A colorful (yet dark) mirror solution to the strong CP problem

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IJCLab
23/04/2024

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

$$\mathcal{L}_{\rm SM} \supset \frac{i}{\sqrt{2}}\overline{u_L}\gamma^\mu W^+_\mu V_{\rm CKM} d_L + h.c. + \frac{g_s^2\bar{\theta}}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

complex matrix !
CP-odd part

(C)P-odd

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

The strong CP problem

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

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

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

[Jarlskog '85]

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

The strong CP problem

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

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

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

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

[Pendlebury et al '15]

The strong CP problem

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Total derivative : invisible in perturbation theory

But non-perturbativ

In particular, **neutr** **ent** (EDM)

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

Strong CP problem :

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

predicted to be

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

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

measured to be

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

[Pendlebury et al '15]

Solutions to the strong CP problem

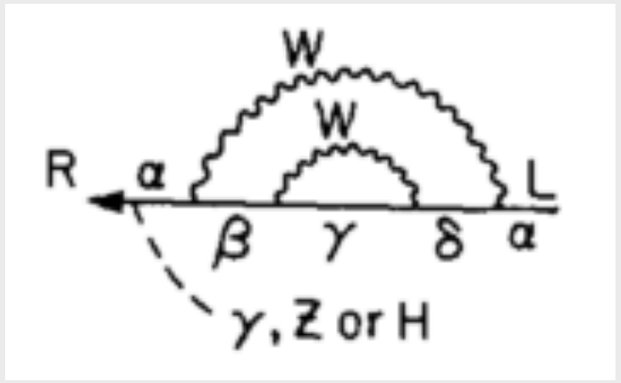
$$\mathcal{L}_{\rm SM} \supset \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

How to 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]



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

An effective field theorist's nightmare ! IR solutions.

Make it unphysical	Make it dynamical
$\bar{\theta} = \theta + \arg\det(Y_u Y_d)$	$\mathcal{L} \supset \frac{g_s^2}{16\pi^2} \frac{a}{f_a} G\tilde{G}$
Massless quark : ambiguous ! **['t Hooft '76]**	**[Peccei/Quinn '77, Weinberg '78, Wilczek '78]**
Ruled out by lattice **[Aoki et al '16]**	Relaxes to zero ! **[Vafa/Witten '84]**
	Also DM !

Solutions to the strong CP problem

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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

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New fermions ?

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

same +

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

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Higgs couplings : too light !

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$$Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix} (\mathbf{3},\mathbf{1},\mathbf{2},1/6)$$
$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)$$

Higgsed

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Higgsed : broken parity

same + $Q_R(\mathbf{3},\mathbf{2},1/6)$
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Dim-5 masses : need a see-saw !

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

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

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, ...]

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]**

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can mix !

$$\mathbf{1},\mathbf{2}$$
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Not in all extensions **[de Vries/Draper/Patel '21]**

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

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$$\times \mathbf{U(1)'}$$

$\mathbf{1,2}$ $\mathbf{0,1/6}$

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

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In practice, both !

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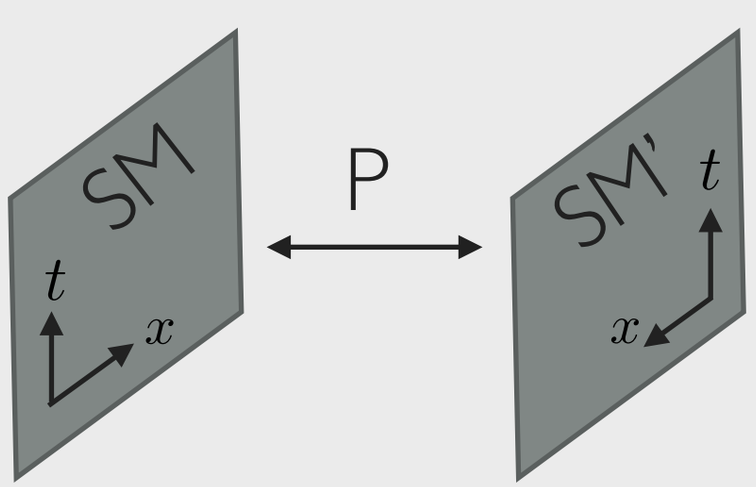
Parity solutions to the strong CP problem

