Overview of (some UK) Neutrino Theory

ECFA-UK Meeting on UK studies for the European Strategy Particle Physics Update

Jessica Turner, IPPP, Durham University

26 September 2024

Neutrinos: what we know

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \cdot \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}} \cdot \begin{pmatrix} e^{i\frac{\alpha_{21}}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_{31}}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin(\theta_{ij}) \qquad c_{ij} = \cos(\theta_{ij})$$

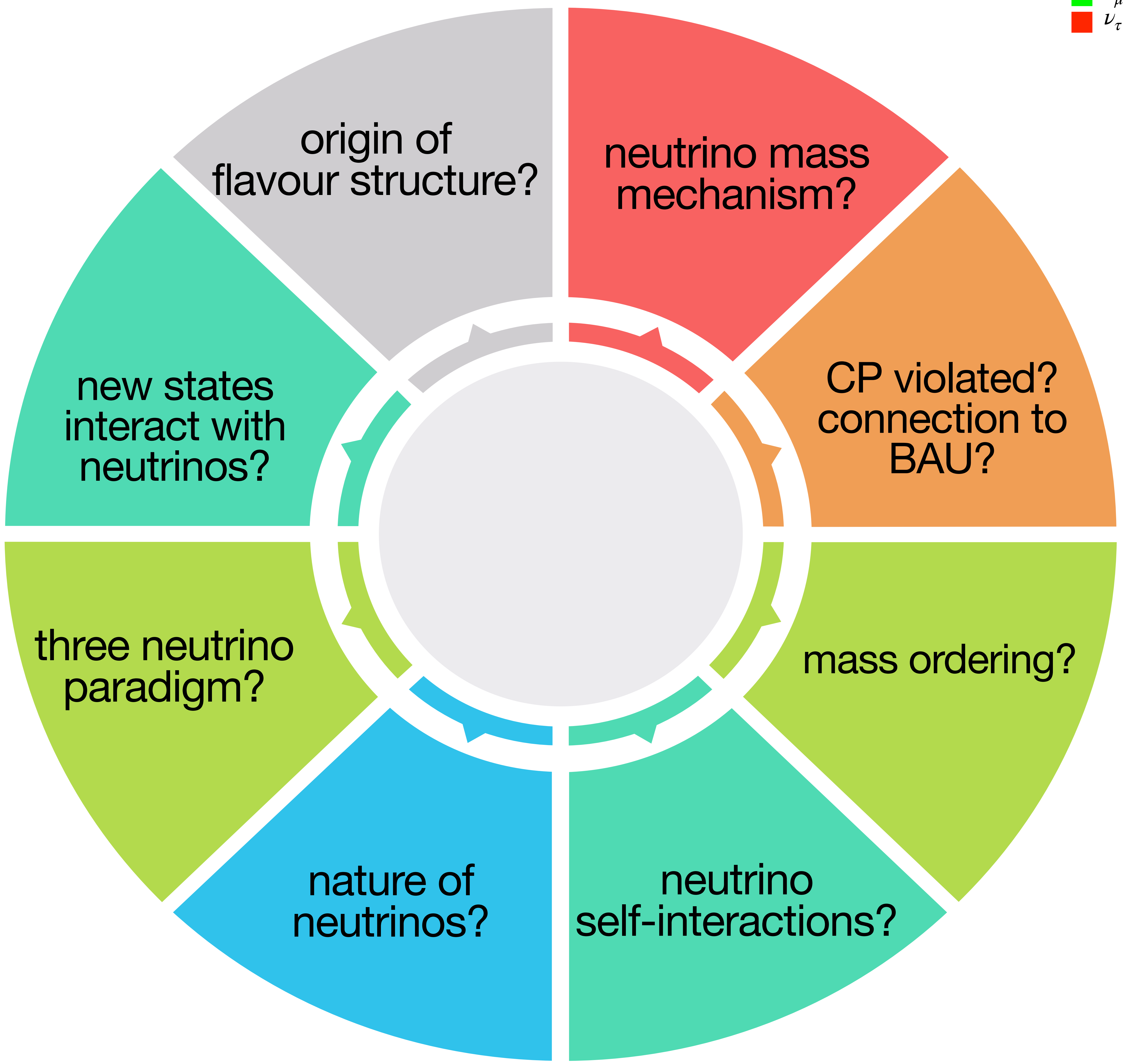
NuFIT 5.2

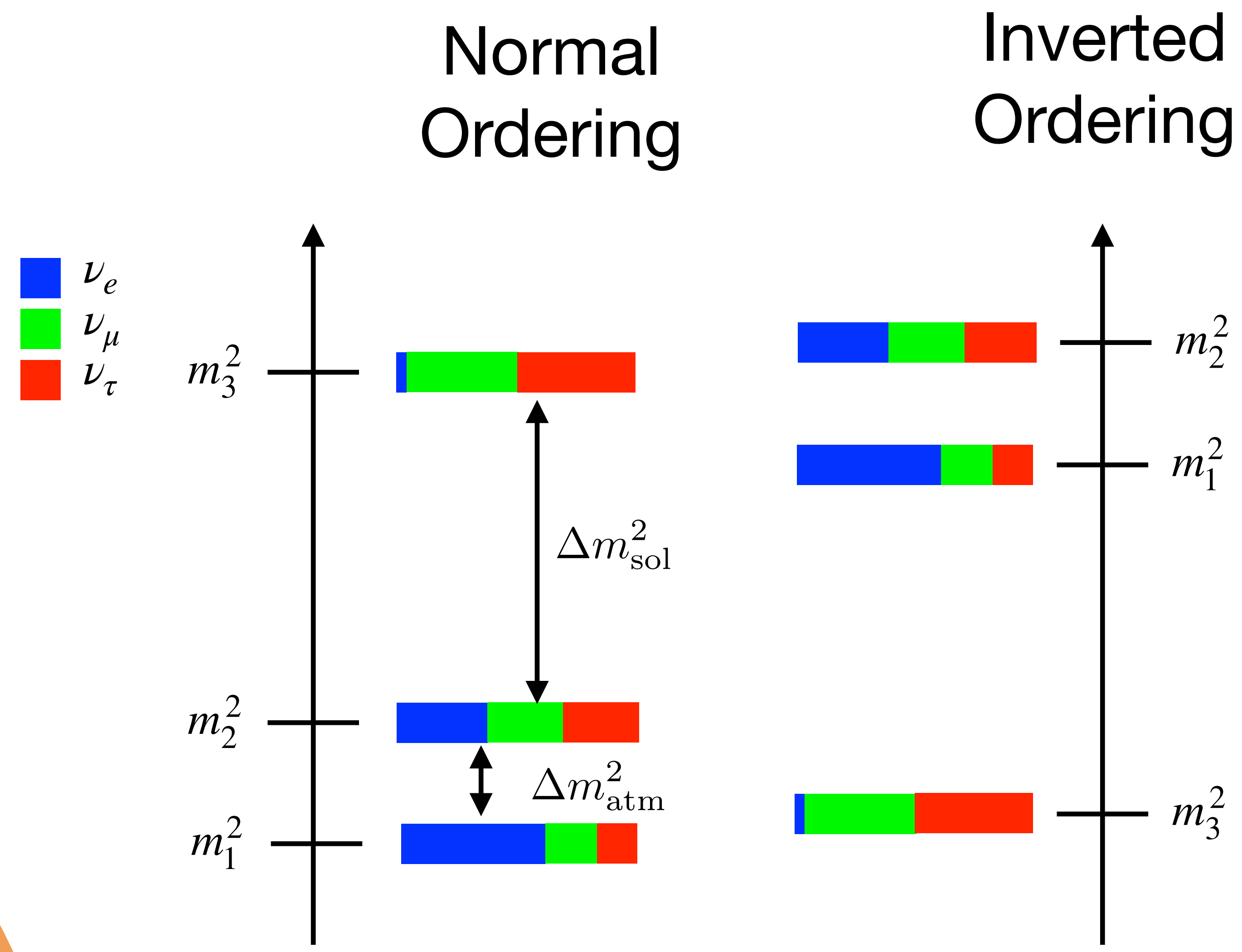
mixing parameter	central value	relative uncertainty (3σ)	
θ_{13} $(^\circ)$	8.6	4.7%	4.0%
θ_{23} $(^\circ)$	42.2	22%	5.2%
θ_{12} $(^\circ)$	33.4	7.3%	0.3%
δ_{CP} $(^\circ)$	232	100%	**Quark sector**

Neutrinos: what we don't know









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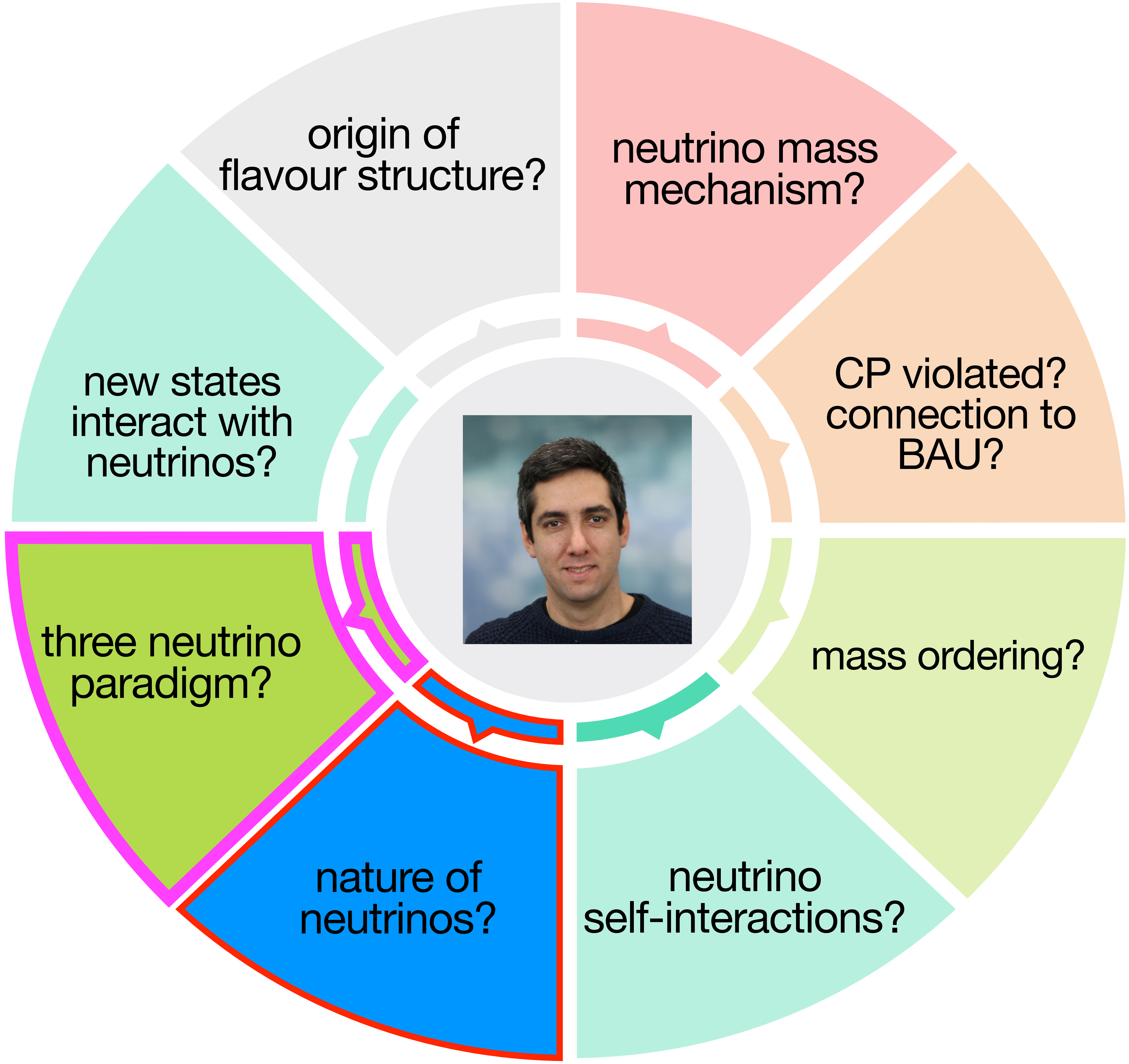


PseudoDirac Neutrinos

$$\mathcal{L} = Y_\nu \overline{L} N \tilde{H} + \frac{1}{2}\overline{N^C} M_N N$$

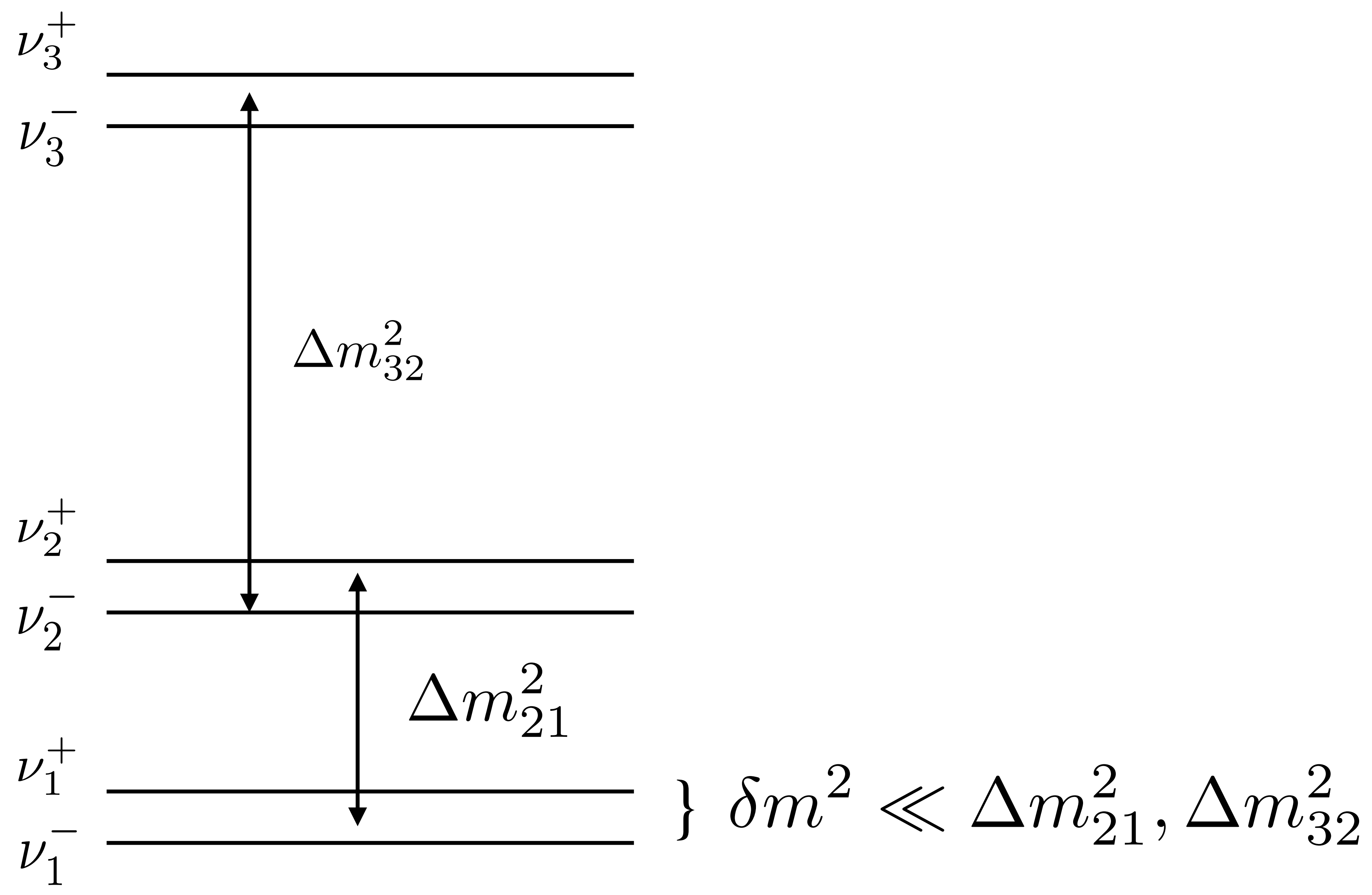
$$M = \begin{pmatrix} 0_3 & m_D \\ m_D & M_N \end{pmatrix}$$

- $M_N = 0 \rightarrow$ Dirac neutrinos
- $M_N \gg m_D \rightarrow$ Usual type I seesaw
- $M_N \ll m_D \rightarrow$ PseudoDirac neutrinos

