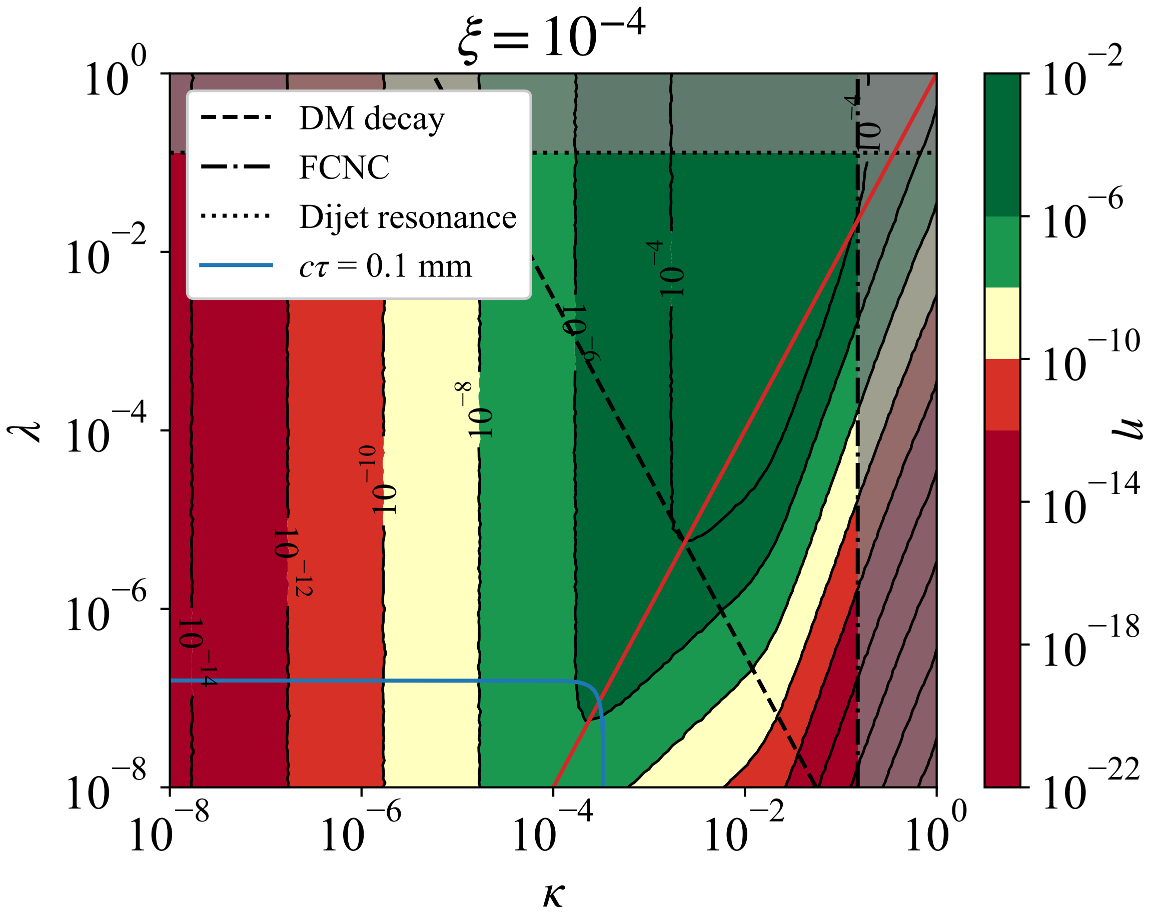
The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics 2022

Twin Quark Dark Matter



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[Phys.Rev.D 104 (2021) 11, 116018, arXiv: 2109:03248]

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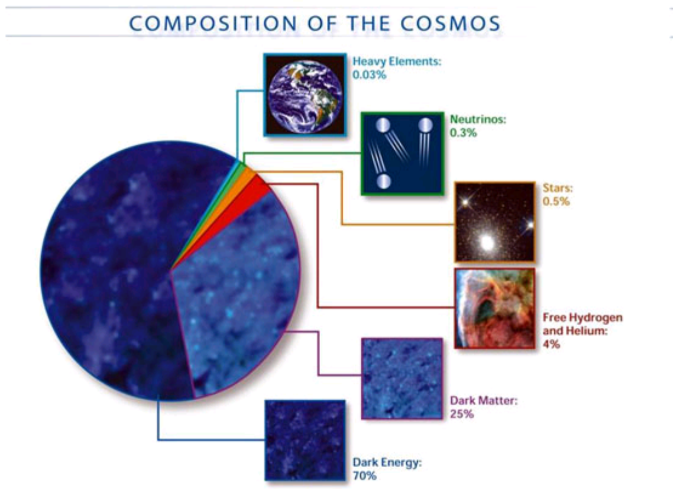
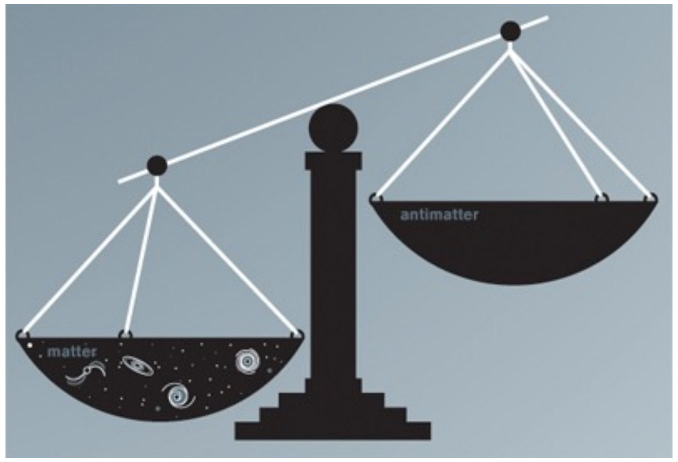
Introduction

The Standard Model has a number of shortcomings.

naturalness



dark matter



matter / antimatter asymmetry

and others

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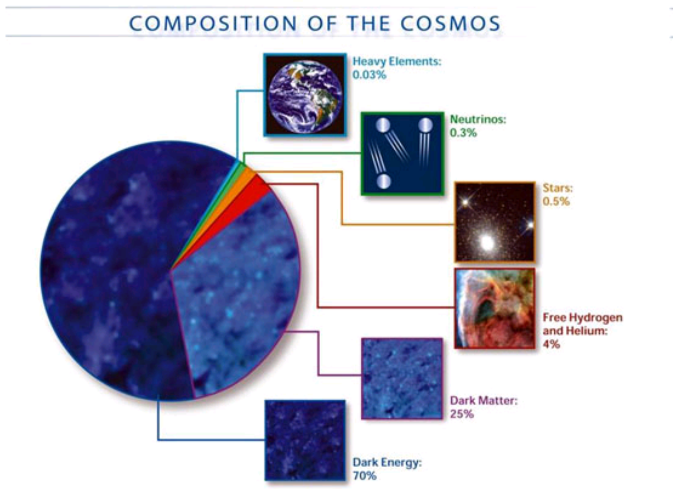
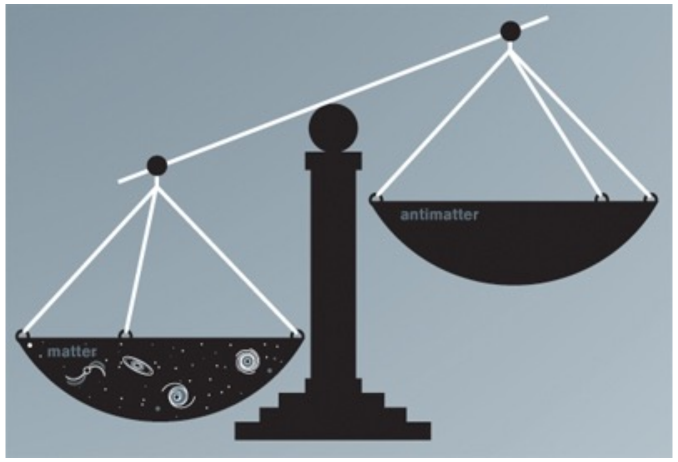


dark matter



matter / antimatter asymmetry

Twin Higgs: Add a copy of the SM, with its own gauge groups. Global SU(4) symmetry in the scalar sector and a Z_2 symmetry between the visible and twin sectors reduces fine tuning. Higgs doublets are a portal between the visible and twin sectors.

