One U(1) To Rule Them All: In The Realm Of Leptoquarks, The Axion Shines

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Based on 2206.09810 in collaboration with Christopher Smith

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Motivation

The Strong CP Problem – The Axion Mechanism

- Purely gauge terms proportional to total derivatives can be added to the SM Lagrangian

$$\theta_{QCD}\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$\frac{\alpha_X}{8\pi}X^{a\mu\nu}\tilde{X}^a_{\mu\nu} = \partial_\mu K^\mu;\ K^\mu = \frac{\alpha_X}{4\pi}\varepsilon^{\mu\nu\alpha\beta}\left(X^a_\nu\partial_\alpha X^a_\beta + \frac{1}{3}f_{abc}X^a_\nu X^b_\alpha X^c_\beta\right)$$

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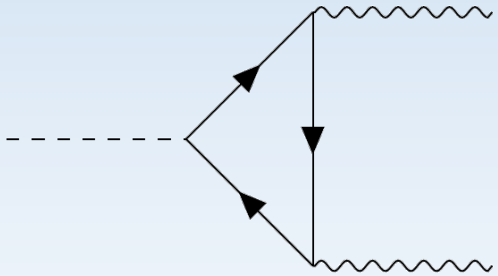
- The $G\tilde{G}$ term is related to quark masses through the chiral anomaly



$$\bar{\theta} = \theta_{QCD} + \mathrm{Arg}\left(\mathrm{Det}\left(M_u M_d\right)\right)$$

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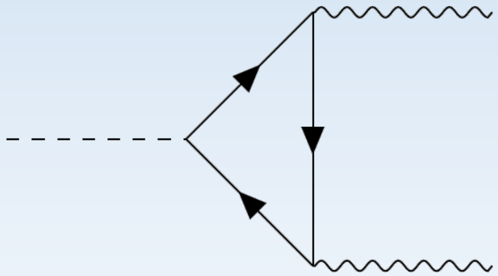

$$\bar{\theta} = \theta_{QCD} + \mathbf{Arg}\left(\mathbf{Det}\left(M_u M_d\right)\right)$$

- The observable parameter, $\bar{\theta}$ is bound by its relation to the neutron EDM, d_n

Crewther, Di Vecchia, Veneziano & Witten, 1980

Baker et al., 0602020 Afach et al., 1509.04411

$$d_n \sim \bar{\theta} \times 10^{-16} e \cdot cm, \qquad \bar{\theta} \lesssim \mathcal{O}(10^{-10})$$

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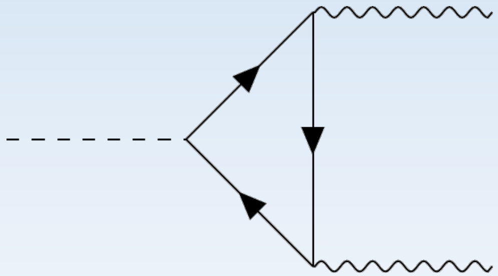

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- Why is a dimensionless parameter so small?

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Peccei and Quinn, PRL 38 (1977) 1440-1443 and PRD 16 (1977) 1791-1797

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- Its NGB, the axion a, couples to gluons through the chiral anomaly

$$\mathscr{L}_{aGG} = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \longrightarrow \theta_{eff} = \bar{\theta} + \frac{a}{f_a}$$

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- Non-perturbative QCD creates a potential that ensures CP conservation

$$V_{eff} \sim 1 - \sqrt{1 + \cos\left(\bar{\theta} + \frac{a}{f_a}\right)} \longrightarrow \langle a \rangle = -f_a\bar{\theta}$$

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- More elusive axions are required!

The Strong CP Problem – Invisible Axions

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- Axion-gluon coupling implies a scale-mass relation shared by all these axions

$$m_a = 5.691(51)\left(\frac{10^9\ \text{GeV}}{f_a}\right)\ \text{meV}$$

The Strong CP Problem – Invisible Axions

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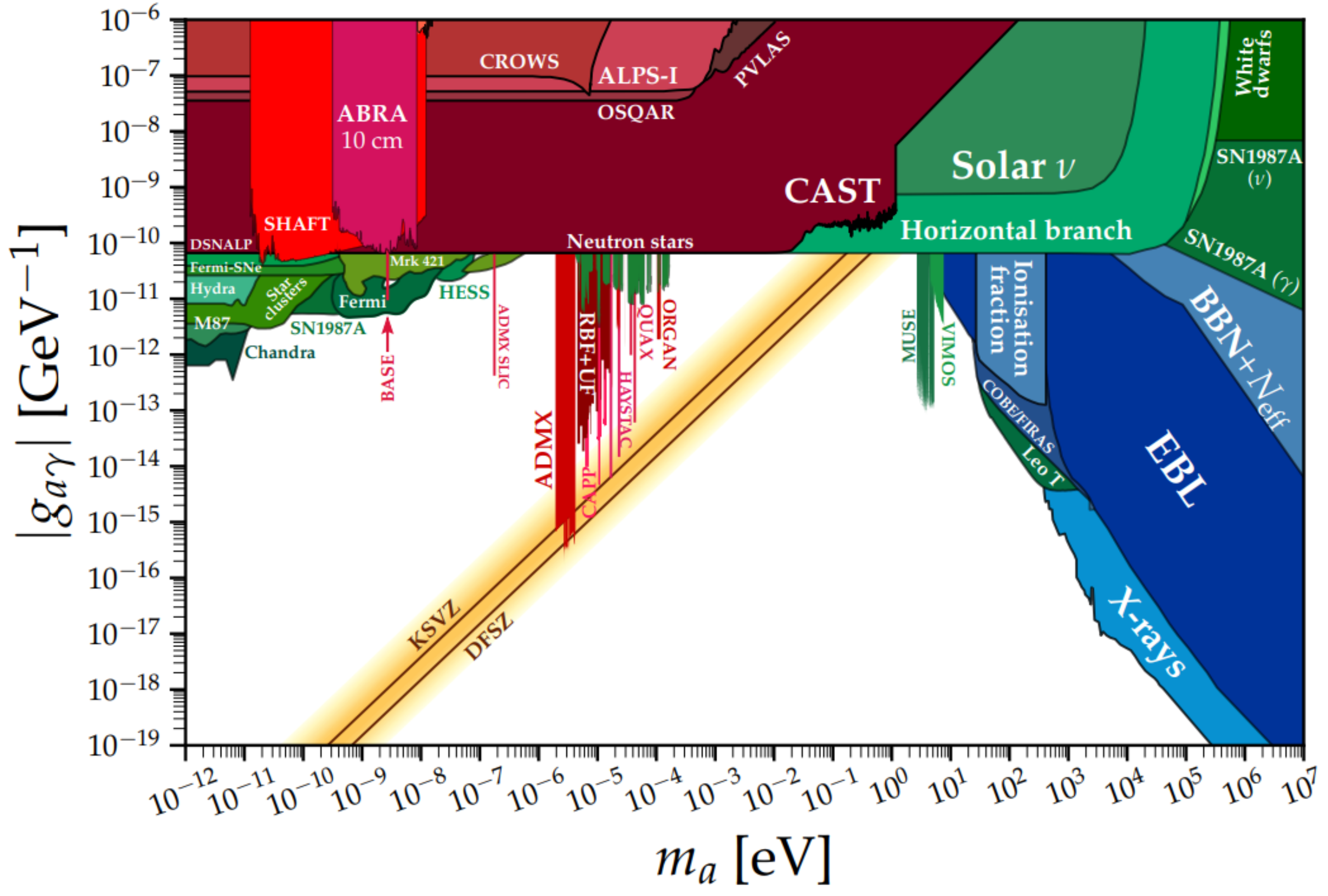

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$$(\mathbf{3},\mathbf{2},+1/3):S_2^{1/3}\times(\bar{d}_R\ell_L\ ,\ \bar{q}_L\nu_R)$$

$$(\mathbf{3},\mathbf{2},+7/3):S_2^{7/3}\times(\bar{u}_R\ell_L\ ,\ \bar{q}_Le_R)$$

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$\mathcal{B}$ and $\mathcal{L}$ in Axion Models

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- In KSVZ and DFSZ models PQ charges are defined as

KSVZ	ϕ	H
$U(1)_\phi$	1	0
$U(1)_H$	0	1

$\Longrightarrow$

KSVZ	ϕ	H
$U(1)_{PQ}$	1	0
$U(1)_Y$	0	1

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$U(1)_{Hd}$	$-1/2$	0	1

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DFSZ	ϕ	H_u	H_d
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- However, what happens with fermions?

