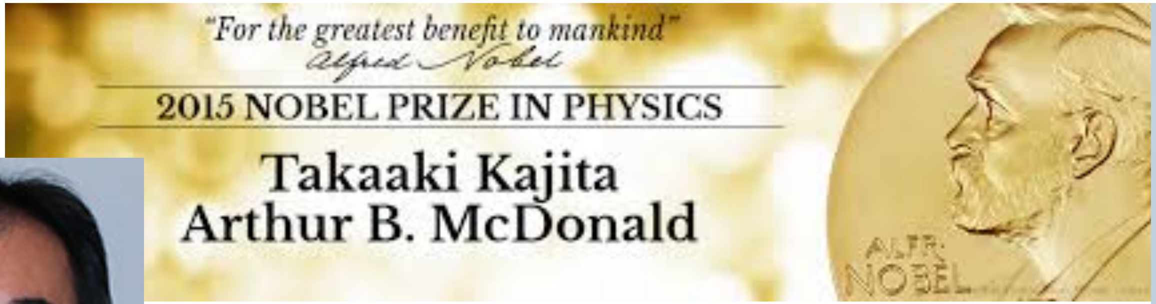
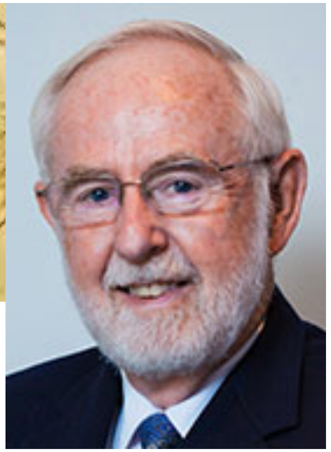
Some news in ν physics

P. Hernandez

IFIC, Universidad de Valencia & CERN

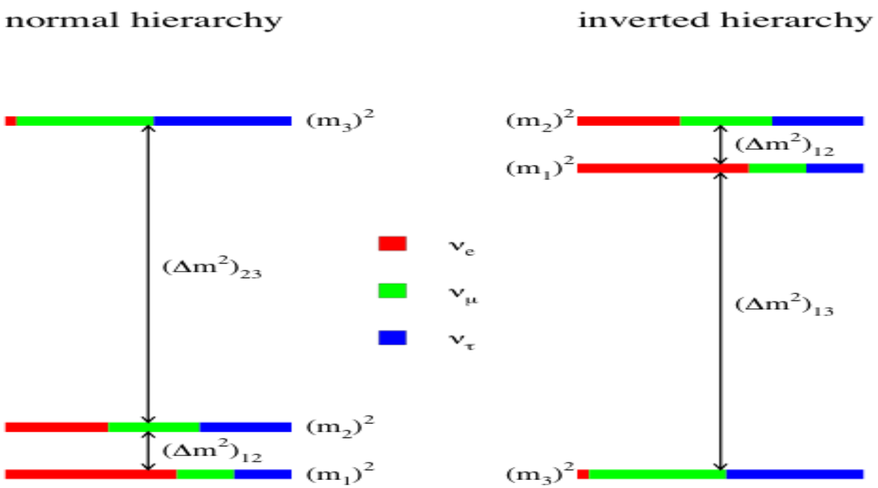
"For the discovery of neutrino oscillations,
which shows that neutrinos have mass"





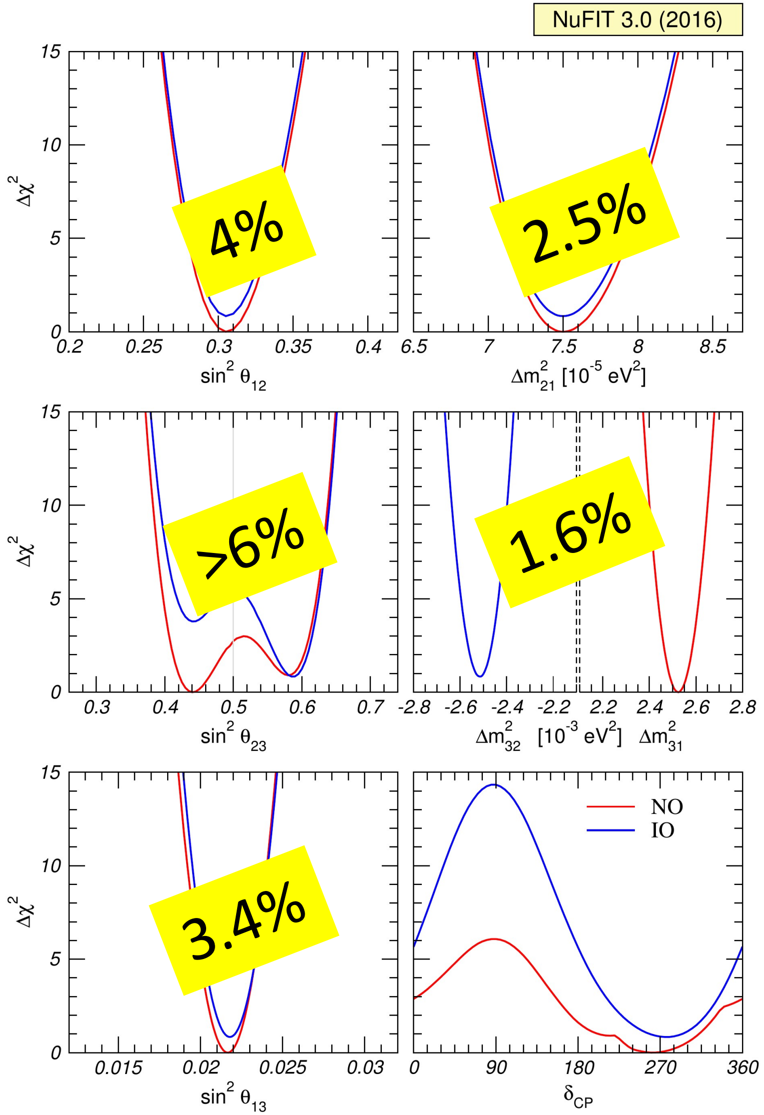
SM+3 massive neutrinos: Global Fits

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



?

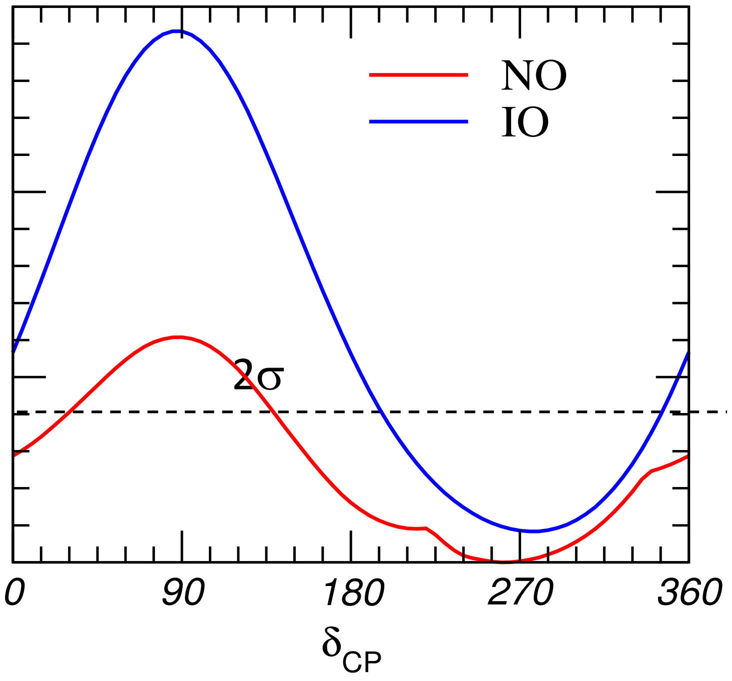
$\Delta m^2_{13} > 0$ $\Delta m^2_{13} < 0$



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

Absolute mass scale

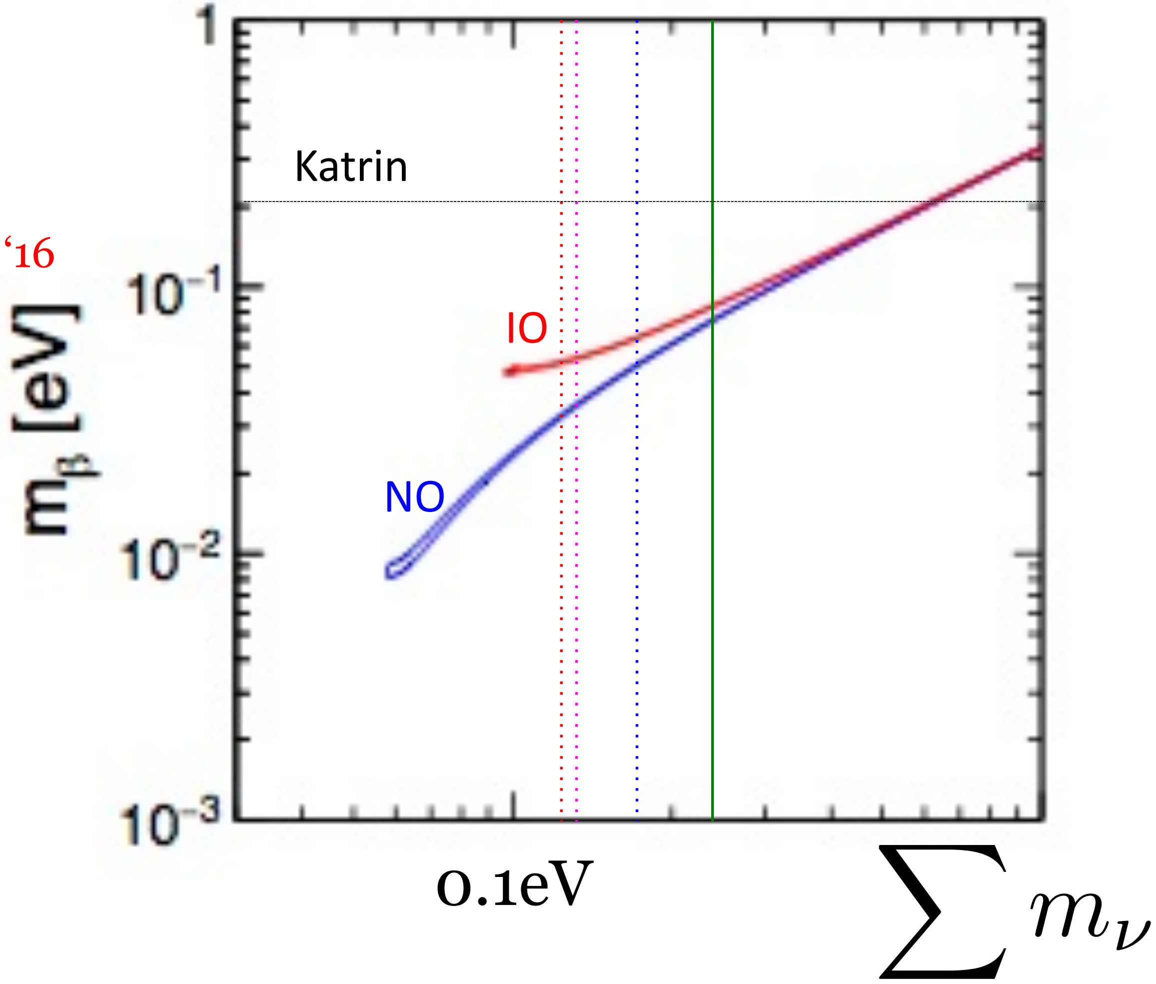
Neutrinos as light as 0.1-1eV modify the large scale structure and CMB

Planck '15

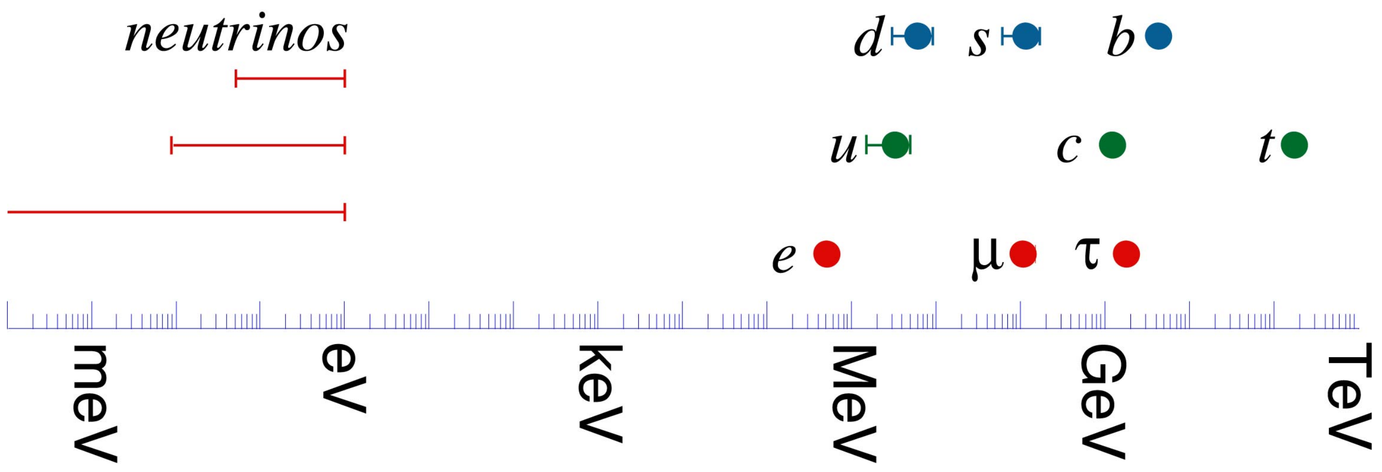
Giusarma et al '16

Palanque-Delabrouille et al '16

Cuesta et al '16



A new flavour perspective



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)

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

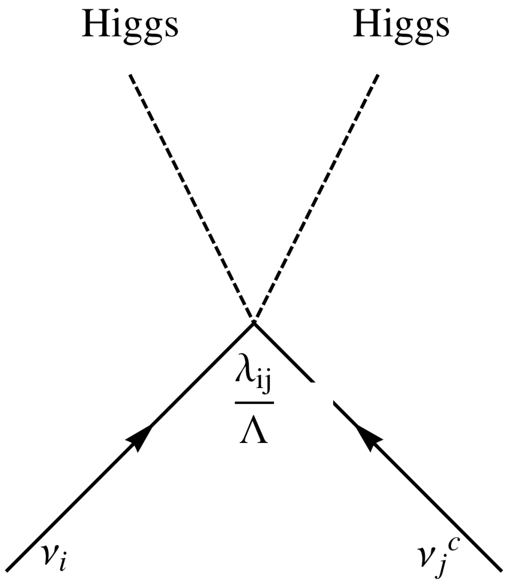
A new physics scale ?

