A colorful mirror solution to the strong CP problem

Quentin Bonnefoy
UC Berkeley & LBNL

L2C & LUPM — Montpellier
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with L. Hall, C. A. Manzari & C. Scherb
2303.06156 [hep-ph]

The strong CP problem

$$\mathcal{L}_{\rm SM} \supset \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

Total derivative : invisible in perturbation theory

But non-perturbative effects !

In particular, **neutron electric dipole moment** (EDM)

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

$$\mathcal{L}_{\rm EDM} \supset \frac{i d_n}{2} \bar{n} \gamma_5 \gamma_{\mu\nu} n F^{\mu\nu}$$

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measured to be
$\lesssim 10^{-12}\, e\, \mathrm{GeV}^{-1}$

[Pendlebury et al '15]

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

Strong CP problem :

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

predicted to be

$\approx 10^{-2} \bar{\theta}\, e\, \mathrm{GeV}^{-1}$

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The strong CP problem

$$\mathcal{L}_{\rm SM} \supset \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

Even worse : valid in the basis where **all fermion masses are real**

Before EW symmetry breaking :

$$\mathcal{L}_{\rm SM} \supset \frac{g_s^2 \theta}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} + \bar{Q}_L Y_u u_R \tilde{H} + ...$$

$$\bar{\theta} = \theta + \arg\det(Y_u Y_d)$$

Two unrelated quantities cancel almost perfectly !

Solutions to the strong CP problem

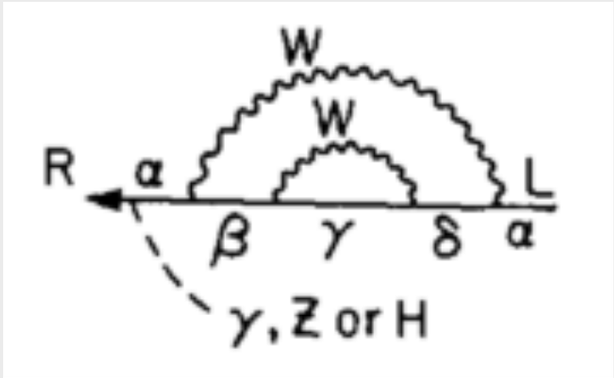
$$\mathcal{L}_{\rm SM} \supset \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

How to get $\bar{\theta} \approx 0$?

An effective field theorist's nightmare !

- non-decoupling contributions at all scales
- barely regenerated by renormalization group flow

[Ellis/Gaillard '79]



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An effective field theorist's nightmare ! IR solutions.

Make it unphysical	Make it dynamical
$\bar{\theta} = \theta + \arg\det(Y_u Y_d)$ Massless quark : ambiguous ! **['t Hooft '76]**	$\mathcal{L} \supset \frac{g_s^2}{16\pi^2} \frac{a}{f_a} G\tilde{G}$ **[Peccei/Quinn '77, Weinberg '78, Wilczek '78]**
Chiral sym. breaking : spurion $\theta - \langle \eta' \rangle$	Spurion $\bar{\theta} - \langle a \rangle / f_a$
Relaxes to zero ! **[di Vecchia/Veneziano '80, Vafa/Witten '84]**	Relaxes to zero !
Disfavored by lattice… **[Aoki et al '16]**	

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Non-minimal model building

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Make it zero

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

Parity solutions to the strong CP problem

(C)P is not a symmetry of the SM ! Spontaneous breaking

CP : $\langle \phi \rangle \in \mathbb{C}$

[Nelson '84, Barr '84]

Parity solutions to the strong CP problem

P is not a symmetry of the SM ! Spontaneous breaking

$$Q_L(\mathbf{3},\mathbf{2},1/6)$$
$$u_R(\mathbf{3},\mathbf{1},2/3)$$
$$d_R(\mathbf{3},\mathbf{1},-1/3)$$

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New fermions ? New gauge fields ?

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masses ?

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$$Q_L(\mathbf{3},\mathbf{2},\mathbf{1},1/6)$$
$$Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix} (\mathbf{3},\mathbf{1},\mathbf{2},1/6)$$

$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)$

same +

$$Q_R(\mathbf{3},\mathbf{2},1/6)$$
$$d_L(\mathbf{3},\mathbf{1},-1/3)$$
$$u_L(\mathbf{3},\mathbf{1},2/3)$$

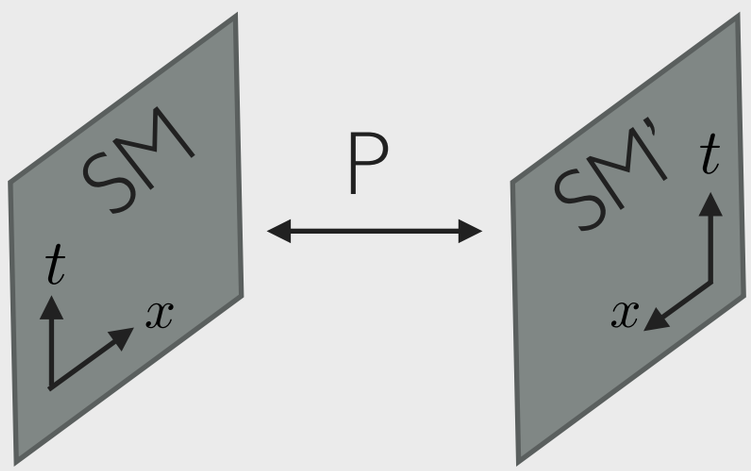
too light !

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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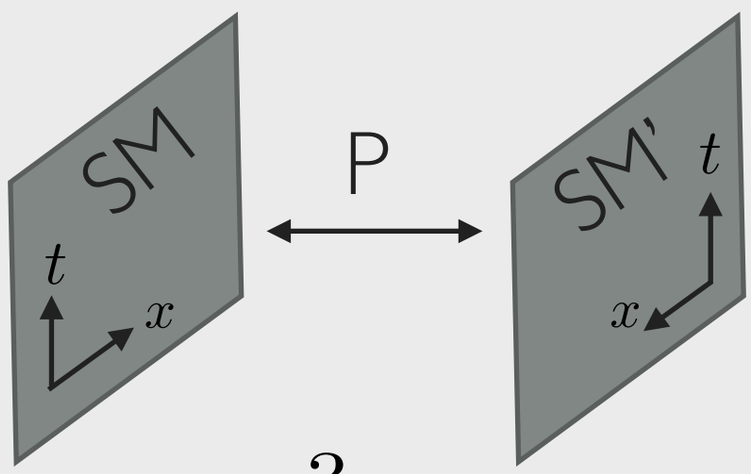
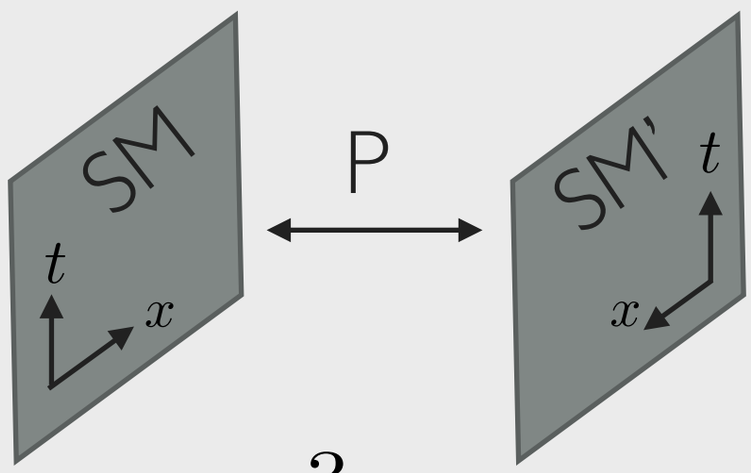


