

# NEUTRINOS: OPEN QUESTIONS

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The elusive neutrinos have been key in the discovery of the weak interactions and in establishing the two most intriguing features of the SM:

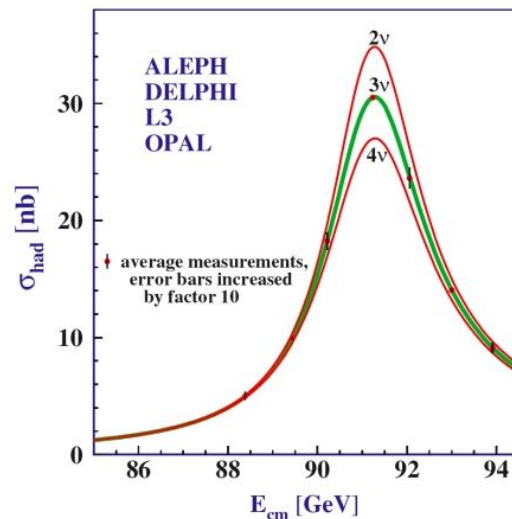
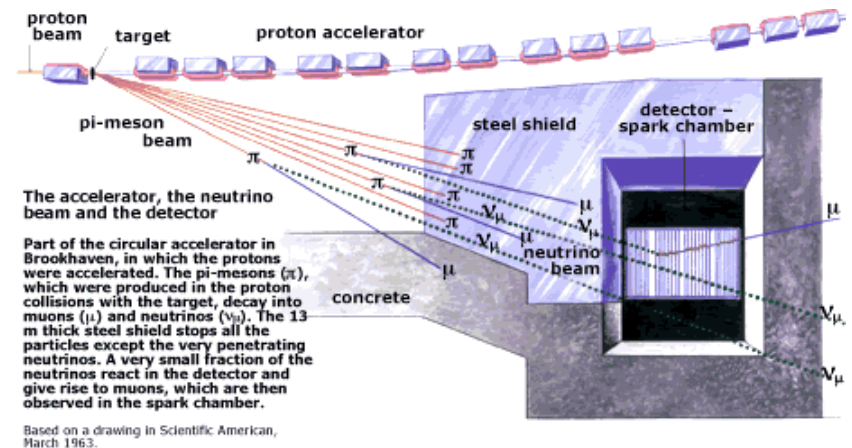
parity breaking of the weak interactions

3-fold repetition of family structures



Reactor neutrinos : 1956 first neutrino detection by **Reines & Cowan**

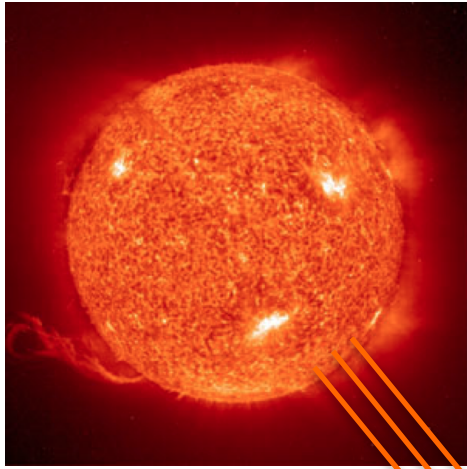
Accelerator neutrinos : 1962 established the family structure of the SM by **Lederman, Schwartz, Steinberger**



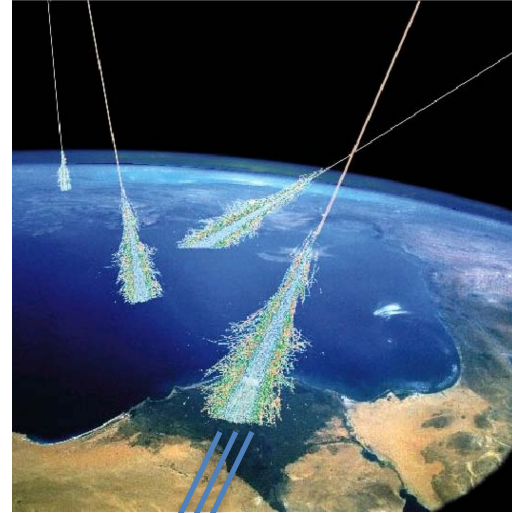
Collider neutrinos 90s'  
**LEP** established 3 SM families

# Ubiquitous Neutrinos

They are everywhere...



Sun:  $5 \times 10^{12}$ /second

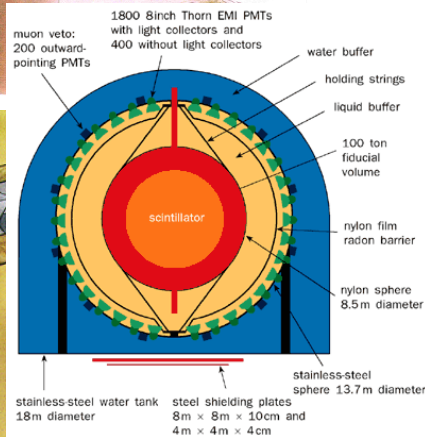
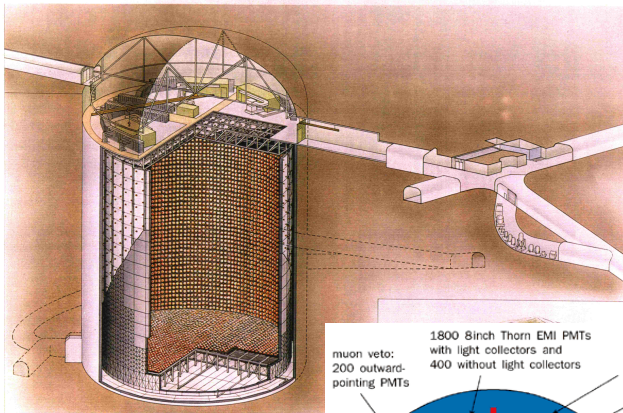


Atmosphere:  $\sim 20$ /second



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

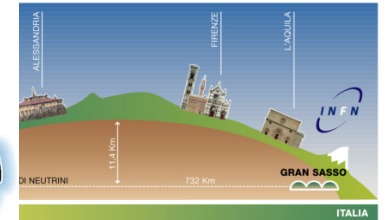
SuperKamiokande



SNO Borexino

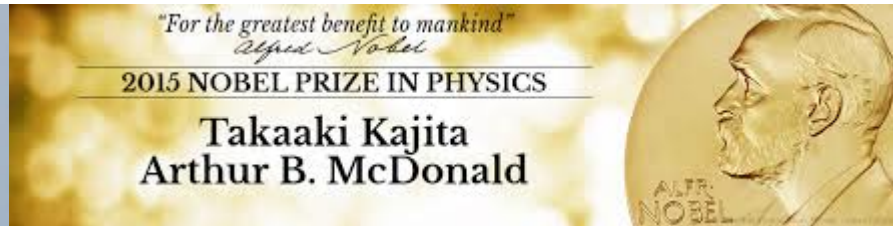


MINOS, Opera



...and more

“For the discovery of **neutrino oscillations**,  
which shows that **neutrinos have mass**”

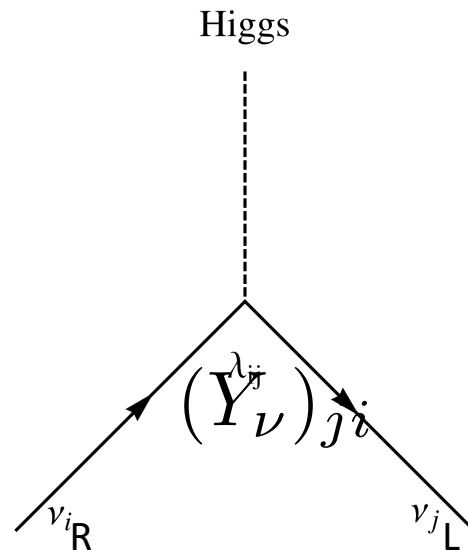


# Massive Dirac neutrinos & SSB ?

$$\tilde{\phi} \equiv \sigma_2 \phi^*, \quad \tilde{\phi} : (1, 2)_{-\frac{1}{2}}, \quad L : (1, 2)_{-\frac{1}{2}}$$

Yukawa neutrino coupling: SM +  $\nu_R$

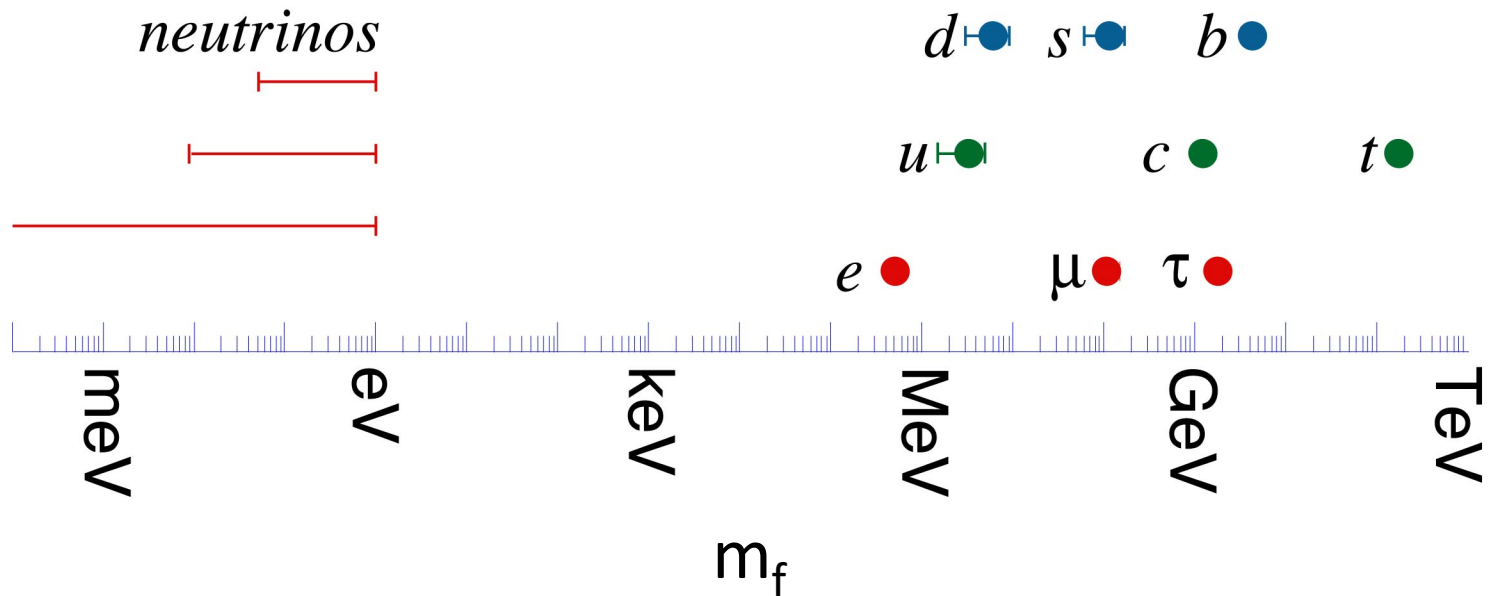
$$-\mathcal{L}_m^{\text{Dirac}} = Y_\nu \underbrace{\bar{L}\tilde{\phi}}_{(1,1)_0} \nu_R + h.c.$$



$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

# Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?

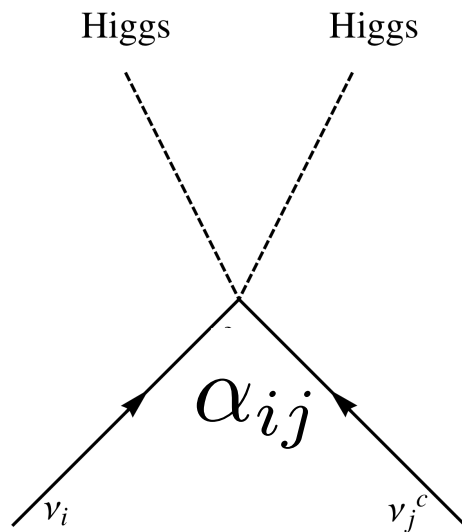


# Massive Majorana neutrinos & SSB ?

$$\tilde{\phi} \equiv \sigma_2 \phi^*, \quad \tilde{\phi} : (1, 2)_{-\frac{1}{2}}, \quad L : (1, 2)_{-\frac{1}{2}}$$

Weinberg coupling:

$$-\mathcal{L}^{\text{Majorana}} = \alpha \bar{L} \tilde{\phi} C \tilde{\phi}^T \bar{L}^T + h.c. \rightarrow SSB \rightarrow \alpha \frac{v^2}{2} \bar{\nu}_L C \bar{\nu}_L^T + h.c.$$



$$m_\nu = \alpha \frac{v^2}{2}$$

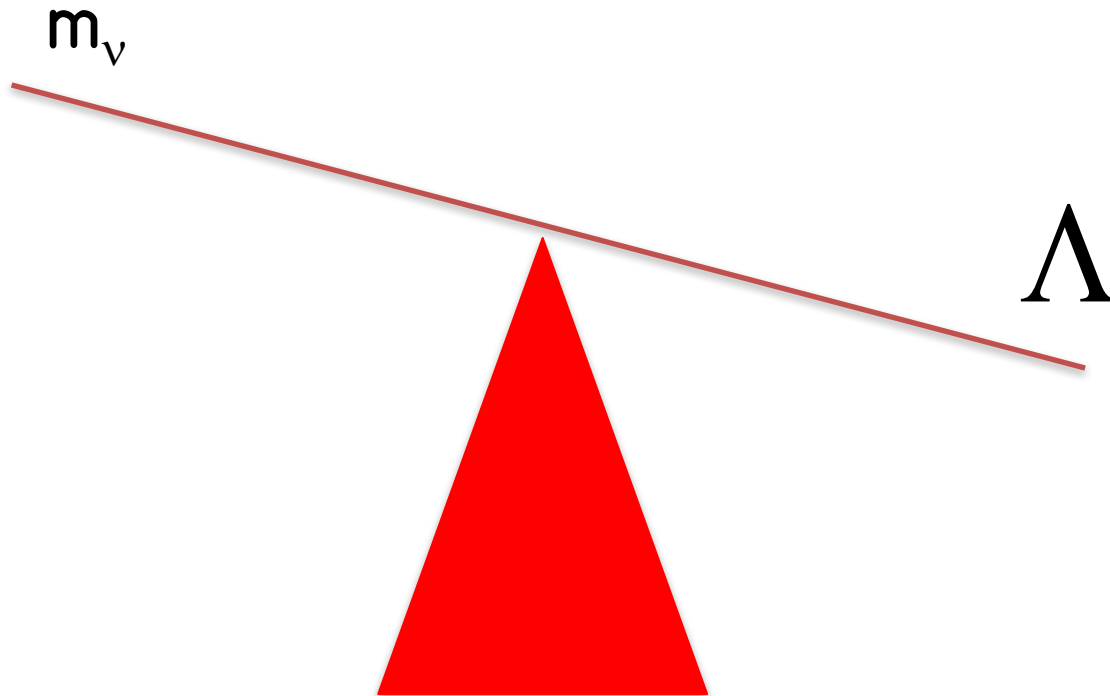
$$[\alpha] = -1$$

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

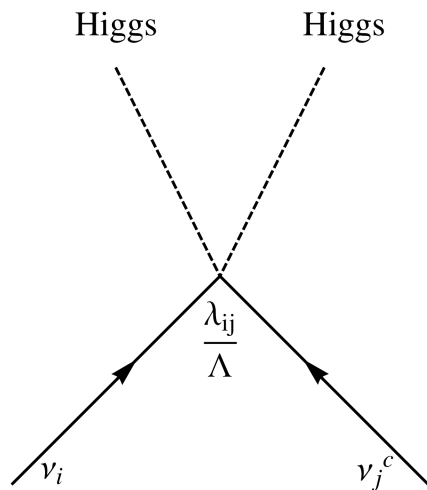
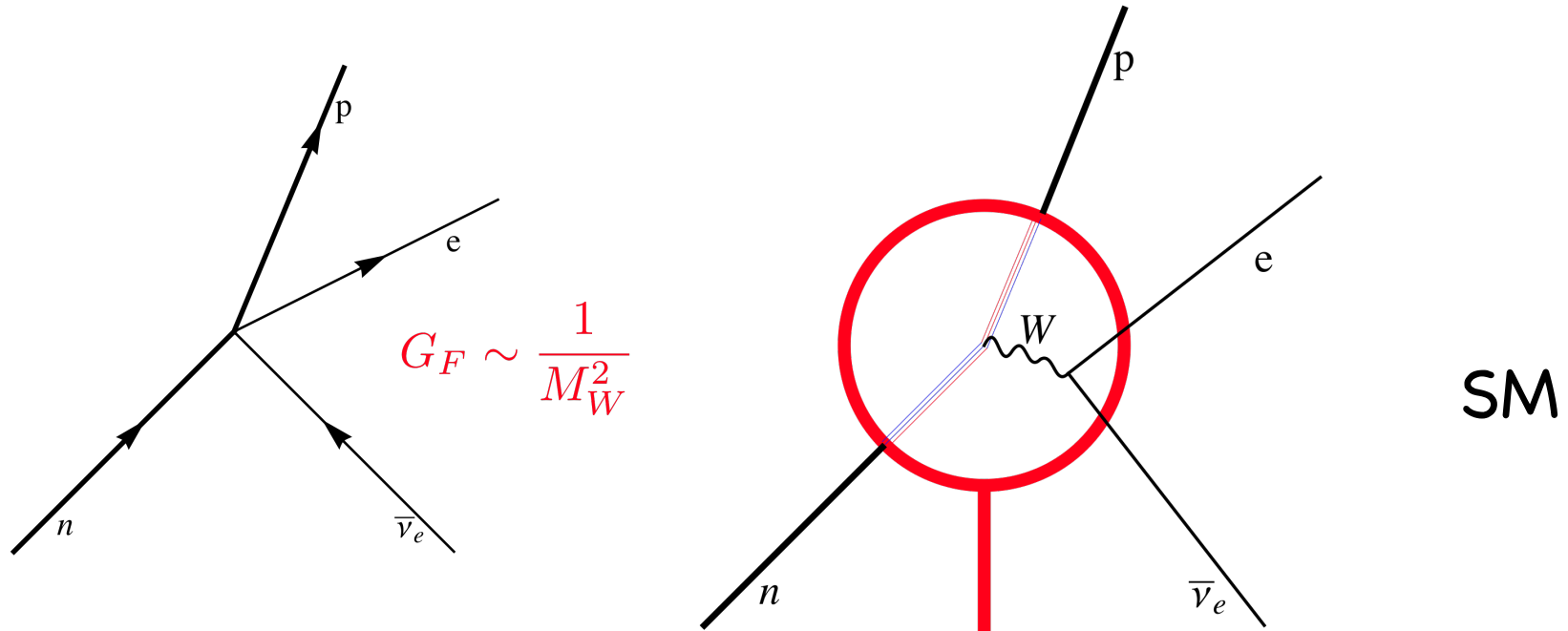
Implies the existence of a new physics scale !

# Seesaw mechanism:

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



# Majorana neutrinos -> a new physics scale



$\nu$ SM ?

