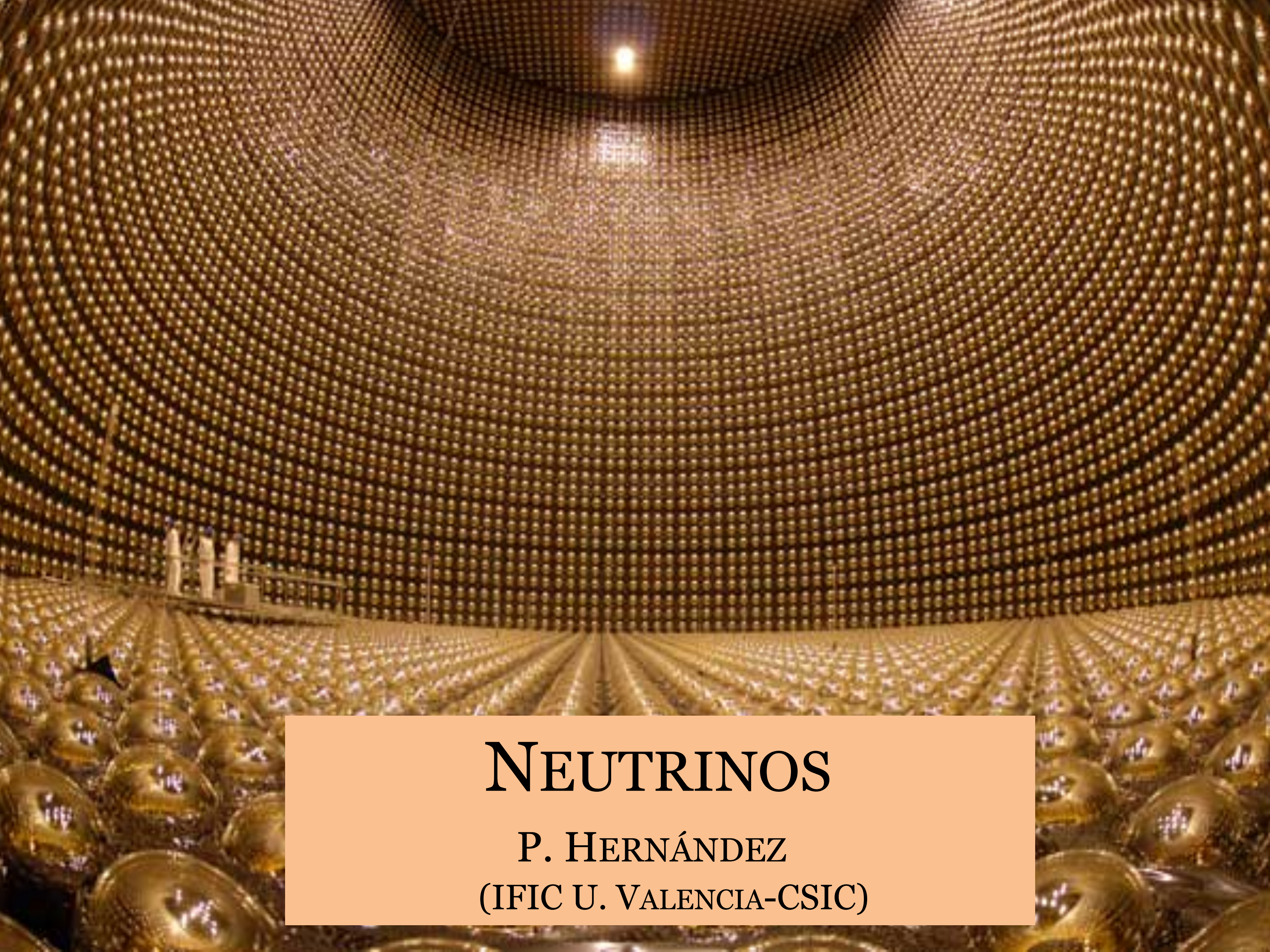


NEUTRINOS

P. HERNÁNDEZ
(IFIC U. VALENCIA-CSIC)

LECTURE II

- The standard 3ν scenario and its unknowns: status and prospects

- Neutrinos and beyond the Standard Model physics

Standard 3ν scenario

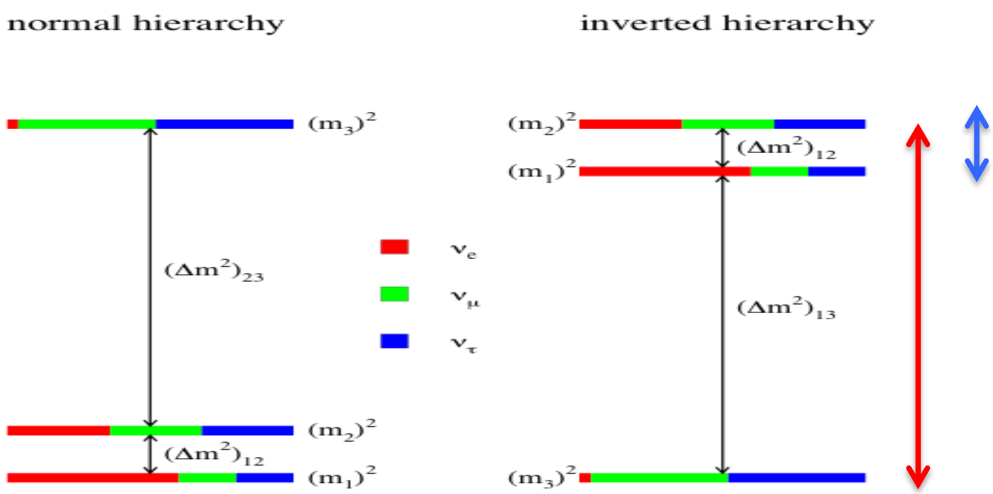
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$\theta_{23} \sim 42^\circ$ o 48°

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

$\delta \sim \ ?$

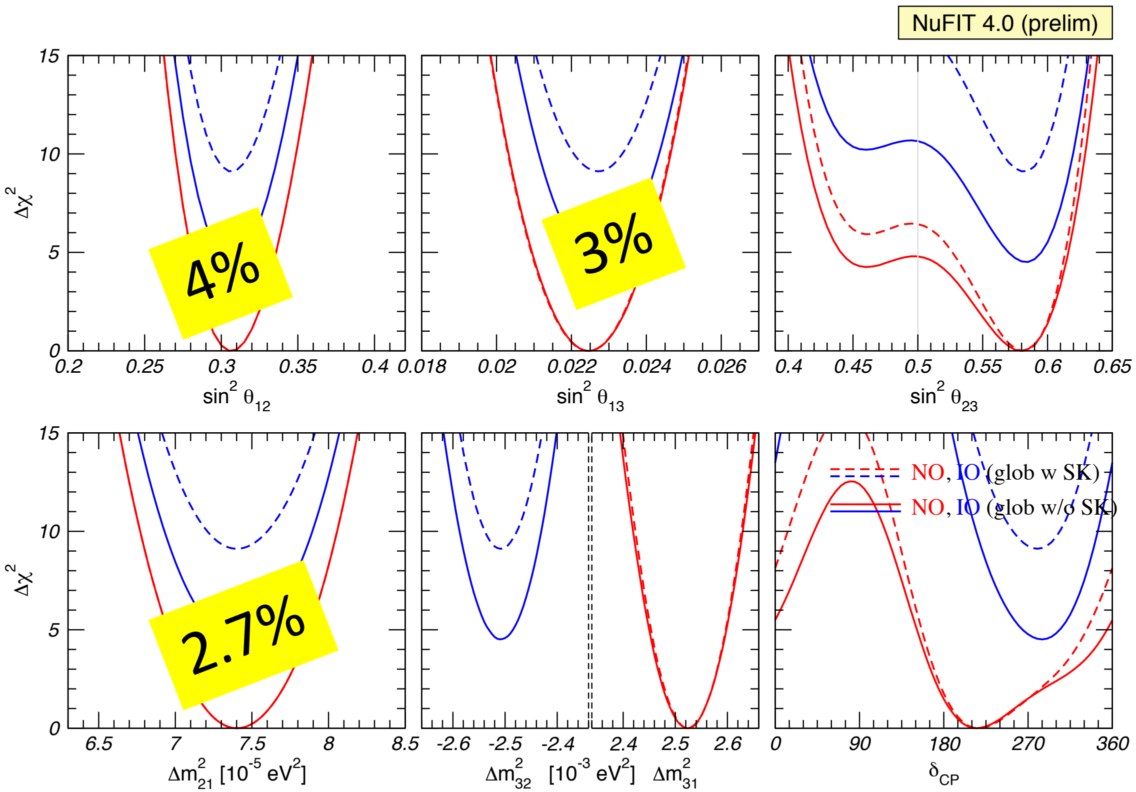


$7.5 \cdot 10^{-5} \mathrm{eV}^2$

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

SM+3 massive neutrinos: Global Fits

+T2K '18 +NoVA '18+ Daya Bay '18 + RENO '18 (+ SK '18 χ^2 table)



Esteban, González-García, Hernández-Gabezudo, Maltoni, Schwetz '18

(see also Cappozzi et al '18, de Salas et al '18)

The big open questions

What is the neutrino ordering normal or inverted ?

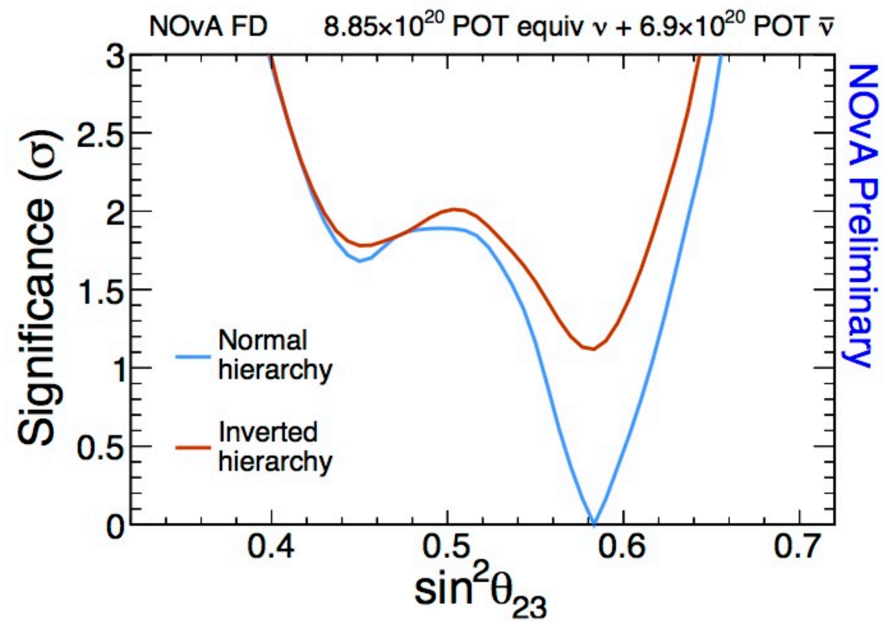
Is there leptonic CP violation ?

Absolute mass scale: minimum m_ν

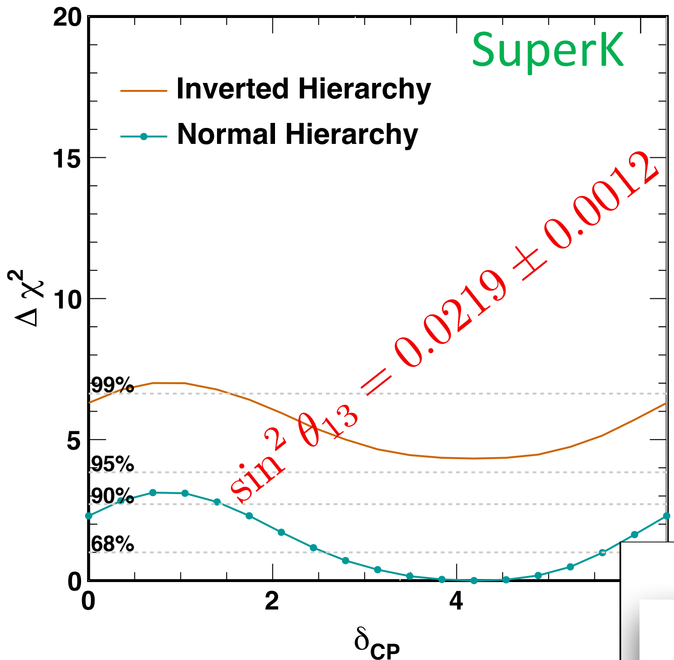
Are neutrinos Majorana and if so, what new physics lies behind this fact ?

