Predictions of m_{ee} and neutrino mass from a consistent Froggatt-Nielsen model

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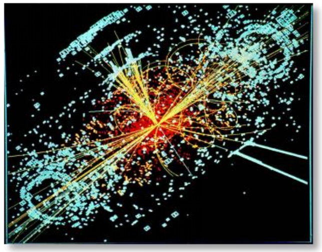
Outline

- **Introduction and motivation**
- **Froggatt-Nielsen model**
- **Methodology and parameter choosing**
- **Predictions on m_{ee} and neutrino mass**
- **Summary**

Why New Physics?



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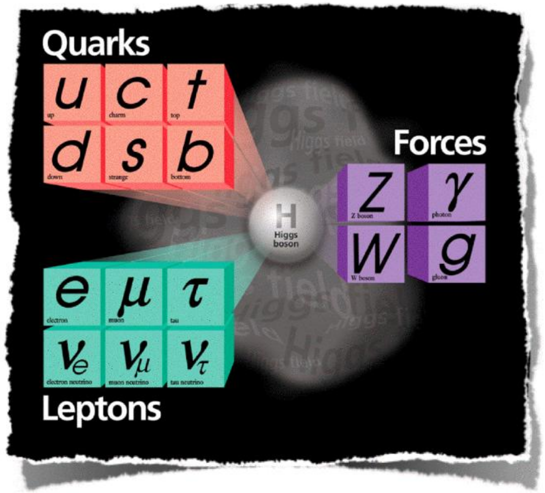

Not Perfect!

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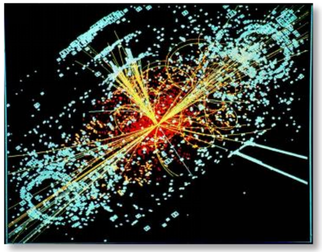

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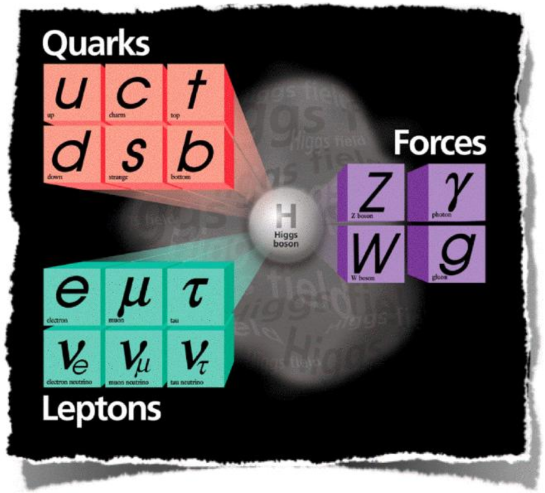
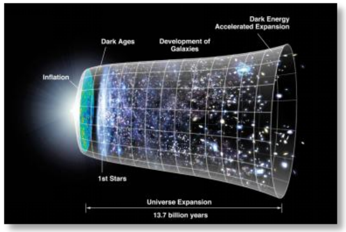


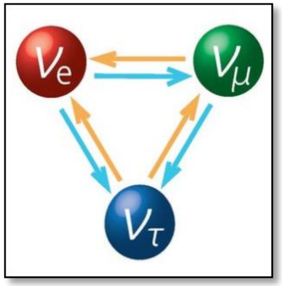
Not Perfect!

So many unsolved problems:

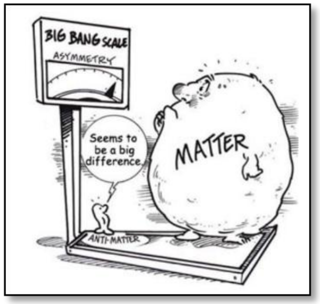
Dark Matter



Dark Energy

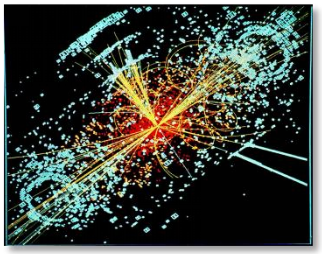


Neutrino Mass



Bayron Genesis

Why New Physics?



