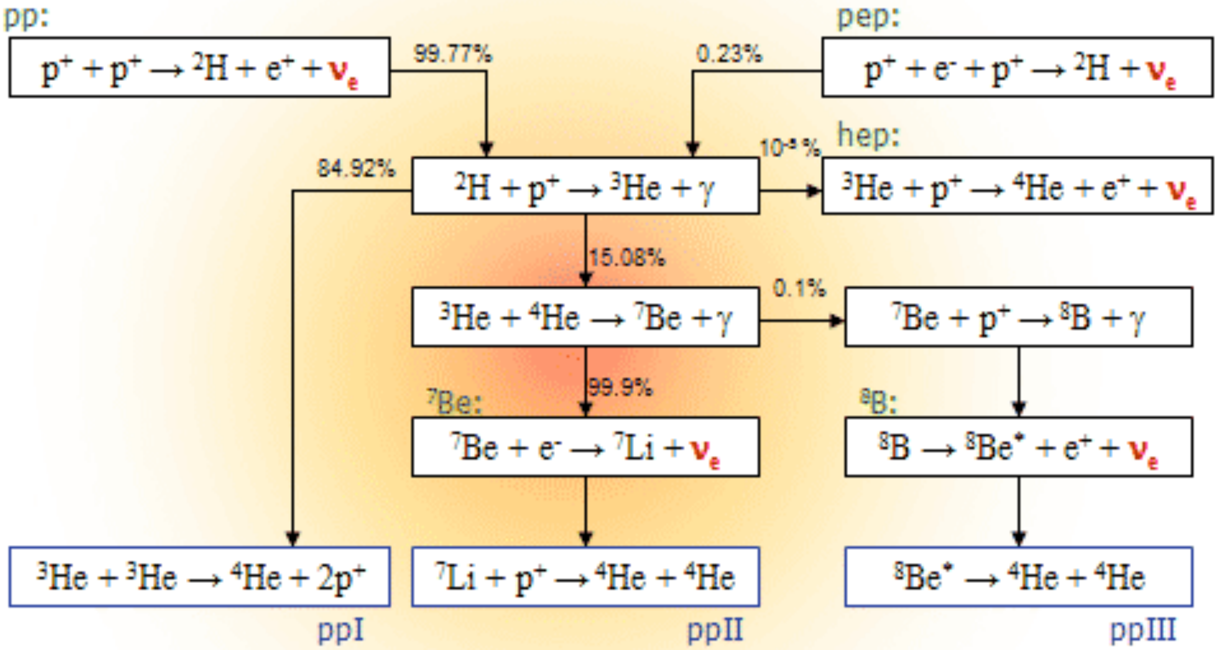
LECTURE II

- The standard 3ν scenario and its unknowns
- Experimental prospects to discover leptonic CP and determine the neutrino hierarchy
- Neutrinos and beyond the Standard Model physics

Stars shine neutrinos

1939 Bethe

Stablishes the theory of stelar nucleosynthesis



pp:

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

pep:

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

99.77%

0.23%

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

84.92%

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%

^{7}Be:

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

^{8}B:

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

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

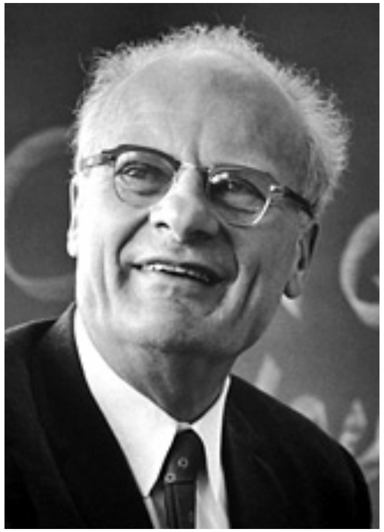
ppI

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

ppII

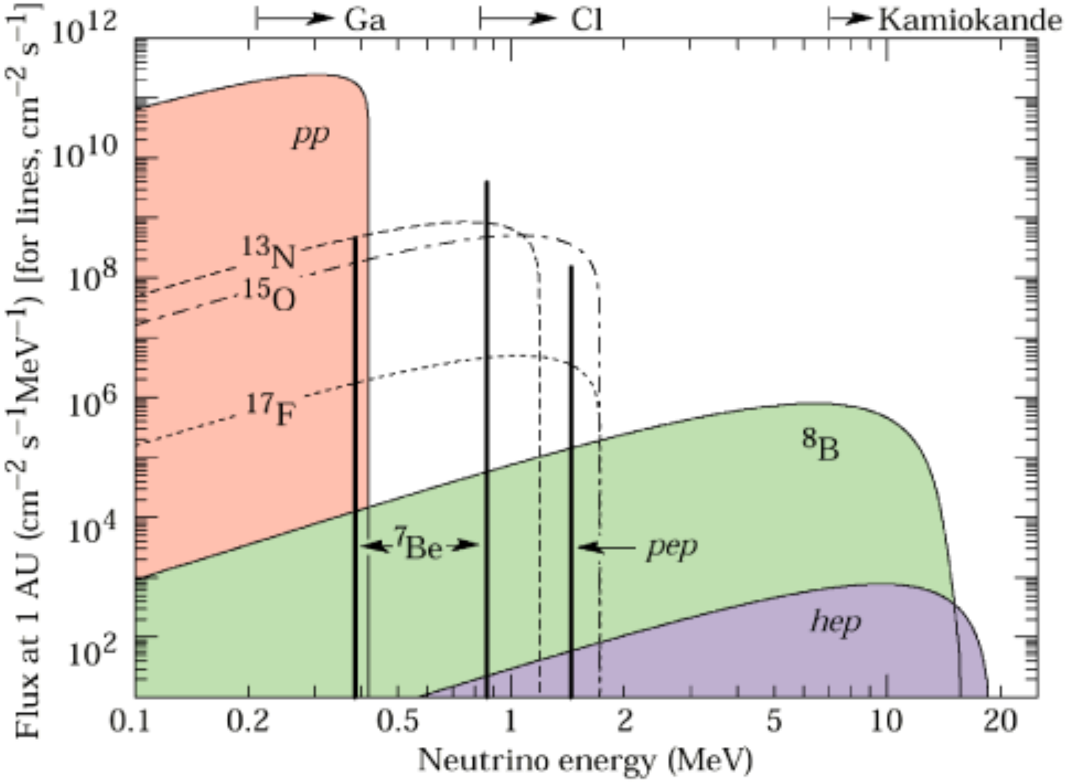
$^8Be^* \rightarrow {}^4He + {}^4He$

ppIII



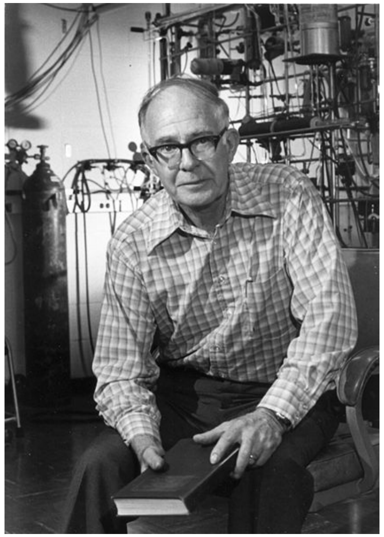
Nobel 1967

¿How many neutrinos from the Sun ?



Bahcall (died 2005)

The hero of the caves



Raymond Davies

Nobel 2002

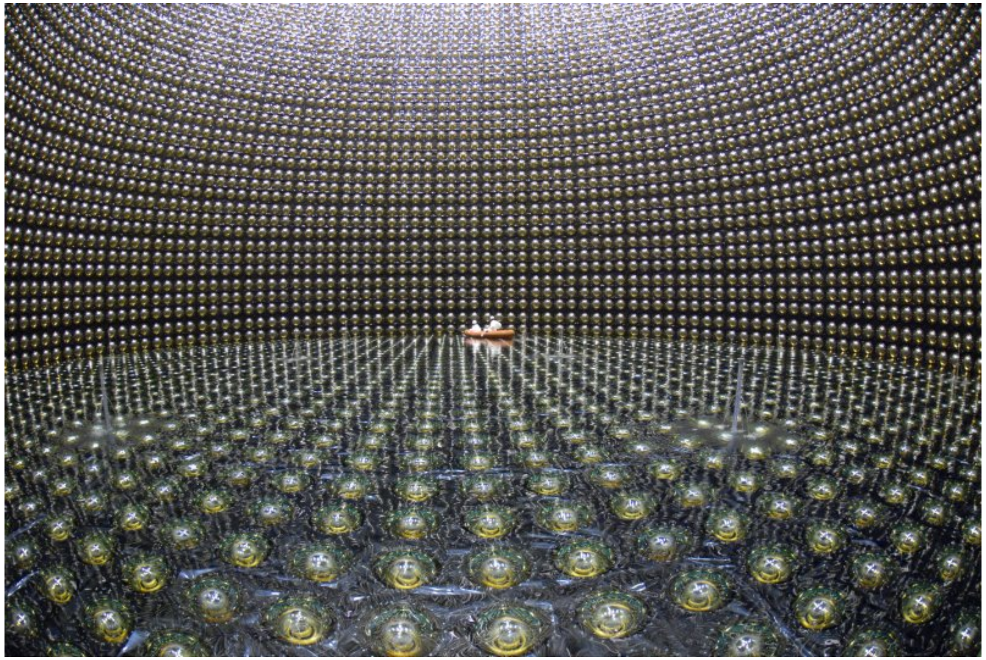
1966 he detects for the first time solar neutrinos in a tank of 400000 liters 1280m underground (Homestake mine)

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

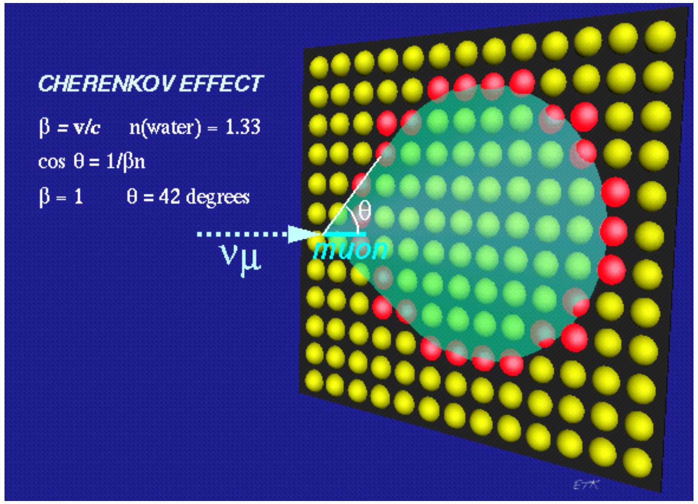
Problem in detector ? In solar model ? In neutrinos ?

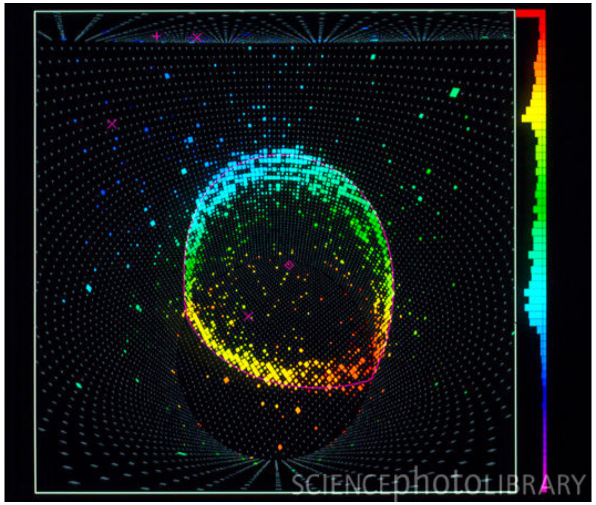
Other radiochemical experiments: Gallium with lower-threshold confirmed

Underground cathedrals of light



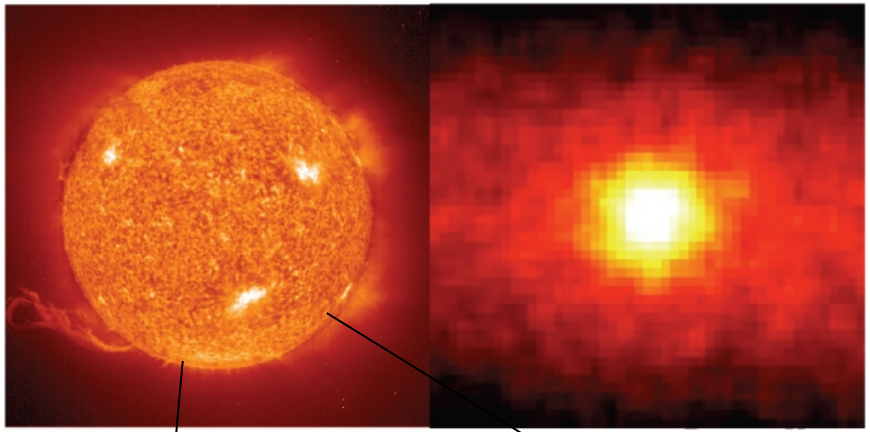
Koshiba (Nobel 2002)





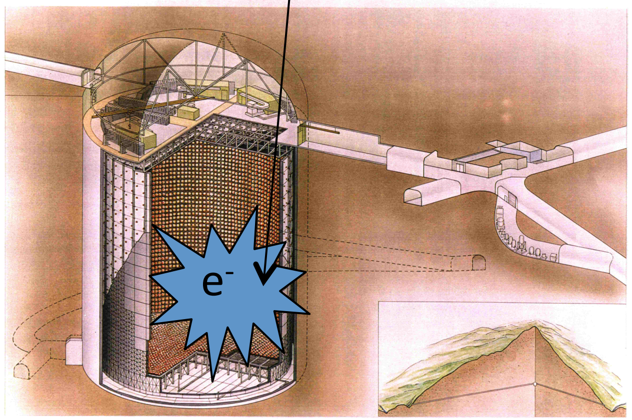
Allows to reconstruct velocity and direction, e/μ particle identification

Solar Neutrinos



Neutrinography of the sun

SuperKamiokande (22.5 kton!)



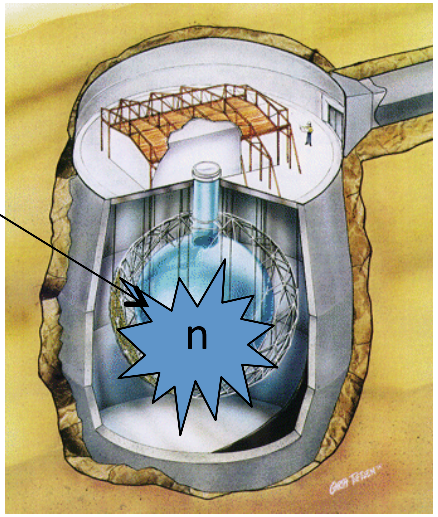
SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

NIKKEN SEKKEI

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

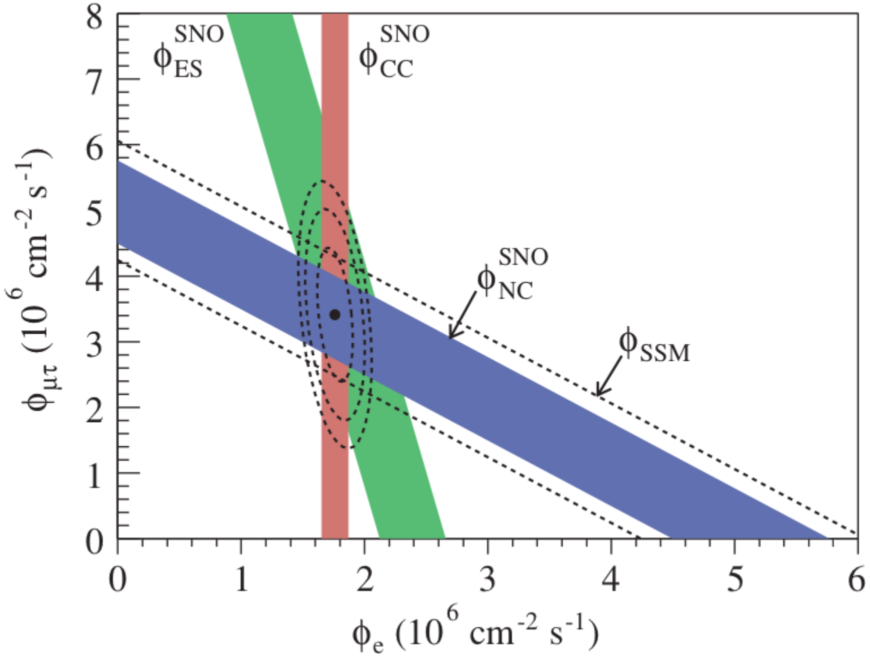
SNO

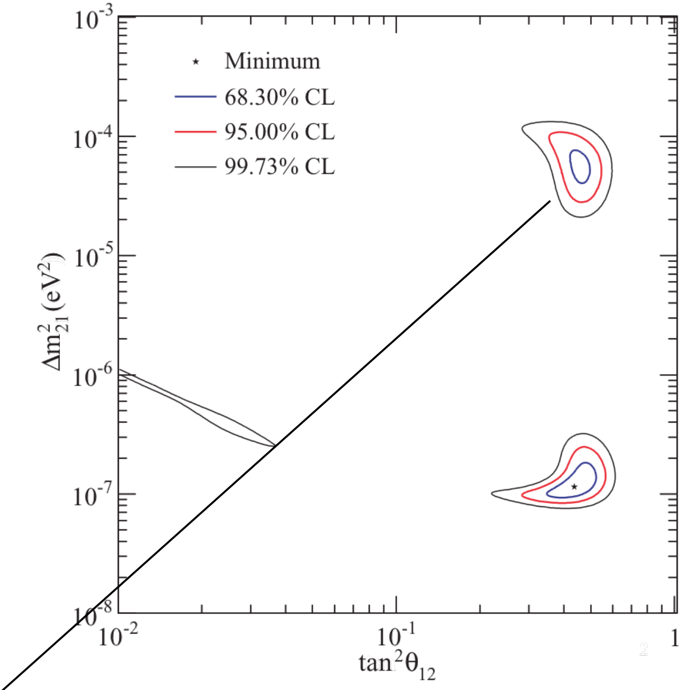


$$NC: \quad \nu_i + d \rightarrow p + n + \nu_i$$

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

Flavour of solar neutrinos





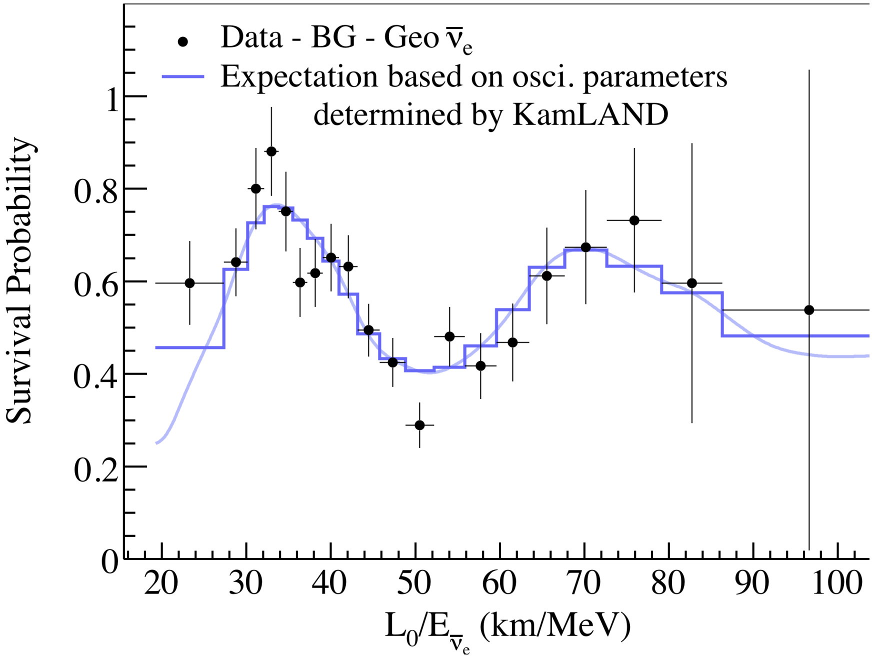
$$|\Delta m^2|^{-1} \sim \frac{O(100Km)}{O(MeV)}$$

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

KamLAND: solar oscillation

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

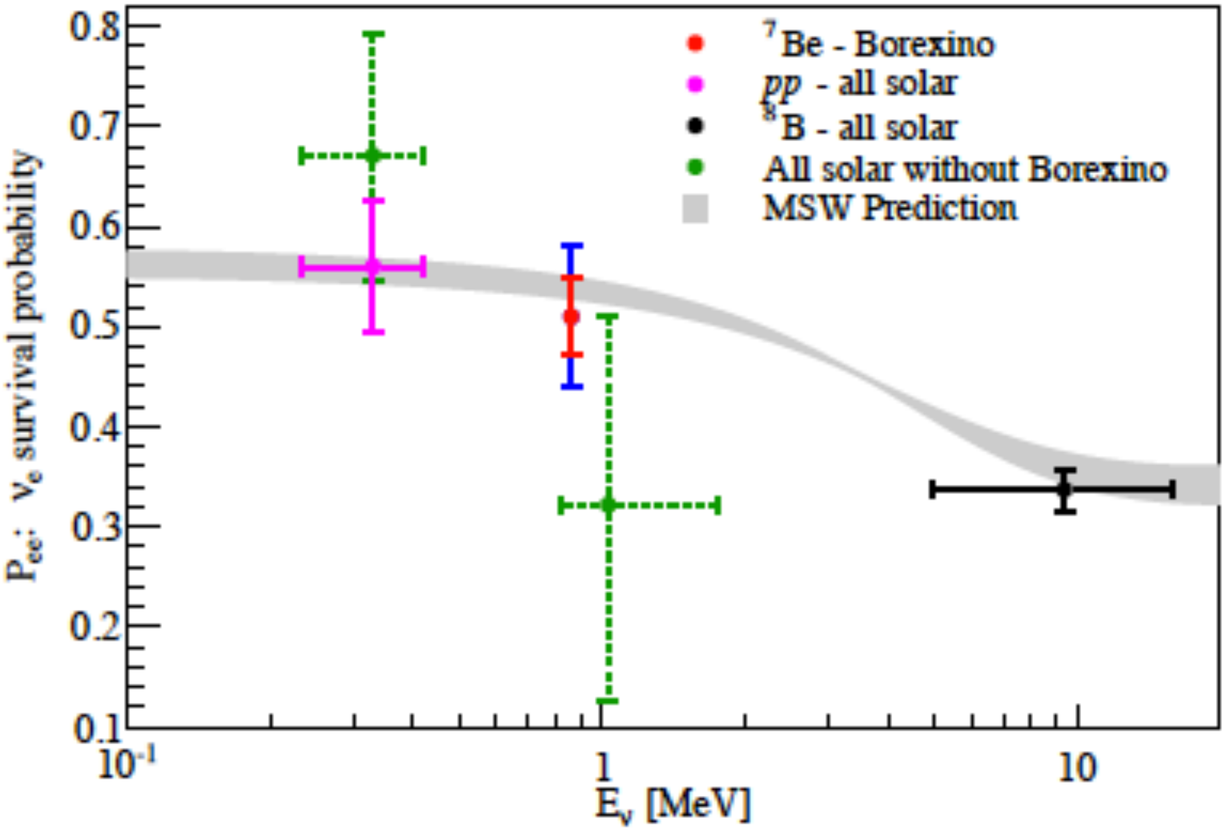
Reines&Cowan experiment ½ century afterwards
at 170 km from Japenese reactors …



