Neutrino Physics: status&prospects

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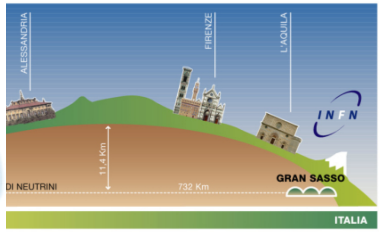
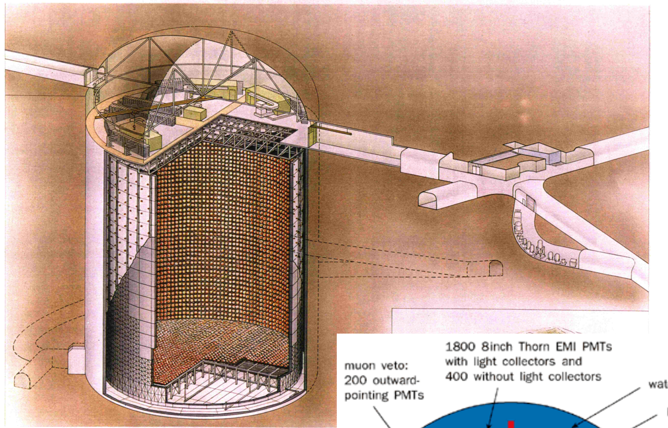
University of Valencia/IFIC

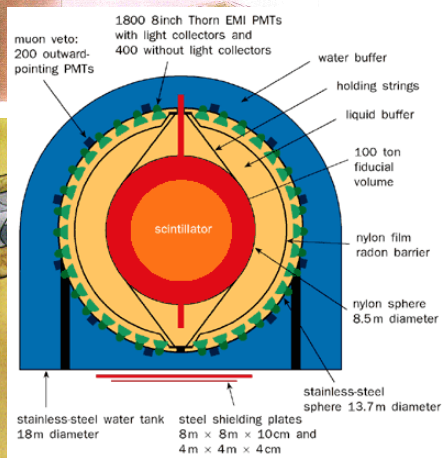
A decade of revolutionary neutrino experiments have discovered a new flavour sector, which does not quite fit in the Standard Model

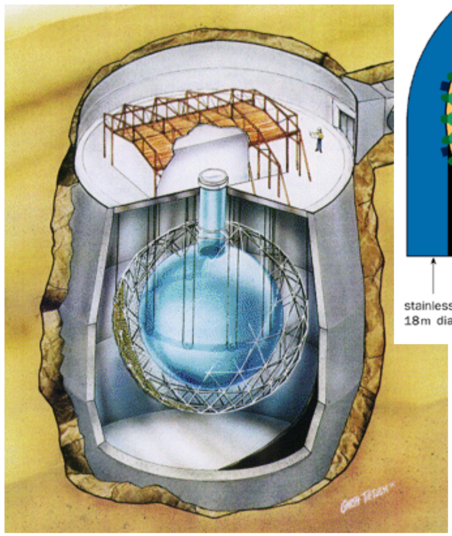
MINOS, Opera



SuperKamiokande





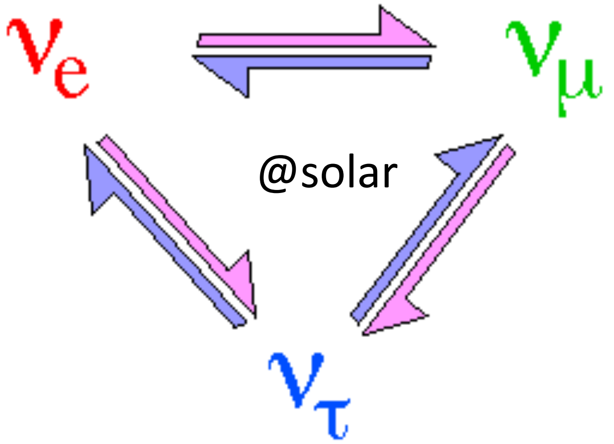


Borexino

SNO

...and more

Solar oscillation of ν_e

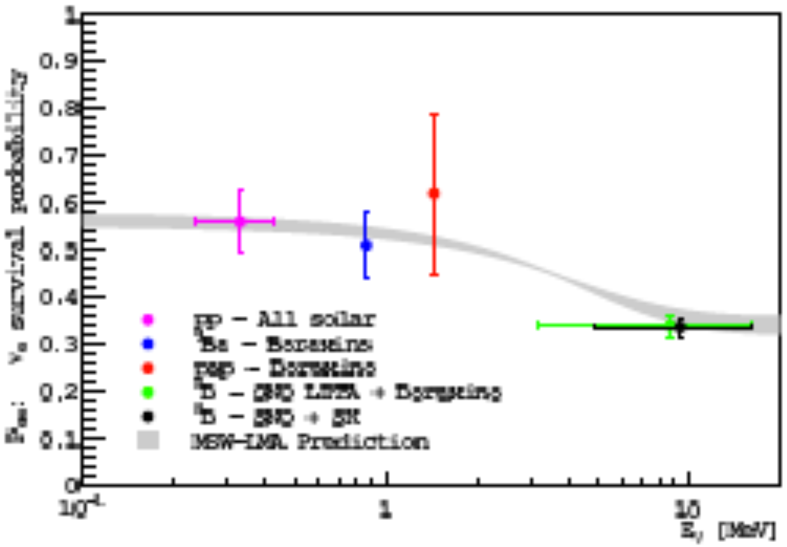


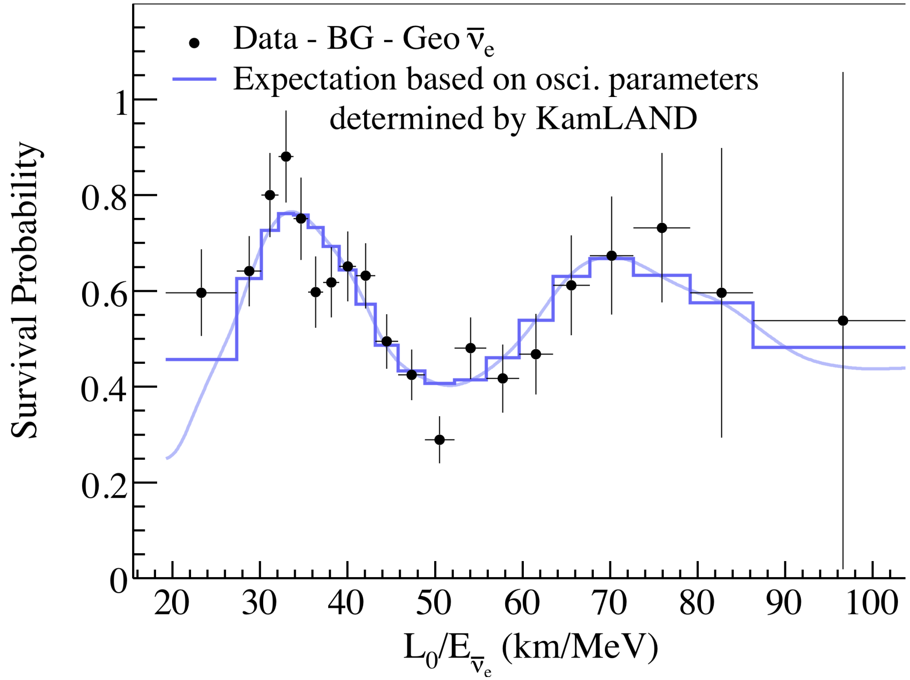
$$P_{\alpha\beta}(L) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

Pontecorvo

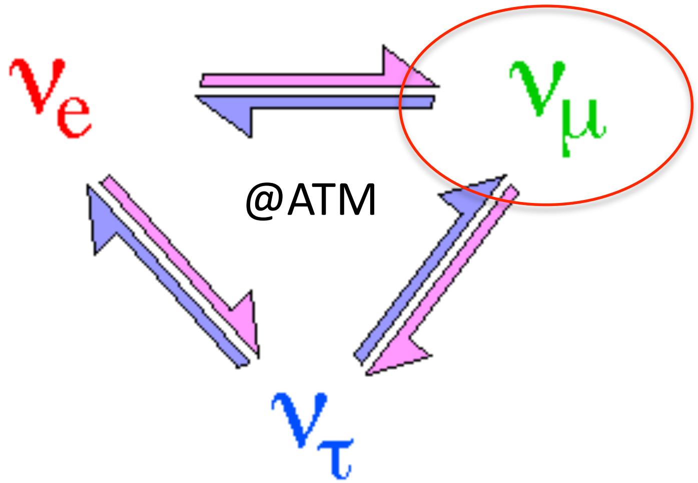
$$|\Delta m^2_{12}| \sim \frac{O(\mathrm{MeV})}{O(100km)}$$