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



Scale at which new particles will show up

# Lepton mixing

$$\mathcal{L}_{\text{gauge-lepton}} \supset -\frac{g}{\sqrt{2}} \bar{l}'_{Li} \underbrace{(U_l^\dagger U_\nu)_{ij}}_{U_{PMNS}} \gamma_\mu W_\mu^- \nu'_{Lj} + h.c.$$

The neutrino flavour basis:

$$\begin{array}{l} \text{States produced in a CC} \\ \text{interaction in} \\ \text{combination with} \\ \text{e, } \mu, \tau \end{array} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \begin{array}{l} \text{Eigenstates of the} \\ \text{free Hamiltonian} \end{array}$$

# Neutrino oscillations

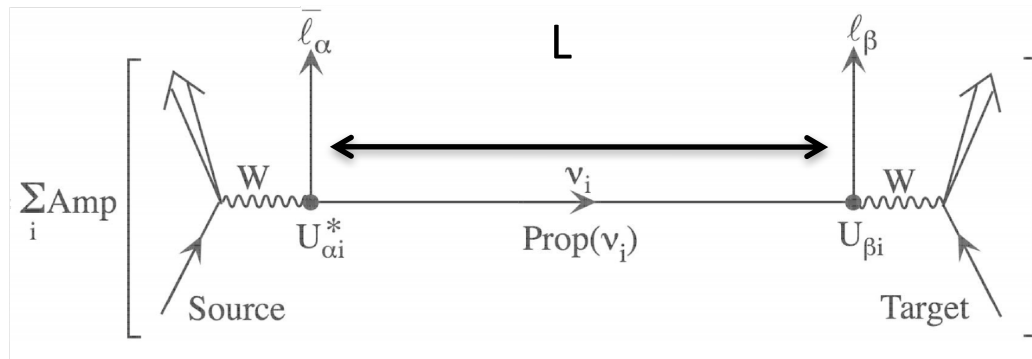
Neutrinos are produced and detected via weak interactions as flavour states:

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle, \quad \alpha = e, \mu, \tau$$



Бруно Понтекорво

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



# Neutrino oscillations

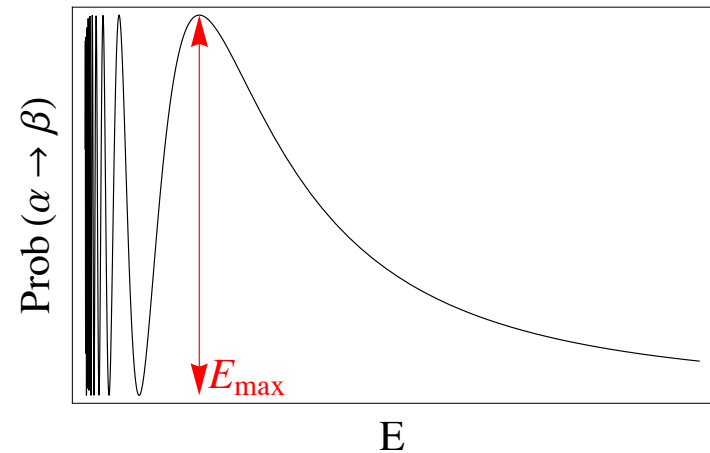
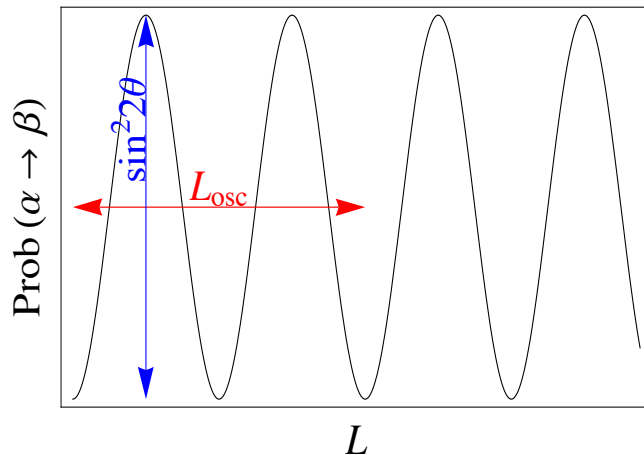
As they propagate in vacuum they oscillate

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

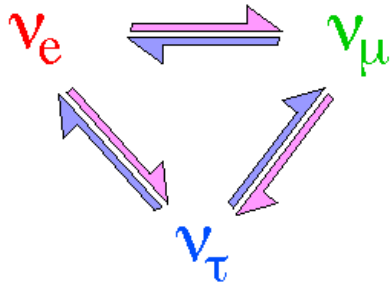
$$L_{osc} \sim \frac{E}{m_i^2 - m_j^2}$$



Бруно Понтекорво



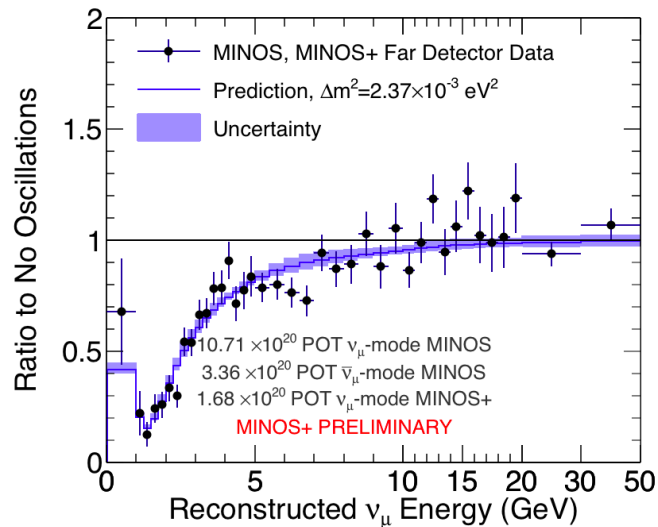
# Two oscillation frequencies measured



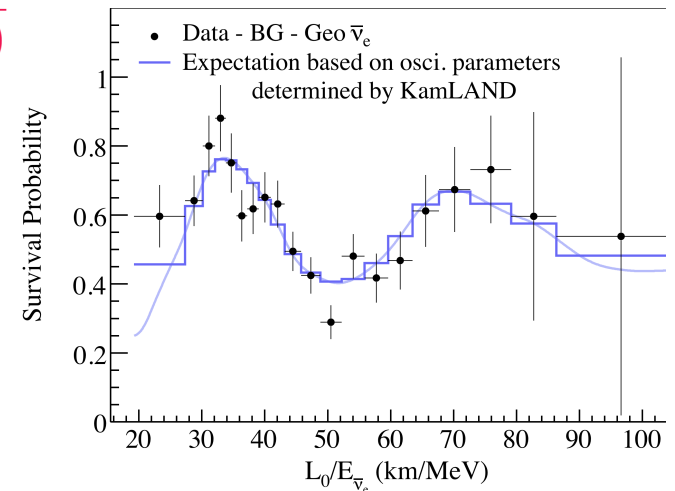
$$\Delta m_{\text{sol}}^2 \sim \frac{\mathcal{O}(\text{MeV})}{\mathcal{O}(100\text{km})}$$

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

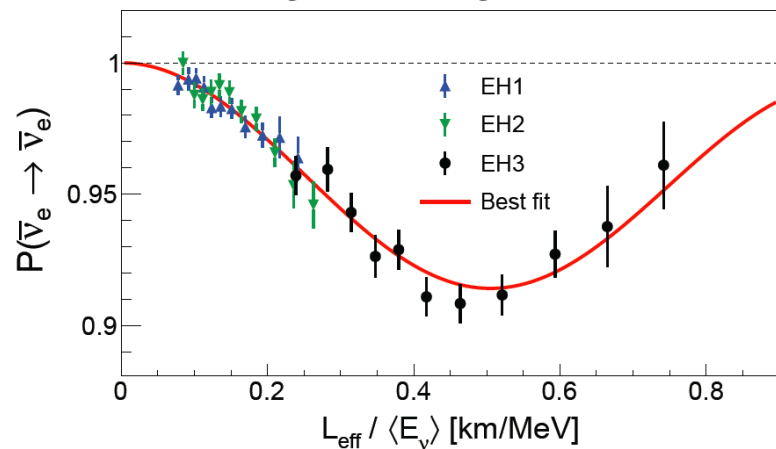
$$\nu_\mu \rightarrow \nu_\mu$$



$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$



$$\bar{\nu}_e \rightarrow \bar{\nu}_e \quad \text{Daya Bay}$$



# Standard 3ν scenario

$$\Delta m_{23}^2 = m_3^2 - m_2^2 \equiv \Delta m_{atm}^2$$

$$\Delta m_{12}^2 = m_2^2 - m_1^2 \equiv \Delta m_{sol}^2$$

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

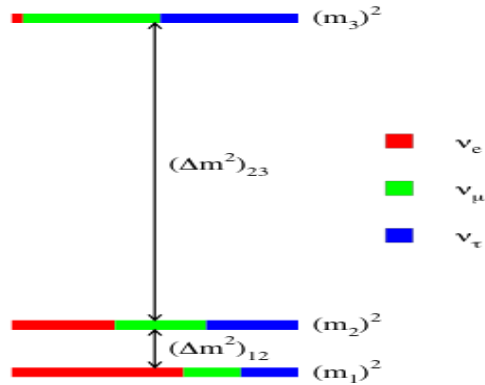
Generically **all flavour oscillate to all flavours at both wavelengths...**

Atmospheric oscillation: large  $\nu_\mu, \nu_\tau$  and small  $\nu_e$

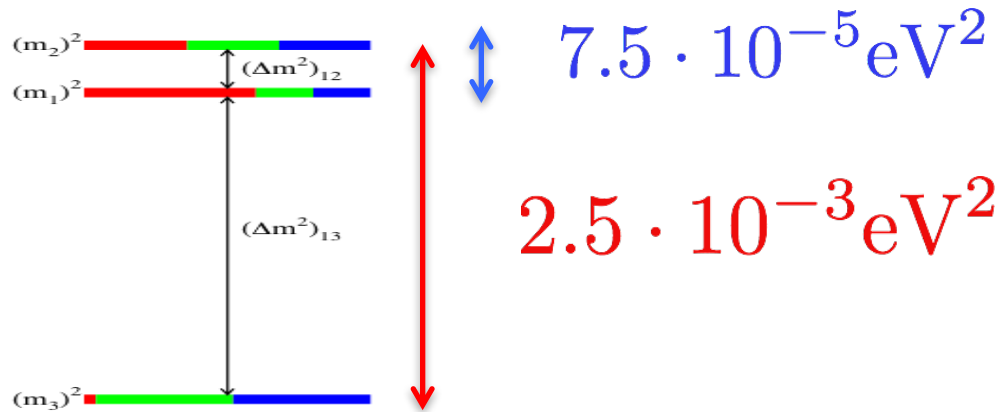
Solar oscillation: large for  $\nu_e$

# Standard 3ν scenario

normal hierarchy



inverted hierarchy



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

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

$$\theta_{23} \sim 42^\circ \text{ or } 48^\circ$$

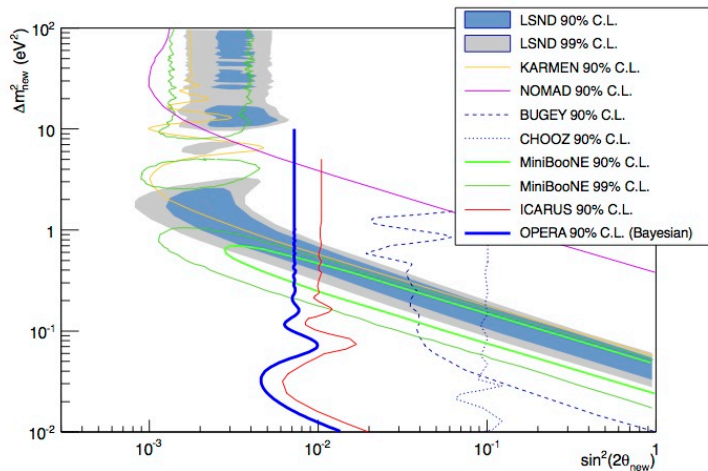
$$\theta_{13} \sim 8.5^\circ$$

$$\delta \sim ?$$

# Outliers: SBL anomalies

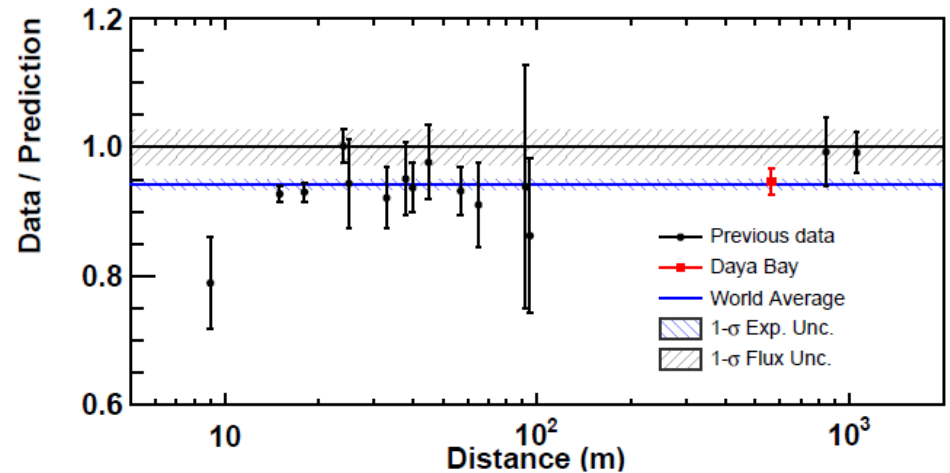
LSND

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



$$|\Delta m^2| \sim 1 \text{eV}^2$$

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

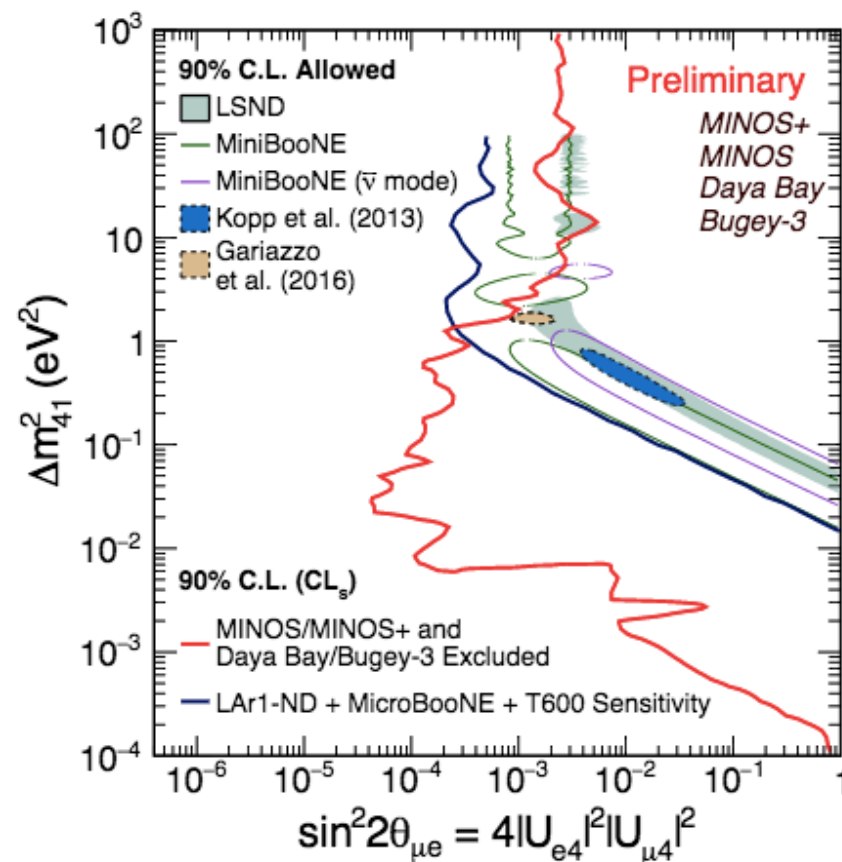


+Gallium anomaly+ MiniBOONE low-energy excess...

# O(eV) sterile neutrinos ?

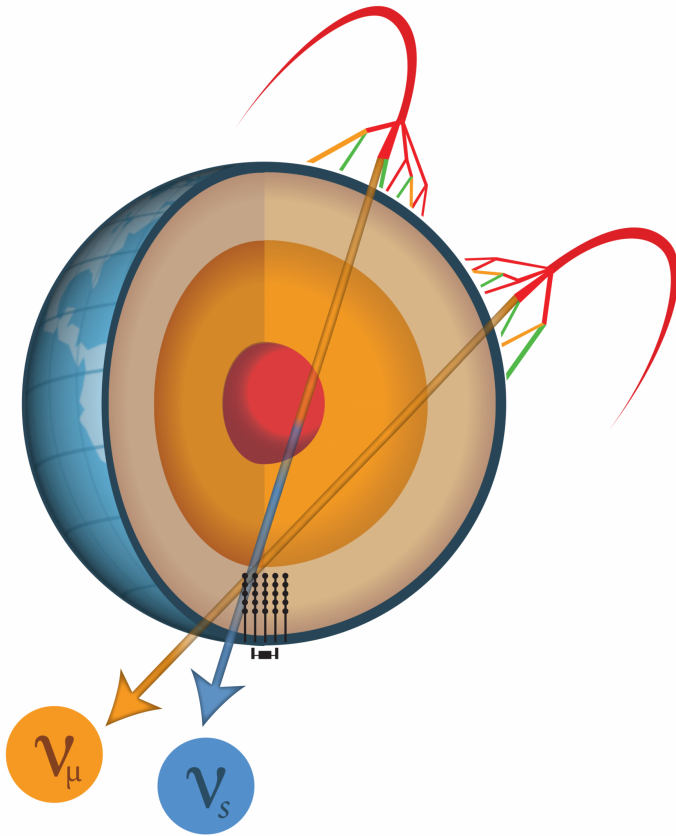
Two necessary implications not found

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

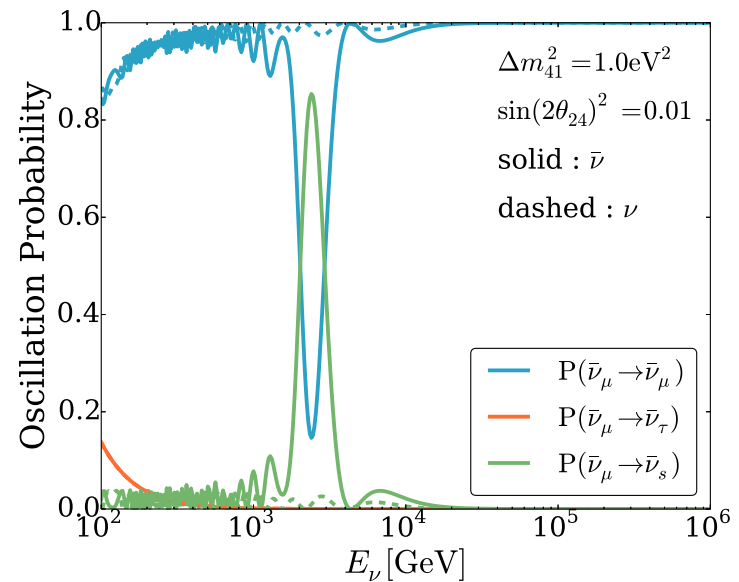


# O(eV) sterile neutrinos?

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



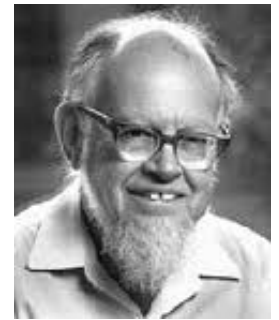
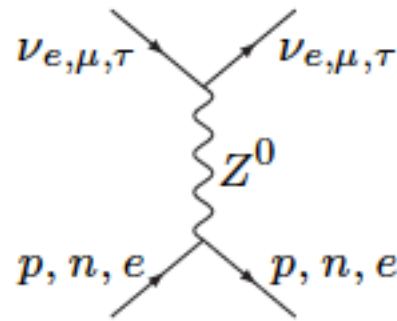
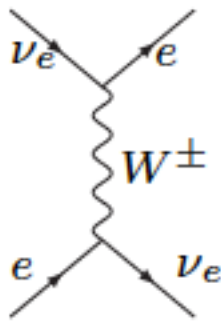
$$E_\nu^{\text{res}} \equiv \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N_e} \sim \mathcal{O}(TeV)$$



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

# Neutrino Oscillations in matter

Index of refraction (coherent forward scattering) different for electron and  $\mu/\tau$  neutrinos



