A U(1) symmetry for Dark Matter and neutrino masses

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WHAT WE DON'T KNOW

In this talk

- Neutrino masses
- Dark Matter
- Hierarchy Problem
- Baryon asymmetry
- Flavor
- Strong CP
- ....

2 FACTS about the SM

1. There are no fermion gauge singlets. In fact all fermions are charged under a gauge U(1) (hypercharge)

2. Fermion content is CHIRAL. If particle with charge Q => NO particle with charge -Q

⬇

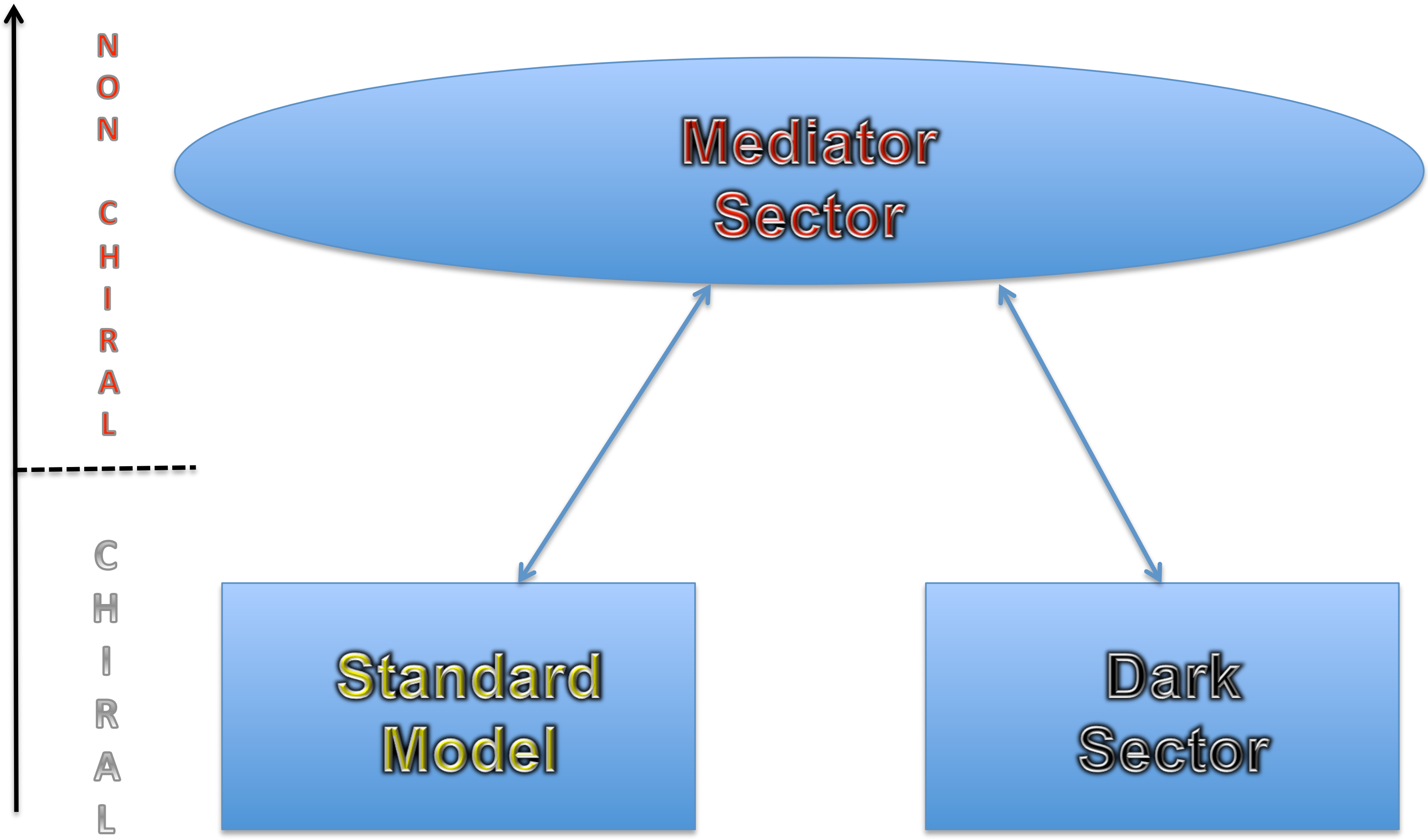
Need Higgs mechanism to give particles a mass

All SM fermions are massless above some scale

ASSUMPTIONS

New degrees of freedom are needed - **Dark Sector (DS)**. The DS has, at least, one gauge chiral U(1) symmetry

Chiral fermionic degrees have mass bounded from above – they are “light”. They acquire mass through a Higgs-like mechanism.


