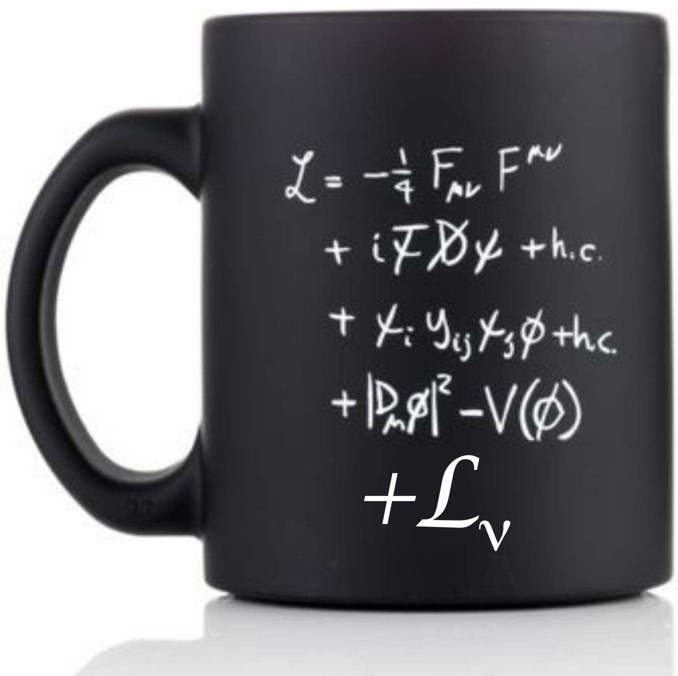
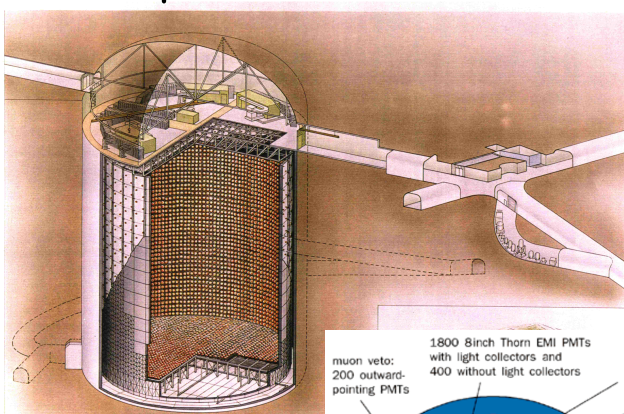
Towards a standard model with massive neutrinos

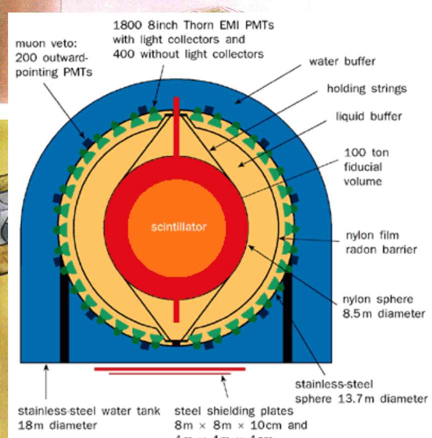
Pilar Hernández
CERN & University of Valencia/IFIC

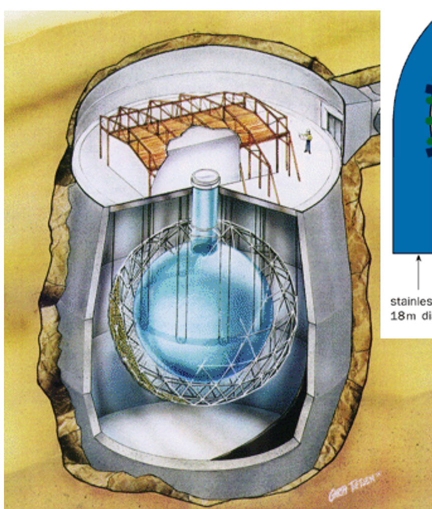


Two decades of revolutionary neutrino experiments have revealed a new flavour sector, which does not quite fit in the Standard Model

SuperKamiokande



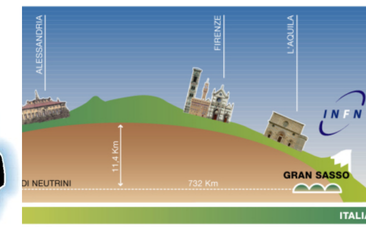




SNO

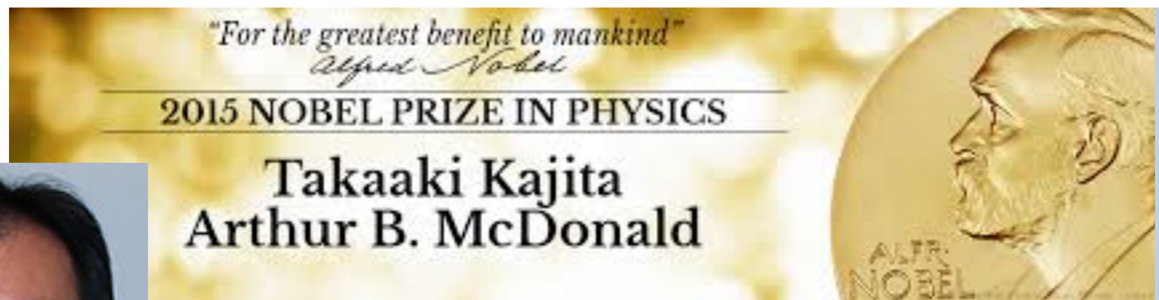
Borexino

MINOS, Opera



...and more

"For the discovery of neutrino oscillations,
which shows that neutrinos have mass"

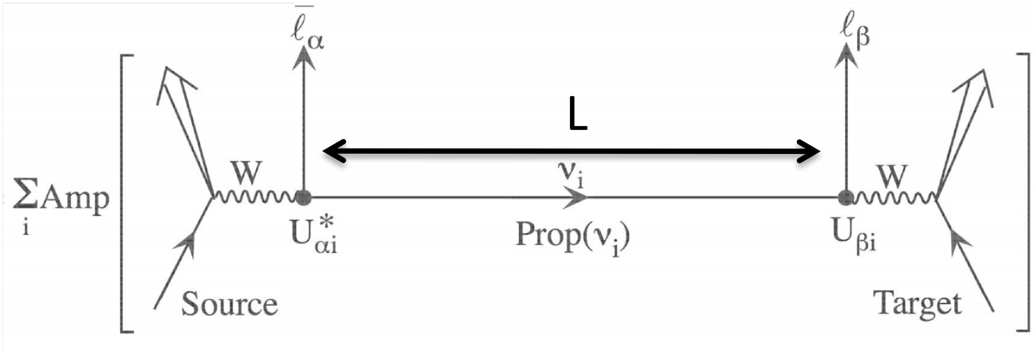


Neutrino Mixing

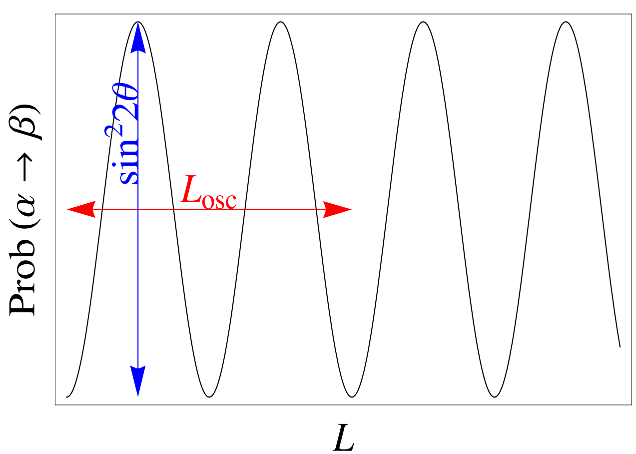
Mass eigenstates ≠ flavour eigenstates

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

Neutrino Interferometry



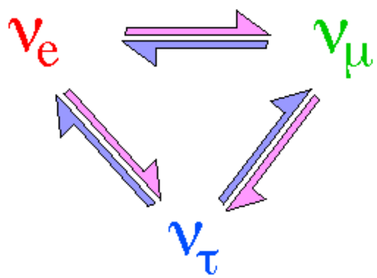
A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances !



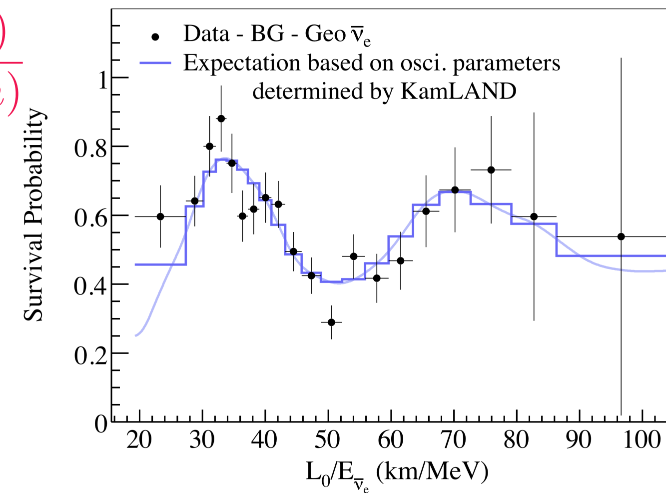
$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i \frac{(m_i^2 - m_j^2) L}{2E}}$$

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

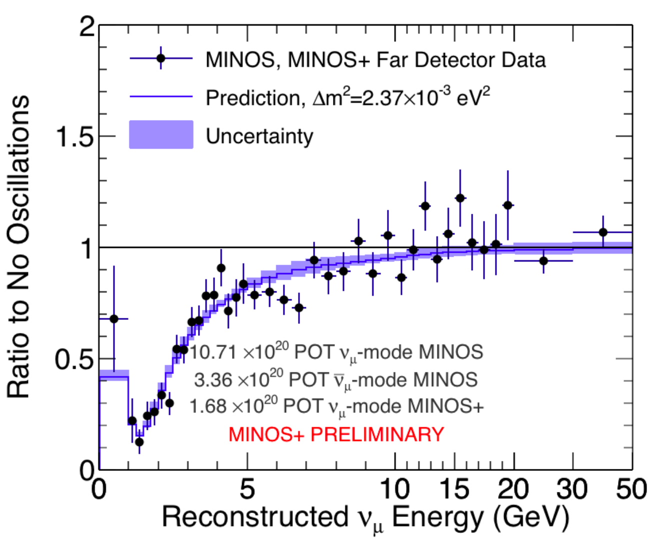
Two frecuencies precisely measured

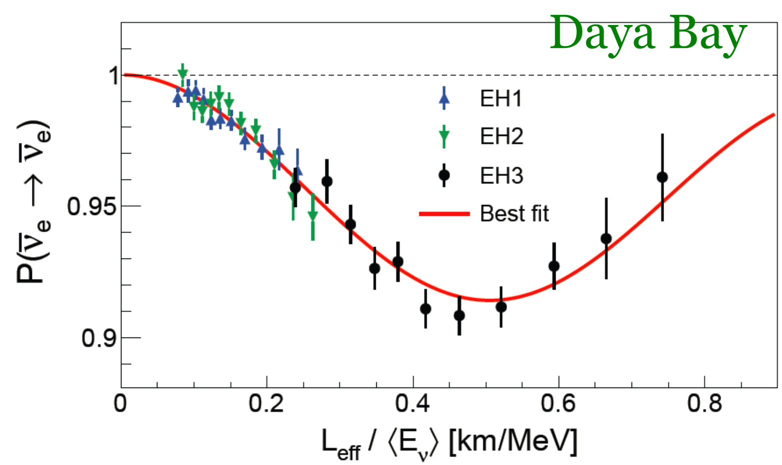


$$\Delta m^2_{\rm sol} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(100km)}$$



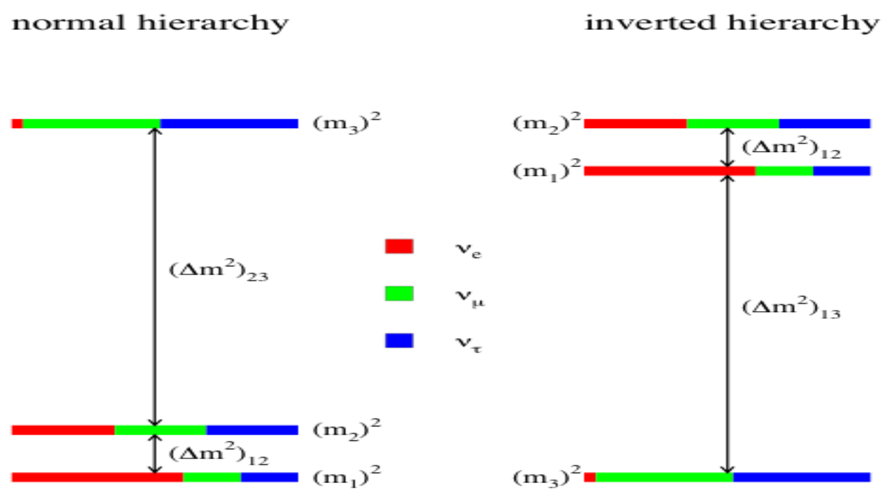
$$|\Delta m^2_{\rm atm}| \sim \frac{\mathcal{O}(GeV)}{\mathcal{O}(1000km)} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1km)}$$





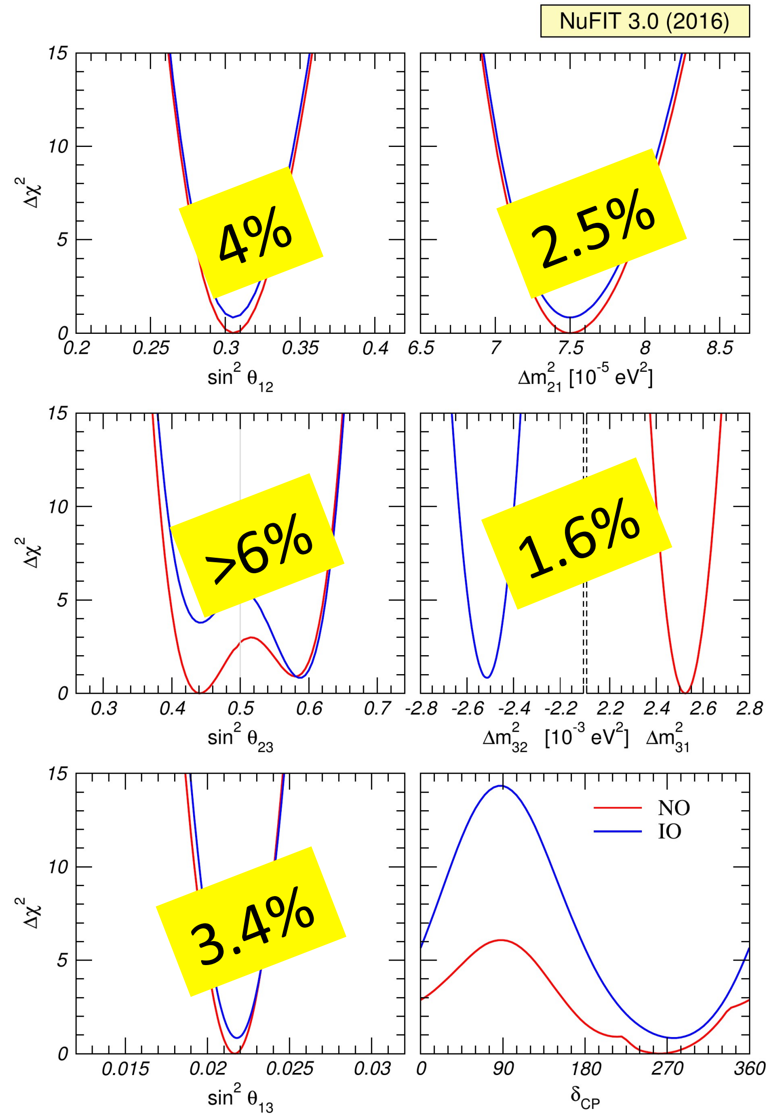
SM+3 massive neutrinos: Global Fits

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



?

