Explaining the cosmological coincidence with infrared fixed points

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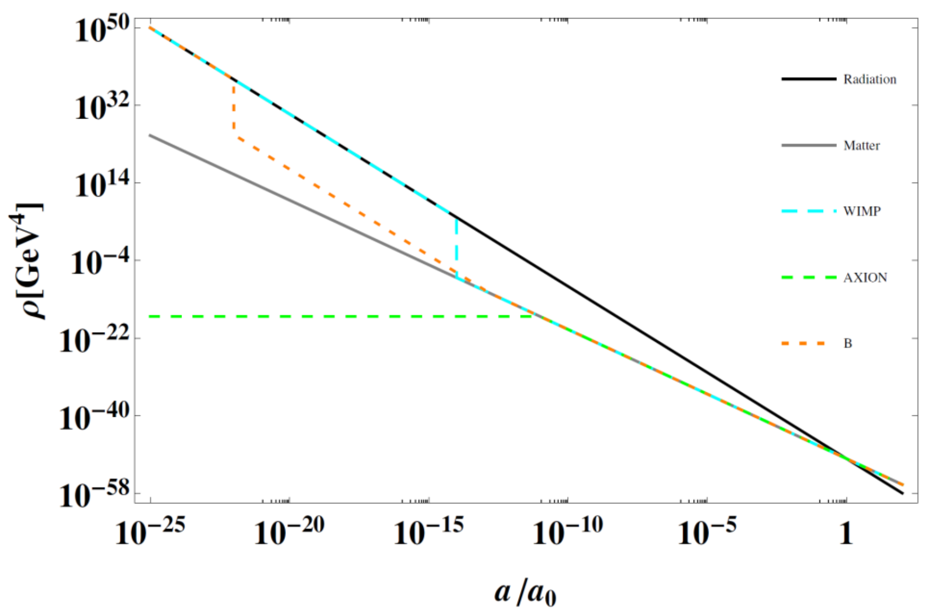
The cosmological coincidence

There are a plethora of dark matter models in the literature with a large variety of motivations. This lead us to look through the scant observational evidence for dark matter for any clues that can guide our model building. One interesting piece of evidence is the apparent coincidence between the present-day cosmological mass densities:

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

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



Why is it a coincidence?

The generation mechanisms for visible matter are entirely unrelated from those of most dark matter candidates.

- **Visible baryons:** an unknown baryogenesis mechanism generates an asymmetry between protons and antiprotons
- **WIMPs:** thermal freeze-out
- **Axions:** misalignment mechanism

There is no underlying reason for the cosmological abundances of dark and visible matter to be of the same order of magnitude.

How do we use this for model-building?

Asymmetric dark matter models[1] are a paradigm that explains why the number densities of baryons and dark matter are similar. However, they do not address why the particle masses of visible and dark matter are similar, and so are **not** satisfactory explanations of the coincidence problem.

$$\Omega_X = n_X \times m_X$$

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

Dark QCD and Infrared Fixed Points

Since the mass of visible baryons arises mainly from the confinement energy of QCD, we posit the dark matter to be a baryon-like state of some dark confining gauge group $SU(N_d)$. Our goal is then to build models in which the confinement scales of visible and dark QCD are of a similar order:

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

This can be done by introducing a symmetry between the two gauge groups – which has been explored in some detail in the literature[2] – or by exploiting *infrared fixed points* to relate the gauge coupling in the IR.

An *infrared fixed point* is where the β-functions for both gauge couplings become zero, and thus the gauge couplings evolve towards this point as the energy scale decreases. We denote the point (α_s^*, α_d^*) and define it by

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

The model of Bai and Schwaller[3]

Bai and Schwaller introduced a dark QCD gauge group $SU(N_d)$ and a set of new field content as given in Table 1. The IRFP of the theory depends on the multiplicity of the new field content, which defines each "model" of the theory. All new field content has a heavy mass M of 1 TeV or higher, except for at least one of the dark fundamental fermions.