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

Large mixing

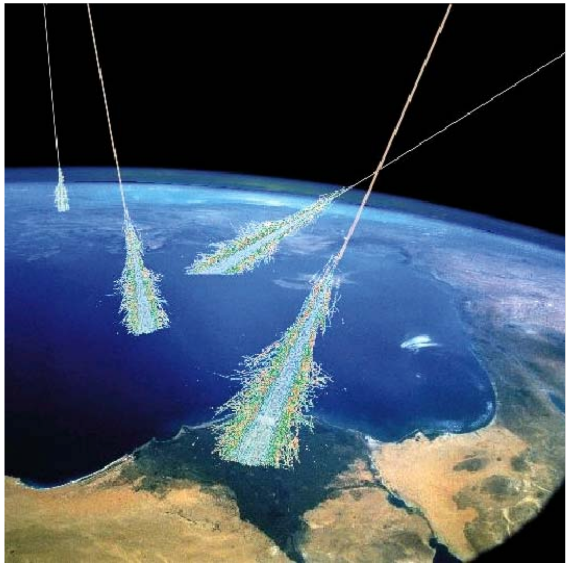
Solar neutrinos and MSW

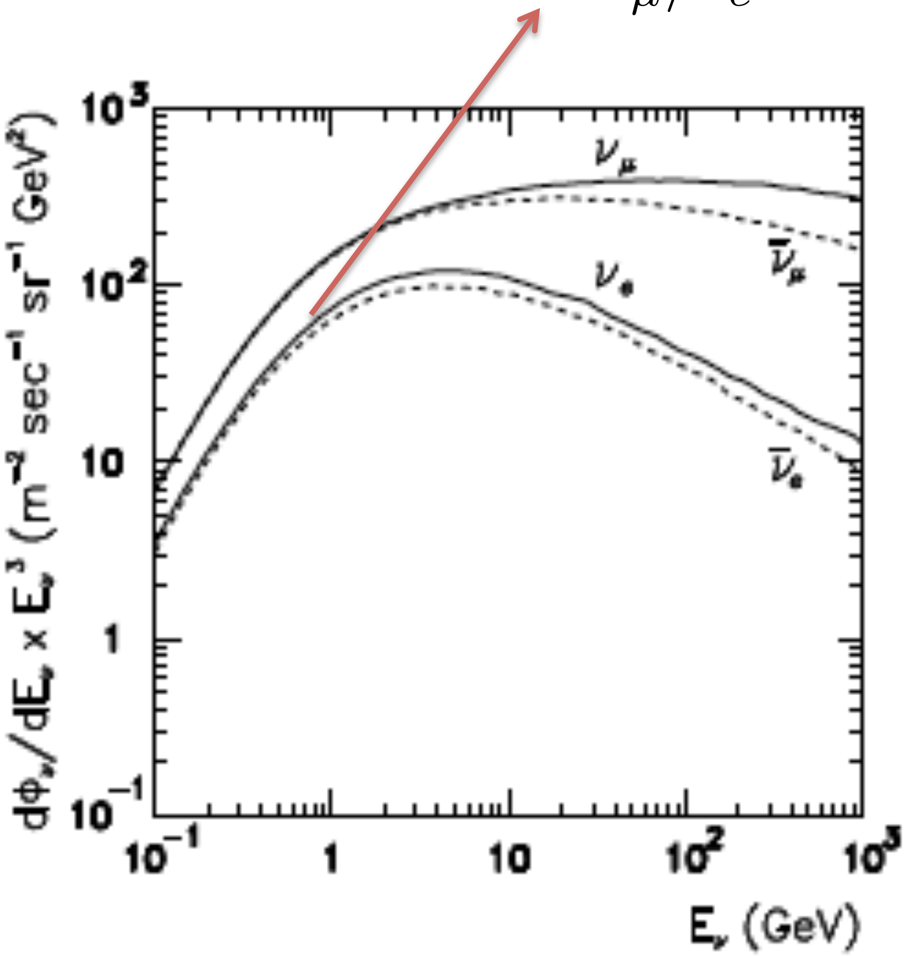


Exercise: from what we saw yesterday and this plot estimate the mixing angle

Atmospheric Neutrinos

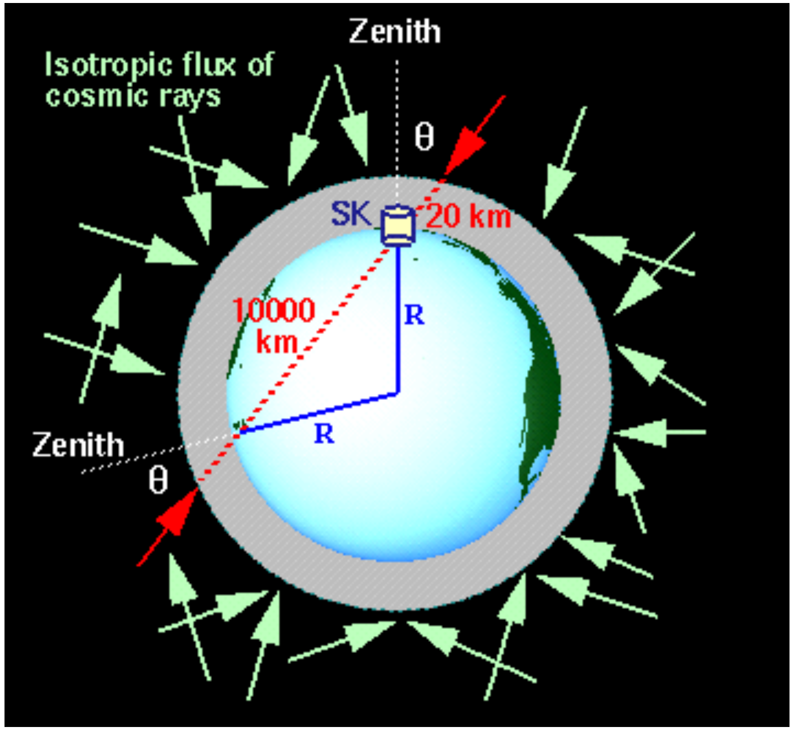
$\nu_\mu / \nu_e \sim 2$



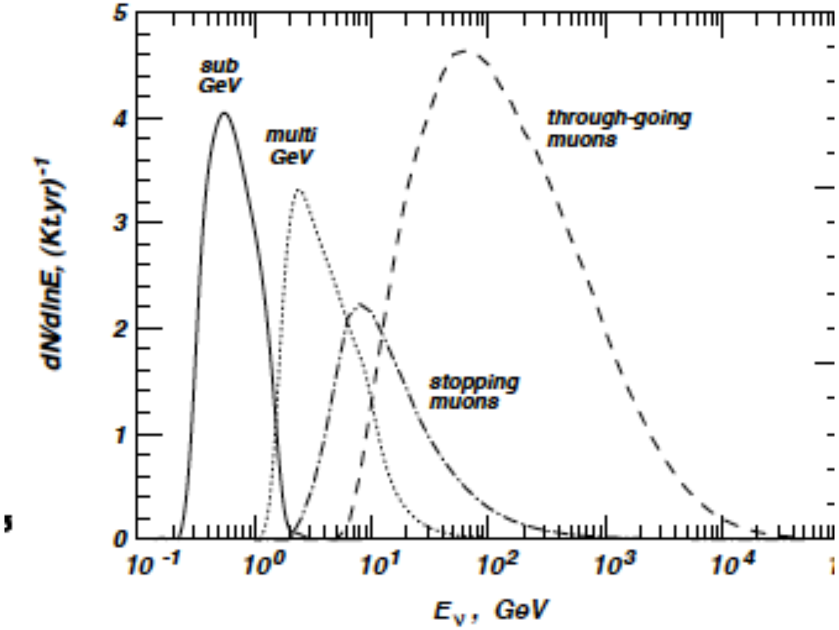


Produced in the atmosphere when primary cosmic rays collide with it, producing π, K

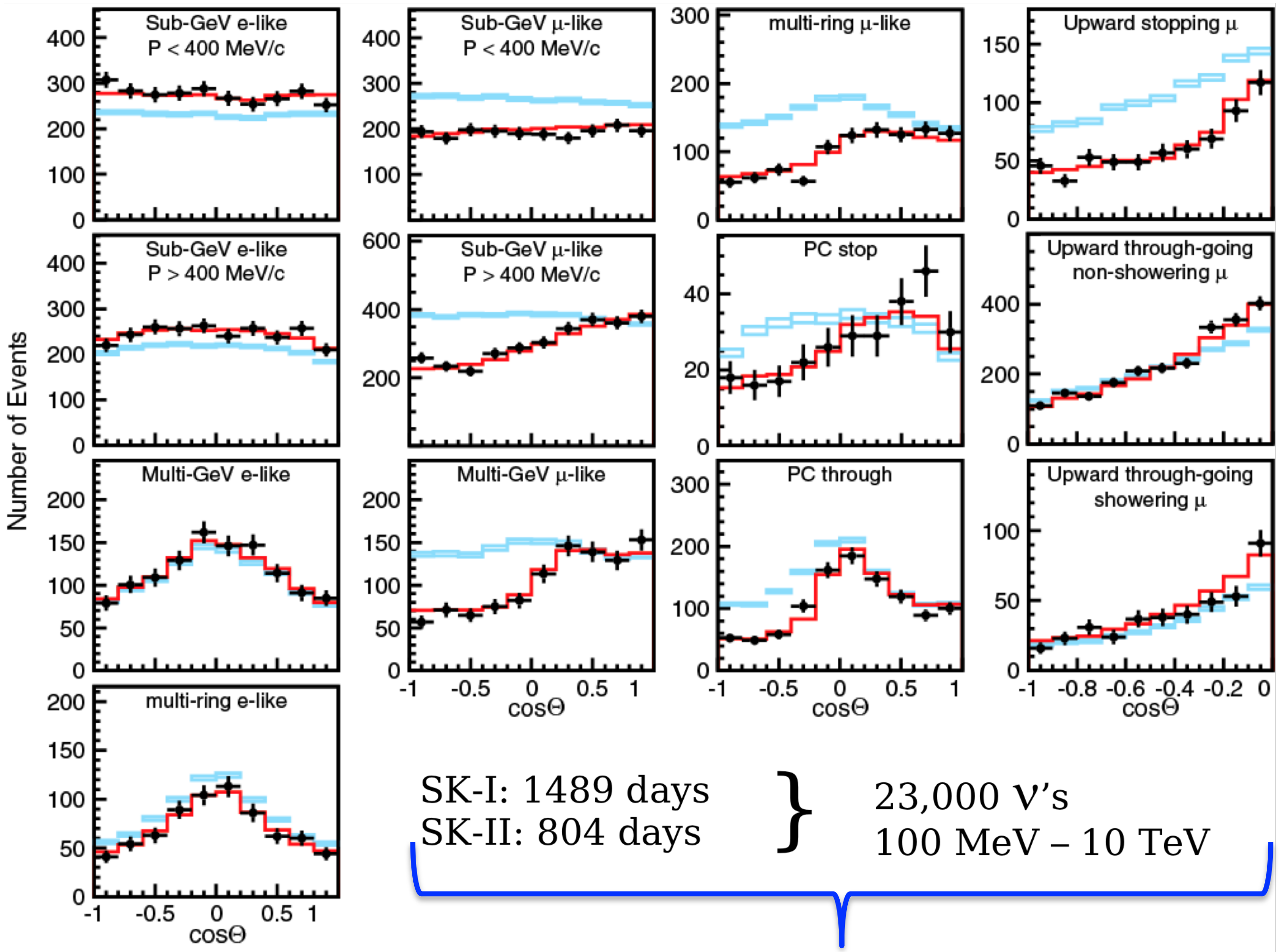
Atmospheric Neutrinos



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



Atmospheric Neutrinos



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

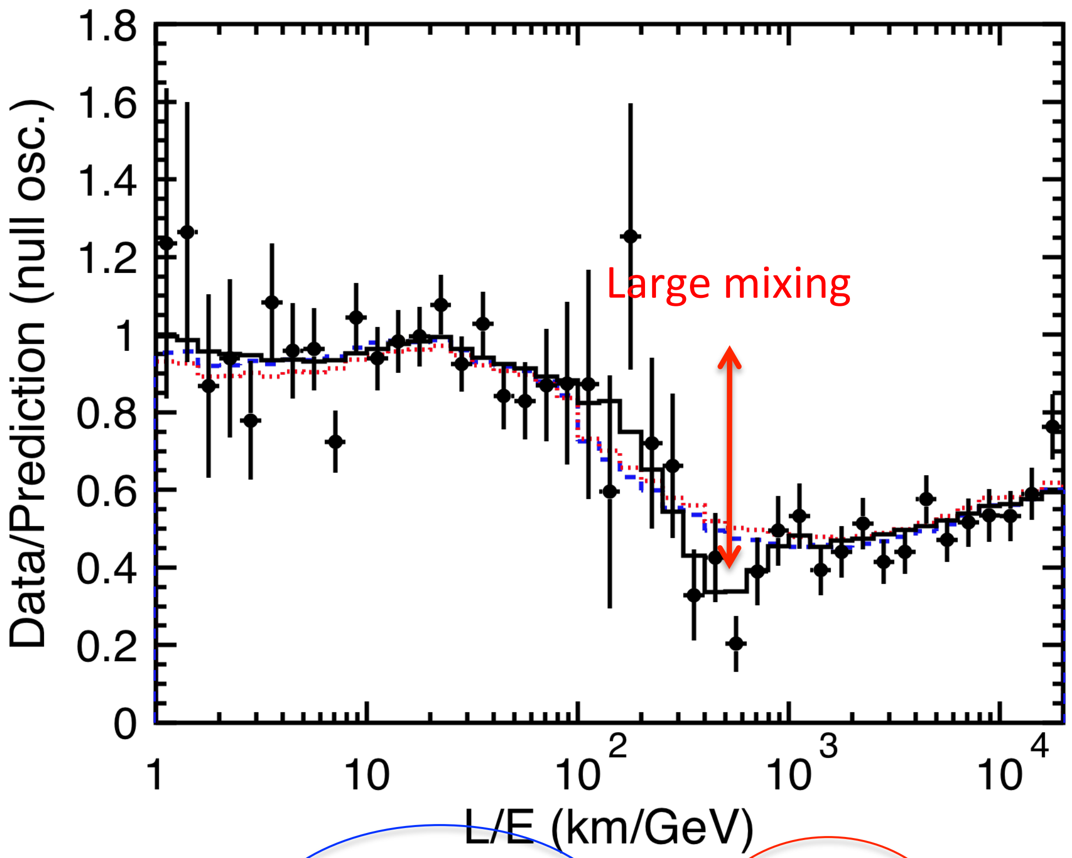
}

23,000 ν's
100 MeV – 10 TeV

e events

μ events

Atmospheric Oscillation



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

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

Reines&Cowan experiment at 1km!

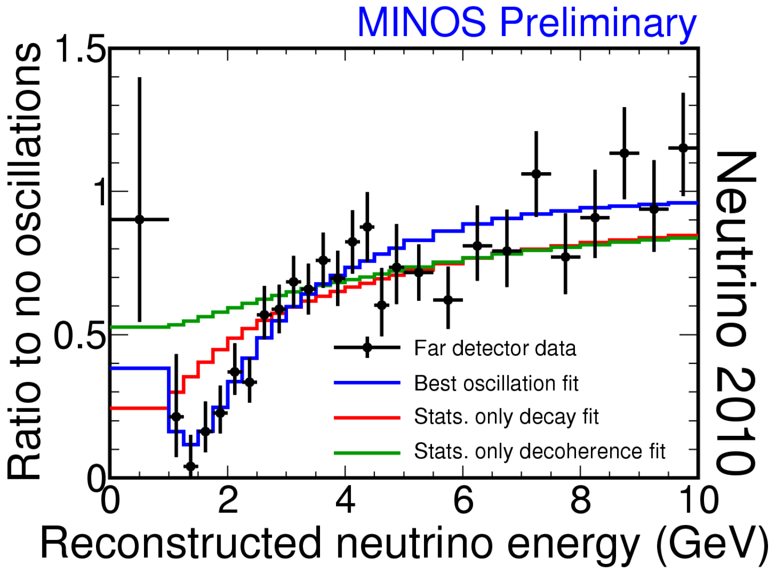
Lederman&co experiment at 1000km!

Lederman&co neutrinos oscillate with the atmospheric wave length

Pulsed neutrino beams to 700 km baselines

MINOS

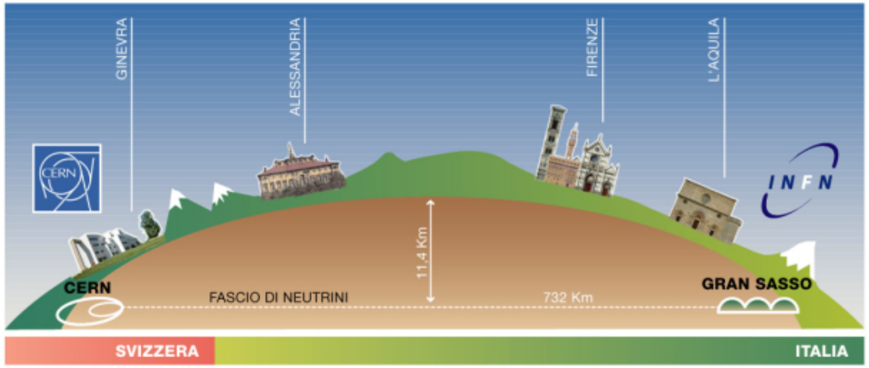
$$\nu_\mu \to \nu_\mu$$



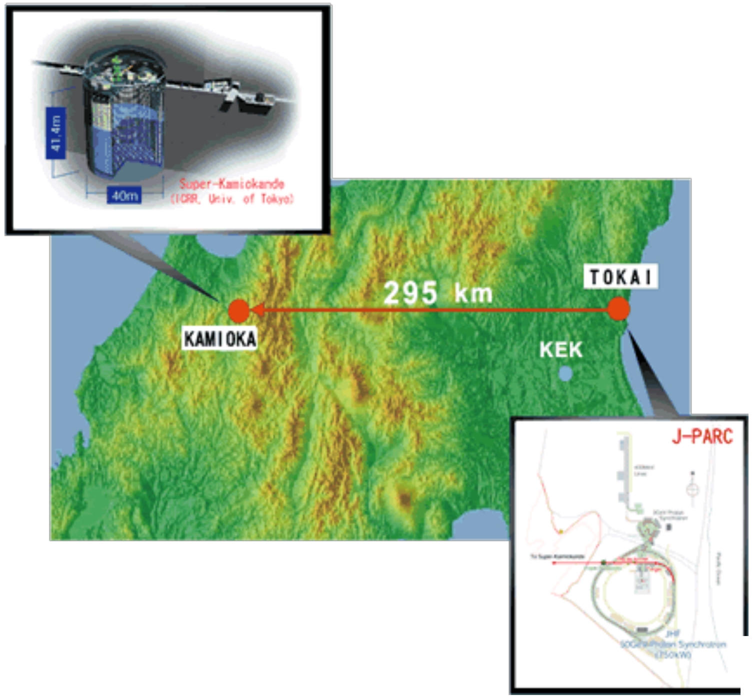
$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3}\ eV^2$$

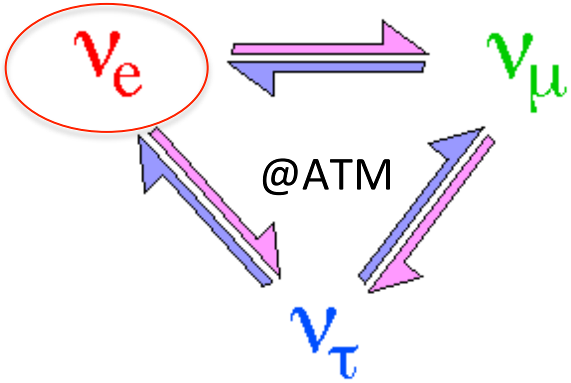
$$\nu_\mu \to \nu_\tau$$

OPERA

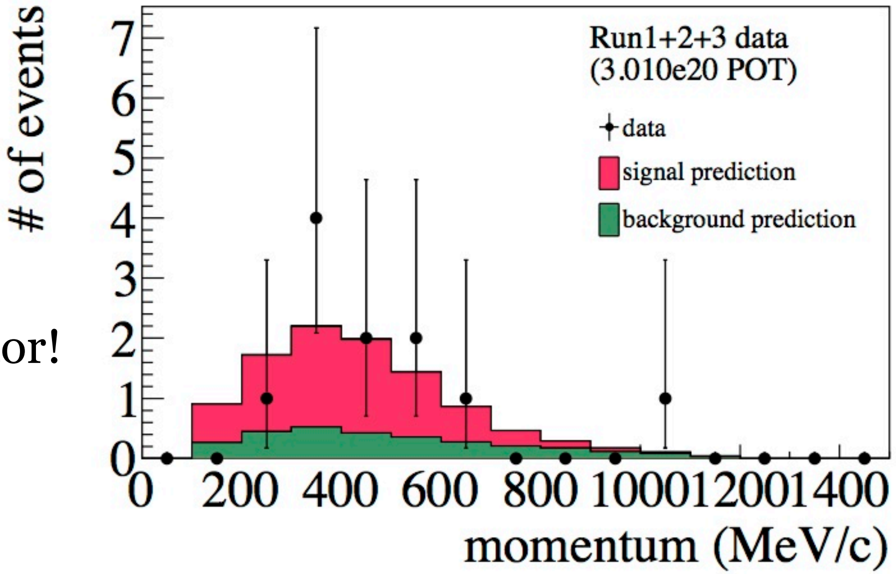


T2K



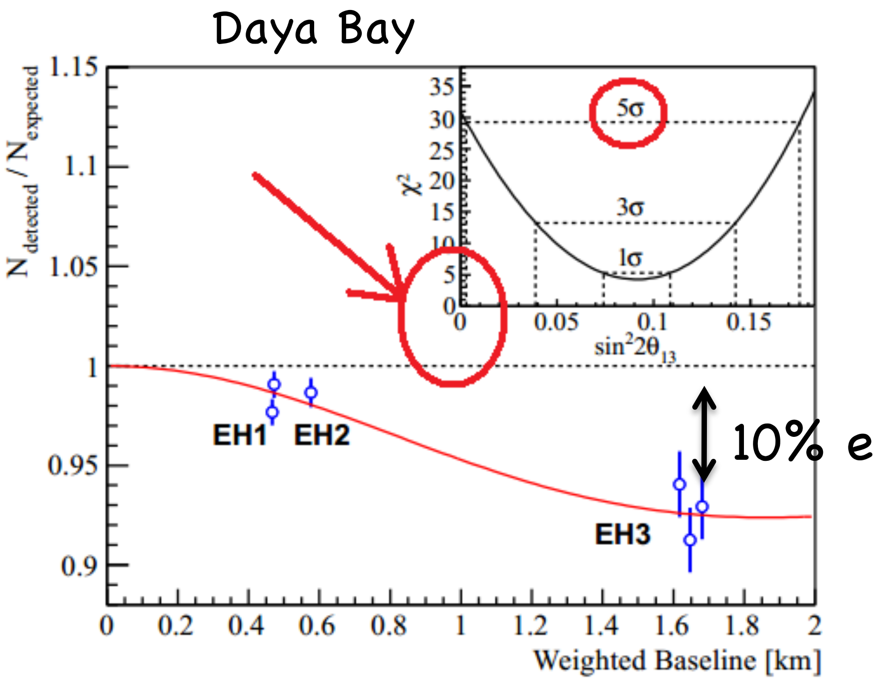


$$\nu_\mu \rightarrow \nu_e$$

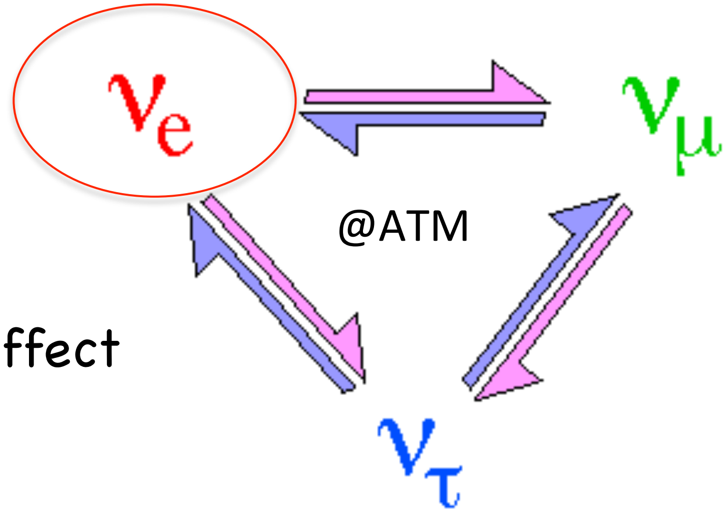


Using the SuperKamiokande detector!

