

Title: A colorful mirror solution to the strong CP problem - VIRTUAL

Speakers: Quentin Bonnefoy

Series: Particle Physics

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URL: <https://pirsa.org/24040075>

Abstract: Theories which spontaneously break spacetime parity can solve the strong CP problem. They usually have few free parameters and are therefore very predictive, but their landscape remains quite unexplored. I will present a construction based on a complete mirror copy of the standard model, linked to our world by colored portal fields. Those induce the partial spontaneous breaking of the color groups, yielding a vanishing theta angle at low energies. The lightest BSM fields could be found at colliders, and are either colored (pseudo-Goldstone or vector) bosons, or some of the vectorlike fermions predicted by parity. The lightest of the latter can actually play the role of thermal dark matter in our model, unlike what was previously found in similar constructions.

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This talk is virtual, but will also be broadcast in the Sky Room.

Zoom link



Université

de Strasbourg

# A colorful, yet dark, mirror solution to the strong CP problem

Quentin Bonnefoy  
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*Perimeter Institute  
April 2nd, 2024*

2303.06156 [hep-ph] (PRL) with L. Hall, C.A. Manzari & C. Scherb  
+ 2311.00702 [hep-ph] (PRD) with the same people & A. McCune

# The strong CP problem

$$\mathcal{L}_{\text{SM}} \supset \frac{i}{\sqrt{2}} \bar{u}_L \gamma^\mu W_\mu^+ V_{\text{CKM}} d_L + h.c. \\ + \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$$

complex matrix !  
CP-odd part

(C)P-odd

# The strong CP problem

$$\mathcal{L}_{\text{SM}} \supset \bar{Q}Y_d dH + \bar{Q}Y_u u\tilde{H} + h.c. + \frac{g_s^2 \theta}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$$

	$U(3)_Q$	$U(3)_u$	$U(3)_d$	$U(3)_L$	$U(3)_e$
$Q_L$	<b>3</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$Y_u$	<b>3</b>	$\bar{\mathbf{3}}$	<b>1</b>	<b>1</b>	<b>1</b>
$Y_d$	<b>3</b>	<b>1</b>	$\bar{\mathbf{3}}$	<b>1</b>	<b>1</b>
$Y_e$	<b>1</b>	<b>1</b>	<b>1</b>	<b>3</b>	$\bar{\mathbf{3}}$

$$J_4 = \text{Im Tr} \left[ Y_u Y_u^\dagger, Y_d Y_d^\dagger \right]^3$$

**[Jarlskog '85]**

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

# The strong CP problem

$$\mathcal{L}_{\text{SM}} \supset \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$$

All known CPV phenomena : CKM-driven. **Where is  $\bar{\theta}$  ?**

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]

predicted to be  
 $\approx 10^{-2} \bar{\theta} e \text{ GeV}^{-1}$

$$\mathcal{L}_{\text{EDM}} \supset \frac{id_n}{2} \bar{n} \gamma_5 \gamma_{\mu\nu} n F^{\mu\nu}$$

# The strong CP problem

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All known CPV phenomena : CKM-driven. **Where is  $\bar{\theta}$  ?**

Total derivative : invisible in perturbation theory

But non-perturbative

**Strong CP problem :**

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

In particular, **neutrino**

**moment (EDM)**

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

predicted to be  
 $\approx 10^{-2} \bar{\theta} e \text{ GeV}^{-1}$

$$\mathcal{L}_{\text{EDM}} \supset \frac{id_n}{2} \bar{n} \gamma_5 \gamma_{\mu\nu} n F^{\mu\nu}$$

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

[Pendlebury et al '15]

# Solutions to the strong CP problem

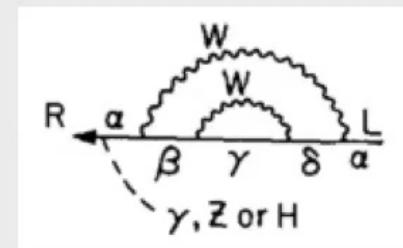
$$\mathcal{L}_{\text{SM}} \supset \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$$

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

## 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]

Ruled out by lattice

[Aoki et al '16]

$$\mathcal{L} \supset \frac{g_s^2}{16\pi^2} \frac{a}{f_a} G\tilde{G}$$

[Peccei/Quinn '77,  
Weinberg '78, Wilczek '78]



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Relaxes to zero !

[Vafa/Witten '84]

**Also DM !**

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Make it zero

---

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

# Parity solutions to the strong CP problem

**P is not a symmetry of the SM !** Spontaneous breaking

New fermions ? New gauge fields ?

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

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

Higgsed : broken parity

$$\begin{array}{l}
 \downarrow \\
 \text{same} + \begin{array}{l} Q_R(\mathbf{3}, \mathbf{2}, 1/6) \\ d_L(\mathbf{3}, \mathbf{1}, -1/3) \\ u_L(\mathbf{3}, \mathbf{1}, 2/3) \end{array}
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Higgs couplings : too light !

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need a see-saw !

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

can mix !

$$\begin{array}{l}
 \text{same} + \begin{array}{l} \mathbf{1}, \mathbf{2} \\ Q_R(\mathbf{3}, \mathbf{1}, 1/6) \\ d_L(\mathbf{3}, \mathbf{1}, -1/3) \\ u_L(\mathbf{3}, \mathbf{1}, 2/3) \end{array}
 \end{array}$$

Higgs couplings : too light !

**In practice, both !**

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

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 \end{array}$$

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

↓

$$\begin{array}{l}
 \mathbf{1}, \mathbf{2}, \mathbf{0}, \mathbf{1/6} \\
 Q_R(\mathbf{3}, \mathbf{1}, \mathbf{1/6}) \\
 \text{same} + \begin{array}{l} d_L(\mathbf{3}, \mathbf{1}, -1/3) \\ u_L(\mathbf{3}, \mathbf{1}, 2/3) \end{array}
 \end{array}$$

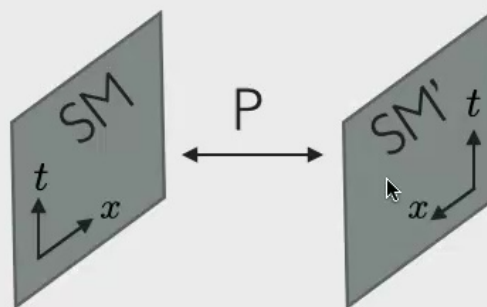
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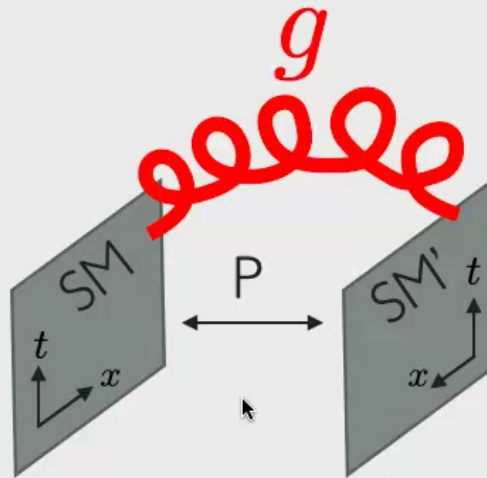
# Parity solutions to the strong CP problem

