Two ideas about dark matter model building

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CATCH22+2, 1-5 May 2024, DIAS

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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What problem are we trying to solve?

A cosmological coincidence: $\rho_{\text{dark}} \simeq 5\ \rho_{\text{baryon}}$

$$n_{\text{dark}}\ m_{\text{dark}} \simeq 5\ n_{\text{baryon}}\ m_{\text{proton}}$$

Asymmetric dark matter models address $n_{dark} \sim n_{baryon}$

But what about $m_{dark} \sim m_{proton}$? That's our concern here.

Relevant papers:

Y. Bai and P. Schwaller, *Scale of dark QCD;* PRD89, 063522 (2013); 1306.4676

J. L. Newstead and R. H. TerBeek, *Reach of threshold corrected dark QCD;* PRD90, 074008 (2014); 1405.7427

A. C. Ritter and RRV, *Exploring the cosmological dark matter coincidence using infrared fixed points*; PRD107, 015029, (2023); 2210.11011

A. C. Ritter and RRV, *Explaining the cosmological dark matter coincidence in asymmetric dark QCD*; 2404.05999

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The framework

Proton mass set by Λ_{QCD}.

Motivates DM mass set by dark QCD with $\Lambda_{dQCD} \sim \Lambda_{QCD}$.

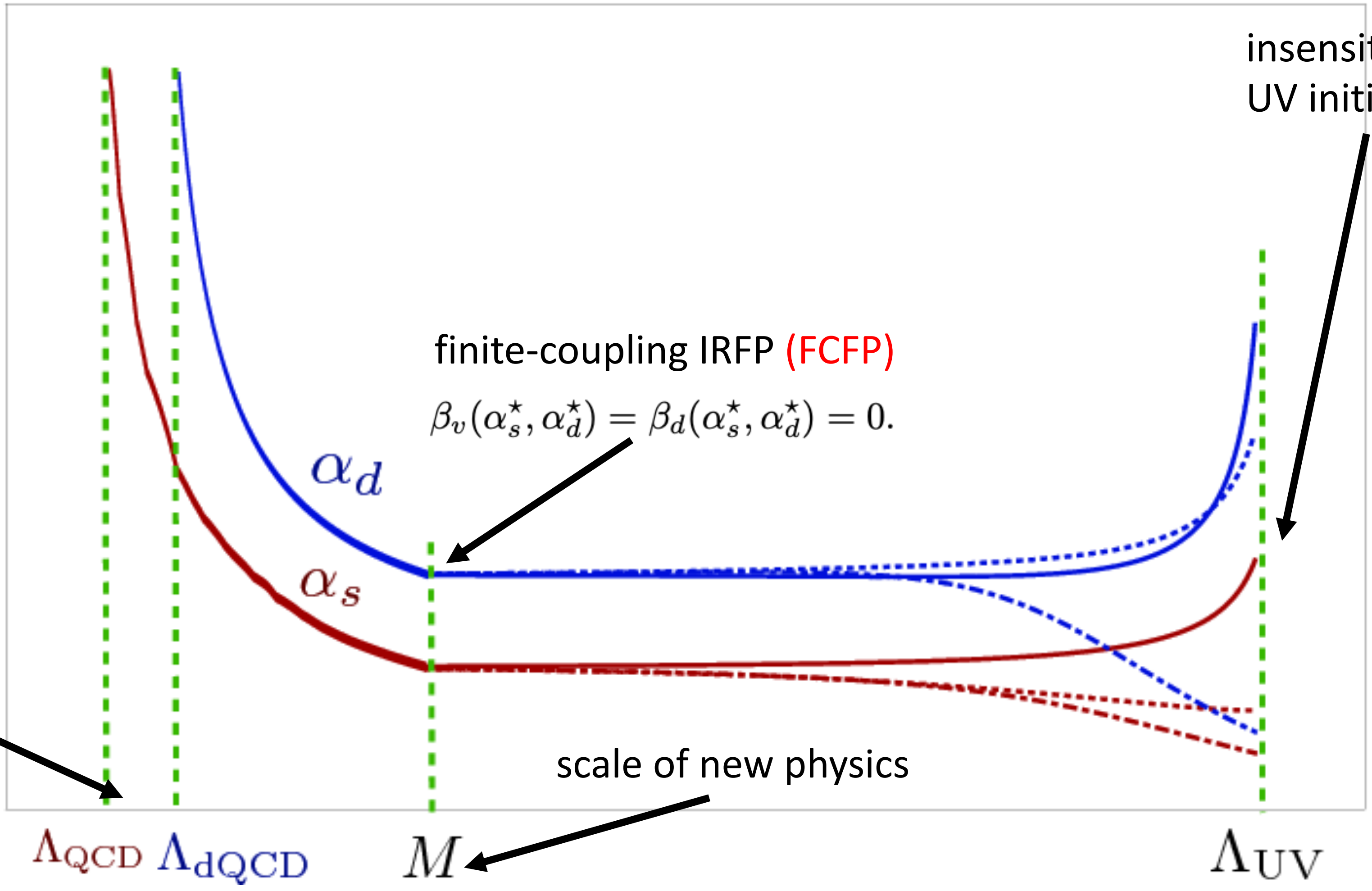
How to get $\Lambda_{dQCD} \sim \Lambda_{QCD}$? Two approaches: symmetry (e.g. mirror matter)

