# The Minimal Phantom Sector of the Standard Model

## Dirac Leptogenesis & Higgs Phenomenology

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# Clarification

- Minimal Lepton Number Conserving Phantom Sector
- "Phantom" $\rightarrow$ singlet under the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Simple model leading to interesting phenomenology:
  - Dirac Neutrino Masses
  - Dirac Leptogenesis
  - Higgs Phenomenology

# Outline

- Dirac Neutrino Masses
- Dirac Leptogenesis
- Higgs Phenomenology

# Model building

- Just 2 openings in the SM for renormalisable operators coupling SU(3)$_c\times$SU(2)$_L\times$U(1)$_Y$ singlet fields to SM fields[1]

- Higgs mass term: $H^\dagger H\ ?^*?$
- Lepton-Higgs Yukawa interaction: $\bar{L}\,\widetilde{H}\ ?_R$

- What would happen if we filled in the gaps?
- But, no evidence for $B-L$ violation yet, so could try to build a $B-L$ conserving model
- Will try to be "natural" in the 't Hooft and the aesthetic sense - couplings either $\mathcal{O}(1)$ or strictly forbidden

[1] B. Patt and F. Wilczek, hep-ph/0605188

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- Augment the SM with two SU(3)$_c\times$SU(2)$_L\times$U(1)$_Y$ singlet fields
  - a complex scalar $\Phi$
  - a Weyl fermion $s_R$

$$-\mathcal{L}_{\rm link} = \left(h_\nu\,\overline{l_L}\cdot\widetilde{H}\,s_R\;+\;{\rm H.c.}\right) - \eta\,H^\dagger H\;\Phi^*\Phi$$

$\widetilde{H} = i\sigma_2 H^*$,
$h_\nu$ and $\eta$ will be $\mathcal{O}(1)$,
$s_R$ carries lepton number $L = 1$.

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- Solution: Postulate the existence of a purely gauge singlet sector; add $\nu_R$ and $s_L$.

$$-\mathcal{L}_{\rm p} = h_{\rm p}\,\Phi\,\overline{s_L}\,\nu_R \;+\; M\,\overline{s_L}\,s_R \;+\; {\rm H.c.}$$

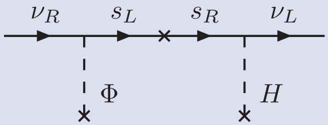
- Forbid other terms by imposing a “phantom sector” global $\mathrm{U}(1)_{\rm D}$ symmetry, such that only

$$\nu_R \to e^{i\alpha}\,\nu_R \quad , \quad \Phi \to e^{-i\alpha}\,\Phi$$

  transform non-trivially
- If we require small Dirac neutrino masses this is the simplest choice for the phantom sector

$$\mathcal{L} = \mathcal{L}_{\rm SM} \;+\; \mathcal{L}_{\rm link} \;+\; \mathcal{L}_{\rm p}$$

## Small effective Dirac neutrino masses – Dirac See-Saw




- Spontaneous breaking of both SU(2)$_L\times$U(1)$_Y$ and U(1)$_{\rm D}$ will result in the effective Dirac mass terms

$$-\mathcal{L} \supset \overline{\nu'_L}\,\mathbf{m}_\nu\,\nu'_R + \overline{s'_L}\,\mathbf{m_N}\,s'_R$$

assuming $M \gg v$ and where

$$\mathbf{m}_\nu = -v\,\sigma\,\mathbf{h}_\nu\,\hat{\mathbf{M}}^{-1}\,\mathbf{h}_{\rm p} \qquad\qquad \mathbf{m_N} = \hat{\mathbf{M}}$$

with $\sigma \equiv \langle\Phi\rangle$ and $v \equiv \langle H\rangle = 175$ GeV.

**Essentially the Froggatt-Nielsen mechanism!**

C. D. Froggatt and H. B. Nielsen, NPB**147**(1979)277.

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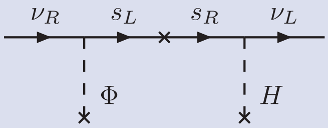


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M. Roncadelli and D. Wyler, PLB**133**(1983)325

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- Dirac Leptogenesis
- Higgs Phenomenology

We can measure the baryon asymmetry of the universe but do we understand where it came from?

