NEUTRINO PHYSICS

Lecture I & II:

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

Lecture III:

- Evidence for neutrino mass: review of experimental landscape
- The standard 3ν scenario
- A few outliers…

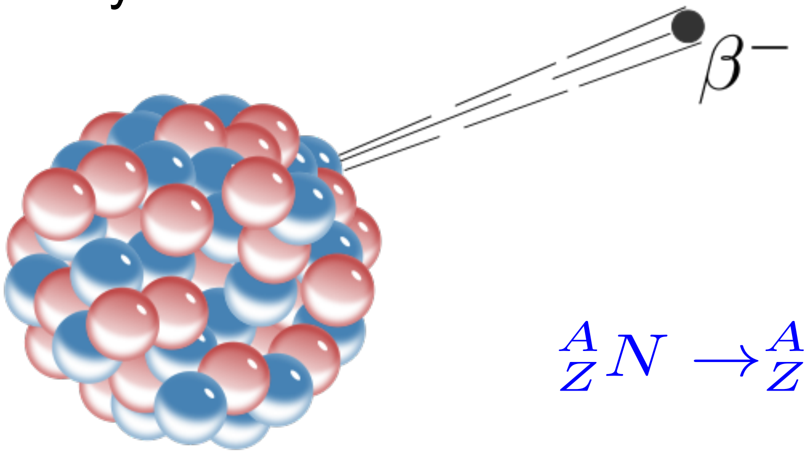
Lecture IV:

- Prospects in neutrino physics
- Leptogenesis & neutrinos in the cosmos
- Theory outlook

Neutrino: the phantom particle

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

β decay

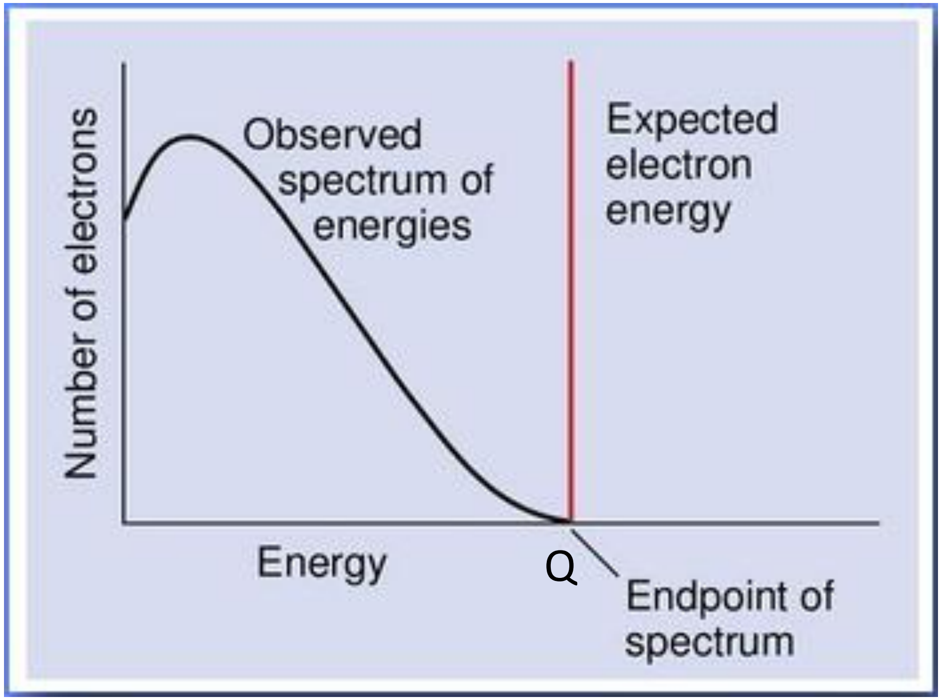


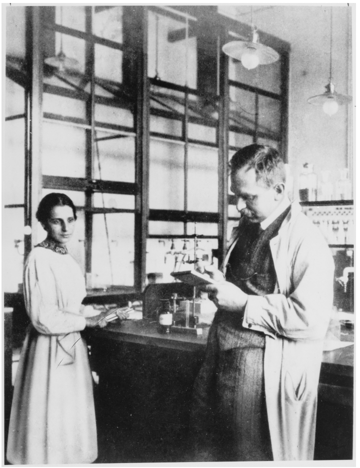
$$^{A}_{Z}N \rightarrow ^{A}_{Z+1}N' + e^-$$

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

1911/1914

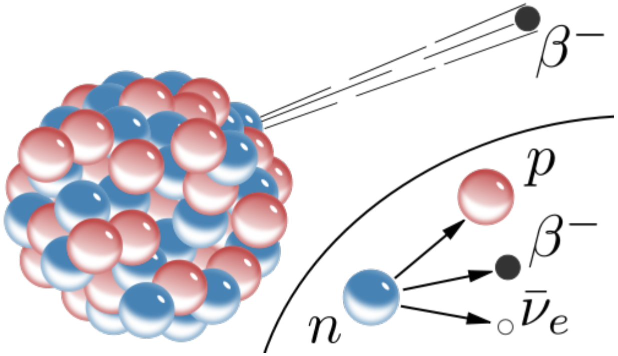
Electron spectrum:





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....

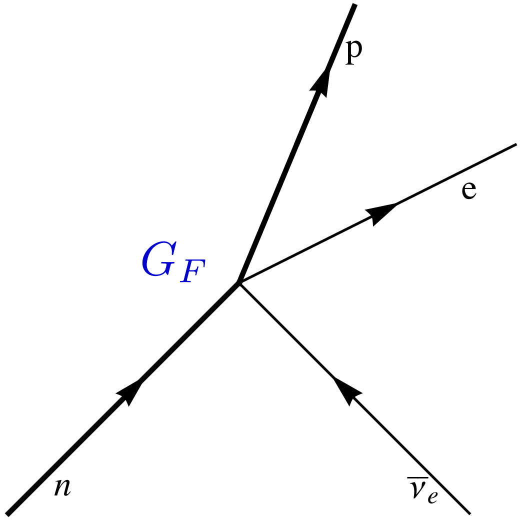
1933: Solvay's conference

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."

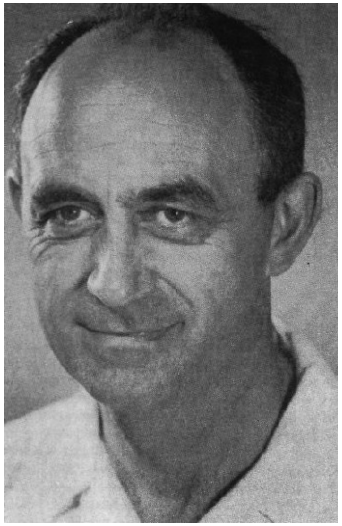
W. Pauli

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 ?

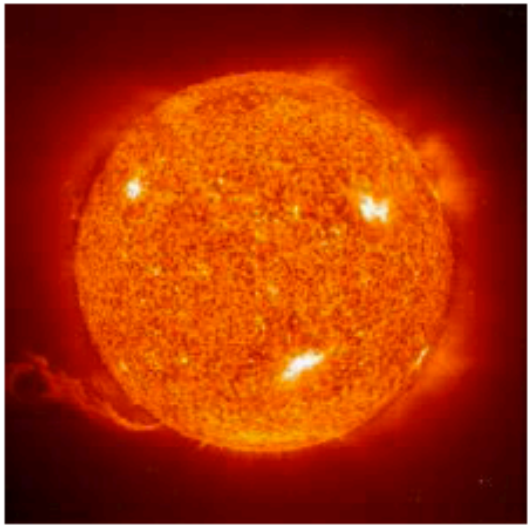
$$\begin{aligned}
\lambda &\simeq \frac{1}{n\sigma} \\
\lambda|_{\text{@water}} &\simeq 1.5\times 10^{21}\ cm \simeq 1600\ \text{Light Years} \\
\lambda|_{\text{@interstelar}} &\simeq 10^{44}\ cm \simeq 10^{26}\ \text{Light Years}
\end{aligned}$$

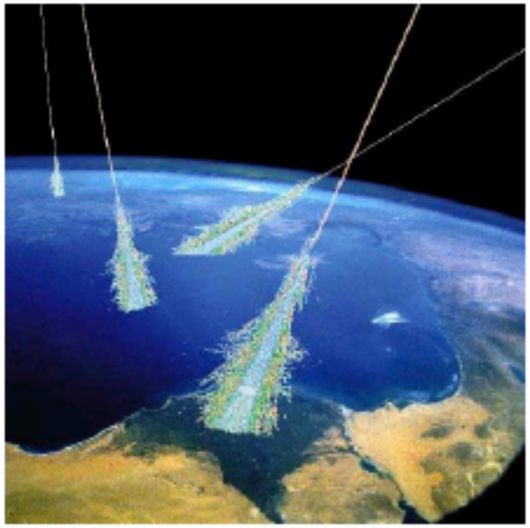
"I have done a terrible thing. I have postulated a particle that cannot be detected"

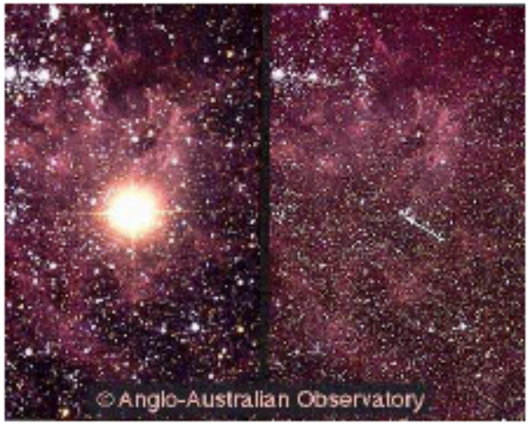
W. Pauli

"Not even wrong"

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







How to detect them?

1946 Pontecorvo

Бруно Понтекорво

Not so desperate...

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

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

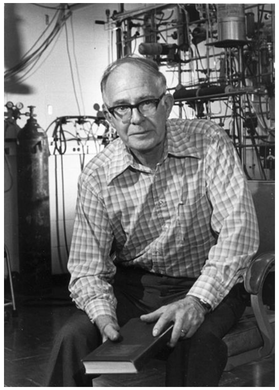
$$^{37}\text{Cl} + \nu_e \rightarrow {}^{37}\,\text{Ar} + e^-$$

Argon can be separated: in ~35 days the inverse reaction takes place

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

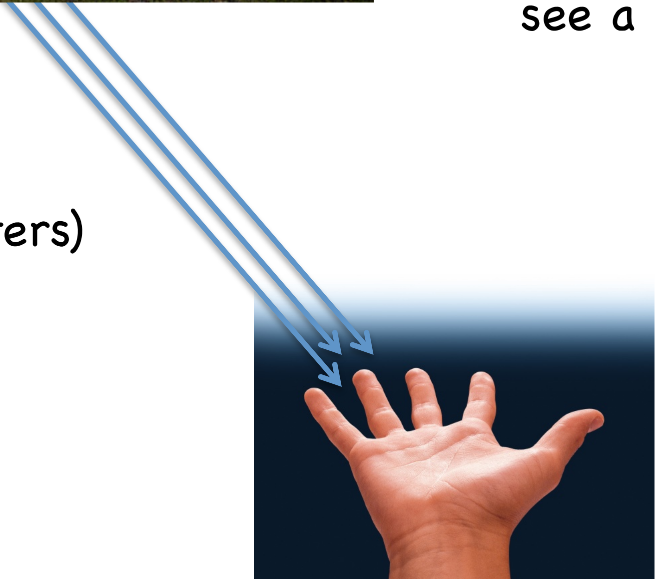
Reactors: ~ 10^{20}/second!

1955 Davies



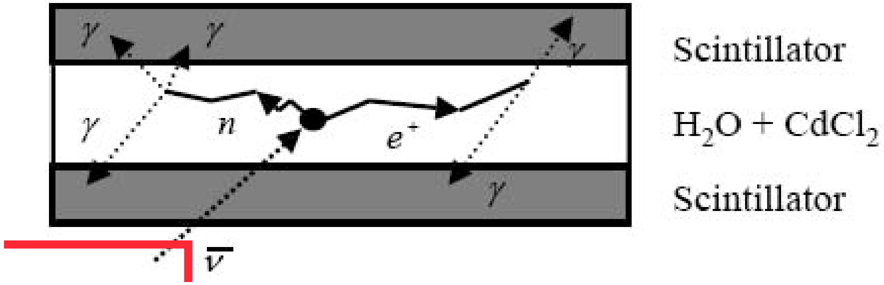
Built a 4000 liter detector, but did not see a thing...

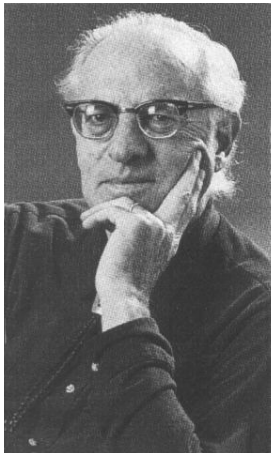
(10^{11}/s@100 meters)



1956 (anti)neutrino detection

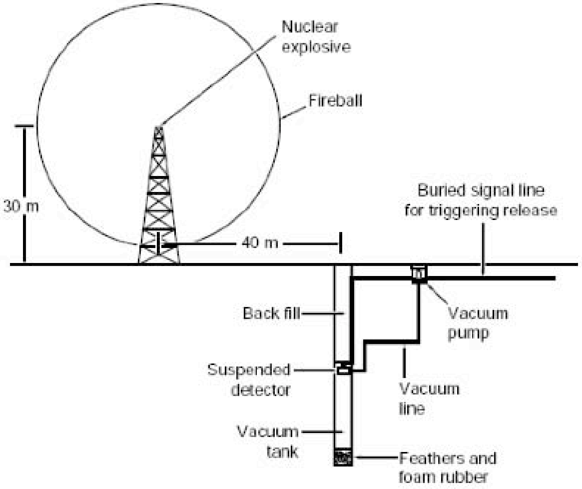
Poltergeist project





Reines Nobel 95

Cowan (died 74)



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

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

The flavour of neutrinos

Бруно Понтекорво

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

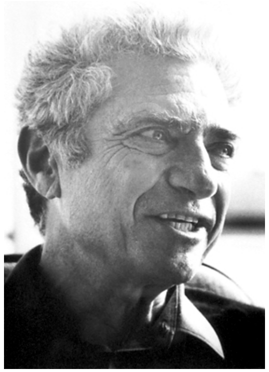
Neutrino cross section in Fermi theory grows with energy: he proposes the first experiment with a neutrino beam !

Neutrino Flavour

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

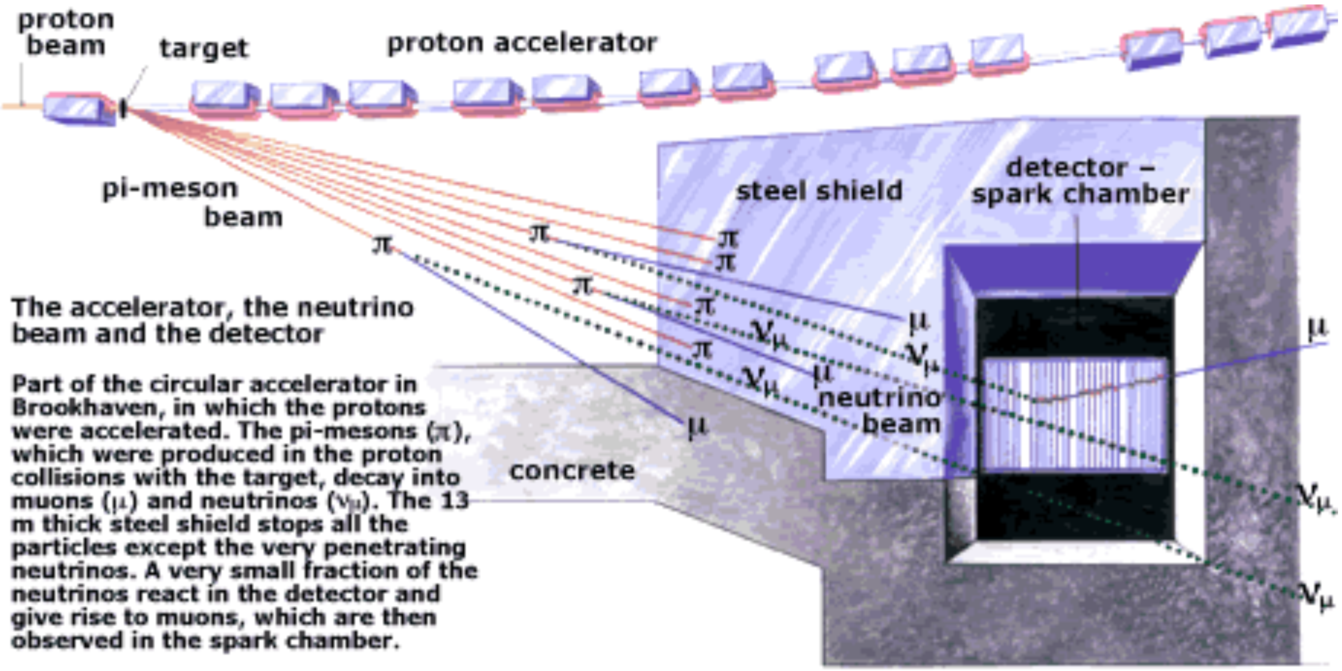
Lederman

Schwartz



Steinberger

Nobel 1988



The accelerator, the neutrino beam and the detector

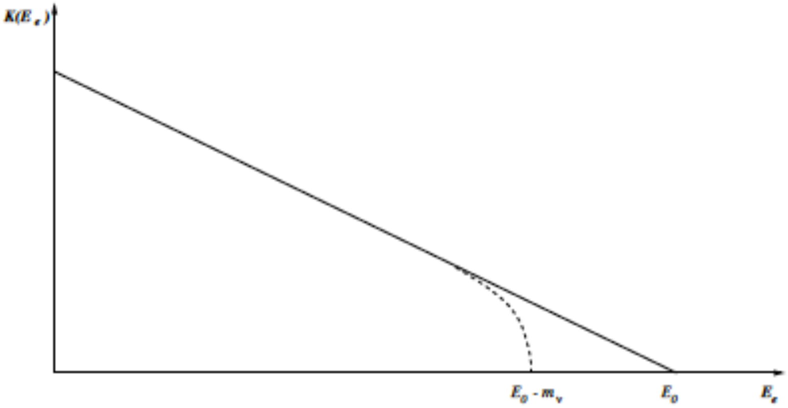
Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

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)

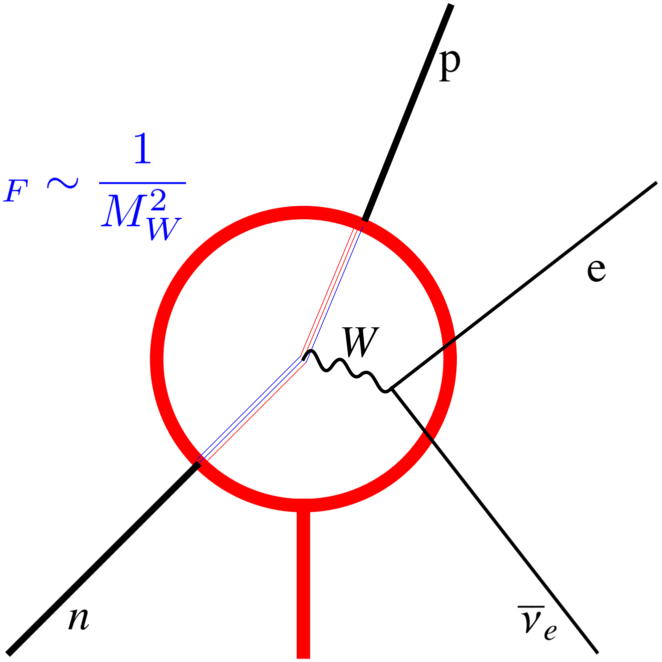
$m_{\nu_\mu} < 170\text{keV}$ (PSI: $\pi^+ \rightarrow \mu^+ \nu_\mu$)

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

Standard Model neutrinos assumed massless

Neutrinos in the Standard Model

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



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

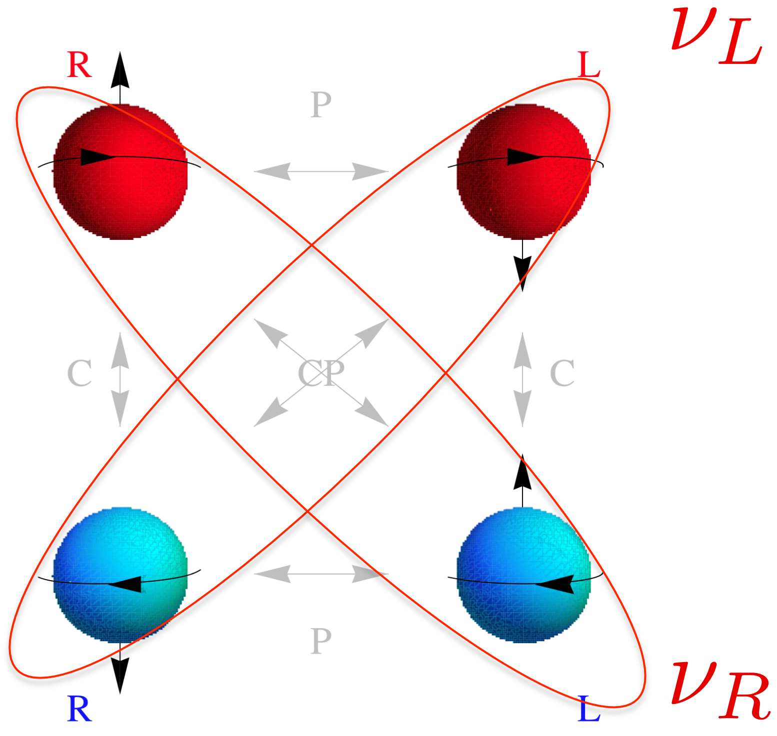
$$\nu = \frac{1-\gamma_5}{2}\,\nu \simeq \frac{1}{2}\left(1 - \underbrace{\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}}_{\text{Helicity}}\right)\nu + \mathcal{O}(v/c)$$

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

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

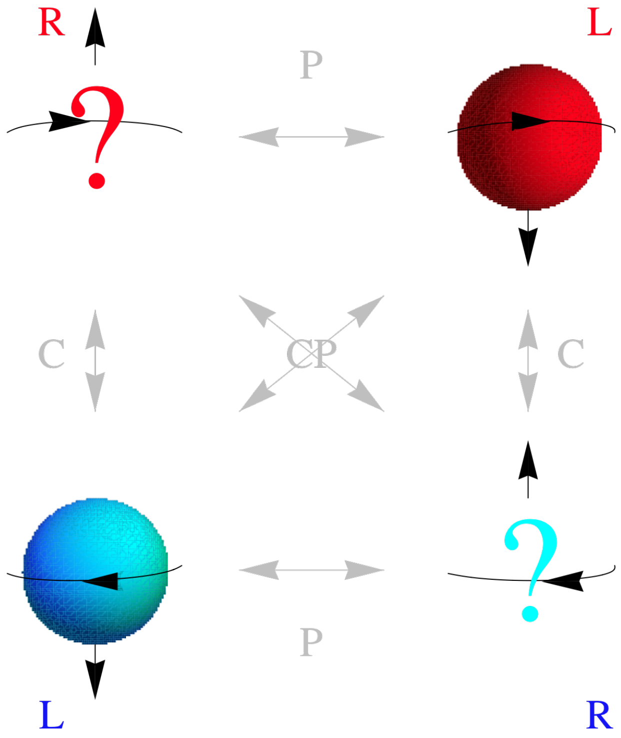
Dirac fermion= 4-component spinor

(Minimal spin ½ + Parity)



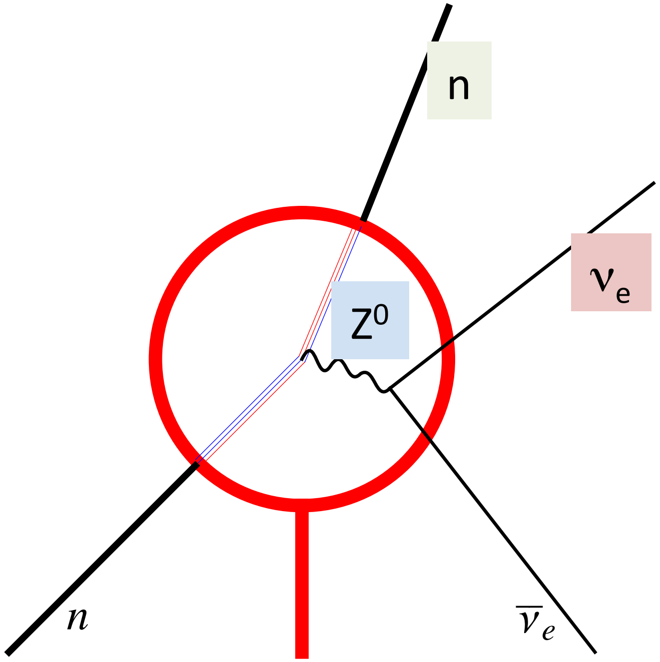
Weyl fermion= 2-component spinor

(Minimal spin ½)



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

Neutrinos in the Standard Model



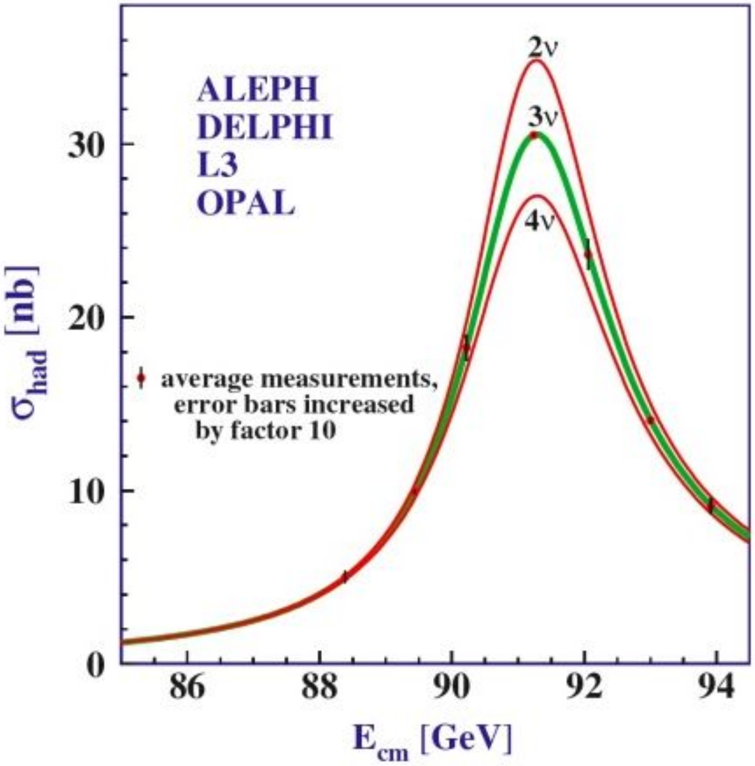
Neutral currents: NC

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

At LEP:

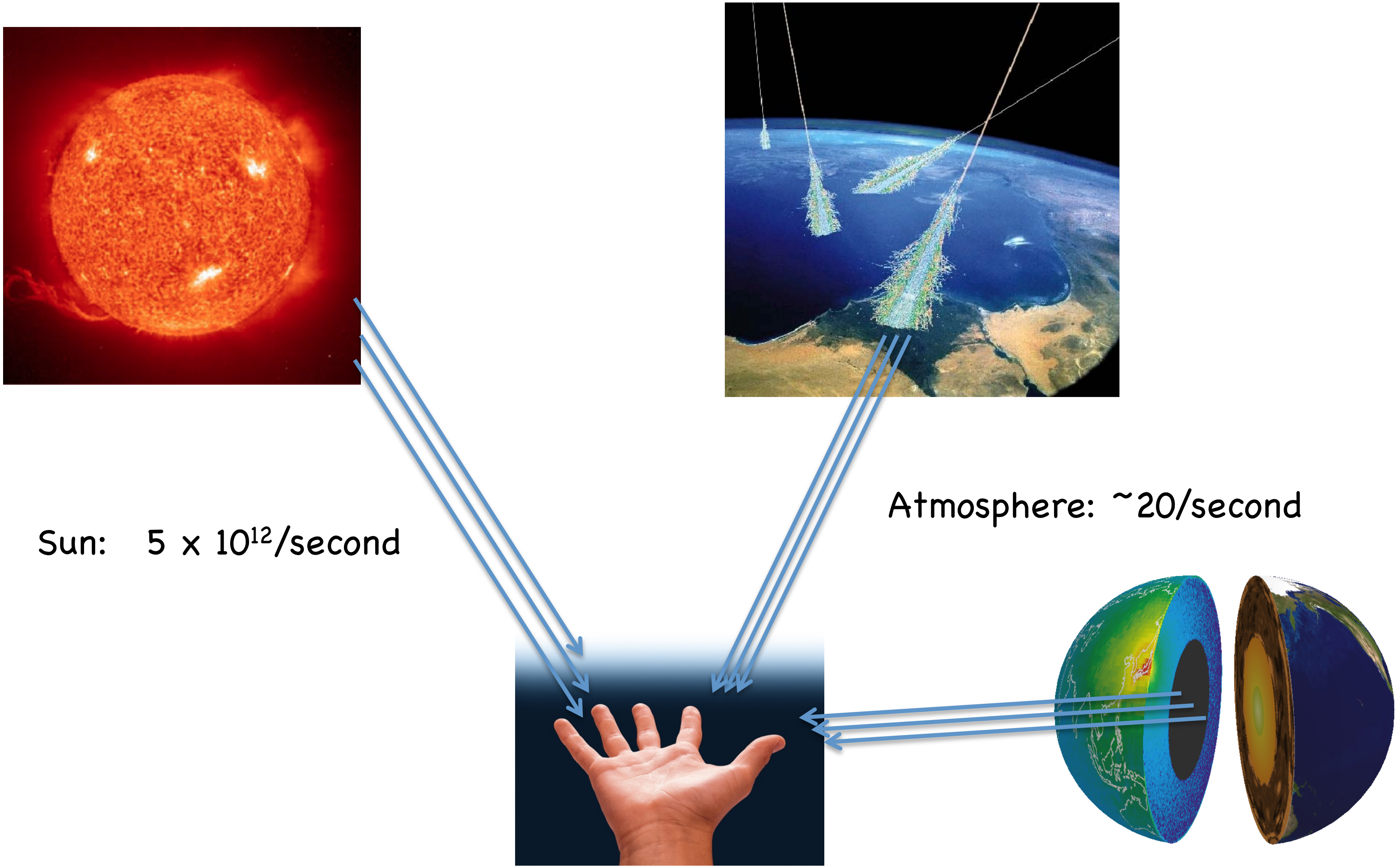
$$e^+e^- \rightarrow Z^0 \rightarrow f\bar{f}$$

Only three neutrinos were found



Ubiquitous Neutrinos

They are everywhere…

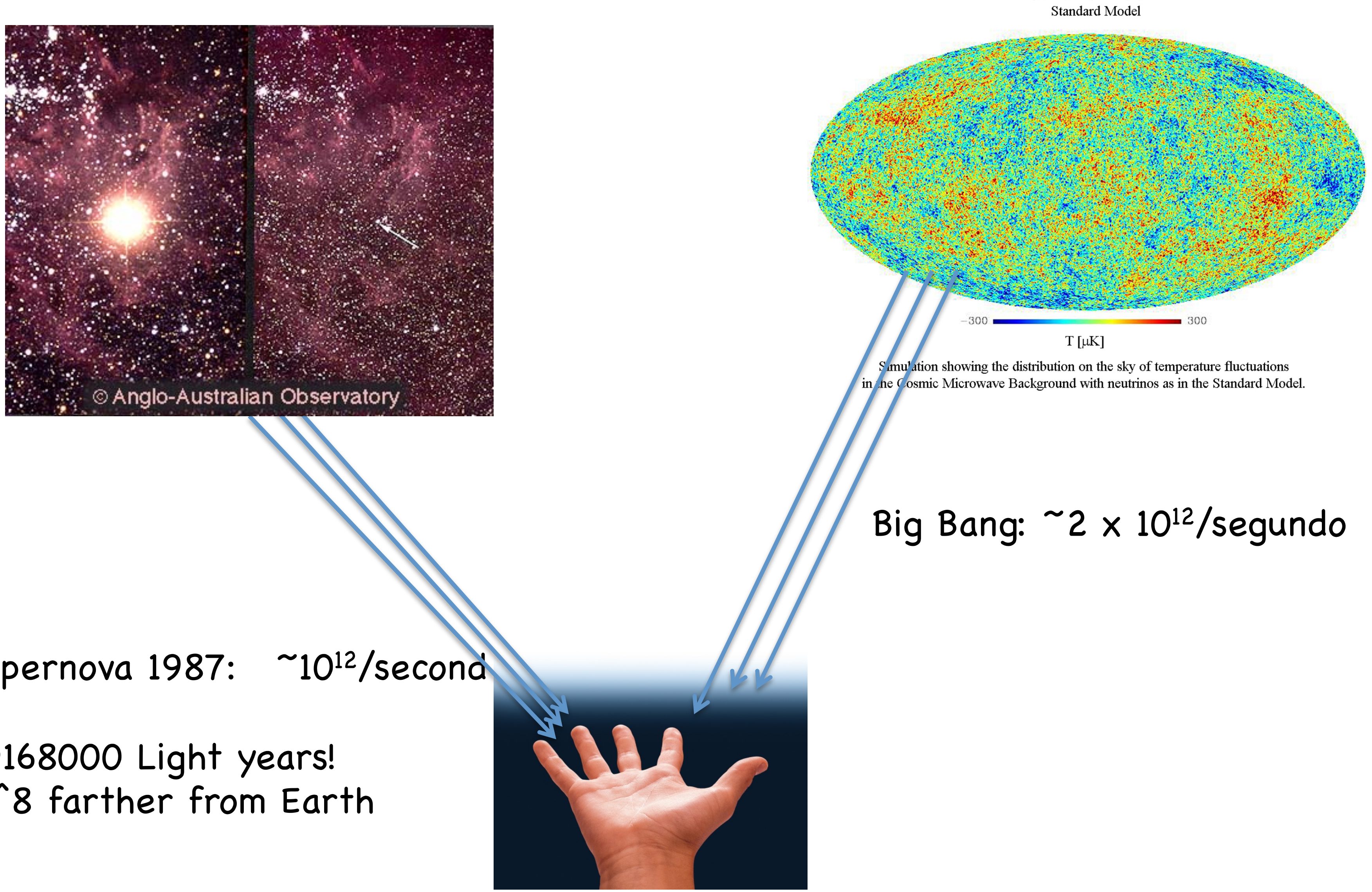


Sun: 5×10^{12}/second

Atmosphere: ~20/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.

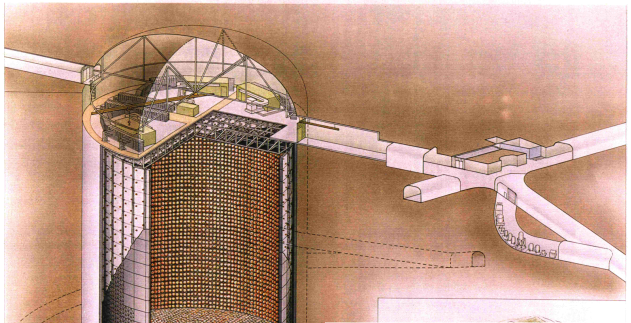
Big Bang: ~2 x 10^{12}/segundo

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!

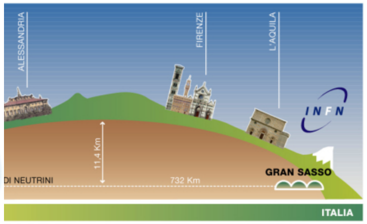
SuperKamiokande

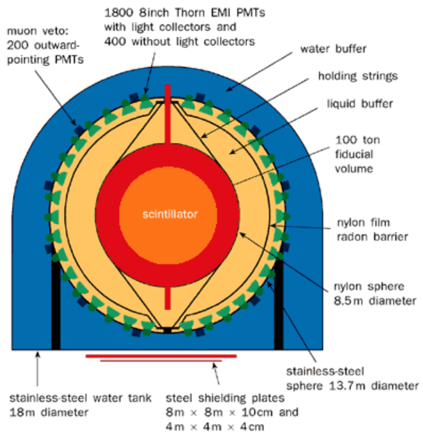


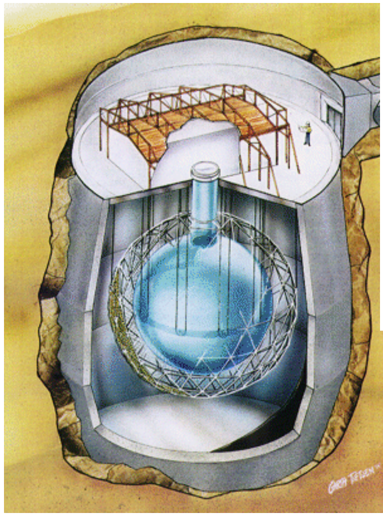
Kam LAND

Kamioka Liquid scintillator Anti-Neutrino Detector

MINOS, Opera







Borexino

SNO

T2K

NOνA

DOUBLE CHOOZ

Daya Bay

θ_{13}

RENO

ν θ_{13}

…and more

Massive (free) fermions ?

