# Exploring the cosmological dark matter coincidence with infrared fixed points

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PAPER COMING SOON

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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# The cosmological coincidence

Large range of DM candidates

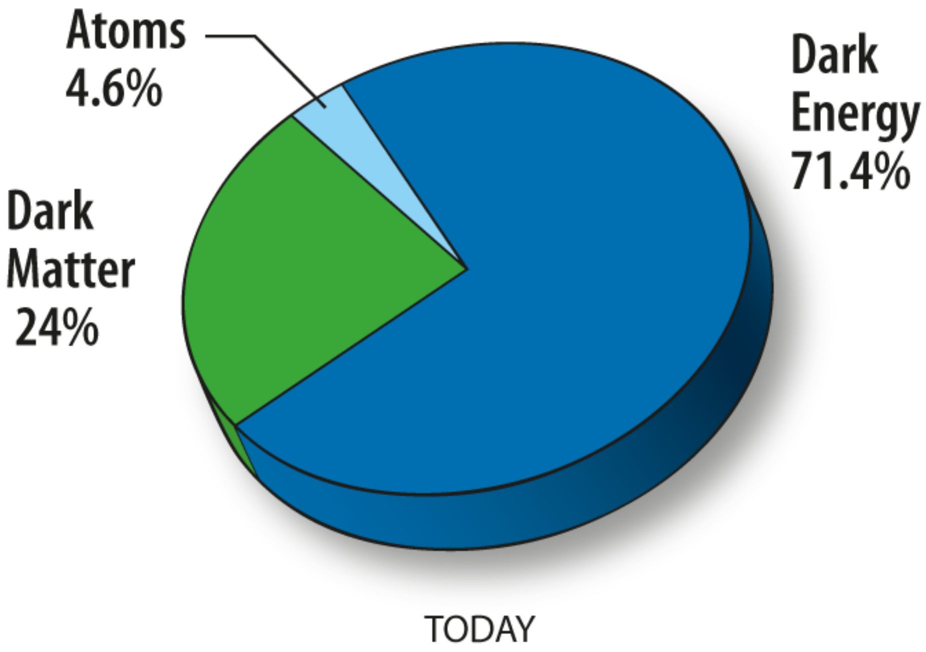
- Axions, WIMPs, sterile neutrinos, PBHs…
- How to guide our model building?

**Clues** from current observational evidence:

- Apparent coincidence between the present-day cosmological mass densities of dark and visible matter

$$\boxed{\Omega_{\rm DM} \simeq 5\Omega_{\rm VM}}$$

We take this to be a hint at some underlying connection between visible and dark matter



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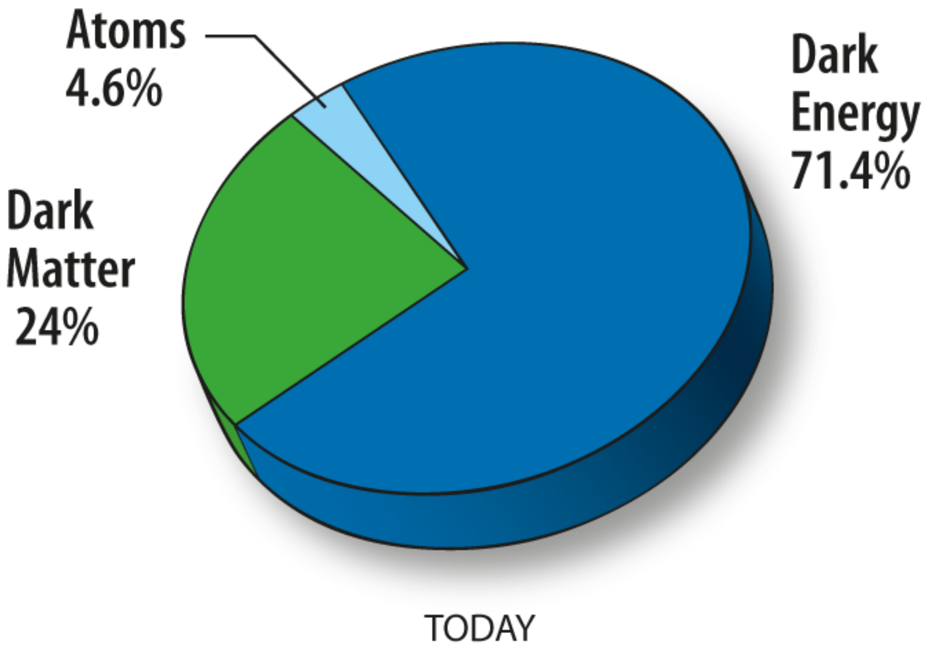