## Mirror world



# Parity solutions to the strong CP problem

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

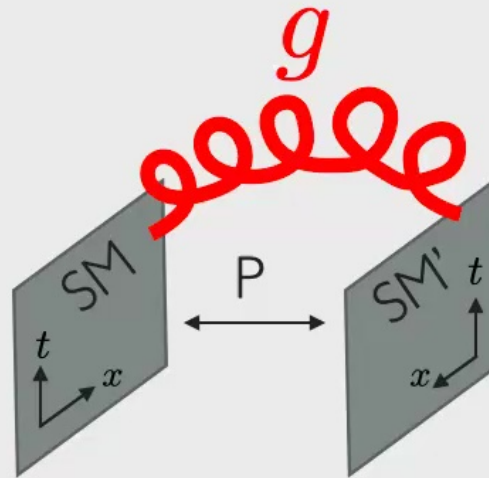


$$\bar{\theta}_{\text{QCD}} = 0$$



# Parity solutions to the strong CP problem

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



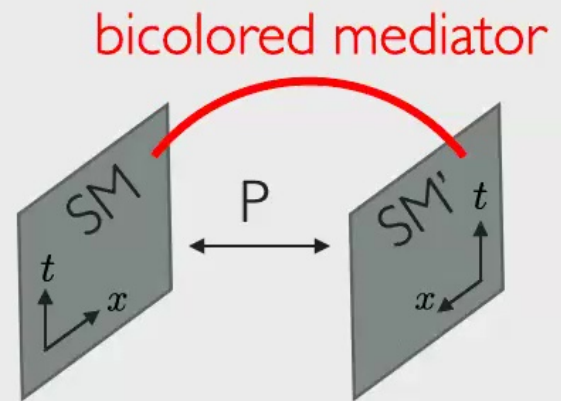
$$\langle H \rangle \neq \langle H' \rangle$$
$$\bar{\theta}_{\text{QCD}} = 0$$

# Our parity solution to the strong CP problem

We notice that



With the same starting point :

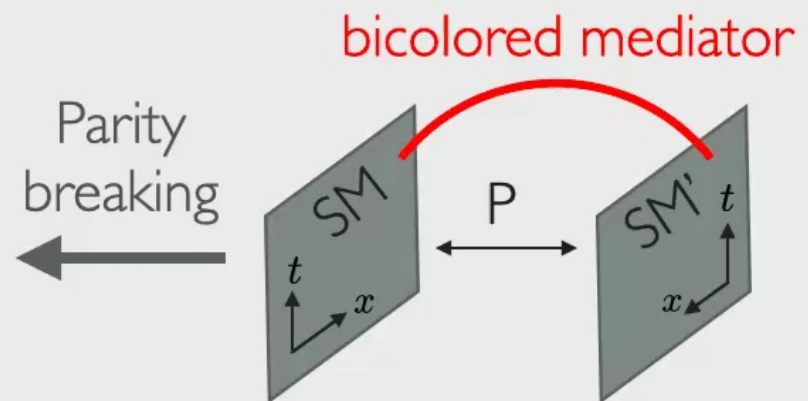


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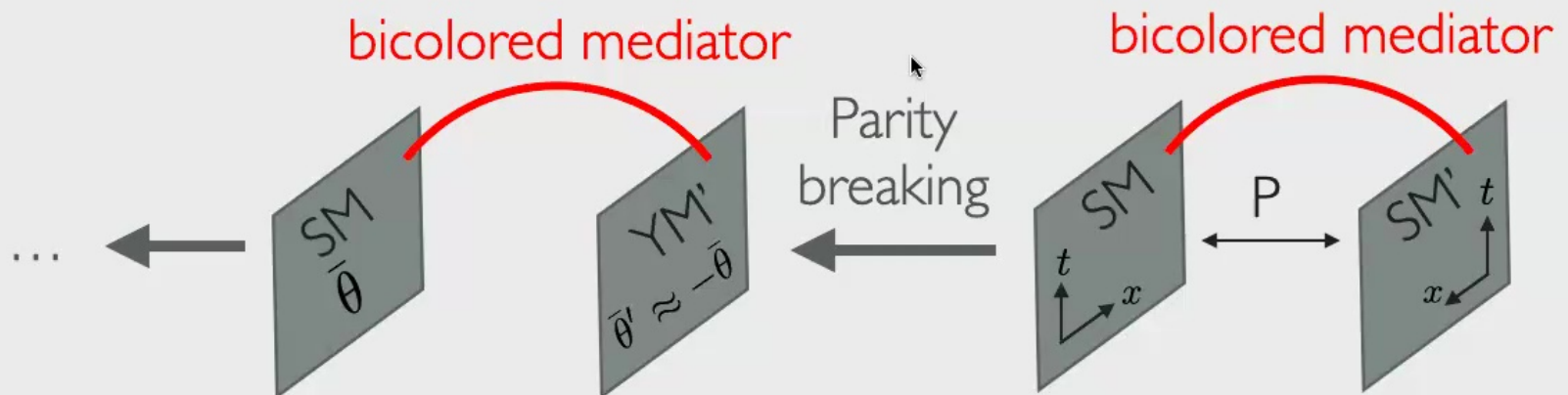


# Our parity solution to the strong CP problem

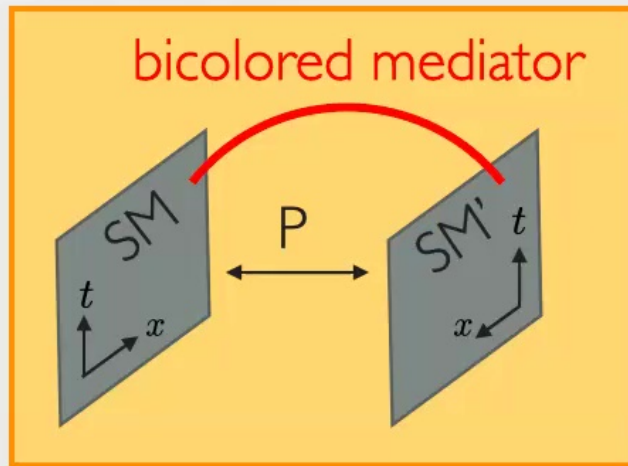
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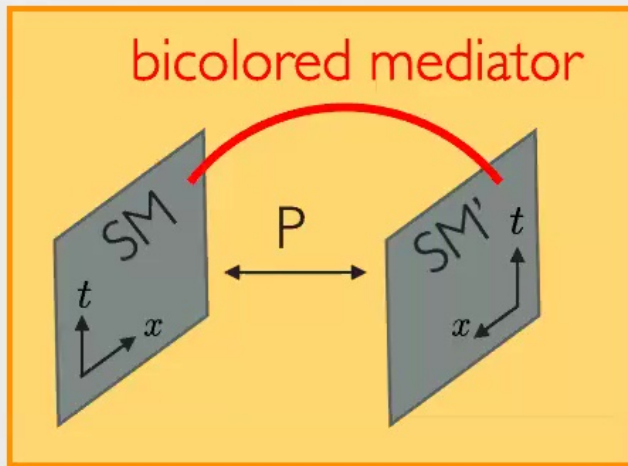
# Our parity solution to the strong CP problem



