Neutrino Physics: theory and phenomenology

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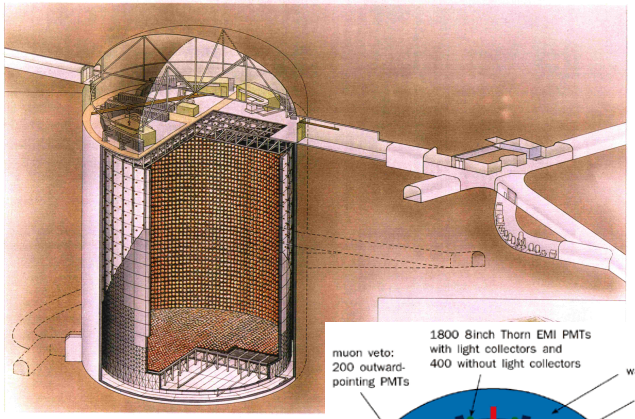
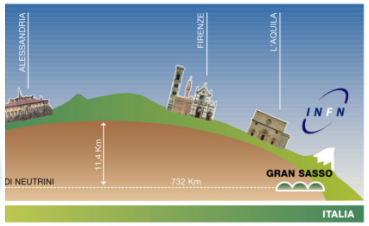
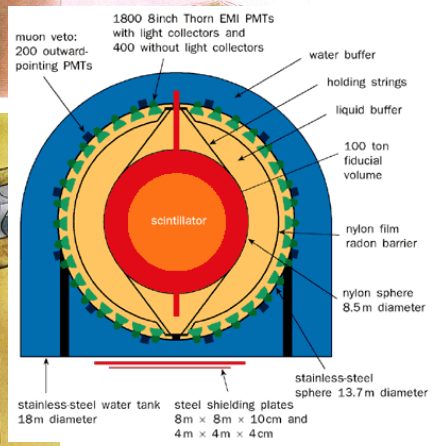
Almost 2 decades of revolutionary neutrino experiments have revealed a new flavour sector, which does not quite fit in the Standard Model

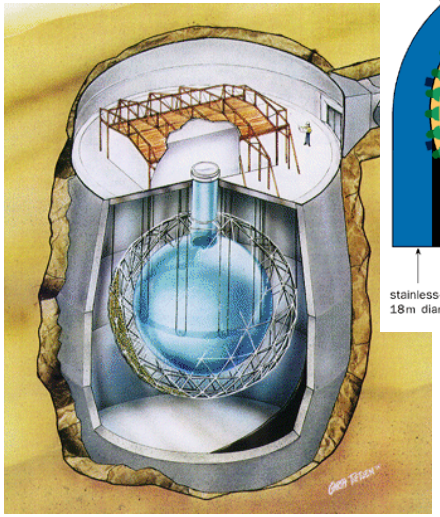
MINOS, Opera

SuperKamiokande





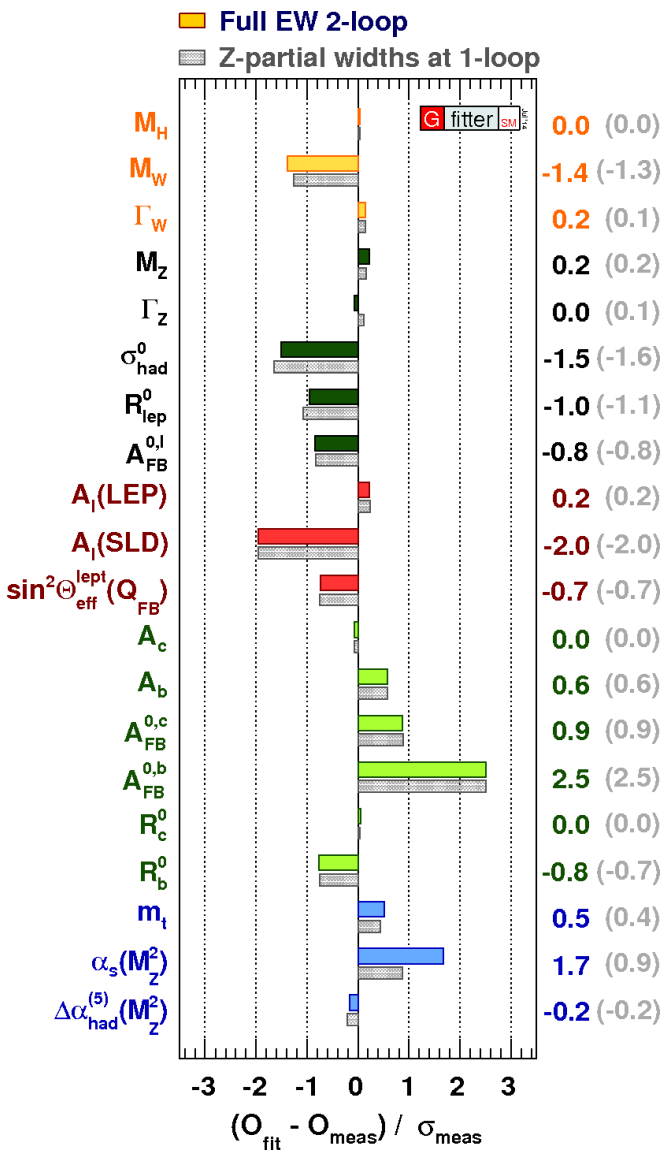




SNO

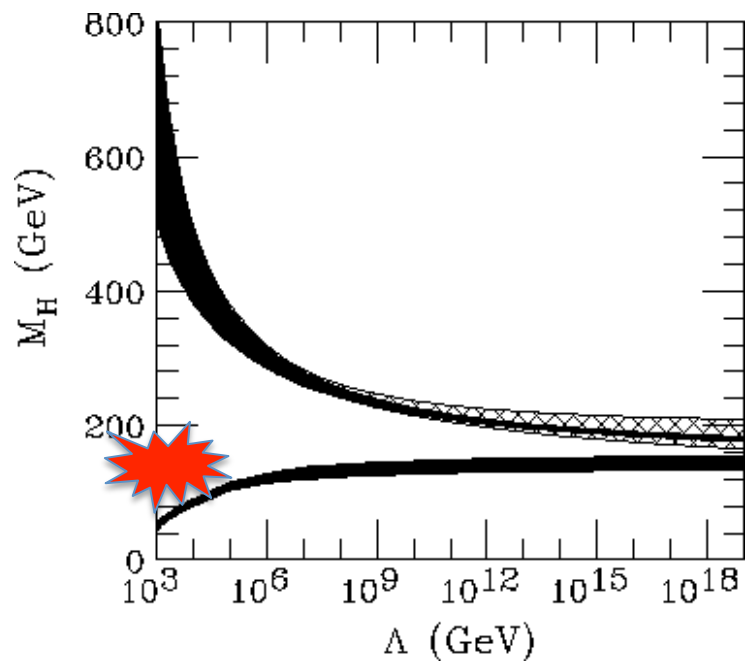
Borexino

...and more



After the discover the Brout-Englert-Higgs particle

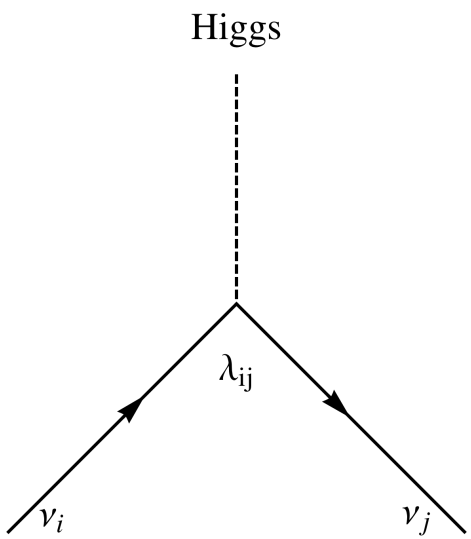
Standard Model as healthy as ever...



What about neutrinos ?

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

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

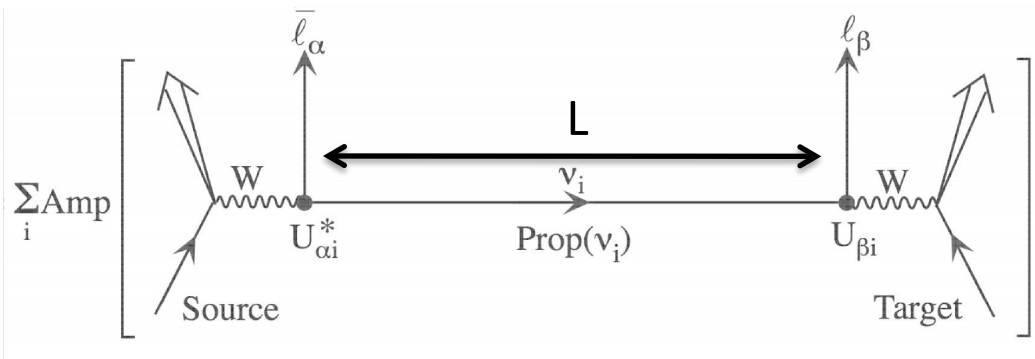


$$m_\nu \sim \lambda v$$

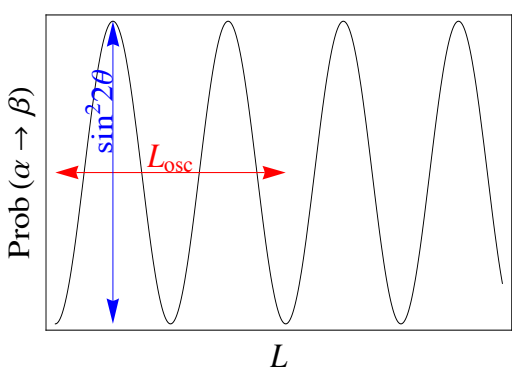
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, ...) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

At least two ν_R....

Neutrino Interferometry

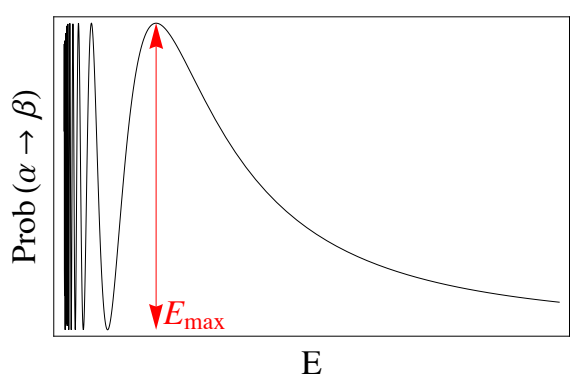


A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances !

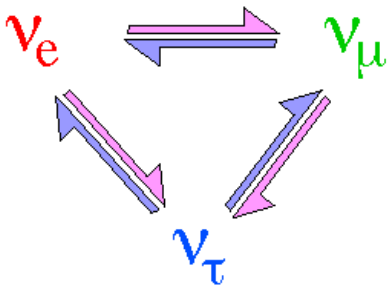


$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{(m_i^2 - m_j^2)L}{2E}}$$

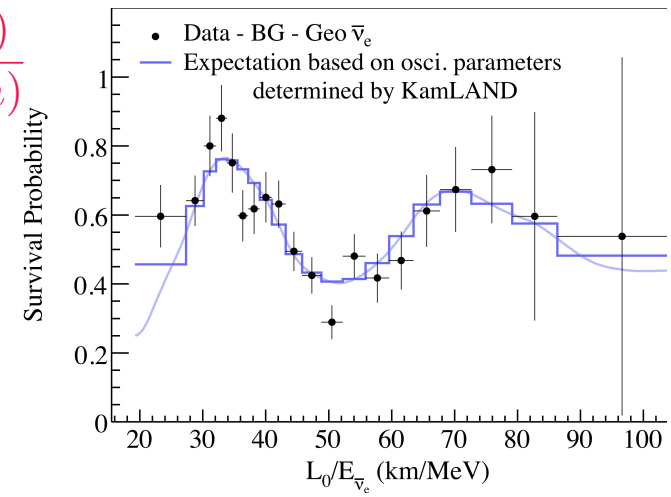
$$L_{osc} \sim \frac{E}{m_i^2 - m_j^2}$$



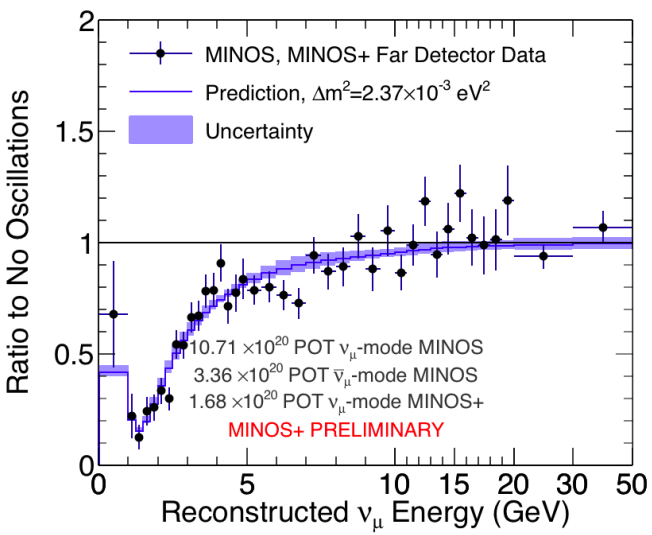
Two frecuencies precisely measured

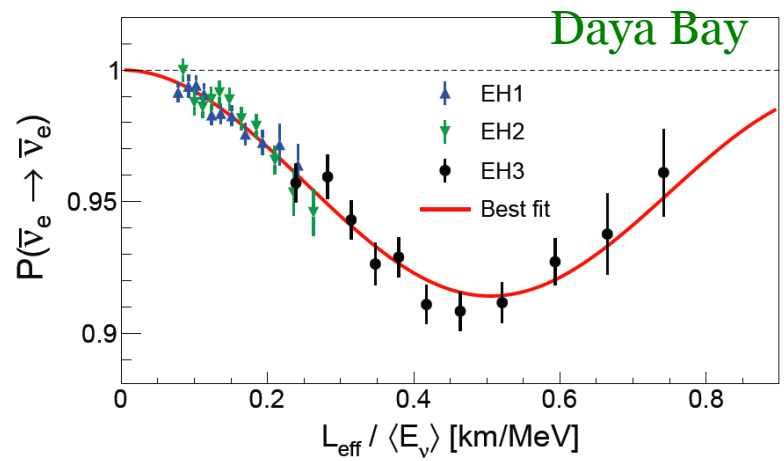


$$\Delta m^2_{\rm sol} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(100km)}$$