Chacko et al: [hep-ph/0506256] + many other models

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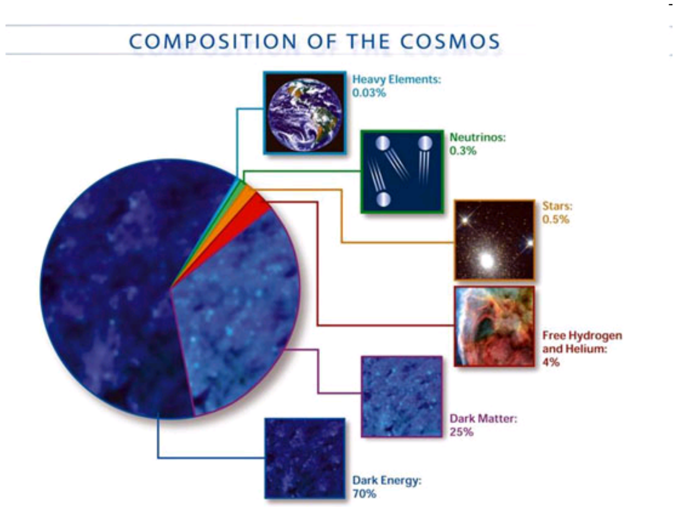
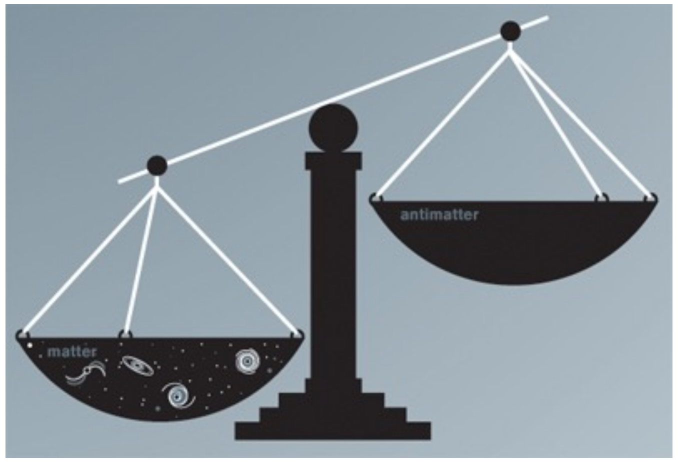


dark matter



matter / antimatter asymmetry

Twin Higgs: Potential DM candidates, for example twin baryons.

Garcia et al: [arXiv: 1505.07109], Craig et al: [arXiv: 1505.07113] + others

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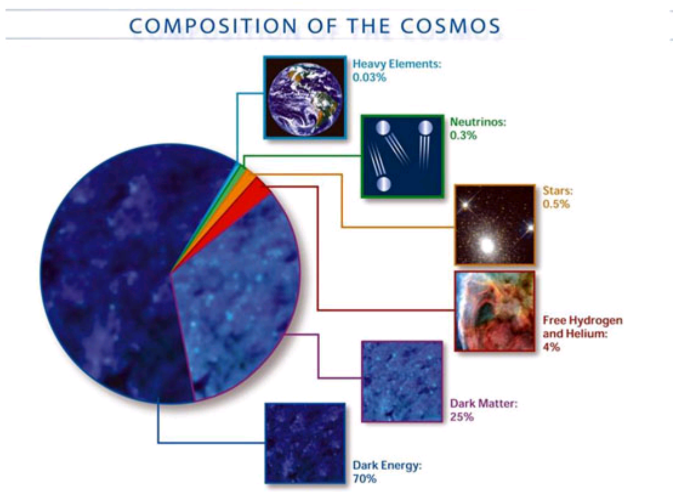
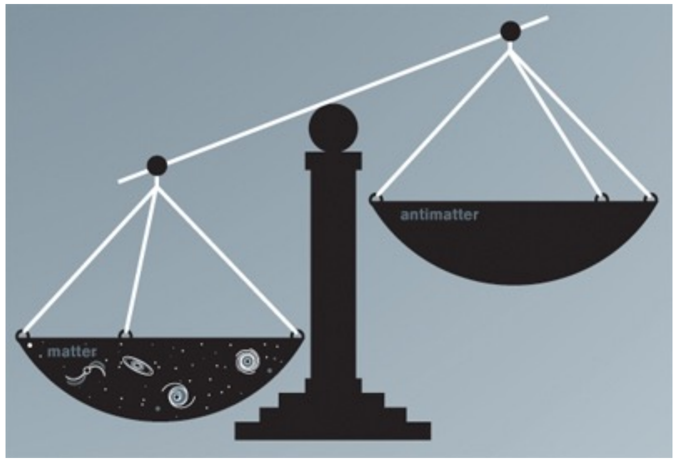


dark matter



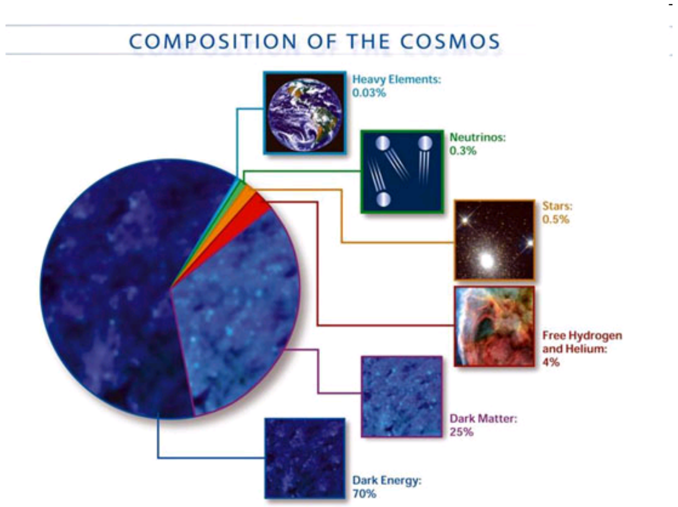
matter / antimatter asymmetry

Twin Higgs: Asymmetry can be co-generated in the visible and twin sectors.

