PLAN

- **Lecture I:** Neutrinos in the SM
  Neutrino masses and mixing: Majorana vs Dirac
- **Lecture II:** Neutrino oscillations and the discovery of neutrino masses and mixings
- **Lecture III:** The quest for the unkowns
  A neutrino look at BSM and the history of the Universe

SM+3 massive neutrinos

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

More fundamental parameters in the SM: 3 angles, 3 masses, 1 or 3 phases

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}}_{\text{Only Majorana}}$$

$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$$

Imaginary entries in leptonic mixing matrix imply violation of CP!

CP violation in oscillations

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$
$$\alpha \neq \beta$$

$$P(\nu_\alpha(\overline{\nu}_\alpha) \to \nu_\beta(\overline{\nu}_\beta)) = \quad -4\sum_{i<j} \mathrm{Re}[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}]\sin^2\left[\frac{\Delta m^2_{ji}L}{4E}\right] \quad \text{CP-even}$$
$$\mp 2\sum_{i<j} \mathrm{Im}[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}]\sin\left[\frac{\Delta m^2_{ji}L}{4E}\right] \quad \text{CP-odd}$$

SM+3 massive neutrinos: Global Fits

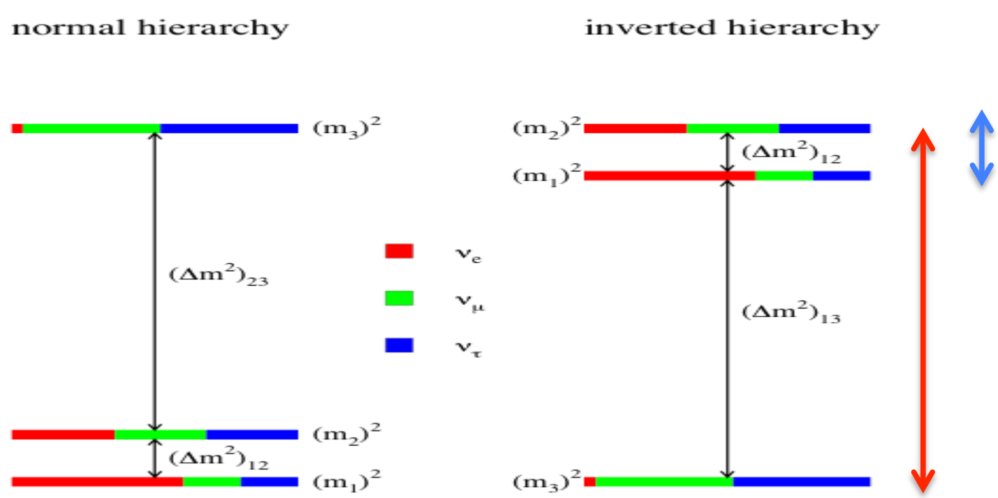
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$\theta_{23} \sim 42^\circ$ o 48°

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

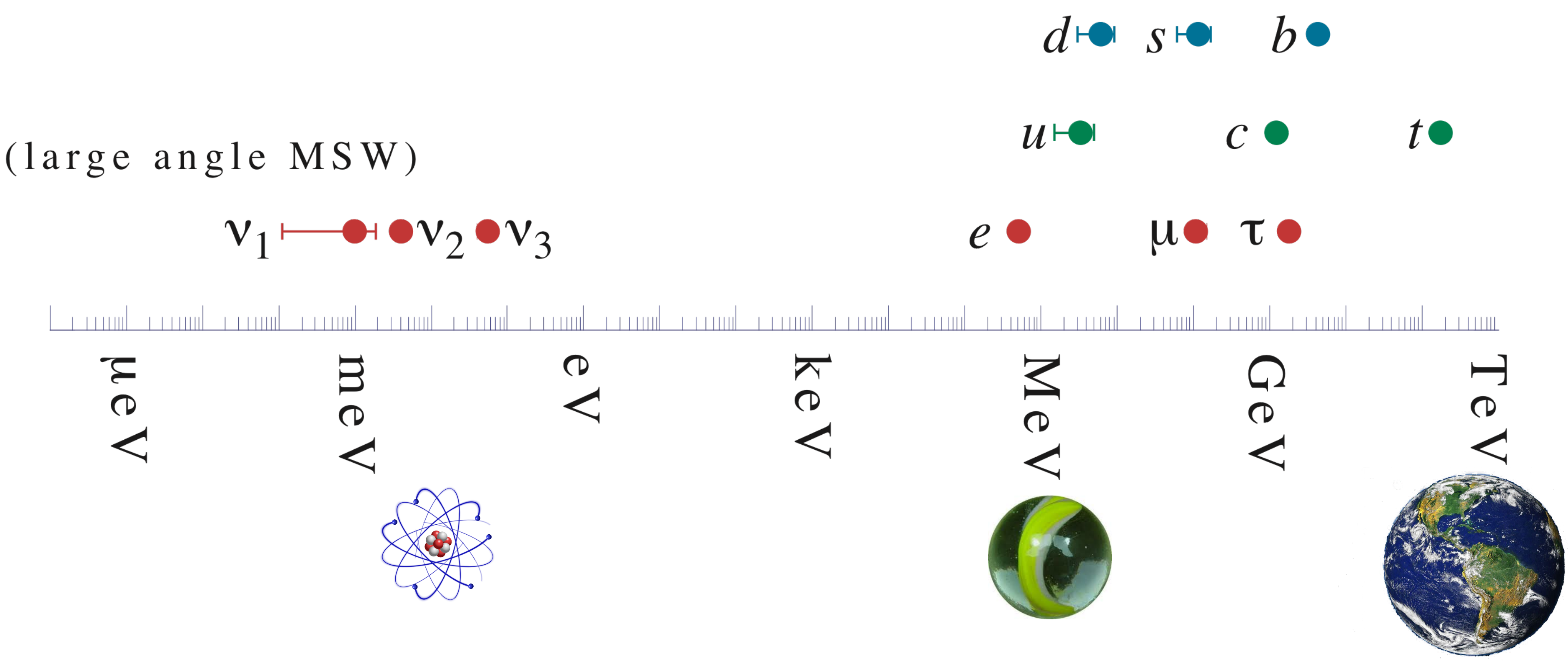
$\delta \sim \ ?$



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

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

The flavour puzzle



Why so different mixing ?

CKM

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

PDG

PMNS

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

NuFIT 2016

Why so different mixing ?

CKM

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

PMNS

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

Where the mixing comes from ?

Discrete or continuous symmetries

Anarchy for leptons ?

The open questions

Absolute mass scale: minimum m_ν

What is the neutrino ordering normal or inverted ?

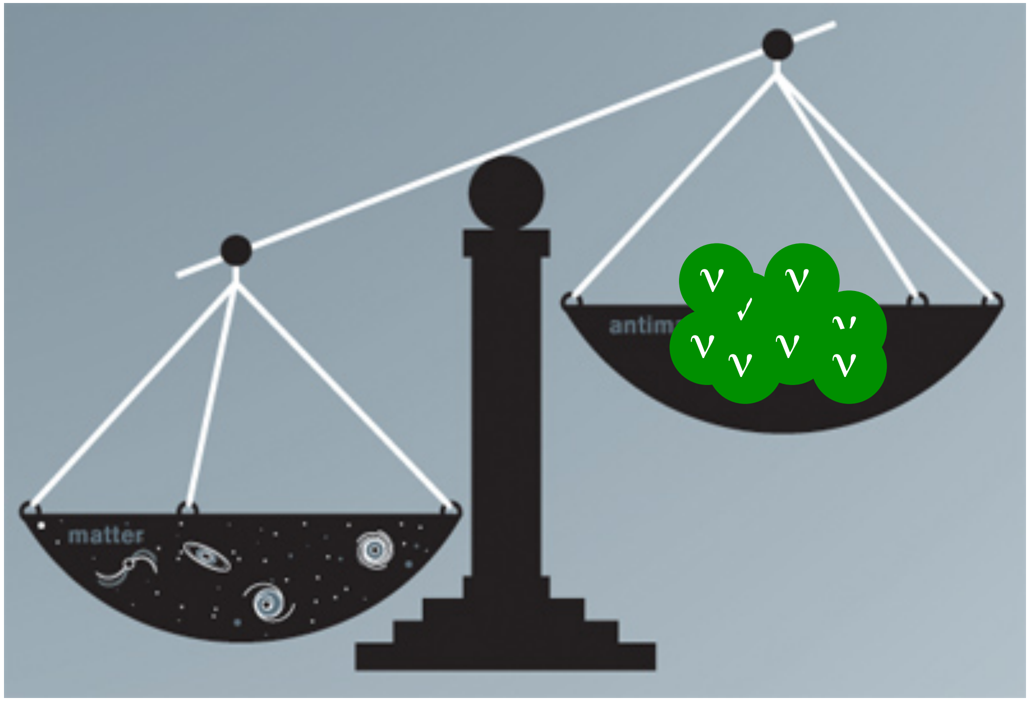
Is there leptonic CP violation ?

Are neutrinos Majorana and if so, what new physics lies behind this fact ?

Can neutrinos explain the matter-antimatter asymmetry in the Universe ?

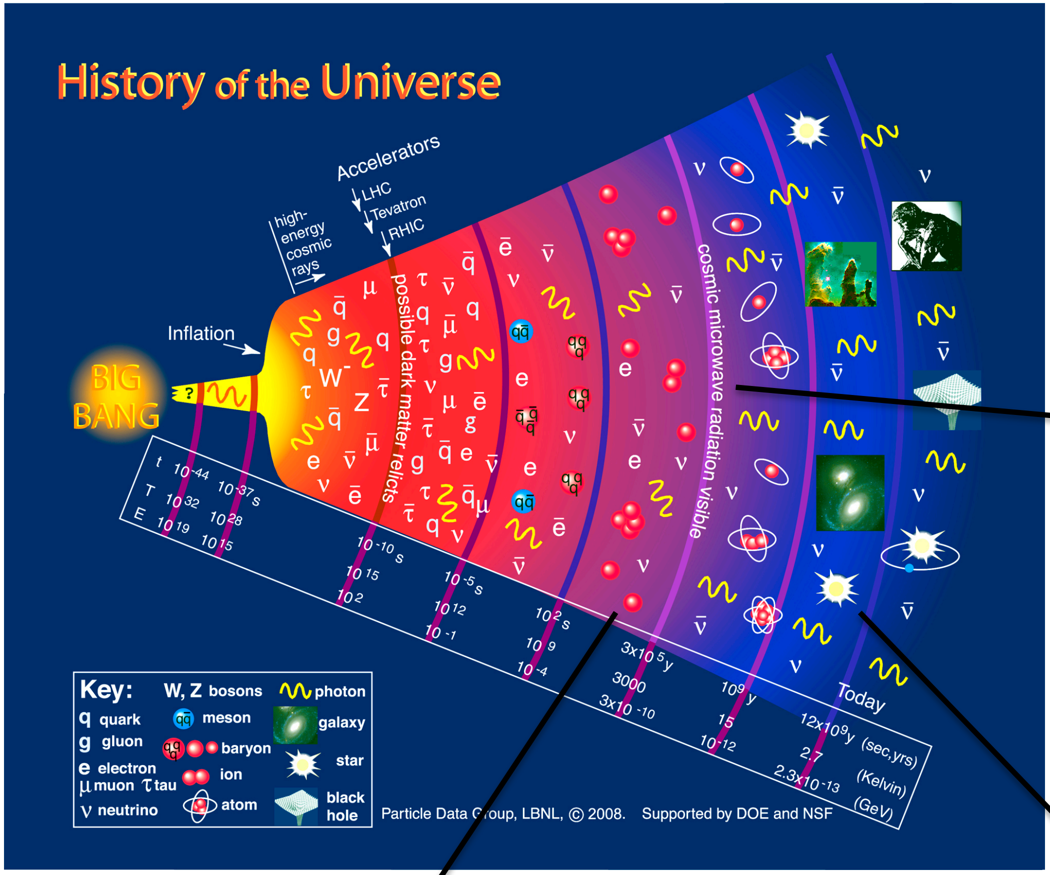
Absolute mass scale

Best constraints at present from cosmology



Cosmological neutrinos

Neutrinos have left many traces in the history of the Universe



Cosmic Microwave background

Galaxy distribution (LSS)

Nucleosynthesis (synthesis of light nuclei)

Neutrinos @ nucleosynthesis (BBN)