IR fixed points (this talk)

The Bai-Schwaller idea

insensitivity to
UV initial values

Related confinement scales

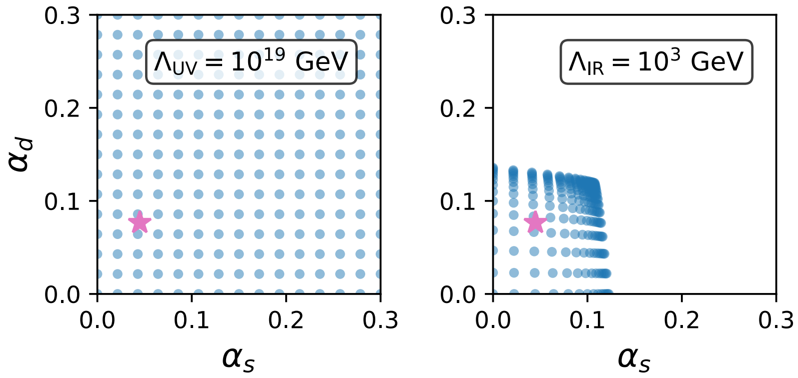


Nice idea, but there are issues.

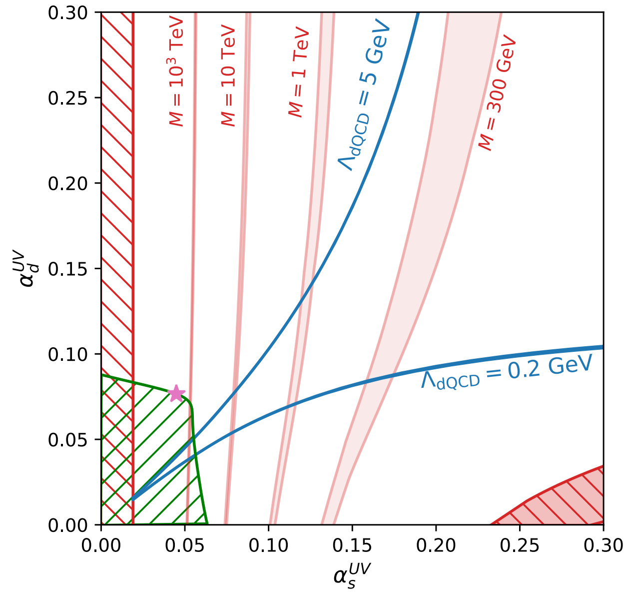
$$\beta_v(\alpha_s,\alpha_d) = b_v^{(0)}\frac{\alpha_s^2}{2\pi} + b_v^{(1)}\frac{\alpha_s^3}{8\pi^2} + b_v^{(1')}\frac{\alpha_s^2\alpha_d}{8\pi^2}$$

$$\alpha_s^\star = 4\pi\frac{b_v^{(0)}b_d^{(1)} - b_v^{(1')}b_d^{(0)}}{b_v^{(1')}b_d^{(1')} - b_v^{(1)}b_d^{(1)}},\quad \alpha_d^\star = 4\pi\frac{b_d^{(0)}b_v^{(1)} - b_d^{(1')}b_v^{(0)}}{b_v^{(1')}b_d^{(1')} - b_v^{(1)}b_d^{(1)}}$$

Only small fraction of models have perturbative FCFPs.
Non-generic.



