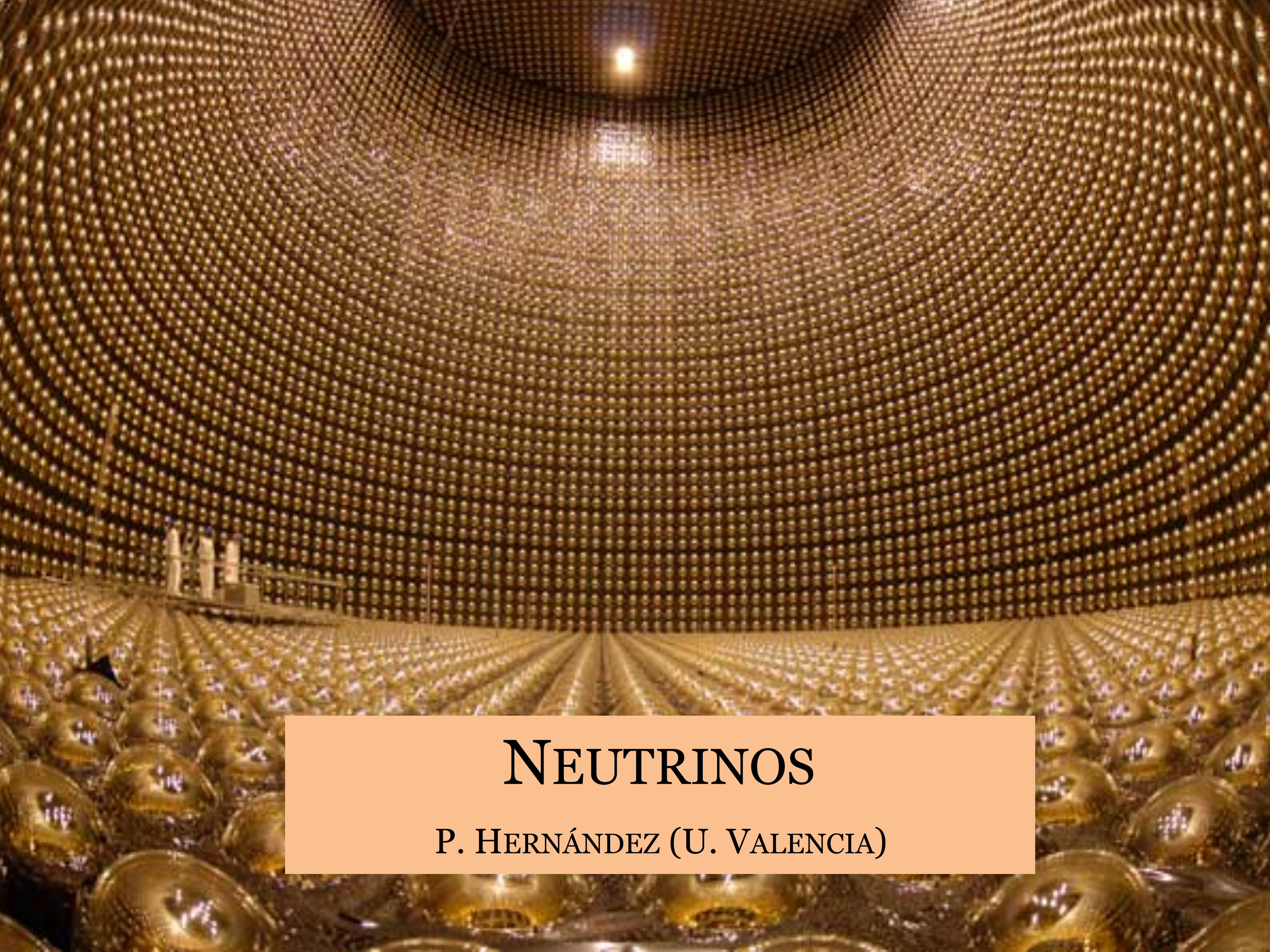


Neutrinos

P. Hernández (U. Valencia)

SM+3 massive neutrinos: Global Fits

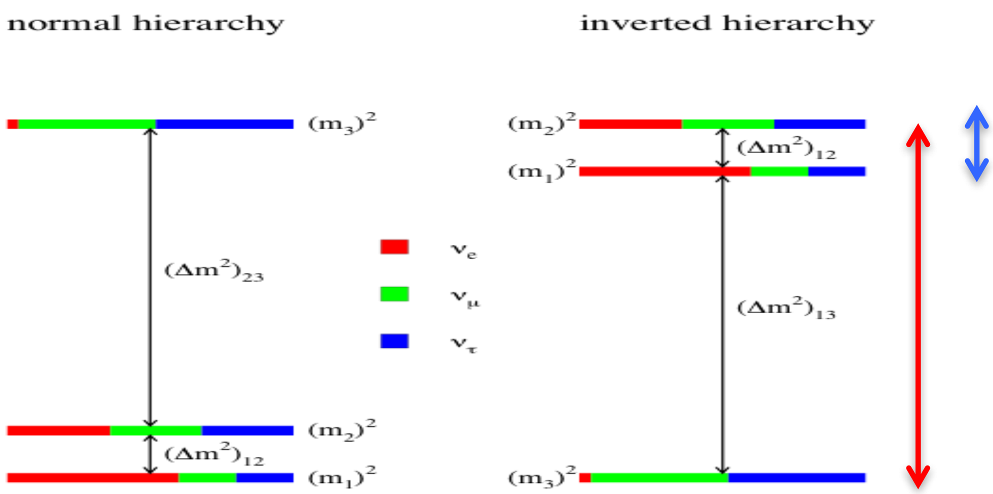
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{12} \sim 34^\circ$

$\theta_{23} \sim 42^\circ$ o 48°

$\theta_{13} \sim 8.5^\circ$

$\delta \sim\ ?$

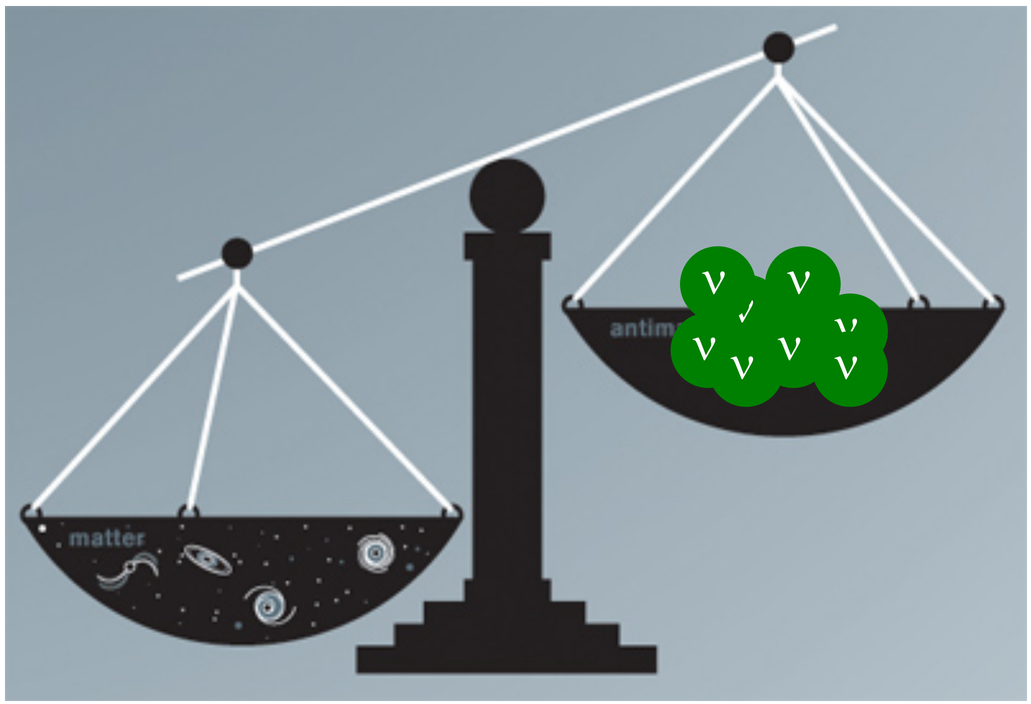


$7.5 \cdot 10^{-5} \mathrm{eV}^2$

$2.5 \cdot 10^{-3} \mathrm{eV}^2$

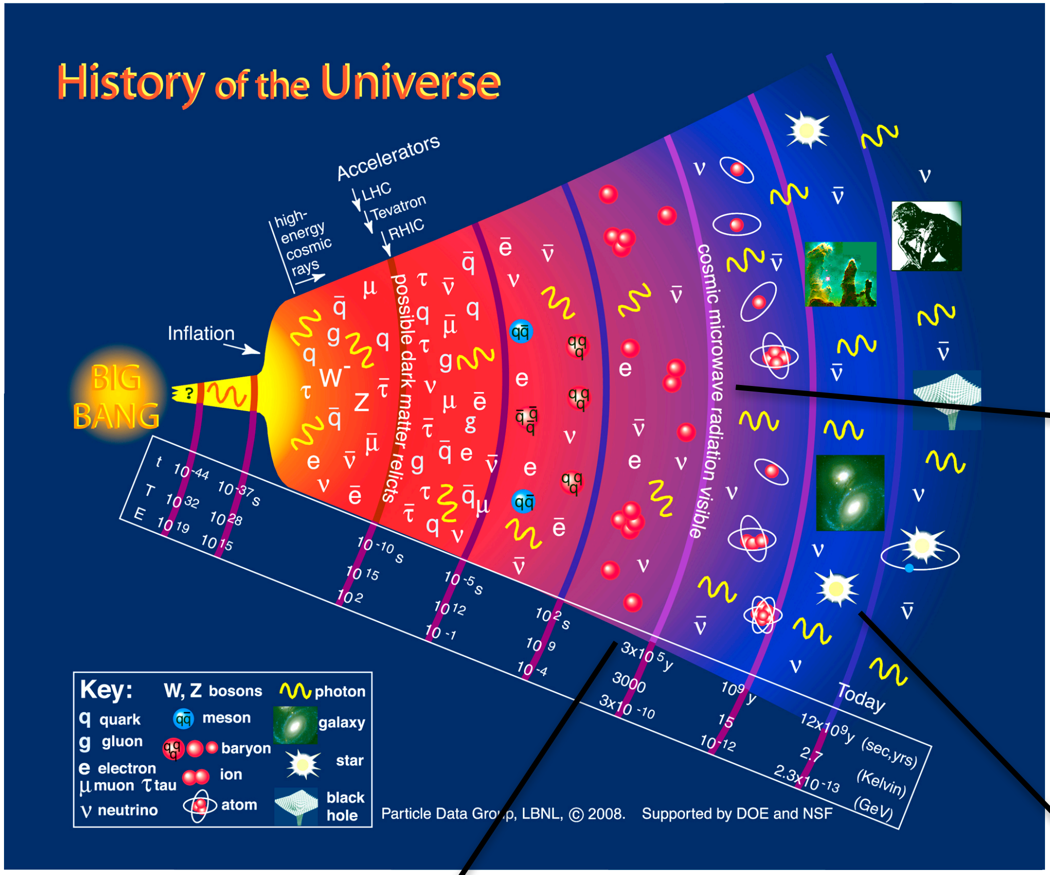
Absolute mass scale

Best constraints at present from cosmology



Cosmological neutrinos

Neutrinos have left many traces in the history of the Universe



CMB

Galaxy distribution (LSS)

Nucleosynthesis

Neutrinos @ nucleosynthesis (BBN)

Before LEP, the best constraint on N_ν came from Big Bang nucleosynthesis!