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j} (\nu_j^+ + i\,\nu_j^-)$$

Flavour

Mass

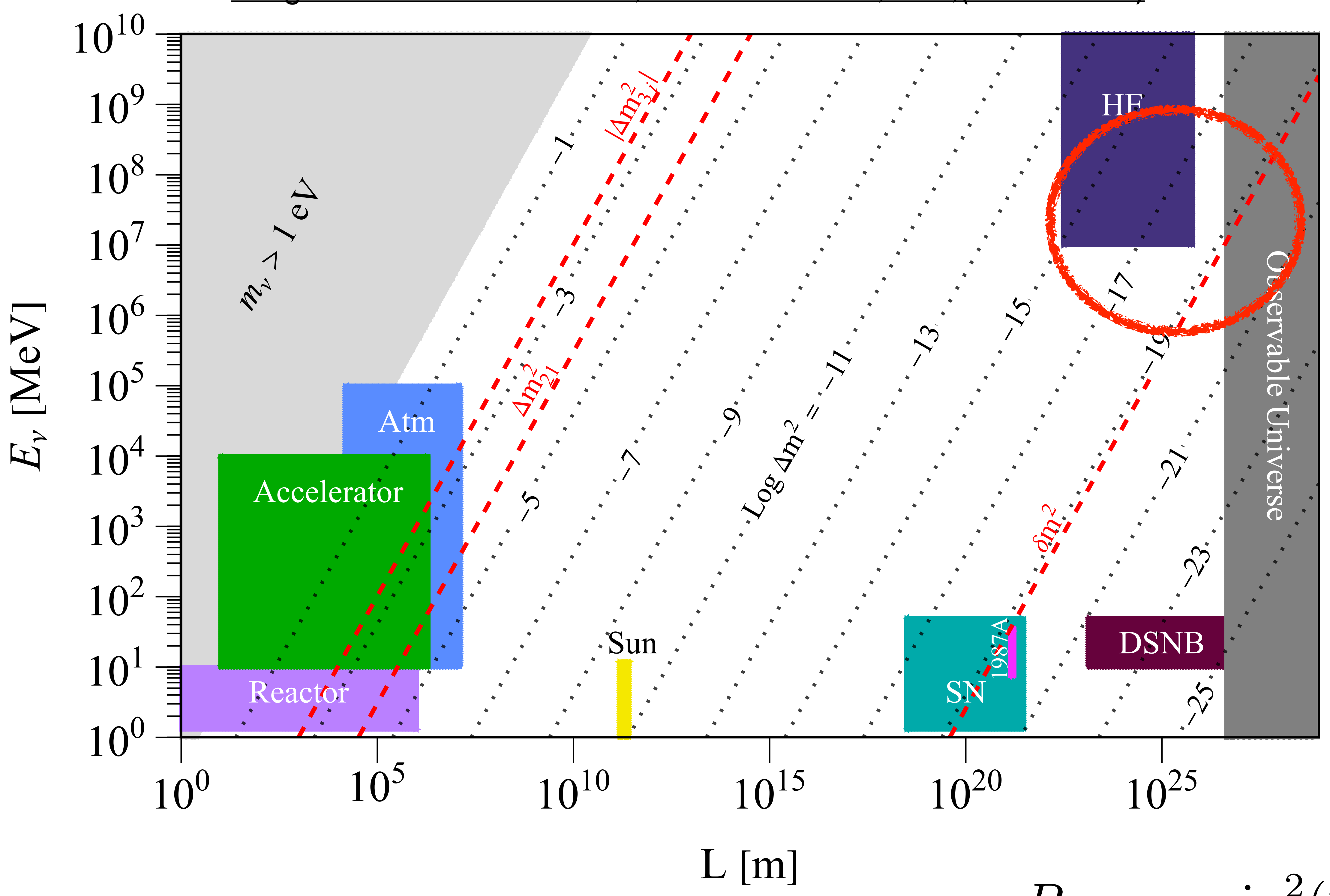


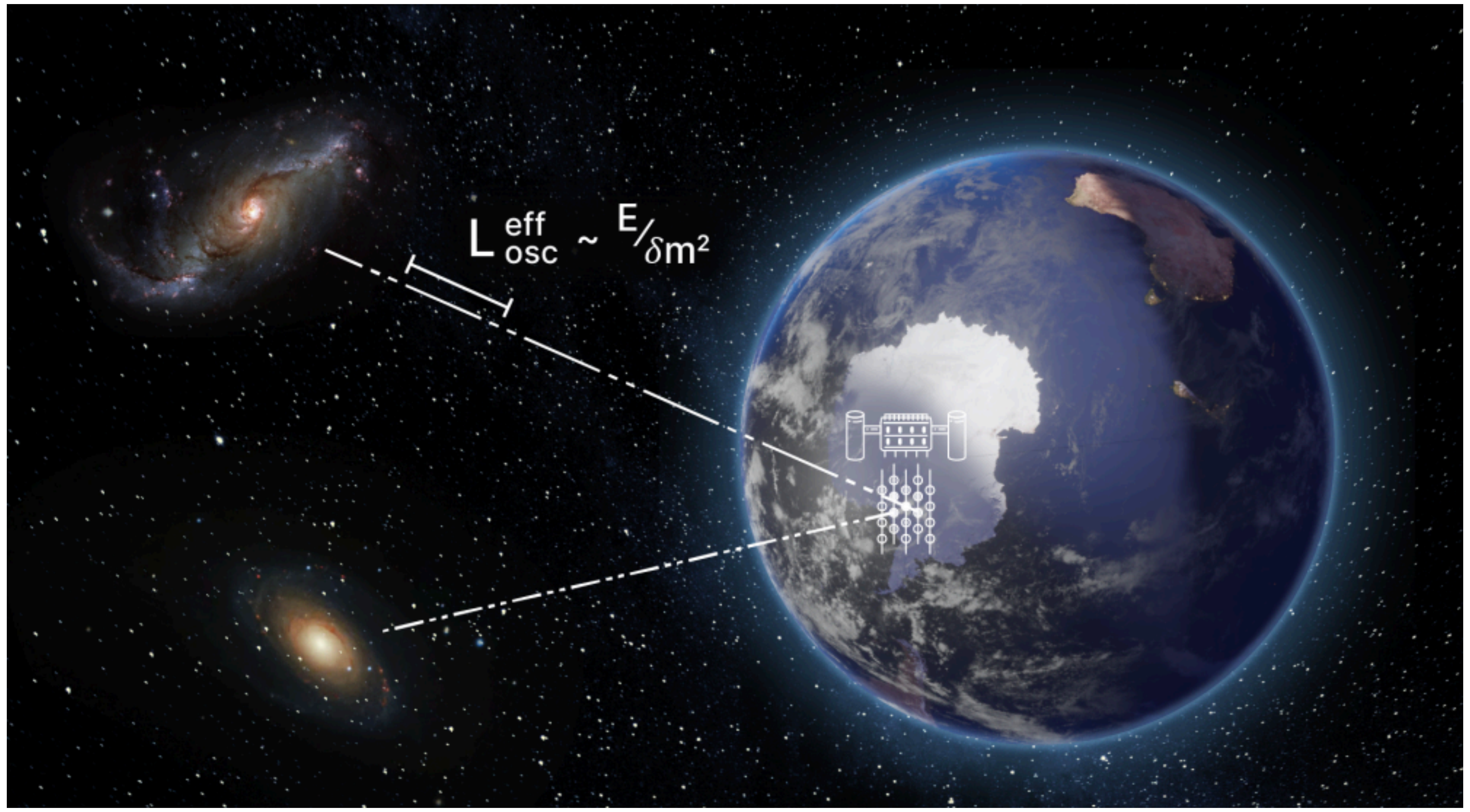
Ivan Martinez Soler, IPPP

- 2212.00737 explore how the pseudo-Dirac neutrino scenario could be probed by observations of extragalactic neutrinos at IceCube

- Perform joint fit of NGC 1068 (14.4 MPc, 4.4×10^{20} km), PKS 1424+240 (1.4 GPc) and TXS 0506+056 (1.16 GPc)

Image credit: Martinez-Soler, Perez-Gonzalez, Sen,(2105.12736)





$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

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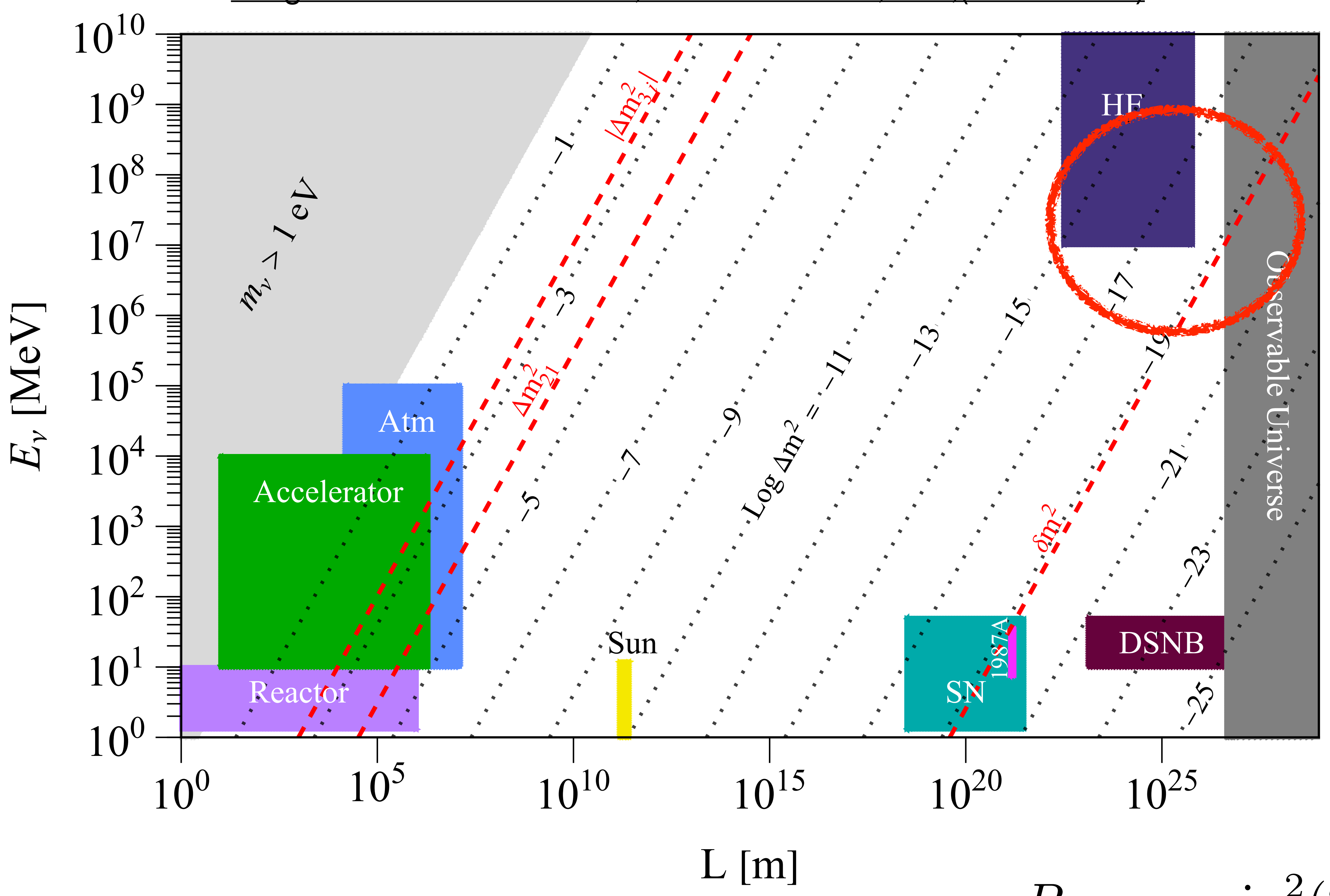

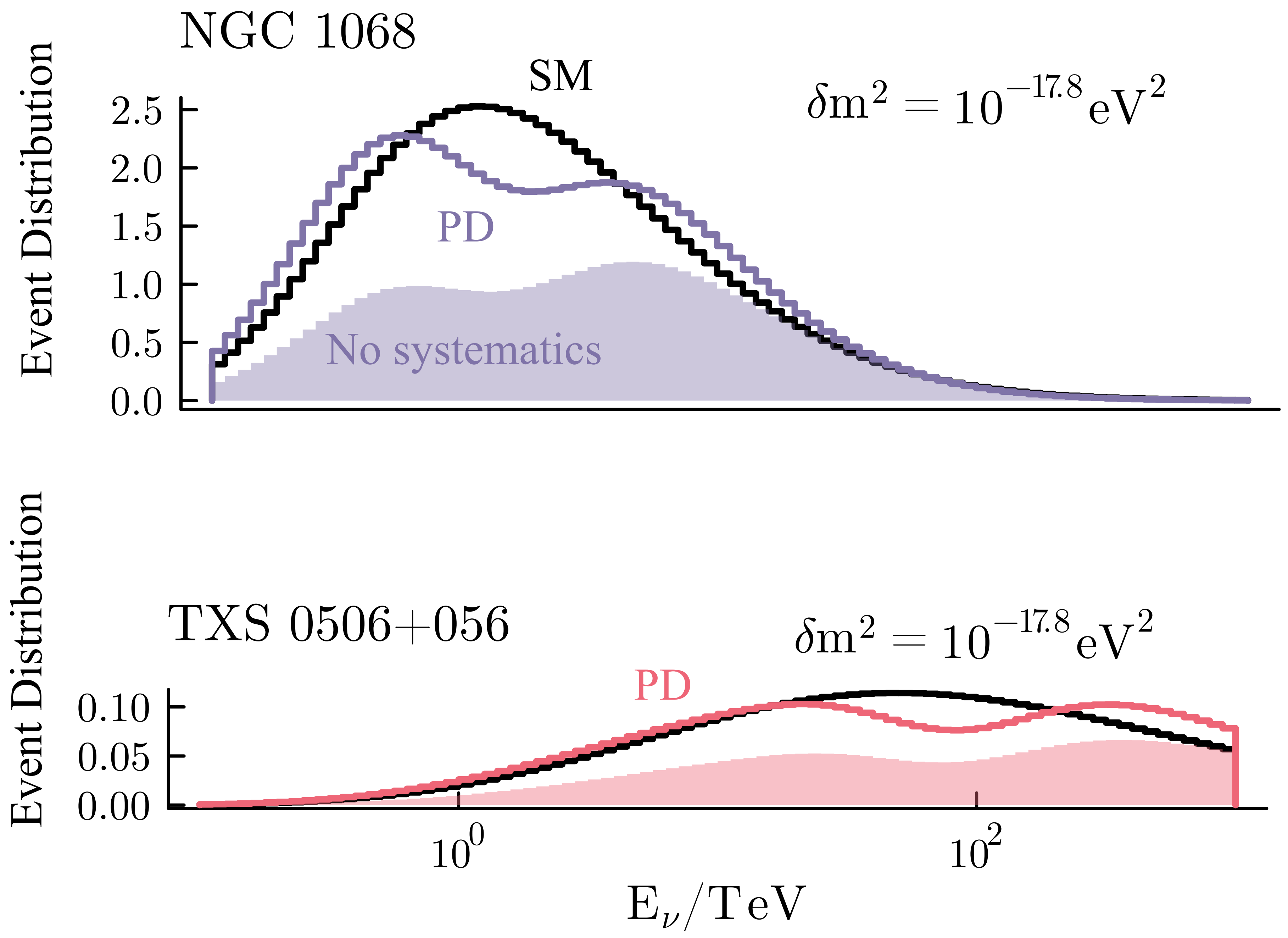

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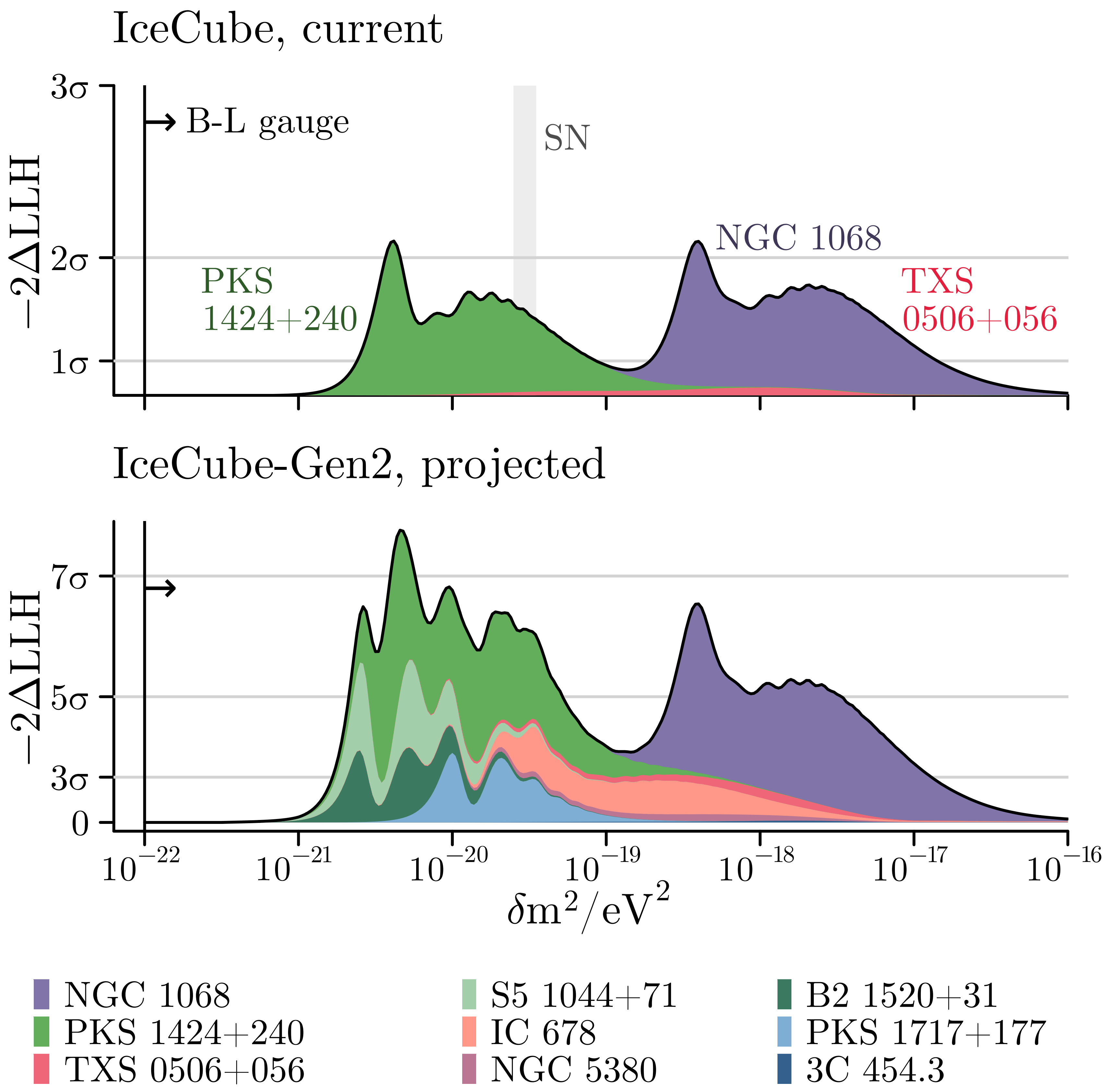
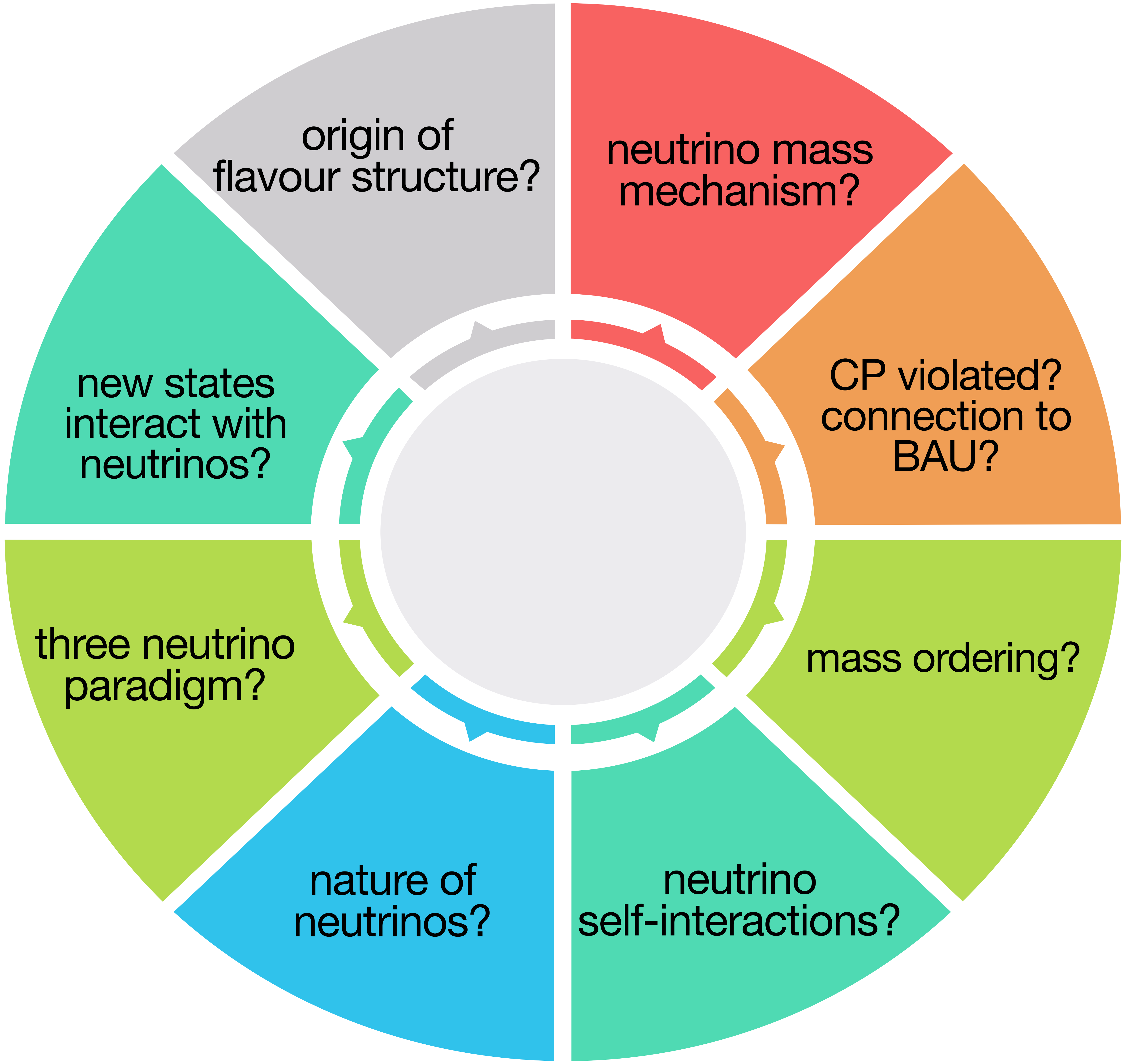


