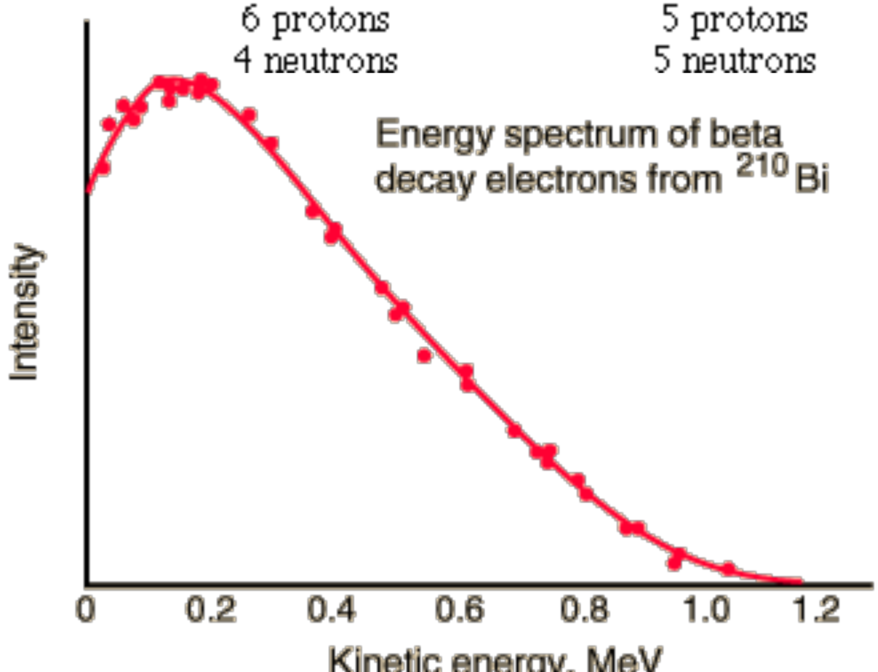
$$\sigma(\bar{\nu}_e p + e^+ n) \simeq 10^{-43}\mathrm{cm}^2 \frac{E_e p_e}{\mathrm{MeV}^2}$$

Neutrino/nuclei scattering

A brief history of our knowledge of neutrinos

Despite being the most abundant fermion in the Universe, we did not even realise they existed till the '30. The idea came about in the study of beta decays and a puzzle which troubled physicists for several decades.

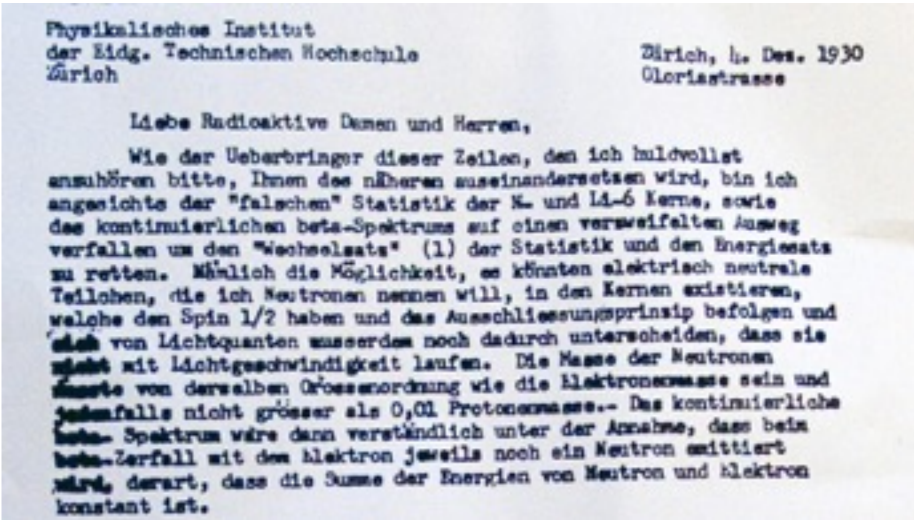




The experimental results were puzzling. The positron (= anti-electron) carries away different amounts of energy in each individual observed decay.

G. J. Neary, Roy. Phys. Soc. (London), A175, 71 (1940).

The proposal of the "neutrino" was put forward by W. Pauli in 1930. [Pauli Letter Collection, CERN]



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

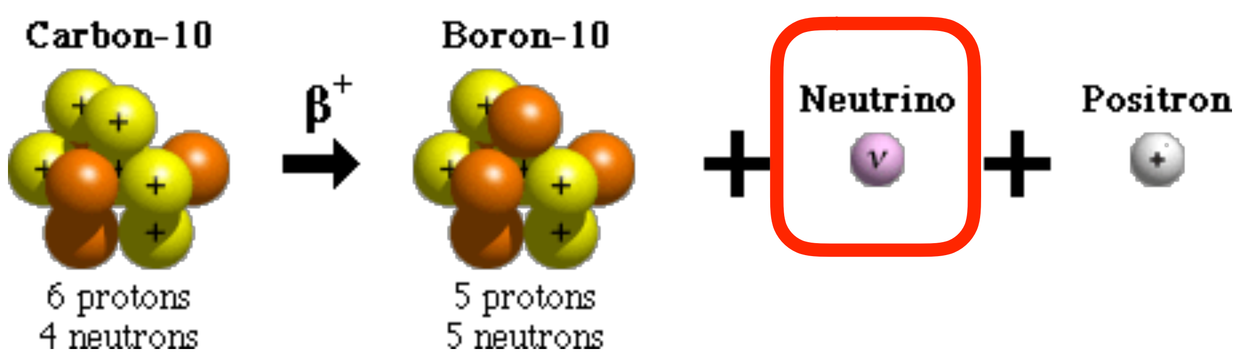
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen dürfte von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Dear radioactive ladies and gentlemen,

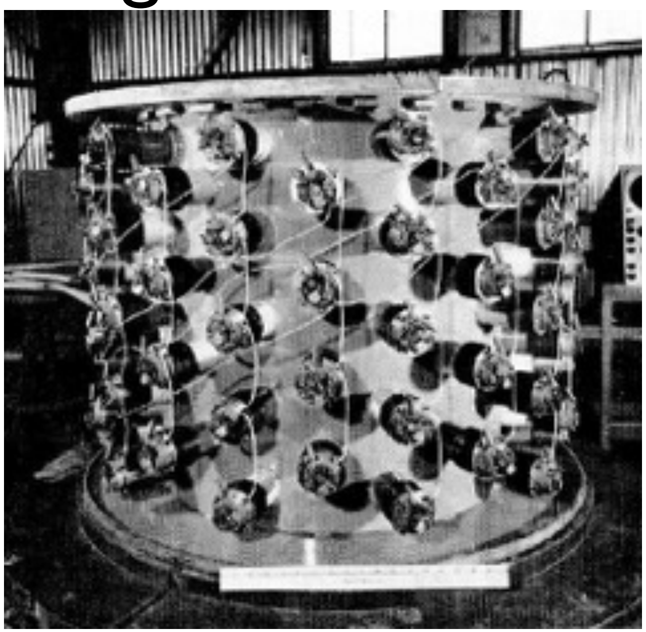
…I have hit upon a desperate remedy to save the … energy theorem. Namely the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 … The mass of the neutron must be … not larger than 0.01 proton mass. …in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

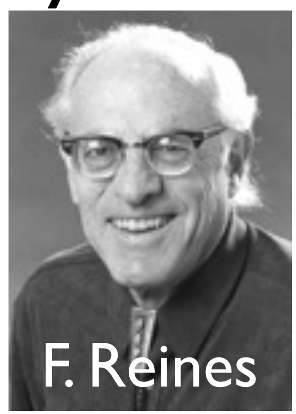


- Fermi, following E. Amaldi, used the name "neutrino" (little neutron) and later proposed the Fermi theory of beta decay.

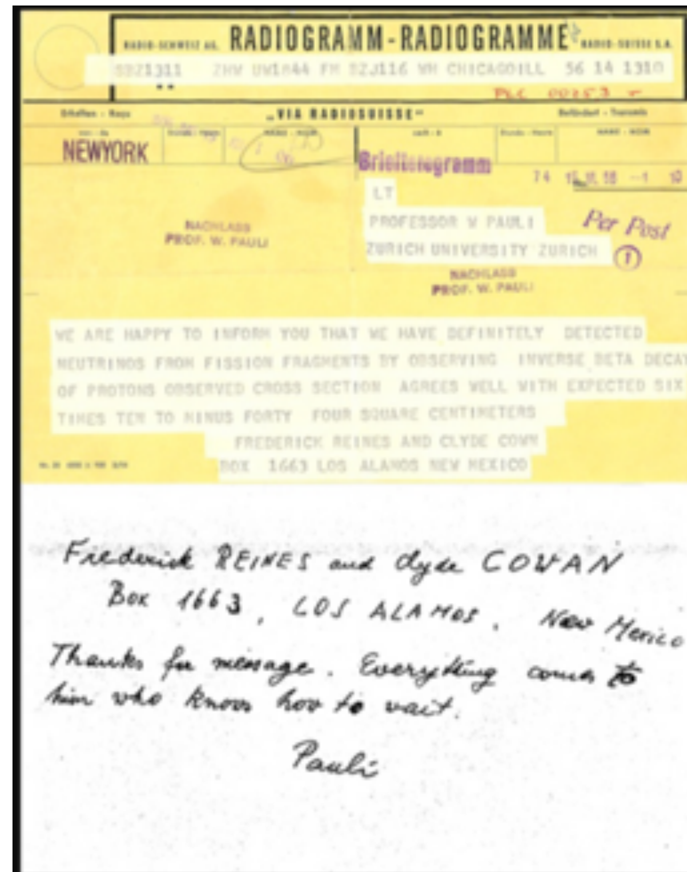

E. Fermi

- Reines and Cowan discovered neutrinos in 1956 using inverse beta decay.


Savannah River experiment


F. Reines

The Nobel Prize in Physics 1995


RADIOGRAMM-RADIOGRAMME

CHICAGOILL

"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

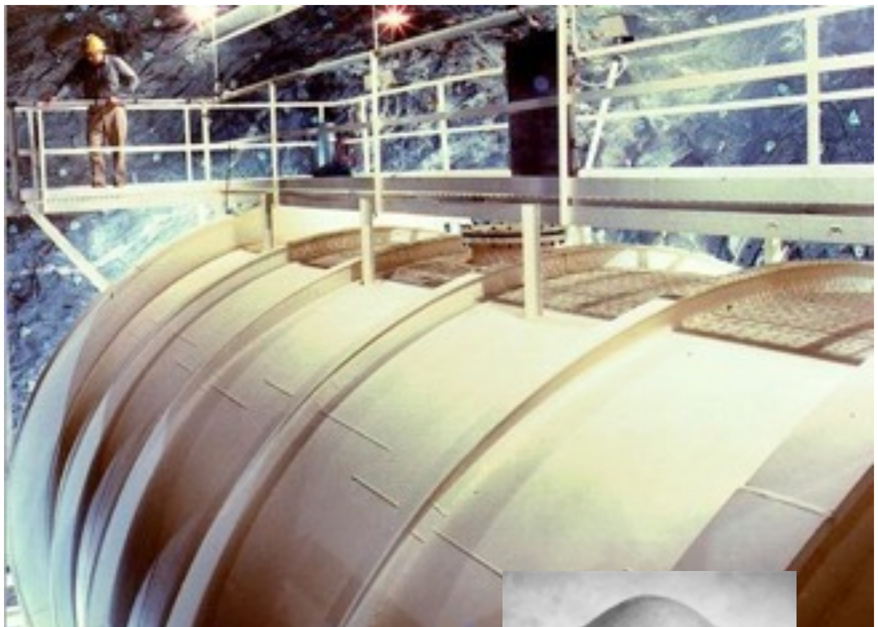
Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

- Madame Wu in 1956 demonstrated that the parity symmetry is violated in weak interactions. Neutrinos come only as left-handed (spin opposite to momentum) differently from all other fermions.

