Theory of neutrino masses and leptonic mixing

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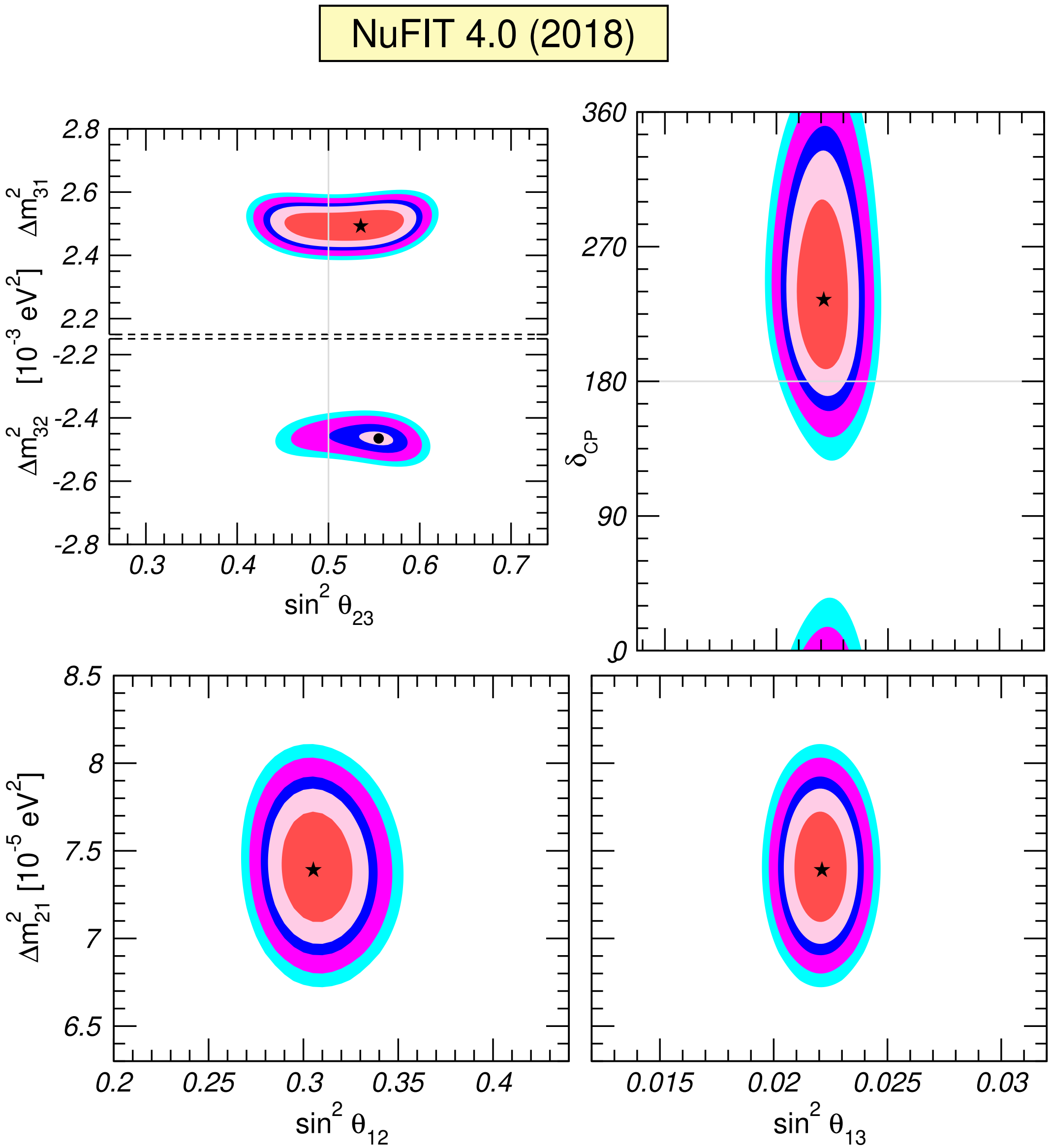
Durham University ~IP3~ elusives invisiblesPlus erc European Research Council νmass

Neutrino properties after Neutrino 2018



http://www.nu-fit.org/

M. C. Gonzalez-Garcia et al., 1811.05487

Neutrinos have masses and mix!

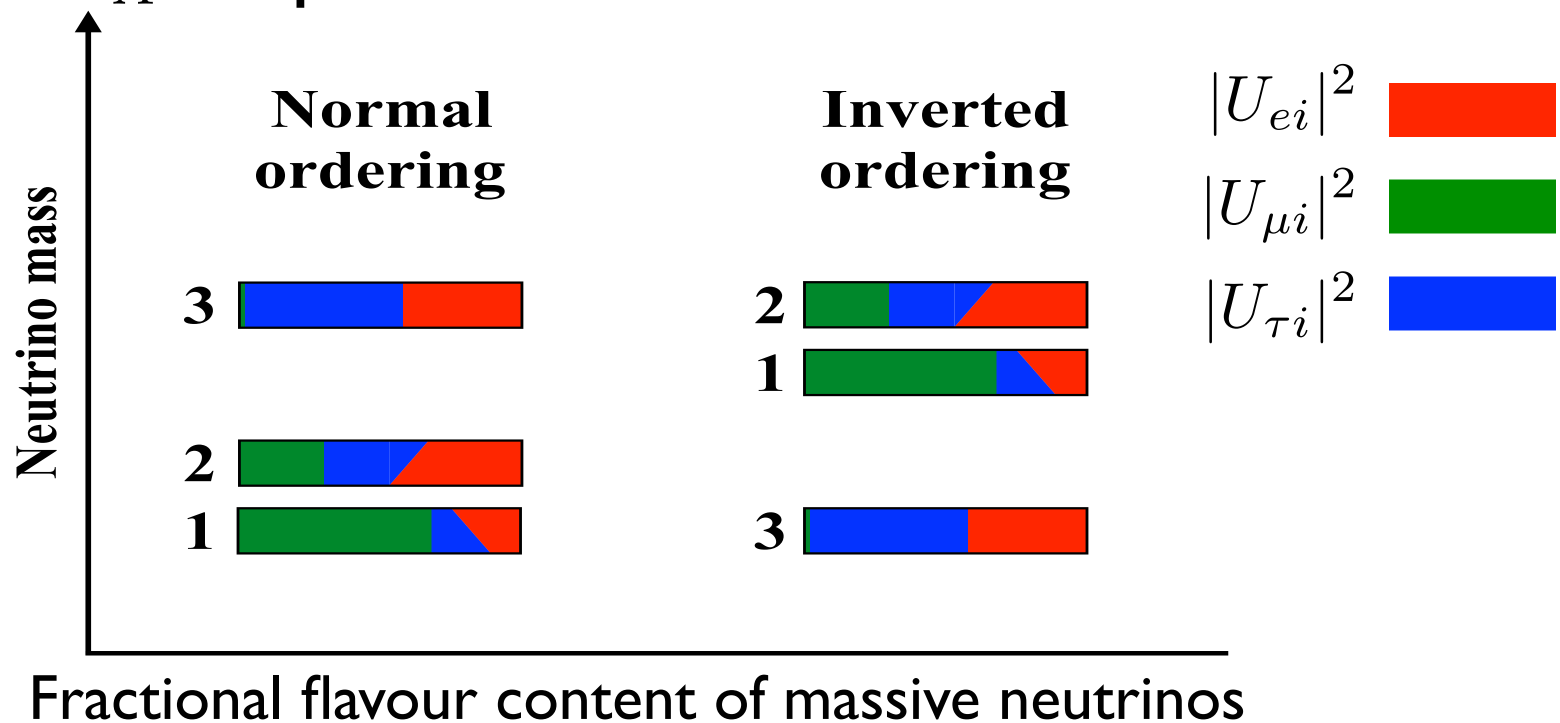
Current knowledge of neutrino properties:

- 2 mass squared differences
- 3 sizable mixing angles,
- some hints of CPV

See E. Lisi's talk

Neutrino masses

$\Delta m^2_{\rm s} \ll \Delta m^2_{\rm A}$ implies at least 3 massive neutrinos.



$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm sol}}$$
$$m_3 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A} - \Delta m^2_{\rm sol}}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering. Some preference for NO.

Leptonic Mixing and CP-violation

The Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

CPV?

- θ_{23} maximal or close to maximal
- θ_{12} large but significantly different from maximal
- θ_{13} quite large: challenge to flavour models
- Mixings very different from those in the quark sector
- Possibly, large leptonic CPV. This is a fundamental question, possibly related to the origin of the baryon asymmetry and to the origin of the flavour structure.

Phenomenology questions for the future

1. **What is the nature of neutrinos?**

2. **What are the values of the masses?** Absolute scale and the ordering.

3. **Is there CP-violation?**

4. **What are the precise values of mixing angles?**

5. **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Non-unitarity? Other effects?