NON CHIRAL
CHIRAL
Mediator Sector
Standard Model
Dark Sector

Looking ahead…

- DS is qualitatively as complicated as the SM (anomalies!)
- Dark Matter emerges as a consequence of accidental symmetries – proton analogy.
- Other features of the DS may help solving other problems - neutrino masses, matter-antimatter asymmetry and so on.
- Not a unique model obviously. We can all play!

ANOMALIES

$$\sum_{i=1}^{16} q_i = 0\,, \qquad \sum_{i=1}^{16} q_i^3 = 0$$

How to build an anomaly-free chiral model?

Babu, Seidl; 2004
Batra, Dobrescu, Spivak; 2006

Consider the SO(10) Cartan subalgebra in the 16 representation

$$
\begin{aligned}
H(a,b,c,d,e) = \frac{1}{N}\mathrm{diag}\{& a+b+c+d+e,\ -a+b+c+d-e, \\
& a-b+c+d-e,\ -a-b+c+d+e, \\
& a+b-c+d-e,\ -a+b-c+d+e, \\
& a-b-c+d+e,\ -a-b-c+d-e, \\
& a+b+c-d-e,\ -a+b+c-d+e, \\
& a-b+c-d+e,\ -a-b+c-d-e, \\
& a+b-c-d+e,\ -a+b-c-d-e, \\
& a-b-c-d-e,\ -a-b-c-d+e\}
\end{aligned}
$$

$$
\begin{aligned}
H(a,b,c,d,e) = \frac{1}{N}\mathrm{diag}\{ & a+b+c+d+e,\ -a+b+c+d-e,\\
& a-b+c+d-e,\ -a-b+c+d+e,\\
& a+b-c+d-e,\ -a+b-c+d+e,\\
& a-b-c+d+e,\ -a-b-c+d-e,\\
& a+b+c-d-e,\ -a+b+c-d+e,\\
& a-b+c-d+e,\ -a-b+c-d-e,\\
& a+b-c-d+e,\ -a+b-c-d-e,\\
& a-b-c-d-e,\ -a-b-c-d+e\}
\end{aligned}
$$

$$H(-a) = -H$$

Automatic solution to U(1) anomaly equations:

$$\sum_{i=1}^{16} q_i = 0\,, \qquad \sum_{i=1}^{16} q_i^3 = 0$$

Some cute things

- Model with minimal highest charge:

$$\mathbf{3} \times 1\,, \quad -\mathbf{2} \times 4\,, \quad \mathbf{1} \times 5$$

- Minimal number of particles: 5

$$\mathbf{10} \times 1\,, \quad -\mathbf{9} \times 1\,, \quad -\mathbf{7} \times 1\,, \quad \mathbf{4} \times 1\,, \quad \mathbf{2} \times 1$$

- Highest charged particle is ALWAYS a singlet of everything else. This would be the RH electron in the SM.

- Does this method generates all possible solutions to the anomaly equations?

Pick up a model

- three fields with charge $+1$ – $\mathbf{1}_{+}^{0,1,2}$;
- two fields with charge -2 – $\mathbf{2}_{-}^{1,2}$;
- two fields with charge -3 – $\mathbf{3}_{-}^{1,2}$;
- three fields with charge $+4$ – $\mathbf{4}_{+}^{0,1,2}$;
- one field with charge -5 – $\mathbf{5}_{-}^{0}$.

Plus minimal Higgs-like Sector

- **One scalar field ϕ with charge +1**

DS Yukawas

$$-\mathscr{L}_{\mathrm{DS-Yuk}} = \underbrace{f_{ik}\,\mathbf{1}^i_+\,\mathbf{2}^k_-\,\phi}_{} + \underbrace{h_{i0}\,\mathbf{4}^i_+\,\mathbf{5}^0_-\,\phi + h_{ik}\,\mathbf{4}^i_+\,\mathbf{3}^k_-\,\phi^*}_{} + \mathrm{h.c.}$$

Two Dirac fermions.
3 conserved symmetries
One massless particle
Neutrino connection?
SM steriles?