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



# Our parity solution to the strong CP problem

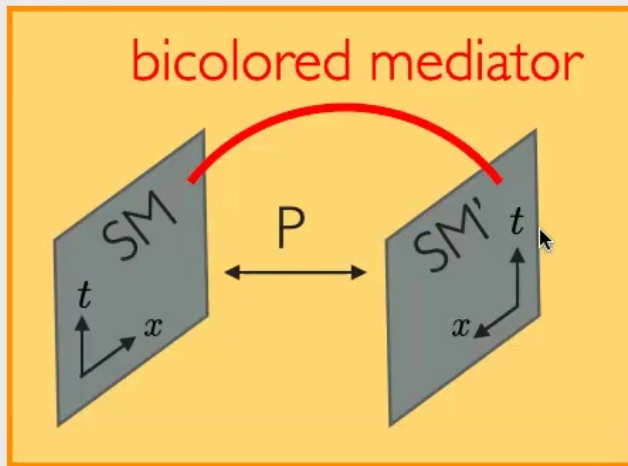


	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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$e^c$	$\mathbf{1}$	$\mathbf{1}$	$-1$	$\mathbf{1}$	$\mathbf{1}$	$0$
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$Q'$	$\mathbf{1}$	$\mathbf{1}$	$0$	$\bar{\mathbf{3}}$	$\mathbf{2}$	$-1/6$
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$d'^c$	$\mathbf{1}$	$\mathbf{1}$	$0$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
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$$\left. \begin{array}{l} \theta' = -\theta \\ Y_q = Y_{q'}^\dagger \end{array} \right\} \implies \bar{\theta}' = -\bar{\theta}$$

# Our parity solution to the strong CP problem



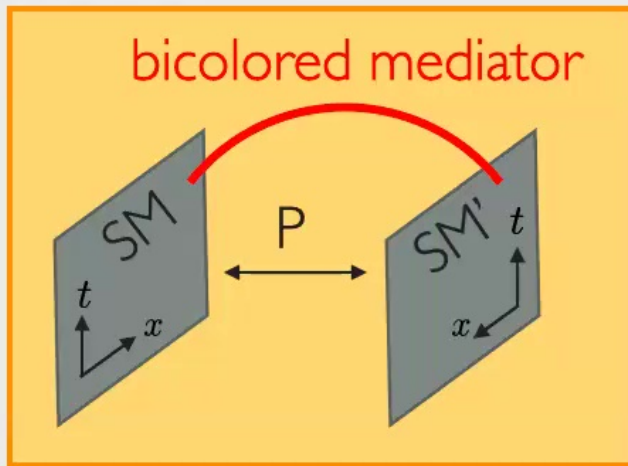
Bicolored mediator here:  
bifundamental order  
parameter  $\langle \Sigma \rangle$

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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Bicolored mediator here:  
bifundamental order  
parameter  $\langle \Sigma \rangle$

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

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

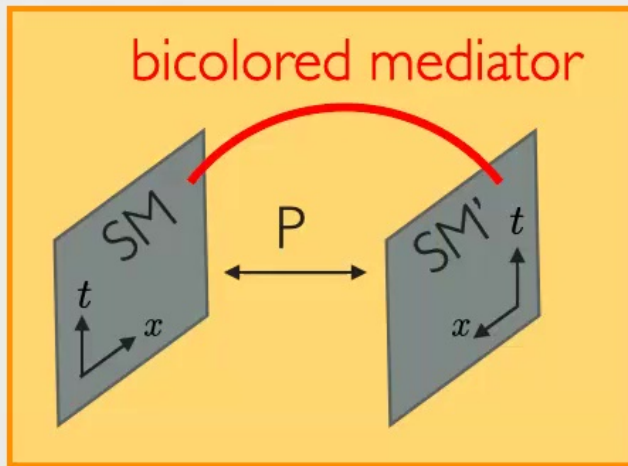
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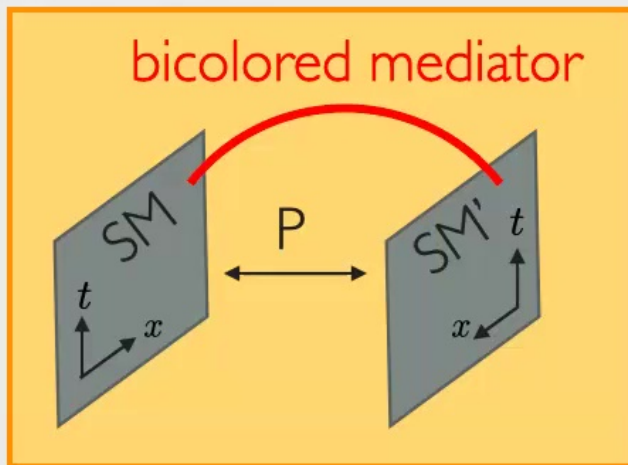
Below  $v_3$ , colored mirror quarks : need  $\langle H' \rangle \gg \langle H \rangle$  (hence P-breaking)

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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$$Y_q = Y_{q'}^\dagger \implies \frac{m_q}{m_{q'}} = \frac{\langle H \rangle}{\langle H' \rangle}$$

# Our parity solution to the strong CP problem



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



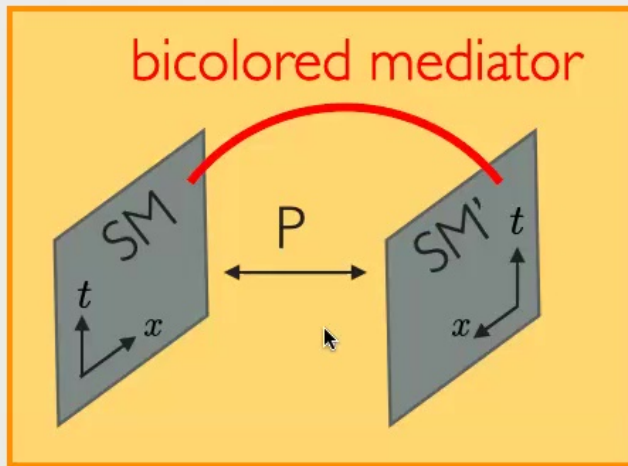
Below  $v_3$ , colored mirror quarks : need  $\langle H' \rangle \gg \langle H \rangle$  (hence P-breaking)  $\equiv v'$

Achieved through soft breaking or radiative corrections

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

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

# Our parity solution to the strong CP problem



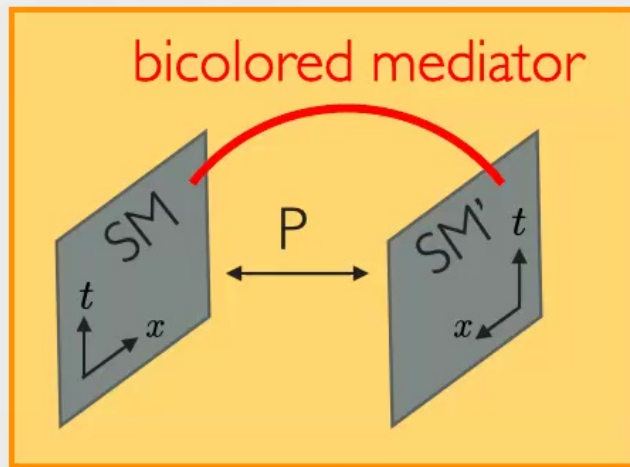
**Very predictive model**, two BSM scales :  $v_3$  and  $v'$

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



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



**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 !

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

# Our parity solution to the strong CP problem

Bicolored mediator : a **scalar** or **strongly interacting fermions**.