- IceCube probes Pseudo-Dirac neutrinos but limited low statistics & energy resolution

- Gen 2: more sources and 8× higher statistics, achieve 5σ $\quad 10^{-21} < \delta m^2\,(\mathrm{eV}^2) < 10^{-18}$

- IceCube's discovery of astrophysical neutrinos opens new avenues for exploring neutrino physics

Neutrinos: what we don't know



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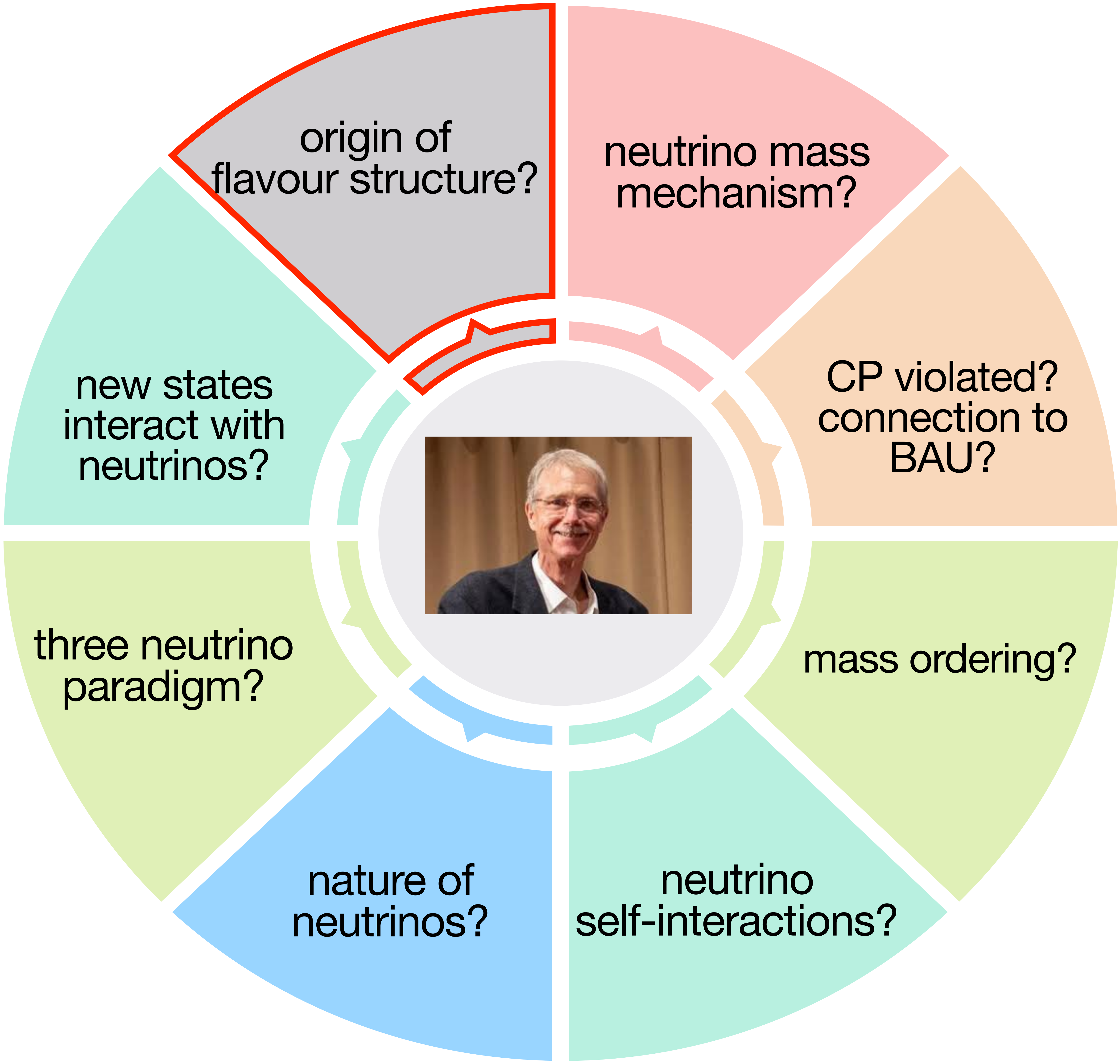
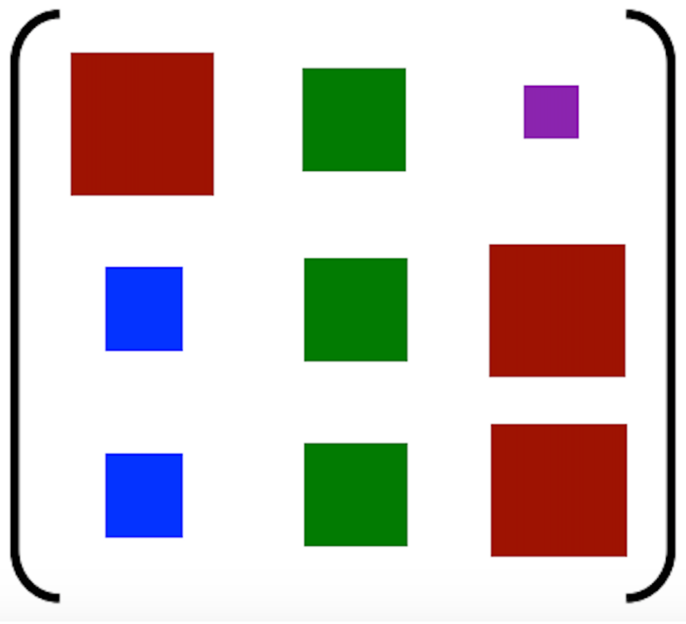


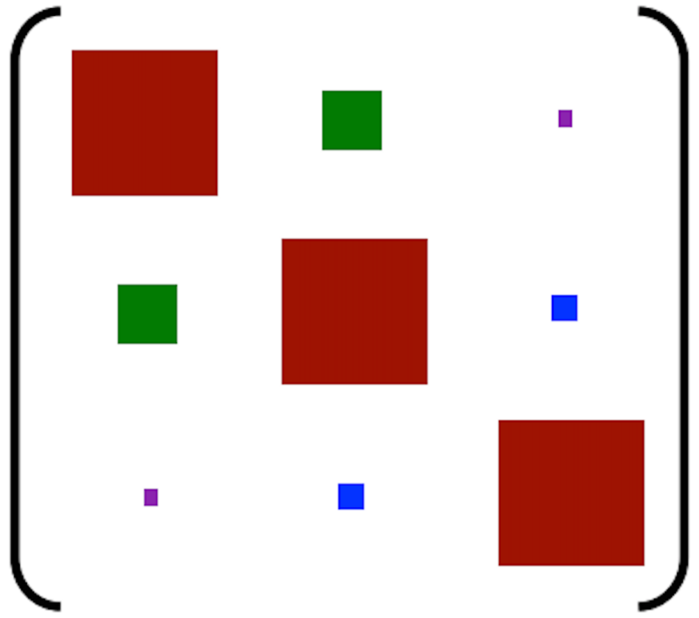
Steve King, Southampton

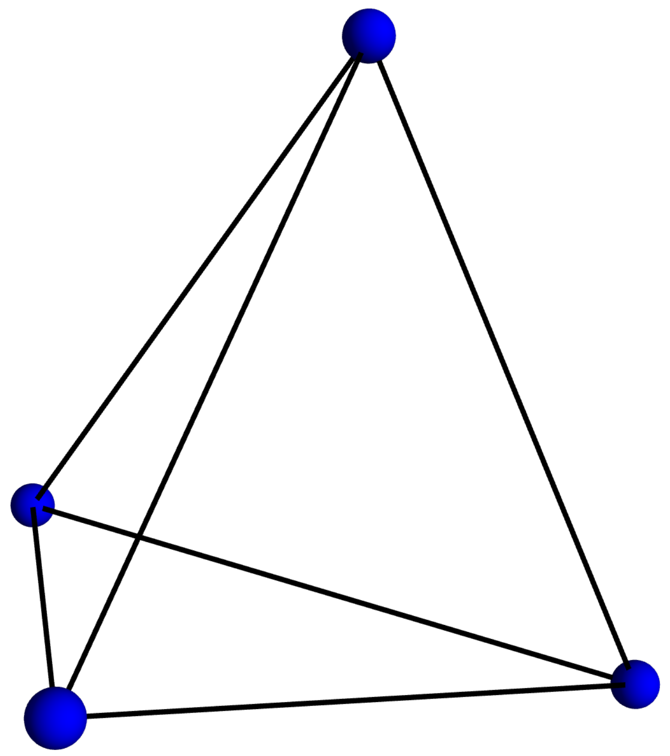
- 2307.13895 studies of neutrino mixing sum rules from discrete symmetries and Littlest Seesaw (LS) models.

leptonic mixing

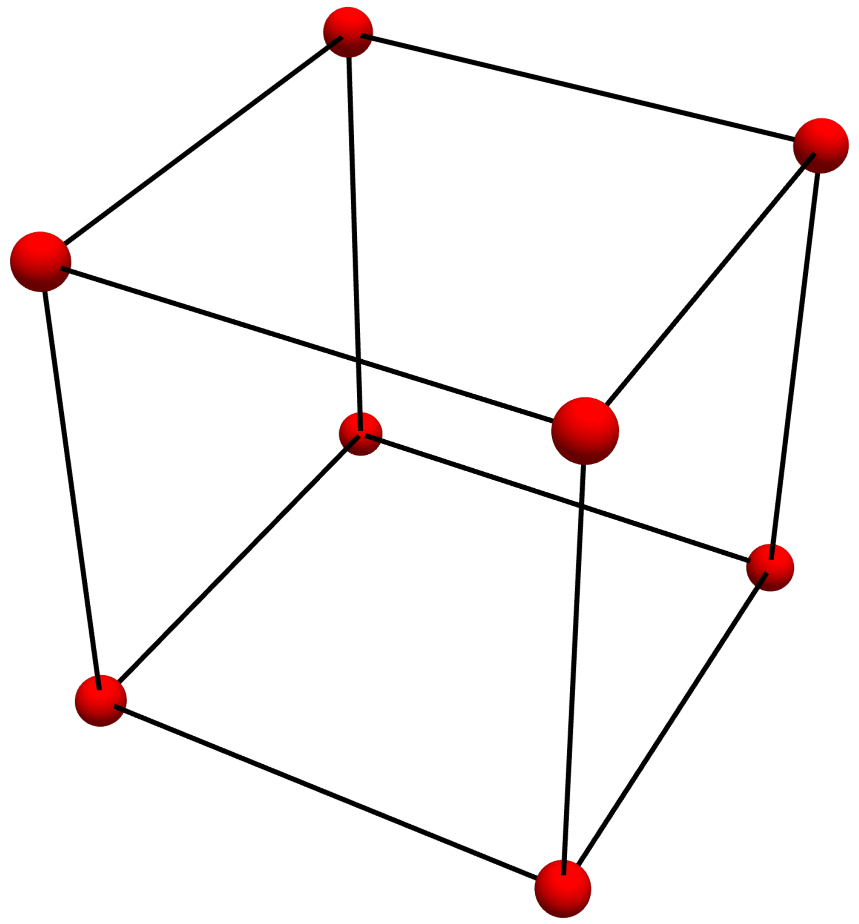


quark mixing

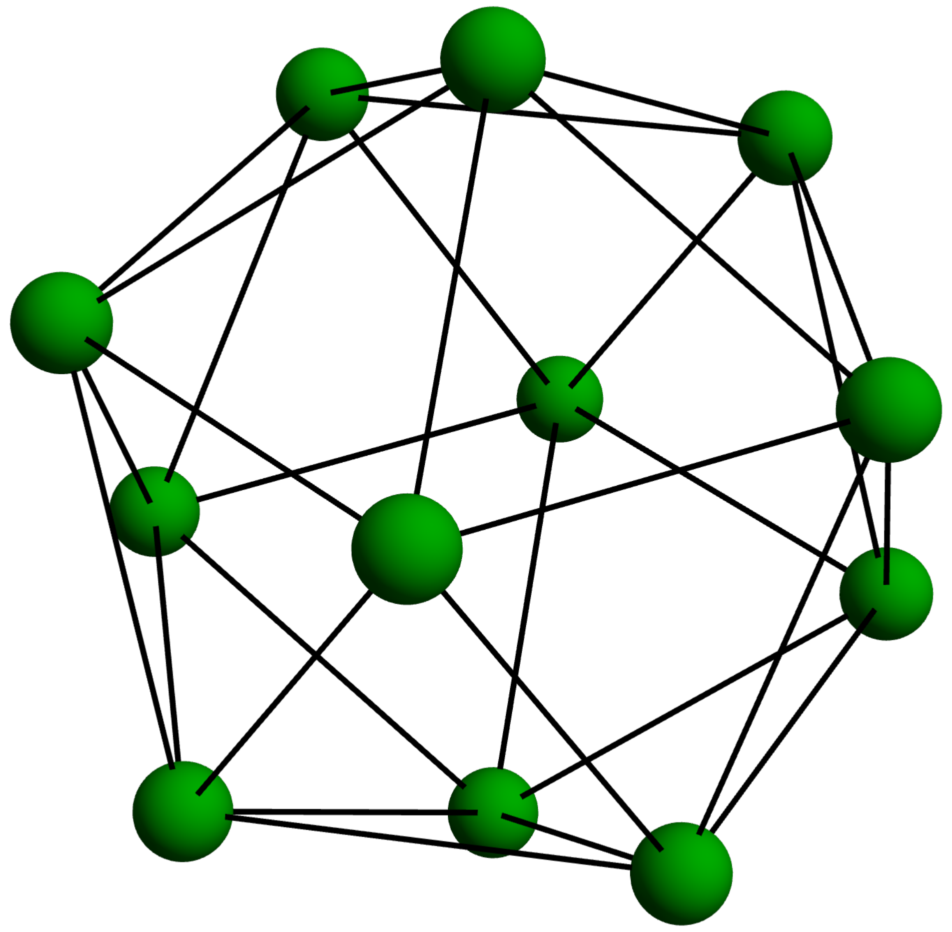




A_4



S_4



A_5

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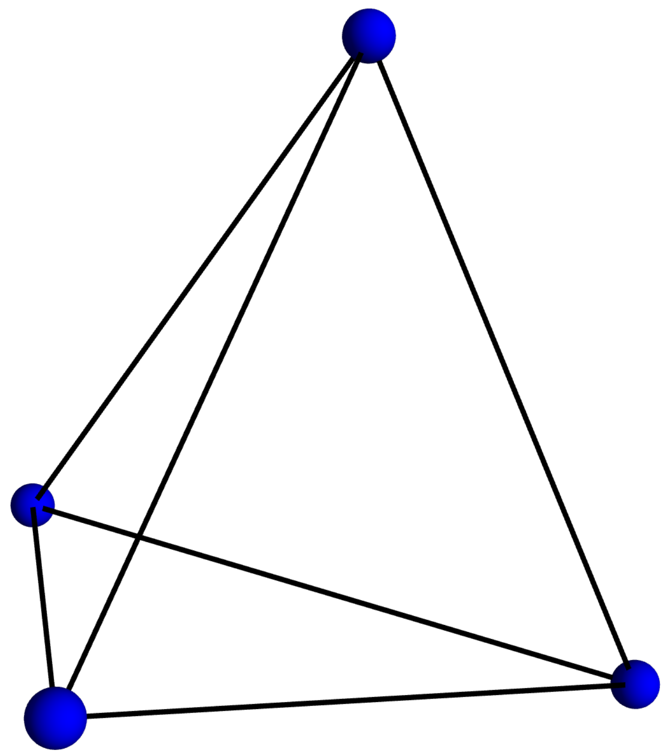

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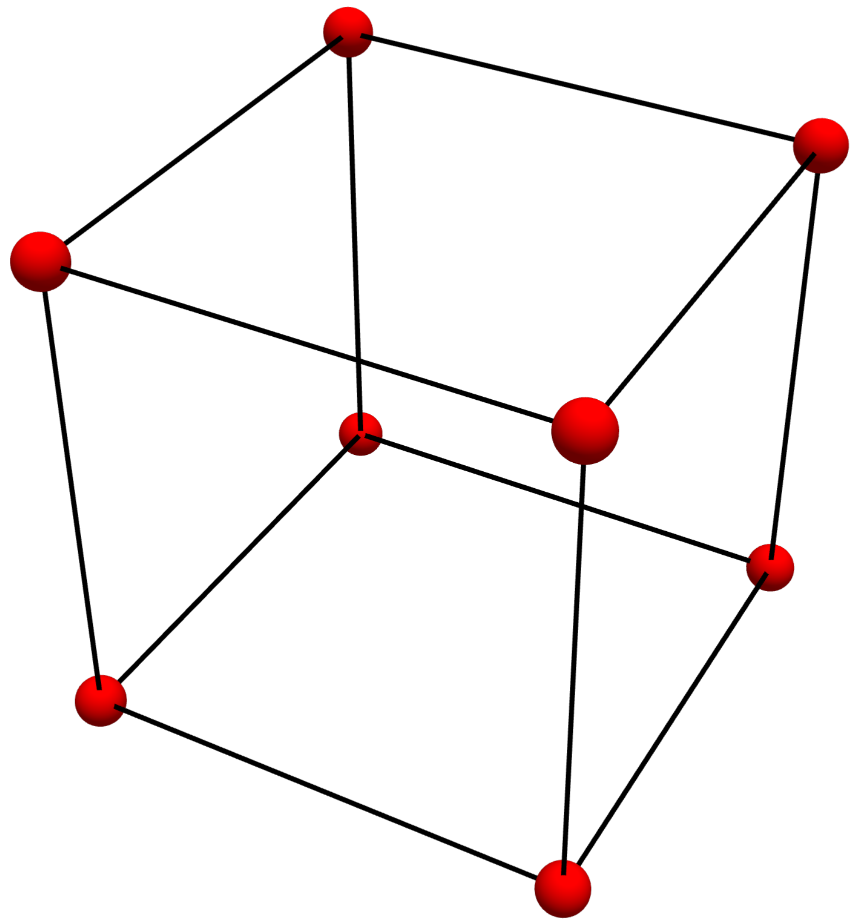