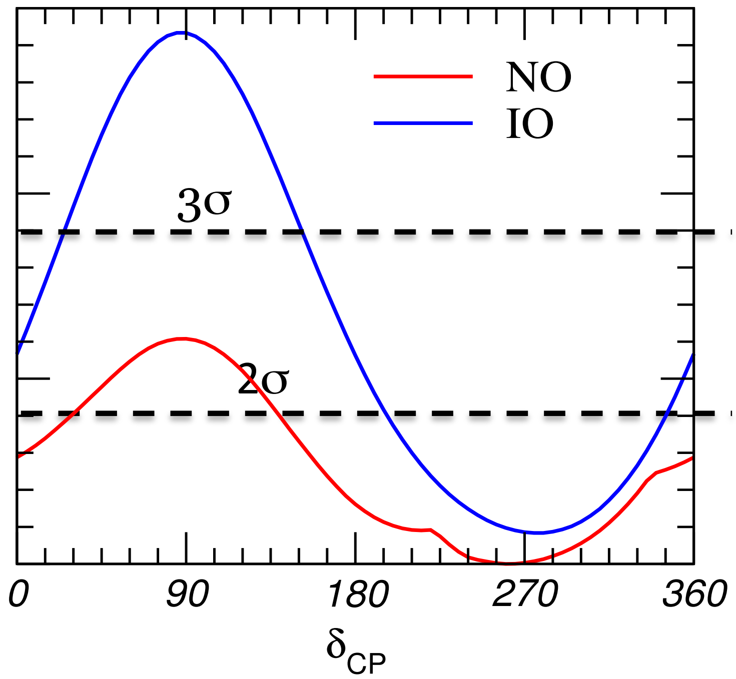
$\Delta m^2_{13} > 0$ $\Delta m^2_{13} < 0$



Gonzalez-Garcia et al

See also Capozzi et al, & Forero et al

Leptonic CP violation

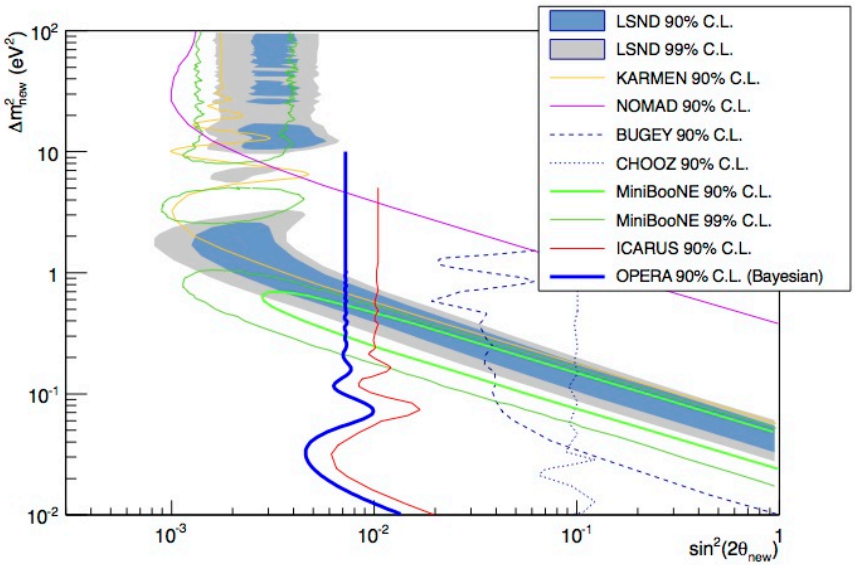


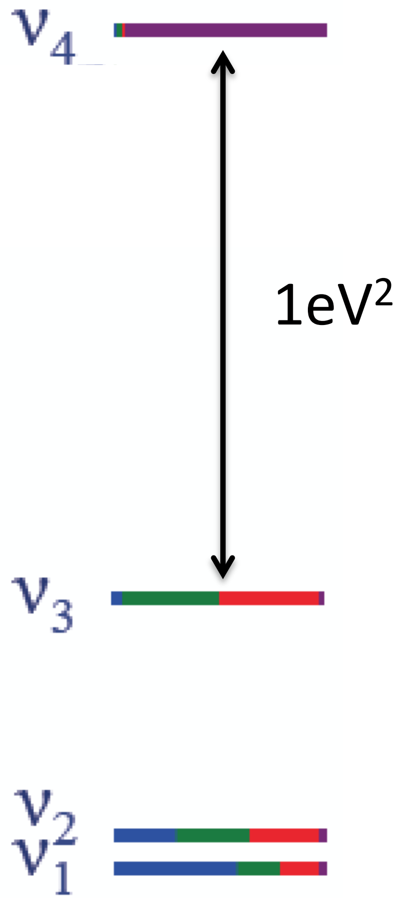
Preference for δ> 180° driven mostly by combination of reactor/T2K, atmospheric add positively

Outliers: SBL anomalies

LSND

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



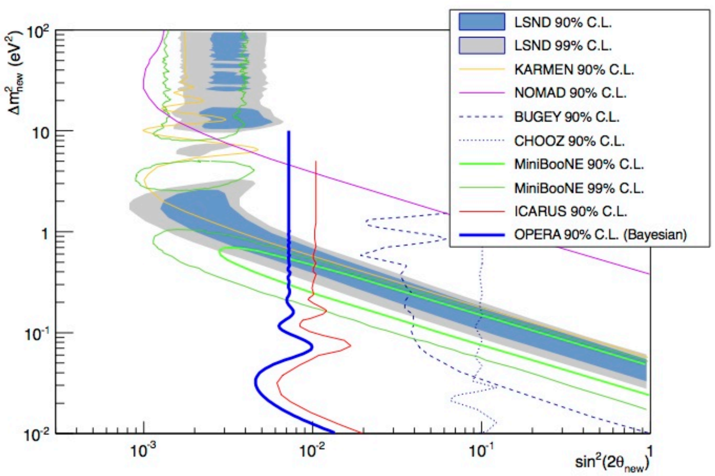


+Gallium anomaly+ MiniBOONE low-energy excess…

Outliers: SBL anomalies

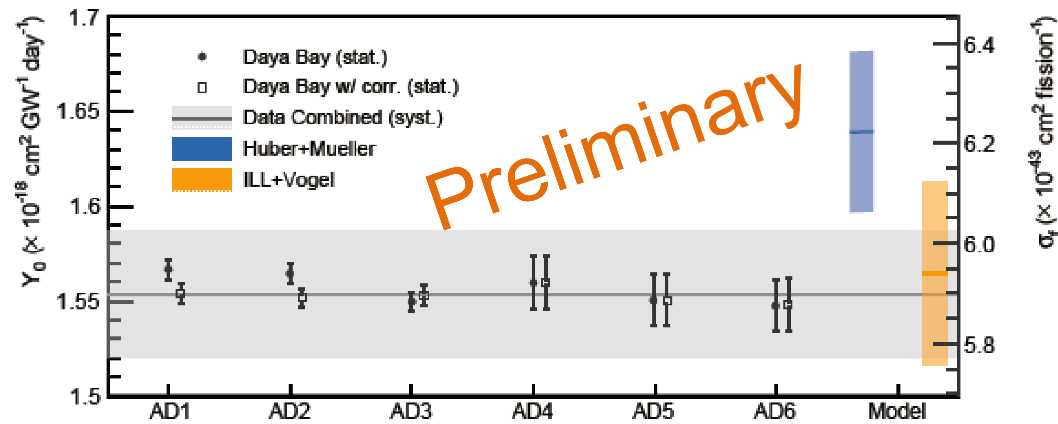
LSND

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



Reactors

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



T. A. Mueller et al; P. Huber

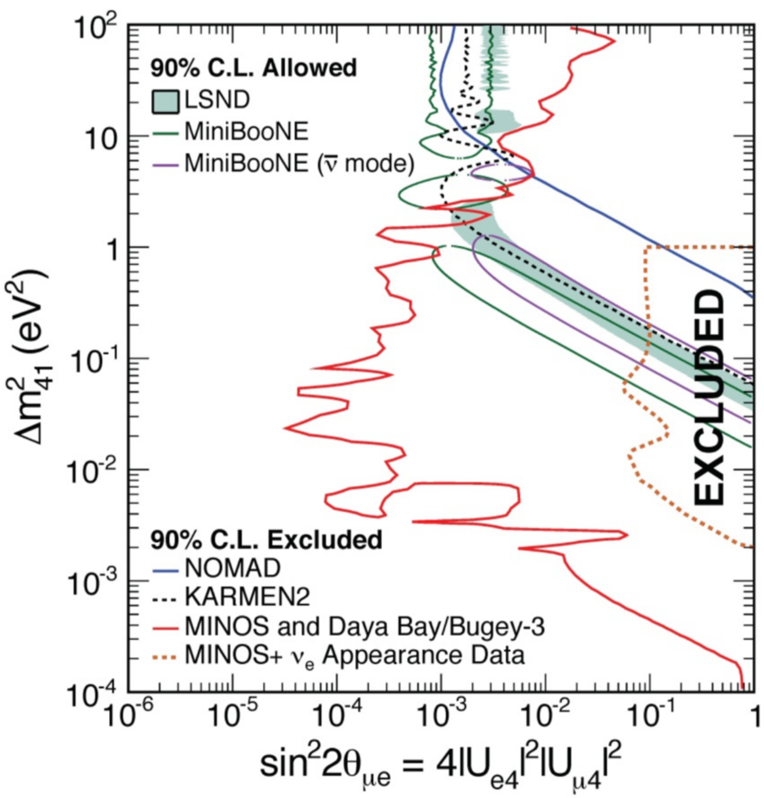
+Gallium anomaly+ MiniBOONE low-energy excess…

O(eV) sterile neutrinos ?

Two other necessary conditions have not been found

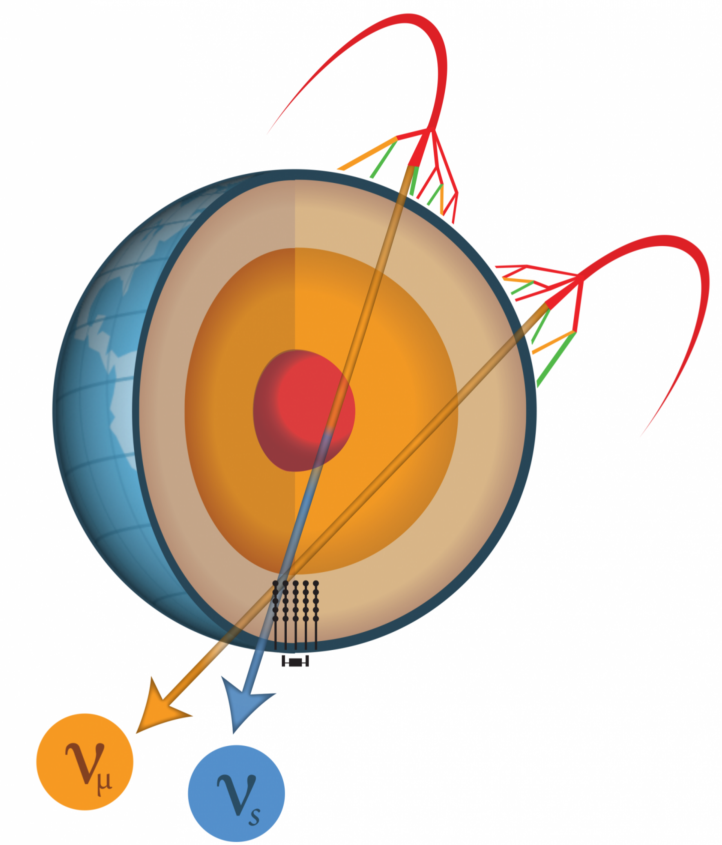
Neutrino muons must disappear also $P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu i}|^2)$

MINOS+Daya Bay

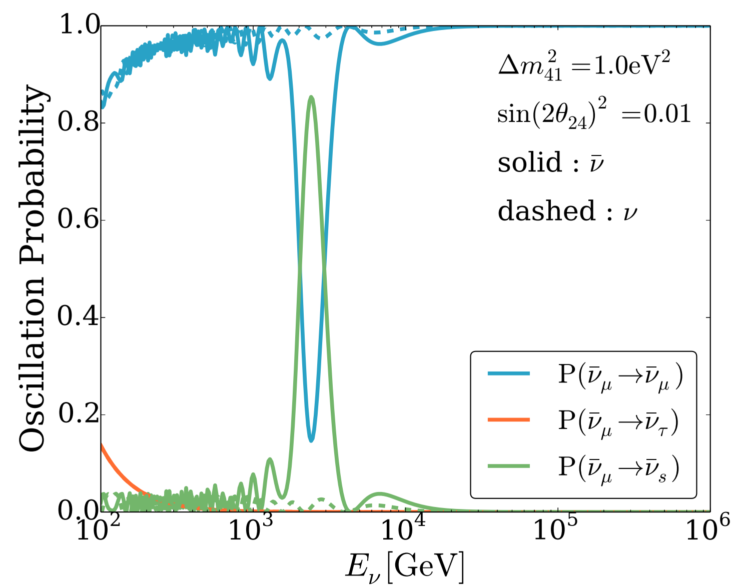


O(eV) sterile neutrinos?

TeV atmospheric neutrinos must resonate into steriles when crossing the nucleus of the Earth

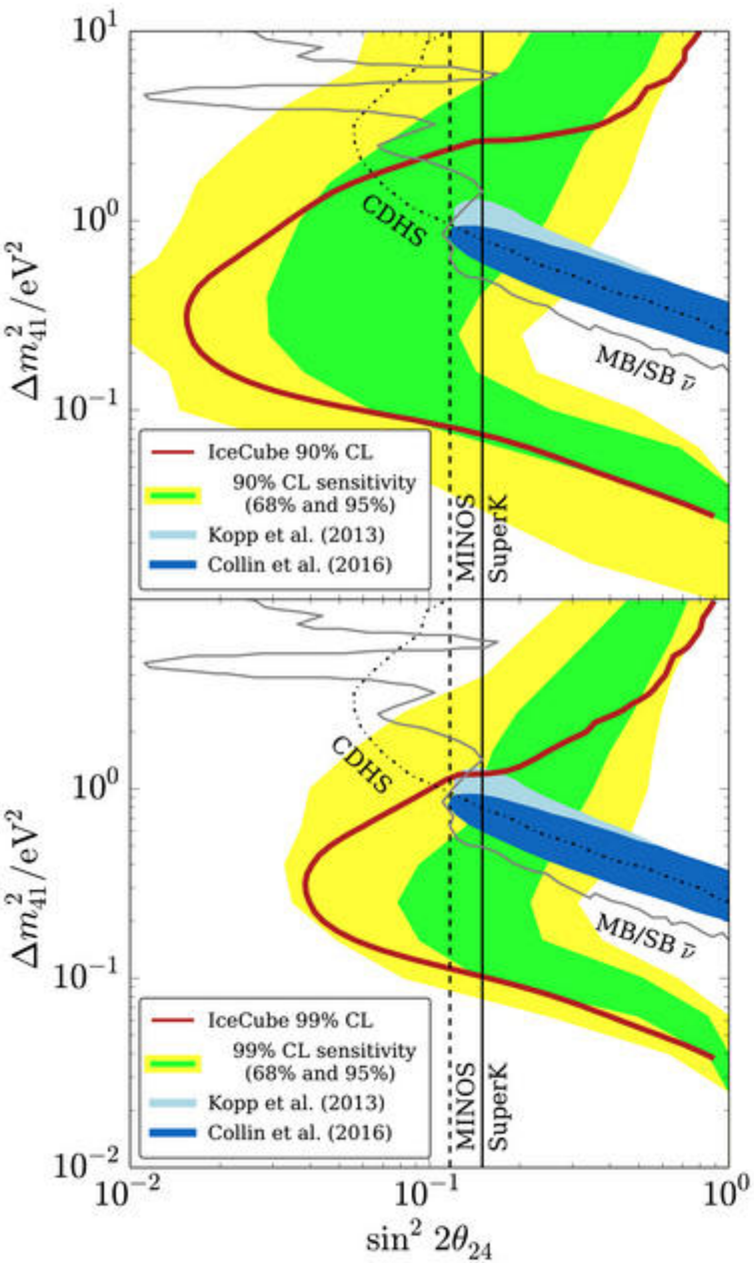


$$E_\nu^{\rm res} \equiv \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N_e} \sim \mathcal{O}(TeV)$$



Chizhov, Petcov; Nunokawa et al; Barger et al; Esmaili et al;

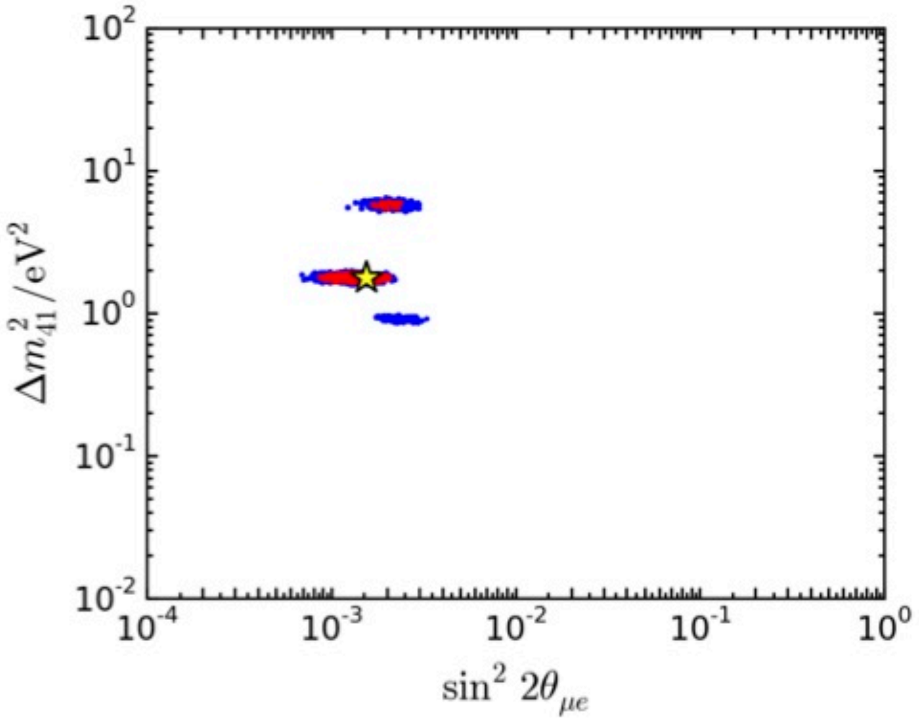
O(eV) sterile neutrinos ?



IceCube coll. '16

O(eV) sterile neutrinos ?

Getting squeezed into inexistence...

