Theory of neutrino masses and leptonic mixing

16 July 2019

EPS-HEP 2019

Ghent, Belgium

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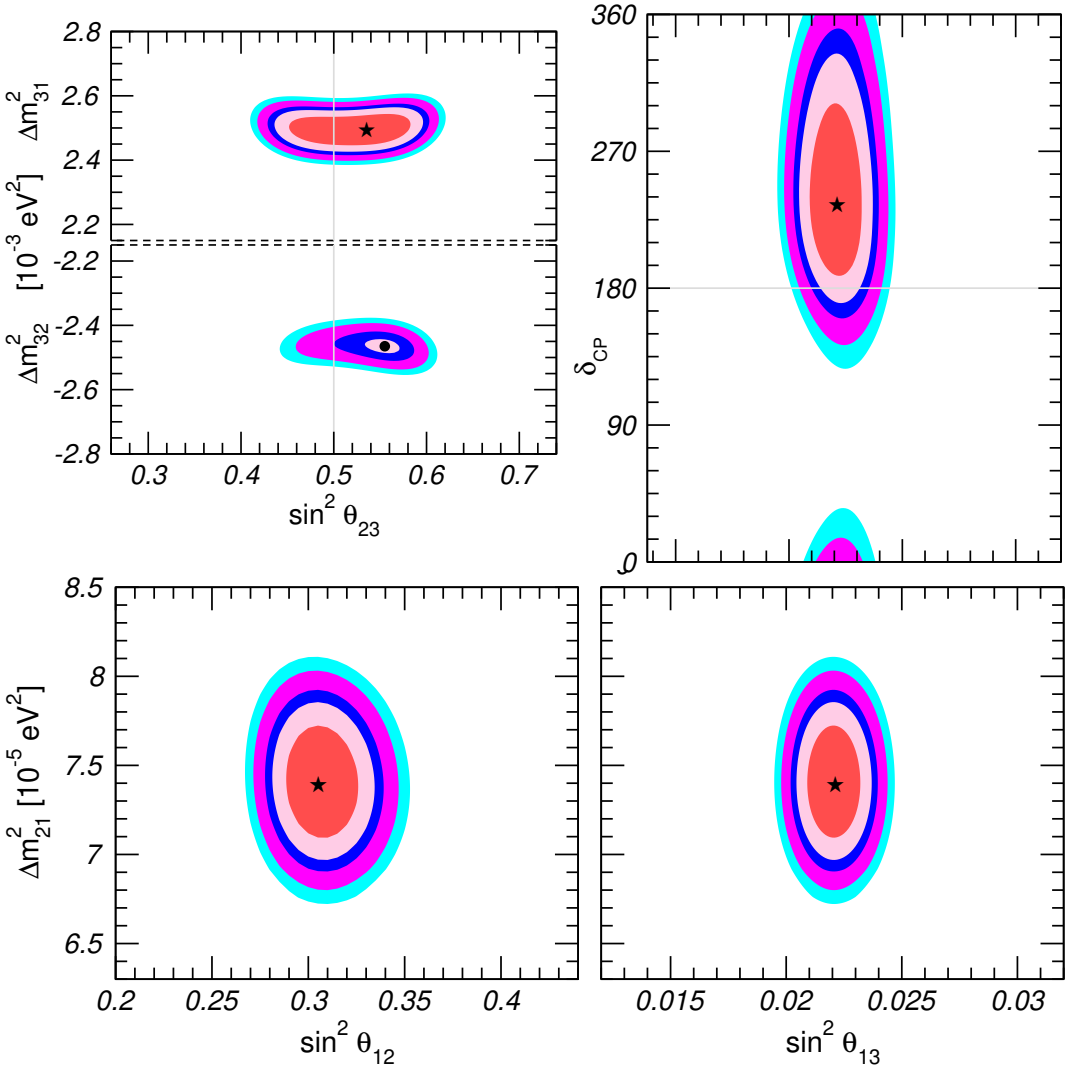
IPPP – Durham University

Neutrino properties after Neutrino 2018

NuFIT 4.0 (2018)



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

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

Neutrinos have masses and mix!

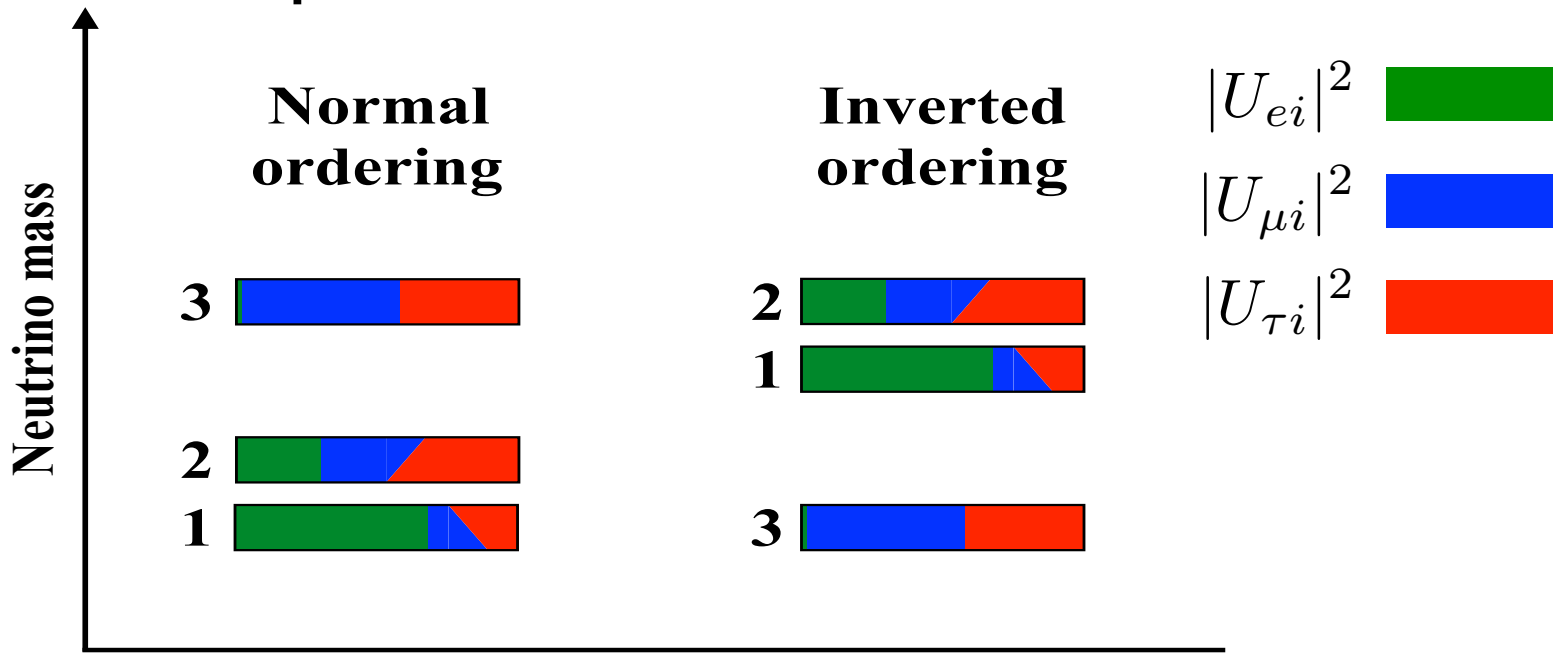
Current knowledge of neutrino properties:

- 2 mass squared differences
- 3 sizable mixing angles,
- some hints of CPV
- indications in favour of NO

See talks by F. di Lodovico and G. Ranucci

Neutrino masses

$\Delta m^2_{21} \ll \Delta m^2_{31}$ implies at least 3 massive neutrinos.



Fractional flavour content of massive neutrinos

$$m_1 = m_{\min}$$
$$m_2 = \sqrt{m_{\min} + \Delta m^2_{21}}$$
$$m_3 = \sqrt{m_{\min} + \Delta m^2_{31}}$$

$$m_3 = m_{\min}$$
$$m_1 = \sqrt{m_{\min} + |\Delta m^2_{32}| - \Delta m^2_{21}}$$
$$m_2 = \sqrt{m_{\min} + |\Delta m^2_{32}|}$$

Measuring the masses requires:

- the mass scale: $m_{\min}$
- the mass ordering: preference for NO ($\Delta\chi^2 \sim 4.7(9.3)$).

Leptonic Mixing and CP-violation

The Pontecorvo-Maki-Nakagawa-Sakata matrix

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

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

CPV?

- Mixings very different from quark sector.
- Possibly, large leptonic CPV.

  CPV 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 leptonic CP-violation?**

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

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

Very exciting experimental programme now and for the future.

Neutrino nature

Neutrinos can be **Majorana or Dirac particles**. In the SM only neutrinos can be Majorana as they are neutral.