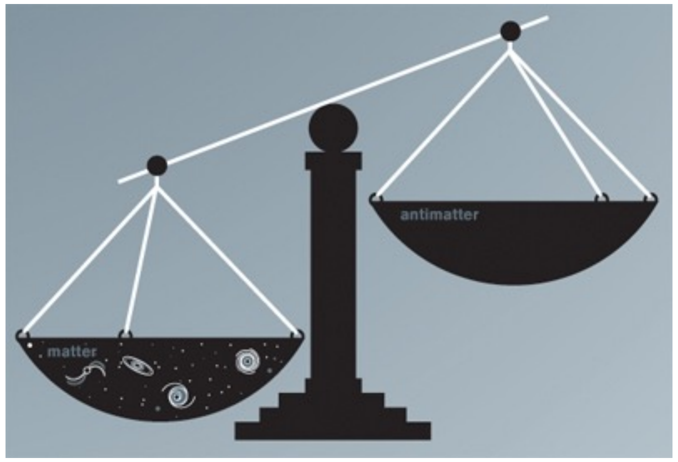
Farina et al: [arXiv: 1604.08211] + others

Introduction

naturalness



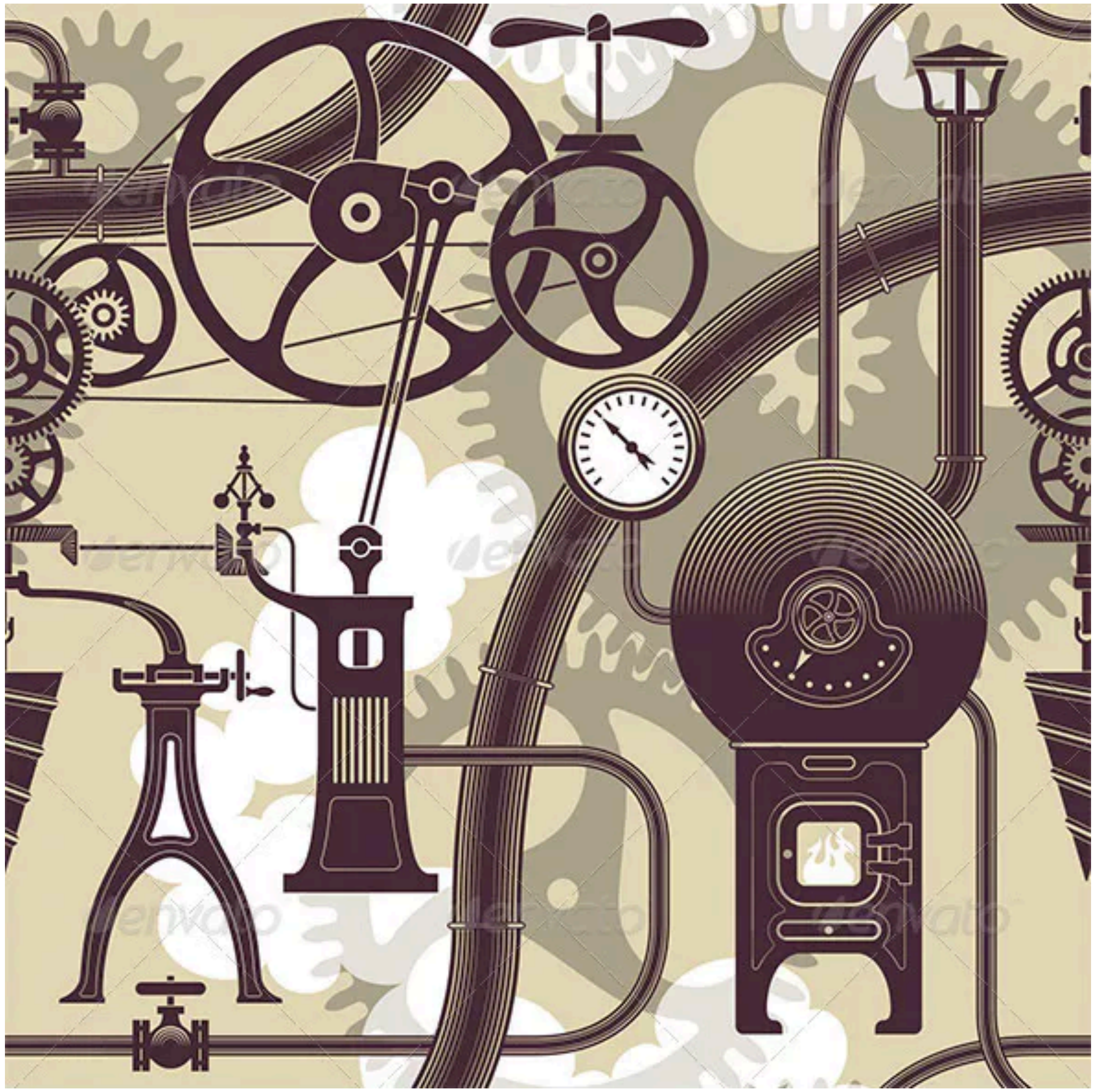
dark matter



matter / antimatter asymmetry

Twin Quark Dark Matter is a way for all three problems to be addressed in the Twin Higgs scenario.

MODEL DETAILS



A Color Triplet Scalar

$$\mathcal{L}_{\text{visible}} \supset -Y_L H_A^\dagger L_A \overline{E}_A - Y_U Q_A H_A \overline{U}_A - Y_D H_A^\dagger Q_A \overline{D}_A \boxed{-\frac{\lambda}{2}\phi_A^\dagger \overline{D}_A \overline{D}_A} + \text{H.c.}$$

Standard Model + color triplet scalar.

We adopt a Fraternal TH model

Craig, Katz, Strassler, Sundrum [1501.05310]

λ coupling is antisymmetric in flavor, absent in twin sector.

$$\mathcal{L}_{\text{twin}} \supset -y_\tau H_B^\dagger L_B \overline{E}_B - y_t Q_B H_B \overline{U}_B - y_b H_B^\dagger Q_B \overline{D}_B + \text{H.c.}$$

Scalar Potential

Scalar potential respects Z_2 when visible and twin sector Higgs and ϕ's are exchanged.

$$\begin{aligned}\mathcal{L}_{\text{scalar}} = {} & \mu^2 \left(H_A^\dagger H_A + H_B^\dagger H_B\right) + \mu_\phi^2 \left(|\phi_A|^2 + |\phi_B|^2\right) \\ & - \lambda \left(H_A^\dagger H_A + H_B^\dagger H_B\right)^2 - \delta \left[\left(H_A^\dagger H_A\right)^2 + \left(H_B^\dagger H_B\right)^2\right] \\ & - \lambda_\phi \left(|\phi_A|^2 + |\phi_B|^2\right)^2 - \delta_\phi \left(|\phi_A|^4 + |\phi_B|^4\right) \\ & - \lambda_{H\phi} \left(H_A^\dagger H_A + H_B^\dagger H_B\right) \left(|\phi_A|^2 + |\phi_B|^2\right) \\ & - \delta_{H\phi} \left(H_A^\dagger H_A - H_B^\dagger H_B\right) \left(|\phi_A|^2 - |\phi_B|^2\right) .\end{aligned}$$

For $\delta_\phi < 0$, ϕ_B develops a vev.

Batell et al: [arXiv: 2004.10761]

$$\phi_B = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_\phi + \varphi_B \end{pmatrix}$$

The ϕ_B vev also results in different vevs for the visible and twin Higgses.

$$\frac{\langle H_B \rangle^2}{\langle H_A \rangle^2} = \frac{\mu^2 \delta + m^2_{\cancel{Z}_2} (2\lambda + \delta)}{\mu^2 \delta - m^2_{\cancel{Z}_2} (2\lambda + \delta)}$$

Twin Color Breaking (TCB)

When ϕ_B gets a vev, twin color breaks down to SU(2)
[RTC: residual twin color]

The unbroken U(1) and baryon numbers are affected by TCB.

$$Q_B'^{\mathrm{EM}} = \sqrt{3} Y_\phi T^8 + \tau^3 + Y \qquad B_B' = B_B + \sqrt{3} B_\phi T^8$$

Quarks with the third color become RTC singlets, and asymptotic states.

b_{3B} is charged under the twin photon, while t_{3B} is neutral. Both carry B'_B number, while RTC-doublet quarks do not.