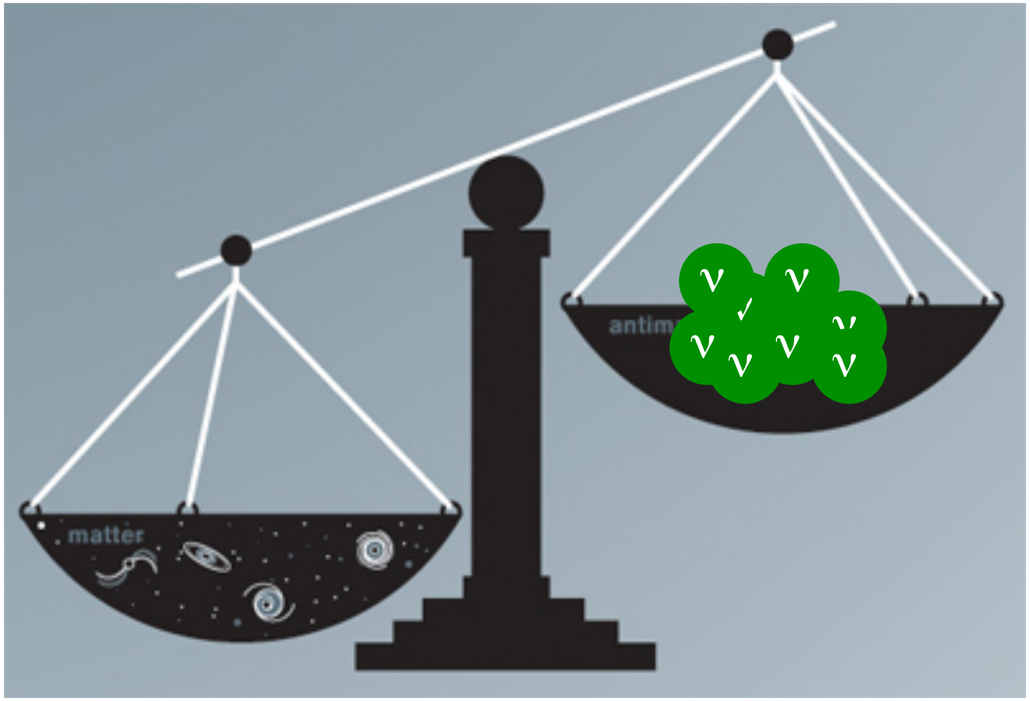


Collin, Argüelles, Conrad, Shaevitz '16

Probably a rather bad fit to all data...

Absolute mass scale

Best constraints at present from cosmology



Neutrinos as light as 0.1-1eV modify the large scale structure and CMB

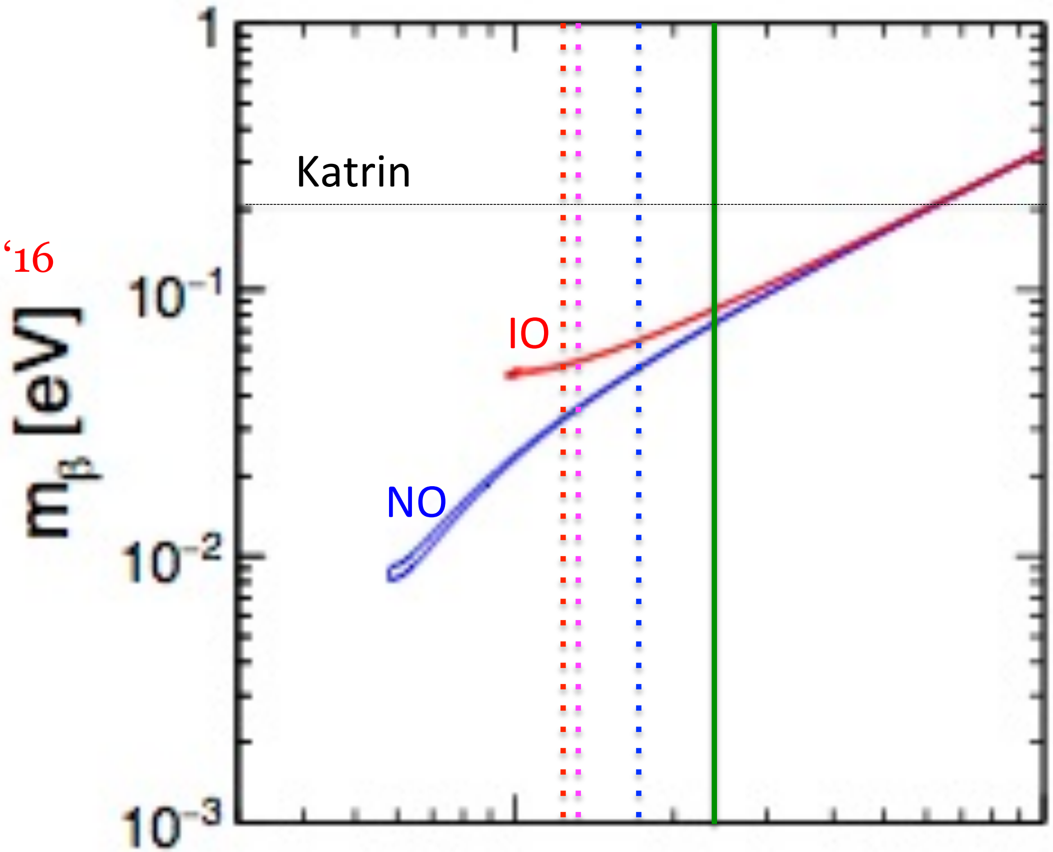
Absolute mass scale

Planck ‘15

Giusarma et al ‘16

Palanque-Delabrouille et al ‘16

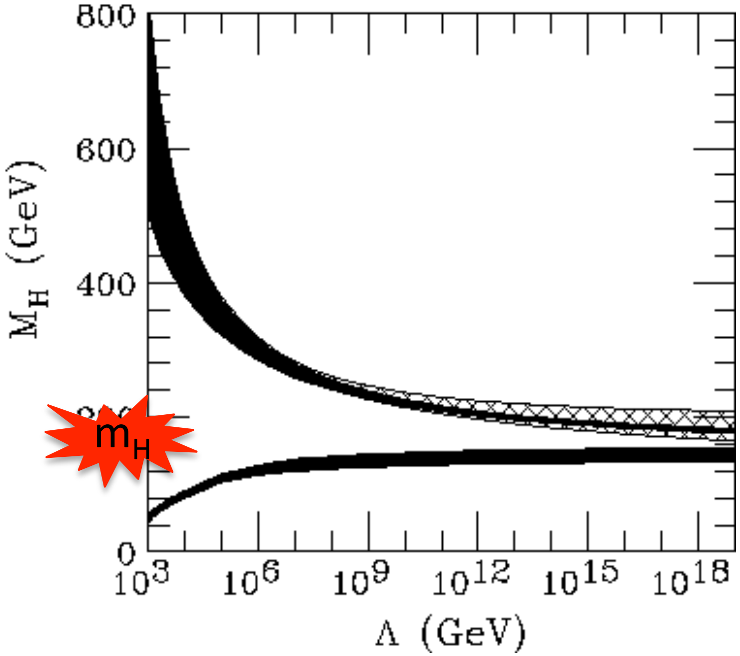
Cuesta et al ‘16



$$\sum m_\nu$$

After the discovery of the Brout-Englert-Higgs particle

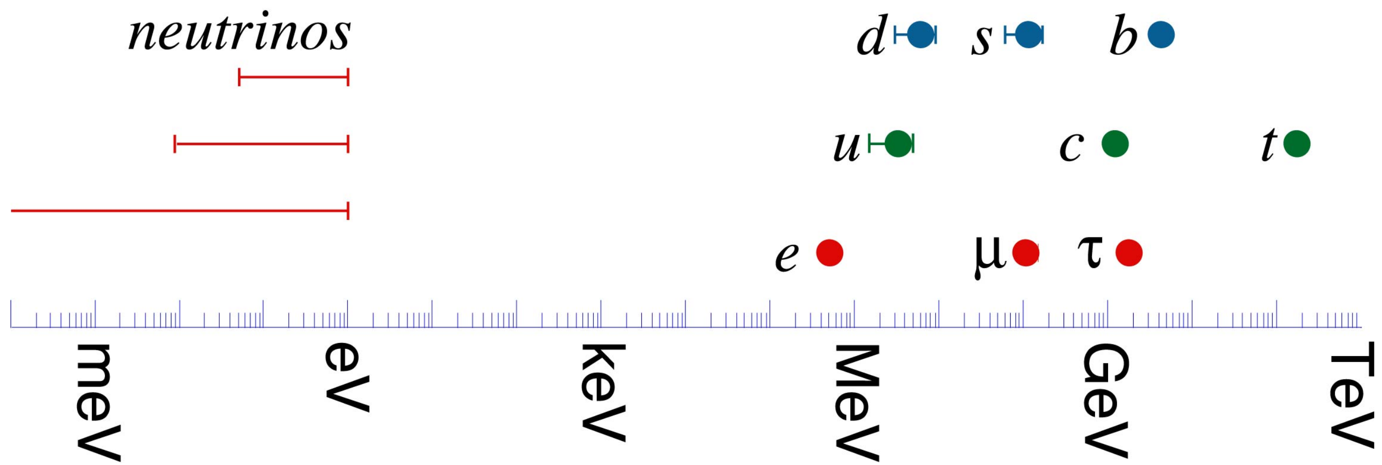
The Standard Model is healthy as far as we can see…



Health up to huge scales strongly suggests:

minimality as guiding principle in BSM

A new flavour perspective



How do we give neutrinos a mass ? Why are neutrinos so much lighter ?

Why do they mix so differently ?

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 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

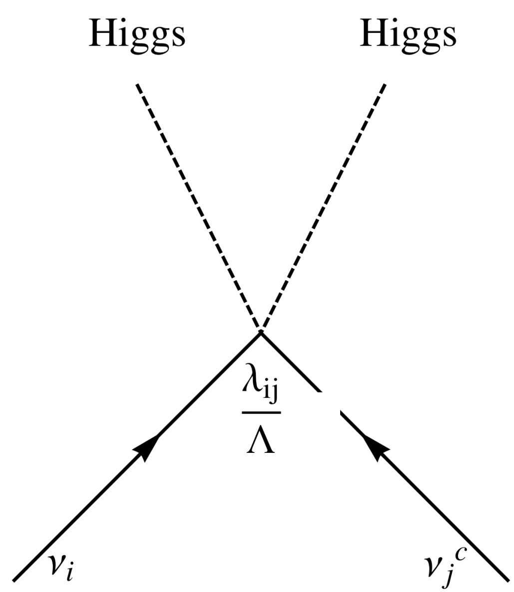
A new physics scale ?

Neutrinos are different...they can have majorana masses:

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

Weinberg

$$[\alpha] = -1$$

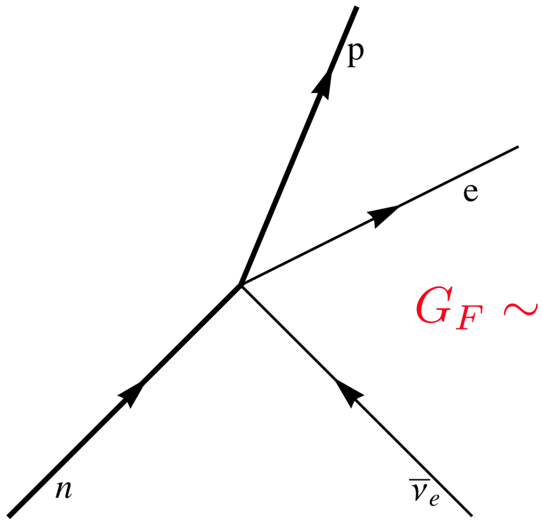


$$m_\nu = \lambda \frac{v^2}{\Lambda}$$

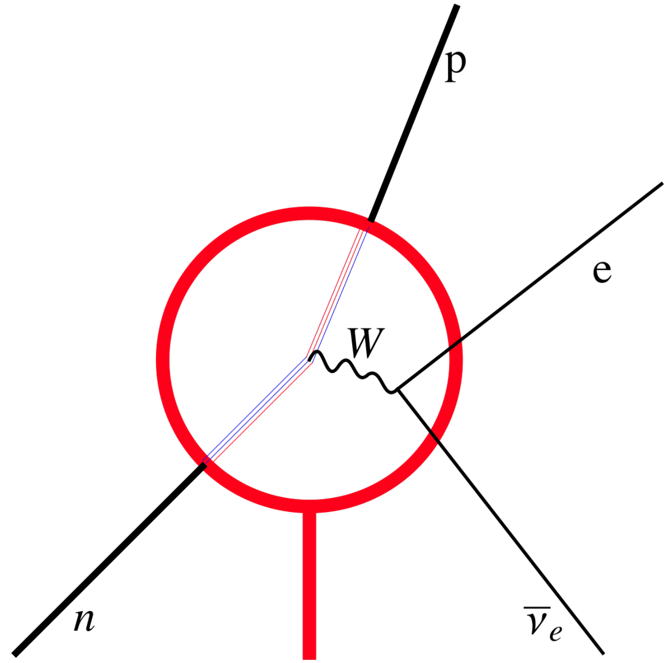
$$\alpha = \frac{\lambda}{\Lambda}$$

Scale at which new particles will show up

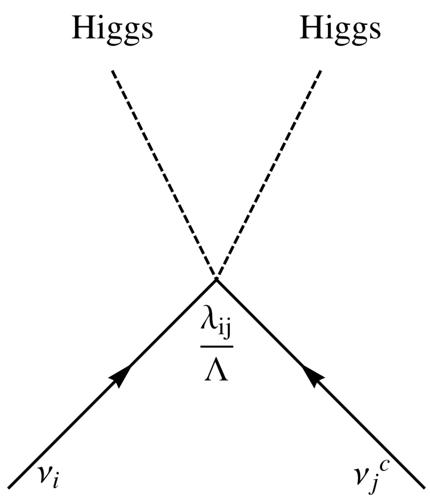
Fermi-era of neutrino physics



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



SM

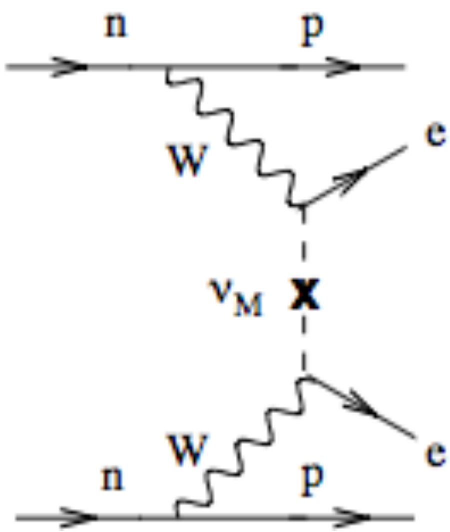


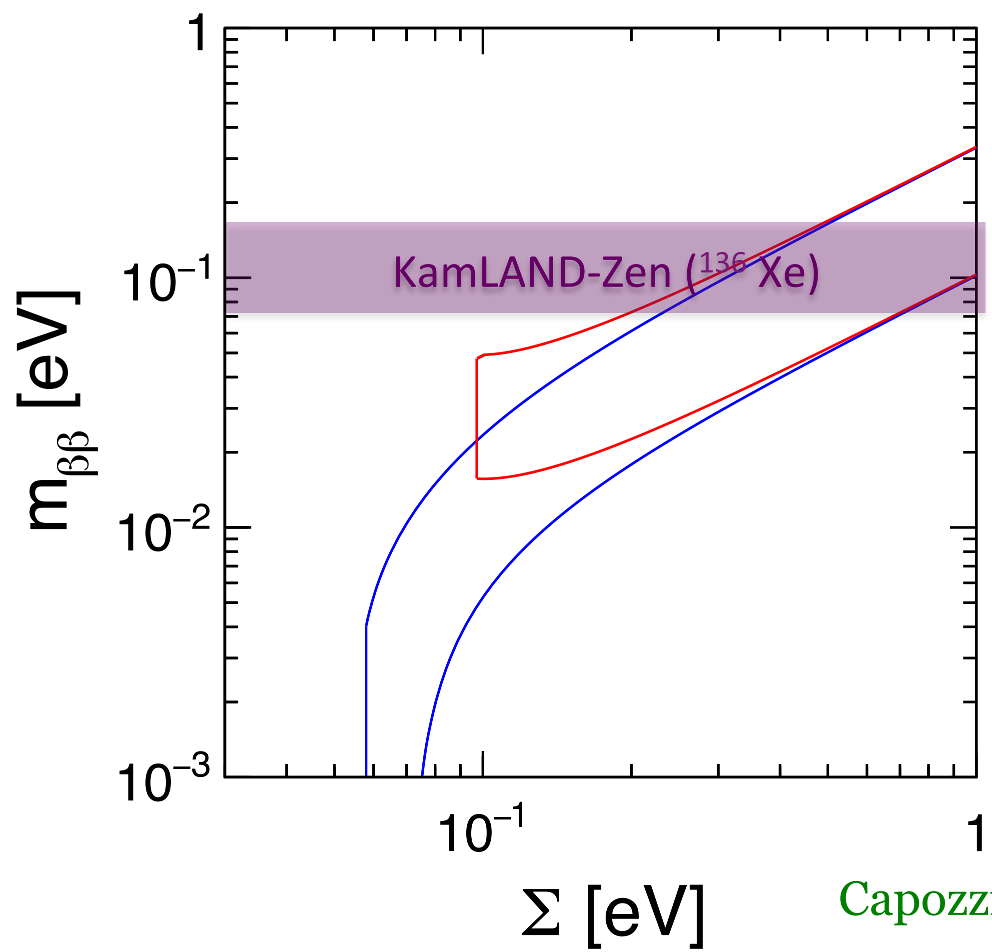
νSM ?