Dirac fermion of mass m:

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

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:

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

Breaks SU(2) gauge invariance!

Majorana fermion of mass m (Weyl representation)

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

No gauge/global symmetry of ψ possible!

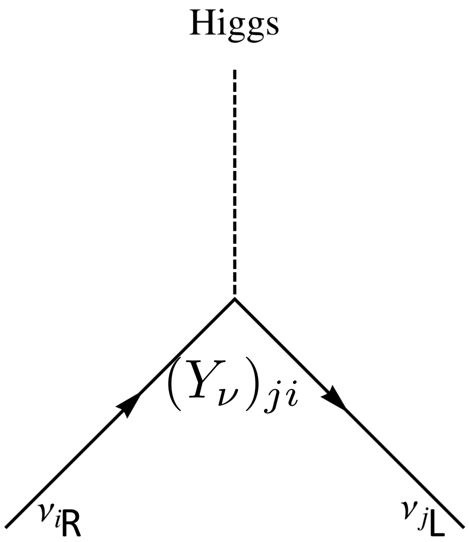
Spontaneous symmetry breaking can induce Dirac masses for all fermions but Majorana masses only for neutrinos !

Massive Dirac neutrinos & SSB ?

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

Massive Dirac neutrino

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



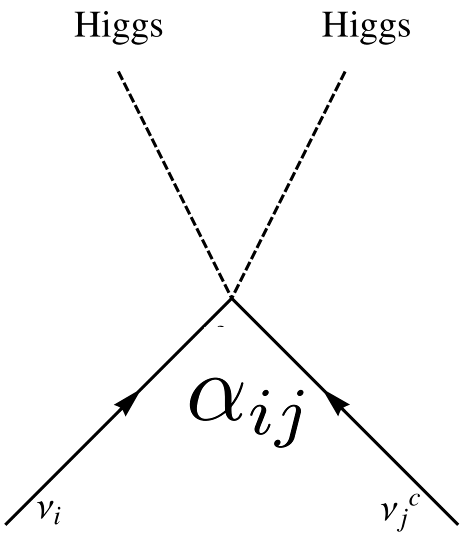
$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

Massive Majorana neutrinos & SSB ?

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

Massive Majorana neutrino

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



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

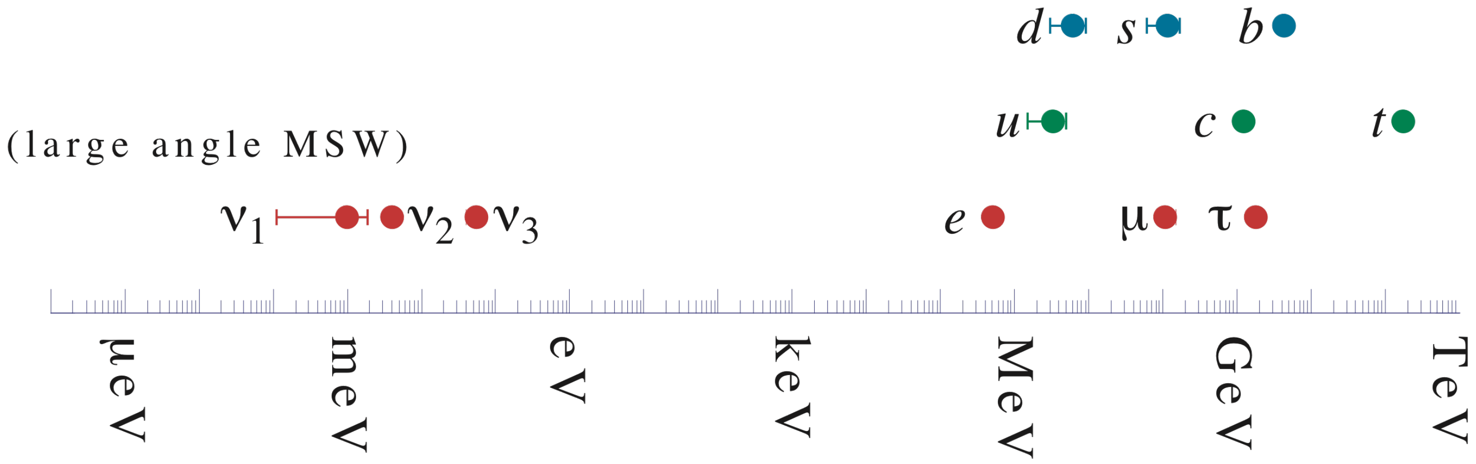
$$[\alpha] = -1$$

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

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

Massive Majorana neutrinos & SSB ?

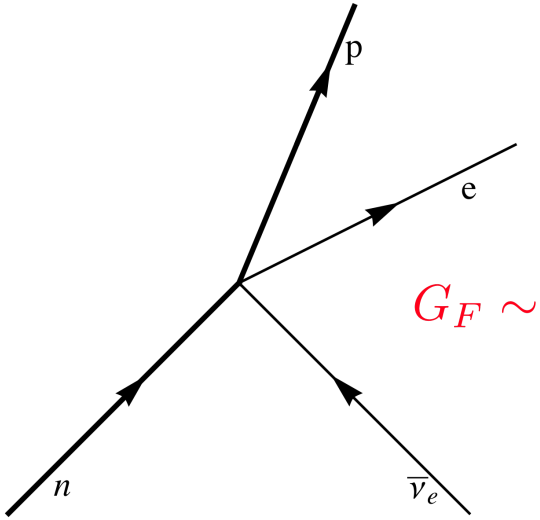
If Λ >> v natural explanation for the smallness of neutrino mass



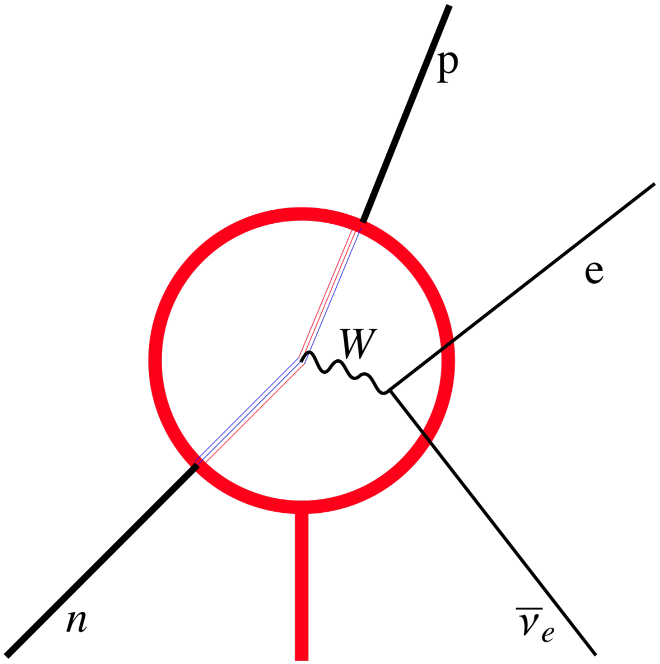
$$m_f(\text{charged}) \sim Y v, \quad m_\nu \sim Y \frac{v^2}{\Lambda}$$

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

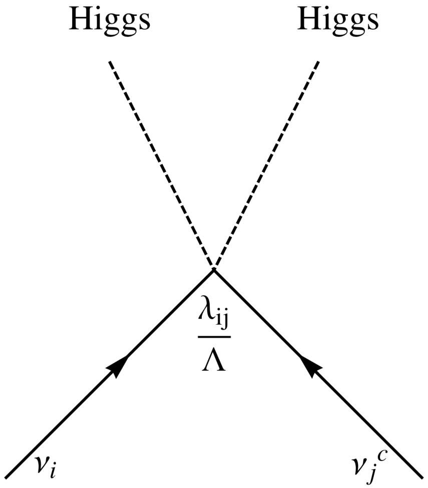
Majorana neutrinos imply a new Standard Model



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



SM



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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 !

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

Generically d=6 operators: rich phenomenology

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

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

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 field redefinitions 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	$n(n-1)/2$

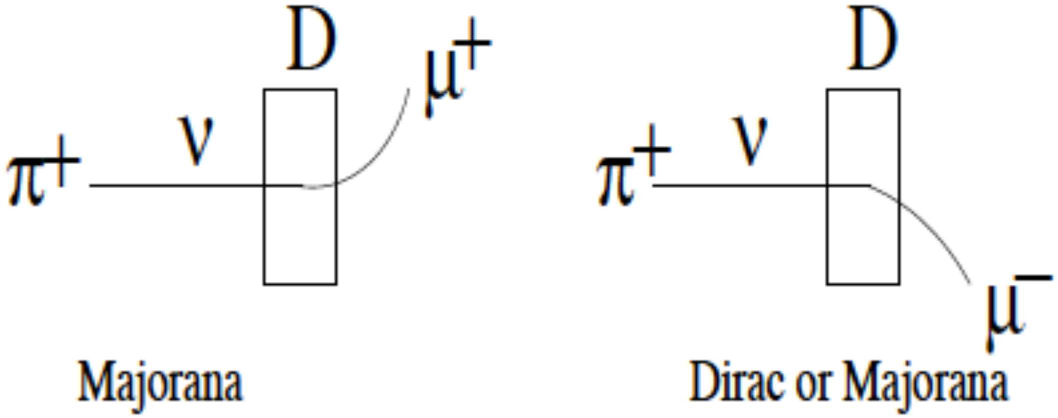
Moduli = 2n masses + n (n–1)/2 angles For n=3: 3 angles, 3 phases

Majorana versus Dirac

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

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

In principle clear experimental signatures



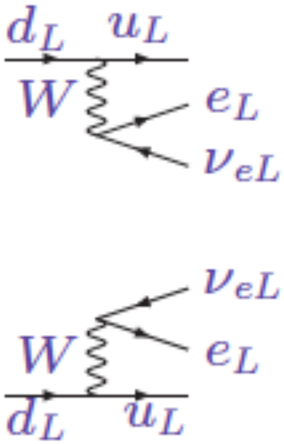
Majorana

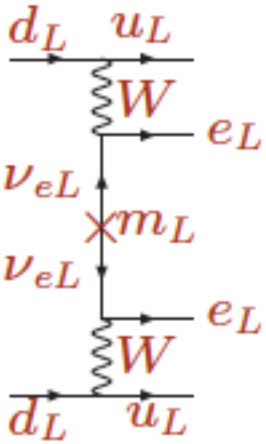
Dirac or Majorana

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

Neutrinoless double-β decay

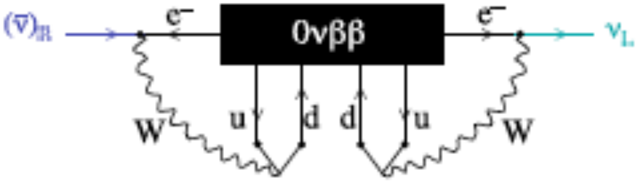
Best hope is neutrinoless double-β decay





$$T_{2\beta2\nu} \sim 10^{18} - 10^{21} \text{ years} \quad T^{-1}_{2\beta0\nu} \sim \left(\frac{m_\nu}{E}\right)^2 10^9\, T^{-1}_{2\beta2\nu}$$

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

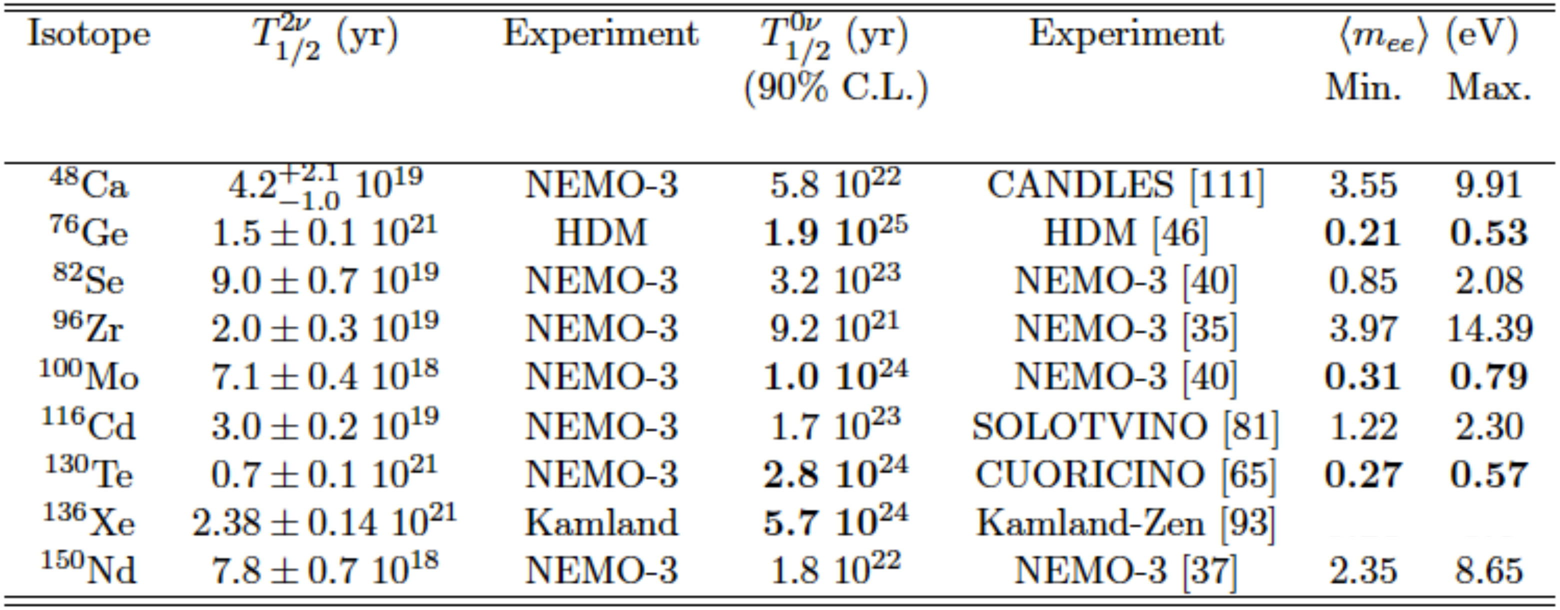


Neutrinoless double-β decay

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

Present bounds:

Sarazin 2012



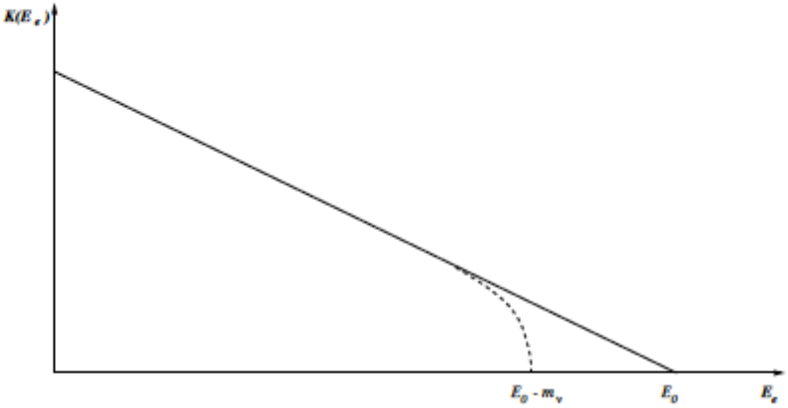
Isotope	$T^{2\nu}_{1/2}$ (yr)	Experiment	$T^{0\nu}_{1/2}$ (yr) (90% C.L.)	Experiment	$\langle m_{ee}\rangle$ (eV) Min.	Max.
^{48}Ca	$4.2^{+2.1}_{-1.0}\ 10^{19}$	NEMO-3	$5.8\ 10^{22}$	CANDLES [111]	3.55	9.91
^{76}Ge	$1.5 \pm 0.1\ 10^{21}$	HDM	$\mathbf{1.9\ 10^{25}}$	HDM [46]	**0.21**	**0.53**
^{82}Se	$9.0 \pm 0.7\ 10^{19}$	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 0.12 0.25

Kinematical effects of neutrino mass

Most stringent from Tritium beta-decay

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



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

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

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

Standard Model neutrinos assumed massless

Neutrino oscillations

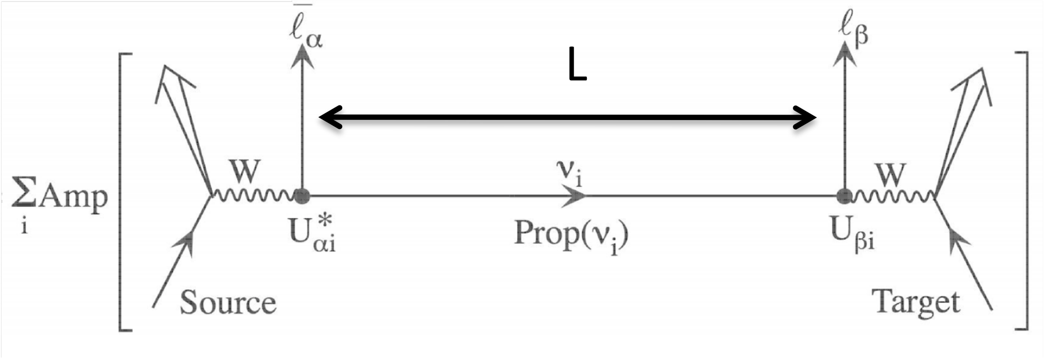
1968 Pontecorvo

If neutrinos are massive

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

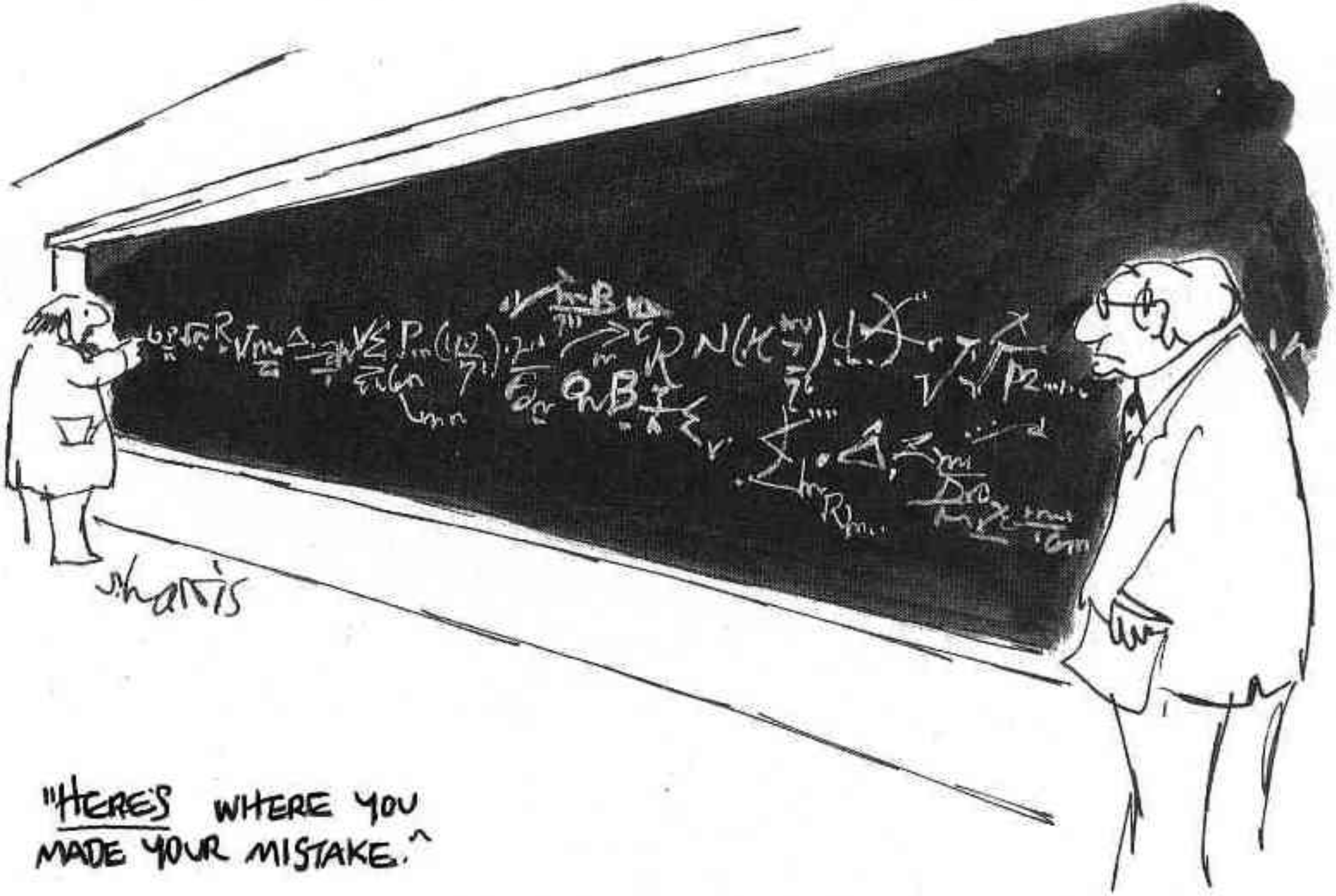
Бруно Понтекорво

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

On the foundations of ν oscillations



"HERE'S WHERE YOU MADE YOUR MISTAKE."

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)

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

$\downarrow$ time evolution

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

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta)(t) &= |\langle \nu_\beta|\nu_\alpha(t)\rangle = |\sum_i U_{\beta i} U^*_{\alpha i} e^{-iE_i(t-t_0)}|^2 \\ &= \sum_{i,j} e^{-i(E_i-E_j)(t-t_0)} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j} \end{aligned}$$

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

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

Neutrino oscillations in QM (plane waves)

Well founded criticism to this derivation

Why same p for the i-th states ?

Why plane waves if the neutrino source is localized ?

Why t <-> L conversion ?

Neutrino oscillations in QM (wavepackets)

B. Kayser 81,... many authors...,Akhmedov, Smirnov

Wave packet created at source @ $(t_0, \mathbf{x}_0) = (0, \mathbf{0})$

$$|\nu_\alpha(t,\mathbf{x})\rangle = \sum_i U^*_{\alpha i} \int_{\mathbf{p}} \underbrace{f_i^S(\mathbf{p}-\mathbf{Q}_i)}_{\text{Wave packet at source}} \quad e^{-iE_i(\mathbf{p})t} \; e^{i\mathbf{p}\cdot\mathbf{x}} \; |\nu_i\rangle$$

$$E_i(\mathbf{p}) \equiv \sqrt{\mathbf{p}^2 + m_i^2}$$

For example: $f_i^S(\mathbf{p}-\mathbf{Q}_i) \simeq e^{-(\mathbf{p}-\mathbf{Q}_i)^2/2\sigma_S^2}$

$\sigma_S \quad \leftrightarrow \quad$ momentum uncertainty

$\mathbf{Q}_i \quad \leftrightarrow \quad$ average momentum of i – th wavepacket

Wave packet created at detector @ $(t_0, \mathbf{x}_0) = (t, \mathbf{L})$

$$|\nu_\beta(t,\mathbf{x})\rangle = \sum_j U^*_{\beta j} \int_{\mathbf{p}} f_j^D(\mathbf{p}-\mathbf{Q}'_j) \; e^{-iE_j(\mathbf{p})(t-T)} \; e^{i\mathbf{p}(\mathbf{x}-\mathbf{L})} \; |\nu_j\rangle$$

Neutrino oscillations in QM (wavepackets)

$$\begin{aligned}\mathcal{A}(\nu_\alpha \to \nu_\beta) &= \int_{\mathbf{x}} \langle \nu_\beta(t,\mathbf{x}) | \nu_\alpha(t,\mathbf{x}) \rangle \\ &= \sum_i U^*_{\alpha i} U_{\beta i} \int_{\mathbf{p}} e^{iE_i(\mathbf{p})T}\; e^{-i\mathbf{p}\mathbf{L}} \; \underbrace{f_i^{D*}(\mathbf{p}-\mathbf{Q}'_i) f_i^{S}(\mathbf{p}-\mathbf{Q}_i)}_{overlap}\end{aligned}$$

For Gaussian wave packets overlap is also gaussian:

$$f_i^{D*} f_i^{S} = f_i^{ov}(\mathbf{p} - \langle \mathbf{Q} \rangle_i)\; e^{-(\mathbf{Q}_i - \mathbf{Q}'_i)^2/4/(\sigma_S^2+\sigma_D^2)}$$

$$\begin{aligned}\langle \mathbf{Q} \rangle_i &\equiv \left(\frac{\mathbf{Q}_i}{\sigma_S^2} + \frac{\mathbf{Q}'_i}{\sigma_D^2} \right) \sigma_{ov}^2 \\ \sigma_{ov}^2 &\equiv \frac{1}{1/\sigma_S^2 + 1/\sigma_D^2}\end{aligned}$$

group velocity

$$E_i(\mathbf{p}) \simeq E_i(\langle \mathbf{Q} \rangle_i) + \overbrace{\left.\frac{\partial E}{\partial p_k}\right|_{\langle \mathbf{Q} \rangle_i}}^{\mathbf{v}_i} (p_k - \langle Q_k \rangle_i) + \mathcal{O}(p_k - \langle Q_k \rangle_i)^2$$

$$\mathcal{A}(\nu_\alpha \to \nu_\beta) \propto \sum_i U^*_{\alpha i} U_{\beta i}\; e^{iE_i(\langle \mathbf{Q} \rangle_i)T}\; e^{-i\langle \mathbf{Q} \rangle_i \mathbf{L}}\; e^{-(\mathbf{Q}_i - \mathbf{Q}'_i)^2/4/(\sigma_S^2+\sigma_D^2)}\; e^{-(\mathbf{L}-\mathbf{v}_i T)^2 \sigma_{ov}^2/2}$$

Neutrino oscillations in QM (wavepackets)

$$\langle \mathbf{Q} \rangle_i \simeq \langle \mathbf{Q}' \rangle_i, \quad \mathbf{L} || \langle \mathbf{Q} \rangle_i$$

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &\propto \int_{-\infty}^{\infty} dT \, |\mathcal{A}(\nu_\alpha \to \nu_\beta)|^2 \\ &\propto \sum_{i,j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \; e^{i \frac{m_j^2 - m_i^2}{2E} L} \times \; e^{-L^2/L_{coh}(i,j)^2} \times e^{-\left(\frac{\Delta_{ij} E(\langle Q \rangle)}{2\sigma_{ov} \langle v \rangle}\right)^2}, \end{aligned}$$

$$L_{coh}^{-1}(i,j) \sim \sigma_{ov} \frac{|\mathbf{v}_i - \mathbf{v}_j|}{\sqrt{\mathbf{v}_i^2 + \mathbf{v}_j^2}} \simeq \frac{|m_j^2 - m_i^2|}{2\langle Q \rangle} \frac{\sigma_{ov}}{\langle Q \rangle}$$

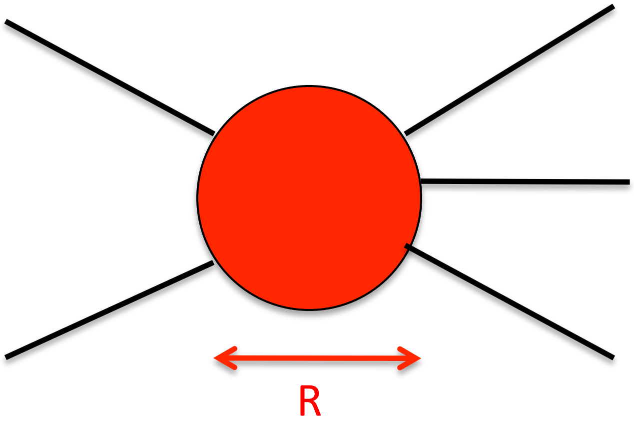
$L > L_{coh}$ coherence is lost

There must be sufficient uncertainty in production & detection so that wave packets include all mass eigenstates: $\Delta E \ll \sigma$

Problems: normalization is arbitrary, needs to be imposed a posteriori

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

Neutrino oscillations in QFT



in-states

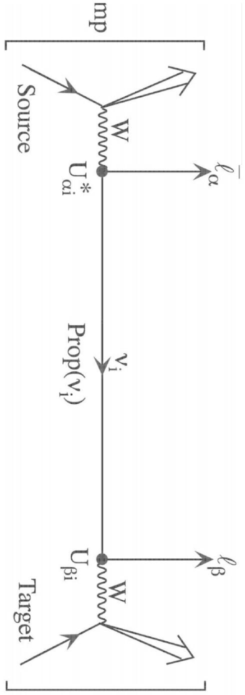
out-states

Idealization: asymptotic states are plane waves if R << Compton wavelength, in reality in-states are wave packets

$$\mathcal{A} = \langle \mathrm{out}; p_1', \ldots, p_n' | \mathrm{in}; p_1, p_2 \rangle$$

Neutrino oscillations in QFT

Neutrinos are not the asymptotic states…



in-states

out-states

$$\mathcal{A} \sim \sum_i \mathcal{A}_S \, U^*_{\beta i} \, \frac{i}{\not{p} - m_i} U_{i\alpha} \mathcal{A}_D$$

Neutrino propagator: intermediate state

Neutrino oscillations in QFT

Example: neutrino beam from π decay at rest

in-states: pion + nucleus (or nucleon) in detector

out-states: μ from π decay + l + hadron jet from ν interaction

Necessary to adapt standard formalism:

1) macroscopic separation of Source and Detector L (eg. localized wave packets of in-states + static approximation)

2) oscillation probability from factorization:

decay x propagation x ν cross-section

$$\frac{dW(\pi n \to p\mu l_\beta)}{dt dp_\mu dp_p dp_l} = \int d|q| \quad \underbrace{\frac{dW(\pi \to \mu\nu)}{L^2 dt d\Omega_\nu d|q| dp_\mu}}_{\text{Flux per unit neutrino momentum}} \times P(\nu_\mu \to \nu_\beta) \times \underbrace{\frac{1}{2|q|}\frac{dW(\nu n \to pl)}{dt dp_p dp_l}}_{\text{interaction probability per unit flux}}$$

Oscillation probability is indeed properly normalized!

Neutrino Oscillation

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

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

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

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

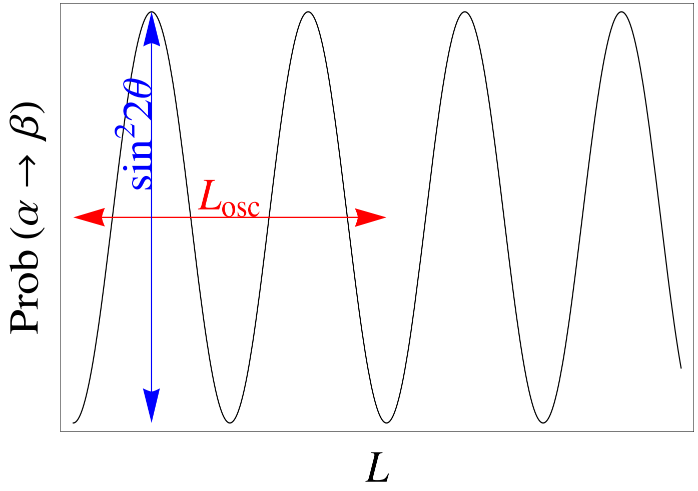
CP-even $\quad - \quad 4\sum_{i<j} \mathrm{Re}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin^2\left[\frac{\Delta m^2_{ji} L}{4E}\right]$

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

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

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

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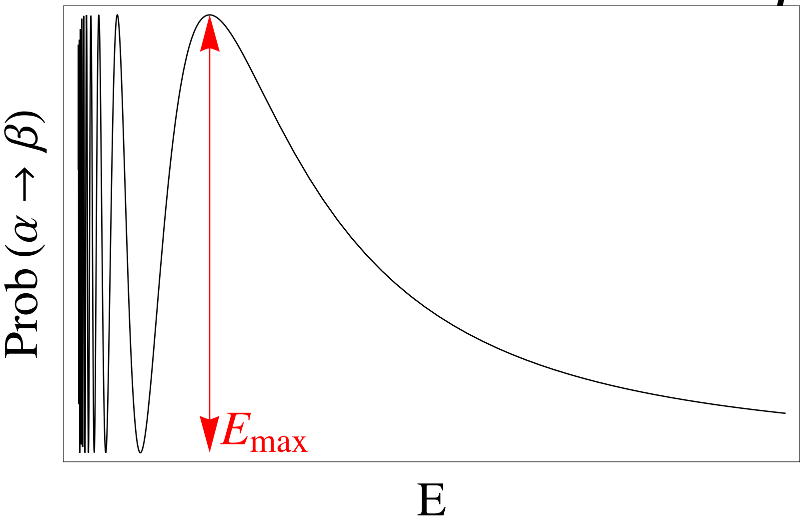


$$E_{max}(GeV) = 1.27\frac{\Delta m^2(eV^2)L(km)}{\pi/2}$$

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

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

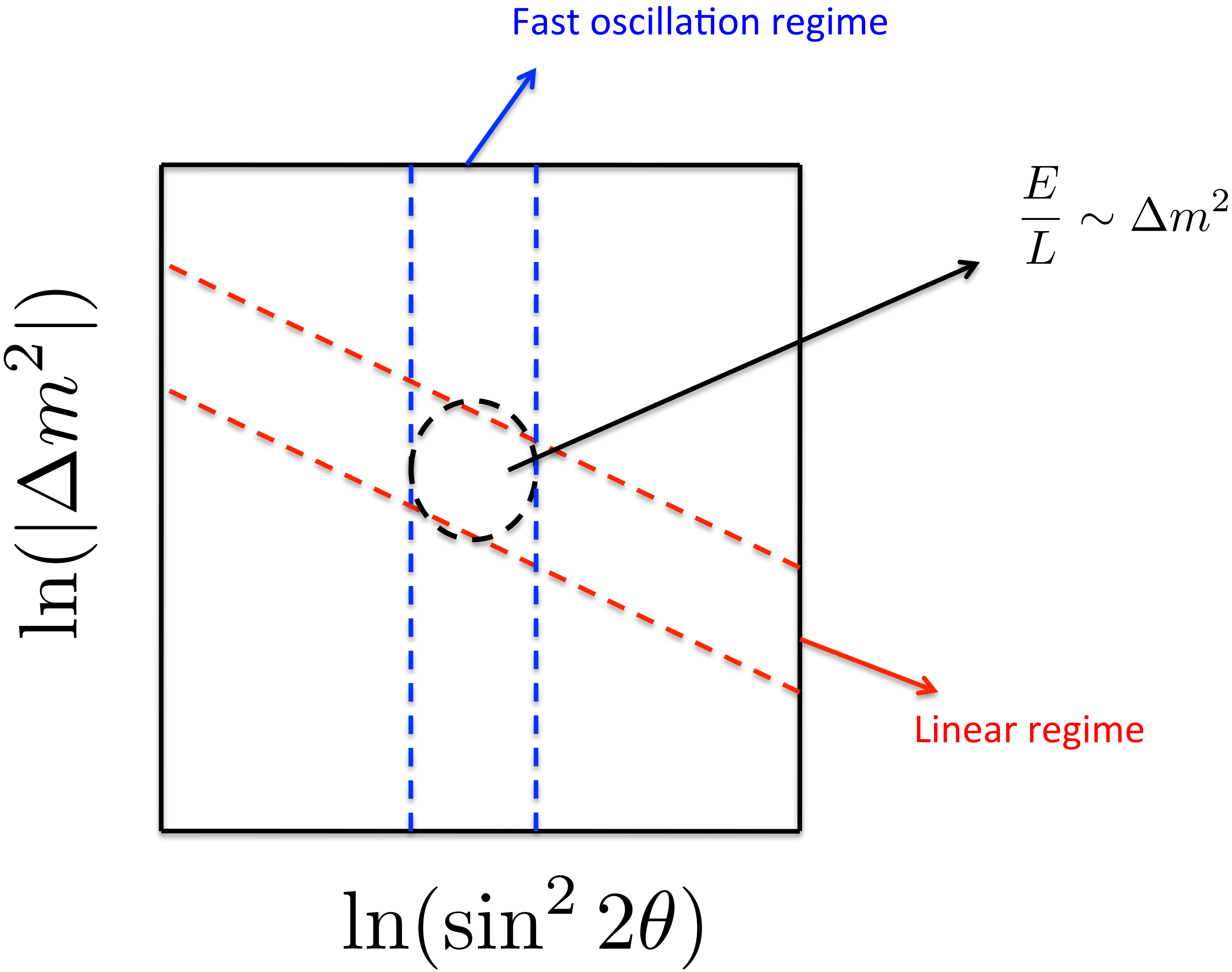
$\frac{E}{L} \gg \Delta m^2$ Oscillation suppressed

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

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

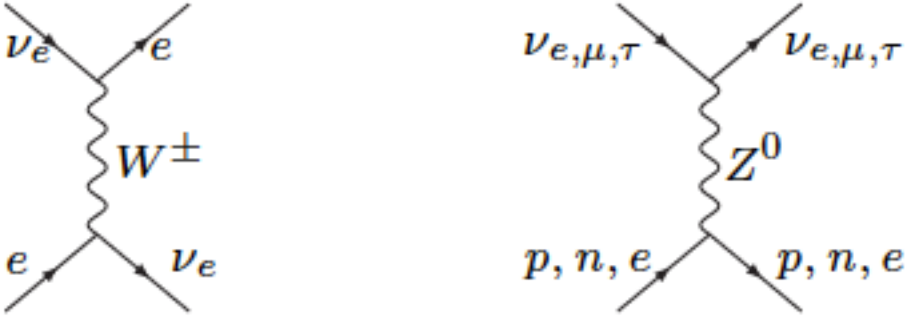
$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \, \langle \sin^2 \frac{\Delta m^2 L}{4E} \rangle \simeq \frac{1}{2} \sin^2 2\theta = |U^*_{\alpha 1} U_{\beta 1}|^2 + |U^*_{\alpha 2} U_{\beta 2}|^2$$

