Leptonic flavor models at neutrino experiments

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Neutrino physics

- neutrinos are the **ideal** laboratory to test symmetries of nature
    - test **CP** $\rightarrow$ measurement of Jarlskog invariant in oscillation experiments

Is CP violated in the lepton sector? How much?

current bound: $|J_{PMNS}|/J_{max} < 0.34$

quark sector: $J_{CKM}/J_{max} = 3.1 \times 10^{-4}$ [PDG '20]

Neutrino physics

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  - **individual lepton number** conservation ($L_e,\ L_\mu,\ L_\tau$) $\rightarrow$ violated in neutrino oscillations!

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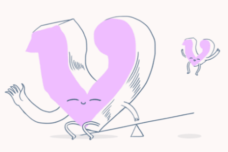
  - **individual lepton number** conservation $(L_e,\ L_\mu,\ L_\tau)$ $\rightarrow$ violated in neutrino oscillations!
  - test **total lepton number** conservation $\rightarrow$ neutrinoless double beta decay experiments
- linked to question of nature of neutrino mass: Dirac vs Majorana fermion
  $\Rightarrow$ insights into neutrino mass generation



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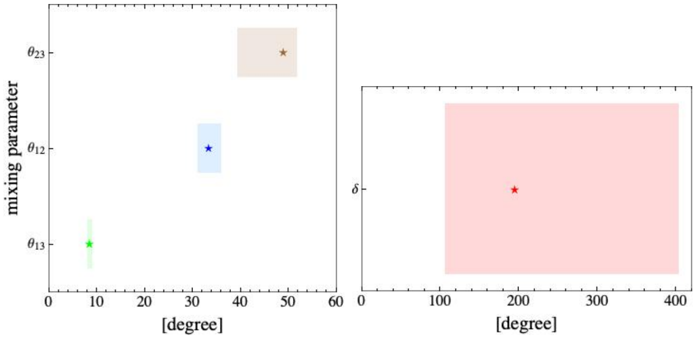
  - test **total lepton number** conservation $\rightarrow$ neutrinoless double beta decay experiments
  - **flavor symmetries**: today's topic

Leptonic mixing

- leptonic mixing matrix: 3×3 matrix parametrized with 3 angles, 1 Dirac CPV phase, 2 Majorana CPV phases

$$U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13},\delta)U_{12}(\theta_{12})P(\alpha_1/2,\alpha_2/2,1)$$

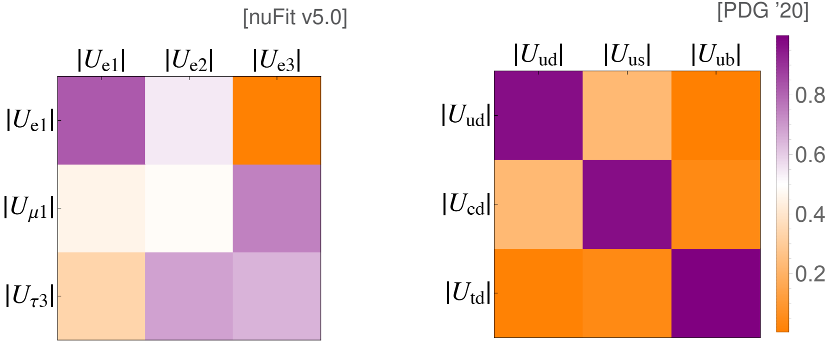
see [Denton, Pestes '20] for other parametrizations



[nuFit v5.0]

Leptonic mixing

- Leptonic mixing pattern very different from the one for quarks



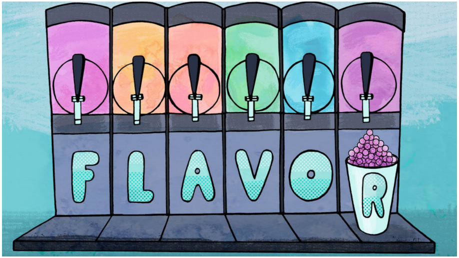
very off-diagonal $\rightarrow$ large flavor mixing

close to diagonal $\rightarrow$ little flavor mixing

Flavor symmetries

- Why is the leptonic mixing matrix so off-diagonal?
- Why is it so different from the one of the quarks?
- Is there any underlying (symmetry) reason for the leptonic mixing pattern?