FCFP ★ approached, but not attained.
Some sensitivity to UV values.
Reduced "successful" parameter space.



Scale of new physics generically too low.
Can be fixed with large multiplicities for fundamental reps. Looks contrived.

New idea: zero-coupling IR fixed point (ZCFP)

The possible FPs:

$$\alpha_s^\star = 0, \quad \alpha_d^\star = 0$$

$$\alpha_s^\star = -4\pi \frac{b_v^{(0)}}{b_v^{(1)}}, \quad \alpha_d^\star = 0$$

$$\alpha_s^\star = 0, \quad \alpha_d^\star = -4\pi \frac{b_d^{(0)}}{b_d^{(1)}}$$

$$\alpha_s^\star = 4\pi \frac{b_v^{(0)} b_d^{(1)} - b_v^{(1')} b_d^{(0)}}{b_v^{(1')} b_d^{(1')} - b_v^{(1)} b_d^{(1)}}, \quad \alpha_d^\star = 4\pi \frac{b_d^{(0)} b_v^{(1)} - b_d^{(1')} b_v^{(0)}}{b_v^{(1')} b_d^{(1')} - b_v^{(1)} b_d^{(1)}}.$$

Ritter-RRV (2024) (arrow pointing to $\alpha_s^\star = 0, \alpha_d^\star = 0$)

Non-asymptotically-free above M, but perturbative up to Planck scale.

Allow higher-dim reps.

Explore $N_{dark} \neq 3$.

Bai-Schwaller (2013)

Advantages: Many models have a ZCFP; more generic.
Higher-dim reps. ⇒ lower field multiplicities.
Stronger running above M ⇒ higher M.

Disadvantages: High M ⇒ naturalness problem.
Very high M ⇒ NP hard to find experimentally
(but may produce detectable GWs from the dark QCD phase transition).

Non-SUSY:

- $M \lesssim 100$ TeV for colour-triplet, electroweak-singlet Dirac fermions.
- $M \lesssim 10$ TeV for colour-triplet, electroweak-singlet complex scalars.

Clarke, Cox 1607.07446
Bounds from naturalness.

Can be achieved, but is non-generic. Example:

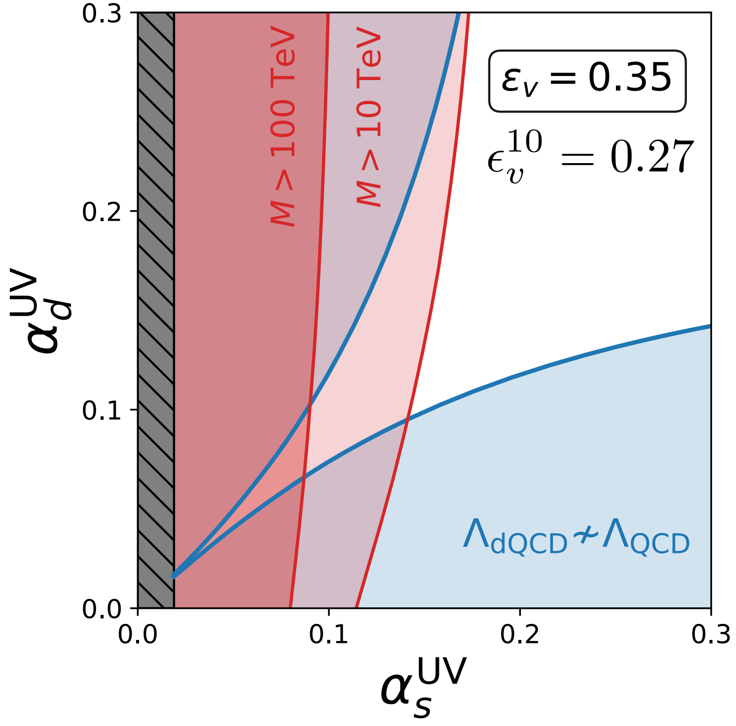
"viability fraction" ε_v = fraction of successful parameter space
ε_v^{10} = fraction with M < 10 TeV