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

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

Weinberg

$$[\alpha] = -1$$



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

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

Scale at which new particles will show up

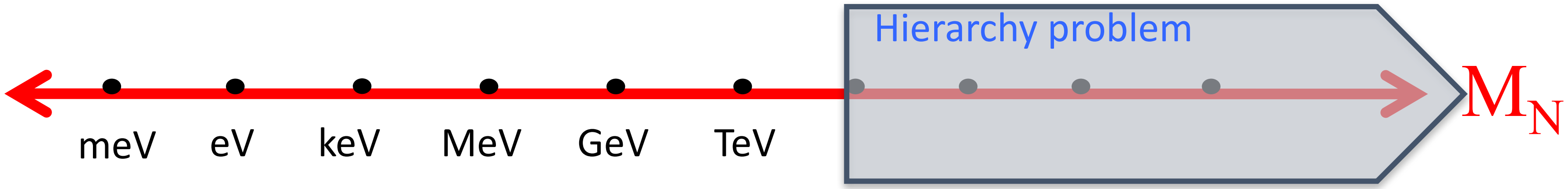
What lies beyond Weinberg's operator?

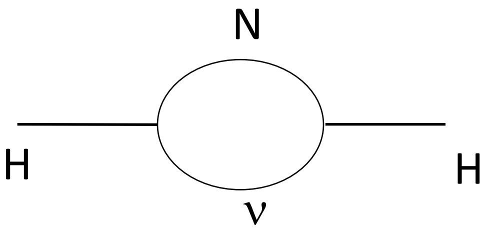
Could be $\Lambda >> v$... the standard lore (theoretical prejudice ?)

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

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 lies beyond Weinberg's operator?

Could be $\Lambda \sim v$?

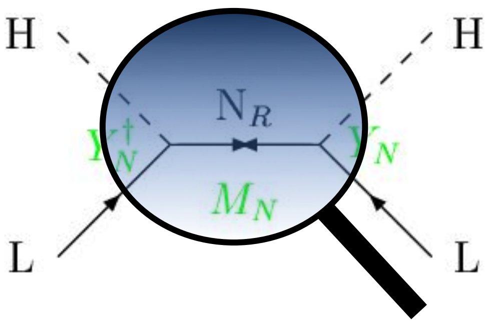
Yes !

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

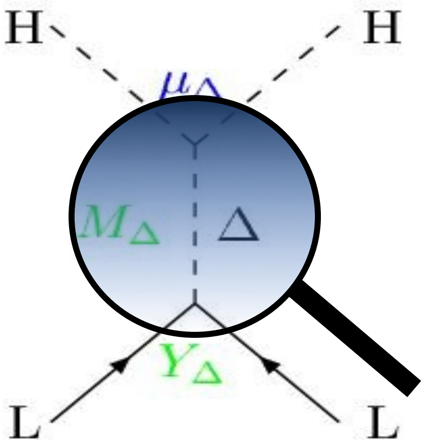


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

$\lambda \sim O(Y^2)$

Type II see-saw:
a heavy triplet scalar

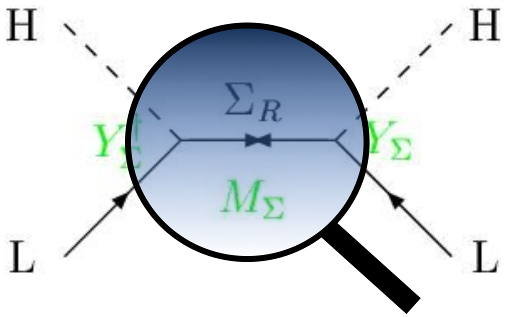


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

$\lambda \sim O(Y\,\mu/M_\Delta)$

Type III see-saw:
a heavy triplet fermion

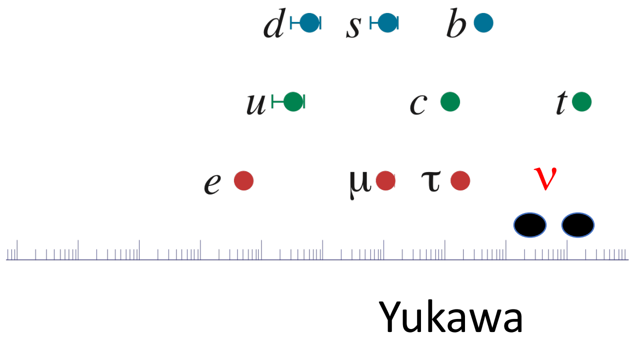


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

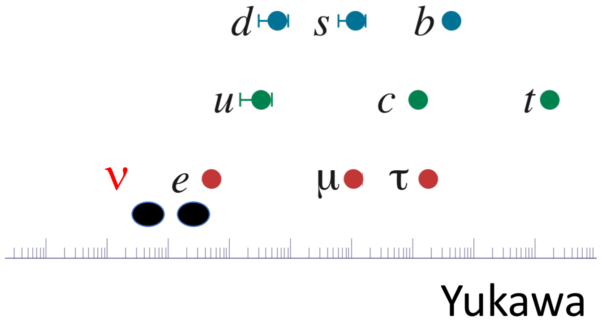
Foot et al; Ma;
Bajc, Senjanovic…

$\lambda \sim O(Y^2)$

M ~ GUT



M = TeV



Why low-scale ($M_N \leq v$) seesaw ?

Testable, falsifiable...

"Once you eliminate the impossible, whatever remains, no matter how improbable/unnatural, must be the truth."

Why low-scale ($M_N \leq v$) seesaw ?

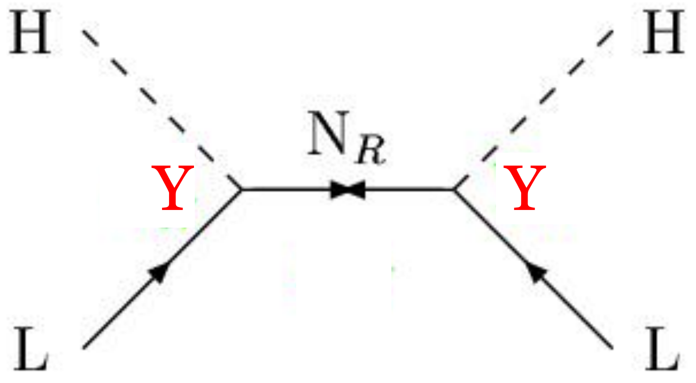
Testable, falsifiable...

In this talk two examples:

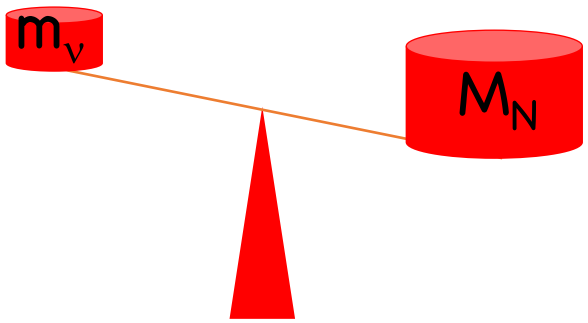
- matter-antimatter asymmetry
- leptonic CP violation

Minimal model of neutrino masses: SM+right-handed neutrinos

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



$$n_R \geq 2$$

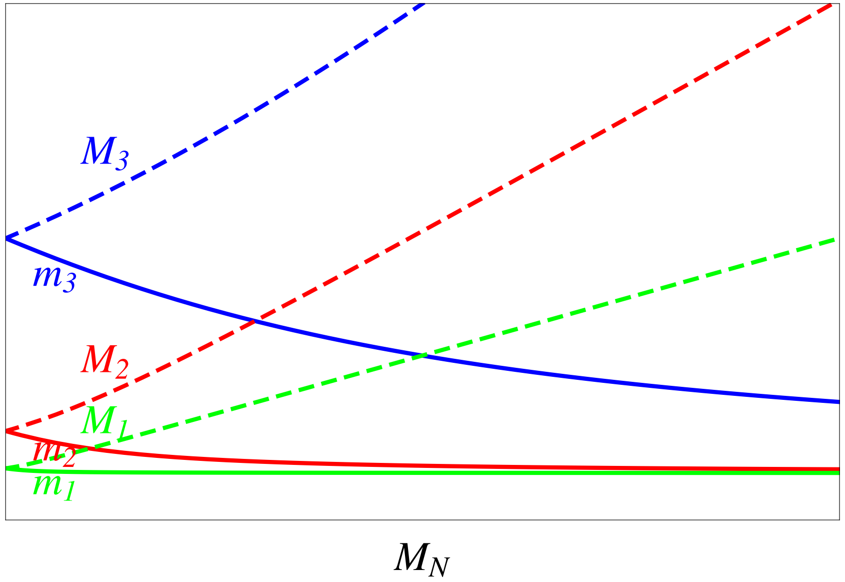


$$m_\nu = \lambda\frac{v^2}{\Lambda} \equiv Y^T\frac{v^2}{M}Y$$

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…

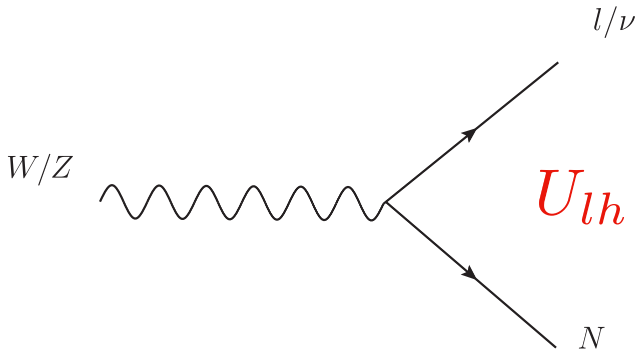


Type I seesaw models

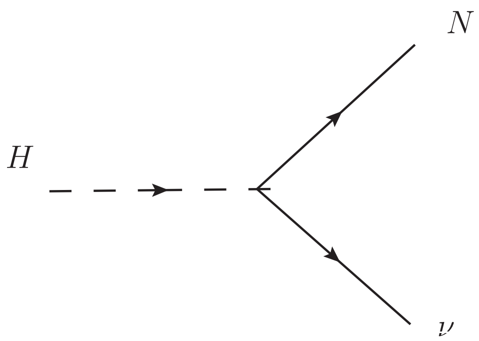
Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

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

Type I seesaw models



U_{lh}



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

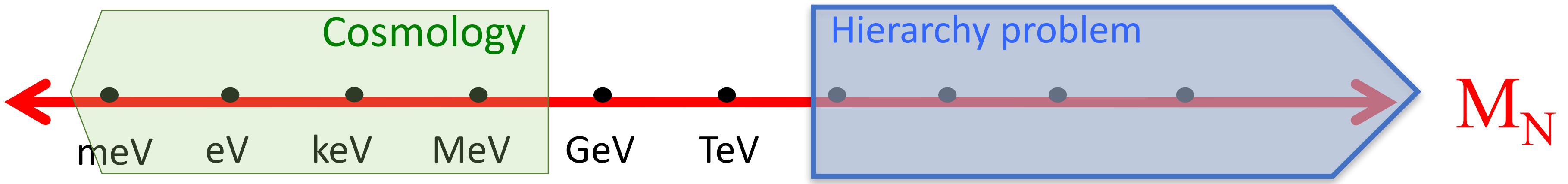
$$U_{lh} \simeq i\underbrace{U_{\mathrm{PMNS}}\sqrt{m_l}}_{\text{light param}}\underbrace{R\frac{1}{\sqrt{M_h}}}_{\text{heavy param}}$$

