Two Models of TeV-scale Decaying Dark Matter

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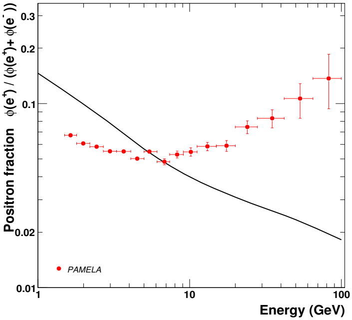
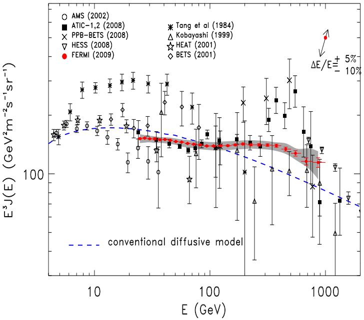
(William and Mary)

Well, mostly one model...

Carone, Erlich and Primulando, Phys. Rev. D **82**, 055028 (2010)

Motivation





PAMELA

Fermi LAT

O. Adriani *et al.* [PAMELA Collaboration], Nature **458**, 607-609 (2009).

A. A. Abdo *et al.* [The Fermi LAT Collaboration], Phys. Rev. Lett. **102**, 181101 (2009).

Possibilities, Part I

• Dark matter annihilates mostly to leptons, with a suitable "boost factor" in the cross section (e.g., Sommerfeld enhancement).

• Dark matter decays mostly to leptons, with an extremely long lifetime. Typically,

$$M_{DM} \sim \text{a few TeV}$$

and

$$\tau_{DM} \sim 10^{26}\ \text{s}$$

can describe the data.

Model-building question:

What is the origin of the long lifetime?

Possibilities, Part II

• Suppression by powers of a high scale:

e.g., for dark matter coupling $g_{eff}\,\psi \bar{f}_L f_R +$ h.c., we require $g_{eff} \sim 10^{-26}$ for $m_\psi \sim 3$ TeV. Can be obtained if

$$g_{eff} \sim (m_\psi/M)^p$$

with $M \sim \mathcal{O}(10^{16})$ GeV and $p = 2$.

•. Suppression by an insanely small dimensionless coupling:

't Hooft: nonperturbative, non-Abelian gauge field dynamics generates exponentially suppressed operators that violate anomalous global symmetries

$$g_{eff} \sim \exp(-8\pi^2/g^2)$$

Our goal: incorporate this effect in a decaying dark matter model...

The Heart of the Model:

Four left-handed doublets under a dark-sector SU(2) gauge group:

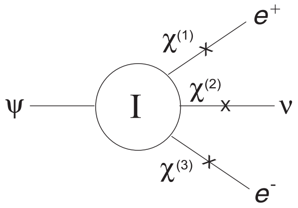
$$\psi_L, \quad \chi_L^{(1)}, \quad \chi_L^{(2)}, \quad \chi_L^{(3)}$$

Instanton-induced operators can lead to three-body decays:

$$\psi \to \chi^{(1)}\,\chi^{(2)}\,\chi^{(3)}$$

If ψ is otherwise stable, decay rate is exponentially suppressed.

Our strategy: assume heavy χ's with the right quantum numbers to mix with ordinary leptons:



The Model in Detail

Dark Gauge Group: G_D =SU$(2)_D \times$U$(1)_D$

Quantum numbers (subscripts = ordinary hypercharges ± 1 and 0):

ψ_L	$(\mathbf{2}, -1/2)_0$	ψ_{uR}, ψ_{dR}	$(\mathbf{1}, -1/2)_0$
$\chi_L^{(1)}$	$(\mathbf{2}, +1/6)_+$	$\chi_{uR}^{(1)}, \chi_{dR}^{(1)}$	$(\mathbf{1}, +1/6)_+$
$\chi_L^{(2)}$	$(\mathbf{2}, +1/6)_0$	$\chi_{uR}^{(2)}, \chi_{dR}^{(2)}$	$(\mathbf{1}, +1/6)_0$
$\chi_L^{(3)}$	$(\mathbf{2}, +1/6)_-$	$\chi_{uR}^{(3)}, \chi_{dR}^{(3)}$	$(\mathbf{1}, +1/6)_-$
H_D	$(\mathbf{2}, 0)_0$	η	$(\mathbf{1}, 1/6)_0$

- Non-zero $\langle H_D \rangle$ and $\langle \eta \rangle$ break G_D completely.

- The theory has a perturbatively unbroken U$(1)_\psi$ global symmetry:

Terms involving $\overline{\psi^c}\psi$:

$\mathrm{U}(1)_\psi$ charge $+2$, $\mathrm{U}(1)_D$ charge -1. No Higgs fields with the $\mathrm{U}(1)_D$ charge ± 1.

Terms involving a χ fermion and ψ or ψ^c:

$\mathrm{U}(1)_\psi$ charge ± 1, $\mathrm{U}(1)_D$ charges $\pm 1/3$ or $\pm 2/3$. No Higgs field with these $\mathrm{U}(1)_D$ charges.

Terms involving a standard model fermion and ψ or ψ^c:

$\mathrm{U}(1)_\psi$ charge ± 1, $\mathrm{U}(1)_D$ charge $\pm 1/2$. Again, no Higgs field with these $\mathrm{U}(1)_D$ charges.

There are no renormalizable invariants that break $\mathrm{U}(1)_\psi$.