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





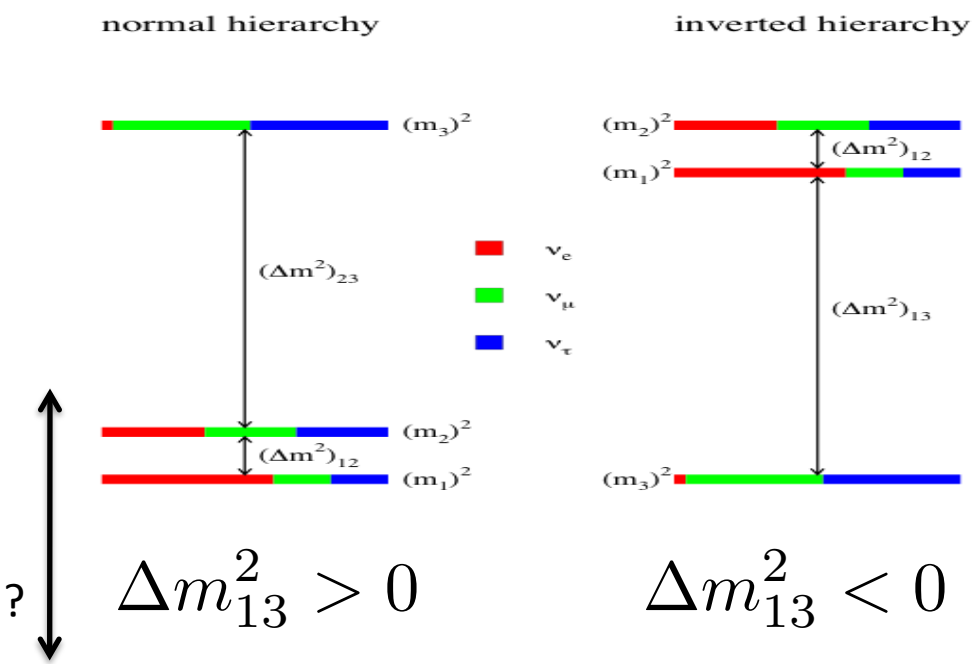
Precision era has arrived: effects from the two frecuencies sizeable

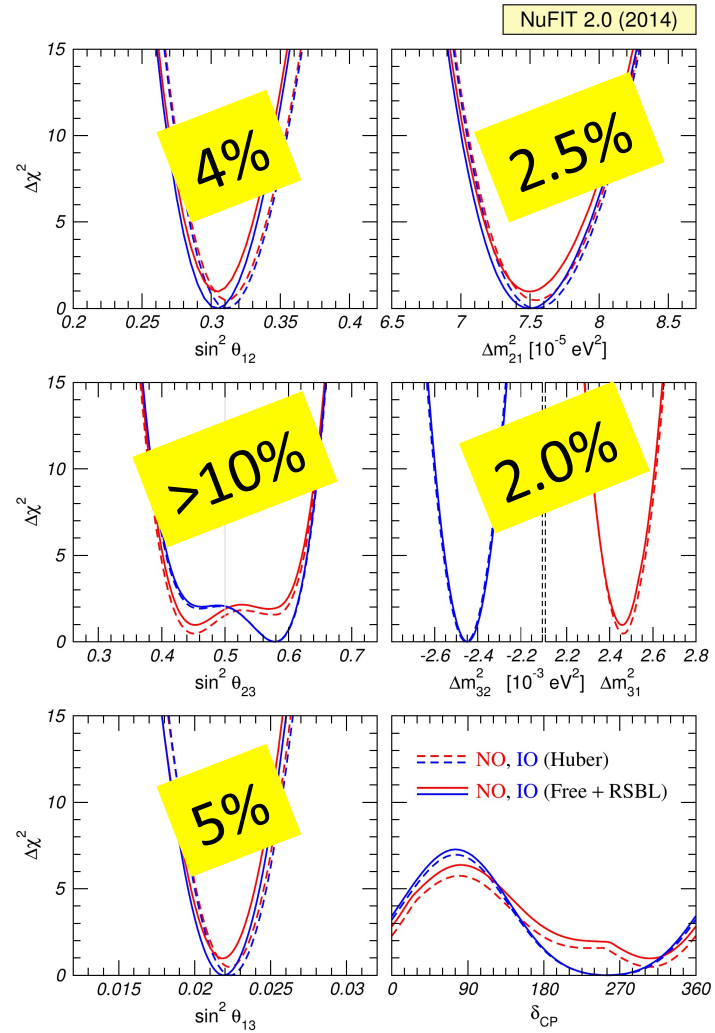
-> different experiments need each other to fix their unkowns

SM+3 massive neutrinos: Global Fits

Marrone's Parallel talk

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

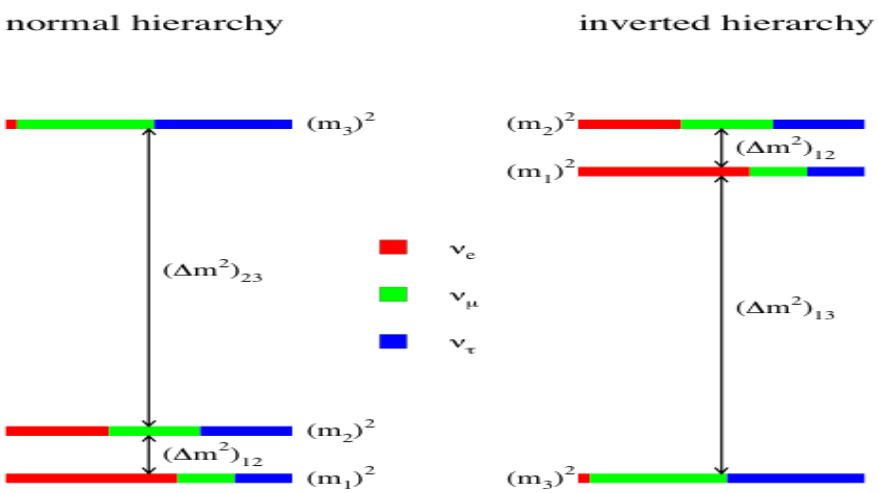


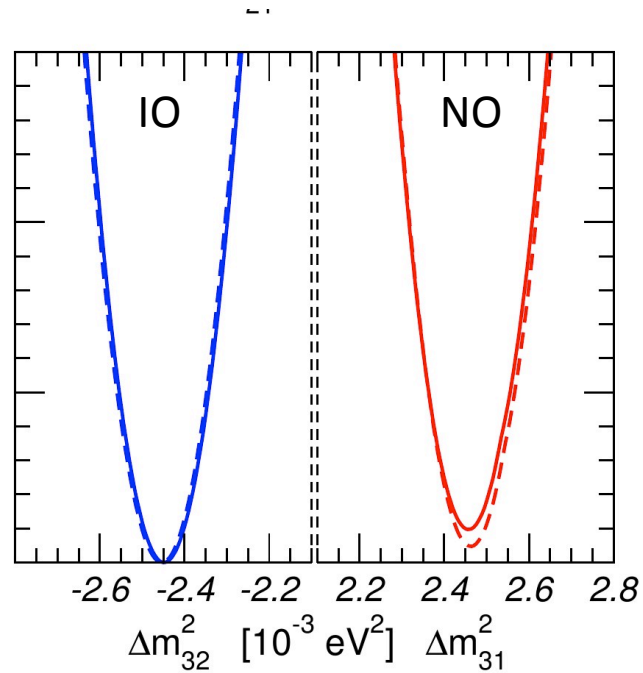


Gonzalez-Garcia et al 1409.5439

See also Capozzi et al, 1312.2878 and Forero et al, 1405.7540

Mass ordering degeneracy





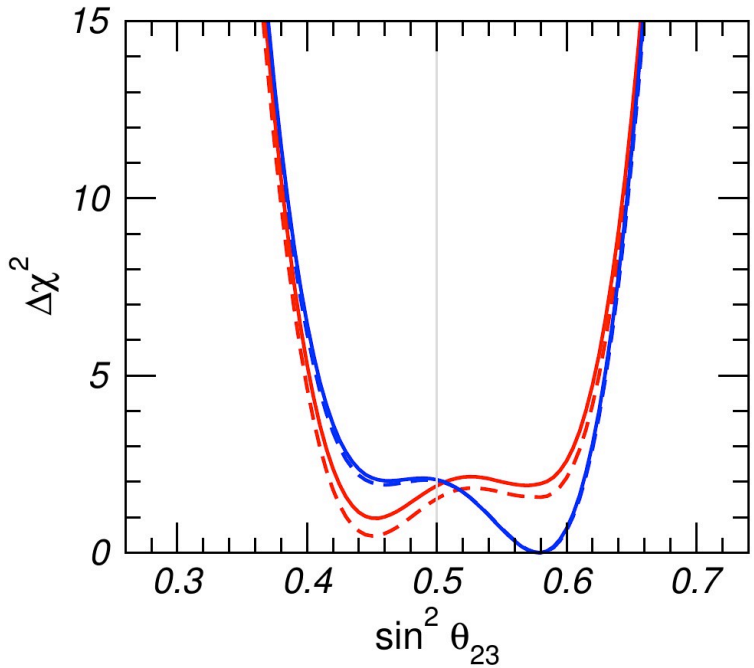
$$\Delta\chi^2 \leq 1\sigma$$

Gonzalez-Garcia et al 1409.5439

No clear tendency: different data sets point in different directions....

θ_{23} octant degeneracy

$$\Delta\chi^2 \leq 1.4\ (1.0)\sigma$$



Gonzalez-Garcia et al 1409.5439

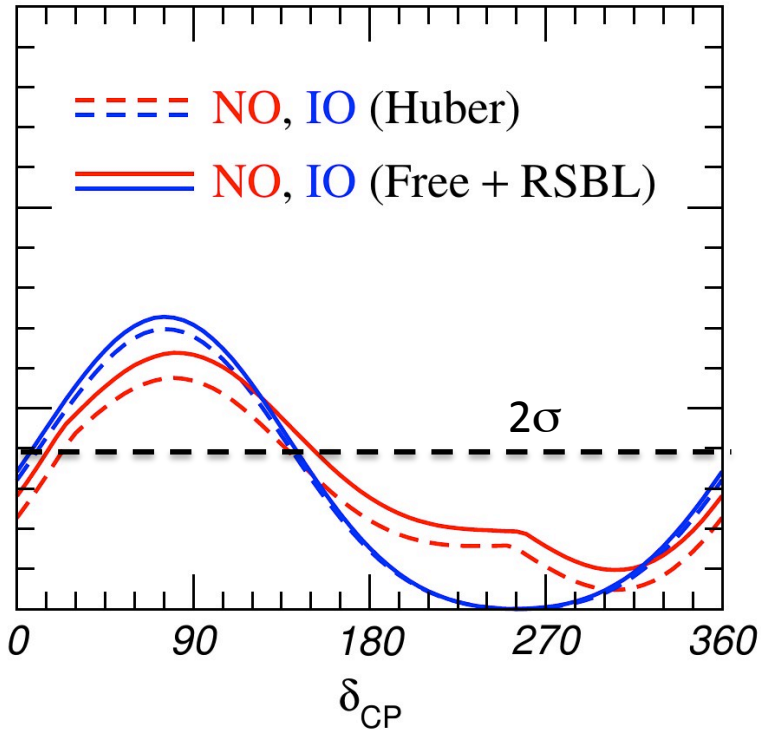
Preference for non-maximal mixing: $\theta_{23} > 45^o$ IO, $\theta_{23} < 45^o$ NO

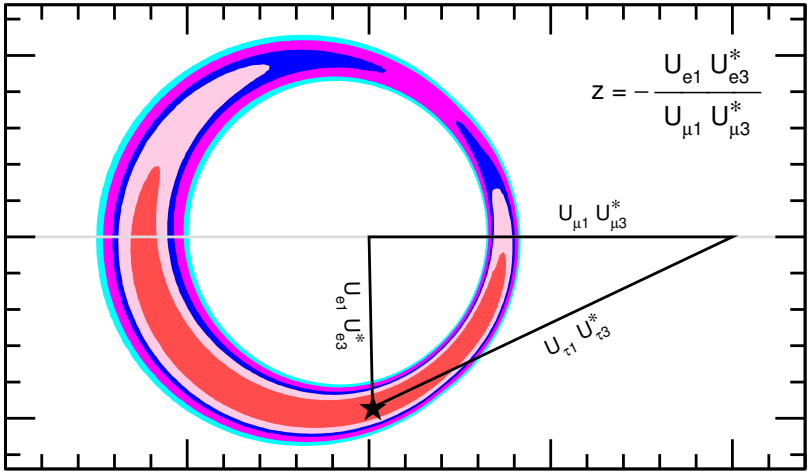
1) MINOS disappearance -> non-maximality

2) θ_{13}(reactor) < θ_{13}(T2K) relieved by non-maximality (depends on IO/NO and δ)

3) Atmospheric data neutral for IO or adds positively for NO

Leptonic CP violation



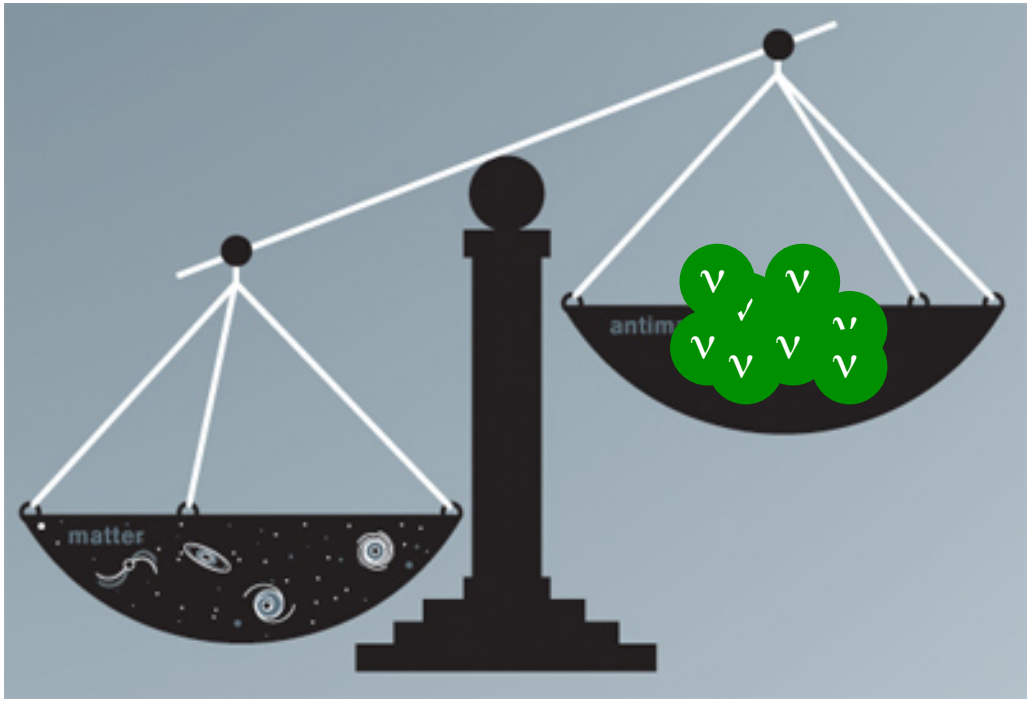


Gonzalez-Garcia et al 1409.5439

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

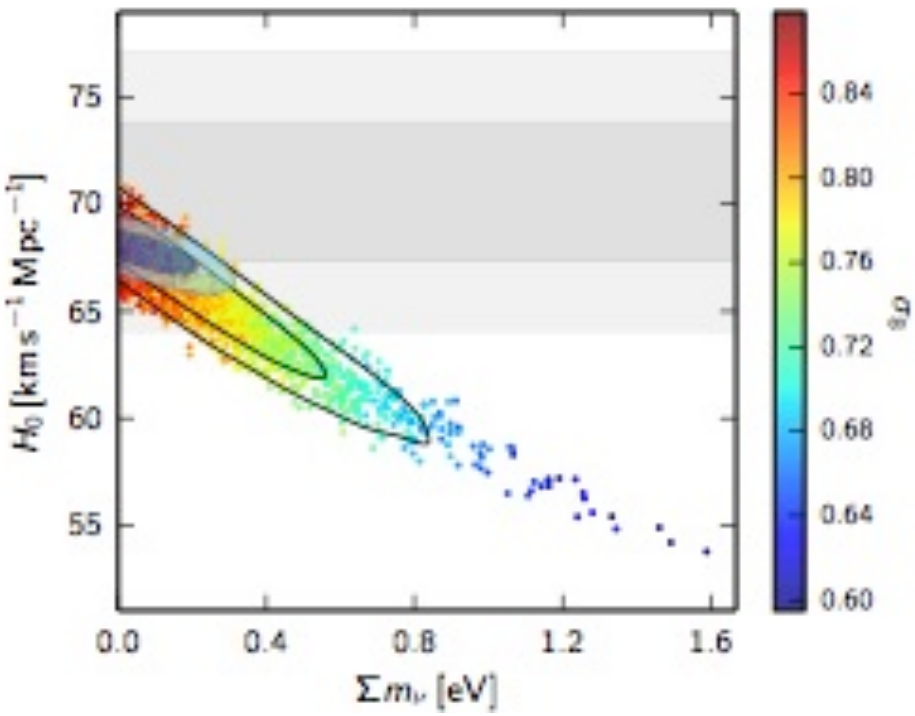
Absolute mass scale

Best constraints at present from cosmology



Absolute mass scale

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



Planck 1502.01589

Conservative limit:

$$\left.\begin{array}{l}\sum m_\nu < 0.23 \text{ eV} \\ \Omega_\nu h^2 < 0.0025\end{array}\right\} \quad 95\%, \textit{Planck} \text{ TT+lowP+lensing+ext.}$$

What next ?

