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

Speakers: Quentin Bonnefoy

Series: Particle Physics

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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.

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

Zoom link

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

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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

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

complex matrix !
CP-odd part

(C)P-odd

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

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

The strong CP problem

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But non-perturbativ

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

Strong CP problem :

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

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]

Solutions to the strong CP problem

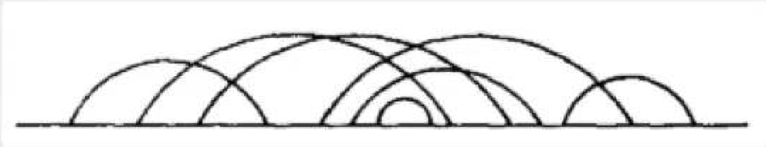
$$\mathcal{L}_{\rm SM} \supset \frac{g_s^2 \bar{\theta}}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

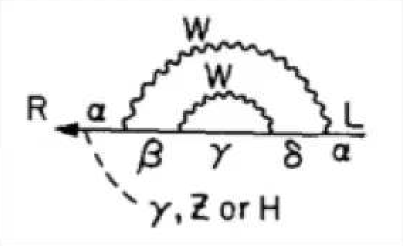
How to set $\bar{\theta} \approx 0$?

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

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

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An effective field theorist's nightmare ! IR solutions.

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

Solutions to the strong CP problem

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Massless quark : ambiguous ! **['t Hooft '76]**	Relaxes to zero ! **[Vafa/Witten '84]**
Ruled out by lattice **[Aoki et al '16]**	**Also DM !**

Solutions to the strong CP problem

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An effective field theorist's nightmare ?

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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 ?

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

→

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

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

Higgsed : broken parity

↓

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

Higgs couplings : too light !

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↓

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

can mix !

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

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

$\mathbf{1}, \mathbf{2}$ $\mathbf{0}, \mathbf{1/6}$
$Q_R(\mathbf{3}, \mathbf{2}, 1/6)$
same + $d_L(\mathbf{3}, \mathbf{1}, -1/3)$
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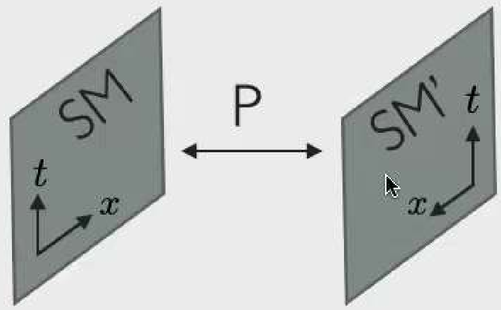
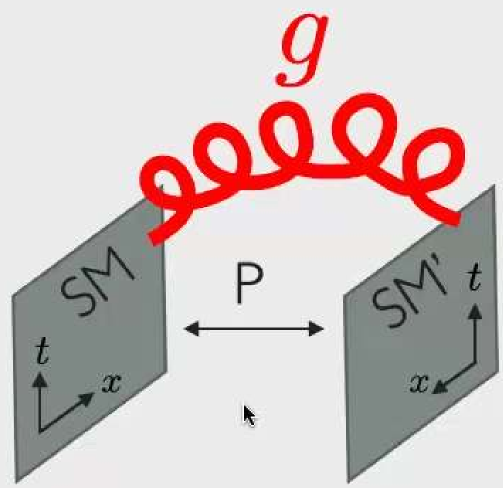
Parity solutions to the strong CP problem

Mirror world



Parity solutions to the strong CP problem

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



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

Parity solutions to the strong CP problem

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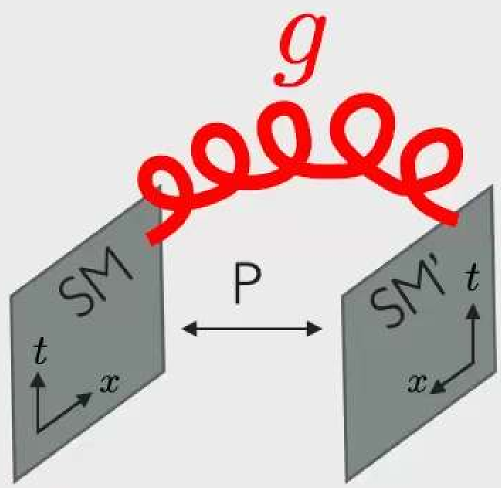


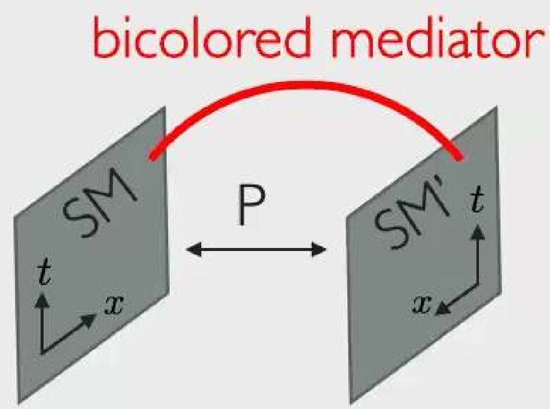
$$\langle H \rangle \neq \langle H' \rangle$$

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

Our parity solution to the strong CP problem

We notice that

With the same starting point :



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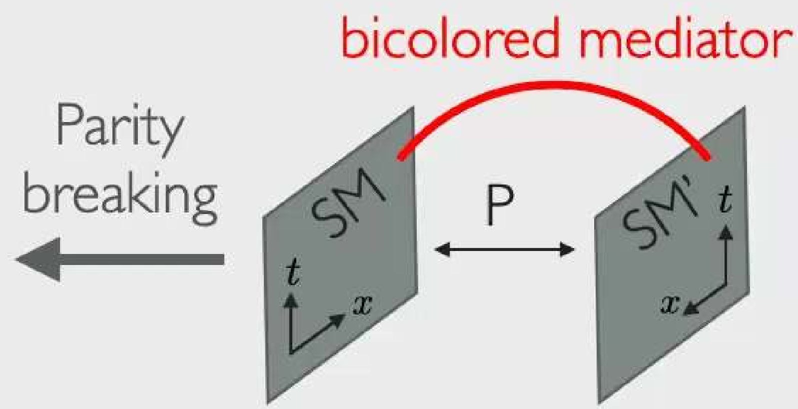