$$\langle H \rangle \stackrel{?}{=} \langle H' \rangle$$

Parity solutions to the strong CP problem

Mirror world and strong CP

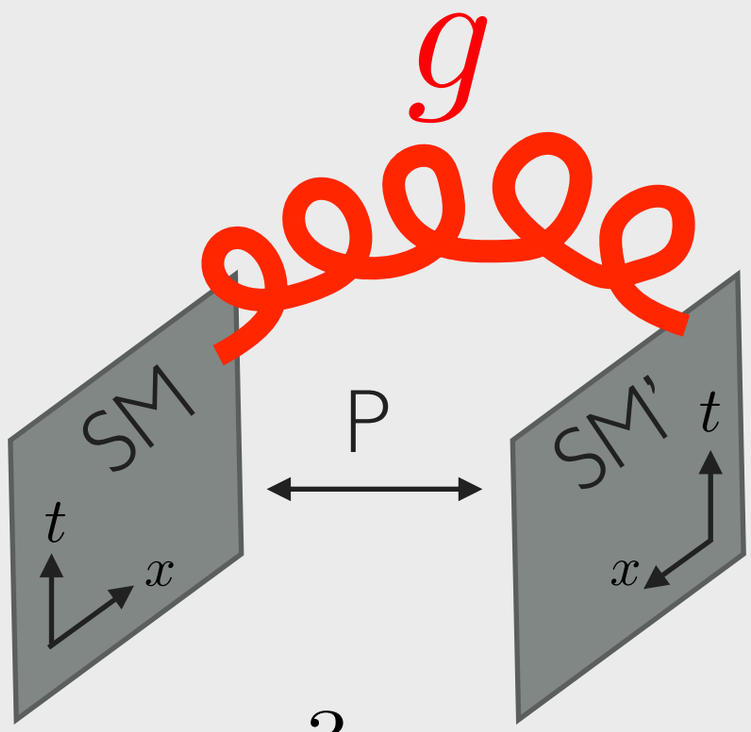


$$\langle H \rangle \stackrel{?}{=} \langle H' \rangle$$

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

Parity solutions to the strong CP problem

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



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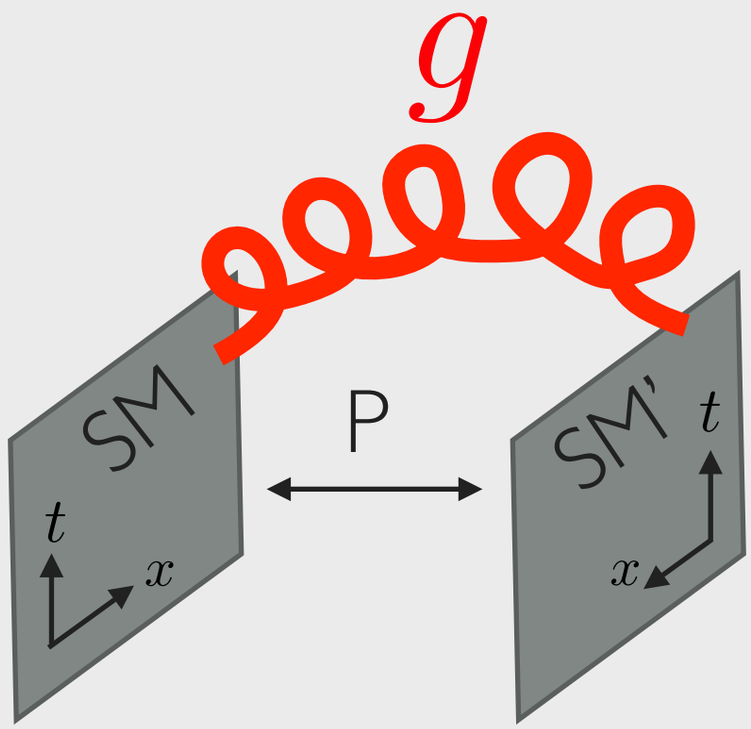

$$\langle H \rangle \neq \langle H' \rangle$$

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

Parity solutions to the strong CP problem

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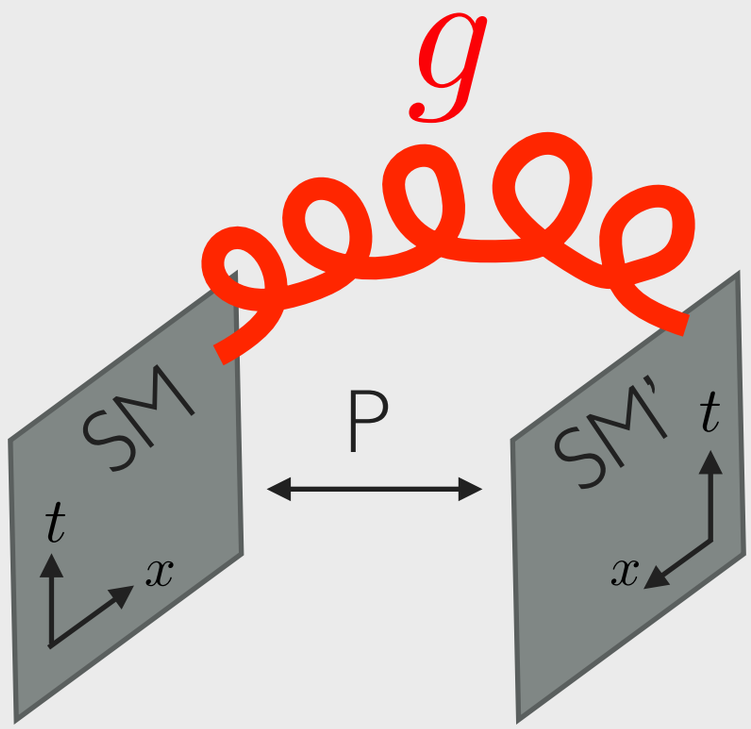

