Neutrinos and Abelian Gauge Symmetries

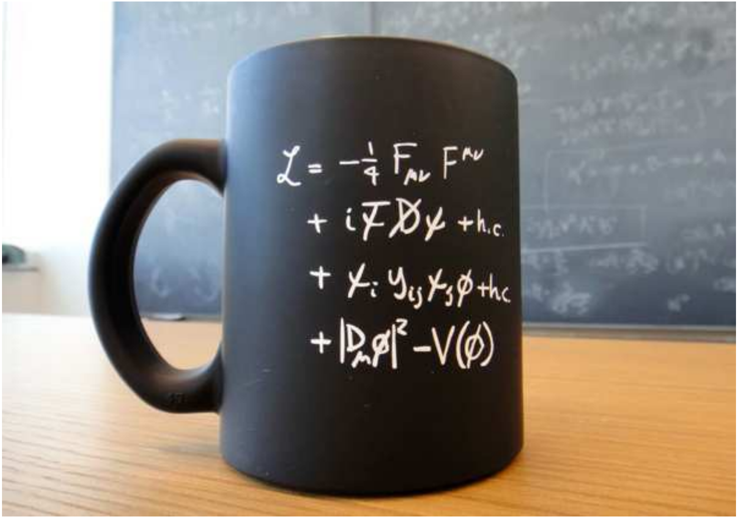
Julian Heeck

24.10.2014 – ULB

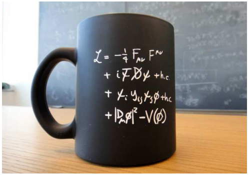
UNIVERSITÉ LIBRE DE BRUXELLES

Standard Model of Particle Physics

Beautiful and simple:



Standard Model of Particle Physics



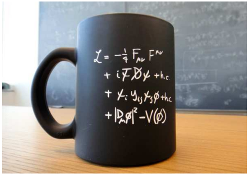
Not shown:

- Gauge group $SU(3)_{\text{color}} \times SU(2)_{\text{isospin}} \times U(1)_{\text{hypercharge}}$;
  $\Rightarrow 8 + 3 + 1$ spin-1 bosons with field strength $F_{\mu\nu}$,
- Three copies of spin-$\frac{1}{2}$ Weyl fields (families/generations) in rep.

$$\Psi_{1,2,3} \sim \underbrace{(\mathbf{3}, \mathbf{2}, \tfrac{1}{6}) \oplus (\mathbf{3}, \mathbf{1}, -\tfrac{2}{3}) \oplus (\mathbf{3}, \mathbf{1}, \tfrac{1}{3})}_{\text{quarks}} \oplus \underbrace{(\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) \oplus (\mathbf{1}, \mathbf{1}, 1)}_{\text{leptons}},$$

- One complex spin-0 field $\phi \sim (\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ which breaks $SU(2) \times U(1) \to U(1)_{\text{EM}}$ via $\langle \phi \rangle \simeq 250\,\text{GeV}$.
- About 18 free parameters, all measured as of 2013 (Brout–Englert–Higgs boson mass).

Standard Model of Particle Physics



Also not shown (because beyond SM):

- Neutrinos have mass and mix.
- Dark matter.
- Baryon asymmetry of our Universe.

Symmetries of the Standard Model

- $\mathcal{L}_{\text{SM}}$ renormalizable $\Rightarrow$ only mass dimension ≤ 4 couplings.
- $\mathcal{L}_{\text{SM}}$ invariant under phase shifts of quarks and individual leptons.

$U(1)^4$: B, L_e, L_μ, and L_τ classically conserved in the Standard Model.

- Nonperturbative instanton/sphaleron solutions break $\Delta(B+L)=6$.

$U(1)_{B-L} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}$ *global* symmetry of quantum SM.

- After introducing three right-handed neutrinos ν_R:

$U(1)_{B-L} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}$ anomaly free *local* symmetry.[1]

(Neutrinos automatically massive due to ν_R.)

Breaking $\Rightarrow$ neutrino nature, hierarchies, mixing, baryon asymmetry,...

[1] J.H., T. Araki, J. Kubo, JHEP **1207** (2012) [arXiv:1203.4951].

Outline

Neutrinos and abelian gauge symmetries

$$\underbrace{\overbrace{\underbrace{U(1)_{B-L}}_{\text{unflavored}} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}}^{\text{flavored}}\;\underbrace{\qquad\quad}_{\text{dark}}}\,.$$

Typically simple models:

- Few new particles and parameters.
- Renormalizable.
- Z' gives additional pheno.

Baryon and Lepton Number

- B and L classically conserved in the Standard Model.
- $B+L$ theoretically broken non-perturbatively: $\Delta(B+L)=6$.
- $B-L$ *globally* conserved.

Fate of fundamental $U(1)_{B-L}$ from **experiments**.
Linked to neutrino nature and matter–antimatter asymmetry.

- $B-L$ *locally* conserved after adding three ν_R.
  $\Rightarrow$ Neutrinos massive!

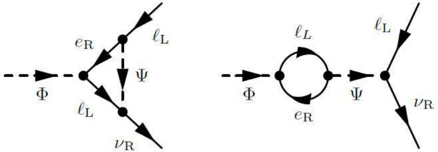
Three possibilities for (local) $U(1)_{B-L}$:

1. Unbroken $B-L$: Dirac neutrinos + neutrinogenesis.
2. Majorana $B-L$: $\Delta(B-L)=2$, Majorana ν + leptogenesis.
3. Dirac $B-L$: $\Delta(B-L)=n\neq 2$, Dirac ν + Dirac leptogenesis.

Unbroken $B-L$

Almost[2] never considered, but very simple:[3]

- Neutrinos are Dirac, with Yukawa couplings $Y_\nu \sim m_\nu/\langle H\rangle \lesssim 10^{-11}$.
- Baryon asymmetry via neutrinogenesis:[4]
  - New heavy scalar doublets decay so that $\Delta(B-L) = \Delta L = 0$, but $\Delta L_{\rm left} = -\Delta L_{\rm right} \neq 0$.



  - Right-handed ν_R not thermalized due to tiny Yukawas.
    $\Rightarrow$ Sphalerons only see $\Delta L_{\rm left}$, generate ΔB via $\Delta(B+L) = 6$!

---

[2] D. Feldman, P. Fileviez Perez, and P. Nath, arXiv:1109.2901.
[3] J.H., arXiv:1408.6845.
[4] K. Dick, M. Lindner, M. Ratz, and D. Wright, arXiv:hep-ph/9907562.

Signatures

- No $0\nu2\beta$ or other $\Delta(B-L) \neq 0$ processes...
- Z' with tiny coupling $\alpha' \lesssim 10^{-50}$ or Stückelberg mass $M_{Z'}$:
  - Introduce *real* scalar σ with gauge trafo $\sigma \to \sigma + M_{Z'}\theta(x)$.

$$\Delta\mathcal{L} = \tfrac{1}{2}\left(M_{Z'}Z'^{\mu} + \partial^{\mu}\sigma\right)\left(M_{Z'}Z'_{\mu} + \partial_{\mu}\sigma\right)$$

  is gauge invariant ($Z'_\mu \to Z'_\mu - \partial_\mu\theta$).
  - Mass term $\frac{1}{2}M_{Z'}^2 Z'_\mu Z'^\mu$ is just gauge fixing, not breaking.

Abelian gauge bosons can have a mass without symmetry breaking.

- $M_{Z'}/g'$ not connected to m_ν or leptogenesis $\Rightarrow$ no preferred scale!
- Limits from modified gravity, stellar energy losses, scattering/collider experiments, and Big Bang nucleosynthesis ($\overline{\nu}_R\gamma^\mu\nu_R Z'_\mu$).

