Shaving Type-I Seesaw Mechanism with Occam's Razor

Jue Zhang (张珏)
IHEP, Beijing
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JZ, arxiv:1502.04043, Phys. Rev. D 91 (2015) 7, 073012
JZ and Shun Zhou, arXiv:1505.04858

Outline

- **Type-I seesaw mechanism** (testability)
- **Occam's Razor** (minimal scenarios)
- **Example I:**
  - Frampton-Glashow-Yanagida (FGY) model
- **Example II:**
  - Generalization to the case with 3 family of right-handed neutrinos

Massive Neutrinos

$$-\mathcal{L}_{\rm SM} \supset \overline{\ell_L}\ \mathbf{Y_e}\ EH + h.c.$$

⇓

$$-\mathcal{L}_{\nu{\rm SM}} \supset \overline{\ell_L}\ \mathbf{Y_e}\ EH + \frac{1}{2}\overline{\nu_L^c}\ \mathbf{M}_\nu\ \nu_L + h.c.$$

Working in the flavor basis where **Ye** is diagonal,
Mν contains all the lepton flavor mixing information:

$$\mathbf{M}_\nu = U_\nu\ D_\nu\ U_\nu^T$$

9 physical parameters:

$$D_\nu = {\rm Diag}(m_1, m_2, m_3)$$
$$U_\nu = R(\theta_{23})R(\theta_{13},\delta)R(\theta_{12}){\rm Diag}(e^{i\rho}, e^{i\sigma}, 1)$$

Only 5 parameters are currently well-measured!

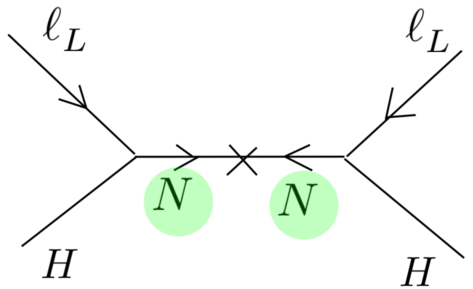
$$(\theta_{12}, \theta_{23}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3i}|)$$

+ one constraint from cosmology $\sum m_i < 0.23\ {\rm eV}$

Type-I Seesaw Mechanism

UV
18 paras
(in $\mathbf{Y}_\nu$ and $\mathbf{M}_\mathbf{R}$)

$$-\mathcal{L}_{\rm SS} = \overline{\ell_L}\,\mathbf{Y_e}\,EH + \overline{\ell_L}\,\mathbf{Y}_\nu\,N\tilde{H} + \frac{1}{2}\overline{N^c}\,\mathbf{M_R}\,N + h.c.$$



$$\mathbf{M}_\nu \approx -v^2 \mathbf{Y}_\nu \frac{1}{\mathbf{M_R}} \mathbf{Y}_\nu^{\mathbf{T}}$$

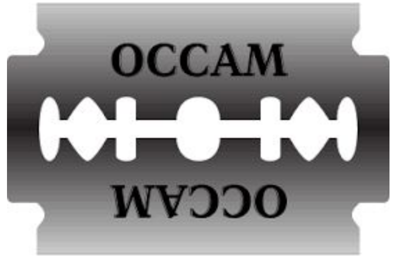
$$-\mathcal{L}_{\nu{\rm SM}} \supset \overline{\ell_L}\,\mathbf{Y_e}\,EH + \frac{1}{2}\overline{\nu_L^c}\,\mathbf{M}_\nu\,\nu_L + h.c.$$

IR
9 paras
(in $\mathbf{M}_\nu$)

Pros:
1. Consistent with GUTs (both ''qualitatively'' and ''quantitatively")
2. Right-handed neutrinos may play roles in generating baryon asymmetry in the Universe (Leptogenesis)

Cons: **HOW TO TEST IT?**

Occam's Razor



> ***"other things being equal, simpler explanations are generally better than more complex ones"***

- Lack of a convincing flavor theory leads us to consider the flavor structure of Yukawa matrices in a phenomenological way:

simpler explanations $\Longleftrightarrow$ **less parameters (minimal scenarios)**

- Less parameters $\Longrightarrow$ more predictive $\Longrightarrow$ better testability
- Example: testing MSSM at LHC
  - ~100 parameters for a general MSSM
  - experimentally one tests CMSSM (5 parameters) first

Test Minimal Scenarios!

Example I:
Frampton-Glashow-Yanagida (FGY) model

Frampton-Glashow-Yanagida (FGY) model

Phys. Lett. B 548, 119 (2002)

- **Assumption I (minimal seesaw):**
  - Only **2** generations of right-handed neutrinos are added .
- **Assumption II:**
  - **2 texture zeros** in the neutrino Yukawa matrix, in the basis where both $\mathbf{Y_e}$ and $\mathbf{M_R}$ are diagonal.
  - 2 is the maximal allowed number of texture zeros

$$\mathbf{Y}_\nu \sim \begin{pmatrix} 0 & \times \\ 0 & \times \\ \times & \times \end{pmatrix}$$

- **Highly predictive:**
  - Only **5** physical parameters in $\mathbf{Y}_\nu$ *vs.* **5** well-measured observables from the neutrino data
  - Only **1** physical phase in $\mathbf{Y}_\nu$: (original motivation for FGY model) CP violations at low energy and high energy are connected!

