Investigating the Effect of Exotic Sources of Decoherence in Flavored Leptogenesis

An exploratory study of the simplest exotic-decoherence class

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Vanilla Leptogenesis

How do we produce a baryon asymmetry? — e.g. Davidson et al. (2008), Buchmüller et al. (2004)

The Sakharov Conditions

Lepton number violation — a process that produces more leptons than antileptons

CP violation — prefer $\Delta L = +1$ to $\Delta L = -1$

Departure from equilibrium — the asymmetry must freeze-out and persist until today

Add two right-handed Majorana neutrinos N_i to the Standard Model with large masses M_i

$$\mathcal{L} \supset -\lambda_{\alpha i} \overline{L}_\alpha \widetilde{\Phi} N_i - \frac{1}{2} M_i \overline{N_i^c} N_i + \text{h.c.}$$

$$m_\nu = -v^2 \lambda M^{-1} \lambda^T$$

Electroweak sphalerons (non-perturbative gauge field configurations) violate B+L, converting lepton asymmetry to baryon asymmetry $\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma}$ — Observed $\eta_B \approx 6 \times 10^{-10}$

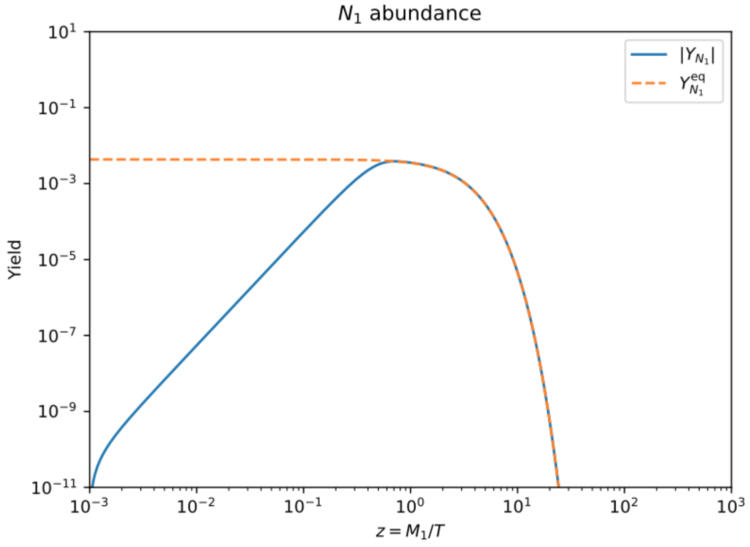
Vanilla Leptogenesis: Density Matrix Equations

How do we describe the asymmetry? — e.g. Blanchet et al. (2013), Dev et al. (2018)

Coupled differential equations describe the number density of leptons

$$\frac{dY_{N_1}}{dz} = -D(z)(Y_{N_1} - Y_{N_1}^{eq})$$

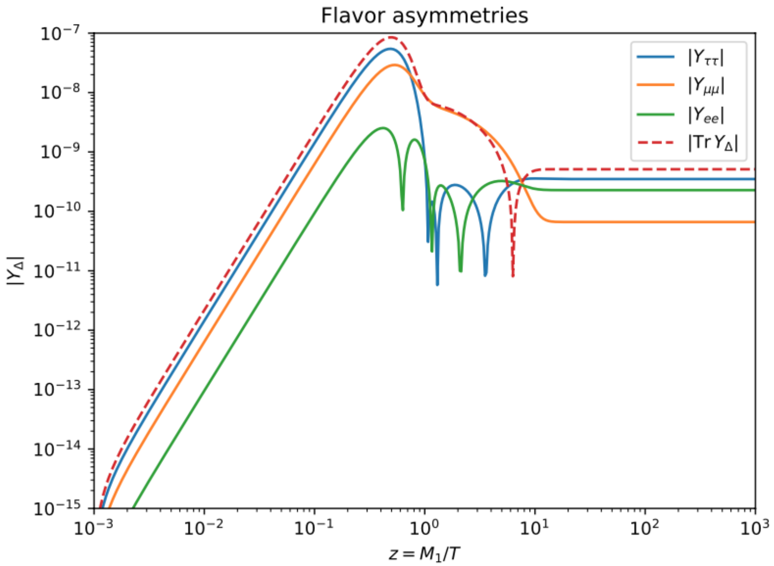
$$\frac{dY_{\alpha\beta}^{B-L}}{dz} = -\,\epsilon_{\alpha\beta}^{(1)} D(z)\left(Y_{N_1}(z) - Y_{N_1}^{\rm eq}\right) - \frac{1}{2} W(z)\left\{P^{(0)1}, Y^{B-L}\right\}_{\alpha\beta}$$
$$-\,\frac{\Gamma_\tau}{Hz}\left[\Pi_\tau, \left[\Pi_\tau, Y^{B-L}\right]\right]_{\alpha\beta} - \frac{\Gamma_\mu}{Hz}\left[\Pi_\mu, \left[\Pi_\mu, Y^{B-L}\right]\right]_{\alpha\beta}$$



Why density matrices?