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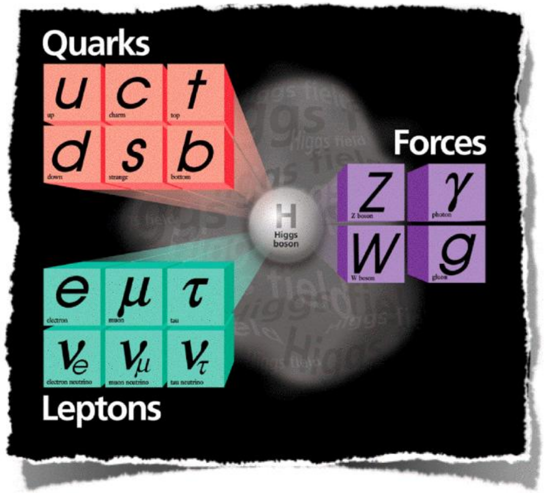
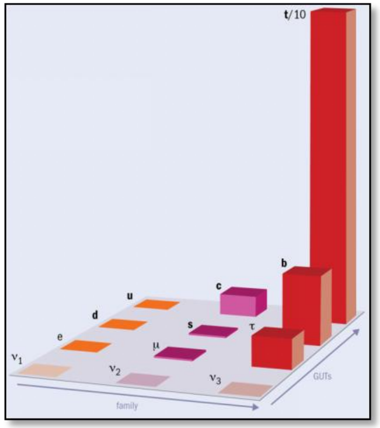


Not Perfect!

Who order that?

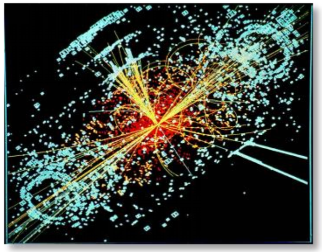
(1) Why do these parameters choose such values?

(2) What is the origin of such a mass and mixing pattern?



Flavor Puzzle

Why New Physics?



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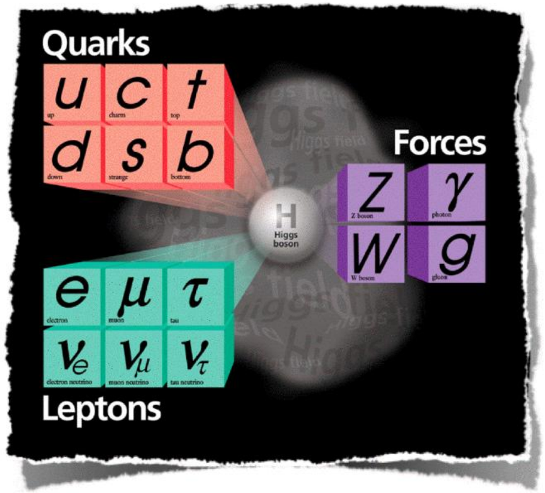

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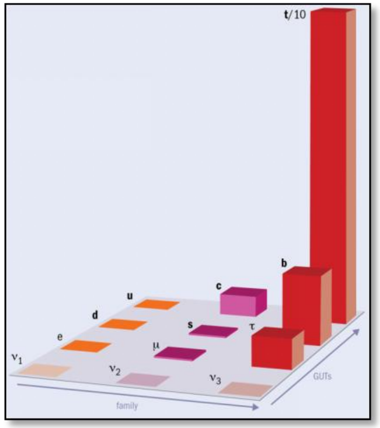
Froggatt-Nielsen model



Flavor Puzzle

Froggatt-Nielsen model

- Extend the SM with **golbal $\boldsymbol{U(1)}$** symmetry, called $U_{FN}(1)$, which is broken by the vacuum expectation value (VEV) scalar field ϕ (FN field) with $U_{FN}(1)$ charge is -1;
- SM particles also carry $U_{FN}(1)$ charge, which is generation dependent, the Higgs carry FN charge 0.
- Quark sector: $-\mathcal{L} \supset y_u^{ij} \overline{Q}_L^i \tilde{H} u_R^j + y_d^{ij} \overline{Q}_L^i H d_R^j + \text{h.c.}$

$$y_u^{ij} = g_{ij} \lambda^{n_u^{ij}} \,, \quad y_d^{ij} = g_{ij} \mathcal{N} \lambda^{n_d^{ij}} \qquad \text{with} \qquad \lambda = \langle \phi \rangle / M_{\rm PL}$$

g_{ij} is the universal couplings, $|g_{ij}|$ fulfill the normal distribution $N(\mu, \sigma^2)$ with $\mu = 1$, and $\sigma = 0.3$, the phase of g_{ij} is from 0~2pi

