Exploring the cosmological dark matter coincidence with infrared fixed points

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Overview

1. The cosmological coincidence problem
2. Approaches to resolving the coincidence problem
3. Dark QCD and infrared fixed points
4. Concluding remarks

The cosmological coincidence

The cosmological coincidence

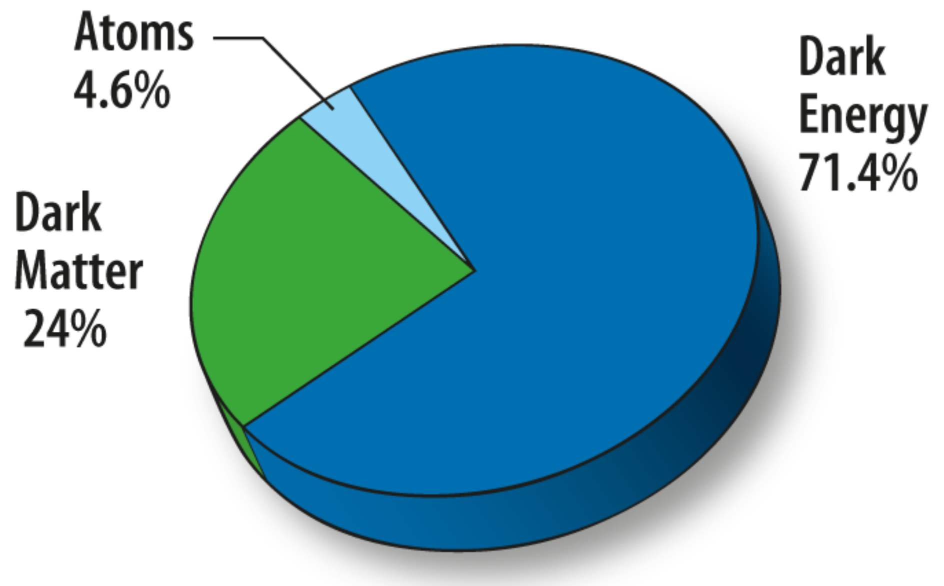
Large range of DM candidates

- 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

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



TODAY

https://wmap.gsfc.nasa.gov/universe/uni_matter.html

Parameter	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02242 ± 0.00014
$\Omega_c h^2$	0.11933 ± 0.00091