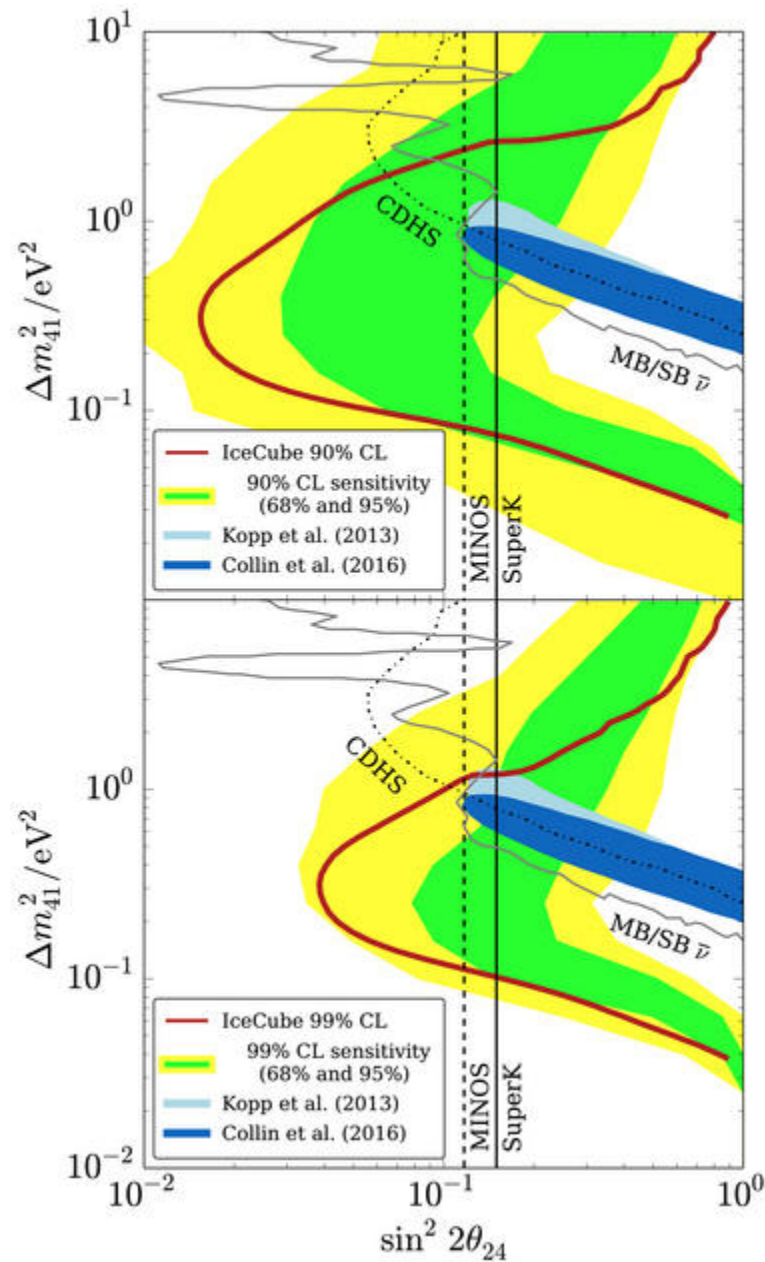
Wolfenstein

$$M_\nu^2 \longrightarrow \pm 2V_m E + M_\nu^2$$

$+$ : neutrinos,  $-$ : antineutrinos

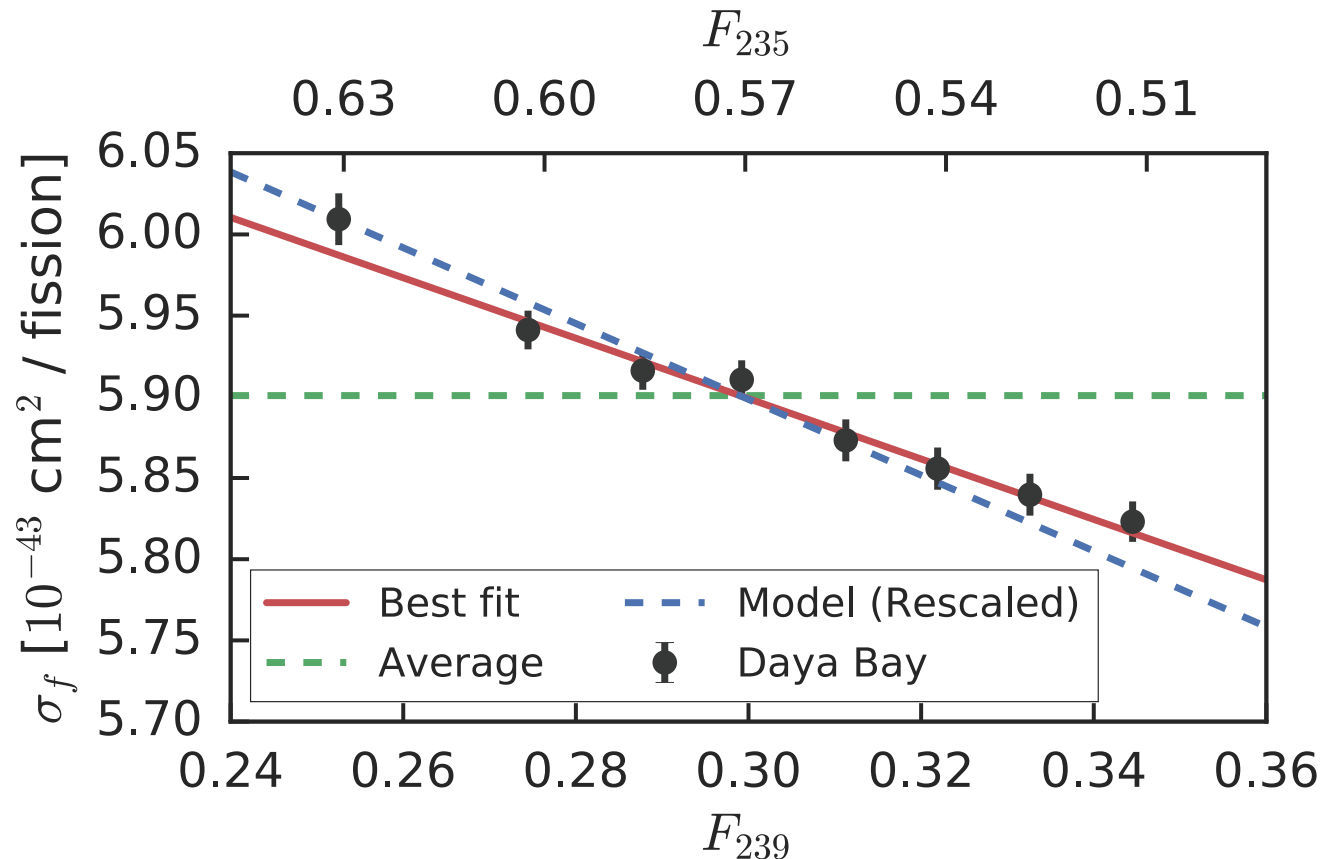
Quasi-degeneracies in matter  $\rightarrow$  **MSW resonance**

# $O(eV)$ sterile neutrinos ?



IceCube coll. '16

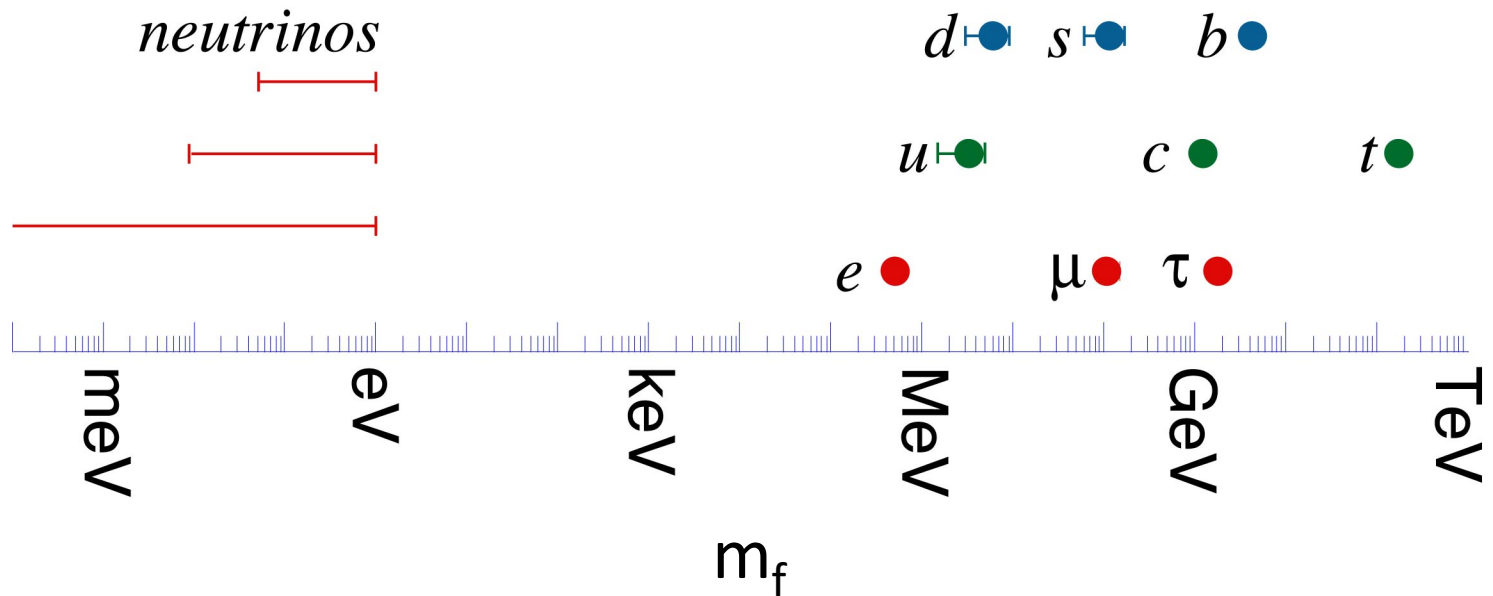
# Reactor anomaly: systematics in flux determination ?



A model with a depleted  $^{235}\text{U}$  flux fits the data equal/better than the oscillation hypothesis : will be clarified soon in dedicated SBL reactor experiments  
(Prospect, SoLID, Stereo, DANSS, Neutrino-4,...)

# Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



# Why so different mixing ?

CKM

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

PDG

PMNS

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

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, Perkins, Scott

# Six open questions

Absolute mass scale: minimum  $m_\nu$

What is the **neutrino ordering** normal or inverted ?

Is there **leptonic CP violation** ?

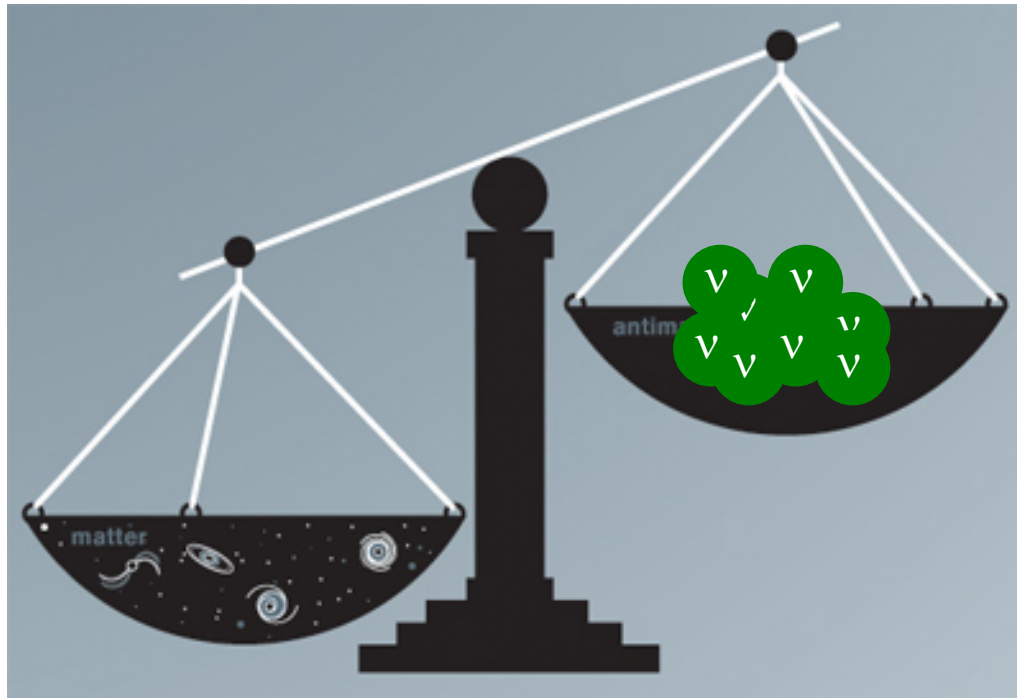
Are neutrinos **Majorana** and if so, what **new physics** lies behind this fact ?

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

Neutrino-mass inspired **new physics** searches

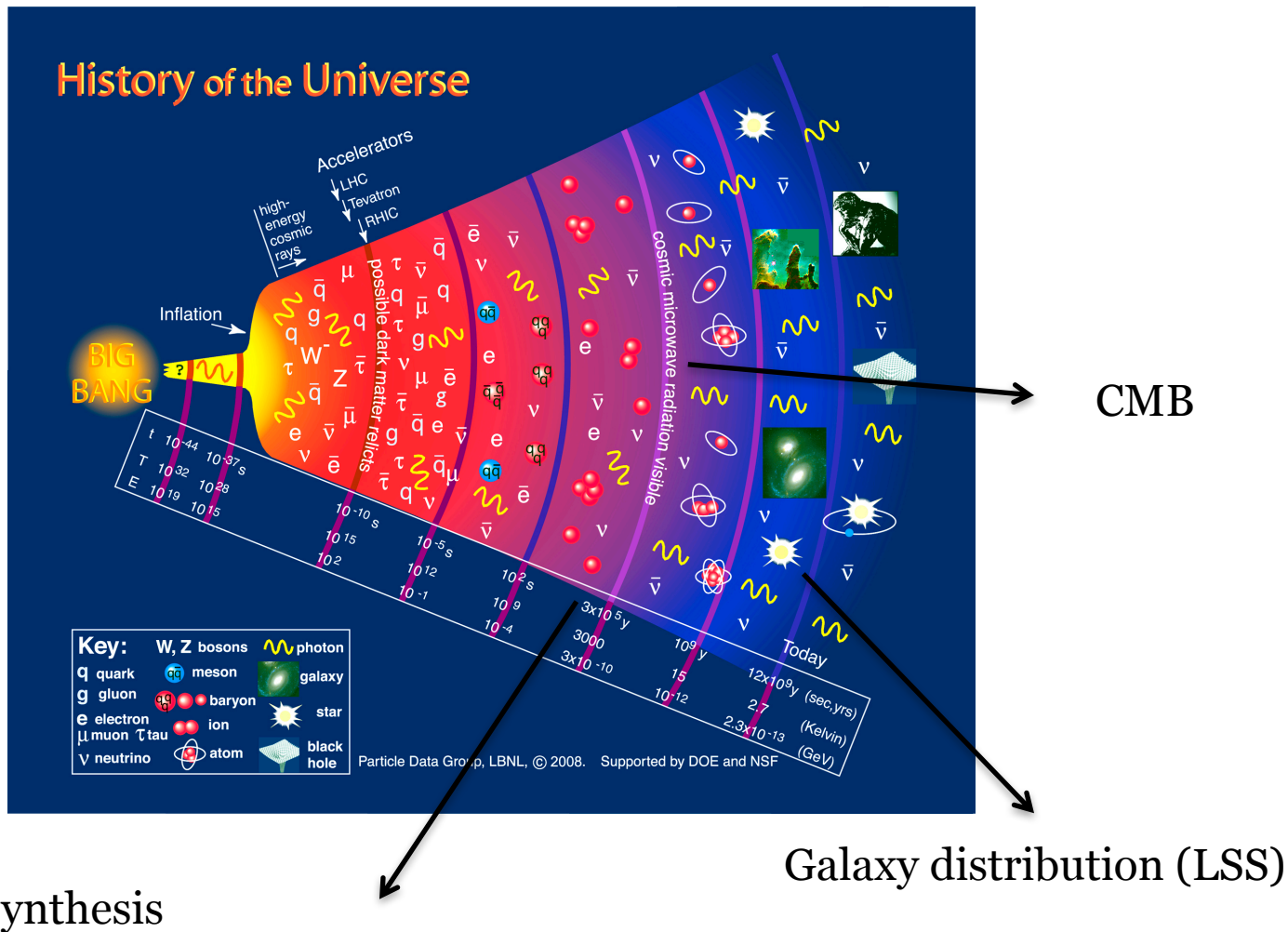
# Absolute mass scale

Best constraints at present from cosmology



# Cosmological neutrinos

Neutrinos have left many traces in the history of the Universe



# Absolute mass scale

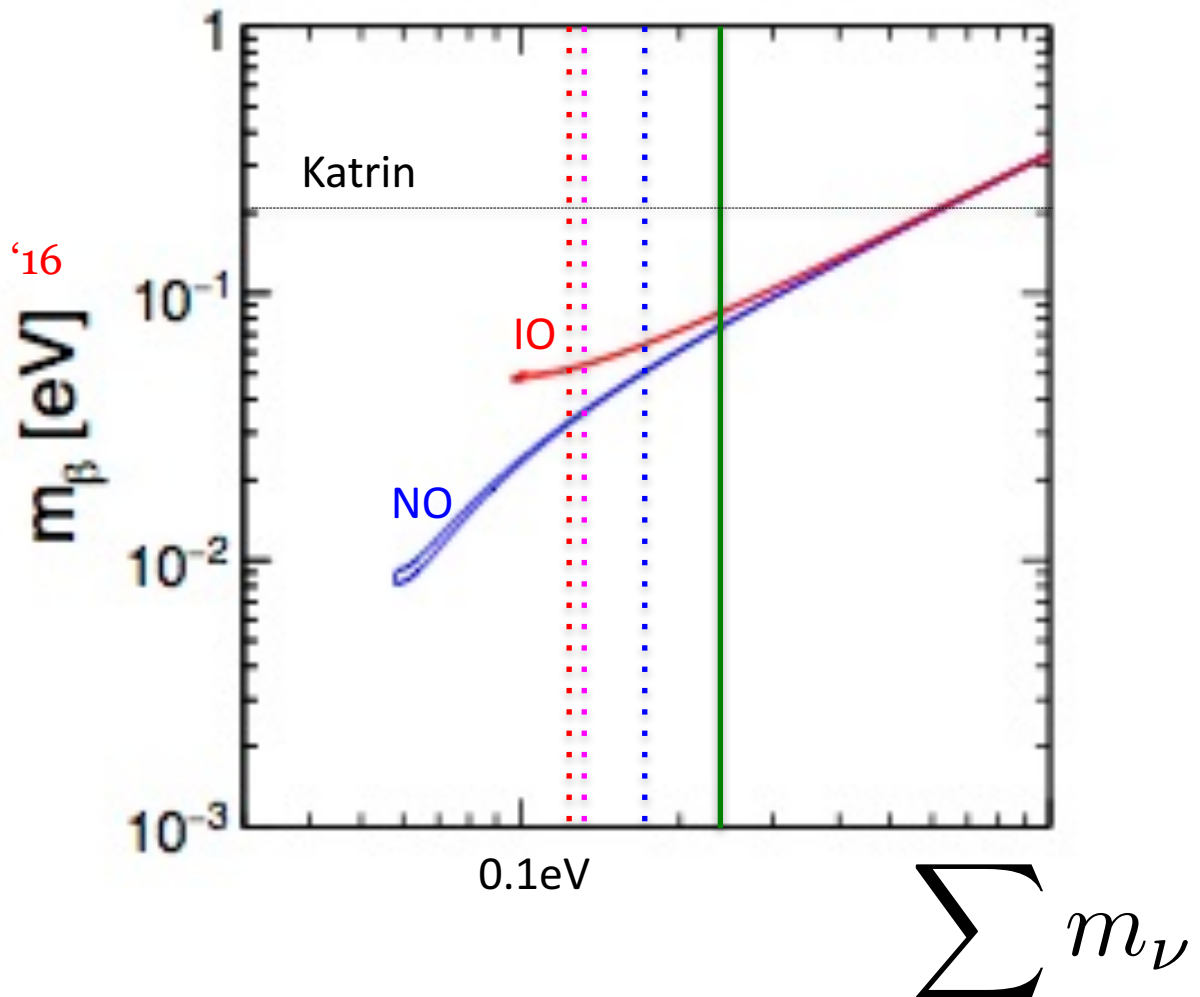
Neutrinos as light as 0.1-eV modify the large scale structure and CMB

Planck '15

Giusarma et al '16

Palanque-Delabrouille et al '16

Cuesta et al '16



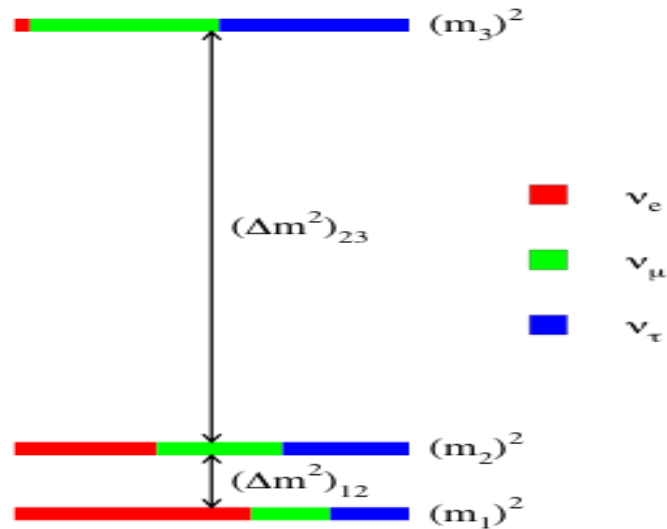
Next generation of tritium beta decay experiment: **Katrin**