Majorana condition $\nu = C\bar{\nu}^T$

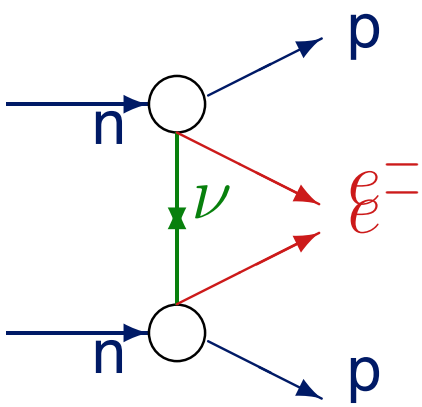
The **nature** of neutrinos is linked to the conservation of **Lepton number (L).**

- This is crucial information to unveil the **Physics BSM: with or without L-conservation**? Lepton number violation is a necessary condition for **Leptogenesis**.

- Tests of LNV:
  - At low energy, neutrinoless double beta decay,
  - LNV tau and meson decays, collider searches.

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2e, will test the nature of neutrinos.



The half-life time depends on neutrino properties

$$(T_{0\nu}^{1/2})^{-1} \propto |M_{NME}|^2 |m_{\beta\beta}|^2$$

- The effective Majorana mass parameter:

$$|m_{\beta\beta}| \equiv |\, m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \,|$$

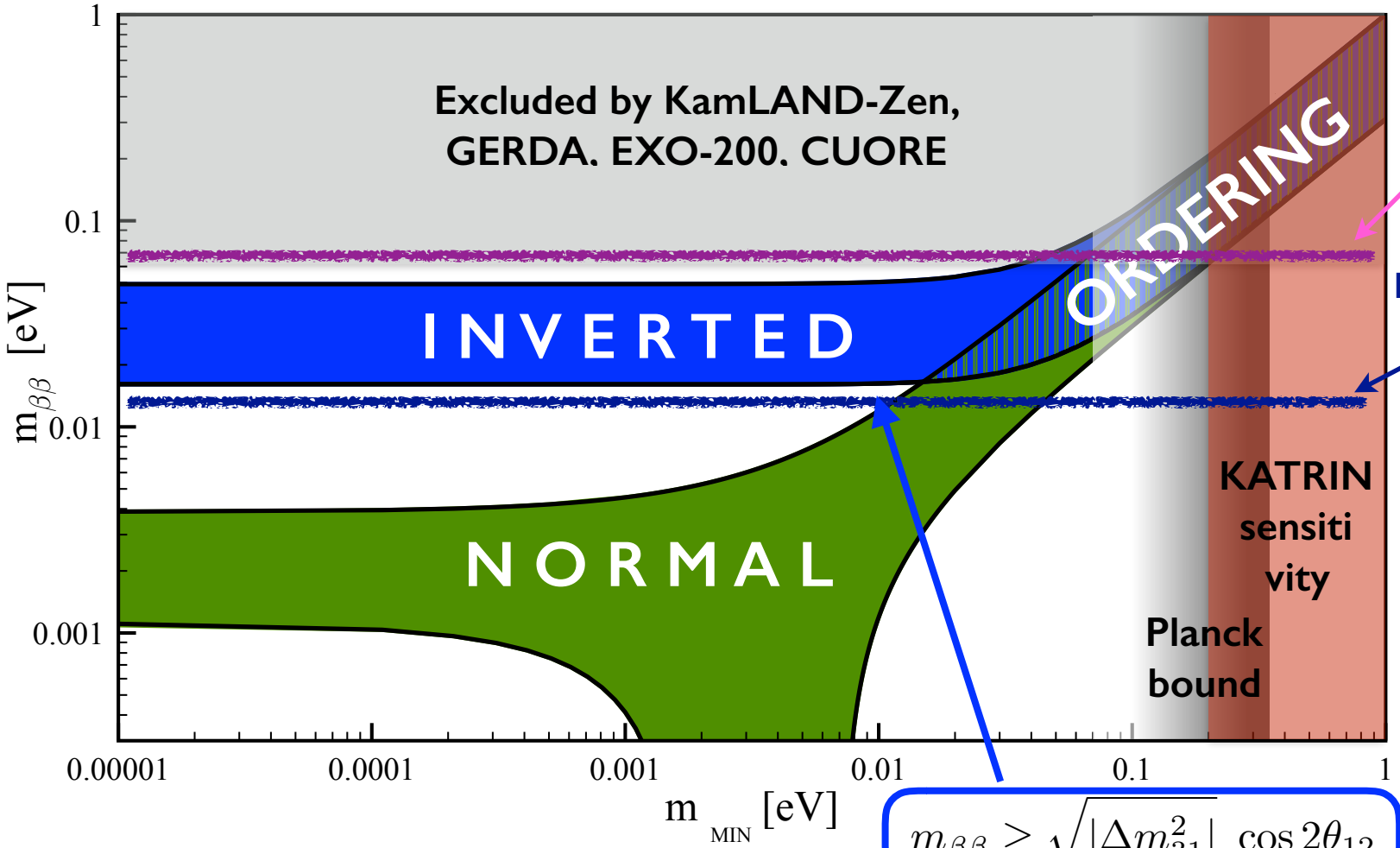
Mixing angles (known)

CPV phases (unknown)

- $|M_{NME}|$ are the nuclear matrix elements

Predictions for betabeta decay

The predictions for m_{bb} depend on the neutrino masses:



Present bounds:
GERDA-II, CUORE,
KamLAND-Zen

Goals of Next generation exp:
LEGEND-1K, CUPID, NEXT-HD, nEXO, SNO+, PANDAX, DARWIN…

R&D for future exp

$$m_{\beta\beta} \geq \sqrt{|\Delta m^2_{31}|}\ \cos 2\theta_{12}$$

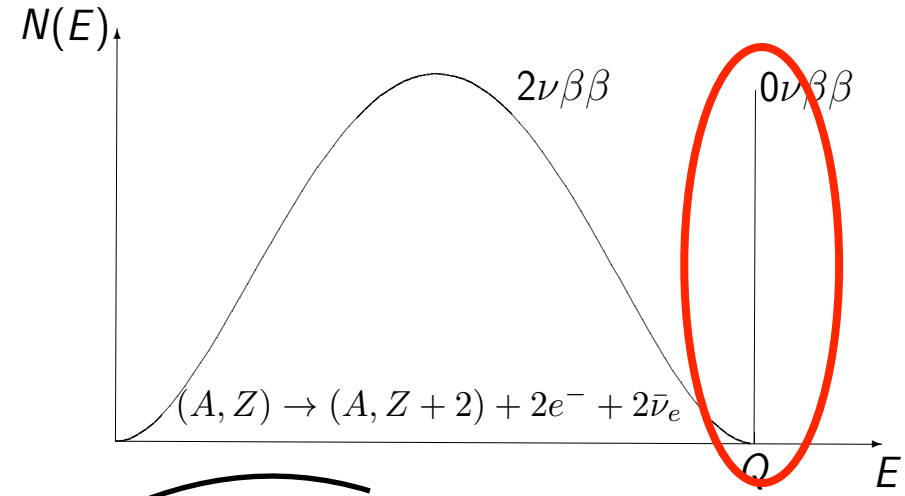
Wide experimental program which is ongoing. The next generation is well into planning and R&D for future.

A positive signal would indicate L violation!

Experimental searches of betabeta decay

Neutrinoless double beta decay can be tested in nuclei in which single beta decay is kinematically forbidden (^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe…).

It is a very rare process



$$T_{0\nu} \propto \sqrt{\frac{M\ t}{B\ \Delta E}}$$

ton-scale

<1% at Q_{bb}

<1 cts/yr/ton/ROI

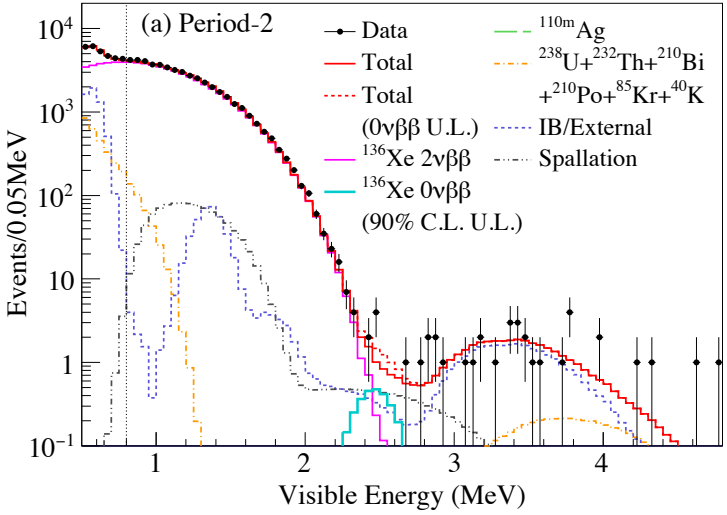
KamLAND-Zen Loaded LSc with 380 kg ^{136}Xe, $T_{1/2}$ >1.07x10^{26}yrs (90% C.L.), m_{bb}< 61-165 meV

EXO-200 ~75 kg LXe TPC, $T_{1/2}$ >3.7x10^{25}yrs

GERDA 31 kg (enriched) ^{76}Ge, $T_{1/2}$ >0.9x10^{26}yrs

MAJORANA 26.0 kg yrs, $T_{1/2}$ >0.27x10^{26}yrs

CUORE ^{130}Te, ~206 kg, $T_{1/2}$ >1.5x10^{25}yrs



KamLAND-Zen, PRL 117 (2016)

See parallel talks by R. Hiller, A. Branca, L. M. Pattavina, P. N. Garijo.