Decay — sterile neutrinos decay into a superposition of flavor states

Charged lepton interactions — measure flavor, destroy coherences



Exotic Decoherence Terms

In analogy with De Romeri et al. (2023), IceCube Collaboration (2024)

Add an exotic dephasing term

Motivation — generic expectation from Planck-scale physics: stochastic QG perturbations might introduce Lindblad-style dephasing

E.g. Ellis et al. (1984), Stuttard & Jensen (2022), Carlip (2023)

Two additional parameters — γ, n

No *direct* effect on lepton populations — diagonal terms 0 by construction

$$-\frac{(T/T_0)^n}{Hz}\gamma_{\alpha\beta}Y_{\alpha\beta}$$

$$T_0 = 1\text{GeV (Arbitrary normalization)}$$

Model B	Vary $\gamma_{\tau\mu} = \gamma_{\tau e}$ and keep $\gamma_{\mu e} = 0$
Model C	Vary $\gamma_{\mu e} = \gamma_{\tau\mu}$ and keep $\gamma_{\tau e} = 0$
Model D	Vary $\gamma_{\tau e} = \gamma_{\mu e}$ and keep $\gamma_{\tau\mu} = 0$

This talk will focus on n = 1

Key relationship: these correspond *identically* to strengthening SM interactions with effective Yukawa

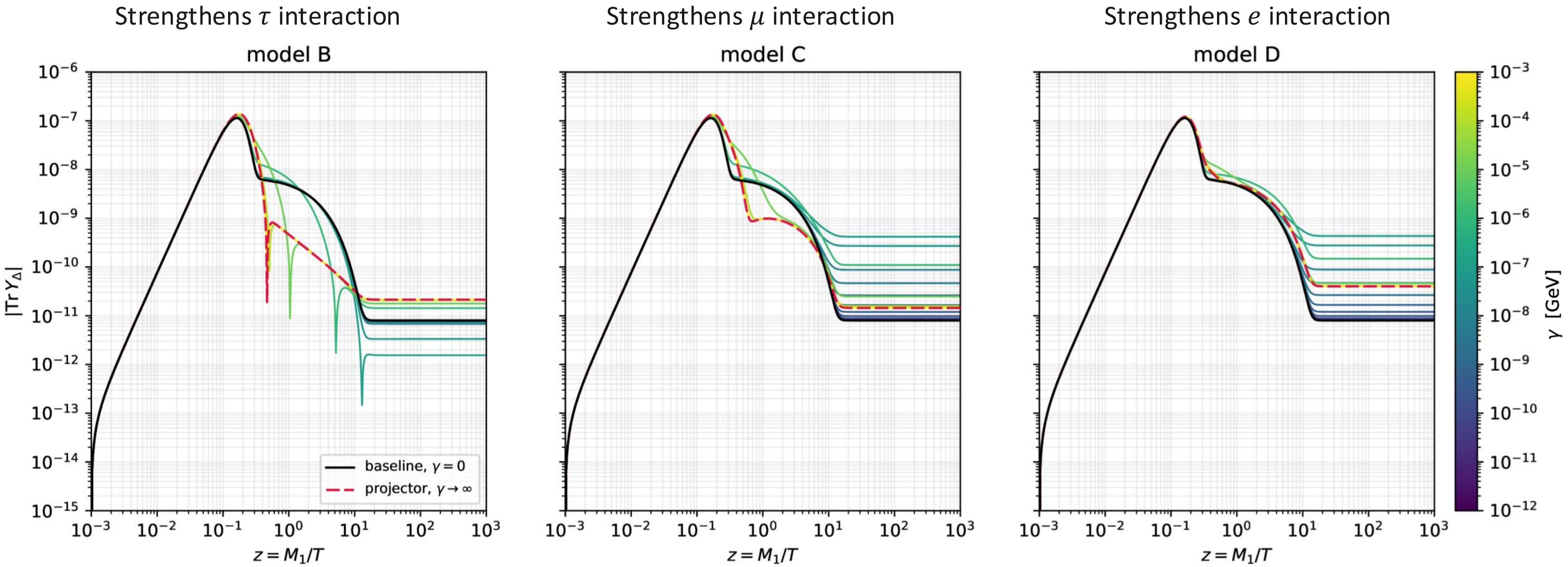
$$h_{\text{eff}} = h\sqrt{1 + \frac{\gamma}{ah^2}}$$

Questions

- How do these terms affect the evolution of Y?
- How do these terms change $|\eta_B|$ and its sign?
- Which flavor channels have the largest effect?

Evolution Examples

Input Parameters: M1 = 5.012e+11 GeV, M2 = 100*M1, Re[z] = 3.998, Im[z] = 2.390, δ = 2.834, α= 2.242, n = 1



Observations

Direction of shift — γ can move η_B in different directions as it strengthens

Limits — after a limiting γ, affected coherence term is sent to 0 immediately, so no further change in η_B

Effects by Flavor Channel

Scan Parameters: N = 400 points — Models B, C, D — $10^{-10} \leq \gamma \leq 10^{-4}$ GeV
$10^9 \leq M_1 \leq 10^{13}$ GeV — $0 \leq \delta \leq 2\pi$ — $0 \leq \alpha \leq 4\pi$ — $0 \leq Re[z] \leq \pi/2$ — $0 \leq Im[z] \leq 2$