Neutrinos decouple from the plasma @T_ν~1MeV

$$Rate\left(\begin{array}{c}\nu_e\ n \leftrightarrow p\ e^- \\ e^+ n \leftrightarrow p\ \bar{\nu}_e\end{array}\right) \simeq \text{ Expansion rate}(g_*(T))$$

$$g_*(T) \equiv \#\text{of relativistic degrees of freedom}$$

Each neutrino species counts like one relativistic d.o.f.:

g* depends on $N_\nu \Rightarrow T_\nu(N_\nu)$

Neutrinos @nucleosynthesis

At $@T_\nu \sim 1\text{MeV}$ the ratio neutrons/protons freezes and light elements start to form:

$$\frac{N_n}{N_p} = \exp\left(\frac{m_p - m_n}{T_\nu(N_\nu)}\right)$$

The abundance of light nuclei depends strongly on the ratio of n/p

$$Y_{^4\mathrm{He}} = \frac{\text{Mass of } {}^4\text{He}}{\text{Total Mass}} = \frac{2N_n}{N_p + N_n}$$

Neutrinos as DM

Neutrino distribution gets frozen at BBN when they are still relativistic

$$N_\nu \simeq N_{\bar{\nu}} \simeq \frac{4}{11} T_\gamma^3$$

Later on they become non-relativistic, but there are many of them

$$\Omega_\nu = \frac{\sum_i m_i}{93.5 \text{ eV}} h^{-2} < \Omega_m \to \sum_i m_i \leq 11.2 \text{ eV}$$

Gershtein, Zeldovich

Massive neutrinos O(eV) contribute significantly to Ω_m

They tend to produce a Universe with too little structure at small scales: hot DM

Absolute mass scale

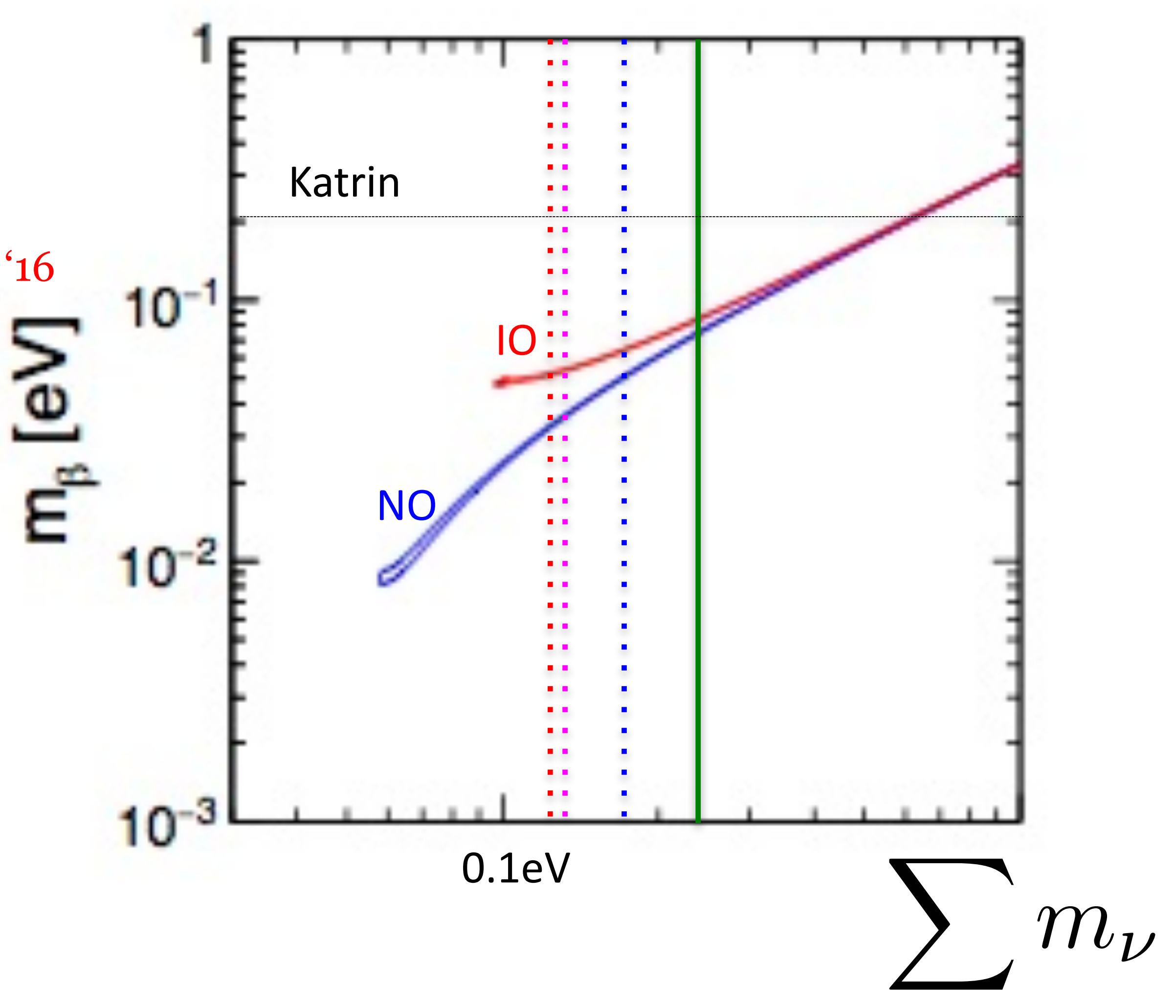
Neutrinos as light as 0.1-1eV modify the large scale structure and CMB

Planck '15

Giusarma et al '16

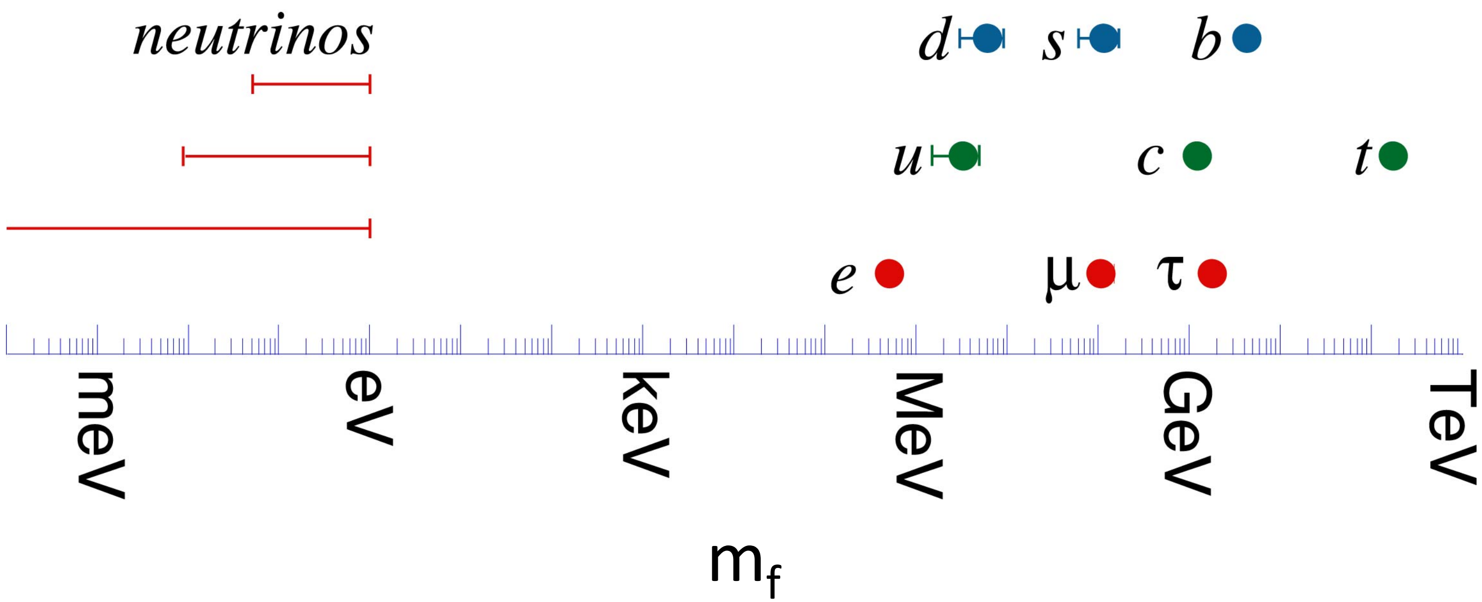
Palanque-Delabrouille et al '16

Cuesta et al '16



Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



Why so different mixing ?

CKM

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

PDG

PMNS

$$|U|^{\rm LID}_{3\sigma} = \begin{pmatrix} 0.798 \to 0.843 & 0.517 \to 0.584 & 0.137 \to 0.158 \\ 0.232 \to 0.520 & 0.445 \to 0.697 & 0.617 \to 0.789 \\ 0.249 \to 0.529 & 0.462 \to 0.708 & 0.597 \to 0.773 \end{pmatrix}$$

NuFIT 2016

Why so different mixing ?

CKM

$$V_{CKM} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PMNS

$$|V_{PMNS}| \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Harrison, Perkings, Scott

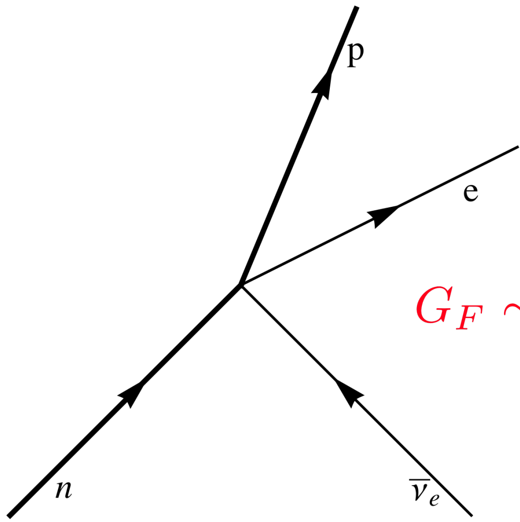
Where the large mixing comes from ?

Anarchy for leptons

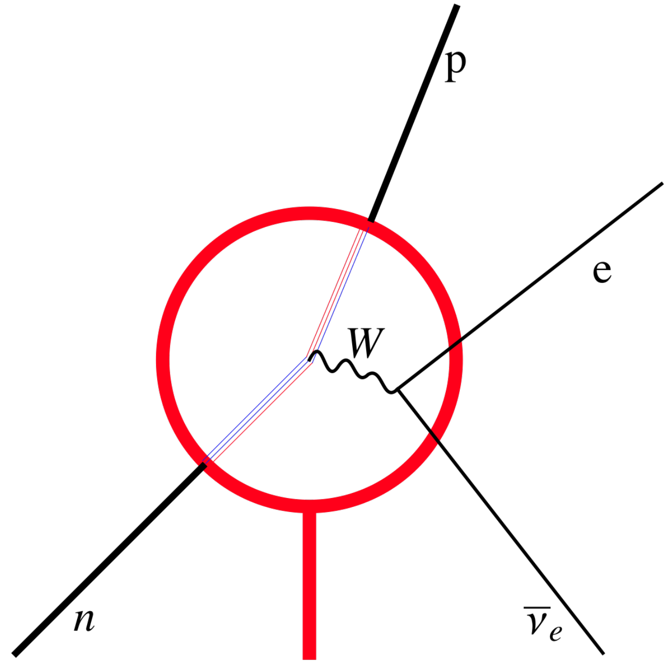
Discrete or continuous symmetries

Lepton-quark flavour connection in GUTs ?

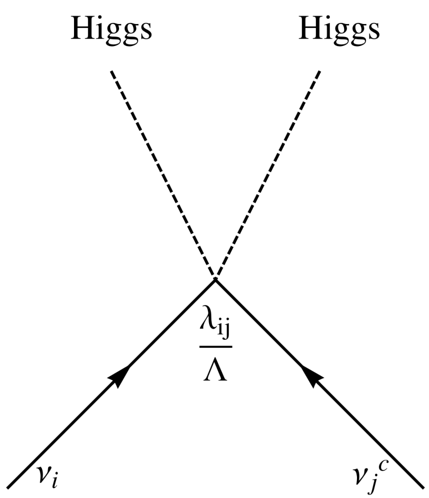
Neutrinos have tiny masses -> a new physics scale, what ?



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



SM



νSM ?

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

Scale at which new particles will show up

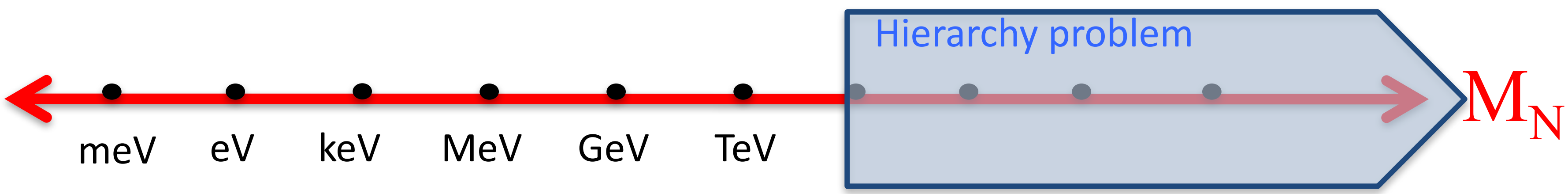
What originates the neutrino mass ?

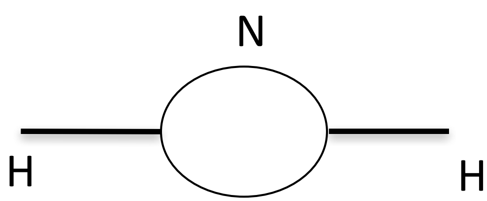
Could be $\Lambda >> v$... the standard lore (theoretical prejudice ?)