Neutrinoless ββ decay: Majorana nature ?

Λ > 100 MeV

$$m_{\beta\beta} = \sum_{i=1}^{3} \left[(U_{PMNS})_{ei} \right]^2 m_i$$





Capozzi et al '16

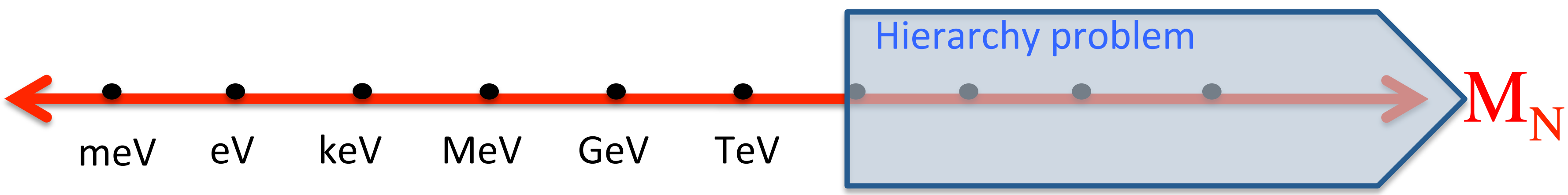
What originates Weinberg's operator?

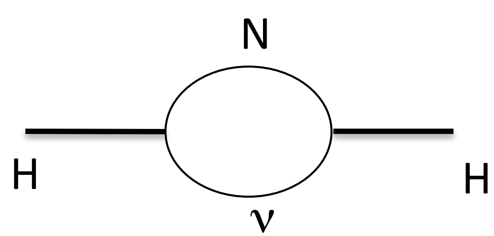
Could be $\Lambda >> v$... the standard lore (theoretical prejudice ?)

$$\left.\begin{array}{l} \Lambda = M_{\rm GUT} \\ \lambda \sim \mathcal{O}(1) \end{array}\right\} \quad m_\nu \ \checkmark$$

To avoid fine-tunning

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





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

Vissani

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

What originates Weinberg's operator?

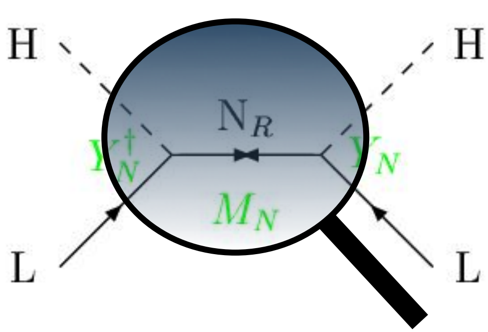
- sensitivity to neutrino masses comes from very low-energy processes: Weinberg's operator description OK for neutrino masses even if $\Lambda < v$...

- λ in front of Weinberg operator might be naturally different to SM Yukawa couplings

Resolving Weinberg's operator at tree level

E. Ma

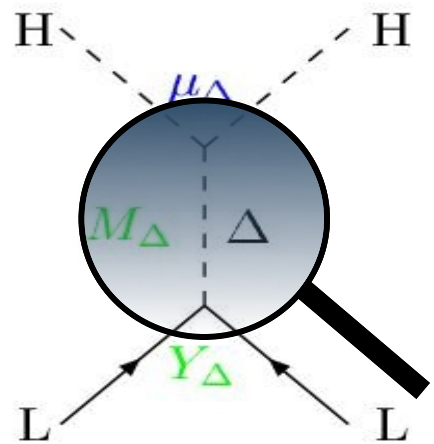
Type I see-saw:
a heavy singlet scalar



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

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

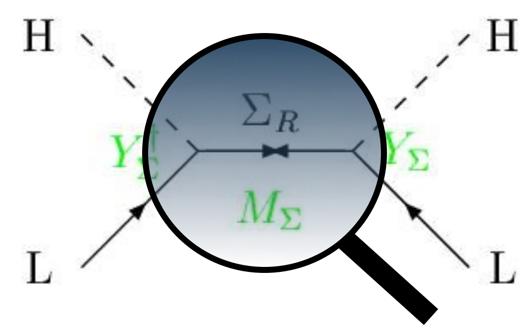
Type II see-saw:
a heavy triplet scalar



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

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

Type III see-saw:
a heavy triplet fermion

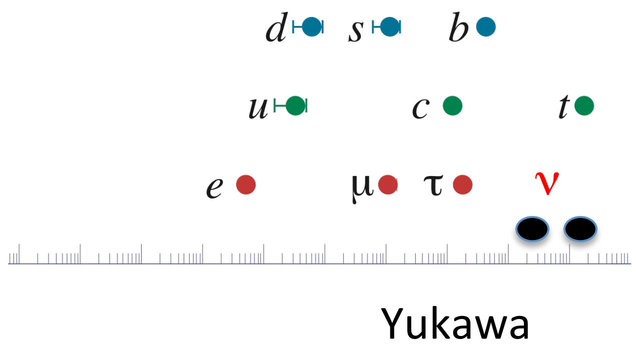


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

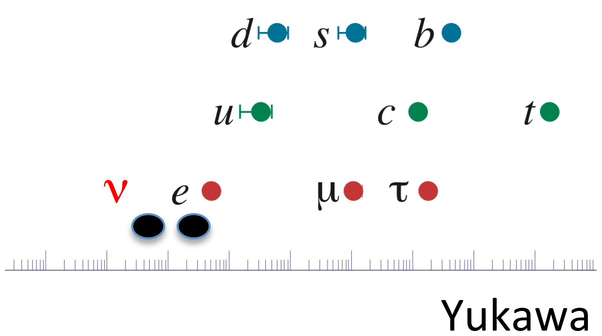
Foot et al; Ma;
Bajc, Senjanovic...

Pinning down the new physics scale: naturalness

M ≤ GUT

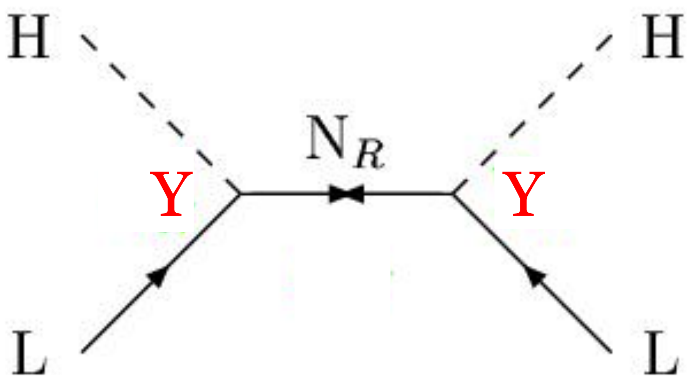


M = TeV

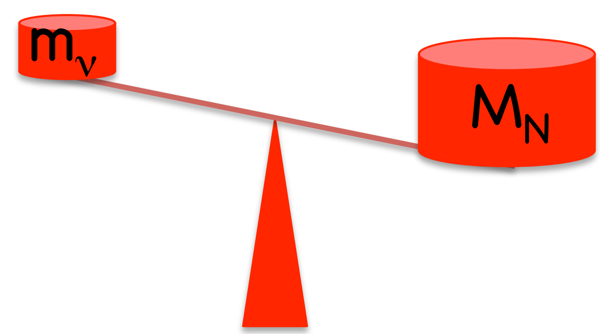


Minimality: SM+right-handed neutrinos

$$\mathcal{L}_\nu = -\bar{l} Y \tilde{\Phi} N_R - \frac{1}{2} \bar{N}_R M N_R + h.c.$$



$$n_R \geq 2$$

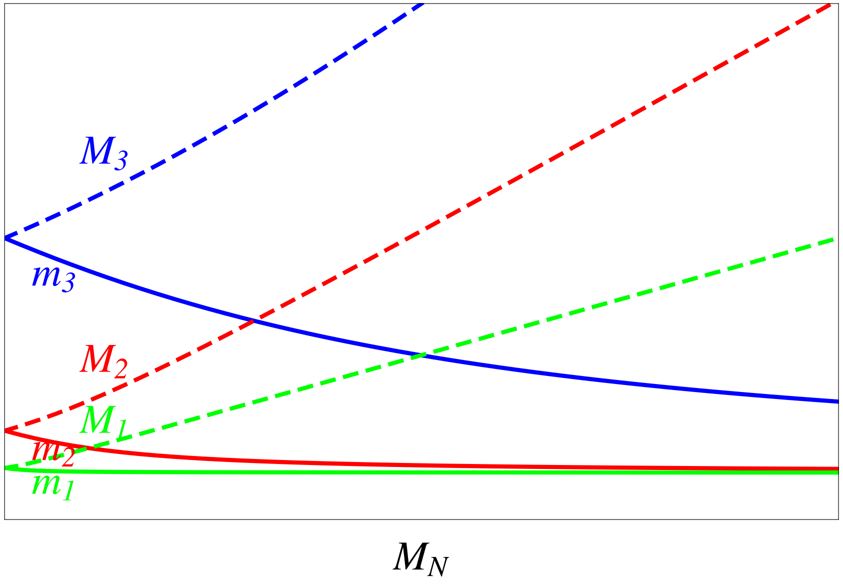


$$m_\nu = \lambda \frac{v^2}{\Lambda} \equiv Y^T \frac{v^2}{M} Y$$

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

Type I seesaw models

$n_R = 3$: 18 free parameters (6 masses+6 angles+6 phases) out of which we have measured 2 masses and 3 angles...

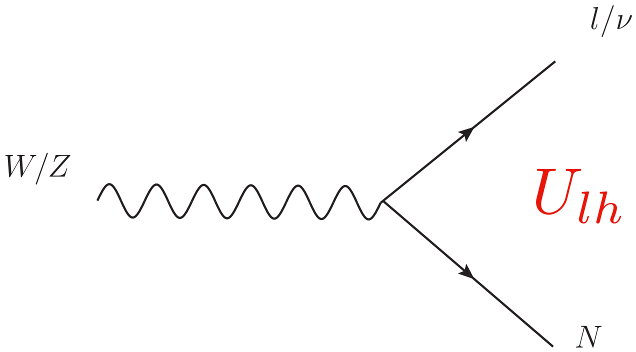


Type I seesaw models

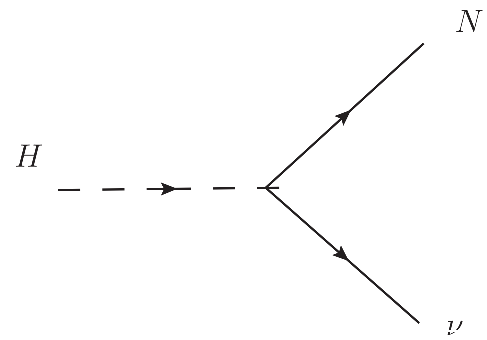
Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{ll} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} + U_{lh} \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

Type I seesaw models



U_{lh}



$U_{lh}\frac{\sqrt{2}M_h}{v}$

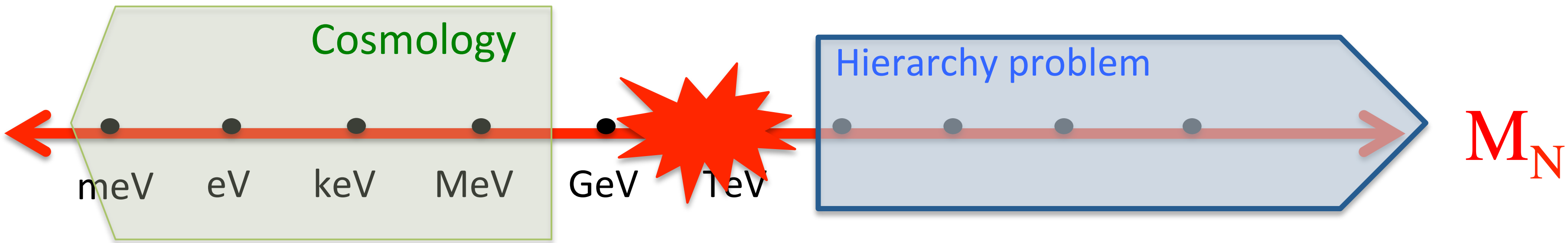
$$U_{lh} \simeq iU_{\rm PMNS}\sqrt{m_l}R\frac{1}{\sqrt{M_h}}$$

Casas-Ibarra

R: general orthogonal complex matrix (contains all the parameters we cannot measure in neutrino experiments)

Strong correlation between active-heavy mixing and neutrino masses, but the naive scaling ($|U_{lh}|^2 \sim m_l/M_h$) too naive...

Pinning down the New physics scale



Sterile neutrinos below 100MeV can strongly modify

Big-Bang Nucleosynthesis
Cosmic Microwave background
Large Scale structure

Notzold, Raffelt; Barbieri&Dolgov; Kainulainen....;
Dolgov, Hansen, Raffelt,Semikoz;
Ruchayskiy, Ivashko;Vincent et al;

Either they contribute too much radiation or too much matter, modifying in unacceptable ways the expansion history and/or growth of perturbations

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:

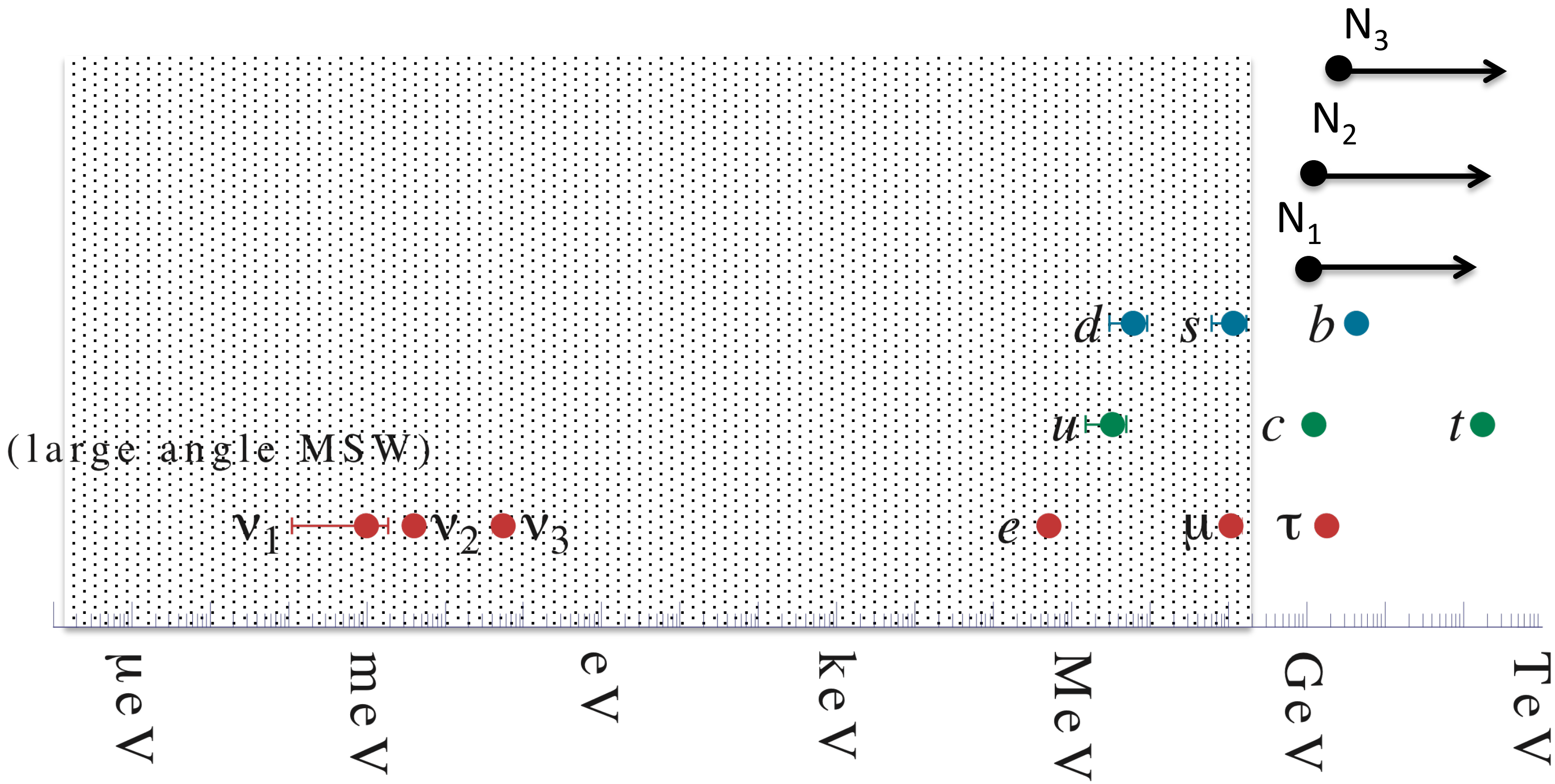
$$\frac{\Gamma_{s_i}(T)}{H(T)} \geq 1$$

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

independent of M ?