$\Rightarrow$ Unbroken (local) $B-L$ perfectly valid![5]

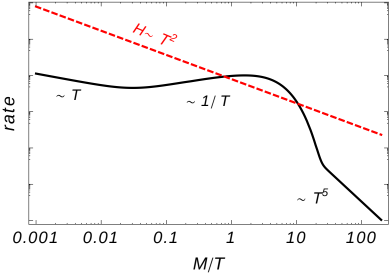
[5] J.H., arXiv:1408.6845.

Big Bang Nucleosynthesis

- ν_R are light (Dirac neutrinos) $\rightarrow N_{\text{eff}} \simeq 6$ for strong Z' interactions.
- Light Z' also contributes to N_{eff}.
- BBN ($T \sim 1\,\mathrm{MeV}$) limit: $N_{\text{eff}} < 4$ at 95% C.L.[6]

Thermally averaged rate via Z':

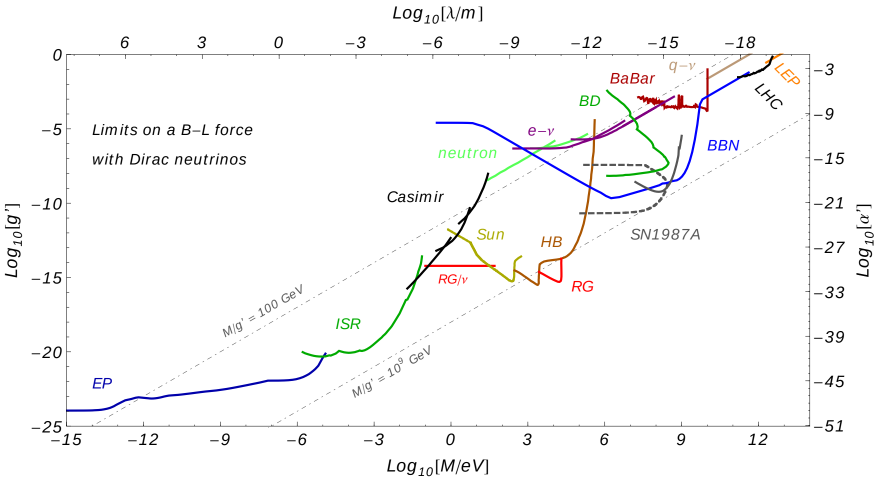
$$\langle\Gamma(\overline{f}f \leftrightarrow \overline{\nu}_R\nu_R)\rangle \propto \begin{cases} g'^4\, T\,, & M_{Z'} \ll T\,,\\ g'^2 \frac{M_{Z'}^2}{T}\,, & M_{Z'} \lesssim T\,,\\ \frac{g'^4}{M_{Z'}^4} T^5\,, & M_{Z'} \gg T\,. \end{cases}$$



- Demand $\langle\Gamma(\overline{f}f \leftrightarrow \overline{\nu}_R\nu_R)\rangle < H(T) \sim T^2/M_{\text{Pl}}$ "at" BBN.

[6] Mangano, Serpico, PLB (2011), [arXiv:1103.1261].

The Money Shot



Applicable to any Z'_{B-L} (BBN, RG/ν, solid SN1987 depend on number of light ν_R).[7]

[7] J.H., arXiv:1408.6845.

Majorana $B-L$

- New scalar $\phi_{B-L=2}$ to break $U(1)_{B-L}$ by two units.

$$\mathcal{L} \supset Y_\nu \overline{\nu}_R H L + \tfrac{1}{2} Y_R \overline{\nu}_R \nu_R^c \phi_{B-L=2}{}^* + \text{h.c.}$$

- Spontaneous symmetry breaking gives mass matrix for (ν_L, ν_R^c):

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu^T \langle H \rangle \\ Y_\nu \langle H \rangle & Y_R \langle \phi_{B-L=2} \rangle \end{pmatrix} .$$

- High scale $Y_R \langle \phi_{B-L=2} \rangle \gg Y_\nu \langle H \rangle$:
  small seesaw Majorana mass for active neutrinos:

$$\mathcal{M}_\nu \simeq -\frac{\langle H \rangle^2}{\langle \phi_{B-L=2} \rangle} \, Y_\nu^T Y_R^{-1} Y_\nu .$$

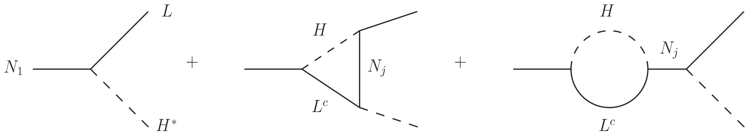
- Signature of Majorana $B-L$: neutrinoless double beta decay

$$(A, Z) \to (A, Z+2) + 2e^- \qquad \Leftrightarrow \qquad \Delta(B-L) = 2.$$

Majorana $B-L$: Leptogenesis

$$\mathcal{L} \supset Y_\nu \overline{\nu}_R H L + \tfrac{1}{2} Y_R \overline{\nu}_R \nu_R^c \, \phi_{B-L=2}{}^* + \text{h.c.}$$

- Heavy ($\mathcal{M}_R \simeq Y_R \langle \phi_{B-L=2} \rangle \gtrsim 10^8\,\mathrm{GeV}$) Majorana neutrinos $N = \nu_R + \nu_R^c$ decay out-of-equilibrium in early Universe.



- If CP violated in loops: $\Gamma(N \to HL) \neq \Gamma(N \to H^* \overline{L})$
$\Rightarrow$ Lepton asymmetry Δ_L!
- Sphalerons with $\Delta B = \Delta L = 3$ above $T \gtrsim \mathrm{TeV}$ transfer Δ_L to baryon asymmetry Δ_B.

Dirac $B-L$

Break $B-L$, but by $n \neq 2$ units.[8]
$\Rightarrow$ Lepton number violating Dirac neutrinos.

- All fermions in SM+ν_R are odd under $B-L$
  $\Rightarrow$ only even $\Delta(B-L)$ possible.
  $\Rightarrow$ Lowest order new processes: $\Delta(B-L)=4$:

$$
\begin{aligned}
\mathcal{O}_{d=6}:&\quad \overline{\nu}_R^c\nu_R\,\overline{\nu}_R^c\nu_R\\
\mathcal{O}_{d=8}:&\quad |H|^2\,\overline{\nu}_R^c\nu_R\,\overline{\nu}_R^c\nu_R\,,\quad (\overline{L}^c\tilde{H}^*)(\tilde{H}^\dagger L)\,\overline{\nu}_R^c\nu_R\,,\quad F_Y^{\mu\nu}\overline{\nu}_R^c\sigma_{\mu\nu}\nu_R\,\overline{\nu}_R^c\nu_R\\
\mathcal{O}_{d=10}:&\quad (\overline{L}^c\tilde{H}^*)(\tilde{H}^\dagger L)\,(\overline{L}^c\tilde{H}^*)(\tilde{H}^\dagger L)\,,\quad |H|^2(\overline{L}^c\tilde{H}^*)(\tilde{H}^\dagger L)\,\overline{\nu}_R^c\nu_R\,,\\
&\quad F_Y^{\mu\nu}(\overline{L}^c\tilde{H}^*)(\tilde{H}^\dagger L)\,\overline{\nu}_R^c\sigma_{\mu\nu}\nu_R\,,\quad W_a^{\mu\nu}(\overline{L}^c\tilde{H}^*)(\tilde{H}^\dagger\tau^a L)\,\overline{\nu}_R^c\sigma_{\mu\nu}\nu_R\,,\\
&\quad (\overline{u}_R d_R^c)(\overline{d}_R\tilde{H}^\dagger L)(\overline{\nu}_R^c\nu_R)\,,\dots\\
\mathcal{O}_{d=18}:&\quad (\overline{d}_R d_R^c\,\overline{u}_R^c u_R\,\overline{e}_R^c e_R)(\overline{d}_R d_R^c\,\overline{u}_R^c u_R\,\overline{e}_R^c e_R)\,,\dots\\
\mathcal{O}_{d=20}:&\quad \left[(\overline{(D_\mu L)}^c\tilde{H})(H^\dagger D_\nu L)\right]^2 \supset (\overline{e}_L^c W_\mu^+ W_\nu^+ e_L)(\overline{e}_L^c W^{+\mu}W^{+\nu}e_L)\,,\dots
\end{aligned}
$$