$$\langle H \rangle \neq \langle H' \rangle$$

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

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**

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

We notice that

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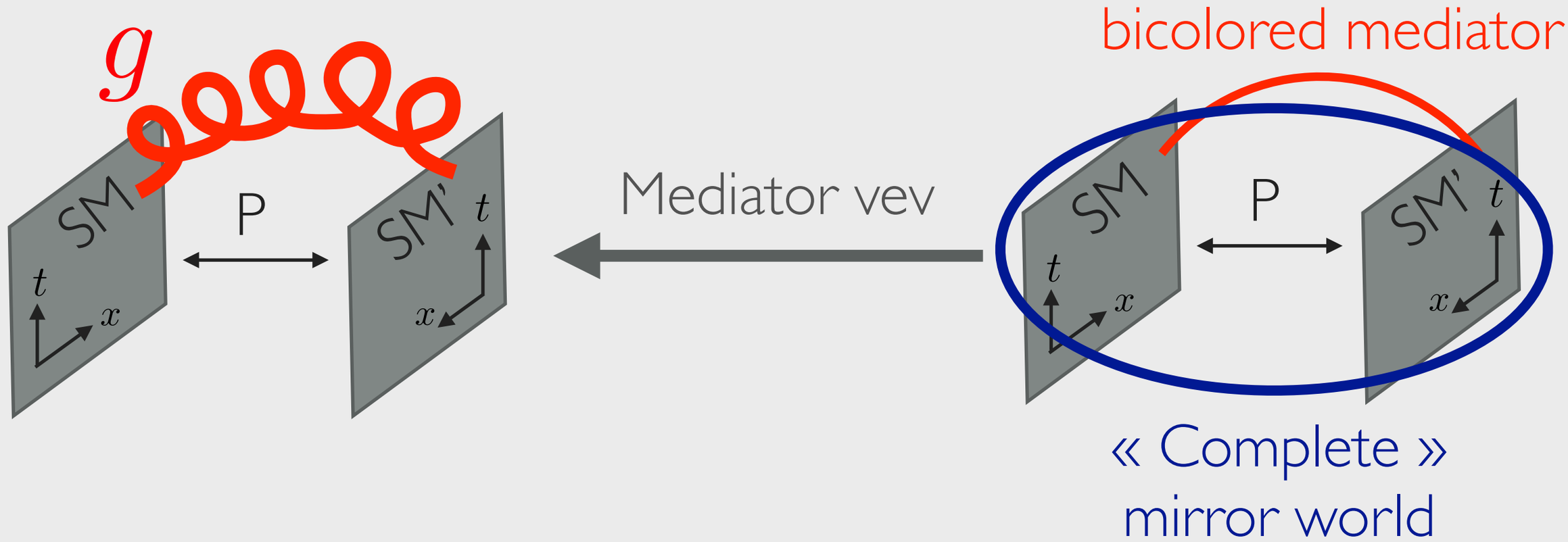

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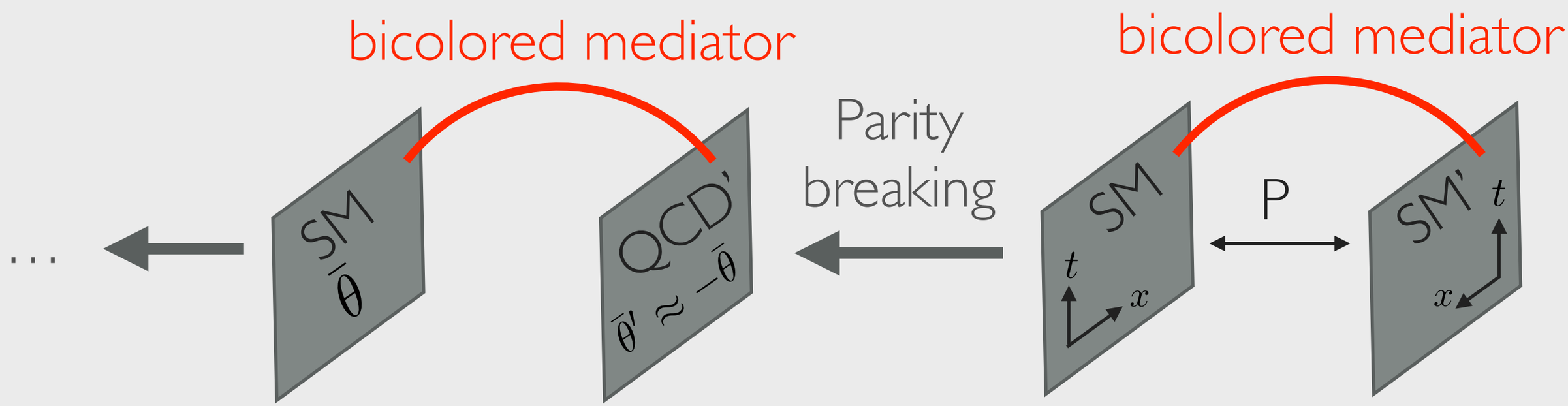
With the same starting point :



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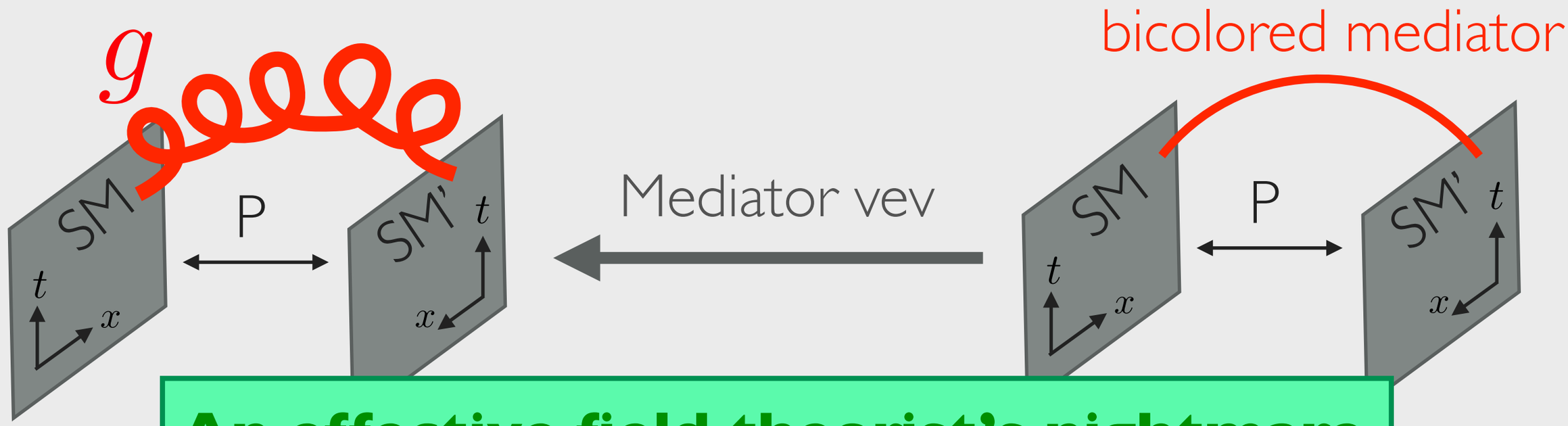