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

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/other solution to the hierarchy problem

What generates the neutrino mass ?

Could be naturally $\Lambda \sim v$?

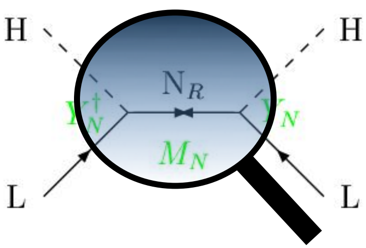
Yes !

λ in front of neutrino mass operator must be small...

Resolving the neutrino mass operator at tree level

E. Ma

Type I see-saw:
a heavy singlet scalar

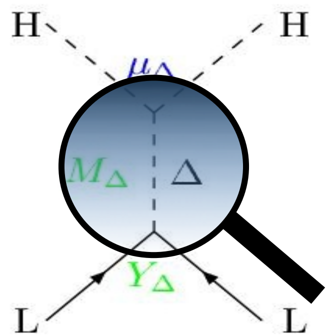


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

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

Type II see-saw:
a heavy triplet scalar

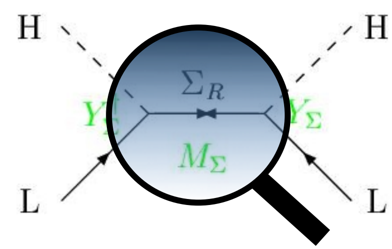


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

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

Type III see-saw:
a heavy triplet fermion

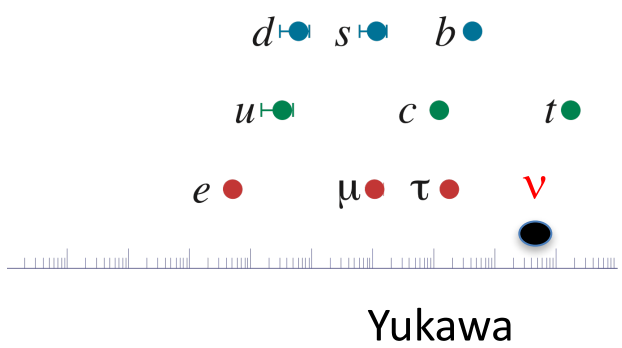


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

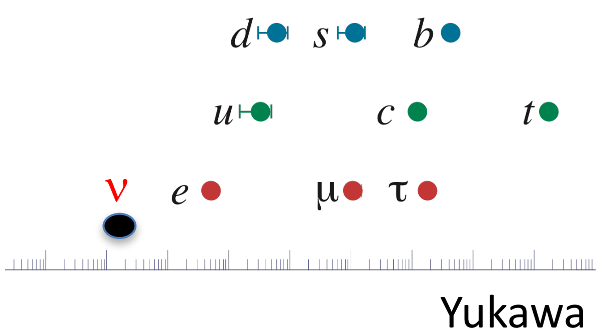
Foot et al; Ma;
Bajc, Senjanovic...

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

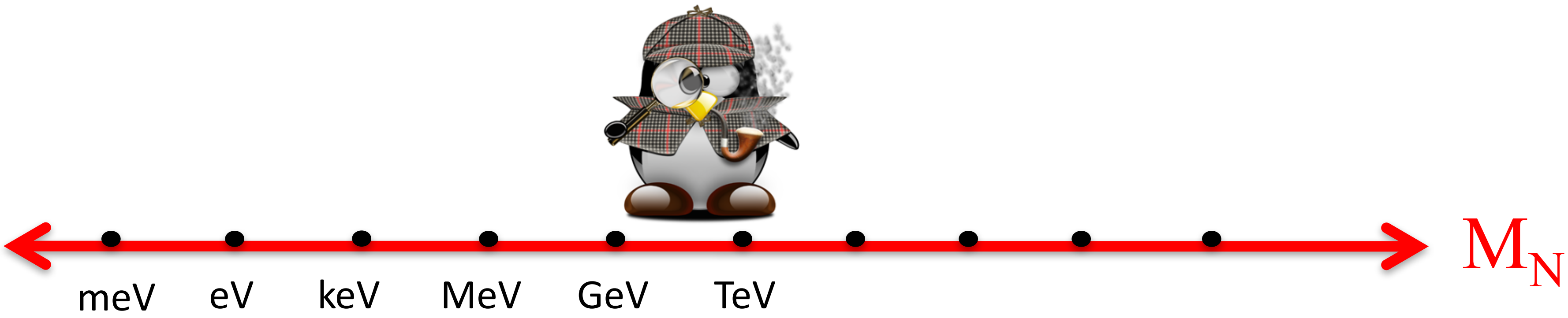
$M_N \sim$ GUT



$M_N \sim \nu$



Where is the new scale ?



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

Where is the new scale ?

Generic predictions

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

model independent contribution from the neutrino mass

Majorana nature: ββ0ν

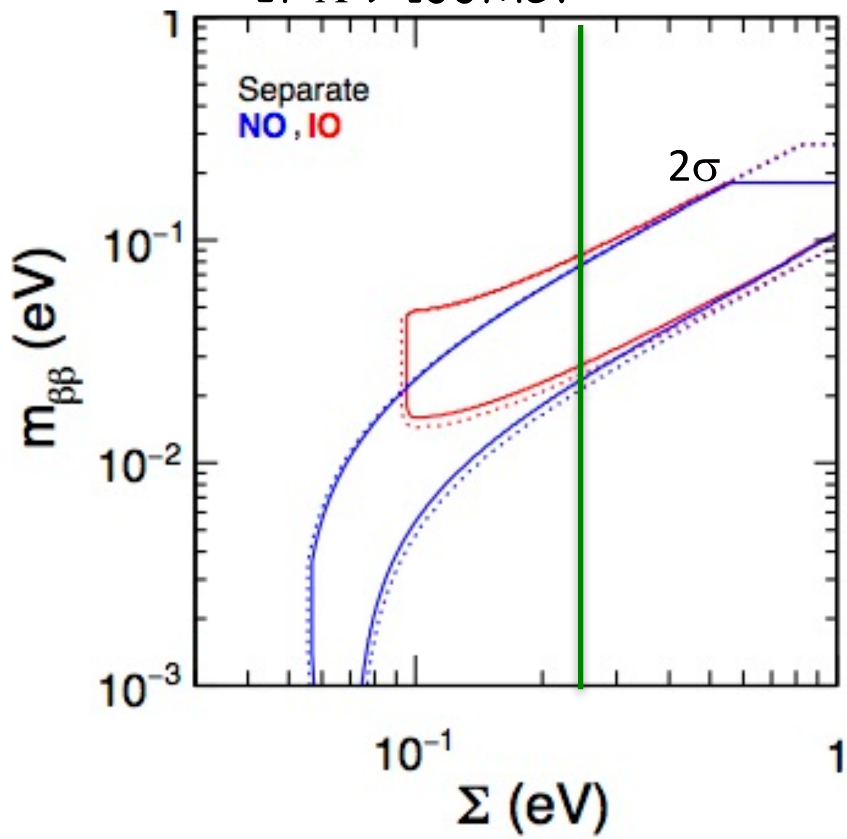
Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT, SuperNEMO, LUCIFER…

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

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

$$\Sigma \equiv \sum_i m_i$$

If Λ > 100MeV



Capozzi et al ‘17

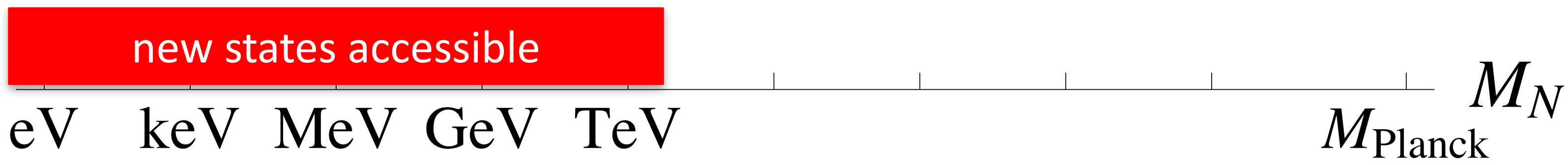
Where is the new scale ?

Generic predictions:

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

model dependent…

Where is the new scale ?



Generic predictions:

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

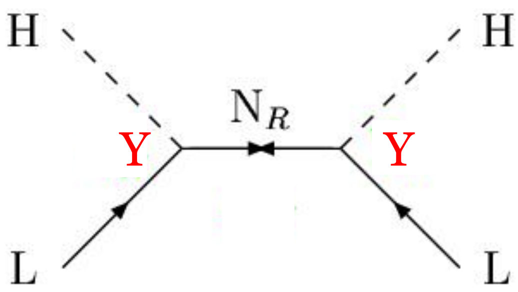
potential impact in cosmology, EW precision tests, LHC, rare searches, $\beta\beta0\nu$, ...

model dependent...

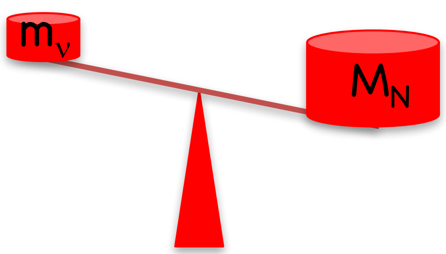
Minimal model of neutrino masses:

Type I seesaw: SM+right-handed neutrinos

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



$$n_R \geq 2$$

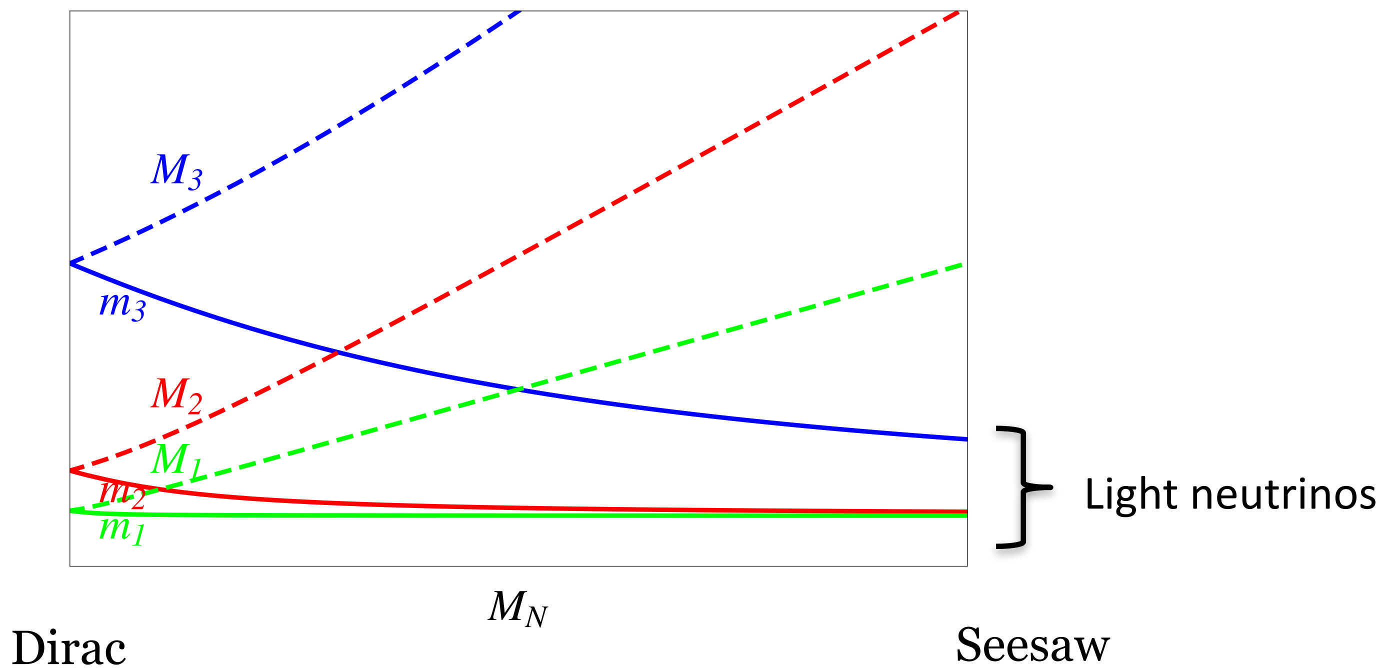


$$m_\nu = \lambda \frac{v^2}{\Lambda} \equiv Y^T \frac{v^2}{M} Y$$

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…

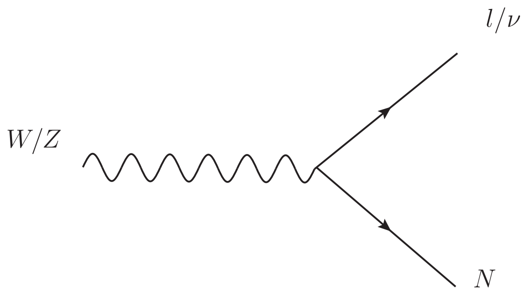


Type I seesaw models

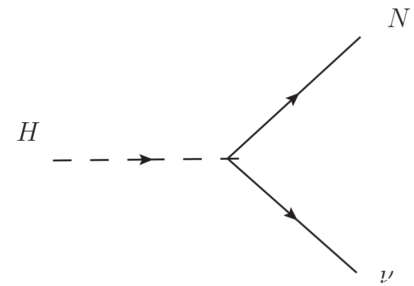
Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

