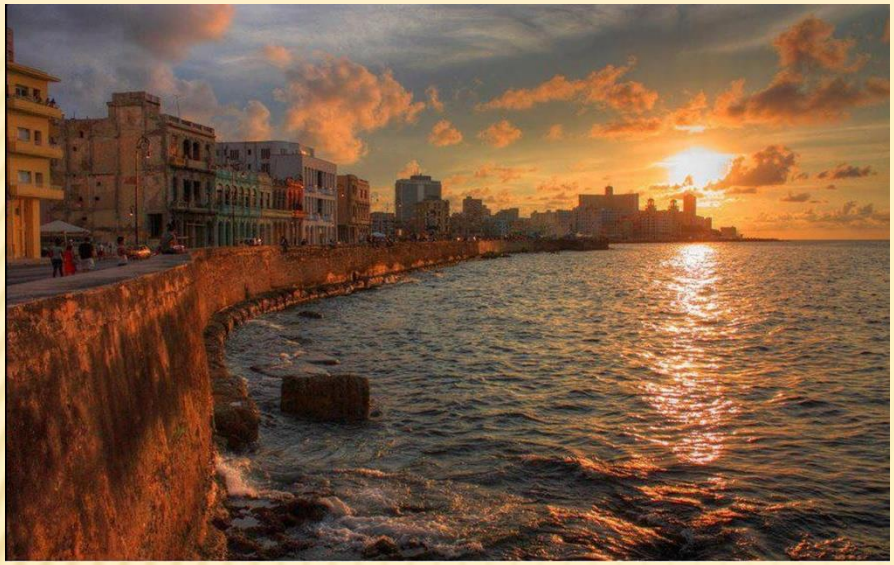

THE NEUTRINO FLAVOR PUZZLE

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OUTLINE

- The neutrino puzzle
- Theoretical framework – seesaw mechanism
- The bonus: baryogenesis via leptogenesis
- Towards the puzzle solution – symmetries
- Predictive 2HDM with flavor symmetries
- Concluding remarks

NEUTRINO PHYSICS – THE PRECISION ERA

- We have witnessed a breakthrough in neutrino physics
- Compelling evidence for **physics beyond the Standard Model**

- **1998** Atmospheric ν_μ disappearance (Super-Kamiokande) - large atmospheric mixing
- **2002** Solar ν_e disappearance (SK); solar ν_e appearance as ν_μ and ν_τ (Sudbury Neutrino Observatory) - large solar mixing
- **2004** Observation of reactor $\overline{\nu_e}$ oscillations (KamLAND); accelerator ν_μ disappearance (K2K)
- **2006** Confirmation of accelerator ν_μ disappearance (MINOS)
- **2010** Accelerator ν_μ appearance as ν_τ (OPERA)
- **2011** Accelerator ν_μ appearance as ν_e (T2K, MINOS)
- **2012** Reactor $\overline{\nu_e}$ disappearance (Daya Bay, RENO) – nonzero reactor angle
- **2014** Accelerator ν_μ appearance as ν_e (T2K) - hint for CP violation
- **2016** Accelerator ν_μ disappearance (NOvA) - maximal atmospheric mixing excluded

NEUTRINO EXPERIMENTS

See talks at this conf.

WHAT WE KNOW

- Fermion mass and mixing problem is more puzzling
  - Neutrinos have very tiny masses: $m_\nu < O(1\ \mathrm{eV})$
  - Lepton and quark mixing patterns are quite different:

$$|U_{\mathrm{PMNS}}| \approx \begin{pmatrix} 0.8 & 0.6 & < 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad |V_{\mathrm{CKM}}| \approx \begin{pmatrix} 0.97 & 0.226 & 0.004 \\ 0.226 & 0.97 & 0.04 \\ 0.009 & 0.04 & 0.99 \end{pmatrix}$$