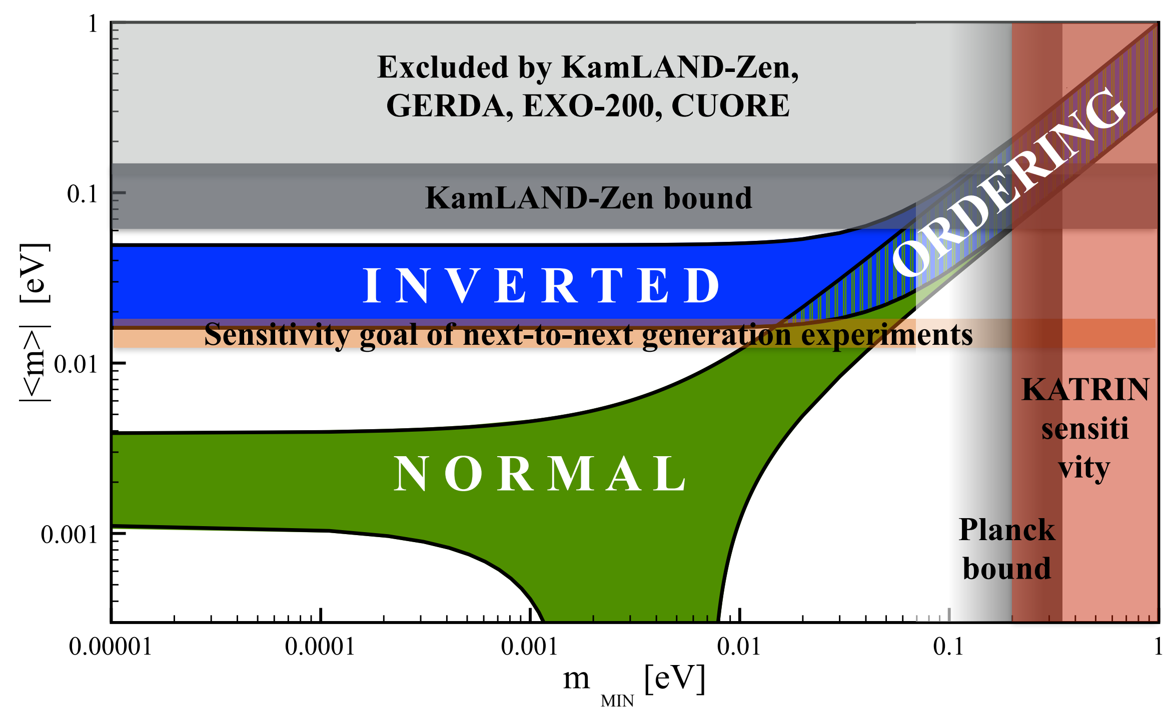
Very exciting experimental programme now and for the future.

1. What is the nature of neutrinos?

Neutrinos can be **Majorana** or **Dirac** particles.

The **nature** of neutrinos is linked to the conservation of **Lepton number (L) =>** Key symmetry for physics **BSM and necessary condition for Leptogenesis.**

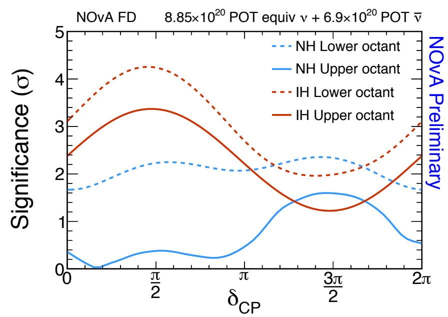
- Tests of LNV:
  - Most sensitive: neutrinoless double beta decay,
  - LNV tau and meson decays, collider searches.



Talk by S. Mertens

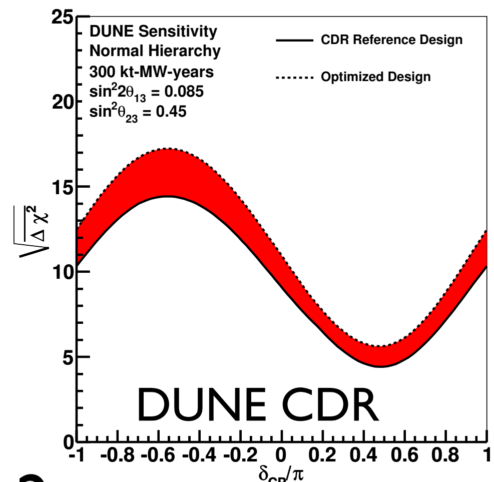
2. *What are the values of the masses?*

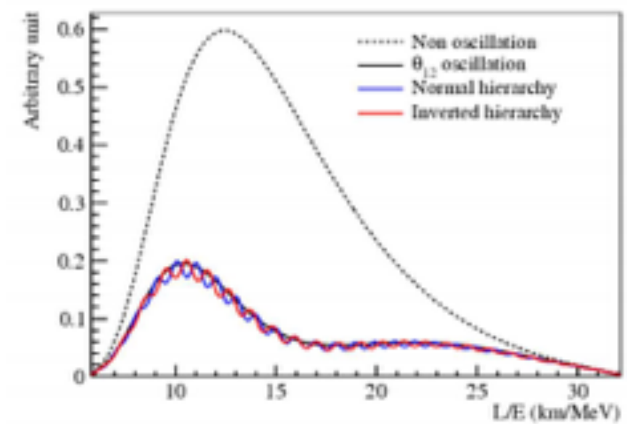
- Mass ordering via neutrino oscillation in matter (DUNE, atmospheric neutrinos) or in vacuum (JUNO). Discovery expected within 10 years. *Talk by M. Mezzetto*



M. Sanchez, for NOvA Coll., Neutrino 2018

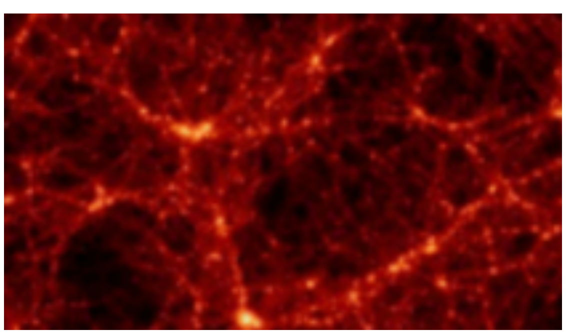
INO, HK, IceCube Gen 2





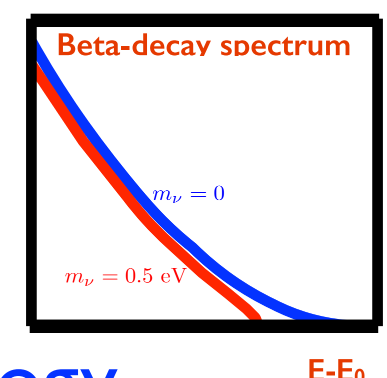
F. An. et al., JUNO Coll., J. Phys. G 43

- Absolute mass scale.

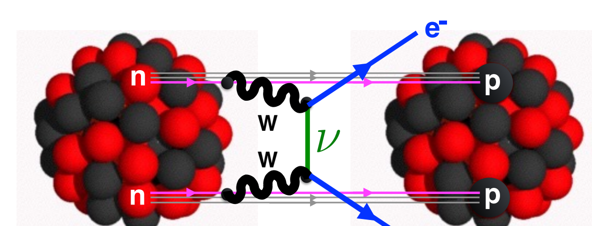


Cosmology

Talk by S. Mertens



Beta decay (KATRIN, Project 8)



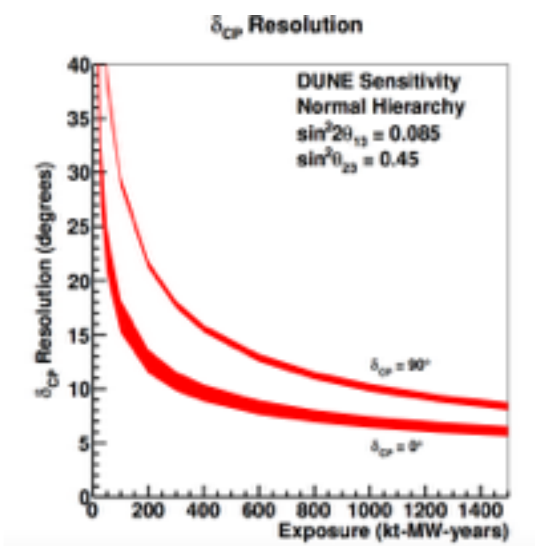
Neutrinoless double beta decay

3. Is there CP-violation?

4. What are the precise values of the mixing parameters?

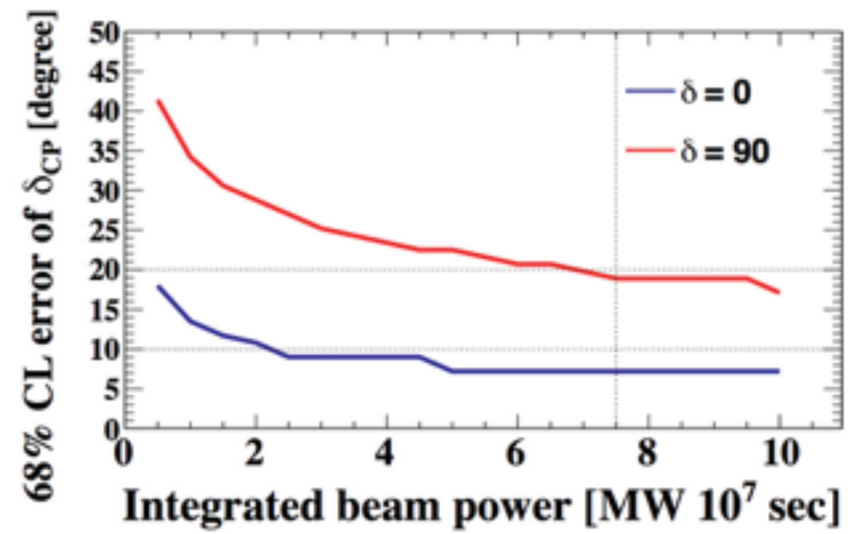
Talk by M. Mezzetto

Hints of leptonic CPV have already been found. T2K and NOvA have been approved for extended running. DUNE and T2HK will get to 5 sigma for a large range of delta.



