Neutrino Physics

Lecture I :

- **Historical introduction: neutrinos in the Standard Model**
- **Neutrino masses and mixing : Majorana versus Dirac**
- **Neutrino oscillations in vacuum and in matter**

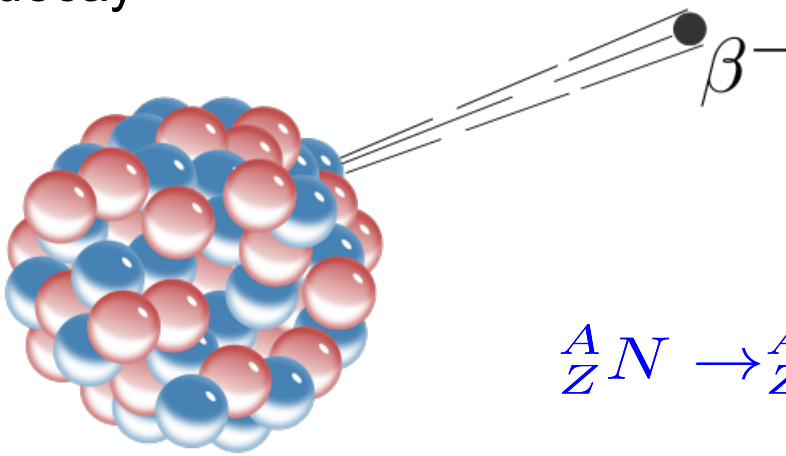
Lecture II:

- The standard 3ν scenario and a few outliers…
- Prospects in neutrino physics

Neutrino: the dark particle

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

β decay

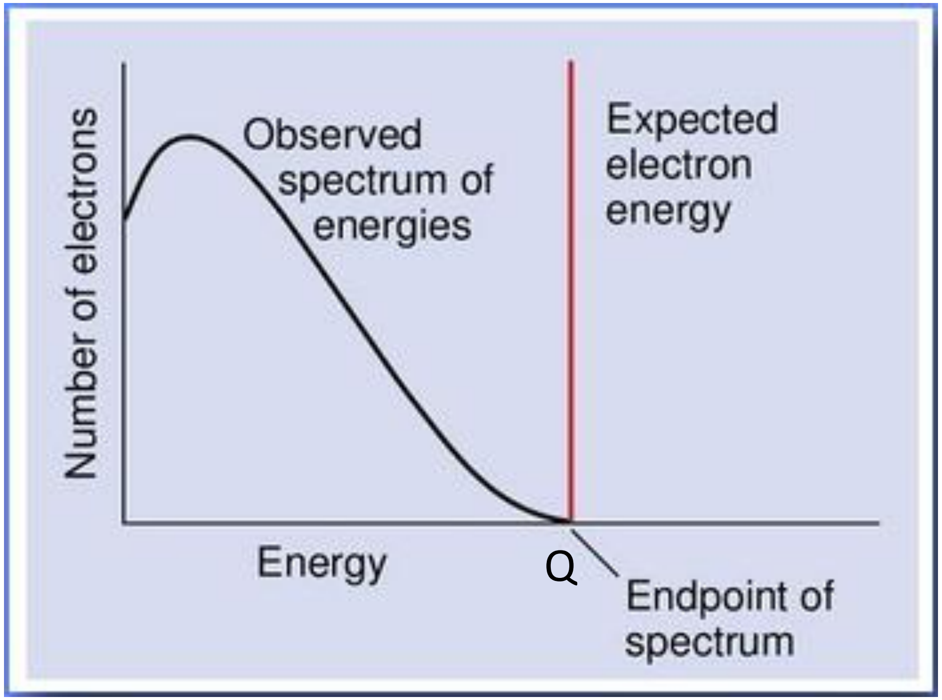


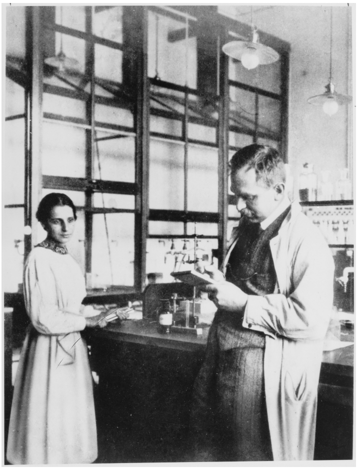
$${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^-$$

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

1911/1914

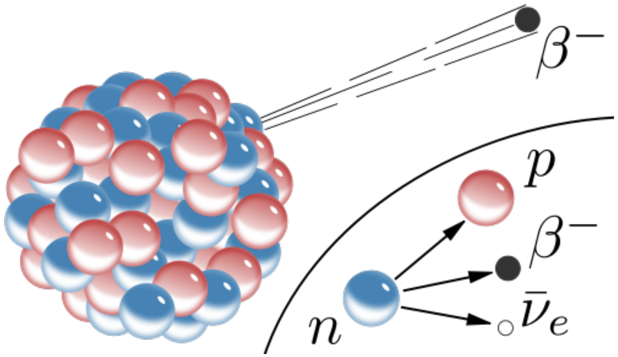
Electron spectrum:



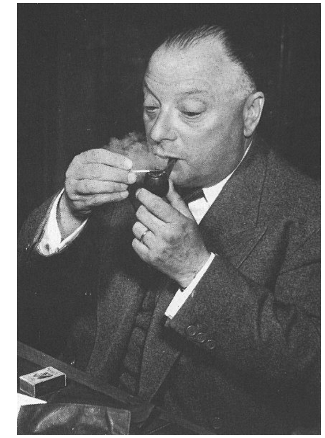


Meitner, Hahn
(Nobel 1944 only him!)

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. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

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....

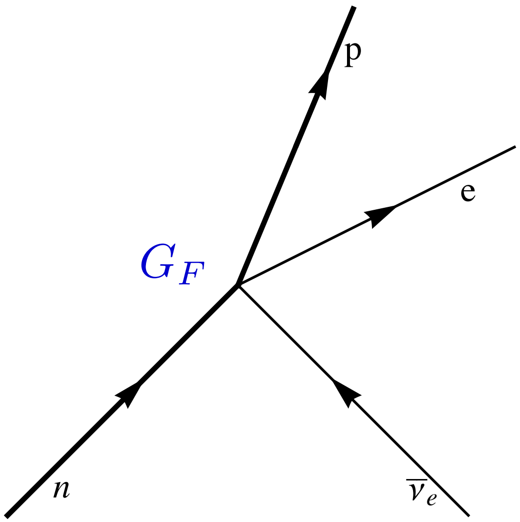
1933: Solvay's conference

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."

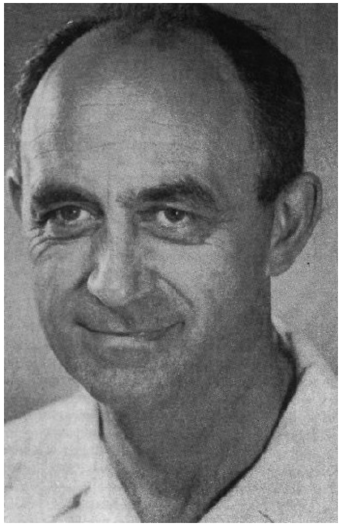
W. Pauli

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): compute 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 ?

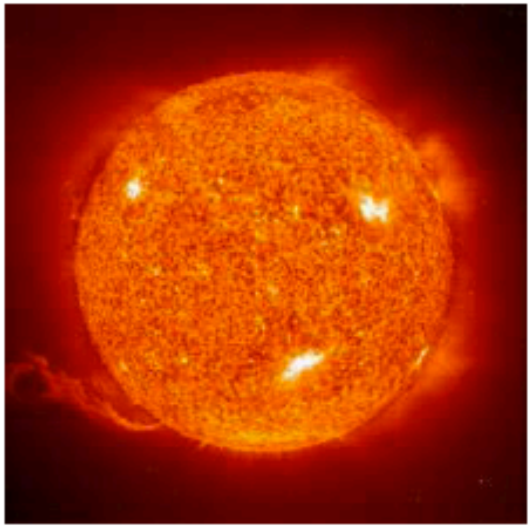
$$\lambda \simeq \frac{1}{n\sigma}$$
$$\lambda|_{@\mathrm{water}} \simeq 1.5 \times 10^{21}\ cm \simeq 1600 \text{ Light Years}$$
$$\lambda|_{@\mathrm{interstelar}} \simeq 10^{44}\ cm \simeq 10^{26} \text{ Light Years}$$

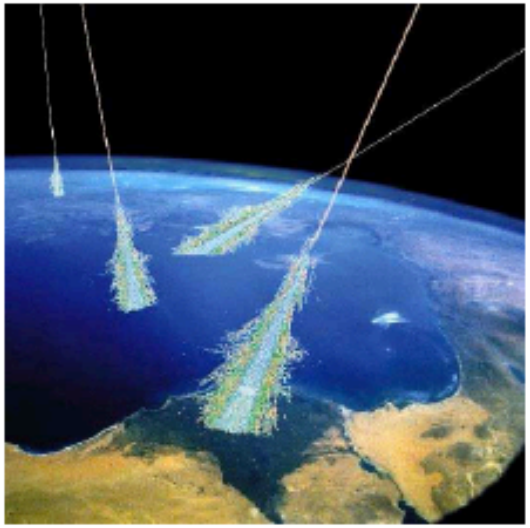
"*I have done a terrible thing. I have postulated a particle that cannot be detected*"

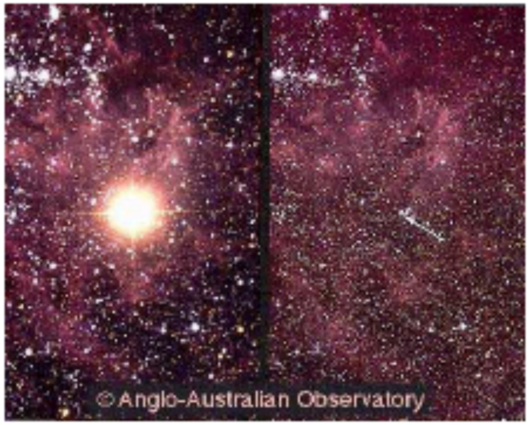
W. Pauli

"*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} ν/s a few events per day

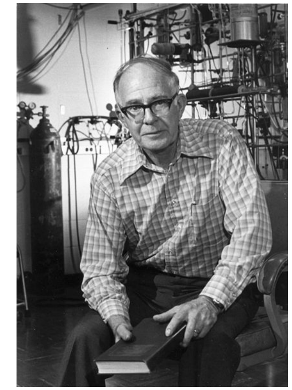
Needs a reaction where the final isotope is radioactive with a proper lifetime

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

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

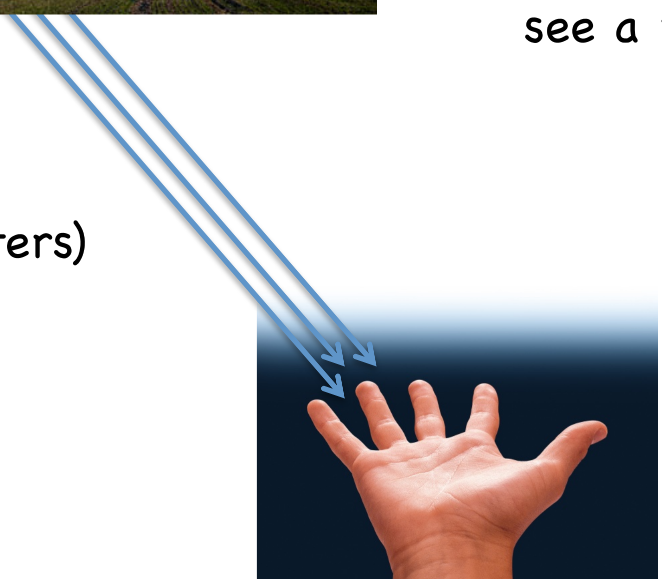
Reactors: ~ 10^{20}/second!

1955 Davies



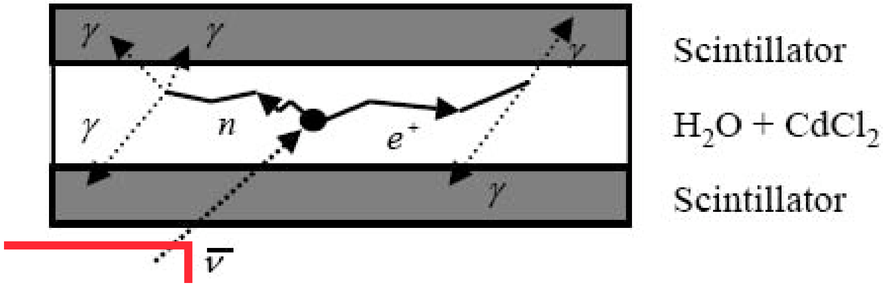
Built a 4000 liter detector, but did not see a thing...

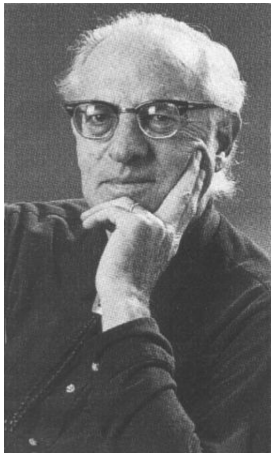
(10^{11}/s@100 meters)



1956 (anti)neutrino detection

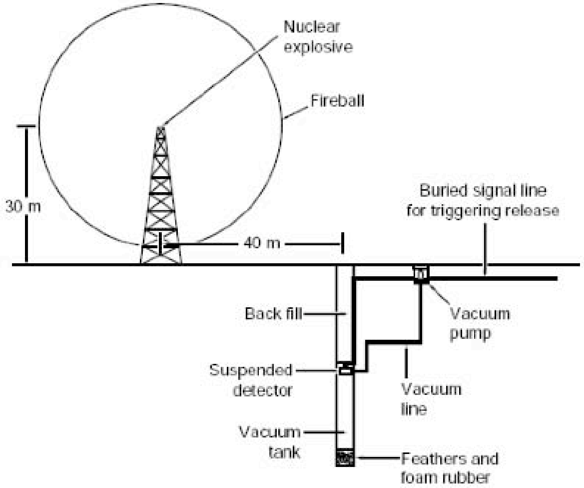
Poltergeist project





Reines Nobel 95

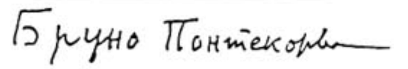
Cowan (died 74)



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

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)

$$\pi \to \mu\ \bar{\nu}_\mu$$

1959 Pontecorvo

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

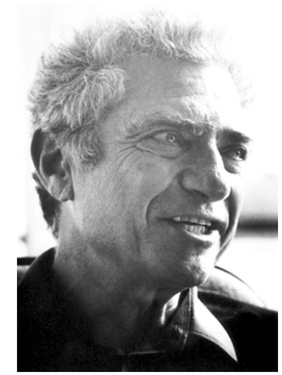
Neutrino cross section in Fermi theory grows with energy: he proposes the first experiment with a neutrino beam !

Neutrino Flavour

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

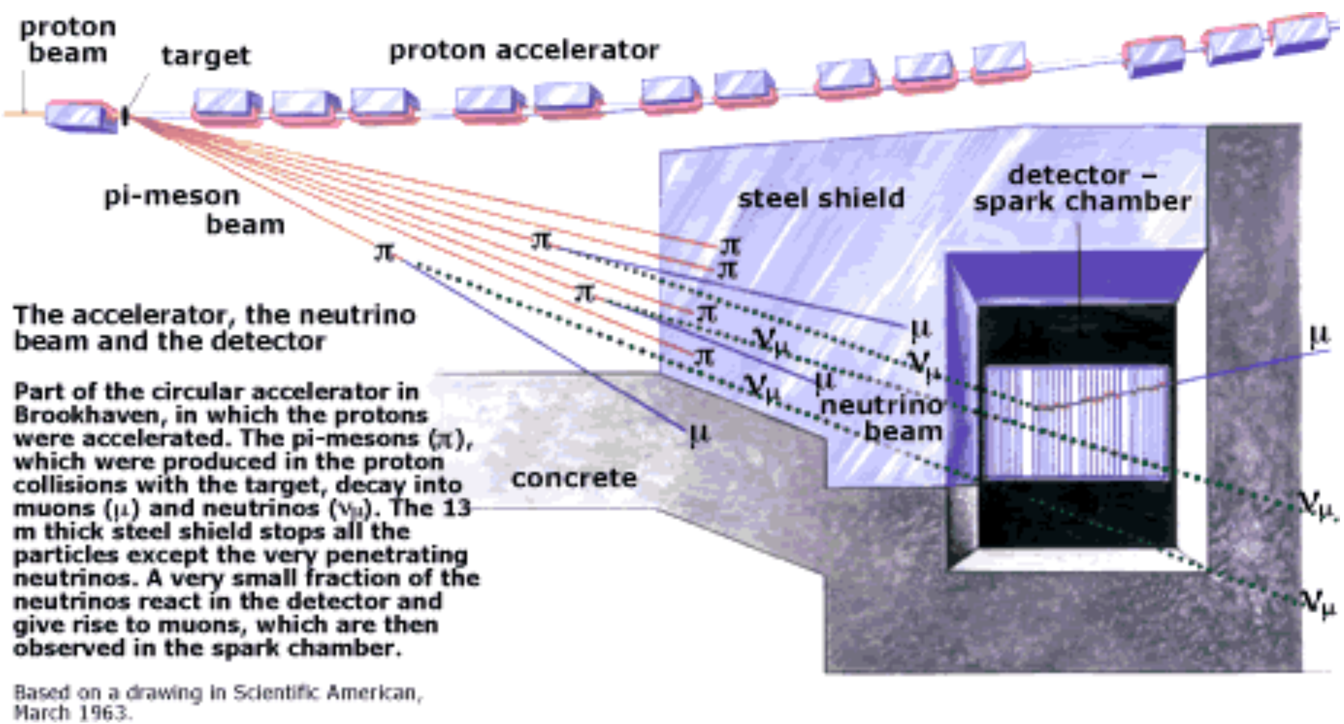
Lederman

Schwartz



Steinberger

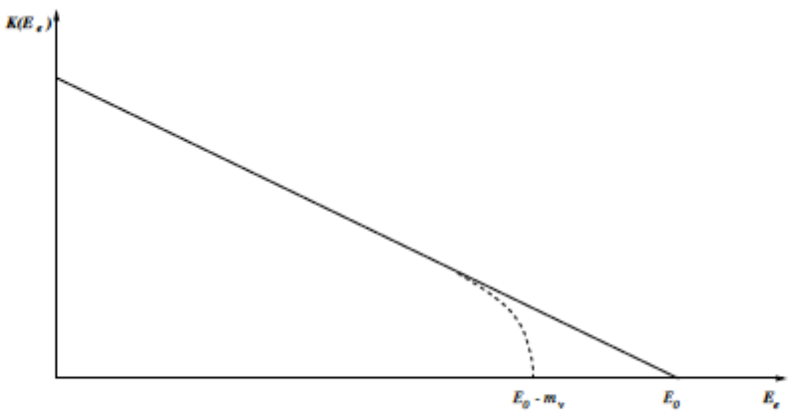
Nobel 1988



Kinematical effects of neutrino mass

Most stringent from Tritium beta-decay

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



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

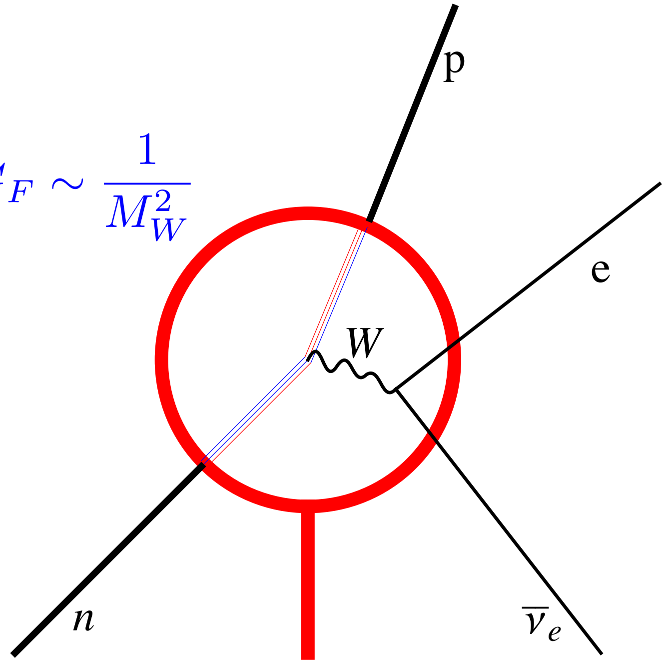
$m_{\nu_\mu} < 170\text{keV}$ (PSI: $\pi^+ \to \mu^+ \nu_\mu$)

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

Standard Model neutrinos assumed massless

Neutrinos in the Standard Model

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



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

Left-handed Right-handed

Weyl fermions

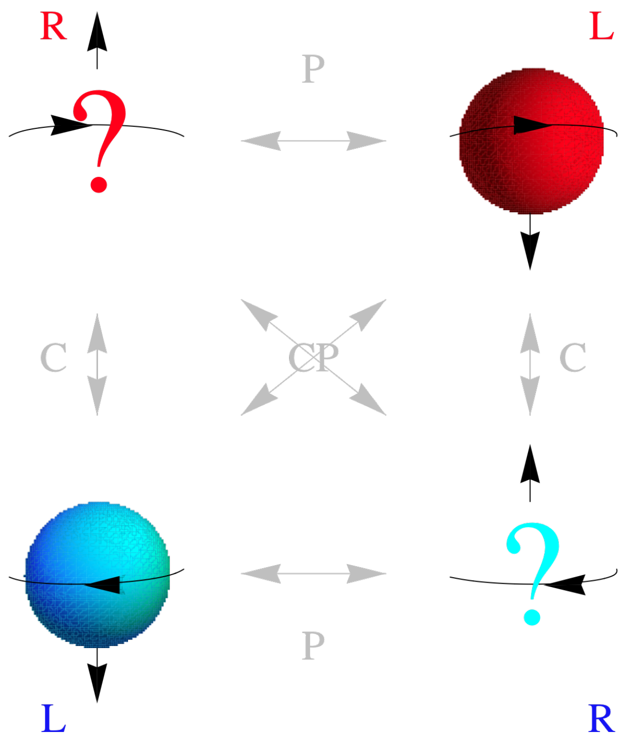
$$\nu = \frac{1-\gamma_5}{2}\,\nu \simeq \frac{1}{2}\left(1 - \underbrace{\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}}_{\text{Helicity}}\right)\nu + \mathcal{O}(v/c)$$

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

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

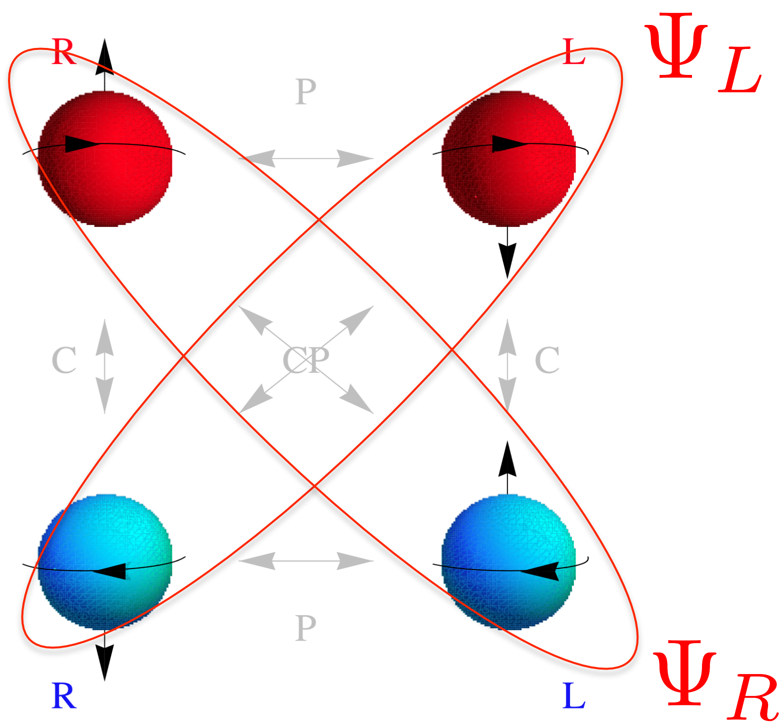
Weyl fermion= 2-component spinor

(Minimal spin ½)



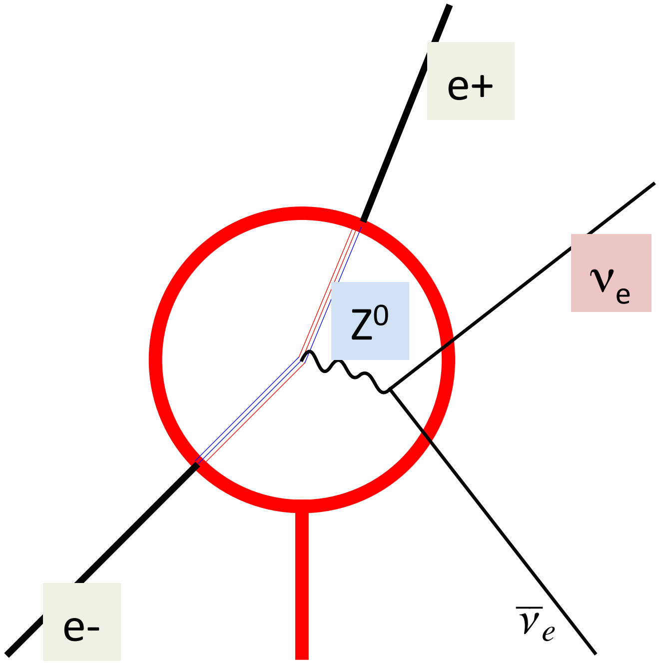
Dirac fermion= 4-component spinor

(Minimal spin ½ + Parity)



Weyl fermion field = negative helicity particle + positive helicity anti-particle