MSW conversion in Sun



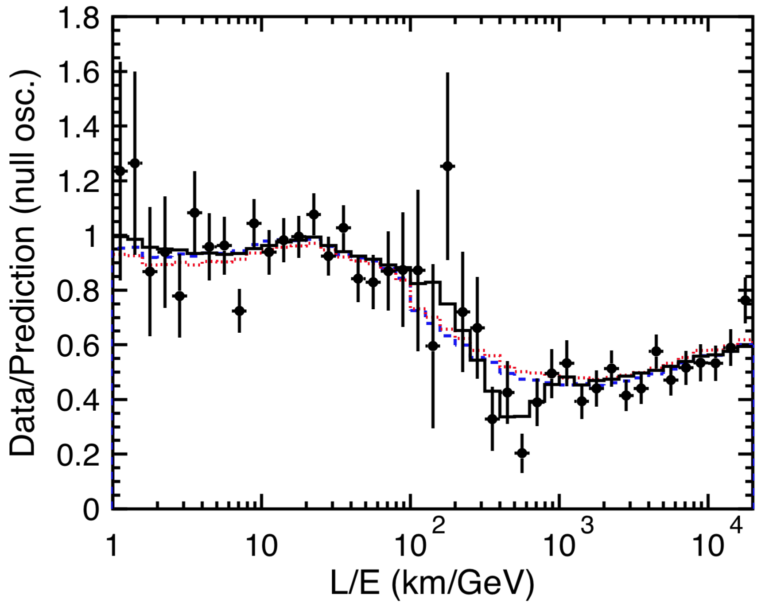


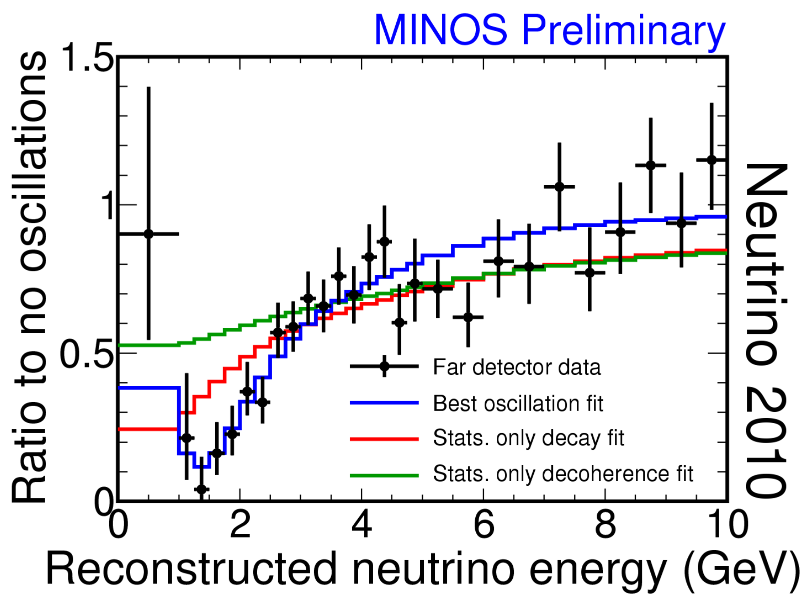
Atmospheric Oscillation of ν_μ



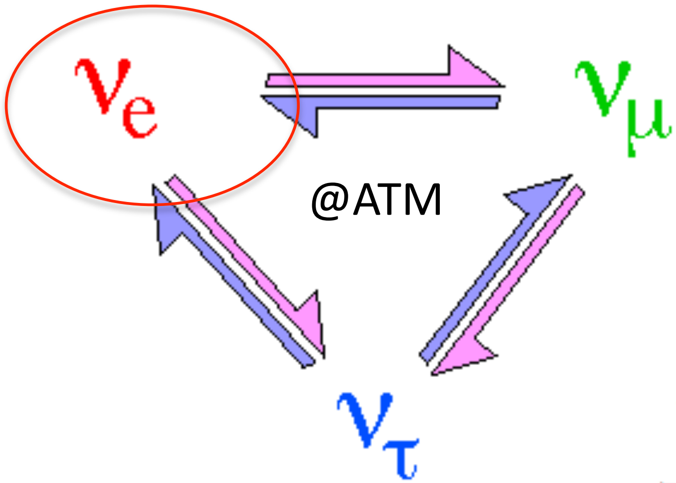
$$|\Delta m^2_{13}| \sim \frac{O(\mathrm{GeV})}{O(1000km)} \sim \frac{O(\mathrm{MeV})}{O(1km)}$$

SuperKamiokande





Atmospheric Oscillation of ν_e



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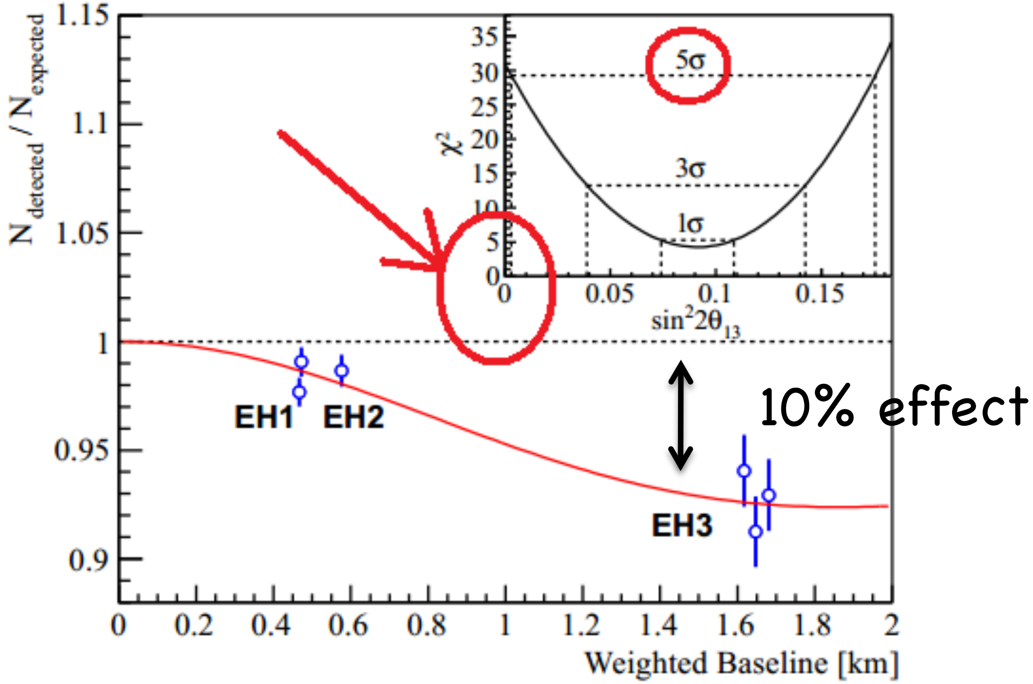


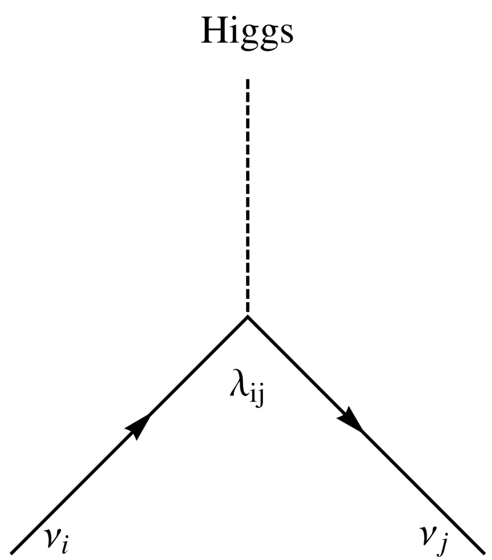
2012

T2K, Double Chooz
Daya Bay, RENO

New dofs needed !

Neutrinos are massive -> there must be new dofs in the SM

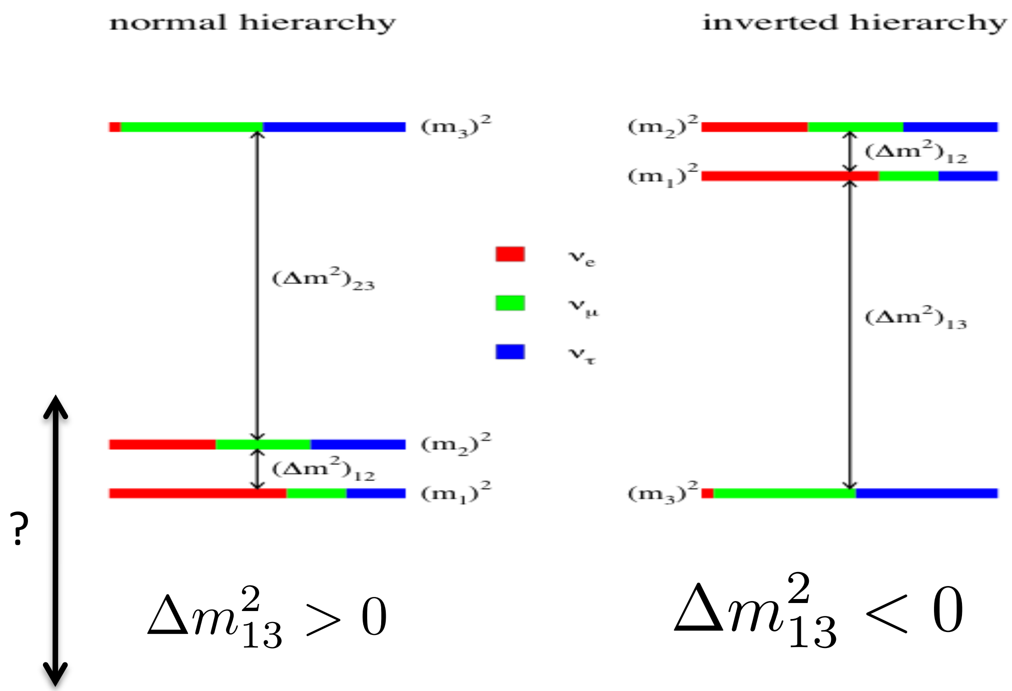
$$-\mathcal{L}_{\rm Dirac} = \bar{\nu}_L m_\nu \nu_R + h.c. \;\leftrightarrow \bar{L}\tilde{\Phi}\lambda\nu_R + h.c.$$



