A colorful mirror solution to the strong CP problem

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DESY
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with L. Hall, C. A. Manzari & C. Scherb
2303.06156 [hep-ph]
+ w.i.p. with the same people & A. McCune

The strong CP problem

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Q_L	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Y_u	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
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$$J_4 = \mathrm{Im}\,\mathrm{Tr}\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]^3$$

[Jarlskog '85]

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[Baluni '79, Crewther/Di Vecchia/Veneziano/Witten '79]

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[Pendlebury et al '15]

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Strong CP problem :

$$\bar\theta \lesssim 10^{-10}$$

[Baluni '79, Crewther/Di Vecchia/Veneziano/Witten '79]

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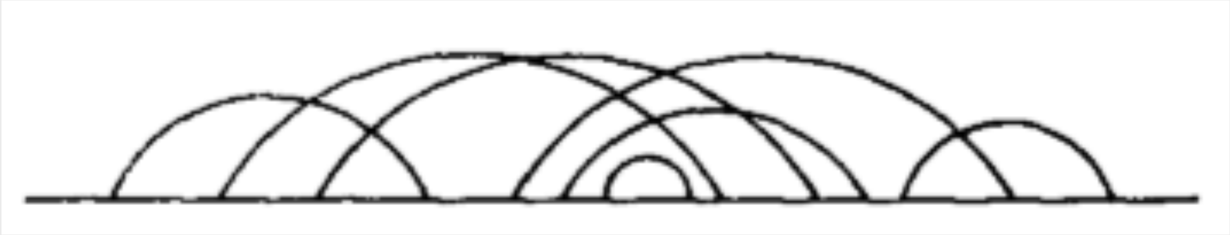
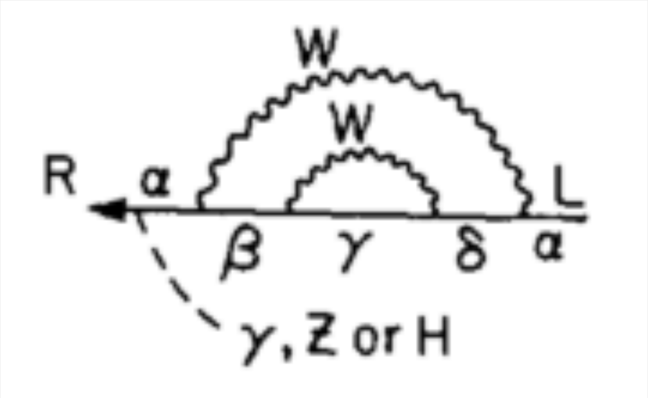
[Ellis/Gaillard '79]





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By symmetry: **(C)P !**

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CP : $\langle \phi \rangle \in \mathbb{C}$ **[Nelson '84, Barr '84]**

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same + $Q_R(\mathbf{3},\mathbf{2},1/6)$
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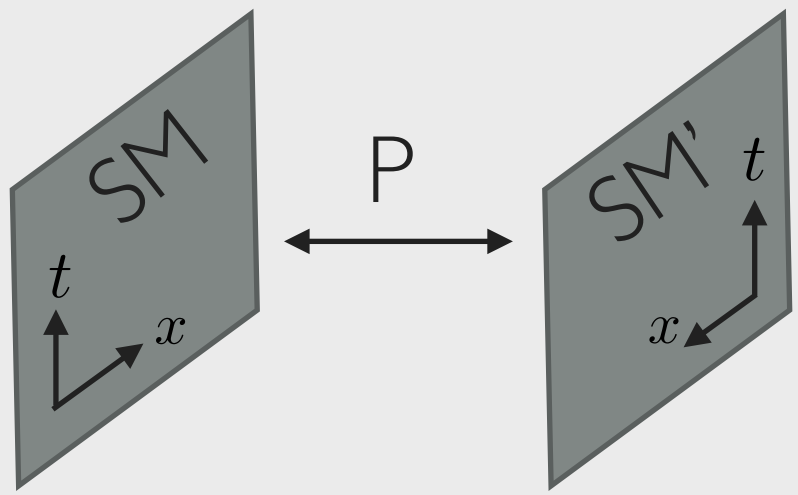
In practice, both !

[Babu/Mohapatra '89, '90, Barr/Chang/Senjanovic '91, Hall/Harigaya '18, +Dunsky '18, Craig/Garcia Garcia/Koszegi/McCune '20, …]

Parity solutions to the strong CP problem

Mirror world



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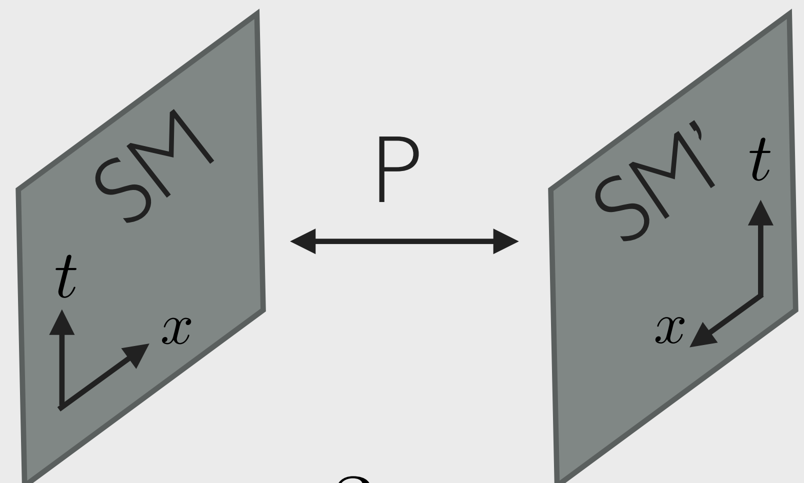
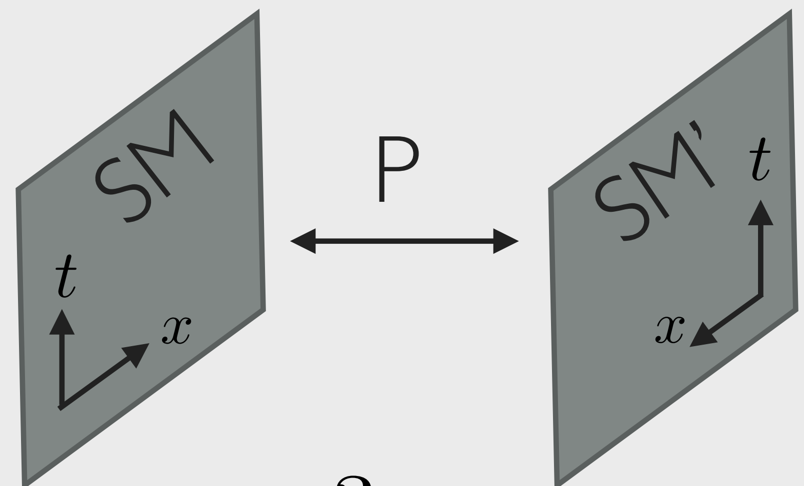


$$\langle H \rangle \overset{?}{=} \langle H' \rangle$$

Parity solutions to the strong CP problem

Mirror world and strong CP



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$$\bar{\theta}' = -\bar{\theta}$$

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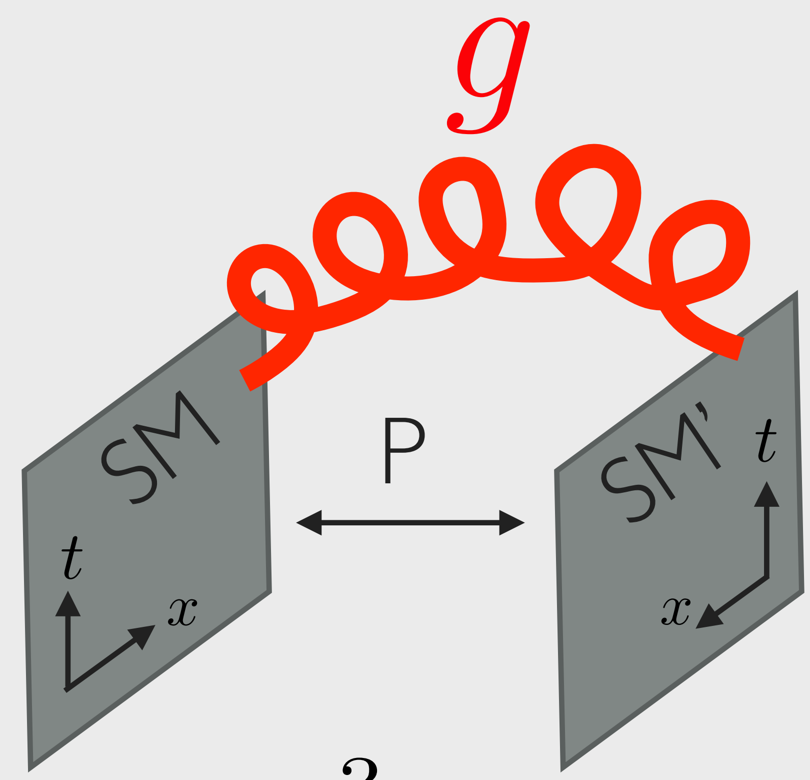
Mirror world and strong CP. Need shared color (P-invariant on its own) !



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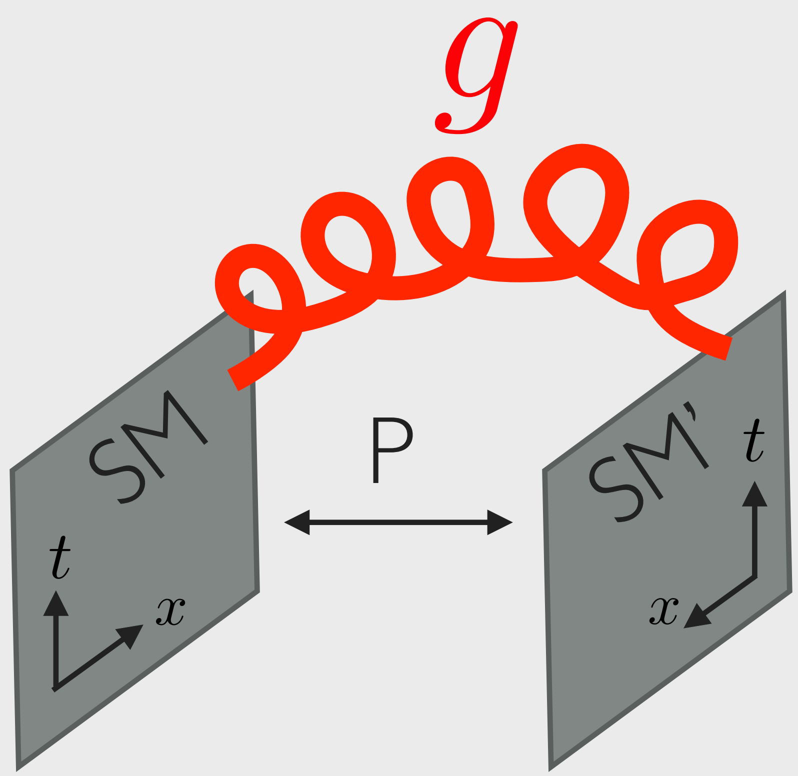
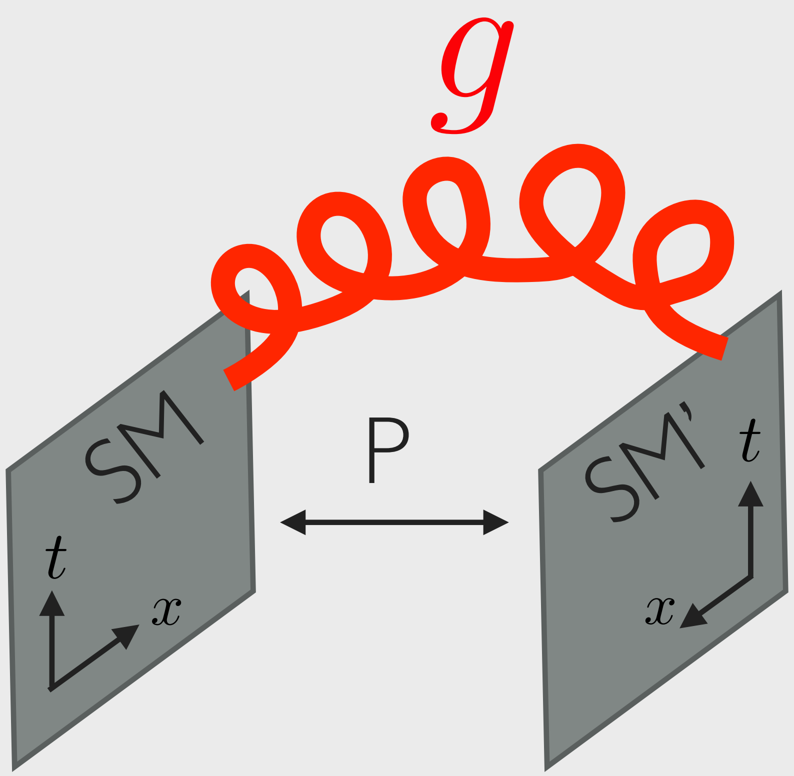


$$\langle H \rangle \neq \langle H' \rangle$$

$$\bar{\theta}_{\rm QCD} = 0$$

Parity solutions to the strong CP problem

Mirror world and strong CP. Need shared color (P-invariant on its own) !



$$\langle H \rangle \neq \langle H' \rangle$$

$$\bar{\theta}_{\mathrm{QCD}} = 0$$

Few parts of that landscape are explored !

Parity solutions to the strong CP problem

? Need $\bar{\theta} \approx 0$ even **below the scale of parity breaking**

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Similar to the SM case **[Ellis/Gaillard '79]**

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Not in all extensions **[de Vries/Draper/Patel '21]**

Parity solutions to the strong CP problem

? Need $\bar{\theta} \approx 0$ even **below the scale of parity breaking**

Similar to the SM case **[Ellis/Gaillard '79]**

Not in all extensions **[de Vries/Draper/Patel '21]**

Easier in mirror models **[Barr/Chang/Senjanovic '91]**

Our parity solution to the strong CP problem

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We notice that

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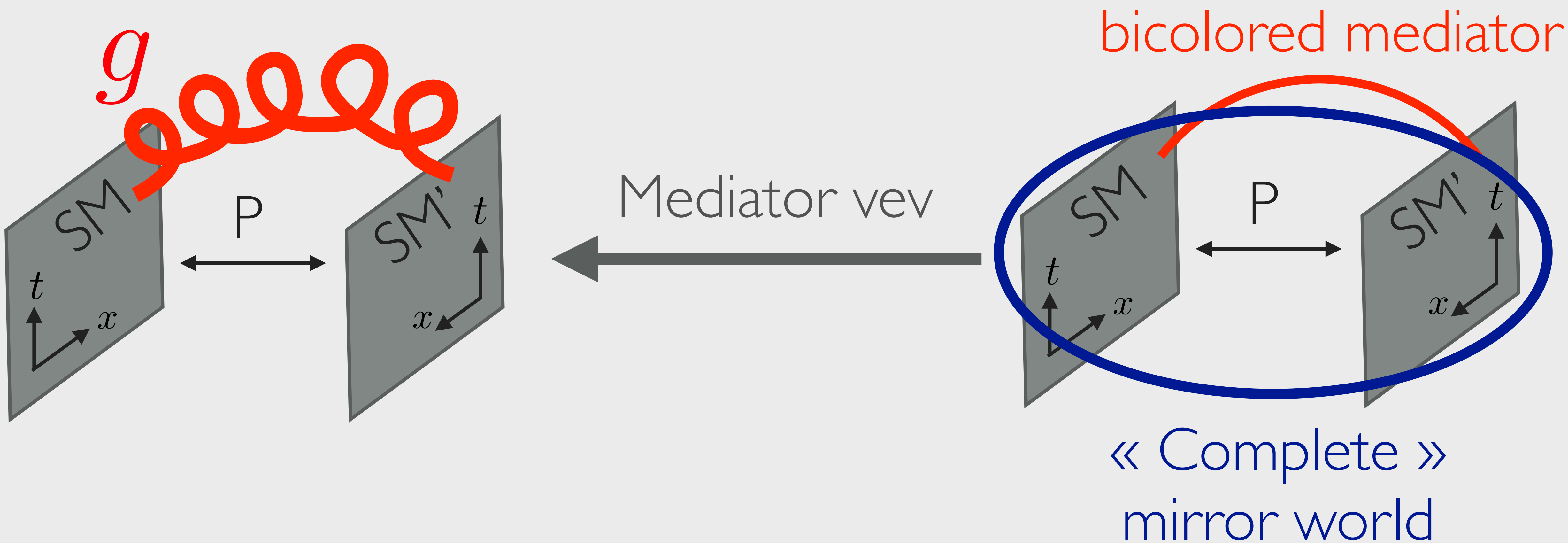
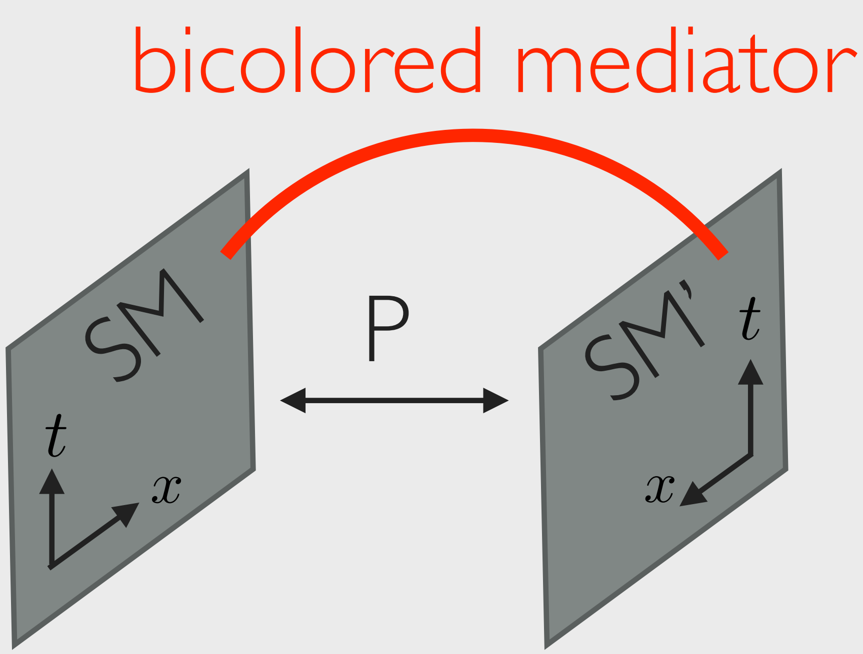