Neutrinos in the Standard Model



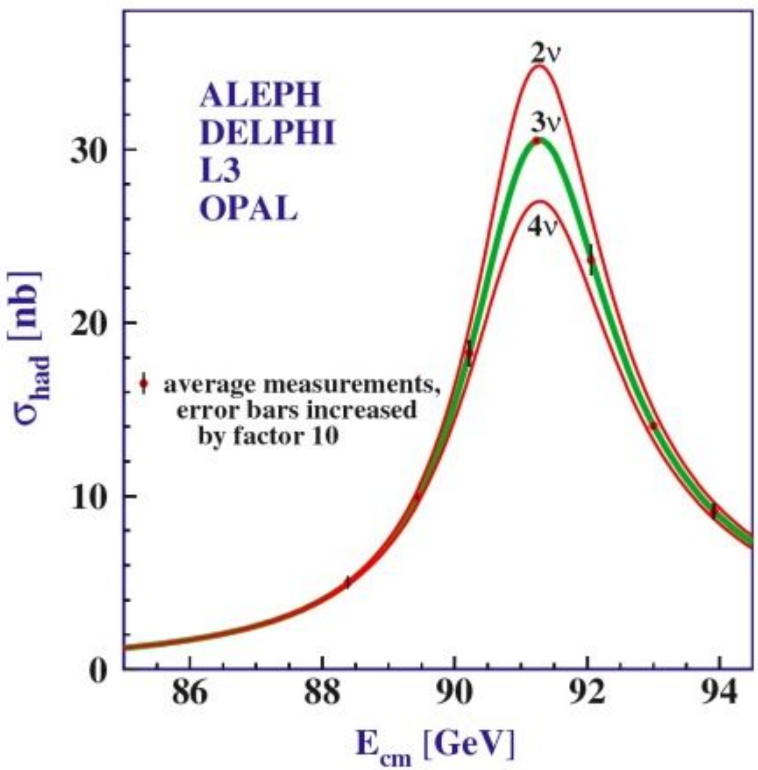
At LEP:

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

Only three neutrinos were found

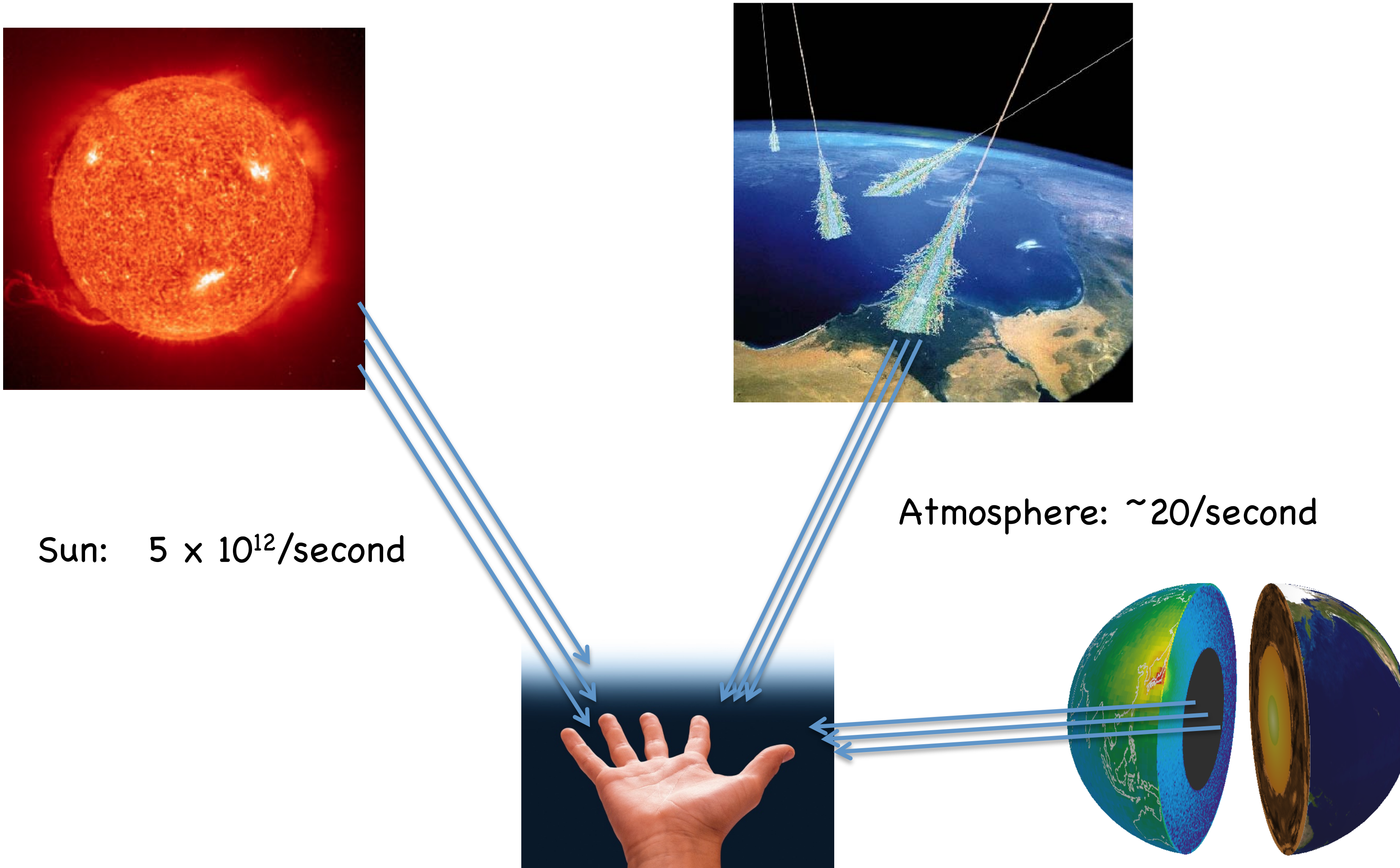
Neutral currents: NC

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

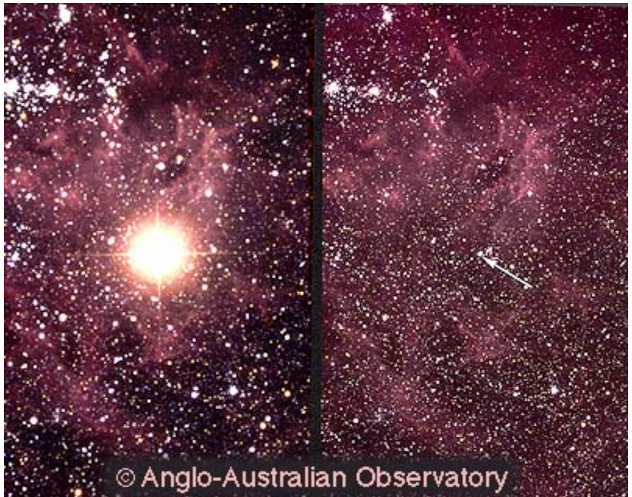


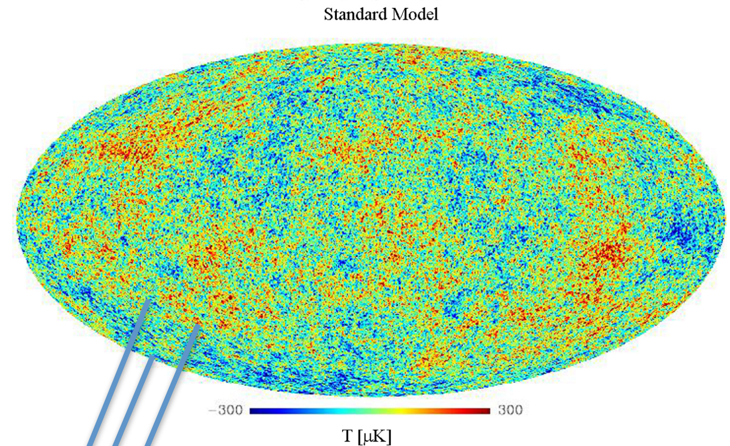
Ubiquitous Neutrinos

They are everywhere…



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

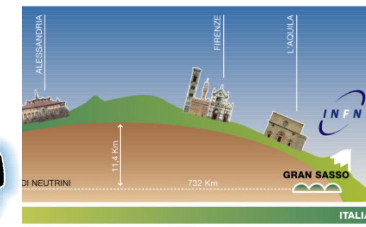
Supernova 1987: ~10^{12}/second

@168000 Light years!
10^8 farther from Earth

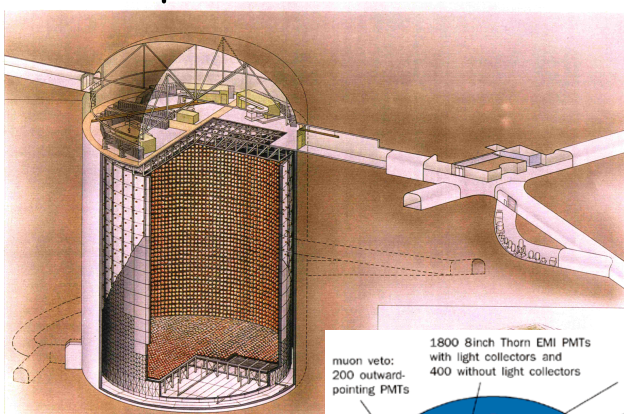
Using many of these sources, and others man-made, a decade of revolutionary neutrino experiments have demonstrated that neutrinos are not quite standard, because they have a tiny mass & massive neutrinos require new dofs!

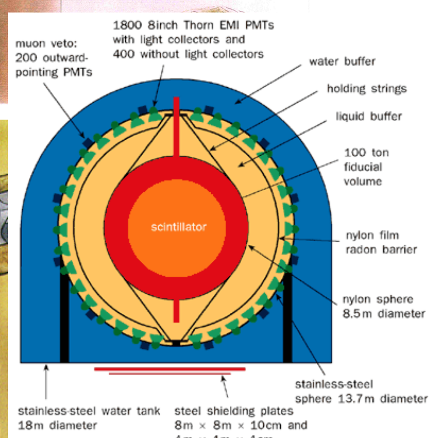
Wark's talk

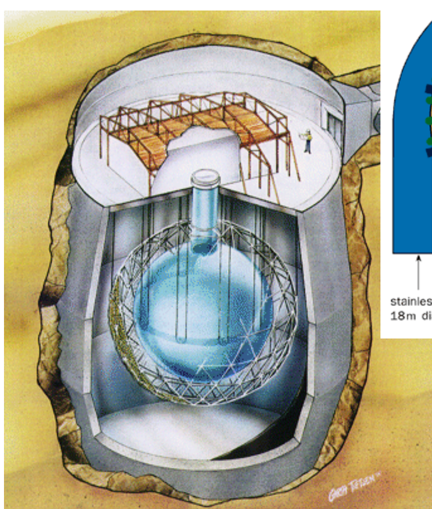
MINOS, Opera



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

Massive fermions & Weak Interactions ?

Dirac fermion of mass m:

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

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!

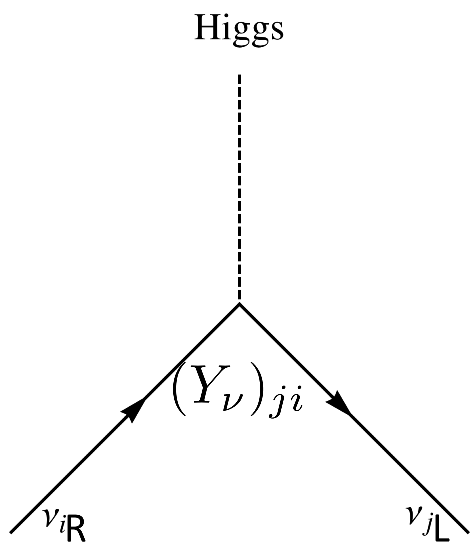
Spontaneous symmetry breaking can induce Dirac masses for all fermions but Majorana masses only for neutrinos !

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

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



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

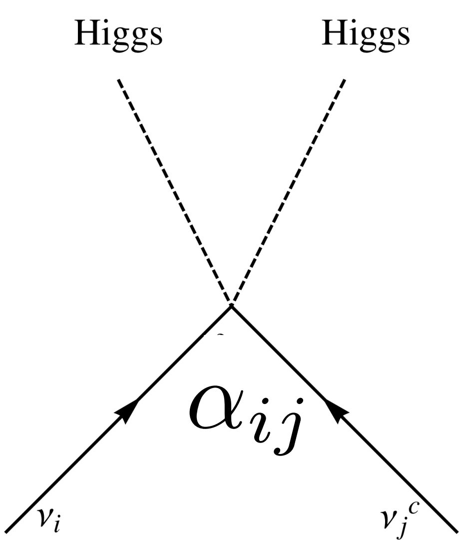
Massive Majorana neutrinos & SSB ?

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

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



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

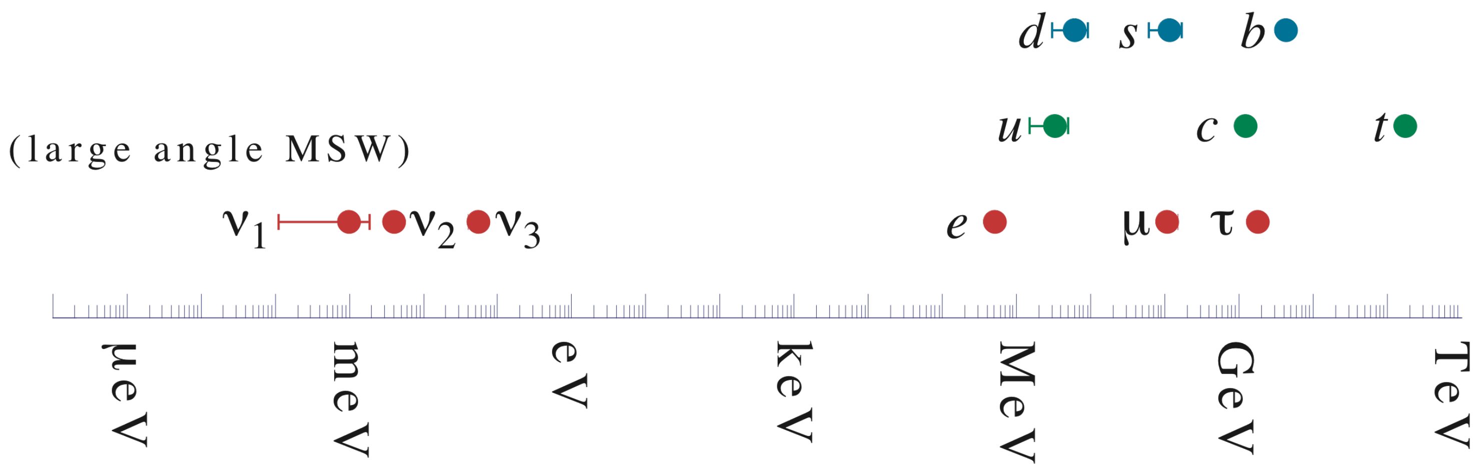
$$[\alpha] = -1$$

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

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

Massive Majorana neutrinos & SSB ?

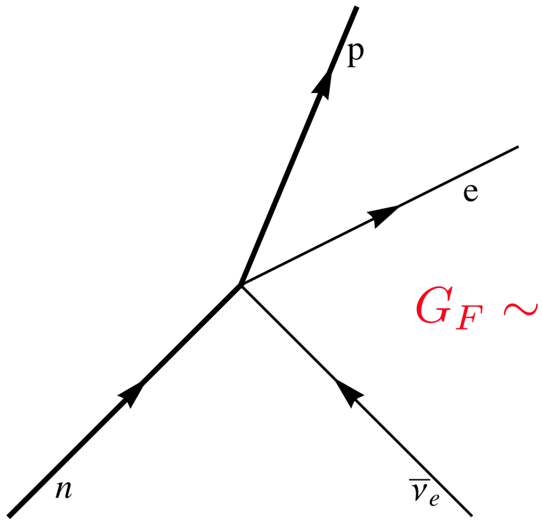
If $\Lambda >> v$ natural explanation for the smallness of neutrino mass



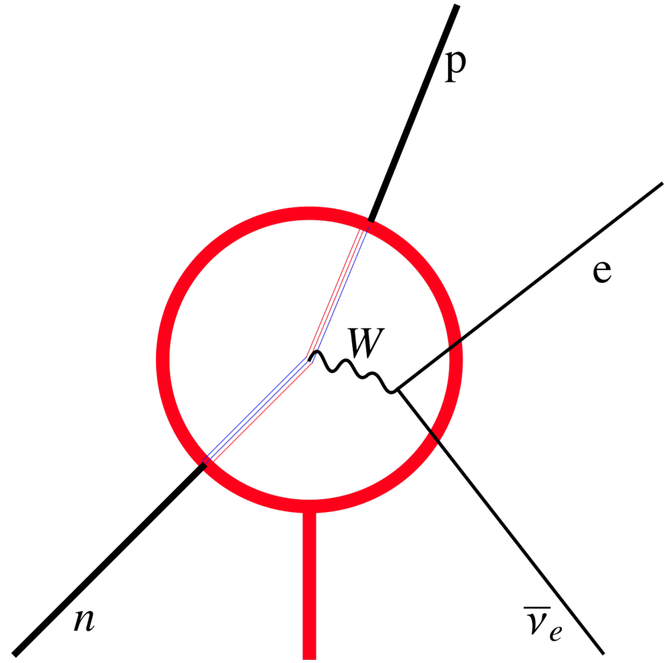
$$m_f(charged) \sim Yv, \quad m_\nu \sim Y\frac{v^2}{\Lambda} \sim m_f\frac{v}{\Lambda}$$

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

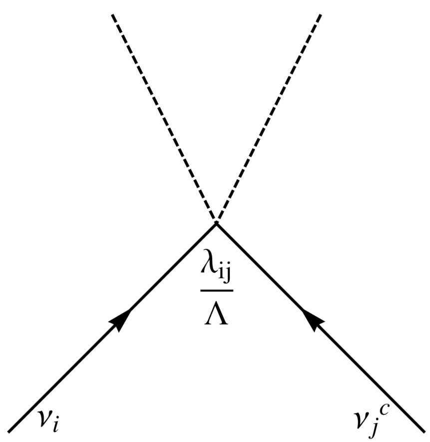
Majorana neutrinos imply a new Standard Model



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



SM



νSM ?

Effective Theories of Neutrino Masses (model-independent)

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 !

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

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

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

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	$U_L(n)xU_{lR}(n)$	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

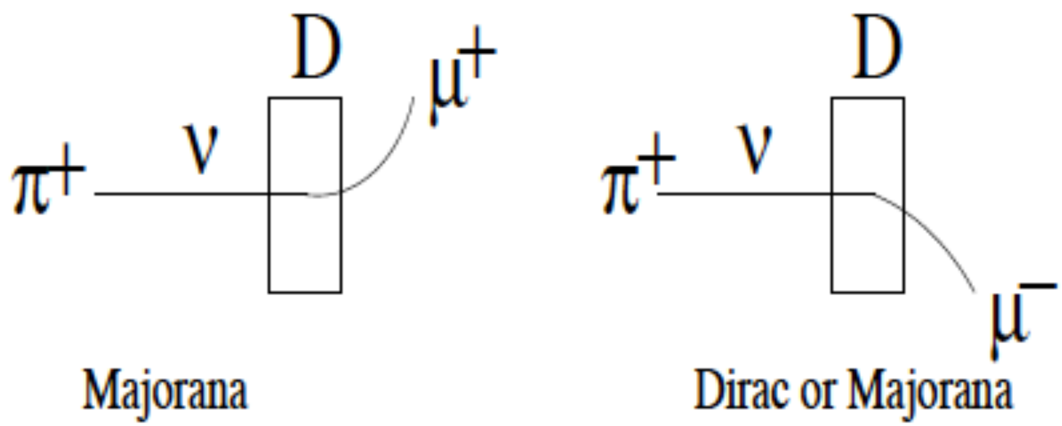
Majorana versus Dirac

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

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

Majorana phases

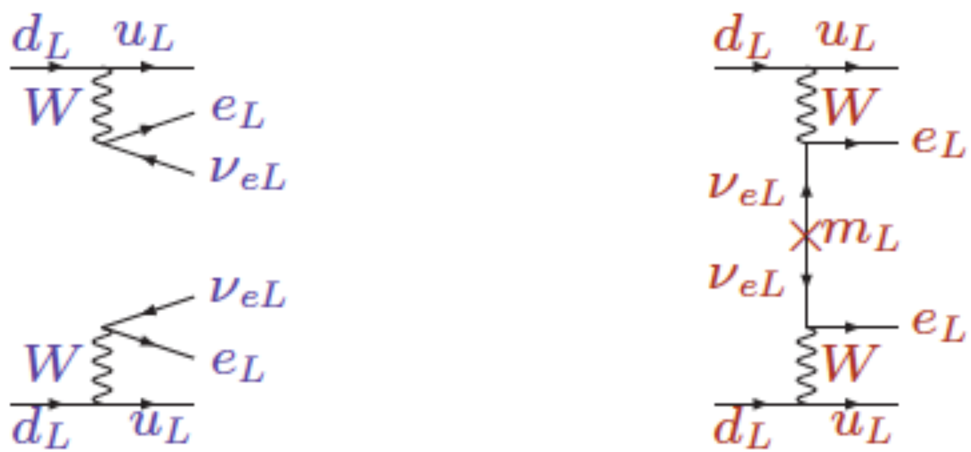
In principle clear experimental signatures



In practice theses processes are extremely rare: suppressed by $\left(\frac{m_\nu}{E}\right)^2$

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.	$\langle m_{ee}\rangle$ (eV) 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	$\mathbf{1.9\ 10^{25}}$	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	$\mathbf{1.0\ 10^{24}}$	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	$\mathbf{2.8\ 10^{24}}$	CUORICINO [65]	**0.27**	**0.57**	
^{136}Xe	$2.38 \pm 0.14\ 10^{21}$	Kamland	$\mathbf{5.7\ 10^{24}}$	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

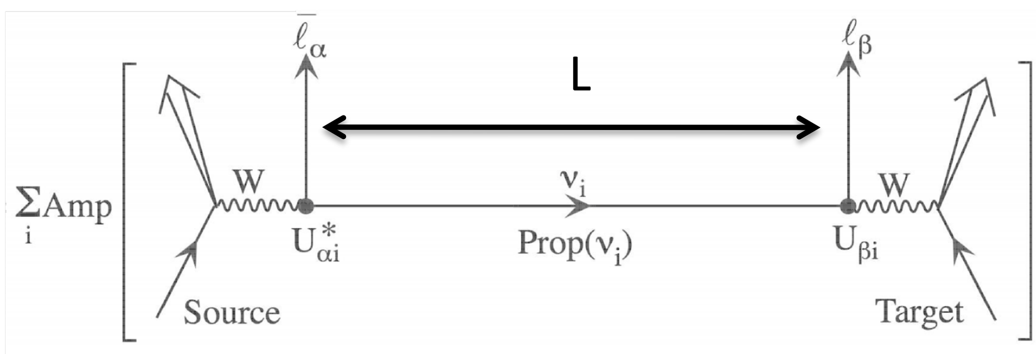
Neutrino oscillations

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

Many ways to derive the oscillation probability master formula

Quantum mechanics with neutrinos as plane waves
Quantum mechanics with neutrinos as wave packets
Quantum Field Theory <-> neutrinos as intermediate states

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 QM (plane waves)

$$|\nu_\alpha(t_0)\rangle = \sum_i U^*_{\alpha i}|\nu_i(\mathbf{p})\rangle, \qquad \hat{H}|\nu_i(\mathbf{p})\rangle = E_i(\mathbf{p})|\nu_i(\mathbf{p})\rangle, \quad \mathbf{p}^2 + m_i^2 = E_i^2(\mathbf{p})$$

$\downarrow$ time evolution

$$|\nu_\alpha(t)\rangle = \sum_i U^*_{\alpha i} e^{-iE_i(\mathbf{p})(t-t_0)}|\nu_i(\mathbf{p})\rangle$$

$$P(\nu_\alpha \to \nu_\beta)(t) = |\langle \nu_\beta|\nu_\alpha(t)\rangle|^2 = |\sum_i U_{\beta i} U^*_{\alpha i} e^{-iE_i(t-t_0)}|^2$$

$$= \sum_{i,j} e^{-i(E_i - E_j)(t-t_0)} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}$$

$$E_i(\mathbf{p}) - E_j(\mathbf{p}) \simeq \frac{1}{2}\frac{m_i^2 - m_j^2}{|\mathbf{p}|} + \mathcal{O}(m^4) \qquad L \simeq t - t_0, v_i \simeq c$$

$$P(\nu_\alpha \to \nu_\beta)(L) \simeq \sum_{i,j} e^{i\frac{\Delta m^2_{ji} L}{2E}} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}$$

Neutrino Oscillation

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

$\alpha \neq \beta$ appearance probability
$\alpha = \beta$ disappearance or survival probability

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

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

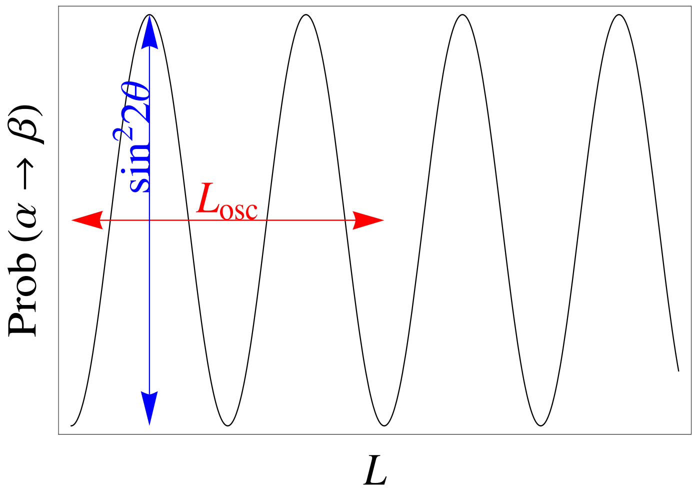
CP-even $\quad - \; 4\sum_{i<j} \mathrm{Re}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin^2\left[\frac{\Delta m^2_{ji} L}{4E}\right]$

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

Neutrino Oscillation: 2ν

Only one oscillation frequency, $U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2(eV^2) L(km)}{E(GeV)}\right)$$



$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$

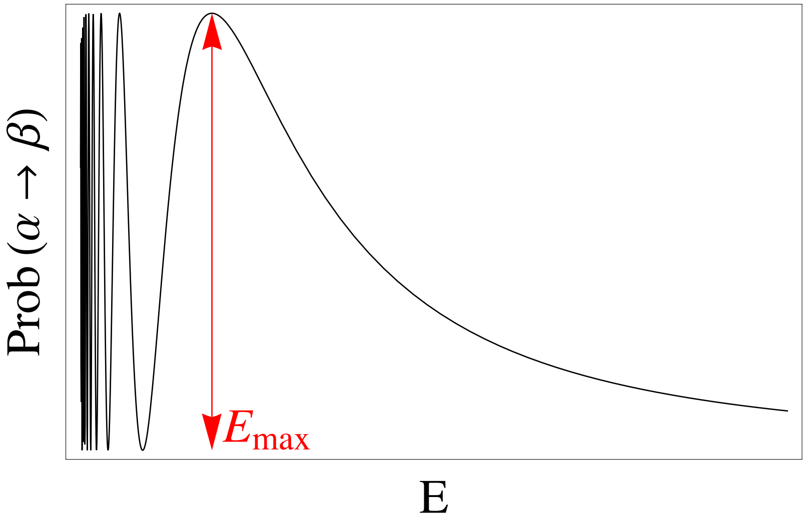
$$L_{osc}(km) = \frac{\pi}{1.27} \frac{E(GeV)}{\Delta m^2(eV^2)}$$