- $\Sigma$  in  $(\mathbf{3}, \mathbf{3}')$  of  $SU(3) \times SU(3)'$  with potential
 
$$V(\Sigma) = -m^2 \text{Tr}(\Sigma \Sigma^\dagger) + c \text{Tr}^2(\Sigma \Sigma^\dagger) + \tilde{c} \text{Tr}(\Sigma \Sigma^\dagger)^2 + (\tilde{m} \det(\Sigma) + h.c.)$$

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

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

- |           | $SU(N)$      | $SU(N)'$     | $SU(3)$            | $SU(3)'$            | Breaking to the diagonal $SU(3)$ à la technicolor<br>[Weinberg '76, Susskind '78] |
|-----------|--------------|--------------|--------------------|---------------------|---|
| $\psi_L$  | $\mathbf{N}$ | $\mathbf{1}$ | $\mathbf{3}$       | $\mathbf{1}$        |   |
| $\psi_R$  | $\mathbf{N}$ | $\mathbf{1}$ | $\mathbf{1}$       | $\mathbf{3}'$       |   |
| $\psi'_L$ | $\mathbf{1}$ | $\mathbf{N}$ | $\bar{\mathbf{3}}$ | $\mathbf{1}$        |   |
| $\psi'_R$ | $\mathbf{1}$ | $\mathbf{N}$ | $\mathbf{1}$       | $\bar{\mathbf{3}}'$ |   |

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| $\psi_R$  | $\mathbf{N}$ | $\mathbf{1}$ | $\mathbf{1}$       | $\mathbf{3}'$       |
| $\psi'_L$ | $\mathbf{1}$ | $\mathbf{N}$ | $\bar{\mathbf{3}}$ | $\mathbf{1}$        |
| $\psi'_R$ | $\mathbf{1}$ | $\mathbf{N}$ | $\mathbf{1}$       | $\bar{\mathbf{3}}'$ |

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

# Our parity solution to the strong CP problem

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

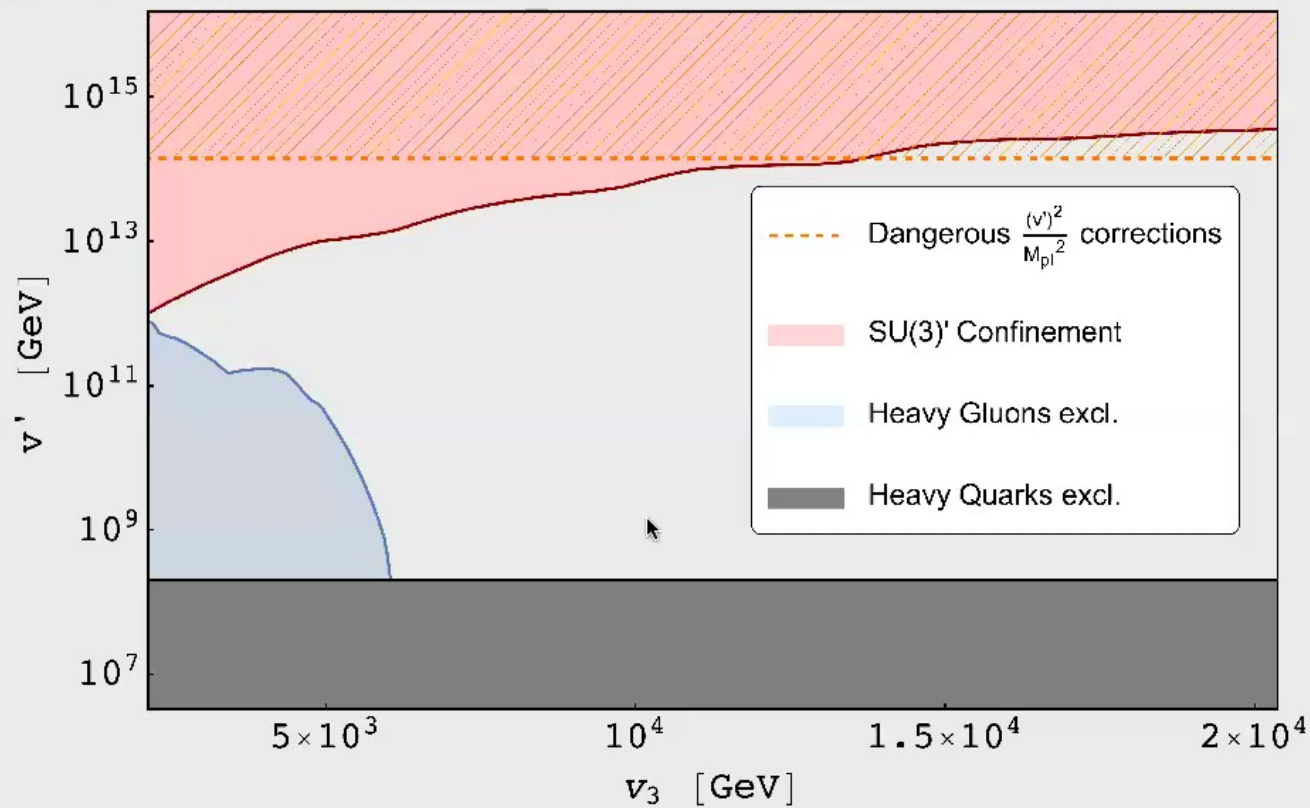
# Our parity solution to the strong CP problem

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

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

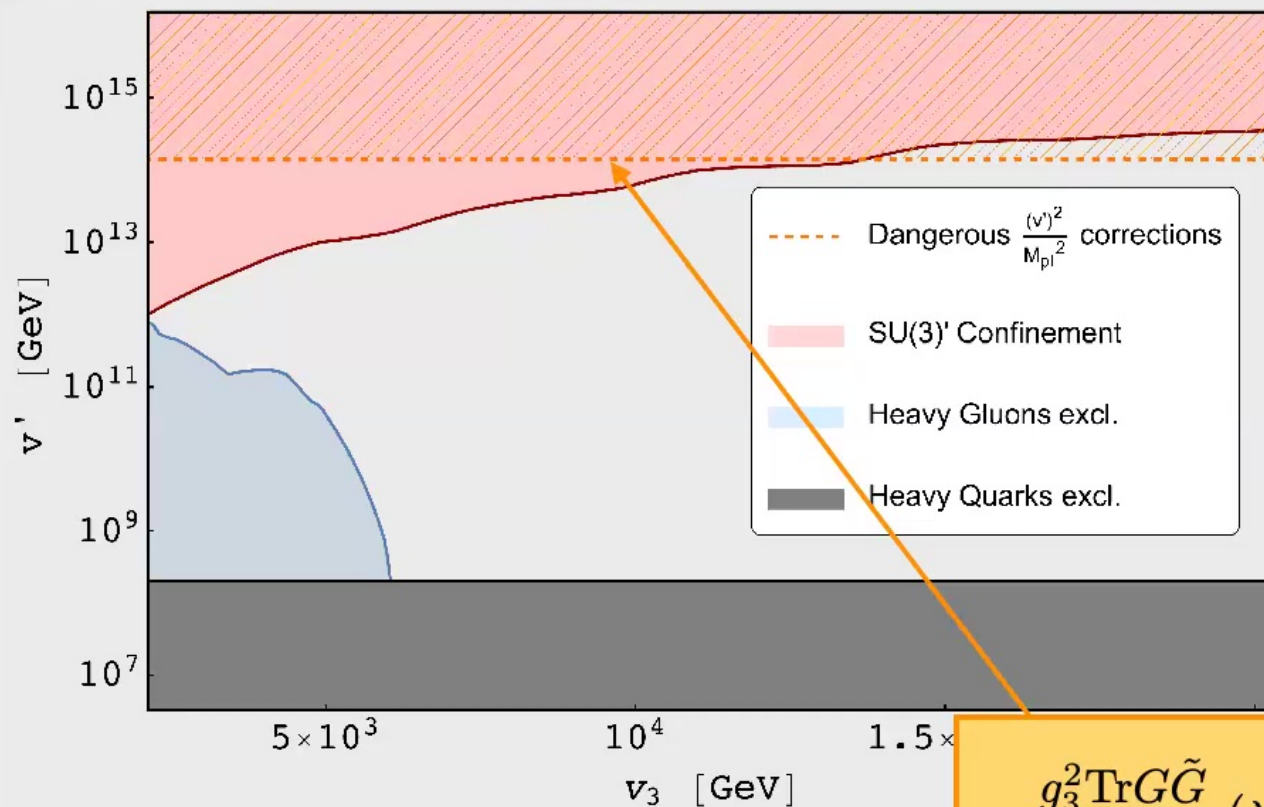


# Our parity solution to the strong CP problem



(scalar  
mediator)