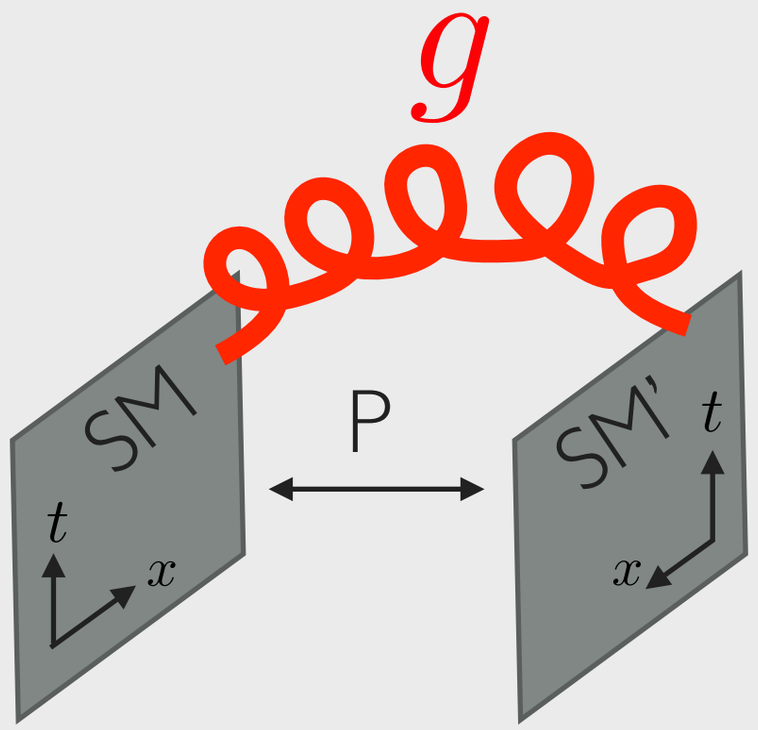
Mirror world



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

Parity solutions to the strong CP problem

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

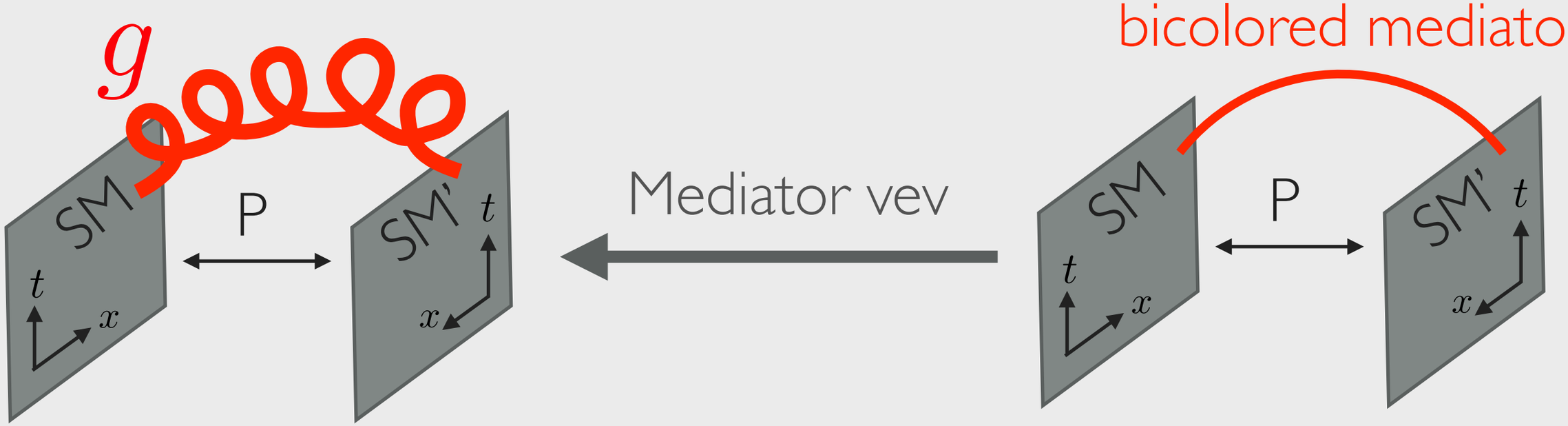


$$\langle H \rangle \neq \langle H' \rangle$$

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

Our parity solution to the strong CP problem

We notice that



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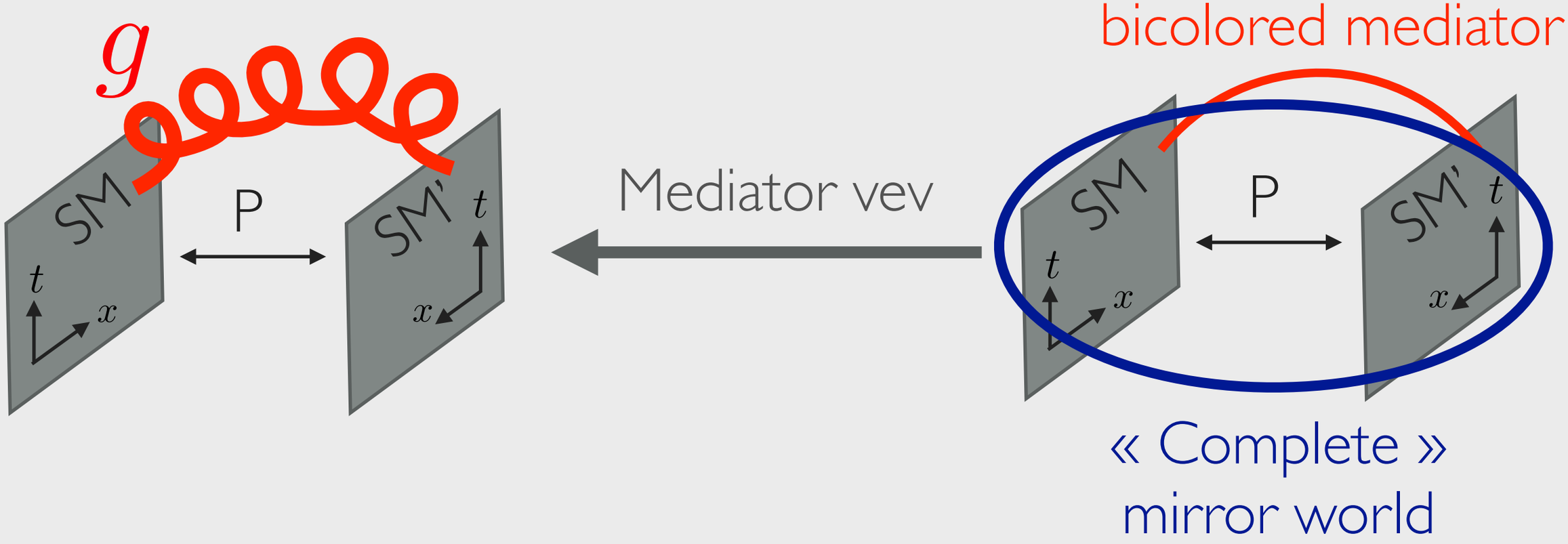
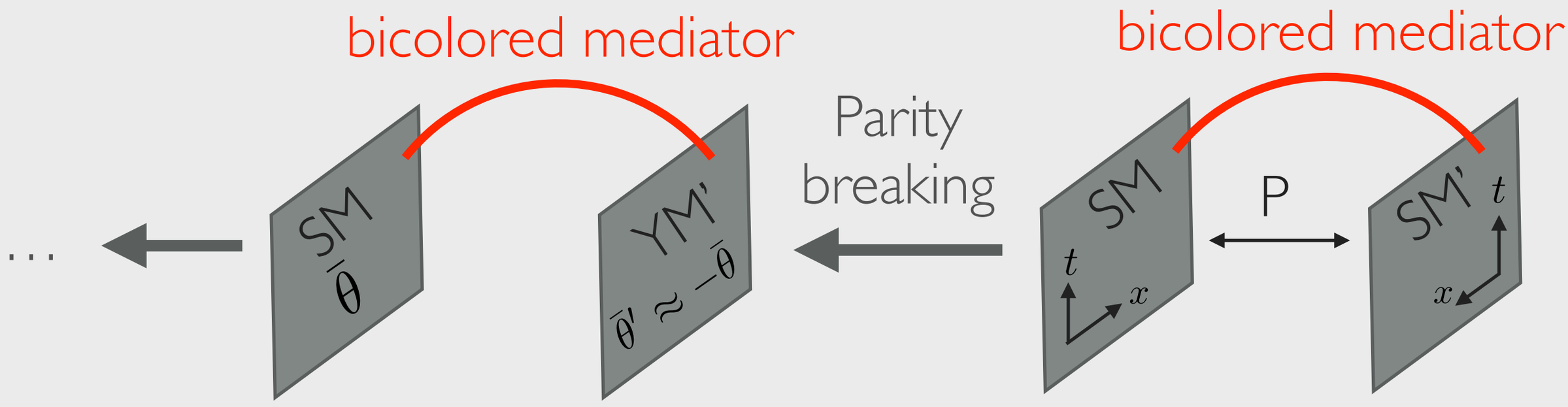


« Complete »
mirror world

Our parity solution to the strong CP problem

We notice that

With the same starting point :



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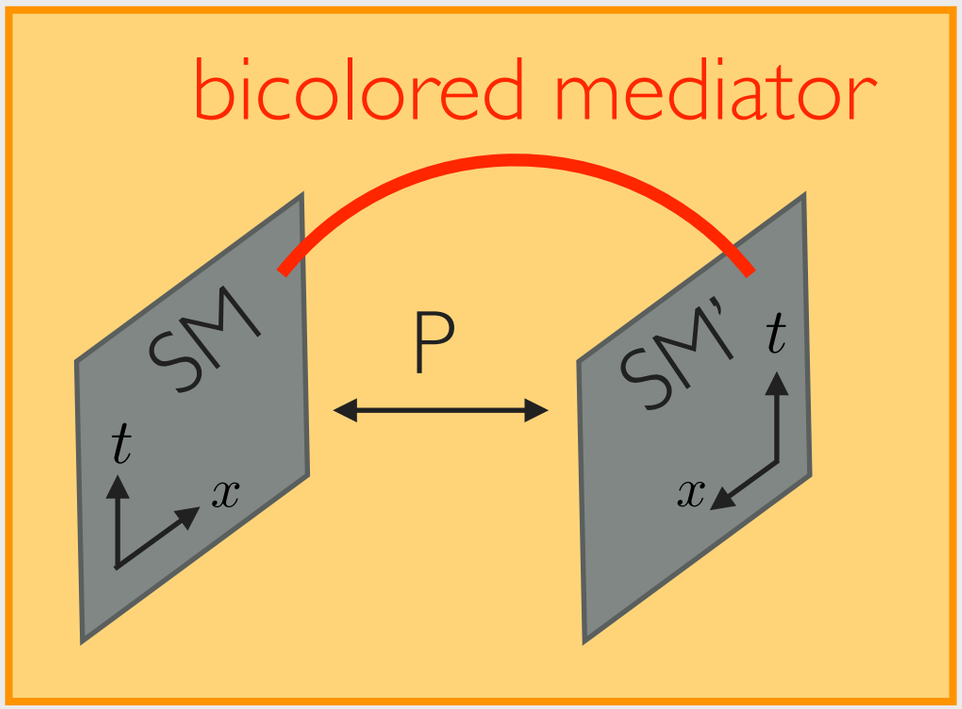
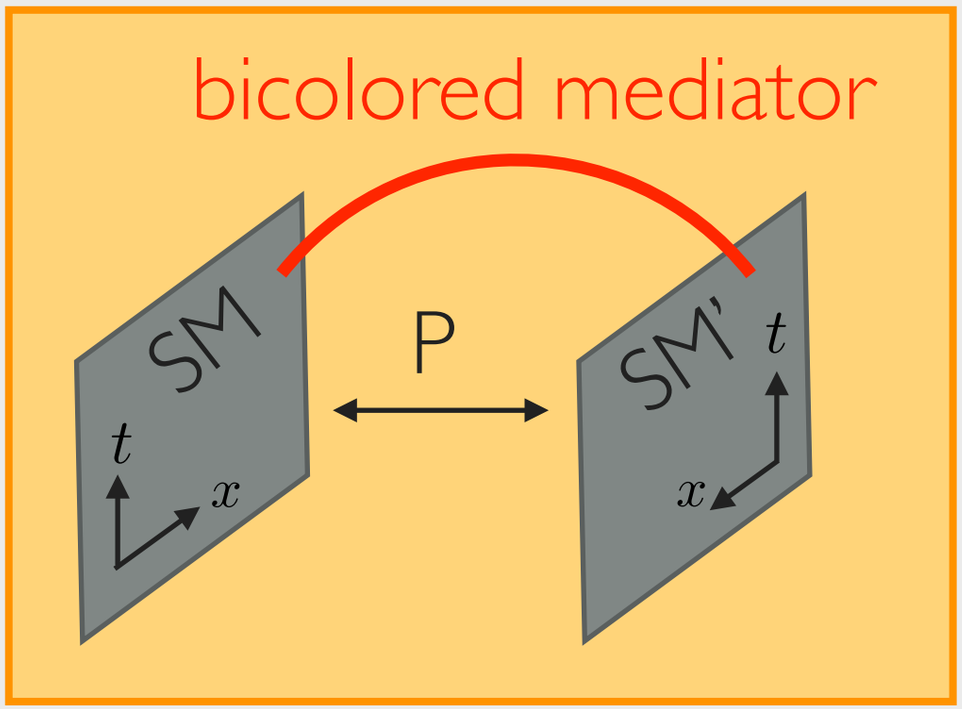


	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
Q	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathbf{1}$	$\mathbf{1}$	0
u^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	$-1/2$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

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

Our parity solution to the strong CP problem



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

$$\langle\Sigma\rangle \propto v_3 \mathbf{1}$$
$$\implies g_3^2 G\tilde{G} = \big|_{\text{along QCD}} g_3'^2 G'\tilde{G}'$$

