Neutrino Mass Generation

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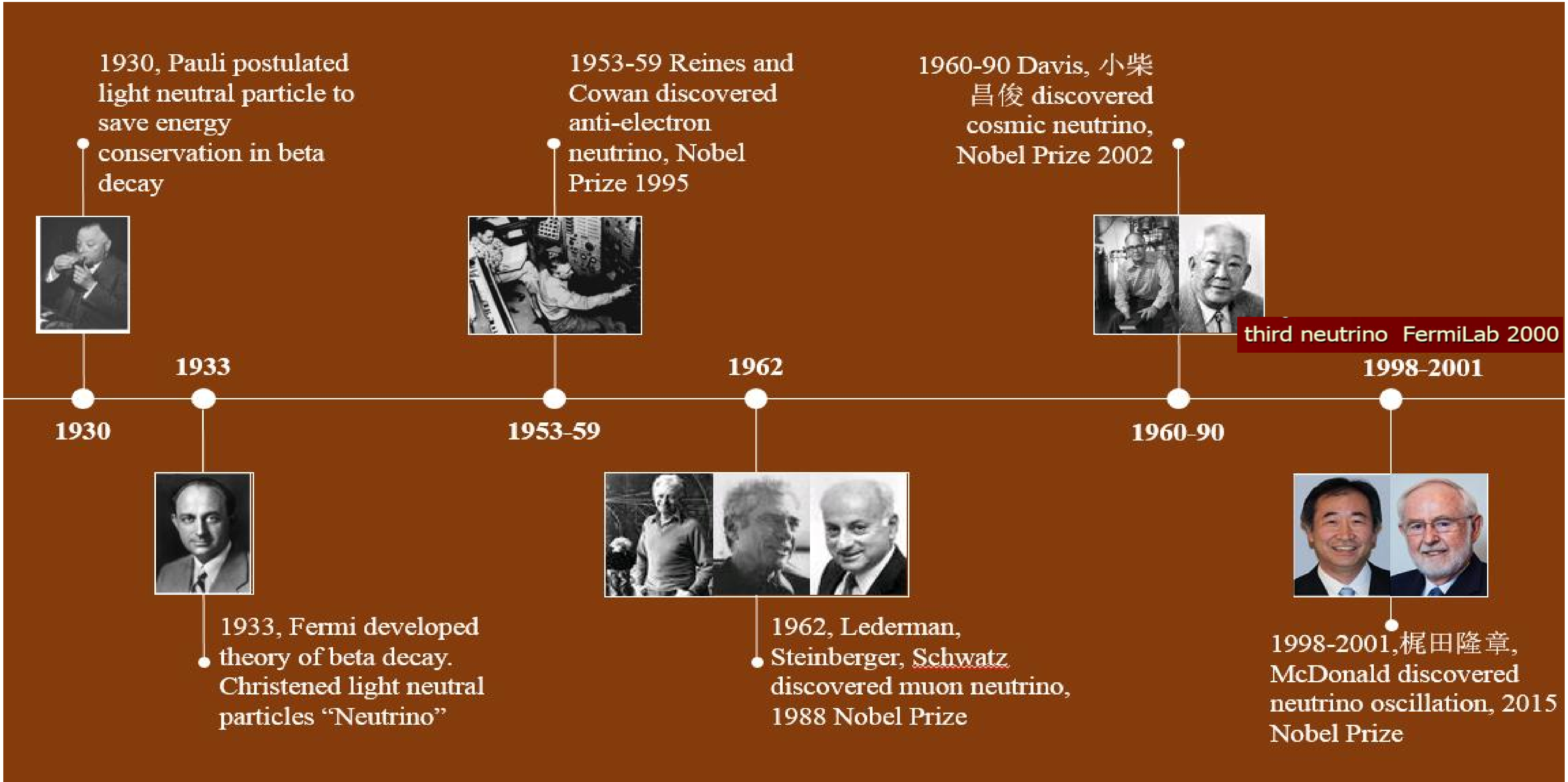
1. Neutrino mass and neutrino oscillations

2. Neutrion mass generation mechanism

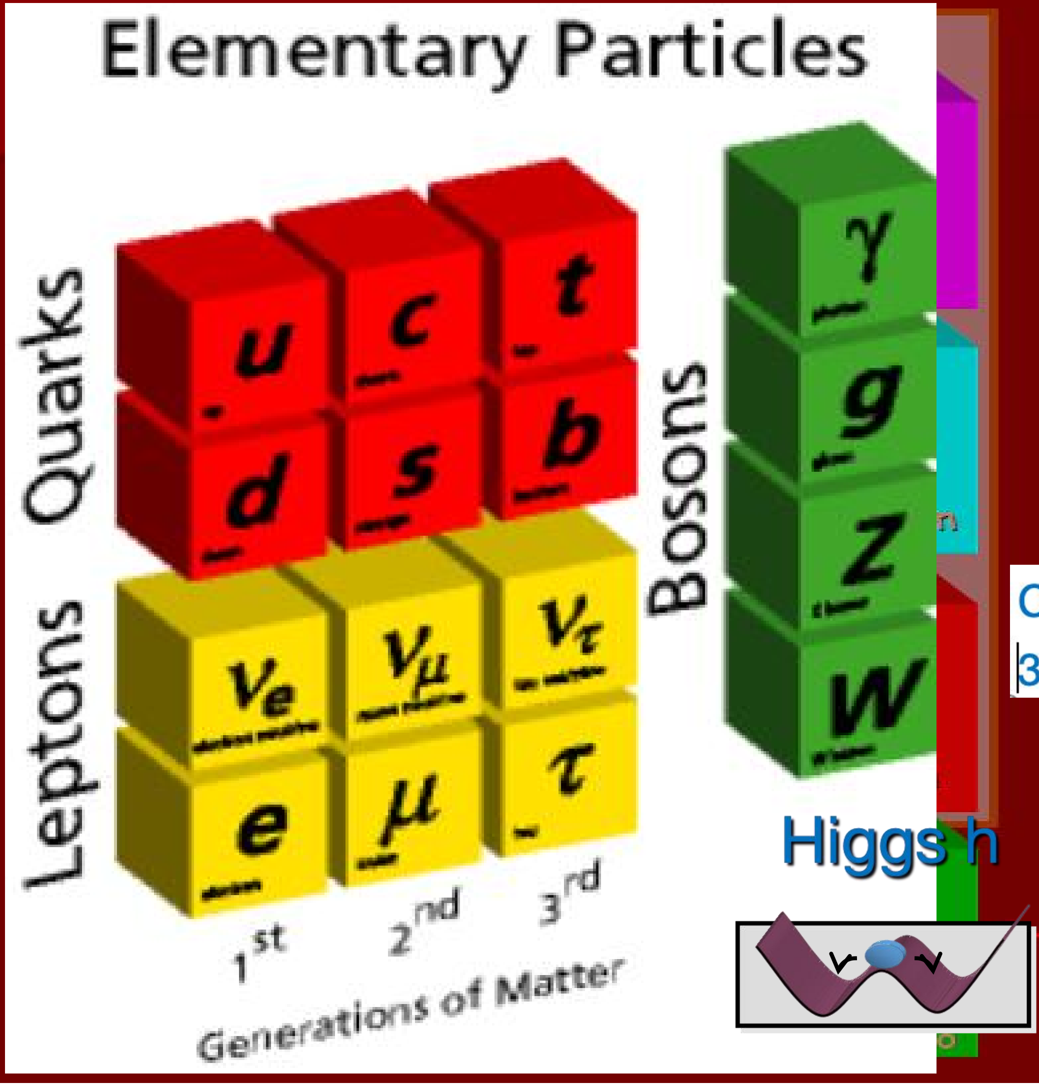
3. Neutrinos In Cosmology And Astrophysics