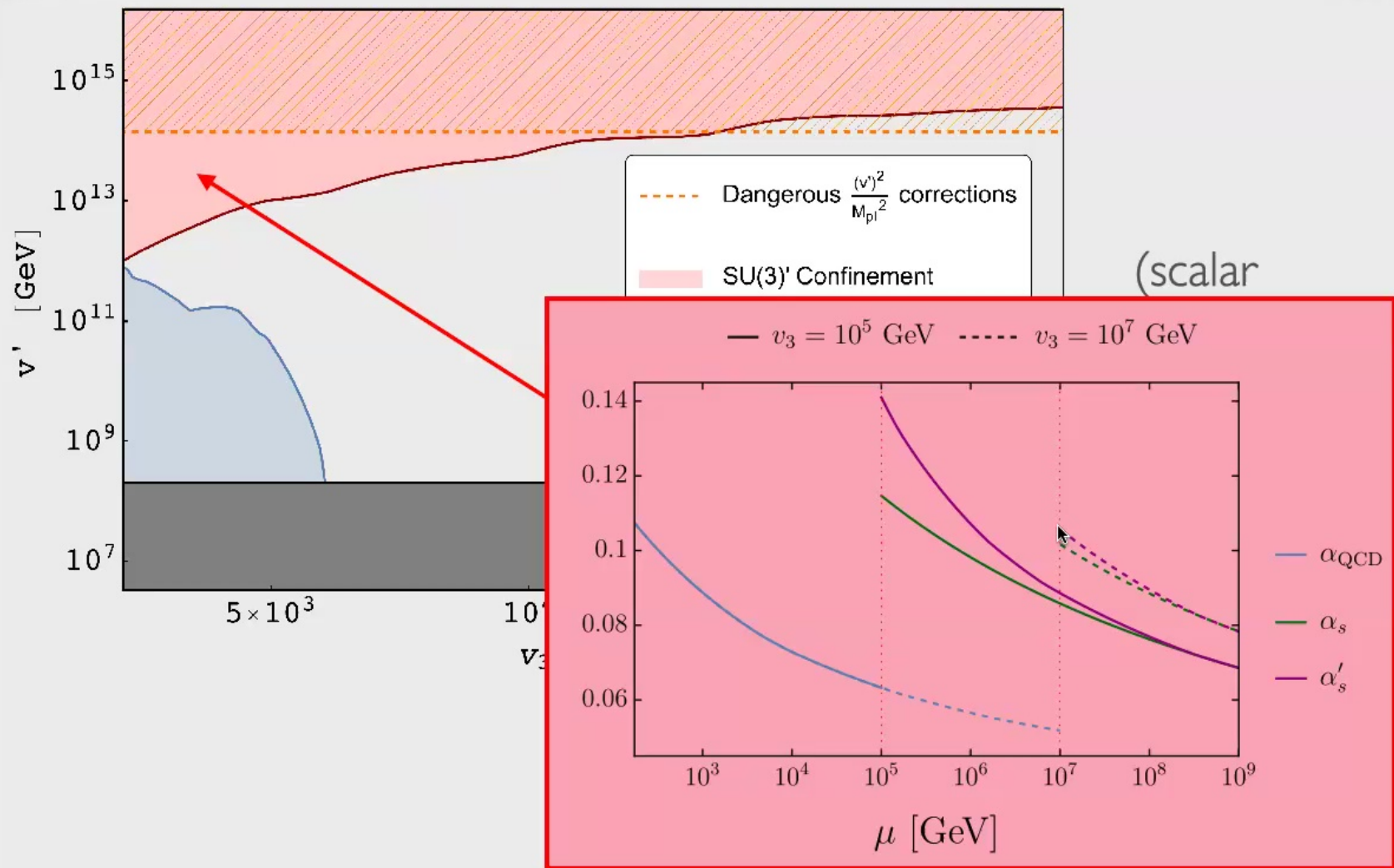
# Our parity solution to the strong CP problem



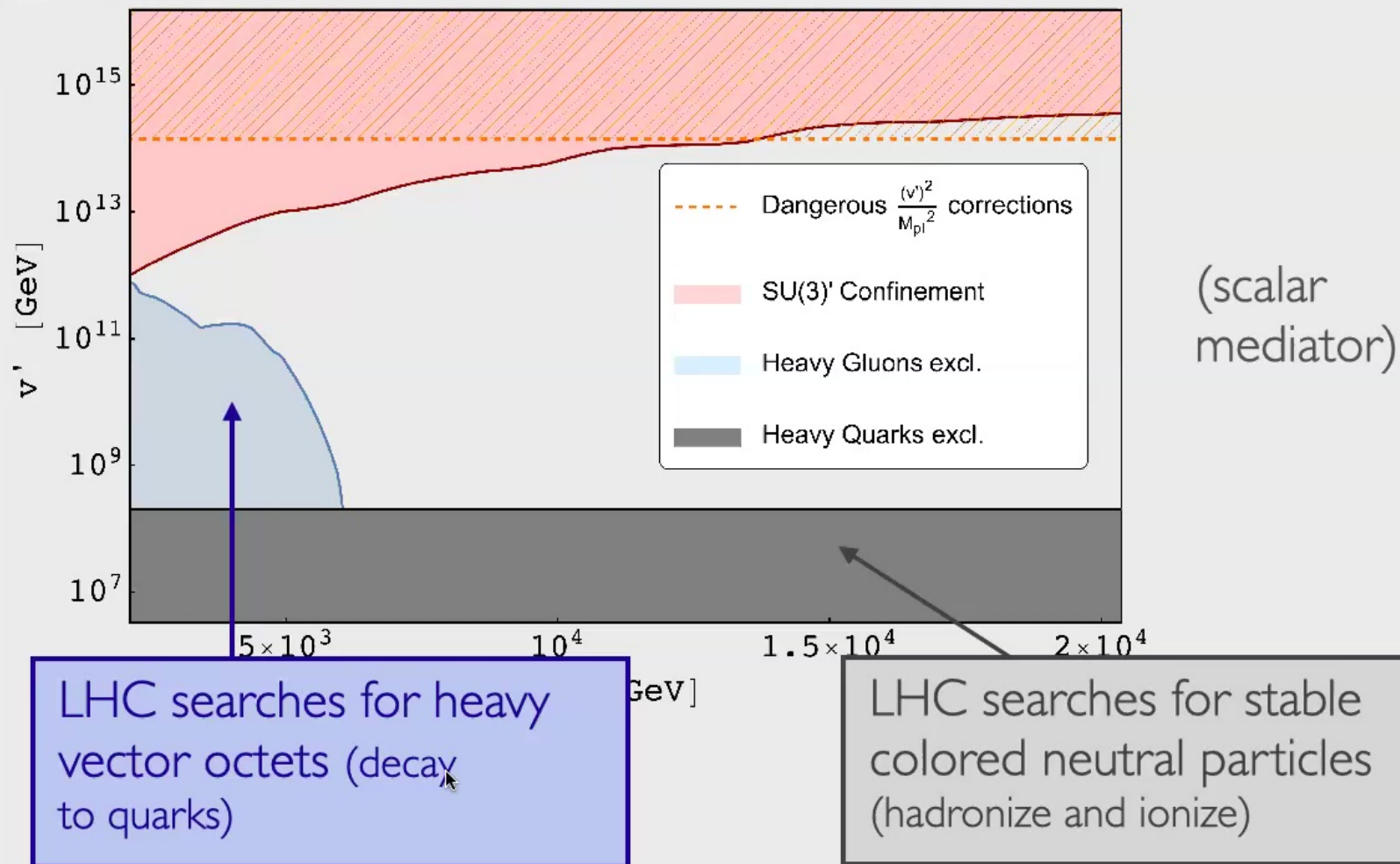
(scalar mediator)

$$\frac{g_3^2 \text{Tr} G \tilde{G}}{16\pi^2 M_P^2} (\lambda |H|^2 + \lambda' |H'|^2) - (g_3, G, H \leftrightarrow g'_3, G', H')$$