Three Dirac fermions.
Mix of fields of different charge (5 and 3).
One conserved symmetry

P1: *Dark Matter candidate*

Neutrino connection

Higher dimensional operators made out of the DS fields and the SM fields?

$$\frac{c}{\Lambda}(\mathbf{1}_+ L)(H\phi)$$

P2: *Dirac neutrino masses*

Requirements: Mediator sector that ties the DS and the SM.
It must break SM accidental LN symmetries and the 3 accidental DS 12-symmetries.

Mediator sector (example)

$$\mathscr{L}_{\rm Med} = i\bar{X}\not{D}X + \underbrace{\Lambda\bar{X}X}_{\text{Dirac mass}} - \underbrace{\left(\kappa_L \bar{L}_L X_R \phi + \kappa_i \bar{\mathbf{1}}^{i}_R X_L \tilde{H} + \text{h.c.}\right)}_{\text{Charged “portal”}}$$

X is a Dirac particle charged under both SM SU(2)xU(1) and DS U(1).

Neutrino mass

Dirac neutrino mass

$$\frac{\kappa_L \kappa_i}{\Lambda} \left(\mathbf{1}^i_+ L\right) (H\phi) + \text{h.c.} \qquad m_i^D = \frac{\kappa_L \kappa_i v v_\phi}{\Lambda}$$

Mass matrix,
one generation

$$\begin{array}{cc} & \begin{array}{ccc} \nu_L & 2_L^1 & 2_L^2 \end{array} \\ M_\nu = & \begin{pmatrix} m_0^D & 0 & 0 \\ m_1^D & M_1 & 0 \\ m_2^D & 0 & M_2 \end{pmatrix} \begin{array}{c} 1_R^0 \\ 1_R^1 \\ 1_R^0 \end{array} \end{array}$$

Active neutrino mix with charge 2 states!

After diagonalization: $2_L^i \to N_{iL}$

Neutral current interactions

$$-\frac{m_1^D}{M_1}\bar{\nu}_L\left(\frac{g}{2c_W}\not{Z}-2g_\nu\tilde{\not{Z}}\right)N_{1L}-\frac{m_2^D}{M_2}\bar{\nu}_L\left(\frac{g}{2c_W}\not{Z}-2g_\nu\tilde{\not{Z}}\right)N_{2L}+\text{h.c.}\,,$$

Charged current interactions

$$\frac{g}{\sqrt{2}}\left(-\frac{m_1^D}{M_1}\bar{\ell}_L\not{W}^-N_{1L}-\frac{m_2}{M_2^D}\bar{\ell}_L\not{W}^-N_{2L}\right)+\text{h.c.}\,,$$

P3: *Long-lived sterile decay*

"Sterile"-Gauge interactions

Decays allowed

$$N_k \to Z\nu \qquad\qquad N_k \to \ell W$$

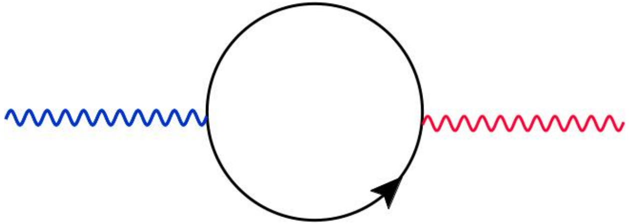
$$\Gamma_{N_1\to SM} \sim N_{ch}\frac{G_F(m_1^D)^2 M_1}{8\pi\sqrt{2}} + \mathcal{O}\left(\frac{M_W^2}{M_1^2}\right)$$

For $M_N \sim 1\ \mathrm{TeV} \quad \Rightarrow \Gamma_{N_1\to\ell W} \sim 0.5\ \mathrm{s}^{-1}$

Kinetic mixing

$$\mathscr{L}_{\text{Kin-Mix}} = -\frac{\sin\eta}{2} B^{\mu\nu} \tilde{B}_{\mu\nu}$$

From quantum corrections:



$$\Delta \sin\eta \sim C_\eta \frac{g' g_\nu}{16\pi^2} \log\left(\frac{\Lambda}{\mu}\right)$$