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 mass



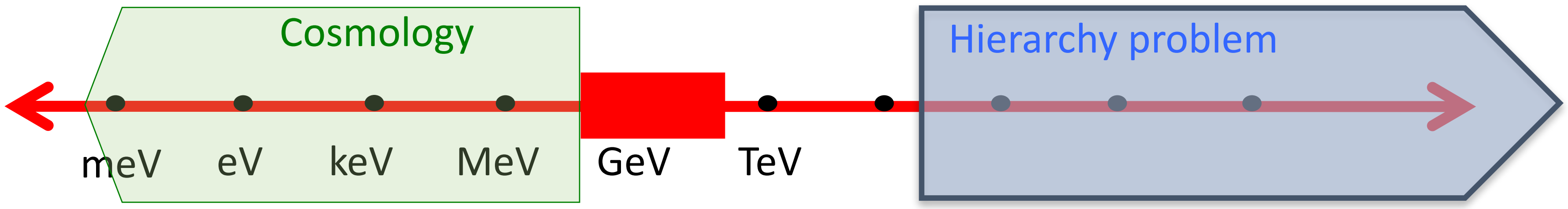
Sterile neutrinos below 100MeV can strongly modify

Big-Bang Nucleosynthesis
Cosmic Microwave background
Large Scale structure

Notzold, Raffelt; Barbieri&Dolgov; Kainulainen....;
Dolgov, Hansen, Raffelt,Semikoz;
Ruchayskiy, Ivashko;Vincent et al;
PH, Kekic, Lopez-Pavon

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

Leptogenesis



Leptogenesis from neutrino oscillations   0.1GeV <M < 100GeV

Akhmedov, Rubakov, Smirnov

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

Sakharov conditions

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

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

Casas-Ibarra

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

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

$$\cancel{L_\alpha} \oplus \cancel{B+L}$$

(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: not all the states reach thermal equilibrium before T_{EW}

ARS Leptogenesis

Akhmedov, Rubakov,Smirnov

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

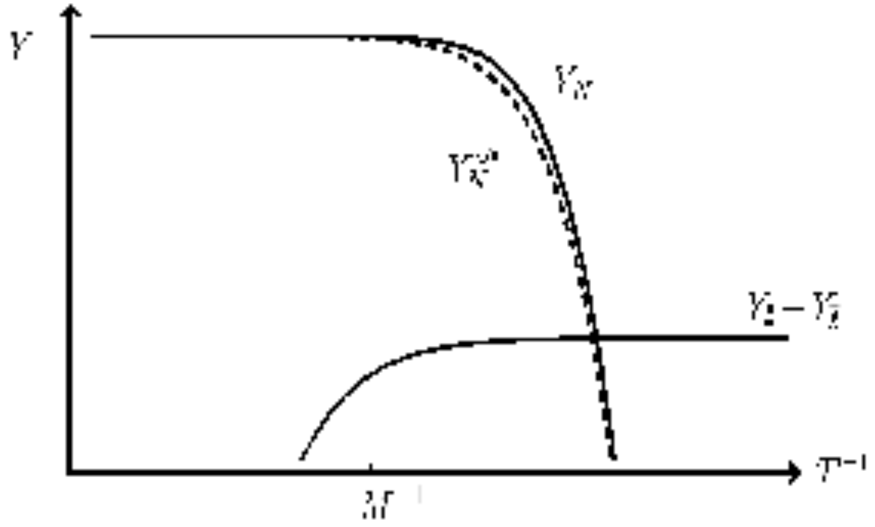
$$\frac{\Gamma_s(T_{EW})}{H(T_{EW})} \sim 5 \left(\frac{M}{1\mathrm{GeV}}\right) \left(\frac{m_\nu}{0.05\mathrm{eV}}\right)$$

$y_3 < y_1, y_2$

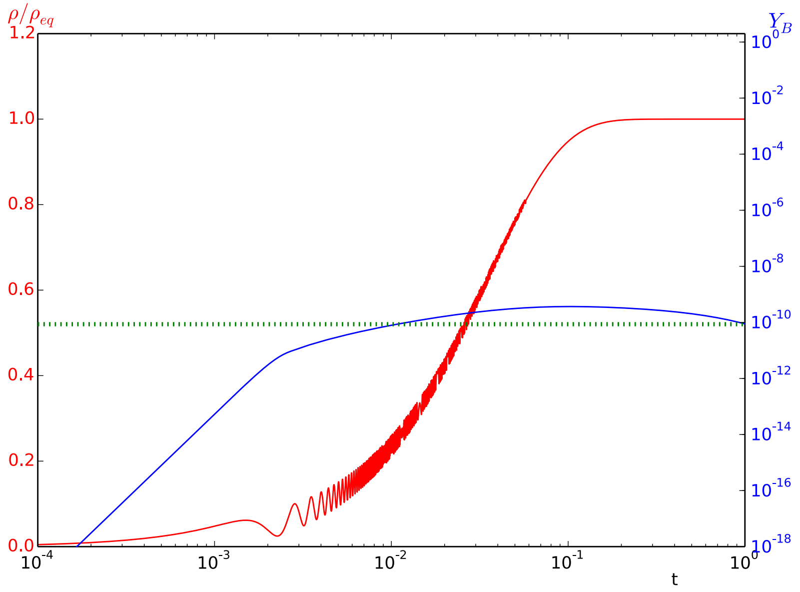
CP asymmetries arise in production of sterile states via the interference of CP-odd phases and CP-even phases from oscillations

High-scale leptogenesis

Fukugita, Yanagida



Low-scale leptogenesis



T_{EW}

Courtesy of M. Kekic

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

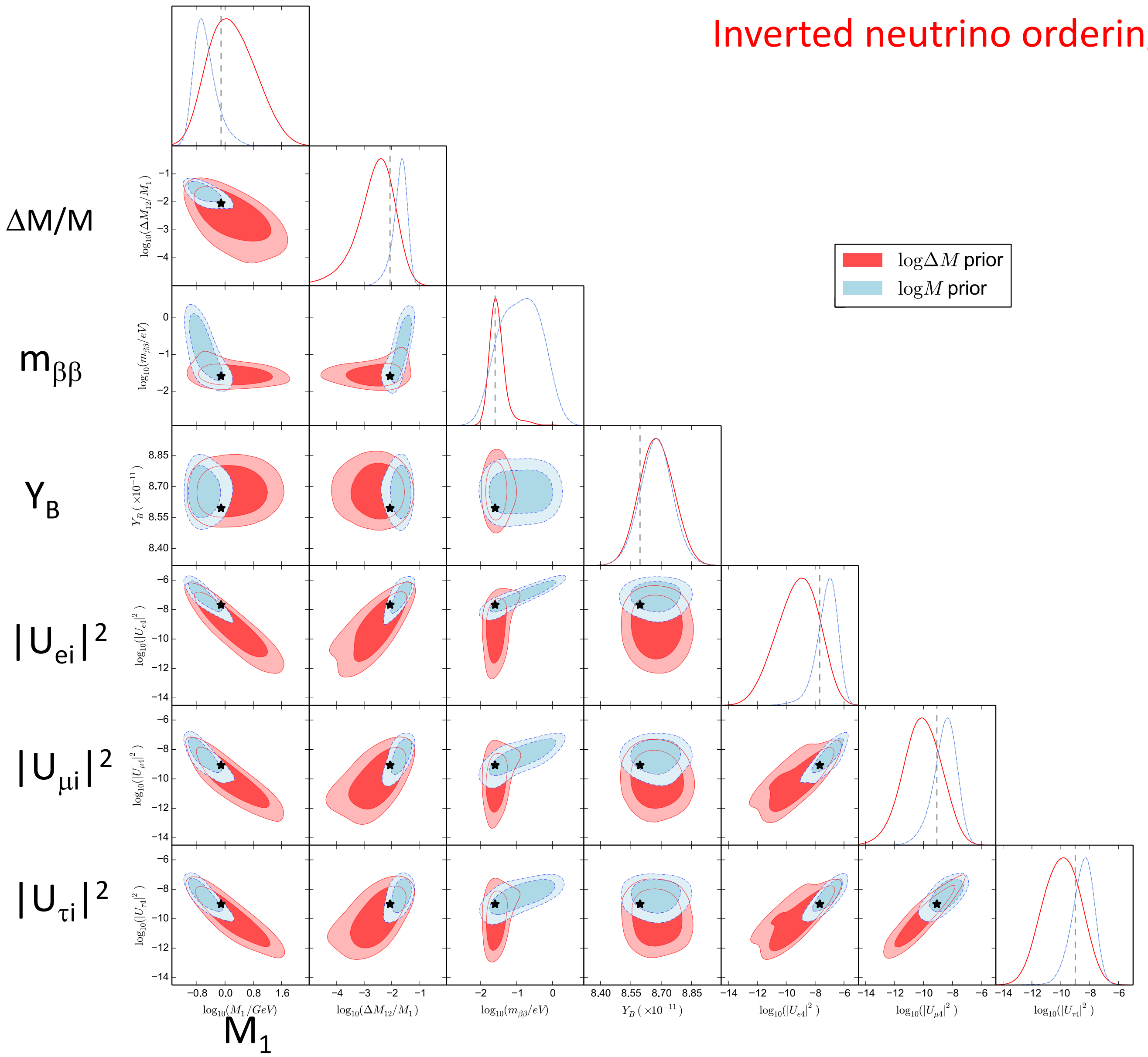
$$R(\theta + i\gamma);\; U_{PMNS}(\delta, \phi_1); M_1, M_2$$

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

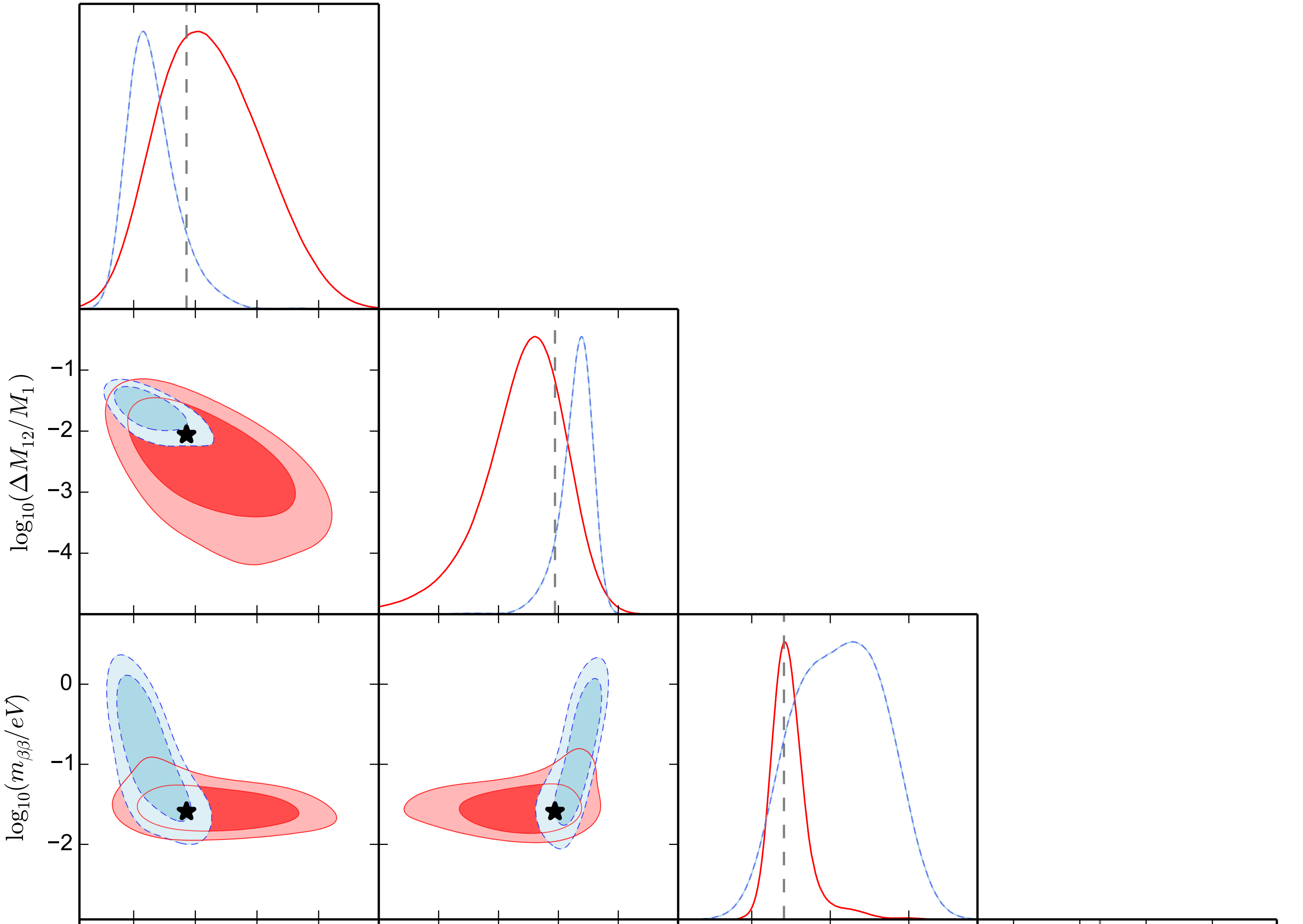
Inverted neutrino ordering (IH)