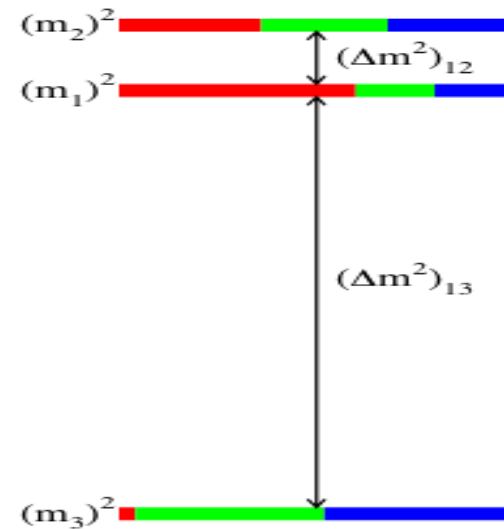
Goal:  $m_{\nu e} < 0.2 \text{ eV}$

# Neutrino ordering?

normal hierarchy

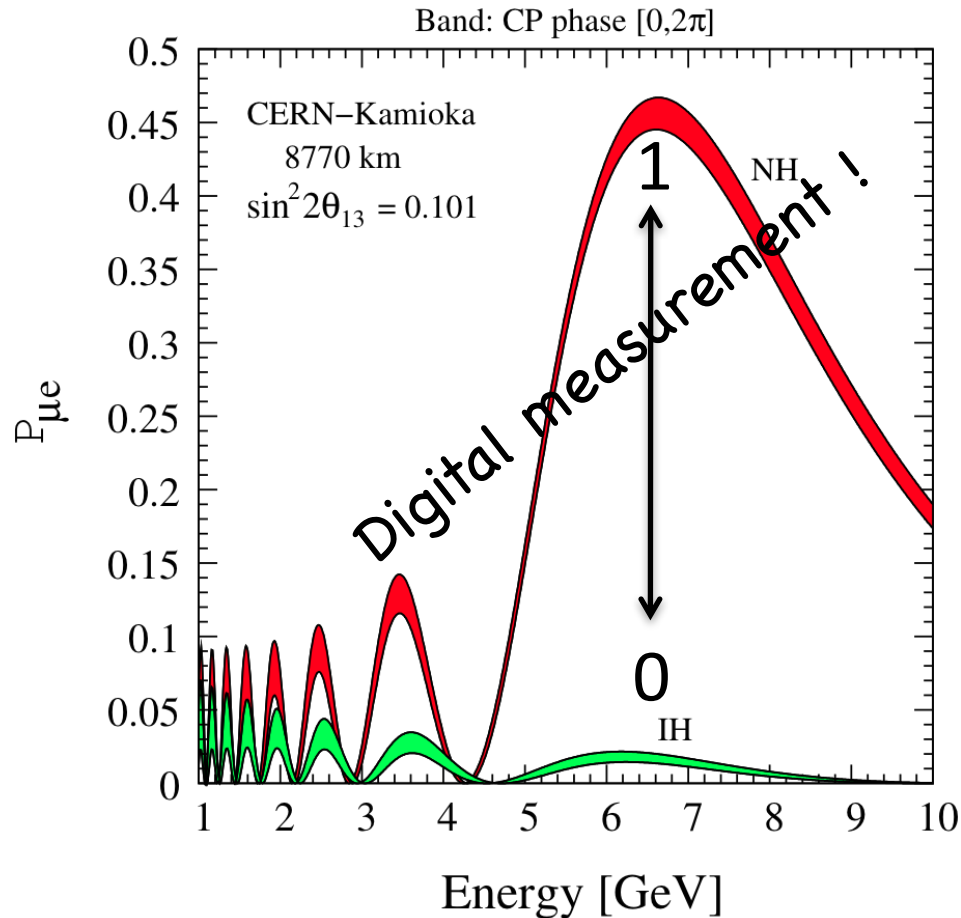


inverted hierarchy



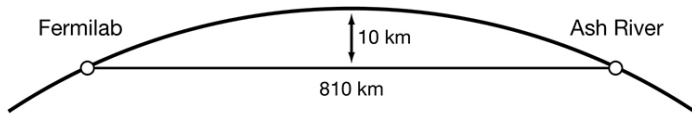
# Hierarchy through MSW@Earth

$$\nu_{\mu} \rightarrow \nu_e$$



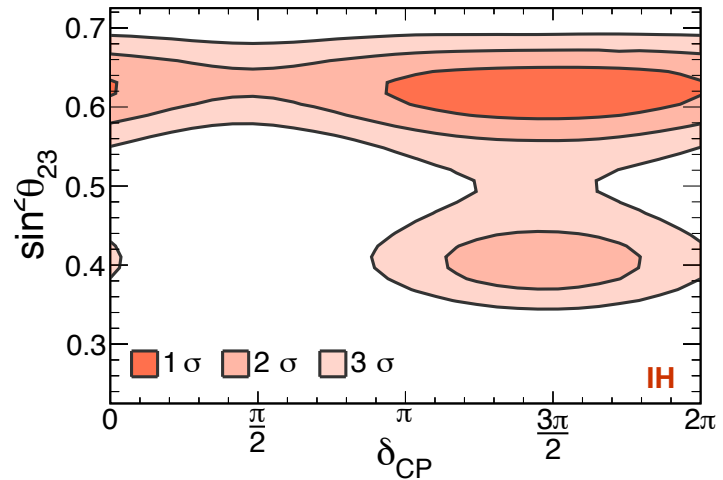
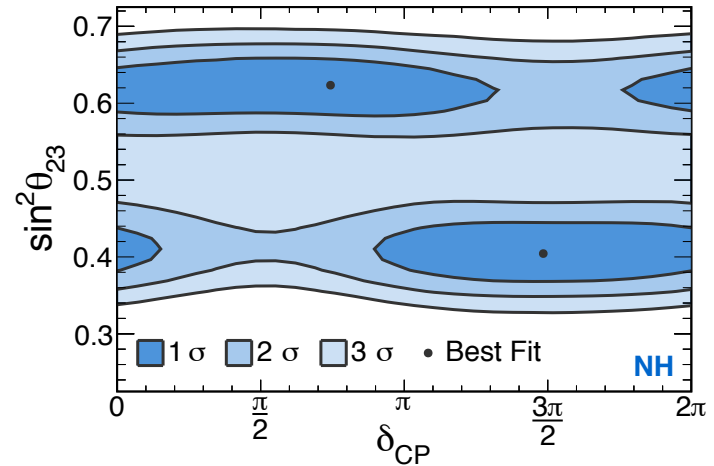
Spectacular MSW effect at O(6GeV) and very long baselines

# First attempt at the hierarchy: $\text{NO}\nu\text{A}$

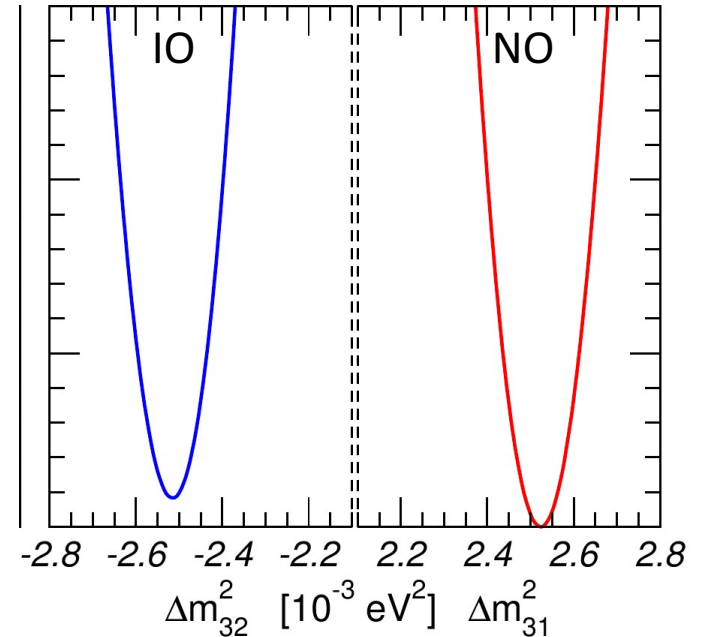
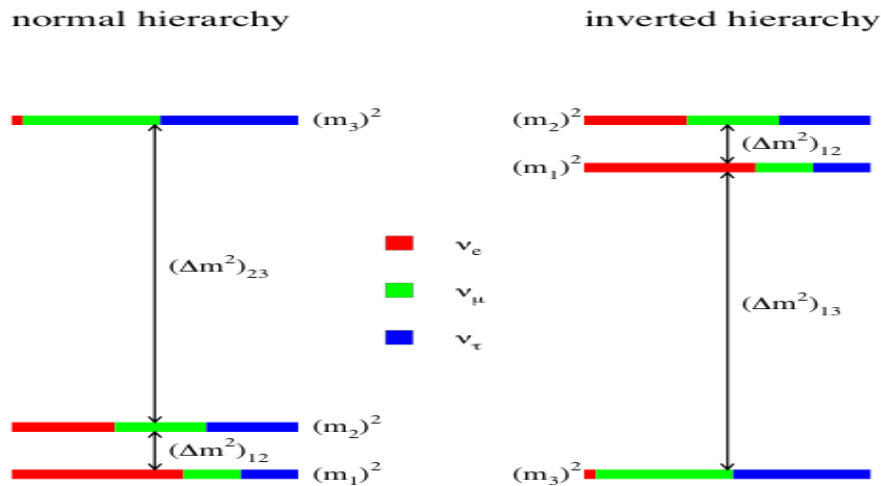


$L=810\text{km}$

$$\nu_\mu \rightarrow \nu_e$$



# Mass ordering degeneracy



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

Esteban et al 1611.01514

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

# CP violation in oscillations

What about the CP violating phase ?

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

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

# Leptonic CP violation

CP violation shows up in a difference between

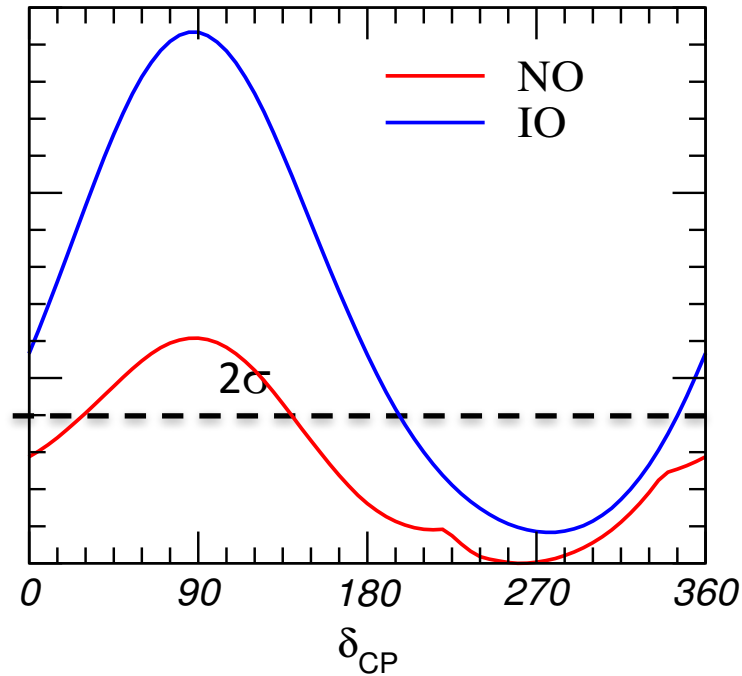
$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \quad \alpha \neq \beta$$

Golden channel (already being measured @ T2K & NoVA):

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

simultaneous sensitivity to both oscillation frequencies is needed

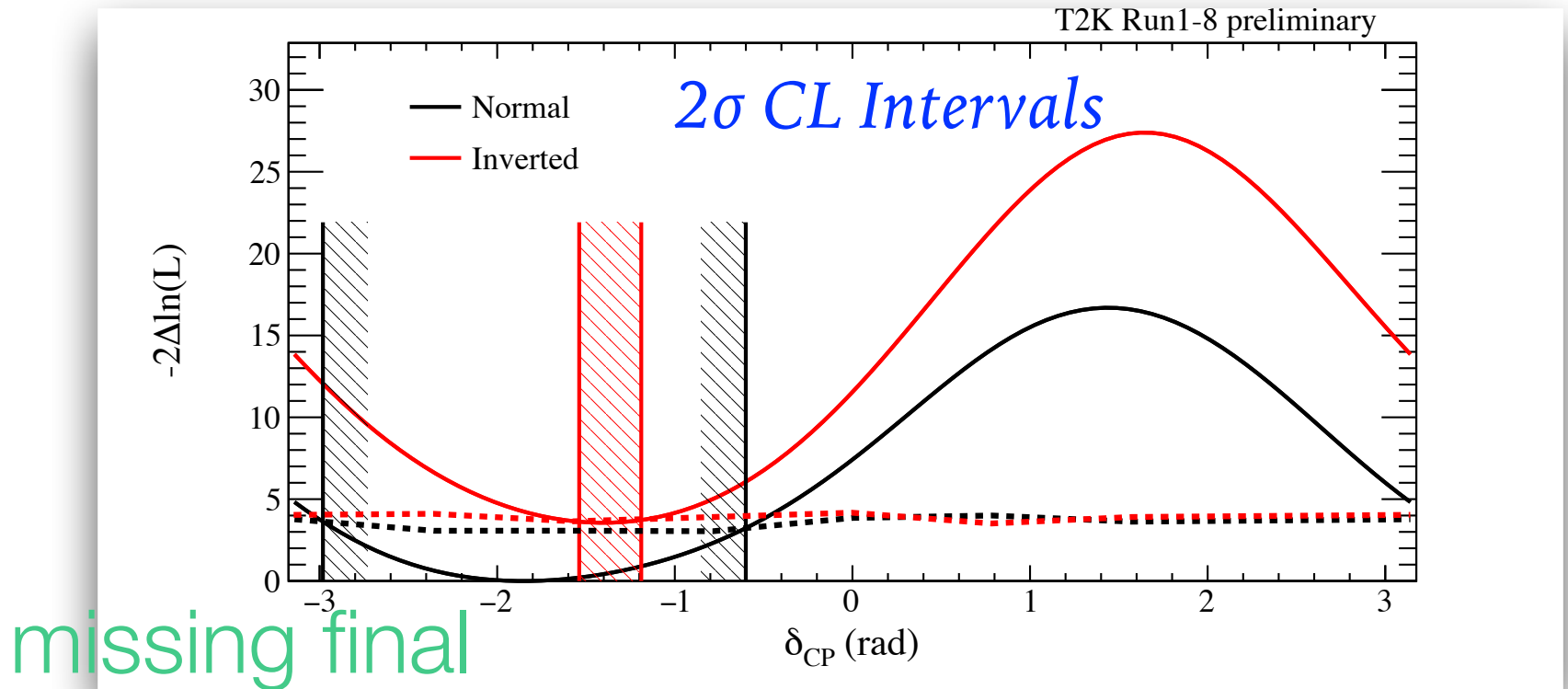
# Leptonic CP violation



Esteban et al 1611.01514

Preference for  $\delta > 180^\circ$  driven mostly by combination of reactor/T2K-NoVA, atmospheric add positively

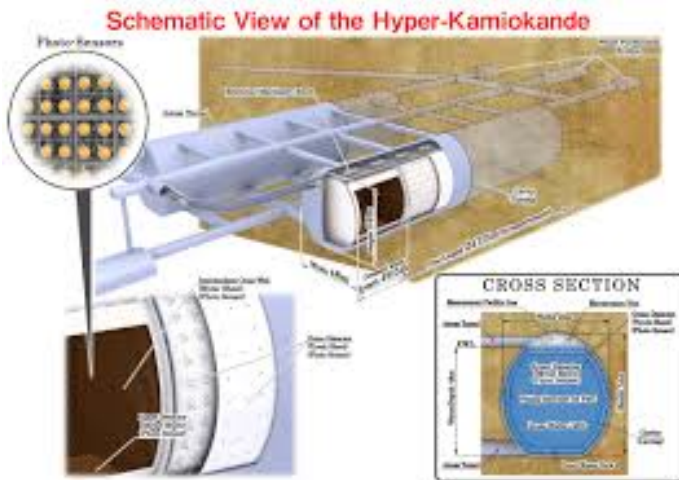
# New results from T2K



$\delta=0, \pi$  excluded at  $2\sigma$

# Hierarchy + CP in one go... superbeams+superdetectors

Japan Hyper-Kamiokande: 230km

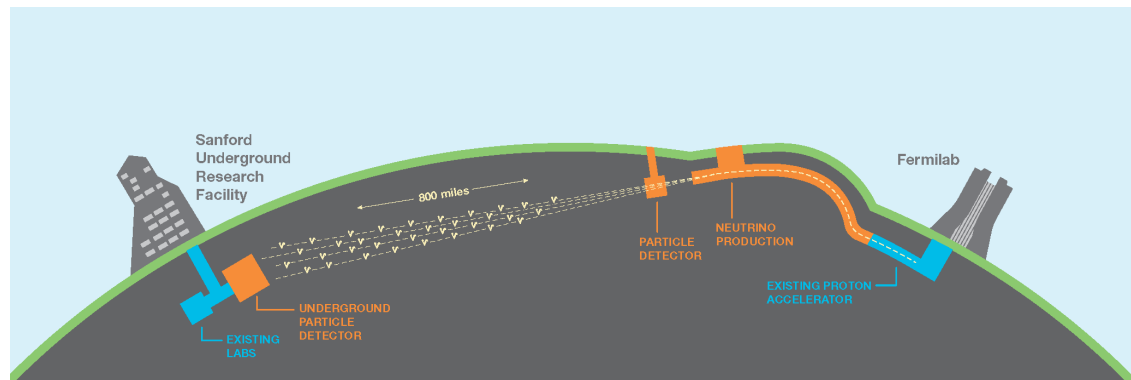


$$\nu_{\mu} \rightarrow \nu_e$$

vs

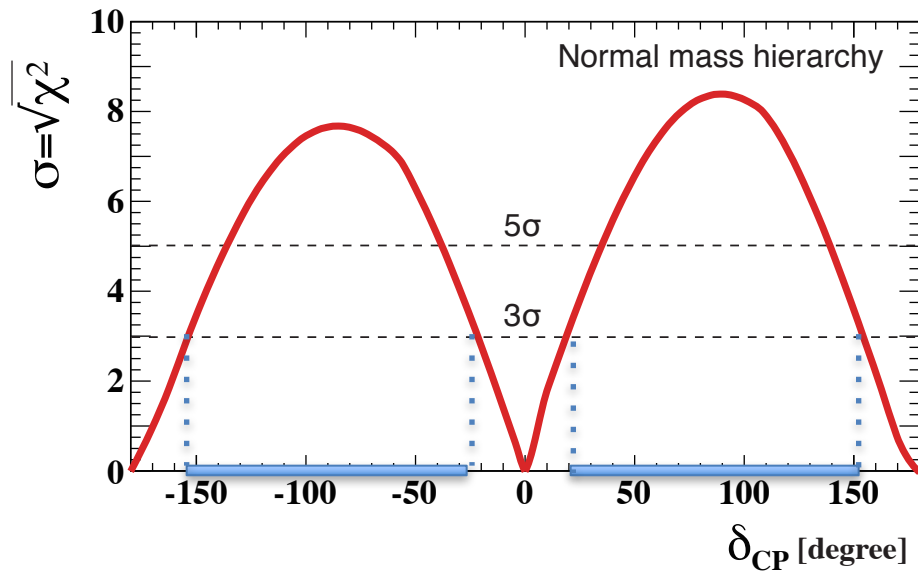
$$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$$

USA DUNE: 1300km

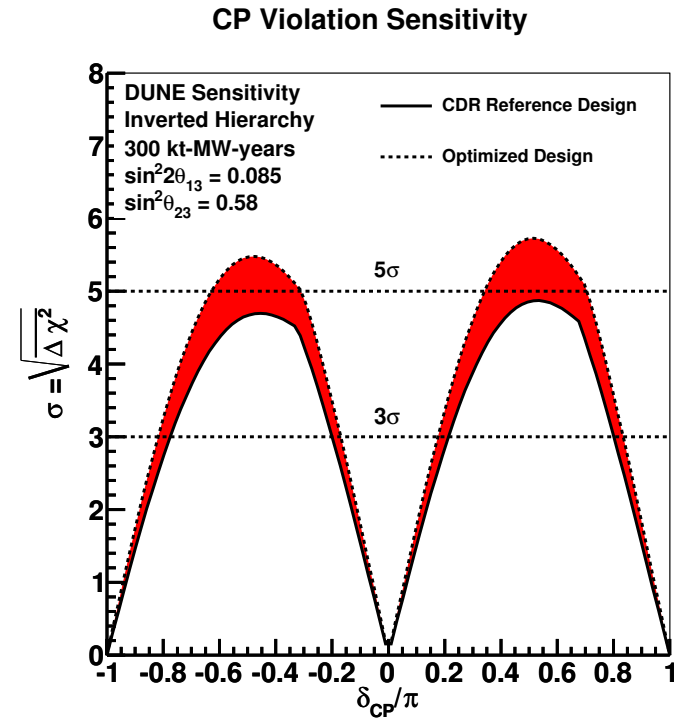


# Hierarchy + CP in one go...

## superbeams+superdetectors

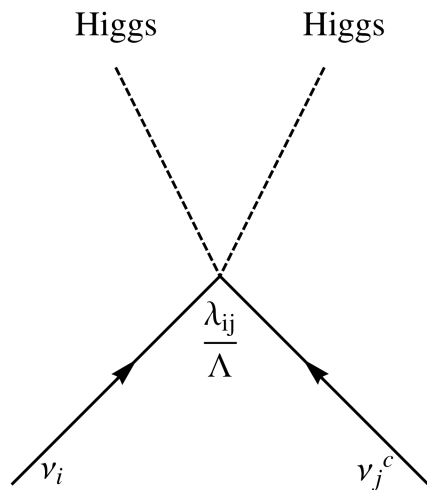
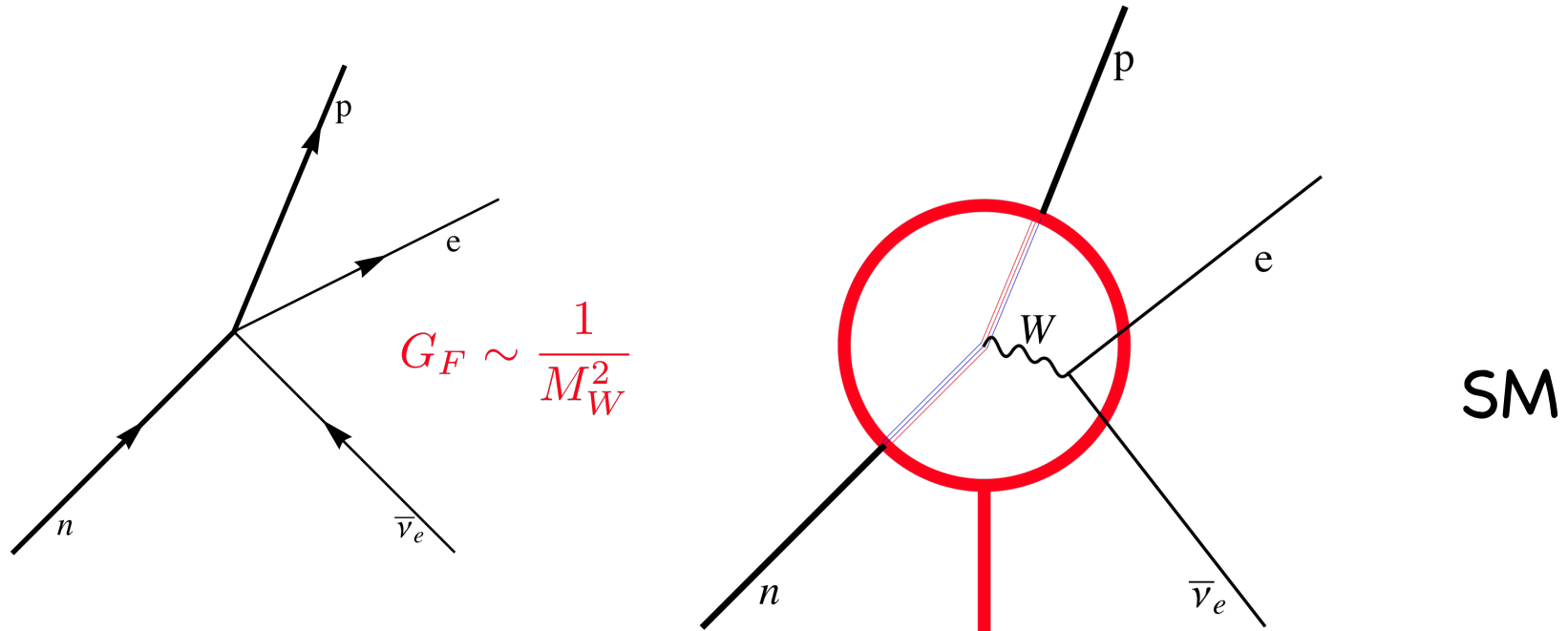


Hyper Kamiokande



DUNE

# Majorana neutrinos -> a new physics scale



$\nu$ SM ?