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

Type I seesaw models



U_{lh}



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

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

Casas-Ibarra

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

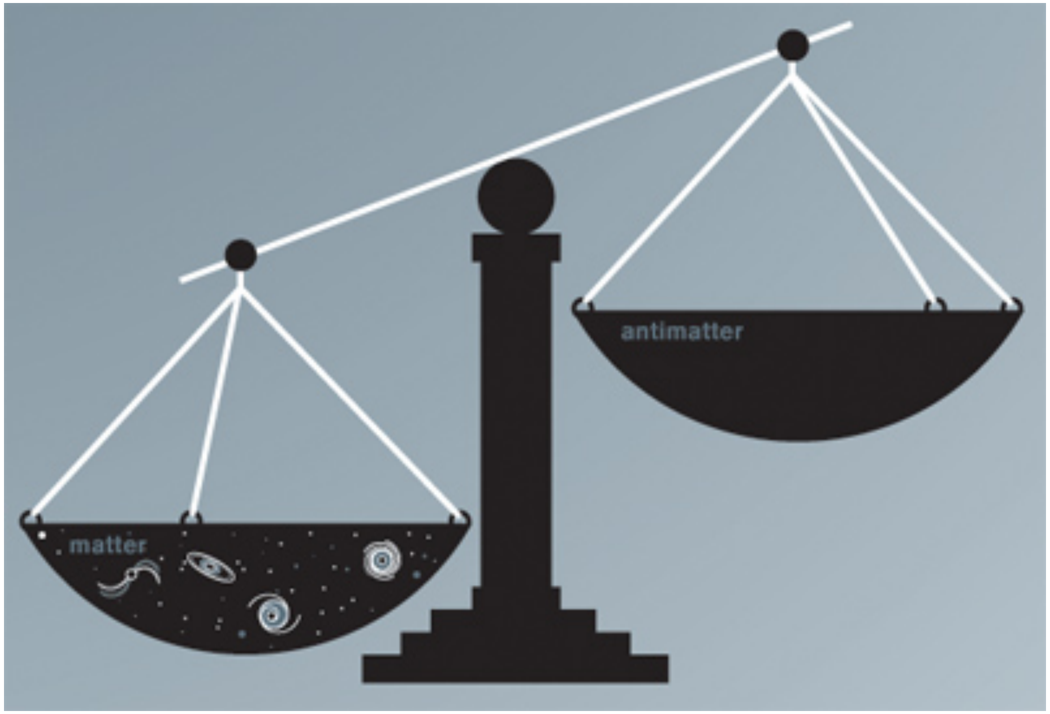
Strong correlation between active-heavy mixing and neutrino masses:

$$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$

(but naive scaling too naive for n_R >1...)

Baryon asymmetry

The Universe seems to be made of matter



$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}$$

Baryon asymmetry

Can it arise from a symmetric initial condition with same matter & antimatter ?

Sakharov's necessary conditions for baryogenesis

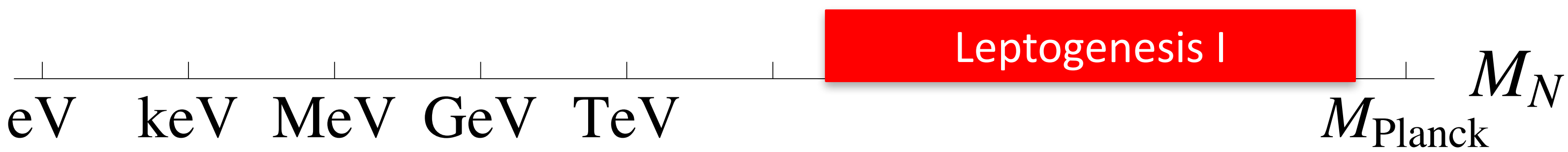
- ✓ Baryon number violation (B+L violated in the Standard Model)
- ✓ C and CP violation (both violated in the SM)
- ✓ Deviation from thermal equilibrium (at least once: electroweak phase transition)

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

CP violation in quark sector far to small, EW phase transition too weak…

Leptogenesis

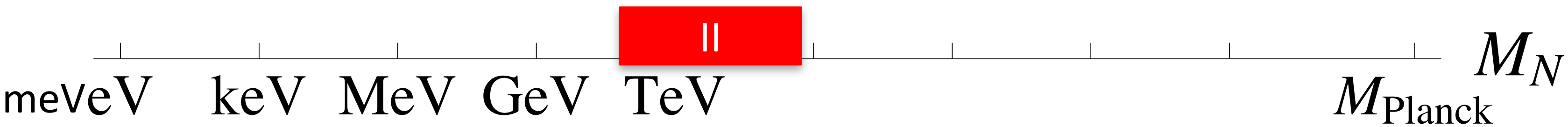
Models with massive neutrinos generically lead togeneration of lepton and therefore baryon asymmetries



Standard leptogenesis in out-of-equilibrium decay $M_N > 10^7$GeV

Fukuyita, Yanagida

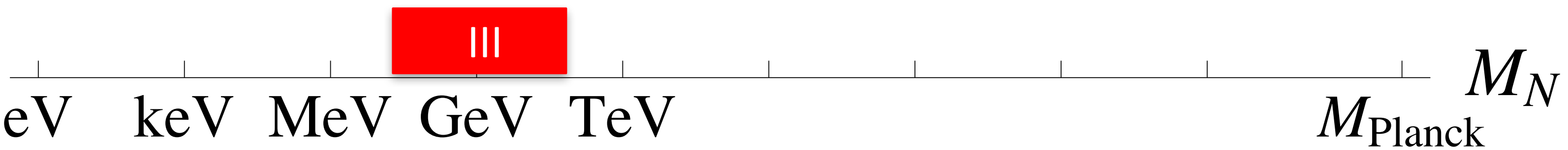
Leptogenesis



Resonant leptogenesis M>100 GeV

Pilaftsis...

Leptogenesis



Leptogenesis from neutrino oscillations
0.1GeV <M < 100GeV

Akhmedov, Rubakov, Smirnov;
Asaka, Shaposhnikov,...

Sakharov conditions

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

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

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

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

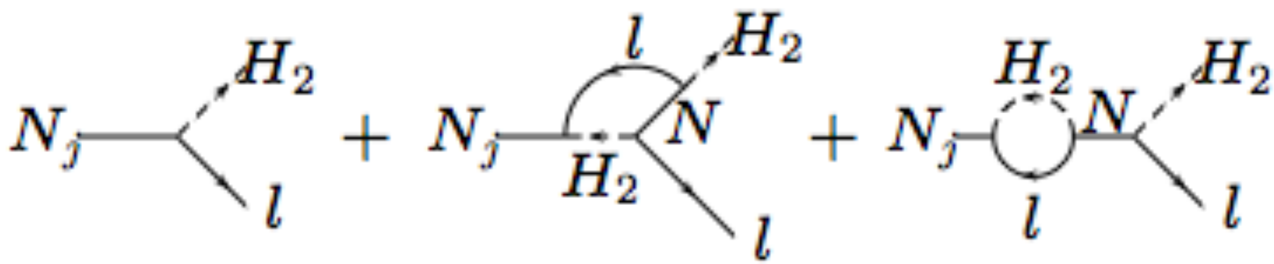
+ L (high-scales)
+ $L\alpha$ (high and low scales)

✔ Out of equilibrium: different for low and high scales

High–scale leptogenesis

New sources of CP violation and L violation in the neutrino sector can induce CP asymmetries in decays of heavy Majorana ν

Fukuyita, Yanagida



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

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

Generic and robust feature of see-saw models for large enough scales $M_N > 10^7$-10^9 GeV (unless an extreme degeneracy exits)

Low-scale Leptogenesis

Akhmedov, Rubakov,Smirnov

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

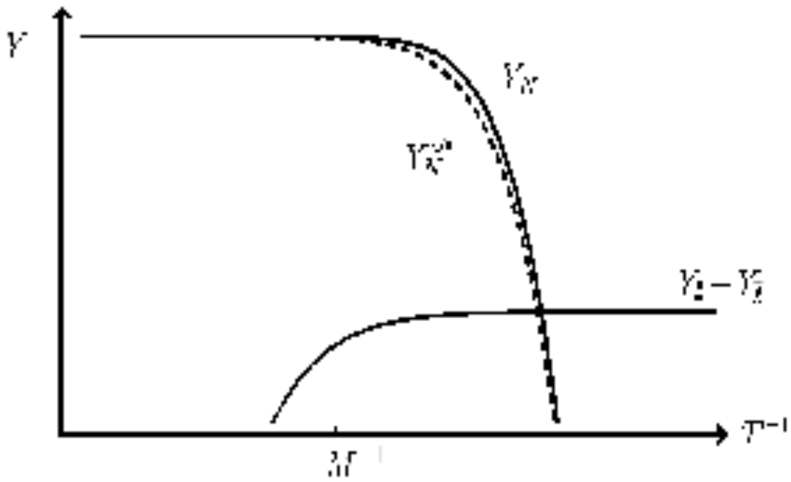
$$L_\alpha \to L_\beta \neq \bar{L}_\alpha \to \bar{L}_\beta$$

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

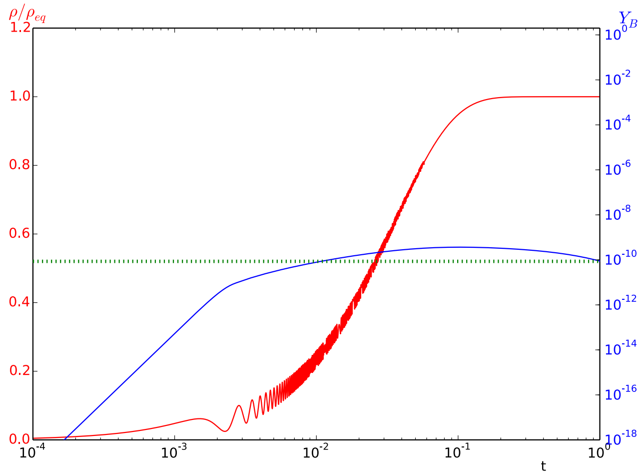
$$\sum_\alpha \Delta^\alpha_{CP} = 0$$

Different flavours different efficiency in transfering it to the baryons

High-scale leptogenesis
(larger Y)



Low-scale leptogenesis
(smaller Y)



T_{EW}

$$\Gamma_N \leq H(M_N)$$

$$\Gamma_s(T_{EW}) \leq H(T_{EW})$$

(decay rate < hubble expansion)

(scattering rate < hubble expansion)

Testability/predictivity ?

