A prototype model for **quasi-Dirac neutrinos**

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Collaborators: K. Earl, T. Gregoire, A. Tonero ...
[CSF, Gregoire, Tonero, 2007.09158] [Earl, CSF, Gregoire, Tonero, 1903.12192]

We need New Physics

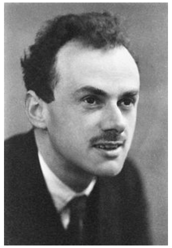
1) Neutrino mass $m_\nu^{\rm obs} \sim 0.05\,{\rm eV}$ (**Dirac** or **Majorana**)

2) Cosmic matter-antimatter asymmetry $Y_B^{\rm obs} \sim 10^{-10}$

3) Dark matter $Y_{\rm DM}^{\rm obs} \sim 5 \times 10^{-10} \left(\frac{1\,{\rm GeV}}{m_{\rm DM}} \right)$

$m_M \bar{\nu}_L \nu_L^c$

$m_D \bar{\nu}_L \nu_R$



Or somewhere in between

Theoretical puzzles: 3-generation fermions, higgs mass stability, hypercharge quantization, no strong CP violation

Neutrino mass

At renormalized level, strictly massless

If we look further ... $\frac{\lambda}{\Lambda}\bar{\ell}_L \tilde{H} \ell_L^c \tilde{H}$ $\Longrightarrow m_M \bar{\nu}_L \nu_L^c$ $m_M = \frac{\lambda v^2}{\Lambda}$

[Photo by Jeff Wilson http://www.jeffwilsonphoto.com/]

Majorana

- Explain lightness
- B-L violation
- L violation (0νββ)

Neutrino mass

To have a **Dirac mass**, need **light degrees of freedom**

$$m_D \bar{\nu}_L \nu_R$$

- Singlet under SM
- B-L is conserved
- L is conversed ~~(0νββ)~~

New symmetr(ies) needed to forbid $M\bar{\nu}_R^c \nu_R$

Can be realized at renormalized level $y\bar{\ell}_L \tilde{\Phi} \nu_R$ New Higgs doublet

Why so **light**? $y\langle\Phi\rangle \ll v$

Let us look further again

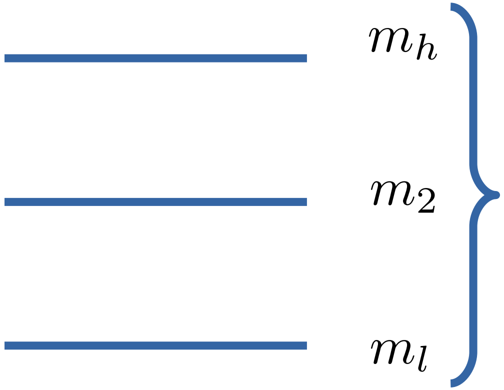
$$\frac{1}{\Lambda}\bar{\ell}_L \tilde{H} \nu_R \phi \quad \Longrightarrow \quad \frac{\lambda v \langle\phi\rangle}{\Lambda}\bar{\nu}_L \nu_R$$

$$\frac{1}{\Lambda}\bar{\ell}_L \tilde{H} \ell_L'^c \tilde{H}' \quad \Longrightarrow \quad \frac{\lambda v v'}{\Lambda}\bar{\nu}_L \nu_L'^c$$

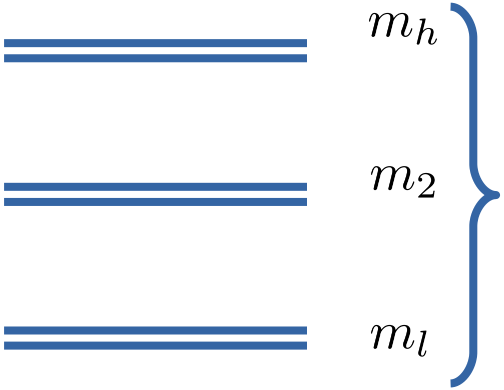
Neutrino mass

We can also have somewhere in between

Light neutrino mass spectrum (not to scale)



Two of them can form a **pseudo-Dirac** pair (excluded)



Each form a **quasi-Dirac** pair (limits exist)

Majorana: only 3 light d.o.f.*

Dirac: 2 or 3 more light d.o.f.