Seesaw scale vs cosmology

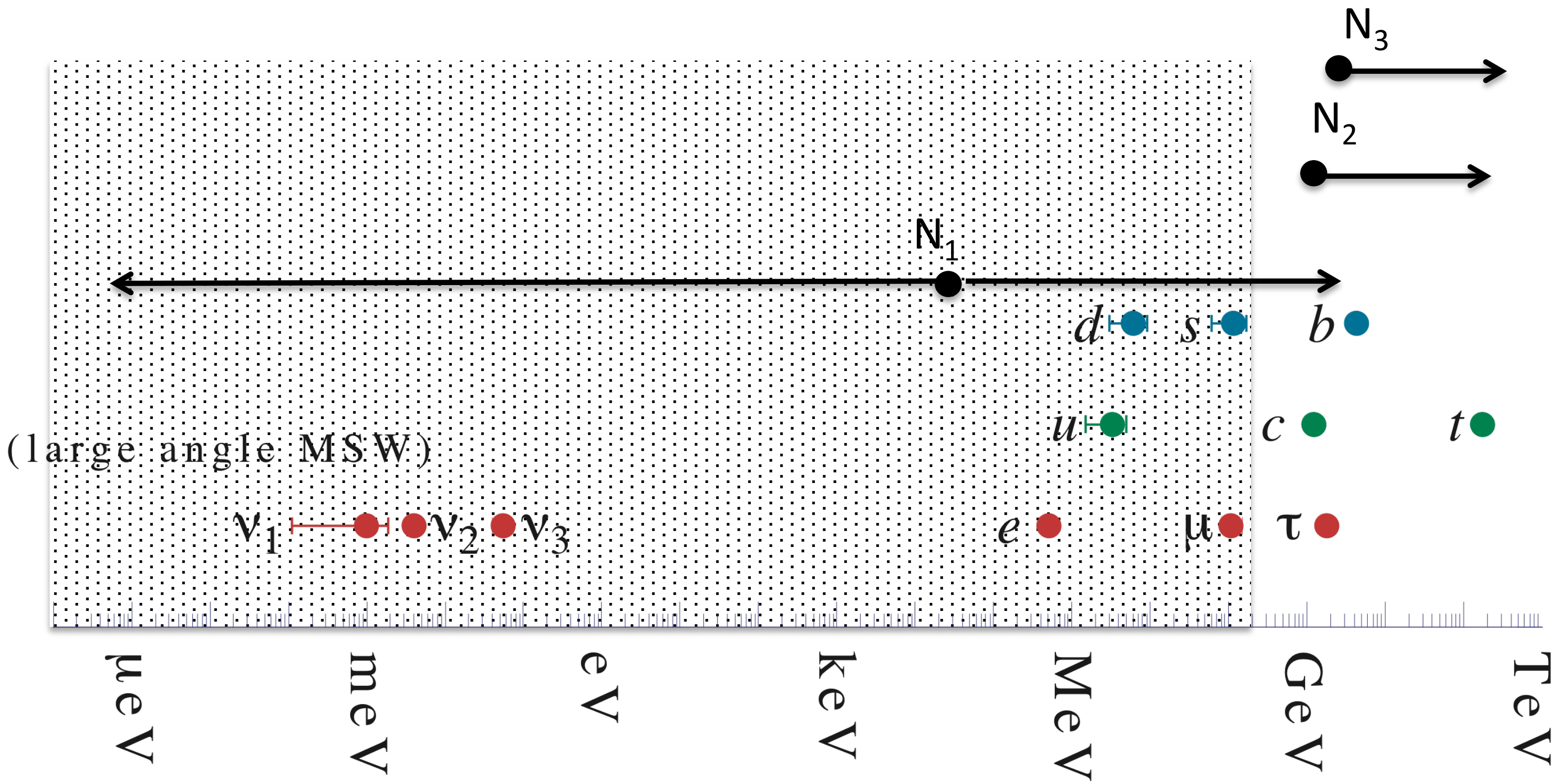
Type I seesaw N =3 that explains neutrino masses



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

PH, M. Kekic, J. López-Pavon

Type I seesaw N =3 that explains neutrino masses

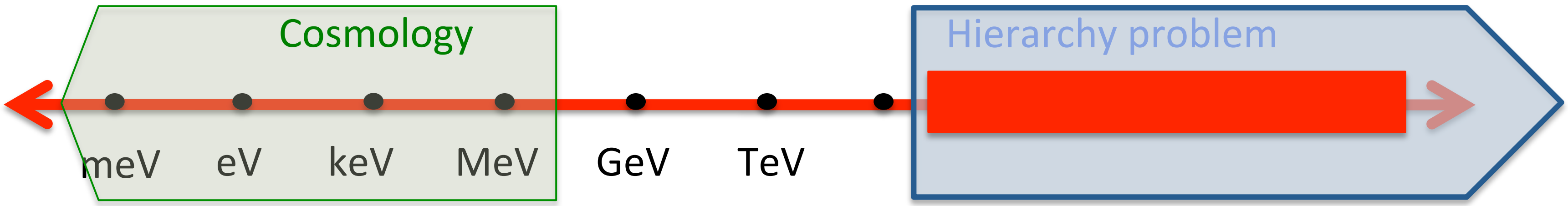


$m_{lightest} < 3.2 \times 10^{-3}$ eV

PH, M. Kekic, J. López-Pavon

M_1 = O(keV) WDM candidate! νMSM Shaposhnikov et al

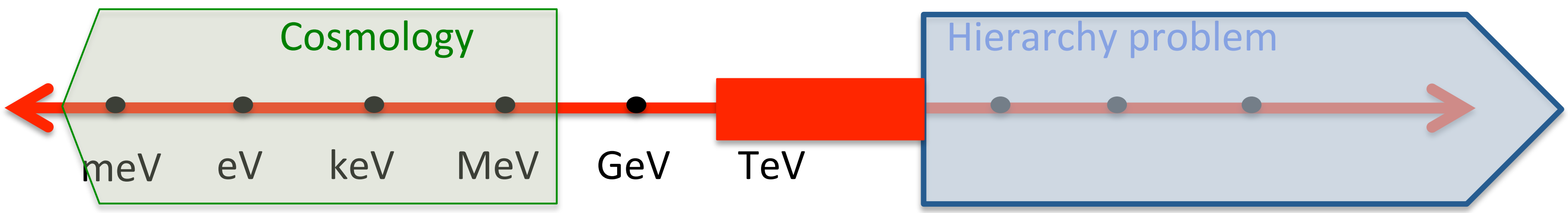
Leptogenesis



Standard leptogenesis in out-of-equlibrium decay M> 10^7GeV

Fukuyita,Yanagida;....

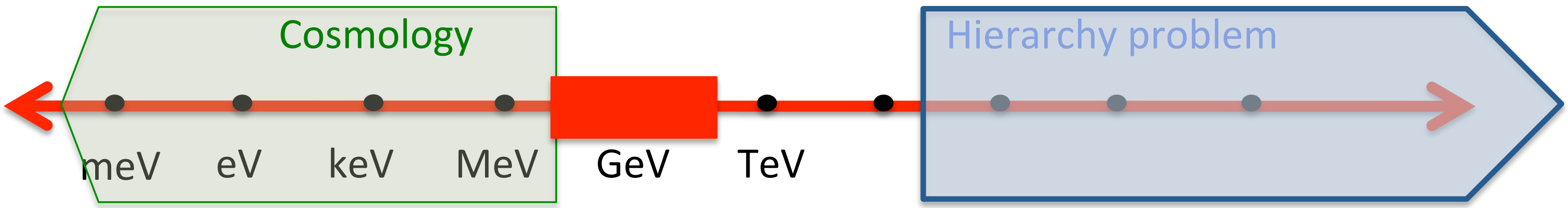
Leptogenesis



Resonant leptogenesis M>100 GeV

Pilaftsis…

Leptogenesis



Leptogenesis from neutrino oscillations
0.1GeV <M < 100GeV

Akhmedov, Rubakov, Smirnov

Sakharov conditions

✔ CP violation (up to 6 new CP phases in the lepton sector)

$$Y = V^\dagger \mathrm{Diag}(y_1, y_2, y_3) W$$

(V, W: 3 phases each)

Sakharov conditions

✔ CP violation (up to 6 new CP phases in the lepton sector)

$$Y = U^*_{\mathrm{PMNS}} \sqrt{m_\nu} R \sqrt{M_h} \frac{\sqrt{2}}{v}$$

Casas-Ibarra

(R: 3 complex angles + U_{PMNS}: 3 phases)

Sakharov conditions

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✔ B+L violation from sphalerons T > T_{EW}

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✔ B+L violation from sphalerons T > T_{EW}

$$\not{L}_\alpha \oplus \not{B}+\not{L}$$

(in contrast with standard leptogenesis in the decay of the heavy states:
the violation of L from Majorana masses is not relevant M/T << 1)

Sakharov conditions

✔ CP violation (up to 6 new CP phases in the lepton sector)

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Casas-Ibarra

(R: 3 complex angles + $U_{\rm PMNS}$: 3 phases)

✔ B+L violation from sphalerons T > $T_{\rm EW}$

$$\not{L}_\alpha \oplus \not{B}+\not{L}$$

(in contrast with standard leptogenesis in the decay of the heavy states: the violation of L from Majorana masses is not relevant M/T << 1)

✔ Out of equilibrium: some states have not reached equilibration at $T_{\rm EW}$

ARS Leptogenesis

Akhmedov, Rubakov,Smirnov

$$\Gamma_s(T) \sim y^2 T \sim \frac{M_N m_\nu}{v^2} T \qquad H(T) = \sqrt{\frac{4\pi^3 g_*(T)}{45}} \frac{T^2}{M_P}$$

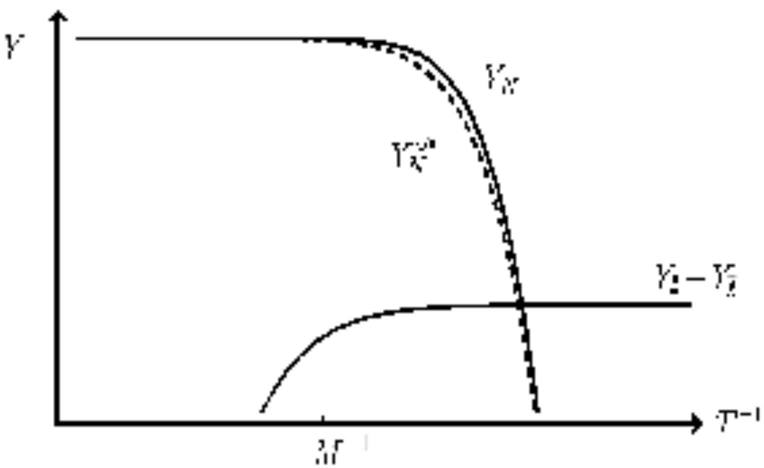
$$\frac{\Gamma_s(T_{EW})}{H(T_{EW})} \sim 5 \left(\frac{M}{1\mathrm{GeV}} \right) \left(\frac{m_\nu}{0.05\mathrm{eV}} \right)$$

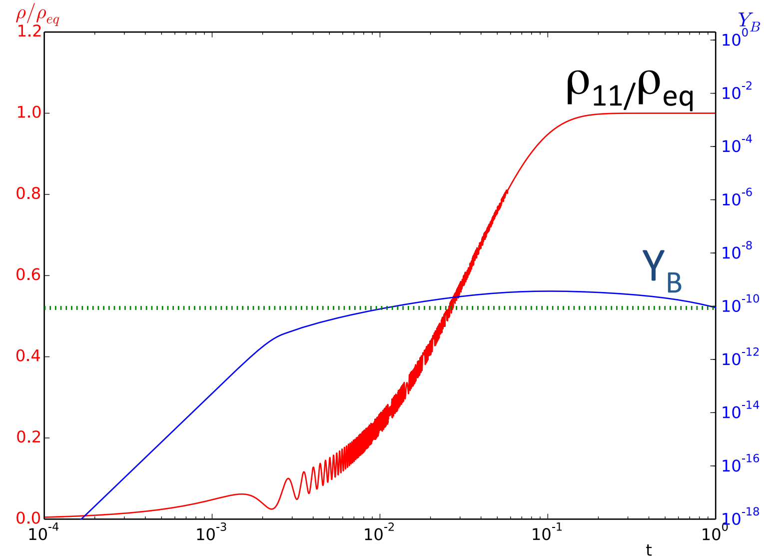
$y_3 << y_1, y_2$

CP asymmetries arise in production of sterile states via the interference of CP-odd phases and CP-even phases from oscillations

High-scale leptogenesis

Low-scale leptogenesis





T_{EW}

Courtesy of M. Kekic

Low-scale Leptogenesis

Asaka, Shaposhnikov;Shaposhnikov;Asaka, Eijima, Ishida;Canetti, Drewes, Frossard, Shaposhnikov; Drewes, Garbrecht;Shuve, Yavin;Abada, Arcadi, Domcke, Lucente; PH, Kekic, Lopez-Pavón,Racker, Rius

Raffelt-Sigl kinetic equations: quantum evolution of number density matrices of the sterile species:

$$\rho_{ss'}(\mathbf{p}) = \langle \hat{a}_s^\dagger(\mathbf{p},t)\hat{a}_{s'}(\mathbf{p},t)\rangle$$

M/T << 1

$$\frac{d\rho(k)}{dt} = -i \underbrace{[H, \rho(k)]}_{\text{oscillations}} \underbrace{-\frac{1}{2}\{\Gamma_N^a, \rho(k)\} + \frac{1}{2}\{\Gamma_N^p, 1-\rho(k)\}}_{\text{scatterings}}$$

$$H \equiv \frac{\Delta M^2}{2k_0} + V_N \qquad \Gamma_N^a/\Gamma_N^p \propto \mathcal{O}(Y^2)$$

annihilation/production

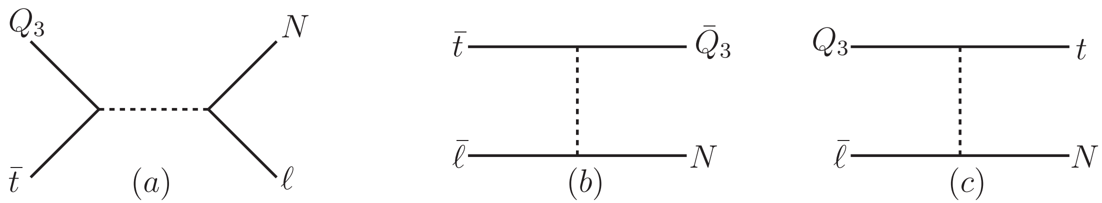
+eq. for $\bar{\rho}$ + evolution of $\mu_{B/3-L\alpha}$

Scattering rates

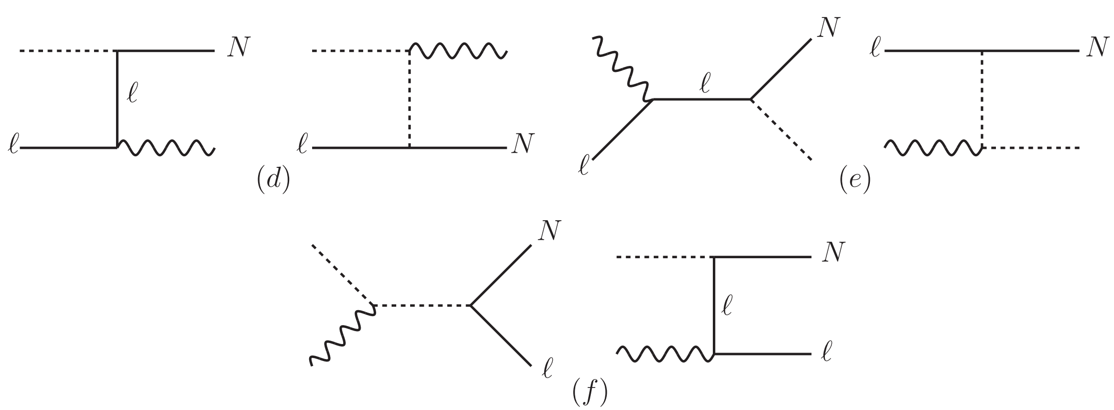
Include all the scattering processes that are believed to be relevant and have been computed

Besak, Bodeker, 1202.1288; Ghisoiu and M. Laine 1411.1765

top



gauge

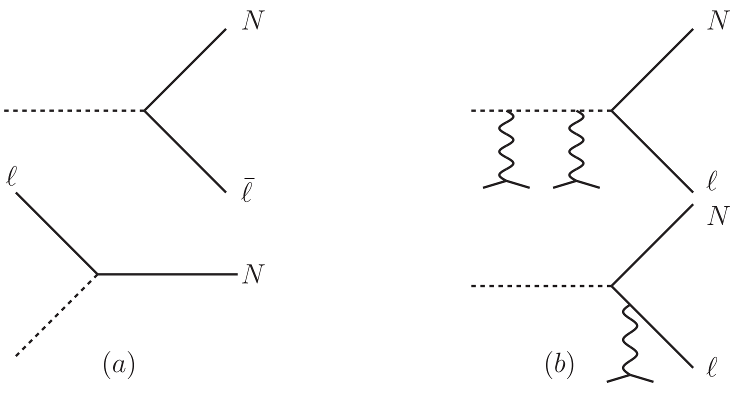


Scattering rates

Include all the scattering processes that are believed to be relevant and have been computed

Besak, Bodeker, 1202.1288; Ghisoiu and M. Laine 1411.1765

Decays+ID



Washouts: Re-evaluated in the presence of μ_α

PH, Kekic, Lopez-Pavon, Racker,Salvado ‘16

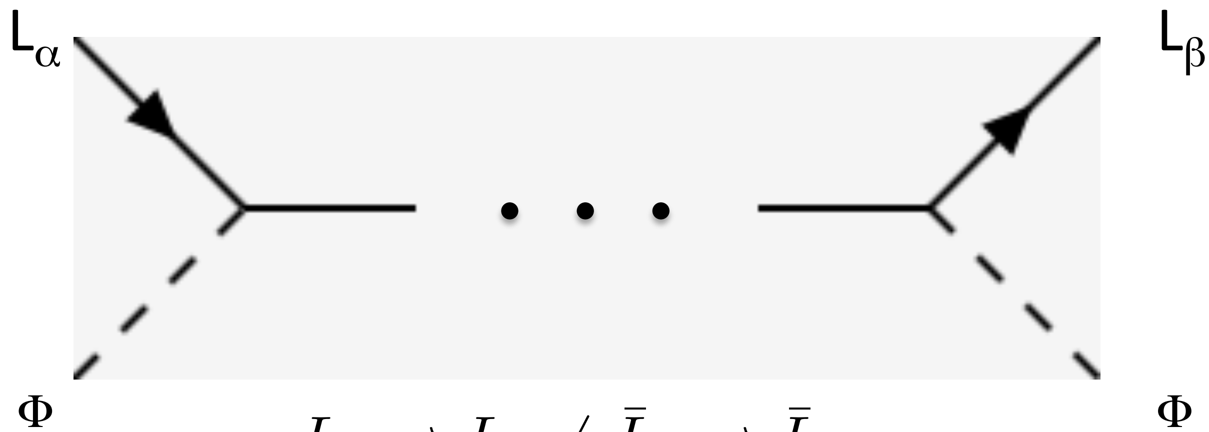
Two time scales relevant in evolution of asymmetries:

$$t_{\rm osc}(ij) \propto (\Delta M_{ij}^2 M_P^*)^{-1/3} \qquad\qquad t_{\rm eq}(\alpha) \propto (Y^2 M_P^*)^{-1}$$

Natural choices of parameters: $t_{\rm osc} \ll t_{\rm eq}(\alpha) \lesssim t_{\rm EW} < t_{\rm eq}(\beta)$

Stiff differential equations: hard to treat numerically...