Our parity solution to the strong CP problem

We notice that

With the same starting point :



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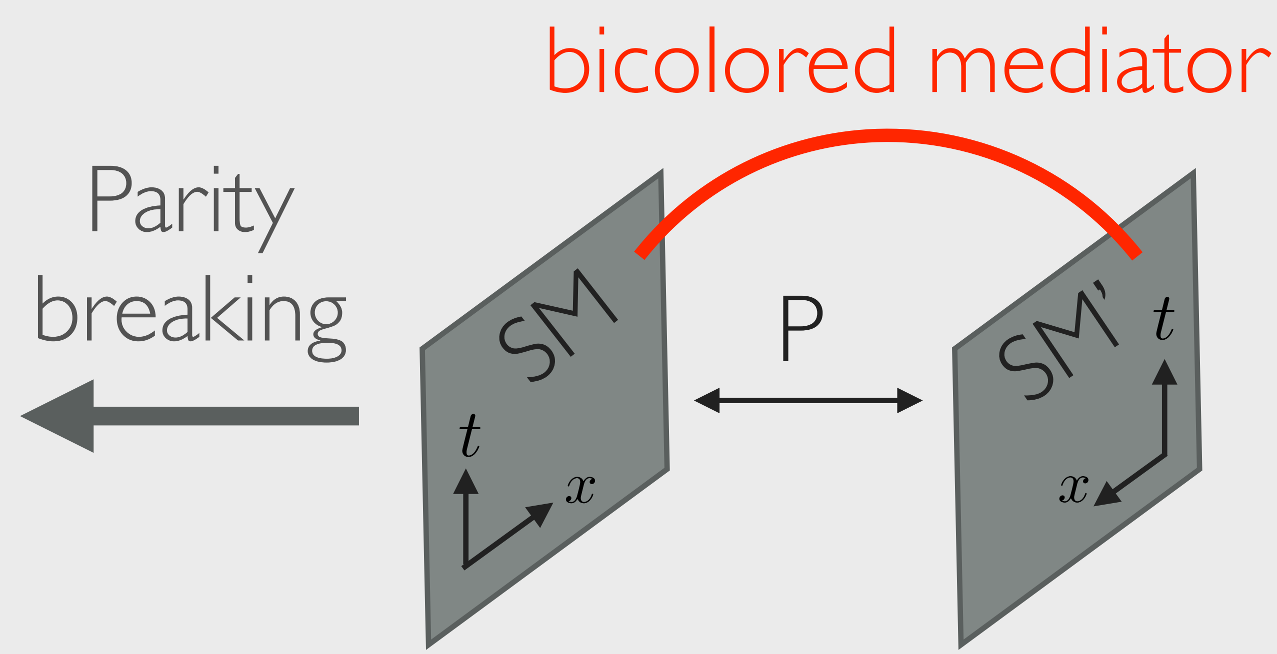

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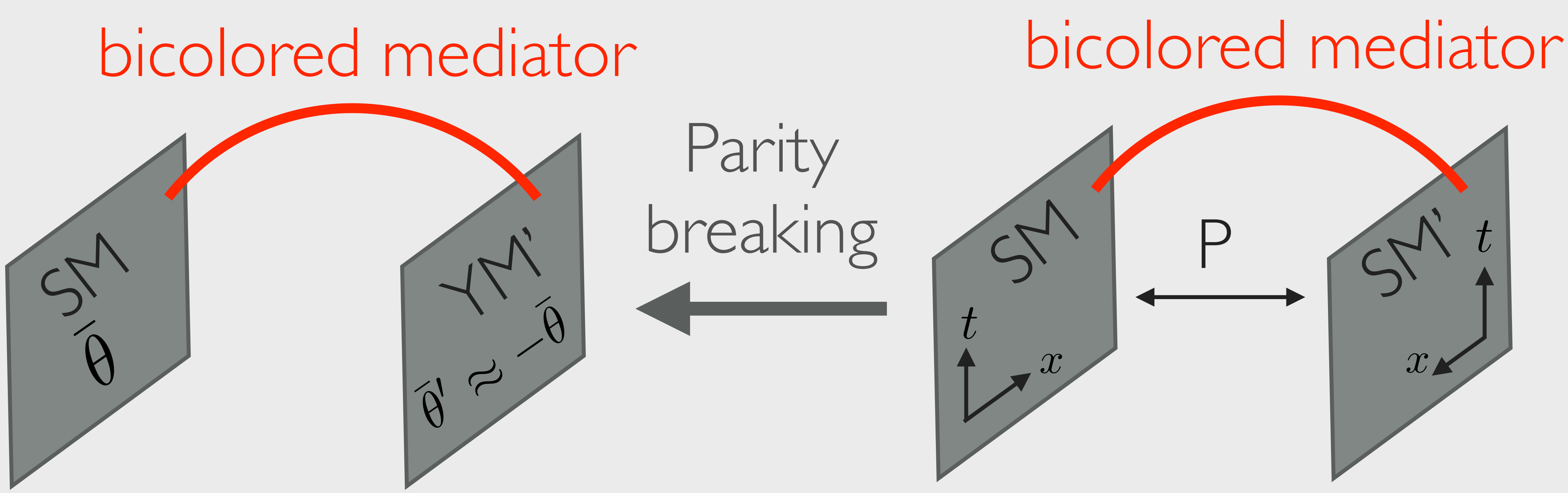

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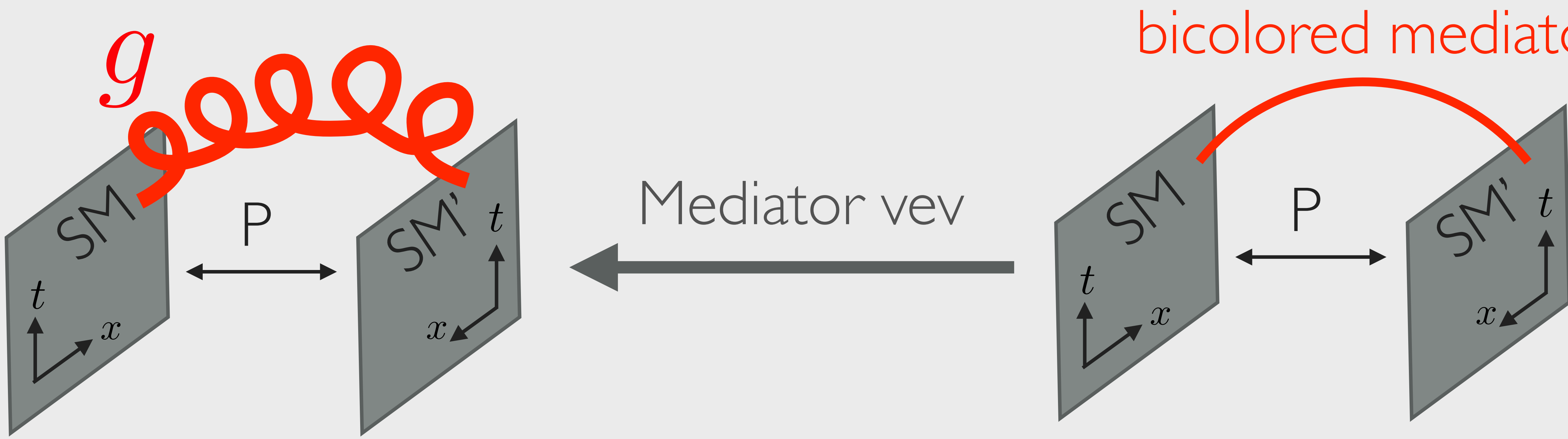

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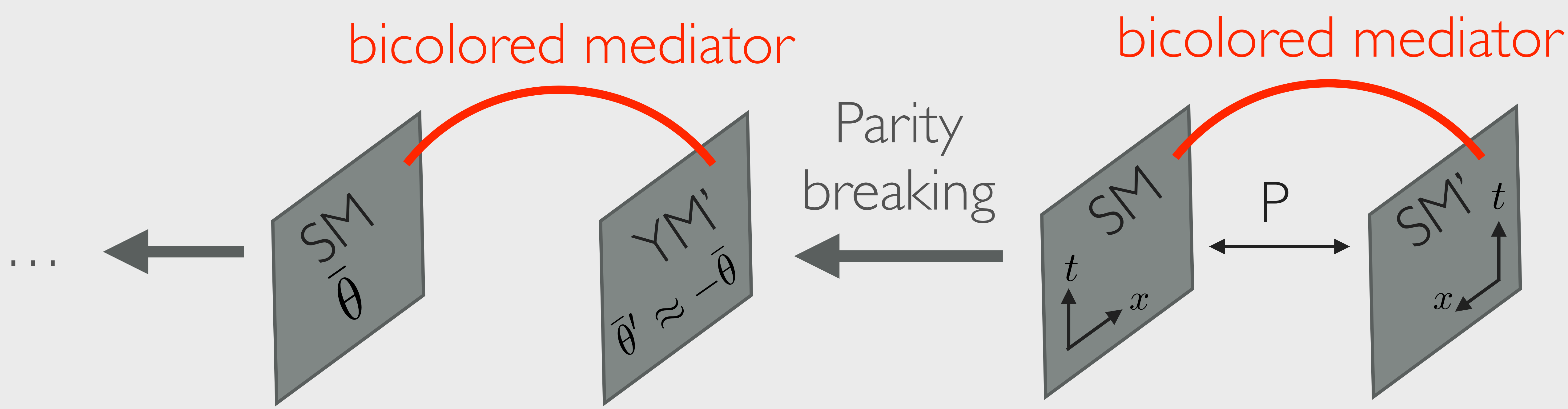
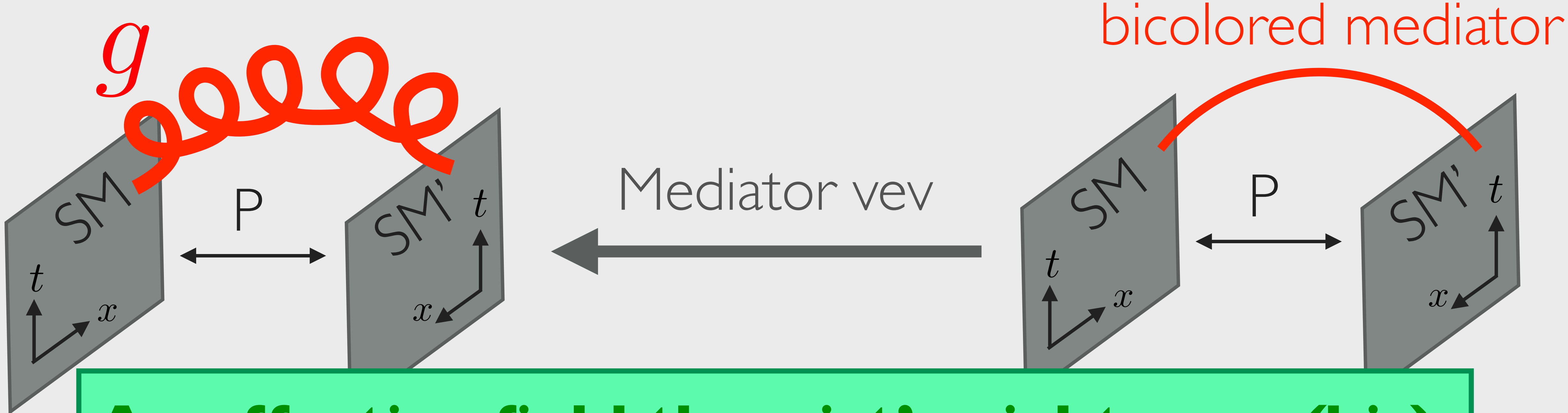


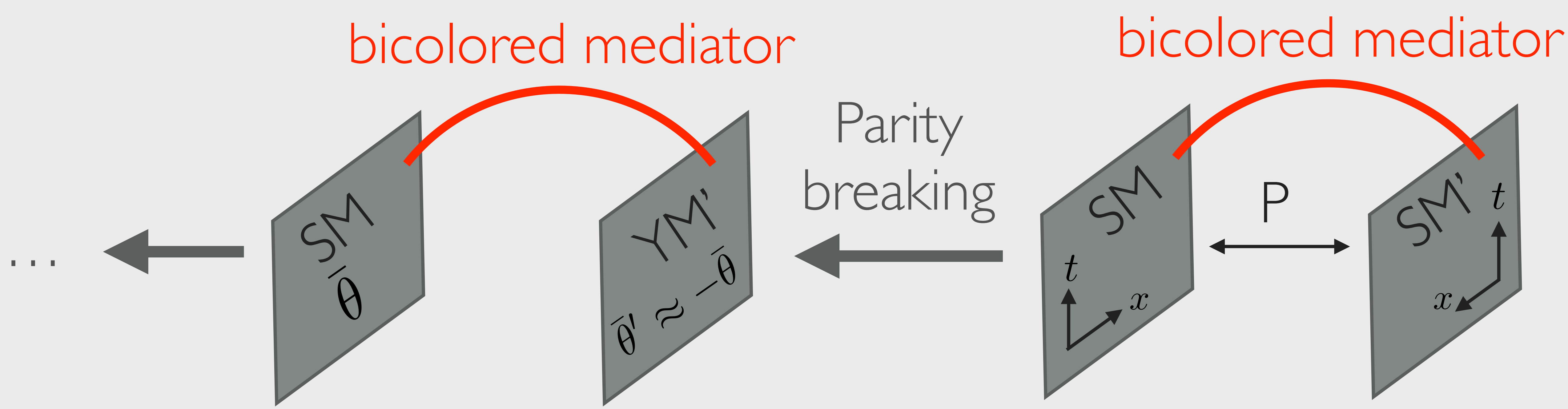
Our parity solution to the strong CP problem

We notice that



An effective field theorist's nightmare (bis)

With the same starting point :



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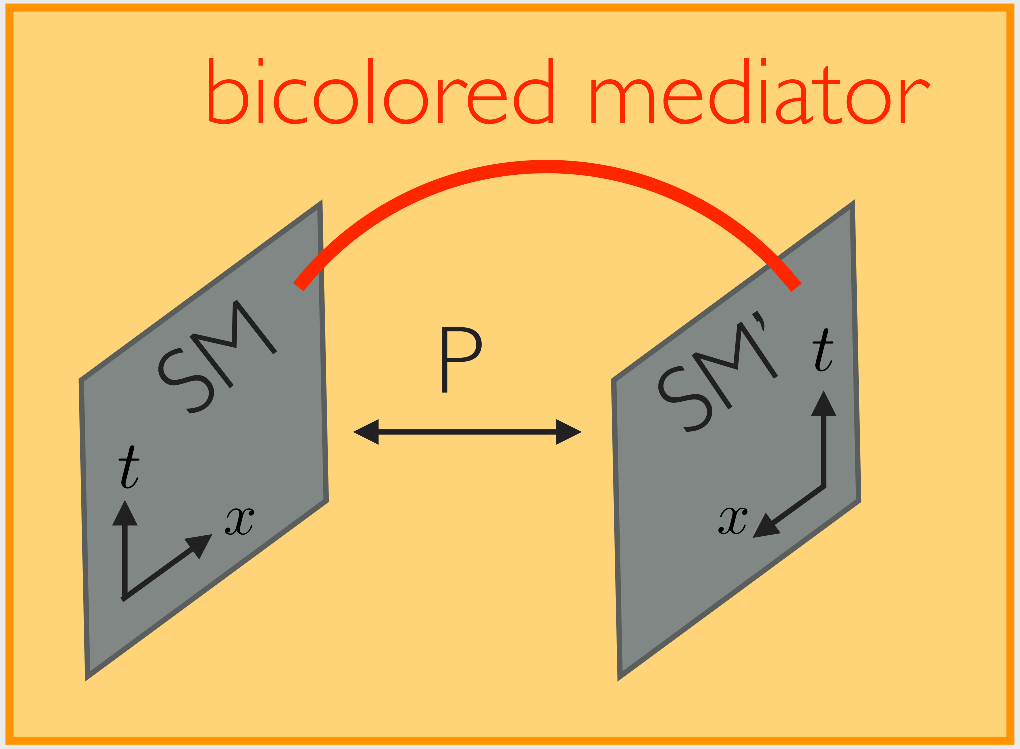

