Non-axion solutions to the strong CP problem and their phenomenology

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Based on
2303.06156, 2311.00702 [hep-ph] + w.i.p.
with L. Hall, C. A. Manzari, A. McCune,
B. Noether & C. Scherb

IPHC
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(sub- to multi-) TeV-scale

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Arises from the following terms of the SM lagrangian :

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

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In there, two **physical** CP-violating quantities :

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

  [Jarlskog '85]

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

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- $\boxed{\bar{\theta} = \theta + \arg\det(Y_u Y_d)}$ — Predicts a **neutron electric dipole moment** [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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Strong CP problem :

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

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The strong CP problem and axions

Leading solution, **axions :** $\bar{\theta} = \left\langle \frac{a}{f_a} \right\rangle$ which dynamically relaxes to zero

[Peccei/Quinn '77,
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Greatly motivated, let’s focus on the pheno : **mostly non-collider BSM signals**

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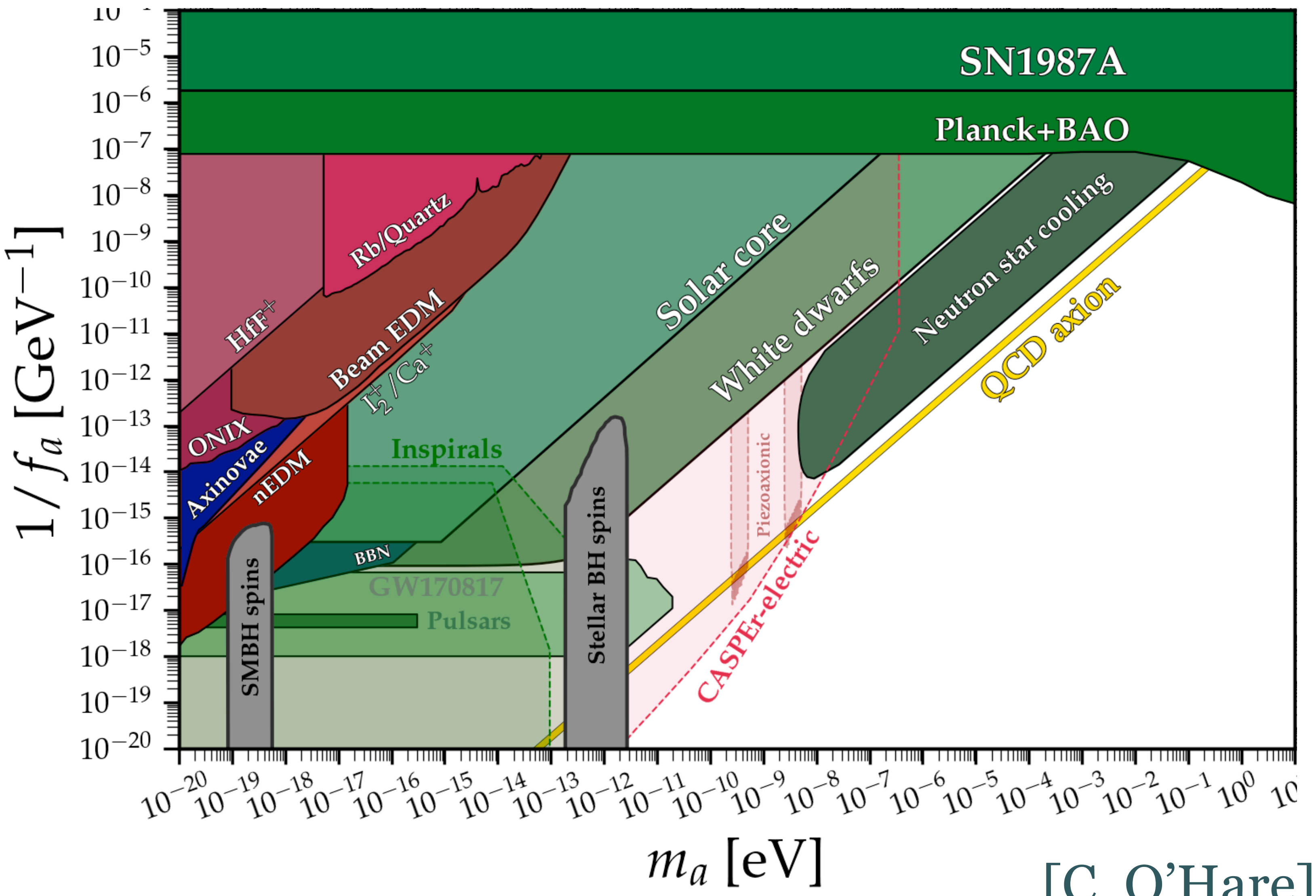
Dominated by low-energy experiments, astrophysics, late-time cosmology (+ flavor, more model-dependent)



[C. O'Hare]