1. Neutrino Mass and Neutrino Oscillations

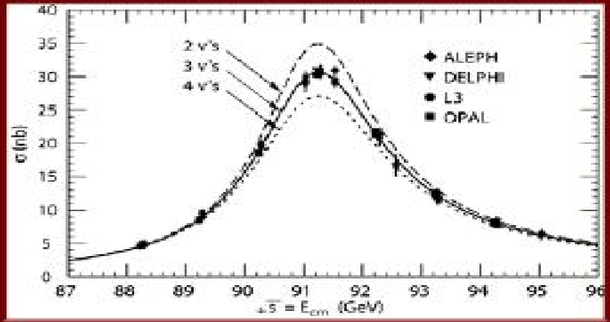
A brief neutrino history



Nature's building blocks



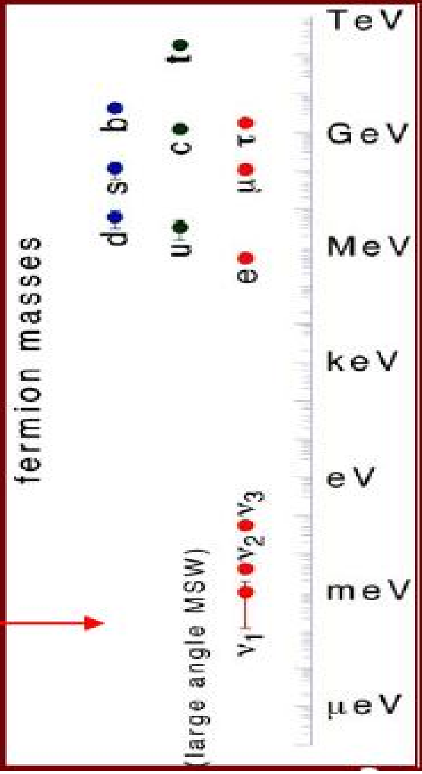
Higgs h



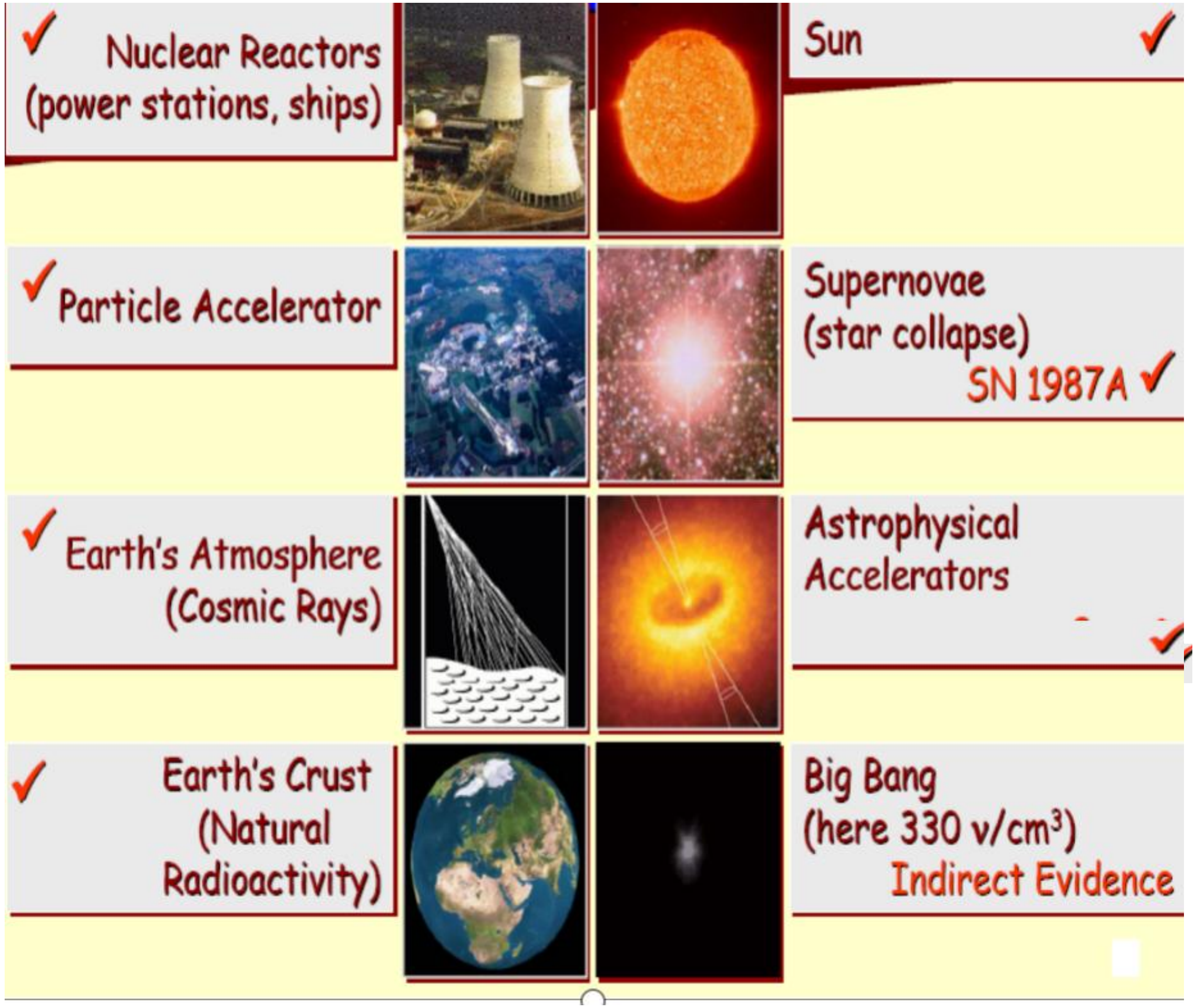
Three flavors or generations, and no more, and we do not know why.

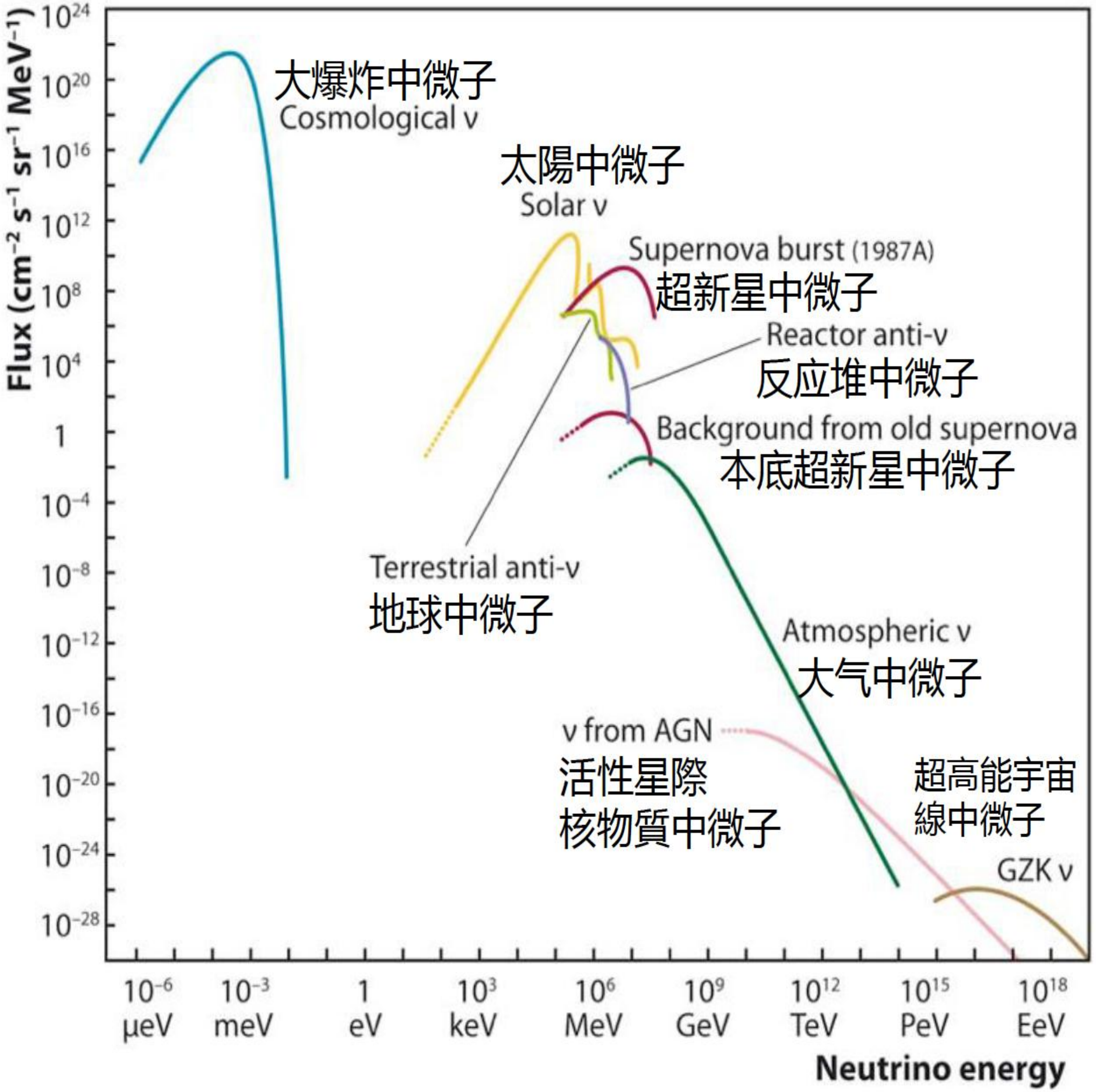
Cosmology BBN also implies
3 generations of neutrinos

Some mass, but curiously little.



Where neutrinos come from ?





Although weakly interacting, can be seen almost everywhere!

Neutrino Mixing

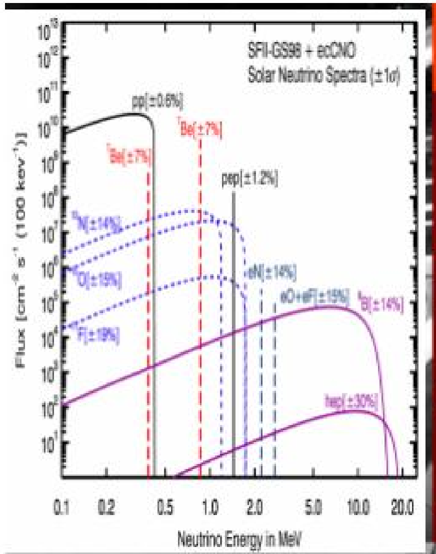
B. Pontecorvo (1957). "Mesonium and anti-mesonium". *Zh. Eksp. Teor. Fiz.* 33: 549–551.

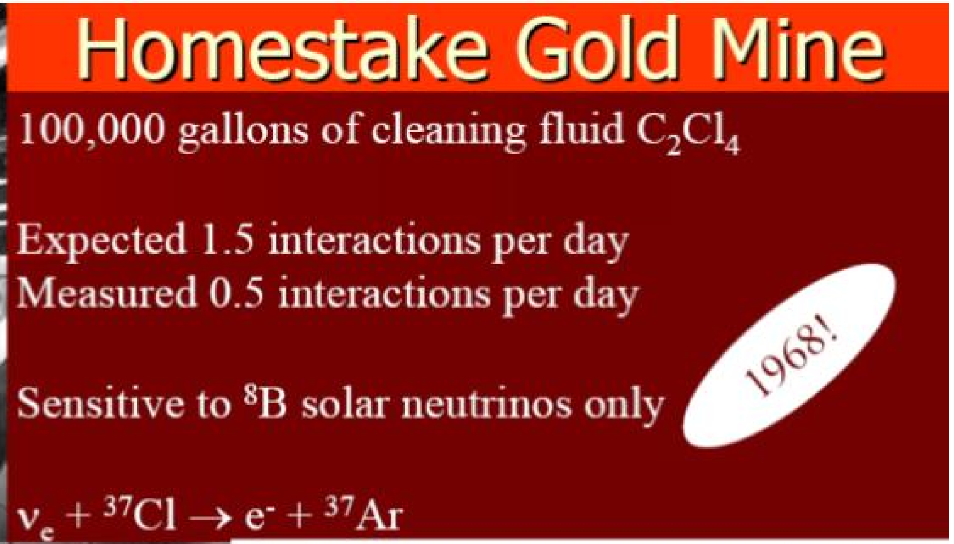
Oscillation between neutrino and anti-neutrino.