DUNE CDR

T2HK, PTEP 2015



Once we see CPV, the key issue will be the precise measurement of $\theta_{23}, \theta_{12}, \delta$. Should we start thinking about the following step? Upgrades? ESSnuSB, P2O, Nu factory?

5. Is the standard 3-neutrino picture correct?

Neutrinos are the least known of the SM fermions.

Sterile neutrinos: The experimental strategy depends on their mass. Hints for eV sterile neutrinos are present but controversial. SBL oscillations (MicroBooNE, SBN, reactor neutrino exp…) can test these. *Talk by B. Fleming*

Non standard interactions: brief introduction later.

Dark sector connection (with dark photons, FIPs): neutrino facilities, cosmology, astrophysics. *Talk by N. Serra*

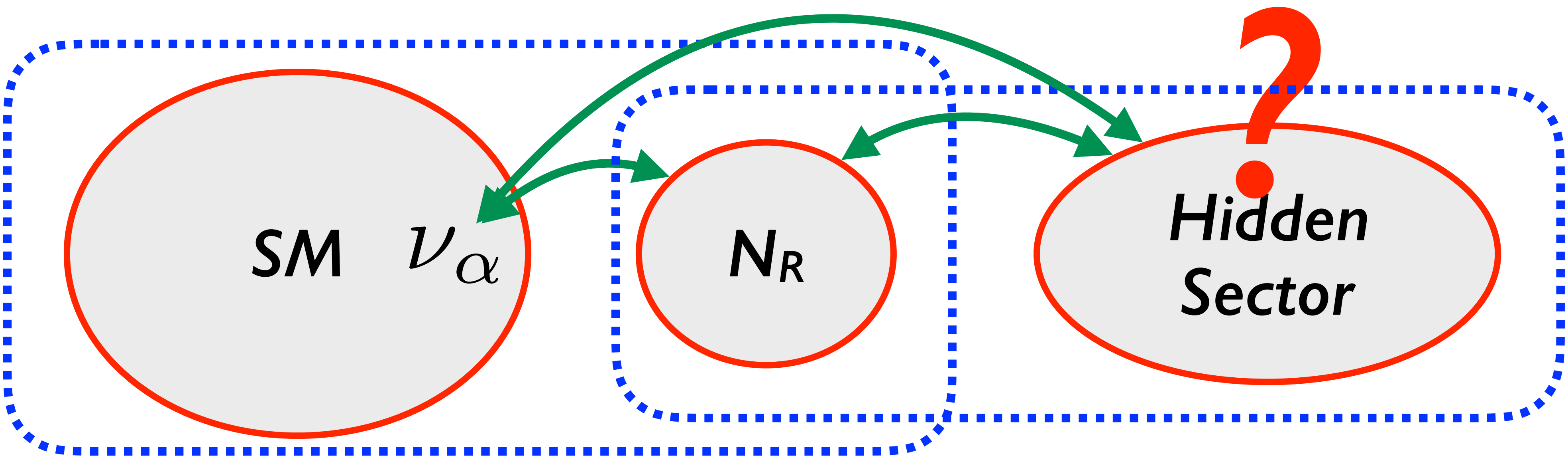
Other exotic effects (decoherence, Lorentz violation…)

The discovery of any signature beyond 3-neutrinos, would be game-changing for experiments and theory.

Neutrino Non Standard Interactions

Neutrinos are one of the key portals to new physics (together with scalar and vector ones).

$$\bar{L} \cdot H N_R \quad (+ ... \overline{N_R} N_S)$$



Generically, gauge invariance implies new interactions for charged leptons, which are very constrained. These can be avoided invoking neutrino mixing.

It is possible to achieve viable large NSI in specific models typically introducing a light new sector.

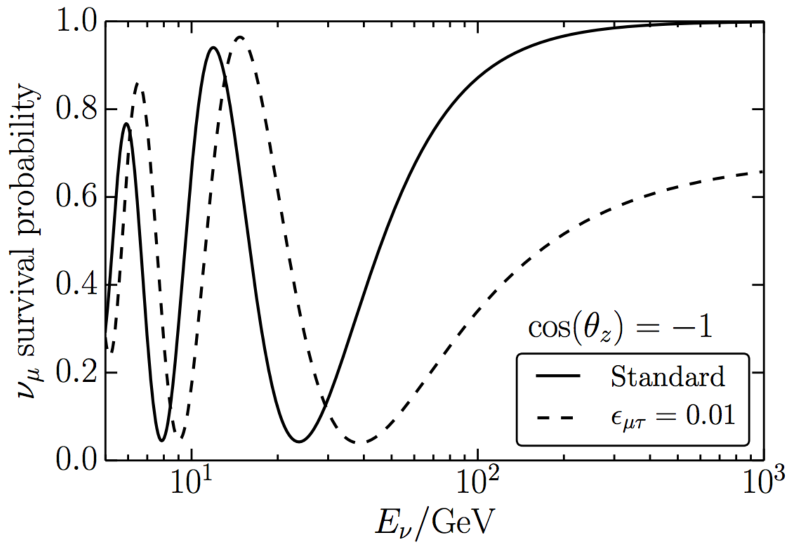
New neutrino interactions would lead to effects in neutrino oscillations, the so-called NSI.

$$\mathcal{L} = -2\sqrt{2}\, G_F\, \epsilon^{\alpha\beta,\delta\eta} (\overline{f_\alpha}\gamma^\mu P_{R,L} f') (\overline{\nu_\delta}\gamma_\mu P_L \nu_\eta)$$

NSI can be tested in SBL (CC in production and detection) and LBL (for NC in propagation) experiments.

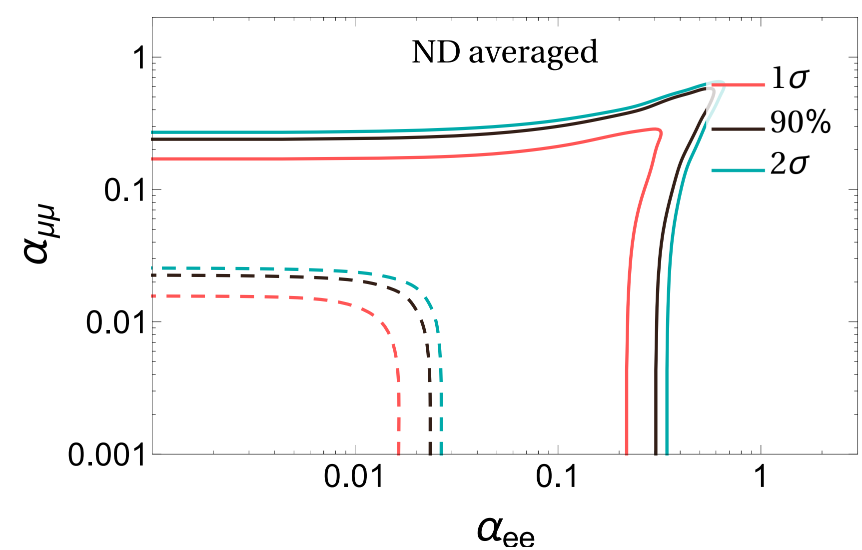
$$H^m = 2\sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