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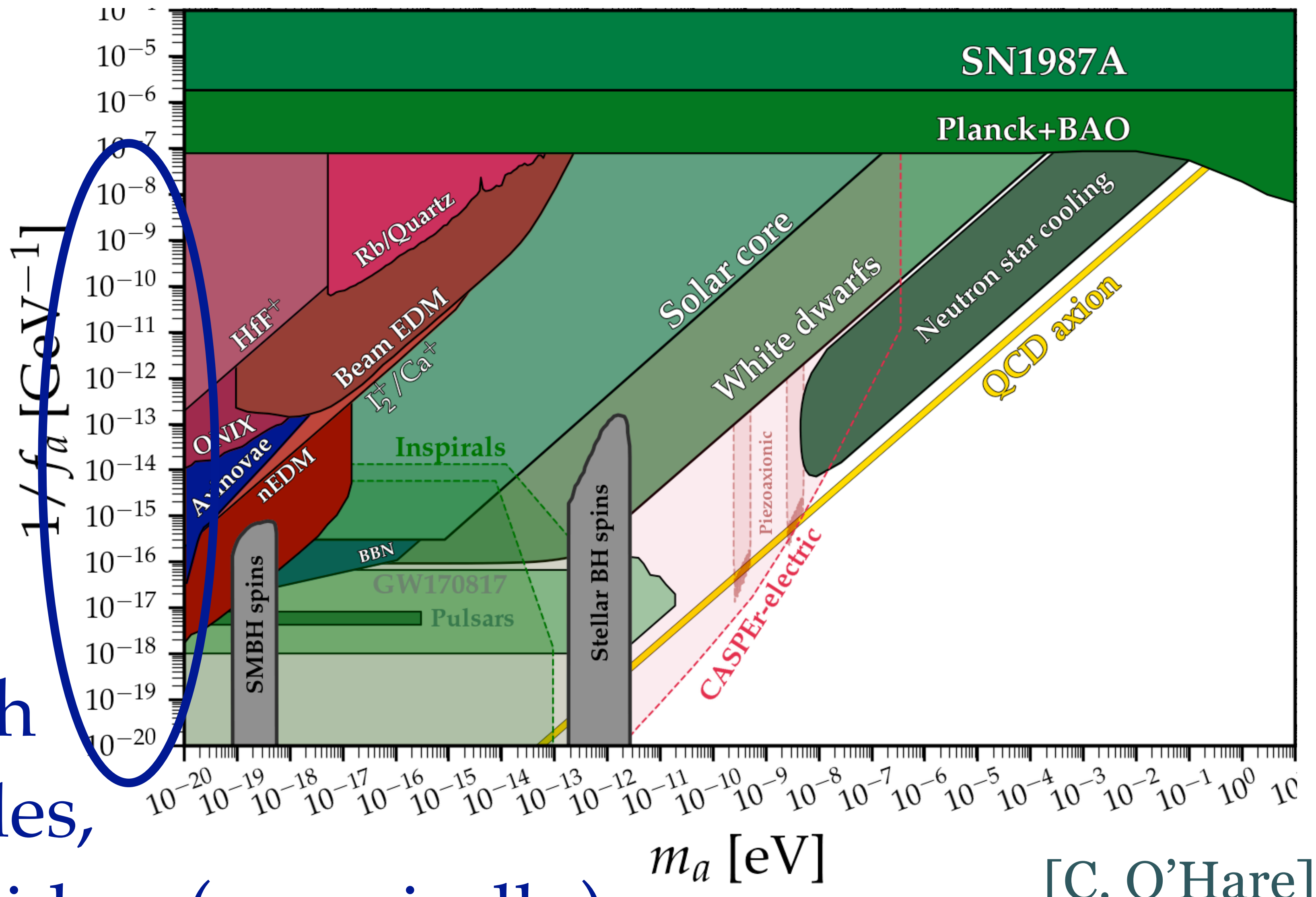

high scales, ~~colliders~~ (generically)

[C. O’Hare]

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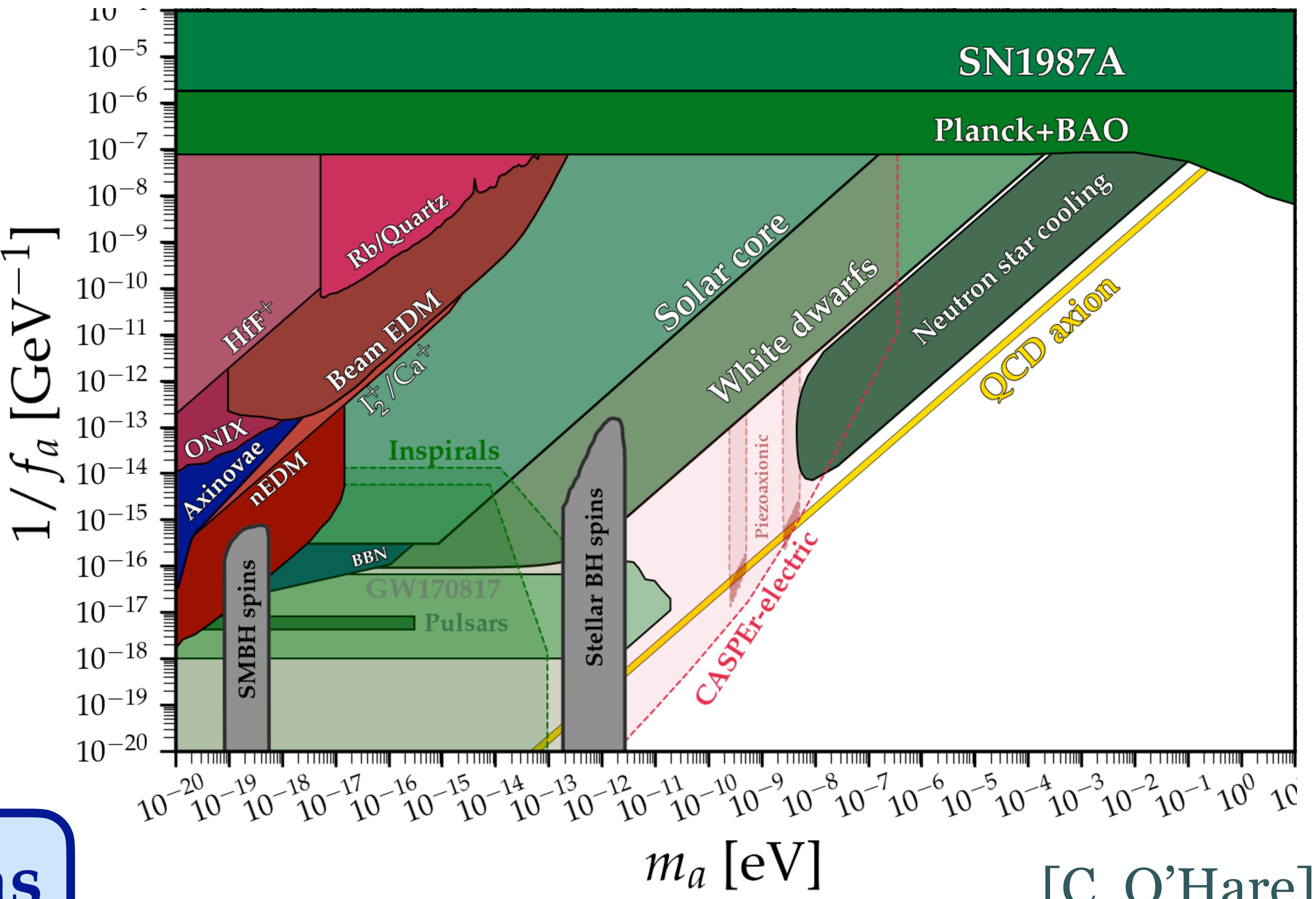

[C. O'Hare]

