Exploring the cosmological dark matter coincidence with infrared fixed points

Alex Ritter, Raymond Volkas

arXiv: 2210.11011

The cosmological coincidence

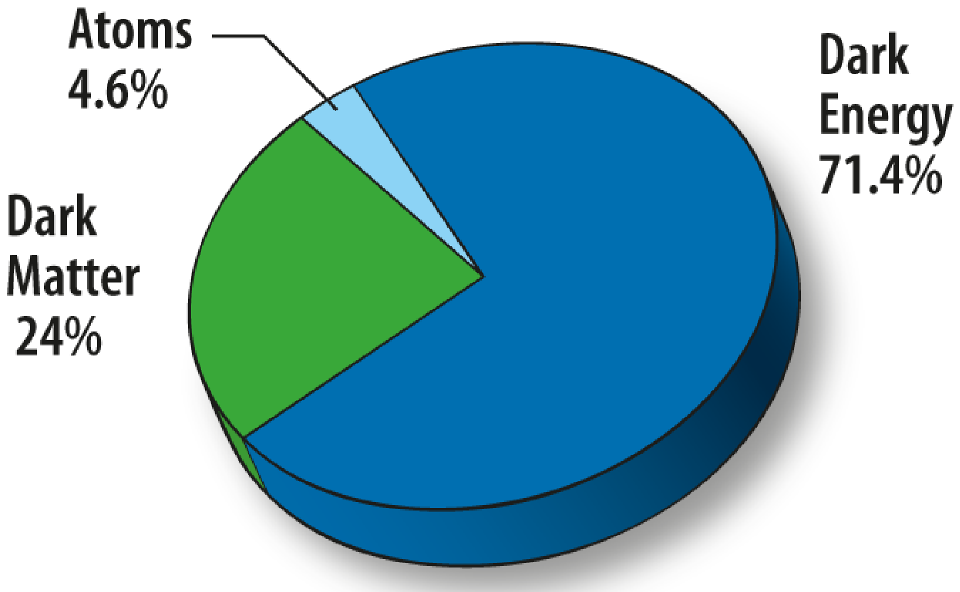
Large range of DM candidates

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

Clues from current observational evidence:

- Apparent coincidence in the mass densities of visible and dark matter

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



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

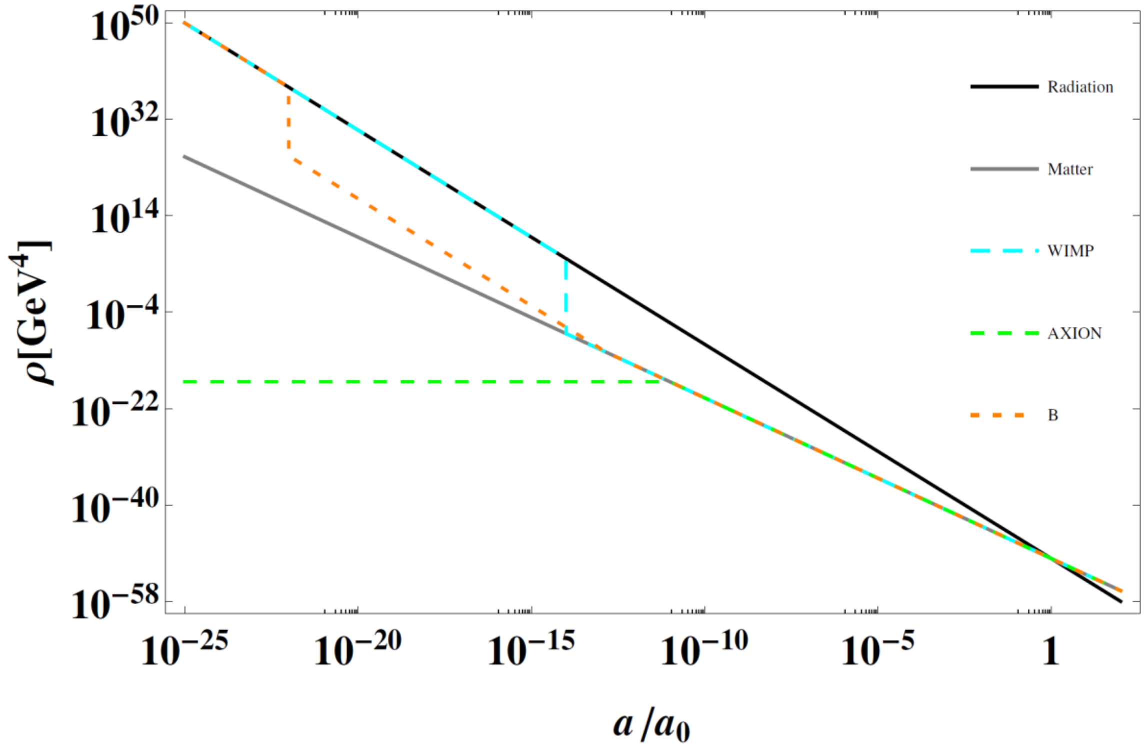
Planck 2018, arXiv: 1807.06209

Why is it a coincidence?

Unrelated mechanisms generate the mass density of visible baryons and most dark matter candidates

- **Visible baryons:** baryon-antibaryon asymmetry from baryogenesis
- **WIMPs:** thermal freeze-out
- **Axions:** 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)

Explaining the coincidence

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

This is a problem in two parts: $\Omega_X = n_X m_X / \rho_c$

Relating number densities

$$n_B \sim n_D$$

Relating particle masses

$$m_B \sim m_D$$

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: largely from the QCD confinement scale Λ_{QCD}

Dark matter: baryon-like bound states of a QCD-like confining gauge group $SU(3)_{dQCD}$ with

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

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 [1306.4676]

- Dark QCD – $SU(3)_{dQCD}$
- New fields
  - All at a heavy mass scale M
  - Except for some light quarks (to be confined into dark baryons)

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	$n_{f_{d,h}}$
	$(\mathbf{3},\mathbf{3})$	M	n_{f_j}
Scalar	$(\mathbf{3},\mathbf{1})$	M	n_{s_c}
	$(\mathbf{1},\mathbf{3})$	M	n_{s_d}
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	$(\mathbf{1}, \mathbf{3})$	M	n_{s_d}
	$(\mathbf{3}, \mathbf{3})$	M	n_{s_j}

Get coupled two-loop beta-functions for the coupling constants

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

$$+ \frac{g_c^5}{(16\pi^2)^2}\left[\frac{38}{3}\left(n_{f_c} + 3n_{f_j}\right) + \frac{11}{3}\left(n_{s_c} + 3n_{s_j}\right) - 102\right]$$

$$+ \frac{g_c^3 g_d^2}{(16\pi^2)^2}\left[8n_{f_j} + 8n_{s_j}\right],$$

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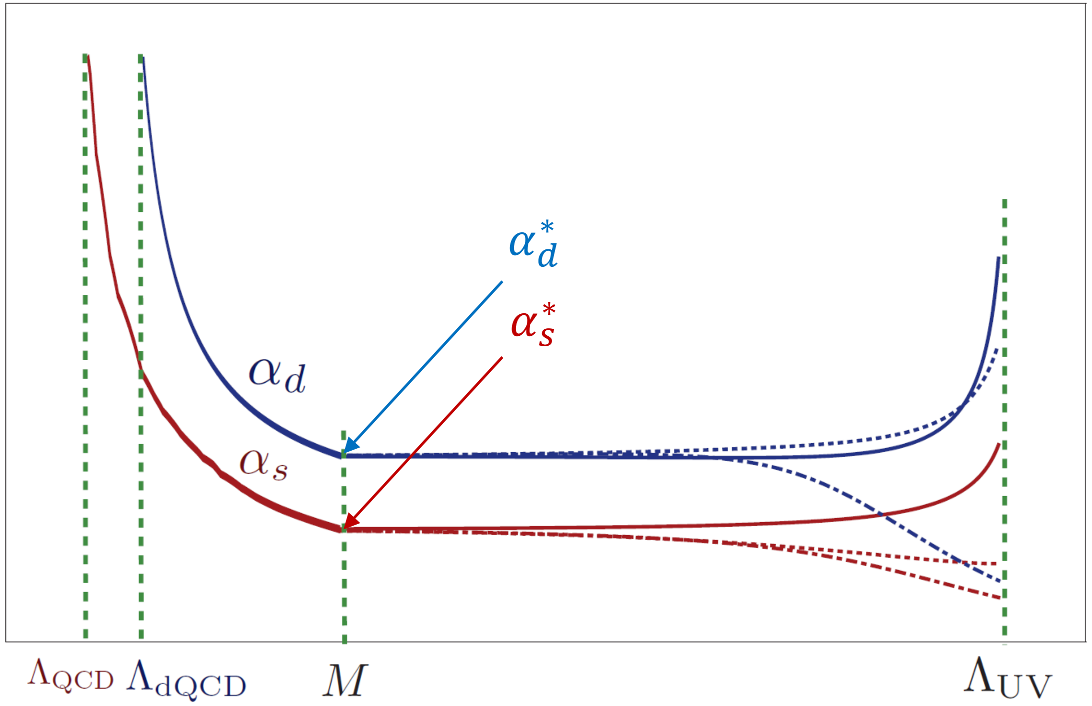
Depending on the field content (model), can have an **infrared fixed point** where