NC NSI affected oscillations



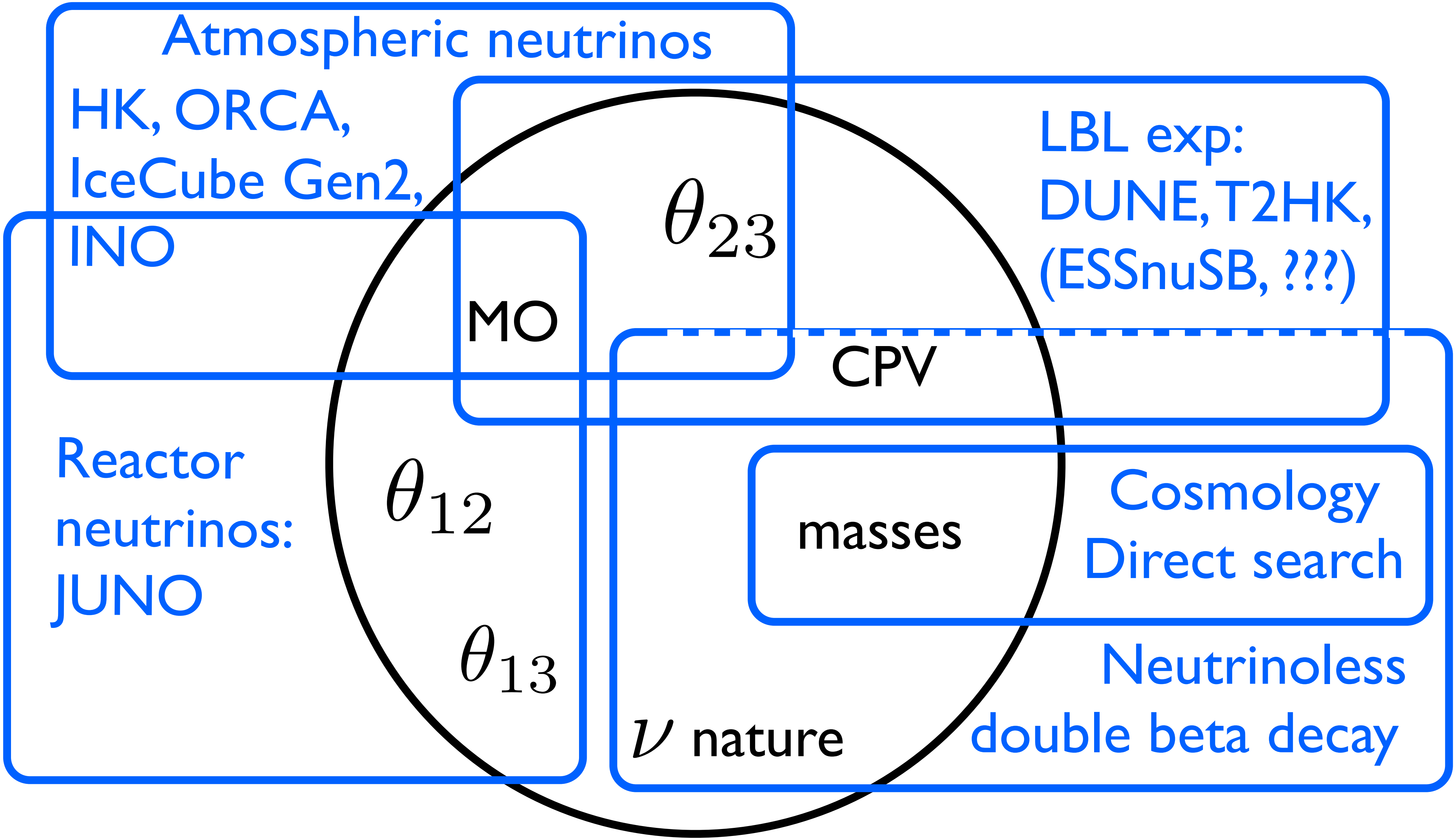
IceCube coll., Phys. Rev. D 97

DUNE sensitivity



M. Blennow et al., JHEP 1704 (2017)

Complementarity



Tests of standard neutrino paradigm: SBL oscillations (SBN, reactor exp), LBL/atm oscillations, neutrino less DBD, beta decays, cosmology (BBN, CMB, LSS), dedicated searches.

Neutrino oscillations imply that neutrinos have mass and mix.

First particle physics evidence of physics beyond the SM.

The ultimate goal is to understand

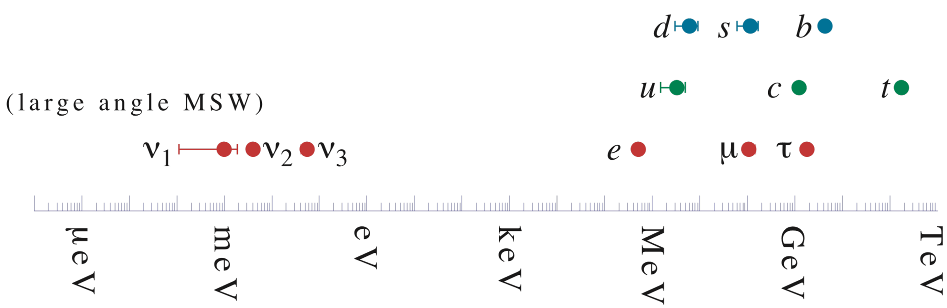
- where do neutrino masses come from?

- what is the origin of leptonic mixing?

Open window on the Physics BSM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so light?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?
Why CPV, if found?

sub-eV   eV   keV   MeV   GeV   TeV   GUT scale

Open window on the Physics BSM

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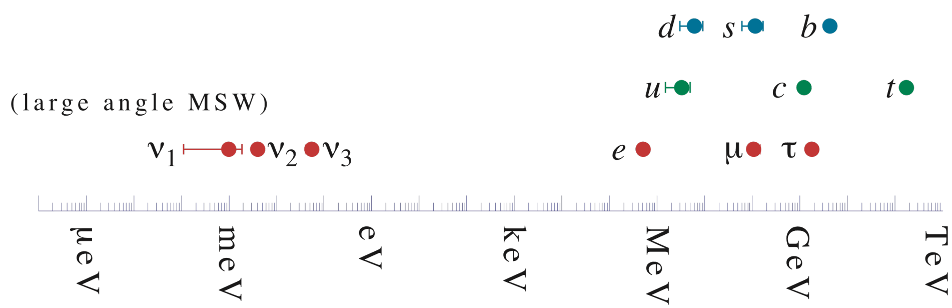

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sub-eV eV keV MeV GeV TeV GUT scale

Neutrino Masses in the SM and beyond

In the SM, neutrinos do not acquire mass and mixing.

- Dirac masses do not arise as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \nu_R$$

If there are RH neutrinos, lepton number would have to be a fundamental symmetry to avoid RH Majorana mass.

- They do not have a Majorana mass term

$$M \nu_L^T C \nu_L$$

as this term breaks the SU(2) gauge symmetry.
This term breaks Lepton Number.

Dirac Masses

If we introduce right-handed neutrinos, then an interaction with the Higgs boson is allowed.

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}$$

$$\downarrow$$

$$m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

This conserves lepton number!

$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$$

Tiny couplings!

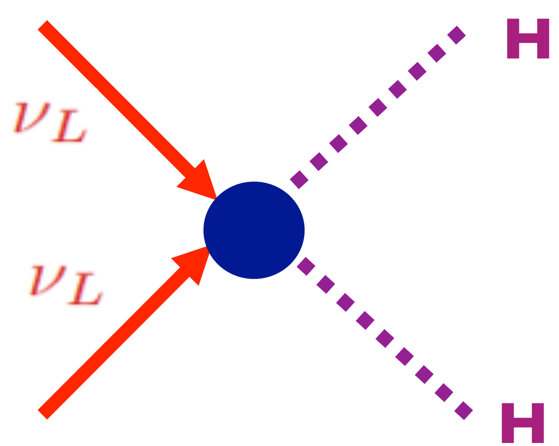
- why the coupling is so small????
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?
- why no Majorana mass term for RH neutrinos? We need to impose L as a fundamental symmetry (BSM).

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow new scalar fields, e.g. a triplet):

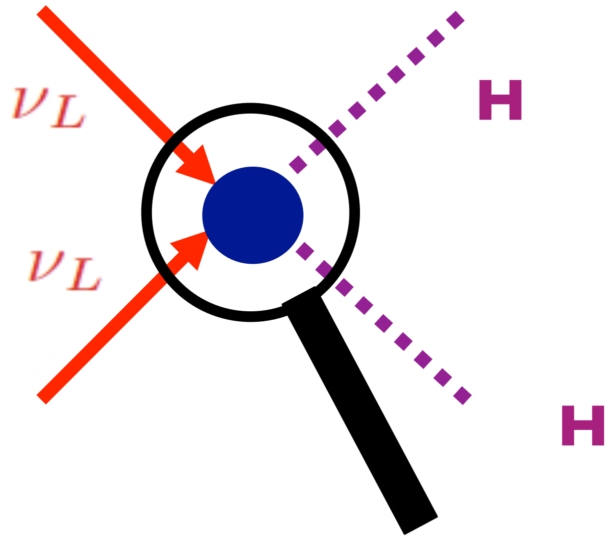
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43



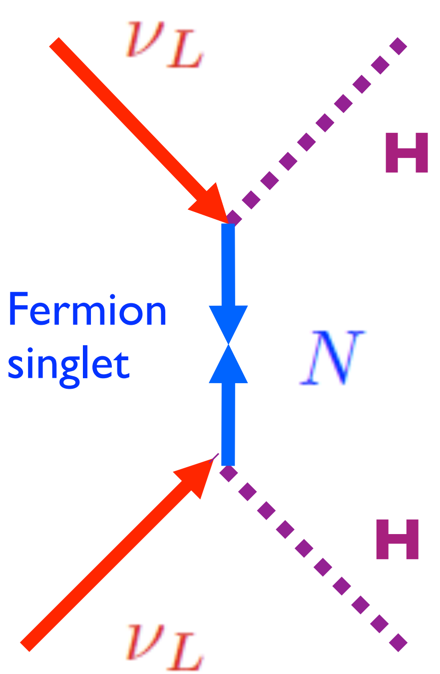
Only D=5 term allowed for the SM

This term breaks lepton number and induces Majorana masses and Majorana neutrinos.