P4: $\eta \sim 10^{-2} - 10^{-3}$ ***is "natural"***

Holdom; 1986
Babu, Kolda, March-Russell; 1998

$$M_Z^2 \ll M_{\tilde{Z}}^2$$

DS – SM boson interactions

$$g_\nu s_W \frac{M_Z^2}{M_{\tilde{Z}}^2} \sin\eta \, (\bar{\nu^c}\bar{\sigma}_\mu \nu^c \; - \bar{N}_R \gamma^\mu N_R - 2\bar{N}_L \gamma^\mu N_L - 4\bar{\chi}_R \gamma^\mu \chi_R$$

$$+\bar{\chi}_L \mathcal{Q}_{35} \gamma^\mu \chi_L) \, Z_\mu$$

SM – DS boson interactions

$$-\frac{e \sin\eta}{c_W} \tilde{Z}_\mu \sum_f Y^{(f)} \bar{f} \gamma^\mu f$$

P5: *Suppressed direct detection, early DS-SM decoupling*

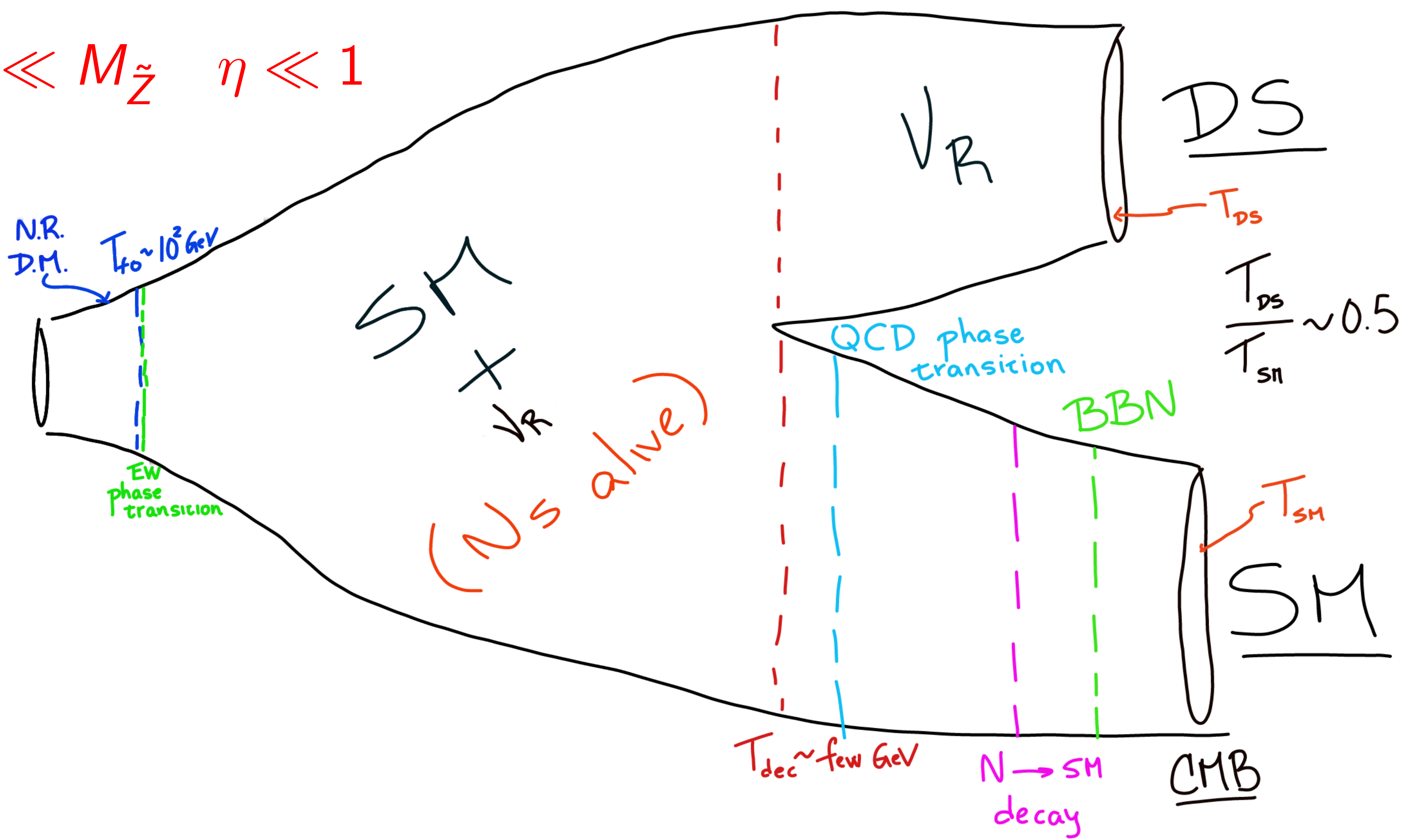
Below DS U(1) breaking
(and EWSB)

- A stable Dirac particle that is a Dark Matter candidate – lowest mass particle in the 345 sector: χ_1

- Two heavy long-lived sterile” neutrinos (w.r.t. the SM) that decay into SM particles: N_1, N_2

- One light Dirac neutrino.