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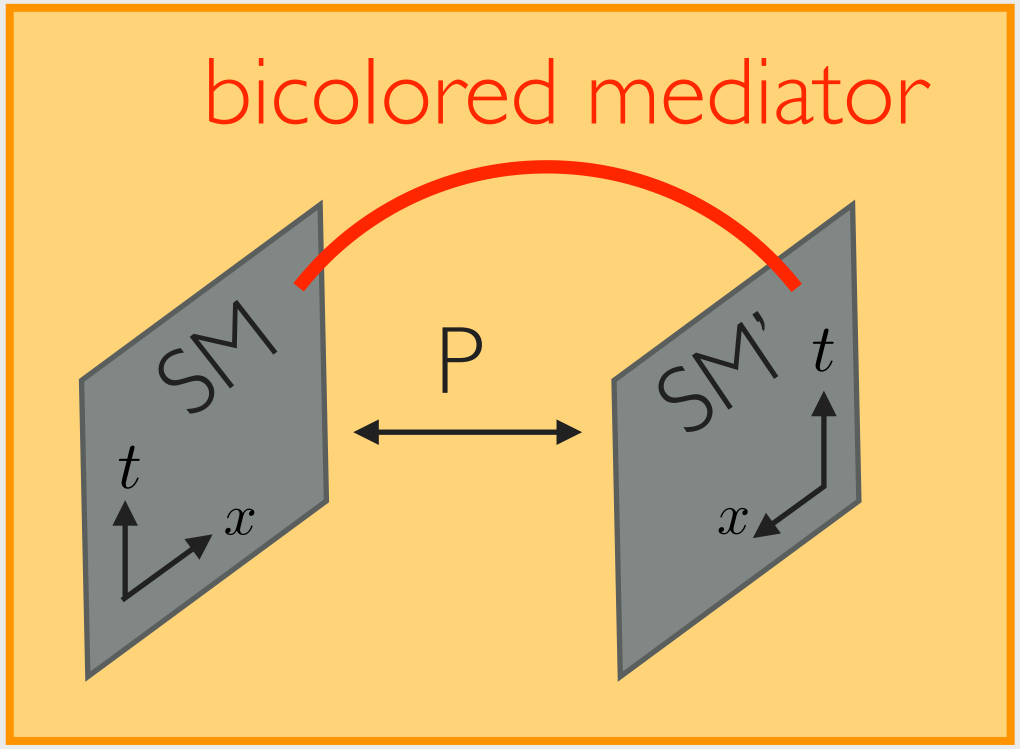
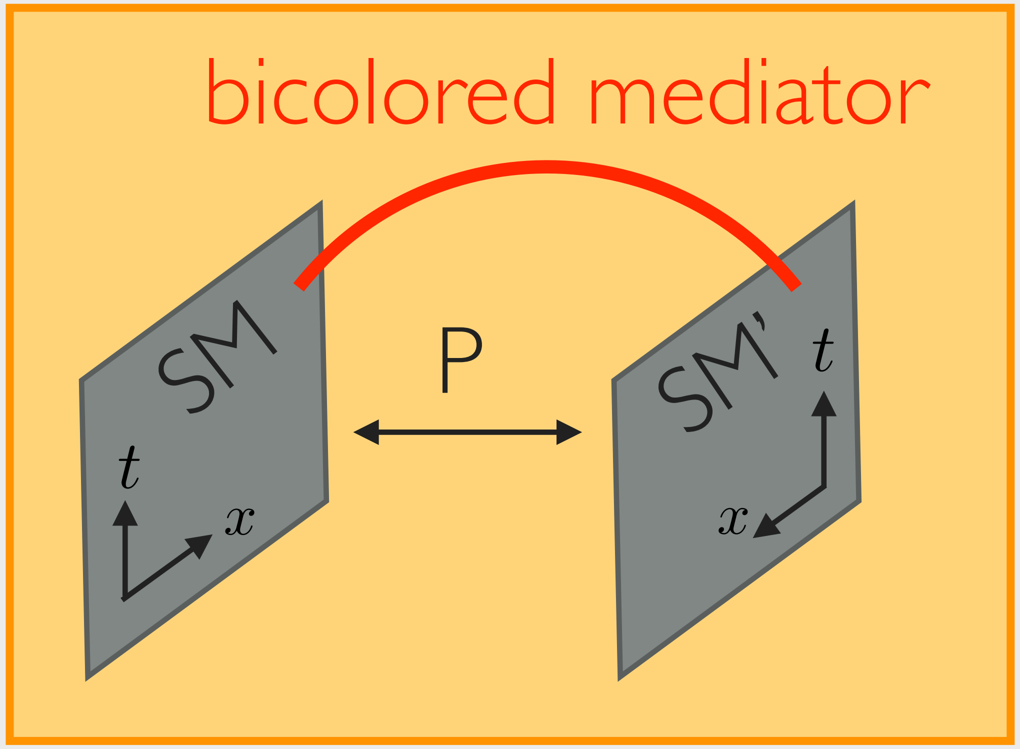


	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	$\mathbf{1}$	$\mathbf{1}$	0
u^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	-2/3	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
e'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	1
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

P

Our parity solution to the strong CP problem



	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	$\mathbf{1}$	$\mathbf{1}$	0
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
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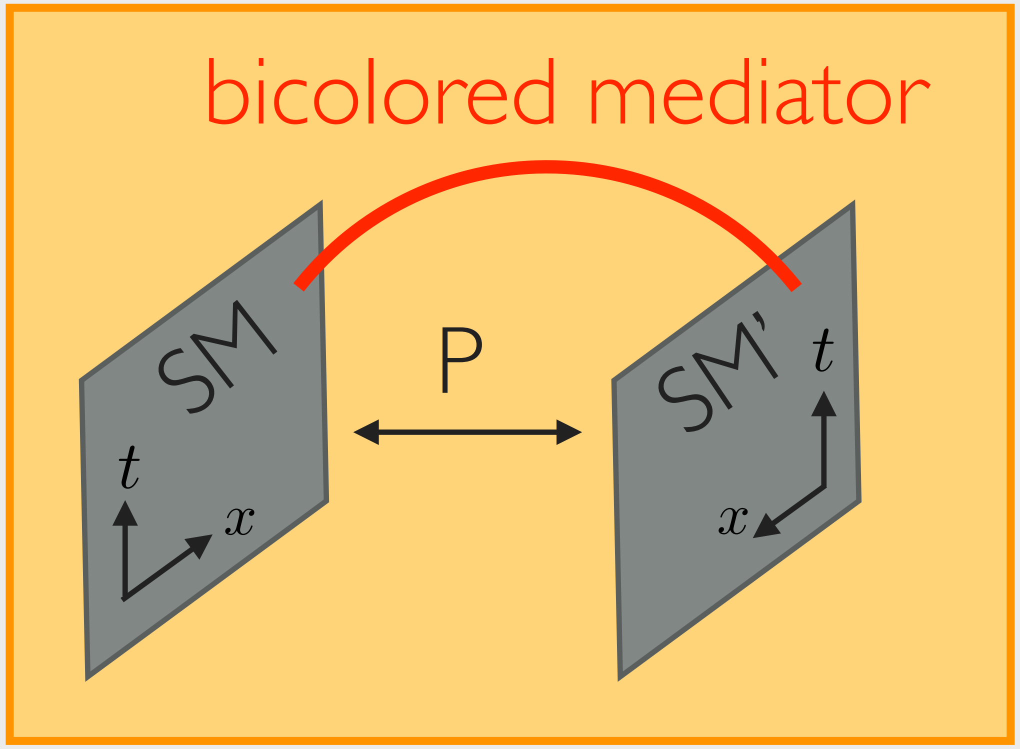
P

$$\left.\begin{aligned} \theta' &= -\theta \\ Y_q &= Y_{q'}^\dagger \end{aligned}\right\} \Longrightarrow \bar{\theta}' = -\bar{\theta}$$

Our parity solution to the strong CP problem



Bicolored mediator here: bifundamental order parameter $\langle\Sigma\rangle$

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	$\mathbf{1}$	$\mathbf{1}$	0
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
e'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	1
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

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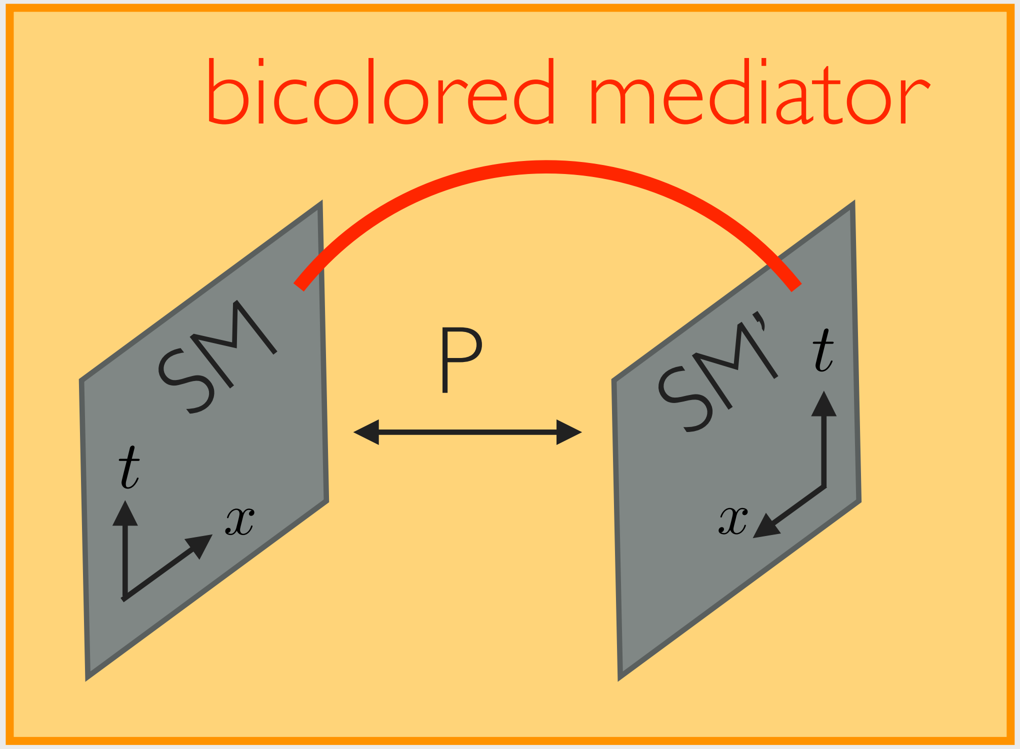


Bicolored mediator here: bifundamental order parameter $\langle \Sigma \rangle$

$$\langle \Sigma \rangle \propto v_3 \mathbf{1}$$

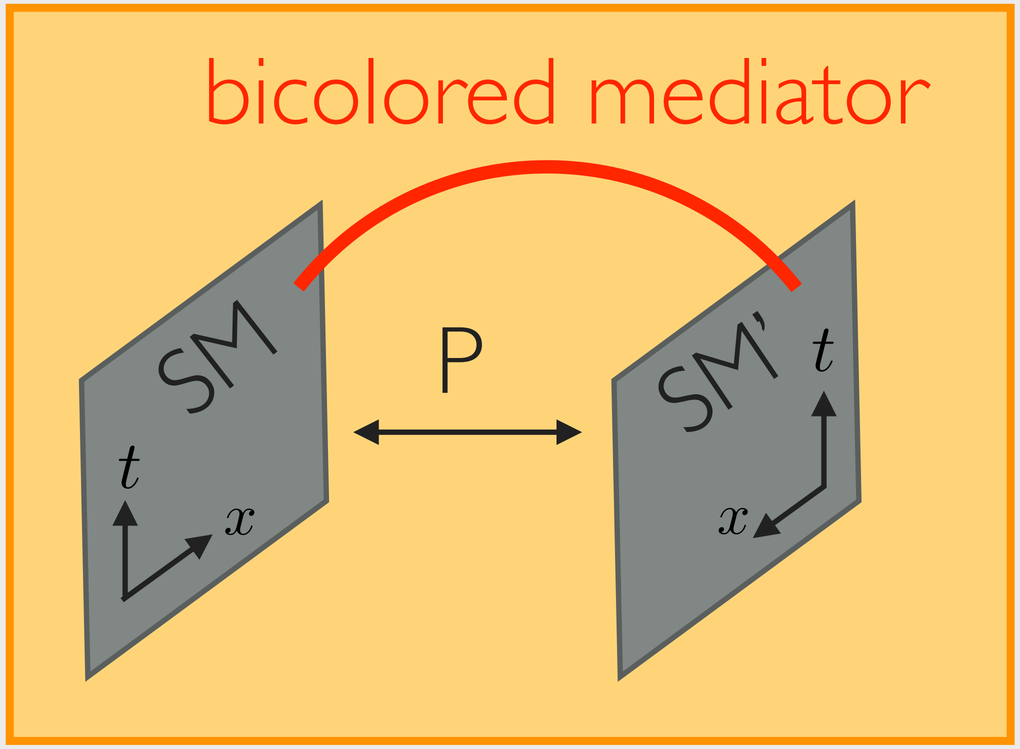
$$\implies g_3^2 G\tilde{G} = \big|_{\text{along QCD}} g_3'^2 G'\tilde{G}'$$

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	$\mathbf{1}$	$\mathbf{1}$	0
u^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	-2/3	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
e'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	1
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

P

$$\left.\begin{array}{l} \theta' = -\theta \\ Y_q = Y_{q'}^{\dagger} \end{array}\right\} \implies \bar{\theta}' = -\bar{\theta}$$

Our parity solution to the strong CP problem



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d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
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P

$$\left.\begin{array}{l}\theta' = -\theta \\ Y_q = Y_{q'}^\dagger\end{array}\right\} \Longrightarrow \bar\theta' = -\bar\theta$$

$$\Longrightarrow \bar\theta_{\mathrm{QCD}} = 0$$

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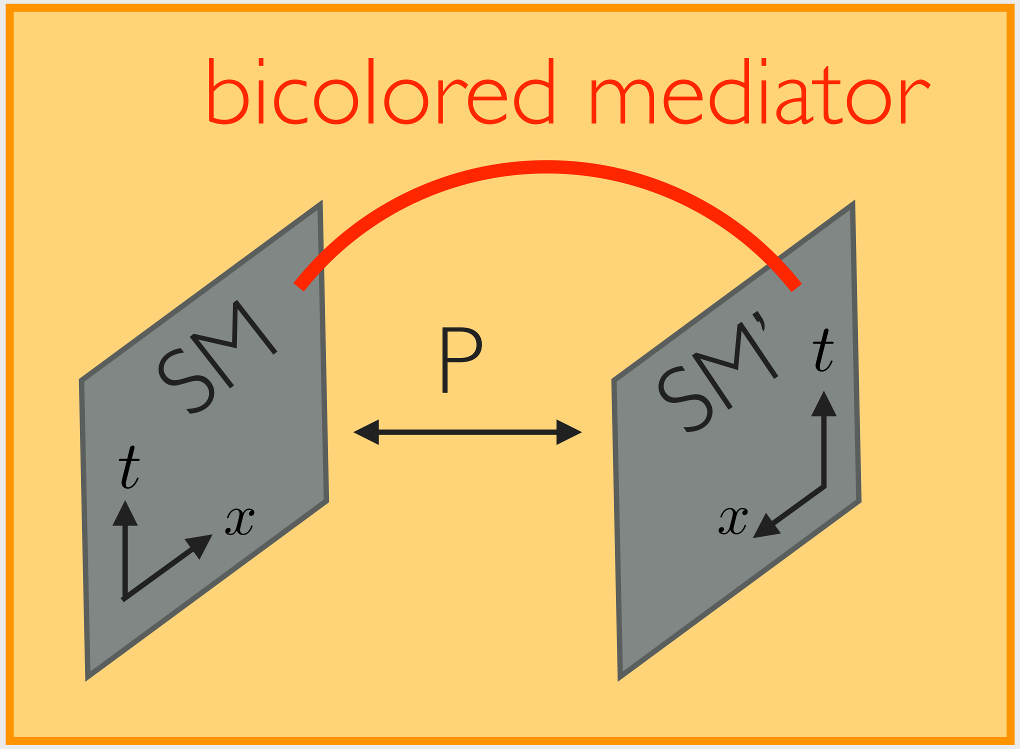
Our parity solution to the strong CP problem