$SU(3)_{\mathrm{QCD}} \times SU(3)_{\mathrm{dQCD}}$

(1,1) (1,3)
(3,1) (3,3)

fermions	n_{dq}	scalars	$b_v^{(0)}/2\pi$	$M_{\min}$	ϵ_v	ϵ_v^{10}
$\begin{pmatrix} & 6 \\ 6 & 3 \end{pmatrix}$	4	$\begin{pmatrix} & 1 \\ 1 & 2 \end{pmatrix}$	$1/12\pi$	1.1	0.35	0.27
$\begin{pmatrix} & 6 \\ 6 & 3 \end{pmatrix}$	5	$\begin{pmatrix} & 1 \\ 2 & 2 \end{pmatrix}$	$1/6\pi$	2.2	0.34	0.15
$\begin{pmatrix} & 6 \\ 6 & 3 \end{pmatrix}$	6	$\begin{pmatrix} & 1 \\ 3 & 2 \end{pmatrix}$	$1/4\pi$	4.2	0.33	0

multiplicities

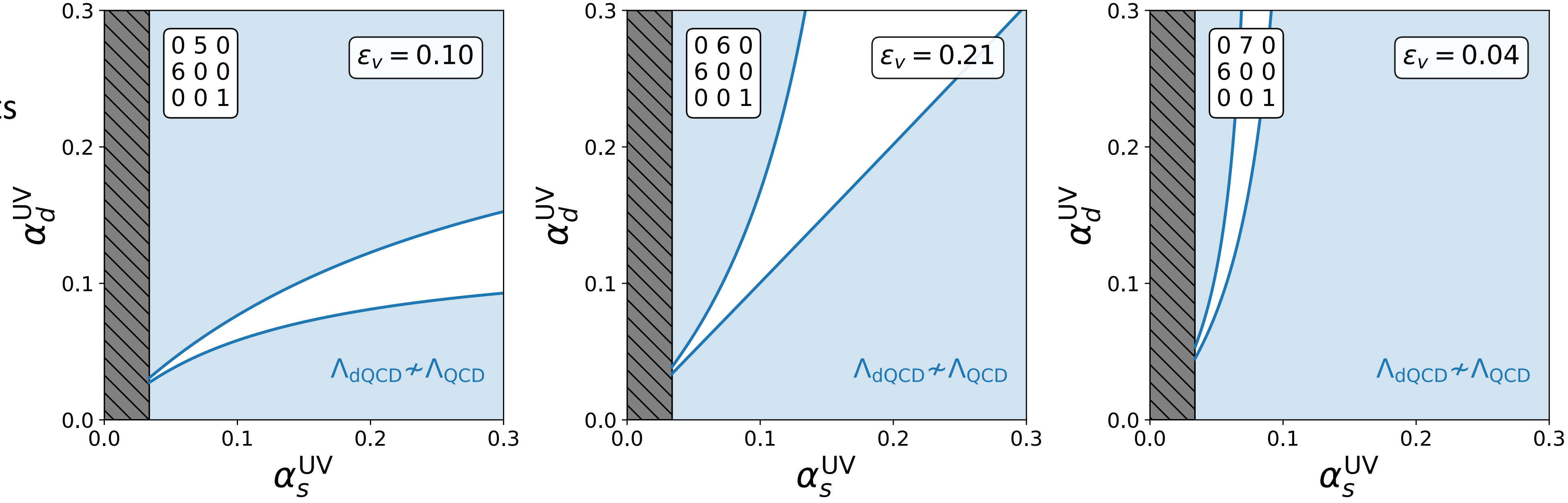


SUSY:

Note: outcome depends strongly on number of light dark quarks

models with sextets

(1,1) (1,3) (1,6)
(3,1) (3,3) (3,6)
(6,1) (6,3) (6,6)