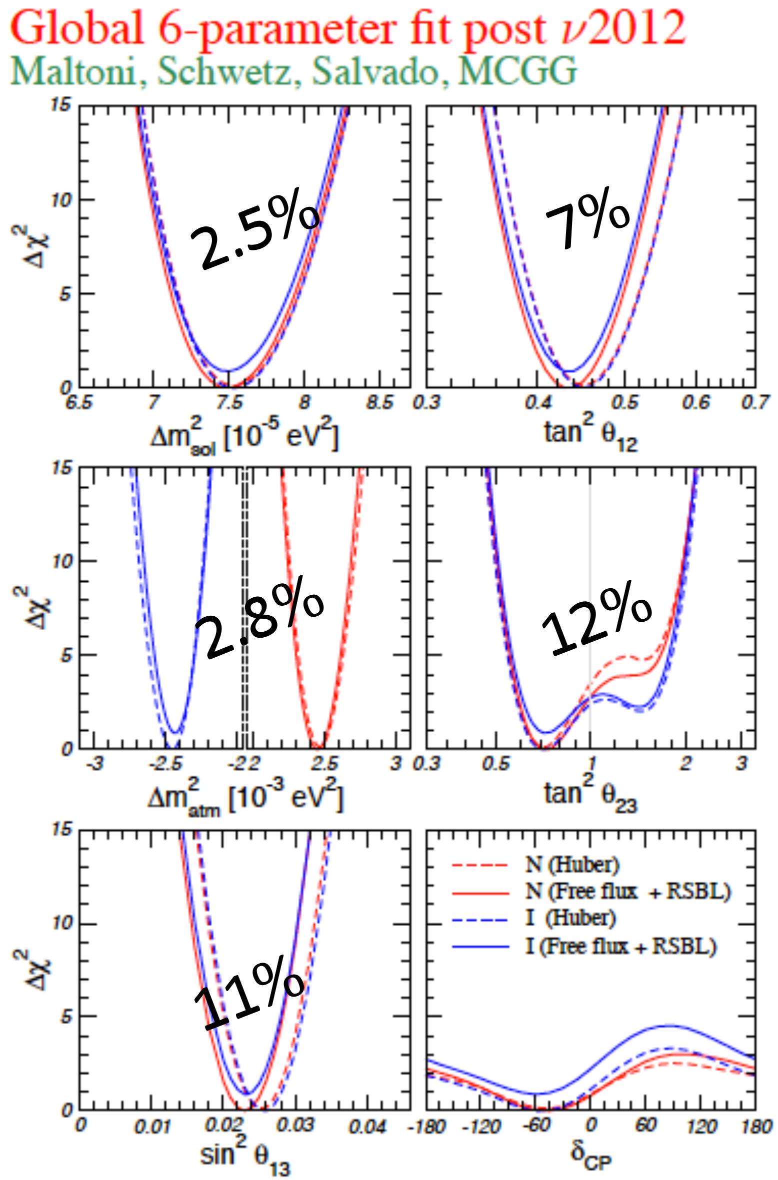
$$m_\nu \sim \lambda v$$

SM +3 massive neutrinos

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



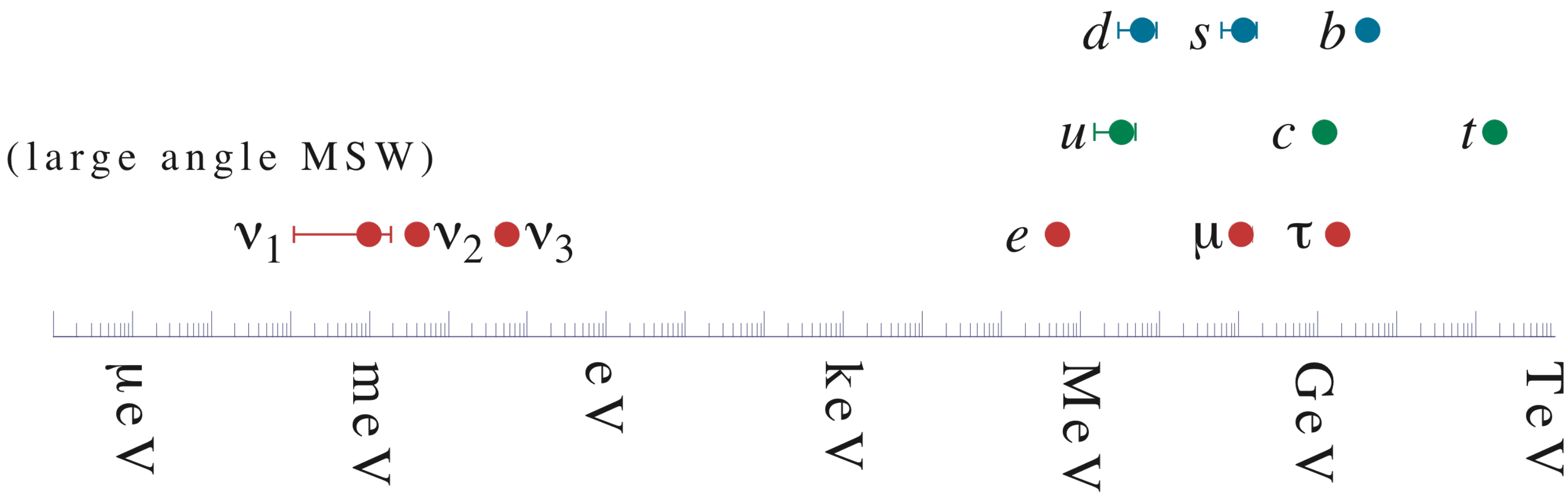
$\Delta m^2_{13} > 0$ $\Delta m^2_{13} < 0$



Gonzalez-Garcia ICHEP 2012

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



$m_f \sim \lambda$

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

$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.795 \to 0.841 & 0.517 \to 0.584 & 0.141 \to 0.179 \\ 0.213 \to 0.543 & 0.425 \to 0.728 & 0.575 \to 0.802 \\ 0.213 \to 0.541 & 0.411 \to 0.720 & 0.576 \to 0.802 \end{pmatrix}$$

Gonzalez-Garcia, ICHEP 2012

A new physics scale

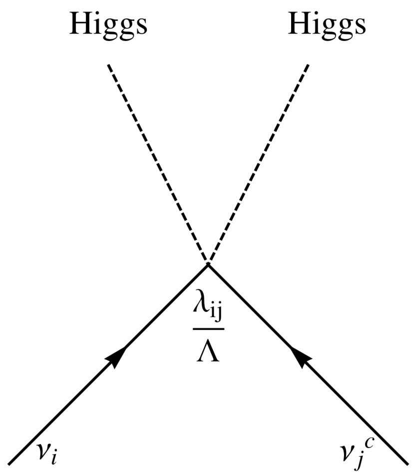
Neutrinos have tiny masses -> a new physics scale

$$-\mathcal{L}_{\rm Majorana} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\leftrightarrow\; \bar{L}\tilde{\Phi} \;\alpha\; \tilde{\Phi} L^c + h.c.$$

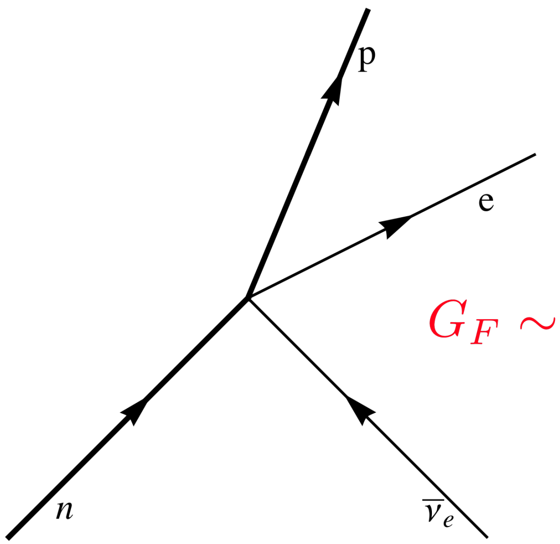
Weinberg

$$[\alpha] = -1$$

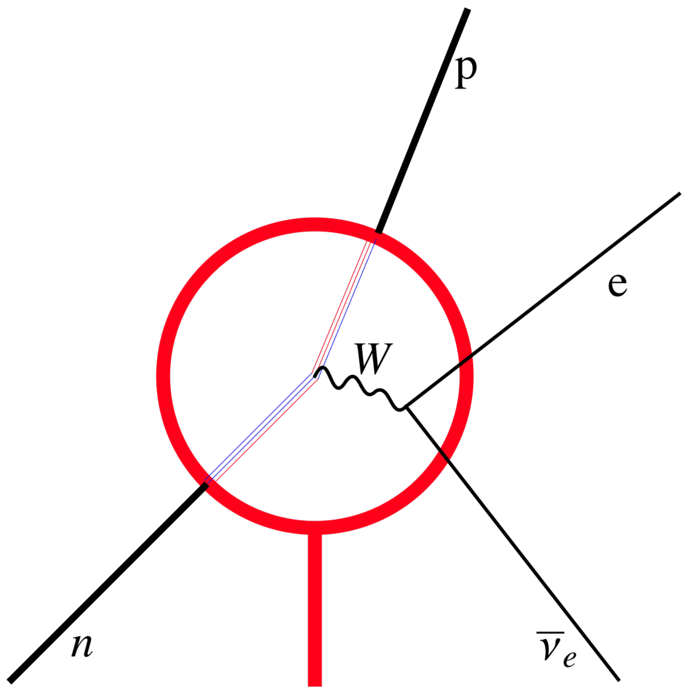
$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$



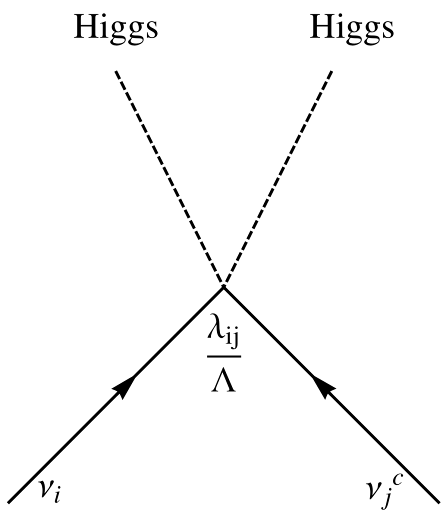
Also the lowest dimension effective operator !



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



SM

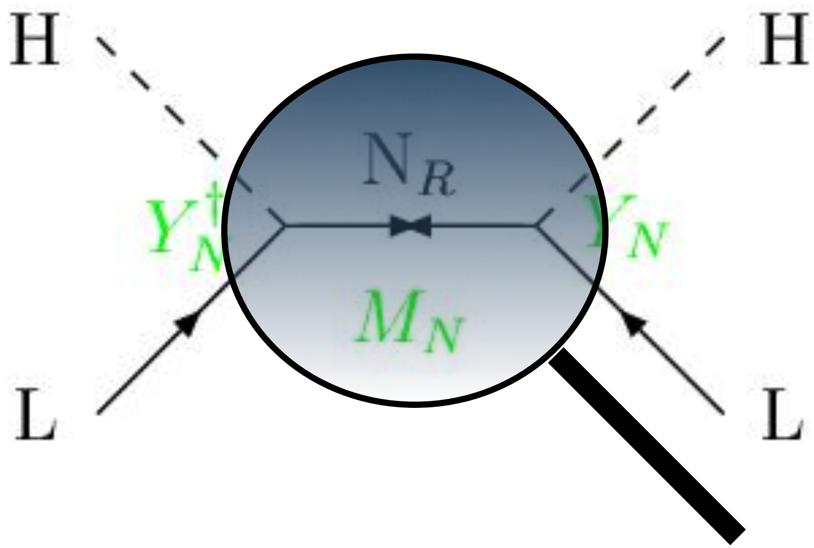


νSM ?

How does the ν scale relates to the EW scale ?

Example: Type I seesaw model

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

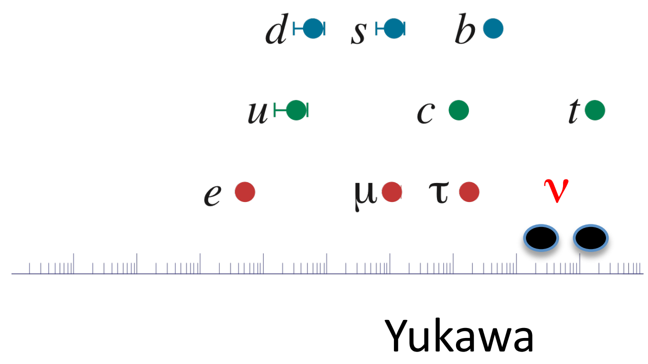


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

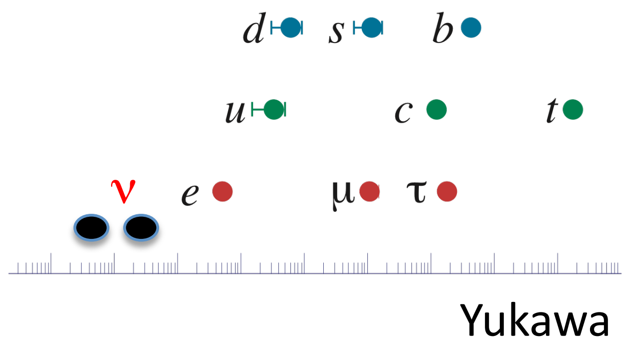
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow...