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

Neutrinos decouple from the plasma @T_ν~1MeV

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

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

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

g* depends on N_ν=> $T_\nu(N_\nu)$

Neutrinos @nucleosynthesis

At $@T_\nu \sim 1$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

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

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

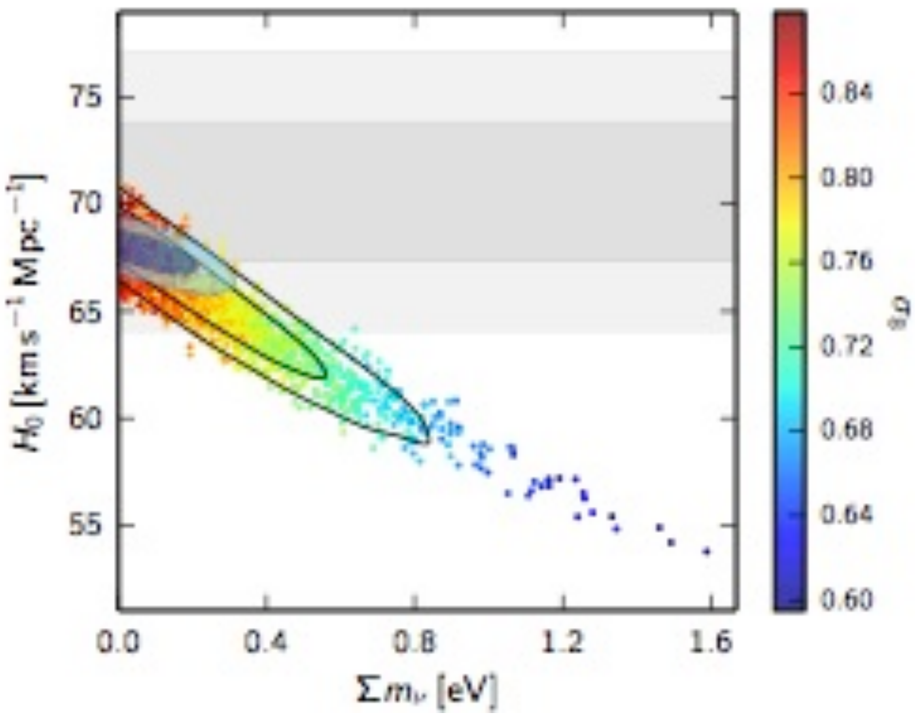
Gershtein, Zeldovich

Massive neutrinos O(eV) contribute significantly to Ω_m

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

Absolute mass scale

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

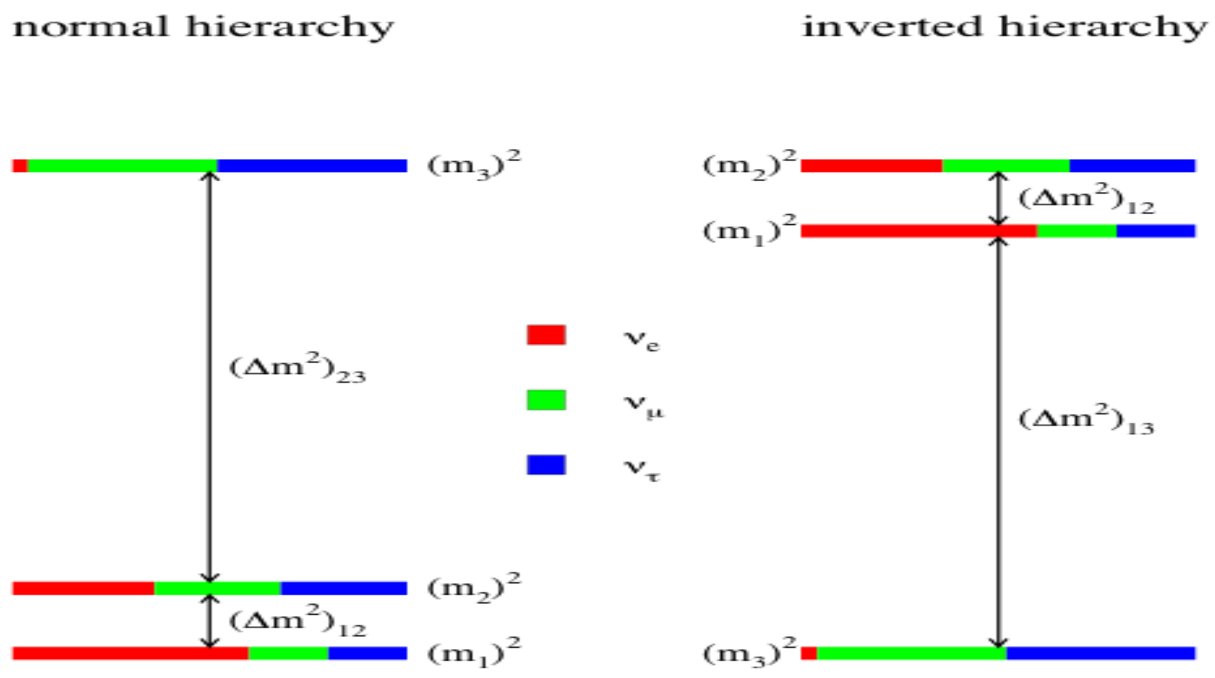


Planck 1502.01589

Conservative limit:

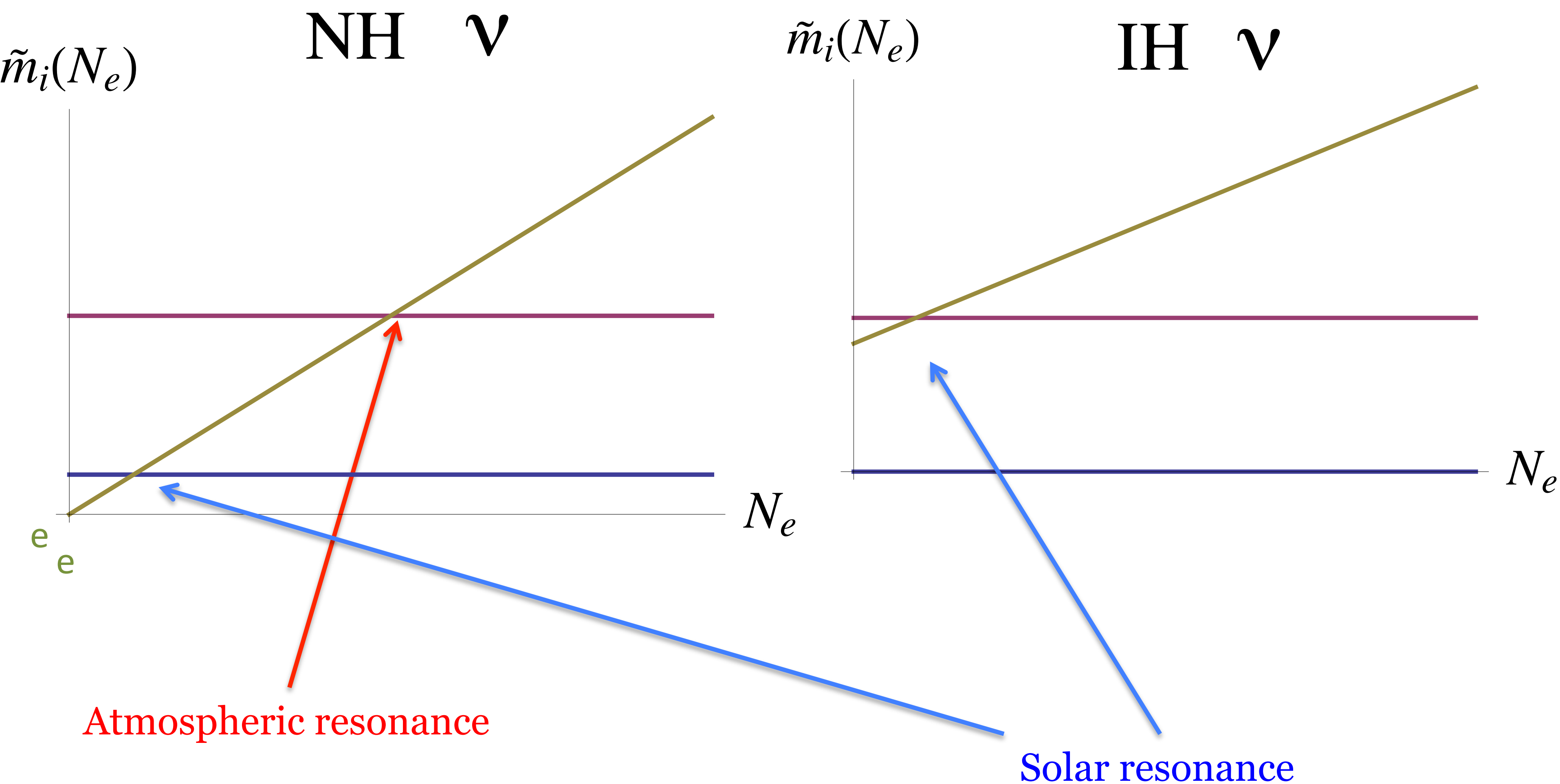
$$\left.\begin{aligned}\sum m_\nu &< 0.23\ \mathrm{eV}\\ \Omega_\nu h^2 &< 0.0025\end{aligned}\right\}\ 95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}ext.}$$

?



normal hierarchy
inverted hierarchy
(m3)2
(Δm2)23
(m2)2
(Δm2)12
(m1)2
νe
νμ
ντ
(m2)2
(Δm2)12
(m1)2
(Δm2)13
(m3)2

Neutrino ordering from MSW



$$\Delta m^2_{23} \cos 2\theta_{13} = \pm 2\sqrt{2} G_F E N_e$$

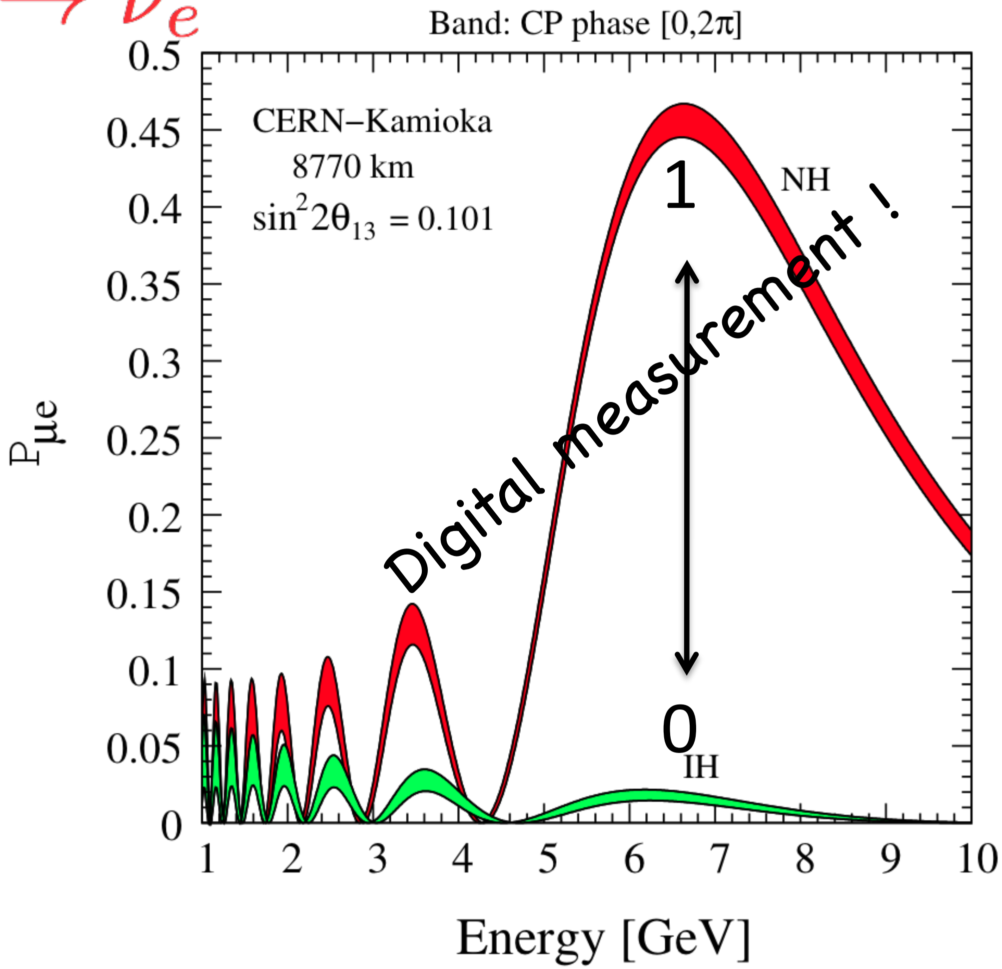
Earth density, E_{res} ~ few GeV !

$$\Delta m^2_{12} \cos 2\theta_{12} = 2\sqrt{2} G_F E N_e$$

Solar density, E_{res} ~ few MeV !