An effective field theorist's nightmare

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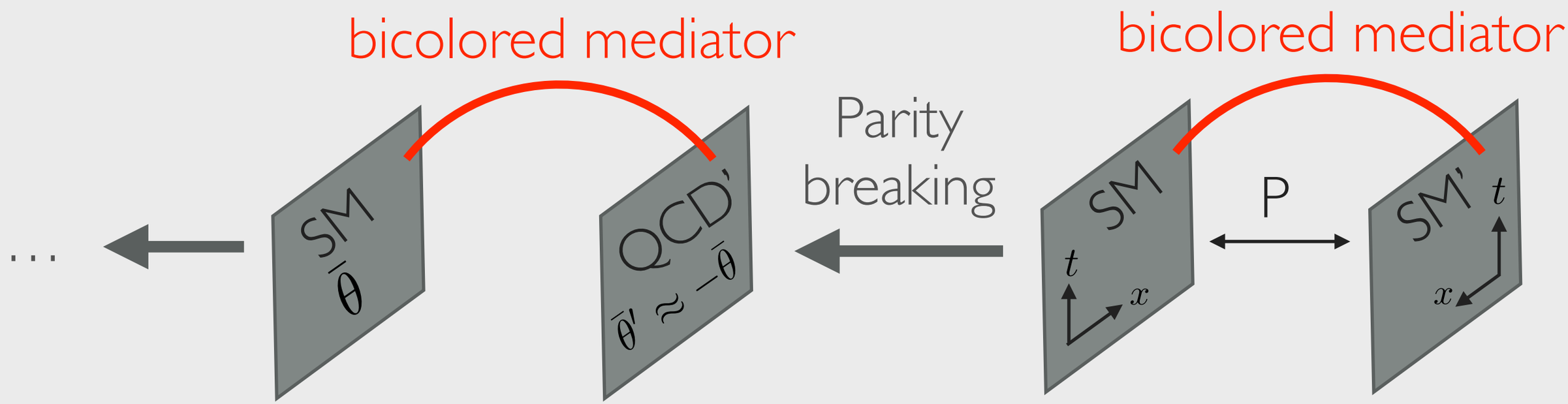

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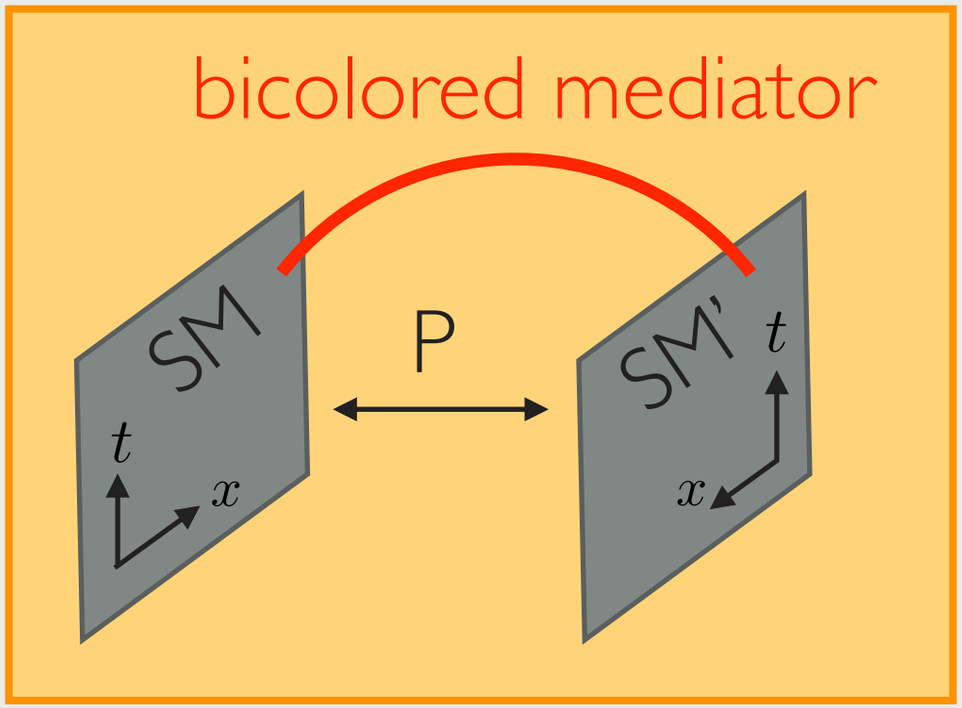

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{1}$	$\mathbf{1}$	0
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e^c	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0
Q'	$\mathbf{1}$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