Our goal is to build models in which the mass densities of visible and dark matter are naturally of a similar order of magnitude

# How do we explain this coincidence?

The coincidence problem has two distinct parts: $\Omega_X = n_X \times m_X$

Relating number densities

$$n_B \sim n_D$$

Relating particle masses

$$m_B \sim m_D$$

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$\boxed{n_B \sim n_D}$

The **visible** number density: asymmetry between baryons and antibaryons (or a nonzero baryon number $B_V$)

$$\Omega_{\rm VM} \equiv \frac{\rho_p - \rho_{\bar{p}}}{\rho_c} \simeq \frac{\rho_p}{\rho_c}$$

proton

critical

In Asymmetric Dark Matter (ADM) models there exists a similar asymmetry in a dark baryon number $B_D$

Wide range of ADM literature where $n_B \sim n_D$

Most ADM models do not motivate $m_B \sim m_D$

These are **not** satisfactory explanations of the coincidence problem

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The **visible** baryon mass: largely from the QCD confinement scale $\Lambda_{QCD}$

Consider dark matter candidates that are baryon-like bound states of a QCD-like confining gauge group $SU(3)_{dQCD}$ with $\Lambda_{\rm QCD} \sim \Lambda_{\rm dQCD}$

There are two main ways to achieve this:

1. Introduce a symmetry between $SU(3)_{QCD}$ and $SU(3)_{dQCD}$ e.g. **AR**, Volkas: 2101.07421
2. The gauge couplings of the two groups can evolve to some ***infrared fixed point***

# Infrared Fixed Points & Dark QCD

**Bai and Schwaller (2013)** [1306.4676]

- To relate confinement scales, only need to relate coupling constants in the IR

| Field | $SU(3)_{\mathrm{QCD}} \times SU(3)_{\mathrm{dQCD}}$ | Mass | Multiplicity |
|---|---|---|---|
| Fermion | $(\mathbf{3},\mathbf{1})$ | $M$ | $n_{f_{c,h}}$ |
| | $(\mathbf{1},\mathbf{3})$ | $< \Lambda_{\mathrm{dQCD}}$ | $n_{f_{d,l}}$ |
| | | $M$ | $n_{f_{d,h}}$ |
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| Scalar | $(\mathbf{3},\mathbf{1})$ | $M$ | $n_{s_c}$ |
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Obtain coupled two-loop beta functions for $g_c$ and $g_d$, e.g.

$$\beta_c = \frac{g_c^3}{16\pi^2}\left[\frac{2}{3}\left(n_{f_c}+3n_{f_j}\right)+\frac{1}{6}\left(n_{s_c}+3n_{s_j}\right)-11\right]$$
$$+\frac{g_c^5}{(16\pi^2)^2}\left[\frac{38}{3}\left(n_{f_c}+3n_{f_j}\right)+\frac{11}{3}\left(n_{s_c}+3n_{s_j}\right)-\frac{136}{9}\right]$$
$$+\frac{g_c^3 g_d^2}{(16\pi^2)^2}\left[8n_{f_j}+8n_{s_j}\right]$$

$$\boxed{\beta(g) = \frac{dg}{d(\log(\mu))}}$$

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The infrared fixed point $(\alpha_s^*, \alpha_d^*)$ of a given model (selection of field content) is defined by