**Sakharov's famous conditions**

- Baryon number violation
- C and CP violation
- Conditions out of thermal equilibrium

**Leptogenesis** is commonly cited as a possible explanation

- In the SM, $B + L$ violation occurs at high temperatures allowing a lepton asymmetry to be partially converted to a baryon asymmetry
- In the Majorana see-saw, lepton number and CP are generally violated in the decays of the heavy Majorana neutrinos
- These decays can occur out of thermal equilibrium

M. Fukugita and T. Yanagida, PLB**174**(1986)45

This model exactly conserves $B - L$, so it seems we cannot create a lepton asymmetry in the same way.
However

- $B + L$ violation in the SM does not directly affect right handed gauge singlet particles
- Small effective Yukawa couplings between the left and right handed neutrinos could prevent asymmetries in this sector from equilibrating
  - $L_{\nu_R}$ could "hide" from the rapid $B + L$ violating processes

V. A. Kuzmin, hep-ph/9701269
K. Dick, M. Lindner, M. Ratz and D. Wright, PRL**84**(2000)4039

*see also*: H. Murayama and A. Pierce, PRL**89**(2002)271601
S. Abel and V. Page, JHEP**0605**(2006)024
B. Thomas and M. Toharia, PRD**73**(2006)063512

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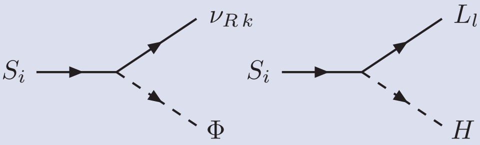
# Generation of the $L_{\nu_R}$ ($L_{\mathrm{SM}}$) asymmetry




$S \equiv s_L + s_R$

- Heavy particle decay – similar to Majorana leptogenesis
- In analogy with Davidson and Ibarra, the CP-asymmetry is bounded

$$|\delta_{R1}| \lesssim \frac{1}{16\pi} \frac{M_1}{v\,\sigma} (m_{\nu_3} - m_{\nu_1})$$

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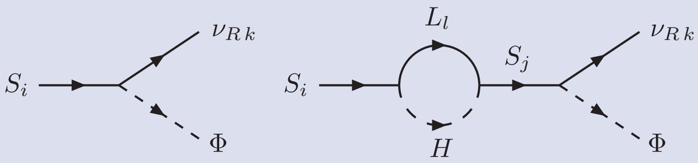


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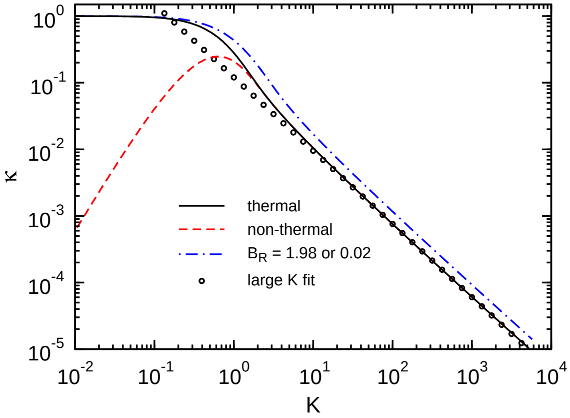
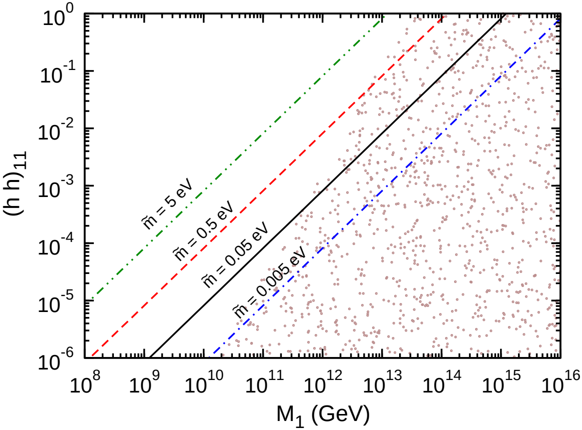



Leptogenesis efficiency, $\kappa$, versus $K$ for thermal and zero initial abundance of $S_1$ ($\bar{S}_1$). Also shown is the efficiency for differing left-right branching ratios.




Area in the $M_1$, $(\mathbf{h}^\dagger\mathbf{h})_{11}$ parameter space allowed by successful baryogenesis when $(\mathbf{h}_\nu^\dagger\mathbf{h}_\nu)_{11} = (\mathbf{h}_\mathrm{p}\mathbf{h}_\mathrm{p}^\dagger)_{11}$ and $\sigma = v = 175$ GeV.