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

Relating the confinement scales



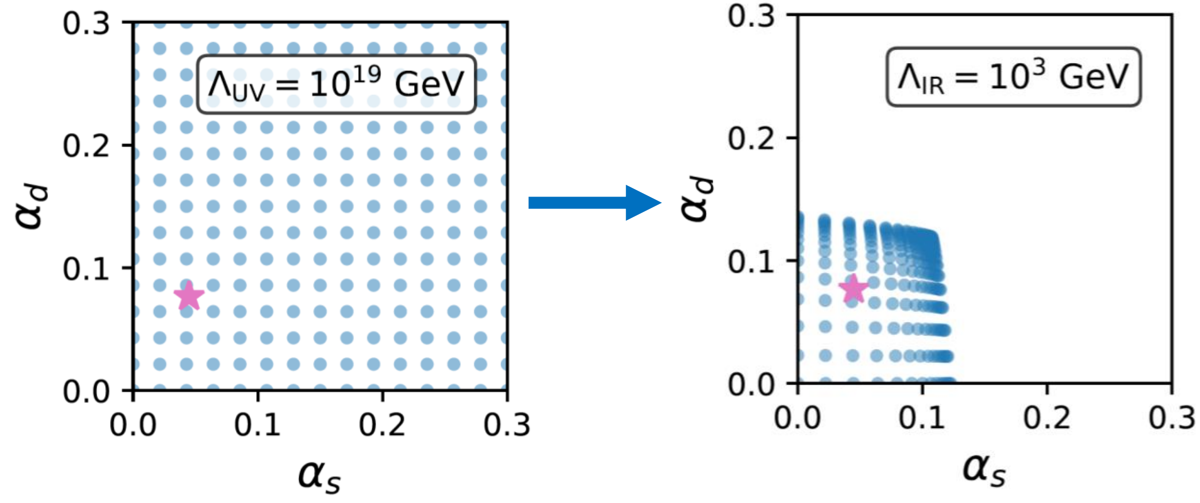
1. the coupling constants evolve to the fixed point (α_s^*, α_d^*) regardless of their initial value in the UV
2. The decoupling scale M is determined by matching the running of α_s below M with experiment
3. The dark confinement scale Λ_{dQCD} is then determined by running α_d until it reaches $\pi/4$

Process: **model (field content)→ $\{\boldsymbol{\alpha_s^*, \alpha_d^*}\}$ → $\boldsymbol{M}$ →$\boldsymbol{\Lambda_{dQCD}}$**

Initial UV conditions

However!

Couplings do not always evolve to their IRFP values by the decoupling scale



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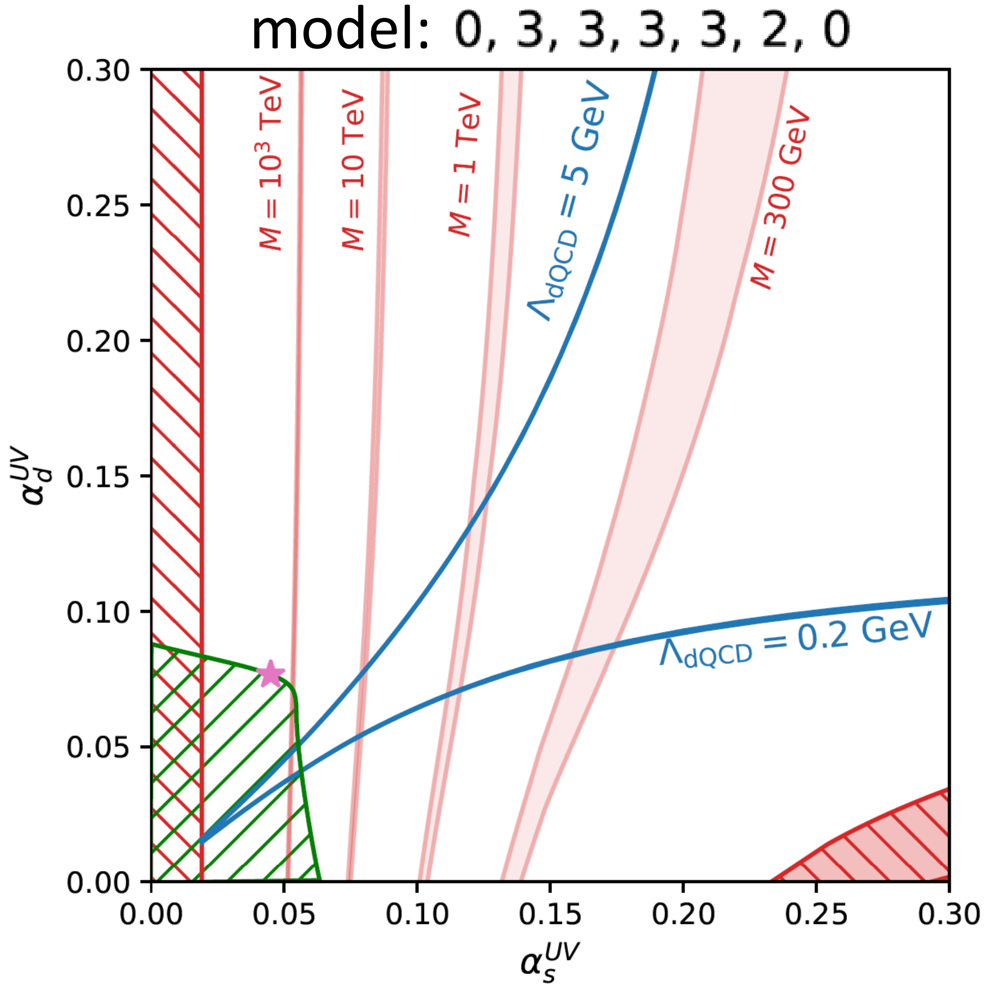
New process: **model, $\{\alpha_s^{UV}, \alpha_d^{UV}\}$ → M →Λ_{dQCD}**