Below v_3 , colored mirror quarks

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
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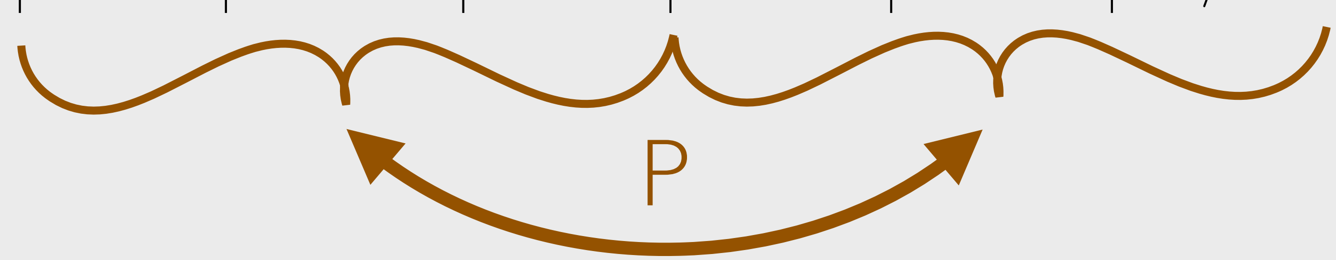
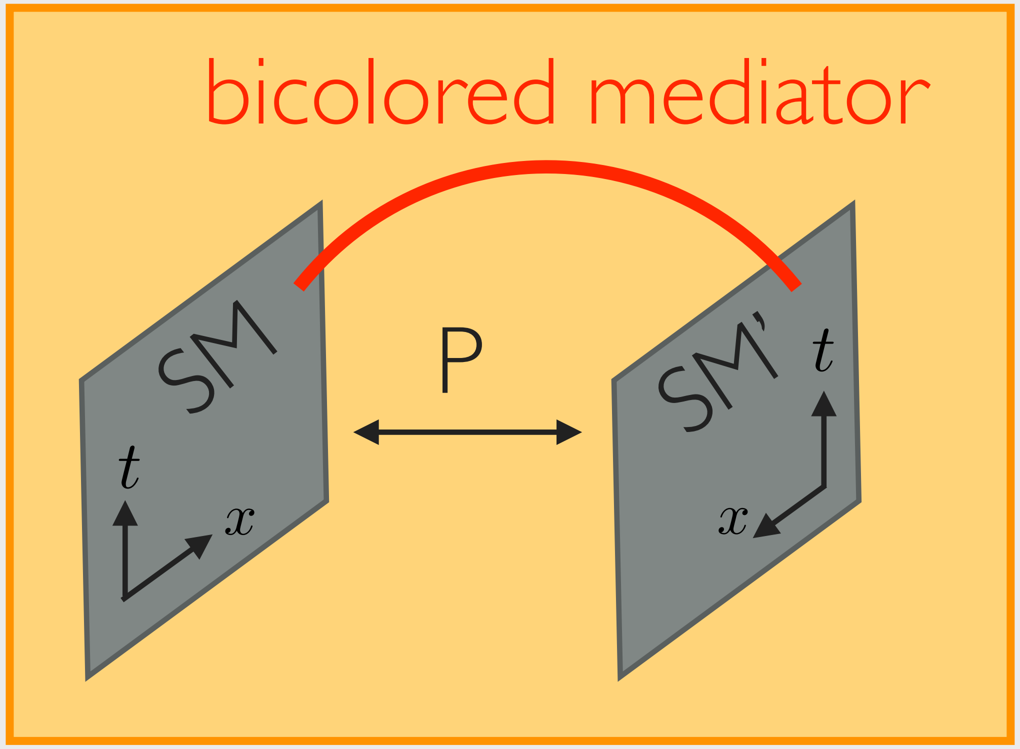
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2



$$Y_q = Y_{q'}^\dagger$$

Our parity solution to the strong CP problem



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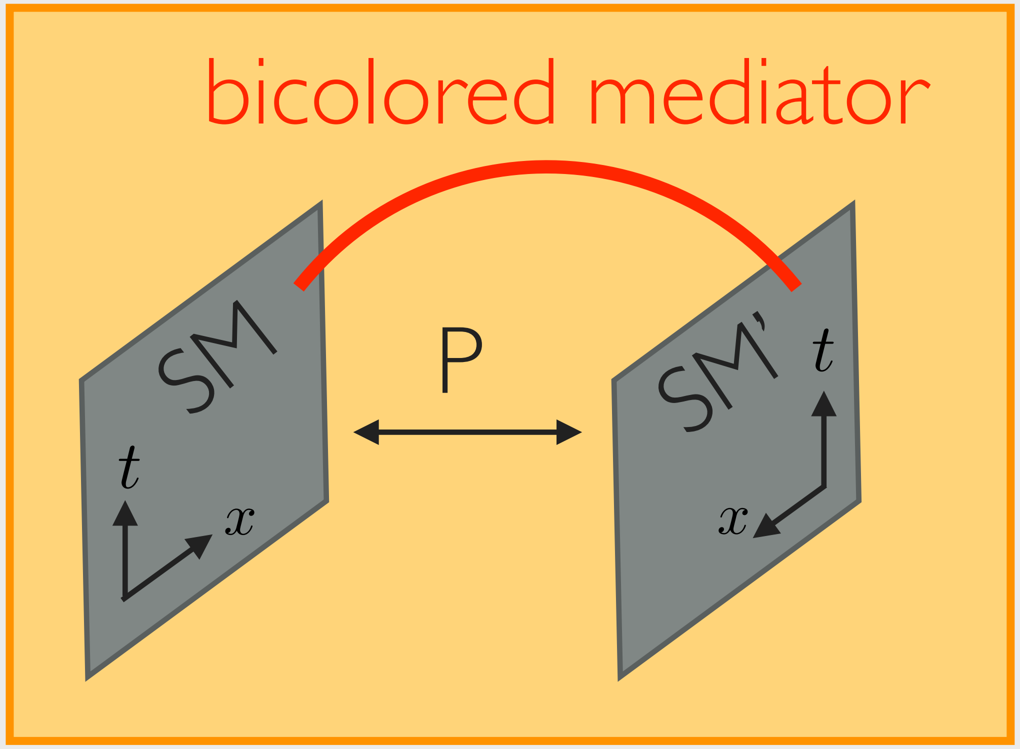
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
e'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	1
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

P

$$Y_q = Y_{q'}^\dagger$$

$$\implies \frac{m_q}{m_{q'}} = \frac{\langle H \rangle}{\langle H' \rangle}$$

Our parity solution to the strong CP problem



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d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
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H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
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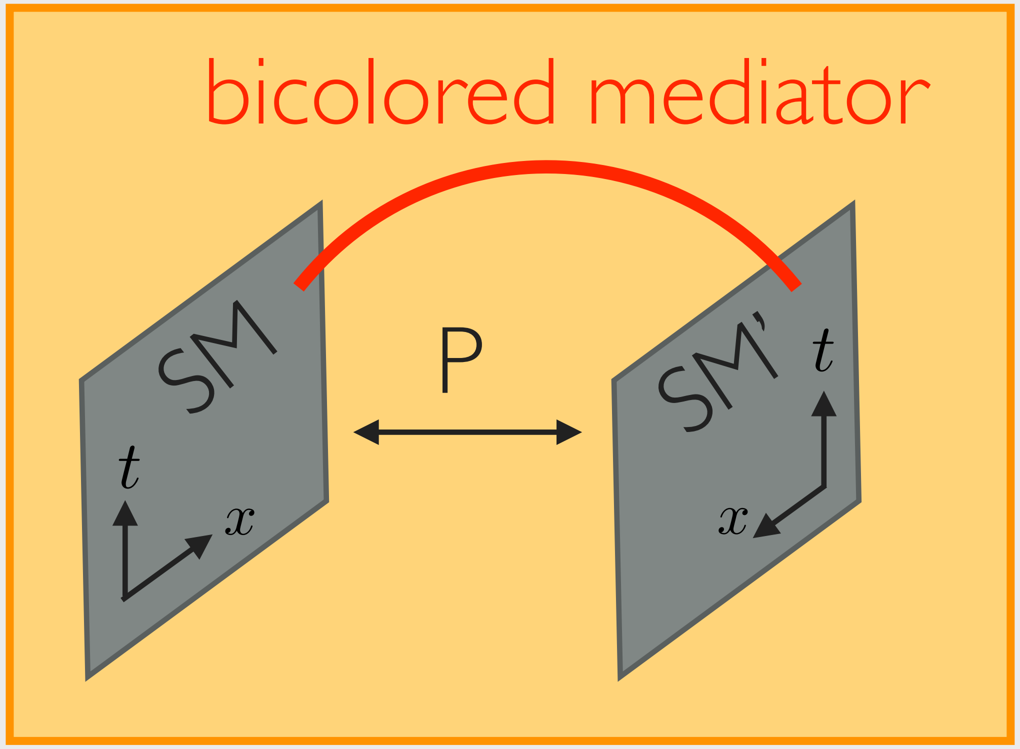
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

P

Below v_3, colored mirror quarks : need $\langle H' \rangle \gg \langle H \rangle$
(hence P-breaking)

$$Y_q = Y_{q'}^\dagger$$
$$\Longrightarrow \frac{m_q}{m_{q'}} = \frac{\langle H \rangle}{\langle H' \rangle}$$

Our parity solution to the strong CP problem



Below v_3 , colored mirror quarks : need $\langle H' \rangle \gg \langle H \rangle$
(hence P-breaking) $\quad \langle H' \rangle \equiv v'$

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	$\mathbf{1}$	$\mathbf{1}$	0
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
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e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
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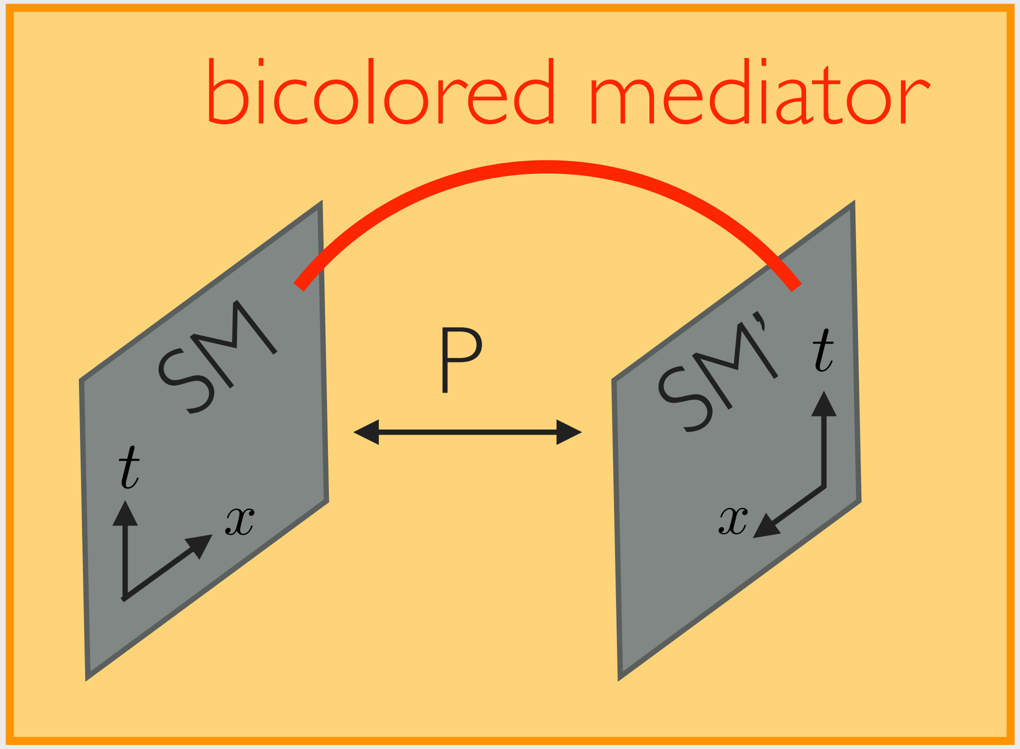
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
e'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	1
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

P

$$Y_q = Y_{q'}^{\dagger}$$

$$\implies \frac{m_q}{m_{q'}} = \frac{\langle H \rangle}{\langle H' \rangle}$$

Our parity solution to the strong CP problem



Below v_3, colored mirror quarks : need $\underbrace{\langle H'\rangle}_{= v'} \gg \langle H\rangle$

(hence P-breaking)

i.e. $v' \gtrsim 10^9\ \text{GeV}$

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	$\mathbf{1}$	$\mathbf{1}$	0
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d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
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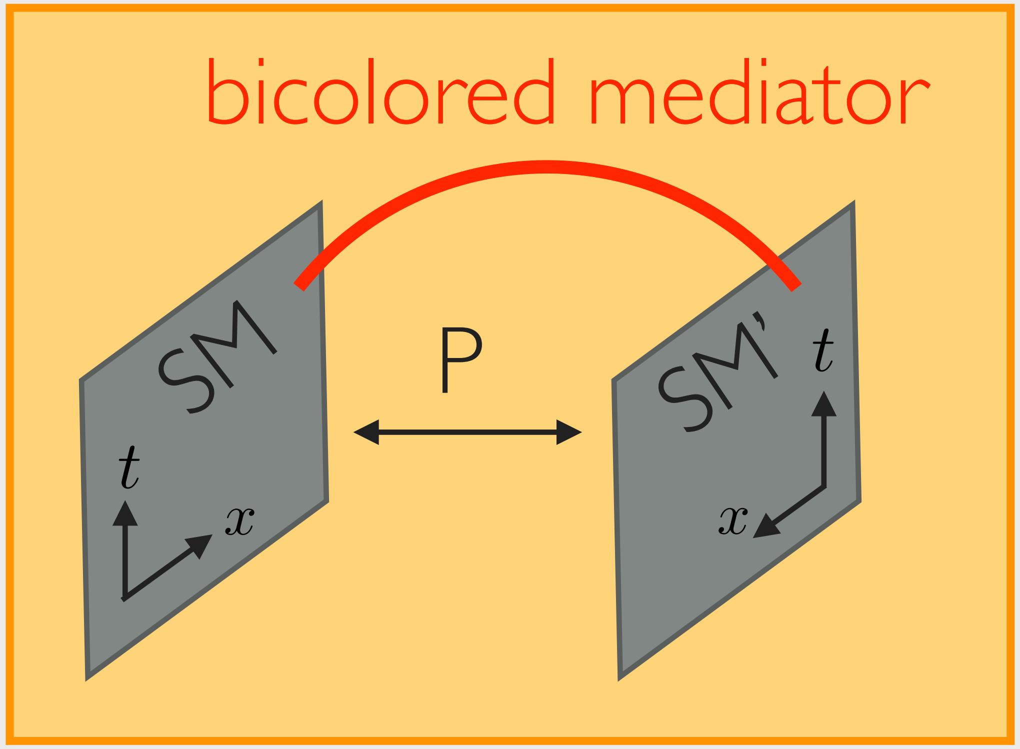
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

P

$$Y_q = Y_{q'}^{\dagger}$$

$$\Longrightarrow \frac{m_q}{m_{q'}} = \frac{\langle H\rangle}{\langle H'\rangle}$$

Our parity solution to the strong CP problem



Below v_3, colored mirror quarks : need $\langle H' \rangle \gg \langle H \rangle$
(hence P-breaking) $\equiv v'$

Achieved through soft breaking or radiative corrections

[Babu/Mohapatra '89, Hall/Harigaya '18]

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	$\mathbf{1}$	$\mathbf{1}$	0
u^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	-2/3	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	1/2	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
e'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{1}$	1
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2

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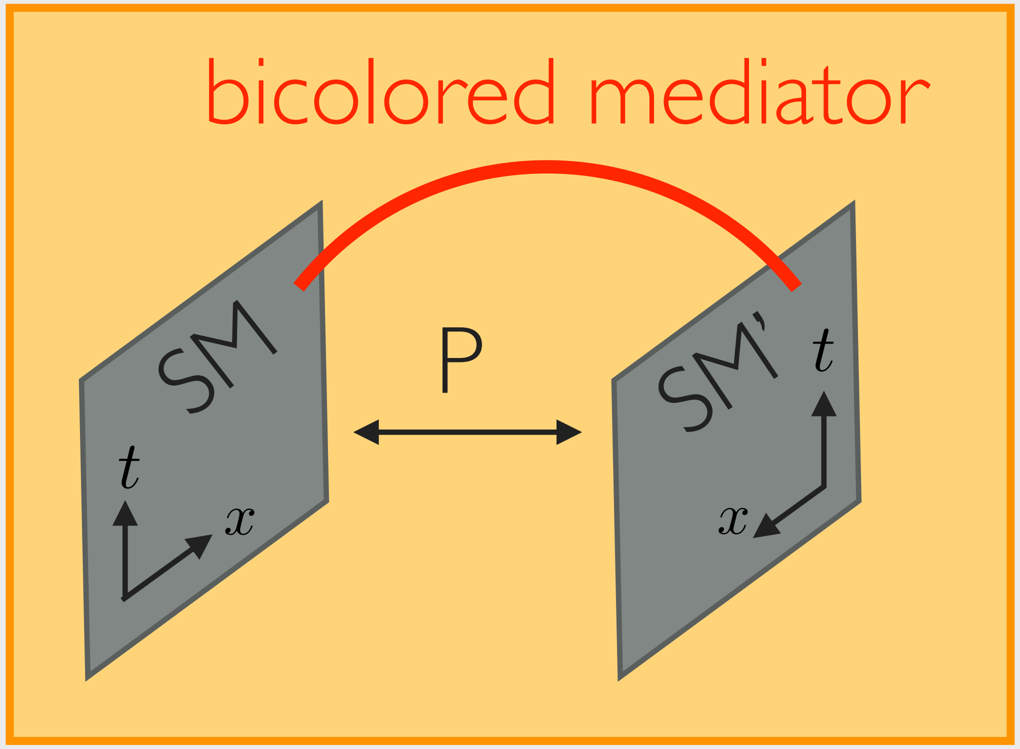

Very predictive model, two BSM scales : v_3 and v'