A ambitious experimental program is underway to pin down the remaining unknowns and reach 1% precision in lepton flavour parameters

difficulty

- Neutrino ordering
- Octant
- Majorana nature
- Leptonic CP violation → requires sensitivity to both osc. frecuencies in the same experiment!

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

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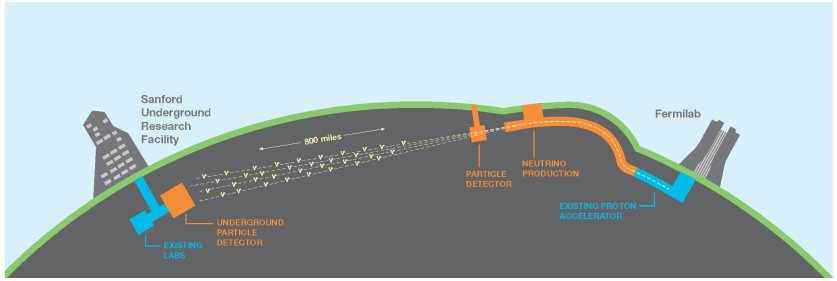
See next talks...

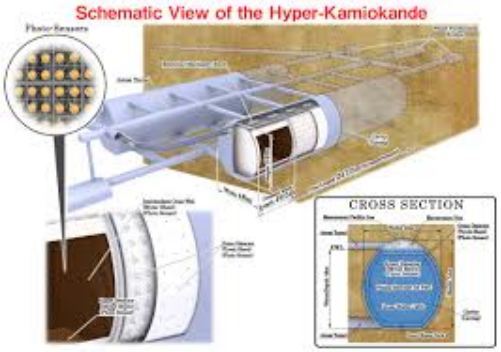
JUNO

RENO ν θ_{13}

INO

ORCA KM3NeT





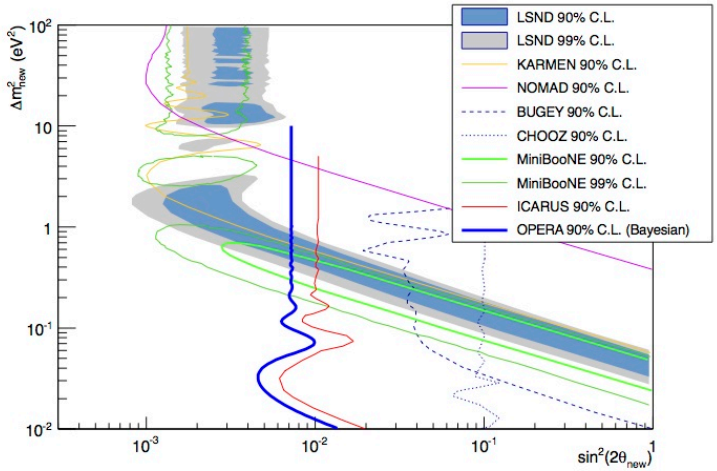
IceCube

Outliers

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

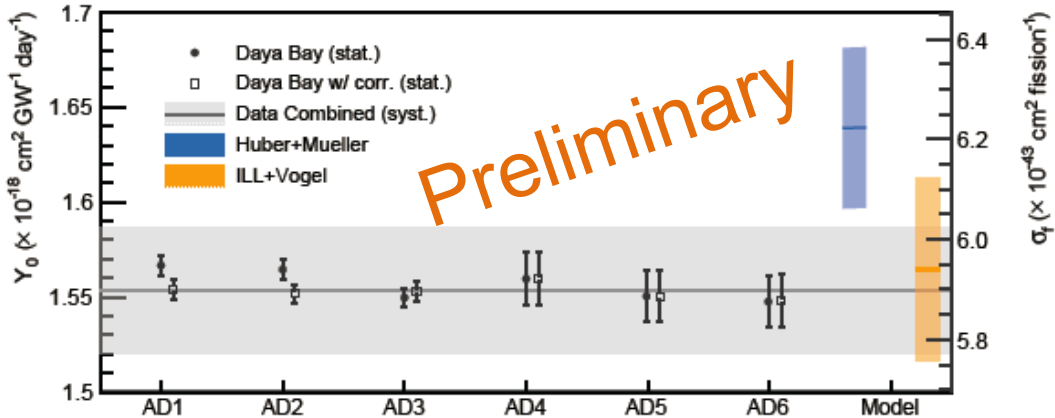
LSND

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



Reactors

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

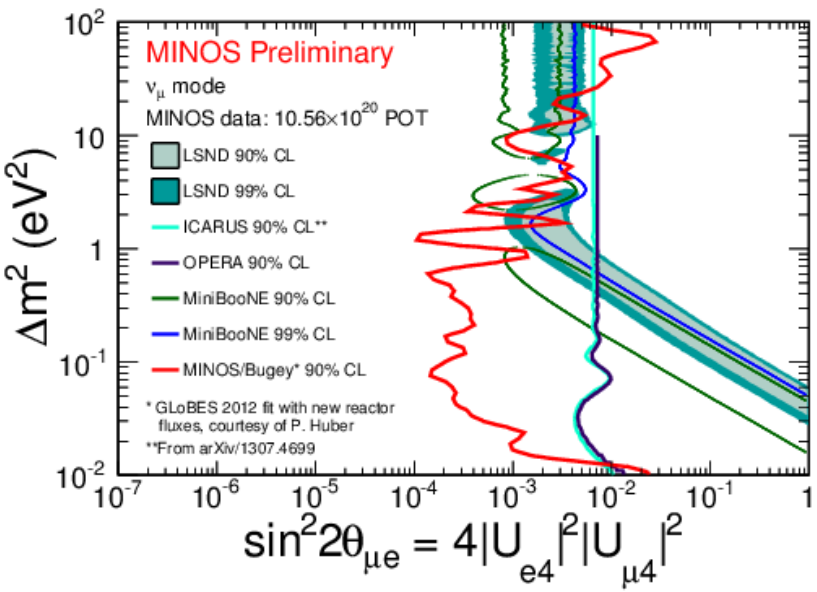


T. A. Mueller et al; P. Huber

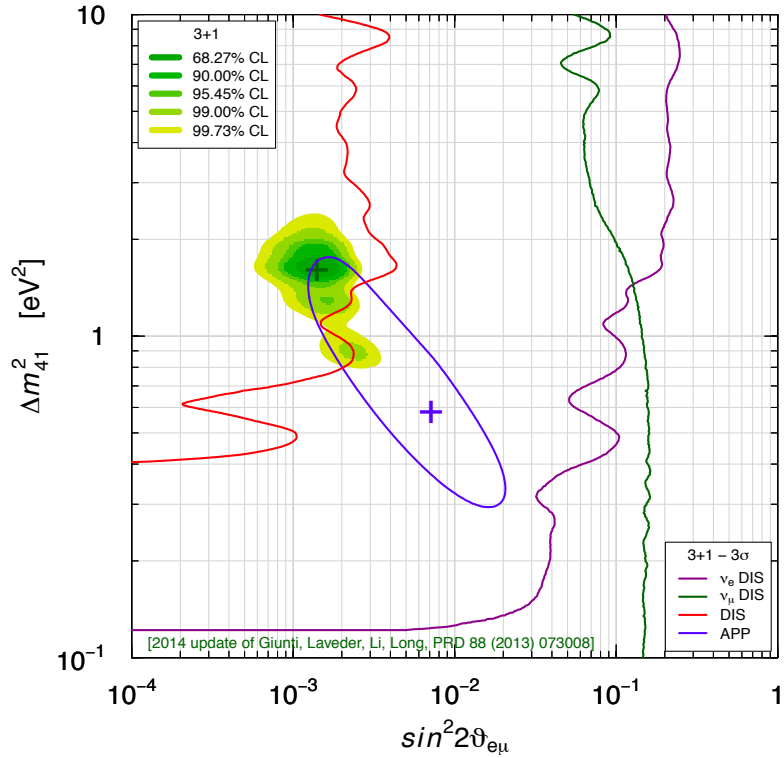
+Gallium anomaly+ MiniBOONE low-energy excess...

Neutrino anomalies

Tension remains because no signal in $P(\nu_\mu \to \nu_\mu) = O(|U_{\mu i}|^2)$



MINOS+ parallel talk



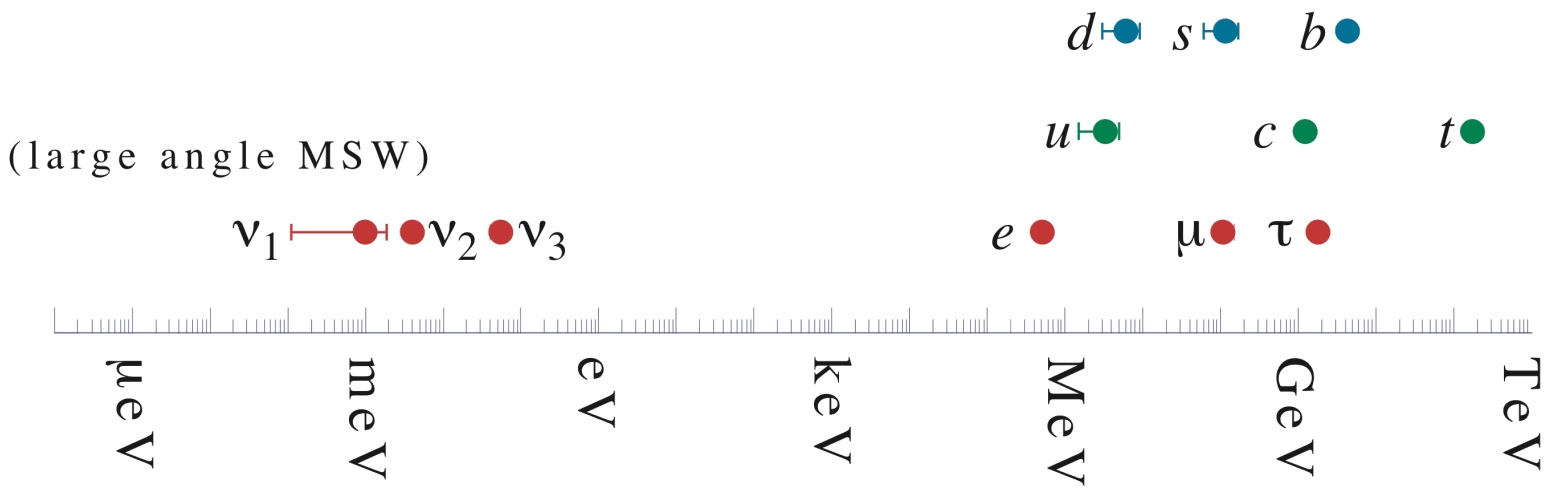
Giunti's parallel talk

Hopefully clarified in the next few years !

See next talks

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



$m_f \sim \lambda v$

Why so different mixing ?

CKM

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

PMNS

3σ

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

A new physics scale

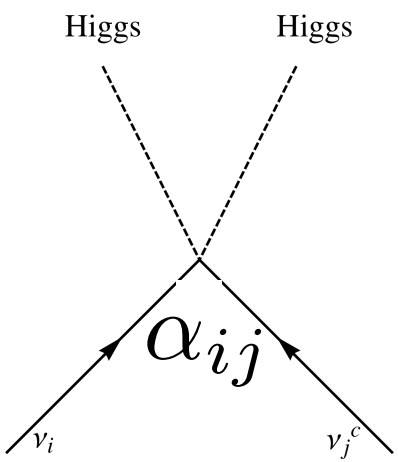
Neutrinos have tiny masses -> a new physics scale

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

Weinberg

$$[\alpha] = -1$$

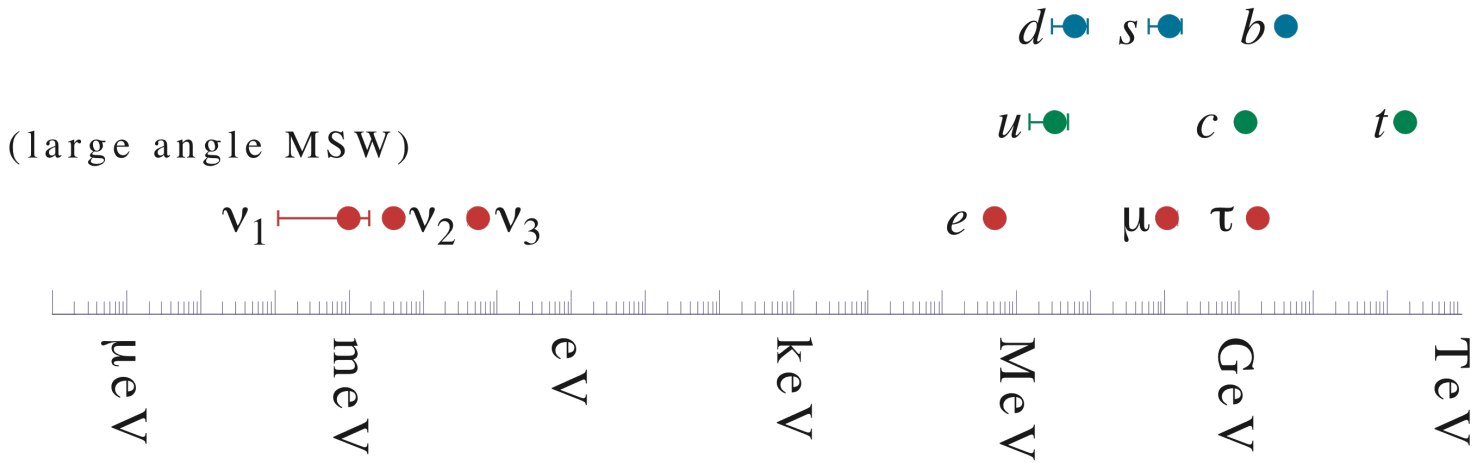
$$\alpha = \frac{Y_\nu}{\Lambda}$$



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

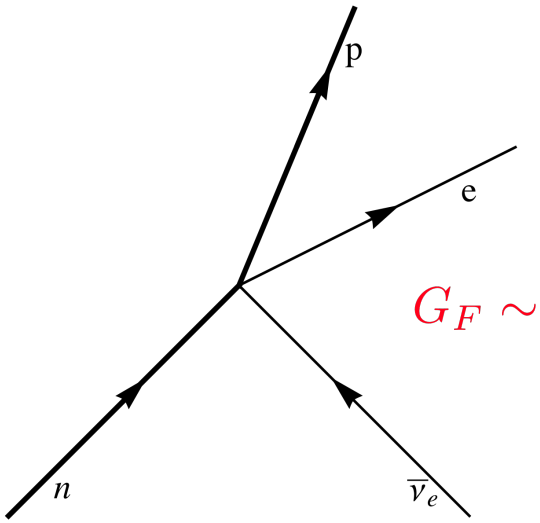
Massive Majorana neutrinos & SSB ?