$$\beta_c(\alpha_s^*,\alpha_d^*) = \beta_d(\alpha_s^*,\alpha_d^*) = 0$$

$$\boxed{\beta(g) = \frac{dg}{d(\log(\mu))}}$$

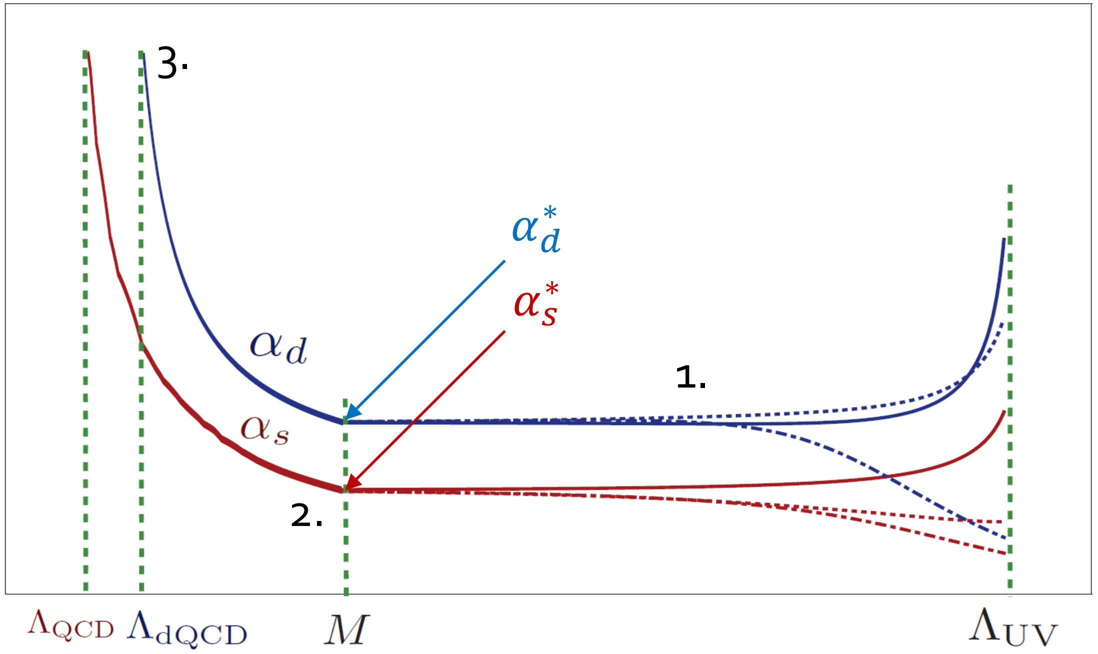
$$\boxed{\alpha = \frac{g^2}{4\pi}}$$

# Bai-Schwaller model

1. the coupling constants evolve to the fixed point $(\alpha_s^*, \alpha_d^*)$ regardless of their initial value in the UV

2. The decoupling scale $M$ is determined by matching the running of $\alpha_s$ below $M$ with experiment

3. The dark confinement scale $\Lambda_{dQCD}$ is then determined by running $\alpha_d$ until it reaches a value of $\pi/4$