Froggatt-Nielsen model

- $U_{FN}(1)$ **charge conservation** → $$n_u^{ij} = U(1)_{\rm FN}^{\overline{Q}_{\rm L}^i} + U(1)_{\rm FN}^{u_{\rm R}^j}\,,$$ $$n_d^{ij} = U(1)_{\rm FN}^{\overline{Q}_{\rm L}^i} + U(1)_{\rm FN}^{d_{\rm R}^j}\,.$$

- Mass hierarchy is indicated by the fermion mass ratio between generations, e.g. m_u/m_t, m_d/m_b

- Taking $\overline{Q}_L^i$ and d_R^j for exaple $U(1)_{\rm FN}^{\overline{Q}_{\rm L}^i} = \{a, b, c\}$ and $U(1)_{\rm FN}^{d_{\rm R}^j} = \{d, e, f\}$

$$\lambda^{n_d^{ij}} = \lambda^{c+f} \begin{pmatrix} \lambda^{a-c+d-f} & \lambda^{a-c+e-f} & \lambda^{a-c} \\ \lambda^{b-c+d-f} & \lambda^{b-c+e-f} & \lambda^{b-c} \\ \lambda^{d-f} & \lambda^{e-f} & 1 \end{pmatrix}$$

Methodology and parameter choosing

- SM values:

TABLE I. Experimental measured quantities. Quark and lepton mass ratios are taken at the scale of 10^{12} GeV [29], which are almost energy scale independent [30]. Mixing angles and CP phases are in the rad unit [31].

m_u/m_t	m_c/m_t	m_d/m_b	m_s/m_b
6.58×10^{-6}	0.00333	0.00104	0.0201
θ_{12}^{C}	θ_{23}^{C}	θ_{13}^{C}	δ^{C}
0.227	0.0418	0.00369	1.14
m_e/m_τ	m_μ/m_τ	$\Delta m_{21}^2/\Delta m_{32}^2$	
0.000279	0.0589	0.0307	
θ_{12}^{P}	θ_{23}^{P}	θ_{13}^{P}	δ^{P}
0.591	0.844	0.150	$-2.41^{+0.663}_{-0.489}$

- Quark and letpton mass ratio are almost same from 10^{12} GeV to M_{PL}
- Only FN field is introduced, the mixing angle running can be ingored.

Methodology and parameter choosing

- Wolfenstein parametrization

$$\sin\theta_{12}^{\rm C} \sim \lambda', \ \sin\theta_{23}^{\rm C} \sim \lambda'^2 \ \text{and} \ \sin\theta_{13}^{\rm C} \sim \lambda'^3, \ \text{where} \ \lambda' \sim 0.2.$$

$$\Rightarrow \quad \lambda \sim \mathcal{O}(\lambda') \ \text{and} \ U(1)_{\rm FN}^{\overline{Q}_{\rm L}^i} = \{3, 2, 0\}$$

- Assuming the FN charges of u_R and d_R are {a, b, 0} and {c, d, 0}

$$n_u = \begin{pmatrix} 3+a & 3+b & 3 \\ 2+a & 2+b & 2 \\ a & b & 0 \end{pmatrix}, n_d = \begin{pmatrix} 3+c & 3+d & 3 \\ 2+c & 2+d & 2 \\ c & d & 0 \end{pmatrix}$$

$$\frac{m_u}{m_t} \sim \lambda'^7, \ \frac{m_c}{m_t} \sim \lambda'^{3.5}, \ \frac{m_d}{m_b} \sim \lambda'^4, \ \frac{m_s}{m_b} \sim \lambda'^2 \quad \Rightarrow \quad \boxed{\begin{array}{ll} a = 4, & b = 1.5 \\ c = 1, & d = 0. \end{array}}$$

Methodology and parameter choosing

- Lepton sector: $$-\mathcal{L} \supset y_\ell^{ij} \overline{\ell}_{\rm L}^i H e_{\rm R}^j + \frac{1}{M} y_\nu^{ij} \left(\overline{\ell_{\rm L}^{\rm c}}^i \tilde{H}^*\right)\left(\tilde{H}^\dagger \ell_{\rm L}^j\right) + {\rm h.c.}$$

$$y_\ell^{ij} = g_{ij} \mathcal{N} \lambda^{n_\ell^{ij}} \,, \quad y_\nu^{ij} = g'_{ij} \lambda^{n_\nu^{ij}}$$