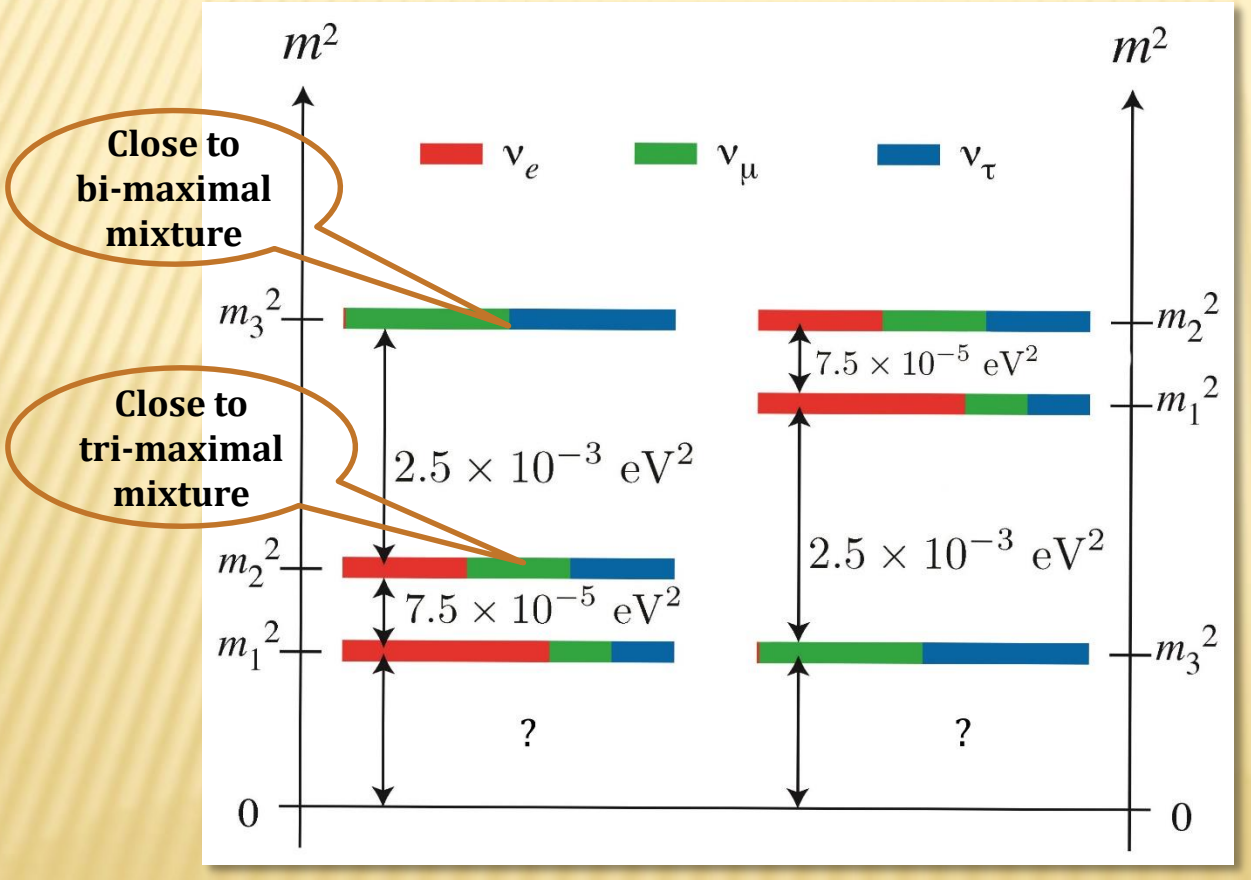
LARGE MIXING **SMALL MIXING**

  - Neutrino mass hierarchy so far not constrained

$$\Delta m^2_{\mathrm{atm}} \equiv |m_3^2 - m_1^2| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$
$$\Delta m^2_{\mathrm{sol}} \equiv m_2^2 - m_1^2 \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$$

THE NEUTRINO MASS HIERARCHY

- Neutrino mass squared splitting and mixing



Mild hierarchy:

$m_3/m_2 < 6$

Compared with quarks:

$m_t/m_c \sim 135$

$m_c/m_u \sim 490$

$m_b/m_s \sim 40$

$m_s/m_d \sim 20$

And with charged leptons:

$m_\tau/m_\mu \sim 17$

$m_\mu/m_e \sim 207$

LEPTONIC MIXING AND CP VIOLATION

- CP violation encoded in the leptonic mixing matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta_1} & 0 \\ 0 & 0 & e^{i\beta_2} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$

