INTRODUCTION TO NEUTRINO PHYSICS

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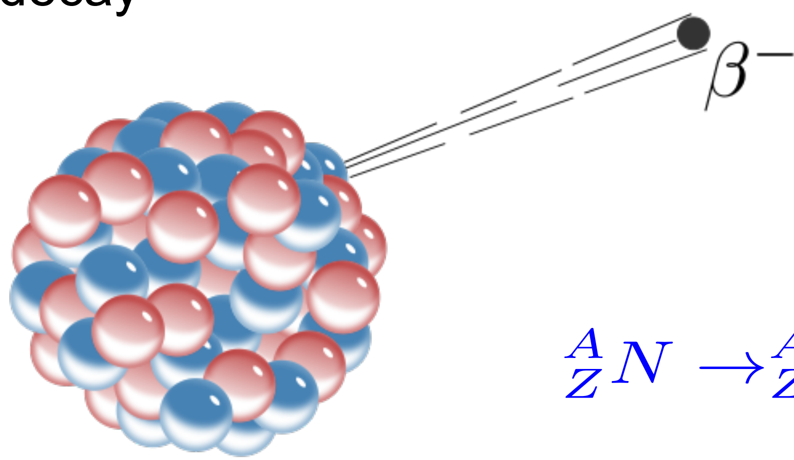
- Historical introduction: ν in the Standard Model
- Neutrino masses and mixing : Majorana versus Dirac
- The standard 3ν scenario and a few outliers...
- The big open questions

Neutrino: the dark particle

1900 Radioactivity: Becquerel, M & P Curie, Rutherford....

β decay

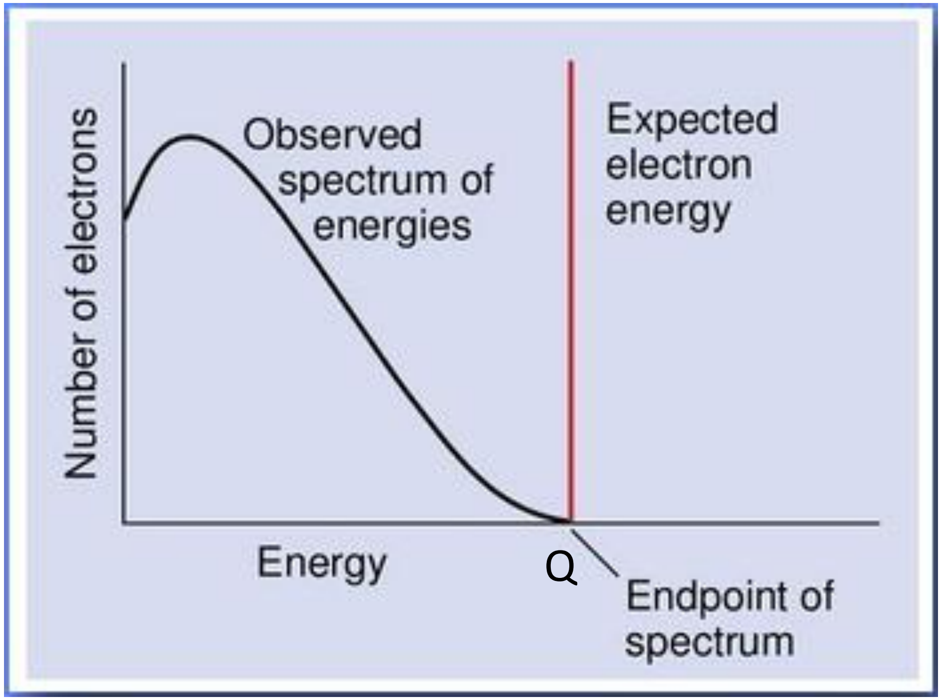


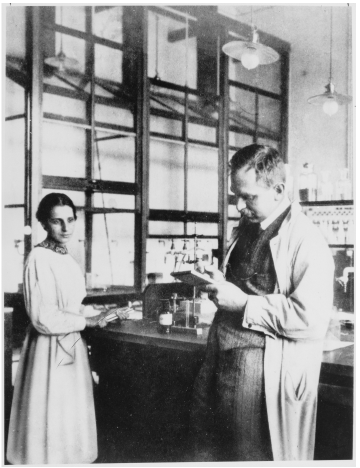
$${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^-$$

Energy conservation: $E_{\text{electron}} \simeq (M_N - M_{N'})c^2 = Q = \text{constante}$

1911/1914

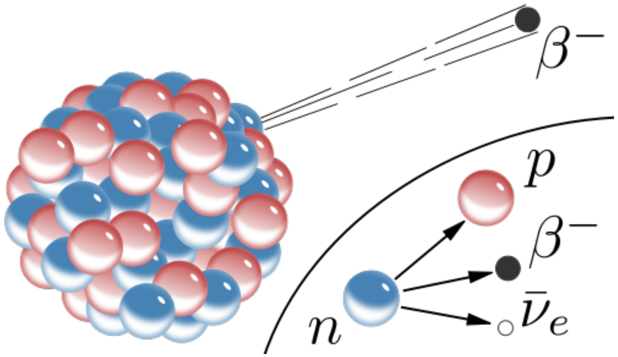
Electron spectrum:





Meitner, Hahn
(Nobel 1944 only him!)

Chadwick (Nobel 1935)



1930

Pauli (Nobel 1945)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.

Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7....

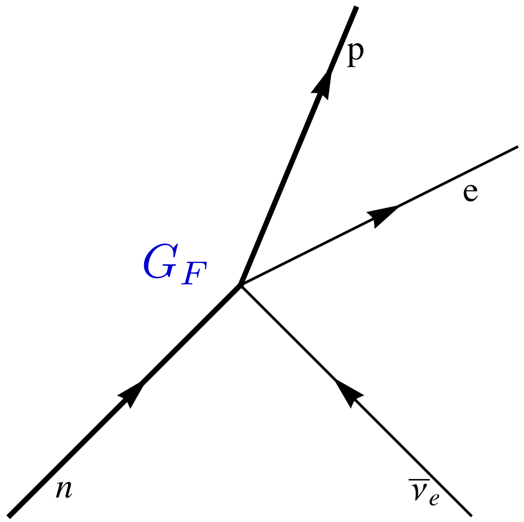
1933: Solvay's conference

The neutron was discovered in 1932 by Chadwick ...

"... their mass can not be very much more than the electron mass. In order to distinguish them from heavy neutrons, mister Fermi has proposed to name them "neutrinos". It is possible that the proper mass of neutrinos be zero... It seems to me plausible that neutrinos have a spin 1/2... We know nothing about the interaction of neutrinos with the other particles of matter and with photons: the hypothesis that they have a magnetic moment seems to me not funded at all."

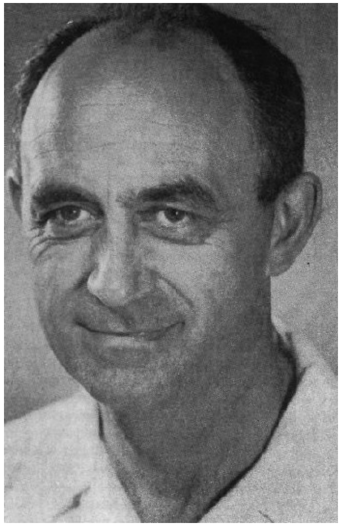
W. Pauli

1934: Theory of beta decay



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

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



E. Fermi
(Nobel 1938)

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

Bethe-Peierls (1934): computed the neutrino cross section using this theory

$$\sigma \simeq 10^{-44} cm^2, \; E(\bar{\nu}) = 2 \text{ MeV}$$

"there is not practically possible way of detecting a neutrino"

How to detect them ?

$$\lambda \simeq \frac{1}{n\sigma}$$

$$\lambda|_{@\mathrm{water}} \simeq 1.5 \times 10^{21}\ cm \simeq 1600 \text{ Light Years}$$

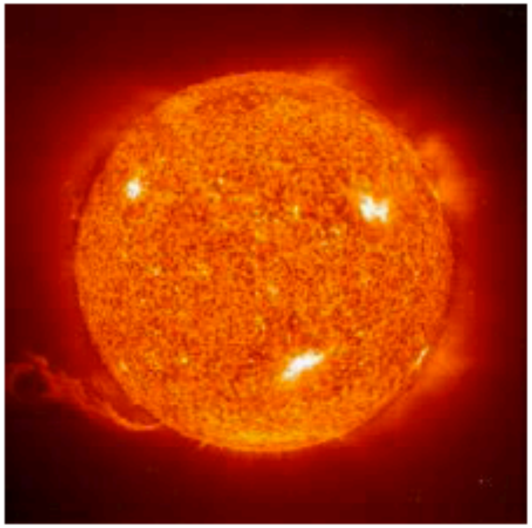
$$\lambda|_{@\mathrm{interstelar}} \simeq 10^{44}\ cm \simeq 10^{26} \text{ Light Years}$$

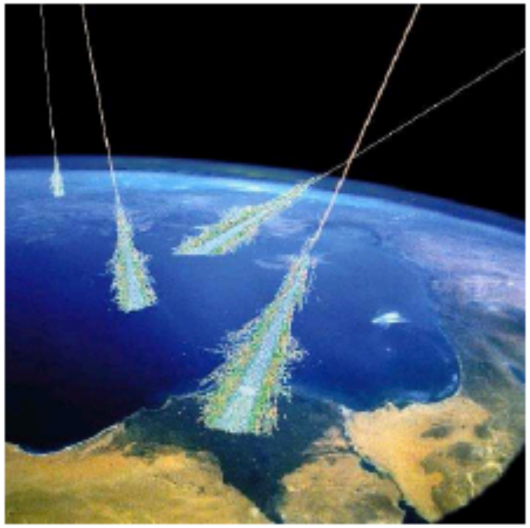
"*I have done a terrible thing. I have postulated a particle that cannot be detected*"

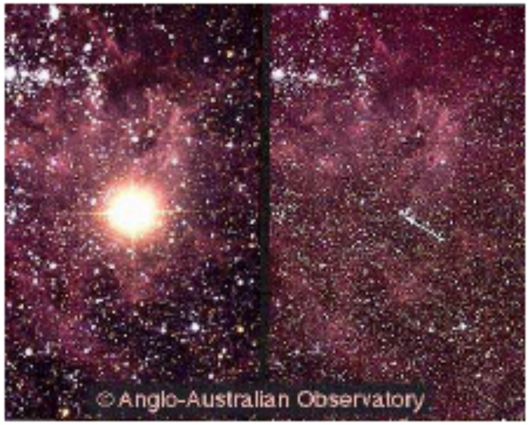
W. Pauli

"*Not even wrong*"

Revealing Pauli's dark matter was just a question of time and ingenuity...







Enjoyable reading "Neutrinos" by F. Close

How to detect them?

1946 Pontecorvo

Not so desperate...

$$
\begin{aligned}
N_{CC} &= \Phi_\nu \times \sigma \times \text{Numero de blancos} \times \Delta T \\
&= \Phi_\nu (cm^{-2}s^{-1}) \times 10^{-44} cm^2 \times N_{\text{Avogadro}} \times \text{Detector mass(gr)} \times 10^5 s \times \#\text{dias}
\end{aligned}
$$

In a 1000kg detector, a 10^{10} $\nu/cm^2/s$ a few events per day

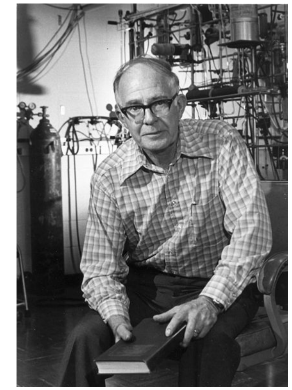
Needs a reaction where the final isotope is radioactive with a proper lifetime

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

Then the (by-then) recently invented nuclear reactors could be this source...

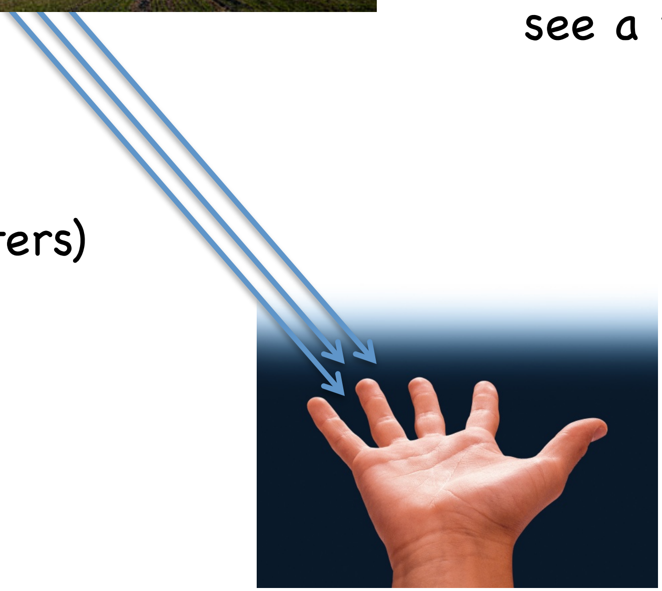
Reactors: ~ 10^{20}/second!

1955 Davies



Built a 4000 liter detector, but did not see a thing...

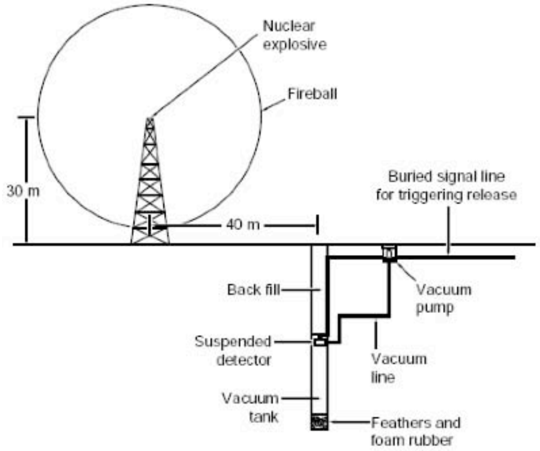
(10^{11}/s@100 meters)

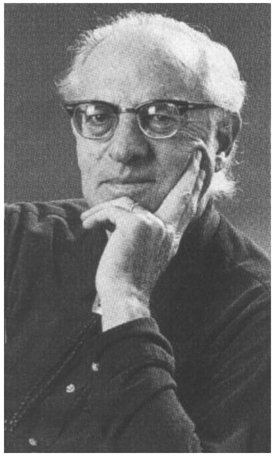


1956 (anti)neutrino detection

Poltergeist project

First idea: put the detector close to a nuclear explosion !

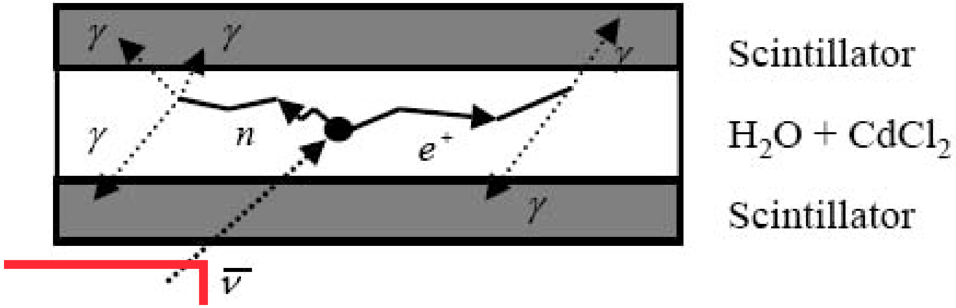




Reines Nobel 95

Cowan (died 74)

Finally used the reactor Savannah River to discover the anti-neutrino



The flavour of neutrinos

1937 μ discovered in cosmic rays

1947 Pontecorvo

Is a heavy version of the electron and not the nuclear agent (pion)

$$\pi \rightarrow \mu \; \bar{\nu}_\mu$$

1959 Pontecorvo

The neutrino that accompanies the μ is different to that in beta decay

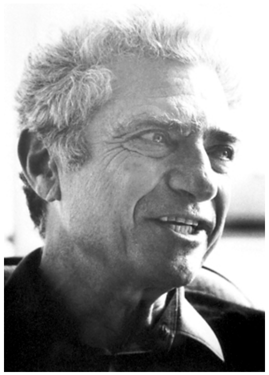
Neutrino cross section in Fermi theory grows with energy: he proposes the first experiment with a neutrino beam !

Neutrino Flavour

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

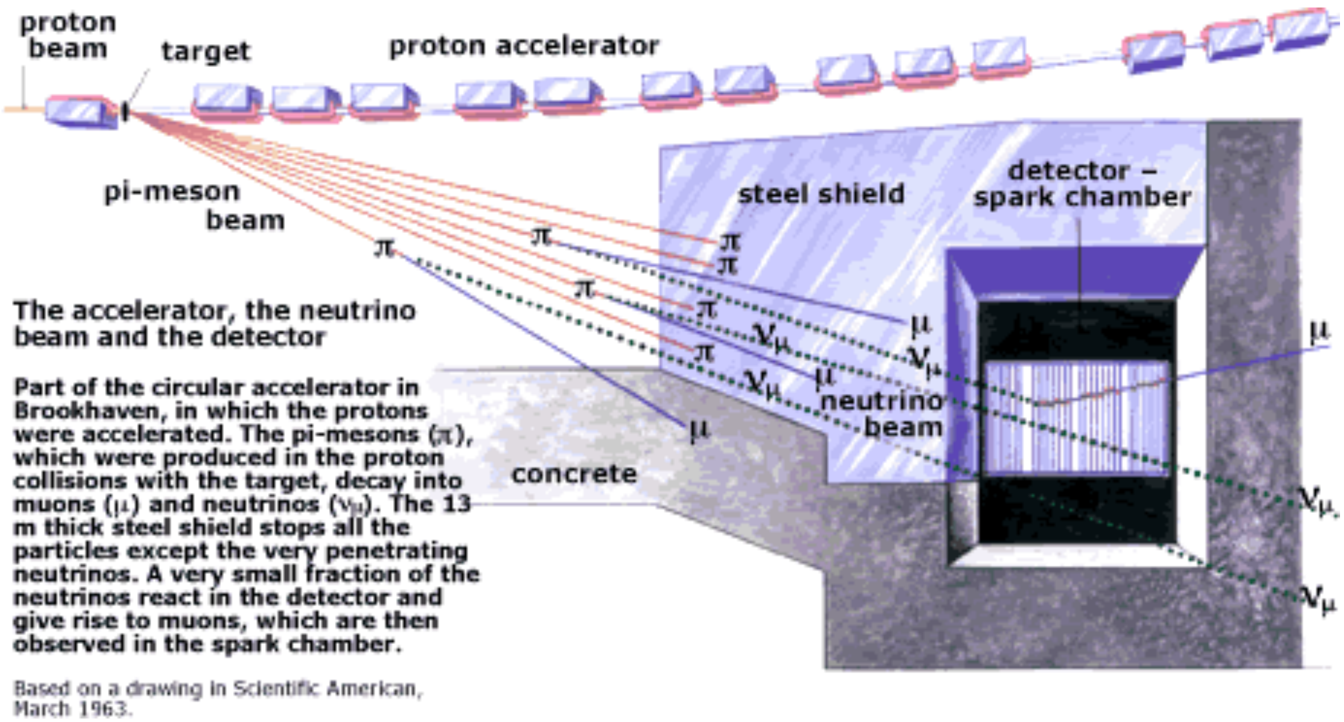
Lederman

Schwartz



Steinberger

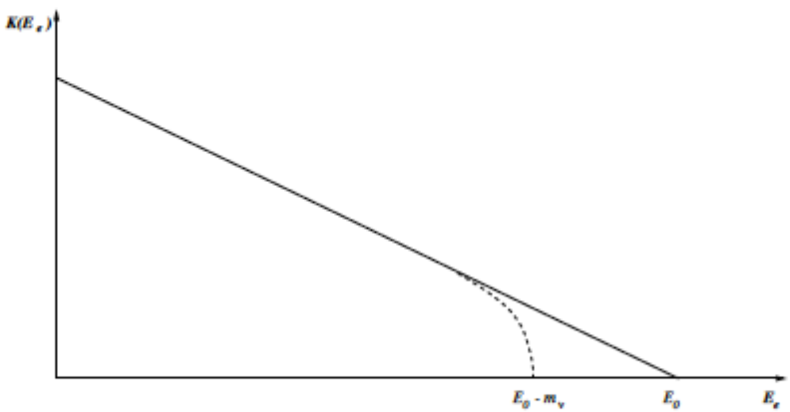
Nobel 1988



Kinematical effects of neutrino mass

Most stringent from Tritium beta-decay

$$H^3 \rightarrow^3 He + e^- + \bar{\nu}_e$$



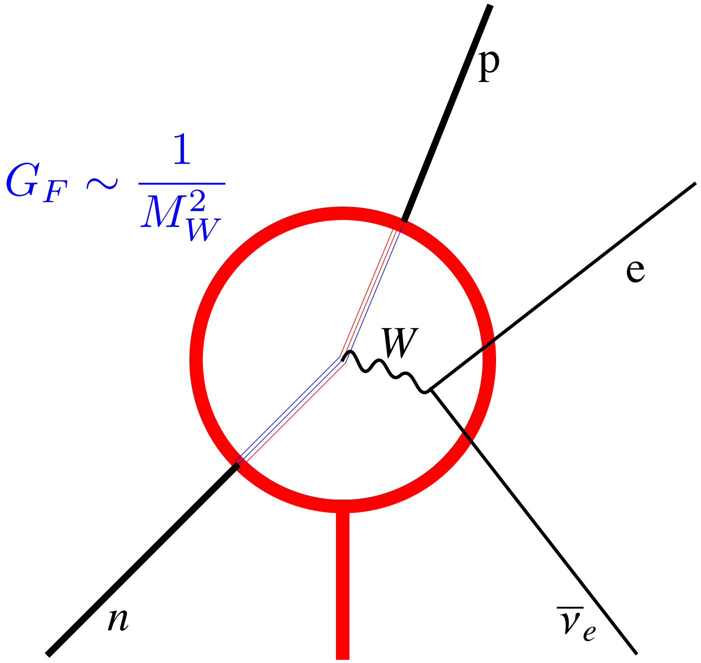
$m_{\nu_e} < 2.2\text{eV}$ (Mainz-Troitsk)

$m_{\nu_\mu} < 170\text{keV}$ (PSI: $\pi^+ \rightarrow \mu^+\nu_\mu$)

$m_{\nu_\tau} < 18.2\text{MeV}$ (LEP: $\tau^- \rightarrow 5\pi\nu_\tau$)

Standard Model neutrinos assumed massless

Neutrinos in the Standard Model



Charged currents: CC

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

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

$$\nu \leftrightarrow \nu^f_\beta, \quad \beta \leftrightarrow \text{spin}, f \leftrightarrow \text{flavour}$$

Only particles in the SM that carry no conserved charge !