Today : other paradigms

UV solutions to the strong CP problem

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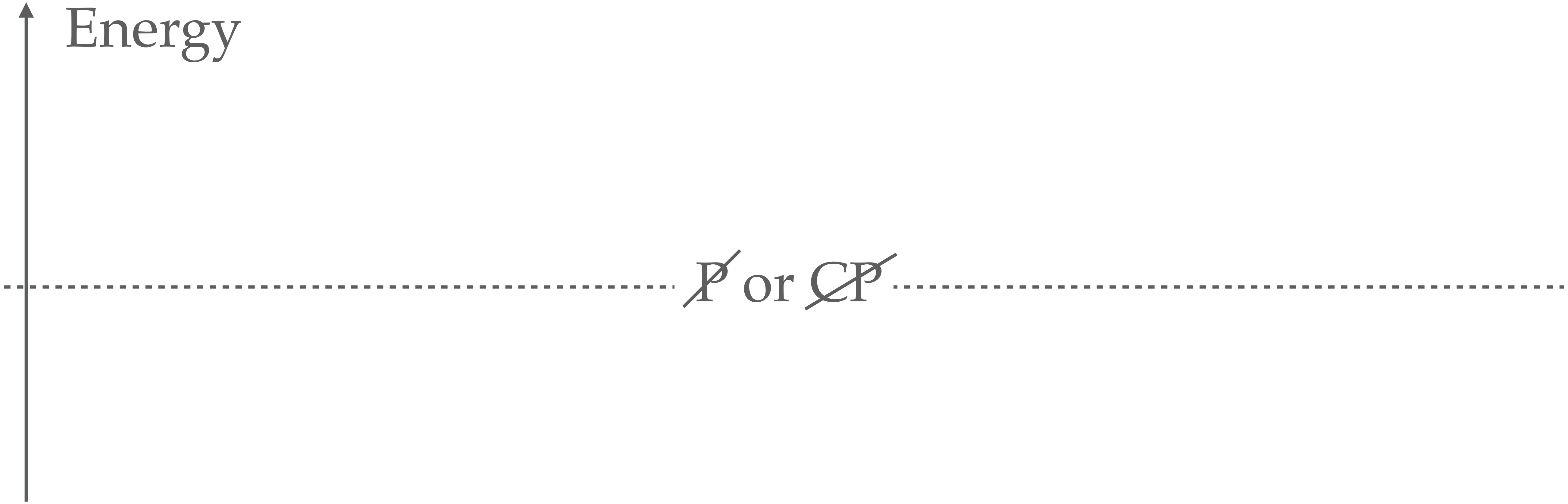

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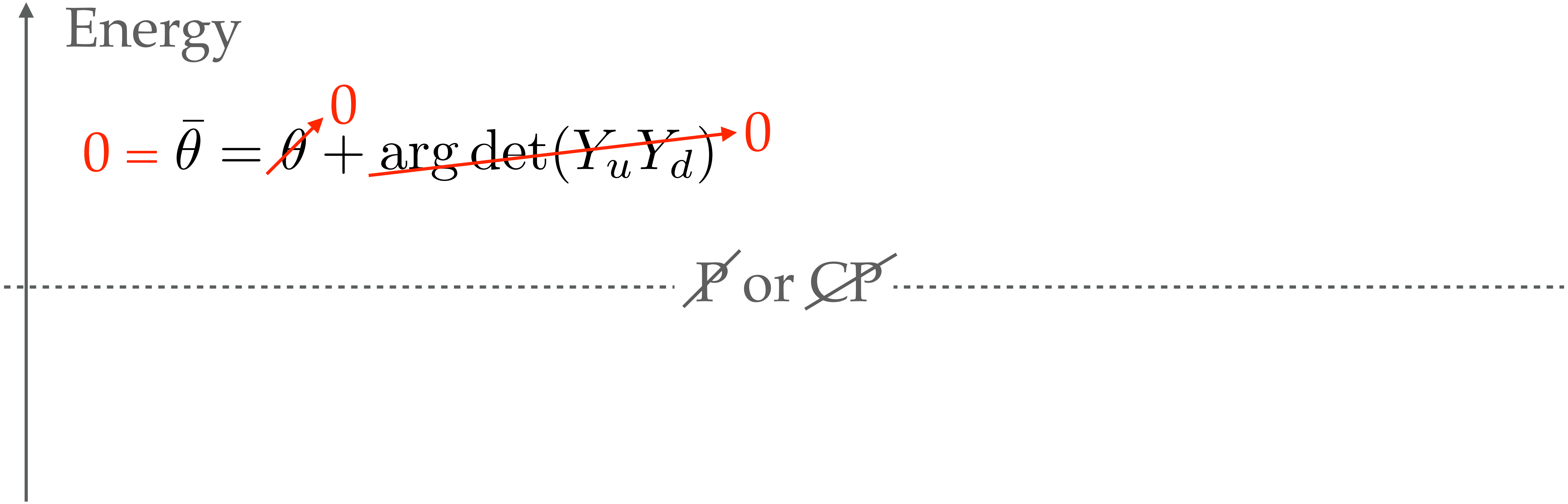

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$$0 \approx \bar{\theta} = \theta + \arg\det(Y_u Y_d)$$

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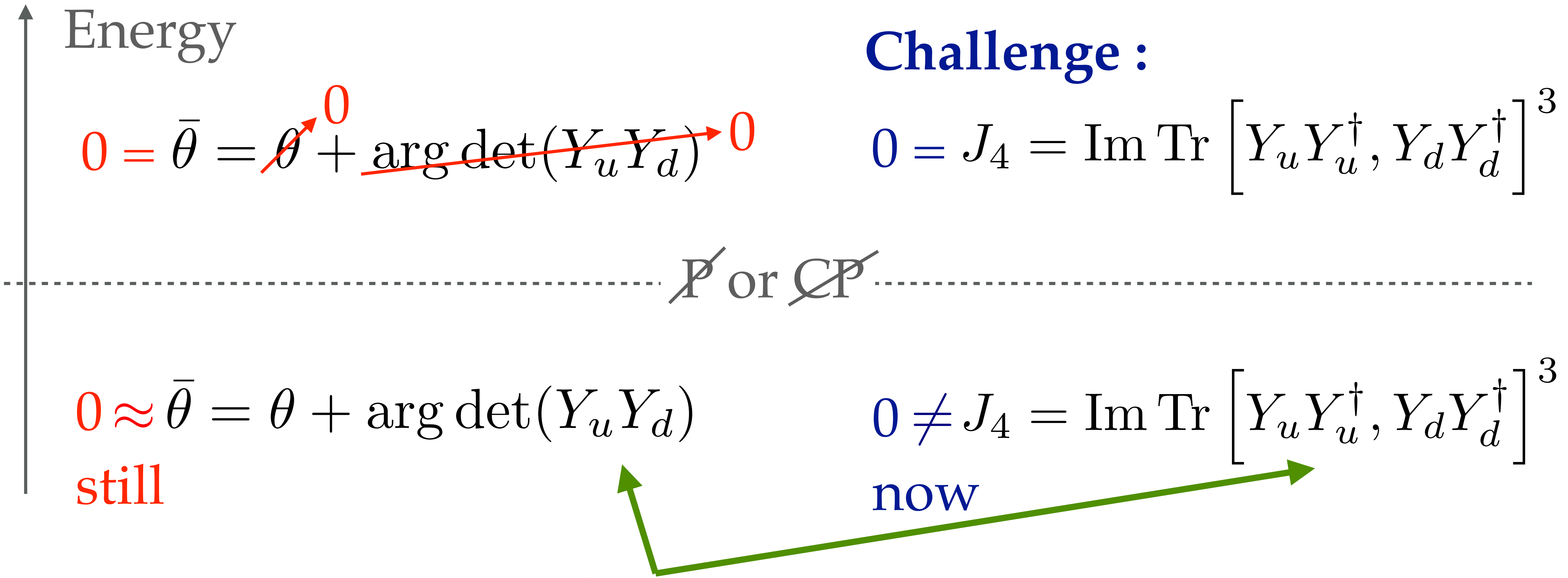

