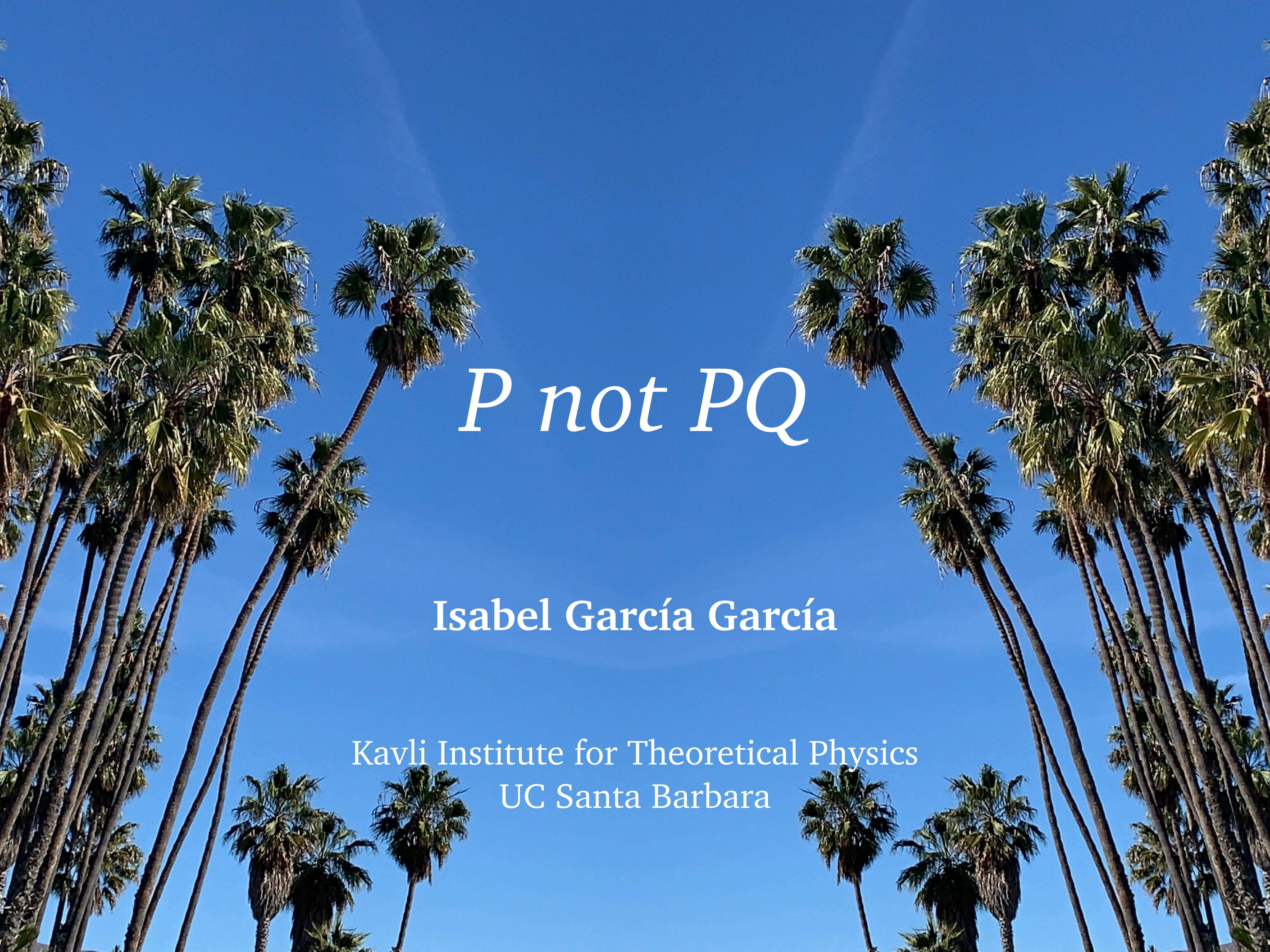

P not PQ

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My talk

N. Craig, **IGG**, G. Koszegi, A. McCune, arXiv:2012.13416

- Introduction / motivation

- Parity solutions to the strong CP problem

different from Nelson-Barr solutions based on restoring CP

Babu, Mohapatra; PRL 62 (1989) & PRD 41 (1990)
Barr, Chang, Senjanovic; PRL 67 (1991)

- Phenomenology
  - Collider, and flavor
  - EDMs
  - Gravitational waves

Criticism of parity solutions: Albaid, Dine, Draper, 1510.03392

will address criticism as we go along

The Yang-Mills vacuum angle

Yang-Mills theory has a discrete set of degenerate classical minima

These are pure-gauge field configurations with non-trivial topology

$$\mathbf{A}_i(\mathbf{x}) = -i\left(\partial_i g(\mathbf{x})\right) g(\mathbf{x})^{-1} \qquad \text{with} \qquad g(\mathbf{x}) \xrightarrow{|\mathbf{x}|\to\infty} 1$$

element of SU(N)

They can be classified in topologically distinct classes in terms of a single integer $n \in \mathbb{Z}$ that we call winding number

Classically, we could choose a vacuum with given winding number

however…

Quantum mechanically, there is tunneling between topologically distinct sectors, as described by the existence of instantons

The Yang-Mills vacuum angle

Non-abelian instantons describe tunneling between vacua with different winding numbers

$$Q = \frac{g^2}{32\pi^2}\int d^4x \; \mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right) \in \mathbb{Z}$$

tunneling between vacua whose winding numbers differ by Q

True vacuum is a linear combination of all the n-vacua

$$\Psi_\theta = \sum_{n\in\mathbb{Z}} e^{in\theta}\Psi_n$$

phase ambiguity

θ is the vacuum angle of Yang-Mills theory

vacuum energy density depends on θ

In the lagrangian formulation:

$$\mathcal{L}_\theta = \frac{\theta g^2}{32\pi^2}\mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$$

$\theta \neq 0, \pi$

violates P and CP

The QCD vacuum angle

The physical significance of the vacuum angle crucially depends on the fermion spectrum

In the Standard Model, only the vacuum angle of the QCD sector, $\bar{\theta}$, is physical

$\bar{\theta}$ is a physical measurement of P and CP violation in the strong sector

Physical quantities depend on $\bar{\theta}$, e.g. the EDM of the neutron:

$$d_n \sim 10^{-16} \, \bar{\theta} \; e \cdot \mathrm{cm}$$

Experimentally: $|d_n| < 1.8 \cdot 10^{-26} \; e \cdot \mathrm{cm} \quad \Rightarrow \quad \bar{\theta} \lesssim 10^{-10}$

The strong CP problem

$$\bar{\theta} = \theta_s + \theta_q$$

$$\mathcal{L} \supset \frac{\theta_s g^2}{32\pi^2} \mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right) \qquad \theta_q = \arg\det \mathcal{M}_q$$

Complex $\mathcal{M}_q$ is a requirement for there to be *CP*-violation in the electroweak sector, which we have measured to be $\delta_{\mathrm{CKM}} = \mathcal{O}(1)$

$\Rightarrow$ expect $\bar{\theta} = \mathcal{O}(1)$, in gross violation of experimental bound

in fact, both CP *and* P are maximally violated by the weak interactions

<u>Strong CP problem:</u> It is not possible to understand the smallness of $\bar{\theta}$ based on the underlying symmetries of the Standard Model

instead, a dynamical mechanism or some additional symmetry structure is necessary to <u>explain</u> why $\bar{\theta}$ is so tiny