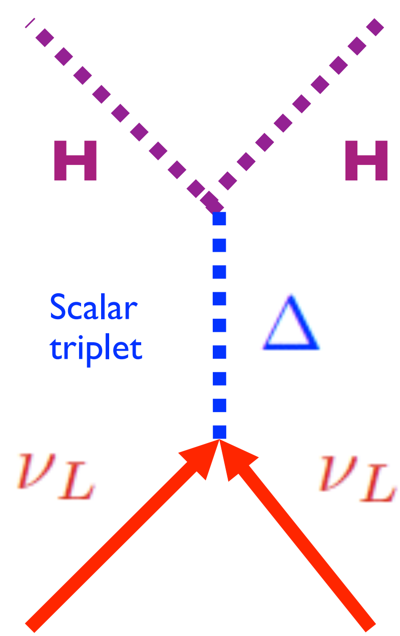
A **Majorana mass** can arise as the low energy realisation of a higher energy theory (new mass scale!).

See-saw Type I



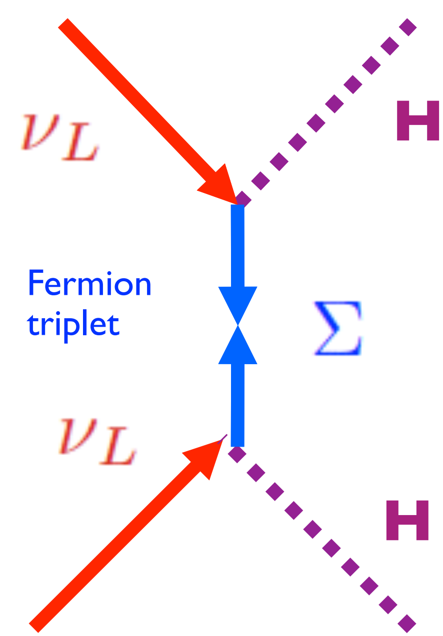
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic…

See-saw Type II



Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle…

See-saw Type III



Ma, Roy, Senjanovic, Hambye…

Neutrino masses BSM: “vanilla” see saw mechanism type I

Particle zoo

Symmetry magazine

- Introduce a right handed neutrino N
- It couples to the Higgs and has a Majorana mass

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

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

As a result, neutrinos can have naturally small masses and are Majorana particles.

Pros:

- they explain "naturally" the smallness of masses
- they can be embedded in GUT theories!
- leptogenesis can be embedded in this framework
- they can have many phenomenological signatures, e.g. CLFV, SHIP, DUNE, … , LNV and LFV at colliders….

Cons:

- *the mass scale can go from eV to GUTs (also in Pros)*
- if M very heavy, the new particles cannot be tested directly, or the mixing with the new states is tiny
- many more parameters than measurable

Many other testable models:

- TeV scale see-saw (II and III)
- Inverse, extended, linear s.-saw:
- radiative neutrino masses
- R-parity violating SUSY…

$$\begin{pmatrix} 0 & Y v_H & \epsilon Y v_H \\ Y v_H & \mu' & \Lambda \\ \epsilon Y v_H & \Lambda & \mu \end{pmatrix}$$

Leptogenesis in see-saw models

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.18 \pm 0.06) \times 10^{-10}$$

Planck, 1502.01589, AA 594

In order to generate it dynamically in the Early Universe, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

- C, CP violation;

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$

$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$

$$X \to \bar{q}q \qquad X \to \ell q$$

- departure from thermal equilibrium.

Leptogenesis

- At T>M, N are in equilibrium:

$$N \leftrightarrow \ell H \quad N \leftrightarrow \ell H \quad N \leftrightarrow \ell H \quad N \leftrightarrow \ell H \quad N \leftrightarrow \ell H$$

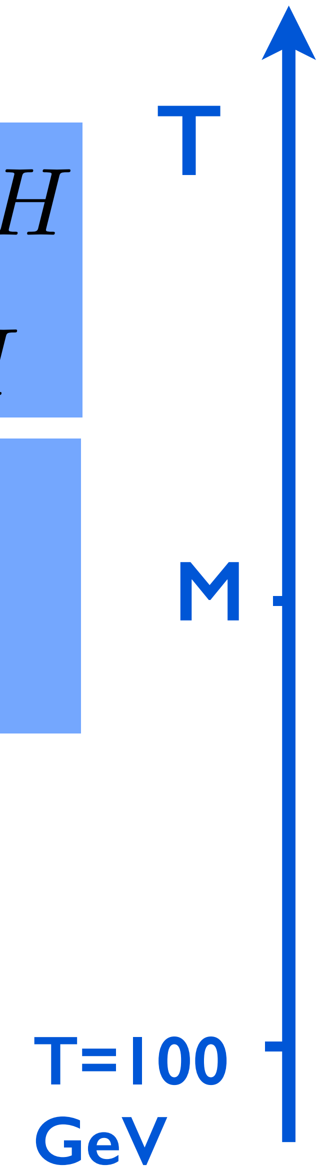
- At T<M, N drops out of equilibrium:

$$N \rightarrow \ell H \quad N \rightarrow \ell^c H^c \quad N \rightarrow \ell H \quad N \rightarrow \ell^c H^c \quad N \rightarrow \ell^c H^c$$

- A lepton asymmetry can be generated if

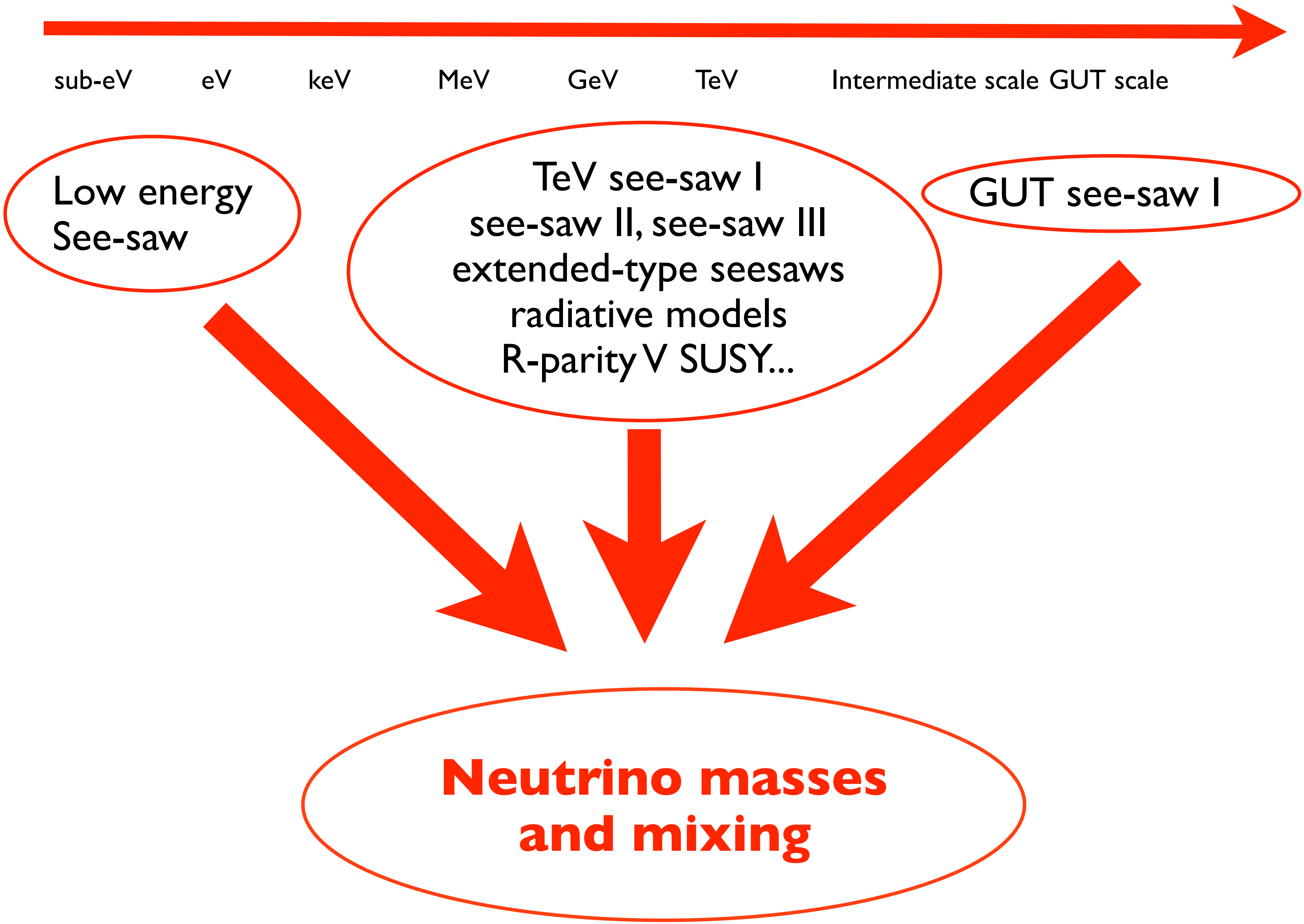
$$\Gamma(N \rightarrow \ell H) \neq \Gamma(N \rightarrow \ell^c H^c)$$

- $$\Delta L \xrightarrow{sphalerons} \Delta B$$



The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.

What is the new physics scale?