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Natural interplay with flavor physics, **often TeV-scale pheno**

Example 1 : Higgs-induced CP breaking

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With n>1 Higgs doublets, one can achieve

[Georgi ’78,
Nebot/Botella/Branco ’18,
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Always produces one light second Higgs doublet !

[Miro/Nebot/Queiroz ’24]

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[Nebot/Botella/Branco ’18]

More work needed to scan the landscape of models : when do those setups really fulfill the strong constraints from the neutron EDM + flavor physics ? What is the interplay with the flavor puzzle ? Are there still light states in the case of soft breaking of CP ? Etc.

[Ferreira/Lavoura ’19, QB/Hall/Manzari/Noether, w.i.p.]

Example 2 : mirror worlds

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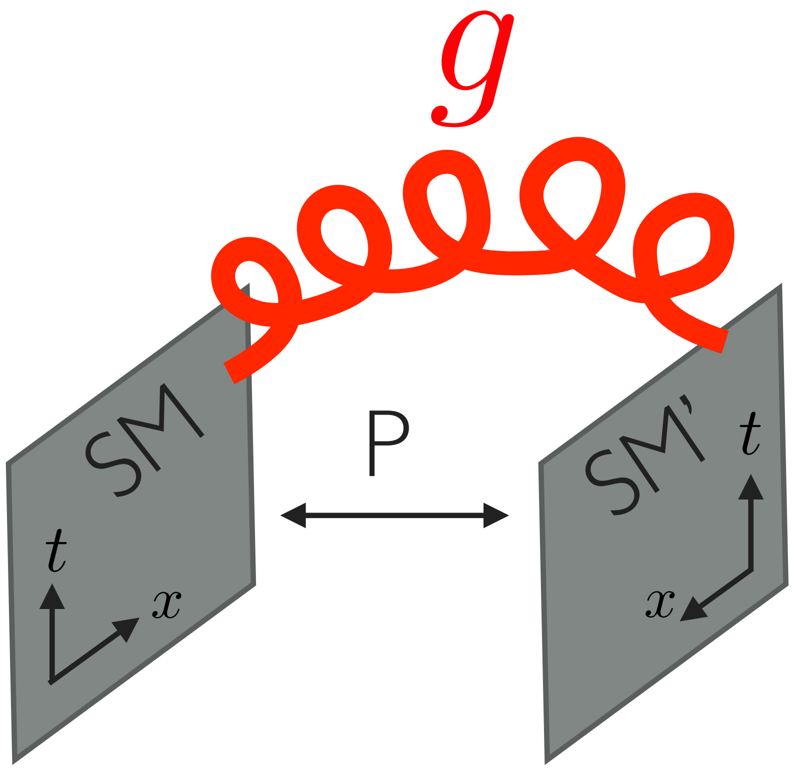

[Babu/Mohapatra '89, '90, Barr/Chang/Senjanovic '91, Hall/Harigaya '18, +Dunsky '18, Craig/Garcia Garcia/ Koszegi/McCune '20, …]

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

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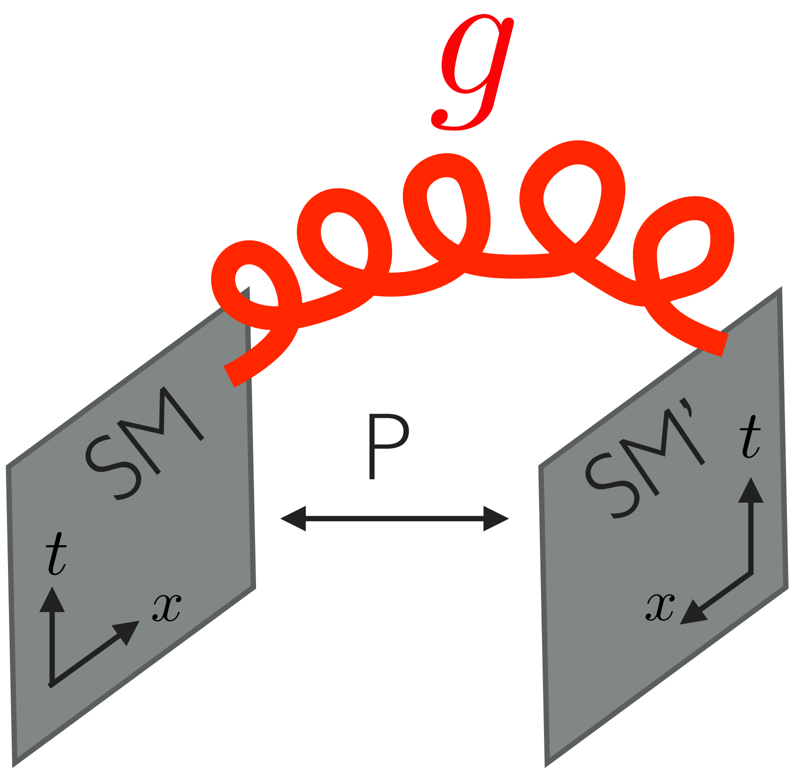