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



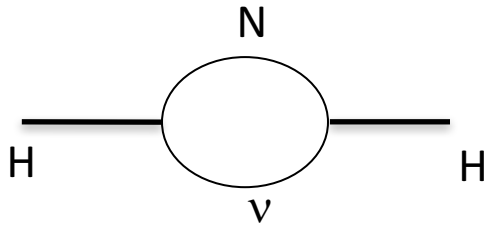
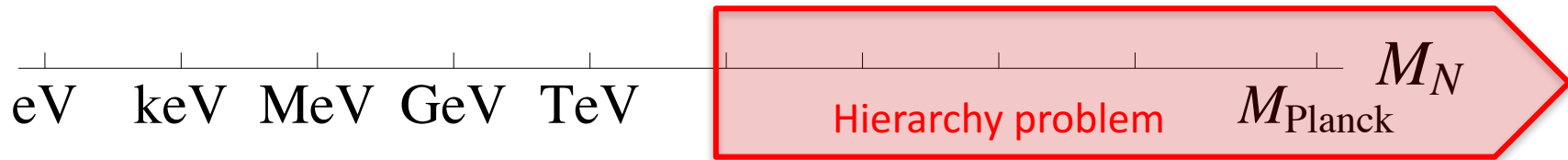
Scale at which new particles will show up

# What originates the neutrino mass ?

Could be  $\Lambda \gg v \dots$  the standard lore (theoretical prejudice ?)

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

# Where is the new scale ?

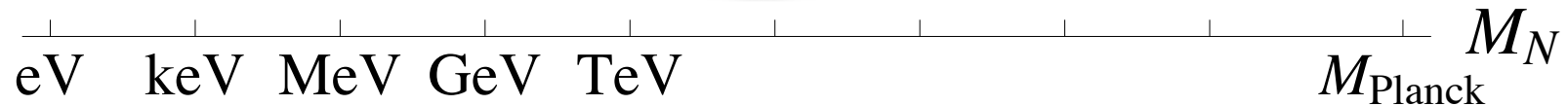


$$\delta m_H^2 = \frac{Y^\dagger Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu}$$

$$M_N \gg m_H$$

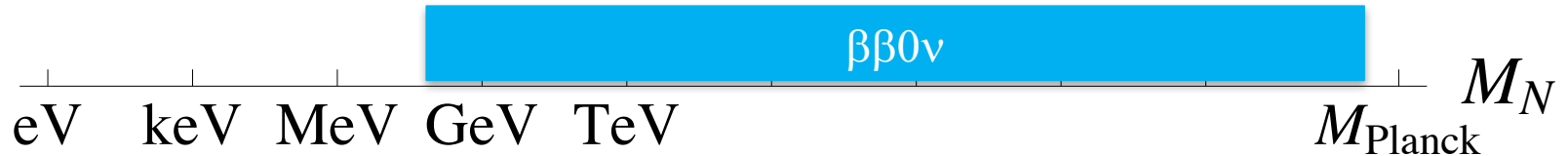
Requires a fine-tuning of the Higgs mass in the absence of other physics, like SUSY

# 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

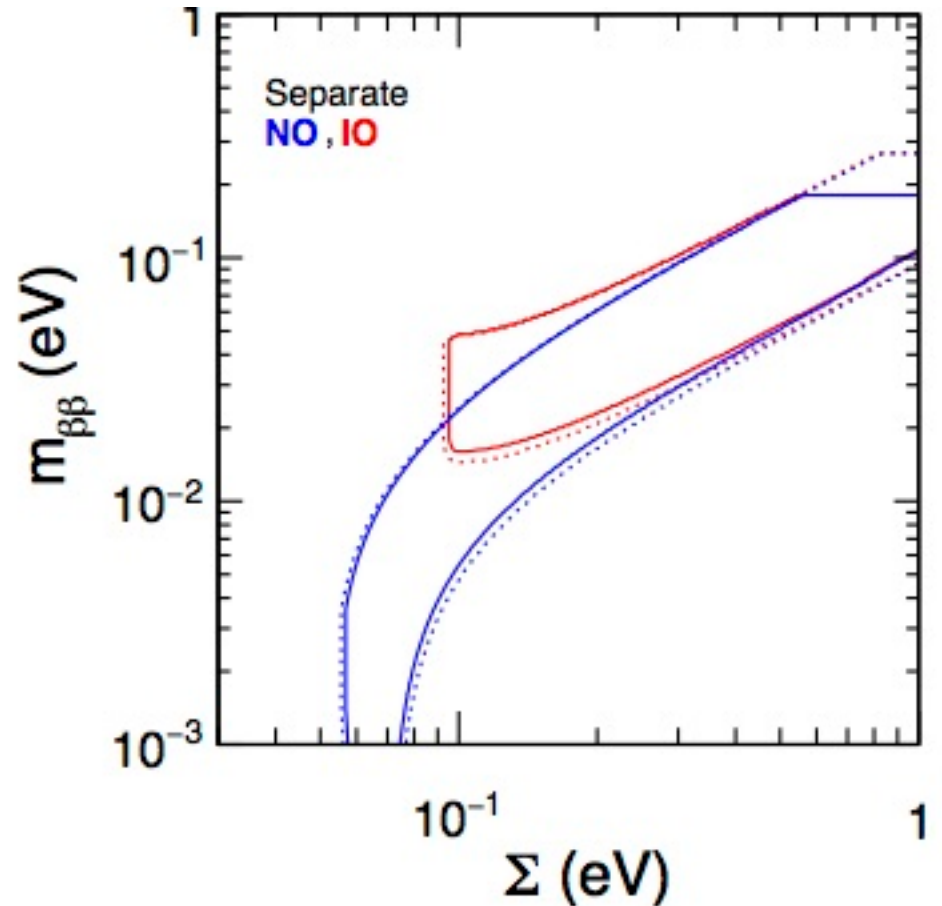
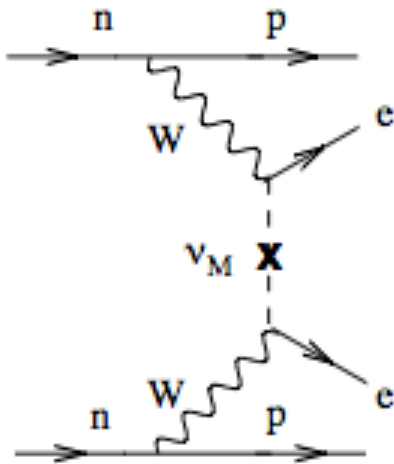
- there is **neutrinoless double beta** decay at some level ( $\Lambda > 100\text{MeV}$ )

model independent contribution from the neutrino mass

# Majorana nature ?

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

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



# Where is the new scale ?

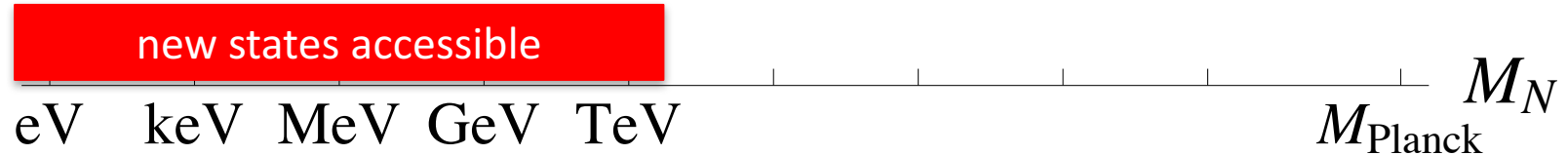


Generic predictions:

➤ 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  $\Lambda$ : **new physics beyond neutrino masses**

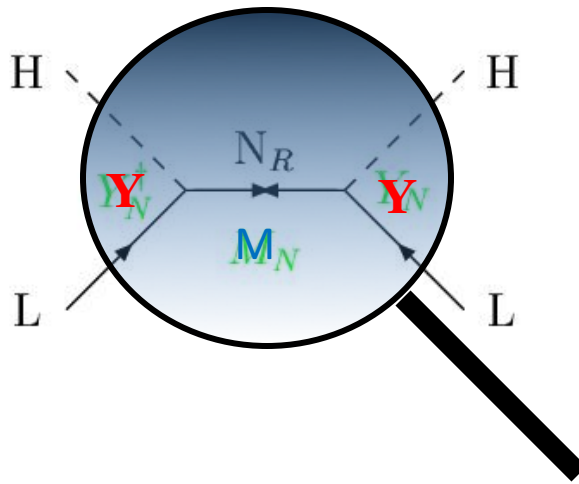
potential impact in cosmology, EW precision tests, LHC, rare searches,  $\beta\beta 0\nu$ , ...

**model dependent...**

# Neutrino BSM: the **Seesaw** Model

SM + heavy singlet fermions = Seesaw model

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

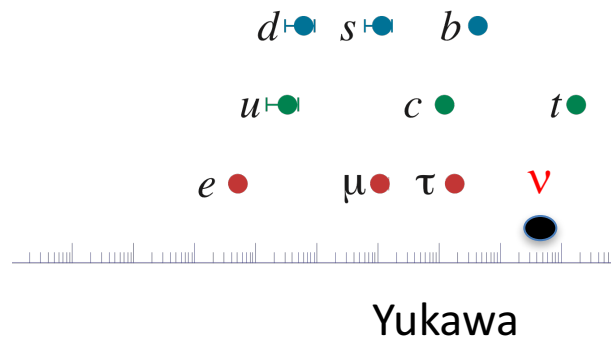


$$m_\nu = \lambda \frac{v^2}{\Lambda} \equiv \mathbf{Y}^T \frac{v^2}{M} \mathbf{Y}$$

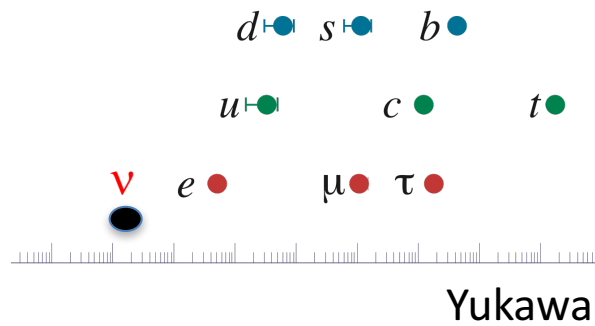
$$\lambda \sim \mathcal{O}(Y^2)$$

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

$$M_N \sim \text{GUT}$$



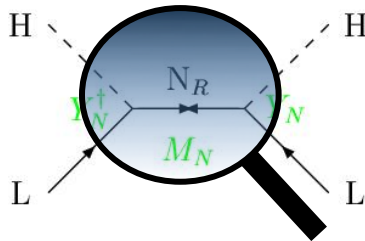
$$M_N \sim \nu$$



# Resolving the neutrino mass operator at tree level

E. Ma

Type I see-saw:  
a heavy singlet scalar

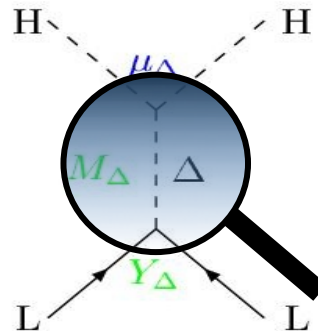


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

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

Type II see-saw:  
a heavy triplet scalar

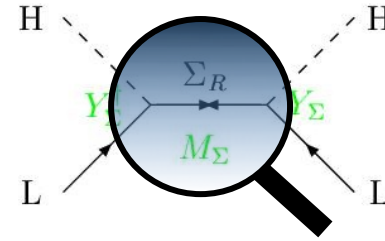


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

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

Type III see-saw:  
a heavy triplet fermion



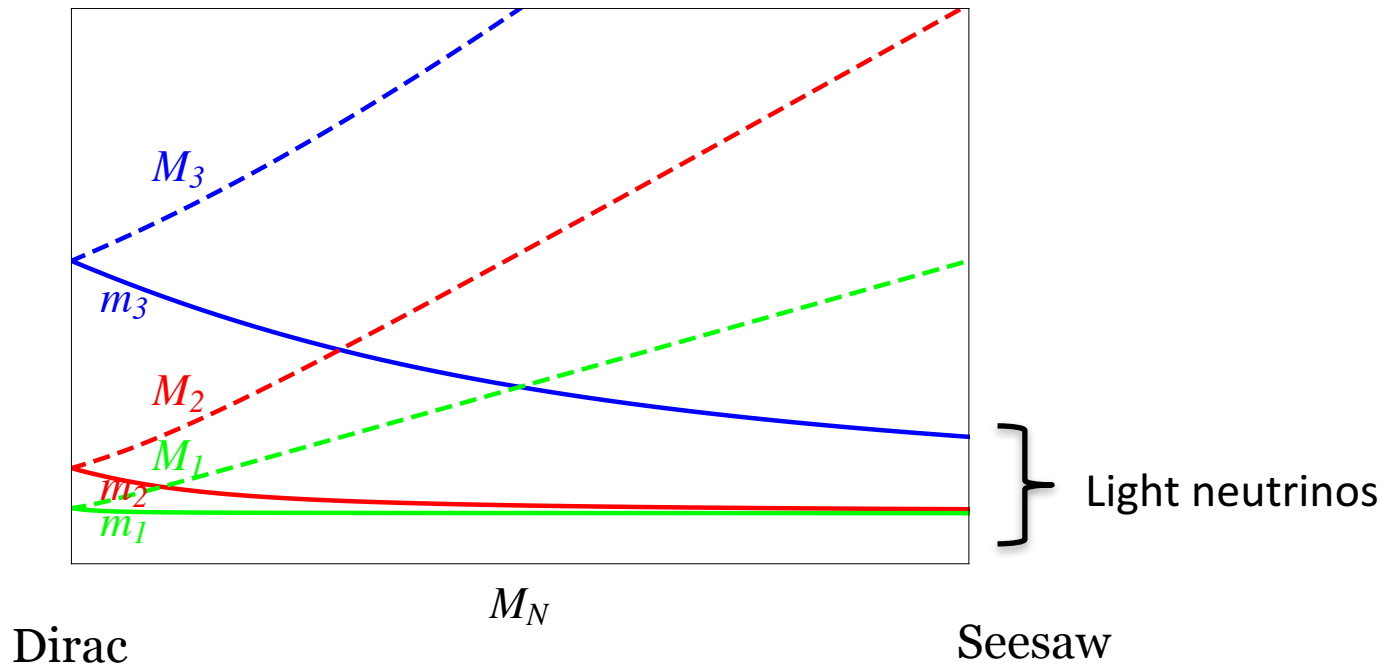
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

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

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

# Type I seesaw models

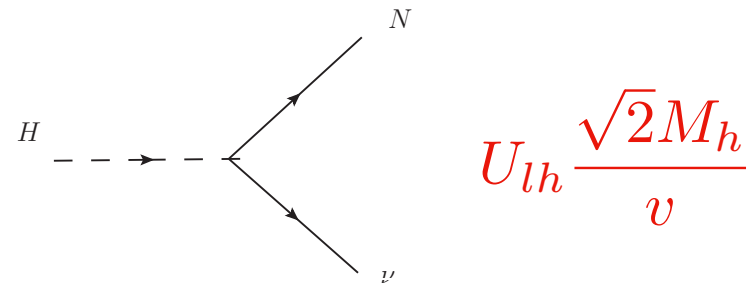
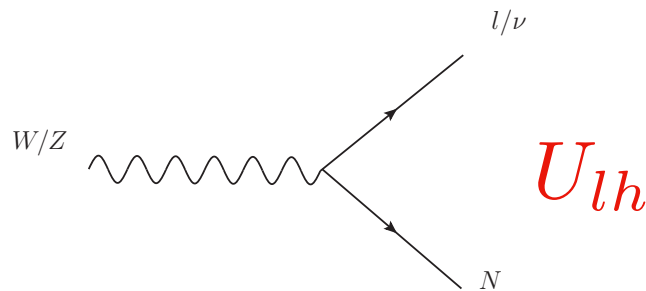
$n_R = 3$  : 18 free parameters (6 masses+6 angles+6 phases)  
out of which we have measured 2 masses and 3 angles...



# Type I seesaw models

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

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

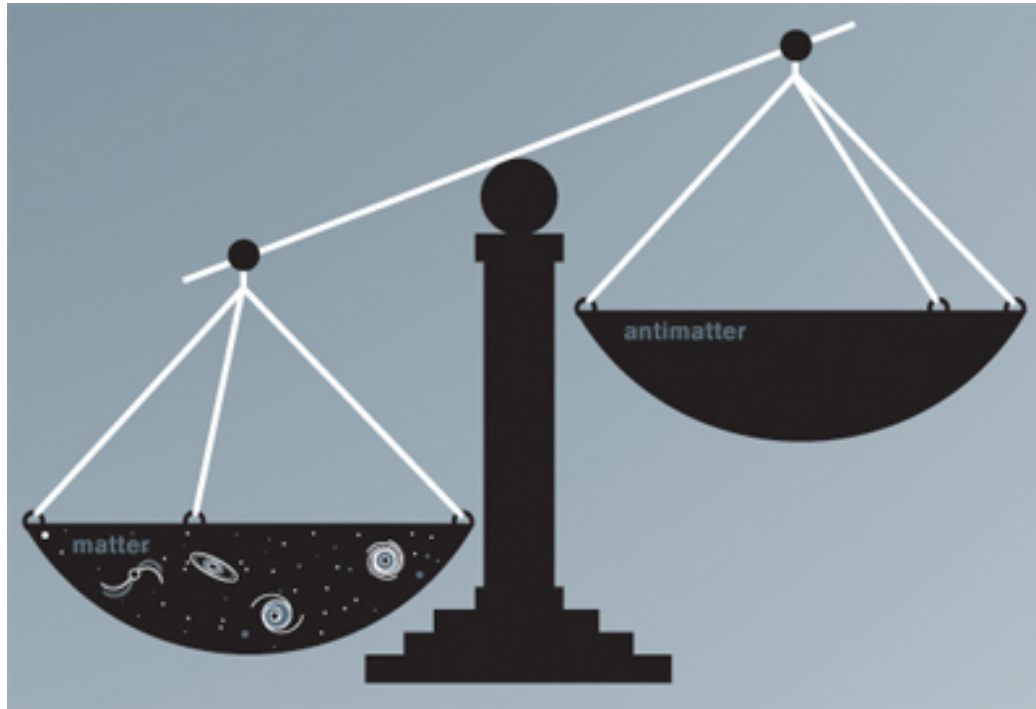


Generically strong correlation between active-heavy mixing and neutrino masses:

$$|U_{lh}|^2 \sim \frac{m_{\nu l}}{M_h} \quad (\text{but naive scaling too naive for } n_R > 1 \dots)$$

# Matter-antimatter asymmetry

The Universe seems to be made of matter



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

# 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 ...

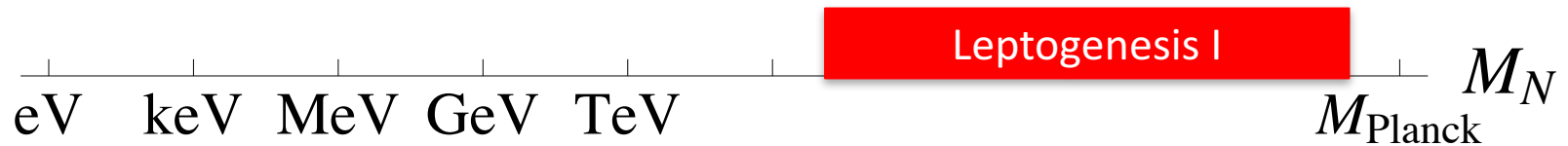
CP violation too small ✗

EW phase transition too weak ✗

Massive neutrinos provide new sources of CP violation and non-equilibrium conditions