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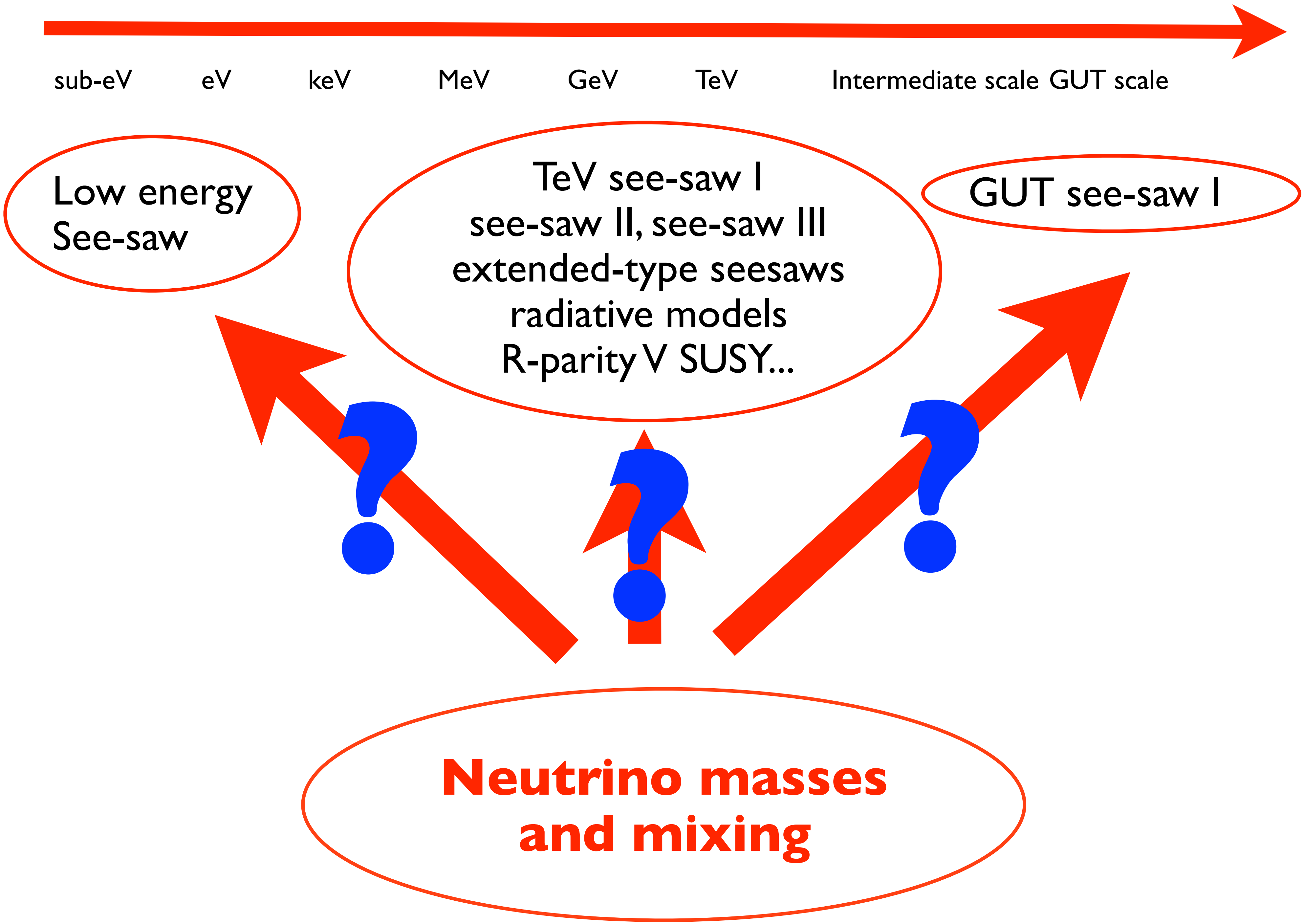
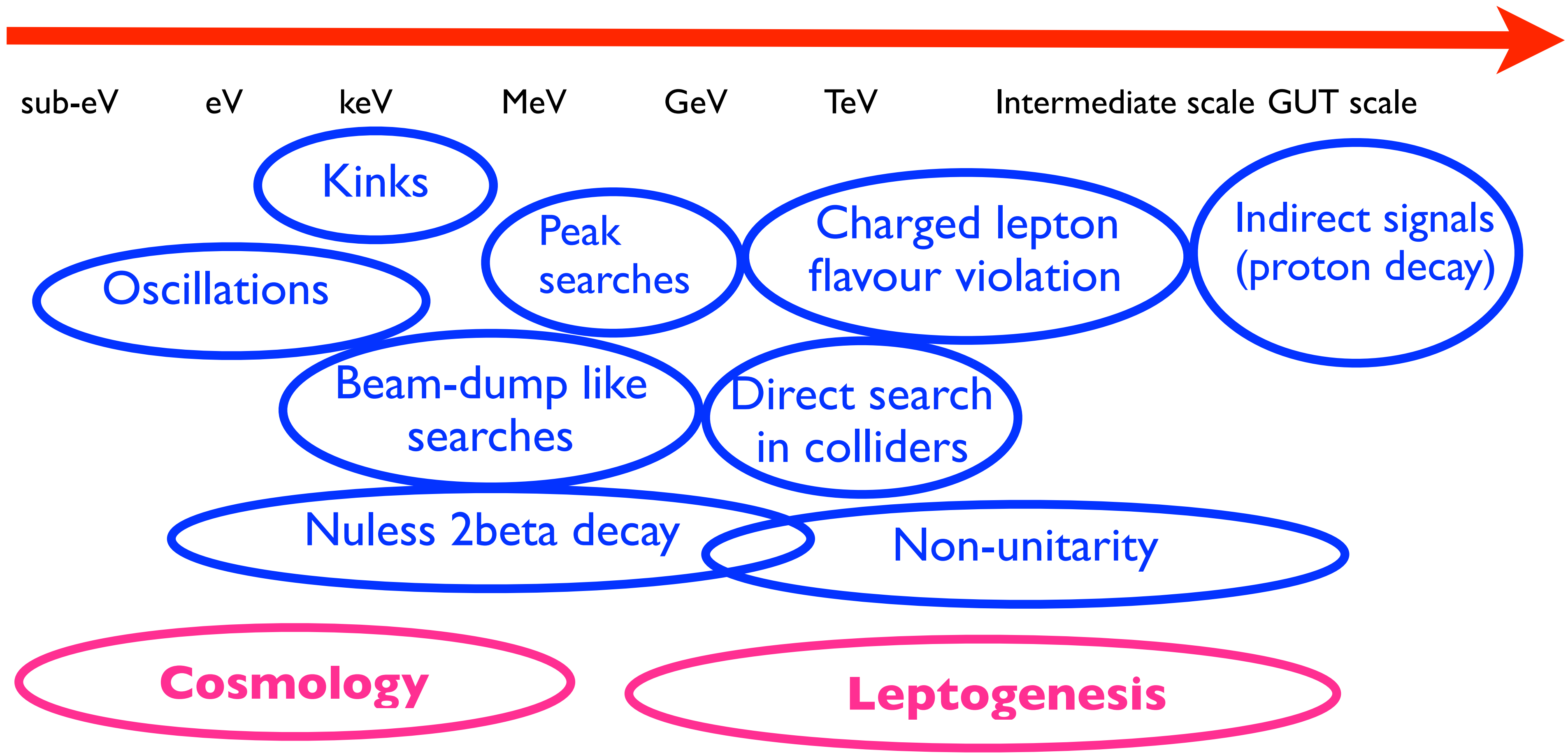


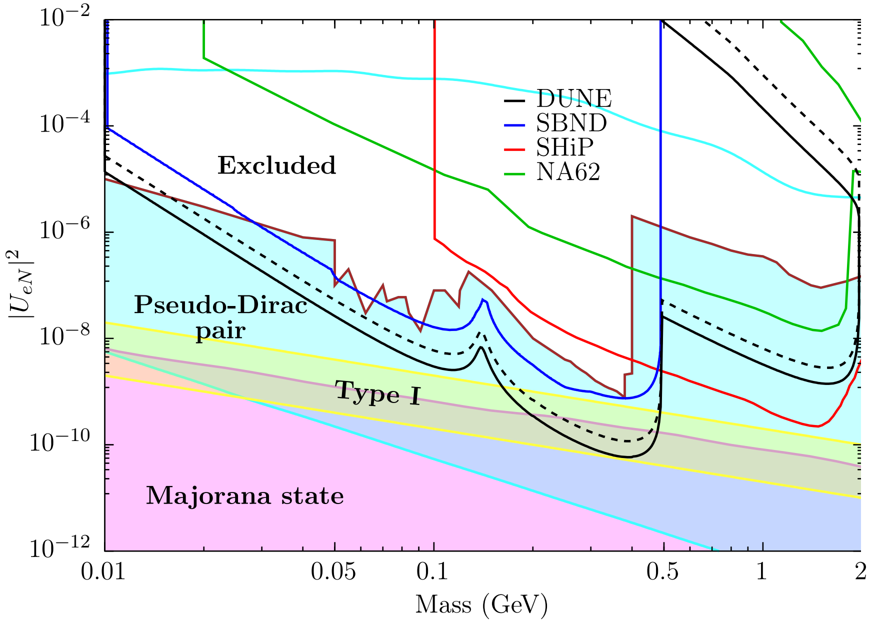
The need for a multi prong approach

There are many (direct and indirect) signatures of these extensions of the SM.