Systematic increase in $|\eta_B|$

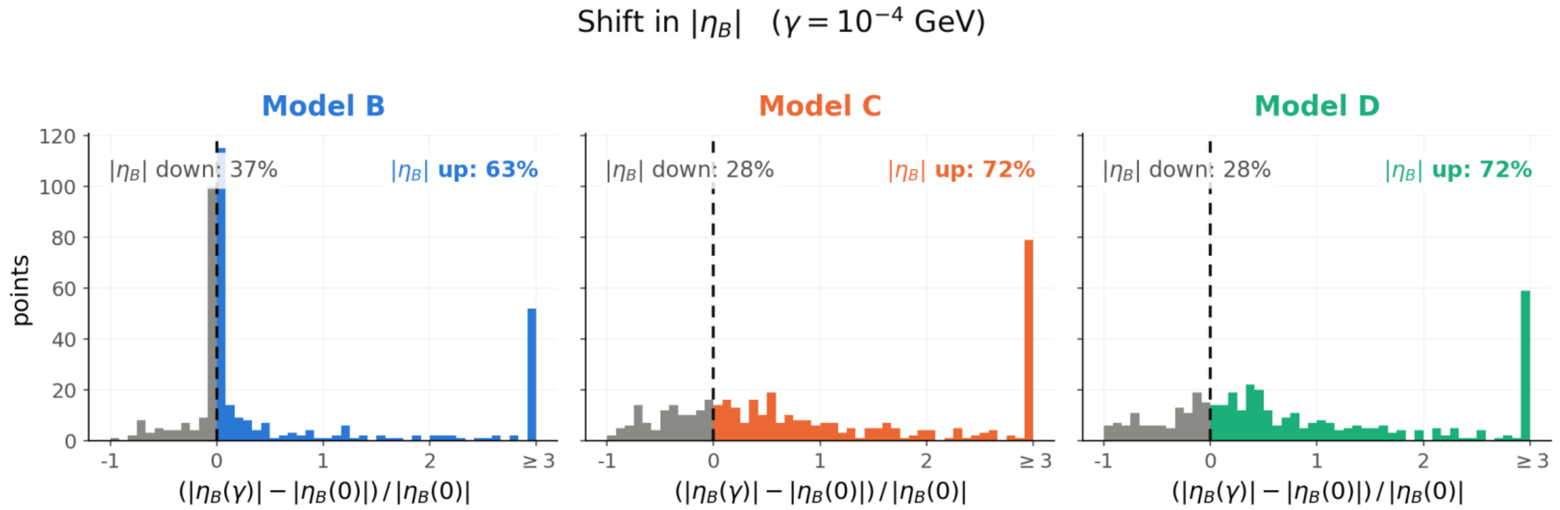
$|\eta_B|$ increases for a majority of points

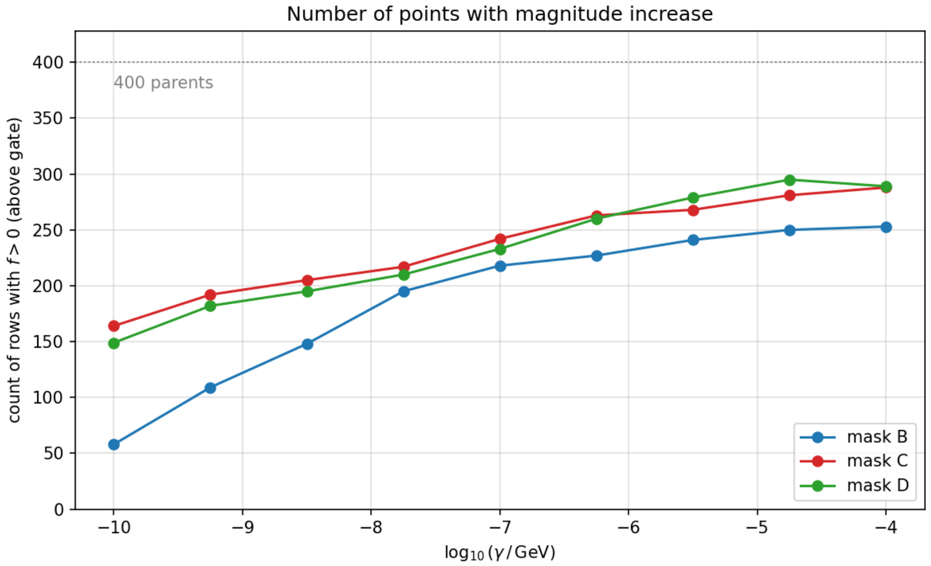
$$f = \frac{|\eta_B(\gamma)| - |\eta_B(0)|}{|\eta_B(0)|}$$

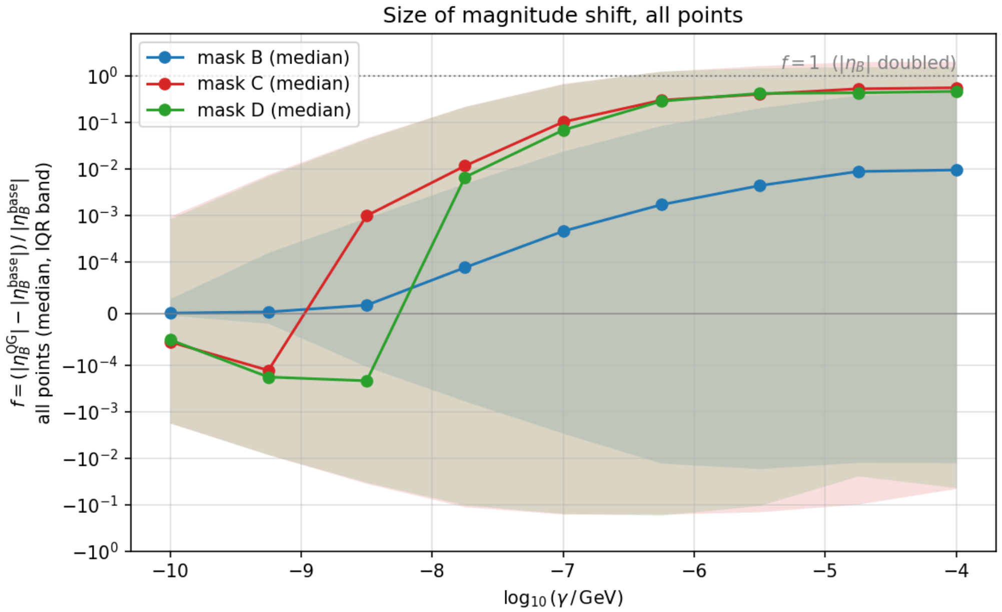
Number of points with $f > 0$ increases with γ