Neutrinos in the Standard Model

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

$$\Psi_{L/R} \equiv P_{L/R}\Psi$$

$$P_{L/R} \equiv \frac{1 \mp \gamma_5}{2}$$

$$\nu = \frac{1-\gamma_5}{2}\,\nu \simeq \frac{1}{2}\left(1 - \underbrace{\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}}_{\text{Helicity}}\right)\nu + \mathcal{O}(v/c)$$

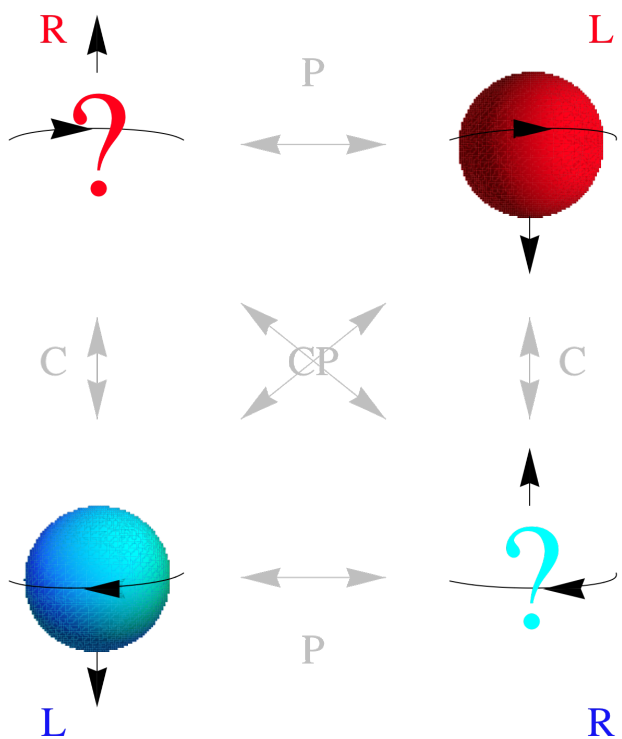
Left-handed   Right-handed

Neutrinos are Weyl fermions: two component spinor describing a massless fermion with negative helicity + antifermion with positive helicity

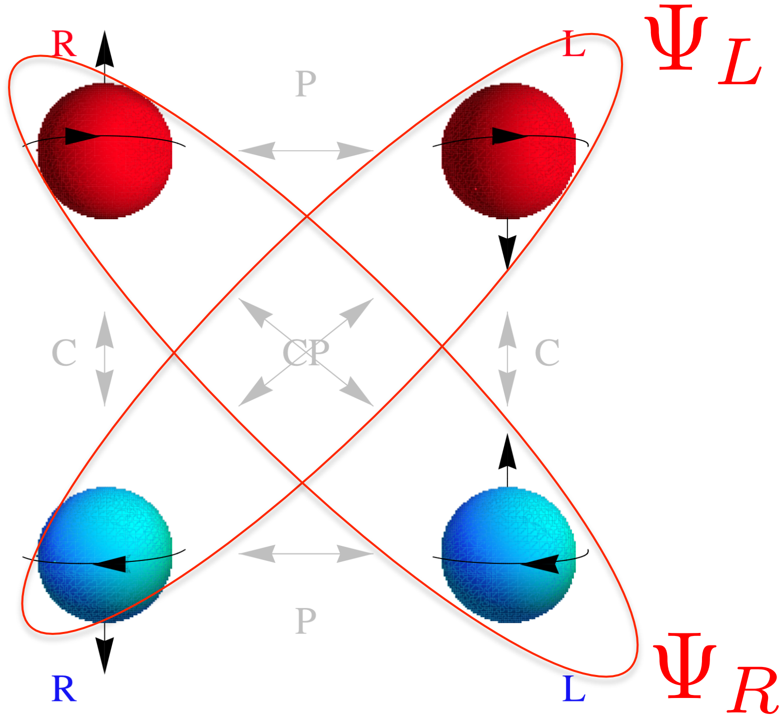
$$\not{p}\nu = 0 \to \begin{cases} E > 0, & \hat{h}\nu = -\nu \\ E < 0, & \hat{h}\nu = \nu \end{cases}$$

Breaking of C and P

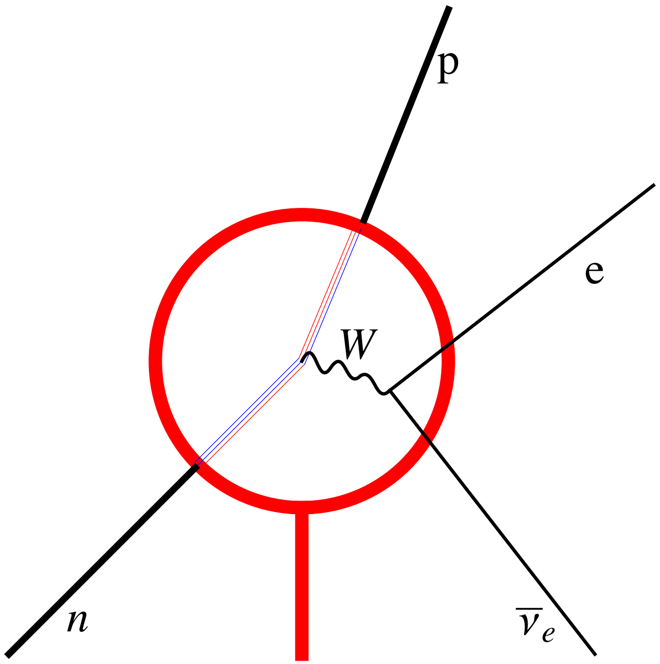
Weyl fermion= 2-component spinor
(Minimal spin ½)



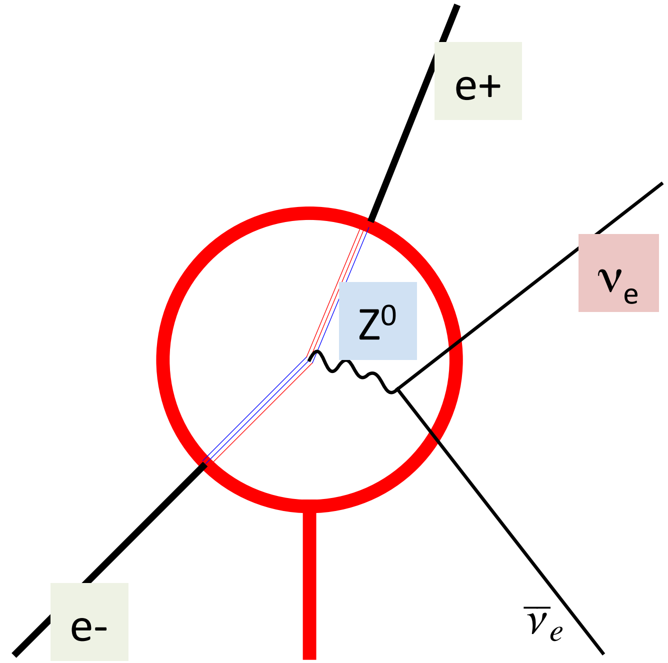
Dirac fermion= 4-component spinor
(Minimal spin ½ + Parity)



Neutrinos interactions in the SM



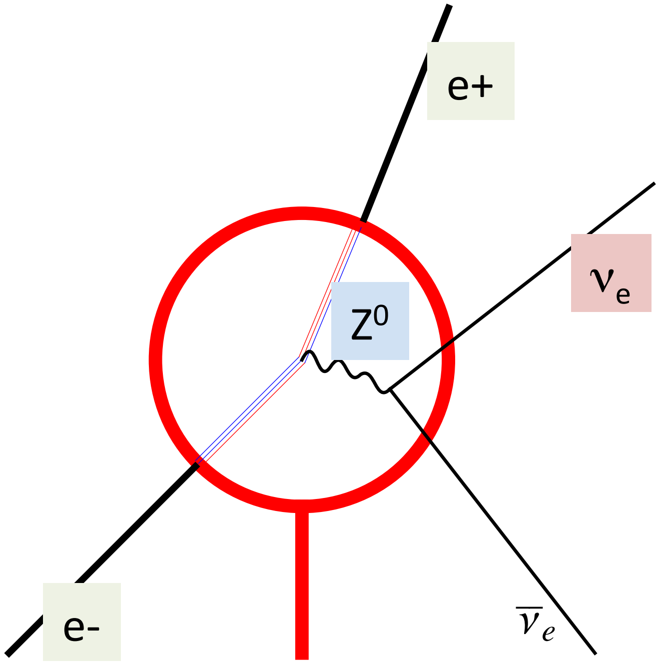
Charged currents: CC



Neutral currents: NC

$$\mathcal{L}_{SM} \supset -\frac{g}{\sqrt{2}} \sum_f \bar{\nu}_{Lf} \gamma_\mu l_{Lf} W^+_\mu - \frac{g}{2\cos\theta_W} \sum_f \bar{\nu}_{Lf} \gamma_\mu \nu_{Lf} Z_\mu + h.c.$$

Neutrinos in the Standard Model



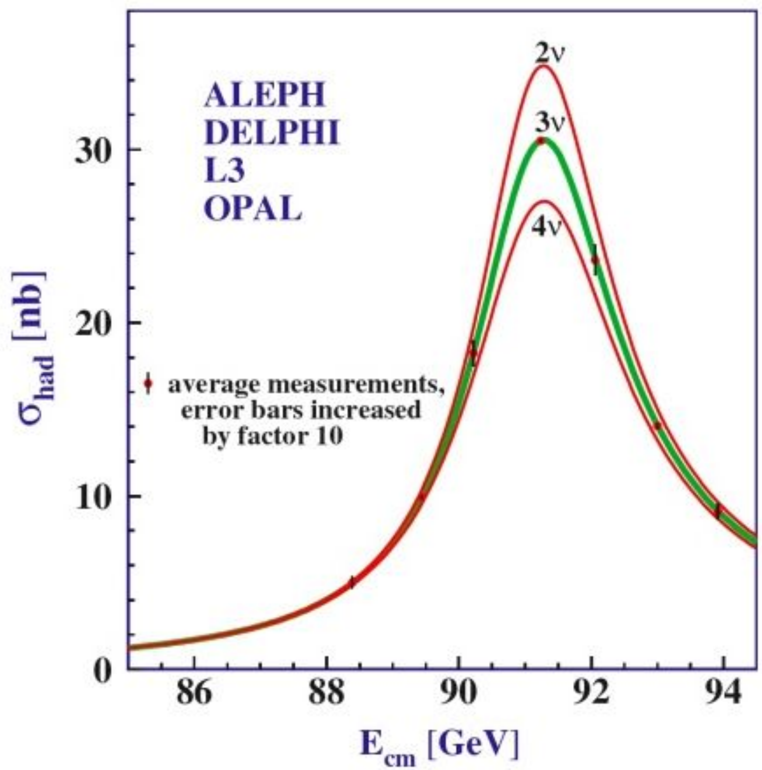
At LEP:

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

Only three neutrinos -> three SM families

Neutral currents: NC

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



Neutrinos in the Standard Model

Neutrinos have been essential in establishing the two most intringuing features of the SM:

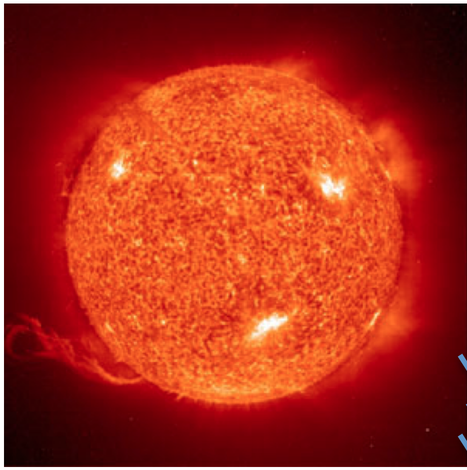
3-fold repetition of family structures

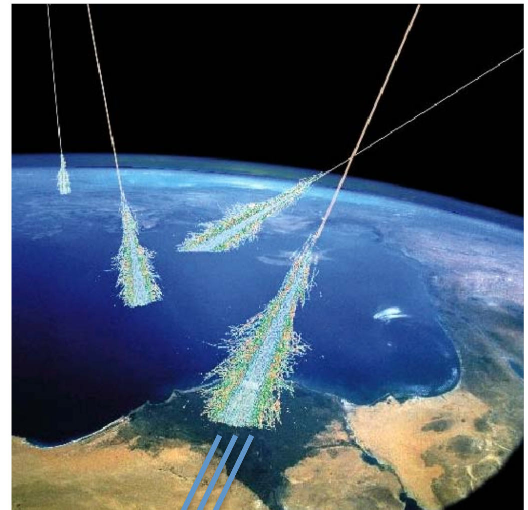
parity violation of the weak interactions

They might also have the clue of the underlying principle...

Ubiquitous Neutrinos

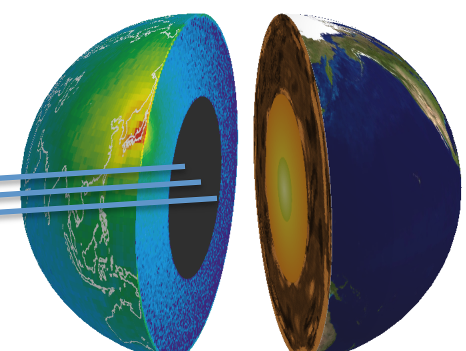
They are everywhere…





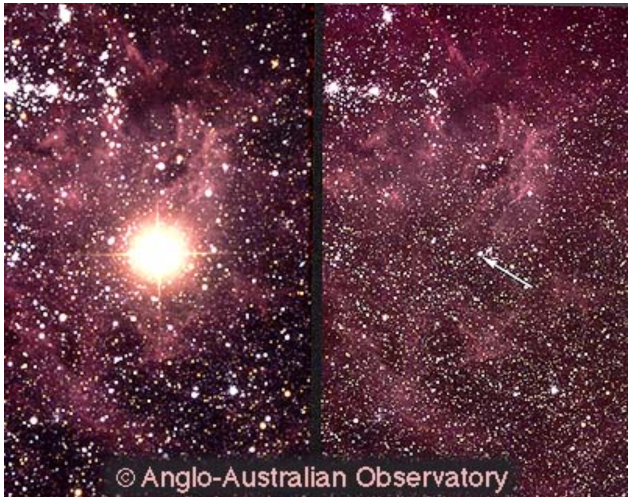
Atmosphere: ~20/second

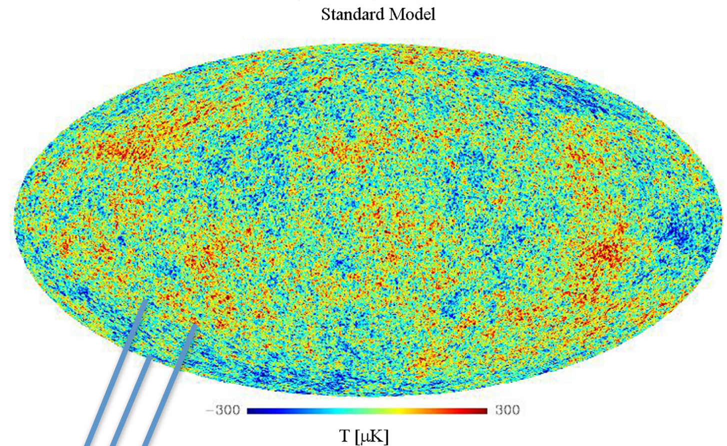
Sun: 5 x 10^{12}/second



Earth: ~10^{9}/second

Ubiquitous Neutrinos





Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

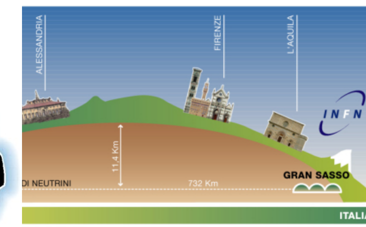
Big Bang: ~2 x 10^{12}/second

Supernova 1987: ~10^{12}/second

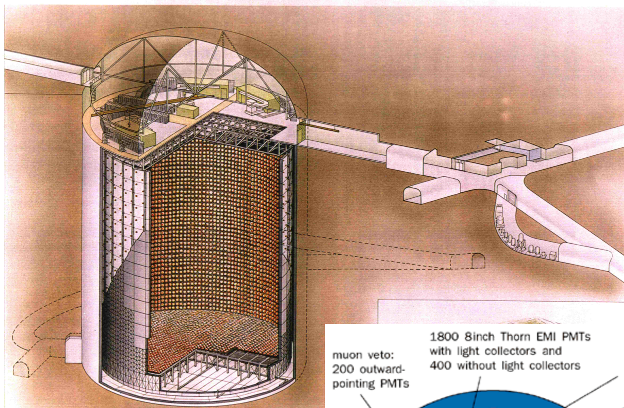
@168000 Light years!
10^8 farther from Earth

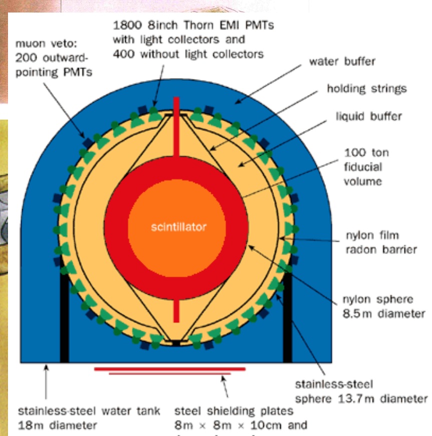
Using many of these sources, and others man-made, a decade of revolutionary neutrino experiments have demonstrated that neutrinos are not quite standard, because they have a tiny mass & massive neutrinos require new dofs!

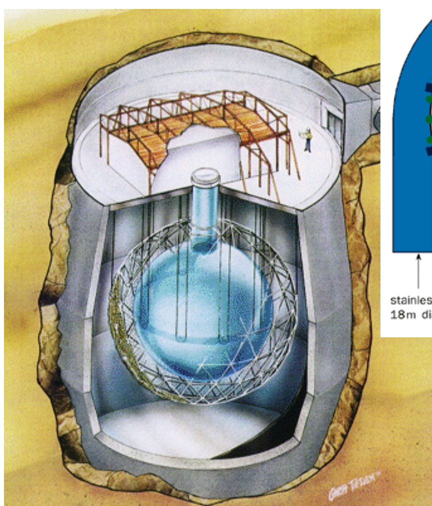
MINOS, Opera



SuperKamiokande







SNO

Borexino

...and more

Massive (free) fermions

Dirac fermion of mass m:

$$-\mathcal{L}_m^{\rm Dirac} = m\bar{\psi}\psi = m(\overline{\psi_L + \psi_R})(\psi_L + \psi_R) = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

Majorana fermion of mass m (Weyl representation)

$$-\mathcal{L}_m^{Majorana} = \frac{m}{2}\overline{\psi^c}\psi + \frac{m}{2}\overline{\psi}\psi^c \equiv \frac{m}{2}\psi^T C\psi + \frac{m}{2}\bar{\psi}C\bar{\psi}^T,$$

$$\psi^c \equiv C\bar{\psi}^T = C\gamma_0\psi^* \quad C = i\gamma_2\gamma_0$$

- ✔ Non-zero for Weyl fermion: $\Psi = P_L\Psi \to \Psi^T C\Psi = \Psi_L^T i\sigma_2\Psi_L$
- ✔ Lorentz invariant
- ✔ Massive fermion: dispersion relation $E^2 - \mathbf{p}^2 = m^2$

Massive fermions & Weak Interactions ?

Dirac fermion of mass m:

$$-\mathcal{L}_m^{\rm Dirac} = m\bar{\psi}\psi = m(\overline{\psi_L + \psi_R})(\psi_L + \psi_R) = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

Breaks SU(2)xU(1) gauge invariance!

Majorana fermion of mass m (Weyl representation)

$$-\mathcal{L}_m^{Majorana} = \frac{m}{2}\overline{\psi^c}\psi + \frac{m}{2}\overline{\psi}\psi^c \equiv \frac{m}{2}\psi^T C\psi + \frac{m}{2}\bar{\psi}C\bar{\psi}^T,$$

No gauge/global symmetry of ψ possible!