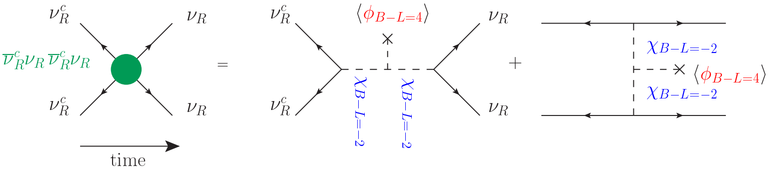
[8] Witten, hep-ph/0006332.

UV Completion

- One scalar $\phi_{B-L=4}$ to break $B-L$, one scalar $\chi_{B-L=-2}$ as mediator.

$$\mathcal{L} \supset y_{\alpha\beta}\,\overline{L}_\alpha H \nu_{R,\beta} + \kappa_{\alpha\beta}\,\chi_{B-L=-2}\,\overline{\nu}_{R,\alpha}\nu^c_{R,\beta} + \text{h.c.}$$

- Neutrinos are Dirac (and $\Delta L = 2$ forbidden) if $\langle \chi_{B-L=-2}\rangle = 0$.
- Scalar potential $V \supset \mu\, \phi_{B-L=4}(\chi_{B-L=-2})^2 + \text{h.c.}$
- Lepton number violation $\Delta L = 4$ still possible![9]



- Extension to left–right model can enhance rates.

[9] J.H. and W. Rodejohann, EPL **103**, 32001 (2013) [arXiv:1306.0580].

Phenomenology of LNV Dirac Neutrinos

How to check for $\Delta L = 4$?

- Collider processes:
  - LHC: $pp \to W^- W^- W^- W^- \ell^+ \ell^+ \ell^+ \ell^+ + X$,
  - Like-sign lepton collider: $e^- e^- \to W^- W^- W^- W^- \ell^+ \ell^+$.
- Nuclear decays ($0\nu 4\beta$?).[10]
- Rare meson decays etc.?

All tough, many particles in final state! (Even harder for $\Delta L > 4\ldots$)

$\Delta L = 4$ can however easily be relevant in the early Universe
$\Rightarrow$ new Dirac leptogenesis mechanism![11]

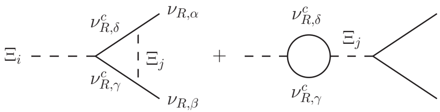
[10] J.H. and W. Rodejohann, EPL **103**, 32001 (2013) [arXiv:1306.0580].
[11] J.H., PRD **88**, 076004 (2013) [arXiv:1307.2241].

Dirac $B-L$: Leptogenesis

- Scalar potential $V(H,\phi,\chi) \supset -\mu\, \phi_{B-L=4} (\chi_{B-L=-2})^2$ breaks complex $\chi_{B-L=-2} = (\Xi_1 + i\,\Xi_2)/\sqrt{2}$ into two real scalars with mass

$$m_1^2 = m_c^2 - 2\mu\langle \phi_{B-L=4}\rangle\,, \qquad m_2^2 = m_c^2 + 2\mu\langle \phi_{B-L=4}\rangle\,.$$

- Heavy mediator scalar Ξ_j decays to $\nu_R\nu_R$ or $\overline{\nu}_R\overline{\nu}_R$ out-of-equilibrium in early Universe.



- *CP* violation requires *second* scalar $\chi_{B-L=-2}$.

$$Y_{\nu_R} \equiv \frac{n_{\nu_R}}{s} \sim \frac{1}{g_*}\, \frac{\Gamma\left(\Xi_i \to \nu_R\nu_R\right) - \Gamma\left(\Xi_i \to \nu_R^c\nu_R^c\right)}{\Gamma\left(\Xi_i \to \nu_R\nu_R\right) + \Gamma\left(\Xi_i \to \nu_R^c\nu_R^c\right)}\,.$$

Asymmetry in ν_R. ✓ How to translate to baryon asymmetry?

Baryon Asymmetry

- Dirac-Yukawa coupling $Y_\nu = m_\nu/\langle H\rangle$ too small to equilibrate ν_R...

Add second scalar doublet H_2 with large Yukawa $\overline{L}H_2\nu_R$:

- Neutrinophilic H_2 with small VEV $\langle H_2\rangle \sim 1\,\mathrm{eV}$.[12]
  $\Rightarrow$ Dirac neutrinos light with large Yukawas.
- H_2 moves Y_{ν_R} to Y_{ν_L}.
- Sphalerons move Y_{ν_L} to Y_B.

$\Rightarrow$ Different from neutrinogenesis!

- Necessary thermalization of $\nu_R \Rightarrow N_\mathrm{eff} > 3$!
- $3.14 \lesssim N_\mathrm{eff} \lesssim 3.29$ depending on H_2^+ mass and Yukawa coupling.
- Specific collider signatures of neutrinophilic H_2.[13]

[12] E. Ma, PRL **86** (2001), F. Wang, W. Wang, J. M. Yang, EPL **76** (2006), S. Gabriel and S. Nandi, PLB **655** (2007).
[13] Davidson and Logan, PRD **80** (2009), arXiv:0906.3335.

Unflavored Summary

name	$\Delta(B-L)$	neutrino	BAU	signatures
Unbroken $B-L$	0	Dirac	neutrinogenesis	$Z'(?)$, $N_{\rm eff} \simeq 3$
Majorana $B-L$	2	Majorana	leptogenesis	$0\nu 2\beta$
Dirac $B-L$	>2, e.g. 4	Dirac	Dirac leptogenesis	$0\nu 4\beta$, $N_{\rm eff} \gtrsim 3.14$

- $B-L$ mystery: global, local, unbroken, broken by 2, 4, ... units?
- Currently testing: $\Delta L = 2$ via $0\nu 2\beta$.
- $\Delta L \geq 4$ way more challenging (experimentally and theoretically).
- Lepton number violation not synonymous with Majorana neutrinos.
- $\Delta L = 4$ lowest LNV of Dirac neutrinos.
- New Dirac leptogenesis ($3.14 \lesssim N_{\rm eff} \lesssim 3.29$).

Let's add some flavor...