If $\Lambda \gg v$ natural explanation for the smallness of neutrino mass

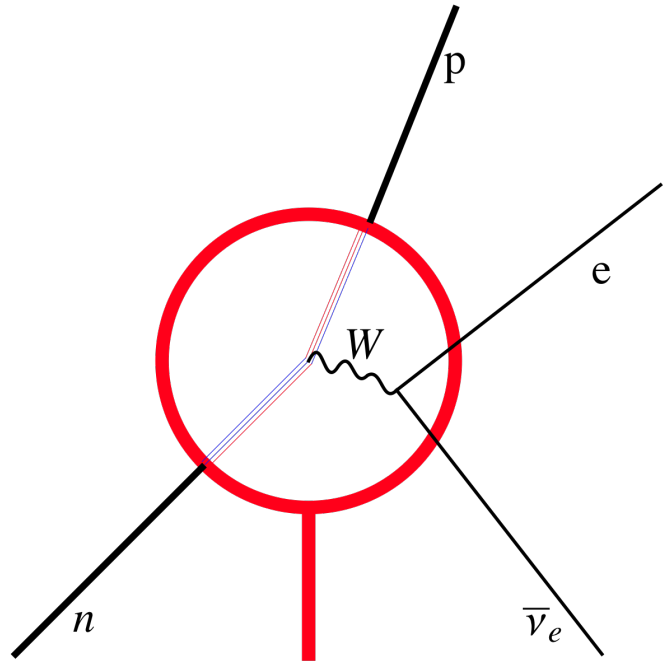


$$m_f(\text{charged}) \sim Yv, \quad m_\nu \sim Y\frac{v^2}{\Lambda}$$

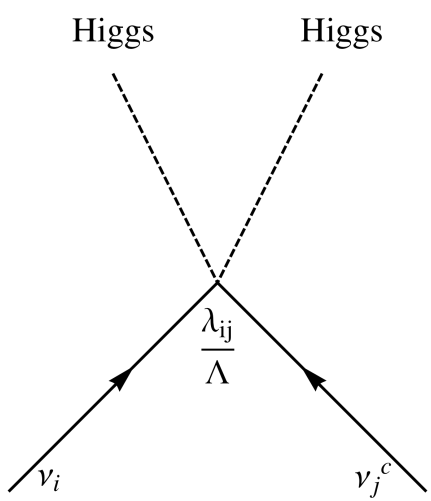
Fermi-era of neutrino physics



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



SM



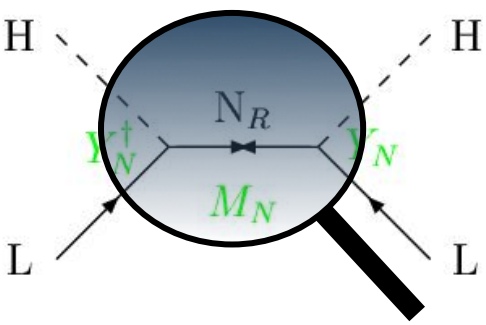
νSM ?

Data-driven BSM: such that gives the Weinberg operator !

Resolving Weinberg's operator at tree level

E. Ma

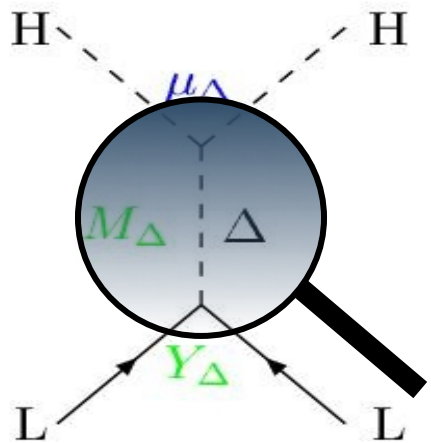
Type I see-saw:
a heavy singlet scalar



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

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

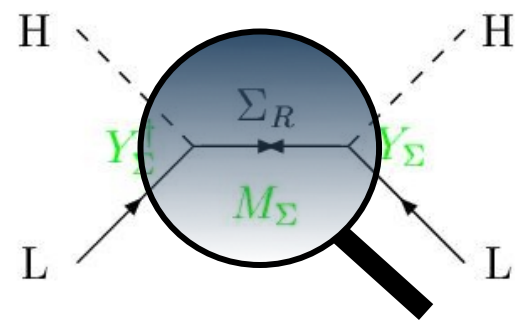
Type II see-saw:
a heavy triplet scalar



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

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

Type III see-saw:
a heavy triplet fermion



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

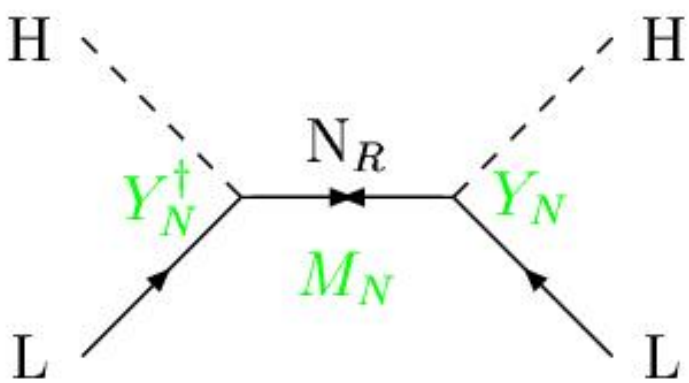
Foot et al; Ma;
Bajc, Senjanovic...

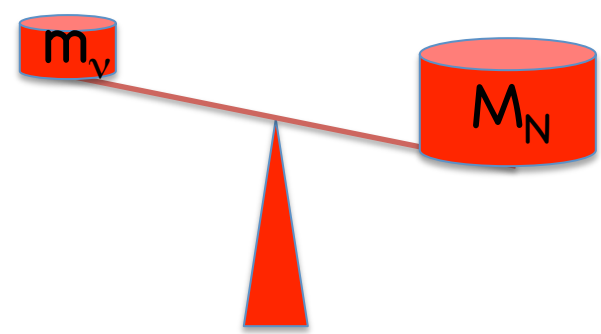
Resolved at one and even two loops ! Aristizabal's parallel talk

How does the ν scale relates to the EW scale ?

Example: Type I seesaw model

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



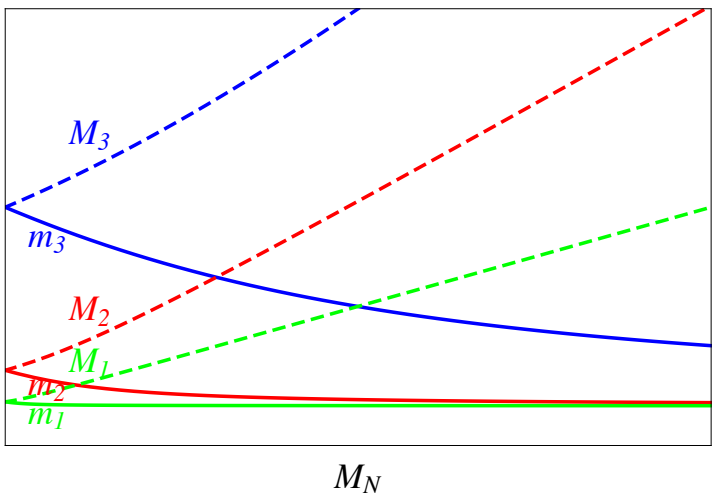


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

Spectra of Type I seesaw models

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



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

$$U_{ll} \simeq U_{PMNS} + \mathcal{O}\left(\frac{m_l}{M}\right)$$

Unitarity violations

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

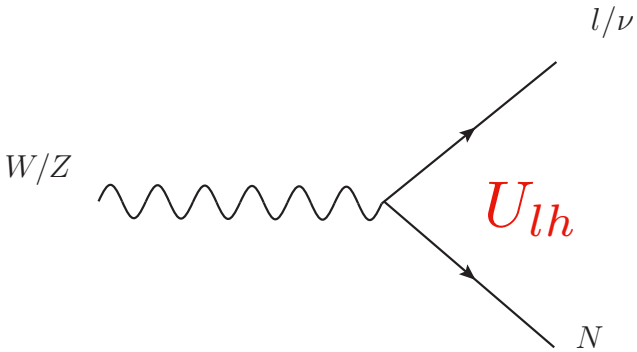
$$R^T R = 1$$

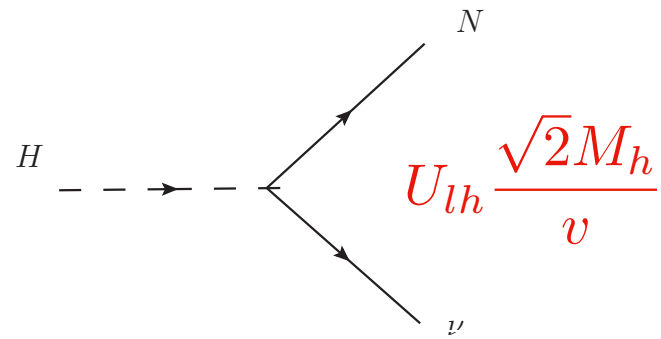
Casas-Ibarra parametrization

Parameters we can know from neutrino experiments

R: contains all the parameters we cannot measure in neutrino experiments

Spectra of Type I seesaw models





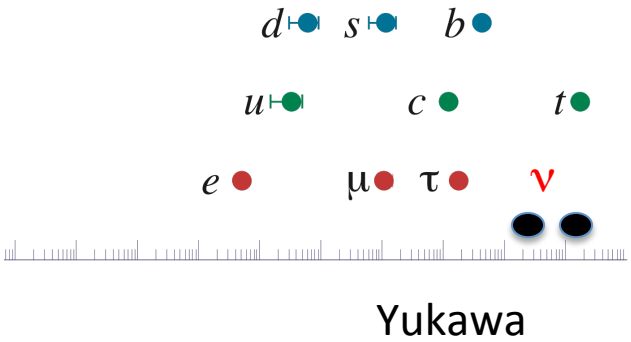
The lower the seesaw scale M_N

- Lower kinematical threshold to produce new states
- Larger mixing with flavour states

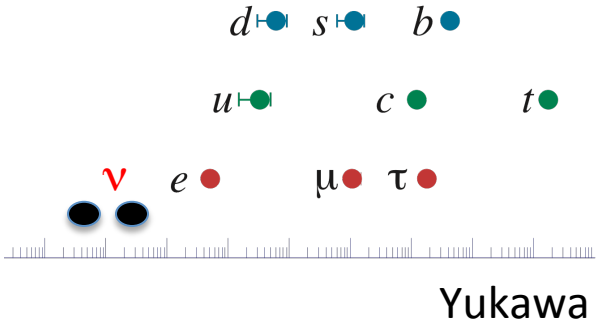
MANY NAMES: right-handed neutrinos, sterile neutrinos, neutral heavy leptons, singlet fermions

Pinning down the new physics scale: naturalness

$M_N \leq$ GUT

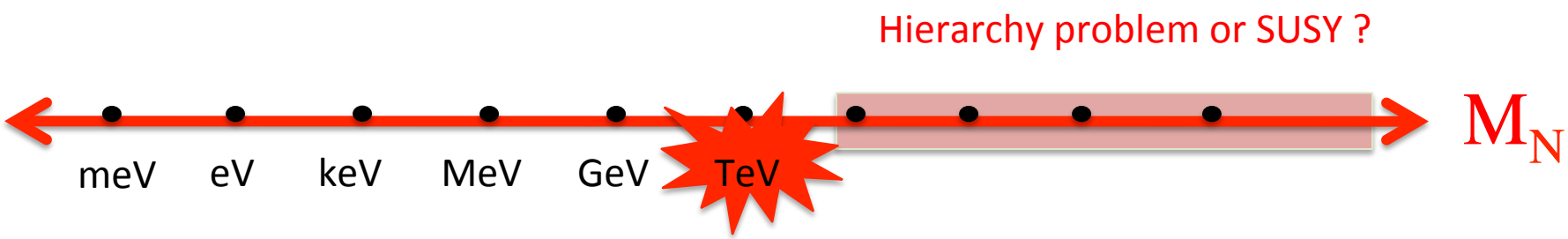


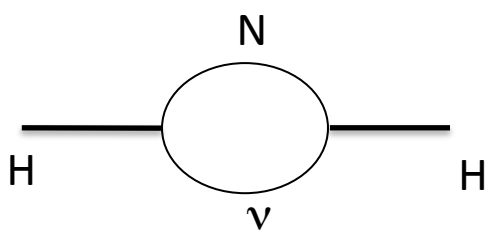
M_N = TeV



Pinning down the New physics scale: naturalness

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





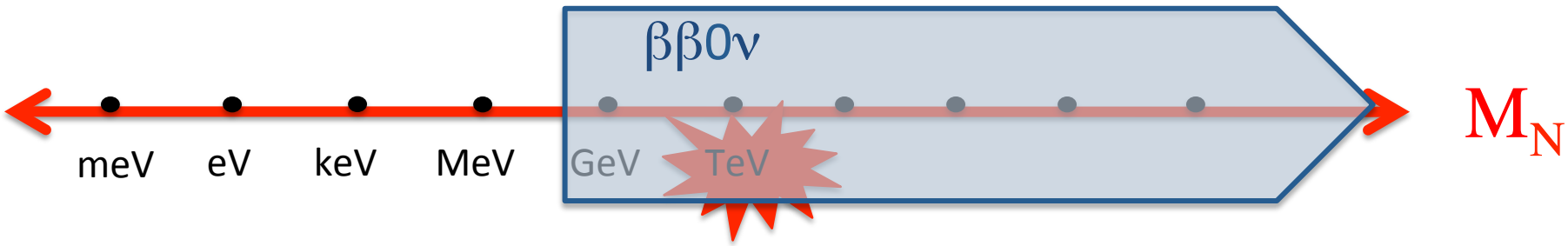
$$\delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu}$$