Neutrino Oscillation: 2ν

Only one oscillation frequency, $U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) L(km)}{E(GeV)}\right)$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$



$$E_{max}(GeV) = 1.27 \frac{\Delta m^2 (eV^2) L(km)}{\pi/2}$$

L, E dependence give Δm^2 amplitude of oscillation gives θ

Optimal experiment: $\frac{E}{L} \sim \Delta m^2$

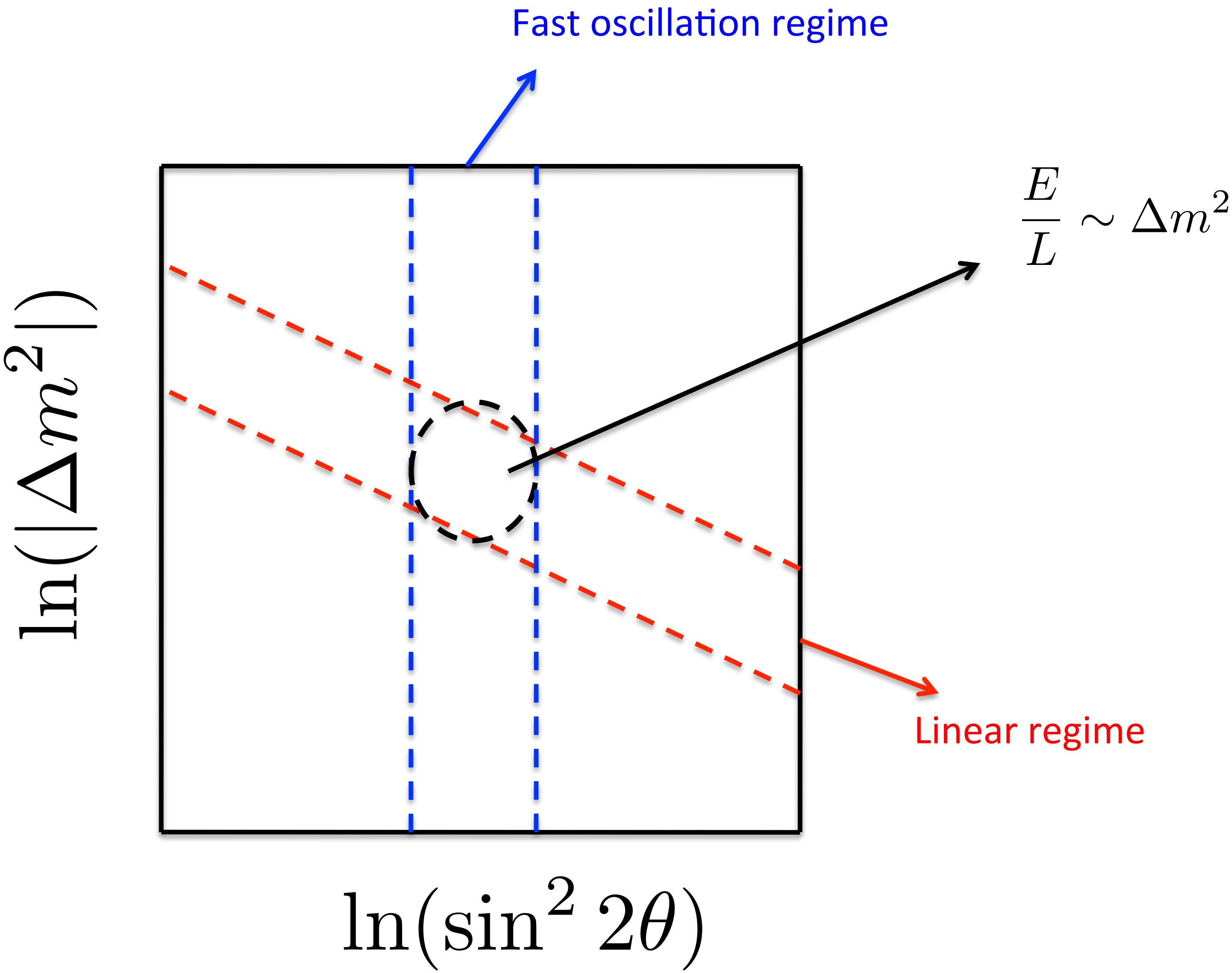
$\frac{E}{L} \gg \Delta m^2$ Oscillation suppressed

$$P(\nu_\alpha \to \nu_\beta) \propto \sin^2 2\theta \left(\Delta m^2\right)^2$$

$\frac{E}{L} \ll \Delta m^2$ Fast oscillation regime

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \, \langle \sin^2 \frac{\Delta m^2 L}{4E} \rangle \simeq \frac{1}{2} \sin^2 2\theta = |U^*_{\alpha 1} U_{\beta 1}|^2 + |U^*_{\alpha 2} U_{\beta 2}|^2$$

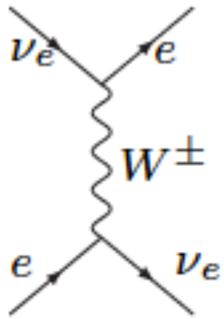
Equivalent to incoherent propagation: sensitivity to mass splitting is lost

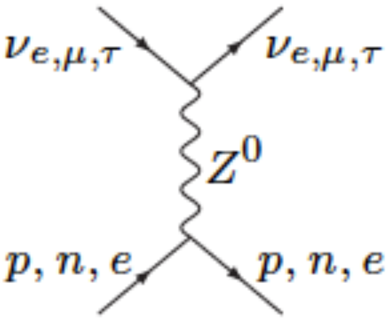


Fast oscillation regime
$\frac{E}{L} \sim \Delta m^2$
Linear regime
$\ln(|\Delta m^2|)$
$\ln(\sin^2 2\theta)$

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

$$\mathcal{H}_{CC} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e][\bar{\nu}_e\gamma^\mu(1-\gamma_5)e] = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\mu(1-\gamma_5)e][\bar{\nu}_e\gamma^\mu(1-\gamma_5)\nu_e]$$

$$\langle \bar{e}\gamma_\mu P_L e\rangle_{\text{unpol.medium}} = \delta_{\mu 0}\frac{N_e}{2}$$

Neutrino propagation in matter

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

$$\mathcal{L} \simeq \bar{\nu}\,(i\partial\!\!\!/ - M_\nu - \gamma_0 V_m)\,\nu + ...$$

$$\mathcal{O}(V_m^2, M_\nu^2 V_m) \qquad \boxed{E^2 - \mathbf{p}^2 \quad = \quad \pm 2\, V_m E + M_\nu^2}$$

Earth: $V_m \simeq 10^{-13} eV \to 2V_m E \simeq 10^{-4} eV^2 \left[\frac{E}{1GeV}\right]$

Sun: $V_m \simeq 10^{-12} eV \to 2V_m E \simeq 10^{-6} eV^2 \left[\frac{E}{1MeV}\right]$

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):

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

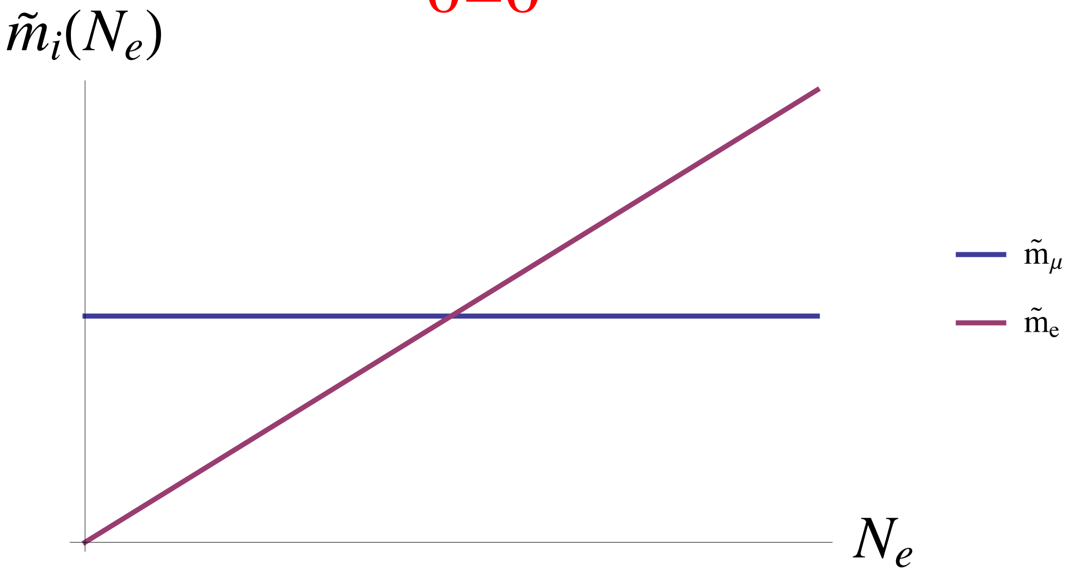
$$\Delta\tilde{m}^2 = \sqrt{\left(\Delta m^2 \cos 2\theta \pm 2\sqrt{2} E\, G_F\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

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

MSW resonance

Mikheyev, Smirnov '85

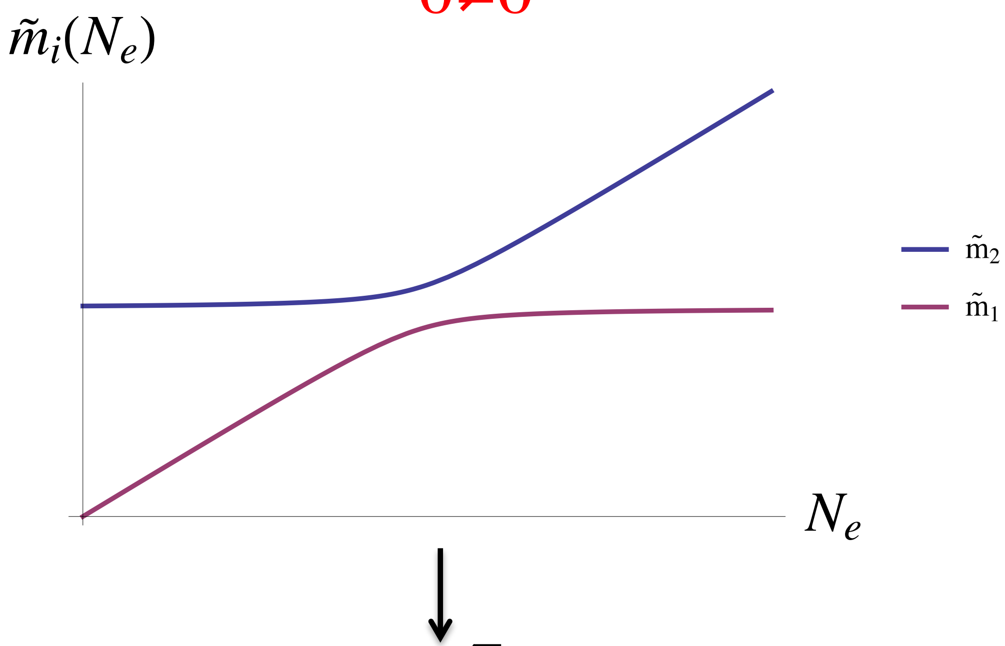
$\theta=0$



MSW resonance

Mikheyev, Smirnov '85

θ≠0



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

MSW Resonance:

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

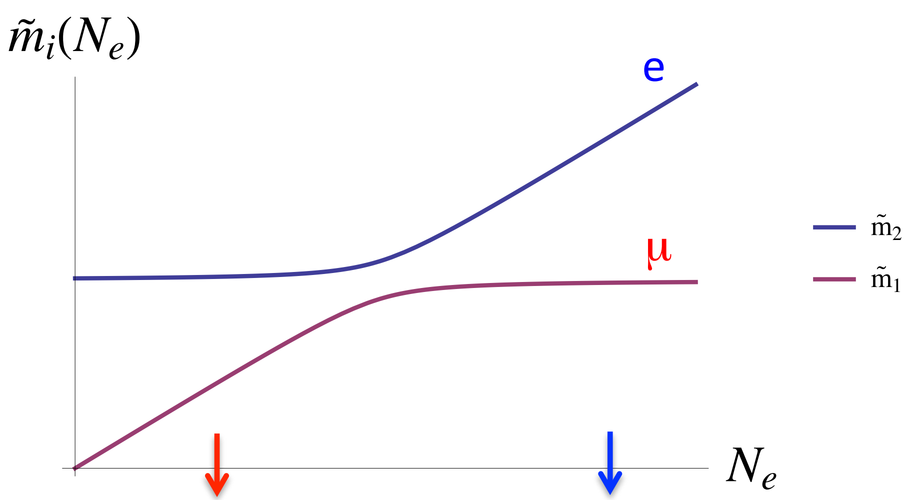
Neutrinos in variable matter

Solar neutrinos propagate in variable matter:

$$N_e(r) \propto N_e(0)e^{-r/R}$$

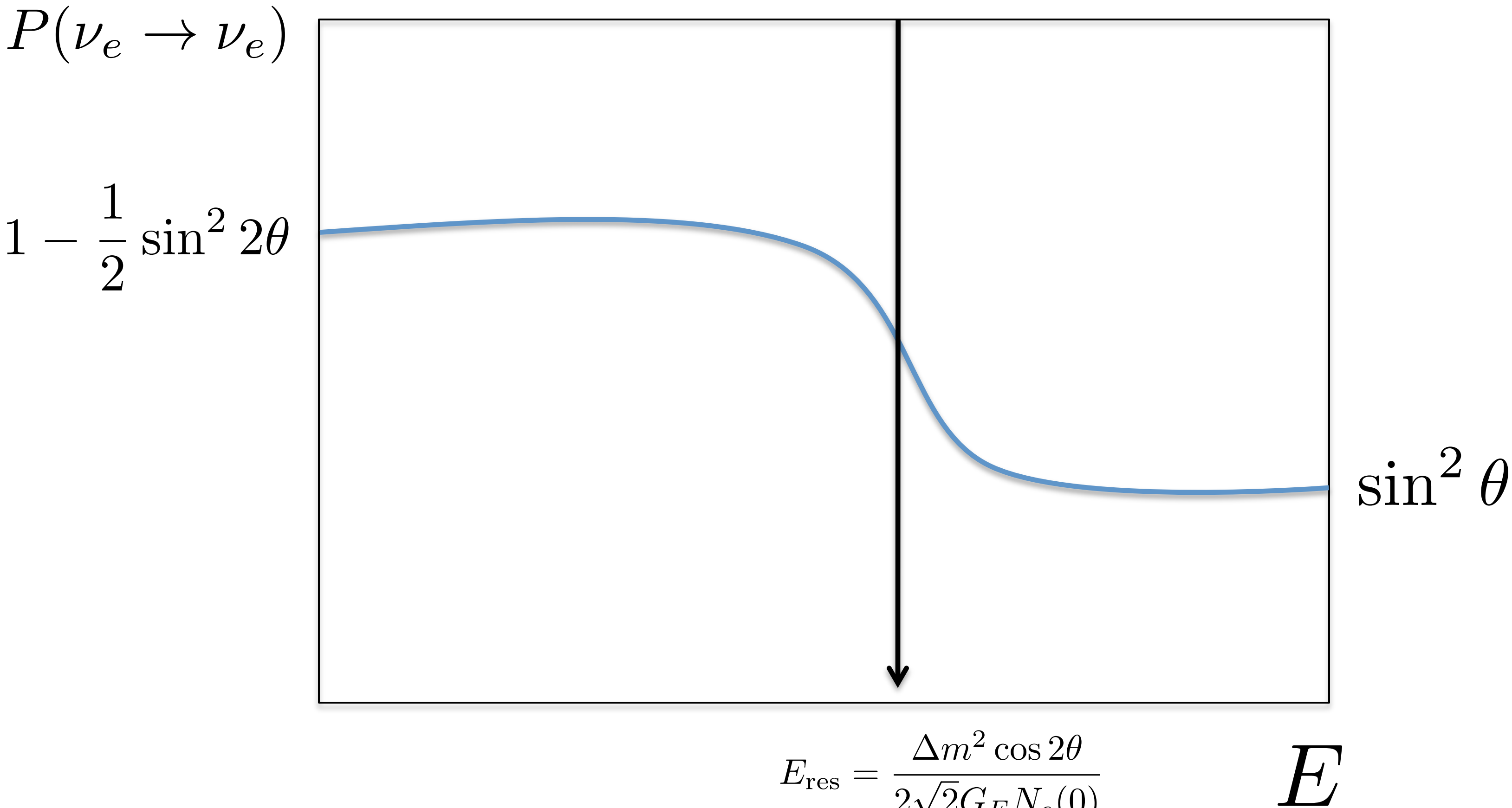
If the variation is slow enough: adiabatic approximation (if a state is at r=0 in an eigenstate $\tilde{m}_i^2(0)$ it remains in the i-th eigenstate until it exits the sun)

$$P(\nu_e \to \nu_e) = \sum_i |\langle \nu_e | \tilde{\nu}_i(\infty)\rangle|^2 |\langle \tilde{\nu}_i(0)|\nu_e\rangle|^2$$



$$P(\nu_e \to \nu_e) \simeq 1 - \frac{1}{2}\sin^2 2\theta \qquad P(\nu_e \to \nu_e) \simeq \sin^2\theta$$

Solar neutrinos



$$E_{\rm res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N_e(0)}$$

MSW resonance energy

In most physical situations: piece-wise constant matter or adiabatic approx. good enough

NEUTRINO PHYSICS

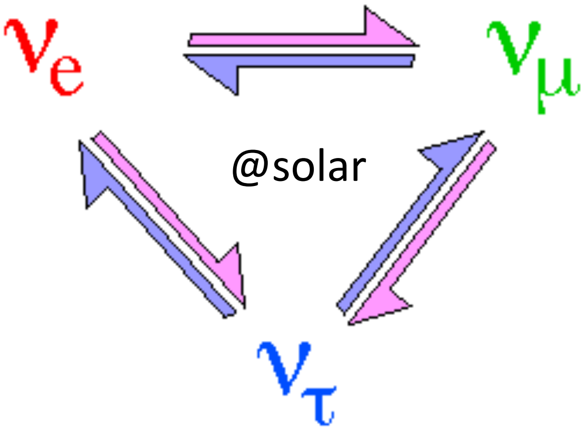
Lecture I :

- A bit of history: neutrinos in the Standard Model
- Neutrino masses and mixing : Majorana versus Dirac
- Neutrino oscillations in vacuum and in matter

Lecture II:

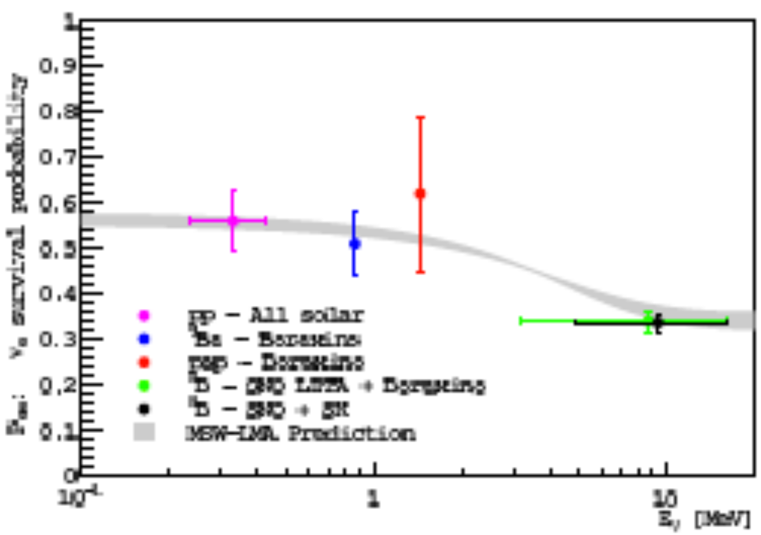
- **The standard 3ν scenario and a few outliers…**
- **Prospects in neutrino physics**

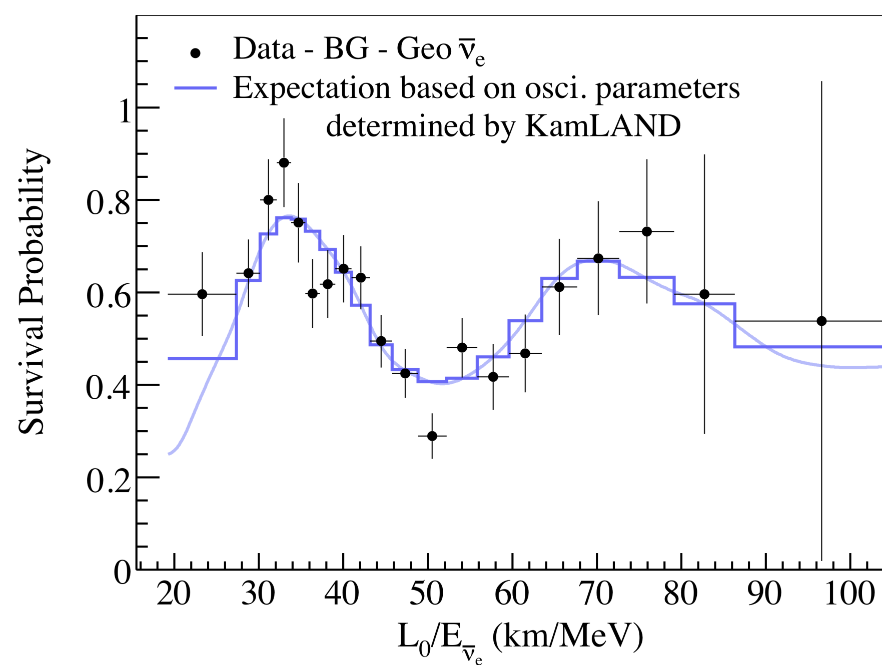
Solar oscillation of ν_e



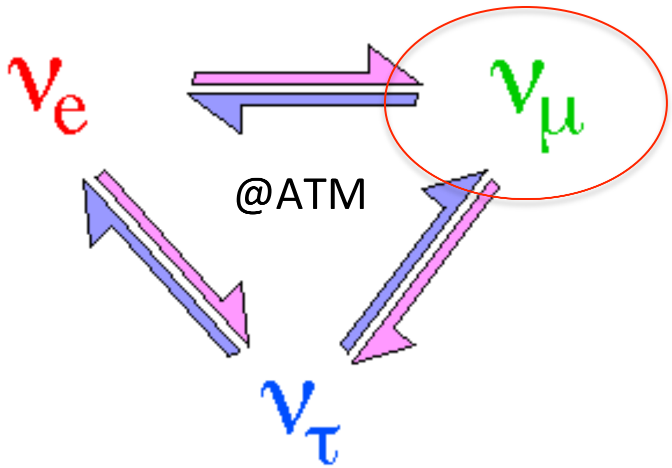
$$|\Delta m^2| \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(100km)}$$

MSW conversion in Sun

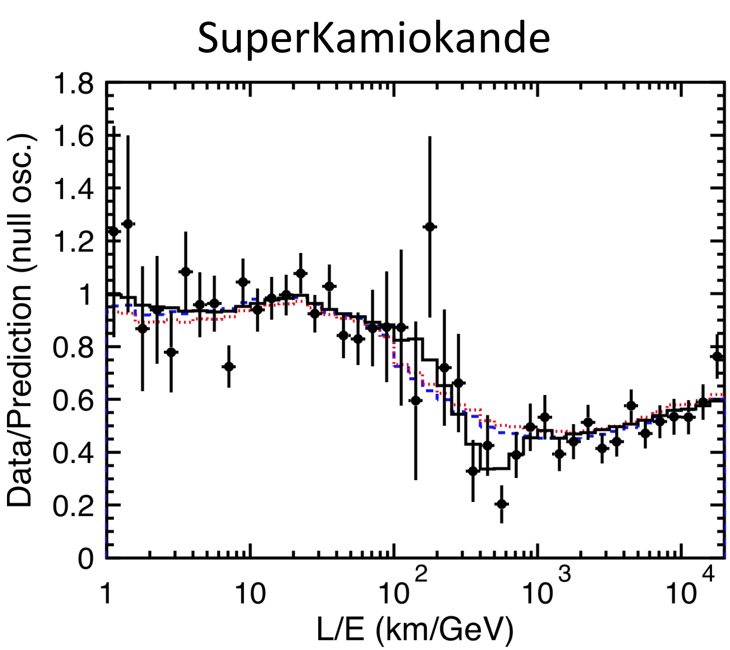


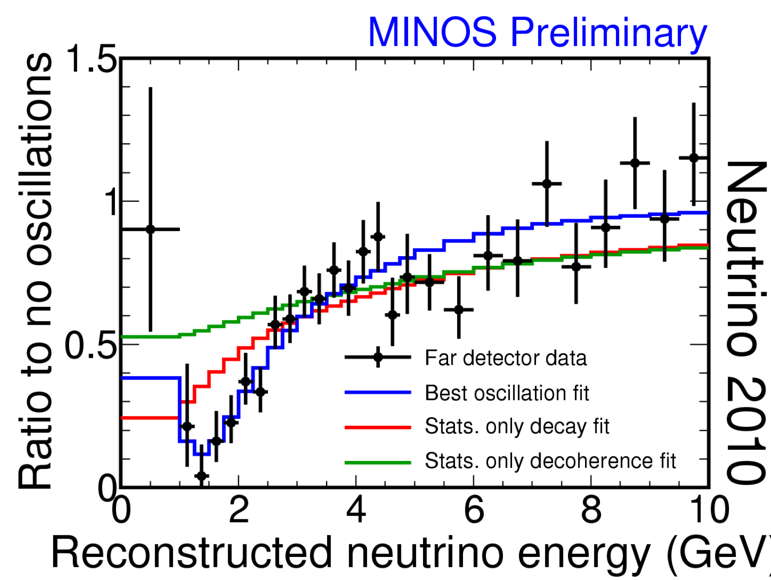


Atmospheric Oscillation of ν_μ

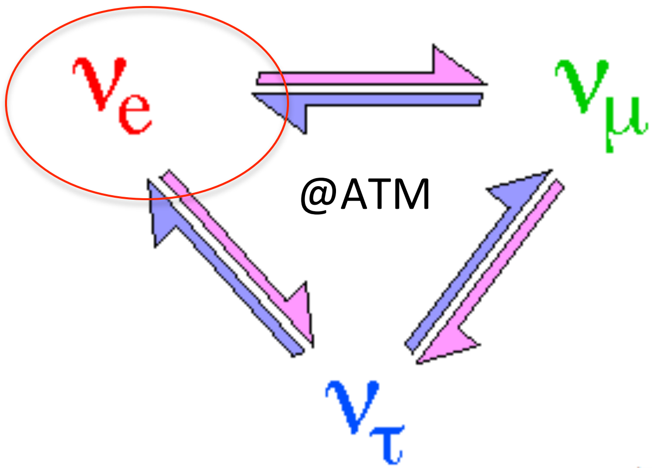


$$|\Delta m^2| \sim \frac{\mathcal{O}(GeV)}{\mathcal{O}(1000km)} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1km)}$$