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
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Q'	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6
u'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	2/3
d'^c	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$\mathbf{1}$	-1/3
L'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	1/2
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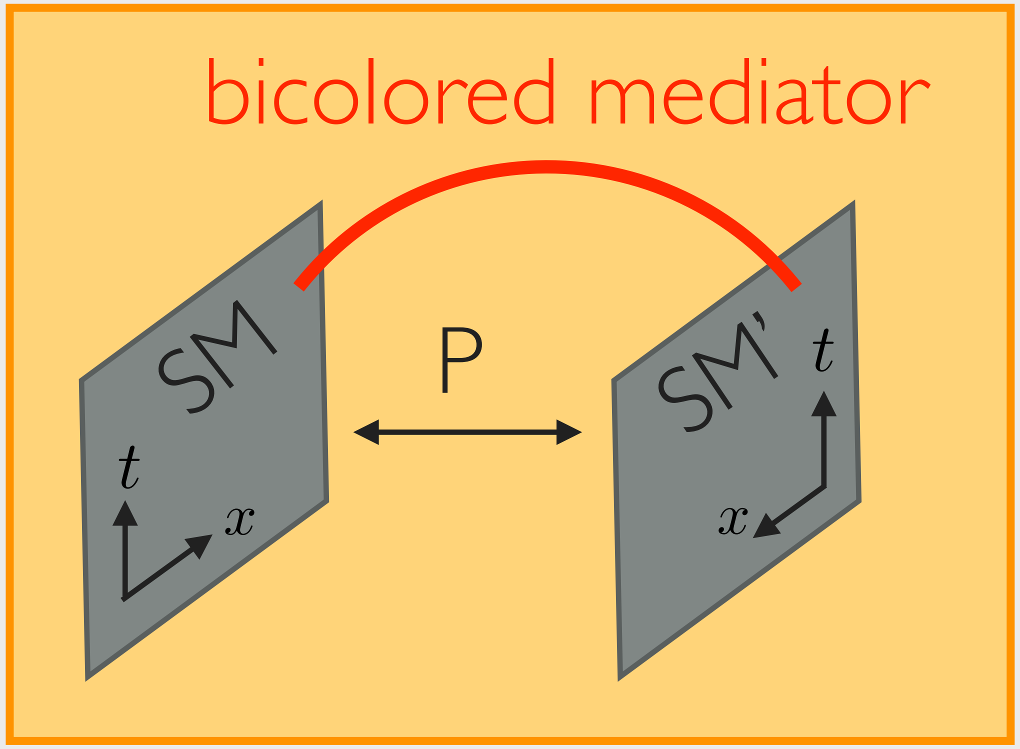

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P

Very predictive model, two BSM scales : v_3 and v'

Different pheno on the parameter space. For $v_3 \ll v'$, **colored bosons** as lightest BSM states !

$$Y_q = Y_{q'}^\dagger$$

$$\Longrightarrow \frac{m_q}{m_{q'}} = \frac{\langle H \rangle}{\langle H' \rangle}$$

Our parity solution to the strong CP problem

Bicolored mediator : a scalar or strongly interacting fermions.

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- Σ in $(\mathbf{3}, \mathbf{3}')$ of $SU(3) \times SU(3)'$

$\mathbf{3}$ or $\bar{\mathbf{3}}$

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Bicolored mediator : a scalar or strongly interacting fermions.

- Σ in $(\mathbf{3}, \mathbf{3}')$ of $SU(3) \times SU(3)'$ with potential

$\mathbf{3}$ or $\bar{\mathbf{3}}$

$$V(\Sigma) = -m^2 \mathrm{Tr}(\Sigma\Sigma^\dagger) + c\mathrm{Tr}^2(\Sigma\Sigma^\dagger) + \tilde{c}\mathrm{Tr}(\Sigma\Sigma^\dagger)^2 + (\tilde{m}\det(\Sigma) + h.c.)$$

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Breaking to the diagonal $SU(3)$ in a large fraction of parameter space

[Bai/Dobrescu '17]

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Breaking to the diagonal $SU(3)$ à la technicolor

[Weinberg '76, Susskind '78]

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  Breaking to the diagonal $SU(3)$ in a large fraction of parameter space (but no (C)P breaking) **[Bai/Dobrescu '17]**

-

	$SU(N)$	$SU(N)'$	$SU(3)$	$SU(3)'$
ψ_L	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$
ψ_R	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}'$
ψ'_L	$\mathbf{1}$	$\mathbf{N}$	$\bar{\mathbf{3}}$	$\mathbf{1}$
ψ'_R	$\mathbf{1}$	$\mathbf{N}$	$\mathbf{1}$	$\bar{\mathbf{3}}'$

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ψ'_R	$\mathbf{1}$	$\mathbf{N}$	$\mathbf{1}$	$\bar{\mathbf{3}}'$

P for $\mathbf{3}'{=}\mathbf{3}$

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Our parity solution to the strong CP problem

? Need $\bar{\theta} \approx 0$ even **below the scale of parity breaking**

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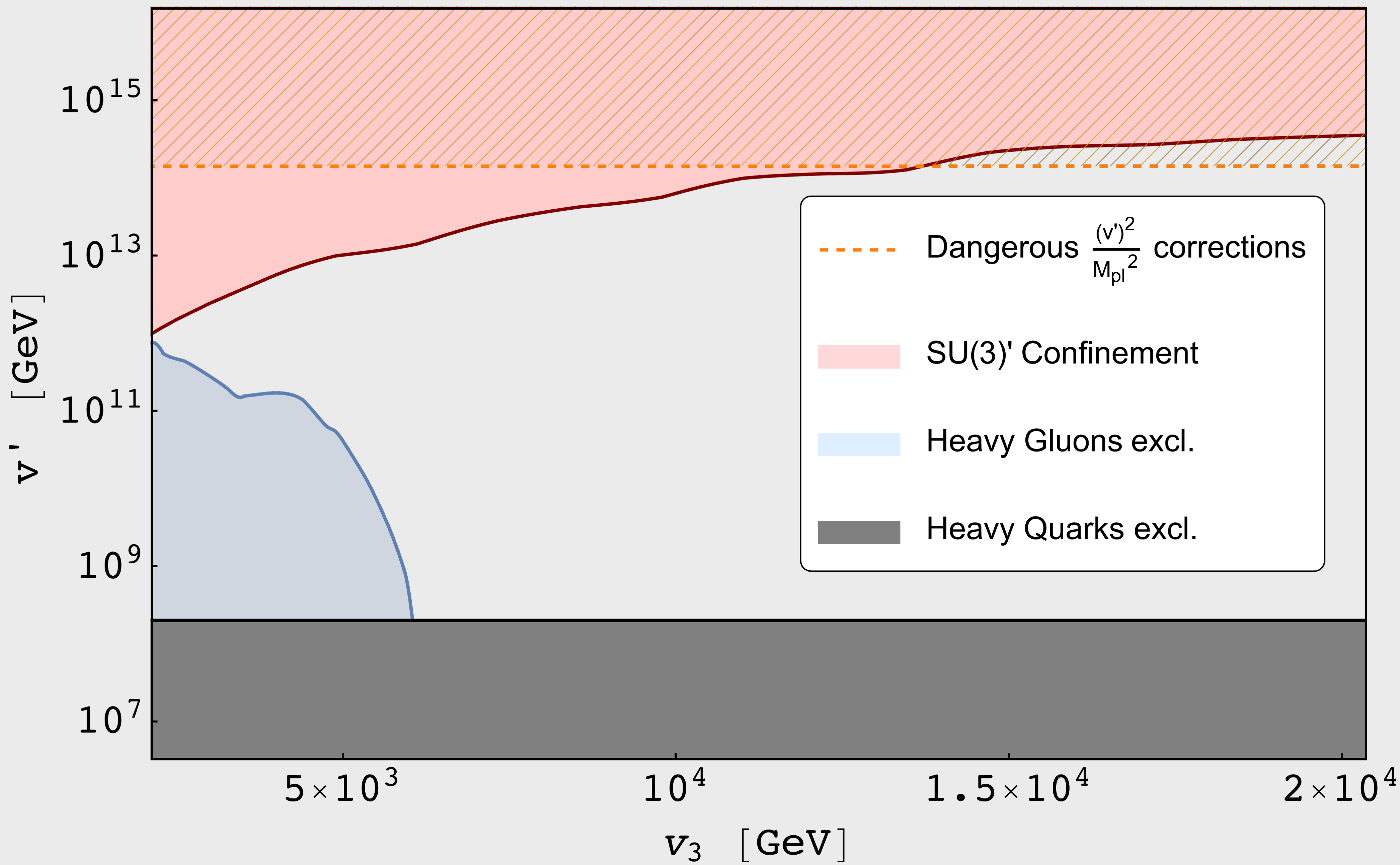
Only mediators: gluons, bicolored mediator or heavy Higgs. Only CP phase: CKM. **Very small contributions** (at least 3-loops) **to** $\bar{\theta}_{\mathrm{QCD}}$. Effect of small instantons also suppressed

Our parity solution to the strong CP problem



(scalar mediator)

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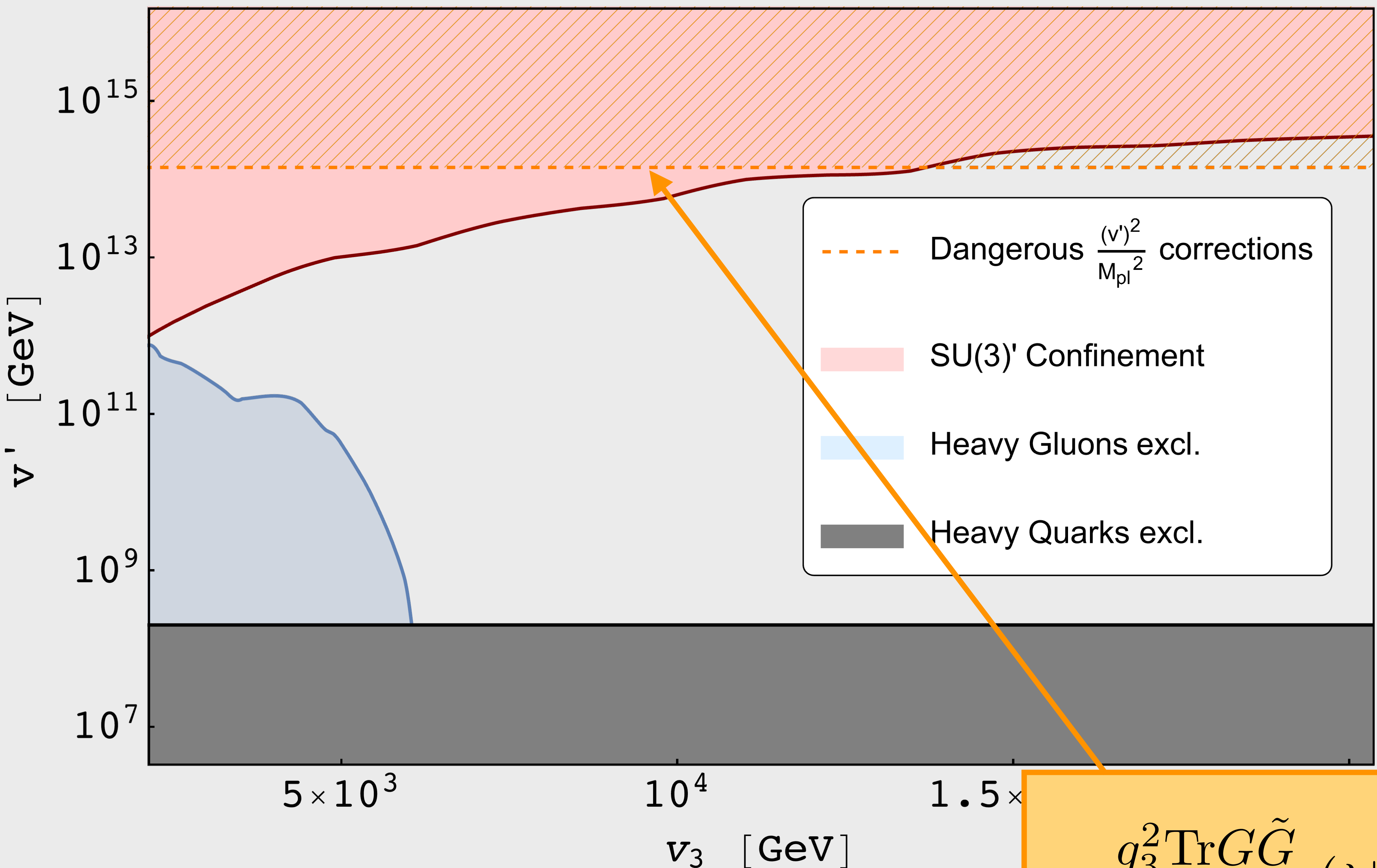

(scalar mediator)

$$\frac{g_3^2 \mathrm{Tr} G\tilde{G}}{16\pi^2 M_P^2}\left(\lambda|H|^2 + \lambda'|H'|^2\right)$$
$$-\,(g_3, G, H \leftrightarrow g_3', G', H')$$

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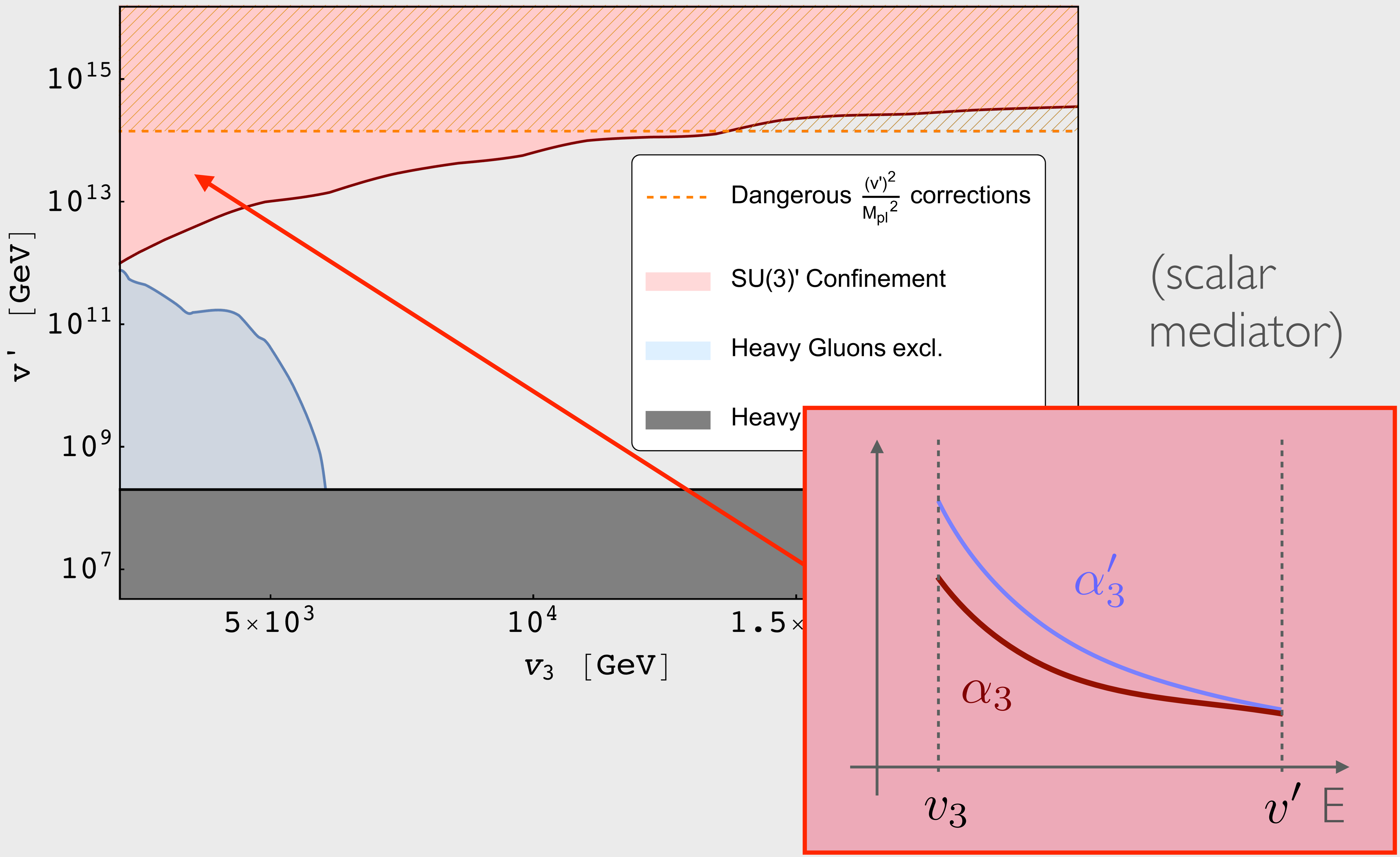