Vissani

$$M_N \gg m_H$$

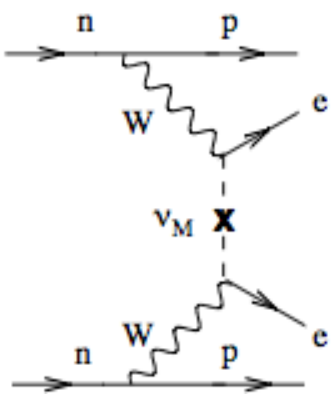
not natural in the absence of SUSY

Pinning down the New physics scale: experiment



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

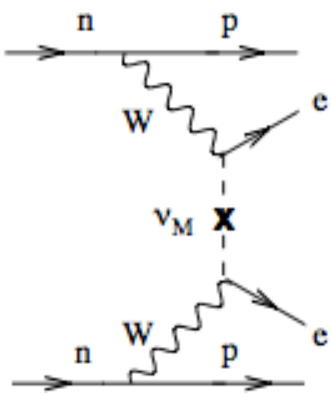
Neutrinoless double-β decay



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

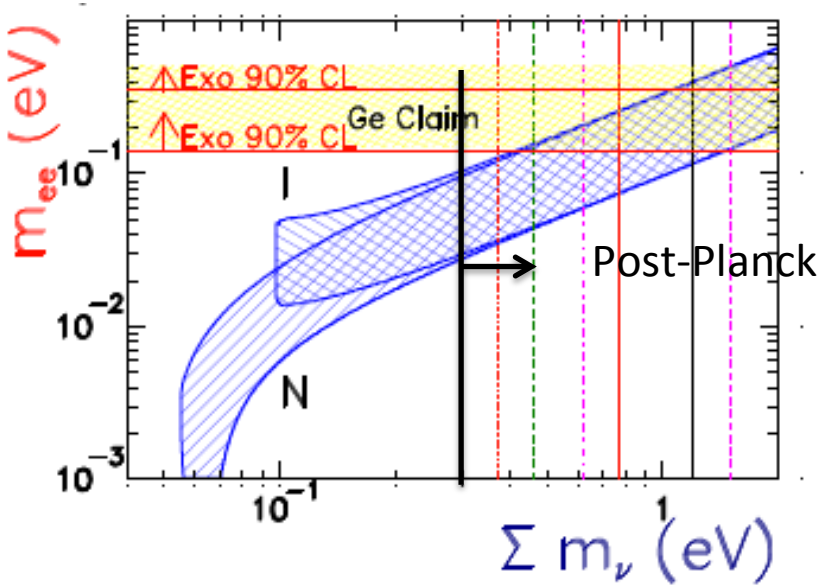
$$M_j \to \infty \qquad \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)} \propto \left(\frac{100 \text{ MeV}}{M_j} \right)^2$$

Neutrinoless double-β decay



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

For M_j>> 100 MeV, amplitude dominated by light contribution



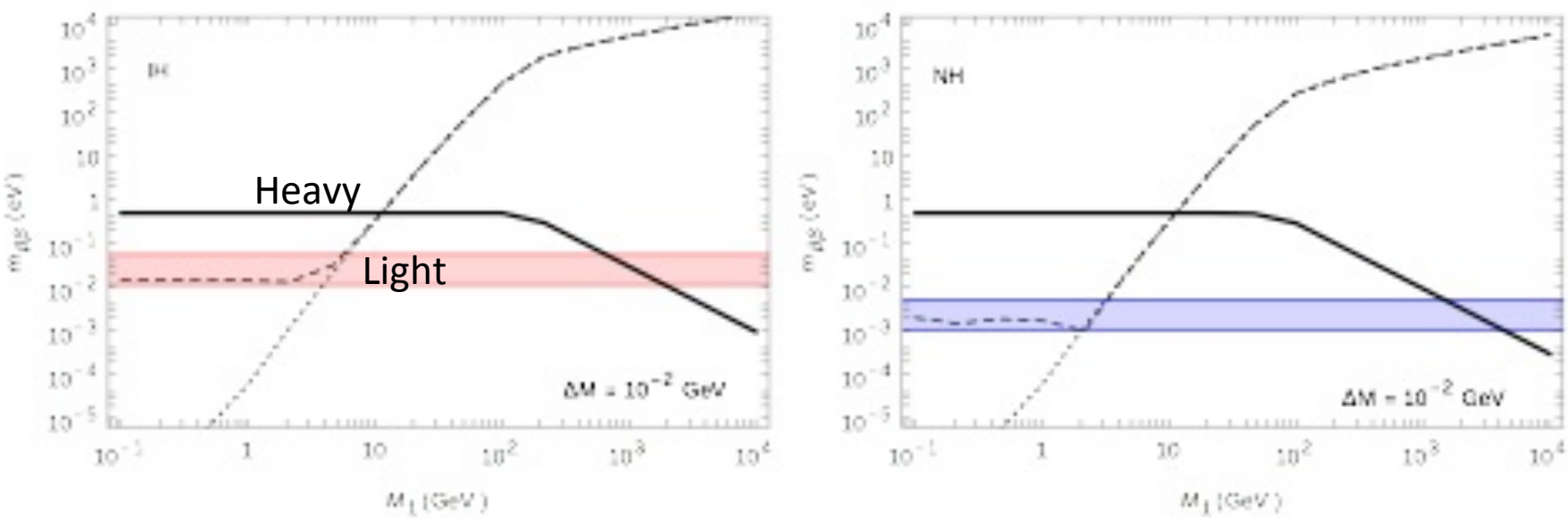
Vissani 2002, Fogli et al,

Updated by Gonzalez-Garcia et al, 2012

Neutrinoless double-β decay

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

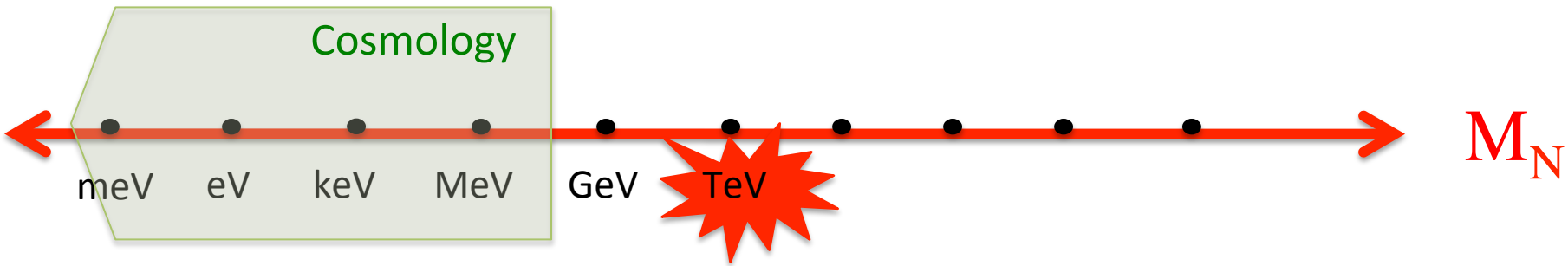
Heavy contributions might be naturally sizeable for M_j [100 MeV- few GeV]



Above a few GeV large cancellation between tree and 1 loop ν mass

Lopez-Pavon, Molinaro, Petcov 1506.05296

Pinning down the New physics scale



Sterile neutrinos below 100MeV can strongly modify

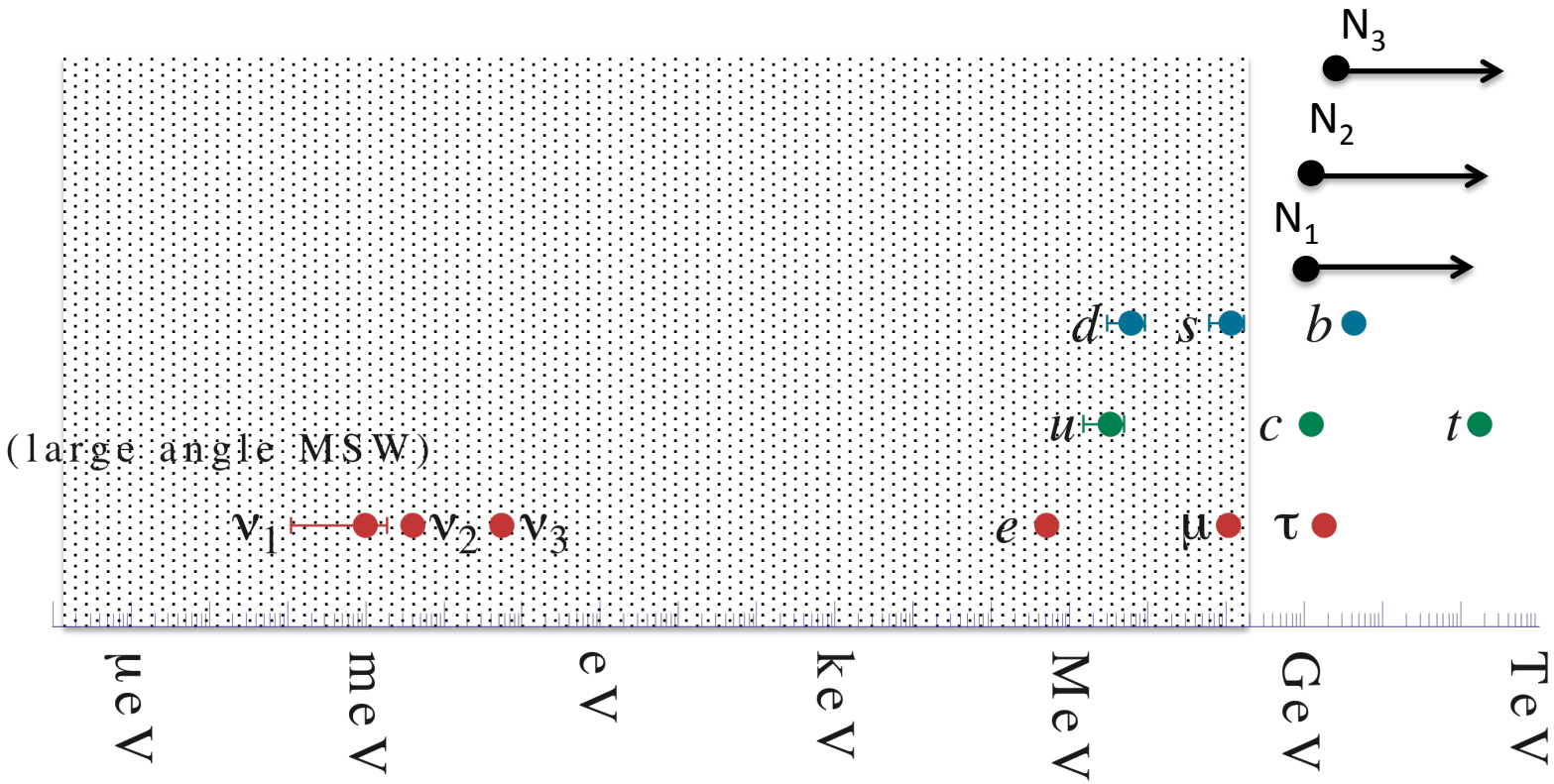
Big-Bang Nucleosynthesis
Cosmic Microwave background
Large Scale structure

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

Seesaw scale vs cosmology

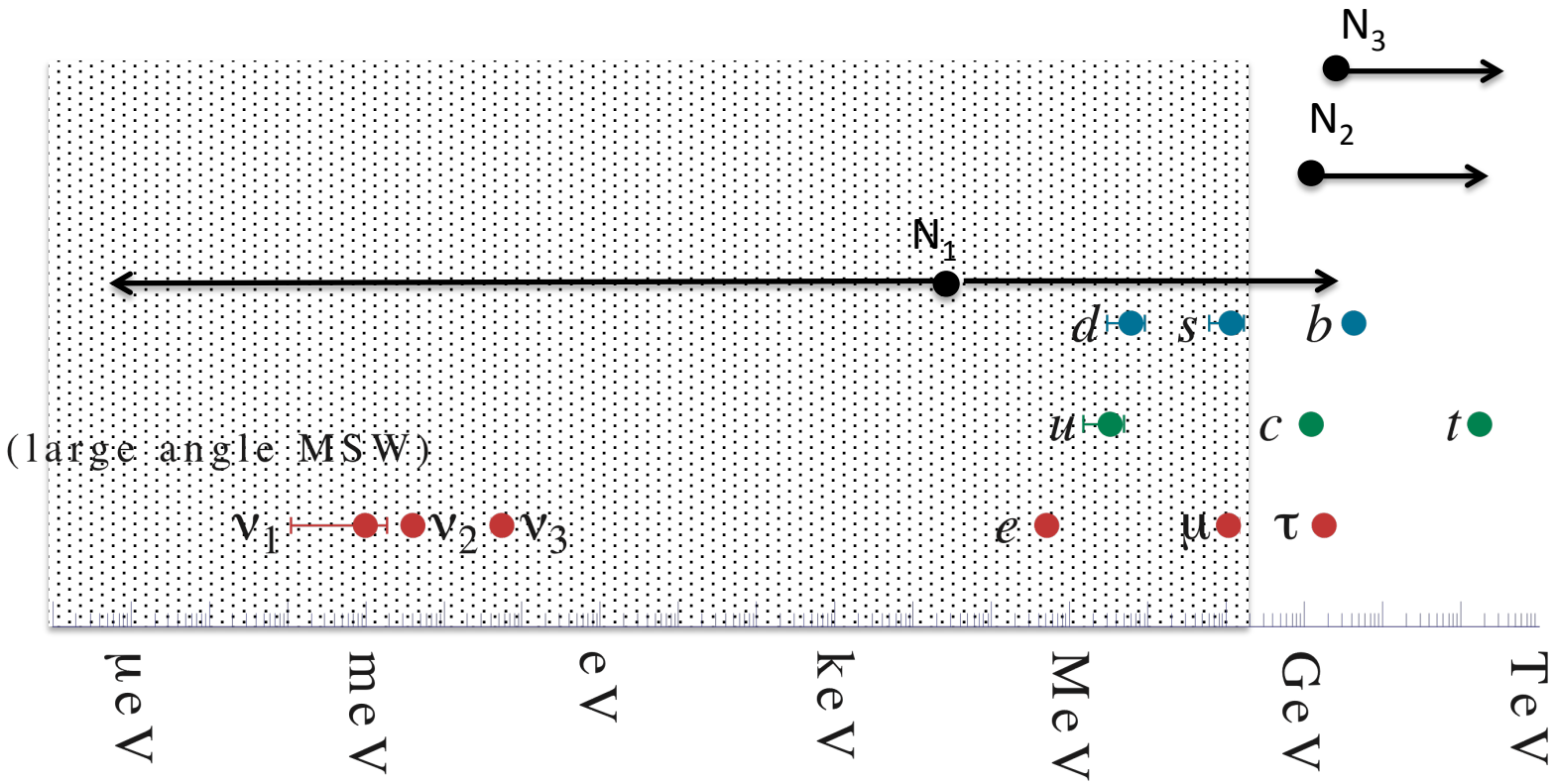
Type I seesaw N =3 that explains neutrino masses



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

PH, M. Kekic, J. López-Pavon 1311.2614;1406.2961

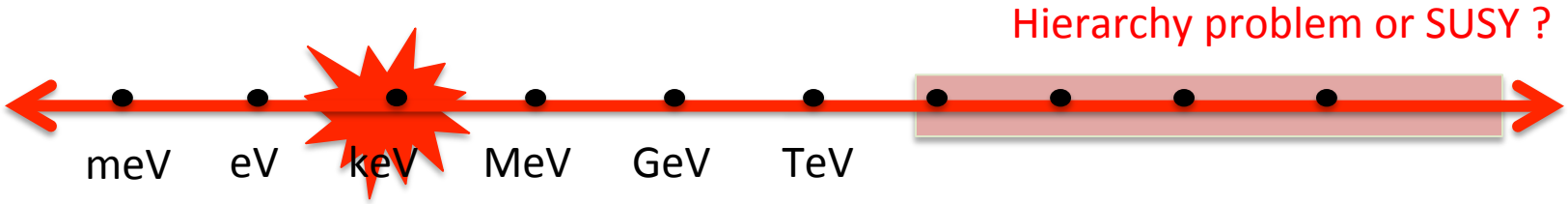
Type I seesaw N =3 that explains neutrino masses



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

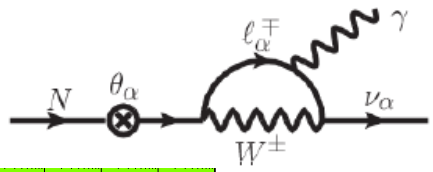
PH, M. Kekic, J. López-Pavon 1311.2614;1406.2961

Warm Dark Matter ?