The QCD axion

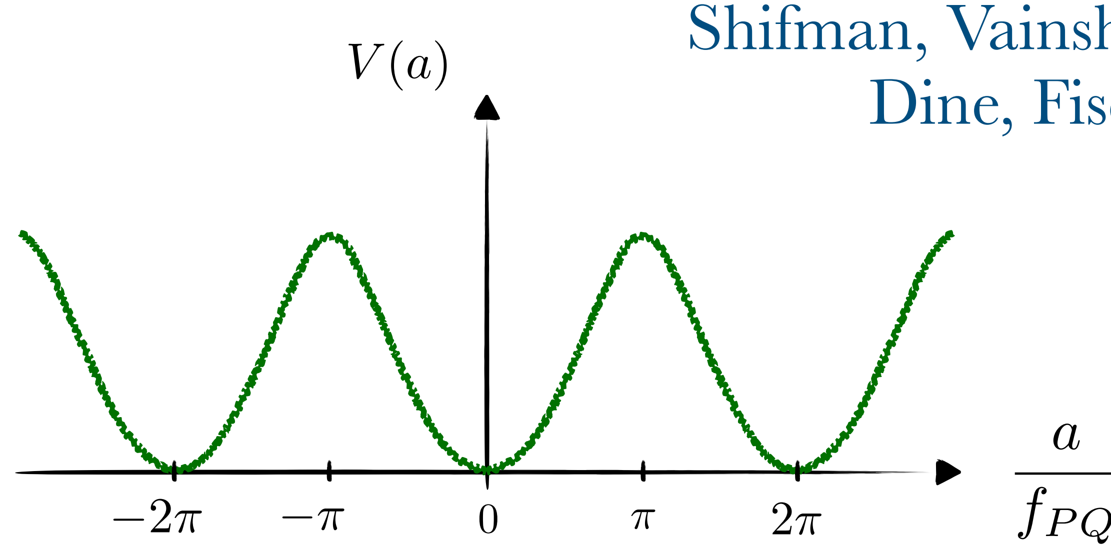
$\bar{\theta}$ promoted to dynamical field, the axion, which a pseudo-Nambu-Goldstone boson of a spontaneously broken $U(1)_{PQ}$ global symmetry, which must also be broken explicitly by QCD

Peccei, Quinn (1977)
Wilczek (1978); Weinberg (1978)
Shifman, Vainshtein, Zakharov (1980)
Dine, Fischler, Srednicki (1981)

axion

$$\mathcal{L} \supset \frac{\alpha_s}{4\pi} \frac{a}{f_{PQ}} G\tilde{G}$$

$U(1)_{PQ}$ breaking scale



QCD dynamics generate a potential for a

In turn, the axion gets a non-zero vacuum expectation value s.t. $\bar{\theta} = 0$

huge experimental effort to probe the axion paradigm

The axion quality problem

To solve strong CP, the QCD contribution to the axion potential must dominate to 1 part in 10^{10} over any other contribution

* but… *

Quantum gravity violates global symmetries

Zeldovich (1976); Banks, Dixon (1988);
Abbott, Wise (1989); Coleman, Lee (1990); etc

The violation of the $U(1)_{PQ}$ global symmetry by gravity generates a potential for the axion, deviating the theory away from a vanishing $\bar{\theta}$

$$\mathcal{L} \supset \epsilon \frac{|\Phi|^4 \Phi}{M_{Pl}} \qquad \Rightarrow \qquad |\epsilon| \lesssim 10^{-55} \left(\frac{10^{12} \text{ GeV}}{f_{PQ}} \right)^5$$

Barr, Seckel; Kamionkowski, March-Russell;
Holman et al. (1992); etc

axion solution in tension with “no global symmetries” in quantum gravity

The axion quality problem

Not impossible to solve the axion quality problem, but it comes at the expense of minimality

Randall, PLB 284 (1992)
Cheng, Kaplan, hep-ph/0103346
Fukuda *et al*, 1703.01112
Lillard, Tait, 1707.04261 & 1811.03089
…

More generally, "saving" the QCD axion solution in the context of string theory implies the existence of a plenitude of axions

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, hep-th/0905.4720

"The String Axiverse"

We have discovered neither the QCD axion nor any of the Axiverse axions

motivates considering alternative solutions to the strong CP problem

Spacetime symmetry solutions to strong CP

Non-zero $\bar{\theta}$ breaks both P and CP

$\Rightarrow$ restoring either can provide a solution to strong CP

The origin of the strong CP problem lies in the electroweak sector — natural to consider extensions that restore spacetime symmetries

CP

Nelson; PLB 136 (1984)
Barr; PRL 53 (1984)

P

Babu, Mohapatra; PRL 62 (1989) & PRD 41 (1990)
Barr, Chang, Senjanovic; PRL 67 (1991)

Spacetime symmetries can arise as gauge symmetries in the context of string theory, and can only be broken spontaneously (not explicitly!)

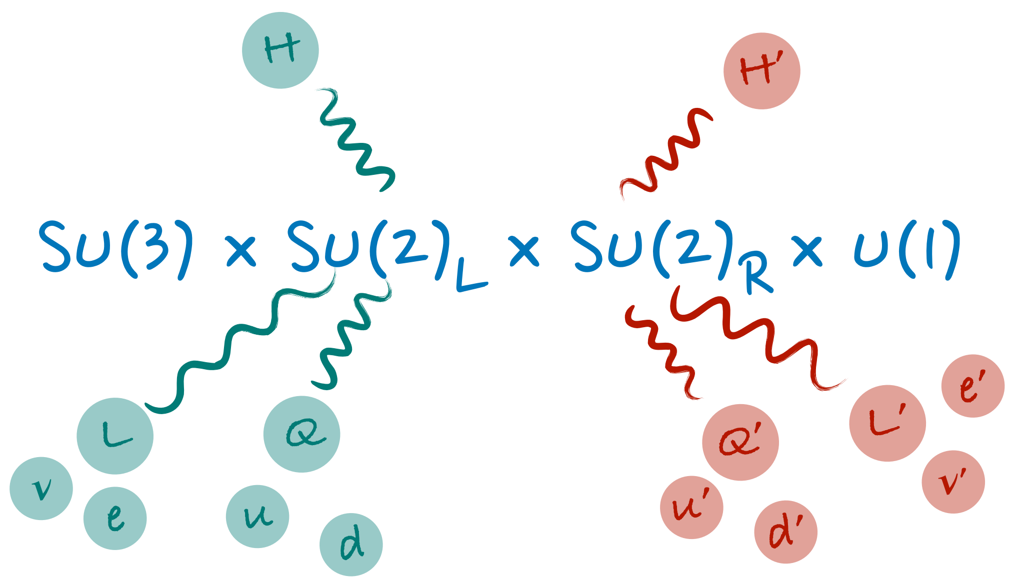
Dine, Leigh, MacIntire (1992)
Choi, Kaplan, Nelson (1993)

small QCD vacuum angle an "accident"

Parity solutions to strong CP

Babu, Mohapatra; PRL 62 (1989) & PRD 41 (1990)
Barr, Chang, Senjanovic; PRL 67 (1991)

Solving strong CP by restoring parity requires extending both the gauge group, and the matter content of the Standard Model



"Mirror" sector is an exact copy of the Standard Model, except that $SU(2)_L$ doublets become doublets of $SU(2)_R$

	$Q = \begin{pmatrix} u \\ d \end{pmatrix}$	$U^\dagger$	$D^\dagger$	H	$Q'^\dagger = \begin{pmatrix} u'^\dagger \\ d'^\dagger \end{pmatrix}$	U'	D'	H'^*
$SU(3)$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\cdot$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\cdot$
$SU(2)_L$	$\mathbf{2}$	$\cdot$	$\cdot$	$\mathbf{2}$	$\cdot$	$\cdot$	$\cdot$	$\cdot$
$SU(2)_R$	$\cdot$	$\cdot$	$\cdot$	$\cdot$	$\mathbf{2}$	$\cdot$	$\cdot$	$\mathbf{2}$
$U(1)_{\hat{Y}}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$

Parity solutions to strong CP

<u>"Generalized" parity</u>

= ordinary parity

+ exchange of Standard Model and mirror sector fields

$$SU(2)_L \leftrightarrow SU(2)_R$$

$$Q, U, D \leftrightarrow Q'^{\dagger}, U'^{\dagger}, D'^{\dagger}$$

$$H \leftrightarrow H'^{*}$$

optional *in principle* (more soon)