Charged/neutral hierarchy

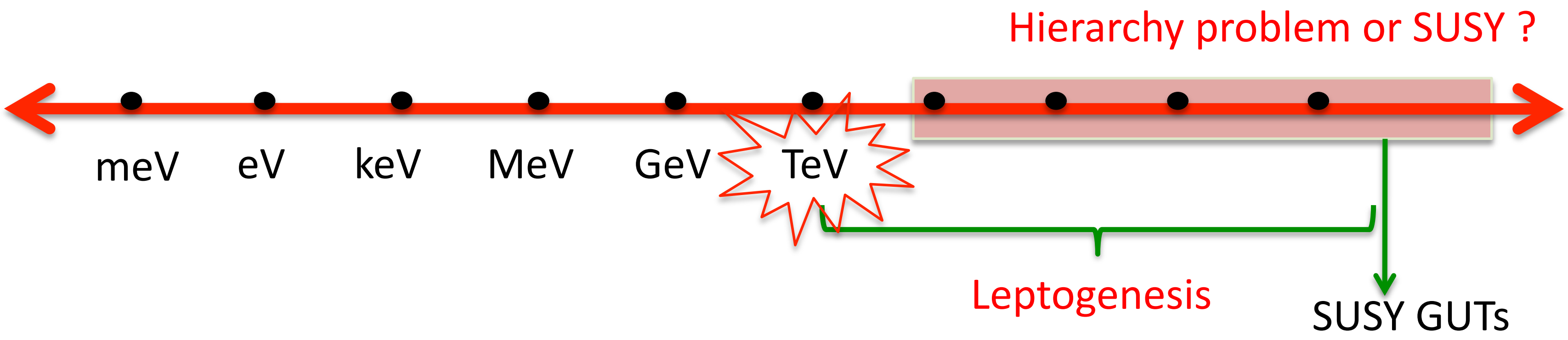
M_N = GUT



M_N = TeV



Pinning down the New physics scale



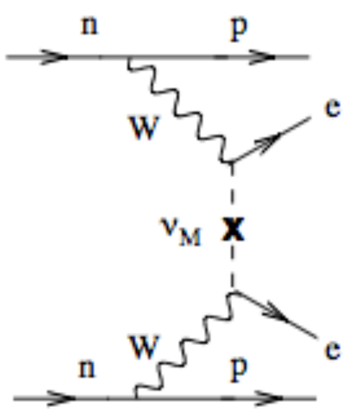
Robust&testable prediction of high scale seesaw models:

there is neutrinoless double beta decay at some level

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

Majorana nature: ββ0ν

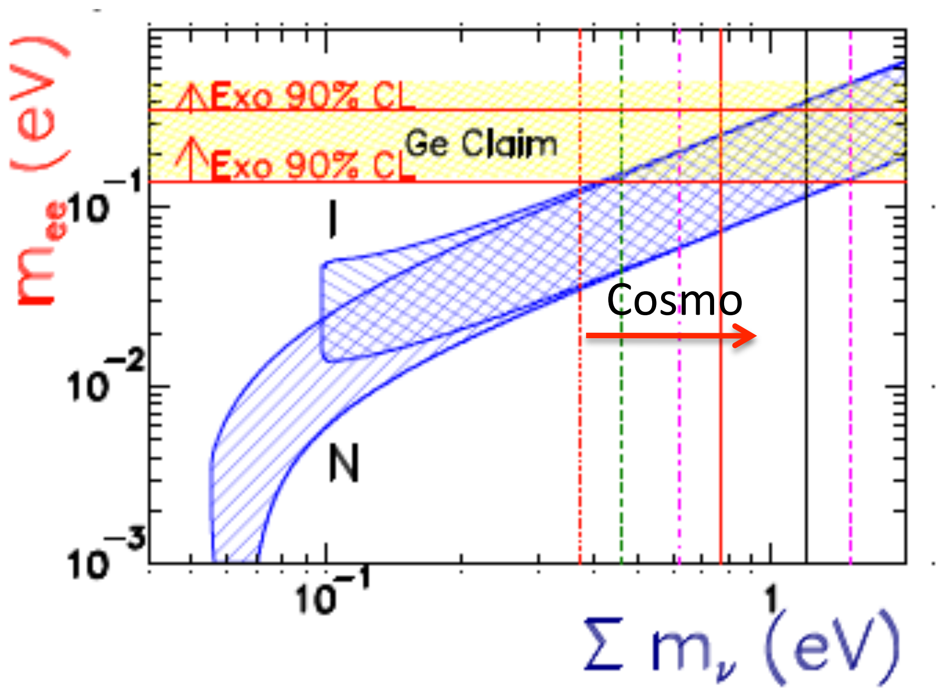
Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT, SuperNEMO, LUCIFER…



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

$$\Sigma \equiv \sum_i m_i$$

If $M_N > 100$MeV



Update Maltoni et al, 2012

Leptonic CP violation

Golden channel (eμ)

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

$$+ \; c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) \equiv P^{solar}$$

$$+\tilde{J} \cos\left(\pm\delta - \frac{\Delta_{23} L}{2}\right) \frac{\Delta_{12} L}{2} \sin\left(\frac{\Delta_{23} L}{2}\right) \equiv P^{inter}$$

$$\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \qquad \Delta_{23} \equiv \frac{\Delta m_{23}^2}{2E}$$

δ dependence is sizeable, statistically most significant at 1st atmospheric peak

$$\frac{L}{\langle E \rangle} = \frac{2\pi}{\Delta m_{atm}^2}$$

Leptonic CP violation

In matter:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$
$$+\tilde{J} \frac{\Delta_{12}}{A} \sin(\frac{AL}{2}) \frac{\Delta_{13}}{B_\pm} \sin\left(\frac{B_\pm L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

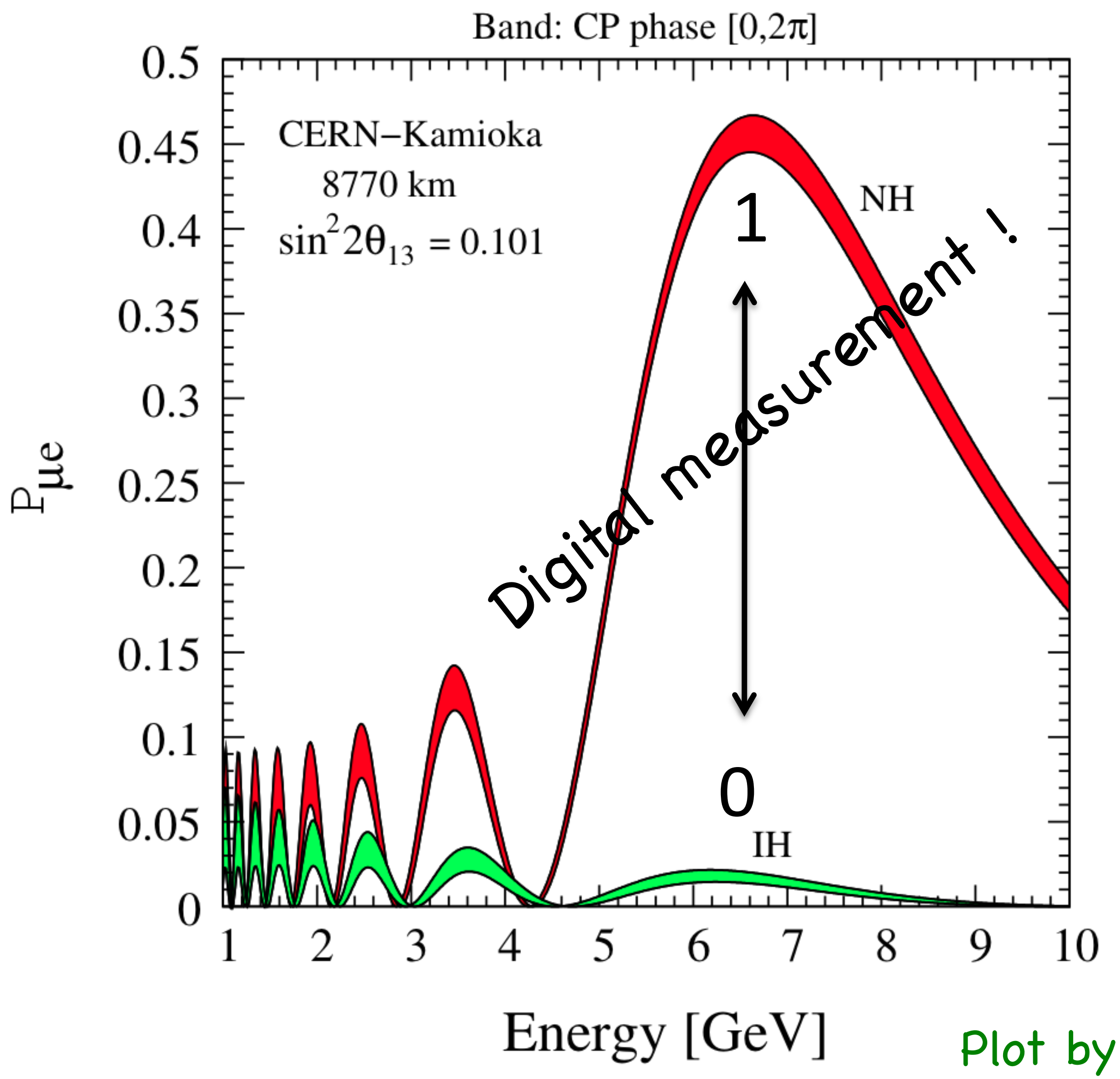
$$\tilde{J} \equiv c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{12} \ \sin 2\theta_{23} \qquad B_\pm \equiv \sqrt{2} G_F n_e \pm \Delta_{13}$$

Cervera et al

Parameter degeneracies (eg neutrino hierarchy) compromise δ sensitivity

Burguet et al
Barger, Marfatia, Whisnant
Minakata, Nunokawa

Hierarchy requires optimally



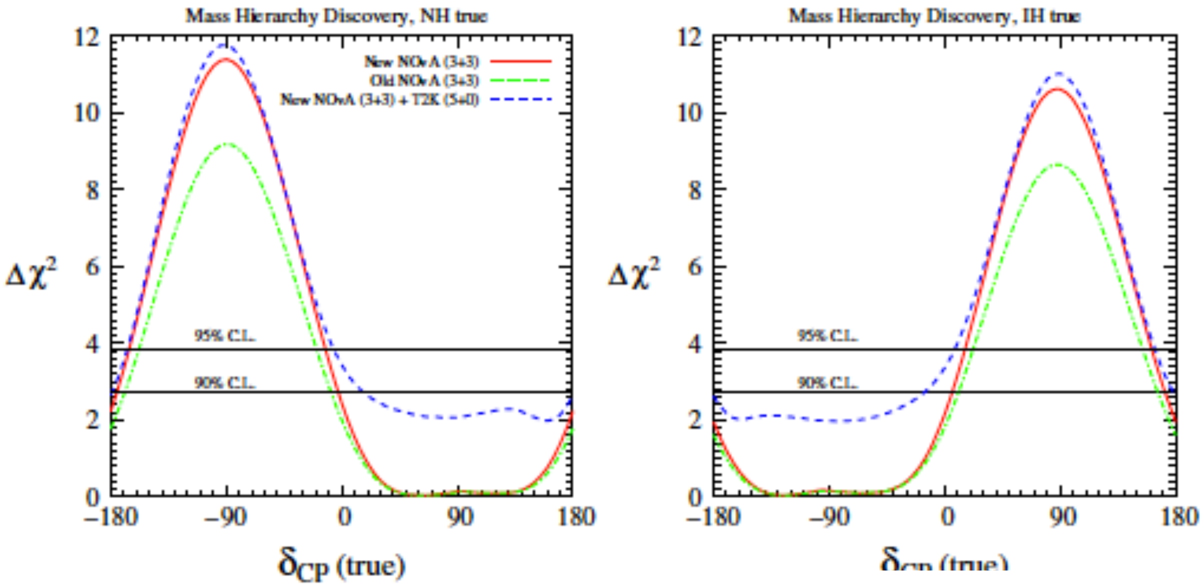
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F n_e},$$

