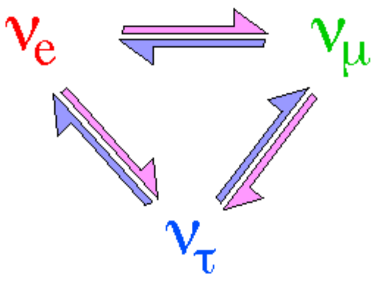
LECTURE III & IV

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

- Neutrinos and beyond the Standard Model physics



Standard 3ν scenario

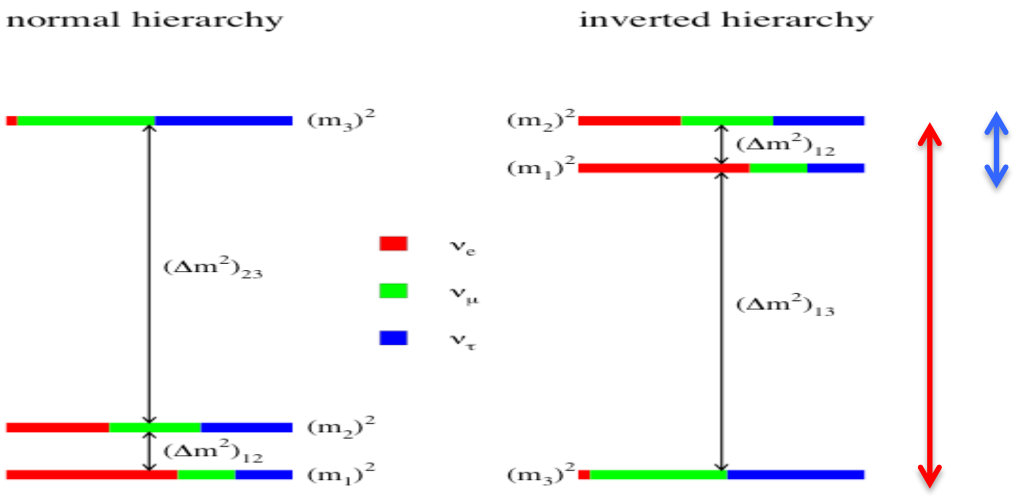
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

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

$$\delta \sim \;?$$



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

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

NO/NH

IO/IH

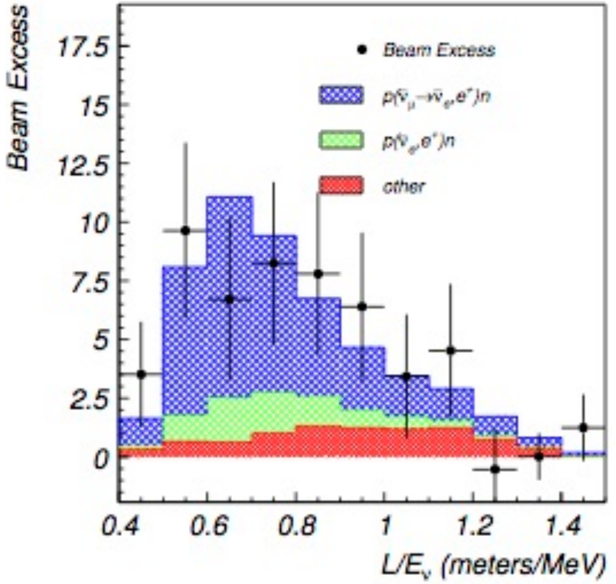
Caveat: O(eV) neutrinos…reactor/short baseline anomalies still unresolved

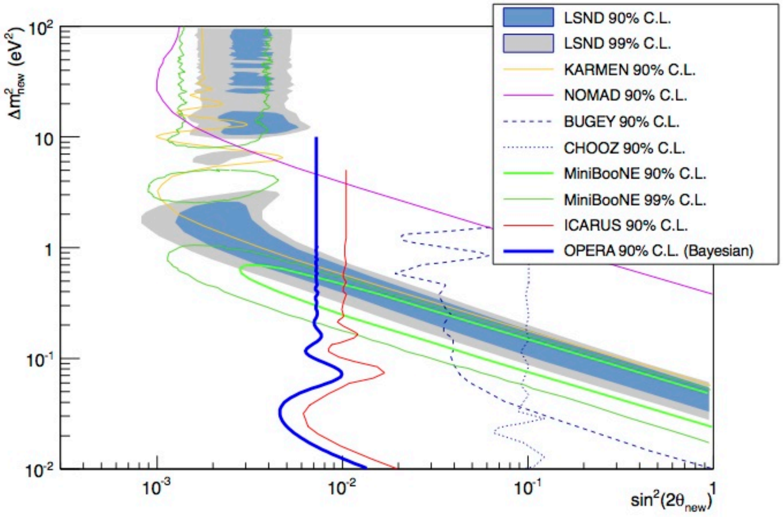
Outliers: LSND anomaly

$$
\begin{aligned}
\pi^+ \rightarrow \quad & \mu^+ \quad \nu_\mu \\
& \nu_\mu \quad \rightarrow \nu_e \ \text{DIF} \ (28 \pm 6/10 \pm 2)
\end{aligned}
$$

$$
\begin{aligned}
\mu^+ \rightarrow \quad & e^+ \quad \nu_e \ \bar{\nu}_\mu \\
& \bar{\nu}_\mu \quad \rightarrow \bar{\nu}_e \ \text{DAR} \ (64 \pm 18/12 \pm 3)
\end{aligned}
$$

$$P(\nu_\mu \rightarrow \nu_e)$$

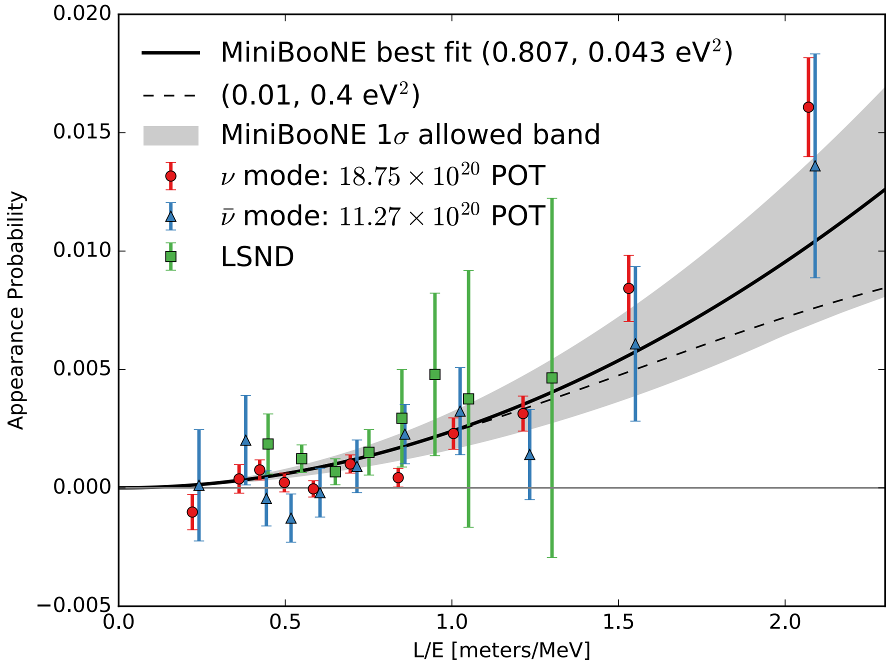


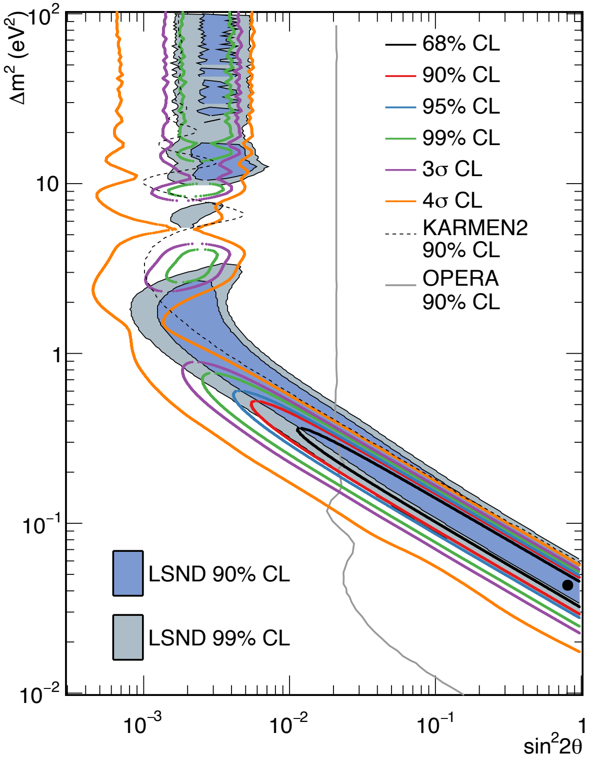


$$|\Delta m^2| \gg |\Delta m^2_{atm}|$$

Outliers: LSND anomaly

+ MiniBOONE

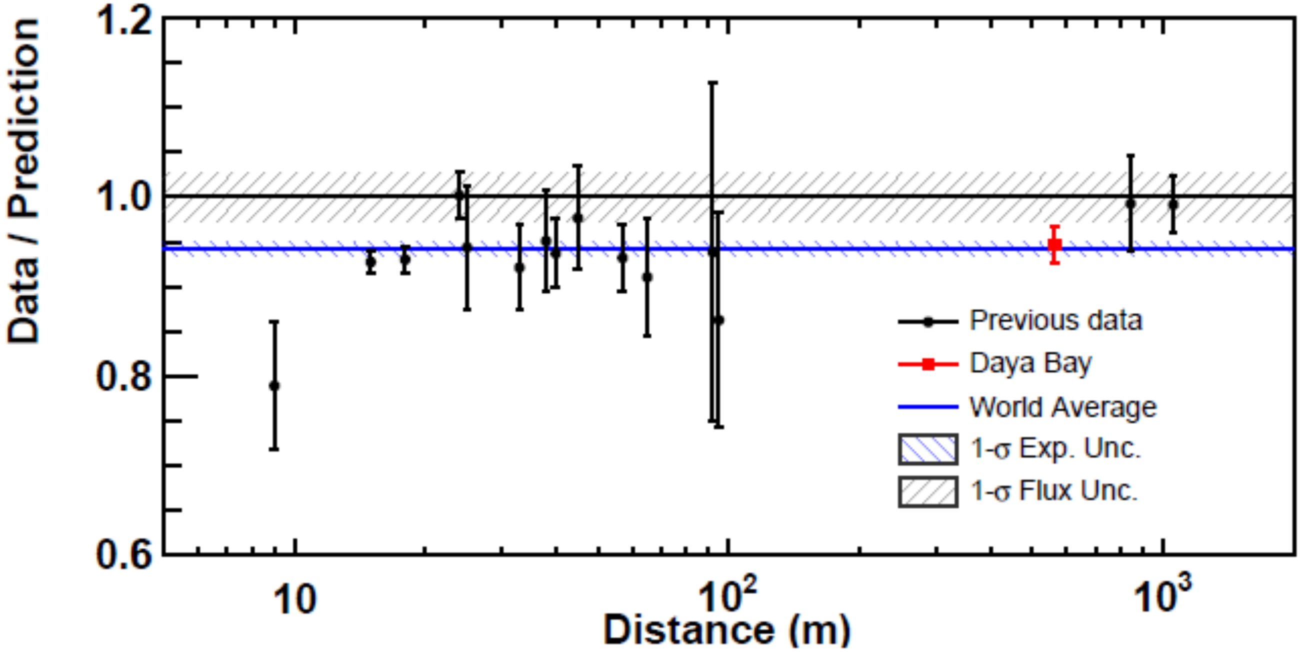




4.8σ discrepancy with SM !