$SU(3)$ and $U(1)$ gauge sectors are not duplicated

$\Rightarrow$ transform as usual under parity

ensures that $\bar{\theta}$ remains odd under ~~"generalized"~~ parity

— crucial to solve strong CP problem

we'll just call it parity

Parity solutions to strong CP

With this extended gauge sector and matter content,
parity can be a good symmetry

this requires…

- Vanishing coefficient of the $SU(3)$ topological operator:

$$\mathcal{L} \supset \frac{\theta_s g^2}{32\pi^2} \mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right) \qquad \theta_s = 0$$

- Equal Yukawa couplings in the Standard Model and mirror sectors:

$$\mathcal{L} \supset -\left\{(y_u)_{ij} Q_i H U_j + (y'_u)_{ij} Q'^{\dagger}_i H'^{*} U'^{\dagger}_j\right\} + \text{h.c.} \qquad \text{with} \qquad y'_u = y_u$$

$$\Rightarrow \quad \theta_q = \arg\det(y_u y_d) + \arg\det(y'^{*}_u y'^{*}_d) = 0$$

at tree-level, parity enforces $\bar{\theta} = 0$!

Fine-tuning

Parity must be broken, e.g. softly in the scalar potential:

$$V(H,H') = -m_H^2(|H|^2 + |H'|^2) + \lambda(|H|^2 + |H'|^2)^2$$
$$+\kappa(|H|^4 + |H'|^4) + \mu^2|H|^2$$

parity-breaking mass term

Different vev's in the Standard Model and mirror sectors requires fine-tuning, already at tree-level:

$$\Delta^{-1} \simeq \frac{2v^2}{v'^2}$$

$$\Delta^{-1} \gtrsim 10^{-10} \qquad \Rightarrow \qquad v' \lesssim 10^7 - 10^8 \text{ GeV}$$

same as in Twin Higgs theories (Higgs as a pNGB)

(

Twin Higgs

Higgs as a pseudo-NGB of an approximate $SU(4)$ global symmetry

Chacko, Goh, Harnik, hep-ph/0506256
& hep-ph/0512088

Ingredients:

- Twin sector that is a copy of the Standard Model ✔
- $\mathbb{Z}_2$ that exchanges Standard Model and mirror sector fields ✔

the internal part of our generalized parity symmetry

$\Rightarrow$ Higgs quadratic term satisfies an $SU(4)$ global symmetry

$SU(4) \rightarrow SU(3)$: 7 Goldstone bosons

- 3 eaten by $SU(2)_L$
- 3 eaten by $SU(2)_R$
- 1 left: the SM Higgs

Quadratic sensitivity of mass-squared parameter in the scalar potential remains $SU(4)$-symmetric $\Rightarrow$ doesn't affect the mass of the pseudo-NGB

Twin Higgs

Chacko, Goh, Harnik, hep-ph/0506256
& hep-ph/0512088

Mirror (twin) Higgs vev is pulled up to the cutoff

$\Rightarrow$ UV-completion needed at scale $\Lambda \lesssim 4\pi v'$

Solving the full hierarchy problem requires explaining $v'^2 \ll M_{Pl}^2$,
but v already stabilized by the Twin Higgs mechanism

we only need to stabilize one scale, not two!

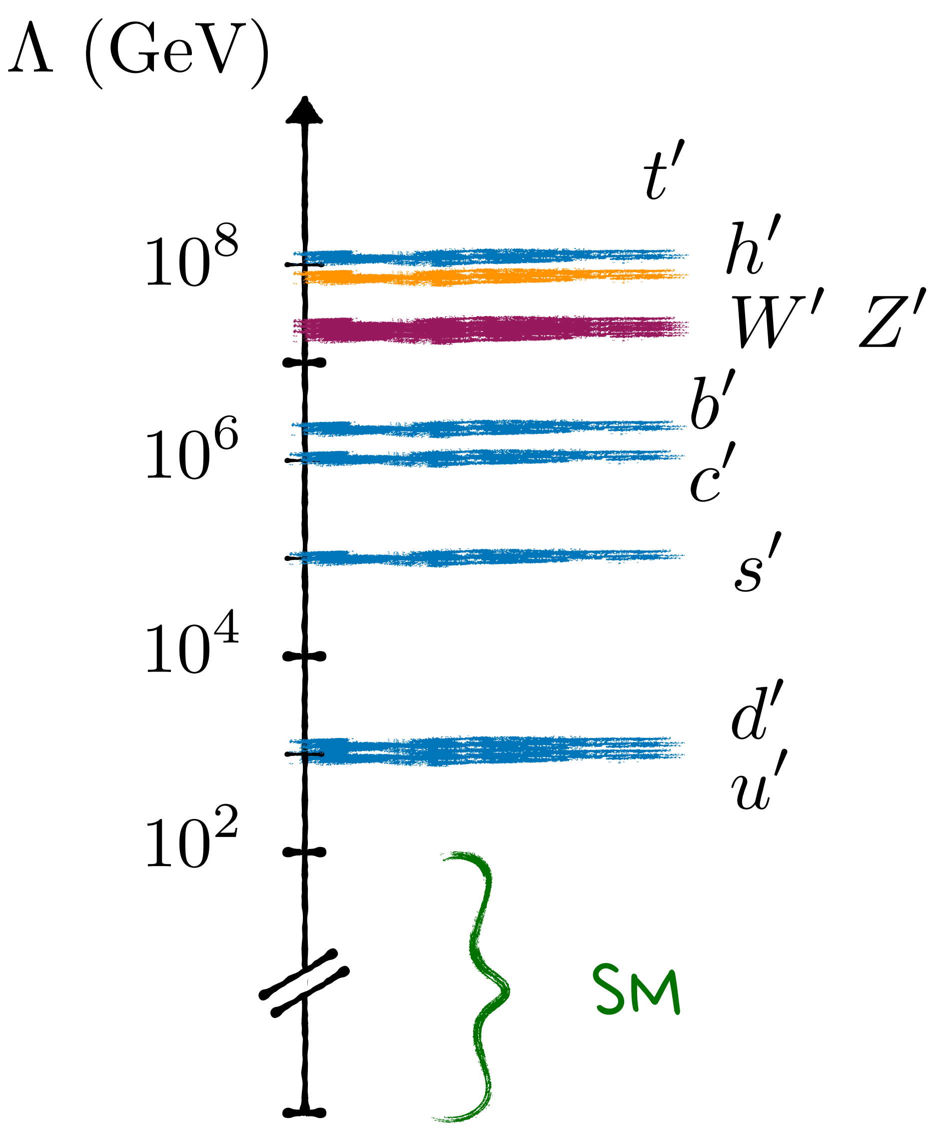
Parity solutions to the strong CP problem do **not** introduce a second hierarchy problem, because of their "built-in" Twin Higgs structure

(cf. Albaid, Dine, Draper, 1510.03392)

)

Parity-breaking scale

Naively, mirror spectrum is just a copy of the Standard Model, just heavier by a factor of v'/v



$$m_{u'} = m_u \times \frac{v'}{v} \gtrsim 1 \text{ TeV}$$

$$\Rightarrow \quad v' \gtrsim 10^8 \text{ GeV}$$

$$\Delta^{-1} \simeq \frac{2v^2}{v'^2} \sim 10^{-11}$$

fine-tuning worse than 1 in 10^{10}!!

Bounds on colored particles seemingly put the theory in a regime of unacceptable fine-tuning

D'Agnolo, Hook; 1507.00336

end of my talk??