Note: Non-renormalizable, Planck-suppressed effects are negligible compared to the instanton effects we consider.

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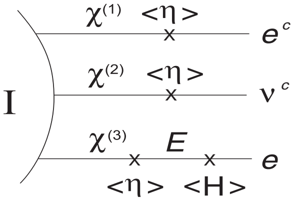
The remaining ingredient

$$E_L \sim E_R \sim (\mathbf{1}, 0)_-$$

i.e., a vector-like lepton pair, same quantum numbers as e_R. Leads to mass mixing after G_D is broken:



I = Instanton vertex, arising from

$$\begin{aligned}\mathcal{L}_I &= \frac{C}{6\, g_D^8} \exp\left(-\frac{8\pi^2}{g_D^2}\right)\left(\frac{m_\psi}{v_D}\right)^{35/6} \frac{1}{v_D^2}\,(2\,\delta_{\alpha\beta}\delta_{\gamma\sigma} - \delta_{\alpha\sigma}\delta_{\beta\gamma}) \\ &\cdot \left[(\overline{\chi_{L\,\beta}^{(2)\,c}}\psi_L^\alpha)(\overline{\chi_{L\,\sigma}^{(1)\,c}}\chi_L^{(3)\,\gamma}) - (\overline{\chi_{L\,\beta}^{(1)\,c}}\psi_L^\alpha)(\overline{\chi_{L\,\sigma}^{(2)\,c}}\chi_L^{(3)\,\gamma})\right] + \text{ h.c.}\,.\end{aligned}$$

Typical mixing angles:

$$\begin{array}{ll} \chi_L^{(1)} - e_R^c & \mathcal{O}(\langle\eta\rangle/M_\chi) \\ \chi_L^{(2)} - \nu_R^c & \mathcal{O}(\langle\eta\rangle/M_\chi) \\ \chi_L^{(3)} - e_L & \mathcal{O}[\langle\eta\rangle\langle H\rangle/(M_\chi M_E)] \end{array}$$

For each $\approx 10^{-2}$, one finds

$$\Gamma(\psi \to \ell^+\ell^-\nu) \approx \frac{1}{g_D^{16}} \exp(-16\pi^2/g_D^2) \left(\frac{m_\psi}{v_D}\right)^{47/3} m_\psi \quad .$$

For example, for $m_\psi = 3.5$ TeV and $v_D = 4$ TeV, one obtains a dark matter lifetime of 10^{26} s for

$$g_D \approx 1.15$$

Communication with the Visible Sector

Higgs Portal (simplified version):

$$V = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2 - \mu_D^2 H_D^\dagger H_D + \lambda_D (H_D^\dagger H_D)^2 + \lambda_{mix}(H^\dagger H)(H_D^\dagger H_D)$$

Let ψ denote lightest ψ_u-ψ_d mass eigenstate. Annihilation via exchanges of the Higgs field mass eigenstates h_1, h_2:

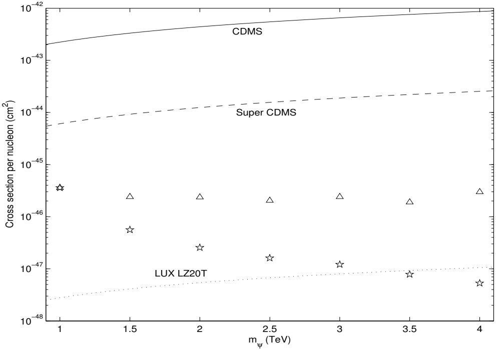
$$\psi\bar{\psi} \to W^+W^-, ZZ, h_i h_i, t\bar{t}$$

For $v_D = 4$ TeV, the following sample points yield $\Omega_D h^2 \approx 0.1$:

m_ψ(TeV)	$\sqrt{2\lambda v^2}$(TeV)	$\sqrt{2\lambda_D v_D^2}$(TeV)	λ_{mix}	m_1(GeV)	m_2(TeV)
1.0	0.19	1.98	0.30	117	1.99
1.5	0.18	2.98	0.40	122	2.98
2.0	0.19	3.97	0.57	127	3.97
2.5	0.18	4.97	0.65	125	4.97
3.0	0.18	5.96	0.80	122	5.96
3.5	0.18	6.96	0.90	127	6.96
4.0	0.18	7.95	1.10	117	7.95

Higgs mixing also determines dark matter-nucleon scattering cross section ($h_1 = h\cos\theta - h_D \sin\theta$, $h_2 = h\sin\theta + h_D\cos\theta$):

$$\mathcal{L}_{int} = \sum_q \frac{m_q m_\psi \sin\theta\cos\theta}{v\, v_D} \left(\frac{1}{m_1^2} - \frac{1}{m_2^2} \right) \bar{\psi}\psi\, \bar{q}q \ ,$$



$\triangle$'s = sample points in previous table

Conclusions and an Advertisement

- Long lifetime for a decaying dark matter candidate might arise from a small coupling due to nonperturbative gauge dynamics.
- Work presented here: existence proof of a viable model.
- A possibility: simpler models with a new non-Abelian gauge groups coupling directly to leptons?
- Advertisement: Dark matter decay can be a consequence of higher-dimension operators arising from heavy particle exchange and Planck-suppressed corrections. See:

C. D. Carone, R. Primulando,
"A Froggatt-Nielsen Model for Leptophilic Scalar Dark Matter Decay,"
Phys. Rev. **D84**, 035002 (2011). [arXiv:1105.4635 [hep-ph]].