Singlet Portal

We introduce a second portal between the two sectors

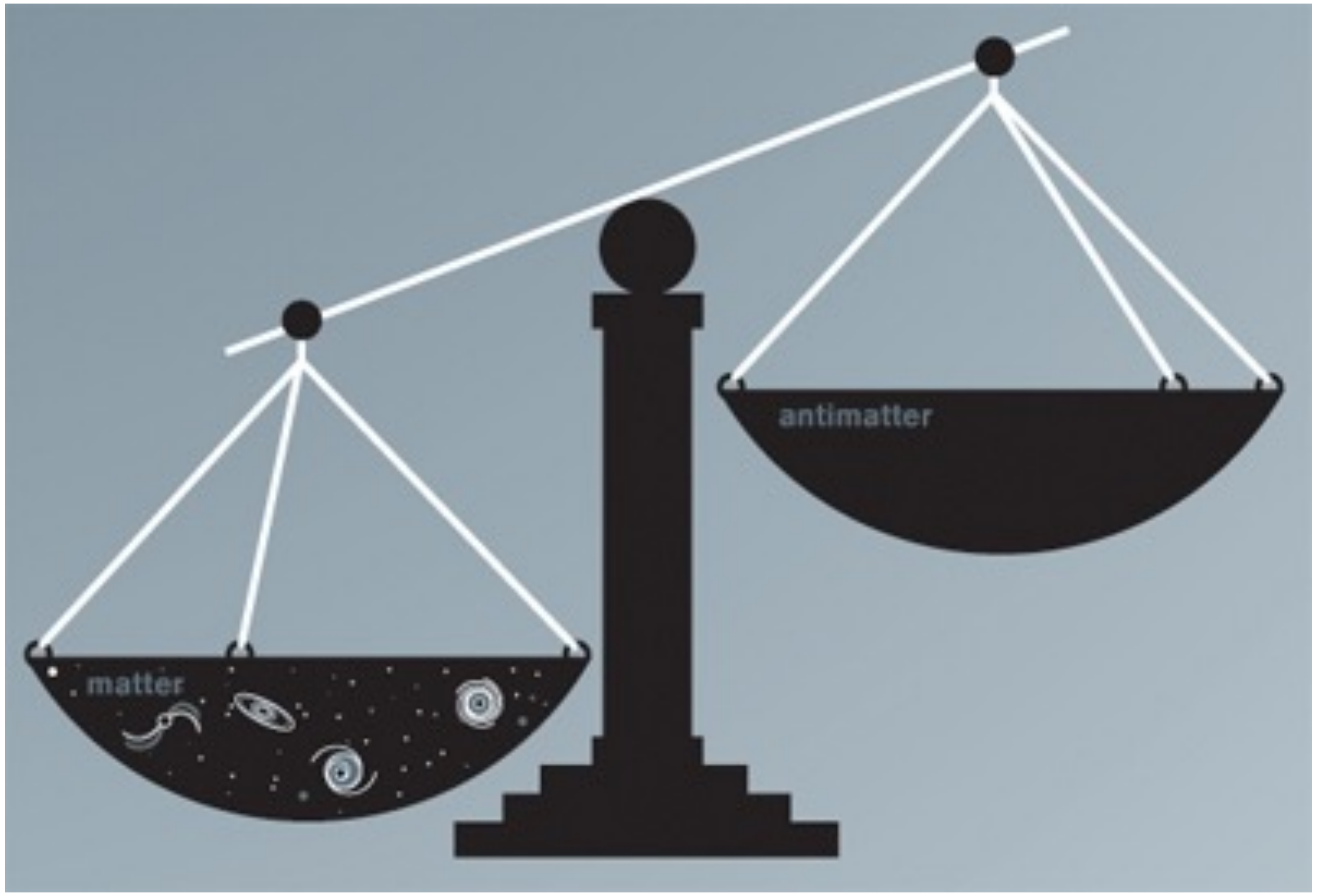
$$\mathcal{L}_{\text{portal}} \supset -M_N \overline{N}_A N_B - \kappa_A \phi_A \overline{U}_A \overline{N}_A - \kappa_B \phi_B \overline{U}_B N_B + \text{H.c.}$$

The N mass terms break the twin and visible baryon numbers to a diagonal combination.

After TCB, RTC singlet quarks can decay to the SM, if kinematically allowed. Also, t_{3B} mixes with the N's.

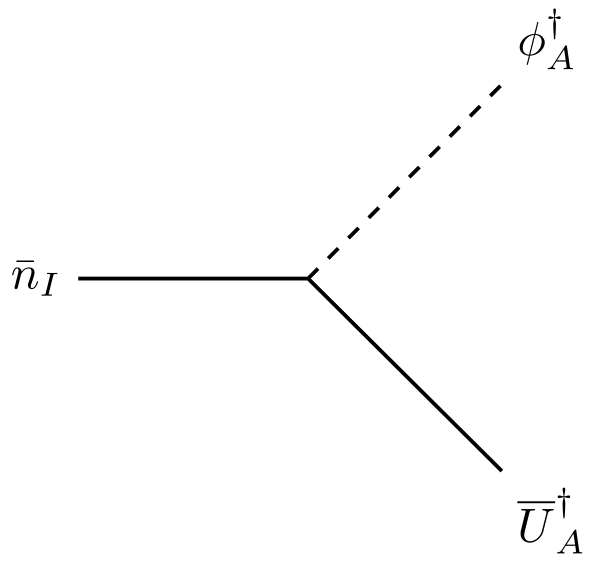
To simplify the discussion of the phenomenology, we will take the portal couplings κ to be of the same order of magnitude (and similarly for the Yukawa couplings λ)

ASYMMETRY GENERATION

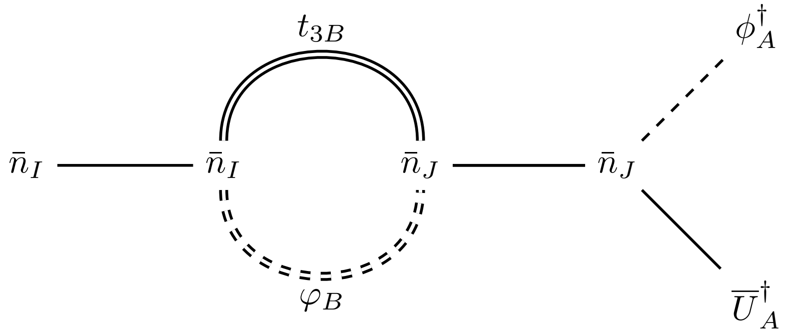


Sakharov Conditions

Assume that N’s are produced first after reheating. They then decay to both the visible and twin sectors.



$B_A - B'_B$ number is unbroken - equal asymmetries generated in the two sectors.



Resonant enhancement possible if N’s are near-degenerate

Portal couplings contain CPV phases.

Reheat temperature needs to be low to avoid washout processes $\phi_A q_A \leftrightarrow \phi_B^* q_B^\dagger$

b_{3B} and τ_B as DM

No asymmetry generated in RTC quarks, they annihilate efficiently.

In the twin sector, N decays produce t_{3B}, which further decays to b_{3B}, τ_B and twin neutrinos.

Symmetric components annihilate to twin photons (which then decay to SM fermions through kinetic mixing).

Relic abundance requires that the b_{3B} and τ_B masses add up to 5 GeV.