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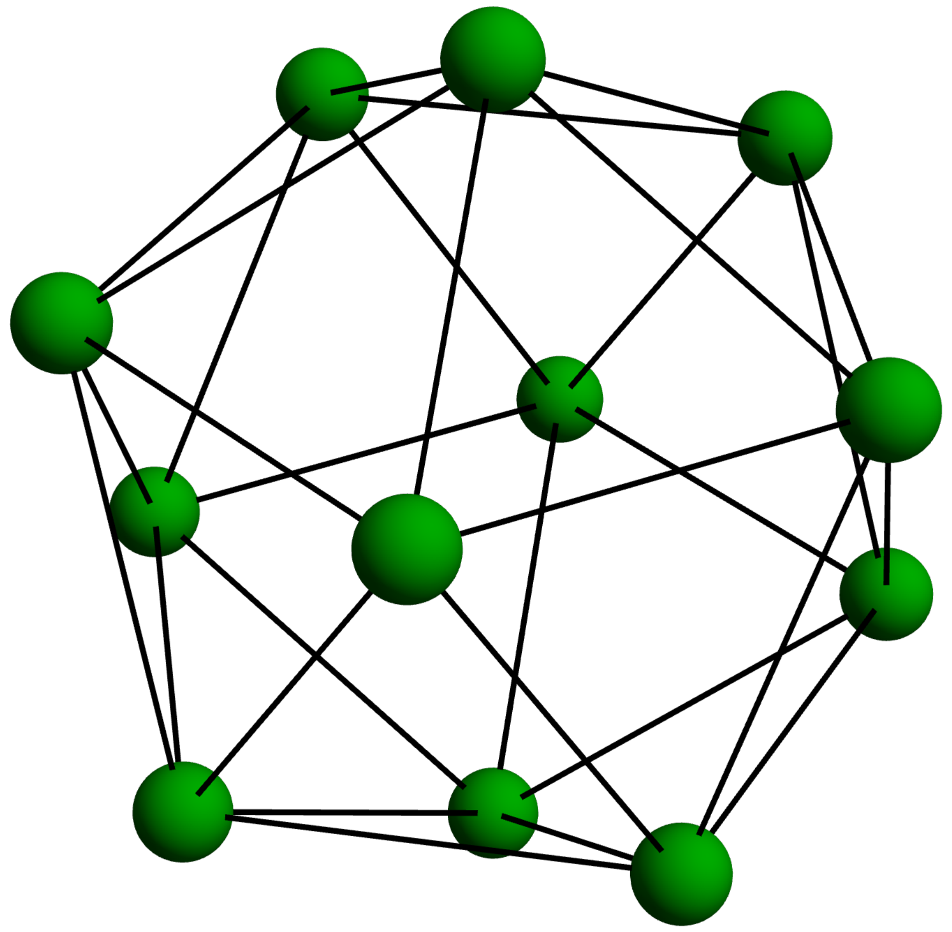

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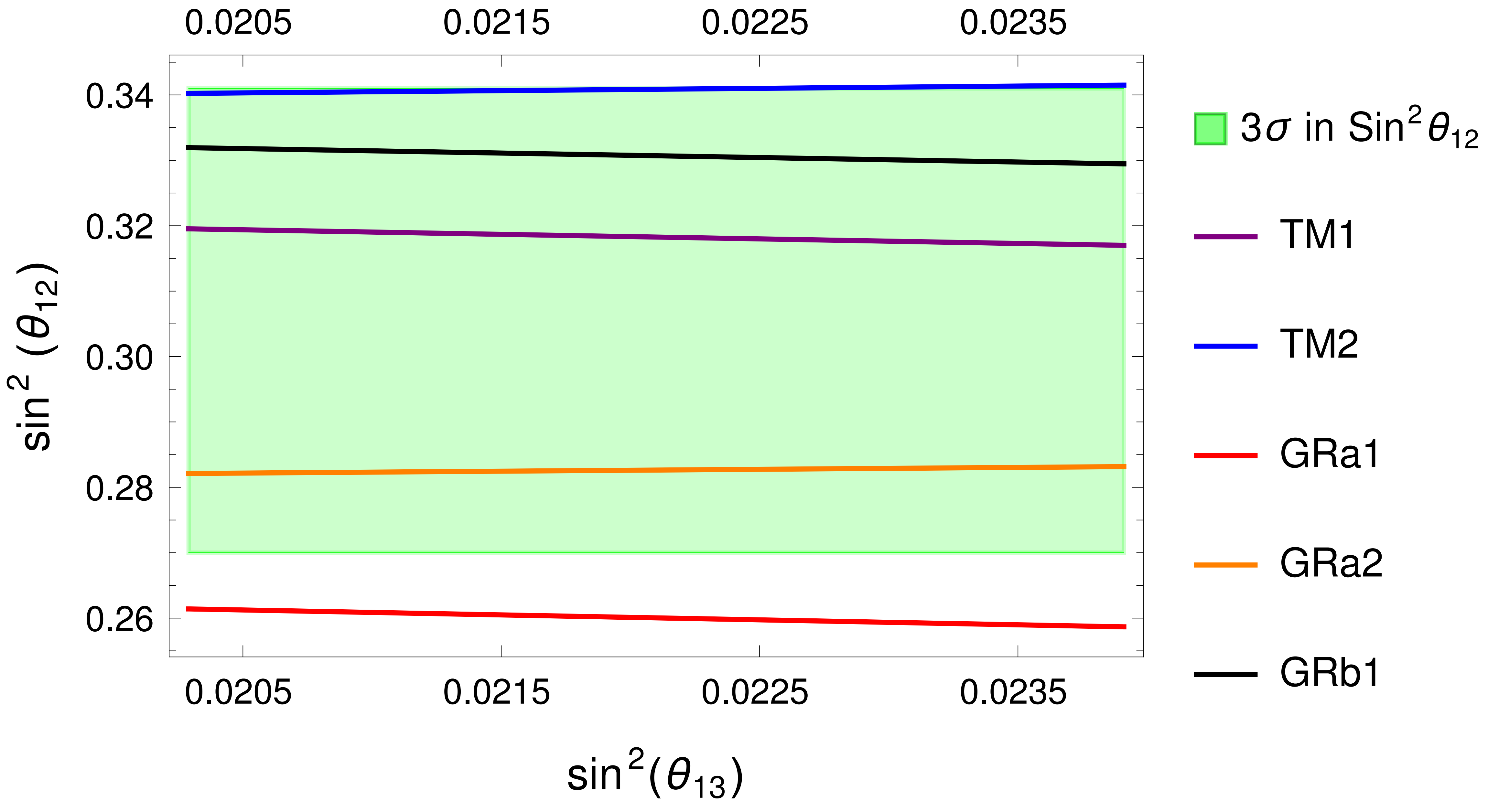

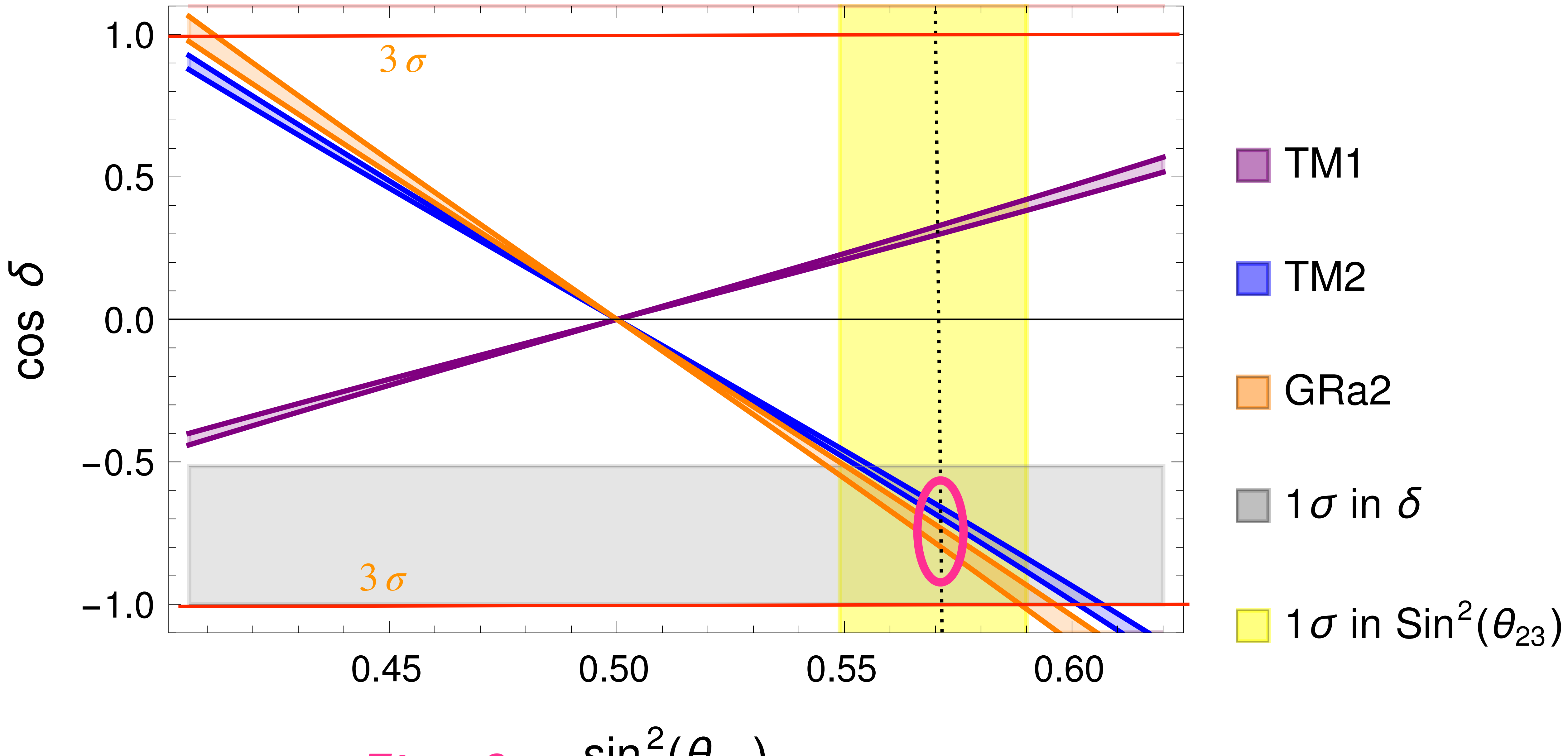

Need to resolve < 7° in δ

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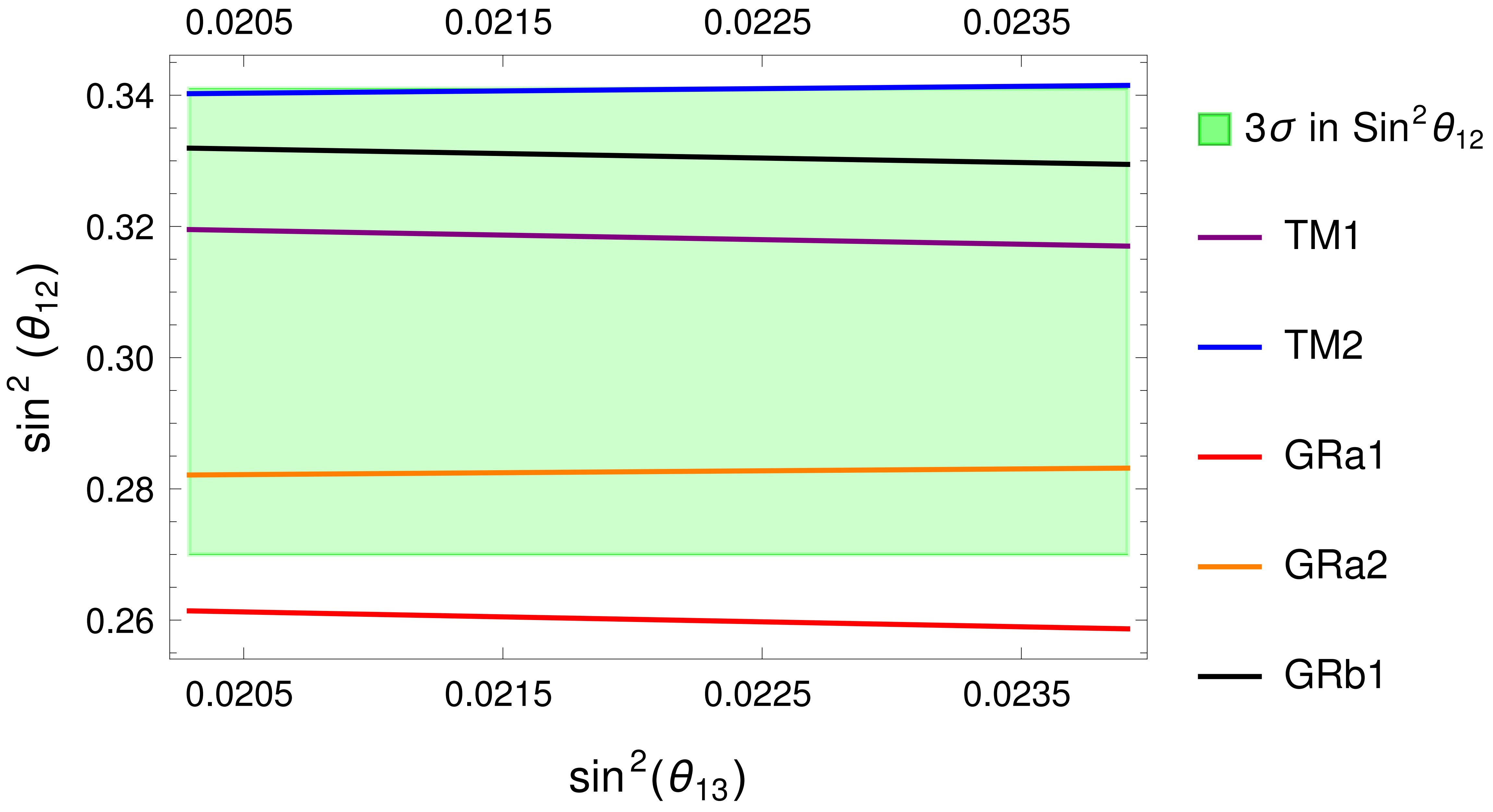
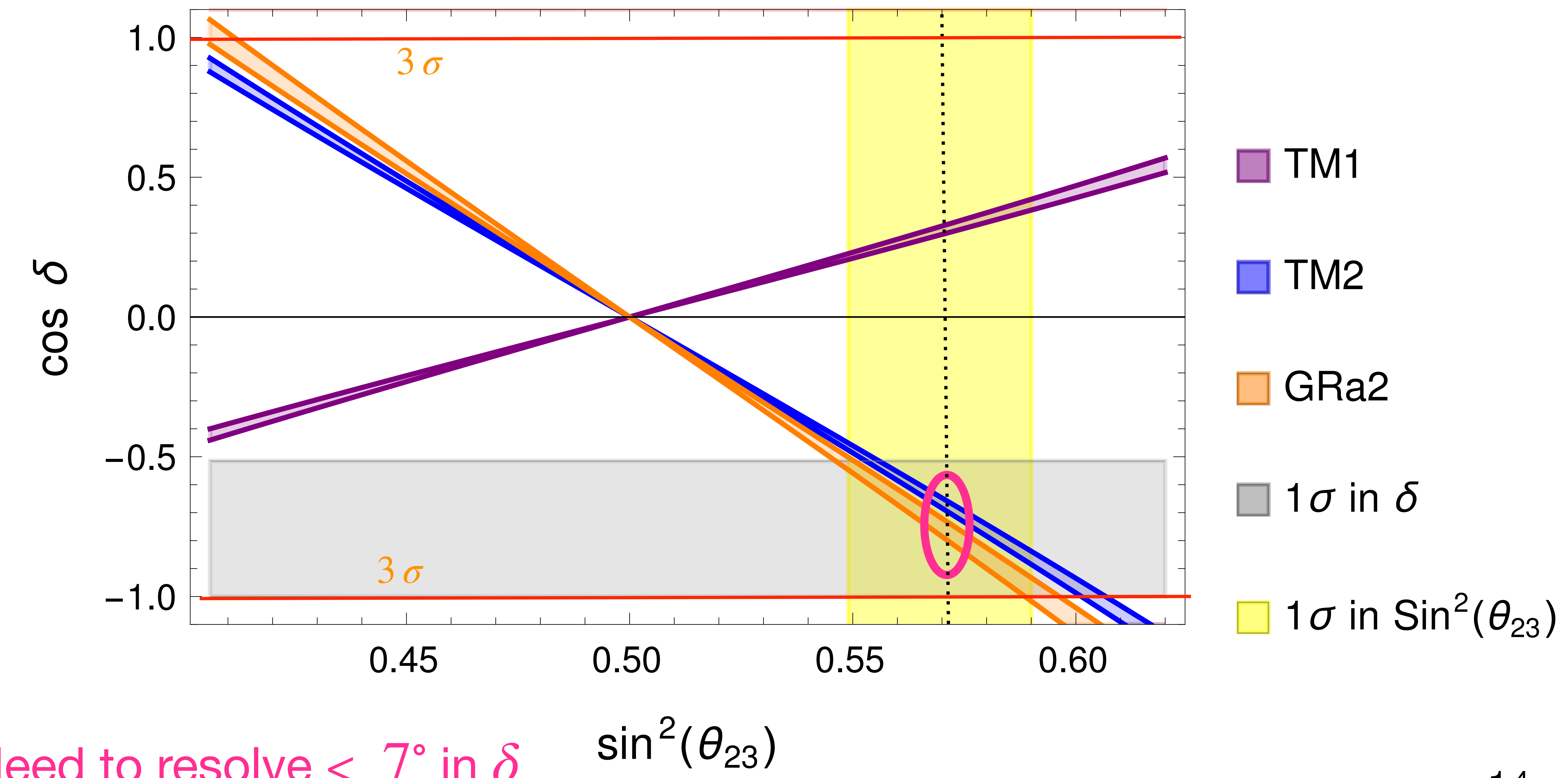
- Future data, **especially improved measurements δ & θ_{23}**, will reduce # viable flavour models & lead to a deeper understanding of the flavour problem