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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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
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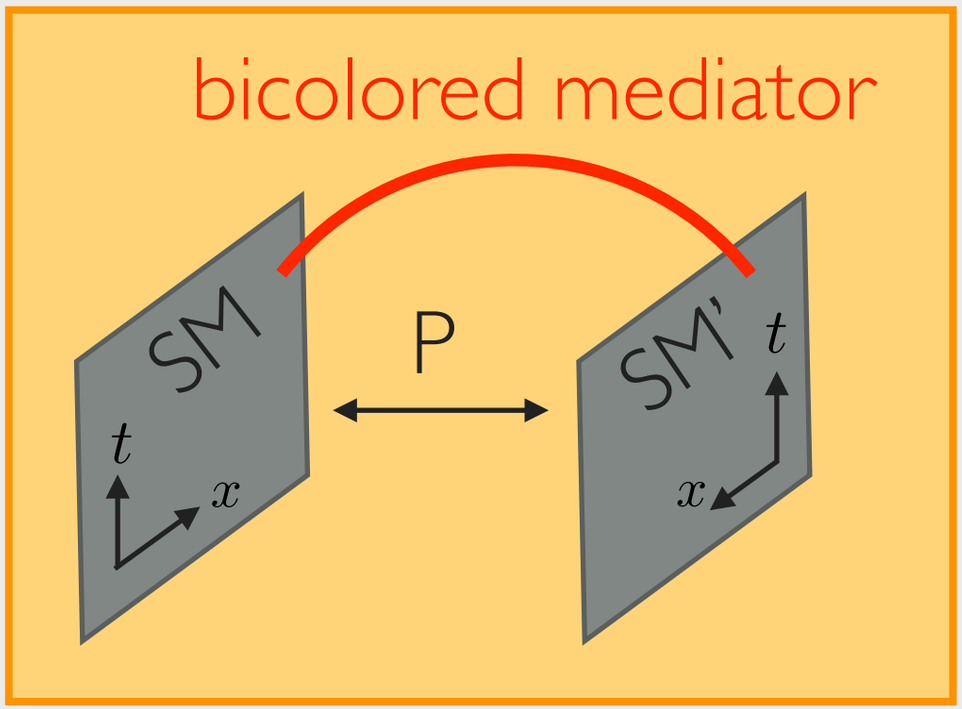
P

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

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

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) $\gtrsim v'$

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

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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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	$\mathbf{3}$	$\mathbf{1}$	$2/3$
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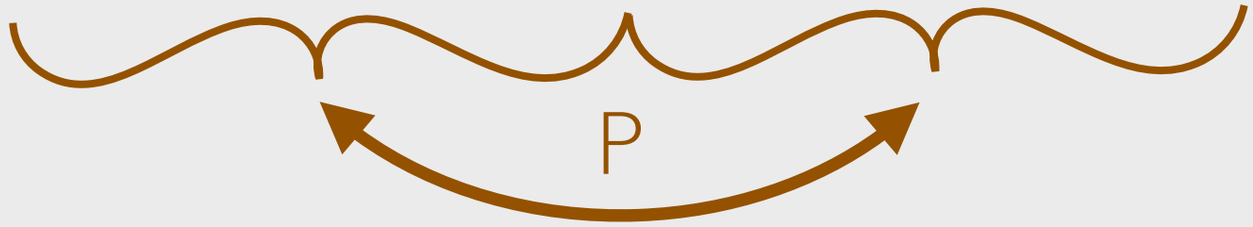
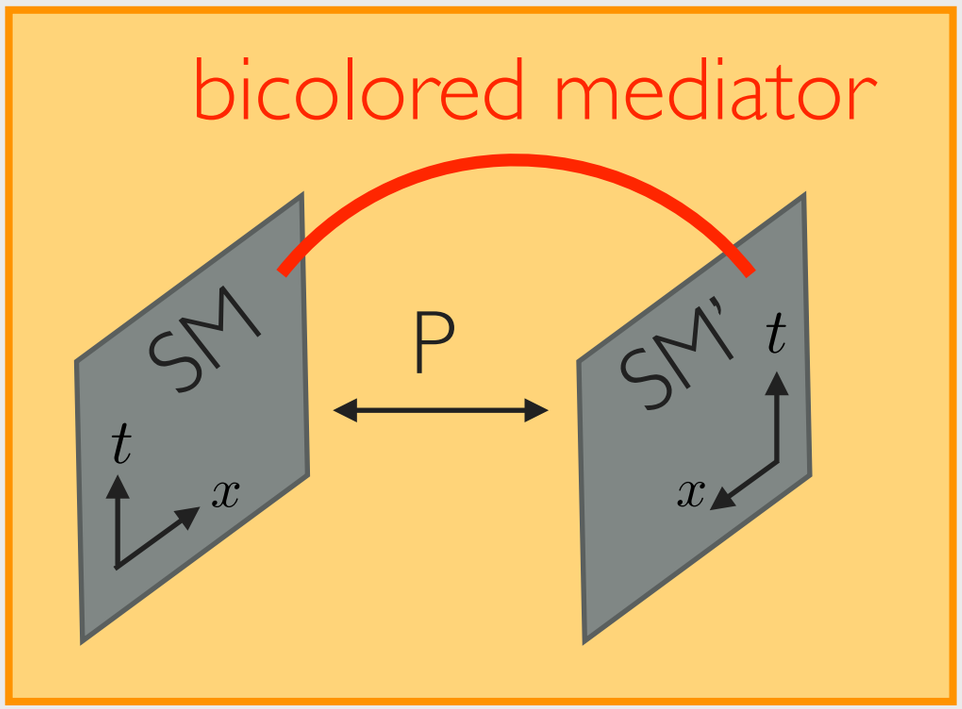


$$Y_q = Y_{q'}^\dagger \quad \Longrightarrow \quad \frac{m_q}{m_{q'}} = \frac{\langle H \rangle}{\langle H' \rangle}$$

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]

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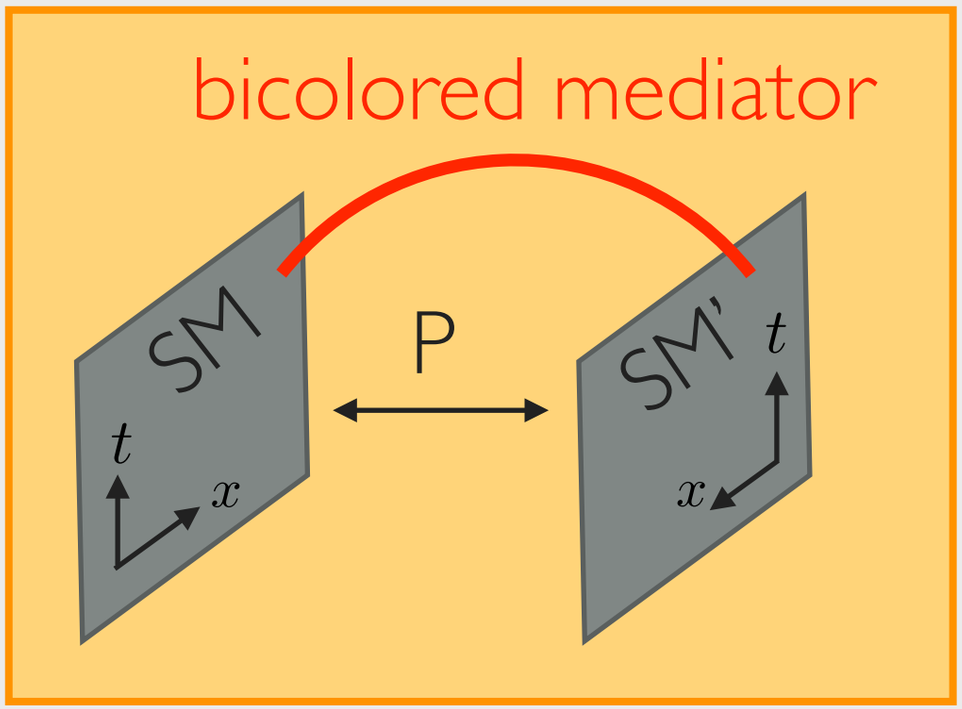
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	$-1/2$

P

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

Our parity solution to the strong CP problem



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

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

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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