Scalability	**Fluid embedded source**	Xe-based TPC	EXO-200 NEXT-10	NEXT-100 PandaX-III	nEXO NEXT-HD PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High ΔE and ε	**Crystal embedded source**	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
		Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II	CUPID

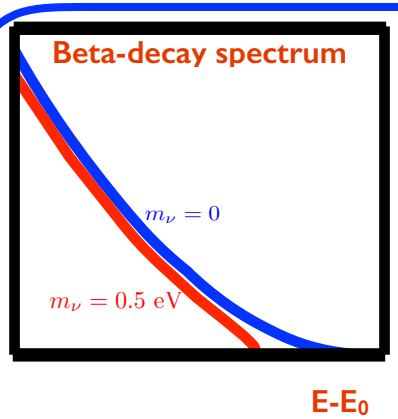
A. Giuliani, Neutrino 2018

The ultimate goal of next generation is m_{bb}~15-20 meV.

Measuring neutrino masses

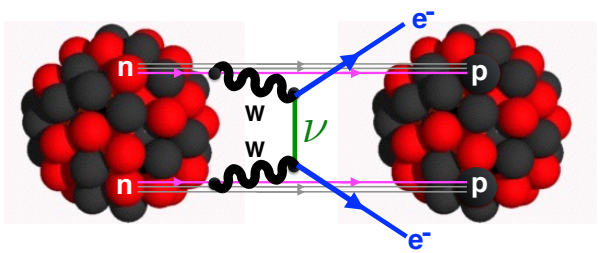
- Mass ordering via neutrino oscillation in matter (NOvA, DUNE, atmospheric neutrinos) or in vacuum (JUNO). Discovery expected within 10 years. Talk by F. di Lodovico

- Absolute mass scale.



Beta decay

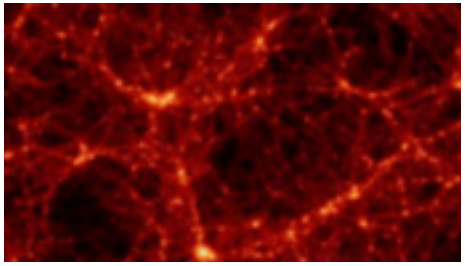
$$m_\beta \equiv \sqrt{\sum_i U_{ei}^2 m_i^2}$$



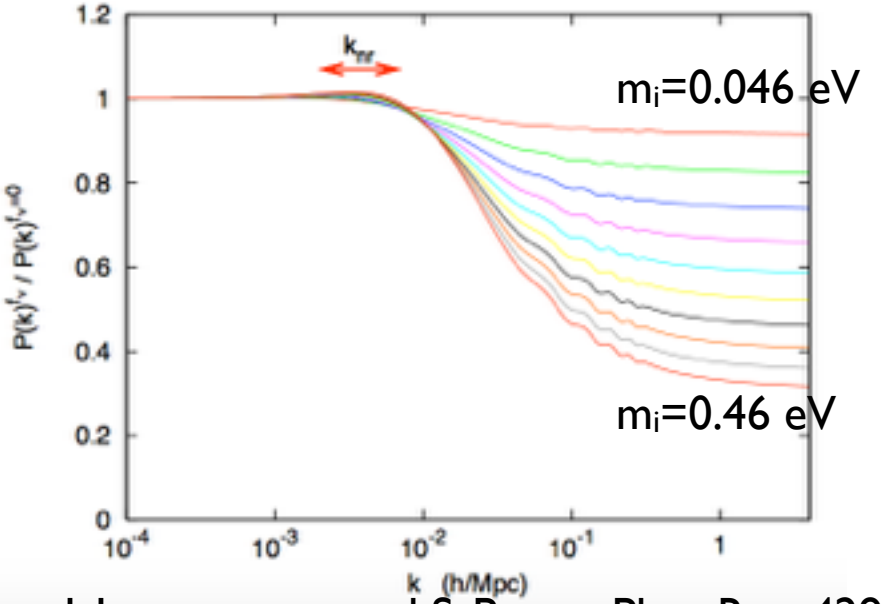
Neutrinoless dbeta decay

$$m_{\beta\beta} = f(m_i, \alpha_{21}, \alpha_{31}, \delta)$$

Cosmology

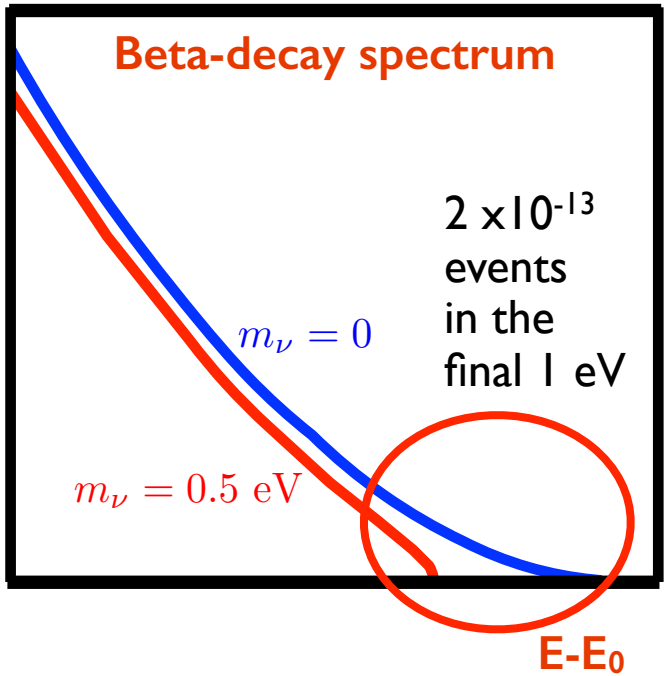


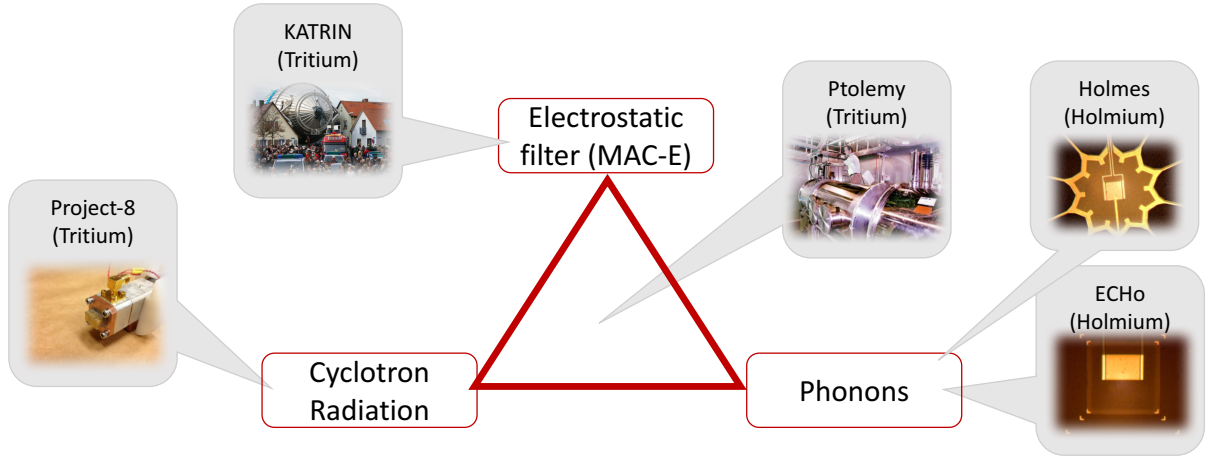
$$\sum_i m_i$$



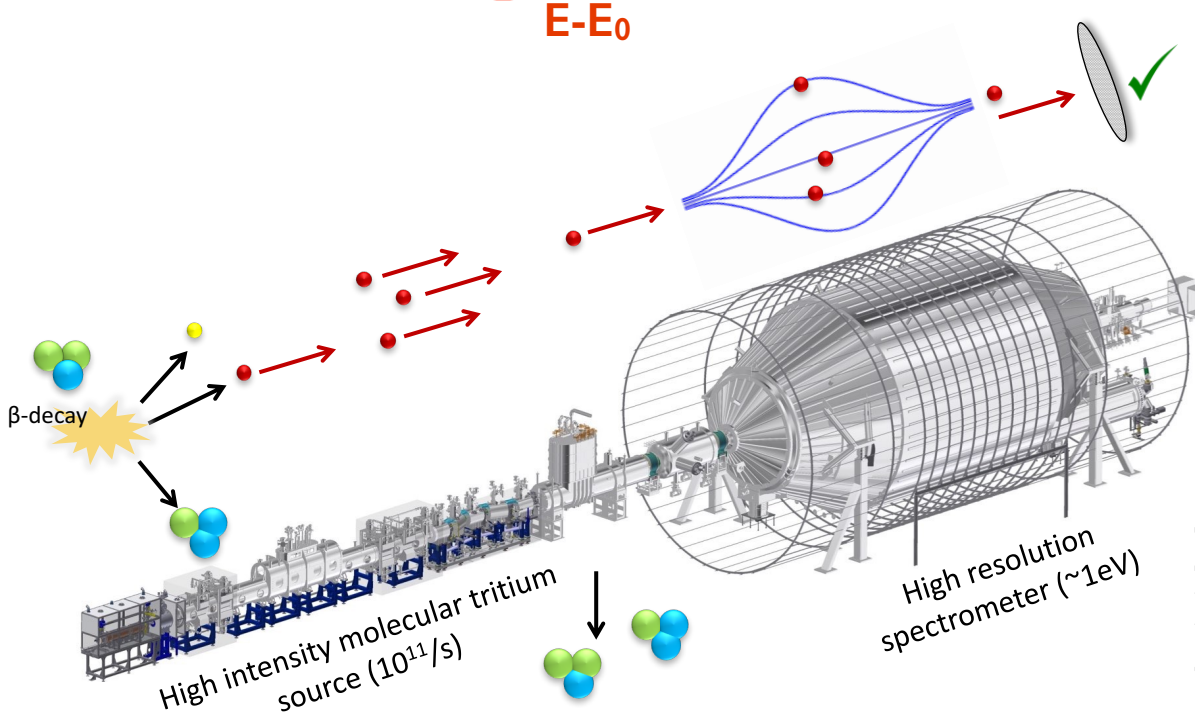
J. Lesgourgues and S. Pastor, Phys. Rep. 429