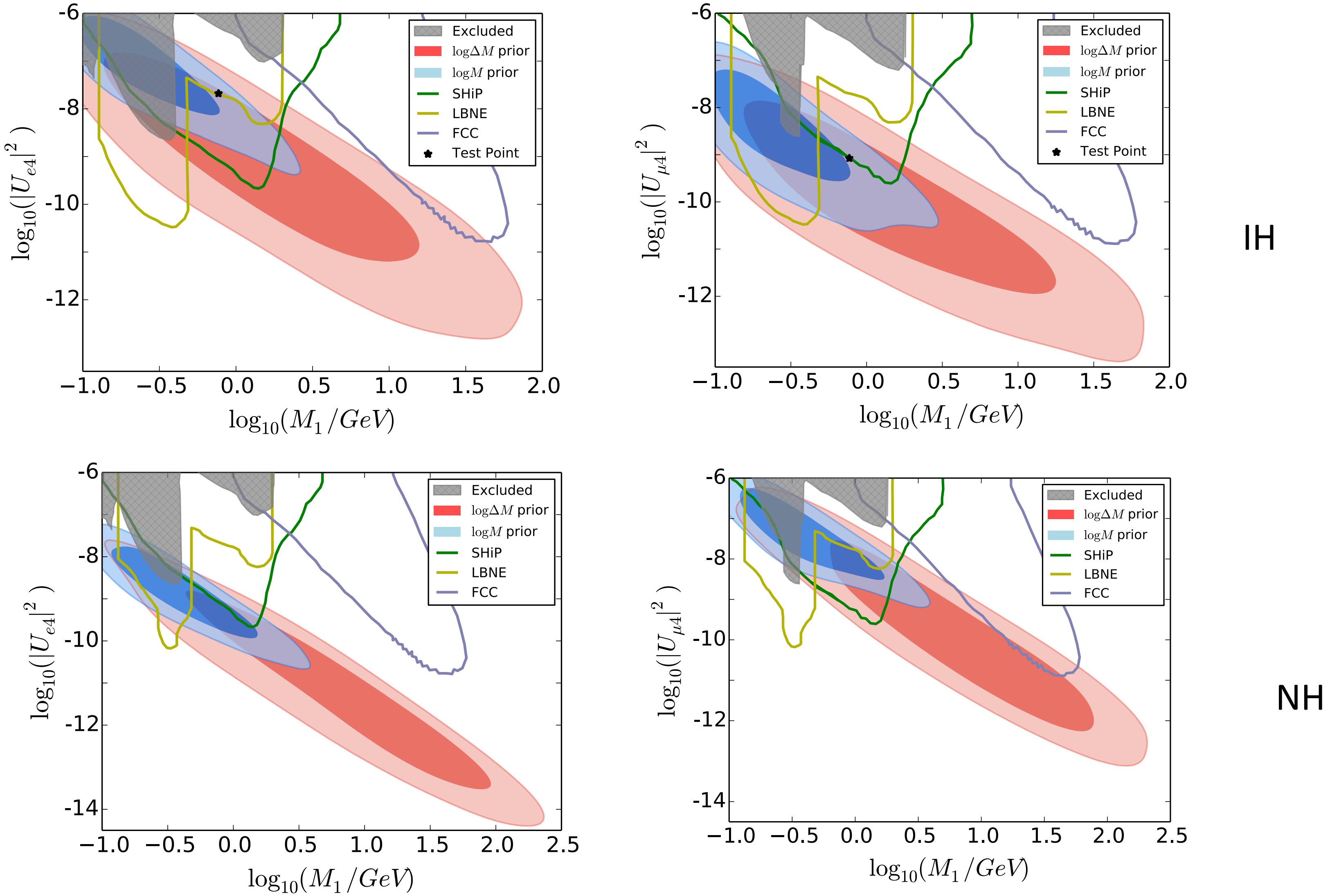
Full exploration of the minimal model N=2

Fine tunning in masses

Generically large non-standard effect in ββ0ν

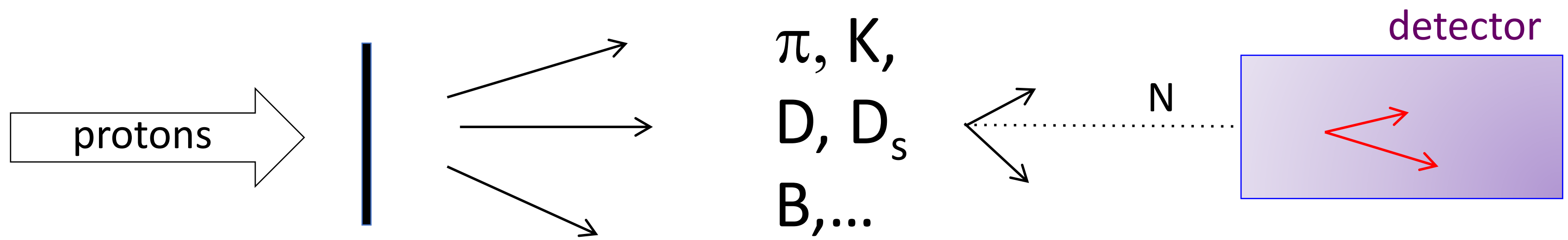


Full exploration of the minimal model N=2



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

Searches in rare meson decays



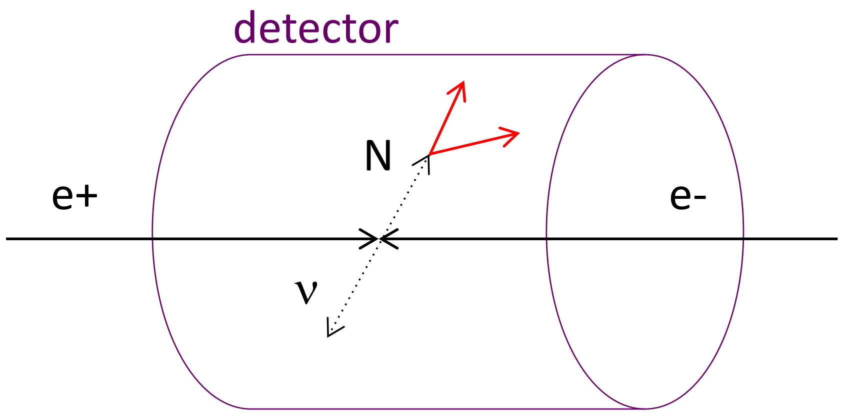
DEEP UNDERGROUND NEUTRINO EXPERIMENT

$M < M_K$

SHiP
Search for Hidden Particles

$M < M_D$

Searches in e+e- @ Z FCCee



Golden signal: displaced vertex

Predicting Y_B in the minimal model N=2 ?

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 new flavour parameters !

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

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

Heavy sector

- Spectrum M_1, M_2 @SHIP
- Complex angle $z = \theta + i\,\gamma$

γ from mixings $|U_{\alpha h}|$ @SHIP

$$|U_{\alpha h}|^2 \propto e^{2\gamma}$$

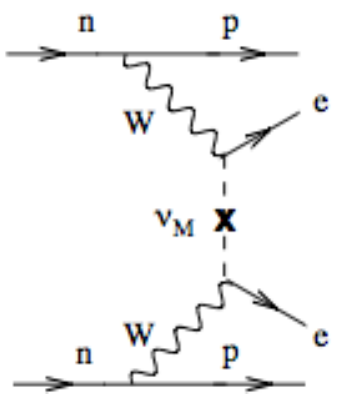
θ from heavy contribution to $\beta\beta 0\nu$!

Light sector

- δ from neutrinos oscillations
- ϕ_1 from light contribution to $\beta\beta 0\nu$
- ϕ_1, δ from flavour ratios $|U_{eh}|/|U_{\mu h}|$ @SHIP

Predicting Y_B in the minimal model N=2

Heavy states also contribute to the ββ0ν amplitude…



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

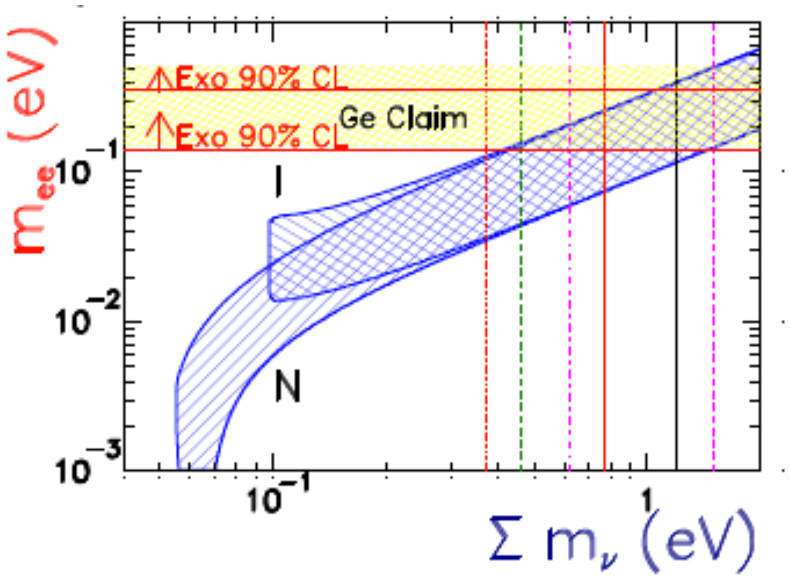
$$M_j \to \infty \qquad \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)} \propto \left(\frac{100 \text{ MeV}}{M_j}\right)^2$$

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

Heavy states also contribute to the ββ0ν amplitude...



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Lopez-Pavon, Pascoli, Wong; Lopez-Pavon, Molinaro, Petcov

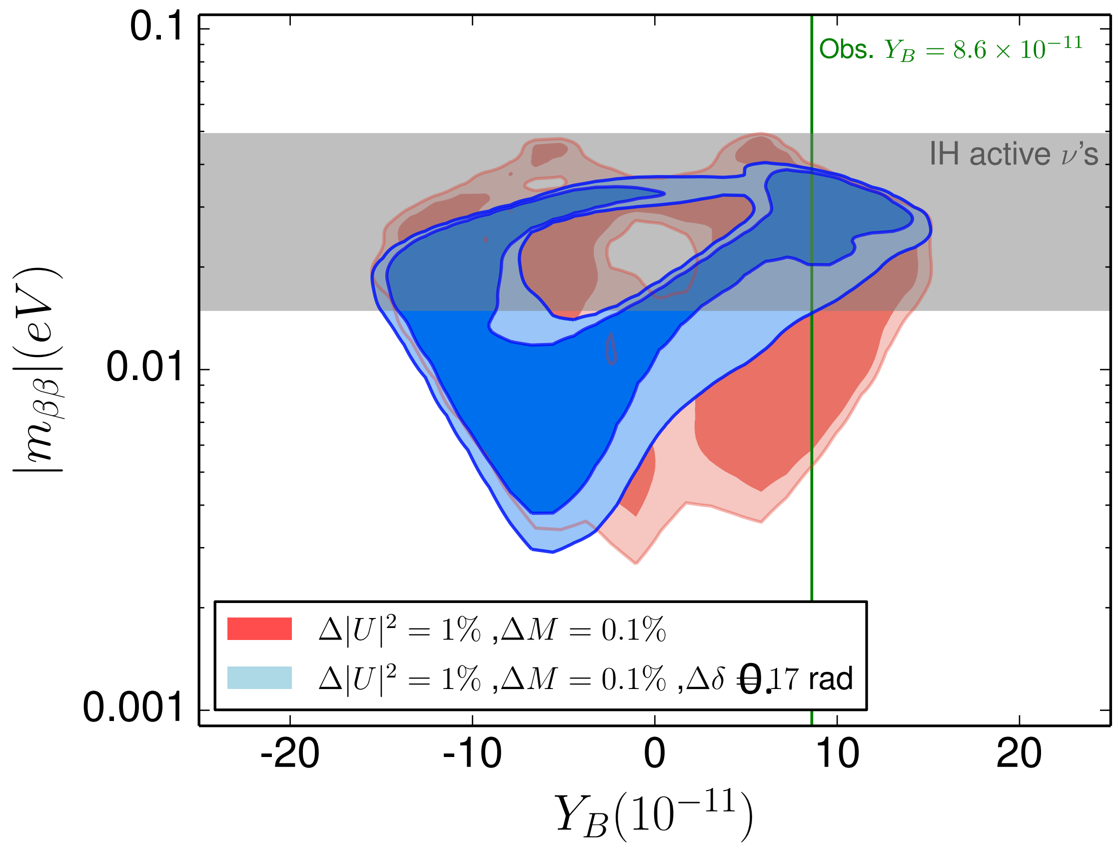
Predicting Y_B in the minimal model N=2 (IH)

$$|m_{\beta\beta}|_{IH} \simeq \sqrt{\Delta m^2_{atm}} \Big| \overbrace{c^2_{13}\left(c^2_{12} + e^{2i\phi_1} s^2_{12}\left(1 + \frac{x^2}{2}\right)\right)}^{\text{Light neutrino contribution}} \tag{4.13}$$

$$\underbrace{- f(A)\, e^{2i\theta} e^{2\gamma}(c_{12} - i e^{i\phi_1} s_{12})^2 (1 - 2e^{i\delta} s_{23}\theta_{13}) \frac{(0.9\,\mathrm{GeV})^2}{4M_1^2}\left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}}\right)^2\right)}_{\text{Heavy neutrino contribution}} \Big| ,$$