- Large mixing angles $$U(1)_{\rm FN}^{\overline{\ell}_{\rm L}} = \{1, 0.5, 0\} \qquad U(1)_{\rm FN}^{e_{\rm R}} = \{e, f, 0\}$$

$$\Rightarrow \quad n_\ell = \begin{pmatrix} 1+e & 1+f & 1 \\ 0.5+e & 0.5+f & 0.5 \\ e & f & 0 \end{pmatrix}$$

$$\frac{m_e}{m_\tau} \sim \lambda'^5 \,, \quad \frac{m_\mu}{m_\tau} \sim \lambda'^{1.5} \quad \Rightarrow \quad e = 4 \,, \quad f = 1$$

Methodology and parameter choosing

- For neutrino $$n_\nu = \begin{pmatrix} 2 & 1.5 & 1 \\ 1.5 & 1 & 0.5 \\ 1 & 0.5 & 0 \end{pmatrix}$$

- The rank of n_ν is 1, which indicates that the FN mechanism naturally prefers normal order (NO).

- By sampling 10^6 times using our FN charge with λ = 0.171 and σ = 0.3, we find that NO takes up about 98%.

FN charge assignment

- FN charge:

TABLE II. FN charge of quarks and leptons.

Generation i	1	2	3
$\overline{Q}_{\mathrm{L}}$	3	2	0
u_{R}	4	1.5	0
d_{R}	1	0	0
$\overline{\ell}_{\mathrm{L}}$	1	0.5	0
e_{R}	4	1	0

- Minimum chi-square methoed to fix the value of λ

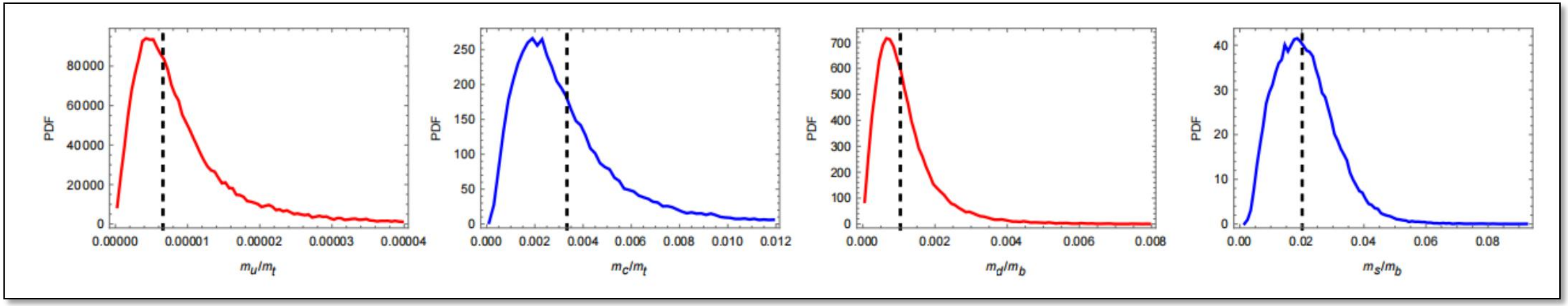
$$\chi^2(\lambda) = \sum_i \left(\frac{E(X_i) - X_i^{\mathrm{exp}}}{\sqrt{V(X_i)}} \right)^2$$