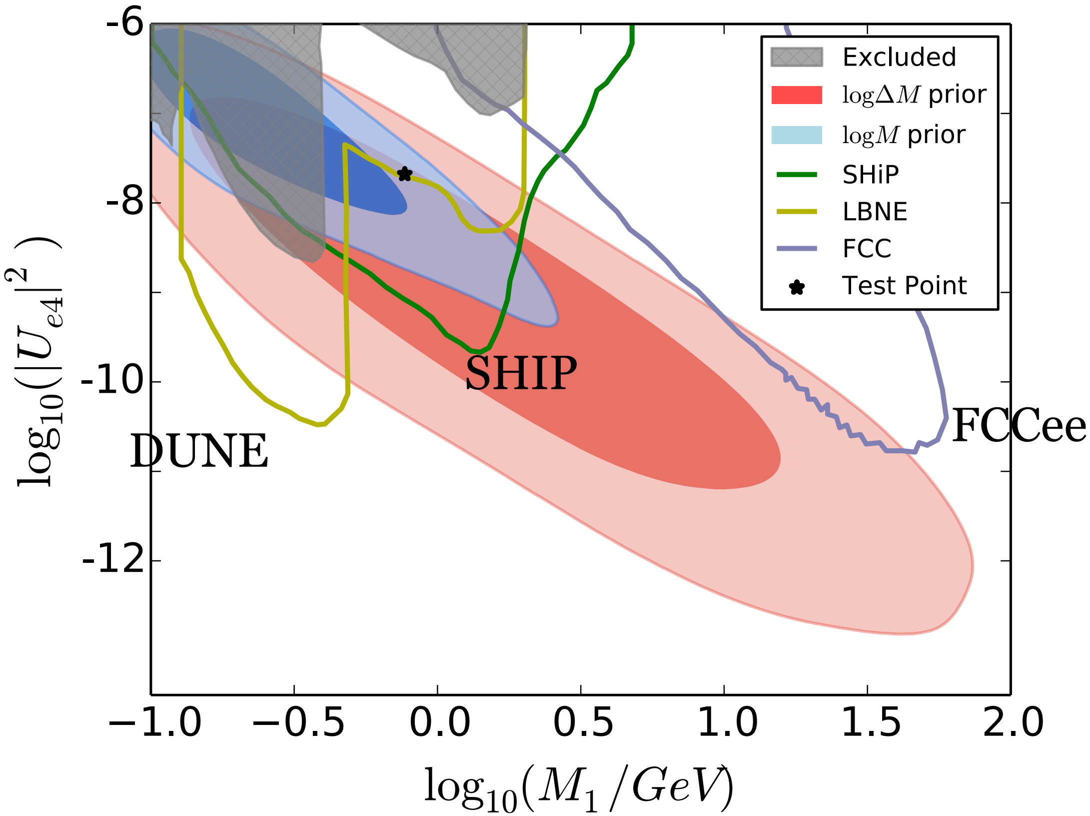
- Y_B cannot be determined from neutrino masses and mixings only

- More information from the heavy sector is needed:

High-scale scenarios: very difficult for $M_N > 10^7$ GeV

Low-scale scenarios: N's can be produced in the lab
and could be in principle detectable !

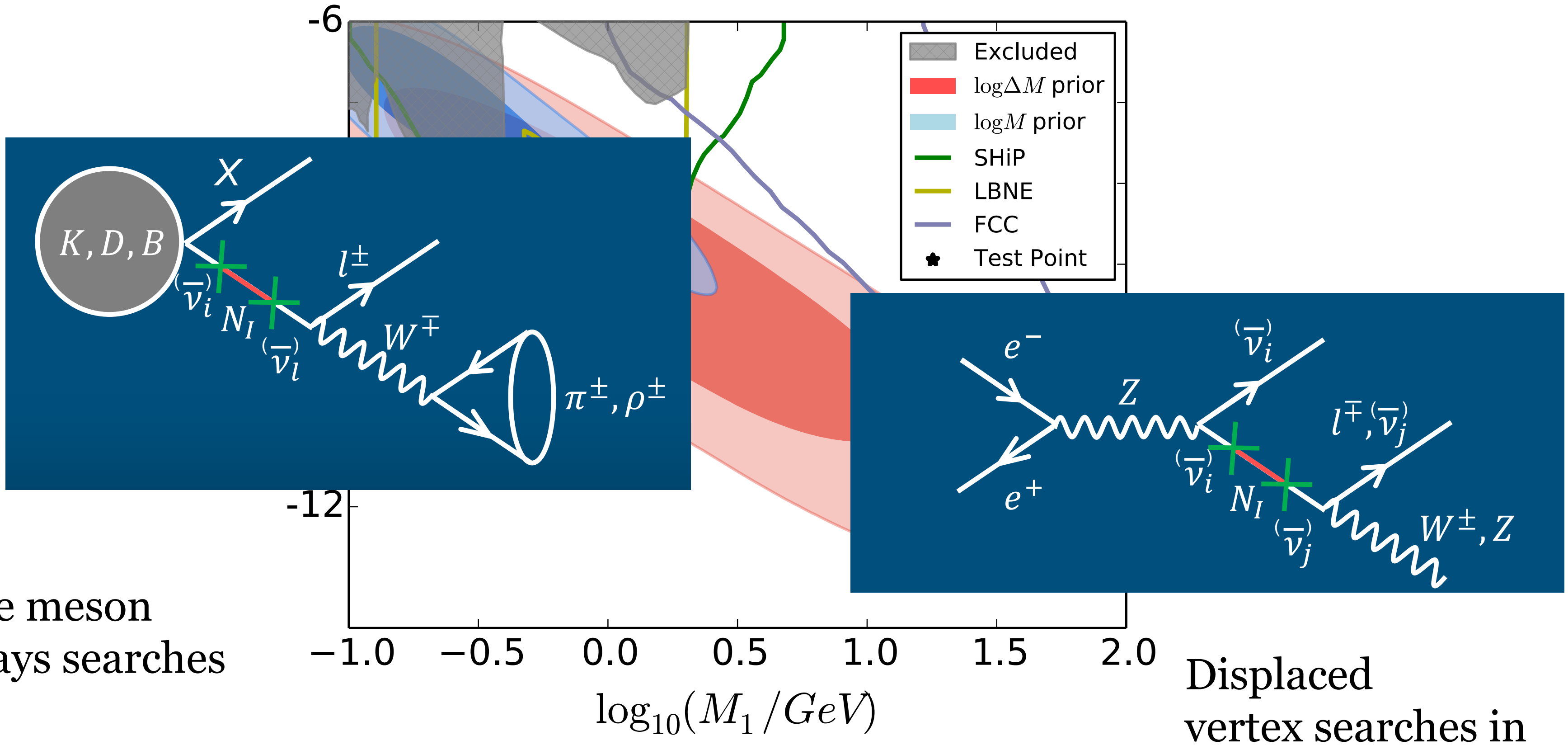
In the minimal model with just n_R=2 neutrinos (IH)



PH, Kekic, Lopez-Pavon, Racker, Salvado

Colored regions: posterior probabilities of successful Y_B

In the minimal model with just n_R=2 neutrinos (IH)



Rare meson decays searches

Displaced vertex searches in Z decays

Predicting Y_B in the minimal model n_R=2 ?

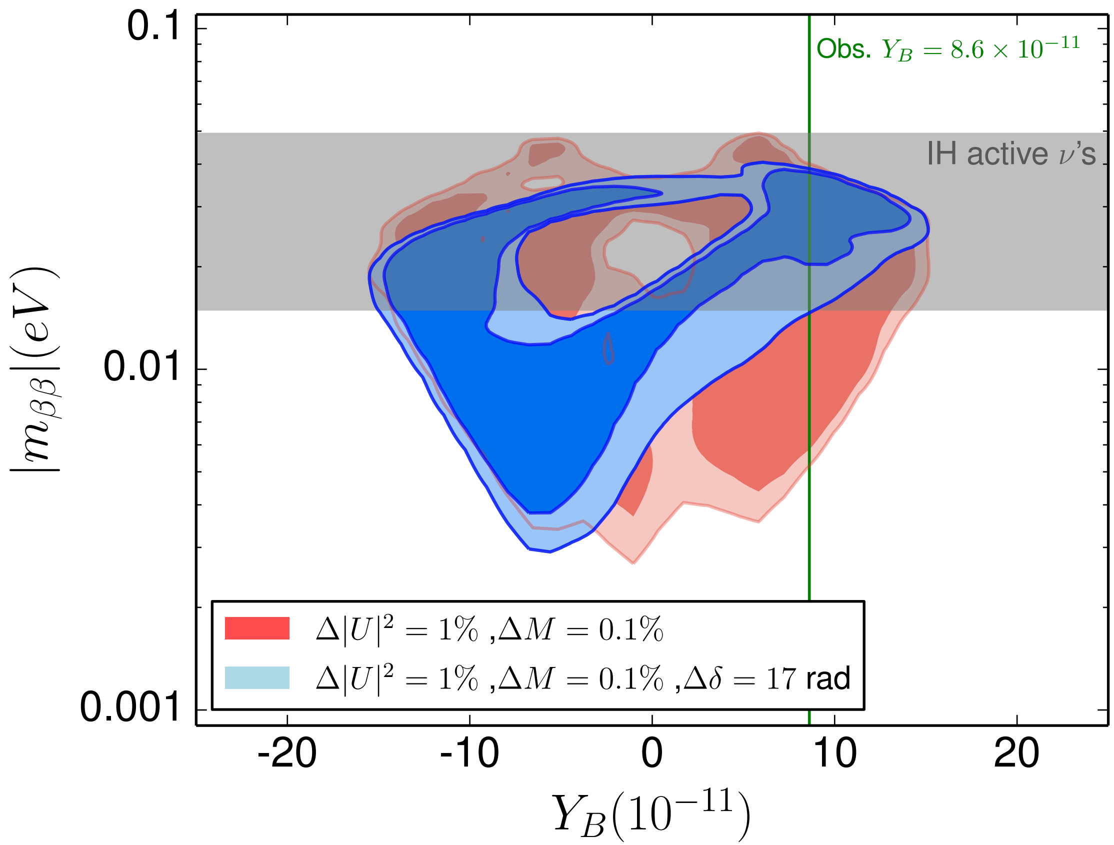
Assume black point within SHIP reach that gives the right Y_B

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

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

- Future neutrino oscillations: δ phase in the U_{PMNS}

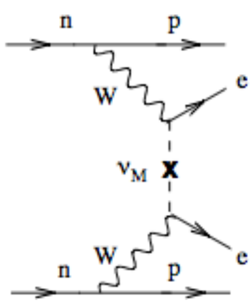
Predicting Y_B in the minimal model n_R=2 (IH)



PH, Kekic, Lopez-Pavon, Racker, Salvado

Predicting Y_B in the minimal model $n_R=2$

Heavy states also contribute to the ββ0ν amplitude…



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

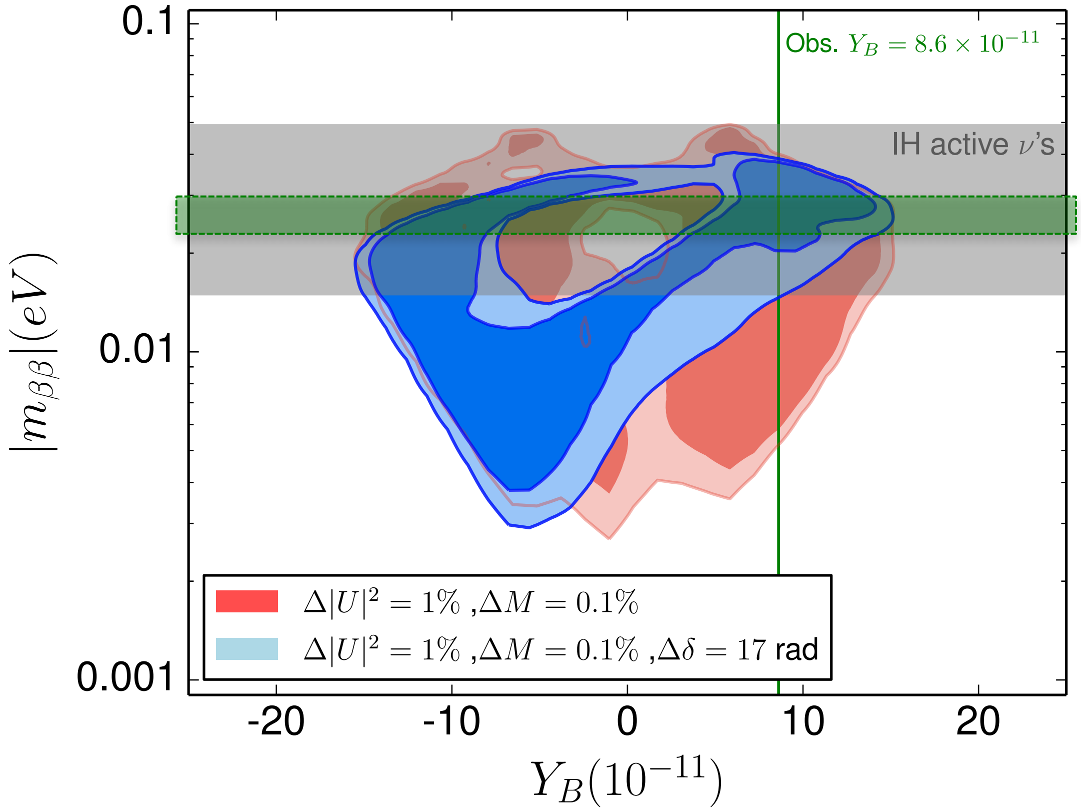
$$M_j \to \infty \qquad \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)} \propto \left(\frac{100\ \text{MeV}}{M_j}\right)^2$$

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

The heavy contributions bring essential information of some CP phases
ad other unknown parameters

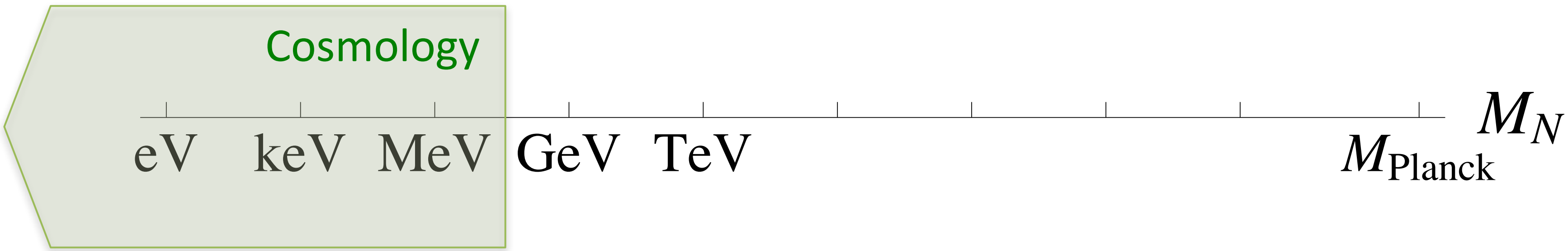
Predicting Y_B in the minimal seesaw model M~GeV



PH, Kekic, López-Pavón, Racker, Salvado

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

Where are the new states ?

