Unified Scenario for Composite Right-handed Neutrinos and Dark Matter

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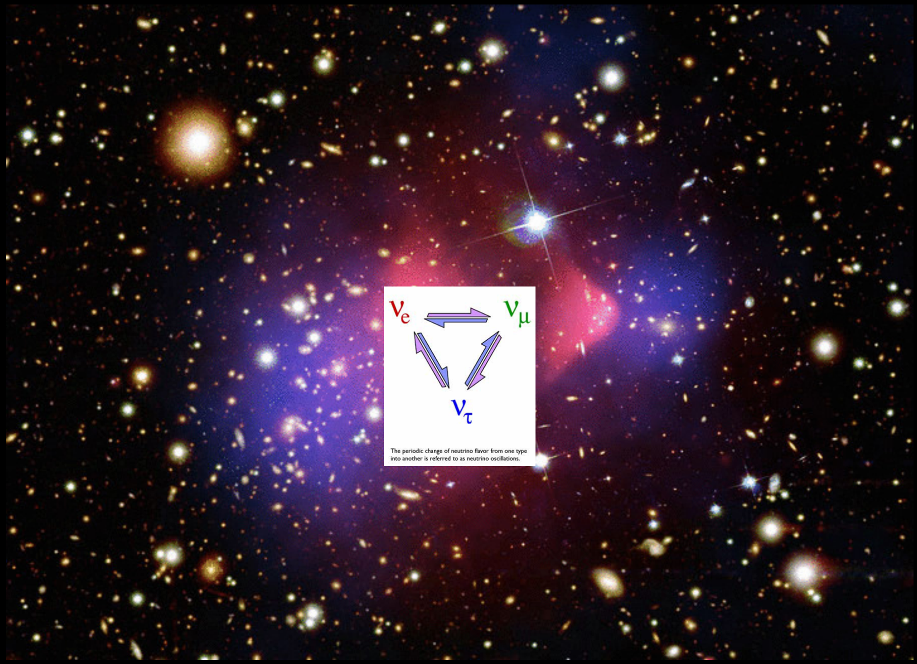


Based on: H.D., Giardino, Neil, Rinaldi, arXiv:1709.01082 [hep-ph]

(To be published in PRD)

Scalars 2017, University of Warsaw

November 30 - December 3, 2017

Introduction

- Standard Model (SM): a great success, yet incomplete:

(1) Dark matter (DM)

- $\Omega_{\rm DM} \sim 0.27$, strong evidence from cosmology and astrophysics: CMB, BBN, rotation curves of galaxies, lensing, Bullet Cluster, . . .

(2) Massive neutrinos

- Δm_ν^2 measured through neutrino oscillation experiments: Solar, atmospheric, accelerators, reactors

$$\boldsymbol{\Delta m_{21}^2 \approx 7.5 \times 10^{-5}\ \textbf{eV}^2\ \textbf{and}\ \Delta m_{32}^2 \approx 2.5 \times 10^{-3}\ \textbf{eV}^2}$$

- Particle identity of neutrinos as yet undetermined: Dirac, Majorana ($0\nu\beta\beta$ decay)

- (1) and (2) unexplained in SM, require new physics

- Separate origins for DM and $m_\nu \neq 0$ typically assumed

- DM elusive, weakly coupled to the SM

- $m_\nu \lesssim 0.1$ eV suggests suppressed interaction

- Tiny Yukawa couplings $\mathcal{O}(10^{-12})$

- Seesaw mechanism, typically heavy right-handed neutrinos N_R

Minkowski, 1977; Yanagida, 1979; Glashow, 1979; Gell-Mann, Ramond, Slansky, 1980; Mohapatra, Senjanović, 1980

★ This talk: *Common origin from dark sector confinement*

- Composite N_R and pseudo-scalar DM

- Neutrino mass from inverse seesaw   Mohapatra, 1986; Mohapatra, Valle, 1986

Recent work on 5D warped seesaw, dual to a composite scenario: Agashe, Hong, Vecchi, 2015