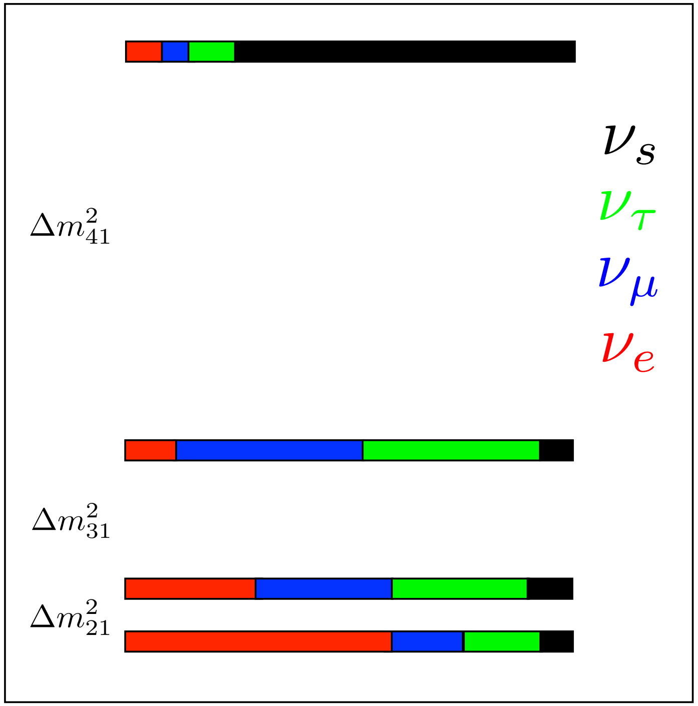
Outliers: SBL reactor anomalies

Reactor $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$



Re-evaluation of the predicted fluxes indicates an L-independent deficit (averaged oscillations ?)

SBL anomalies: 4th neutrino ?



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

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

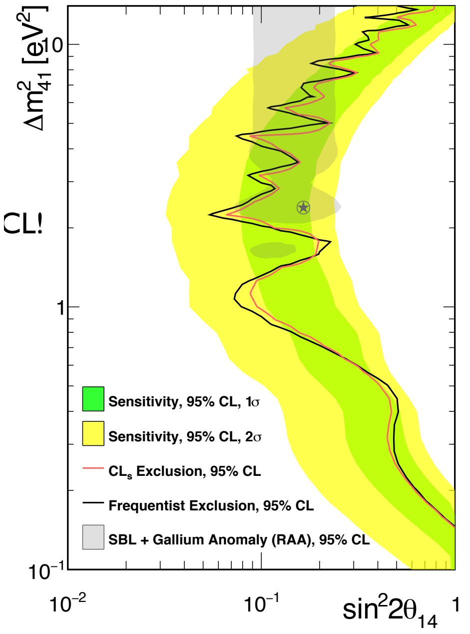
$P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu 4}|^2)$

Oscillations at @meters for MeV neutrinos: short baseline reactor experiment

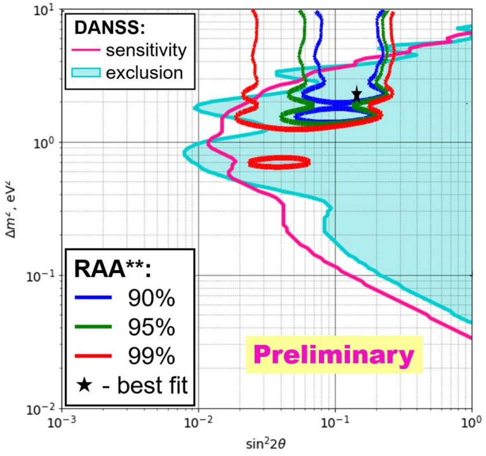
SBL reactor anomaly Vews

New SBL reactor strategies: L-dep of signal

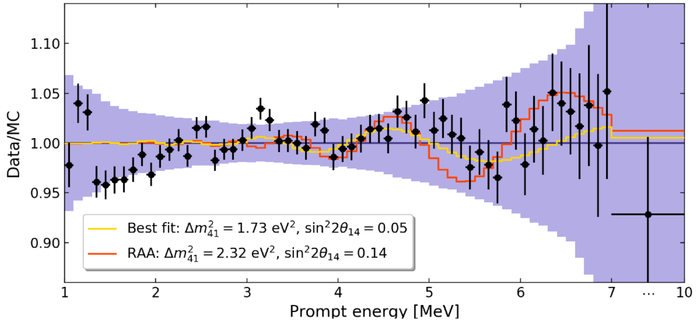
Prospect



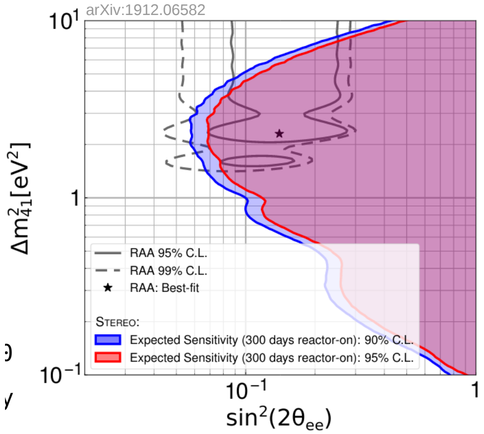
DANSS



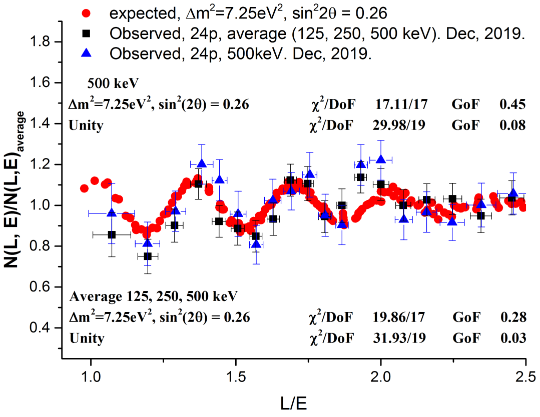
NEOS



Stereo



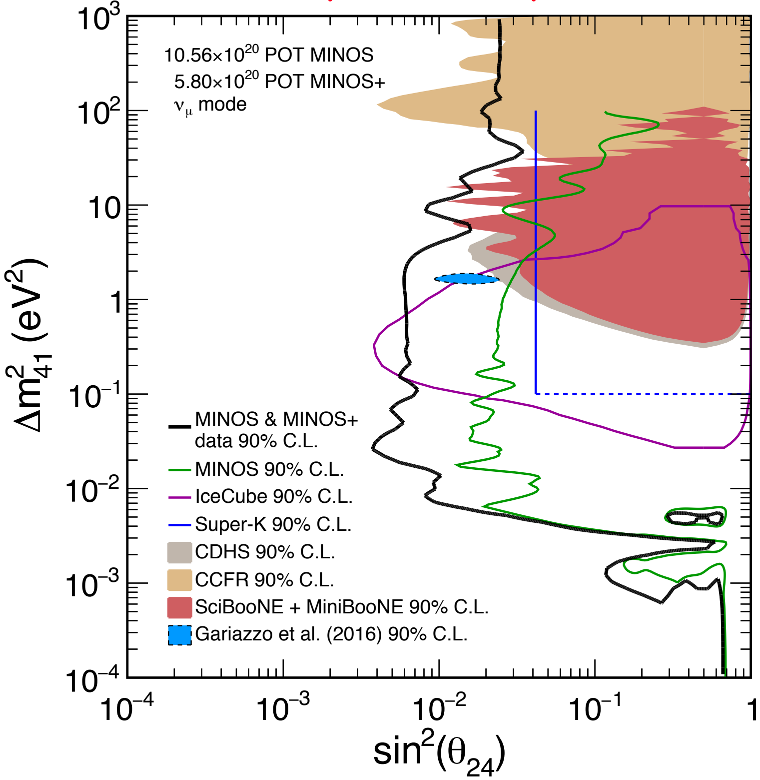
NEUTRINO-4



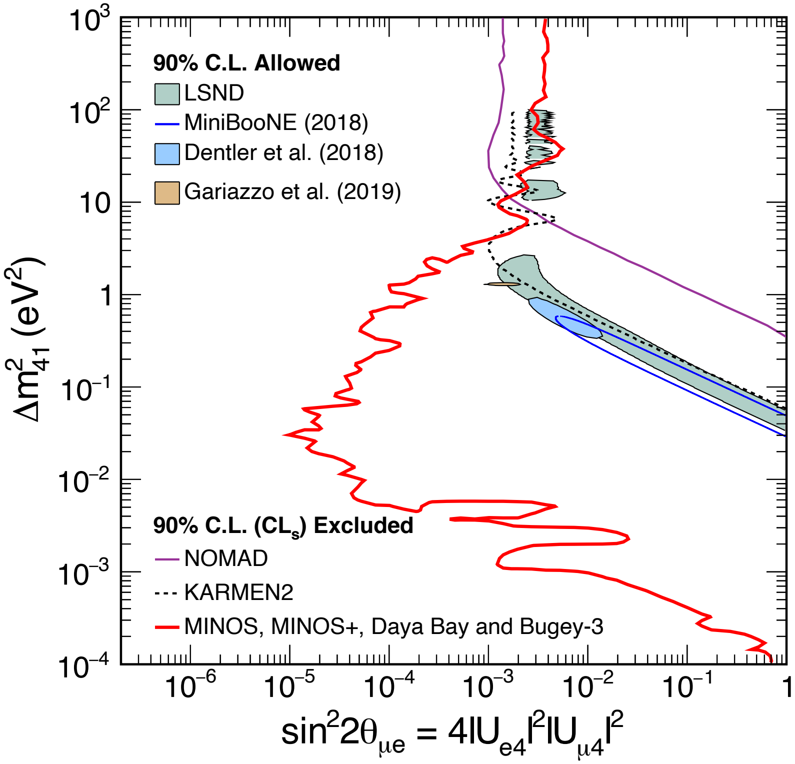
O(eV) sterile neutrinos ?

Neutrino muons must disappear also but they don’t Minos, Minos+

$P(\nu_\mu \rightarrow \nu_\mu)$



$P(\nu_\mu \rightarrow \nu_\mu)$ & $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$



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

Exercise: what about MSW resonances in the 4ν model ? Can the steriles oscillation be resonantly enhanced ? Estimate the resonance energy for Earth density and think where to look for this effect.

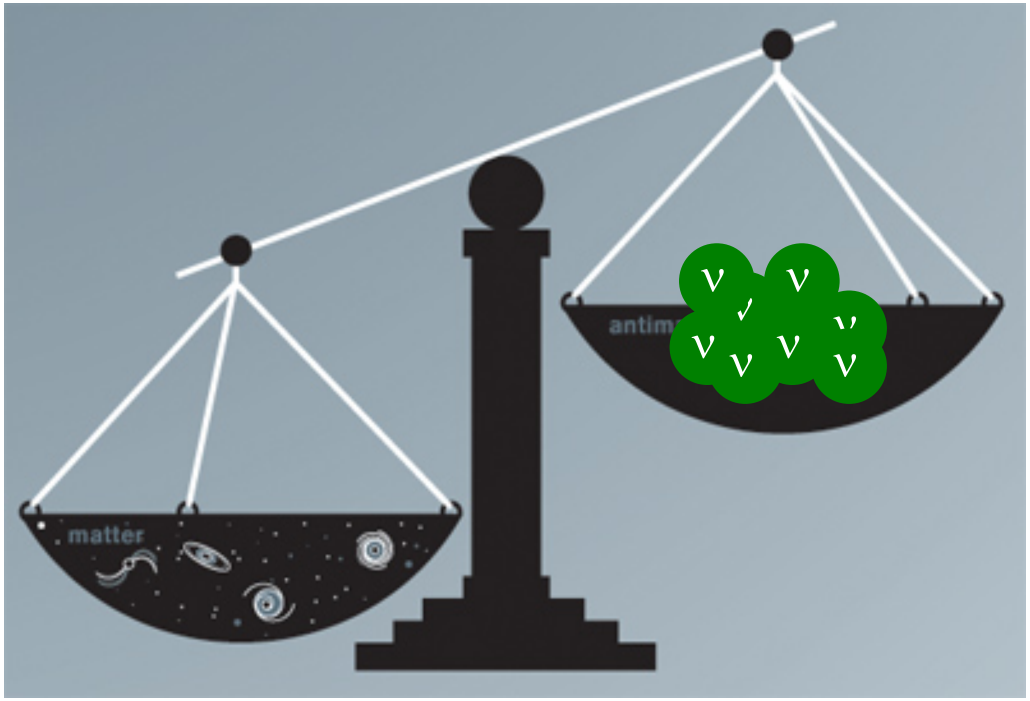
The other big open questions

Absolute mass scale: minimum m_ν

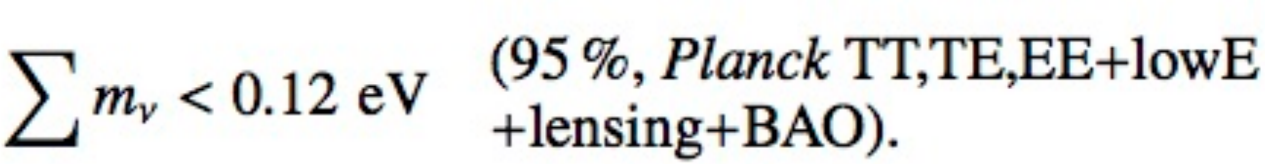
Are neutrinos Majorana and if so, what new physics lies behind this fact ?