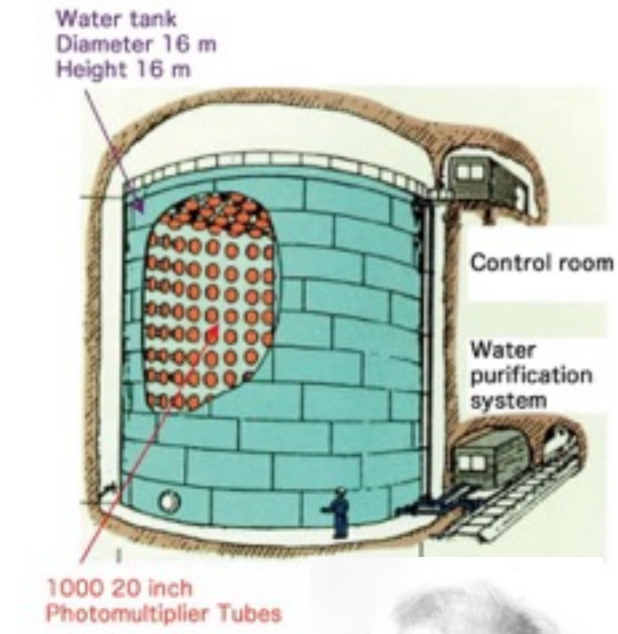
- Muon neutrinos were discovered in 1962 by L. Lederman, M. Schwartz and J. Steinberger.

The Nobel Prize in Physics 1988

After their discovery by Cowan and Reines, searches were performed for **astrophysical neutrinos**, produced in the Sun, Supernova and in the atmosphere.



The Homes take experi ment.



Kami okan de

R. Davis Jr.

Nobel prize in 2002

M. Koshiba

The first atmospheric neutrinos were observed in 1965 by the Kolar Gold Field (KGF) and Reines' experiments.

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

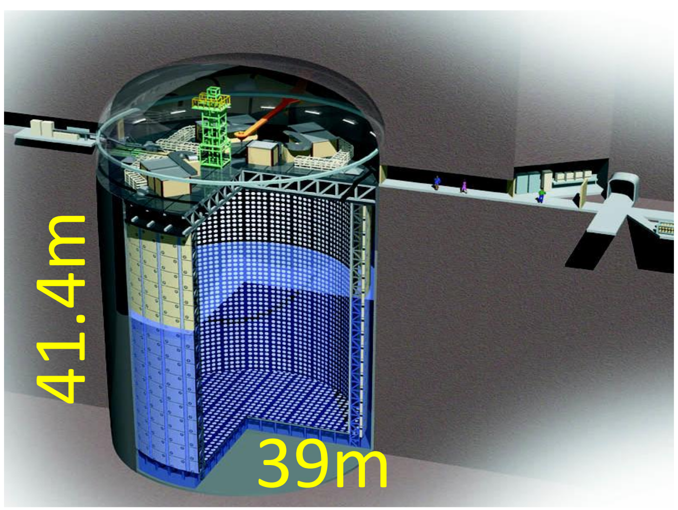
K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Neutrinos seemed to fit well in the picture of the SM which was forming. But soon some anomalies started to appear.

- First indications of ν oscillations came from solar ν: less electron neutrinos were observed than expected. Where did the others go?

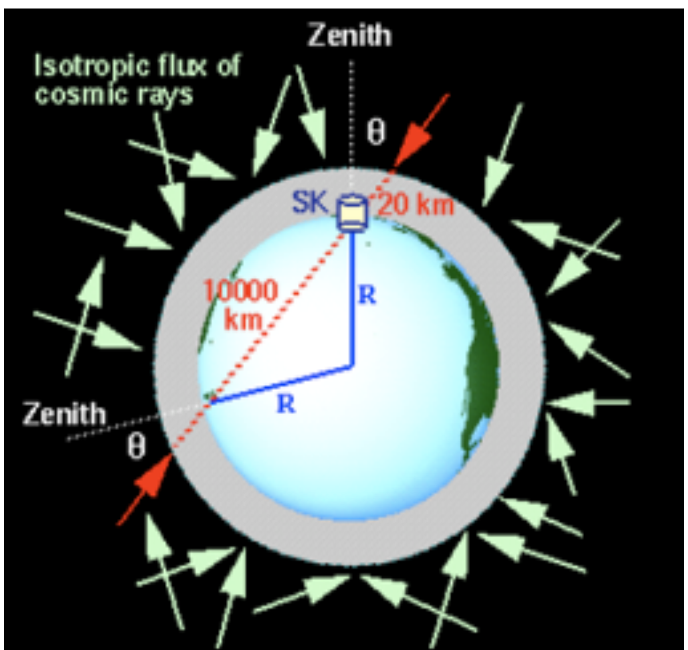


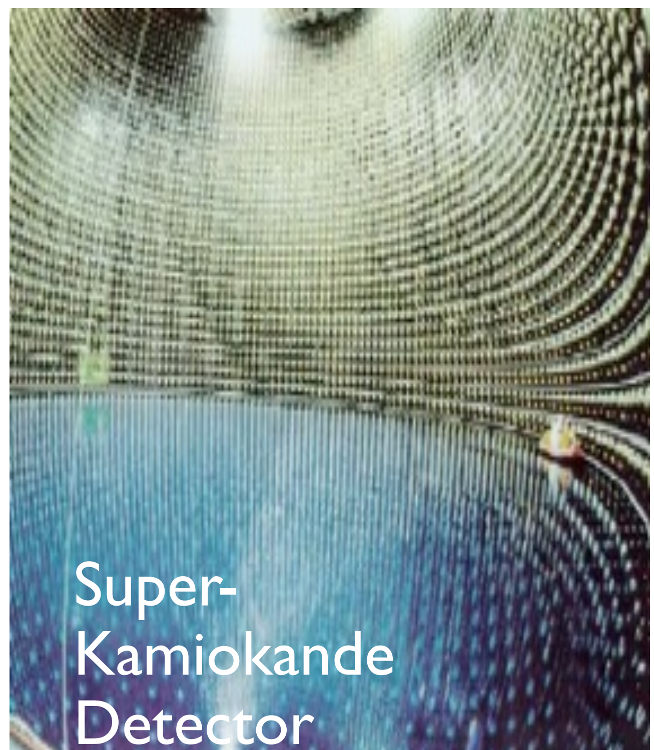
Super-Kamiokande

The SNO Detector

Nobel Prize in Physics 2015

- Indications of an anomaly in atmospheric neutrinos was presented in 1988, subsequently confirmed by MACRO.
- More muon neutrinos were seen going down than coming up from the other side of the Earth.
- Discovery was presented in 1998 by SuperKamiokande.





Nobel Prize in Physics 2015

What was going on?

These experiments showed that neutrinos oscillate, i.e. that can change flavour (going into flavours that some detectors cannot see).

Neutrinos are **chameleon** particles.

Neutrino oscillations: a quantum mechanical phenomenon

The first idea of neutrino oscillations was put forward by B. Pontecorvo in 1957.

In a SM interaction a neutrino of one type (electron, muon or tau) is produced. While travelling it changes its “flavour” and can even become another type of neutrino.

Neutrino mixing

Mixing is described by the *Pontecorvo-Maki-Nakagawa-Sakata* matrix:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

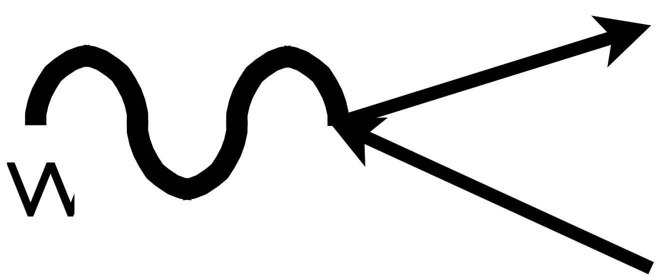
Flavour field

Mass field

which enters in the CC interactions

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{k\alpha} (U^*_{\alpha k} \bar{\nu}_{kL} \gamma^\rho l_{\alpha L} W_\rho + \mathrm{h.c.})$$

This implies that in an interaction with an electron, the corresponding (anti-)neutrino will be produced, as a superposition of different mass eigenstates.



Positron

electron neutrino $= \sum_i U^*_{ei} \nu_i$

- 2-neutrino mixing matrix depends on 1 angle only. The phases get absorbed in a redefinition of the leptonic fields (a part from 1 Majorana phase).

$$\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

- 3-neutrino mixing matrix has 3 angles and 1(+2) CPV phases.

$$\begin{pmatrix} \bar{\nu}_1 & \bar{\nu}_2 & \bar{\nu}_3 \end{pmatrix} e^{i\psi} \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \text{CKM-} \\ \text{type} \end{pmatrix} \begin{pmatrix} e^{i\rho_e} & 0 & 0 \\ 0 & e^{i\rho_\mu} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

One can always rephrase a field as:

$$\begin{aligned} e &\rightarrow e^{-i(\rho_e+\psi)} e \\ \mu &\rightarrow e^{-i(\rho_\mu+\psi)} \mu \\ \tau &\rightarrow e^{-i\psi} \tau \end{aligned}$$

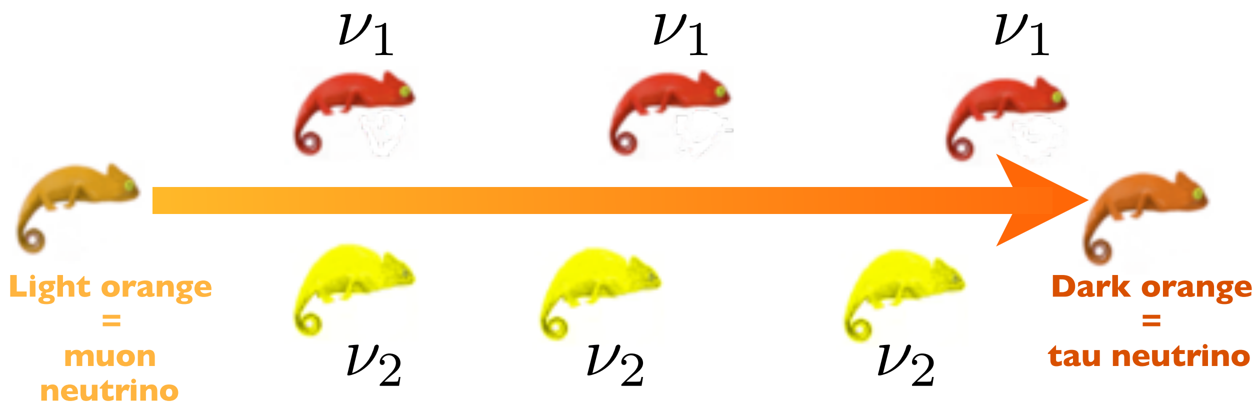
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}$$
$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

For antineutrinos, $U \to U^*$

CP-conservation requires $U \text{ is real} \Rightarrow \delta = 0, \pi$

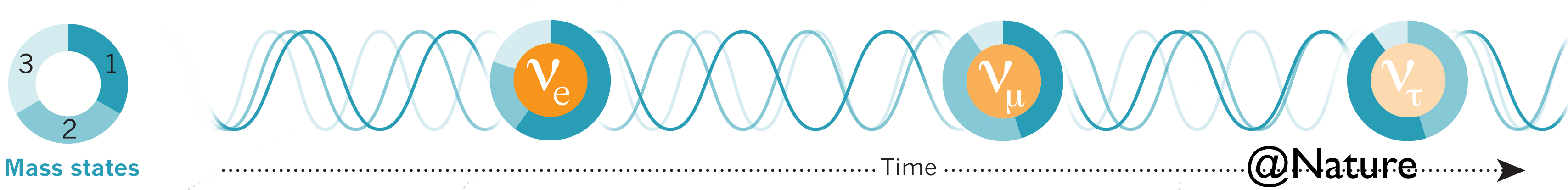
It is useful to express the CP violating effects in a rephrasing invariant manner (Jarlskog invariant):

$$J \equiv \Im[U_{\mu 3} U_{e2} U^*_{\mu 2} U^*_{e3}] = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