Majorana: 2 or 3 more light d.o.f.

Nomenclature of [Anamiati,Fonseca, Hirsch, 1710.06249]

Sorry, **Yuber Perez** (see his talk)

A Dirac seesaw model

Extended **gauge** symmetries $SU(2) \times U(1) \times SU(2)' \times U(1)'$

$$-\mathcal{L} \supset M_{ab} \bar{N}'^{c}_{Ra} N_{Rb} + y_{\alpha a} \bar{l}_{L\alpha} \tilde{H} N_{Ra} + y'_{\alpha a} \bar{l}'_{L\alpha} \tilde{H}' N'_{Ra} + \text{H.c.}$$

$a, b = 1, 2, ..., N_f$ [Gu, 1209.4579] [Earl, CSF, Gregoire, Tonero, 1903.12192]

For anomaly cancellation, quarks prime have to be introduced

Perturbative level $L_{\text{tot}} = L - L'$

$$L_{\text{tot}}(l_{L\alpha}) = L_{\text{tot}}(N_{Ra}) = -L_{\text{tot}}(l'_{L\alpha}) = -L_{\text{tot}}(N'_{Ra})$$

Quantum level $\boxed{\Delta_{\text{tot}} = B - B' - L_{\text{tot}}}$

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After EW & EW' breaking

$$(\bar{\nu}_L \ \bar{N}'^{c}_R) \begin{pmatrix} 0 & vy \\ v'y'^T & M \end{pmatrix} \begin{pmatrix} \nu'^{c}_L \\ N_R \end{pmatrix}$$

Dirac seesaw formula

$$\boxed{\mathcal{M}_\nu^D \simeq -vv' y M^{-1} y'^T}$$

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We have conserved $\Delta_{\mathrm{tot}} = B - B' - L_{\mathrm{tot}}$

Can we generate a cosmic baryon asymmetry through **leptogenesis**?

Yes! $$\sum_\alpha Y_{B/3-L_\alpha} - \sum_\alpha Y_{B'/3-L'_\alpha} - \sum_a Y_{\Delta N_a} = 0$$

$$\boxed{\sum_\alpha Y_{B/3-L_\alpha} = \sum_\alpha Y_{B'/3-L'_\alpha} \neq 0} \quad \Bigg\} \quad \begin{array}{l} Y_B = \kappa Y_{B-L} \\ \boxed{Y'_B = \kappa' Y_{B-L}} \end{array}$$

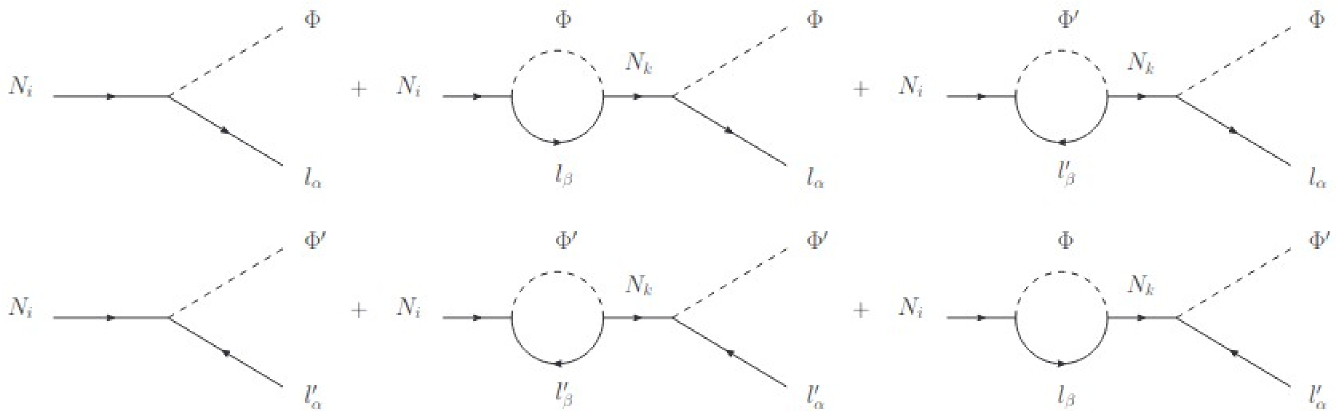
Asymmetric Dark Matter

A Dirac seesaw model: leptogenesis

From heavy N decays [Gu, 1209.4579] [Earl, CSF, Gregoire, Tonero, 1903.12192]