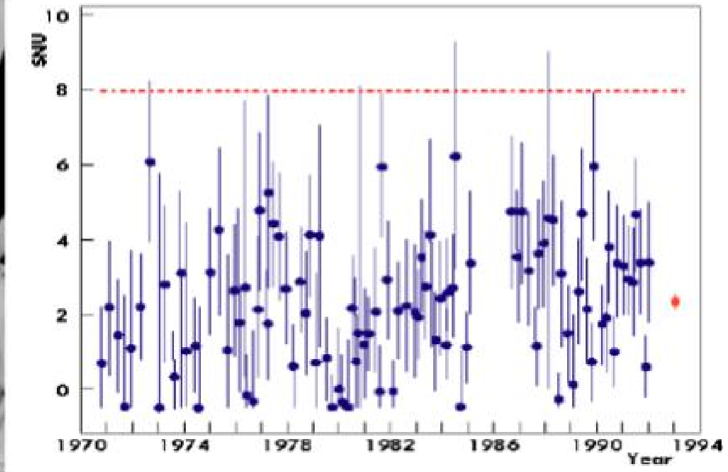
Z. Maki, M. Nakagawa, and S. Sakata (1962).
"Remarks on the Unified Model of Elementary Particles".
Progress of Theoretical Physics 28 (5): 870.
B. Pontecorvo (1967).
"Neutrino Experiments and the Problem of Conservation of Leptonic Charge". *Zh. Eksp. Teor. Fiz.* 53: 1717.

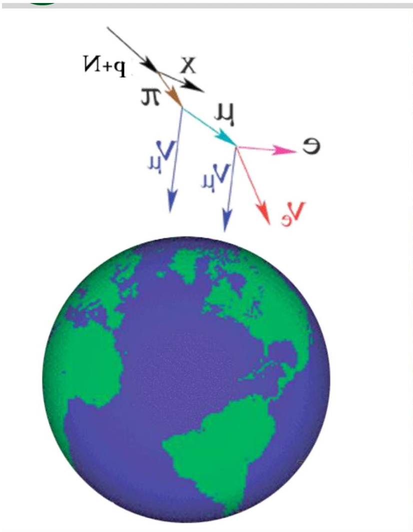
Oscillations between different flavors.

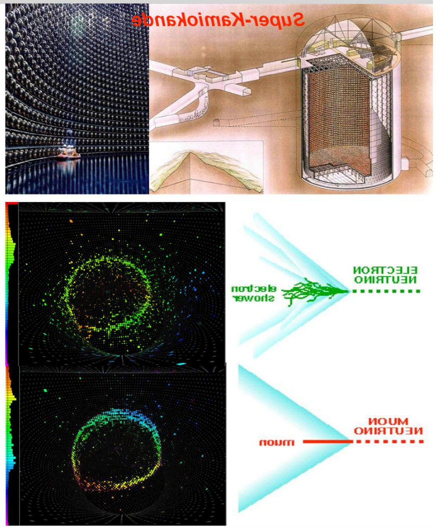
Experimental Discovery Of Nuetrino Mixing

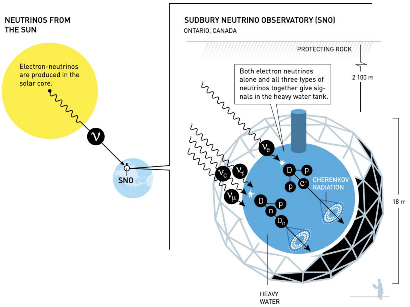


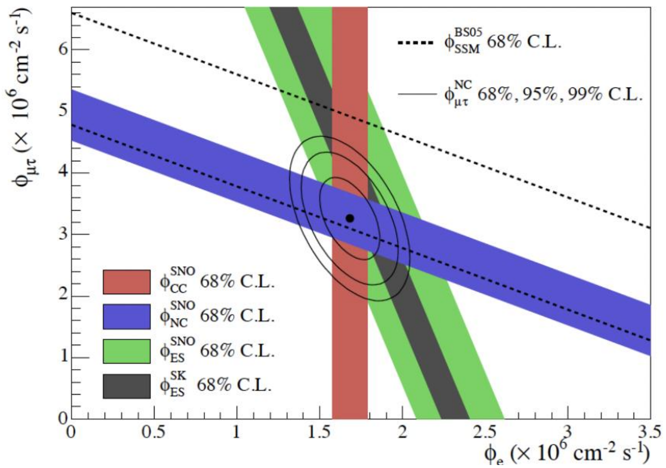












Mixing and Non-zero Neutrino Masses

$$\begin{pmatrix} \nu_1(0) \\ \nu_2(0) \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \end{pmatrix}$$

At t=0, neutrino $\nu_1(0)$ produced, at t, the state becomes

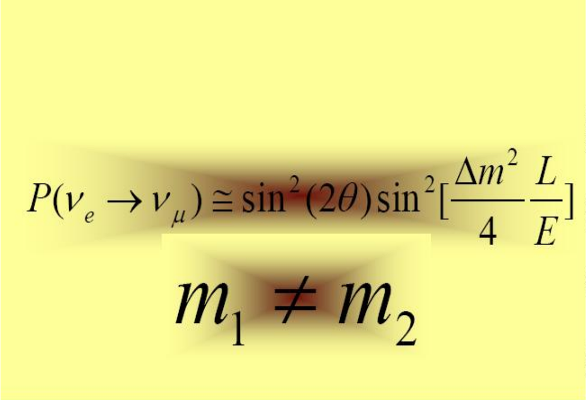
$$|\nu_1(0)> = \quad \cos\theta e^{-i(Et-p_1 L)}|\nu_{m1}> \quad -\sin\theta e^{-i(Et-p_2 L)}|\nu_{m2}>.$$

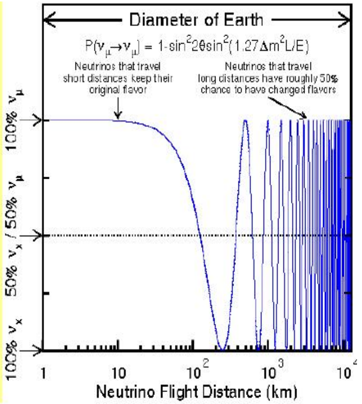
Using $t \approx L$ and $E - P_i = E - \sqrt{E^2 - m_i^2} \approx m_1^2/2E$,
the probability amplitude of find $\nu_2(0)$ at time t is given by

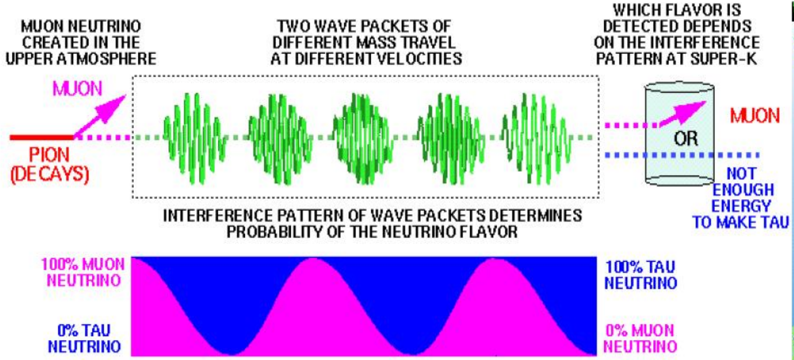
$$< \nu_2(0)|\nu_1(t) > = \cos\theta \sin\theta (e^{-im_1^2 L/2E} - e^{-im_2^2 L/2E})$$

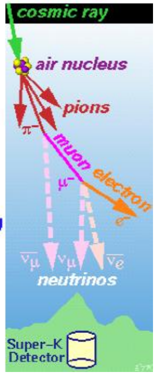
which leads to the probability of finding $\nu_2(0)$ is

$$P(\nu_1 \to \nu_2) = | < \nu_1(0)|\nu_2(t) > |^2 = \sin^2(2\theta)\sin^2(\Delta m_{21}^2 L/4E),$$
$$\Delta m_{21}^2 = m_2^2 - m_1^2.$$









Need mixing and non-zero mass to have oscillation!

Active neutrinos mix with each other and have non-zero masses!
Must go beyond SM to have neutrino masses!

2. Neutrion mass generation mechanisms

Neutrino mass, what mass?

Gravitational mass or inertia mass? Equavilence principle, they are the same.

$E = mc^2$ hadrons due to color confiments, not all masses of hadrons are due to quark masses. For neutrinos, no confinement, all masses are due to masses in the primary SM Lagrangian.

Masses due to Higgs mechanism, may be “bare” masses?

Neutrions can have “bare” masses which is not due to the usual mechanism like those other SM particles, quarks, W and Z from the VEV of a Higgs doublet.

Neutrions are special due to neutral electric charge, it can have masses not due to the usual Higgs mechnism, due to Higgs doublet non-zero VEV. Can have Dirac mass or Majorana mass!

In the minimal SM neutrion mass is zero

In the minimal SM: Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$G(8,1)\ (0), W(1,3)\ (0), B\ (1,1)(0)\ ,$$

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix} (3,2)(1/6)\ ,\ \ U_R\ (3,1)(2/3)\ ,\ \ D_R\ (3,1)(-1/3)\ ,$$

$$L_l = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} (1,2)(-1/2)\ ,\ \ E_R\ (1,1)(-1)\ ,$$

$$H = \begin{pmatrix} h^+ \\ (v+h^0)/\sqrt{2} \end{pmatrix} (1,2,1/2)\ ,\ \ \text{v - vev of Higgs}\ .$$

Quark and charged lepton masses are from the following Yukawa coupolings

$$\bar{Q}_L \tilde{H} U_R\ ,\ \ \bar{Q}_L H D_R\ ,\ \ \bar{L}_L H E_R\ .$$

Nothing to pair up with $L_L(\nu_L)$. In minimal SM, neutrinos are massless!

Extensions needed: Give neutrino masses and small ones!

Invluding higher dimension operator:

HH L Lc / Λ the Weinberg operator => (v2/Λ) $\nu_L \nu_L^c$ Majorana mass

This term is not renormalizable!! Can one construct a renormalizable one???

How To Generate Neutrino Masses?

Introduce right handed neutrinos ν_R: (1,1)(0) to pair up with L to form Dirac mass: Dirac neutrino mass term

$$L = -\bar{L}_L Y_\nu \tilde{H} \nu_R + H.C \;, \rightarrow \quad -\bar{\nu}_L m_\nu \nu_R \;, \rightarrow m_\nu = \frac{v}{\sqrt{2}} Y_\nu$$

$$m_{\nu_e} < 0.3 \text{ eV}, \rightarrow \quad Y_{\nu_e}/Y_e < 10^{-5}, \text{ very much fine tuned!}$$

Neutrino is its own anti-particle, particle and anti-particle to pair up for mass term: $\bar{\nu}_R^c M_R \nu_R/2$ gauge invariant should be included.