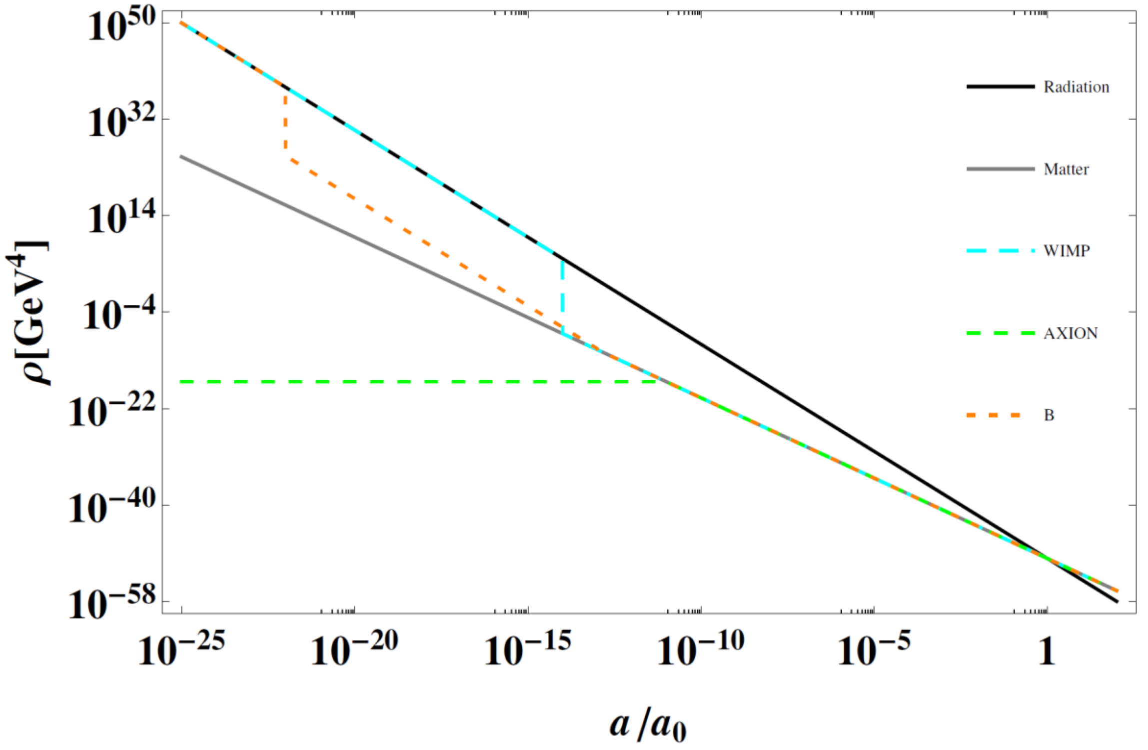
Planck 2018, arXiv: 1807.06209

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)

How do we explain this coincidence?

A similarity such as this often derives from some deep underlying connection

- e.g. electric charge neutrality of the universe $\Rightarrow n_{p^+} = n_{e^-}$

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

The coincidence problem has two distinct parts:

$$\Omega_X = n_X \times m_X$$

1. Relating number densities

$$n_B \sim n_D$$

2. Relating particle masses

$$m_B \sim m_D$$

Approaches to resolving the coincidence problem

Relating number densities - ADM

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 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

Relating particle masses

The **visible** baryon mass arises from the QCD confinement scale Λ_{QCD}

We consider dark matter candidates that are baryon-like bound states of a QCD-like confining gauge group $SU(N_d)$

To relate the particle masses the confinement scales must naturally be of the same order

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

There are two main ways to achieve this:

1. Introduce a symmetry between $SU(3)_C$ and $SU(N_d)$
   - Exact: Foot (2004) [astro-ph/0407623]
   - Carefully broken: Ritter, Volkas – PRD104 (2021) 035032 [2101.07421]

Implementing asymmetric dark matter and dark electroweak baryogenesis in a mirror two-Higgs-doublet model

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2. The gauge couplings of the two groups can evolve to some *infrared fixed point*

Dark QCD and infrared fixed points

Dark QCD and infrared fixed points

Bai and Schwaller (2013) [1306.4676]

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

Introduce a dark confining gauge group and new field content, including bifundamentals

Field	$SU(N_c)_{\text{QCD}}$	$SU(N_d)_{\text{darkQCD}}$	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}

Obtain coupled two-loop beta functions for g_c and g_d

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

$$\begin{aligned}\beta_c = \frac{g_c^3}{16\pi^2}\left[\frac{2}{3}T(R_f)2\left(n_{f_c}+N_d n_{f_j}\right)+\frac{1}{3}T(R_s)\left(n_{s_c}+N_d n_{s_j}\right)-\frac{11}{3}C_2(G_c)\right] \\ +\frac{g_c^5}{(16\pi^2)^2}\left[\left(\frac{10}{3}C_2(G_c)+2C_2(R_f)\right)T(R_f)2\left(n_{f_c}+N_d n_{f_j}\right)\right. \\ \left.+\left(\frac{2}{3}C_2(G_c)+4C_2(R_s)\right)T(R_s)\left(n_{s_c}+N_d n_{s_j}\right)-\frac{34}{3}C_2^2(G_c)\right] \\ +\frac{g_c^3 g_d^2}{(16\pi^2)^2}\left[2C_2(R_f)T(R_f)2N_d n_{f_j}+4C_2(R_s)T(R_s)N_d n_{s_j}\right]\end{aligned}$$