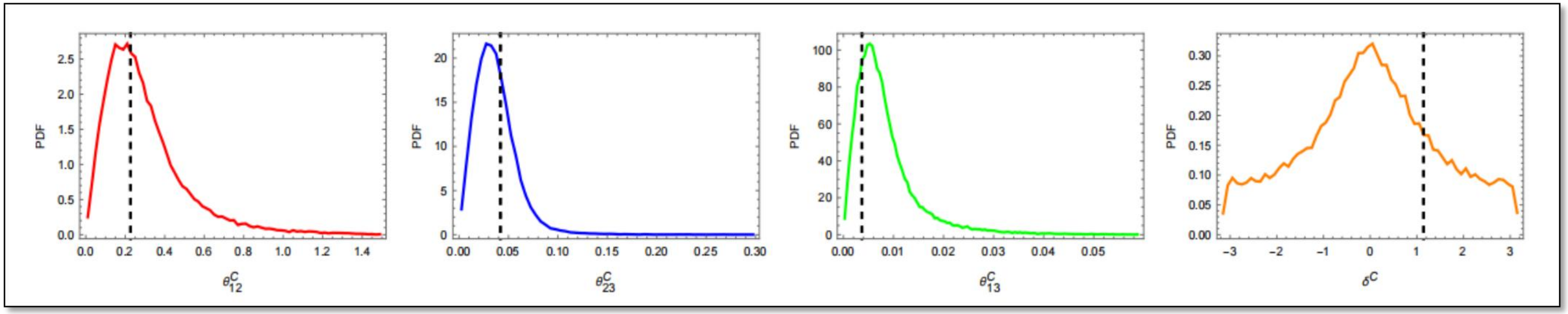
$$X_i \in \left\{ \frac{m_u}{m_t}, \frac{m_c}{m_t}, \frac{m_d}{m_b}, \frac{m_s}{m_b}, \frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}, \frac{\Delta m_{21}^2}{\Delta m_{32}^2}, \theta_{12}^{\mathrm{C}}, \theta_{23}^{\mathrm{C}}, \theta_{13}^{\mathrm{C}}, \delta^{\mathrm{C}}, \theta_{12}^{\mathrm{P}}, \theta_{23}^{\mathrm{P}}, \theta_{13}^{\mathrm{P}} \right\},$$

$$\Rightarrow \quad \lambda = 0.171 \quad \text{with} \quad \chi^2 = 4.69\ .$$

Fitting results

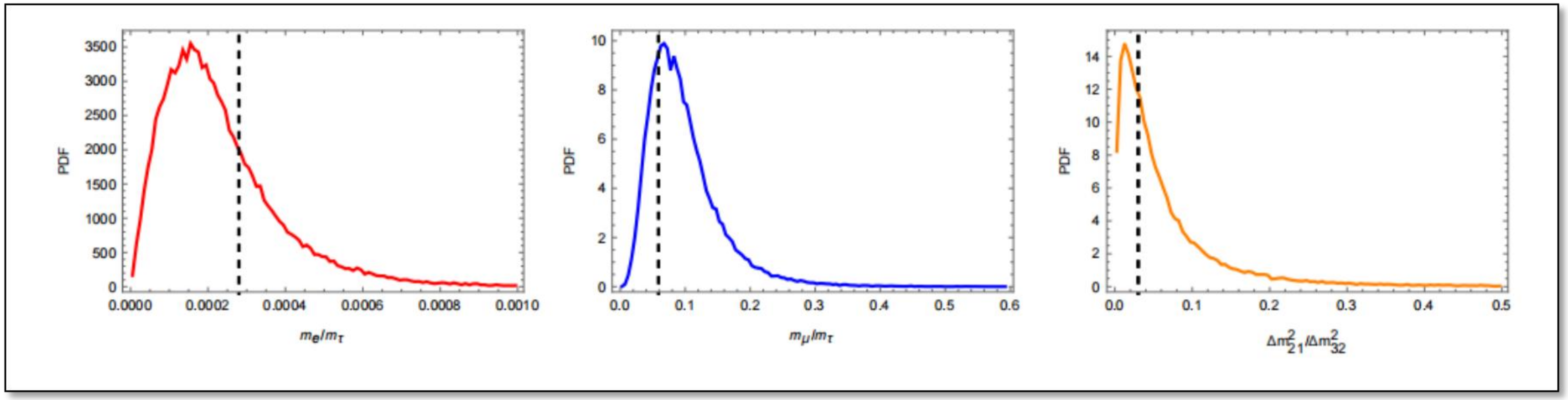
- The PDF of quark mass ratios and quark mixing angles with λ = 0.171 and σ = 0.3, while the dashed lines are observations.