One can also make the above a Higgs-like generation of mass. Introduce a singlet scalae S couple to $\bar{\nu}_R^c M_R \nu_R/2$ S/vs. When S develops a VEV vs, generate the ν_R mass

This term is not directly related to the usual Higgs mechanis, no need to have Higgs H to give mass. It is a “bare” mass.

Non-zero M_R is called Majorana mass.

How to generation small neutrino masses?

Dirac neutrino mass term

$L = -\bar{L}_L Y_\nu \tilde{H} \nu_R + H.C \;, \rightarrow \quad -\bar{\nu}_L m_\nu \nu_R \;, \rightarrow m_\nu = \frac{v}{\sqrt{2}} Y_\nu$

$m_{\nu_e} < 0.3$ eV, $\rightarrow \quad Y_{\nu_e}/Y_e < 10^{-5}$, very much fine tuned!

Fine tune Yukawa couplings
Not natural

The Seesaw Mechanism $\quad L = \bar{\nu}_L (Y_\nu v/\sqrt{2}) \nu_R + \bar{\nu}_R^c M_R \nu_R / 2$

The Seesaw mechanism refers to the neutrino mass matrix of the form

$$L_m = -\frac{1}{2} (\nu_L^c, \nu_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} .$$

For one generation, if $M_R >> m_D$, the eigenmasses are

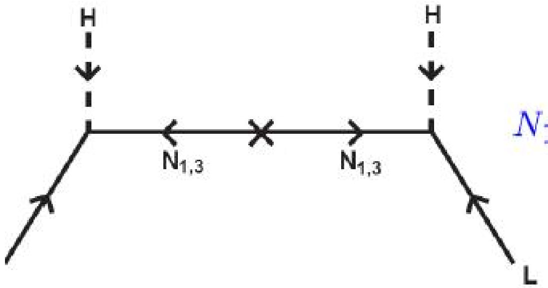
$$m_\nu \approx -m_D M_R^{-1} m_D^T, \quad m_N \approx M_R$$

A very nice way to explain why light neutrino masses are so much lighter than their charged lepton partners.

(Minkowski (1977); Gell-Mann, Ramond, and Slansky (1979); Yanagida (1979); Glashow (1980); Mohapatra and Senjanovic(1980))

Majorana Neutrinos and Seesaw Mechanism

Type (I,III) seesaw

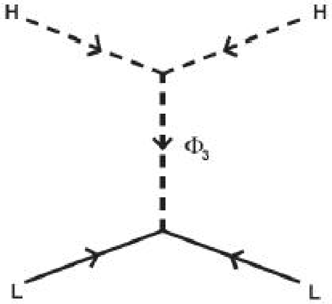


$N_1 : (1,1,0),\ N_3 : (1,3,0)$

Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, & Slansky (1980)
Mohapatra & Senjanovic (1980)

Foot, Lew, He, & Joshi (1989)

Type II seesaw

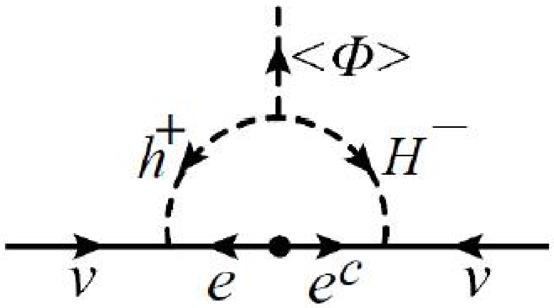


$\Phi_3 : (1,3,+1)$

Mohapatra & Senjanovic (1980)
Schechter & Valle (1980)
Lazarides, Shafi, & Wetterich (1981)

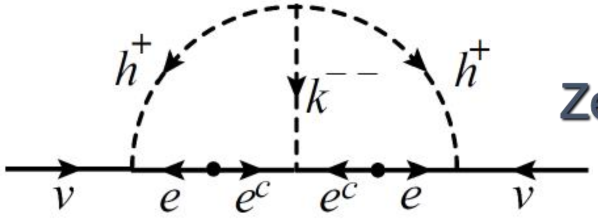
$$\mathcal{L}_{\text{eff}} = \frac{LLHH}{M} \Rightarrow m_\nu \sim \frac{v^2}{M}$$

Loop generation neutrino masses



Zee, 1980

Simplest model ruled out
XG He, EPJC34(2004)371



Zee, 1985, Babu 1988

Provide understanding why neutrino masses are small
but no information about mixing!

Three Generations and Their Mixing

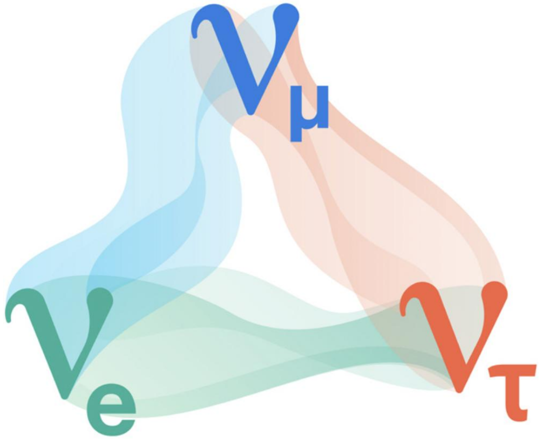
Quark mixing the Cabibbo-Kobayashi-Maskawa (CKM) matrix $V_{\rm CKM}$,

lepton mixing the Pontecorvo-Maki-Nakawaga-Sakata (PMNS) matrix $U_{\rm PMNS}$

$$L = -\frac{g}{\sqrt{2}}\overline{U}_L\gamma^\mu V_{\rm CKM} D_L W^+_\mu - \frac{g}{\sqrt{2}}\overline{E}_L\gamma^\mu U_{\rm PMNS} N_L W^-_\mu + H.C.\,,$$

$U_L = (u_L, c_L, t_L, ...)^T$, $D_L = (d_L, s_L, b_L, ...)^T$, $E_L = (e_L, \mu_L, \tau_L, ...)^T$, and $N_L = (\nu_1, \nu_2, \nu_3, ...)^T$

For n-generations, $V = V_{\rm CKM}$ or $U_{\rm PMNS}$ is an $n \times n$ unitary matrix.



A commonly used form of mixing matrix for three generations of fermions is given by

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ are the mixing angles and δ is the CP violating phase.

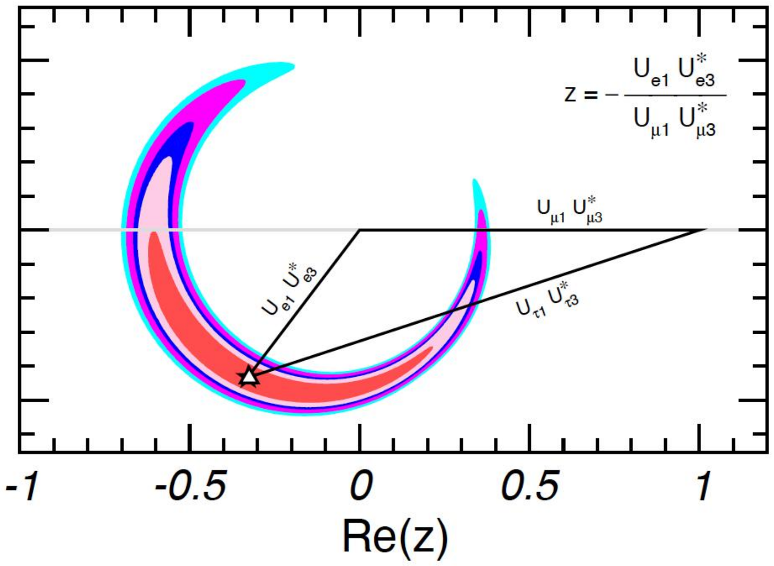
If neutrinos are of Majorana type, for the PMNS matrix one should include an additional diagonal matrix with two Majorana phases $\mathrm{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$ multiplied to the matrix from right in the above.

Neutrion Oscillation With Three Generations

$$\begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix}$$

Table 14.7: 3ν oscillation parameters obtained from different global analyses of neutrino data. In all cases, the numbers labeled as NO (IO) are obtained assuming NO (IO), *i.e.*, relative to the respective local minimum. SK-ATM makes reference to the tabulated χ^2 map from the Super-Kamiokande analysis of their data in Ref. [184].