Absolute ν mass scale

Best constraints at present from cosmology



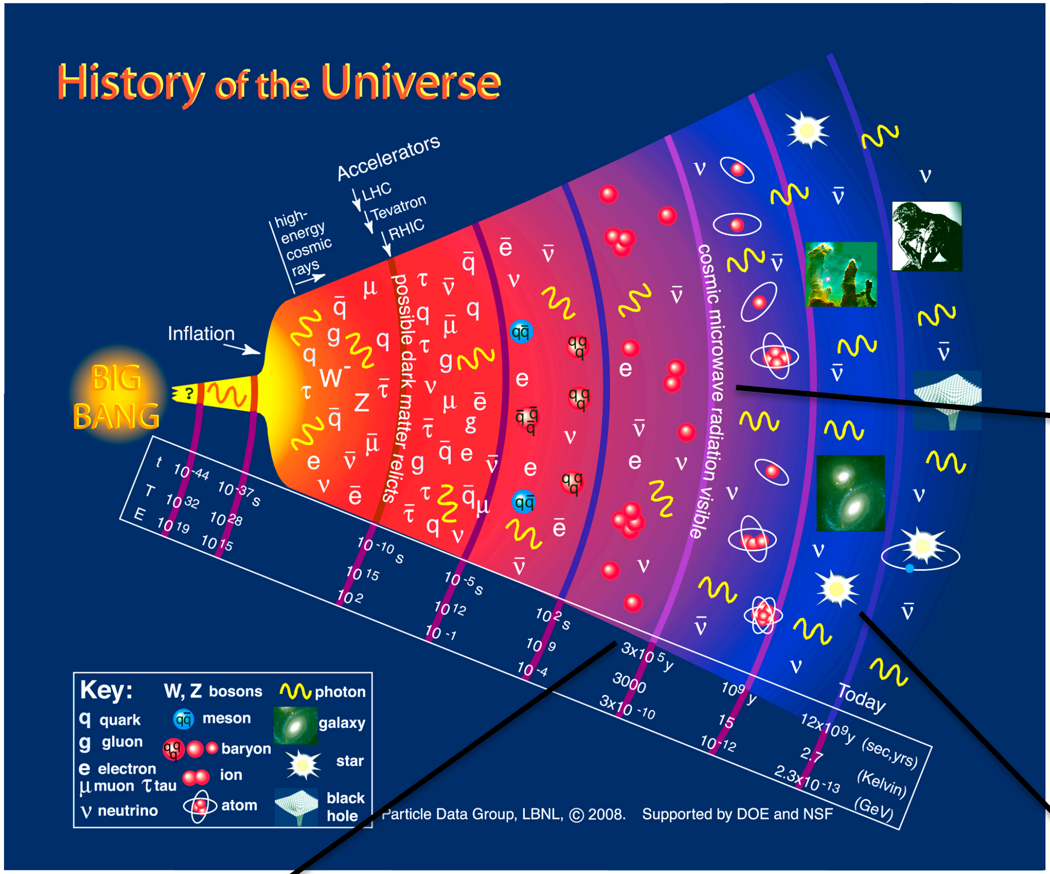
Planck ‘18



$$\sum m_\nu < 0.12\ \mathrm{eV}$$ (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

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_ν ~1MeV the ratio neutrons/protons freezes and light elements start to form:

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

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

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

Neutrinos as DM

Neutrino distribution gets frozen at BBN when they are still relativistic

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

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

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

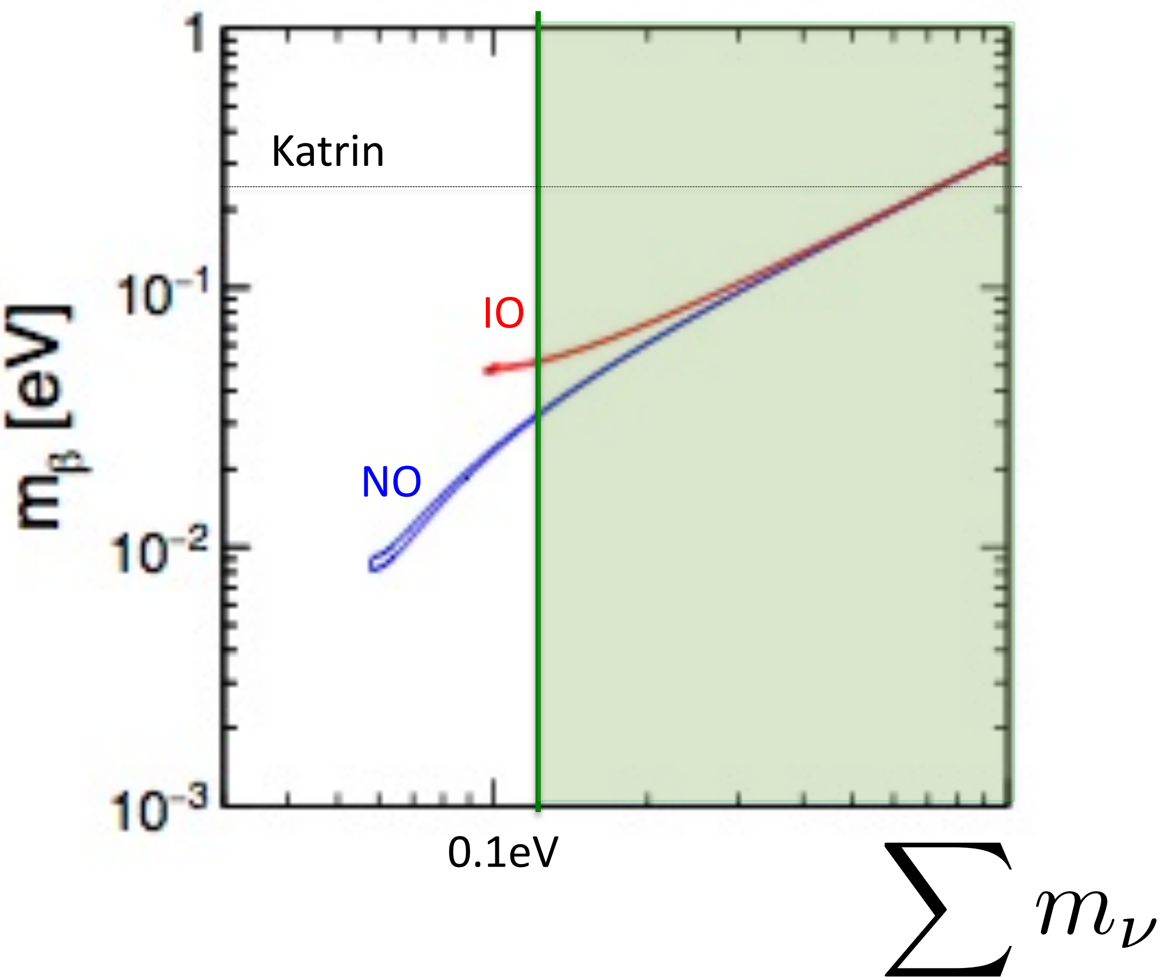
Gershtein, Zeldovich

Massive neutrinos O(eV) contribute significantly to Ω_m

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

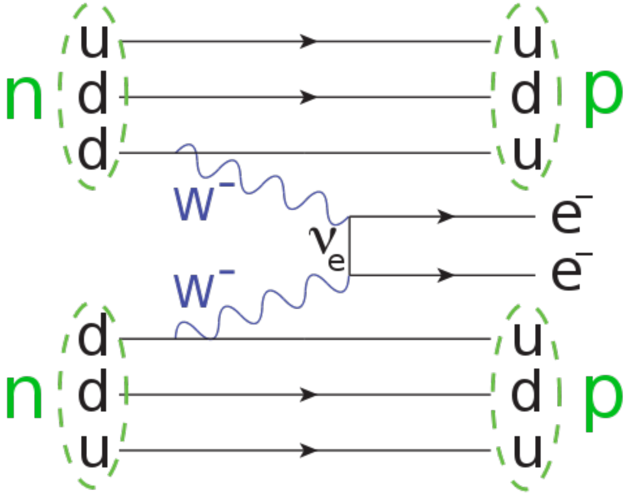
Absolute ν mass scale

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



Majorana nature: ββ0ν

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

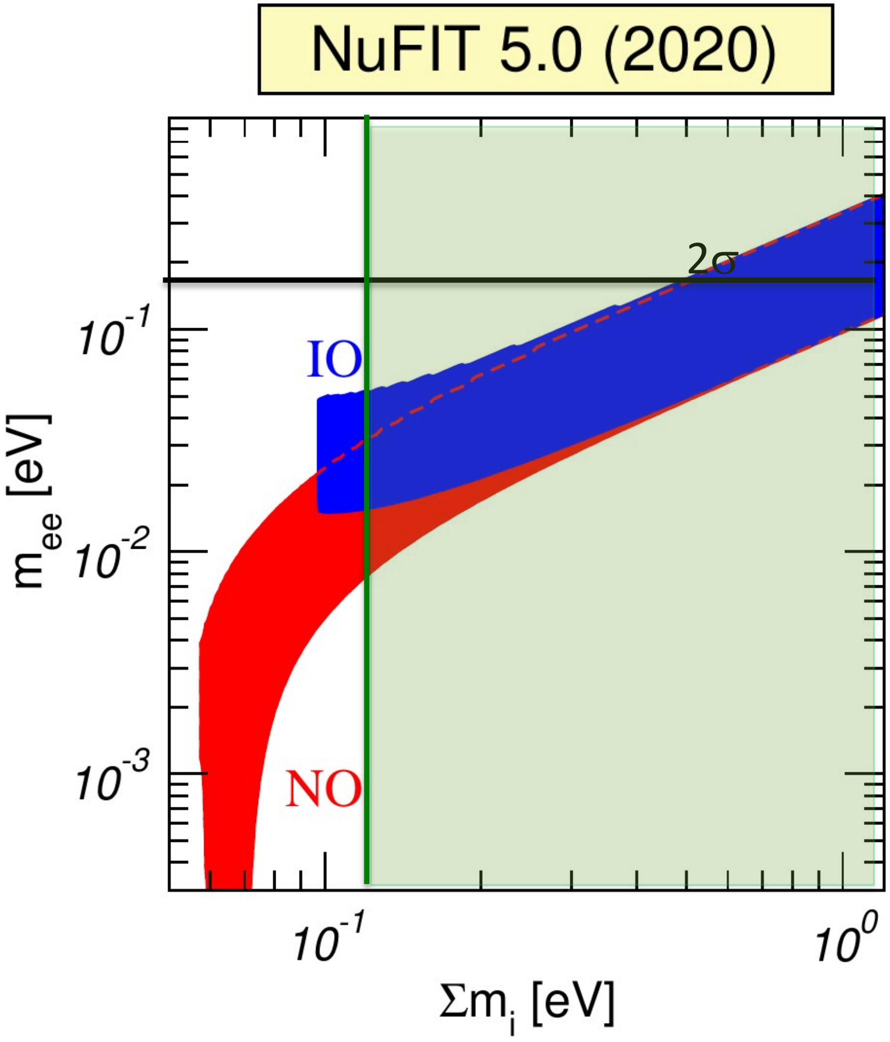


$$T^{-1}_{2\beta 0\nu} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear M.E.}} \underbrace{\left|\sum_i \left(V^{ei}_{MNS}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

$$|m_{ee}| = |c^2_{13}(m_1 c^2_{12} + m_2 e^{i\alpha} s^2_{12}) + m_3 e^{i\beta} s^2_{13}|$$

Majorana nature: ββ0ν

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



Next generation of experiments @Ton scale to cover the IO region

Massive neutrinos: a new flavour perspective

Why do they mix so differently ?