$\mathcal{B}$ and $\mathcal{L}$ in Axion Models

- Fermion charges present some freedom

KSVZ	Ψ_L	Ψ_R	q_L	u_R	d_R	ℓ_L	e_R	ν_R
$U(1)_{PQ}$	α	$\alpha - 1$	β	β	β	γ	γ	γ
$U(1)_Y$	Y	Y	$1/3$	$4/3$	$-2/3$	-1	-2	0

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- Should we just fix all free parameters to 0? Quevillon and Smith, 2006.06778

$$\gamma = 0 \Rightarrow \frac{1}{\Lambda}\left(\bar{\ell}^C_L H_u^T\right)(H_u \ell_L) \text{ forbidden by } U(1)_{PQ} \text{ in DFSZ}$$

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- How could $\mathcal{B}$ and $\mathcal{L}$ entangle with the axion symmetry?

$$U(1)_\phi \otimes U(1)_\mathcal{B} \otimes U(1)_\mathcal{L} \overset{\text{Explicit}}{\rightarrow} U(1)_\mathcal{B} \otimes U(1)_\mathcal{L} \simeq U(1)_{PQ} \otimes U(1)_X \overset{\text{Spontaneous}}{\rightarrow} U(1)_X$$

$$U(1)_X = U(1)_\mathcal{B} \otimes U(1)_\mathcal{L},\ U(1)_{\mathcal{B}\pm\mathcal{L}}\ , U(1)_\mathcal{B}\ ,\ U(1)_\mathcal{L},\ U(1)_{3\mathcal{B}\pm\mathcal{L}}\ , \ldots$$

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$$U(1)_\phi \otimes U(1)_\mathcal{B} \otimes U(1)_\mathcal{L} \overset{\text{Explicit}}{\rightarrow} U(1)_\mathcal{B} \otimes U(1)_\mathcal{L} \simeq U(1)_{PQ} \otimes U(1)_X \overset{\text{Spontaneous}}{\rightarrow} U(1)_X$$

$$U(1)_X = U(1)_\mathcal{B} \otimes U(1)_\mathcal{L},\ U(1)_{\mathcal{B}\pm\mathcal{L}}\ , U(1)_\mathcal{B}\ ,\ U(1)_\mathcal{L},\ U(1)_{3\mathcal{B}\pm\mathcal{L}}\ , \ldots$$

- May answer a cosmological question: DM relic density related to the barionic one?

Entangling $U(1)_{PQ}$, $\mathcal{B}$ and $\mathcal{L}$ With Leptoquarks

Setup

- Leptoquarks can induce a variety of $\mathcal{B}$ and/or $\mathcal{L}$ violating operators

$\Delta\mathcal{B}$	$\Delta\mathcal{L}$	Dim.	Operators (no ν_R)				
+0	+2	5	$H^{\dagger 2}\ell_L^2$				
+1	+1	6	$q_L^3\ell_L$	$u_R^2 d_R e_R$	$q_L u_R d_R \ell_L$	$q_L^2 u_R e_R$	
+1	−1	7	$H^\dagger d_R^3 \ell_L^C$	$H d_R^2 q_L e_R^C$	$H d_R^2 u_R \ell_L^C$	$H q_L^2 d_R \ell_L^C$	
+2	+0	9	$d_R^4 u_R$	$d_R^3 u_R q_L^2$	$d_R^2 q_L^4$		
+1	+3	9	$u_R^2 q_L \ell_L^3$	$u_R^3 \ell_L^2 e_R$			
+1	−3	10	$H d_R^3 \ell_L^{C,3}$				
$\Delta\mathcal{B}$	$\Delta\mathcal{L}$	Dim.	Operators (one ν_R)				
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+1	+1	6	$q_L^2 d_R \nu_R$	$d_R^2 u_R \nu_R$			
+1	−1	7	$H^\dagger d_R^2 q_L \nu_R^C$	$H d_R q_L u_R \nu_R^C$	$H q_L^3 \nu_R^C$		
+2	+0	9	–				
+1	+3	9	$d_R u_R^2 \ell_L^2 \nu_R$	$d_R q_L u_R \ell_L^2 \nu_R$	$u_R^3 e_R^2 \nu_R$	$u_R^2 q_L \ell_L e_R \nu_R$	$q_L^2 u_R \ell_L^2 \nu_R$
+1	−3	10	$H d_R^3 \ell_L^C e_R^C \nu_R^C$	$H d_R^2 q_L \ell_L^{C,2} \nu_R^C$			

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- Depending on implementation, different scenarios are possible
  - One state with only LQ or DQ → Exact $U(1)_{\mathcal{B}} \times U(1)_{\mathcal{L}}$

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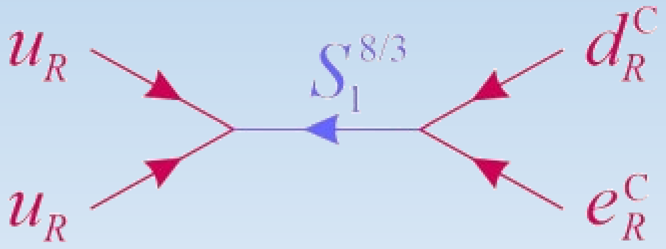

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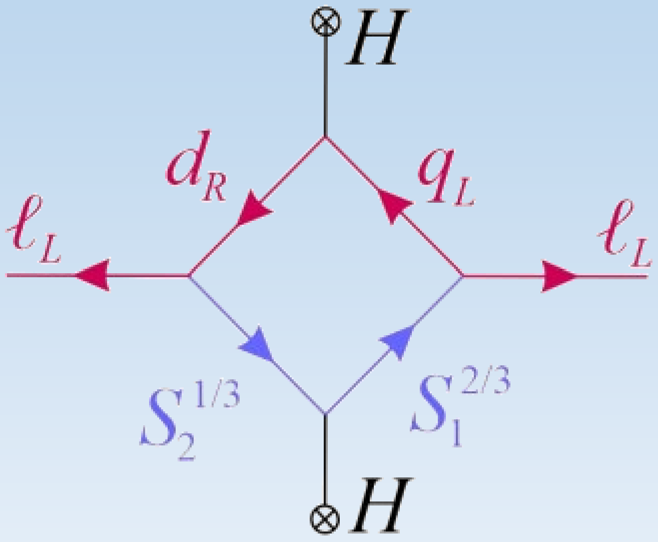

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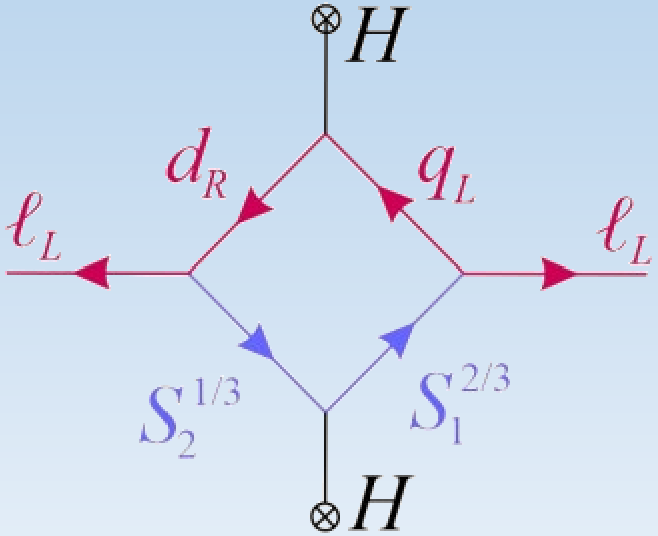