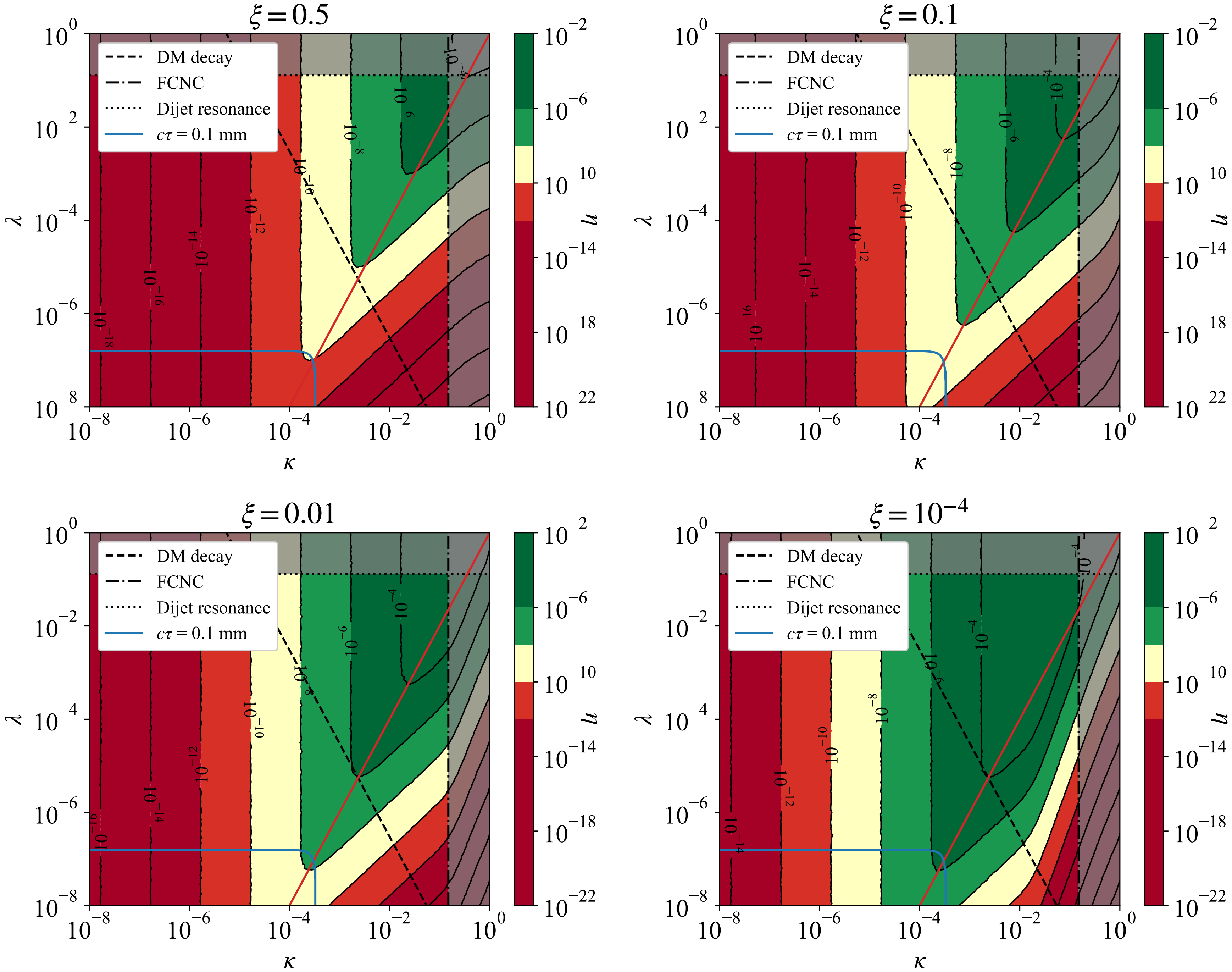
Parameter Space

$$Y_N \sim T_\mathrm{r}/M_\mathrm{r}$$

$$Y_{B_A} = Y_{B'_B} = \eta Y_N$$

$$\eta = (\epsilon_{A+} + \epsilon_{A-}) \times W$$

$m_\phi = 2$ TeV, $f_\phi = 4$ TeV, and $m_N = 4$ TeV



ξ denotes fractional mass splitting of portal fermions in the UV.

Monte Carlo scan over the κ and λ couplings (complex).

Below η=10^{-8}, the reheaton is forced to be too light.

SIGNATURES AND CONSTRAINTS

Dark Photon

Twin Higgs induced mixing is of order 10^{-11}.

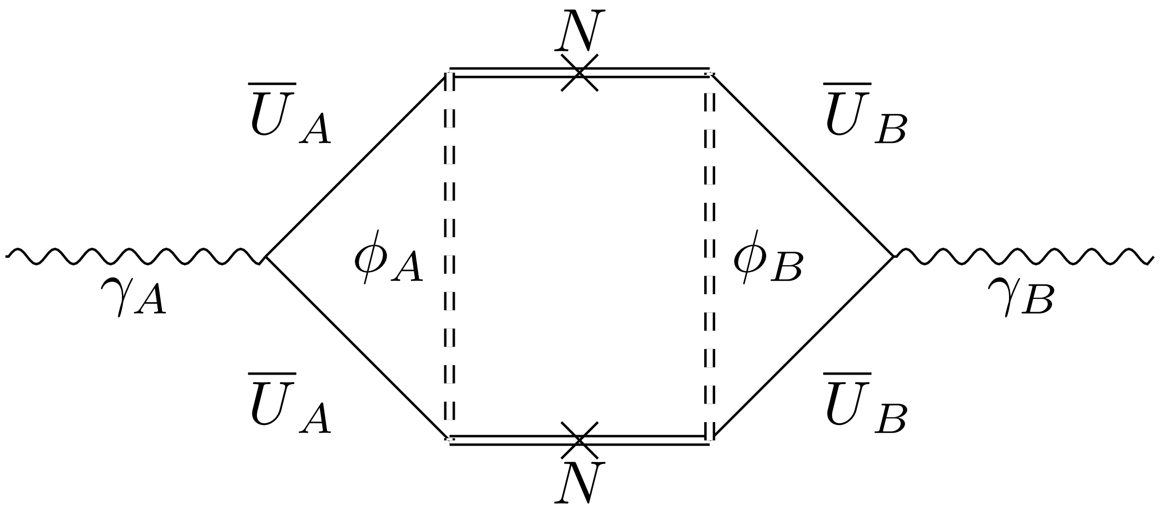
Portal photons also cause additional mixing.

Finally, mixing can be added by hand.

We take $m_{A'} \sim 1$GeV.

Current bounds exclude $\varepsilon > 10^{-3}$.

For efficient annihilation of the symmetric DM component, mixing has to be above $\sim 10^{-8}$.



$$\varepsilon_{\text{portal}} \sim \frac{e^2\kappa^4}{(16\pi^2)^3} \approx 2.5 \times 10^{-8}\kappa^4$$

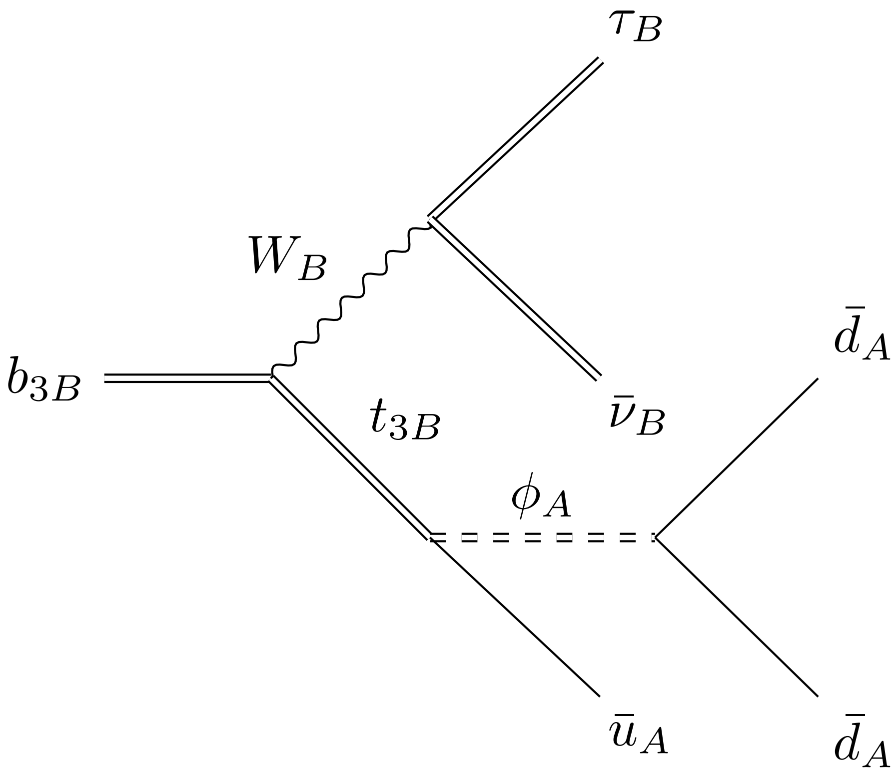
Decaying DM

Relic abundance requires that $m_{b_{3B}} + m_{\tau_B} = 5\ \mathrm{GeV}$

We take both particles to be heavier than 1GeV for the symmetric component to annihilate to twin photons.

