Majorons Echoes of Leptogenesis

DPF- PHENO 2024

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2 Motivation

3 Model

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- If Baryon asymmetry generated from Leptogenesis, Lepton number violation required
- Assuming Lepton number violation generated by SSB of $U(1)_L$ global $\implies$ Irreducible Majoron Production
- If Majorons long lived, decay signatures observable today

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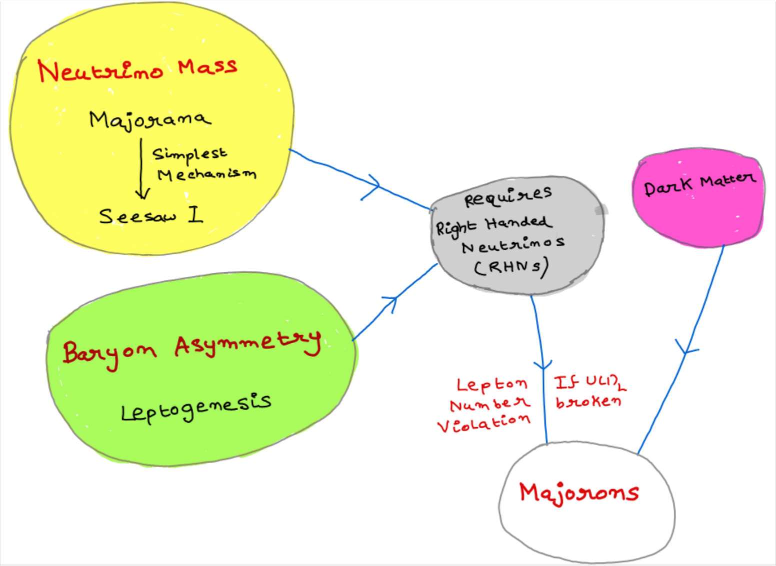

Killing three birds with one stone?

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Welcome to the singlet Majoron Model!

- $\mathcal{L}_{\text{int}} \supset \lambda \Phi NN + y_D LHN + h.c. + V(\Phi)$
- Scalar Φ (carries Lepton number), 3 SM singlet Majorana Neutrinos $N_{1,2,3}$
- $V(\Phi) = \kappa\left(\Phi^2 - f^2\right)^2$
- Has $U(1)_L$ global symmetry
- $U(1)_L$ spontaneously broken
- Φ gets a VEV

Cosmological Irreducible Majoron Production $\rightarrow$ Signatures of Leptogenesis ??

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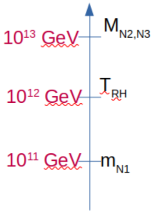
Leptogenesis I

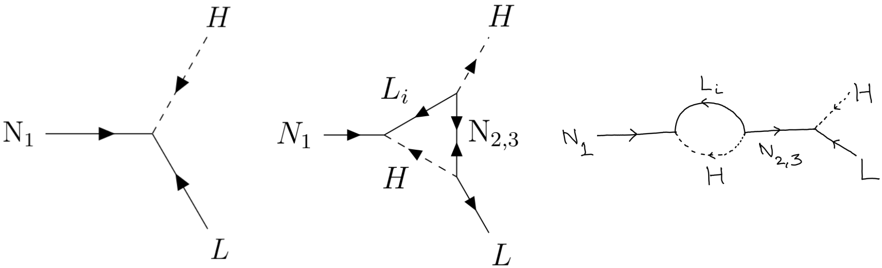
- Assumption-
  $m_{N2} = m_{N3} \geq 100 m_{N1}$



- Lepton asymmetry generated through N_1 decay out of equilibrium, converted to Baryon asymmetry through sphalerons [**M. Fukugita, T. Yanagida, 1986**]
- Decay quantified by parameter $K \equiv \frac{\Gamma_D}{H(T=m_{N_1})}$[**Buchmüller et al. 2005**]