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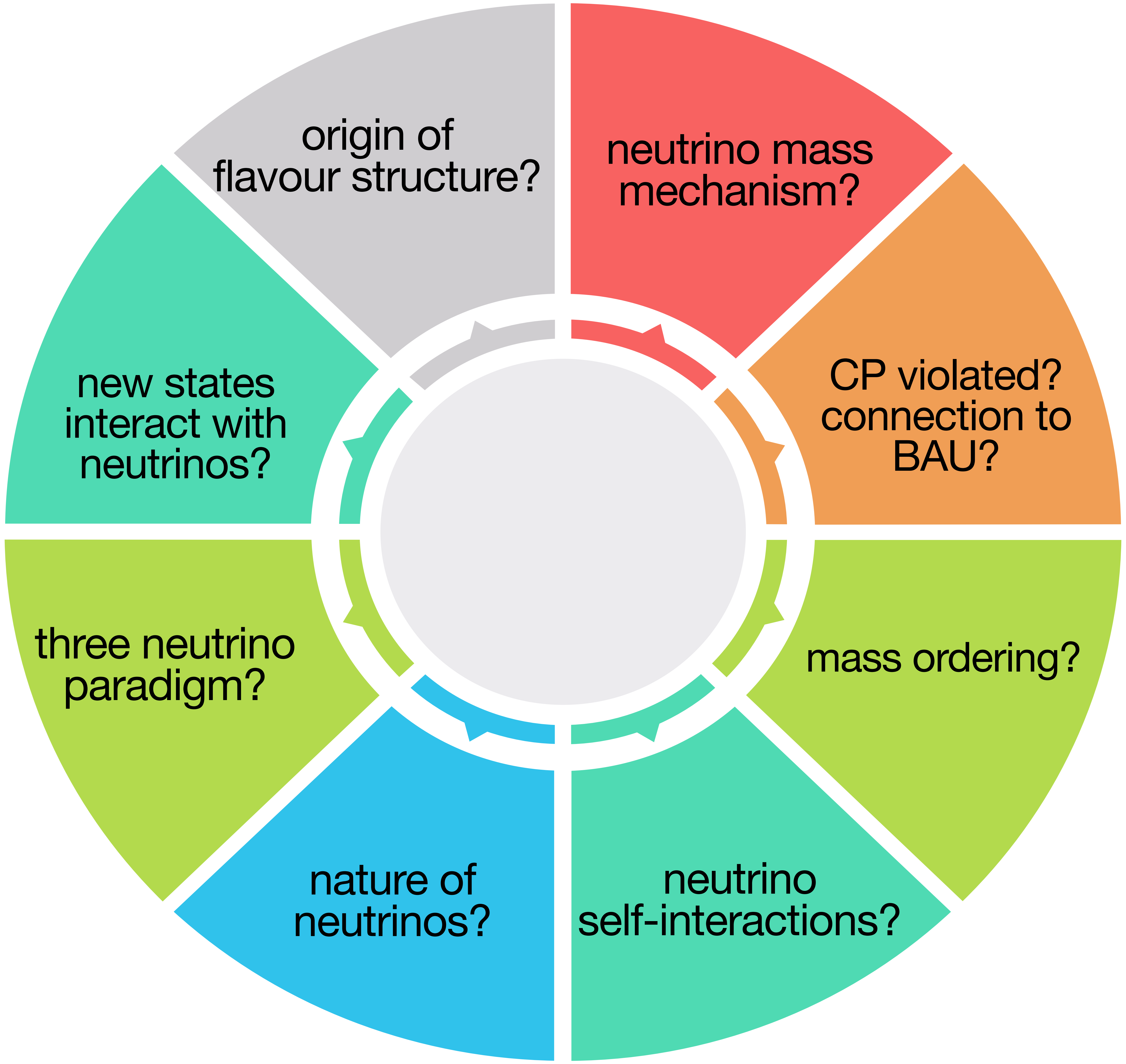
Neutrinos: what we don't know



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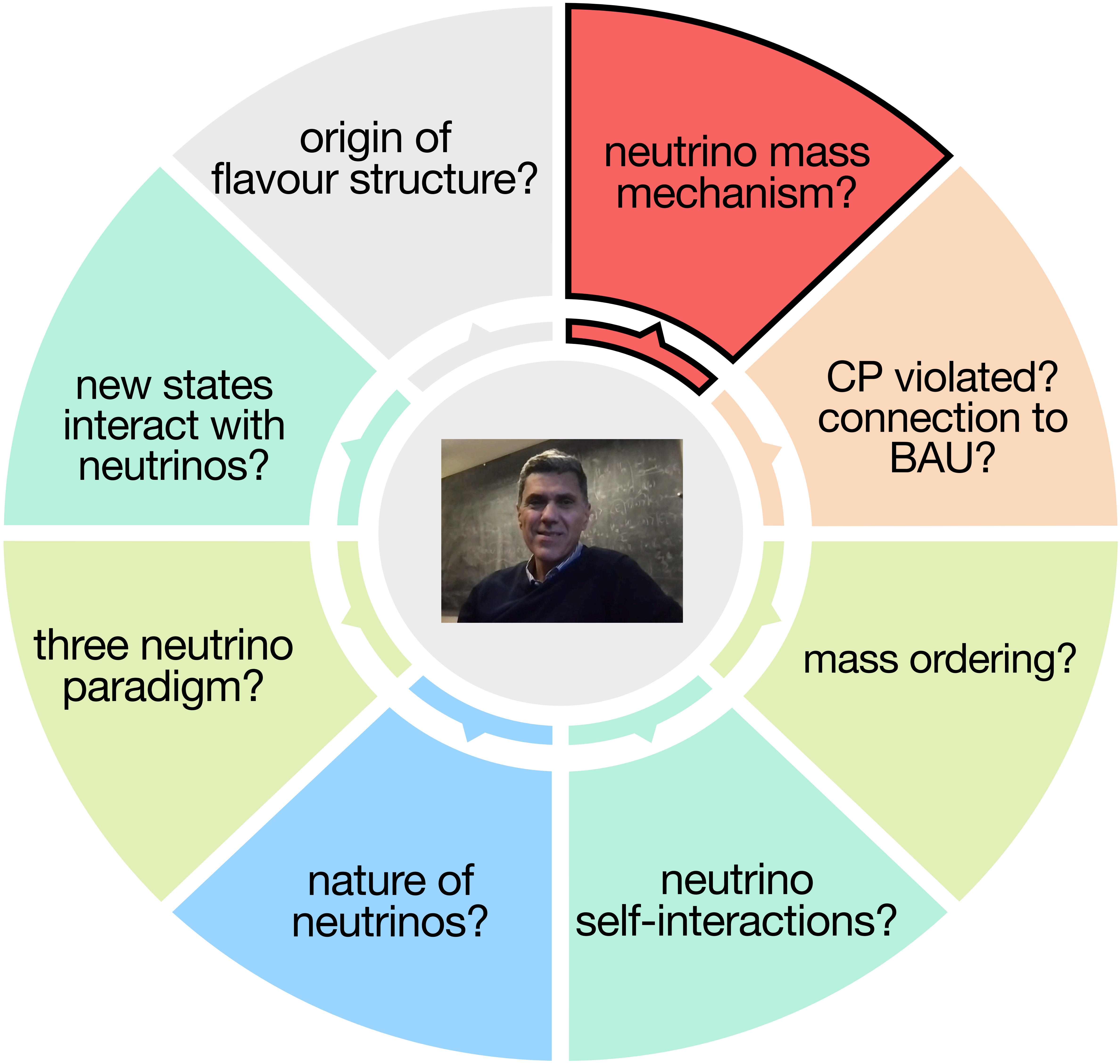

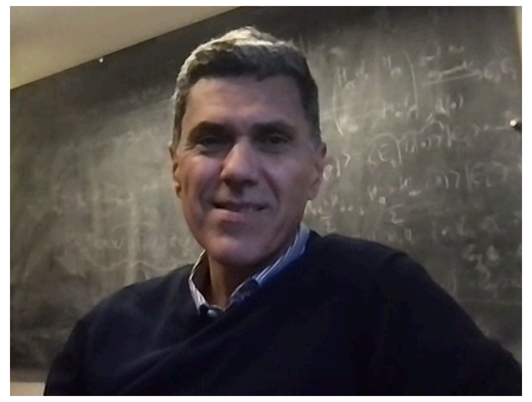

- 2307.03184 investigates how majoron model can alleviate cosmological tensions and help explain the PTA signal

- RHNs acquire mass from majoron getting a VEV. In multiple majoron model each RHN generation associated with majoron

$$\mathcal{L} = Y_{\alpha I}\overline{L_\alpha}N_I\widetilde{\Phi} + Y_{\alpha I'}\overline{L_\alpha}N_{I'}\widetilde{\Phi} + \frac{\lambda_I}{2}\phi\overline{N_I^c}N_I + \frac{\lambda_{I'}}{2}\phi'\overline{N_{I'}^c}N_{I'}$$

Seesaw mechanism →

$$m_\nu = \frac{v_{\rm ew}^2}{2}\frac{Y_{\alpha I}Y_{\beta I}}{M_I}$$

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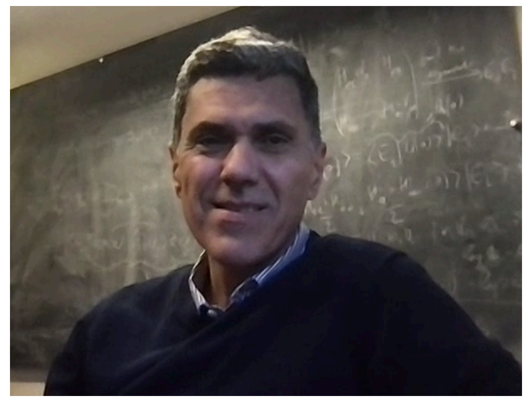

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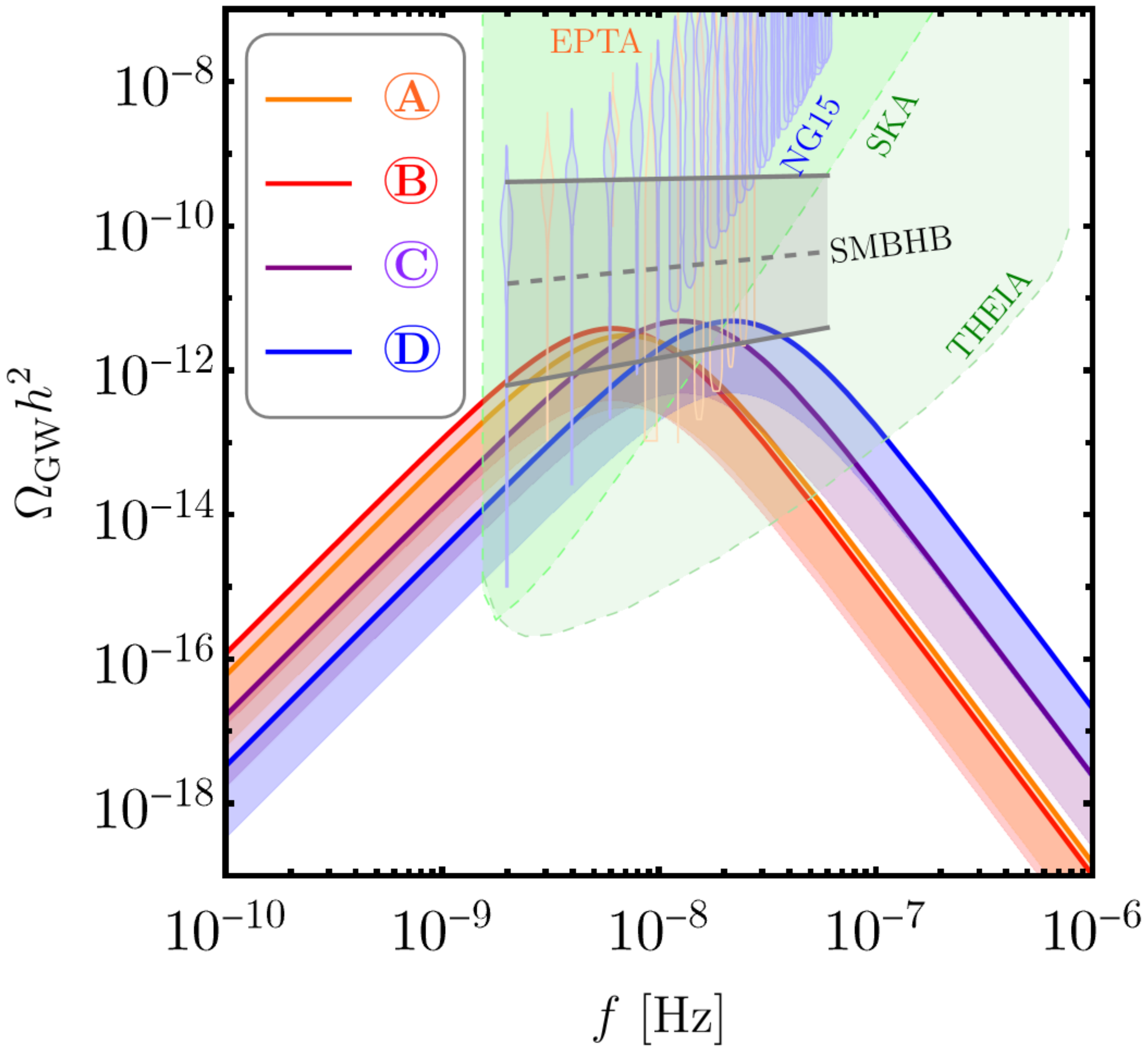
- Cosmological tensions: Hubble tension & Deuterium problem can be Alleviated by present of majorons after neutrino decoupling

- ϕ undergoes first-order PT at $T > T_{\rm ew}$ & ϕ' at $T \sim {\rm MeV}$

- MeV scale PT → nano-Hertz GW signal which can help (in addition to mergers of SMBH) explain PTA signal



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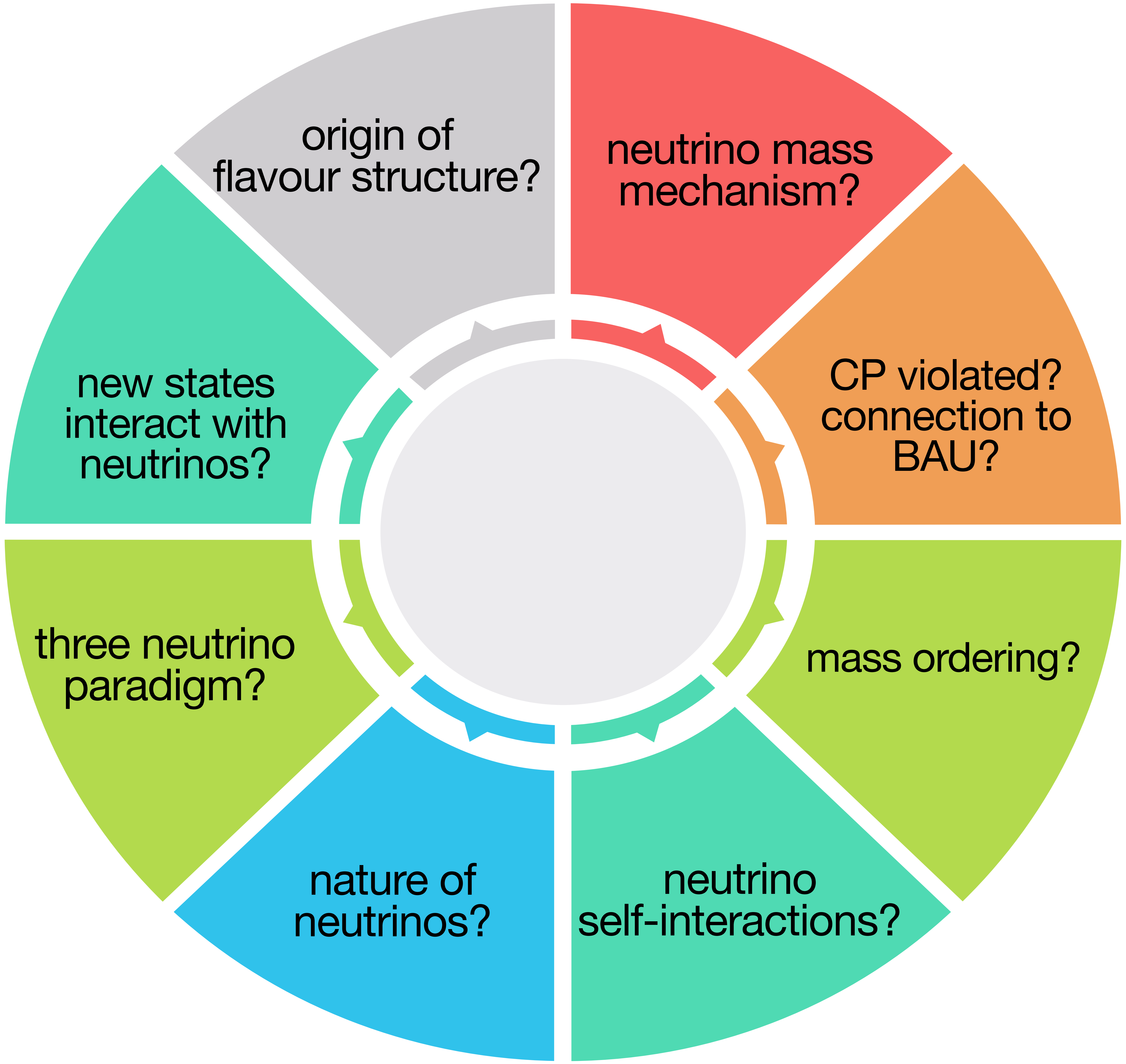