	Ref. [181] w/o SK-ATM		Ref. [181] w SK-ATM		Ref. [182] w SK-ATM		Ref. [183] w SK-ATM	
NO	Best Fit Ordering		Best Fit Ordering		Best Fit Ordering		Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$	$3.03^{+0.12}_{-0.12}$	$2.70 \to 3.41$	$3.03^{+0.13}_{-0.13}$	$2.63 \to 3.45$	$3.18^{+0.16}_{-0.16}$	$2.71 \to 3.69$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.40^{+0.80}_{-0.82}$	$30.85 \to 35.97$	$34.3^{+1.0}_{-1.0}$	$31.4 \to 37.4$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.72^{+0.18}_{-0.23}$	$4.06 \to 6.20$	$4.51^{+0.19}_{-0.16}$	$4.08 \to 6.03$	$4.55^{+0.18}_{-0.15}$	$4.16 \to 5.99$	$5.74^{+0.14}_{-0.14}$	$4.34 \to 6.10$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$42.4^{+1.0}_{-0.9}$	$40.2 \to 50.7$	$49.3^{+0.8}_{-0.8}$	$41.2 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.203^{+0.056}_{-0.059}$	$2.029 \to 2.391$	$2.225^{+0.056}_{-0.059}$	$2.052 \to 2.398$	$2.23^{+0.07}_{-0.06}$	$2.04 \to 2.44$	$2.200^{+0.069}_{-0.062}$	$2.00 \to 2.405$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.59^{+0.13}_{-0.12}$	$8.21 \to 8.99$	$8.53^{+0.13}_{-0.12}$	$8.13 \to 8.92$
$\delta_{\rm CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	232^{+36}_{-26}	$144 \to 350$	223^{+32}_{-23}	$139 \to 355$	194^{+24}_{-22}	$128 \to 359$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.36^{+0.16}_{-0.15}$	$6.93 \to 7.93$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\frac{\Delta m^2_{32}}{10^{-3}\ \rm eV^2}$	$2.437^{+0.028}_{-0.027}$	$2.354 \to 2.523$	$2.433^{+0.026}_{-0.027}$	$2.353 \to 2.516$	$2.448^{+0.023}_{-0.031}$	$2.367 \to 2.521$	$2.47^{+0.02}_{-0.03}$	$2.40 \to 2.46$
IO	$\Delta\chi^2 = 2.3$		$\Delta\chi^2 = 6.4$		$\Delta\chi^2 = 6.5$		$\Delta\chi^2 = 6.4$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$	$3.03^{+0.13}_{-0.13}$	$2.63 \to 3.45$	$3.18^{+0.16}_{-0.16}$	$2.71 \to 3.69$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.40^{+0.80}_{-0.82}$	$30.85 \to 35.97$	$34.3^{+1.0}_{-1.0}$	$31.4 \to 37.4$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.78^{+0.16}_{-0.21}$	$4.12 \to 6.23$	$5.69^{+0.16}_{-0.21}$	$4.12 \to 6.13$	$5.69^{+0.13}_{-0.21}$	$4.17 \to 6.06$	$5.78^{-0.10}_{+0.17}$	$4.33 \to 6.08$
$\theta_{23}/^\circ$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$	$49.0^{+0.7}_{-1.4}$	$40.2 \to 51.1$	$49.5^{+0.6}_{-1.0}$	$41.2 \to 51.2$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.219^{+0.060}_{-0.057}$	$2.047 \to 2.396$	$2.223^{+0.058}_{-0.058}$	$2.048 \to 2.416$	$2.23^{+0.06}_{-0.06}$	$2.03 \to 2.45$	$2.225^{+0.064}_{-0.070}$	$2.02 \to 2.42$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$	$8.59^{+0.13}_{-0.12}$	$8.19 \to 9.00$	$8.58^{+0.12}_{-0.14}$	$8.17 \to 8.96$
$\delta_{\rm CP}/^\circ$	286^{+27}_{-32}	$192 \to 360$	276^{+22}_{-29}	$194 \to 344$	274^{+25}_{-27}	$193 \to 342$	284^{+26}_{-28}	$200 \to 353$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.36^{+0.16}_{-0.15}$	$6.93 \to 7.93$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\frac{\Delta m^2_{32}}{10^{-3}\ \rm eV^2}$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$	$-2.486^{+0.028}_{-0.025}$	$-2.570 \to -2.406$	$-2.492^{+0.025}_{-0.030}$	$-2.578 \to -2.413$	$-2.52\pm^{+0.03}_{-0.02}$	$-2.60 \to -2.44$



PDG

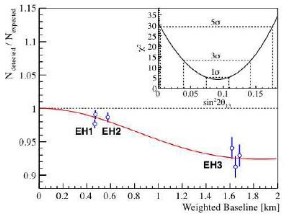
Problems related to neutrino masses

Mixing pattern: Very different quark and lepton mixing patterns

Mixing pattern in quark sector

$$V_{CKM} \sim \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}.$$



ArXiv:1203.1669 (hep-ex)

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

Read as $\theta_{13} = 8.8^\circ$ with significance 5.2σ

Mixing pattern in lepton sector

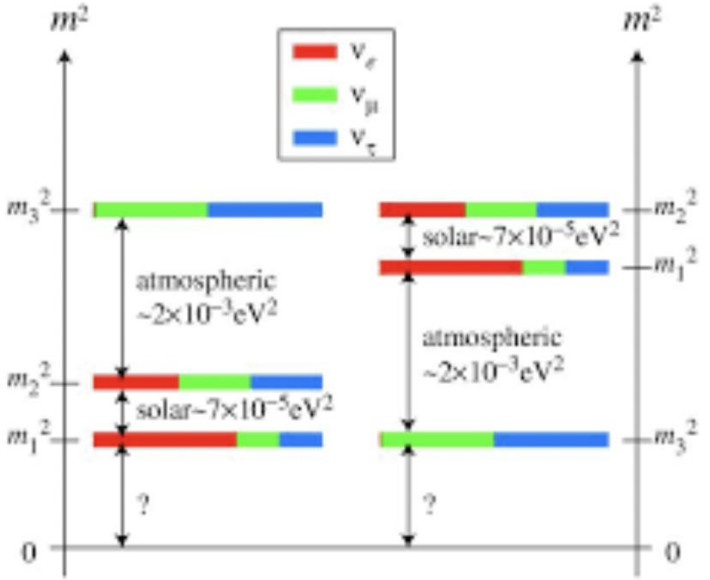
$$= 13.021^\circ \pm 0.039^\circ, \quad \theta^Q_{23} = 2.350^\circ \pm 0.052^\circ,$$

$$= 0.199^\circ \pm 0.008^\circ. \quad \delta^Q = 68.9^\circ$$

$$|U| = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix},$$

Neutrion mass hierarchy

Normal or Inverted



More precise data needed to determine mixing pattern

T2K, NOvA, JUNO, DUNE ...   Stay tuned!

Theory before and after Daya-Bay/Reno results

Before: popular mixing -The Tribimaximal Mixing

Harrison, Perkins, Scott (2002) , Z-Z. Xing (2002), He& Zee (2003)

The mixing pattern is consistent, within 2σ, with the tri-bimaximal mixing

$$V_{tri-bi} = \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

A4 a promising model (Ma&Ranjasekara, 2001) and realizations (Altarelli&Feruglio 2005, Babu&He 2005). Later many realizations: S4, D3, S3,D4, D7,A5,T',S4, Δ(27, 96), $PSL_2(7)$ … discrete groups Altarelli&Feruglio for review. (H. Lam; Mohapatra et al), T. Mahanthanpa&M-C. Chen; Frampton&Kephart; Y-L Wu, ….

After: Need to have a nonzero θ_{13}

Modification to tri-bimaximal mixing pattern need to b made. (Keum&He&Volkas; He&Zee, 2006).

In fact, more generically, A_4 symmetry leads to

$$V = \begin{pmatrix} \frac{2c}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{2se^{i\delta}}{\sqrt{6}} \\ -\frac{c}{\sqrt{6}} - \frac{se^{-i\delta}}{\sqrt{2}} & \frac{1}{\sqrt{3}} & \frac{c}{\sqrt{2}} - \frac{se^{i\delta}}{\sqrt{6}} \\ -\frac{c}{\sqrt{6}} - \frac{se^{-i\delta}}{\sqrt{2}} & \frac{1}{\sqrt{3}} & -\frac{c}{\sqrt{2}} - \frac{se^{i\delta}}{\sqrt{6}} \end{pmatrix}.$$

Mixing pattern very differnt than their quark conter parts. Mass hierarchy not yet determined!
Mass hierarchy soon be answered by JUNO? Stay tuned! CP V, DUNE, HyperK ... within 10 years?

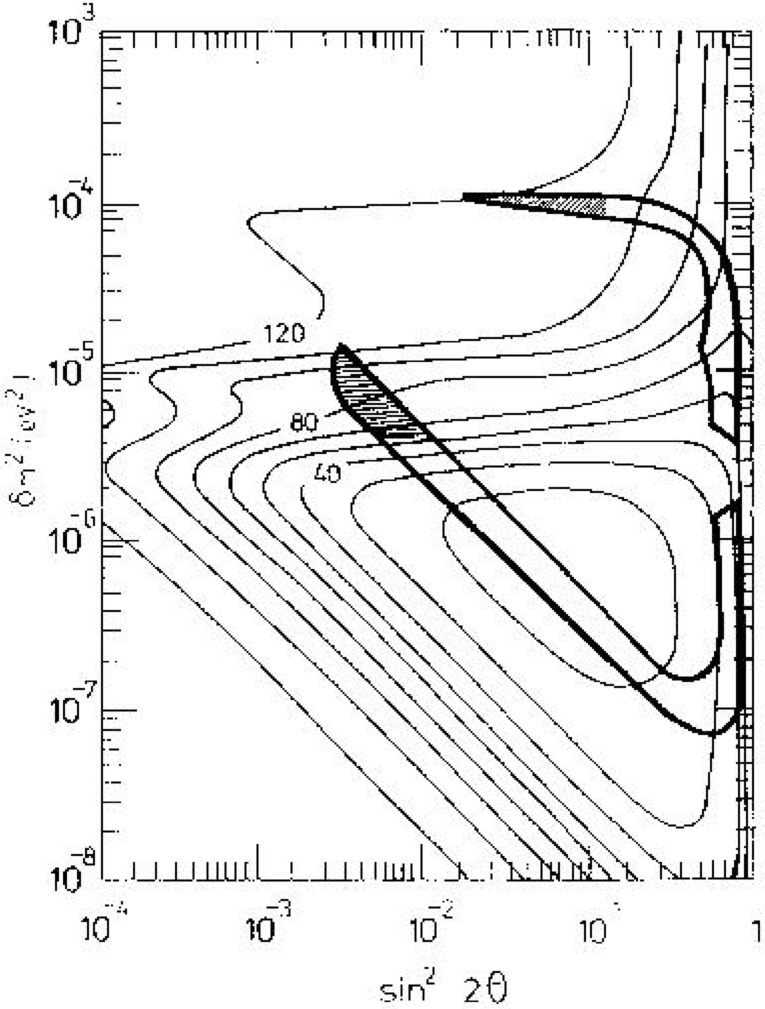
Neutrino Mixing Pattern

Early days, expecting neutrino mixing might be following a similar pattern as quarks, mixing angles are small.

For example, 1992 people are

trying to produce mixing on the right

(Davies and He, PRD46, 3208)



But both solar and atmospheric show large mixing angles!

Model building for θ_{23} = π/4 and δ=+(-)π/2

X-G He,Chin. J. Phys. 53(2015) 100101 E Ma, PRD92(2015)051301; G-N Li, X-G He, PLB750(2015)620

In the charged lepton mass eigenstate basis, $m_\nu = V_{PMNS} \hat{m}_\nu V^T_{PMNS}$

$$\delta = -\pi/2 \text{ and } \theta_{23} = \pi/4,$$

$$m_\nu = \begin{pmatrix} A & C & C^* \\ C & D^* & B \\ C^* & B & D \end{pmatrix}$$

$\mu - \tau$ conjugate symmetry

W. Grimus and L. Lavoura, PLB579(2004)113;
Z.-z Xing and Y. L. Zhou, PLB693(2010)584.

For δ=+π/2, C <-> C* and D< -> D*

A A4 model to achieve this: under A4

$\nu_R = (\nu_R^1,\ \nu_R^2,\ \nu_R^3)$ $l_L = (l_L^1,\ l_L^2,\ l_L^3)$, (l_R^1, l_R^2, l_R^3), 3 , $(1, 1'', 1')$ and 3

$\Phi = (\Phi_1,\ \Phi_2,\ \Phi_3)$ (SM doublet), ϕ (SM doublet) $\chi = (\chi_1,\ \chi_2,\ \chi_3)$ (SM singlet)

Φ and χ both transform as 3, and ϕ as 1

$$< \Phi_{1,2,3} >= v_\Phi,\ < \chi_{1,3} >= 0,\ < \chi_2 >= v_\chi, \text{ and } < \phi >= v_\phi,$$

Absolute Neutrino masses and Neutrinos Are Dirac Or Majorana Particle?