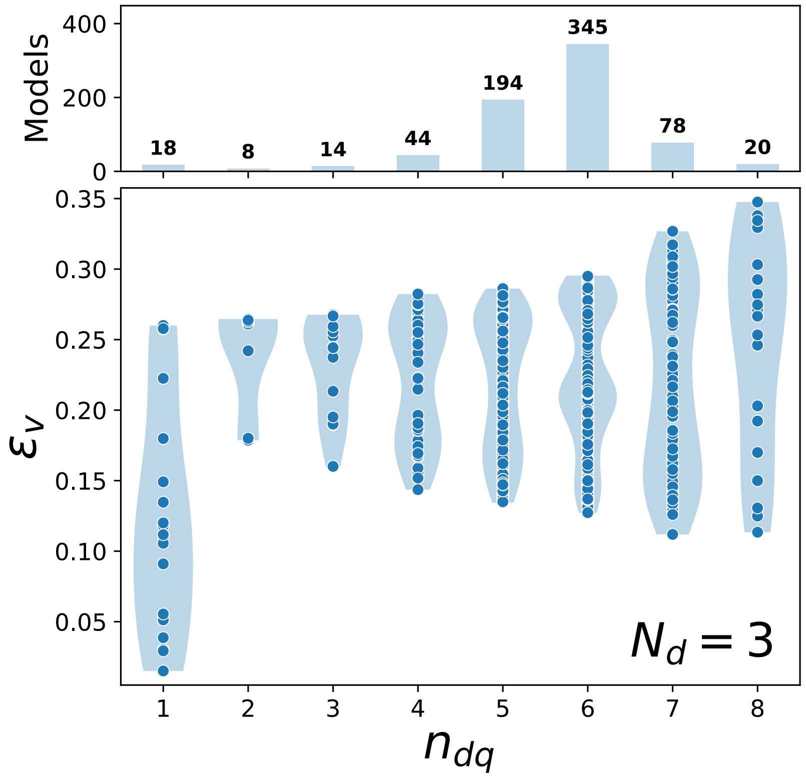


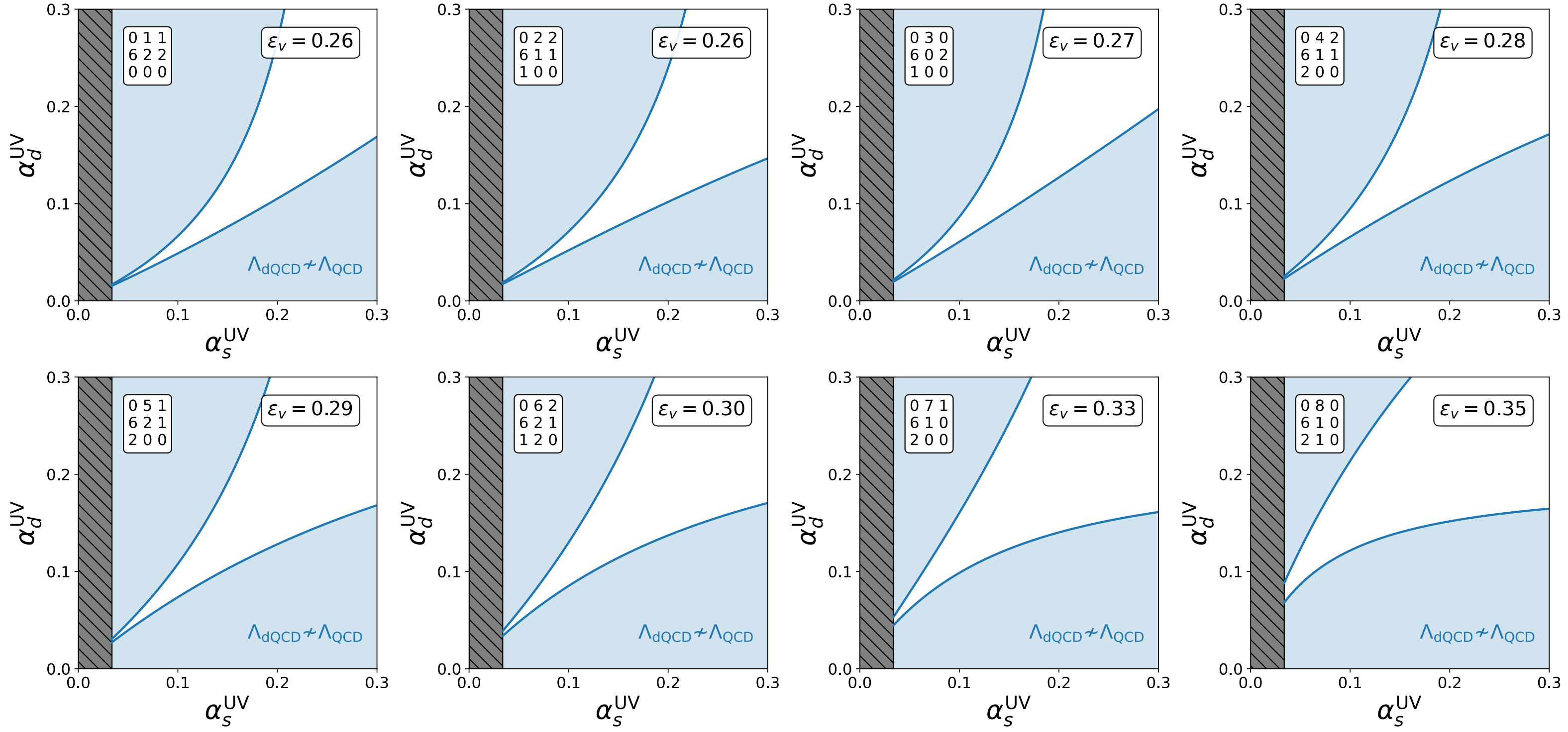
$n_{dq} = 5$ $n_{dq} = 6$ $n_{dq} = 7$