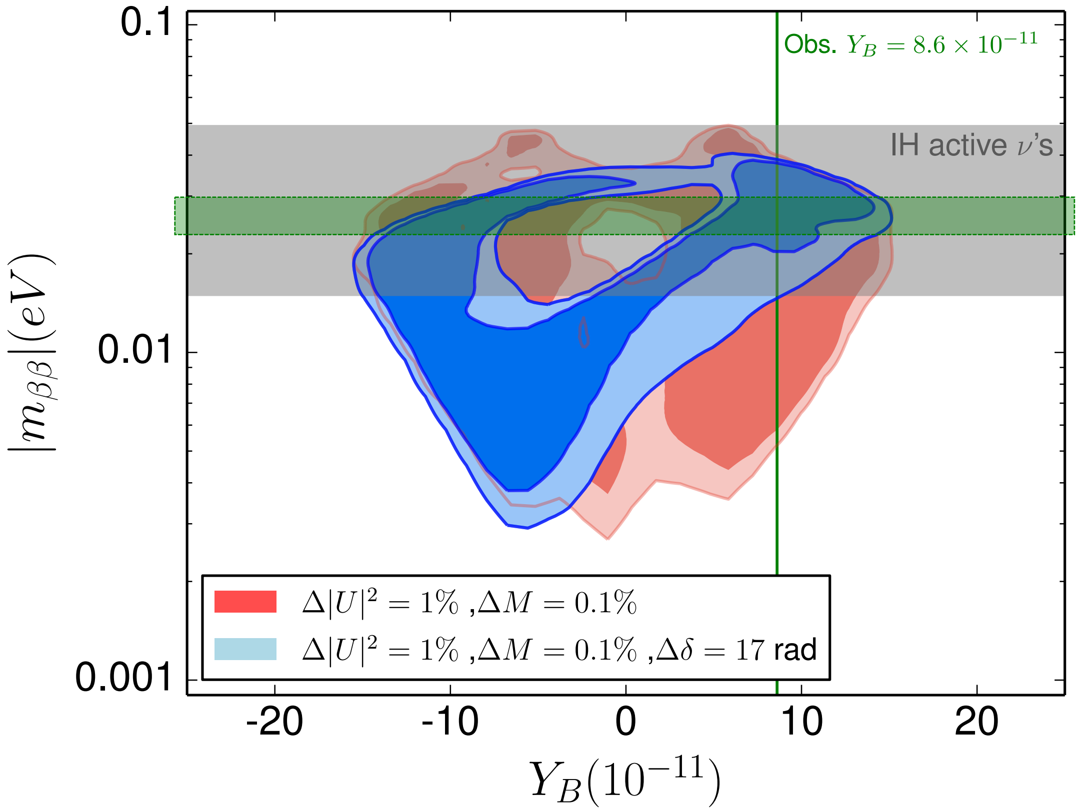
θ controls the interference of heavy and light contributions !

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



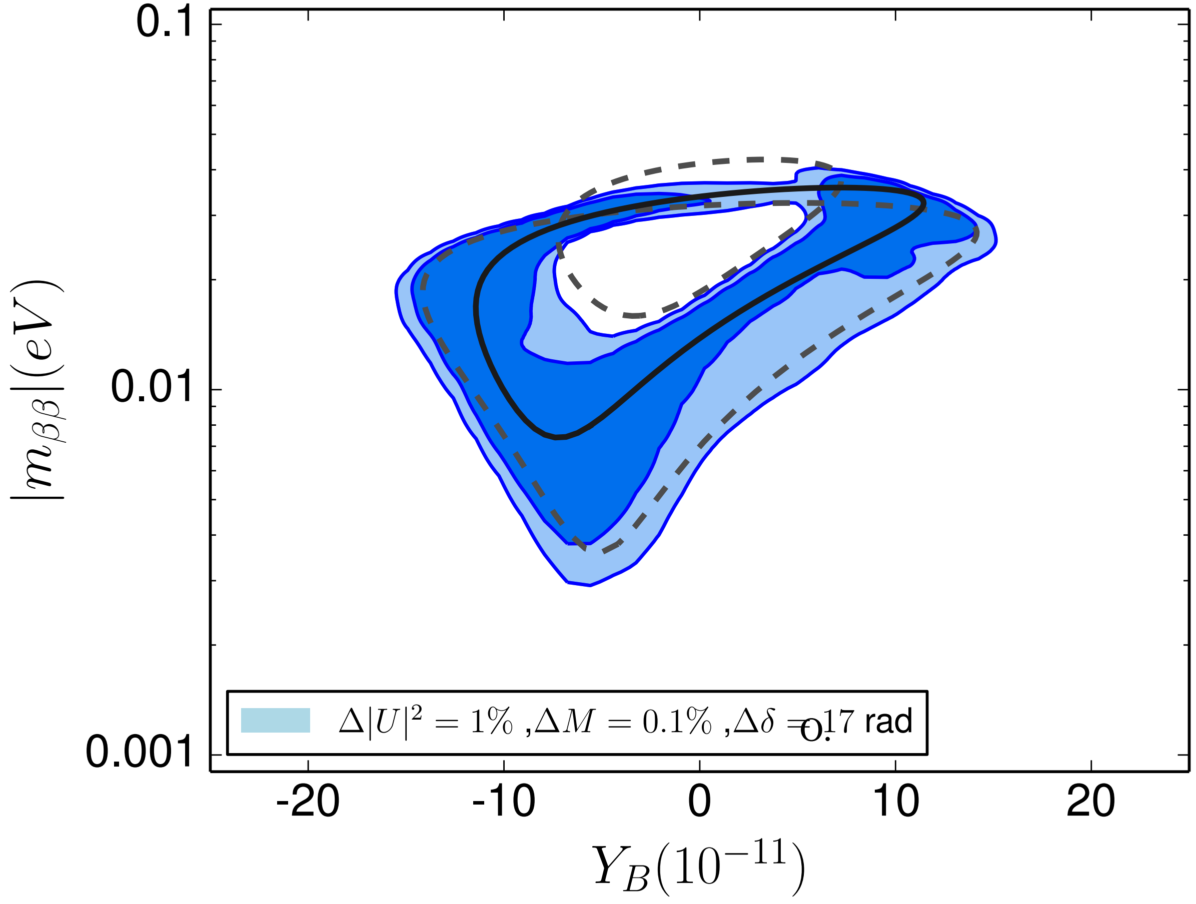
PH, Kekic, López-Pavón, Racker, Salvadó 1606.06719

Predicting Y_B in the minimal seesaw model M~GeV



PH, Kekic, López-Pavón, Racker, Salvadó

A 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 !



Shape can be understood from the residual error in δ

The seesaw path to leptonic CP violation

Caputo, PH, Kekic, Lopez-Pavon, Salvado 1611.05000

Flavour ratios of heavy lepton mixings strongly correlated with $U_{\rm PMNS}$ matrix: δ, ϕ_1

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

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

$$\begin{aligned}|U_{\mu4}|^2 M_1 \simeq |U_{\mu5}|^2 M_2 \simeq A \Bigg[& \left(1 - \sin\phi_1 \sin 2\theta_{12}\left(1+\frac{1}{4}x^2\right) + \frac{1}{2}x^2 c_{12}^2\right) c_{23}^2 \\ & + \theta_{13}(\cos\phi_1 \sin\delta - \sin\phi_1 \cos 2\theta_{12}\cos\delta)\sin 2\theta_{23} \\ & + \theta_{13}^2(1+\sin\phi_1\sin 2\theta_{12}) s_{23}^2 + \mathcal{O}(\epsilon^3) \Bigg],\end{aligned}$$

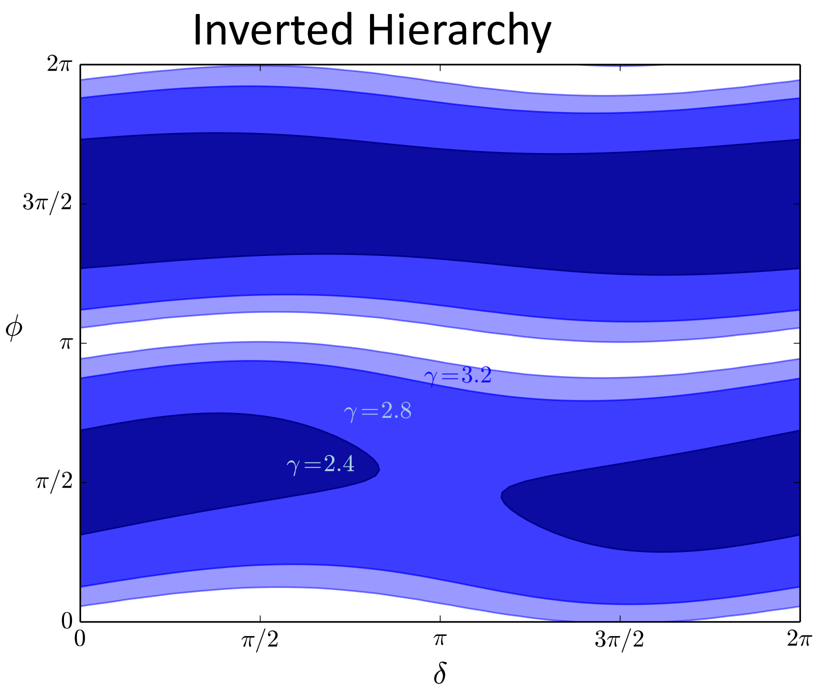
$$A \equiv \frac{e^{2\gamma}\sqrt{\Delta m^2_{atm}}}{4},$$

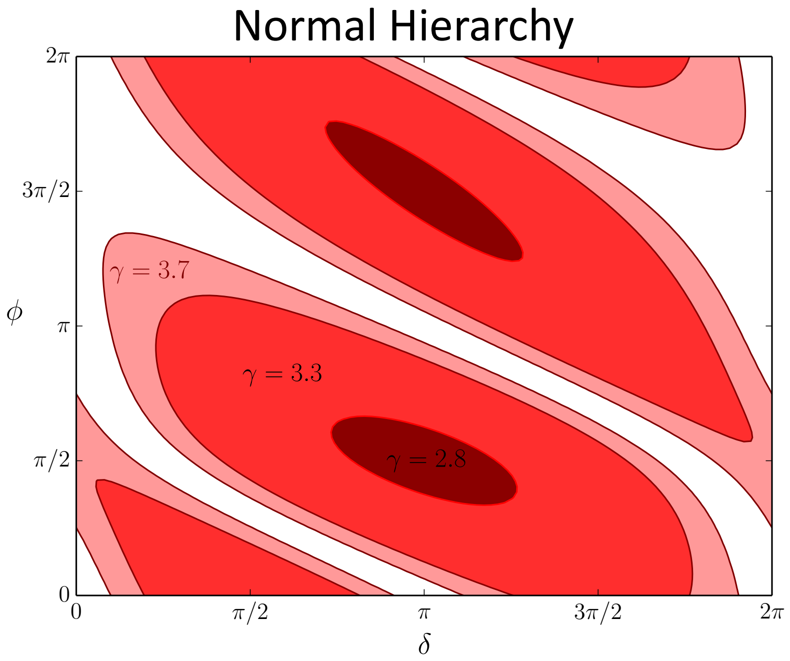
If SHIP/FCC-ee measures the heavy neutrinos and their mixings to e/μ:

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 5σ CL discovery regions



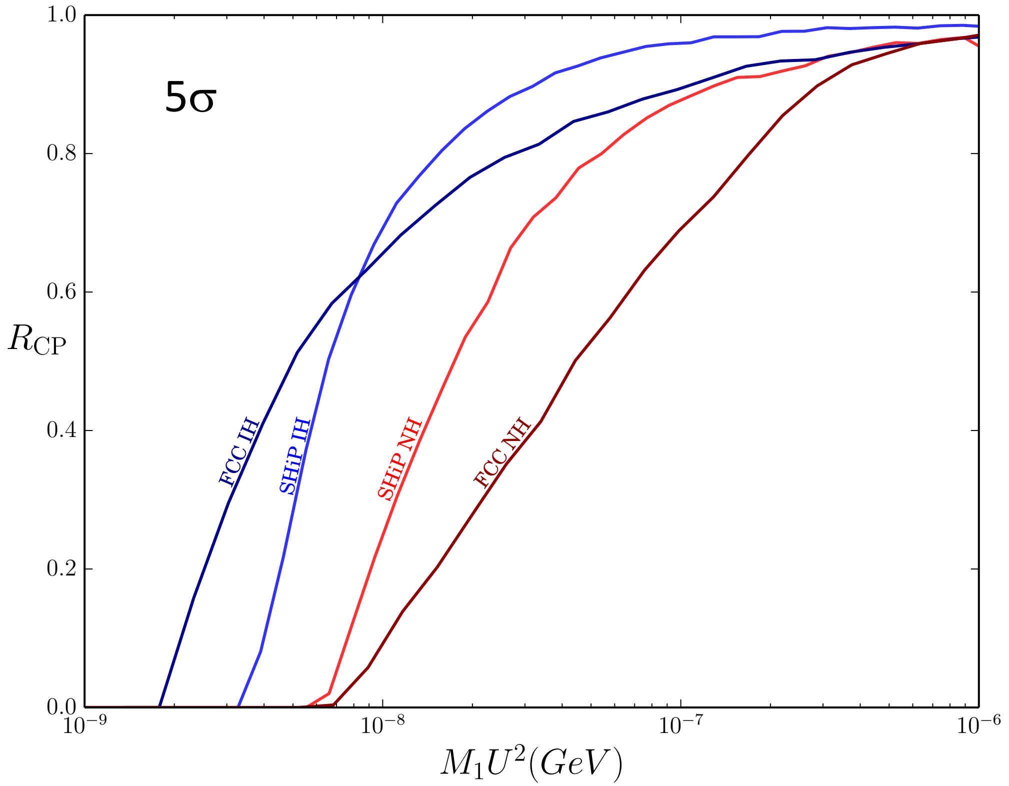


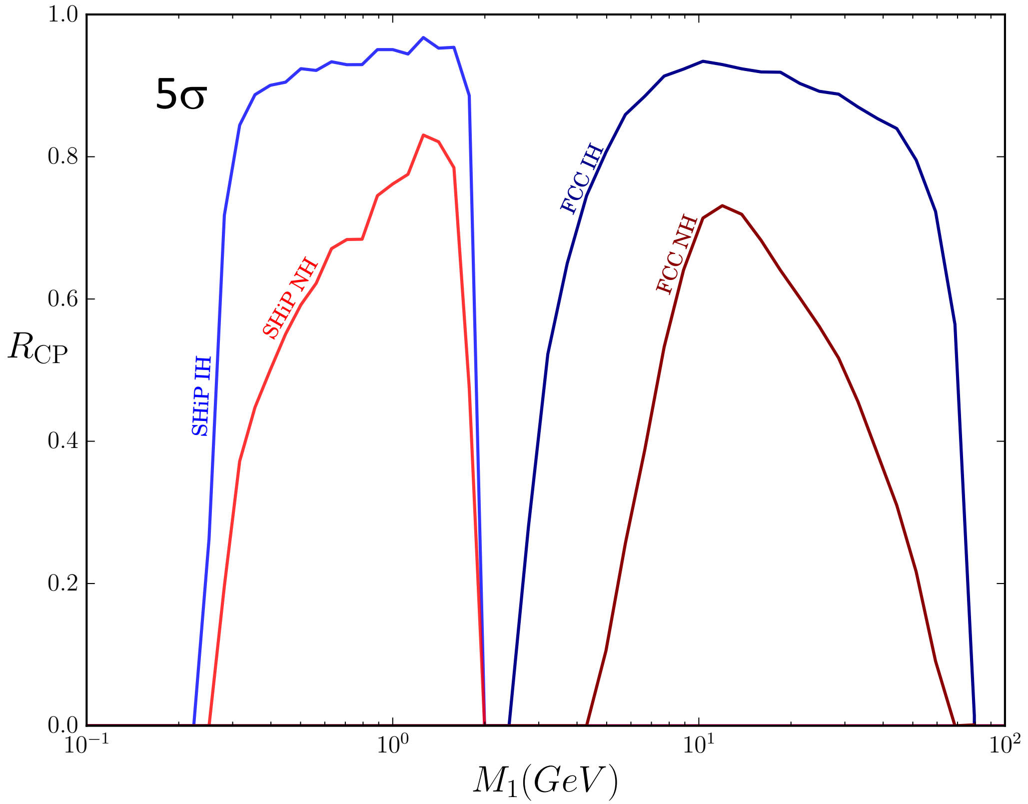
(no systematic error included)

R_{CP}=5σ CP-fraction =

fraction of the area of the CP rectangle which is colored

Discovery potential for leptonic CP violation in mixing





Conclusions

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

- A new scale $\Lambda < v$ could explain the smallness of neutrino masses without introducing stronger flavour hierarchies 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)

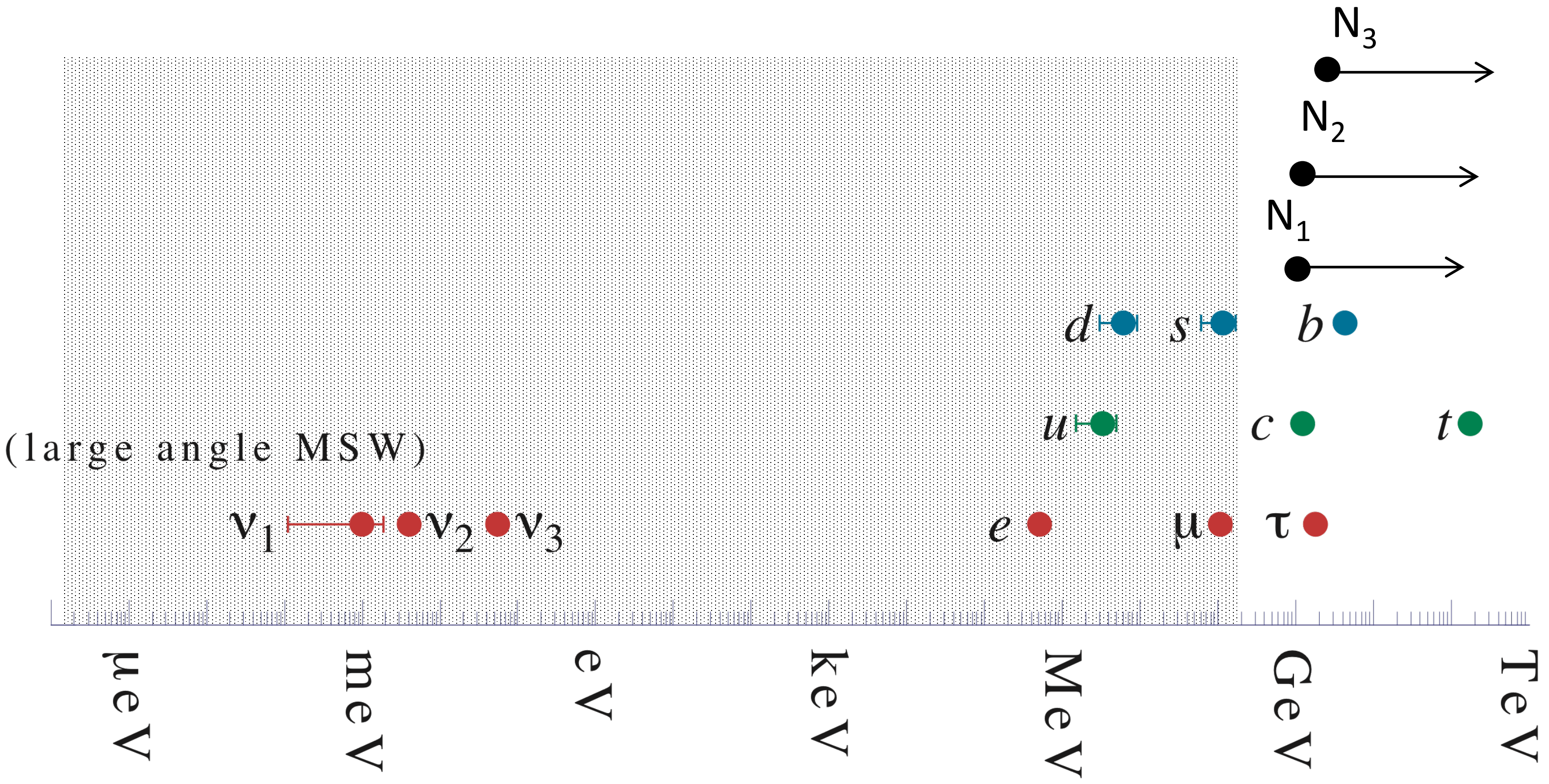
- Complementarity of different experimental approaches: $\beta\beta 0\nu$, CP violation in neutrino oscillations, direct searches in meson decays, colliders…

- Flavour ratios of heavy neutrino mixings strongly correlated with CP phases in U_{PMNS}

BACKUPS

Seesaw scale vs cosmology

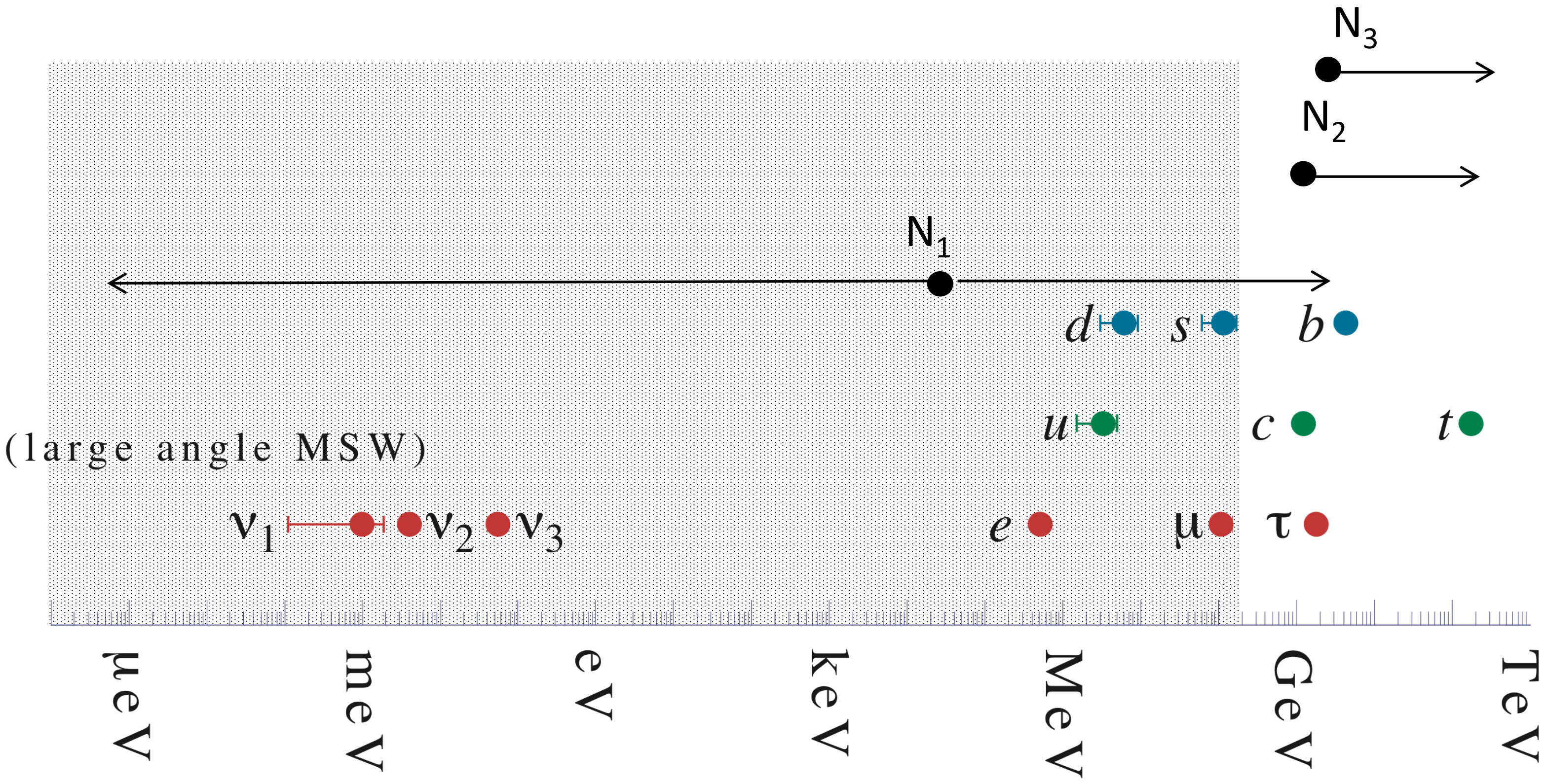
Type I seesaw N =2, 3 that explains neutrino masses