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



10% effect



$$\bar{\nu}_e \longrightarrow \bar{\nu}_e$$

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

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

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

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

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

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

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

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

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

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

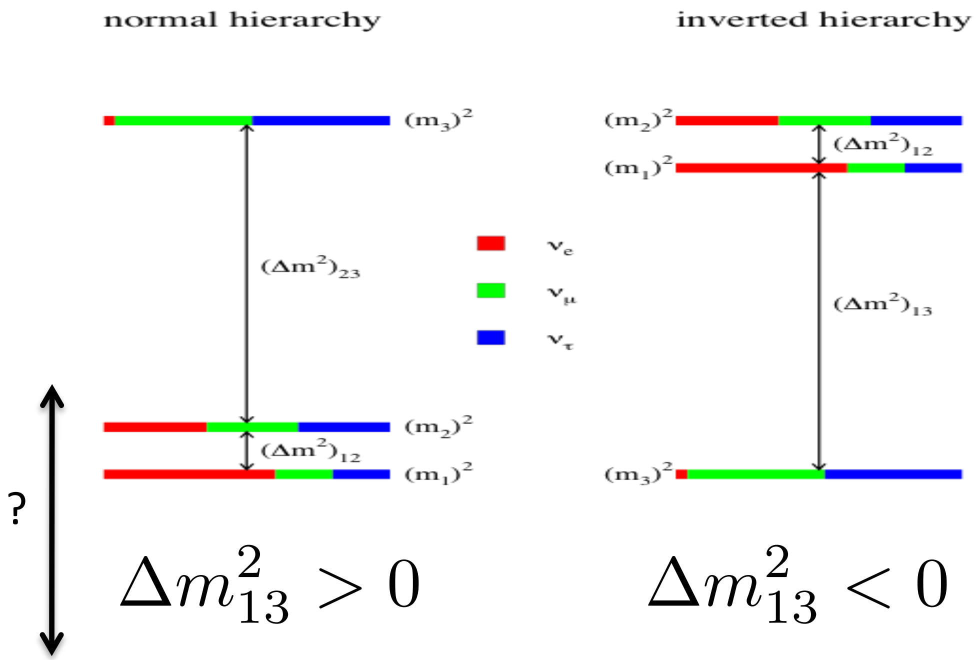
Experiments in the solar range are described approximately by 2x2 mixing with

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

The measuremed oscillation of ne in T2K, DayaBay, RENO and Dchooz implies gives $\theta_{13} \sim 9^\circ$

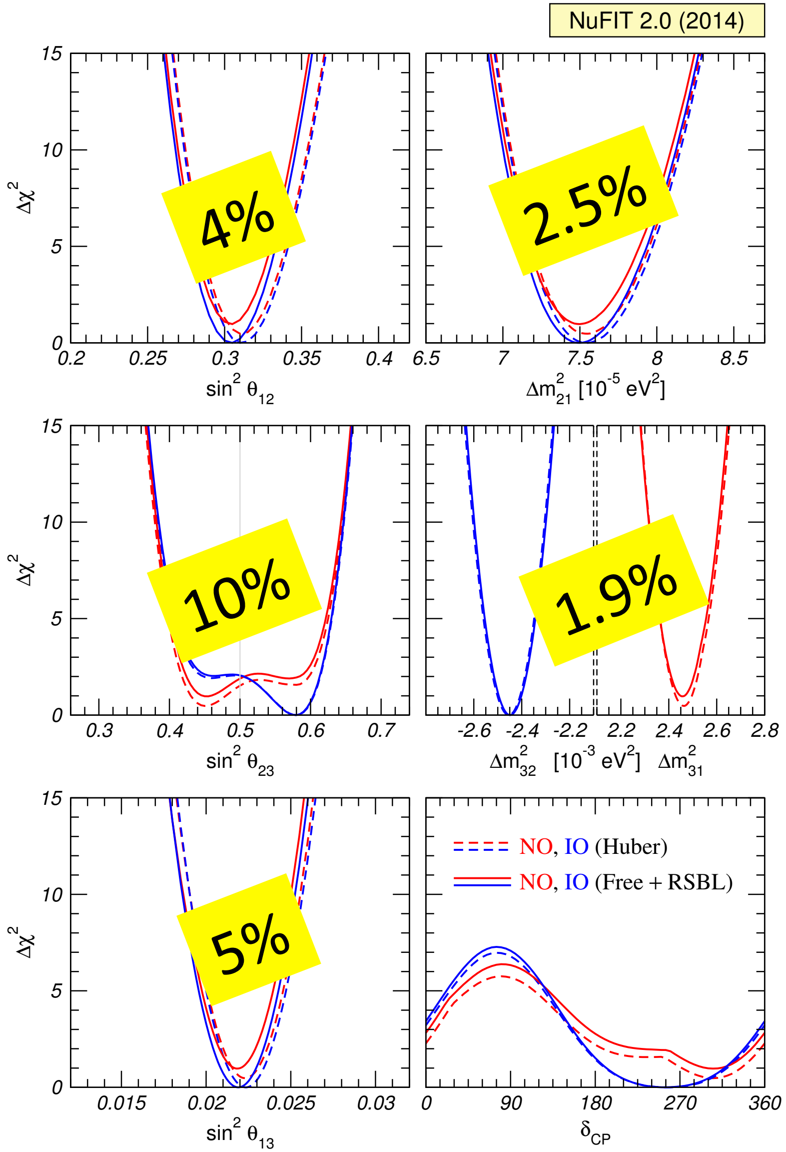
Standard 3ν scenario

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



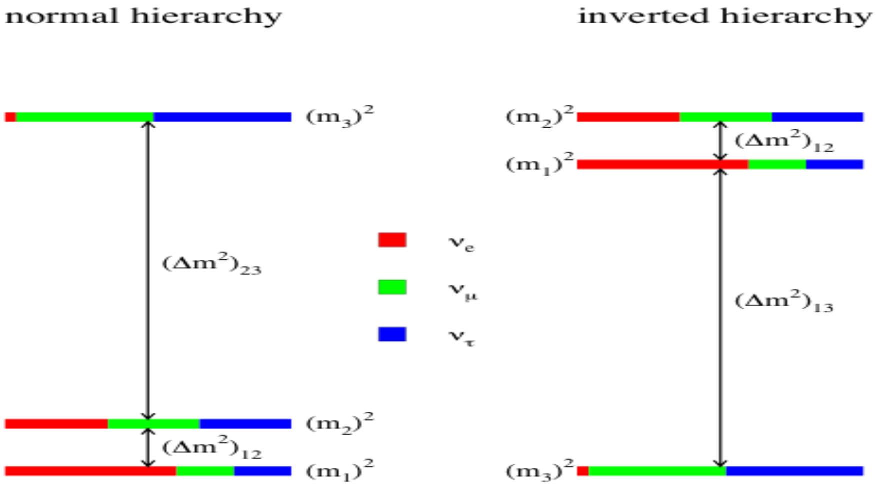
$$\Delta m^2_{13} > 0$$

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

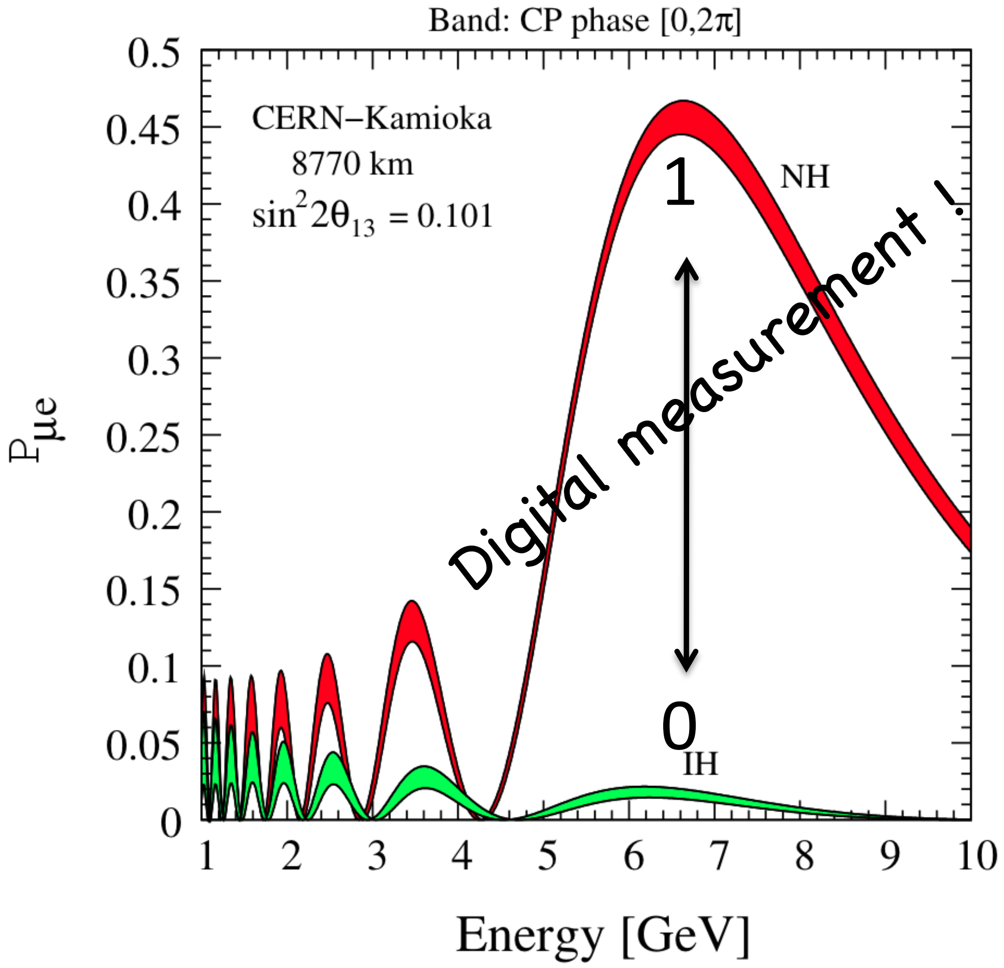


Gonzalez-Garcia et al 1209.3023

Can we measure the hierarchy with existing neutrino sources ?



Hierarchy through MSW @Earth



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

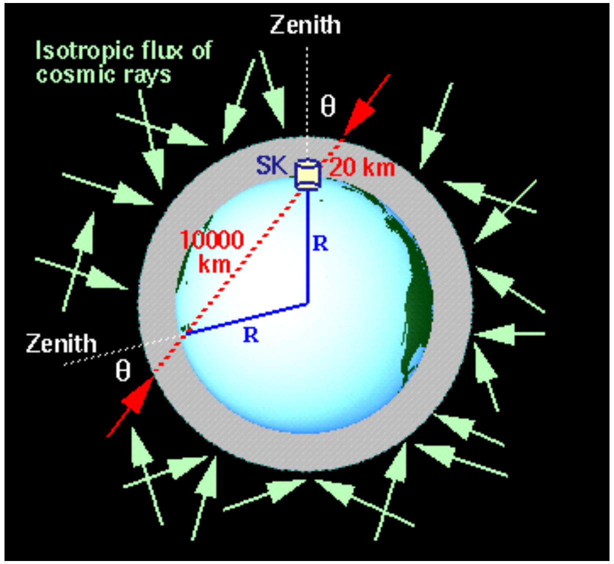
$$n_e(L)L|_{L_{\rm max}} = \frac{\pi}{\sqrt{2}G_F \tan 2\theta_{13}}$$

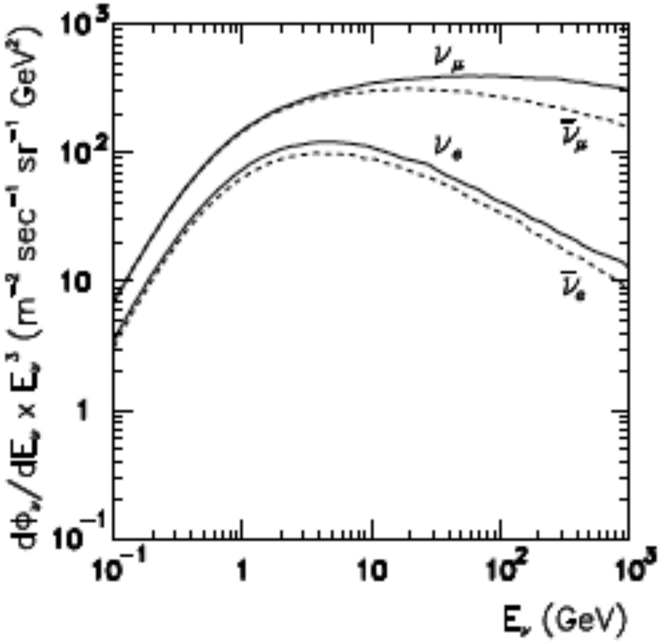
Spectacular MSW effect at O(6GeV) and very long baselines: no need for spectral info nor two channels

Mikheev, Smirnov; Wolfenstein

Hierarchy from atmospherics ? the hard way…

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



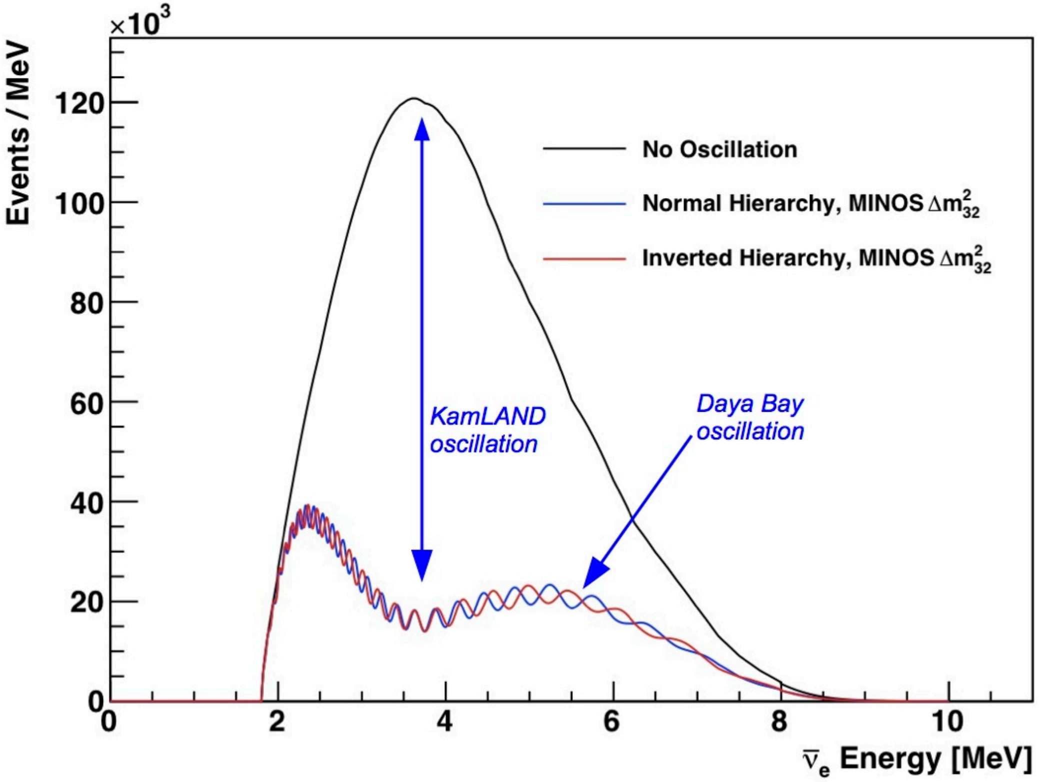


Atmospheric data contain the golden signal but hard to dig…
neutrino telescopes (PINGU, ORCA) or improved atmospheric detectors (HyperK, INO)

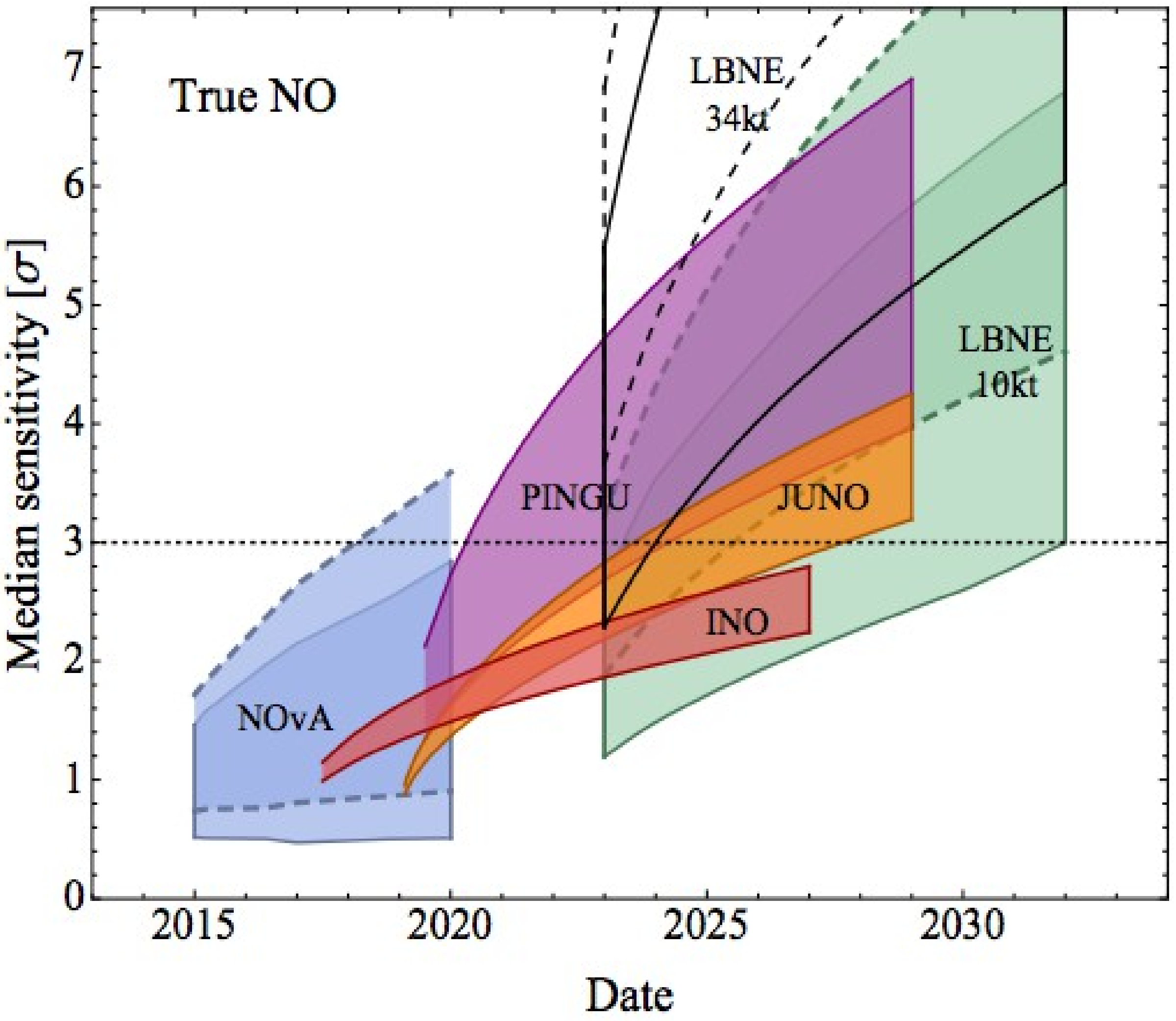
Hierarchy from reactor ν's

Petcov, Piai; Choubey et al; Learned et al

L = 50 km



Hierarchy propects



Blennow, Coloma, Huber, Schwetz 1311.1822

Leptonic CP violation (in vacuum)

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

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

Best S/N:

$$P^{atmos} \gg P^{solar} \qquad\qquad @E/L \sim \Delta_{23}$$

Golden Channel in matter

In matter:

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

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

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

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

Cervera et al, 2000

Golden Channel in matter

Octant dependence

Hierarchy dependence

In matter:

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

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

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

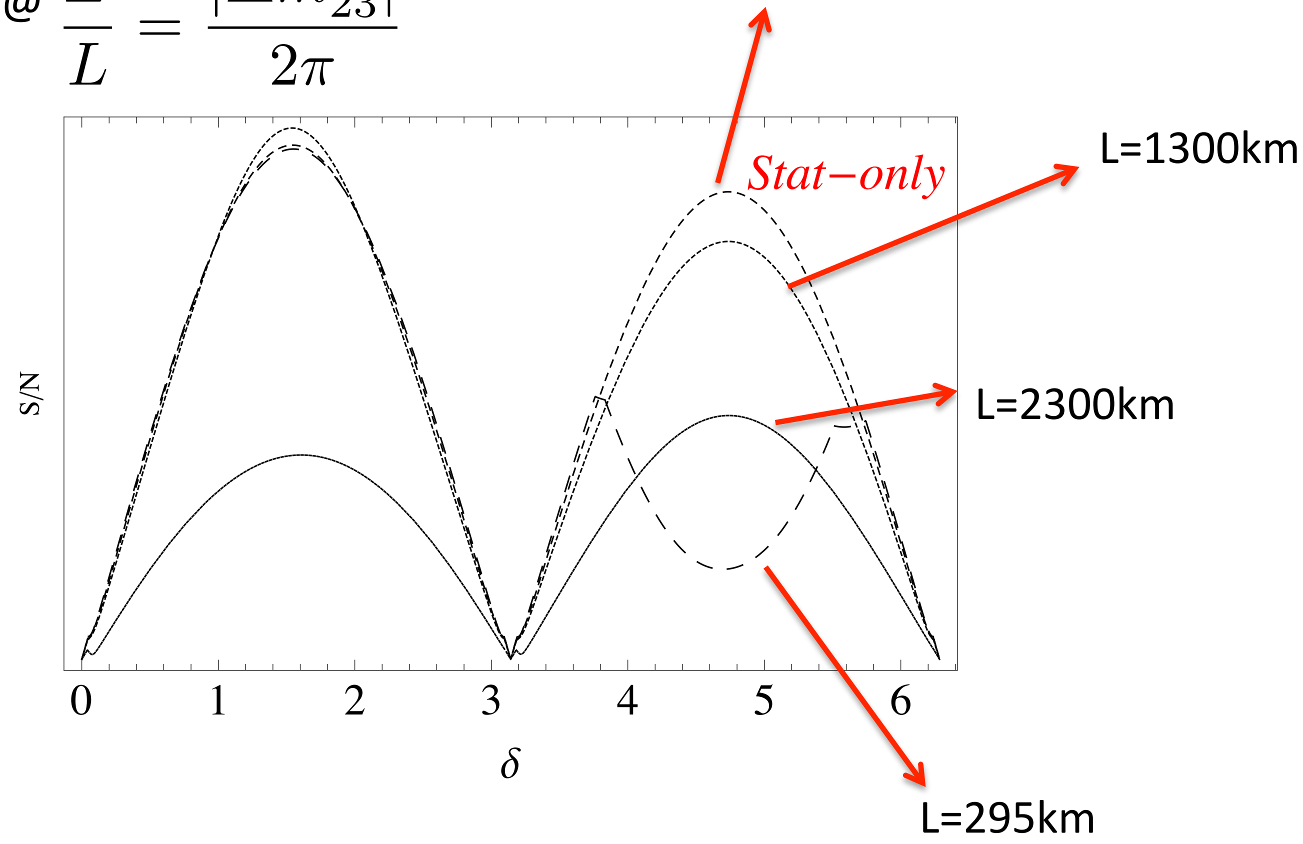
$$\tilde{J} \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23} \qquad B_\pm \equiv \sqrt{2}G_F n_e \pm \Delta_{13}$$