Absolute mass measurement

Tritium decay spectrum

Katrin, Mainz, Troitsk...

$$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \qquad m^{\text{eff}}_{\nu_e} < 0.8 \text{ eV}$$

$$\frac{dN}{dE} = C\, p\, E\, (Q-T) \sqrt{(Q-T)^2 - (m^{\text{eff}}_{\nu_e})^2}\, F(E) \equiv R(E) \sqrt{(E_0 - E)^2 - (m^{\text{eff}}_{\nu_e})^2}$$

$m^{\text{eff}}_{\nu_\mu} < 190$ keV (90% CL) from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$m^{\text{eff}}_{\nu_\tau} < 18.2$ MeV (95% CL) from $\tau^- \rightarrow n\pi + \nu_\tau$

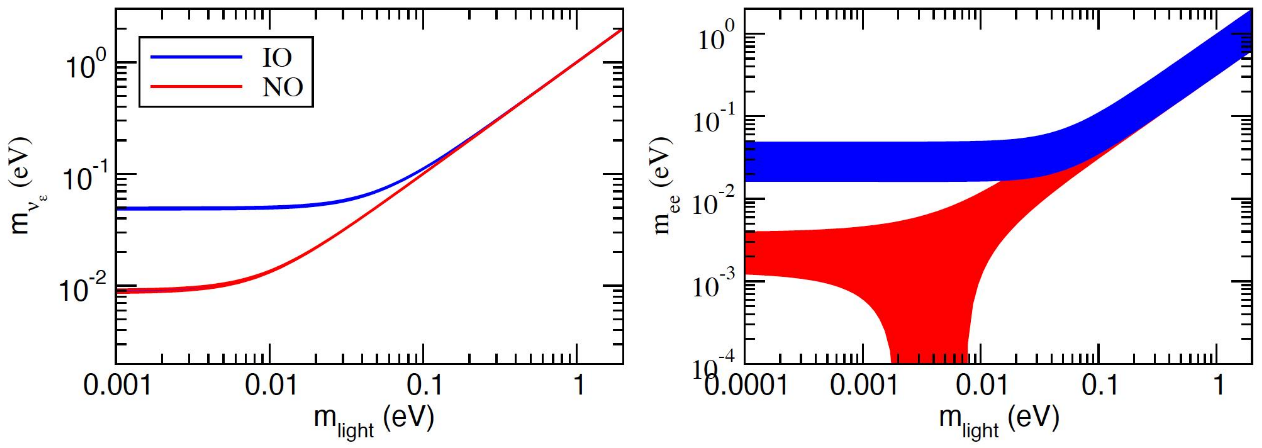


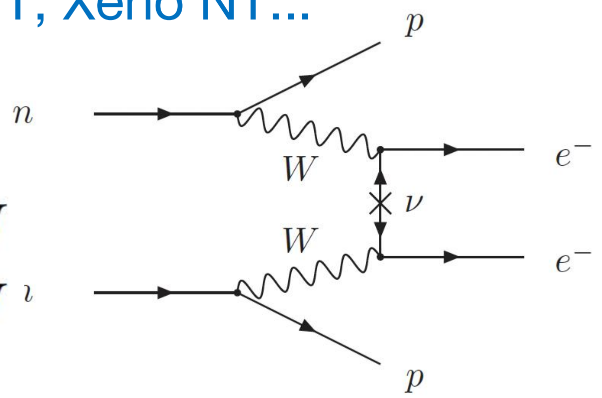
Figure 14.11: Allowed 95% CL ranges (1 dof) for the neutrino mass observable determined in ^{3}H beta decay (left panel) and in $0\nu\beta\beta$ (right panel) in the framework of 3ν mixing as a function of the lightest neutrino mass. The ranges are obtained by projecting the results of the global analysis of oscillation data (w/o SK-atm) in Ref. [184]. The region for each ordering is defined with respect to its local minimum.

Neutrinoless double beta decay

Test Majorana mass nature

KamLAND-Zen, LEGEND, CUORE, GERDA...
and more to come, PandaX NT, Xeno NT...

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^- . \qquad (T^{0\nu}_{1/2})^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \left(\frac{m_{ee}}{m_e} \right)^2$$



KamLAND-Zen (Xenon) $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr, $m_{ee} < 36 - 156$ meV

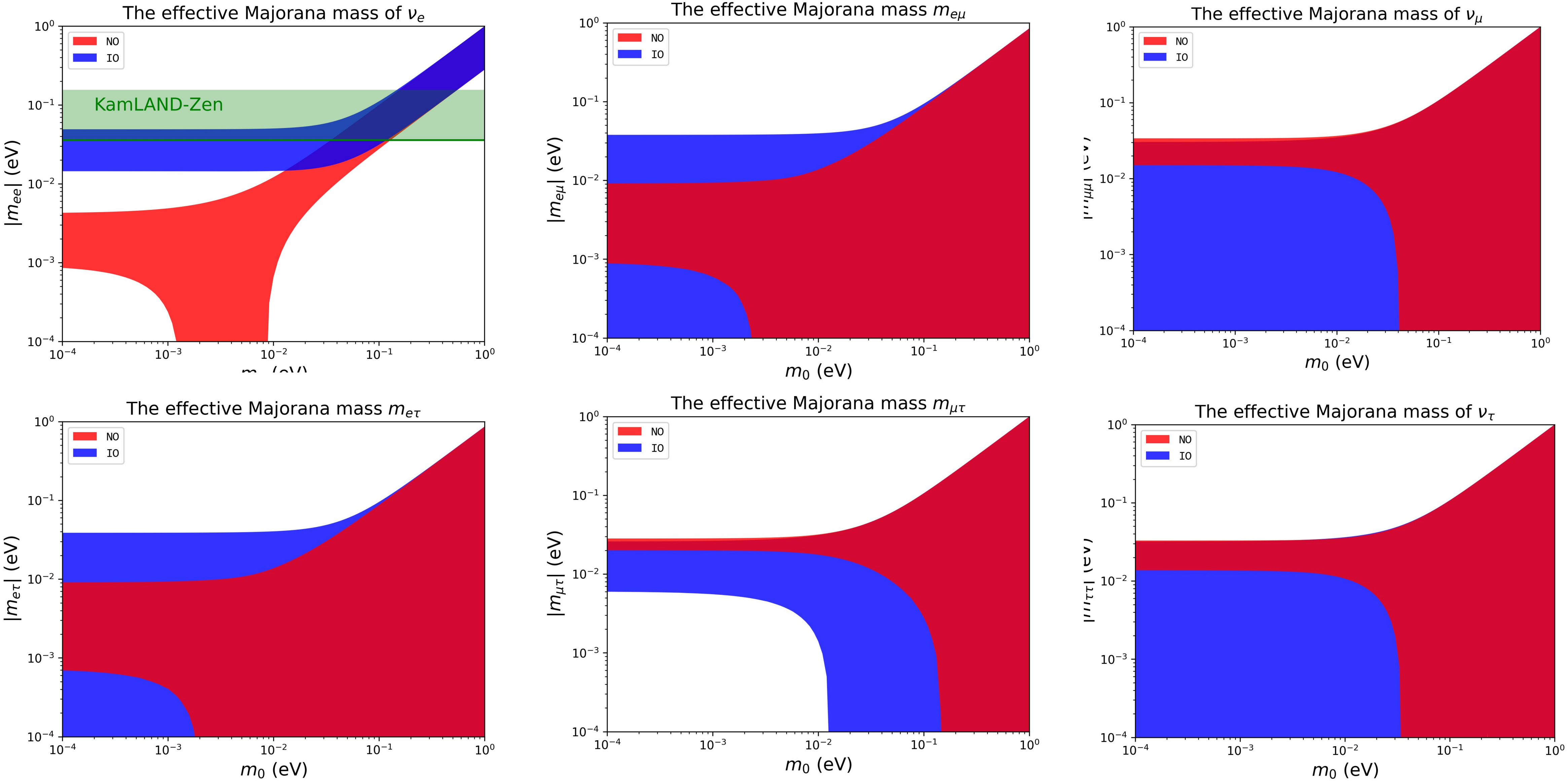
GERDA (Germanium) $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr, at 90% CL $m_{ee} < 79 - 180$ meV

Other propertise of neutrions: dipole moment... Are there light right handed neutrions

Constraints on Majhorana neutrino mass matrix

$m_\nu = (m_{ij}) = (V_{il} m_l V_{lj})$

$$m_\nu = V_{PMNS}\hat{m}_\nu V_{PMNS}^T$$



Grand Unification Theory SO(10) Predictions

Minimal SO(10) Model without 120

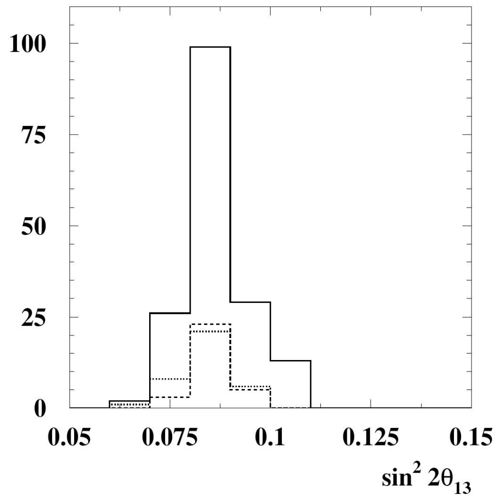
$$16_F(Y_{10}10_H + Y_{\overline{126}}\overline{126}_H + Y_{120}120_H)16_F$$

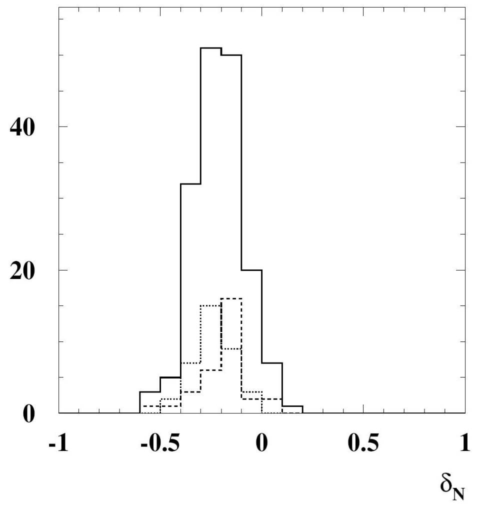
$$\mathcal{L}_{\text{Yukawa}} = Y_{10}\,\mathbf{16}\,\mathbf{16}\,\mathbf{10}_H + Y_{126}\,\mathbf{16}\,\mathbf{16}\,\overline{\mathbf{126}}_H$$

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa_u' Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa_d' Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa_u' Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa_d' Y_{126} \end{aligned}$$

$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle Y_{126} \end{aligned}$$

Good prediction for $\theta_{13}\delta$ Away from $-\pi/2$!