Model	n_{f_c}	n_{f_d}	n_{f_j}	n_{s_c}	n_{s_d}	n_{s_j}	α_s^*	α_d^*
A	6	5	3	0	2	0	0.095	0.175
B	6	6	3	1	0	0	0.083	0.120
C	6	6	3	2	2	0	0.070	0.070
D	7	7	2	2	0	2	0.078	0.168
E	7	7	2	2	1	2	0.090	0.133
F	8	8	2	2	0	1	0.074	0.149
G	8	8	2	2	1	1	0.082	0.118

The infrared fixed point (α_s^*, α_d^*) of a given model (selection of field content) is defined by

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

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

Tables from Bai, Schwaller [1306.4676]

Bai-Schwaller model

All new fields have a mass $M \gtrsim m_t$ except for the dark fermions.

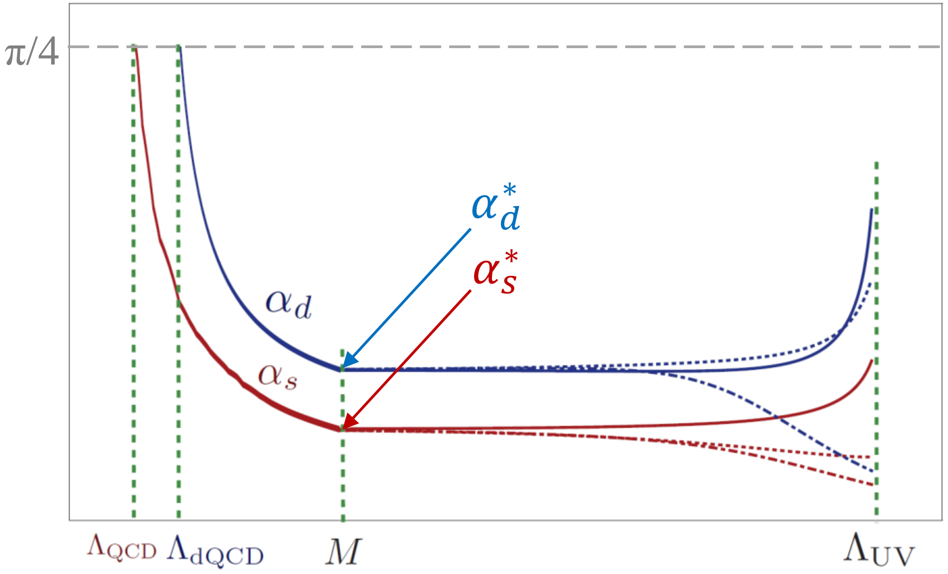
So, for a given model:

1. the coupling constants evolve to the fixed point (α_s^*, α_d^*) regardless of their initial value in the UV
2. The decoupling scale M is determined by matching the running of α_s below M with experiment
3. The dark confinement scale Λ_{dQCD} is then determined by running α_d until it reaches a value of $\pi/4$

General idea:

$$\text{model} \Rightarrow (\alpha_s^*, \alpha_d^*) \Rightarrow M \Rightarrow \Lambda_{dQCD}$$

Calculate dark matter particle mass from $m_D \simeq 1.5\Lambda_{dQCD}$ for each model (selection of field content)



Model	n_{f_c}	n_{f_d}	n_{f_j}	n_{s_c}	n_{s_d}	n_{s_j}	α_s^*	α_d^*	M (GeV)	m_D (GeV)
A	6	5	3	0	2	0	0.095	0.175	518	31
B	6	6	3	1	0	0	0.083	0.120	2030	8.6
C	6	6	3	2	2	0	0.070	0.070	13500	0.32
D	7	7	2	2	0	2	0.078	0.168	3860	72
E	7	7	2	2	1	2	0.090	0.133	869	3.5
F	8	8	2	2	0	1	0.074	0.149	7700	29
G	8	8	2	2	1	1	0.082	0.118	2244	1.2

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 .