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Mirror particles

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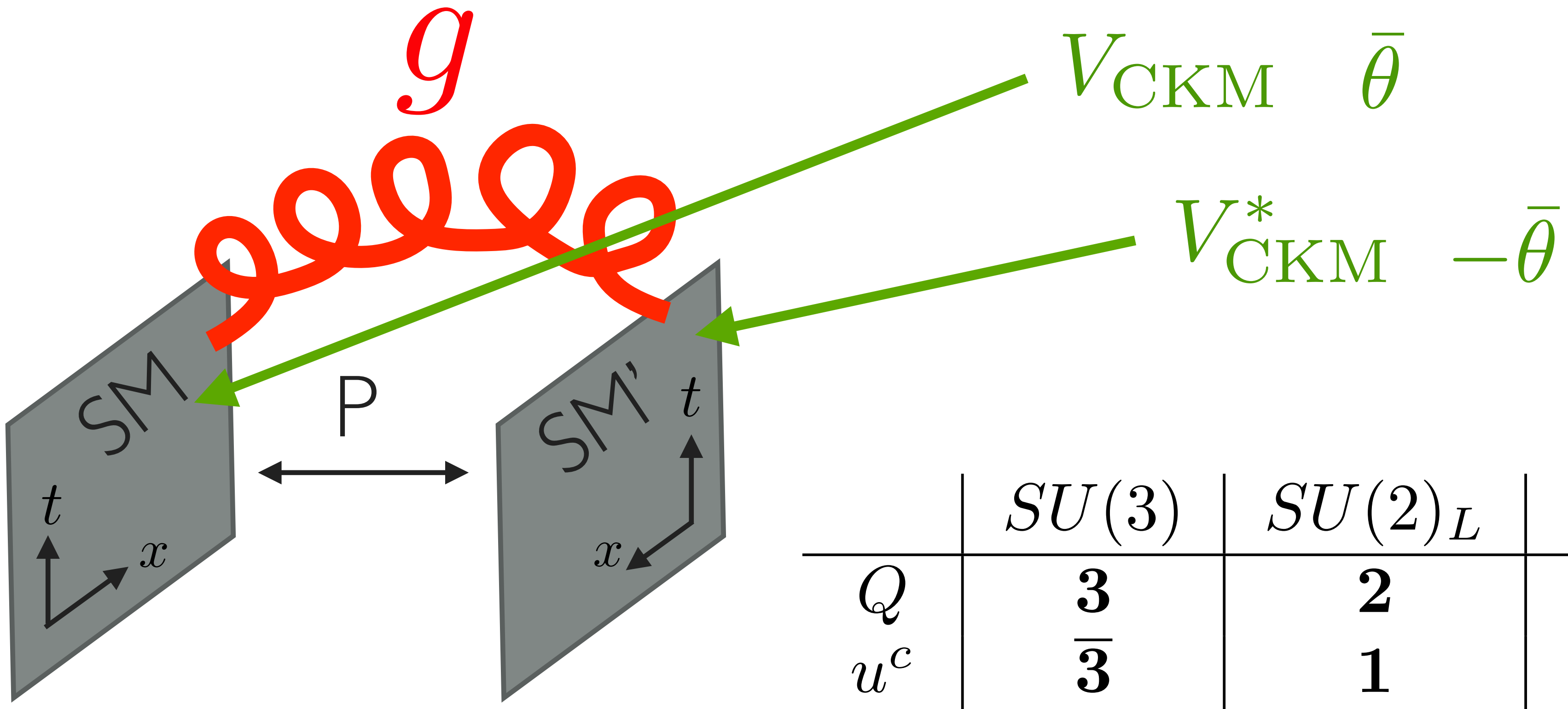

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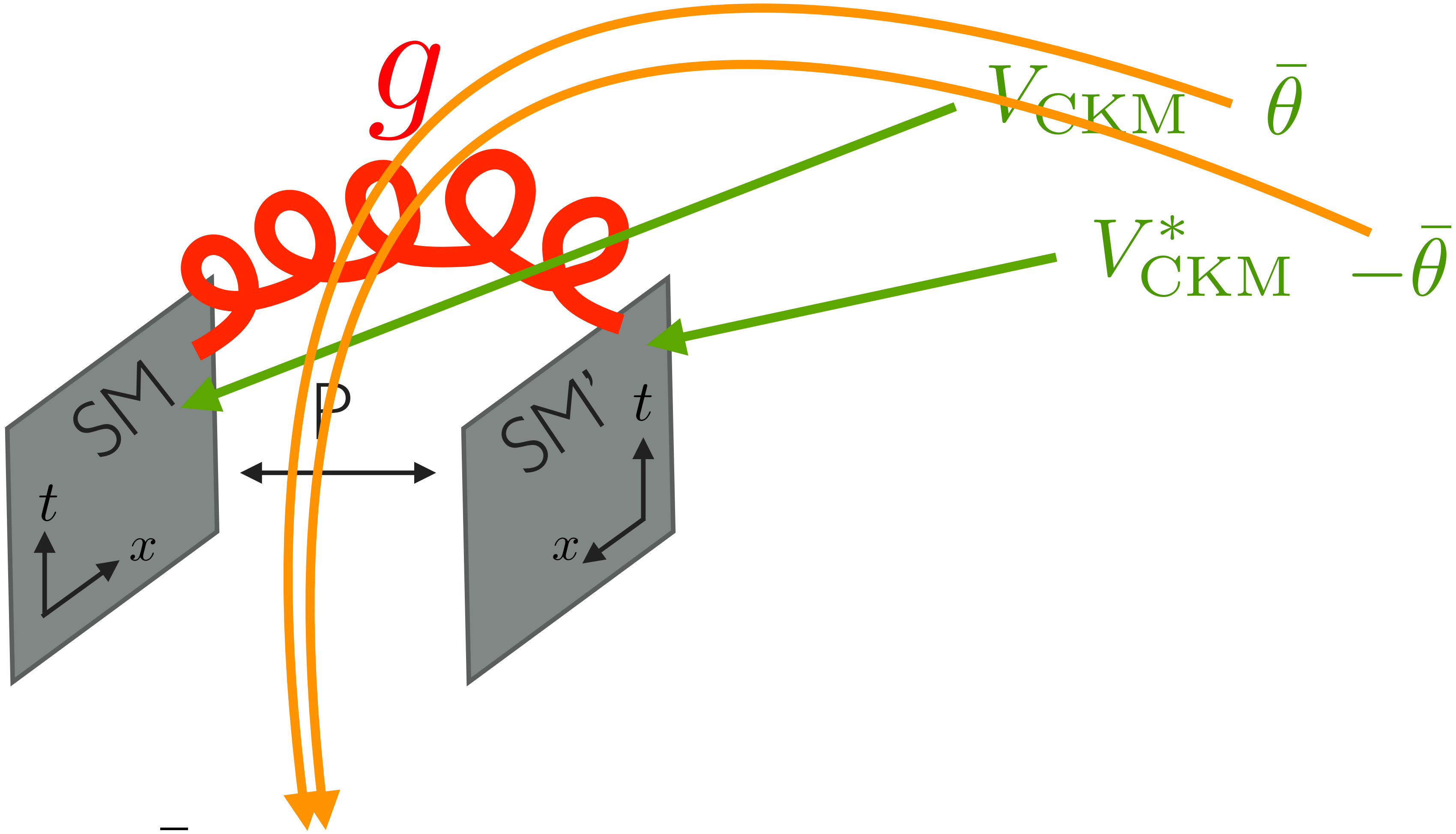