CKM

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

$$J = (3.18 \pm 0.15) \times 10^{-5}$$

NuFIT 5.0 (2020)

PMNS

$$|U|^{\text{w/o SK-atm}}_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.631 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}$$

$$J \simeq 0.033 \sin\delta$$

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 large mixing comes from ?

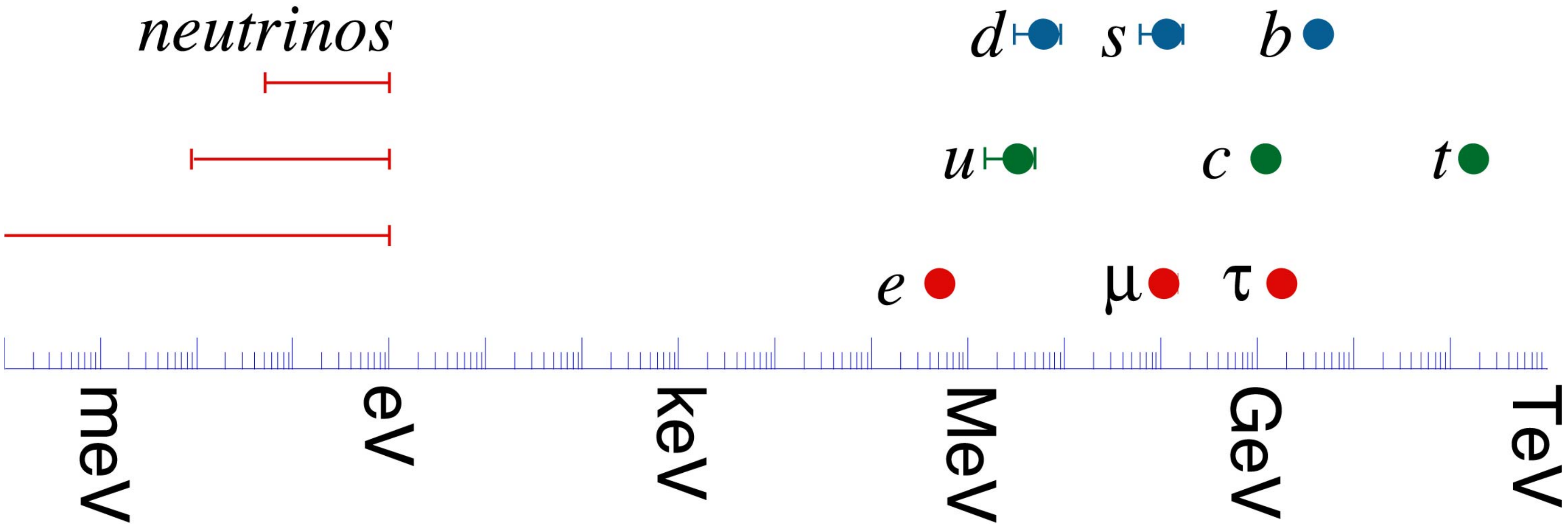
Anarchy for leptons

Discrete or continuous symmetries

Lepton-quark flavour connection in GUTs ?

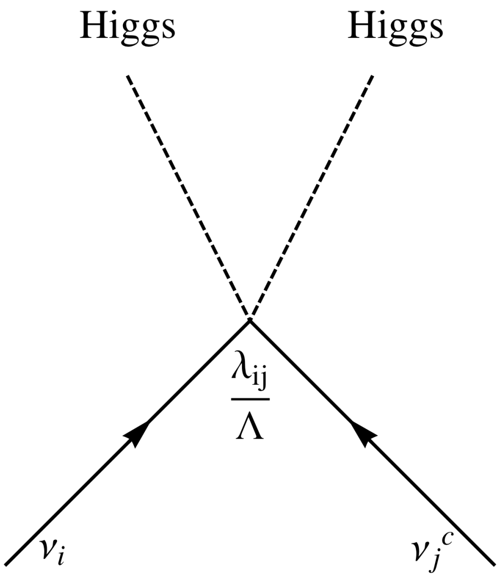
Massive neutrinos: a new flavour perspective

Why are neutrinos so much lighter ?



They get their masses differently!

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



νSM ?

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

Scale at which new
particles will show up

What originates the neutrino mass ?

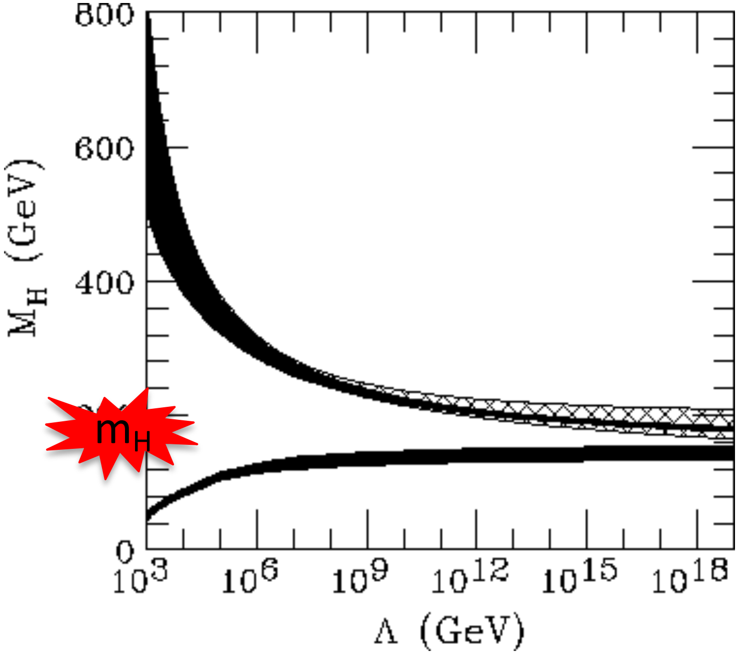
Could be $\Lambda >> v$… the standard lore (theoretical prejudice ?)

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

Hierarchy problem $m_H^2 \propto \Lambda^2$ 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…

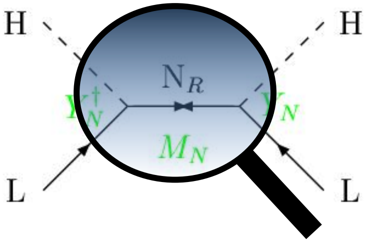


Could be naturally $\Lambda \sim v$?

Yes ! λ in front of neutrino mass operator must be small…

Resolving the neutrino mass operator at tree level

Type I see-saw:
a heavy singlet scalar

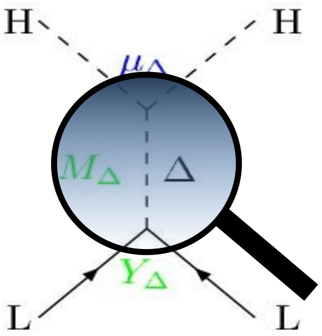


$$m_\nu = \frac{\overset{\lambda}{\cancel{\alpha}} v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

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

Type II see-saw:
a heavy triplet scalar



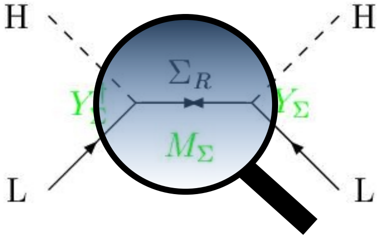
$$m_\nu = \frac{\overset{\lambda}{\cancel{\alpha}} v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

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

E. Ma

Type III see-saw:
a heavy triplet fermion

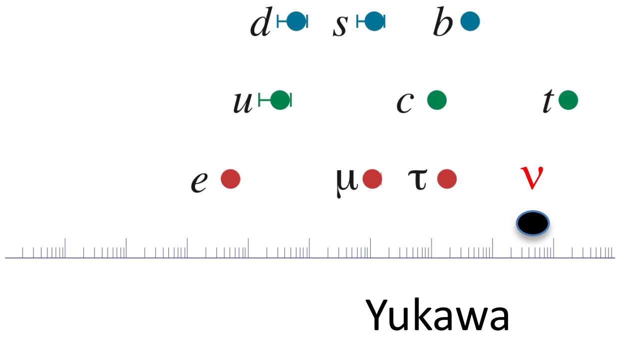


$$m_\nu = \frac{\overset{\lambda}{\cancel{\alpha}} v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

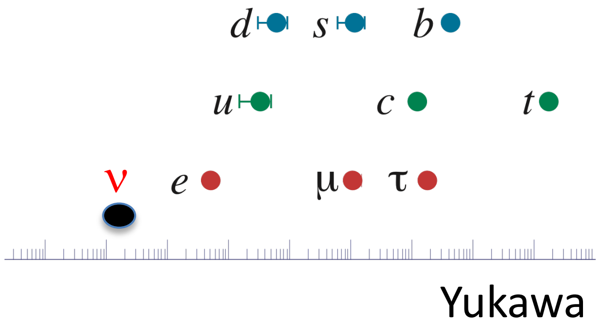
Foot et al; Ma;
Bajc, Senjanovic…

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

$M_N \sim$ GUT



$M_N \sim \nu$



Where is the new scale ?

Generic predictions

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

model independent contribution from the neutrino mass

Where is the new scale ?

Leptogenesis

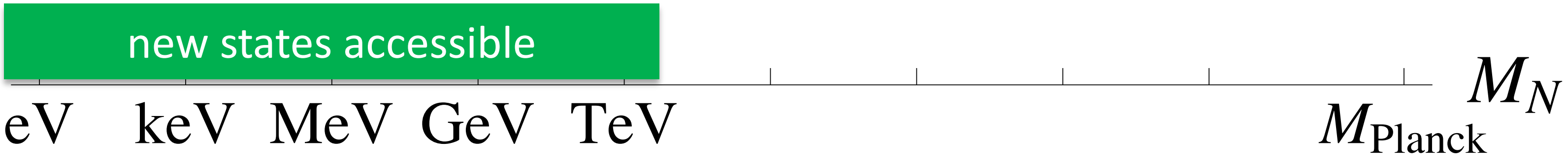
eV keV MeV GeV TeV M_{Planck} M_N

Generic predictions:

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

model dependent… 😪

Where is the new scale ?



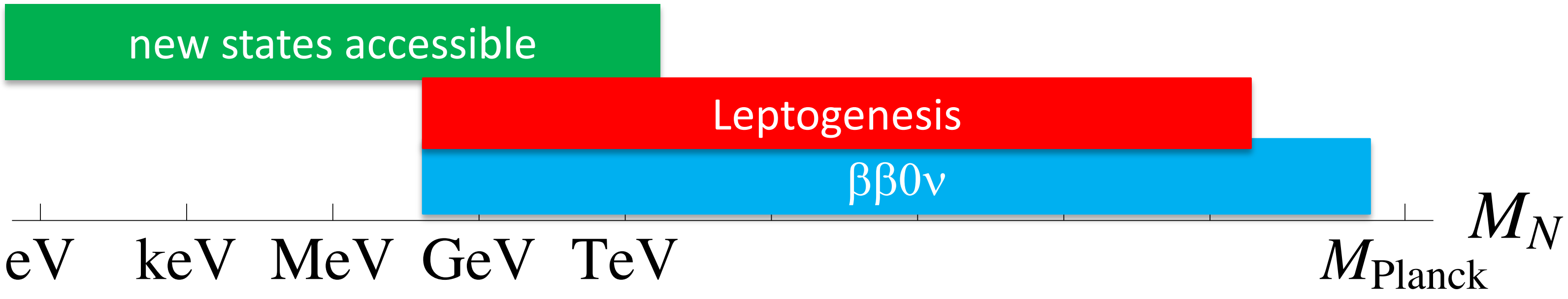
Generic predictions:

- ➢ 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 ?