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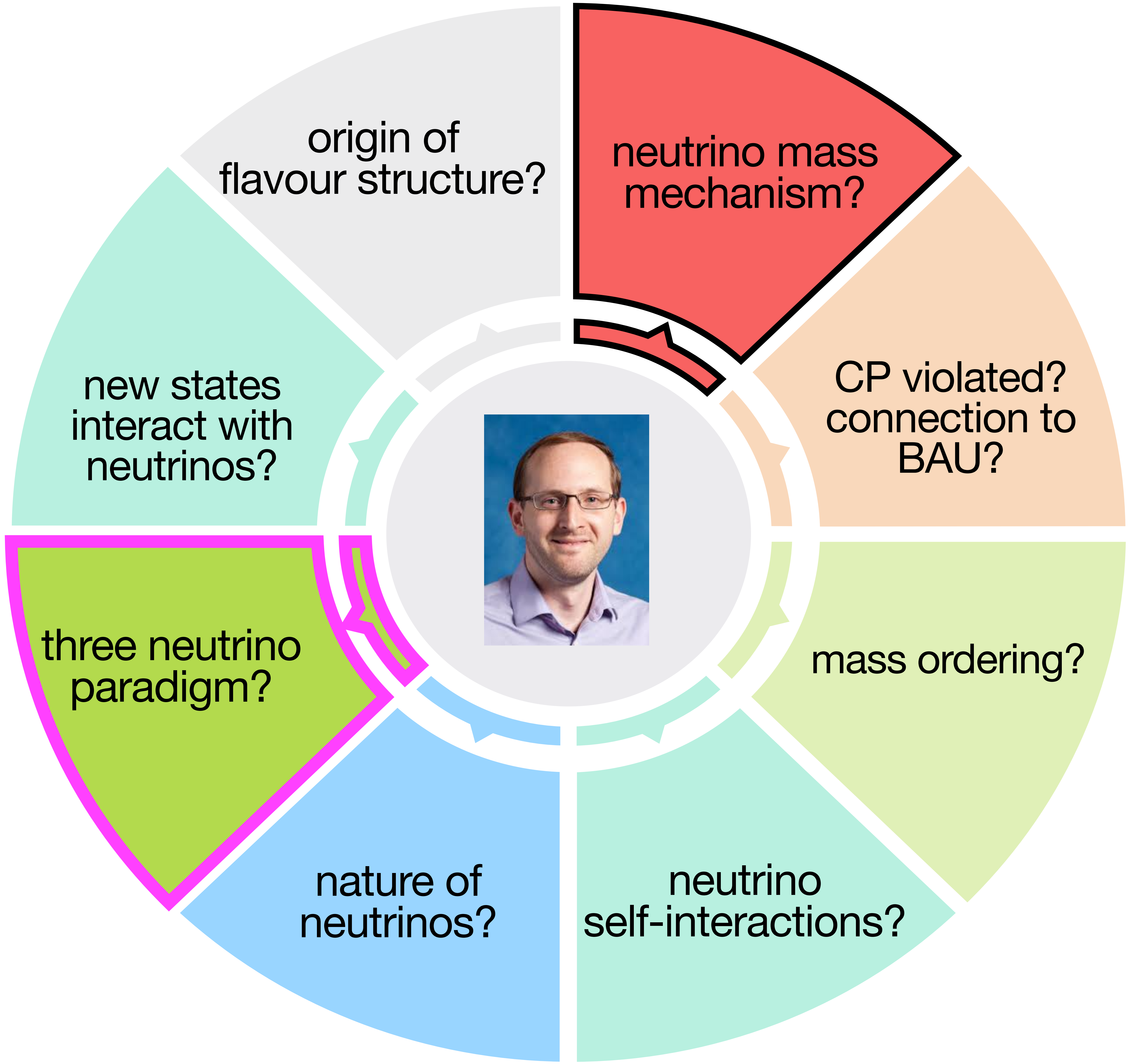
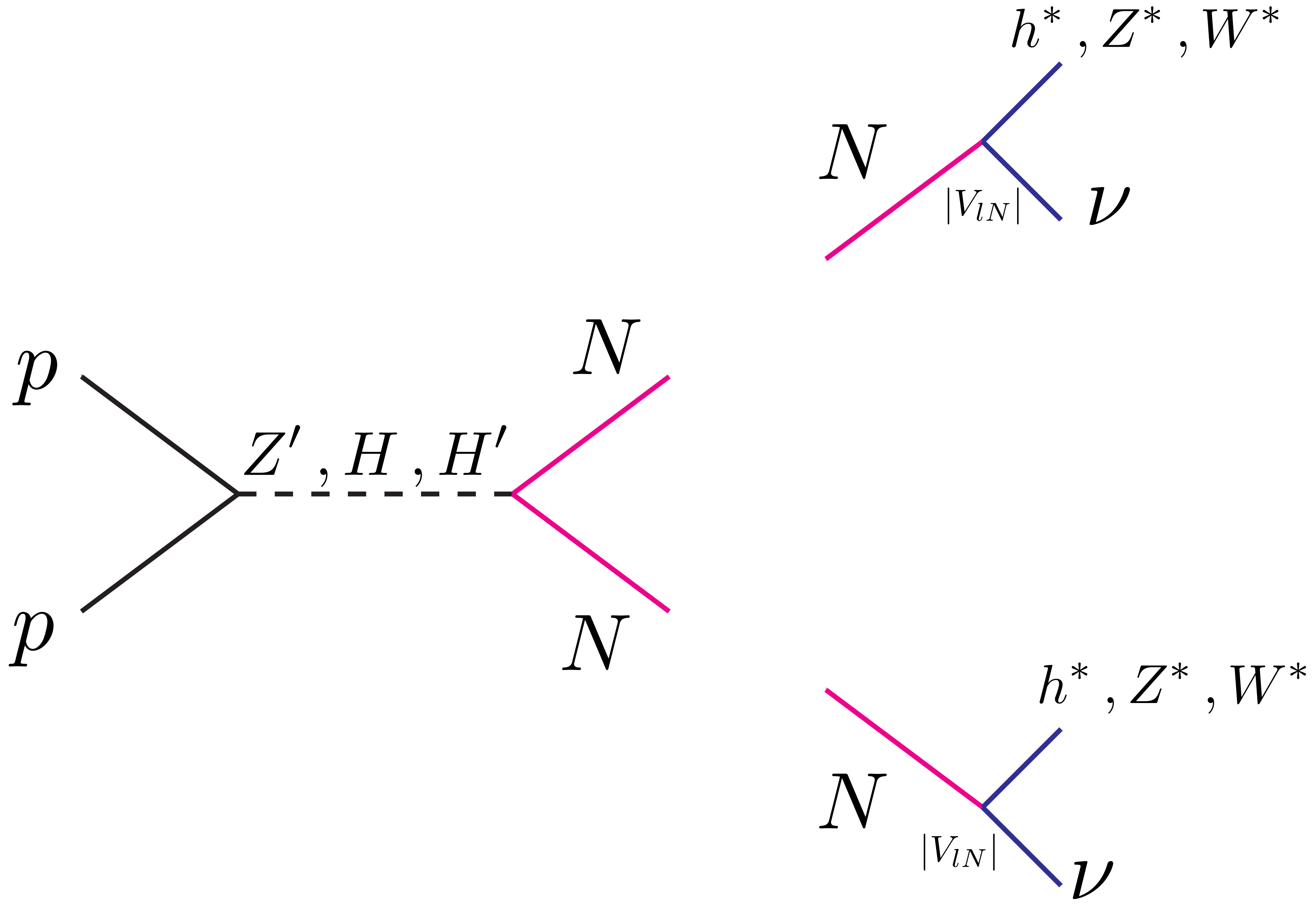


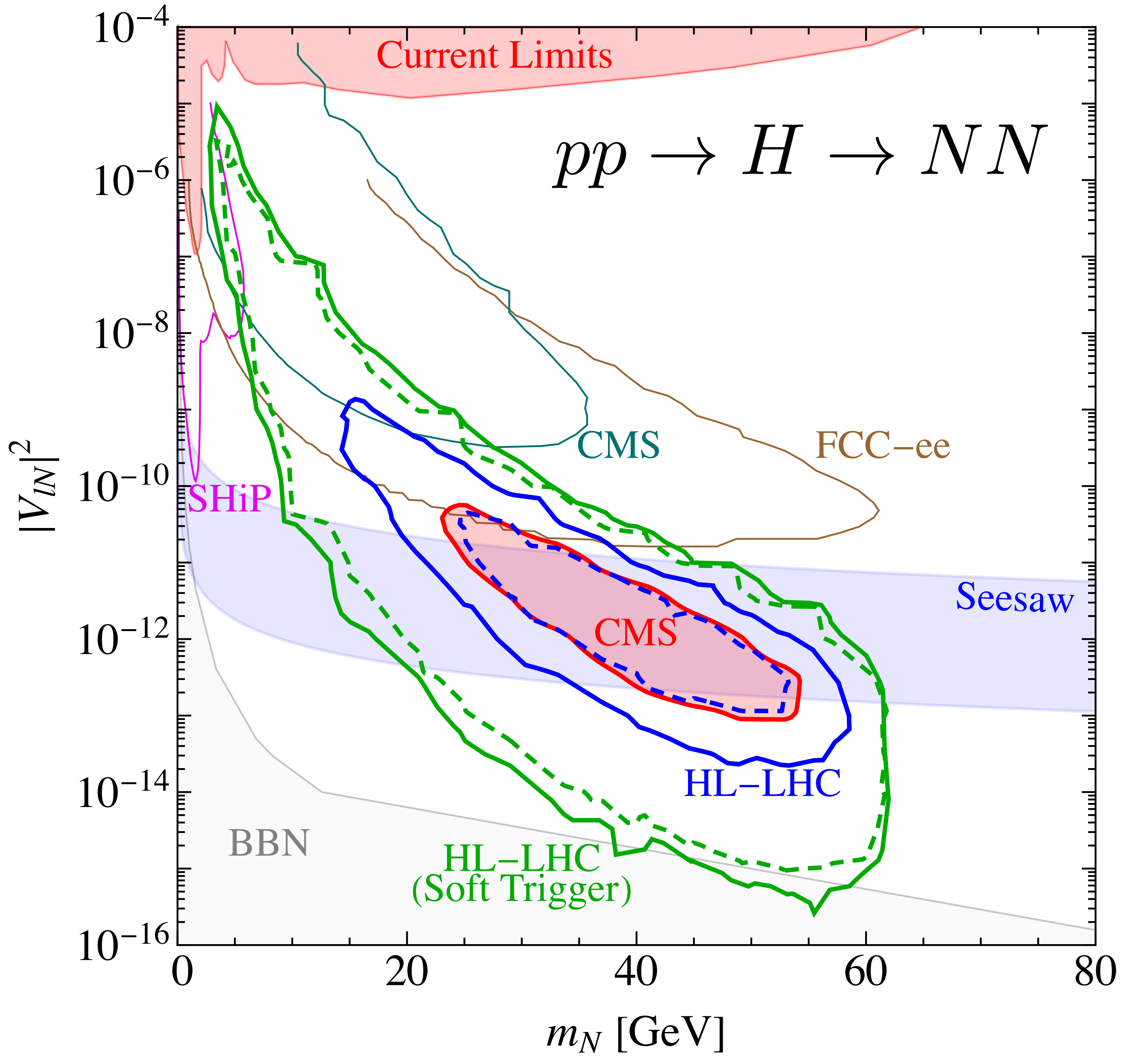
Frank Deppsich. UCL

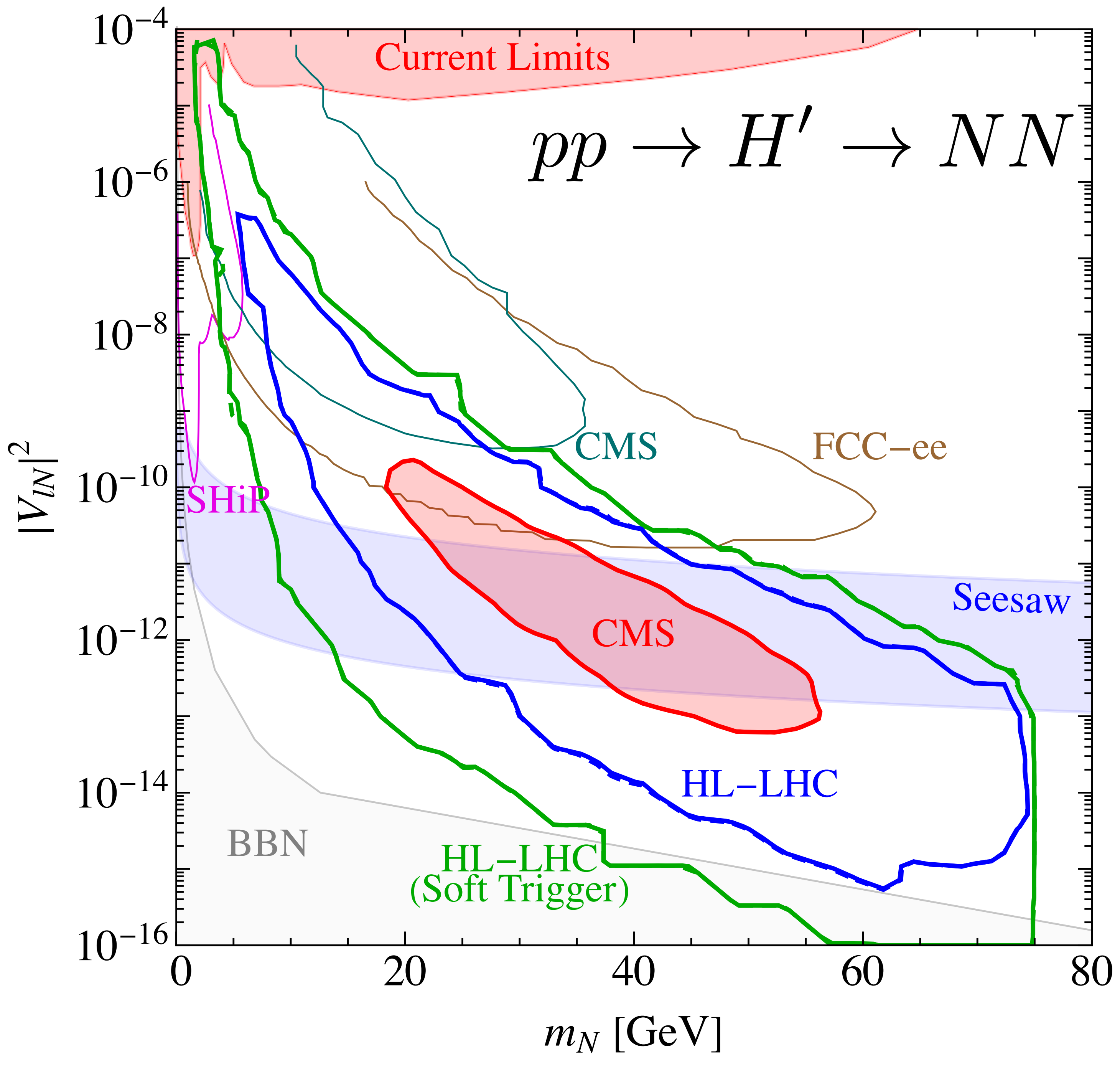
- 2407.20676 investigated breaking of gauge $B-L$ theory lead to GeV-scale RHNs along with exotic Higgs & Z'



- RHNs produced via pp collision and because mixing to active neutrinos is small $\Longrightarrow$ displaced vertices (~ meter scale).

- Focus on a search for displaced showers in the CMS muon system



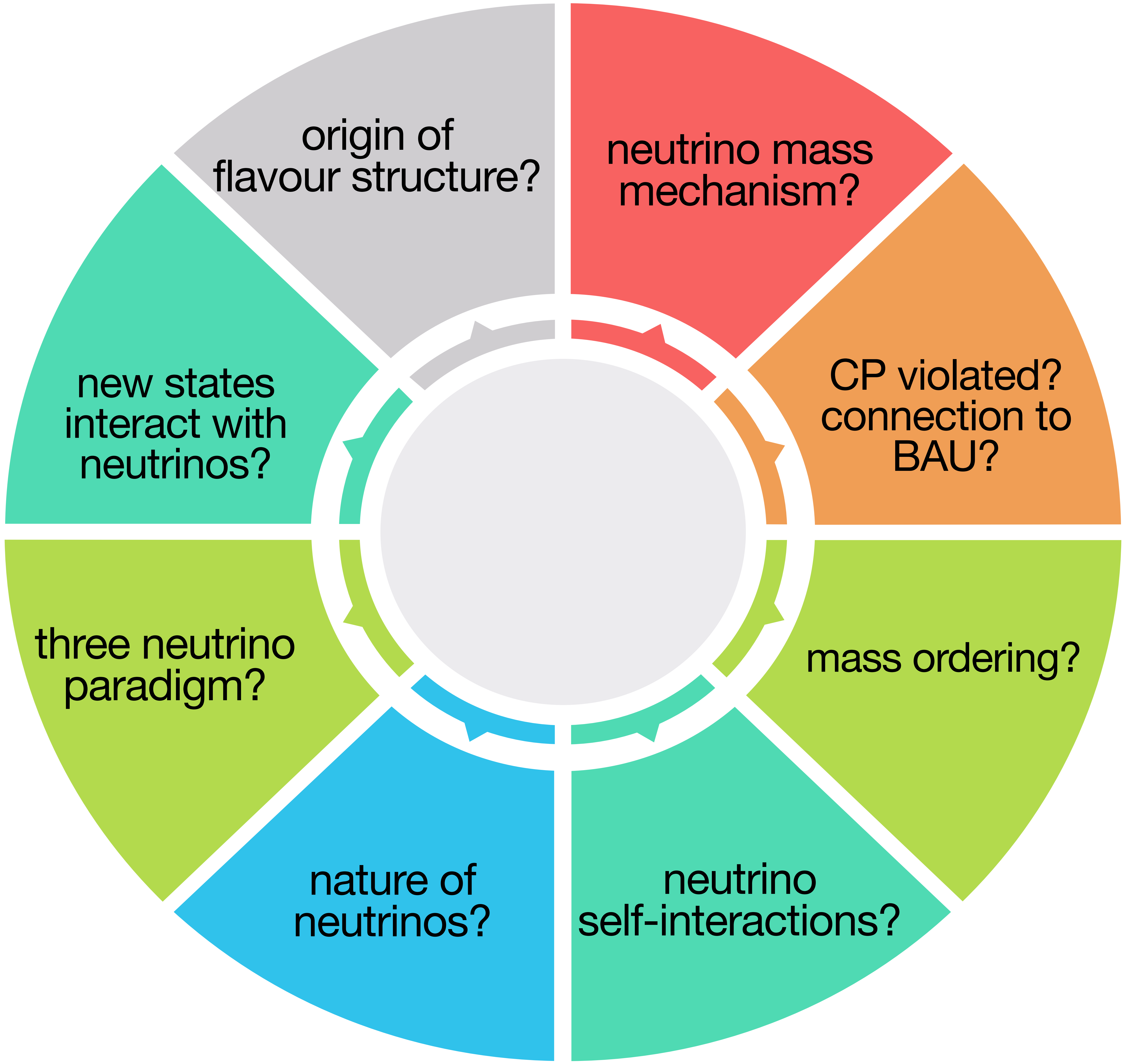


Frank Deppsich. UCL

- CMS search for long-lived particles reinterpreted to explore RHNs via Higgs & exotic Higgs portals $\Longrightarrow$ potential to probe RHN masses around 40 GeV with existing data.

- Current CMS data is already excluding unexplored parameter space in the $B-L$ gauge model, motivating further searches for displaced showers in the muon system to better probe RHN signatures.