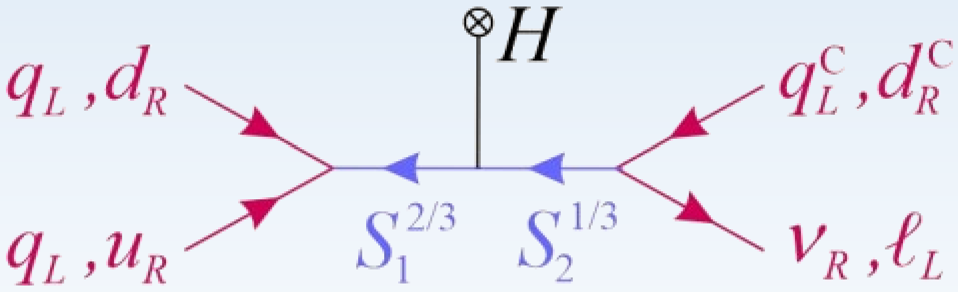

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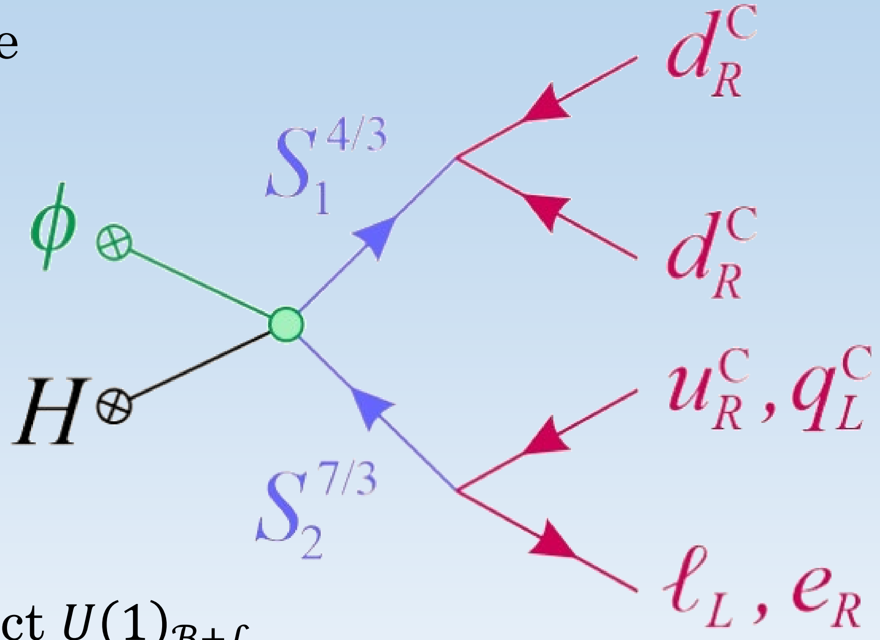

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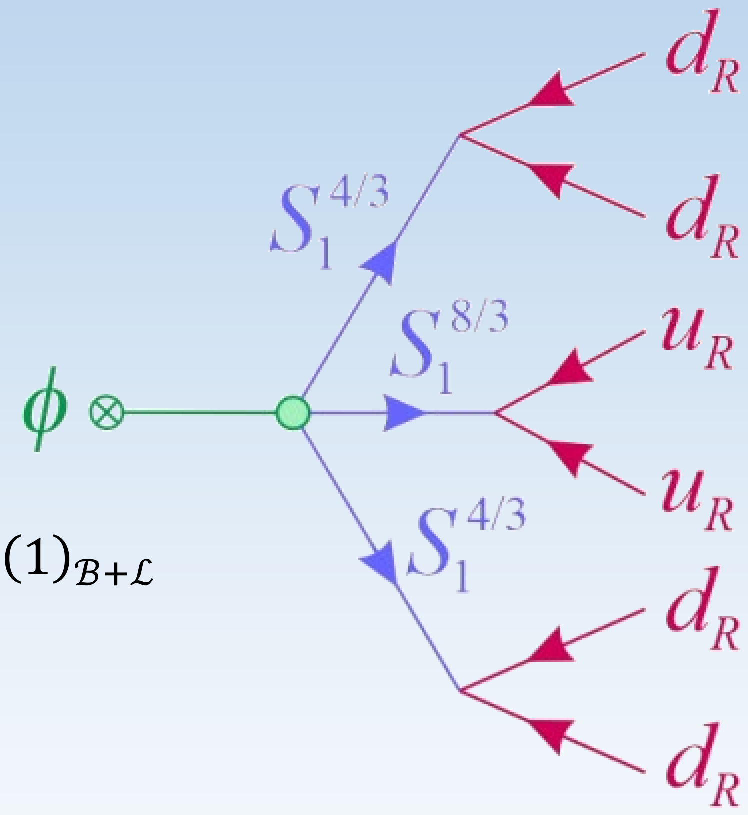

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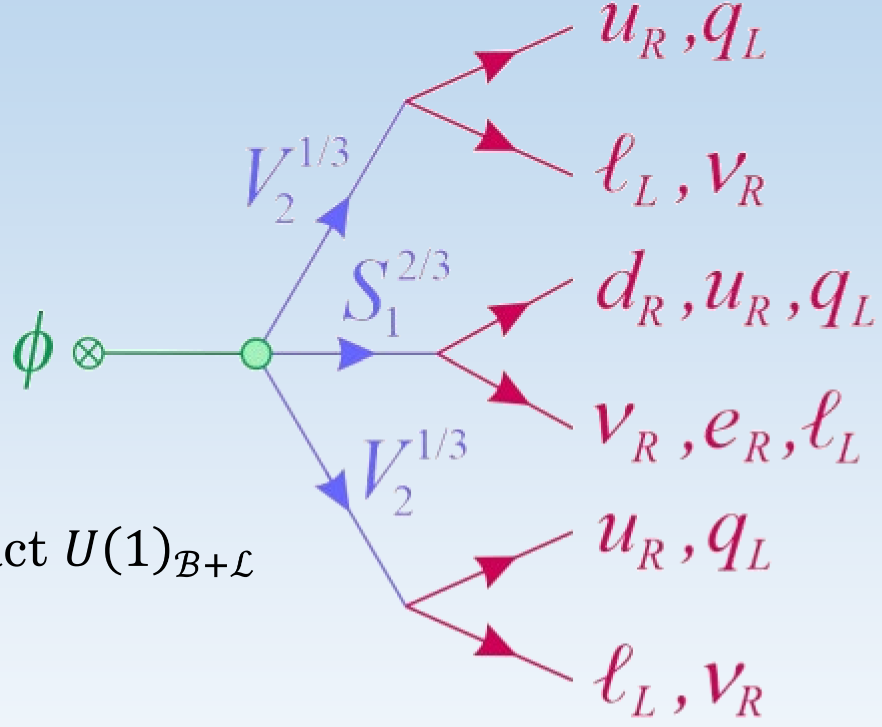
  - Two states with mixing with only LQ → Exact $U(1)_{3\mathcal{B}-\mathcal{L}}$