Leptogenesis II

- CP violation

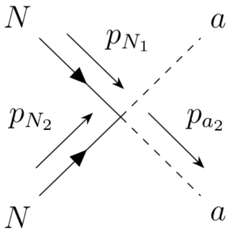


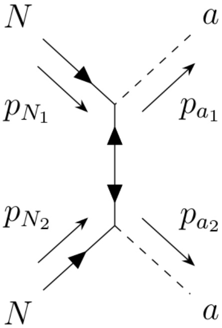
- Baryon asymmetry $\eta_B \equiv \frac{n_B}{n_\gamma} = \frac{3}{4}\frac{a_{sph}}{f}\varepsilon_1\kappa_f \simeq 0.96 \times 10^{-2}\varepsilon_1\kappa_f$
- ε_1, κ_f - Quantitative dependence on $K \equiv \frac{\Gamma_D}{H\left(T=m_{N_1}\right)}$

Majoron Production I

- Two dominant channels of Majoron production
  - $NN \to aa$
  - $NL \to Ha$

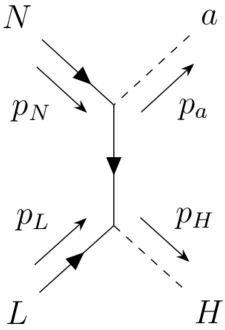
$$NN \to aa$$





Majoron Production II

$NL \to Ha$



- N in thermal bath → Freezes in irreducible Majoron density

Irreducible Majoron production I

- $m_\nu = \frac{{m_D}^2}{m_N}$
- $m_D = iU\sqrt{d_l}R^T\sqrt{d_h}$ **[J. Casas, A. Ibarra, 2001]**
- U- PMNS matrix, d_l=diag($m_{\nu_1}, m_{\nu_2}, m_{\nu_3}$), d_h=diag($m_{N_1}, m_{N_2}, m_{N_3}$), R- orthogonal matrix
- Majoron relic density at late times Y_a
    - Depends on mass of lightest active neutrino m_ν, Neutrino mass hierarchy, K, R matrix from Cassas-Ibarra Parameterization[1], m_{N_1} ($m_{N_2} = m_{N_3} = 100 m_{N_1}$)
    - Majoron yield minimized for Normal Hierarchy, $m_\nu = 0$,

$$R = \begin{pmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

Thus, these parameters fixed from now on

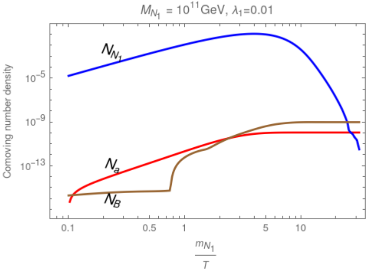
Irreducible Majoron production II

- Irreducible minimal Majoron relic density at late times

$$Y_a = 10^{-11}\left(\frac{10}{z_{eq}(K)}\right)\left(\frac{10^{11}}{M_{N_1}}\right)\times \tag{2}$$

$$\left(\frac{\lambda_1}{10^{-2}}\right)^2\left(1+33.3\left(\frac{\lambda_1}{10^{-2}}\right)^2\left(\frac{10^{11}}{M_{N_1}}\right)\right) \tag{3}$$

- $\lambda_1 = \frac{m_{N_1}}{\sqrt{2}f}$, f- $U(1)_L$ SSB scale



Majoron Decay

Decay channels at tree level

$a \rightarrow \nu\nu$

$\Gamma(a \rightarrow \nu\nu) \simeq \frac{m_a}{16\pi f^2} \sum_{i=1}^{3} {m_{\nu i}}^2$

[C. Garcia-Cely, J. Heeck, 2017]

Decay channel at two loops

$a \rightarrow \gamma\gamma$

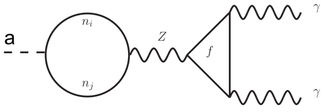


Figure 1: **[C. Garcia-Cely, J. Heeck, 2017]**,**[J. Heeck, H. Patel, 2019]**

Decay channels at one loop

$a \rightarrow \bar{f} f$

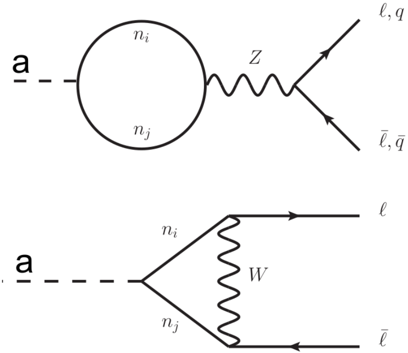


Figure 2: **[C. Garcia-Cely, J. Heeck, 2017]**

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Irreducible majoron relic as fraction of Dark Matter