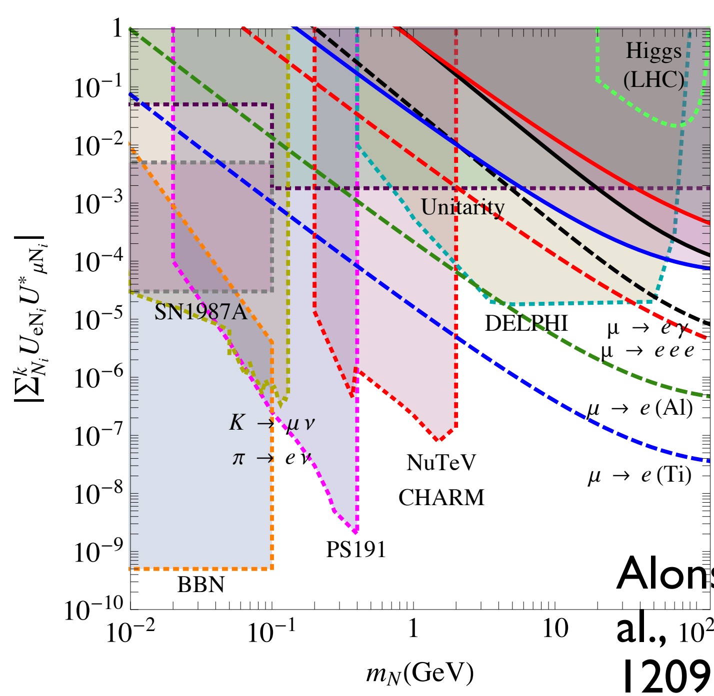


Establishing the origin of neutrino masses requires to have as much information as possible about the masses and to combine it with other signatures of the models.

Searches for heavy neutrinos (keV to TeV) Talk by N. Serra



Ballett, Boschi, SP, 1905.0284



Alonso et al., 1209.2679

Kinks in the keV mass range

Peak searches

Neutrinoless double beta decay (LNV): usually subdominant contribution w.r.t. light masses

$$\mathcal{A} \propto U_{e4}^2 1/m_4^2$$

Decays at beam dump exp (including neutrino facilities) and colliders (LNV, LFV), depending on mass.

CLFV (does not depend on LNV but requires LFV):

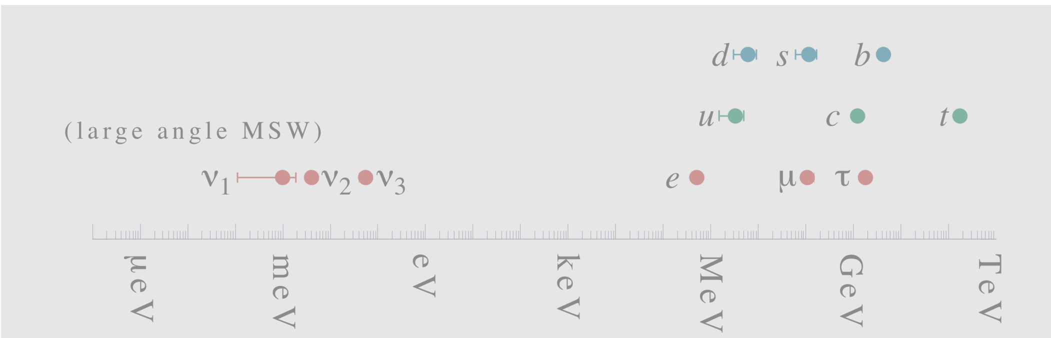
$$Br(\mu \to e\gamma) \sim \frac{3\alpha}{8\pi}(\sum_j U^*_{\mu j} U_{ej} g(\frac{M_N^2}{m_W^2}))^2$$

Resonant or ASR leptogenesis

Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass? and why are they so lighter? and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?
Why CPV, if found?

This points towards a different origin of neutrino masses and leptonic mixing from the ones for quarks.

Masses and mixing from the mass matrix

Neutrino masses and the mixing matrix arises from the diagonalisation of the neutrino mass matrix

$$M_M = (U^\dagger)^T m_{\text{diag}} U^\dagger \quad \Rightarrow \quad n_L = U^\dagger \nu_L$$

Theory **Experiments**

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U_{\text{osc}} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} W_\mu$$

with $U_{\text{osc}} = V_L^\dagger U_\nu$

Example. In the diagonal basis for the leptons

$$\mathcal{M}_\nu = \begin{pmatrix} a & b \\ b & c \end{pmatrix}$$

the angle is $\tan 2\theta = \frac{2b}{a-c} \gg 1 \quad \text{for} \quad a \sim c \text{ and, or } a, c \ll b$

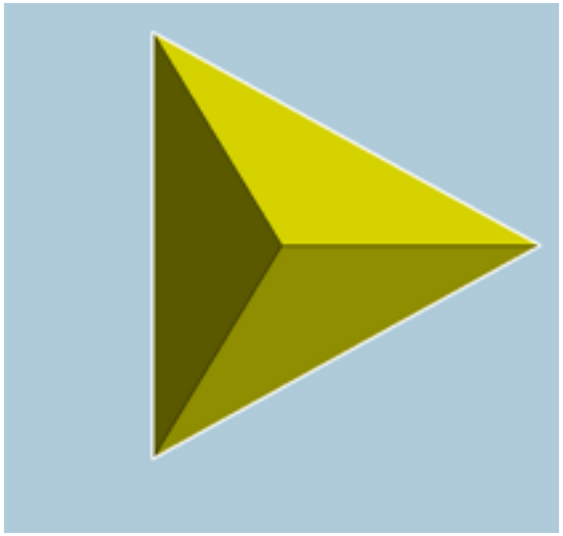
Various strategies and ideas can be employed to understand the observed pattern (many many models!): anarchy, texture zeros, symmetry approach, ...

Symmetry approach

- Choose a leptonic symmetry (e.g. A4, S4, A5, $\mu - \tau$ ...)

- Use the fact that one can arrange for $U_\nu \neq V_L$

- Obtain the mixing matrix (possibly invoking corrections).



$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{pmatrix} = \begin{pmatrix} 2/3 & 1/3 & 0 \\ 1/6 & 1/3 & 1/2 \\ 1/6 & 1/3 & 1/2 \end{pmatrix}$$

E.g. Tribimaximal mixing

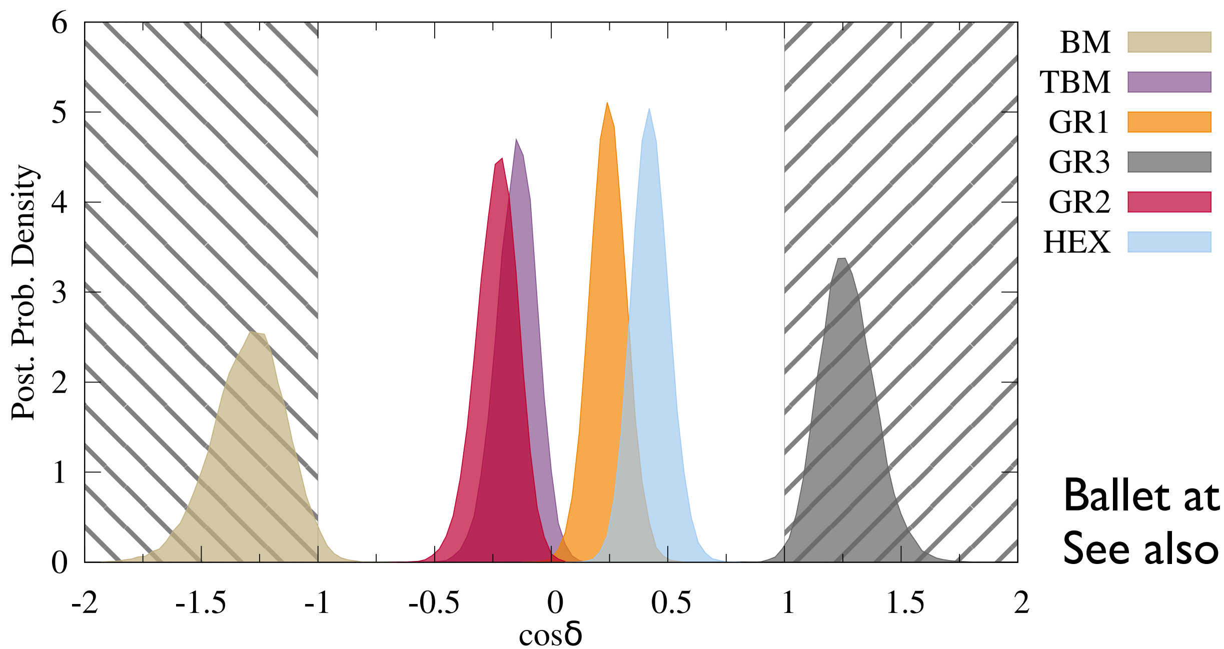
Tests of flavour models

Typically, the models considered have a reduced number of parameters, leading to relations between the masses and/or mixing angles and CPV phase.