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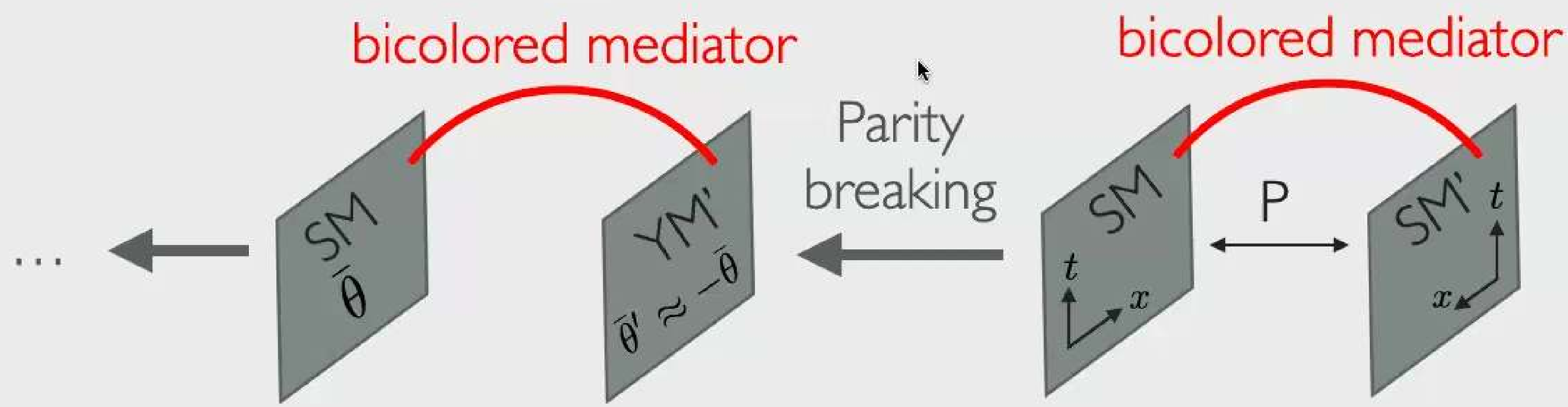
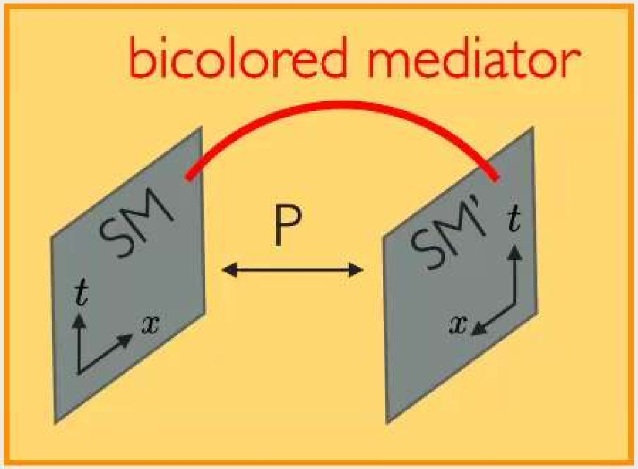


Our parity solution to the strong CP problem



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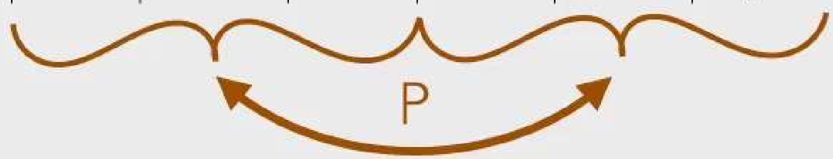
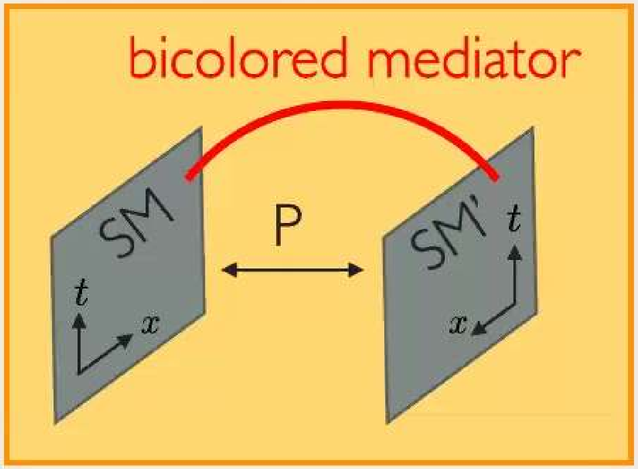
H'	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{2}$	-1/2



Our parity solution to the strong CP problem



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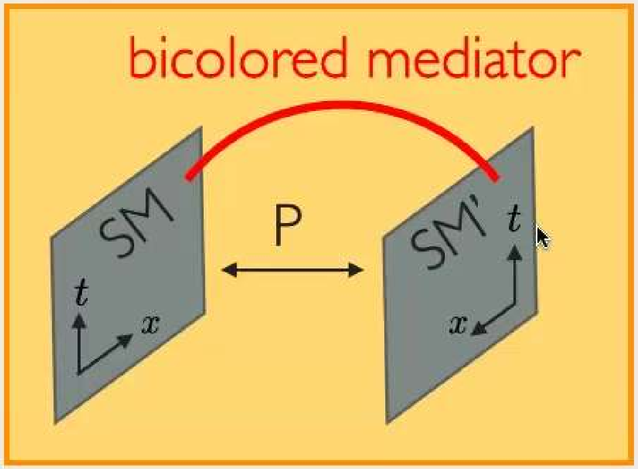
$$\left.\begin{array}{l}\theta' = -\theta \\ Y_q = Y_{q'}^{\dagger}\end{array}\right\} \Longrightarrow \bar{\theta}' = -\bar{\theta}$$

Our parity solution to the strong CP problem



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

	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$SU(3)'$	$SU(2)'$	$U(1)'$
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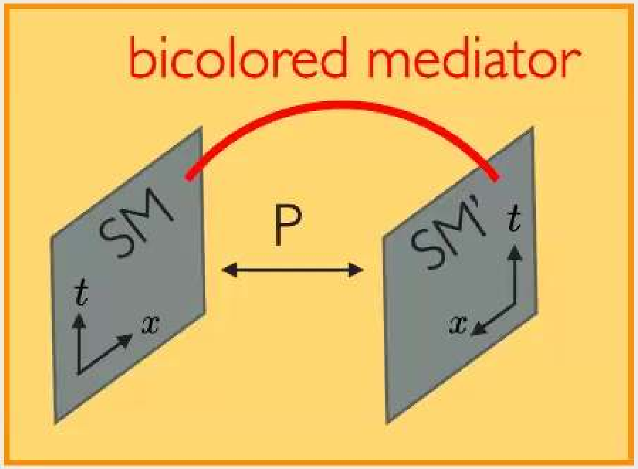
Our parity solution to the strong CP problem