Direct mass searches



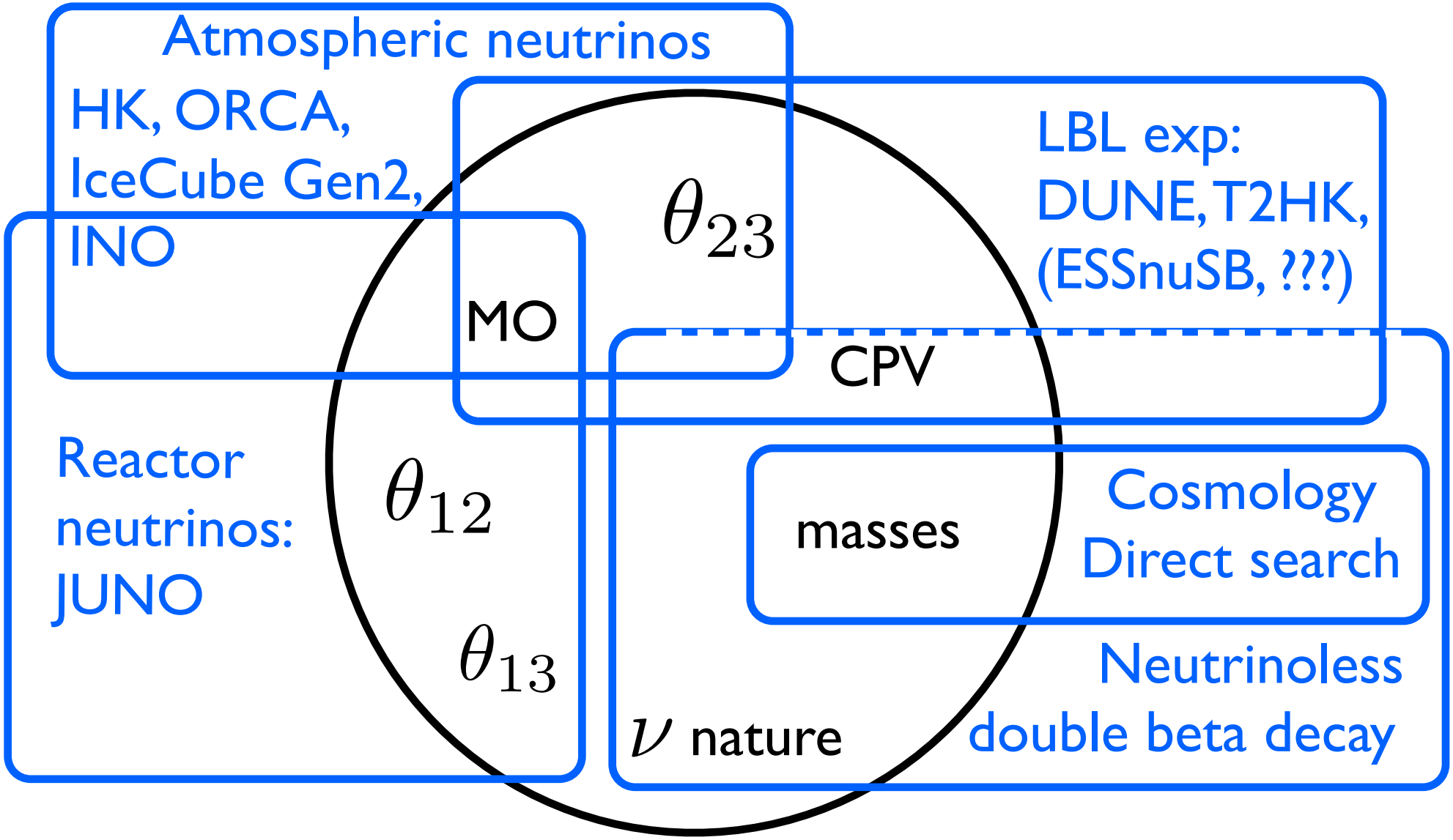


S. Mertens, Granada Open Symposium ESPP



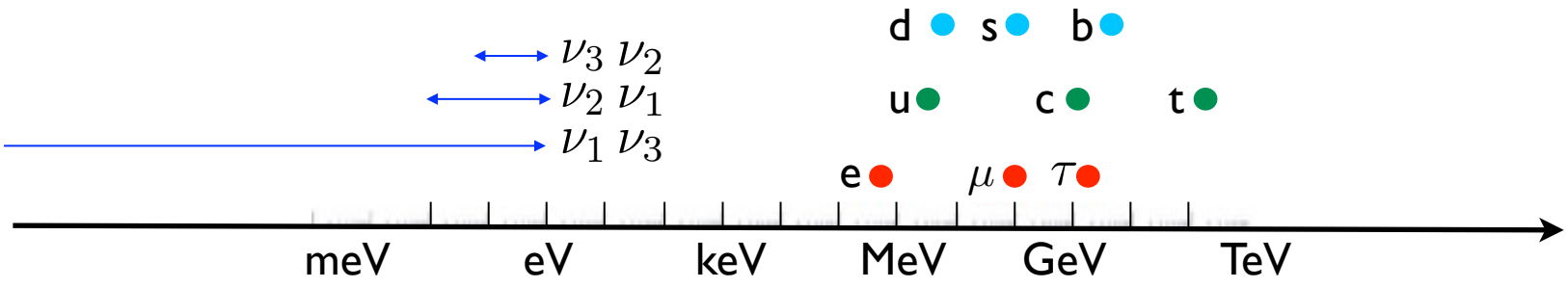
KATRIN has started data taking this year. First results are expected in 2019. The ultimate sensitivity is to $m_b < 0.2$ eV.

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.

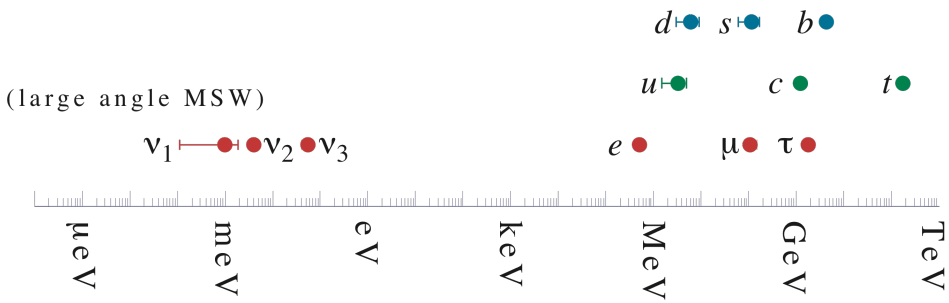


The ultimate goal is to understand
- where do neutrino masses come from?
- what is the origin of leptonic mixing?

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?
Is there CPV?

sub-eV eV keV MeV GeV TeV GUT scale

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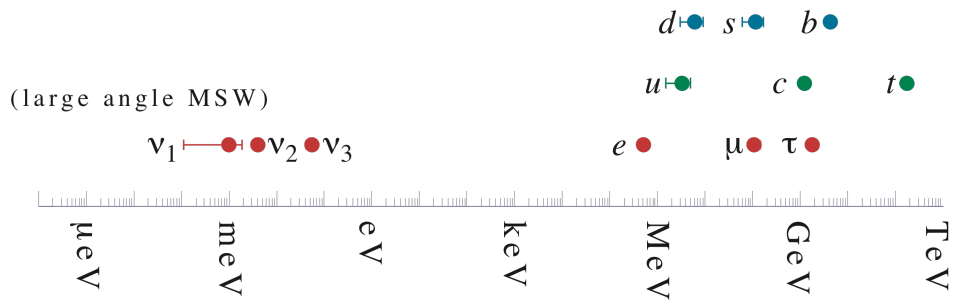

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sub-eV eV keV MeV GeV TeV GUT scale

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.

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

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 a right-handed neutrino, then an interaction with the Higgs boson is allowed. We need to impose L as a fundamental symmetry (BSM).

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

This conserves lepton number!

$$\downarrow$$

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

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

Tiny couplings!