CPT: $$\sum_\alpha [\Gamma(N_a \to \ell_\alpha H) - \Gamma(\bar{N}_a \to \bar{\ell}_\alpha H^*)] = \sum_\alpha [\Gamma(\bar{N}_a \to \ell'_\alpha H') - \Gamma(N_a \to \bar{\ell}'_\alpha H'^*)]$$

$$\sum_\alpha \epsilon_{a\alpha} = \sum_\alpha \epsilon'_{a\alpha}$$



$\Phi = H, \Phi' = H'$

$i, k, a = 1, 2, ..., N_f$

Require $N_f \geq 2$

A Dirac seesaw model: leptogenesis

From heavy N decays [Gu, 1209.4579] [Earl, CSF, Gregoire, Tonero, 1903.12192]

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$$\sum_\alpha \epsilon_{a\alpha} = \sum_\alpha \epsilon'_{a\alpha}$$

We obtain analogous of **Davidson-Ibarra bound**

$$\boxed{\left|\sum_\alpha \epsilon_{a\alpha}\right| \leq \frac{M_1 |m_3^2 - m_1^2|}{16\pi(m_3 + m_1)vv'}}$$

High scale leptogenesis $M_1 \gtrsim 10^6 \,\mathrm{GeV}$

A **quasi-Dirac** seesaw model

Introducing small violation of $\Delta_{\rm tot} = B - B' - L_{\rm tot}$ [CSF, Gregoire, Tonero, 2007.09158]

$$-\mathcal{L} \supset \frac{1}{2} m_{ab} \bar{N}^c_{Ra} N_{Rb} + \frac{1}{2} m'_{ab} \bar{N}'^c_{Ra} N'_{Rb} + \tilde{y}_{\alpha a} \bar{l}_{L\alpha} \tilde{H} N'_{Ra} + \tilde{y}'_{\alpha a} \bar{l}'_{L\alpha} \tilde{H}' N_{Ra} + \text{H.c.}$$

$$\boxed{m, m' \ll M, \qquad \tilde{y}, \tilde{y}' \ll y, y'}$$

Can arise from spontaneously broken $U(1)_{\Delta_{\rm tot}}$

$$\frac{\phi^2}{\Lambda} \bar{N}^c_R N_R \qquad \frac{\phi^{*2}}{\Lambda} \bar{N}'^c_R N'_R \qquad \frac{\phi^{*2}}{\Lambda^2} \bar{l}_L \tilde{H} N'_R \qquad \frac{\phi^2}{\Lambda^2} \bar{l}'_L \tilde{H}' N_R$$

Even if no “soft” breaking $m, m' = 0$

$$\delta m \sim \frac{(y\tilde{y}^\dagger + \tilde{y}' y'^T) M}{8\pi^2} \qquad \delta m' \sim \frac{M(\tilde{y}'^\dagger y' + y^T \tilde{y})}{8\pi^2}$$

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Many new parameters!

We can consider some symmetries [Lee & Yang, Phys.Rev. 104 (1956) 254-258]

[Berezinsky, Narayan, Vissani, hep-ph/0210204] [Berezhiani, hep-ph/0312335]

$$Z_{2M} : \Psi_{L,R}(t,\vec{x}) \leftrightarrow \Psi'_{R,L}(t,-\vec{x})$$

$$M = M^\dagger \qquad m^* = m' \qquad y^* = y' \qquad \tilde{y}^* = \tilde{y}'$$

$$Z_{2D} : \Psi_{L,R} \leftrightarrow \Psi'_{L,R}$$

$$M = M^T \qquad m = m' \qquad y = y' \qquad \tilde{y} = \tilde{y}'$$

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Heavy quasi-Dirac N

$$\mathcal{M} = \begin{pmatrix} m & M^T \\ M & m' \end{pmatrix}$$

$$M_a^{\mp 2} = M_a^2 \mp \delta M_a^2 \qquad \delta M_a^2 \sim M_a^2 \times \frac{|m' + m^*|}{M_a}$$