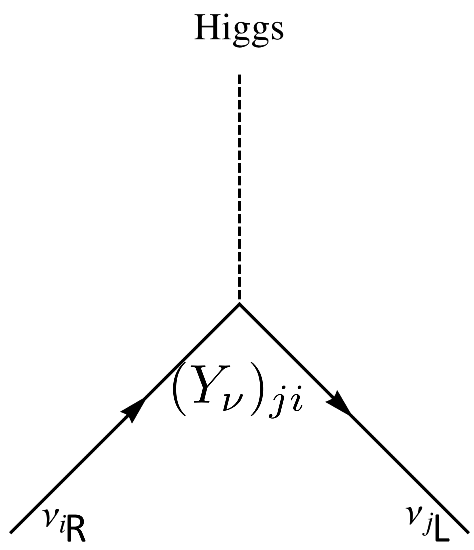
Spontaneous symmetry breaking can induce Dirac masses for all fermions but Majorana masses only for neutrinos !

Massive Dirac neutrinos & SSB ?

$$\widetilde{\phi} \equiv \sigma_2 \phi^*, \qquad \widetilde{\phi} : (1, 2, -\frac{1}{2}), \ \left\langle \widetilde{\phi} \right\rangle = \begin{pmatrix} \frac{v}{2} \\ 0 \end{pmatrix}$$

Massive Dirac neutrino

$$-\mathcal{L}_m^{\rm Dirac} = Y_\nu \ \underbrace{\bar{L} \ \widetilde{\phi}}_{(1,1,0)} \ \underbrace{\nu_R}_{(1,1,0)} \ + h.c \rightarrow SSB \ \rightarrow Y_\nu \bar{\nu}_L \frac{v}{\sqrt{2}} \nu_R + h.c.$$



$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

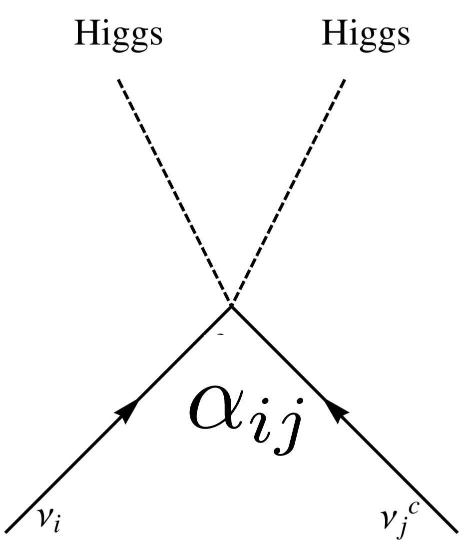
Massive Majorana neutrinos & SSB ?

$$\widetilde{\phi} \equiv \sigma_2 \phi^*, \qquad \widetilde{\phi} : (1, 2, -\frac{1}{2}), \;\; \left\langle \widetilde{\phi} \right\rangle = \begin{pmatrix} \frac{v}{2} \\ 0 \end{pmatrix}$$

Massive Majorana neutrino

$$-\mathcal{L}^{\mathrm{Majorana}} = \alpha \bar{L}\; \widetilde{\phi}\; C \widetilde{\phi}^T \bar{L}^T + h.c. \rightarrow SSB \rightarrow \alpha \frac{v^2}{2} \bar{\nu}_L C \bar{\nu}_L^T + h.c.$$

Weinberg's operator



$$m_\nu = \alpha \frac{v^2}{2}$$

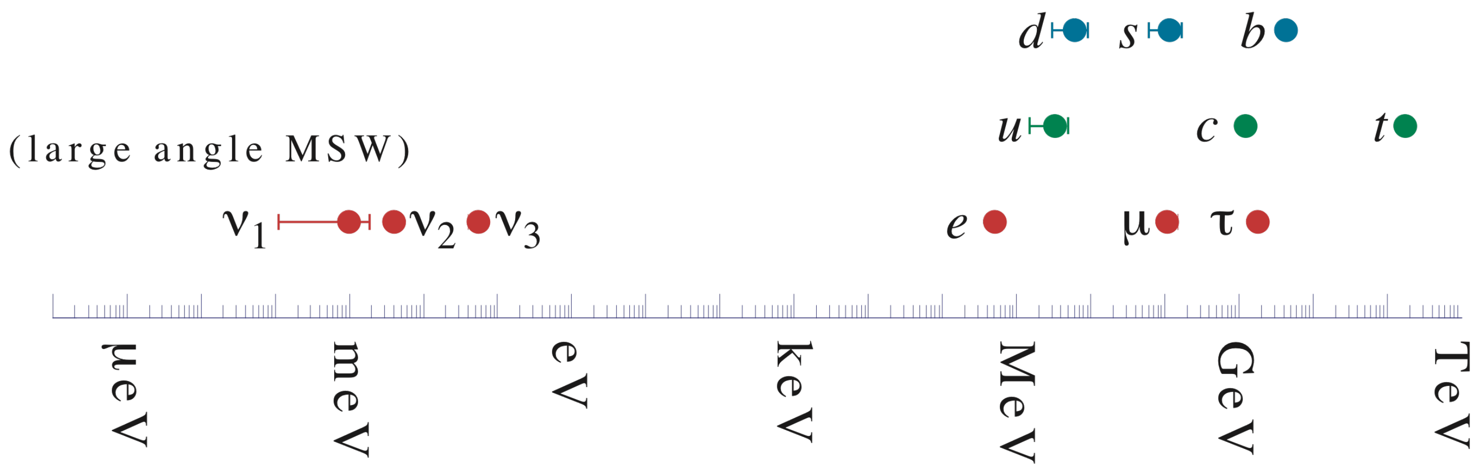
$$[\alpha] = -1$$

$$\alpha = \frac{Y_\nu}{\Lambda}$$

Implies the existence of a new physics scale unrelated to v !

Massive Majorana neutrinos & SSB ?

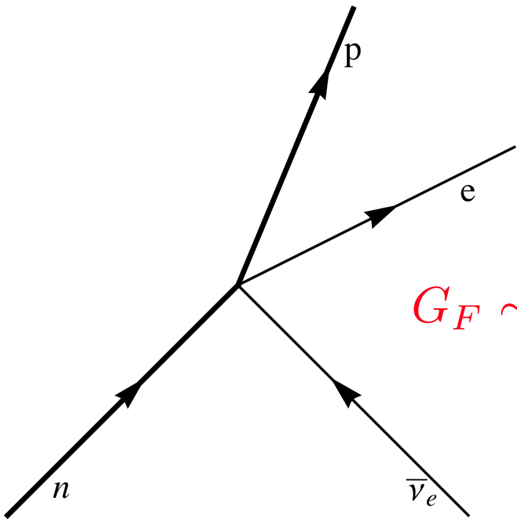
If $\Lambda >> v$ natural explanation for the smallness of neutrino mass



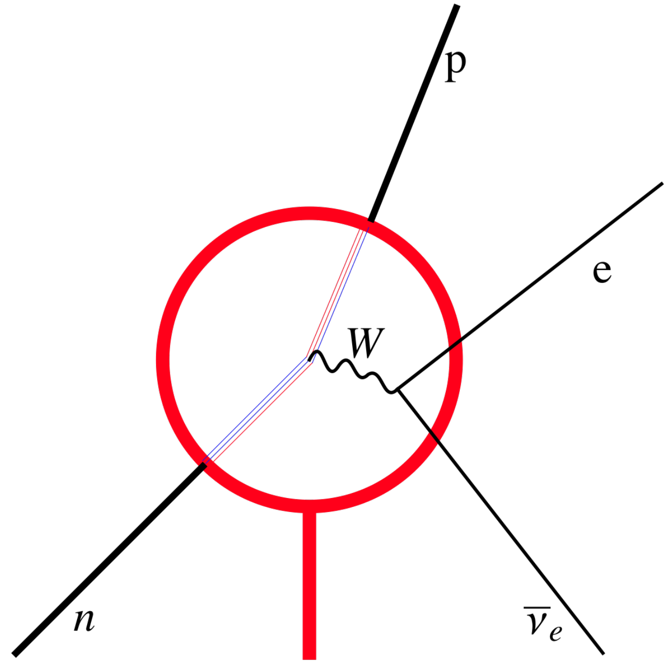
$$m_f(charged) \sim Yv, \quad m_\nu \sim Y\frac{v^2}{\Lambda} \sim m_f\frac{v}{\Lambda}$$

Lepton number is not conserved -> a new mechanism to explain the matter/antimatter asymmetry emerges

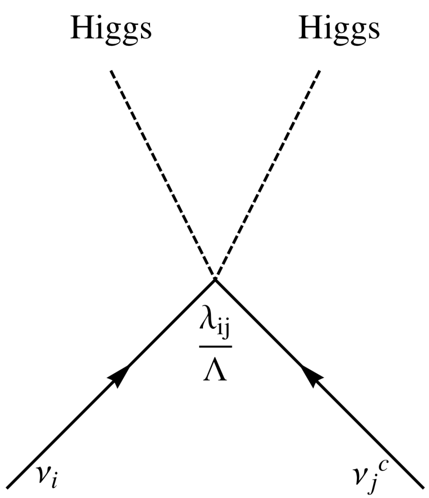
Majorana neutrinos imply a new Standard Model



$$G_F \sim \frac{1}{M_W^2}$$



SM



→ νSM ?

Generic new physics implies neutrino masses

If $\Lambda >> v$ low-energy effects should be well described by an effective field theory:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha_i}{\Lambda} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2} O_i^{d=6} + \ldots$$

Weinberg; Buchmuller, Wyler;...

O_i^d built from SM fields satisfying the gauge symmetries

Only one with d=5: Weinberg's operator or neutrino masses !

$$O^{d=5} = \bar{L}\tilde{\Phi}C\tilde{\Phi}^T\bar{L}^T + h.c.$$

There must be also d=6, ...

Neutrino masses & lepton mixing (Dirac)

Are generic complex matrices in flavour space

$$-\mathcal{L}_m^{lepton} = \bar{\nu}_{Li} \underbrace{(M_\nu)_{ij}}_{3\times n_R} \nu_{Rj} + \bar{l}_{Li} \underbrace{(M_l)_{ij}}_{3\times 3} l_{Rj} + h.c.$$

$$M_\nu = U_\nu^\dagger \, \mathrm{Diag}(m_1, m_2, m_3) \, V_\nu, \;\; M_l = U_l^\dagger \, \mathrm{Diag}(m_e, m_\mu, m_\tau) \, V_l$$

In the mass eigenbasis

$$l'_i \leftrightarrow (e, \mu, \tau)$$

$$\nu'_i \leftrightarrow (\nu_1, \nu_2, \nu_3)$$

$$\mathcal{L}_{\mathrm{gauge-lepton}} \supset -\frac{g}{\sqrt{2}} \bar{l}'_{Li} \underbrace{(U_l^\dagger U_\nu)_{ij}}_{U_{PMNS}} \gamma_\mu W_\mu^- \nu'_{Lj} + h.c.$$

Pontecorvo-Maki-Nakagawa-Sakata

$U_{\mathrm{PMNS}}(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ unitary matrix analogous to CKM

Why only one phase ?

Counting physical parameters in lepton mixing (Dirac)

\# physical parameters = # parameters in Yukawas
- \# parameters in field redefinitions
+ \# parameters of exact symmetries

		Field Redef.	Symmetries	Physical
	Y_ν , Y_l	$U_L(n)xU_{lR}(n)xU_{\nu R}(n)$	$U(1)_L$	
Moduli	$2n^2$	$3(n^2-n)/2$	0	$n^2/2+3n/2$
Phases	$2n^2$	$3(n^2+n)/2$	1	$n^2/2-3n/2+1$

Moduli = 2n masses + n (n–1)/2 angles For n=3: 3 angles, 1 phase

Neutrino masses & lepton mixing (Majorana)

Are generic complex matrices in flavour space

$$-\mathcal{L}_m^{lepton} = \frac{1}{2}\bar{\nu}_{Li}(M_\nu)_{ij}\nu^c_{Lj} + \bar{l}_{Li}(M_l)_{ij}l_{Rj} + h.c.$$

$$M_\nu^T = M_\nu \to M_\nu = U_\nu^T \mathrm{Diag}(m_1, m_2, m_3) U_\nu$$

In the mass eigenbasis

$$\mathcal{L}_{\mathrm{gauge-lepton}} \supset -\frac{g}{\sqrt{2}}\bar{l}'_{Li}\underbrace{(U_l^\dagger U_\nu)_{ij}}_{U_{PMNS}}\gamma_\mu W^-_\mu \nu'_{Lj} + h.c.$$

$$U_{\mathrm{PMNS}}(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \alpha_1, \alpha_2)$$ depends on three phases

Counting physical parameters in lepton mixing (Majorana)

\# physical parameters = # parameters in Yukawas
− # parameters in field redefinitions
\+ # parameters of field redefinitions of exact symmetries

	Yukawas	**Field. Red.**	**Symmetries**	**Physical**
	α_ν , Y_l	$U_L(n) x U_{lR}(n)$	0	
Moduli	$n(n+1)/2+n^2$	n^2-n	0	$n^2/2+3\,n/2$
Phases	$n(n+1)/2+n^2$	n^2+n	0	$n(n-1)/2$

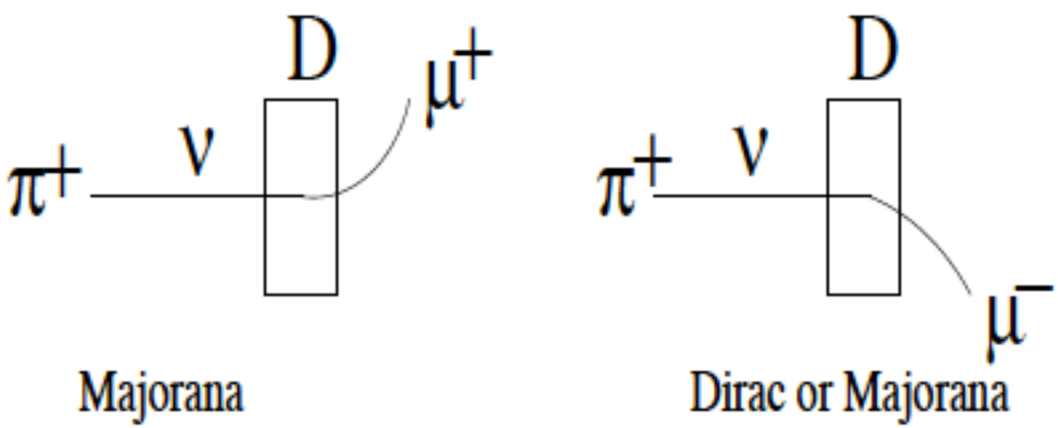
Moduli = 2n masses + n (n−1)/2 angles   For n=3: 3 angles, 3 phases

Majorana versus Dirac

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}}_{\text{Majorana phases}}$$

$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$$

In principle clear experimental signatures

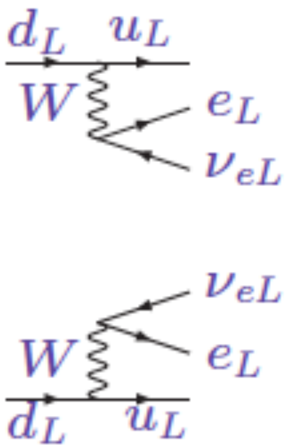


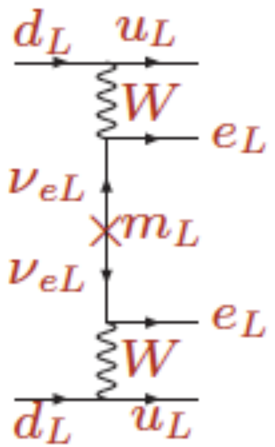
In practice theses processes are extremely rare:

$$\text{Rate}(+) = \text{Rate}(-)\left(\frac{m_\nu}{E}\right)^2$$

Neutrinoless double-β decay

Best hope is neutrinoless double-β decay





$$T_{2\beta 2\nu} \sim 10^{18} - 10^{21} \text{ years} \quad T^{-1}_{2\beta 0\nu} \sim \left(\frac{m_\nu}{E}\right)^2 10^9 \, T^{-1}_{2\beta 2\nu}$$

If neutrinos are Majorana this process must be there at some level

Neutrinoless double-β decay

$$T^{-1}_{2\beta 0\nu} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear M.E.}} \underbrace{\left|\sum_i \left(V^{ei}_{MNS}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

Present bounds:

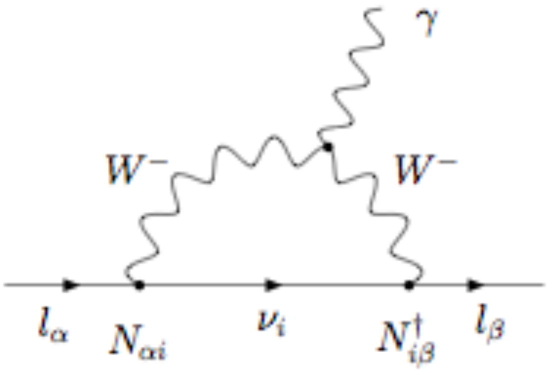
Sarazin 2012

Isotope	$T^{2\nu}_{1/2}$ (yr)	Experiment	$T^{0\nu}_{1/2}$ (yr) (90% C.L.)	Experiment	$\langle m_{ee}\rangle$ (eV) Min.	Max.	
^{48}Ca	$4.2^{+2.1}_{-1.0}\ 10^{19}$	NEMO-3	$5.8\ 10^{22}$	CANDLES [111]	3.55	9.91	
^{76}Ge	$1.5 \pm 0.1\ 10^{21}$	HDM	**$1.9\ 10^{25}$**	HDM [46]	0.2	0.4	GERDA '13
^{82}Se	$9.0 \pm 0.7\ 10^{19}$	NEMO-3	$3.2\ 10^{23}$	NEMO-3 [40]	0.85	2.08	
^{96}Zr	$2.0 \pm 0.3\ 10^{19}$	NEMO-3	$9.2\ 10^{21}$	NEMO-3 [35]	3.97	14.39	
^{100}Mo	$7.1 \pm 0.4\ 10^{18}$	NEMO-3	**$1.0\ 10^{24}$**	NEMO-3 [40]	**0.31**	**0.79**	
^{116}Cd	$3.0 \pm 0.2\ 10^{19}$	NEMO-3	$1.7\ 10^{23}$	SOLOTVINO [81]	1.22	2.30	
^{130}Te	$0.7 \pm 0.1\ 10^{21}$	NEMO-3	**$2.8\ 10^{24}$**	CUORICINO [65]	**0.27**	**0.57**	
^{136}Xe	$2.38 \pm 0.14\ 10^{21}$	Kamland	**$5.7\ 10^{24}$**	Kamland-Zen [93]			
^{150}Nd	$7.8 \pm 0.7\ 10^{18}$	NEMO-3	$1.8\ 10^{22}$	NEMO-3 [37]	2.35	8.65	
^{136}Xe				EXO-Kamland '12	0.12	0.25	

Klapdor et al claim has been excluded by GERDA

Lepton flavour violation

$\mu \to e\gamma$ $\mu^- \to eee$ $\mu^- \to e$ conversion



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i V^*_{\mu i} V_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 \leq 10^{-56}$$

$$Br(\mu \to e\gamma)_{\rm exp} \leq 5.7 \times 10^{-13}$$

MEG Coll. 2013

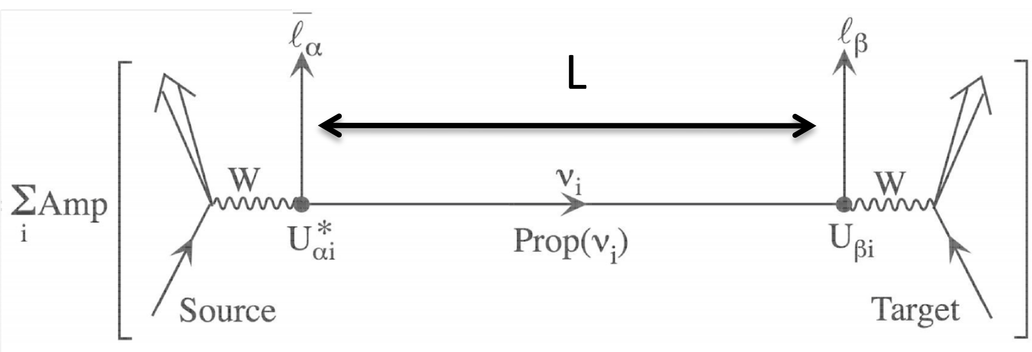
Neutrino oscillations

1968 Pontecorvo

If neutrinos are massive

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances !

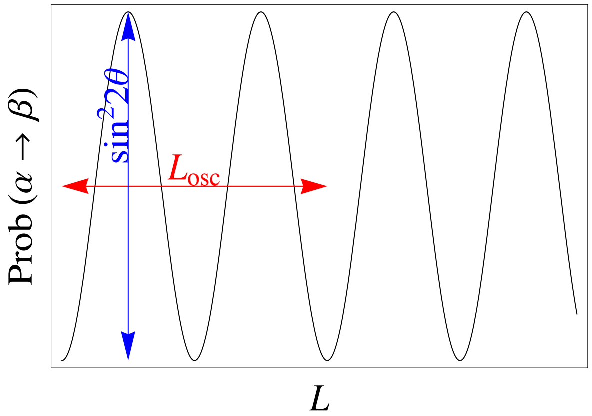


ν_i travel at different velocities in vacuum: neutrino oscillations

Neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{(m_i^2 - m_j^2)L}{2E}}$$

$$L_{osc} \sim \frac{E}{m_i^2 - m_j^2}$$



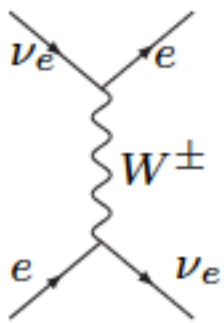
The basic ingredients:

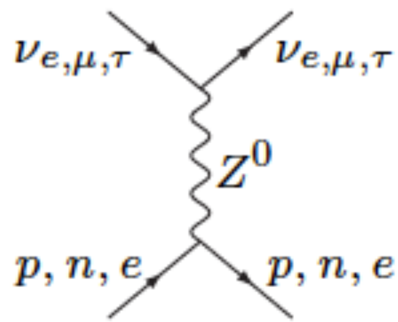
✓ Uncertainty in momentum at production & detection (they must be better localized than baseline)

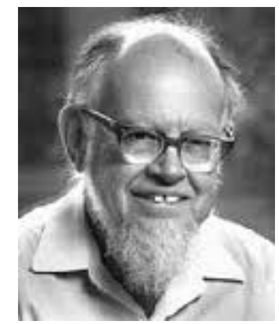
✓ Coherence of mass eigenstates over macroscopic distances

Neutrino Oscillations in matter

Many neutrino oscillation experiments involve neutrinos propagating in matter (Earth for atmospheric neutrinos or accelerator experiments, Sun for solar neutrinos)







Wolfenstein

Index of refraction (coherent forward scattering) can strongly affect the oscillation probability

$$\langle \mathcal{H}_{CC} + \mathcal{H}_{NC} \rangle_{\text{medium}} = \sqrt{2}\, G_F\, \bar{\nu}\, \gamma_0 \begin{pmatrix} N_e - \frac{N_n}{2} & & \\ & -\frac{N_n}{2} & \\ & & -\frac{N_n}{2} \end{pmatrix} \nu \equiv \bar{\nu}\, \gamma_0 V_m \nu$$

$$E^2 - \mathbf{p}^2 \quad = \quad \pm 2\, V_m E + M_\nu^2$$

Neutrino oscillations in constant matter

Effective mixing angles and masses depend on energy

$$\begin{pmatrix} \tilde{m}_1^2 & 0 & 0 \\ 0 & \tilde{m}_2^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} = \tilde{U}^\dagger_{\rm PMNS} \left(M_\nu^2 \pm 2E \begin{pmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{pmatrix} \right) \tilde{U}_{\rm PMNS}$$

For two families (- neutrinos, + antineutrinos):

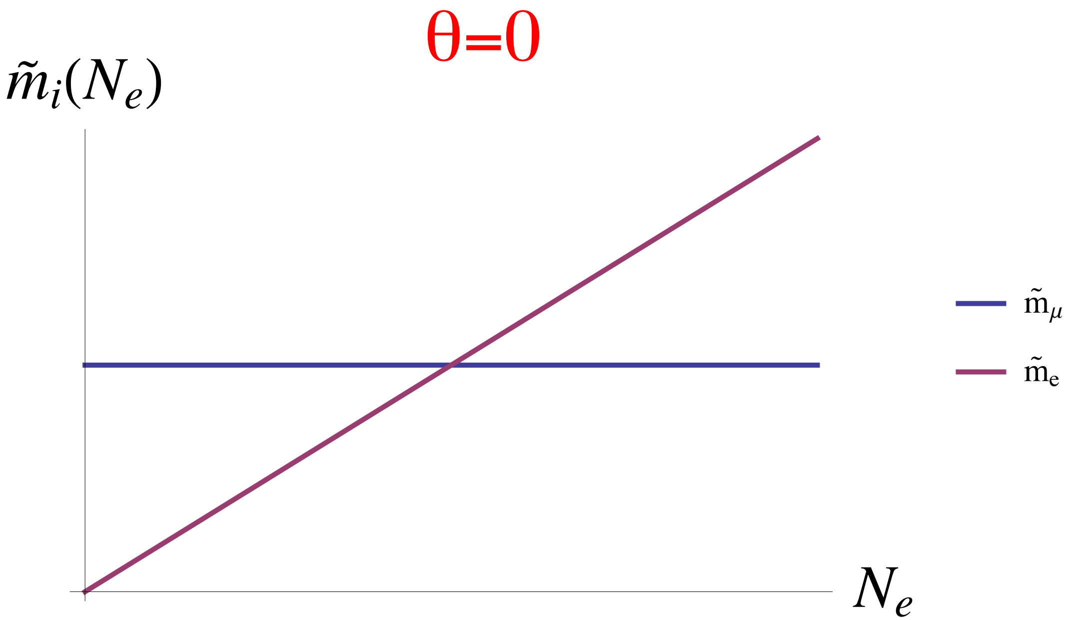
$$\sin^2 2\tilde{\theta} = \frac{\left(\Delta m^2 \sin 2\theta\right)^2}{\left(\Delta m^2 \cos 2\theta \pm 2\sqrt{2}\, G_F E\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\Delta\tilde{m}^2 = \sqrt{\left(\Delta m^2 \cos 2\theta \pm 2\sqrt{2} E\, G_F\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\Delta m^2 \cos 2\theta \pm 2\sqrt{2}\, G_F E\, N_e = 0 \qquad \sin^2 2\tilde{\theta} = 1, \quad \Delta\tilde{m}^2 = \Delta m^2 \sin 2\theta$$

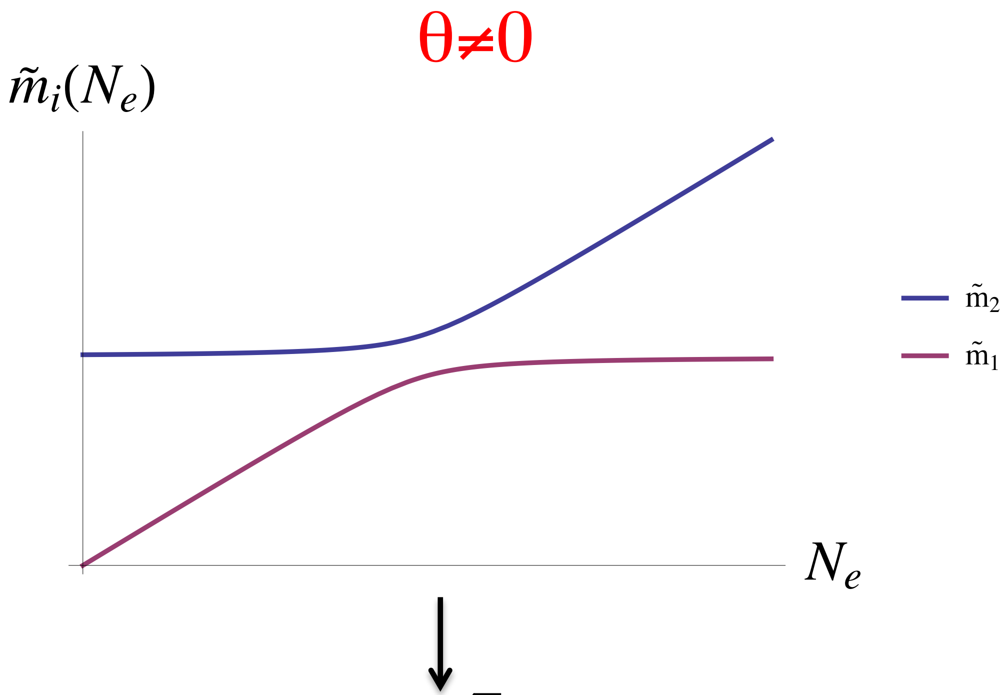
MSW resonance

Mikheyev, Smirnov '85



MSW resonance

Mikheyev, Smirnov '85

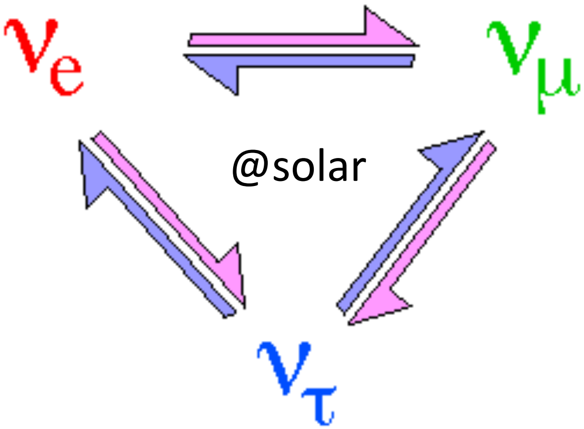


$$\Delta m^2 \cos 2\theta \pm 2\sqrt{2}\, G_F E\, N_e = 0$$

MSW Resonance:

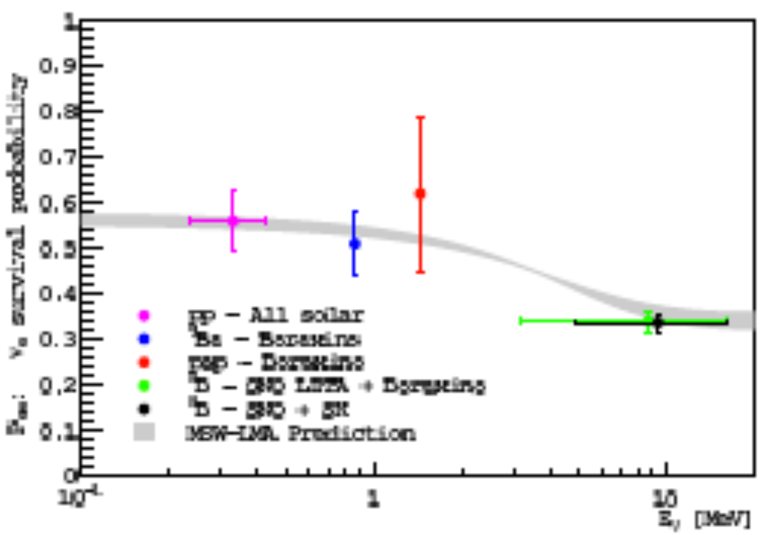
- Only for ν or $\bar{\nu}$, not both
- Only for one sign of $\Delta m^2 \cos 2\theta$

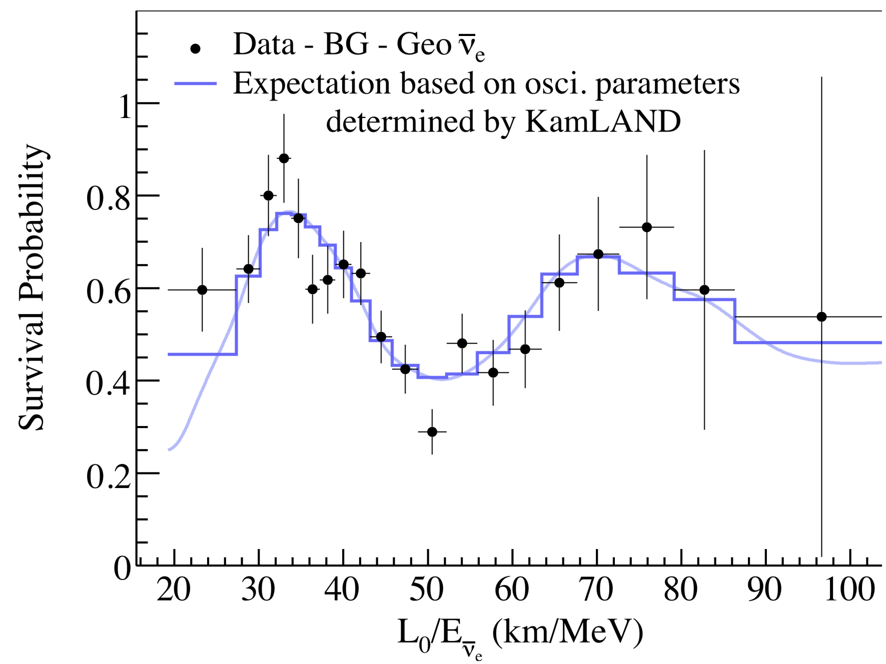
Solar oscillation of ν_e



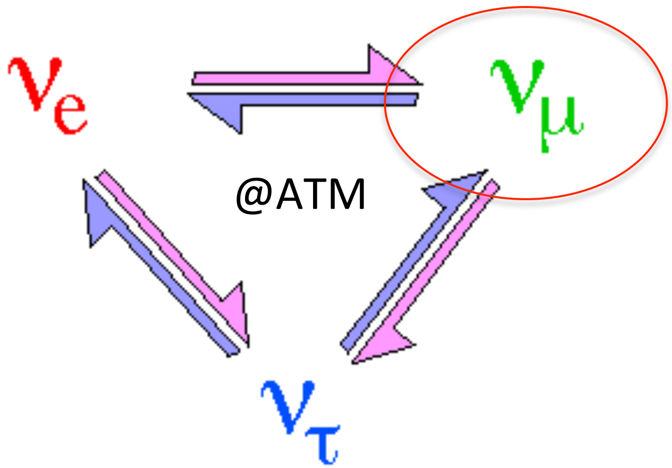
$$|\Delta m^2| \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(100km)}$$

MSW conversion in Sun

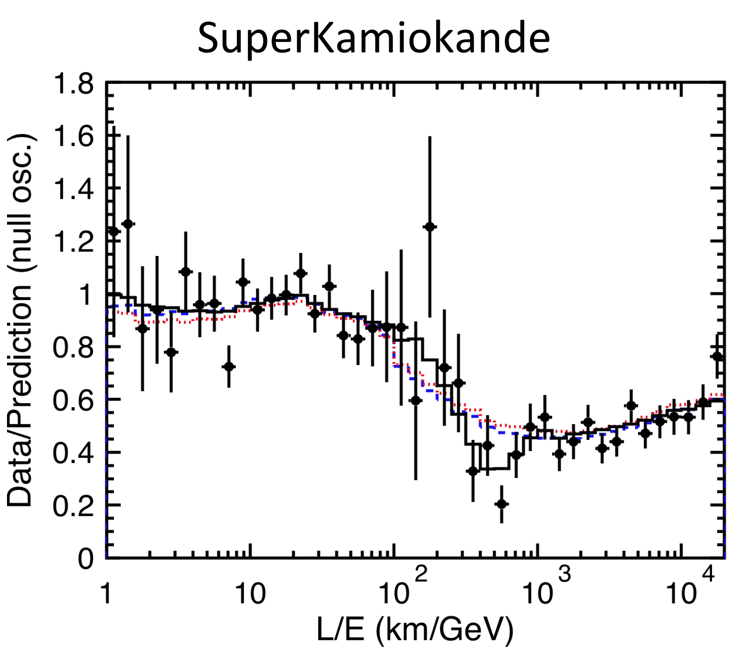


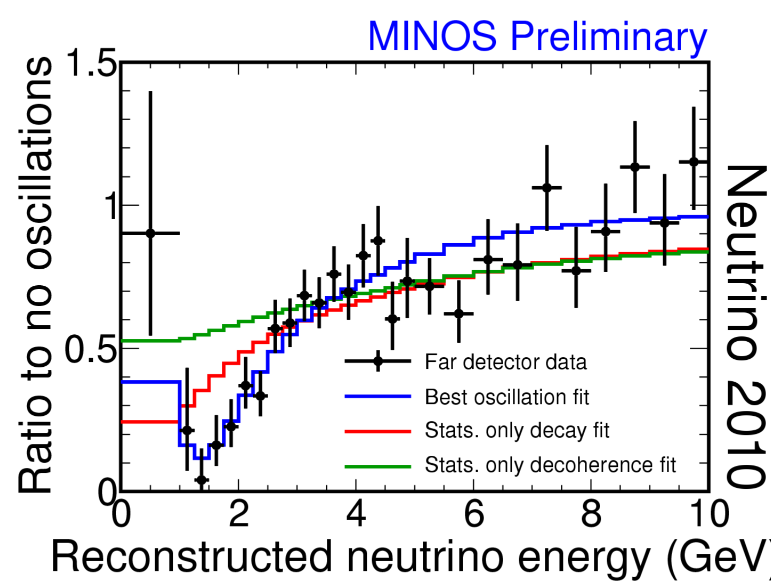


Atmospheric Oscillation of ν_μ

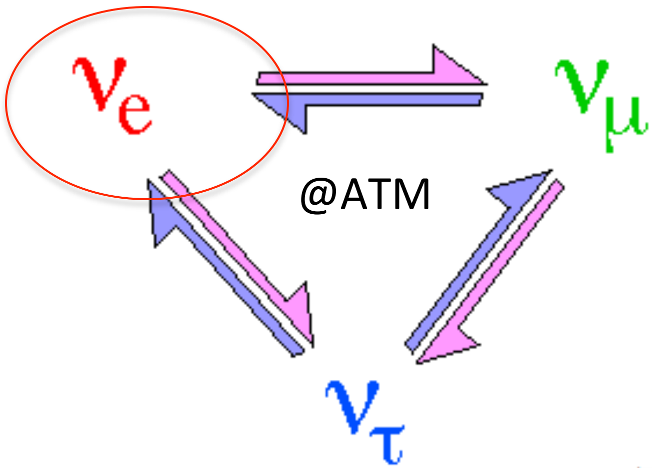


$$|\Delta m^2| \sim \frac{\mathcal{O}(GeV)}{\mathcal{O}(1000km)} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1km)}$$





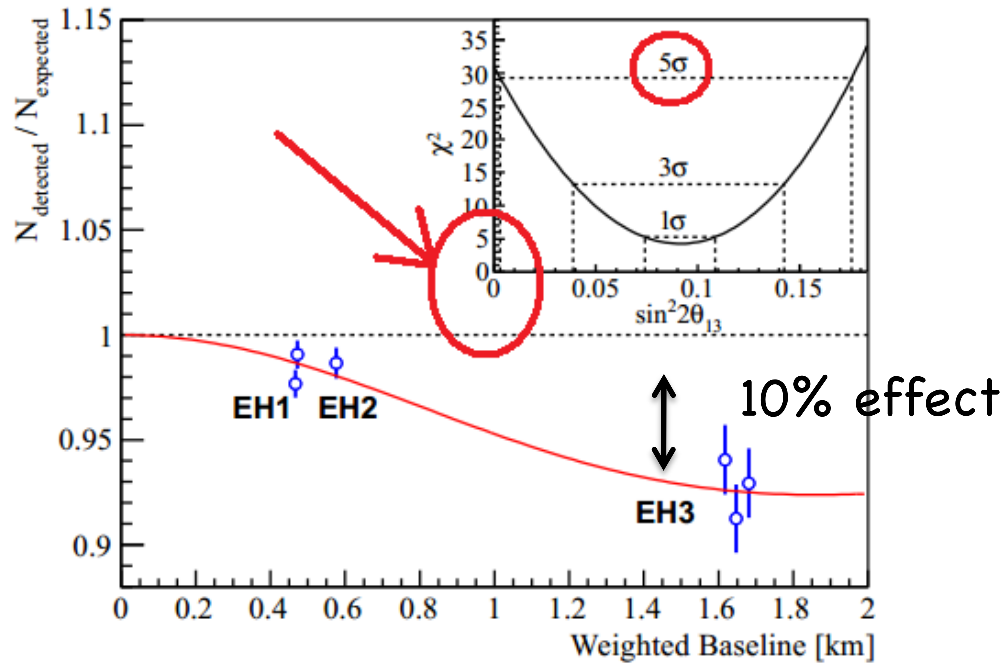
Atmospheric Oscillation of ν_e



$$|\Delta m^2| \sim \frac{\mathcal{O}(GeV)}{\mathcal{O}(1000km)} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1km)}$$