CP asymmetries build up in different flavours though "oscillations":



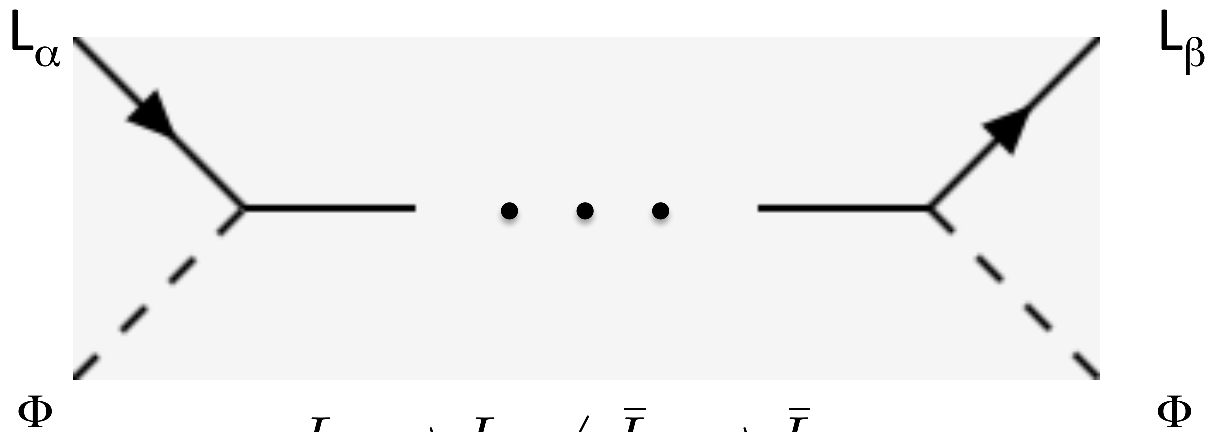
$$L_\alpha \to L_\beta \neq \bar{L}_\alpha \to \bar{L}_\beta$$

$$Y_B \propto \sum_\alpha \Delta^\alpha_{CP} \eta_\alpha \qquad \sum_\alpha \Delta^\alpha_{CP} = 0$$

$$t > t_{\rm osc}(ij): \;\; \Delta^\alpha_{CP} \propto \; {\rm Im}\Big((Y^\dagger Y)_{ji} Y^\dagger_{i\alpha} Y_{\alpha j}\Big)$$

$$\eta_\alpha \propto \frac{t}{t_{eq}(\alpha)}$$

CP asymmetries build up in different flavours though "oscillations":



$$L_\alpha \to L_\beta \neq \bar{L}_\alpha \to \bar{L}_\beta$$

$$Y_B \propto \sum_\alpha \Delta^\alpha_{CP} \eta_\alpha \qquad \sum_\alpha \Delta^\alpha_{CP} = 0$$

$$t > t_{\rm eq}(\alpha) : \ \eta_\alpha \propto \exp\left(-t/t_{eq}(\alpha)\right)$$

Analytical results in GeV Leptogenesis

PH, Kekic, Lopez-Pavón,Racker, Rius 1508.03676

Equations can be solved analytically quite accurately in a perturbative expansion in mixing angles of V, W to third order for $y_3 << y_1, y_2$

$$Y_B \propto \sum_{I_{CP}} I_{CP} A_{I_{CP}}(t), \quad I_{CP} = \underbrace{I_1^{(2)}, I_2^{(3)}, I_2^{(3)}, J_W}$$

Rephasing invariants (like J_{ckg})

One example (first νMSM invariant)

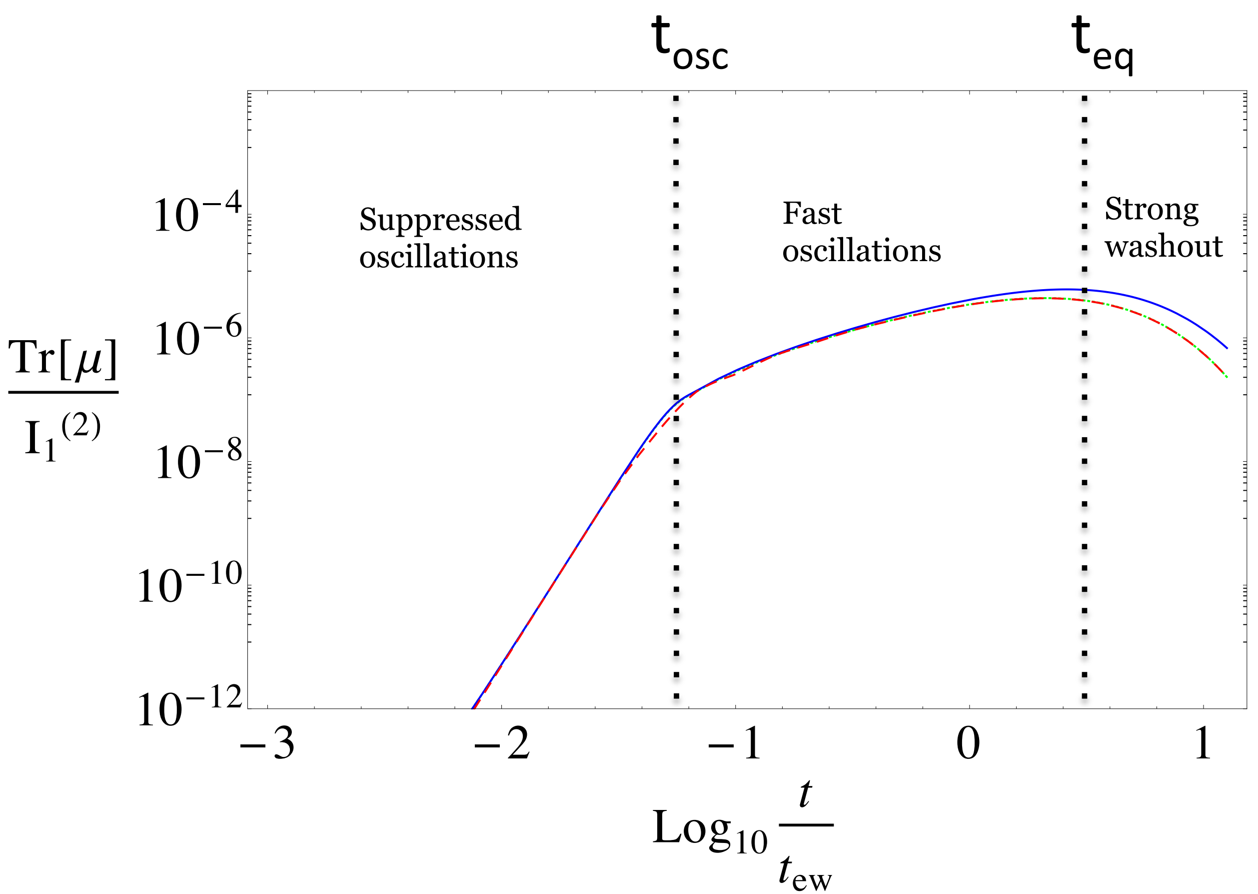
$$A_{I_1^{(2)}}(t) = y_1 y_2 (y_2^2 - y_1^2) \left(1 - \frac{\gamma_N}{\bar{\gamma}_N}\right) \gamma_N^2 G_1(t),$$

$$G_1(t) \equiv \left(e^{-\bar{\gamma}_2 t} - e^{-\bar{\gamma}_1 t}\right) \mathrm{Re}\left[i J_{20}(\Delta_{12}, -\Delta_{12}, t) + 2\Delta_v J_{201}(\Delta_{12}, -\Delta_{12}, t)\right] + \frac{1}{2}\sum_{k=1}^{2} (-1)^k e^{-\bar{\gamma}_k t} \mathrm{Re}\left[J_{210}(\Delta_{12}, -\Delta_{12}, t)\left(-2\Delta_v + i(2\bar{\gamma}_k - \gamma_1 - \gamma_2)\right)\right],$$

washouts

$$\bar{\gamma}_i \propto y_i^2 \bar{\gamma}_N$$

Analytical vs numerical results



PH, Kekic, Lopez-Pavón,Racker, Rius 1508.03676

Full exploration of the minimal model N=2

PH, Kekic, López-Pavón, Racker, Salvadó 1606.06719

Bayesian posterior probabilities (using nested sampling Montecarlo Multinest)

$$\mathcal{L} = -\left(\frac{Y_B(\text{param}) - Y_B^{\text{obs}}}{\sigma_{Y_B}}\right)^2$$

Use Casas-Ibarra parametrization: fix light neutrino masses and mixings to the best fit oscillation points (IH/NH) and vary

$$R(\theta + i\gamma);\ U_{PMNS}(\delta, \phi_1); M_1, M_2$$

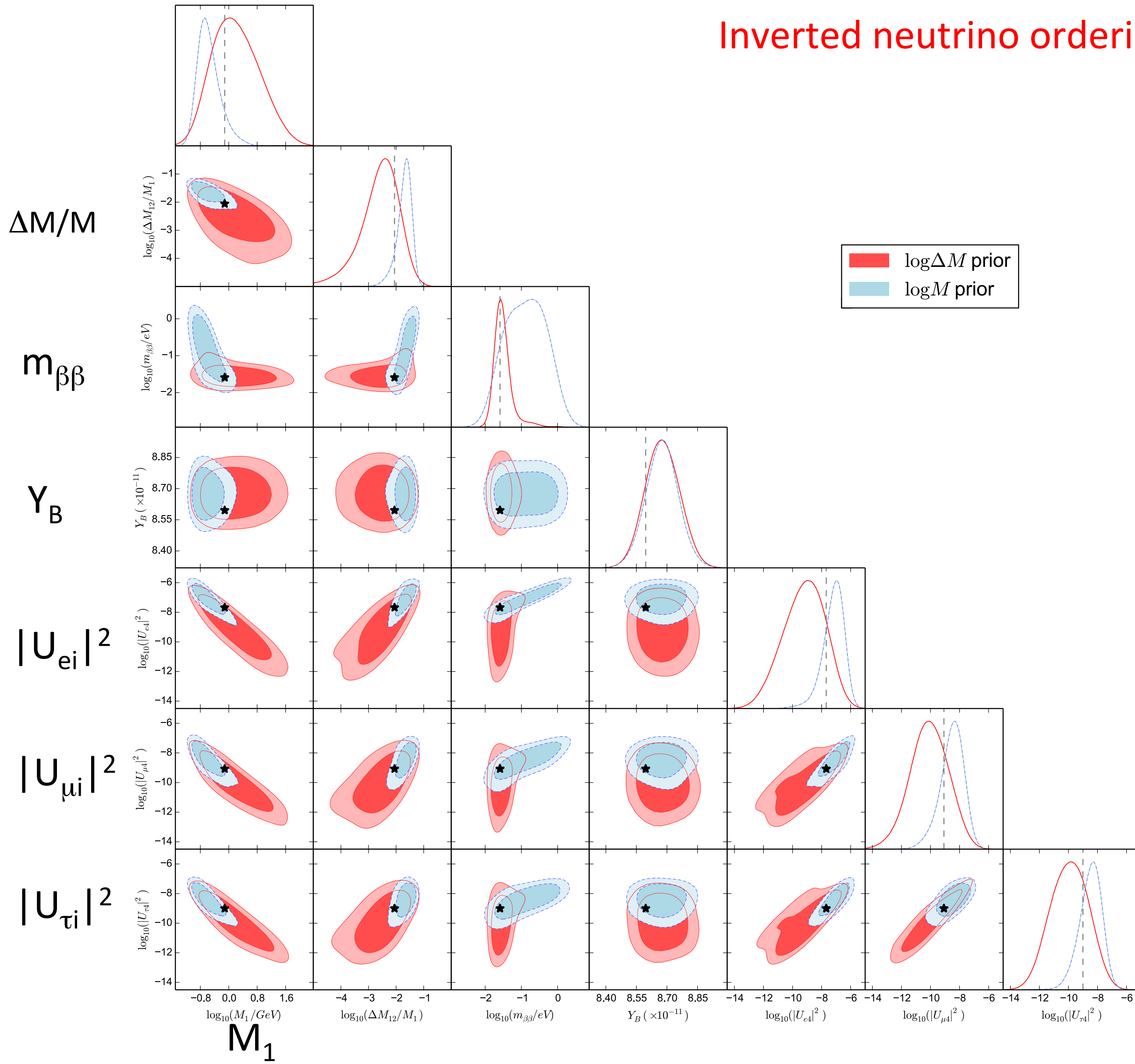
Flat priors in:

$$\theta = [0, \pi]; \delta = [0, 2\pi]; \phi_1 = [0, 2\pi]; \gamma = [-9, 9];$$

$$\log_{10} M_1 \ \text{ and } \ \log_{10} M_2 / \log_{10}(M_2 - M_1)$$

Full exploration of the minimal model N=2

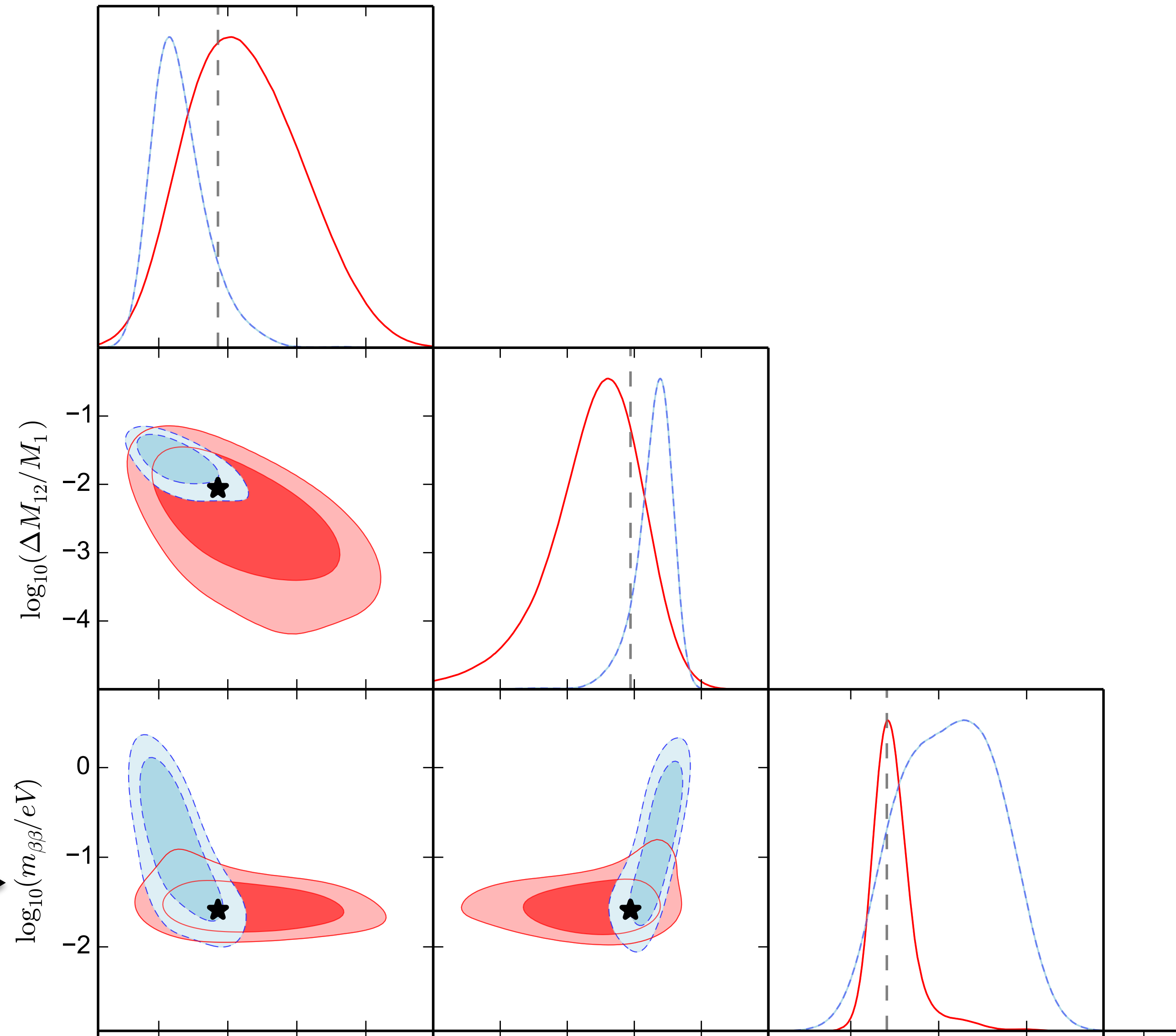
Inverted neutrino ordering (IH)