Model has only 11 real parameters plus 7 phases

Loop generated Dirac mass models also work!
Eax:Babu, He, Su &Thapa, JHEP 08 (2022) 140

More data will help to finally determine mixing pattern, whether there is CPV!

3. Neutrinos In Cosmology And Astrophysics

In early universe, all energy forms existed in form of elementary particles, or ….
Temperature is high and were in thermal equilibrium

Criteria for thermal equilibrium: particle interaction length $1/\Gamma$ (Γ interaction rate) is smaller than Hubble length $1/H_0$

???Planck mass T ~ 10^{19}GeV

Inflation

Big Bang ~ T> 10^{16} GeV

(Not in thermal equillibrium by SM for particle physics)

Grand Unification ~ 10^{16} GeV

EW symmetry breaking 300GeV

Color confinement ~300 MeV

BBN ~ 1 MeV

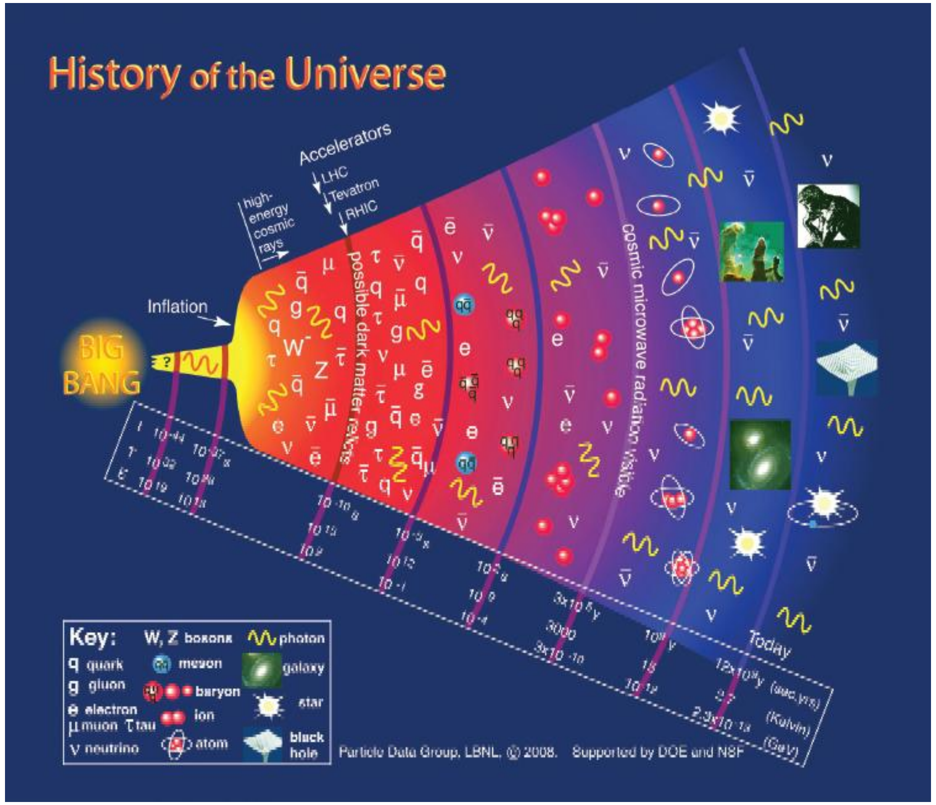
CνB ~ 1 MeV

CMB ~0.3 eV

Large structure formation

...

Today ~2.7K



Relic neutrino density: $$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{\text{eff}} \left(\frac{4}{11}\right)^{4/3}$$

Big-Bang Nucleothynsis: N_{eff} ~ 3 light neutrinos, consistent with Z decay witdth.

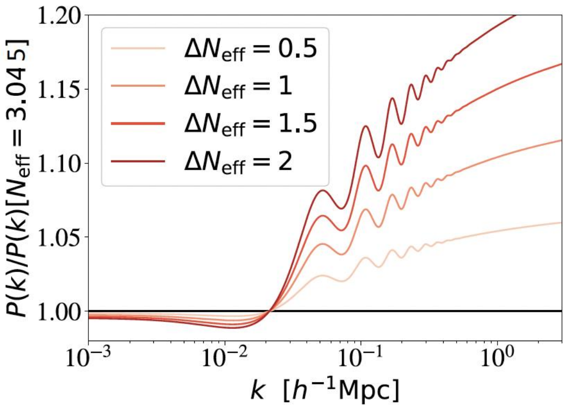


Table 26.1: Summary of N_{eff} constraints.

	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+N_{eff}	$2.92^{+0.36}_{-0.37}$	[22]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+N_{eff}	$2.99^{+0.34}_{-0.33}$	[22]
" + BAO + R21	ΛCDM+N_{eff}	3.34 ± 0.14 (68%CL)	[11]
"	" +5-params.	2.85 ± 0.23 (68%CL)	[23]

Neutrino back ground temperature: $T_\nu/T_\gamma = (4/11)^{1/3} = 1.95$ K

$n_\gamma = 440/\text{cm}^3$, $n_\nu = 339/\text{cm}^3$

Energy density from neutrinos: $$\Omega_\nu = \frac{\rho_\nu^0}{\rho_{\text{crit}}^0} = \frac{\sum m_\nu}{93.14 h^2 \text{ eV}}$$

Neutrino Mass On CMB And Matter Spectrum

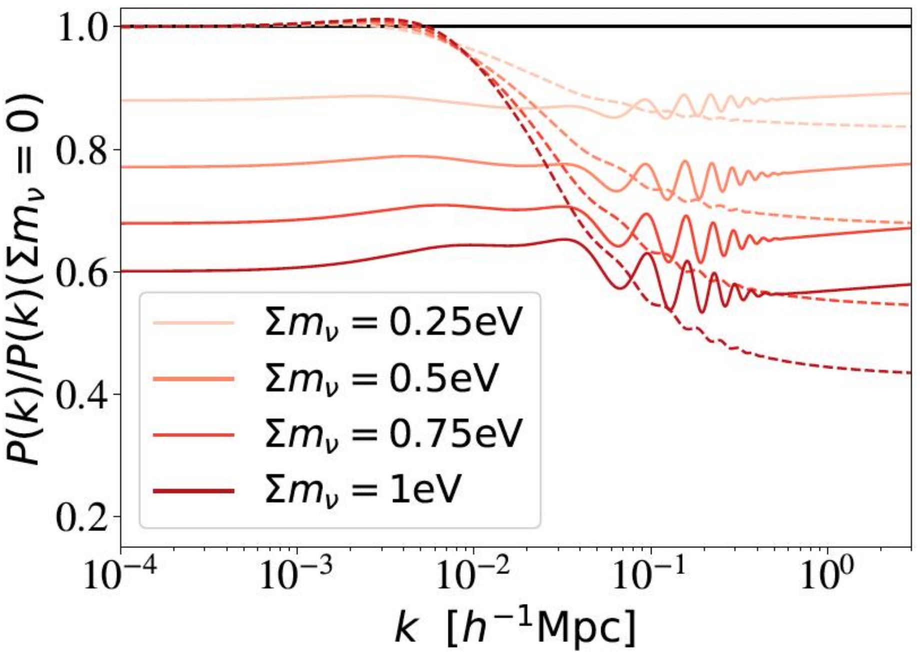


Table 26.2: Summary of $\sum m_\nu$ constraints.

	Model	95% CL (eV)
CMB alone		
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26
CMB + probes of background evolution		
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515
CMB + LSS		
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24
CMB + probes of background evolution + LSS		
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13

The sum of the neutrino masses should be less than 0.6 eV.

Future, reach 0.06 eV reaching the allowed range by neutrino oscillation!
DESI, Euclid, LSST, SPHEREx, SKA.

Neutrinos play important role in BBN!
Cosmology constraint their masses compareable to neutrino oscillation data!

Neutrino And Our Matter Universe

In our Universe, matter dominates over anti-matter

- Why this is so is the problem of Baryon Asymmetry of our Universe (BAU)

Andrei Sakharov on *Soviet Nobel Peace Prize winners*, the USSR stamp issued on 14 May 1991

In cosmological terms, the problem is as follows

If initially, the universe is matter and anti-matter symmetric

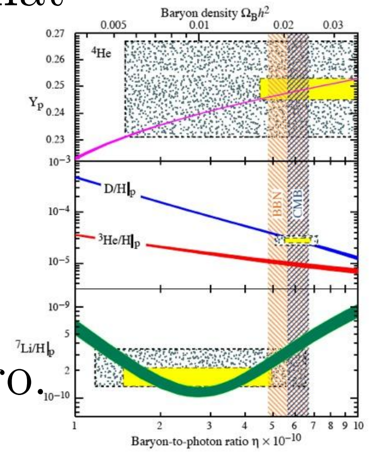
$n_B/n_\gamma = n_{\bar{B}})/n_\gamma \sim 10^{-20}$

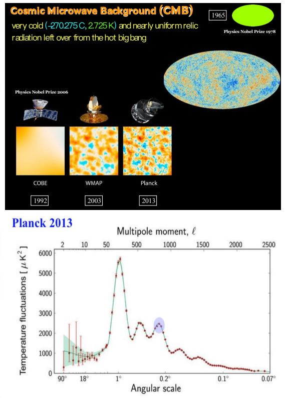
$n_B(n_{\bar{B}})$ - baryon (anti-baryon) number density, n_γ - photon number density

However observation, BBN and CMB, show that

$\eta = (n_B - n_{\bar{B}})/n_\gamma \sim 6 \times 10^{-10}$

There is a 10^{10} order of magnitude difference.