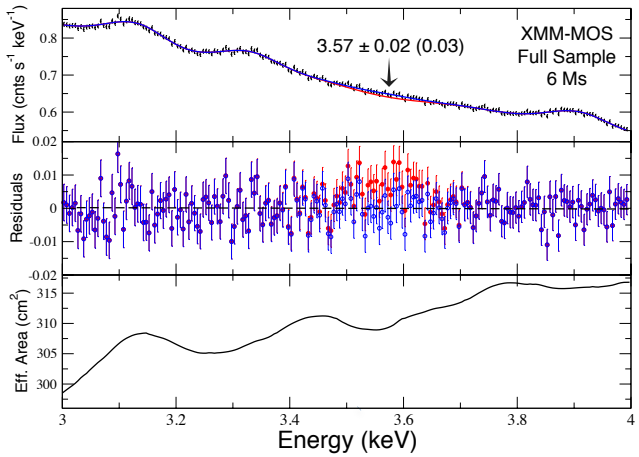


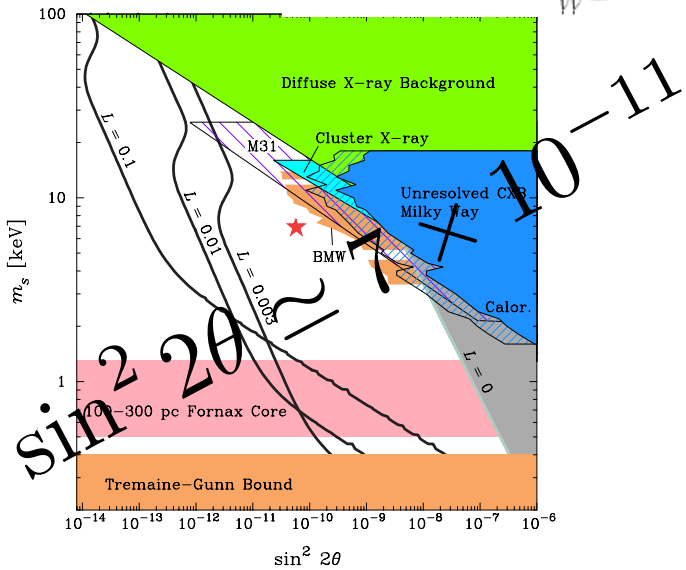
Dodelson, Widrow
Fuller et al...
Shaposhnikov et al

7 keV neutrino ?



Bulbul et al 1402.2301; Boyarsky 1402.4119

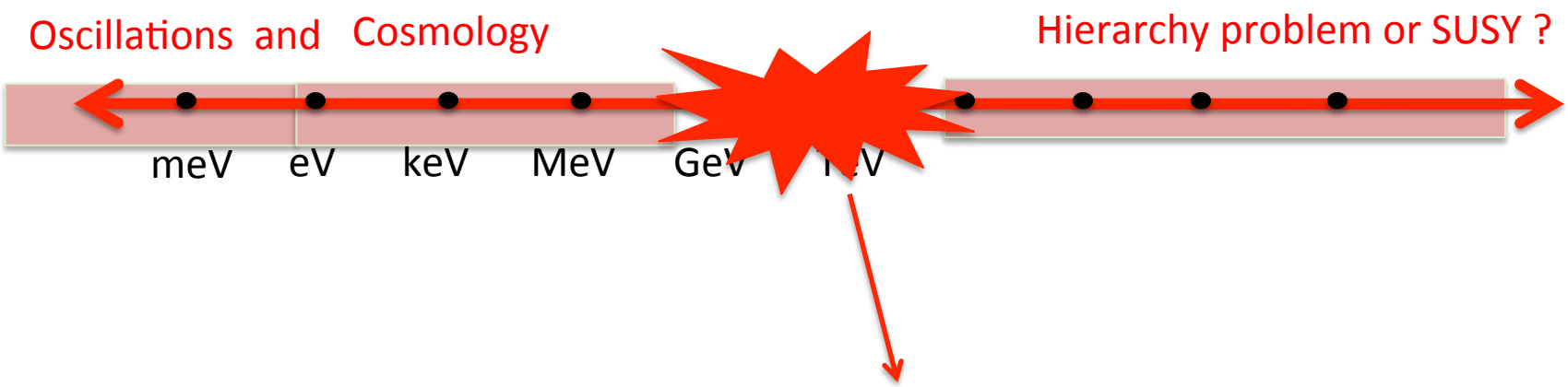




Intense debate: Jeltema et al;M Carlson et al;Boyarsky et al; Bulbul et al

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

EW Leptogenesis



Resonant Leptogenesis M>100GeV

Pilaftsis

Leptogenesis via oscillations M=0.1-10GeV

Akhmedov, Smirnov; Shaposnikov et al

EW Leptogenesis

Sakharov conditions:

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

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

✔ Out of equilibrium: at least one of the sterile states does not reach thermal equilibrium before T_{EW}

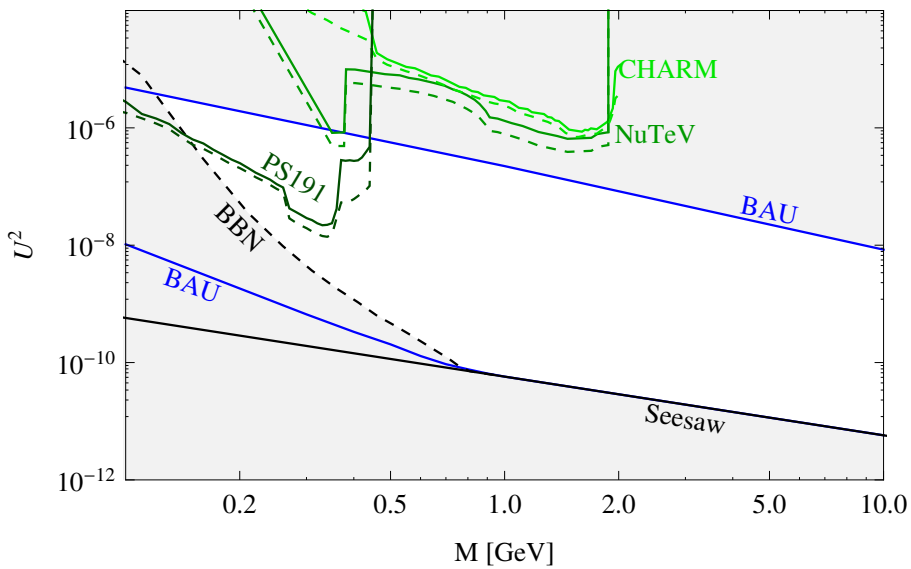
(in contrast with standard leptogenesis in the decay of the heavy states: the violation of L from Majorana masses is not relevant $M/T << 1$)

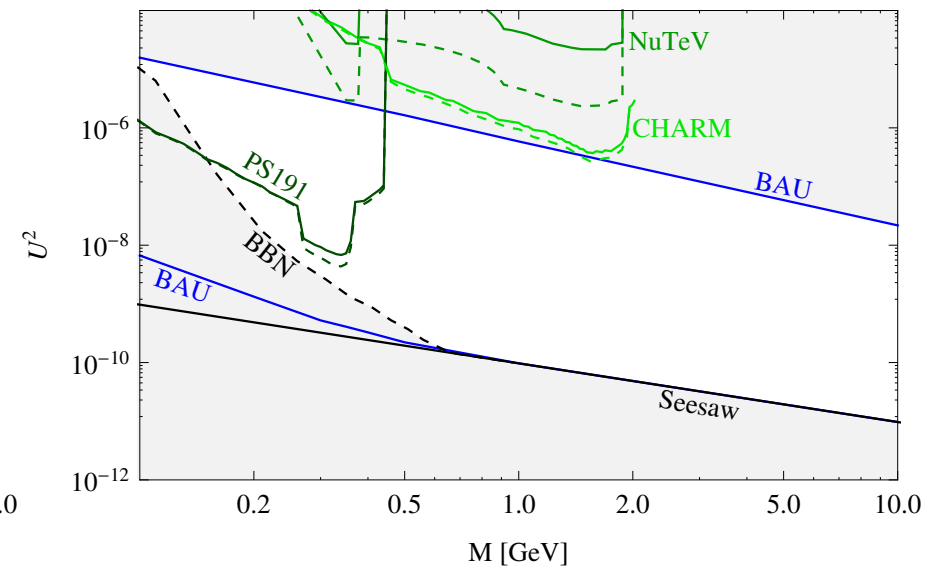
"Flavoured" CP asymmetries arise in production of sterile states via the interference of CP-odd phases and CP-even phases from oscillations

Assumptions: $y_3 << y_1, y_2$, M_i [0.1, 100] GeV

GeV Leptogenesis

In model with only two sterile neutrinos



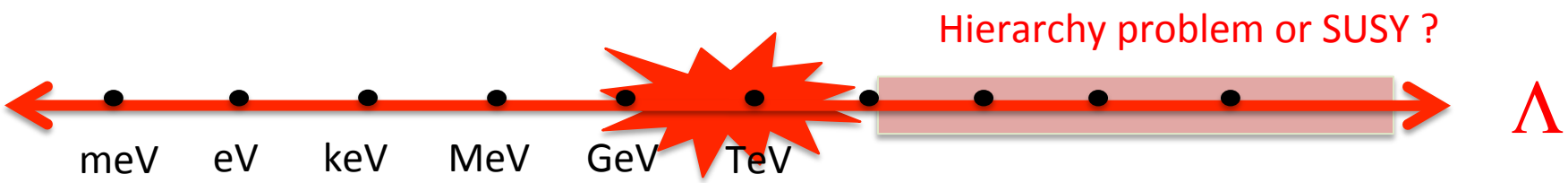


Canetti, Drewes,Frossard, Shaposhnikov 12084607

exploration of three neutrino underway...

Is EW leptogenesis testable ?

Other states out there EW scale ?



Can be produced in flavoured via CC, NC, Higgs interactions:

$$|\,(U_{lh})_{\alpha i}\,|^2 \propto \frac{m_\nu}{M_N}$$

too small couplings unless....

Seesaw models + approx Lepton number

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

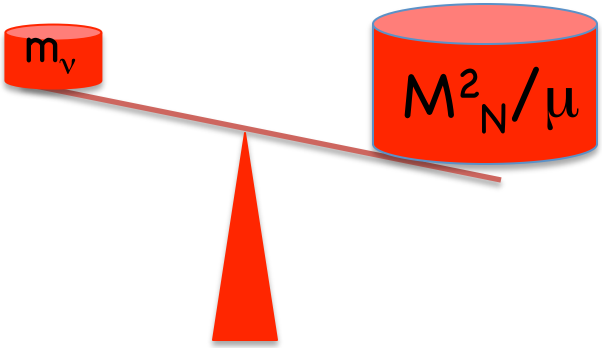
$$\begin{array}{cccc} & & \multicolumn{2}{c}{\overbrace{\hphantom{Yv \qquad M_N}}^{n_R}} \\ & \multicolumn{3}{c}{\begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}} \\ & \downarrow & \downarrow & \downarrow \\ L= & +1 & -1 & +1 \end{array}$$

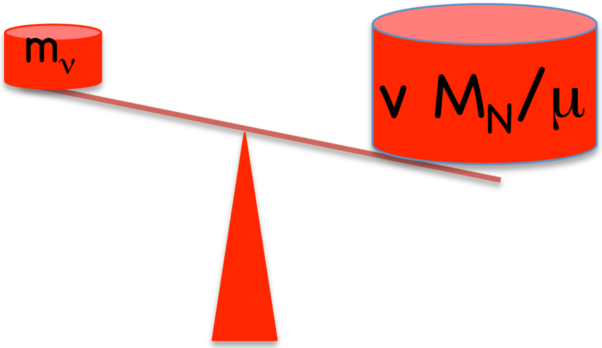
Inverse Seesaw

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

Direct Seesaw

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

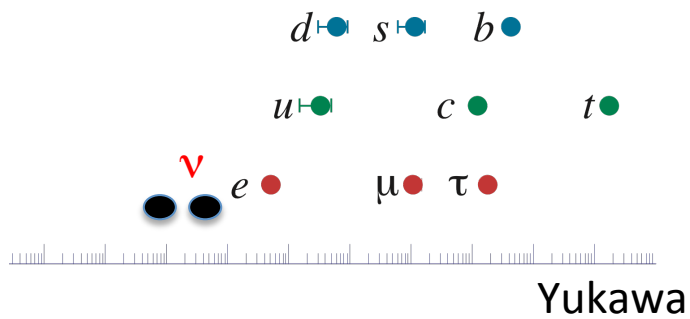




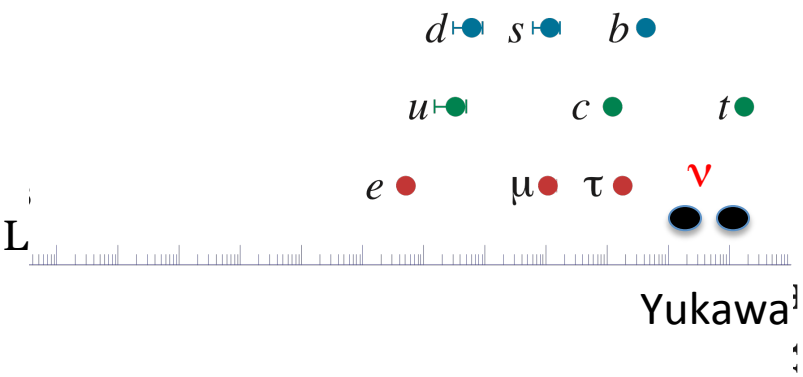
They are all a subclass of type I seesaw models (different choices of R)

