The Scale of Dark QCD

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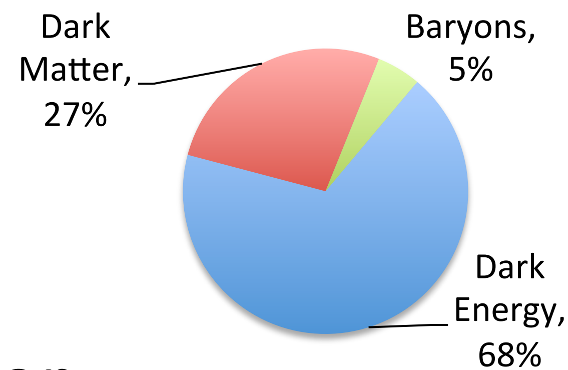
Based on arxiv:1306.4676 (with Yang Bai)

Outline

- Motivation
- The mass of Asymmetric DM
- $M_{DM} \sim M_p$ from Infrared Fixed Points
- Creating a DM and Baryon Asymmetry
- Phenomenology

Asymmetric DM



- The universe after Planck
- Similar amounts of dark and visible (baryonic) matter
- Baryon energy density determined by baryon asymmetry and proton mass $\rho_B = n_B M_p$
- Similar for DM? Same asymmetry? $n_{DM} \sim n_B$

The Mass of ADM

- If $n_{DM} \sim n_B$, we need $M_{DM} \approx 5M_p$ to obtain the correct DM energy density
- Generic weak scale particle mass anywhere from MeV (electron) to 100s of GeV (top)
- Instead M_p is almost independent of the weak scale: $M_p \sim \Lambda_{QCD}$
- More natural explanation of $M_{DM} \sim M_p$?

Dark QCD

- DM is composite "techni-Baryon" of new confining $SU(N_d)$ gauge group – dark QCD
- Mass set by confinement scale Λ_{dQCD}
- Depends on coupling in UV and on particle content – still no relation with QCD scale

Previous attempts using "mirror" symmetry: Introduce full copy of SM, demand equal couplings in the UV. See e.g.

Foot & Volkas, 2004; An, Chen, Mohapatra, Zhang, 2010

Particle Content

Field	$SU(N_c)_{\text{QCD}}$	$SU(N_d)_{\text{dark}}$	multiplicity
SM fermion	N_c	1	n_{f_c}
SM scalar	N_c	1	n_{s_c}
DM fermion	1	N_d	n_{f_d}
DM scalar	1	N_d	n_{s_d}
joint fermion	N_c	N_d	n_{f_j}
joint scalar	N_c	N_d	n_{s_j}

[Vector-like (Dirac) fermions, complex scalars]

Perturbative Fixed Points

- Beta function for $SU(N_c) \times SU(N_d)$ system

$$\beta_c(g_c, g_d) = \frac{g_c^3}{16\pi^2}\left[\frac{4}{3}T(R_f)(n_{fc} + N_d\, n_{fj}) - \frac{11}{3}C_2(G_c)\right]$$ 1-Loop

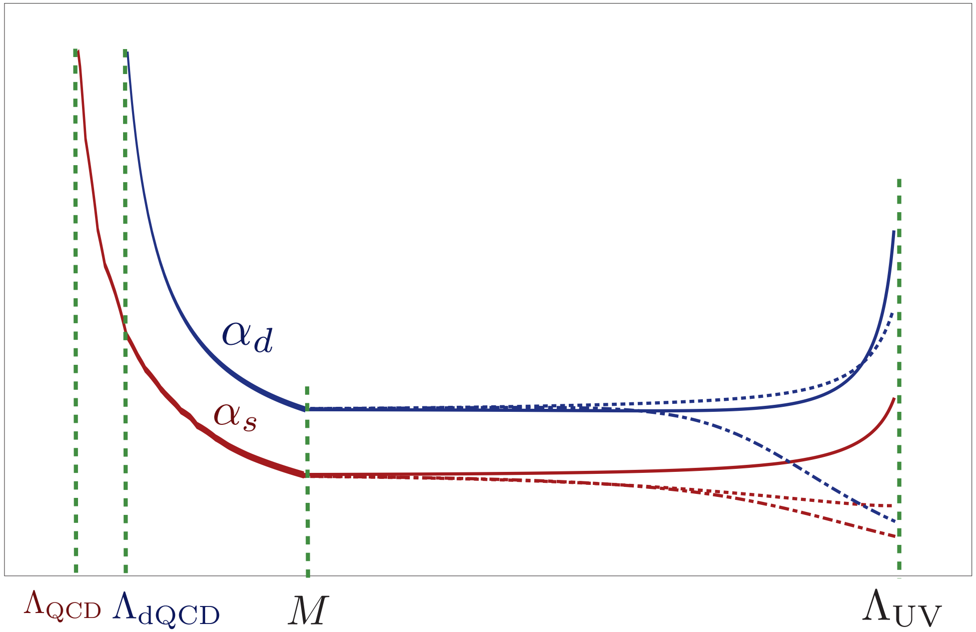
$$+ \frac{g_c^5}{(16\pi^2)^2}\left[\left(\frac{20}{3}C_2(G_c) + 4C_2(R_f)\right)T(R_f)(n_{fc} + N_d\, n_{fj}) - \frac{34}{3}C_2^2(G_c)\right]$$ 2-Loop single