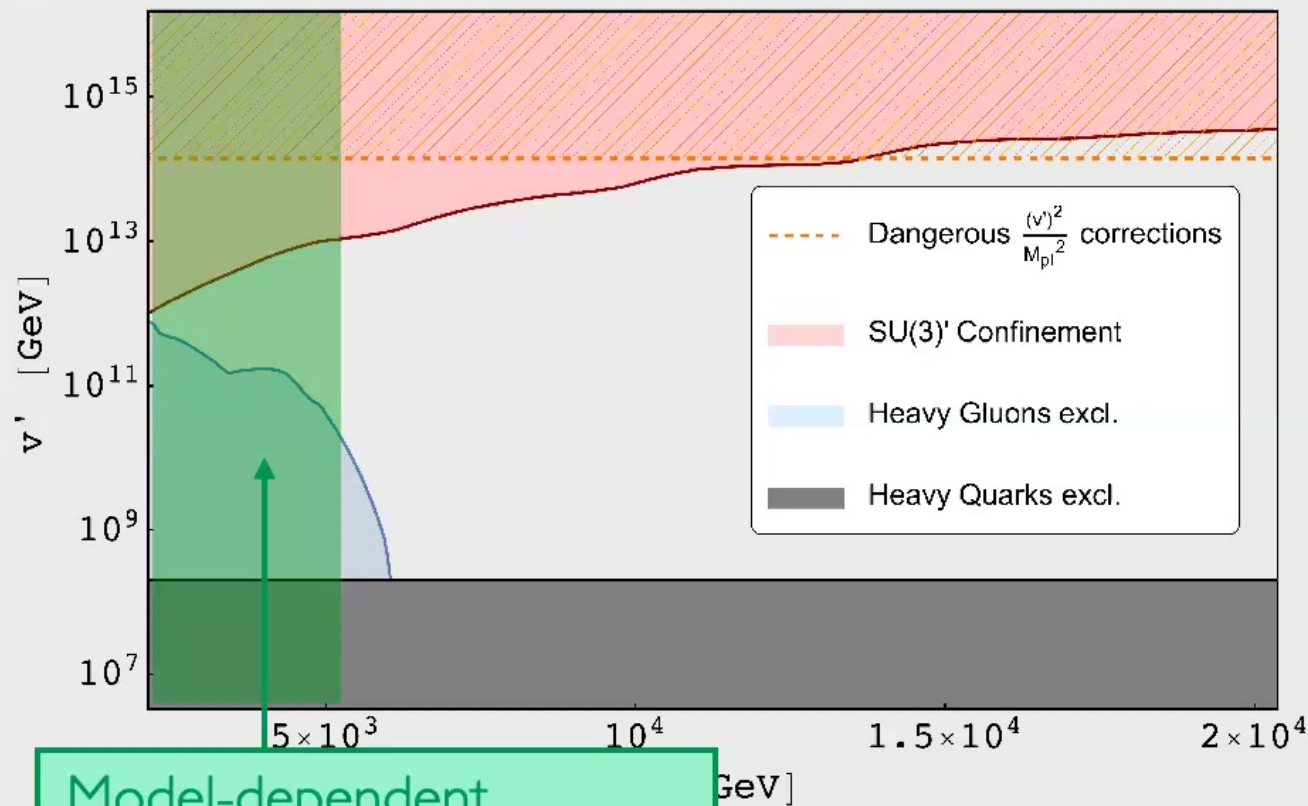
# Our parity solution to the strong CP problem



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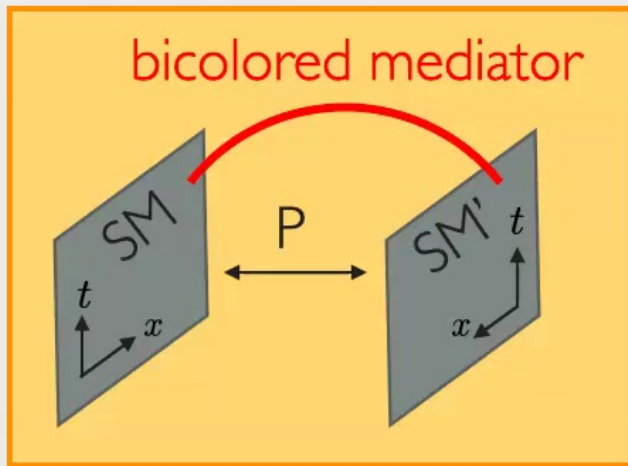
# Our parity solution to the strong CP problem



(scalar mediator)

Model-dependent bounds on colored scalars

# 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)

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$e'^c$	$\mathbf{1}$	$\mathbf{1}$	$0$	$\mathbf{1}$	$\mathbf{1}$	$1$
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# Dark matter from the mirror world

Many new particles, mirror B and L quantum numbers...

**dark matter candidates !**

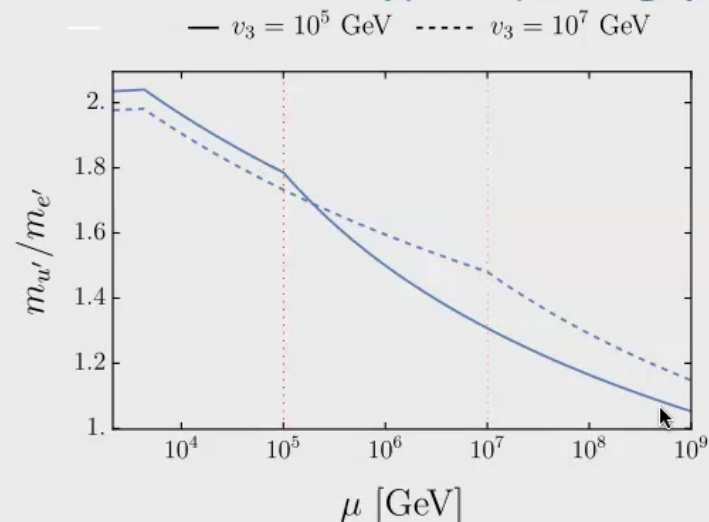
Only one viable : **mirror electron**

Strong bounds on the stable mirror up quark relic density

$$Y_{u'} \lesssim 10^{[-14, -8]} Y_{\text{DM}}$$

Masses are fixed by parity !