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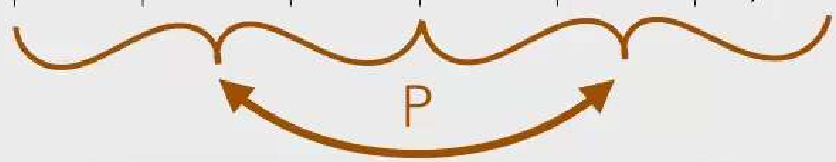


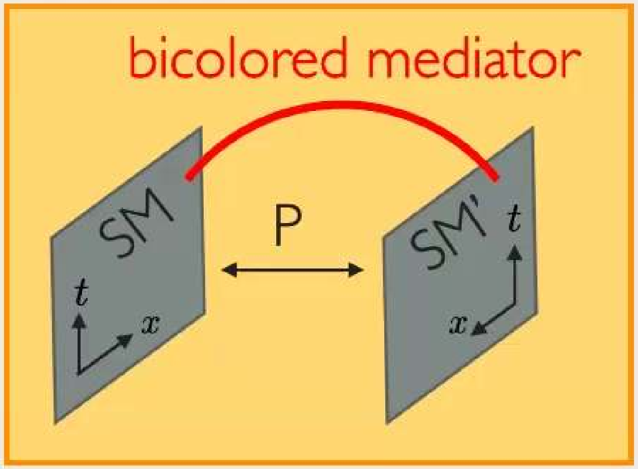
Bicolored mediator here: bifundamental order parameter $\langle \Sigma \rangle$

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

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

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

Our parity solution to the strong CP problem



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

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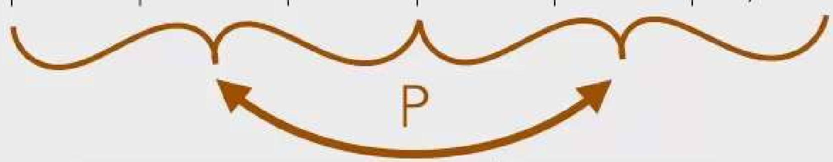
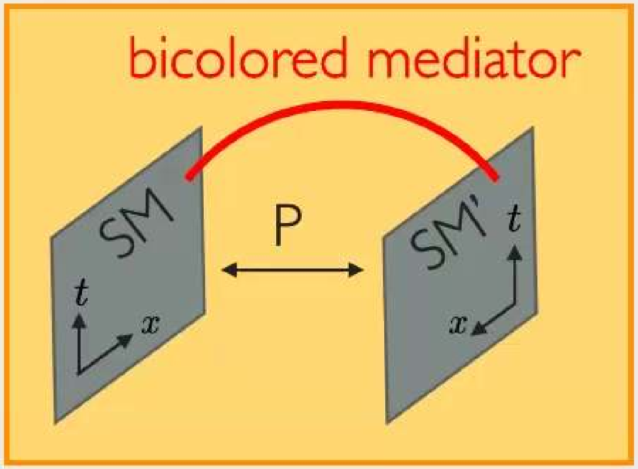


$$Y_q = Y_{q'}^\dagger \implies \frac{m_q}{m_{q'}} = \frac{\langle H \rangle}{\langle H' \rangle}$$

Our parity solution to the strong CP problem



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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	$\bar{\mathbf{3}}$	$\mathbf{2}$	-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

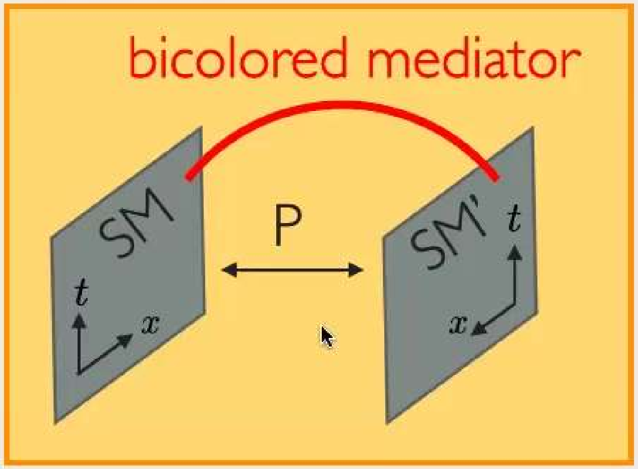
Below v_3, colored mirror quarks : need $\langle H' \rangle \gg \langle H \rangle$
(hence P-breaking) $\equiv v'$

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'

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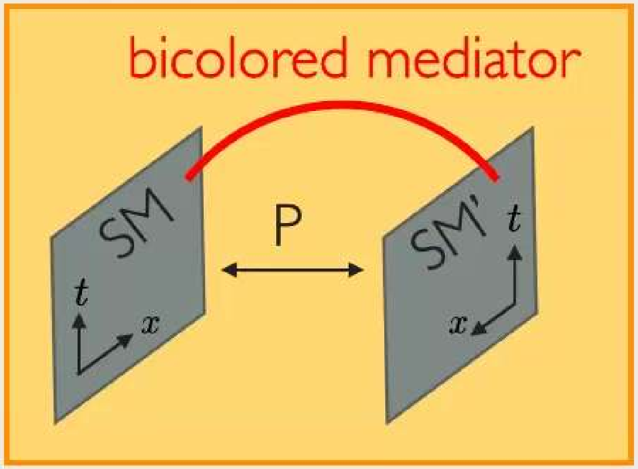

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u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	$\mathbf{1}$	$\mathbf{1}$	0
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	$\mathbf{1}$	$\mathbf{1}$	0
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
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H'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

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

  ($\mathbf{3}'$: $\mathbf{3}$ 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 $\mathbf{3}'=\mathbf{3}$