Examples are the so-called sumrules, e.g.:

$$\sin\theta_{23} - \frac{1}{\sqrt{2}} = \sin\theta_{13}\cos\delta$$

$$\cos\delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12}^2/t_{23} - s_{12}^{\nu 2}(t_{23} + s_{13}^2/t_{23})}{\sin 2\theta_{12} s_{13}}$$



Ballet at al., JHEP 1412,
See also Petcov et al.

@Silvia Pascoli

Needed:

- A precise measurement of the oscillation parameters (including the delta phase). Essential to guide the theoretical effort!
- Mass ordering and neutrino mass spectrum.
- Useful information can come from CLFV.

Is the precision reachable at DUNE and T2HK enough or should we start thinking about the following step? *Talk by M. Mezzetto*

Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2 \theta_{12}$	$\sin^2 \theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

Albright, Chen, PRD 74 (2006)

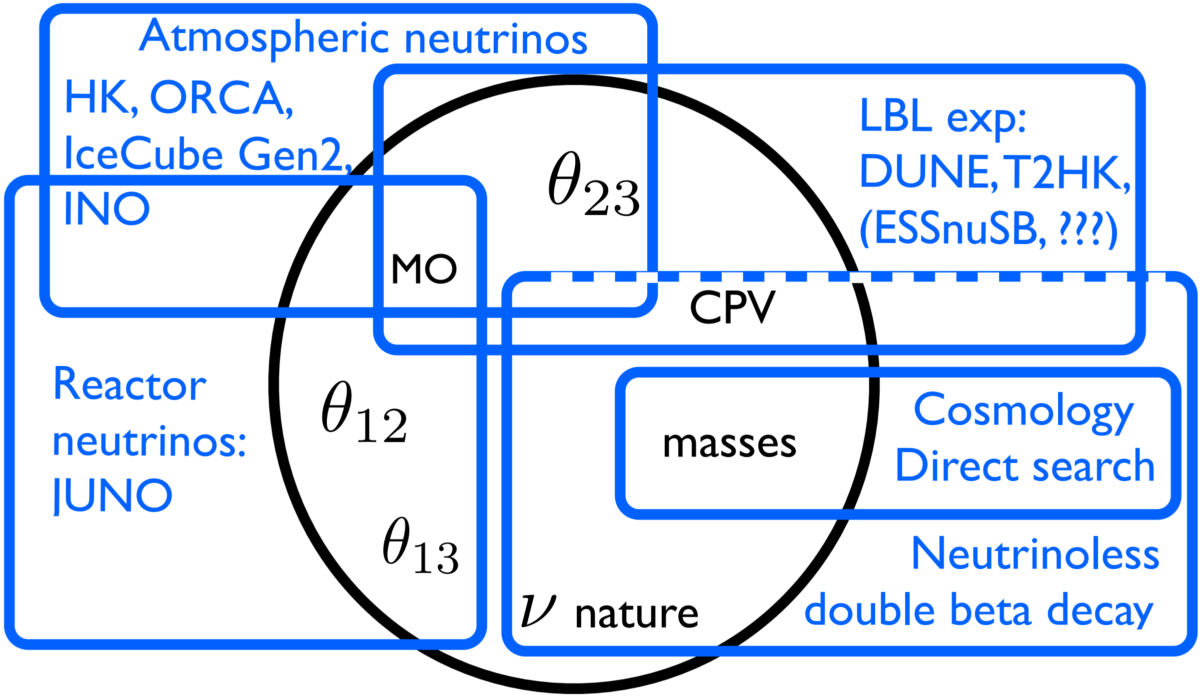
Conclusions

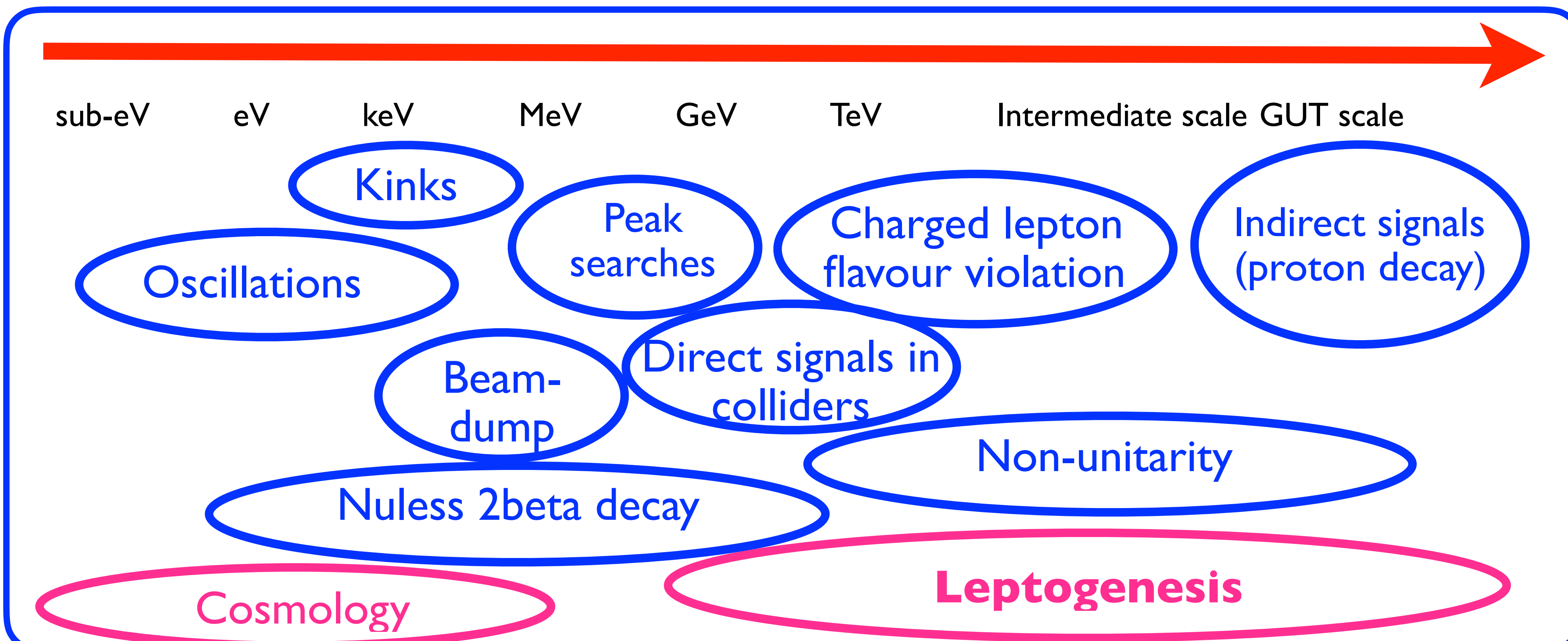
- Neutrino masses are the first particle physics evidence of Physics BSM. Neutrinos provide a new complementary window w.r.t. collider and flavour physics searches.

- It is necessary to known the values of the masses and of the mixing angles and CPV phase (with precision). This is crucial to understand the origin of the leptonic flavour structure (e.g. flavour symmetries).

- Determining the New Standard Model (nuSM), responsible also for neutrino masses, is the ultimate goal. It requires complementary information: CLFV, leptogenesis, direct searches at TeV scale and below, low energy probes (e.g. SBL experiments)…

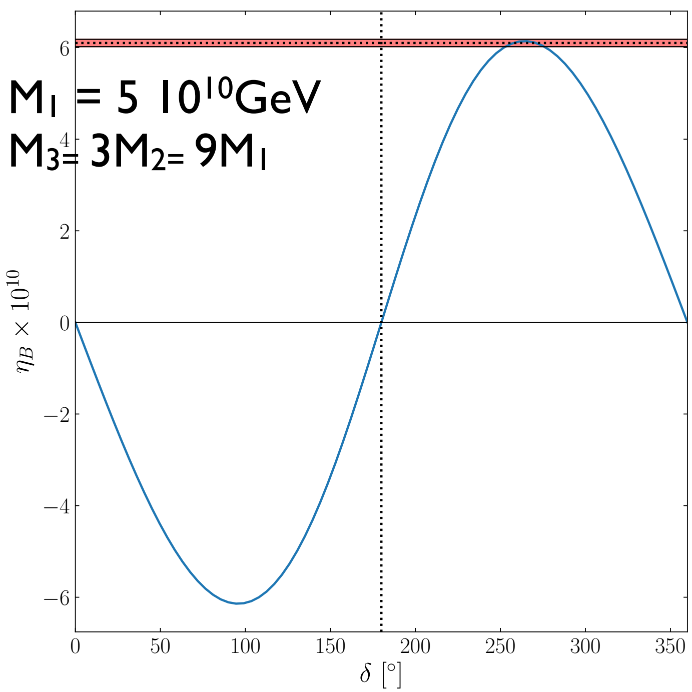
Complementarity and synergy of experimental searches





- Has leptogenesis anything to do with the low energy delta phase? Generically, NO. Many models, lots of parameters…

An interesting example. Vanilla high-energy see-saw type I:



A detailed study shows that delta can give an important (even dominant) contribution to the baryon asymmetry. For Majorana CPV, effects enhanced by a factor of ~10.

Moffat, SP, Petcov, Turner, PRD 98, JHEP 1903

The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.