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

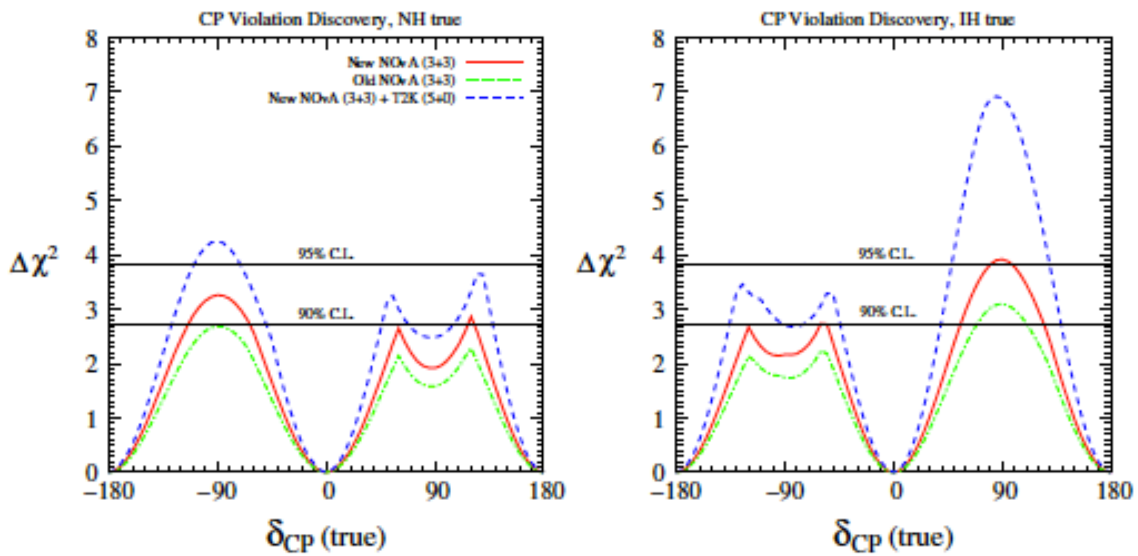
Plot by S. Agarwalla

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

First experiments in < 10y : T2K, NOVA



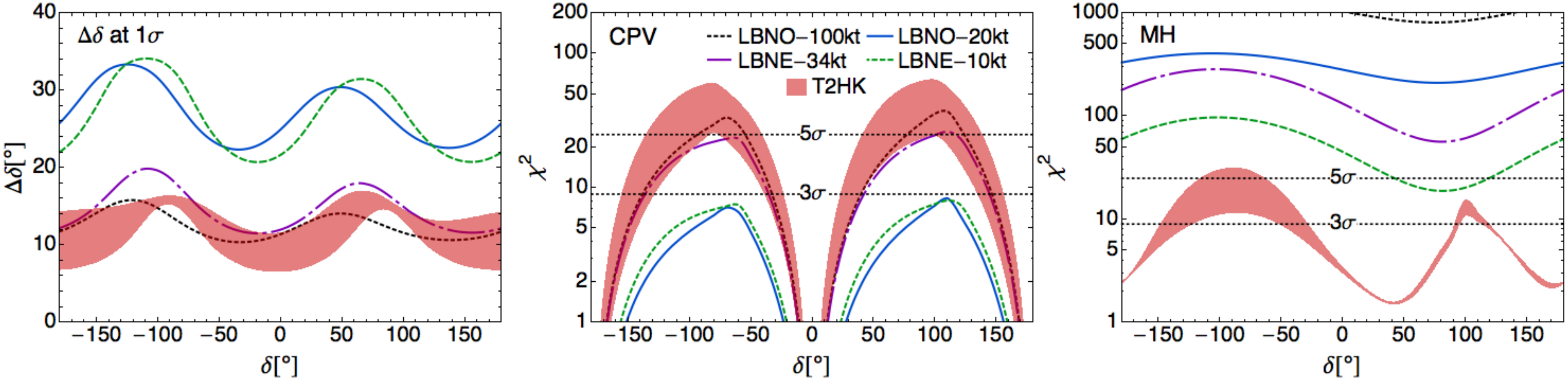
T2K L=300 km
NOVA L=800km



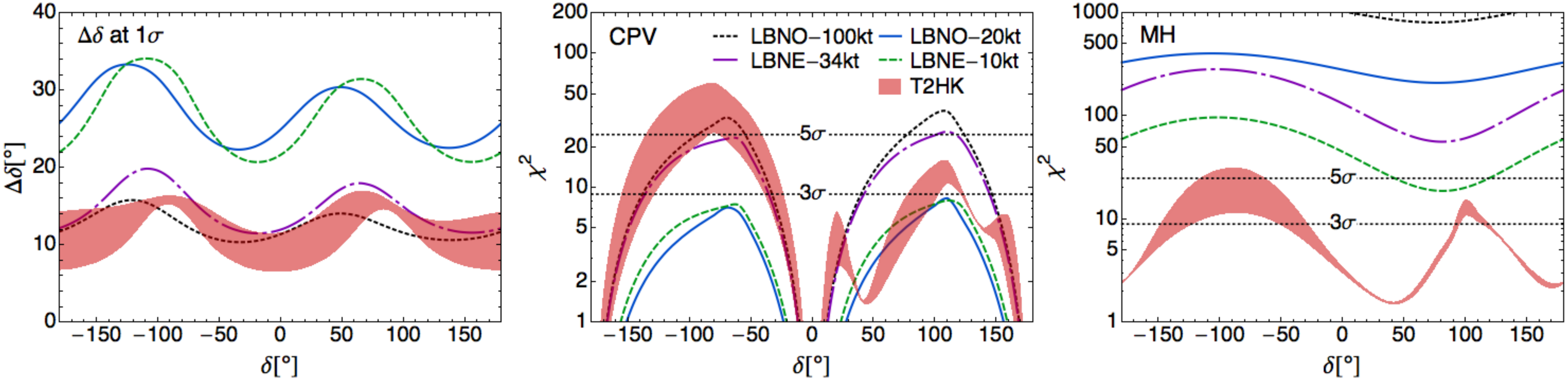
Hierarchy from atmospheric & reacto r ? Hagner's   Agarwalla et al

In 20 years from now with conventional beams…

Hierarchy known



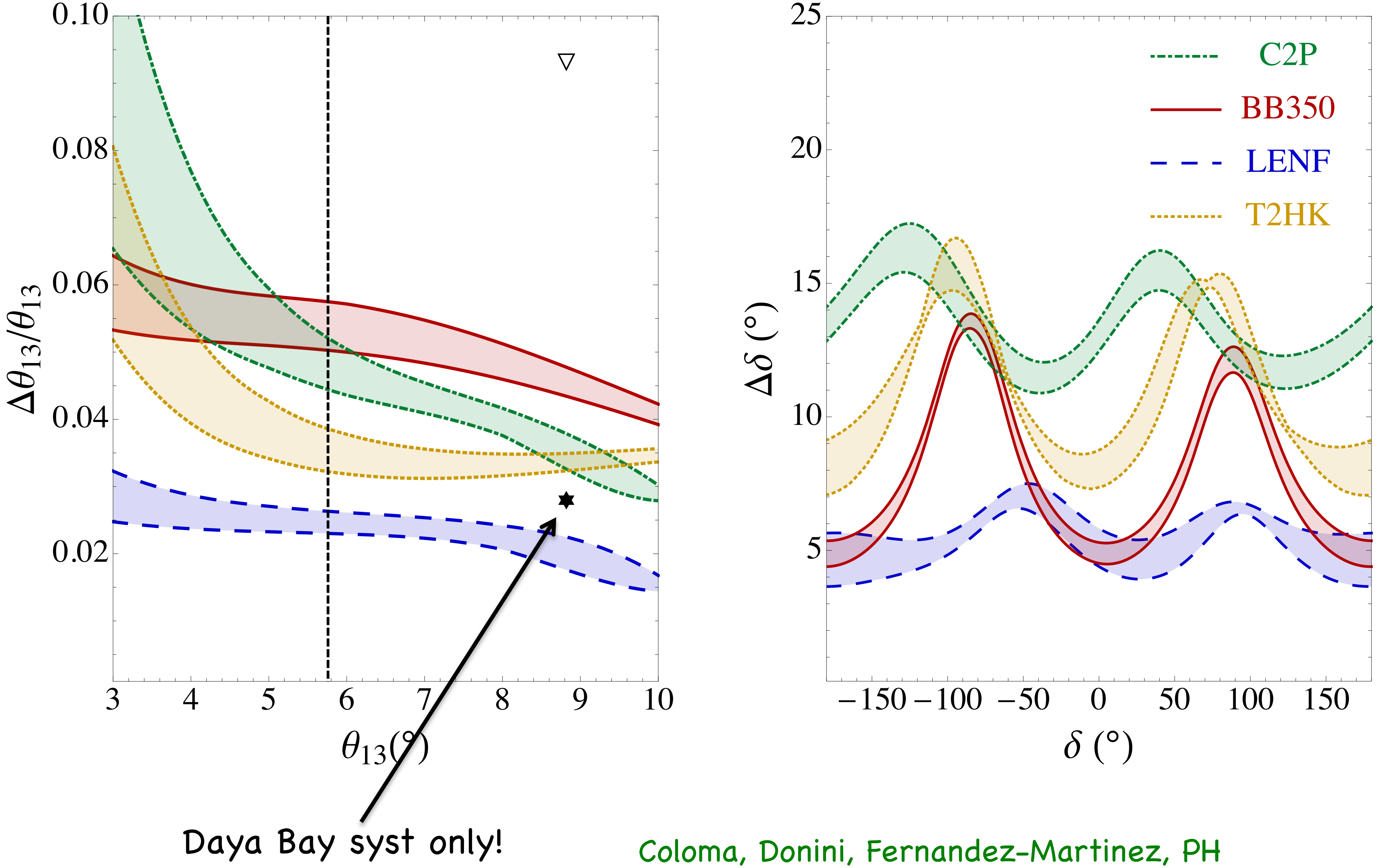
Hierarchy not known



Compiled by P. Coloma

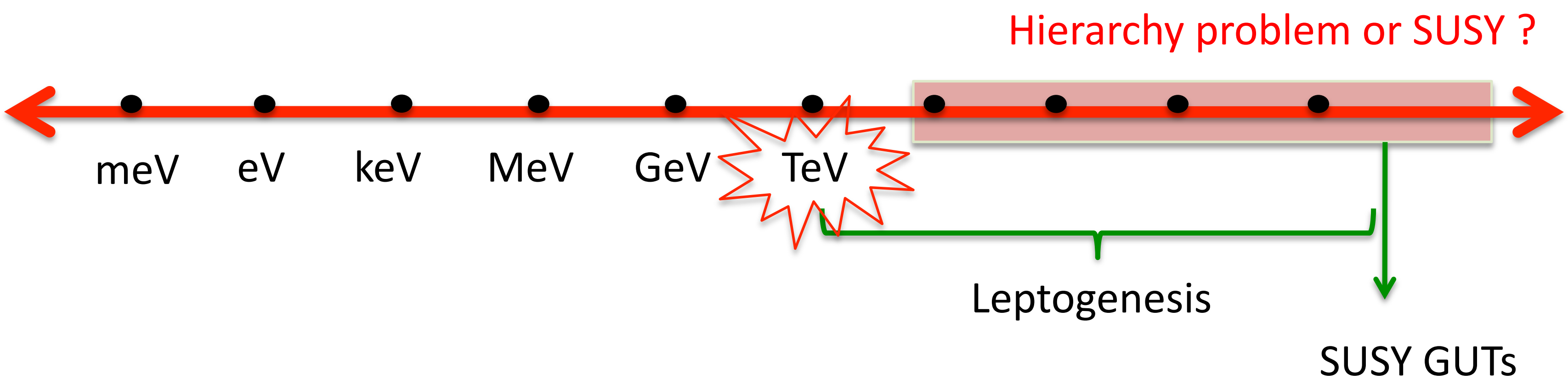
Systematics as in Coloma, Huber, Kopp, Winter to appear

With better beams in XX years...