How can we probe this?



Flavor symmetries

How to test flavor models? How to distinguish them?

- Most promising way to probe and disentangle models is via **precision measurements of mixing parameters**

  $\Rightarrow$ make it a **goal** of upcoming experiments to reach the sensitivity to probe flavor models

Leptonic sum rules

- Most predictive models don't only predict the mixing angles but correlations among them $\Rightarrow$ **Leptonic sum rules**
- two types of sum rules:
  1. **mixing sum rules**: connect the leptonic mixing angles as well as the CP-violating phase $\rightarrow$ tested at oscillation experiments
  2. **mass sum rules**: relate the three (complex) neutrino mass eigenvalues to each other $\rightarrow$ tested at neutrinoless double beta decay experiments & experiments sensitive to absolute neutrino mass scale

Sum rules

- new approach to model building and flavor symmetries based on modular symmetries [Feruglio '17]

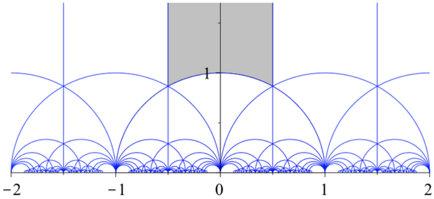
$$U_{PMNS} \sim U(\theta, \phi)$$

- minimal amount of parameters $\leftrightarrow$ maximal amount of correlations

$\Rightarrow$ **Sum rules arise in models with modular symmetries**

Sum rules

Julia Gehrlein and Martin Spinrath,
"Leptonic Sum Rules from Flavour Models with Modular Symmetries,"
published in JHEP **03** (2021), 177, arXiv:2012.04131 [hep-ph]



Modular mixing sum rules [JG, Spinrath '20]

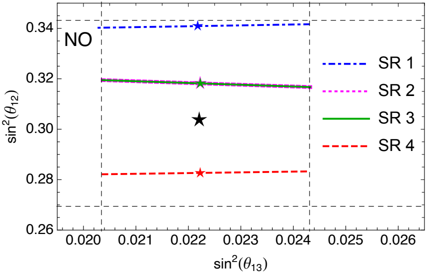
- surveyed over 70 models, 5 of them had maximal amount of correlations
- 4 mixing parameters described by 2 free parameters
- example: [Novichkov, Petcov, Tanimoto '18, JG, Spinrath '20]

$$
\begin{aligned}
\sin^2\theta_{12}(\theta) &= \frac{1}{3 - 2\sin^2\theta} \,, \\
\sin^2\theta_{13}(\theta) &= \frac{2}{3}\sin^2\theta \,, \\
\sin^2\theta_{23}(\theta,\phi) &= \frac{1}{2} + \frac{\sin\theta_{13}(\theta)}{2}\frac{\sqrt{2 - 3\sin^2\theta_{13}(\theta)}}{1 - \sin^2\theta_{13}(\theta)}\cos\phi \,, \\
\delta(\theta,\phi) &= \arcsin\left(-\frac{\sin\phi}{\sin 2\theta_{23}(\theta,\phi)}\right)
\end{aligned}
$$

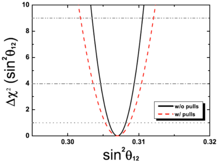
sum rules depend on the specific models however the dependencies are the same

Modular mixing sum rules [JG, Spinrath '20]

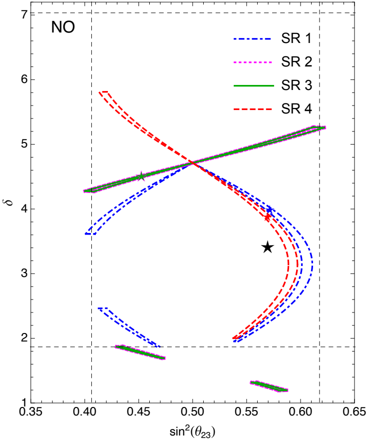
- Determine 3σ regions for $\theta,\ \phi$ from χ^2 profile of mixing parameters from [nuFit v5.0]



model prediction for θ_{12} deviate from its BF point! $\rightarrow$ **precision measurement of θ_{12} can rule out these models!**