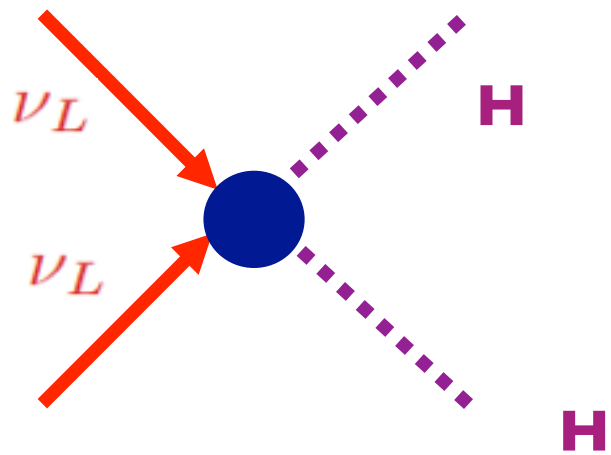
- why no Majorana mass term for RH neutrinos?
- why the coupling is so small????
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?

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):

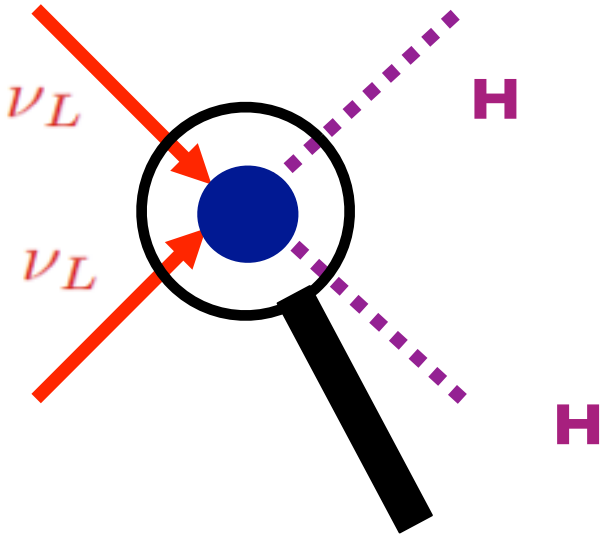
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43



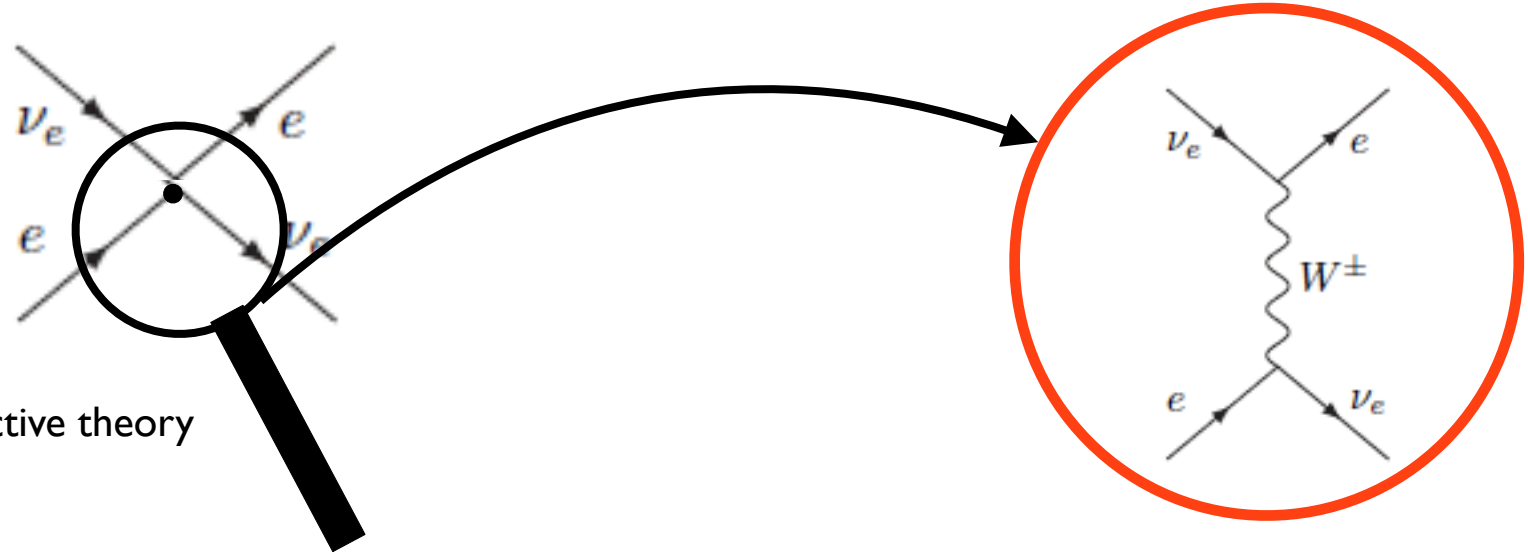
Only D=5 term allowed for the SM

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!).

A similar known example

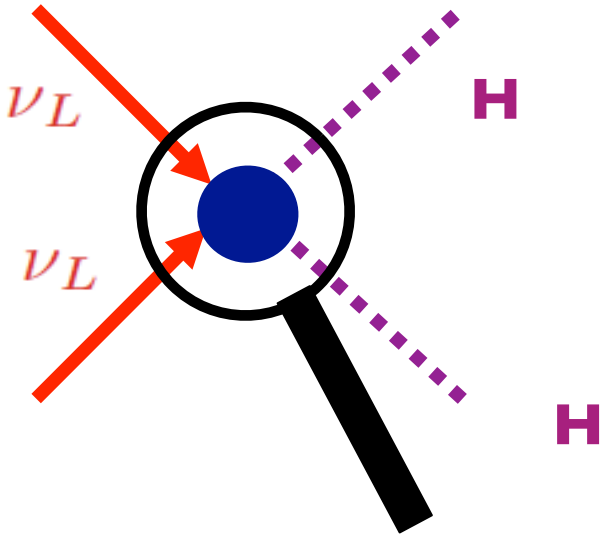


effective theory

Standard Model: W exchange

$$\mathcal{L} \propto G_F(\bar{e}_L\gamma_\mu\nu_L)(\bar{\nu}_L\gamma^\mu e_L)$$

$$\mathcal{L}_{SM} \propto g\bar{\nu}_L\gamma^\mu e_L W_\mu \Rightarrow G_F \propto \frac{g^2}{m_W^2}$$



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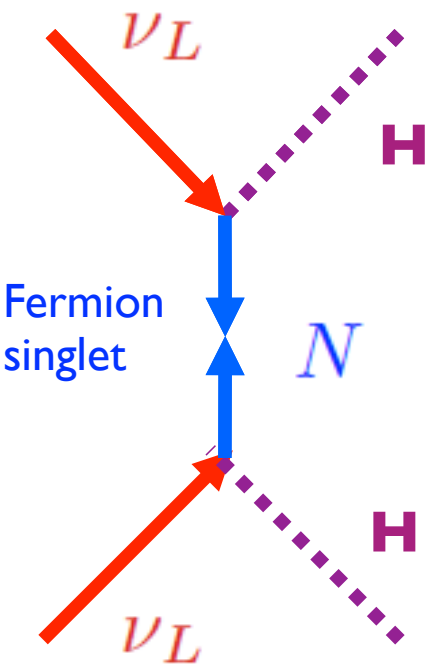
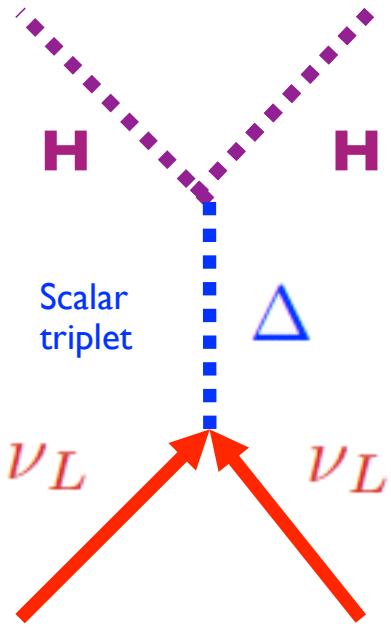
See-saw Type I



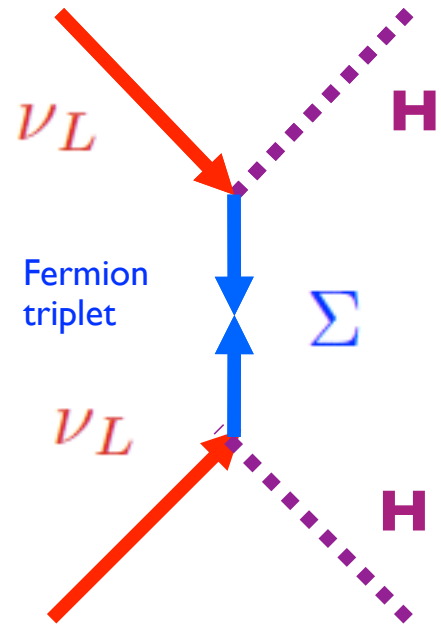
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic…

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

Symmetry magazine

- Introduce a right handed neutrino **N**
- Couples to the Higgs and has a Majorana mass