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

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

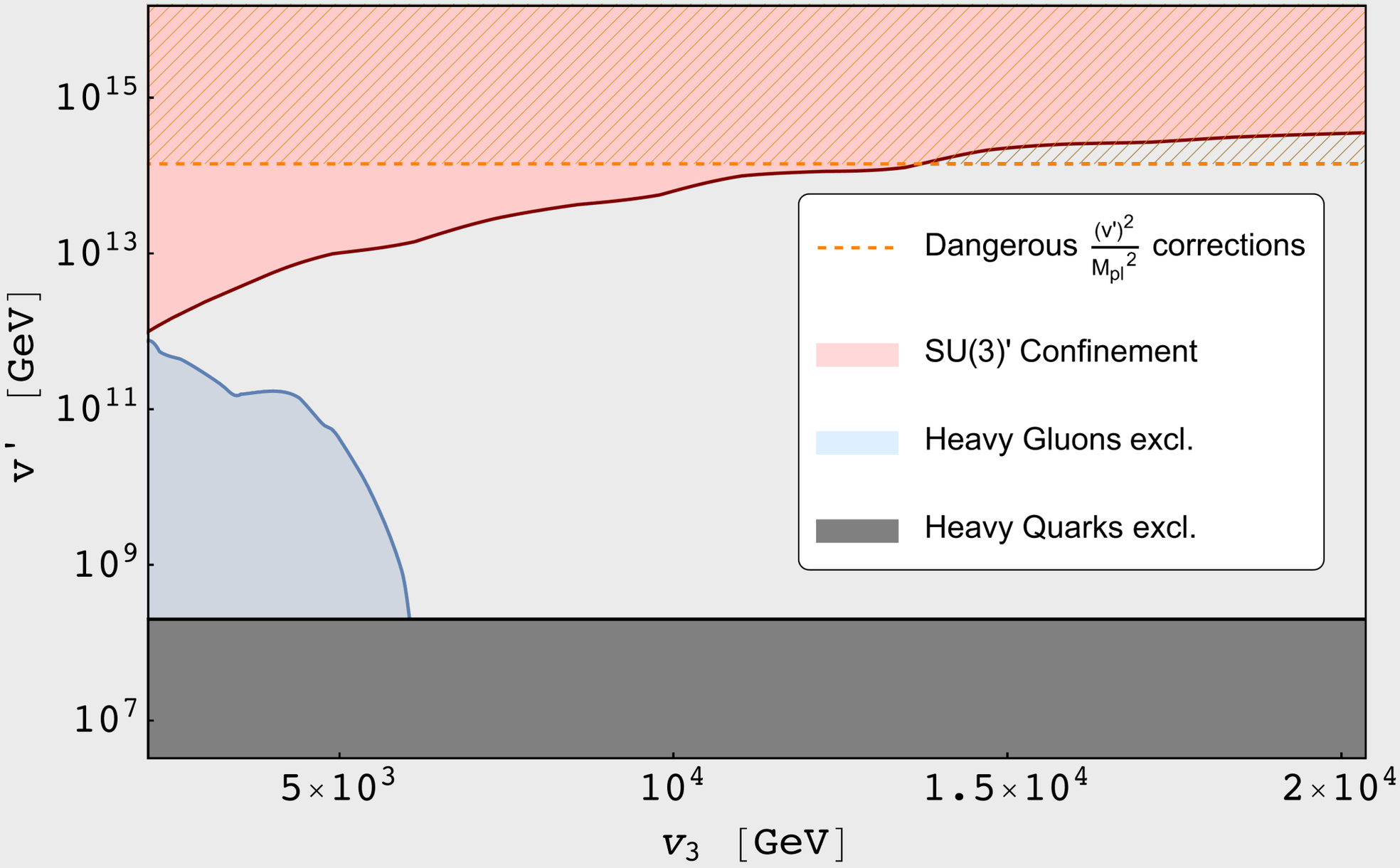
P for $\mathbf{3'=\bar{3}}$

Our parity solution to the strong CP problem

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

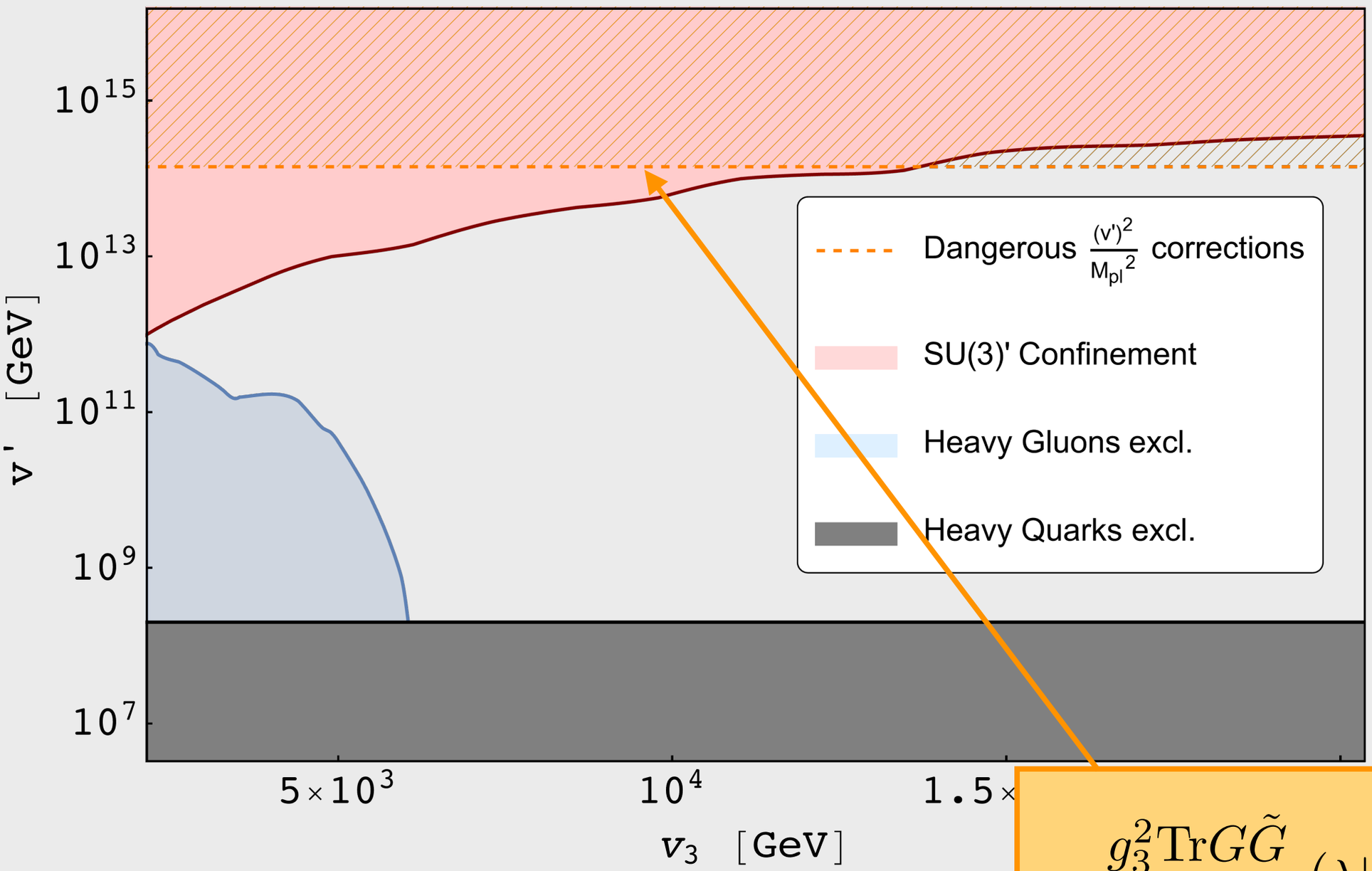
Only mediators: gluons, bicolored mediator or heavy Higgs. Only CP phase: CKM. **Very small contributions** (at least 3-loops) **to** $\bar{\theta}_{\rm QCD}$. Effect of small instantons also suppressed

Our parity solution to the strong CP problem



(scalar mediator)

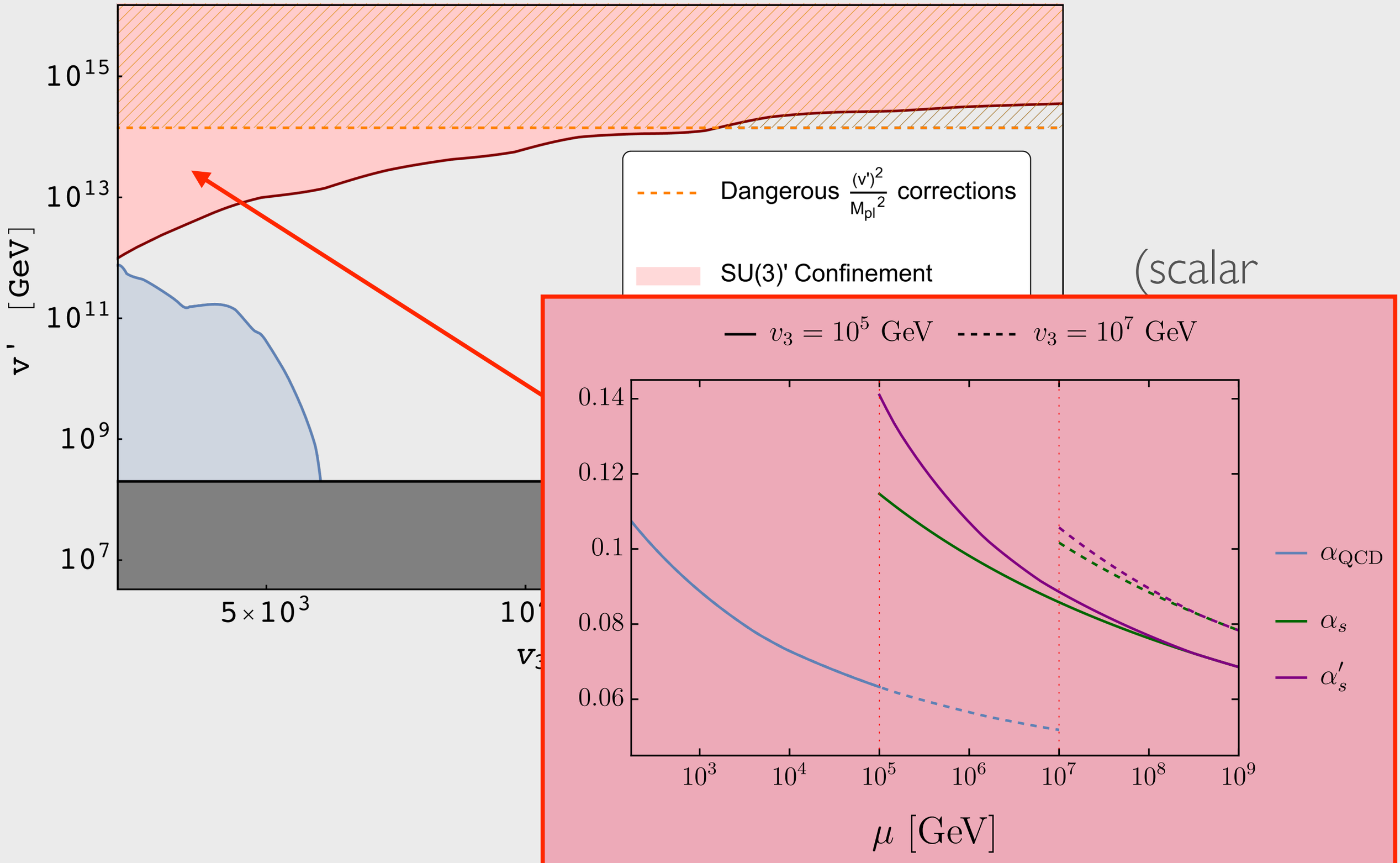
Our parity solution to the strong CP problem