[JUNO '15]

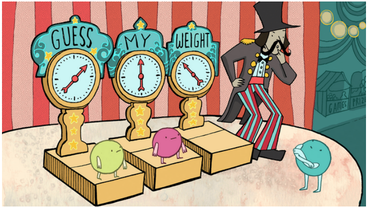


- if θ_{23}=max $\rightarrow \delta = 3\pi/2$, $\delta = 0, \pi$ not favored
- if $\delta = \pi \rightarrow \theta_{23}$ >max
- Precision needed to disentangle models depends on true value of mixing parameters

Very interesting correlations to test!

Modular mass sum rules

- oscillation experiments not sensitive to all neutrino parameters: no sensitivity to absolute neutrino mass scale nor Majorana phases
- **mass sum rules**: different type of sum rules, connects the three light (complex) neutrino masses
- constraints on absolute neutrino mass scale, $|m_{ee}|$, mass ordering

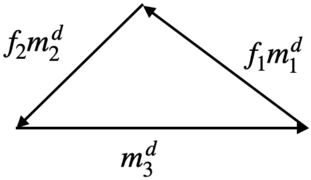


Modular mass sum rules

- mass sum rules: [King, Merle, Stuart '13, Barry, Rodejohann '10]

$$f_1 m_1^d e^{i\alpha_1} + f_2 m_2^d e^{i\alpha_2} + m_3^d = 0$$

- parametrized as triangle in complex plane



- models with constant f_i studied in [King, Merle, Stuart '13, Barry, Rodejohann '10, JG, Merle, Spinrath '16 '17, JG, Spinrath '17]

Modular mass sum rules [JG, Spinrath '20]

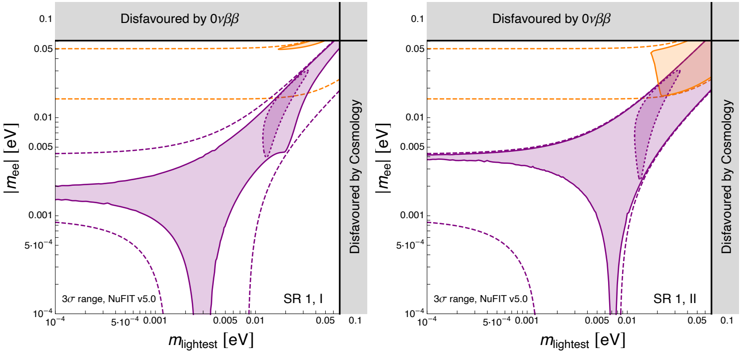
- mass sum rule coefficients **depend on mixing parameters**!
- example:

$$f_1 = -e^{-2i\phi} \frac{\sqrt{3}\sin 2\theta - \cos\phi\cos 2\theta - i\sin\phi}{\sqrt{3}\sin 2\theta - \cos\phi\cos 2\theta + i\sin\phi},$$

$$f_2 = -e^{-i\phi} \frac{2}{\sqrt{3}\sin 2\theta - \cos\phi\cos 2\theta + i\sin\phi},$$

$$d = \pm 1$$

- predictions for $|m_{ee}|$



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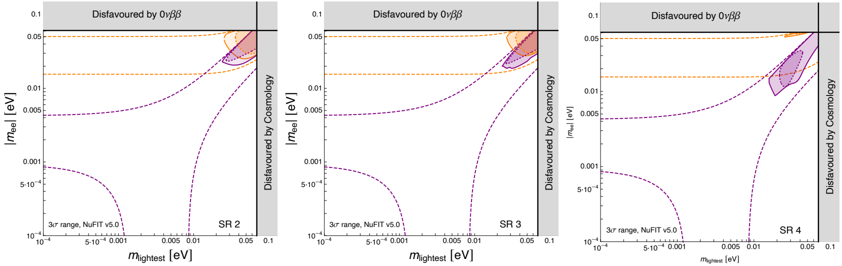
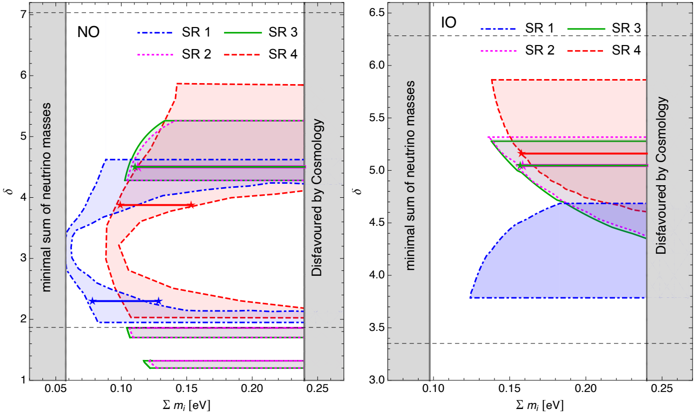