Explaining the coincidence

For a given model, plot M and Λ_{dQCD} on $\alpha_s^{UV}, \alpha_d^{UV}$ axes



Explaining the coincidence

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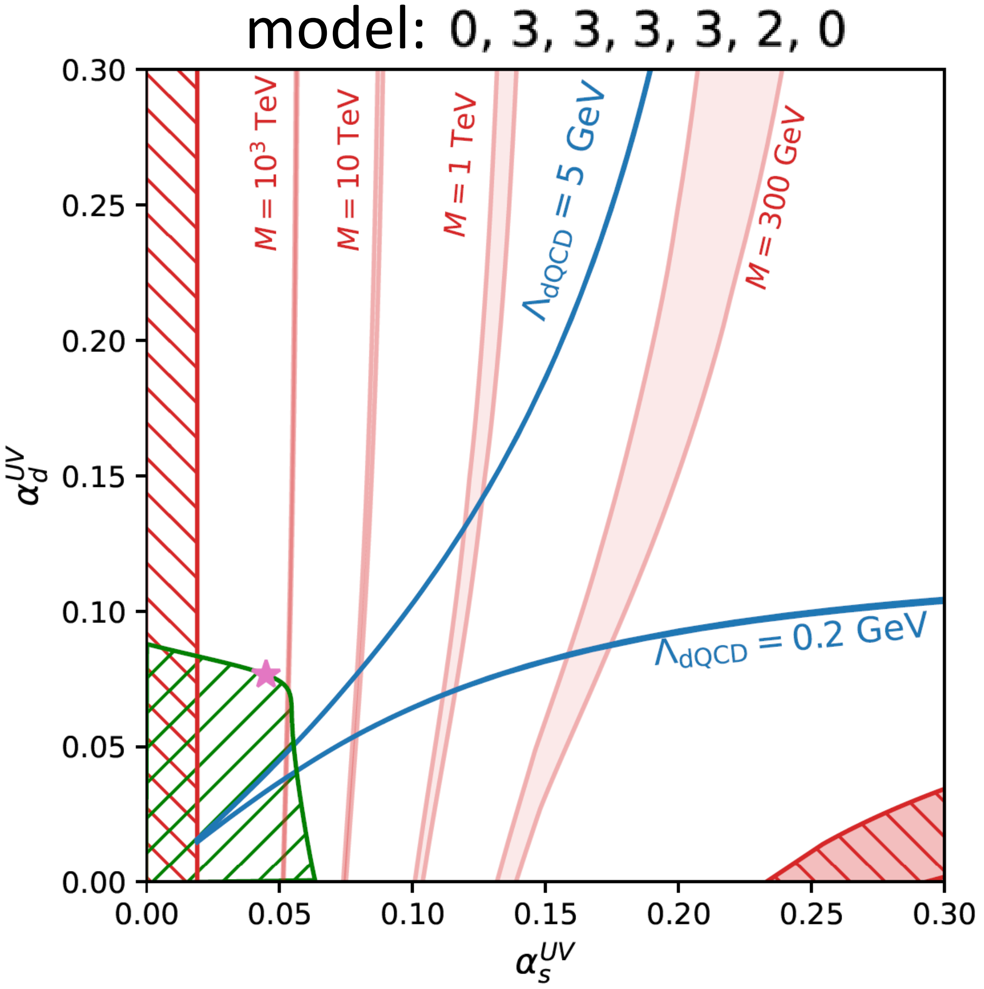
Goal : obtain similar confinement scales for visible and dark QCD

$$0.2 \text{ GeV} < \Lambda_{dQCD} < 5 \text{ GeV}$$



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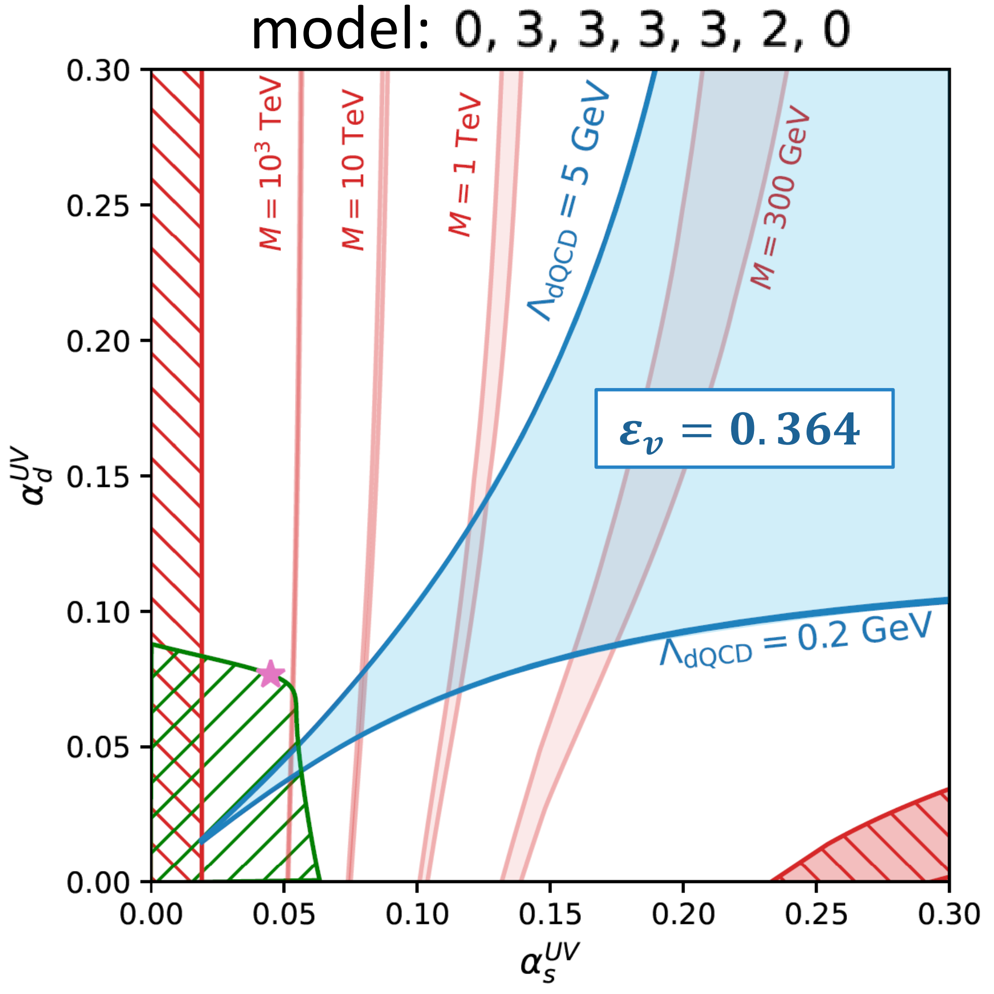
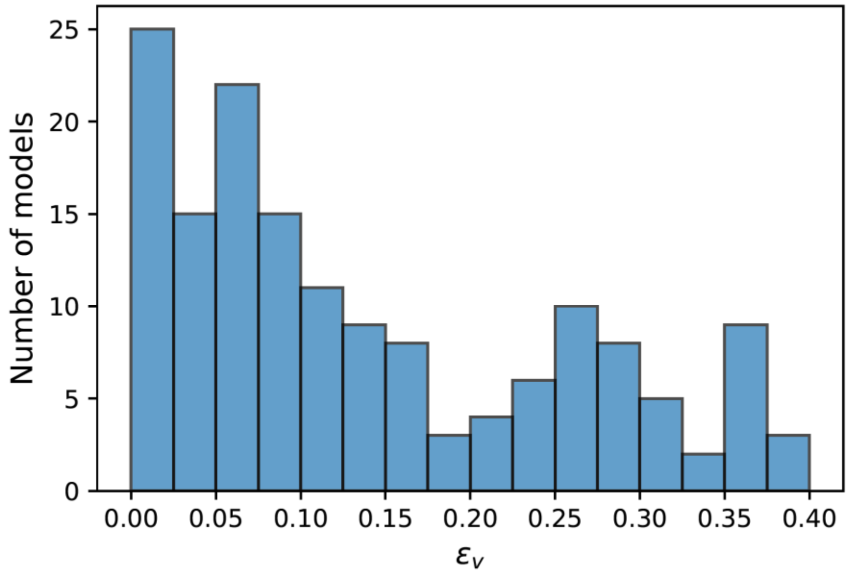
Define ε_v

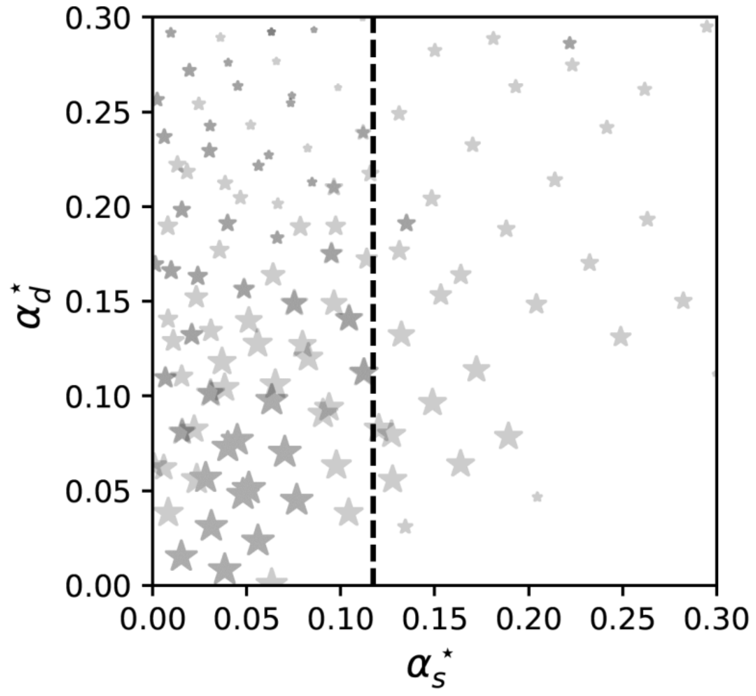
- 'viable fraction' of $\{\alpha_s^{UV}, \alpha_d^{UV}\}$ parameter space
- simple heuristic for the naturalness of a given model