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

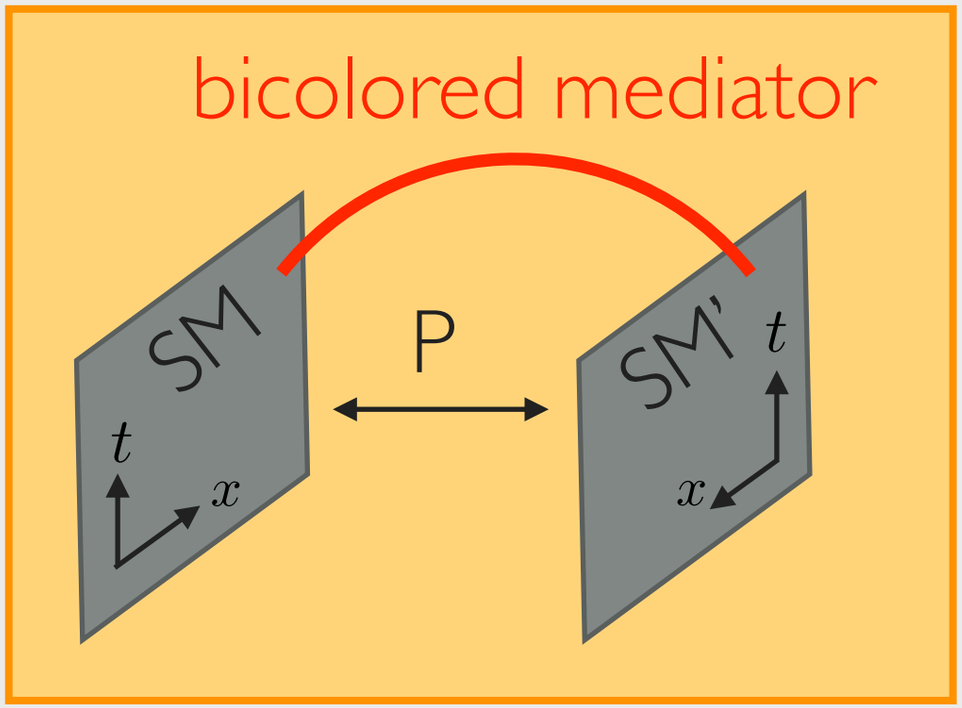
$$\left.\begin{array}{l}\theta' = -\theta \\ Y_q = Y_{q'}^\dagger\end{array}\right\} \Longrightarrow \bar{\theta}' = -\bar{\theta}$$

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

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

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

Our parity solution to the strong CP problem



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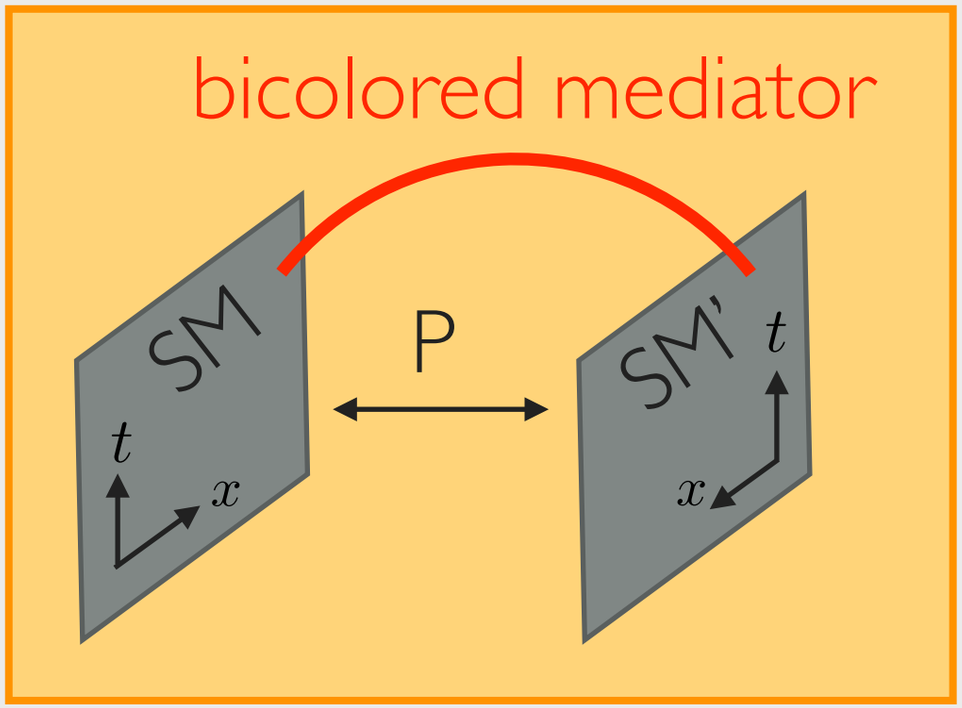
P

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

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

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

Our parity solution to the strong CP problem



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Achieved through soft breaking or radiative corrections

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

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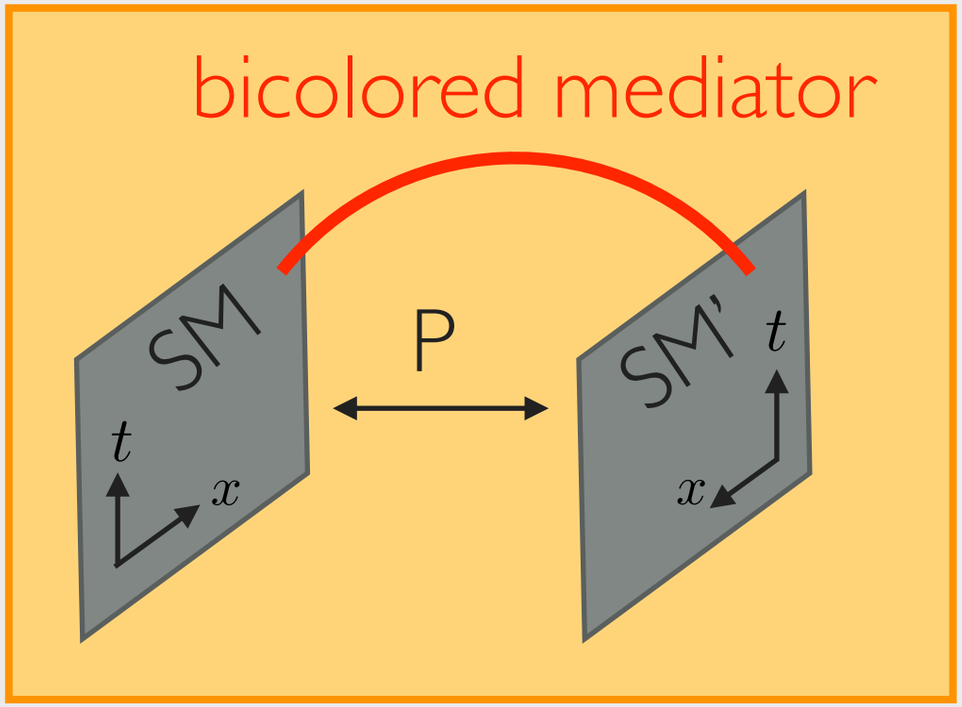

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P

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.