$\rightarrow$ generally predict large absolute neutrino masses

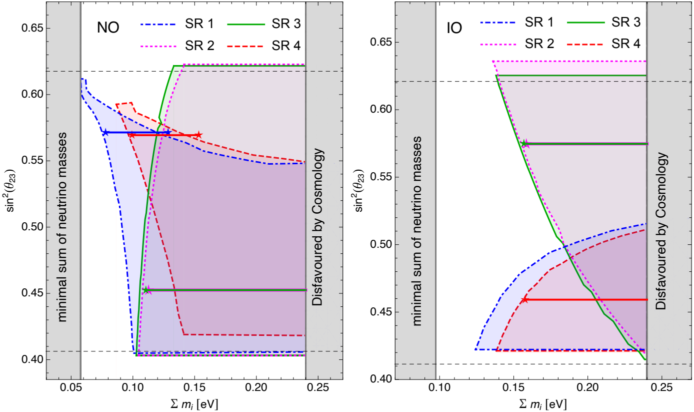
$\Rightarrow$ can be probed soon by cosmology

- correlations $\delta - \sum m_i$



Modular leptonic sum rules [JG, Spinrath '20]

- correlations $\theta_{23} - \sum m_i$



- **unique synergy** between LBL and experiments sensitive to absolute neutrino mass

Conclusion

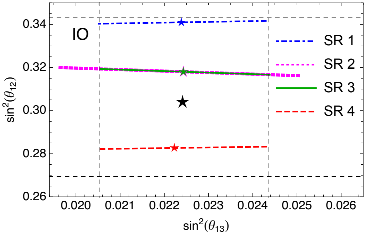
- future experiments will thoroughly probe the neutrino sector
  $\rightarrow$ test flavor symmetries
- predictions of leptonic sum rules:
  - use to plan stages of experiments
  - identify parameter space of interest
  - necessary precision to discriminate among different flavor models

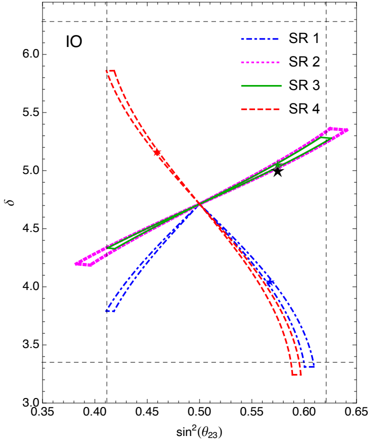
$\Rightarrow$ sum rules: opportunity for model builders, phenomenologists, and experimentalists to gain more insights into the mysteries hidden in the neutrino sector

Thank you for your attention!

[Artwork by Sandbox Studio, Chicago]

Backup: Modular sum rules [JG, Spinrath '20]





Backup: Modular sum rules [JG, Spinrath '20]

- similar values of Jarlskog invariant predicted in all models

$$J_{CP} = \sin\theta_{13}\sin\theta_{12}\sin\theta_{23}\cos^2\theta_{13}\cos\theta_{12}\cos\theta_{23}\sin\delta$$

$$-3.5\times 10^{-2} \lesssim J_{CP} \lesssim 3.5\times 10^{-2} \text{ for NO,}$$

$$-3.5\times 10^{-2} \lesssim J_{CP} \lesssim -2.5(-0.5)\times 10^{-2} \text{ for IO}$$