Unified Scenario for Composite N_R and DM

HD, Giardino, Neil, Rinaldi, 1709.01082

- Effective field theory (EFT) approach

- We will provide a UV completion for the EFT

- Assume a "dark" $SU(n_c)_D$ and associated quarks ψ_i

- N_R a composite baryon $\Rightarrow n_c$ odd; for simplicity set $n_c = 3$

- $SU(3)_D$ confinement at scale μ_D

- EFT $\rightarrow$ neutron-anti-neutron oscillation (NANO)

- EFT operators made up of ψ_i with $i = 1, 2, 3$ and SM

- Below $SU(3)_D$ confinement scale, EFT yields dim-4 interactions

- DM stability: $\mathbb{Z}_2(\psi_1) = \mathbb{Z}_2(\psi_2) = \mathbb{Z}_2(\text{SM}) = +1$; $\mathbb{Z}_2(\psi_3) = -1$

EFT Ingredients

- In addition to SM and "dark QCD" interactions, assume

$$\mathcal{L}_{\text{eff}} = \frac{\tilde{H}^* \bar{L}_f \, [\psi_i^3]}{\Lambda_f^3} + \frac{[\psi_i^6]}{\Lambda_N^5} + \frac{\bar{\psi}_i \psi_i H^\dagger H}{\Lambda_H} + \text{H.C.}$$

- H is the Higgs and L_f a lepton doublet of family $f = 1, 2, 3$ in SM

- $[\psi_i^n]$: $SU(3)_D$, $\mathbb{Z}_2$, and Lorentz invariant combinations of n ψ_i

- Assumption: chiral symmetry of ψ_i broken by EWSB $\boxed{m_i \sim \frac{\langle H \rangle^2}{\Lambda_H}}$

- Strong dynamics will not break $\mathbb{Z}_2$
  - $U(1)$ flavor symmetry of each ψ_i preserved   Vafa, Witten, 1984
  - $\langle \bar{\psi}_3 \psi_1 \rangle = \langle \bar{\psi}_3 \psi_2 \rangle = 0$ [similar to $U(1)_{EM}$ preservation in QCD]

- We will assume $m_1 < m_2 < m_3$, and $m_i \ll \mu_D$

Low-lying Spectrum below μ_D

- pseudo-Nambu-Goldstone bosons (pNGBs)
- $P \sim \bar{\psi}_1\psi_2,\ \kappa \sim \bar{\psi}_1\psi_3,\ \kappa' \sim \bar{\psi}_2\psi_3$
- Linear combinations of $\bar{\psi}_i\psi_i$: P' and P'' (QCD π^0 and η)

- "Dark" kaons κ and κ', lightest $\mathbb{Z}_2$-odd states, with **κ as DM**

- $\mathbb{Z}_2$-even right-handed neutrinos N_R (dark neutrons):
- $N_1 \sim \psi_1^2\psi_2,\ N_2 \sim \psi_1\psi_2^2,\ N_3 \sim \psi_1\psi_3^2,\ N_4 \sim \psi_2\psi_3^2$
- $M_{N_1} < M_{N_2} < M_{N_3} < M_{N_4}$

- $\mathbb{Z}_2$-even $[\psi_1^3]$ and $[\psi_2^3]$ spin-3/2 cannot mix with ν (Δ^{++} in SM)

- $\mathbb{Z}_2$-odd $X \sim \psi_1^2\psi_3,\ X' \sim \psi_2^2\psi_3,\ Y_{3/2} \sim \psi_3^3$ unstable, decay into κ, κ'

For $m_3 \ll m_1, m_2$, $Y_{3/2}$ lightest $\mathbb{Z}_2$-odd state, possibly a composite spin-3/2 DM candidate.