Equivalent to incoherent propagation: sensitivity to mass splitting is lost


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

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

Coherent forward scattering can strongly affect the oscillation probability

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

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

Neutrino Oscillations in matter

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

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

$$\mathcal{O}(V_m^2, M_\nu^2 V_m)$$

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

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

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

Neutrino Oscillations in matter

In constant matter density: effective mixing angles and masses depend on energy

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

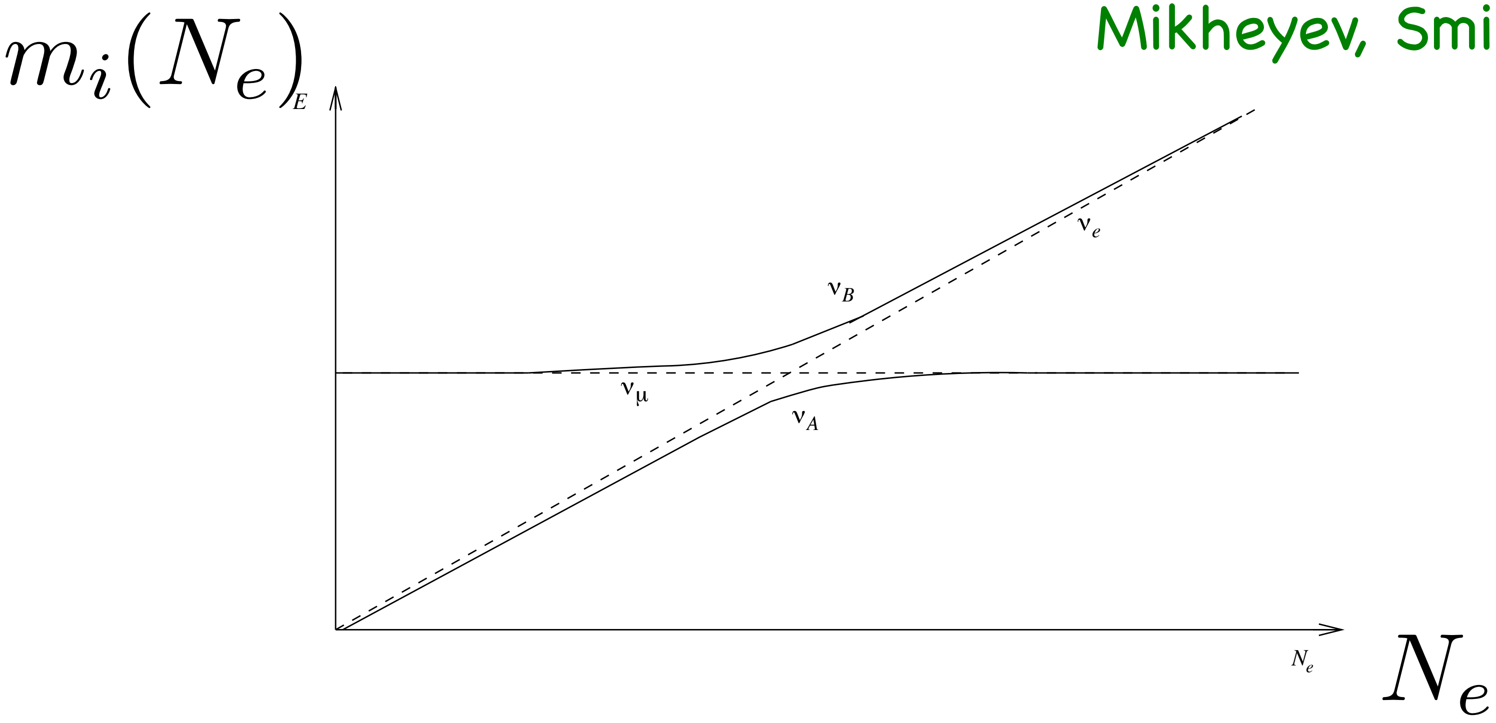
For two families (- neutrinos, + antineutrinos):

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

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

MSW resonance

Mikheyev, Smirnov '85



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

$$\sin^2 2\tilde{\theta} = 1, \quad \Delta\tilde{m}^2 = \Delta m^2 \sin 2\theta$$

-Maximal mixing any $\theta \neq 0$
-Only for ν or $\bar{\nu}$, not both
-Only for one sign of Δm^2

Neutrinos in variable matter

Solar neutrinos propagate in variable matter (the electron density varies exponentially as a function of radius)

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

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)

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

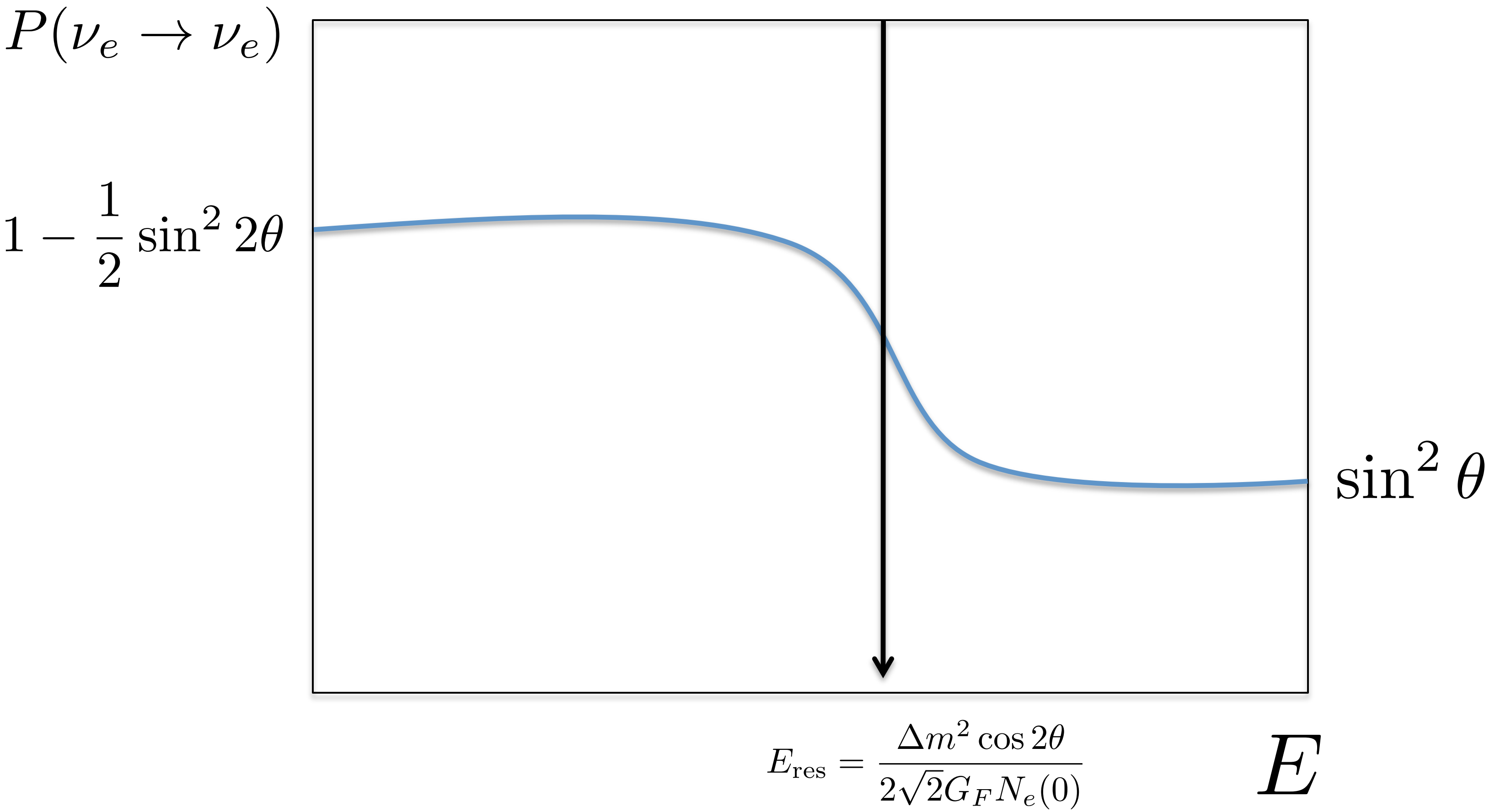
$$2\sqrt{2}G_F E N_e(0) \ll \Delta m^2 \cos 2\theta \to \tilde{\theta}(0) \simeq \theta$$

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

$$2\sqrt{2}G_F E N_e(0) \gg \Delta m^2 \cos 2\theta \to \tilde{\theta}(0) \simeq \frac{\pi}{2}$$

$$P(\nu_e \to \nu_e) \simeq \sin^2 \theta$$

Solar neutrinos



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

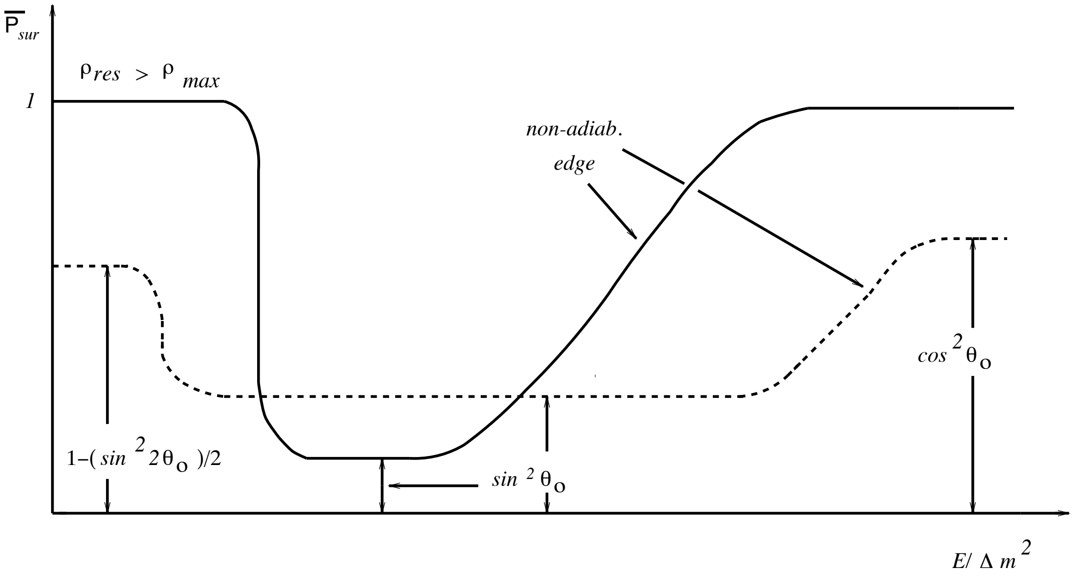
MSW resonance energy

Beyond adiabaticity

When the splitting of the energy levels is similar to the energy injected in the system by the variation of the density: transitions between energy levels occur

$$\left|\frac{d\theta_m}{dt}\right| \sim |\Delta E_m|$$

$$\gamma \equiv min_r \left(\frac{\sin^2 2\theta}{\cos 2\theta} \frac{\Delta m^2}{2E} \frac{1}{|\nabla_r \log N_e|} \right)$$



$$P(\nu_e \to \nu_e) = \sum_{i,j\neq i} \left[|\langle \nu_e|\tilde{\nu}_i(\infty)\rangle|^2 (1-P_C) + |\langle \nu_e|\tilde{\nu}_j(\infty)\rangle|^2 P_C \right] |\langle \tilde{\nu}_i(0)|\nu_e\rangle|^2$$

Level-transition probability: $P_C = e^{-\pi\gamma/2}$

Neutrino Oscillations in a cosmic thermal soup

In the early universe neutrinos propagate in the presence of a thermal ensemble: particles and antiparticles Fermi distributions at T

$$N_i^{\pm}(E) = \frac{g_i}{e^{-(E \mp \mu)/T} + 1}$$

Dirac fermions: $g_i = 2$

Processes involving scattering+ production + annhilation of i-th particle keep it in equilibrium if

$$\Gamma_i \simeq \sum_{\text{processes}} \text{density} \times \text{cross section} \gg H(T)$$

$$T \ll T_{QCD} \sim 200 MeV \qquad e^{\pm}, \nu_{\alpha}, \bar{\nu}_{\alpha}, p, n$$

Neutrino Oscillations in a cosmic thermal soup

$$\eta_i \equiv \frac{N_i - N_{\bar{i}}}{N_\gamma} \qquad\qquad T \ll T_{QCD} \sim 200 MeV$$

$$V_m^{(e)} \simeq \mp 0.95(2\eta_{\nu_e} + \eta_{\nu_\mu} + \eta_{\nu_\tau} + \eta_e - \frac{1}{2}\eta_n) G_F T^3 + 0.61 \frac{E_\nu G_F^2 T^4}{\alpha}$$

$$V_m^{(\mu)} \simeq \mp 0.95(\eta_{\nu_e} + 2\eta_{\nu_\mu} + \eta_{\nu_\tau} - \frac{1}{2}\eta_n) G_F T^3 + 0.17 \frac{E_\nu G_F^2 T^4}{\alpha}$$

$$V_m^{(\tau)} \simeq \underbrace{\mp 0.95(\eta_{\nu_e} + \eta_{\nu_\mu} + 2\eta_{\nu_\tau} - \frac{1}{2}\eta_n) G_F T^3}_{} + \underbrace{0.17 \frac{E_\nu G_F^2 T^4}{\alpha}}_{}$$

Matter/antimatter asymmetric/symmetric backgrounds

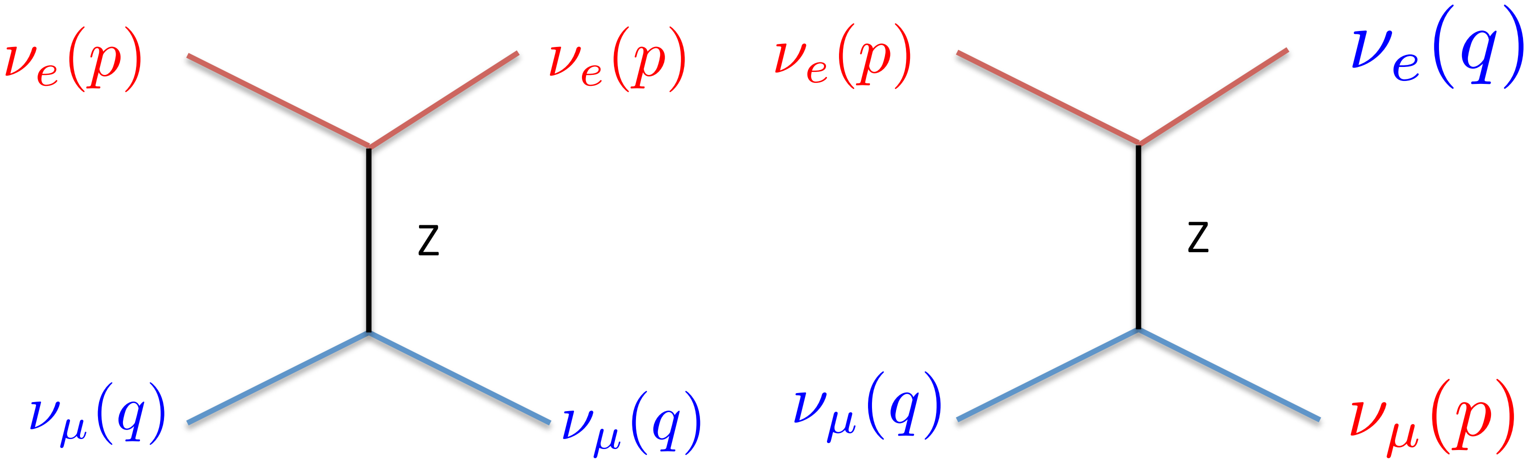
Nötzold, Raffelt

Important application: thermalization of extra neutrino species !

Neutrino Oscillations in Supernova

Neutrino density is very high: coherent scattering on background neutrinos important

Pantaleone

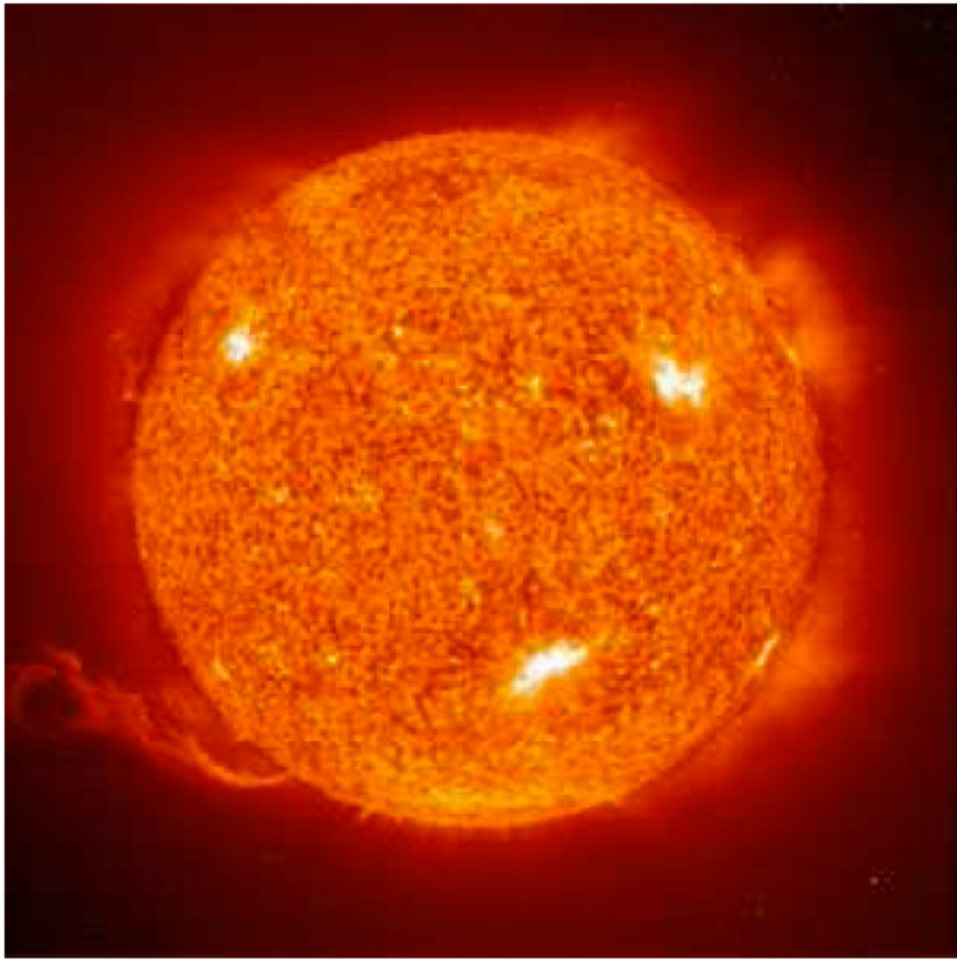


New level of complexity: flavour changing coherent scattering, the problem becomes non-linear, collective effects...

Lecture III:

- Evidence for neutrino mass: experimental landscape
- The standard 3ν scenario
- A few outliers…

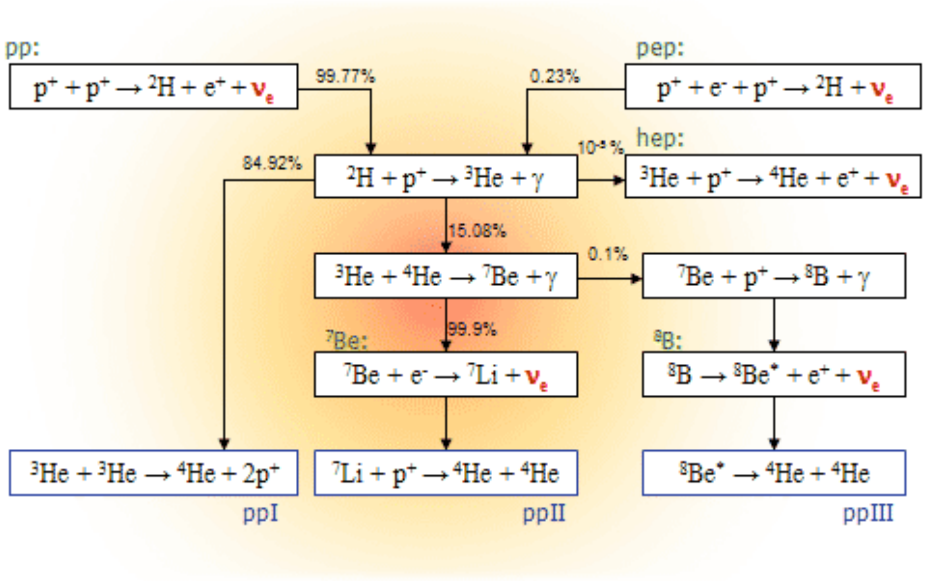
SOLAR Neutrinos



Stars shine neutrinos

1939 Bethe

Stablishes the theory of stelar nucleosynthesis



pp:

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99.77%

pep:

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

0.23%

84.92%

${}^2H + p^+ \rightarrow {}^3He + \gamma$

10^{-5} %

hep:

${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

15.08%

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

0.1%

${}^7Be + p^+ \rightarrow {}^8B + \gamma$

99.9%

${}^7Be$:

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^8B$:

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^3He + {}^3He \rightarrow {}^4He + 2p^+$

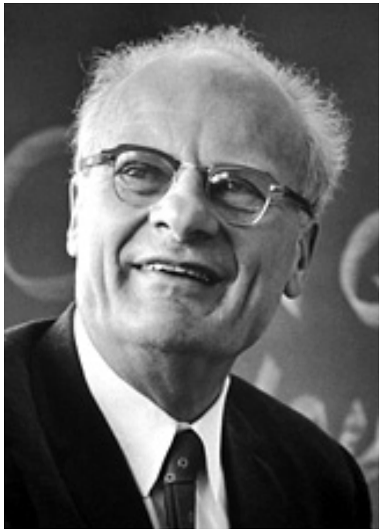
ppI

${}^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

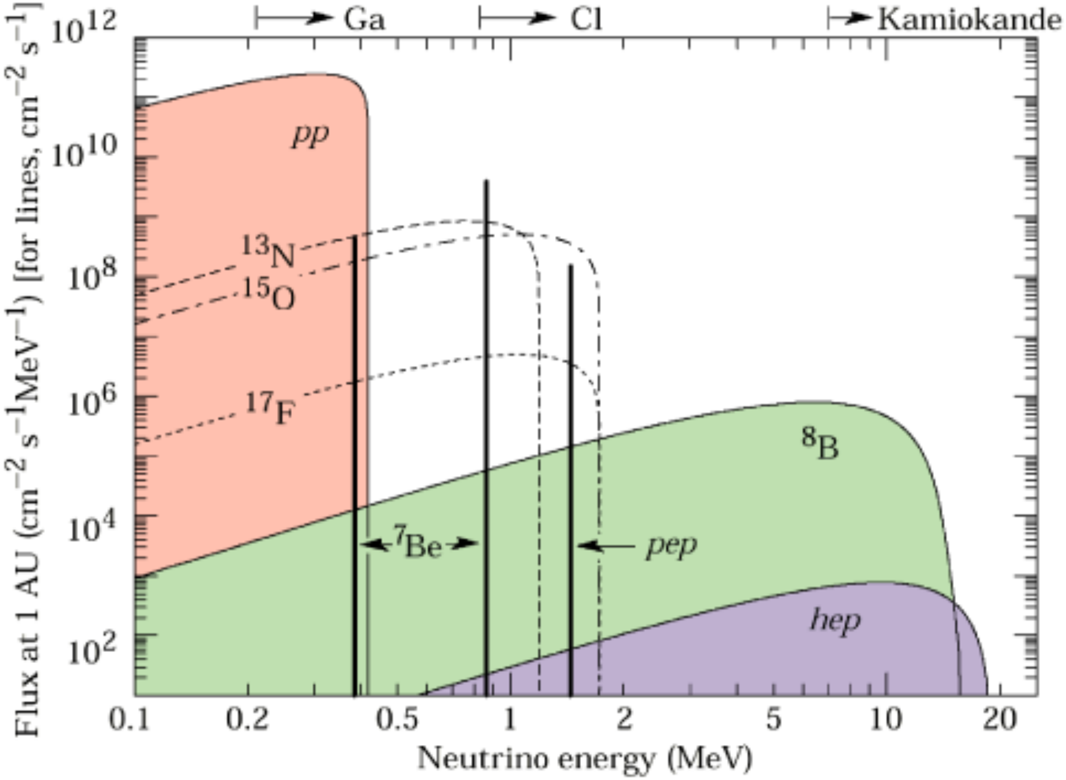
${}^8Be^* \rightarrow {}^4He + {}^4He$

ppIII



Nobel 1967

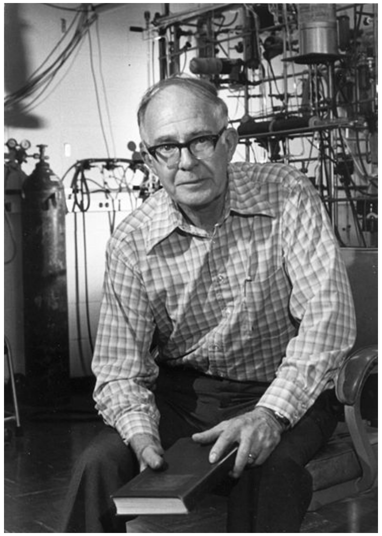
¿How many neutrinos from the Sun ?



Bahcall (died 2005)

1 ν each day in a olympic swimming pool (400000 liters of clorine)...

The hero of the caves



Raymond Davies

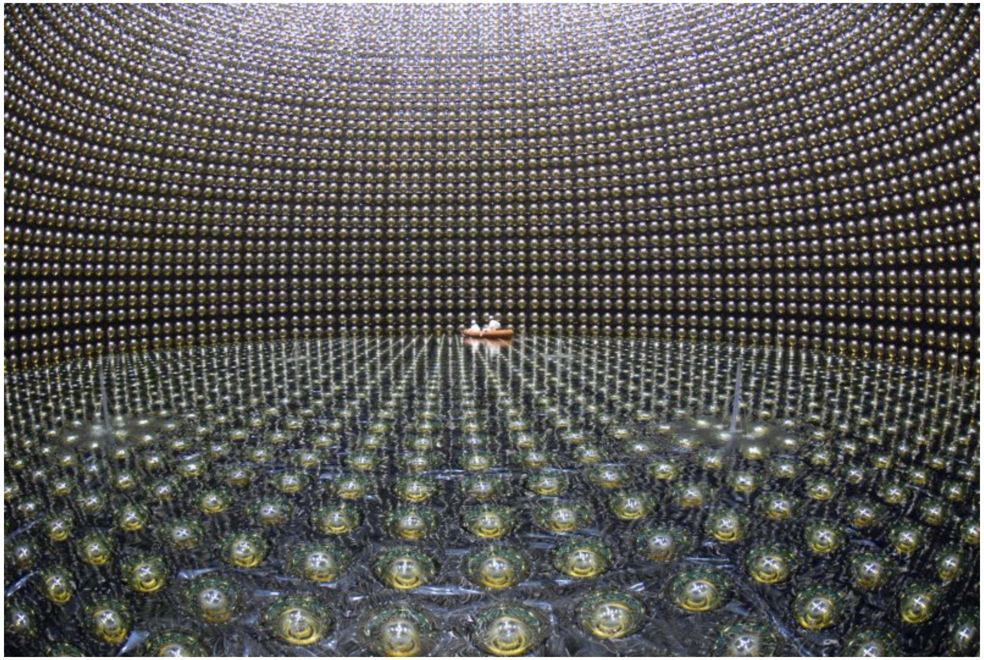
Nobel 2002

1966 he detects for the first time solar neutrinos in a pool of 400000 liters 1280m underground (Homestake mine)

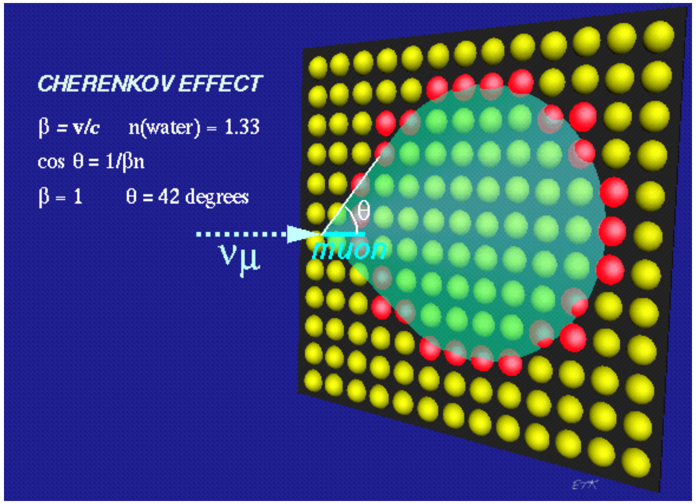
Did not convince because he saw 0.4 of the expected….

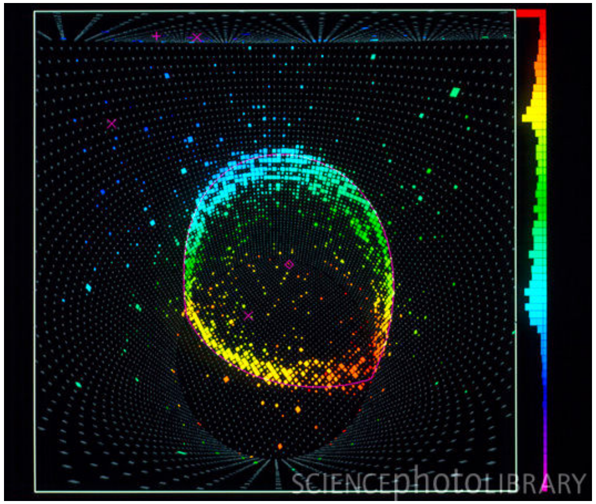
Problem in detector ? In solar model ? In neutrinos ?

Underground cathedrals of light



Koshiba (Nobel 2002)
and the anti-bulb





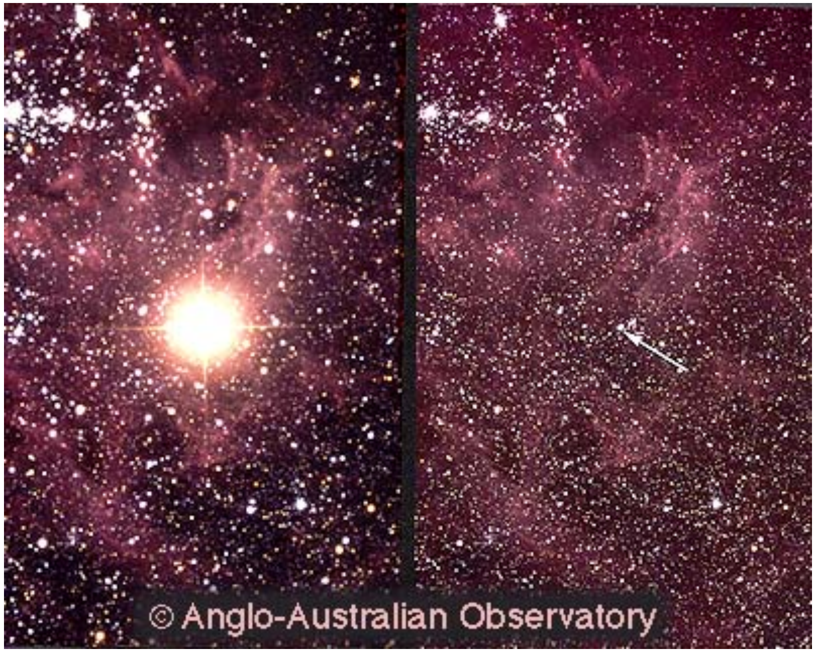
Allows to reconstruct velocity and direction

In reality they were looking for proton decay and neutrinos were the background…

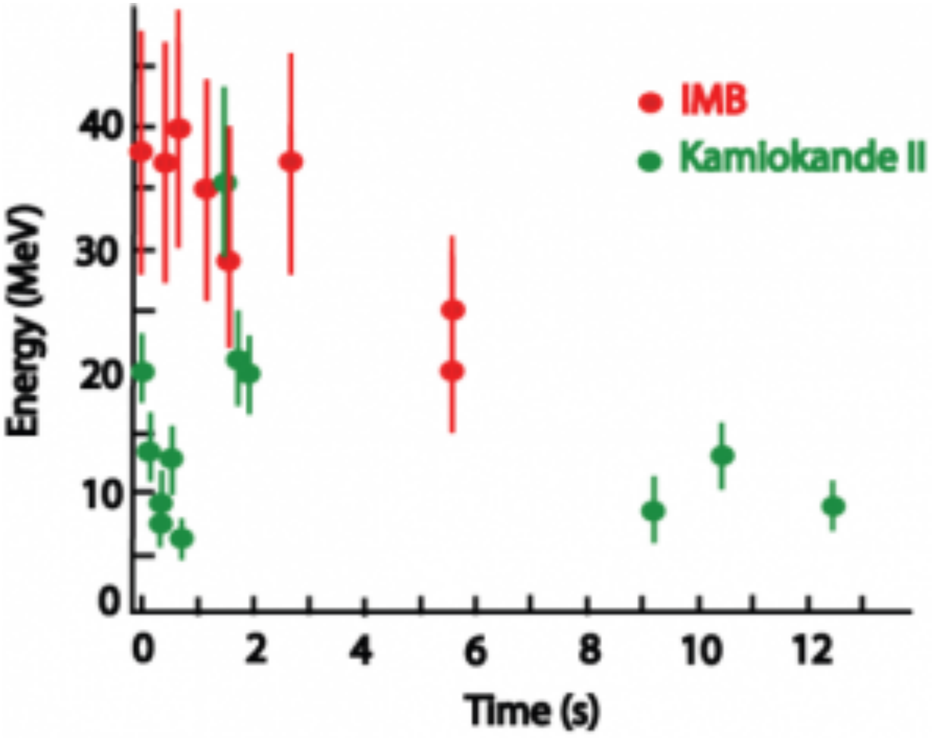
The decenium mirabilis of neutrino physics had started…

Supernova 1987

7:36 (UT) 23/2/1987



© Anglo-Australian Observatory

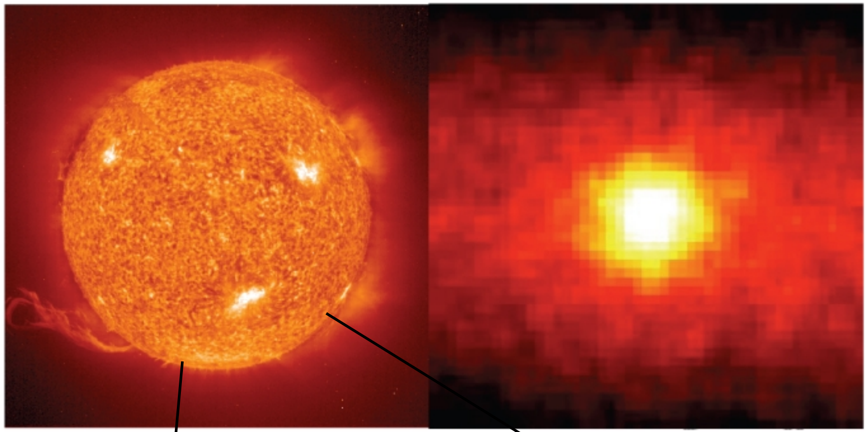


First seen in neutrinos than photons: neutrinos travel at speed of light (~10^{-9})

$$\Delta t = 5.1ms \left(\frac{D}{10\ kpc}\right)\left(\frac{10\ MeV}{E_\nu}\right)^2\left(\frac{m_\nu}{1\ eV}\right)^2$$

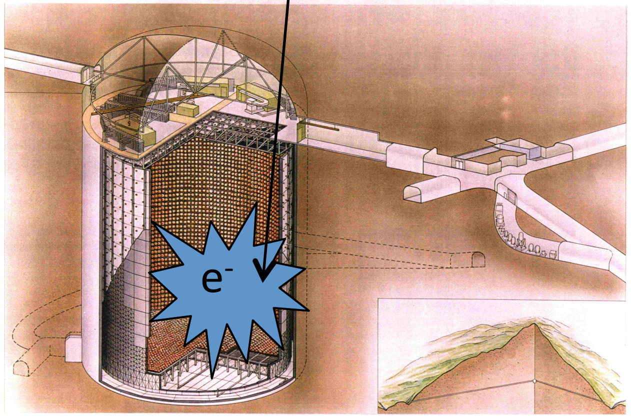
Zatsepin

Solar Neutrinos



Neutrinography of the sun

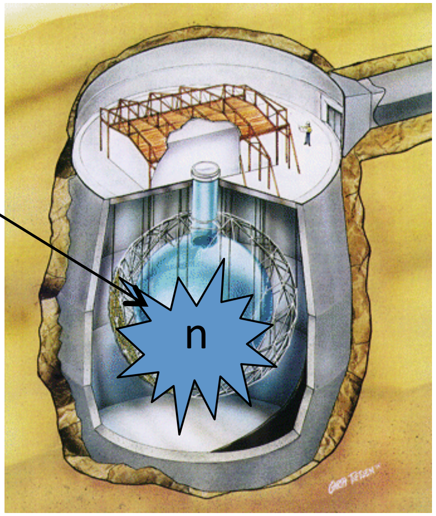
SuperKamiokande (22.5 kton!)