sweet spot at 6 in this case

$N_d = 3$:

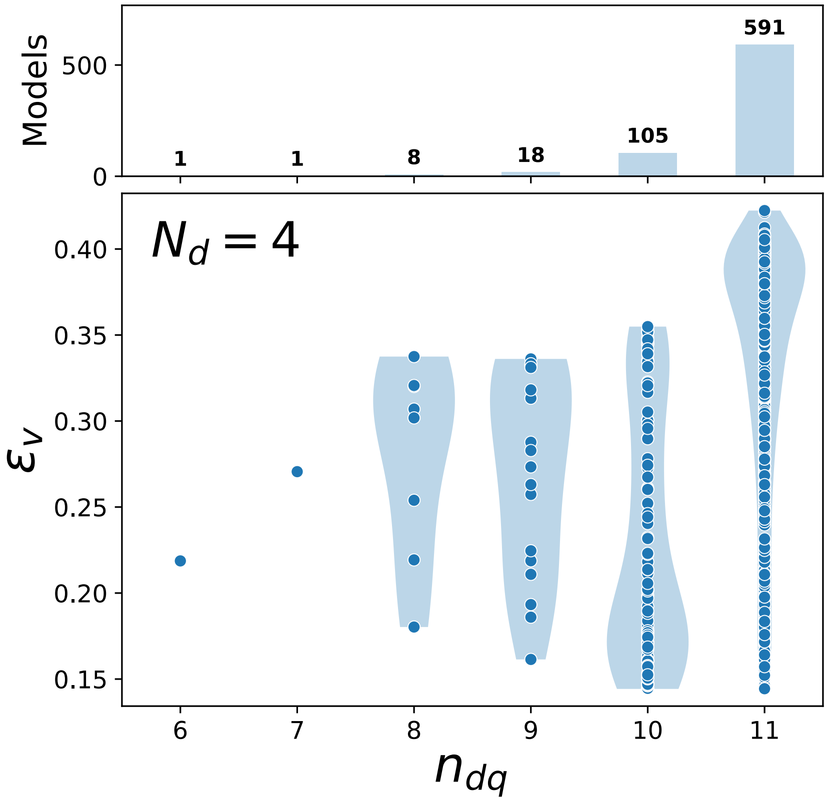
Models with highest ε_v for each $n_{dq} = 1, \ldots, 8$