Cervera et al 00

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

Burguet et al; Minakata, Nunokawa;
Barger, Marfatia, Whisnant
Minakata, Parke

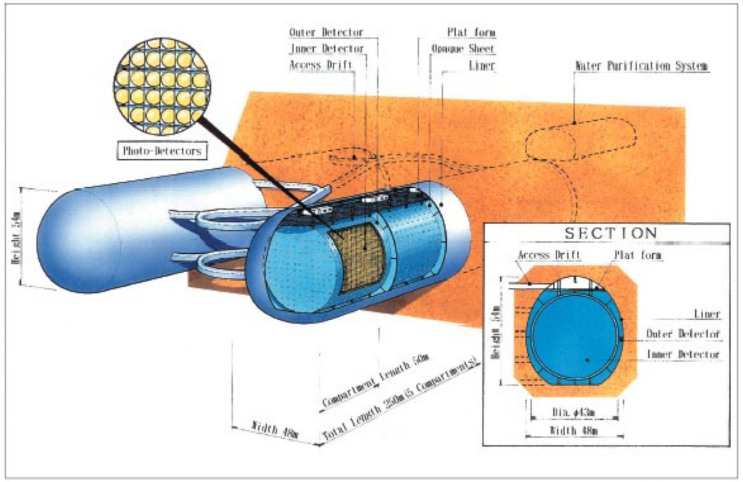
$$@ \; \frac{E}{L} = \frac{|\Delta m^2_{23}|}{2\pi}$$



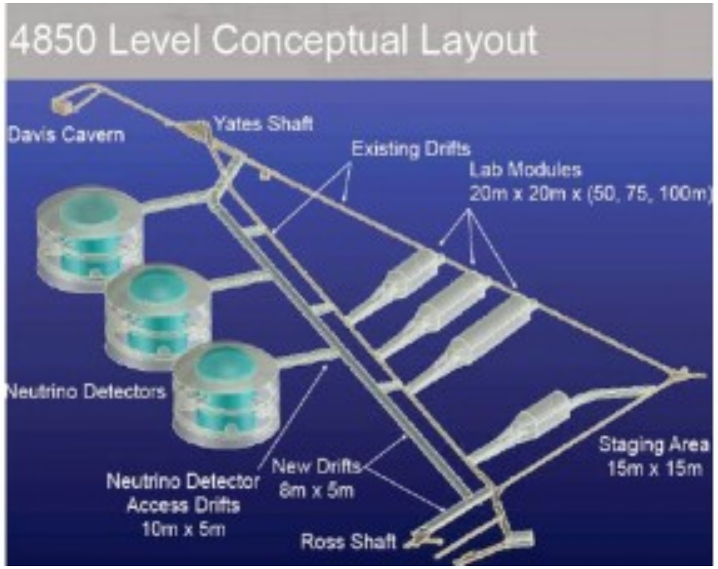
Naive scaling of S/N assuming statistical errors dominate …

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

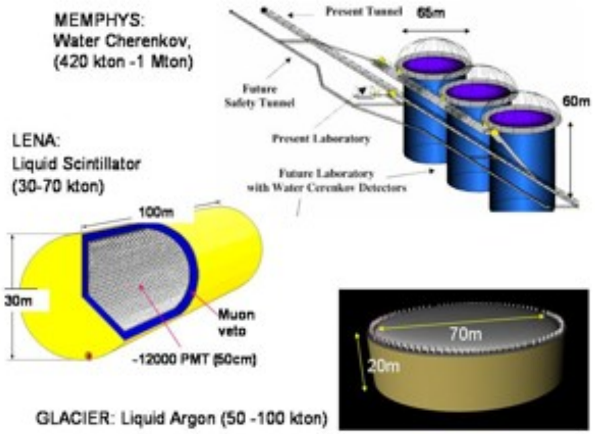
Hierarchy + CP in one go…
superbeams+superdectectors



Japan HK: 230km

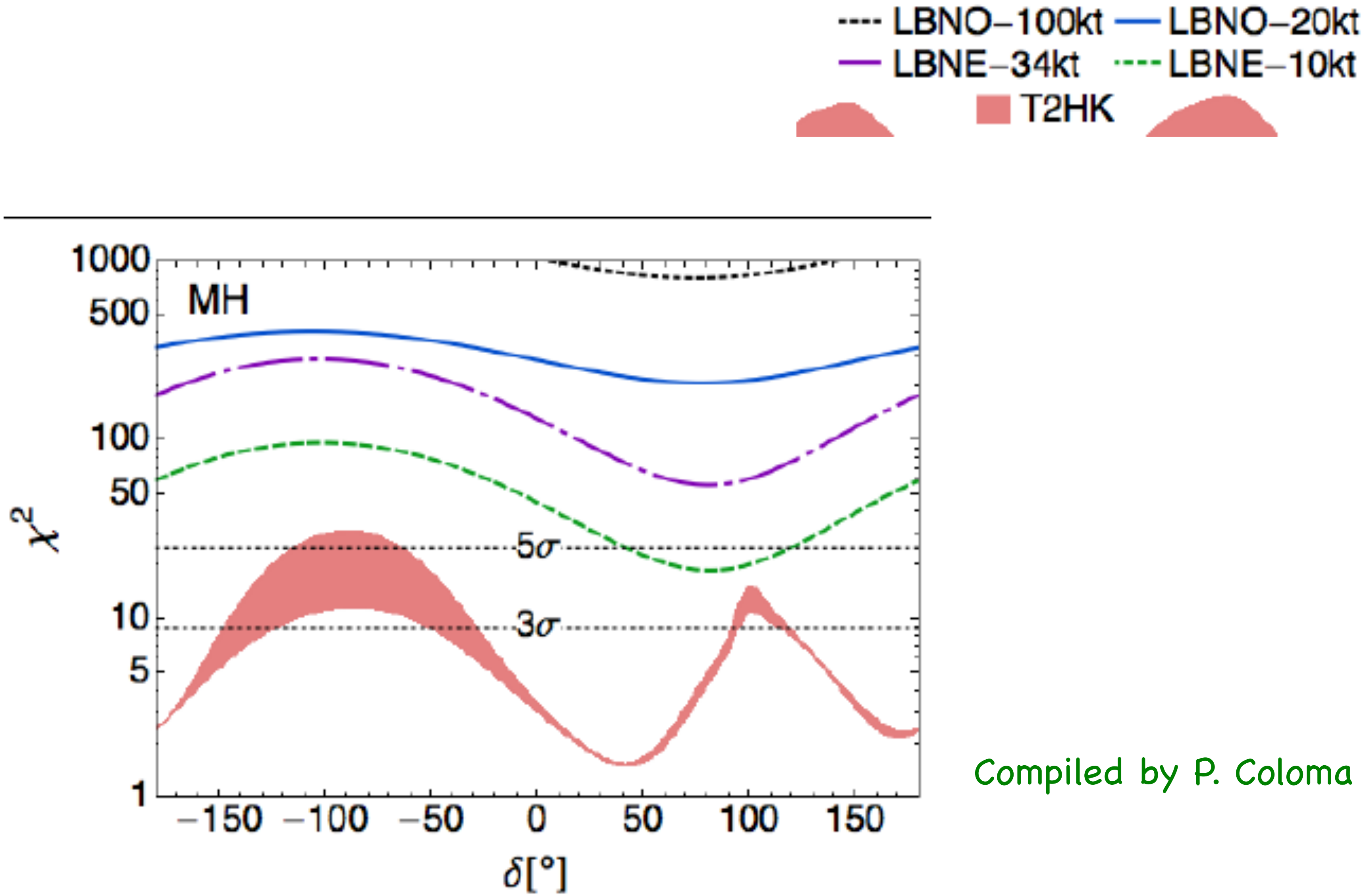


USA LBNE: 1300km



Europe LBNO: 2300km

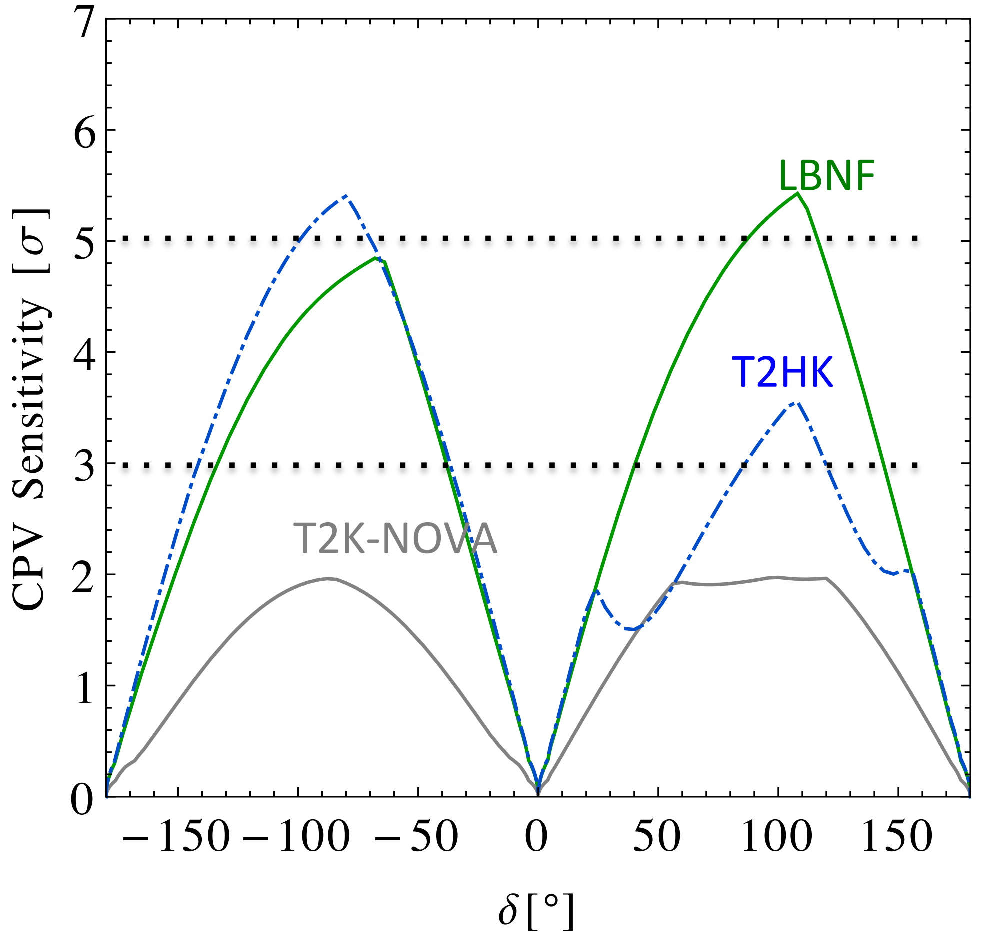
In 20 years from now with conventional beams…



Compiled by P. Coloma

O(10kton) LAr can do the job easily

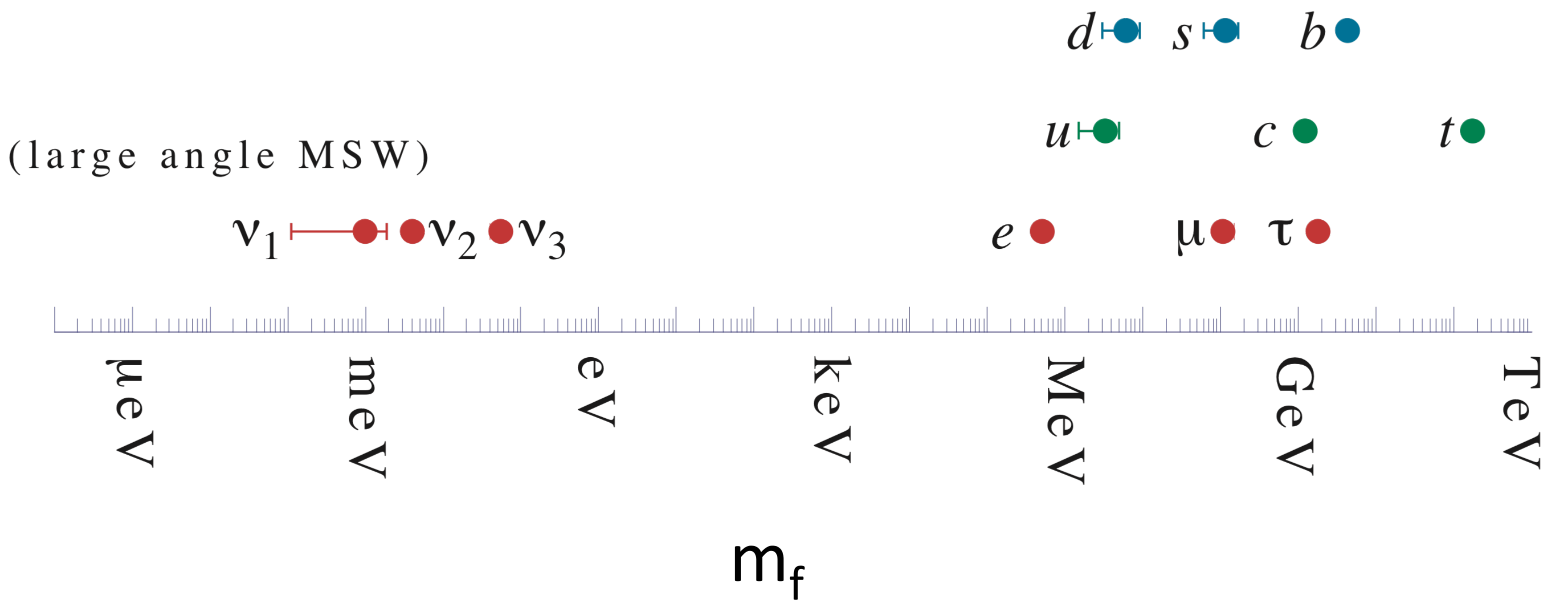
In 20 years from now with conventional beams…



Courtesy of P. Coloma

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



Why so different mixing ?

CKM

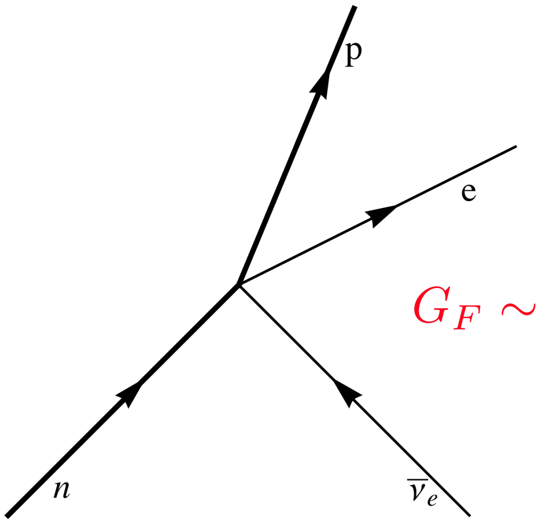
$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046}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

PMNS

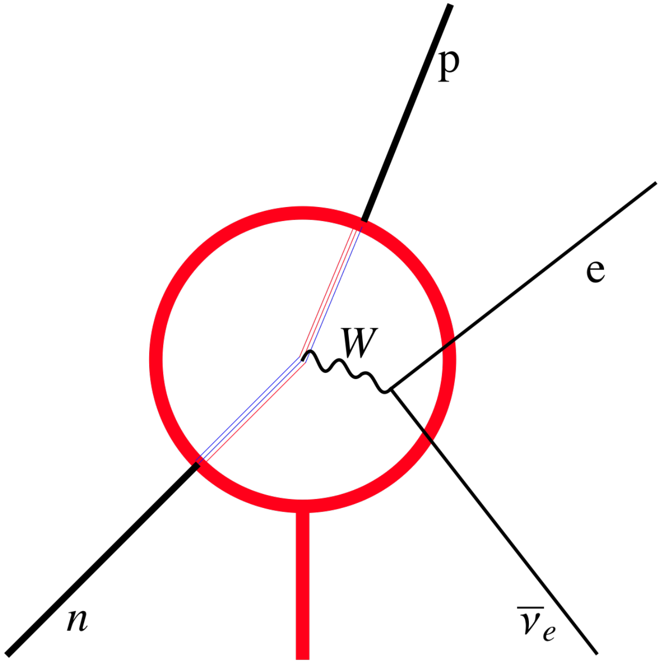
NuFIT 2.0 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

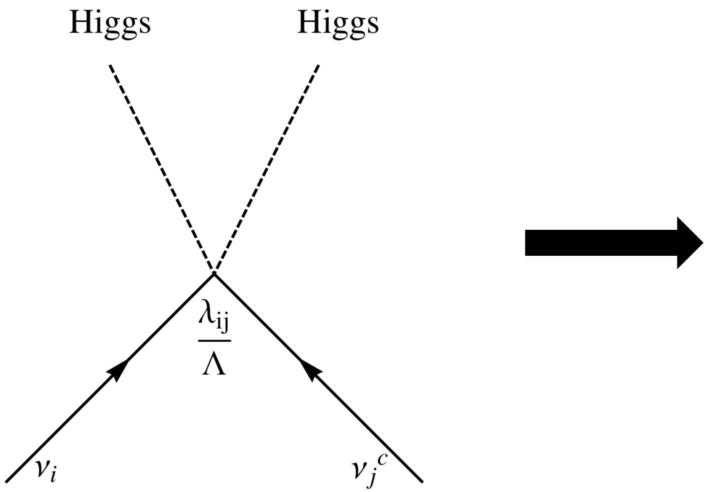
Neutrinos have tiny masses -> a new physics scale, what ?



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



SM

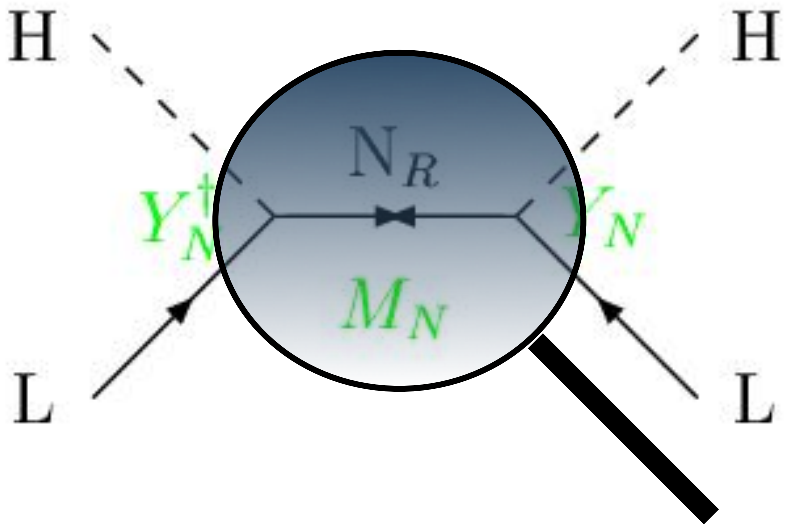


νSM ?

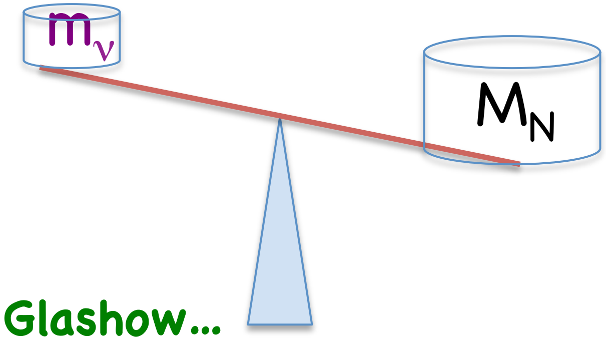
What is this ν scale?