(scalar mediator)

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

Our parity solution to the strong CP problem



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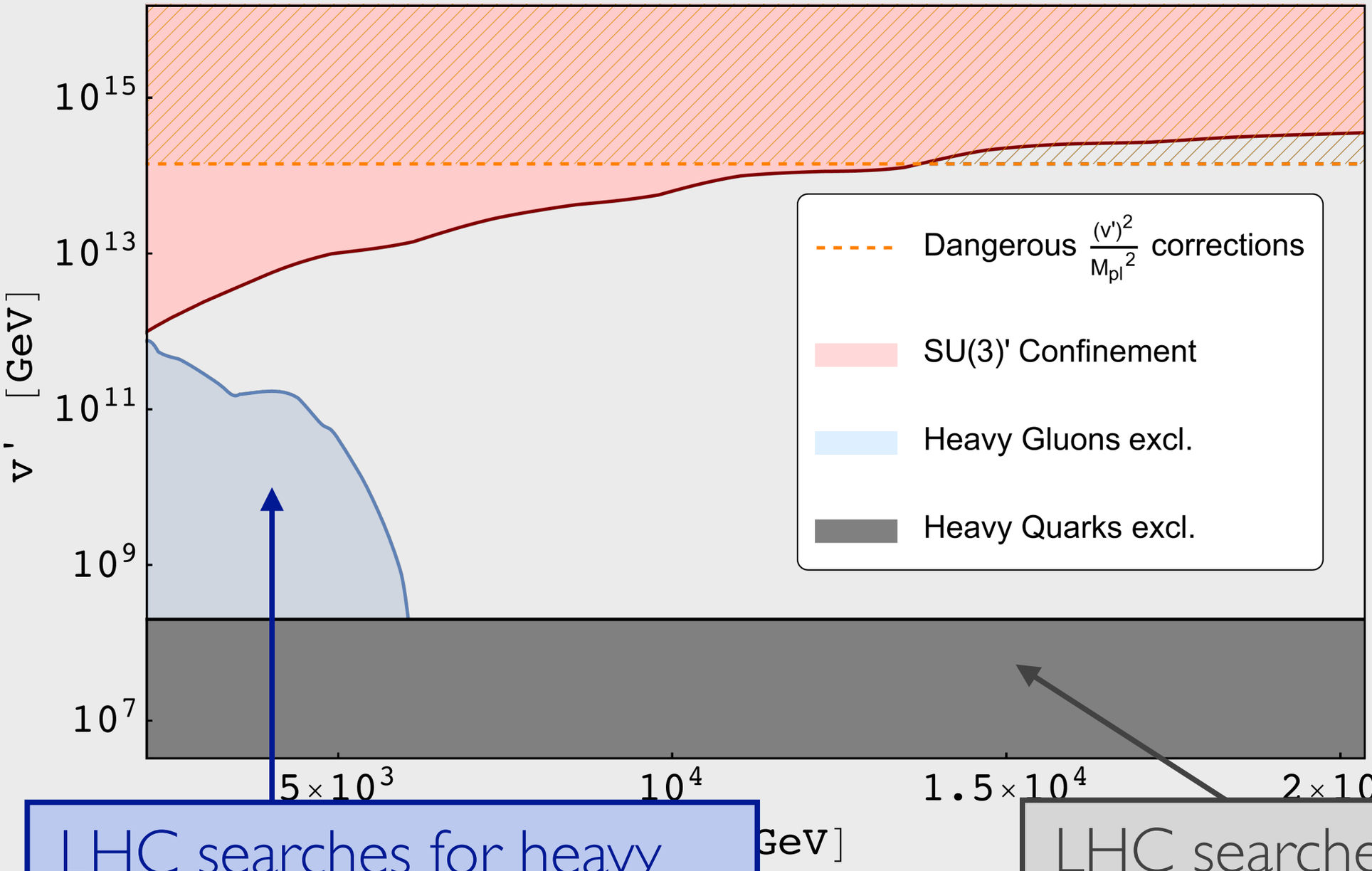
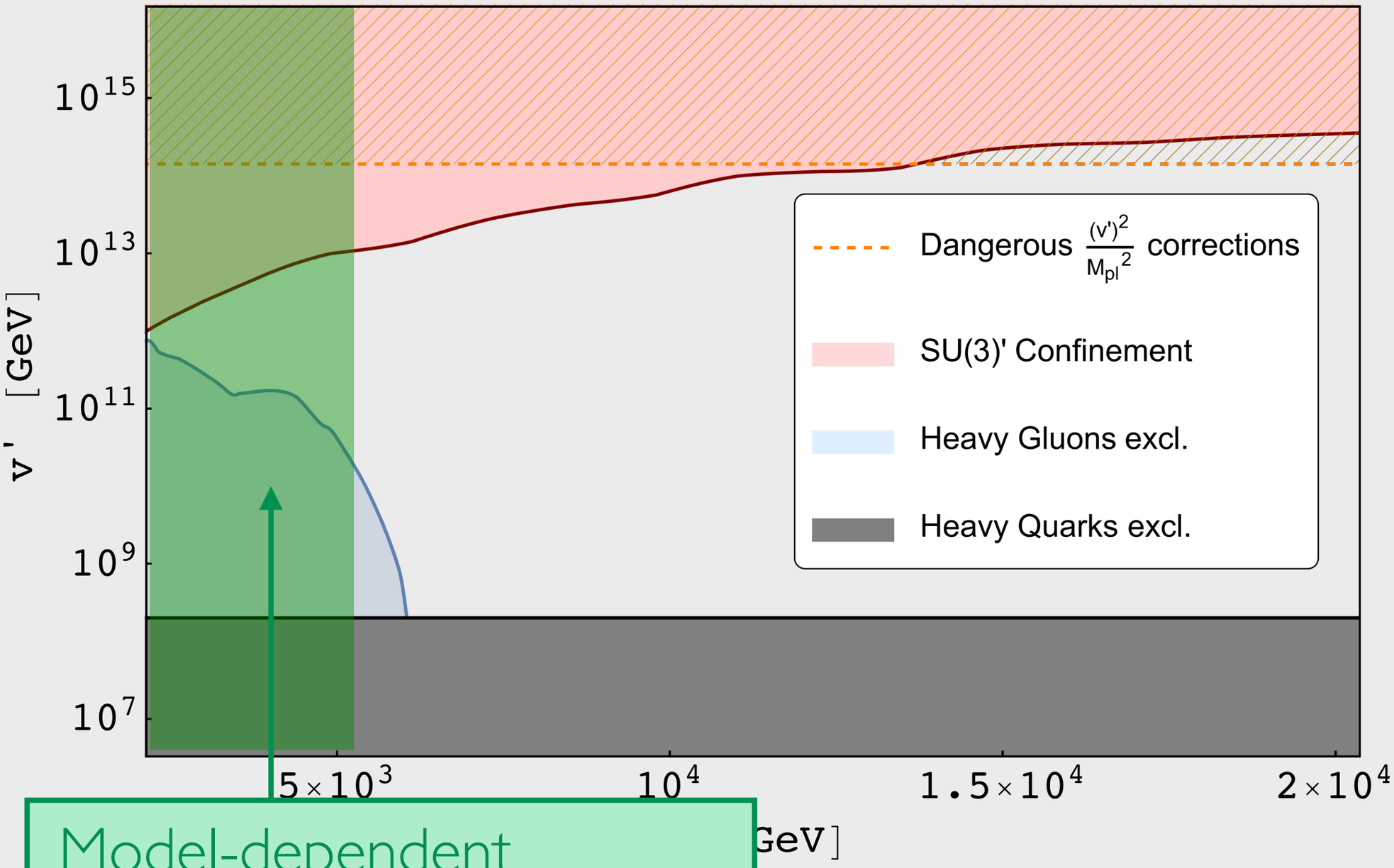