Conservation of $B_A - B'_B$ number requires that there is at least one SM baryon in the final state if b_{3B} decays to τ_B.

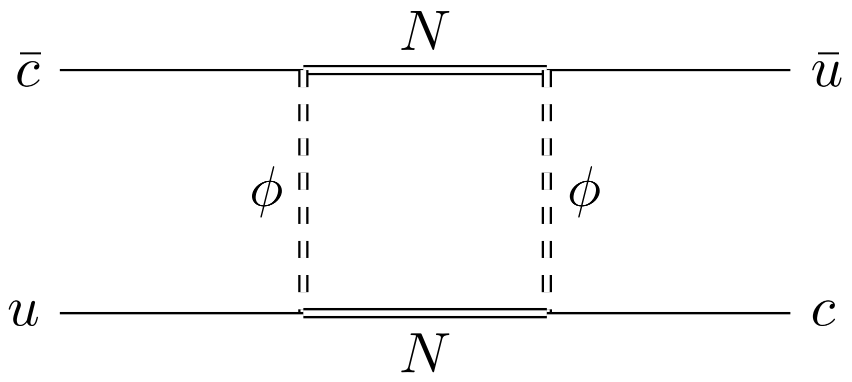
For b_{3B} to decay to τ_B, the mass difference needs to be above 1GeV. In this case, there is a constraint on the κ and λ couplings.



$$\Gamma_{b_{3B}\to\bar{n}+\text{invisible}} < \frac{m_{b_{3B}}^{11}}{8\pi(16\pi^2)^4}\frac{g_W^4}{m_{W_B}^4}\frac{f_\phi^2}{M_N^2}\frac{\kappa^4\lambda^2}{m_{t_{3B}}^2 m_\phi^4}$$

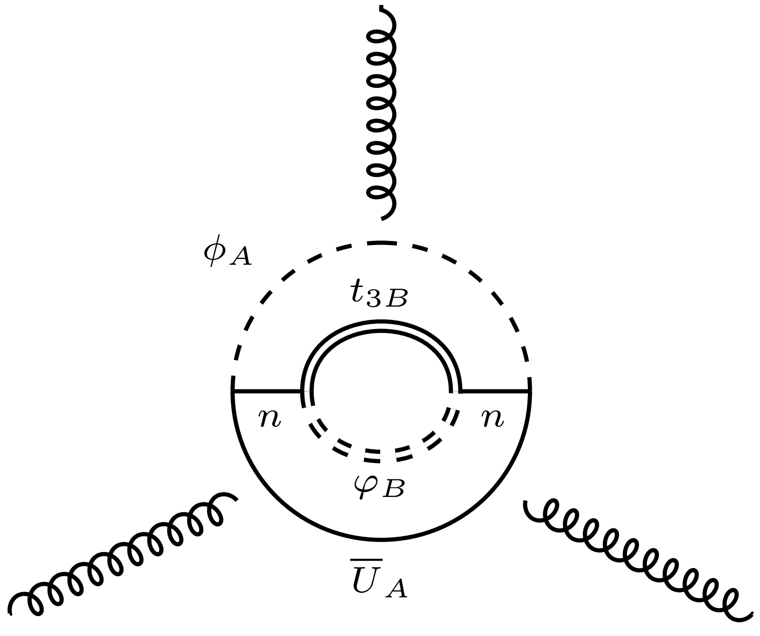
Precision Observables

The portal interactions can contribute to FCNC's, but only in the charm sector. These are suppressed by κ^4 / M_N^2



Phases in the κ couplings can also give rise to EDM's via the operator

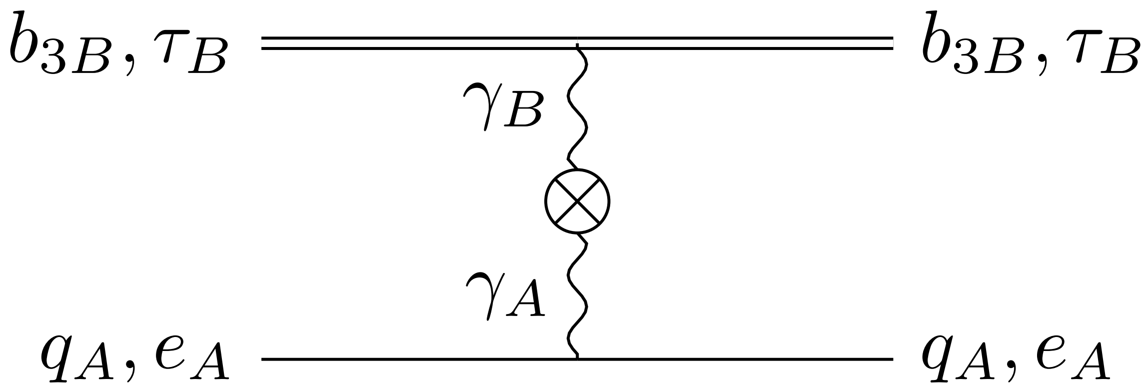
$$\mathcal{L}_{\not{CP}} = -\frac{1}{3}\tilde{C}_G f^{ABC} e^{\mu\nu\rho\sigma} G^A_{\mu\lambda} G^{B\lambda}_{\nu} G^C_{\rho\sigma}$$



$$\frac{3g_s^3}{(16\pi^2)^3}\frac{\kappa^4}{M_N^2}$$

The contribution to the neutron EDM is below current bounds, but it can lie above the SM value.

Direct Detection



Direct detection (both for b_{3B} and for τ_B) proceeds through kinetic mixing of the visible and twin photons.

For the mass range of interest, this is below nuclear recoil thresholds.

Electron recoil experiments do not currently have sensitivity for $\varepsilon < 10^{-3}$, but with an exposure of 10^5 kg yr, the reach will come down to $\varepsilon < O(\text{few} \times 10^{-4})$.