Vector-like fermion masses

There is an additional fermion mass term we can write

$$\mathcal{L} \supset (\mathcal{M}_u)_{ij} U_i U'_j + \text{h.c.} \qquad \text{with} \qquad \mathcal{M}_u^\dagger = \mathcal{M}_u$$

$$\mathbb{M}_u = \begin{pmatrix} \mathbf{0} & \frac{v'}{\sqrt{2}} y_u'^* \\ \frac{v}{\sqrt{2}} y_u^T & \mathcal{M}_u \end{pmatrix}$$

6x6 fermion mass matrix

$$\theta_q = \arg\,\det(\mathbb{M}_u \mathbb{M}_d) = \arg\det(y_u y_d) + \arg\det(y_u'^* y_d'^*) = 0$$

true even if the vector-like mass were not hermitian!

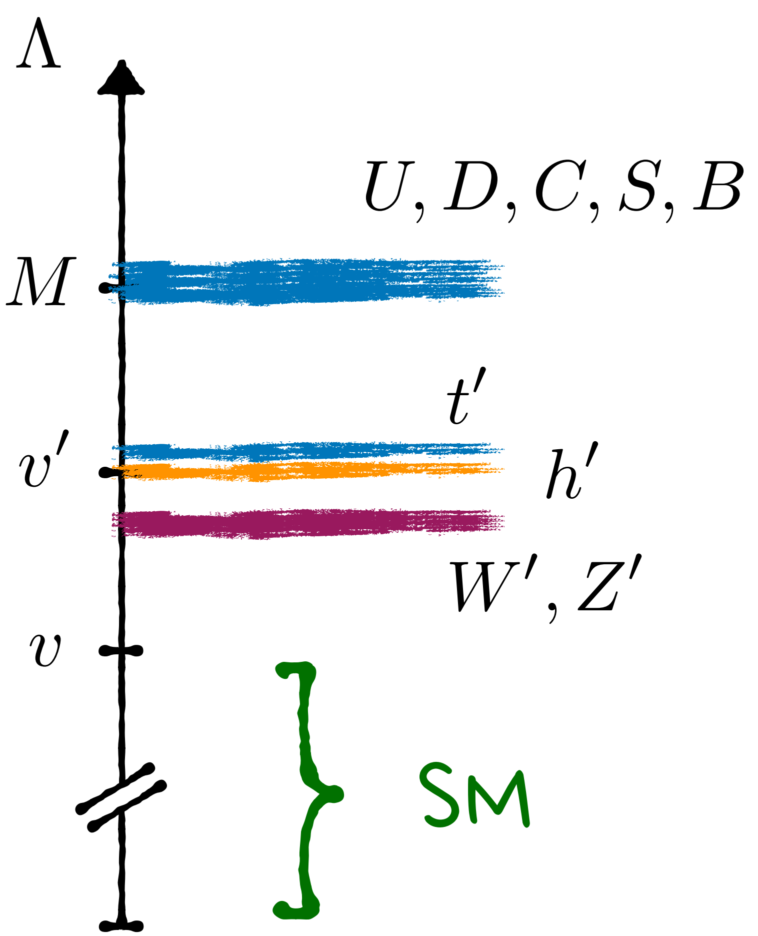
Vector-like masses for $SU(2)$-singlets are only possible in the version of the model with a single $U(1)$ factor

See-saw fermions

Two limiting realizations of the fermion spectrum:

- $M \ll v, v' \;\Rightarrow\; v' \gtrsim 10^8$ GeV
- $M \gg v, v' \;\Rightarrow$ "see-saw" mechanism for SM fermions $m_f \sim \dfrac{|y|^2 v v'}{M}$

(except top)



mirror quarks are heavy because M, not v', is large

Upper bound on M from perturbativity:

$$m_b \sim \frac{|y|^2 v v'}{M} \lesssim \frac{v v'}{M} \quad \Rightarrow \quad M \lesssim v' \times \frac{v}{m_b} \sim 10^2\, v'$$

N. Craig, **IGG**, G. Koszegi, A. McCune, arXiv:2012.13416

See-saw fermions

Because of see-saw implementation of light fermions masses, right-handed SM fermions belong in $SU(2)_R$ doublets, and mirror (heavy) fermions are made of $SU(2)$-singlets

$$\mathcal{L} \sim \frac{|y|^2 \left(Q'^\dagger H'\right)\left(H^\dagger Q\right)}{M} \sim \underbrace{\frac{|y|^2 v v'}{M}}_{m_d} d' d$$

same for leptons + 1st and 2nd generation up-quarks

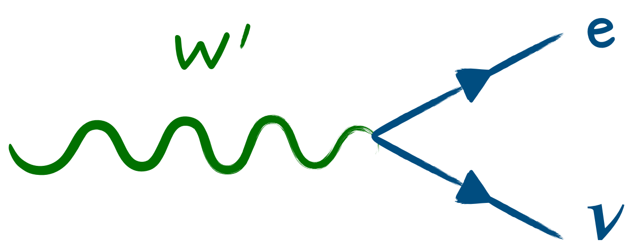
Exception:

$$\mathcal{L} \simeq \frac{y_t v}{\sqrt{2}} T t + \frac{y_t v'}{\sqrt{2}} t' T' + \text{h.c.}$$

Collider bounds

$\Rightarrow$ right-handed fermions have unsuppressed couplings to W' and Z'

Leading constraint on the parity-breaking scale from direct production of exotic gauge bosons at the LHC



$$m_{W'} \simeq \frac{gv'}{2} \gtrsim 6 \text{ TeV}$$ ATLAS; 1906.05609

$$\Rightarrow \quad v' \gtrsim 18 \text{ TeV} \qquad \Delta^{-1} \sim 10^{-3}$$

Future colliders such as FCC-hh (100 TeV *pp* machine) will be sensitive to $m_{W'}, m_{Z'} \sim 40$ TeV (equivalent to $\Delta^{-1} \sim 10^{-5}$)

colliders are *central* to probe parity solutions to strong CP

Collider bounds

- Mirror top partner at scale $m_{t'} \simeq m_t \times \frac{v'}{v} \approx v'$

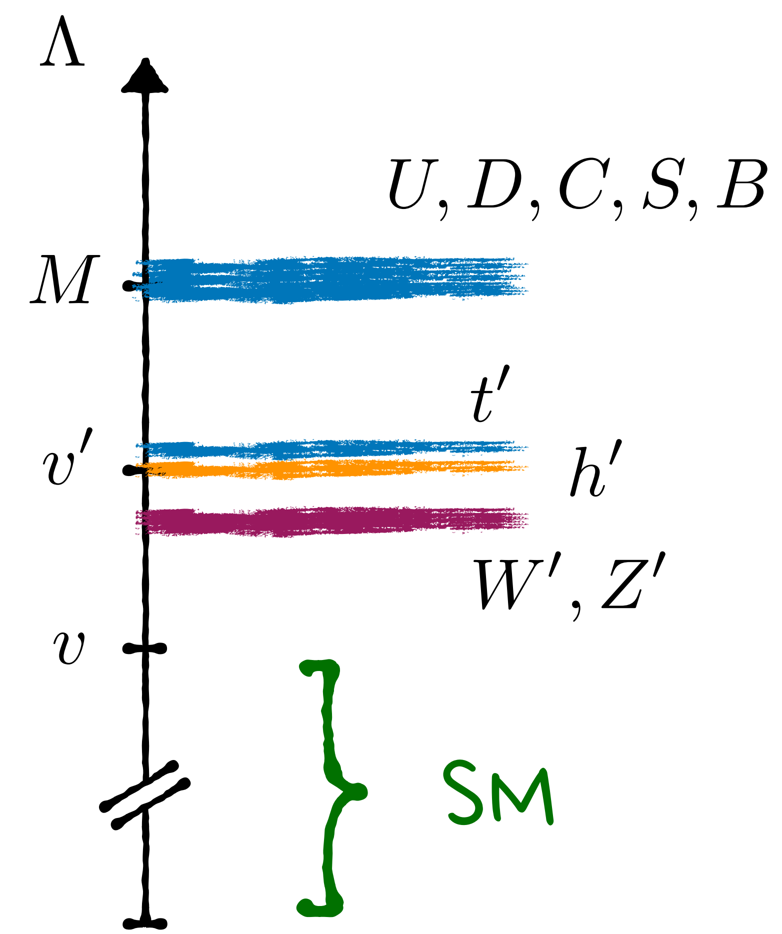
  Current bound $m_{t'} \gtrsim 2$ TeV ATLAS, 1808.02343; CMS, 1805.04758