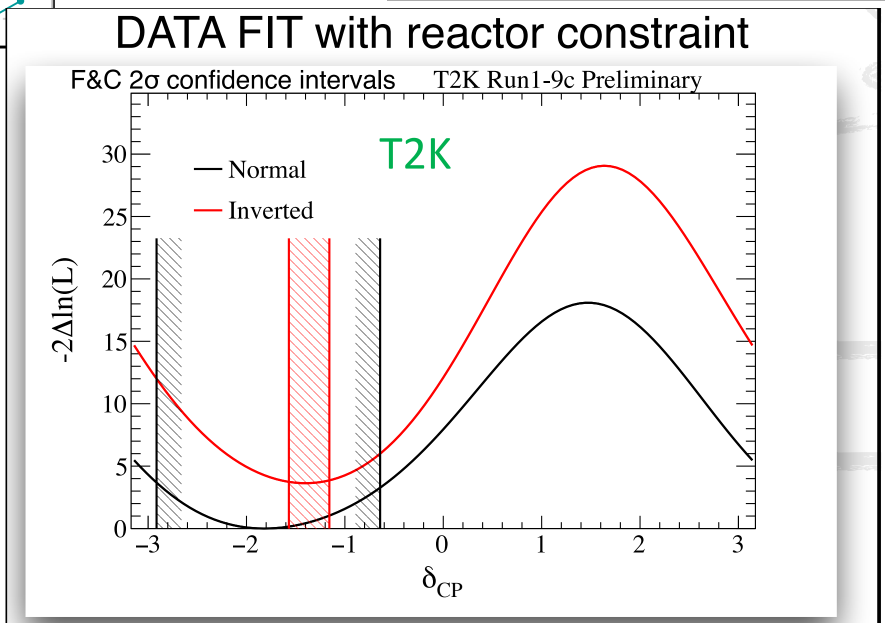
2018 2σ-vews

2σ hint of octant



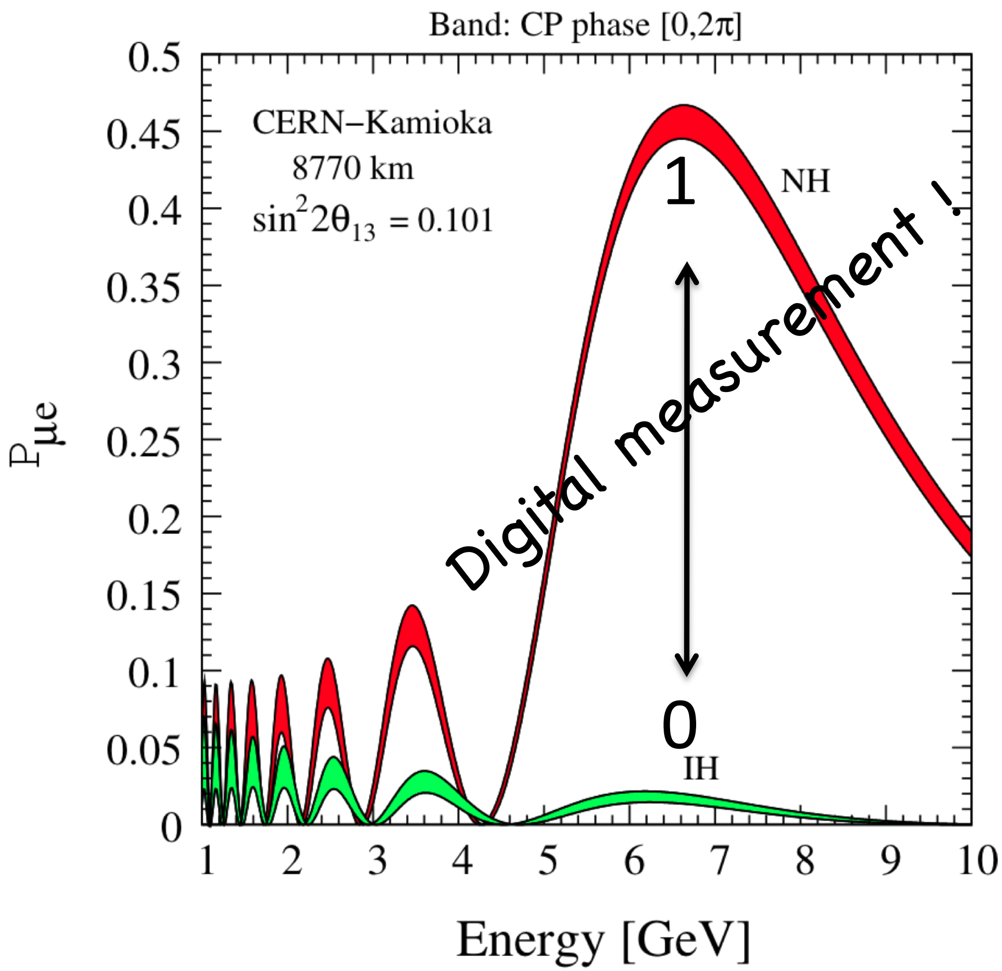
2σ hint for NO





2σ hint of CP violation

Hierarchy through MSW @Earth



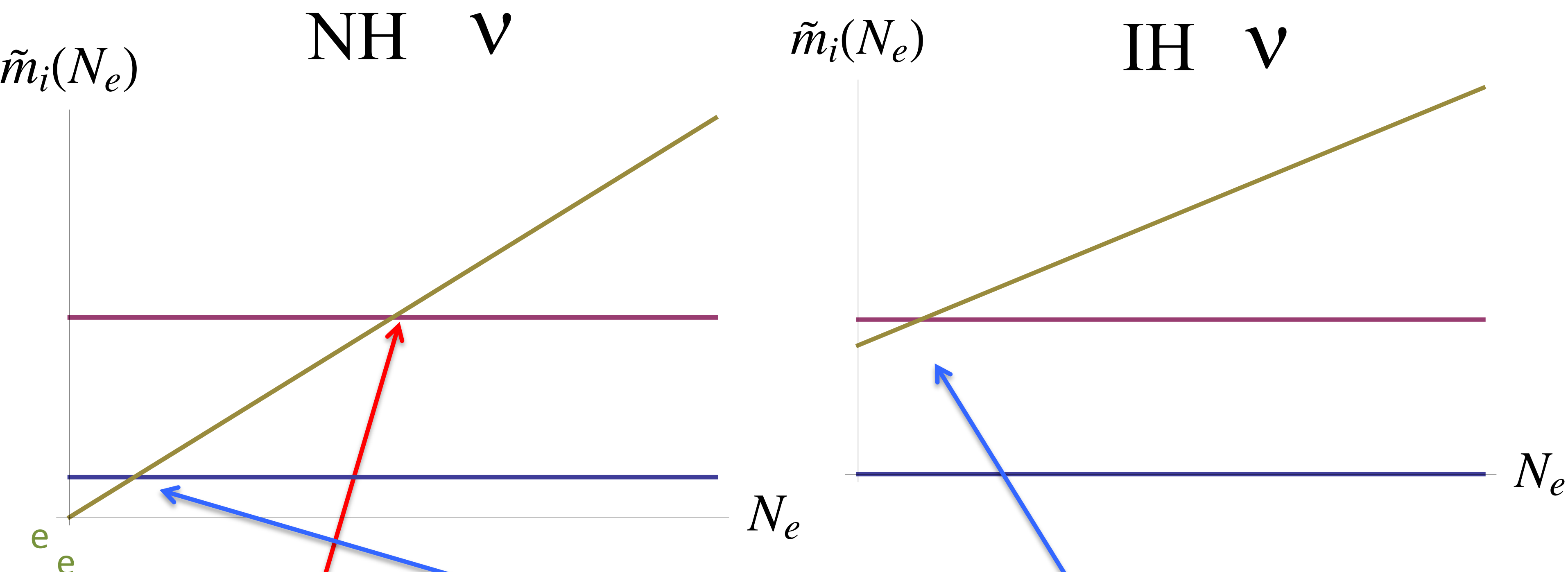
$$E_{\rm res} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F n_e},$$

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

Spectacular MSW effect at O(6GeV) and very long baselines: no need for spectral info nor two channels

Mikheev, Smirnov; Wolfenstein

Neutrino ordering from MSW



Atmospheric resonance

Solar resonance

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

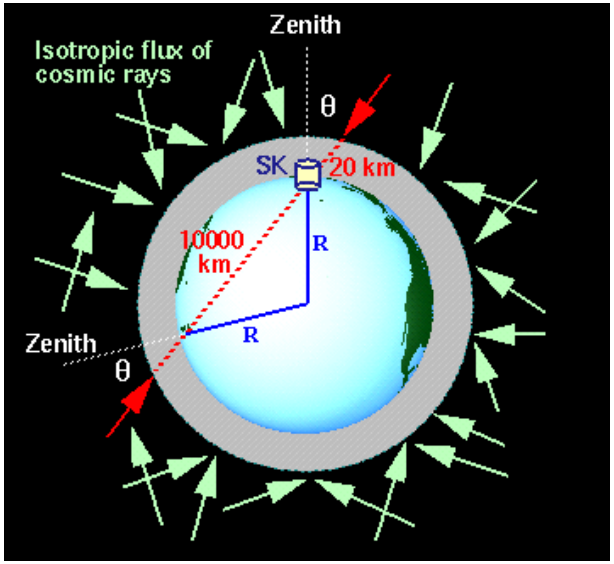
Earth density, E_{res} ~ few GeV !

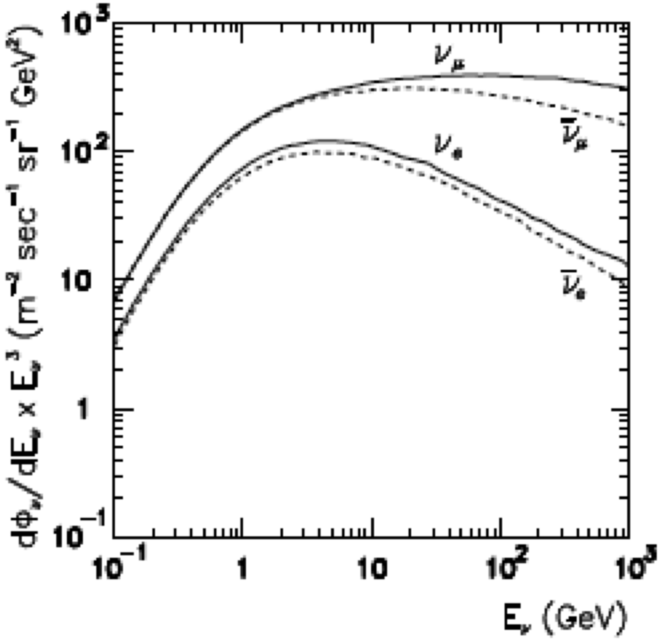
$$\Delta m^2_{12} \cos 2\theta_{12} = 2\sqrt{2} G_F E N_e$$

Solar density, E_{res} ~ few MeV !

Hierarchy from atmospherics ? the hard way…

$$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$$



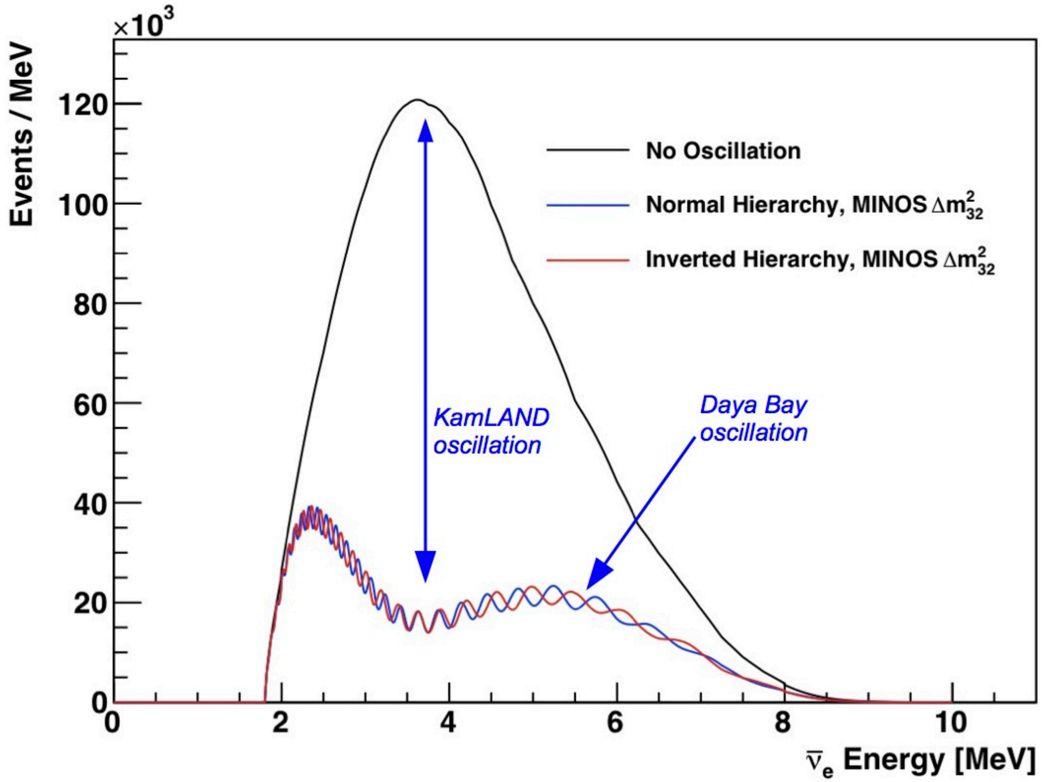


Atmospheric data contain the golden signal but hard to dig…
neutrino telescopes (PINGU, ORCA) or improved atmospheric detectors (HyperK, INO)

Hierarchy from reactor ν's

Petcov, Piai; Choubey et al; Learned et al

L = 50 km



JUNO experiment is planning to do this measurement

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:

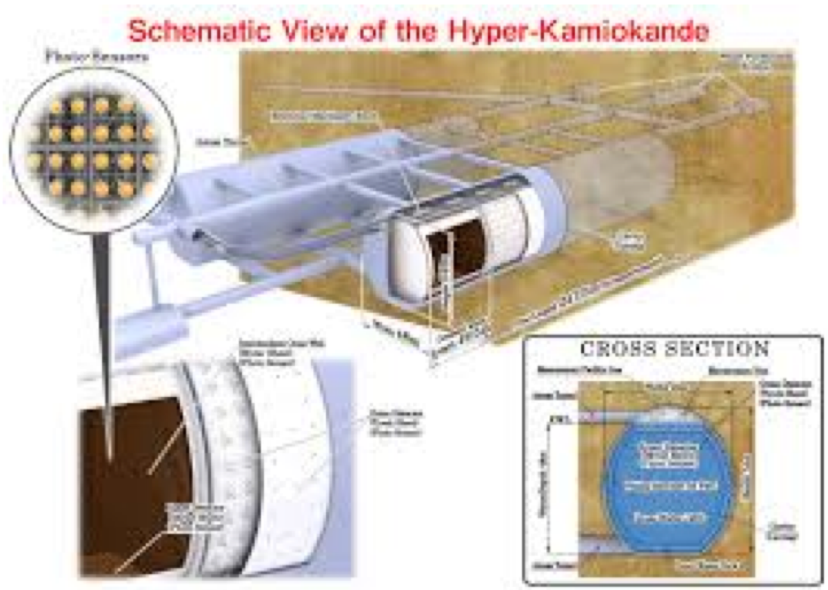
$$\begin{aligned} P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23} L}{2}\right) && \equiv P^{atmos} \\ &+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) && \equiv P^{solar} \\ +\tilde{J} &\cos\left(\pm\delta - \frac{\Delta_{23}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

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

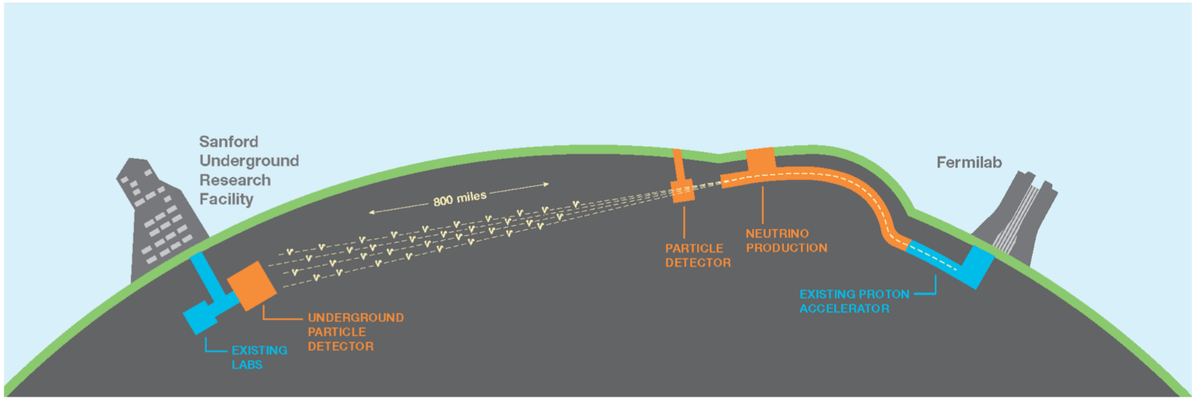
simultaneous sensitivity to both splittings is needed

Hierarchy + CP in one go…
superbeams+superdectectors

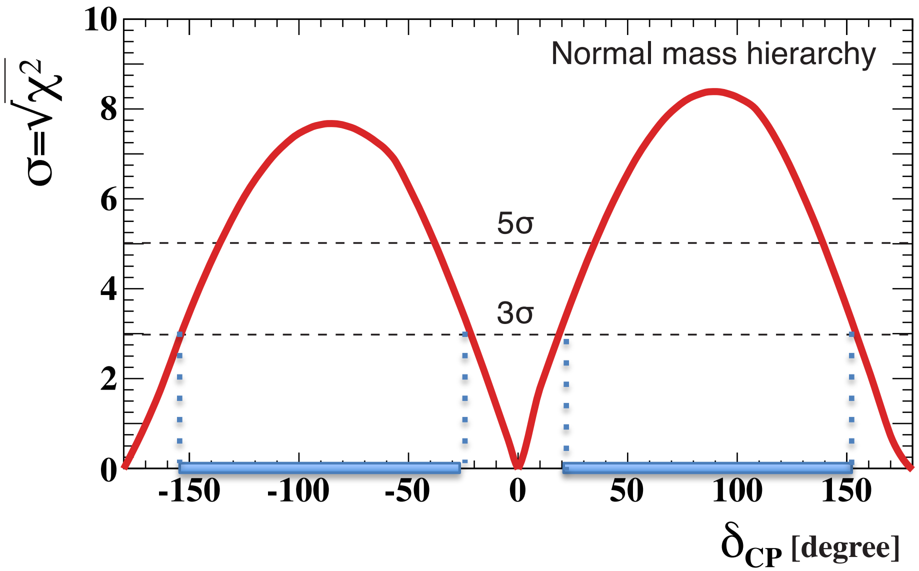
Japan Hyper-Kamiokande: 230km



USA DUNE: 1300km



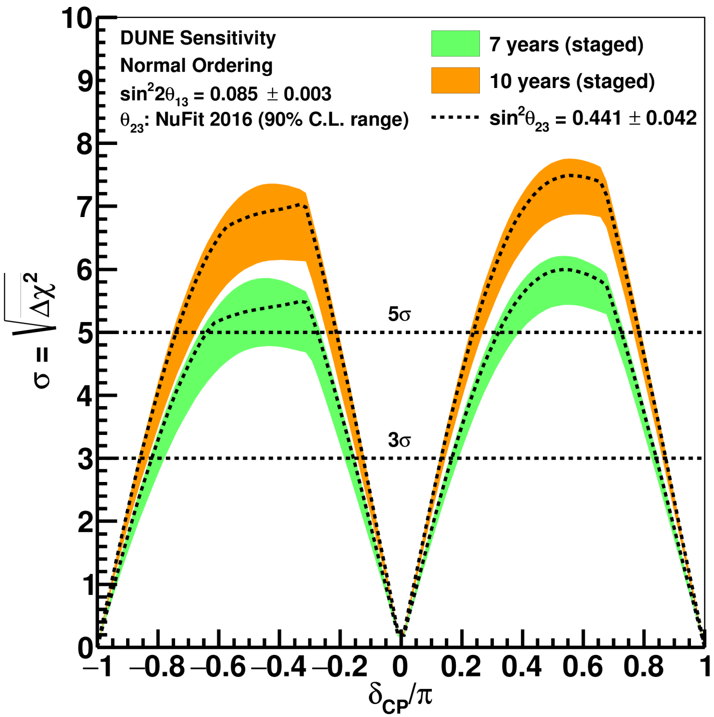
Hierarchy + CP in one go...
superbeams+superdectectors



Hyper Kamiokande (10y)

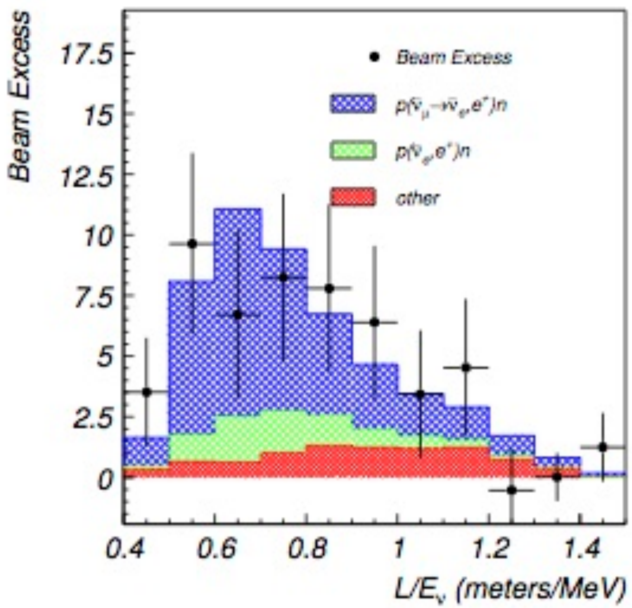
DUNE CDR:

CP Violation

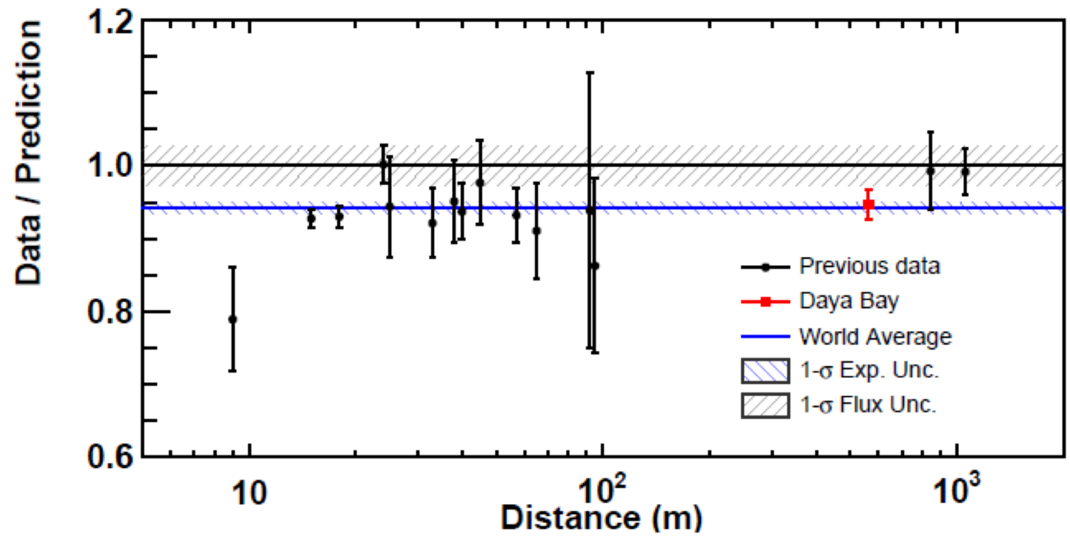


Outliers: SBL anomalies

LSND

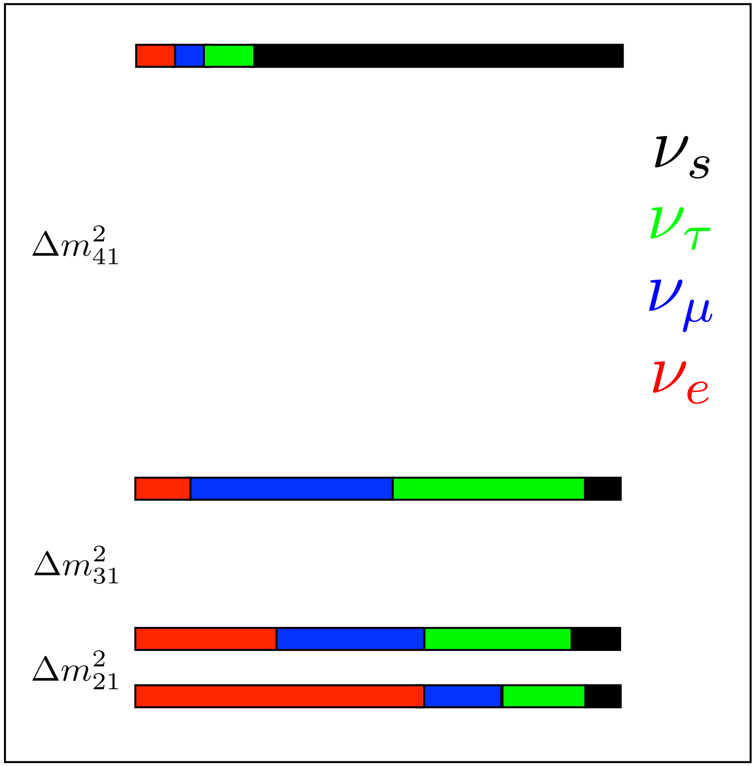


Reactors



+Gallium anomaly...

SBL anomalies: 4th neutrino ?



$P(\nu_\mu \rightarrow \nu_e) = O(|U_{e4}|^2 \, |U_{\mu 4}|^2)$

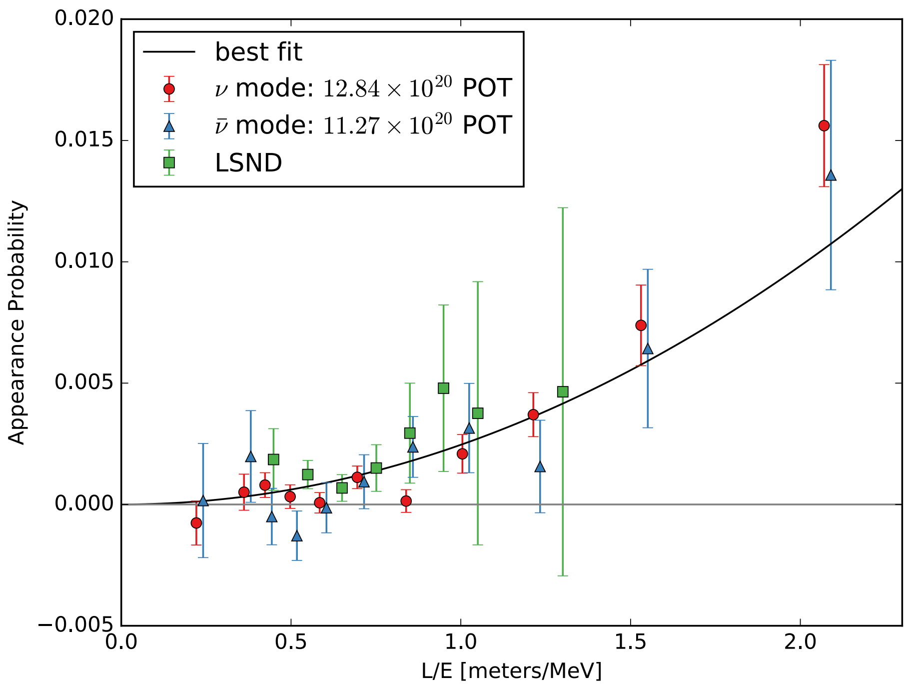
$P(\nu_e \rightarrow \nu_e) = O(|U_{e4}|^2)$

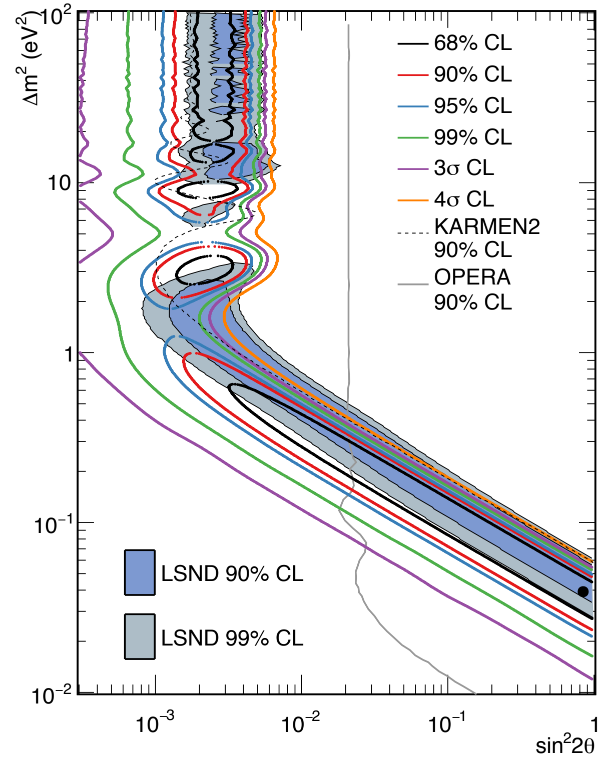
$P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu 4}|^2)$

Oscillations at @meters for MeV neutrinos

2018 SBL Anomaly Vews

MiniBOONE +LSND excess



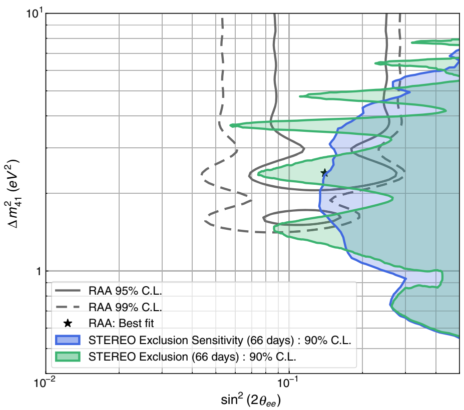


6σ discrepancy with SM !

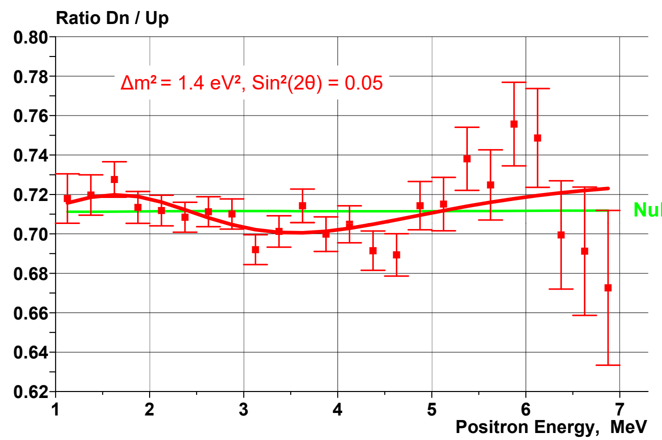
2018 SBL Anomaly Vews

New SBL reactor strategies: L-dep of signal

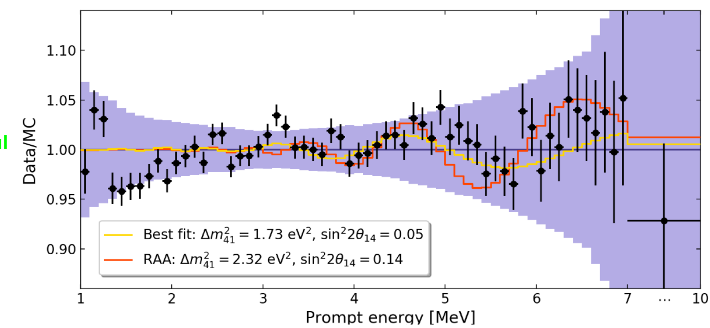
Stereo



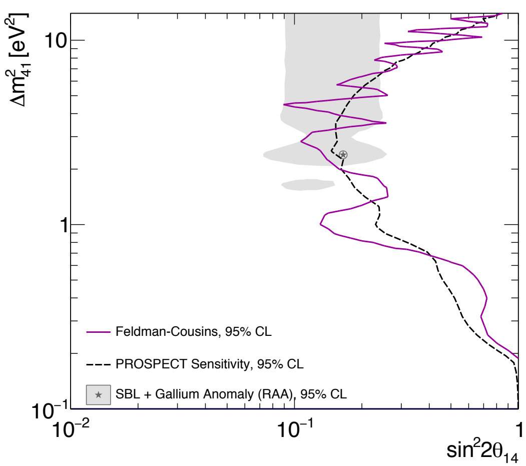
DANSS



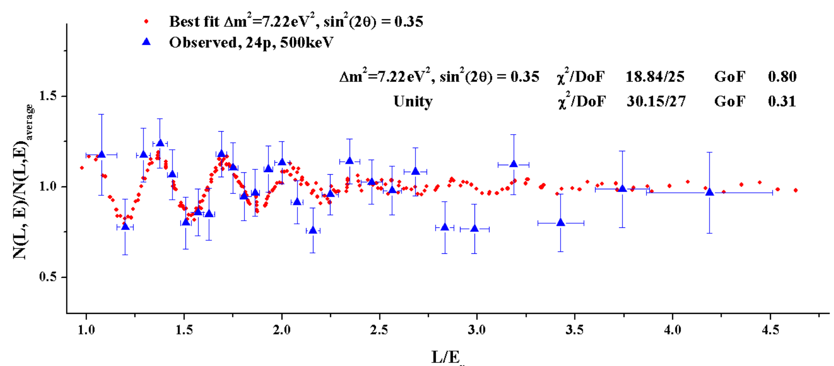
NEOS



Prospect



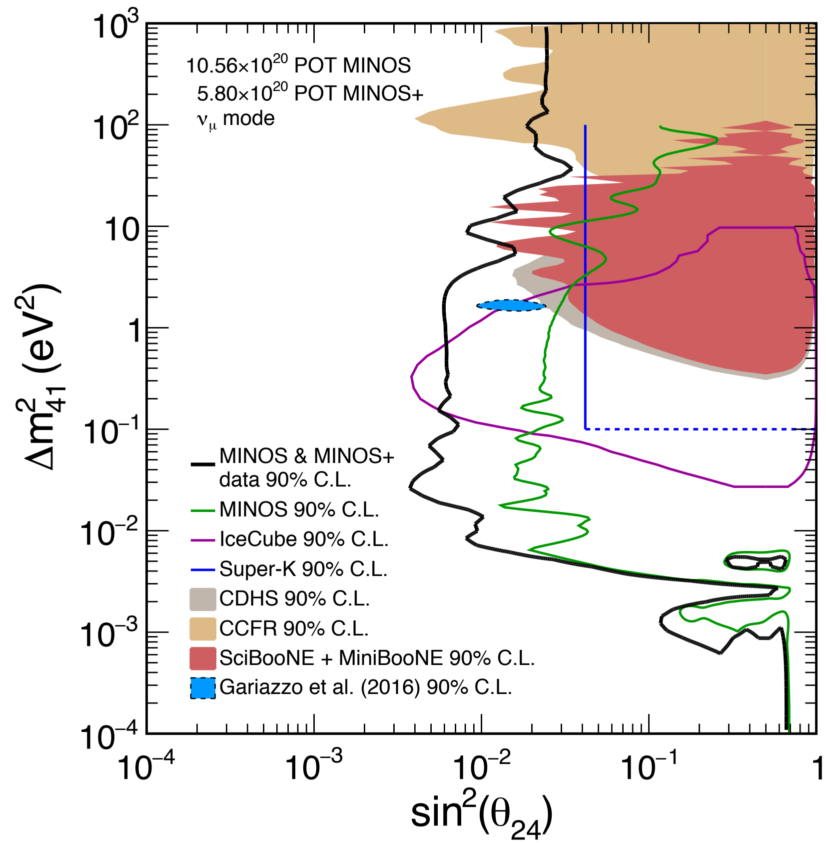
NEUTRINO-4



O(eV) sterile neutrinos ?

No evidence for the involvement of muons:

1) Neutrino muons must disappear also but they don't   Minos, Minos+

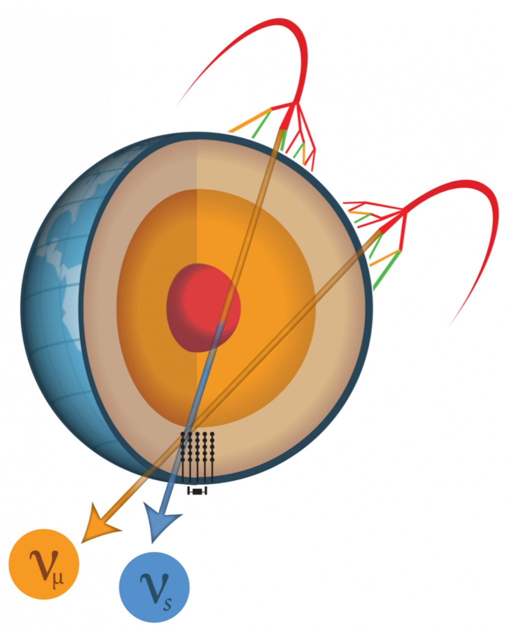


O(eV) sterile neutrinos ?