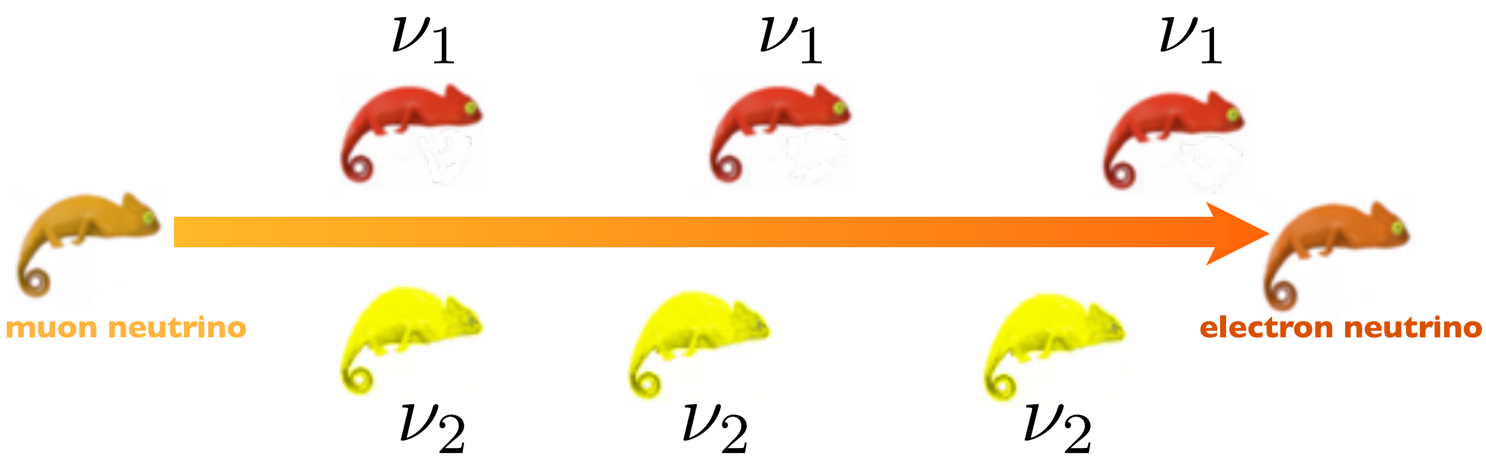


A flavour neutrino is a superposition of different mass states. If their mass is different, then they will evolve in time differently and later their combination can correspond to a different type of neutrino.

This is an eminently quantomechanical effect, similar to other observed ones, such as spin precession. It has an oscillatory behaviour.



Neutrinos oscillations in vacuum: the theory



Production	Propagation	Detection
Flavour states	Massive states (eigenstates of the Hamiltonian)	Flavour states

At production, coherent superposition of mass states:

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

Let's assume that at t=0 a muon neutrino is produced

$$|\nu, t=0\rangle = |\nu_\mu\rangle = \sum_i U^*_{\mu i} |\nu_i\rangle$$

The time-evolution is given by the solution of the Schroedinger equation with free Hamiltonian:

$$|\nu, t\rangle = \sum_i U^*_{\mu i} e^{-iE_i t} |\nu_i\rangle$$

In the same-momentum approximation:

$$E_1 = \sqrt{p^2 + m_1^2} \quad E_2 = \sqrt{p^2 + m_2^2} \quad E_3 = \sqrt{p^2 + m_3^2}$$

Note: other derivations are also valid (same E formalism, etc).

At detection one projects over the flavour state as these are the states which are involved in the interactions. The probability of oscillation is

$$
\begin{aligned}
P(\nu_\mu \to \nu_\tau) &= |\langle \nu_\tau | \nu, t\rangle|^2 \\
&= \left| \sum_{ij} U^*_{\mu i} U_{\tau j} e^{-iE_i t} \langle \nu_j | \nu_i \rangle \right|^2 \\
&= \left| \sum_{i} U^*_{\mu i} U_{\tau i} e^{-iE_i t} \right|^2
\end{aligned}
$$

Typically, neutrinos are very relativistic: $E_i \simeq p + \frac{m_i^2}{2p}$

$$
\begin{aligned}
&= \left| \sum_{i} U^*_{\mu i} U_{\tau i} e^{-i \frac{m_i^2}{2E} t} \right|^2 \\
&= \boxed{\left| \sum_{i} U^*_{\mu i} U_{\tau i} e^{-i \frac{m_i^2 - m_1^2}{2E} t} \right|^2}
\end{aligned}
$$

Δm^2_{i1}

Implications of the existence of neutrino oscillations

The oscillation probability implies that

$$P(\nu_\alpha \to \nu_\beta) \quad = \quad \left| \sum_i U^*_{\alpha 1} U_{\beta 1} e^{-i \frac{\Delta m^2_{i1}}{2E} L} \right|^2$$

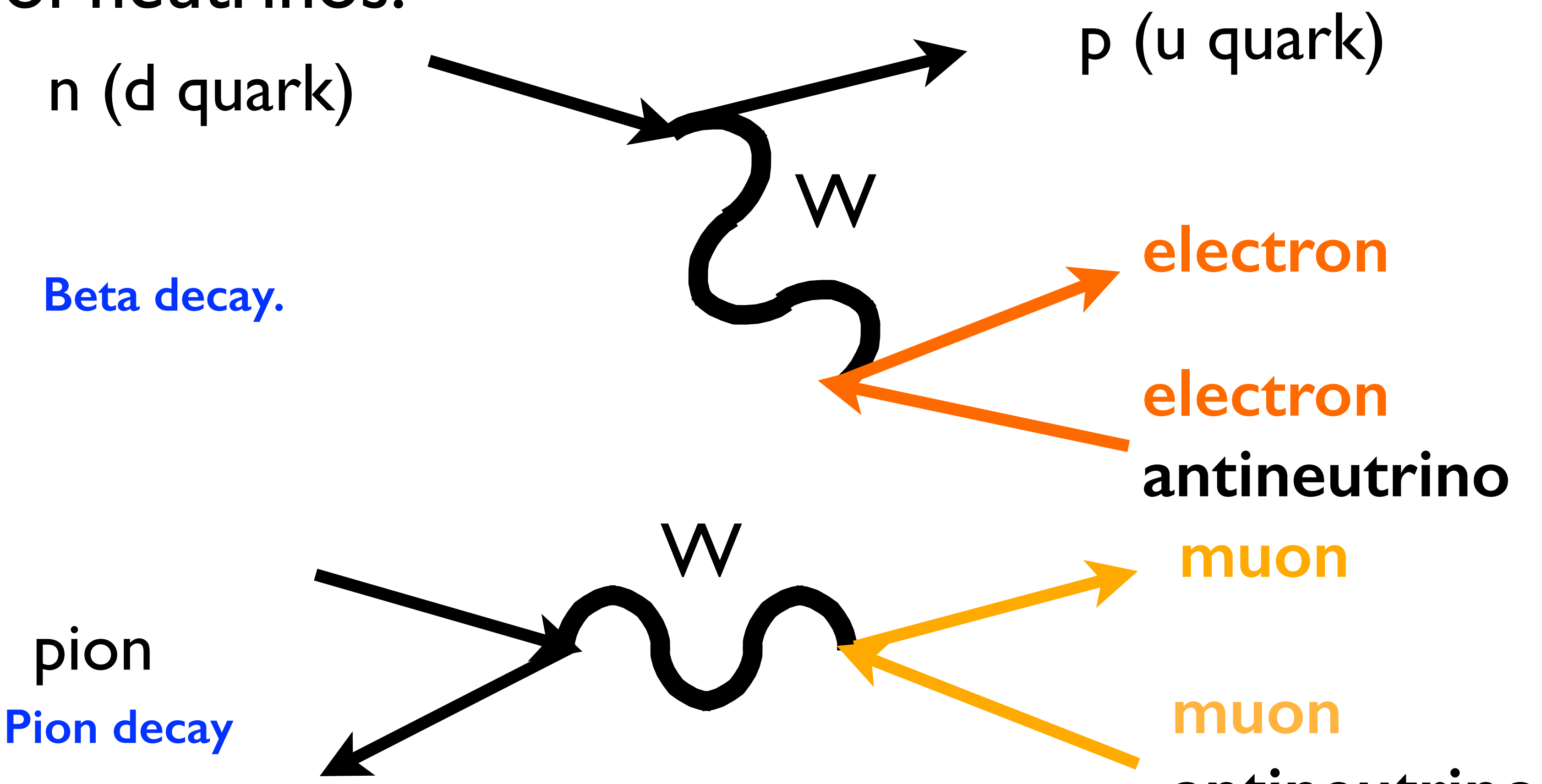
- **neutrinos have mass** (as the different components of the initial state need to propagate with different phases)

- **neutrinos mix** (as U needs not be the identity. If they do not mix the flavour eigenstates are also eigenstates of the propagation Hamiltonian and they do not evolve)

Neutrinos oscillations in experiments

Neutrino production

In CC (NC) SU(2) interactions, the W boson (Z boson) will be exchanged leading to the production of neutrinos.



Decay into electrons is suppressed.

Neutrino propagation

At the neutrino energy of beta decays, the average distance before an interaction (mean free path) in water (1 g/cm^3) is
d= 2 x 10^17 m ~ 200 lightyears!

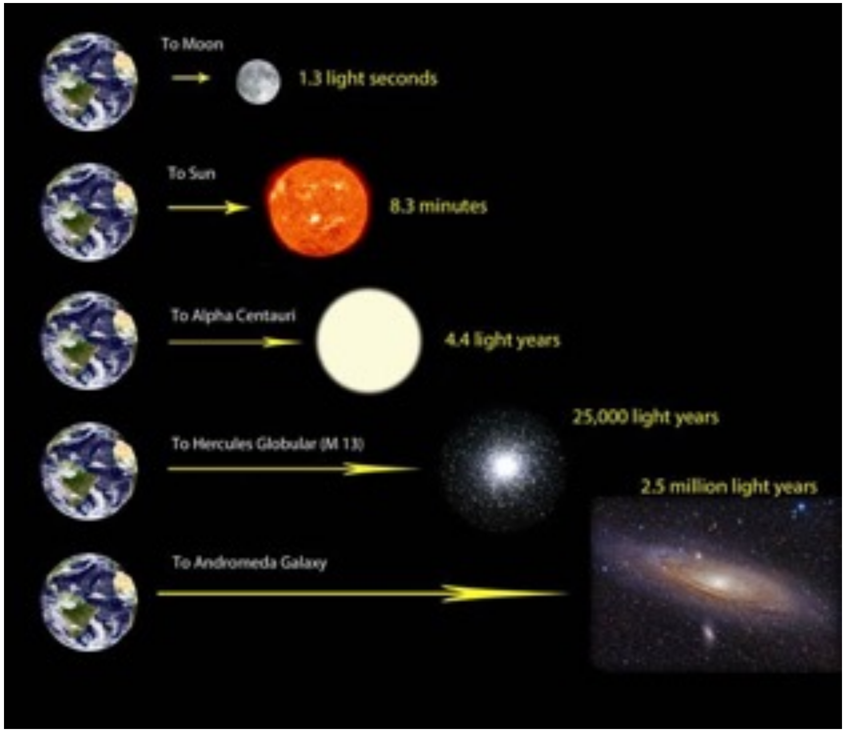
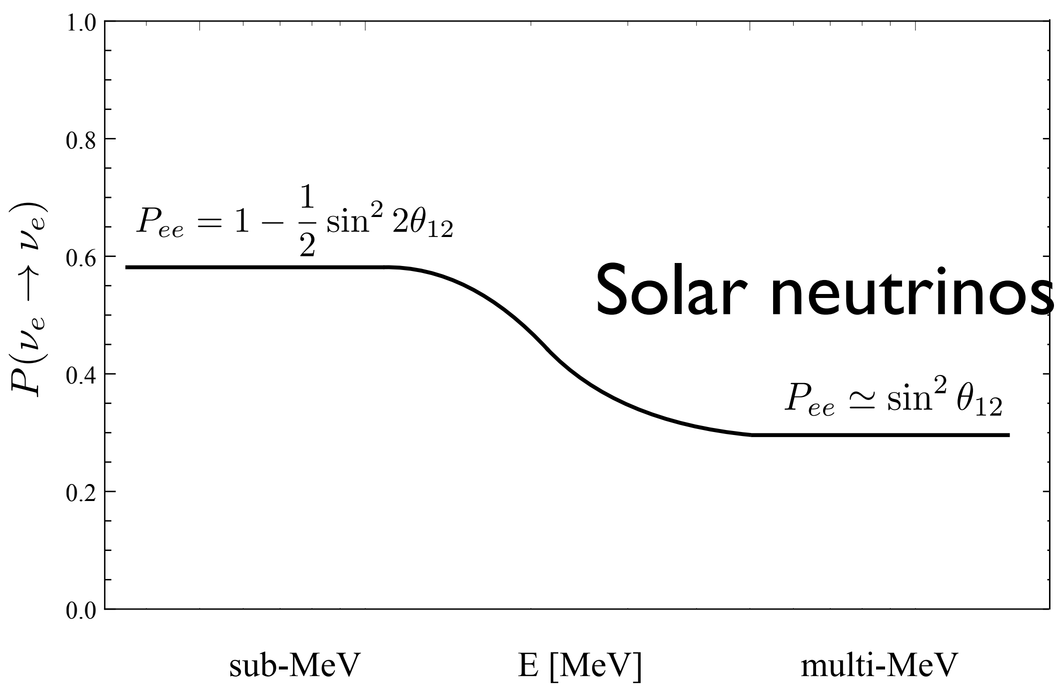