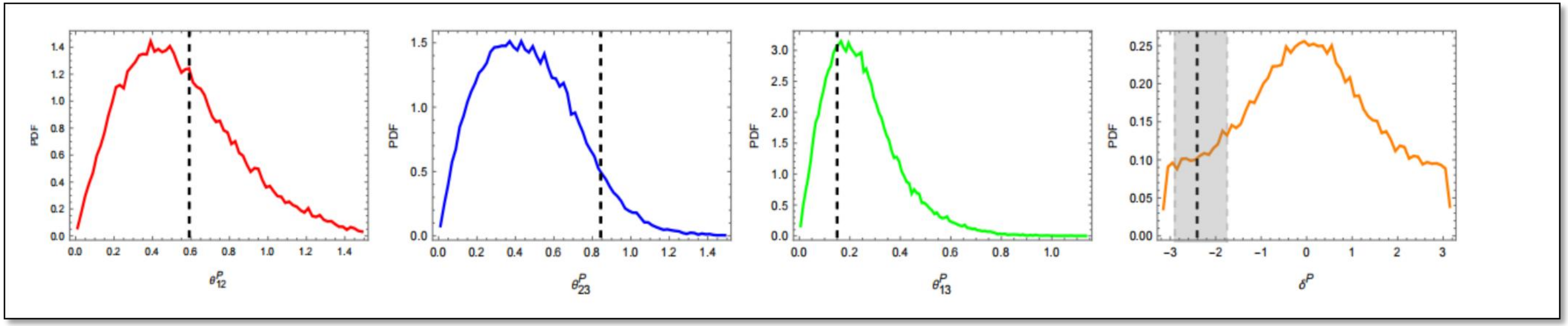




Fitting results

- The PDF of lepton mass ratios and neutrion mixing angle with λ = 0.171 and σ = 0.3, while the dashed lines are observations.