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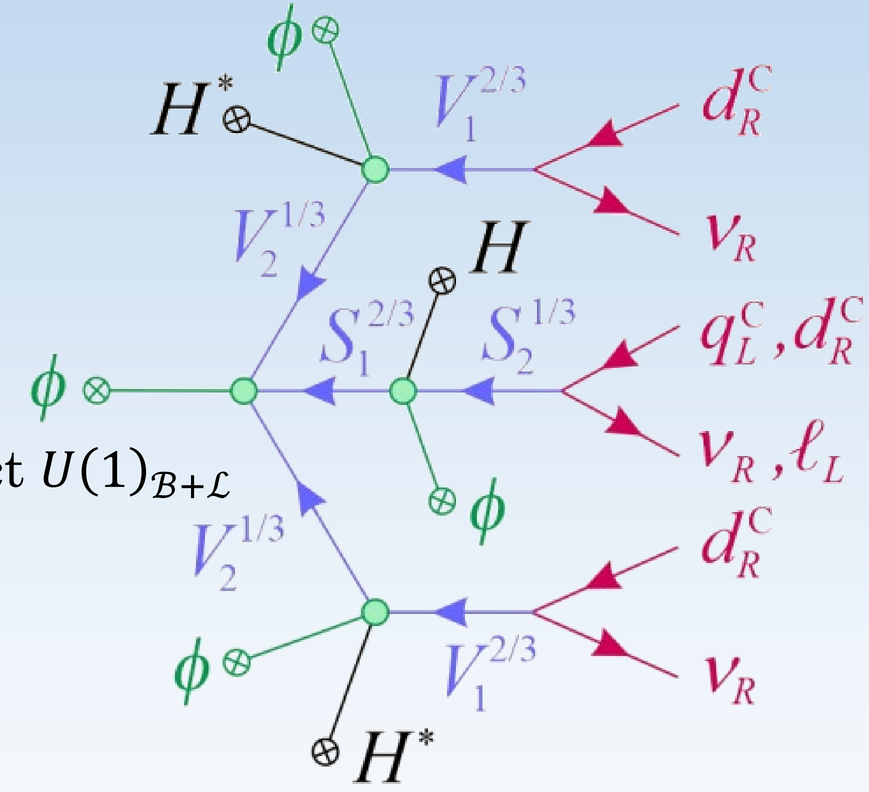
  - Two states with mixing with only DQ → Exact $U(1)_{\mathcal{L}}$
  - Two states with mixing with only LQ → Exact $U(1)_{3\mathcal{B}-\mathcal{L}}$
  - Three states → Exact $U(1)_{3\mathcal{B}+\mathcal{L}}$



Example in the KSVZ model

- Choose some couplings of LQs to SM fermions and to ϕ while preserving $\mathcal{B}$ and $\mathcal{L}$

$$\mathcal{L}_{\mathrm{KSVZ+LQ}} = \mathcal{L}_{\mathrm{KSVZ}} + S_1^{8/3} \bar{d}_R e_R^{\mathrm{C}} + \tilde{S}_1^{8/3} \bar{u}_R^{\mathrm{C}} u_R + \phi^2 S_1^{8/3\dagger} \tilde{S}_1^{8/3} + h.c.$$

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	ϕ	$S_1^{8/3}$	$\tilde{S}_1^{8/3}$	Ψ_L	Ψ_R	q_L	u_R	d_R	ℓ_L	e_R	ν_R
$U(1)_\Psi$	0	0	0	1	1	0	0	0	0	0	0
$U(1)_\mathcal{B}$	$1/2$	$1/3$	$-2/3$	$-1/2$	0	$1/3$	$1/3$	$1/3$	0	0	0
$U(1)_\mathcal{L}$	$1/2$	1	0	$-1/2$	0	0	0	0	1	1	1

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- It breaks however the orthogonal combination $U(1)_{\mathcal{B}+\mathcal{L}}$

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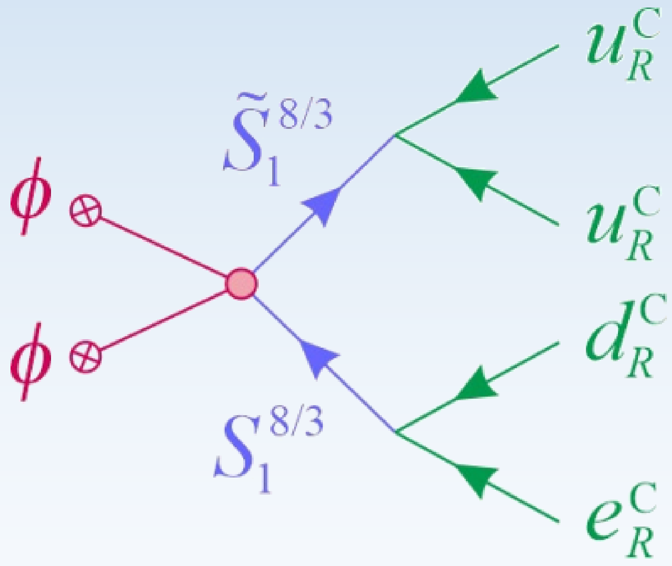
- Broken $U(1)_{\mathcal{B}+\mathcal{L}}$ → Spontaneous proton decay



$$\rightarrow \frac{v_\phi^2}{m_S^4}\exp(2ia^0/v_\phi)\bar{u}_R^C u_R \bar{d}_R^C e_R$$

$$\Rightarrow m_S > 10^{11}\ GeV$$

Example in the KSVZ model

- What if we supplement this by a Seesaw?

$$\mathcal{L}_{\mathrm{KSVZ+LQ}} = \mathcal{L}_{\mathrm{KSVZ}} + S_1^{8/3}\bar{d}_R e_R^{\mathrm{C}} + \tilde{S}_1^{8/3}\bar{u}_R^{\mathrm{C}} u_R + \phi^2 S_1^{8/3\dagger}\tilde{S}_1^{8/3} + \phi\bar{\nu}_R^{\mathrm{C}}\nu_R + h.c.$$

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- $\mathcal{B}$ and $\mathcal{L}$ get further entangled and only one $U(1)_{PQ}$ survives

	ϕ	$S_1^{8/3}$	$\tilde{S}_1^{8/3}$	q_L	u_R	d_R	ℓ_L	e_R	ν_R
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- The breaking pattern allows for

$$(\Delta\mathcal{B}, \Delta\mathcal{L}) = (1,1) \rightarrow \text{Proton decay}$$

$$(\Delta\mathcal{B}, \Delta\mathcal{L}) = (0,2) \rightarrow \text{Neutrino masses}$$

$n - \bar{n}$ oscillations in the KSVZ model

- Let us consider the following Lagrangian

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- We can add a term like $S_1^{8/3} \overline{\Psi}_L^C q_L$ to fix the charges of Ψ

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$U(1)_{\mathcal{B}}$	2	$-2/3$	$-2/3$	$1/3$	$-5/3$	$1/3$	$1/3$	$1/3$	0	0	0
$U(1)_{\mathcal{L}}$	0	0	0	0	0	0	0	0	1	1	1

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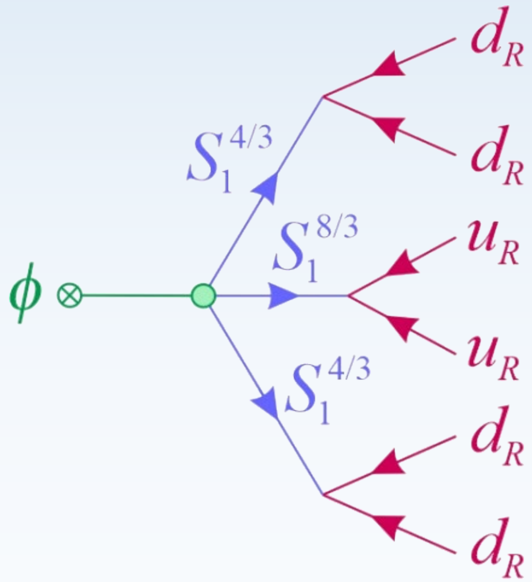

$$\exp(ia^0/v_\phi)\frac{v_\phi}{m^4_{S^{4/3}} m^2_{S^{8/3}}}\bar{d}_R^{\rm C} d_R \bar{d}_R^{\rm C} d_R \bar{u}_R^{\rm C} u_R$$