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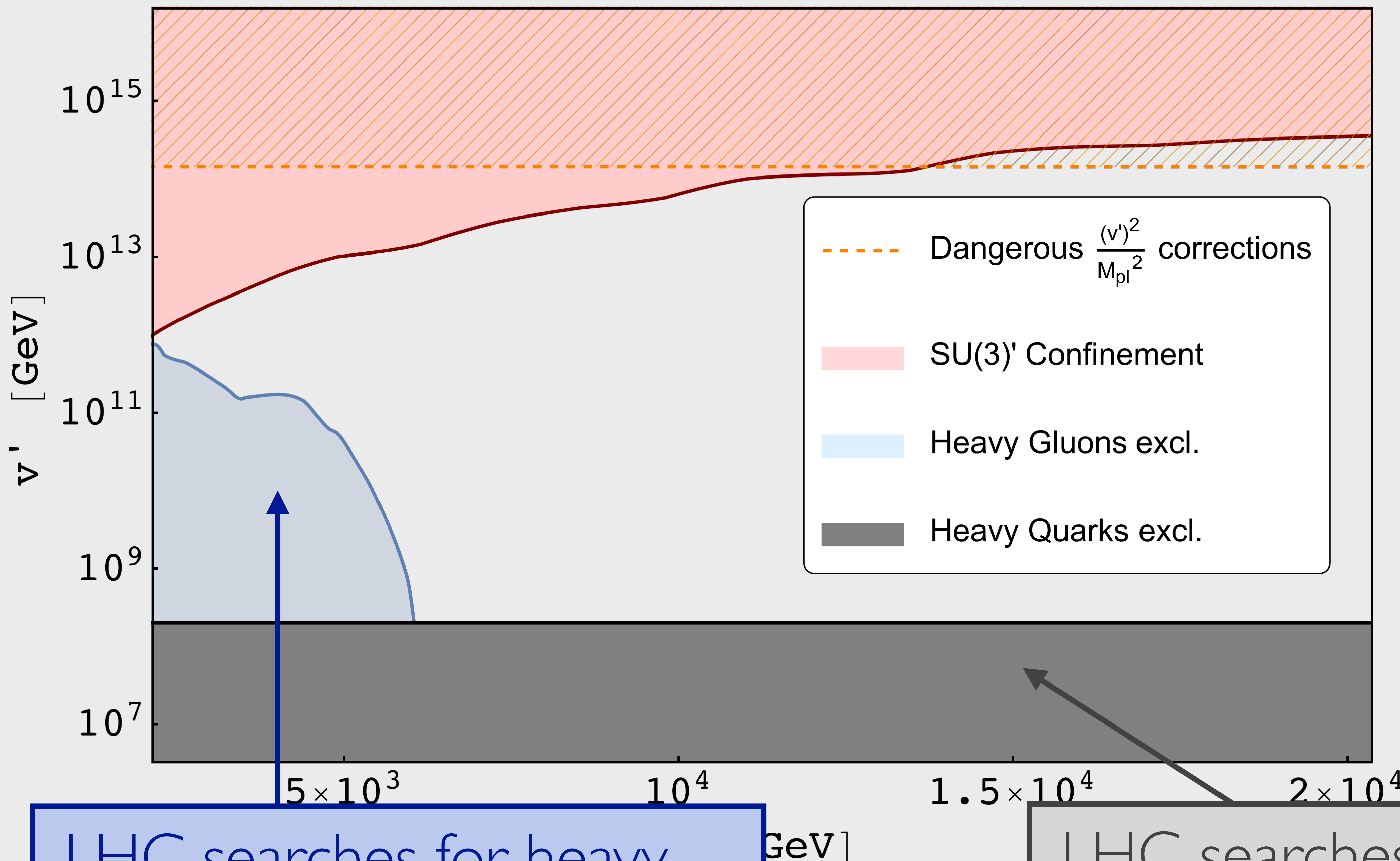
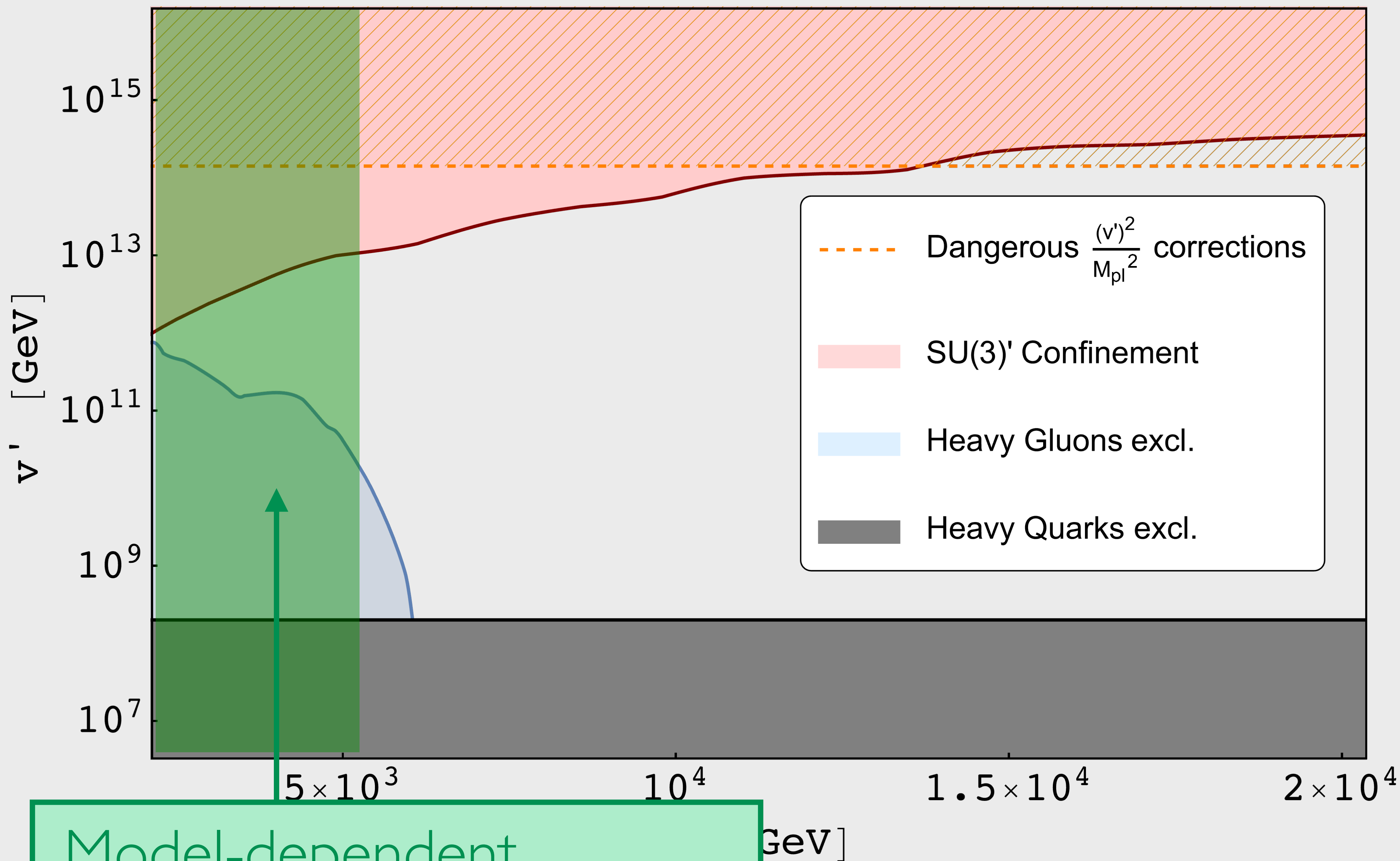


(scalar mediator)

LHC searches for heavy vector octets (decay to quarks)

LHC searches for stable colored neutral particles (hadronize and ionize)

Our parity solution to the strong CP problem



Model-dependent bounds on colored scalars

(scalar mediator)

Dark matter from the mirror world

Dark matter from the mirror wo

w.i.p.

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Many new particles, mirror B and L quantum numbers…
dark matter candidates !

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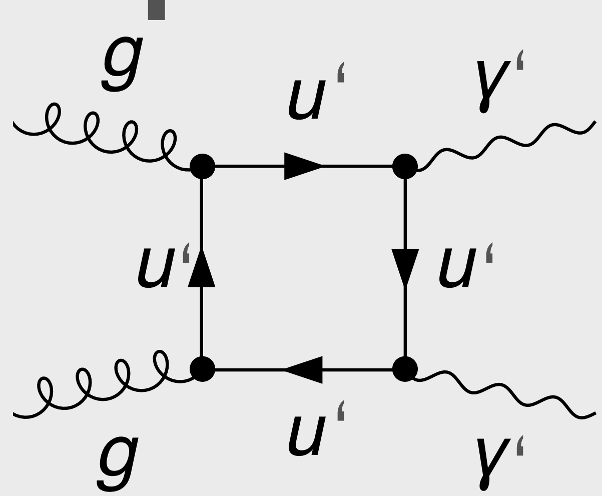
Sequential freeze-in from the mirror photon

**[Hambye/Tytgat/Vandecasteele/Vanderheyden ’18,
Bélanger/Delaunay/Pukhov/Zaldivar ’19]**



then $\gamma'\gamma' \to e'\bar{e}'$

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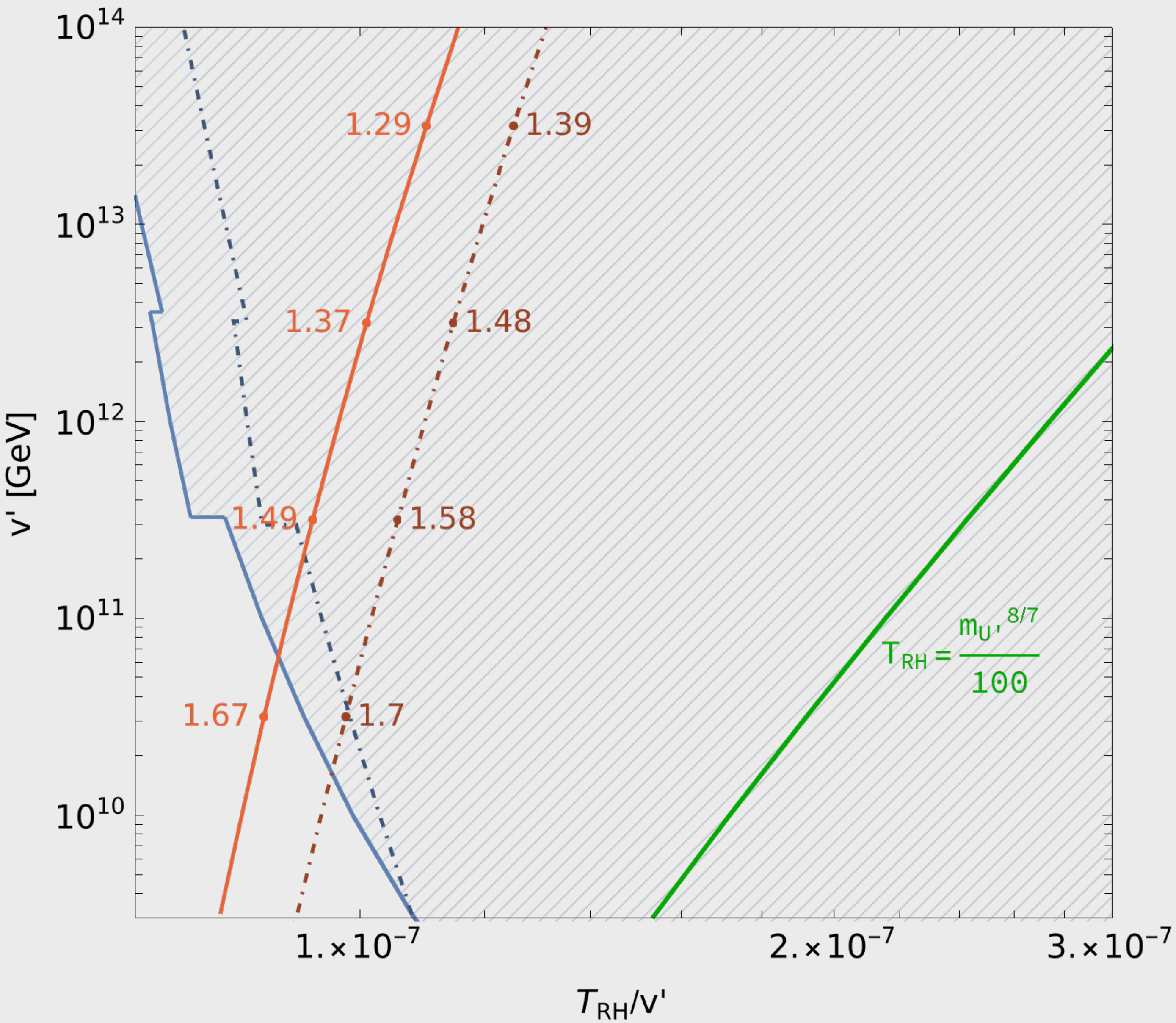

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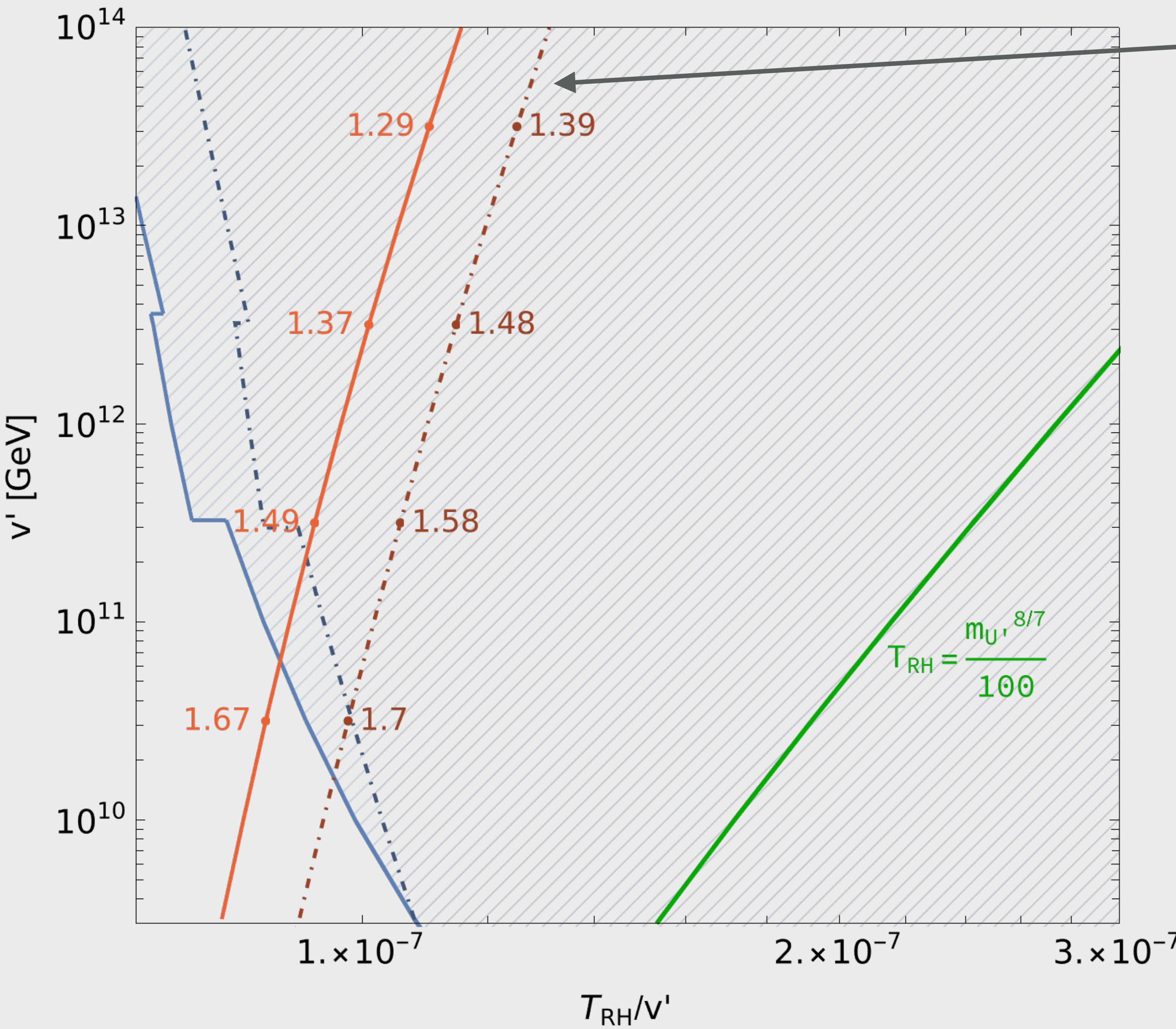