Hierarchy through MSW @Earth

$\nu_\mu \rightarrow \nu_e$

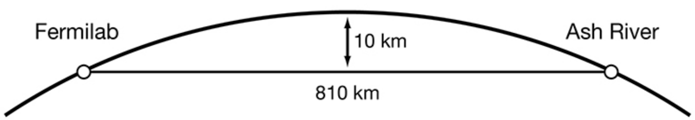


$$E_{\rm res} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F n_e},$$

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

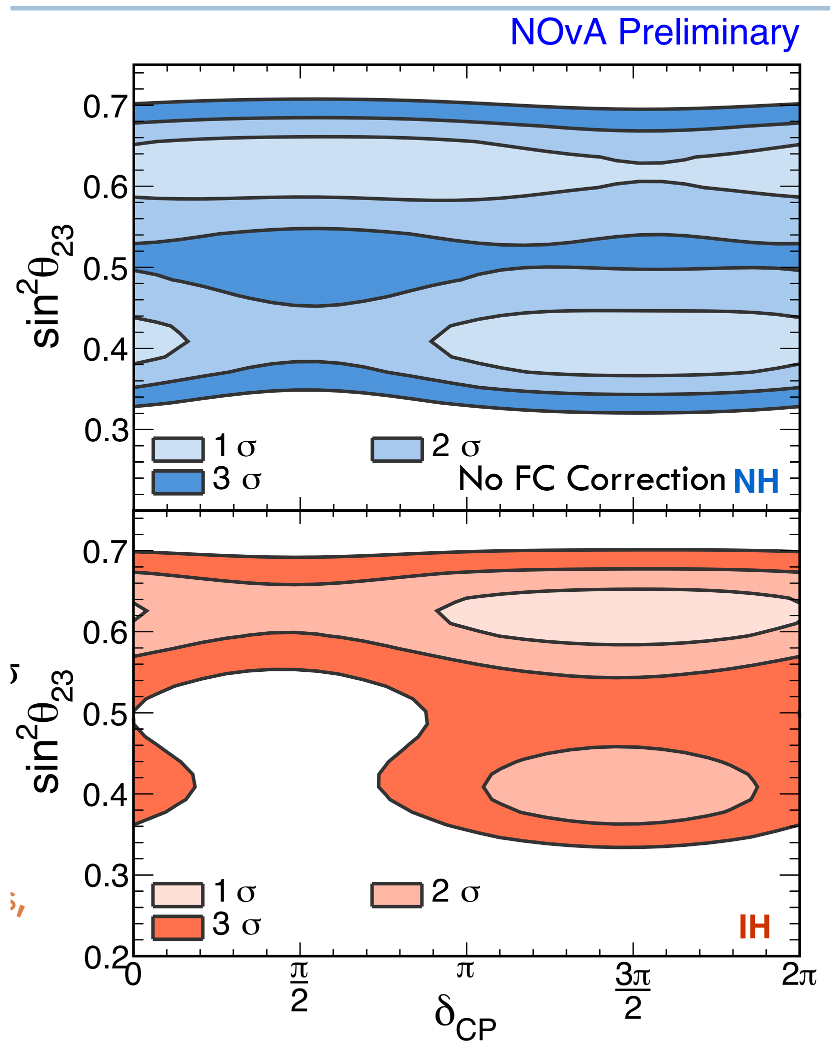
Spectacular MSW effect at O(6GeV) and very long baselines

First attempt at the hierarchy: NOνA

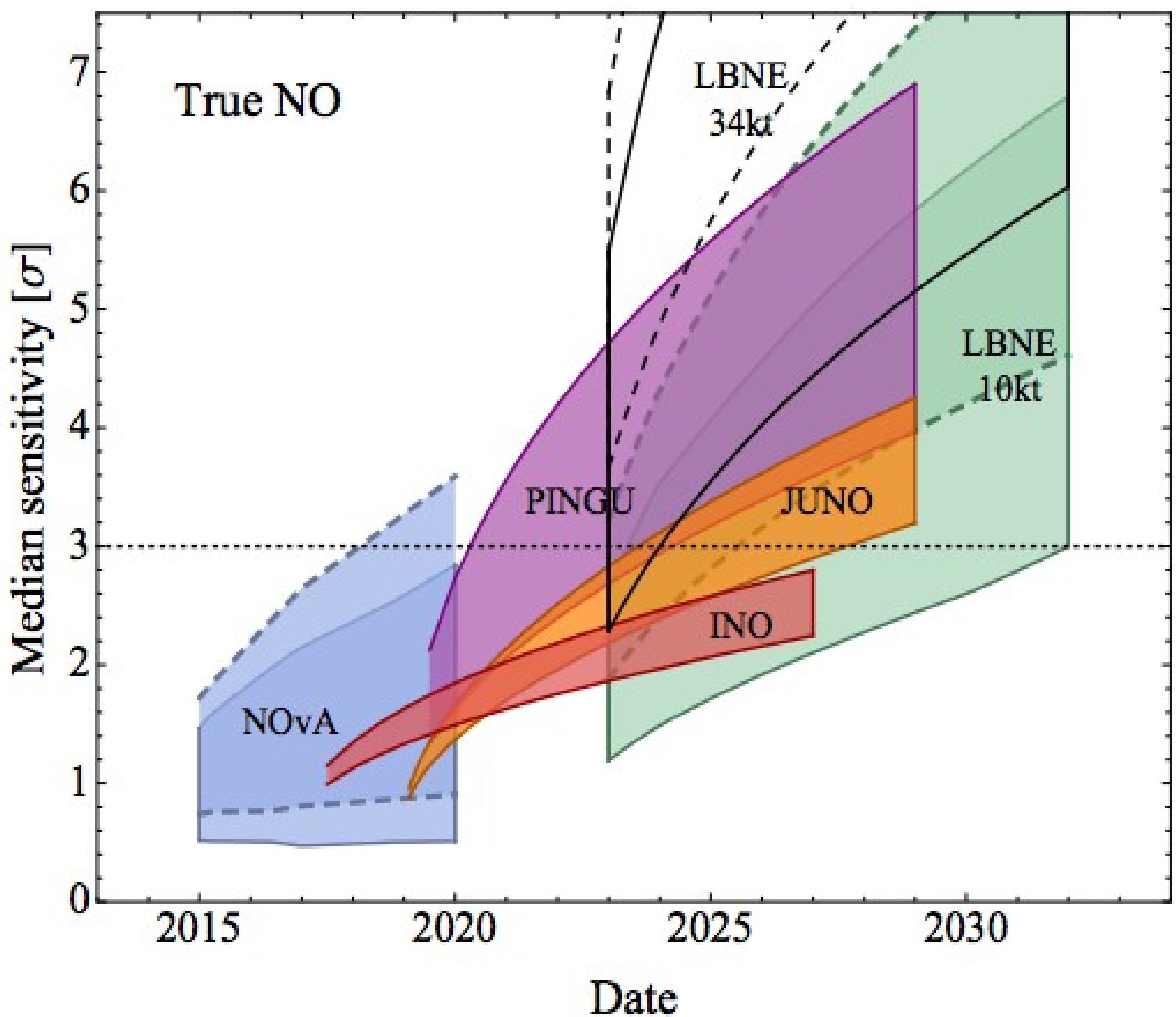


L=810km

$$\nu_\mu \to \nu_e$$



Hierarchy propects



Blennow, Coloma, Huber, Schwetz 1311.1822

Leptonic CP violation

CP violation shows up in a difference between

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \qquad \alpha \neq \beta$$

Golden channel:

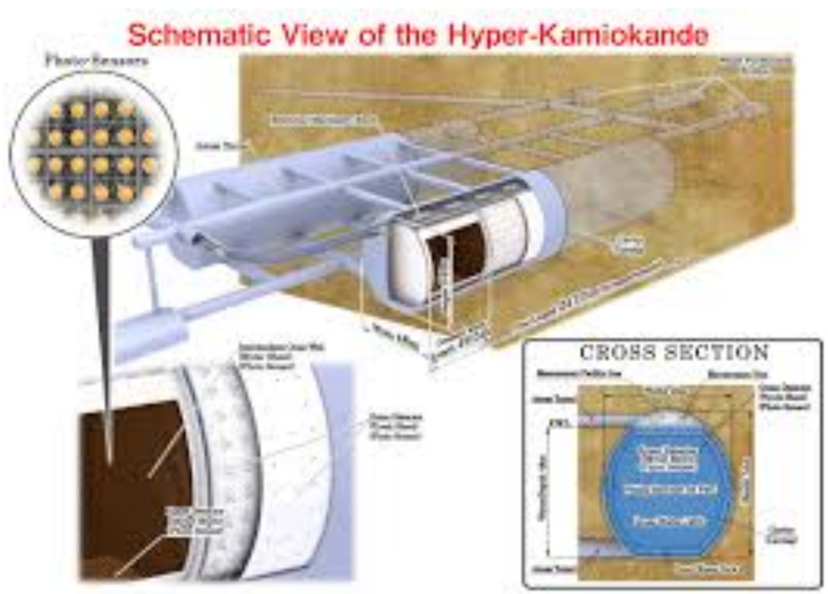
$$\begin{aligned} P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23} L}{2}\right) \equiv P^{atmos} \\ &+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) \equiv P^{solar} \\ +\tilde{J} &\cos\left(\pm\delta - \frac{\Delta_{23}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

$$\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

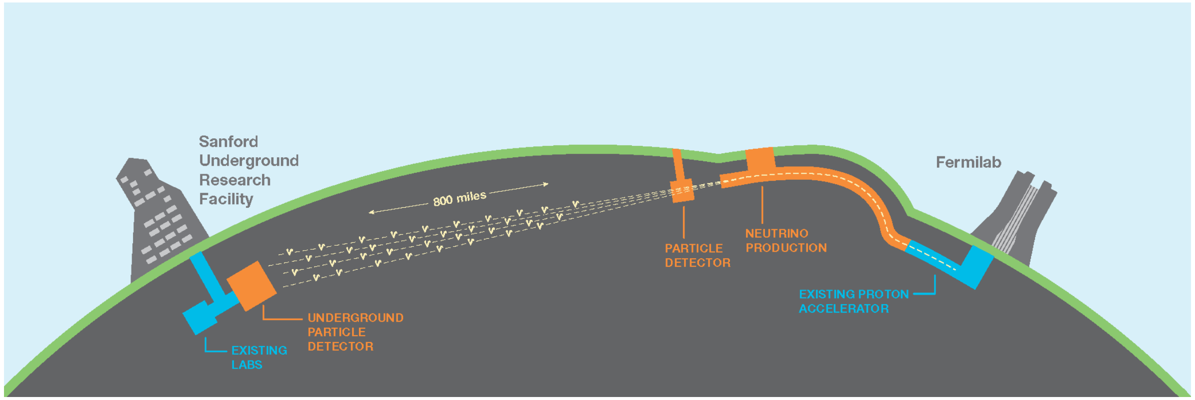
simultaneous sensitivity to both splittings is needed