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

Table 1: The field content of the model charged under the two confining gauge groups, along with their multiplicities

The value for the dark confinement scale Λ_{dQCD} is determined by the following process, given by the schematic Fig. 1:

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 $\pi/4$

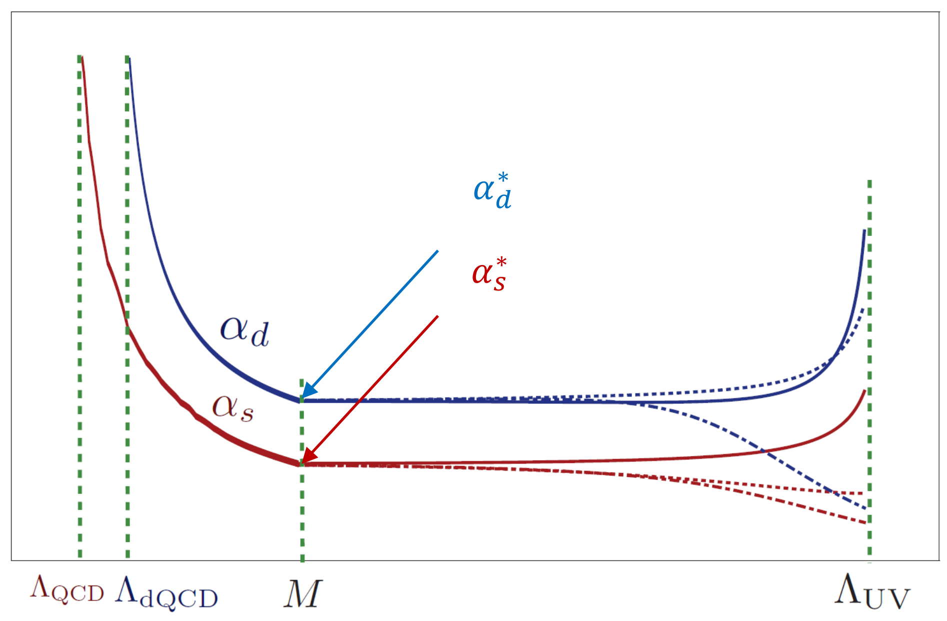


Fig 1: Schematic of the evolution of the visible and dark gauge couplings against the energy scale from the UV down to the confinement scales

The issues with Bai and Schwaller

Bai and Schwaller made a number of incorrect assumptions.

1. They ignored threshold corrections. With threshold corrections, Λ_{dQCD} depends on the model and M^4.
2. They assumed that the gauge couplings would reach the IRFP by the decoupling scale. We found this assumption to be invalid, as shown in Figures 2 and 3. Λ_{dQCD} now depends on the model, M, and $(\alpha_s^{UV}, \alpha_d^{UV})$.