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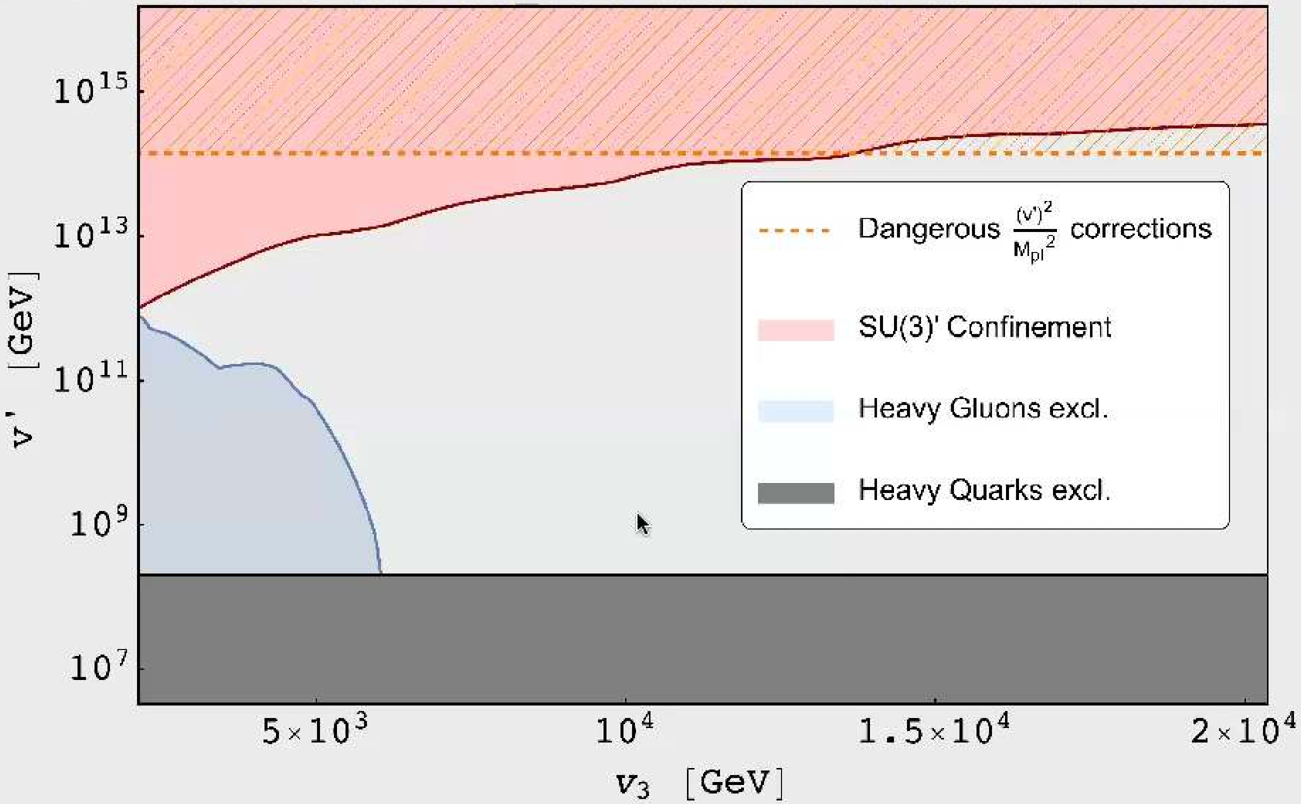
Only mediators: gluons, bicolored mediator or heavy Higgs. Only CP phase: CKM. **Very small contributions** (at least 3-loops) **to** $\bar{\theta}_{\rm QCD}$. Effect of small instantons also suppressed

Our parity solution to the strong CP problem



(scalar mediator)

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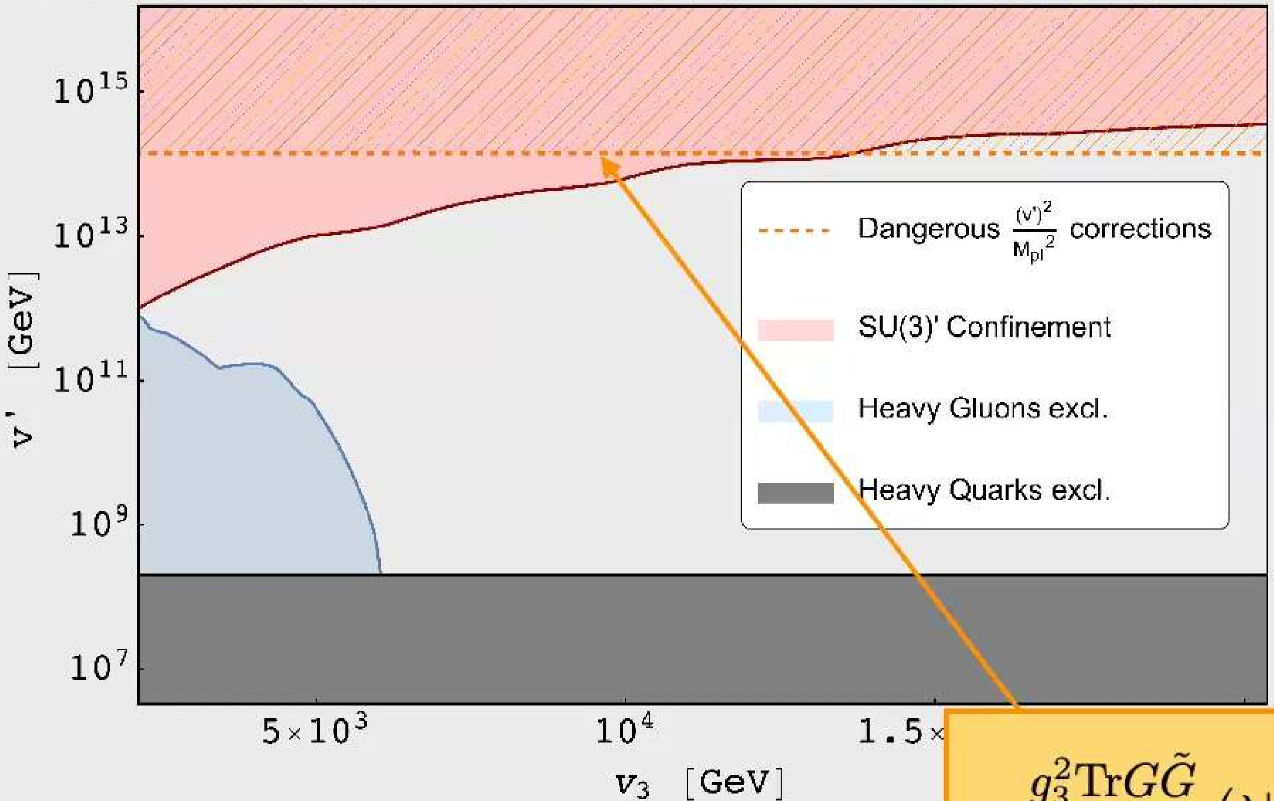

$$\frac{g_3^2 \mathrm{Tr} G\tilde{G}}{16\pi^2 M_P^2}\left(\lambda|H|^2 + \lambda'|H'|^2\right) - (g_3, G, H \leftrightarrow g_3', G', H')$$