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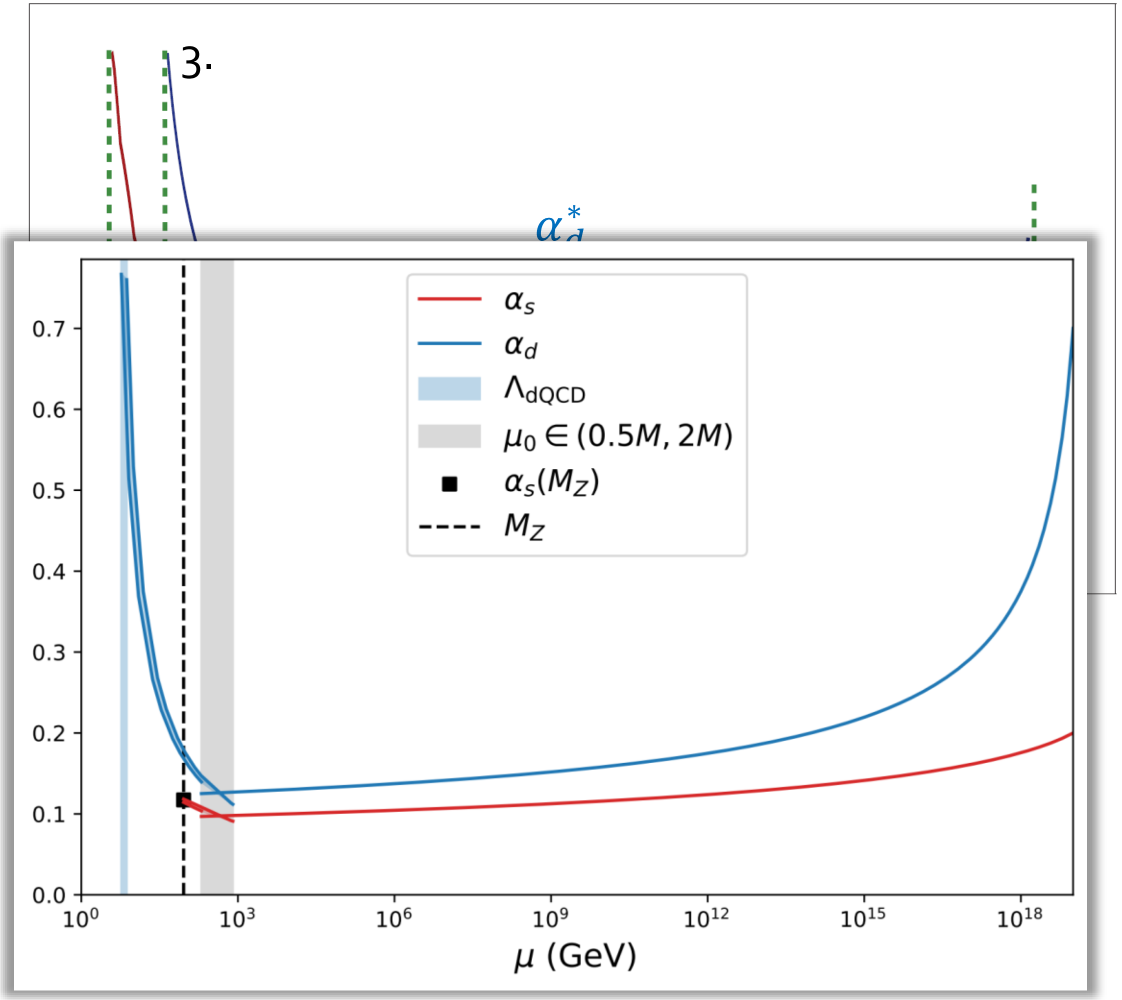
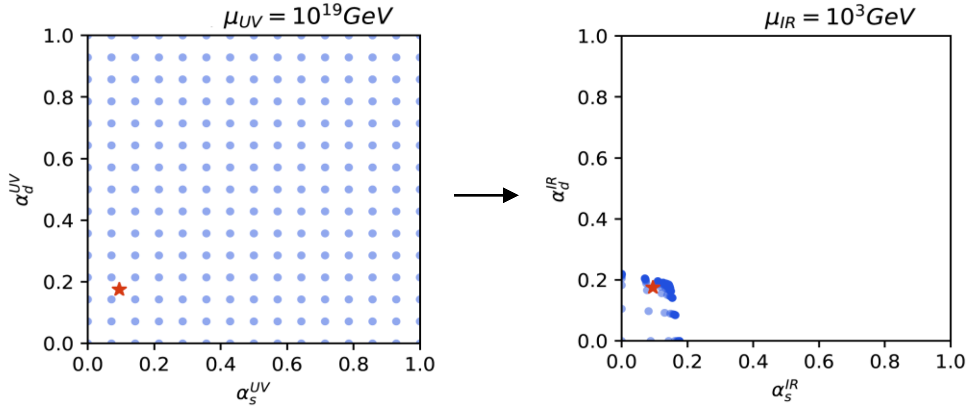