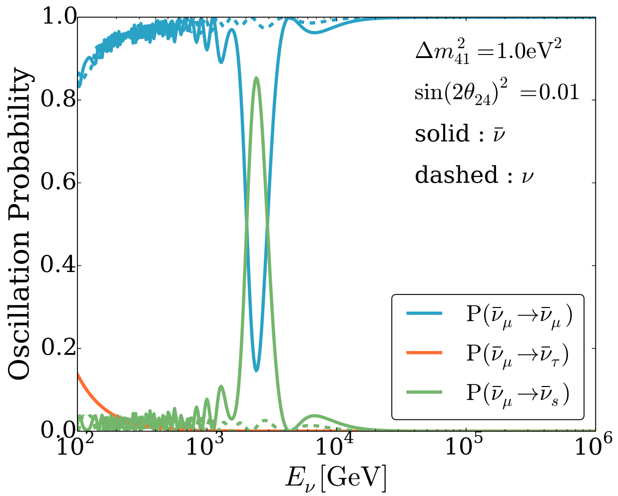
No evidence for the involvement of muons:

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

Icecube

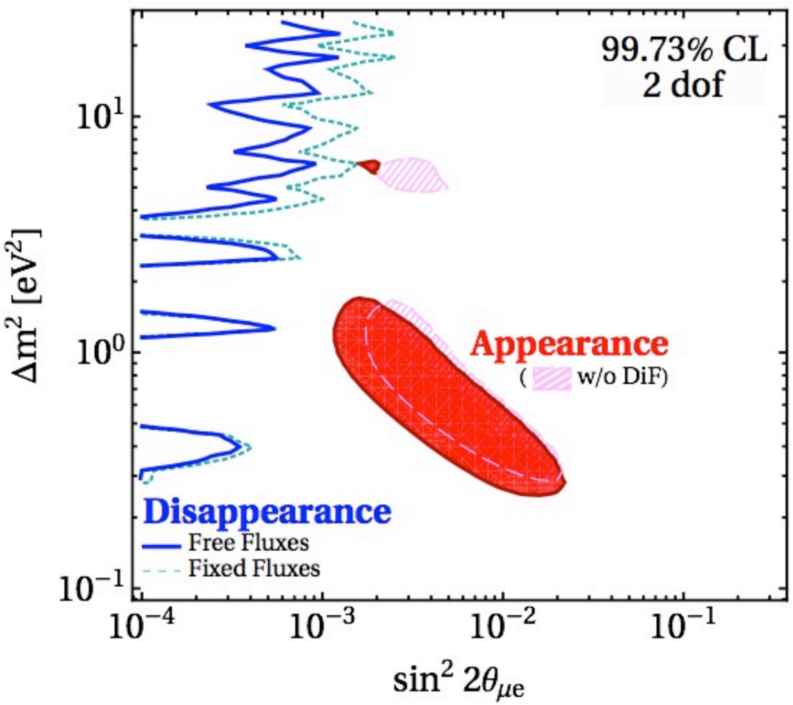


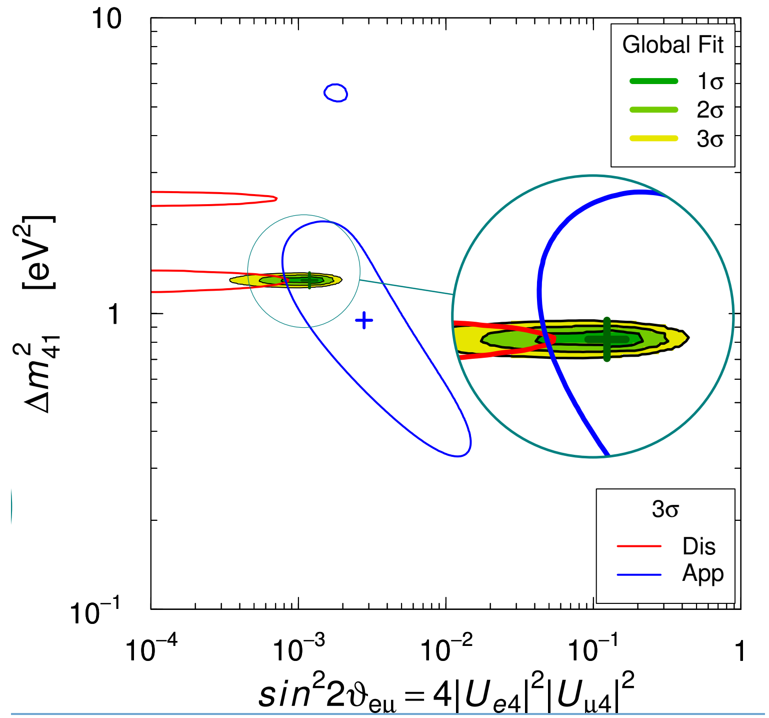
$$E_\nu^{\rm res} \equiv \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N_e} \sim \mathcal{O}(TeV)$$



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

O(eV) 4th neutrino is not a good fit
(all things considered...)



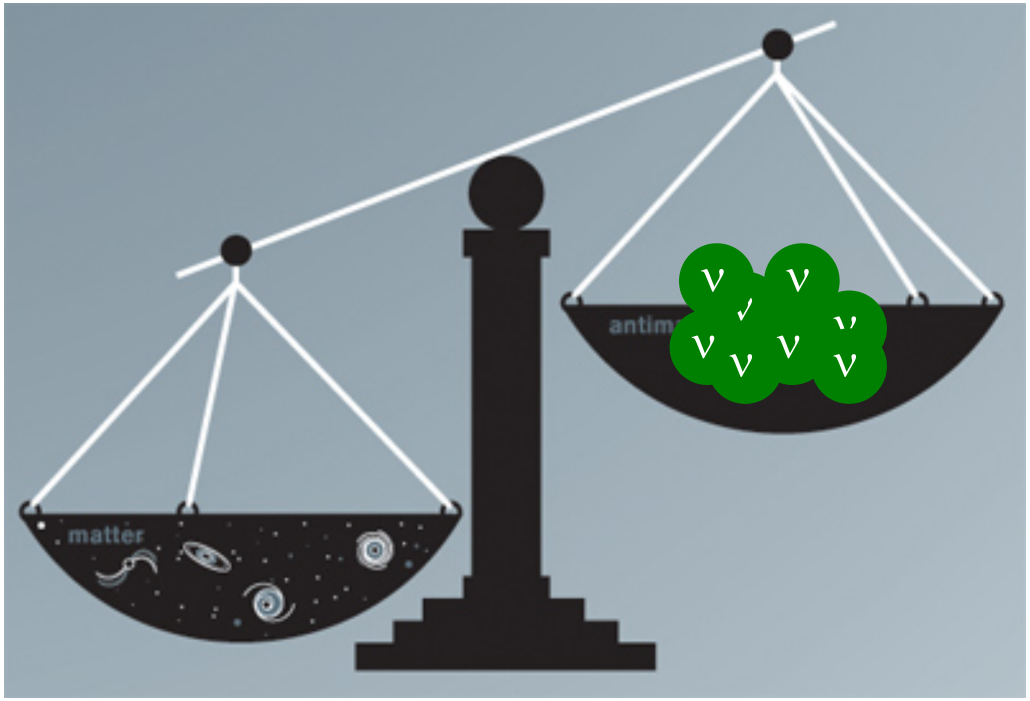


Dentler et al, 1803.10661

More exotic BSM posibilities...

Absolute ν mass scale

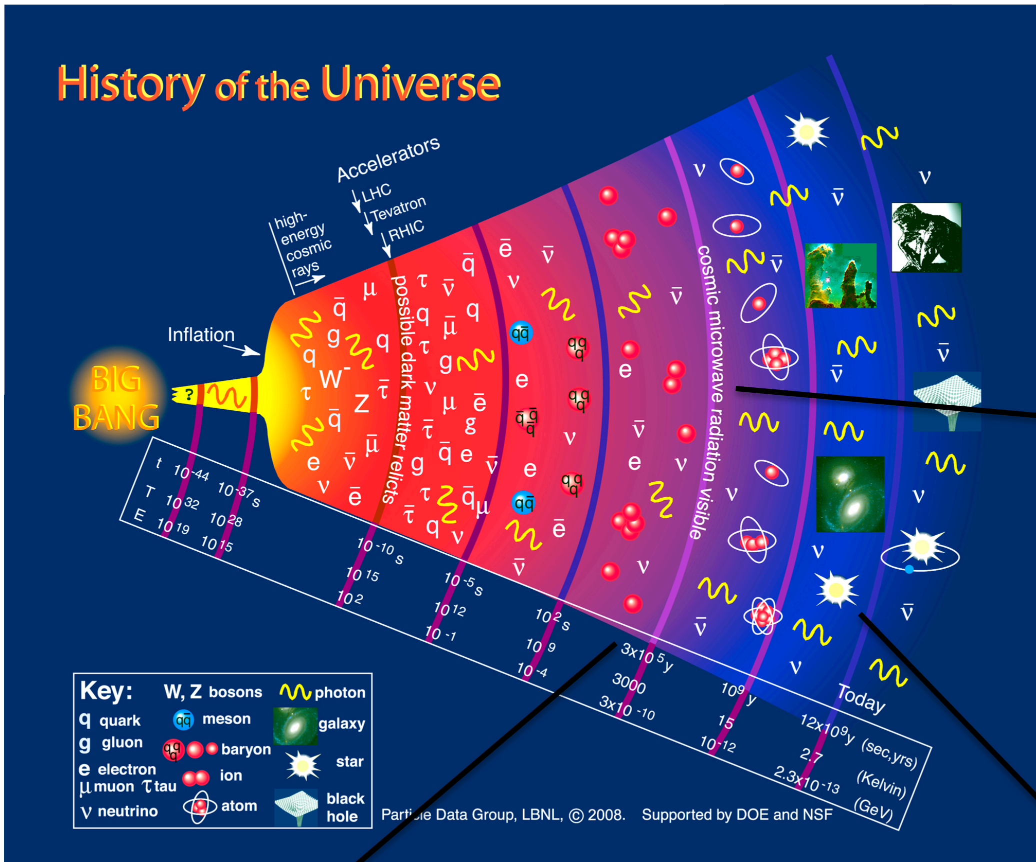
Best constraints at present from cosmology



Planck '18 $\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

Cosmological neutrinos

Neutrinos have left many traces in the history of the Universe



CMB

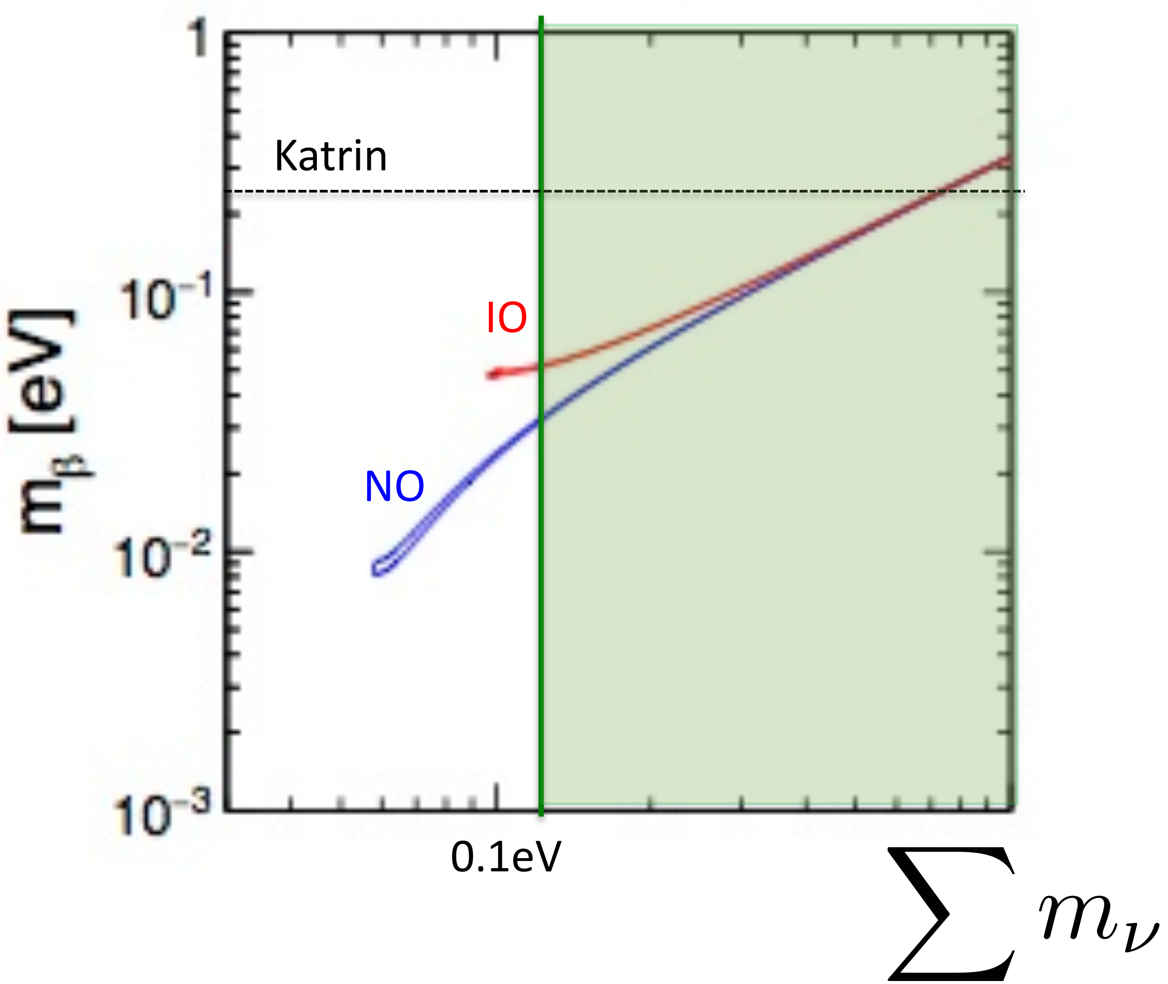
Galaxy distribution (LSS)

Nucleosynthesis

Rosenfeld's lecture

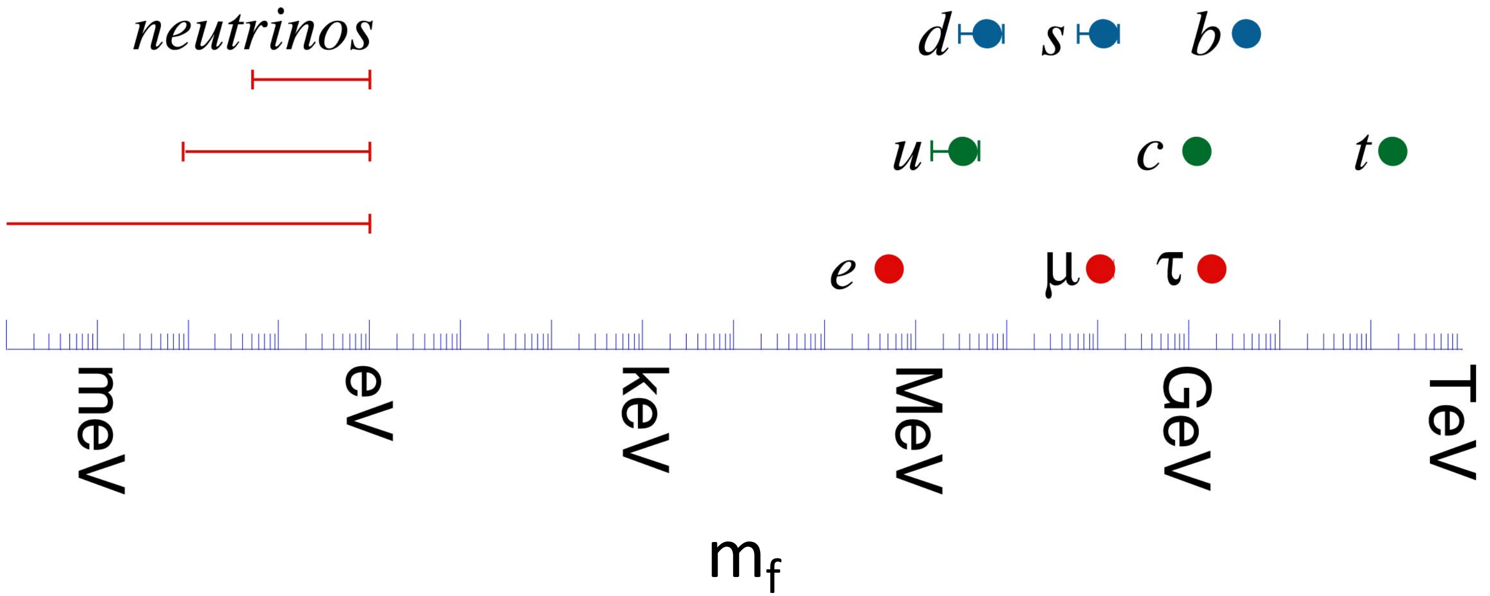
Absolute ν mass scale

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



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, Perkins, Scott

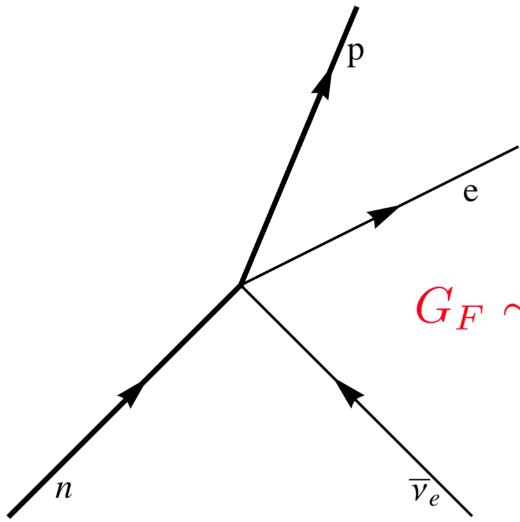
Where the large mixing comes from ?

Anarchy for leptons

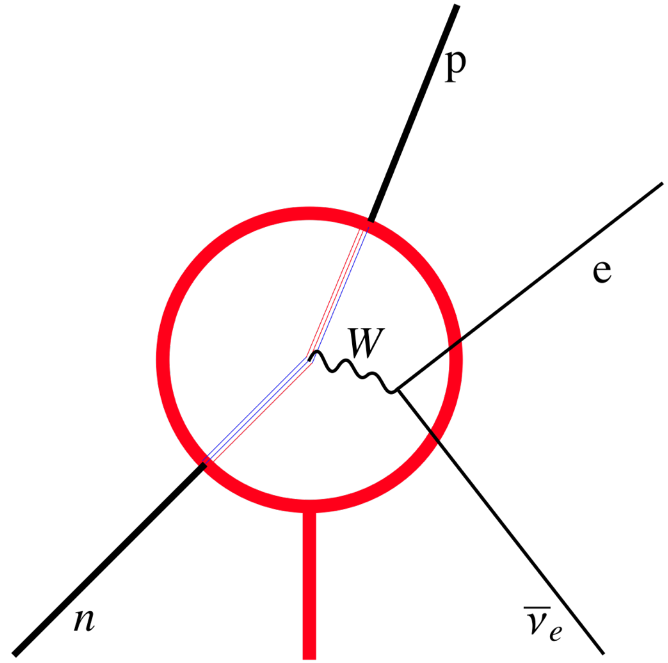
Discrete or continuous symmetries

Lepton-quark flavour connection in GUTs ?