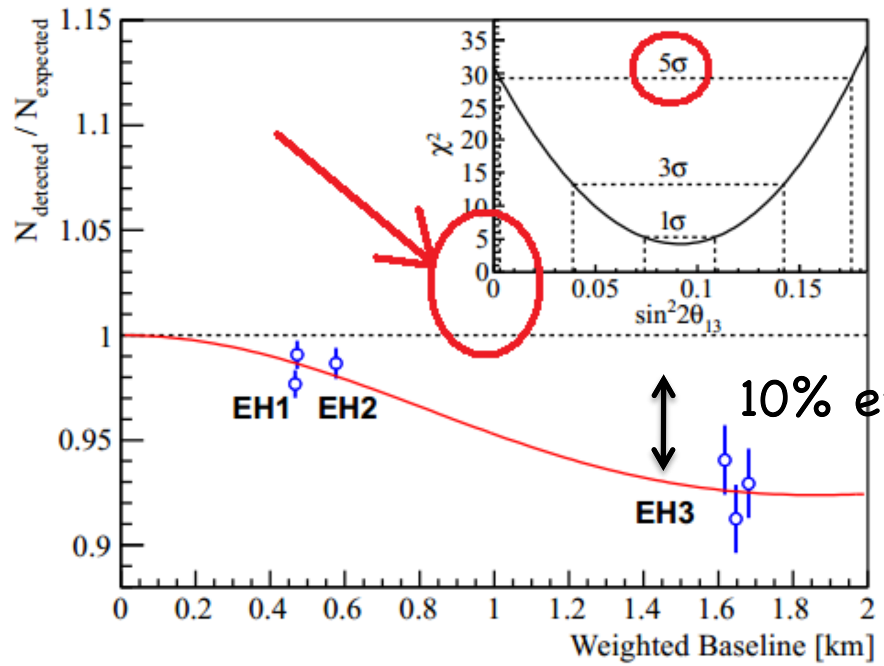
Atmospheric Oscillation of ν_e



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

2012

T2K, Double Chooz
Daya Bay, RENO



10% effect

Standard 3ν scenario

$$\Delta m^2_{23} = m^2_3 - m^2_2 \equiv \Delta m^2_{atm}$$

$$\Delta m^2_{12} = m^2_2 - m^2_1 \equiv \Delta m^2_{sol}$$

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

Solar and atmospheric osc. decouple as 2x2 mixing phenomena:

- hierarchy $\frac{|\Delta m^2_{atm}|}{|\Delta m^2_{sol}|} > 10$
- small θ_{13}

$$E_\nu/L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

Chooz

$$P(\nu_e \to \nu_\mu) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\nu_e \to \nu_\tau) = c^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\nu_\mu \to \nu_\tau) = c^4_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\bar\nu_e \to \bar\nu_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$ $\approx 1 \Rightarrow \theta_{13}=0$

$$E_\nu/L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

Chooz

$$P(\nu_e \to \nu_\mu) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \approx 0$$

$$P(\nu_e \to \nu_\tau) = c^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \approx 0$$

$$P(\nu_\mu \to \nu_\tau) = c^4_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\bar\nu_e \to \bar\nu_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \approx 1$$

Experiments in the atmospheric are described approximately by 2x2 mixing with

$$(\Delta m^2_{23}, \theta_{23}) = (\Delta m^2_{atm}, \theta_{atm})$$

$$E_\nu / L \sim \Delta m^2_{12} \ll \Delta m^2_{23}$$

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq c^4_{13} \left(1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{12}}{4E} L \right) \right) + s^4_{13}$$

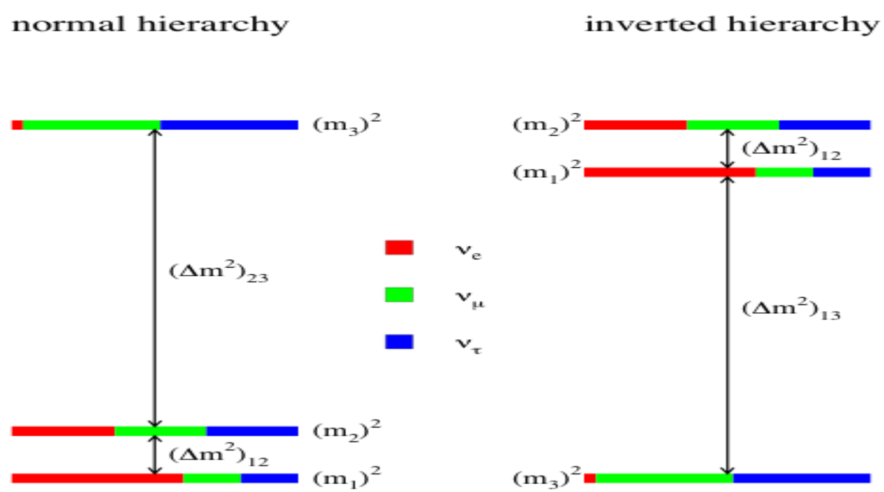
Experiments in the solar range are described approximately by 2x2 mixing with

$$(\Delta m^2_{12}, \theta_{12}) = (\Delta m^2_{\rm sol}, \theta_{\rm sol})$$

The measurement of $\theta_{13} \sim 9^\circ$ implies that corrections to these approximations are sizeable and need to be included in all analyses

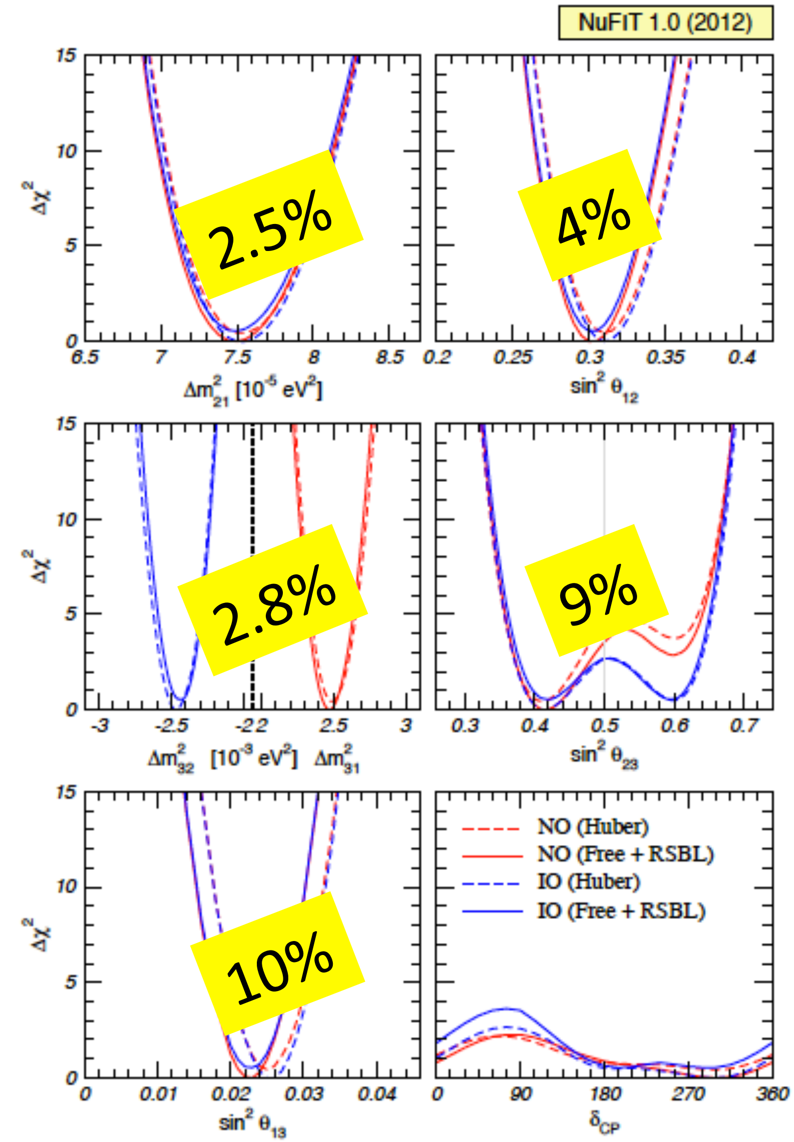
Standard 3ν scenario

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



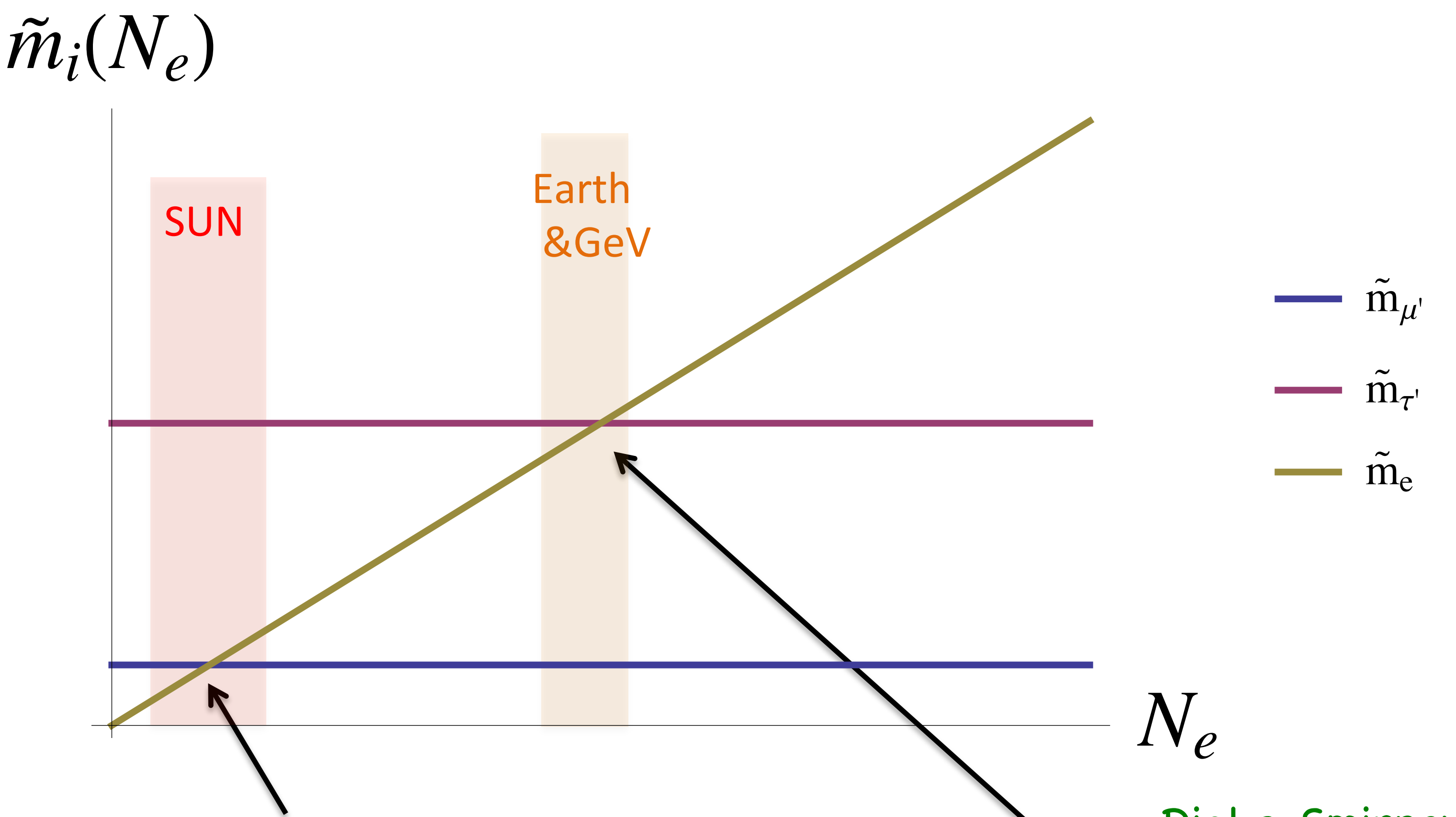
?

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



Gonzalez-Garcia et al 1209.3023

3ν in matter if NH



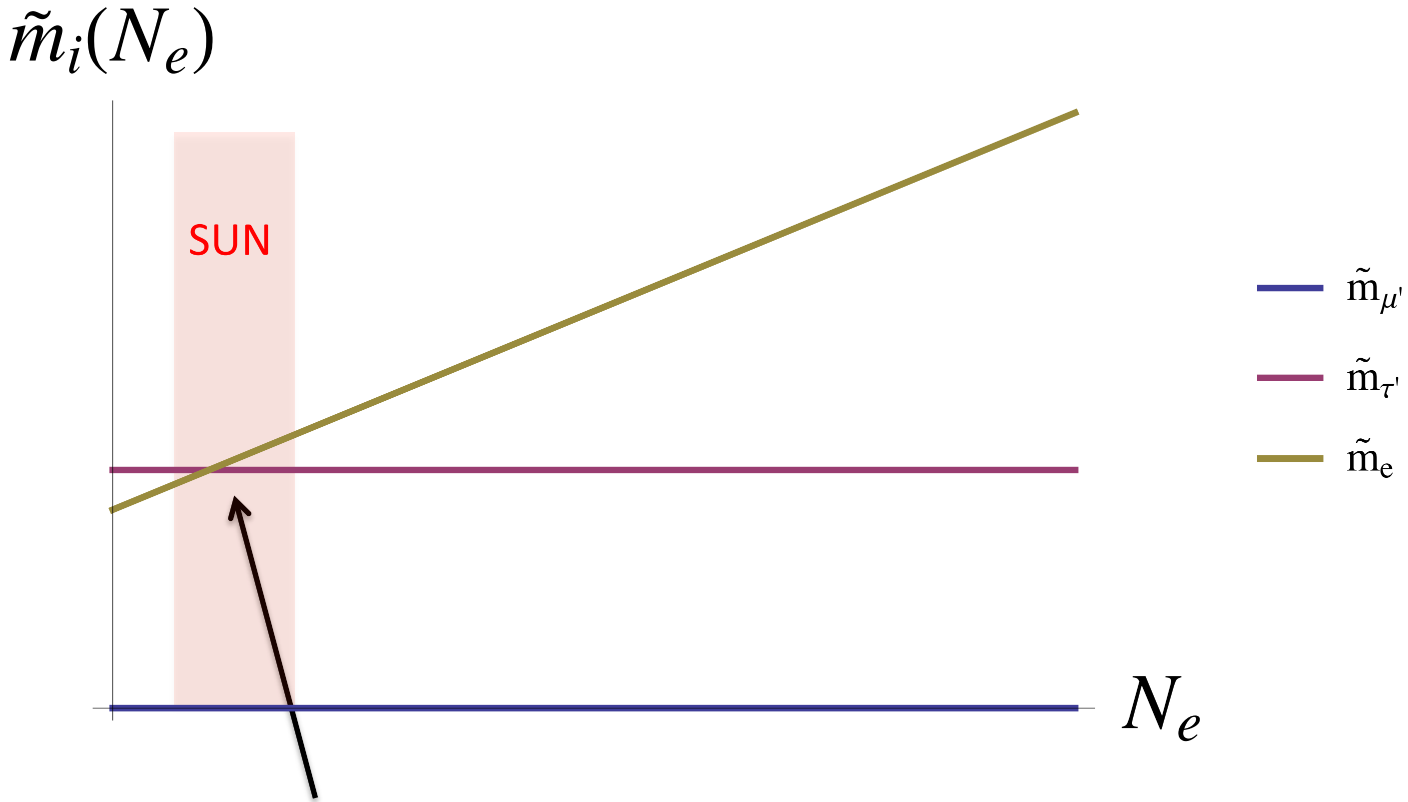
Solar resonance

$$\Delta m^2_{12} \cos 2\theta_{12} = 2\sqrt{2} G_F E N_e$$

Atmospheric resonance

$$\Delta m^2_{23} \cos 2\theta_{13} = \pm 2\sqrt{2} G_F E N_e$$

3ν in matter if IH



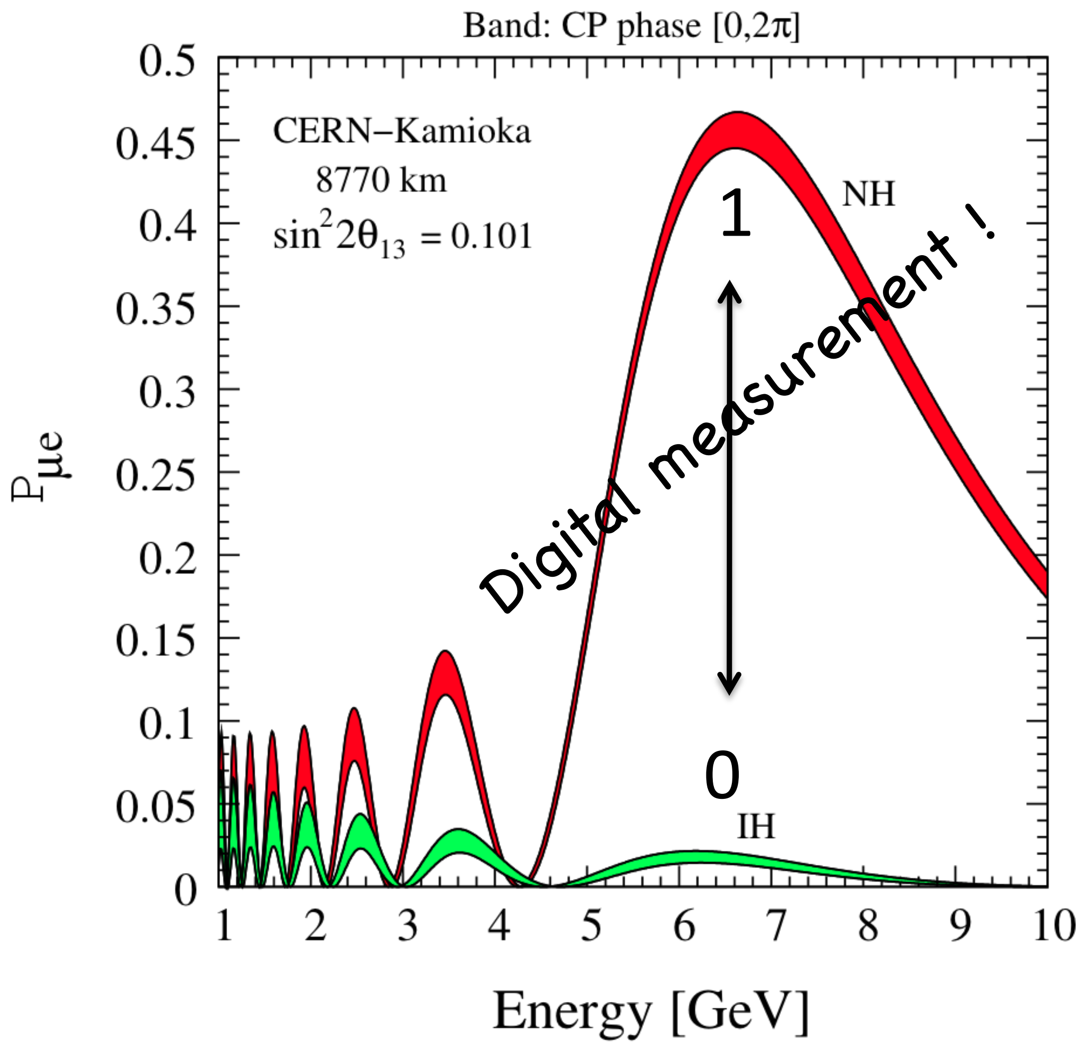
Only solar resonance

Dighe-Smirnov

$$\Delta m^2_{12} \cos 2\theta_{12} = 2\sqrt{2} G_F E N_e$$

Opposite situation for anti-neutrinos

Hierarchy through MSW



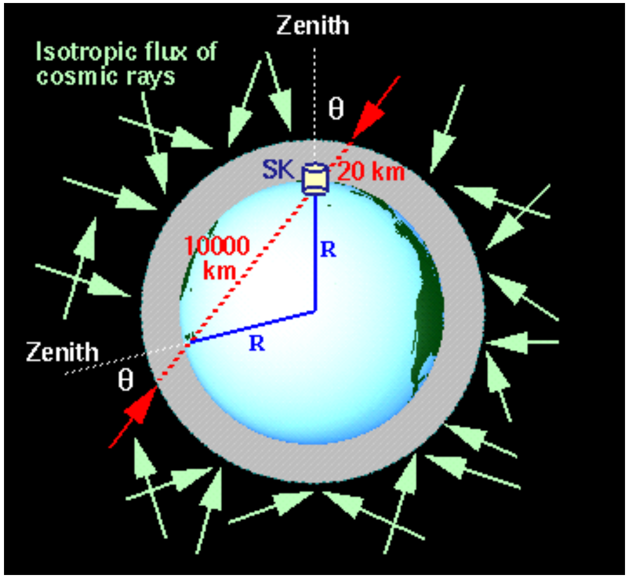
$$E_{\rm res} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F n_e},$$

$$n_e(L)L|_{L_{\rm max}} = \frac{\pi}{\sqrt{2} G_F \tan 2\theta_{13}}$$

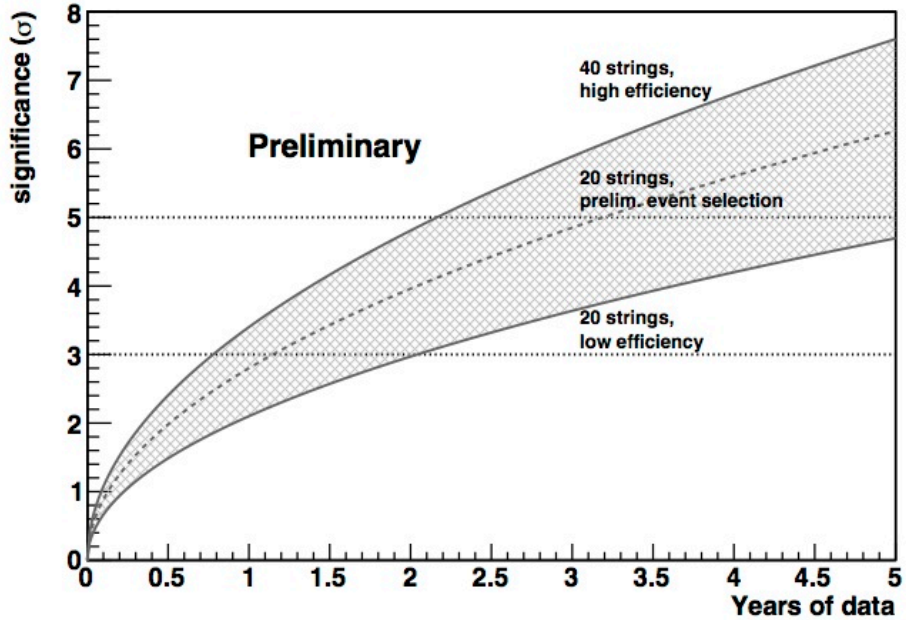
Spectacular MSW effect at O(6GeV) and very long baselines: no need for spectral info nor two channels

Hierarchy from atmospherics ?

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$



PINGU@ South Pole



Atmospheric data contain the golden signal but not so easy to dig...