Results

First looked at models with at most 3 of each new field
- **12,288** models
- **155** with a perturbative IRFP

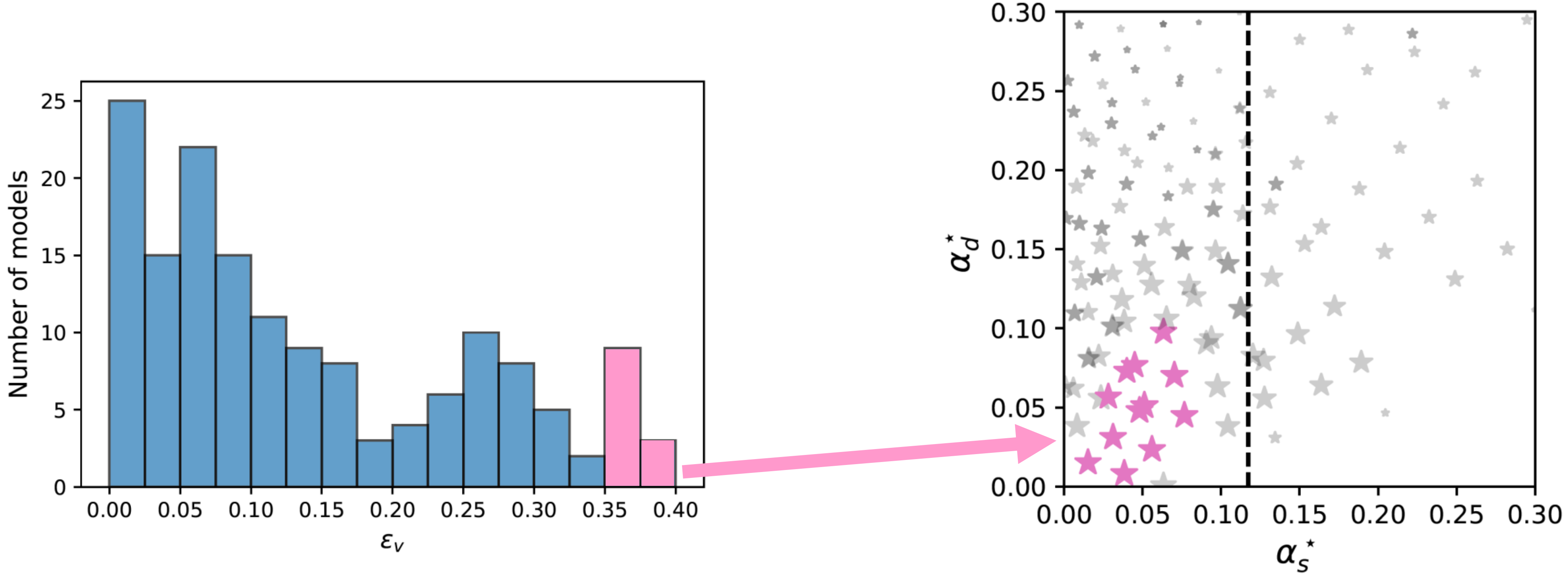


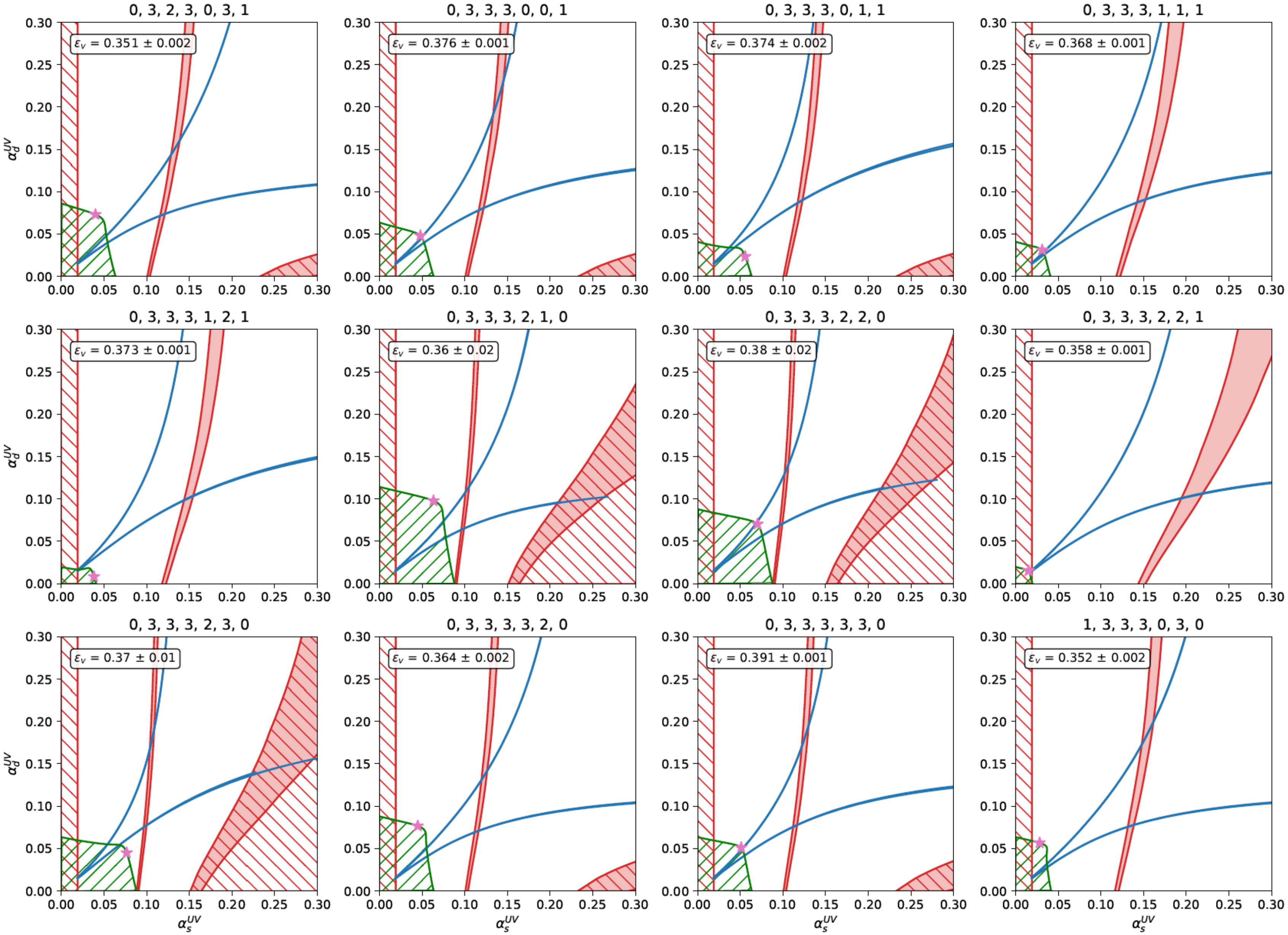


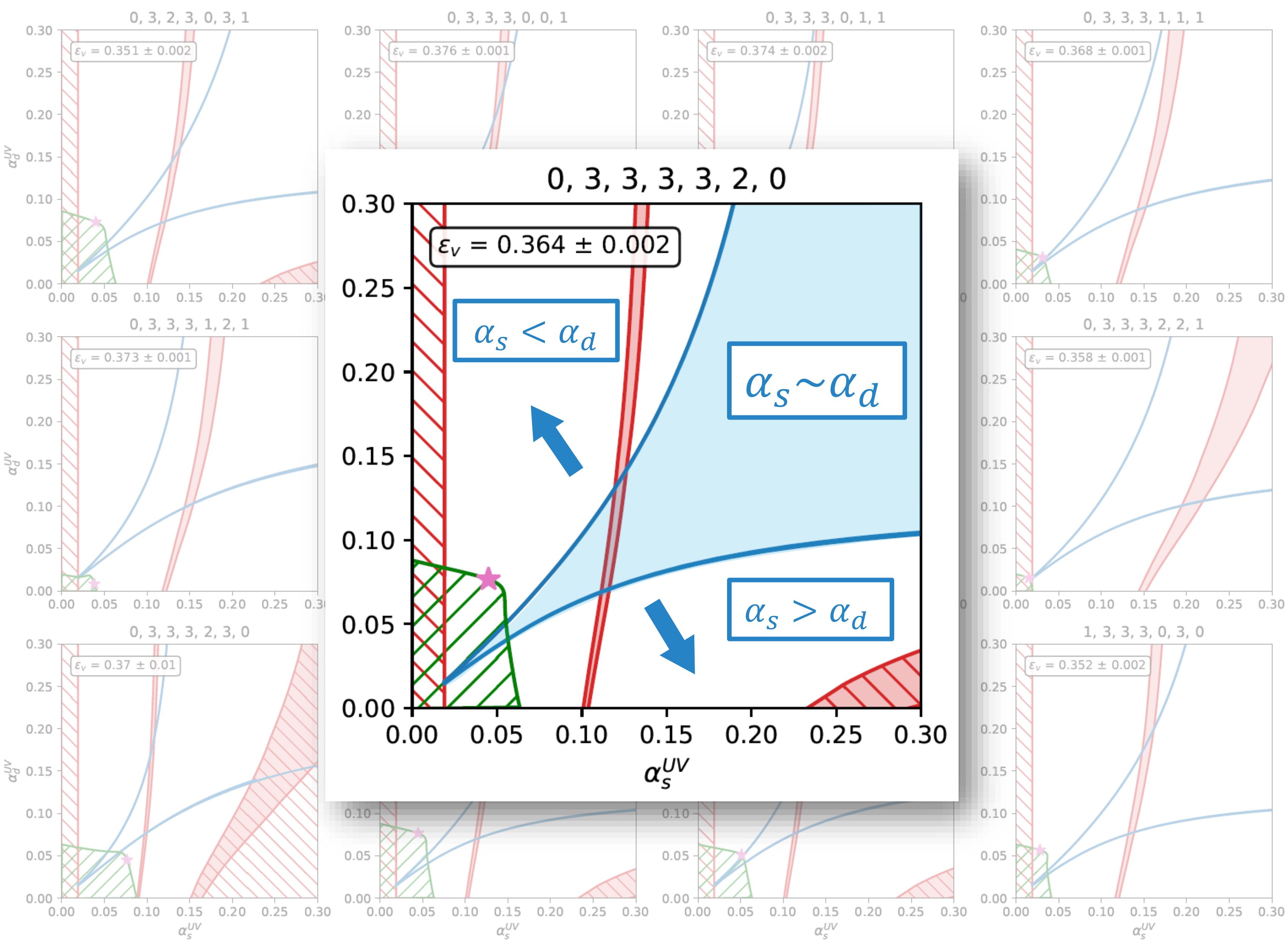
Results

General observations

- ε_v is at most ~ 0.4
- IRFPs with smaller coupling values generally lead to larger ε_v




0, 3, 2, 3, 0, 3, 1
ϵ_v = 0.351 ± 0.002
0, 3, 3, 3, 0, 0, 1
ϵ_v = 0.376 ± 0.001
0, 3, 3, 3, 0, 1, 1
ϵ_v = 0.374 ± 0.002
0, 3, 3, 3, 1, 1, 1
ϵ_v = 0.368 ± 0.001