$m_{lightest} > 3.2 \ \text{x} \ 10^{-3}\,\text{eV}$

PH, M. Kekic, J. López-Pavon

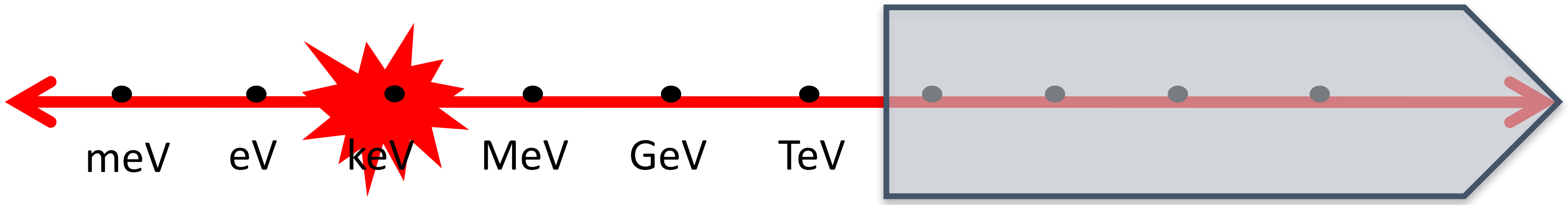
Type I seesaw N =3 that explains neutrino masses



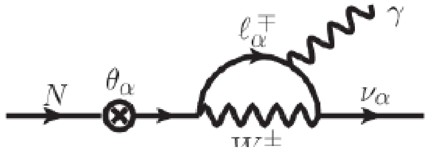
$m_{lightest} < 3.2 \times 10^{-3}$ eV

PH, M. Kekic, J. López-Pavon

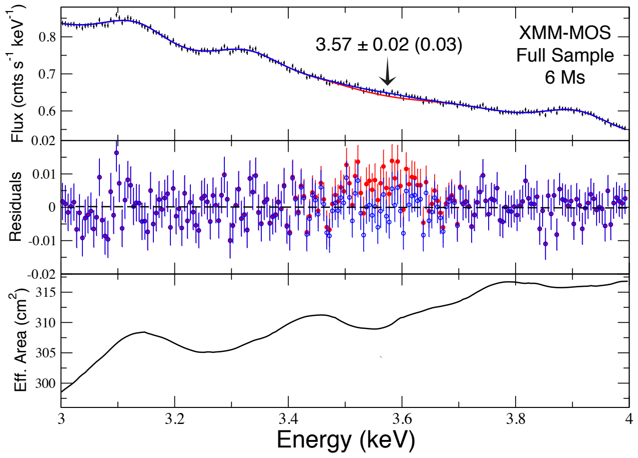
νMSM: Warm Dark Matter ?

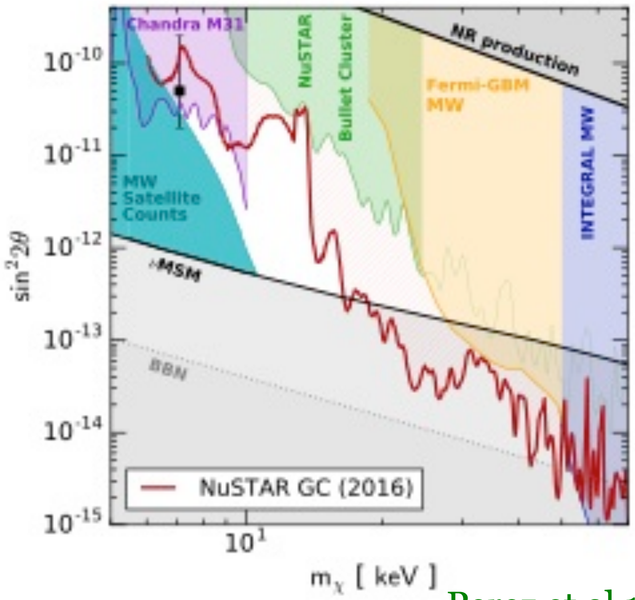


Dodelson, Widrow; Fuller et al…; Shaposhnikov et al…



7 keV neutrino ?





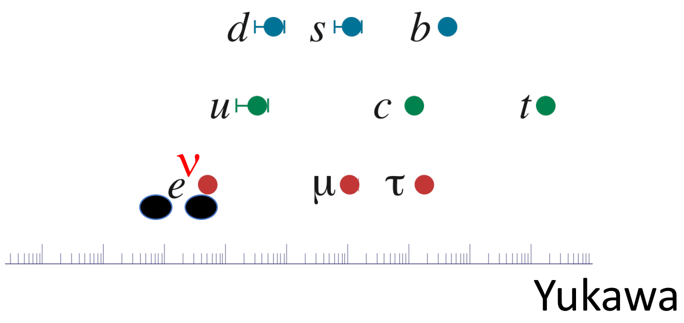
Bulbul et al 1402.2301; Boyarsky 1402.4119

Perez et al 1609.00667

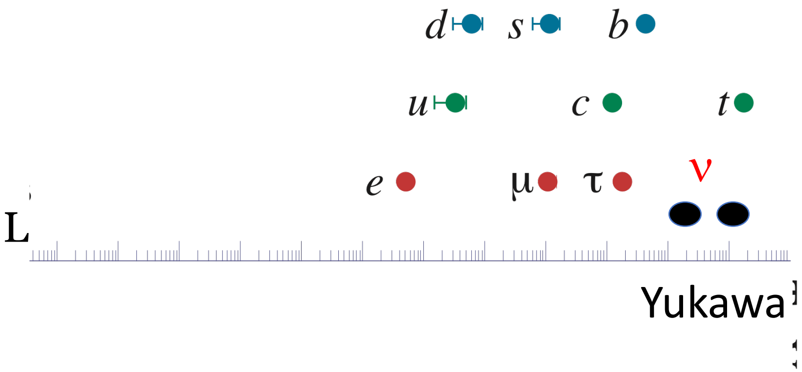
Caveat: huge lepton asymmetries are necessary, otherwise cannot produce sufficient DM !

Charged/neutral hierarchy in seesaw

M_N = TeV



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



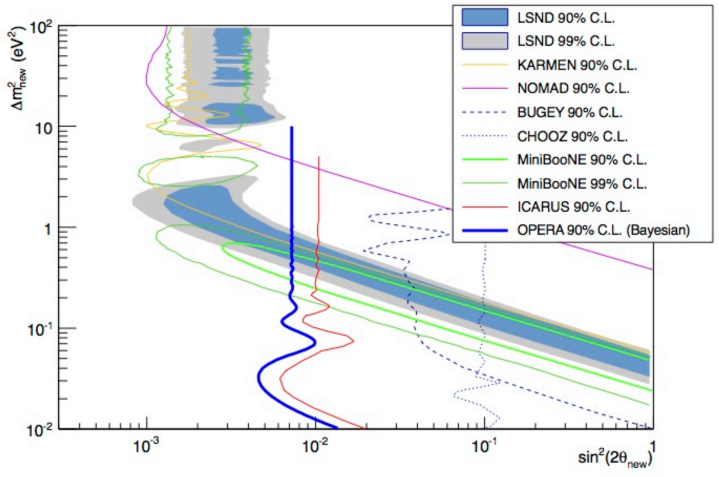
Room for improvement in these searches at LHC, LFV, future colliders: but
Must look for not lepton number violating processes

Outliers: SBL anomalies

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

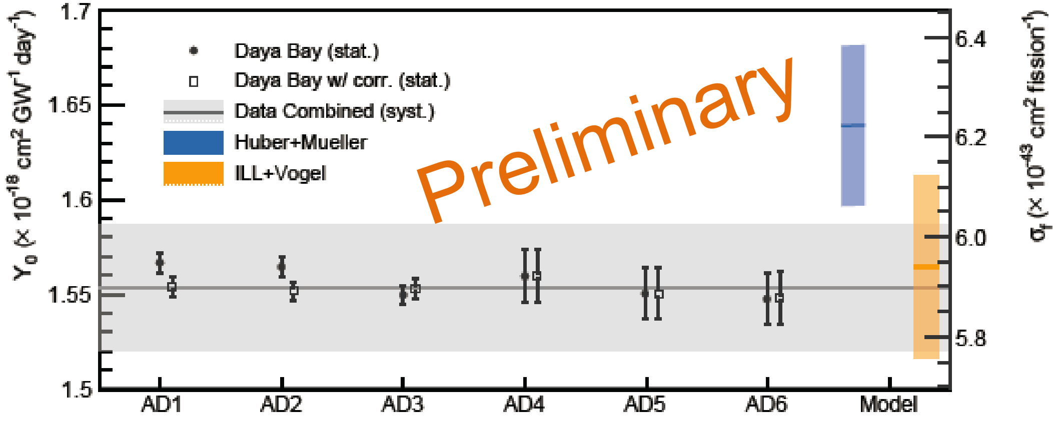
LSND

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



Reactors

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



T. A. Mueller et al; P. Huber

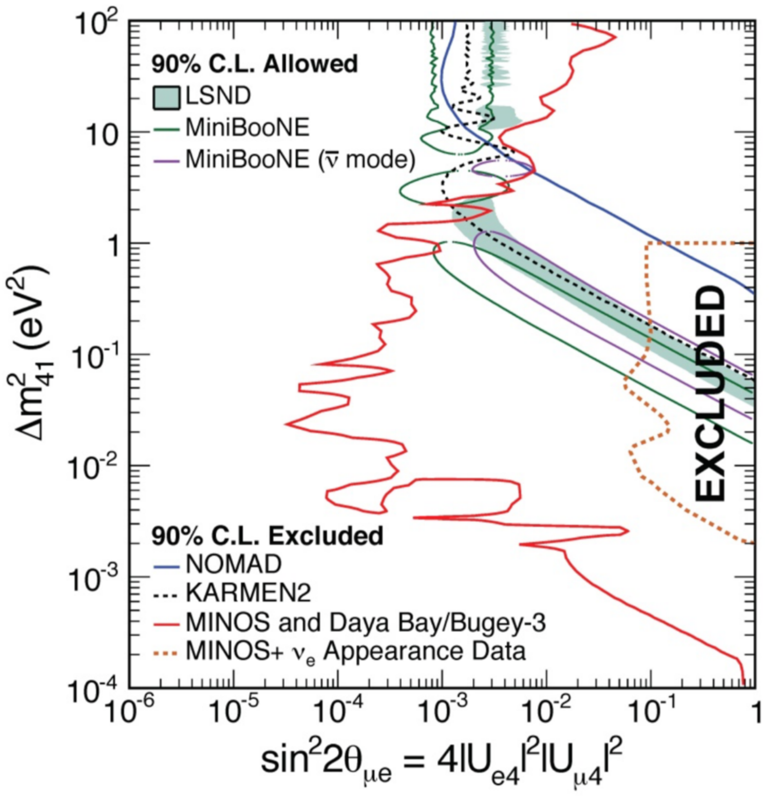
+Gallium anomaly+ MiniBOONE low-energy excess…

O(eV) sterile neutrinos ?

Two necessary smoking guns not found

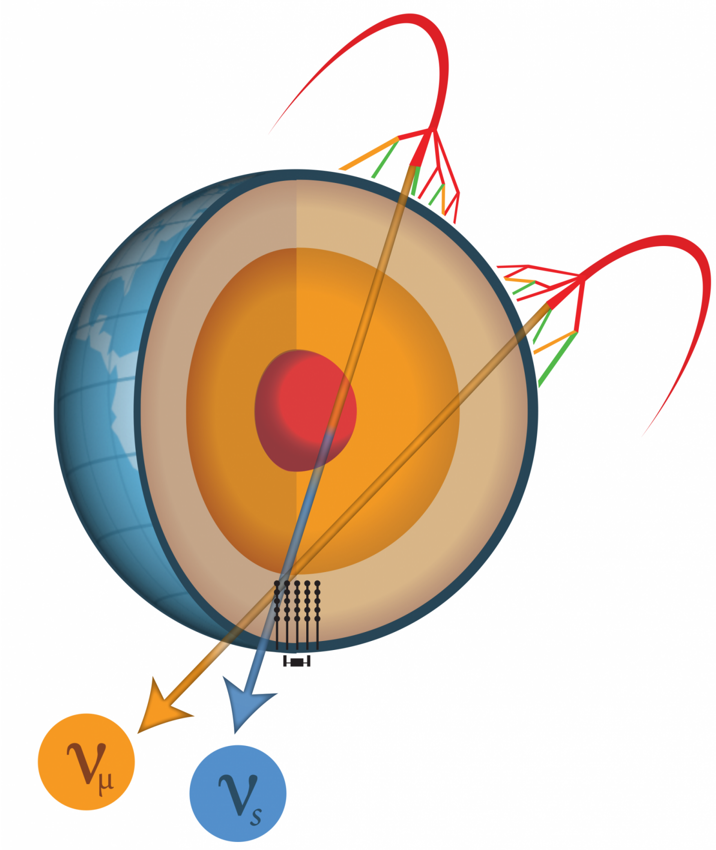
Neutrino muons must disappear also $P(\nu_\mu \to \nu_\mu) = O(|U_{\mu i}|^2)$

MINOS+Daya Bay

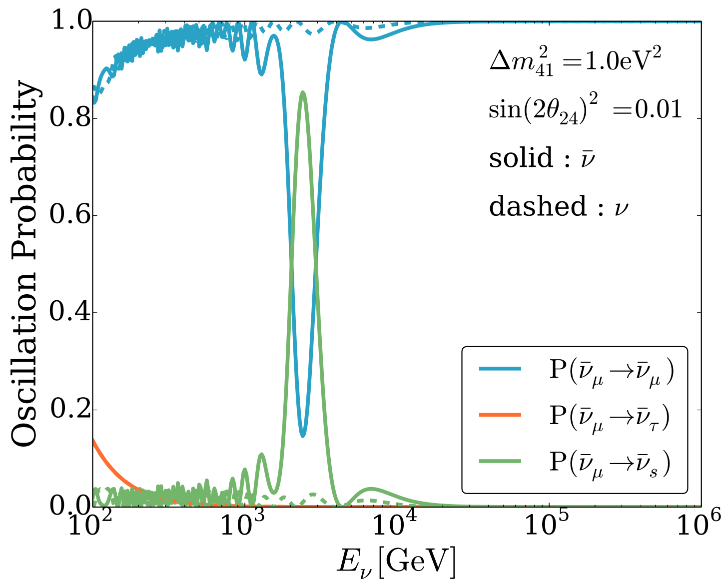


O(eV) sterile neutrinos?