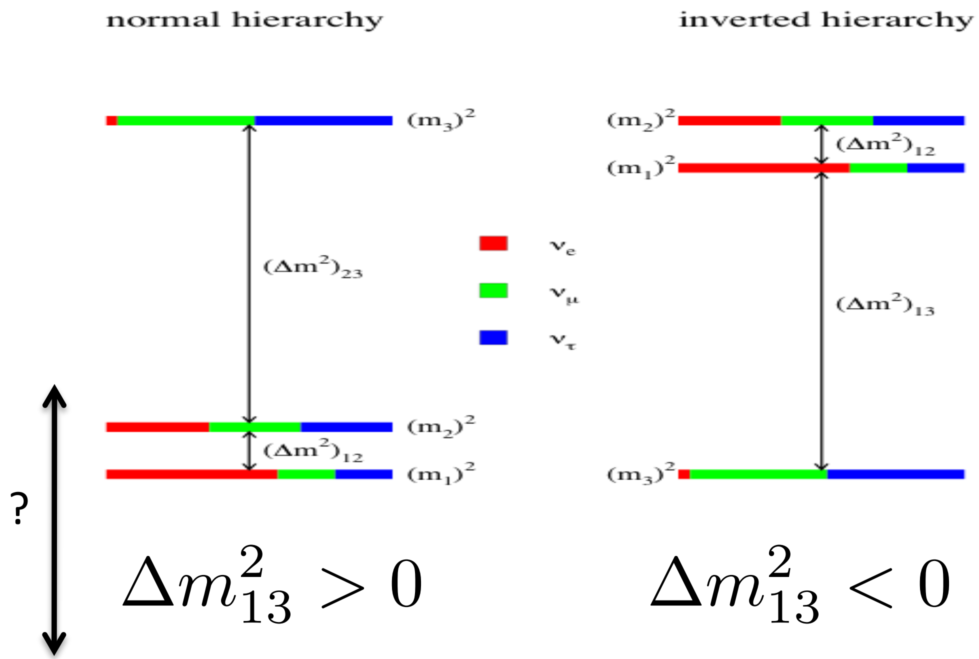
2012

T2K, Double Chooz
Daya Bay, RENO

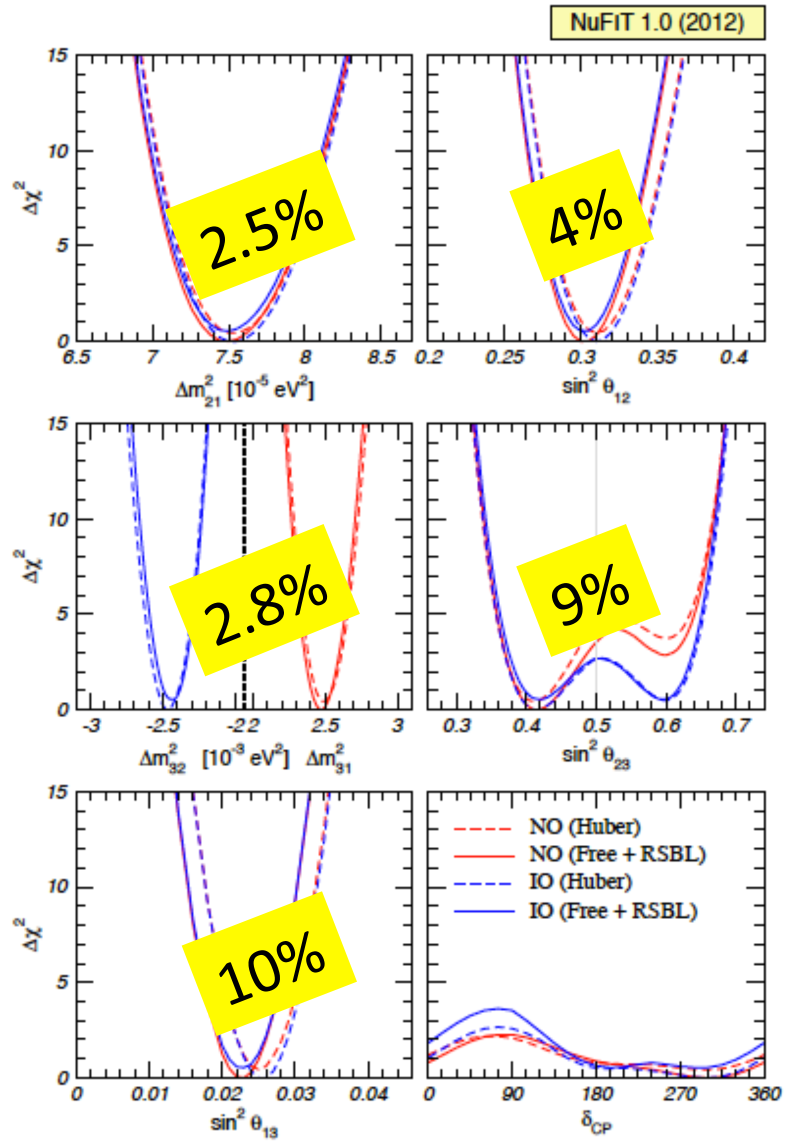


Standard 3ν scenario

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$\Delta m^2_{13} > 0$ $\Delta m^2_{13} < 0$



Gonzalez-Garcia et al 1209.3023

Outliers: LSND anomaly

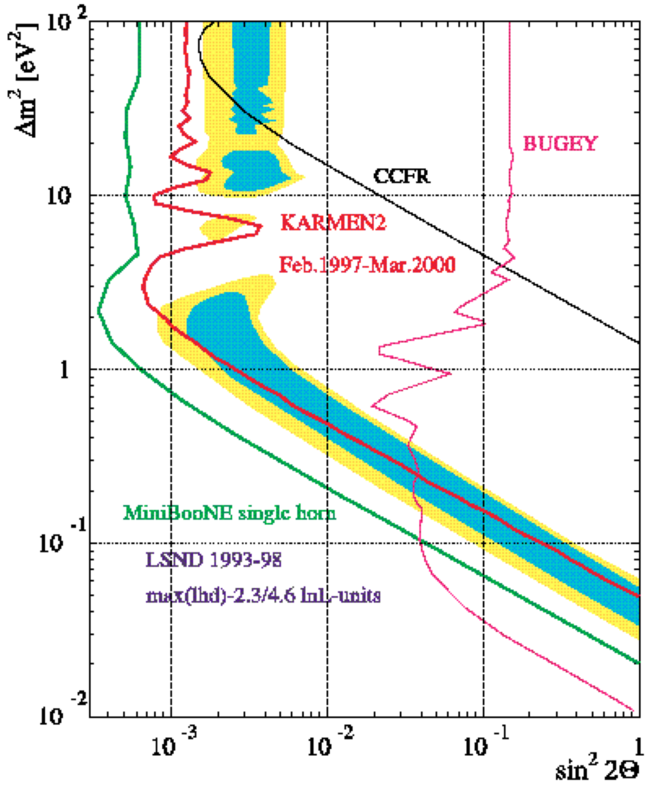
LSND vs KARMEN

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

$$\nu_\mu \quad \to \nu_e \text{ DIF } (28 \pm 6/10 \pm 2)$$

$$\mu^+ \to \quad e^+ \quad \nu_e \; \bar{\nu}_\mu$$

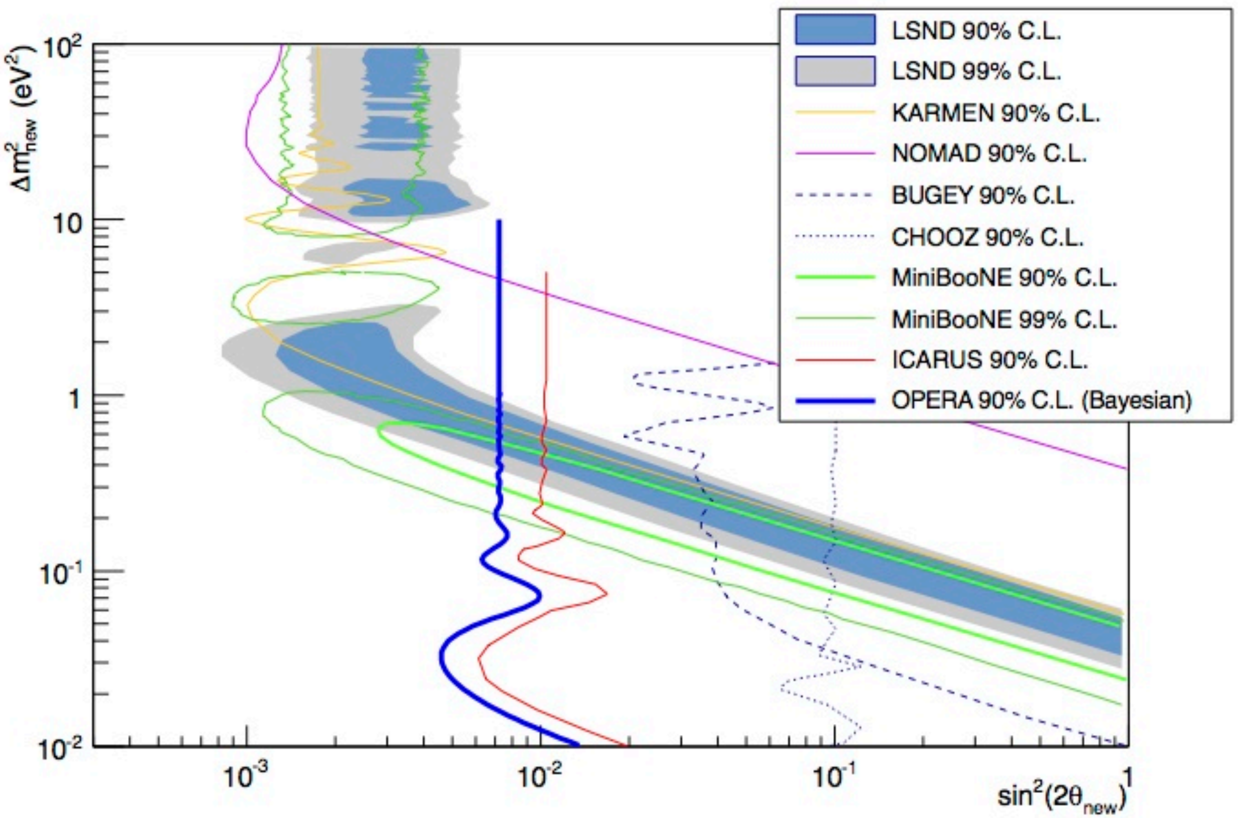
$$\bar{\nu}_\mu \quad \to \bar{\nu}_e \text{ DAR } (64 \pm 18/12 \pm 3)$$



Appearance signal with very different

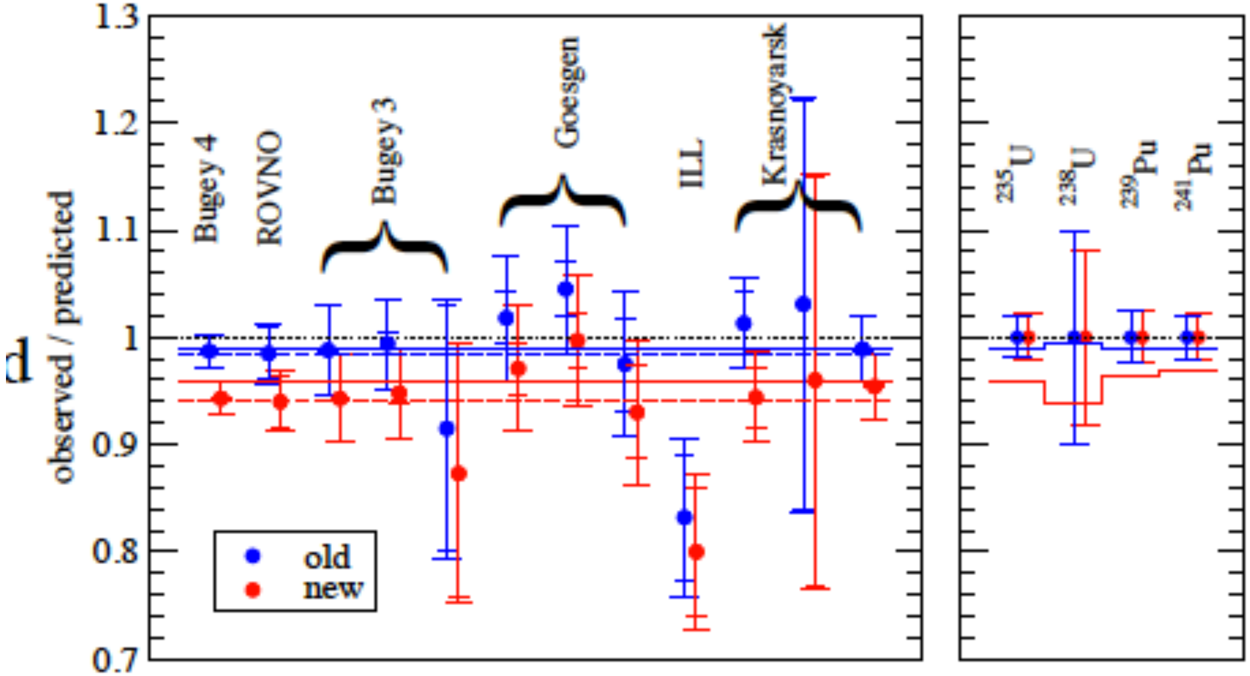
$$|\Delta m^2| \gg |\Delta m^2_{atm}|$$

Still alive…



LSND 90% C.L.
LSND 99% C.L.
KARMEN 90% C.L.
NOMAD 90% C.L.
BUGEY 90% C.L.
CHOOZ 90% C.L.
MiniBooNE 90% C.L.
MiniBooNE 99% C.L.
ICARUS 90% C.L.
OPERA 90% C.L. (Bayesian)
Δm^2_{new} (eV^2)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta_{new})$

Outliers: reactor anomaly



T. A. Mueller et al; P. Huber

Recent re-evaluation of reactor fluxes found to be 3% underestimated

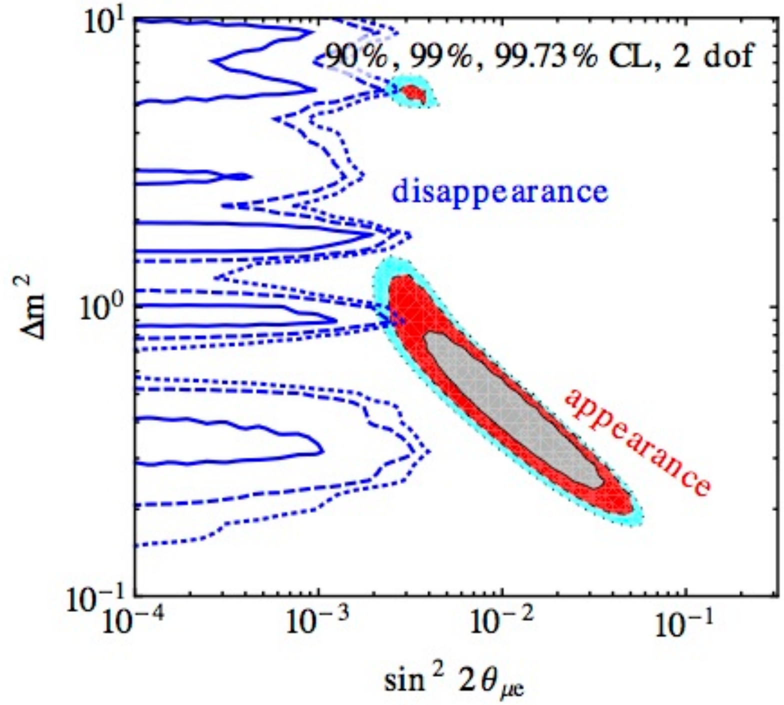
+Gallium anomaly…

3+1, 3+2 neutrino mixing models ?

$P(\nu_e \to \nu_\mu) = O(|U_{ei}|^2 \, |U_{\mu i}|^2)$ ✔

$P(\nu_e \to \nu_e) = O(|U_{ei}|^2)$ ✔

$P(\nu_\mu \to \nu_\mu) = O(|U_{\mu i}|^2)$ ✗

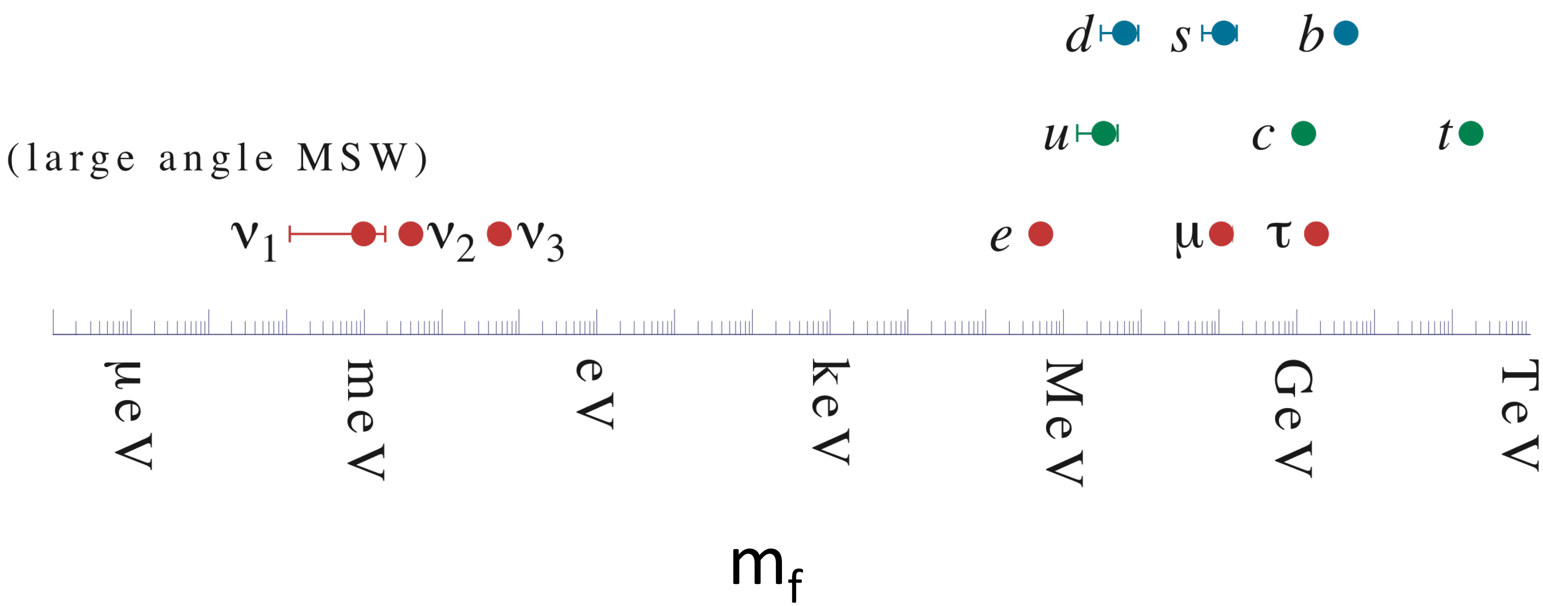


Kopp et al

Strong tension remains:
a convincing signal would be to find it in all the three...

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



Why so different mixing ?

CKM

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

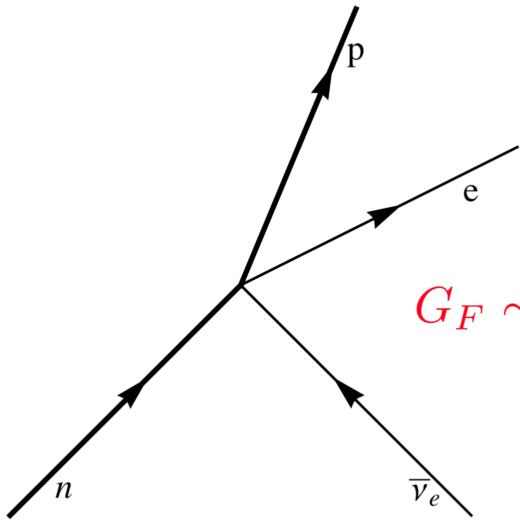
PMNS

3σ

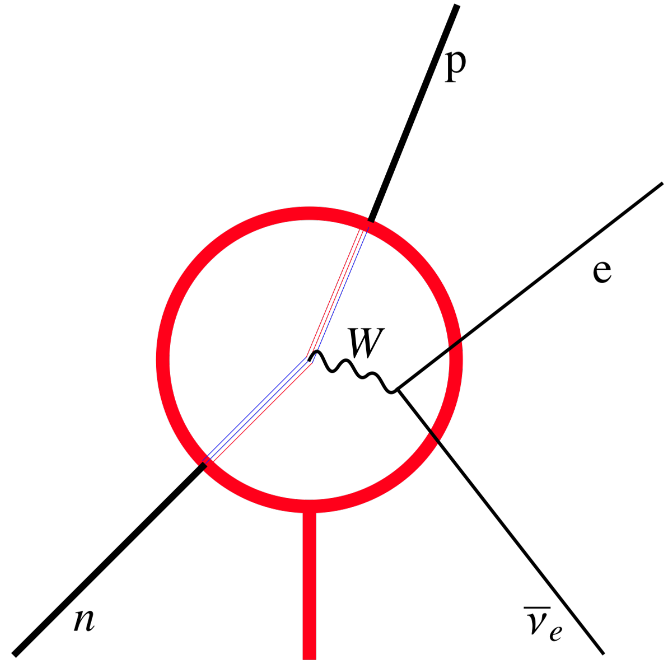
$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

Gonzalez-Garcia, et al 1209.3023

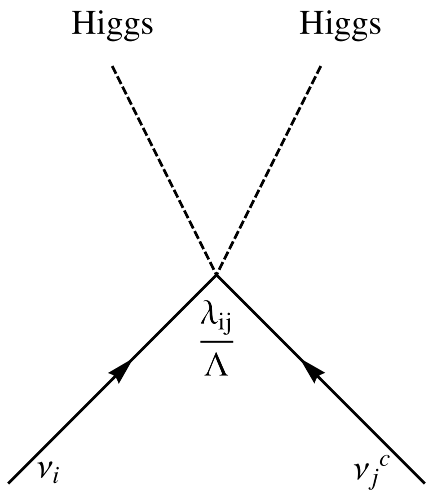
Neutrinos have tiny masses -> a new physics scale, what ?



$$G_F \sim \frac{1}{M_W^2}$$



SM



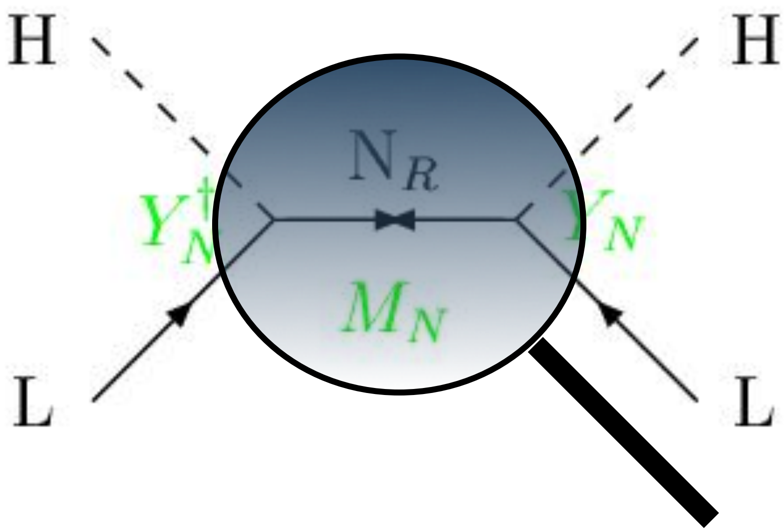
→

νSM ?