Dirac phase: CP violation measurable in neutrino oscillations

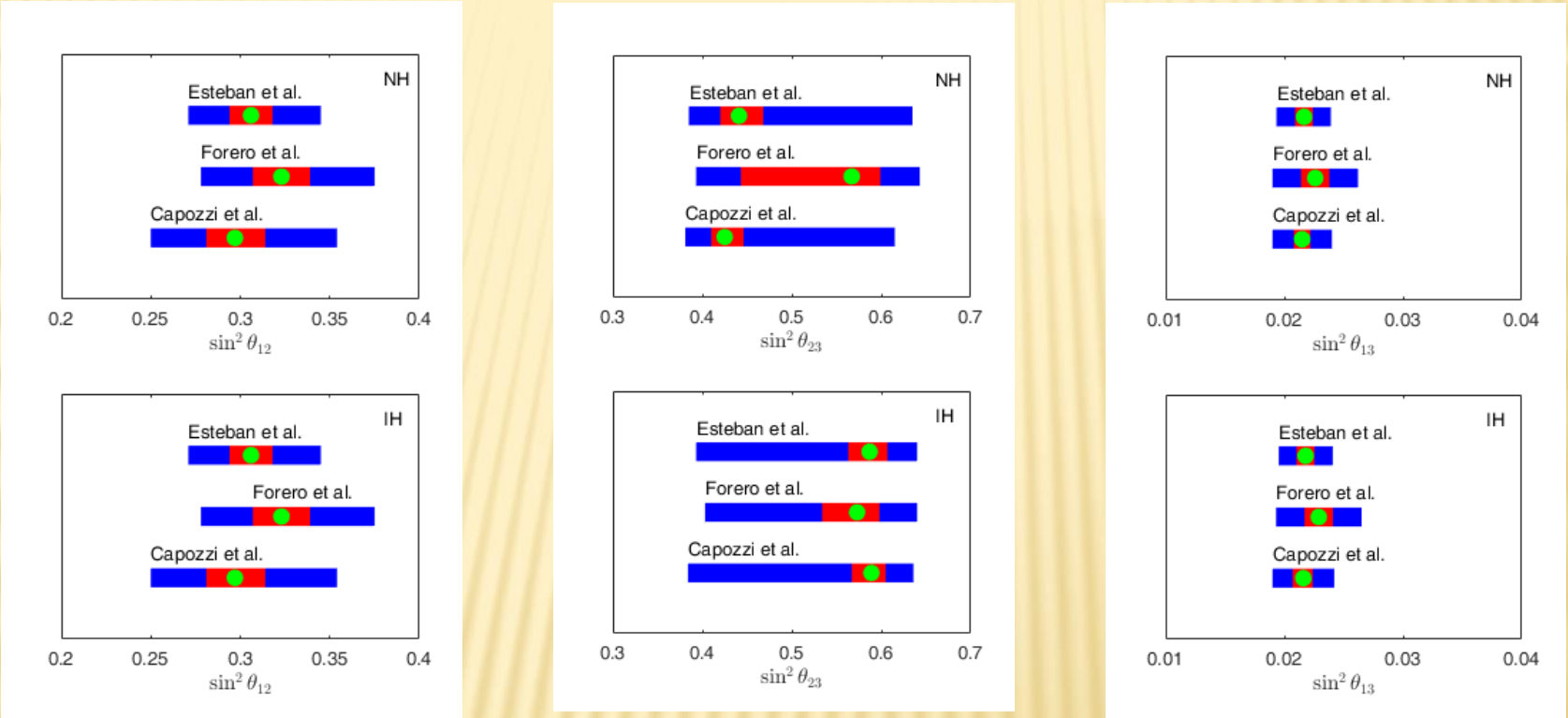
Majorana phases: 0νββ decay

$$U_{\ell L}^{\dagger} m_{\ell} U_{\ell R} = \mathrm{diag}(m_e\ , m_\mu\ , m_\tau)$$

$$U_{\nu L}^{\dagger} m_{\nu} U_{\nu L}^{*} = \mathrm{diag}(m_1\ , m_2\ , m_3)$$

$$U_{PMNS} = U_{\ell L}^{\dagger} U_{\nu}$$

GLOBAL FITS OF NEUTRINO OSCILLATION DATA



● best fit 1σ 3σ

[I. Esteban et al., arXiv:1611.01514, NuFIT 3.0]
[F. Capozzi et al., arXiv:1703.04471]
[D.V. Forero et al., arXiv:1405.7540]