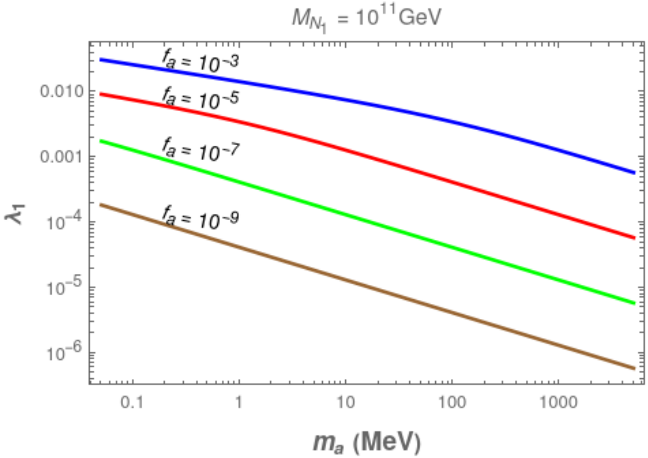

Figure 3: $f_a = \frac{\rho_a}{\rho_{\mathrm{DM}}}$, $\lambda_1 = \frac{m_{N_1}}{\sqrt{2}f}$, $f - U(1)_L$ SSB scale

Constraints from decay to photons: INTEGRAL

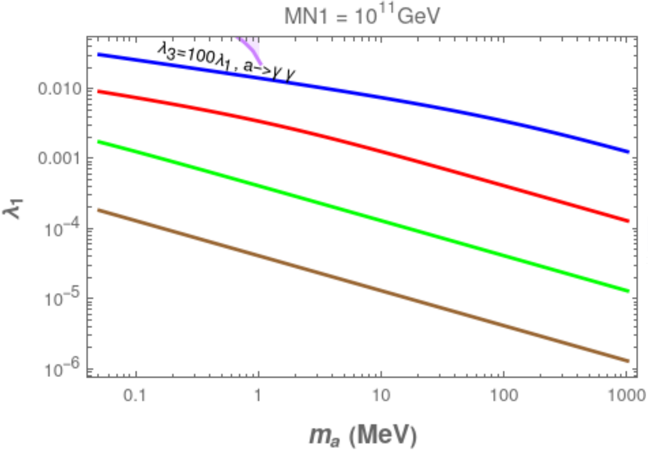

Figure 4: [K. Zurek et al., 2013]