$\bar{\theta}_{\mathrm{QCD}} = 0$

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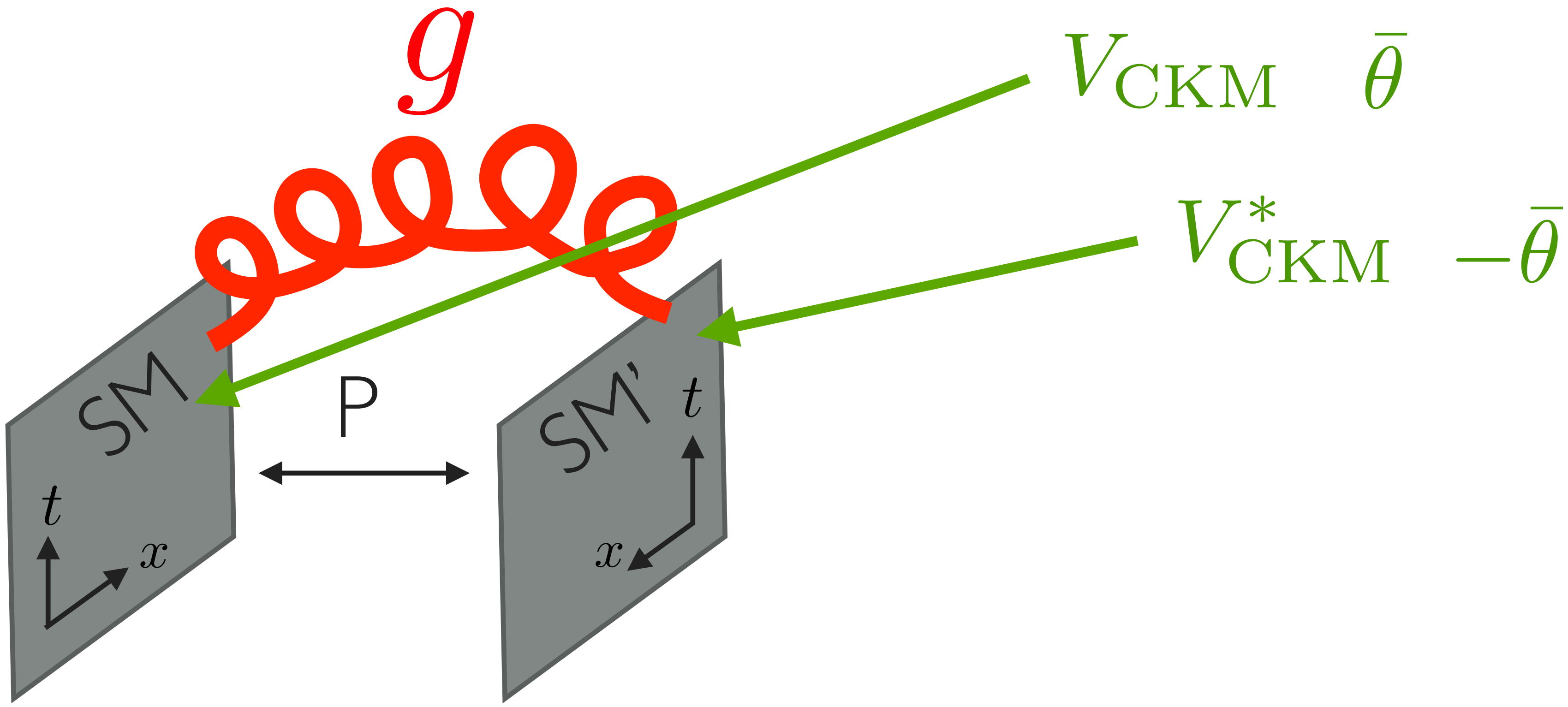

$\langle H \rangle \neq \langle H' \rangle$: **broken parity**

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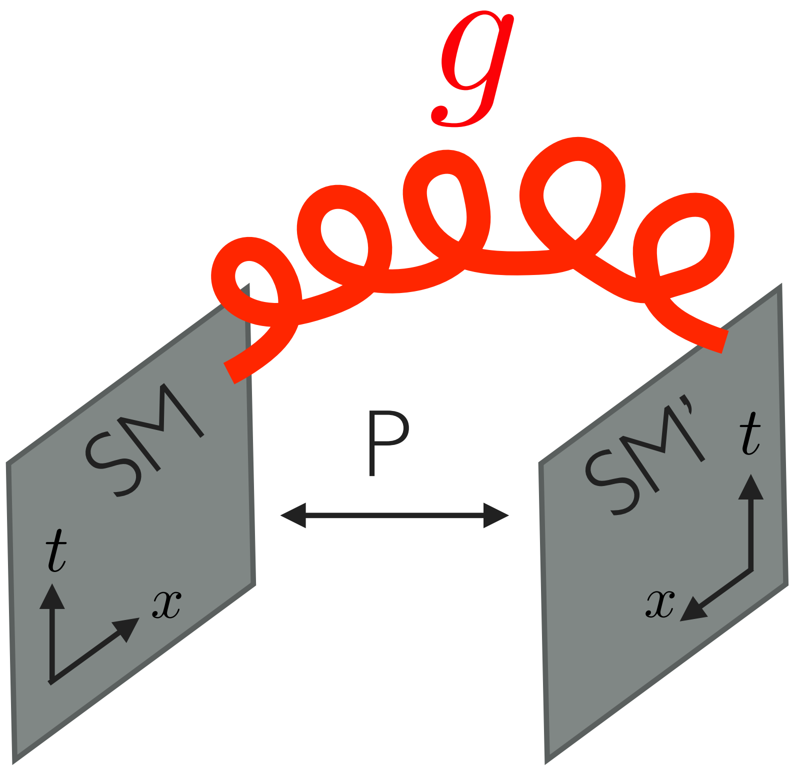

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Can have TeV scale pheno
(colored vector-like fermions,
RH-coupled gauge fields, …)

[D'Agnolo/Hook '15,
Craig/Garcia Garcia/Koszegi/McCune '20]