[Goodman/Witten '85,  
Kawamura/Okawa/Omura/Tang '18,  
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Earlier literature : non-thermal mechanisms (inflaton decays), other DM candidates (mirror neutrinos), extended spectra

[Dunsky/Hall/Harigaya '19, +Dror '20,  
Kawamura/Okawa/Omura/Tang '18]

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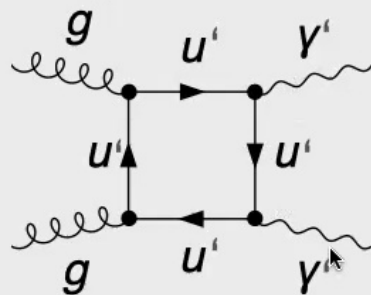
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**Sequential freeze-in** from the mirror photon



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

$$\text{then } \gamma' \gamma' \rightarrow e' \bar{e}'$$

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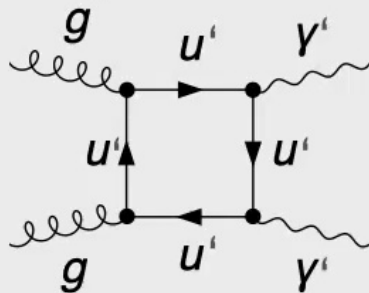
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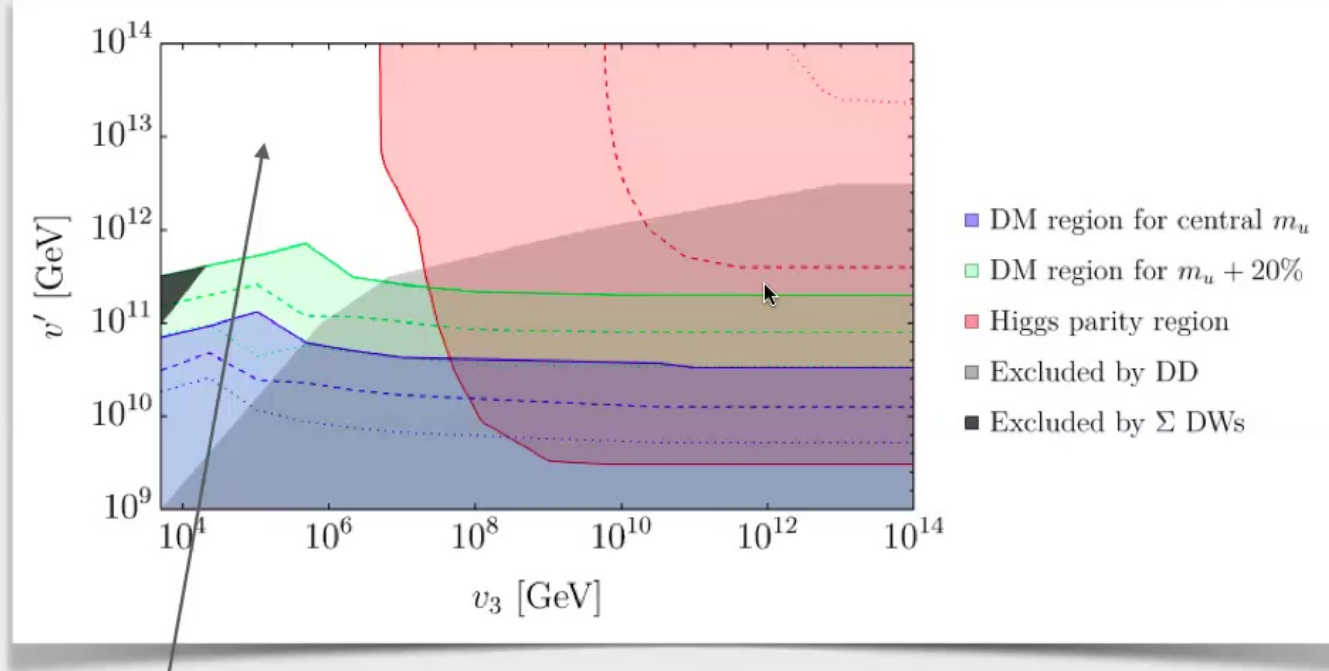


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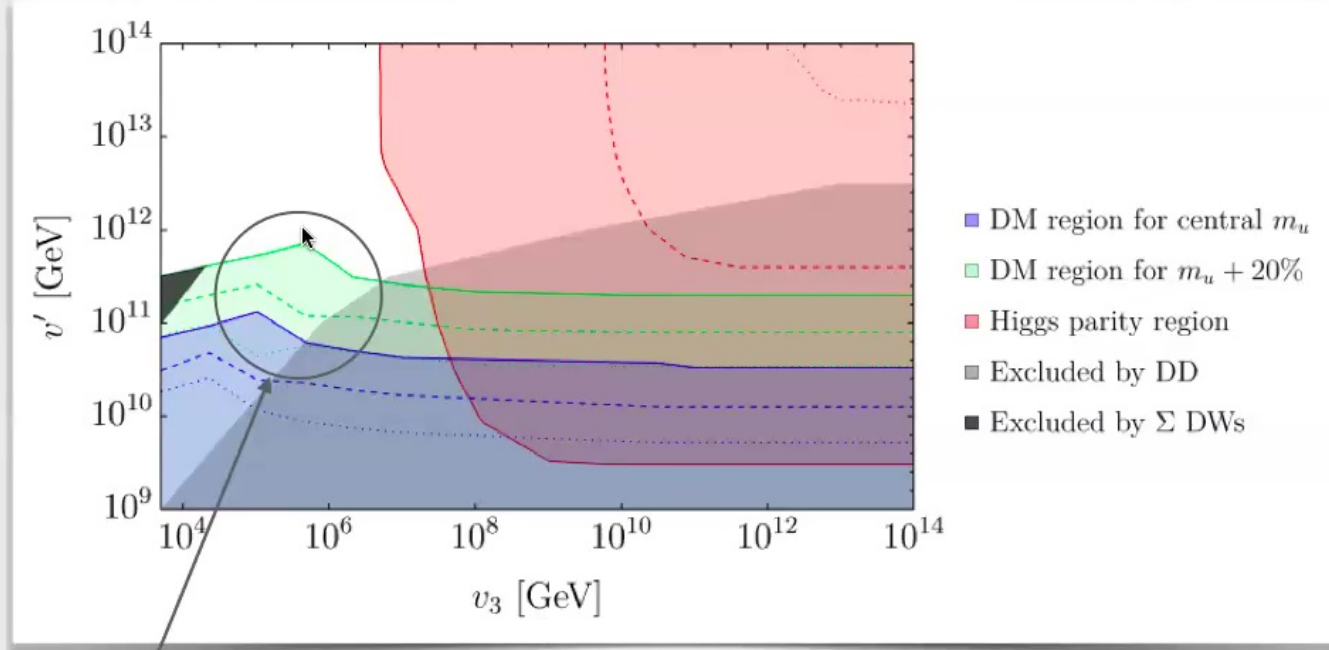
**Inflation ?** Reheating to  
the SM and  $T_{\text{max}} \approx T_{\text{rh}}$