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

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

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

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

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

[Weinberg '76, Susskind '78]

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

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

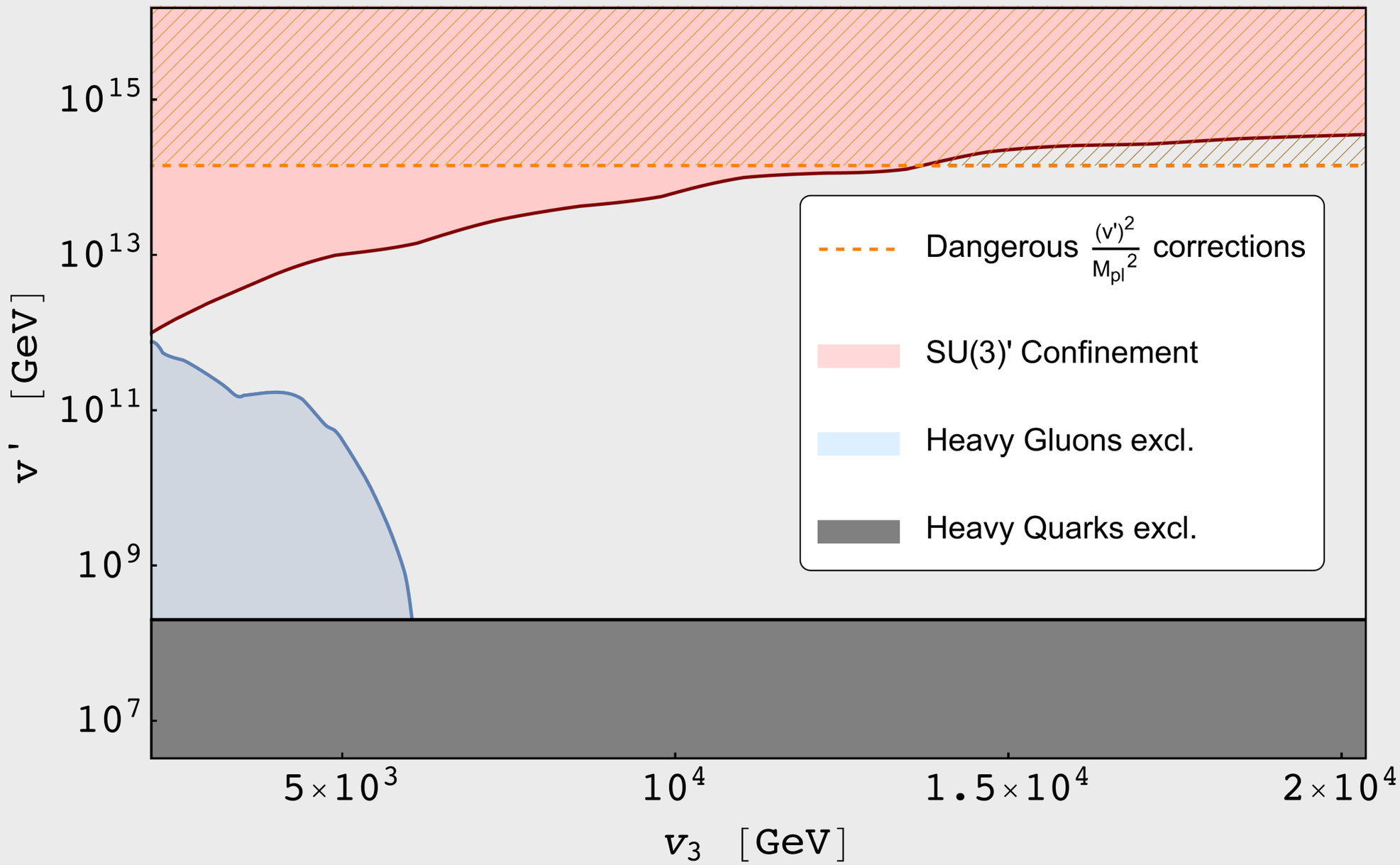
P for $\mathbf{3}'=\mathbf{3}$

Our parity solution to the strong CP problem

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

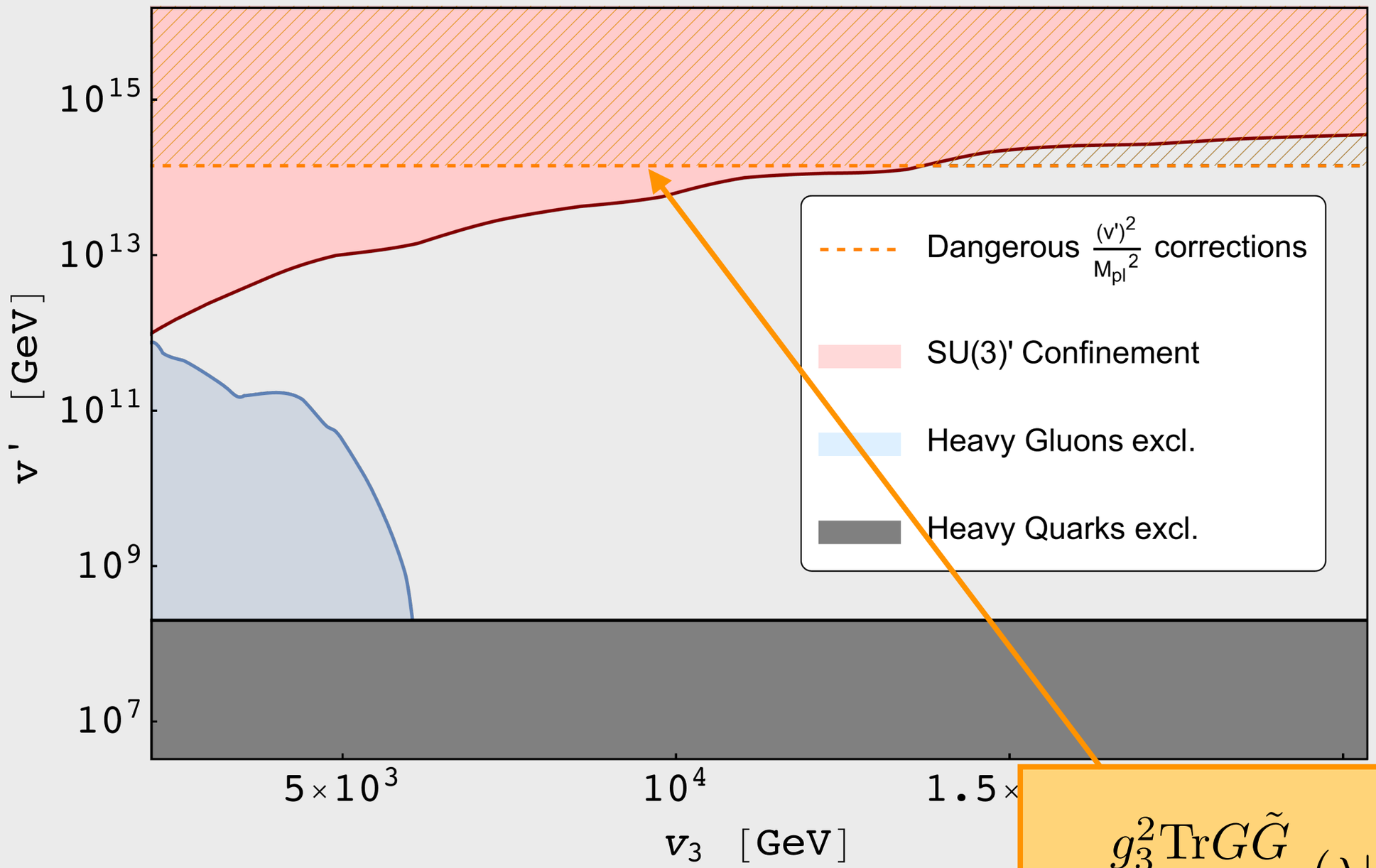
Only mediators: gluons, bicolor mediator or heavy Higgs. Only CP phase: CKM. **Very small contributions** (at least 3-loops) **to** $\bar{\theta}_{\mathrm{QCD}}$