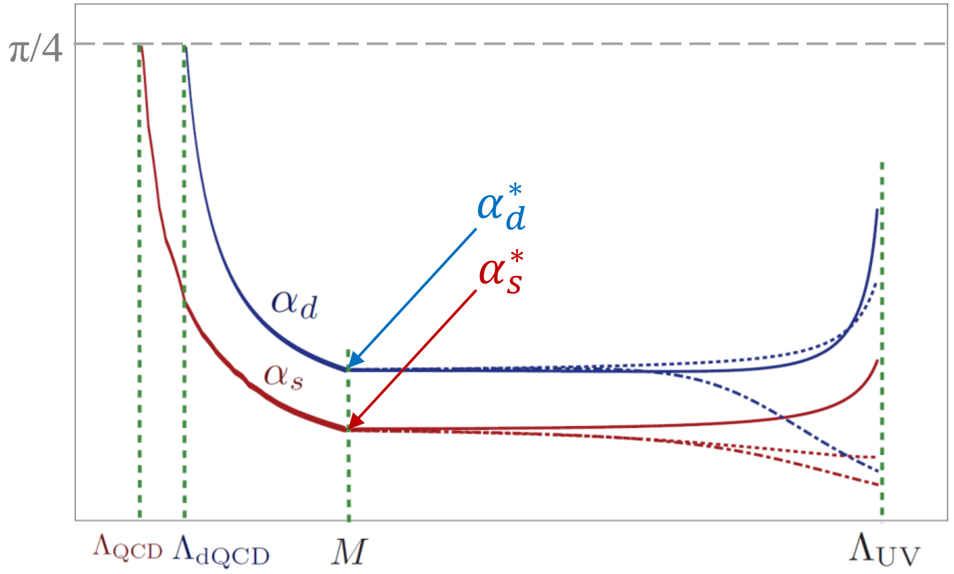
- Matching is performed at a **decoupling scale μ_0** and is governed by the consistency condition:

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

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

New physics mass scale M no longer uniquely determined for a given model

New general idea: model, $M \Rightarrow \mu_0 \Rightarrow \Lambda_{dQCD}$

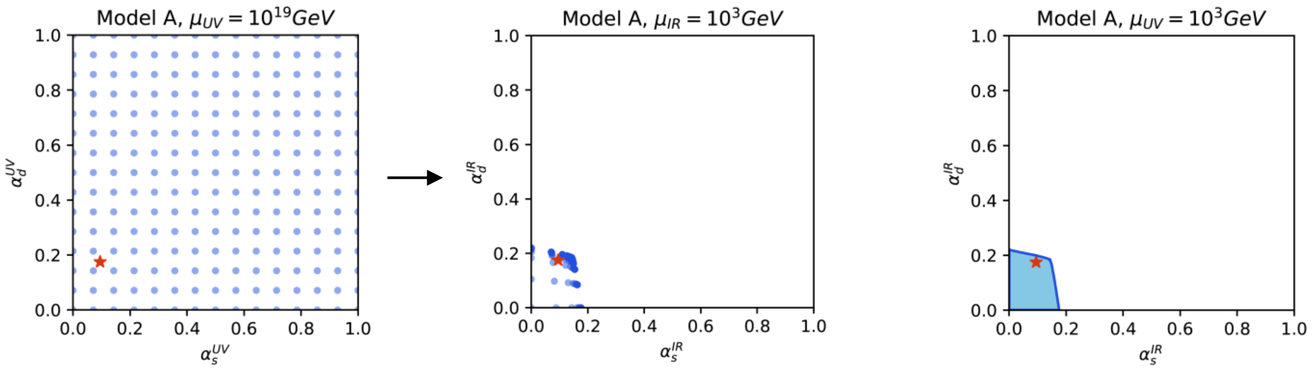


Initial conditions in the UV

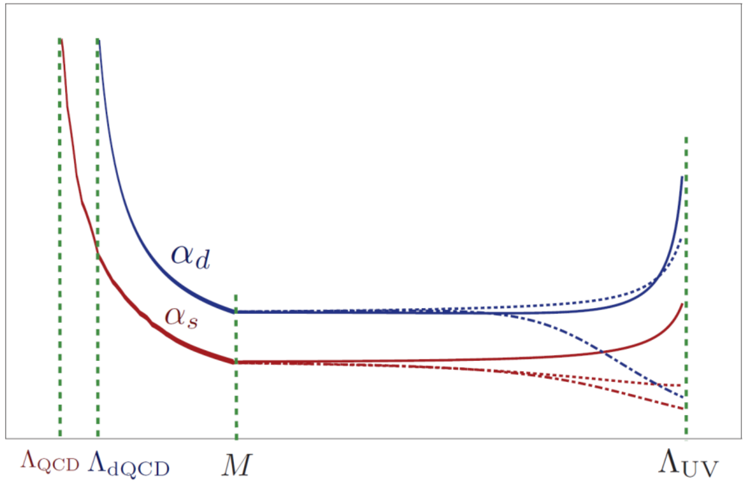
Bai and Schwaller also assumed that the couplings would always reach the IRFP by the decoupling scale M, regardless of the initial UV conditions $(\alpha_s^{UV}, \alpha_d^{UV})$

This is not true in general

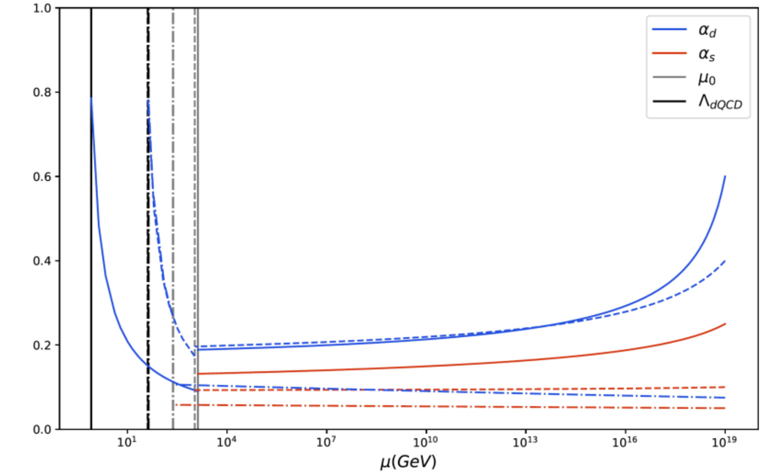
- we plot this for points satisfying $0 < \alpha_s^{UV}, \alpha_d^{UV} < 1$



New new general idea: model, M, $(\alpha_s^{UV}, \alpha_d^{UV}) \Rightarrow \mu_0 \Rightarrow \Lambda_{dQCD}$



Model A, $M = 10^3 GeV$



Explaining the coincidence problem

For a given model and choice of M, we can plot Λ_{dQCD} on $(\alpha_s^{UV}, \alpha_d^{UV})$ axes

Goal:

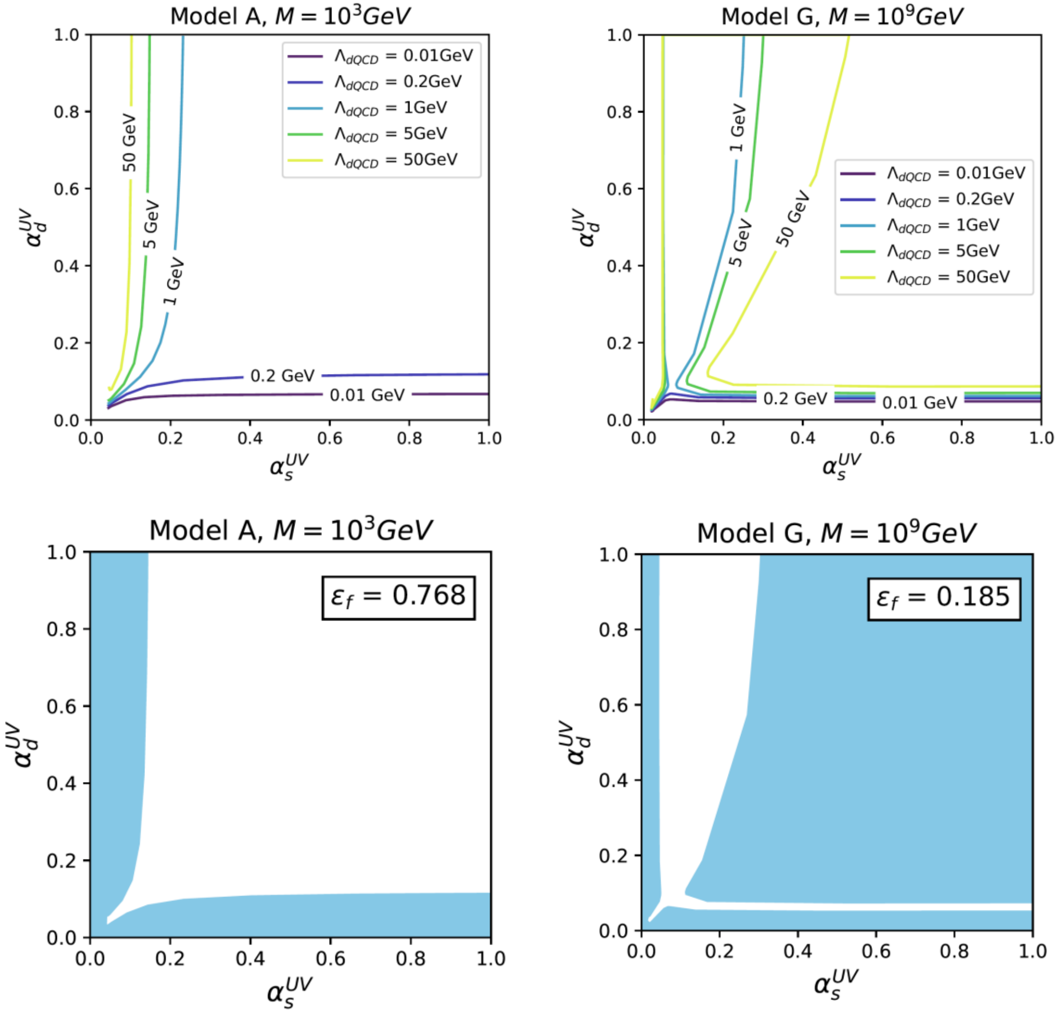
- we want models that naturally obtain $\Lambda_{dQCD} \sim \Lambda_{QCD}$