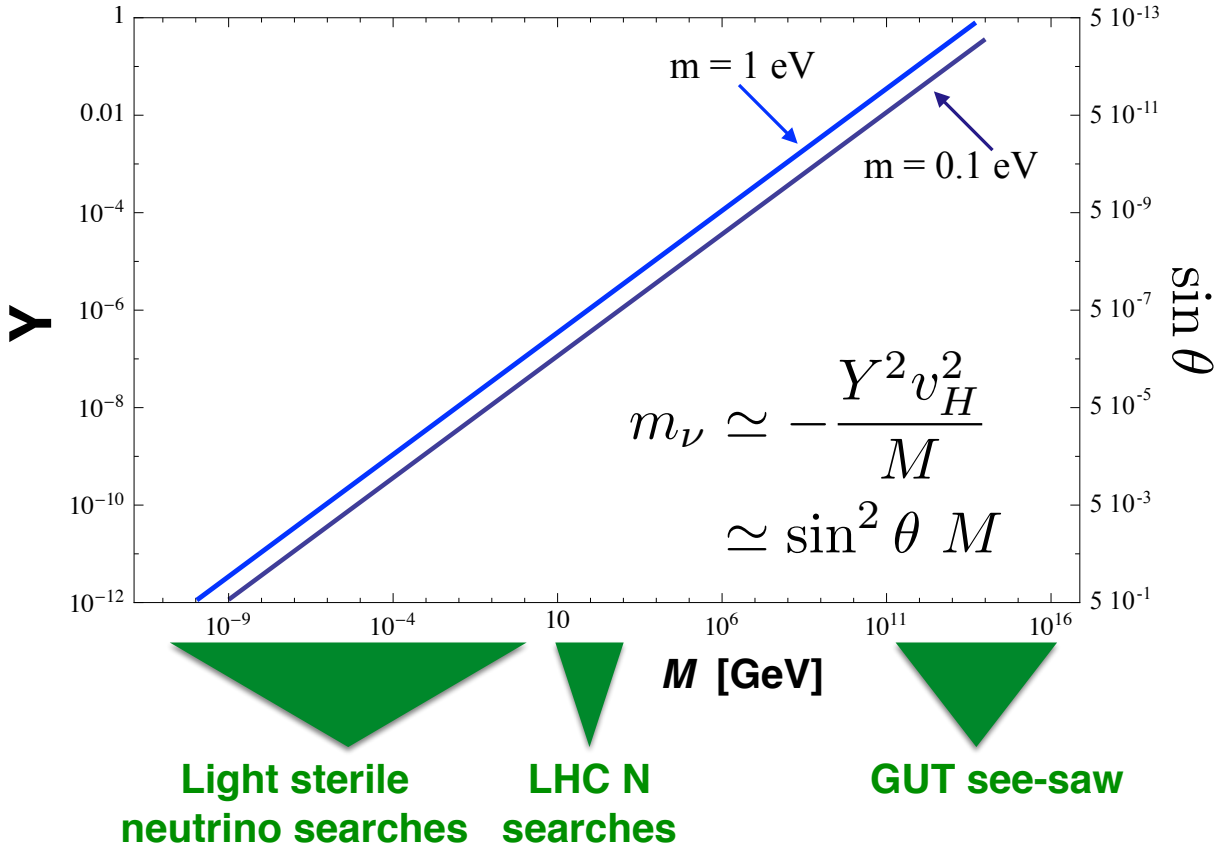
$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

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

See-saw type I models can be embedded in GUT and explain the baryon asymmetry via leptogenesis. HNL masses can go from eV to GUT scale.



HNLs can be too heavy or have too small mixing for searches.

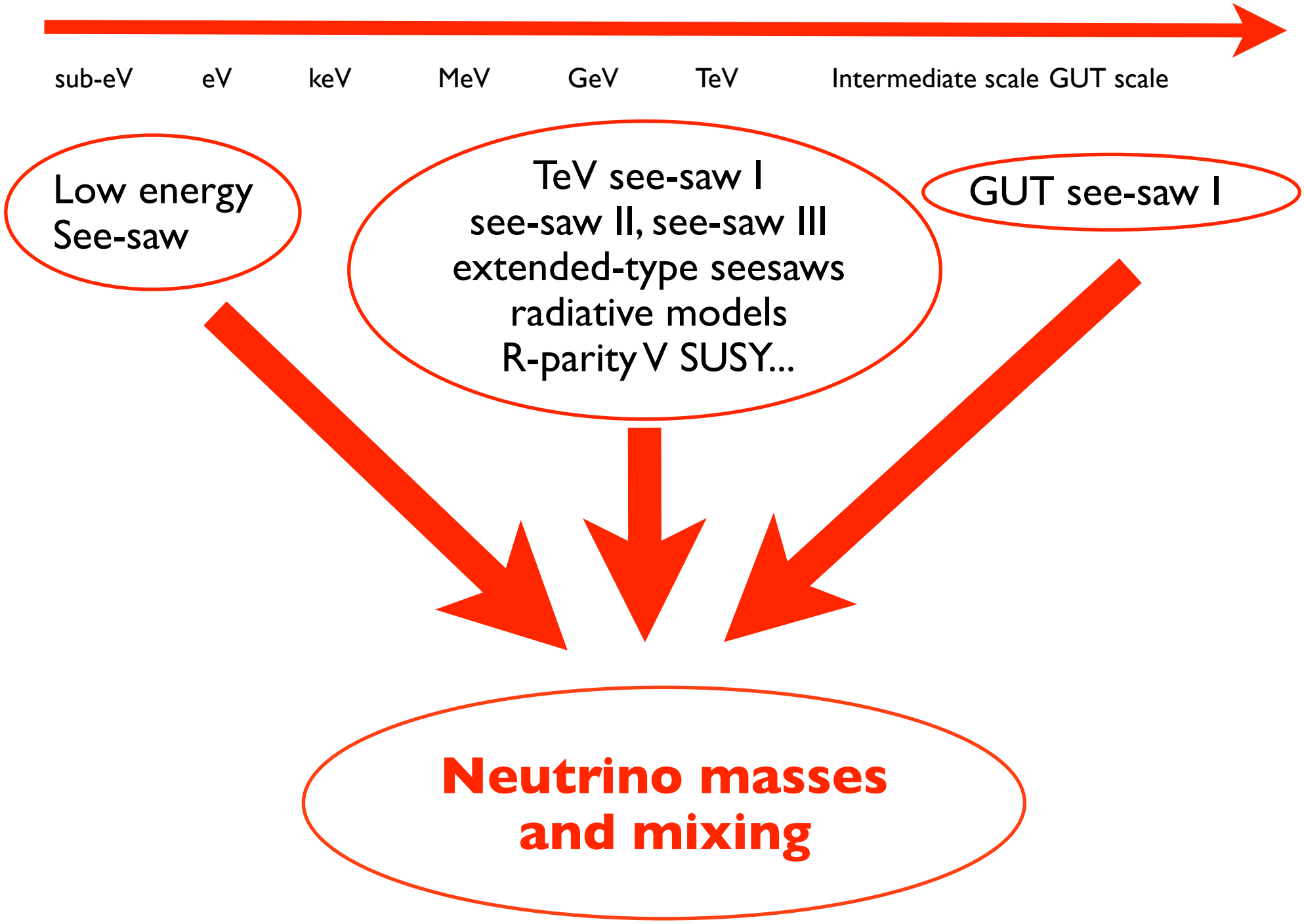
Many other testable models:

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

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

See talk by M.-H. Genest

What is the new physics scale?