Median value of $f(\gamma)$ increases with γ, but lowest quartile remains negative

Model B (tau strengthening) is the least active







Effects by Flavor Channel

Scan Parameters: N = 400 points — Models B, C, D — $10^{-10} \le \gamma \le 10^{-4}$ GeV

Sign-flips concentrate on the baseline carrying the domain-disfavored sign

Parameter mirrors — two parameter transformations result in $\eta_B \to -\eta_B$ (Appendix B):

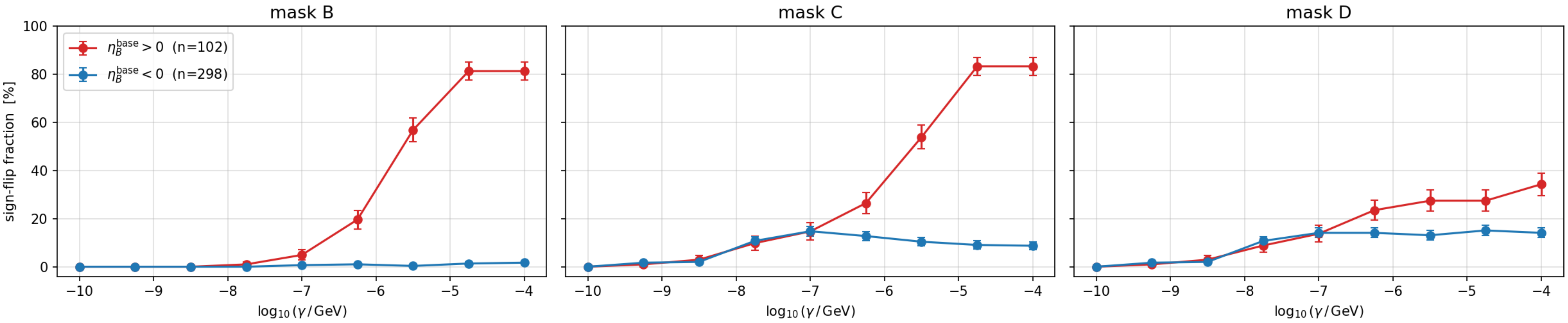
- $(\delta, \alpha, Im[z]) \to (-\delta, -\alpha, -Im[z])$
- $(\delta, \alpha, Re[z]) \to (-\delta, 2\pi - \alpha, -Re[z])$

Sign-flip statistics — fraction of sign flips by baseline sign is odd under the above transformations, so would produce a 50-50 result *identically*

Removing the mirrors from the scan — we restrict the domain of the scan to one "half" of the mirrored space; 75% of the points in our scan have $\eta_B < 0$

Sign flips — A much larger fraction of baseline-positive η_B points change sign due to additional decoherence effects

Fraction of sign-flips, split by baseline sign



Summary & Conclusions

What we've seen

The identity (n = 1) — these terms add no new operators, they just strengthen SM's own flavor measurement

Evolution — trajectories deform non-monotonically and saturate at an exact $\gamma \to \infty$ limit

Across the space — $|\eta_B|$ grows for 63-72% of scanned points, increasing in magnitude and number with γ

Sign flip — QG effects produce sign flips in the baseline carrying the domain-disfavored sign

Flavor channels — Model B, affecting the τ interactions, is the most inert, because it is not turning on the $\mu - e$ channel in a new temperature regime

Future Work

Open questions

Can we import constraints on γ from the neutrino oscillation papers?

- Generate data at higher n
- Determine how their below-EWSB mass basis compares to our above EWSB flavor basis
- Consider running of couplings

Are there regions of the parameter space that are newly excluded or that open-up due to these effects?

- Run larger scans and compare
- Find analytic approximations for faster scanning

Are there interesting models based on more physically motivated measurement bases?

- E.g. RHN measurement basis rather than flavor basis

Can we predict the γ for $\Delta\eta_B$ onset, maximum, plateau?