# Dark matter from the mirror world



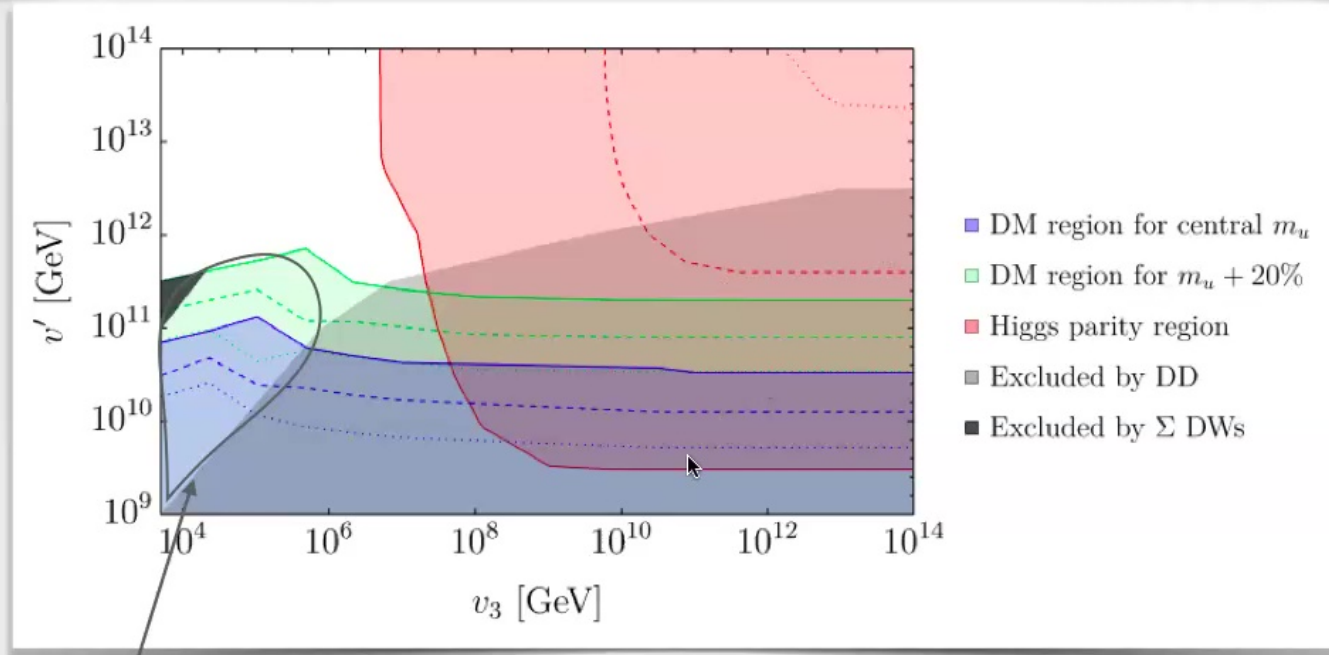
No appropriate  
reheating temperature

# Dark matter from the mirror world

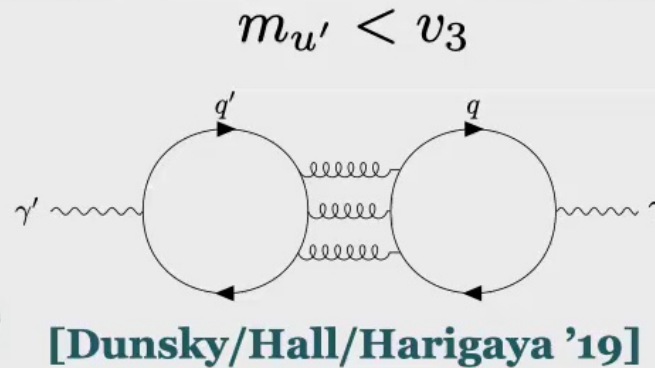


First interest of  
low  $v_3$   
(ratio  $m_{u'}/m_{e'}$ )

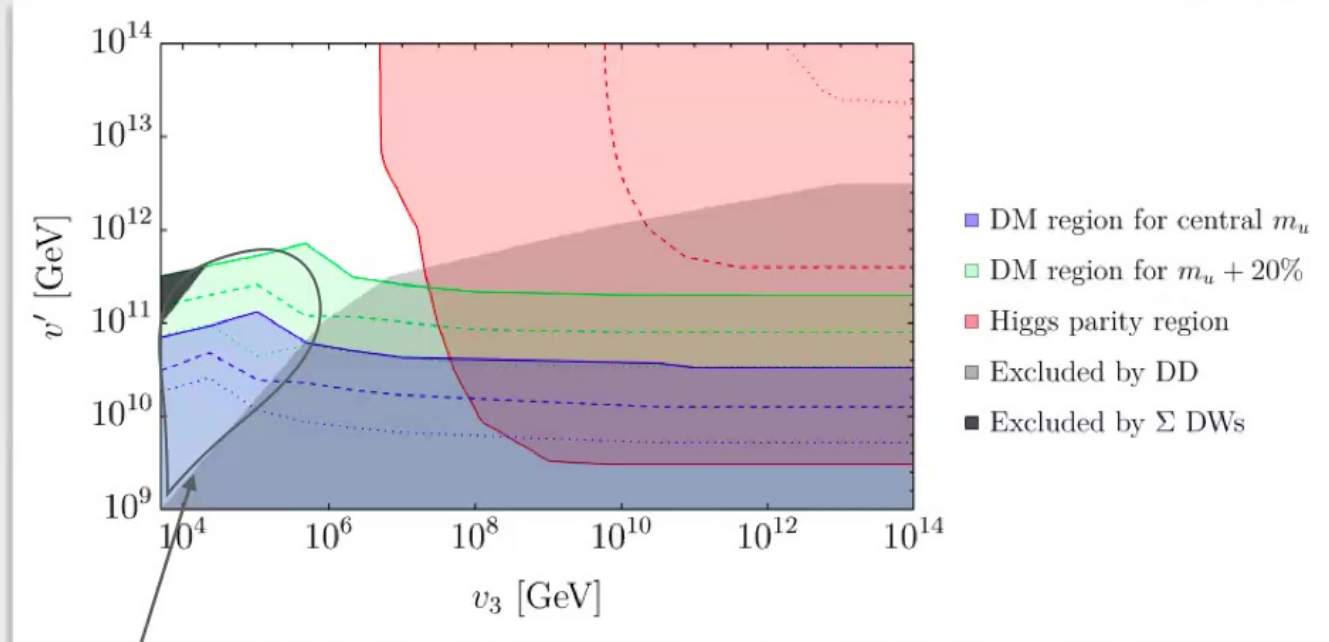
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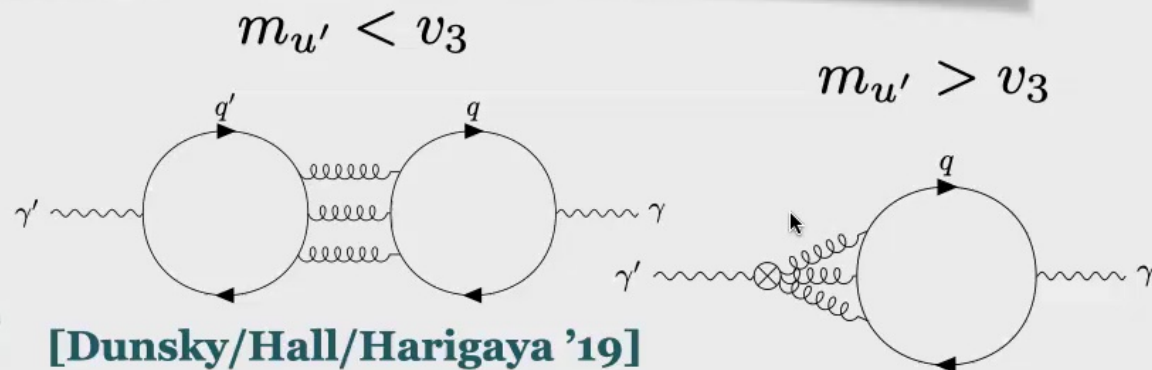
Main interest of  
 low  $v_3$   
**(kinetic mixing)**



# Dark matter from the mirror world



Main interest of  
 low  $v_3$   
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# Outlook

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

Many lessons left to learn. Ex : there is room for a **thermal dark matter candidate** !



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Many lessons left to learn. Ex : there is room for a **thermal dark matter candidate** !

Few free parameters, but quite different physics in the parameter space ! Ex : colored bosons, possible (companion) DM signals