Neutrinos and abelian flavor symmetries

$$\overbrace{\underbrace{U(1)_{B-L}}_{\text{unflavored}} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}}^{\text{flavored}} \underbrace{\qquad\quad}_{\text{dark}} .$$

Neutrino Mixing

Pontecorvo–Maki–Nakagawa–Sakata leptonic mixing matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\alpha} & s_{13}e^{i(\beta-\delta_{CP})} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta_{CP}} & (c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta_{CP}})e^{i\alpha} & s_{23}c_{13}e^{i\beta} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta_{CP}} & -(s_{23}c_{12} + c_{23}s_{13}s_{12}e^{i\delta_{CP}})e^{i\alpha} & c_{23}c_{13}e^{i\beta} \end{pmatrix}$$

with [Gonzalez-Garcia et al, arXiv:*1409.5439*]

$\sin^2\theta_{13} \simeq 0.02\,,$

$\sin^2\theta_{12} \simeq 0.30\,,$

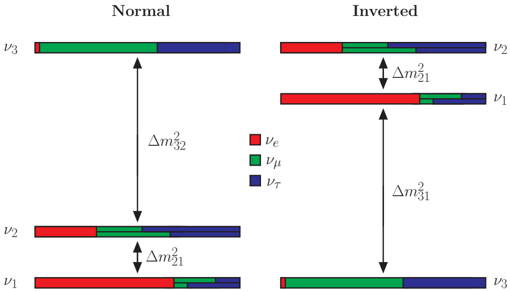
$\Delta m^2_{21} \simeq 7.5\times 10^{-5}\,\mathrm{eV}^2,$

$\sin^2\theta_{23} \simeq 0.45$ (NO) or

$\sin^2\theta_{23} \simeq 0.58$ (IO),

$\Delta m^2_{31} \simeq 2.46\times 10^{-3}\,\mathrm{eV}^2$ (NO) or

$\Delta m^2_{32} \simeq -2.45\times 10^{-3}\,\mathrm{eV}^2$ (IO).



Ordering (normal or inverted), absolute scale, phases?

Why these values? Symmetries!?

Neutrino Hierarchies

Majorana mass matrix $\mathcal{M}_\nu = U \text{diag}(m_1, m_2, m_3) U^T$ in special cases:

1. Normal hierarchy ($m_1 \simeq 0$) and best-fit values (phases zero):

$$\mathcal{M}_\nu \simeq \begin{pmatrix} 0.37 & 0.75 & 0.24 \\ \cdot & 2.47 & 2.11 \\ \cdot & \cdot & 2.99 \end{pmatrix} 10^{-2}\,\text{eV} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix} \leftarrow L_e$$

2. Inverted hierarchy ($m_3 \simeq 0$) and $\alpha = \pi/2$:

$$\mathcal{M}_\nu \simeq \begin{pmatrix} 1.84 & -3.11 & 3.22 \\ \cdot & -0.14 & 0.88 \\ \cdot & \cdot & -1.77 \end{pmatrix} 10^{-2}\,\text{eV} \sim \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix} \leftarrow L_e - L_\mu - L_\tau$$

3. Quasi-degenerate ($m_{1,2,3} \simeq 1\,\text{eV}$) and $\beta = \pi/2$:

$$\mathcal{M}_\nu \simeq \begin{pmatrix} 0.96 & -0.20 & -0.22 \\ \cdot & 0.11 & -0.97 \\ \cdot & \cdot & -0.07 \end{pmatrix} \text{eV} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \leftarrow L_\mu - L_\tau$$

Now what?

- Three interesting zeroth order approximations:

$$\mathcal{M}_\nu^{L_e} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}, \quad \mathcal{M}_\nu^{L_e - L_\mu - L_\tau} \sim \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix}, \quad \mathcal{M}_\nu^{L_\mu - L_\tau} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

[G. Branco, W. Grimus, L. Lavoura, *NPB (1989)*; S. Choubey, W. Rodejohann, *EPJC 40 (2005)*]

- Impose $U(1)_X$ to get $\mathcal{M}_\nu^X$, then slightly break it.
  $\Rightarrow$ Goldstone boson. . .
- Here: promote to local symmetry. Goldstone $\rightarrow$ massive Z'.
- Remember: SM $+3\nu_R$ has anomaly free
  $U(1)_{B-L} \times U(1)_{L_e - L_\mu} \times U(1)_{L_\mu - L_\tau}$.

Simply take $U(1)_{B-3L_e}$, $U(1)_{B+3(L_e - L_\mu - L_\tau)}$, or $U(1)_{L_\mu - L_\tau}$?

Wrong end of the seesaw

- Imposing $U(1)_{B-3L_e}$ gives L_e symmetric $\mathcal{M}_R$, but not L_e symmetric

$$\mathcal{M}_\nu \simeq -m_D^T \mathcal{M}_R^{-1} m_D \,,$$

because $\mathcal{M}_R^{L_e}$ not invertible!

- Weird coincidence:

$$\mathcal{M}_R^{L_e-L_\mu-L_\tau} \sim \begin{pmatrix} \varepsilon & 1 & 1 \\ \cdot & \varepsilon & \varepsilon \\ \cdot & \cdot & \varepsilon \end{pmatrix} \quad \Rightarrow \quad \mathcal{M}_\nu \sim \mathcal{M}_R^{-1} \sim \begin{pmatrix} \varepsilon^2 & \varepsilon & \varepsilon \\ \cdot & 1 & 1 \\ \cdot & \cdot & 1 \end{pmatrix} .$$

$L_e - L_\mu - L_\tau$ gives approximate L_e symmetry after seesaw!

Broken $U(1)_{B+3(L_e-L_\mu-L_\tau)}$ (say $\varepsilon = 0.05$) gives normal hierarchy.[14]

- (Inverted hierarchy requires additional $\mathbb{Z}_2$ symmetry.)

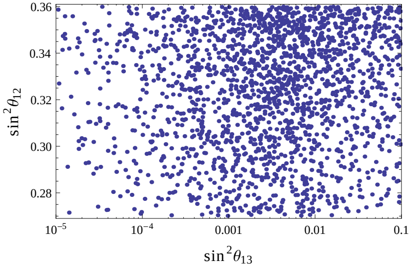
[14] J.H. and W. Rodejohann, PRD **85**, 113017 (2012) [arXiv:1203.3117].

Mixing Angles and Collider

- $U(1)_{B+3(L_e-L_\mu-L_\tau)}$ broken by scalar $S \sim 6$ in RHN sector:

$$S^* \, \overline{\nu}^c_{R,1}\nu_{R,1}\,, \quad S\, \overline{\nu}^c_{R,2}\nu_{R,2}\,, \quad S\, \overline{\nu}^c_{R,2}\nu_{R,3}\,, \quad S\, \overline{\nu}^c_{R,3}\nu_{R,3} \quad \Rightarrow \quad \Delta\mathcal{M}_R \sim \langle S \rangle\,.$$

- VEV $v_S \sim \varepsilon|\mathcal{M}_R|$ gives:



- μ and τ same $U(1)'$ charge: θ_{23} random (large...).
- LEP-II constraint on $U(1)_{B+3(L_e-L_\mu-L_\tau)}$: $v_S > 2.3\,\mathrm{TeV}$, LHC prospects in [H. S. Lee and E. Ma, *PLB 688 (2010)*].