Neutrinos: what we don't know



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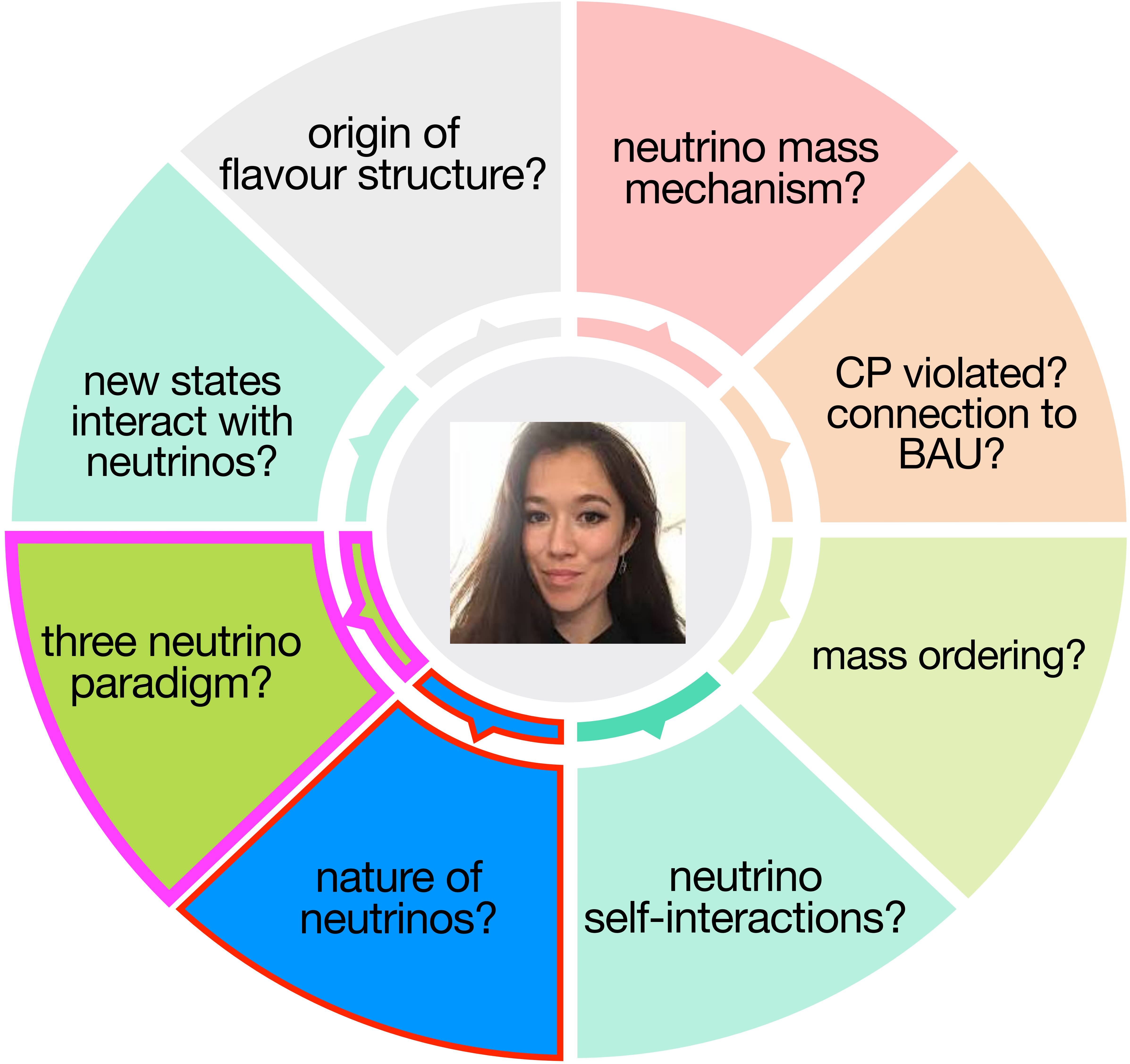
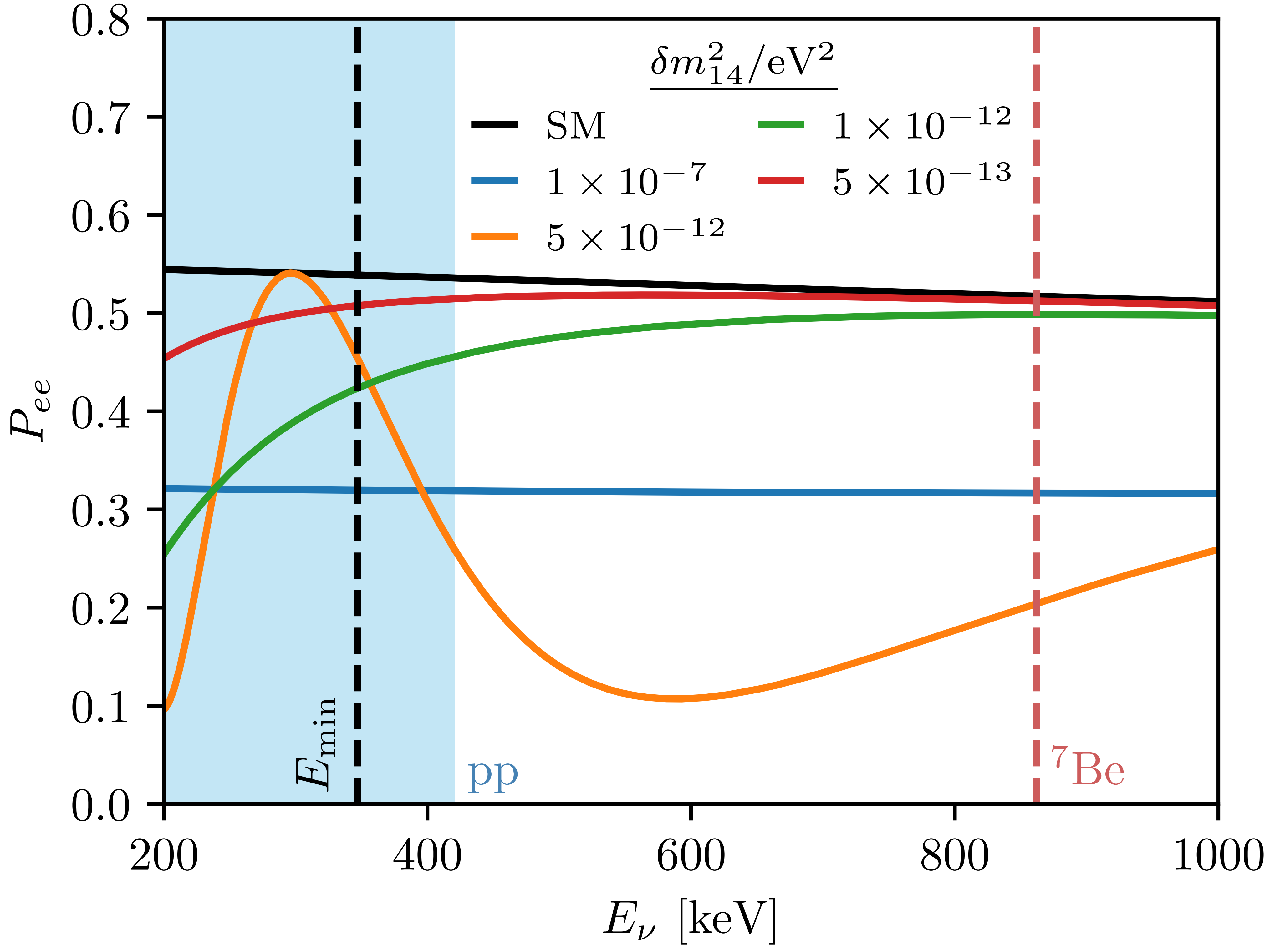
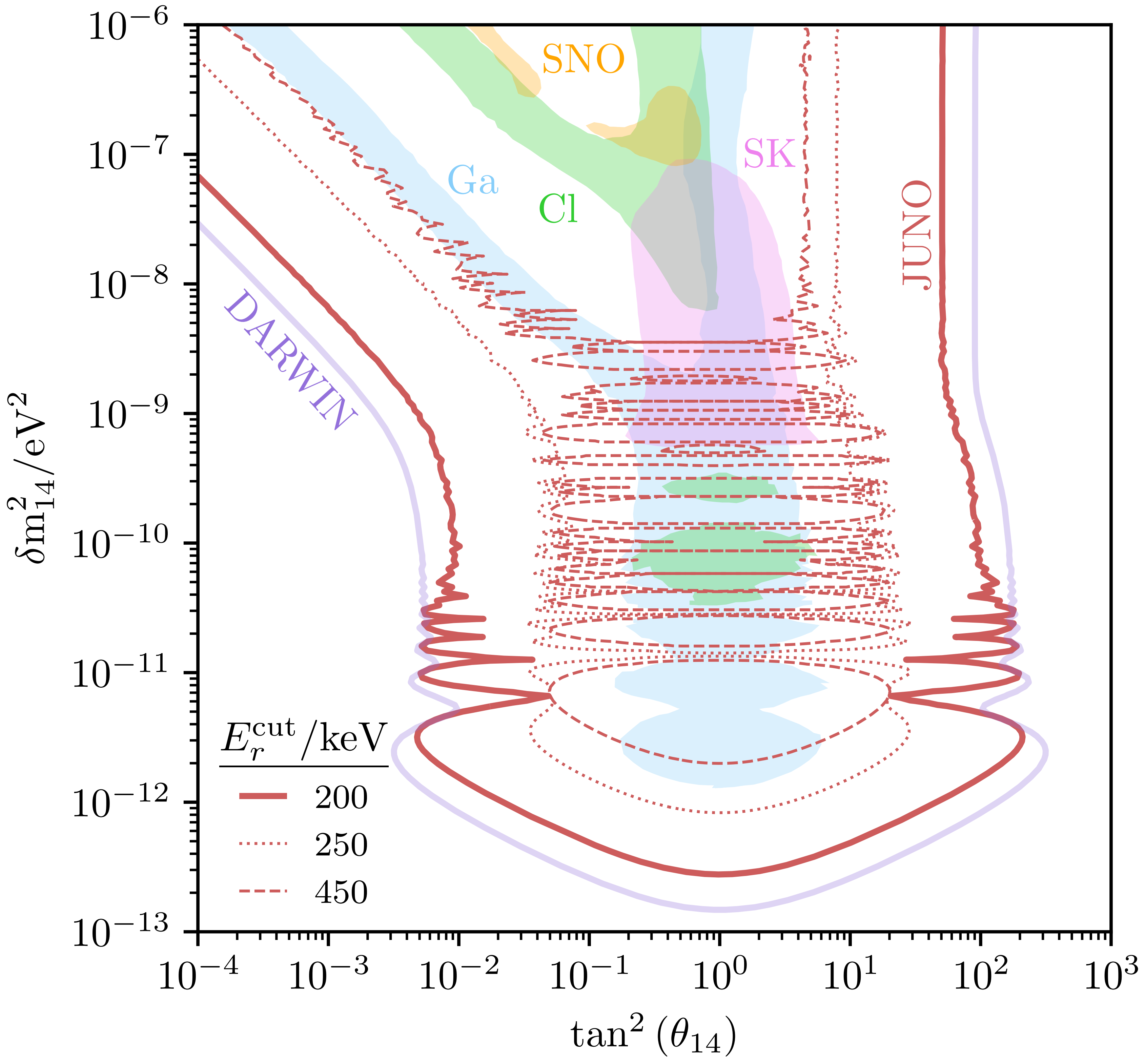


- 2304.05418 investigates JUNO's potential to investigate possible pseudo-Dirac nature of neutrinos using solar neutrinos





- JUNO competitive with DARWIN in probing nature of neutrinos.

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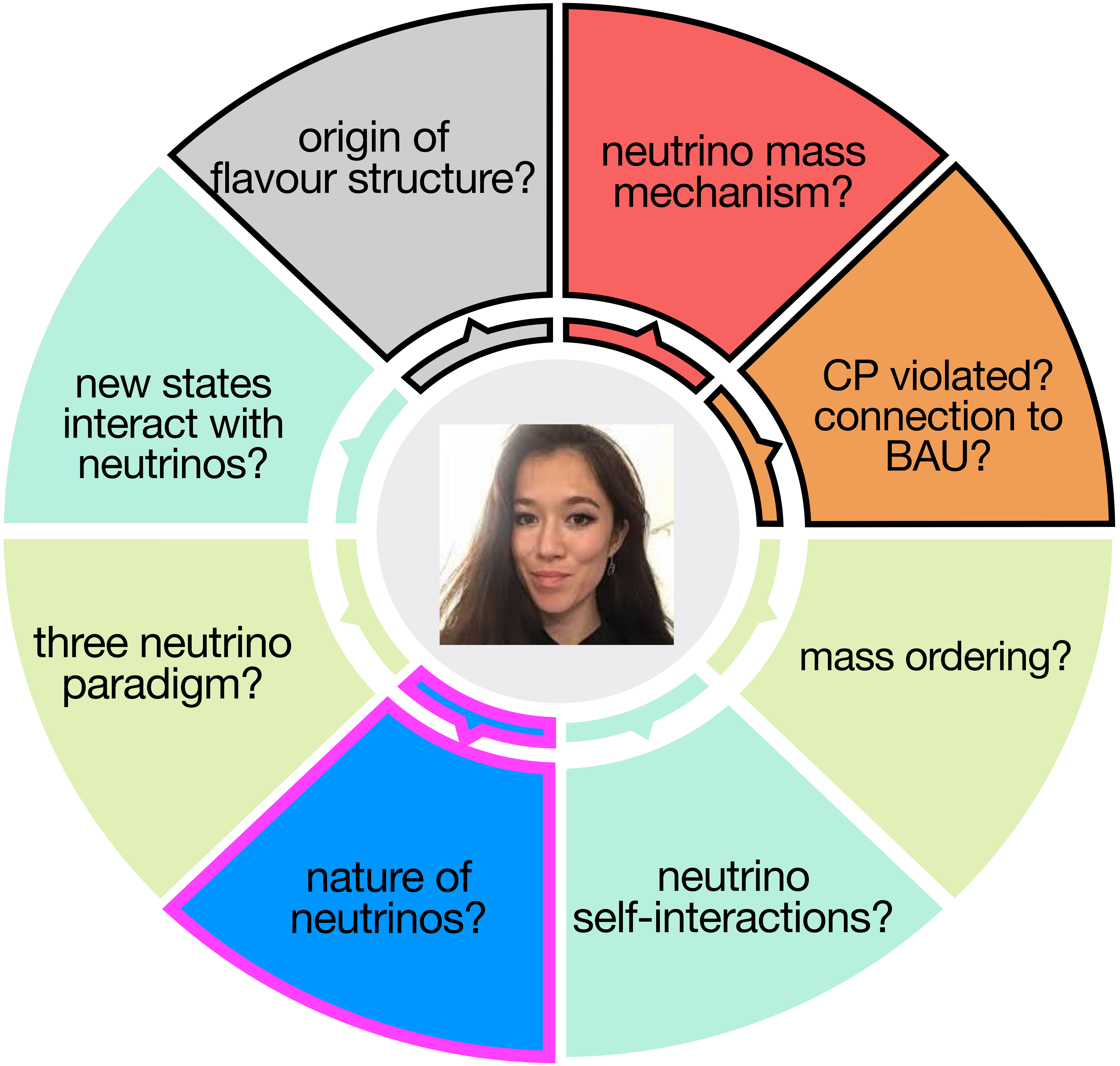
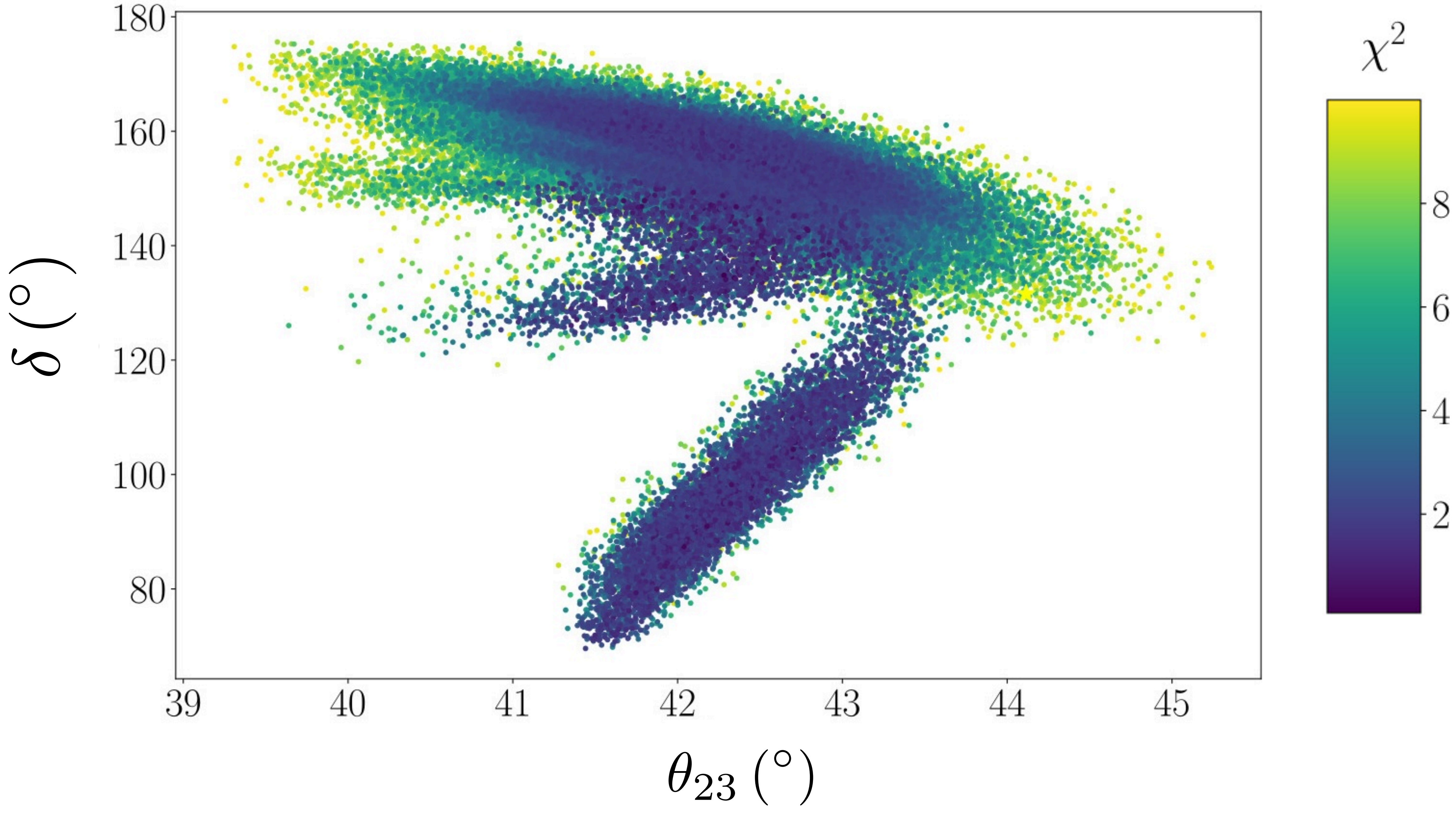
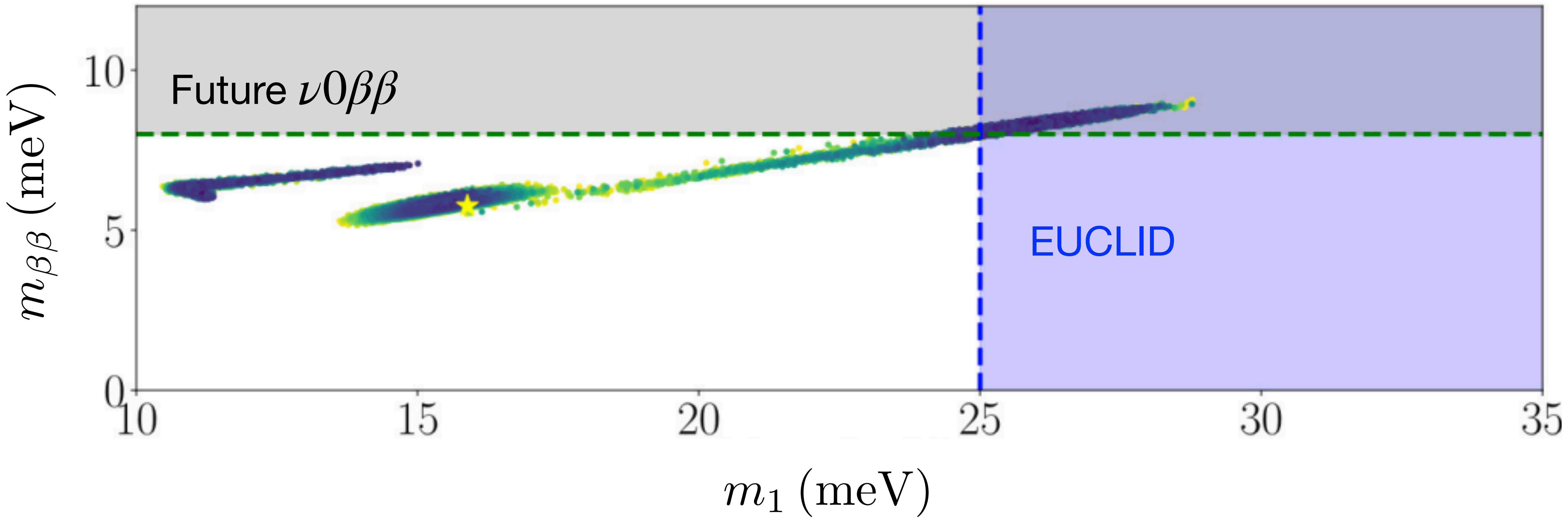
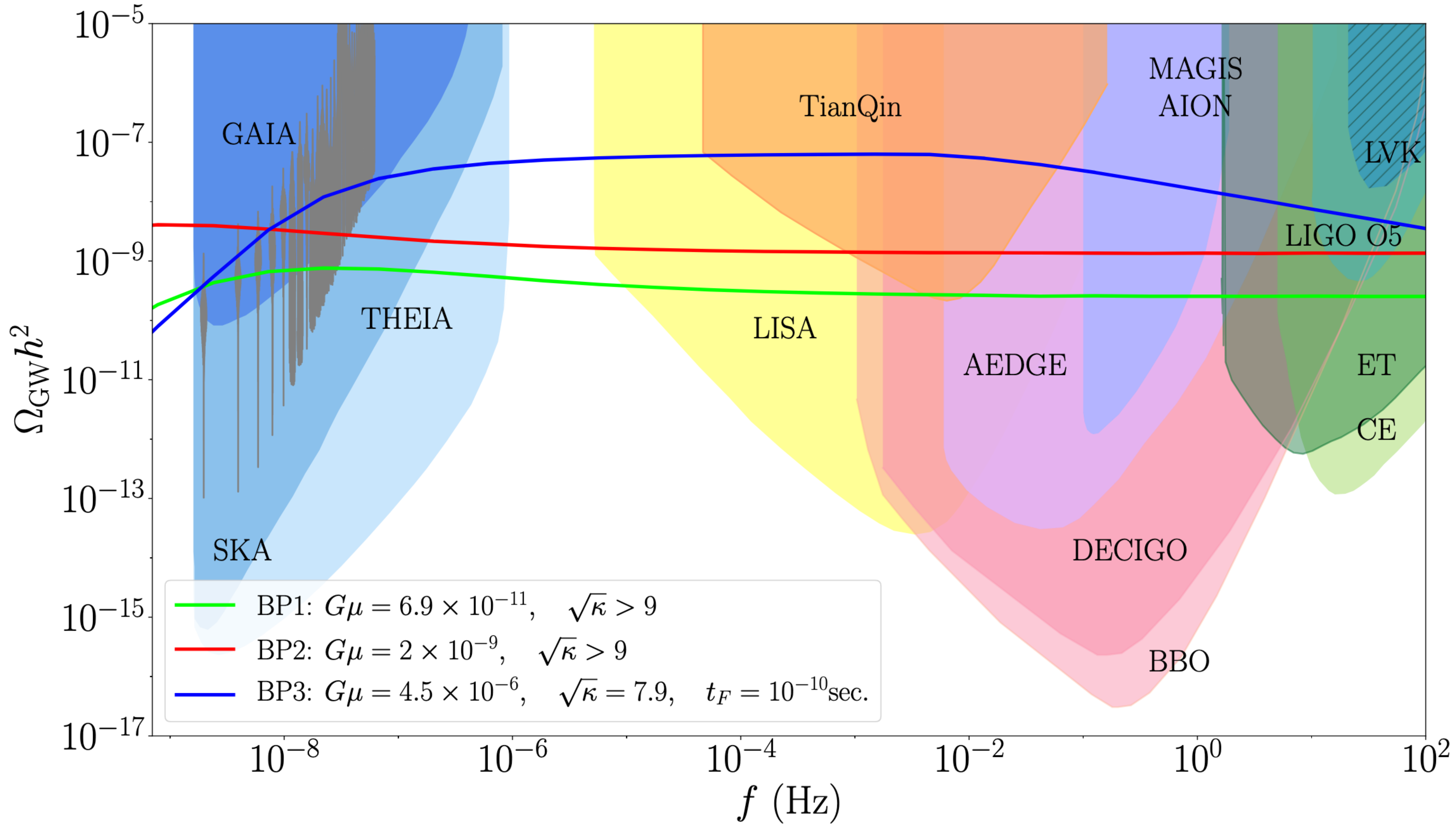