Constraints from decay to e^+e^-: 511 KeV line INTEGRAL SPI

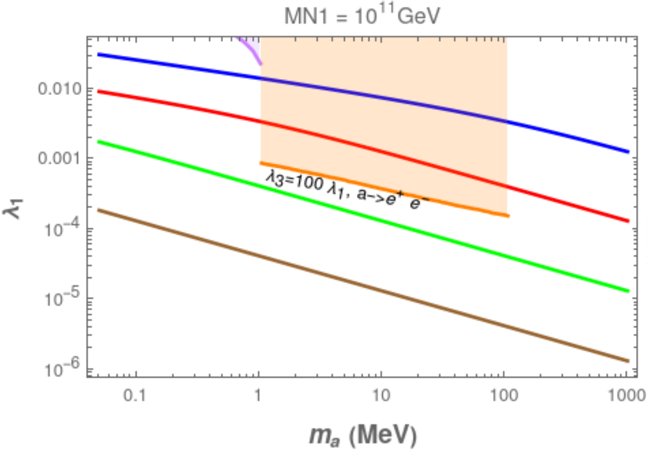

Figure 5: **[P.D. la Torre Luque, S. Balaji, J. Silk, 2024]**

Constraints from decay to e^+e^-: 511 KeV INTEGRAL SPI

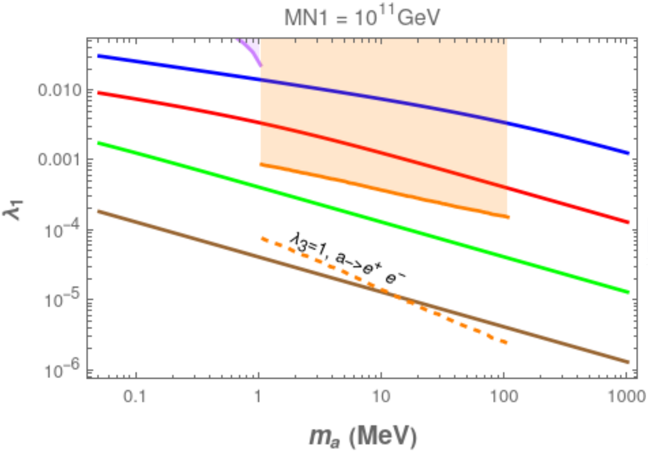

Figure 6: [**P.D. la Torre Luque, S. Balaji, J. Silk, 2024**]

CMB Constraints from decay to muons: From CMB anisotropy

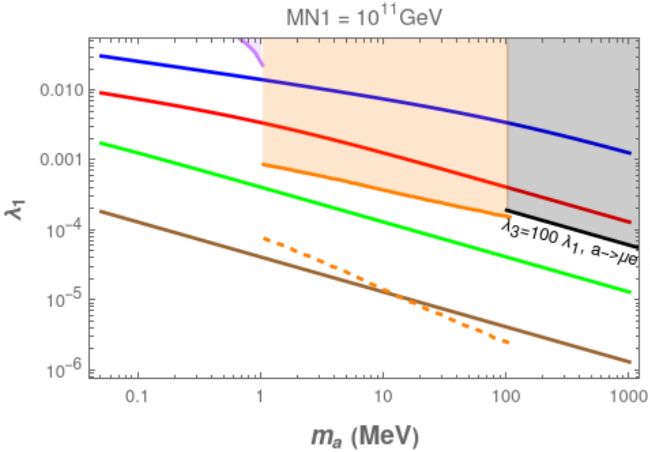

Figure 7: **[T.R. Slatyer, C.-L. Wu, 2017]**

CMB Constraints from decay to muons: From CMB anisotropy

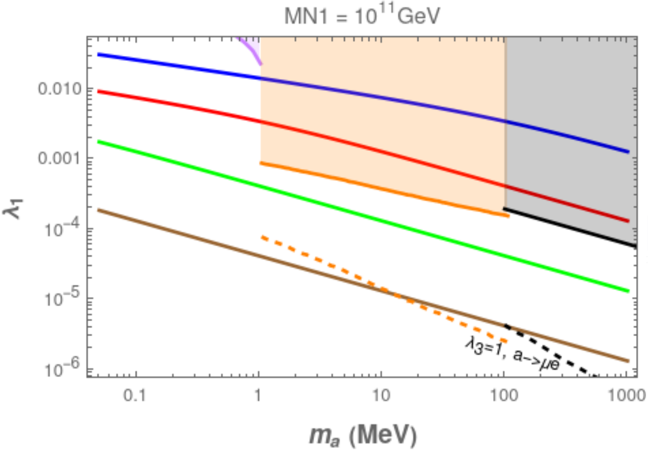

Figure 8: From CMB anisotropy induced by DM decay

- Plots are preliminary and we are working on decays into more channels which make the parameter space more constrained.
- Also, the above plots are being refined.

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Conclusion

- Leptogenesis signatures obtained from irreducible Majoron density
- Signatures observable in current experiments
- Certain parts of parameter space ruled out from current experiments

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References

[1] J. Casas and A. Ibarra, "Oscillating neutrinos and e,," *Nuclear Physics B*, vol. 618, no. 1–2, p. 171–204, Dec. 2001. [Online]. Available: http://dx.doi.org/10.1016/S0550-3213(01)00475-8

[2] M. Fukugita and T. Yanagida, "Baryogenesis Without Grand Unification," *Phys. Lett. B*, vol. 174, pp. 45–47, 1986.