Outliers: LSND anomaly

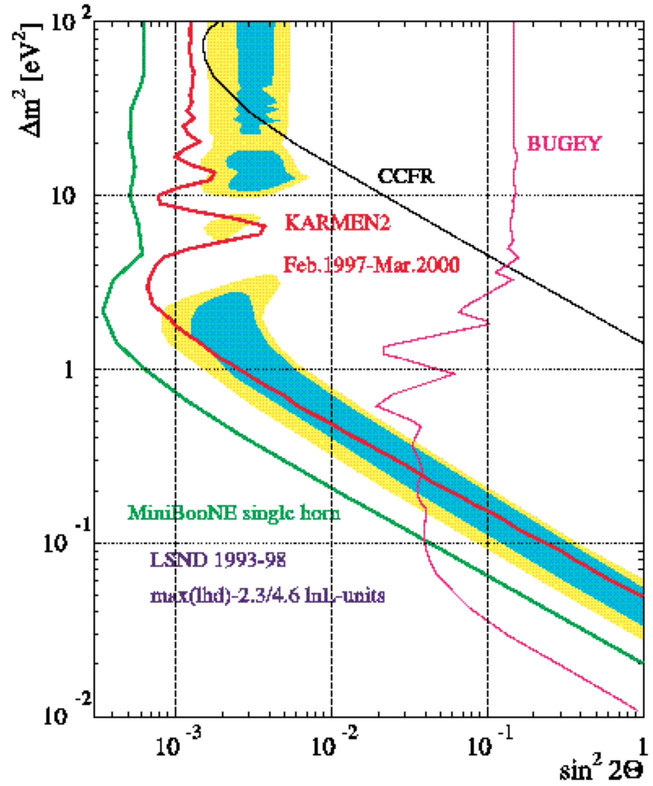
$$\pi^+ \to \quad \mu^+ \quad \nu_\mu$$
$$\nu_\mu \quad \to \nu_e \text{ DIF } (28 \pm 6/10 \pm 2)$$

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

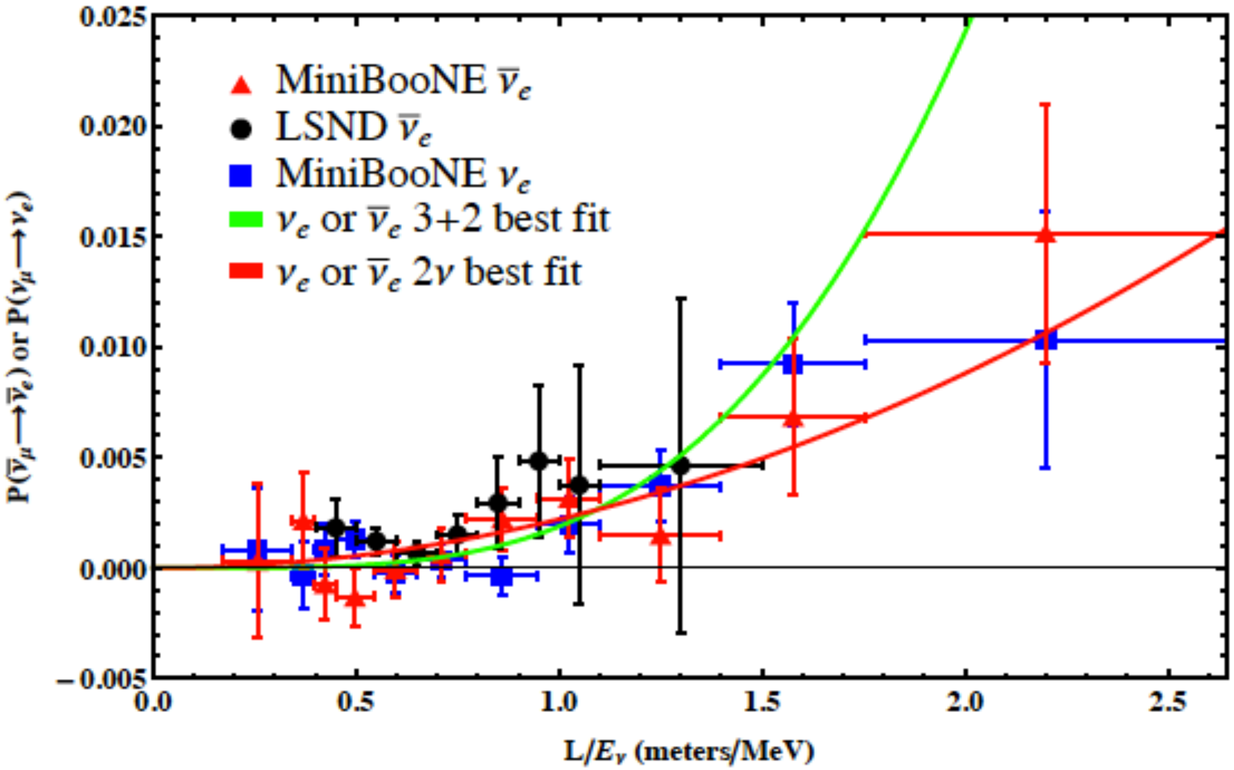
Appearance signal with very different

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

LSND vs KARMEN

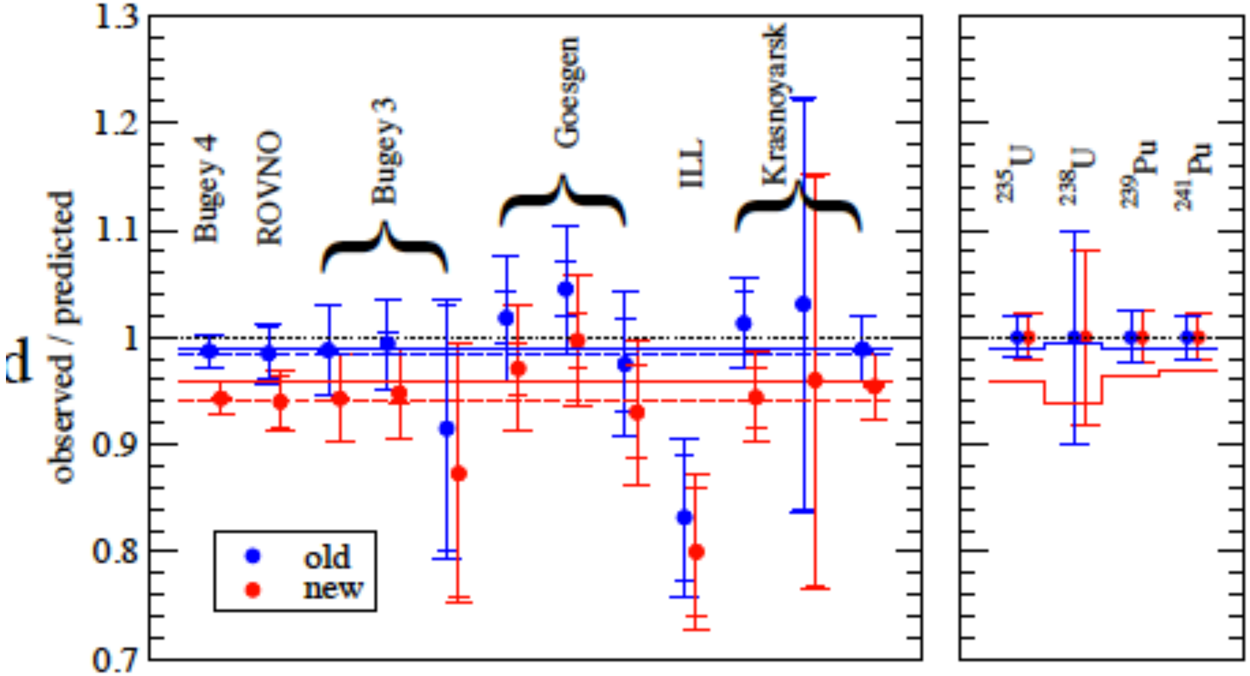


MINIBOONE



Extremely confusing situation!

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{4\times4} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_s' \end{pmatrix} = U_{5\times5} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \end{pmatrix}$$

Conrad et al; Kopp, et al; Giunti et al

New mass splitting:

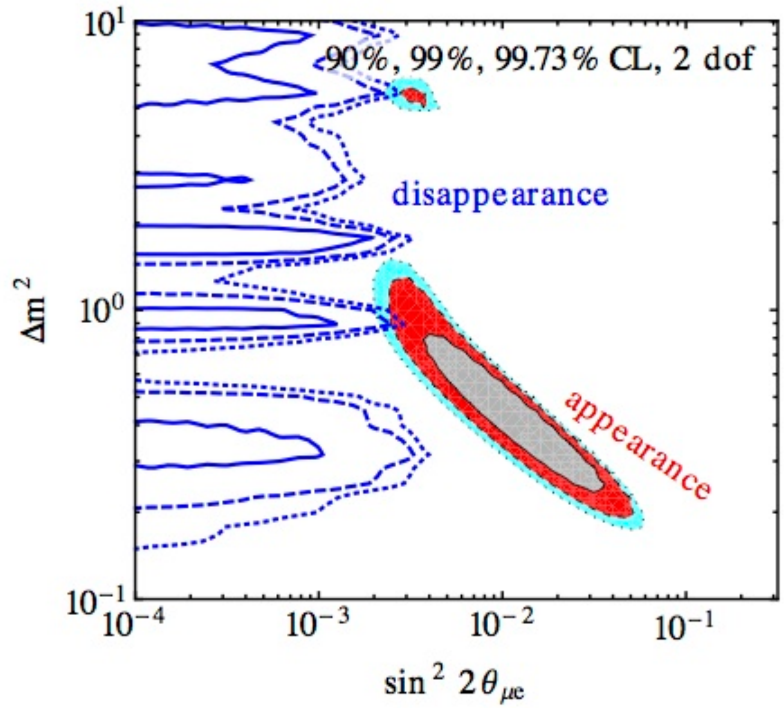
$$|\Delta m^2| \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1-10m)} \sim \frac{\mathcal{O}(1GeV)}{\mathcal{O}(1-10km)}$$

Significant improvement over 3ν scenario, but tension appearance/disappearance remains

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

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

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

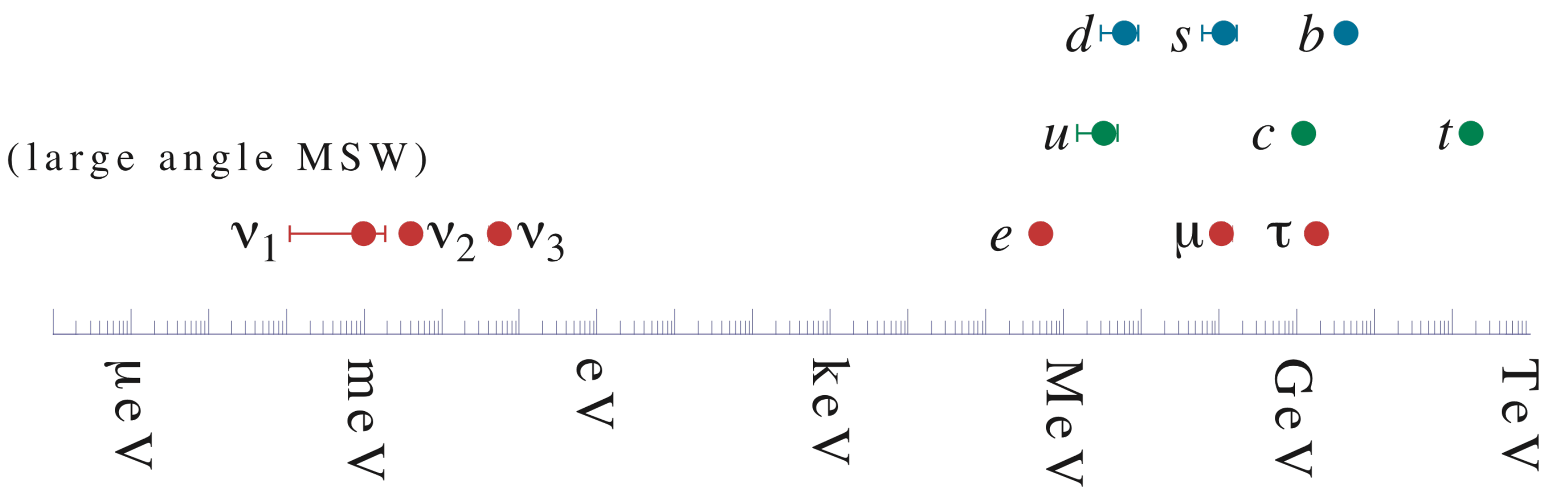


Kopp et al

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 ?



m_f

Why so different mixing ?

CKM

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

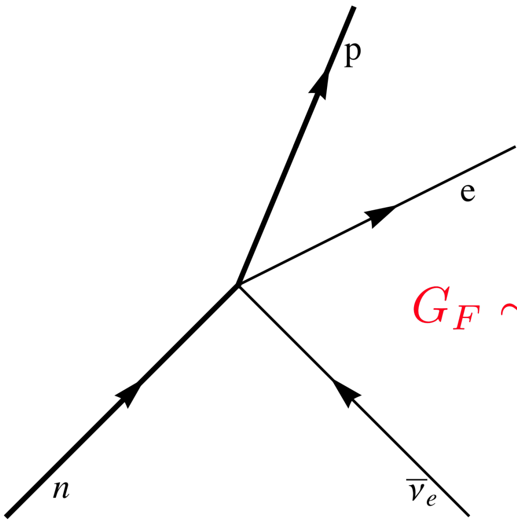
PMNS

3σ

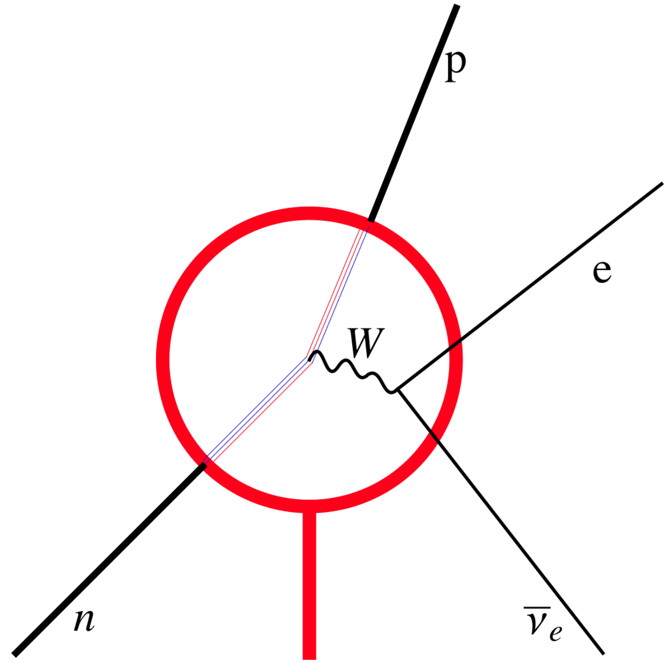
$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

Gonzalez-Garcia, et al 1209.3023

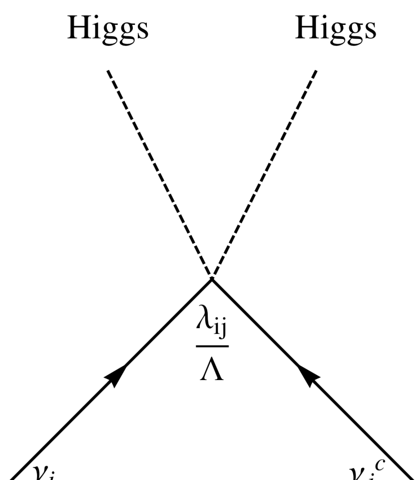
Neutrinos have tiny masses -> a new physics scale, what ?



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



SM

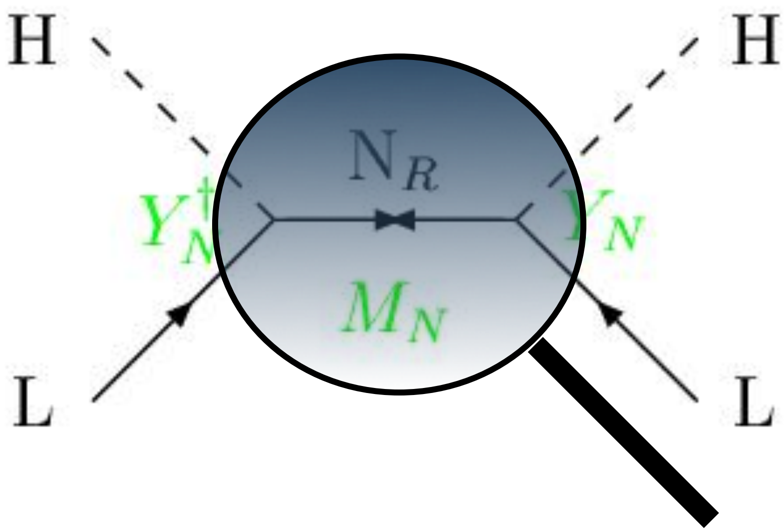


νSM ?

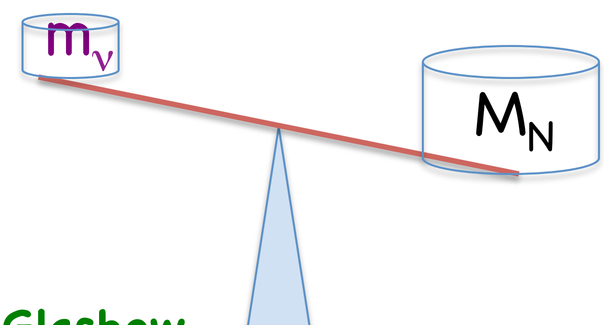
How does the ν scale relates to the EW scale ?

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

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



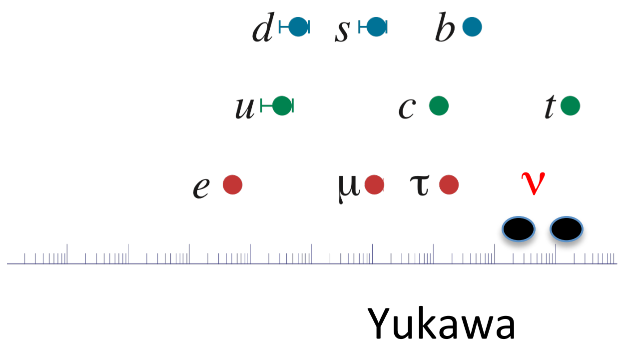
$$\frac{\lambda}{\Lambda} \equiv Y_N^T \frac{1}{M_N} Y_N$$



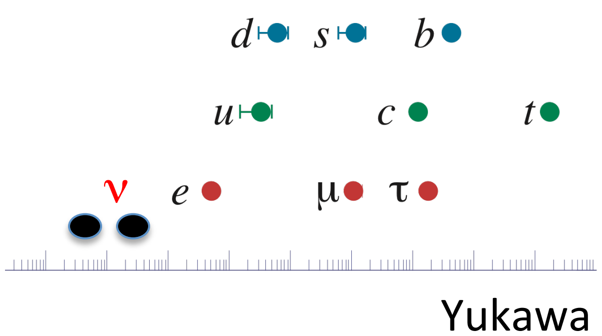
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow...

Charged/neutral hierarchy in seesaw (I)

M_N= GUT

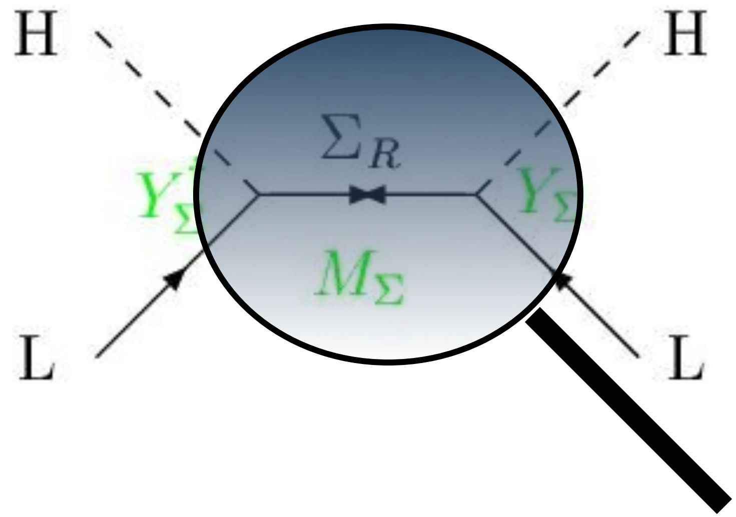


M_N= TeV



New physics scale

Type III see-saw: interchange a heavy triplet fermion

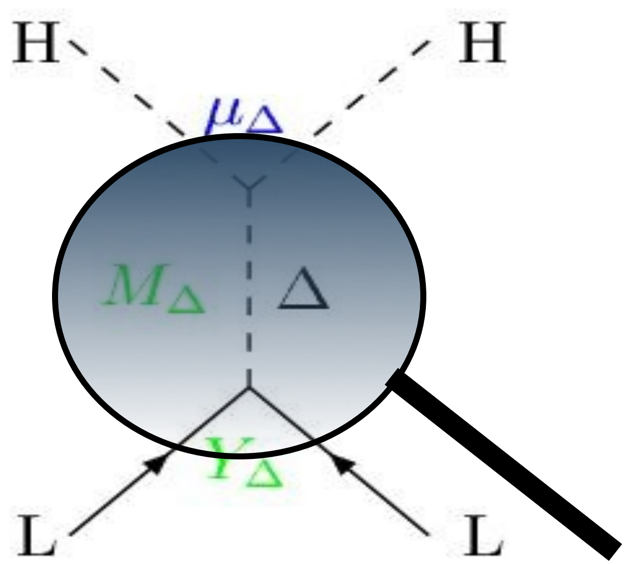


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

Foot et al; Ma; Bajc, Senjanovic...

New physics scale

Type II see-saw: interchange a heavy triplet scalar



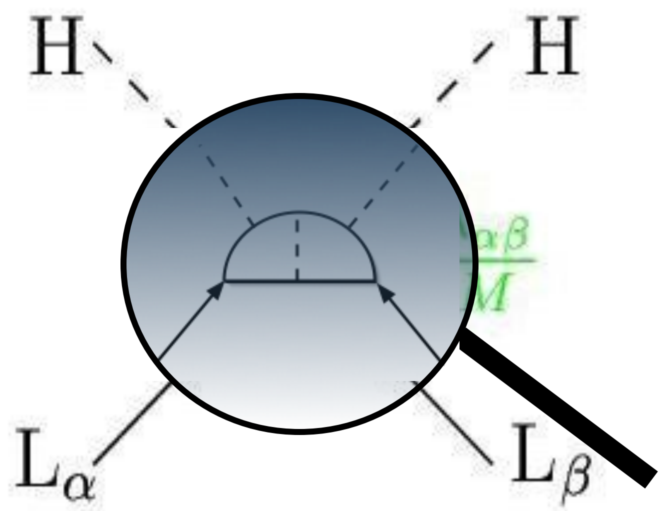
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

New physics scale

Also from loops !

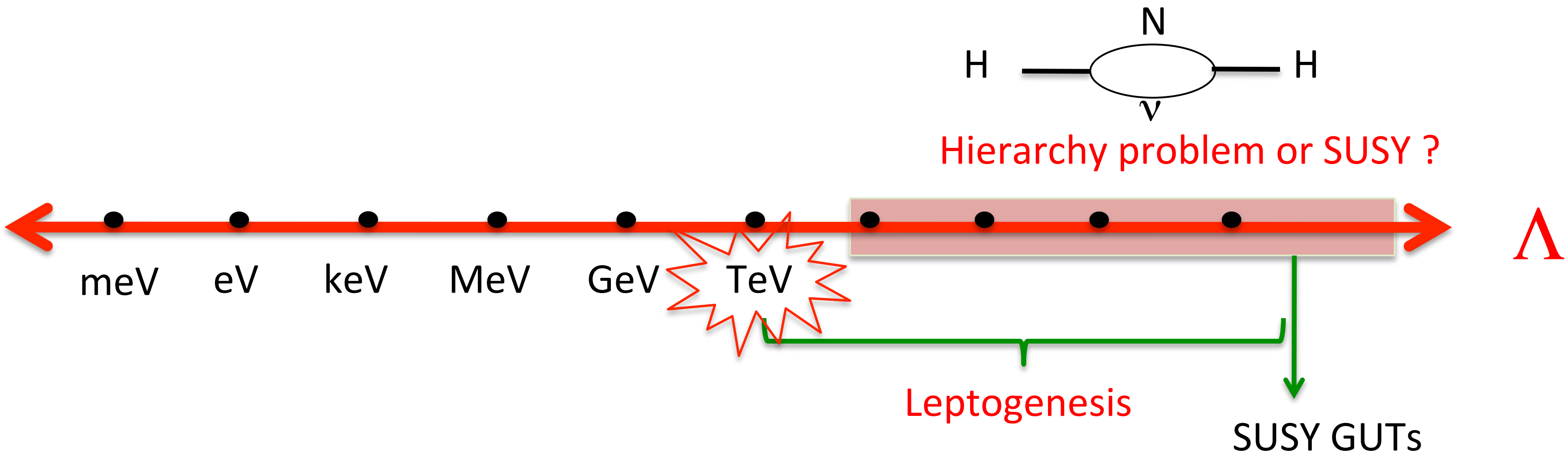
Zee-Babu



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

Pinning down the New physics scale

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



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

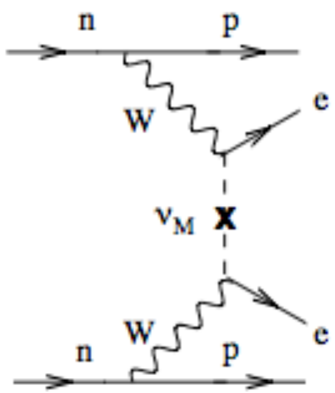
there is neutrinoless double beta decay at some level ($\Lambda > 100$MeV)

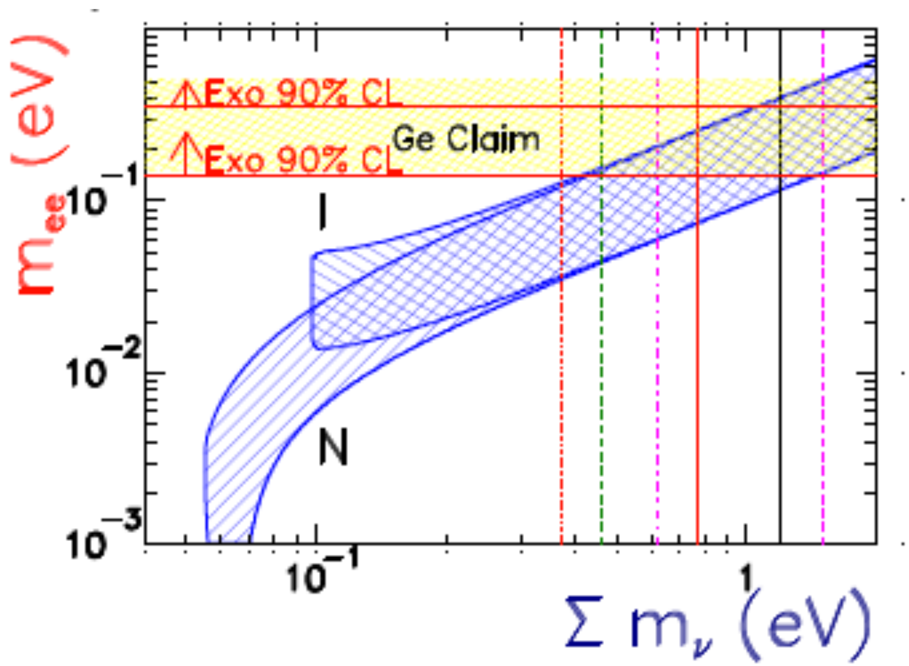
a matter-antimatter asymmetry if there is CP violation in the lepton sector !