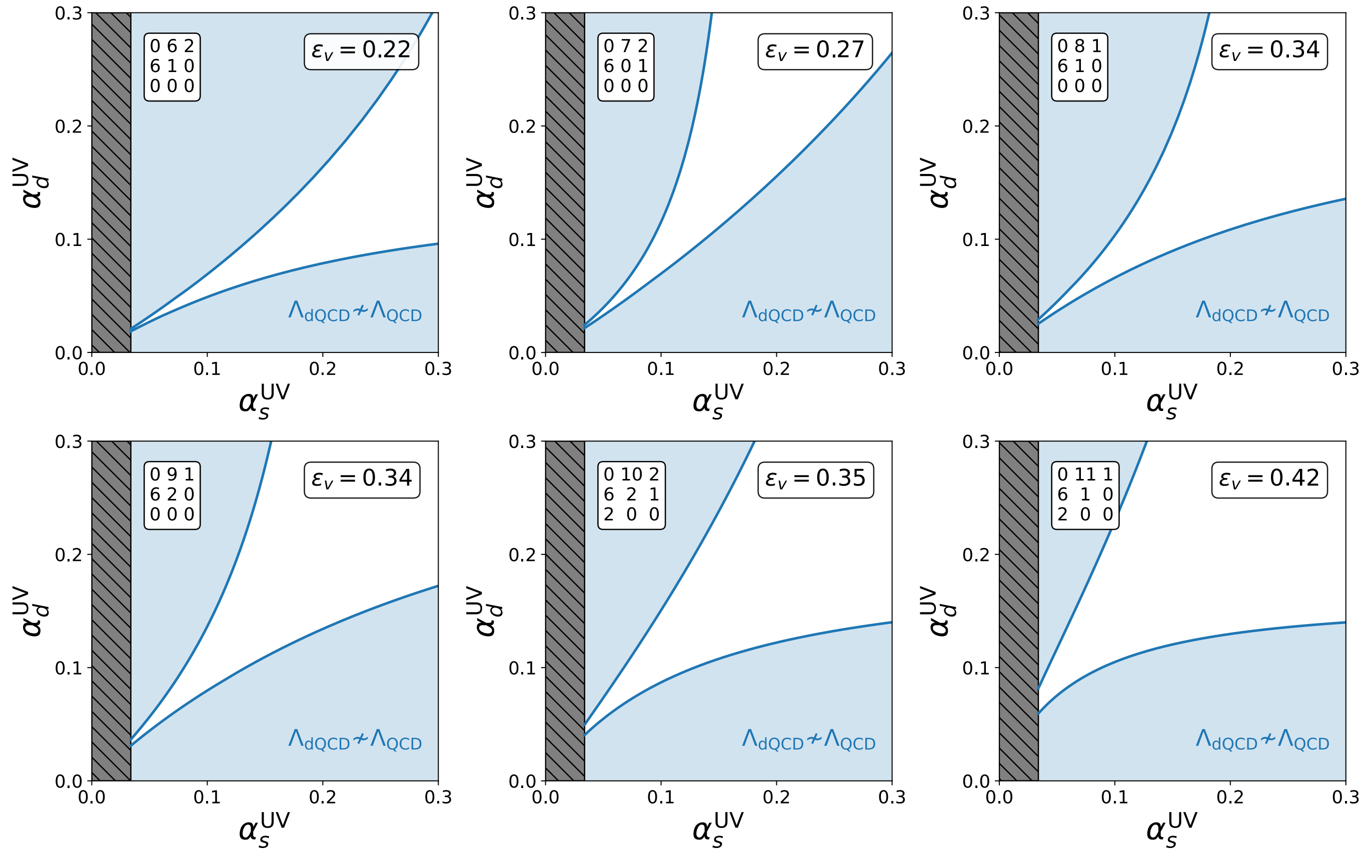




~40% of models have $\varepsilon_v > 0.25$

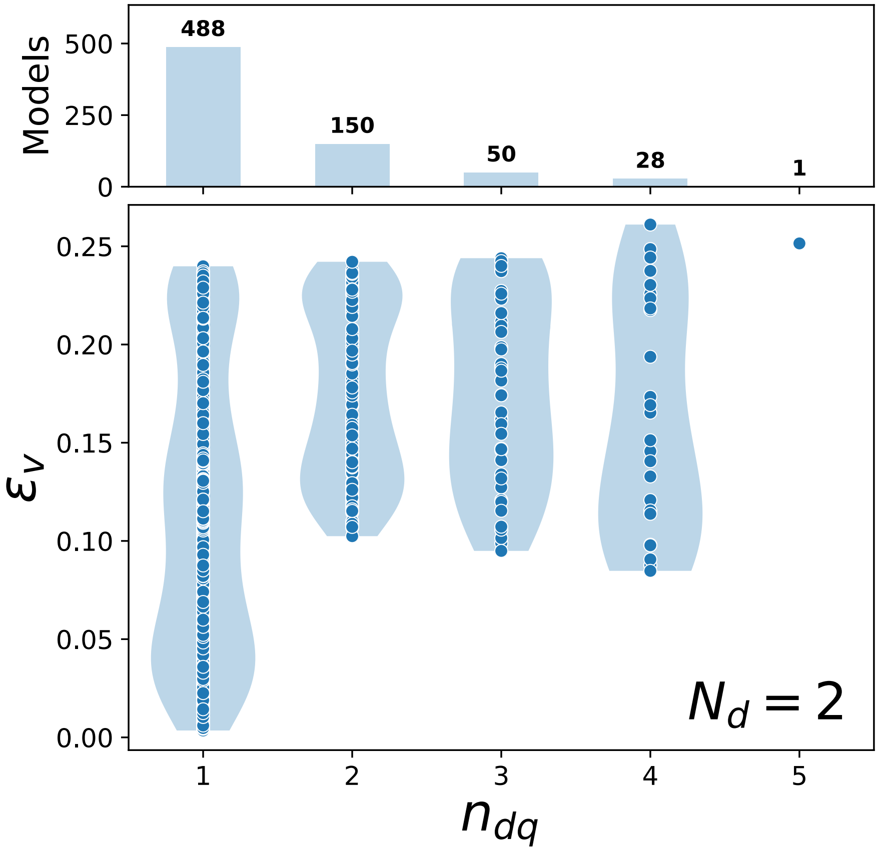
$N_d = 4$:





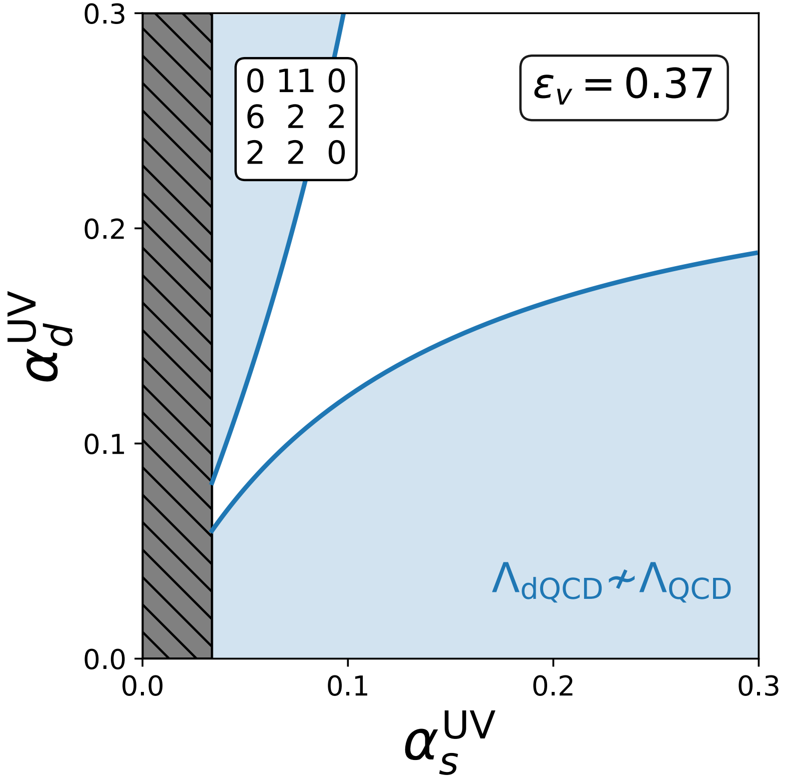
~65% of models have $\varepsilon_v > 0.3$

$N_d = 2$:



<1% of models have $\varepsilon_v > 0.25$

Towards complete models



In our paper, we show this SU(4) SUSY model with high ε_v contains the superfield content that permits successful asymmetry generation in both sectors via leptogenesis and reprocessing.

The detailed model-building is still in its infancy.

To take home

- The Bai-Schwaller IR fixed point idea is a good one.
- The new zero-coupling IR fixed point idea permits generic models with improved features.
- SUSY is relevant to avoid a naturalness issue with a high new physics scale.
- SU(4) dark QCD is better than SU(3). SU(2) is not successful.
- There are interesting cases that allow for asymmetry generation in both sectors.
- Possible stochastic GW signal from a first-order dark QCD phase transition.
- Model building has only just begun.

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