Lattice Studies of SU(2) Dark Matter

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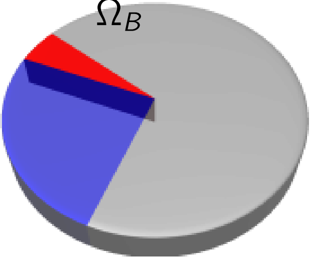
$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$



Light sector is composite

(and complicated)

Why not dark matter

- Natural way to produce stable, neutral particles
- Can arise from other models

SU(2) gauge, 2 fundamental fermions

- A simple model with complex phenomenology

SIMP [1]

Light asymmetric [2]

Massive symmetric [3]

Dark nuclei [4]

As technicolor (light asymmetric)

$$f_\pi = 256 GeV, \;\; m_\pi = 0 + \text{ SM corrections}$$

[1] Y. Hochberg et al. Phys. Rev. Lett. **115**, (2015)

[2] R. Lewis, C. Pica and F. Sannino, Phys. Rev. D **85**, (2012)

[3] M. R. Buckley and E. T. Neil, Phys. Rev. D **87**, (2013)

[4] W. Detmold et al., Phys. Rev. D **90** (2014)

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\ \mu\nu} + \bar{\psi}\left(i\partial\!\!\!/ - m\right)\psi$$

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\ \mu\nu} + \bar{\psi}i\partial\!\!\!/\psi + \frac{im}{2}\left[Q^T(-i\sigma_2)CEQ + \Big(Q^T(-i\sigma_2)CEQ)\Big)^\dagger\right]$$

$$Q = \begin{pmatrix} u_L \\ d_L \\ \tilde{u}_L = -i\sigma_2 C\bar{u}_R^T \\ \tilde{d}_L = -i\sigma_2 C\bar{d}_R^T \end{pmatrix} \text{ and } E = \begin{pmatrix} 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & +1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

$$SU(4) \to SP(4)$$

Five Goldstone bosons

$$\begin{aligned}
\pi^a &= Q^T(-i\sigma_2)CEY^a\gamma_5 Q + \text{h.c.} \\
&= \begin{cases} \bar{\psi}\gamma_5\tau^a\psi \text{ if } a = 1,2,3 \\ \psi^T\gamma_5(-i\sigma_2)C(-i\tau^2)\psi + \text{h.c. if } a = 4,5 \end{cases}
\end{aligned}$$

TC

	Y	Q_L	Q_{EM}
$\psi_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	0	**2**	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$
$\tilde{u}_L$	$\frac{1}{2}$	0	$\frac{1}{2}$
$\tilde{d}_L$	$-\frac{1}{2}$	0	$-\frac{1}{2}$

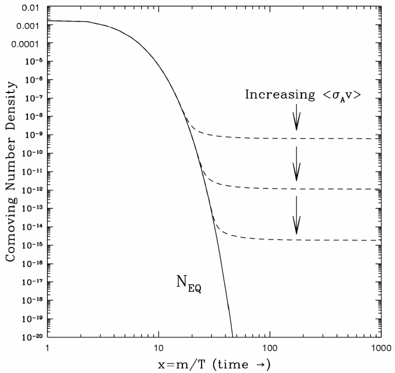
EC

	Y	Q_L	Q_{EM}
u_L	$\frac{1}{2}$	0	$\frac{1}{2}$
d_L	$-\frac{1}{2}$	0	$-\frac{1}{2}$
$\tilde{u}_L$	$\frac{1}{2}$	0	$\frac{1}{2}$
$\tilde{d}_L$	$-\frac{1}{2}$	0	$-\frac{1}{2}$