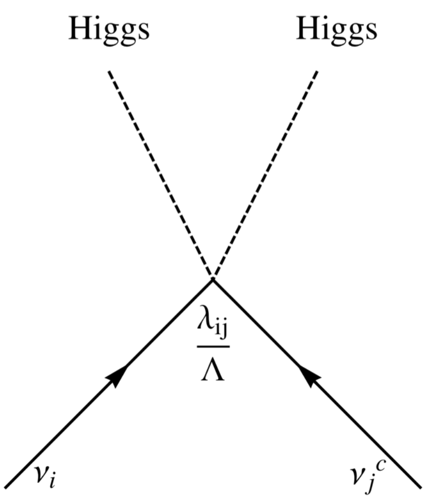
Neutrinos have tiny masses -> a new physics scale, what ?



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



SM



νSM ?

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

Scale at which new particles will show up

What originates the neutrino mass ?

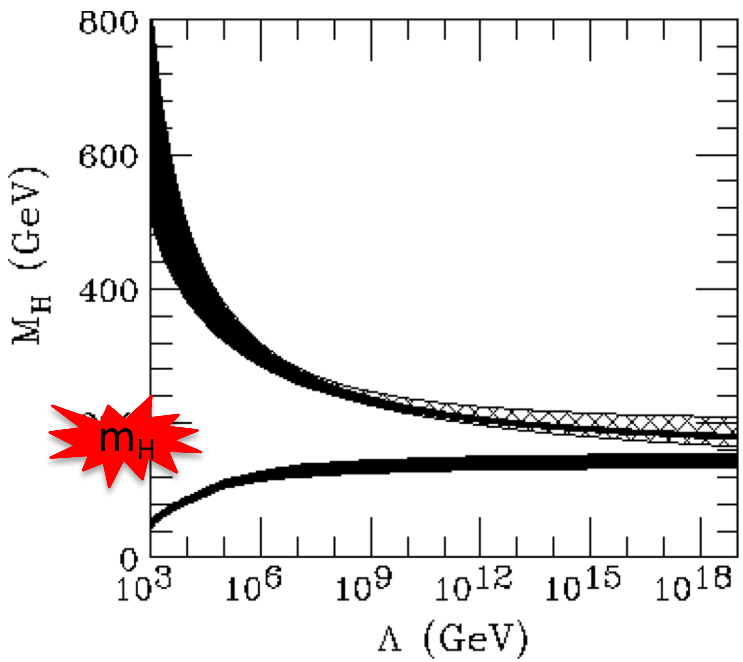
Could be $\Lambda >> v$... the standard lore (theoretical prejudice ?)

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

Hierarchy problem $\qquad m_H^2 \propto \Lambda^2$ $\qquad$ Vissani

not natural in the absence of SUSY/other solution to the hierarchy problem

The Standard Model is healthy as far as we can see…



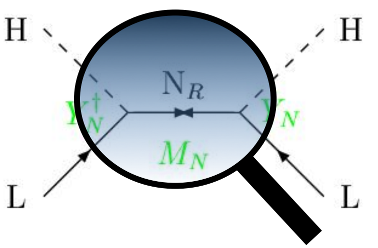
Could be naturally $\Lambda \sim v$?

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

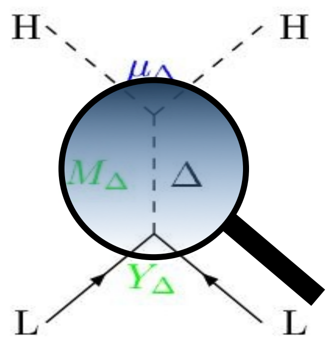


$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

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

Type II see-saw:
a heavy triplet scalar

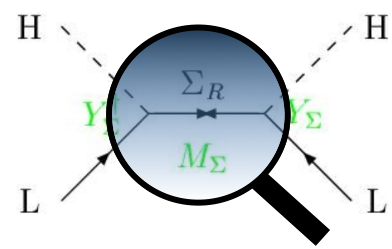


$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

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

Type III see-saw:
a heavy triplet fermion

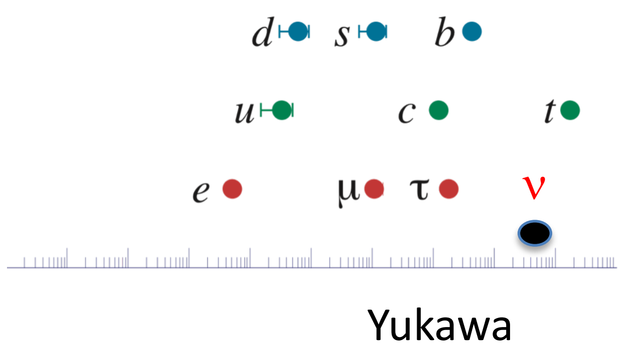


$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

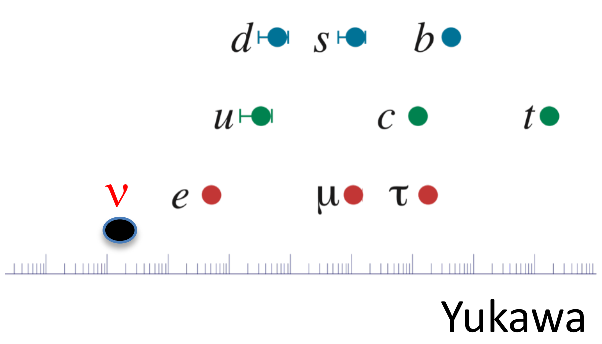
Foot et al; Ma;
Bajc, Senjanovic…

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

$M_N \sim$ GUT



$M_N \sim$ v



Where is the new scale ?

Generic predictions

➢ there is neutrinoless double beta decay at some level ($\Lambda > 100$MeV)

model independent contribution from the neutrino mass

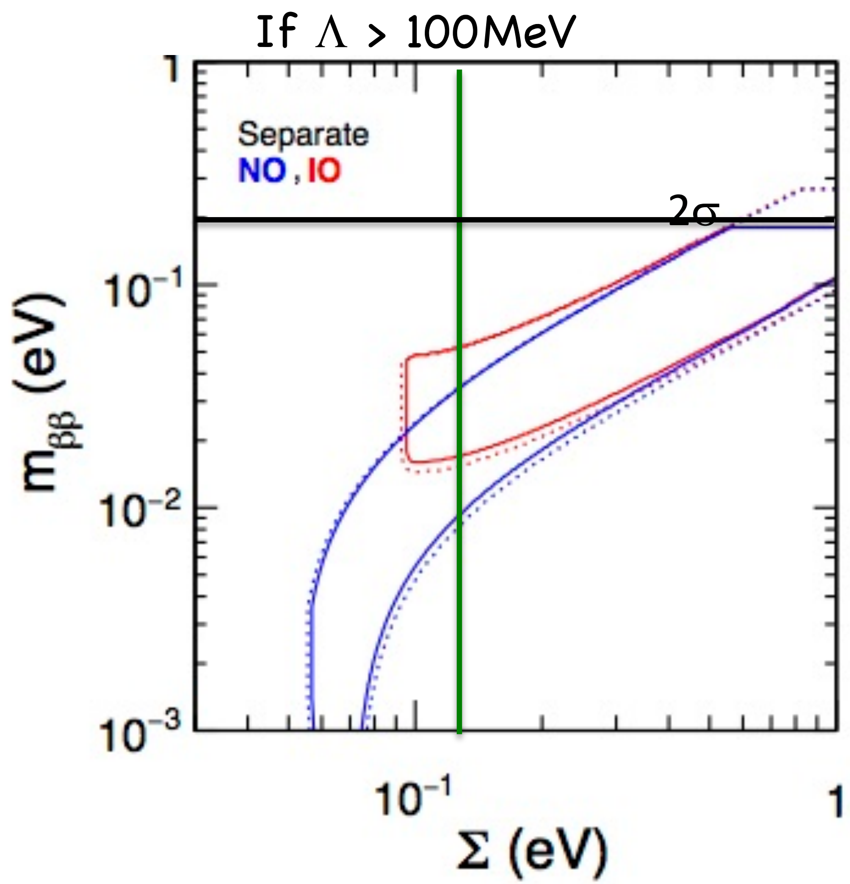
Majorana nature: ββ0ν

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

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

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

$$\Sigma \equiv \sum_i m_i$$



Capozzi et al '17

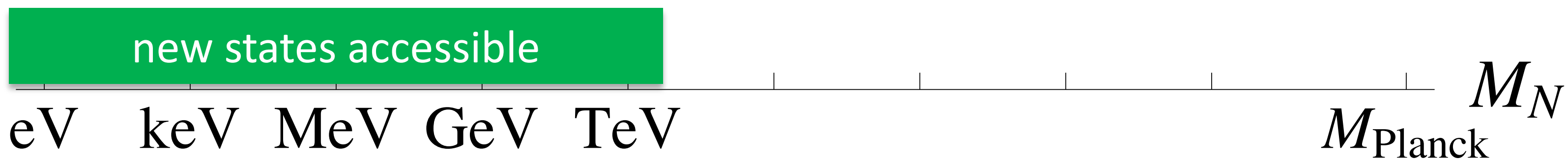
Where is the new scale ?

Generic predictions:

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

model dependent…

Where is the new scale ?



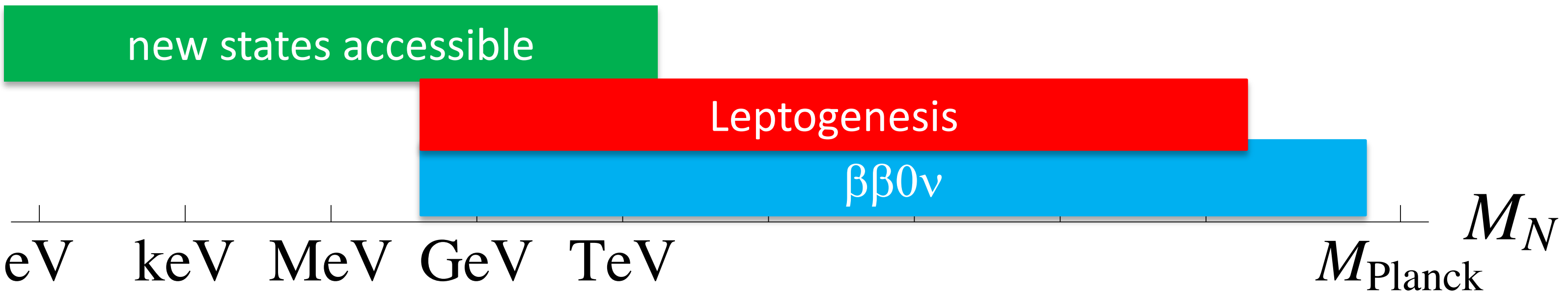
Generic predictions:

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

potential impact in cosmology, EW precision tests, collider, rare searches, ββ0ν, …

model dependent… 

Where is the new scale ?

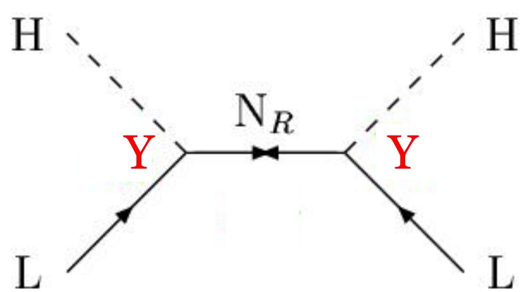


The EW scale is an interesting region: new physics underlying the matter-antimatter asymmetry could be predicted & tested !

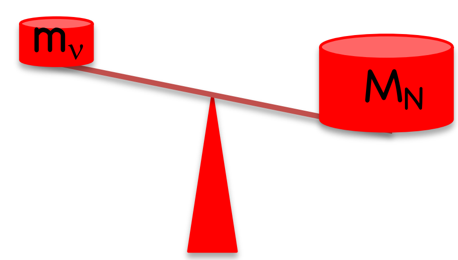
Minimal model of neutrino masses:

Type I seesaw: SM+right-handed neutrinos

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



$$n_R \geq 2$$

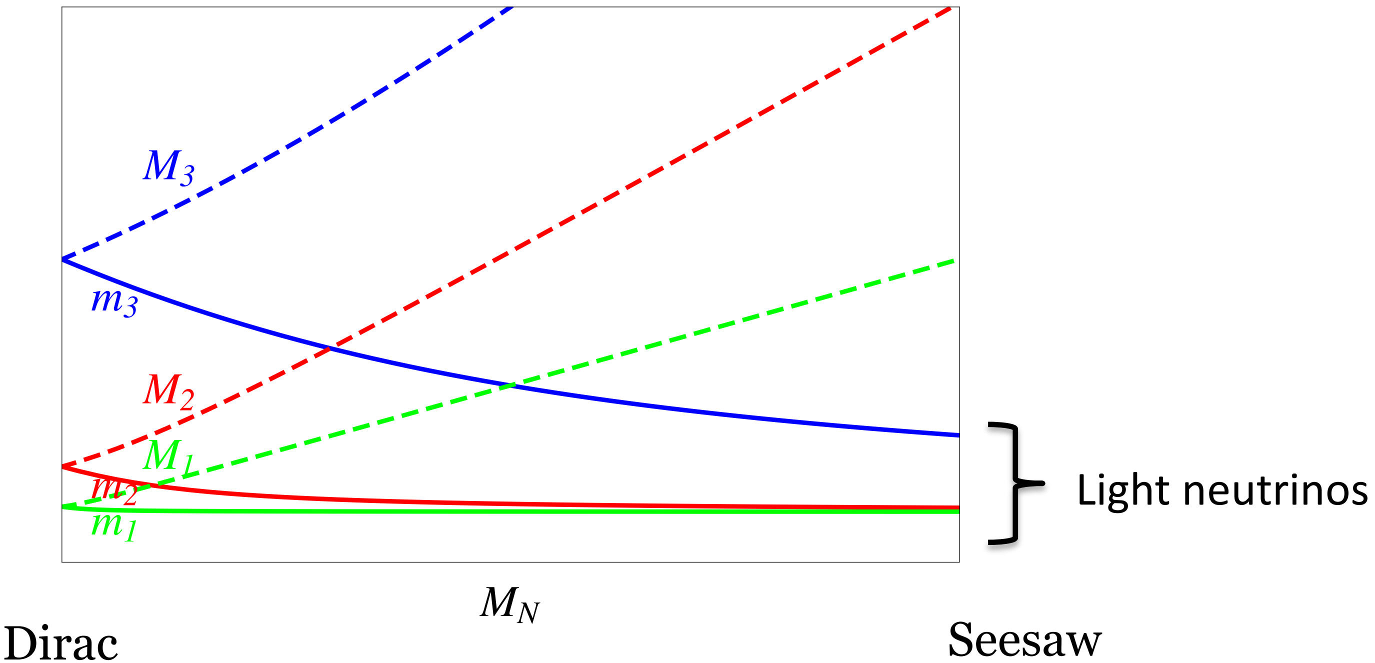


$$m_\nu = \lambda \frac{v^2}{\Lambda} \equiv Y^T \frac{v^2}{M} Y$$

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…

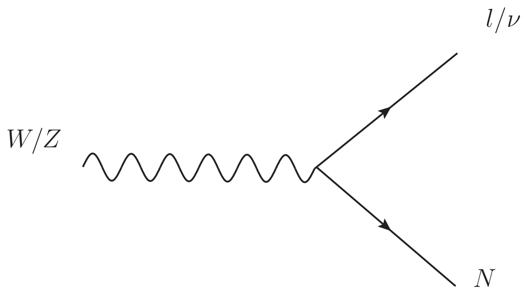


Type I seesaw models

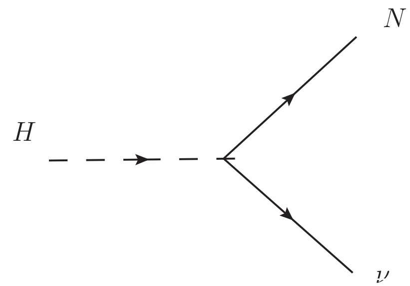
Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

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

Type I seesaw models



U_{lh}



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

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

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:

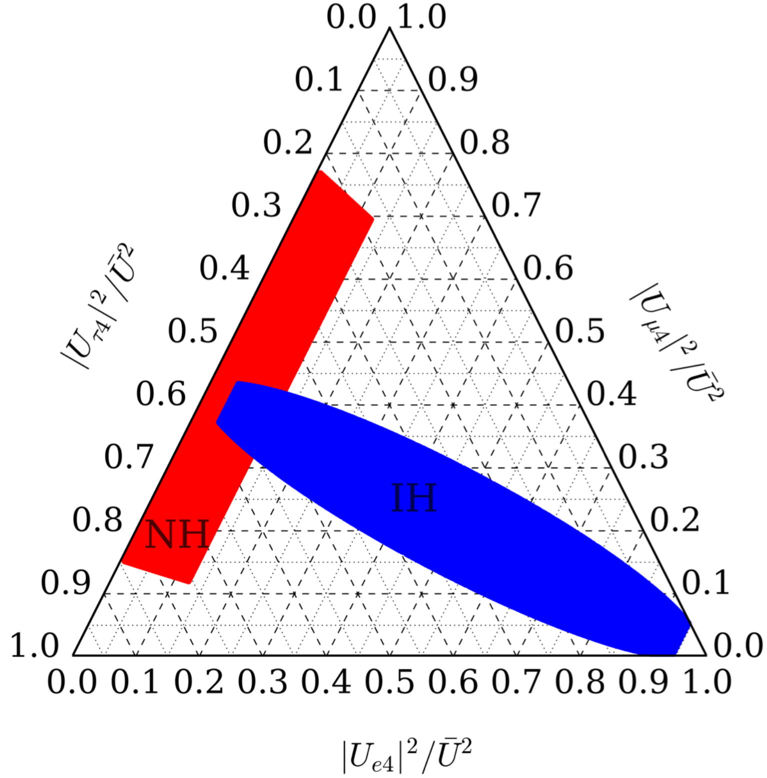
$$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$

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

Seesaw correlations:

flavour ratios of heavy lepton mixings strongly correlated with ordering, U_{PMNS} matrix: δ, ϕ_1

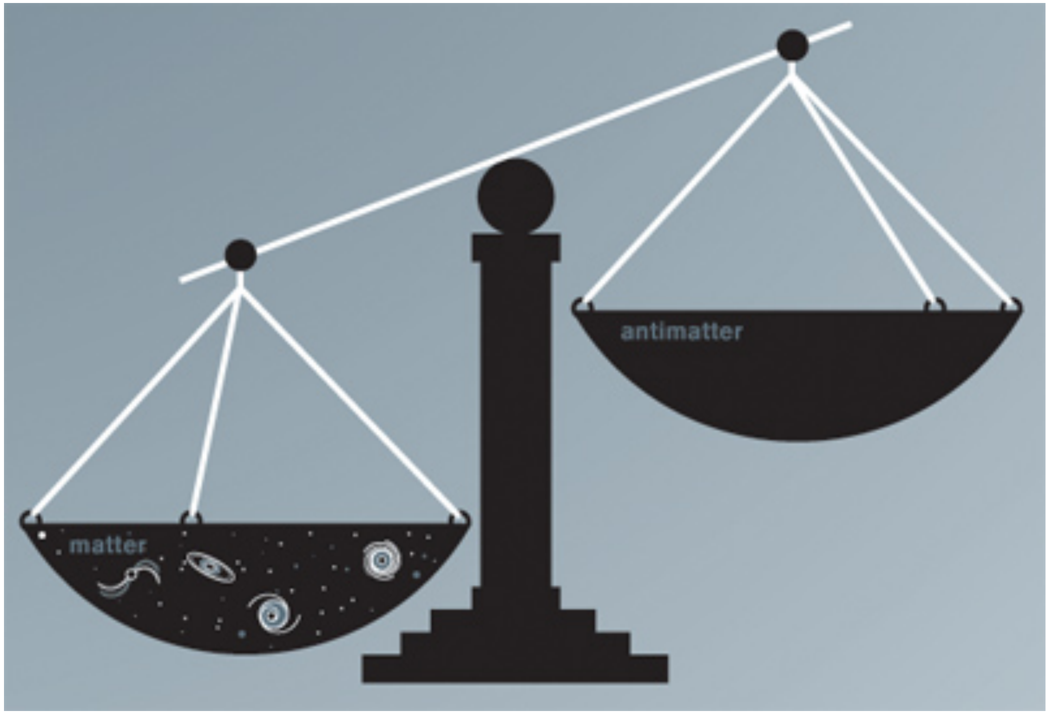
n_R=2:



Caputo, PH, Lopez-Pavon, Salvado arxiv:1704.08721

Baryon asymmetry

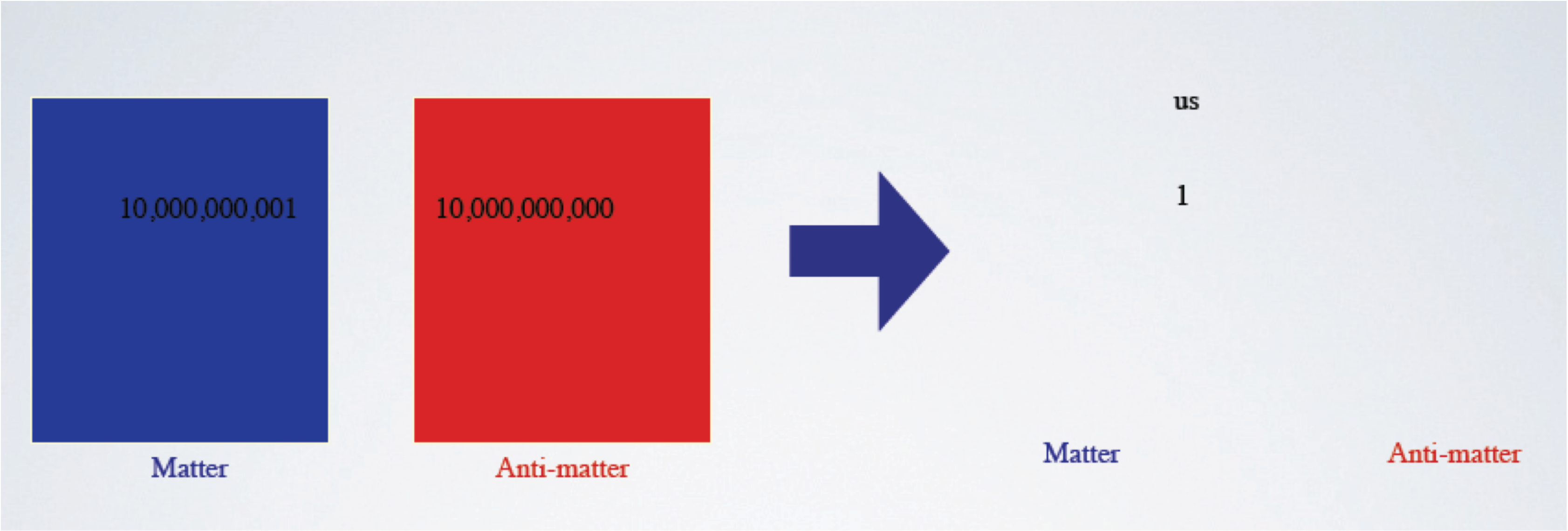
The Universe seems to be made of matter



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

Baryon asymmetry

In the early Universe this implies



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

Baryon asymmetry

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

Sakharov's necessary conditions for baryogenesis

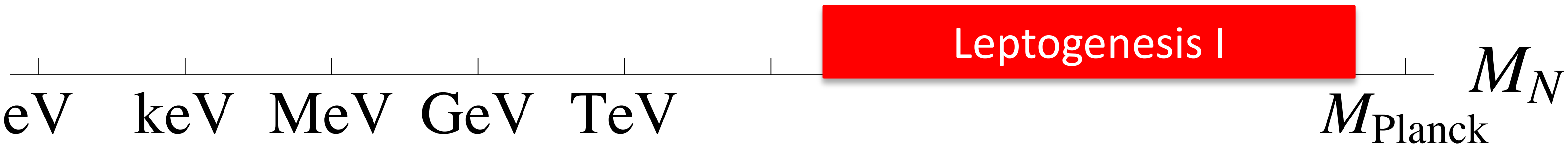
- ✓ Baryon number violation (B+L violated in the Standard Model)
- ✓ C and CP violation (both violated in the SM)
- ✓ Deviation from thermal equilibrium (at least once: electroweak phase transition)

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

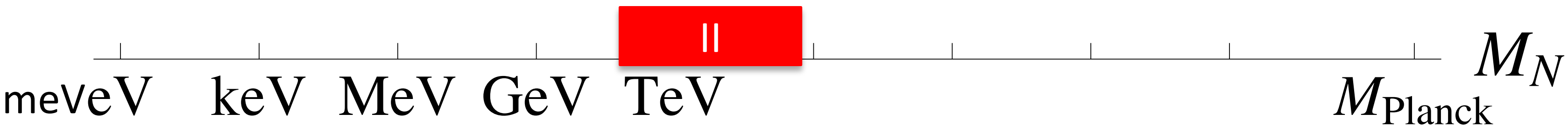
Models with massive neutrinos generically lead togeneration of lepton and therefore baryon asymmetries



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

Fukuyita, Yanagida

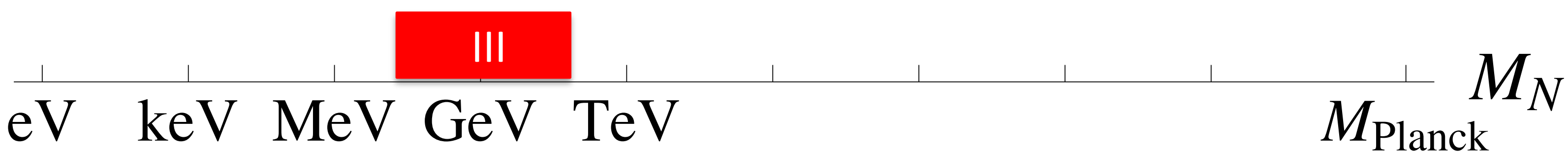
Leptogenesis



Resonant leptogenesis M>100 GeV

Pilaftsis...

Leptogenesis



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

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 $T > T_{EW}$

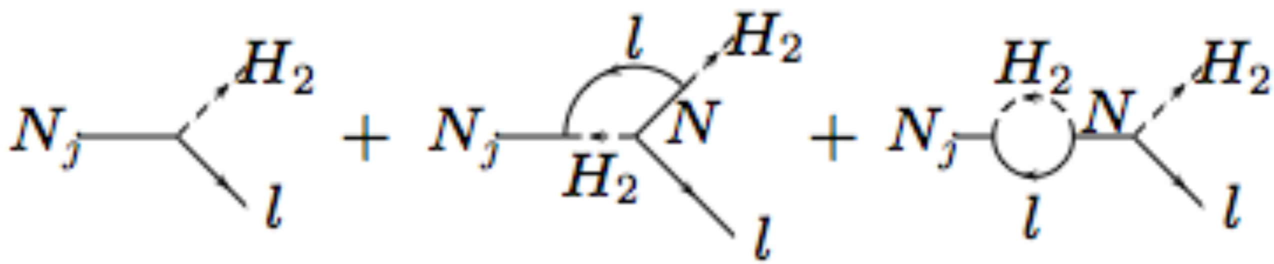
+ L (high-scales)
+ Lα (high and low scales)

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

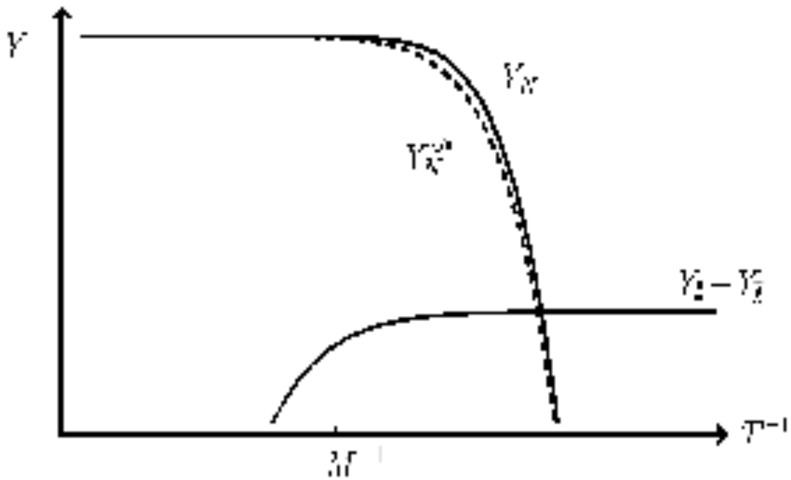
$$L_\alpha \to L_\beta \neq \bar{L}_\alpha \to \bar{L}_\beta$$

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

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

Different flavours different efficiency in transfering it to the baryons

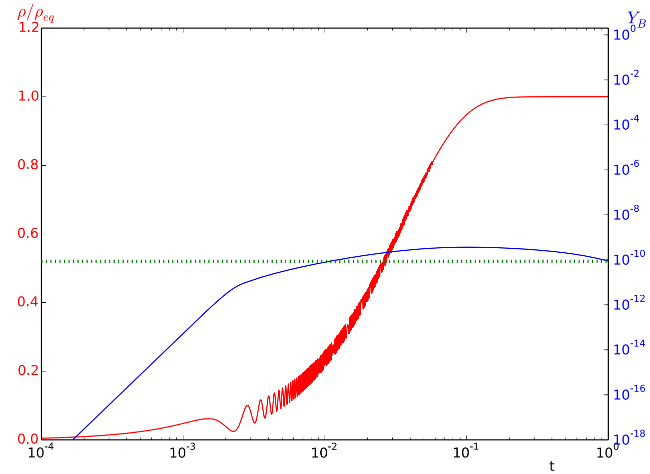
High-scale leptogenesis
(larger Y)



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

(decay rate < hubble expansion)

Low-scale leptogenesis
(smaller Y)



T_{EW}

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

(scattering rate < hubble expansion)

Testability/predictivity ?

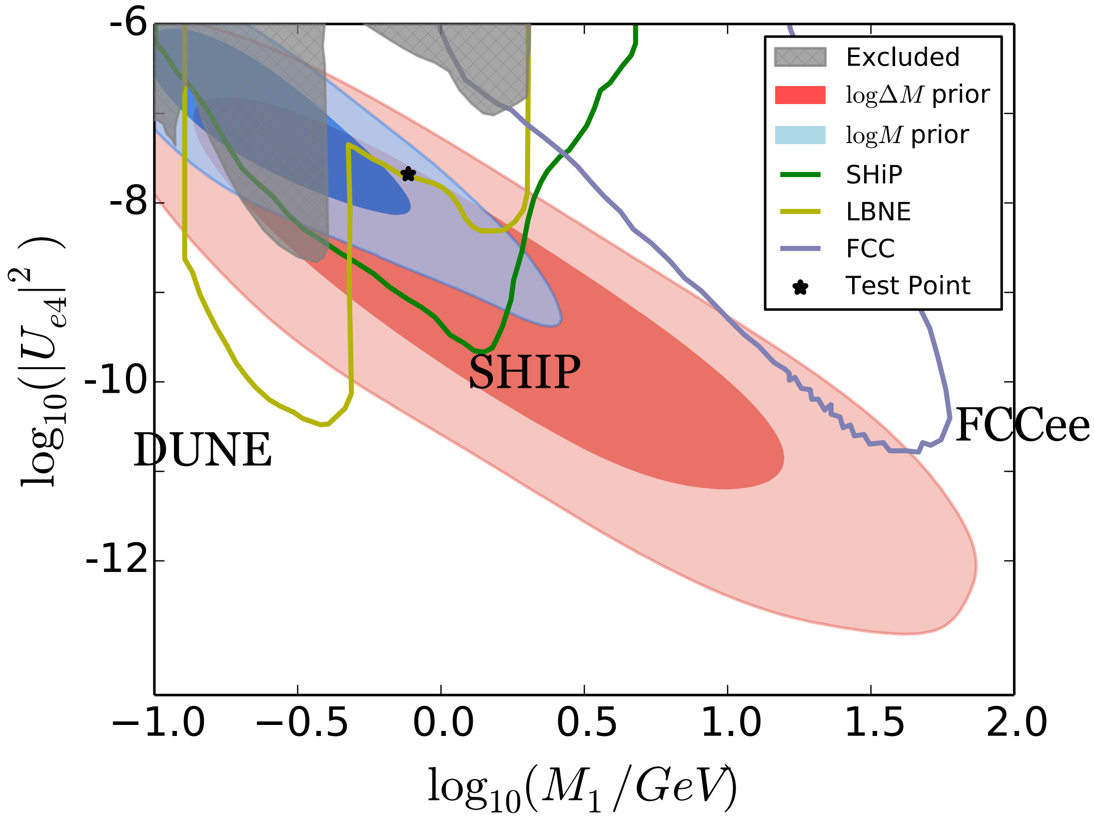
- Y_B cannot be determined from neutrino masses and mixings only

- More information from the heavy sector is needed:

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

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

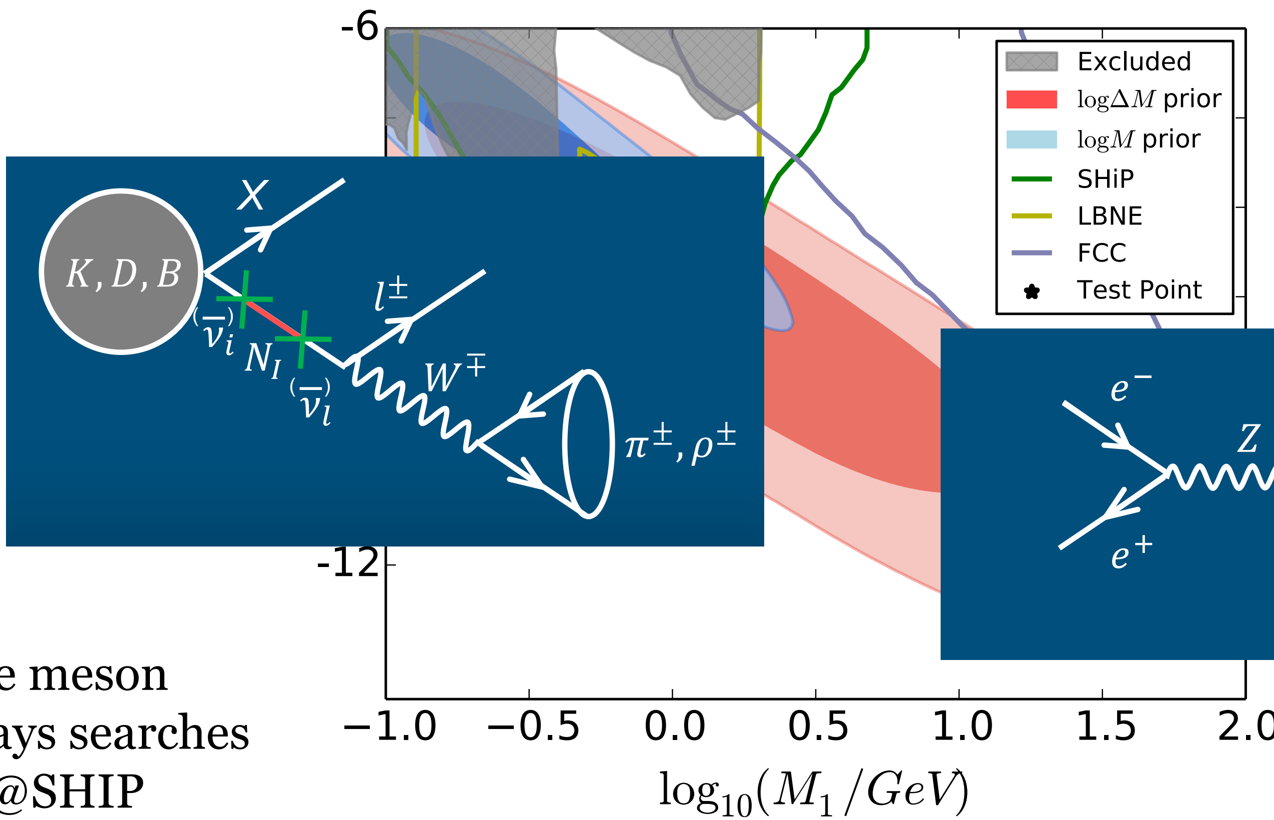
In the minimal model with just n_R=2 neutrinos (IH)

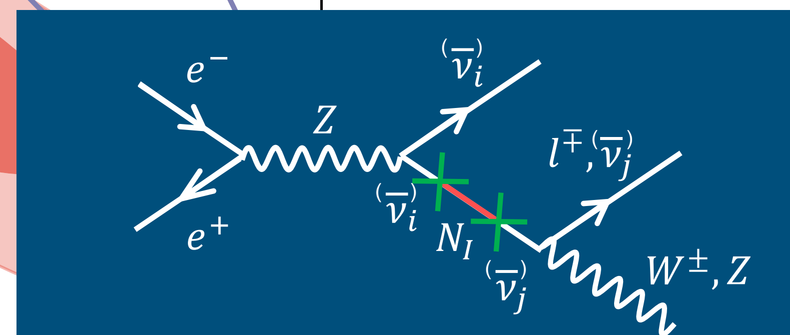


PH, Kekic, Lopez-Pavon, Racker, Salvado

Colored regions: posterior probabilities of successful Y_B

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





Rare meson decays searches Eg:@SHIP

Displaced vertex searches in Z decays Eg: @FCC-ee

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

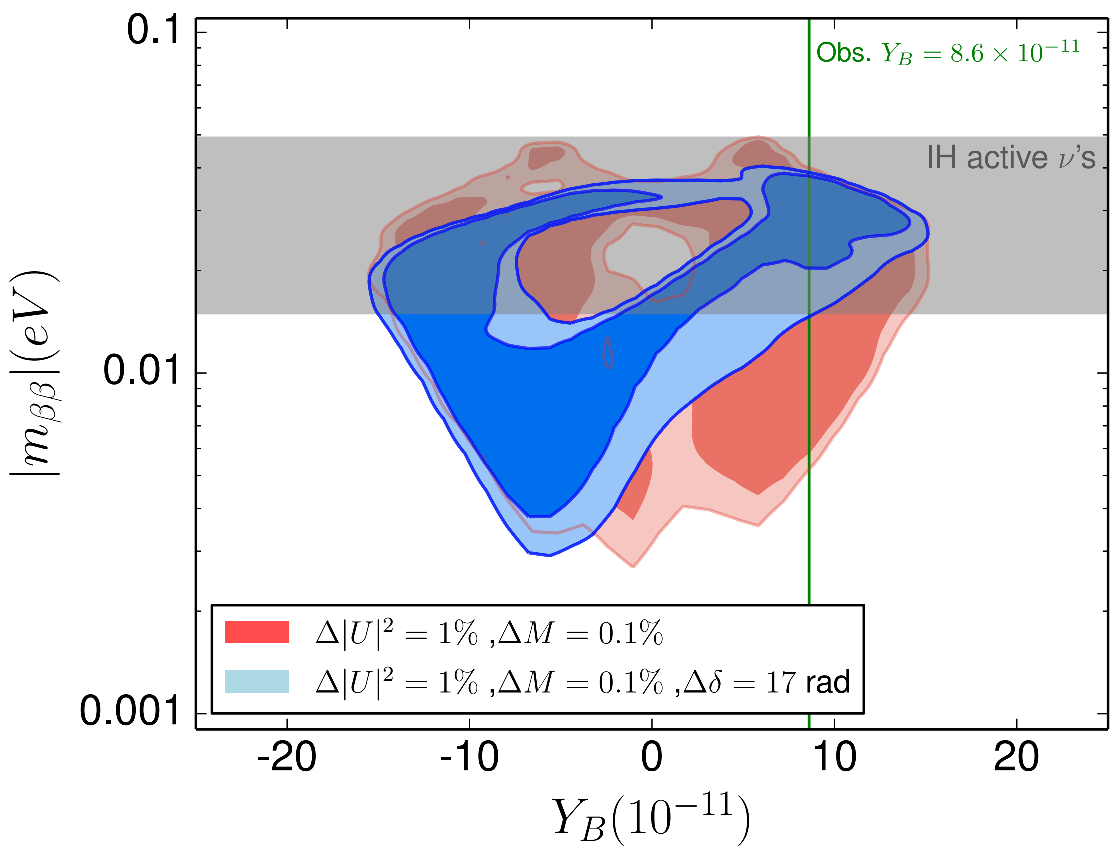
Assume a point within SHIP reach that gives the right baryon asymmetry

- 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: δ phase in the U_{PMNS}

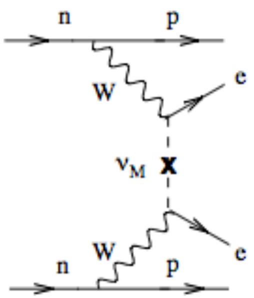
Predicting Y_B in the minimal model n_R=2 (IH)



PH, Kekic, Lopez-Pavon, Racker, Salvado

Predicting Y_B in the minimal model n_R=2

Heavy states also contribute to the ββ0ν amplitude…



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

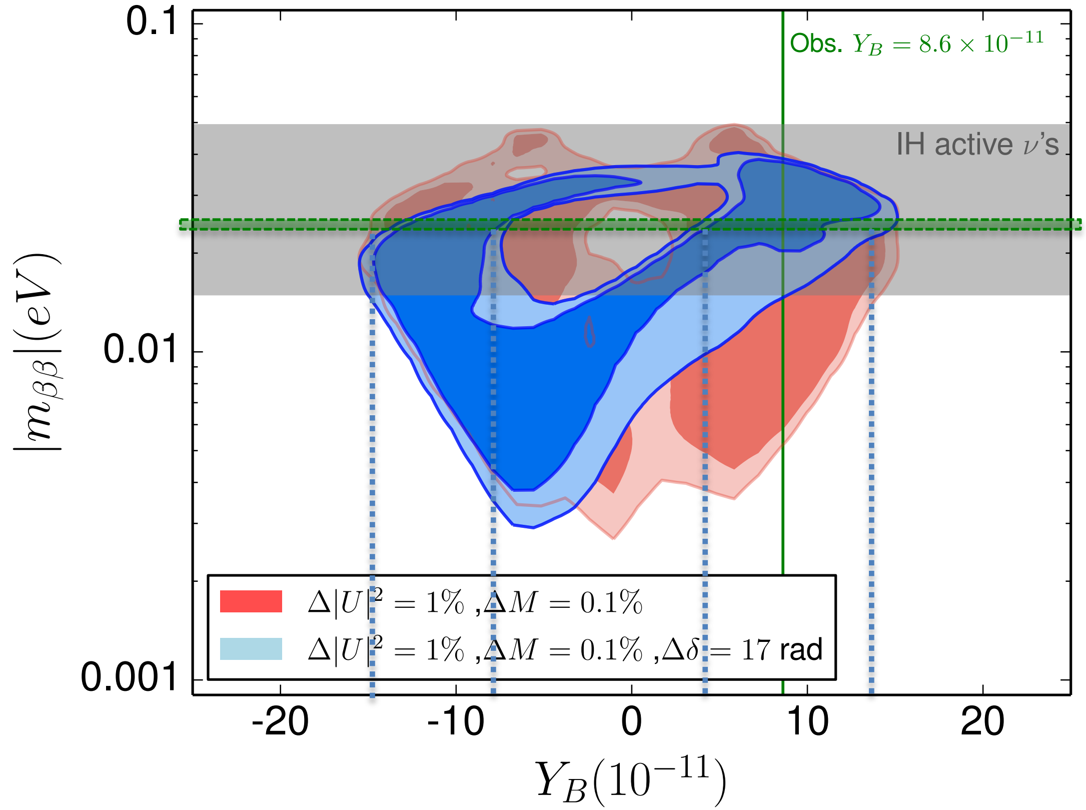
$$M_j \to \infty \qquad \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)} \propto \left(\frac{100 \text{ MeV}}{M_j} \right)^2$$

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 non standard contributions bring essential information of some CP phases and other unknown parameters

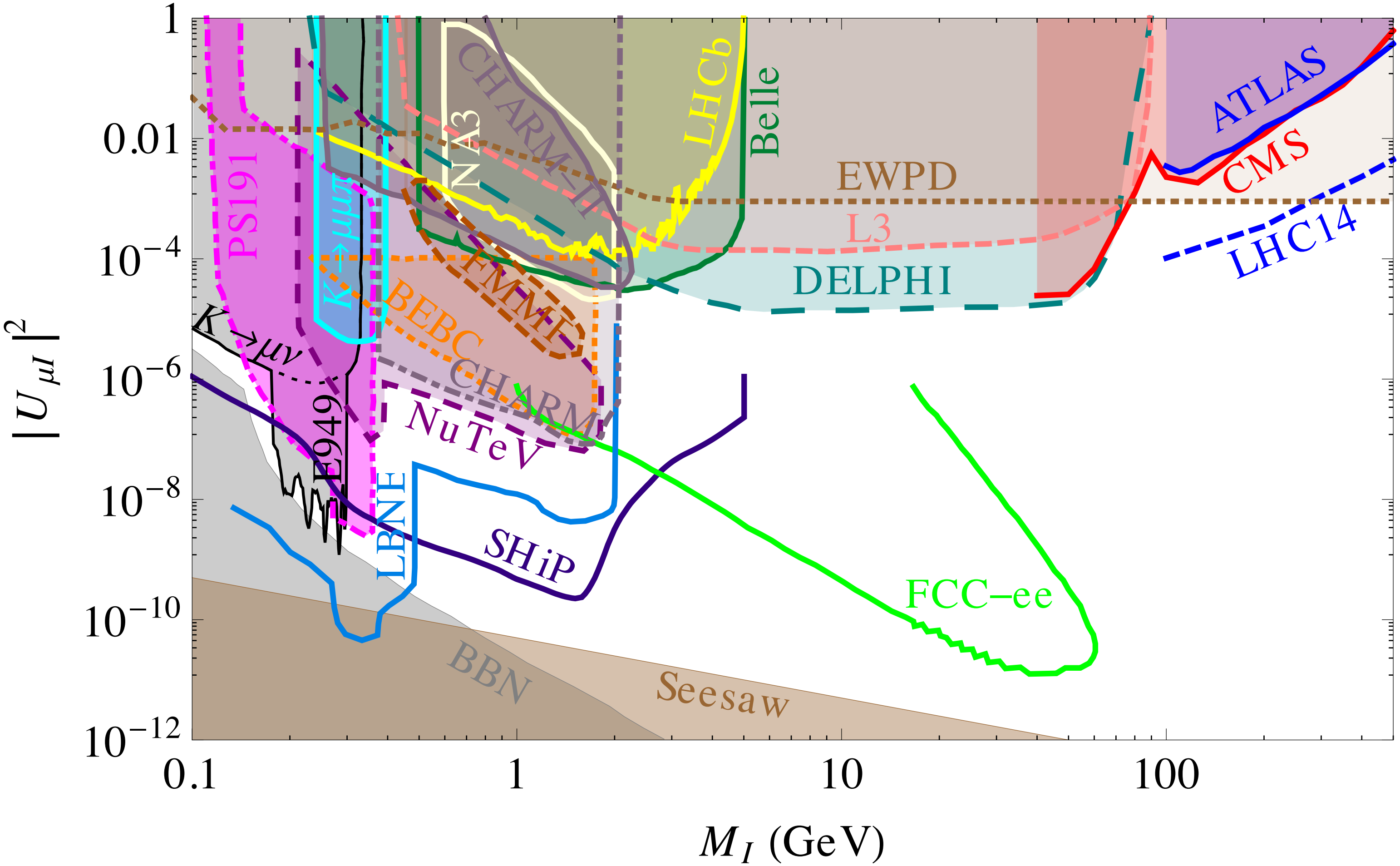
Predicting Y_B in the minimal seesaw model M~GeV



PH, Kekic, Lopez-Pavon, Racker, Salvado
arxiv:1606.06719

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

Exploring the EW region



Reviews Atre, Han, Pascoli, Zhang; Gorbunov, Shaposhnikov; Ruchayskiy, Ivashko; Deppisch, Dev, Pilaftsis

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

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

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

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

Does not induce neutrino masses: Y unbounded by them

Seesaw models + approx Lepton number

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

$$\begin{pmatrix} 0 & Y_1 v & \epsilon Y_2 v \\ Y_1 v & \mu' & M_N \\ \epsilon Y_2 v & M_N & \mu \end{pmatrix}$$

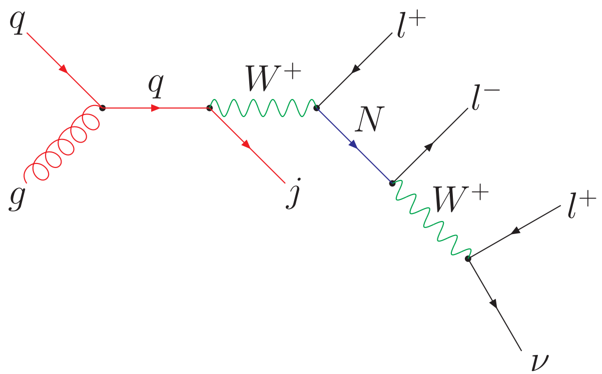
direct seesaw
inverse seesaw
extended seesaw

They are all a subclass of type I seesaw models with the generic features:

- quasi-Dirac heavy states
- LNV (neutrino masses, same-sign W decays, etc) ~ $O(\mu, \mu', \varepsilon)$
- Yukawa hierarchies

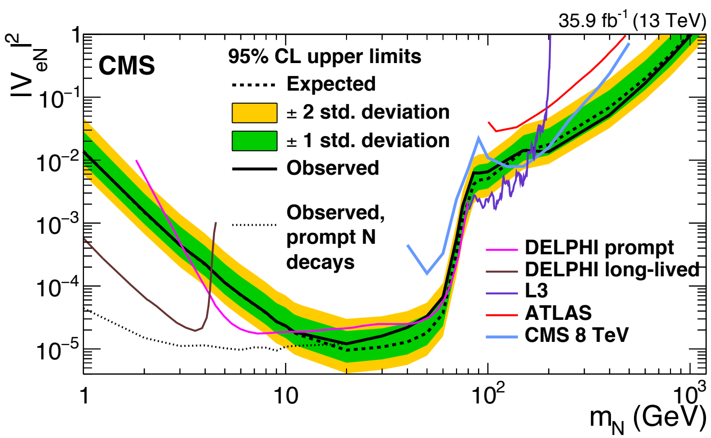
Look for LNC processes ! Can we test their Majorana nature ?