- Parent dependent, will require larger scans over the space
- Already a graveyard of ideas

Backup

Landmarks in Ordinary Leptogenesis

What are some generic features of the leptogenesis parameter space? — Granelli et al. (2021)

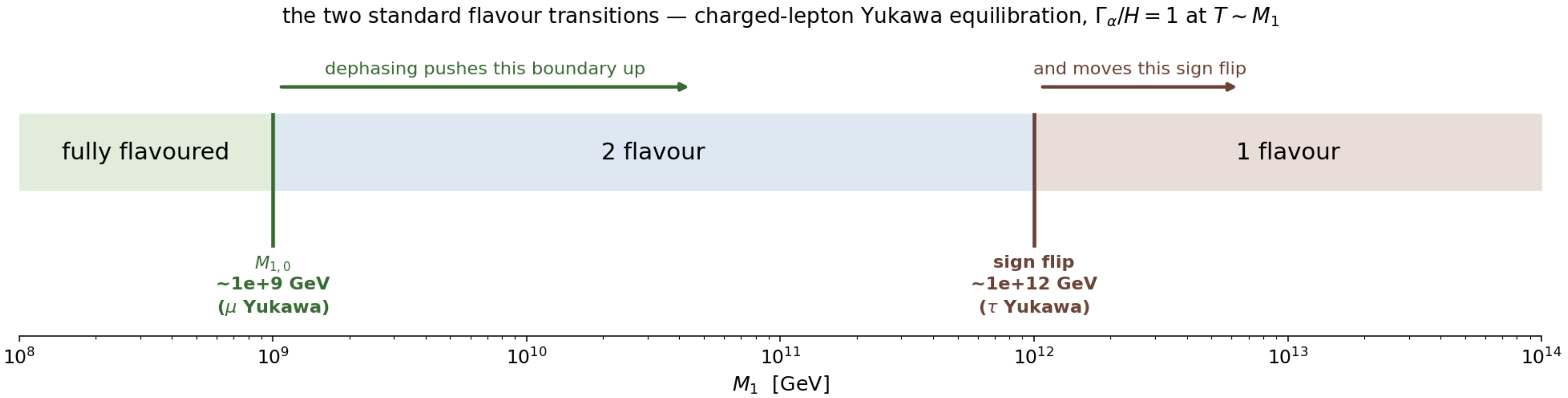
Landmarks in the parameter space track flavor-transition regimes

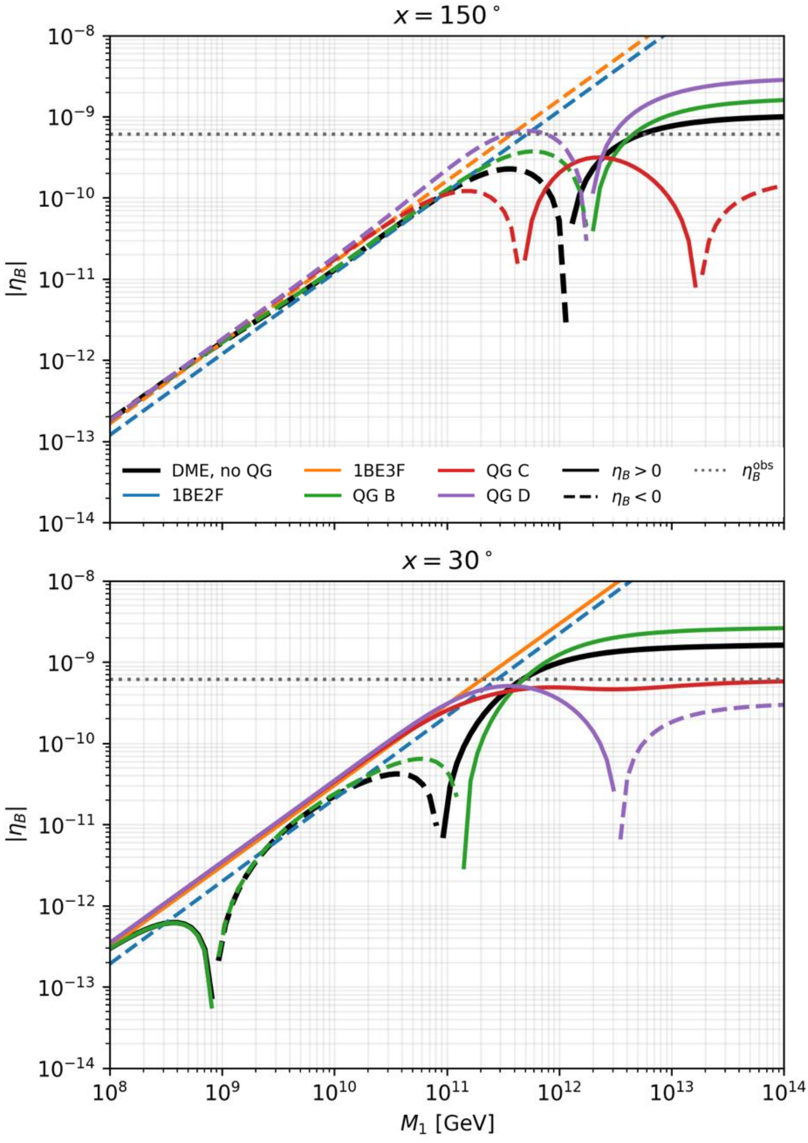
Comparison with Hubble rate — when an interaction rate $\Gamma \sim H(z)$, then the interaction distinguishes particles of that flavor

Classical approximation — above $\Gamma \sim H(z)$, the coherence term zeros out quickly, leaving classical particle number description (Boltzmann equations)

Flavor approximations — At high energies, 1 flavor; intermediate, 2 flavors; low, 3 flavors

- τ transition at $\sim 1 \times 10^{12}$ GeV
- μ transition at $\sim 1 \times 10^{9}$ GeV





Landmark Shifting

The landmarks can be predicted algebraically

The 2-3 flavor transition landmark

Define $M_{1,dep}$ — where the DME solution departs from the 3-flavor classical approximation