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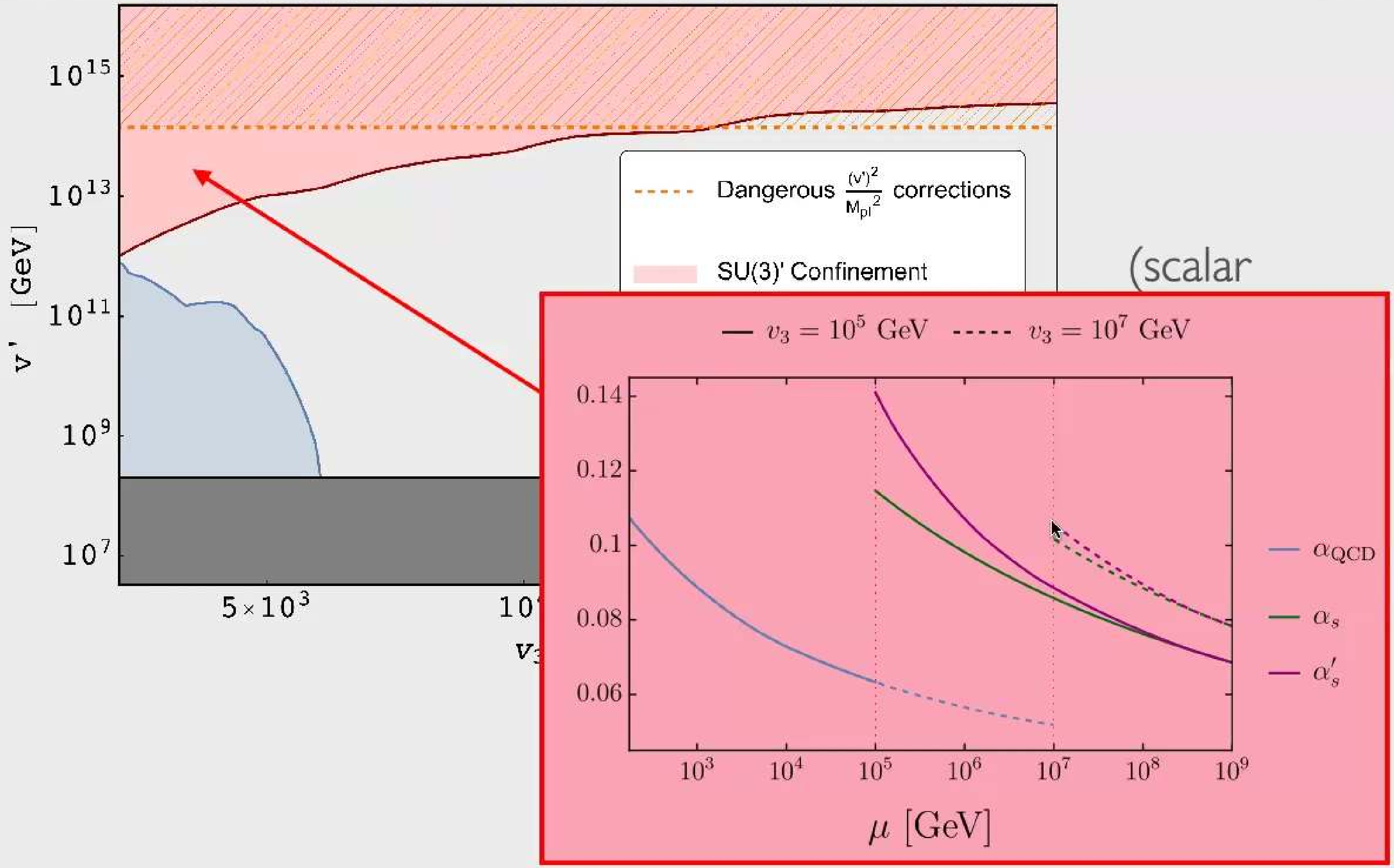

(scalar

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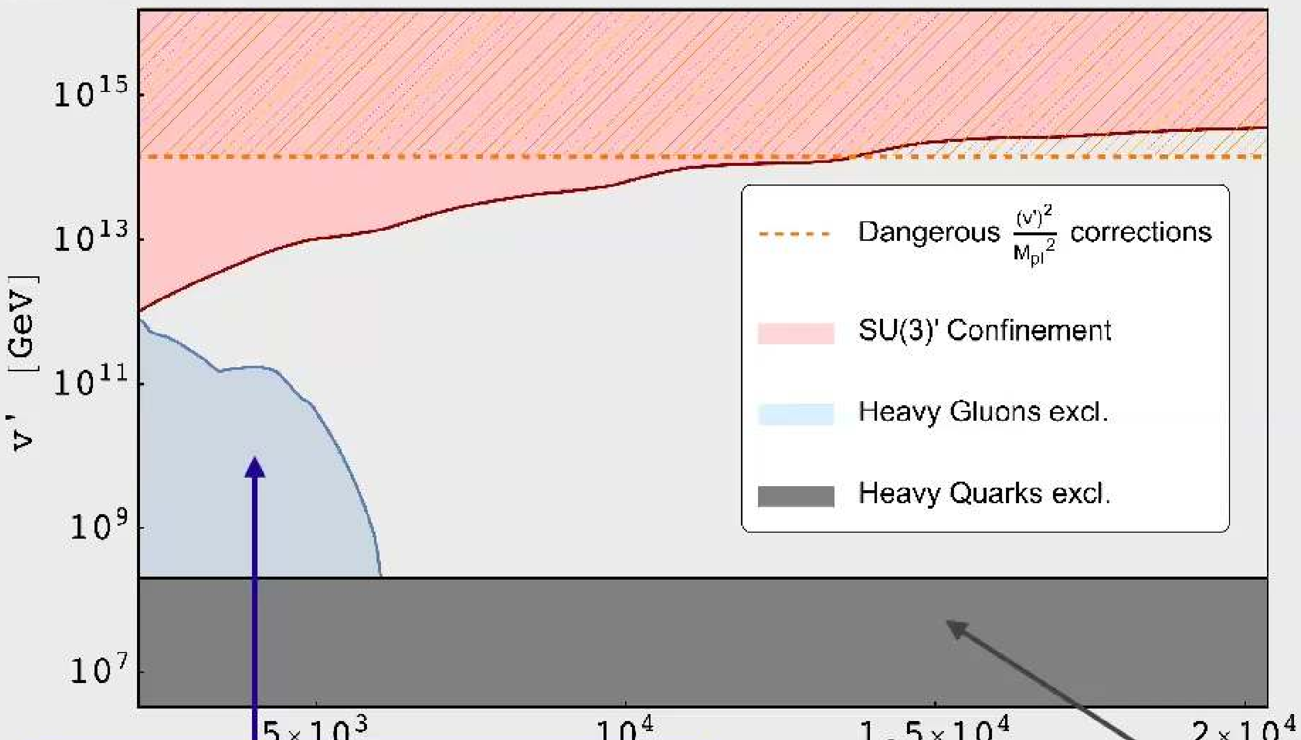