0, 3, 3, 3, 1, 2, 1
ϵ_v = 0.373 ± 0.001
0, 3, 3, 3, 2, 1, 0
ϵ_v = 0.36 ± 0.02
0, 3, 3, 3, 2, 2, 0
ϵ_v = 0.38 ± 0.02
0, 3, 3, 3, 2, 2, 1
ϵ_v = 0.358 ± 0.001
0, 3, 3, 3, 2, 3, 0
ϵ_v = 0.37 ± 0.01
0, 3, 3, 3, 3, 2, 0
ϵ_v = 0.364 ± 0.002
0, 3, 3, 3, 3, 3, 0
ϵ_v = 0.391 ± 0.001
1, 3, 3, 3, 0, 3, 0
ϵ_v = 0.352 ± 0.002
α_d^{UV}
α_s^{UV}

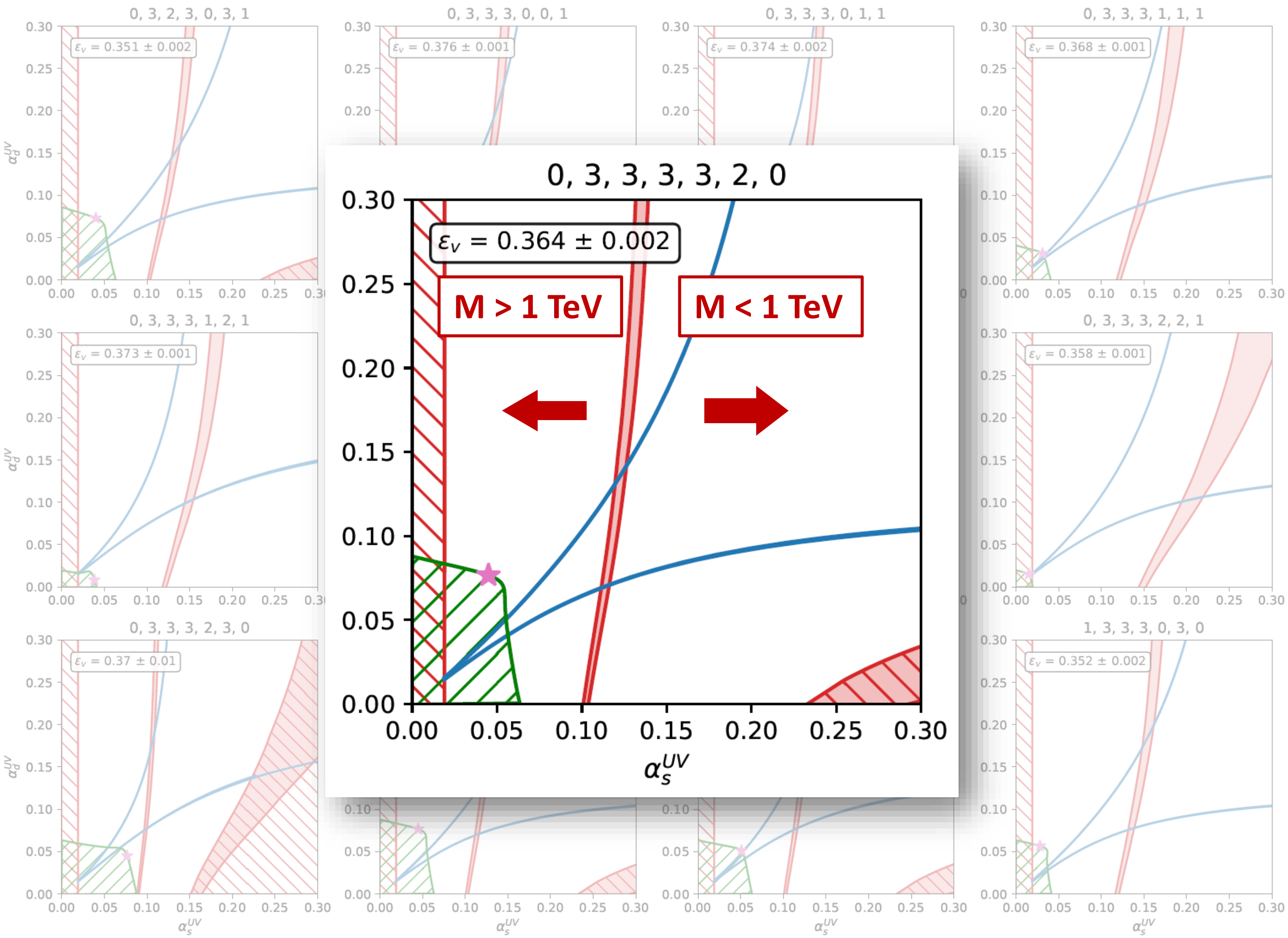


ε_v is at most ~ 0.4

- to have similar confinement scales, need $\alpha_s \sim \alpha_d$ at the decoupling scale
- so, can't have α_s, α_d too dissimilar in the UV