(scalar mediator)

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



(scalar mediator)

Model-dependent bounds on colored scalars

Dark matter from the mirror world

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

Only one viable : **mirror electron**

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Strong bounds on the stable mirror up quark relic density

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

[Goodman/Witten '85, Kawamura/Okawa/Omura/Tang '18, Dunsky/Hall/Harigaya '19]

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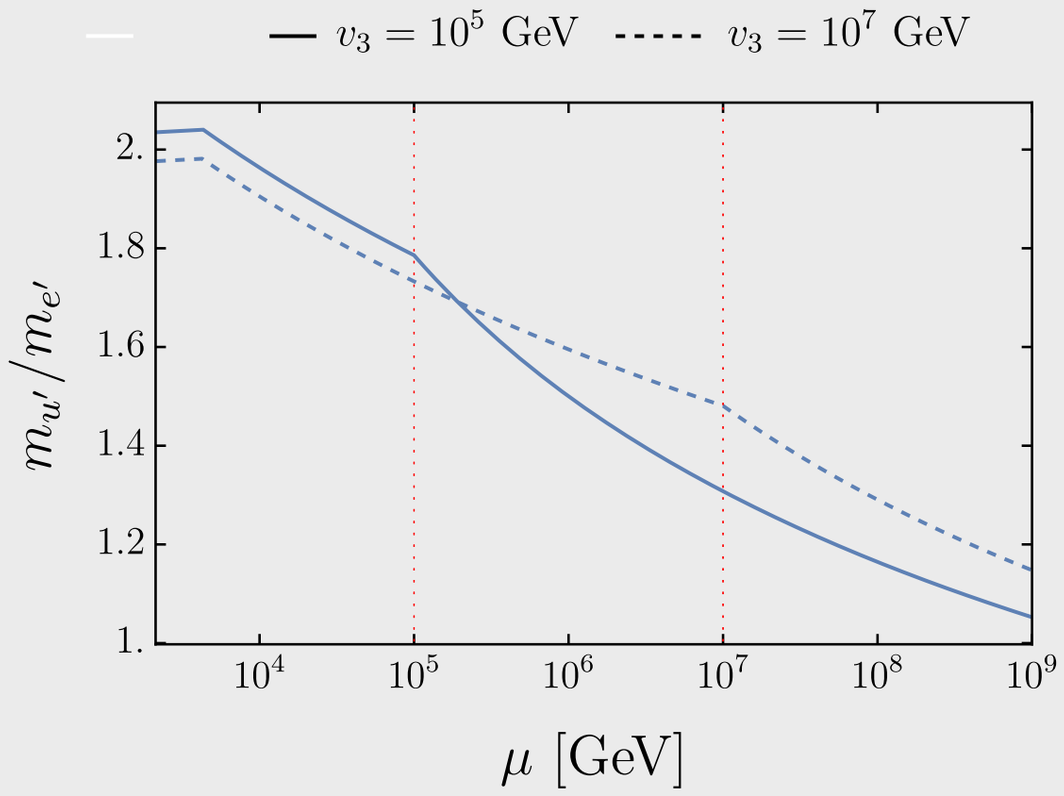

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Masses are fixed by parity ! Cannot do freeze-out (w/ or w/o dilution)

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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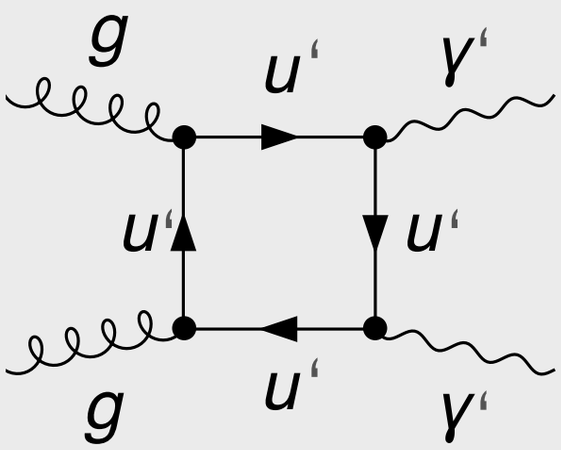
Sequential freeze-in from the mirror photon

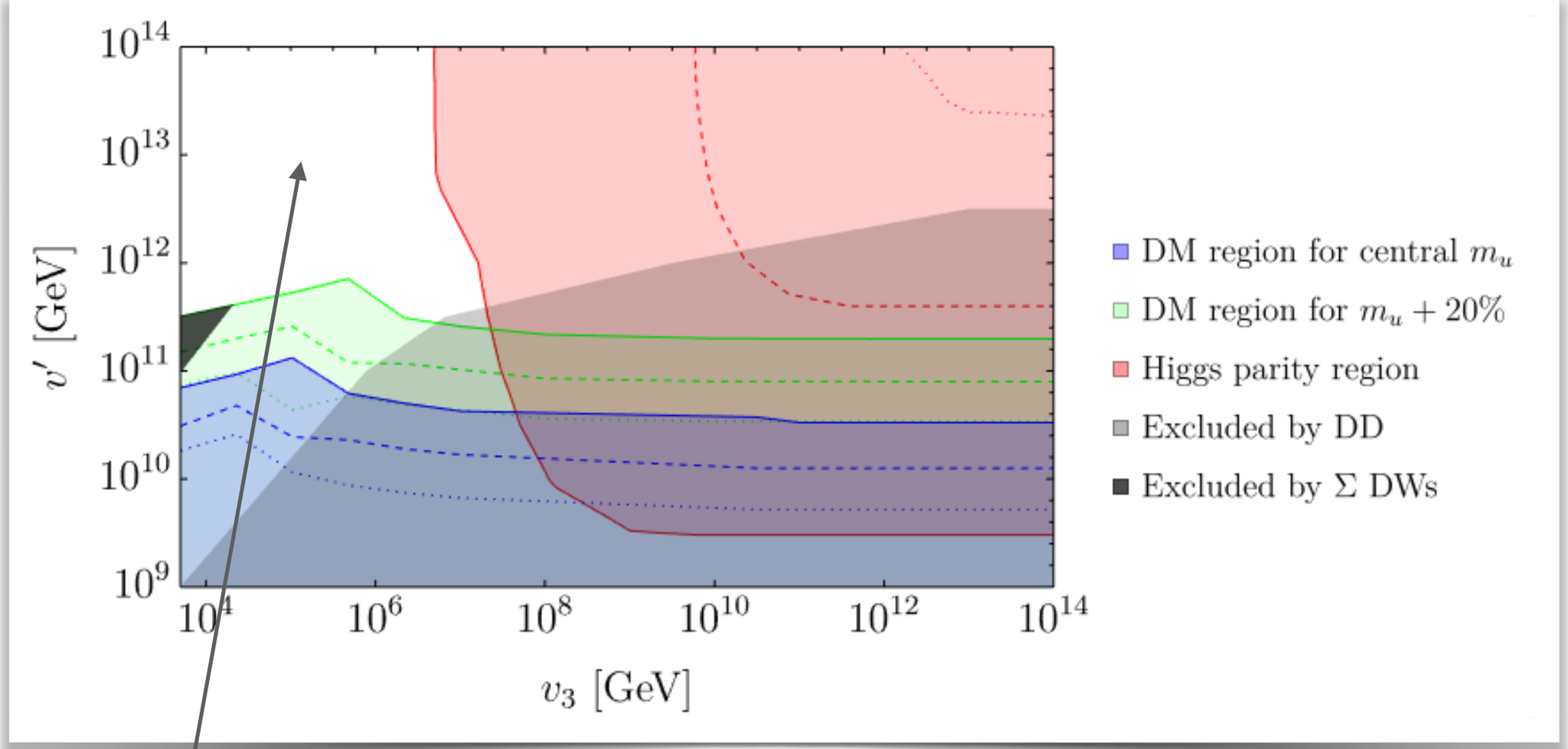


[Hambye/Tytgat/Vandecasteele/Vanderheyden '18, Bélanger/Delaunay/Pukhov/Zaldivar '19]