Compare SM + exotic strength with unperturbed rate

$$\left.\frac{\Gamma_\mu + \Gamma_{\mathrm{QG}}}{H}\right|_{M_{1,\mathrm{dep}}} = \left.\frac{\Gamma_\mu}{H}\right|_{M_{1,0}} \implies \frac{(a\,h_\mu^2 + \gamma)\,\widetilde{M}_{\mathrm{Pl}}}{M_{1,\mathrm{dep}}} = \frac{a\,h_\mu^2\,\widetilde{M}_{\mathrm{Pl}}}{M_{1,0}}$$

$$M_{1,\mathrm{dep}}(\gamma) \;=\; M_{1,0}\left(1 + \frac{\gamma}{a\,h_\mu^2}\right)$$

$\gamma \to \infty$ limit: $M_{1,\infty}$ — still makes physical sense! Zero-out the masked coherence terms through the entire evolution

Propose the relationship

$$M_1^{\mathrm{dep}}(\gamma) \;=\; \min\left(M_{1,\infty},\;\; M_{1,0}\left(1 + \frac{\gamma}{a\,h_\mu^2}\right)\right)$$

Testing the Landmark Shift: 2-3 Flavor Transition

The magnitude of the landmark shift can be predicted algebraically

$$M_1^{\mathrm{dep}}(\gamma) \;=\; \min\!\left(M_{1,\infty},\;\; M_{1,0}\left(1+\frac{\gamma}{a\,h_\mu^2}\right)\right)$$

Zero free-parameter prediction of shift

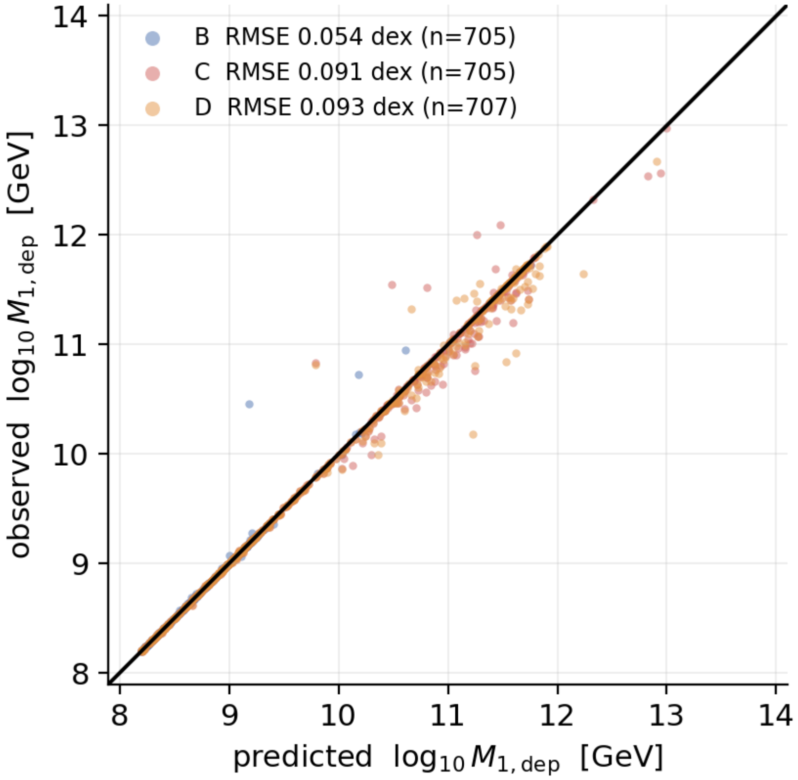
Method — for each parent point, run the baseline evolution, the $\gamma \to \infty$ limit, and one random γ for prediction

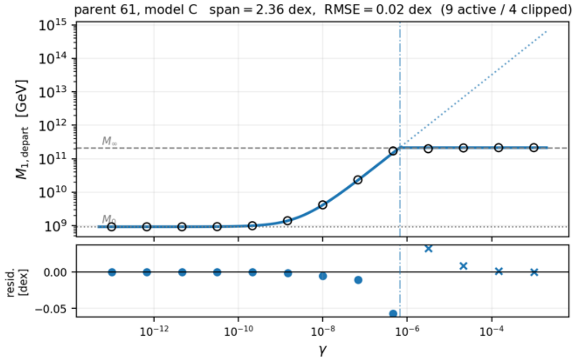
Relationship predicts departure landmark to 24% — since $\Gamma{\sim}H$ is an order-of-magnitude (OOM) heuristic, sub-OOM precision is decent

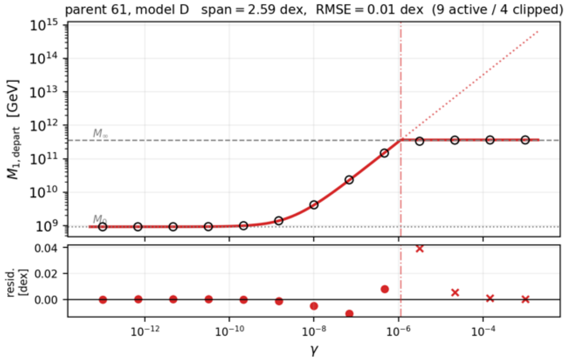
The worst predictions are at the corner near the plateau (1.4x overshoot) — failure at corner is predicted by discontinuous slope