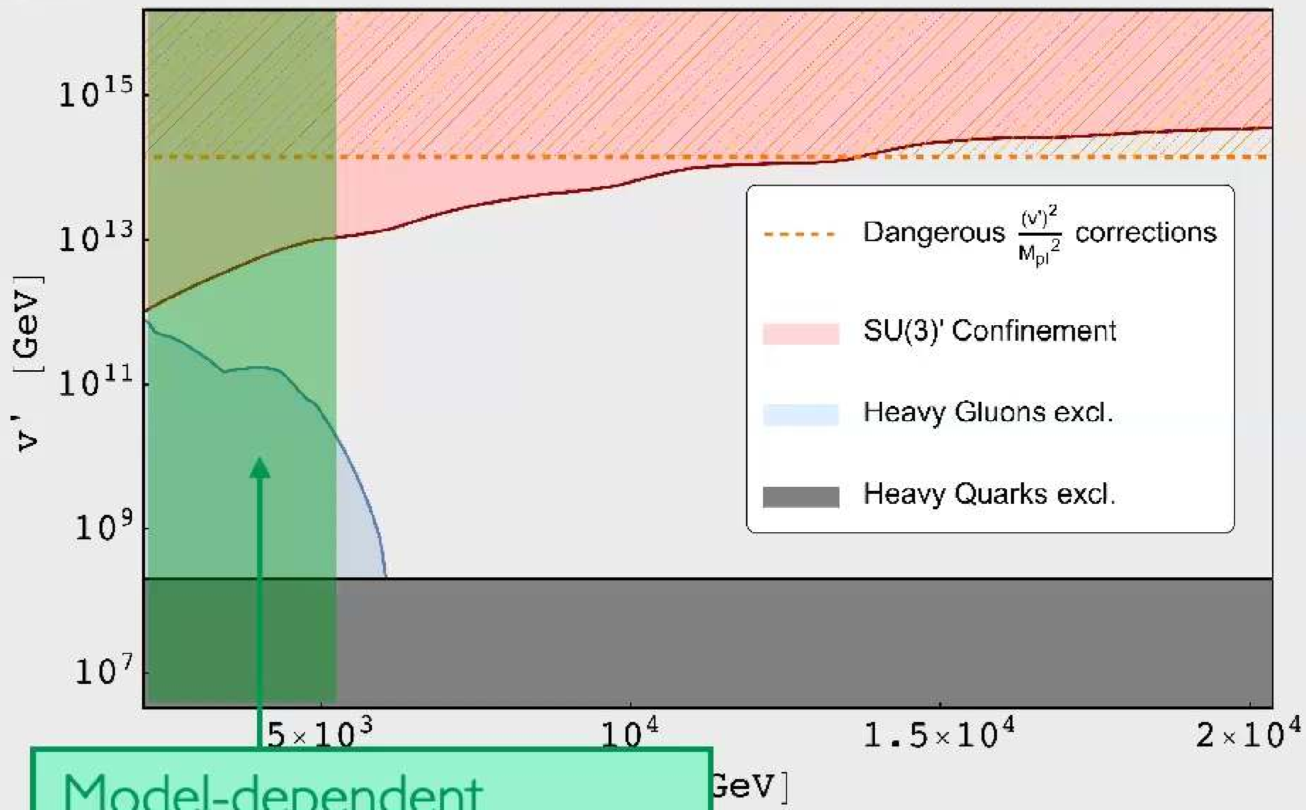
GeV]

(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)

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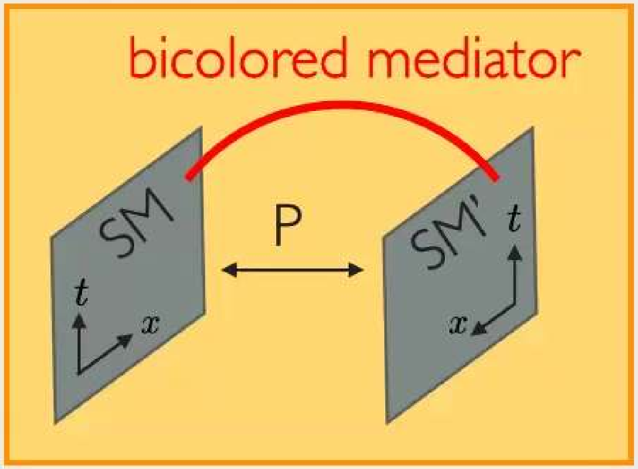

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L	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{1}$	$\mathbf{1}$	0
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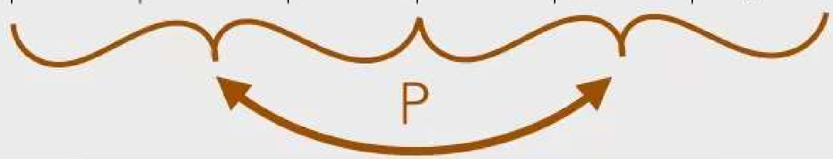

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Dark matter from the mirror world

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

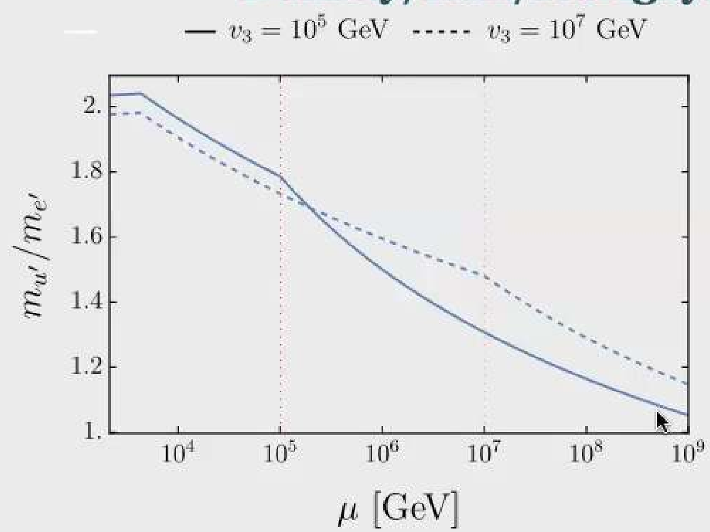
Only one viable : **mirror electron**

Strong bounds on the stable mirror up quark relic density

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

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

Masses are fixed by parity !