**However**, this assumption is wrong



# Explaining the coincidence

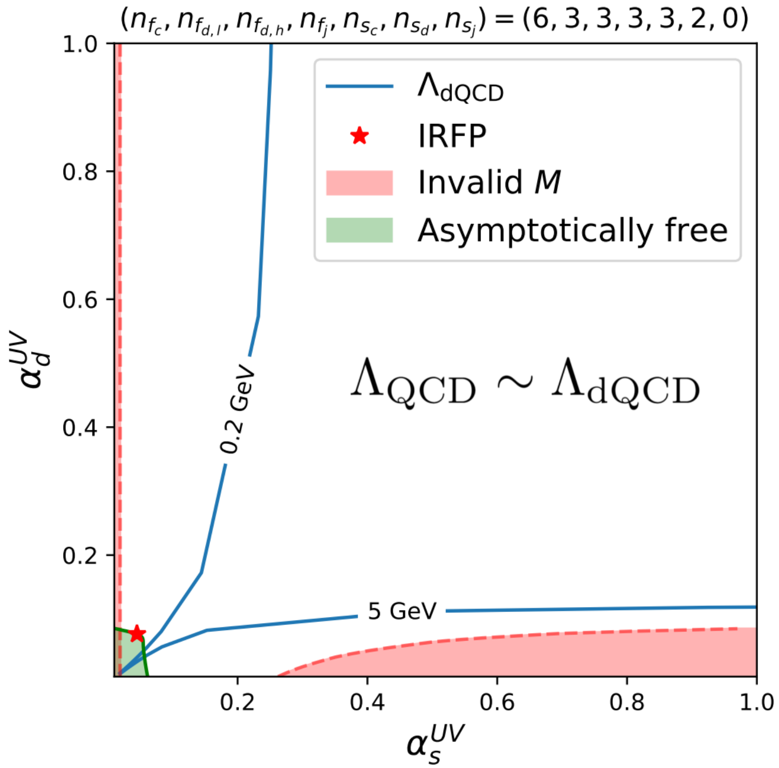
So, $\Lambda_{dQCD}$ depends on $\alpha_s^{UV}$, $\alpha_d^{UV}$ - we can plot $\Lambda_{dQCD}$ contours on $(\alpha_s^{UV}, \alpha_d^{UV})$ axes

We choose a range of $\Lambda_{dQCD}$ values that would feasibly explain the coincidence problem :

$$0.2GeV \leq \Lambda_{dQCD} \leq 5GeV$$

Define $\varepsilon_f$:

- the proportion of the $(\alpha_s^{UV}, \alpha_d^{UV})$ parameter space that lies between the contours for $0.2GeV$ and $5GeV$
- i.e. the proportion of parameter space that results in a feasible value of $\Lambda_{dQCD}$



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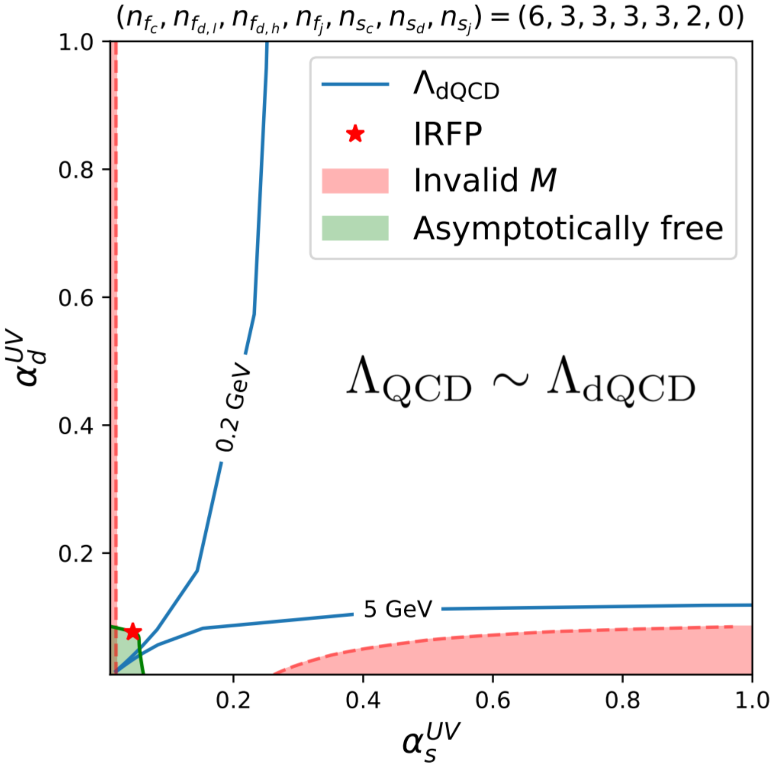