Charged/neutral hierarchy in seesaw

M_N = TeV



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



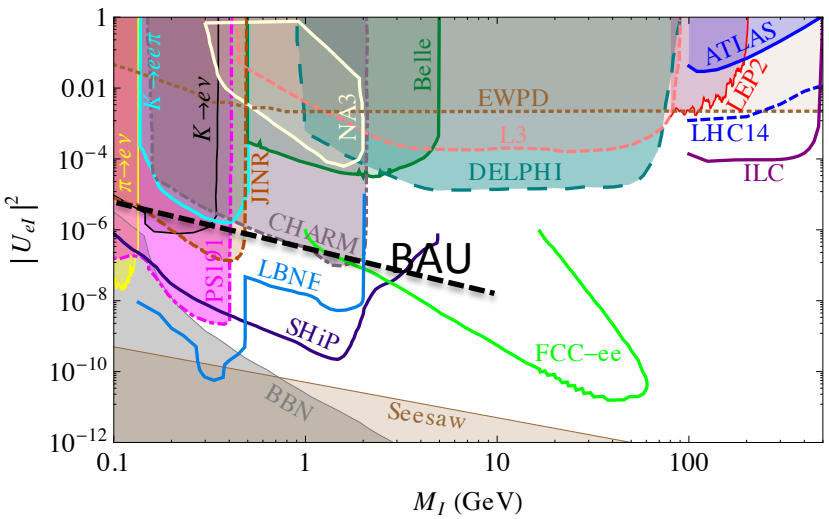
Eg: Inverse seesaw/direct seesaw

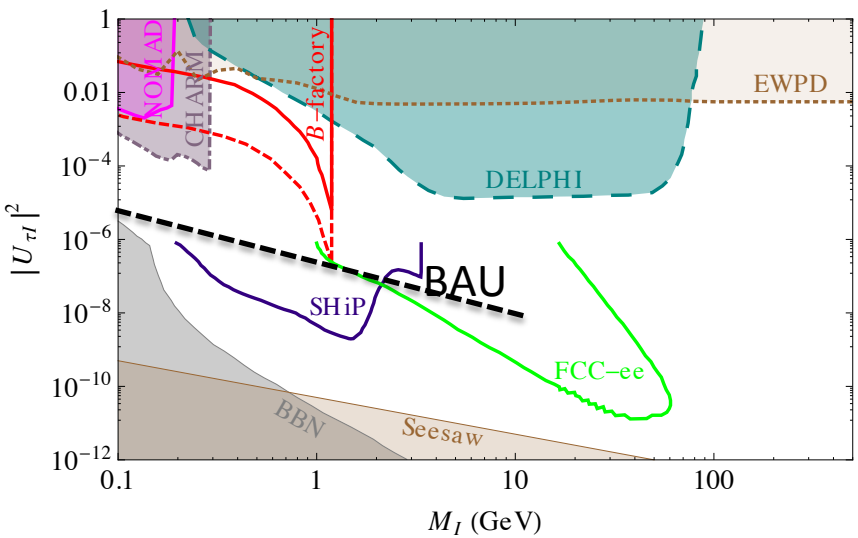
Generically degenerate heavy neutrinos: pseudo-dirac pairs

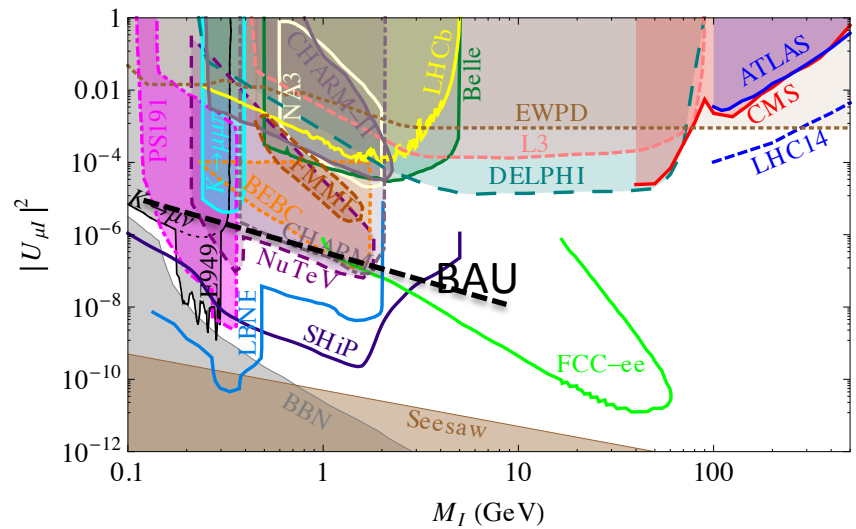
Rich phenomenology of low-scale models with U(1)

Direct production in meson decays, beam dump experiments, electroweak precision tests: sensitive to active-sterile mixings and heavy masses

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



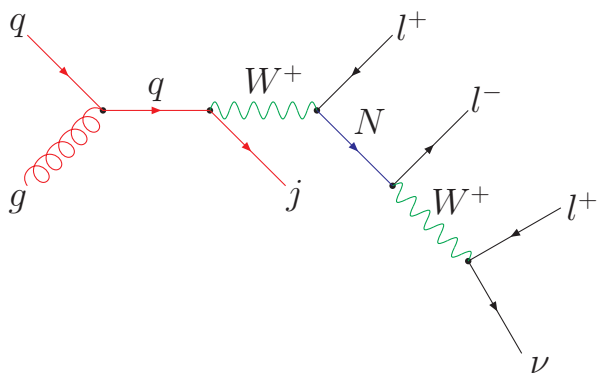


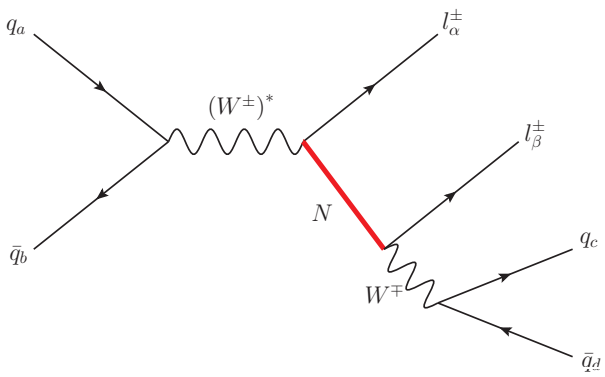


From 1504.04855

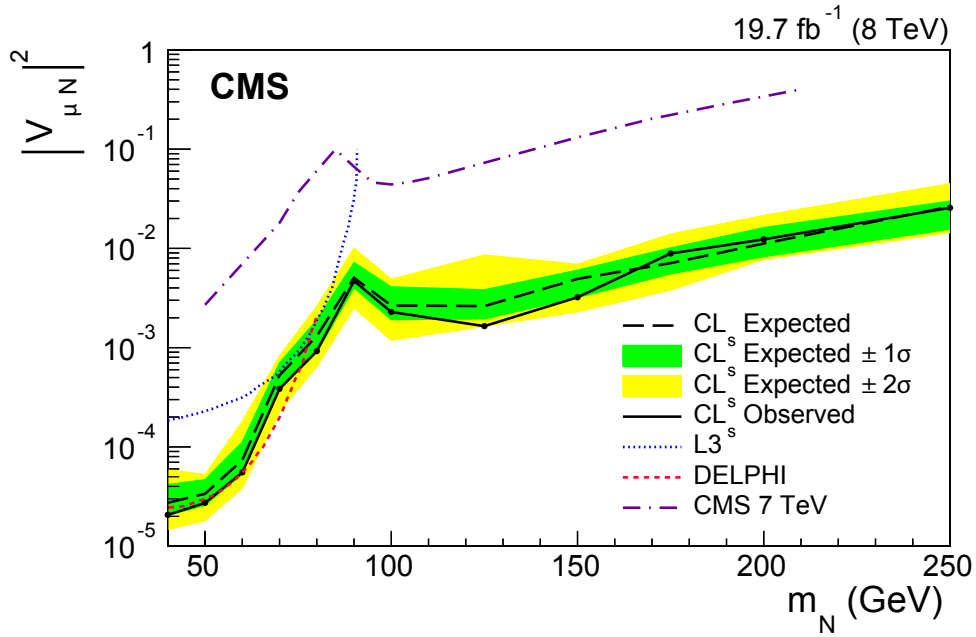
Parallel talks: De Romeri,
M. Drewes
J. Hernandez

LHC Searches





σ X $B_R > 10^{-3}$ pb



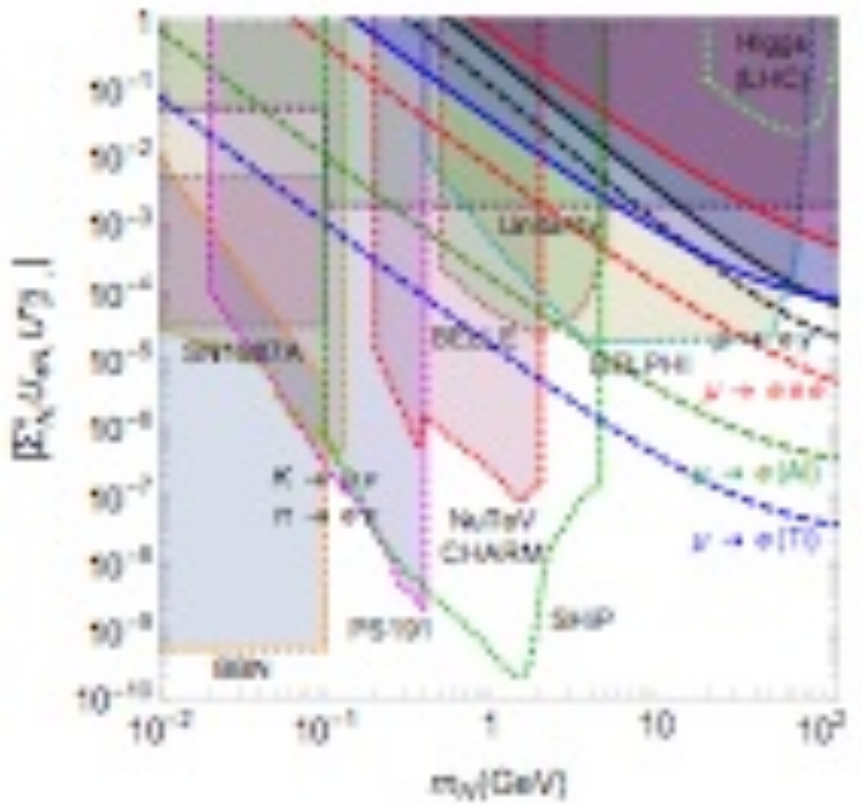
CMS 1501.05566

ATLAS 1506.06020

LFV decays

$\mu \to e\gamma$ $\mu^- \to eee$ $\mu^- \to e$ conversion

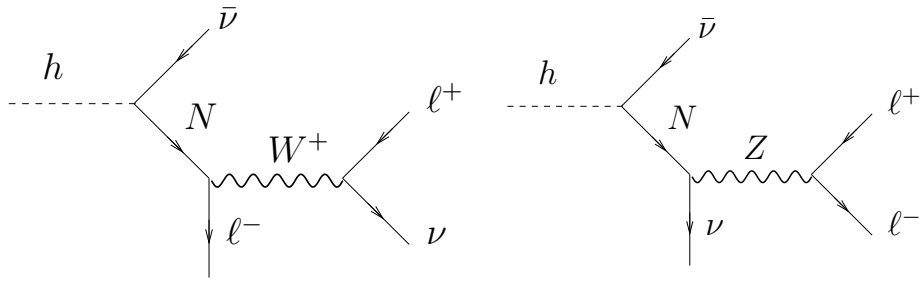
Recent analysis Alonso, et al; Dinh et al



From 1504.04855

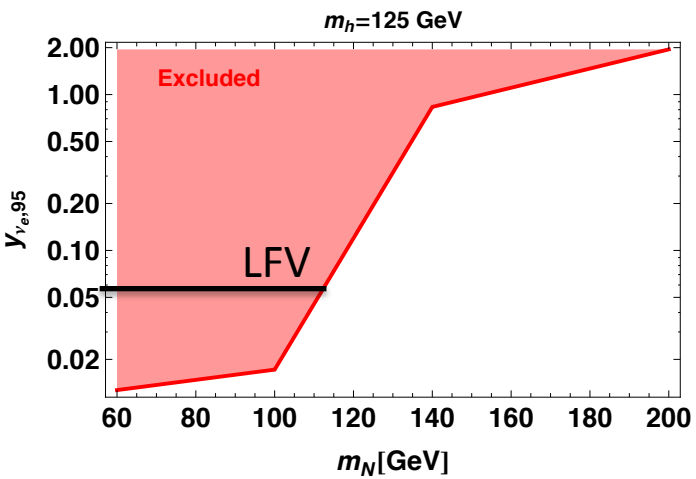
Very strong constraints and extremely good prospects !