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

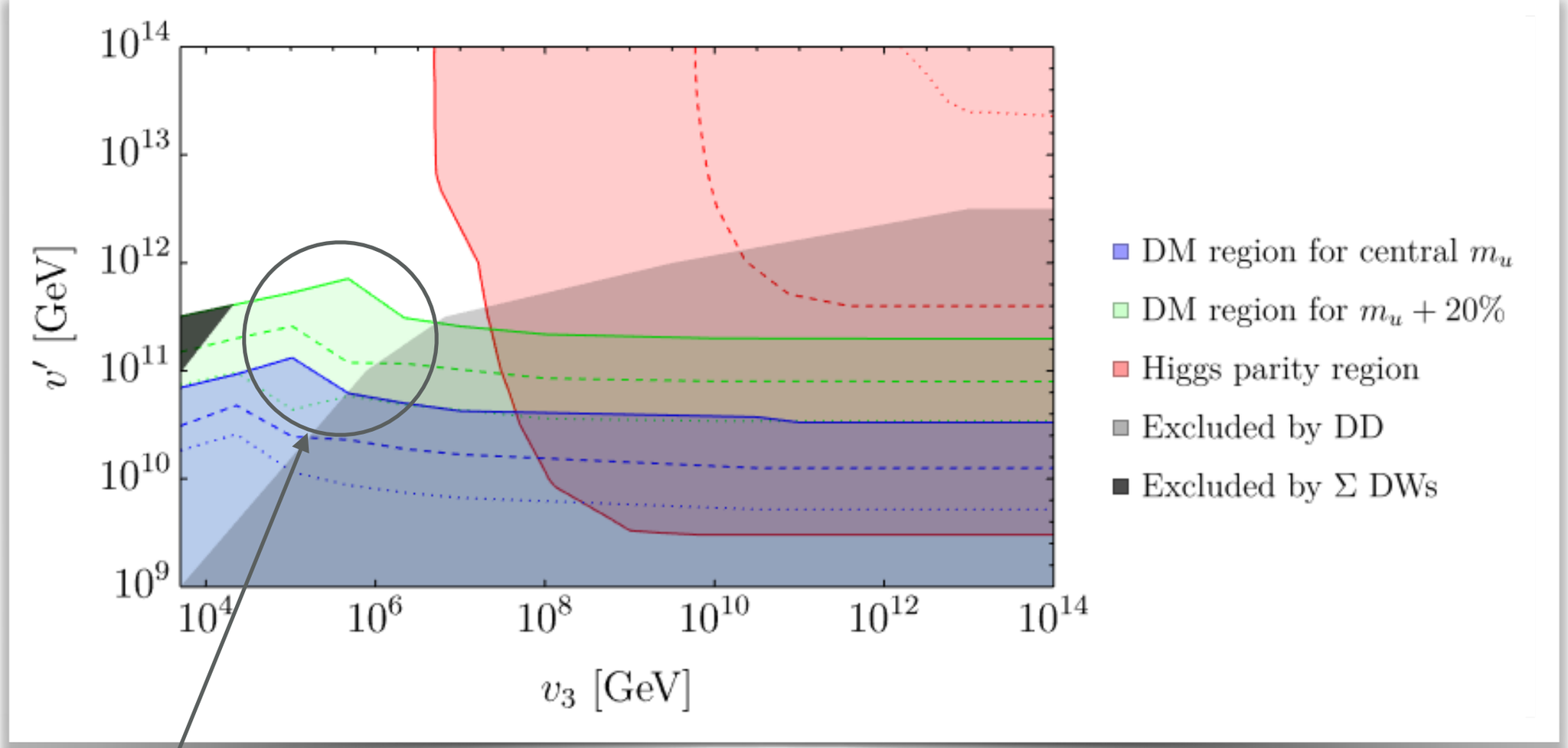
Inflation ? Reheating to the SM and $T_{\rm max} \approx T_{\rm rh}$

Dark matter from the mirror world



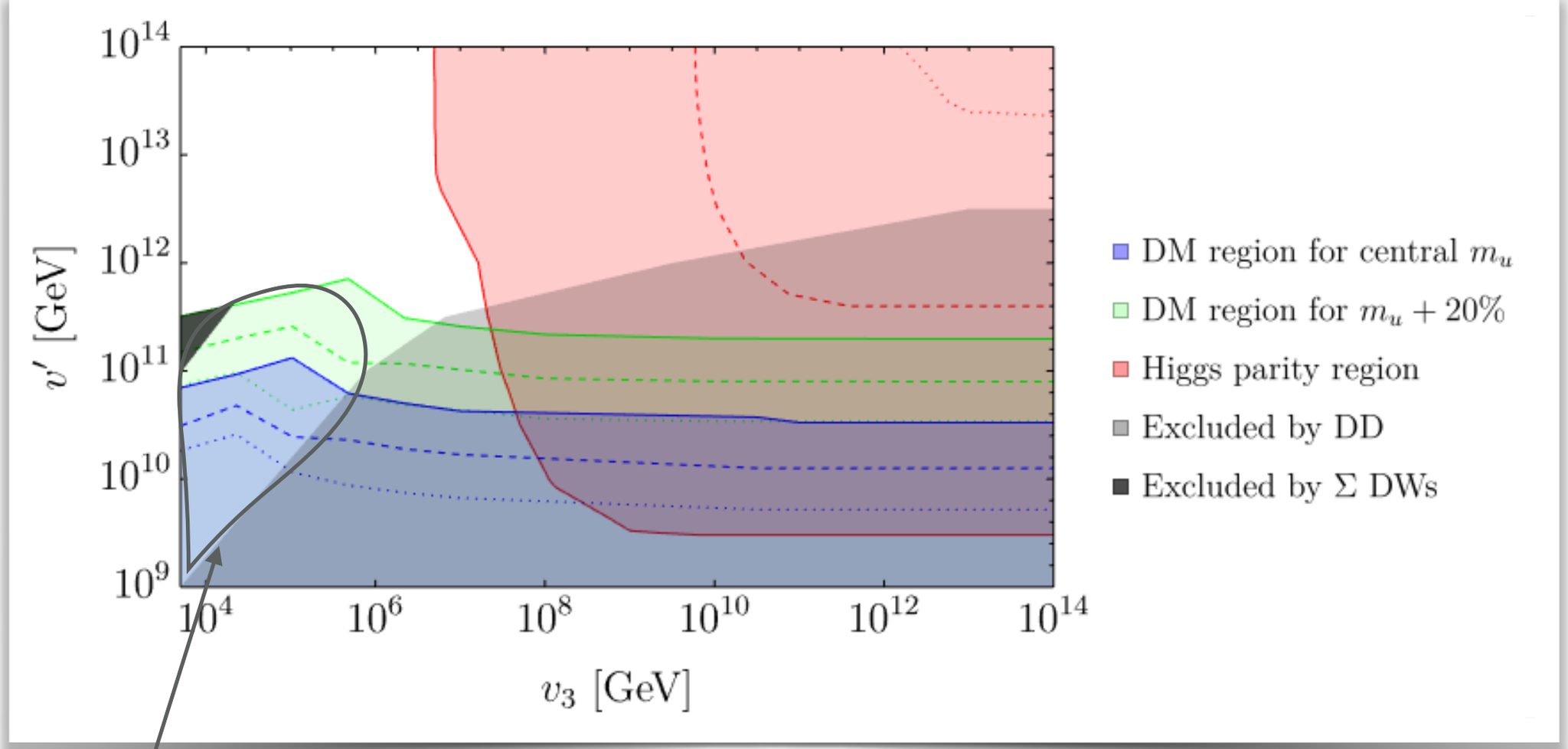
No appropriate
reheating temperature

Dark matter from the mirror world



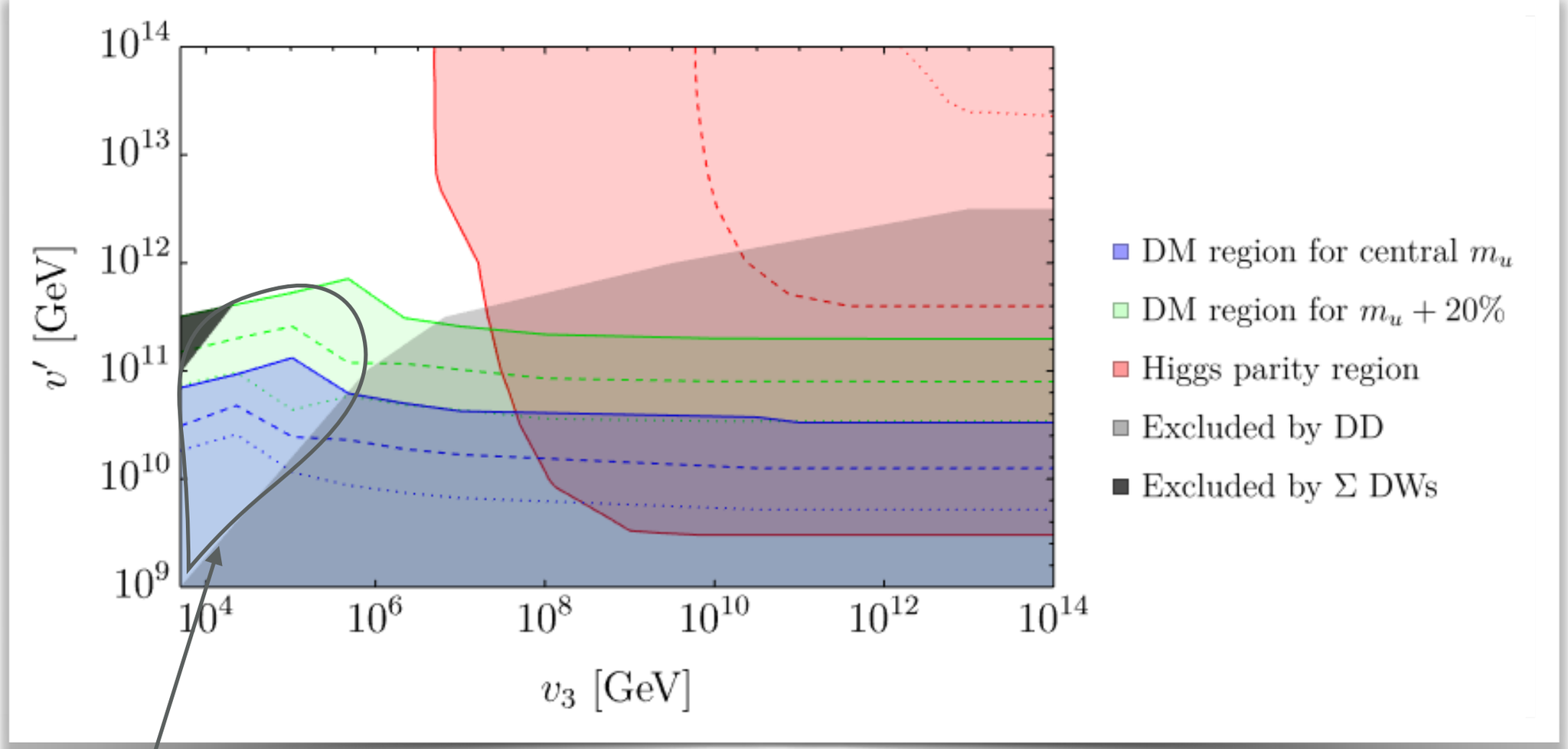
First interest of low v_3 (ratio $m_{u'}/m_{e'}$)