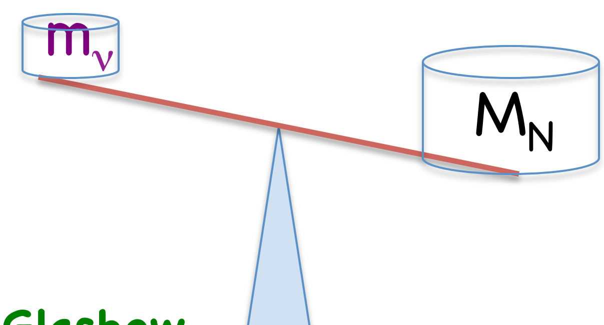
How does the ν scale relates to the EW scale ?

Example: Type I seesaw model (interchange heavy singlet fermions)

$$\mathcal{L} = \mathcal{L}_{SM} - \sum^{n_R} \bar{l}_L^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$



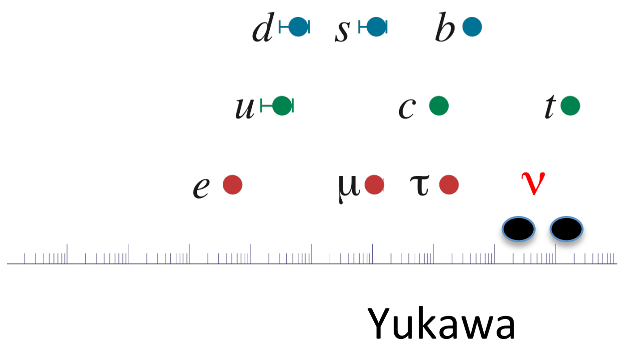
$$\frac{\lambda}{\Lambda} \equiv Y_N^T \frac{1}{M_N} Y_N$$



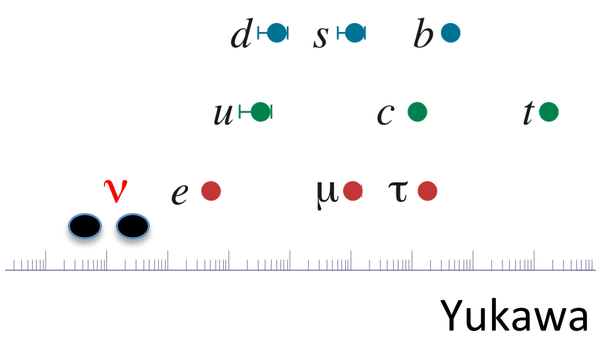
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow...

Charged/neutral hierarchy in seesaw (I)

M_N= GUT

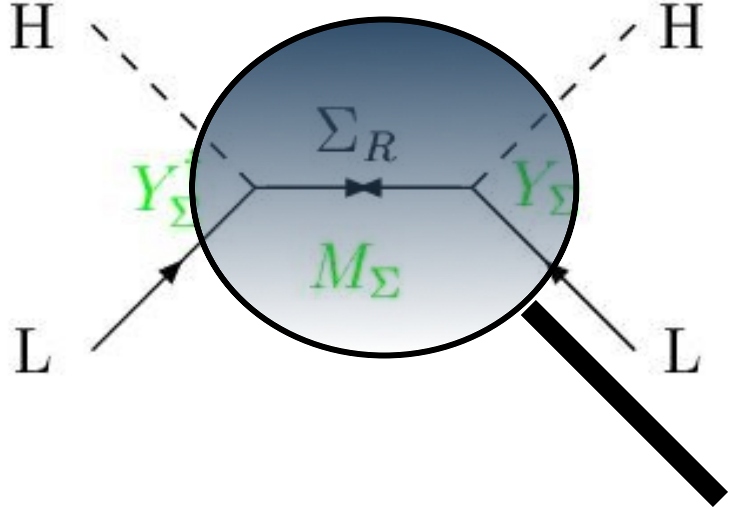


M_N= TeV



New physics scale

Type III see-saw: interchange a heavy triplet fermion

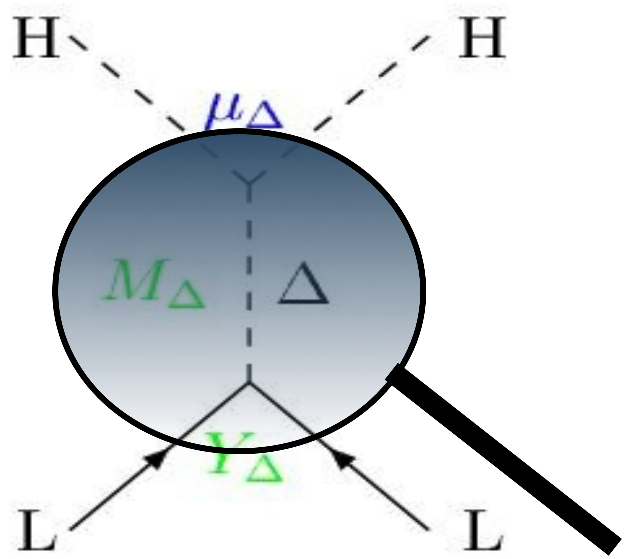


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

Foot et al; Ma; Bajc, Senjanovic…

New physics scale

Type II see-saw: interchange a heavy triplet scalar



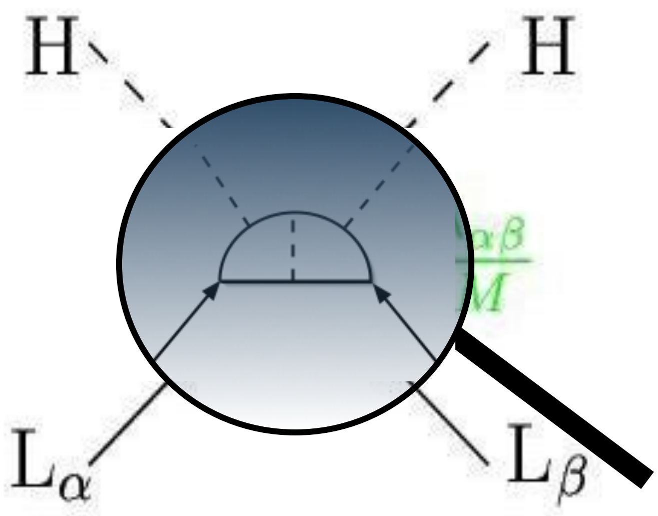
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Konetschny, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich ...

New physics scale

Also from loops !

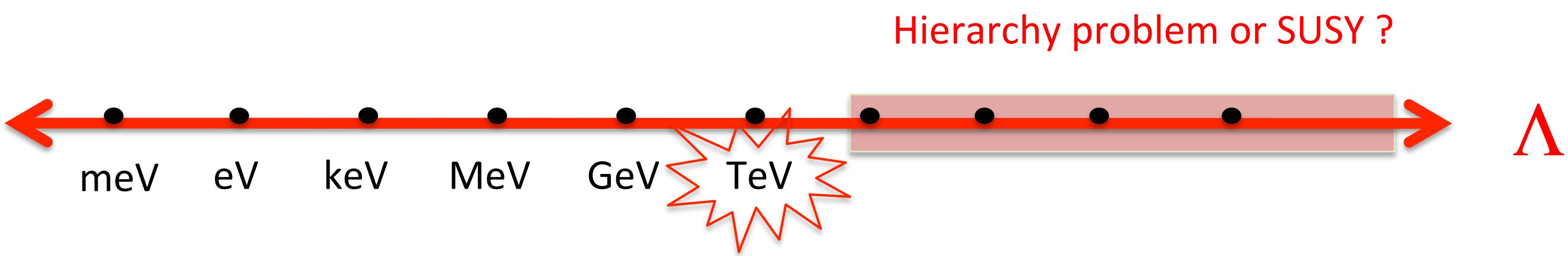
Zee-Babu

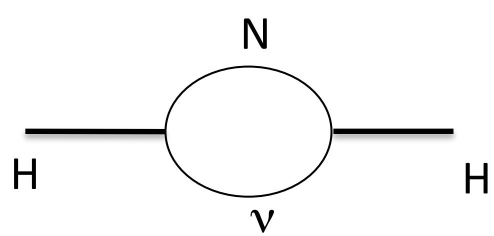


$$m_\nu \sim \mathcal{O}\left(\frac{1}{(16\pi^2)^2} \times \frac{\mu m_l^2}{M^2}\right)$$

Pinning down the New physics scale

The new scale is stable under radiative corrections due to Lepton Number symmetry but the EW is not!





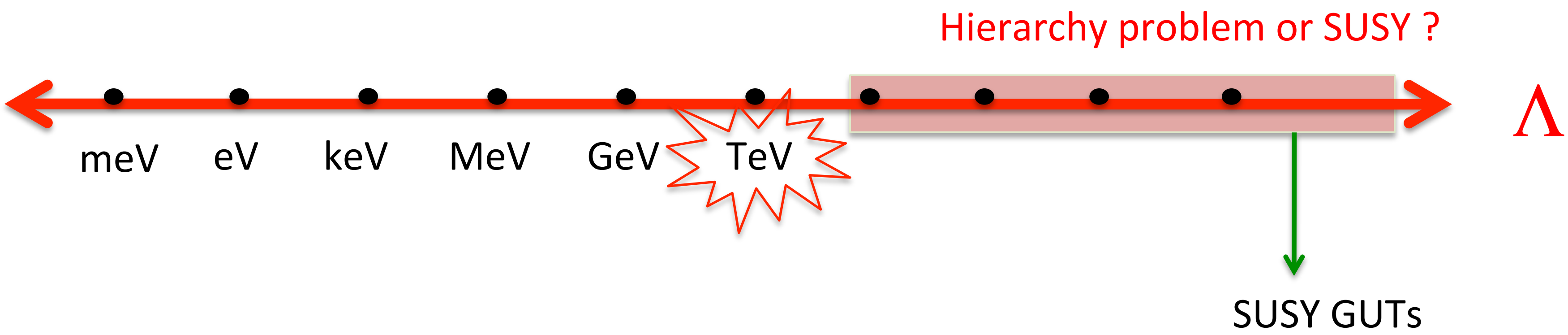
$$\delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu}$$

$$M_N \gg m_H$$

not natural in the absence of SUSY

Pinning down the New physics scale

The new scale is stable under radiative corrections due to Lepton Number Symmetry but the EW is not!



Robust predictions of high (and not so high) scale seesaw models:

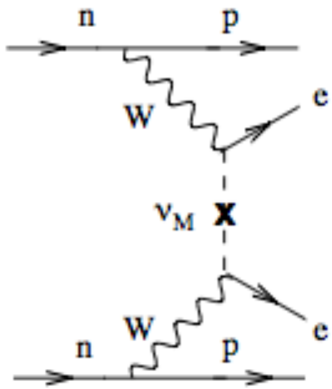
there is neutrinoless double beta decay at some level (Λ > 100MeV)

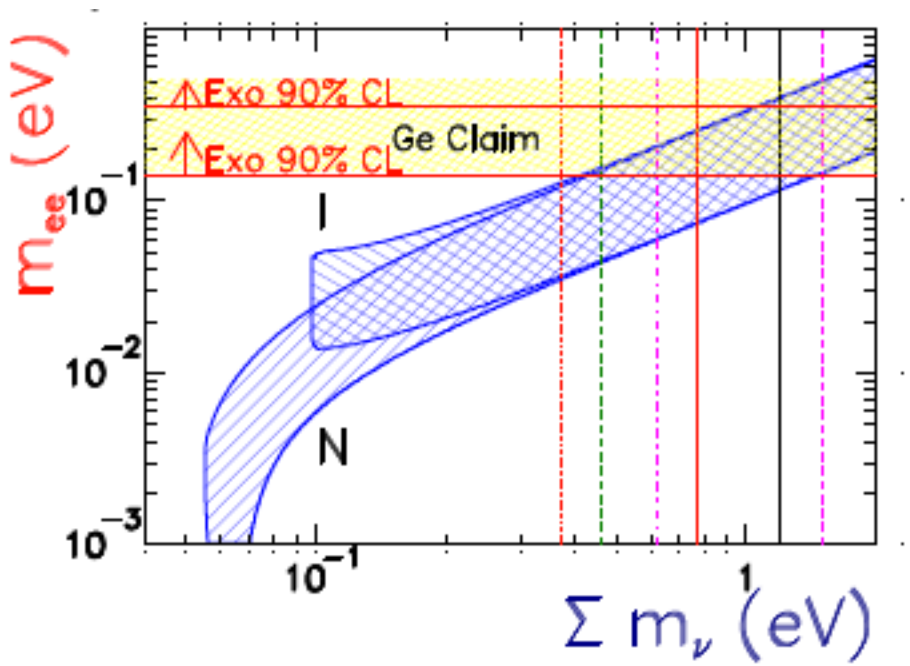
a matter-antimatter asymmetry if there is CP violation in the lepton sector !

there are other states out there at scale Λ !

Lepton Number violation: Majorana nature

Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT, SuperNEMO, LUCIFER…





$$m_{\beta\beta} \equiv |m_{ee}|$$

$$\Sigma \equiv \sum_i m_i$$

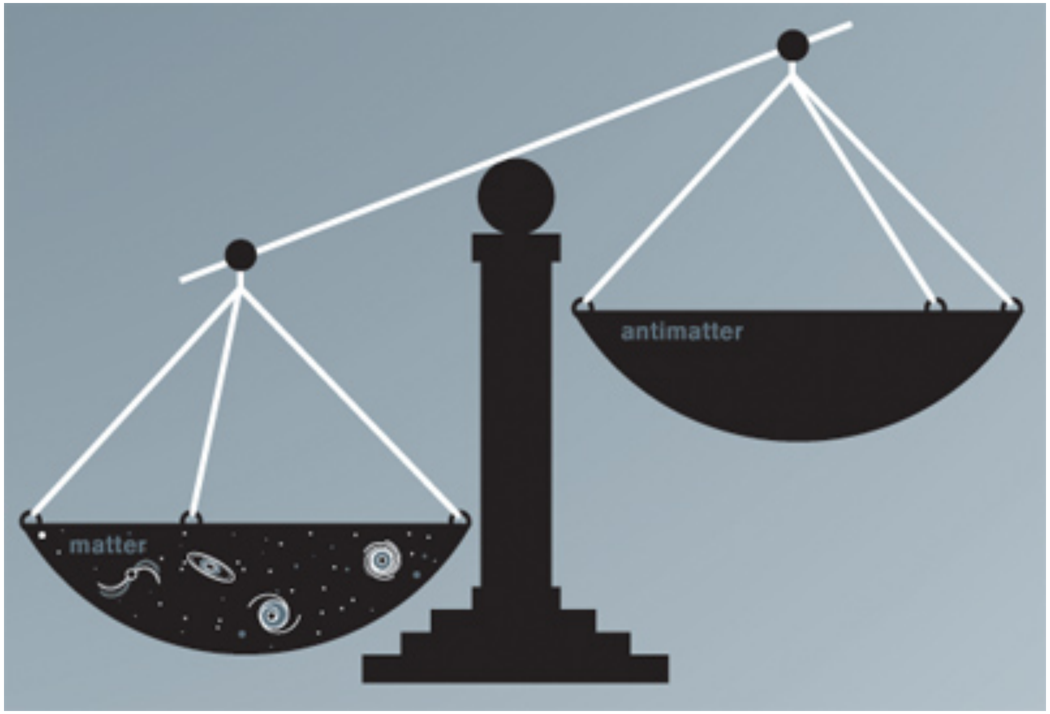
Vissani 2002; Pascoli et al 2005; (Fogli *et al* (04))

Update Maltoni, Schwetz,Salvado, MCGG (95%)

$$|m_{ee}| = |c_{13}^2(m_1 c_{12}^2 + m_2 e^{i\alpha} s_{12}^2) + m_3 e^{i\beta} s_{13}^2|$$

Baryon asymmetry

The Universe seems to be made of matter



WMAP

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}$$

Baryon asymmetry

Can it arise from a symmetric initial condition with same matter & antimatter ?

Sakharov's necessary conditions for baryogenesis

- ✓ Baryon number violation (B+L violated in the Standard Model)
- ✓ C and CP violation (both violated in the SM)
- ✓ Deviation from thermal equilibrium (at least once: electroweak phase transition)

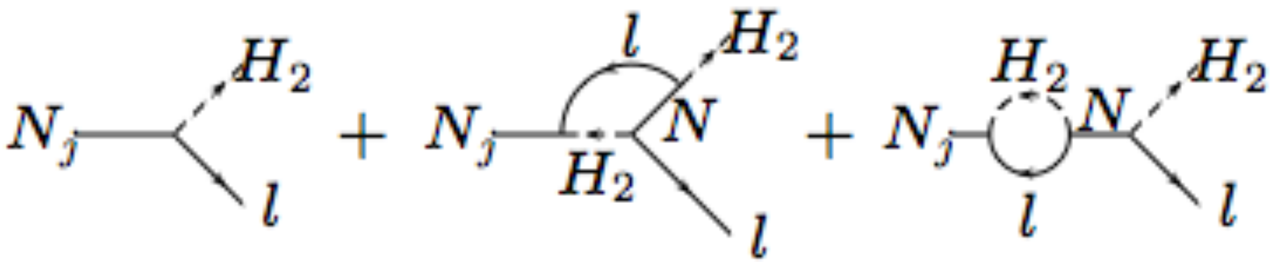
It does not seem to work in the SM with massless neutrinos ...

CP violation in quark sector far to small, EW phase transition too weak...

L, C and CP violation

New sources of CP violation and L violation in the neutrino sector can induce CP asymmetries in decays of heavy Majorana ν

Fukuyita, Yanagida



$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

Generic and robust feature of see-saw models

Lepton asymmetry

$M_{2,3} >> M_1$

$$Y_B = 4 \times 10^{-3} \overbrace{\epsilon_1}^{\mathrm{CP-asym}} \overbrace{\kappa}^{\mathrm{eff.\ factor}}$$

$$\epsilon_1 = -\frac{3}{16\pi} \sum_i \frac{Im[(\lambda_\nu^\dagger \lambda_\nu)^2_{i1}]}{(\lambda^\dagger \lambda)_{11}} \frac{M_1}{M_i} \longleftrightarrow m_\nu = \lambda_\nu^T \frac{1}{M} \lambda_\nu$$

Different combinations

Even if we know the neutrino mass we cannot predict the asymmetry accurately…a necessary condition if leptonic CP violation

Leptonic CP violation

$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{(m_i^2 - m_j^2)L}{2E}}$$

α ≠ β appearance probability
α = β disappearance or survival probability

$$L_{osc} \sim \frac{E}{m_i^2 - m_j^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \underbrace{2\sum_{i<j} Re[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] + \sum_{i=j} |U_{\alpha i}|^2 |U_{\beta i}|^2}_{\delta_{\alpha\beta}}$$

CP-even

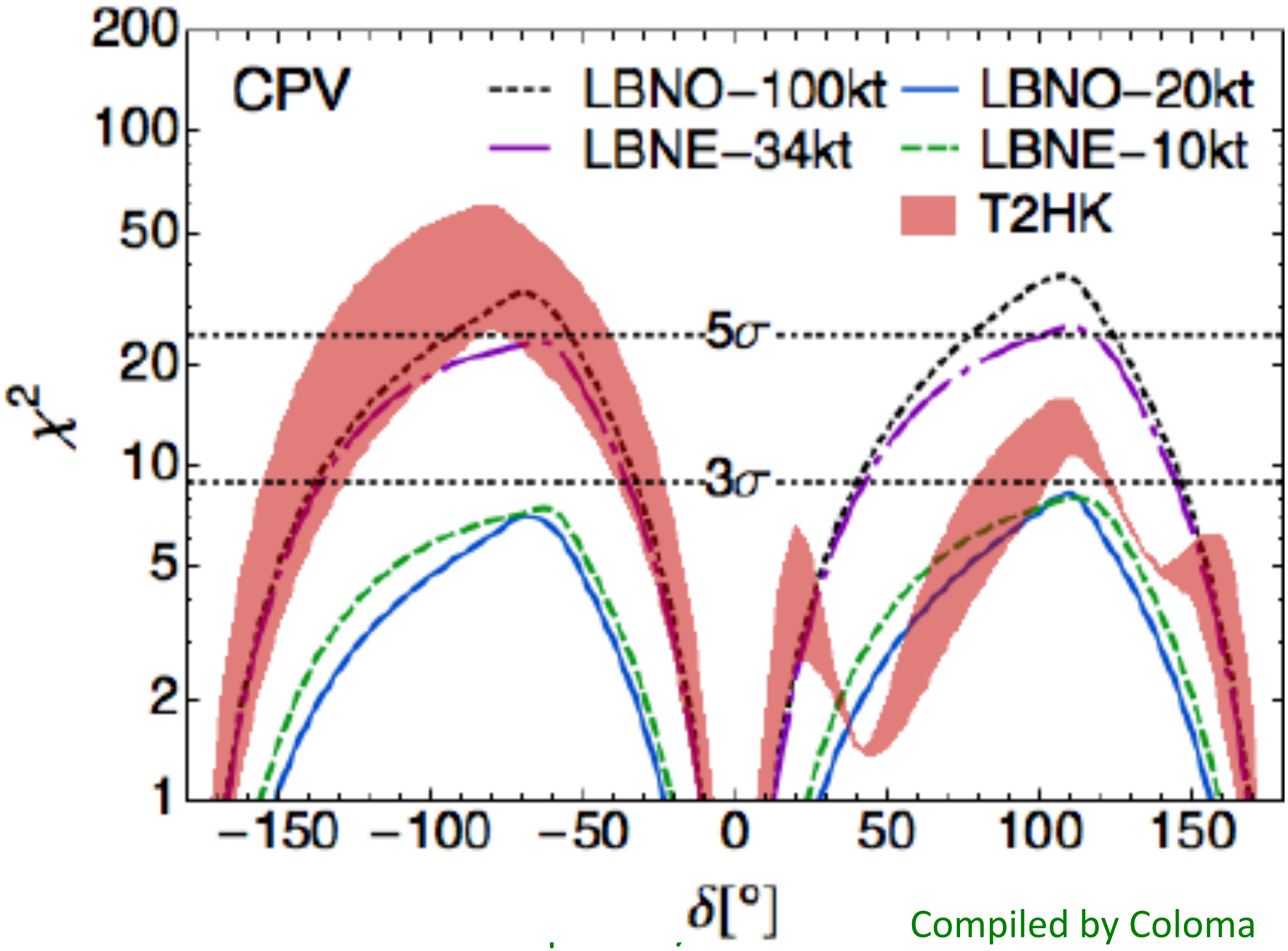
$$- 4\sum_{i<j} \mathrm{Re}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin^2\left[\frac{\Delta m^2_{ji} L}{4E}\right]$$