$L_\mu - L_\tau$

- Anomaly free in SM even without ν_R.[15]
- $\mathcal{M}^{L_\mu - L_\tau}$ invertible $\Rightarrow$ Seesaw gives $L_\mu - L_\tau$ symmetric $\mathcal{M}_\nu$.
- Add one or two scalars S that couple to $\overline{\nu}^c_{R,i}\nu_{R,j}$ and get a VEV.
- VEV fills zeros in $\mathcal{M}_R$ and $\mathcal{M}_\nu$ and gives mass to Z' boson $M_{Z'}/g' \sim \langle S \rangle$.
- No Z' coupling to first generation $\rightarrow$ "Weak" limits for heavy Z':

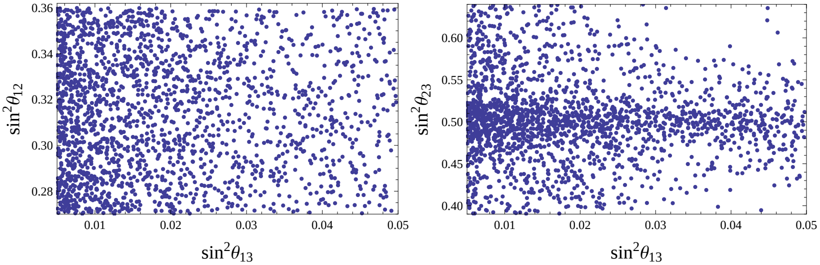
$$M_{Z'}/g' > 550\,\mathrm{GeV} \quad \text{at} \quad 95\%\ \text{C.L.}$$

  from trident production at CCFR $\nu_\mu N \to \nu_\mu N \to \nu_\mu N \mu^+ \mu^-$.[16]
- Light Z' (below $400\,\mathrm{MeV}$) can resolve muon's magnetic moment anomaly.[17]

[15] Foot (1991), He, Joshi, Lew, Volkas (1991).
[16] Altmannshofer Gori, Pospelov, Yavin, PRD **89** (2014) [arXiv:1403.1269].
[17] Altmannshofer Gori, Pospelov, Yavin, PRL **113** (2014) [arXiv:1406.2332].

$L_\mu - L_\tau$

Two scalars, $\varepsilon = v_S/|\mathcal{M}_R| = 0.02$:



$L_\mu - L_\tau$ and Lepton Flavor Violation

- LFV in charged leptons if we break $L_\mu - L_\tau$ with a scalar doublet.[18]
- Can source $h \to \mu\tau$.[19]

SM-like doublet Φ_2, new doublet Φ_1 with $L_\mu - L_\tau$ charge -2, and singlet S with $+1$:

$$\begin{aligned} V(\Phi_1, \Phi_2, S) = {} & m_1^2|\Phi_1|^2 + \tfrac{\lambda_1}{2}|\Phi_1|^4 - m_2^2|\Phi_2|^2 + \tfrac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ & - \mu_S^2|S|^2 + \tfrac{\lambda_S}{2}|S|^4 + \lambda_{\Phi_1 S}|\Phi_1|^2|S|^2 + \lambda_{\Phi_2 S}|\Phi_2|^2|S|^2 \\ & - \delta\ S^2\Phi_2^\dagger\Phi_1 + \text{h.c.} \end{aligned}$$

S heavy and large VEV: 2HDM with softly broken $U(1)$:

$$\begin{aligned} V(\Phi_1, \Phi_2) \simeq {} & m_1^2|\Phi_1|^2 + \tfrac{\lambda_1}{2}|\Phi_1|^4 - m_2^2|\Phi_2|^2 + \tfrac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ & - m_3^2\Phi_2^\dagger\Phi_1 + \text{h.c.} \end{aligned}$$

Small VEV for Φ_1: $\langle\Phi_1\rangle \simeq \langle\Phi_2\rangle m_3^2/m_1^2 \simeq \delta\langle\Phi_2\rangle\langle S\rangle^2/m_1^2$.

[18] J.H., Rodejohann, PRD **84** (2011) [arXiv:1107.5238].
[19] J.H., Holthausen, Rodejohann, Shimizu, arXiv:1411.XXXX.

Yukawa Structure

$$
\begin{aligned}
-\mathcal{L}_Y = {}& \overline{L}_L Y_{\ell_1} \Phi_1 \ell_R + \overline{L}_L Y_{N_1} \tilde{\Phi}_1 N_R \\
&+ \overline{L}_L Y_{\ell_2} \Phi_2 \ell_R + \overline{L}_L Y_{N_2} \tilde{\Phi}_2 N_R + \overline{Q}_L Y_u \tilde{\Phi}_2 u_R + \overline{Q}_L Y_d \Phi_2 d_R \\
&+ \tfrac{1}{2} \overline{N}_R^c \mathcal{M}_N N_R + \tfrac{1}{2} \overline{N}_R^c Y_{S_1} S N_R + \tfrac{1}{2} \overline{N}_R^c Y_{S_2} \overline{S} N_R + \text{h.c.}
\end{aligned}
$$

with matrices

$$
Y_{\ell_2} = \operatorname{diag}(y_e, y_\mu, y_\tau)\,, \qquad Y_{N_2} = \operatorname{diag}(y_1, y_2, y_3)\,,
$$

$$
Y_{\ell_1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \xi_{\tau\mu} & 0 \end{pmatrix}, \qquad Y_{N_1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \xi_{23} \\ 0 & 0 & 0 \end{pmatrix}.
$$

$$
\mathcal{M}_N = \begin{pmatrix} M_1 & & \\ & & M_2 \\ & M_2 & \end{pmatrix}, Y_{S_1} = \begin{pmatrix} 0 & 0 & a_{13} \\ 0 & 0 & 0 \\ a_{13} & 0 & 0 \end{pmatrix}, \quad Y_{S_2} = \begin{pmatrix} 0 & a_{12} & 0 \\ a_{12} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.
$$

Charged Lepton Masses

$$M_e = \frac{v}{\sqrt{2}} \begin{pmatrix} y_e s_\beta & & \\ & y_\mu s_\beta & \\ & \xi_{\tau\mu} c_\beta & y_\tau s_\beta \end{pmatrix} \equiv V_{e_L} \mathrm{diag}(m_e, m_\mu, m_\tau) V_{e_R}^\dagger \,,$$

with

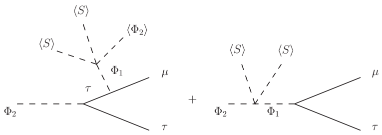
$$\frac{\tan\theta_L}{\tan\theta_R} = \frac{m_\mu}{m_\tau} \ll 1 \quad \text{and} \quad \sin\theta_R \simeq \frac{v}{m_\tau}\frac{\xi_{\tau\mu}}{\sqrt{2}} \cos\beta \,.$$

SM-like scalar h couples

$$y \simeq \underbrace{\mathrm{diag}(m_e, m_\mu, m_\tau)\frac{c_\alpha}{v s_\beta}}_{\text{type-I 2HDM}} - s_R \frac{m_\tau}{v} \frac{\cos(\alpha-\beta)}{c_\beta s_\beta} \begin{pmatrix} 0 & & \\ & -c_R s_L & -s_L s_R \\ & c_L c_R & c_L s_R \end{pmatrix} .$$

Only LFV in μ–τ sector, quarks and electrons save!

$h \to \mu\tau$



CMS 2.5σ excess in $h \to \mu\tau$ for[20]

$$|y^h_{\tau\mu}| = \frac{m_\tau}{v} \left|\frac{\cos(\alpha-\beta)}{c_\beta s_\beta} c_R c_L s_R\right| \simeq 7\times 10^{-3} \quad \left|\frac{\cos(\alpha-\beta)}{s_\beta c_\beta} c_R s_R\right| \overset{!}{\simeq} 3\times 10^{-3}\,.$$

- Either $c_\beta, s_R \ll 1$ and $\xi_{\tau\mu} c_{\alpha-\beta} \simeq 4\times 10^{-3}$,
- or larger s_R and correlations with $h \to \tau\tau$, $\mu\mu$:

$$\frac{\mathrm{BR}(h\to\tau\tau)}{\mathrm{BR}(h\to\tau\tau)|_{\rm SM}} \simeq \left(\frac{c_\alpha}{s_\beta} - y^h_{\tau\mu}\frac{v}{m_\tau} t_R\right)^2 \simeq (1\pm 0.4\,|t_R|)^2\,,$$

compared to 0.78 ± 0.27 (CMS) or $1.4^{+0.5}_{-0.4}$ (ATLAS).