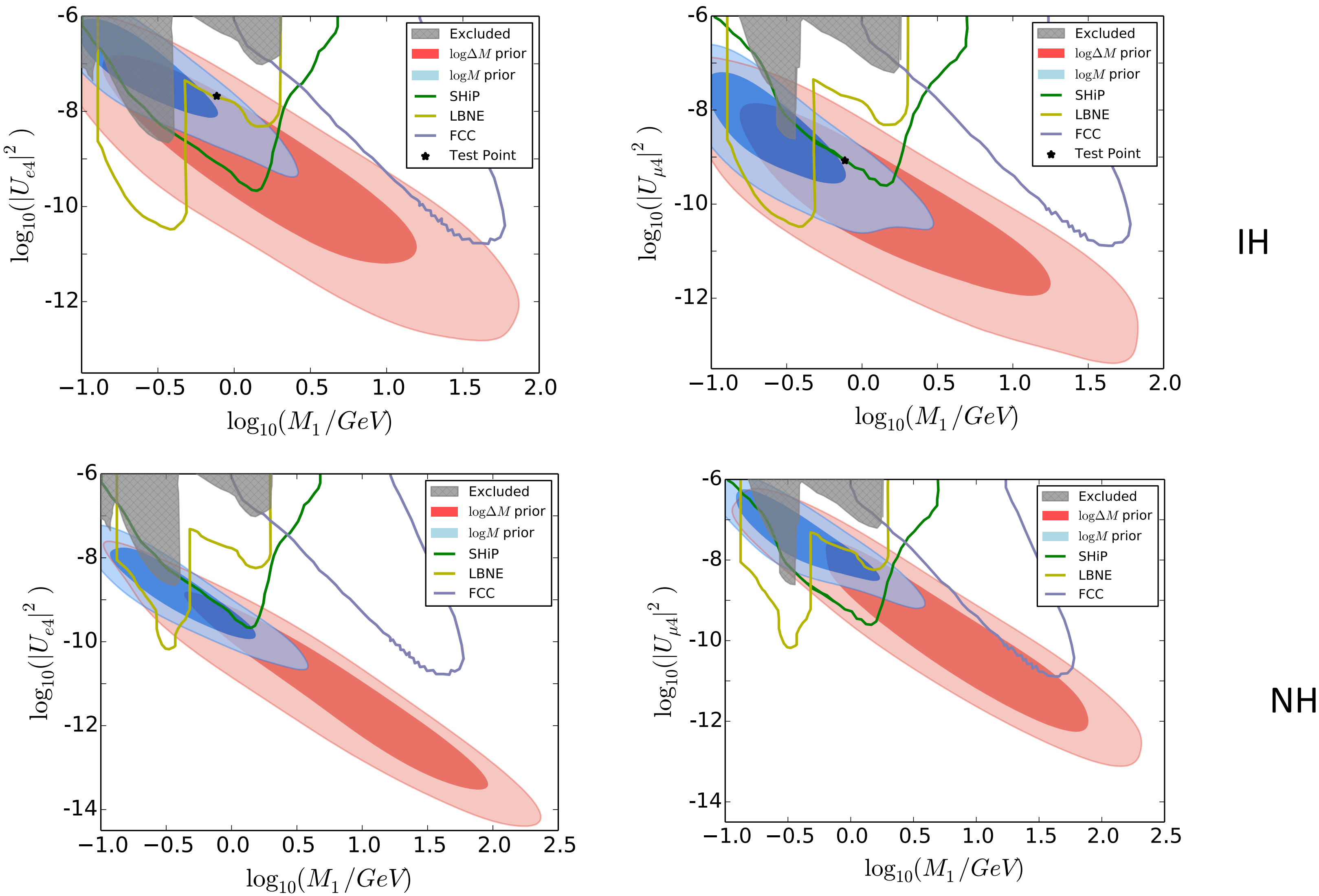
Full exploration of the minimal model N=2

Fine tunning in masses

Generically large non-standard effect in ββ0ν

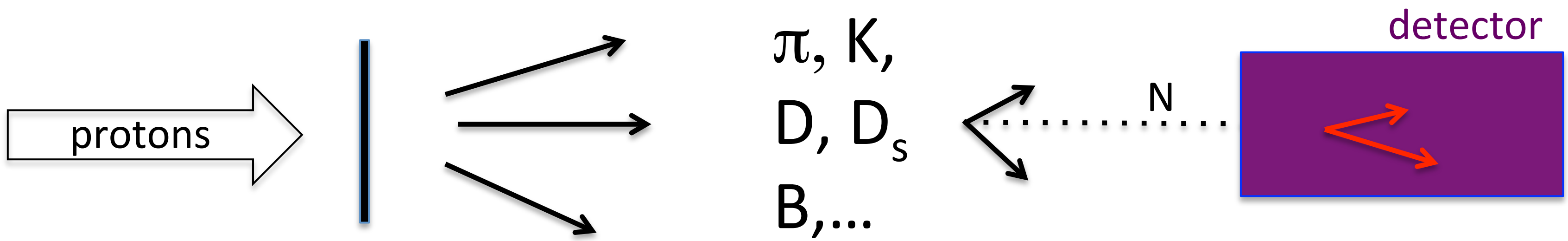


Full exploration of the minimal model N=2



Less fine-tunned region prefers the range of SHIP & DUNE!

Searches in rare meson decays



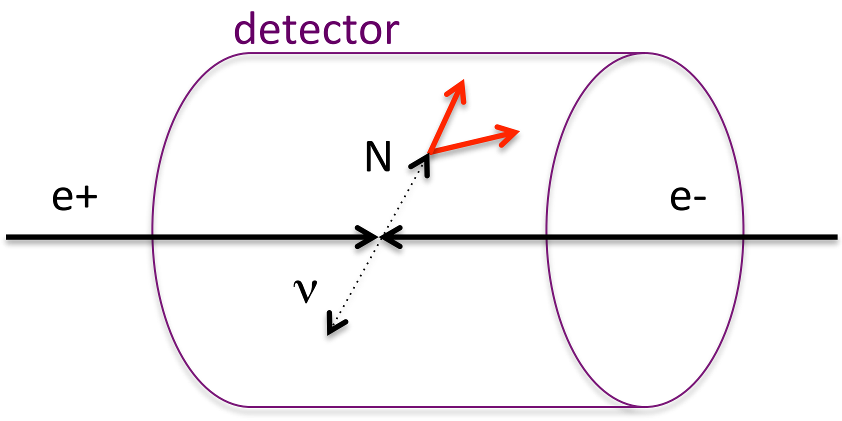
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

$M< M_K$

SHiP
Search for Hidden Particles

$M< M_D$

Searches in e+e- @ Z



Golden signal: displaced vertex

Predicting Y_B in the minimal model N=2 (IH) ?

If the heavy sterile neutrinos would be within reach of SHIP to what extent can we predict the baryon asymmetry from experiment ?

- SHIP measurement could provide (if states not too degenerate)

$$M_1, M_2, |U_{e1}|^2, |U_{\mu 1}|^2, |U_{e2}|^2, |U_{\mu 2}|^2$$

- Neutrinoless double beta decay amplitude: $|m_{\beta\beta}|$

- Neutrino oscillations: δ phase in the U_{PMNS}

Predicting Y_B in the minimal model N=2 (IH) ?

If the heavy sterile neutrinos would be within reach of SHIP to what extent can we predict the baryon asymmetry from experiment ?

It can be shown that Y_B depends sizeably on every one of the unknown parameters of the model !

Light sector: $U_{PMNS}(\phi_1, \delta)$, Δm^2_{atm}, Δm^2_{sol}

Heavy sector: M_1, M_2, $z = \theta + i\,\gamma$

Predicting Y_B in the minimal model N=2 ?

From SHIP for IH:

$$\epsilon \sim e^{-\gamma} \sim \theta_{13} \sim x \equiv \sqrt{\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}}}$$

$$|U_{e4}|^2 M_1 \simeq |U_{e5}|^2 M_2 \simeq A\left[(1+\sin\phi_1 \sin 2\theta_{12})(1-\theta_{13}^2) + \frac{1}{2}x^2 s_{12}(c_{12}\sin\phi_1 + s_{12}) + \mathcal{O}(\epsilon^3)\right],$$

$$|U_{\mu 4}|^2 M_1 \simeq |U_{\mu 5}|^2 M_2 \simeq A\left[\left(1-\sin\phi_1 \sin 2\theta_{12}\left(1+\frac{1}{4}x^2\right) + \frac{1}{2}x^2 c_{12}^2\right)c_{23}^2 \right.$$
$$+\theta_{13}(\cos\phi_1 \sin\delta - \sin\phi_1 \cos 2\theta_{12}\cos\delta)\sin 2\theta_{23}$$
$$\left. +\theta_{13}^2(1+\sin\phi_1\sin 2\theta_{12})s_{23}^2 + \mathcal{O}(\epsilon^3)\right], \qquad A \equiv \frac{e^{2\gamma}\sqrt{\Delta m^2_{atm}}}{4},$$

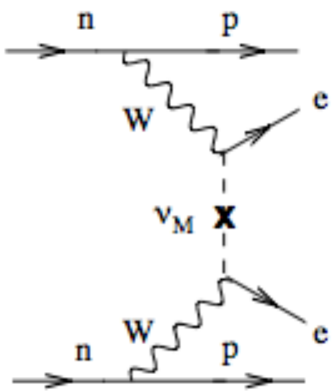
Ratios of e/μ mixings depend on the two phases of the U_{PMNS} matrix: δ, ϕ_1

Amplitude of either: γ

But the baryon asymmetry also depends on the last unknown θ

Predicting Y_B in the minimal model N=2 (IH)

Neutrinoless double beta decay comes to rescue...



$$m_{\beta\beta} = \underbrace{\sum_{i=1}^{3} \left[(U_{PMNS})_{ei} \right]^2 m_i}_{\text{Light states}} + \underbrace{\sum_{i=j}^{3} U_{ej}^2 M_j \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)}}_{\text{Heavy states}}$$

$$M_j \to \infty \qquad \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)} \propto \left(\frac{100 \text{ MeV}}{M_j} \right)^2$$

The heavy contribution is sizeable for M_i of O(GeV) !

Blennow,Fernandez-Martinez, Lopez-Pavon, Menendez;
Lopez-Pavon, Pascoli, Wong; Lopez-Pavon, Molinaro, Petcov

Predicting Y_B in the minimal model N=2 (IH)

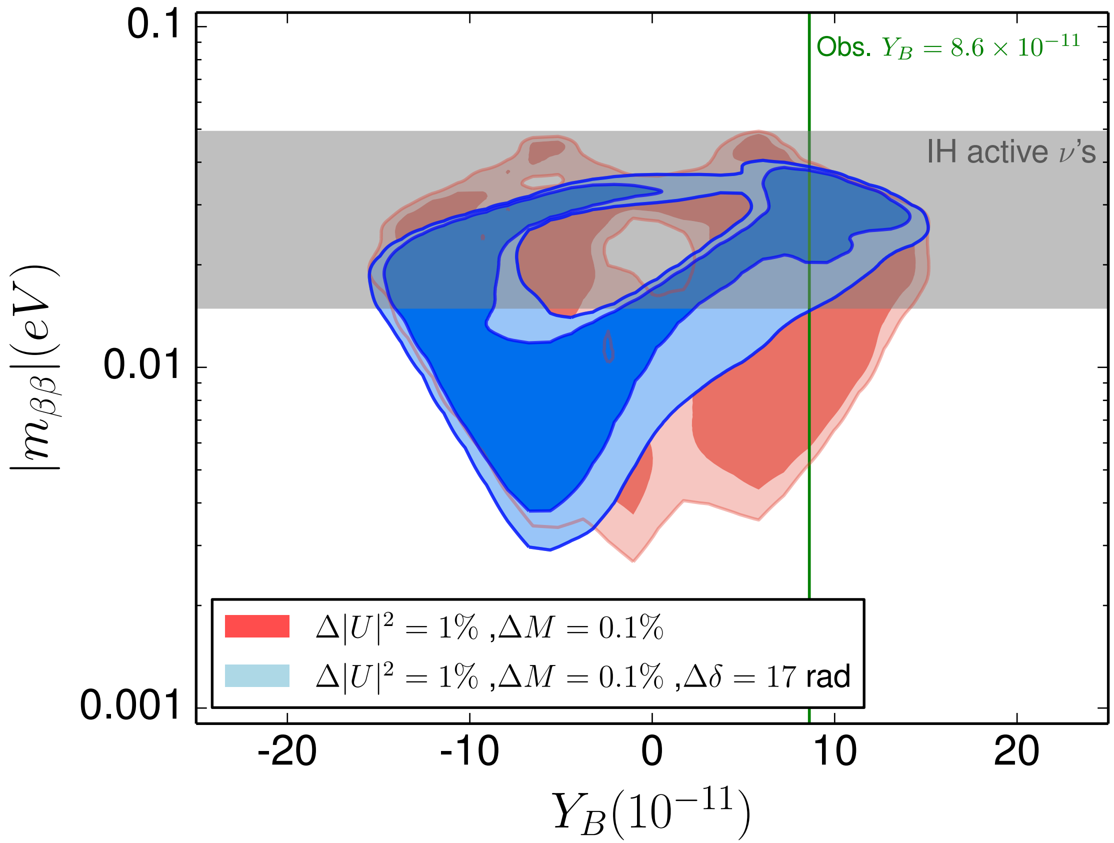
Light neutrino contribution

$$|m_{\beta\beta}|_{IH} \simeq \sqrt{\Delta m^2_{atm}} \Bigg| c^2_{13}\left(c^2_{12} + e^{2i\phi_1} s^2_{12}\left(1 + \frac{x^2}{2}\right)\right) - f(A)\, e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 (1 - 2e^{i\delta} s_{23}\theta_{13}) \frac{(0.9\,\mathrm{GeV})^2}{4M_1^2}\left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}}\right)^2\right)\Bigg|, \quad (4.13)$$

Heavy neutrino contribution

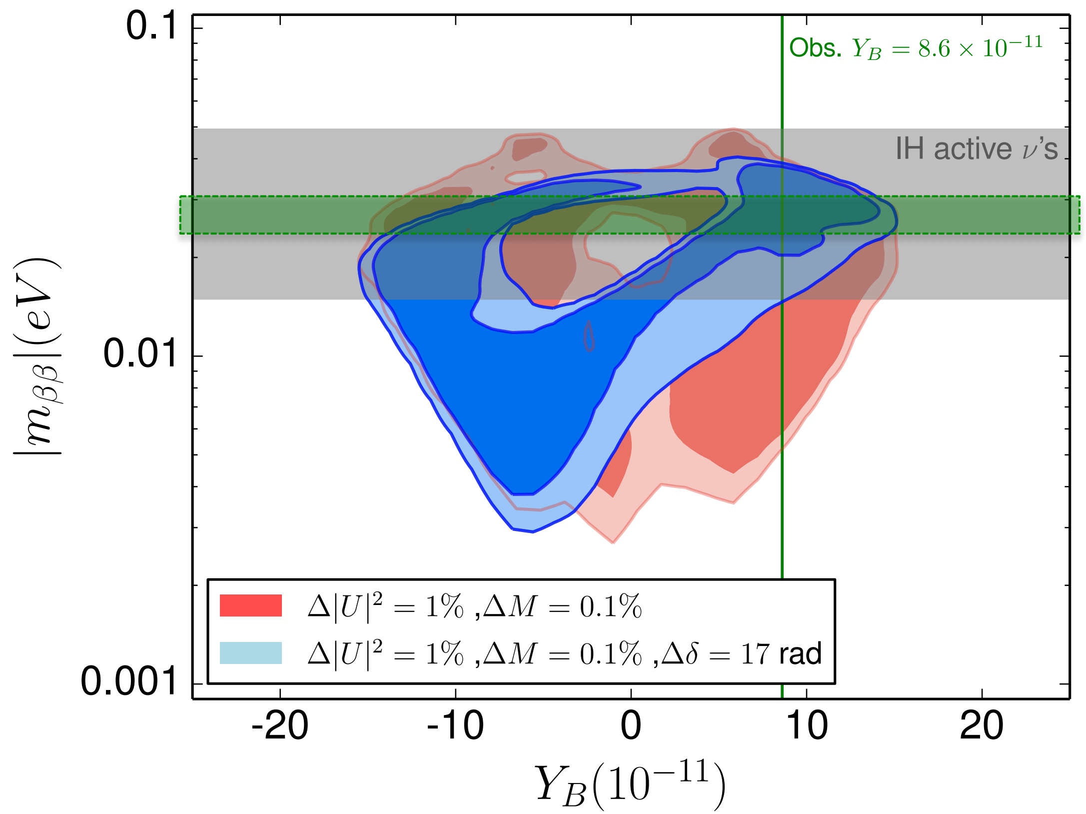
θ controls the interference of heavy and light contributions !