# Leptogenesis

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



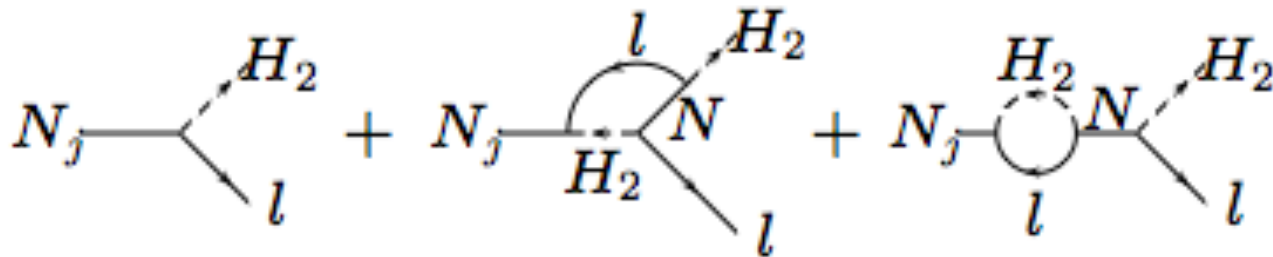
Standard leptogenesis in out-of-equilibrium  
decay  $M_N > 10^7 \text{ GeV}$

Fukuyita, Yanagida

# High-scale leptogenesis

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

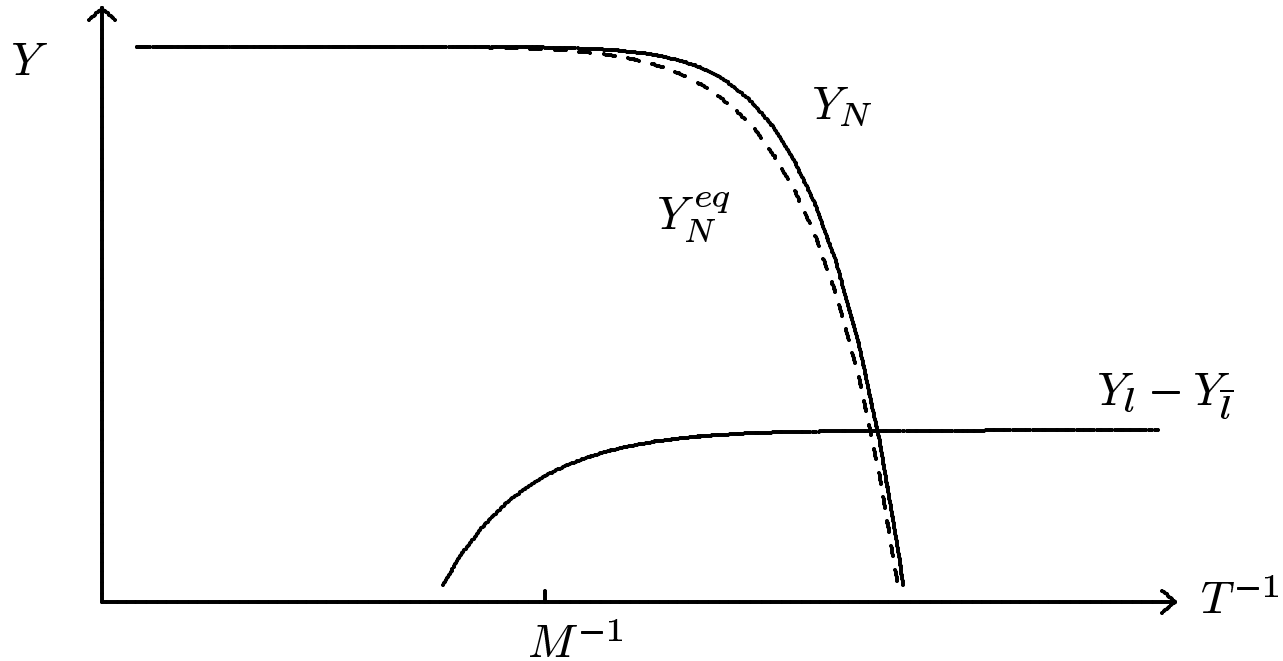
Fukuyita, Yanagida



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

Generic and robust feature of see-saw models for large enough scales  
 $M_N > 10^7\text{-}10^9 \text{ GeV}$

# High-scale leptogenesis



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

(decay rate < hubble expansion)

# Leptogenesis (low scale)

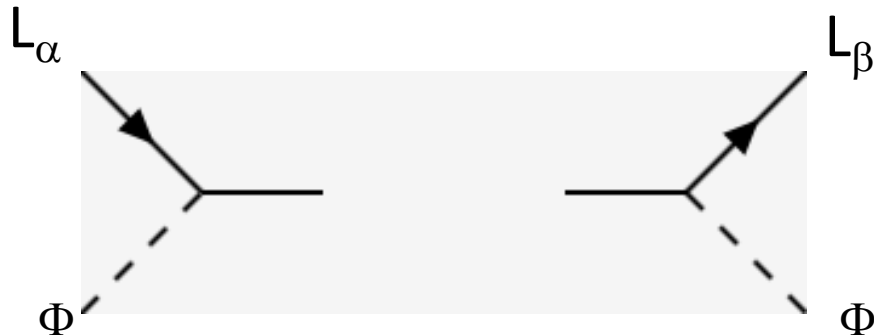


Leptogenesis from neutrino oscillations  
 $0.1\text{GeV} < M < 100\text{GeV}$

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

# Low-scale Leptogenesis

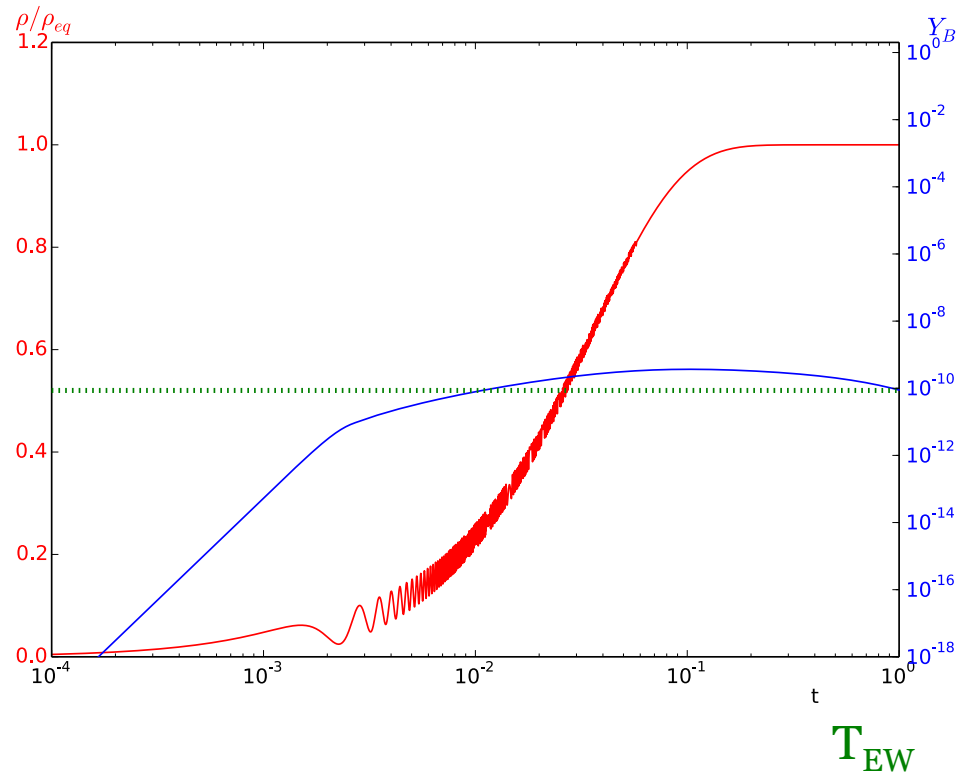
CP asymmetries arise in production of sterile states oscillations



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

Different flavours different efficiency in transferring it to the baryons

# Low-scale leptogenesis



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

(scattering rate < hubble expansion)

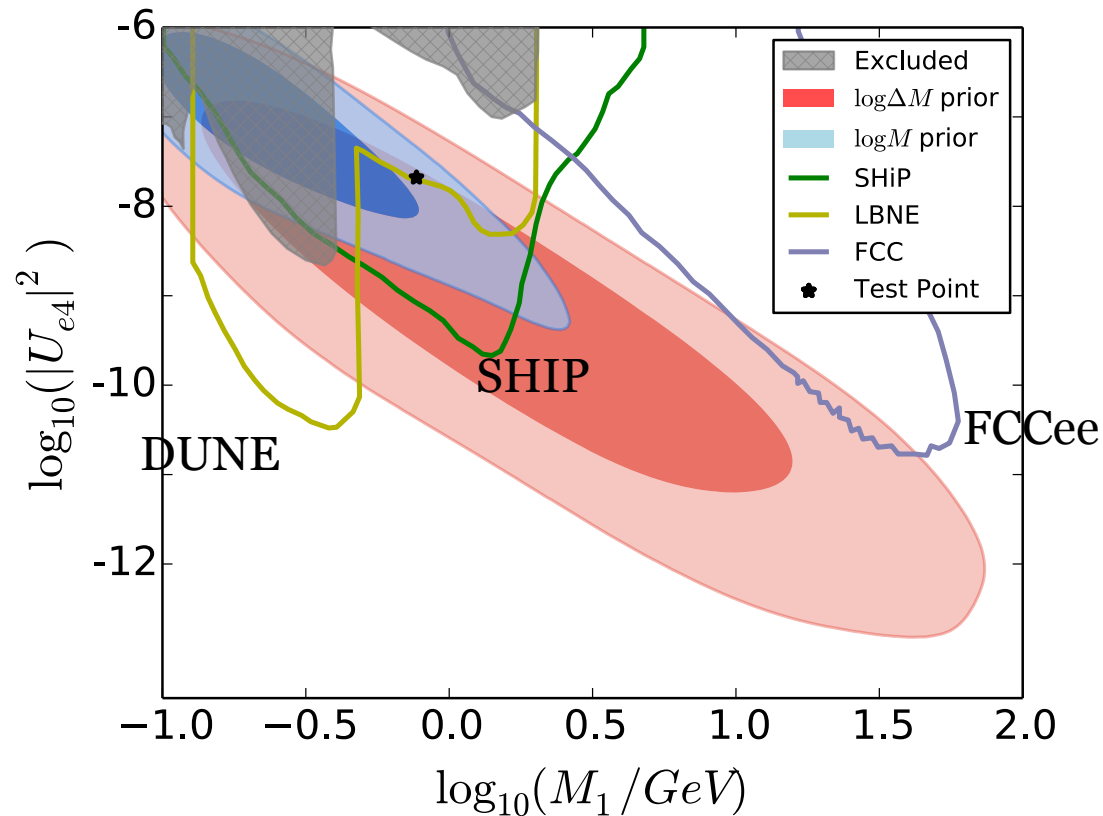
# Testability/predictivity ?

- $Y_B$  cannot be determined from neutrino masses and mixings only
- More information from the heavy sector is needed:

High-scale scenarios: very difficult for  $M_N > 10^7 \text{ GeV}$

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

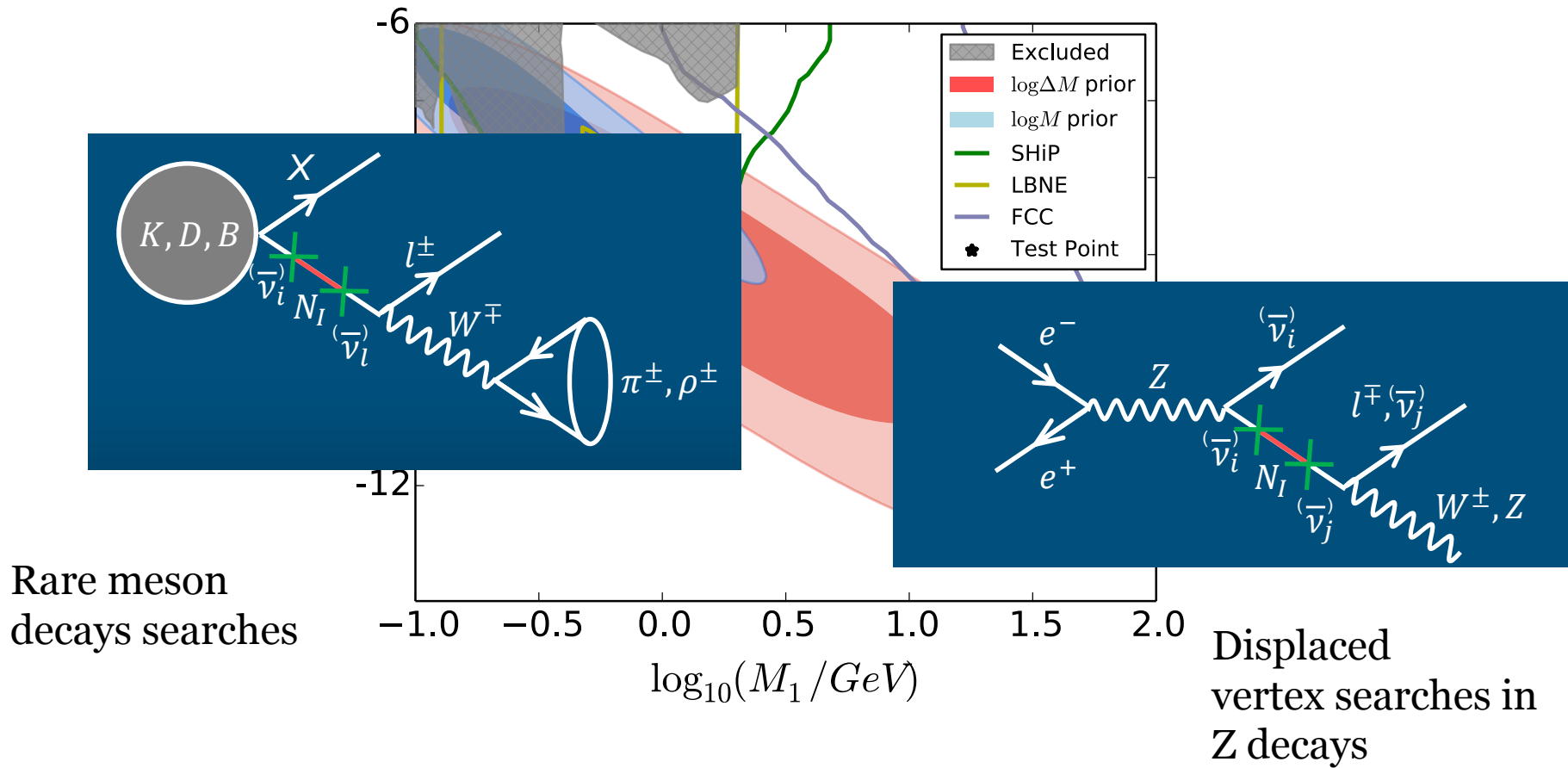
In the minimal model with just  $n_R=2$  neutrinos (IH)



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)



# Predicting $Y_B$ in the minimal model $n_R=2$ ?

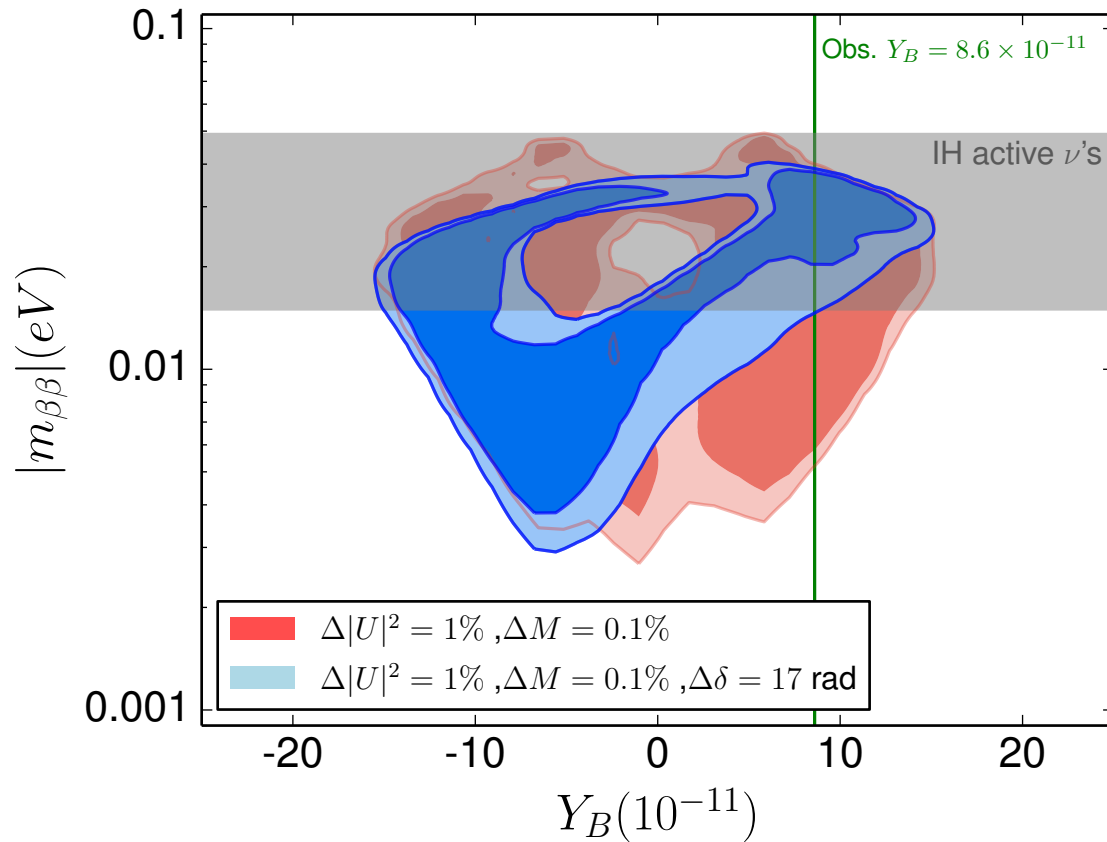
Assume a point within SHIP reach that gives the right baryon asymmetry

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

$$M_1, M_2, |U_{e1}|^2, |U_{\mu1}|^2, |U_{e2}|^2, |U_{\mu2}|^2$$

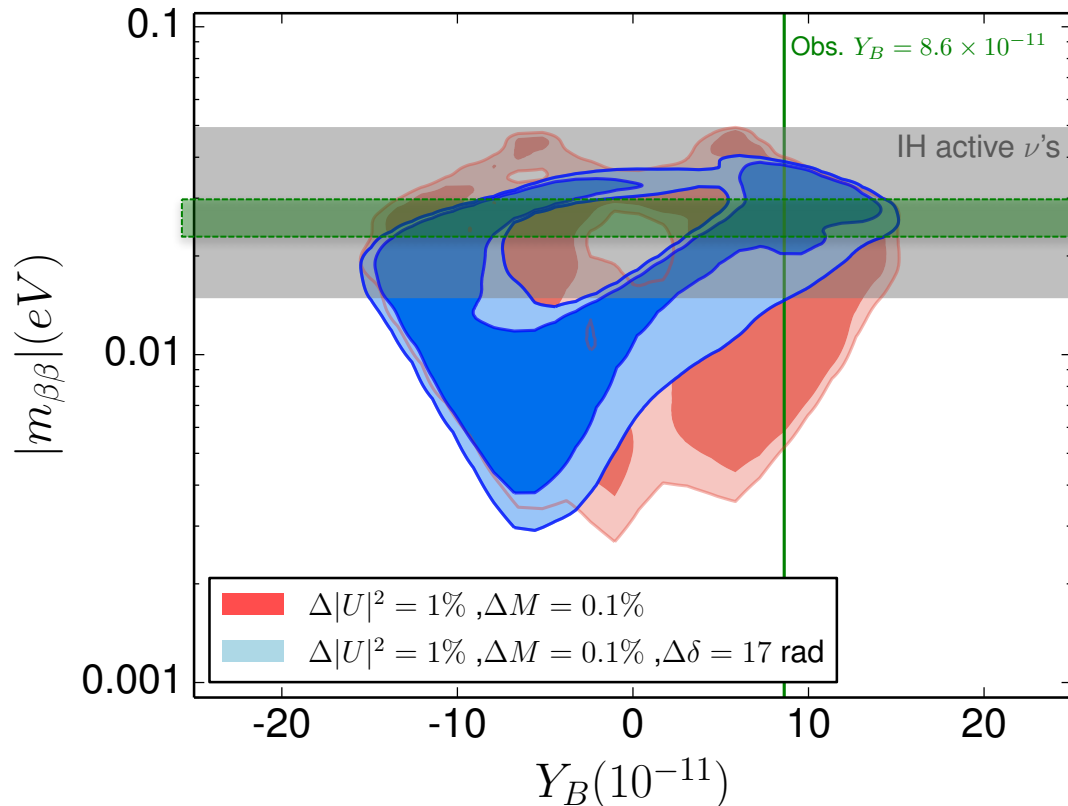
- Future neutrino oscillations:  $\delta$  phase in the  $U_{\text{PMNS}}$