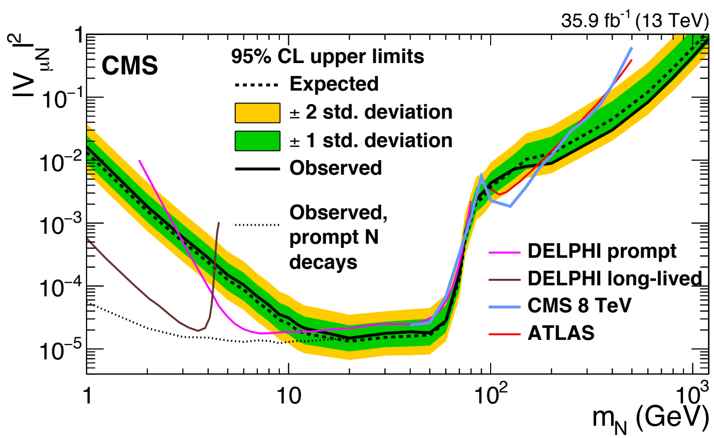
LNC @LHC: trilepton + missing energy



Del Aguila, Aguilar-Saavedra; …Chen,Dev; Izaaguirre, Shuve; Dib et al; many more

CMS '18

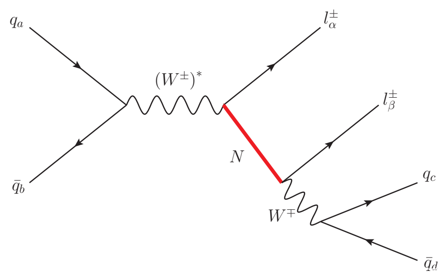


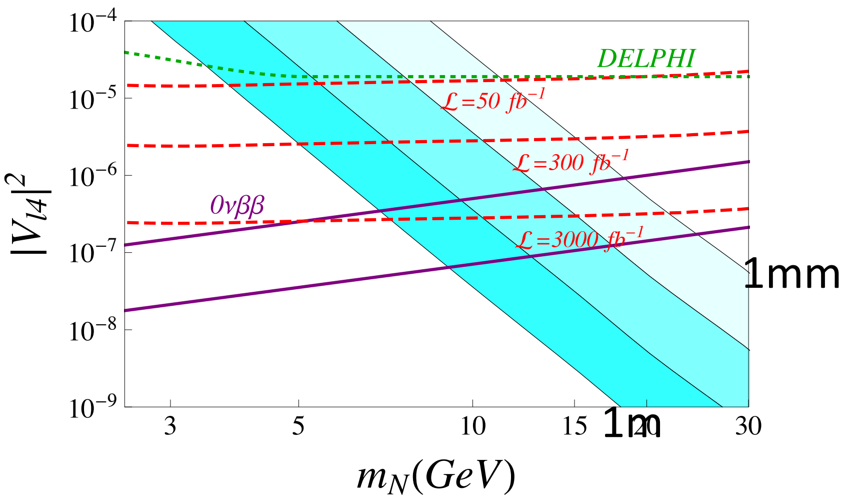


Reaching significantly lower mixings (& lower masses) via displaced decays

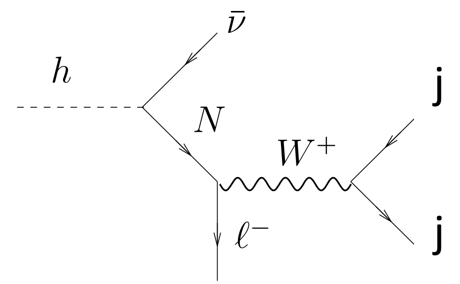
Helo, Kovalenko, Hirsch ; Gago, PH, Jonez-Perez, Losada, Moreno; Blondel, Graverini,Serra, Shaposhnikov;Antush, Cazzato, Ficher;…

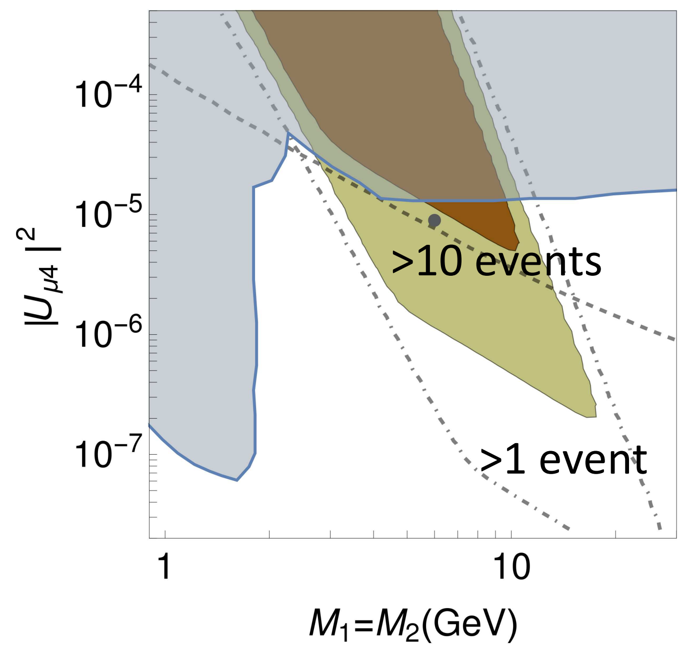
Golden signal: Displaced Vertices



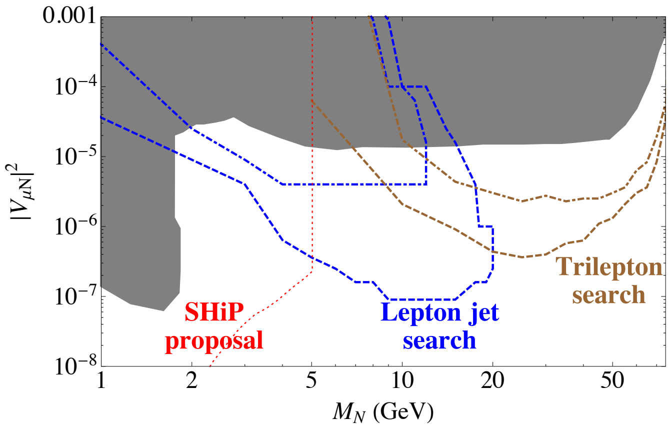


Helo, Kovalenko,Hirsch



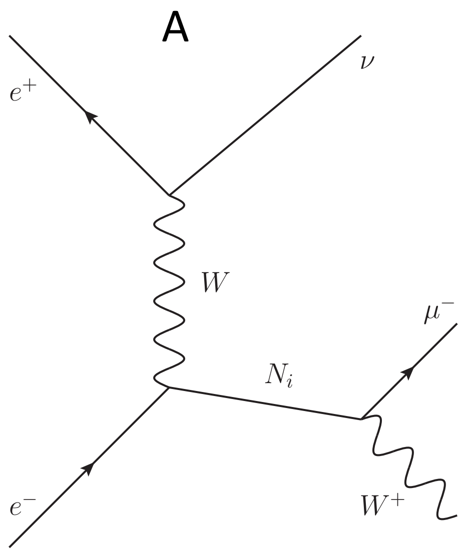


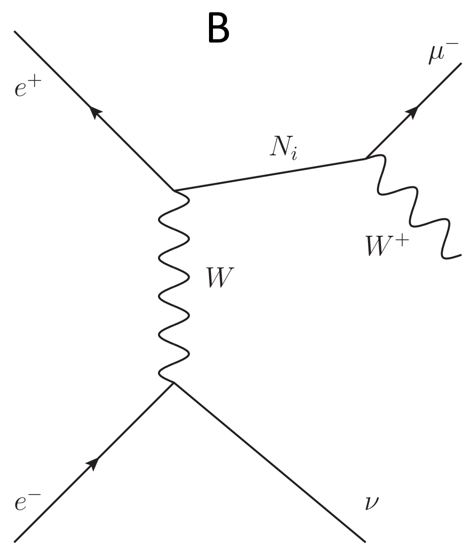
Gago, PH, Jones-Perez, M.Losada, A. Moreno

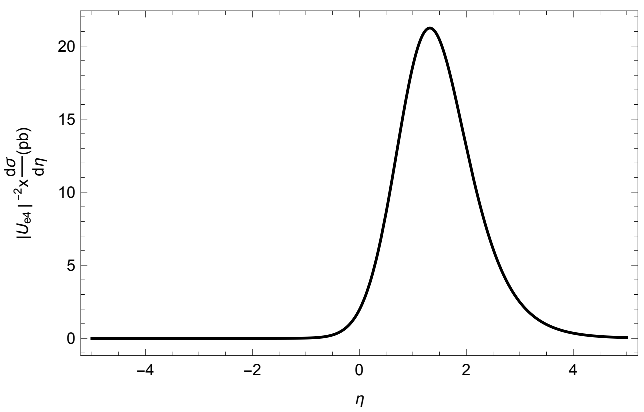


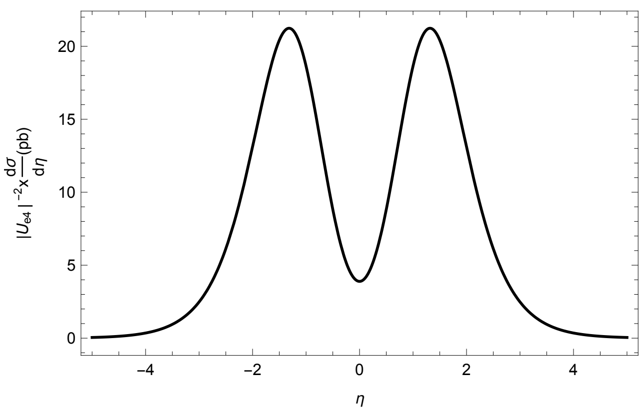
Izaguirre, Shuve

Majorana vs pseudo-Dirac @ e+e-





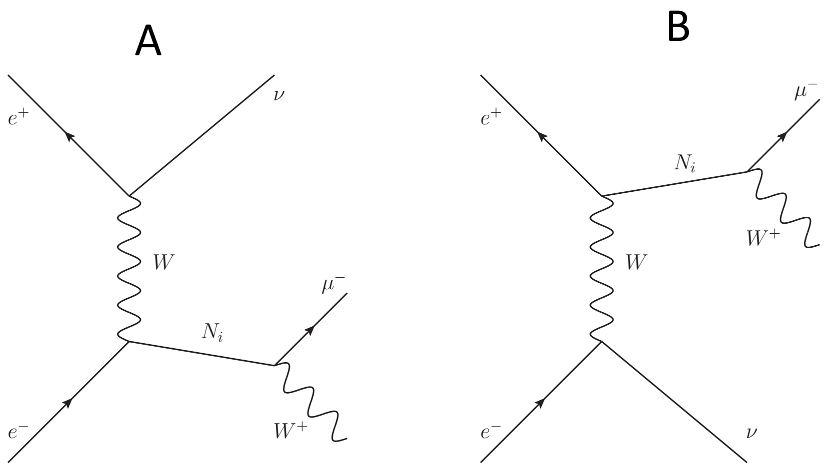




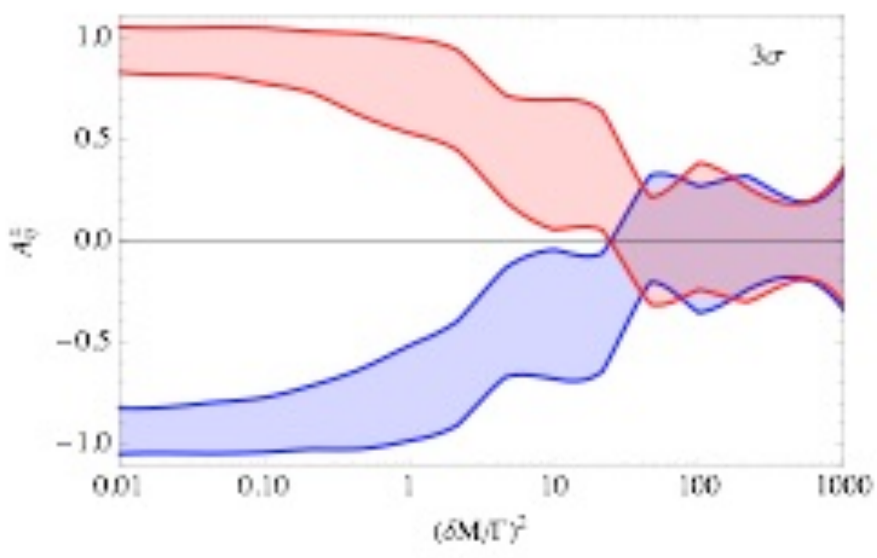
A ⇔ LNC

A+B ⇔ LNV

Majorana vs pseudo-Dirac @ e+e-



$$A_\eta^\pm = \frac{N^\pm(\eta > 0) - N^\pm(\eta < 0)}{N^\pm_{\rm tot}} \,,$$



PH, Jones-Pérez, Suárez-Navarro

Beyond the minimal model

Many possibilities:

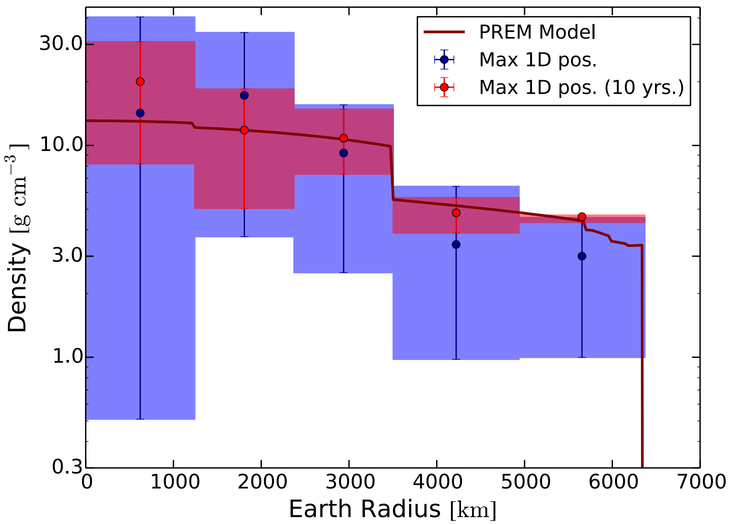
Examples: type I + extra Z',
type II, III
left-right symmetric models
GUTs, etc

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

- Generically new gauge interactions can enhance the production in colliders: richer phenomenology
- But also make leptogenesis more challenging (out-of-equilibrium condition harder to meet)

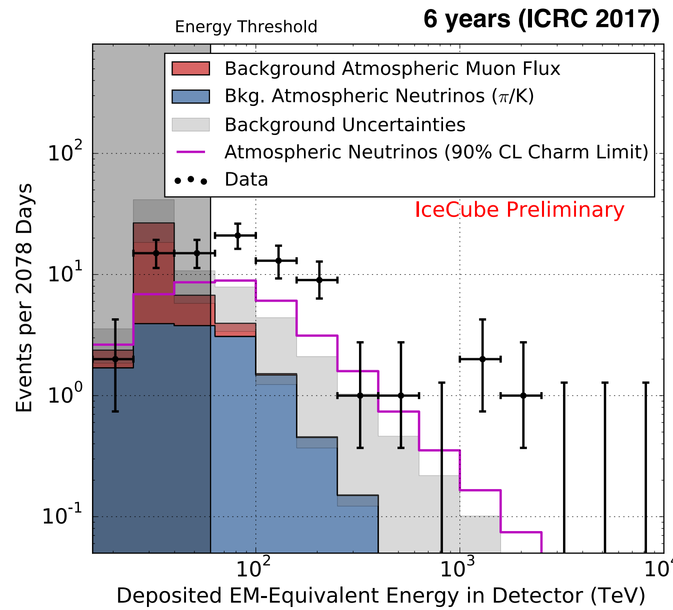
New era of ν phyiscs:
neutrino astronomy, geology,...

Understand the Earth



Donini, Palomares-Ruiz, Salvado, 1803.05901

Understand Astrophysical sources



Icecube '17

Whole new lecture !

Conclusions

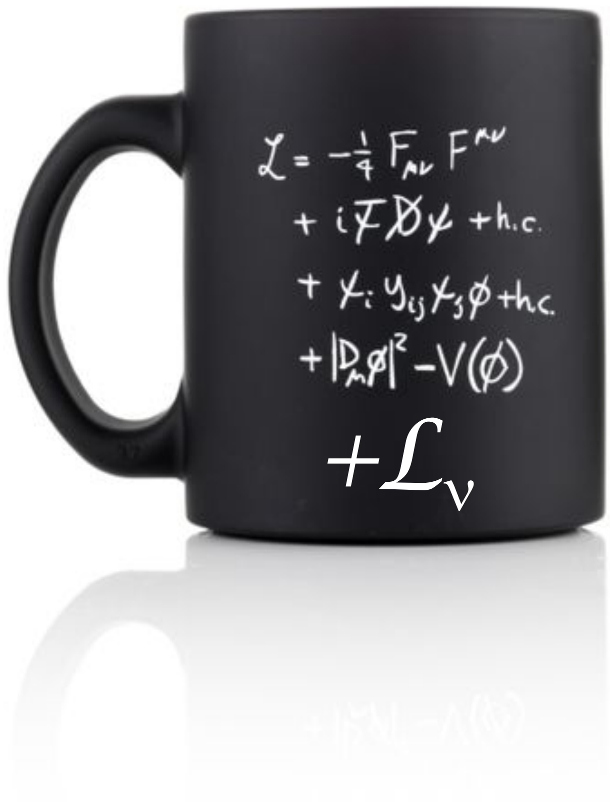
• The results of many beautiful experiments have demonstrated that ν are (for the time-being) the less standard of the SM particles

• 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: ββ0ν, 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)

The νSM ?


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
$+\mathcal{L}_\nu$