- Small quark masses: $M_N \sim \mu_D$ Corresponding to $\Lambda_{QCD} \sim 1$ GeV in QCD

- Estimate pNGB mass using Gell-Mann-Oakes-Renner realtion

$$M_\Pi^2 = 2b\mu_D \widehat{m}$$

- pNGBs collectively denoted by Π

- Average quark mass $\widehat{m}$ and b a constant

- SM kaons: $\widehat{m} \approx 50$ MeV, $m_K \approx 500$ MeV, $\Lambda_{QCD} \sim 1$ GeV $\Rightarrow b \sim 2.5$

$$\boxed{M_\Pi \sim \sqrt{5\mu_D \widehat{m}} \sim \langle H \rangle \sqrt{\frac{5\mu_D}{\Lambda_H}}}$$

- Assume $\mu_D \sim 1$ TeV

- Motivation: Extensions of EW sector, thermal relic DM, collider accessibility

- Later see that $\mu_D \sim 1$ TeV $\rightarrow$ DM mass $M_\kappa \sim 10$ GeV

- $M_\kappa \sim M_\Pi \sim 10$ GeV $\Rightarrow \Lambda_H \sim 1000$ TeV $\quad \left(\frac{\bar{\psi}_i \psi_i H^\dagger H}{\Lambda_H}\right)$

Neutrino Mass Generation

- Upon confinement: $[\psi_i^3] \to \mu_D^3 N_\alpha + \ldots$ and $[\psi_i^6] \to \mu_D^6 N_\alpha N_\beta + \ldots$

- The EFT will then yield

$$M_\alpha \bar{N}_\alpha N_\alpha + Y^{f\alpha}\, \tilde{H}^* \bar{L}_f\, N_\alpha + \mu_N^{\alpha\beta} \bar{N}_\alpha^c N_\beta + \text{H.C.}$$

M_α Dirac mass, $Y^{f\alpha}$ Yukawa couplings, and $\mu_N^{\alpha\beta}$ Majorana mass matrix (NANO)

- Estimates: $M_\alpha \approx M_N \approx \mu_D \quad ; \quad Y^{f\alpha} \sim \frac{\mu_D^3}{\Lambda_f^3} \quad ; \quad \mu_N^{\alpha\beta} \sim \frac{\mu_D^6}{\Lambda_N^5}$

- Inverse seesaw for SM neutrinos masses: $m_\nu \sim \frac{y^2 v_H^2 \mu_N}{M_N^2} \Rightarrow m_\nu \sim \frac{\mu_D^{10} v_H^2}{\Lambda_f^6 \Lambda_N^5}$

y and μ_N: typical eigenvalues of $Y^{f\alpha}$ and $\mu_N^{\alpha\beta}$

- Example: $m_\nu \sim 0.1$ eV for $\mu_D \sim 1$ TeV and $(\Lambda_f, \Lambda_N) \sim 10$ TeV

$\mu_N \sim 10$ MeV and $y \sim 10^{-3}$

DM Relic Density

- $\kappa\kappa \leftrightarrow \Pi^\dagger\Pi$ followed by fast decay of Π at freezeout $T \sim T_\star$:

$\Gamma(\Pi) > H_\star \sim g_\star^{1/2} T_\star^2 / M_{\text{Planck}}$ $M_{\text{Planck}} \approx 1.2 \times 10^{19}$ GeV; $g_\star \sim 50$

- Thermal contact with SM: $\frac{\bar{\psi}_i \psi_i H^\dagger H}{\Lambda_H} \to \xi \Pi^\dagger \Pi H^\dagger H$

$\xi \sim 2b\mu_D/\Lambda_H$ with $b \sim 2.5$

- $\Pi\, c \leftrightarrow \Pi\, c$: SM-DM thermal contact until $T_d \lesssim 1$ GeV (charm mass)

- pNGB scattering freeze-out: $x_{f.o.} = M_\kappa / T_\star \sim 20$

- If Π width $\Gamma_\Pi > H_\star$, could get correct relic density for

  $M_\Pi \sim M_\kappa$ and $M_\Pi \lesssim F_\Pi$ with $F_\Pi \sim \frac{\mu_D}{4\pi}$ Based on Buckley, Neil, 1209.6054

- Benchmark $M_\kappa \sim 10$ GeV $\to T_\star \sim 1$ GeV and $F_\Pi \sim 80$ GeV

A Concrete UV Model

- Vector-like fermions F and F'
- $(3,2,-1/2,+)$ and $(3,2,-1/2,-)$ under $SU(3)_D \times SU(2)_L \times U(1)_Y \times \mathbb{Z}_2$