Image from Bob King/ Skyandtelescope. com.

When neutrinos travel through a medium, they interact with the background of electrons, protons, neutrons (and possibly other particles), acquiring an effective mass. This modifies the oscillation probability w.r.t. vacuum.

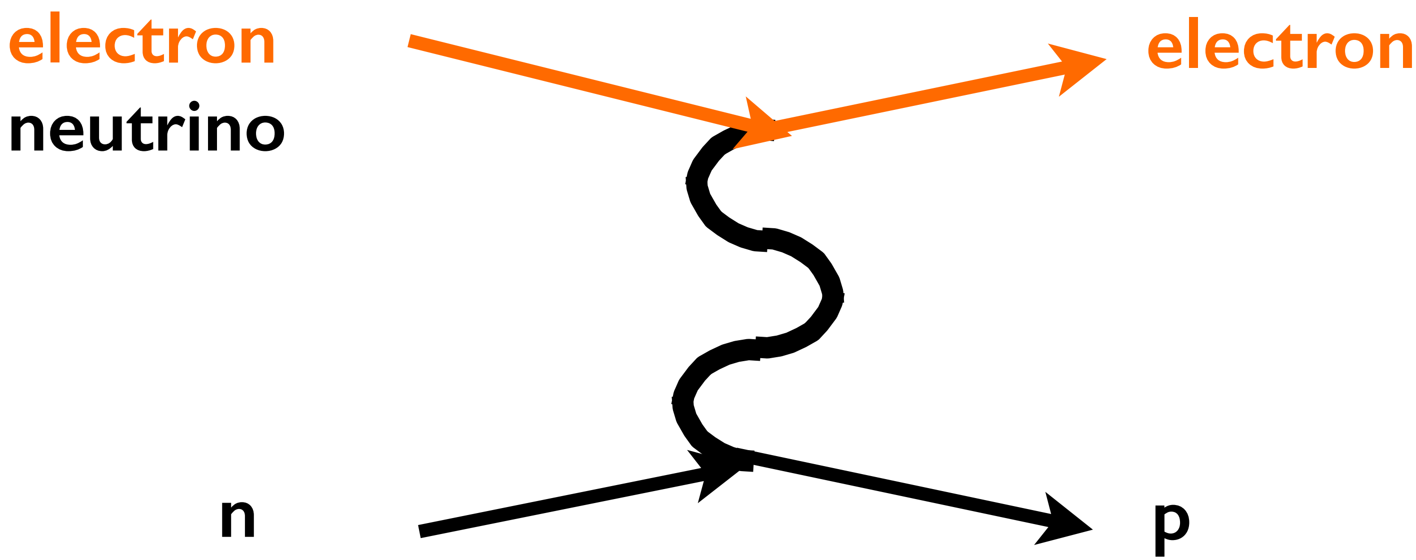
$$\tan(2\theta_m) = \frac{\frac{\Delta m^2}{2E}\sin(2\theta)}{\frac{\Delta m^2}{2E}\cos(2\theta) - \sqrt{2}G_F N_e}$$



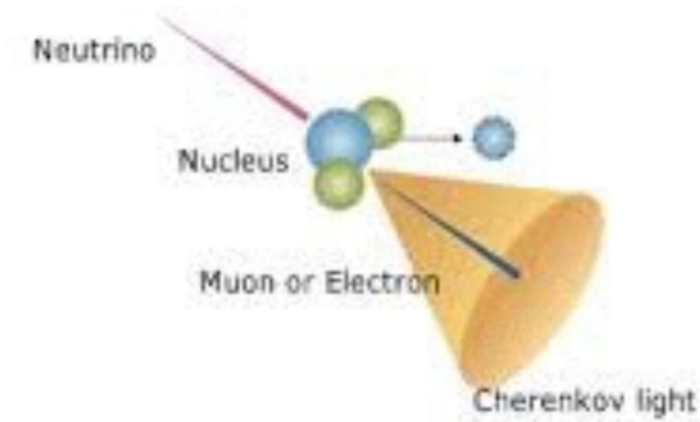
Solar neutrinos: MSW effect

Neutrino detection

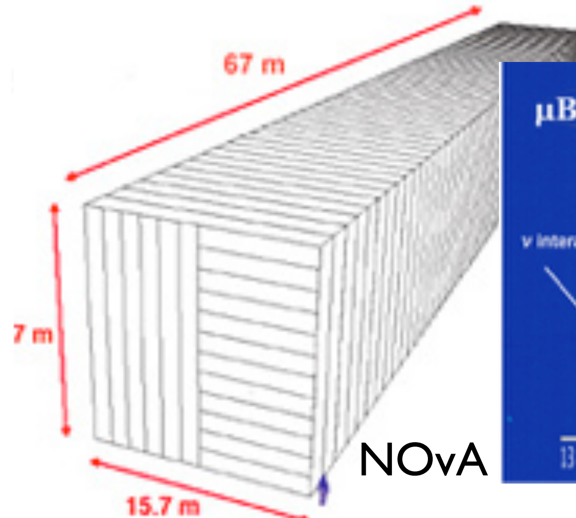
Neutrino detection proceeds via CC (and NC) SU(2) interactions. Example:

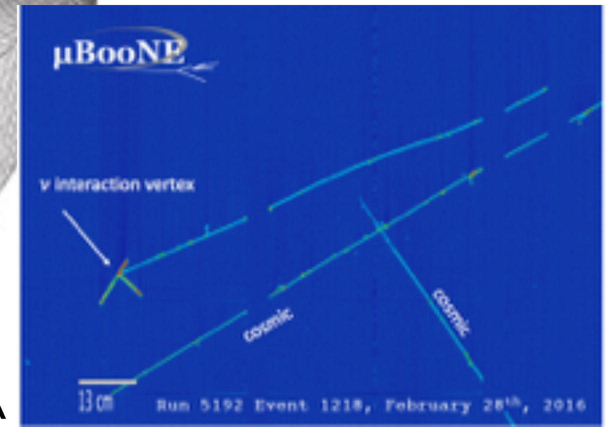


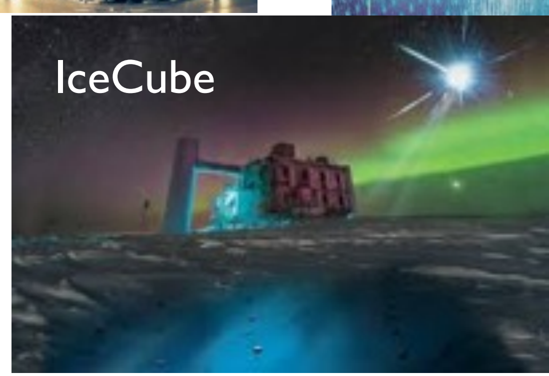
We are interested mainly in produced charged particles as these can emit light and/or leave tracks in segmented detectors (magnetisation -> charge reconstruction). Notice that the leptons have different masses:
me = 0.5 MeV < mmu = 105 MeV < mtau= 1700 MeV.