Successful mirror electron freeze-in with color breaking before parity breaking

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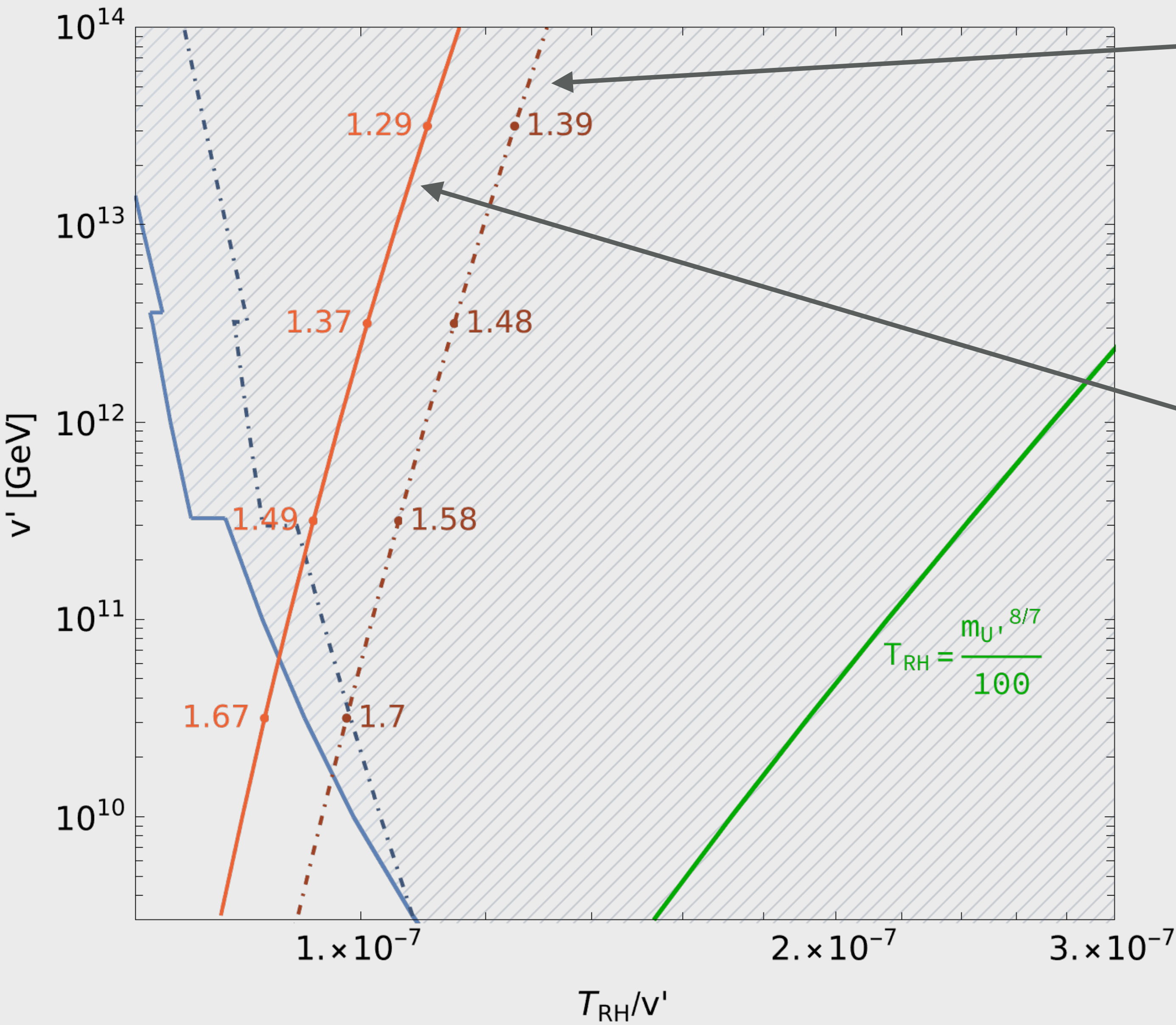

Successful mirror electron freeze-in with color breaking before parity breaking

… with lowest possible scale of color breaking

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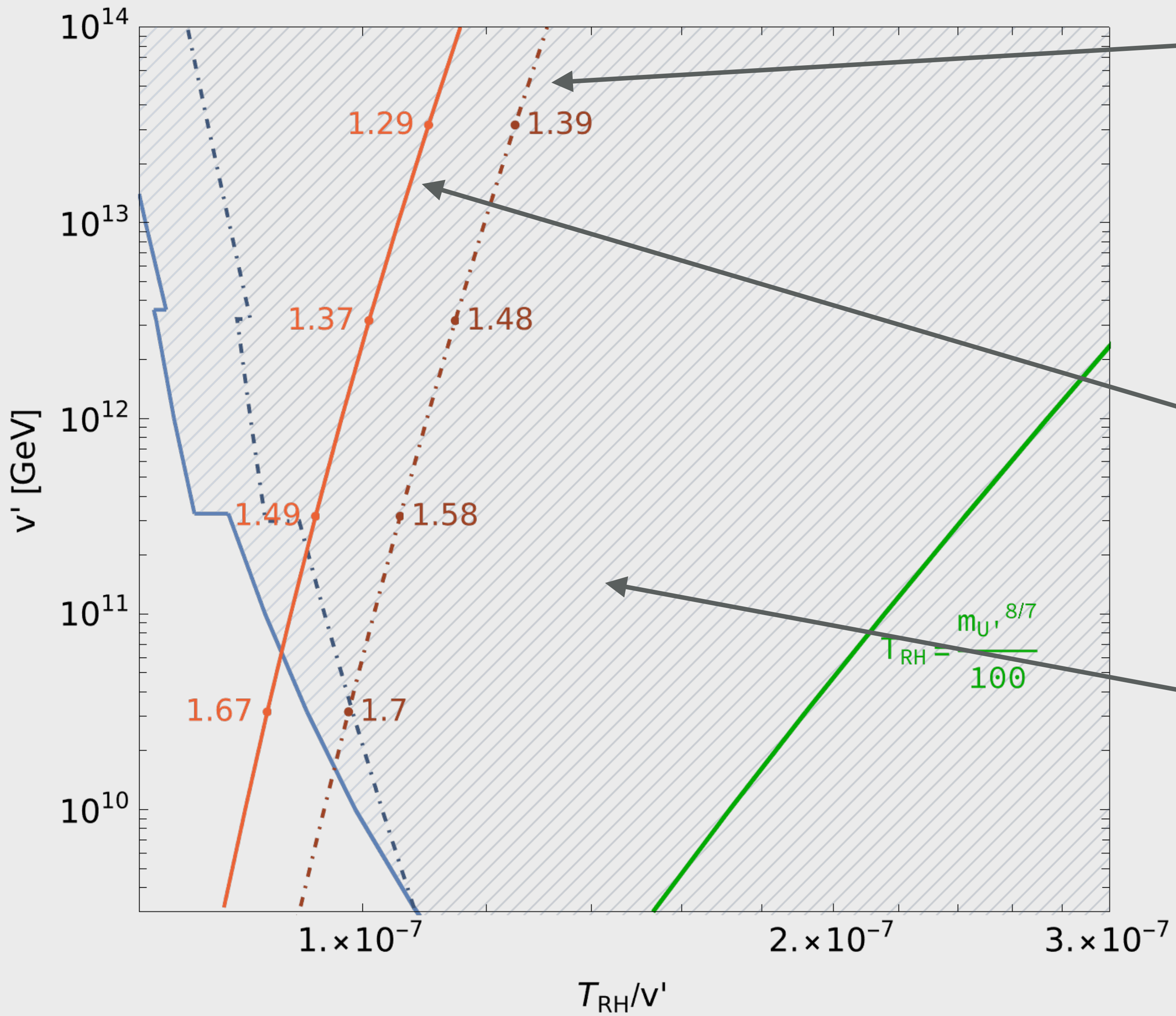

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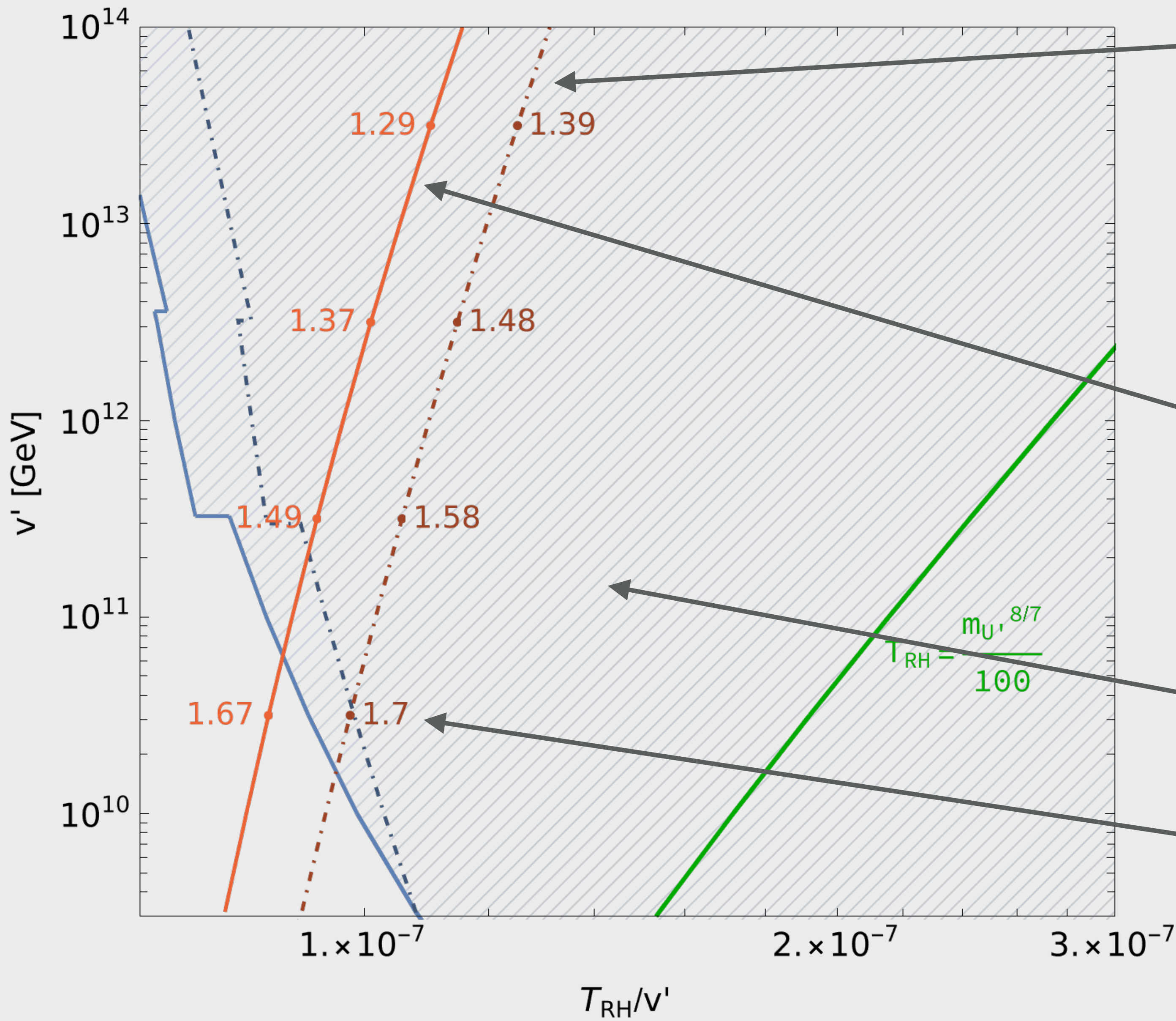

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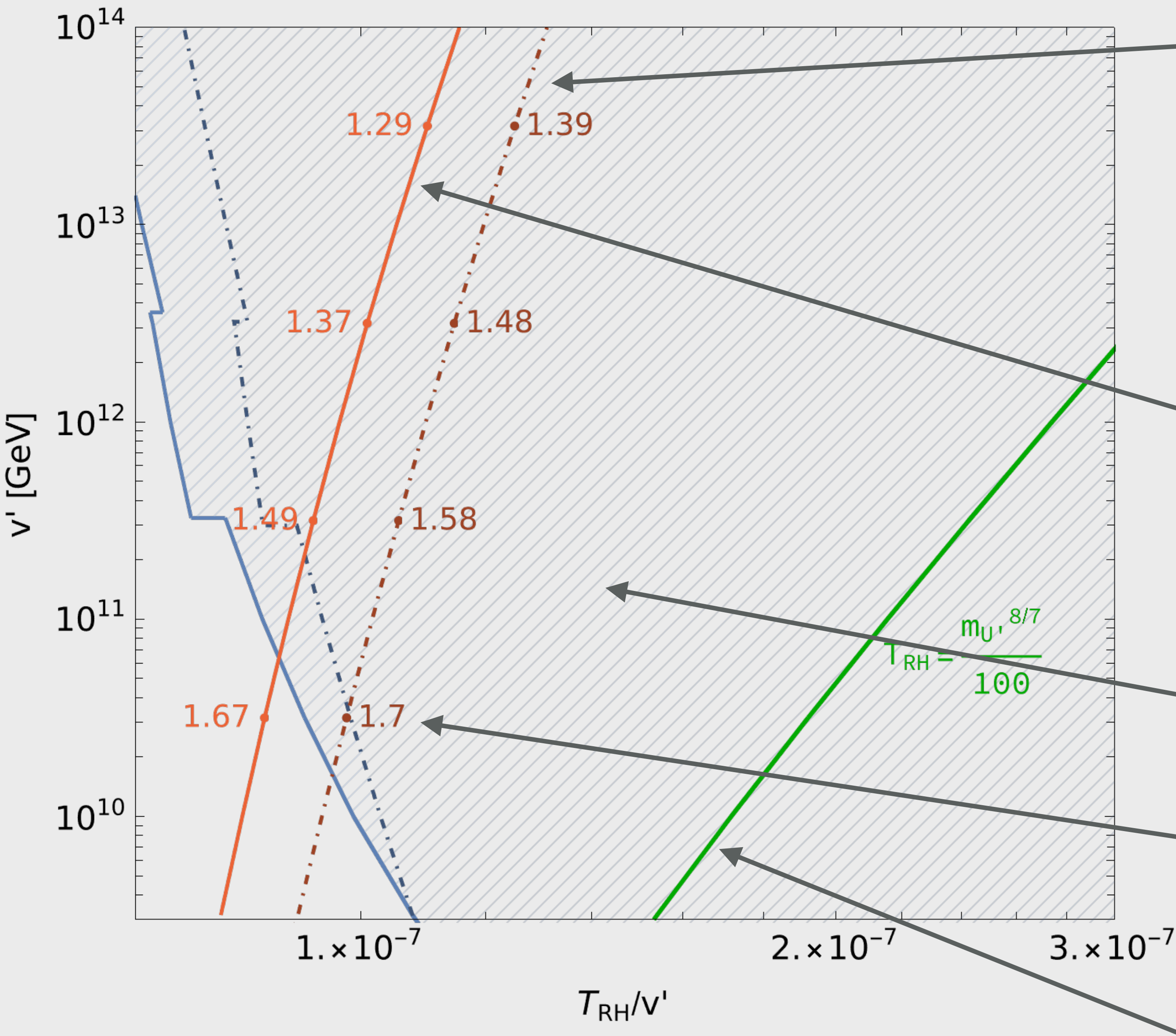

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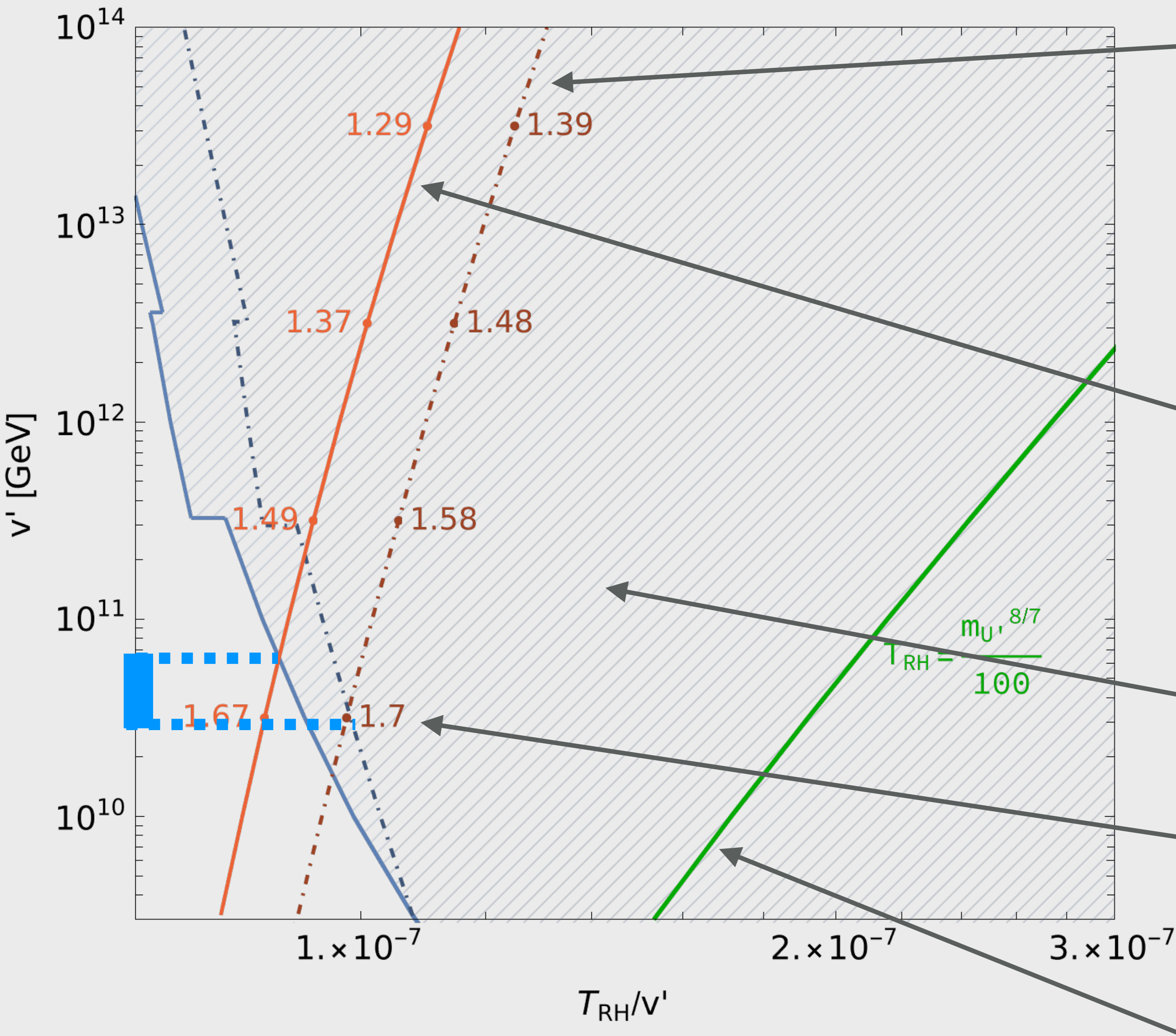