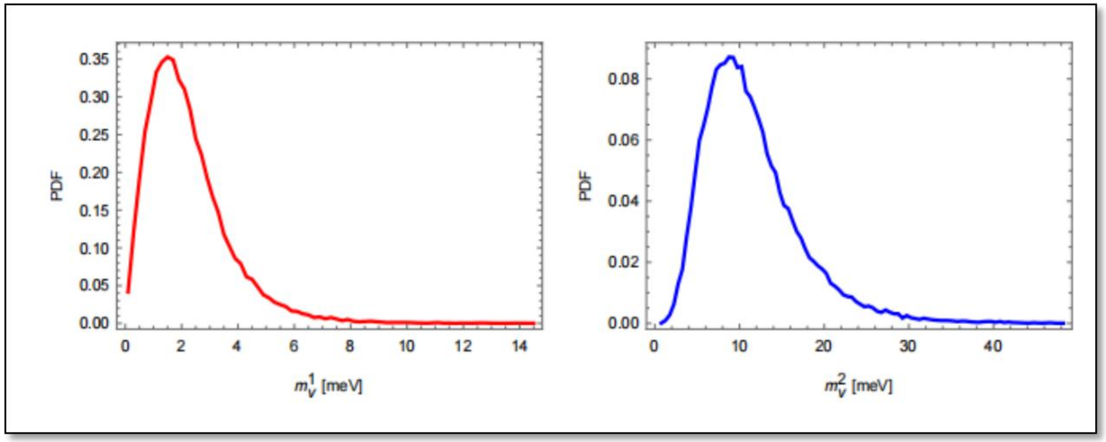
Predictions on neutrion mass and m_{ee}

- the absolute neutrino mass can be predicted

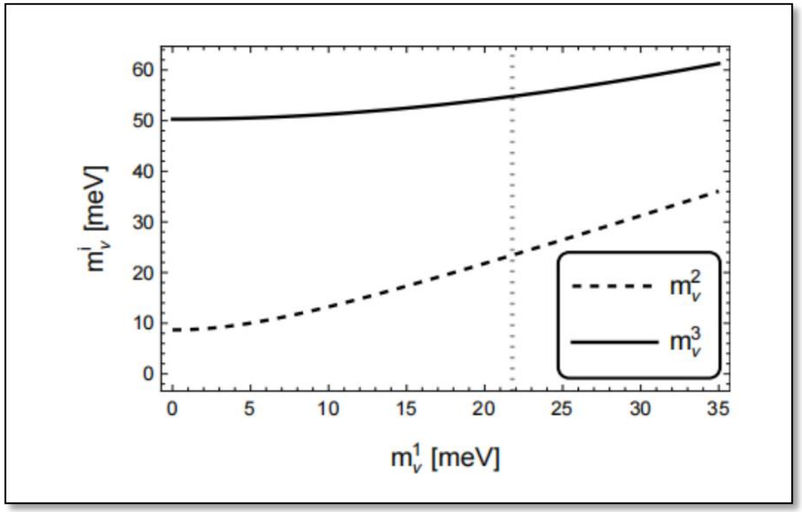
$$m_v^1 = 1.6\ \text{meV}$$

$$m_v^2 = 9\ \text{meV}$$

$$m_v^3 = 50\ \text{meV}$$



- **the predictions are consistent with current observations!**

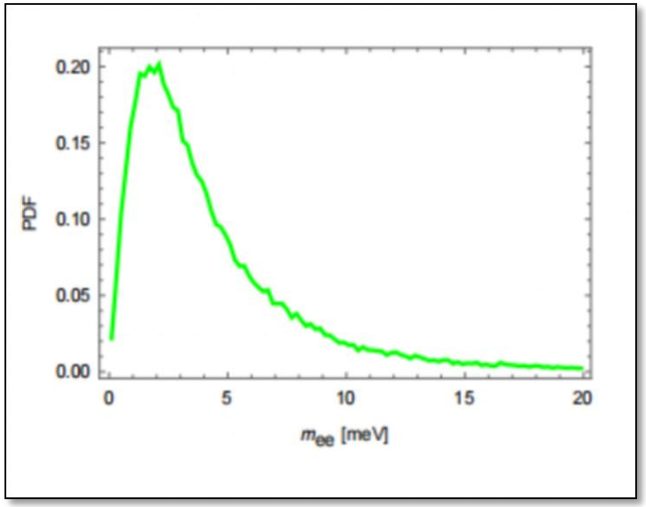


Predictions on neutrion mass and m_{ee}

- the effective Majorana mass

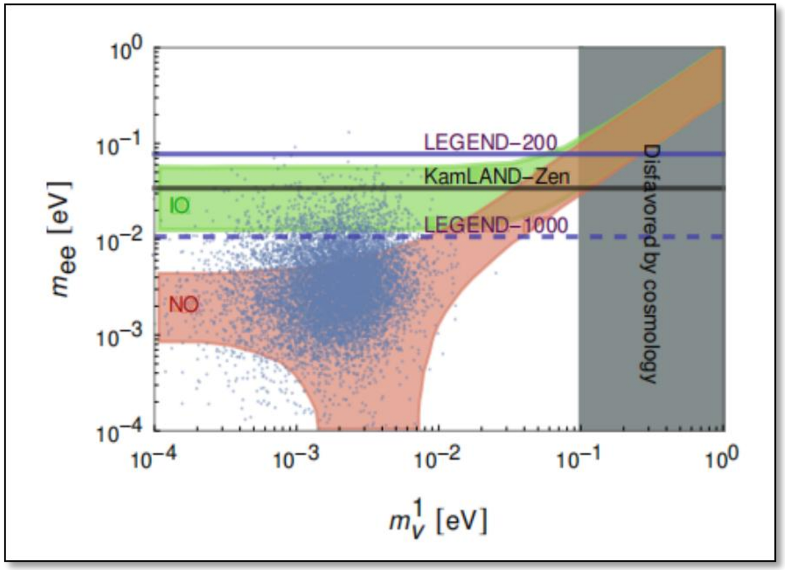
$$m_{ee} = \left| \sum_i (U^*_{\text{PMNS}})^2_{1i} m^i_\nu \right|$$

$$0.503\,\text{meV} \lesssim m_{ee} \lesssim 18.0\,\text{meV}$$



- the cosmology constrains

$$\sum_i m^i_\nu < 0.1\,\text{eV}$$



Summary

- **The Froggatt-Nielsen model provides a good explaination for the flavor pzzle;**
- **We propose a consistant FN model that is consitent with the current observation of mass ratio and the mixing angle. The FN charge is derive by doing a qualitative analysis;**
- **The FN model is naturally prefer NO case and predict a set of consistent neutrion mass, i.e., $\{m_v^1, m_v^2, m_v^3\} \approx \{1.6,\ \ 9,\ \ 50\}$ meV. Besides, a relatively large part of the preferred parameter space of m_{ee} can be detected in the near future.**

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Thank you