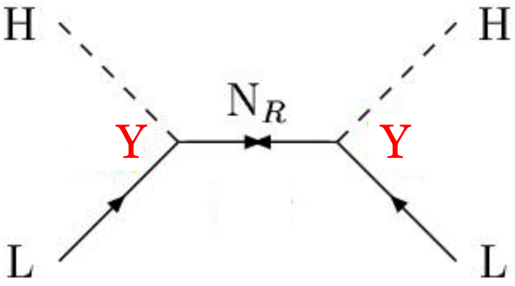


The EW scale is an interesting region: new physics underlying the
matter-antimatter asymmetry
could be predicted & tested !

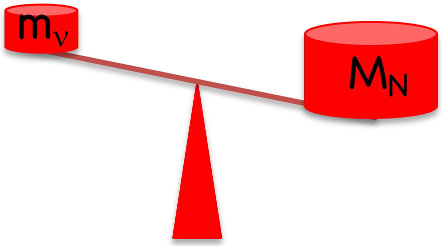
Minimal model of neutrino masses:

Type I seesaw: SM+right-handed neutrinos

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



$n_R \geq 2$

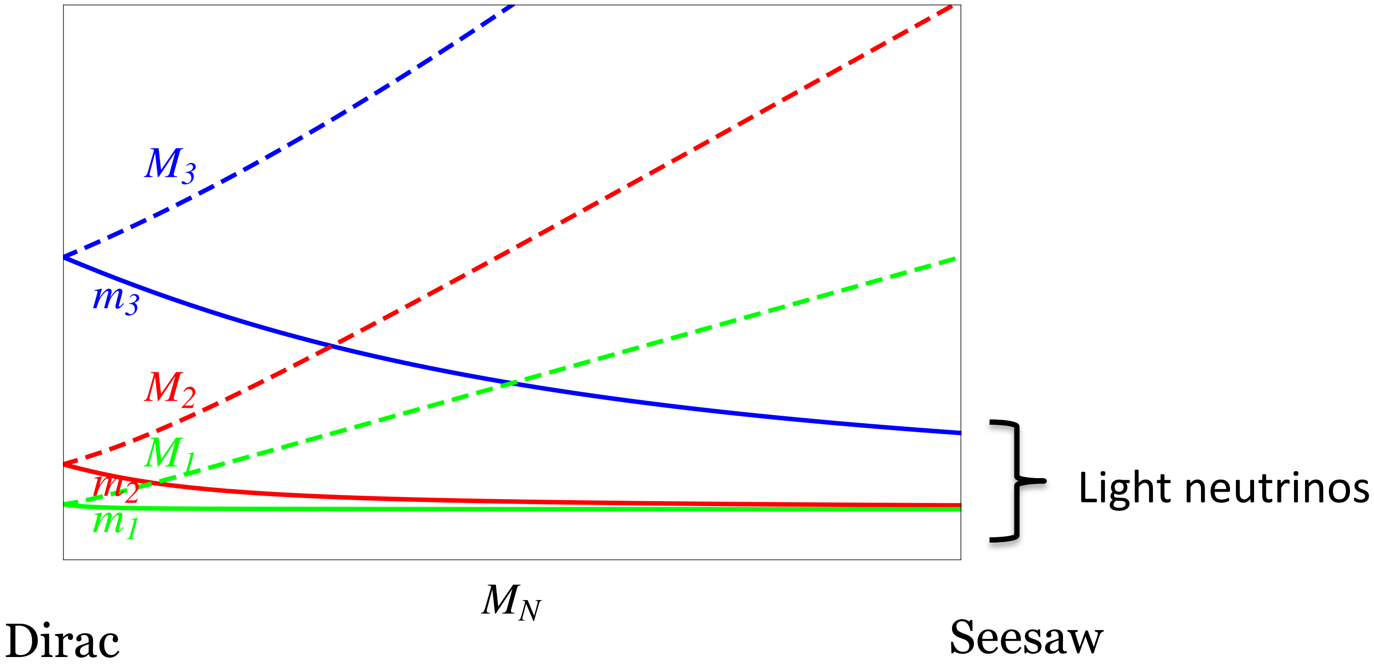


$$m_\nu = \lambda \frac{v^2}{\Lambda} \equiv Y^T \frac{v^2}{M} Y$$

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…

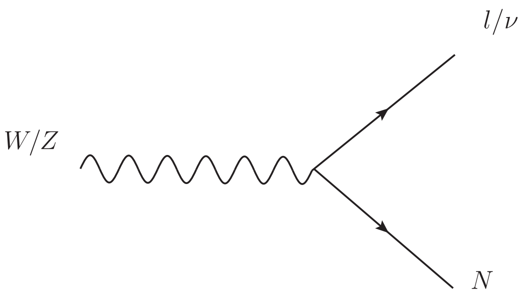


Type I seesaw models

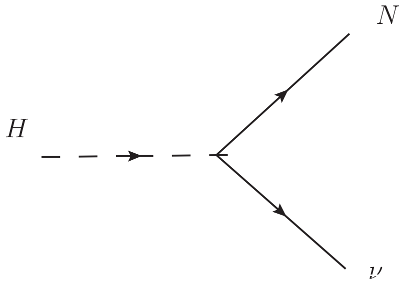
Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

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

Type I seesaw models



$$U_{lh}$$



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

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

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:

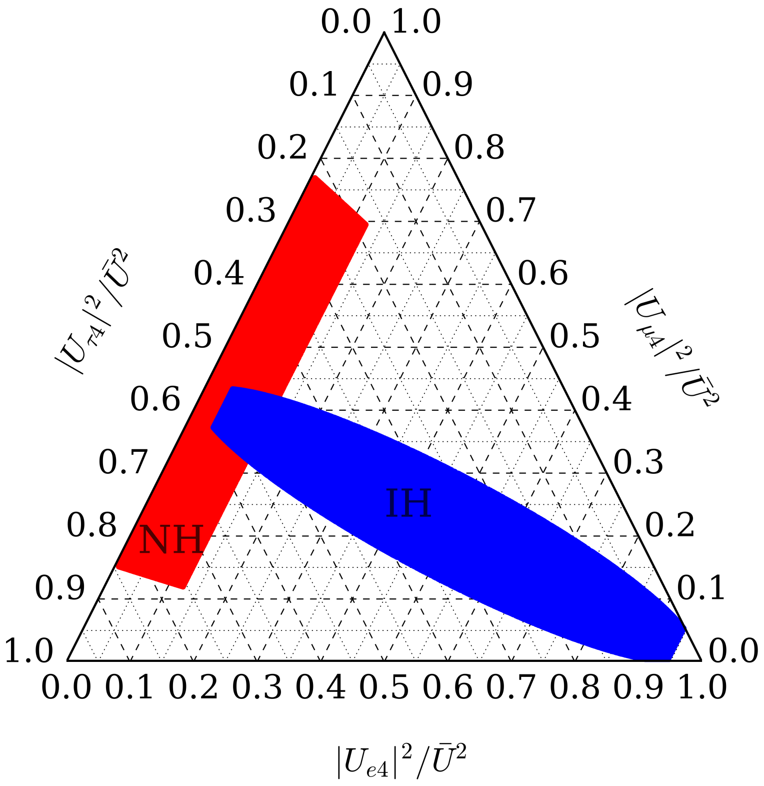
$$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$

(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

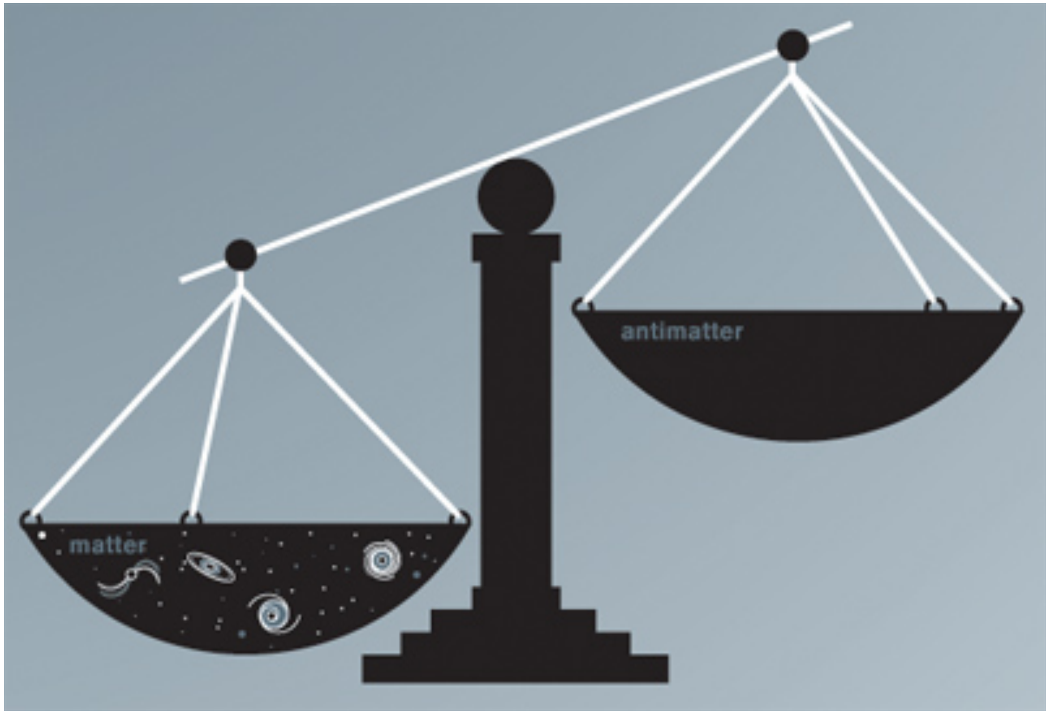
n_R=2:



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

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 to generation of lepton and therefore baryon asymmetries

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

Fukuyita, Yanagida

II Resonant leptogenesis $M_N > 100$ GeV

Pilaftsis…

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

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)

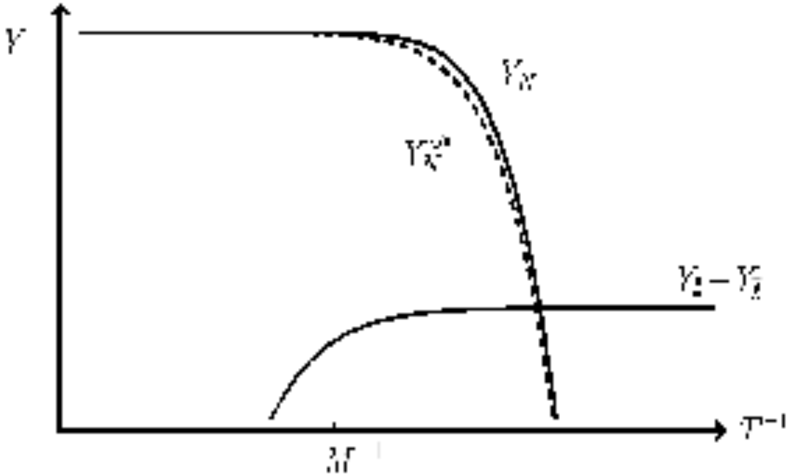
✓ B+L violation from sphalerons T > T_{EW}

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

✓ Out of equilibrium condition: different for low and high scales

High-scale leptogenesis

(larger Y)

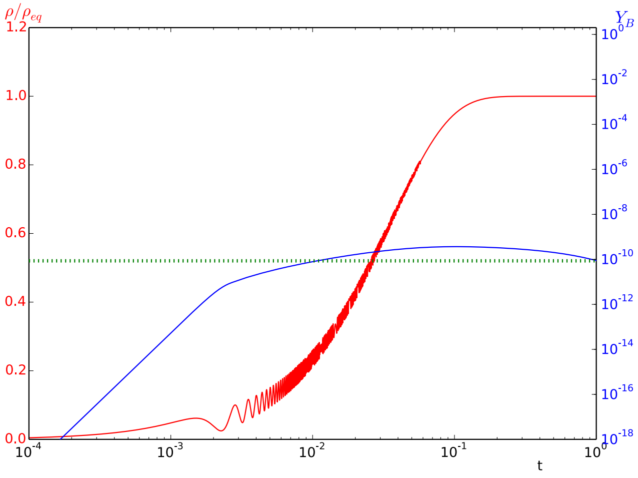


$$\Gamma_N \leq H(M_N)$$

(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 ?