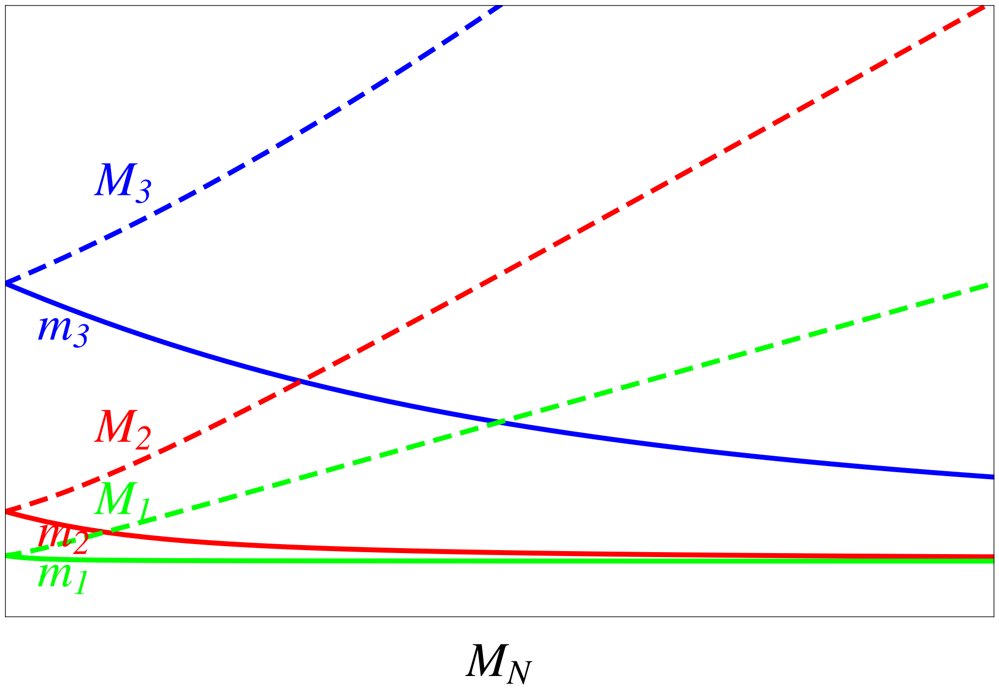
Coloma, Donini, Fernandez-Martinez, PH

Pinning down the New physics scale



But could it be lower ? Yes...

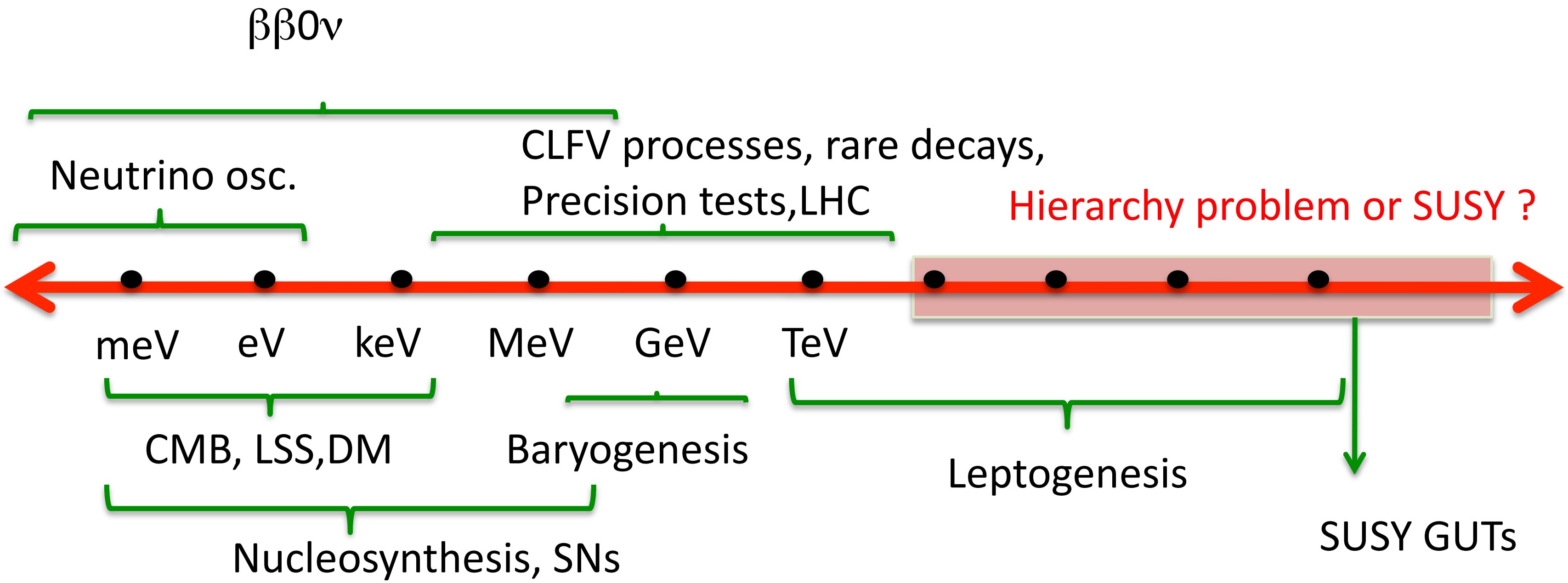
Low scale seesaw models



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

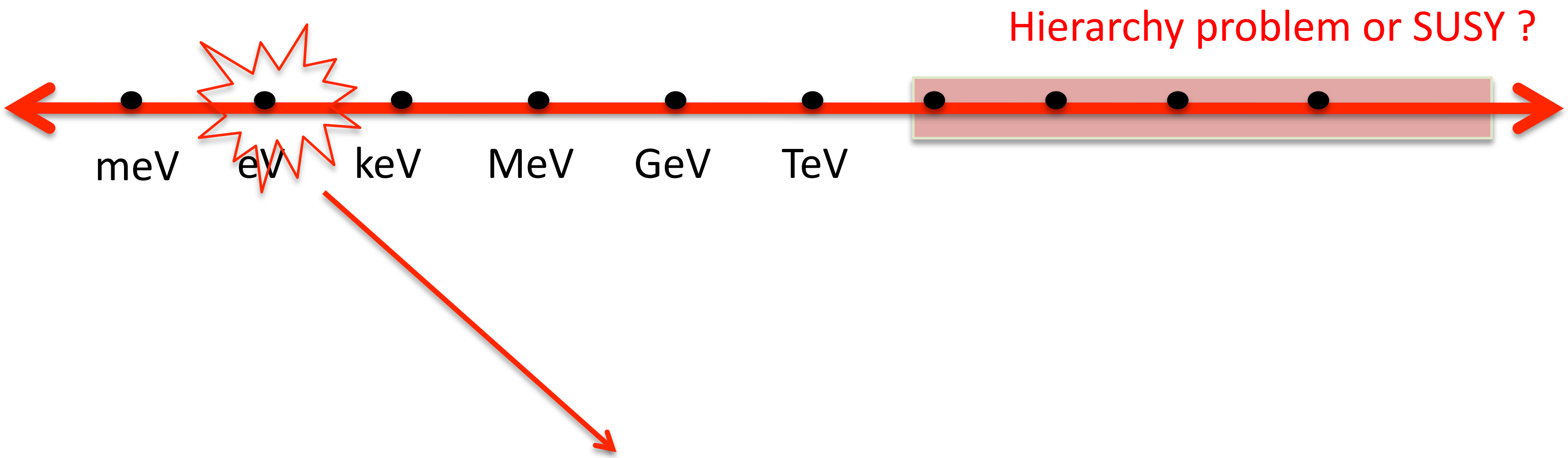
- More than three neutrinos -> extra steriles
- Non unitarity in standard mixing
- Heavy states could be detected !

Pinning down the New physics scale



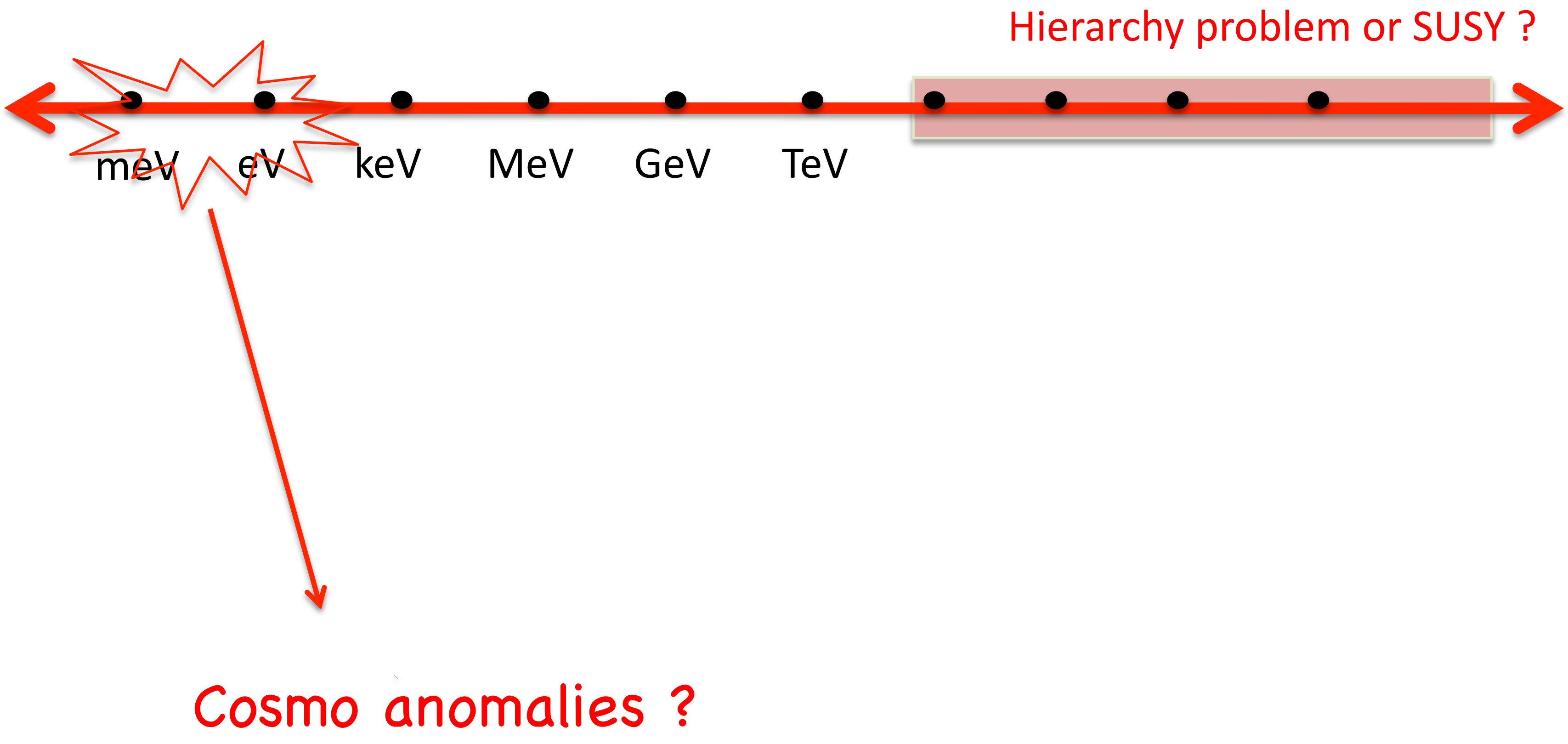
Light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