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

POSTERA CRESCAM LAUDE THE UNIVERSITY OF MELBOURNE



Issue:

M < 1 TeV for much of the viable parameter space

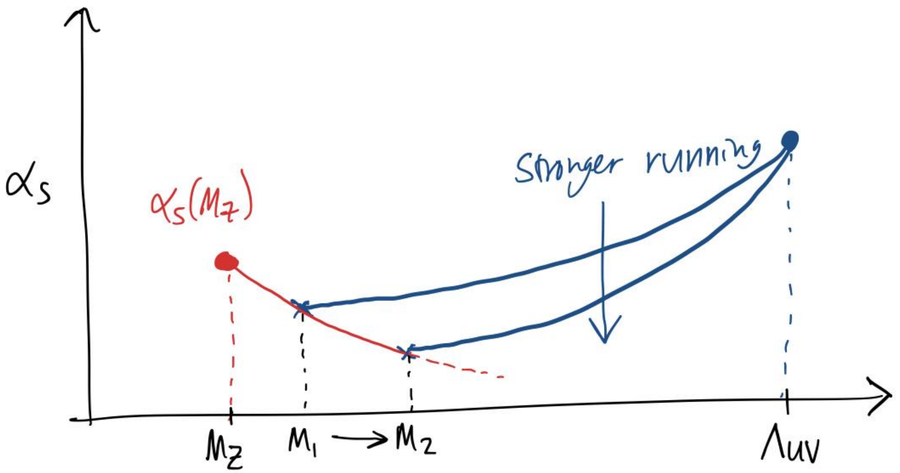
New sub-TeV coloured fields would be produced at colliders

Looking for models with large M

Look at models with large n_{s_j} (# of joint scalars)

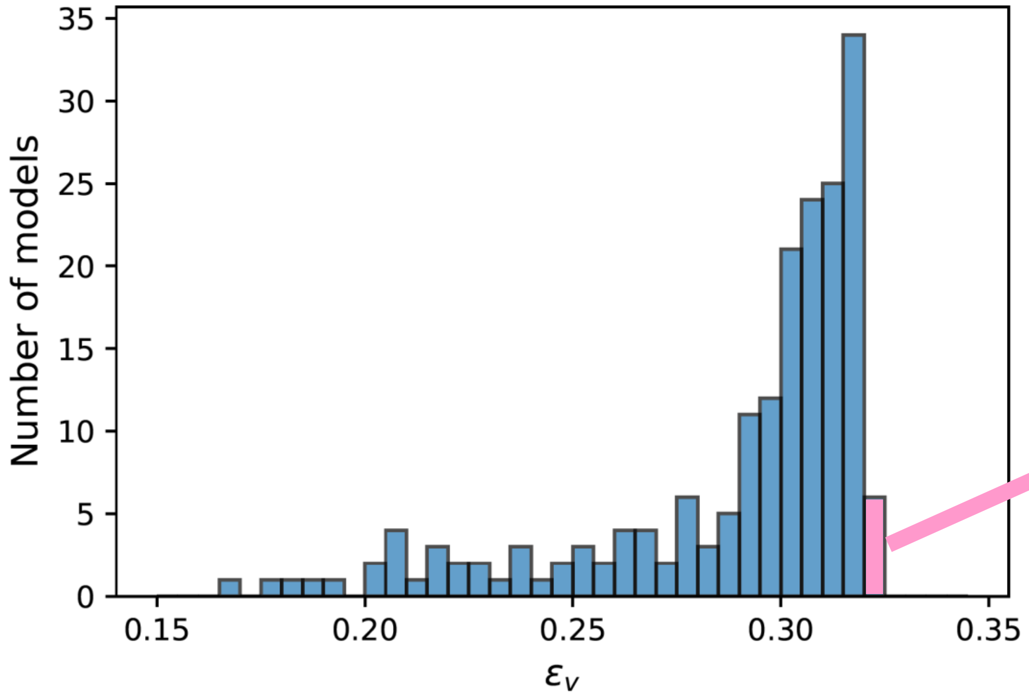
- Increases the magnitude of all beta-function coefficients
- Increased coefficients = stronger running
- Couplings reach lower values at higher energy scales, so the decoupling scale can be higher

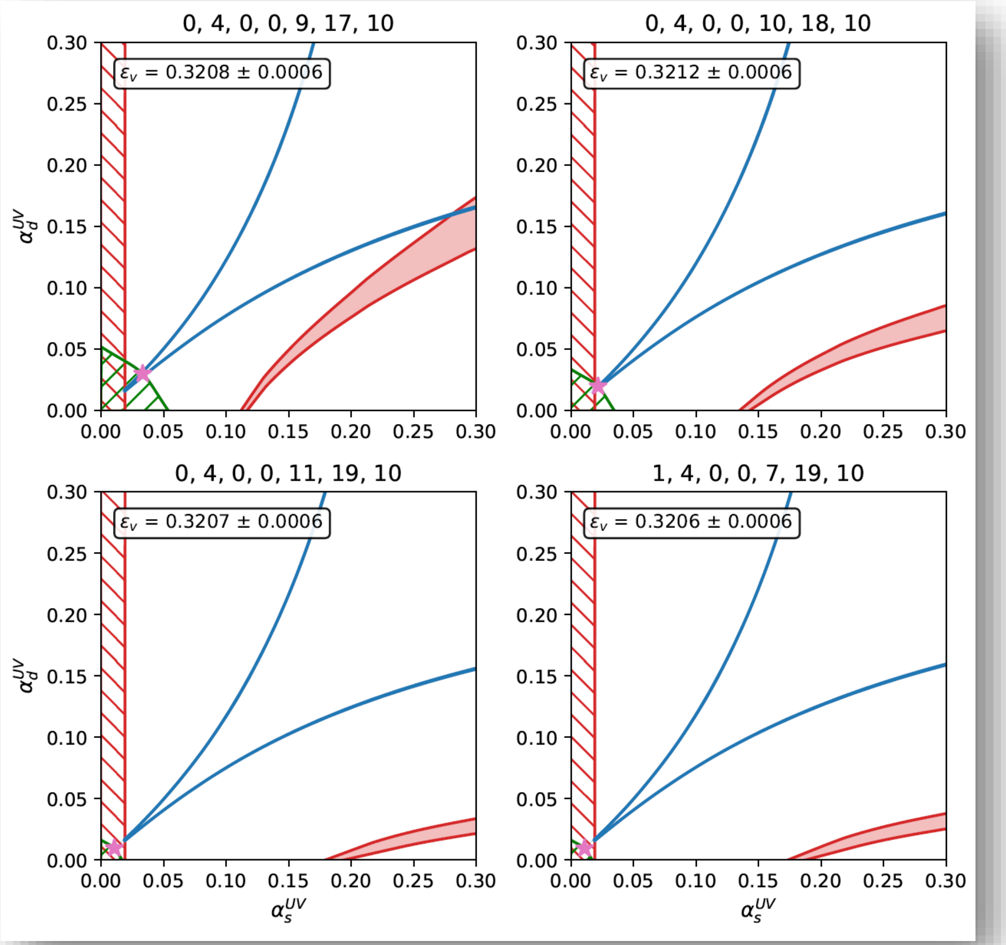
$$\beta_c = \frac{g_c^3}{16\pi^2}\left[\frac{2}{3}\left(n_{f_c} + 3n_{f_j}\right) + \frac{1}{6}\left(n_{s_c} + 3n_{s_j}\right) - 11\right] + \frac{g_c^5}{(16\pi^2)^2}\left[\frac{38}{3}\left(n_{f_c} + 3n_{f_j}\right) + \frac{11}{3}\left(n_{s_c} + 3n_{s_j}\right) - 102\right] + \frac{g_c^3 g_d^2}{(16\pi^2)^2}\left[8n_{f_j} + 8n_{s_j}\right],$$