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



PH, Kekic, Lopez-Pavon, Racker, Salvado

# Predicting $Y_B$ in the minimal seesaw model $M \sim \text{GeV}$

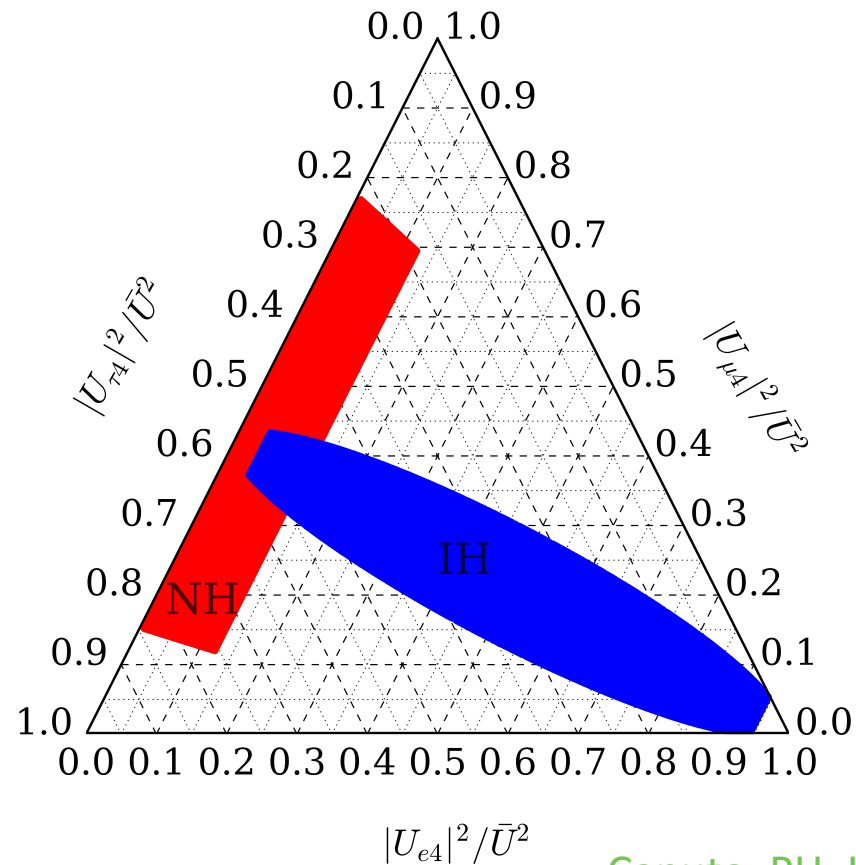


PH, Kekic, López-Pavón, Racker, Salvado

**The GeV-miracle:** the measurement of the mixing to  $e/\mu$  of the sterile states, neutrinoless double-beta decay and  $\delta$  in neutrino oscillations have a chance to give a prediction for  $Y_B$

The seesaw path to leptonic CP violation:

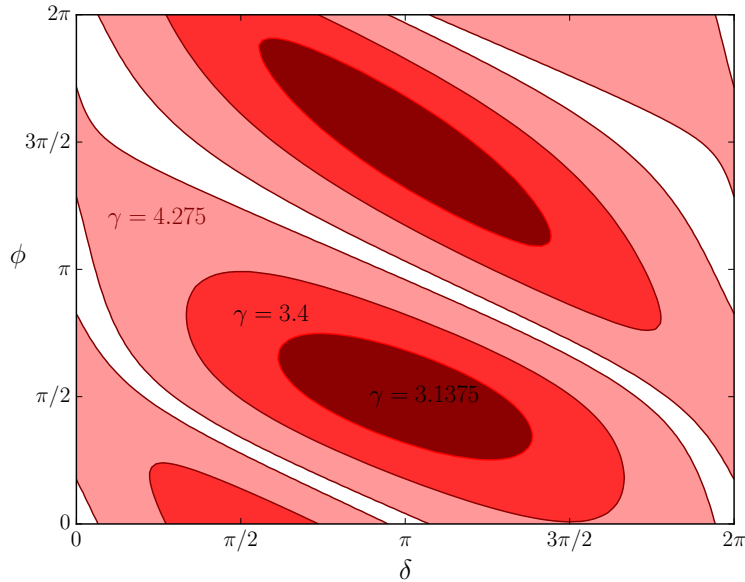
flavour ratios of heavy lepton mixings strongly correlated with ordering,  $U_{\text{PMNS}}$  matrix:  $\delta, \phi_1$



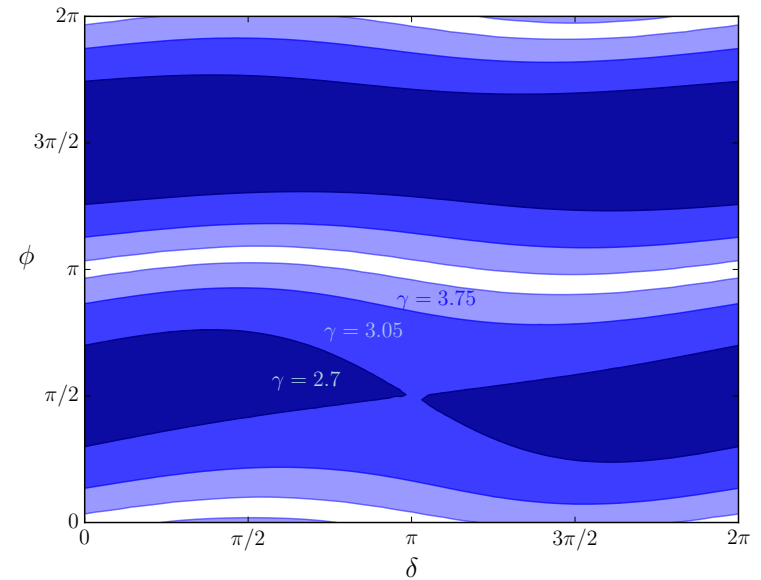
Caputo, PH, Lopez-Pavon, Salvado '17

# Leptonic CP violation $5\sigma$ CL discovery regions

Normal Hierarchy



Inverted Hierarchy

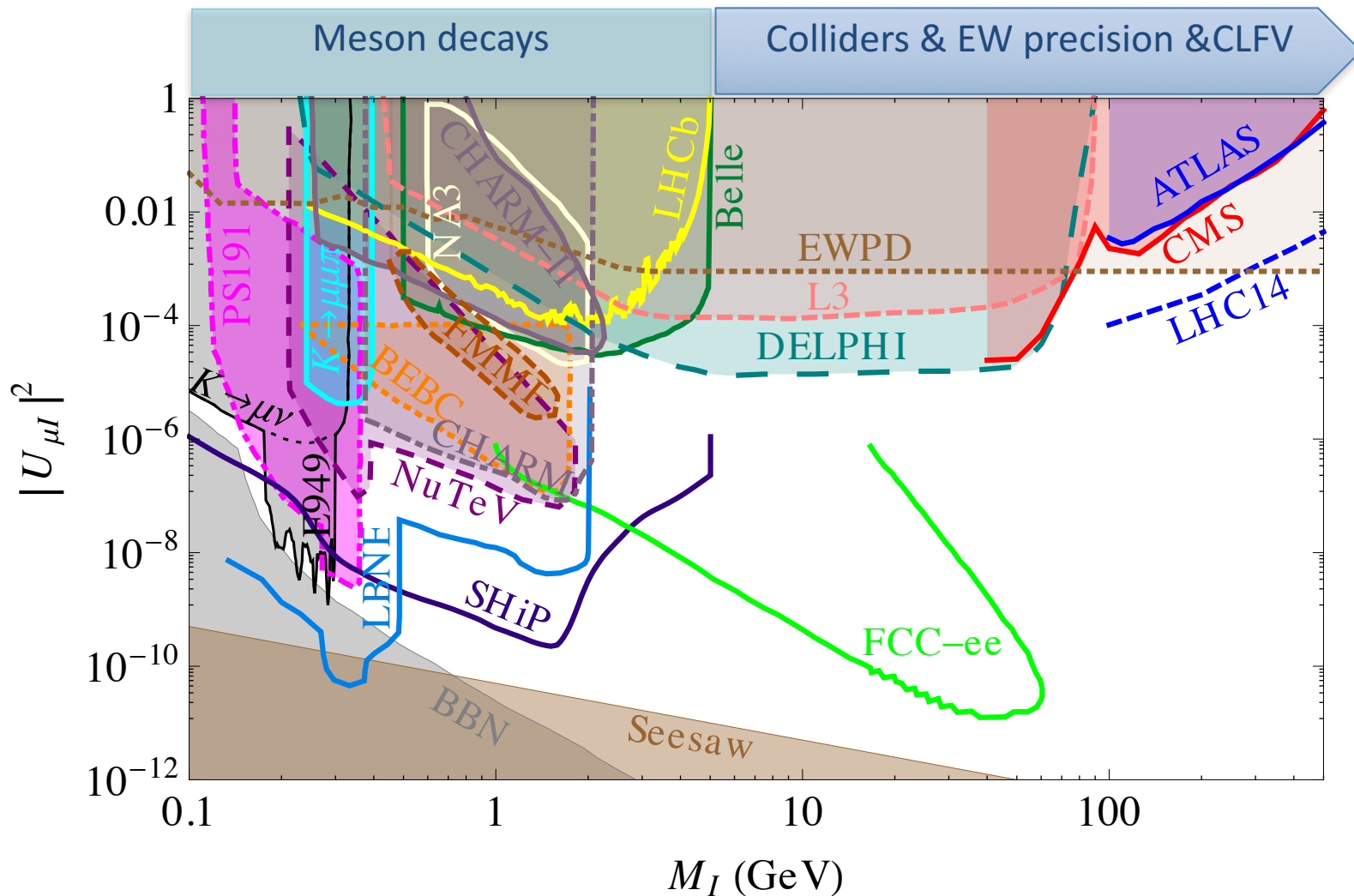


(no systematic error included)

$R_{\text{CP}} = 5\sigma$  CP-fraction =  
fraction of the area of the CP rectangle which is colored

# 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**:

eg: **cancellation between tree level and 1 loop contribution to neutrino masses**

- But also technically natural textures (inverse seesaw, direct seesaw, etc):

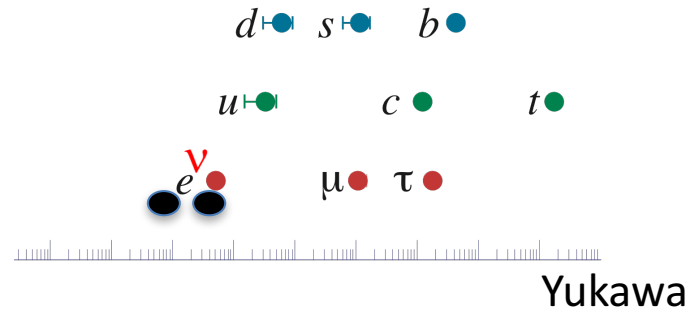
ex. **protected by an approximate global  $U(1)_L$**

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

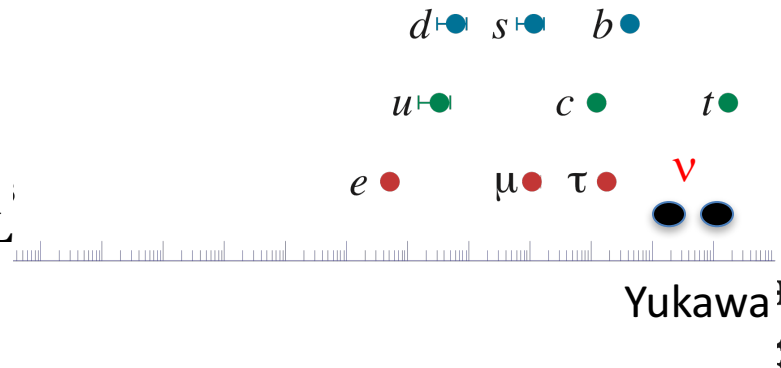
$$-\mathcal{L}_\nu \supset \bar{N}_1 M N_2^c + Y \bar{L} \tilde{\Phi} N_1 + h.c.$$

# Seesaw + approx $U(1)_L$

$$M_N = \text{TeV}$$



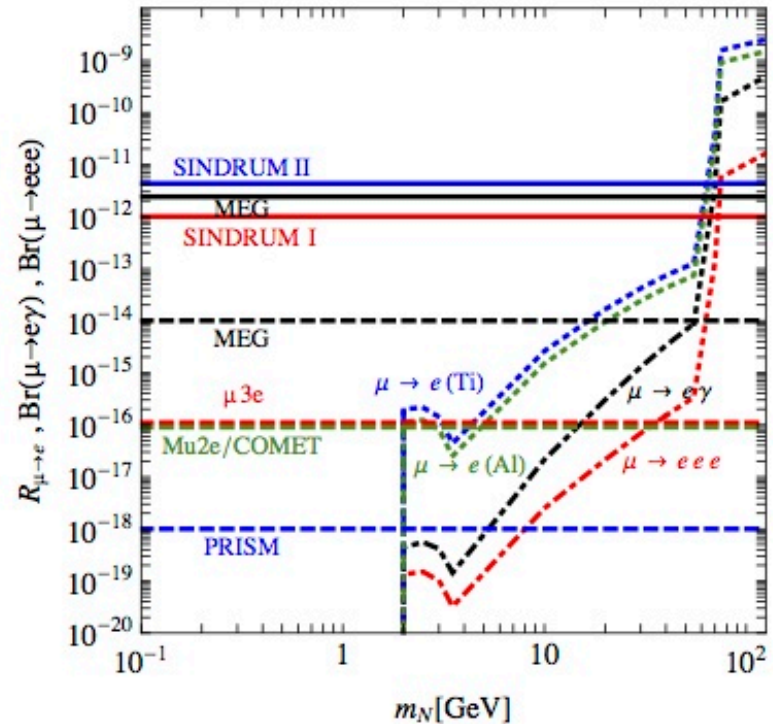
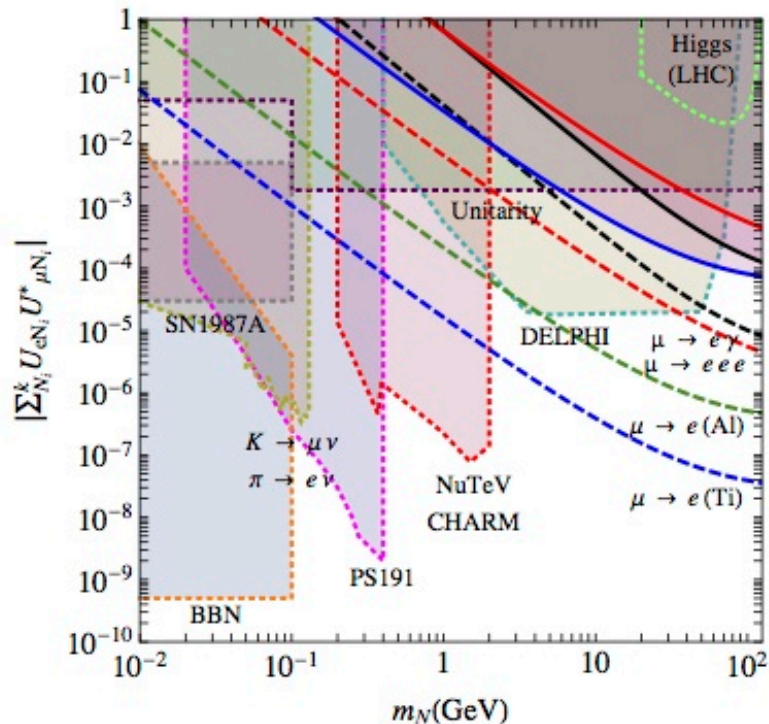
$$M_N \leq \text{TeV} + \text{aprox. } U(1)_L$$



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) (inverse seesaw, direct seesaw, etc)

$\mu \rightarrow e \gamma$      $\mu \rightarrow eee$      $\mu \rightarrow e$  conversion



recent analysis Alonso et al 2012

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

# Beyond the minimal model

Extra gauge interactions can enhance production

Examples: type I +  $W'$ ,  $Z'$ ,  
left-right symmetric models  
GUTs, etc

Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic;  
Ferrari et al + many recent refs...

# Model independent approach: EFT

$$\mathcal{L}_{BSM} = \mathcal{L}_{\text{mSS}} + \sum_{d,i} \frac{1}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

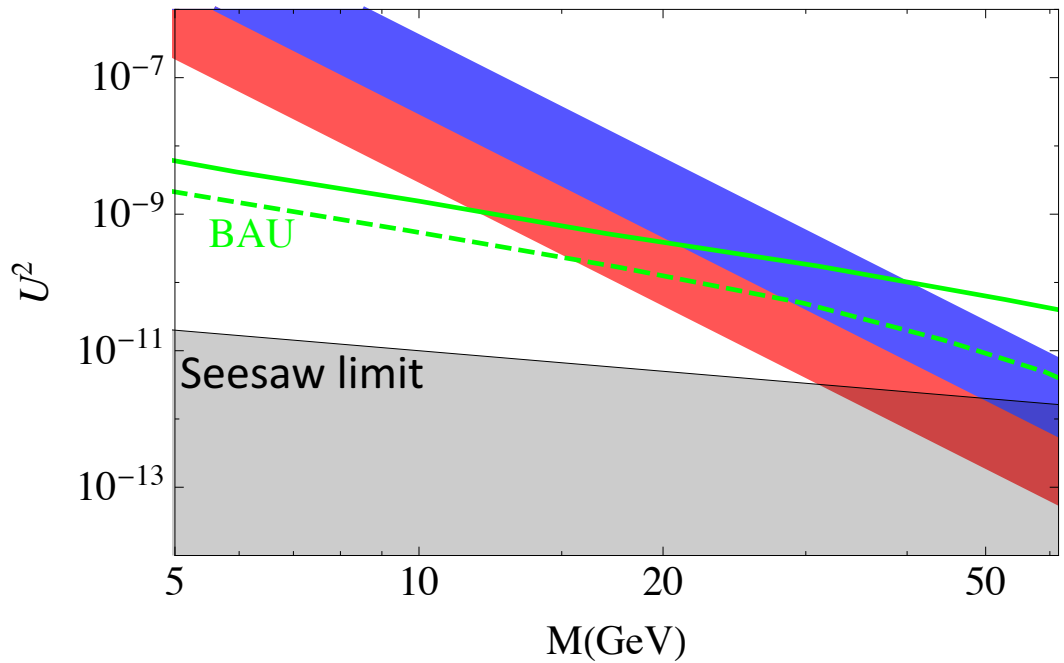
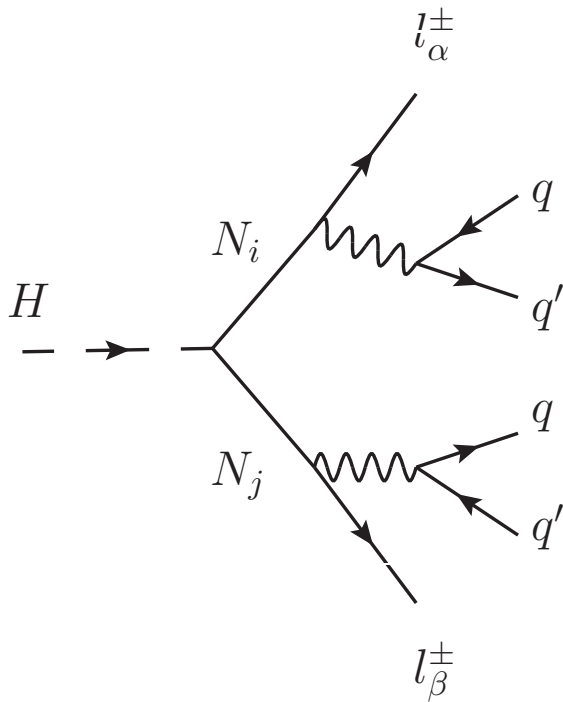
The **seesaw portal** to BSM:

**d=5**

$$\begin{aligned}\mathcal{O}_W &= \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \bar{L}_\alpha \tilde{\Phi} \Phi^\dagger L_\beta^c + h.c., \\ \mathcal{O}_{N\Phi} &= \sum_{i,j} \frac{(\alpha_{N\Phi})_{ij}}{\Lambda} \bar{N}_i N_j^c \Phi^\dagger \Phi + h.c., \\ \mathcal{O}_{NB} &= \sum_{i \neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \bar{N}_i \sigma_{\mu\nu} N_j^c B_{\mu\nu} + h.c.\end{aligned}$$

$\mathcal{O}_{N\Phi}$

could lead to spectacular signals at LHC/colliders of two displaced vertices from higgs decays (production independent of U)



Caputo, PH, LopezPavon, Salvado al '17

**LHC:  $300 \text{ fb}^{-1}$ , 13TeV**

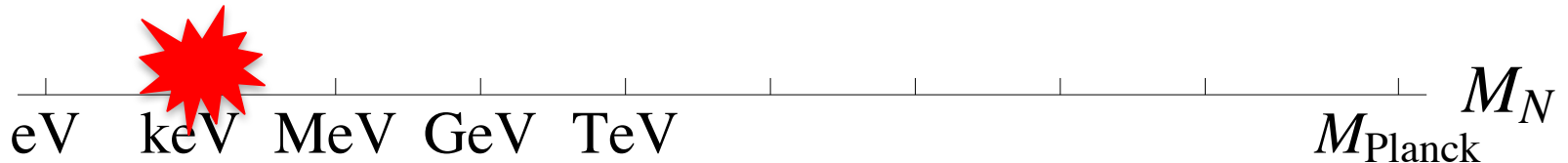
$$\left| \frac{\alpha_{N\Phi} v}{\sqrt{2} \Lambda} \right| \leq 10^{-3} - 10^{-2} \rightarrow \frac{\alpha_{N\Phi}}{\Lambda} \leq 6 \times (10^{-3} - 10^{-2}) \text{TeV}^{-1}.$$