Jessica Turner, IPPP

- 2308.05799 investigates how GUT model predicts correlations in flavour data, matter antimatter asymmetry, GW signal generated by cosmic strings & are testable at Hyper-K & DUNE via proton decay



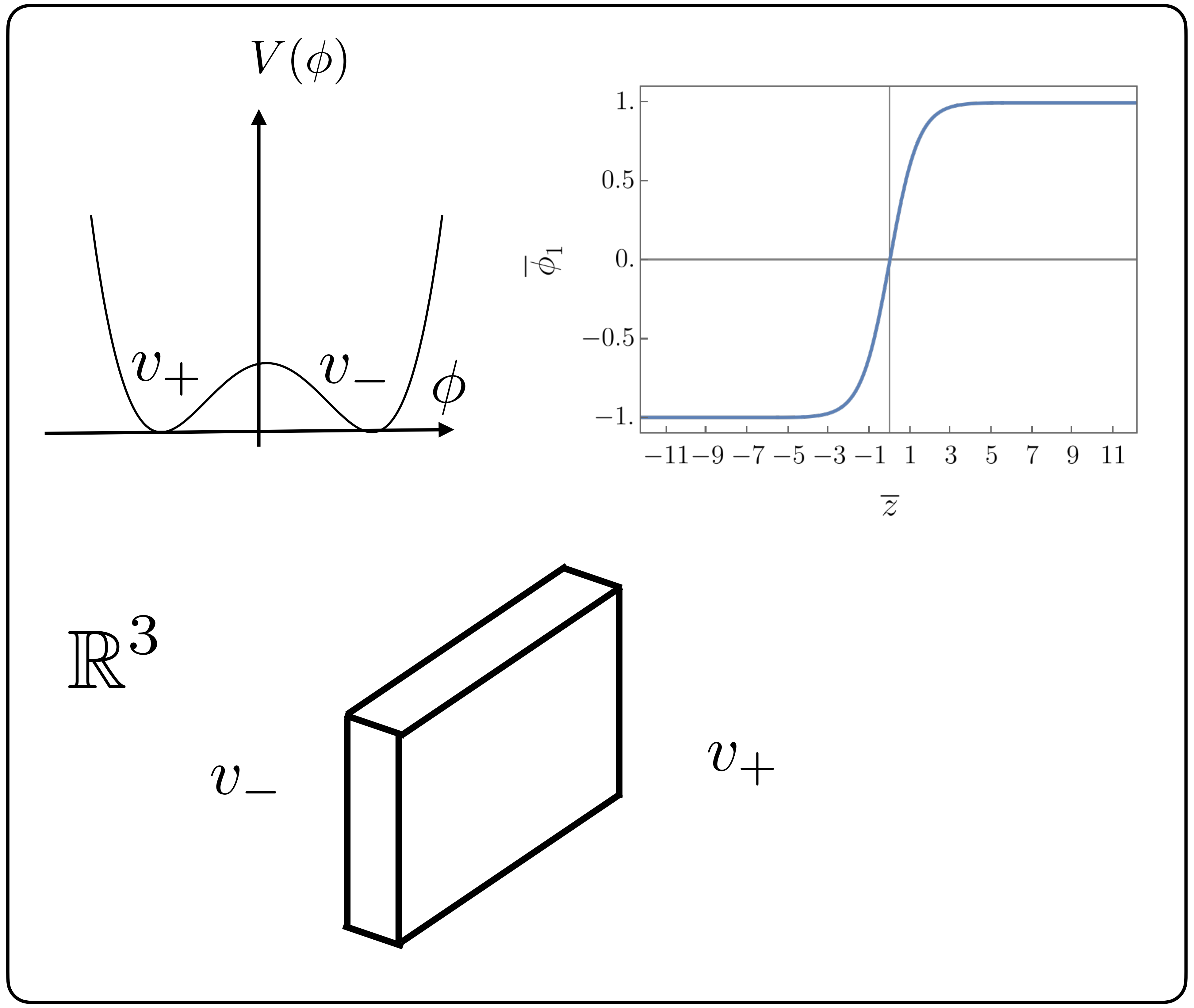




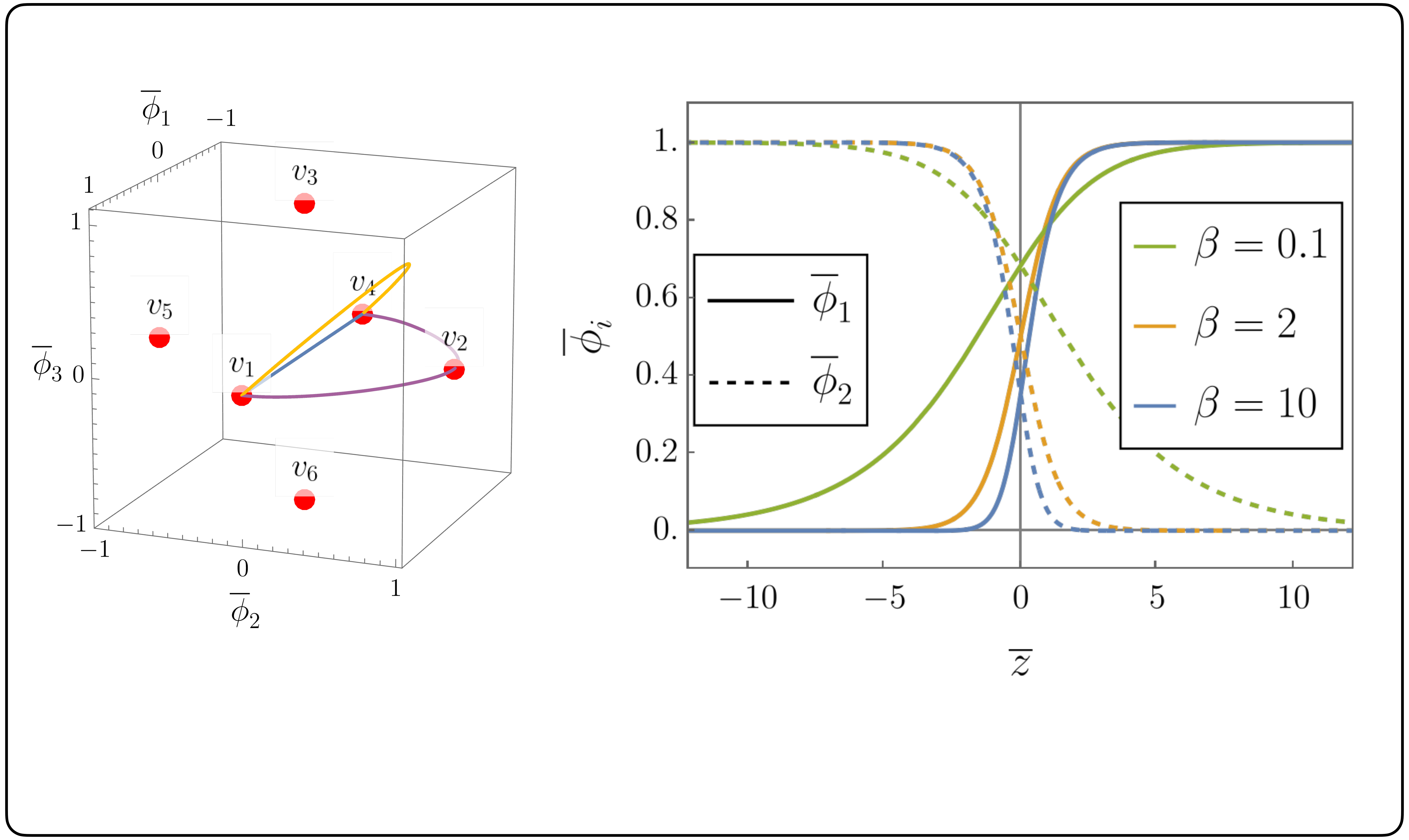
Jessica Turner, IPPP

- 2409.16359 (today!) work on cosmological signatures of non-abelian flavour models with S. King. Upcoming flavour data complemented by GW data
- Vacuum manifold of most flavour models is rich and generate domain walls which are more complex than typical $\mathbb{Z}_2$ domain wall

Abelian Domain Wall



Non-Abelian Domain Wall



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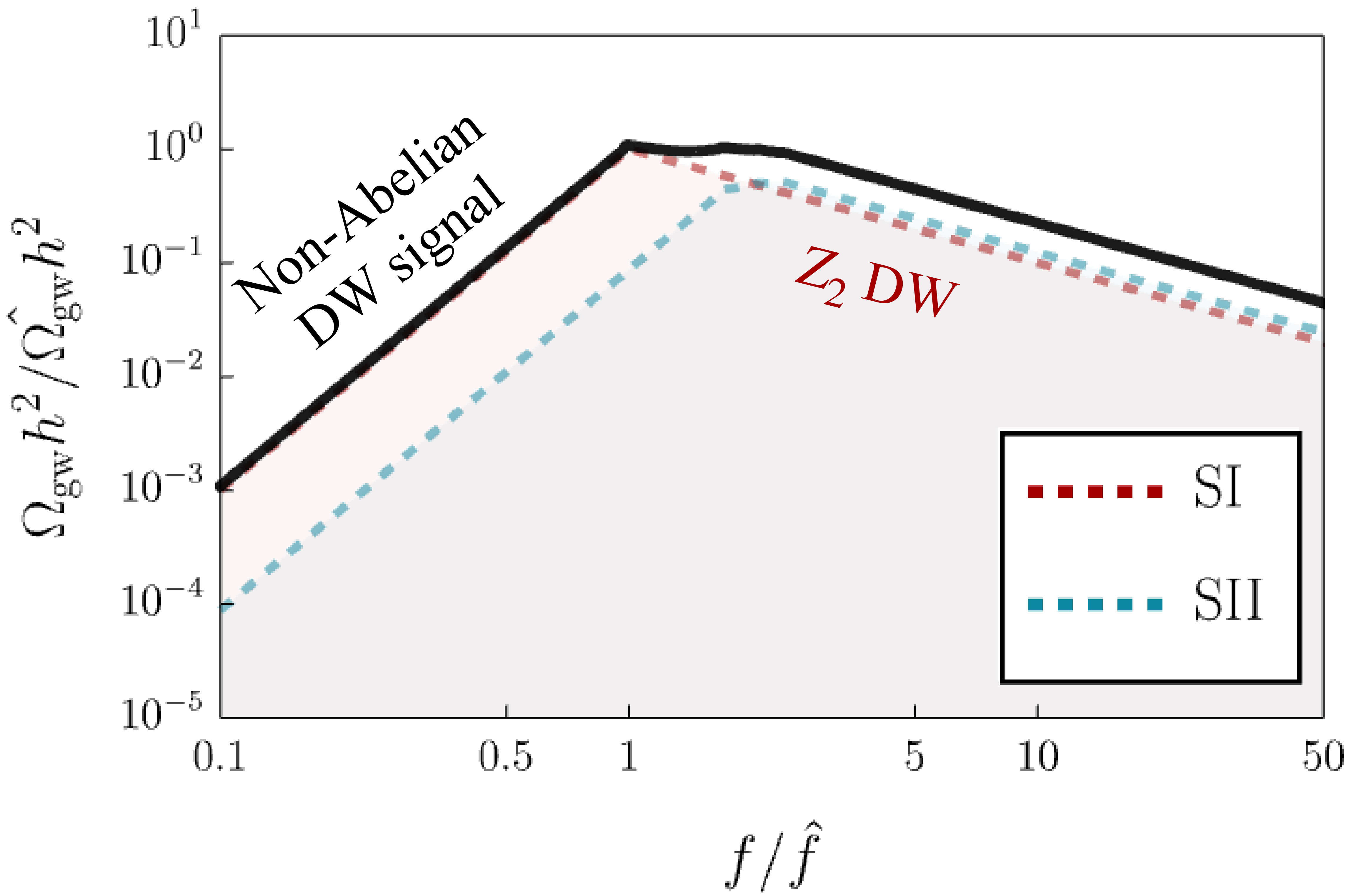

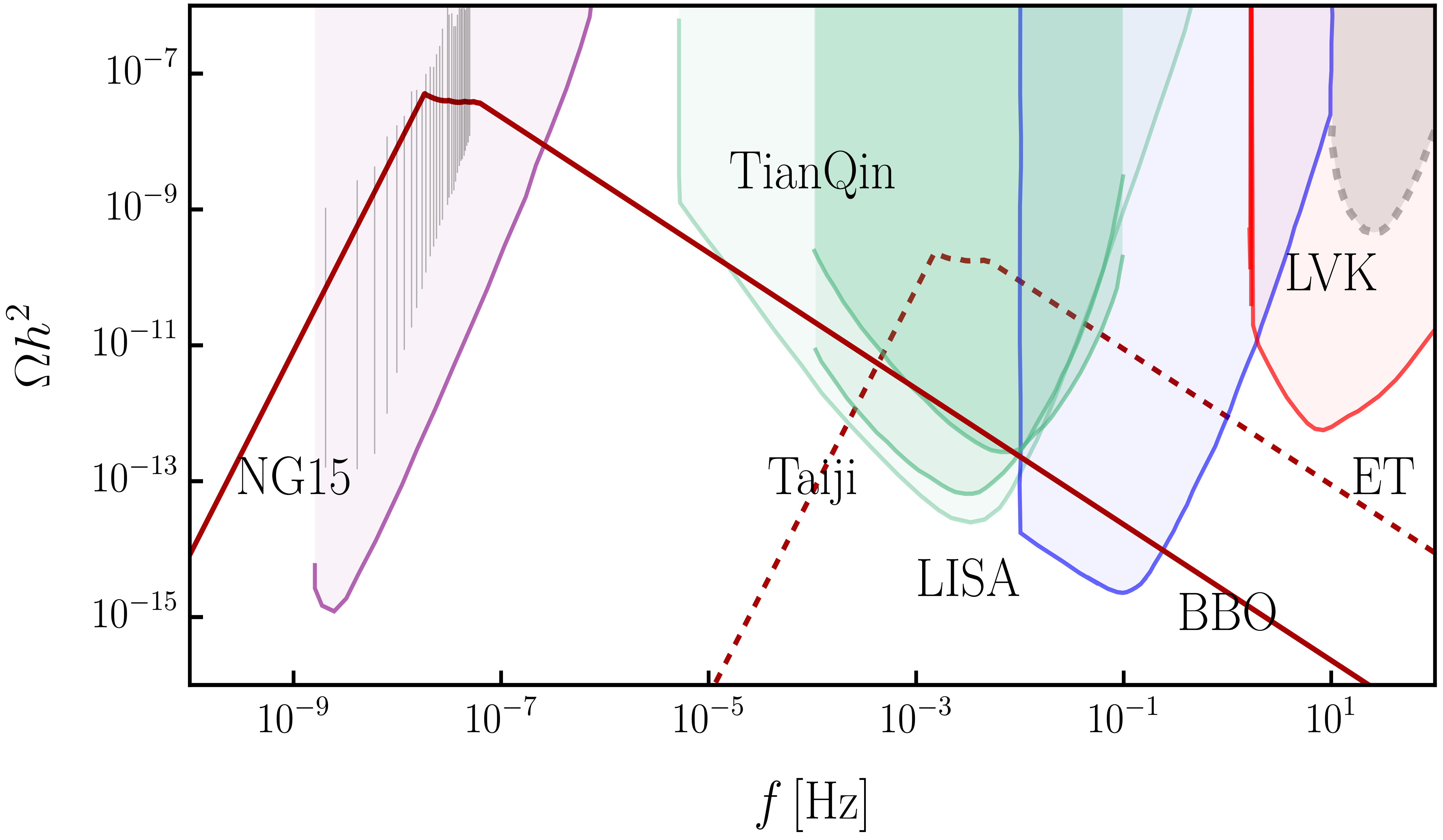

Summary

- Neutrino theory in the UK is a small but vibrant community but covers a wide array of key open questions in neutrino physics
- Current & upcoming neutrino oscillation & $\nu 0\beta\beta$ exps will allow us to test many neutrino theories including flavour & GUTs. Complemented by GW exps
- Astrophysical neutrinos are playing an increasingly important role in understanding neutrinos, more data will come and this will complement accelerator & reactor neutrino experiments.
- Colliders & forward physics facilities (see S. Sarkar's talk) provide a complementary method of understanding neutrino mass (leptogenesis)
- Theoretical developments of neutrino cross section is a key area that requires more attention