Resonant leptogenesis from each quasi-Dirac pair

See **Juan Racker**'s talk

CP violation for leptogenesis is bounded

$$\boxed{|\epsilon_a| \lesssim \frac{\max(|\tilde{y}|, |\tilde{y}'|)}{\max(|y|, |y'|)}}$$

Nonzero for each generation

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Light quasi-Dirac ν

$$\mathcal{M}_\nu \simeq -\mathcal{M}_D \mathcal{M}^{-1} \mathcal{M}_D^T \qquad \mathcal{M}_D = \begin{pmatrix} vy & v\tilde{y} \\ f\tilde{y}' & fy' \end{pmatrix}$$

$$m_a^\mp = m_a \mp \delta m_a \qquad m_a \sim \frac{|yy'|vv'}{M_a} \qquad \delta m_a \sim m_a \times \frac{|y^* \tilde{y}^* v^2 + y' \tilde{y}' v'^2|}{|yy'|vv'}$$

Quasi-Dirac seesaw mechanism

A **quasi-Dirac** seesaw model

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We can connect “high” and low scale observables

1) Resonant leptogenesis ends by T > 132 GeV $\quad M_a, |\epsilon_a| \lesssim \frac{\delta m_a}{2 m_a}$

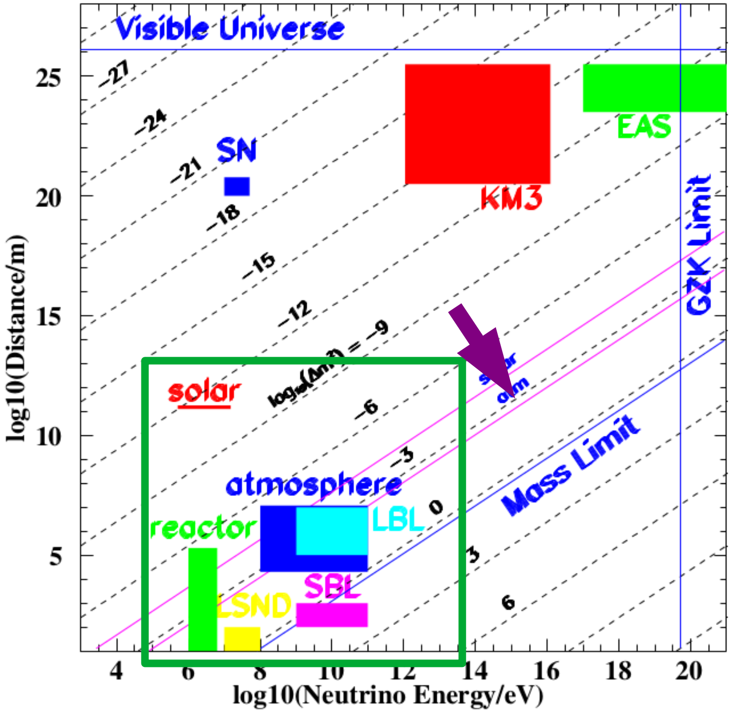
$$Y_B^{\text{obs}} \sim 10^{-10} \qquad |\epsilon_a| \gtrsim 10^{-6} \implies \delta m_a \gtrsim 10^{-7}\,\text{eV} \left(\frac{m_a}{0.05\,\text{eV}} \right)$$