CP-odd

$$- 2\sum_{i<j} \mathrm{Im}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin\left[\frac{\Delta m^2_{ji} L}{2E}\right]$$

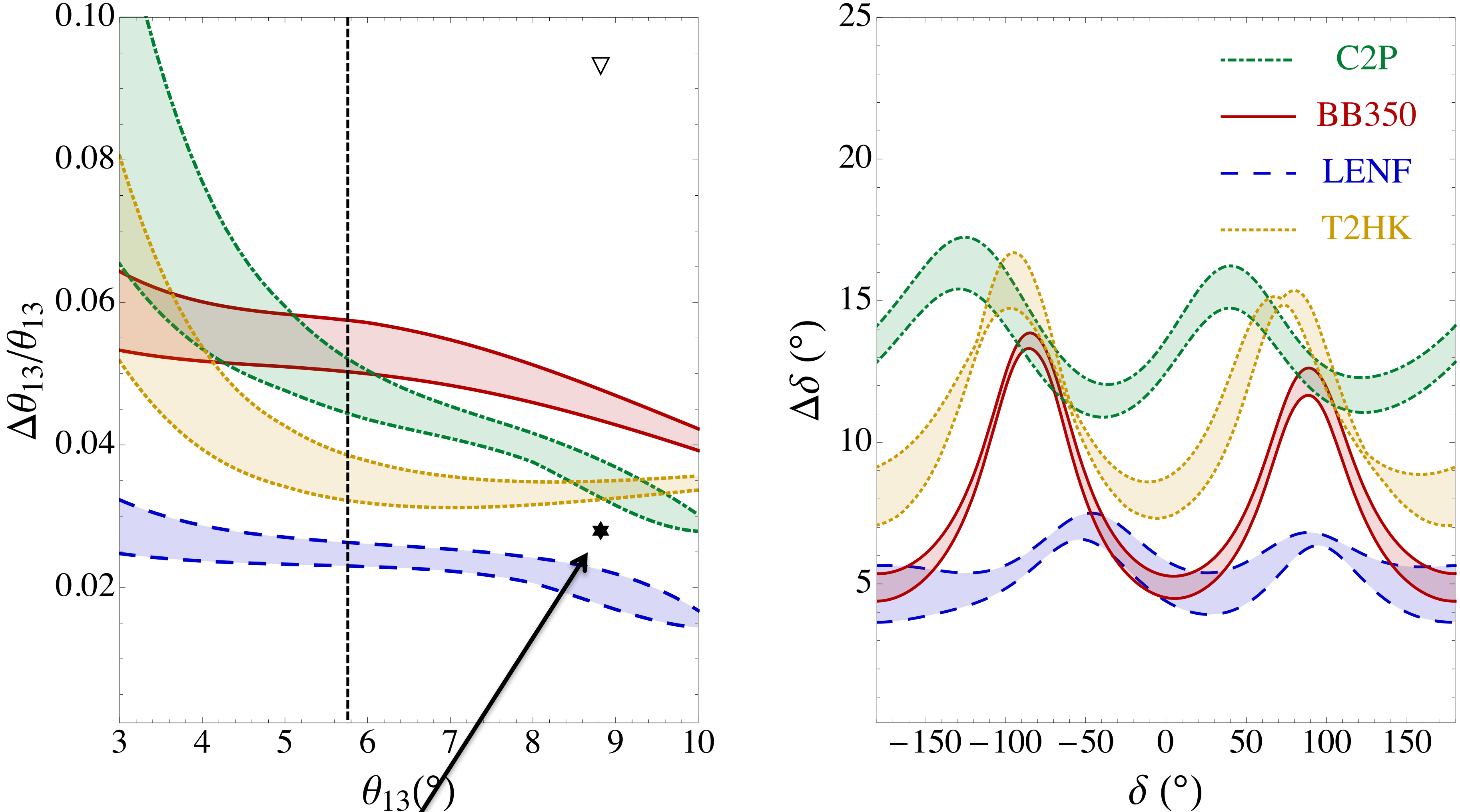
In 20 years from now with conventional beams…

Hierarchy unknown



Compiled by Coloma

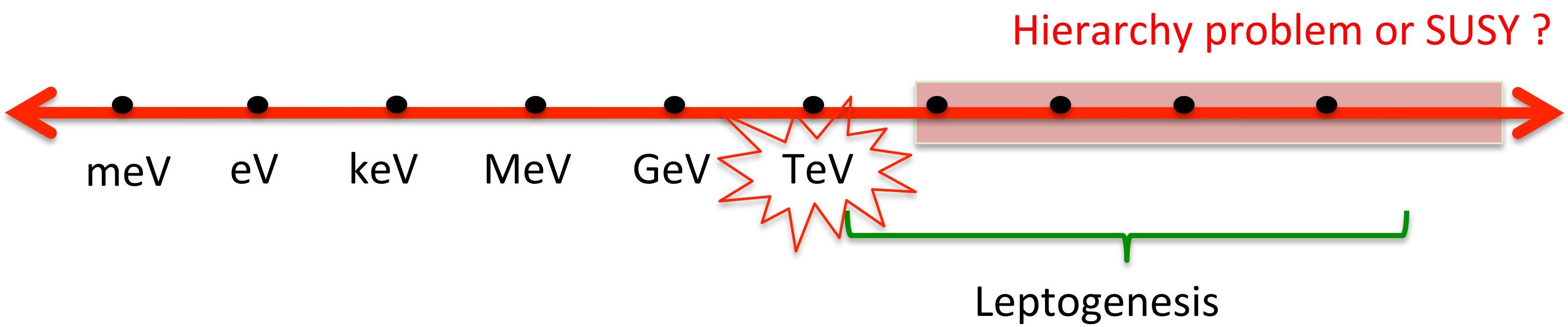
With better beams (eg NUFACT) in XX years...



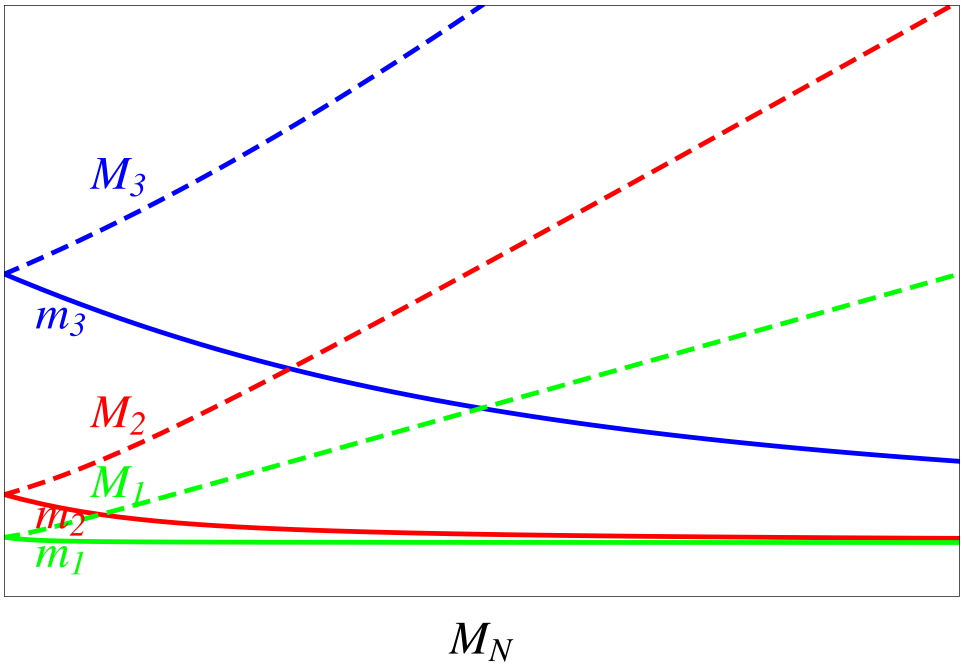
Daya Bay syst only!

Coloma, et al 1203.5651

Other states out there...



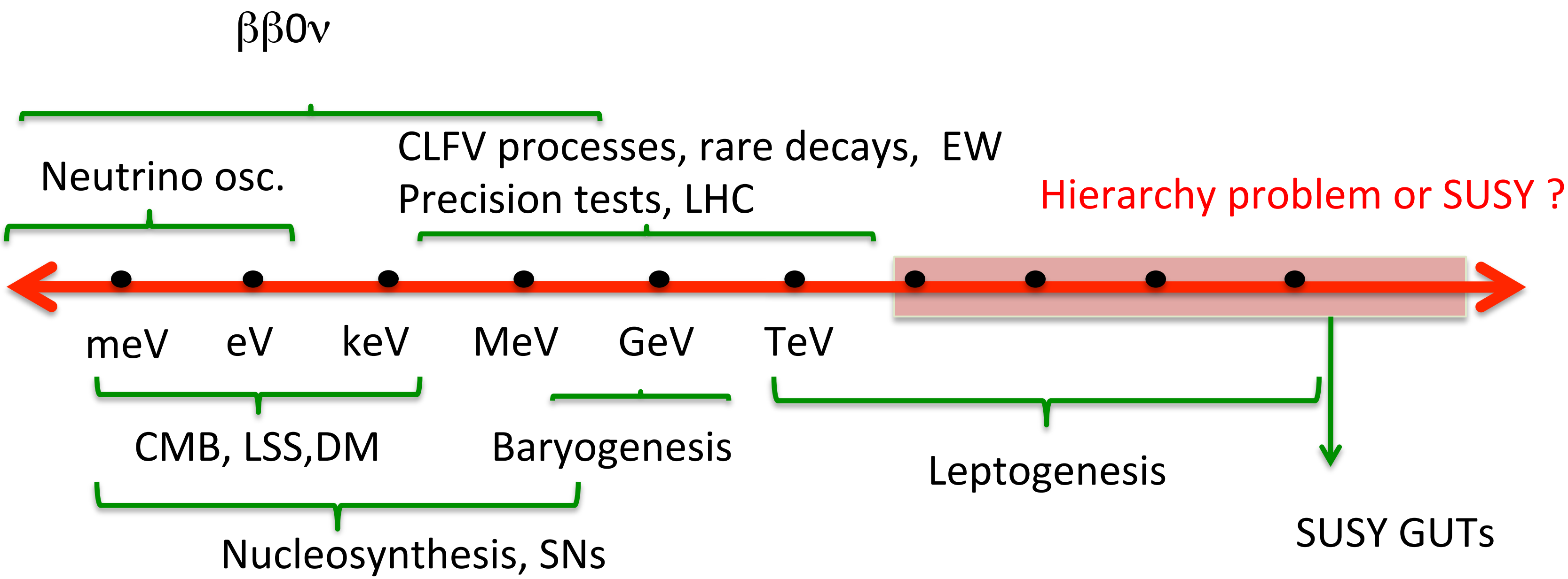
Low scale Type I seesaw models



$$\theta_{hl} \sim \frac{Yv}{M_N} \sim \sqrt{m_\nu / M_N}$$

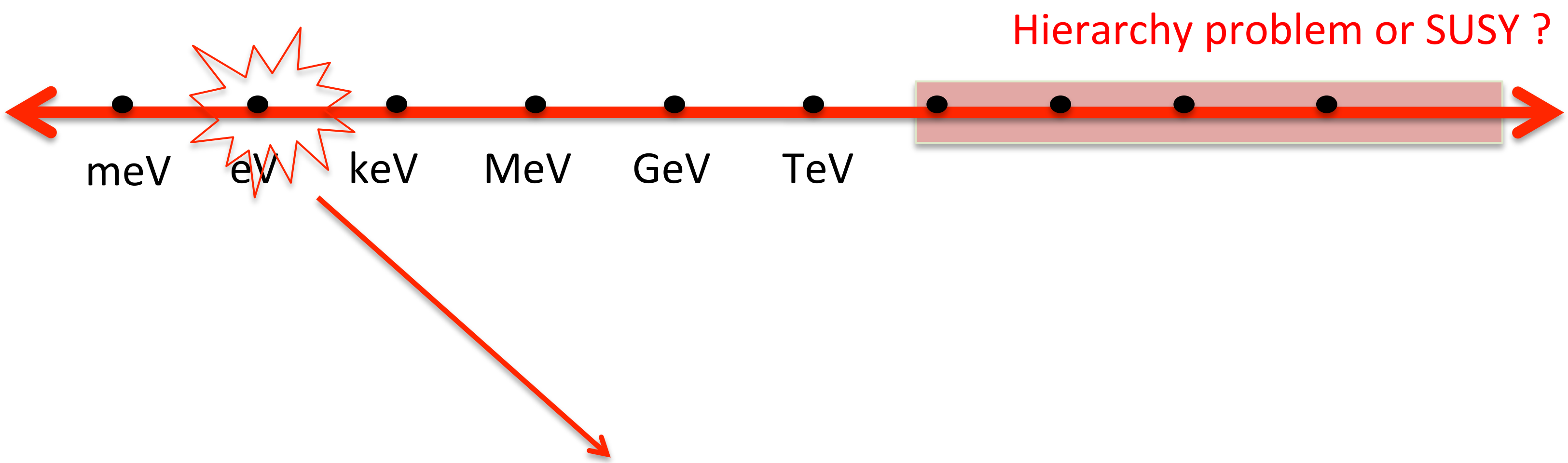
- kinematically allowed (the lower the mass the better)
- they mix significantly with the rest of the SM (the lower the mass the better)

Other states out there ?



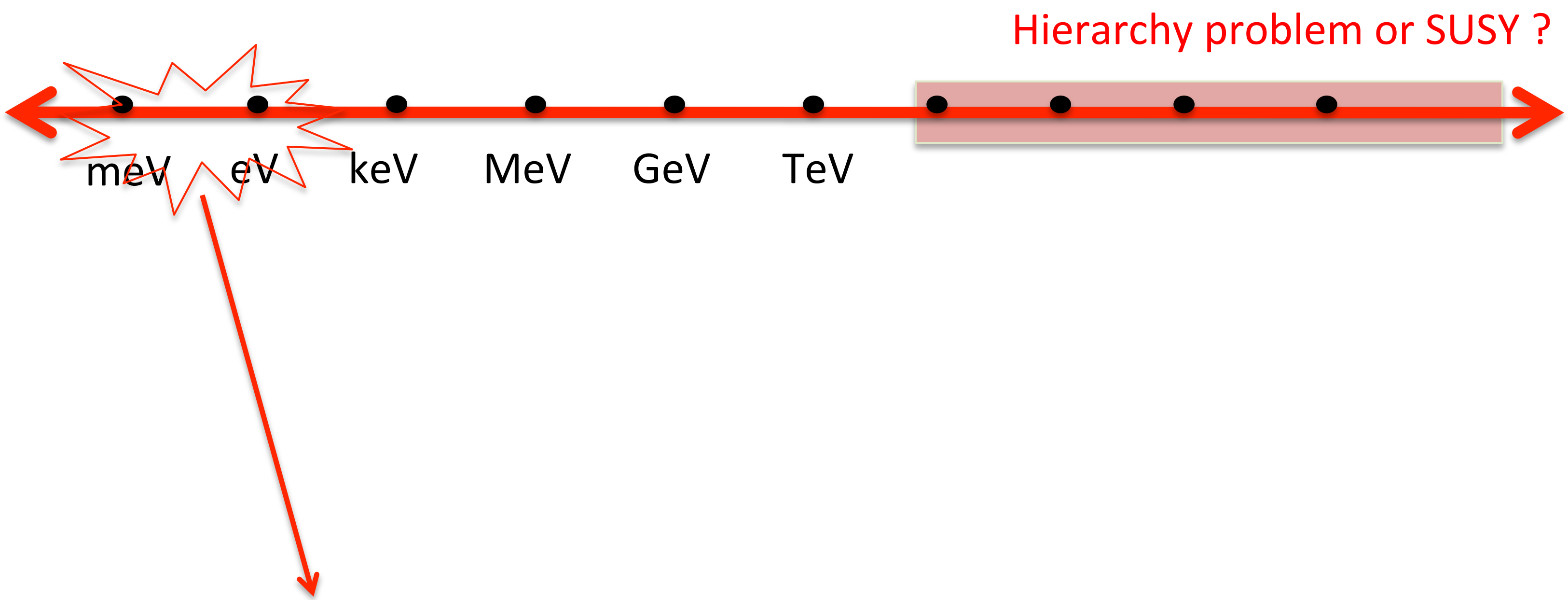
Light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

Other states out there ?



Neutrino anomalies: LSND…

Other states out there ?

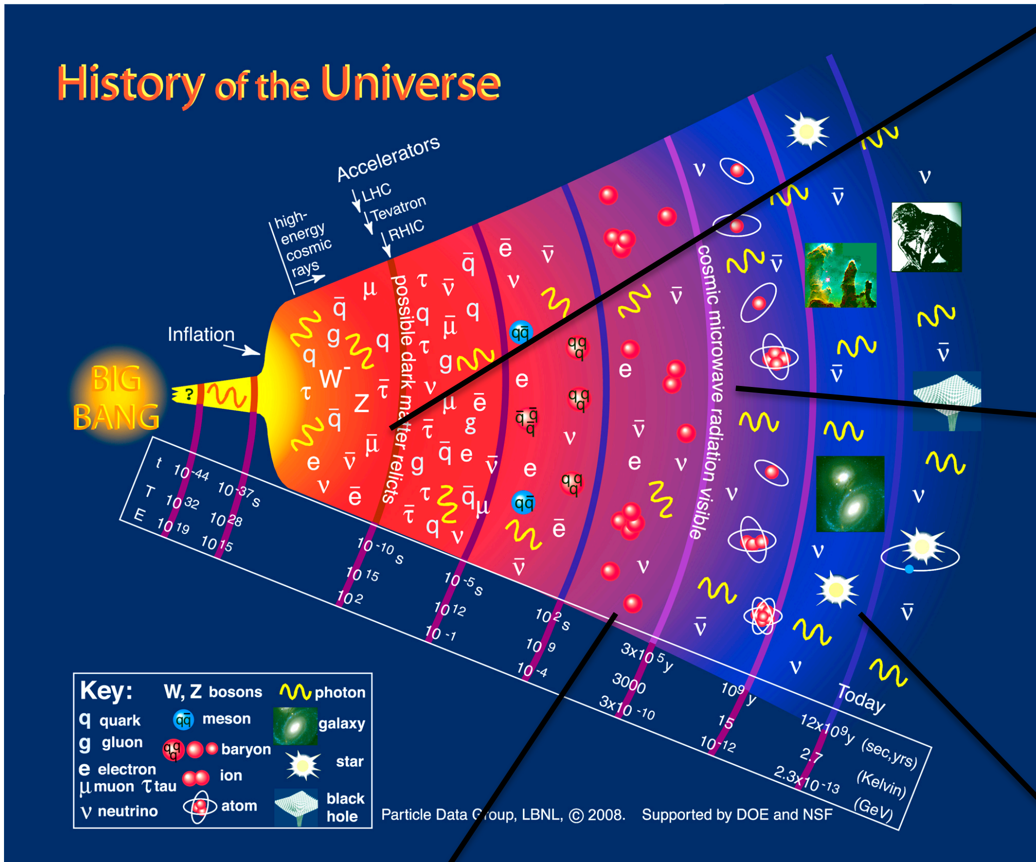


Cosmo anomalies ?