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO (c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo NIKKEN SEKKEI

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

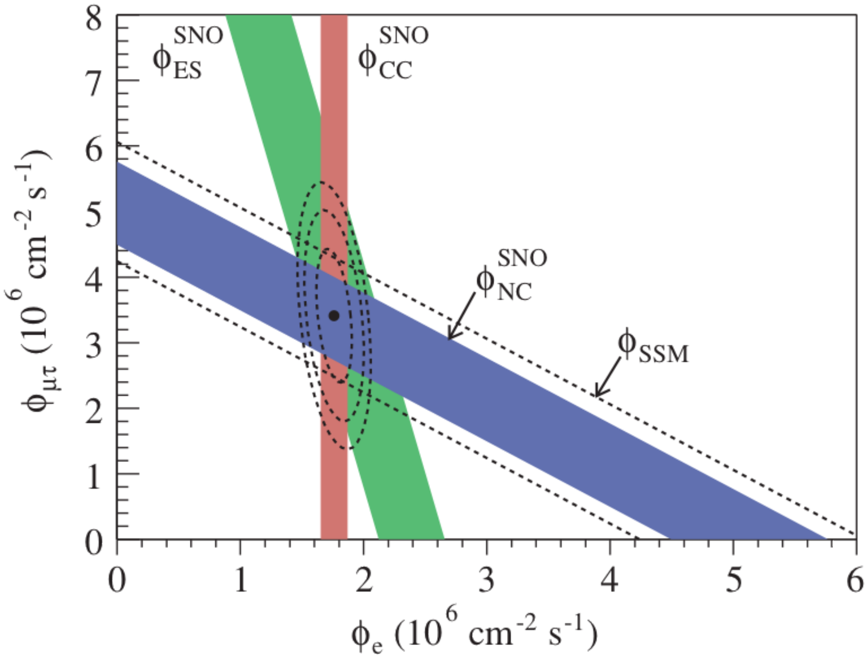
SNO

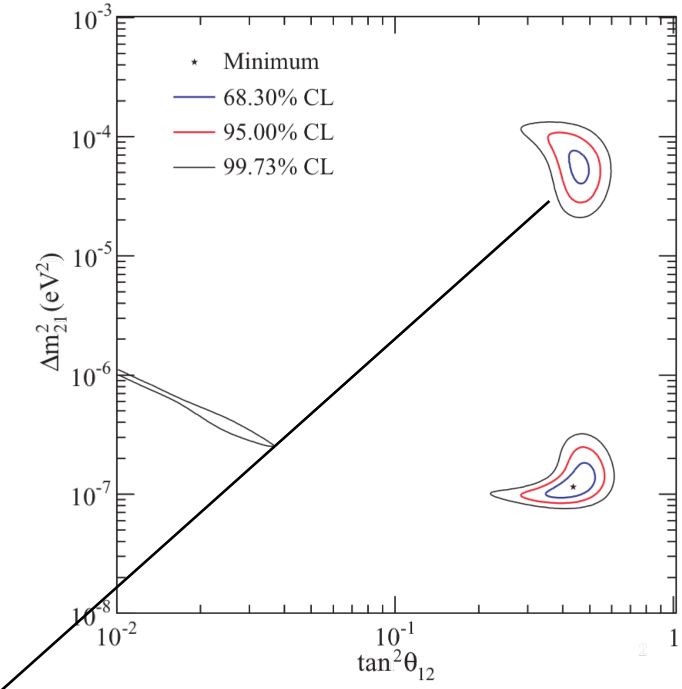


$$NC: \quad \nu_i + d \rightarrow p + n + \nu_i$$

$$CC: \quad \nu_e + d \rightarrow p + p + e^-$$

Flavour of solar neutrinos





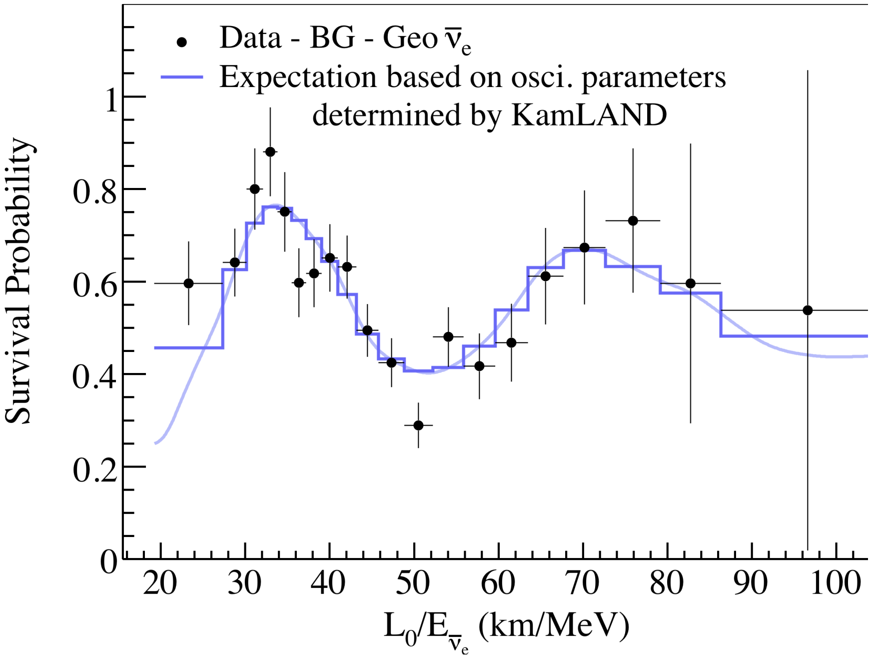
$$|\Delta m^2| \sim \frac{O(100Km)}{O(MeV)}$$

Can be tested in the Earth with Reines&Cowen experiment !

KamLAND: solar oscillation

$$\overline{\nu}_e \to \overline{\nu}_e$$

Reines&Cowan experiment ½ century afterwards
at 170 km from Japenese reactors (before the Big One)..



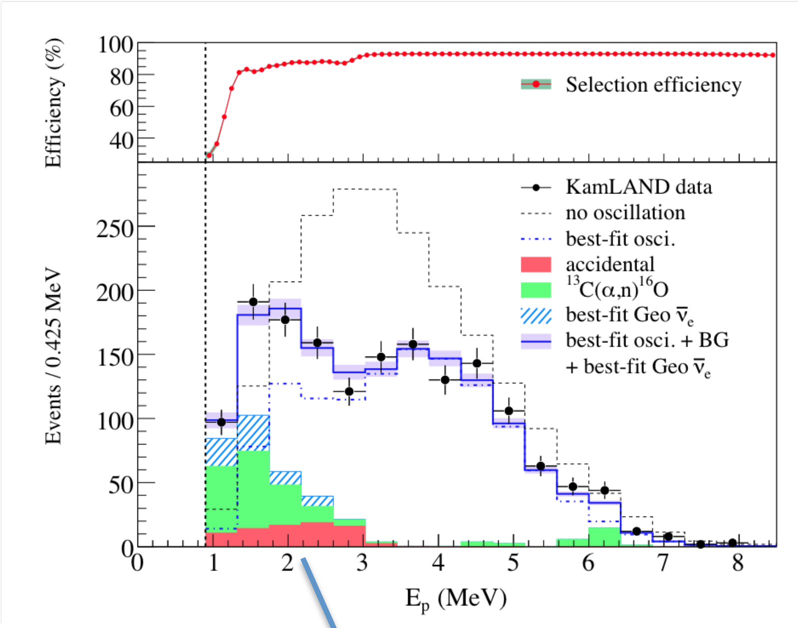
$$\boxed{\Delta m^2_{\text{solar}} \simeq 8 \times 10^{-5}\ eV^2}$$

Large mixing

KamLAND: solar oscillation

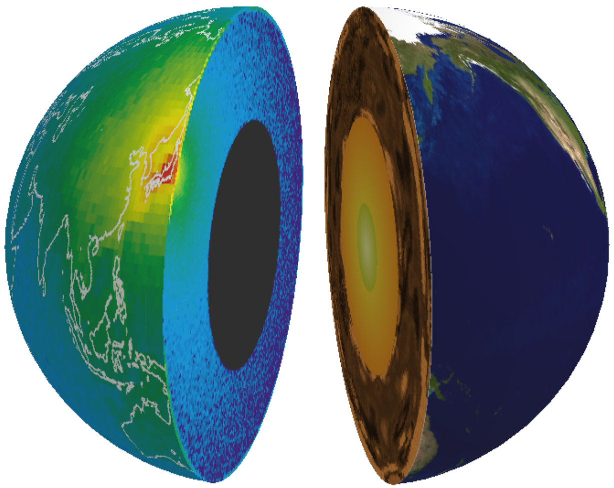
$$\overline{\nu}_e \rightarrow \overline{\nu}_e$$

Reines&Cowan experiment ½ century afterwards
at 170 km from Japenese reactors (before the Big One)..



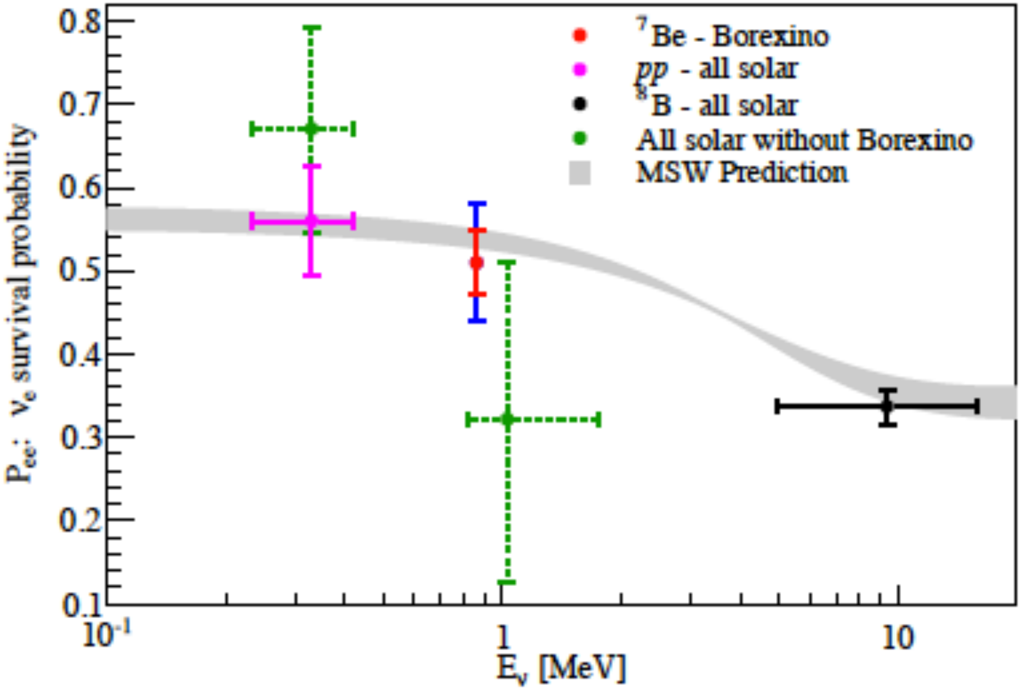
Geoneutrinos!!

$$\boxed{\Delta m^2_{\text{solar}} \simeq 8 \times 10^{-5}\ eV^2}$$



Start of Earth science with neutrinos !

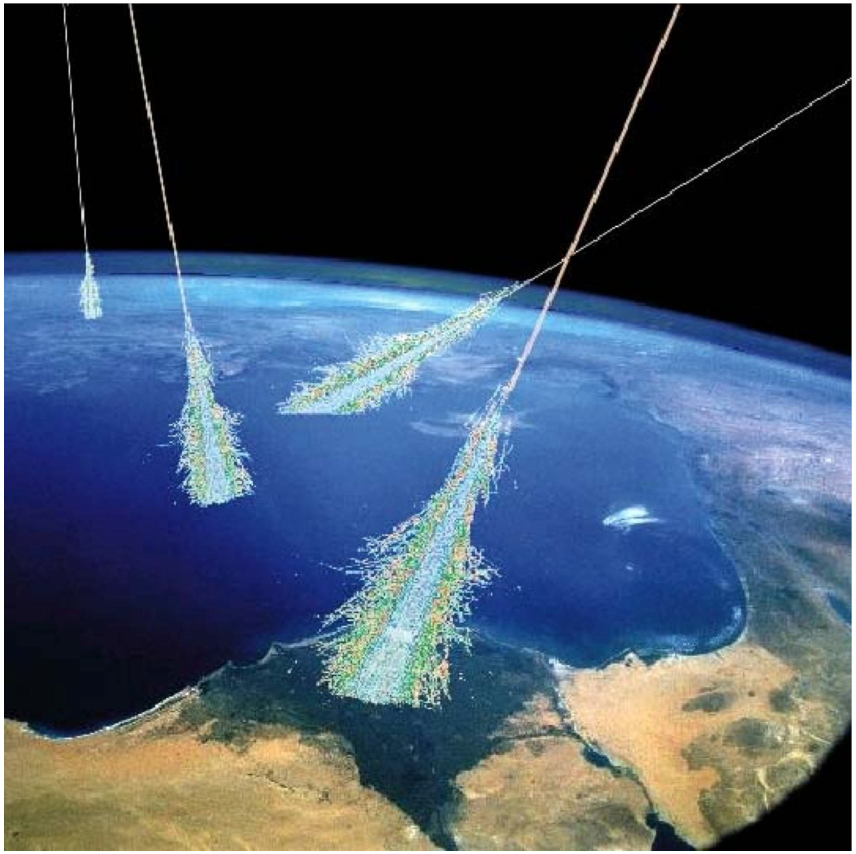
Borexino: precision era



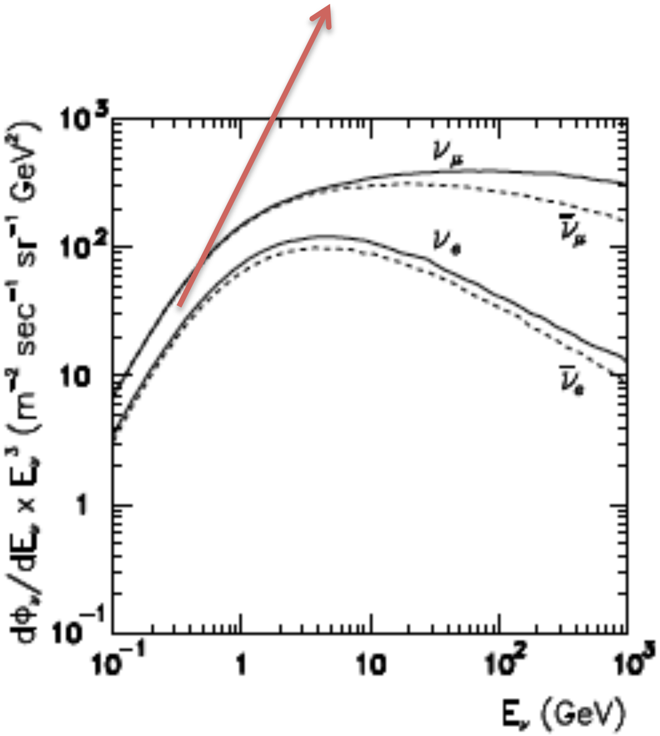
Borexino 2011

Solar neutrinos have become a tool to test solar models, to study the Earth...

Atmospheric Neutrinos

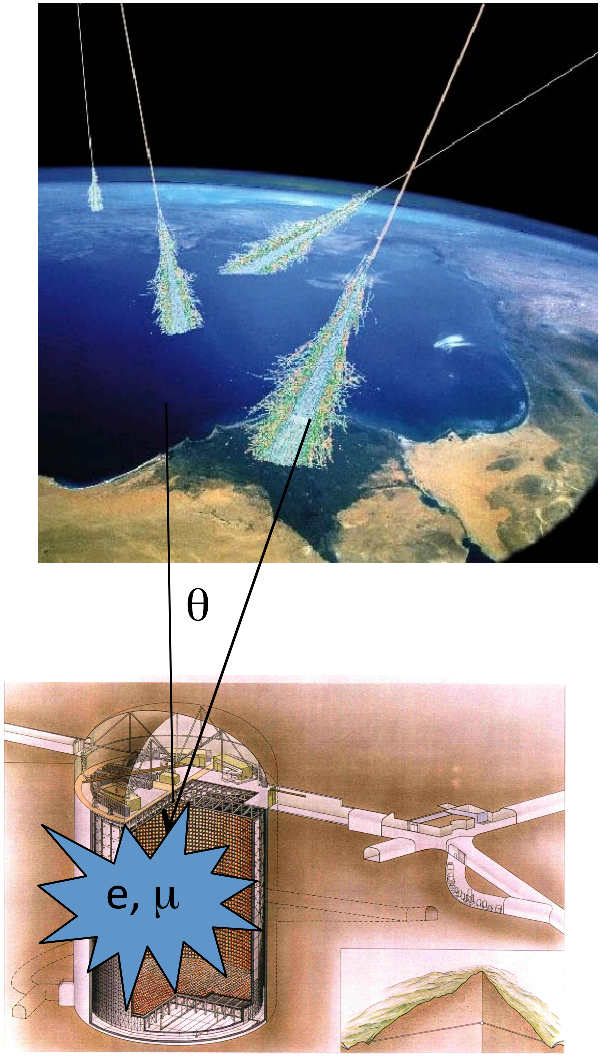


$\nu_\mu/\nu_e \sim 2$



Produced in the atmosphere when primary cosmic rays collide with it, producing π, K

Atmospheric Neutrinos



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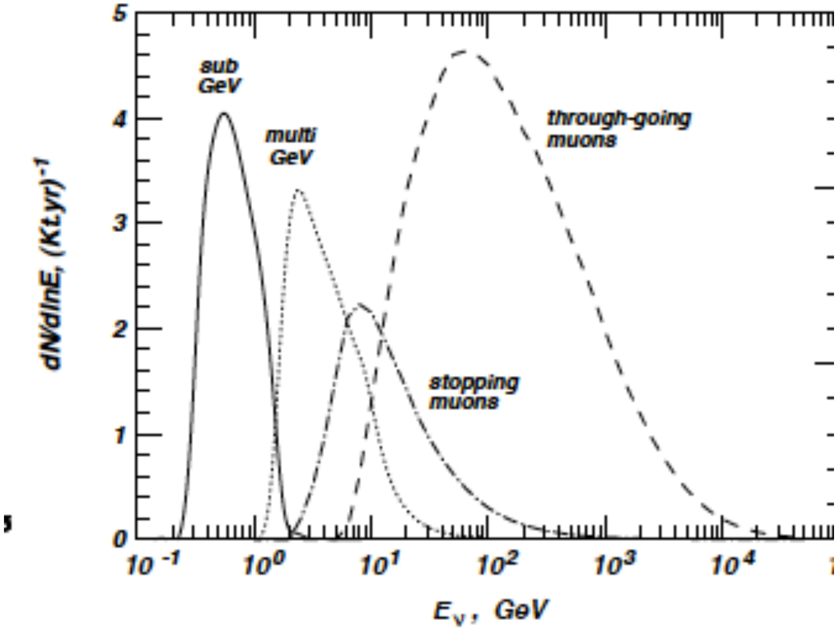
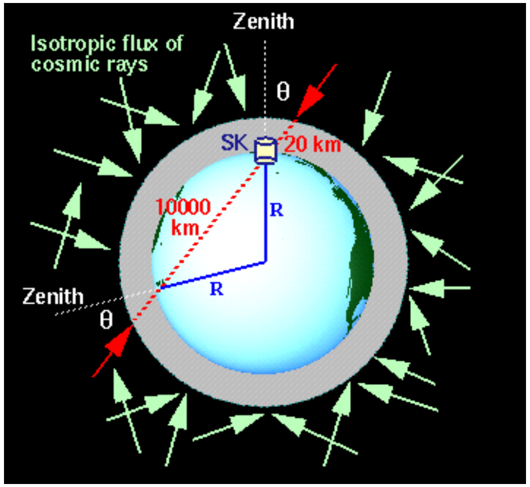
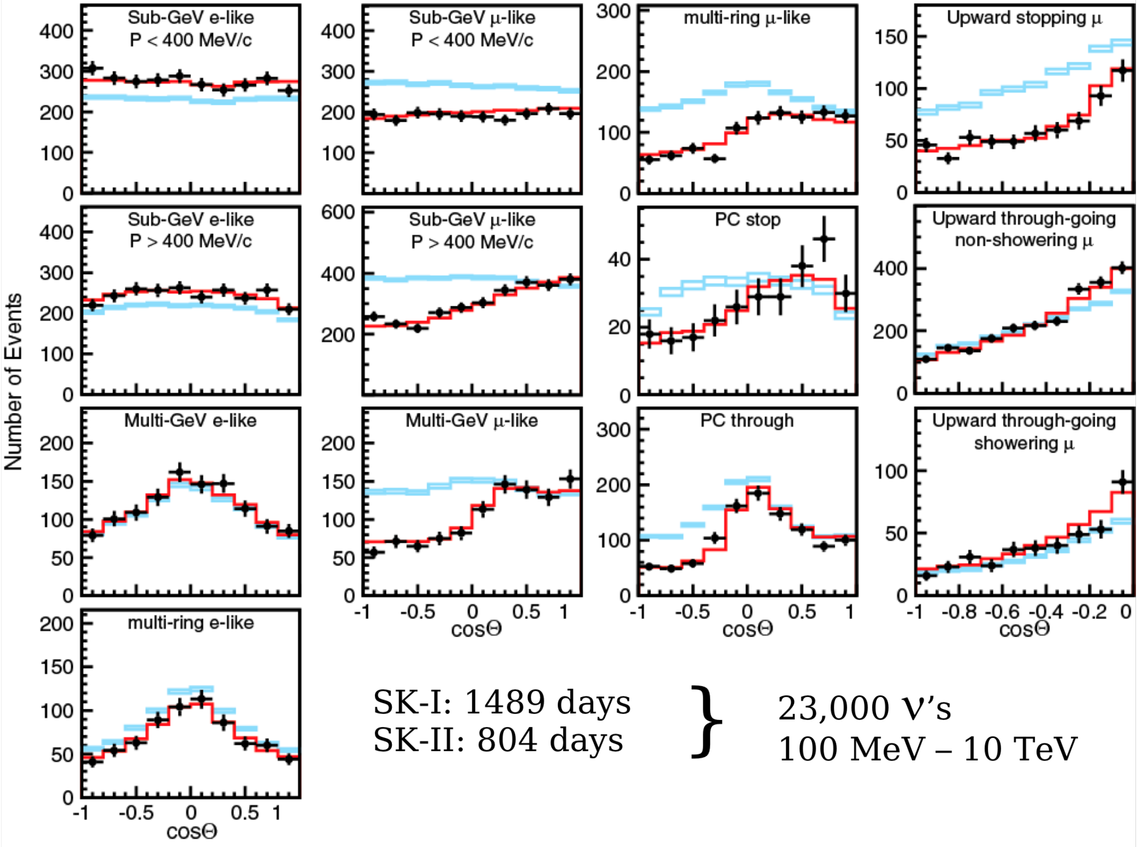
NIKKEN SEKKEI





$$L = 10 - 10^4 \text{ Km}$$

Atmospheric Neutrinos

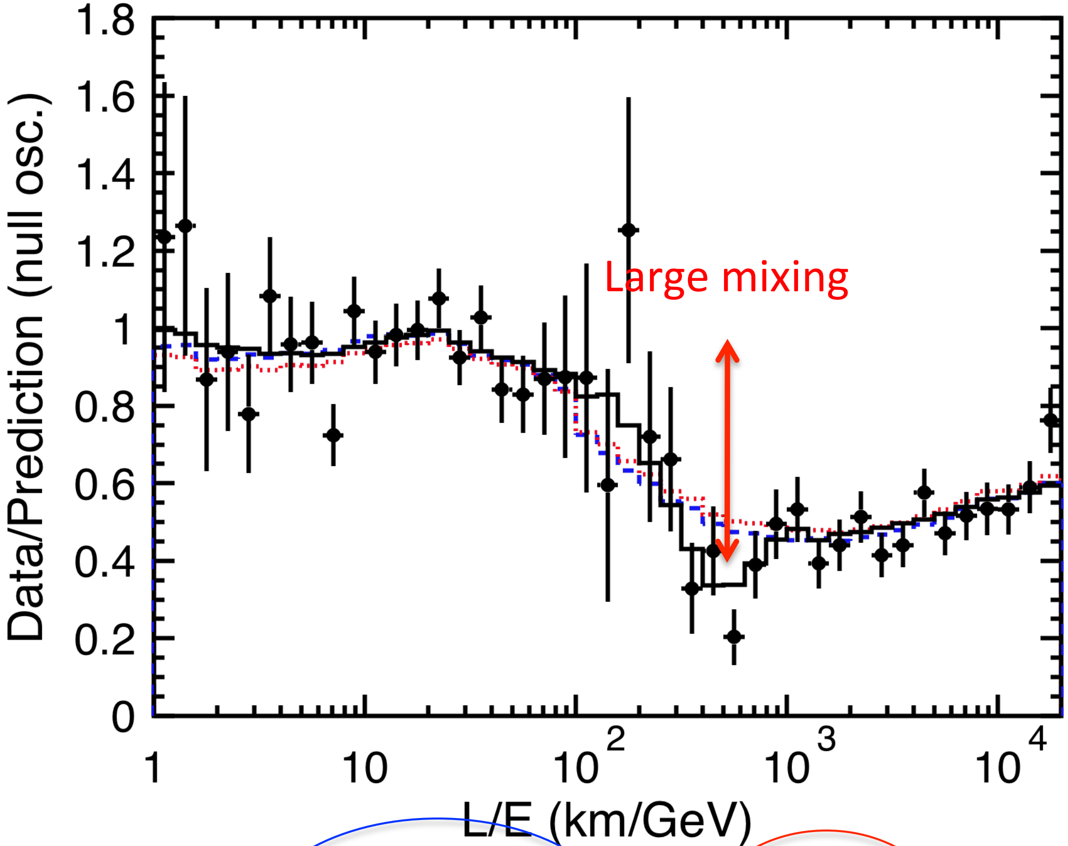


SK-I: 1489 days
SK-II: 804 days

}

23,000 ν's
100 MeV – 10 TeV

Atmospheric Oscillation



Large mixing

$$\Delta m^2_{\rm atm} = 2.5 \times 10^{-3} eV^2$$

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

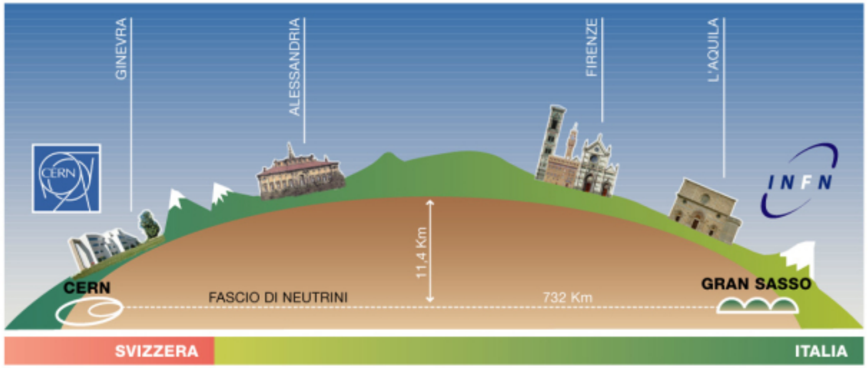
Reines&Cowan experiment at 1km!

Lederman&co experiment at 1000km!

Lederman&co neutrinos oscillate with the atmospheric wave length

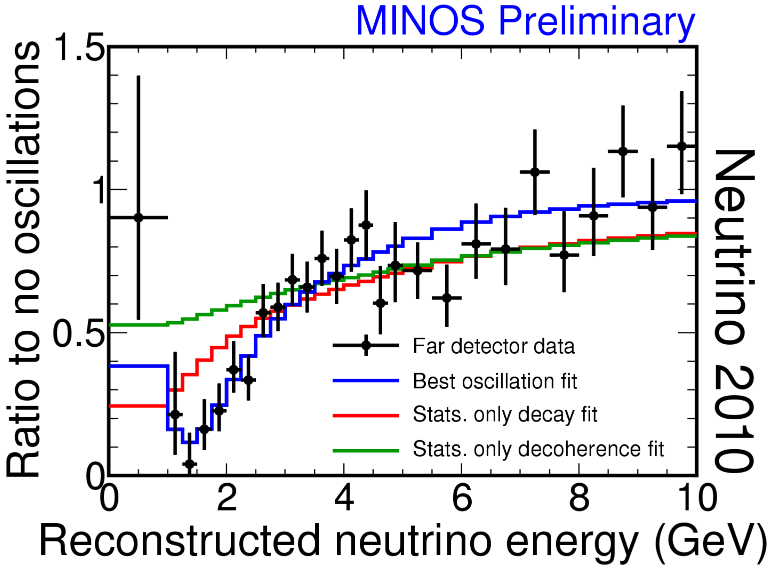
Pulsed neutrino beams to 700 km baselines

Opera



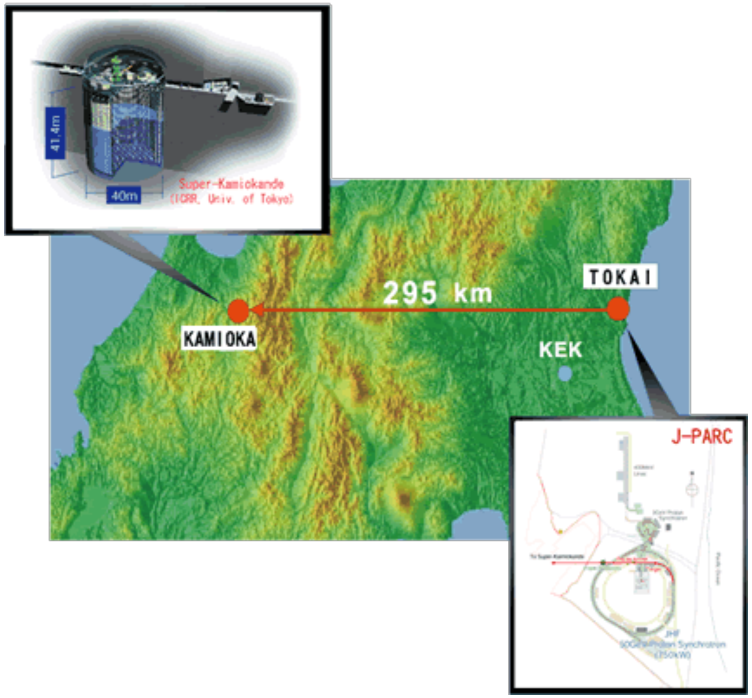
MINOS

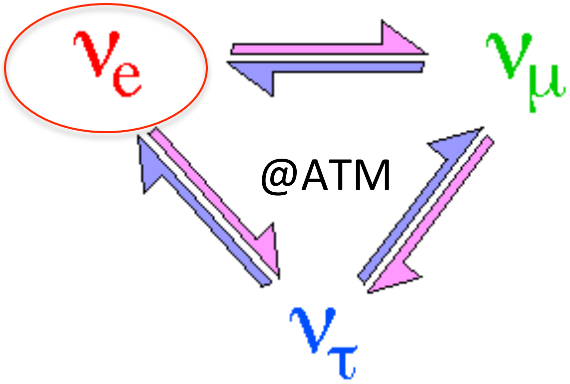
$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3}\ eV^2$$



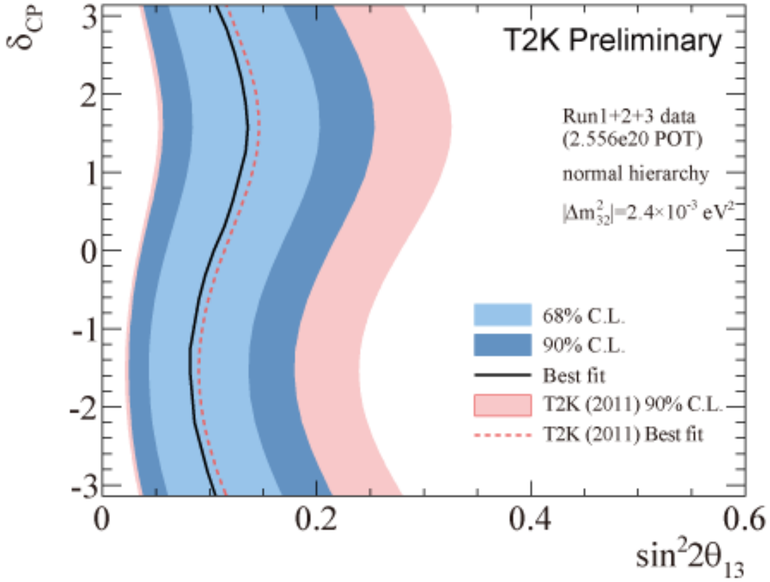
$$\nu_\mu \to \nu_\mu$$

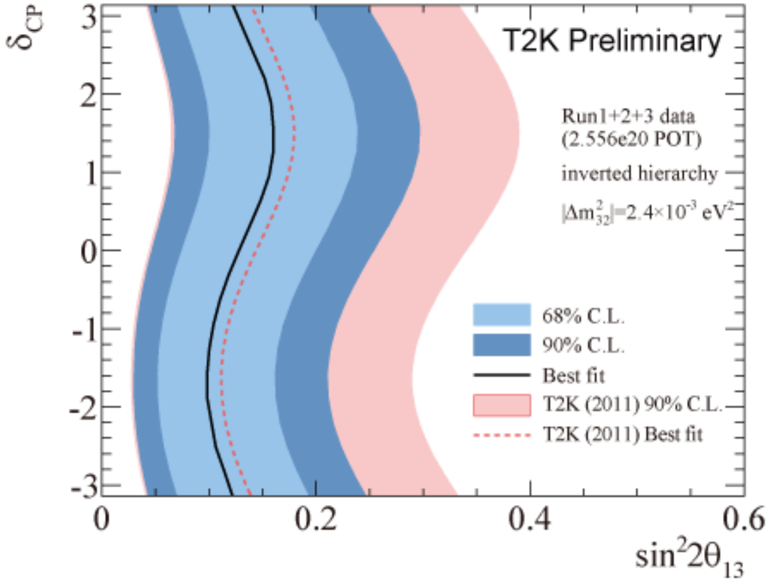
T2K





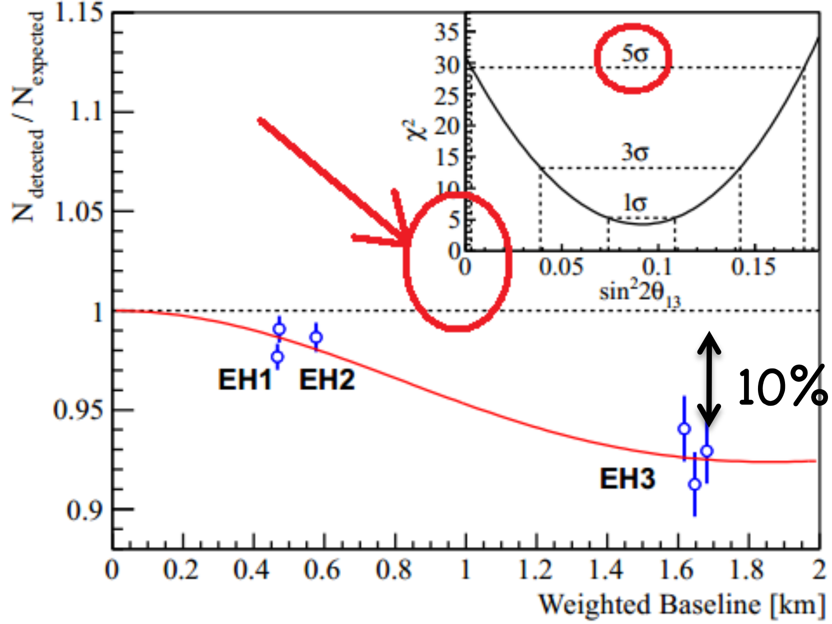
$$\nu_\mu \rightarrow \nu_e$$



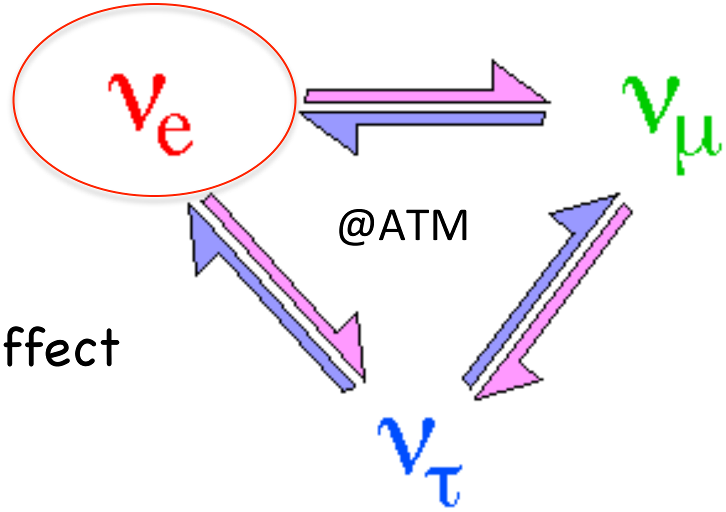


Reines&Cowan (reactor) neutrinos oscillate with atmospheric wave length

Daya Bay



10% effect



$$\bar{\nu}_e \to \bar{\nu}_e$$

Two different wave lengths

2012 Double Chooz, Daya Bay, RENO

Modern copies of the influential experiment Chooz that barely missed the effect and set a limit