Collider Signatures

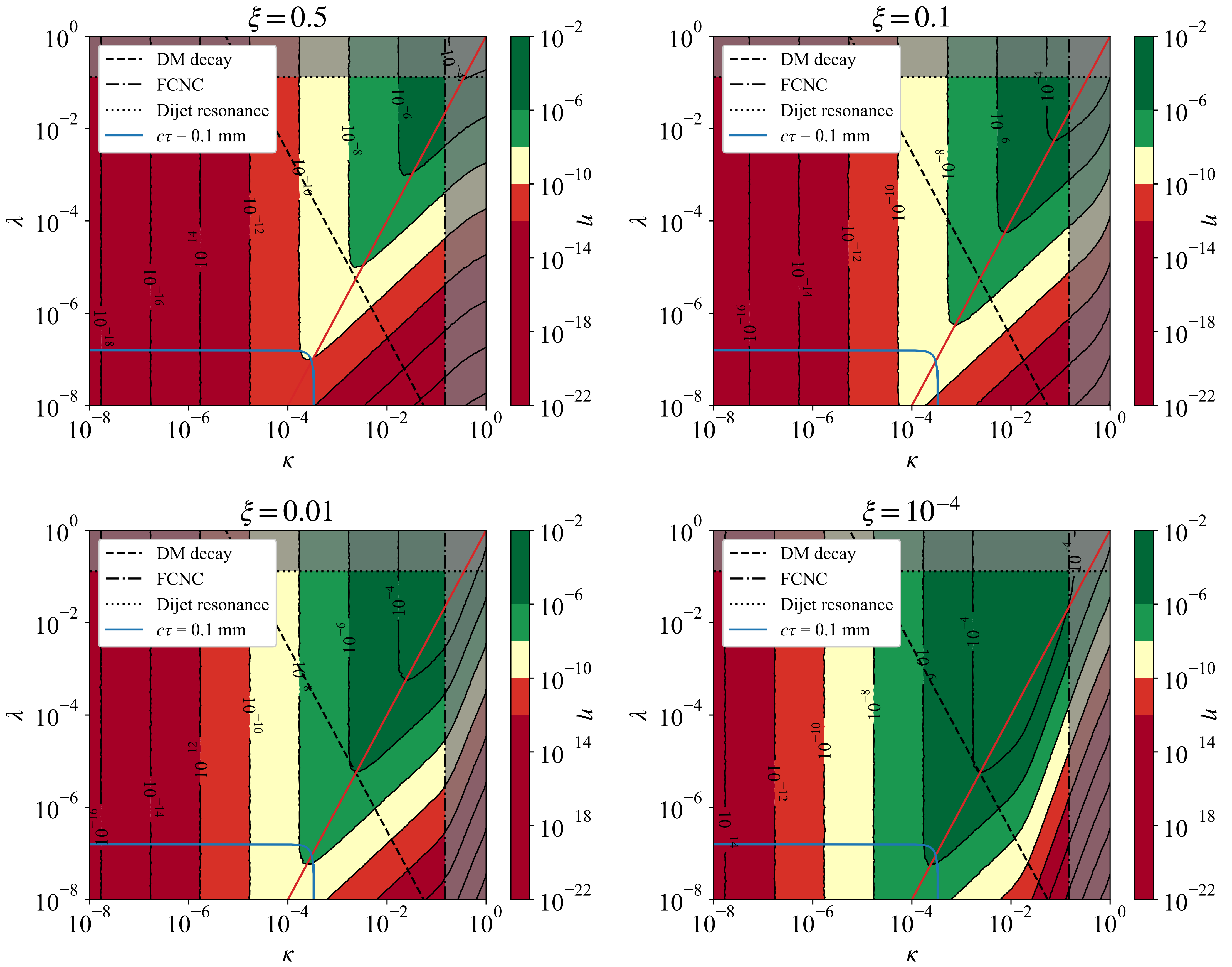
Color triplet scalars can be pair produced from QCD, and also singly produced via the λ interactions.

They decay either to u/c/t + MET (portal interactions) or to dijets. Dijet resonance constraints limit $\lambda < 0.1$

If both κ and λ couplings are very small, displaced decays are possible. The asymmetry tends to be small, needs large resonant enhancement.

Portal and twin states are neutral under SM gauge groups, and heavy. The LHC does not have sensitivity, however searches at a 100 TeV collider seem promising (in progress).

One More Look at the Parameter Space



Summary

We have explored an extension of a Fraternal Twin Higgs model with scalar color triplets, and a singlet fermion portal.

The scalar potential breaks twin color, as a result of which a twin quark degree of freedom becomes a neutral asymptotic state and a DM candidate.

The portal fermion decays can co-generate equal M/AM asymmetries in the visible and twin sectors.

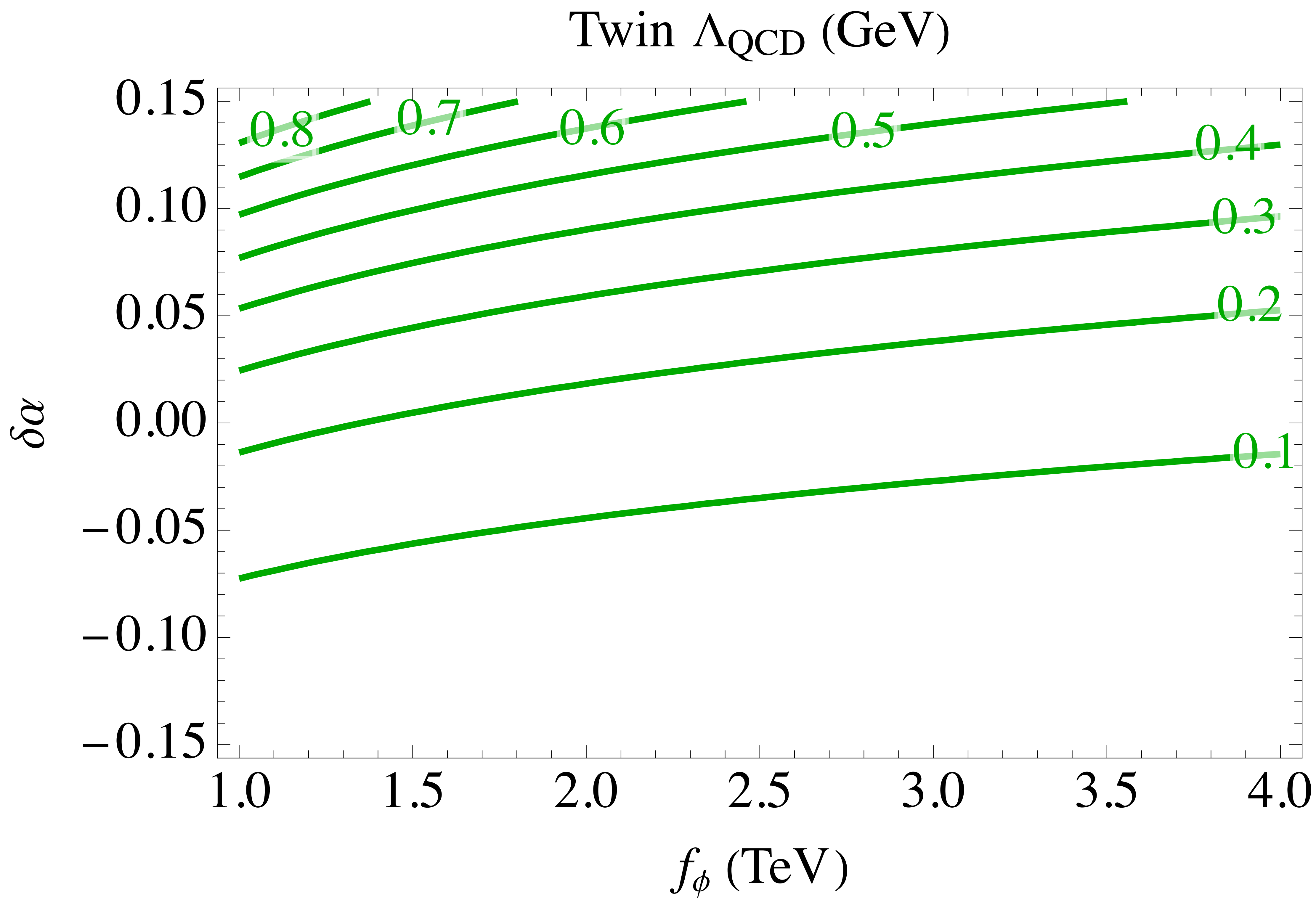
The model is consistent with all experimental bounds. Future discovery possibilities include dark photon searches, EDM’s, (electron recoil) direct detection, collider searches for the color triplet scalars.