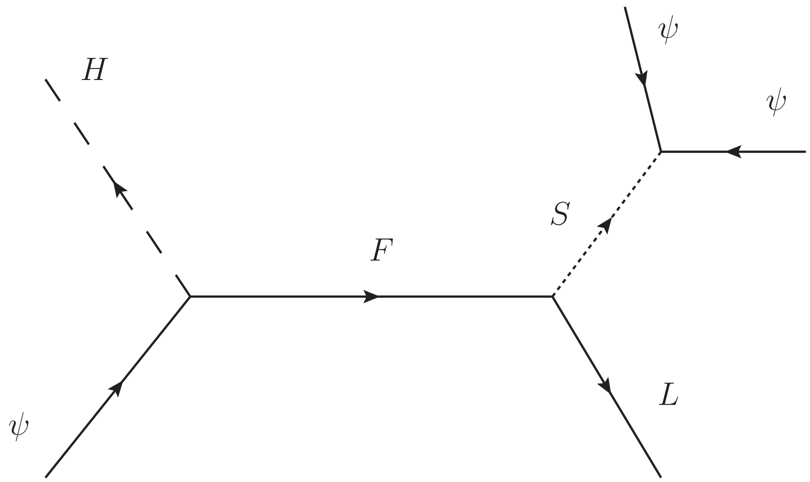
- Three $SU(3)_D$ triplet scalars S_a, with $a = e, \mu, \tau$
- $(3,1,0,+)$; flavor structure: avoid large LFV, *e.g.* $\mu^- \to e^-\gamma$

$$\begin{aligned}\mathcal{L}_{\rm UV} &= \lambda_1 \tilde{H}^* \bar{F} \psi_1 + \lambda_2 \tilde{H}^* \bar{F} \psi_2 + \lambda_3 \tilde{H}^* \bar{F}' \psi_3 + \lambda'_a S_a \bar{F} L_a \\ &+ \sum_{i,j=1}^{3} g_a^{ij} S_a \psi_i \psi_j \Big|_{\mathbb{Z}_2=+} + \mu_S S_e S_\mu S_\tau + \text{H.C.}\end{aligned}$$

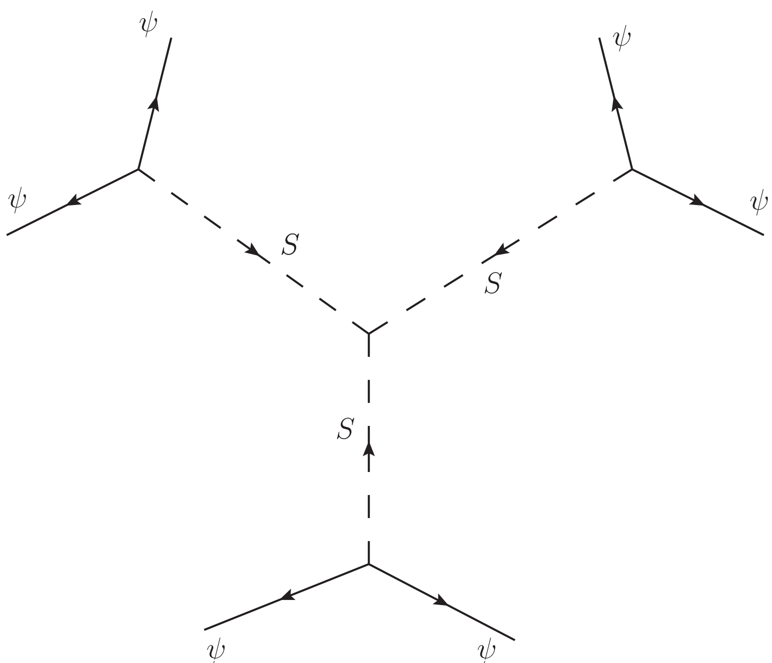
$$\boxed{\Lambda_f^{-3} \sim \frac{\lambda_i \, \lambda'_a \, g_{ja}}{M_F \, M_S^2} \quad ; \quad \Lambda_N^{-5} \sim \frac{g_{ia}^3 \, \mu_S}{M_S^6} \quad ; \quad \Lambda_H^{-1} \sim \frac{\lambda_i^2}{M_F}}$$