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

$$\begin{aligned}
P(\nu_e \to \nu_\mu) &= s^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)\\
P(\nu_e \to \nu_\tau) &= c^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)\\
P(\nu_\mu \to \nu_\tau) &= c^4_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)\\
P(\bar\nu_e \to \bar\nu_e) &= 1 - \sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)
\end{aligned}$$

$\approx 1 \Rightarrow \theta_{13}=0$

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

Chooz

$$\begin{aligned}
P(\nu_e \to \nu_\mu) &= s^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right) \approx 0\\
P(\nu_e \to \nu_\tau) &= c^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right) \approx 0\\
P(\nu_\mu \to \nu_\tau) &= c^4_{13}\,\boxed{\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)}\\
P(\bar\nu_e \to \bar\nu_e) &= 1 - \sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right) \approx 1
\end{aligned}$$

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

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

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

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

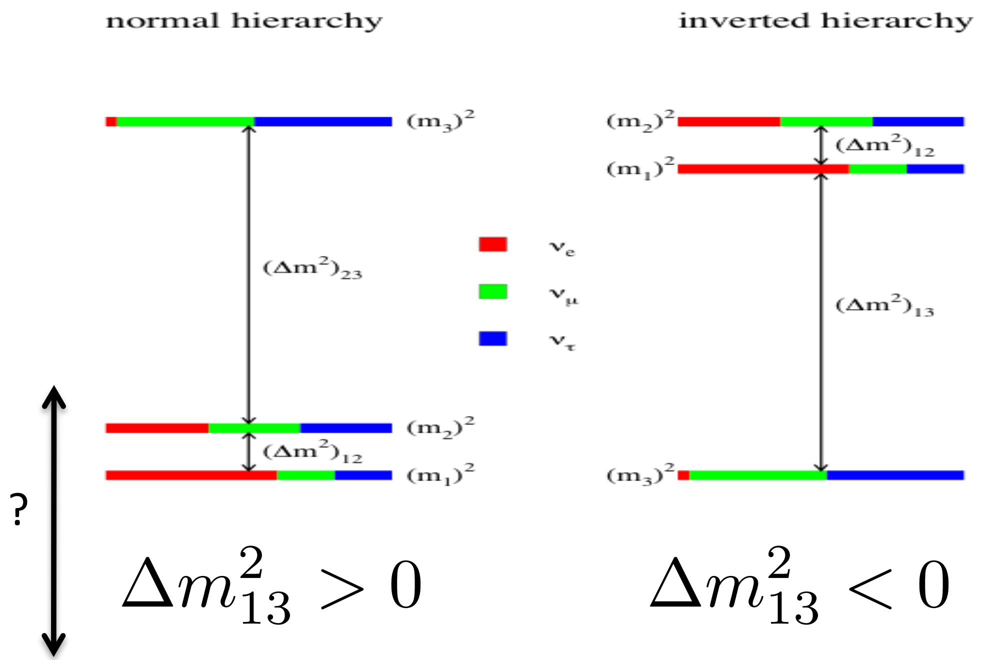
Experiments in the solar range are described approximately by 2x2 mixing with

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

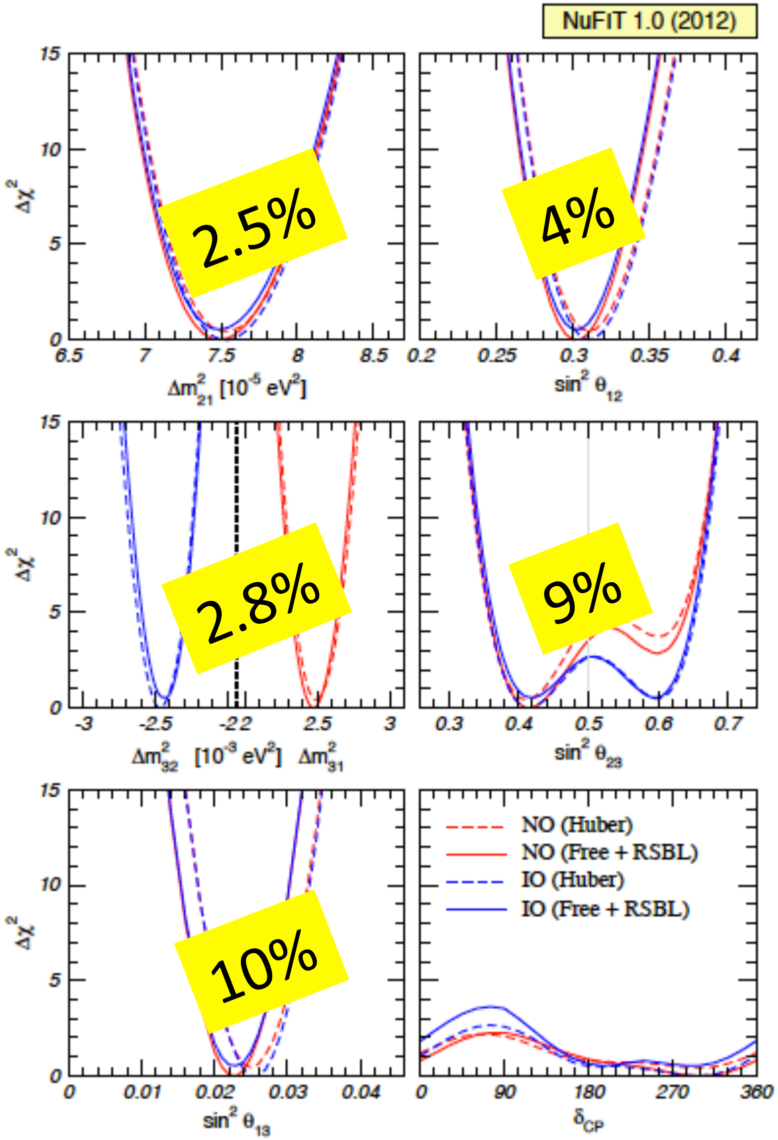
The measurement of $\theta_{13} \sim 9^\circ$ implies that corrections to these approximations are sizeable and need to be included in all analyses

Standard 3ν scenario

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



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



Gonzalez-Garcia et al 1209.3023

Outliers: LSND anomaly

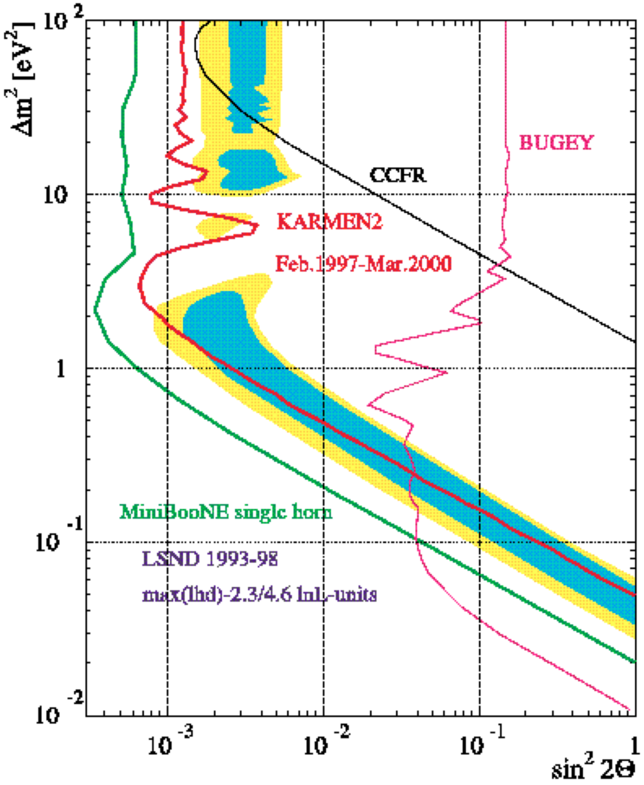
LSND vs KARMEN

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

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

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

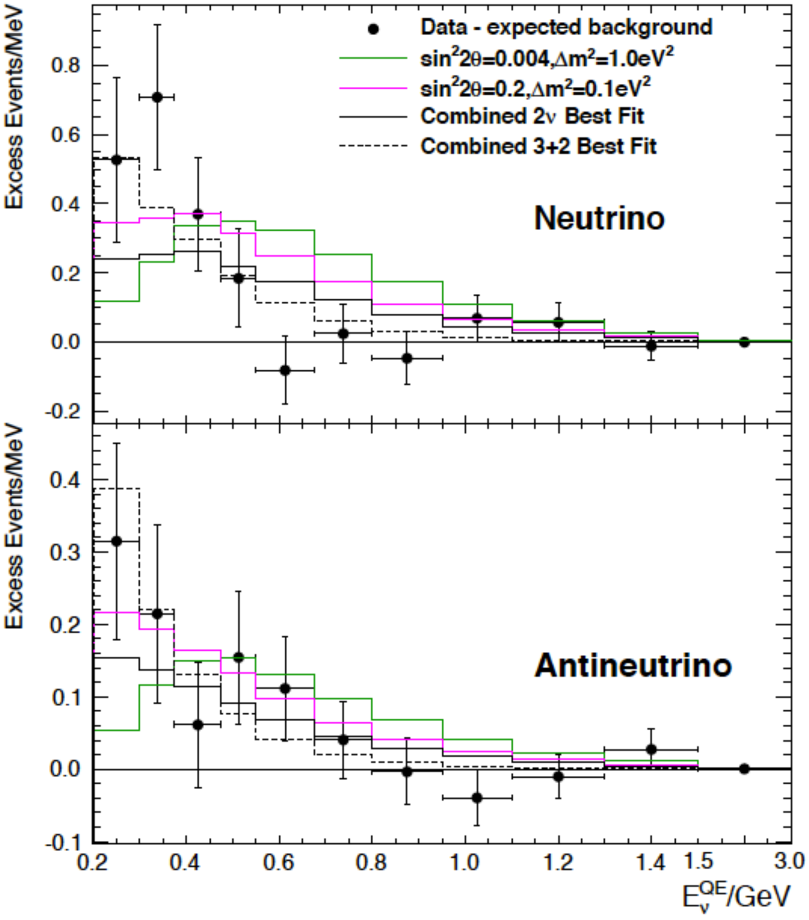
$$\bar{\nu}_\mu \to \bar{\nu}_e \text{ DAR } (64 \pm 18/12 \pm 3)$$

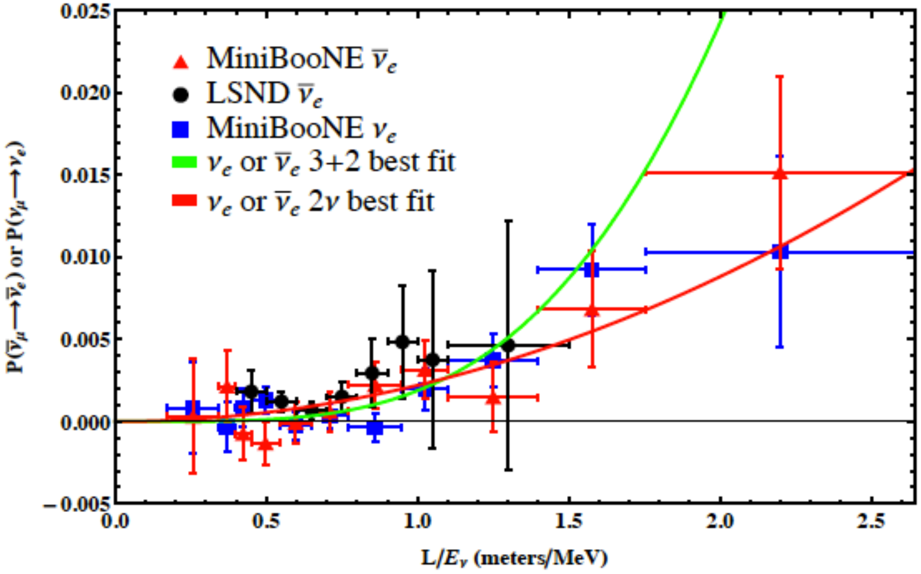


Appearance signal with very different

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

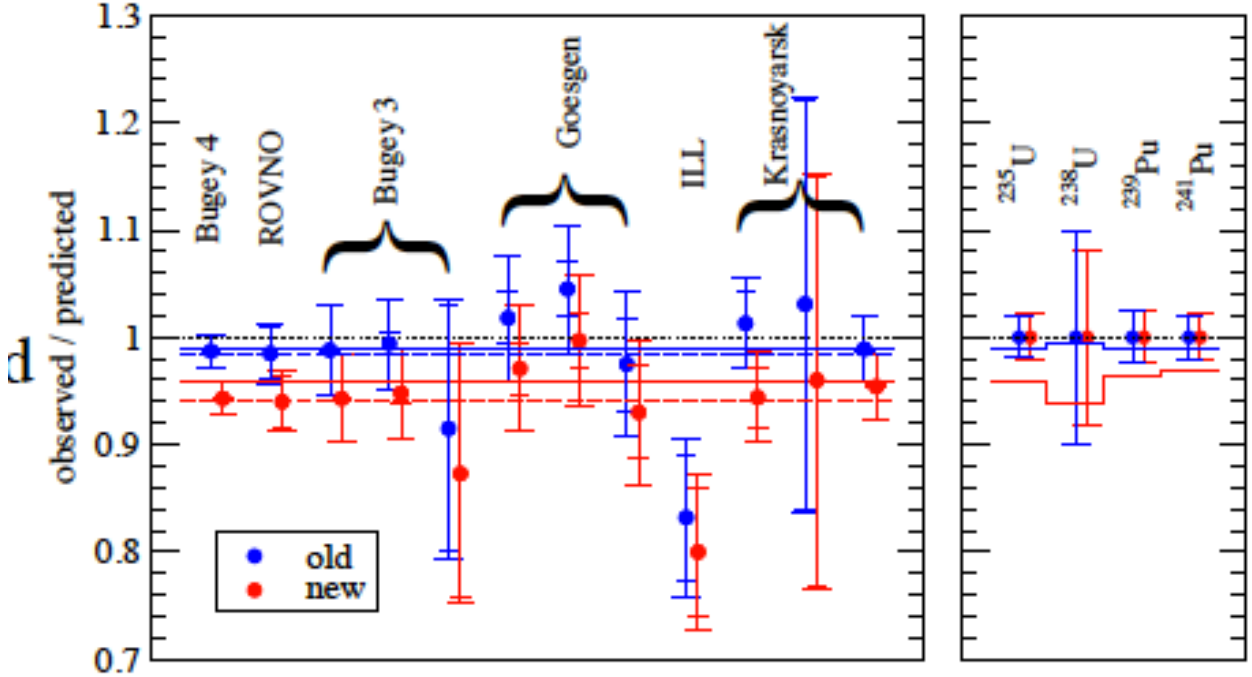
MINIBOONE





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 model

Parametrized in terms of a general unitary 5x5 mixing matrix
(9 angles, >6 phases physical)

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

	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

	3+1	3+2
χ^2_{min}	100.2	91.6
NDF	104	100
GoF	59%	71%
Δm^2_{41} [eV^2]	0.89	0.90
$\lvert U_{e4}\rvert^2$	0.025	0.017
$\lvert U_{\mu 4}\rvert^2$	0.023	0.018
Δm^2_{51} [eV^2]		1.60
$\lvert U_{e5}\rvert^2$		0.017
$\lvert U_{\mu 5}\rvert^2$		0.0064
η		1.52π
$\Delta\chi^2_{\mathrm{PG}}$	24.1	22.2
$\mathrm{NDF}_{\mathrm{PG}}$	2	5
PGoF	6×10^{-6}	5×10^{-4}

Kopp, Maltoni, Schwetz (KMS) arXiv:1103.4570

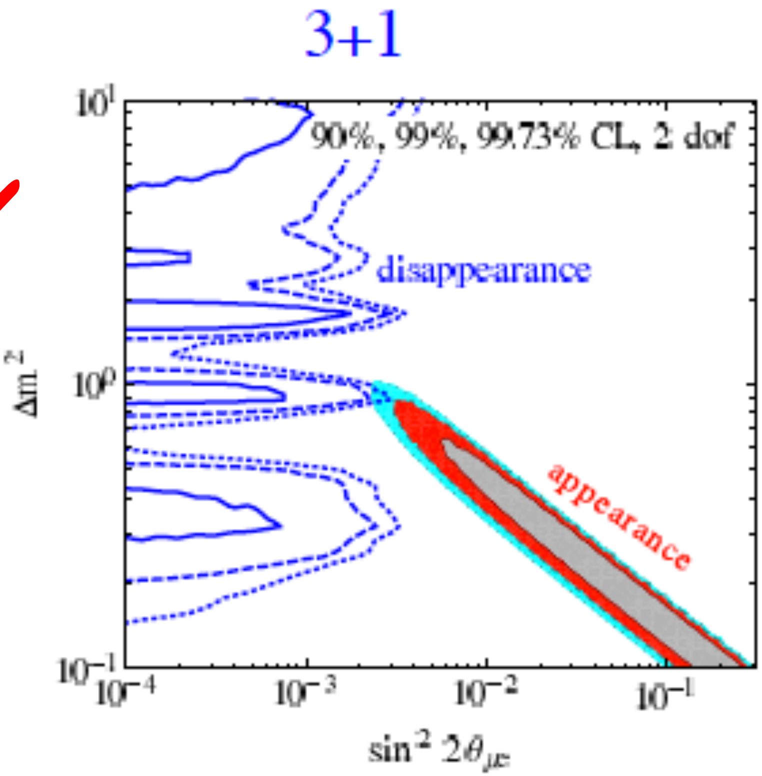
Giunti, Laveder, (GL) arXiv:1107.1452

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

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

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

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



T.Schwetz, talk ν2012

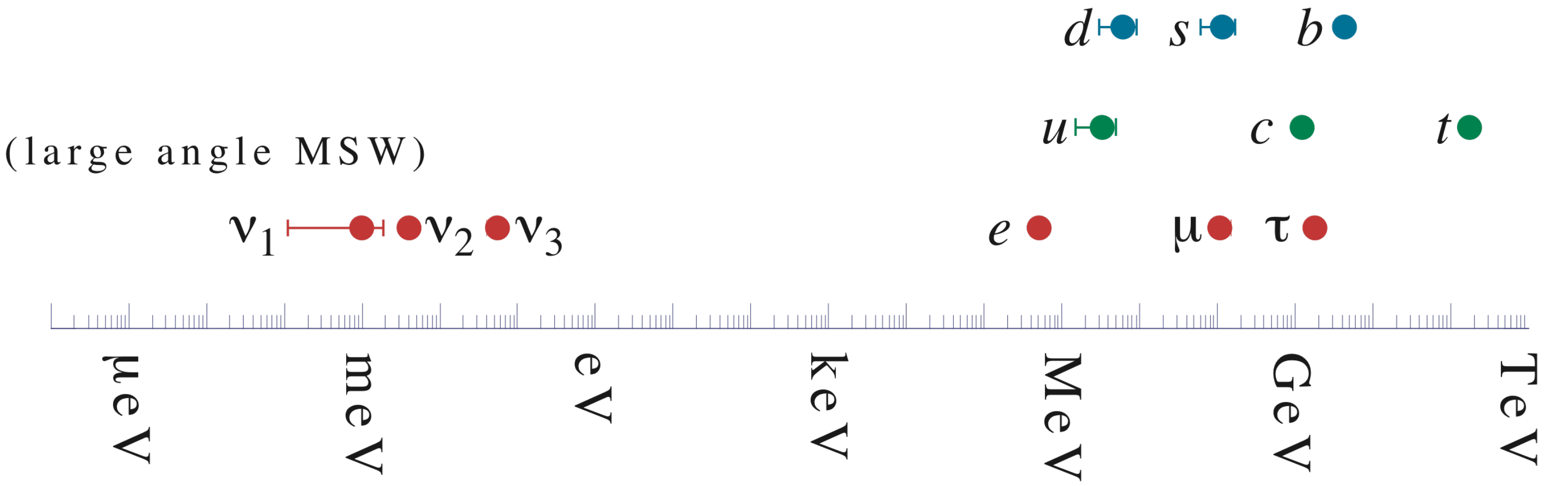
Strong tension remains:
a convincing signal would be to find it in all the three...

Lecture IV:

- Prospects in neutrino physics
- Leptogenesis & neutrinos in the cosmos
- Theory outlook
- Conclusions

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

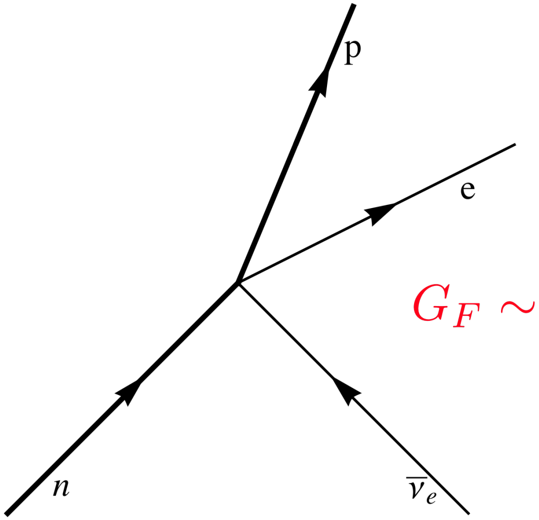
3σ

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

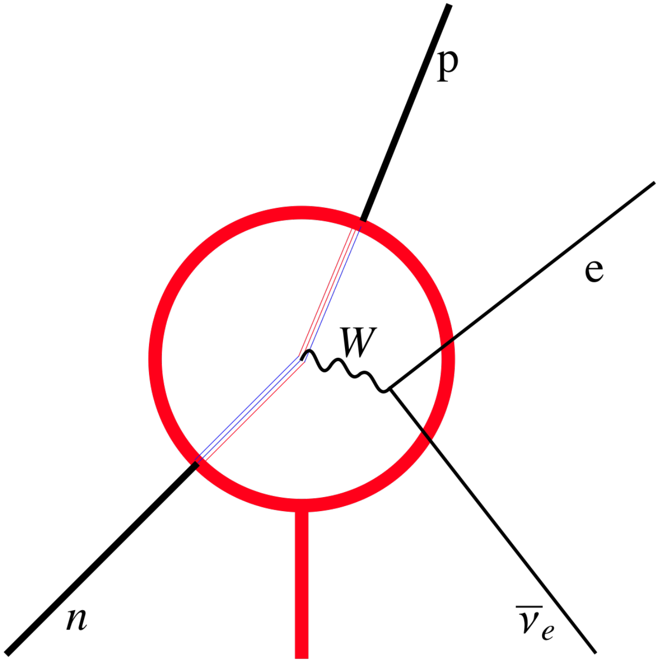
Gonzalez-Garcia, et al 1209.3023

PMNS no longer looks bi-maximal,tri-bimaximal, golden...no more than anarchy

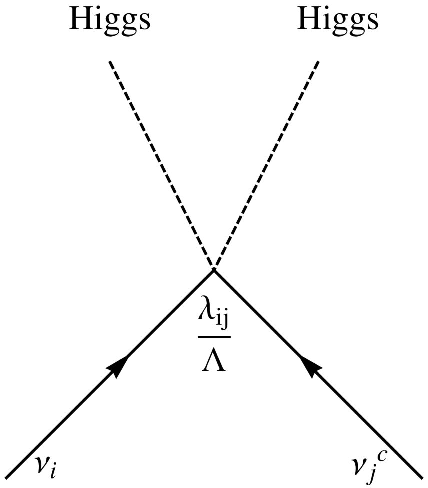
Neutrinos have tiny masses -> a new physics scale, what ?



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



SM

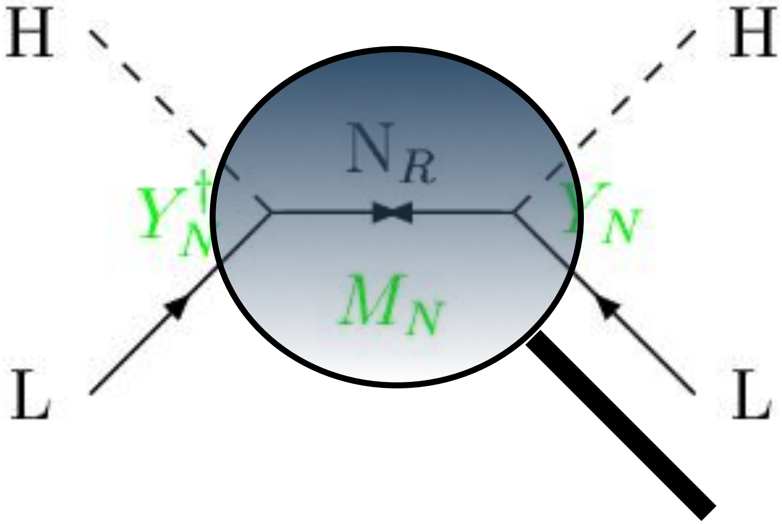


→ νSM ?

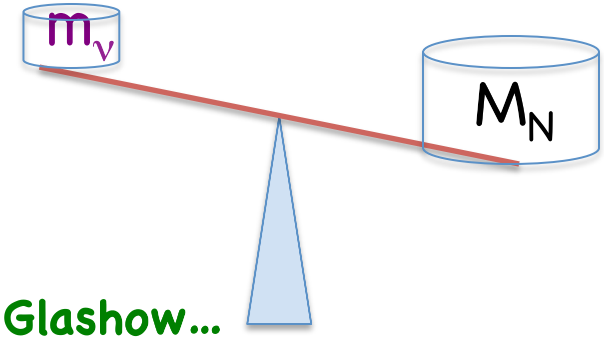
How does the ν scale relates to the EW scale ?

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

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



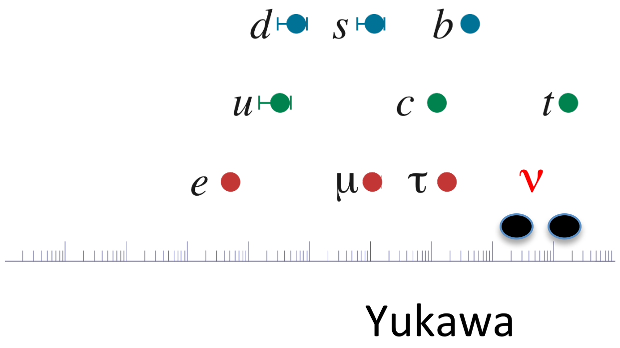
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$



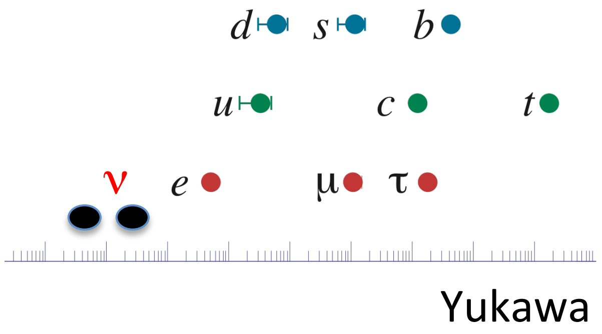
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow…

Charged/neutral hierarchy in seesaw (I)

$\Lambda \lesssim$ GUT



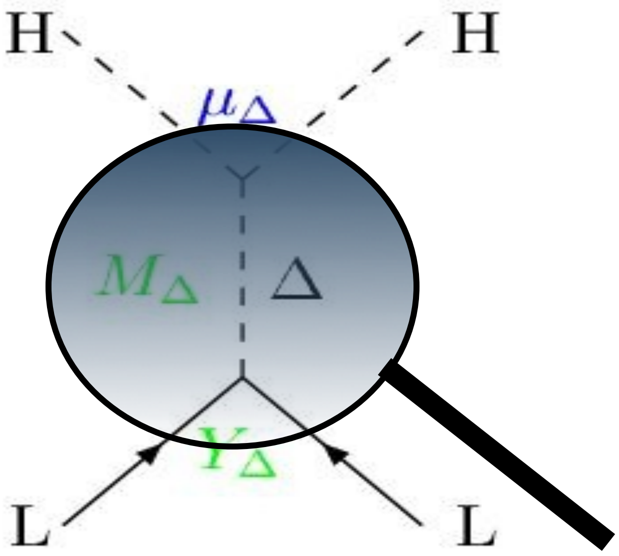
Λ = TeV



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

New physics scale

Type II see-saw: interchange a heavy triplet scalar

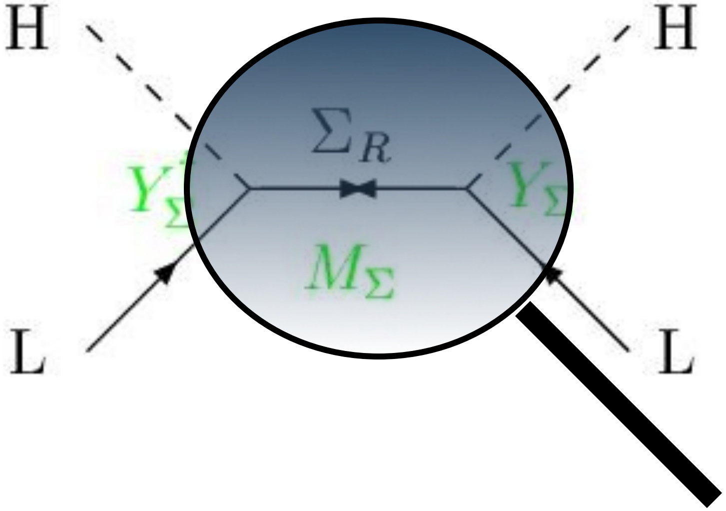


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

New physics scale

Type III see-saw: interchange a heavy triplet fermion



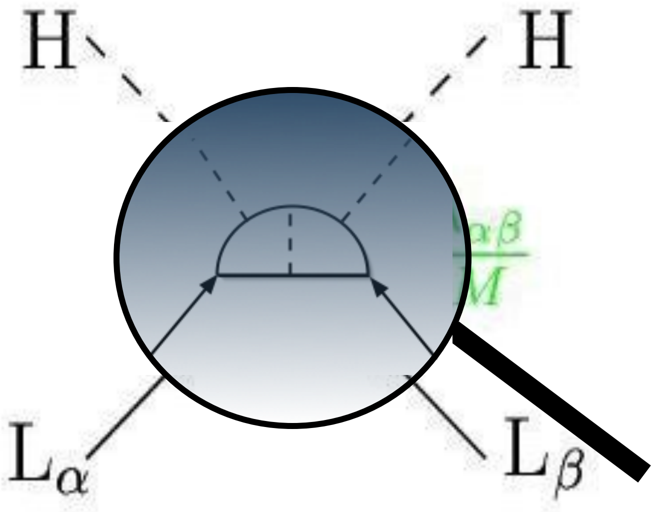
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

Foot et al; Ma; Bajc, Senjanovic…

New physics scale

Also from loops !

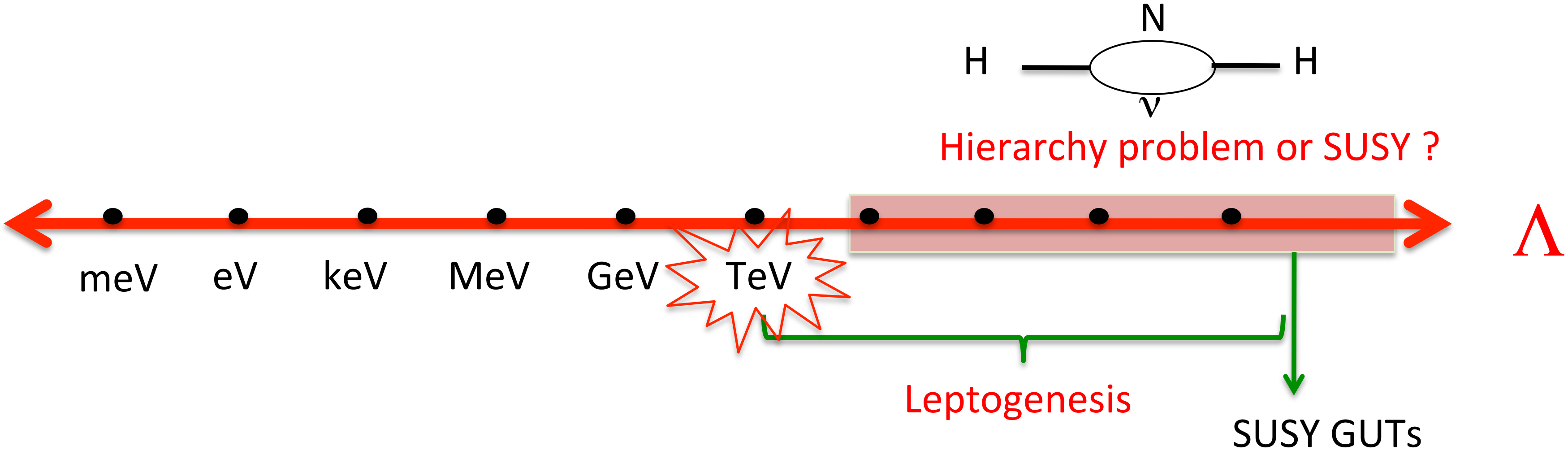
Zee-Babu



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

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:

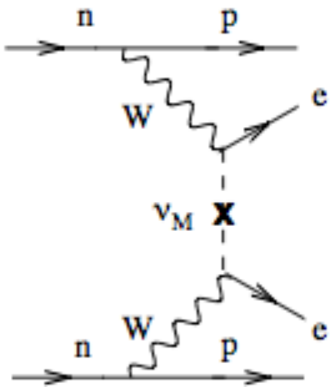
there is neutrinoless double beta decay at some level ($\Lambda > 100$MeV)

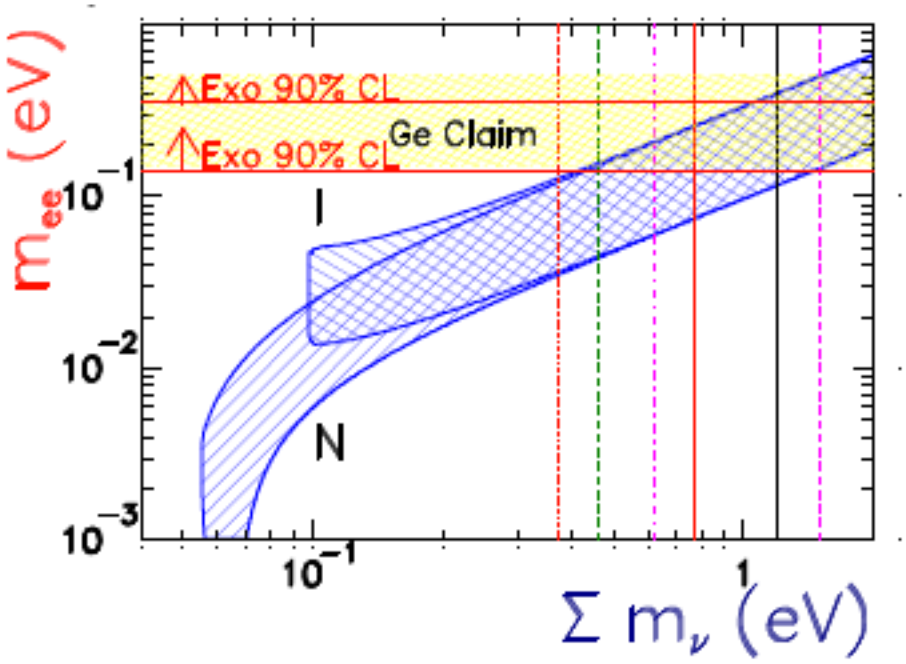
a matter-antimatter asymmetry if there is CP violation in the lepton sector !