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

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

Define ε_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 Λ_{dQCD}



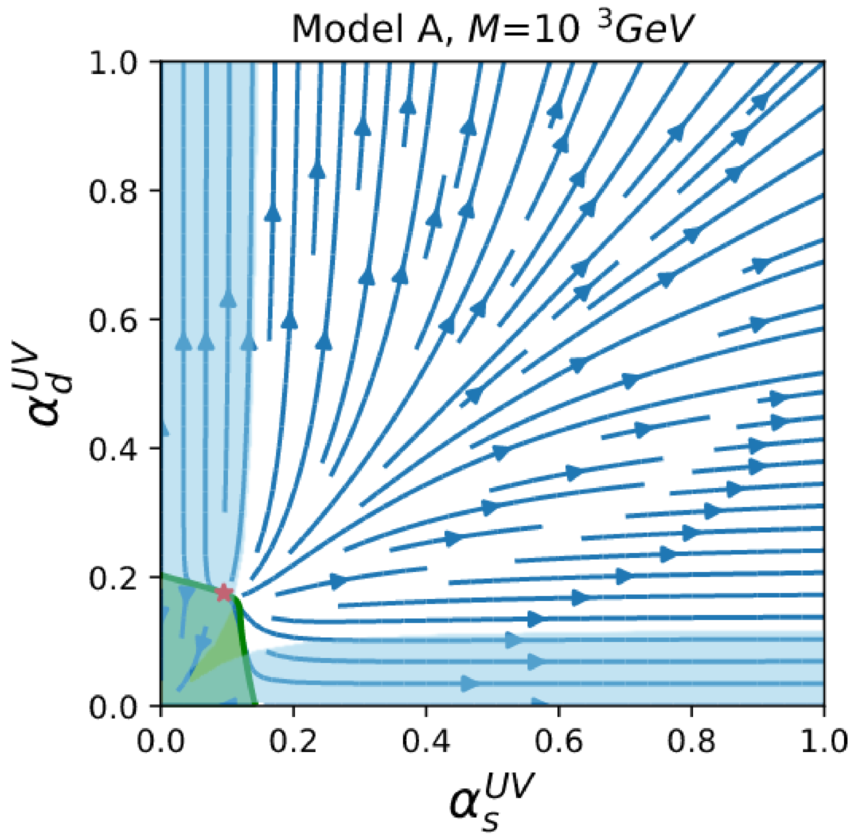
Asymptotic Freedom

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

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

Also define ε_f^{AF}:

- the proportion of the asymptotically free $(\alpha_s^{UV}, \alpha_d^{UV})$ parameter space that produces feasible Λ_{dQCD}



Explaining the coincidence problem

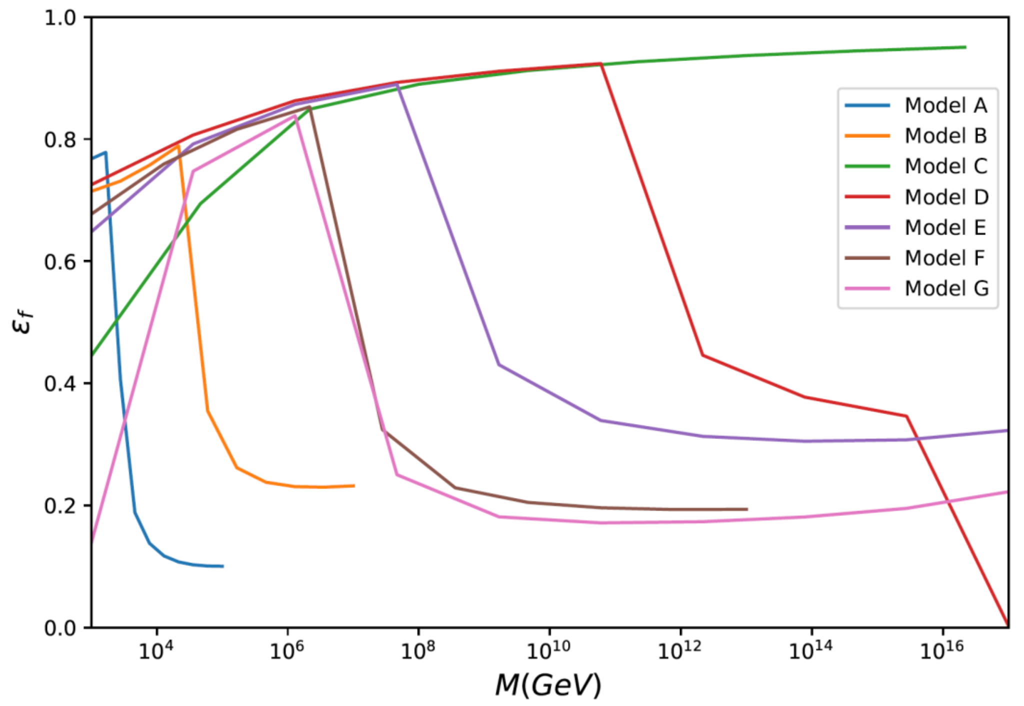
To quantify the feasibility of a model, we choose a minimum value for $\varepsilon_f \sim 0.7$

For a particular model, this defines $\{M\}_f$: the range of values for M for which $\varepsilon_f > 0.7$

Want to determine how robust the general theory is in explaining the coincidence problem.