↓

$m_S \gtrsim 100$ TeV

$n - \bar{n}$ oscillations in the KSVZ model

- This could again be supplemented with a Seesaw, with just $U(1)_{PQ}$ remaining

$$\mathcal{L}_{\text{KSVZ+LQ}} = \mathcal{L}_{\text{KSVZ}} + S_1^{4/3}\bar{d}_R^{\text{C}} d_R + S_1^{8/3}\bar{u}_R^{\text{C}} u_R + \phi S_1^{4/3} S_1^{4/3} S_1^{8/3} + \phi \bar{\nu}_R^{\text{C}} \nu_R + h.c.$$

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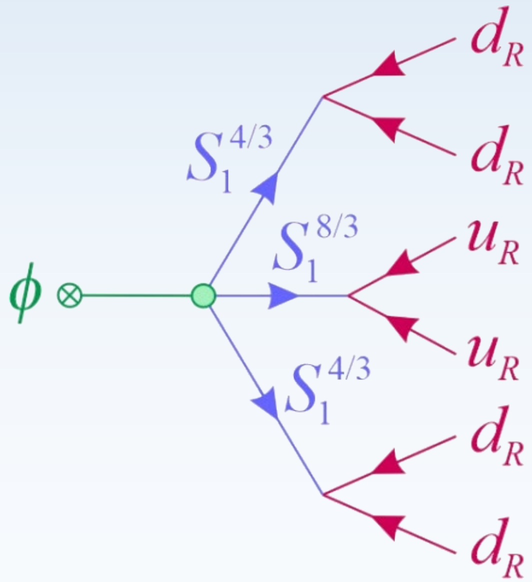
$U(1)_{PQ}$	2	$-2/3$	$-2/3$	$1/3$	$-5/3$	$1/3$	$1/3$	$1/3$	-1	-1	-1

- $n - \bar{n}$ oscillations and neutrino masses, but no proton decay



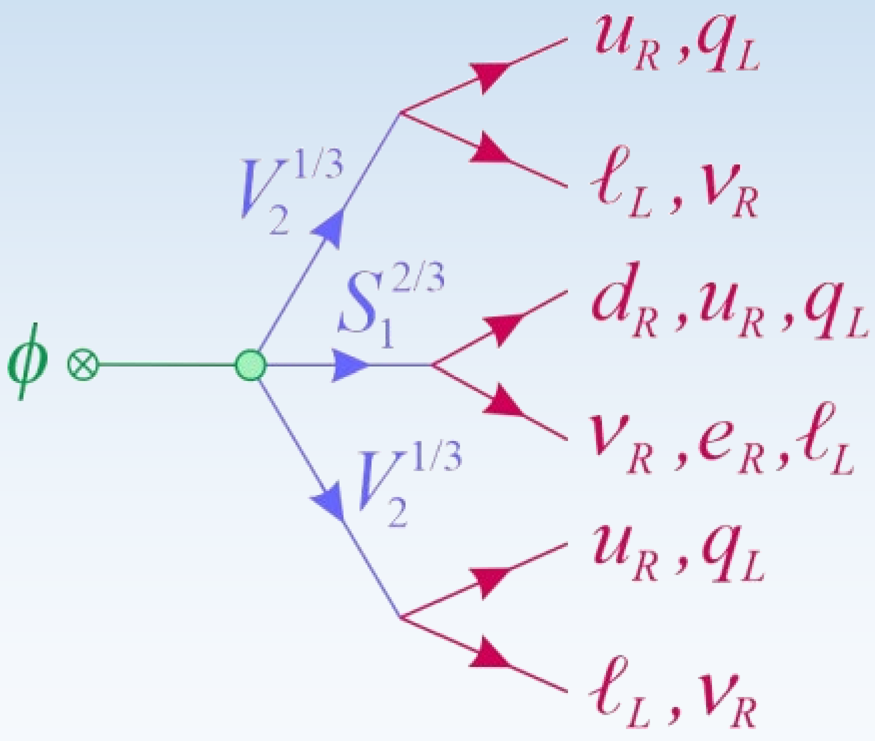
$$\exp(ia^0/v_\phi)\frac{v_\phi}{m_{S^{4/3}}^4 m_{S^{8/3}}^2}\bar{d}_R^{\text{C}} d_R \bar{d}_R^{\text{C}} d_R \bar{u}_R^{\text{C}} u_R$$

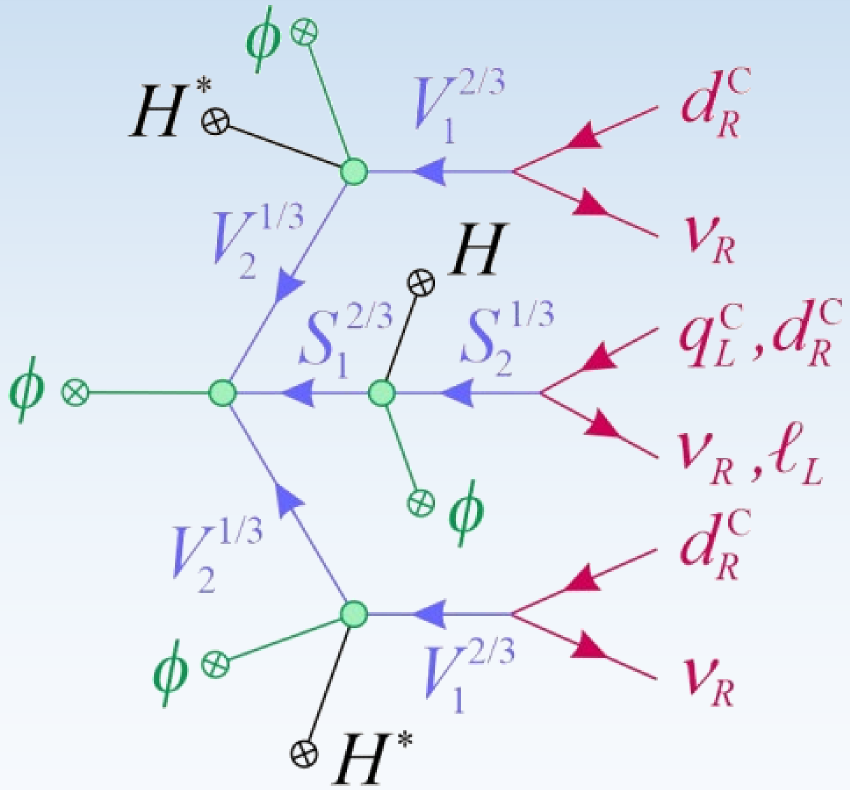
$\downarrow$

$m_S \gtrsim 100$ TeV

Other Breaking Patterns in the KSVZ model

- Spontaneously broken $U(1)_{\mathcal{B}\pm3\mathcal{L}}$ can be achieved as well
- Both scenarios allow for a Seesaw to be included
- The higher dimensionality allows for $m_{LQ} \sim 100$ TeV





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- Identifying the SSB symmetry fixes β and γ
- Fermion PQ charges are no longer fully aligned with a combination of $\mathcal{B}$ and $\mathcal{L}$

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- Identifying the SSB symmetry fixes β and γ
- Fermion PQ charges are no longer fully aligned with a combination of $\mathcal{B}$ and $\mathcal{L}$
- Scalar PQ charges are fixed to $x_{H_u} = x, x_{H_d} = -\frac{1}{x}, x_\phi = \left(1 + \frac{1}{x}\right)/2$

DFSZ model and Leptoquarks

- Let us consider one example to illustrate

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	$S_1^{8/3}$	$\tilde{S}_1^{8/3}$	q_L	u_R	d_R	ℓ_L	e_R	ν_R
$U(1)_{PQ}$	$\frac{1}{x} - x - 2\xi$	$-2x - 2\xi$	ξ	$x + \xi$	$\frac{1}{x} + \xi$	$-\frac{1}{x} - x - 3\xi$	$-x - 3\xi$	$-\frac{1}{x} - 3\xi$

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- The conserved symmetry associated to $\xi = 1/3$ is $U(1)_{\mathcal{B}-\mathcal{L}}$ in this case

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$U(1)_{PQ}$	$\frac{1}{x} - x$	$-2x$	0	x	$\frac{1}{x}$	$-\frac{1}{x} - x$	$-x$	$-\frac{1}{x}$
$U(1)_{\mathcal{B}-\mathcal{L}}$	$-2/3$	$-2/3$	$1/3$	$1/3$	$1/3$	-1	-1	-1

Frobidding axion-free $\mathcal{B}/\mathcal{L}$ violation

- The presence of v_ϕ in the induced operators pushes m_{LQ} to high values

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- New search venue for axions?
- Link to DM?