WHAT WE DO NOT KNOW YET

- **Neutrino mass spectrum**: normal hierarchy, inverted hierarchy or quasi-degenerate
- **Absolute neutrino mass scale**
- **Nature: Dirac or Majorana particles**
  - The introduction of Dirac mass terms in the SM requires extremely small Yukawa couplings $h_\nu < 10^{-12}$
  - A Majorana mass term is more appealing: it can be interpreted as the lowest-order (5-dim) operator beyond the SM $\sim \frac{\ell\phi\ell\phi}{\Lambda}$ [Weinberg 1980]
- **Leptonic CP violation**: Dirac and/or Majorana type

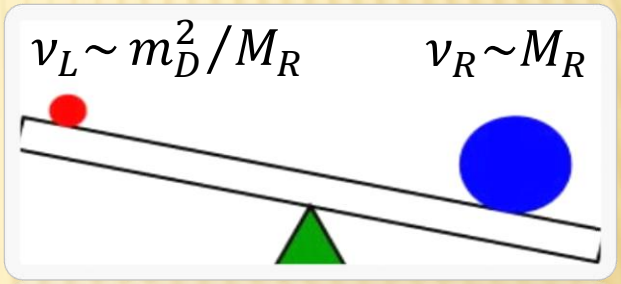
THE FLAVOR PUZZLE

- Rigorously speaking, several questions to answer:
  - Origin of the 3 lepton families
  - Tiny neutrino masses
  - Two heavier neutrino masses less hierarchical than for other fermion masses
  - Theory behind the neutrino masses
  - Neutrino nature: Dirac or Majorana particles
  - Large lepton mixing
  - Physics responsible for leptonic CP violation

THEORETICAL FRAMEWORK – SEESAW MECHANISM

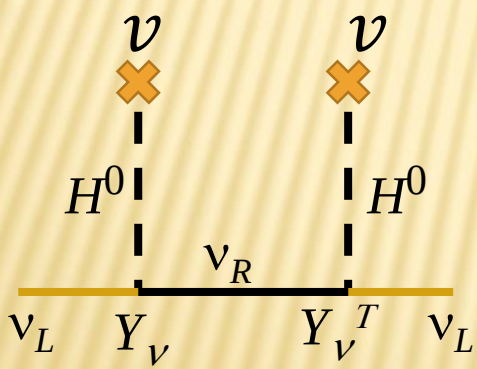
- A natural and elegant theoretical framework to understand why ν masses are tiny

$$L_{\text{mass}} = \frac{1}{2}(\nu_L^T \nu_R^T) C^{-1} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + \text{h.c.}$$



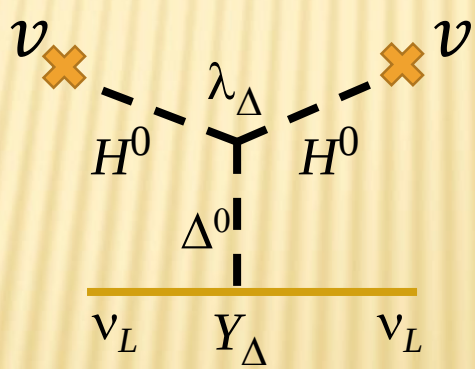
- Simplest seesaw realizations

Type I



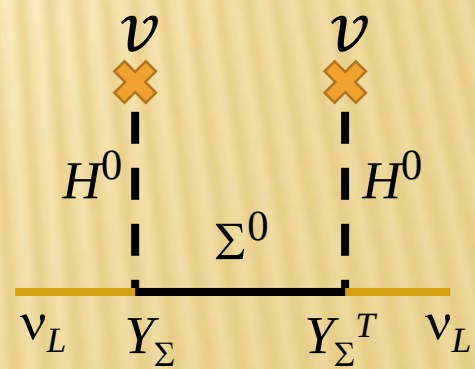
$$m_\nu = -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$