Testable Predictions of FGY Model

1. Only **Inverted Hierarchy (IH)** of neutrinos are allowed, because of the measurement of θ_{13}! **K. Harigaya, M. Ibe and T. T. Yanagida, Phys. Rev. D 86, 013002 (2012)**

- several neutrino oscillation experiments are trying to determine neutrino mass hierarchy (JUNO, T2K, NovA, PINGU…)
- maybe known in the next ten years

2. Three individual neutrino masses are known.

- $m_1 \sim 0.048$ **eV**, $m_2 \sim 0.049$ **eV**, $m_3 = 0$
- $\Sigma m_i \sim 0.097$ **eV** may be tested by cosmology

3. Dirac CP-violating phase $\delta \sim \pm 90^\circ$

- testable by T2K, LBNF, ...

4. Neutrinoless double decay:

- the predicted effective neutrino mass $m_{ee} \sim 50$ **meV**
- reachable by next generation of experiments

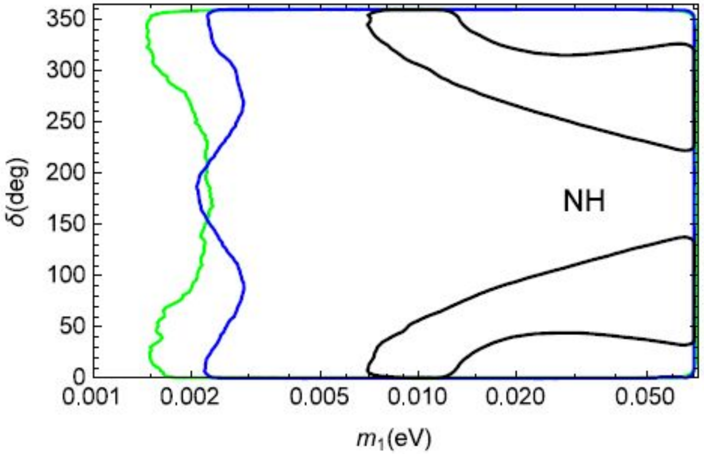
Note: The above predictions are valid even with the renormalization group running effects considered. **JZ and Shun Zhou, arXiv:1505.04858**

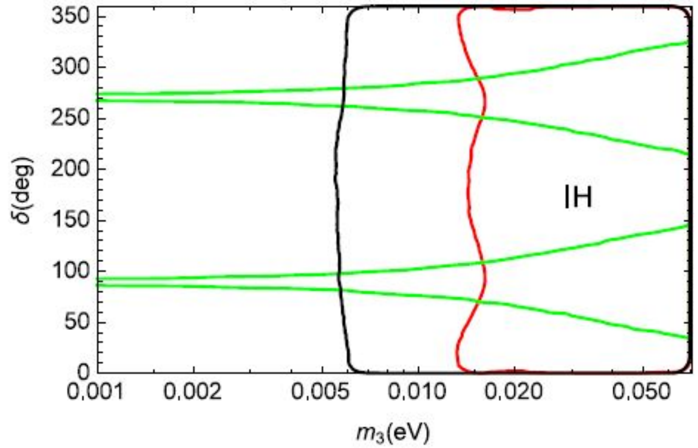
Example II:
Generalization to 3-family case

Four Texture Zeros in Yν

$$\mathbf{Y}_\nu \sim \begin{pmatrix} \times & 0 & \times \\ \times & 0 & 0 \\ \times & \times & 0 \end{pmatrix}$$

- Conventional type-I seesaw
- In the basis where both **Ye** and **MR** are diagonal, **4** is the maximal number of texture zeros in **Yν**, assuming that none of the light neutrino masses vanishes.
  - **72** possible patterns
- **Low testability!!!**
  - **7** physical parameters in **Yν** vs. **5** well-measured neutrino observables
  - The allowed parameter space is weakly constrained.
  - too many allowed patterns (**54 for NH, 66 for IH**)





Not a minimal scenario regarding the neutrino data!

Look for a More Minimal Scenario

- Impose **additional theoretical assumptions** to reduce free parameters:
  - motivated from GUTs: **up-quark Yukawa coupling $Y_u \sim Y_\nu$**
  - Assumption: **Y_ν exhibits a similar hierarchy to Y_u.**
  - Three eigenvalues of Y_ν have a ratio of **Eigen(Y_ν) ~ (λ^8, λ^4, 1)** **λ=0.23**
- Introduce **additional observables:**
  - Study **leptogenesis** so that one more observable from cosmology
  - the observed baryon asymmetry in the Universe
- **A problem:** the above two treatments are not easy to realize simultaneously.
  - Highly hierarchical Y_ν usually leads to a even **more hierarchical M_R**
  - **Eigen(M_R) ~(10^3, 10^{10}, 10^{14}) GeV** to give sub-eV neutrino masses
  - **Davidson-Ibarra bound in leptogenesis:**

    the mass of the **lightest** right-handed neutrino has to be greater than **10^9** GeV, assuming hierarchical right-handed neutrinos and no flavor effects