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- Let us take the KSVZ framework for an example

$$\mathcal{L}_{\mathrm{KSVZ+LQ}} = \mathcal{L}_{\mathrm{KSVZ}} + S_1^{2/3}(\bar{q}_L^{\mathrm{C}} q_L + \bar{d}_R^{\mathrm{C}} u_R) + V_{1,\mu}^{2/3} \bar{d}_R \gamma^\mu \nu_R + \partial_\mu \phi S_1^{2/3\dagger} V_1^{2/3,\mu} + h.c.$$

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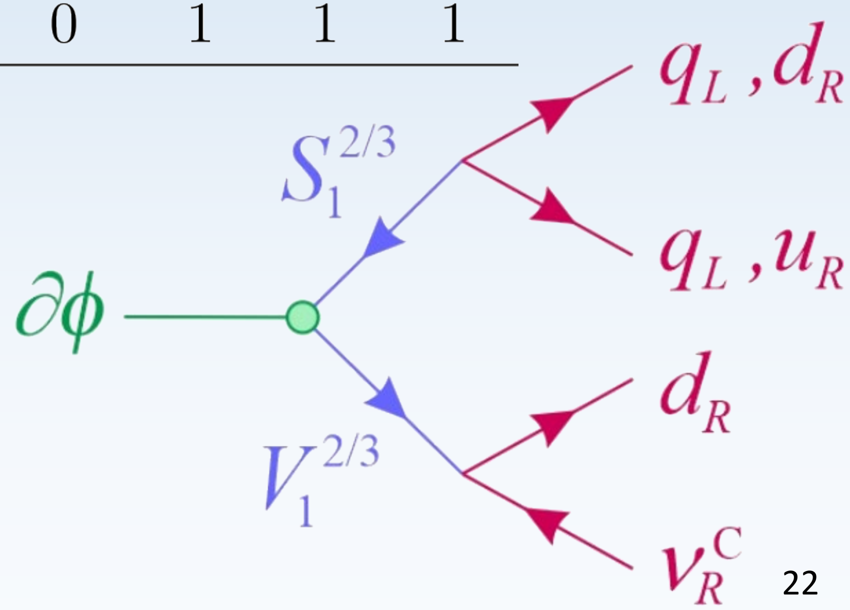
- This leads to conserved $U(1)_{\mathcal{B}+\mathcal{L}}$ and a $U(1)_{\mathcal{B}-\mathcal{L}}$ breaking operator

	ϕ	$S_1^{2/3}$	$V_{1,\mu}^{2/3}$	q_L	u_R	d_R	ℓ_L	e_R	ν_R
$U(1)_\mathcal{B}$	-1	$-2/3$	$1/3$	$1/3$	$1/3$	$1/3$	0	0	0
$U(1)_\mathcal{L}$	1	0	-1	0	0	0	1	1	1

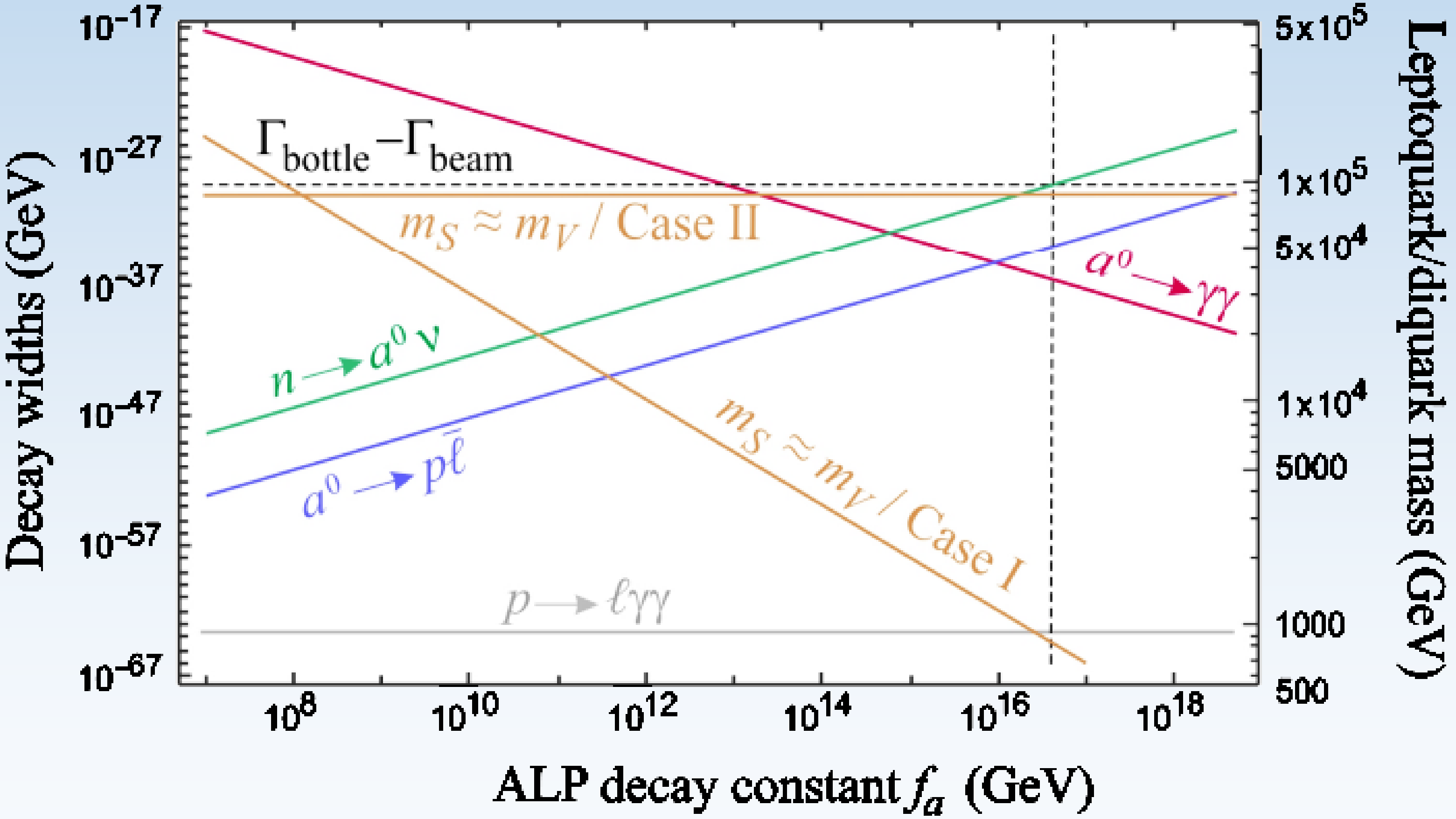
$$\frac{1}{m_S^2 m_V^2} \partial_\mu \phi (\bar{q}_L^{\text{C}} q_L + \bar{d}_R^{\text{C}} u_R) \bar{d}_R^{\text{C}} \gamma^\mu \nu_R^{\text{C}}$$