	Y	Q_L	Q_{EM}	P
(π^+, π^0, π^-)	0	**3**	(1,0,-1)	-
ϕ, ϕ^*	0	0	0	$+$

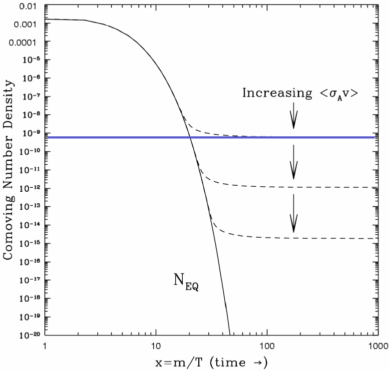
Symmetric

- Thermal production
- Indirect detection suppressed (in χPT)
- Direct detection



Asymmetric

- Dark baryogenesis [5]
- No indirect detection (nucleosynthesis)
- Direct detection
- SM corrections break $SU(4)$ $\rightarrow$ nonzero m_ϕ



[5] S. Nussinov, Phys. Lett. B **165**, 55 (1985)

Direct detection

At low energies

- No Z-exchange
- Higgs exchange
- Charge radius, electric dipole moment ($m_u \neq m_d$)
- Polarizability

Electromagnetic form factor:

$$\langle \pi(\vec{p_f}|V_\mu(0)|\pi(\vec{p_i})\rangle = F_\pi(Q^2)(p_i + p_f)_\mu,$$
$$Q^2 = (\vec{p_f} - \vec{p_i})^2 - (E_\pi(\vec{p_f}) - E_\pi(\vec{p_i}))^2$$

With the electromagnetic current

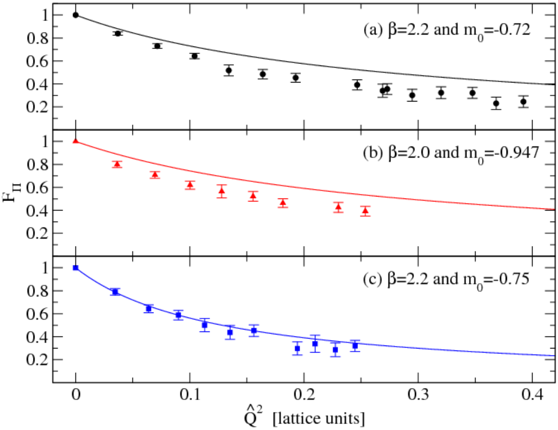
$$V_\mu(x) = \frac{1}{2}V_\mu^u(x) - \frac{1}{2}V_\mu^d(x) \text{ and}$$
$$V_\mu^u(x) = \frac{1}{2}\bar{u}(x+\hat{\mu})(1+\gamma_\mu)U_\mu^\dagger(x)u(x) - \frac{1}{2}\bar{u}(x)(1-\gamma_\mu)U\mu(x)u(x+\hat{\mu})$$

Vector meson dominance in QCD

$$F_{\pi^+}(Q) \approx \left(\frac{m_\rho^2}{m_\rho^2 + Q^2}\right)$$

$$F_{K^+}(Q) \approx \frac{2}{3}\left(\frac{m_\rho^2}{m_\rho^2 + Q^2}\right) + \frac{1}{3}\left(\frac{m_\phi^2}{m_\phi^2 + Q^2}\right)$$

Also seems to work in SU(2) lattice results



A. Hietanen, R. Lewis, C. Pica and F. Sannino, JHEP **1412**, 130 (2014)

Charge radius:

$$L_B = ie\frac{d_B}{\Lambda^2}\phi^* \overleftrightarrow{\partial}_\mu \phi \partial_\nu F^{\mu\nu}$$

$$\frac{d_B}{\Lambda^2} = \frac{m_{\rho_u}^2 - m_{\rho_d}^2}{2m_{\rho_u}^2 m_{\rho_d}^2}$$

DM - nucleon scattering cross section:

$$\sigma_p^\gamma = \frac{m_\phi^2 m_N^2}{4\pi(m_\phi + m_N)}\left(\frac{8\pi\alpha d_B}{\Lambda^2}\right)^2$$

Higgs exchange:

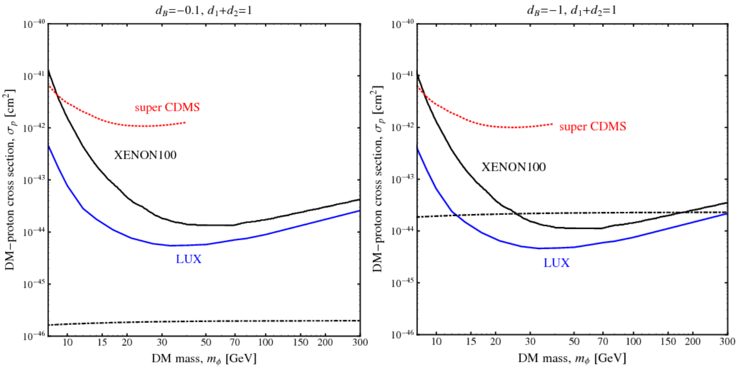
$$\frac{d_1}{\Lambda} h \partial_\mu \phi^* \partial^\mu \phi + \frac{d_2}{\Lambda} m_\phi^2 h \phi^* \phi$$

With ordinary Higgs interactions:

$$\sigma_A = \frac{\mu_A^2}{4\pi} \left[Z f_p + (A - Z) f_n \right]^2$$

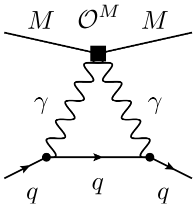
$$f_n = d_H f \frac{m_p}{m_H^2 m_\phi}, \qquad f_p = f_n - \frac{8\pi\alpha d_B}{\Lambda^2},$$

$$d_H = -\frac{d_1 + d_2}{v_{ew}\Lambda}, \qquad f \sim 0.3,$$



d_B=−0.1, d_1+d_2=1
d_B=−1, d_1+d_2=1
DM−proton cross section, σ_p [cm^2]
DM mass, m_ϕ [GeV]
super CDMS
XENON100
LUX
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10
15
20
30
50
70
100
150
200
300

The Electric Polarizability



$$L_{EP} = \frac{1}{24 f_\pi^2} D_\mu \pi^+ D^\mu \pi^- \phi^* \phi$$
$$+ \frac{d_4}{f_\pi^4} D_\mu \pi^+ D^\mu \pi^- m_\phi^2 \phi^* \phi + \frac{d_5}{f_\pi^4} D_\mu \pi^+ D^\mu \pi^- \partial_\mu \phi^* \partial^\mu \phi$$

In stealth dark matter T. Appelquist *et al.*, Phys. Rev. Lett. **115**, no. 17, 171803 (2015)

In a classical constant background field

$$m_\phi^{(\mathcal{E})} = m_\phi^0 + \frac{1}{2} 4\pi\alpha_E \mathcal{E}^2 + \dots ,$$

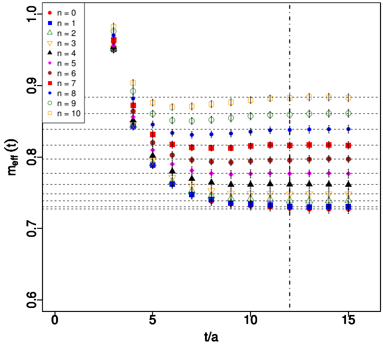
On the lattice add the background field

$$U_\mu^{(E)} = e^{iQA_\mu(x)} e^{iQEN_t x_3 \delta_{\mu,4}\delta x_4, N_t - 1}, \quad A_\mu(x) = (0, 0, -Ex_4, 0),$$