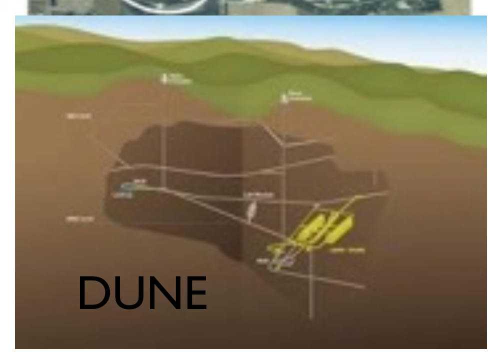


Credit: Super-Kamiokande



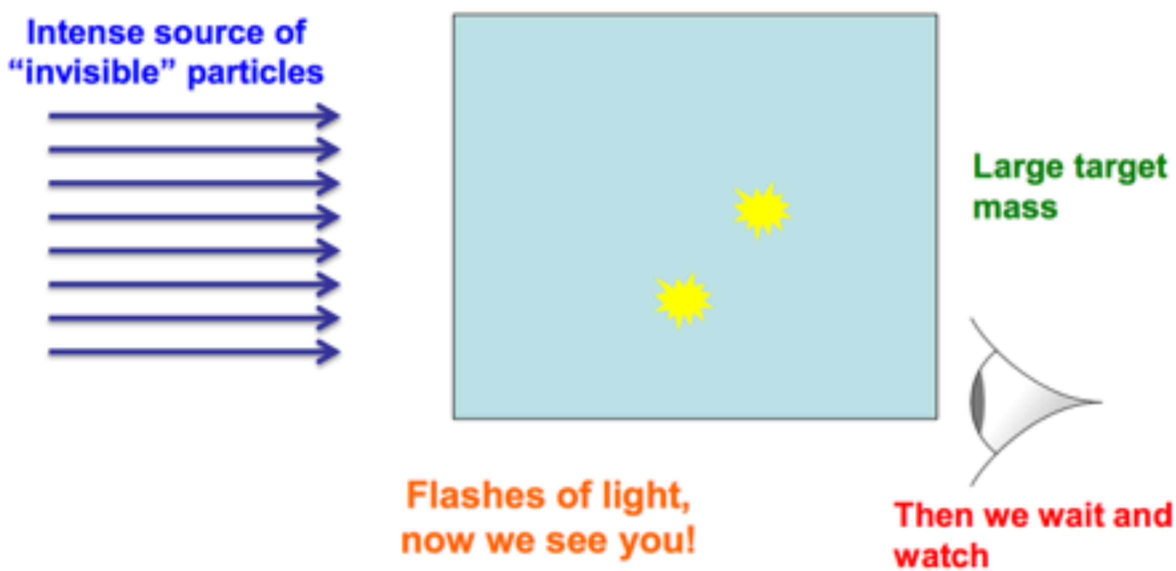






Recipe to build a neutrino experiment

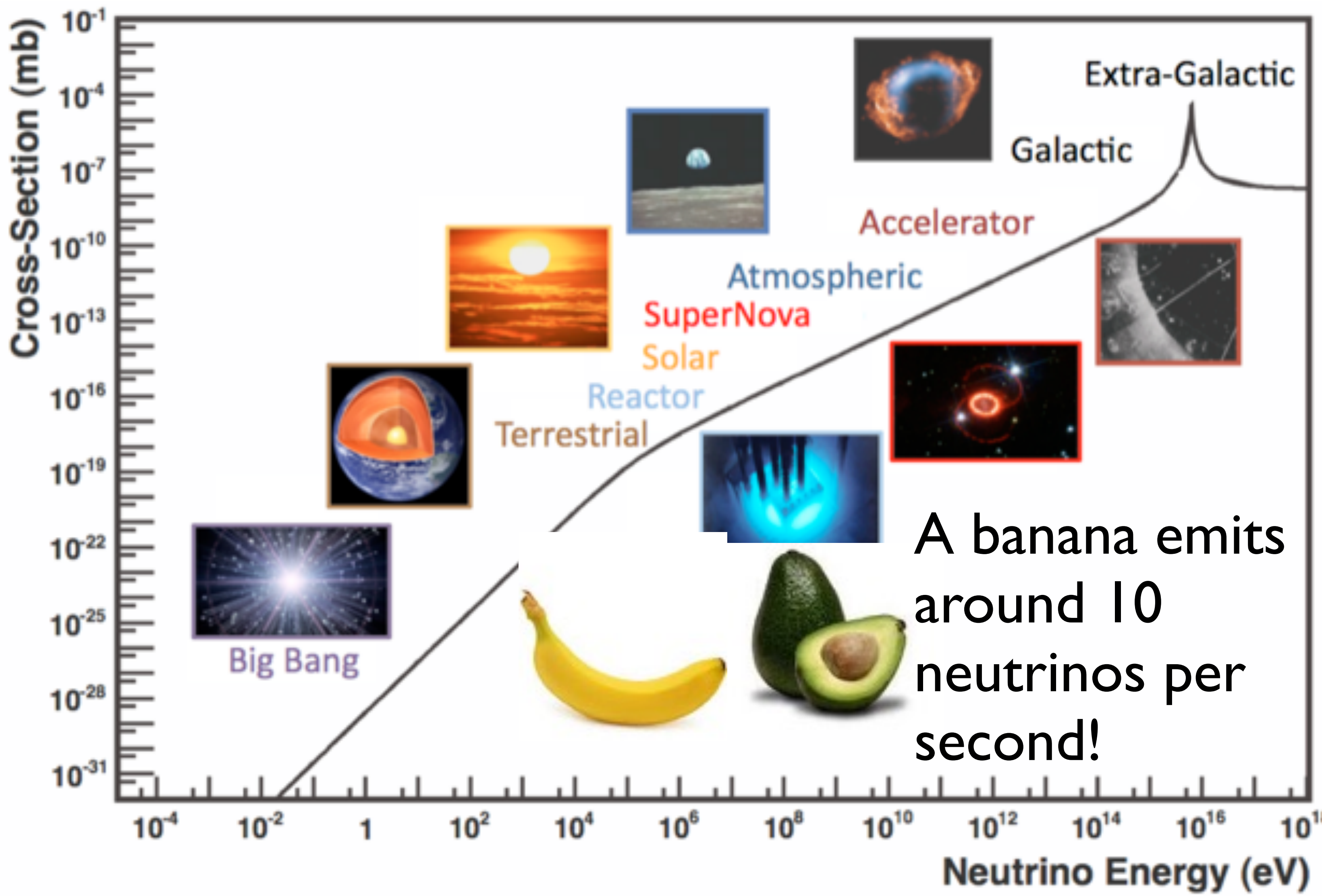
- Take lots neutrinos to hunt for ("intense fluxes");
- Take as many kilotons of detector mass as you can afford;
- Use a very efficient way to distinguish the very few neutrino interaction events from other stuff ("backgrounds"), for example photons from radioactivity, electrons, neutrons, muons from cosmic rays etc.;
- If needed, go deep underground (even 1000 m!).



@Liang Yang

Electronic eyes are Photomultipliers (PMTs).

Neutrino sources



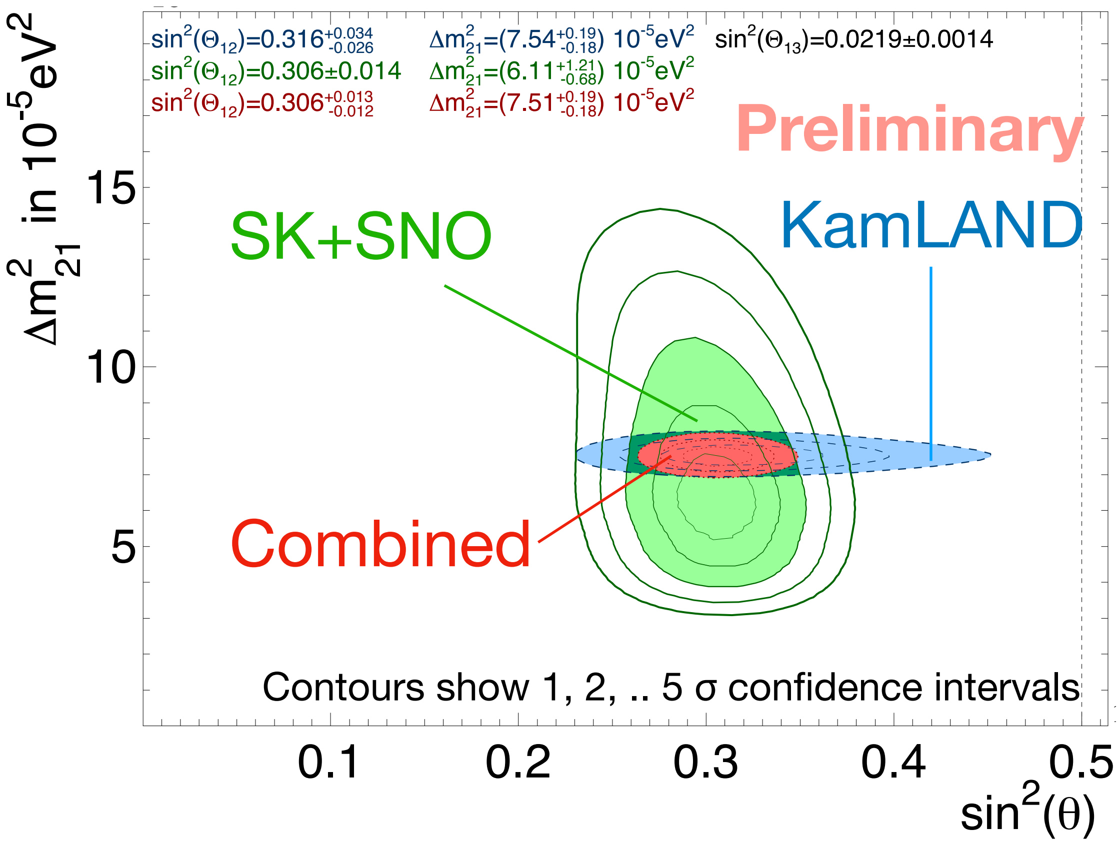
J. Formaggio and S. Zeller, 1305.7513

Current knowledge of neutrino properties

Neutrino experiments

Solar neutrinos:
E~0.1-10 MeV
matter effects

LBL Reactor neutrinos exp:
E~3 MeV,
L~100 Km



Y. Nakajima, for Super-Kamiokande, Neutrino 2020

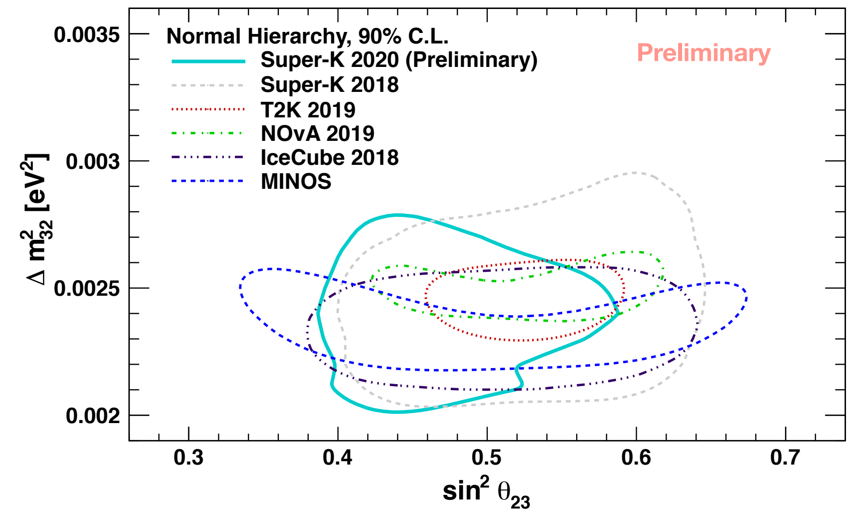
Neutrino experiments

SBL Reactor neutrino exp:
E~3 MeV,
L~1 Km

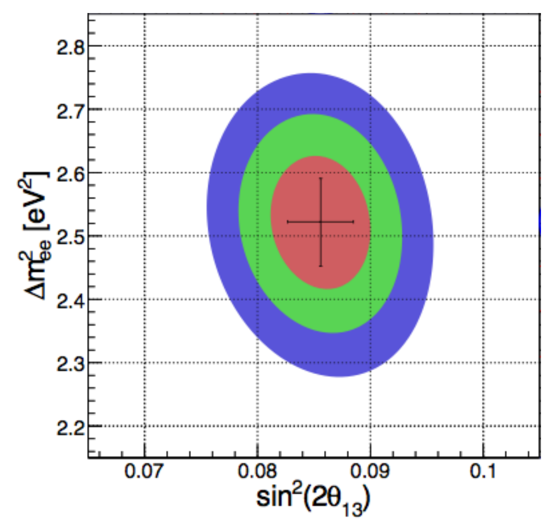
Atmospheric neutrinos:
E~100 MeV-100GeV,
L~10-10000 Km

Accelerator neutrinos:
E~500 MeV-few GeV,
L~295-1300 Km

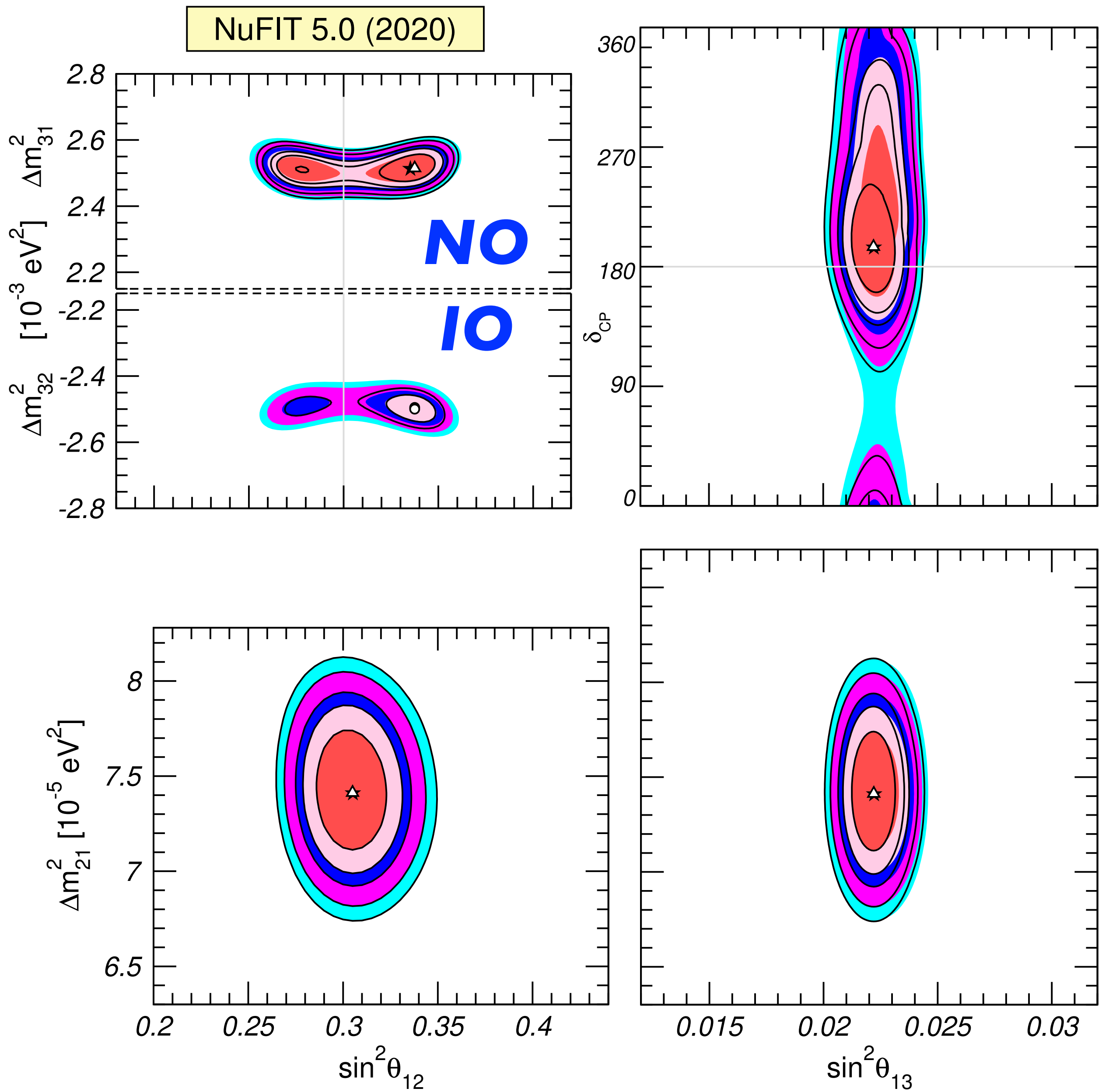
Δm^2_{32} vs $\sin^2\theta_{23}$ constraints