[20] J.H., Holthausen, Rodejohann, Shimizu, arXiv:1411.XXXX.

One step further: texture zeros

- $U(1)_{B-L} \times U(1)_{L_e - L_\mu} \times U(1)_{L_\mu - L_\tau}$ subgroups forbid entries in $\mathcal{M}_R$ $\Rightarrow$ texture zeros![21]
- Choose subgroup so that some entries are allowed, others filled by $\langle S \rangle$, e.g. $B - L_e + L_\mu - 3L_\tau$ with $Y'(S) = 2$:

$$\mathcal{M}_R = M_0 \begin{pmatrix} 0 & \times & 0 \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{pmatrix} + \langle S \rangle \begin{pmatrix} \times & 0 & \times \\ \cdot & \times & 0 \\ \cdot & \cdot & 0 \end{pmatrix}$$
$$\sim \begin{pmatrix} \times & \times & \times \\ \cdot & \times & 0 \\ \cdot & \cdot & 0 \end{pmatrix} \sim \begin{pmatrix} 0 & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix}^{-1} \simeq \mathcal{M}_\nu^{-1} .$$

- Dirac matrices diagonal by symmetry, so $\mathcal{M}_R \sim \mathcal{M}_\nu^{-1}$.
- Texture zeros imply testable correlations among neutrino parameters, *seven* out of 15 two-zero patterns currently viable.

[21] J.H., Araki, Kubo, JHEP **1207** (2012) [arXiv:1203.4951].

Simplest $U(1)'$ models with just one scalar

- With just one scalar S, we can get five of the seven valid patterns:[22]

Symmetry generator Y'	$\lvert Y'(S)\rvert$	Texture zeros in $\mathcal{M}_R$	Texture zeros in $\mathcal{M}_\nu$
$L_\mu - L_\tau$	1	$(\mathcal{M}_R)_{33}$, $(\mathcal{M}_R)_{22}$ ($\boldsymbol{C}^R$)	–
$B - L_e + L_\mu - 3L_\tau$	2	$(\mathcal{M}_R)_{33}$, $(\mathcal{M}_R)_{13}$ ($\boldsymbol{B}_4^R$)	$(\mathcal{M}_\nu)_{12}$, $(\mathcal{M}_\nu)_{22}$ ($\boldsymbol{B}_3^\nu$)
$B - L_e - 3L_\mu + L_\tau$	2	$(\mathcal{M}_R)_{22}$, $(\mathcal{M}_R)_{12}$ ($\boldsymbol{B}_3^R$)	$(\mathcal{M}_\nu)_{13}$, $(\mathcal{M}_\nu)_{33}$ ($\boldsymbol{B}_4^\nu$)
$B + L_e - L_\mu - 3L_\tau$	2	$(\mathcal{M}_R)_{33}$, $(\mathcal{M}_R)_{23}$ ($\boldsymbol{D}_2^R$)	$(\mathcal{M}_\nu)_{12}$, $(\mathcal{M}_\nu)_{11}$ ($\boldsymbol{A}_1^\nu$)
$B + L_e - 3L_\mu - L_\tau$	2	$(\mathcal{M}_R)_{22}$, $(\mathcal{M}_R)_{23}$ ($\boldsymbol{D}_1^R$)	$(\mathcal{M}_\nu)_{13}$, $(\mathcal{M}_\nu)_{11}$ ($\boldsymbol{A}_2^\nu$)

- Many patterns are hard to distinguish via neutrino experiments, e.g. $\boldsymbol{D}_1^R$ and $\boldsymbol{D}_2^R$, but the symmetries $B + L_e - 3L_\mu - L_\tau$ and $B + L_e - L_\mu - 3L_\tau$ are very different

$\Rightarrow$ new possibilities to disentangle texture zeros.

- More scalars or discrete $\mathbb{Z}_N$ subgroups can generate other allowed patterns.

[22] J.H., Araki, Kubo, JHEP **1207** (2012) [arXiv:1203.4951].

Flavored Summary

- SM+3ν_R has anomaly free local $U(1)_{B-L} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}$.

Can use subgroups to influence

- Neutrino hierarchies:
  - $U(1)_{B+3(L_e-L_\mu-L_\tau)}$ for normal hierarchy,
  - $(U(1)_{B+3(L_e-L_\mu-L_\tau)} \times \mathbb{Z}_2$ for inverted hierarchy,)
  - $U(1)_{L_\mu-L_\tau}$ for quasi-degenerate.
- Texture zeros in $\mathcal{M}_\nu$ or $\mathcal{M}_\nu^{-1}$.
- Specific LFV modes, e.g. $h \to \mu\tau$ via $L_\mu - L_\tau$.
- (Z' pheno on top: muon's magnetic moment, leptophilic DM,...)

Very simple models, surprisingly potent framework!

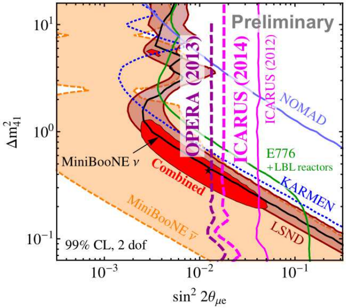
Dark Symmetries and Light Sterile Neutrinos

Neutrinos and *dark* gauge symmetries

$$\overbrace{\underbrace{U(1)_{B-L}}_{\text{unflavored}} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}}^{\text{flavored}} \underbrace{\qquad\qquad}_{\text{dark}} .$$

- LSND, MiniBooNE: ν_S with eV mass and mixing $U_{as} \sim 0.1$?
- Tension appearance vs. disappearance...
- Tension with cosmology...

[Kopp, Neutrino 2014]



If we ever observe a sterile neutrino, it's lighter than "expected" ($10^9\,\mathrm{GeV}$). Why?

How to make ν_s light?

Isn't new physics always at TeV?

- Use seesaw partners ν_R as steriles: eV-seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

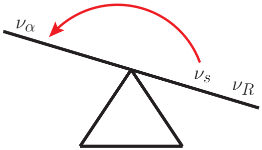
with $m_D \sim 0.1\,\mathrm{eV}$, $M_R \sim 1\,\mathrm{eV}$. [de Gouvêa, *PRD (2005)*]

- Active–sterile mixing automatically large:
$U_{as} \sim m_D/M_R \sim \sqrt{m_\nu/m_s} \sim 0.1$.
- Minimal $3+2$ scheme: two ν_R at eV scale, works fine.
[Donini, Schwetz et al., *JHEP (2012)*]
- Just throw in random $\mathcal{O}(1)$ couplings: sterile neutrino anarchy.
[JH, Rodejohann, *PRD (2013)*]

$\Rightarrow$ The "heavy" eV-scale suppresses the "light" 0.1 eV?

How to make ν_s light? II

- Put ν_s on the other side of the seesaw:



- Suppressed *BY* seesaw: need additional right-handed singlet S and mass matrix for $(\nu_\alpha, \nu_{R,j}^c, S^c)$

$$\mathcal{M}_{\rm MES} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & m_S \\ 0 & m_S^T & 0 \end{pmatrix}.$$

Minimal Extended Seesaw (MES) [Chun, Joshipura, Smirnov, *PLB (1995)*, Babu, Seidl, *PRD,PLB (2004)*, Barry, Rodejohann, Zhang, *JHEP (2011)*, Zhang, *PLB (2012)*]

- Works also for $3+2$, $3+3$,..., just add more singlets.