**Results:**

Sample of ~**12000** models w/ up to 3 of each field

- **554** with a perturbative infrared fixed point
  - **17** with a large $\varepsilon_f$

Bai and Schwaller is not a generic framework

- Models that work have small infrared fixed points
- Prefer similar numbers of dark and visible fields
- Prefer M ~ 100 GeV – TeV (strongly constrained)

# Concluding remarks

The cosmological coincidence is an interesting starting point for novel dark matter model building

Building models with similar particle masses for visible and dark matter is a non-trivial task

Infrared fixed points in dark QCD are an interesting but difficult direction to tackle this problem with

$$\boxed{\Omega_{\mathrm{DM}} \simeq 5\Omega_{\mathrm{VM}}}$$

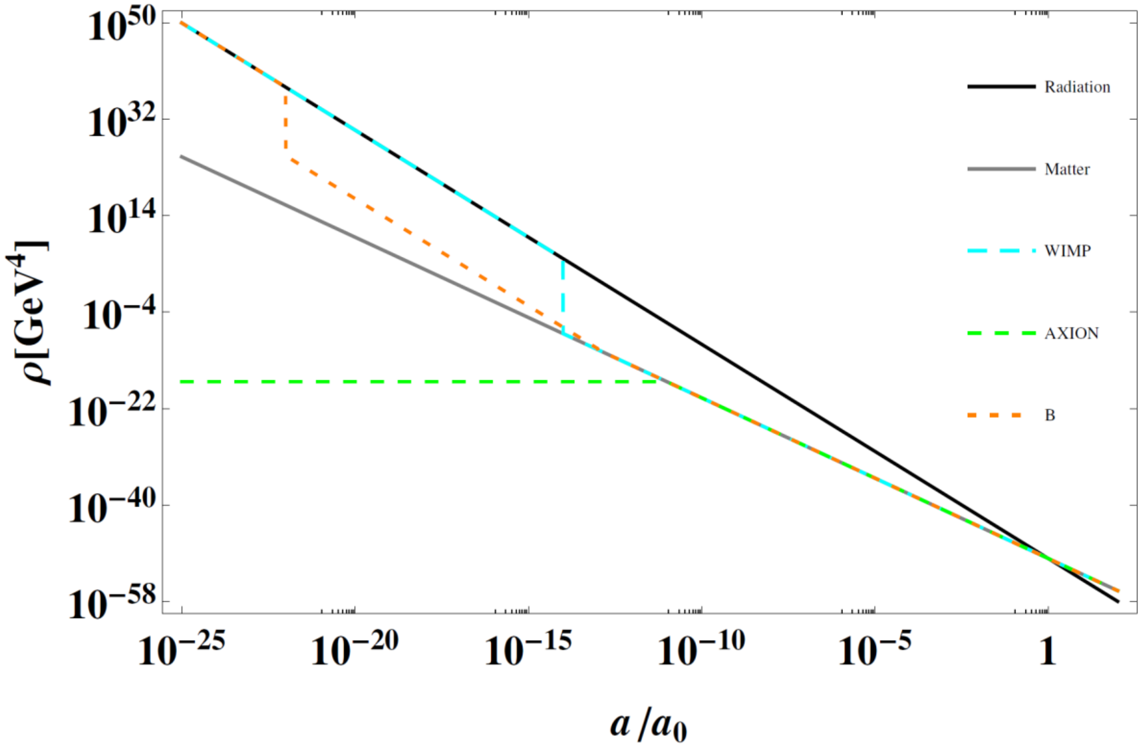
Thanks for listening!