Higgs decays



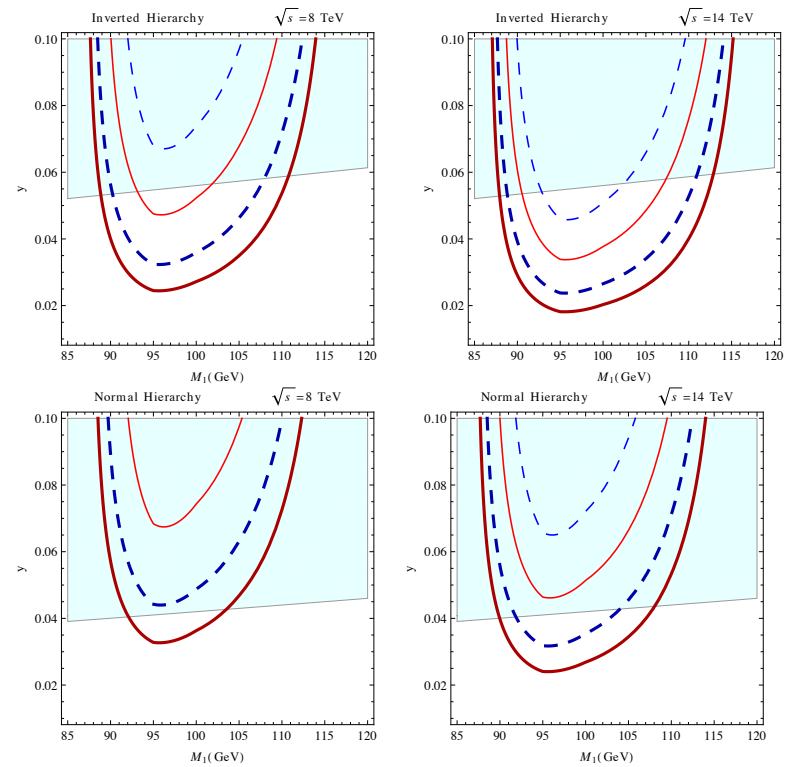
@LHC

Lepton channels



Bhupal Dev et al 1207.2756

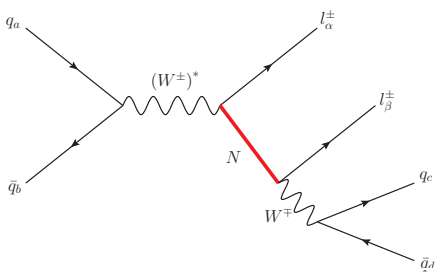
Jet channels

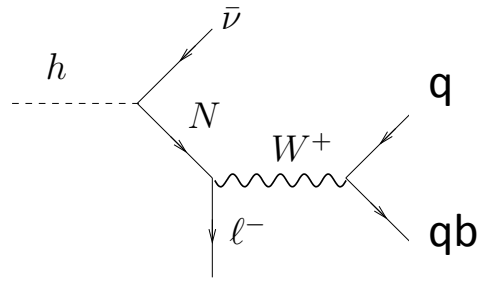


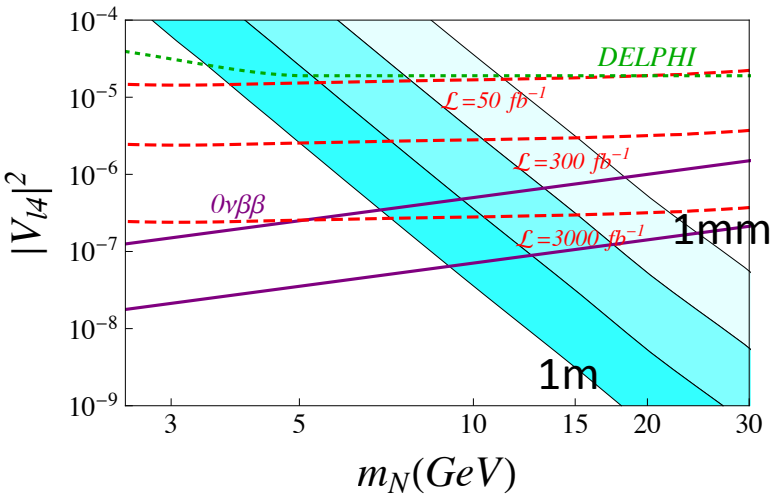
Cely et al 1208.3654

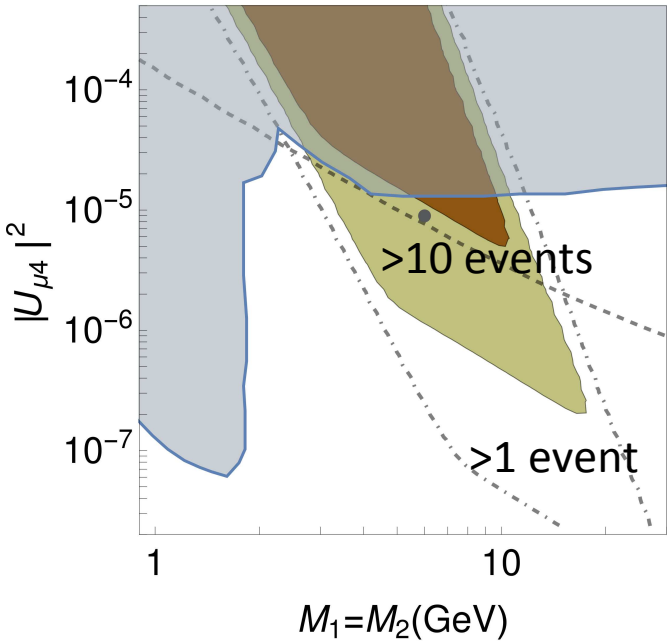
Competitive bounds with the stringent LFV bounds!

Lower mass: Displaced Vertices









Helo, Kovalenko,Hirsch 1312.2900

Gago, PH, Jones-Perez, M.Losada, A. Moreno
1505.05880

Weinberg's operator from some more fundamental principle ?

Grand Unification e.g. SO(10)

Babu. Mohapatra;Fukuyama Okada; Bajc,Senjanovic, Vissani;Joshipura, Patel; Altarelli, Meloni;...

Left-right symmetric models ...

Pati, Salam; Mohapatra, Pati; Mohapatra, Senjanovic...

These models aswell, as type II, III, richer phenomenology because new states with gauge interactions (easier to produce)

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

Parallel talks: Meloni
Titov

- Minimal flavour violation and dynamical origin of Yukawas

  R. Alonso, et al

Conclusions

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

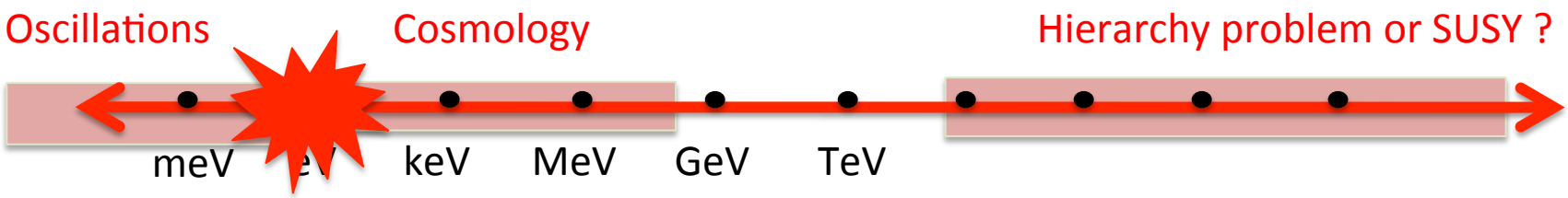
- Many fundamental questions remain to be answered however: Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ? Lepton vs quark flavour ?

- A rich experimental neutrino programme lies ahead, that will answer some of these important questions

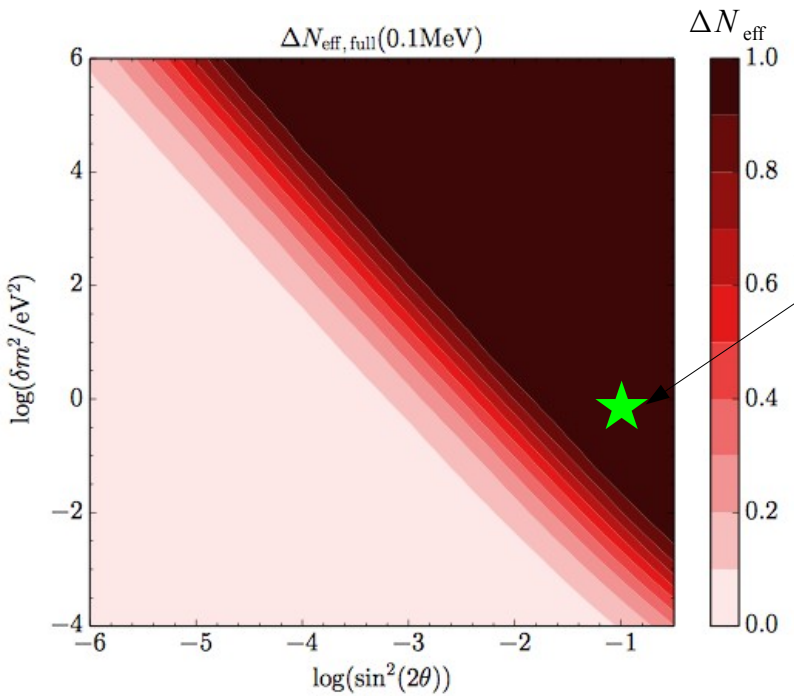
- LHC, LFV, SHiP, future colliders… could provide essential information on the new physics underlying neutrino masses if it lies naturally close to the EW scale

BACKUP

Neutrino Anomalies ?



Neutrino anomaly explained by oscillations is in strong tension with cosmology



$$\left.\begin{aligned} N_{\rm eff} &= 3.2 \pm 0.5 \\ \sum m_\nu &< 0.32 \text{ eV} \end{aligned}\right\} \text{ 95\%, } \textit{Planck} \text{ TT+lowP+lensing+BA}$$

Reconciling LSND and cosmology:
suppress sterile neutrino production
with exotic physics

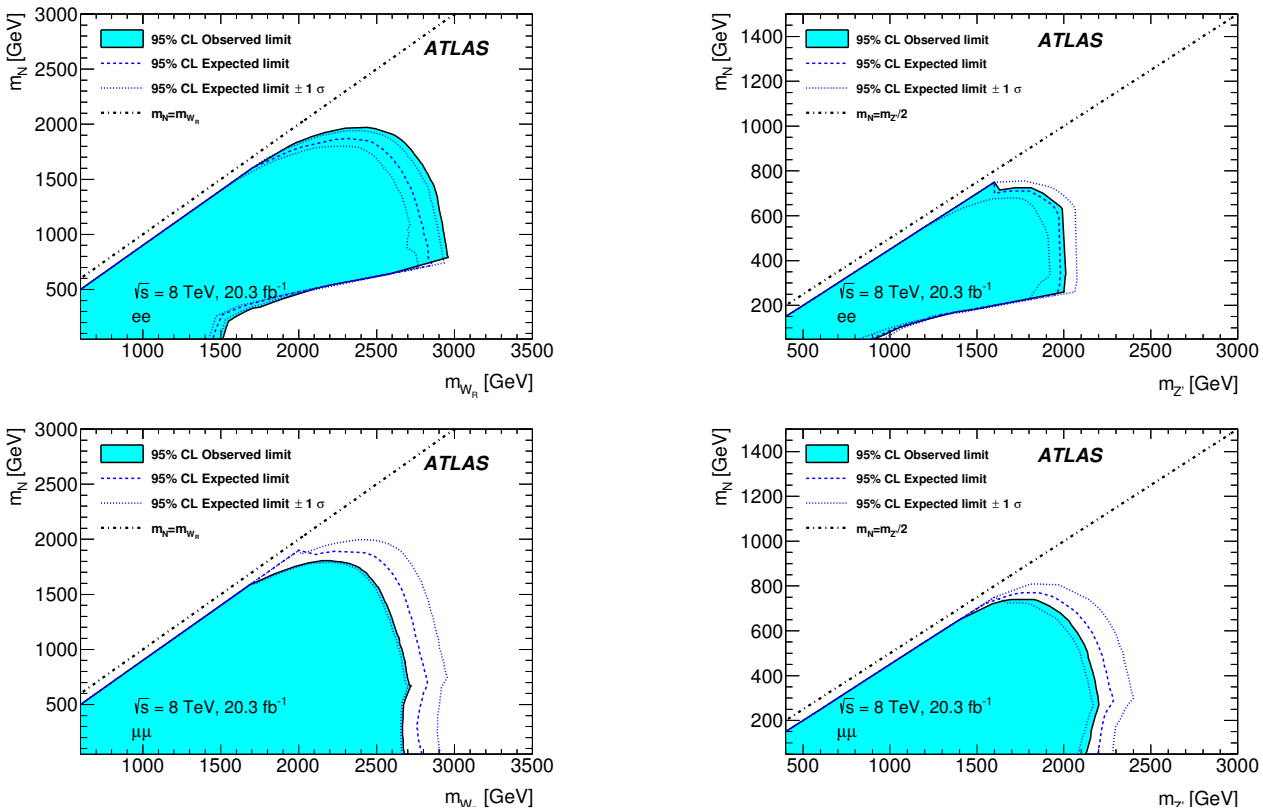
Foot, Volkas; Mirizzi, et al; Saviano et al;
Hannestad, Tamborra, Tram; Dasgupta, Kopp ;Hannestad,
Hasen,Tram; Archidiacono, et al;
Bringmann, Hasenkamp, Kersten

Hannestad, Hansen, Tram, Wong 2015

Several updated analyses from ATLAS: Grancagnolo's parallel talk

- Type III: m_L+- < 400 GeV ATLAS 1506.01291, 1506.01839

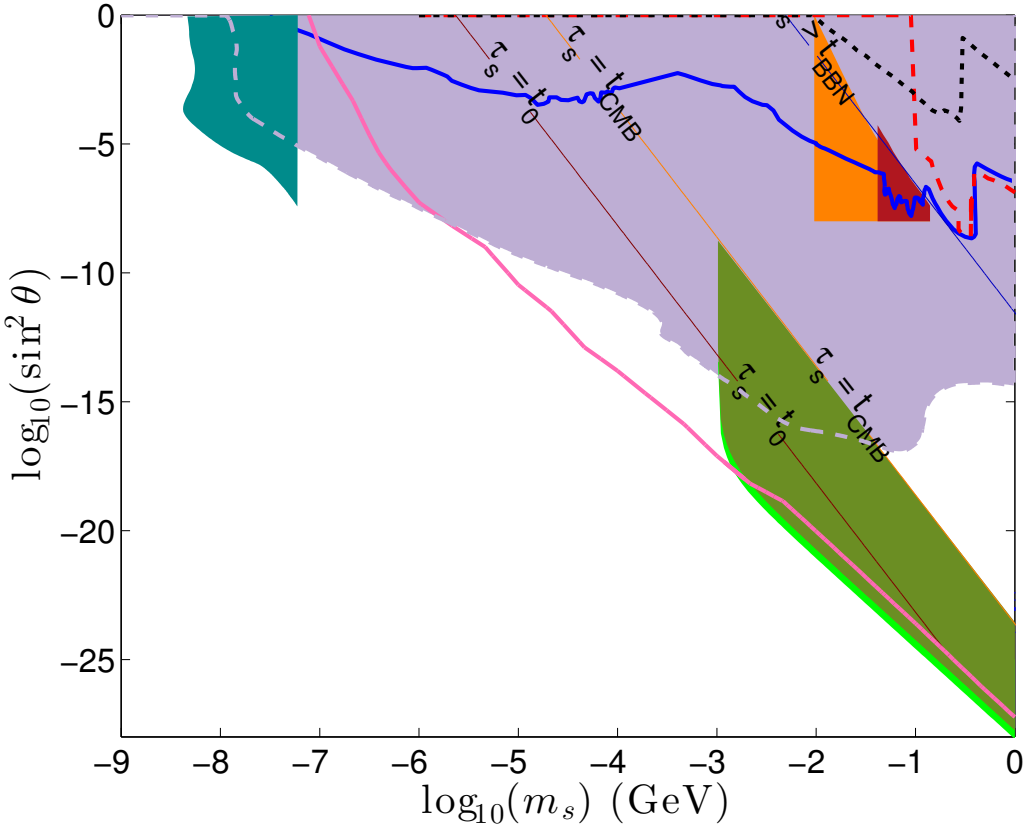
- LR Type I symmetric models:



ATLAS 1506.0620

Cosmology constraints on one sterile species

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



Vincent, Fernandez-Martinez, PH, Lattanzi,Mena 1408.1956

Their only escape: that they do not thermalize because of small mixing/
extra exotic physics