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first interest of low v_3

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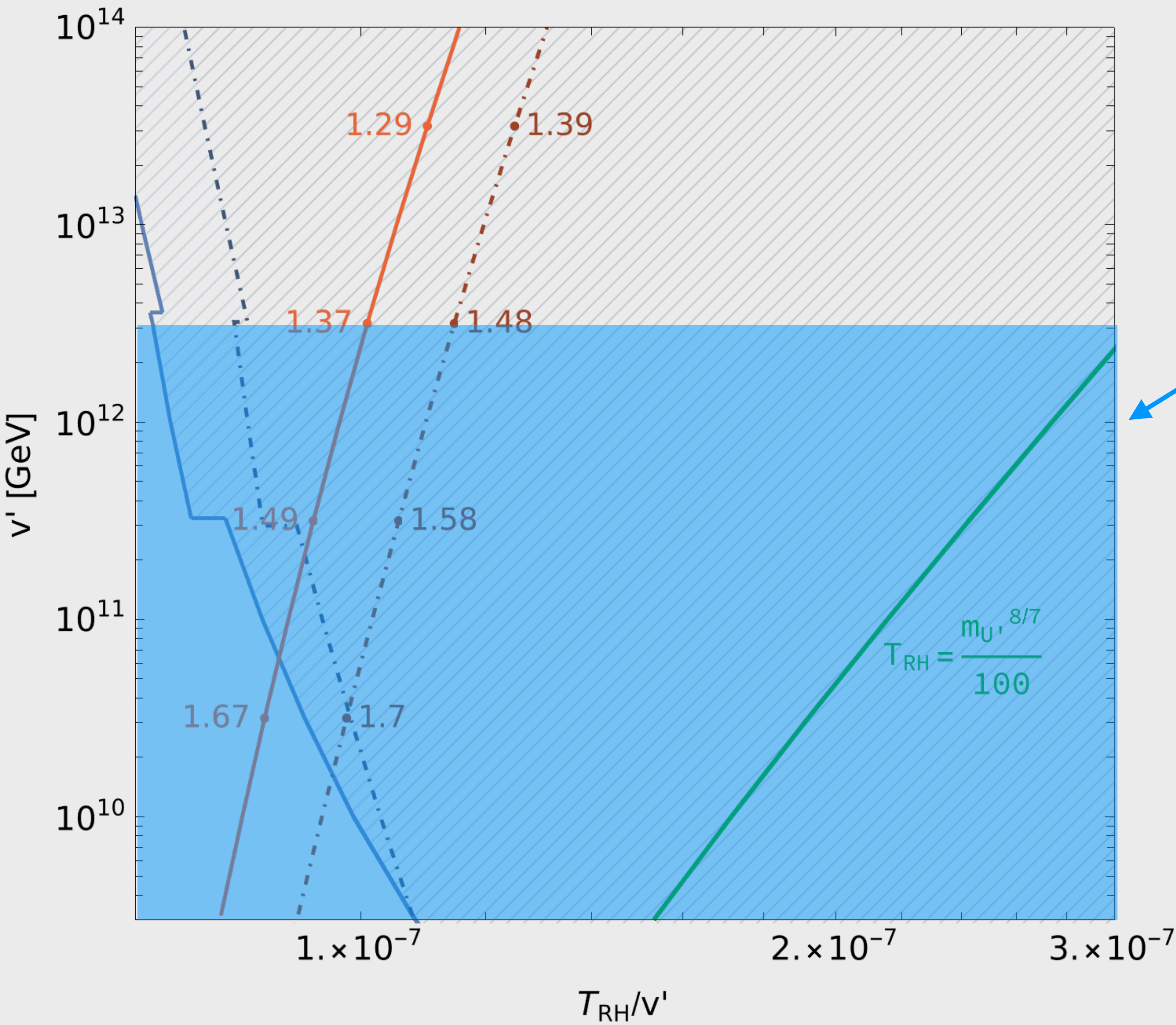

excluded by irreducible kinetic mixing and direct detection

main interest of low v_3

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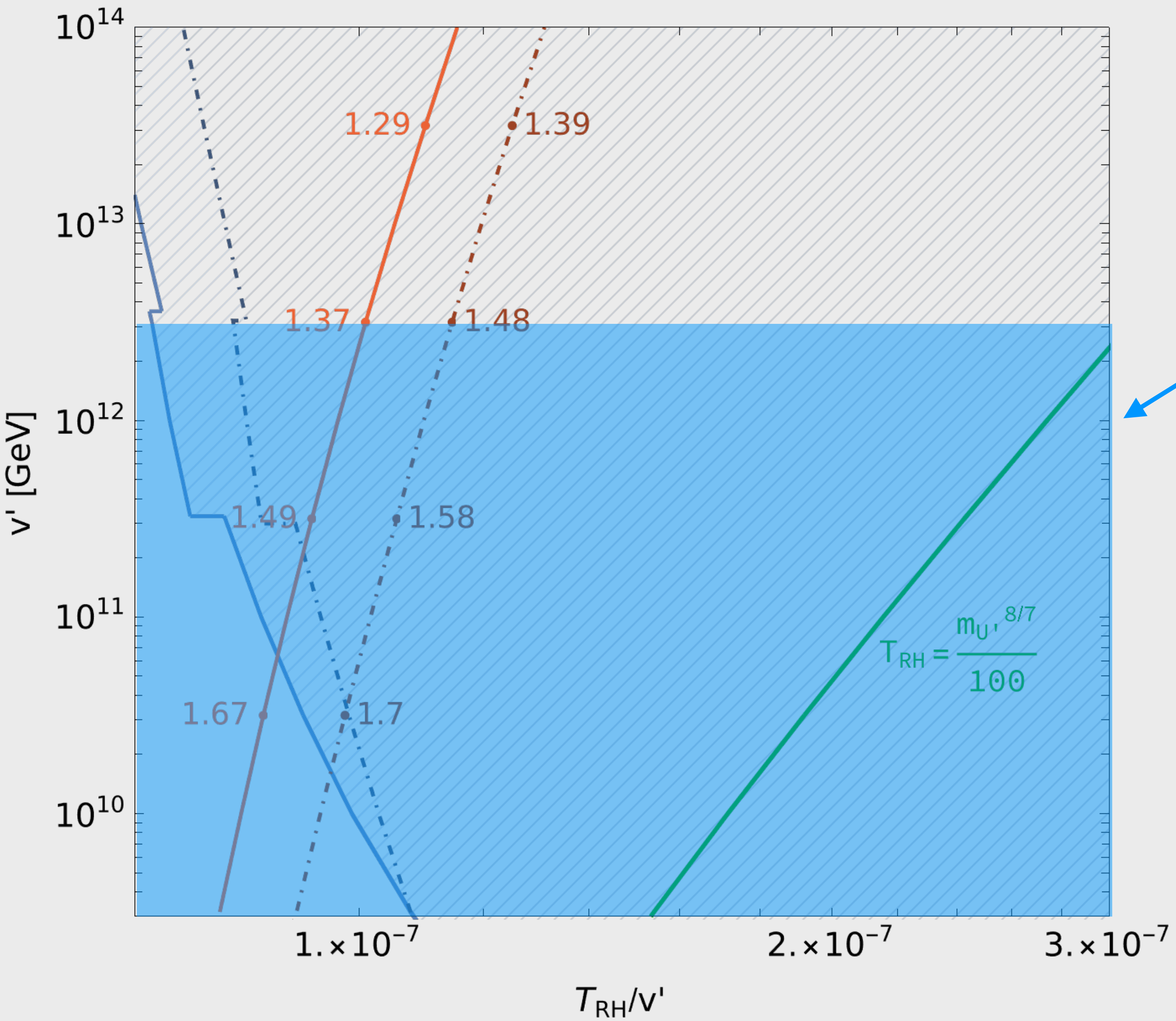

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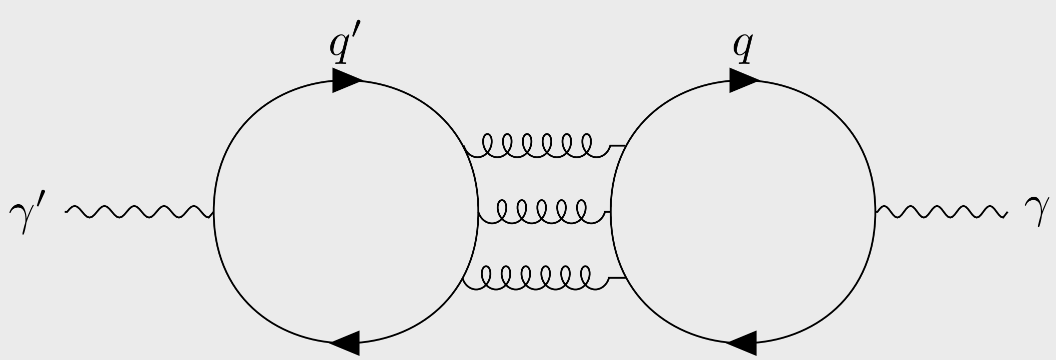
$$m_{u'} < v_3$$



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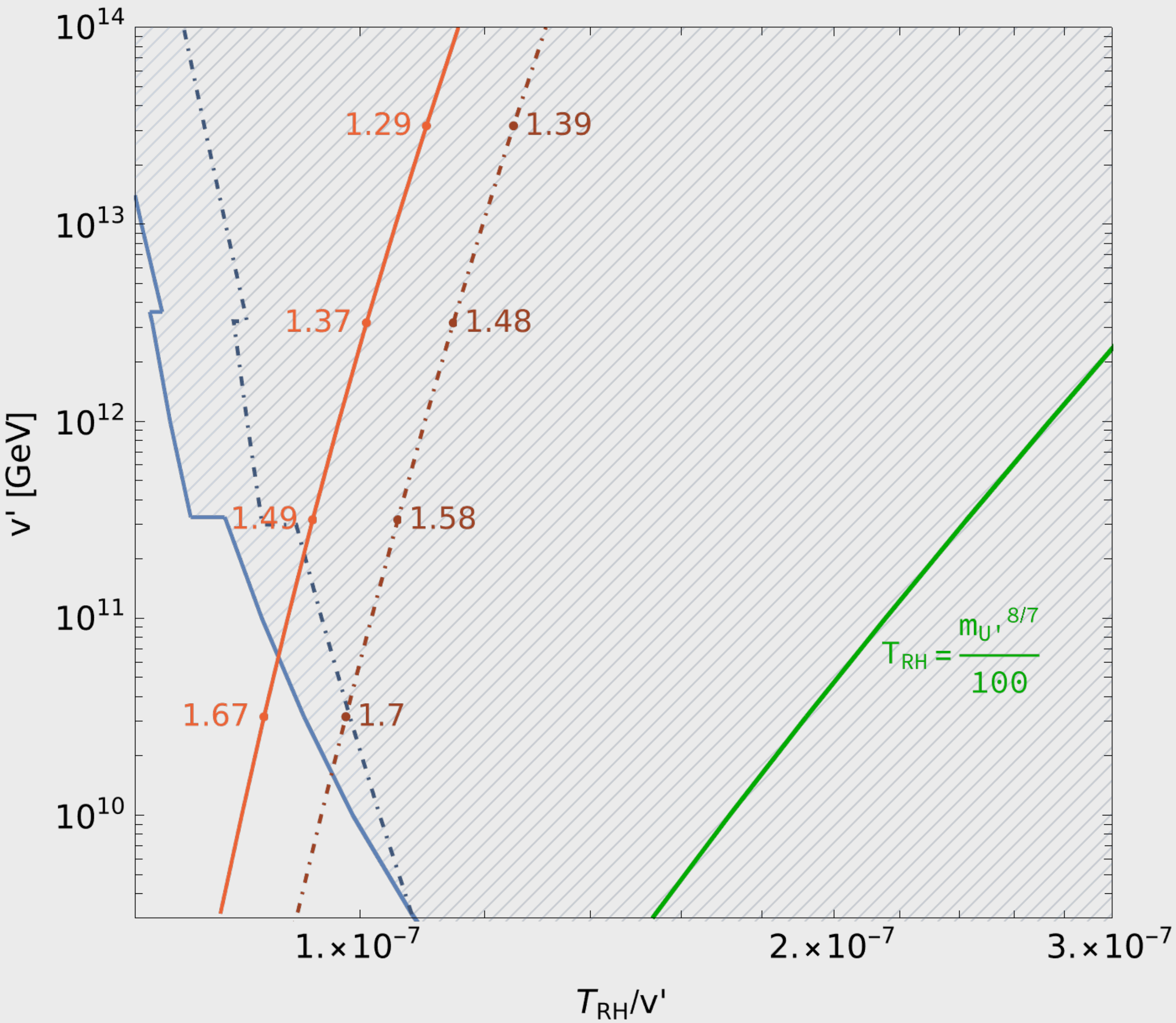

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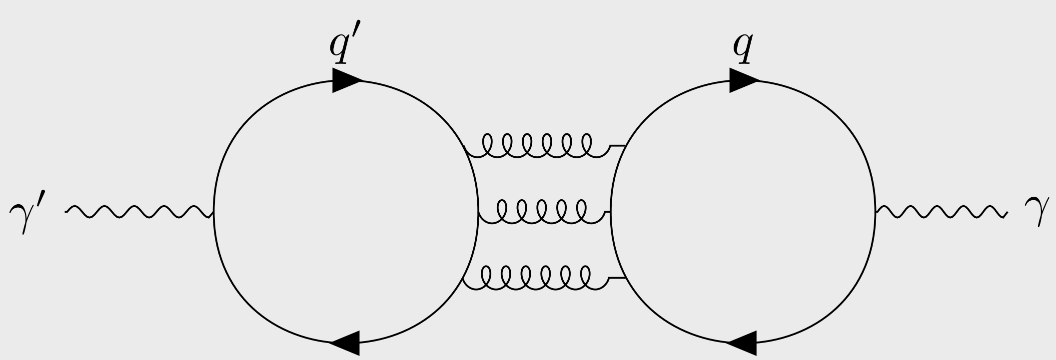

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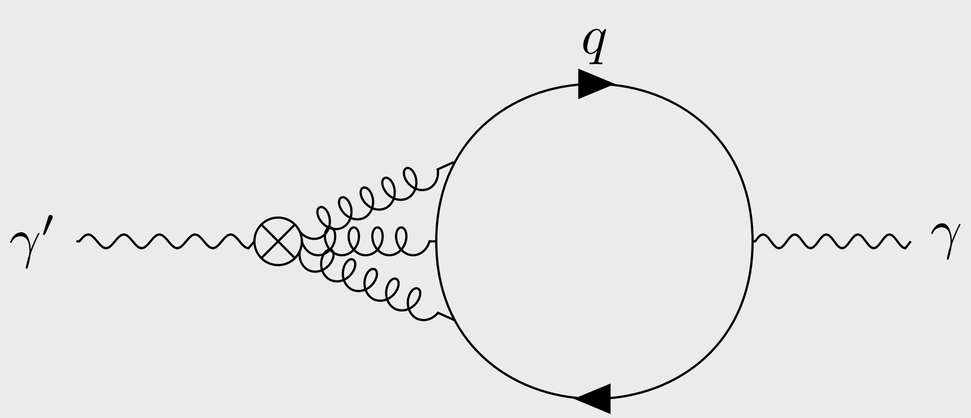

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Outlook

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First study of a **parity solution to the strong CP problem in a « complete » mirror world** (a « UV solution »)

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Corrections to $\bar{\theta}_{\rm QCD}$ very much under control

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Few free parameters, but quite different physics in the parameter space !

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There is room for a **thermal dark matter candidate** !
Possible companion signals

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THANK YOU

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Solutions to the strong CP problem

Need for UV input for the axion solution :

axion quality problem **[Georgi/Hall/Wise ’81, Barr/Seckel ’92, Holman/Hsu/Kolb/Watkins/Widrow ’92, Kamionkowski/March-Russell ‘92]**

No global symmetries :

$$\mathcal{L}_{\not{PQ}} = \frac{\delta m_a^2}{2} a^2 \quad \text{with} \quad \delta m_a^2 \xrightarrow[M_P \to \infty]{} 0$$

Need $\boxed{\dfrac{\delta m_a^2}{m_a^2} \lesssim 10^{-10}}$

$$\mathcal{L}_{\not{PQ}} = \frac{c_{\not{PQ}}}{M_P^{n-4}} \phi^n + h.c.$$

$\phi \sim f_a e^{ia/f_a}$

could be $M_P^m \Lambda_h^{n-m-4}$

[QB ’22]

Need to understand physics all the way to M_P

… without IR impact

An effective field theorist’s nightmare (bis)