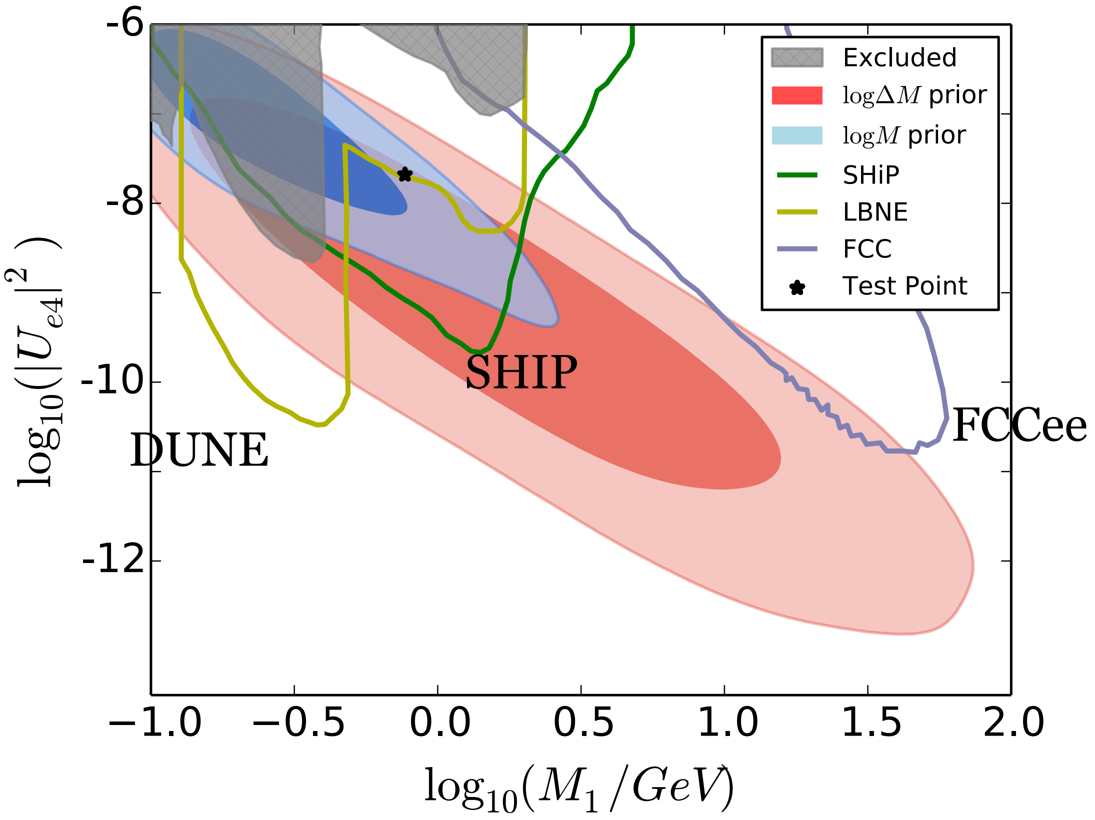
- Y_B cannot be determined from neutrino masses and mixings only

- 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 !

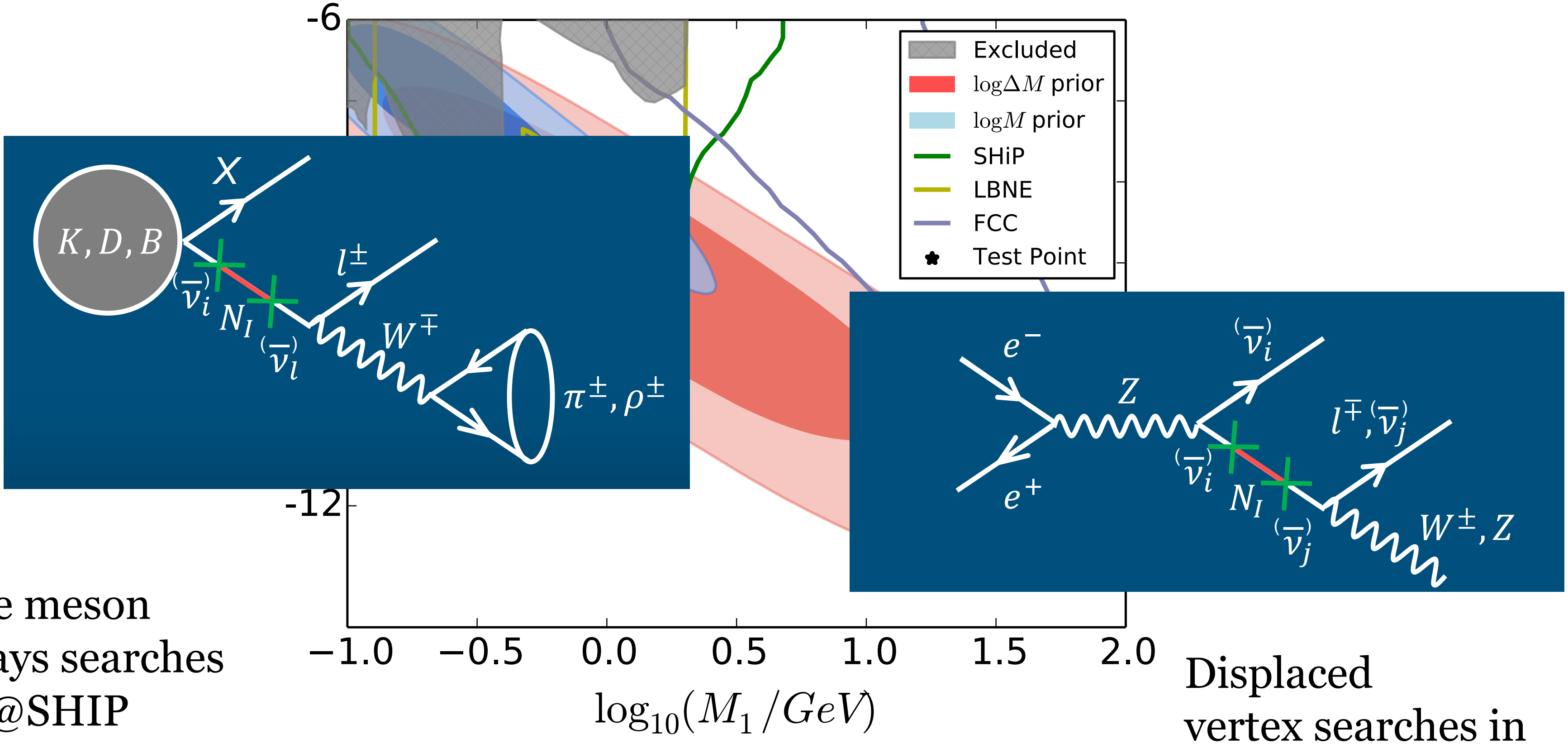
In the minimal model with just n_R=2 neutrinos (IH)



PH, Kekic, Lopez-Pavon, Racker, Salvado

Colored regions: posterior probabilities of successful Y_B (for not too degenerate states)

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 $n_R=2$?

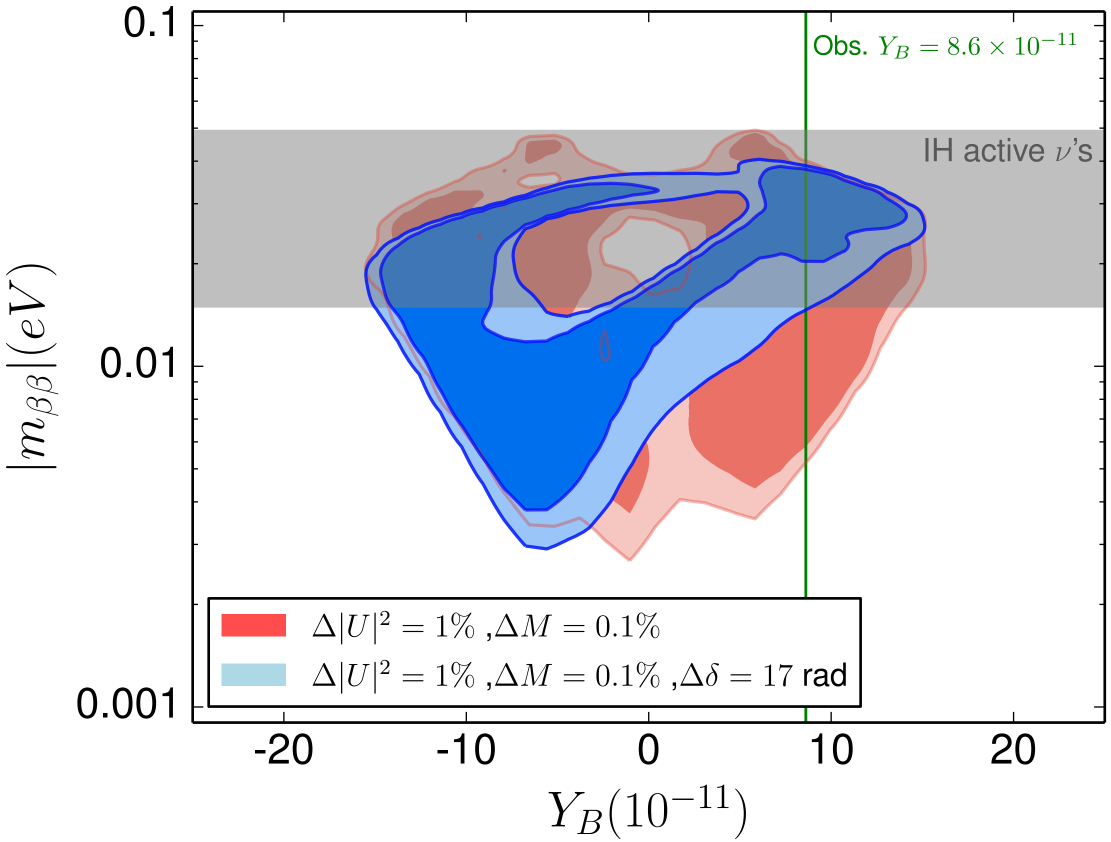
Assume a point within SHIP reach that gives the right baryon asymmetry

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

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

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

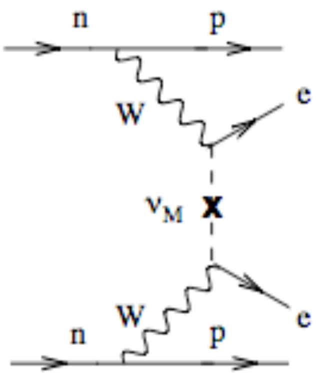
Predicting Y_B in the minimal model n_R=2 (IH)