Y. Nakajima, for Super-Kamiokande, Neutrino 2020



Days Bay coll., PRL 121 (2018)



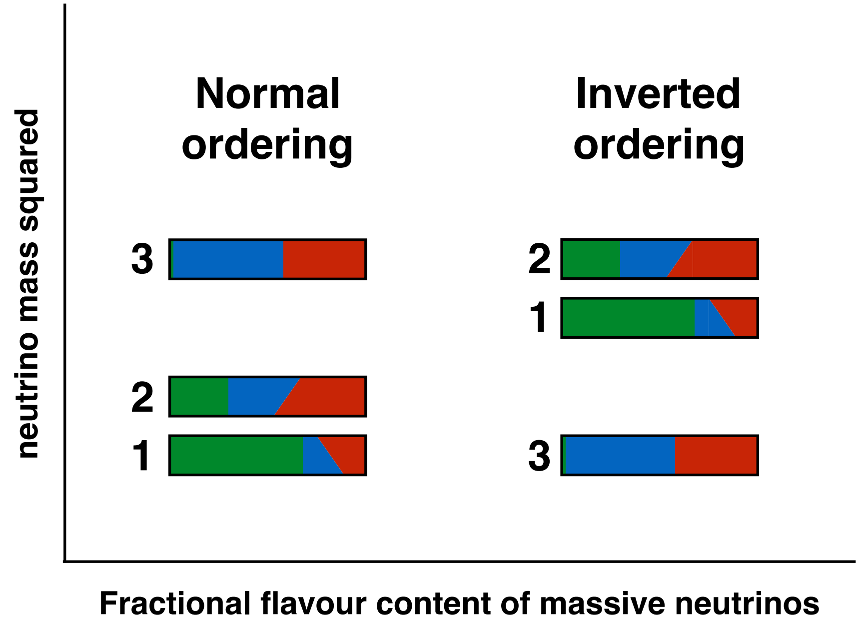
Current knowledge of neutrino properties:

- 2 mass squared differences
- 3 sizable mixing angles,
- hints of CPV
- mild indications in favour of NO

http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 2007.14792

Neutrino masses

$\Delta m^2_{\rm s} \ll \Delta m^2_{\rm A}$ implies at least 3 massive neutrinos.



Using

$$m_2 = \sqrt{m_2^2} = \sqrt{m_2^2 \pm m_1^2} = \sqrt{m_1^2 + \Delta m^2_{21}}$$

we can express the masses in terms of MO and $m_{\rm MIN}$:

$$\begin{aligned} m_1 &= m_{\rm min} \\ m_2 &= \sqrt{m^2_{\rm min} + \Delta m^2_{\rm sol}} \\ m_3 &= \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A} + \Delta m^2_{\rm sol}/2} \end{aligned}$$

$$\begin{aligned} m_3 &= m_{\rm min} \\ m_1 &= \sqrt{m^2_{\rm min} + |\Delta m^2_{\rm A}| - \Delta m^2_{\rm sol}/2} \\ m_1 &= \sqrt{m^2_{\rm min} + |\Delta m^2_{\rm A}| + \Delta m^2_{\rm sol}/2} \end{aligned}$$

What do we still need to know?

- **What is the nature of neutrinos? Dirac vs Majorana?**
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

What do we still need to know?

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  Neutrinoless dbeta decay

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  LBL: T2K, NOvA, DUNE, T2HK, ESSnuSB, Daedalus, nuFACT..., PINGU, ORCA, INO, JUNO

- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?

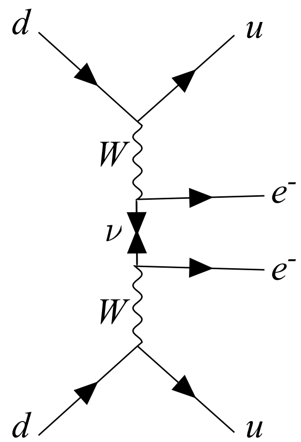
  reactor SBL and MBL, atm, LBL, ...

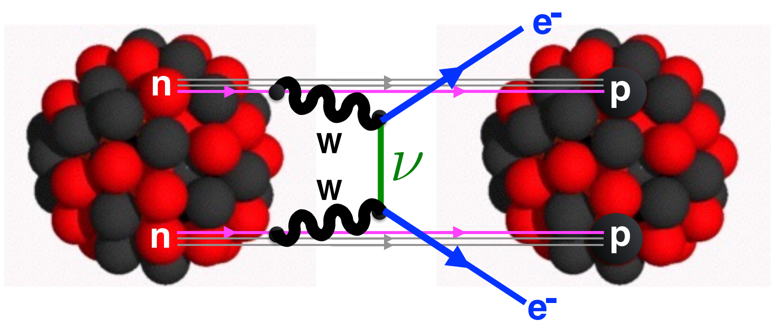
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

  MINOS+, MicroBooNE, SoLid, ...

Neutrinoless double beta decay

A key question regarding neutrinos is whether they are distinguishable from antineutrinos or not (they are called a Majorana particles).





Neutrinoless double beta decay ((A,Z) -> (A, Z +2) + 2 e) experiments can test the nature of neutrinos because Majorana neutrinos can make this decay happen.

Neutrinoless double beta decay

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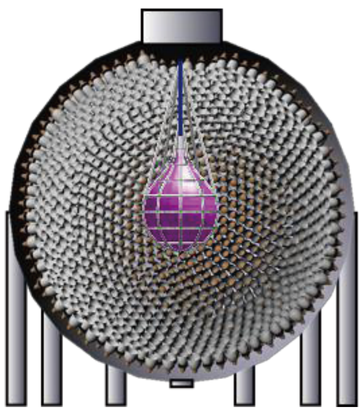
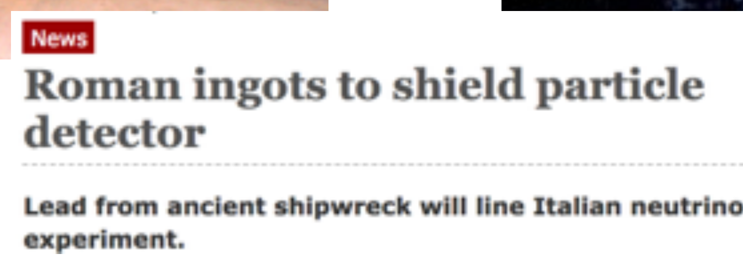


KamLAND-Zen


News

Roman ingots to shield particle detector

Lead from ancient shipwreck will line Italian neutrino experiment.

@Nature

Neutrinoless double beta decay ((A,Z) -> (A, Z +2) + 2 e) experiments can test the nature of neutrinos because Majorana neutrinos can make this decay happen.

What can neutrino tell us about the most fundamental rules of Nature?

Game-changing information

What can neut

tell us abo

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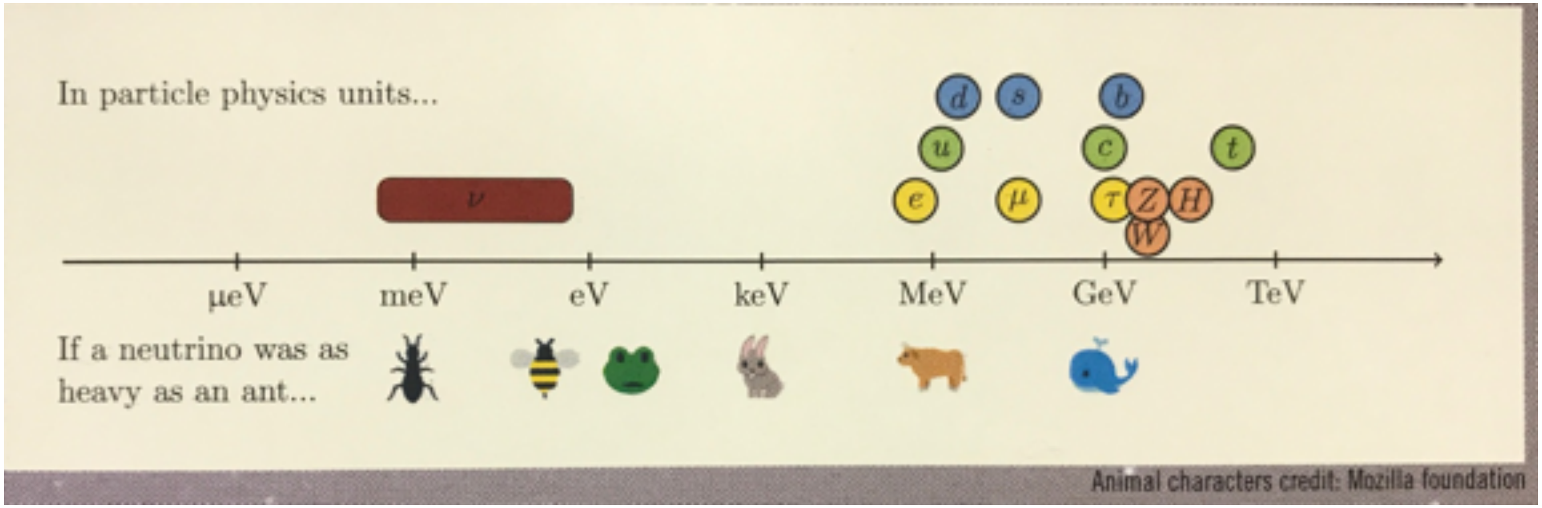
nformation

Nobel prize in Physics in 2015

Crucially neutrino oscillations require neutrino masses, that are tiny compared to the others.



@Ghosts in the Universe

The Standard Model of Particle Physics would tell us that neutrinos are massless. But we know have proof that this is not the case.

First (and so far unique) particle physics evidence of Physics beyond the Standard Model

The ultimate goal is to understand

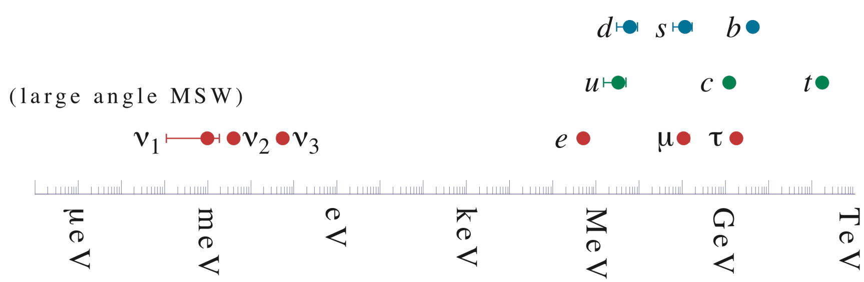
- where do neutrino masses come from?