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

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



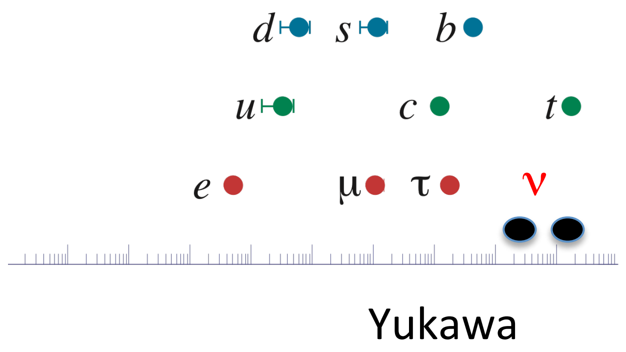
$$\frac{\lambda}{\Lambda} \equiv Y_N^T \frac{1}{M_N} Y_N$$



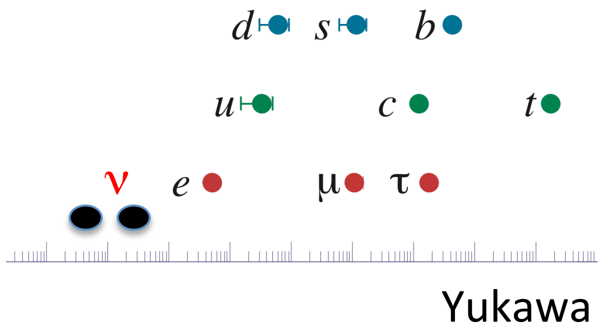
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow…

Charged/neutral hierarchy in seesaw (I)

M_N= GUT

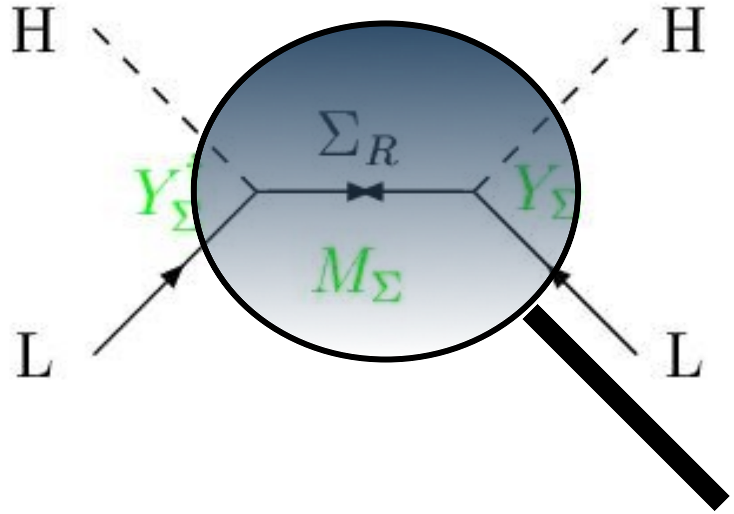


M_N= TeV



New physics scale

Type III see-saw: interchange a heavy triplet fermion

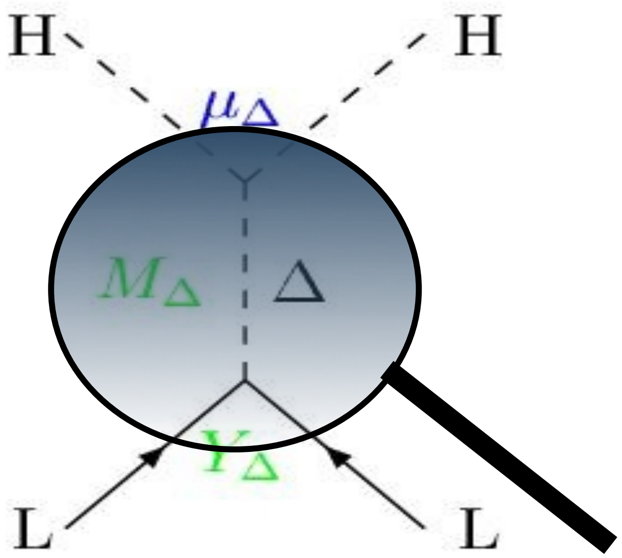


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

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

New physics scale

Type II see-saw: interchange a heavy triplet scalar



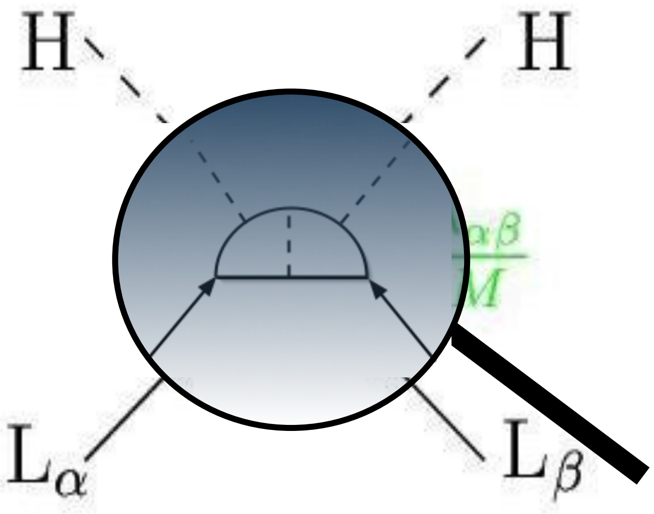
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

New physics scale

Also from loops !

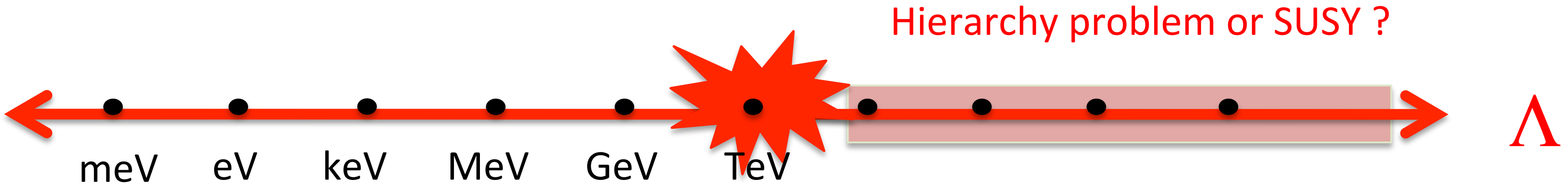
Zee-Babu

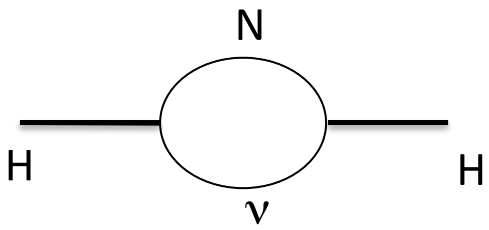


$$m_\nu \sim \mathcal{O}\left(\frac{1}{(16\pi^2)^2} \times \frac{\mu m_l^2}{M^2}\right)$$

Pinning down the New physics scale

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

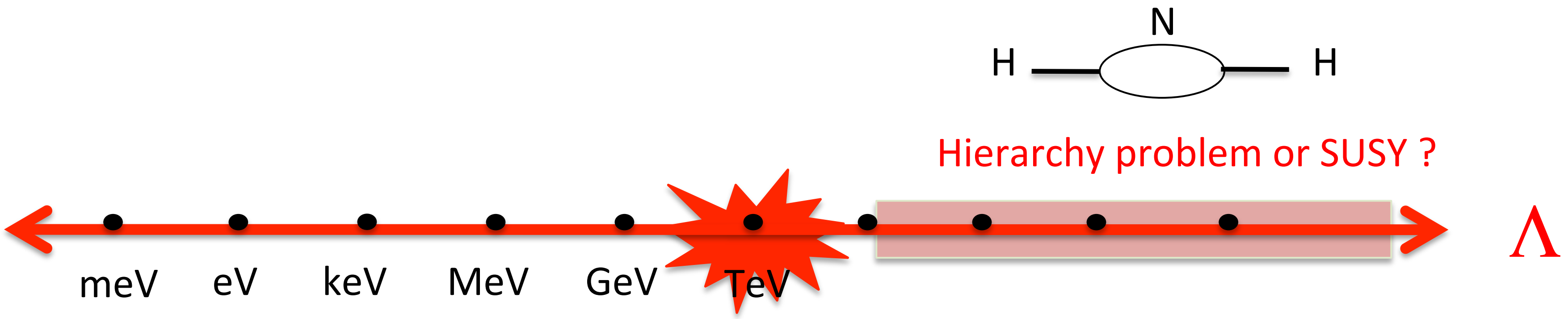




$$\delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu}$$

$M_N \gg m_H$ not natural in the absence of SUSY

Pinning down the New physics scale



Robust predictions of high (and not so high) scale νSM

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

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

there are other states out there at scale Λ: new physics beyond neutrino masses

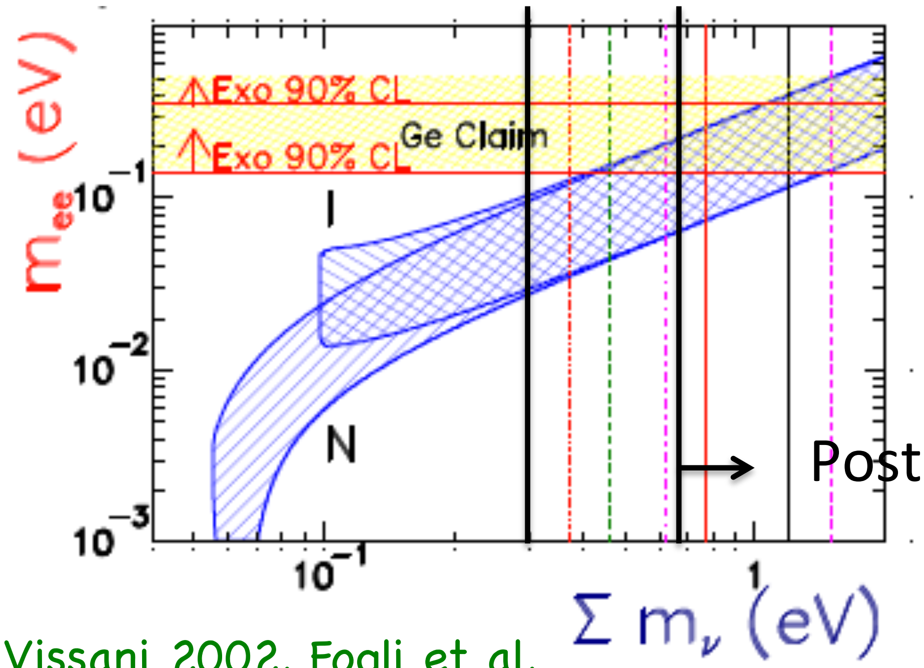
Majorana nature: ββ0ν

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

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

$$\Sigma \equiv \sum_i m_i$$

If Λ > 100MeV



Post-Planck

Vissani 2002, Fogli et al,

Updated by Gonzalez-Garcia et al, 2012

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

Type I Seesaw Model

Most general (renormalizable) Lagrangian compatible with SM gauge symmetries:

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

Y: 3 x n_R

M_N: n_Rx n_R

Phenomenology and predictivity depends on n_R and global symmetries (patterns in Y and M_N)

Minimal models

Most general (renormalizable) Lagrangian compatible with SM gauge symmetries:

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

Y: $3 \times n_R$

M_N: $n_R \times n_R$

Number of Physical Parameters

Complexity ↓

predictivity ↑

n_R	L_i	# zero modes	# masses	# angles	# CP phases
1	-	2	2	2	0
	+1	2	1	2	0
2	-	1	4	4	3
	(+1,+1)	1	2	3	1
	(+1,-1)	3	1	3	1
3	-	0	6	6	6
	(+1,+1,+1)	0	3	3	1
	(+1,-1,+1)	2	2	6	4
	(+1,-1,-1)	4	1	4	1

✗

→ 1 Dirac ✗

→ 3+2 Minim

→ 2 Dirac

→ 3+3 Minim

→ 3 Dirac

Minimal models

Most general (renormalizable) Lagrangian compatible with SM gauge symmetries:

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

$$= \mathcal{L}_{SM} - \frac{1}{2} n^T \mathcal{M}_\nu \, C n + h.c.$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \qquad n = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

$$m_D \equiv Y^* \frac{v}{\sqrt{2}} \qquad M_N = \mathrm{diag}(M_1, M_2, \ldots)$$

Spectrum: 3+n_R Majoranas

If $m_D << M_N$

$$U^T \mathcal{M} U \simeq \begin{pmatrix} m_l & 0 \\ 0 & m_h \end{pmatrix}$$

To leading order in $\epsilon \equiv m_D^* M_N^{-1}$

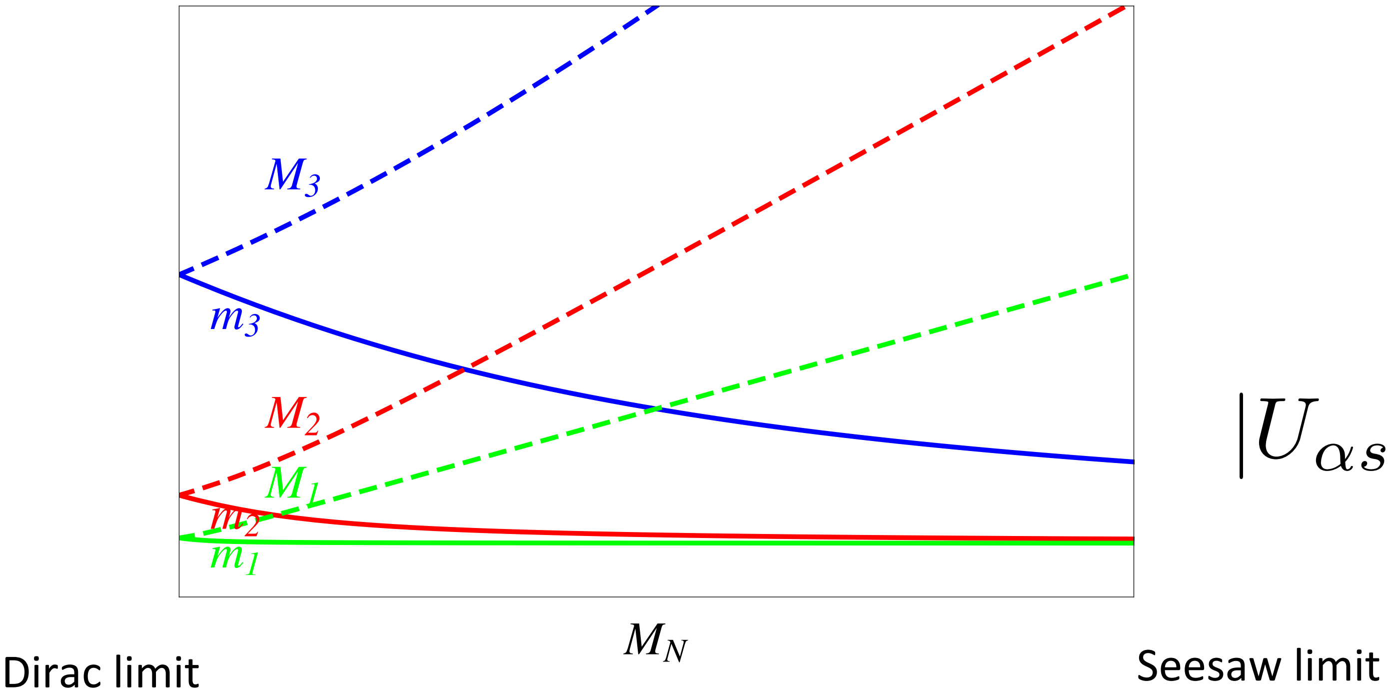
-3 light states (mostly active with O(ε) admixture of sterile):

$$m_l = -m_D M_N^{-1} m_D^T + \mathcal{O}(\epsilon^2)$$

-n_R heavy ones (mostly sterile with O(ε) admixture of active):

$$m_h = M_N + \mathcal{O}(\epsilon^2)$$

Spectrum: n_R=3



$$|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$$

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

(the lower the mass the better)

Casas&Ibarra parametrization

- Physical parameters only
- Convenient to impose existing constraints

$$m_l = U^*_{PMNS}\mathrm{Diag}(m_1, m_2, m_3)U^+_{PMNS}$$

$$m_l = -m_D M_N^{-1} m_D^T + \mathcal{O}(\epsilon^2)$$

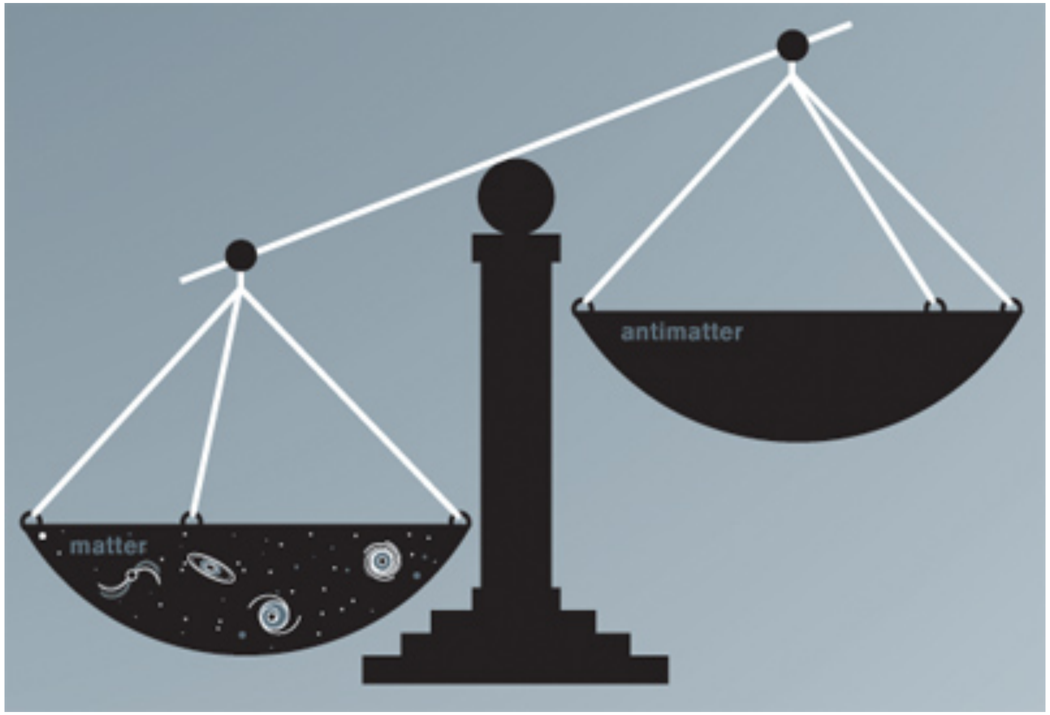
$$\Downarrow$$

$$1 = RR^T \qquad R = i m_\nu^{1/2} U^T_{PMNS} m_D M_N^{-1/2}$$

$$m_D = \underbrace{U^*_{\mathrm{PMNS}} m_\nu^{-1/2}}_{\text{Light neutrino masses \& mixings}} \underset{\substack{\downarrow \\ \text{General orthogonal } 3 \text{ x } n_R \text{ matrix}}}{R} \underbrace{M_N^{-1/2}}_{\text{Heavy neutrino masses}}$$

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)

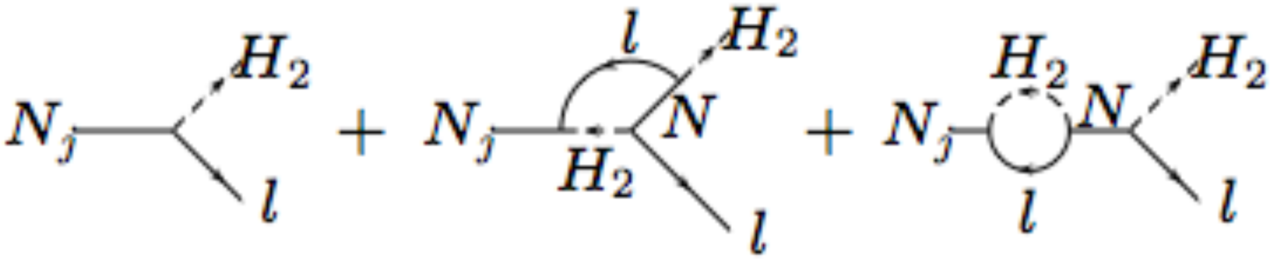
It does not seem to work in the SM with massless neutrinos …

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



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

Generic and robust feature of see-saw models

Lepton asymmetry

$M_{2,3} \gg M_1$

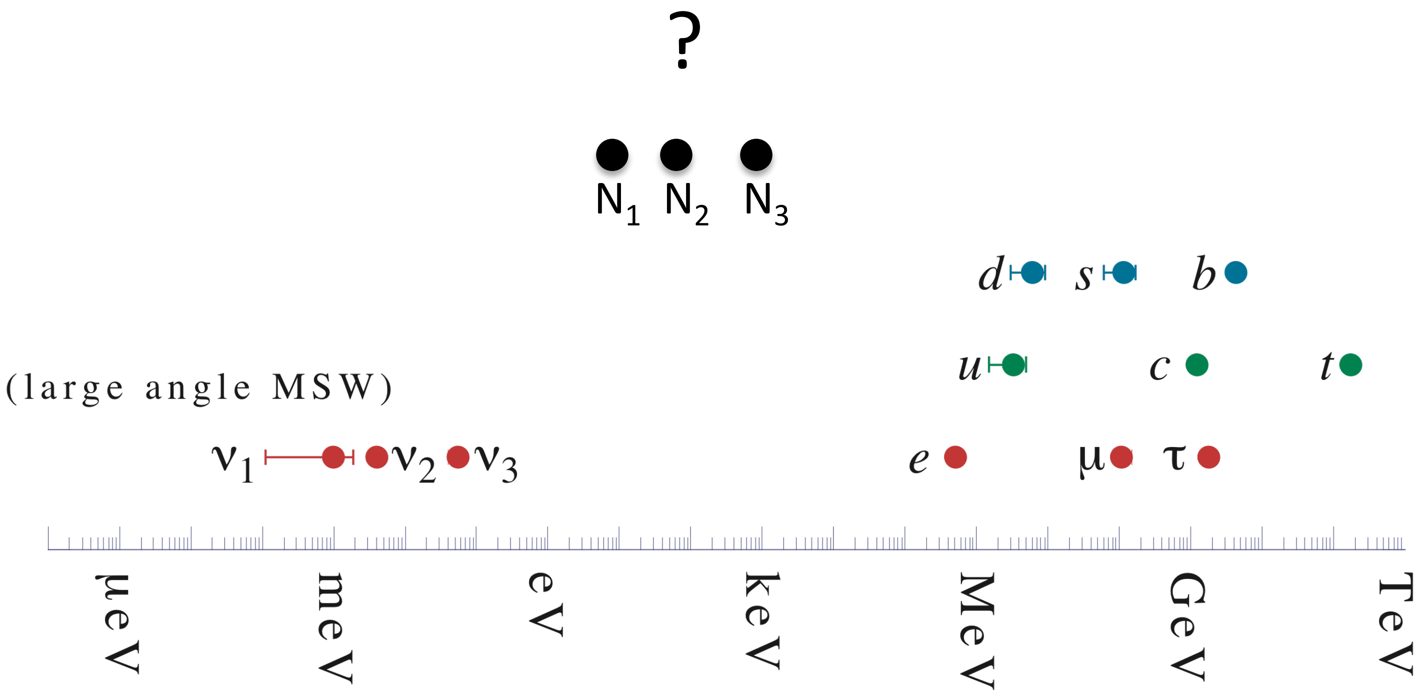
$$Y_B = 4 \times 10^{-3} \; \overbrace{\epsilon_1}^{\mathrm{CP-asym}} \; \overbrace{\kappa}^{\mathrm{eff.\ factor}}$$

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

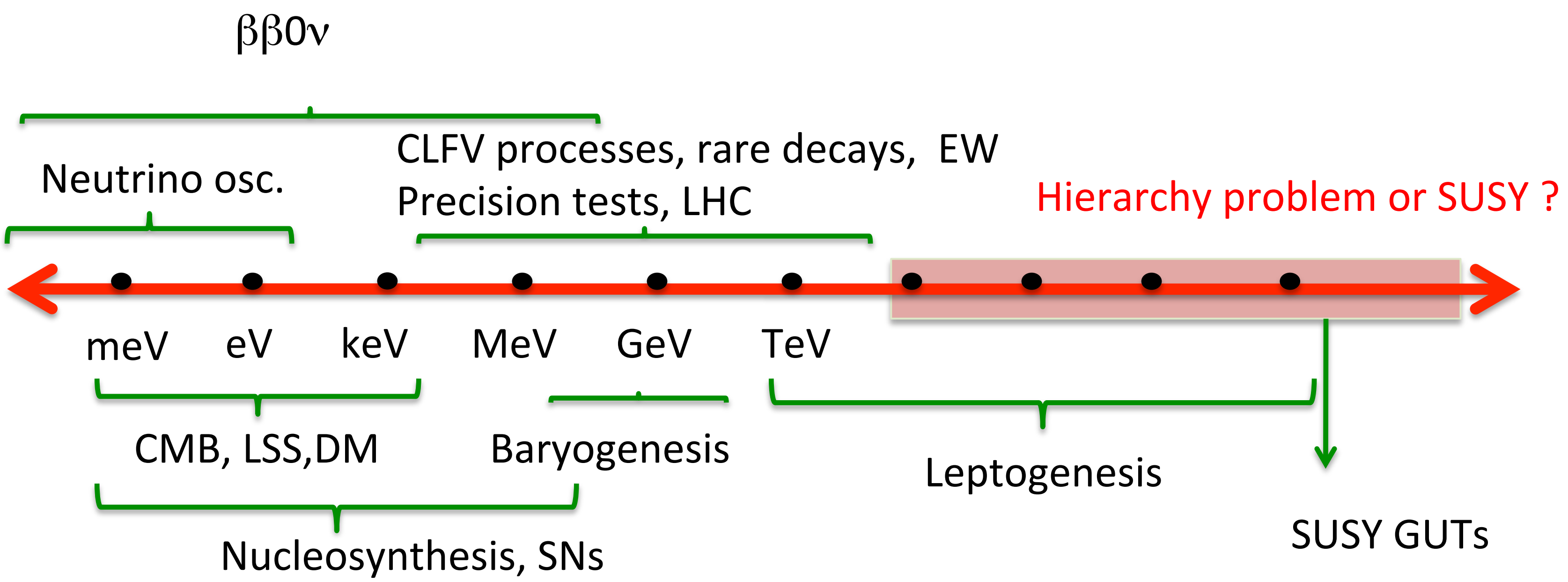
Different combinations

Even if we know the neutrino mass we cannot predict the asymmetry quantitatively…

Can we see them ?