Cosmological neutrinos

they have left traces in the history of the Universe

Leptogenesis

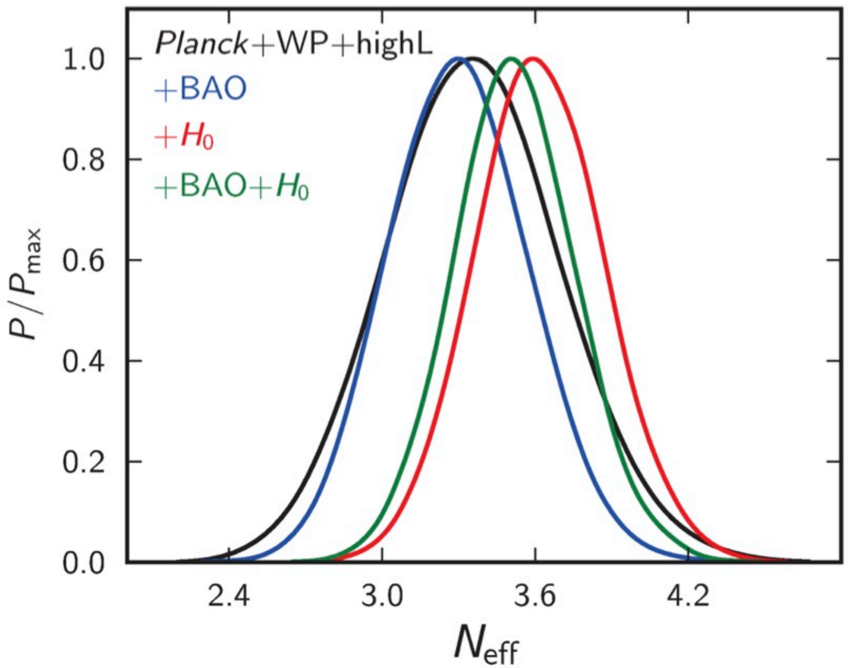


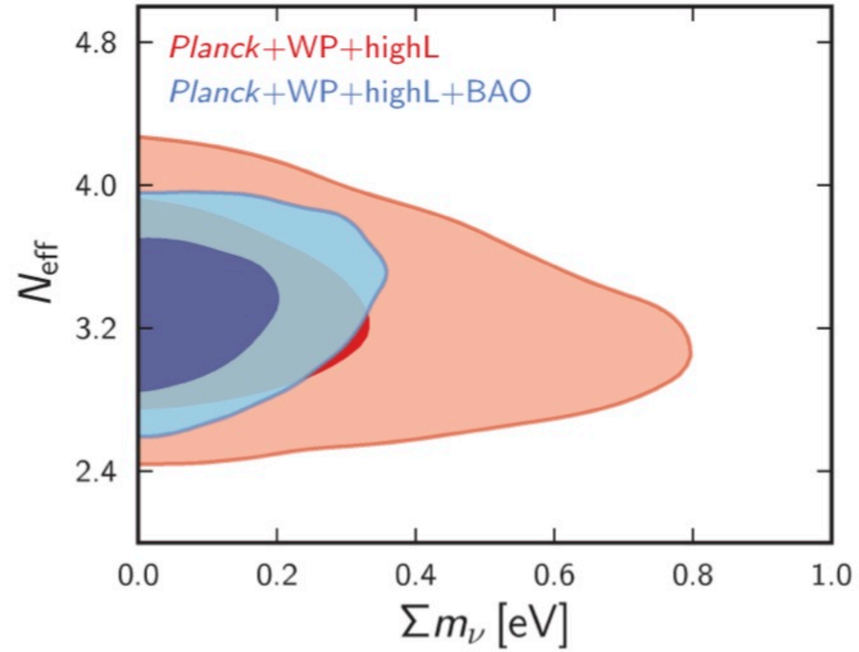
CMB <-> N_ν

Galaxy distribution (LSS) <-> $\sum_i m_i$

Nucleosynthesis <-> N_ν

Extra relativistic species welcome…

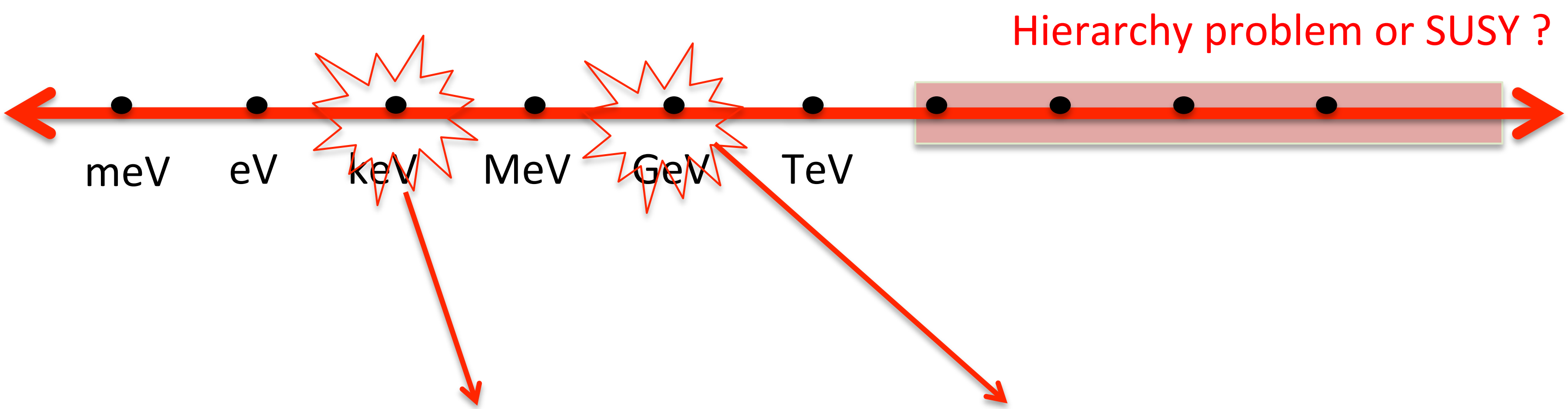




Ade et al 2013

but not too heavy or not too thermal…

Other states out there ?



Warm DM

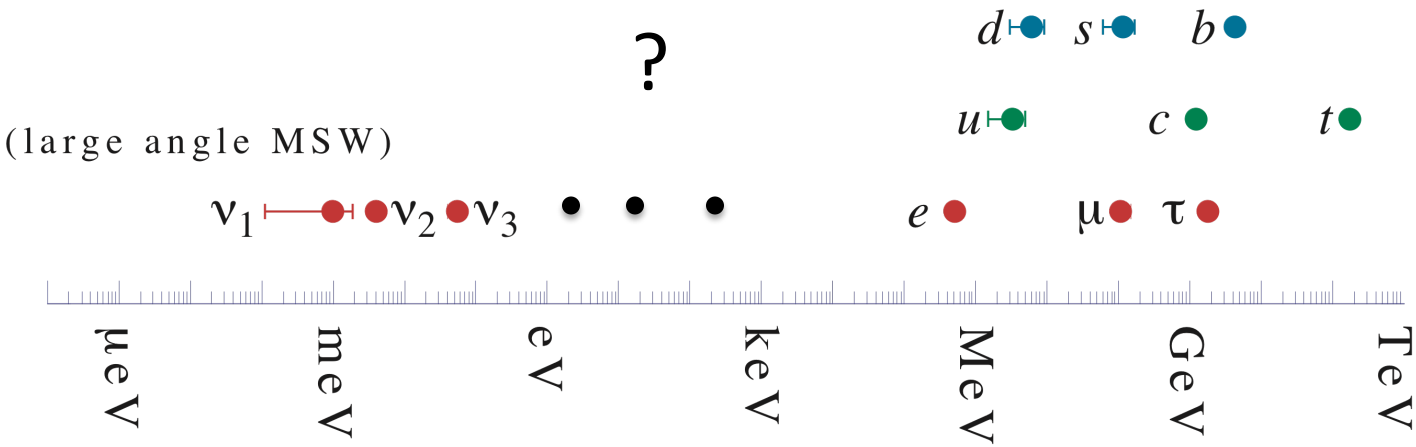
Dodelson, Widrow
Fuller et al

Baryogenesis

Akhmedov, Smirnov;
Shaposnikov et al

Even though there are typically more parameters than those in the neutrino mass, there are strong correlations…

Low-scale models...what about the hierarchy ?



Maybe no gap... but still small Yukawa's...

Other states out there: other constraints ?

Other interesting flavour effects ?

Direct production at LHC of heavy states ? Keung, Senjanovic;...

Generically it is needed

• Gauge interactions of extra fields for large enough production (ex. type II and type III or type I +W', Z')

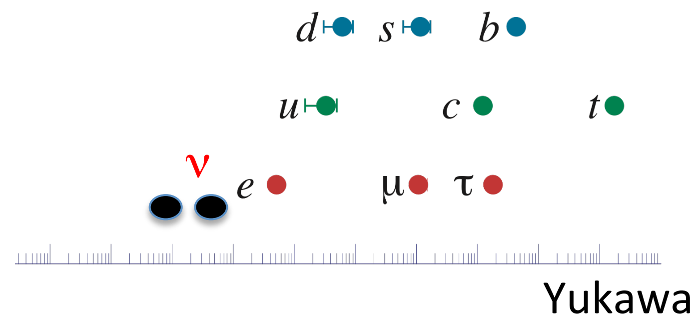
• Flavour effects unsuppressed by small Yukawas: approximate $U(1)_L$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha}{\Lambda_{LN}} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda_{LFV}^2} O_i^{d=6} + \ldots$$

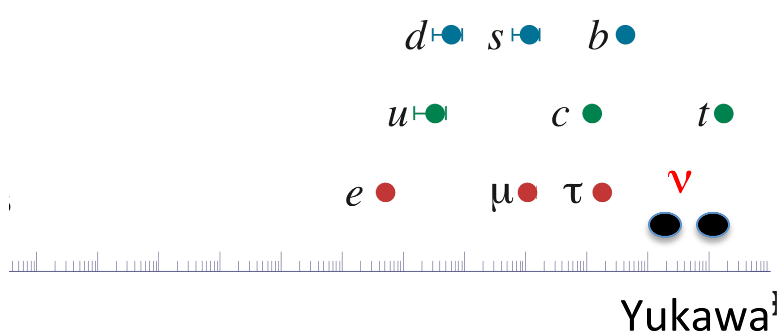
$$\Lambda_{LN} \gg \Lambda_{LFV}$$

Charged/neutral hierarchy in seesaw

Λ = TeV



$\Lambda \lesssim$ TeV + aprox. $U(1)_L$

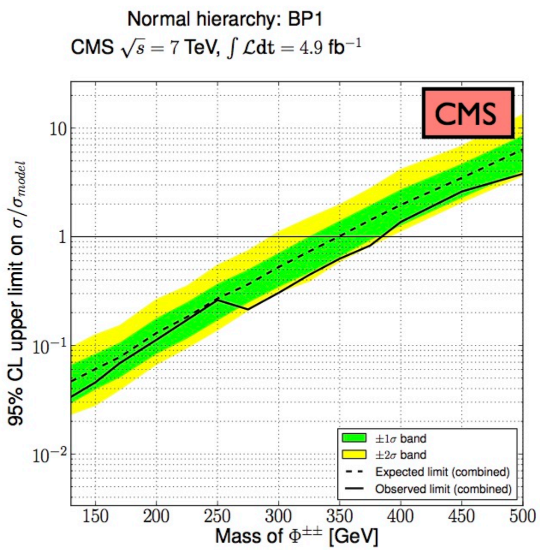


Eg: Inverse seesaw/direct seesaw type I&III or type II

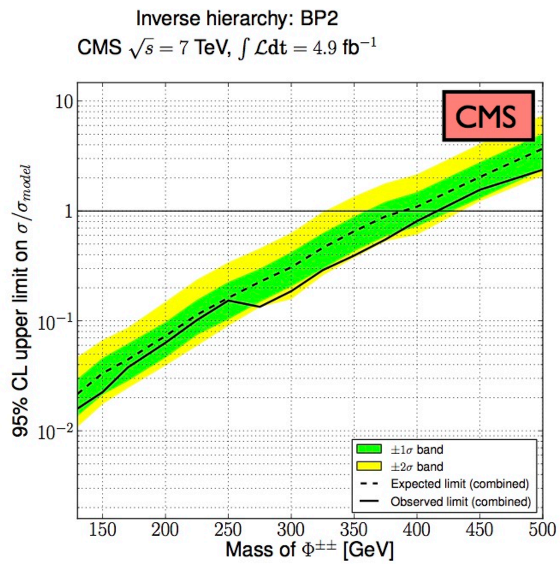
Wyler, Wolfenstein; Mohapatra, Valle;
Branco, Grimus, Lavoura, Malinsky, Romao,
...

pp-> H++ H-- -> l+l+l-l-

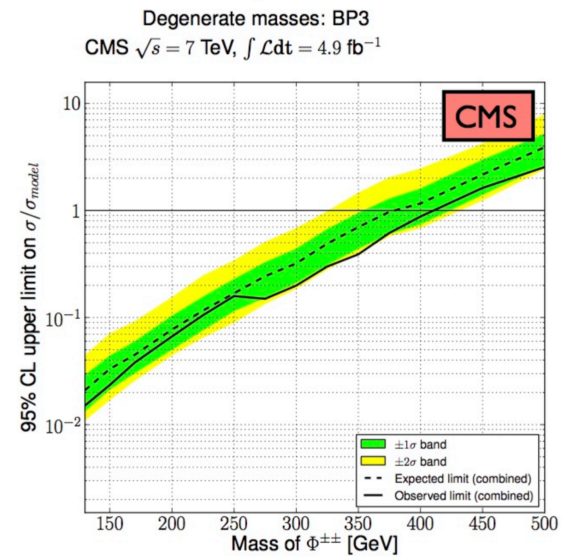
Normal hierarchy



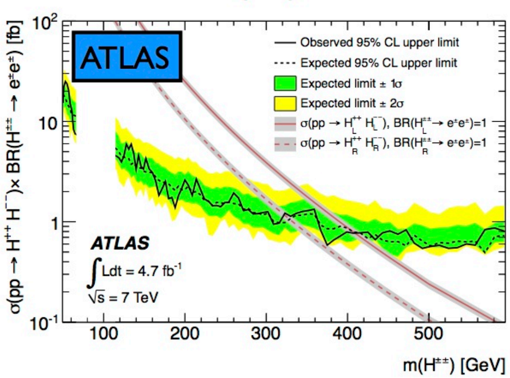
Inverted hierarchy



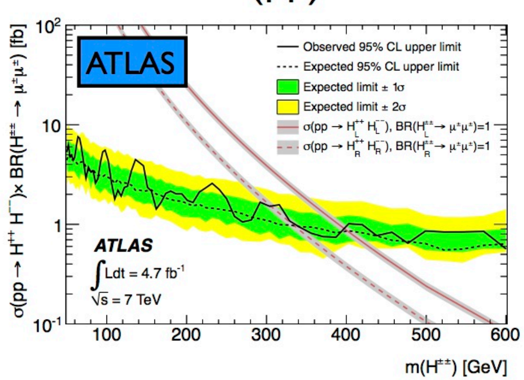
Degenerate ν



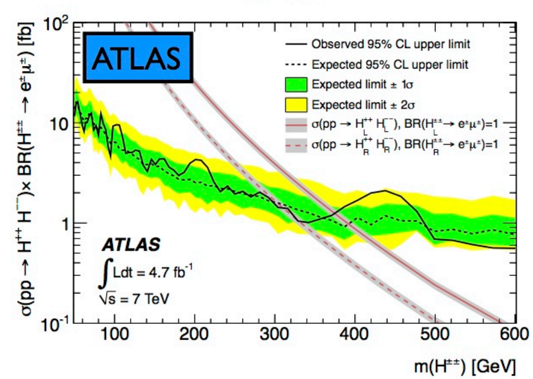
Br(ee)=1



Br(μμ)=1



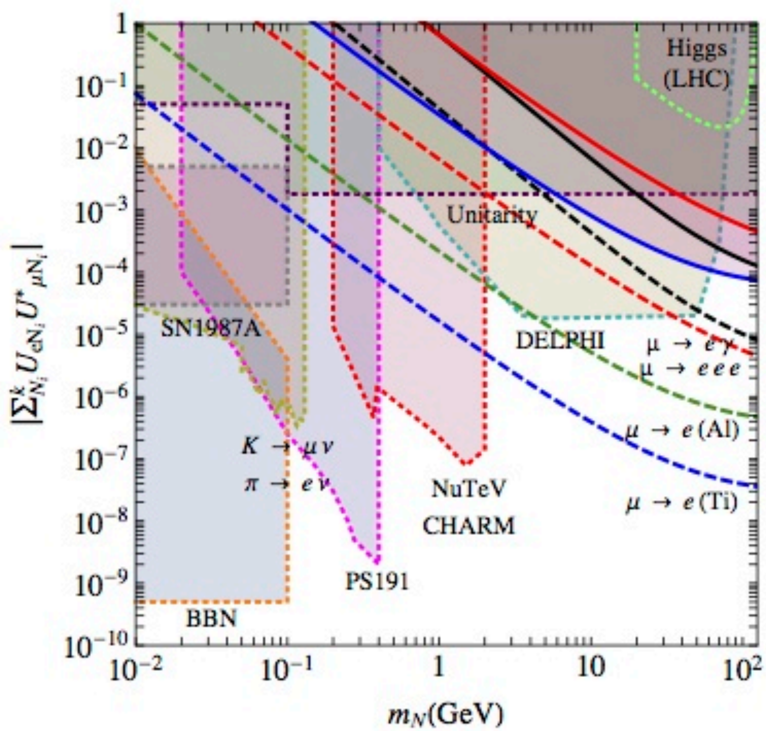
Br(eμ)=1

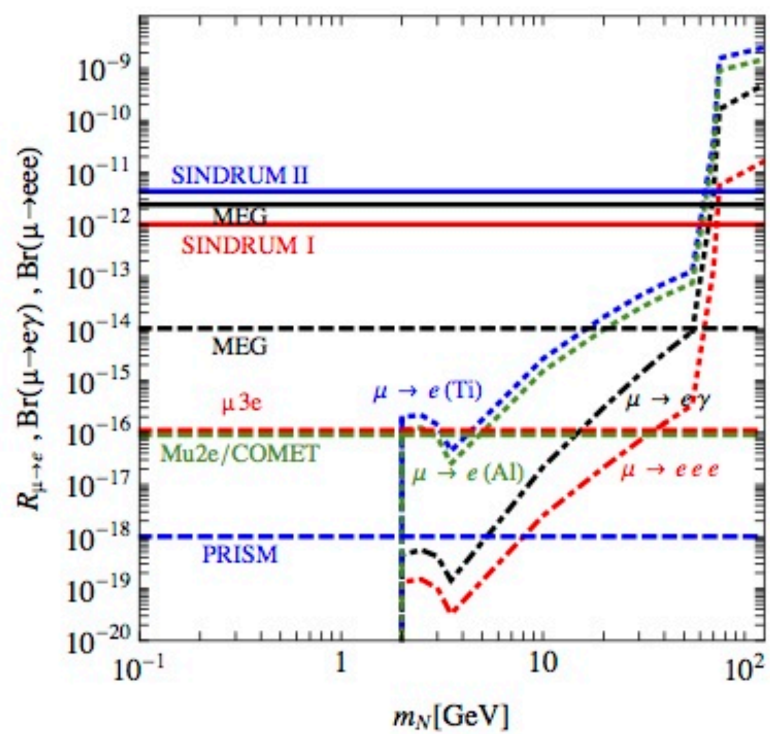


Rich phenomenology of low-scale models with U(1)

μ -> e γ   μ–> eee   μ–> e conversion

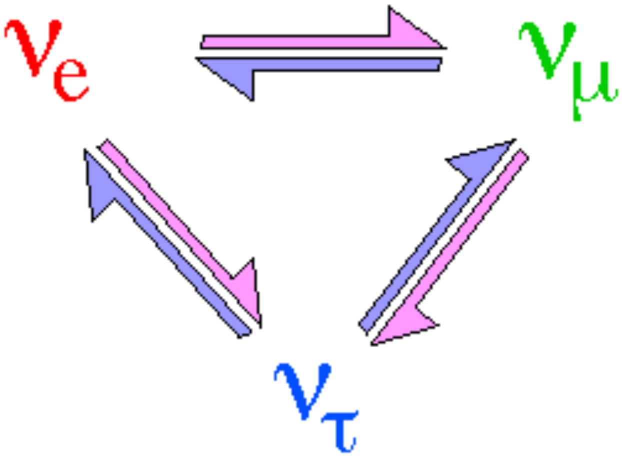
Petcov and many others





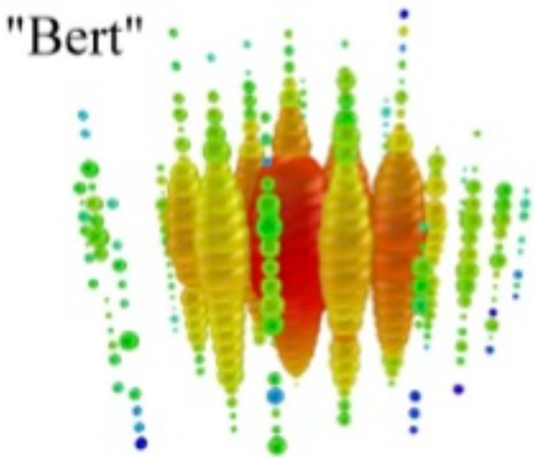
recent analysis Alonso et al 2012

Detecting such a signal would be a major breakthrough in clarifying the origin of neutrino masses

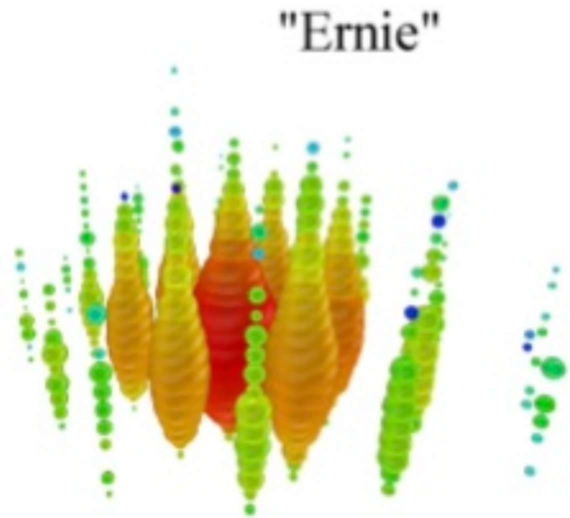


These elusive pieces of reality have brought many surprises, maybe they will continue with their tradition…

Extraterrestrial ν news ?



1150 TeV



1050 TeV

Icecube coll. 1304.5356