PH, Kekic, Lopez-Pavon, Racker, Salvado

Predicting Y_B in the minimal model $n_R=2$

Heavy states also contribute to the ββ0ν amplitude…



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

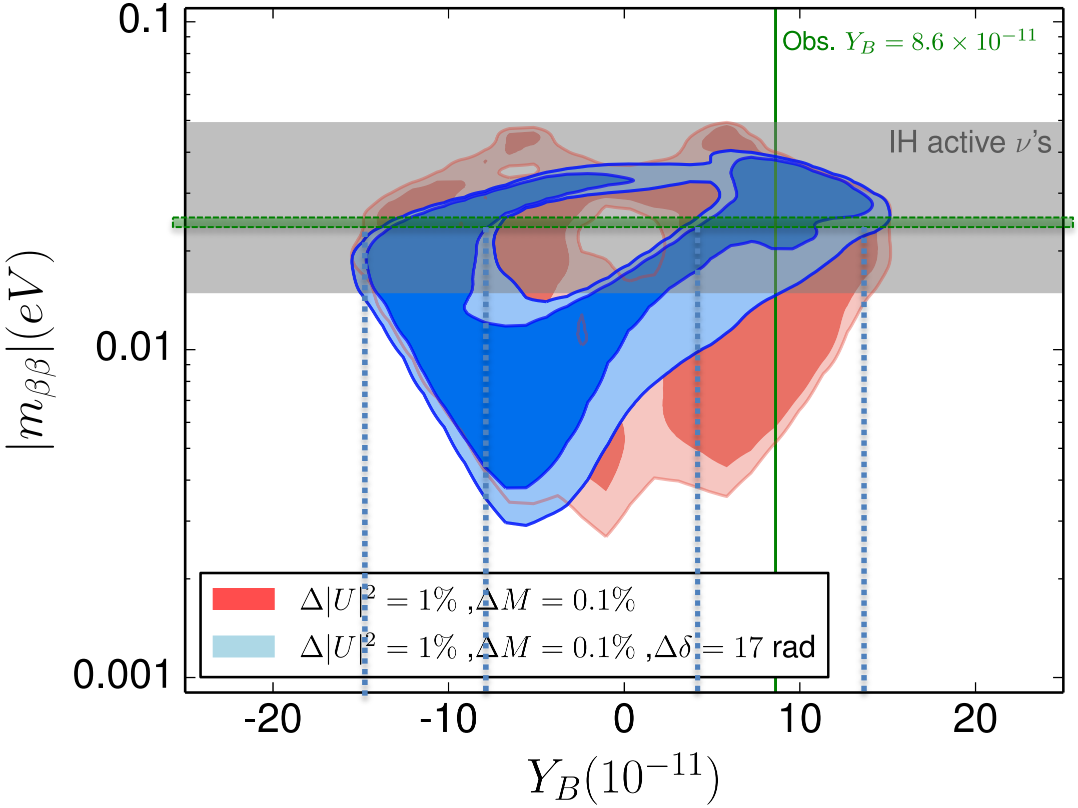
$$M_j \to \infty \qquad \frac{\mathcal{M}^{0\nu\beta\beta}(M_j)}{\mathcal{M}^{0\nu\beta\beta}(0)} \propto \left(\frac{100\ \text{MeV}}{M_j}\right)^2$$

the heavy contribution is sizeable for M_i of O(GeV)

Blennow,Fernandez-Martinez, Lopez-Pavon, Menendez;
Lopez-Pavon, Pascoli, Wong; Lopez-Pavon, Molinaro, Petcov

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

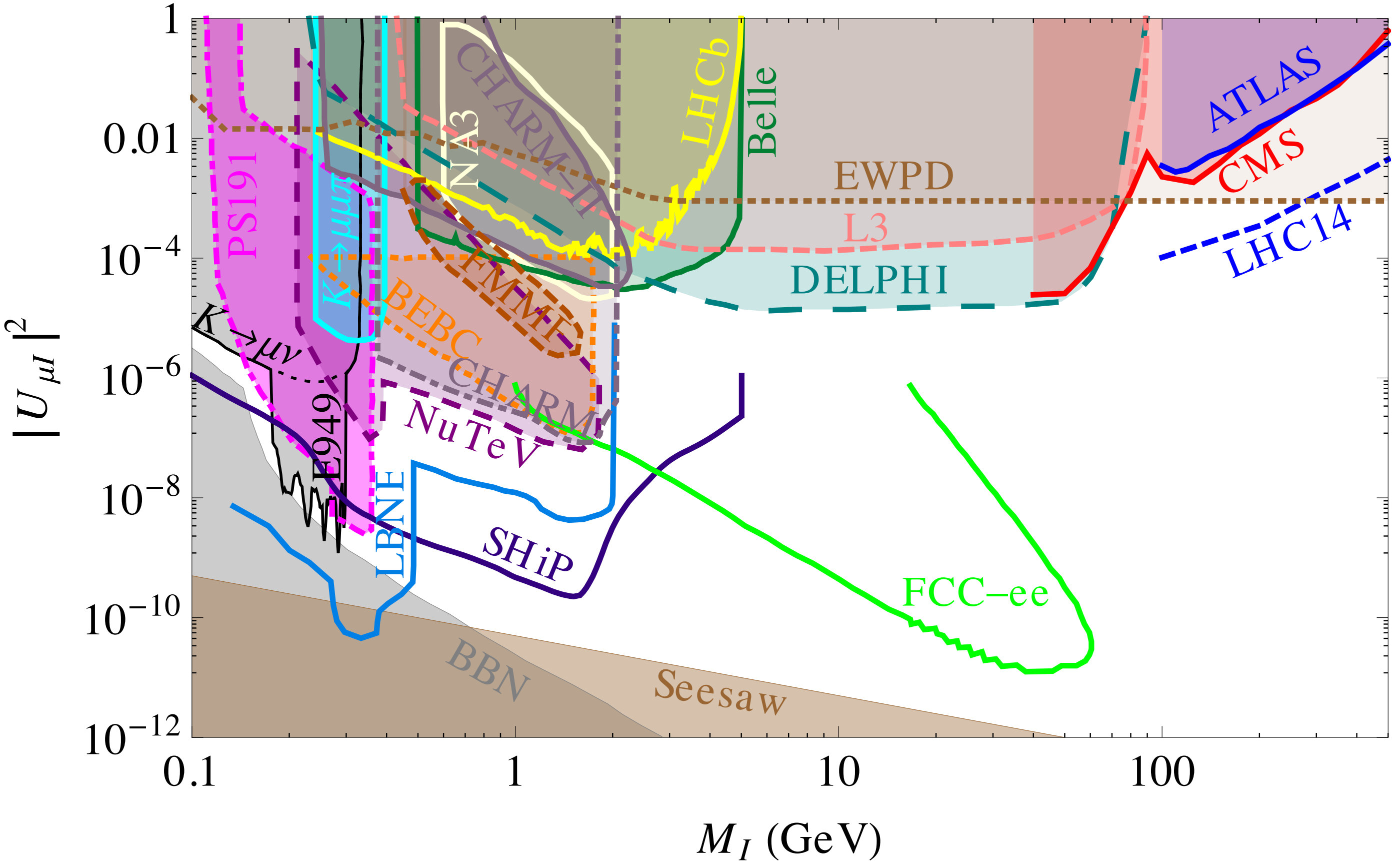
Predicting Y_B in the minimal seesaw model M~GeV



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

Looking for neutrino mass mediators in the EW region



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

Bounds in the EW 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

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

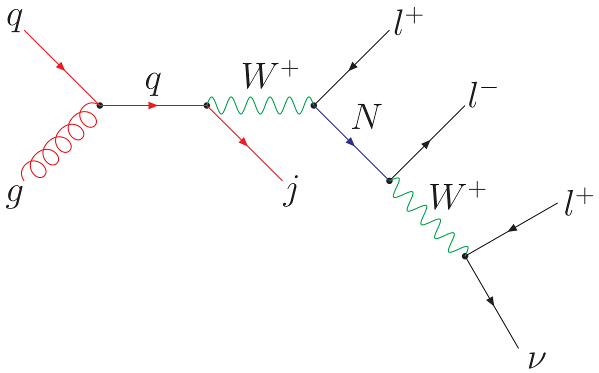
direct seesaw
inverse seesaw
extended seesaw

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) ~ $\mathcal{O}(\mu, \mu', \varepsilon)$
- Yukawa hierarchies

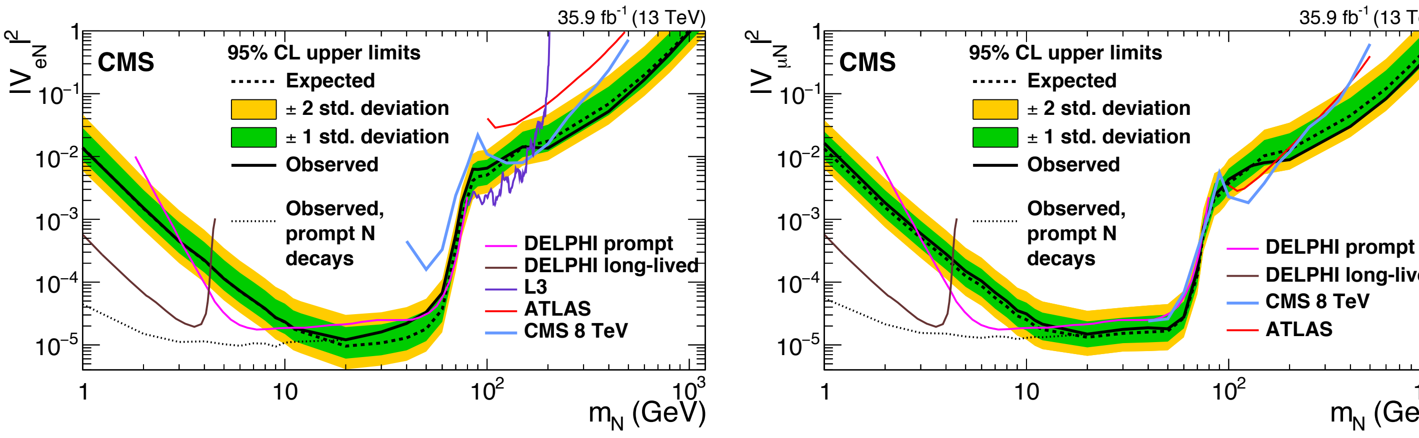
Look for LNC processes ! Can we test their Majorana nature ?

LNC @LHC: trilepton + missing energy



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

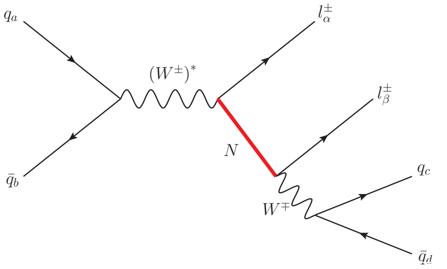
CMS '18

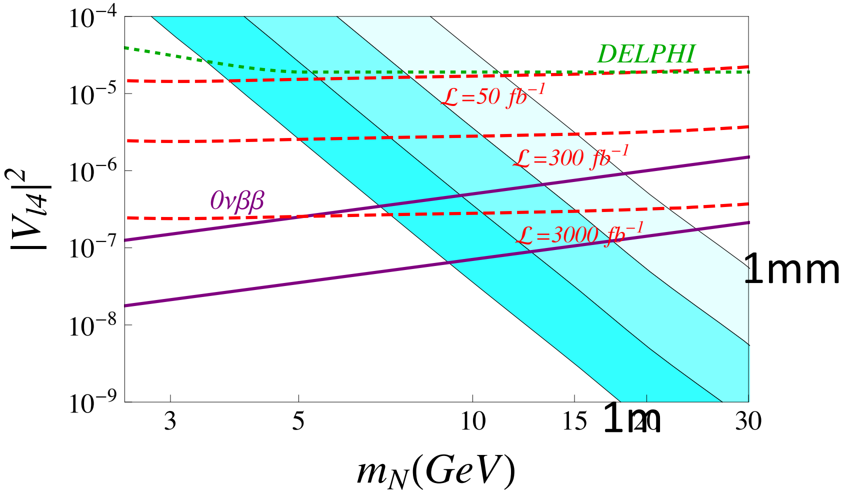


Reaching significantly lower mixings (& lower masses) via displaced decays

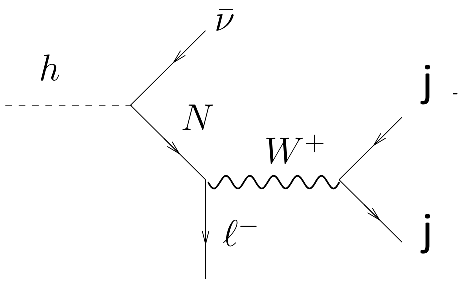
Helo, Kovalenko, Hirsch ; Gago, PH, Jonez-Perez, Losada, Moreno;
Blondel, Graverini,Serra, Shaposhnikov;Antush, Cazzato, Ficher;…