Can ask a number of questions:

- In the landscape of random field content selections, what is the distribution of $\{M\}_f$?
- Do many models have a wide $\{M\}_f$?
- Do many models have a narrow $\{M\}_f$?
- Are there correlations between $\{M\}_f$ and the field content of the model?



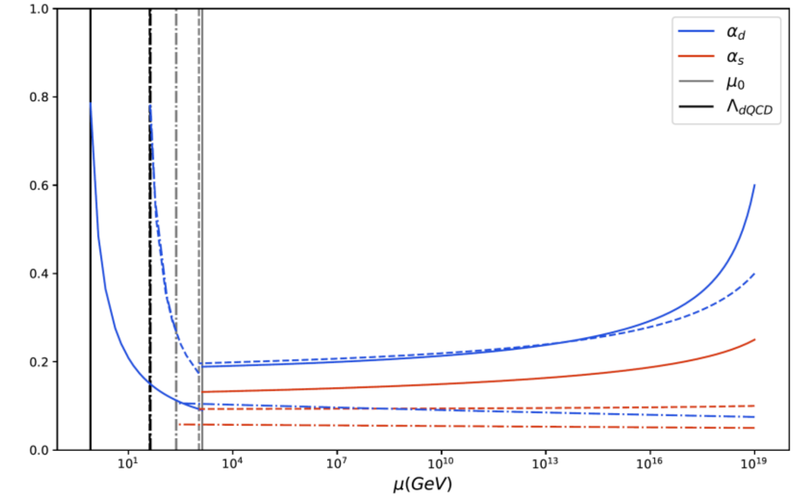
Concluding remarks

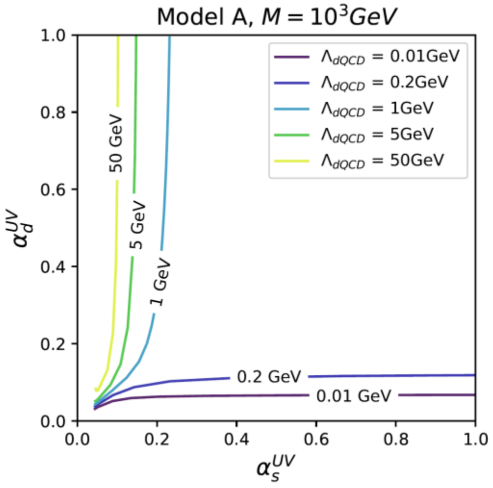
The cosmological coincidence is an interesting starting point for novel dark matter model building

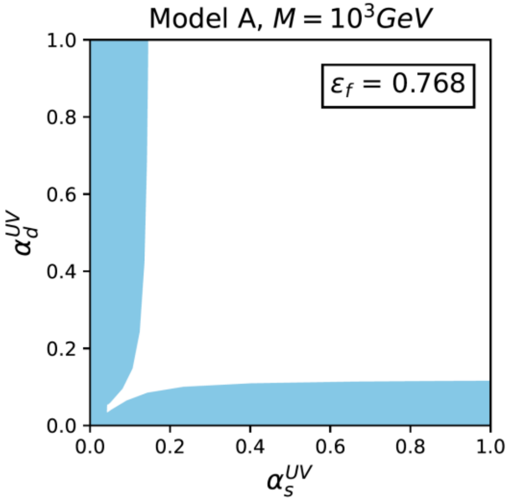
Building models with similar particle masses for visible and dark matter is a non-trivial task

Infrared fixed points for dark QCD provide an interesting new direction for motivating the similarity of the visible and dark confinement scales

Thanks for listening!







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Dark QCD & IRFPs in an ADM model

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS
THE UNIVERSITY OF MELBOURNE

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, Φ

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

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:

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