Atmospheric neutrinos must resonate into steriles when crossing the nucleus of the Earth

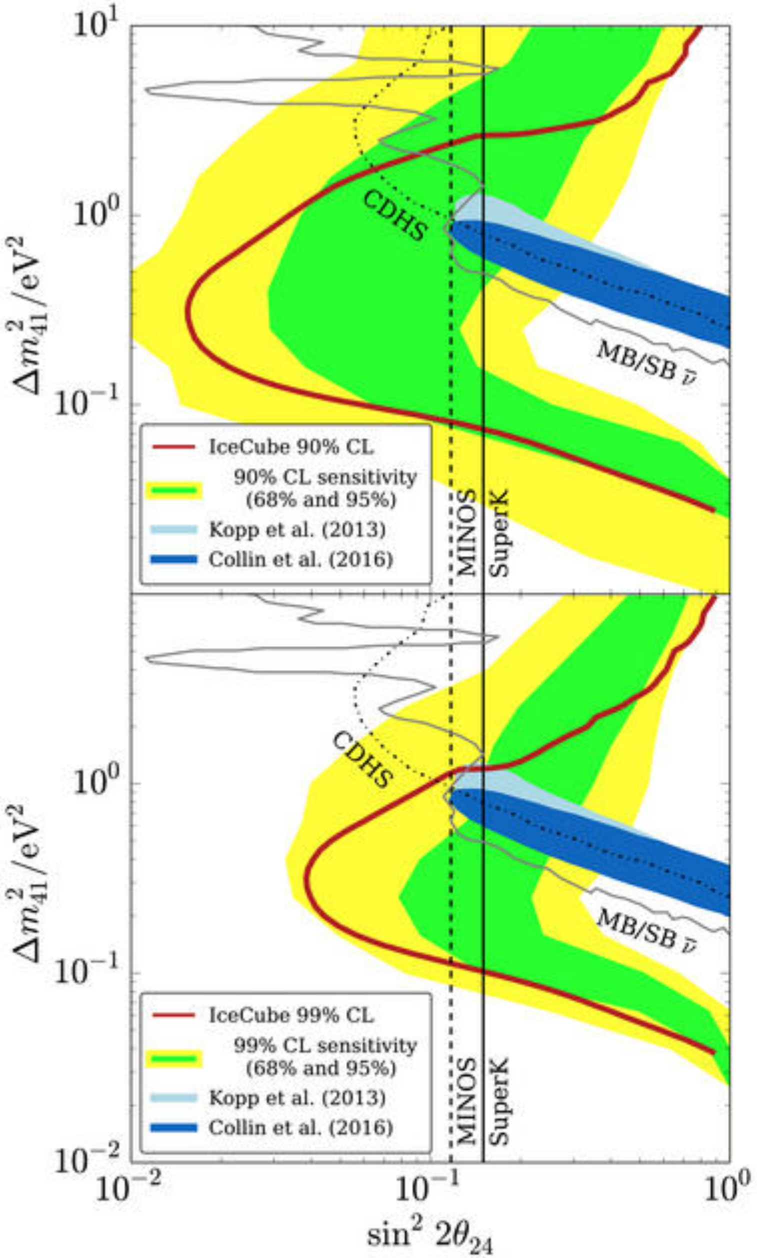


$$E_\nu^{\rm res} \equiv \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N_e} \sim \mathcal{O}(TeV)$$



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

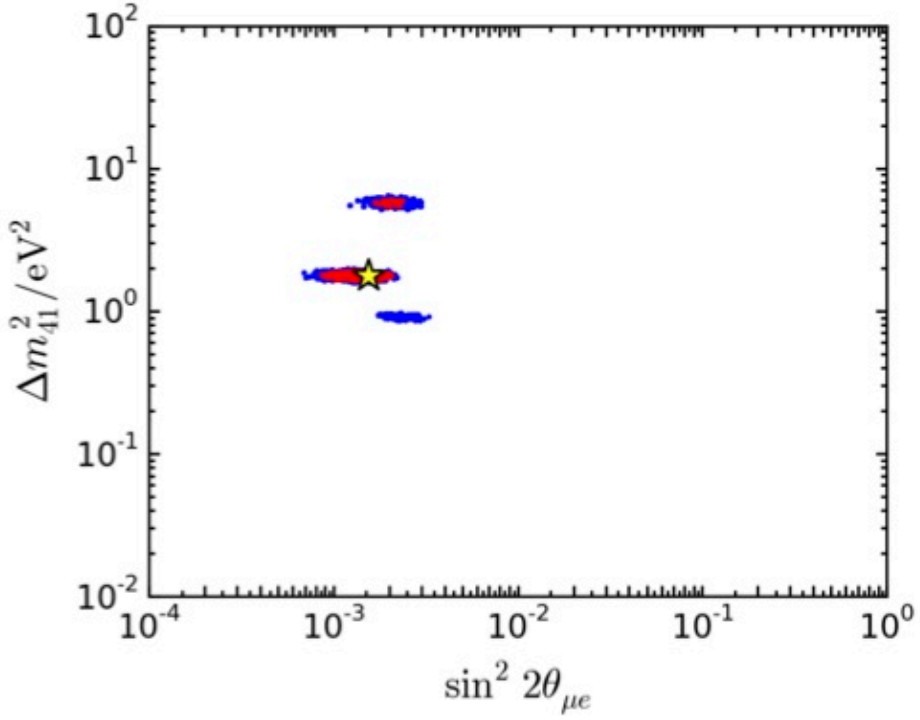
O(eV) sterile neutrinos ?



IceCube coll. ‘16

O(eV) sterile neutrinos ?

Getting squeezed into inexistence…

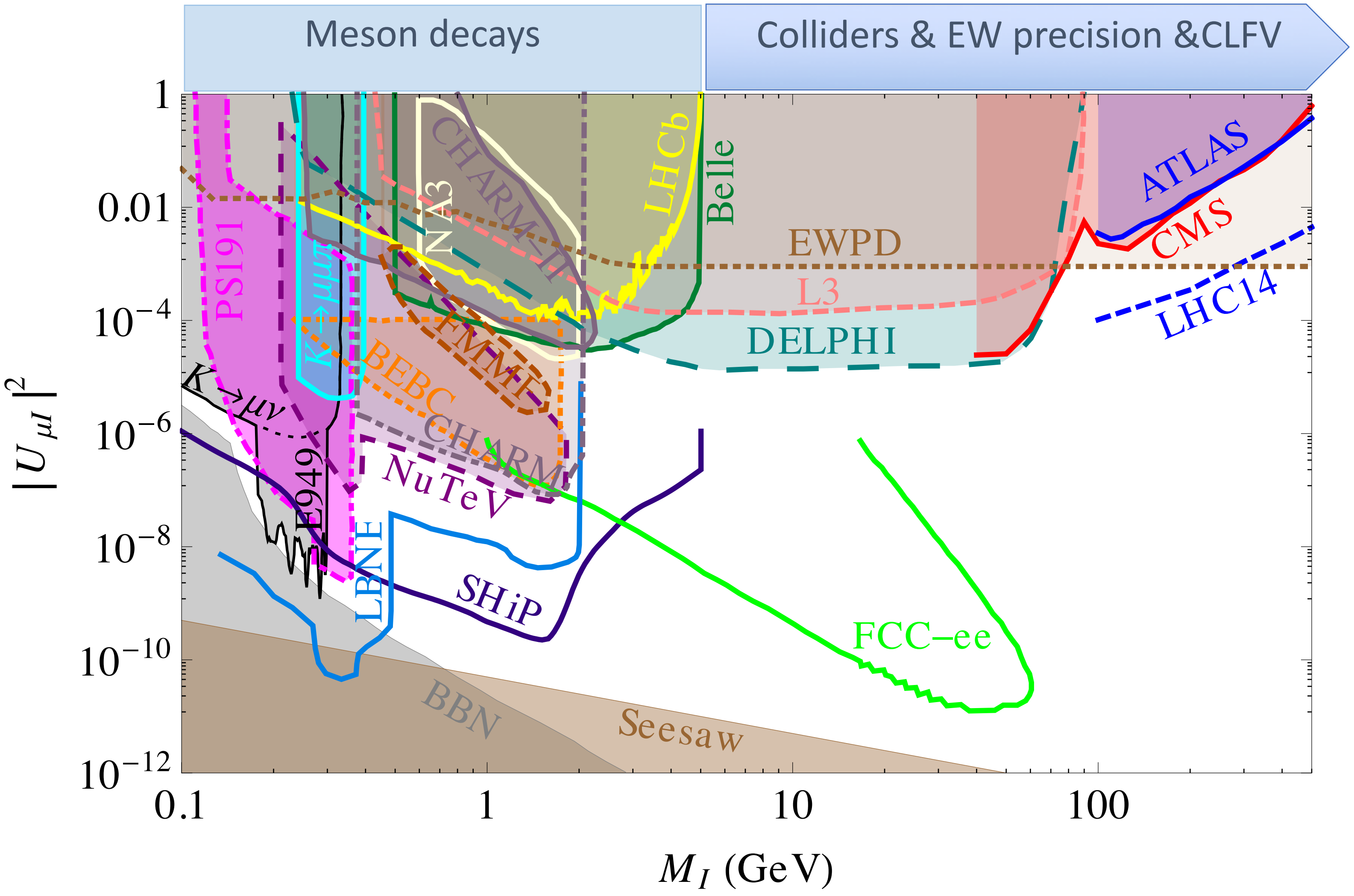


Collin, Argüelles, Conrad, Shaevitz ‘16

Probably a rather bad fit to all data…

Larger Mixings ?

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



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

- In some cases unnatural:

cancellation between tree level and 1 loop contribution to neutrino masses

Lopez-Pavon, Pascoli, Wang

- But also technically natural textures:

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

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

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

Seesaw models + approx $U(1)_L$

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

Neutrino masses proportional to the small breaking terms

$$\begin{array}{cc} \mathrm{L}= & \begin{array}{ccc} +1 & +1 & -1 \end{array} \\ & \begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix} \end{array}$$

Inverse Seesaw

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

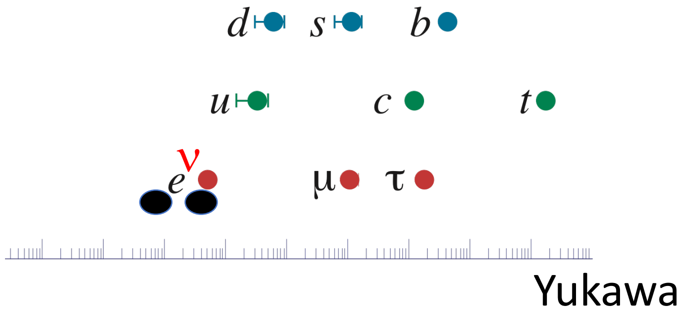
Direct Seesaw

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

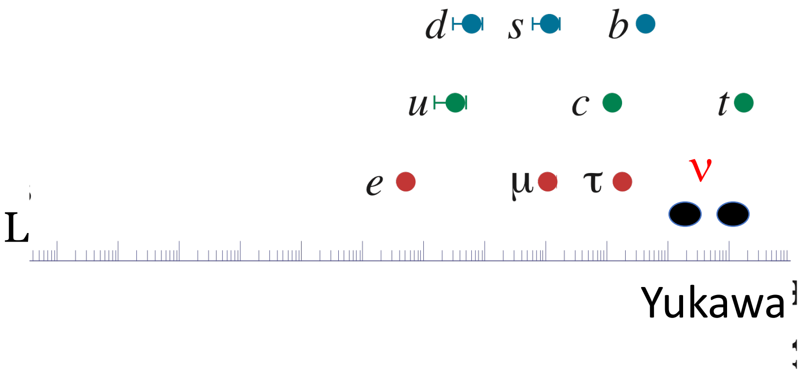
They are all a subclass of type I seesaw models (different choices of R)

Charged/neutral hierarchy in seesaw

M_N = TeV



M_N ≤ TeV + aprox. $U(1)_L$



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What about mixing ?

- Anarchy for leptons ?

  Murayama, Naba, De Gouvea

- Discrete symmetries: e.g. tri-bimaximal mixing   Harrison, Perkings, Scott

  not so much motivated with large θ_{13} -> understanding corrections

  -> + GUTs

- Minimal flavour violation and dynamical origin of Yukawas

  R. Alonso, et al