much weaker bound on v' than that from w' and z' gauge bosons

- Mirror Higgs with mass $m_{h'} \simeq \sqrt{2\lambda} v'$

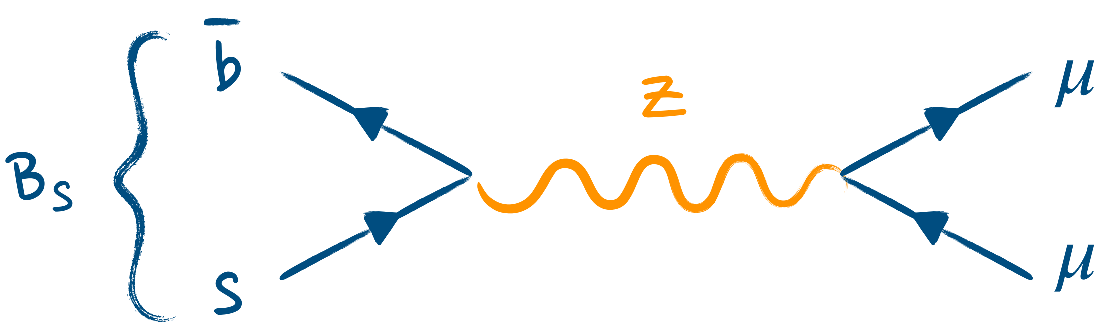
  Only competitive bound on v' for extremely small λ

- Additional colored particles at the see-saw scale $M \gg v'$



Flavor

Tree-level FCNCs mediated by the Z and h bosons, as well as their (much heavier) mirror counterparts



$$(\epsilon_d^\dagger \epsilon_d)_{32} = \frac{v^2}{2} \sum_i \frac{(\tilde{y}_d)_{3i} (\tilde{y}_d)^*_{2i}}{m^2_{D_i}}$$

$$\lesssim \frac{v}{M} \frac{\sqrt{m_b m_s}}{v'} \ll 1$$

$$\Delta \mathcal{H}_{\rm eff} \simeq -\sqrt{2} G_F \cos(2\theta_w) (\epsilon_d^\dagger \epsilon_d)_{32} (\bar{b}_L \gamma^\mu s_L)(\bar{\mu}_L \gamma_\mu \mu_L) + \text{h.c.}$$

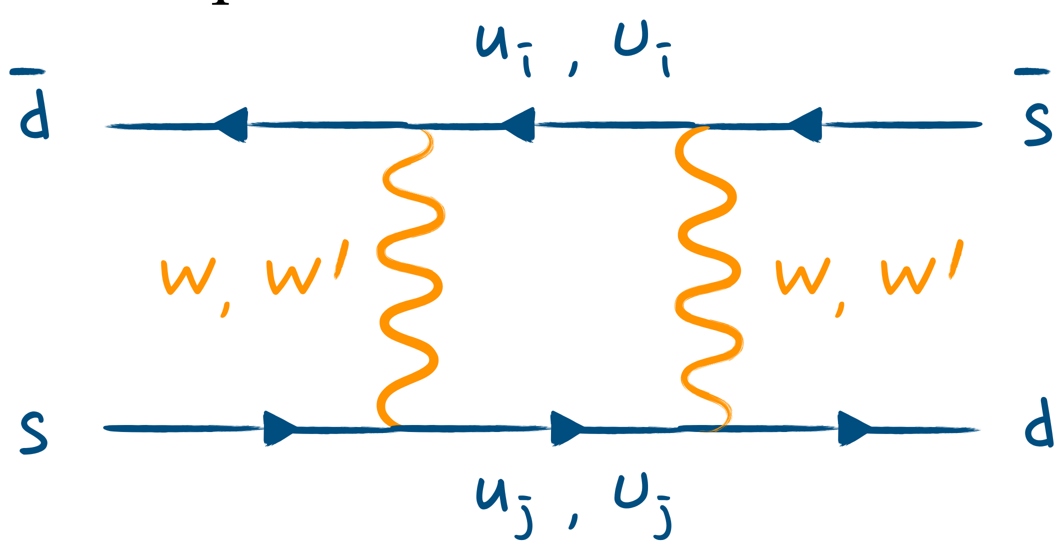
$$\frac{\text{BR}(B_s^0 \to \mu^+ \mu^-)_{\rm BSM}}{\text{BR}(B_s^0 \to \mu^+ \mu^-)_{\rm SM}} - 1 \lesssim 10^{-3} \left(\frac{18 \text{ TeV}}{v'} \right)^2 \left(\frac{v'}{M} \right)$$

(cf. uncertainty in the SM prediction of O(10%))

built-in suppression of tree-level FCNCs as a result of see-saw mechanism

Flavor

At one-loop:



Leading correction from diagrams involving one W and one W'

$$\Delta m_K \approx -6 \cdot 10^{-16} \text{ GeV} \left(\frac{6 \text{ TeV}}{m_{W'}} \right)^2$$

<< theoretical uncertainty on SM prediction

Correction to $|\epsilon_K|$ can be large. For anarchic Yukawa coupling structure:

$$M \gtrsim 750 - 1000 \text{ TeV}$$

see-saw scale in the up sector

theory consistent with current bounds, but careful analysis could reveal constraints on the flavor structure of these models

Soft breaking of parity

If parity is only broken softly in the Higgs potential, then $\bar{\theta} \lesssim 10^{-19}$

no larger than in the SM

Second source of soft-breaking in non-hermitian vector-like masses

$$\mathcal{L} \supset (\mathcal{M}_u)_{ij} U_i U'_j + \text{h.c.} \qquad \text{with} \qquad \mathcal{M}_u^\dagger \neq \mathcal{M}_u$$

breaks both P and CP

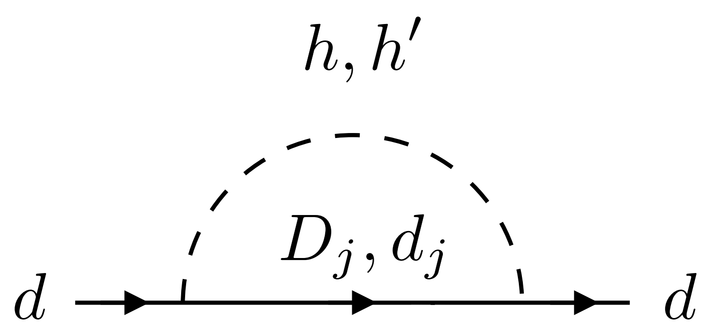
<u>At tree-level:</u>

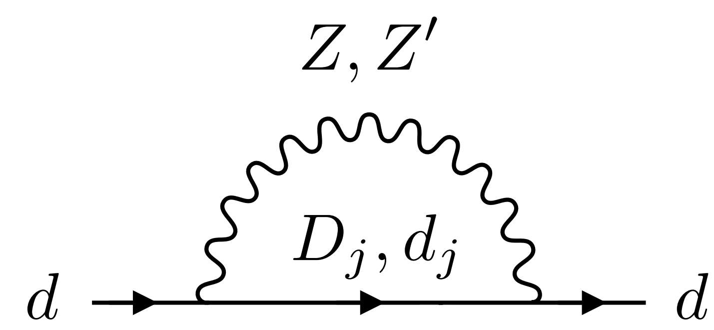
$$\mathbb{M}_u = \begin{pmatrix} \mathbf{0} & \frac{v'}{\sqrt{2}} y_u'^* \\ \frac{v}{\sqrt{2}} y_u^T & \mathcal{M}_u \end{pmatrix} \qquad \begin{aligned} \theta_q &= \arg\,\det(\mathbb{M}_u \mathbb{M}_d) \\ &= \arg\det(y_u y_d) + \arg\det(y_u'^* y_d'^*) = 0 \end{aligned}$$

$$\Rightarrow \ \bar{\theta} = 0 \ \text{ at tree-level if the breaking is soft}$$