Looking for models with large M

188 models with $n_{s_j} \geq 10$, one-loop beta-function coefficients between -0.1 and 0, and a perturbative IRFP



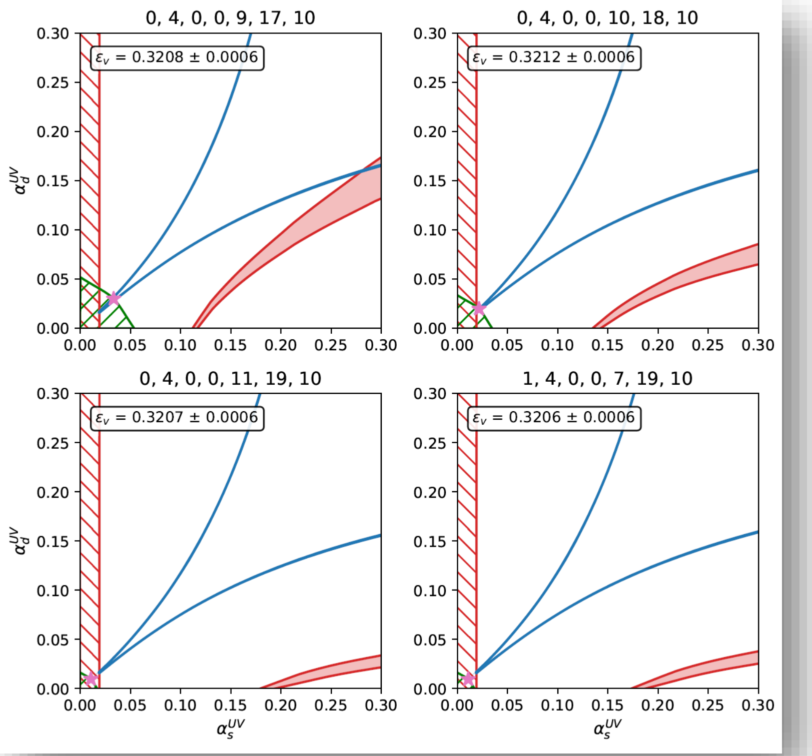


Conclusions

Cosmological coincidence inspires interesting model building

We've found a set of phenomenologically viable models that could naturally have $m_B \sim m_D$

Questions?



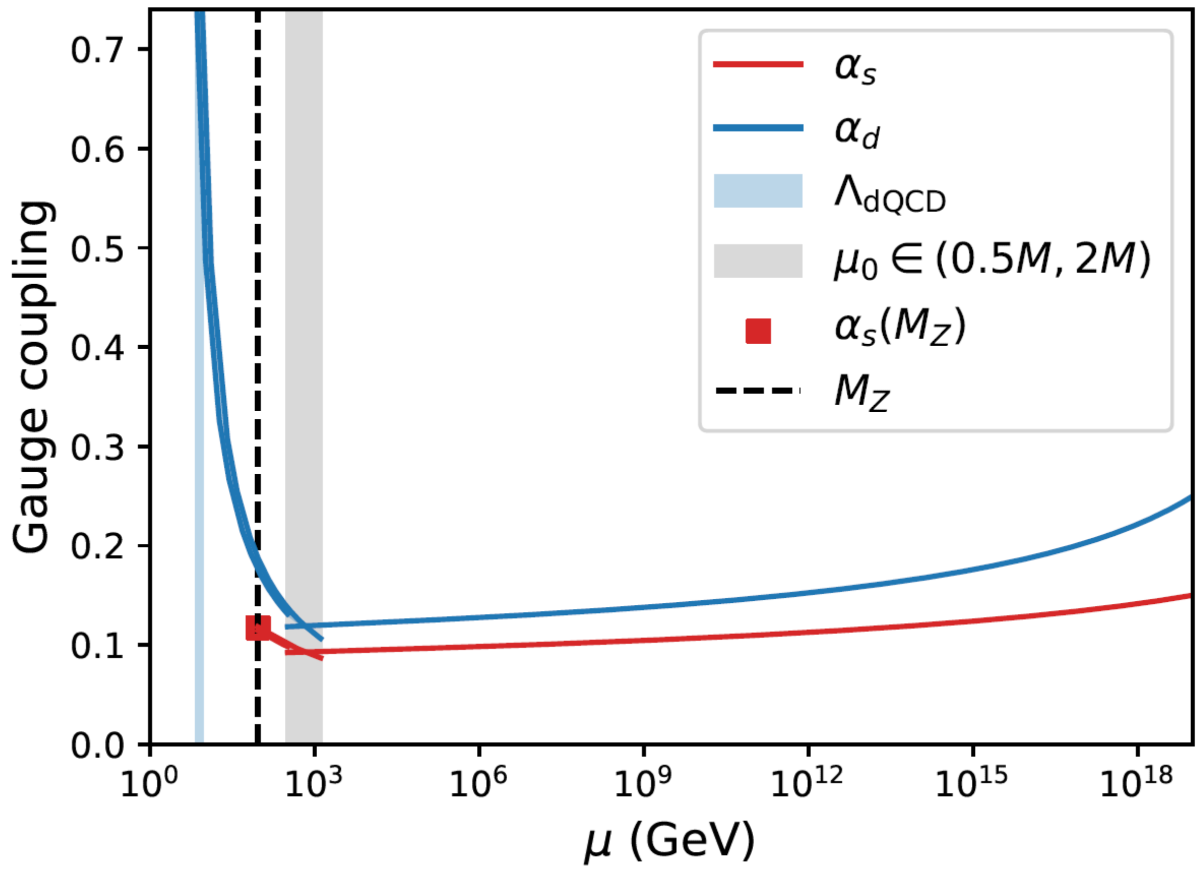
Backup Slides

Threshold corrections

Heavy fields can still affect beta-functions at energies below their mass scale M

Need to apply threshold conditions at a decoupling scale $\mu_0 = \mathcal{O}(M)$

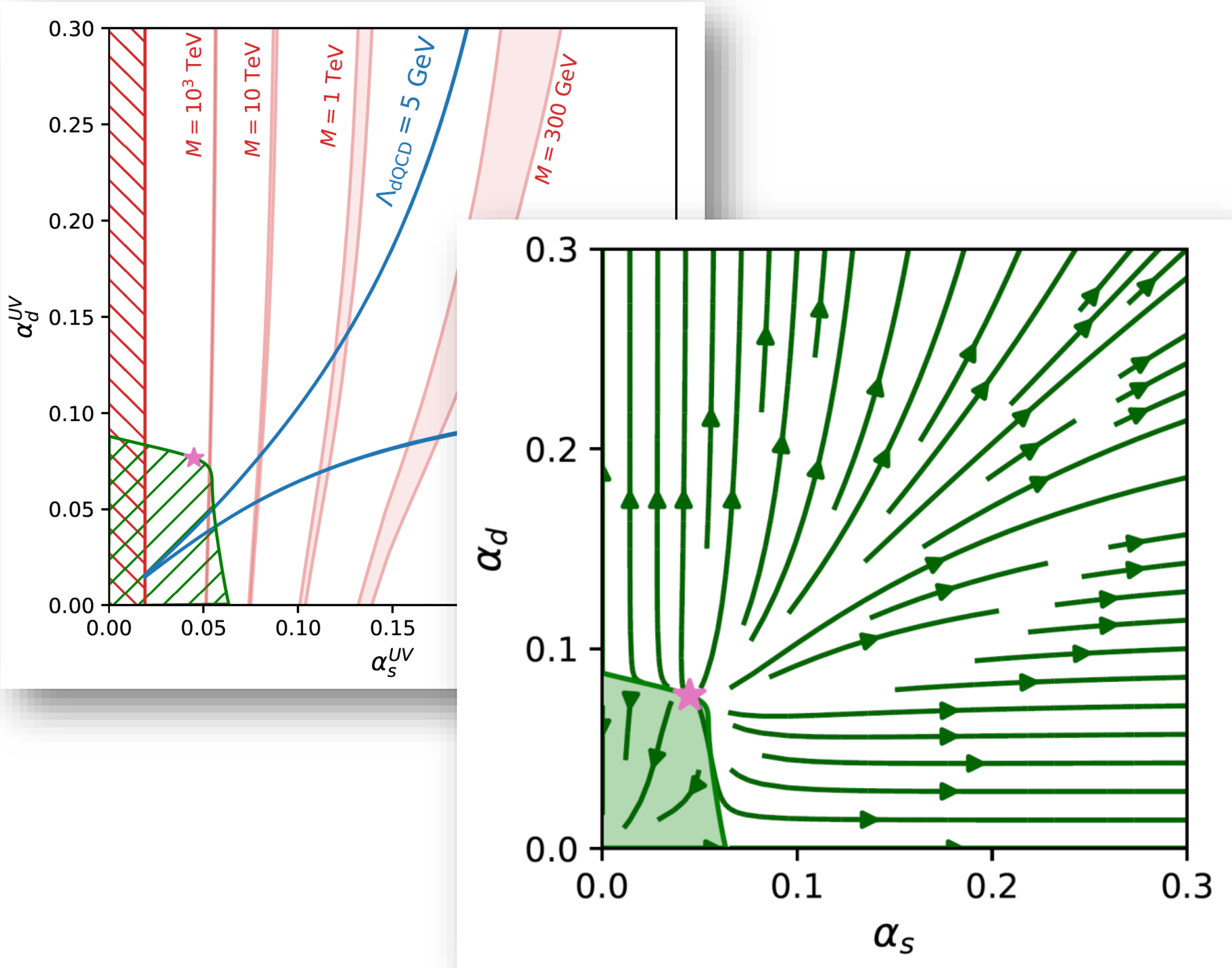
This introduces an uncertainty into M, Λ_{dQCD} for a given $\{\alpha_s^{UV}, \alpha_d^{UV}\}$