# Why is it a coincidence?

The cosmological mechanisms responsible for the mass density of visible baryons and most dark matter candidates are unrelated

- **Visible baryons** result from a baryon-antibaryon asymmetry generated through an unknown baryogenesis mechanism
- **WIMPs** result from thermal freeze-out
- **Axions** result from the misalignment mechanism

*A priori* we would not expect the dark and visible mass densities to be on the same order of magnitude




Stephen J. Lonsdale, Thesis (2018)

# Threshold corrections

Bai and Schwaller assumed no threshold corrections

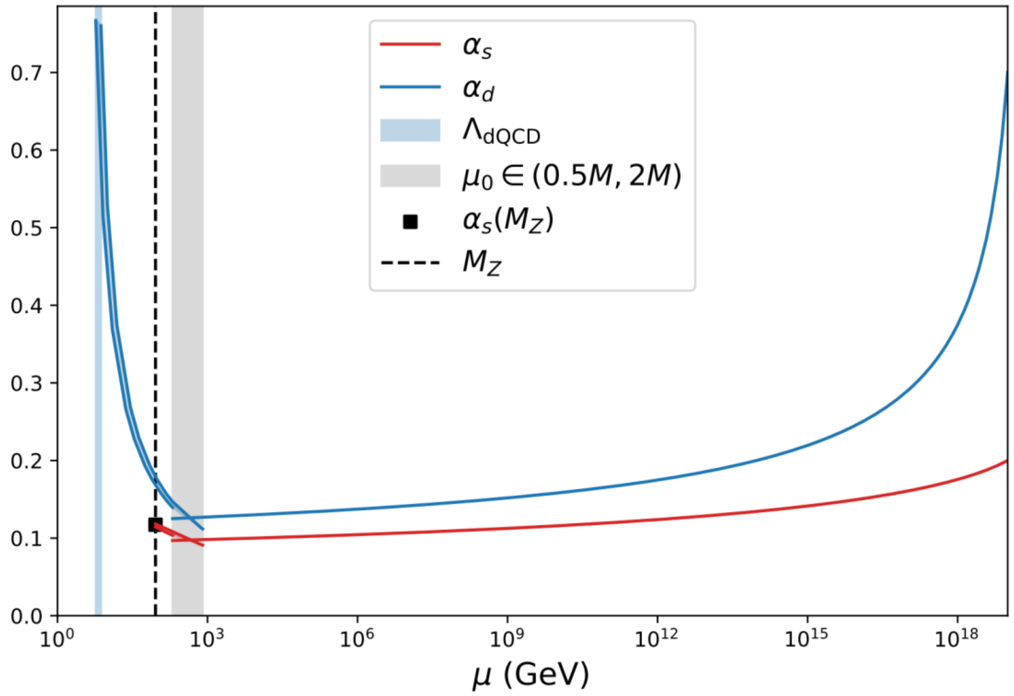
- They were implemented by Newstead and TerBeek [1405.7427]

When decoupling the heavy fields, need to match the full theory onto the low energy EFT to obtain the correct running of the couplings constants .