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

(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)

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

θ_{13} measurement

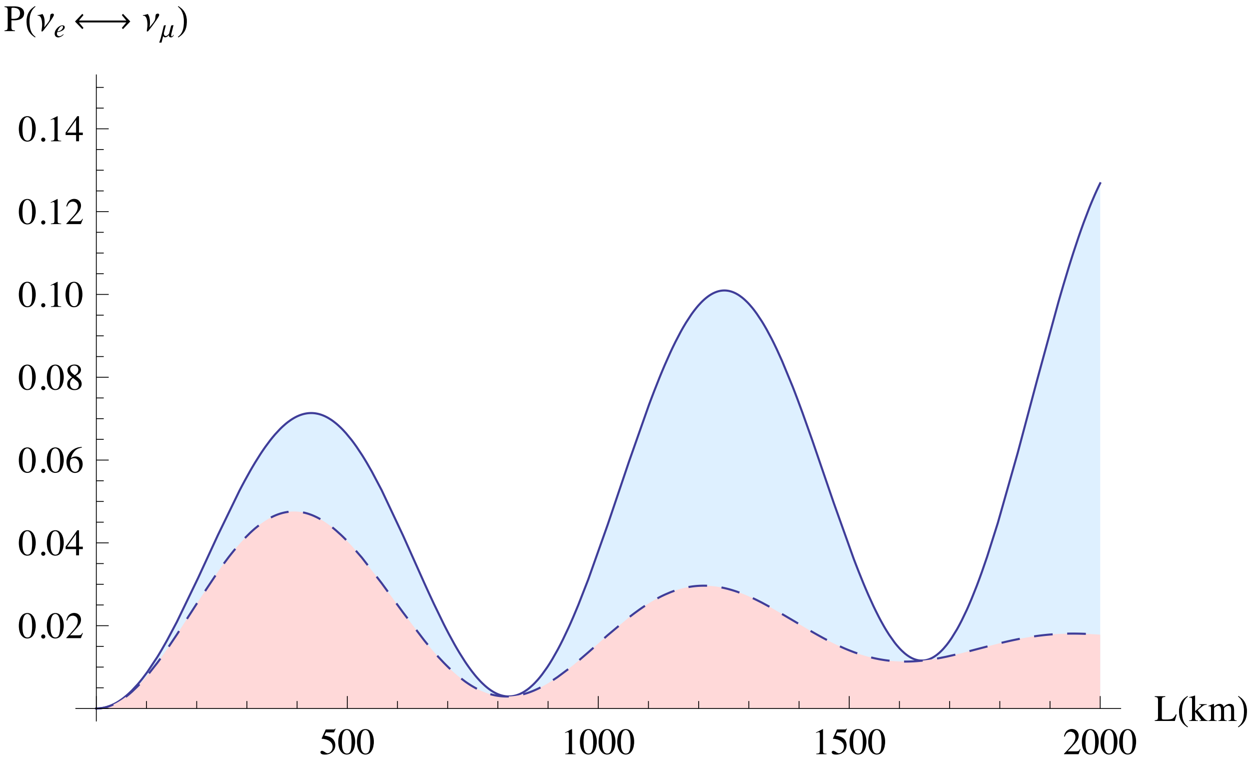
$$\tilde{J} \equiv c_{13} \; \sin 2\theta_{13} \; \sin 2\theta_{12} \; \sin 2\theta_{23}$$

$$P^{atmos} \gg P^{solar} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\Delta_{12}L}{\sin 2\theta_{13}}$$

$$P^{solar} \gg P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\sin 2\theta_{13}}{\Delta_{12}L}$$

$$P^{solar} \simeq P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} = O(1)$$

$P(\nu_e \to \nu_\mu)$ vs $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



Golden Channel in matter

Hierarchy dependence

Octant dependence

In matter:

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

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

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

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

Cervera et al

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

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

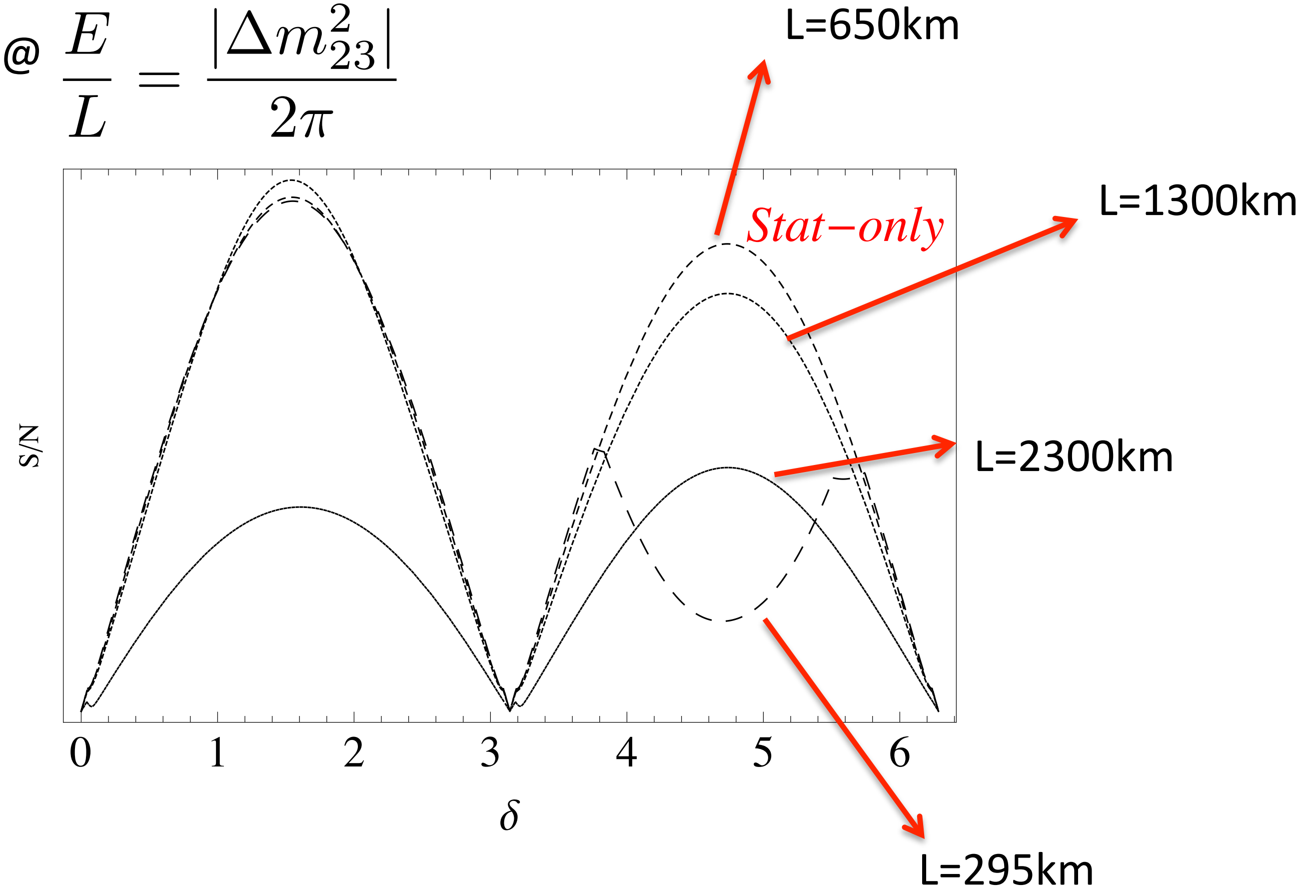
Optimization E, L

$$
\begin{aligned}
N_{events}(E,L) &= \Phi(E,L) \otimes \sigma(E) \otimes P_{osc}(E,L) \\
&= \frac{E^{\alpha}}{L^2} \times E^{\beta} \times P(E,L)
\end{aligned}
$$

Ignoring the hierarchy degeneracy: Signal/Noise ($\delta \neq 0$, $\delta \neq \pi$) maximizes at

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

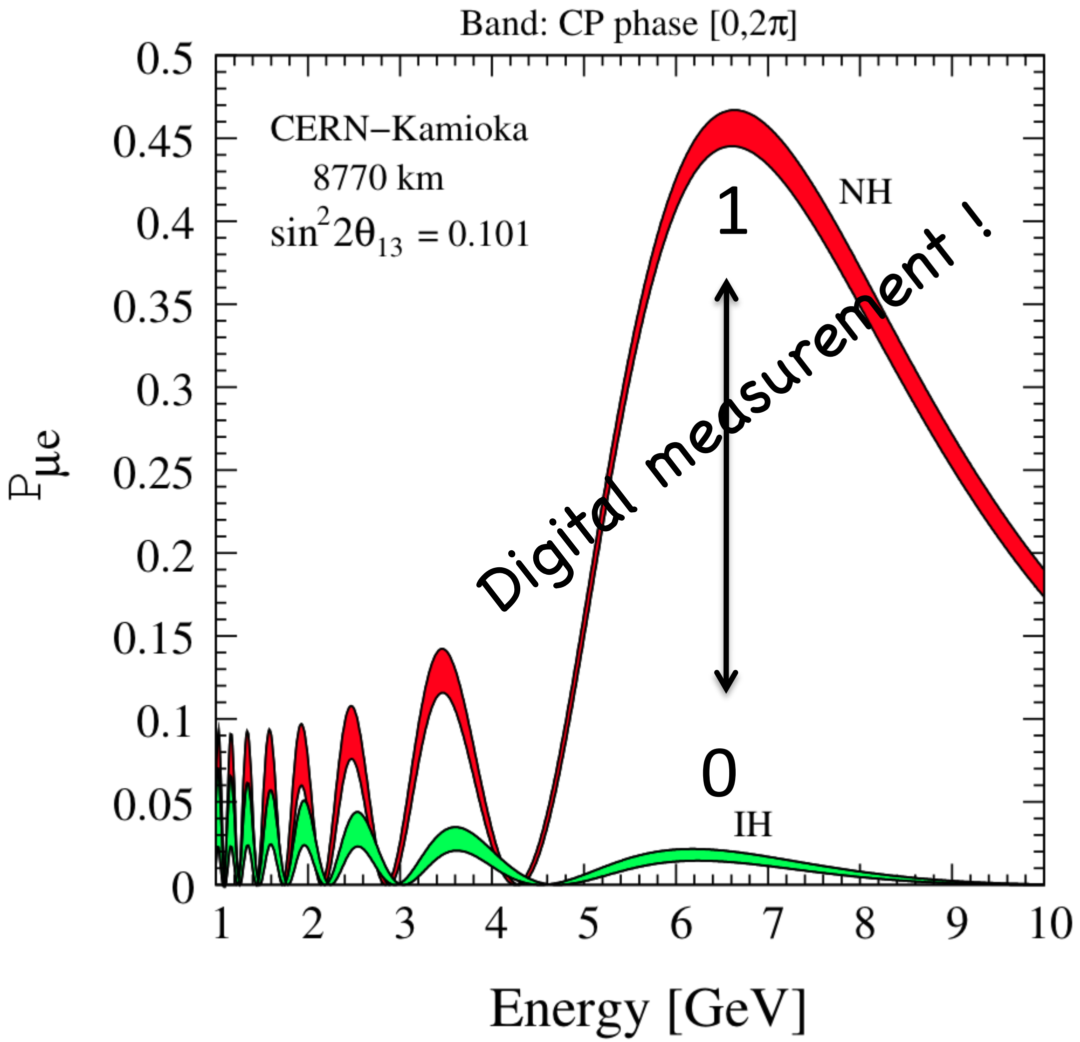
$$@\ \frac{E}{L} = \frac{|\Delta m^2_{23}|}{2\pi}$$



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 through MSW



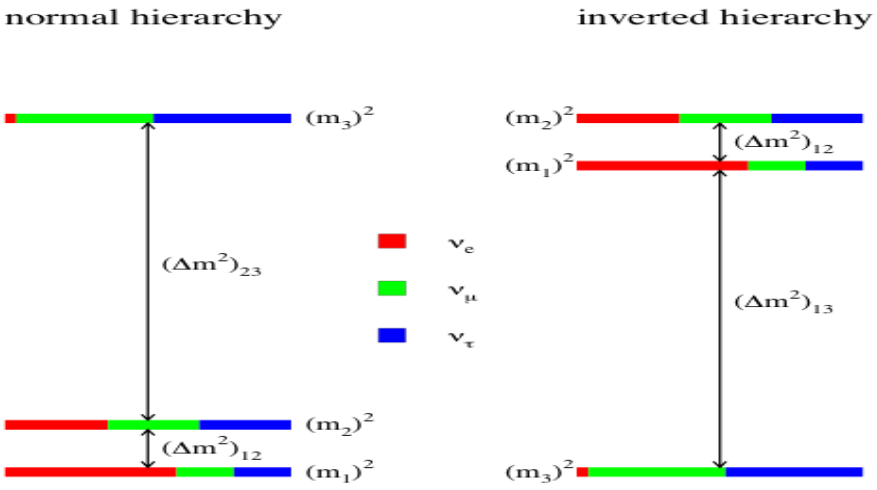
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F n_e},$$

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

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

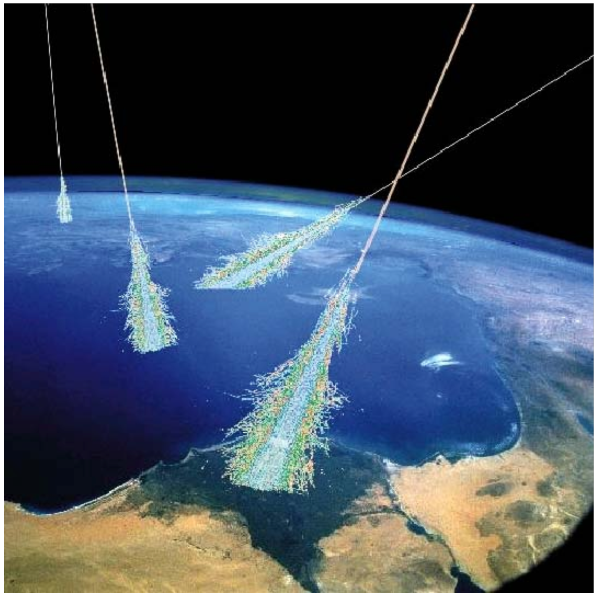
Mikheev, Smirnov;Wolfenstein

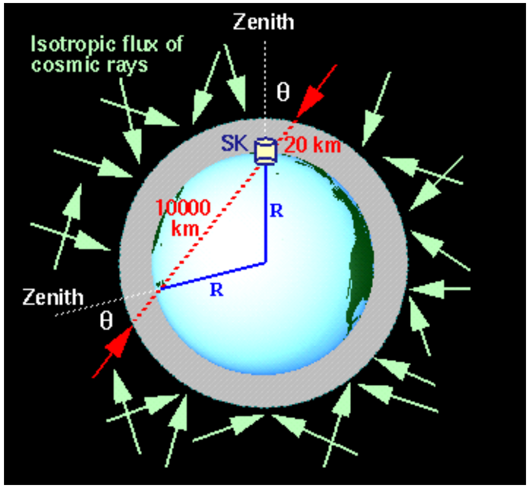
Can we measure the hierarchy with existing neutrino sources ?



Hierarchy from atmospherics ? the hard way...

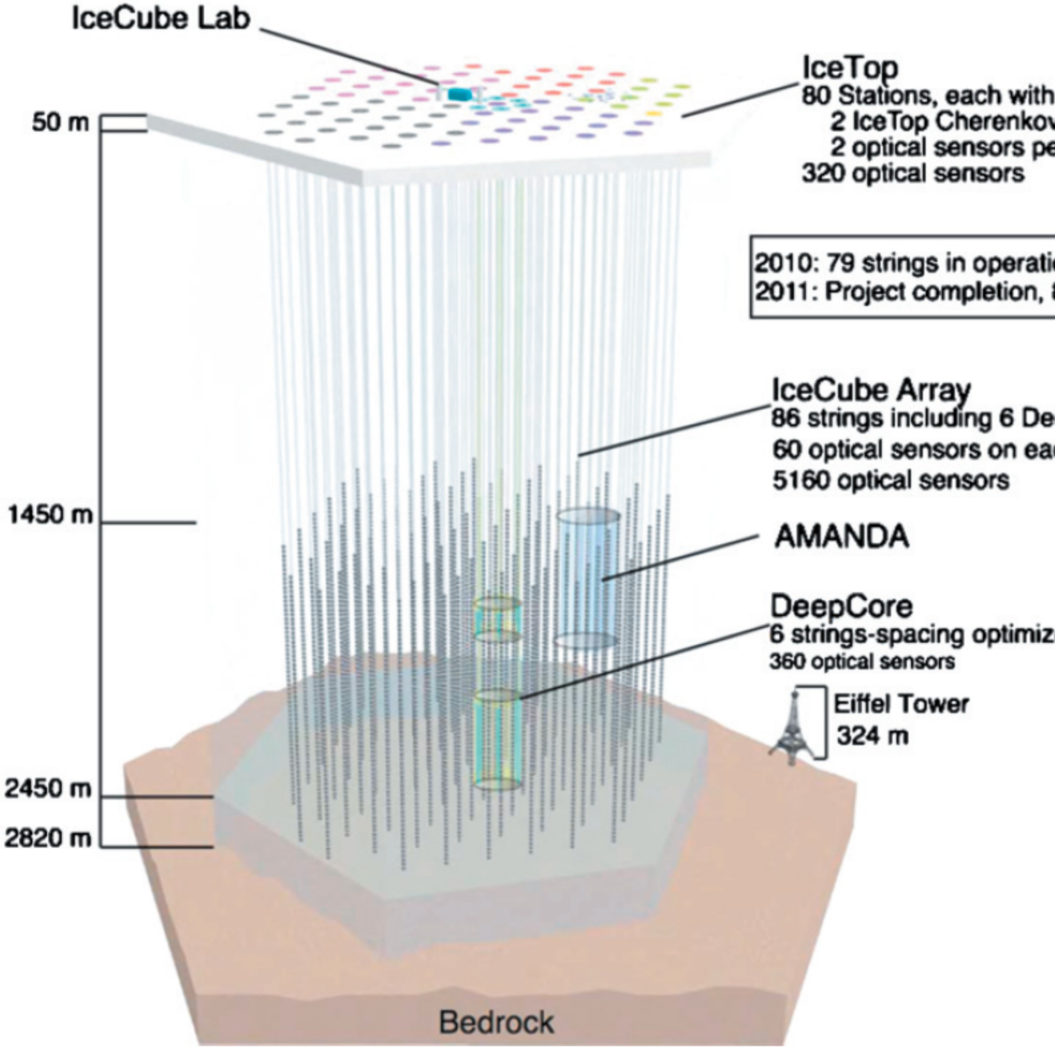
$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$





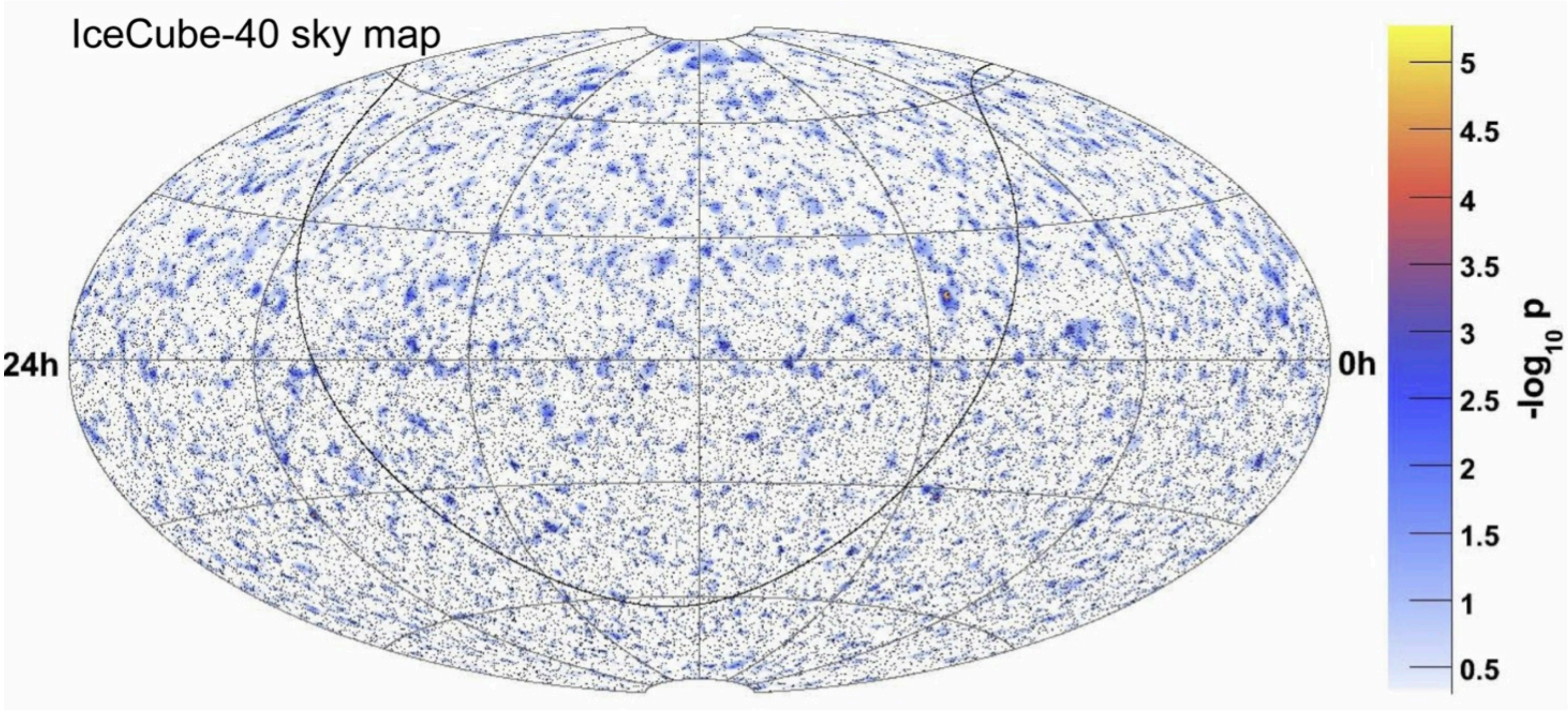
Atmospheric data contain the golden signal but not so easy to dig...

No experiment is large enough in neutrino physics…



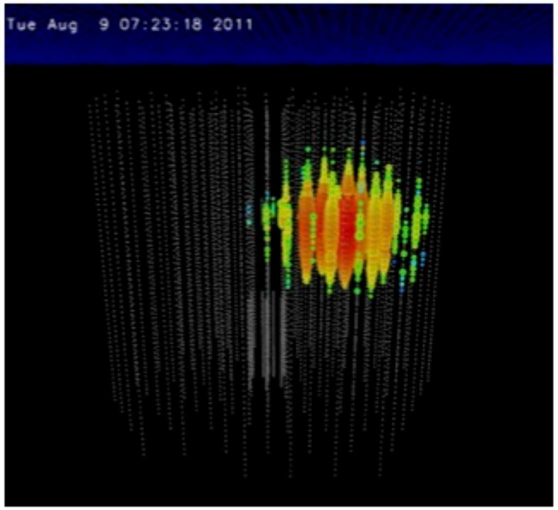
Neutrino astronomy

Full-sky map, based on 40 strings



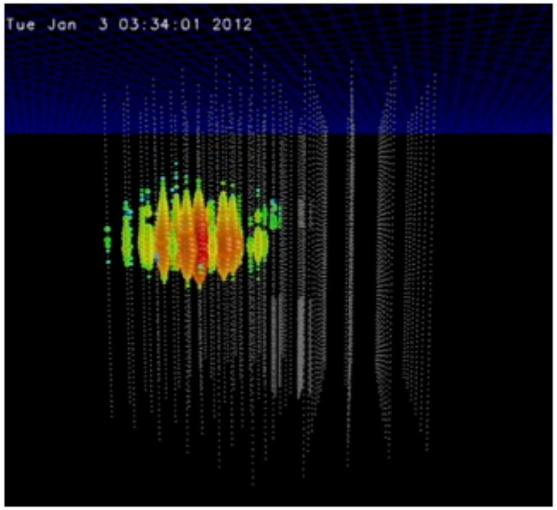
Some unexpected events…

Appearance of ~ 1 PeV neutrinos at lower energy threshold



"Bert"

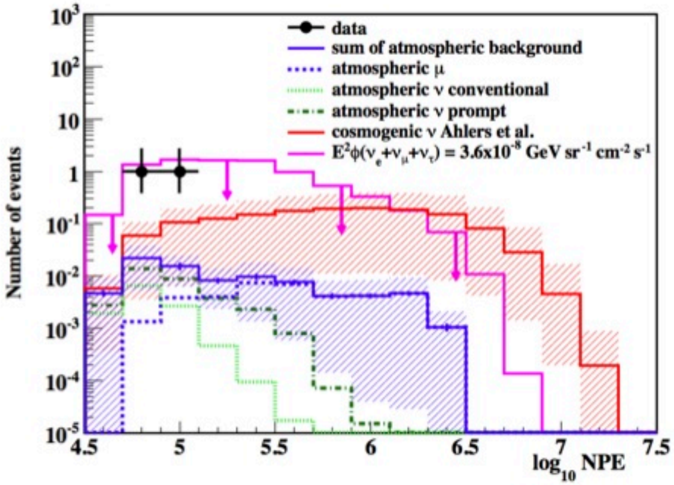
~ 1050 TeV



"Ernie"

~ 1150 TeV

arXiv:1304.5356

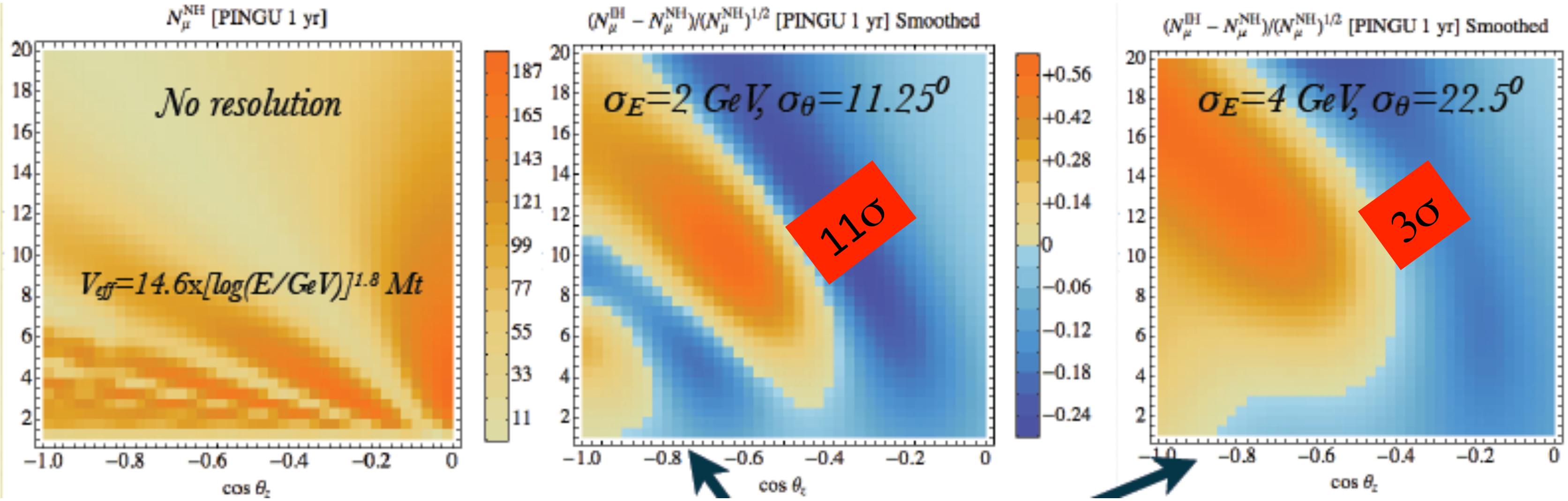


- Too low in energy for GZK
- Seems too high in energy for atmospheric

Hierarchy with atmospherics: sea water/Ice

PINGU (Icecube), ORCA (ANTARES) nu-telescopes

$$V_{eff} = 14.6\ log[E/GeV]^{1.8} Mton$$



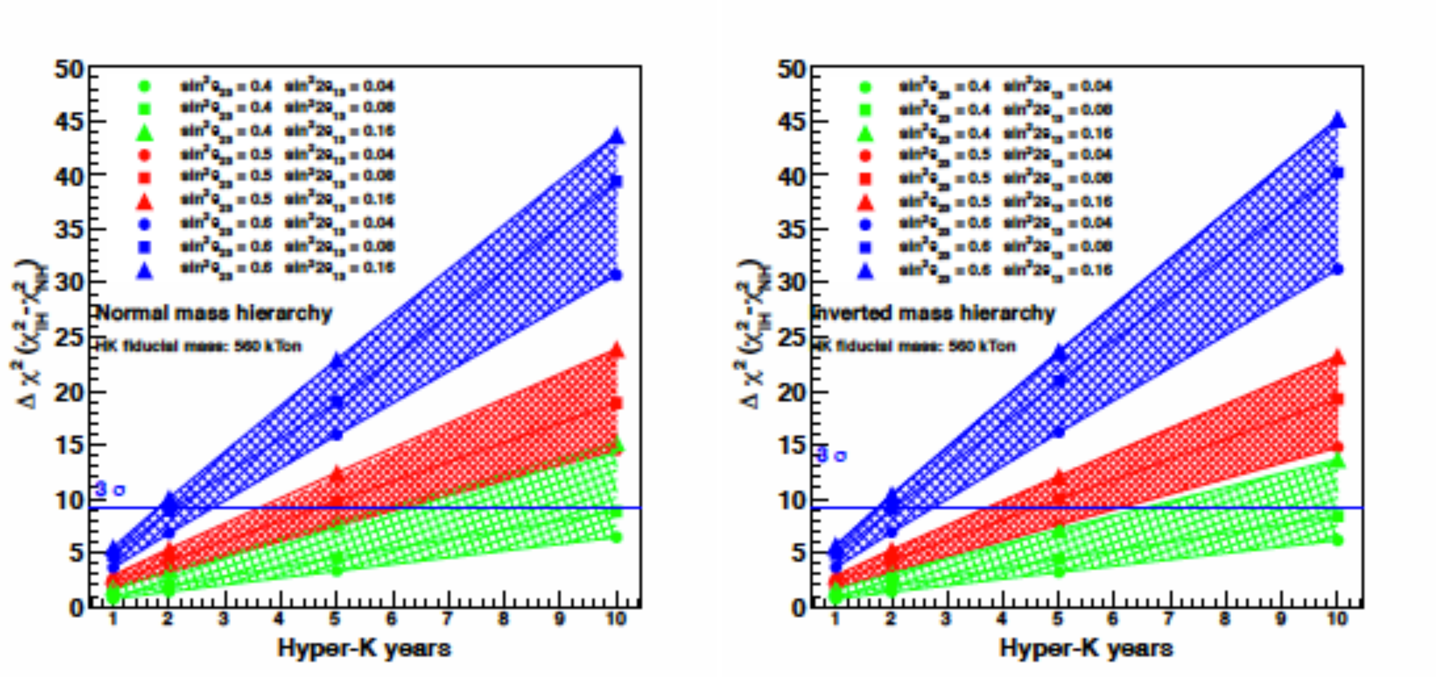
Ahkmedov, Razzaque, Smirnov 1206.7071

Reach still under intense investigation….

Hierarchy with atmospherics

HyperKamiokande: 560kton

3σ in 2y-10y



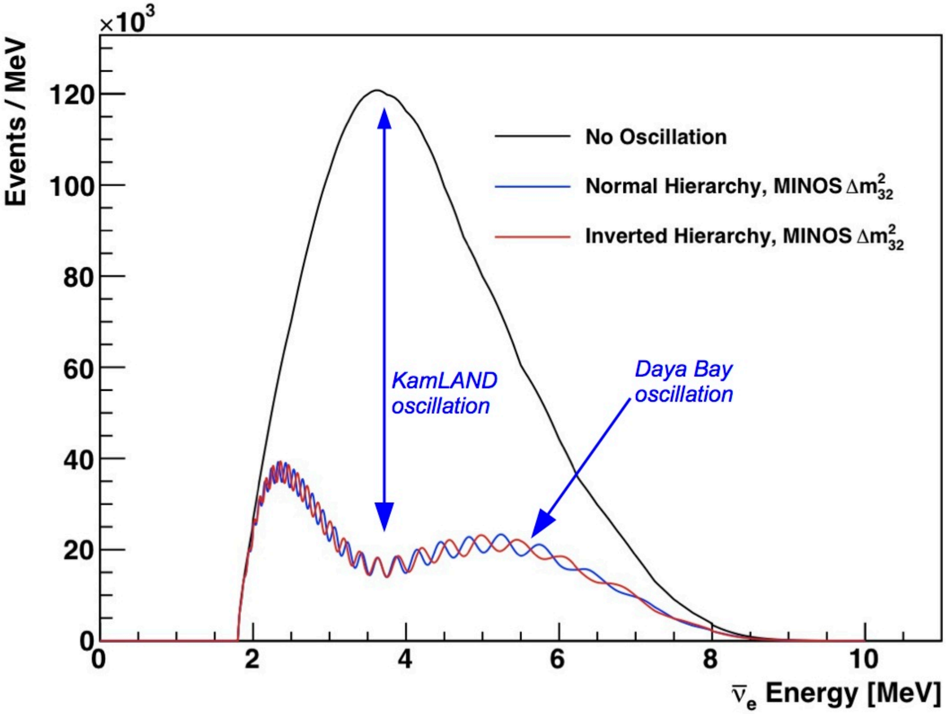
HK LOI

INO 50kton Magnetized Iron (charge discrimination)

3σ in 12 y

Hierarchy from reactor ν's

Petcov, Piai; Choubey et al; Learned et al



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

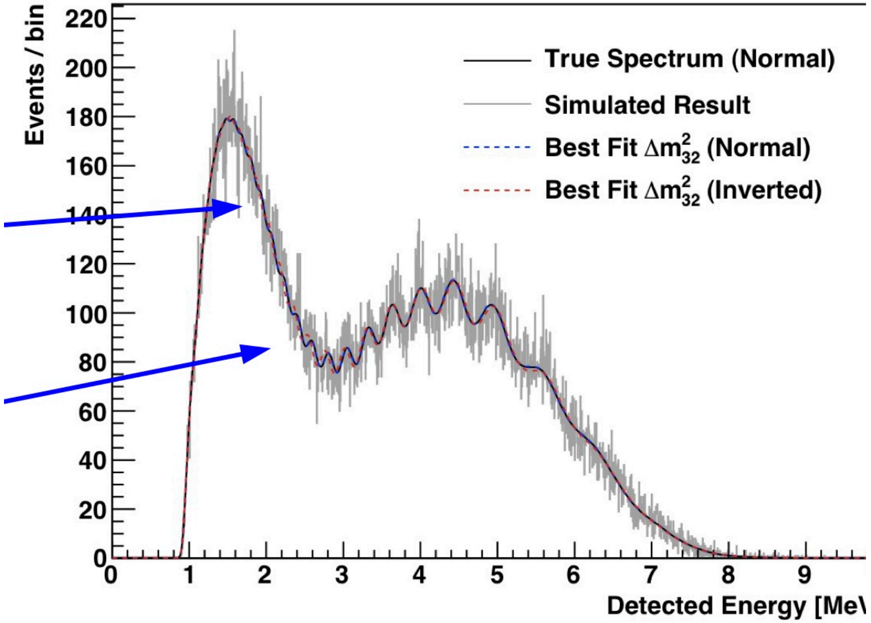
$$\sin\phi = \frac{c_{12}^2 \sin 2\Delta_{21}}{\sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}}} \qquad \phi \simeq 0.12 \times 10^{-3} eV^2 \qquad \pm\mathrm{NH(IH)}$$

Hierarchy in reactors

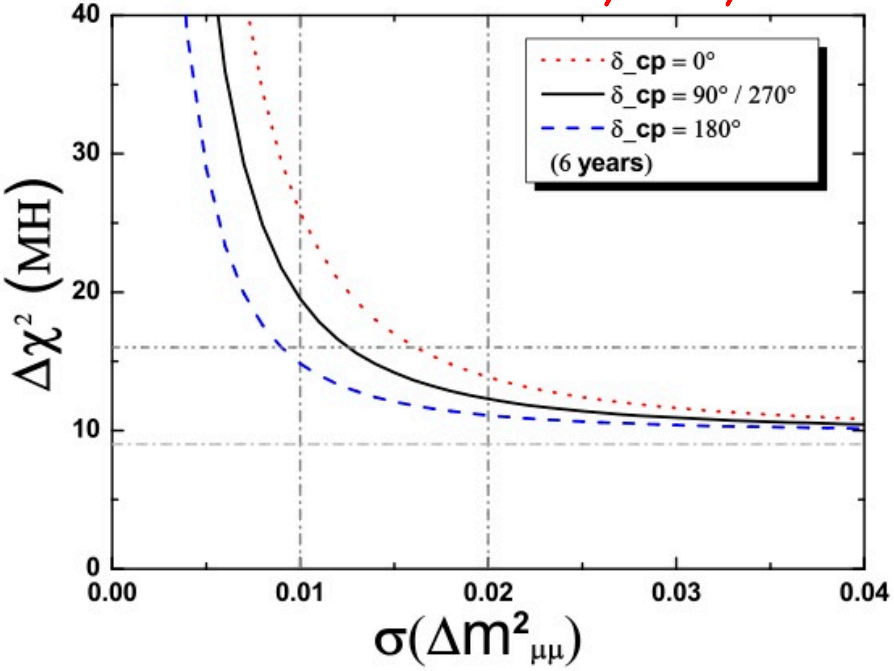
Extremely challenging

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



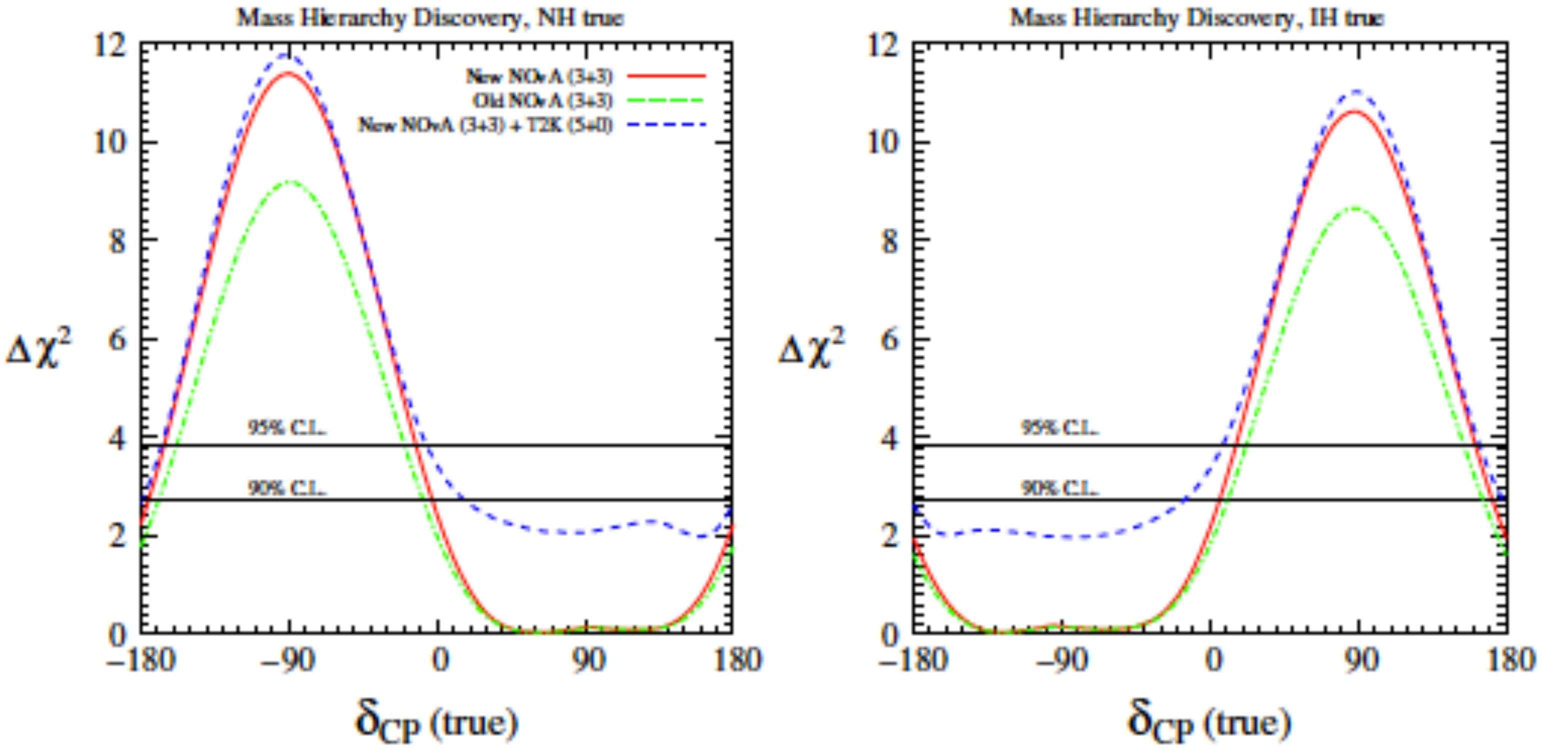
Li et al 1303.6733

Hierarchy from accelerator neutrinos:
the easy way if long enough baseline...