Asymptotic Freedom

With coupled beta-functions, asymptotic freedom depends on the values of the gauge couplings

We only work with couplings that are perturbative below the Planck scale, so do consider non-asymptotically free regions



Combining with an ADM model

To fully explain the coincidence problem, need to relate number densities (embed in an ADM model)

Bai and Schwaller: thermal leptogenesis model, taking advantage of the new fields introduced for the IRFP mechanism

The ingredients:

- 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

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

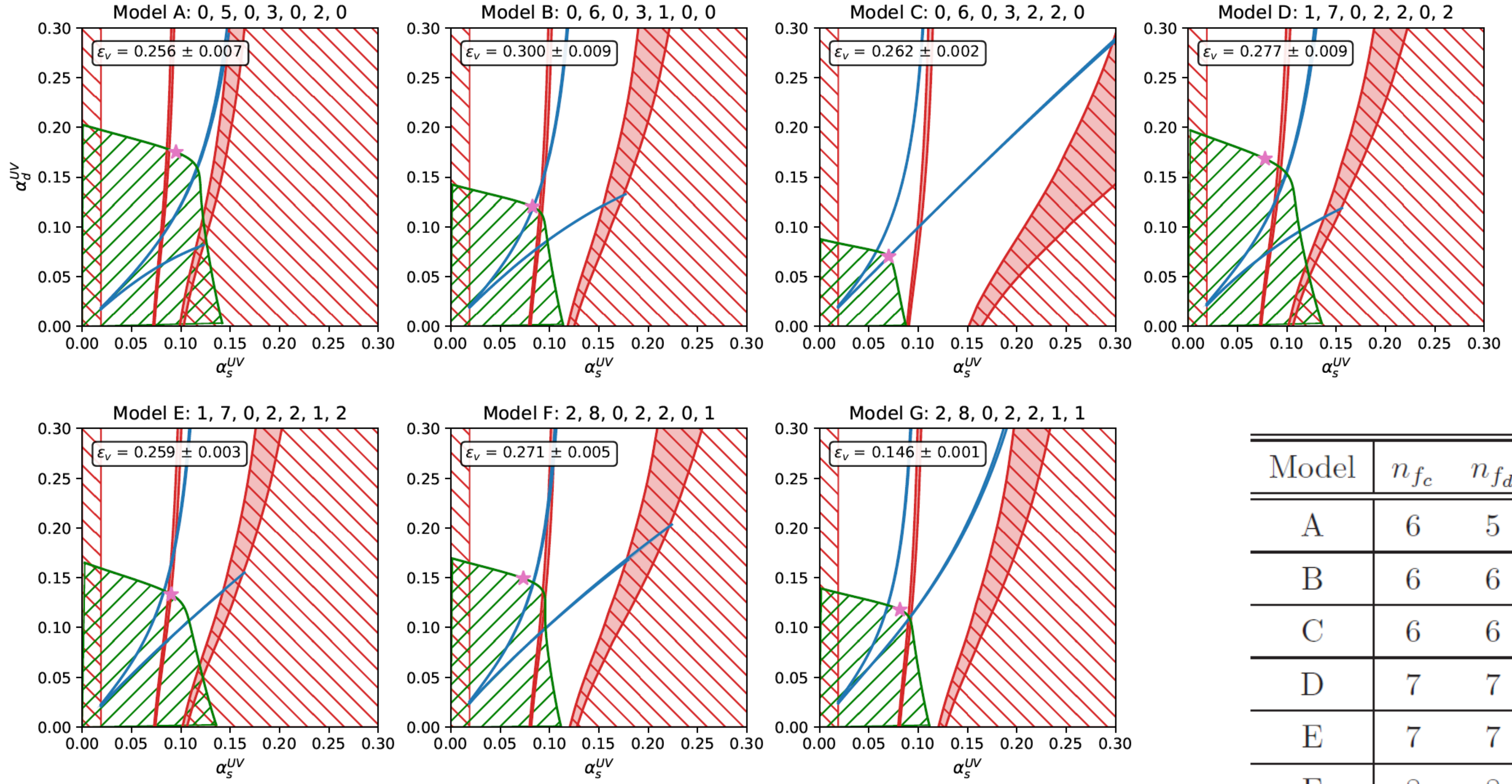
2. These asymmetries are transferred into visible matter and dark fermions X_L

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

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

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

Bai-Schwaller results

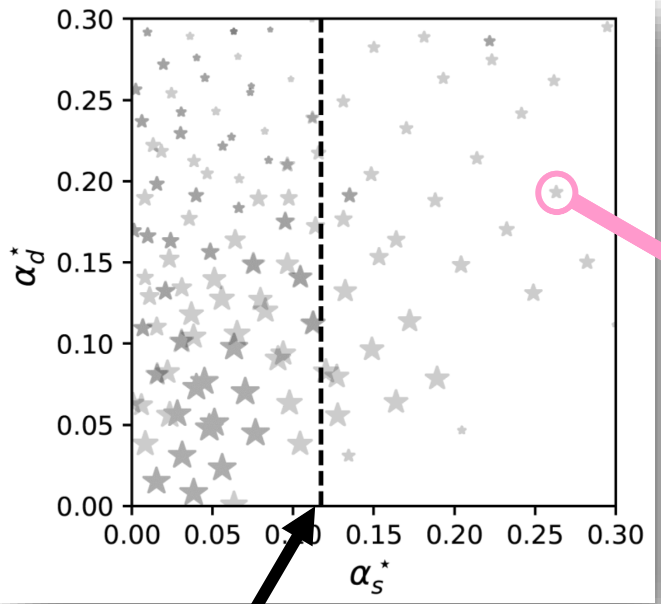


Model	n_{f_c}	n_{f_d}	n_{f_j}	n_{s_c}	n_{s_d}	n_{s_j}	α_s^*	α_d^*
A	6	5	3	0	2	0	0.095	0.175
B	6	6	3	1	0	0	0.083	0.120
C	6	6	3	2	2	0	0.070	0.070
D	7	7	2	2	0	2	0.078	0.168
E	7	7	2	2	1	2	0.090	0.133
F	8	8	2	2	0	1	0.074	0.149
G	8	8	2	2	1	1	0.082	0.118

Small IRFPs have larger ε_v

To match with $\alpha_s(M_Z)$, α_s needs to evolve below 0.11729 by the decoupling scale

If $\alpha_s^* > \alpha_s(M_Z)$, then for many initial UV couplings, will not be able to match α_s to experiment



$\alpha_s(M_Z) = 0.11729$