[3] W. Buchmüller, P. Di Bari, and M. Plümacher, "Leptogenesis for pedestrians," *Annals of Physics*, vol. 315, no. 2, p. 305–351, Feb. 2005. [Online]. Available: http://dx.doi.org/10.1016/j.aop.2004.02.003

[4] C. Garcia-Cely and J. Heeck, "Neutrino lines from majoron dark matter," *Journal of High Energy Physics*, vol. 2017, no. 5, May 2017. [Online]. Available: http://dx.doi.org/10.1007/JHEP05(2017)102

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Backup I

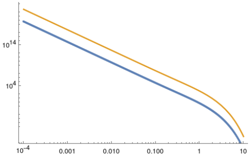

Figure 9: Dimensionless integral in $\gamma_{NN\to aa}$ (blue) and 1000* Interpolated function of $\gamma_{NN\to aa}$ vs z

Backup II

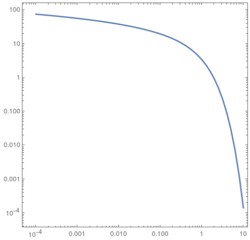

Figure 10: Dimensionless integral in $\gamma_{NL \to Ha}$ vs z

Backup III

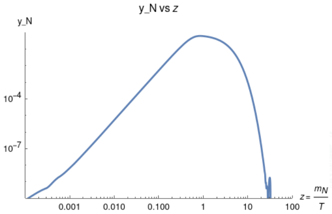

Figure 11: Evolution of N_1 starting from zero initial abundance

Singlet Majoron Model and Majoronic seesaw

- SM + 3 singlet Majorana neutrino + scalar $\sigma = \frac{(f+\sigma_0)e^{i\theta}}{\sqrt{2}}$, $\theta = \frac{a}{f}$
- f = Lepton Number breaking scale, σ_0= Heavy scalar
- $U(1)_L$ broken spontaneously
- $L = -\bar{L}yHN - \frac{1}{2}\bar{N}^C\kappa\sigma N$ +h.c.,
  SSB$\rightarrow \kappa\sigma \rightarrow M_R = \frac{\kappa f}{\sqrt{2}}, yH \rightarrow m_D = \frac{yv}{\sqrt{2}}$
- Mass term for active and sterile neutrinos

$$\begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

- For $M_R >> m_D$: $M_\nu \simeq -m_D M_R^{-1} m_D^T$

-

$$NN \to aa$$

- At tree level
  $\sum_{\text{spin} N1,N2} |\mathcal{M}_{NN\to aa}|^2 = \frac{|\lambda|^4 s}{8m_N^2} - \frac{5}{2}|\lambda|^4 + |\lambda|^4 \left\{ \frac{u-m_N^2}{t-m_N^2} + \frac{t-m_N^2}{u-m_N^2} \right\}$
- λ is the ΦNN coupling constant
- $\sigma \propto |\lambda|^4$
- Contribution to Boltzmann equation
  $\gamma_{NN\to aa} = \frac{T m_N^7}{2048\pi^5 f^4}\gamma^{\text{dimless}}_{NN\to aa}(z = \frac{m_N}{T})$
  $\Gamma_{NN\to aa} = 2\left(\frac{N}{N^{eq}}\right)^2 \gamma_{NN\to aa}$=Fudge factor $\times\gamma_{NN\to aa}$, Fudge factor=$2\left(\frac{N}{N^{eq}}\right)^2$