$$+ \frac{g_c^3 g_d^2}{(16\pi^2)^2}\left[4C_2(R_f)T(R_f)N_d\, n_{fj}\right]$$ 2-Loop mixed

- Perturbative FP: $\beta_c = \beta_d = 0 \quad \text{for } \frac{g_{c,d}^2}{4\pi} \ll 1$

How does this help?

Running - Schematic



- FP predicts ratio of couplings at intermediate scale M
- Bi-fundamentals decouple at M
- Independent running, but similar confinement scales

$$\Lambda_{dQCD} \sim \Lambda_{QCD}$$

Looking for models

- Choose particle content
- Solve FP equation $\beta_c = \beta_d = 0$
- Check $\alpha_c^* < \alpha_c(M_t)$
- Determine M using $\alpha_c(M_t)$
- Estimate confinement scale of dQCD from running of α_d below M
- No free adjustable parameters!

A Specific Model

- 7 QCD fermions
- 2 QCD scalars
- 7 dQCD fermions X_i
- 1 dQCD scalar
- 2 joint fermions $Y_{1,2}$
- 1 joint scalar Φ

- Fixed points:

  $\alpha_s^* = 0.090 \quad \alpha_d^* = 0.168$

  $M = 870\ GeV$

- DM mass:

  $M_{DM} \approx 3.5\ GeV$

DM mass estimate:

$$\alpha_d(\Lambda_{dQCD}) \equiv \frac{\pi}{4}$$

$$M_{DM} \approx 1.5 * \Lambda_{dQCD}$$

Asymmetry

- From decay of a heavy Majorana fermion

$$\mathcal{L} \supset k_i \bar{Y}_1 \Phi N_i + \text{h.c.}$$

- Asymmetry in bi-fundamental fields
- Decay to quarks, dark quarks and leptons via

$$\mathcal{L} \supset \kappa_1 \, \Phi \, \bar{Y}_1^c \, Y_2 + \kappa_2 \, \Phi \, \bar{Y}_2 \, e_R + \kappa_3 \, \Phi \, \bar{X}_L \, d_R + \text{h.c.}$$

Baryon and Dark Asymmetries

- Per unit asymmetry, get two units of (B-L) and one unit of dark Baryon number
- After EW Sphalerons:

$$\frac{|n_D|}{n_B} = \frac{79}{56} \approx \frac{7}{5}$$

- Energy densities:

$$\frac{\rho_{DM}}{\rho_B} = \frac{7}{5}\,\frac{3.5\ \mathrm{GeV}}{0.94\ \mathrm{GeV}} \approx 5$$

Phenomenology

- Direct detection
  - Mediated by bi-fundamental fields

$$\frac{\kappa_3^2}{M_\Phi^2}\bar{X}_L\gamma_\mu X_L \bar{d}_R\gamma^\mu d_R$$

  - Order $10^{-40}\ \mathrm{cm}^2$ (CDMS/CoGeNT/CRESST range)
- No indirect detection
- Collider: Pair production of bi-fundamentals

  Jets + missing energy, or exotic jets

Conclusions

- Infrared fixed points can be used to relate DM and proton masses
- Possible road to build more "natural" models of asymmetric DM
- One proof of concept model, with interesting phenomenology
- Future: Lots of room for model building, collider studies, flavor, DM dynamics, etc.

Also recent work by Hambye, Strumia and Kearney, Pierce

THANK YOU

Dark Pions

- Must decay, otherwise could dominate relic density
  - Mass through Higgs portal (GeV-ish)
  - Decay through same operator as direct detection
  - Either to jets or QCD pions, depending on mass
- Lifetime: Possibly stable at colliders
  - Missing energy or displaced vertices

Collider (LHC) Signals

- Pair production of messenger fields Φ
- Decay to QCD and exotic jets
- If dark pions are long lived
  - Di-jet plus large missing energy: Already probed at LHC
- With prompt dark pion decay
  - Missing energy only from dark Baryons inside jets