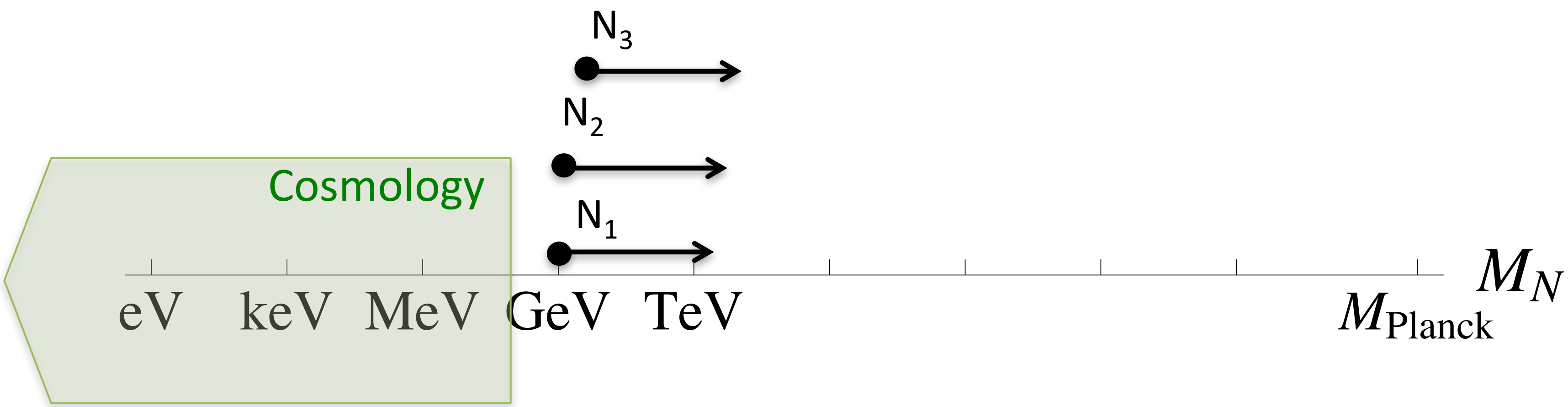


Sterile neutrinos below 100MeV can strongly modify

Big-Bang Nucleosynthesis
Cosmic Microwave background
Large Scale structure

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

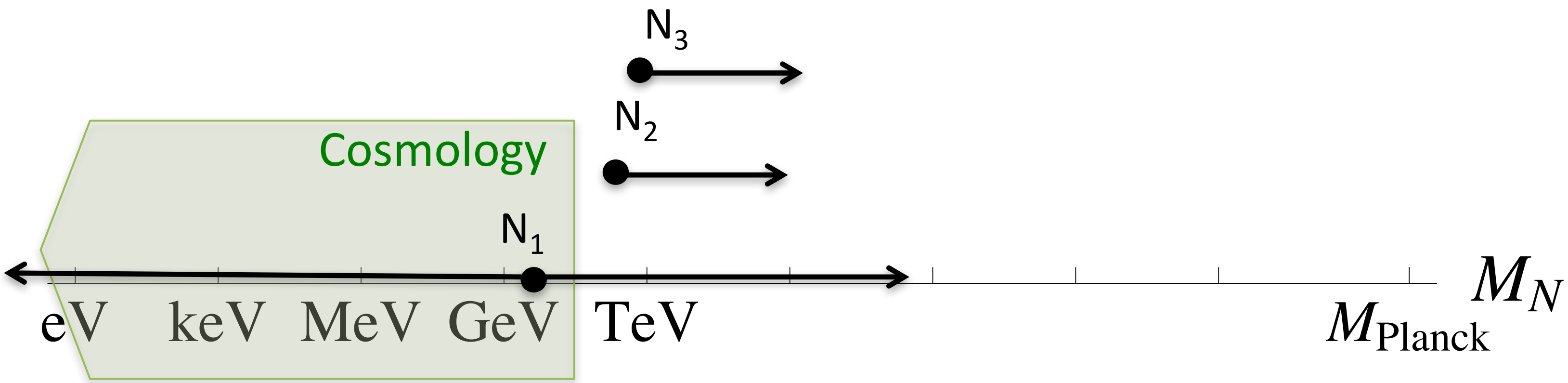
Contribute as DM (Ω_{DM}) and/or extra radiation (ΔN_{eff})



In the seesaw model $n_R=3$

$$m_{lightest} > 3.2 \times 10^{-3}\,\text{eV} \qquad M_i > 100\text{MeV}$$

PH, M. Kekic, J. López-Pavon

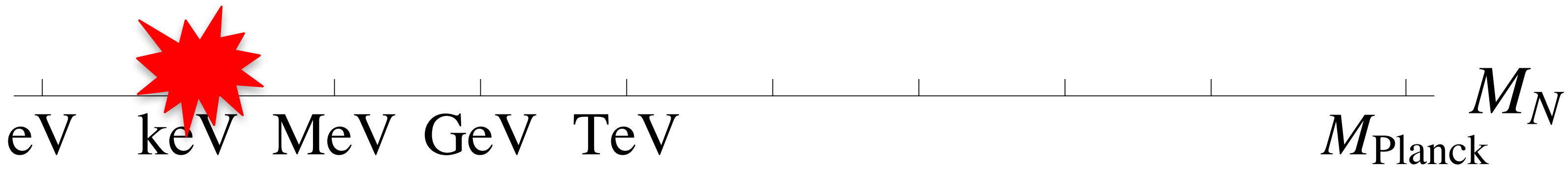


In the seesaw model $n_R=3$

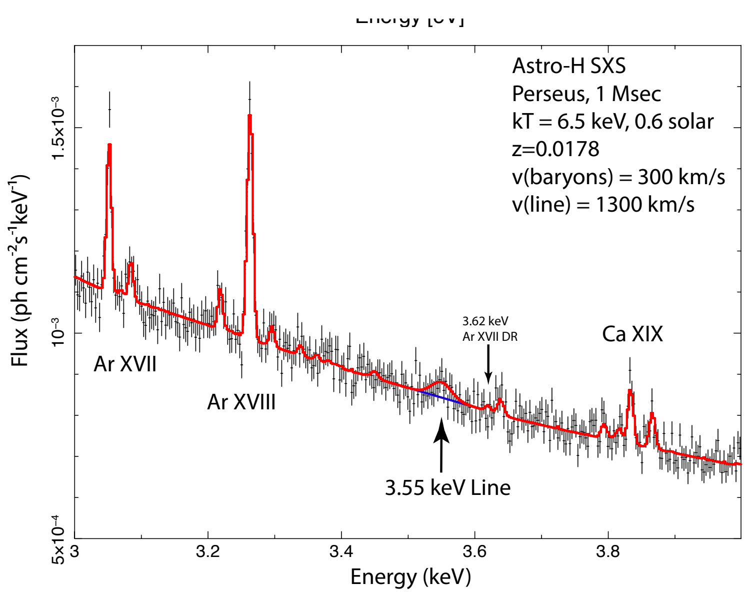
$m_{lightest} < 3.2 \times 10^{-3}$ eV $\quad M_{2,3} > 100$MeV

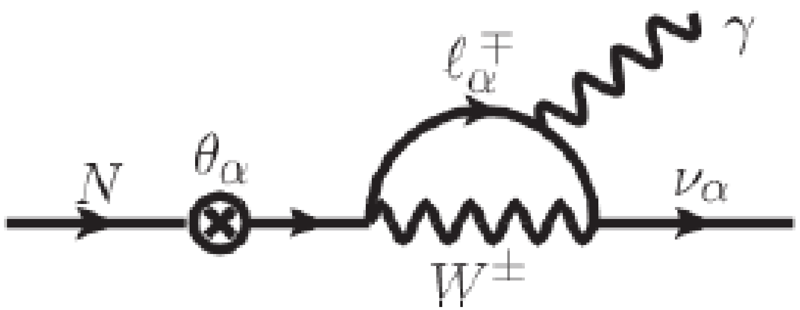
PH, M. Kekic, J. López-Pavon

νMSM: Warm Dark Matter ?