Minimal extended seesaw

$$\mathcal{M}_{\mathrm{MES}} = \begin{pmatrix} 0^{3\times 3} & m_D & 0 \\ m_D^T & M_R^{3\times 3} & m_S \\ 0 & m_S^T & 0^{1\times 1} \end{pmatrix}$$

Assume $M_R \gg m_D, m_S$, usual seesaw:

$$\mathcal{M}_\nu^{4\times 4} \simeq -\begin{pmatrix} (m_D M_R^{-1} m_D^T)^{3\times 3} & m_D M_R^{-1} m_S \\ m_S^T M_R^{-1} m_D^T & (m_S^T M_R^{-1} m_S)^{1\times 1} \end{pmatrix}.$$

- all masses suppressed by seesaw scale $M_R \sim 2 \times 10^{14}\,\mathrm{GeV}$. ✓
- sterile mass $m_4 \sim 1$ eV for $m_S \sim 5$–$10 m_D$.
- active–sterile mixing $U_{as} = \mathcal{O}(m_D/m_S)$ automatically right. ✓

$\Rightarrow$ SBL sterile neutrinos. ✓

Great, but how to get MES structure?

How to get MES

Need

$$\overline{L}\langle H\rangle\nu_R\,, \qquad m_S\overline{S^c}\nu_R\,, \qquad M_R\overline{\nu_R^c}\nu_R$$

and forbid couplings

$$\overline{L}\langle H\rangle S\,, \qquad \overline{S^c}S\,.$$

- Flavor symmetry $A_4 \otimes \mathbb{Z}_4$ (messy. . .). [Zhang, *PLB (2012)*]
- Abelian gauge symmetry $U(1)'$: simple, but need additional fermions to cancel anomalies. [Babu, Seidl, *PLB (2004)*]
  - Cancel anomalies, make new fermions massive, and not disturb MES structure? With few scalars? **Yes!**

Magic numbers

	$\nu_{R,1}$	$\nu_{R,2}$	$\nu_{R,3}$	S_1	S_2	S_3	S_4	S_5	S_6	S_7	ϕ
Y'	0	0	0	11	-5	-6	1	-12	2	9	11

Mass matrix has nice block structure:

$$\mathcal{M} = \begin{pmatrix} (\mathcal{M}_{\text{MES}})_{7\times 7} & 0 \\ 0 & (\mathcal{M}_S)_{6\times 6} \end{pmatrix}$$

with

$$\mathcal{M}_S = \begin{pmatrix} 0 & y_1\langle\phi\rangle & 0 & 0 & 0 & 0 \\ y_1\langle\phi\rangle & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & y_2\langle\phi\rangle & 0 & 0 \\ 0 & 0 & y_2\langle\phi\rangle & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & y_3\langle\phi\rangle \\ 0 & 0 & 0 & 0 & y_3\langle\phi\rangle & 0 \end{pmatrix} .$$

$\Rightarrow$ S_1 gives MES, $S_{2,3,4,5,6,7}$ decouple and form 3 Dirac fermions $\Psi_{1,2,3}$!

More numbers

- Happy "accident": ϕ breaks $U(1)'$ to $\mathbb{Z}_{11}$.
  $\Rightarrow$ all three Ψ_j stable!
- Active–sterile mixing $V_{4j} \sim \mathcal{O}(m_D/m_S) \stackrel{!}{=} \mathcal{O}(0.1)$.
- For $\mathcal{O}(1)$ Yukawas $\Rightarrow$ $U(1)'$ breaking at $\langle\phi\rangle \sim 10\langle H\rangle \sim \mathrm{TeV}$.

  $\Rightarrow$ masses for Z', $\mathrm{Re}(\phi)$, $\Psi_{1,2,3}$ around $100\,\mathrm{GeV}$–TeV.

$\Rightarrow$ Multicomponent stable dark matter.

Breakdown of neutral fermions:

$$\underbrace{\nu_e, \nu_\mu, \nu_\tau, S_1, \overbrace{\nu_{R,1}, \nu_{R,2}, \nu_{R,3}}^{\text{seesaw/leptogenesis}}}_{\text{(3+1) MES}}, \underbrace{\overbrace{S_2, S_3}^{\Psi_1}, \overbrace{S_4, S_5}^{\Psi_2}, \overbrace{S_6, S_7}^{\Psi_3}}_{\text{DM}}$$

Dark matter interactions

Lagrangian:

$$\sum_j \left[\mathrm{i}\overline{\Psi}_j \gamma^\mu \partial_\mu \Psi_j - M_j \left(1 + \frac{\mathrm{Re}(\phi)}{\langle \mathrm{Re}(\phi) \rangle} \right) \overline{\Psi}_j \Psi_j + \frac{g'}{2} Z'_\mu \overline{\Psi}_j \gamma^\mu \left(g_j^V + g_j^A \gamma_5 \right) \Psi_j \right]$$

with $g_1^V = 1$, $g_2^V = 13$, $g_3^V = -7$, $g_1^A = -11$, $g_2^A = -11$, $g_3^A = 11$.

Connection to the Standard Model just like all other $U(1)_{\mathrm{DM}}$ models:

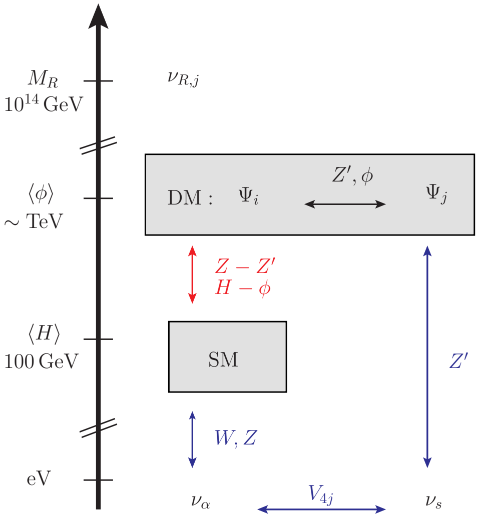
- Scalar mixing (Higgs portal): $\mathcal{L} \supset \delta \, |H|^2 |\phi|^2$
  $\Rightarrow \Psi_j$ couple to Brout–Englert–Higgs boson.
- Vector mixing (kinetic-mixing portal): $\mathcal{L} \supset \sin\xi \; F_Y^{\mu\nu} F'_{\mu\nu}$
  $\Rightarrow \Psi_j$ couple to Z boson.

New:

- Fermion mixing (neutrino portal):

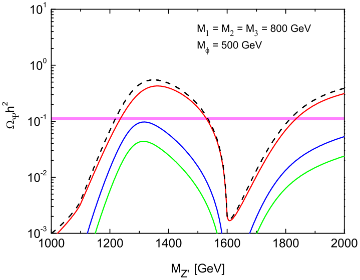
$$\mathcal{L} \supset \frac{11 g'}{2} Z'_\mu \sum_{i,j=1}^{4} V_{4i}^* V_{4j} \left(\overline{\nu}_i \gamma^\mu \gamma_5 \nu_j + \overline{\nu}_i \gamma^\mu \nu_j \right) .$$

Neutrino portal



Relic density via neutrino portal

- Relic density via annihilation $\Psi\Psi \to Z' \to \nu_s\nu_s$ into sterile neutrinos.



- Direct detection is loop-suppressed: $\sim \Delta m^2_{41}/(100\,\mathrm{GeV})^2 \sim 10^{-22}$.
- Indirect detection: $\mathrm{BR}(\Psi\Psi \to \nu\nu) \simeq 100\%$ gives monochromatic neutrinos from Galactic halo. Too small for IceCube...
- Including Higgs portal and kinetic-mixing portal gives the usual measurable effects.