Hierarchy + CP in one go…
superbeams+superdectectors

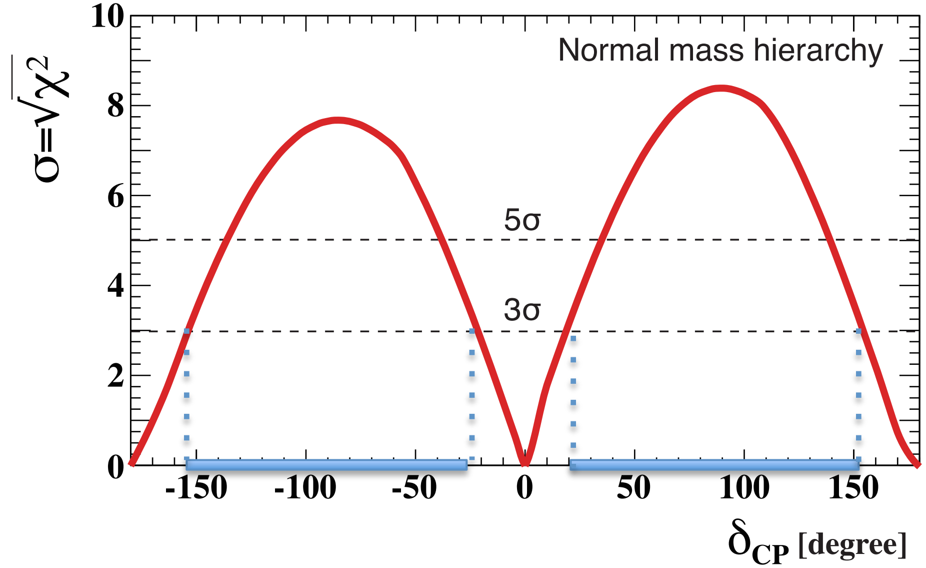
Japan Hyper-Kamiokande: 230km



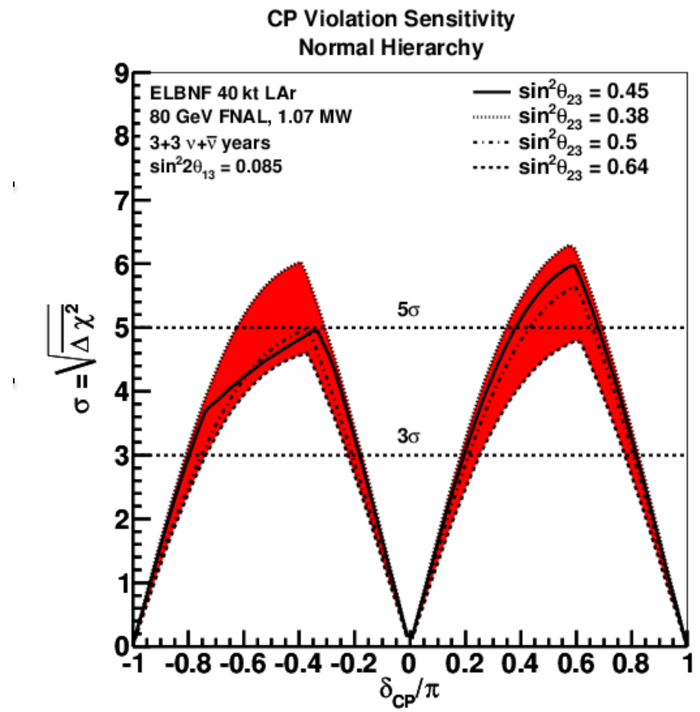
USA DUNE: 1300km



Leptonic CP violation

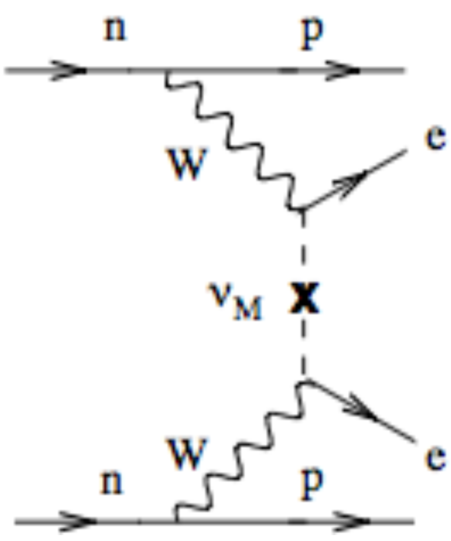


Hyper Kamiokande

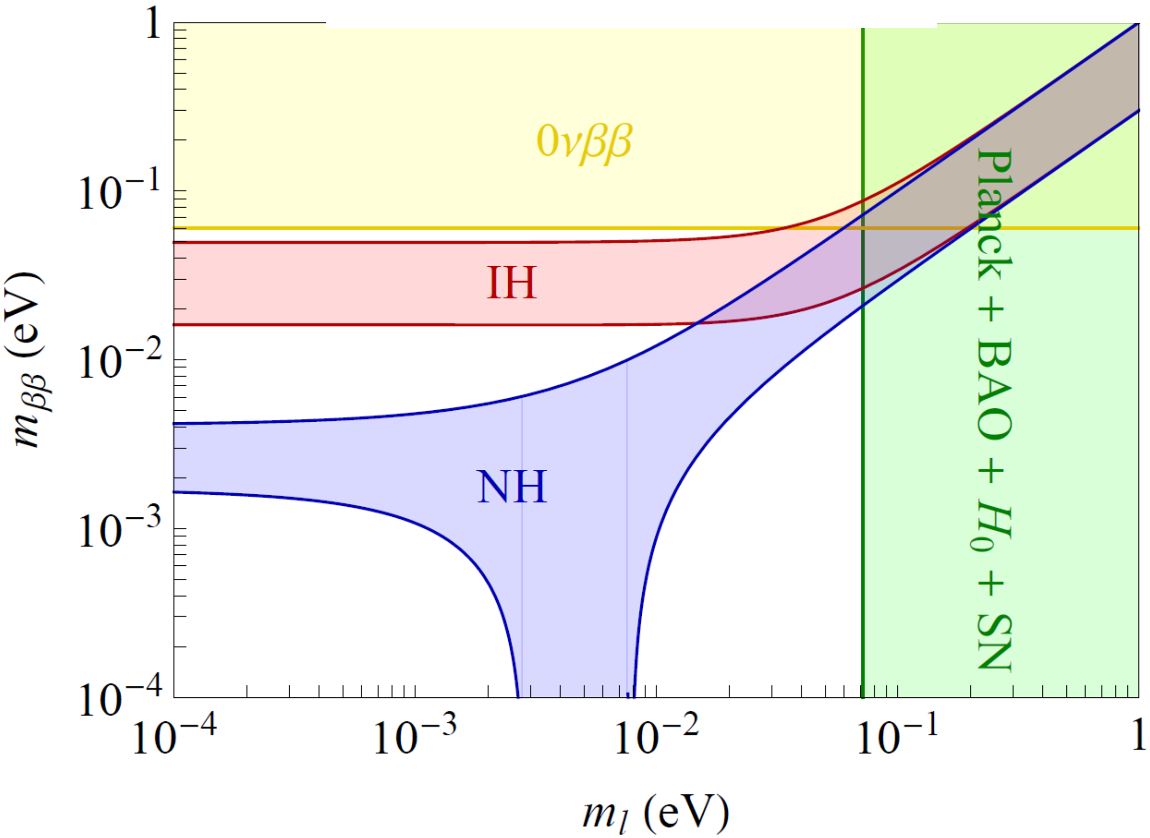


DUNE

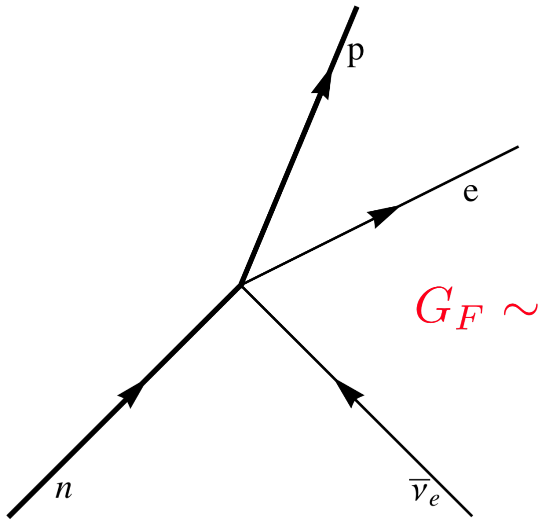
Majorana nature ?



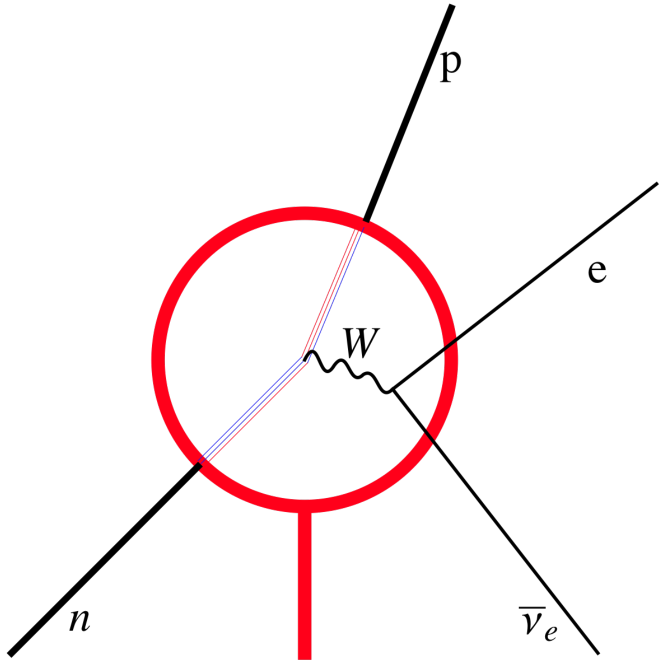
$$m_{\beta\beta} = \sum_{i=1}^{3} \left[(U_{PMNS})_{ei}\right]^2 m_i$$



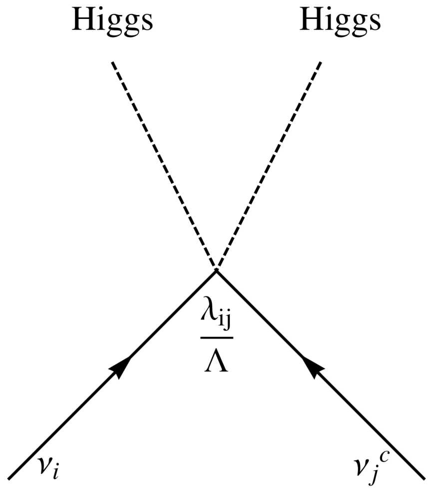
Majorana neutrinos -> a new physics scale



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



SM



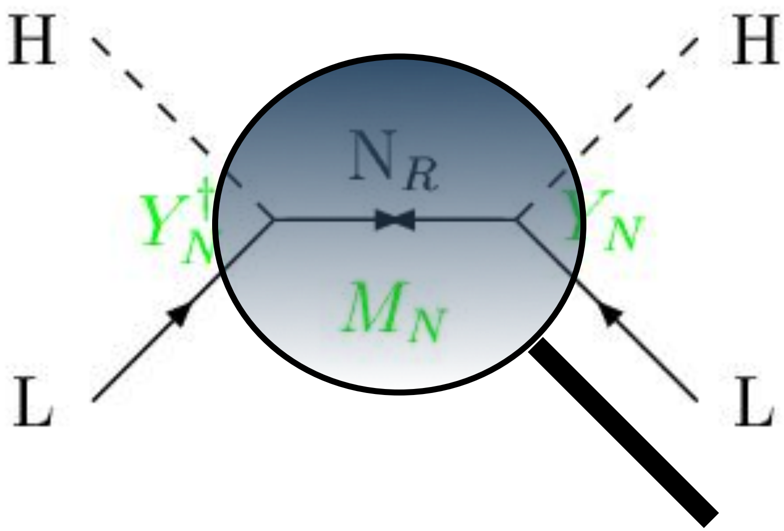
➡

νSM ?