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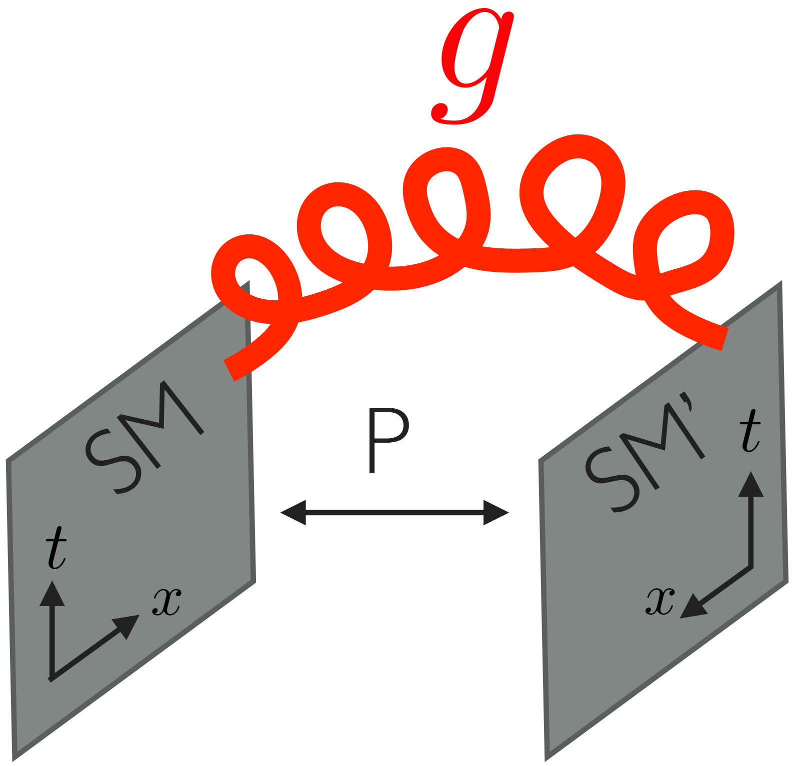

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But the mechanism works even when $\langle H' \rangle$ is quite high …
experimental probes ?

Genericaliy : only a (computable) large-ish neutron EDM.

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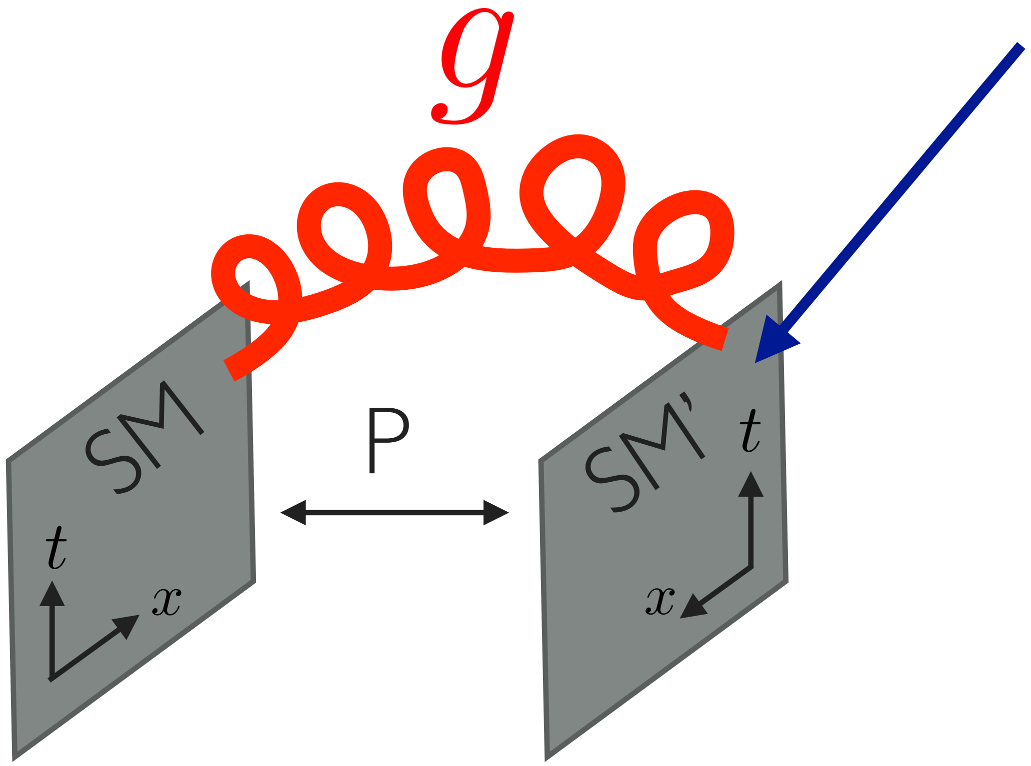

$$\langle H \rangle \neq \langle H' \rangle$$

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There is a **dark matter candidate** here, the mirror electron

[Dunsky/Hall/Harigaya '19]

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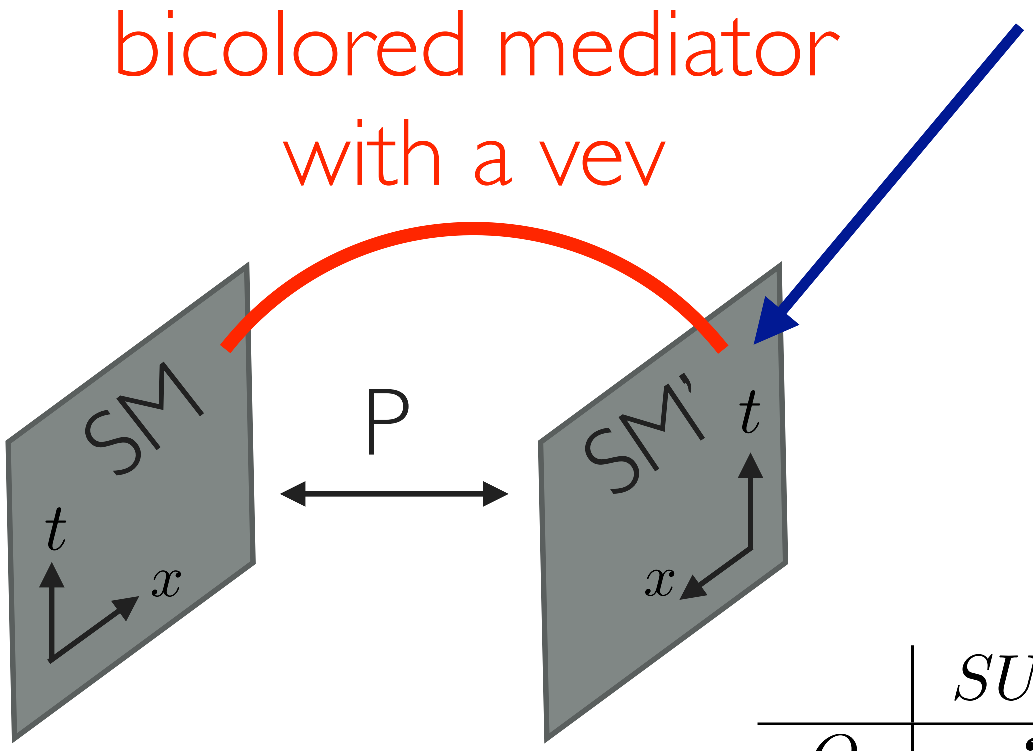