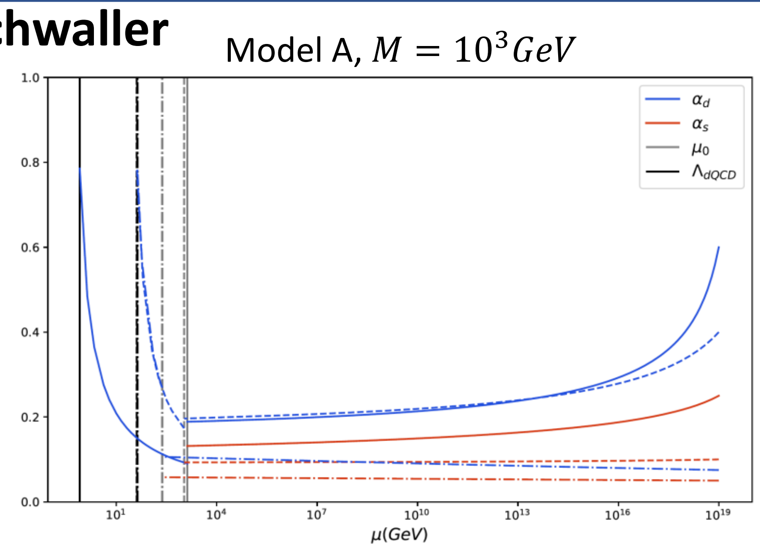


Fig 2: A realistic version of the schematic in Fig. 1

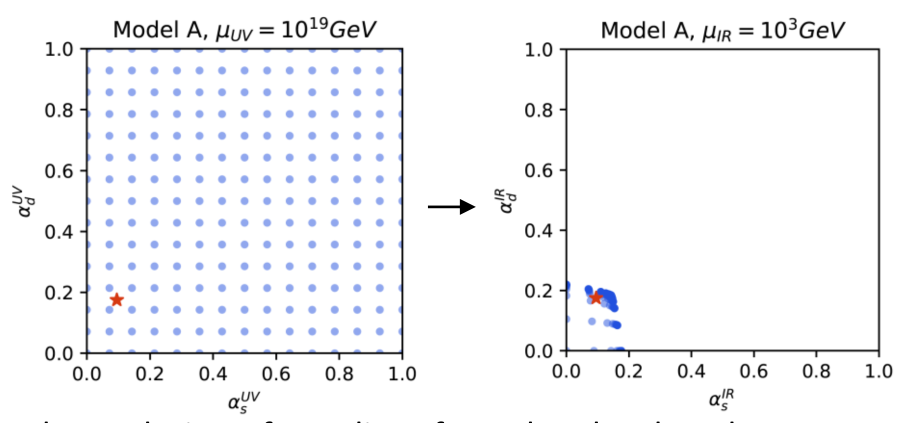
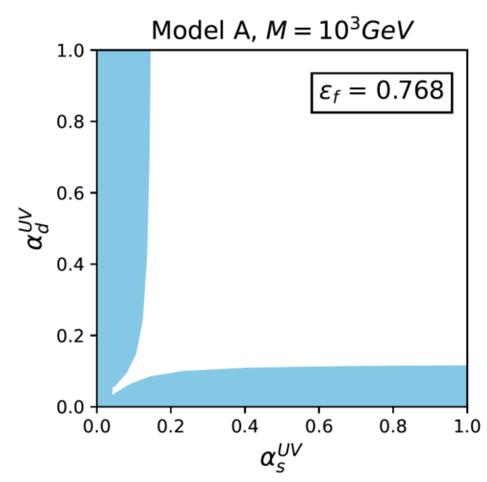


Fig 3: The evolution of couplings from the Planck scale to 1 TeV

Explaining the coincidence problem

Goal: models in which the visible and dark confinement scales are naturally similar. For each model and mass scale M, we plot Λ_{dQCD} on $(\alpha_s^{UV}, \alpha_d^{UV})$ axes and calculate the area of the parameter space between the contours for 0.2 GeV and 5 GeV. This defines a "feasibility proportion" ε_f. We can then use this to find the range of mass scales for each model that have a sufficiently large value of ε_f.



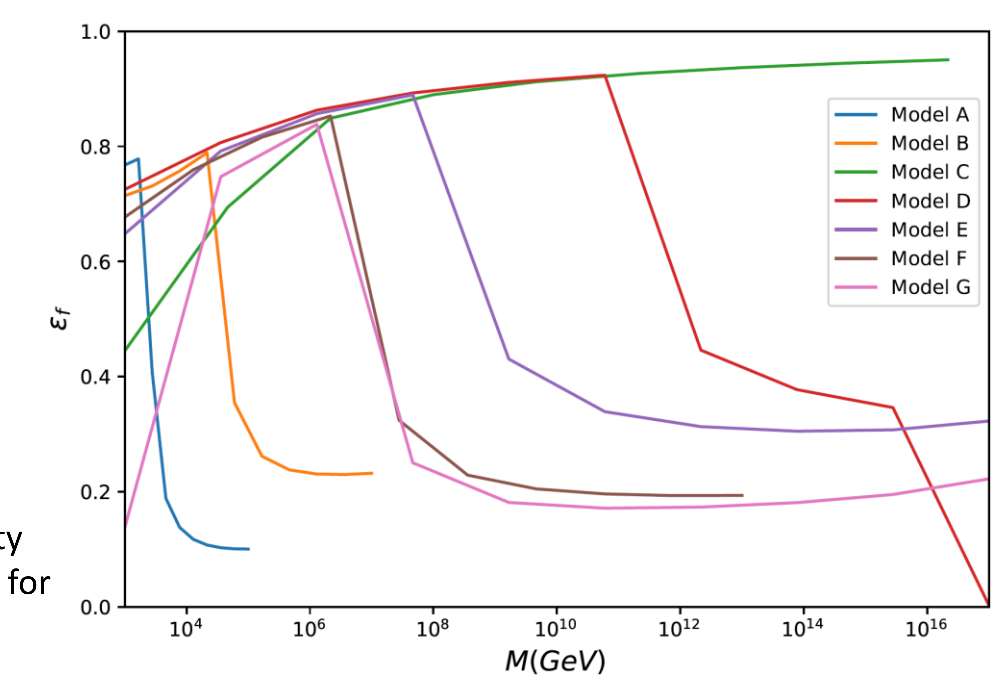


Fig 4 (a): A feasible region of parameter space. (b) The feasibility proportion against the mass scale for a selection of models

References

[1] Petraki, Volkas: 10.1142/S0217751X13300287
[2] ACR, Volkas: 10.1103/PhysRevD.104.035032
[3] Bai, Schwaller: 10.1103/PhysRevD.89.063522
[4] Newstead, TerBeek: 10.1103/PhysRevD.90.074008

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