Neutrino BSM: the Seesaw Model

SM + heavy singlet fermions

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



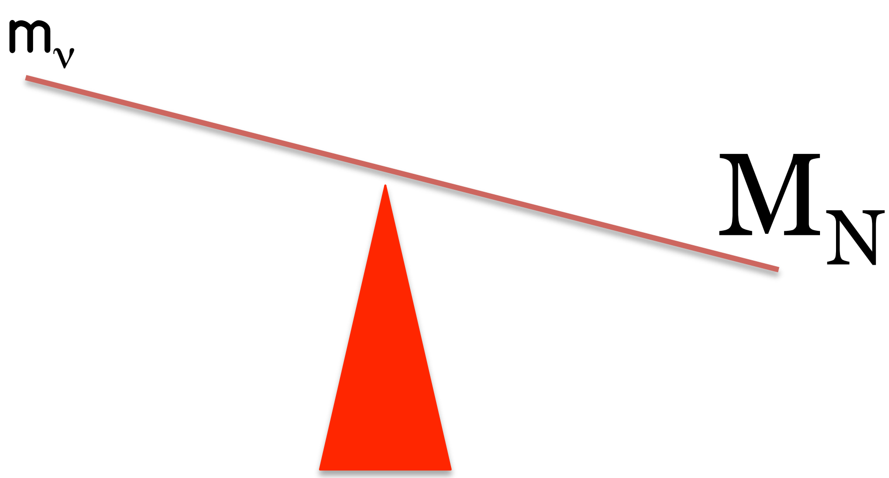
$$\frac{\lambda}{\Lambda} \equiv Y_N^T \frac{1}{M_N} Y_N$$

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

Neutrino BSM: the Seesaw Model

SM + 3 singlet Majorana fermions

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

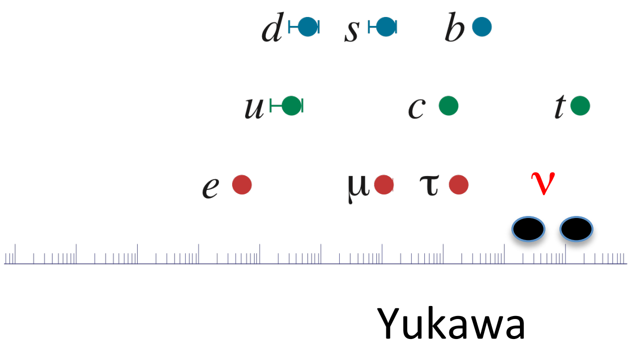


$$m_\nu \propto Y_N^T \frac{v^2}{M_N} Y_N^T$$

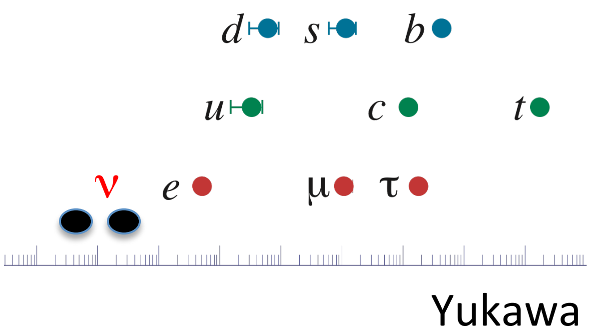
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow; Mohapatra, Senjanovic...

Pinning down the new physics scale: naturalness

M_N ~ GUT

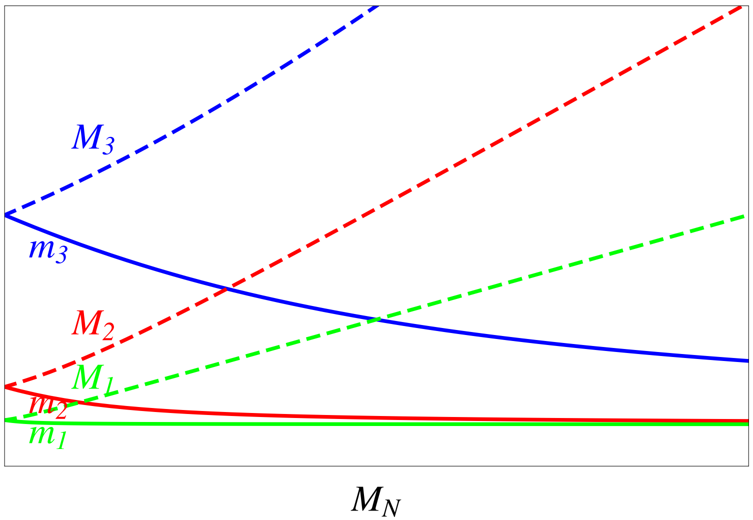


M_N ~ TeV



Spectra of the seesaw model

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



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

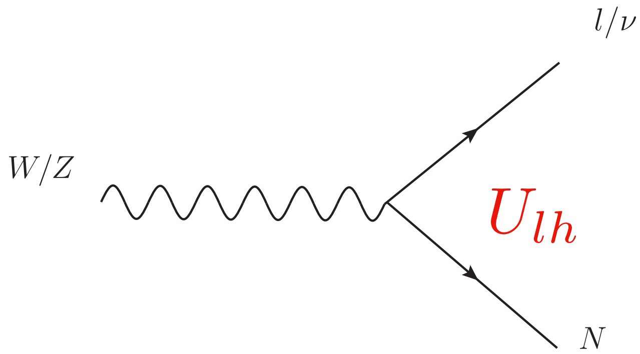
$$U_{ll} \simeq U_{PMNS} + \mathcal{O}\left(\frac{m_l}{M}\right)$$

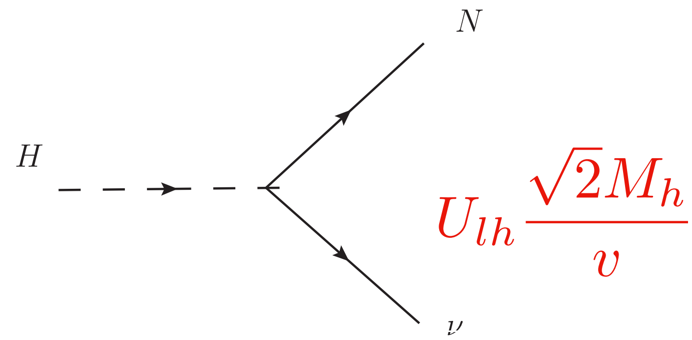
Unitarity violations

$$U_{lh} \propto \sqrt{\frac{m_l}{M_N}}$$

Strong correlation between active-heavy mixing and neutrino masses

Spectra of seesaw models

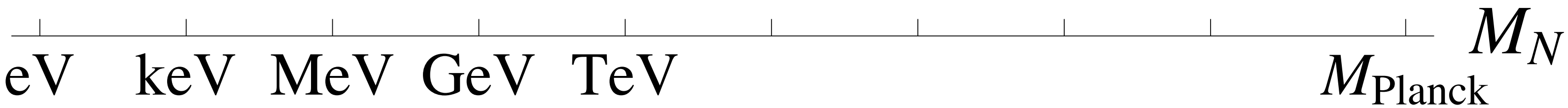




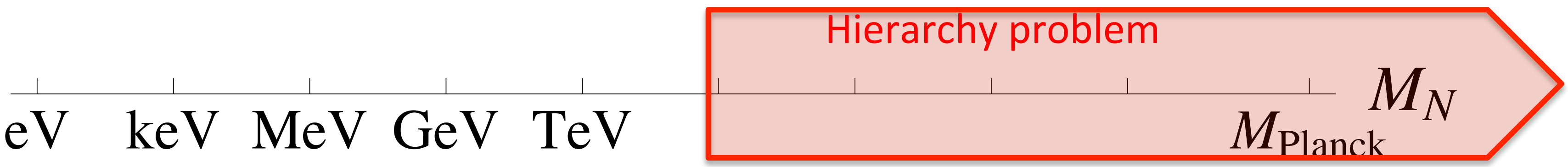
The lower the seesaw scale M_N

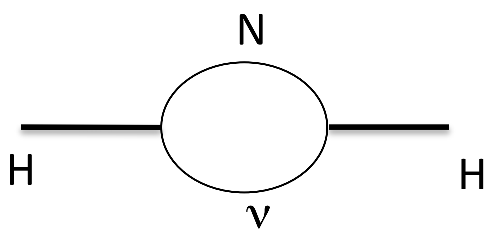
- the lower kinematical threshold to produce new states
- the larger mixing with flavour states

Searching for heavy Majorana neutrinos



Searching for heavy Majorana neutrinos





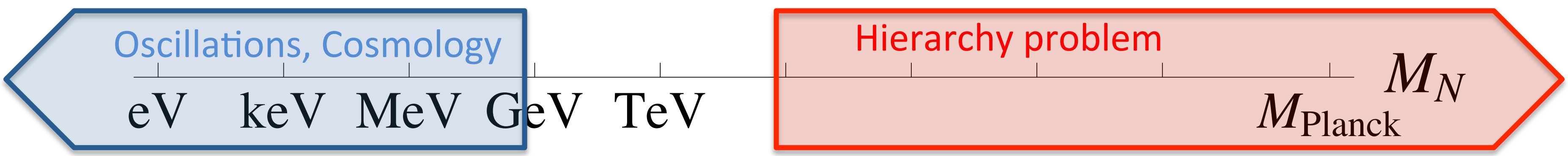
$$\delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu}$$

$$M_N \gg m_H$$

Requires a fine-tunning of the Higgs mass in the absense of other physics, like SUSY

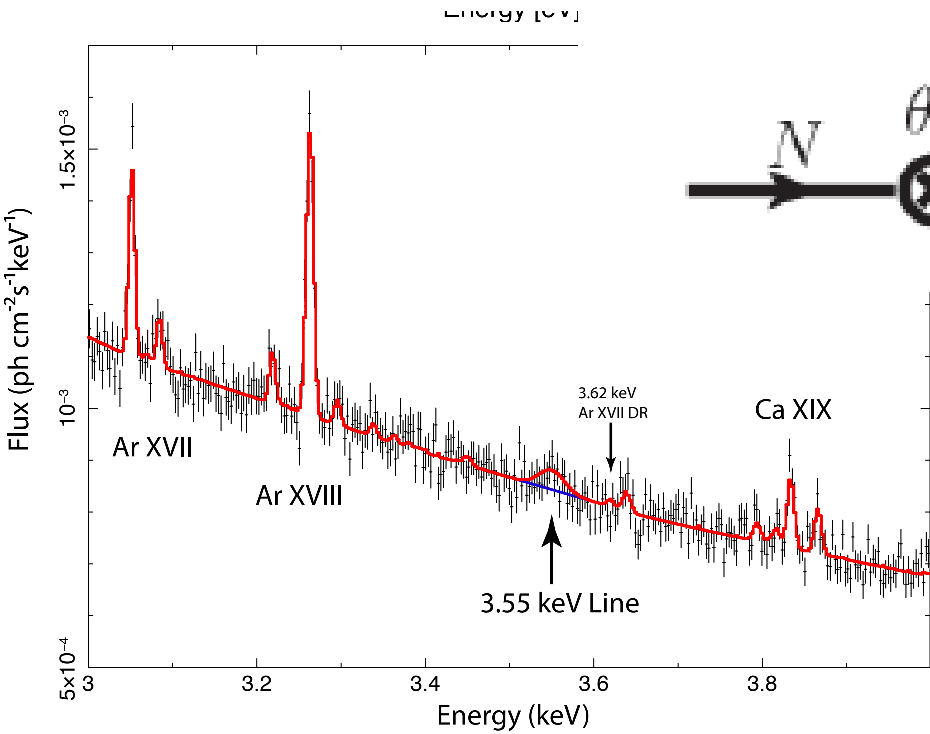
Searching for heavy Majorana neutrinos

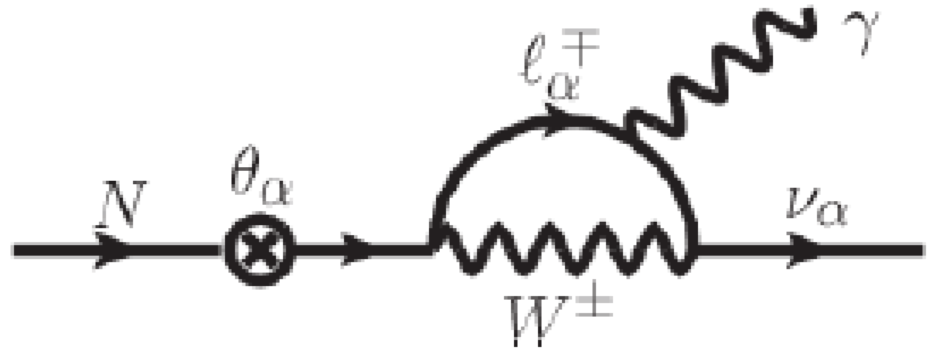
These heavy states can contribute as DM (Ω_{DM}) and/or extra radiation (ΔN_{eff})



One exception: the lighter of the heavy states could be at keV and be the Dark Matter

Neutrino Warm Dark Matter ?