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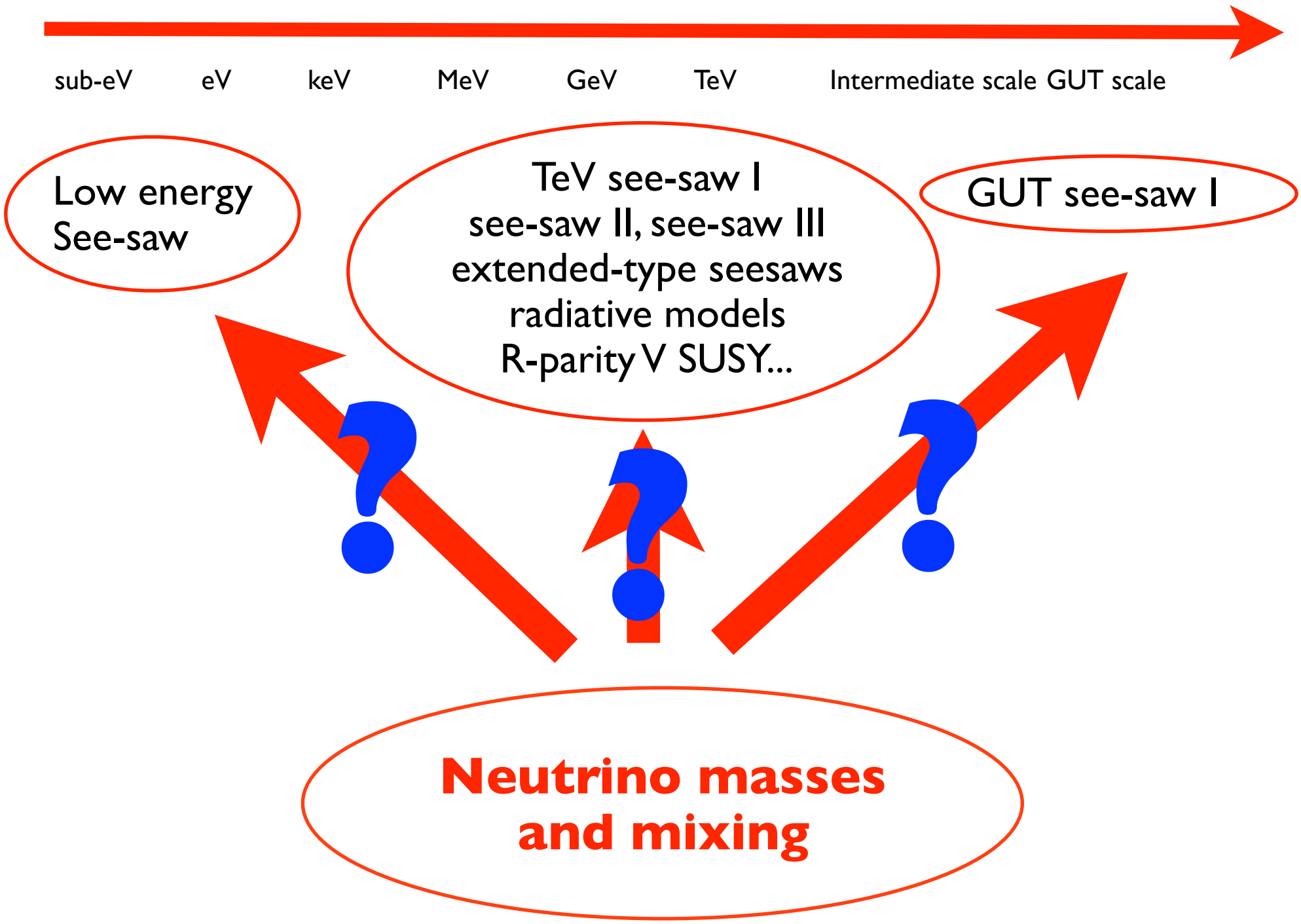
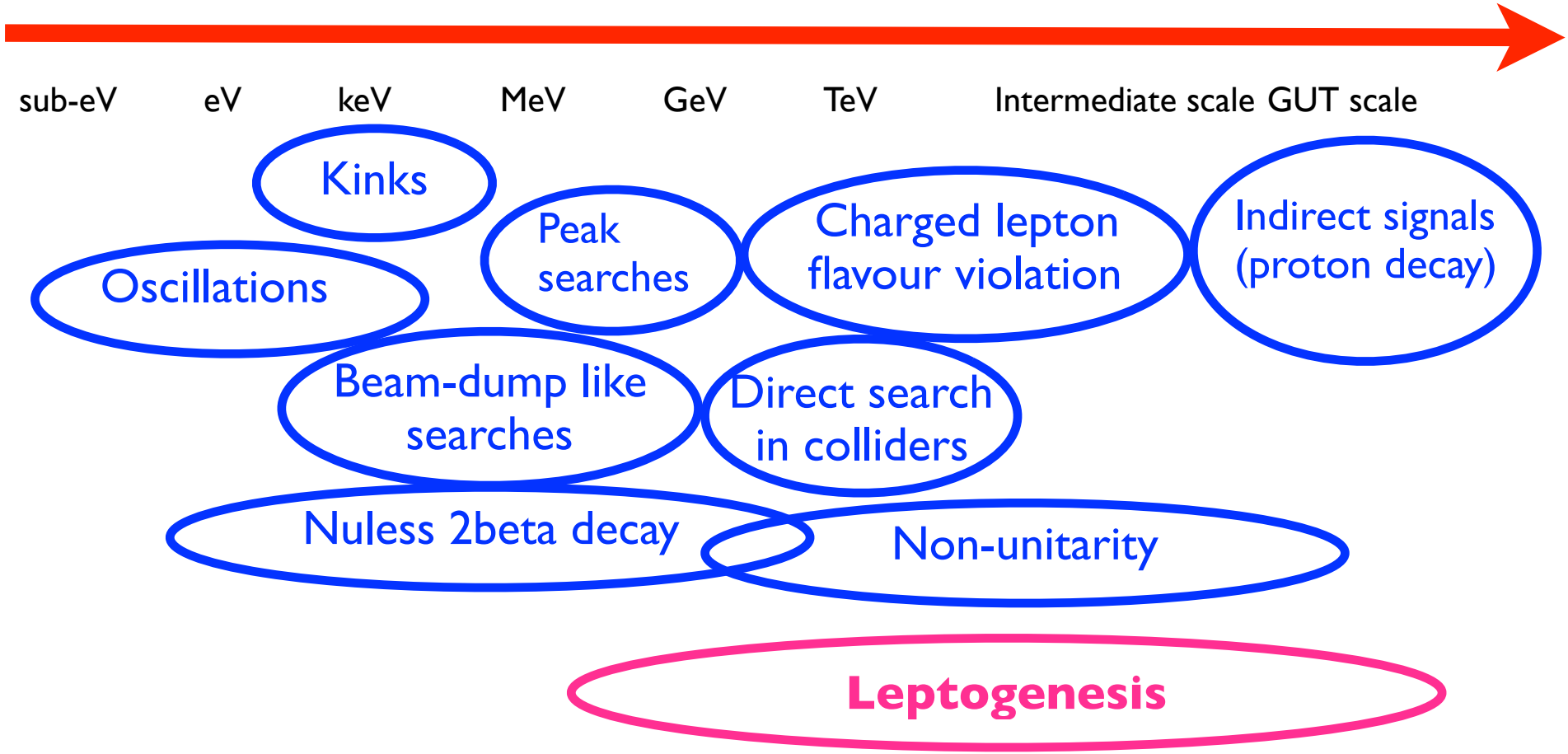


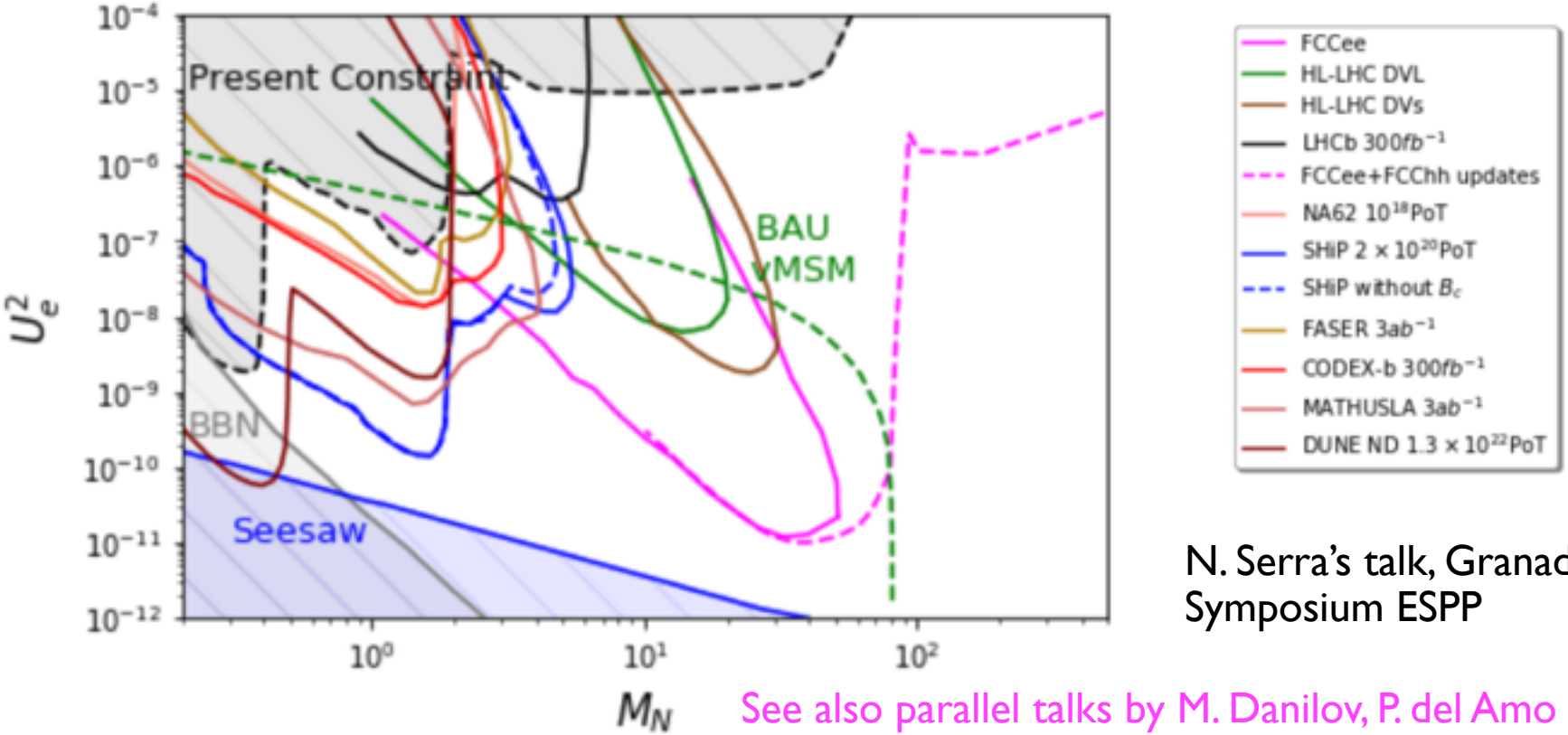
A multi prong approach

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)



N. Serra's talk, Granada Open Symposium ESPP

See also parallel talks by M. Danilov, P. del Amo Sanchez, C. Giunti, X. Marcano, A. Menegolli, I. Michiels, A. Pastore

- Kinks in the keV mass range;
- Peak searches in meson decays (NA62);
- Decays at beam dump (including neutrino facilities);
- Neutrinoless dbeta decay: $\mathcal{A} \propto m_4 U_{e4}^2$, $\mathcal{A} \propto U_{e4}^2 1/m_4^2$
- Colliders looking for LNV, LFV, displaced vertices;
- CLFV: $Br(\mu \to e\gamma) \sim \frac{3\alpha}{8\pi}(\sum_j U_{\mu j}^* U_{ej} g(\frac{M_N^2}{m_W^2}))^2$

See talk by M.-H. Genest

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.