Radiatively induced EDMs

At one-loop:





$$\bar{\theta} \simeq \sum_i \left\{ \frac{\mathrm{Im}(\delta m_{d_i})}{m_{d_i}} + \frac{\mathrm{Im}(\delta m_{u_i})}{m_{u_i}} \right\} = 0$$

Babu, Mohapatra; PRD 41 (1990)

However, individual EDMs for elementary fermions are non-zero…
for both quarks and leptons!

$$d_f \sim \frac{Q_f m_f}{32\pi^2 M^2} \times \mathcal{O}\left(\frac{|\Delta \mathcal{M}|}{M}\right)$$

deviation from hermiticity in vector-like mass

N. Craig, **IGG**, G. Koszegi, A. McCune, arXiv:2012.13416

Radiatively induced EDMs

If the soft breaking of parity is $\mathcal{O}(1)$:

twice the parity-breaking scale

$$d_u, d_d \sim 10^{-28} \left(\frac{40 \text{ TeV}}{M} \right)^2 e \cdot \text{cm}$$

O(10^2) below current but within reach of near-future improvements

$$d_e \sim 10^{-29} \left(\frac{90 \text{ TeV}}{M} \right)^2 e \cdot \text{cm}$$

cf. with current bound on eEDM: $|d_e| < 1.1 \cdot 10^{-29} \; e \cdot \text{cm}$

potentially observable neutron and electron EDMs

Spontaneous breaking of parity

More realistically, we might expect parity-breaking to be spontaneous

In principle, it can happen with or without breaking *CP*

e.g.

$$V \supset -\frac{m_\sigma^2}{2}(\sigma^2 + \sigma'^2) + \frac{\lambda_1}{4}(\sigma^2 + \sigma'^2)^2 + \frac{\lambda_2}{4}\sigma^2\sigma'^2$$

$$+ \lambda_\sigma \left(\sigma^2|H|^2 + \sigma'^2|H'|^2\right) + \lambda'_\sigma(\sigma'^2|H|^2 + \sigma^2|H'|^2)$$

if $\lambda_2 < 0 \Rightarrow$

$\langle\sigma\rangle = 0$ and $\langle\sigma'\rangle \neq 0$

(and v.v.)

$$\Rightarrow v^2 \neq v'^2 \text{ if } \lambda_\sigma \neq \lambda_{\sigma'}$$

possible (at least in principle) to break P without breaking CP

Spontaneous breaking of parity

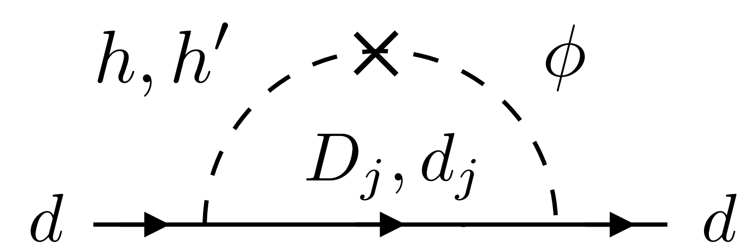
More generally, *P* and *CP* might be broken simultaneously, e.g.

$$V \supset \underbrace{\lambda_\phi \left(\phi^2 - v'^2\right)^2}_{\langle \phi \rangle = \pm v'} + \underbrace{\mu_\phi \phi \left(|H|^2 - |H'|^2\right)}_{v^2 \ll v'^2}$$

However…

$$\mathcal{L} \supset i(\bar{y}_\phi)_{ij} \phi D_i D'_j + \text{h.c.} \qquad \text{with} \qquad \bar{y}_\phi^\dagger = \bar{y}_\phi$$

$$\theta_q \sim \frac{|\bar{y}_\phi| v'}{16\pi^2 M} \quad \Rightarrow \quad \bar{y}_\phi \lesssim 10^{-8} \frac{M}{v'} \lesssim 10^{-6}$$



Albaid, Dine, Draper, 1510.03392

interactions between quarks and symmetry breaking sector must be small

(not the most attractive feature of these models, but technically natural)

Gravity breaks P

Gravity can break *P* without spoiling the solution to strong CP

Leading parity-breaking HDO that contributes to $\bar{\theta}$

$$\mathcal{L} \supset \frac{1}{M_{Pl}} \left[(\alpha_u)_{ij} (H' Q'_i)(H Q_j) + (\alpha_d)_{ij} (H'^{\dagger} Q'_i)(H^{\dagger} Q_j) \right] + \text{h.c.}$$

Breaks parity provided $\alpha_{u,d} \neq \alpha^{\dagger}_{u,d}$

$$\delta m_u \simeq \frac{v v' (\alpha_u)_{11}}{2 M_{Pl}} \quad \text{and} \quad \delta m_d \simeq \frac{v v' (\alpha_d)_{11}}{2 M_{Pl}}$$

Gravity breaks P

$$\theta_q \simeq \frac{\mathrm{Im}(\delta m_u)}{m_u} + \frac{\mathrm{Im}(\delta m_d)}{m_d} \sim 10^5 \frac{|\alpha| v'}{2M_{Pl}}$$

$$\Rightarrow \qquad v' \lesssim 20 \text{ TeV} \left(\frac{\bar{\theta}}{10^{-10}} \right)$$

cf. lower bound from production at LHC $v' \gtrsim 18$ TeV

P solution to strong CP + gravity violates all global symmetries

$\Rightarrow$ neutron EDM could be observed in upcoming experiments

Gravity breaks P

<u>What if parity was a gauge symmetry?</u>

Previous HDO allowed, but must be parity symmetric:

$$\alpha_{u,d} = \alpha^\dagger_{u,d} \qquad \Rightarrow \qquad \bar{\theta} = 0$$

There can be no explicit breaking of parity, only spontaneous

$$\mathcal{L} \supset \eta_s \frac{\phi g_s^2}{32\pi^2 M_{Pl}} \mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right) \qquad \Rightarrow \qquad v' \lesssim 10^9 \text{ GeV}$$

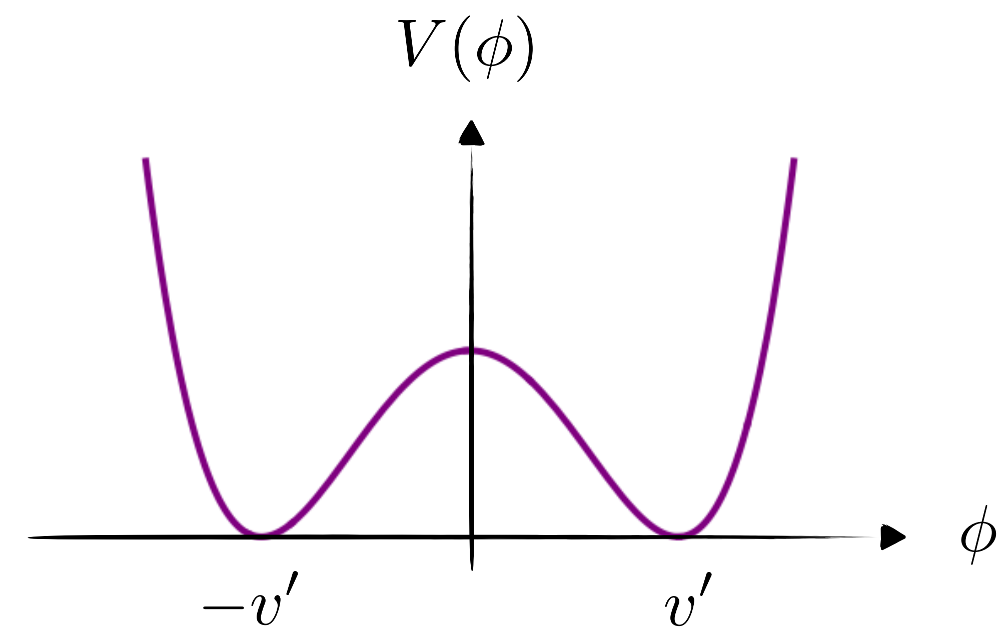
$$\mathcal{L} \supset \frac{i\phi}{M_{Pl}} \left\{(\zeta_u)_{ij} Q_i H U_j + (\zeta'_u)_{ij} Q'_i H' U'_j\right\} + \text{h.c.} \qquad \text{with} \qquad \zeta'_u = \zeta^*_u$$

$$\Rightarrow \quad v' \lesssim 10^7 \text{ GeV}$$

Domain walls

$$V \supset \lambda_\phi \left(\phi^2 - v'^2\right)^2 + \mu_\phi \phi \left(|H|^2 - |H'|^2\right)$$