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





$$E_\gamma = \frac{M_N}{2}$$

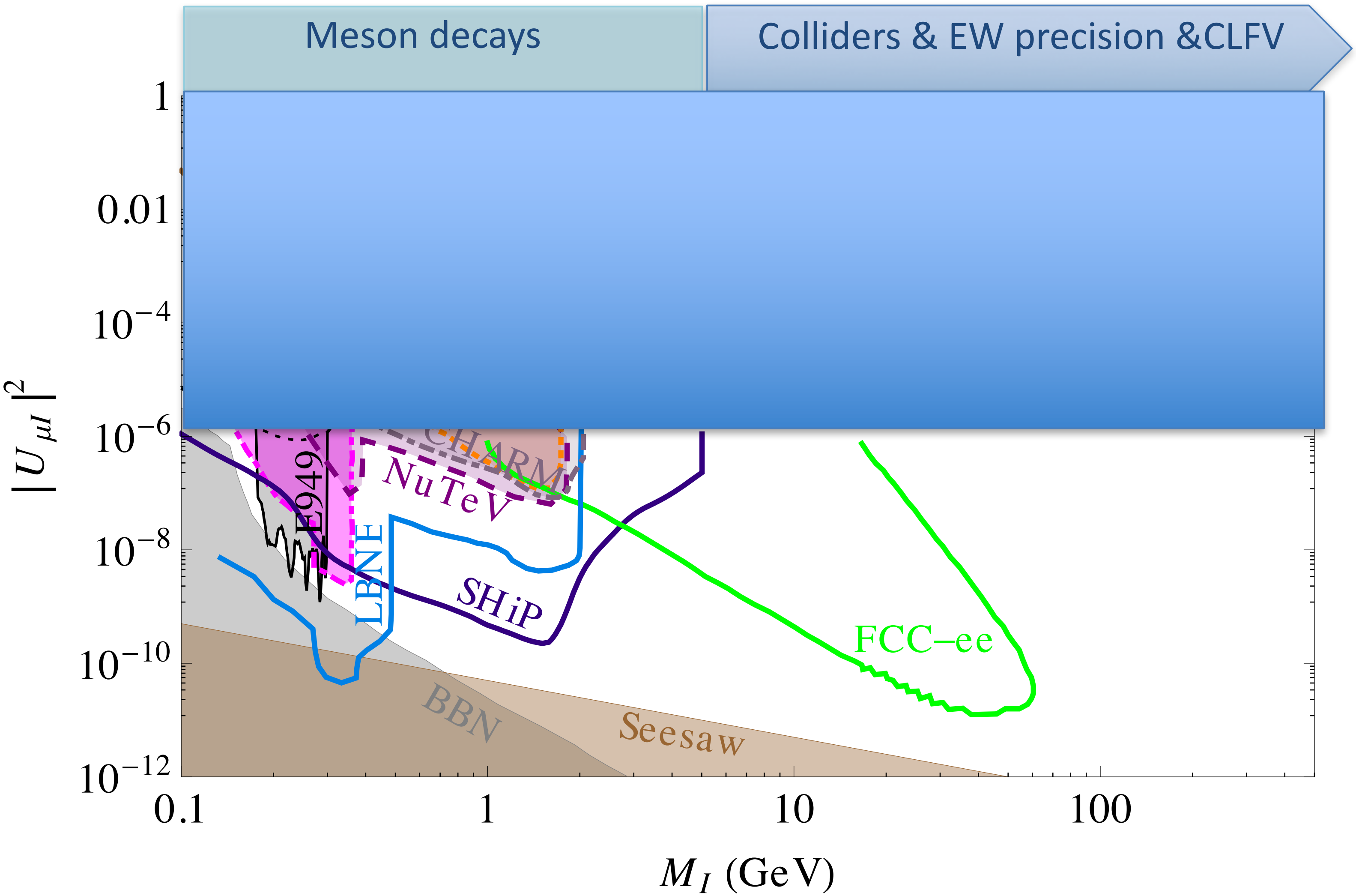
$$M_N \simeq 7\ \mathrm{keV}$$

Bulbul et al 1402.2301; Boyarsky 1402.4119

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

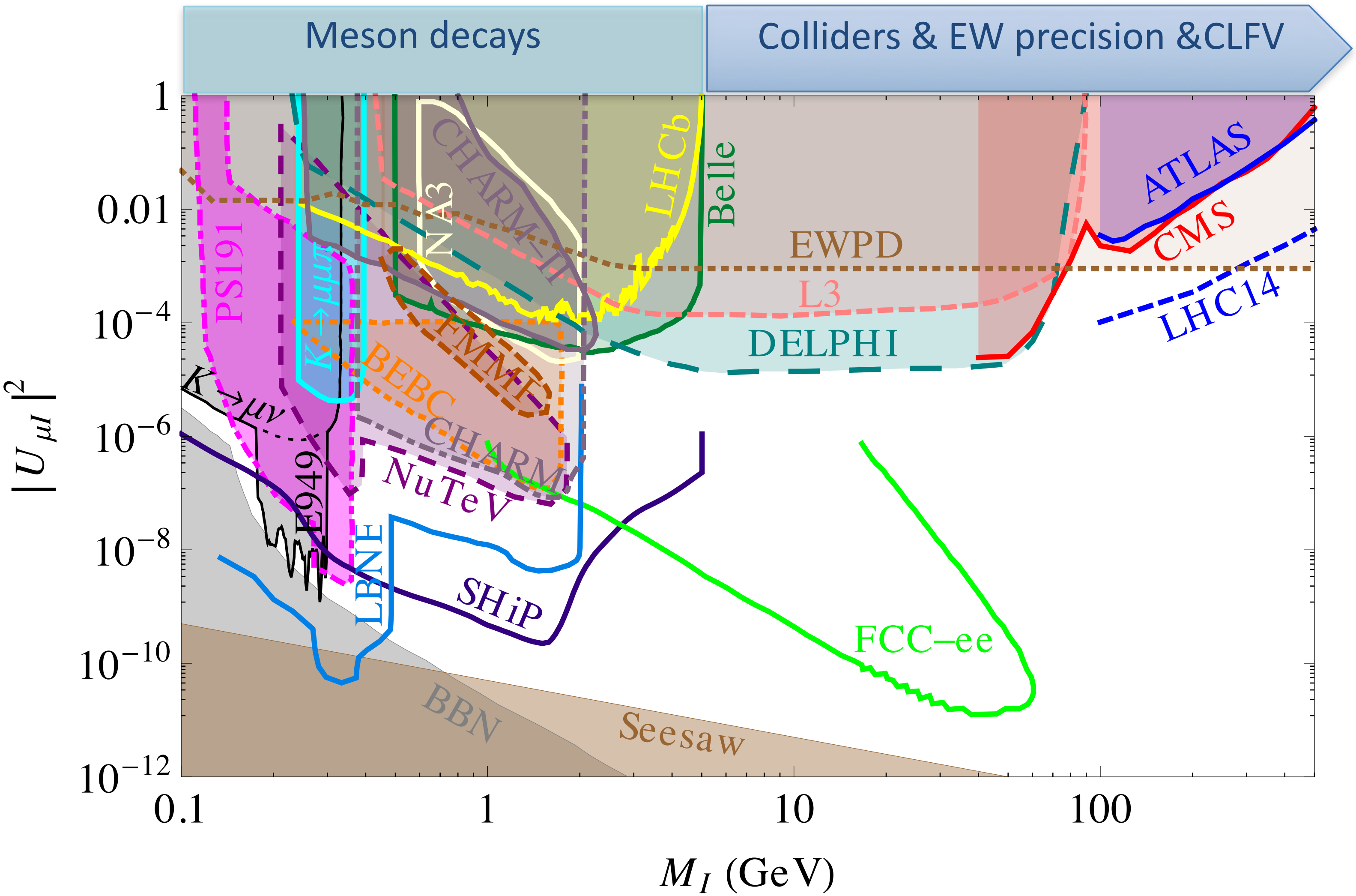
Where are the new states ?

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

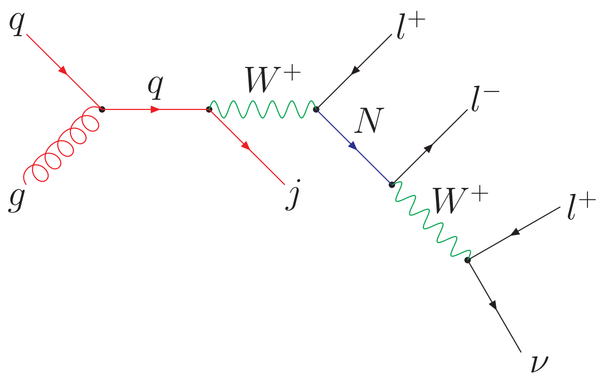


Larger Mixings ?

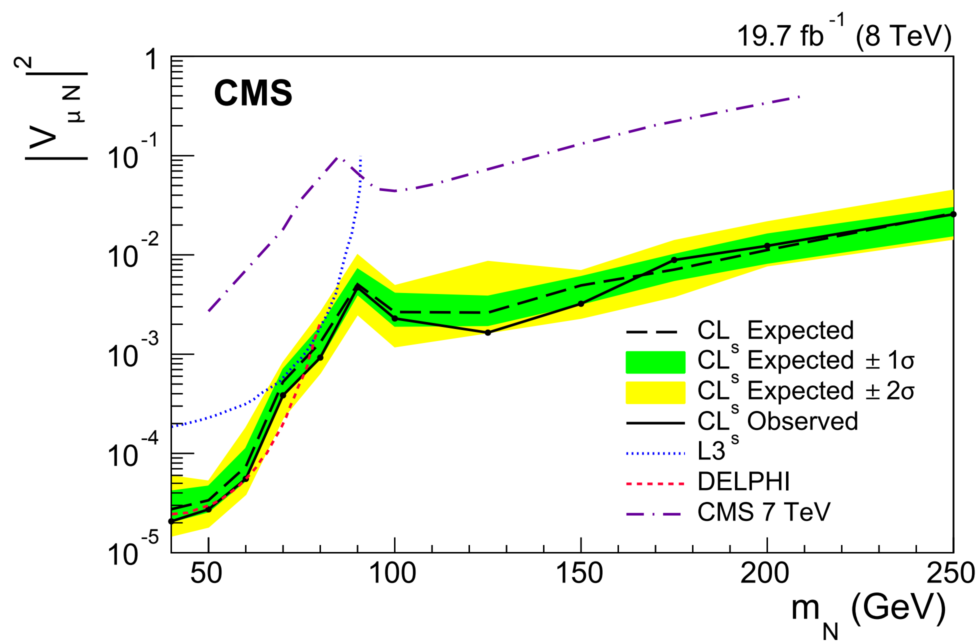
Reviews Atre, Han, Pascoli, Zhang; Gorbunov, Shaposhnikov; Ruchayskiy, Ivashko

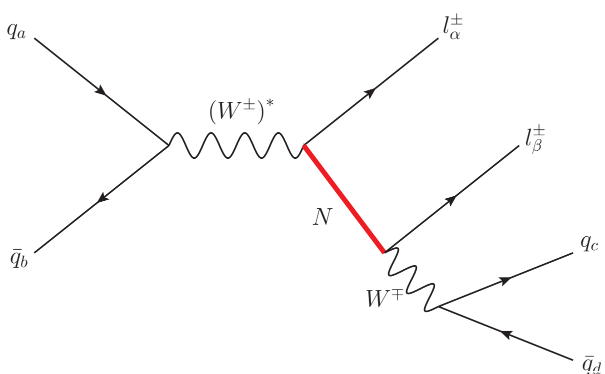


Standard LHC Searches



σ X $B_R > 10^{-3}$ pb

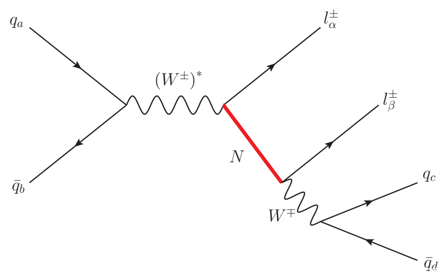


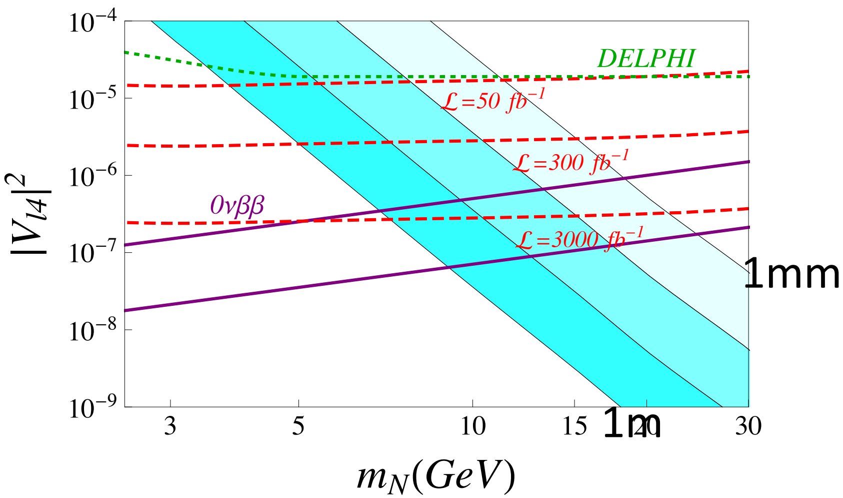


CMS 1501.05566

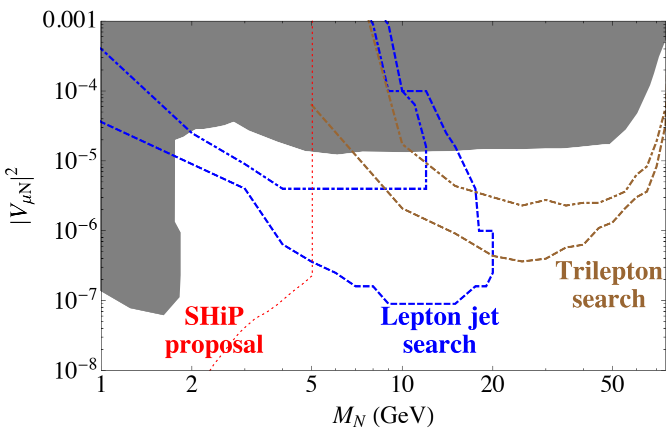
ATLAS 1506.06020

Low-mass $m_N < m_W$: Displaced Vertices

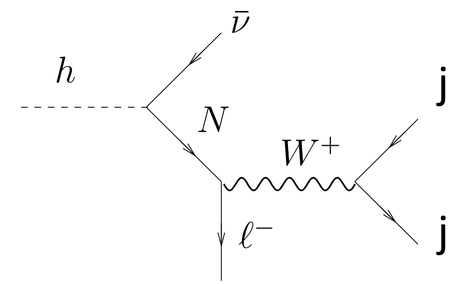


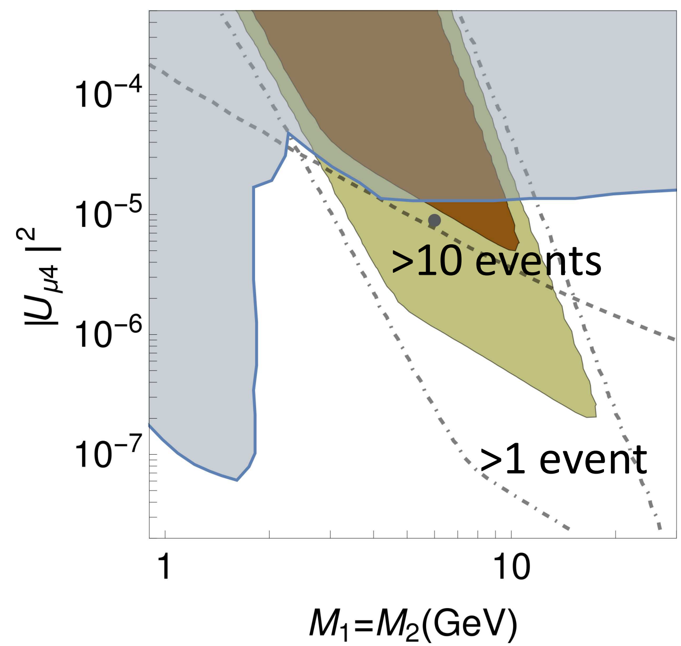


Helo, Kovalenko,Hirsch



Izaguirre, Shuve





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

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

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

Does not induce neutrino masses: Y unbounded by them

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

$$\begin{array}{cccc} L= & +1 & +1 & -1 \\ & \multicolumn{3}{c}{\begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix}} \end{array}$$