N_2-dominated Leptogenesis

- **Leptogenesis:**
  - Decay of right-handed neutrinos generates lepton number asymmetry
  - Out-of-equilibrium decay of right-handed neutrinos preserves such an asymmetry
  - In the later evolution, non-perturbative spaleron processes convert the preserved lepton number asymmetry into the observed baryon asymmetry
- **''N_1-dominated'' leptogenesis with no flavor effects**
  - Without flavor effects, the lepton number asymmetry generated by heavier $\mathbf{N_2}$ and $\mathbf{N_3}$ can be fully washed out by $\mathbf{N_1}$
  - Only $\mathbf{N_1}$ contributes the generation of lepton number asymmetry
  - $\mathbf{N_1}$ needs to be heavy than $\mathbf{10^9}$ GeV.
- **N_2-dominated leptogenesis with flavor effects**
  - **Flavor effects:** the generated lepton asymmetry is distinguished by the lepton flavor.
  - Lepton asymmetry in some flavor generated by $\mathbf{N_2}$ may not be washed out by $\mathbf{N_1}$
  - **A bonus:** it is then sensitive to the flavor structure of **Yν**.

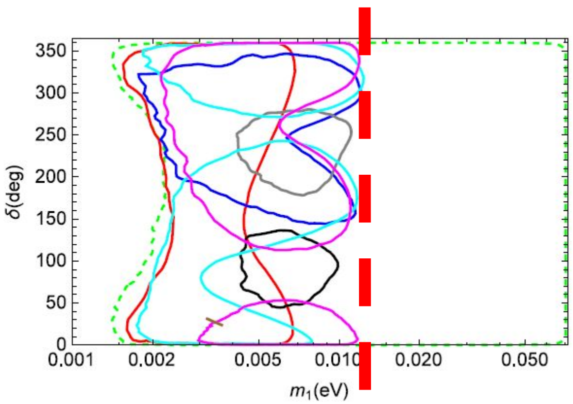
$$\begin{pmatrix} 0 & \times & 0 \\ 0 & 0 & \times \\ \mathbf{X} & \mathbf{X} & \mathbf{X} \end{pmatrix}$$

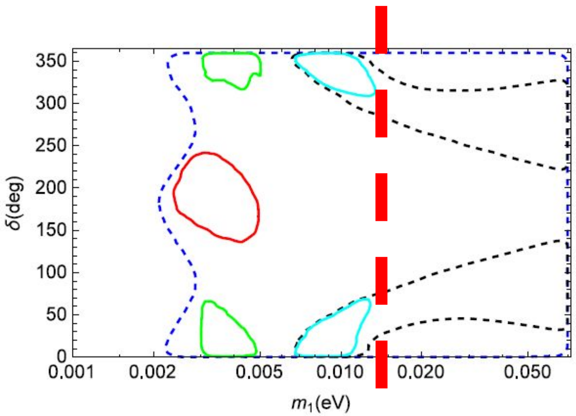
Improved Testability

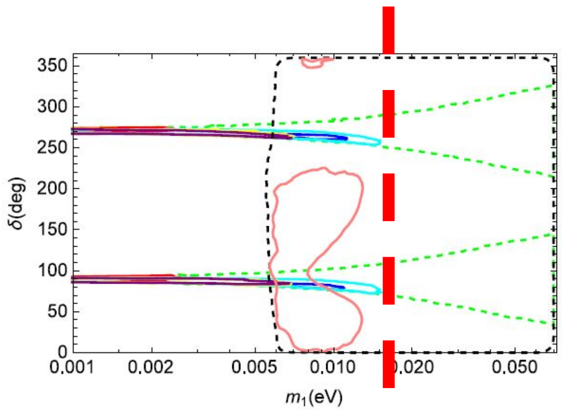
- **Large reduction of allowed textures**

	NH			IH		
	LE	LE+LG(QA)	LE+LG(NS)	LE	LE+LG(QA)	LE+LG(NS)
Class IA	0	0	0	18	10	0
Class IB	18	10	7	18	10	5
Class IC	18	8	4	18	8	5
Class IIA	6	4	2	0	0	0
Class IIB	6	4	1	6	4	1
Class IIC	6	4	1	6	4	1

- **Shrink of the allowed parameter space**







Prediction: neutrinos can NOT be quasi-degenerate!

Summary

- **Discussed the testability of a general type-I seesaw mechanism**
- **Adopted the spirit of Occam's Razor to examine minimal scenarios**
- **Example I: Frampton-Glashow-Yanagida (FGY) model**
  - highly predictive, and can be soon tested (only IH is allowed!)
- **Example II: Generalization to the 3-family case**
  - four texture zeros in **Y_ν**
  - low testability without additional requirements
  - Imposing requirements from GUT and leptogenesis improves the testability.
  - An indication of quasi-degenerate neutrinos will disfavor the above scenario.

Thank you for your attention!