Pinning down the New physics scale

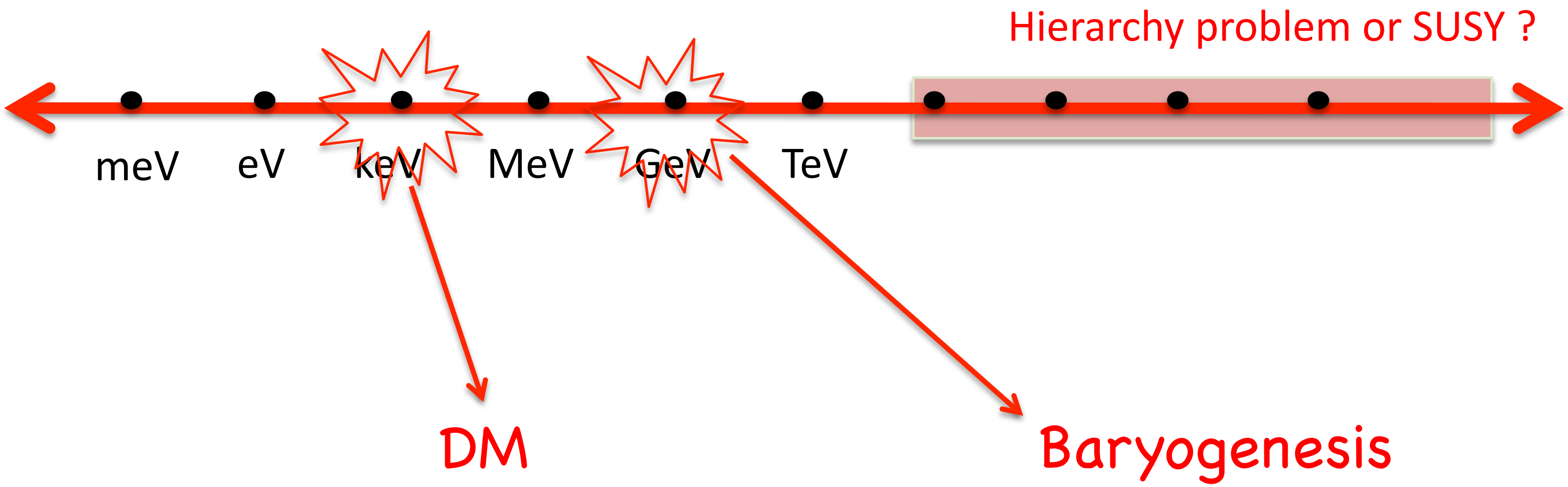


Neutrino anomalies

Pinning down the New physics scale



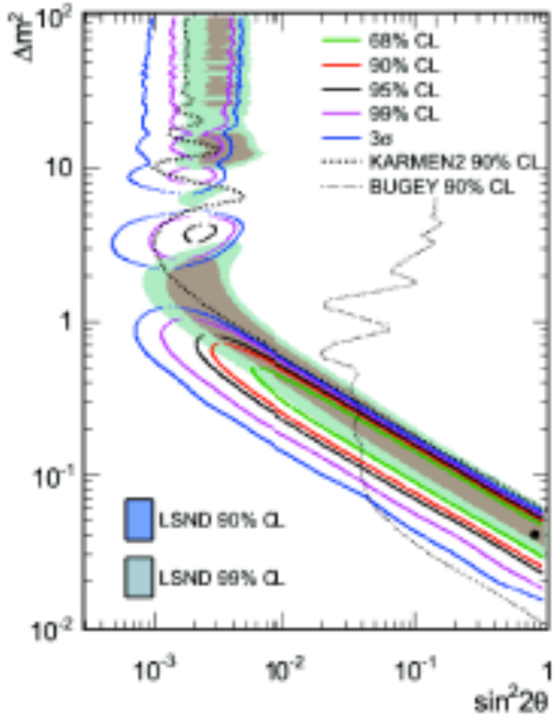
Pinning down the New physics scale



Neutrino anomalies

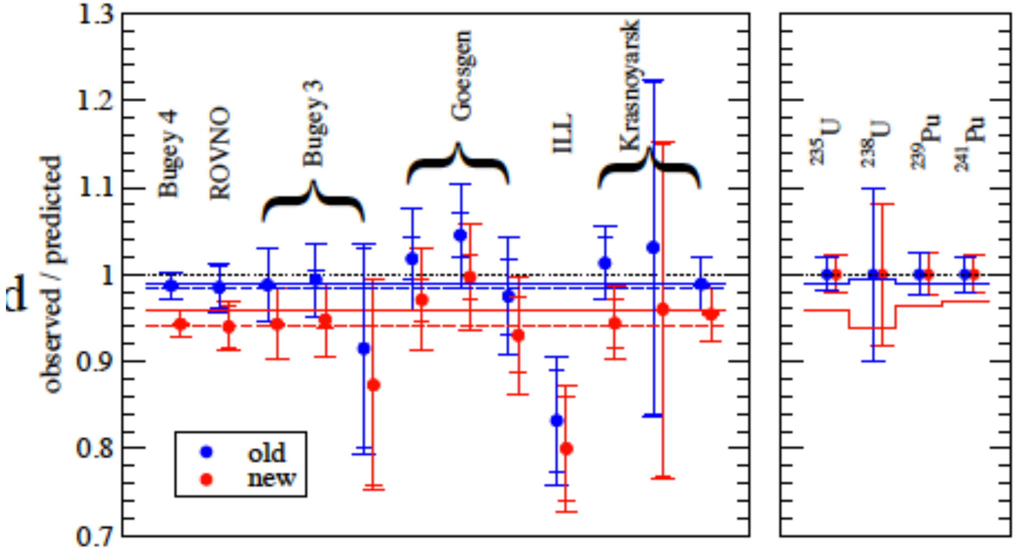
LSND

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



Reactors

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



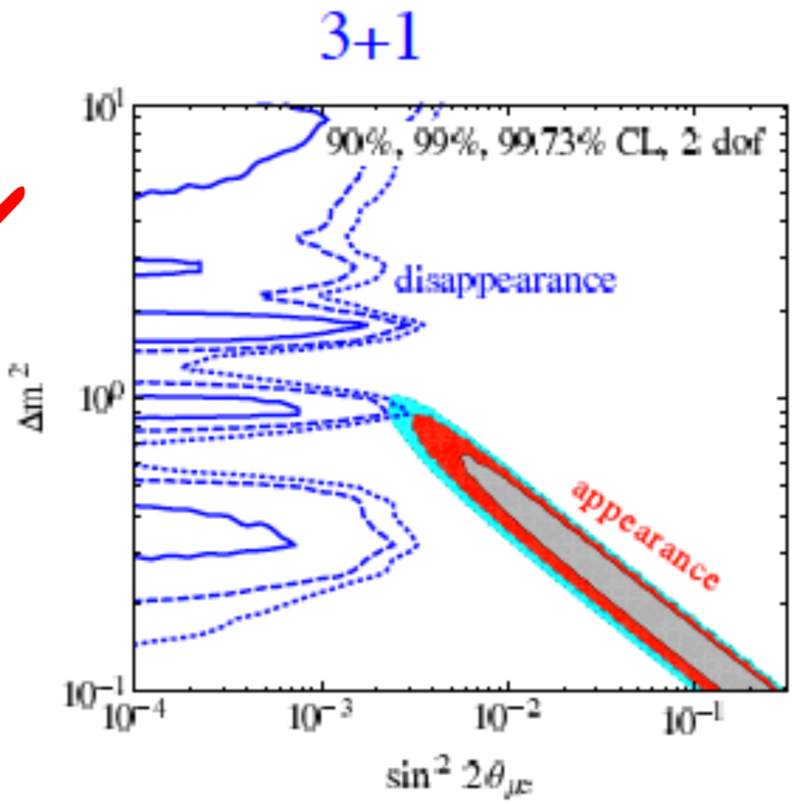
T. A. Mueller et al; P. Huber

+Gallium anomaly+ MiniBOONE low-energy excess…

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

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

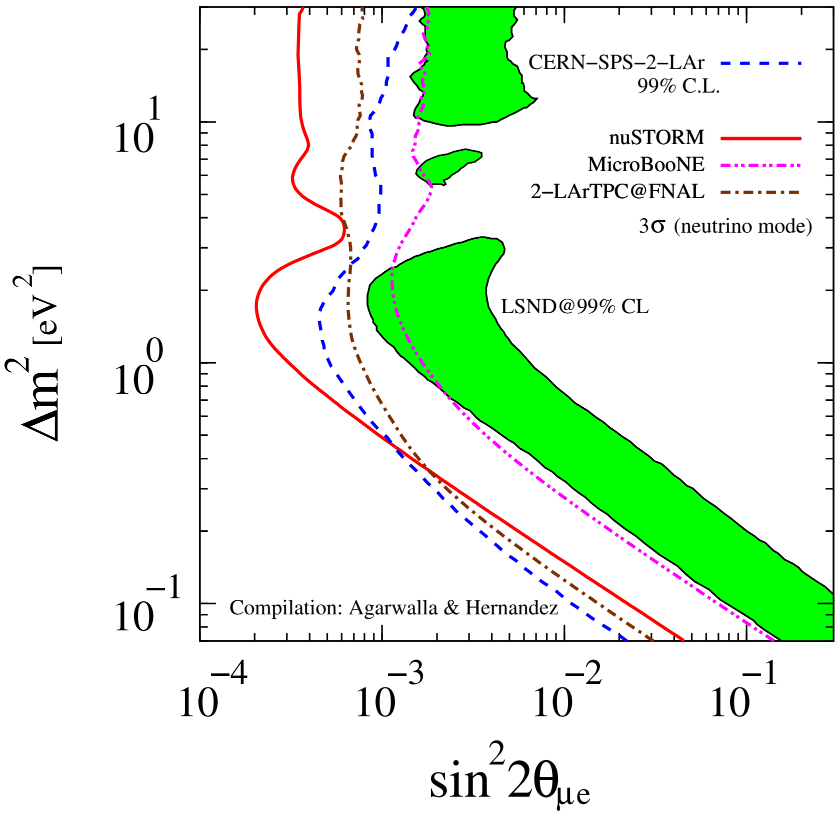
$P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu i}|^2)$ ✗



T.Schwetz, talk ν2012

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

Testing neutrino anomalies (in few y)



1) Conventional beams with near detector and better capabilities (LAr):
MicroBooNe (Fermilab), ICARUS-Nessie (CERN) (ν_μ -> ν_e) or nuSTORM (ν_e->ν_μ)
2) Reactors: near detector fluxes vs theoretical flux predictions
3) Atmospheric: SuperK, Icecube & LBL ....
4) Borexino

If there are other light sterile states we must know…

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

depend on it !