bicolored mediator
with a vev

There is a **dark matter candidate** here, the mirror electron

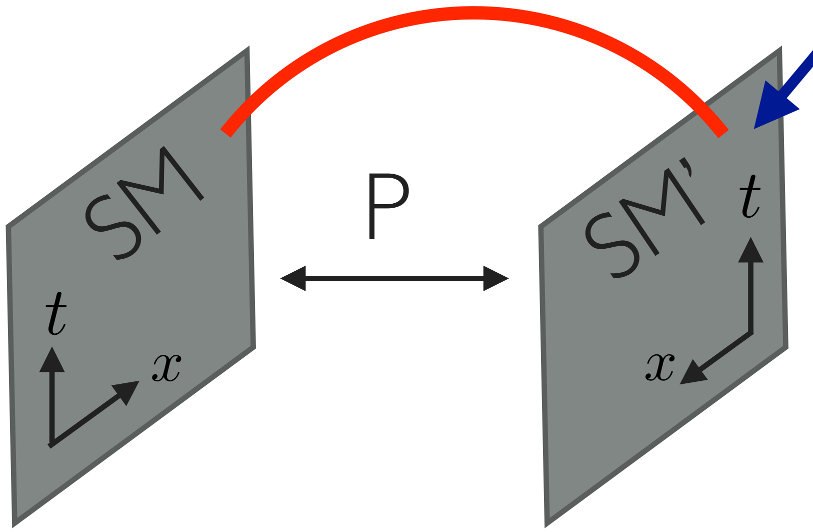
To produce it thermally, need to embed into

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

[QB/Hall/Manzari/
Scherb '23, + McCune '23]

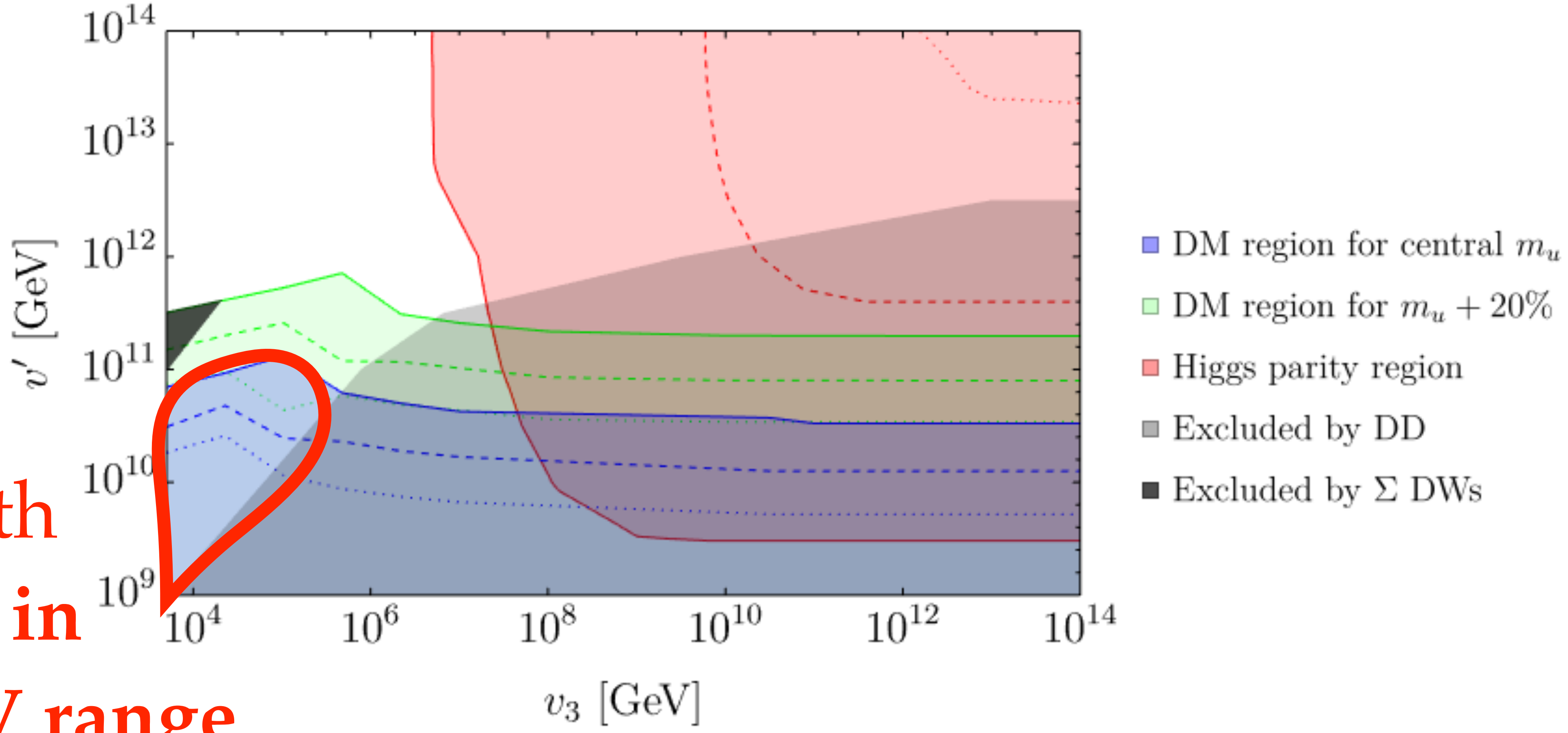
Example 2 : mirror worlds

bicolored mediator
with a vev



There is a **dark matter candidate** here, the mirror electron

To produce it thermally, now **not all $\langle H' \rangle$ work !**



Viable region, with **colored particles in the TeV - 100 TeV range**

Outlook

The strong CP problem is usually associated to low-energy probes (or very high-energy ones, usually in cosmology)

Not the case for **« UV » solutions to the problem, which may manifest themselves around the TeV**: the strong CP problem can thus be investigated at those scales

A lot of work remains to be done regarding this (old) non-axion paradigm ! Rich interplay with collider and flavor physics, but also cosmology, the hierarchy problem, etc