- **why there is leptonic mixing? and what is at the origin of the observed structure?**
- **what was neutrino's role in the evolution of the Universe**

Open window on Physics beyond the SM

Neutrinos give a new perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so much lighter?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

This information is **complementary** with the one from flavour physics experiments and from colliders.

Neutrino masses in the SM and beyond

In the SM, neutrinos do not acquire mass and mix:

- like the other fermions as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \cancel{\nu_R}$$

Solution: Introduce ν_R for Dirac masses

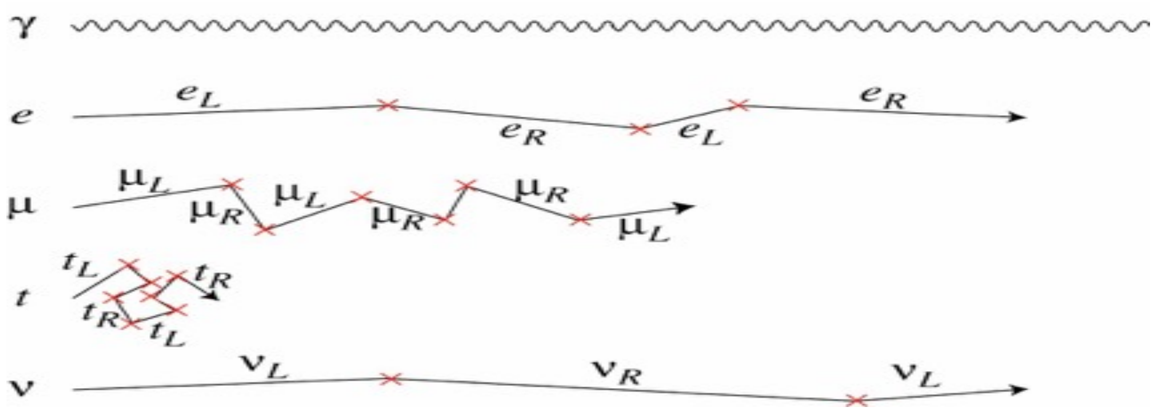
- they do not have a Majorana mass term

$$M \nu_L^T C \nu_L$$ lepton number violation

as this term breaks the SU(2) gauge symmetry.
Solution: Introduce an SU(2) scalar triplet or D>4.

Dirac Masses

If we introduce a right-handed neutrino, then a lepton-number conserving interaction with the Higgs boson emerges.



Thanks to
H. Murayama

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}$$

with $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ and $\tilde{H} = \begin{pmatrix} H^{0,*} \\ -H^- \end{pmatrix}$

This term is
- SU(2) invariant and
- respects lepton number

$$m_\nu \sim y_\nu v_H$$

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow for new scalar fields, e.g. a scalar triplet):

D=5 term

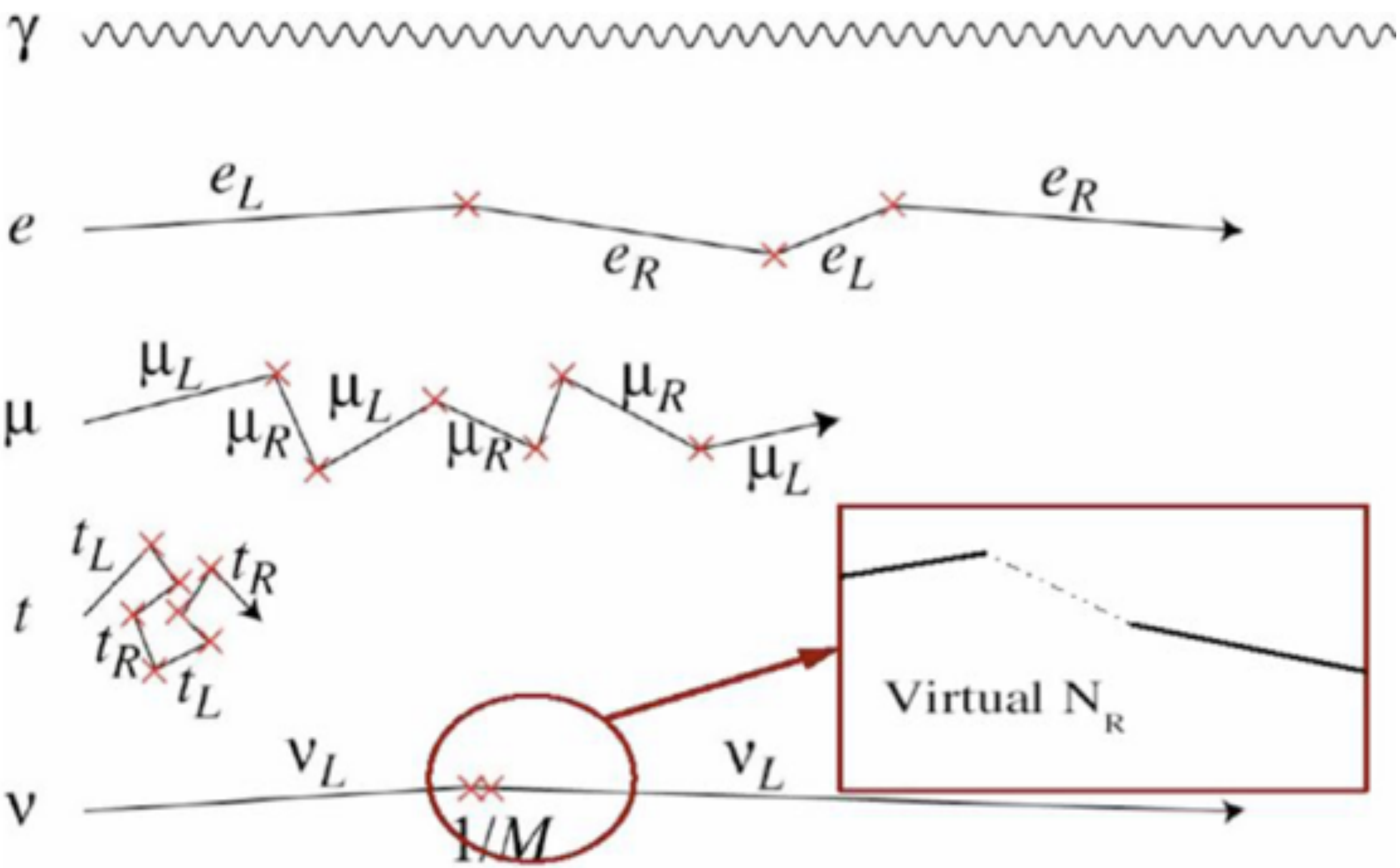
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43

Lepton number violation!

If neutrino are Majorana particles, a **Majorana mass** can arise as the **low energy realisation of a higher energy theory (new mass scale!)**.

In the see-saw mechanism, neutrinos acquire a mass due to their interactions with **heavy sterile neutrinos N**.



See-saw type I

- Introduce a right handed neutrino **N (sterile neutrino)**
- Couple it to the Higgs and left handed neutrinos

breaks lepton number

The Lagrangian is

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

When the Higgs boson gets a vev, Dirac masses will be generated. The mass matrix will be

$$\mathcal{L} = \left(\nu_L^T N^T\right) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

This is of the Dirac+Majorana type we discussed earlier. The massive states are found by diagonalising the mass matrix and will be Majorana neutrinos.

$$\begin{vmatrix} -\lambda & m_D \\ m_D & M-\lambda \end{vmatrix} = 0$$

$$\lambda^2 - M\lambda - m_D^2 = 0$$

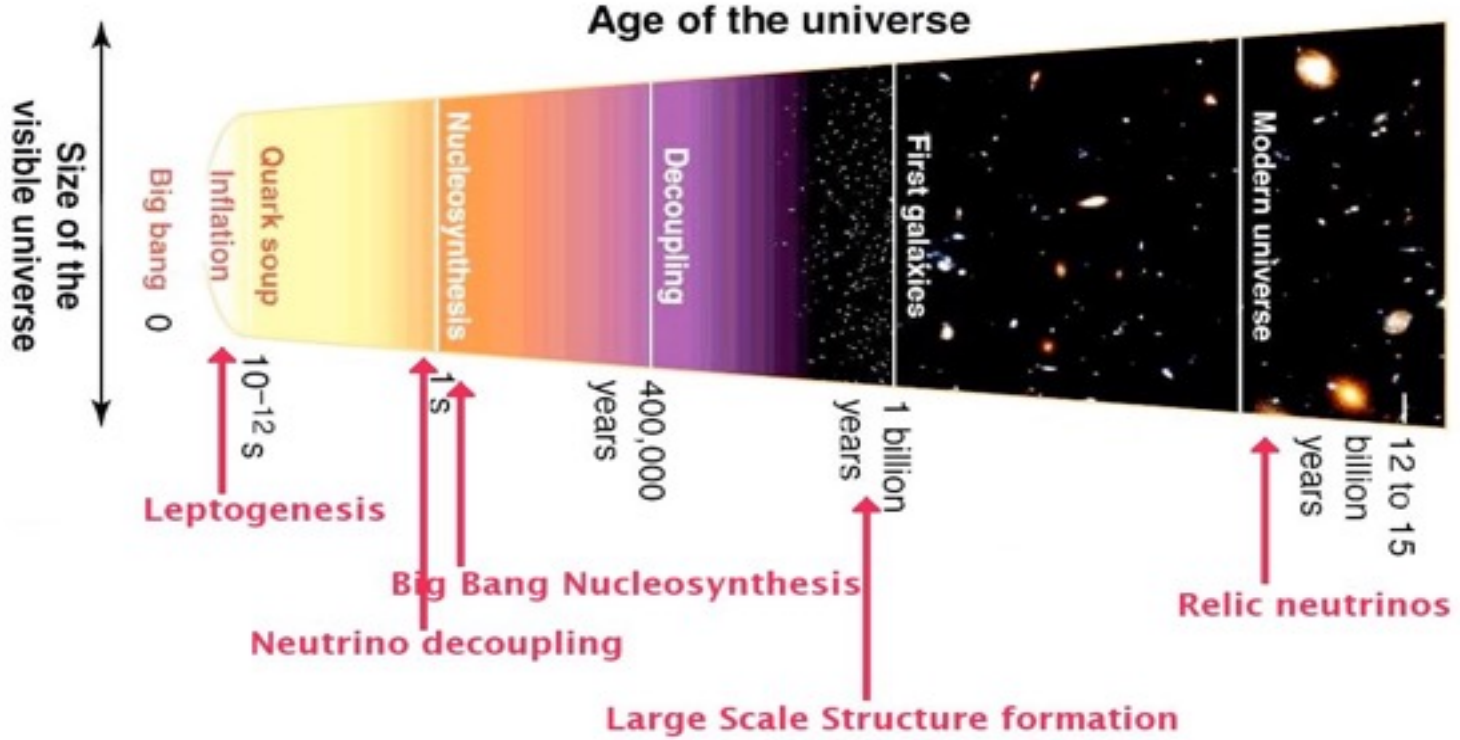
$$\lambda_{1,2} = \frac{M \pm \sqrt{M^2 + 4m_D^2}}{2} \simeq \begin{matrix} M \\ \frac{M-M}{2} - \frac{4m_D^2}{4M} = -\frac{m_D^2}{M} \end{matrix}$$

The light neutrino masses acquires a tiny mass!

$$m_\nu \simeq \frac{m_D^2}{M} \sim \frac{1\,\mathrm{GeV}^2}{10^{10}\,\mathrm{GeV}} \sim 0.1\,\mathrm{eV}$$

Do neutrinos matter in the Universe?

Neutrinos have played an important role in shaping the Universe.



How many **relic neutrinos** are in a **cup of tea**?

5000!