Type II



$$m_\nu = \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

Type III



$$m_\nu = -v^2 Y_\Sigma \frac{1}{M_\Sigma} Y_\Sigma^T$$

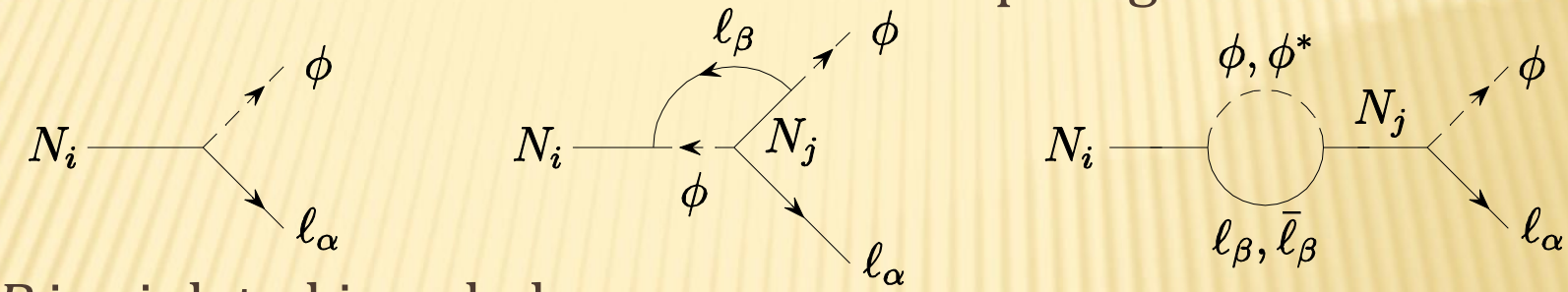
THE BONUS – BARYOGENESIS VIA LEPTOGENESIS

- A simple and attractive mechanism to generate the baryon asymmetry [Fukugita & Yanagida, 1986]
- It relies on physics beyond the SM that has been observed – relation between leptogenesis and low-energy neutrino physics
- The asymmetry can be generated via decays of heavy states, which fit nicely in GUT; for e.g. right-handed neutrinos N
  - Minimal extension of the SM:

$$-\mathcal{L}_Y = Y_\ell \bar{\ell} \phi e_R + Y_\nu \bar{\ell} \tilde{\phi} N + \frac{1}{2} M_R \overline{N^c} N + \text{H.c.}$$

LEPTOGENESIS AND THE ORIGIN OF MATTER

- Interference of tree-level and one-loop diagrams



- B is violated in sphaleron processes
- CP is violated in the decay of heavy neutrinos:

$$\varepsilon_i = \frac{\Gamma(N_i \to \ell\phi) - \Gamma(N_i \to \bar{\ell}\phi^\dagger)}{\Gamma(N_i \to \ell\phi) + \Gamma(N_i \to \bar{\ell}\phi^\dagger)} \neq 0$$

- At some temperature T, decays are out of equilibrium (parameterized by the decay rate Γ and the Hubble rate H):

$$K_i \equiv \frac{\Gamma(N_i \to \ell\phi)}{H(T = M_i)}$$

TOWARDS THE PUZZLE SOLUTION – SYMMETRIES

- Continuous/Discrete flavor symmetries
- Guiding principles – models must be:
  - **Minimal** – simple and economical enough
  - **Predictive** – possibility to test/exclude them by experiments
  - **Robust** – based on some theoretical symmetry and/or dynamics

LEPTON MASS MATRICES WITH TEXTURE ZEROS

- **Texture zeros** – a common approach towards the solution of the fermion flavor puzzle
- Zeros can be enforced by means of **Abelian symmetries**
- **Maximally restrictive patterns** – no additional zero can be placed into the charged-lepton or neutrino mass matrix while keeping compatibility with the experimental data
- Textures can be implemented via flavor symmetries in one of the simplest SM extensions – **two-Higgs-doublet model (2HDM)** [R.G. Felipe & H. Serôdio, 2017]

PREDICTIVE 2HDM WITH FLAVOR SYMMETRIES

- Without any correlation, at least 8 physical parameters are required to explain the 8 experimentally known observables $(m_e\,, m_\mu\,, m_\tau\,, \Delta m_{21}^2\,, \Delta m_{31}^2\,, \theta_{12}\,, \theta_{23}\,, \theta_{13})$
- Minimize the χ^2 function

$$\chi^2(x) = \sum_i \frac{(\mathcal{P}_i(x) - \overline{\mathcal{O}_i})^2}{\sigma_i^2}$$