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%)

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

Leptonic CP violation (in vacuum)

$$E_\nu / L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

$$\begin{aligned} P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} &= s^2_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta_{23} L}{2} \right) && \equiv P^{atmos} \\ &+ c^2_{23} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta_{12} L}{2} \right) && \equiv P^{solar} \\ +\tilde{J} & \cos \left(\pm\delta - \frac{\Delta_{23} L}{2} \right) \frac{\Delta_{12} L}{2} \sin \left(\frac{\Delta_{23} L}{2} \right) && \equiv P^{inter} \end{aligned}$$

$$\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

$$\Delta_{ij} \equiv \frac{m_j^2 - m_i^2}{2E}$$

Leptonic CP violation (in vacuum)

$$E_\nu/L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

$$\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} \;&=\; s^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta_{23}\,L}{2}\right) && \equiv P^{atmos} \\
&+\; c^2_{23}\,\sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta_{12}\,L}{2}\right) && \equiv P^{solar} \\
+\tilde J \quad & \cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right)\,\frac{\Delta_{12}\,L}{2}\,\sin\left(\frac{\Delta_{23}\,L}{2}\right) && \equiv P^{inter}
\end{aligned}$$

$$\tilde J \equiv c_{13}\;\sin 2\theta_{13}\;\sin 2\theta_{12}\;\sin 2\theta_{23} \qquad\qquad \Delta_{ij} \equiv \frac{m^2_j - m^2_i}{2E}$$

Golden Channel in matter

Octant dependence

Hierarchy dependence

In matter:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$

$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\sin\left(\frac{AL}{2}\right)\frac{\Delta_{13}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)$$

$$\tilde{J} \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23} \qquad B_\pm \equiv \sqrt{2}G_F n_e \pm \Delta_{13}$$

Cervera et al; Freund et al

Parameter degeneracies (eg. neutrino hierarchy, octant) compromise δ sensitivity

Burguet et al;Minakata, Nunokawa;Barger, et al

Golden Channel in matter

Octant dependence

Hierarchy dependence

In matter:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

$$+ \tilde{J} \frac{\Delta_{12}}{A} \sin(\frac{AL}{2}) \frac{\Delta_{13}}{B_\pm} \sin\left(\frac{B_\pm L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

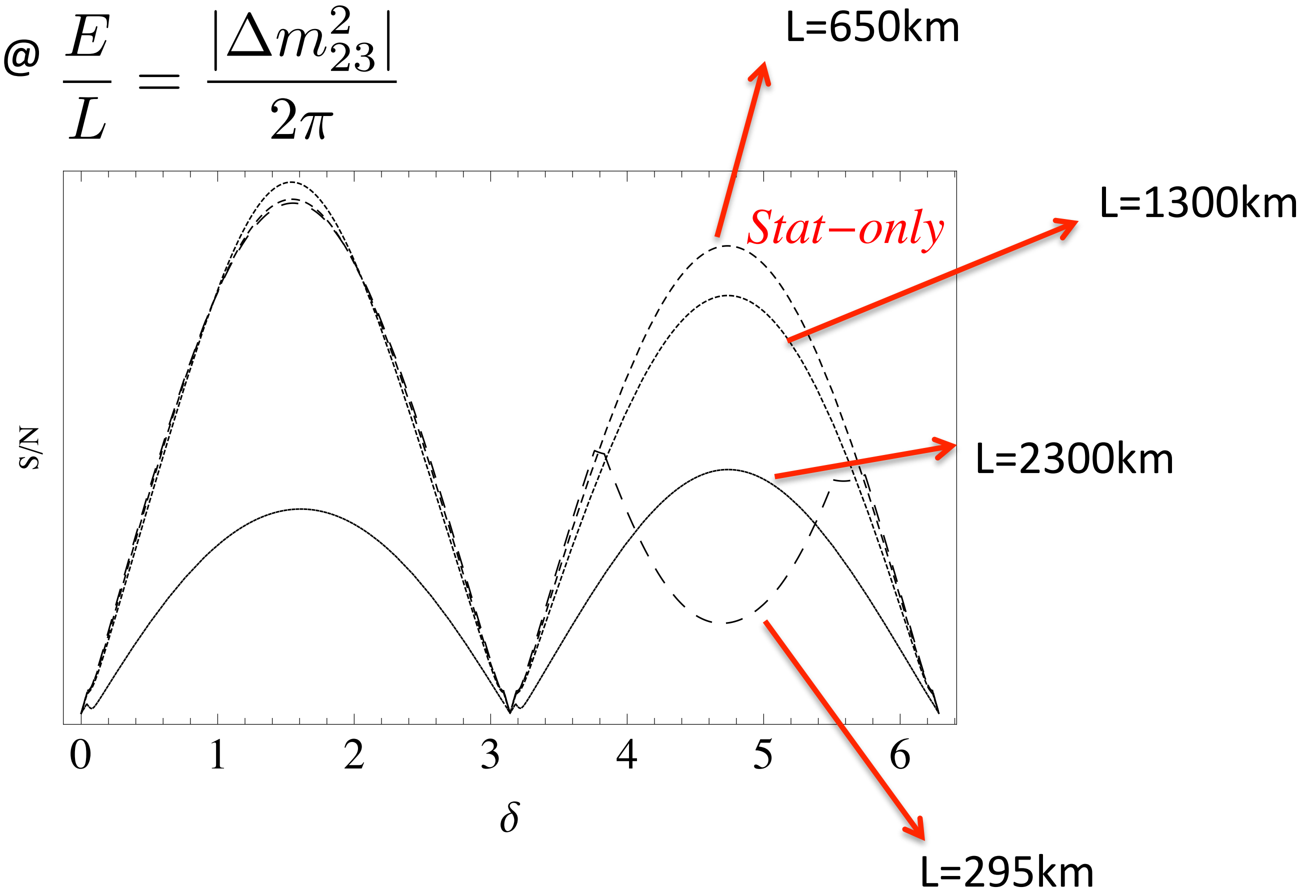
$$\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \qquad B_\pm \equiv \sqrt{2} G_F n_e \pm \Delta_{13}$$

Cervera et al

Parameter degeneracies (eg. neutrino hierarchy, octant) compromise δ sensitivity

Burguet et al; Minakata, Nunokawa;Barger, et al

$$@\ \frac{E}{L} = \frac{|\Delta m^2_{23}|}{2\pi}$$



Naive scaling of S/N assuming statistical errors dominate …
But systematics could change this conclusion…

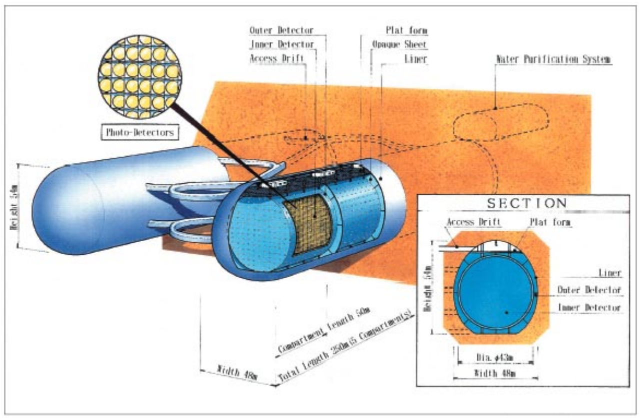
To maximize sensitivity to CP violation don't go too far

Hierarchy + CP in one go…

Three concrete superbeam proposals (to be ready in 10y)

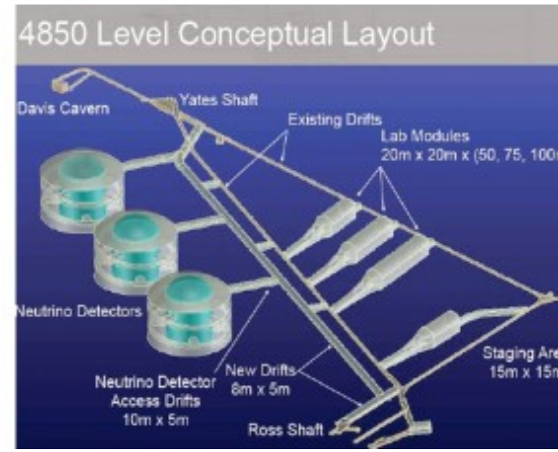
$p \rightarrow \text{Target} \rightarrow K,\pi\ \ \nu_\mu,\ \%\ \nu_e$

HyperK (Japan)



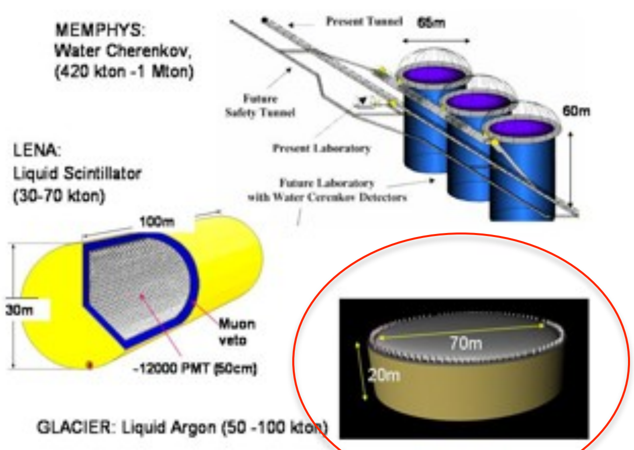
750MW, 560kton WC, Tokai-Kamioka (295km)

LBNE (USA)



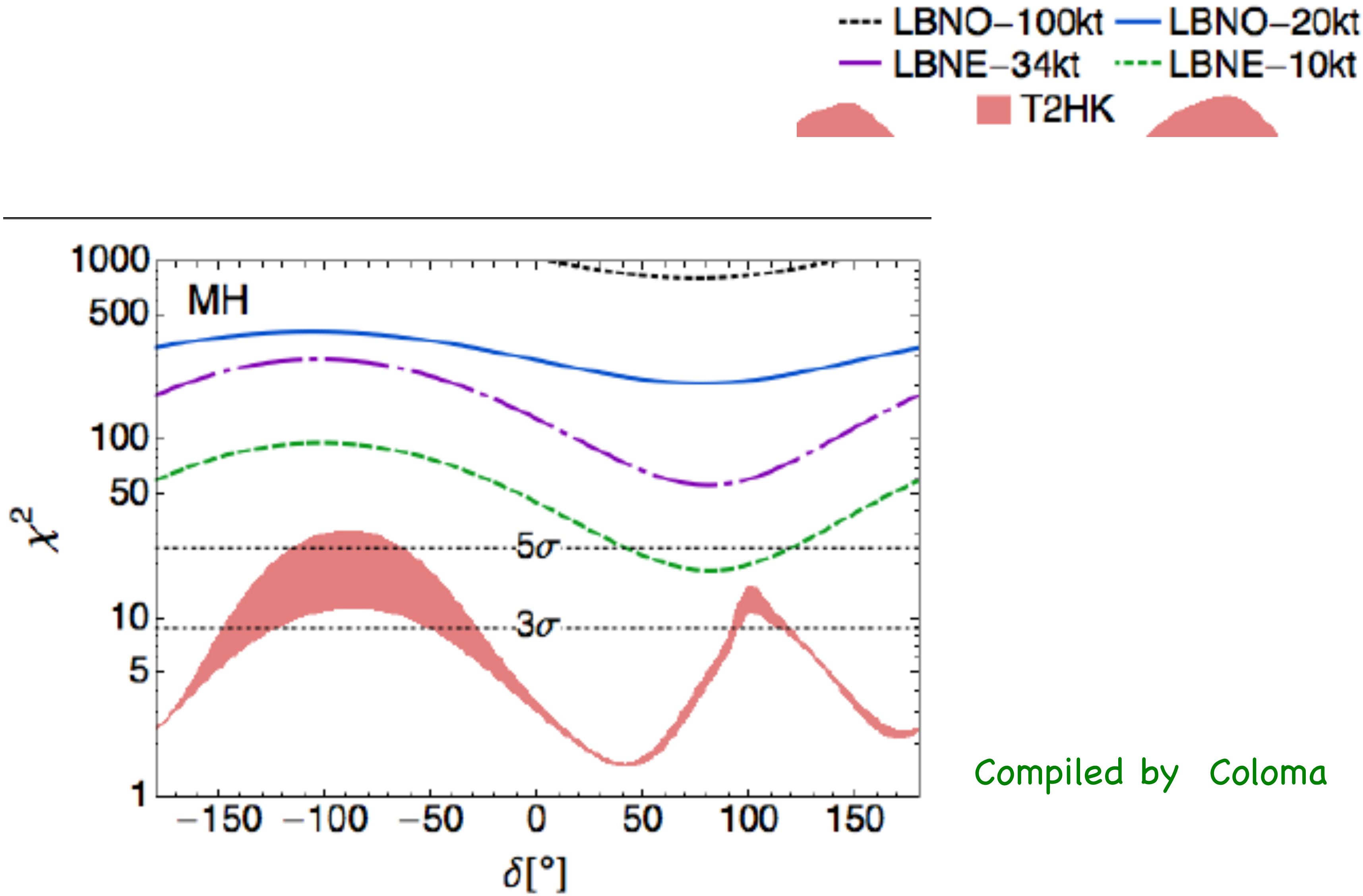
800MW, 10kton-> 35kton LAr,
Fermilab-Homestake(1300km)

LBNO (Europe)



800MW, 20kton-> 100kton LAr, CERN-Pyhäsalmi (2300km)

In 20 years from now with conventional beams…

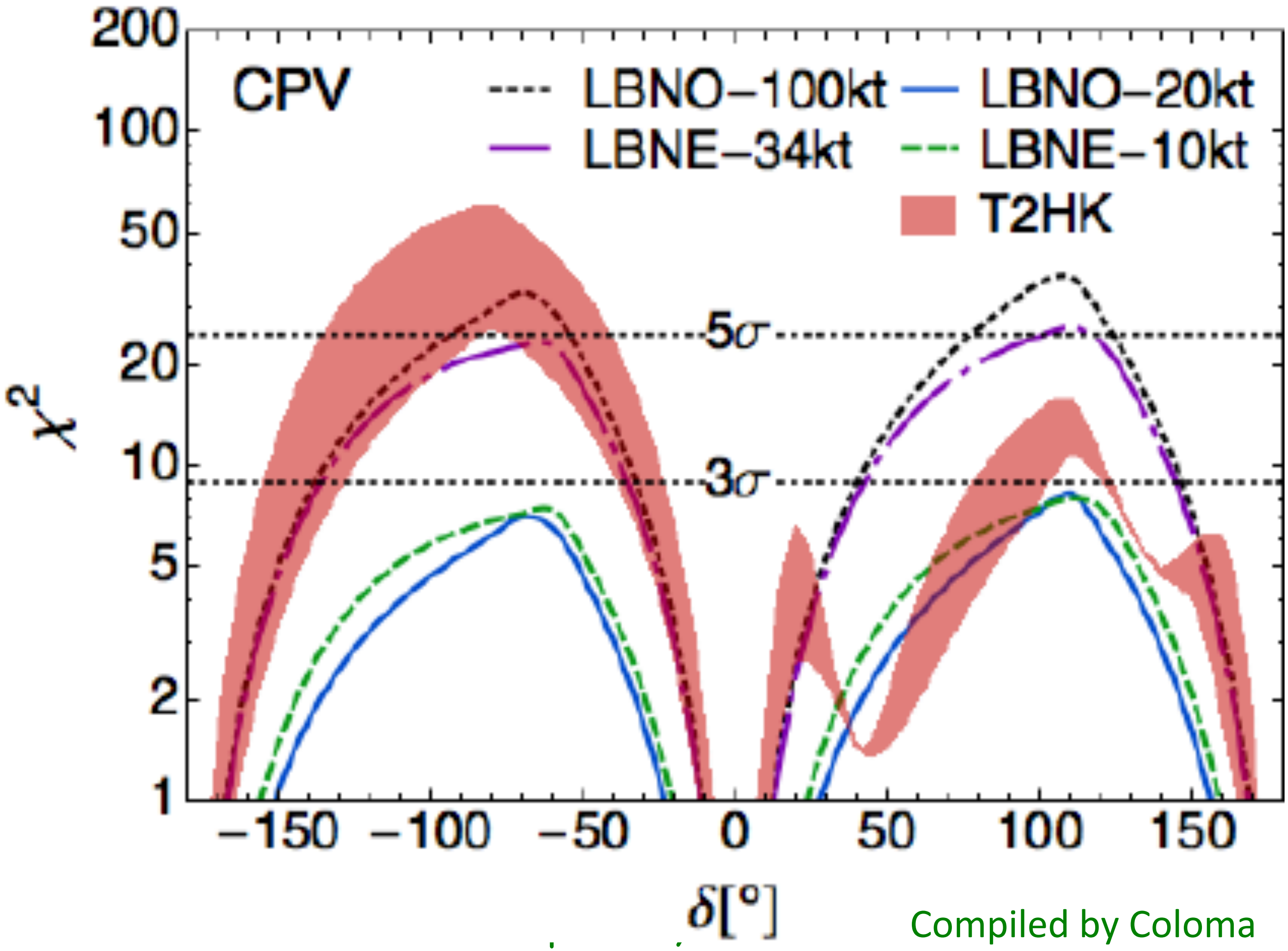


Compiled by Coloma

O(10kton) LAr can do the job easily

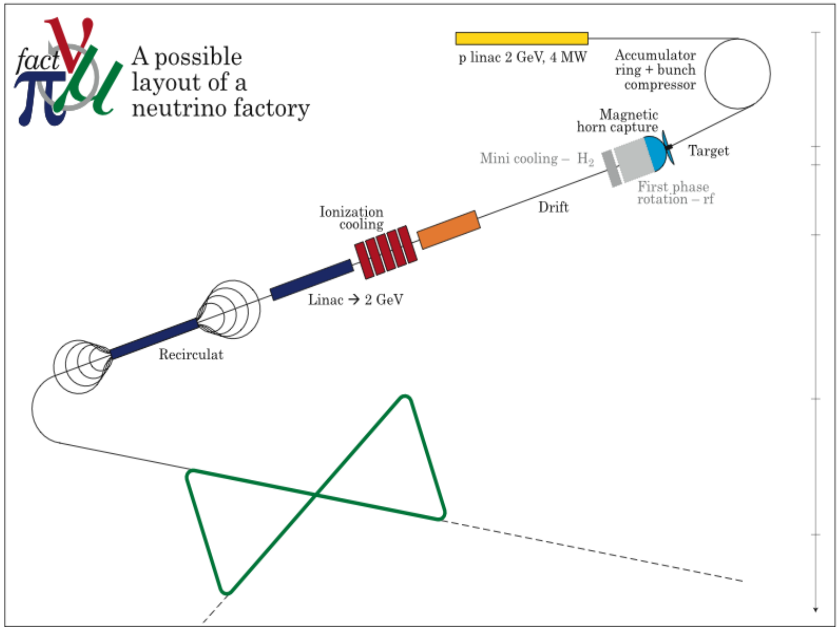
In 20 years from now with conventional beams…

Hierarchy unknown



Compiled by Coloma

Neutrino factory



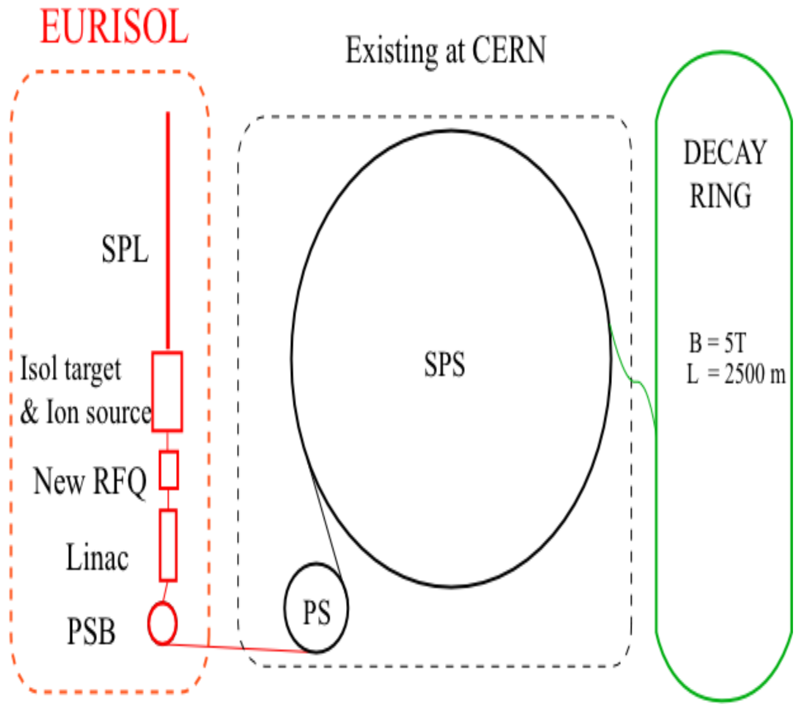
From μ decays

$$\mu^- \longrightarrow e^- \quad \nu_\mu \quad \bar{\nu}_e\,;$$

$$\bar{\nu}_e \longrightarrow \bar{\nu}_\mu \longrightarrow \mu^+$$

$$\nu_\mu \longrightarrow \nu_\mu \longrightarrow \mu^-$$

β beam

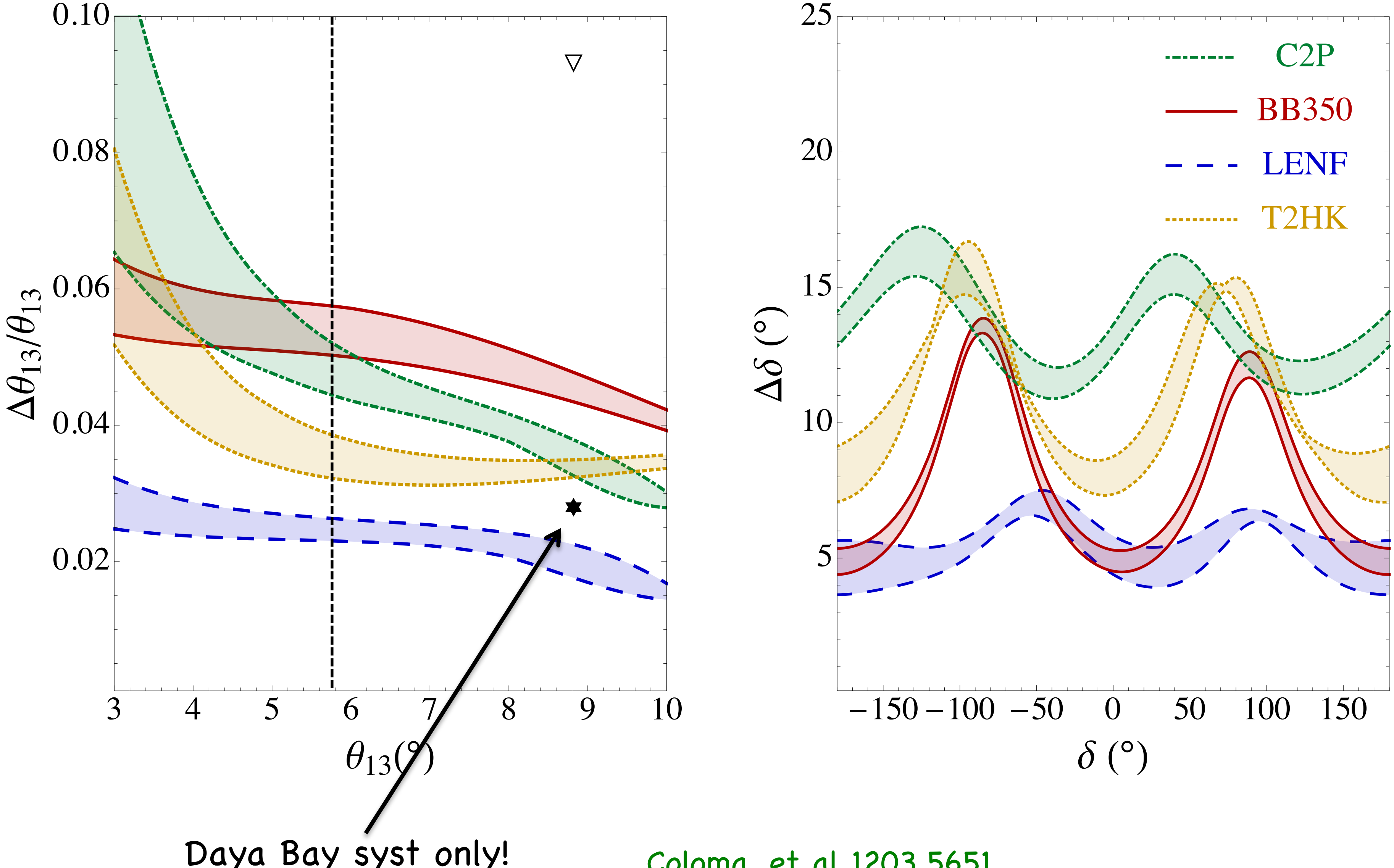


From radioactive ions

$${}^6He^{++} \longrightarrow {}^6_3Li^{+++}\; e^- \quad \bar{\nu}_e$$

$$\bar{\nu}_e \longrightarrow \bar{\nu}_\mu \longrightarrow \mu^+$$

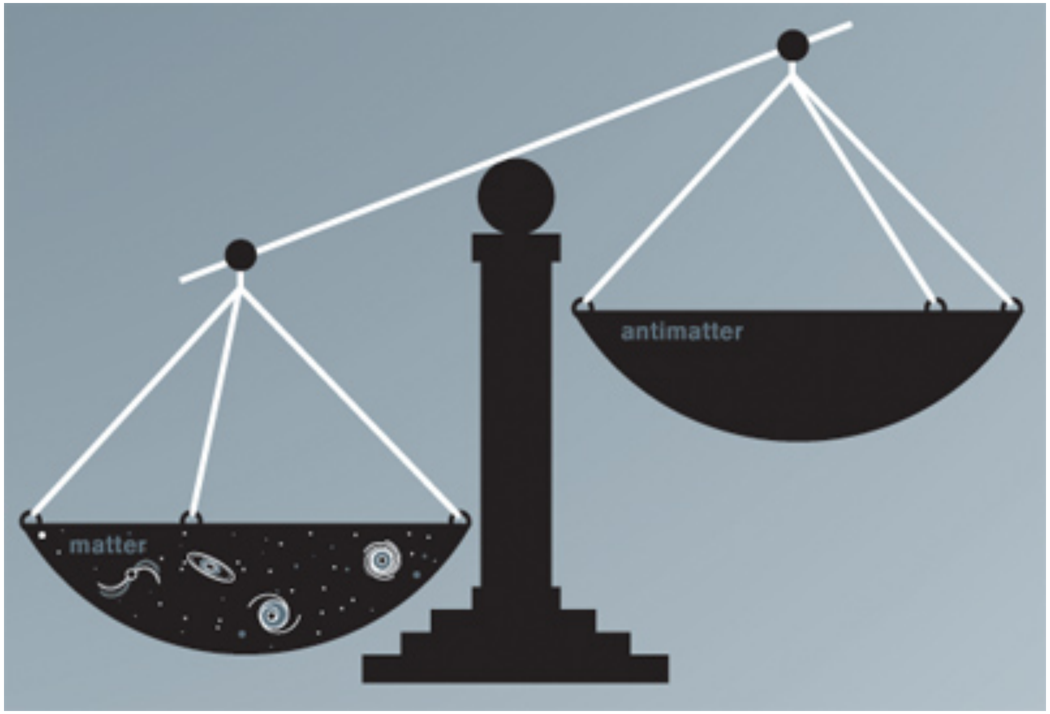
With better beams in XX years...



Coloma, et al 1203.5651

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)

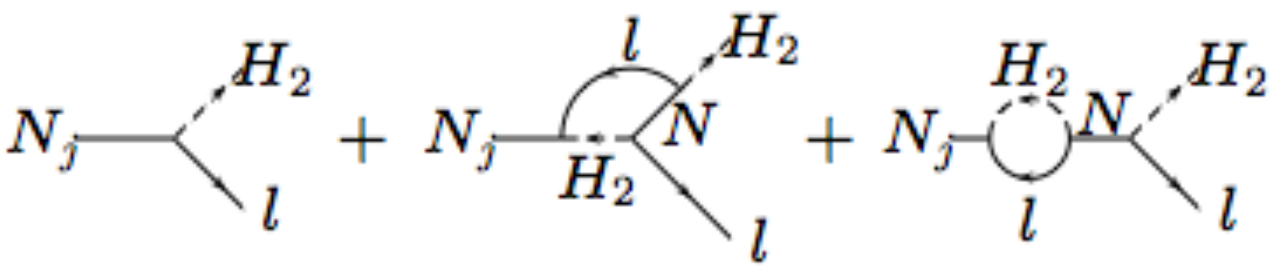
It does not seem to work in the SM with massless neutrinos ...

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...