Concluding Observations

Obs 1: Neutrinos add at least as many parameters as quarks to the puzzle, but with features that might hint to a new physics scale

Obs 2: We still don't know what the νSM is

Obs 3: 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

Obs 4: The observation of neutrinoless double beta decay would be the discovery of such a new physics scale !

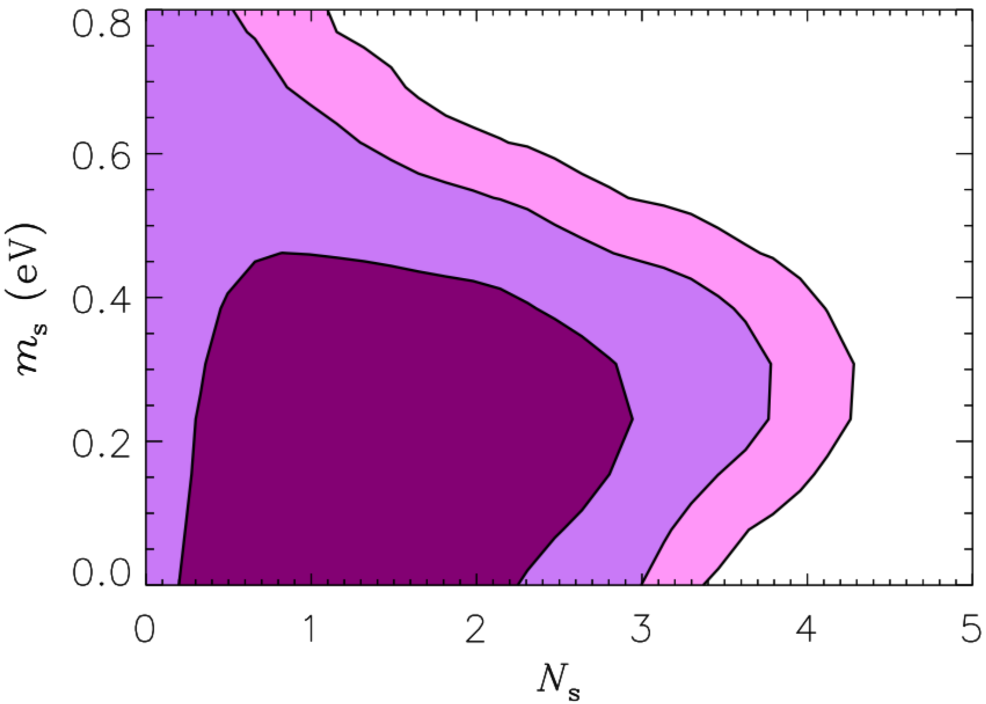
Obs 5: Predicting the matter-antimatter asymmetry in the Universe would be a major achievement of the νSM

Two key ingredients: Leptonic CP violation
Lepton number violation

Obs 6: Mass Hierarchy essential for reconstructing the underlying model of neutrino masses & predictions for other observables

BACKUP

Cosmology



Hamann et al, ArXiv: 1006.5276

Sterile species favoured by LSS and CMB

Nucleosynthesis:

$$N_s = 0.68^{+0.80}_{-0.70}$$

Izotov, Thuan

Hierarchy earlier ?

1) Atmospheric data contain this golden signal but hard to dig out

INO: 2 σ (250 kton-y), 2.7 σ (500 kton-y)

HK: 3σ (2.8 Mton-y), 4σ (5.6 Mton-y)

PINGU@ICECUBE: sensitivity depends a lot on systematic assumptions

Choubey Neutrino 2012

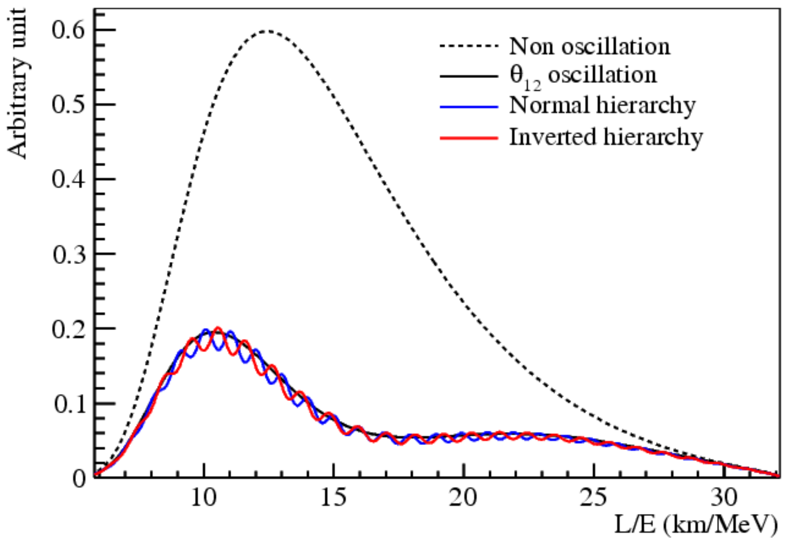
Hierarchy earlier ?

2) LBL Reactor neutrinos

$$P_{\nu_e\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}L}{2}\right) - c_{12}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{31}L}{2}\right) - s_{12}^2 \sin^2 \theta_{13} \sin^2\left(\frac{\Delta_{32}L}{2}\right)$$

$|\Delta_{32}| < |\Delta_{31}|$ NH

$|\Delta_{32}| > |\Delta_{31}|$ IH



Petcov et al

Extremely challenging: 20kton, 2-3% energy resolution, 1% linearity in energy scale, error on $|\Delta m^2_{23}|$

Qian, Dwyer, McKeown, Vogel, Wang, Zhang arXiv:1208.1551

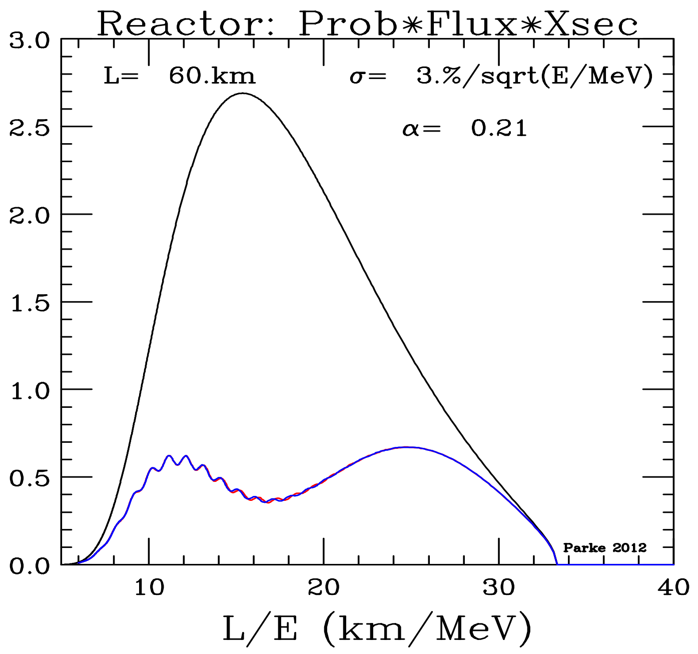
Hierarchy earlier ?

2) LBL Reactor neutrinos

$$P_{\nu_e\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}L}{2}\right) - c_{12}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{31}L}{2}\right) - s_{12}^2 \sin^2 \theta_{13} \sin^2\left(\frac{\Delta_{32}L}{2}\right)$$

$|\Delta_{32}| < |\Delta_{31}|$ NH

$|\Delta_{32}| > |\Delta_{31}|$ IH



Parke

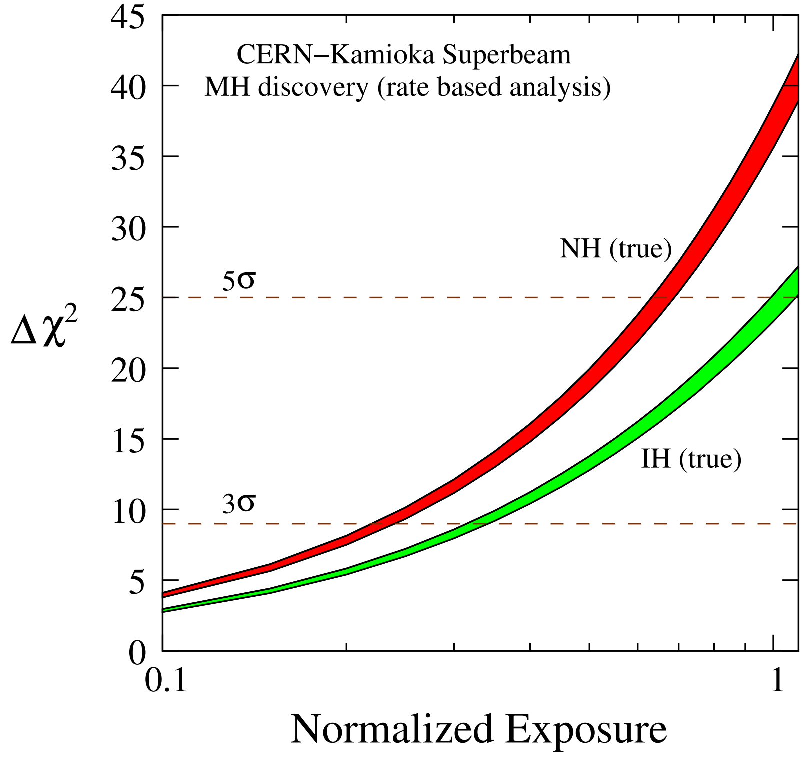
Extremely challenging: 20kton, 2-3% energy resolution, 1% linearity in energy scale, error on $|\Delta m^2_{23}$

Qian, Dwyer, McKeown, Vogel, Wang, Zhang arXiv:1208.1551

Hierarchy is very easy for a sufficiently long baseline conventional beam even with existing detectors !

One example:

4.5y of LBNO beam



Agarwalla, PH