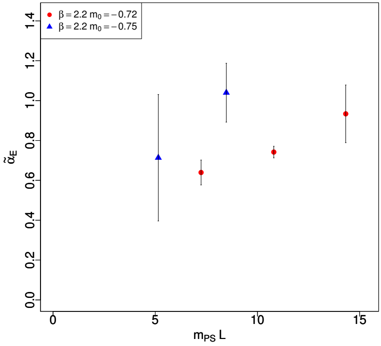
$$E = \frac{2\pi n}{qN_t N_L}$$

And just measure the mass

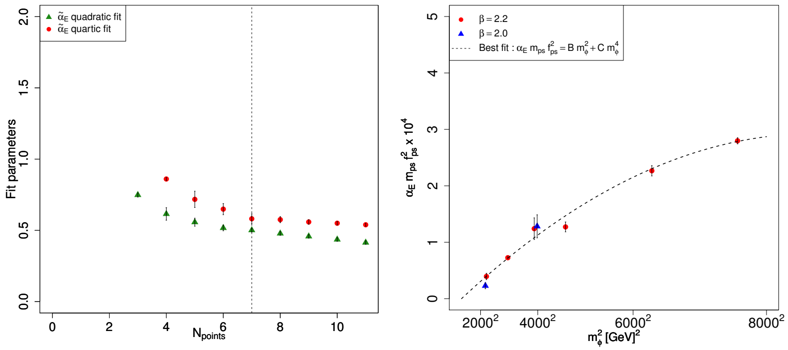
$$am_\phi^{(\mathcal{E})} = am_\phi^0 + \frac{1}{2} 4\pi\tilde{\alpha}_E E^2, \quad \tilde{\alpha}_E = \frac{\alpha_E}{4\pi\alpha a^3}$$



n = 0
n = 1
n = 2
n = 3
n = 4
n = 5
n = 6
n = 7
n = 8
n = 9
n = 10
$m_{eff}(t)$
t/a



$\beta = 2.2\ m_0 = -0.72$
$\beta = 2.2\ m_0 = -0.75$
$\tilde{\alpha}_E$
$m_{PS}\ L$

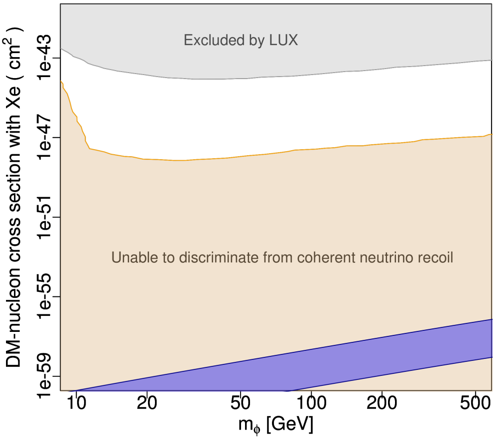


$\tilde{\alpha}_E$ quadratic fit
$\tilde{\alpha}_E$ quartic fit
Fit parameters
N_{points}
0.0
0.5
1.0
1.5
2.0
0
2
4
6
8
10
$\beta = 2.2$
$\beta = 2.0$
Best fit : $\alpha_E\, m_{ps}\, f_{ps}^2 = B\, m_\phi^2 + C\, m_\phi^4$
$\alpha_E\, m_{ps}\, f_{ps}^2 \times 10^4$
$m_\phi^2\ [\mathrm{GeV}]^2$
2000^2
4000^2
6000^2
8000^2
0
1
2
3
4
5

We get the per nucleon rate

$$\sigma(Z,A) = \frac{Z^4}{A^2}\frac{9\pi\alpha^2\mu_{n\phi}(M_F^A)^2}{R^2}\alpha_E^2,$$

$$\text{with } R = 1.2A^{1/3}$$



Excluded by LUX
Unable to discriminate from coherent neutrino recoil
DM-nucleon cross section with Xe (cm^2)
1e-43
1e-47
1e-51
1e-55
1e-59
10
20
50
100
200
500
m_ϕ [GeV]

SU(2) with 2 flavours

- A template for several DM models
- Light stable baryons
- Not very constrained by direct detection
- Higgs exchange from χPT