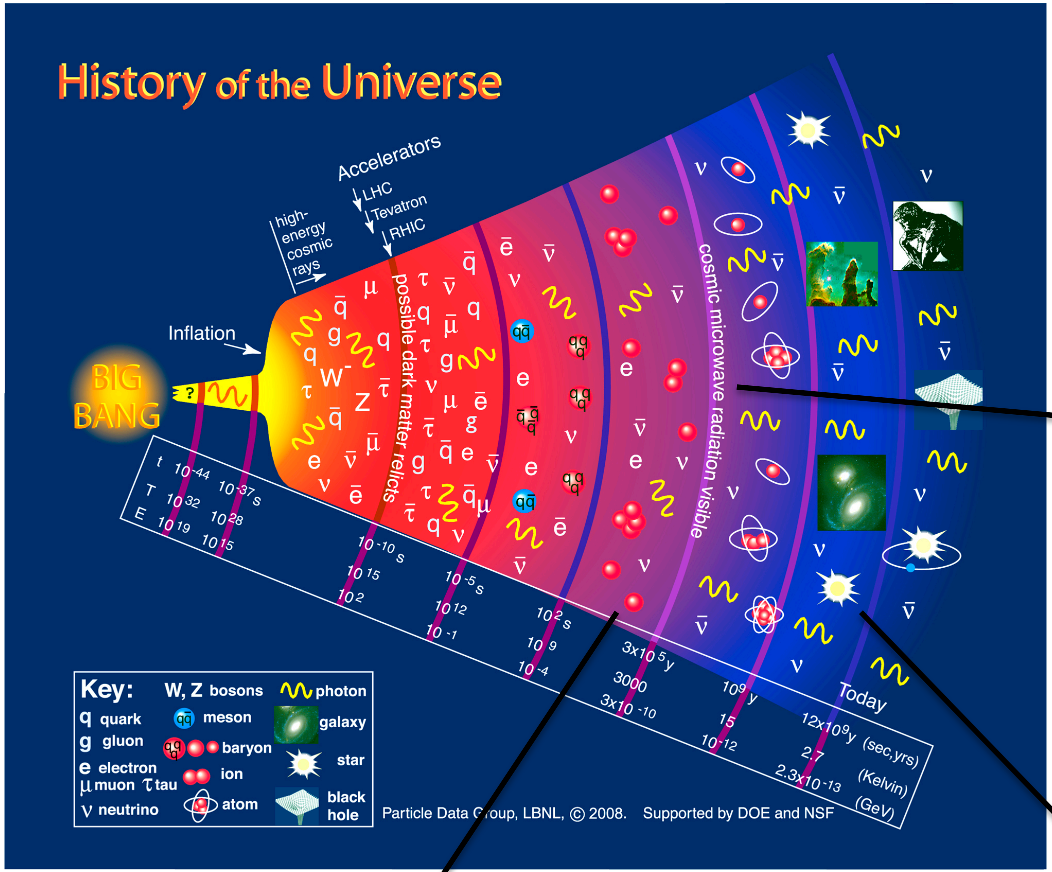
Pinning down the New physics scale



Could have very important implications in cosmology and rare processes

Cosmological neutrinos

Neutrinos have left many traces in the history of the Universe, because in a radiation dominated Universe they are in important fraction of the radiation component



$$\Omega_{\nu,0}h^2 = \sum_i \frac{m_{\nu_i}}{94eV}$$

CMB <-> N_ν

Nucleosynthesis <-> N_ν

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

Sterile neutrinos @ early Universe

The extra states contribute to the energy density of the Universe:
$T < T_{EW}$ produced via mixing...

$$\Gamma_{s_i} \simeq \sum_{\alpha} \langle P(\nu_\alpha \to \nu_{s_i}) \rangle \times \Gamma_{\nu_\alpha}$$

Barbieri&Dolgov; Kainulainen

Thermalisation will occur if for some T:

$$\frac{\Gamma_{s_i}(T)}{H(T)} \geq 1$$

Neutrinos propagation is modified by forward scattering on the plasma particles

$$V_\alpha \propto \frac{G_F}{M_W^2} T^5$$

Notzold, Raffelt

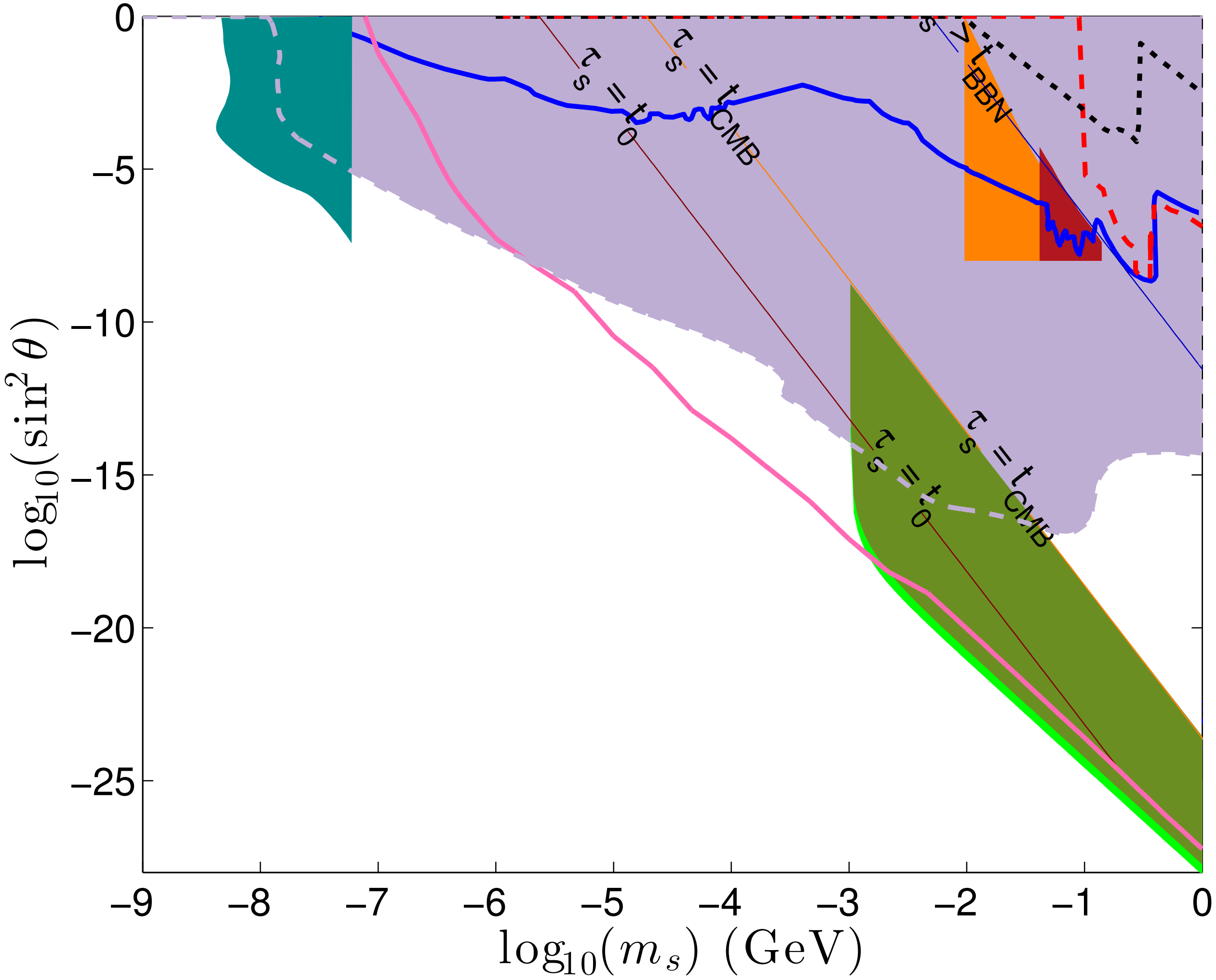
Sterile neutrinos @ early Universe

$\frac{\Gamma_{s_i}(T)}{H(T)}$ reaches a maximum at $T_{\max} \sim (M_i^2 M_W^2 / G_F)^{1/6}$

$$\frac{\Gamma_{s_i}(T_{\max})}{H(T_{\max})} \sim \frac{\sum_\alpha |U_{\alpha s_i}|^2 M_i}{\sqrt{g_*(T_{\max})}}$$

If this combination > 1, the sterile neutrino reaches full thermalization:
very strong constraints from cosmology in a wide range of masses

Cosmology constraints on one sterile species



A. Vincent et al '14

Seesaw scale vs cosmology

With the naive seesaw scaling law

$$|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$$

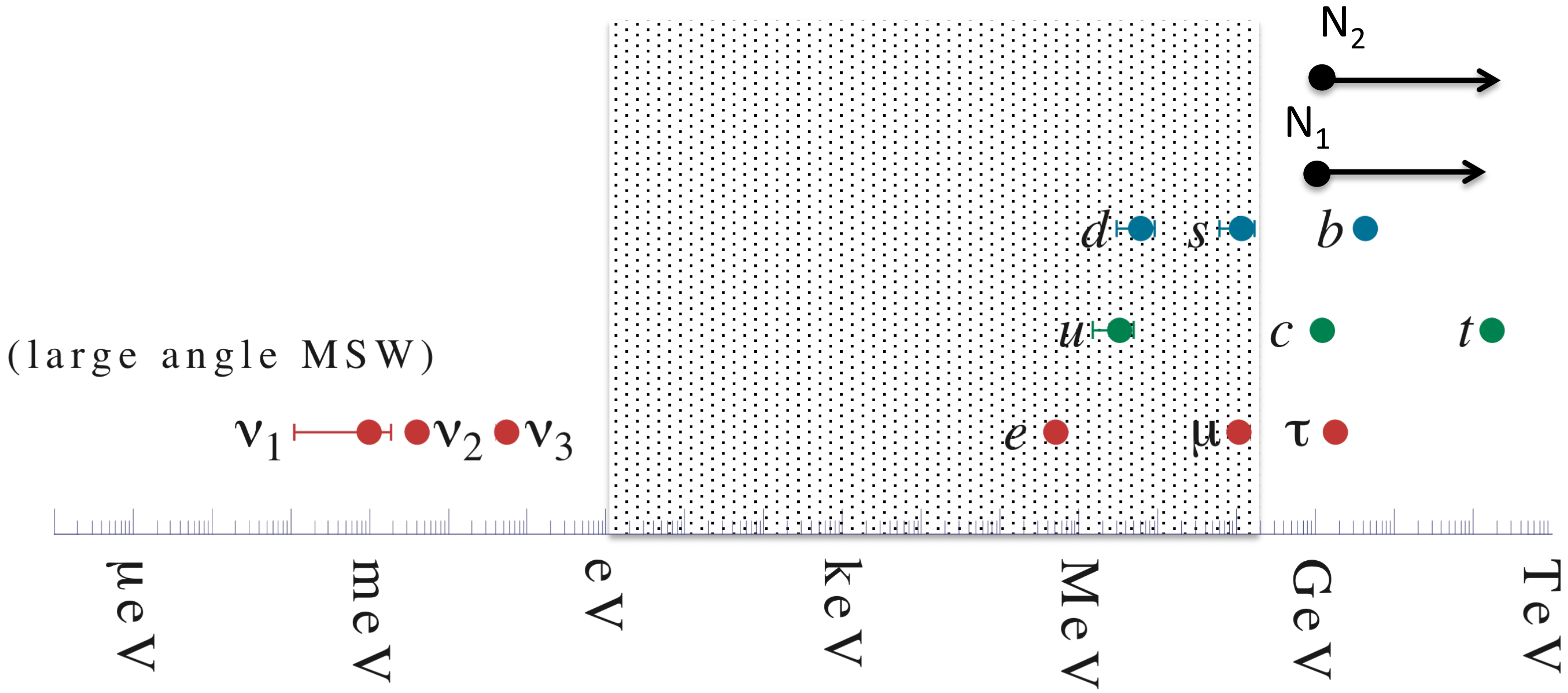
$$\frac{\Gamma_{s_i}(T_{\max})}{H(T_{\max})} \sim \frac{\sum_\alpha |U_{\alpha s_i}|^2 M_i}{\sqrt{g_*(T_{\max})}}$$

Is approximately fixed by the light neutrino masses:

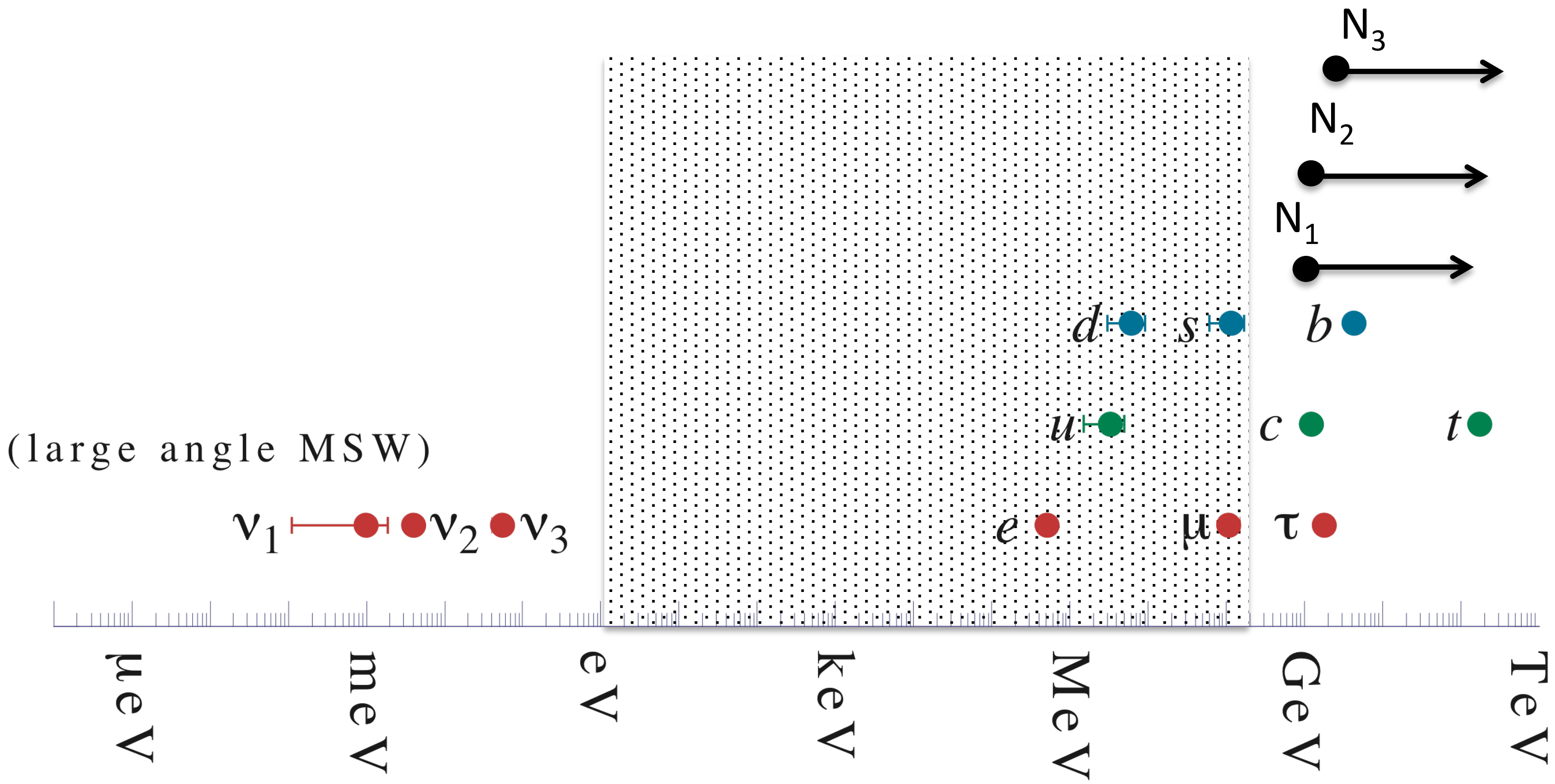
thermalisation independent of seesaw scale !!

PH, M. Kekic, J. López-Pavon

Minimal model: N =2

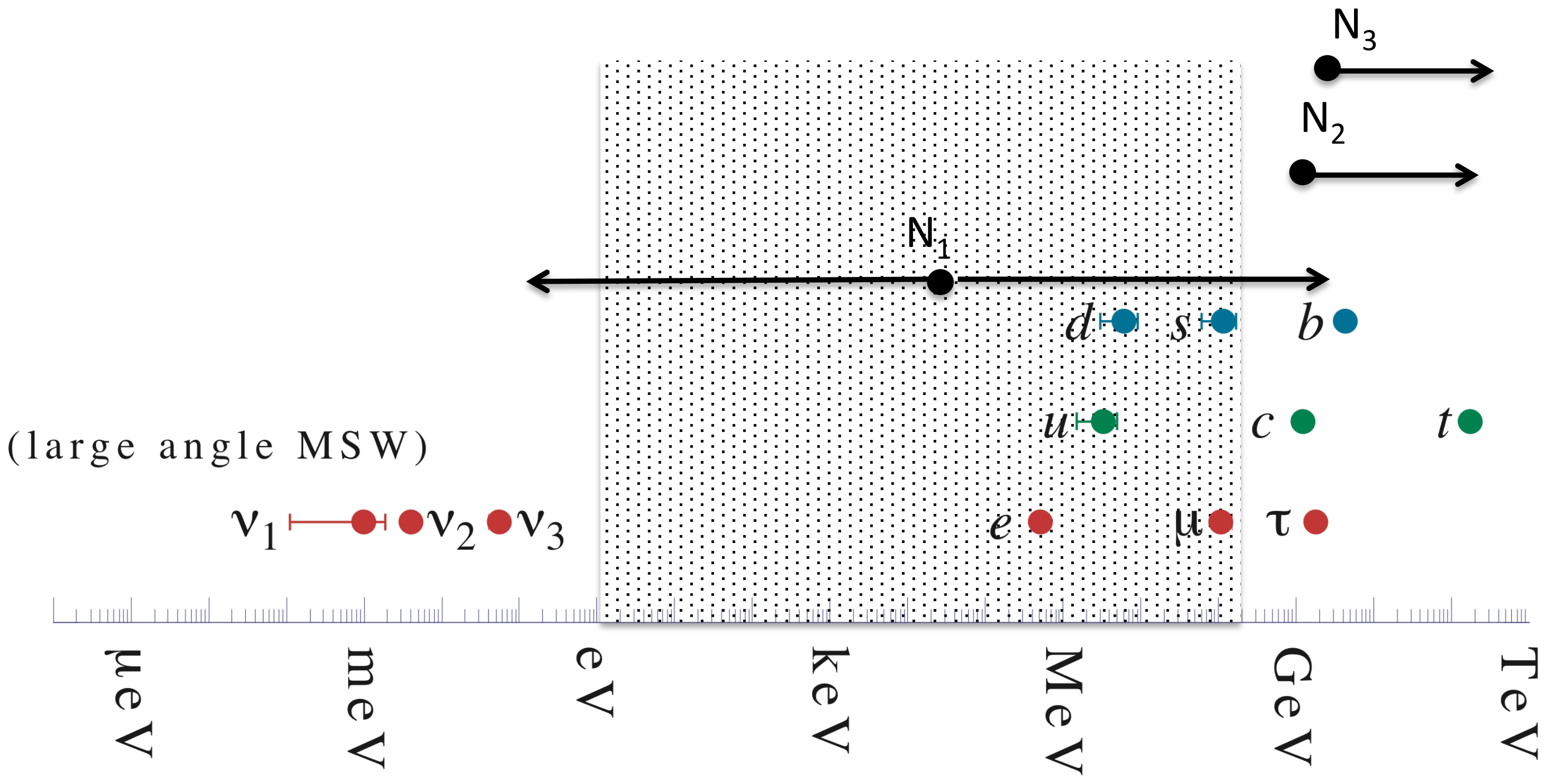


Minimal model: N =3



$m_1 > 3.2 \times 10^{-3}$ eV

Minimal model: N =3

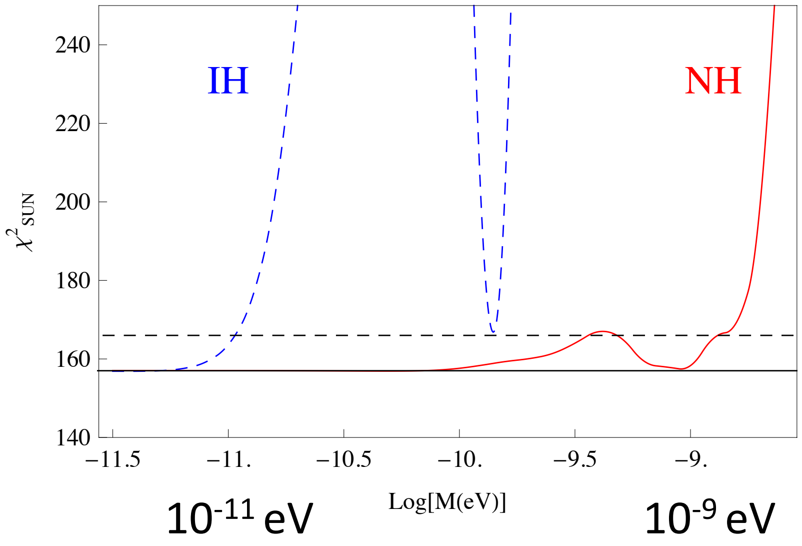


$m_1 < 3.2 \times 10^{-3}$ eV

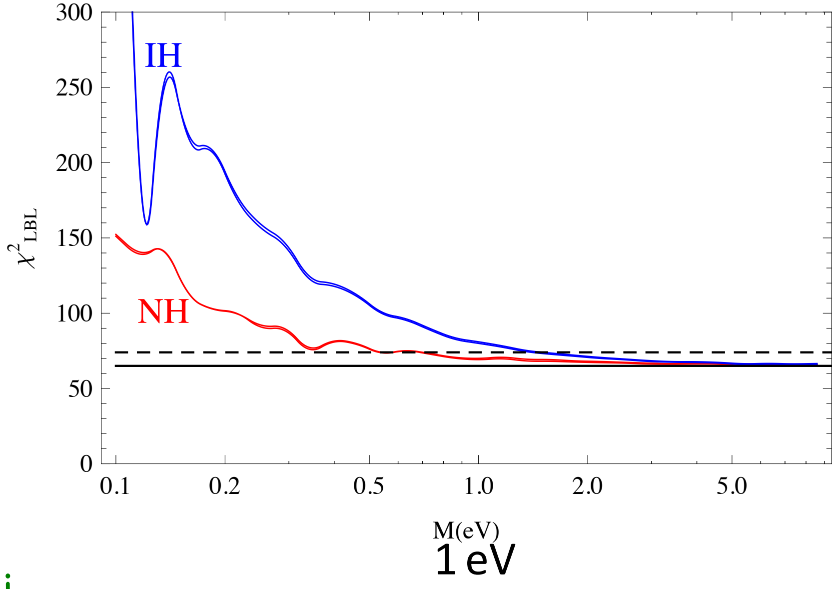
Other states out there ?