T2K(L=295km) and NOVA (L=800km) too short...

First LBL experiments in < 10y : T2K, NOVA

T2K L=300 km
NOVA L=800km

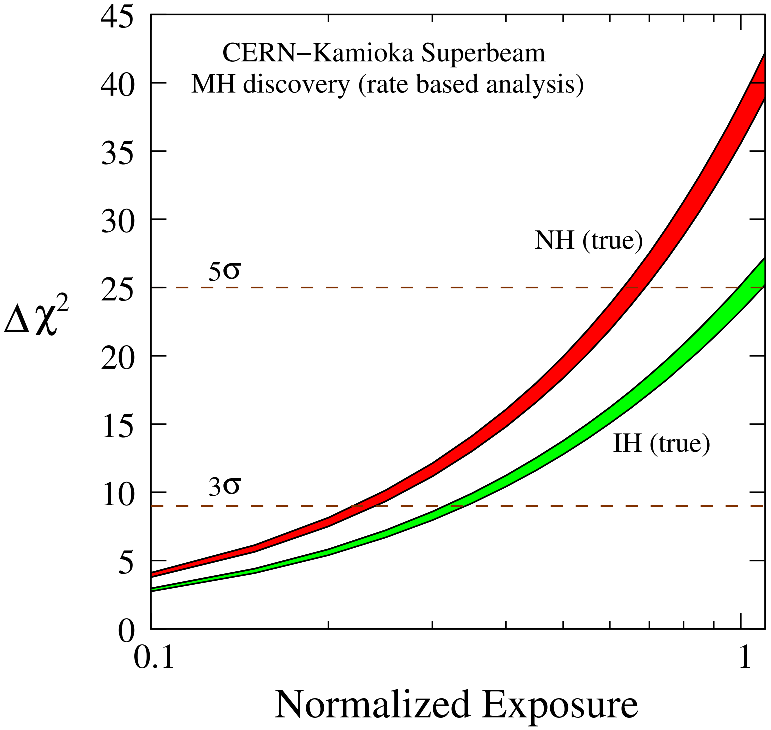


Agarwalla et al 1208.3644

With a new conventional beam (only ν) even with existing detectors, but shooting down !

One example: counting e-events at SuperK

4.5y of LBNO beam



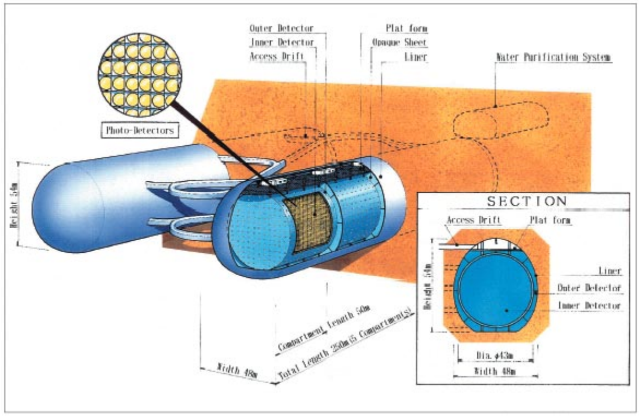
Agarwalla, PH 1204.4217

Hierarchy + CP in one go...

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

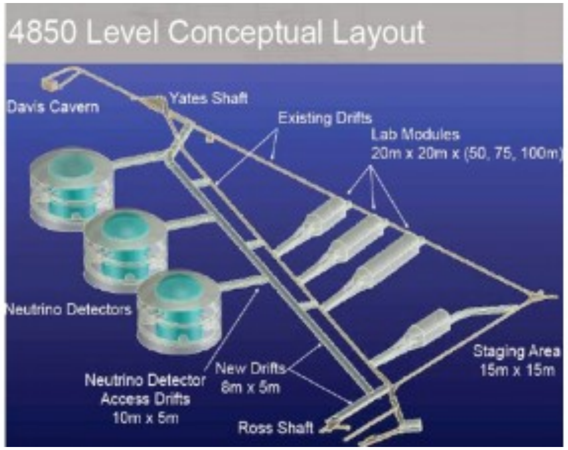
$p \rightarrow \text{Target} \rightarrow K,\pi\ \ \nu_\mu, \%\ \nu_e$

HyperK (Japan)



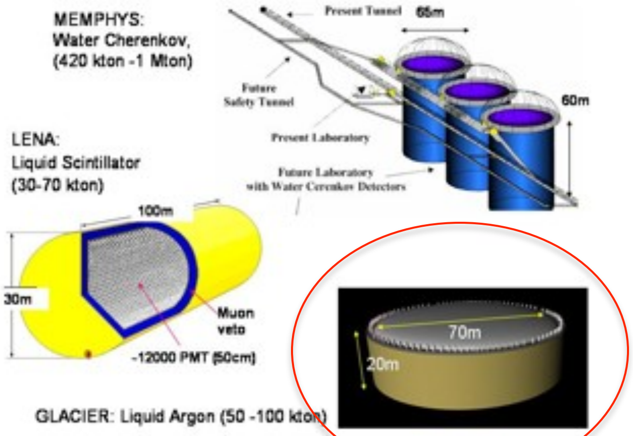
750MW, 560kton WC, Tokai-Kamioka (295km)

LBNE (USA)



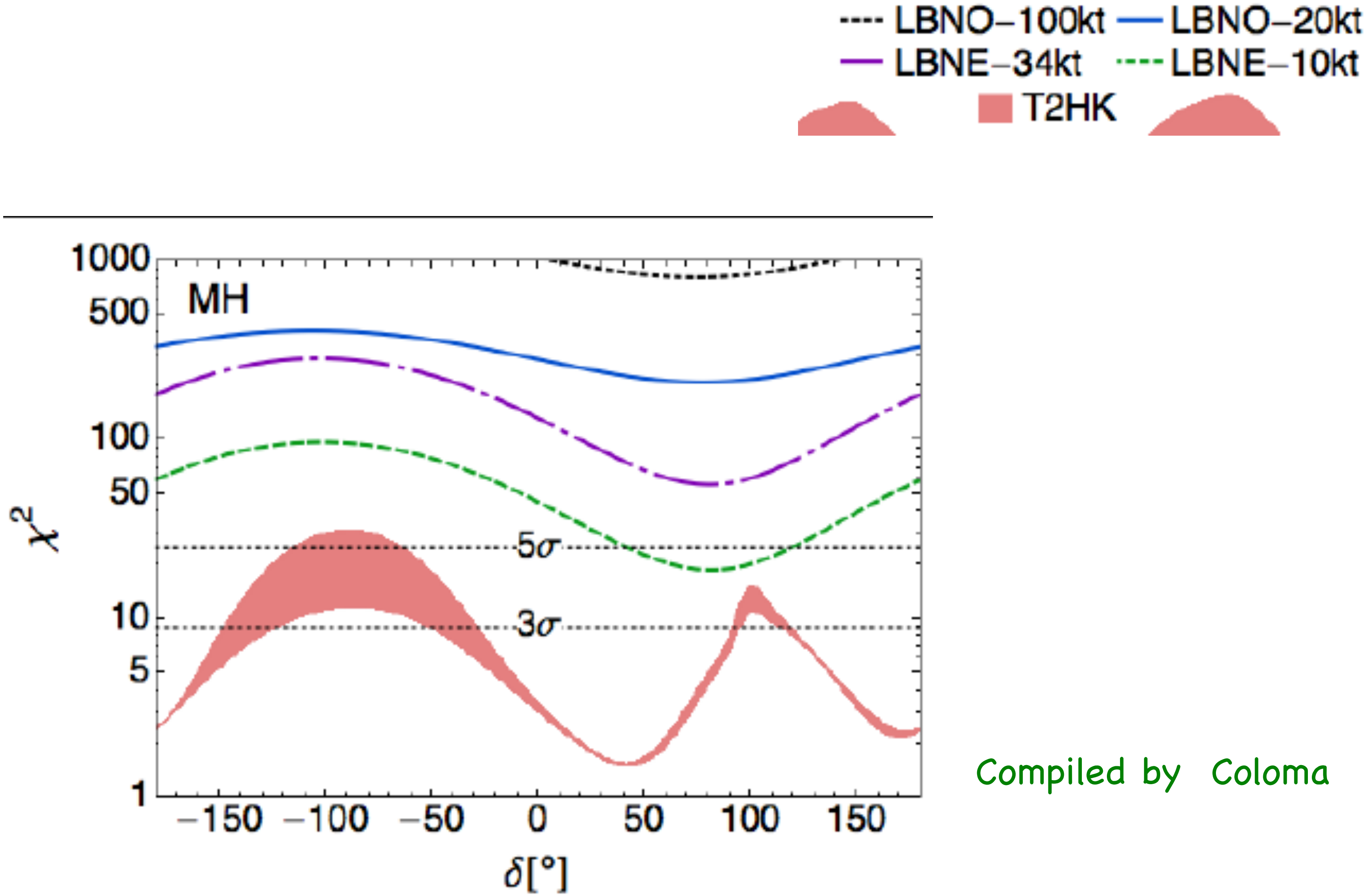
800MW, 10kton-> 35kton LAr, Fermilab-Homestake(1300km)

LBNO (Europe)



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

In 20 years from now with conventional beams…

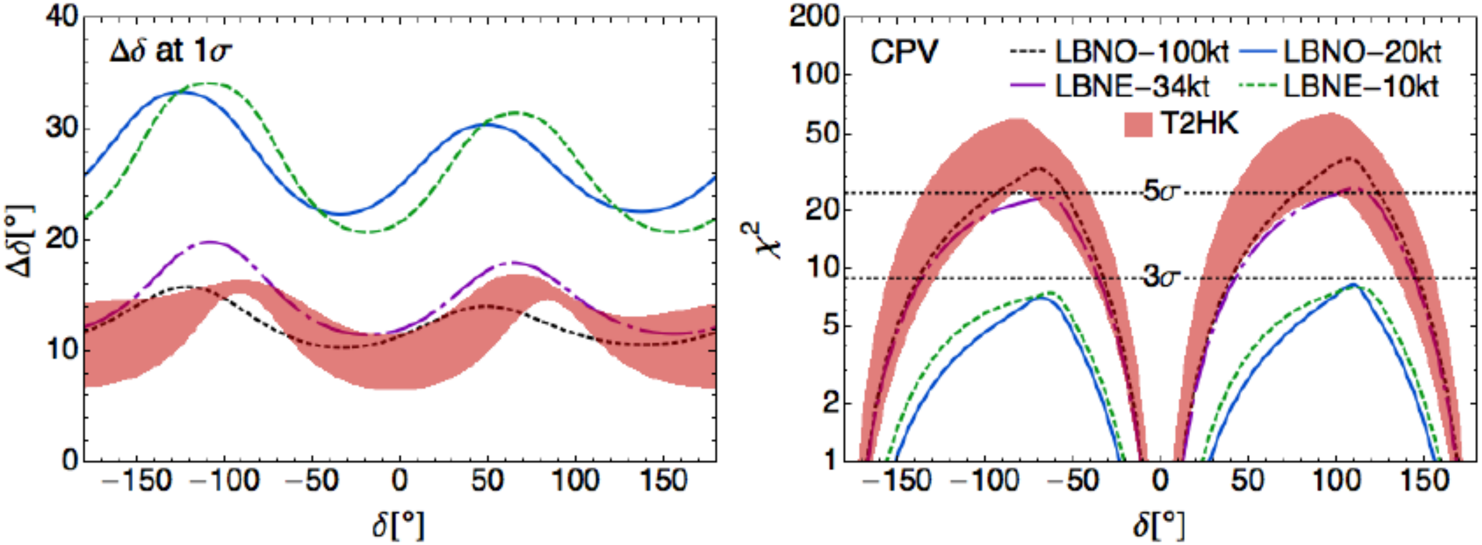


Compiled by Coloma

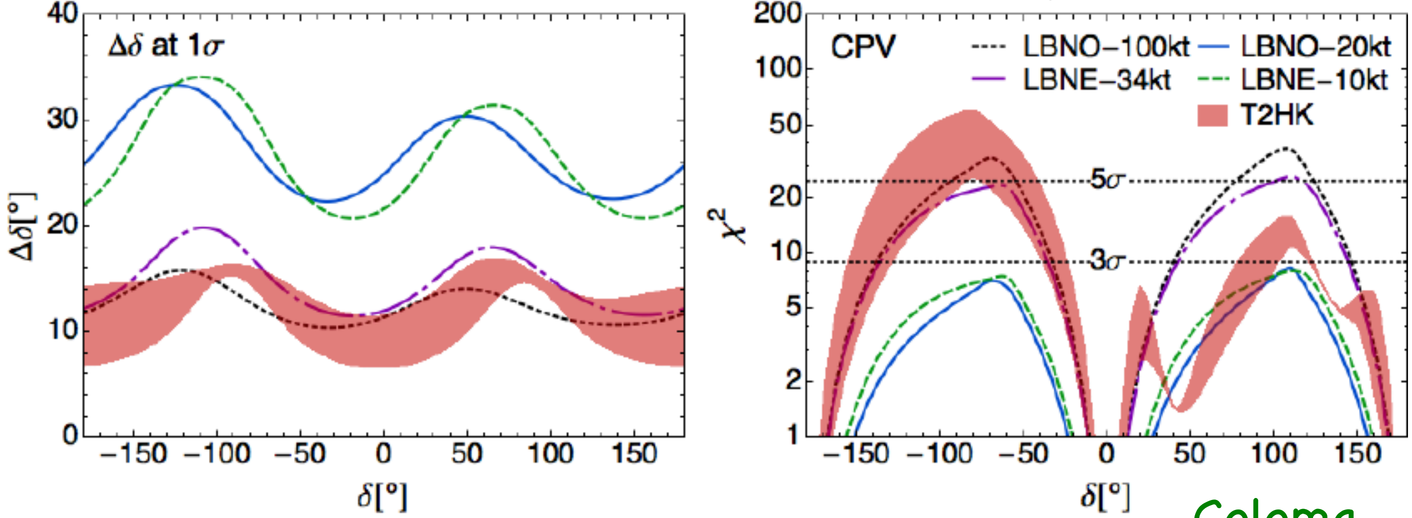
O(10kton) LAr can do the job easily

In 20 years from now with conventional beams…

Hierarchy known

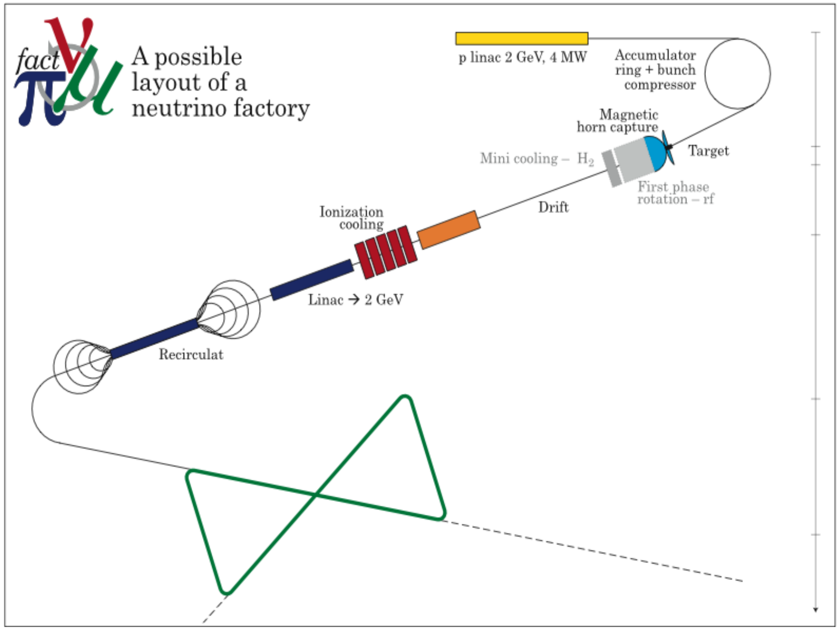


Hierarchy not known



Coloma

Neutrino factory



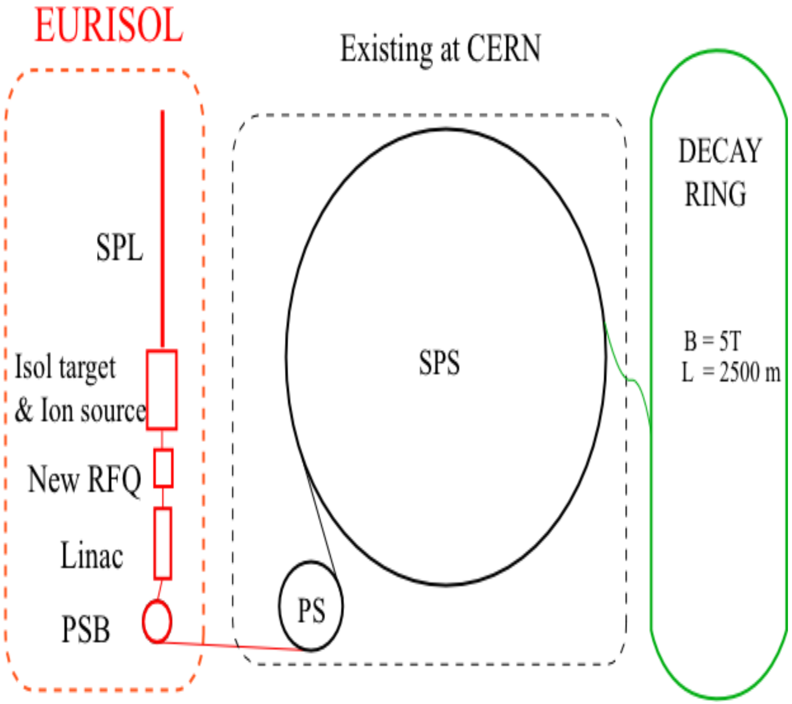
From μ decays

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

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

$$\nu_\mu \to \nu_\mu \to \mu^-$$

β beam

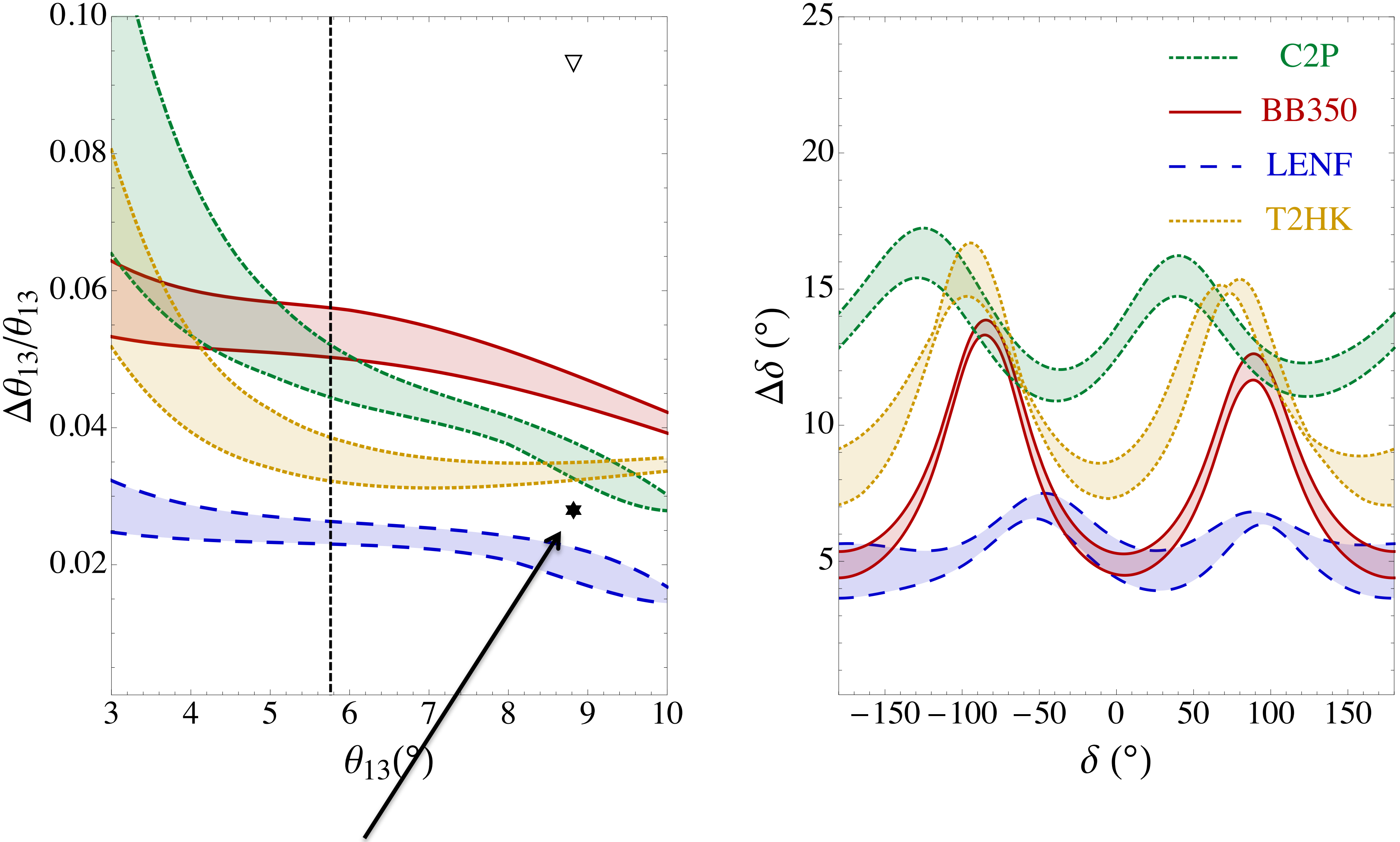


From radioactive ions

$$^{6}He^{++} \to ^{6}_{3}Li^{+++} \; e^- \qquad \bar{\nu}_e$$

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

With better beams in XX years...

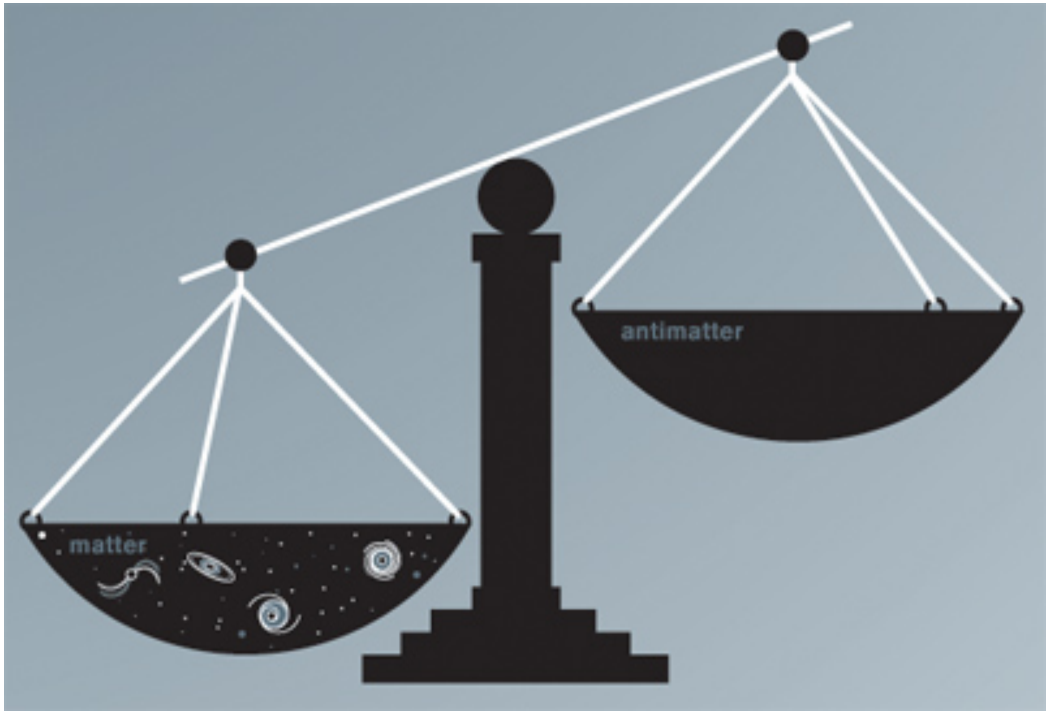


Daya Bay syst only!

Coloma, et al 1203.5651

Baryon asymmetry

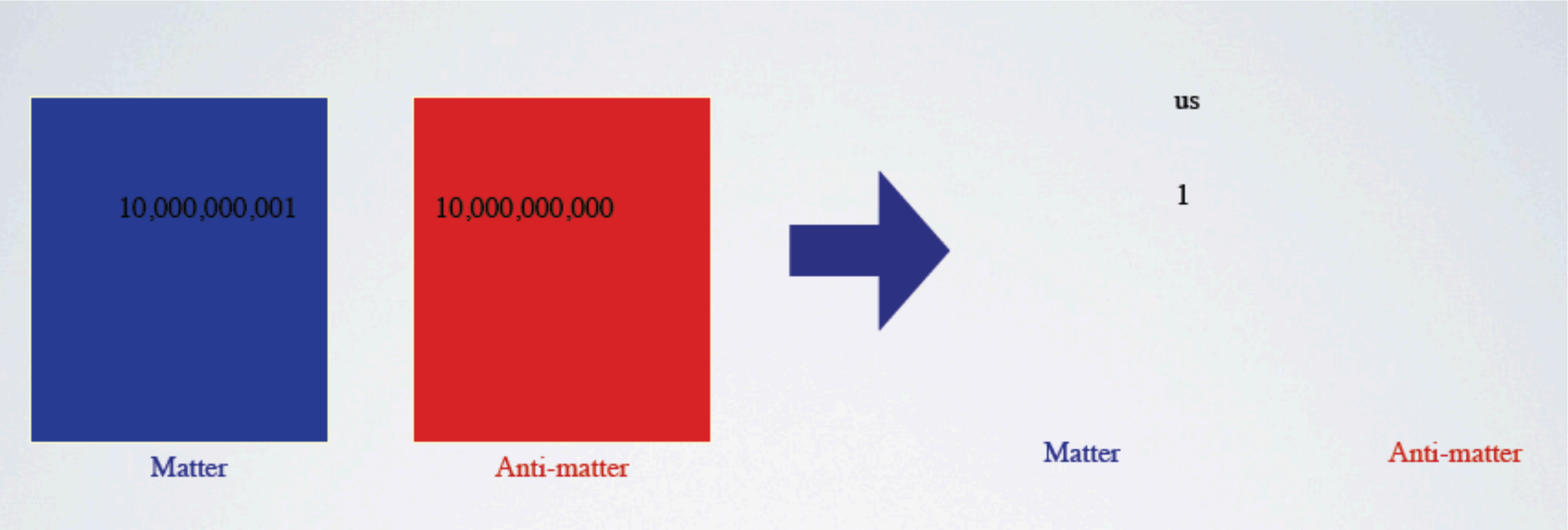
The Universe seems to be made of matter



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

Baryon asymmetry

In the early Universe this implies



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)

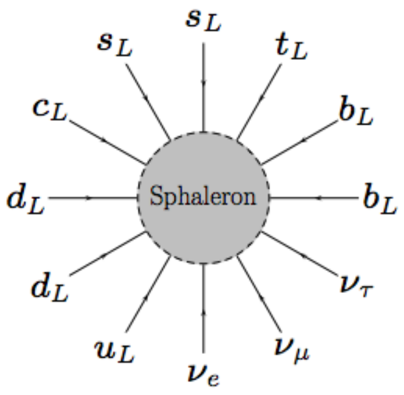
It does not seem to work in the SM with massless neutrinos ...

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

Baryon number violation

In the SM there is violation of B+L, preserve B-L

These processes are strongly suppressed at $T < T_{EW}$ and in equilibrium at $T > T_{EW}$



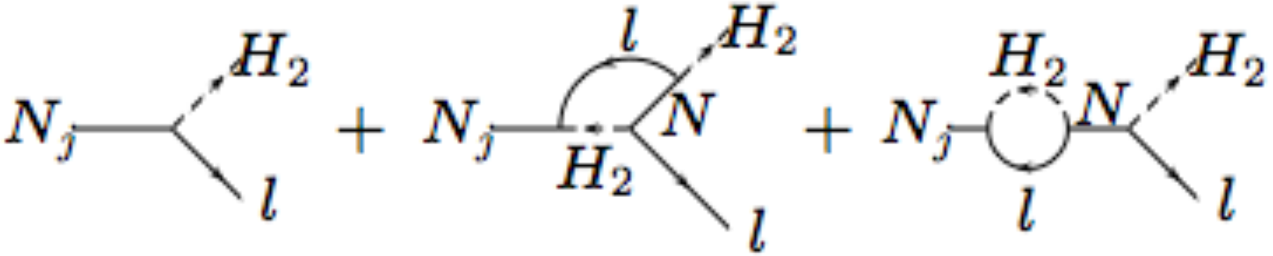
If (B-L) is generated above T_{EW} sphalerons produce B

$$Y_B \simeq \frac{12}{37} Y_{B-L}$$

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



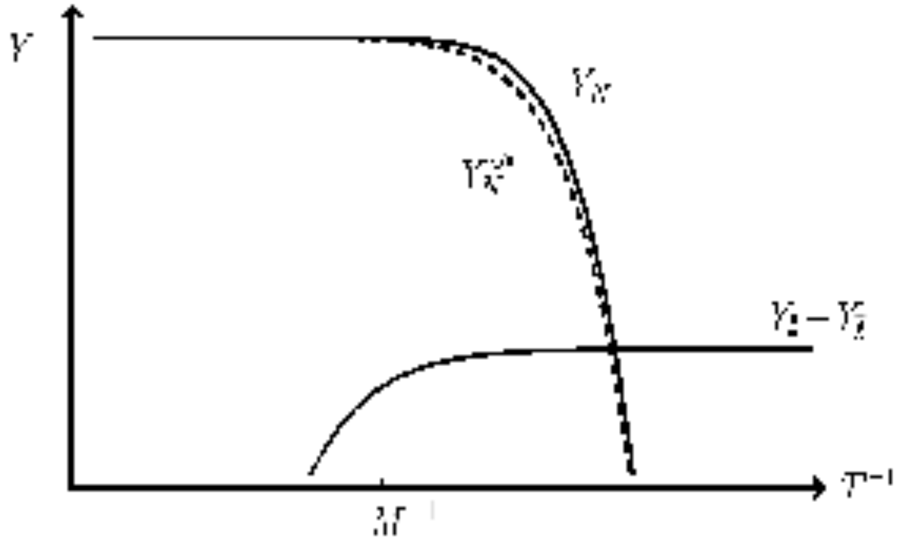
$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

Generic and robust feature of see-saw models

Out-of-equilibrium

The Majorana neutrinos decay out-of-equilibrium

$$\Gamma_N < \text{expansion rate} \quad \Rightarrow N_N > N_N^{\text{thermal}}$$



Lepton asymmetry (seesaw I)

$M_{2,3} \gg M_1$

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

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

Different combinations

Large enough asymmetry

$$|\epsilon_1| \leq \frac{8}{16\pi}\frac{M_1}{v^2}\left|\Delta m^2_{\mathrm{atm}}\right|^{1/2}$$

$\boxed{M_1 \geq 10^{9}\ \mathrm{GeV}}$

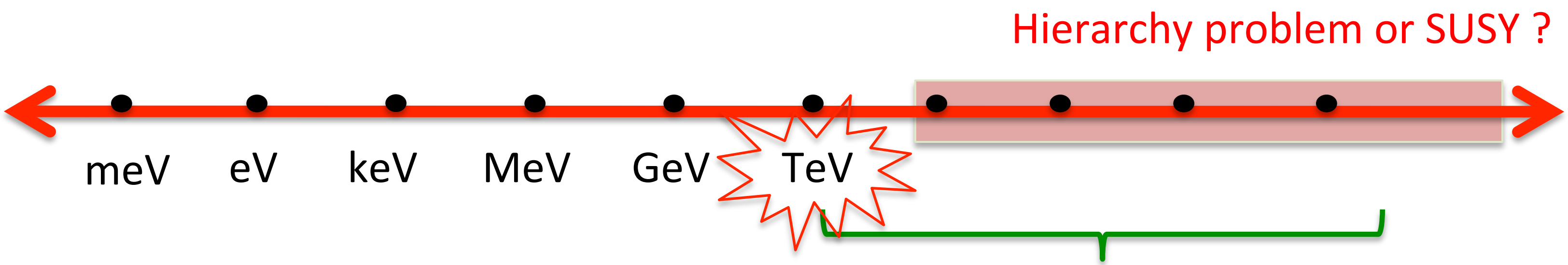
Davidson, Ibarra

Sufficiently large wash-out factor κ $\boxed{m_{\nu(\mathrm{min})} < \mathcal{O}(\mathrm{eV})}$

Leptogenesis stew

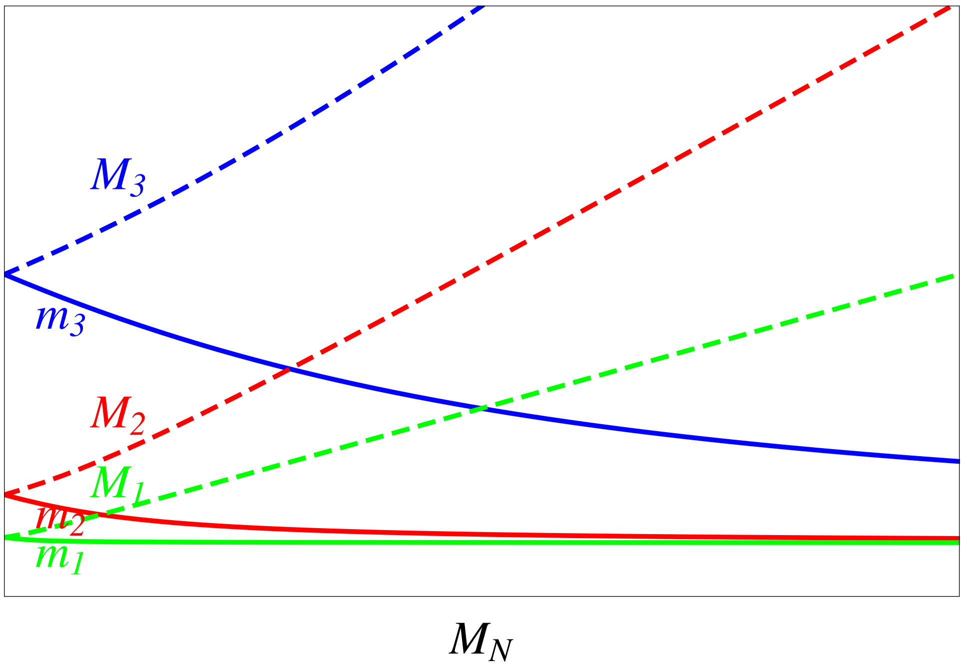
But neutrino mass matrix does not provide the exact recipe for a precise prediction!