- If we take a 'natural' scenario with $(\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{11} = (\mathbf{h}_\mathrm{p} \mathbf{h}_\mathrm{p}^\dagger)_{11} \simeq 1$ and $\widetilde{m} = 0.05$ eV (hierarchical light neutrinos) we can use the bound on the CP-asymmetry and the observed baryon asymmetry to put a bound on $\sigma$

$$\sigma \gtrsim 0.1 \text{ GeV}$$

- If we require that $S_1$ be produced thermally after inflation there exists an approximate bound $M_1 \lesssim T_{RH}$.
- Given the same reasonable assumptions, this implies an approximate upper bound on $\sigma$

$$0.1 \text{ GeV} \;\lesssim\; \sigma \;\lesssim\; 2 \text{ TeV} \left( \frac{T_{RH}}{10^{16} \text{ GeV}} \right)$$

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The potential of the neutral scalars in the model reads

$$V = \mu_H^2 H^* H + \mu_\Phi^2 \Phi^* \Phi + \lambda_H (H^* H)^2 + \lambda_\Phi (\Phi^* \Phi)^2 - \eta H^* H \Phi^* \Phi$$

where $H \equiv H^0$

- After spontaneous breaking of U(1)$_{\mathrm{D}}$, $\Phi$ will develop a non-zero vev, and this through the $\eta$ term would trigger electroweak SU(2)$_L\times$U(1)$_Y$ symmetry breaking
- Expanding the fields around their minima

$$H = v + \frac{1}{\sqrt{2}}(h + iG) \quad , \quad \Phi = \sigma + \frac{1}{\sqrt{2}}(\phi + iJ)$$

- We have
  - the Goldstone bosons: $G$ (eaten...) and $J$
  - $h$ and $\phi$ mix (due to the $\eta$ term) and become two massive Higgs bosons $H_1$ and $H_2$

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$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = O \begin{pmatrix} h \\ \phi \end{pmatrix} \quad \text{with} \quad O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

and the mixing angle

$$\tan 2\theta = \frac{\eta v \sigma}{\lambda_\Phi \sigma^2 - \lambda_H v^2}$$

- The limits $v \ll \sigma$ and $\sigma \ll v$ both lead to the SM with an isolated hidden sector
- These limits need an unnaturally small $\eta$, and would present problems with baryogenesis and small neutrino masses.
- A ‘natural’ choice of parameters would be

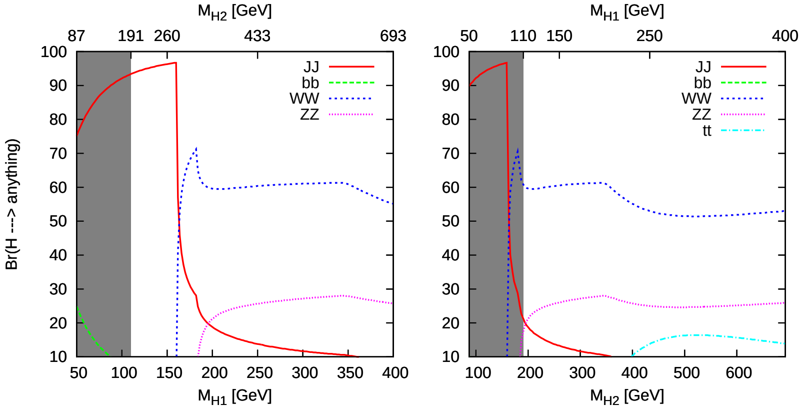
$$\lambda_H \sim \lambda_\Phi \sim \eta \sim 1 \quad , \quad \tan\theta \sim 1 \quad , \quad \tan\beta \equiv v/\sigma \sim 1$$

- $h = O_{i1} H_i$ – the couplings of the Higgs bosons $H_i$ to SM fermions and gauge bosons will be reduced by a factor $O_{i1}$ (relative to the SM)
- $H_i$ will also couple to the massless Goldstone pair $JJ$
- For light Higgs masses $\lesssim$ 160 GeV, in the SM the $H \to b\bar{b}$ decay mode dominates. Here we find a different picture:

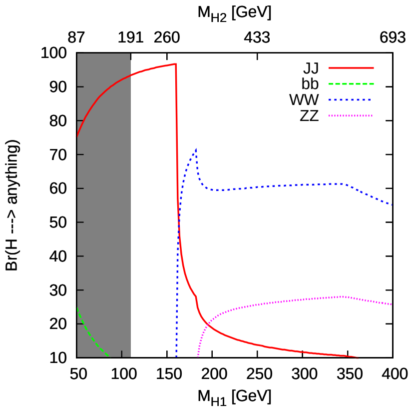
$$\frac{\Gamma(H_1 \to JJ)}{\Gamma(H_1 \to bb)} = \frac{1}{48}\left(\frac{m_{H1}}{m_b}\right)^2 \tan^2\beta \, \tan^2\theta$$

$$\frac{\Gamma(H_2 \to JJ)}{\Gamma(H_2 \to bb)} = \frac{1}{48}\left(\frac{m_{H2}}{m_b}\right)^2 \tan^2\beta \, \cot^2\theta$$

- In this model a 'light' Higgs boson will decay dominantly into invisible $JJ$ as long as it is heavier than 60 GeV.