Dark Summary

- Additional right-handed neutrinos with exotic charges under a broken $U(1)'$ can generate structure in neutral fermions.
- Here: generate seesaw-suppressed sterile neutrino.
- Magic numbers: necessary anomaly-cancelling fermions form multicomponent DM.
- Gauge interactions open new SM–DM portal through sterile neutrinos.

$\Rightarrow$ Huge unexplored playground!

Other charges: $3+2$, $3+3$, Majorana DM, unstable DM, ...

Conclusion

- Abelian gauge symmetries $U(1)'$ versatile framework.
- Simple, minimalistic, renormalizable.
- SM-motivated symmetries

$$\overbrace{\underbrace{U(1)_{B-L}}_{\text{unflavored}} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}}^{\text{flavored}} \underbrace{\qquad\qquad}_{\text{dark}} .$$

connected to neutrino properties:

- $B-L$ for Majorana vs. Dirac and leptogenesis.
- $B-L$ only possible unbroken symmetry acting on SM particles.
- $L_\mu - L_\tau$, $B+3(L_e - L_\mu - L_\tau)$,... for hierarchies, mixing angles, texture zeros, LFV, $h \to \mu\tau$, muon's magnetic moment, R-parity,...
- Dark $U(1)'$ for sterile neutrino pheno, dark matter stability and abundance,...

Conclusion

- Abelian gauge symmetries $U(1)'$ versatile framework.
- Simple, minimalistic, renormalizable.
- SM-motivated symmetries

$$\overbrace{\underbrace{U(1)_{B-L}}_{\text{unflavored}} \times U(1)_{L_e-L_\mu} \times U(1)_{L_\mu-L_\tau}}^{\text{flavored}} \underbrace{}_{\text{dark}} .$$

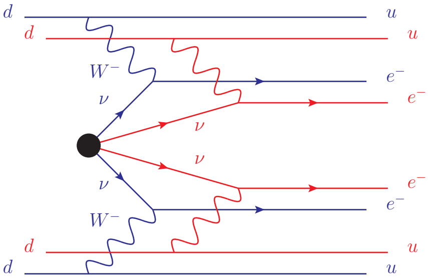
connected to neutrino properties:

  - $B - L$ for Majorana vs. Dirac and leptogenesis.
  - $B - L$ only possible unbroken symmetry acting on SM particles.
  - $L_\mu - L_\tau$, $B + 3(L_e - L_\mu - L_\tau)$,... for hierarchies, mixing angles, texture zeros, LFV, $h \to \mu\tau$, muon's magnetic moment, R-parity,...
  - Dark $U(1)'$ for sterile neutrino pheno, dark matter stability and abundance,...

Merci!

How to check for $\Delta L = 4$?

- Neutrinoless quadruple beta decay[23] $(A, Z) \to (A, Z+4) + 4\, e^-$
  e.g. via $\mathcal{O}_{\Delta L=4} = (\overline{\nu}_L^c \nu_L)^2/\Lambda^2$:

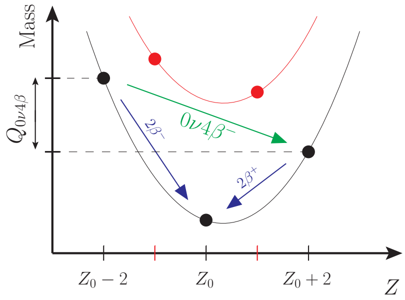


- Collider process $e^- e^- \to W^- W^- W^- W^- \ell^+ \ell^+$.
- Rare meson decays etc.?

[23] J.H. and W. Rodejohann, EPL **103**, 32001 (2013) [arXiv:1306.0580].

Candidate Nuclei for $0\nu4\beta$

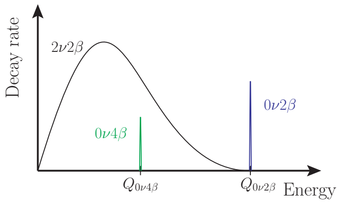
	$Q_{0\nu4\beta}$	Other decays	NA/%
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$ y	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$ y	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$ y	5.6



Best Candidate: Neodymium $^{150}\mathrm{Nd}$

Decay channels:

- $^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$ via $2\nu 2\beta$ ($\tau^{2\nu 2\beta}_{1/2} \simeq 7 \times 10^{18}\,\mathrm{y}$): the two electrons have a continuous energy spectrum and total energy $E_{e,1} + E_{e,2} < 3.371\,\mathrm{MeV}$.
- $^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$ via $0\nu 4\beta$. Four electrons with continuous energy spectrum and summed energy $Q_{0\nu 4\beta} = 2.079\,\mathrm{MeV}$ are emitted. In this special case, the daughter nucleus is α-unstable with half-life $\tau^{\alpha}_{1/2}({}^{150}_{64}\mathrm{Gd} \to {}^{146}_{62}\mathrm{Sm}) \simeq 2 \times 10^{6}\,\mathrm{y}$.



$0\nu 4\beta$ kinematically allowed, but expected rates unobservable.

Texture Zeros

- Take $\mathcal{M}_\nu$ and set two independent entries to zero $\Rightarrow$ four constraints on the nine low-energy parameters (m_1, m_2, m_3), $(\theta_{23}, \theta_{12}, \theta_{13})$ and (δ, α, β) (CP violating phases)
- 15 two-zero textures possible, only 7 allowed at 3σ: [H. Fritzsch et al, *JHEP 1109 (2011)*]

$$\boldsymbol{A}_1^\nu : \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad \boldsymbol{A}_2^\nu : \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}, \quad \boldsymbol{B}_1^\nu : \begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix}, \quad \boldsymbol{B}_2^\nu : \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix},$$

$$\boldsymbol{B}_3^\nu : \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}, \quad \boldsymbol{B}_4^\nu : \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}, \quad \boldsymbol{C}^\nu : \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}.$$

Vanishing Minors

- Same idea, but with $\mathcal{M}_\nu^{-1}$ instead of $\mathcal{M}_\nu$.
- Seven patterns for $\mathcal{M}_\nu^{-1}$ allowed:

$$\boldsymbol{D}_1^R : \begin{pmatrix} \times & \times & \times \\ \cdot & 0 & 0 \\ \cdot & \cdot & \times \end{pmatrix}, \quad \boldsymbol{D}_2^R : \begin{pmatrix} \times & \times & \times \\ \cdot & \times & 0 \\ \cdot & \cdot & 0 \end{pmatrix}, \quad \boldsymbol{B}_3^R : \begin{pmatrix} \times & 0 & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{pmatrix}, \quad \boldsymbol{B}_4^R : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix},$$

$$\boldsymbol{B}_1^R : \begin{pmatrix} \times & \times & 0 \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{pmatrix}, \quad \boldsymbol{B}_2^R : \begin{pmatrix} \times & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix}, \quad \boldsymbol{C}^R : \begin{pmatrix} \times & \times & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & 0 \end{pmatrix}.$$

- Two-zero texture in $\mathcal{M}_\nu^{-1}$ corresponds to two vanishing minors in $\mathcal{M}_\nu$. E.g.

$$\mathcal{M}^{-1} = \begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix} \quad \Rightarrow \quad \begin{vmatrix} \mathcal{M}_{11} & \mathcal{M}_{13} \\ \mathcal{M}_{31} & \mathcal{M}_{33} \end{vmatrix} = 0 = \begin{vmatrix} \mathcal{M}_{21} & \mathcal{M}_{22} \\ \mathcal{M}_{31} & \mathcal{M}_{32} \end{vmatrix}$$