# Conclusions

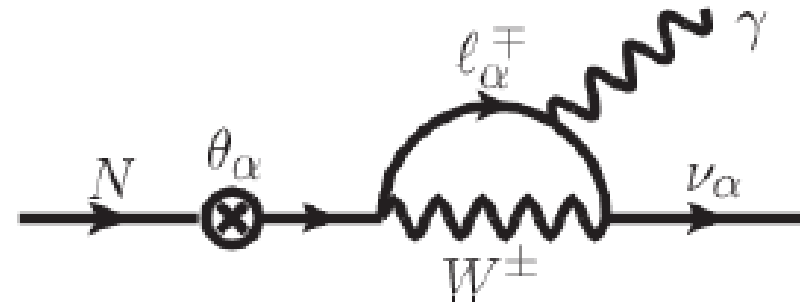
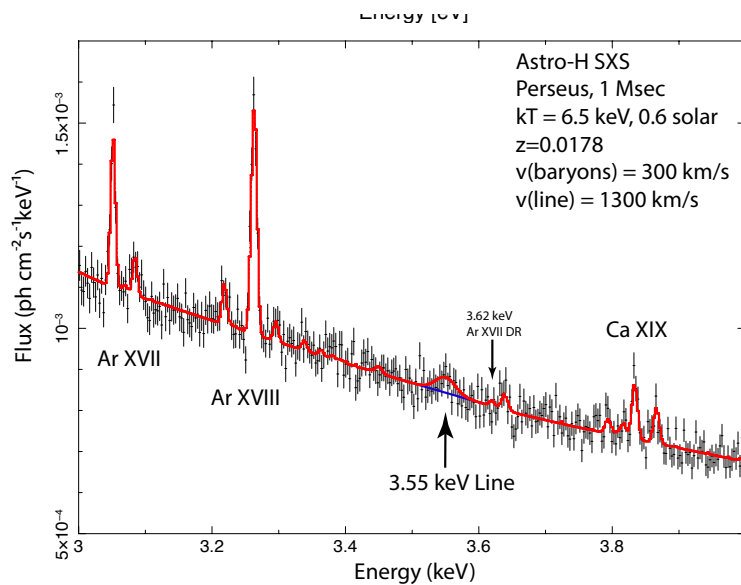
- The results of many beautiful experiments have demonstrated that  $\nu$  are (for the time-being) the less standard of the SM particles
- Many fundamental questions remain to be answered however:  
Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ?  
Lepton vs quark flavour ?
- Complementarity of different experimental approaches:  $\beta\beta\nu$ , 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  $\Lambda$  (GeV scale very interesting)

$$\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + \text{h.c.} \\
& + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\
& + |D_\mu \phi|^2 - V(\phi) \\
& + \mathcal{L}_v
\end{aligned}$$

# $\nu$ MSM: Warm Dark Matter ?



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



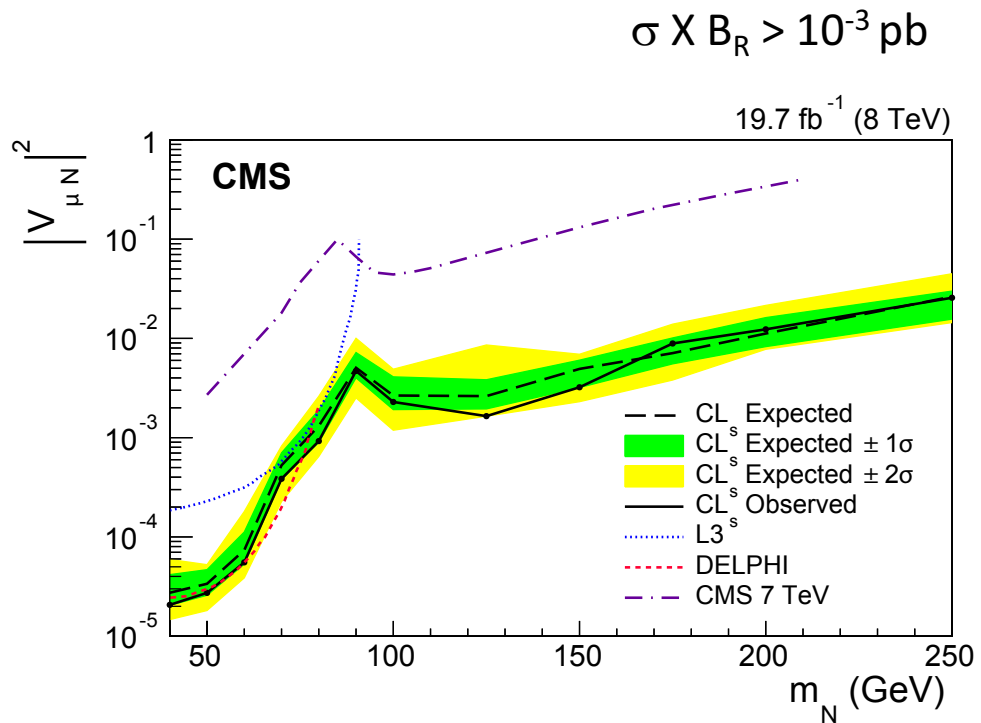
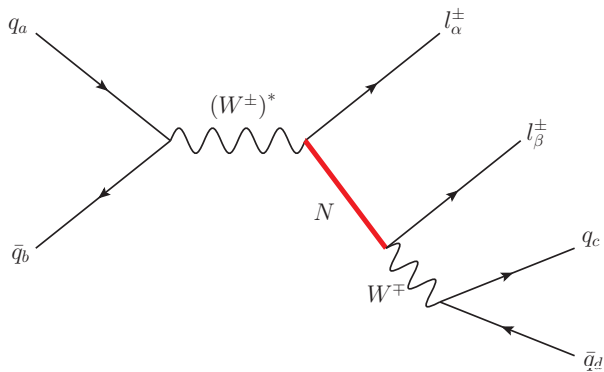
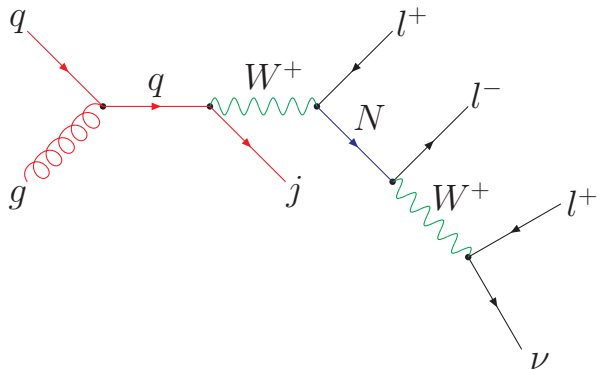
$$E_\gamma = \frac{M_N}{2}$$

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

Bulbul et al 1402.2301; Boyarsky 1402.4119

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

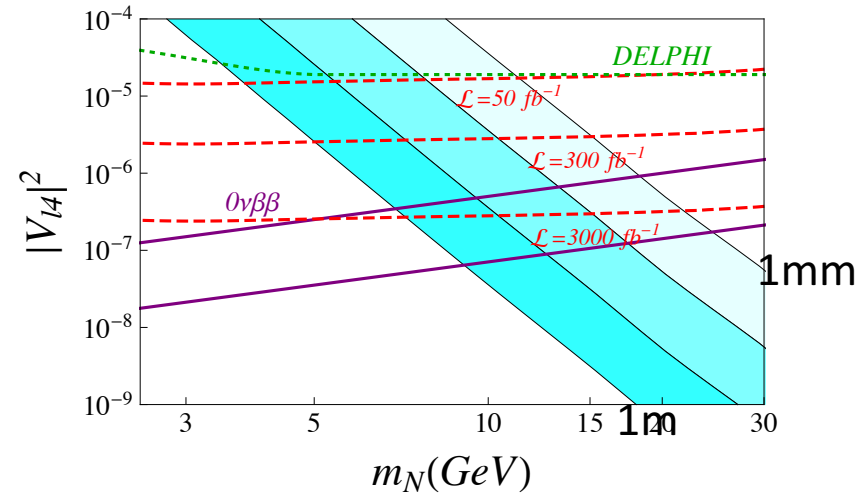
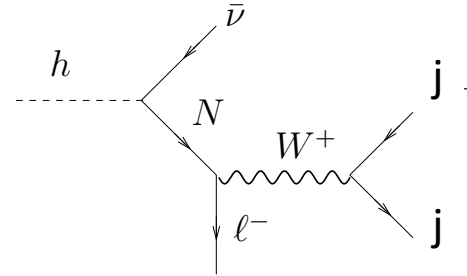
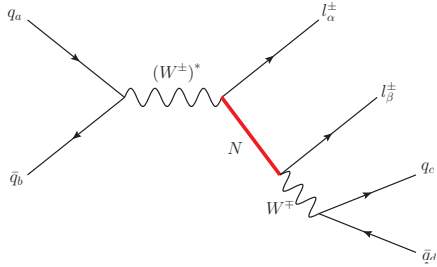
# Standard LHC Searches



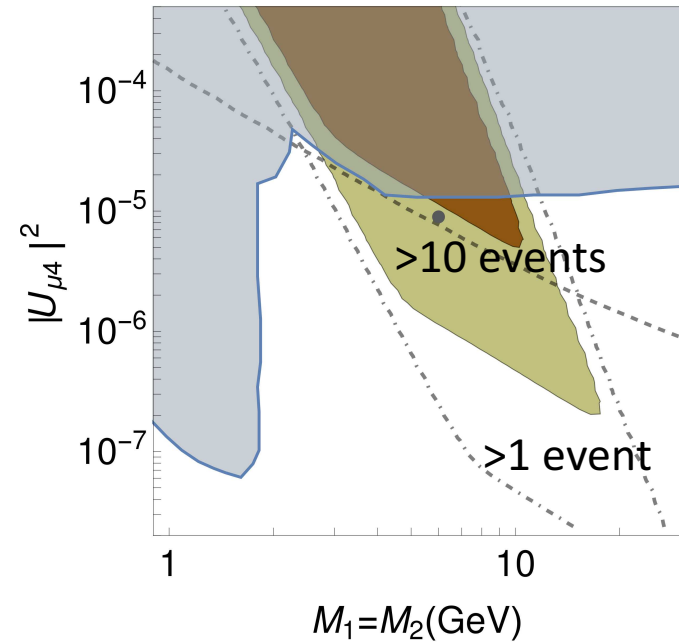
CMS 1501.05566

ATLAS 1506.06020

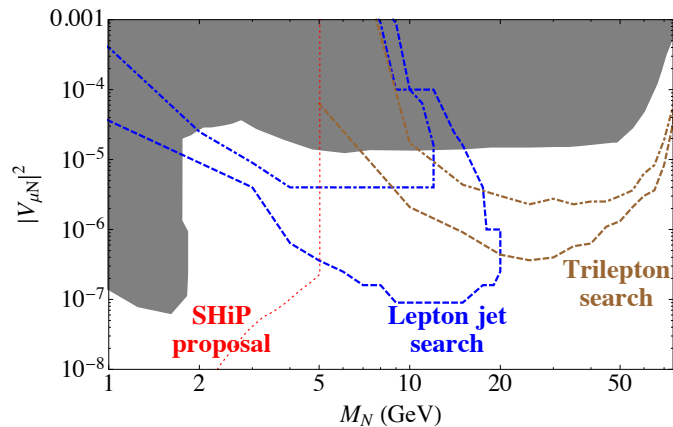
# Low-mass $m_N < m_W$ : Displaced Vertices



Helo, Kovalenko, Hirsch



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

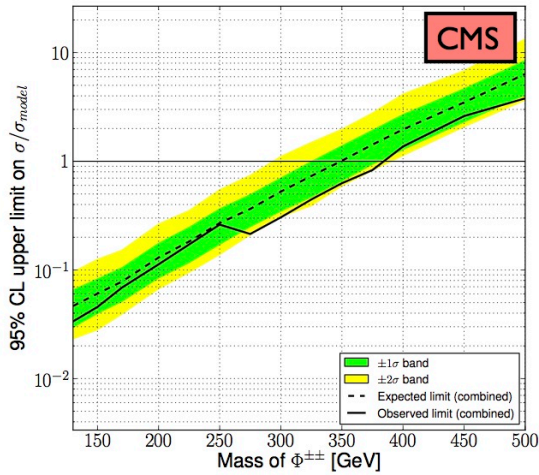


Izaguirre, Shuve

# pp-> H<sup>++</sup> H<sup>--</sup> -> l<sup>+</sup>l<sup>+</sup>l<sup>-</sup>l<sup>-</sup>

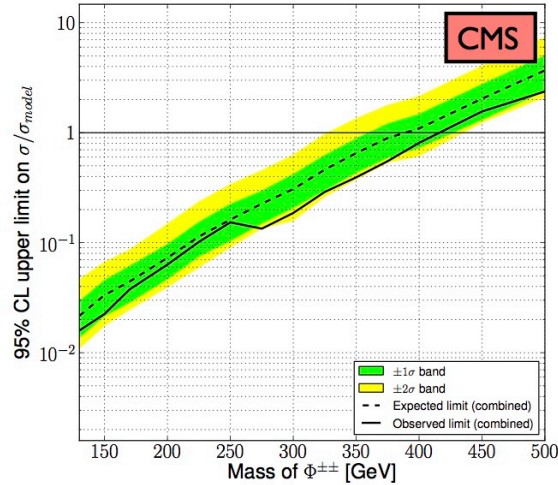
## Normal hierarchy

Normal hierarchy: BP1  
CMS  $\sqrt{s} = 7$  TeV,  $\int \mathcal{L} dt = 4.9$  fb<sup>-1</sup>



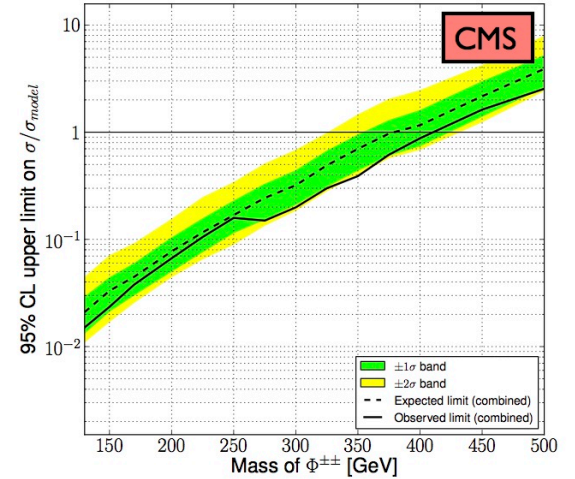
## Inverted hierarchy

Inverse hierarchy: BP2  
CMS  $\sqrt{s} = 7$  TeV,  $\int \mathcal{L} dt = 4.9$  fb<sup>-1</sup>

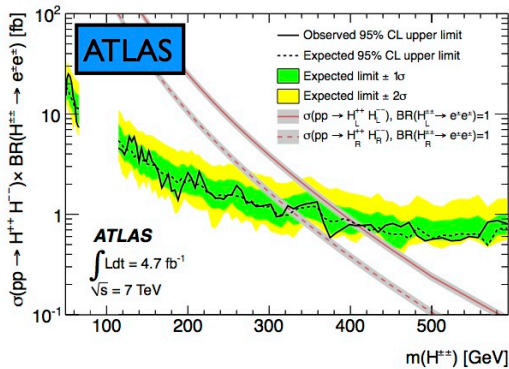


## Degenerate v

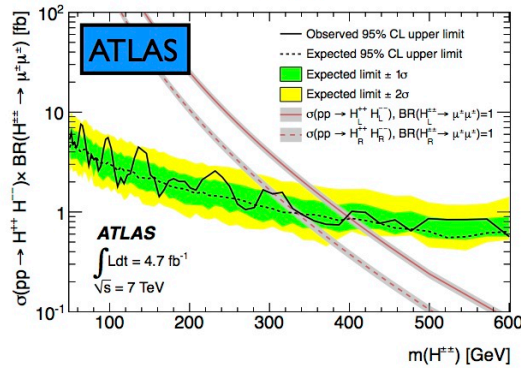
Degenerate masses: BP3  
CMS  $\sqrt{s} = 7$  TeV,  $\int \mathcal{L} dt = 4.9$  fb<sup>-1</sup>



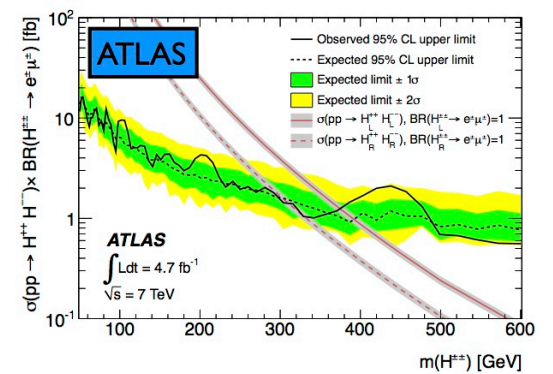
## Br(ee)=1



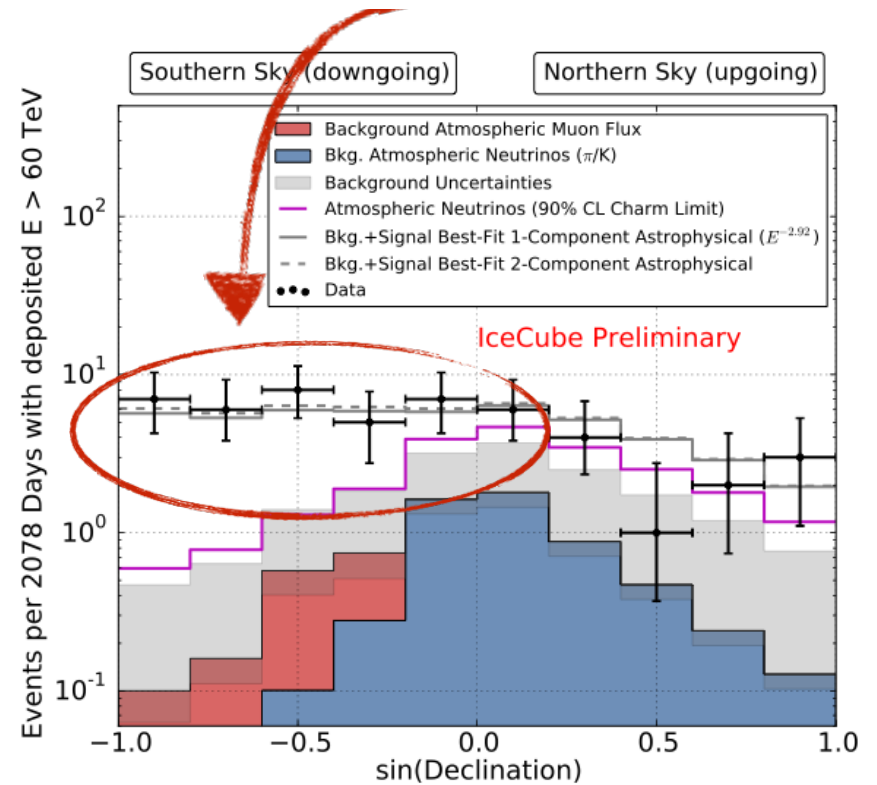
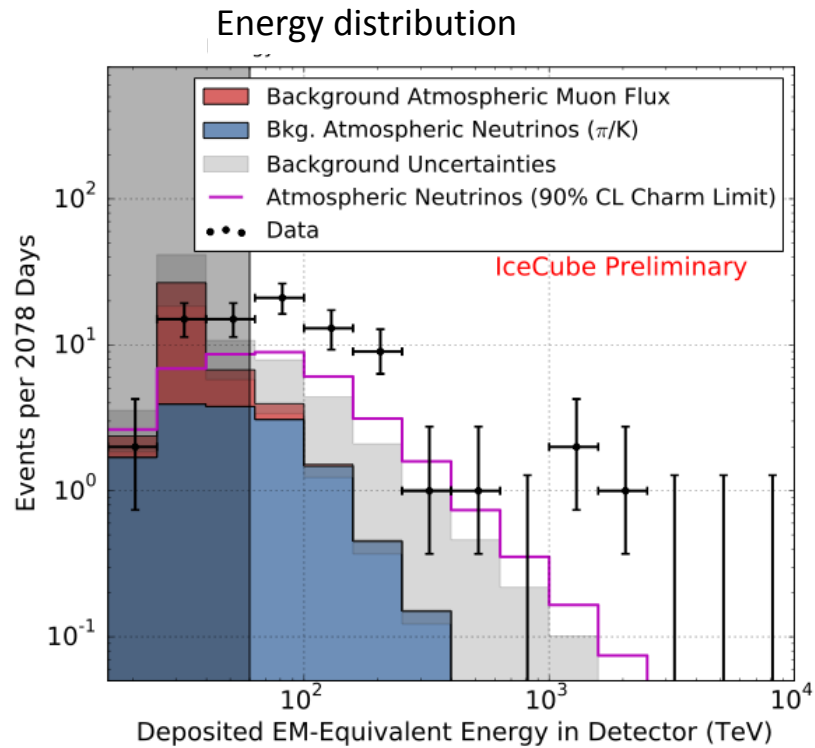
## Br(mu mu)=1



## Br(e mu)=1



# Origin still unknown...



82 events/41 expected