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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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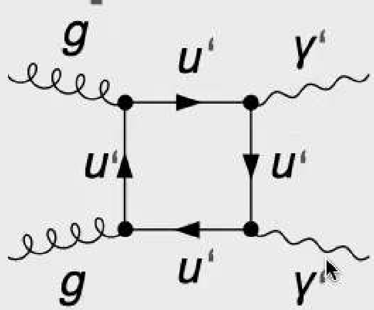
Sequential freeze-in from the mirror photon



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

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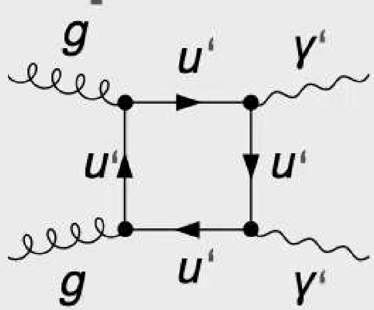

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Inflation ? Reheating to the SM and $T_{\max} \approx T_{\mathrm{rh}}$

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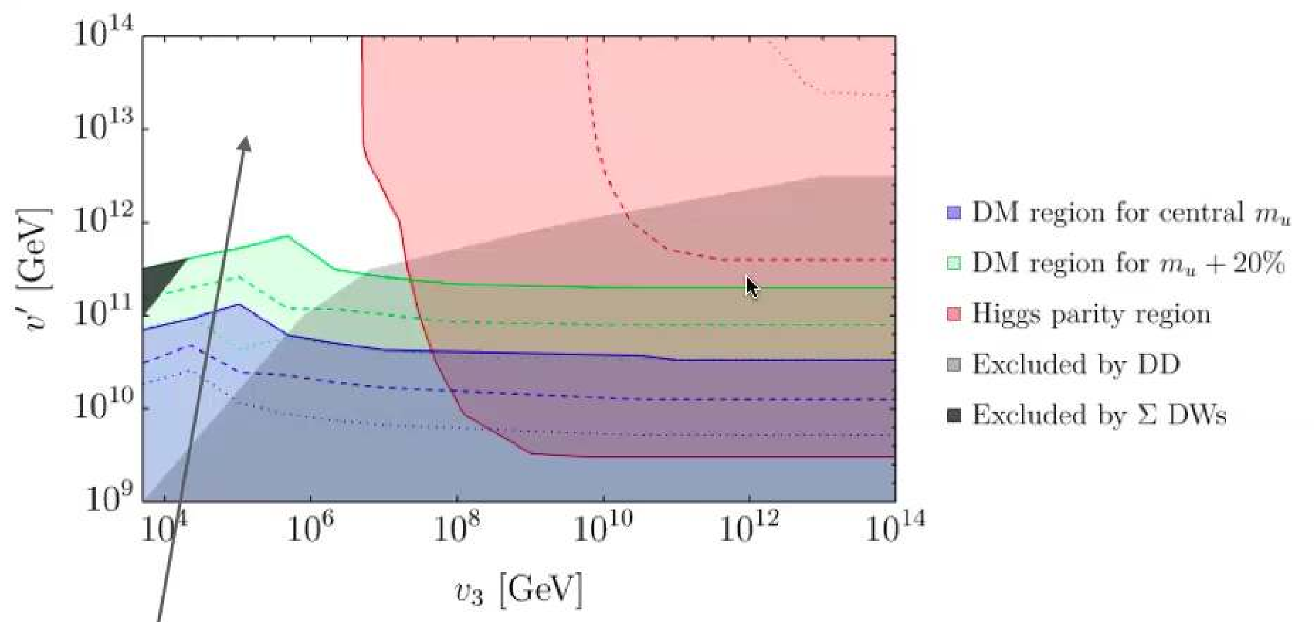
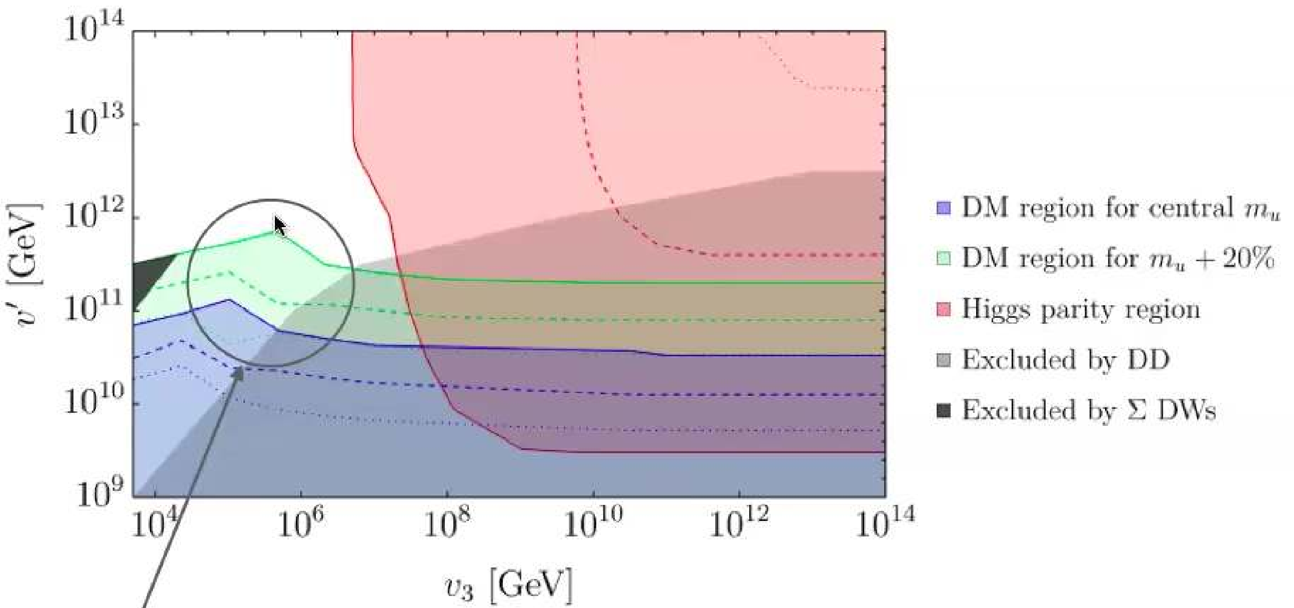