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani PLB 384; Buchmuller, Plumacher, Annal. Phys. 315, ...

- At T>M, N are in equilibrium:

$$N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H \qquad N \leftrightarrow \ell H$$

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

$$N \to \ell H \qquad N \to \ell^c H^c \qquad N \to \ell H \qquad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

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

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

T

M

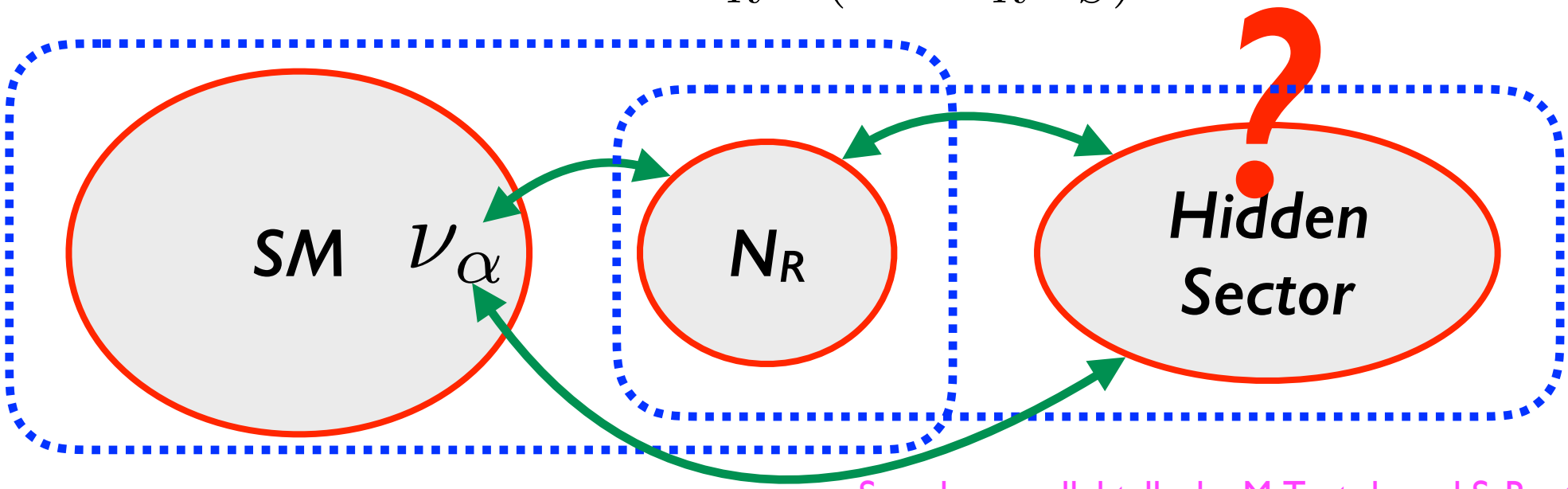
T=100 GeV

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.

Neutrinos: a window on the dark sector?

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

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



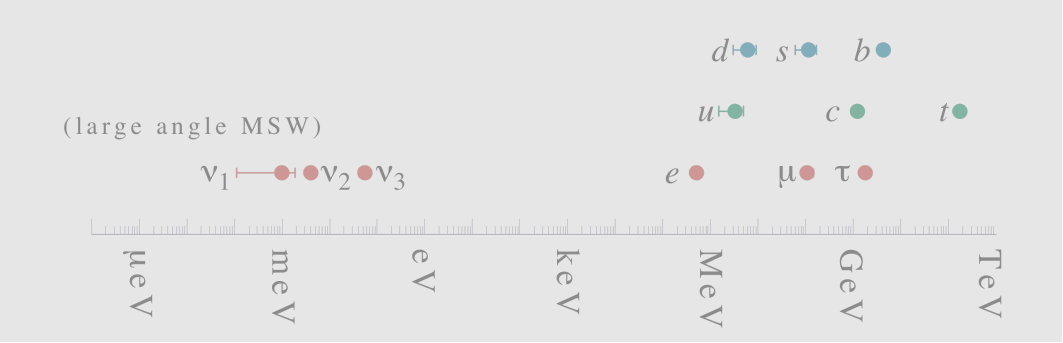
See also parallel talks by M. Tortola and S. Raut

The dark sector could include new gauge interactions (e.g. dark photons), new scalars and new fermions.
There is a possible connection between neutrinos and dark photon/Z', dark scalars, dark matter studies.

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?
Is there CPV?

Masses and mixing from the mass matrix

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

$$M_M = (U^\dagger)^T m_{\rm diag} U^\dagger \quad \Longrightarrow \quad \nu_i = U^\dagger \nu_\alpha$$

Theory

Experiments

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

Example. In the diagonal basis for the leptons

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

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

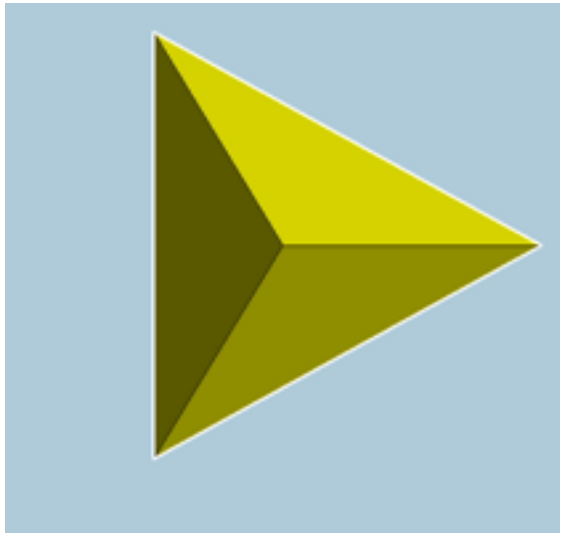
Various strategies and ideas can be employed to understand the observed pattern (many many models!): anarchy, texture zeros, symmetry approach, …

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

Typically, the symmetry restricts the number of free parameters leading to relations between masses and /or mixing angles and CPV phase.
E.g. the so-called sumrules:

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

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

Ballet et al., Girardi et al.

In order to test these relations and get information on the underlying symmetry, we need:

- A precise measurements of the oscillation parameters (including the delta phase).
- Mass ordering and neutrino mass spectrum.

Conclusions

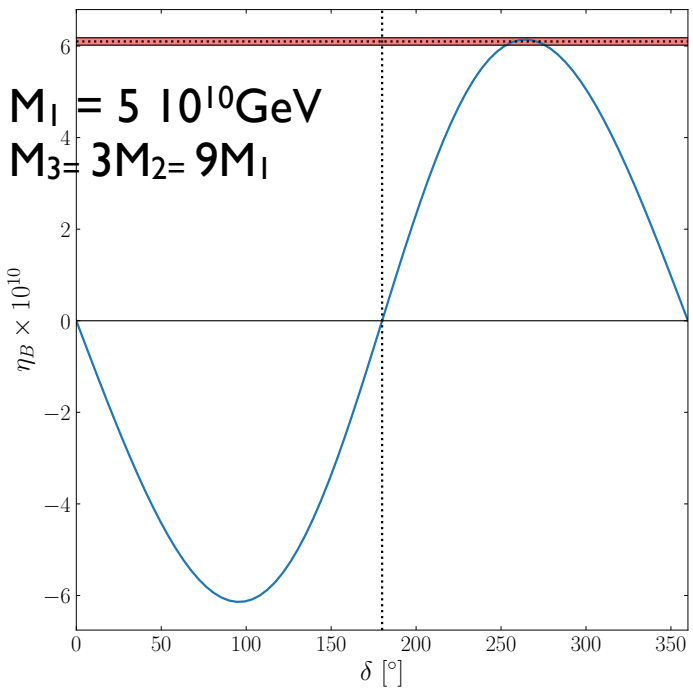
- Neutrino masses are the first particle physics evidence of Physics Beyond the Standard Model. Neutrinos provide a new complementary window w.r.t. collider and flavour physics searches.

- 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, 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).

- 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