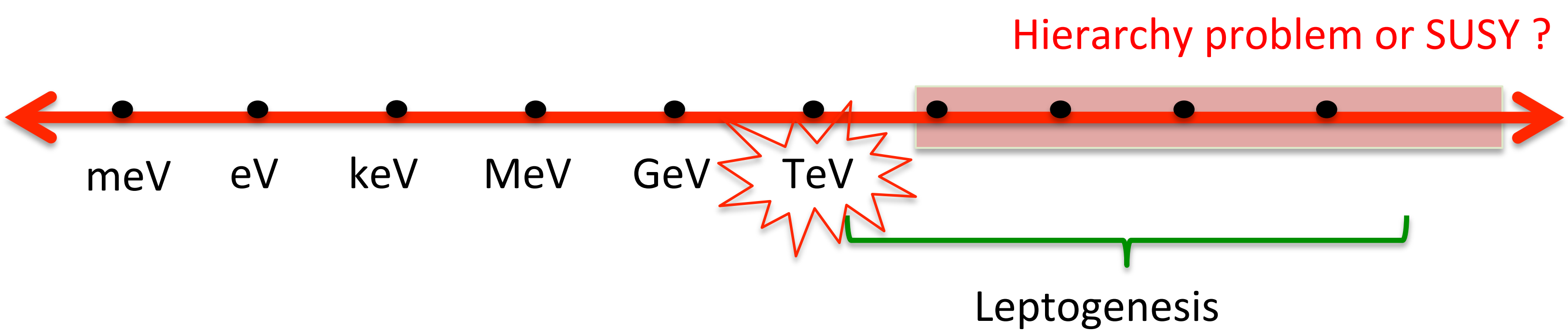
Counting physical parameters in lepton mixing (seesaw I)

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

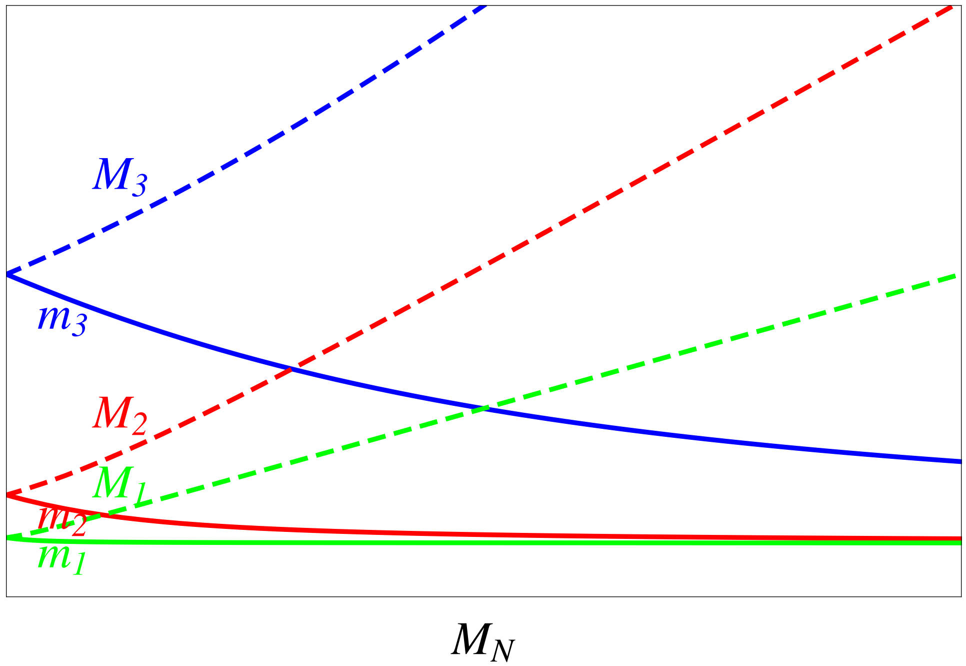
	Yukawas	**Field. Red.**	**Symmetries**	**Physical**
	Y_ν , Y_l, M	$U_L(n)xU_{lR}(n)xU_{\nu R}(n)$	0	
Moduli	$2n^2+n(n+1)/2$	3n(n-1)/2	0	3n+n(n-1)
Phases	$2n^2+n(n+1)/2$	3n(n+1)/2	0	n(n-1)

For n=3: 9 masses, 6 angles, 6 phases

Other states out there…



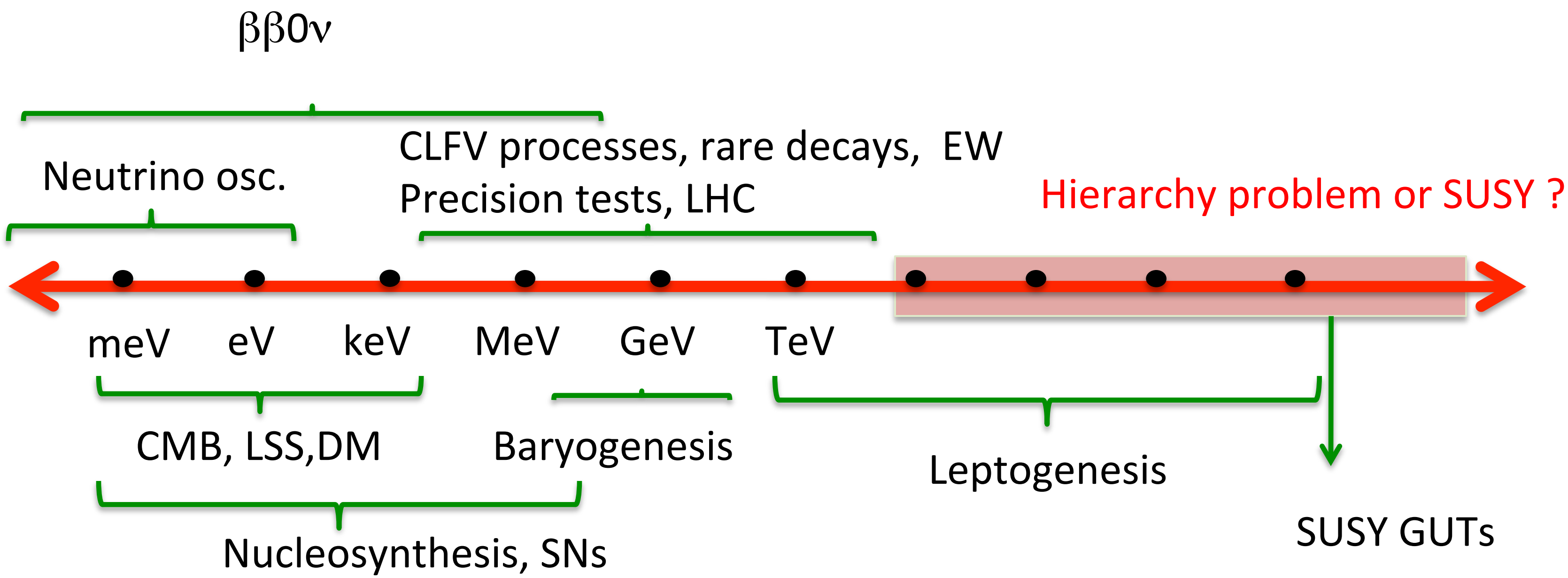
Low scale Type I seesaw models



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

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

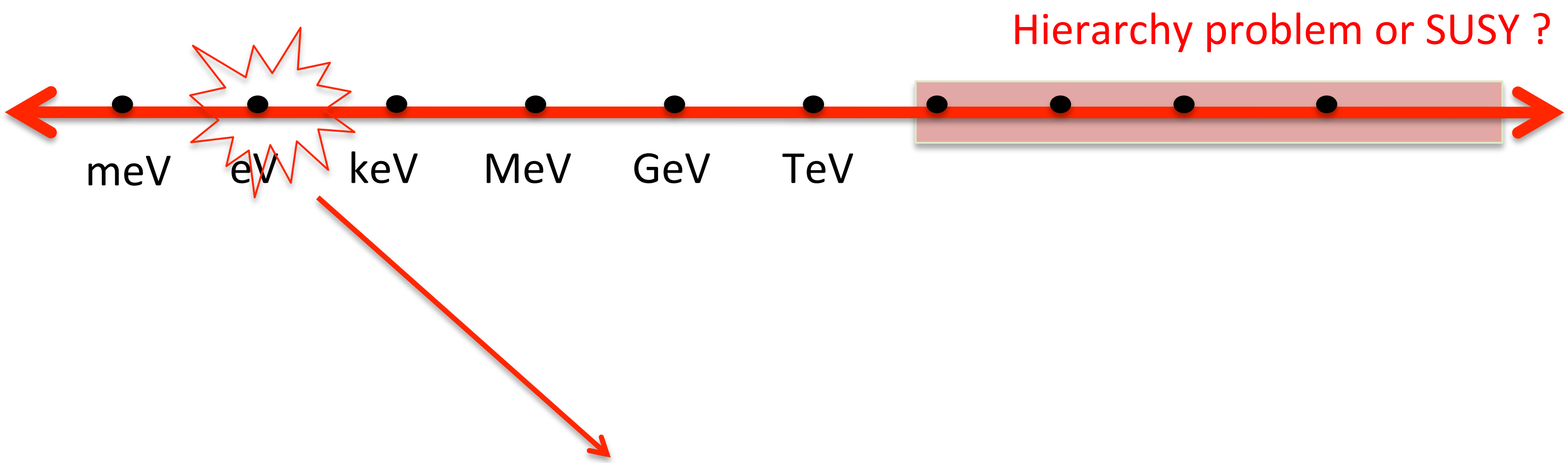
Other states out there ?



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

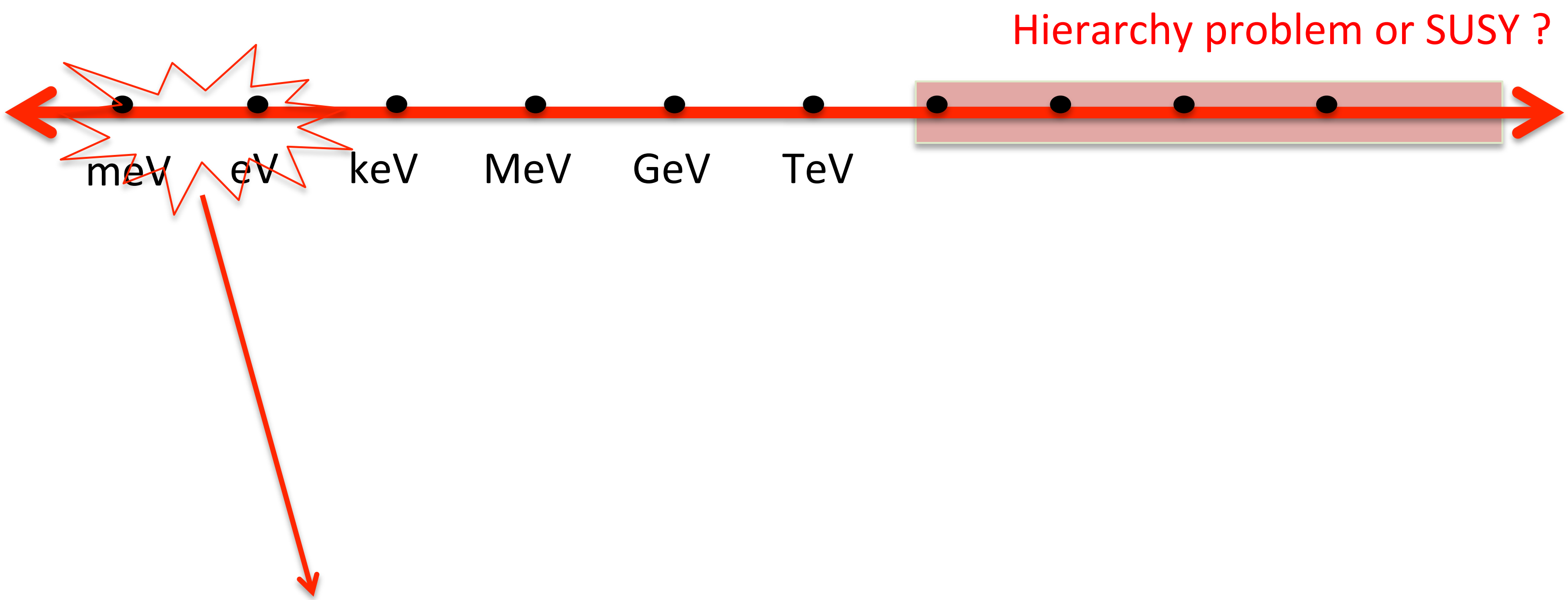
The measurement of any of these additional observables would give complementary information to that in neutrino masses, making the models much more predictive ...

Other states out there ?



Neutrino anomalies: LSND…

Other states out there ?

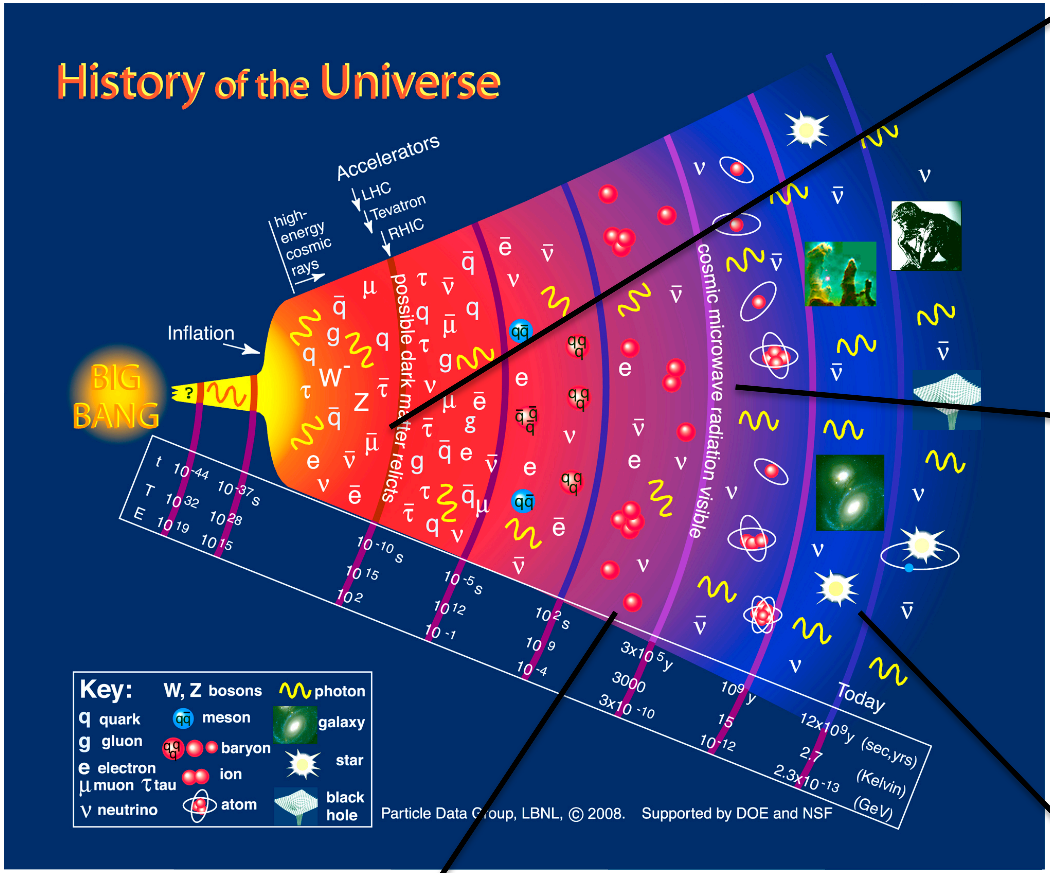


Cosmo anomalies ?

Cosmological neutrinos

they have left traces in the history of the Universe

Leptogenesis

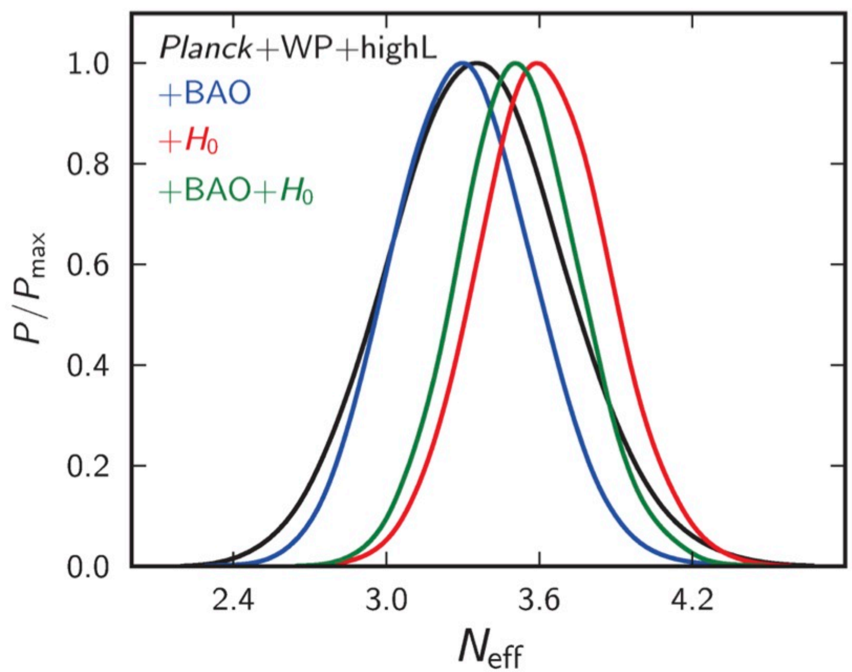


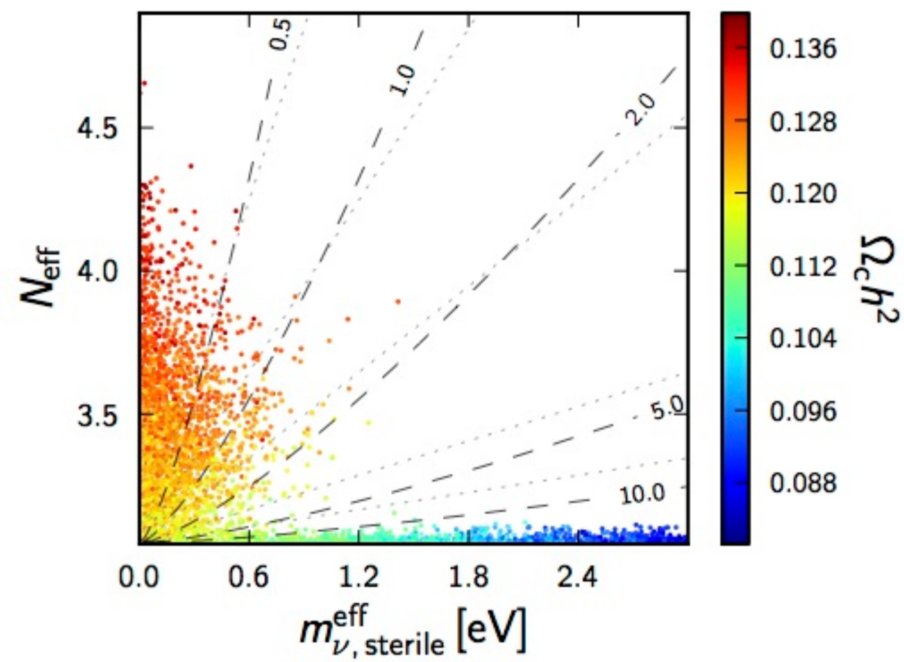
CMB <-> N_ν

Nucleosynthesis <-> N_ν

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

Extra relativistic species welcome…

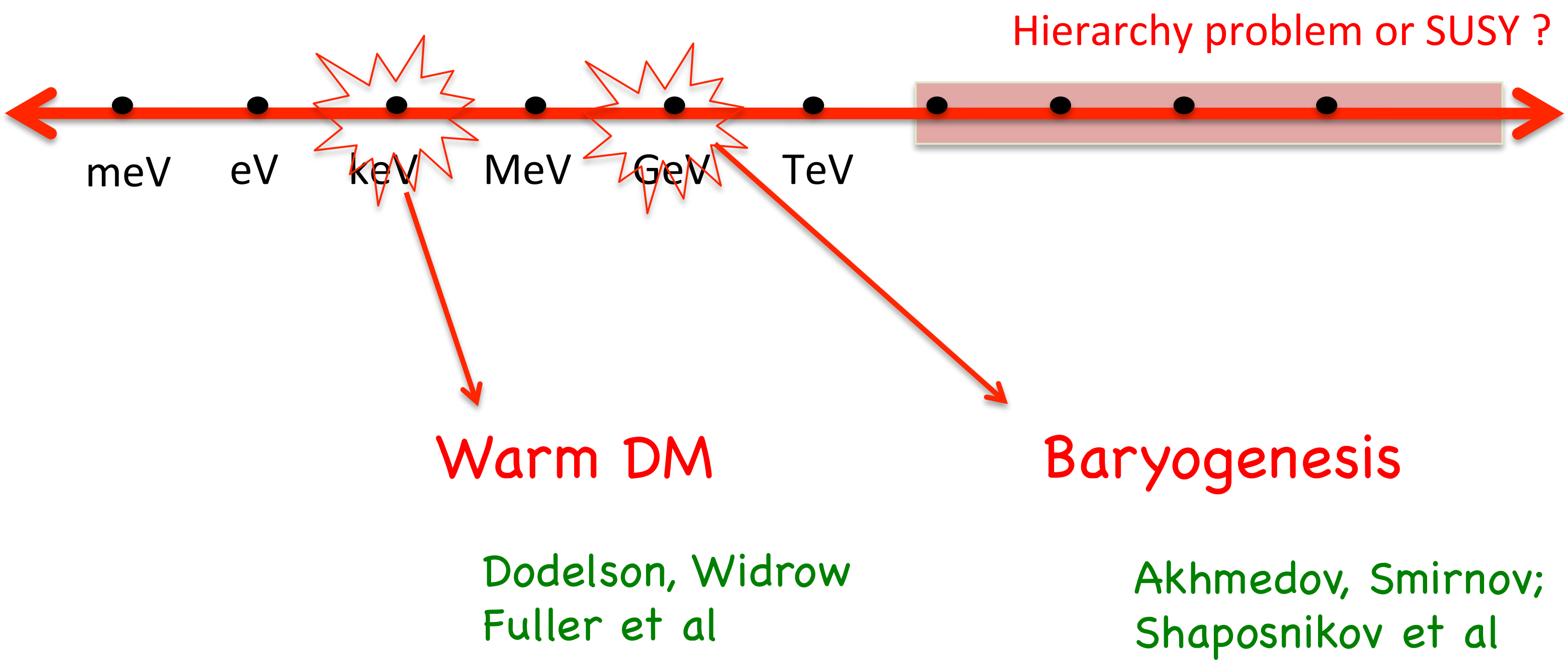




Ade et al 2013

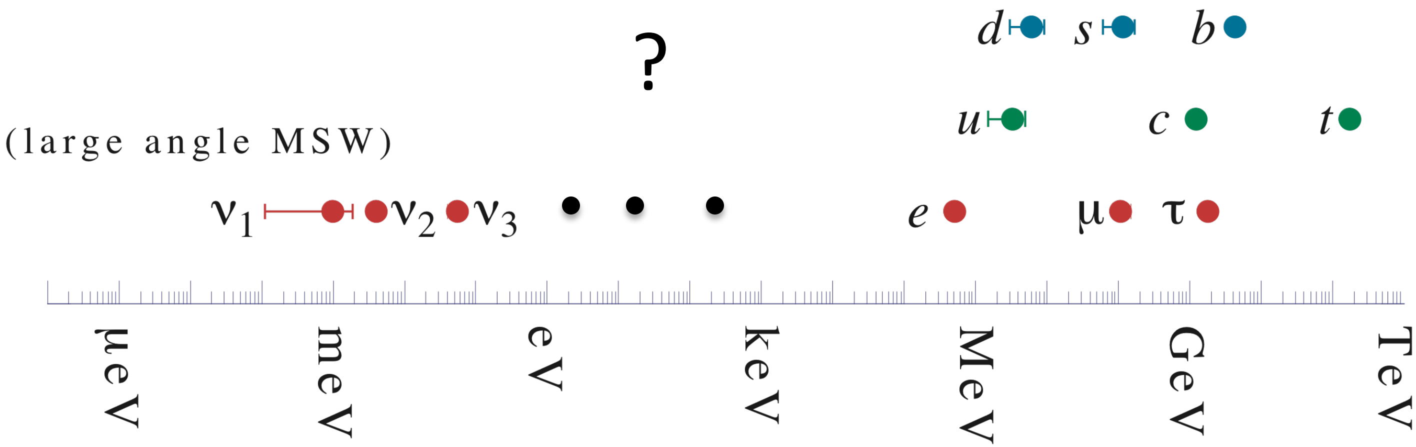
but not too heavy or not too thermal…

Other states out there ?



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 ?

Stringent constraints from peak and decay searches, unitarity, EW...