Backup Slides

Quantum Numbers

	$SU(3)_A$	$SU(2)_A$	$U(1)_A$	$SU(3)_B$	$SU(2)_B$	$U(1)_B$	B_A	B_B	L_A	L_B
Q_A	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\mathbf{1}$	$\mathbf{1}$	0	$\frac{1}{3}$	0	0	0
$\overline{U}_A$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{1}{3}$	0	0	0
$\overline{D}_A$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{1}{3}$	0	0	0
L_A	$\mathbf{1}$	$\mathbf{2}$	-1	$\mathbf{1}$	$\mathbf{1}$	0	0	0	1	0
$\overline{E}_A$	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{1}$	$\mathbf{1}$	0	0	0	-1	0
ϕ_A	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{2}{3}$	0	0	0
$\overline{N}_A$	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	0	1	0	0	0
Q_B	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	0	$\frac{1}{3}$	0	0
$\overline{U}_B$	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	0	$-\frac{1}{3}$	0	0
$\overline{D}_B$	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	0	$-\frac{1}{3}$	0	0
L_B	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1	0	0	0	1
$\overline{E}_B$	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	1	0	0	0	-1
ϕ_B	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	0	$-\frac{2}{3}$	0	0
N_B	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	0	0	1	0	0

Twin QCD scale



Mixing of Portal Fermions

$$(M_N)_{\bar{I}J} = M_0\left(\delta_{\bar{I}J} + \xi\ \sigma^3_{\bar{I}J}\right) + \frac{c_\Delta M_0}{16\pi^2}\left(\sum_i \kappa_{A,i\bar{I}}\kappa^*_{A,iJ} + \kappa^*_{B,\bar{I}}\kappa_{B,J}\right)$$

UV and IR mass splitting of portal fermions

mass matrix before diagonalization

$$\left(\overline{N}_{A,1},\ \overline{N}_{A,2},\ \overline{U}_{3B}\right)\frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}M_+ & 0 & 0 \\ 0 & \sqrt{2}M_- & 0 \\ \kappa_{B,1}f_\phi & \kappa_{B,2}f_\phi & y_t v_B \end{pmatrix}\begin{pmatrix} N_{B,1} \\ N_{B,2} \\ u_{3B} \end{pmatrix}$$

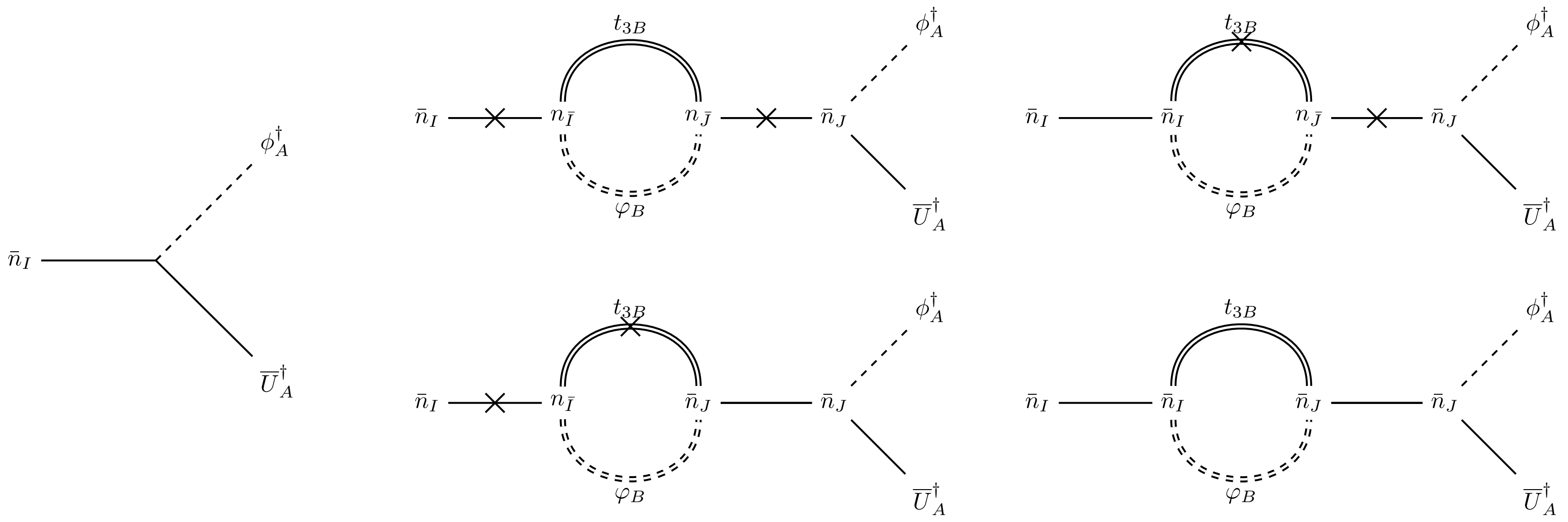
$$\left(\overline{N}_{A,1},\ \overline{N}_{A,2},\ \overline{U}_{3B}\right) = \left(\overline{n}_+,\ \overline{n}_-,\ \bar{t}_{3B}\right)U^\dagger, \qquad \begin{pmatrix} N_{B,\bar{1}} \\ N_{B,\bar{2}} \\ U_{3B} \end{pmatrix} = V\begin{pmatrix} n_+ \\ n_- \\ t_{3B} \end{pmatrix}$$

portal interactions in the mass basis

$$\begin{aligned} &-\phi_A\overline{U}_A\left(\overline{n}_+\kappa_{A+} + \overline{n}_-\kappa_{A-} + \bar{t}_{3B}\kappa_{At}\right) + \text{H.c.} \\ &-\frac{\varphi_B}{\sqrt{2}}\left(\overline{n}_+U^*_{3,1} + \overline{n}_-U^*_{3,2} + \bar{t}_{3B}U^*_{3,3}\right)\left(n_+\kappa_{B+} + n_-\kappa_{B-} + t_{3B}\kappa_{Bt}\right) + \text{H.c.} \end{aligned}$$

Details on Asymmetry Generation

$$\epsilon_{A\pm} = \sum_X B_A(X)\left[\mathrm{BR}\left(n_\pm \to X_A\right) - \mathrm{BR}\left(n^\dagger_\pm \to X^\dagger_A\right)\right]$$



$$\epsilon_{A+} = \epsilon_{B+} \approx \mathcal{R} \times \frac{M_{n_-}}{4\pi M_{n_+}}\left(\frac{\mathrm{Im}\left\{\kappa_{A+}\kappa^*_{A-}\left[U_{3,1}U^*_{3,2}|\kappa_{Bt}|^2 + |U_{3,3}|^2\kappa_{B+}\kappa^*_{B-}\right]\right\}}{2|\kappa_{A+}|^2 + |U^*_{3,1}\kappa^*_{Bt}|^2 + |U^*_{3,3}\kappa_{B+}|^2} \right.$$

$$\left. + 2\,\frac{M_{t_{3B}}}{M_{n_+}}\frac{\mathrm{Im}\left\{\kappa_{A+}\kappa^*_{A-}\left[U^*_{3,3}U^*_{3,2}\kappa_{B+}\kappa_{Bt} + U_{3,2}U_{3,3}\kappa^*_{B-}\kappa^*_{Bt}\right]\right\}}{2|\kappa_{A+}|^2 + |U^*_{3,1}\kappa^*_{Bt}|^2 + |U^*_{3,3}\kappa_{B+}|^2}\right)$$

$$\mathcal{R} = \frac{M_{n_+}}{M_{n_-}}\frac{M_{n_+}M_{n_-}(M^2_{n_+} - M^2_{n_-})}{(M^2_{n_+} - M^2_{n_-})^2 + (M_{n_+}\Gamma_{n_+} - M_{n_-}\Gamma_{n_-})^2}$$