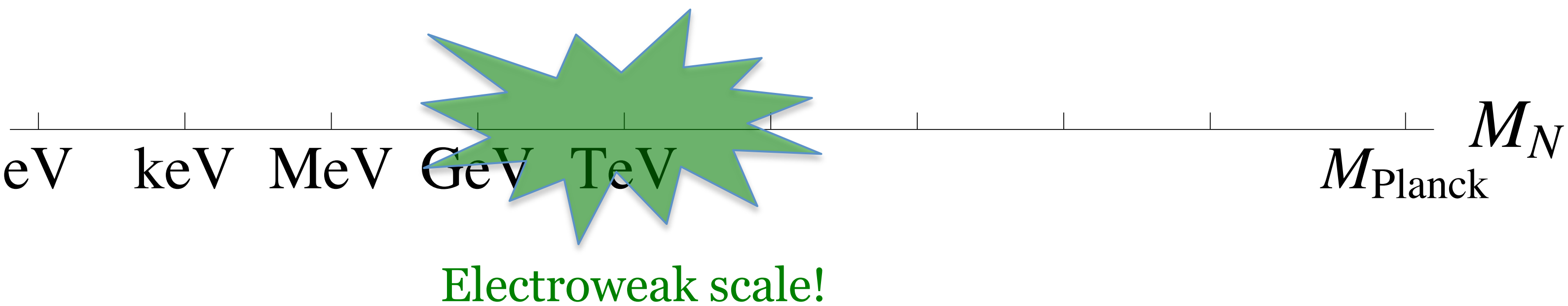




$$E_\gamma = \frac{M_N}{2}$$

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

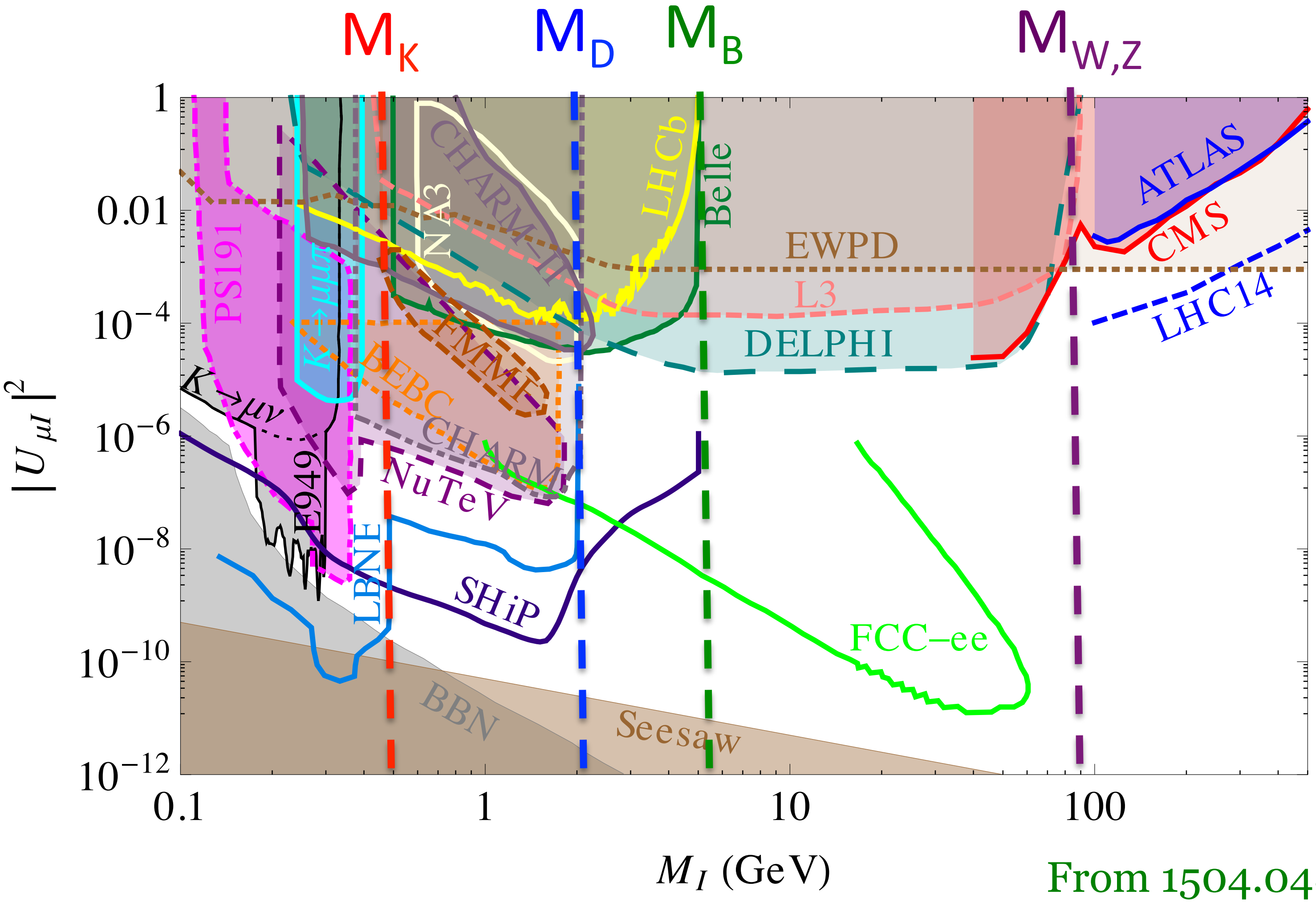
Searching for heavy Majorana neutrinos



Neutrinos in the range $\text{GeV} \leq M_N \leq \text{few TeV}$ can modify:

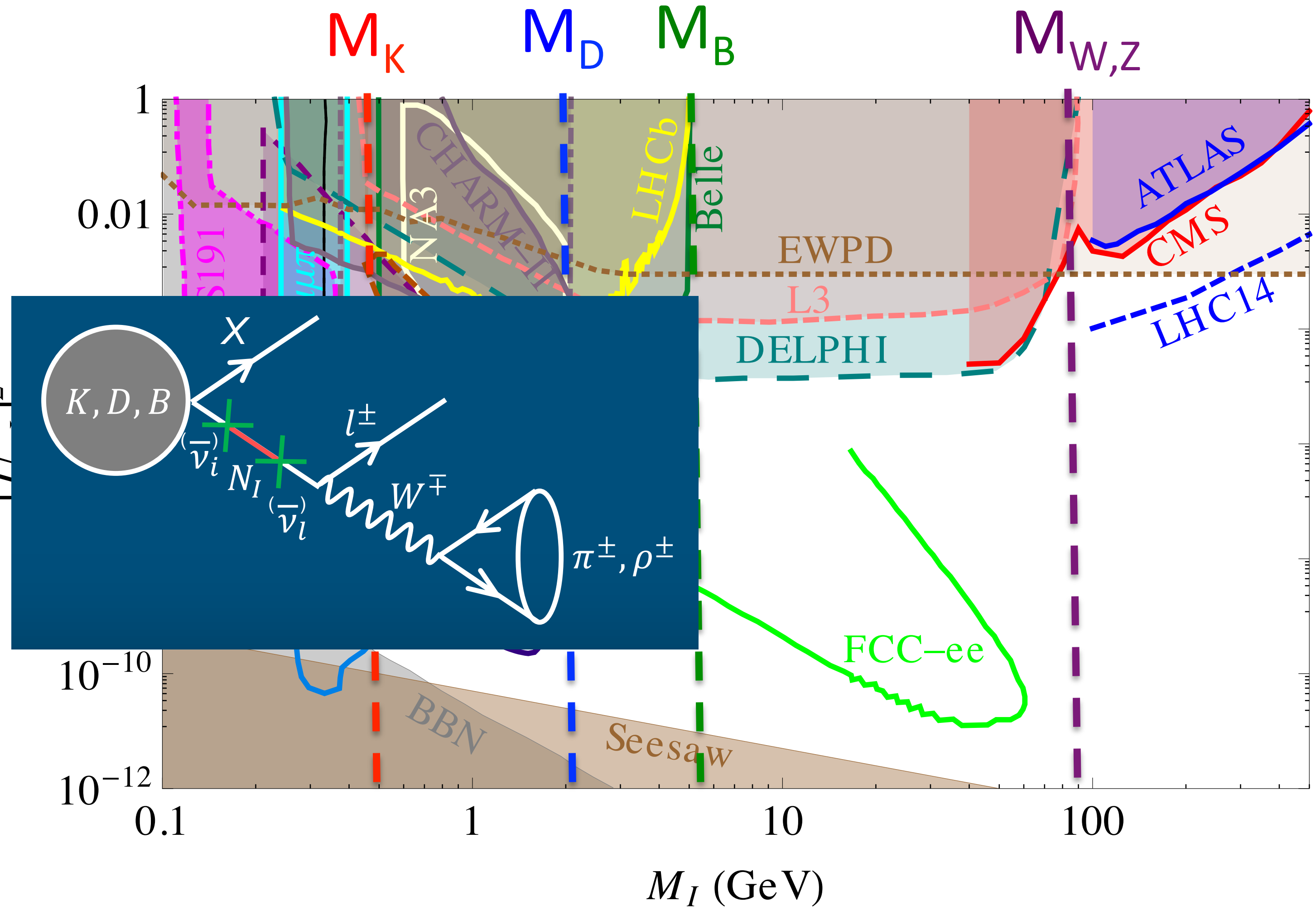
- ✓ Neutrinoless double beta decay
- ✓ Can be directly produced in accelerators: meson decays, W,Z decays
- ✓ Lepton flavour violating processes e.g. $\mu \to e\gamma$