Initially, there is a baryon asymmetry?

But inflation will dilute any asymmetry to zero.

Possible to generate a η which fits observtion from an, initially, matter anti-matter symmetry universe?

Sakharov Conditions (1967)

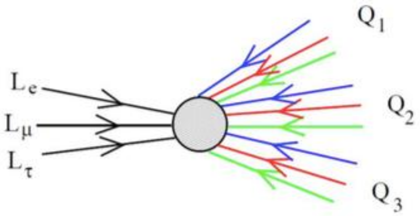
Baryon Number B Violation

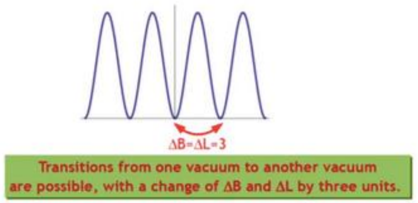
C and CP Violation

Interactions Out Of Thermal Equilibrium

Standard Model Has All Ingradients, But Too Small

Baryon number violation: Sphelaron effects-tunneling effects from different vacuum states with non-zero baryon number differences. Violated B+L, but conserves B-L.





C and CP violation: Electroweak interaction violates C, and phase in Kobayashi-Maskawa mixing matrix violates CP.

Out of thermal equilibrium: Electroweak symmetry breaking

But, CP violation rate too small, out of thermal equilibrium too weak. Not enough to generate a large enough Baryon Asymmetry.

If Higgs mass is less than 70 GeV, second order phase transition at electroweak symmetry breaking, too weak.

$\eta \sim 10^{-20}$ Too small. Needs to go beyond SM!

Electroweak baryogenesis, Leptogenesis, Gut baryogenesis….

Leptogenesis

Fukugita and Yanagida, PLB174, 45(1986)

Translate lepton number asymmetry generated in the early universe to baryon number asymmetry!

Requires lepton asymmetry generated before Sphelaron effects to be in effective ($T \sim 10^{12}$ – a few TeV). Initial $a_L(i)=a$, $a_B(i)=0$.

Sphelaron effect: Conserve B-L, but violates B+L

After: $a_L(f)+a_B(f) = 0$, $a_L(i) - a_B(i) = a_L(f) - a_B(f)$

$$a_L(f) = a/2; \quad a_B(f) = -a/2$$

half of initial lepton asymmetry will be translated into baryon asymmetry if complete.

SM Sphelaron effect: $a_B = -(28/79)a_L$

Seesaw Model Plays The Right Role

$$L_M = -\bar{L}_L Y_e \tilde{H} E_R - \bar{L}_L Y_\nu H \nu_R - \frac{1}{2}(\bar{\nu}_L, \bar{\nu}_R^{'c}) M^\nu \begin{pmatrix} \nu_L^{'c} \\ \nu_R' \end{pmatrix} + H.C.$$

The last term violates lepton number L by two units!

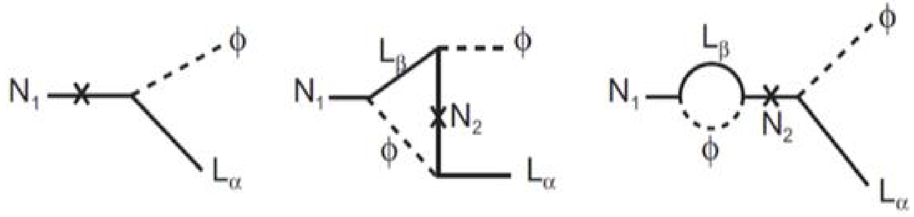
Out of thermal equilibrium decay, new CP violation in N -> L h(ϕ)

N decays into L and anti-L differently

$$a_i = \frac{\Gamma(N_i \to L\phi) - \bar{\Gamma}(N_i \to \bar{L}\phi)}{\Gamma(N_i \to L\phi) + \bar{\Gamma}(N_i \to \bar{L}\phi)}$$

$$a_i \approx -\frac{1}{8\pi} \frac{1}{[\hat{Y}_\nu \hat{Y}_\nu^\dagger]_{ii}} \sum_j Im\{[\hat{Y}_\nu \hat{Y}_\nu^\dagger]_{ij}^2\} f\left(\frac{M_j^2}{M_i^2}\right)$$

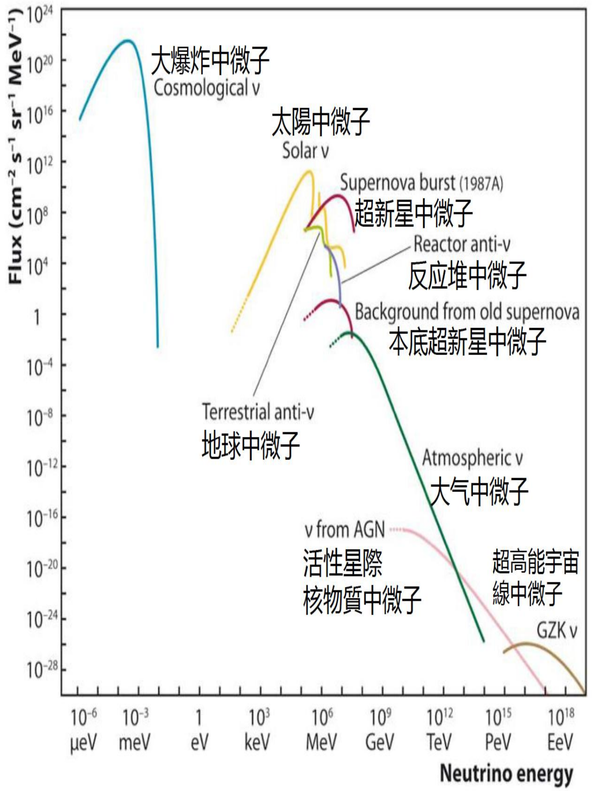
$$f(x) = \sqrt{x}\left(\frac{2}{x-1} + \ln\frac{1+x}{x}\right).$$



M_N and m_ν masses are correlated to obtain the right number for η,
m_ν of order 0.05 eV, M_N ~ 1000 GeV.

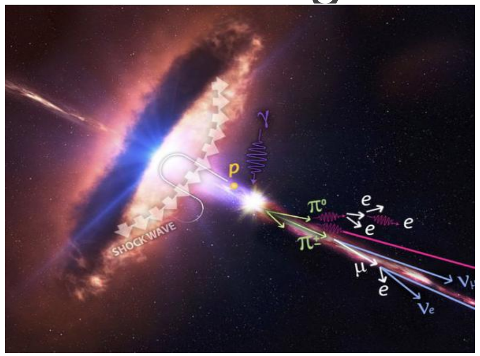
Neutrino Seesaw model is a viable model for Baryon Asymmetry of our Universe

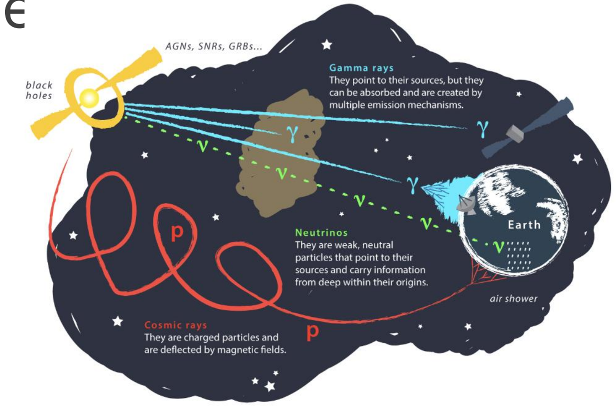
Cosmic Neutrino Ray As Messenger For Our Universe



Where the very high energy neutrino ray come from? How they are acceleratted to have such high energie

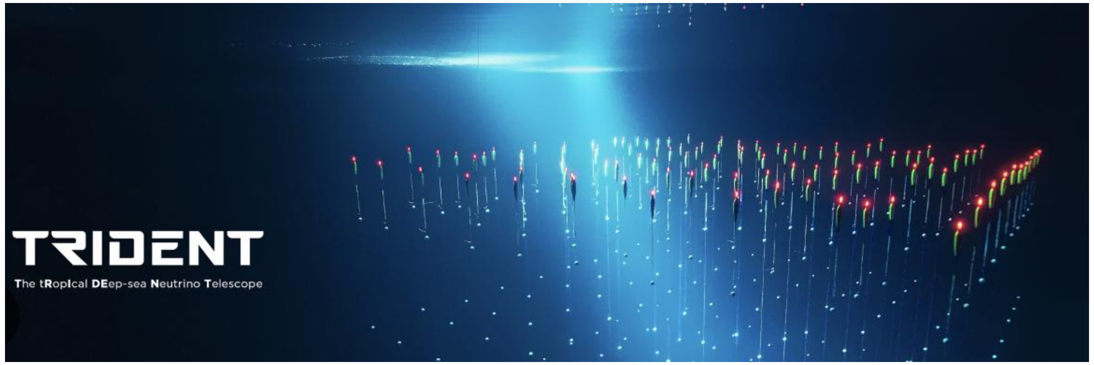
Any use of the neutrino cosmic ray?

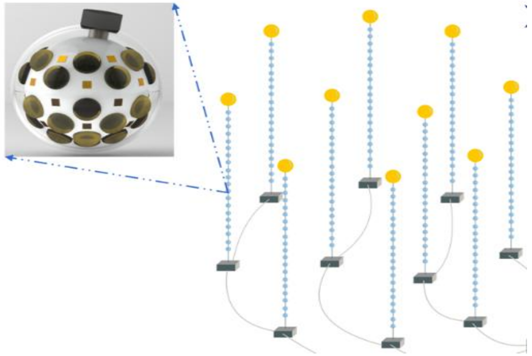




Like we use neutrino beam on earth to probe new interactions, human being can use cosmic neutrino beams as messengers to probe our universe with much less disturbances compared with hadrons, photons!

Extremely low energy: CνB and super high energy neutrino rays.





Messenger for our universe! Icecube, KM3net and future:Trident and Hunt projects are initiatives for this!

Thank you for your attentions!