Below eV, strong constraints from oscillations…

Solar data

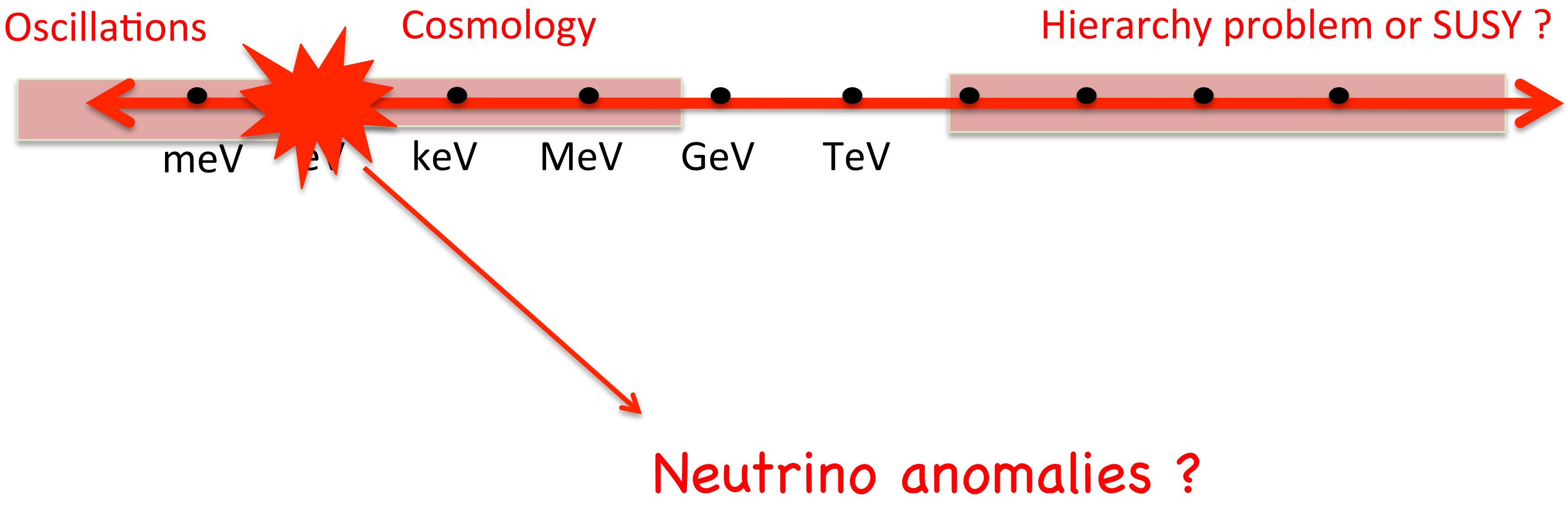


LBL data



Donini, PH, J. López-Pavon, M. Maltoni

Other states out there ?



Oscillations

Cosmology

Hierarchy problem or SUSY ?

meV

eV

keV

MeV

GeV

TeV

Neutrino anomalies ?

Outliers: LSND anomaly

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

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

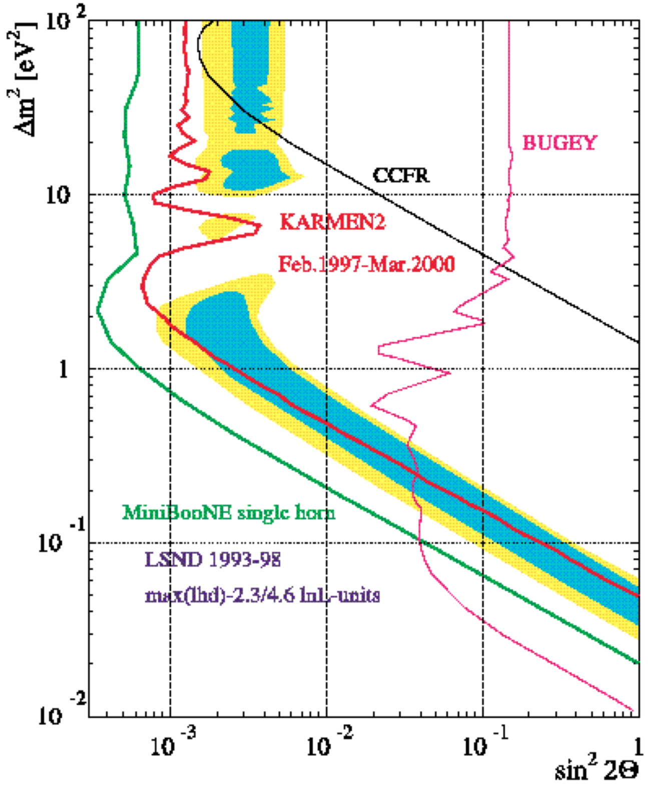
$$\mu^+ \to \quad e^+ \quad \nu_e \; \bar{\nu}_\mu$$

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

Appearance signal with very different

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

LSND vs KARMEN

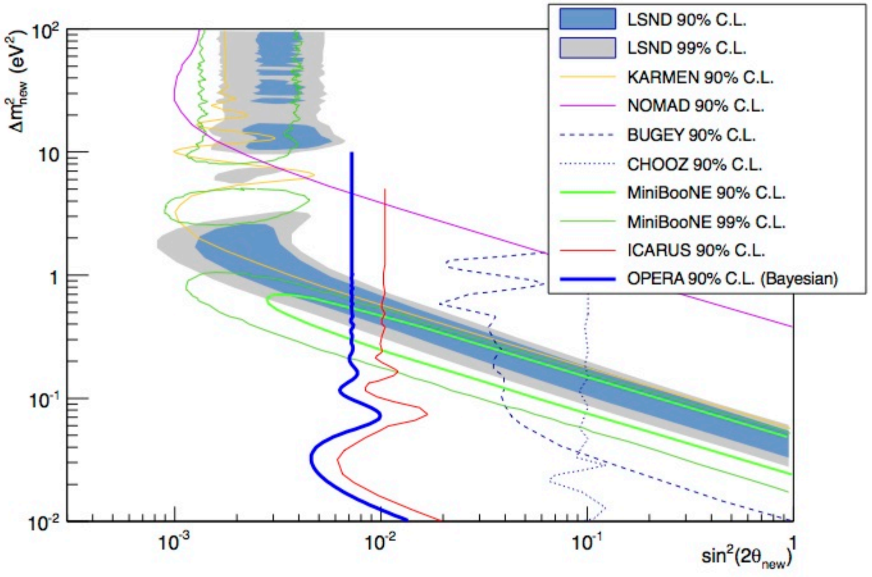


Neutrino anomalies

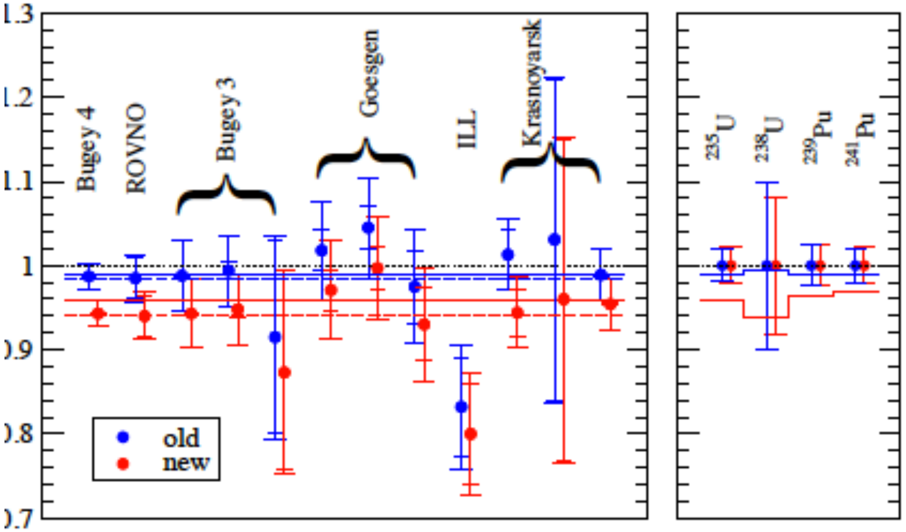
$$|\Delta m^2| \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1-10m)} \sim \frac{\mathcal{O}(1GeV)}{\mathcal{O}(1-10km)}$$

LSND

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



Reactors $P(\nu_e \ {-}{>} \nu_e) = O(|U_{ei}|^2)$



T. A. Mueller et al; P. Huber

+Gallium anomaly+ MiniBOONE low-energy excess...

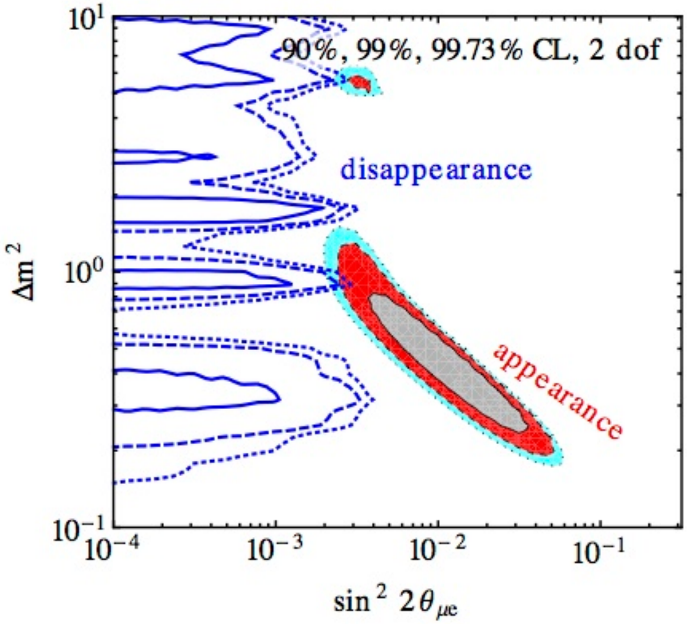
Neutrino anomalies

Smoking gun still not there…

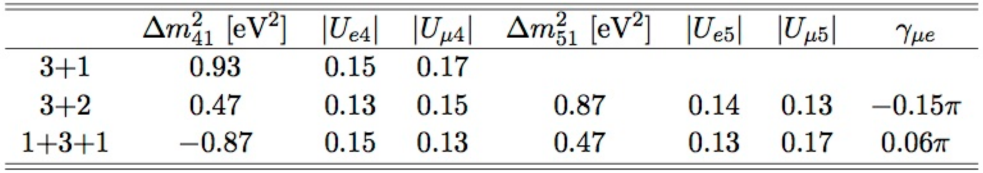
$P(\nu_e \to \nu_\mu) = O(|U_{ei}|^2\ |U_{\mu i}|^2)$ ✔

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

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



Kopp et al; Conrad et al, Archidiacono et al



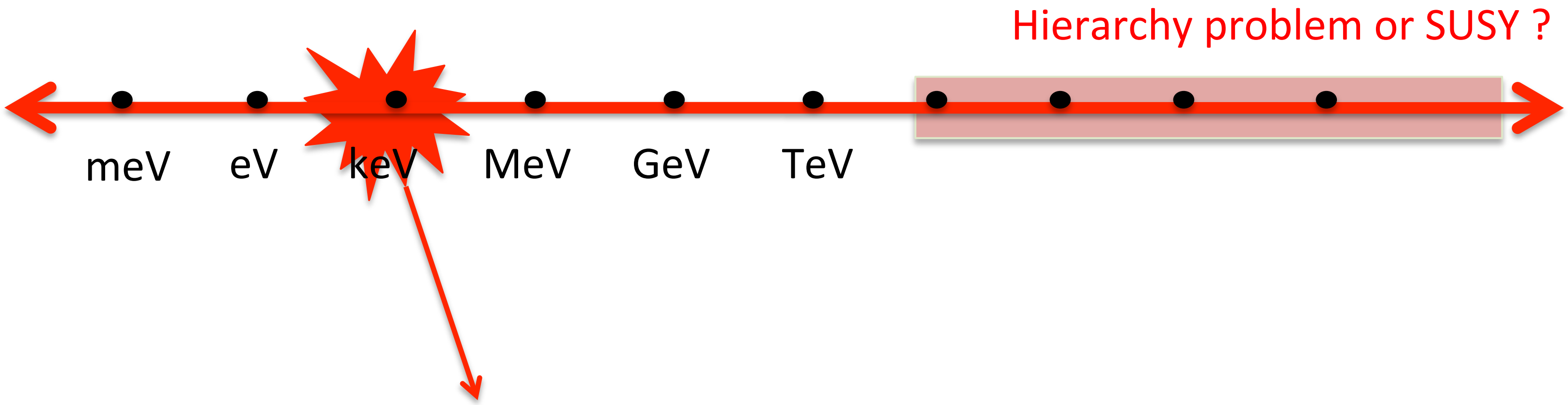
	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	$\gamma_{\mu e}$
3+1	0.93	0.15	0.17				
3+2	0.47	0.13	0.15	0.87	0.14	0.13	-0.15π
1+3+1	-0.87	0.15	0.13	0.47	0.13	0.17	0.06π

Consistent with $$|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$$

O(1eV) seesaw scale models provide similar fits to the data while being much more constrained

Donini, PH, Lopez-Pavon, Maltoni; Fan, Langacker;

Other states out there ?



Hierarchy problem or SUSY ?

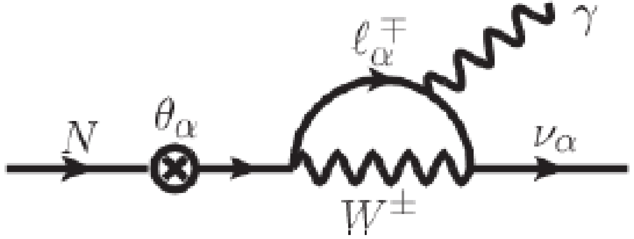
meV eV keV MeV GeV TeV

Warm DM (N>2)

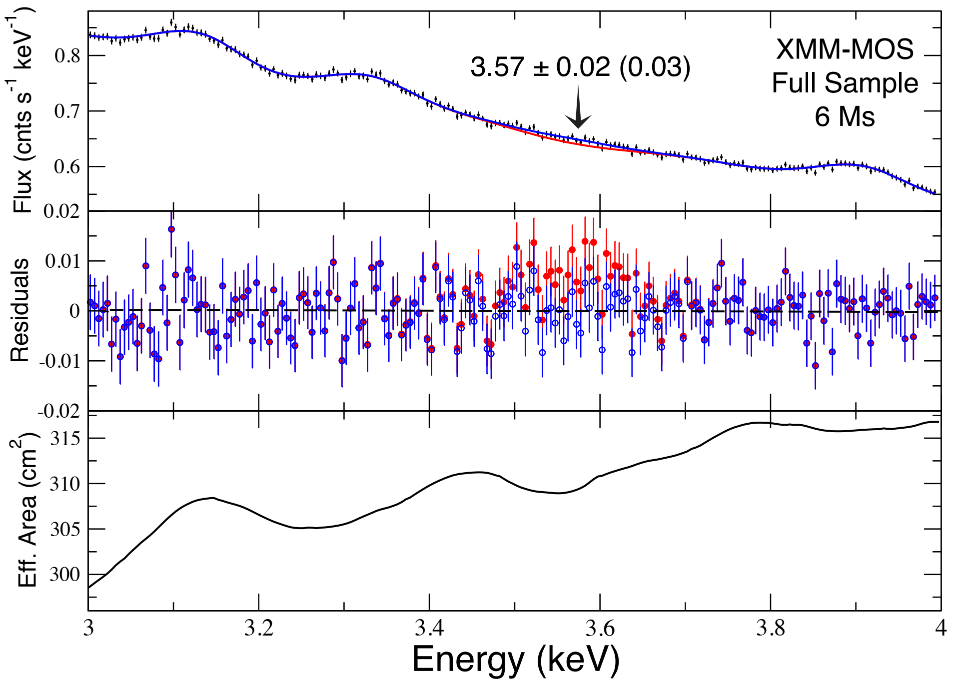
Dodelson, Widrow
Fuller et al

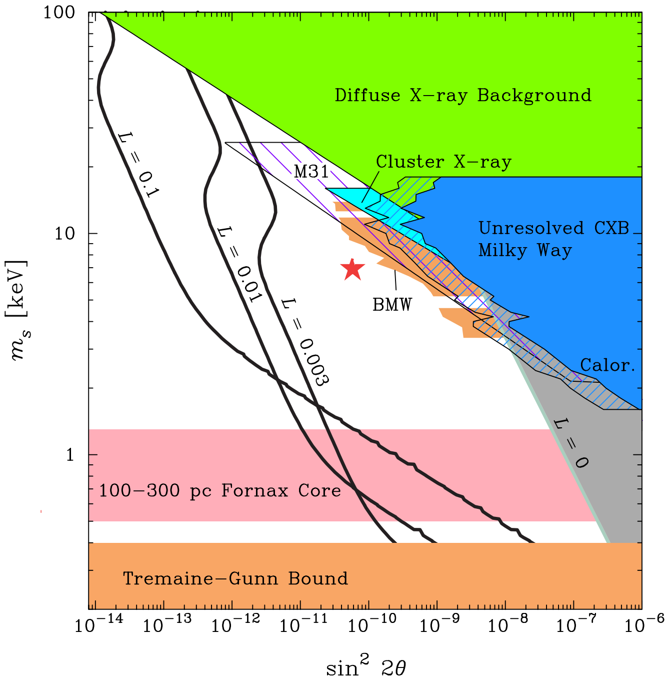
Non-trivial thermalization mechanism required: large lepton asymmetries

7 keV neutrino ?



Bulbul et al 1402.2301



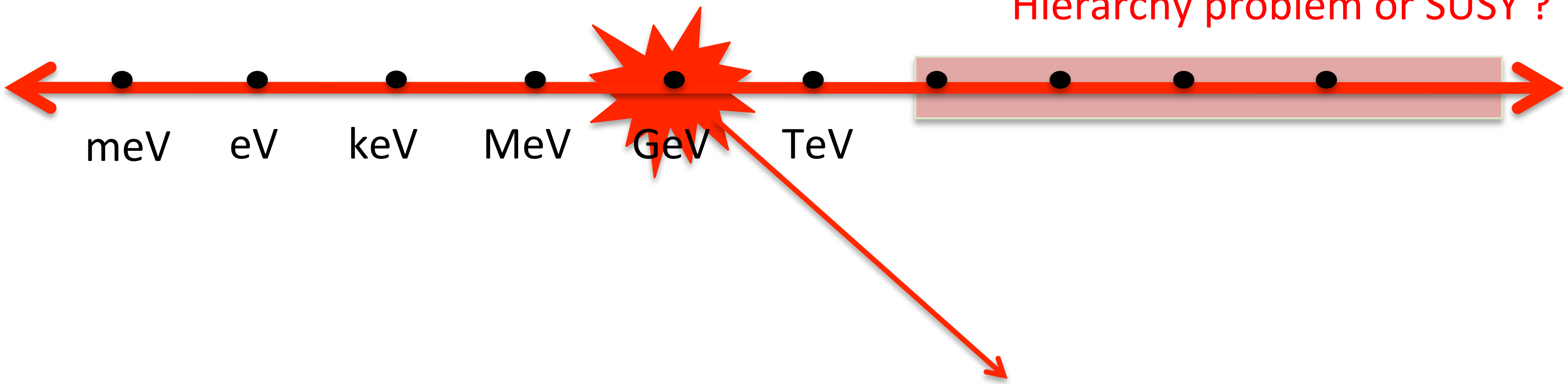


$$M_s \simeq 7\text{keV}, \quad \sin^2 2\theta = 7 \times 10^{-11}$$

$$|U_{\alpha s}|^2 \ll \frac{\sqrt{\Delta m^2_{atm}}}{M_s}$$

Other states out there ?

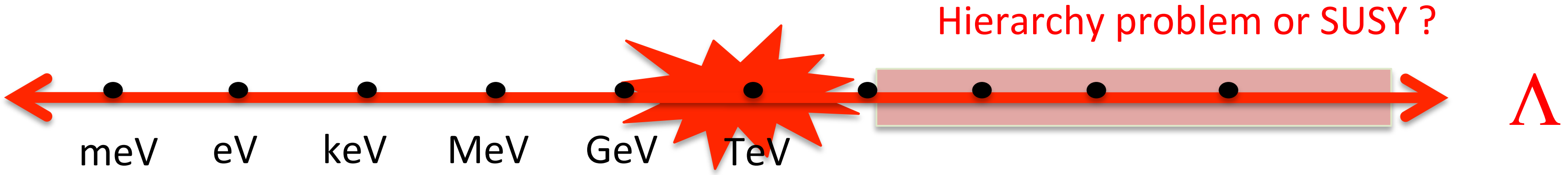
Hierarchy problem or SUSY ?



Leptogenesis in production (oscillations)

Akhmedov, Smirnov;
Shaposnikov et al

Other states out there ?



Can we produce them in colliders or rare decays ?

$$|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$$

too small couplings unless....

Two scale see-saw models (approx) Lepton number

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

$$\begin{array}{ccc} & \multicolumn{2}{c}{\overbrace{\qquad\qquad\quad}^{n_R}} \\ & & \end{array}$$

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

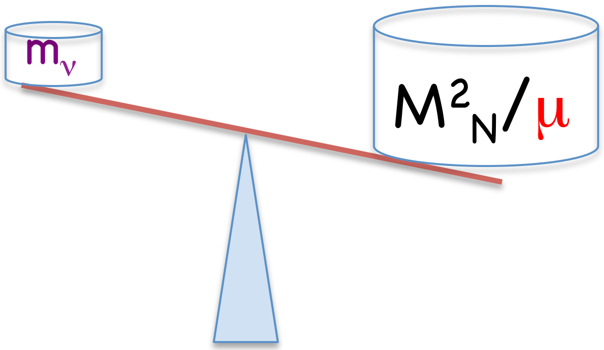
$$\begin{array}{cccc} & \downarrow & \downarrow & \downarrow \\ L= & +1 & -1 & +1 \end{array}$$

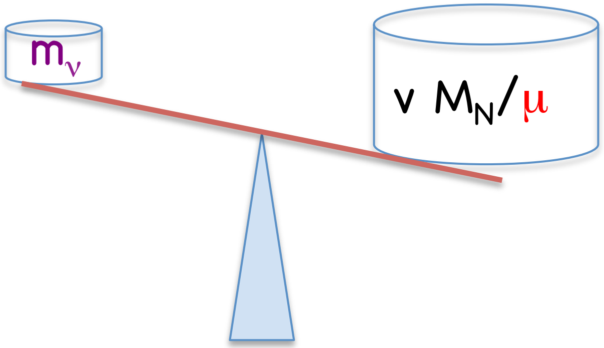
Inverse Seesaw

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

Direct Seesaw

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



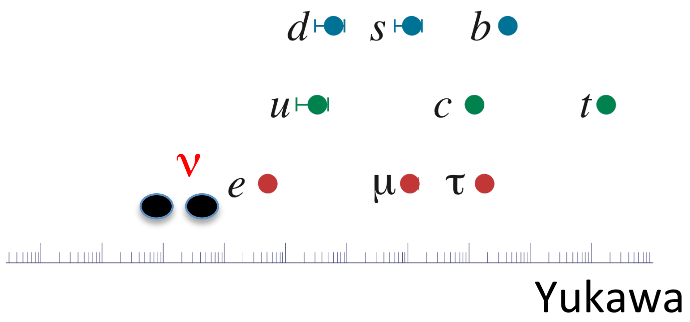


Y unsuppressed: -> LFV effects large m-> e g, etc
-> heavier spectrum $M_{N,}$ Y v, at LHC

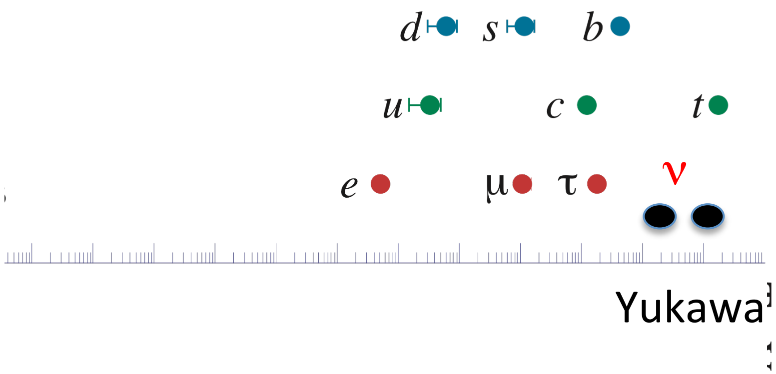
Kersten,Smirnov 07; Abada et al 07; Gavela,et al 09

Charged/neutral hierarchy in seesaw

M = TeV



M ≤ TeV + aprox. $U(1)_L$



Eg: Inverse seesaw/direct seesaw

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.