Searching for heavy Majorana neutrinos

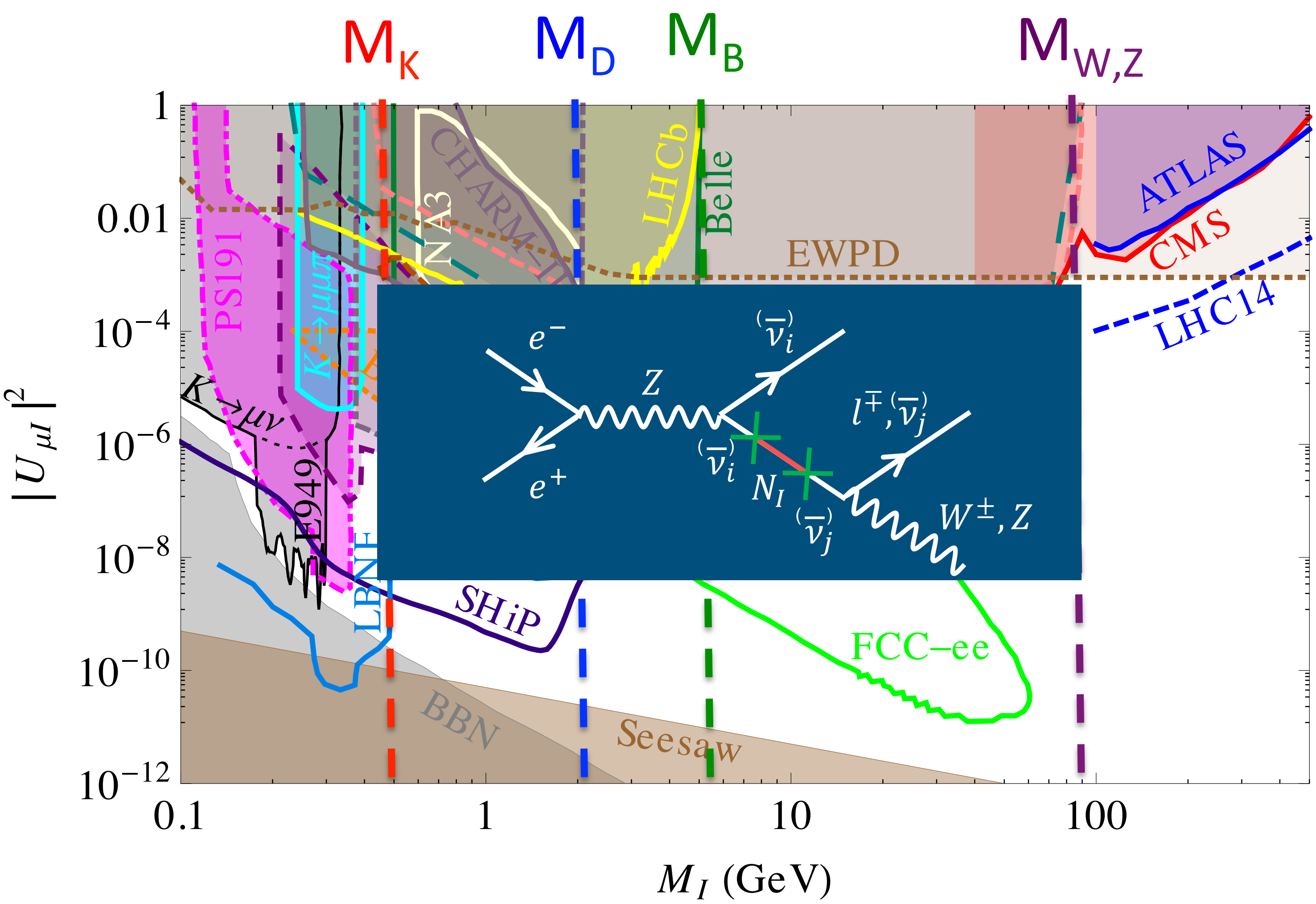


From 1504.04855

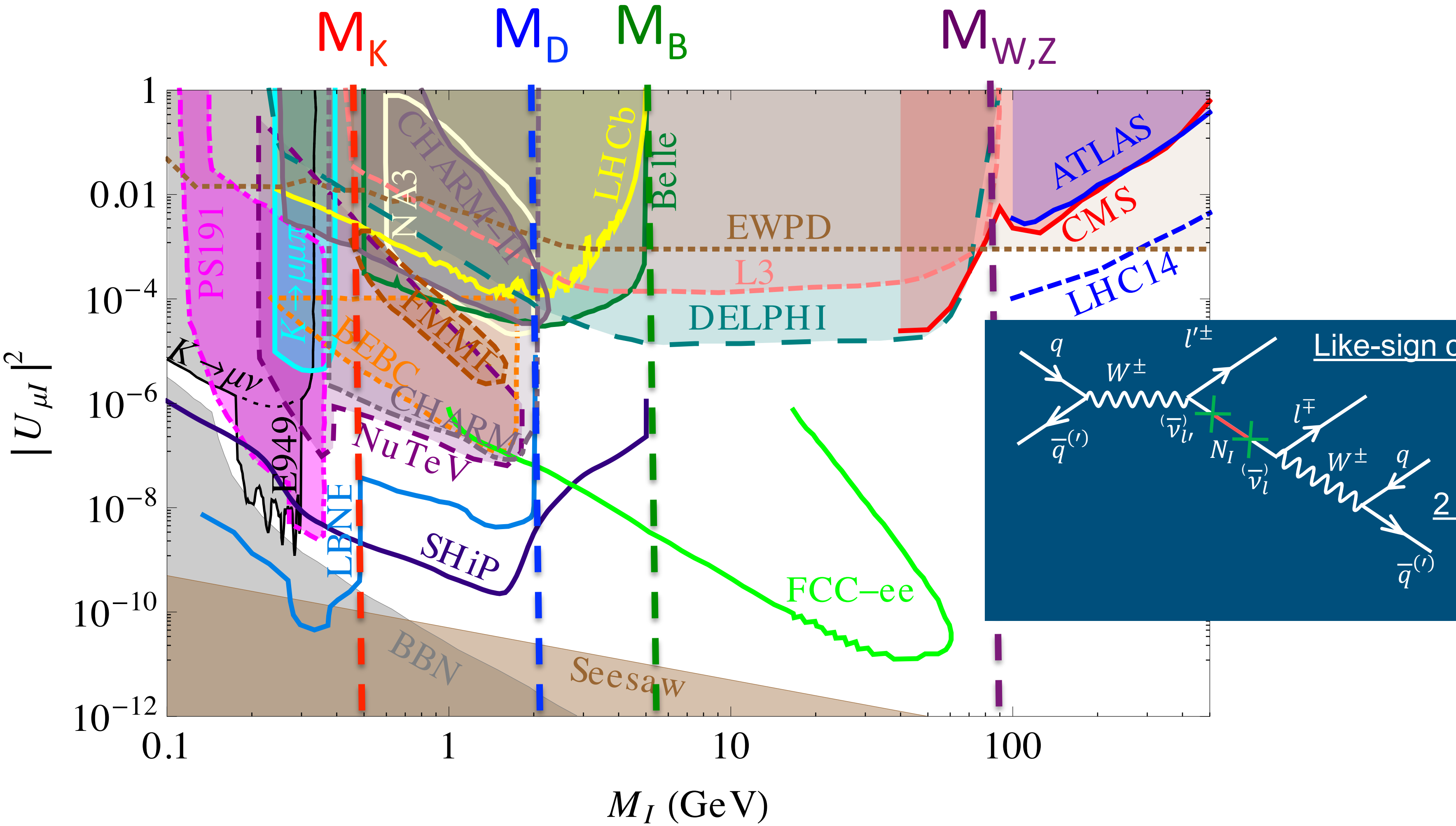
Searching for heavy Majorana neutrinos



Searching for heavy Majorana neutrinos

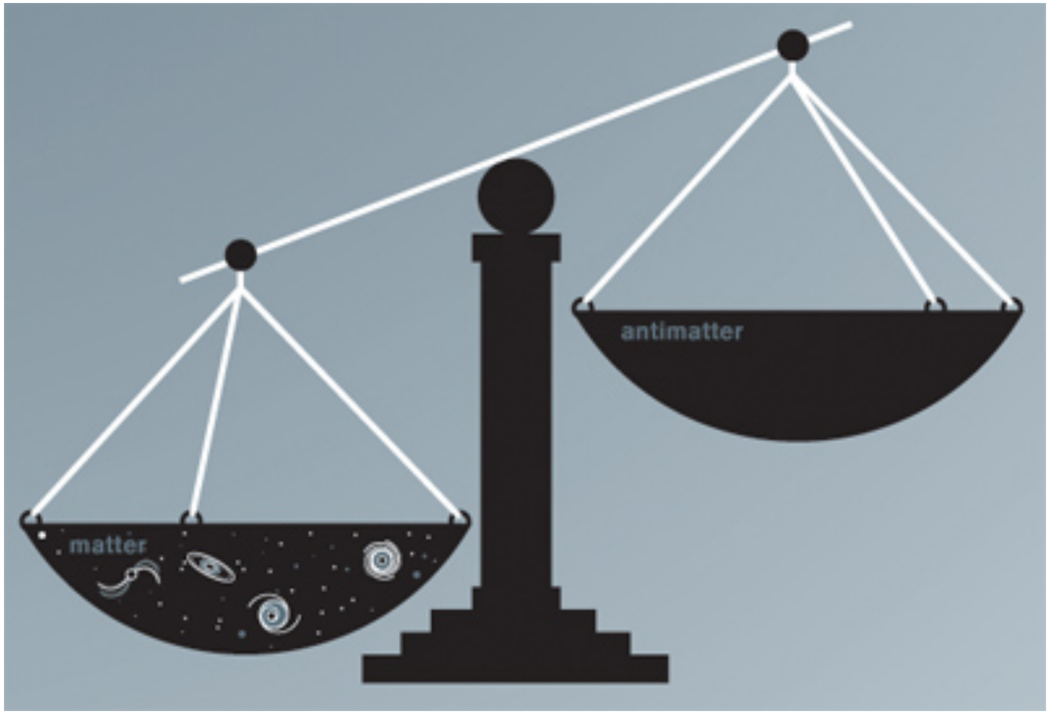


Searching for heavy Majorana neutrinos



Matter-antimatter asymmetry

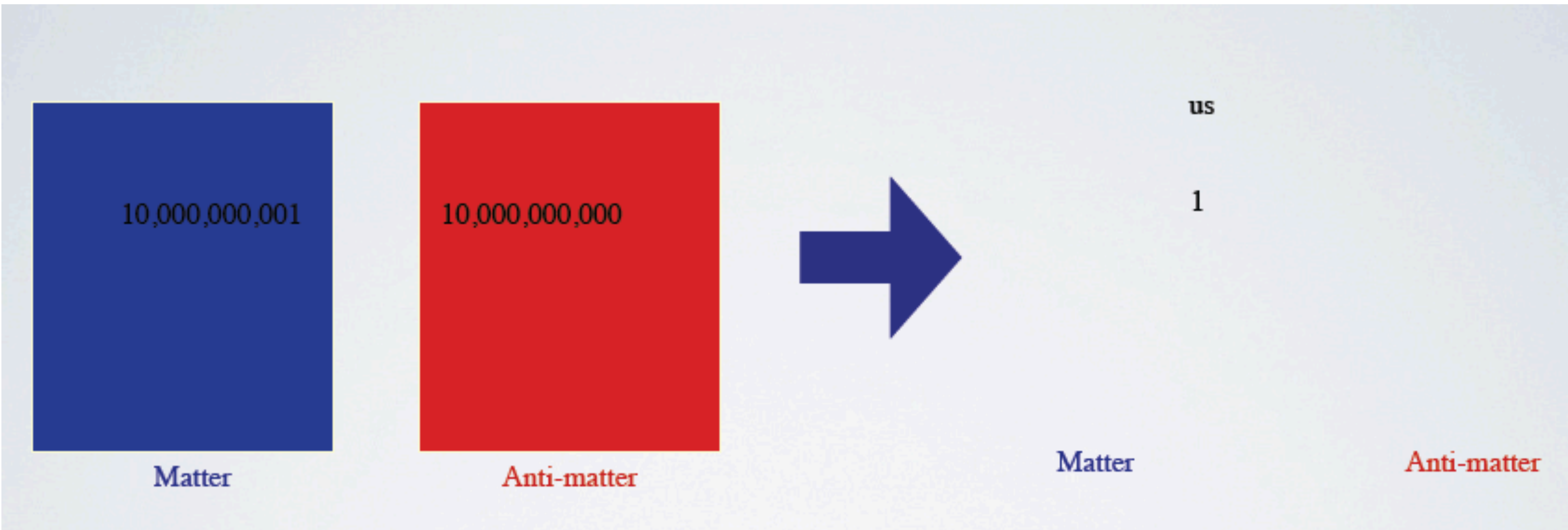
The Universe seems to be made of matter



After Planck $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.09(6) \times 10^{-10}$

Matter-antimatter asymmetry

The Universe seems to be made of matter



After Planck

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.09(6) \times 10^{-10}$$

Matter-antimatter 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 ...

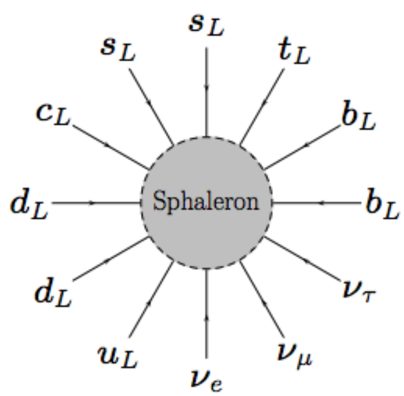
CP violation in quark sector far to small, EW phase transition too weak...

Can we do it with leptons ?

Baryon number violation

In the SM there is violation of B+L, preserve B-L

These processes are strongly suppressed at $T < T_{EW}$ and in equilibrium at $T > T_{EW}$

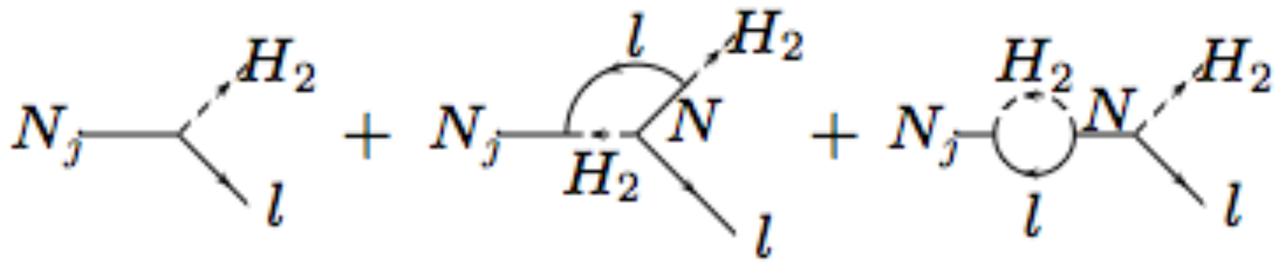


If a net L is generated above T_{EW} sphalerons produce B

Leptogenesis:seesaw model $M_N >> v$

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

Fukuyita, Yanagida



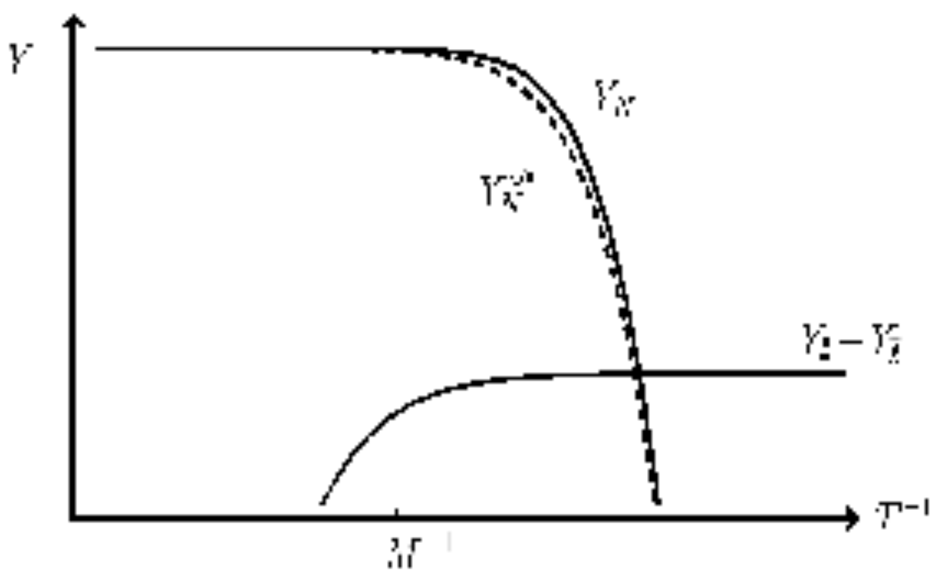
$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