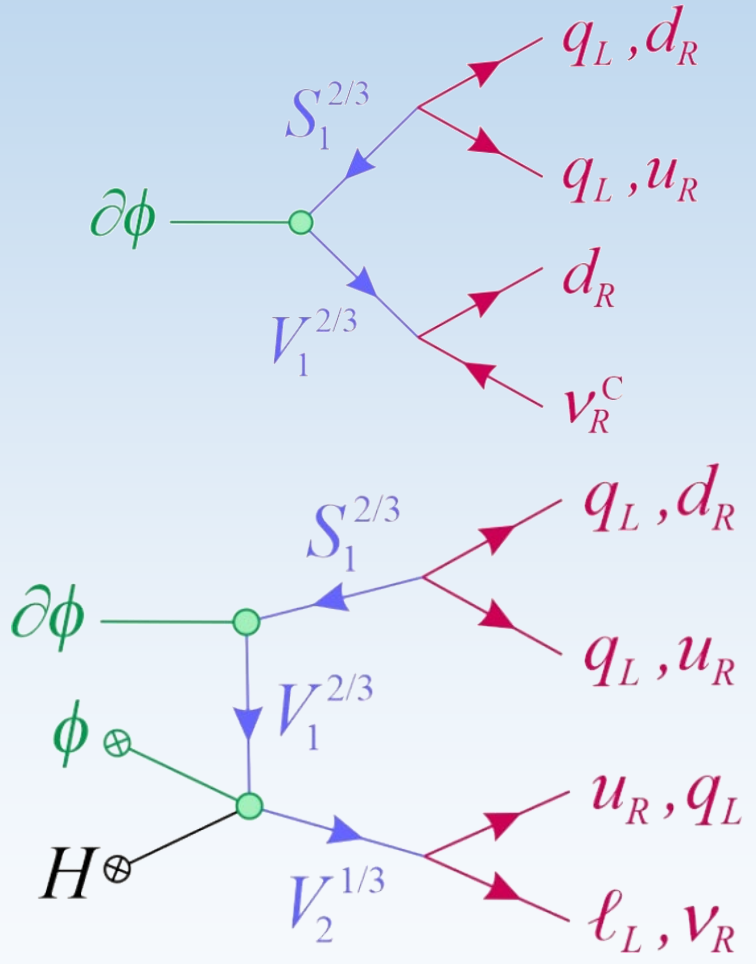
$m_S \gtrsim 10^7$ GeV



Frobidding axion-free $\mathcal{B}/\mathcal{L}$ violation

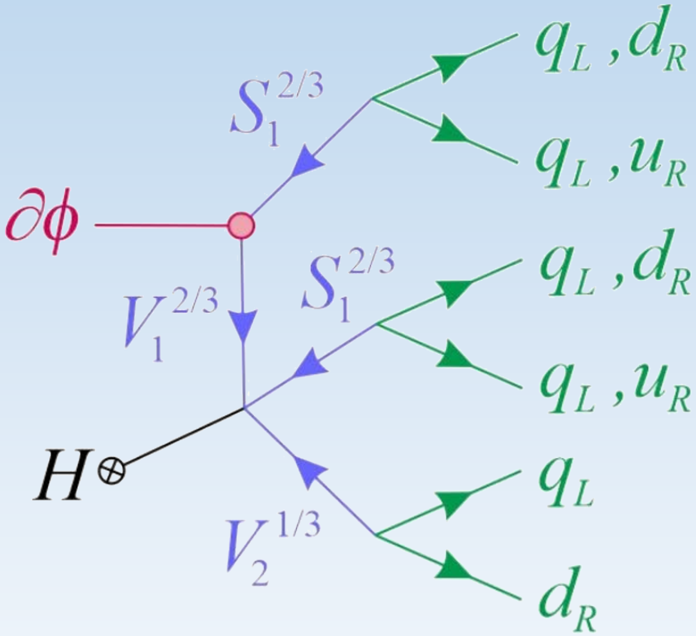
- Interesting for neutron lifetime anomaly, assuming $m_n > m_a > m_p$

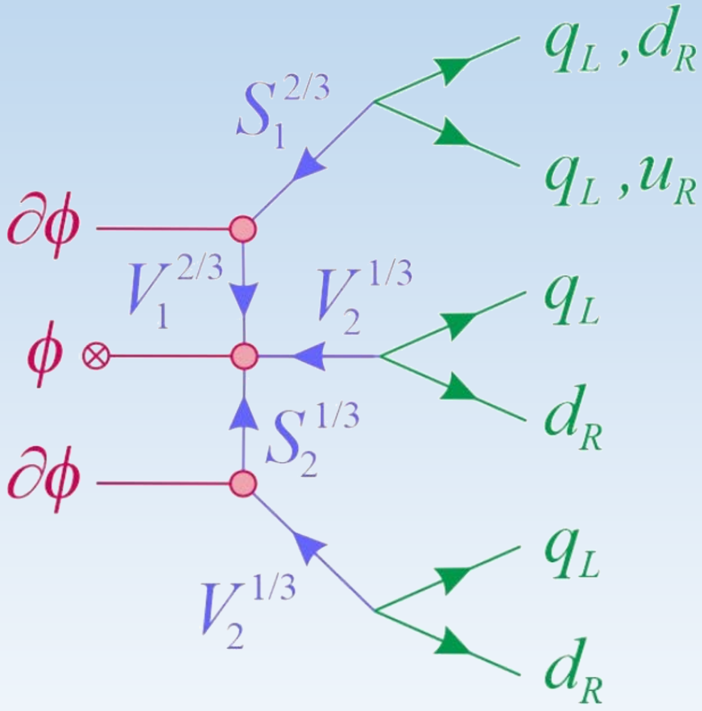




Frobidding axion-free $\mathcal{B}/\mathcal{L}$ violation

- Axion induced $n - \bar{n}$ oscillations





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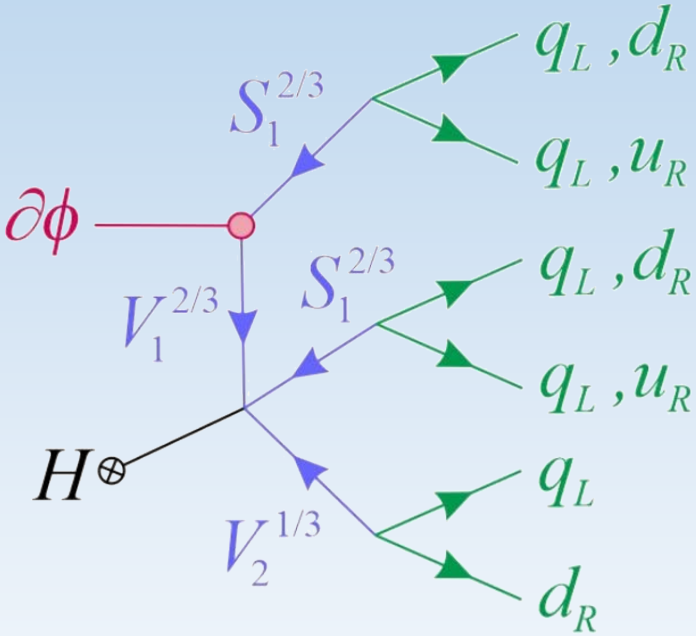

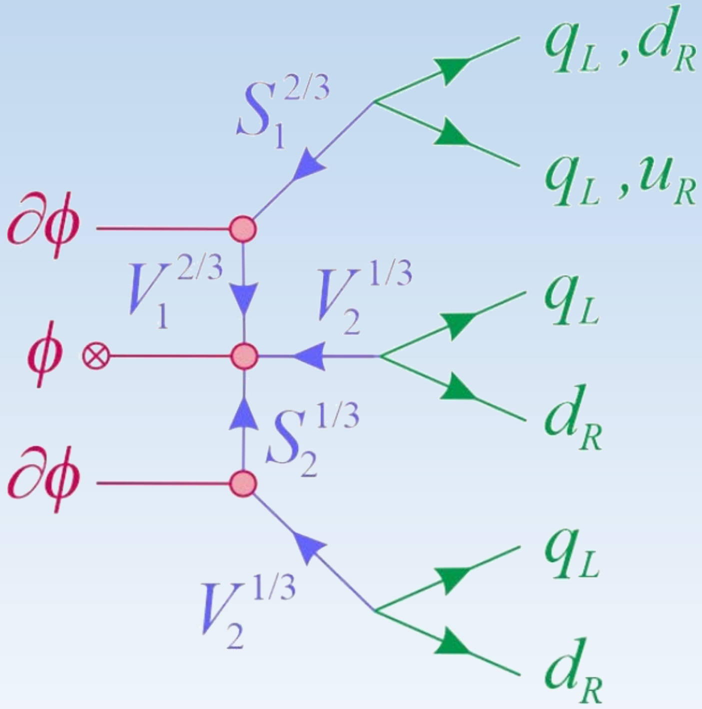

- Oscillations in DM background?