$\Lambda_H \sim 1000$ TeV	$\lambda_i^2 \sim 0.001$
Λ_f, $\Lambda_N \sim 10$ TeV	$\lambda'_i \sim 0.1$
$\mu_D \sim 1$ TeV	$g_i \sim 0.3$
M_F, $M_S \sim 1$ TeV	$\mu_S \sim 1$ GeV
$M_\kappa \sim 10$ GeV	

Benchmark Parameters



$\tilde{H}^* \bar{L} [\psi_i^3] / \Lambda_f^3$ ("Reindeer" diagram)

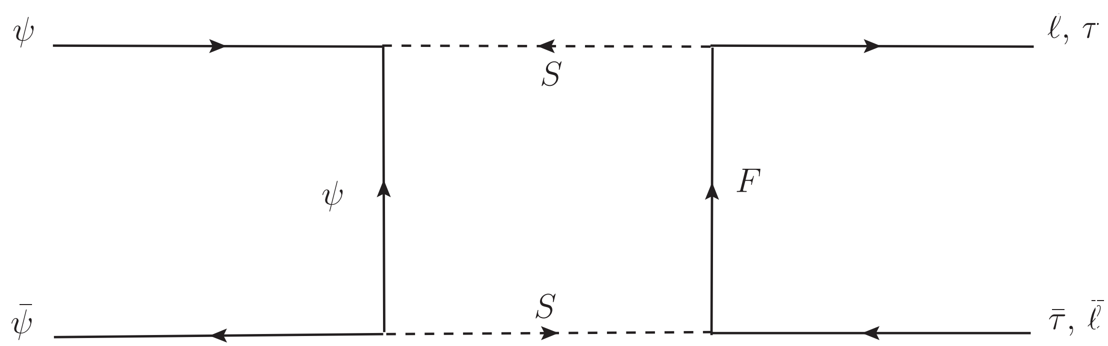


$[\psi_i]^6 / \Lambda_N^5$ ("Snowflake" diagram)

Dark pNGB Decays

- DM relic density: need sufficiently fast $\mathbb{Z}_2$-even Π decay
  - $\Pi\,\bar{N}_\alpha\gamma_5 N_\beta$ (like QCD), $Y^{f\alpha}\bar{H}^*\bar{L}_f N_\alpha$ allow for $\Pi \to \bar{\nu}\nu\bar{b}b$: <u>too slow</u>
  - $\Pi \to \bar{\nu}\nu$ extremely helicity-suppressed by $(m_\nu/M_\Pi)^2$

- UV model allows for an efficient decay channel



$$\Gamma(\Pi \to \tau\ell) \sim \frac{20}{16\pi}\left(\frac{g^2\lambda'^2}{16\pi^2}\right)^2\left(\frac{M_\Pi^2}{M_F^2}\right)^2\left(\frac{m_\tau}{M_\Pi}\right)^2\frac{F_\Pi^2}{M_\Pi}$$

  - τ dominant (helicity); factor of ~ 20 for amplitude multiplicity, 5 final states

- Benchmark: $\Gamma \sim 3\times 10^{-18}$ GeV $\sim 1/(100\,\mathrm{m}) \gg H_\star \sim 10^{-19}$ GeV

- $\mathbb{Z}_2$-odd κ' decay into DM κ cannot be too slow

- Avoid decay after BBN, $H_{\text{BBN}} \sim 10^{-24}$ GeV$\sim 1/\text{s}$

- $\kappa' \to \kappa\, l\, l$ with l any charged lepton or ν, no helicity suppression

- Mediated by the same type of UV model diagram as $\mathbb{Z}_2$-even case

- Similar to semileptonic meson decays in the SM

$$\Gamma(\kappa' \to \kappa\, l\, l) \sim 72 \frac{\Phi_3}{10} \left(\frac{g^2 \lambda'^2}{16\pi^2}\right)^2 \frac{M_{\kappa'}^5}{M_F^4} \left(1 - \frac{M_\kappa^2}{M_{\kappa'}^2}\right)^5$$