Our parity solution to the strong CP problem



(scalar mediator)

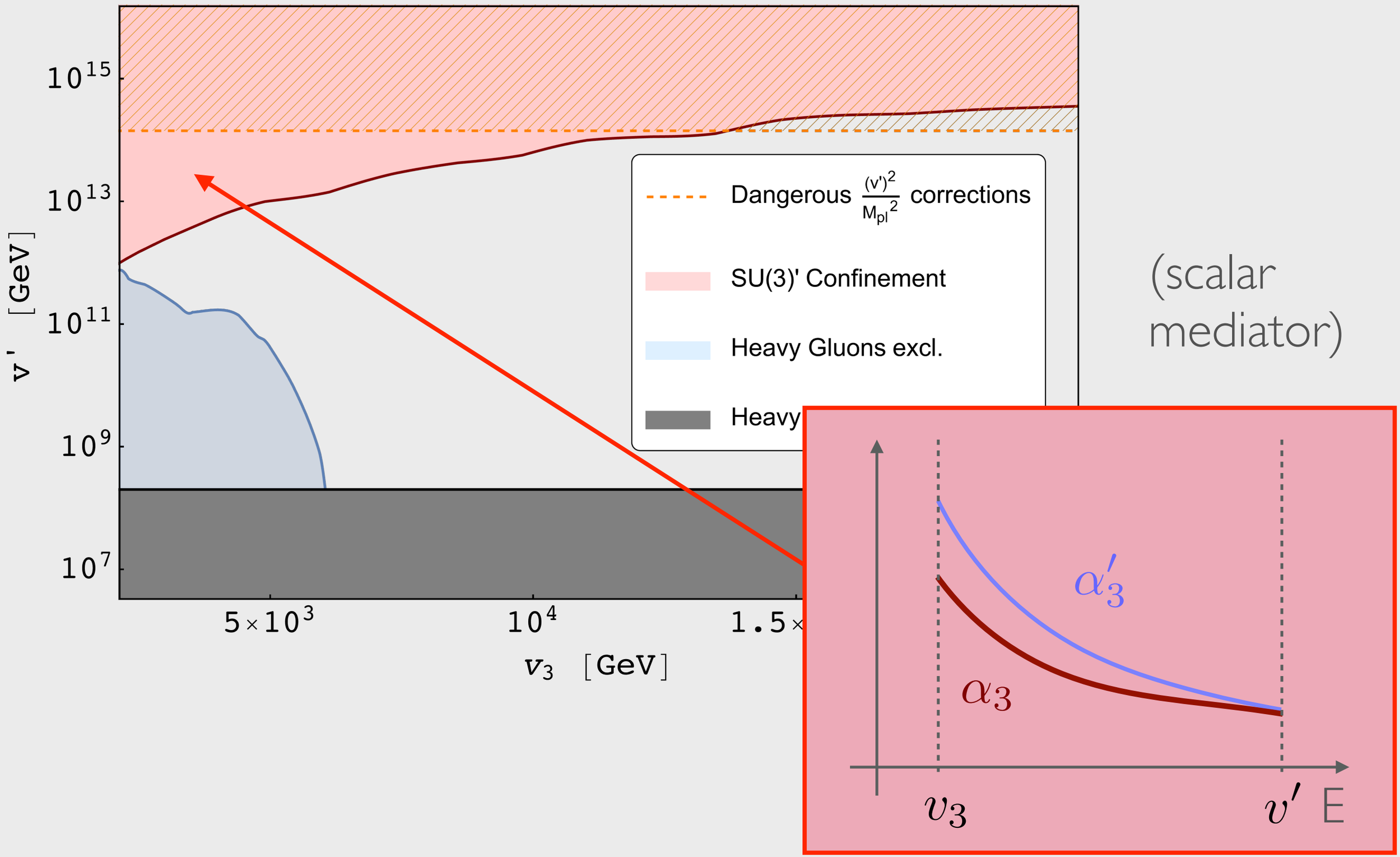
Our parity solution to the strong CP problem



(scalar mediator)