- Find pairs of lepton mass matrices $m_\ell\,, m_\nu$ compatible with oscillation data
- The case of textures constructed in the weak basis where m_ℓ is diagonal (6 zeros) and m_ν has 2 zeros is not discussed here [R.G. Felipe & H. Serôdio, 2014]

PREDICTIVE 2HDM WITH FLAVOR SYMMETRIES

- Leptonic sector of the 2HDM Lagrangian

$$-L_{int} = \bar{\ell}_L Y_i \phi_i e_R + \frac{\kappa_{ij}}{2\Lambda}(\bar{\ell}_L \tilde{\phi}_i)(\tilde{\phi}_j^T \bar{\ell}_L^c) + h.c., \quad i,j = 1,2$$

- Maximally restrictive patterns

1 massless neutrino

$$\mathbf{4}_3^\ell \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix} \qquad \mathbf{3}_6^\nu \sim \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix} \qquad \mathbf{4}_1^\nu \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & \times \end{pmatrix}$$

$$\mathbf{5}_1^\ell \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \qquad \mathbf{3}_8^\nu \sim \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix} \qquad \mathbf{4}_6^\nu \sim \begin{pmatrix} \times & \times & 0 \\ \times & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Charged leptons

Neutrinos

PREDICTIVE 2HDM WITH FLAVOR SYMMETRIES

- Only 4 pairs of maximally restrictive leptonic matrices with 8 physical parameters can be implemented through an Abelian symmetry within the 2HDM [R.G. Felipe & H. Serôdio, 2017]

(m_ℓ, m_ν)	Higgs combination	Symmetry
$(\mathbf{4}_3^\ell, \mathbf{4}_1^\nu)$	[(2,2), (1,2)]	
$(\mathbf{4}_3^\ell, \mathbf{4}_6^\nu)$	[(1,1), (1,2)]	$U(1)$
$(\mathbf{5}_1^\ell, \mathbf{3}_6^\nu)$	[(1,1), (2,2), (1,2)]	
$(\mathbf{5}_1^\ell, \mathbf{3}_8^\nu)$	[(2,2), (1,1), (1,2)]	

Z_7 minimal discrete symmetry

- The discrete symmetry can be useful when looking at UV completions of the effective Weinberg operator – the extra field content may allow for terms distinguishing continuous and discrete transformations

PREDICTIVE 2HDM WITH FLAVOR SYMMETRIES

- Determine the field charges under the flavor U(1)

$$4_3^\ell: \quad \ell_L \to \mathrm{diag}\left(1, e^{-2i\gamma}, e^{-4i\gamma}\right)\ell_L$$

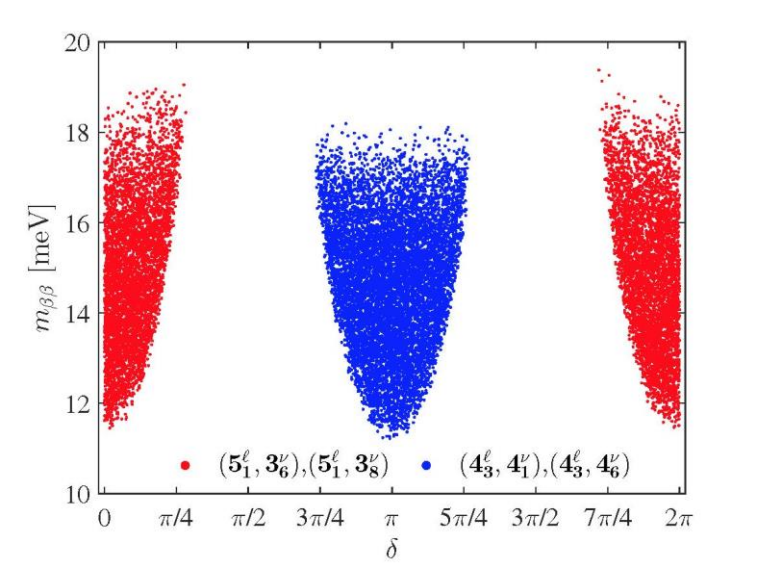
$$4_1^\nu: \quad e_R \to \mathrm{diag}\left(e^{-9i\gamma}, e^{-7i\gamma}, e^{-5i\gamma}\right)e_R$$
$$\phi_1 \to e^{5i\gamma}\phi_1 \qquad \phi_2 \to e^{3i\gamma}\phi_2$$