Pinning down the New physics scale



But could it be lower ? Yes…

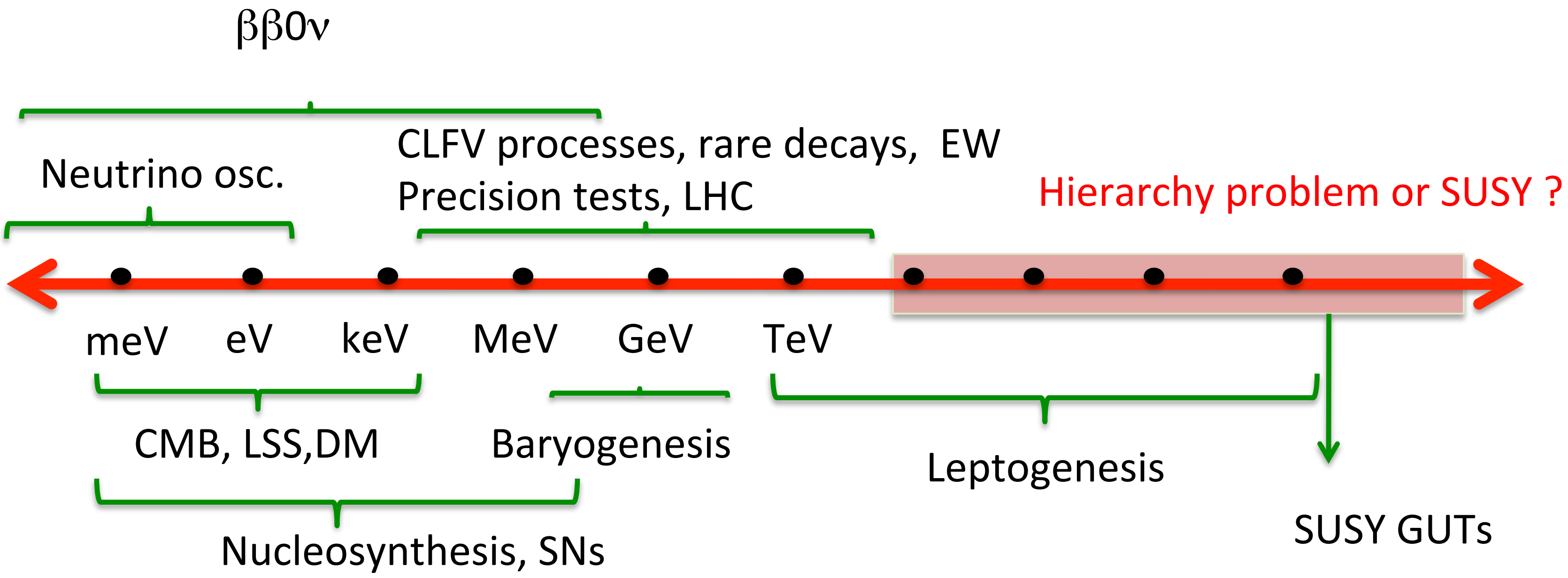
Low scale Type I seesaw models



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

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

Pinning down the New physics scale



ββ0ν

Neutrino osc.

CLFV processes, rare decays, EW Precision tests, LHC

Hierarchy problem or SUSY ?

CMB, LSS,DM

Baryogenesis

Leptogenesis

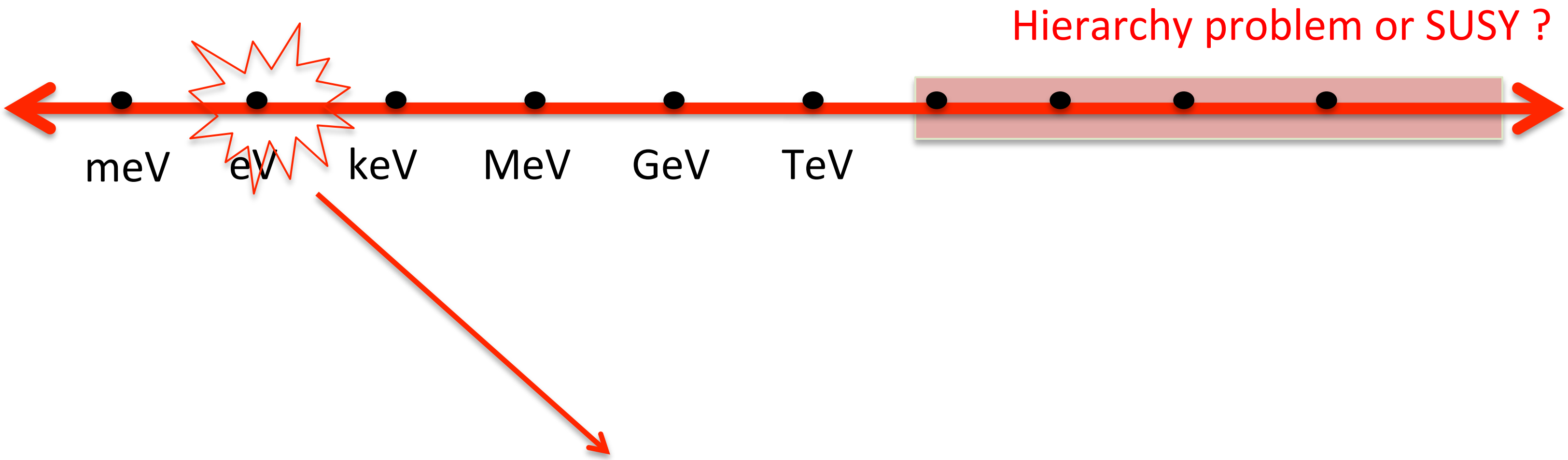
Nucleosynthesis, SNs

SUSY GUTs

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

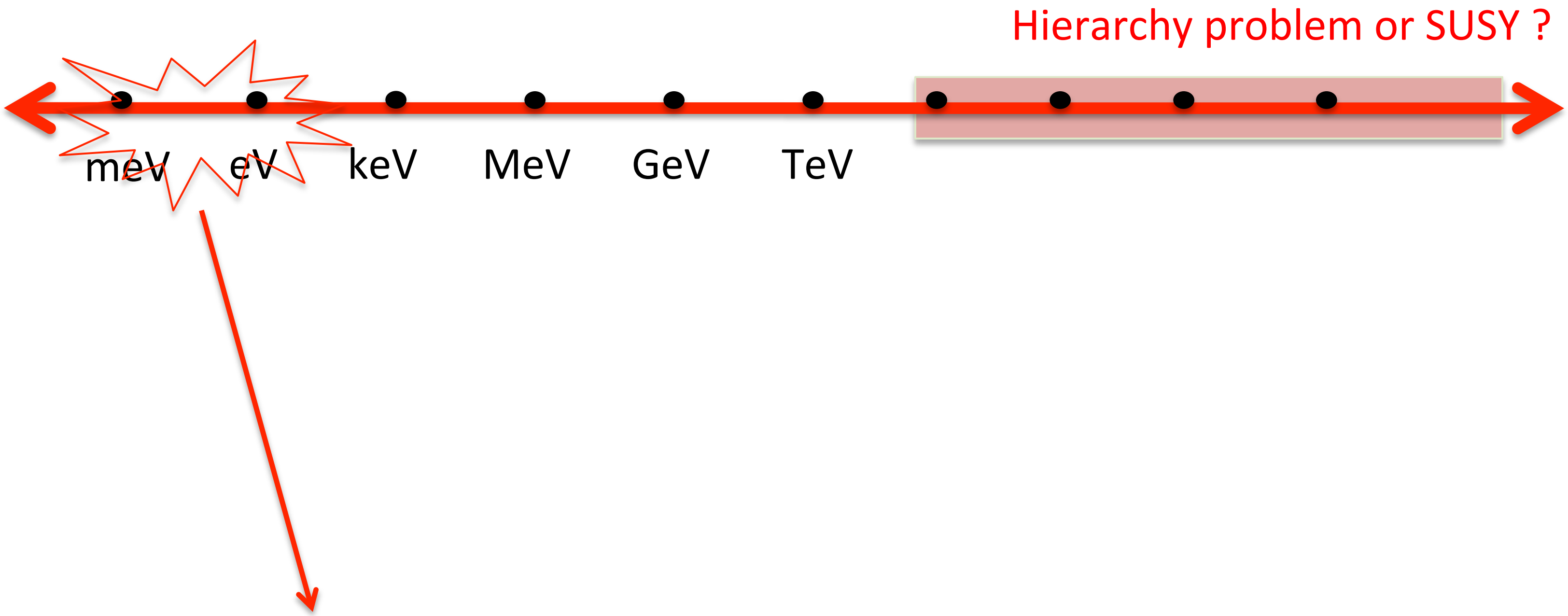
The measurement of any of these additional observables would give complementary information to that in neutrino masses, making the models much more predictive ...

Pinning down the New physics scale



Neutrino anomalies: LSND...

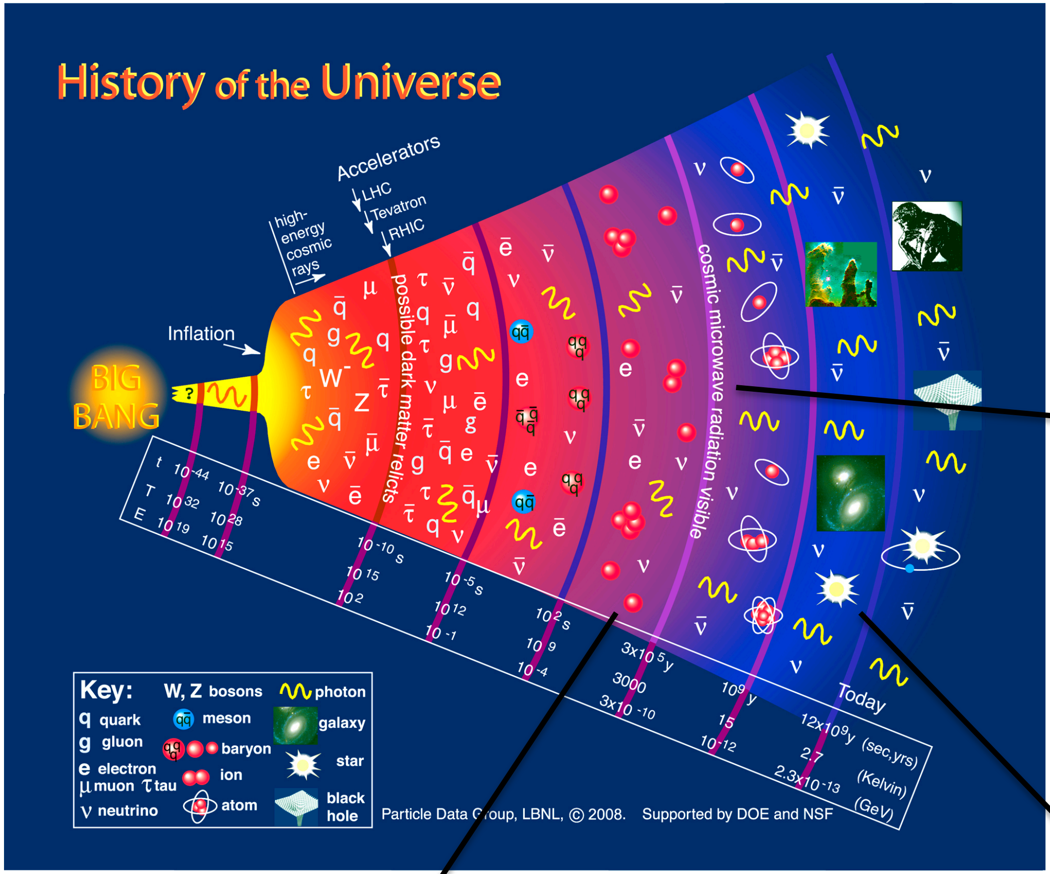
Pinning down the New physics scale



Cosmo anomalies ?

Cosmological neutrinos

Very hard to detect directly today but they have left many traces in the history of the Universe



CMB <-> N_ν

Nucleosynthesis <-> N_ν

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

Cosmological neutrinos @nucleosynthesis

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

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

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

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

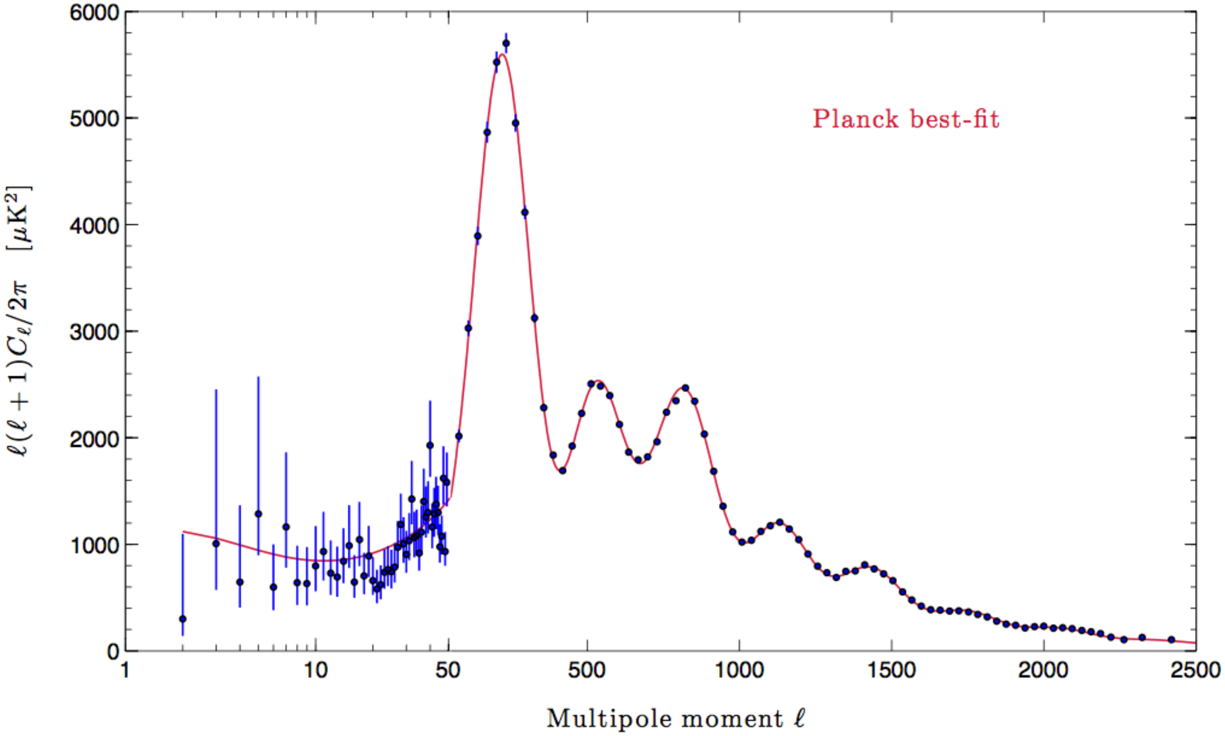
At this temperature the ratio p/n gets fixed and determines the abundance of light elements:

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

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_ν << T_{CMB}):

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

Cosmological neutrinos & LS Structure

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

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

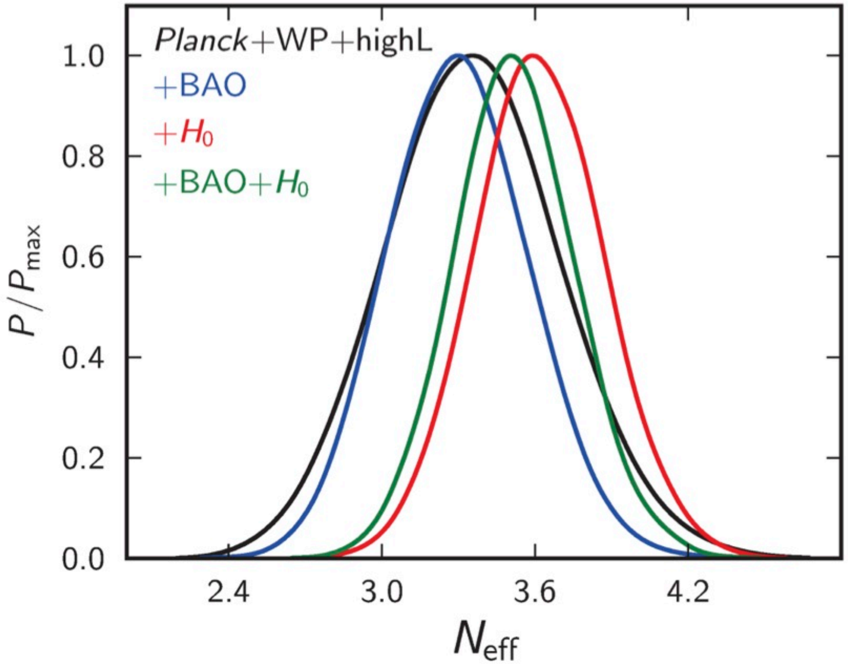
$$\Omega_\nu = \frac{\sum_i m_i}{93.5 \text{ eV}} h^{-2} < \Omega_m \rightarrow \sum_i m_i \leq 11.2 \text{ eV}$$

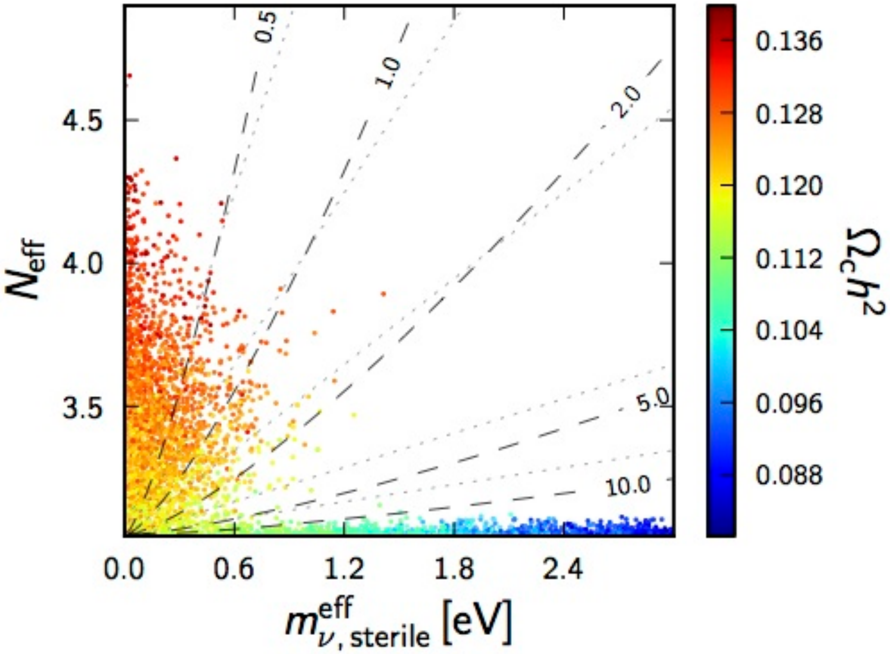
Gershtein, Zeldovich

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

Caldwell's Lectures

Extra relativistic species welcome…

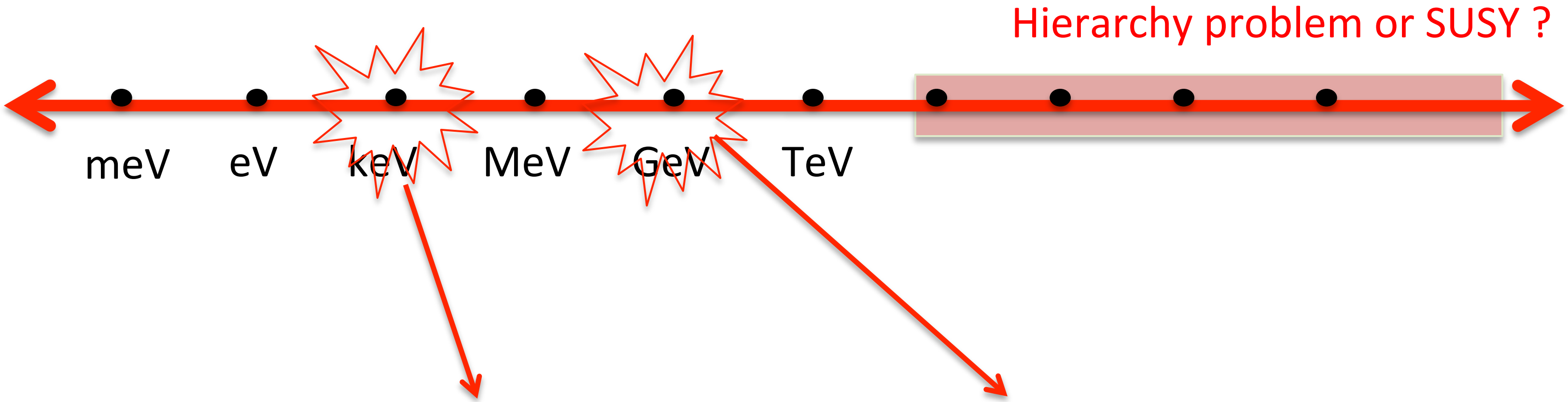




Ade et al 2013

but not too heavy or not too thermal…

Pinning down the New physics scale



Hierarchy problem or SUSY ?

meV eV keV MeV GeV TeV

DM

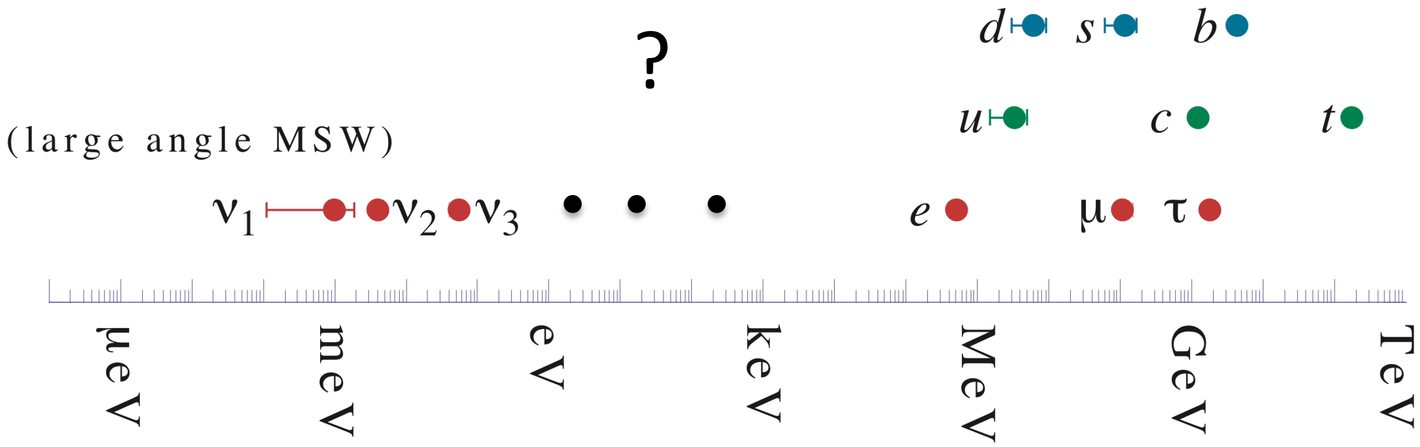
Baryogenesis

Dodelson, Widrow; Fuller et al

Akhmedov, Smirnov; Shaposhnikov

Ruchayskiy's Lectures

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;...**

Han et al; Garayoa, Schwetz; Kadastik,et al ; Akeroyd, et al; Fileviez et al, del Aguila et al; Franceschini et al; Aguilar-Saavedra et al;Arhrib et al; Eboli et al...; Tello et al.

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 $U(1)_L$

Two scale see-saw models (approx) Lepton number

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

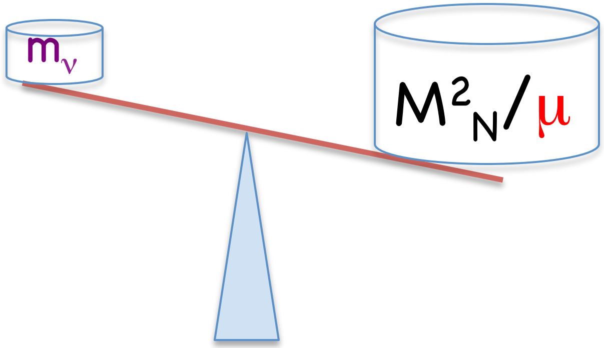
$$\begin{array}{rccc} & & \multicolumn{2}{c}{\overbrace{\hspace{4em}}^{n_R}} \\ & 0 & Yv & 0 \\ & Yv & 0 & M_N \\ & 0 & M_N & 0 \\ & \downarrow & \downarrow & \downarrow \\ L= & +1 & -1 & +1 \end{array}$$

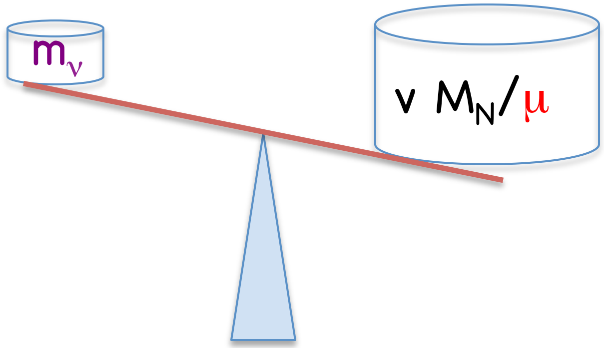
Inverse Seesaw

$$\begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix}$$

Direct Seesaw

$$\begin{pmatrix} 0 & Yv & \mu \\ Yv & 0 & M_N \\ \mu & M_N & 0 \end{pmatrix}$$



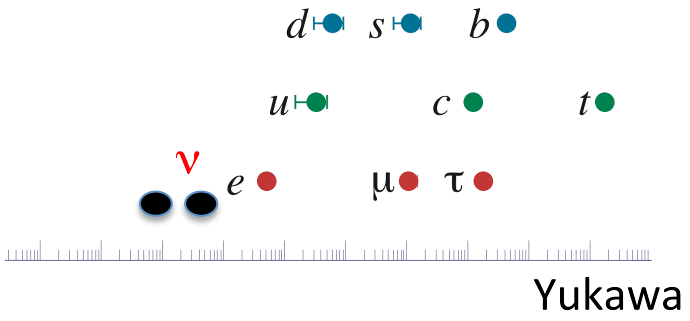


Y unsuppressed: -> LFV effects large μ-> e γ, etc
-> heavier spectrum M_N, Y v, at LHC

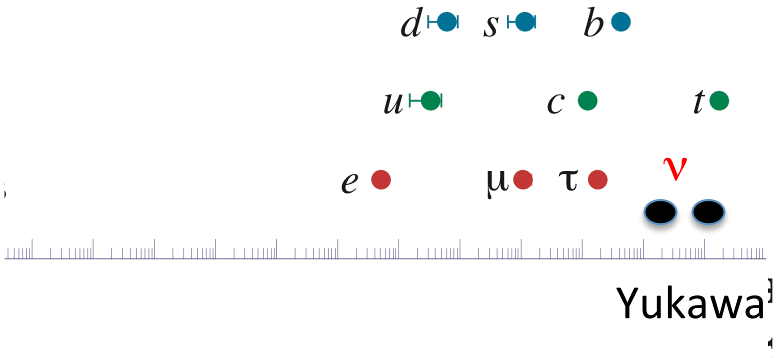
Kersten,Smirnov 07; Abada et al 07; Gavela,et al 09

Charged/neutral hierarchy in seesaw

Λ = TeV



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

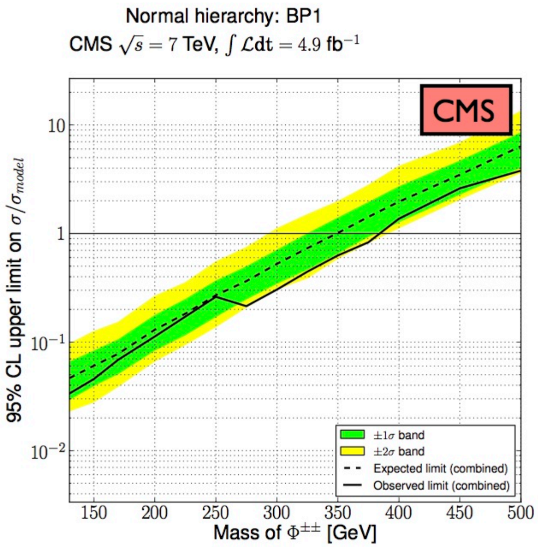


Eg: Inverse seesaw/ direct seesaw

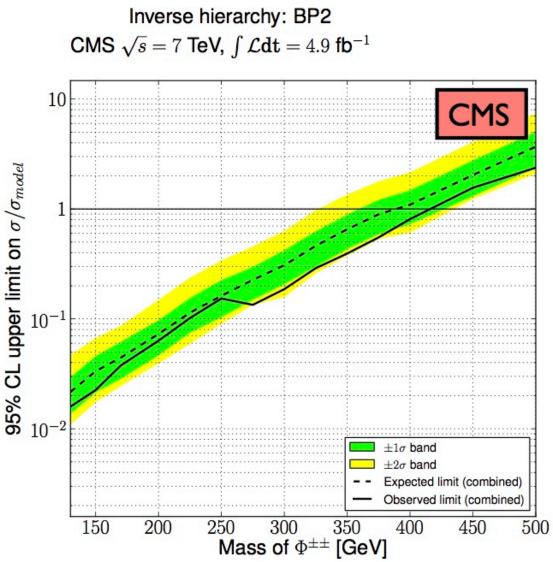
Wyler, Wolfenstein; Mohapatra, Valle;
Branco, Grimus, Lavoura, Malinsky, Romao,
...

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

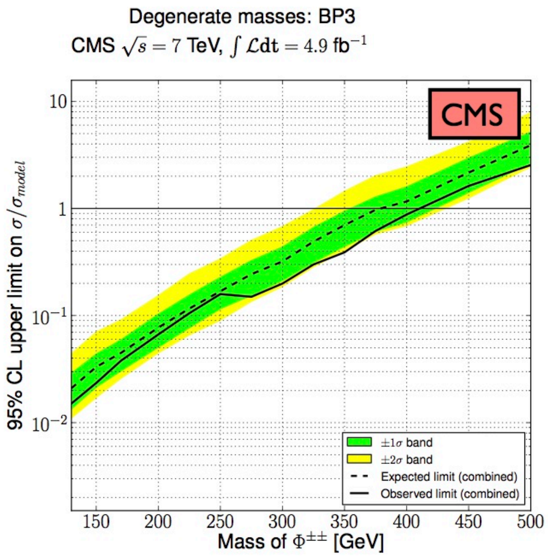
Normal hierarchy



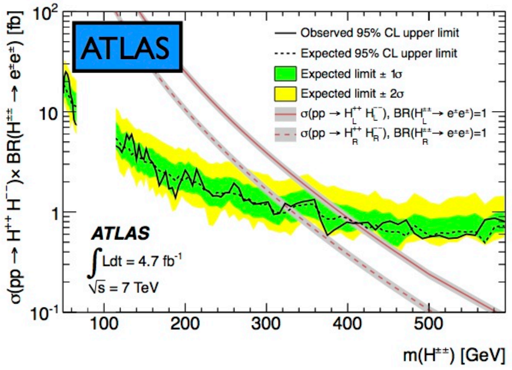
Inverted hierarchy



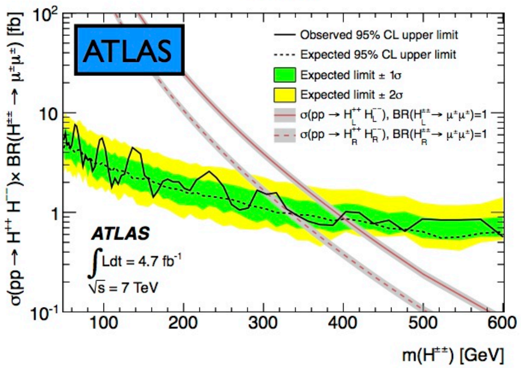
Degenerate ν



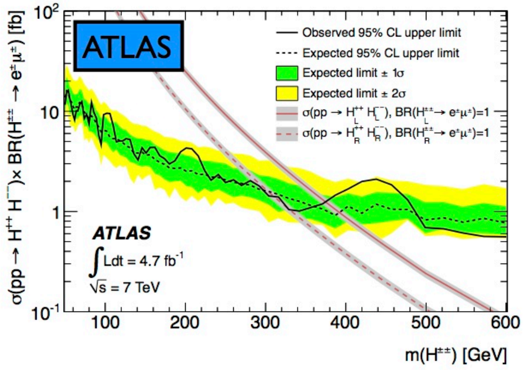
Br(ee)=1



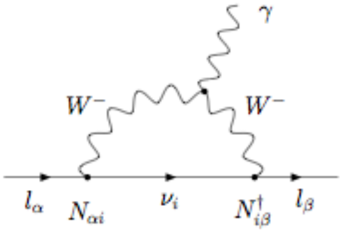
Br(μμ)=1



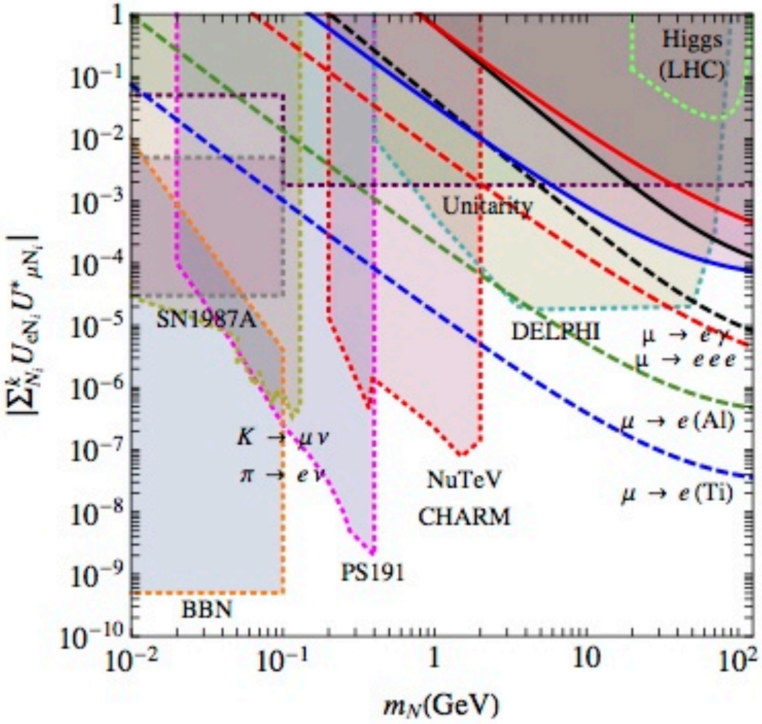
Br(eμ)=1

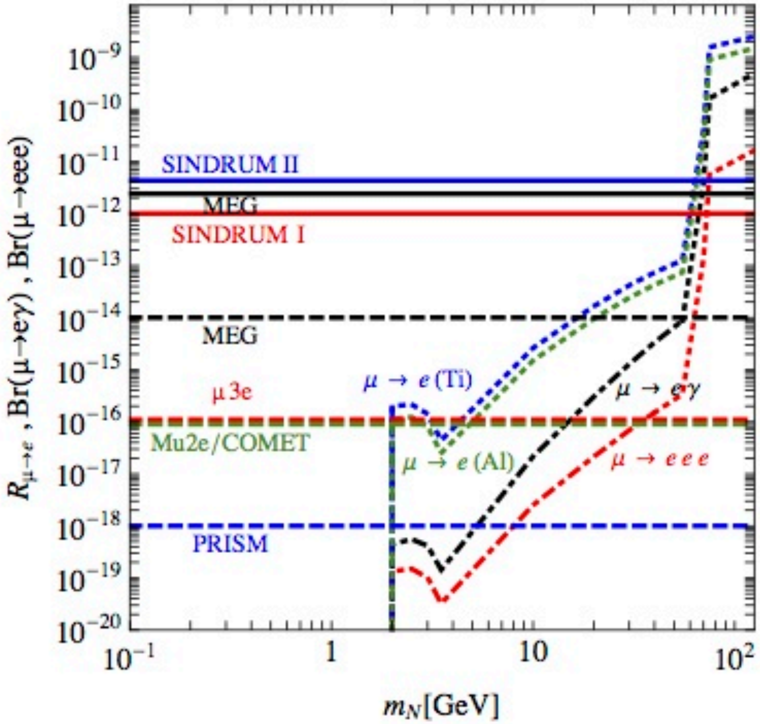


Rich phenomenology of low-scale models with U(1)



μ -> e γ   μ−> eee   μ−> e conversion





recent analysis Alonso et al 2012

Detecting such a signal would be a breakthrough to pin down the new physics scale

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	$\theta_{12}, \theta_{23}, \theta_{13}, \delta$ 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...