$M_Z \ll M_{\tilde{Z}} \quad \eta \ll 1$



SUMMARY

- Light fermions are chiral (hypothesis) and gauge charged
- Some recipe (not unique) to build chiral models. Cute results
- **Model:** Dark matter candidate easy to get in these models
- **Model:** Charged "portal", Dirac neutrino operator at d=5
- **Model:** Cosmology bounds, direct detection, etc, not so hard to pass

Cosmology

Dark matter abundance set by annihilation to Dark Sector RH neutrinos

$$\langle \sigma_{\rm ann} v \rangle \sim \sigma(\chi_1 + \bar{\chi}_1 \to \nu^c + \bar{\nu^c}) \sim N_f Q_\chi^2 \frac{g_\nu^4}{8\pi M_{\chi_1}^2}$$

$$\langle \sigma_{\rm ann} v \rangle \sim 3 \times 10^{-2}\ \mathrm{pb} \times \left(\frac{1\ \mathrm{TeV}}{M_{\chi_1}}\right)^2 \left(\frac{N_f Q_\chi^2}{20}\right) \left(\frac{g_\nu}{0.1}\right)^4$$

Relic density

T : **SM temperature**

$\tilde{T}$: **DS temperature**

$$r_0 \equiv \frac{T_0}{\tilde{T}_0} \lesssim 0.56$$

$$\Omega_{\chi 0} \sim \sqrt{\frac{4\pi^3 G \mathfrak{g}^*(x=1)}{45}} \frac{x_{\rm fo} T_0^3 r_0^3}{\langle \sigma_{\rm ann} v \rangle \rho_{\rm cr}} \frac{\mathfrak{g}^*_{\rm dec}}{\mathfrak{g}^*_{\infty}}$$

$$\Omega_{\chi 0} \sim \frac{10^{-2}}{\langle \sigma_{\rm ann} v \rangle} \, {\rm pb}.$$

Decoupling temperature

DS should decouple before the QCD phase transition!

$$\frac{T_{\nu_L}^{\mathrm{dec}}}{T_{\mathrm{SM-DS}}^{\mathrm{dec}}} \sim \left(\frac{G_\nu G_F}{G_F^2}\right)^{1/3} \sim \left(\frac{M_Z g_\nu}{M_{\tilde{Z}} g} \sin\eta\right)^{2/3}$$

$$\sin\eta \lesssim 10^{-3}$$

Strongest bound on $\sin\eta$

Neff

$$\Delta N_{\text{eff}} = \frac{4\tilde{g}^*}{7}\frac{\tilde{T}^4}{T^4} = \frac{4\tilde{g}^*}{7}\left(\frac{g^*\,\tilde{g}^*_{\text{dec}}}{g^*_{\text{dec}}\,\tilde{g}^*}\right)^{4/3}$$

$$\Delta N_{\text{eff}} = 0.33$$

PLANCK : $N_{\text{eff}} = 3.15 \pm 0.46$

DM Direct Detection

DM – nucleus cross section

$$\sigma(\chi_1 + N \to \chi_1 + N) \sim \alpha \frac{m_N^2}{M_{\tilde{Z}}^4} \frac{g_\nu^2 \sin^2 \eta \, Q_V^2}{\cos^2 \theta_W} (1 - \sin^2 \theta_W)^2 Z^2$$

Notice that protons are the main contribution.
For the standard WIMP, the main contribution is off neutrons

DM Direct Detection

For $M_{\tilde{Z}} \sim 1 \text{ TeV}$

$49 \leq Q_V^2 \leq 64$

$$\sigma_{\chi p} = 1.2 \times \sin^2 \eta \left(\frac{g_\nu^2}{10^{-2}} \right) \frac{Q_V^2}{50} \times 10^{-41} \ \text{cm}^2$$

LUX : $\sigma_{\chi p} < 6 \times 10^{-44} \ \text{cm}^2$