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')

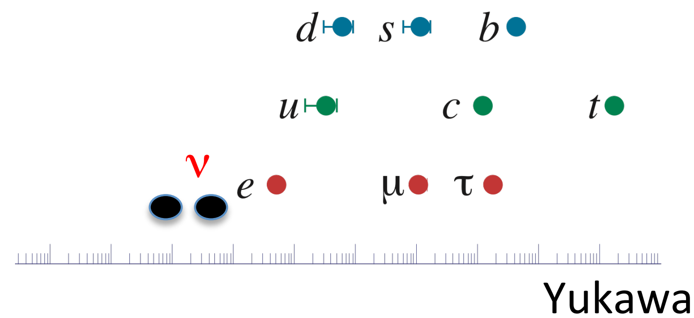
• Flavour effects unsuppressed by small Yukawas: approximate $U(1)_L$

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

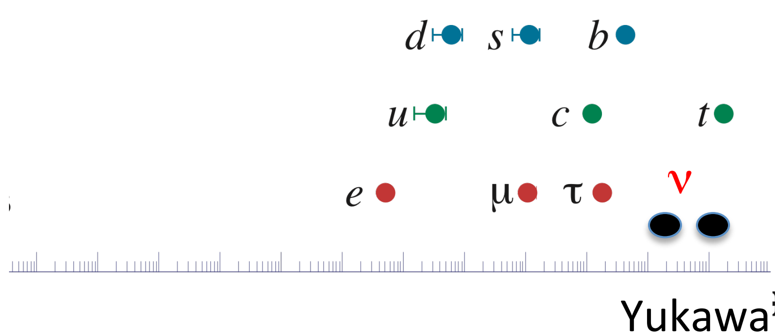
$$\Lambda_{LN} \gg \Lambda_{LFV}$$

Charged/neutral hierarchy in seesaw

Λ = TeV



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

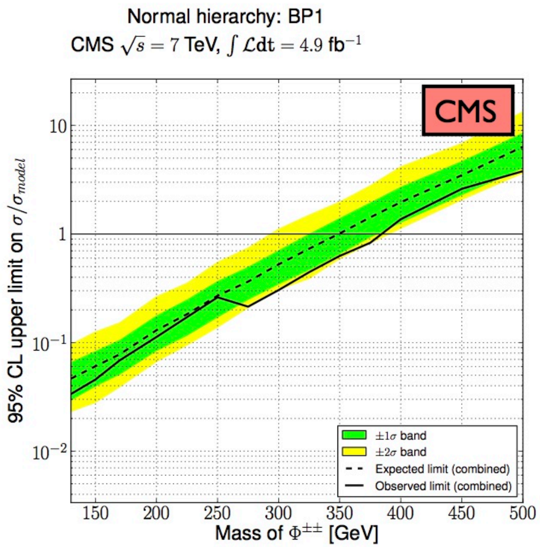


Eg: Inverse seesaw/direct seesaw type I&III or type II

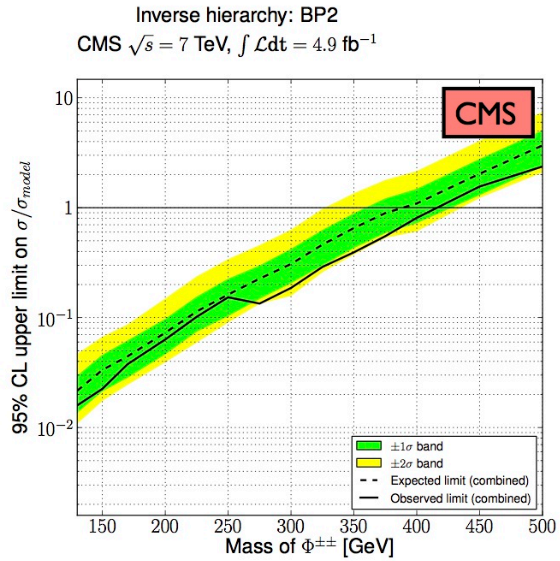
Wyler, Wolfenstein; Mohapatra, Valle;
Branco, Grimus, Lavoura, Malinsky, Romao,
...

pp-> H^{++} H^{--} -> $l^+l^+l^-l^-$

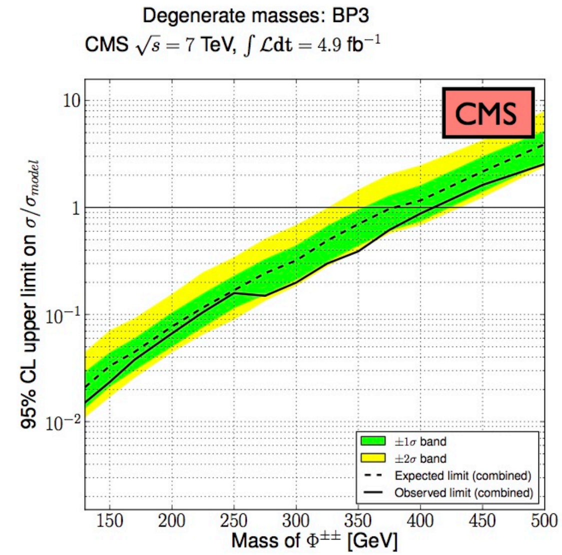
Normal hierarchy



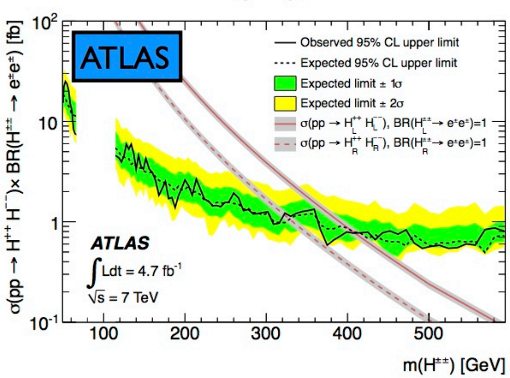
Inverted hierarchy



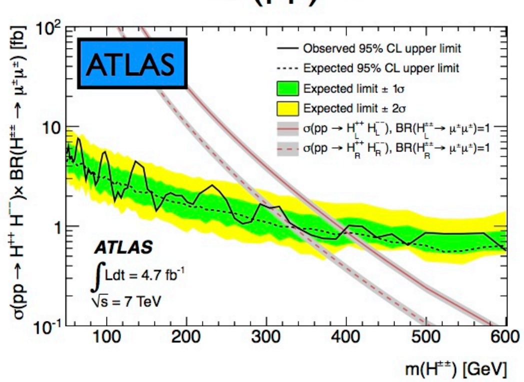
Degenerate ν



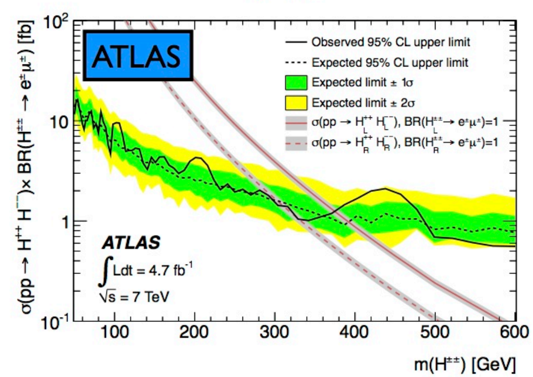
Br(ee)=1



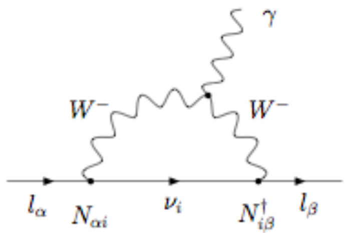
Br(μμ)=1



Br(eμ)=1

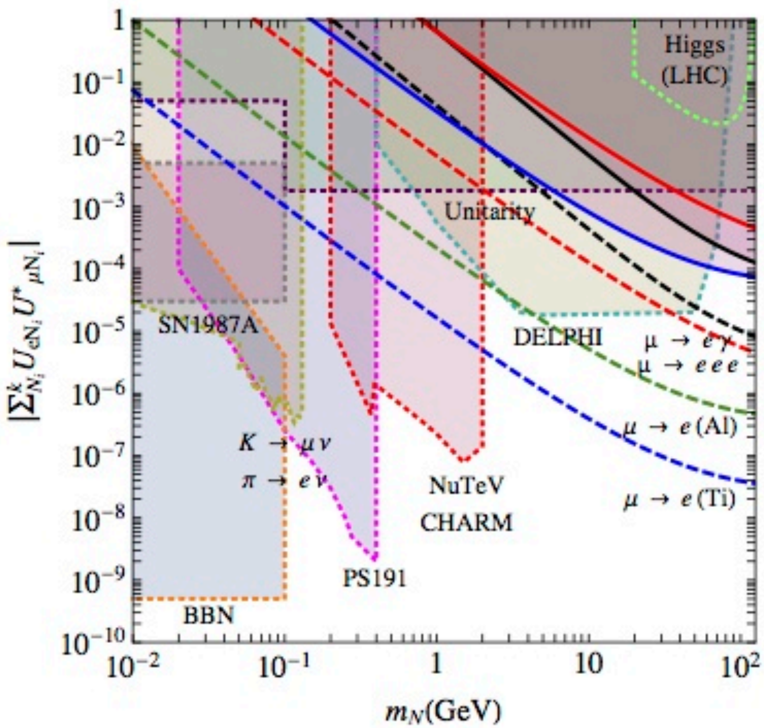


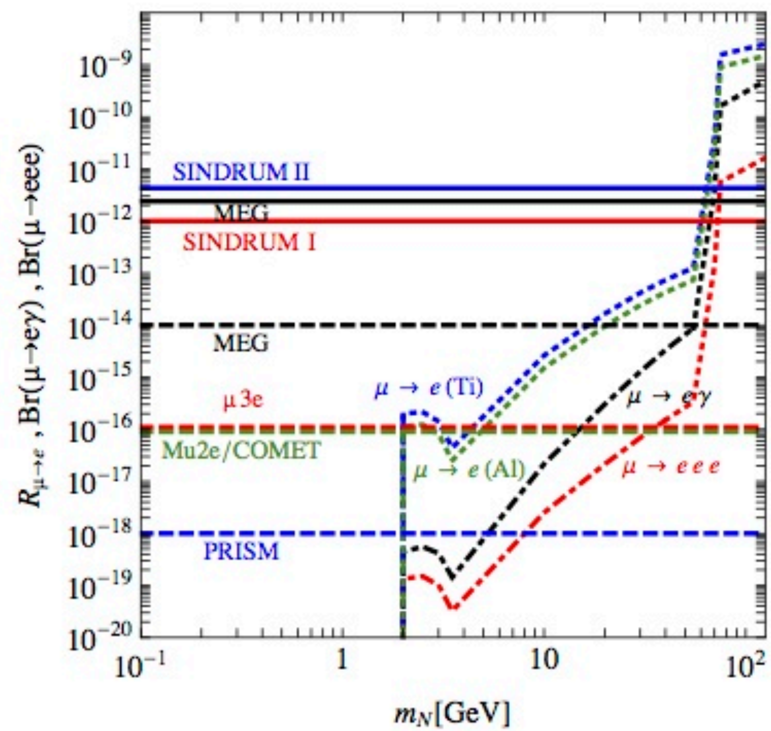
Rich phenomenology of low-scale models with U(1)



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

Conclusions

What the SM does not explain...

Gauge Couplings	EWSB	Quark flavour	Lepton flavour (minimal)
$g_{SU(3)}$, $g_{SU(2)}$, $g_{U(1)}$	m_h, v	$\theta_{12},\theta_{23},\theta_{13},\phi$ m_u,m_c,m_t m_d,m_s,m_b	$\theta_{12},\theta_{23},\theta_{13}$, δ m_1,m_2,m_3 $,m_e,m_\mu,m_\tau$

A more fundamental theory BSM should explain the origin of these parameters

- We still don't know what the νSM is

- Neutrinos add at least as many parameters as quarks to the puzzle, but with features that might hint to a new physics scale

• The existence of a new physics scale in νSM whether related or not to the EW scale would have clear implications for the hierarchy problem and EWSB

• The observation of neutrinoless double beta decay would be the discovery of such a new physics scale

• Predicting the matter-antimatter asymmetry in the Universe would be a major achievement of the νSM

Two key ingredients: Leptonic CP violation
Lepton number violation

• Mass Hierarchy essential for reconstructing the underlying model of neutrino masses & predictions for other observables

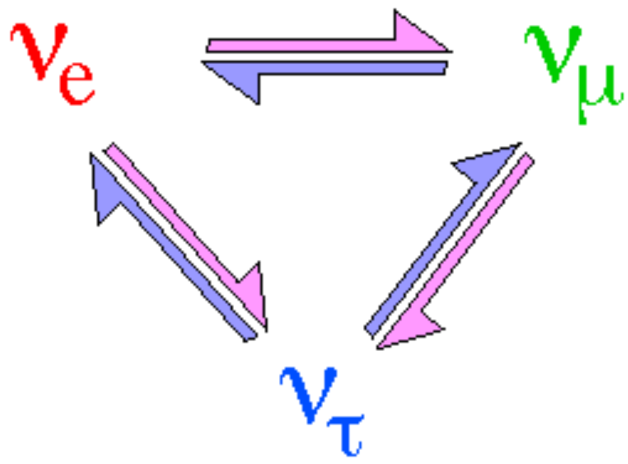
- Sterile neutrinos are not particularly exotic but a generic prediction of seesaw models

It is of extreme importance to clarify neutrino anomalies and establish if there are other light sterile states since

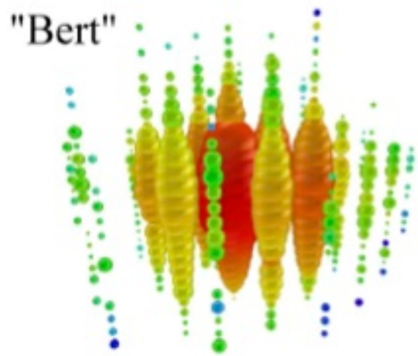
Our predictions/constraints on 1) matter-antimatter asymmetry
2) large-scale structure
3) nucleosynthesis
4) supernova explosions
5) the dark matter content of the Universe
6) rate of neutrinoless double beta decay
....

would depend on it !

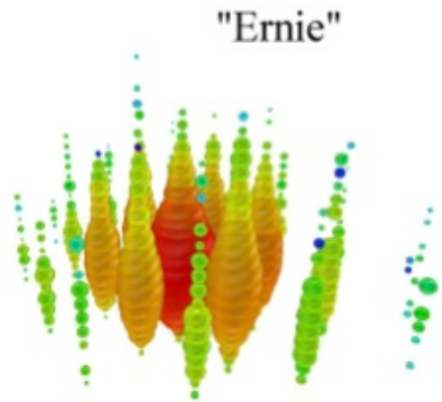
These elusive pieces of reality have brought many surprises, maybe they will continue with their tradition...



Some unexpected PeV ν events...

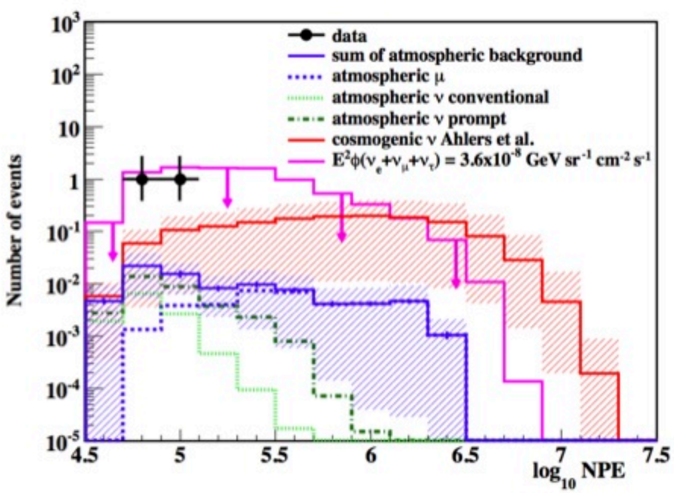


1050 TeV



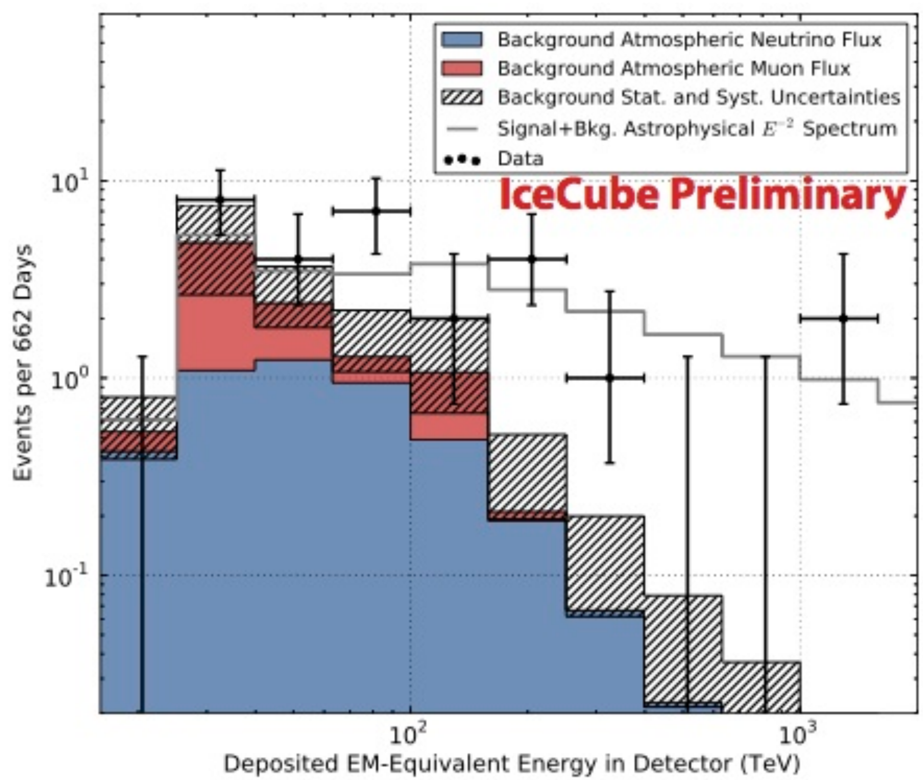
1150 TeV

Icecube col. 1304.5356



- Too low in energy for GZK
- Seems too high in energy for atmospheric

Some more with new analysis…

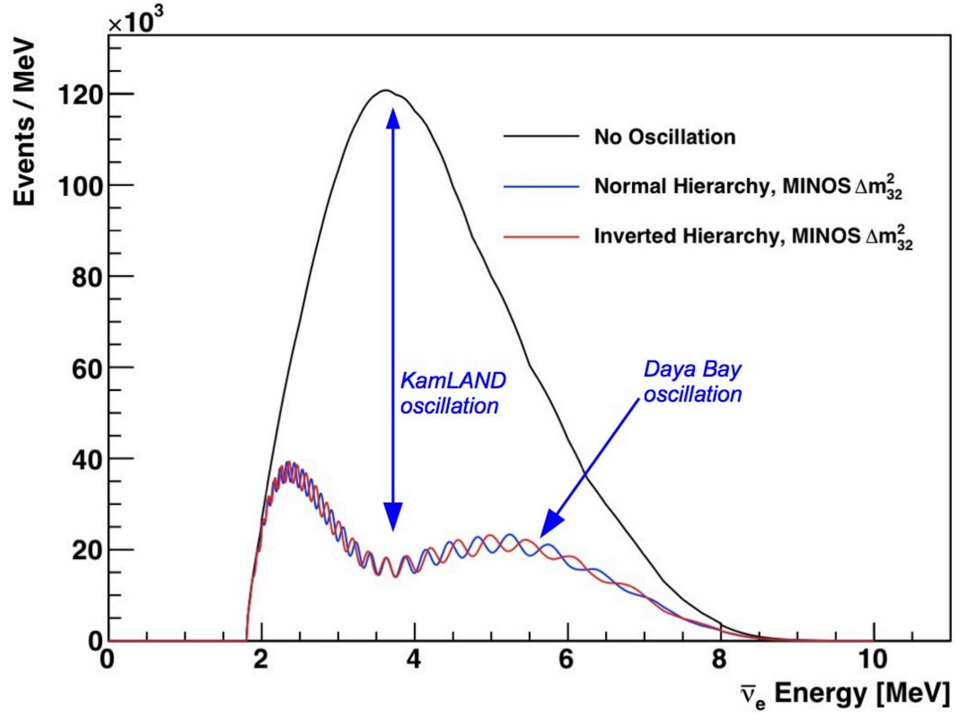


Icecube recent talk

28 events: 21 cascades, 7 muons

Hierarchy from reactor ν's

Petcov, Piai; Choubey et al; Learned et al



$$P_{\nu_e\nu_e} = 1 - c_{13}^2 \sin^2 2\theta_{12} \sin^2 \Delta_{21} - 2 s_{13}^2 c_{13}^2 \left(1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2\Delta_{32} \pm \phi)\right)$$

$$\sin\phi = \frac{c_{12}^2 \sin 2\Delta_{21}}{\sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}}}$$

$$\phi \simeq 0.12 \times 10^{-3} eV^2 \qquad \pm\mathrm{NH(IH)}$$

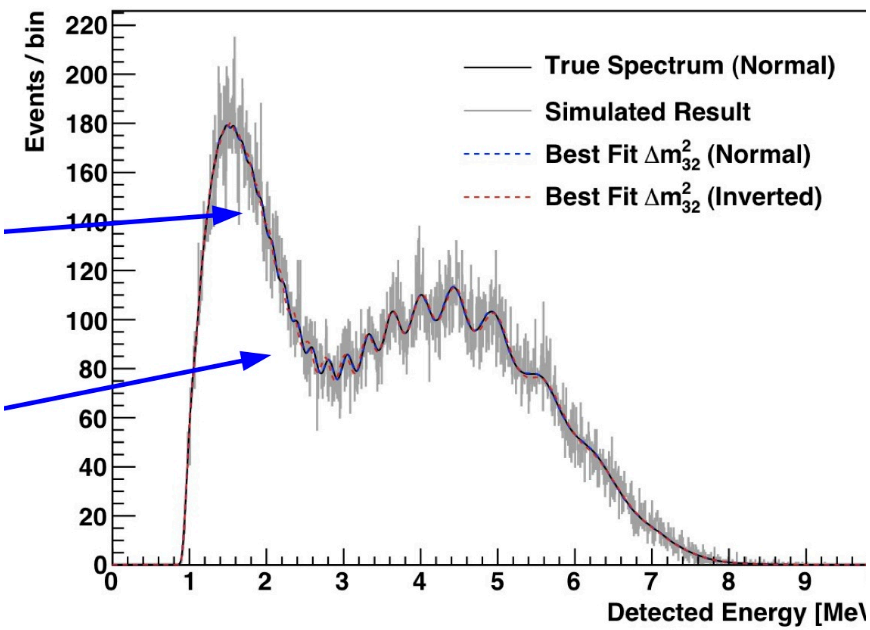
Hierarchy in reactors

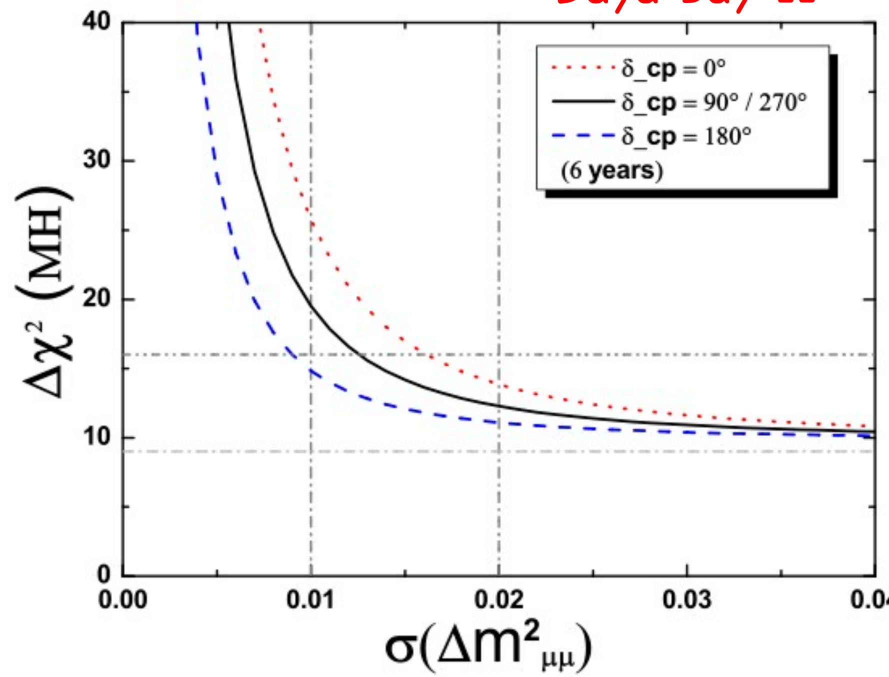
Extremely challenging

large mass 20kton
3% energy resolution (present 6.5%)
<1% linearity in energy scale,
error on $|\Delta m^2_{23}|$

Qian, et al 1208.1551

Daya Bay II





Li et al 1303.6733

Cosmological neutrinos @nucleosynthesis

Before LEP, the best constraint on N_ν came from nucleosynthesis:

$$\nu_e \; n \leftrightarrow p \; e^-$$

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

$$\langle \sigma_\nu N_\nu v \rangle \sim H(T_\nu) \sim \sqrt{g^*}\frac{T_\nu^2}{M_{\rm Planck}} \to T_\nu \sim \left(\frac{\sqrt{g^*}}{G_F^2 M_{\rm Planck}}\right)^{1/3} \sim \mathcal{O}(MeV)$$

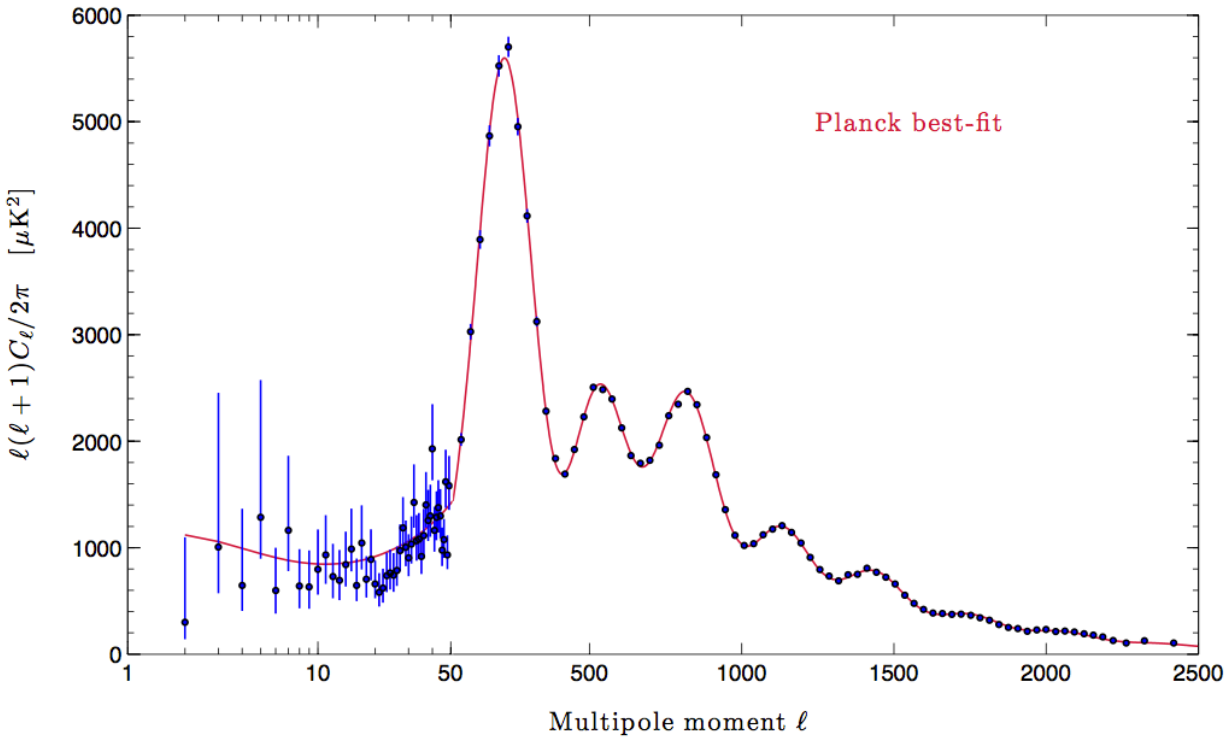
At this temperature the ratio p/n gets fixed and determines the abundance of light elements:

$$\frac{N_n}{N_p} = \exp\left(\frac{m_p - m_n}{T_\nu}\right) \simeq \frac{1}{6} \qquad Y_{^4{\rm He}} = \frac{\text{Mass of } ^4\text{He}}{\text{Total Mass}} = \frac{2N_n}{N_p + N_n}$$

Recent analysis: $N_s = 0.68^{+0.80}_{-0.70}$ Izotov, Thuan

Cosmological neutrinos @ CMB

$$T_{CMB} \sim 0.3 \text{ eV}$$



Anisotropies sensitive to the total energy density in relativistic particles ($m_\nu \ll T_{CMB}$):

$$\rho_\nu \simeq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu^{\rm CMB}$$

Massive neutrinos & LS Structure

Neutrino distribution gets frozen at BBN (T~MeV), therefore if thermal at BBN

$$N_\nu \simeq N_{\bar{\nu}} \simeq \frac{4}{11} T_\gamma^3$$

$$\Omega_\nu = \frac{\sum_i m_i}{93.5 \text{ eV}} h^{-2} < \Omega_m \to \sum_i m_i \leq 11.2 \text{ eV}$$

Gershtein, Zeldovich

But such neutrinos cannot be DM: free-streaming would distort the large scale structure power spectrum...

Sarkar's Lectures