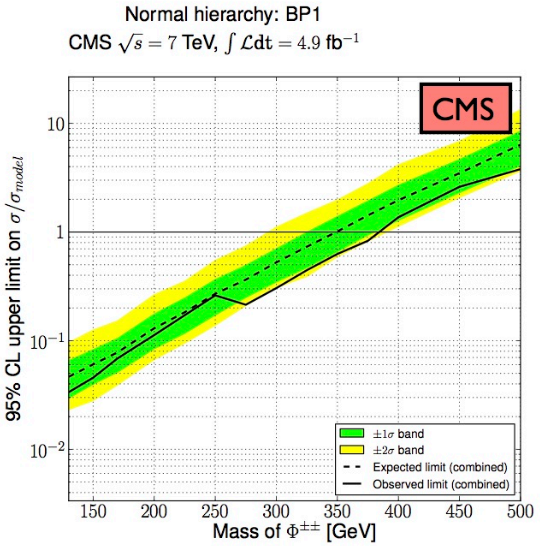
Generically it is needed

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

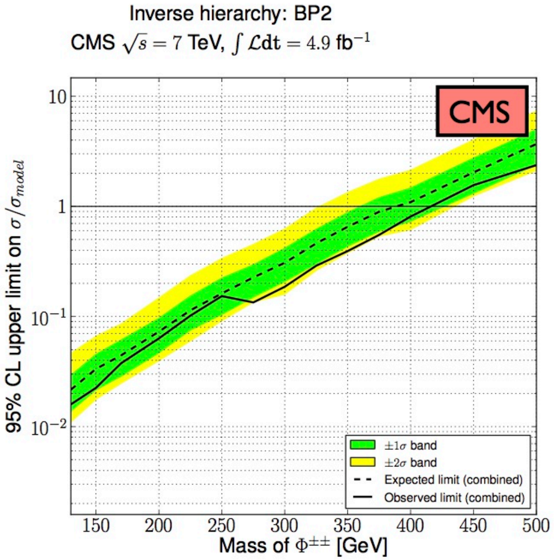
- Flavour effects unsuppressed by small Yukawas: approximate $U(1)_L$

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

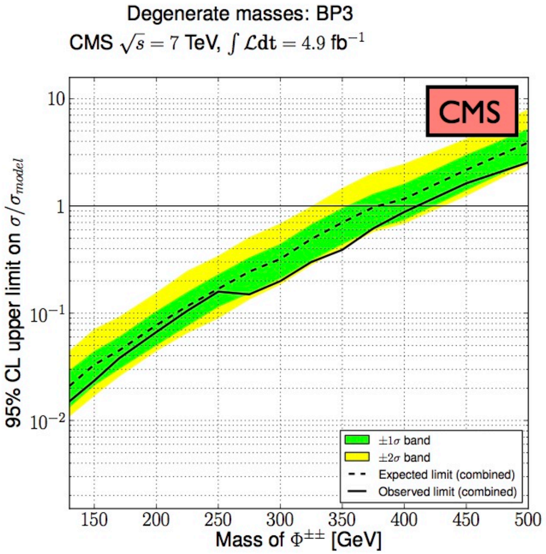
Normal hierarchy



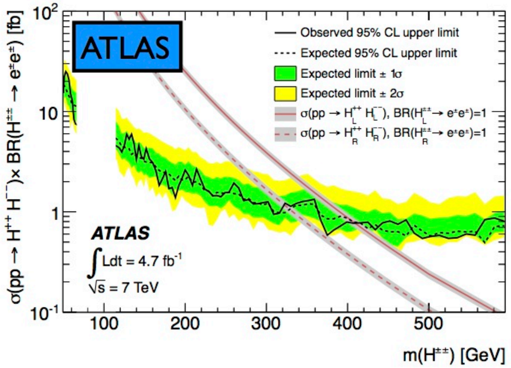
Inverted hierarchy



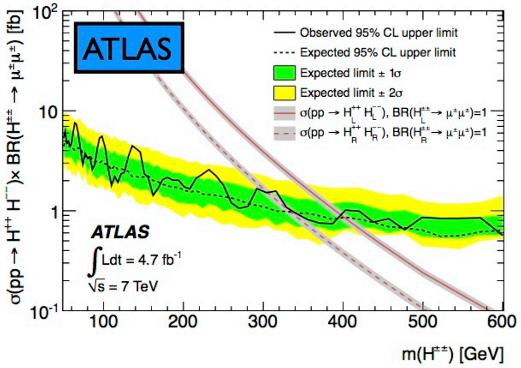
Degenerate ν



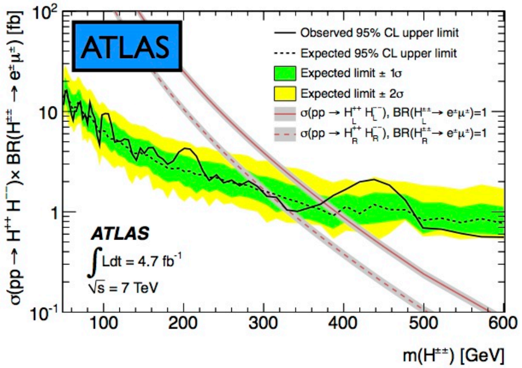
Br(ee)=1



Br(μμ)=1

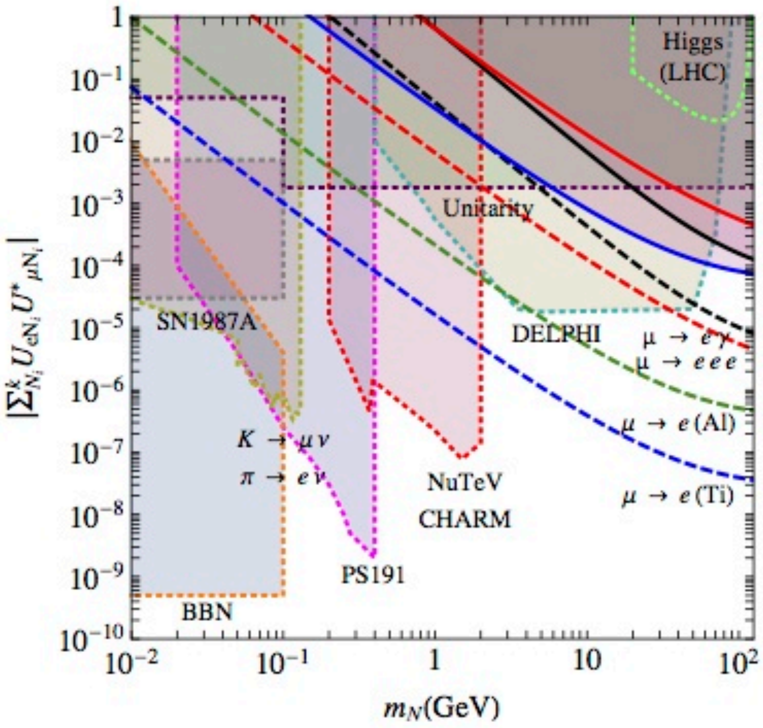


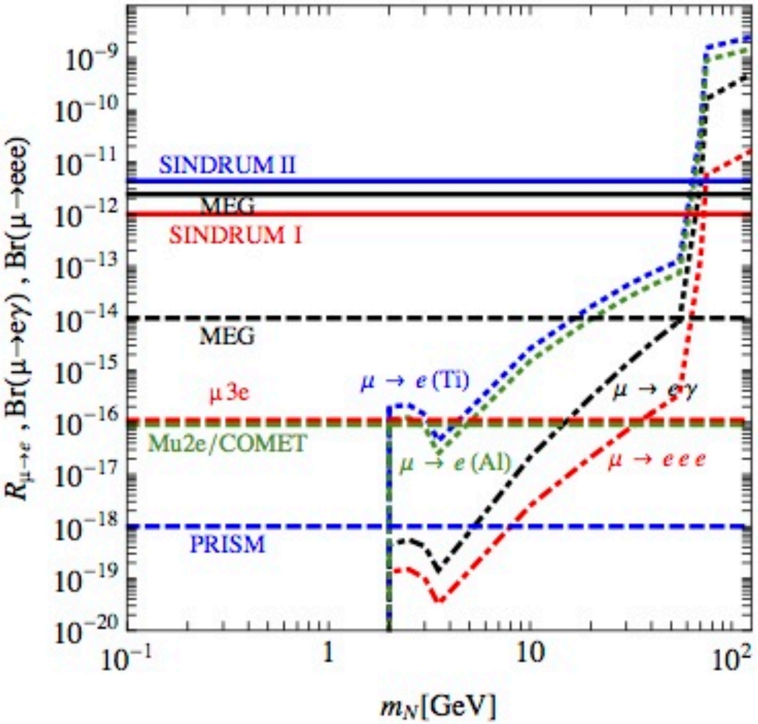
Br(eμ)=1



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

$\mu \to e\,\gamma$ $\quad \mu \to eee \quad$ $\mu \to e$ conversion



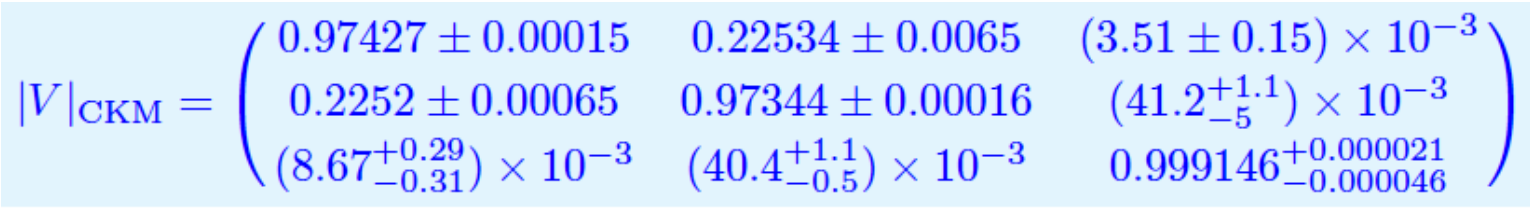


recent analysis Alonso et al 2012

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

Why so different mixing ?

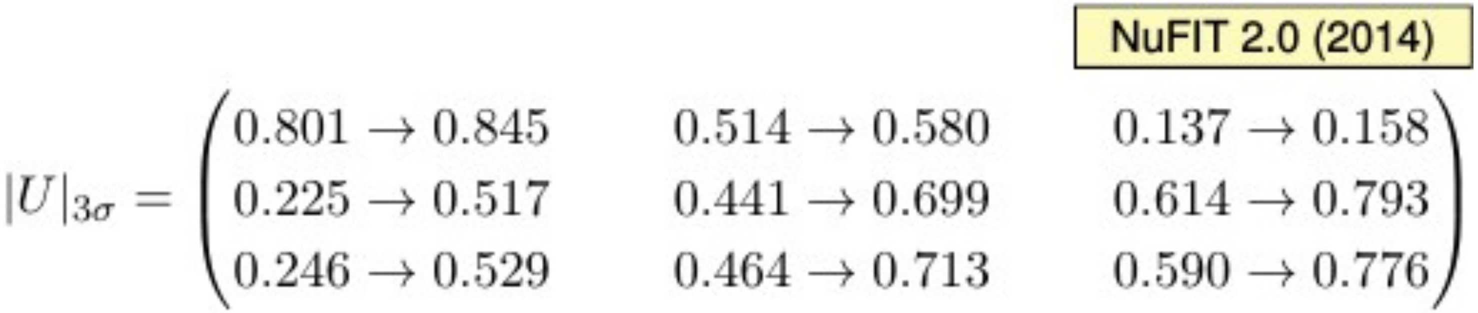
CKM



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

PMNS

3σ



NuFIT 2.0 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

What about mixing ?

Anarchy for leptons ?

Discrete symmetries (TB mixing) not particularly motivated with large θ_{13}

Dynamical origin of Yukawas

What about flavour ?

A “natural” landscape ?

R. Alonso, et al, 1306.5927 and 1306.5922

$$V(I_i(\mathcal{Y}_D,\mathcal{Y}_U,\mathcal{Y}_E,\mathcal{Y}_\nu)), i = 1, .., N_{\text{invariants}}$$

Natural/generic extrema <-> those at boundaries (invariance groups)

$$[SU(3)]^5 \otimes O(3)$$

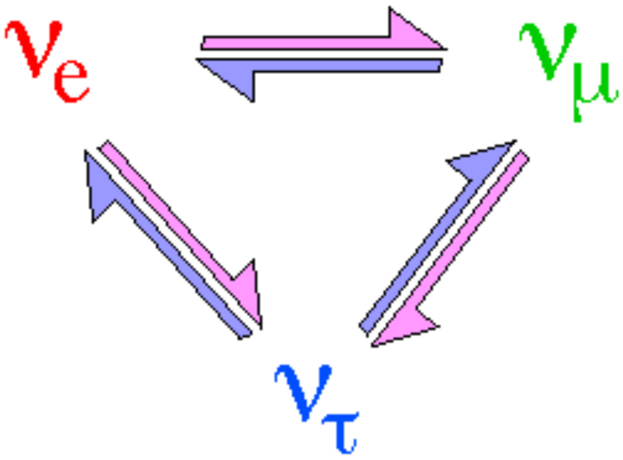
Quarks: (0,0,1) hierarchy + unit CKM
Leptons: degenerate neutrino spectrum
+ large mixings
+ π/2 Majorana phase

- The results of many beautiful experiments have demonstrated that n are (for the time-being) the less standard of the SM particles

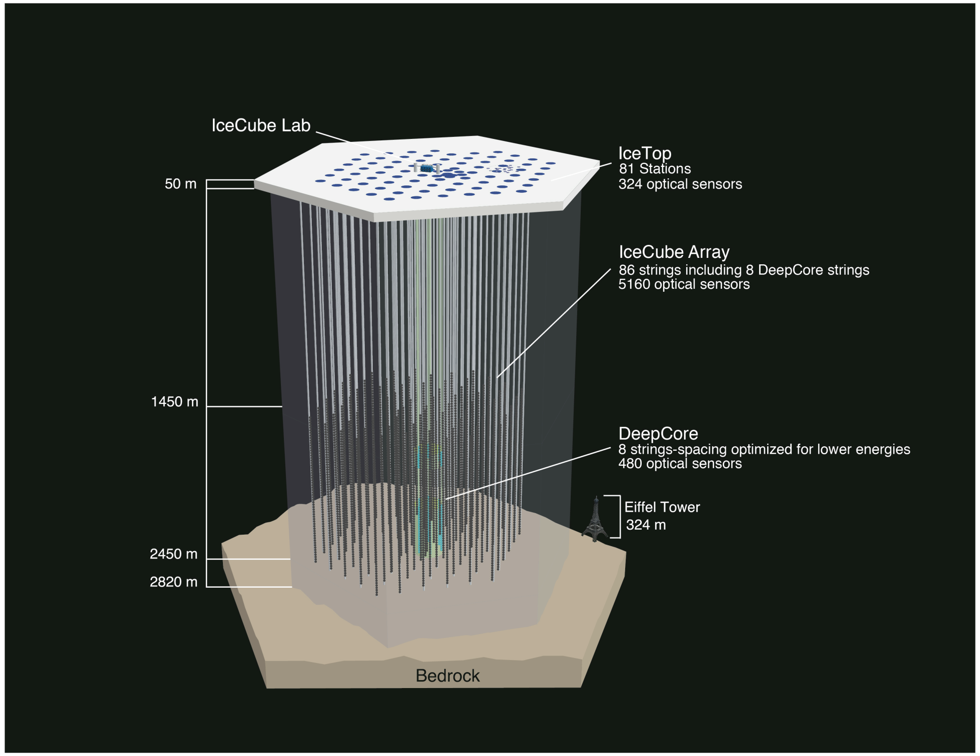
- Many fundamental questions remain to be answered however:
Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ?
Lepton vs quark flavour ?

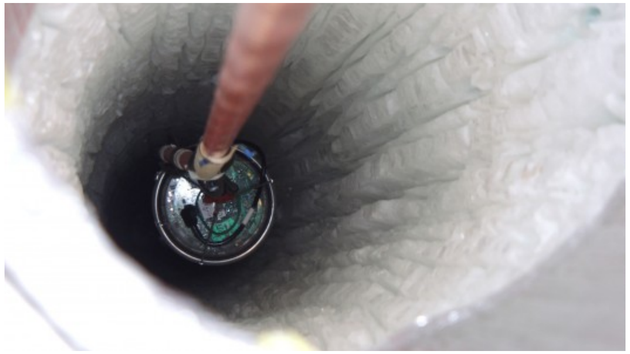
- A rich experimental programme lies ahead where fundamental physics discoveries are very likely (almost warrantied) …

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



Some extraterrestial ν's in ICECUBE



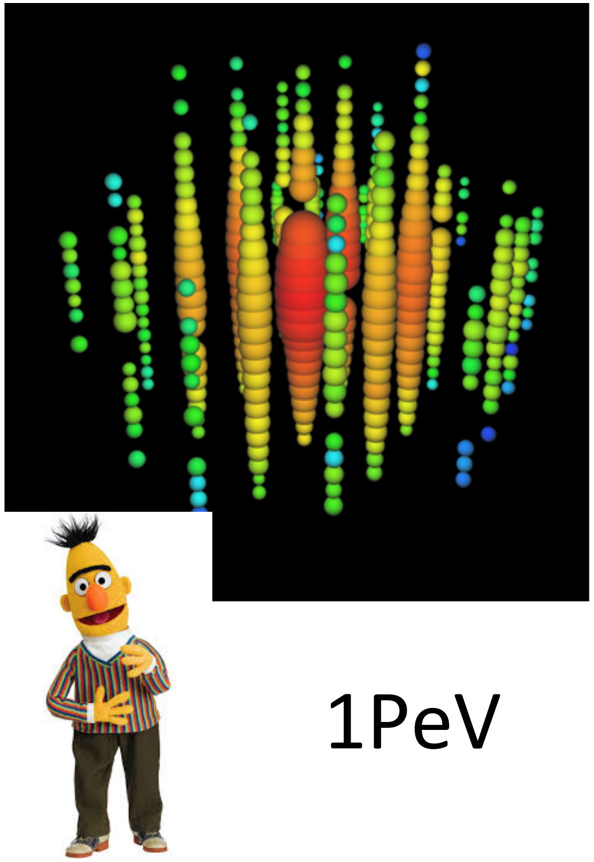


1km^3 Neutrino telescope

Neutrinos are most likely to point at the source

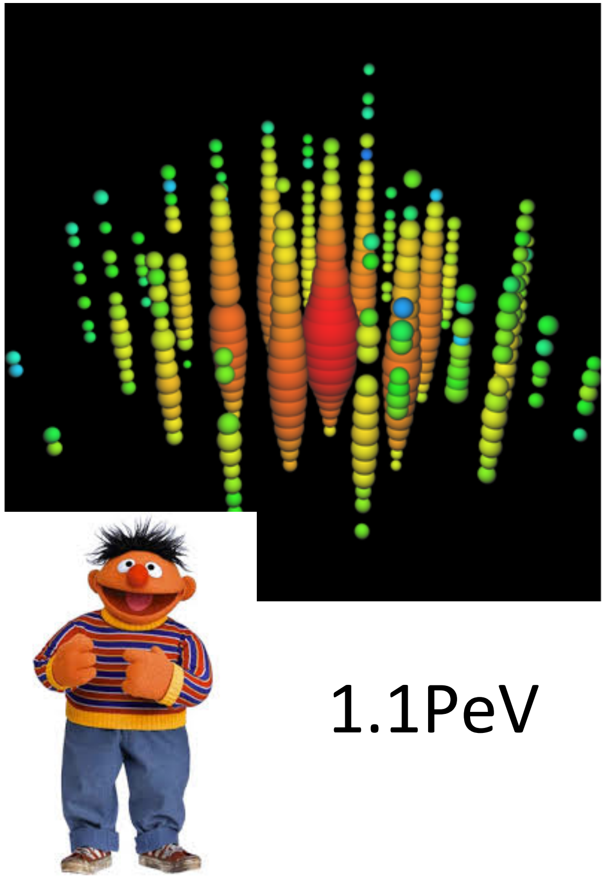
The highest energy neutrinos ever recorded

Bert



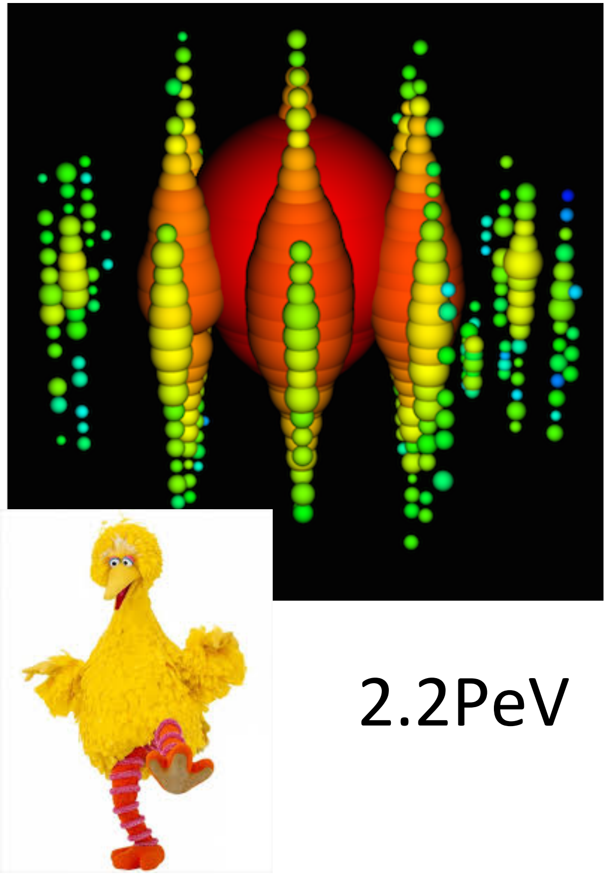
1PeV

Ernie



1.1PeV

Big Bird



2.2PeV

Origin still unknown...