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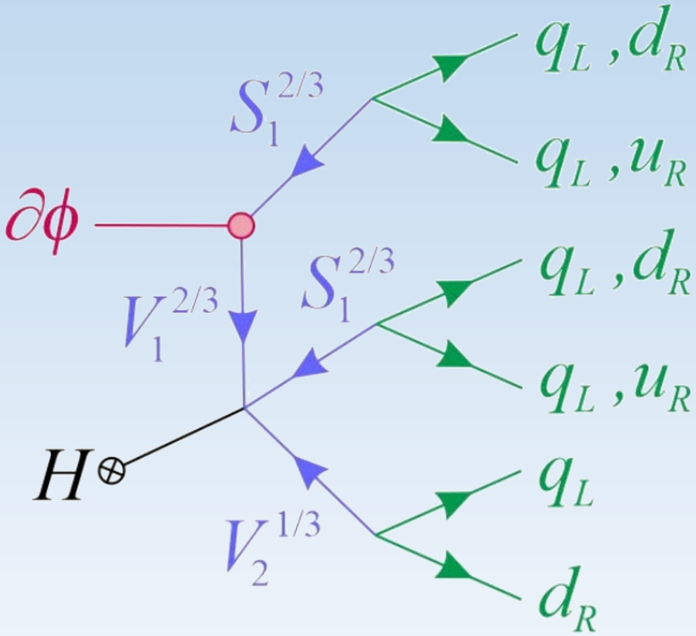

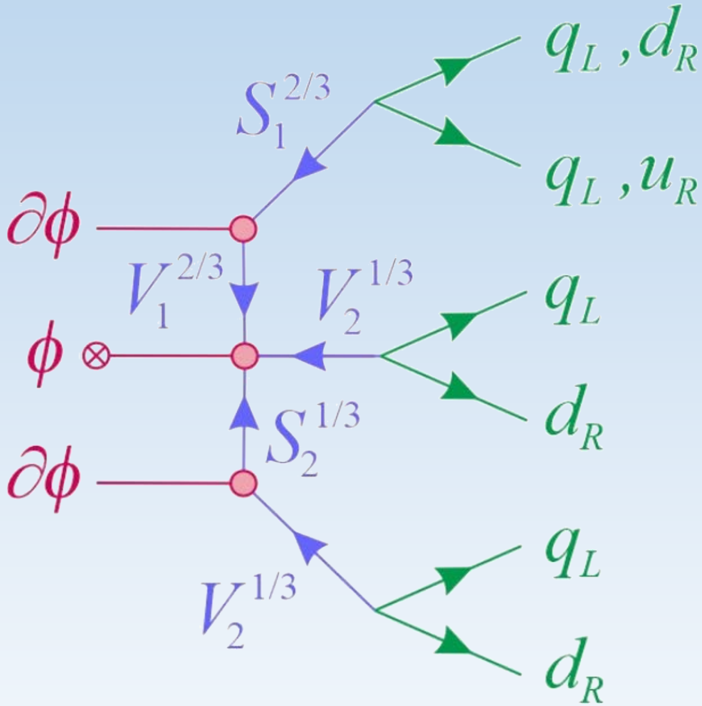

- Oscillations in DM background?
- $n \to \bar{n} + a^0(+a^0)$ in a magnetic field? $\Delta m_{n-\bar{n}}\ (1T) \approx 10^{-7}\mathrm{eV}$

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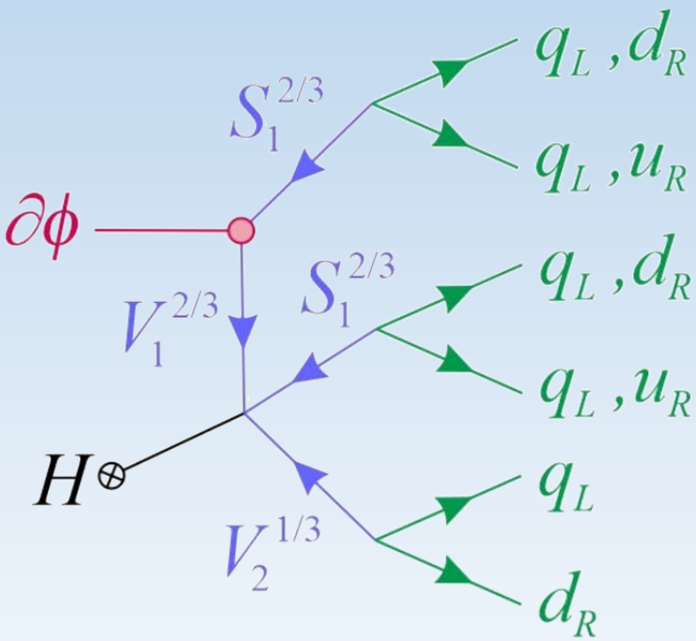

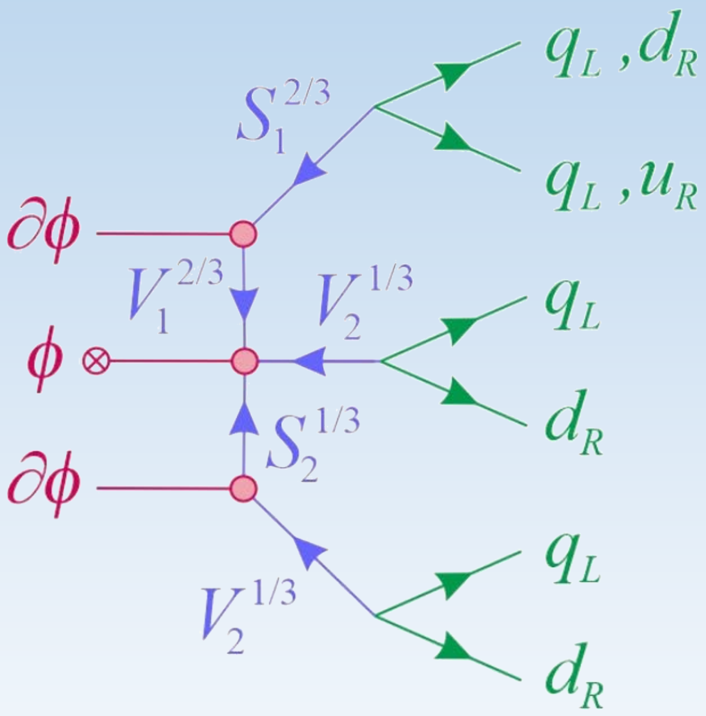

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- Astrophysical and cosmological consequences?

Conclusions

- PQ symmetry, $\mathcal{B}$ and $\mathcal{L}$ unified
- PQ breaking induces proton decay, neutrino masses and $n - \bar{n}$ oscillations
- Axion-free processes can be avoided
- Possible solution to the neutron lifetime anomaly
- Connection between DM and baryogenesis?

Thank you for your attention