- Matching is performed at a **decoupling scale $\boldsymbol{\mu_0 \sim M}$** and is governed by the consistency condition:

$$\alpha_s^{\mathrm{EFT}}(\mu_0) = \zeta_c^2 \alpha_s(\mu_0)$$

$$\zeta_c^2 = 1 - \frac{\alpha_s(\mu)}{6\pi}\left[n_{f_c} - 6 + N_d n_{f_j} + \frac{1}{4}(n_{s_c} + N_d n_{s_j})\right] \ln\left(\frac{\mu^2}{M^2}\right)$$

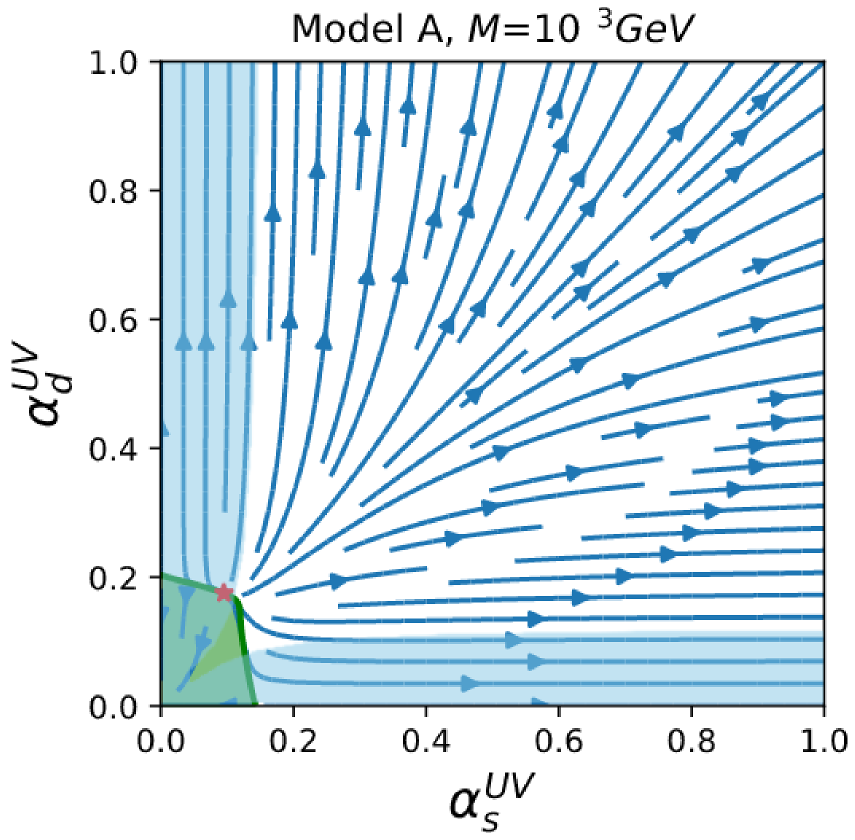


# Asymptotic Freedom

Asymptotic freedom depends on $(\alpha_s^{UV}, \alpha_d^{UV})$

Points in the $(\alpha_s^{UV}, \alpha_d^{UV})$ plane that are ‘closer’ to the origin will be asymptotically free, but points ‘further away’ will not

Since $0 < \alpha_s^{UV}, \alpha_d^{UV} < 1$, our set-up is always perturbative below the Planck scale; however, some cases will be strongly coupled above that



# Dark QCD & IRFPs in an ADM model

This theory can be incorporated in an ADM model to provide a full model that explains the cosmological coincidence problem.

Bai and Schwaller described a simple thermal leptogenesis model to relate $n_B$ and $n_D$, taking advantage of the new fields introduced for the IRFP mechanism

They introduced:

- 3 heavy right-handed Majorana neutrinos $N_i$
- Two bitriplet fermions $Y_1 \sim (\bar{3}, 3)_{1/3}$, $Y_2 \sim (\bar{3}, 3)_{-2/3}$
- One bitriplet scalar $\Phi \sim (\bar{3}, 3)_{1/3}$

The mechanism:

1. Out-of-equilibrium decays of $N_i$ generate asymmetries in $Y_1$,$\Phi$

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

2. These asymmetries are transferred into visible matter and dark fermions $X_L$

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

3. After equilibration and sphaleron reprocessing, the number density ratio is:

$$\frac{|n_D|}{n_B} = \frac{79}{56}$$