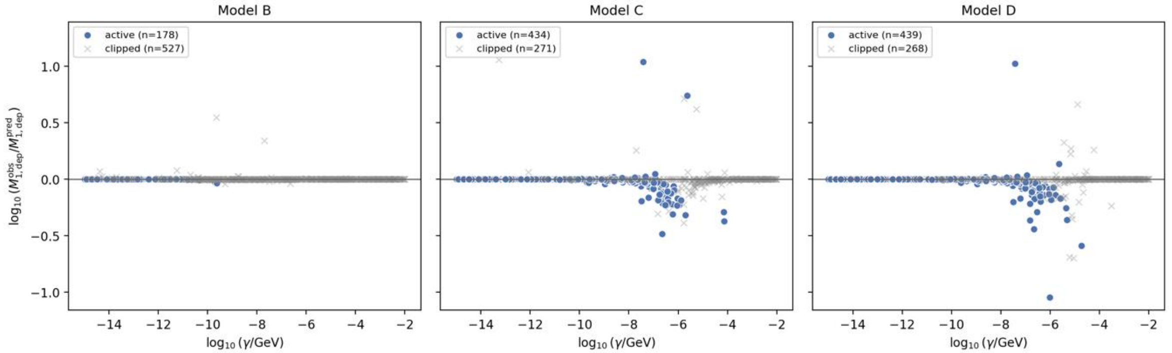
Model B (τ strengthening) doesn't shift 2-3 flavor transition — makes sense given that τ is already resolved at this energy scale

Sigmoids — Zero parameter linear fit is 5-10% more precise than multi-parameter sigmoid fits









Testing the Landmark Shift: 1-2 Flavor Transition

The magnitude of the landmark shift can be predicted algebraically

Model B shifts sign-flip near 10^{12} GeV

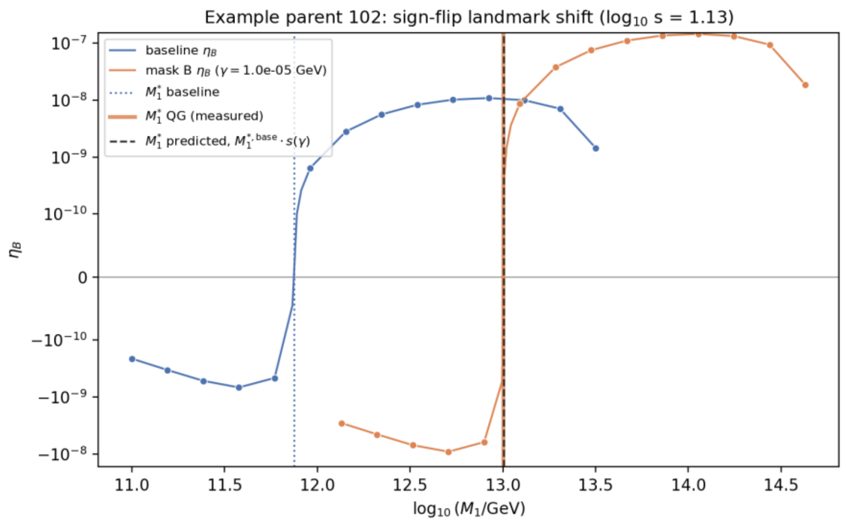
Same principle — replace μ with τ Yukawa coupling

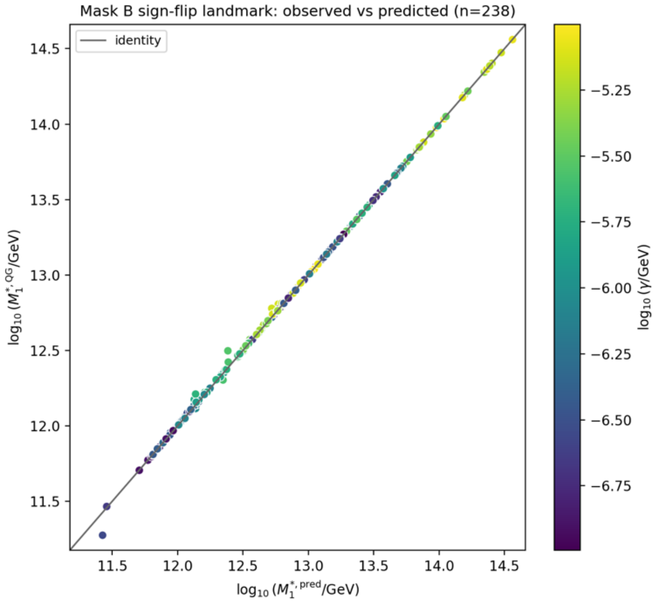
$$M_{1,\mathrm{sf}}(\gamma) \;=\; M_{1,0}\left(1+\frac{\gamma}{a\,h_\tau^2}\right)$$