Dark matter from the mirror world



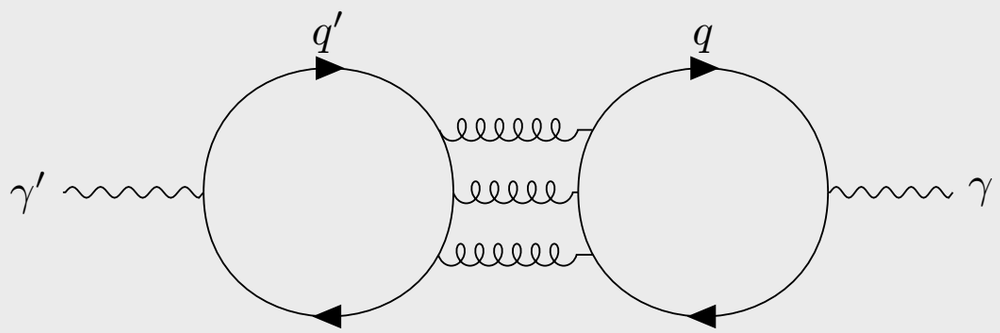
Main interest of
low v_3
(kinetic mixing)

Dark matter from the mirror world



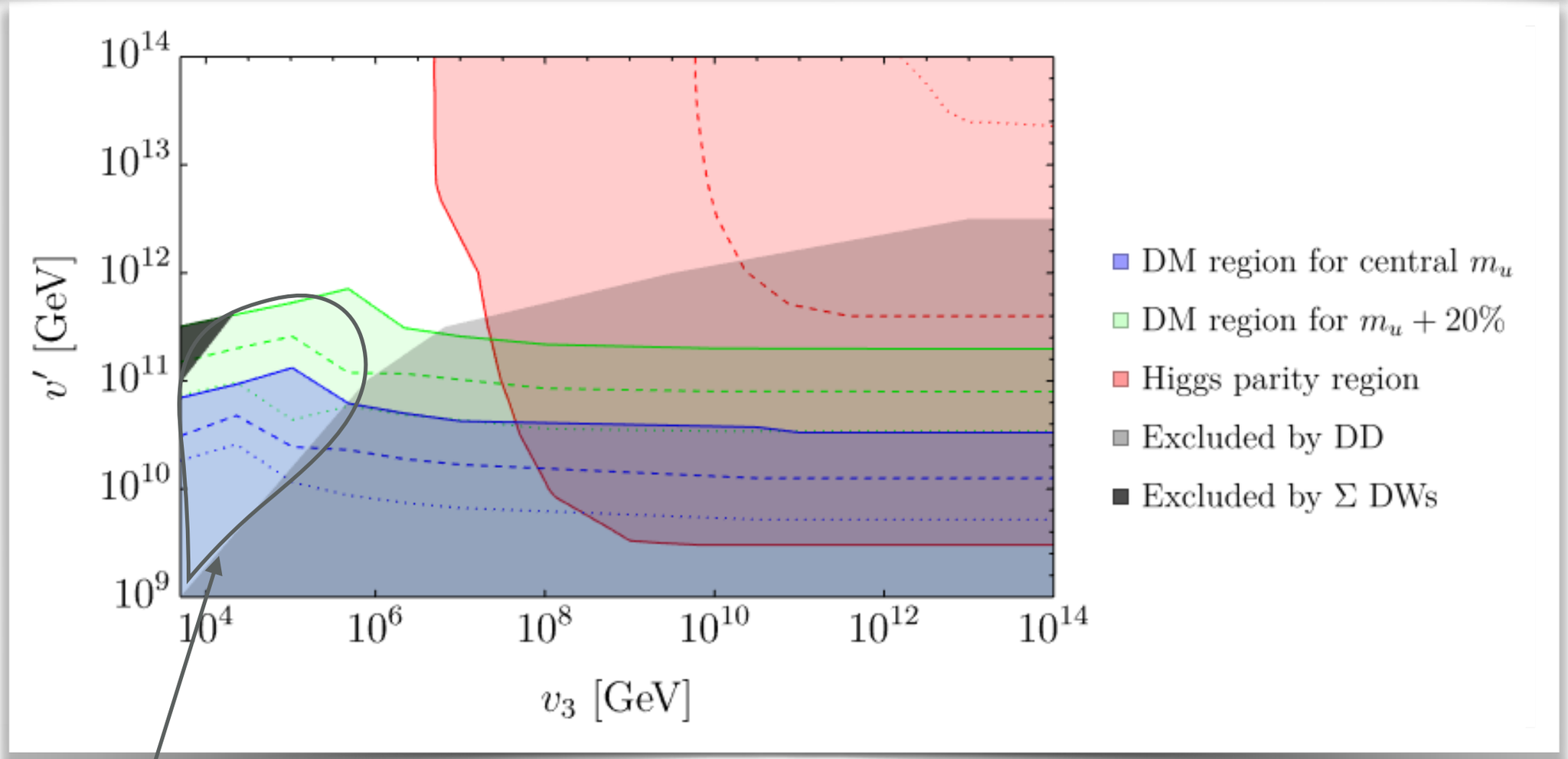
Main interest of low v_3 **(kinetic mixing)**

$$m_{u'} < v_3$$



[Dunsky/Hall/Harigaya '19]

Dark matter from the mirror world



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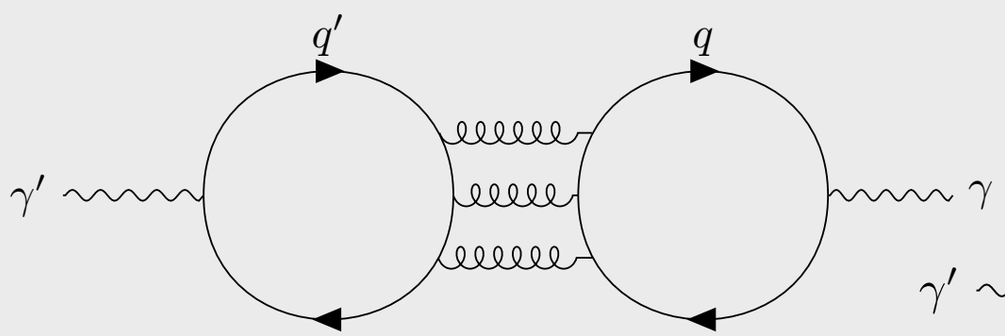

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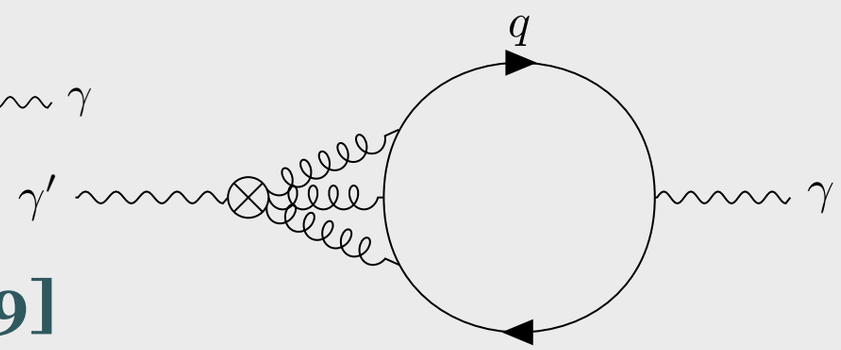

[Dunsky/Hall/Harigaya '19]

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** !

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