2) Mass splitting that can be observed at low scale

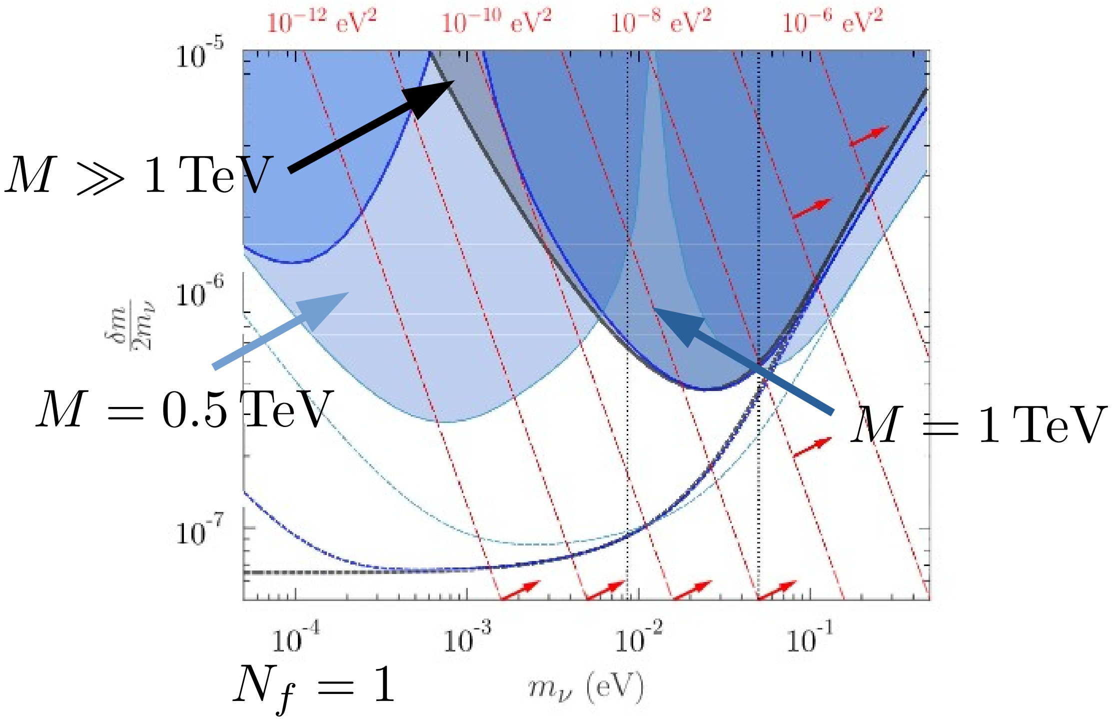
$$\varepsilon_a^2 \equiv m_a^{+2} - m_a^{-2} = 4 m_a \delta m_a \gtrsim 2 \times 10^{-8}\,\text{eV}^2$$

A **quasi-Dirac** seesaw model

Overlapping parameter space with **neutrino oscillation experiments**



[Beacom et al., hep-ph/0307151]



[CSF, Gregoire, Tonero, 2007.09158]

A **quasi-Dirac** seesaw model

On-going effort to identify all the viable parameter space for experimental searches

1) Start with Dirac seesaw parametrization

$$y = \frac{i}{\sqrt{vv'}} U_\nu^* D_{\sqrt{m}} X D_{\sqrt{M}} \qquad y' = \frac{i}{\sqrt{vv'}} V_\nu^* D_{\sqrt{m}} (X^{-1})^T D_{\sqrt{M}}$$

$$Z_{2M} : y = y'^* \implies V_\nu = -U_\nu^*,\ X^{-1,\dagger} = X$$ Complex orthogonal

$$Z_{2D} : y = y' \implies V_\nu = U_\nu,\ X^{-1,T} = X$$ Hermitian

2) Generate $\tilde{y}, \tilde{y}' \ll y, y'$, $\boxed{\delta m, \delta m'} \lesssim m, m' \ll M$ Radiative contributions

3) Verify $Y_B^{\text{obs}} \sim 10^{-10}$

4) Verify if consistent with experimental constraints $\delta m_a, \theta_k, \delta_k$ $(a = 1, 2, 3)$ $(k = 1, ..., 9)$

*Previous results apply for each generation if m, m', M are all diagonal

Outlook

- Light neutrinos can be **quasi-Dirac** with a large parameter space to be explored
- We present a “prototype” model with **quasi-Dirac seesaw mechanism**
- “**Baryogenesis miracle**”: parameter space consistent with leptogenesis can be probed in neutrino oscillation experiments
- Inputs are welcome: how to constraint the parameter space with neutrino oscillation experiments or other observables