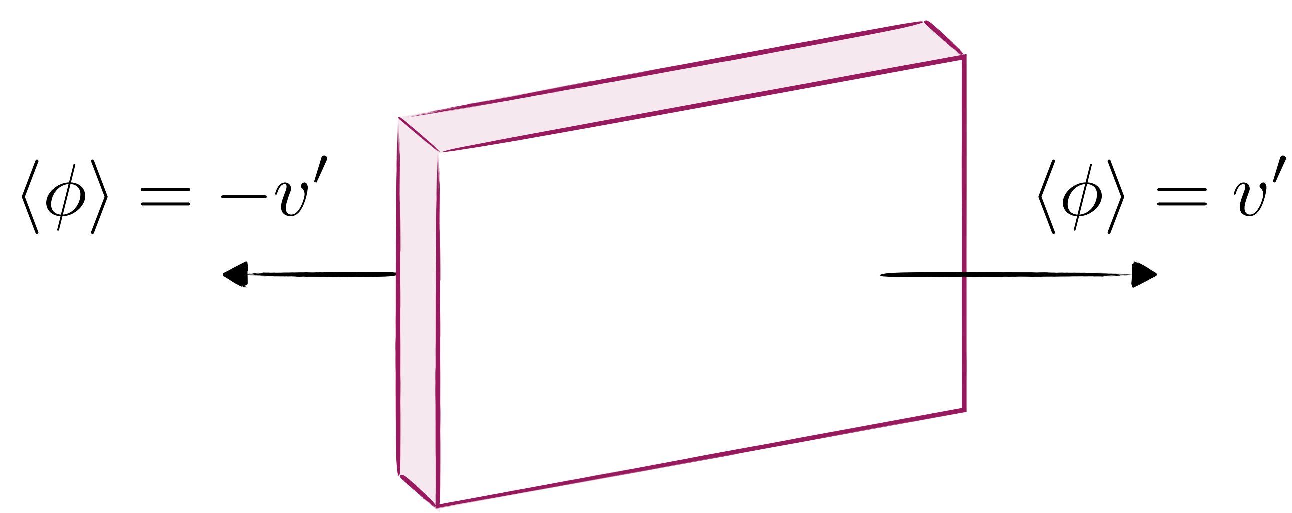
$\langle \phi \rangle = \pm v'$ $\qquad$ $v^2 \ll v'^2$



Spontaneously broken discrete symmetry

$\Rightarrow$ domain wall solutions

topologically stable
(if global)



$$\sigma \sim \sqrt{\lambda_\phi} v'^3$$

Domain walls

<u>Domain wall problem</u>: domain walls formed after inflation eventually dominate the Universe's energy density, in contradiction with observation

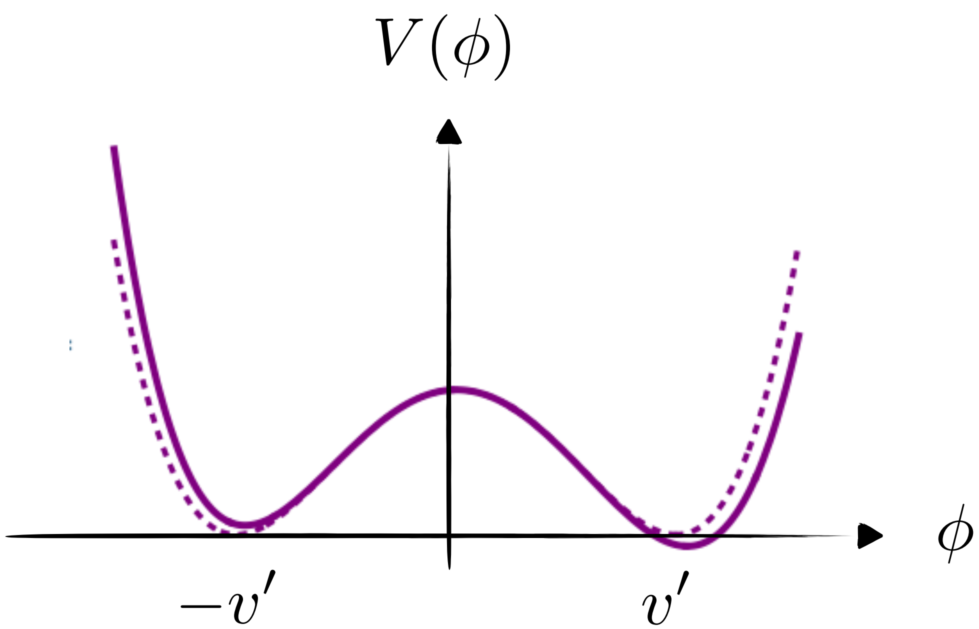
Zeldovich, Kobzarev, Okun (1974)

* However... *

Quantum gravity violates global symmetries

The breaking of parity due to gravitational effects will break the vacuum degeneracy, making the domain walls unstable

$$V \supset \epsilon \frac{\phi^5}{M_{Pl}} \qquad \Rightarrow \qquad \delta V \sim \epsilon \frac{v'^5}{M_{Pl}}$$



network of domain walls collapses, emitting gravitational radiation

Domain wall evolution

Domain wall network evolution determined by two competing effects:

δV

force per u. area due to pressure difference between vacua

$$\frac{\sigma}{R(t)} \sim \frac{\sigma}{t}$$

force per u. area acting on wall with curvature radius R

Time of collapse:

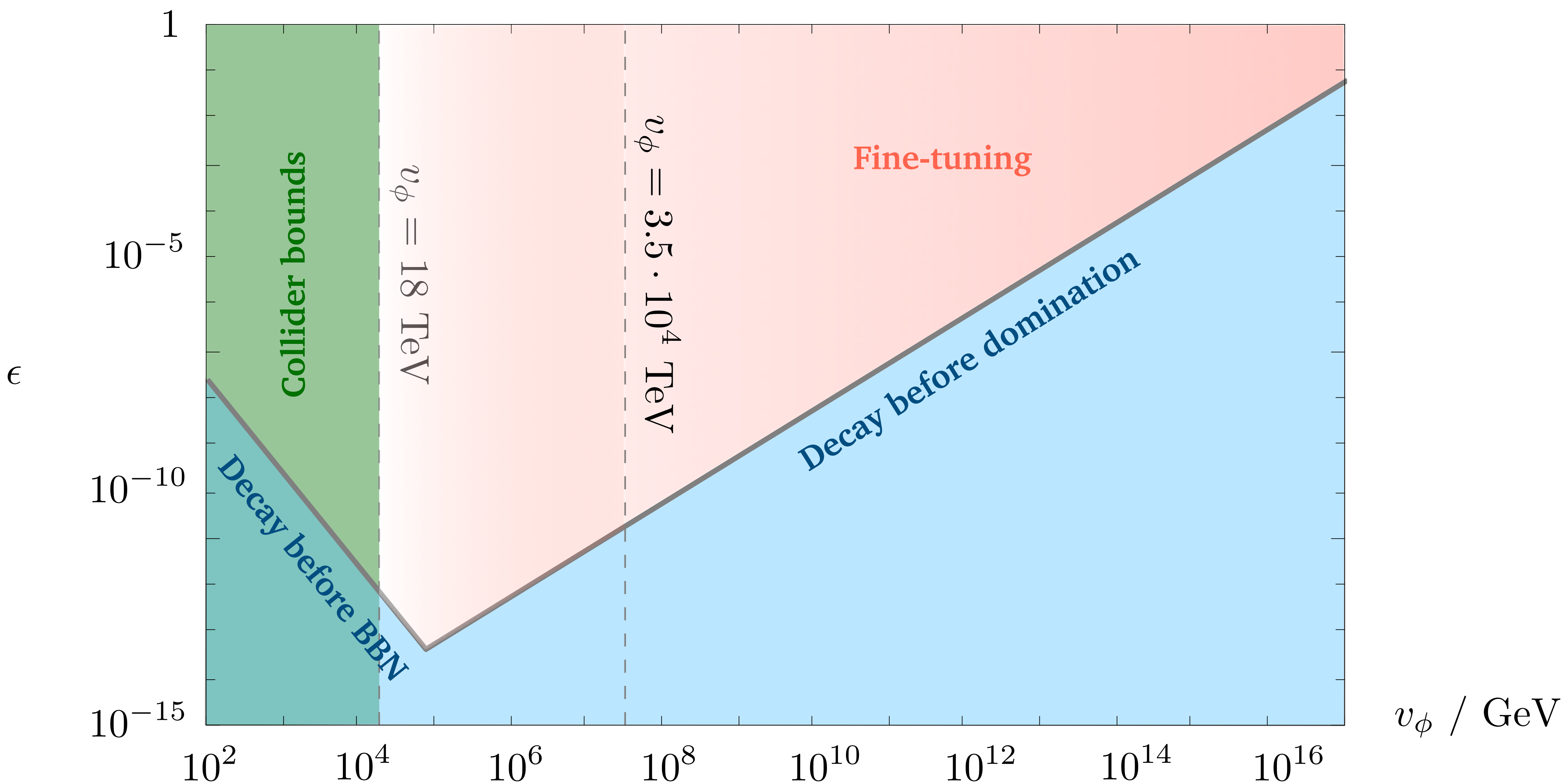
$$t_* \sim \frac{\sigma}{\delta V} \sim \frac{1}{\epsilon} \frac{M_{Pl}}{v'^2}$$

Vilenkin (1981)

The smaller ϵ , the later the collapse takes place

$\Rightarrow$ lower bound on amount of symmetry violation to avoid domain wall domination

Domain wall evolution



N. Craig, **IGG**, G. Koszegi, A. McCune, arXiv:2012.13416

Gravitational wave signal

Two main quantities characterize the resulting gravitational wave signal:

- Peak frequency determined by typical radius of domain walls:

$$R \sim H^{-1} \sim t_*$$

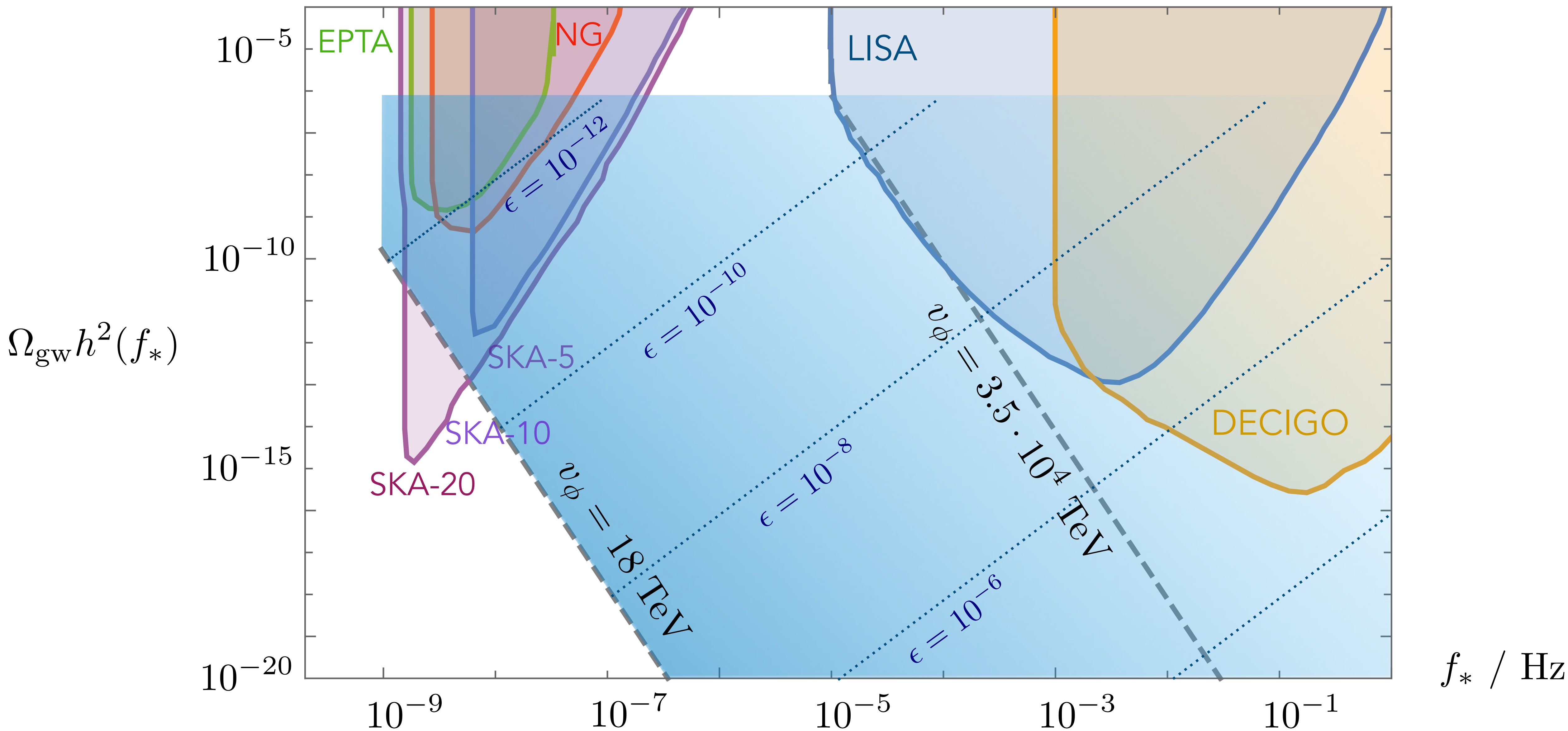
typical domain wall radius ↩ ↪ network collapse

- Strength: $$\rho_{\rm gw} \sim G_N \sigma^2$$

The smaller ϵ, the later the collapse takes place

$\Rightarrow$ lower frequency, stronger signal (less redshift)

Gravitational wave signal



N. Craig, **IGG**, G. Koszegi, A. McCune, arXiv:2012.13416

UV completion

Albaid, Dine, Draper, 1510.03392

A full solution to the strong CP problem must solve the hierarchy problem without spoiling the solution to strong CP

true also for other solutions to the strong CP problem
(e.g. QCD axion, also requires stabilizing the PQ scale)

e.g. supersymmetry tends to spoil the protection of $\bar{\theta}$ since additional parameters in the scalar potential can introduce new phases

an urgent open problem for these models

Conclusions

Parity-symmetric theories can provide an attractive solution to the strong CP problem

They are robust against the breaking of global symmetries expected in a gravitational UV-completion

unlike the QCD axion!

Experimental implications for a wide range of experiments, not only colliders but also EDM experiments and gravitational wave observatories

Many open questions, and an opportunity in light of experimental progress in near future

Thank you!