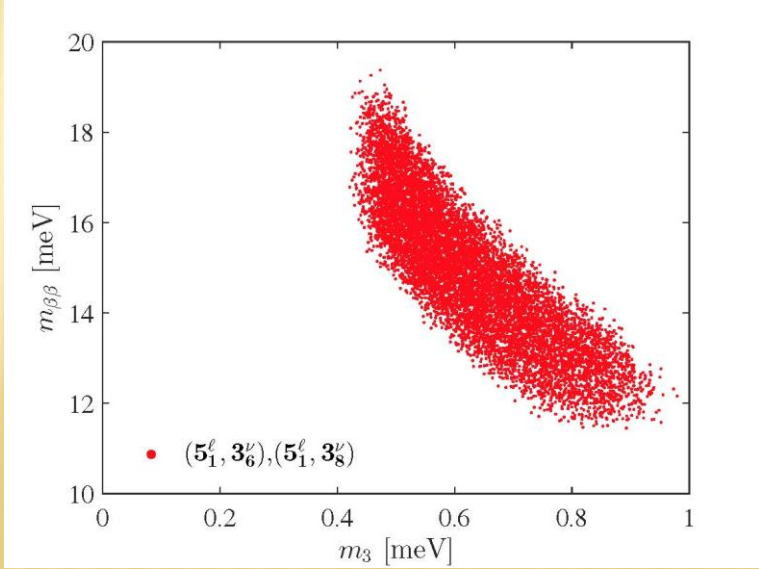
$$4_6^\nu: \quad e_R \to \mathrm{diag}\left(e^{-5i\gamma}, e^{-3i\gamma}, e^{-i\gamma}\right)e_R$$
$$\phi_1 \to e^{i\gamma}\phi_1 \qquad \phi_2 \to e^{-i\gamma}\phi_2$$

- The cases $(5_1^\ell, 3_6^\nu)$ and $(5_1^\ell, 3_8^\nu)$ can be equally analyzed

LOW-ENERGY PREDICTIONS: $m_{\beta\beta}$ AND δ

- Impose the phenomenological constraints (lepton universality, LFV decays mediated by Higgs scalars, LHC Higgs physics)
- The feasible textures lead to an IH mass spectrum for the light neutrinos and definite predictions for the Dirac CP-violating observable phase and the effective Majorana mass in 0νββ decay, $m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$





ULTRAVIOLET COMPLETION AND QUARK SECTOR

- As long as the UV completion does not break the symmetry, all conclusions remain unchanged
- The type-II seesaw is a trivial path for the UV completion of these models
- An UV completion within the type-I seesaw is also possible. However, due to the non-trivial correlation between the UV couplings and the light neutrino mass matrix, such a realization is not always viable
- The same Abelian symmetry can be applied in the quark sector without introducing new Higgs scalars

CONCLUDING REMARKS

- Golden precision era for neutrino physics – many ongoing and planned experiments
- Flavor symmetries offer an elegant solution to the fermion puzzle – symmetries can be implemented in the lepton and quark sectors
- Flavor models contain a reduced number of free parameters – predictivity power, sum rules. UV completions are possible (e.g. via seesaw mechanism)
- Future of particle physics – combined exploration of phenomena at several frontiers, synergies between the **energy**, **intensity and cosmic frontiers**

$\nu's$: INTENSITY, ENERGY AND COSMIC FRONTIERS

INTENSITY FRONTIER

- Neutrinoless double beta decay searches
- Neutrino oscillation experiments: mass and mixing data, CP violation
- LFV searches

- Are neutrinos Dirac or Majorana particles?
- Flavor symmetries (discrete or continuous)
- Origin of leptonic CP violation

ENERGY FRONTIER

Large Hadron Collider (LHC)

- Models with new particles (heavy neutrinos, more Higgs scalars,…)
- New interactions: extended gauge group and symmetries

COSMIC FRONTIER

Cosmological observations

- Baryon asymmetry of the Universe (leptogenesis?)
- Leptonic CP-violating effects
- Models with dark matter candidates