Dominant branching ratios of the two Higgs bosons $H_1$ (left) and $H_2$ (right) for the parameters $\theta = \beta = \pi/4$, with couplings equal to one. The shaded area is excluded by LEP.




- LEP excludes a light invisible Higgs with a mass $m_{H1} \lesssim$ 110 GeV.
- It therefore sets a lower bound on the heavier Higgs $m_{H2} \gtrsim$ 191 GeV.

- There is a mass region

$$110 \lesssim m_{H1} \lesssim 160 \ \ \mathrm{GeV}$$

where $H_1$ decays to invisible $JJ$ with $\mathrm{Br}(H_1 \to JJ) > 90\%$.

- How could this Higgs be found at the LHC?

S. G. Frederiksen, N. Johnson, G. L. Kane and J. Reid, PRD**50**(1994)4244
R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy, PLB**571**(2003)184
K. Belotsky, V. A. Khoze, A. D. Martin and M. G. Ryskin, EPJC**36**(2004)503
H. Davoudiasl, T. Han and H. E. Logan, PRD**71**(2005)115007

- Strategies:
  - $Z + H_1$
  - $W$-boson fusion
  - central exclusive diffractive production

# $Z(\to l^+l^-) + H_{\text{inv}}$

using H. Davoudiasl, T. Han and H. E. Logan, PRD**71**(2005)115007

- multiply $S/\sqrt{B}$ by $1/2$ because of mixing
- assume LHC integrated luminosity of 30$\text{fb}^{-1}$

**Signal significance for discovering the invisible $H_1$ is**

- $m_{H1}$ = 120 GeV 4.9$\sigma$
- $m_{H1}$ = 140 GeV 3.6$\sigma$
- $m_{H1}$ = 160 GeV 2.7$\sigma$

- Although this applies to $\theta = \pi/4$, the situation is rather generic in this region
- Note that for $m_{H1} \lesssim$ 140 GeV, the $H_1 \to \gamma\gamma$ channel may still be usable.

# Summary

- Proposed a minimal, $L$ conserving, phantom sector of the SM leading to
  - Viable Dirac neutrino masses
  - Successful baryogenesis (through Dirac leptogenesis)
  - Interesting ‘invisible’ Higgs phenomenology for the LHC
- $\mathcal{O}(1)$ couplings, correct neutrino masses and baryogenesis seem to suggest an electroweak scale vev in the minimal phantom sector
- Phantom $U(1)_{\mathrm{D}}$ symmetry breaking at this scale would trigger consistent electroweak symmetry breaking

# Other Astro/Cosmo Constraints

$H_i$ couples to $JJ$ as

$$-\mathcal{L}_J \supset \frac{(\sqrt{2}G_F)^{1/2}}{2} \tan\beta \, O_{i2} \, m_{H_i}^2 \; H_i \, JJ$$

- After electroweak/$\mathrm{U(1)_D}$ symmetry breaking the $J$s are kept in equilibrium via reactions of the sort $JJ \leftrightarrow f\bar{f}$ mediated by $H_i$
- A GIM-like suppression exists for these interactions from the orthogonality condition $\sum_i O_{i1} O_{i2} = 0$
- $J$ falls out of equilibrium just before the QCD phase transition and remains as an extra relativistic species thereafter

- BBN/CMB yield a bound on the effective number of neutrino species $N_\nu = 3.24 \pm 1.2$ (90% C.L.)
- Early decoupling of $J$ implies $T_J$ is much lower than $T_\nu$

$$\left(\frac{T_J}{T_\nu}\right)^4 = \left(\frac{g_*(T_\nu)}{g_*(T_D)}\right)^{4/3} \lesssim \left(\frac{10.75}{60}\right)^{4/3}$$

- The increase in the effective number of light neutrinos, due to $J$, at BBN $\Delta N_\nu^J$ is then

$$\Delta N_\nu^J = \frac{4}{7}\left(\frac{T_J}{T_\nu}\right)^4 \lesssim 0.06$$