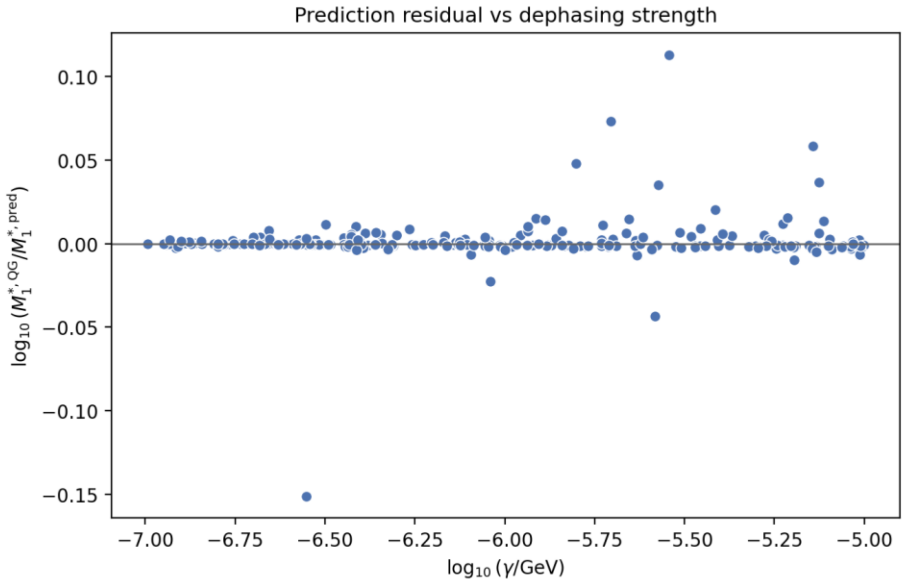
RMSE 3.48% — well within the 17% resolution of the scan

Models C & D don't shift this transition — makes sense because τ interactions are strongest

Note that not all parent points have a resolvable sign-flip (238/300)







Appendices

Appendix A: Equivalence of Exotic Decoherence and SM Strengthening

Only true for n = 1, models B (tau), C (mu), D (e)

Standard Model charged-lepton decoherence

$$-\frac{\Gamma_\tau}{Hz}\left[\Pi_\tau,\left[\Pi_\tau,Y^{B-L}\right]\right]_{\alpha\beta} \qquad \Pi_\tau=\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} \qquad \Gamma_\tau=ah_\tau^2T$$

Exotic dephasing

$$-\frac{(T/T_0)^n}{Hz}\gamma_{\alpha\beta}Y_{\alpha\beta} \qquad T_0=1\mathrm{GeV}\ (\text{Arbitrary normalization})$$

Identical operator structure for n = 1. Only the rate coefficients differ.

$$[\Pi_\tau,[\Pi_\tau,Y]]=\begin{pmatrix}0&Y_{\tau\mu}&Y_{\tau e}\\Y_{\mu\tau}&0&0\\Y_{e\tau}&0&0\end{pmatrix}\ \text{Model B:}\quad \gamma_{\mu\tau}=\gamma_{e\tau}=\gamma,\ \ \gamma_{e\mu}=\gamma_{\alpha\alpha}=0 \quad\Longrightarrow\quad \gamma_{\alpha\beta}Y_{\alpha\beta}=\gamma\begin{pmatrix}0&Y_{\tau\mu}&Y_{\tau e}\\Y_{\mu\tau}&0&0\\Y_{e\tau}&0&0\end{pmatrix}$$

Interactions only damp the off-diagonal terms – no *direct* effect on lepton flavor populations

[Π_α,[Π_α,Y]] damps exactly the two coherences that involve flavour α, and touches nothing else. Models E, F and G are single channel, hence NOT equivalent to SM dephasing.

Appendix B: Mirrored Domain

Parameter space contains at least two exact mirrors

Casas-Ibarra Parametrization

Complex conjugating Yukawa matrix yields $\eta_B \to -\eta_B$

$$\frac{\mathrm{d}Y_{\alpha\beta}}{\mathrm{d}z} = -\,\epsilon_{\alpha\beta}\,D(z)\left(Y_{N_1} - Y_{N_1}^{\mathrm{eq}}\right) - \tfrac{1}{2}\,W(z)\left\{P^0,\,Y\right\}_{\alpha\beta}$$

$$h \;\to\; \pm\,h^* \quad\Longrightarrow\quad P^0 \to P^{0\,*}, \qquad \epsilon_{\alpha\beta} \to -\,\epsilon^*_{\alpha\beta}$$

$$\text{Ansatz solution: } -\,Y^*(z)$$

$$\frac{\mathrm{d}Y^*_{\alpha\beta}}{\mathrm{d}z} = -\,\epsilon^*_{\alpha\beta}\,D(z)\left(Y_{N_1} - Y_{N_1}^{\mathrm{eq}}\right) - \tfrac{1}{2}\,W(z)\left\{P^0,\,Y\right\}^*_{\alpha\beta}$$

$$\eta_B \;\longrightarrow\; -\,\eta_B$$

Parameter mirrors — two parameter transformations result in $h \to \pm h^*$

- $(\delta, \alpha, Im[z]) \to (-\delta, -\alpha, -Im[z])$
- $(\delta, \alpha, Re[z]) \to (-\delta, 2\pi - \alpha, -Re[z])$
- Therefore: restrict $Im[z], Re[z] > 0$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\alpha/2} \end{pmatrix}$$

$$h = \frac{1}{v}\,U\sqrt{\hat{m}_\nu}\,R^{\mathsf{T}}\sqrt{M}$$

$$R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix}$$

Appendix C: Solver Validation

DMEs are stiff; large γ exacerbates the problem

Basic validation tests

Resolution of solver at various rtol, atol

- Compare solver defaults (rtol=1e-9, atol=1e-14) to tight tolerances (rtol=1e-11, atol=1e-16)
- 99-percentile relative deviation 7.12e-5 (marked on plots)

Evolution endpoint

- Compare zf = 1e4 with default 1e3
- 99-percentile relative deviation 1.77e-8

Evolution start point z0 = 1e-3 matches earlier starting values

Large γ runs match expected limit with coherences identically 0