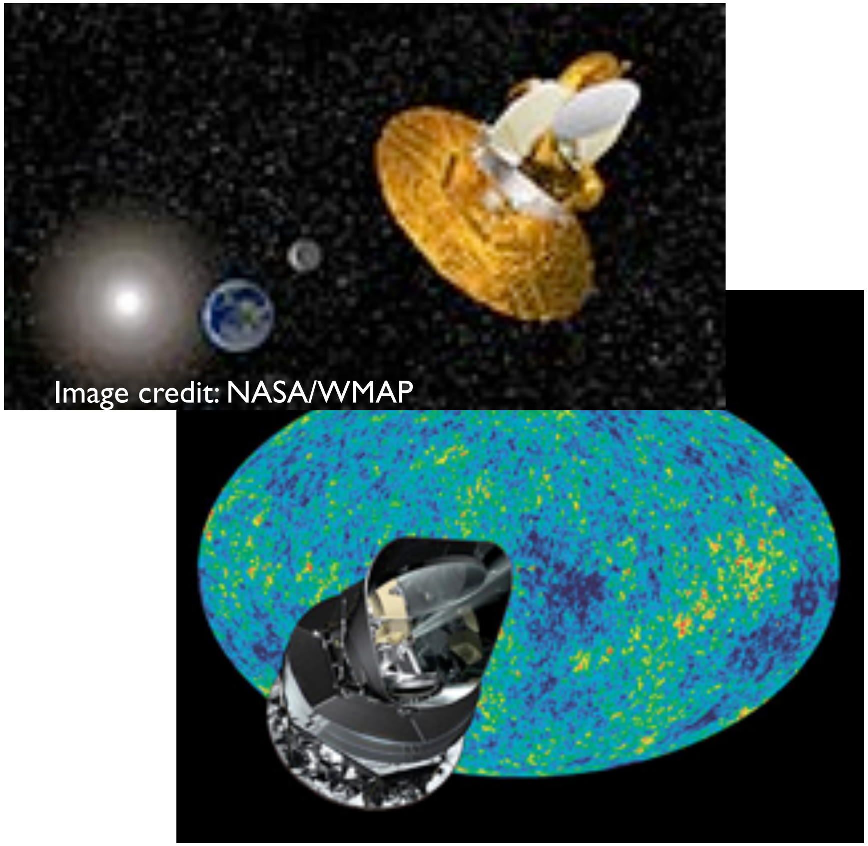
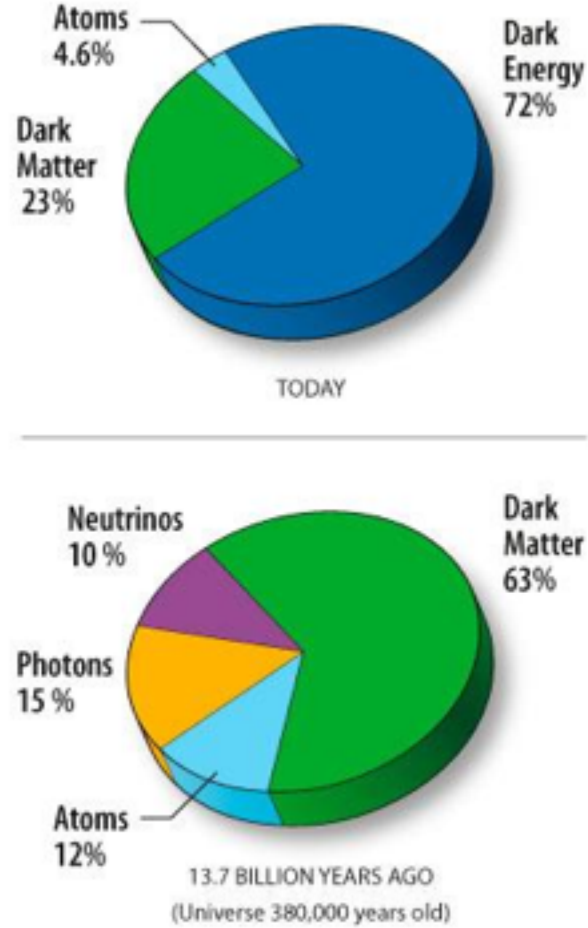


Image credit: NASA/WMAP

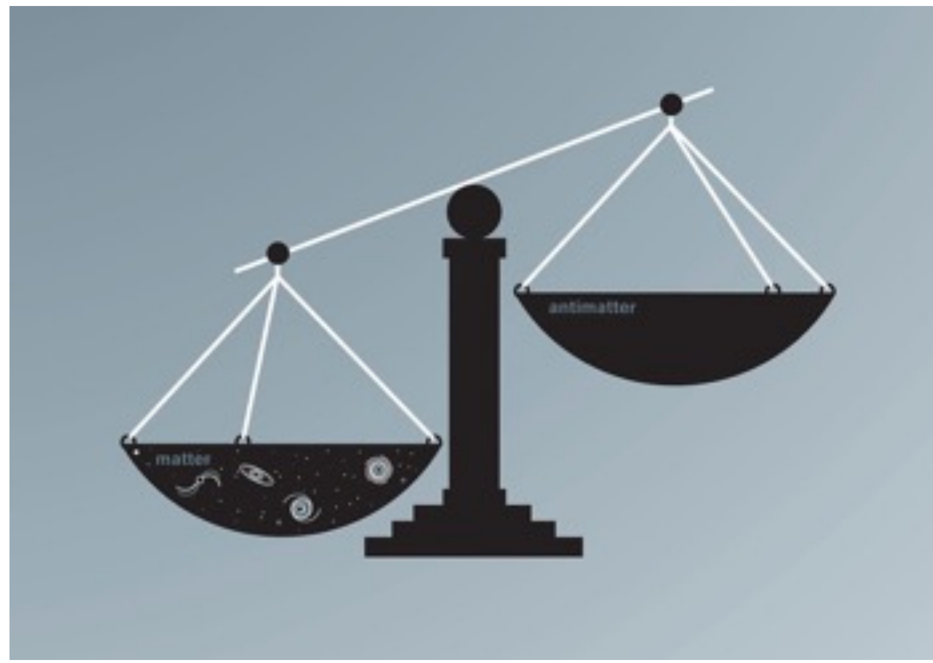


Neutrinos are the only known component of Dark Matter.

Neutrinos constitute HDM and played a role in the formation of clusters of galaxies.

- At the beginning there were equal amounts of matter and antimatter.
- Then, possibly via neutrino interactions, a small difference emerged.
- After matter and antimatter annihilated into photons, this small difference remained and makes up for all the matter we see today.

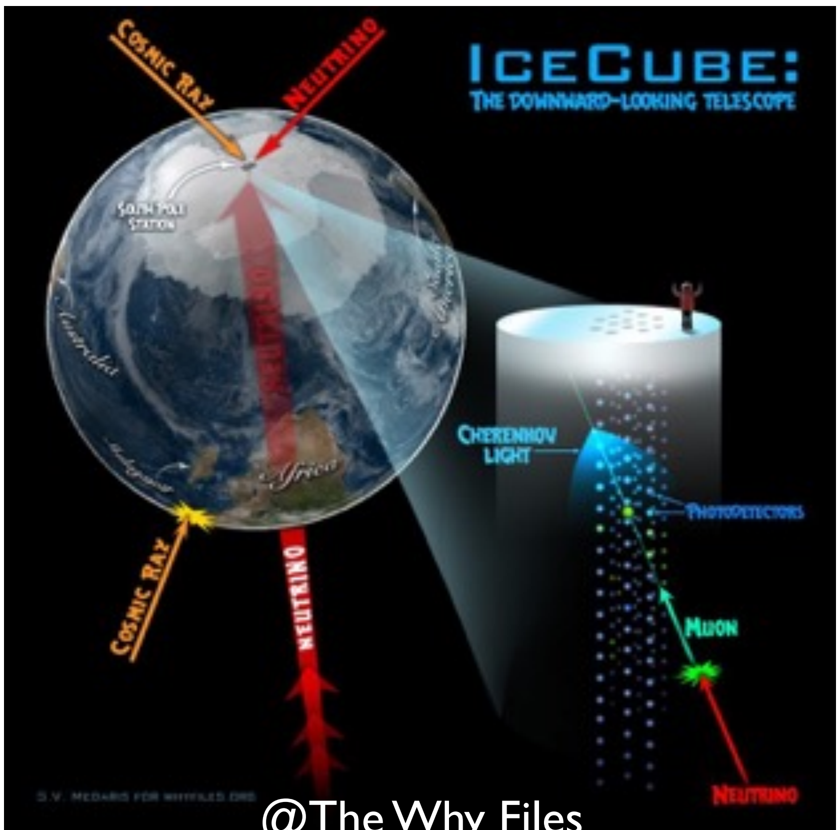
Neutrinos might hold the key to explain why the Universe is basically made only of matter (baryon asymmetry).



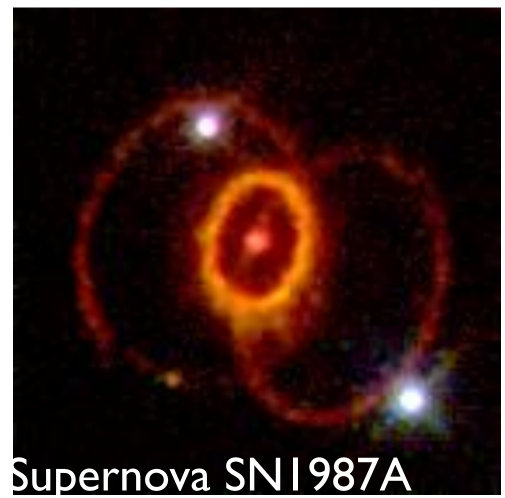
@Symmetry magazine

Astrophysical neutrinos

- Most of the supernovae energy is emitted in neutrinos.
- Astrophysical accelerators can produce the highest energy neutrinos in the Universe.



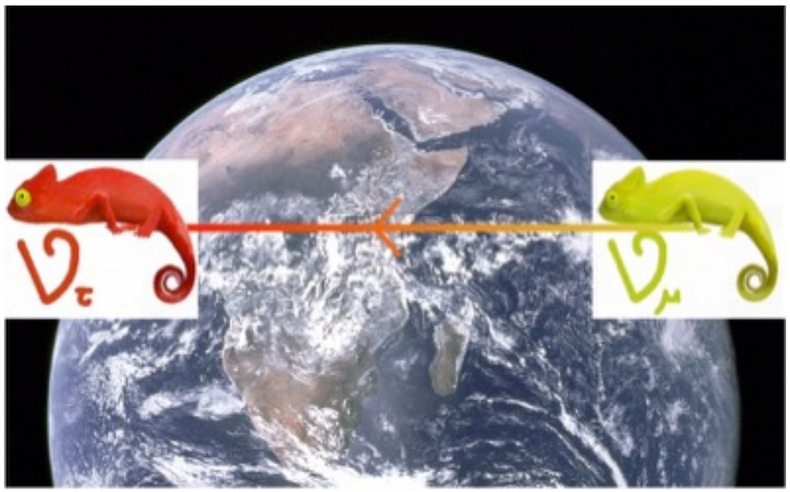
@The Why Files


Supernova SN1987A

Credit: Dr. Christopher Burrows, ESA/STScI and NASA

Conclusions

Neutrinos are the most elusive and mysterious of the known particles.



The discovery of neutrino oscillations has been a game-changer because it means that neutrinos have mass and the Standard Model is incomplete.

Neutrino physics will help open a new window on the fundamental laws of nature, its constituents and the evolution of the Universe.

Why study neutrinos?

- Neutrino masses imply new physics BSM. Their origin is a necessary ingredient for the newSM.

- The least know of all SM fermions (a window on the BSM?): portal to dark sectors.

- Their nature (and the mass) is related to the fundamental symmetries of nature (lepton number?, link with proton decay).

- The most abundant of all fermions in the Universe with strong impact of its evolution.

- Neutrino mass models can explain the baryon asymmetry of the Universe.