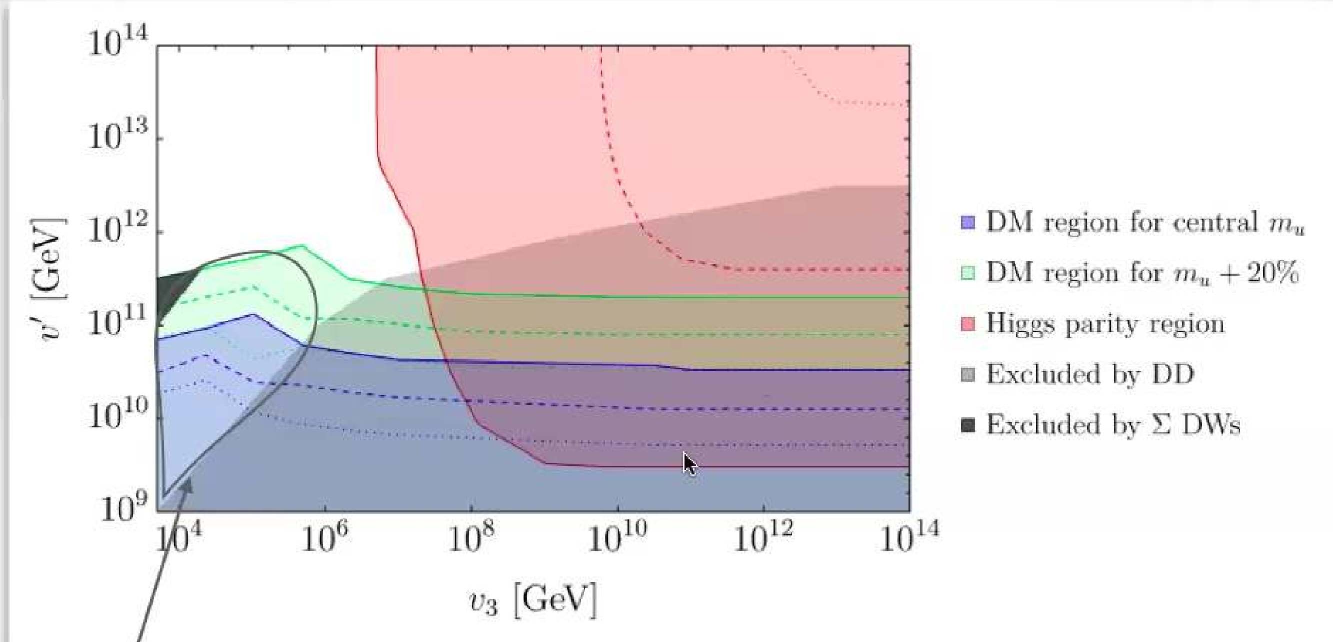
No appropriate reheating temperature

Dark matter from the mirror world



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

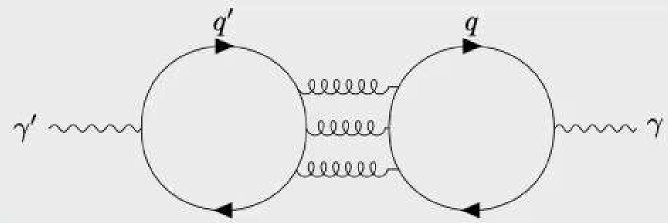
Dark matter from the mirror world



$m_{u'} < v_3$

Main interest of low v_3

(kinetic mixing)



[Dunsky/Hall/Harigaya '19]

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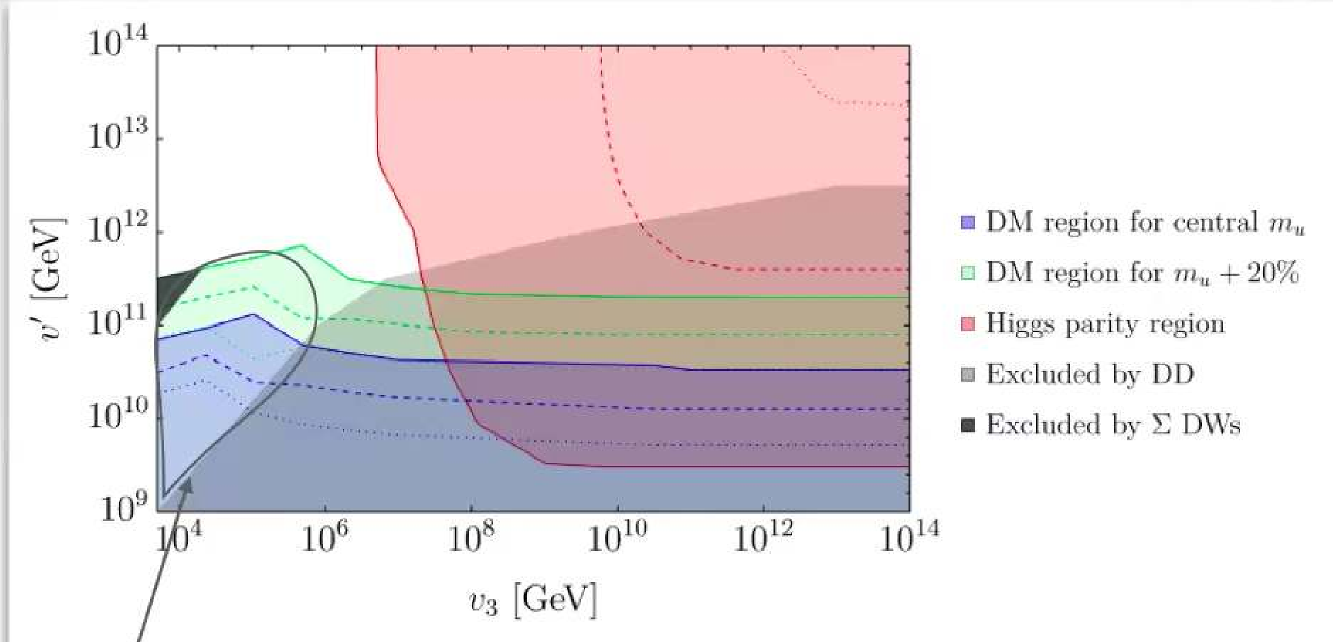

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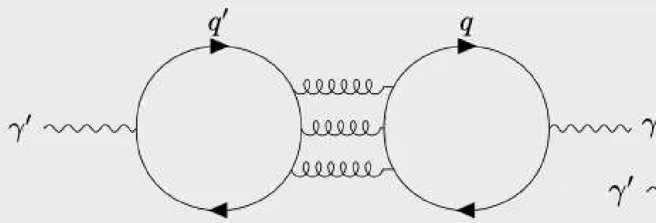

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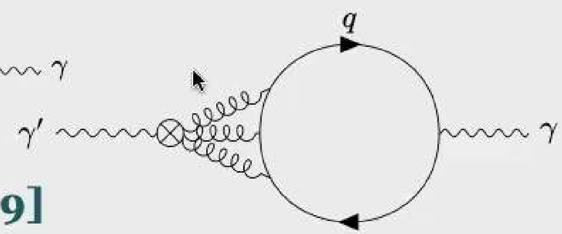

[Dunsky/Hall/Harigaya '19]

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** !

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