- $\Phi_3 \sim 1/(8\pi^2) 1/(16\pi)$, factor of ~ 72 for final states (18) and sum over amplitudes;

$\sim 1/10$ phase space suppression   Ecker, Pich, de Rafael, 1987

- Benchmark point: $\Gamma(\kappa' \to \kappa\, l\, l) \sim \left(1 - \frac{M_\kappa^2}{M_{\kappa'}^2}\right)^5 10^{-20}$ GeV

- For $\delta M / M_{\kappa'} \sim 0.3$ we get $\Gamma \sim 10^{-22}$ GeV ($\gg H_{\text{BBN}}$)

Experimental Signatures

- Direct detection:

• Higgs-mediated nucleon scattering from $\xi \kappa^\dagger \kappa H^\dagger H$
E.g. Burgess, Pospelov, ter Veldhuis, 2000; Cline, Kainulainen, Scott, Weniger 2013; Duerr, Fileviez Pérez, Smirnov, 2015

$$\sigma_{SI} = \frac{\xi^2 f_n^2 \mu_n^2 m_n^2}{4\pi M_H^4 M_\kappa^2}$$

• μ_n nucleon-κ reduced mass, m_n nucleon mass, $f_n \approx 0.3$ nucleon-Higgs coupling
• For $M_\kappa \gg m_n$, $\mu_n \approx m_n$, we have in our model

$$\sigma_{SI} \sim \text{few} \times 10^{-12} \left(\frac{\mu_D}{\Lambda_H}\right)^2 \text{GeV}^{-2} \sim 10^{-39} \left(\frac{\mu_D}{\Lambda_H}\right)^2 \text{ cm}^2$$

• Benchmark: $\mu_D \sim 1$ TeV, $\Lambda_H \sim 1000$ TeV $\rightarrow \sigma_{SI} \sim$ few $\times 10^{-45}$ cm^2, roughly at or below current XENON1T bound experiment XENON Collaboration, 2017

- Gravitational waves

• $SU(3)_D$ phase transition first order if 100 GeV $\lesssim T_c \lesssim \mu_D$ (3 massless dark quarks)
Pisarski, Wilczek, 1984

• Primordial gravitational waves, signal for future space based detectors (LISA)

- Indirect detection via $\kappa^\dagger \kappa \to \Pi^\dagger \Pi$

- $M_\kappa \sim 10$ GeV close to exclusion limits Planck Collaboration, 2016

- Target for future observations

- Colliders

$$\text{Br}(H \to \Pi^\dagger\,\Pi) \sim \text{Br}(H \to \kappa^\dagger\,\kappa, \kappa'^\dagger \kappa') \sim 10\% \text{ (Benchmark)}$$

- For decay length ~ 100 m, $H \to \Pi^\dagger\Pi$ part of "invisible" decay searches

- Current or future data can constrain the benchmark Br(Higgs $\to$ pNGB pair)

- Distinct signal (UV Model):

$$\boldsymbol{H \to \tau^+ \tau^+ (e/\mu)^- (e/\mu)^-}$$

- Correlated with gravitational waves (massless "dark" quarks $\to$ light pNGBs)

- Could be probed at proposed MATHUSLA detector Chou, Curtin, Lubatti, 2016

Conclusions

- Dark matter and neutrino masses strong evidence for new physics
- Often unrelated new physics invoked to explain them

- We propose a common origin: "dark" sector compositeness

- "Dark" $SU(3)_D$ and three massless dark quarks $\oplus$ EFT
- Chiral symmetry breaking by SM Higgs

- Dark neutrons $\leftrightarrow$ right-handed Dirac neutrinos
- Inverse seesaw with "dark" neutron-anti-neutron oscillation

- pNGB "dark" kaons $\leftrightarrow$ dark mater

- Confinement at $\sim$ TeV $\rightarrow$ $\sim$ 10 GeV dark matter
- UV model: $\boldsymbol{H \rightarrow \tau\tau l\,l}$
- Potentially correlated with primordial gravitational wave signal