Inverse Seesaw

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

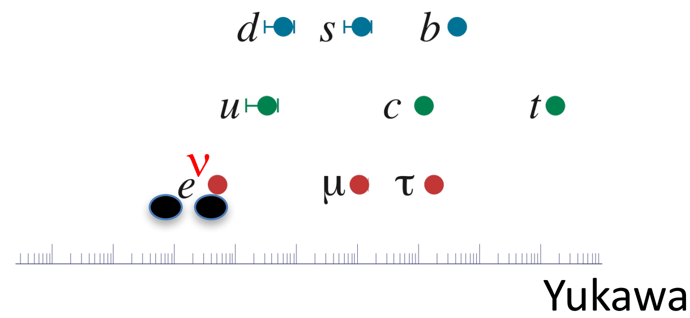
Direct Seesaw

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

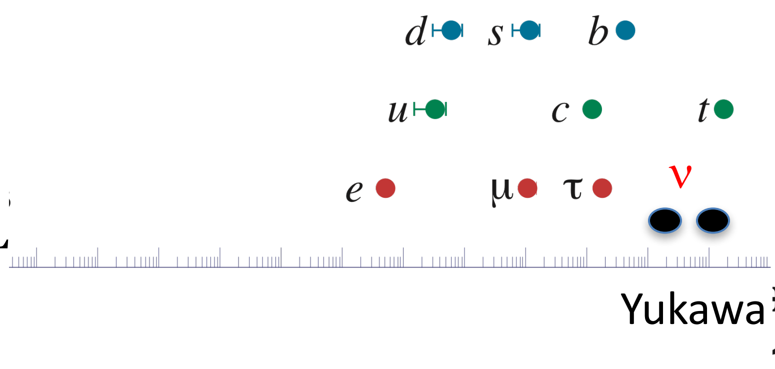
They are all a subclass of type I seesaw models (different choices of R)

Charged/neutral hierarchy in seesaw

M_N = TeV



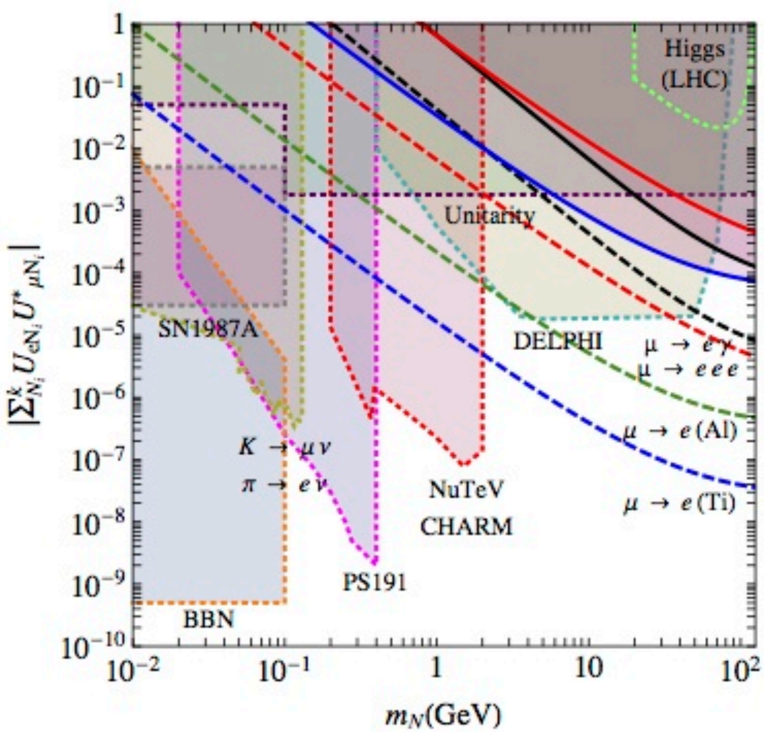
$M_N \leq$ TeV + aprox. $U(1)_L$

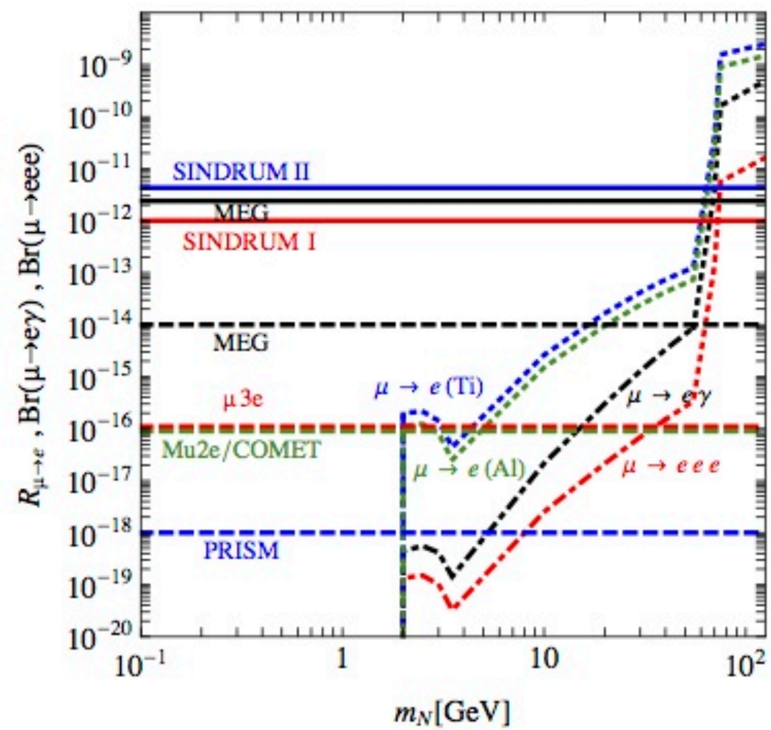


Room for improvement in these searches at LHC, LFV, future colliders: but must look for not lepton number violating processes

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

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





recent analysis Alonso et al 2012

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

Also (many) less minimal models

Gauge interactions of extra fields for large enough production

Examples: type II and type III
type I +W', Z'

Keung, Senjanovic; Han et al; Garayoa, Schwetz; Kadastik,et al ; Akeroyd, et al; Fileviez et al, del Aguila et al; Franceschini et al; Aguilar-Saavedra et al;Arhrib et al; Eboli et al...; Tello et al....

Grand Unification e.g. SO(10)

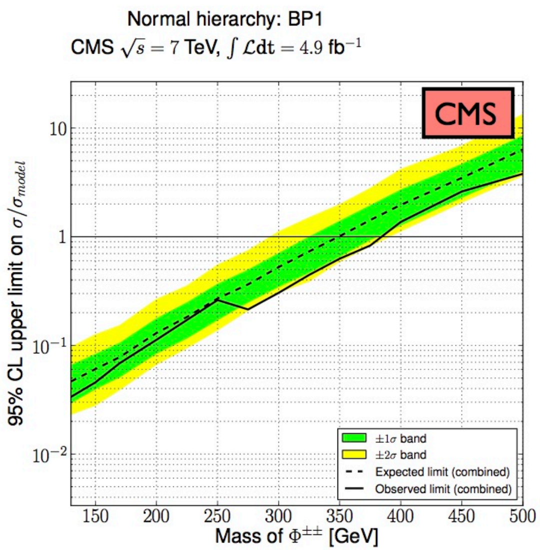
Babu. Mohapatra;Fukuyama Okada; Bajc,Senjanovic, Vissani;Joshipura, Patel; Altarelli, Meloni;...

Left-right symmetric models ...

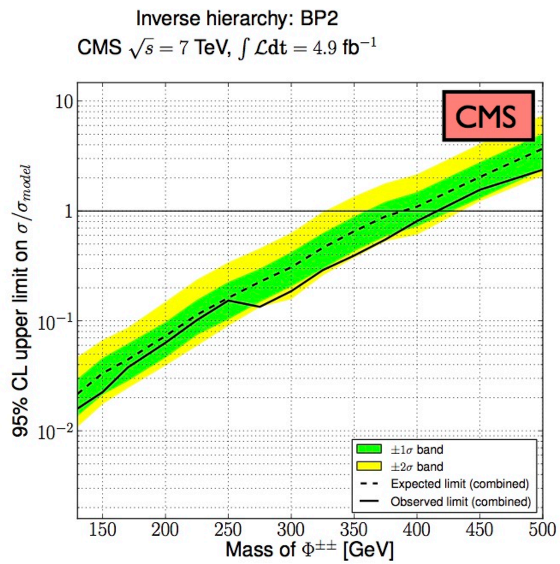
Pati, Salam; Mohapatra, Pati; Mohapatra, Senjanovic...

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

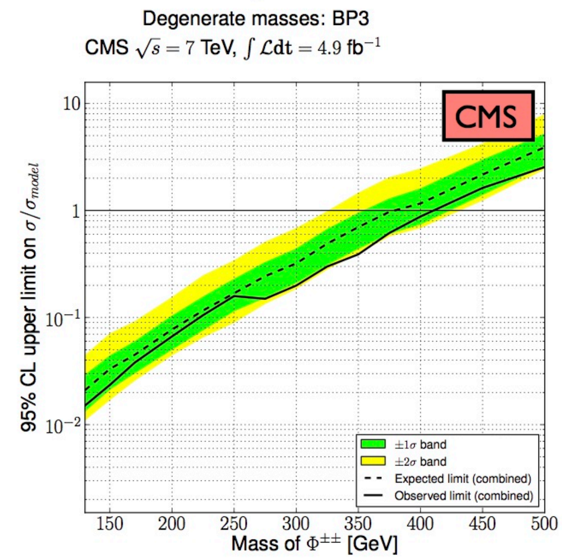
Normal hierarchy



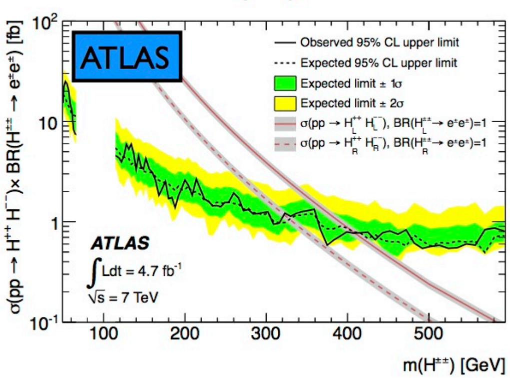
Inverted hierarchy



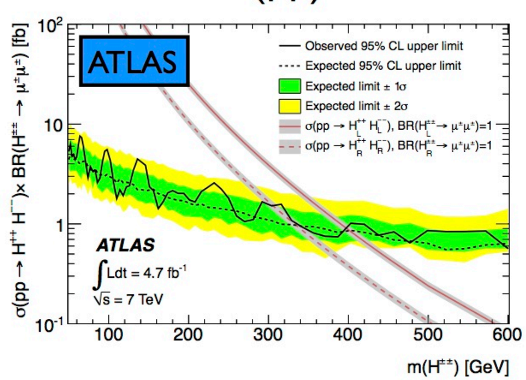
Degenerate ν



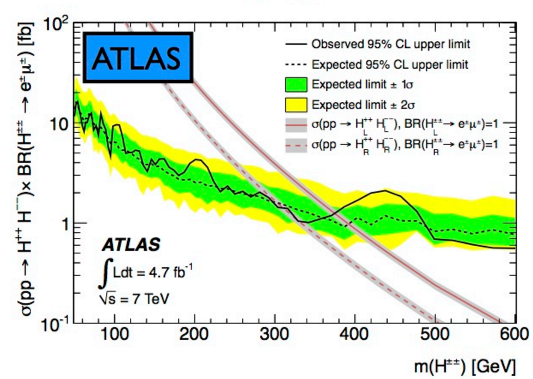
Br(ee)=1



Br(μμ)=1



Br(eμ)=1



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 new scale Λ could explain the smallness of neutrino and other mysteries such as the matter-antimatter asymmetry, DM, etc

• Complementarity of different experimental approaches: $\beta\beta0\nu$, CP violation in neutrino oscillations, direct searches in meson decays, collider searches of displaced vertices, etc…holds in well motivated models with a low scale Λ (GeV scale very interesting)