Predicting Y_B in the minimal model N=2 (IH)



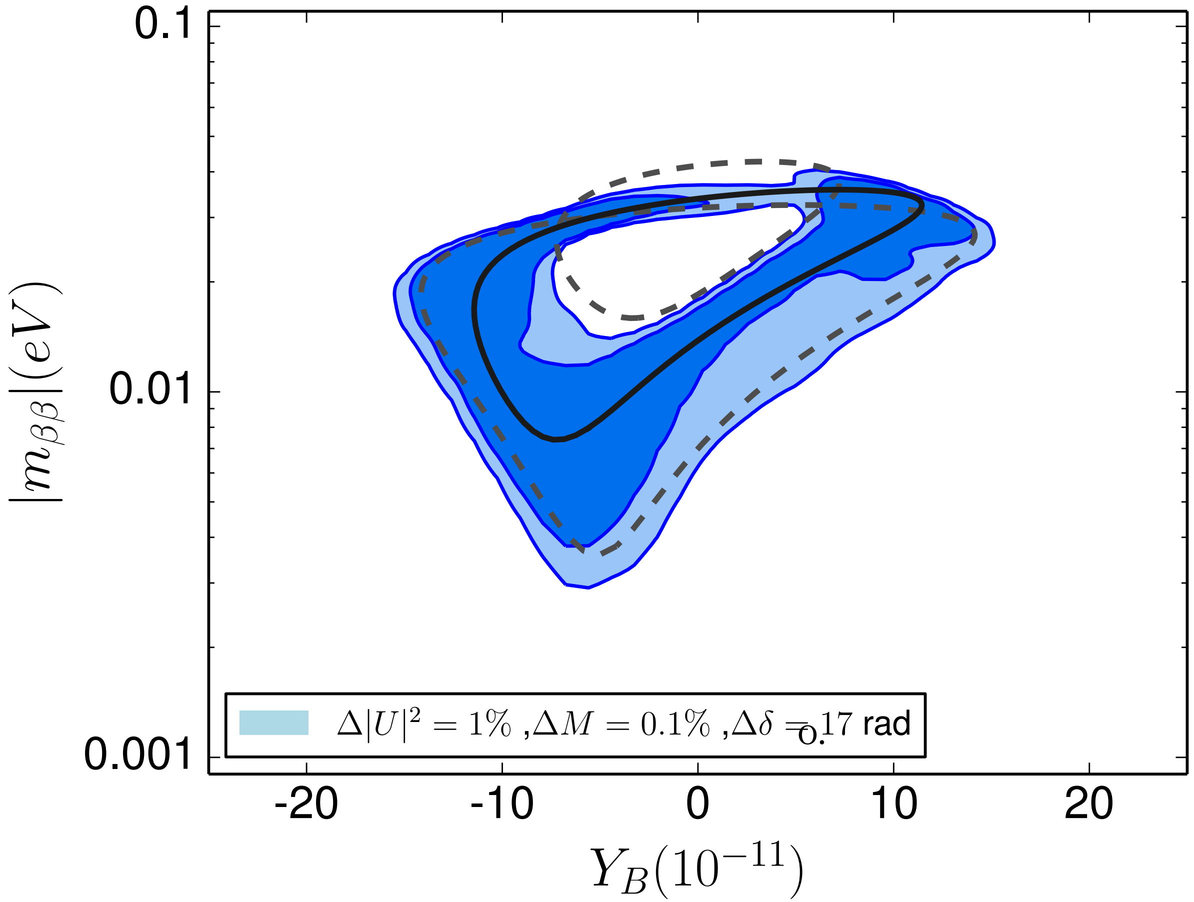
PH, Kekic, López-Pavón, Racker, Salvadó 1606.06719

Predicting Y_B in the minimal seesaw model M~GeV



PH, Kekic, López-Pavón, Racker, Salvadó

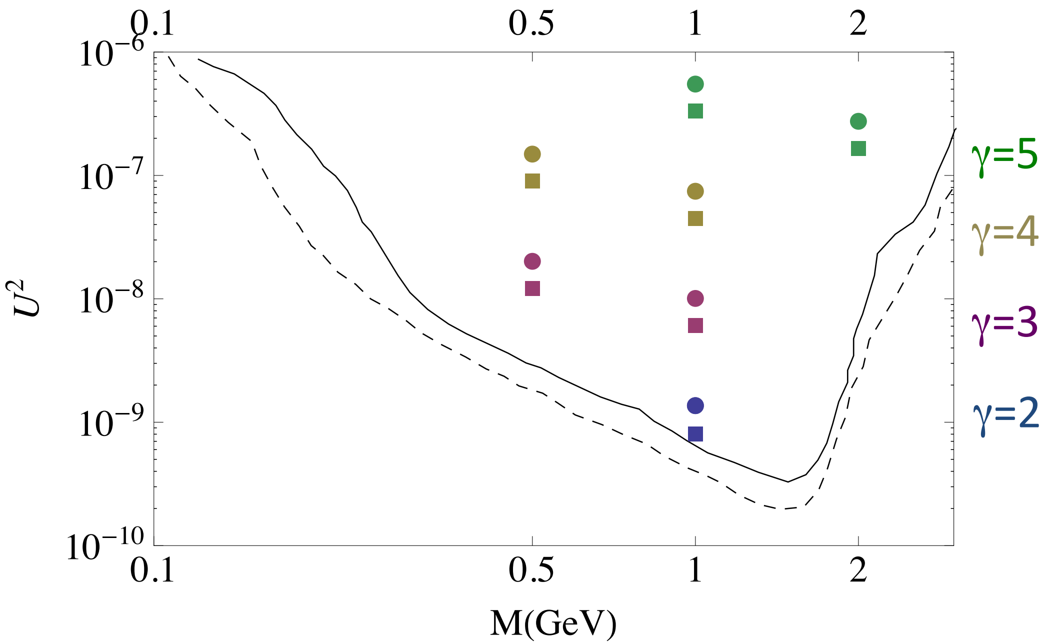
The GeV-miracle: the measurement of the mixing to e/μ of the sterile states, neutrinoless double-beta decay and δ in neutrino oscillations have a chance to give a prediction for Y_B if IH



Shape can be understood from the residual error in δ:

precision in δ is important !

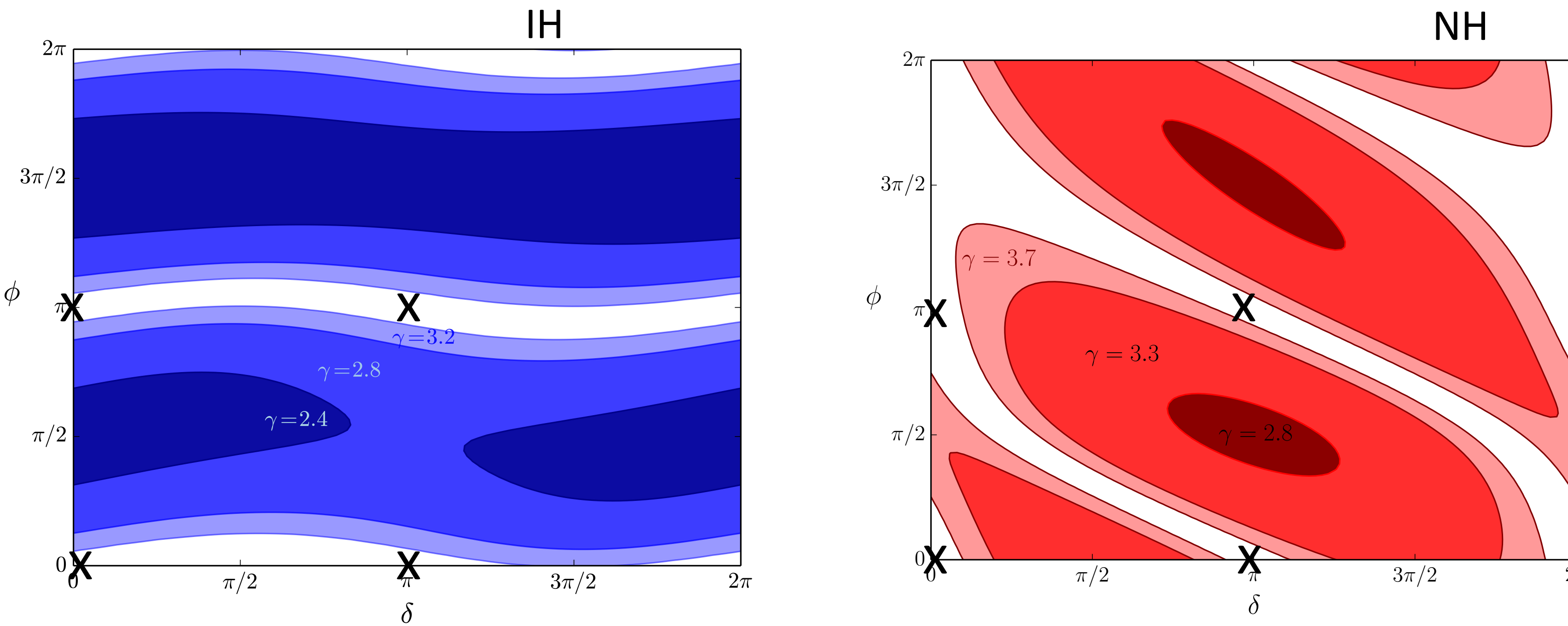
If SHIP measures the heavy neutrinos and their mixings to e/μ:



Can we exclude a real U_{PMNS} matrix ie. discover leptonic CP violation in mixing ?

$$(\delta, \phi_1) \neq (0/\pi, 0/\pi)$$

Leptonic CP violation in U_{PMNS} 5σ CL SHIP discovery regions



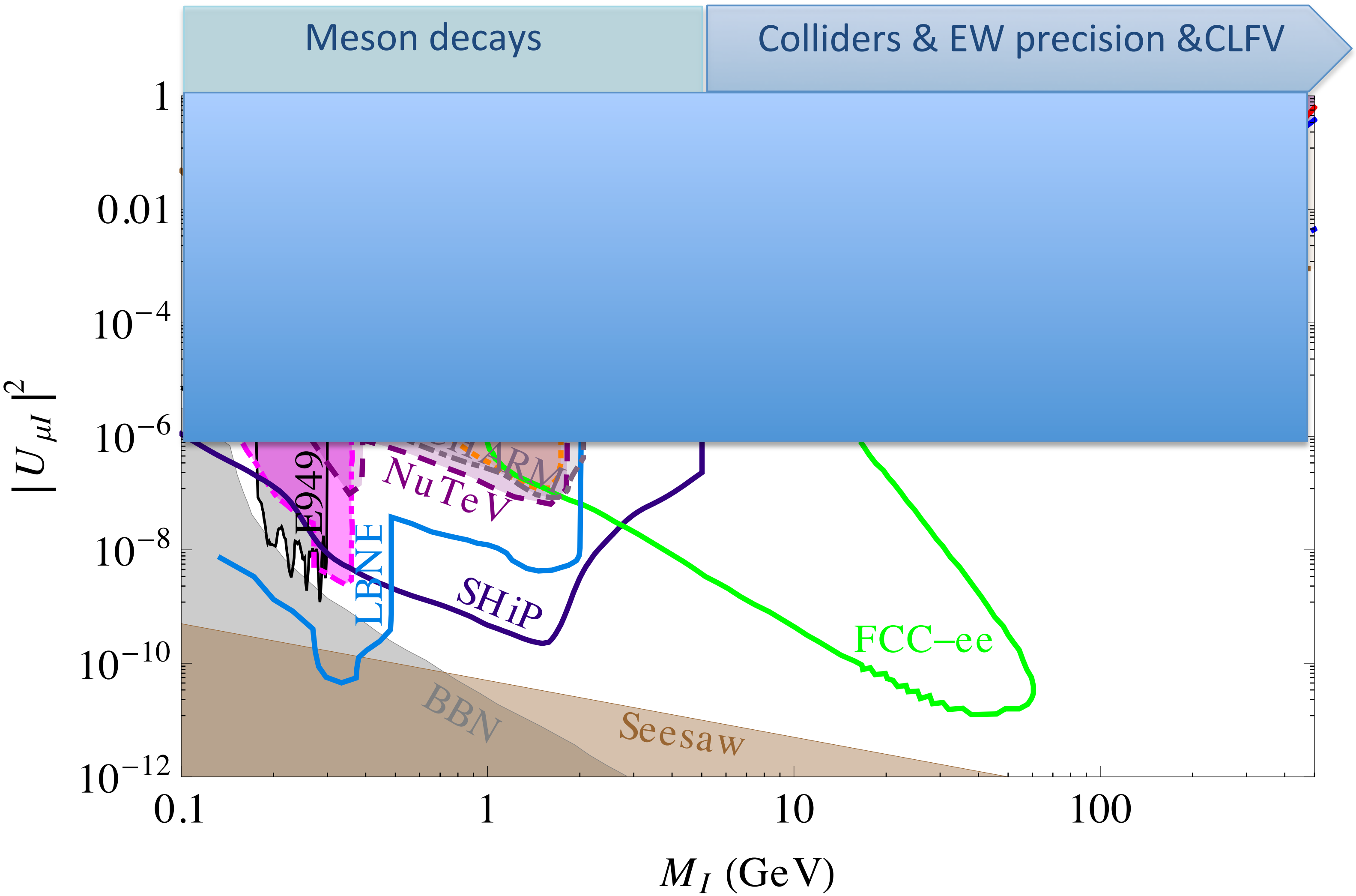
(no systematic error included)

Caputo, PH, Kekic, Lopez-Pavon, Salvado

5σ sensitivity to CP-violation in a large fraction of the CP rectangle !

Larger Mixings ?

Reviews Atre, Han, Pascoli, Zhang; Gorbunov, Shaposhnikov; Ruchayskiy, Ivashko



Bounds only relevant if $|U_{\alpha i}|^2 \gg \frac{m_\nu}{M_i} \leftrightarrow R \gg 1$

Is this natural ?

- In some cases unnatural:

cancellation between tree level and 1 loop contribution to neutrino masses

- But also technically-natural textures:

Lopez-Pavon, Pascoli, Wang

protected by an approximate global $U(1)_L$

Example N=2: $L(N_1) = +1, \; L(N_2) = -1$

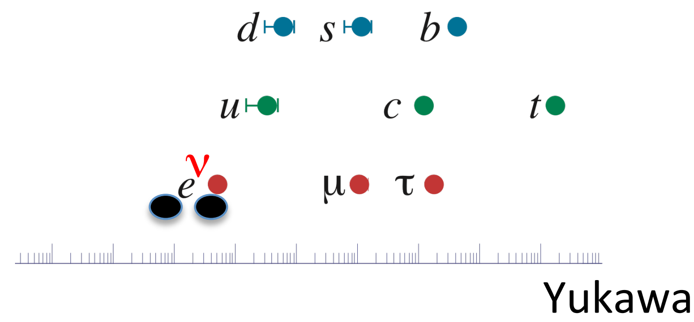
$$-\mathcal{L}_\nu \supset \bar{N}_1 M N_2^c + Y \bar{L} \tilde{\Phi} N_1 + h.c.$$

Eg: inverse, direct seesaw models

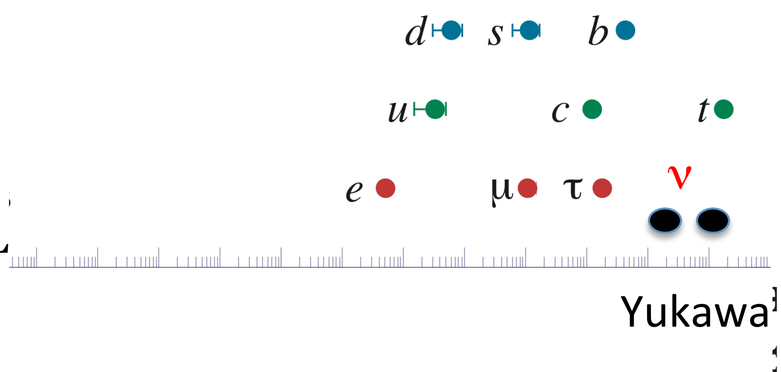
Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao;Kersten, Smirnov; Abada et al; Gavela et al….many others

Charged/neutral hierarchy in seesaw

M_N = TeV



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



Room for improvement in searches at LHC, LFV, future colliders: but must look for not lepton number violating processes

Conclusions

- The results of many beautiful experiments have demonstrated that ν are the less standard of the SM particles

- A new scale Λ < v could explain the smallness of neutrino masses without increasing significantly the flavour hierarchies already existing in the SM

- Low-scale seesaw models can seed the baryon asymmetry in the Universe and do so in a testable way (GeV region particularly interesting!)

- Complementarity of different experimental approaches: $\beta\beta 0\nu$, CP violation in neutrino oscillations, direct searches in meson decays, colliders…