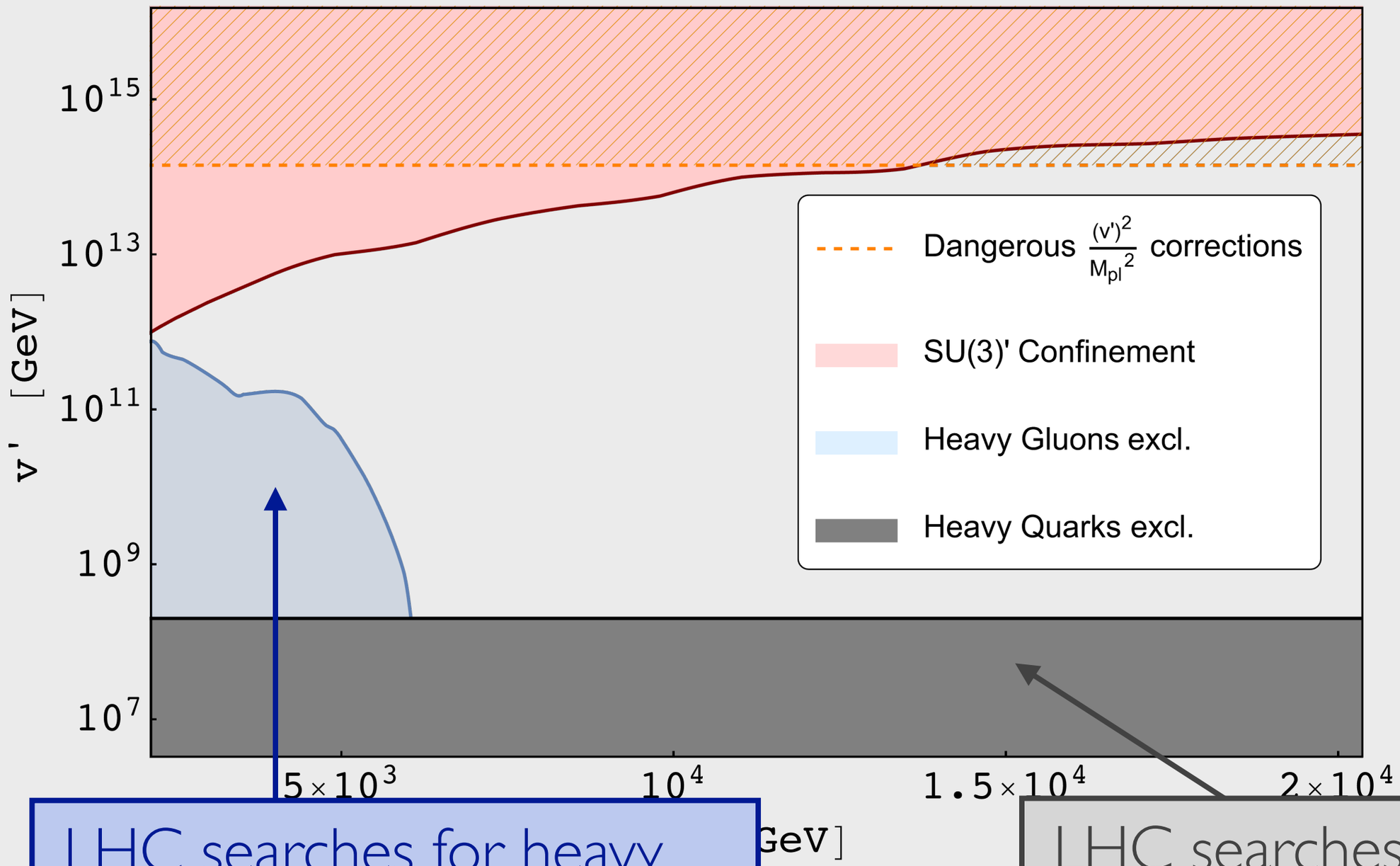
$$\frac{g_3^2 \mathrm{Tr} G\tilde{G}}{16\pi^2 M_P^2}\left(\lambda|H|^2+\lambda'|H'|^2\right) - (g_3, G, H \leftrightarrow g_3', G', H')$$

Our parity solution to the strong CP problem



(scalar mediator)

Our parity solution to the strong CP problem

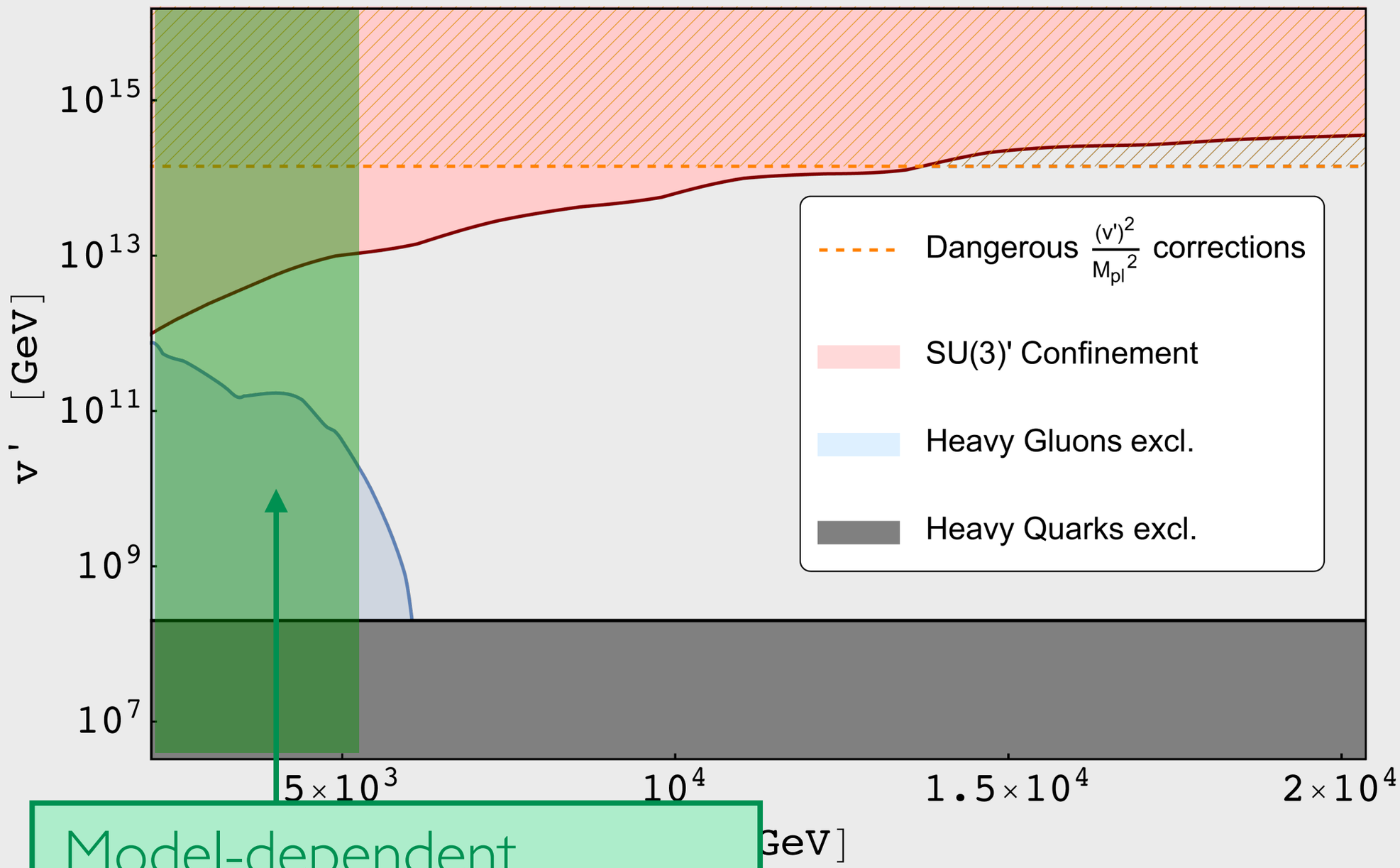


(scalar mediator)

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



(scalar mediator)

Model-dependent bounds on colored scalars

Outlook

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

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

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

Colored bosons could be the first accessible signal

More to explore ! Landscape of models still quite uncharted. In this model: interesting (and new) cosmology, with possible dark matter candidates, phase transitions, …

Outlook

THANK YOU

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