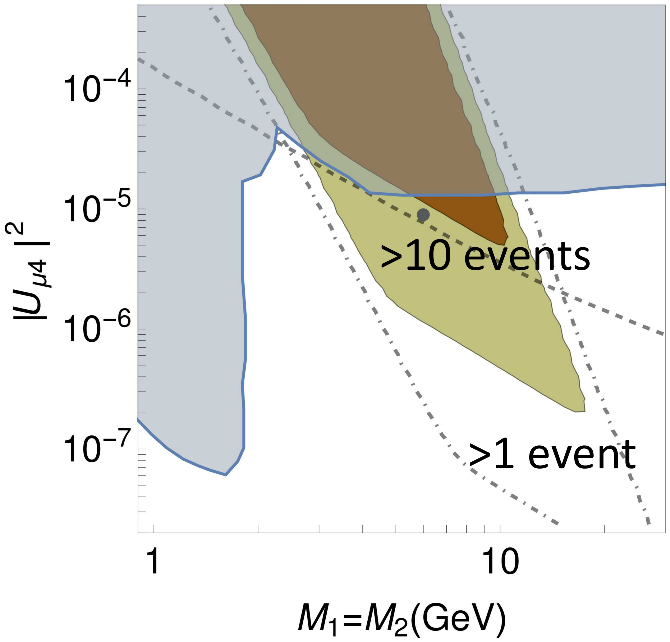
Golden signal: Displaced Vertices



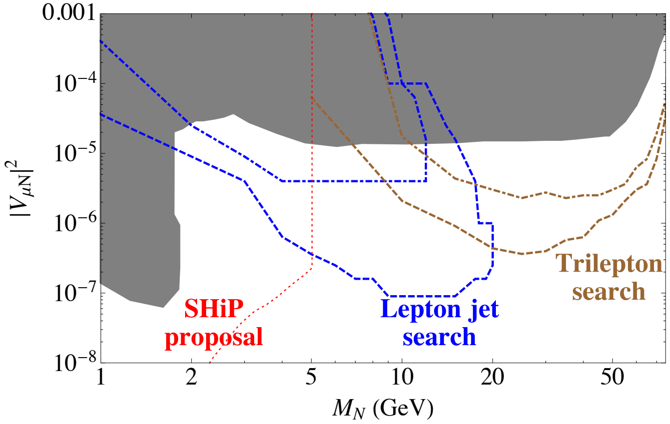


Helo, Kovalenko,Hirsch





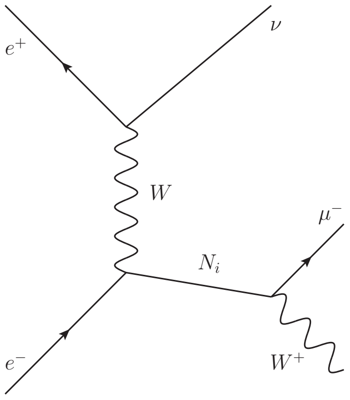
Gago, PH, Jones-Perez, M.Losada, A. Moreno



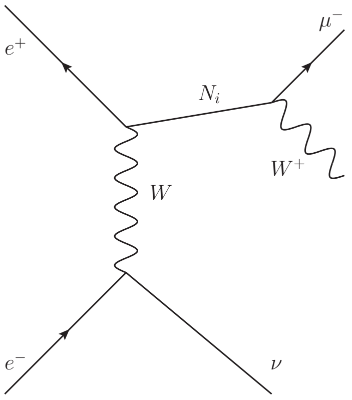
Izaguirre, Shuve

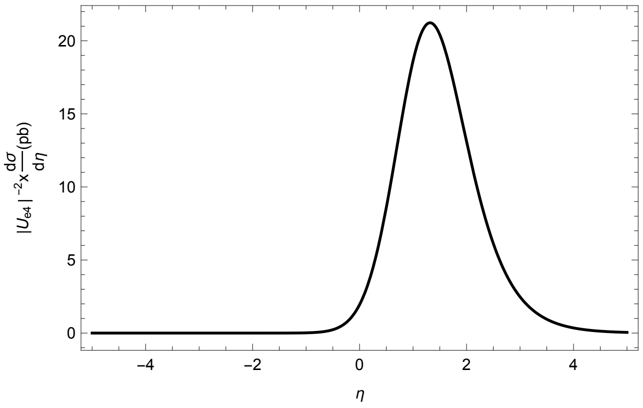
Majorana vs pseudo-Dirac @ e+e-

A

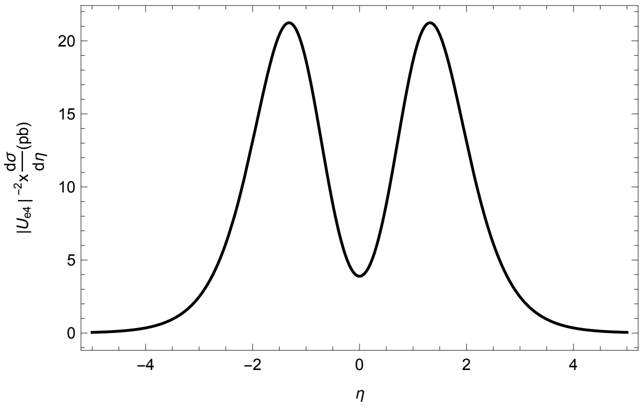


B



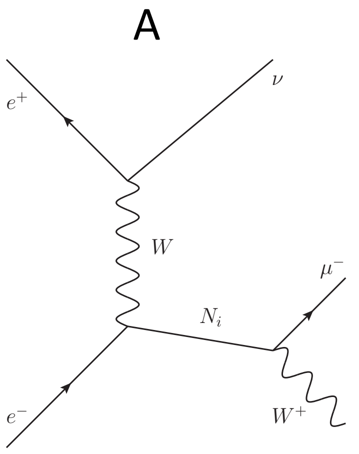


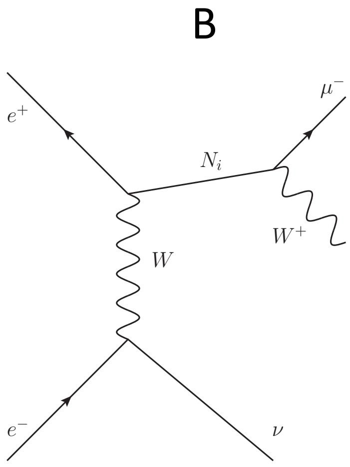
A ⇔ LNC



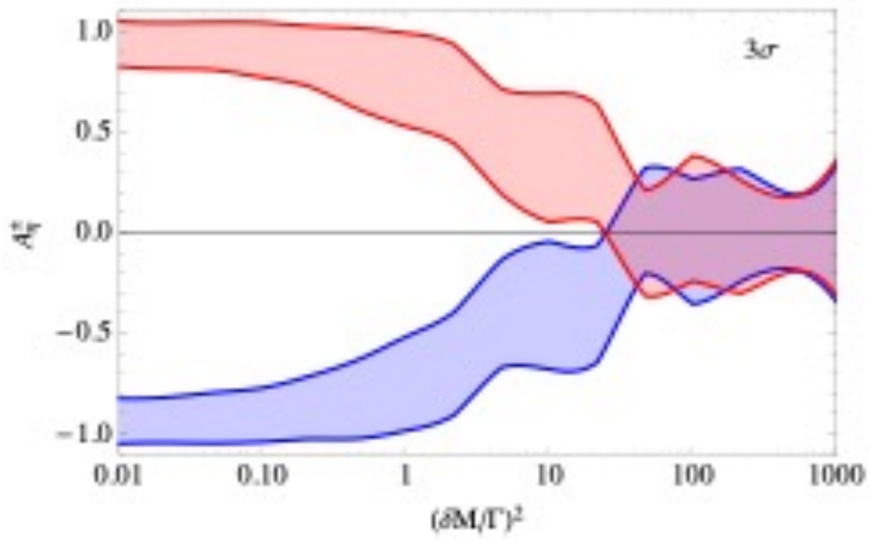
A+B ⇔ LNV

Majorana vs pseudo-Dirac @ e+e-





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



, Jones-Pérez, Suárez-Navarro

Beyond the minimal model

Many possibilities:

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

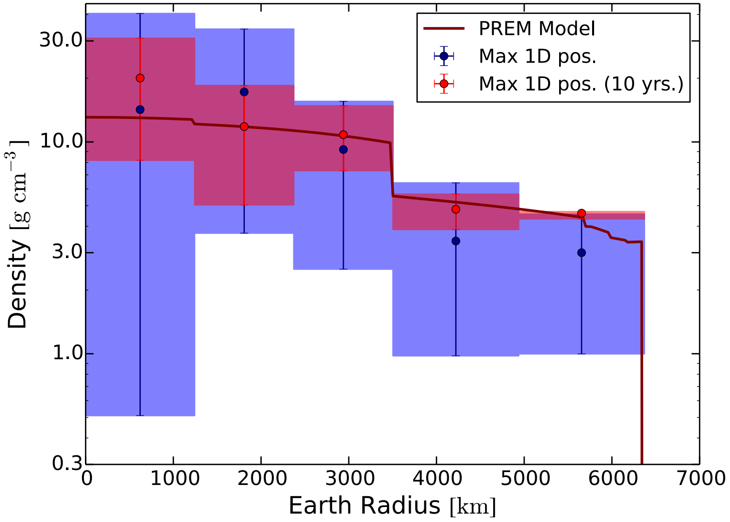
Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic;
Ferrari et al + many recent refs…

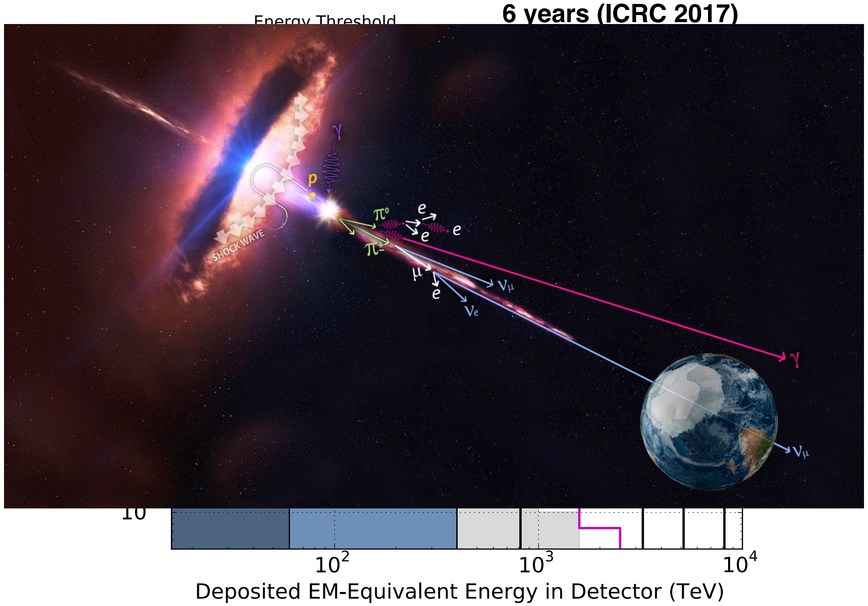
- Generically new gauge interactions can enhance the production in colliders: richer phenomenology
- But also make leptogenesis more challenging (out-of-equilibrium condition harder to meet)

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

Understand the Earth

Understand Astrophysical sources





Donini, Palomares-Ruiz, Salvado, 1803.05901

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)

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