- $NL \to Ha$
  - At tree level
    $\sum_{spin} |\bar{M}|^2 = \frac{1}{4}\frac{\left(m_N^2 y_D^2\right)\left(u - m_L^2\right)}{f^2\left(t - m_N^2\right)}$
  - $\sigma \propto |\lambda|^2 {y_D}^2$
  - Assumption- One generation of L, one Majorana neutrino N
  - Contribution to Boltzmann equation
    $\gamma_{\mathrm{NL}\to\mathrm{Ha}} = \frac{T^4\left(m_N^2 y_D^2\right)}{(512\pi^5)f^2}\gamma_s\left(\frac{m_N}{T}\right)$
    $\gamma_s\left(\frac{m_N}{T}\right)$ dimensionless integral
  - $\Gamma_{\mathrm{NL}\to\mathrm{Ha}} = \left(\frac{N}{N_{eq}}\right)\gamma_{\mathrm{NL}\to\mathrm{Ha}} =$ Fudge factor $\times\gamma_{\mathrm{NL}\to\mathrm{Ha}}$, Fudge factor$= \left(\frac{N}{N_{eq}}\right)$
  - L in thermal equilibrium

- $a \to \bar{f} f$
  - $\Gamma(a \to \bar{q} q) \simeq \frac{3 m_\theta}{8\pi} \left| g^P_{Jqq'} \right|^2$
  - $\Gamma(a \to \bar{l} l') \simeq \frac{3 m_\theta}{8\pi} \left(\left| g^P_{Jll'} \right|^2 + \left| g^S_{Jll'} \right|^2 \right)$
  - $g^P_{Jll'} \simeq \frac{m_l + m_{l'}}{16\pi^2 \nu} \left(\delta_{ll'} {T_3}^l \mathrm{tr} K + K_{ll'} \right)$
  - $g^S_{Jll'} \simeq \frac{m_l - m_{l'}}{16\pi^2 \nu} K_{ll'}$
  - $g^P_{Jqq'} \simeq \frac{m_q}{8\pi^2 \nu} \delta_{qq'} {T_3}^q \mathrm{tr} K$
  - $g^S_{Jqq'} = 0$
  - ${T_3}^{d,l} = -\frac{1}{2} = -{T_3}^u$
  - $K = \frac{m_D {m_D}^\dagger}{vf}$

Casas-Ibarra Parameterization Incorporation I

- $y_D L H^\dagger N$ term generalized to 3 generation of Leptons and in principle, multiple generations of N
- Assume 3 generations of N
- Then, $y_D L H^\dagger N \to (y_D)_{ij} L_i H^\dagger N_j$, $i, j \in \{1, 2, 3\}$
- $(m_D)_{ij} = \frac{(y_D)_{ij} v}{\sqrt{2}}$
- $m_D = iU\sqrt{d_l} R^T \sqrt{d_h}$
- $d_l = \text{diag}\left(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\right), \;\; d_h = \text{diag}\left(m_{N_1}, m_{N_2}, m_{N_3}\right)$
- $R=$ complex Unitary matrix in general
- Our assumption- R= Identity, $m_{N_1} = m_N, m_{N_2} = m_{N_3} = f$

Casas-Ibarra Parameterization Incorporation II

- For $N_1 L \to Ha$, $\sum_{spin} |\mathcal{M}|^2 = \frac{\left(m_N^2 (y_{D1i})^\dagger y_{Di1}\right)\left(u - m_L^2\right)}{f^2\left(t - m_N^2\right)}$
  $= m_N^2 \left(y_D^\dagger y_D\right)_{11} \frac{\left(u - m_L^2\right)}{f^2\left(t - m_N^2\right)}$
- For normal ordering
  - $\sum_{i=1,2,3} \gamma_{N_1 L_i \to Ha} = \frac{T^4\left(m_N^3 m_\nu\right)}{(1024\pi^5)((f^2 v^2))} \gamma_s \left(\frac{m_N}{T}\right)$
  - m_ν mass of lightest active neutrino mass eigenstate (which is $m_{\nu 1}$ for NO)
- For inverted ordering
  - $\sum_{i=1,2,3} \gamma_{N_1 L_i \to Ha} = \frac{T^4\left(m_N^3 \sqrt{\Delta_{m_{32}}{}^2 - \Delta_{m_{21}}{}^2 + m_\nu^2}\right)}{(1024\pi^5)((f^2 v^2))} \gamma_s \left(\frac{m_N}{T}\right)$
  - m_ν mass of lightest active neutrino mass eigenstate (which is $m_{\nu 3}$ for IO)