A significant asymmetry typically requires $M_N > 10^7$ GeV

Out-of-equilibrium

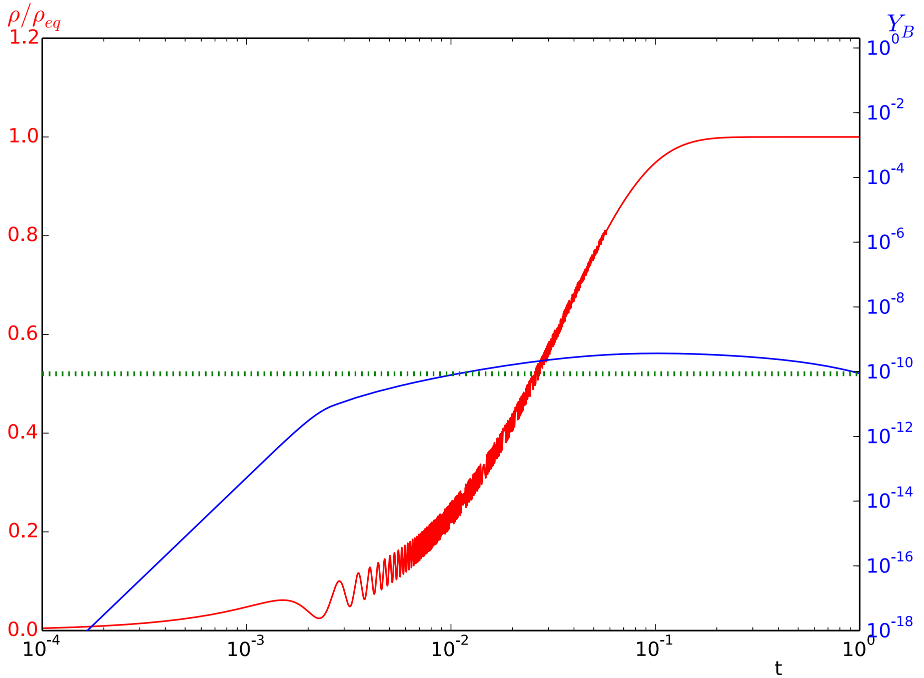
The Majorana neutrinos decay out-of-equilibrium

$$\Gamma_N < \text{expansion rate} \quad \Rightarrow N_N > N_N^{\text{thermal}}$$



Leptogenesis: seesaw model $M_N < v$

Leptogenesis takes place during the production of heavy states

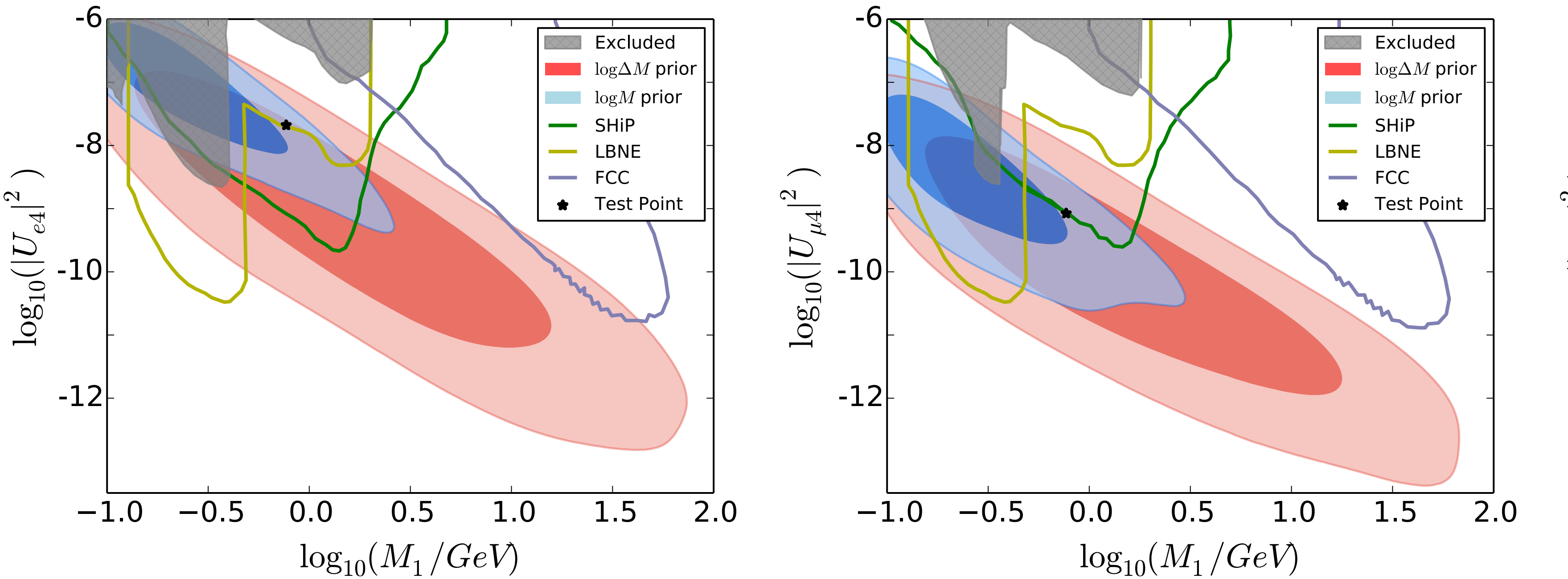


Courtesy of M. Kekic

T_{EW}

Leptogenesis: seesaw model $M_N < v$

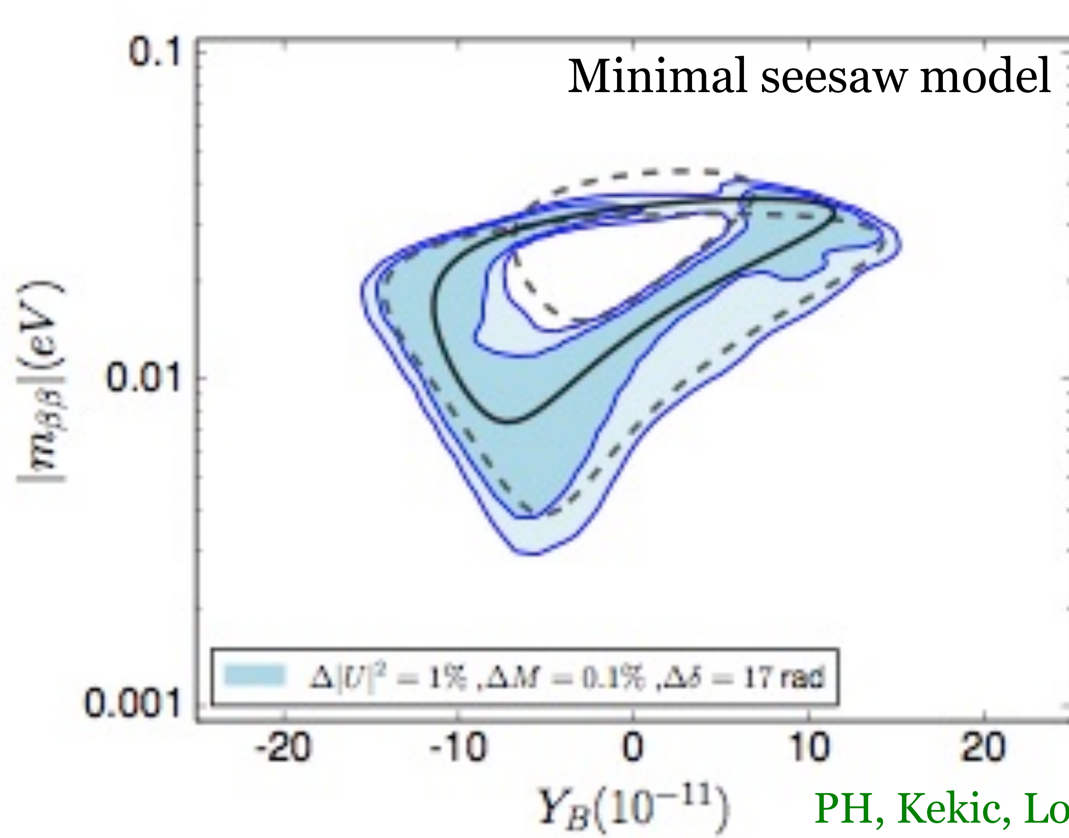
Posterior probabilities mixings vs mass for successful baryon asymmetry



PH, Kekic, Lopez-Pavon, Racker,Salvado

Future searches have a change to discover these states !

One example: sterile neutrinos are discovered in D decays at SHIP and their masses and mixings to e measured with some accuracy + CP phase δ is measured in neutrino oscillations



PH, Kekic, Lopez-Pavon, Salvado

Neutrinoless double beta decay could be key to predict the baryon asymmetry

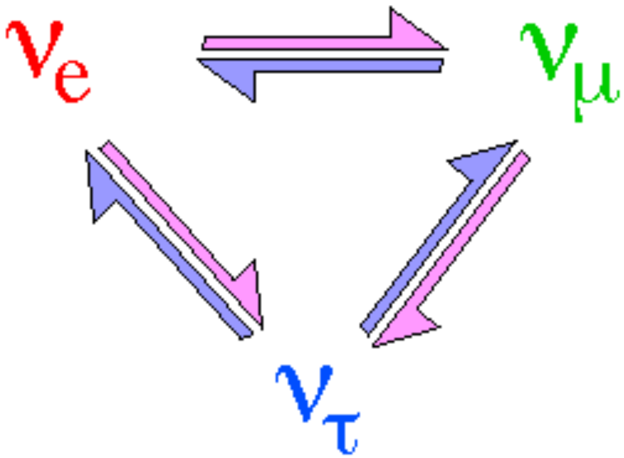
- The results of many beautiful experiments have demonstrated that ν are (for the time-being) the less standard of the SM particles

- Many fundamental questions remain to be answered however:

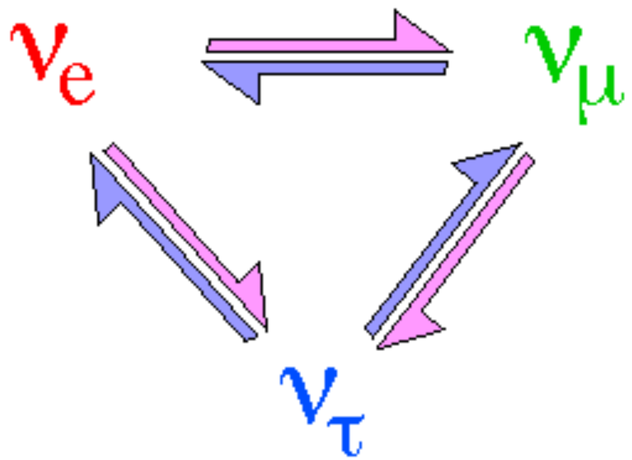
Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ? Lepton vs quark flavour ?

- A rich experimental programme lies ahead where fundamental physics discoveries are very likely (almost warrantied) …

These elusive pieces of reality have brought many surprises, maybe they will continue with their tradition…



These elusive pieces of reality have brought many surprises, maybe they will continue with their tradition…



ENJOY YOUR SUMMER-STUDENT SUMMER!