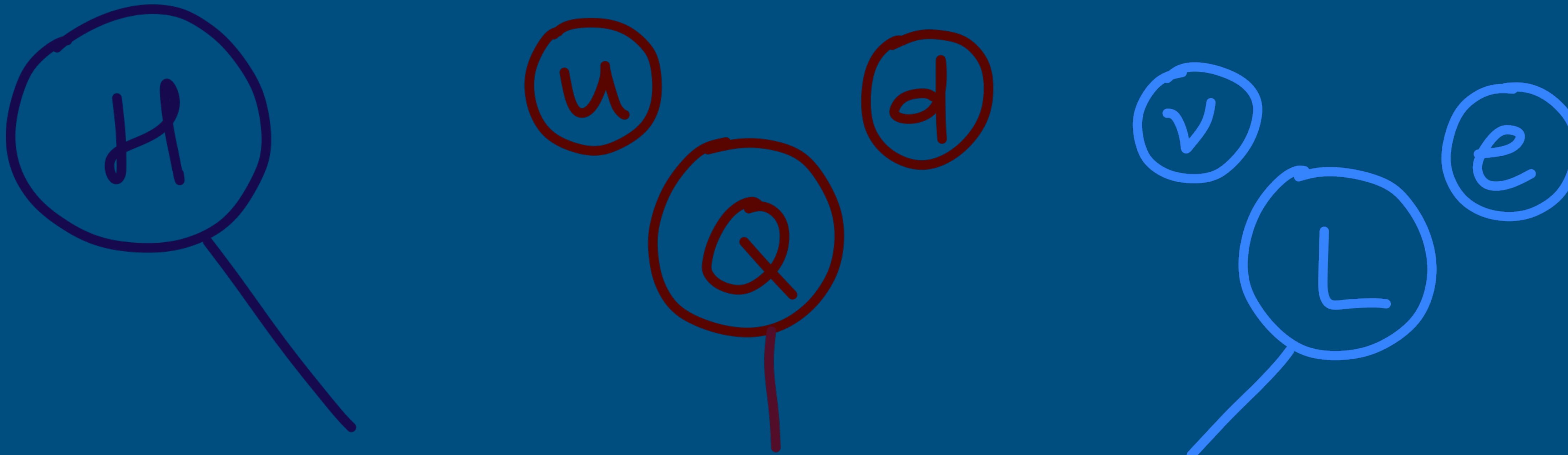
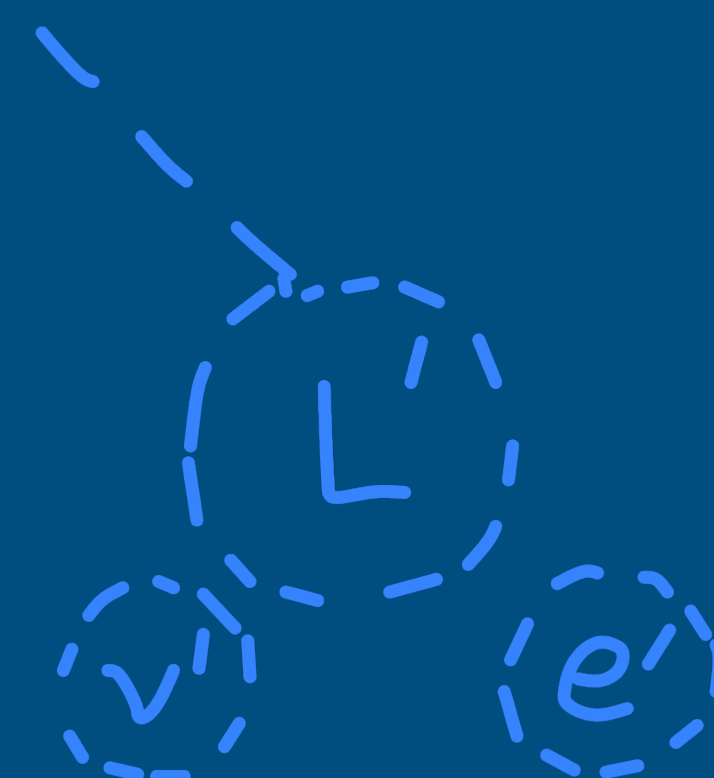


Parity, Not Peccei-Quinn, to Solve Strong CP

APS Division of Particles and Fields, 2021

AMARA MCCUNE, UC SANTA BARBARA



Talk Outline

1. **Motivations**
   1. Defining the strong CP problem
   2. The axion solution & quality problem
2. **Our Model**
   1. Gauge group extension
   2. Generalized parity
   3. Fine-tuning considerations
3. **Experimental Signatures and Constraints**
   1. Collider bounds
   2. Flavor constraints
   3. EDM bounds
   4. Gravitational waves
4. **Conclusions**

The Strong CP Problem

CP violation is observed experimentally in the weak sector, but not in the strong sector. **Amount of violation expected to be $\mathcal{O}(1)$.**

In QCD, CP violation can occur in two places:

1. In the term $\mathscr{L} \supset \dfrac{\theta_s g^2}{32\pi^2}\,\mathrm{tr}\,(G_{\mu\nu}\tilde{G}^{\mu\nu})$
2. Via the quark mass matrix: $\theta_q = \arg\det M_q$

these combine to get

$$\mathscr{L} \supset \frac{\bar{\theta} g^2}{32\pi^2}\,\mathrm{tr}\,(G_{\mu\nu}\tilde{G}^{\mu\nu}),$$

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

$\bar{\theta}$ contributes to the observable neutron electric dipole moment (EDM):

$$d_n \sim 10^{-16}\,\bar{\theta}\,e\cdot\mathrm{cm},\ |d_n| < 1.8\cdot 10^{-26}\,e\cdot\mathrm{cm}$$

This heavily constrains the size of the QCD vacuum angle,

$$\bar{\theta} = \theta_s + \theta_q \lesssim 10^{-10}$$

Unexpectedly tiny

Why is $\bar{\theta}$ so small? This is a fine-tuning problem of 1 part in 10^{10}

The QCD Axion Solution

Goal: to explain smallness of $\bar{\theta}$ as a consequence of some additional structure, rather than a model-building input.

The QCD axion is a dynamical field a that is the pseudo-Nambu Goldstone boson of a spontaneously broken $U(1)_{PQ}$ symmetry.

We can rotate a into $\bar{\theta}$ via PQ, a chiral symmetry, such that $\langle a \rangle = \bar{\theta}$:

$$\mathscr{L} \supset \frac{\alpha_s}{4\pi}\left(\bar{\theta} - \frac{a}{f_{PQ}}\right)(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

Violation of $U(1)_{PQ}$ by gravity induces a potential for the axion, possibly spoiling the $\bar{\theta}$ solution $\Longrightarrow$ Need $U(1)_{PQ}$ to be a high-quality global symmetry

This is known as the **quality problem.**

$\boxed{\text{Are there better solutions?}}$

"P not PQ"

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P not PQ

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ABSTRACT: Parity solutions to the strong CP problem are a compelling alternative to approaches based on Peccei-Quinn symmetry, particularly given the expected violation of global symmetries in a theory of quantum gravity. The most natural of these solutions break parity at a low scale, giving rise to a host of experimentally accessible signals. We assess the status of the simplest parity-based solution in light of LHC data and flavor constraints, highlighting the prospects for near-future tests at colliders, tabletop experiments, and gravitational wave observatories. The origin of parity breaking and associated gravitational effects play crucial roles, providing new avenues for discovery through EDMs and gravity waves. These experimental opportunities underline the promise of generalized parity, rather than Peccei-Quinn symmetry, as a robust and testable solution to the strong CP problem.

Parity Solutions

Observation of CP violation in weak sector but not the strong sector $\implies$ solution could involve a spacetime symmetry of the weak sector.

We restore P symmetry in the UV by extending the SM gauge group to $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_Y$ and adding the following matter content + mirror sector leptons and gauge bosons:

Standard Model sector

"Mirror sector"

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

Generalized Parity

Now, we define a "generalized parity" between the left- and right-chiral $SU(2)$ groups. The new matter content transforms as:

$$\mathrm{W}_L^{\mu} \leftrightarrow \mathrm{W}_{R,\mu}$$

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

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

Strong CP is then solved as follows:

1. θ_s is set to zero since parity is now a good symmetry
2. Additional colored particles $\Longrightarrow$ extended mass matrix & Yukawa terms

$$\mathscr{L} \supset -\{(y_u)_{ij} Q_i H U_j + (y'_u)_{ij} Q_i'^{\dagger} H'^{*} U_j'^{\dagger}\} + \text{h.c.}$$

$$\theta_q = \text{arg det}(y_u y_d) + \text{arg det}(y_u'^{*} y_d'^{*})$$

+similar terms for down-type quarks and leptons

Demanding that Yukawa interactions preserve parity sets $y'_f = y_f$

$\Longrightarrow$ We can now set $\theta_q = 0$ ✓

Fine-Tuning

To be compatible with experiment, we must break parity such that mirror particles are heavy.

Soft breaking in the scalar potential $\rightarrow m_{u'} = \frac{v'}{v} m_u \lesssim 1$ TeV $\Longrightarrow \; v' \gtrsim 10^8$ GeV

$$\Delta^{-1} \simeq \frac{2v^2}{v'^2} \sim 10^{-12} \qquad \boxed{\text{1 part in } 10^{12} \text{ tuning!}}$$

However, we can also write mass terms for vector-like fermions:

$\mathscr{L} \supset (\mathscr{M}_u)_{ij} U_i U_j' +$ h.c., where $\mathscr{M}_u = \mathscr{M}_u^\dagger$ and we can write a full mass matrix

for the fermions: $\mathbb{M}_f = \begin{pmatrix} 0 & \frac{v'}{\sqrt{2}} y_f'^* \\ \frac{v}{\sqrt{2}} y_f^T & \mathscr{M}_f \end{pmatrix}$

Dimensions of 6x6
f = u, d

Goal: to uncover most promising experimental signatures $\Longrightarrow$ make the level of fine-tuning as mild as possible

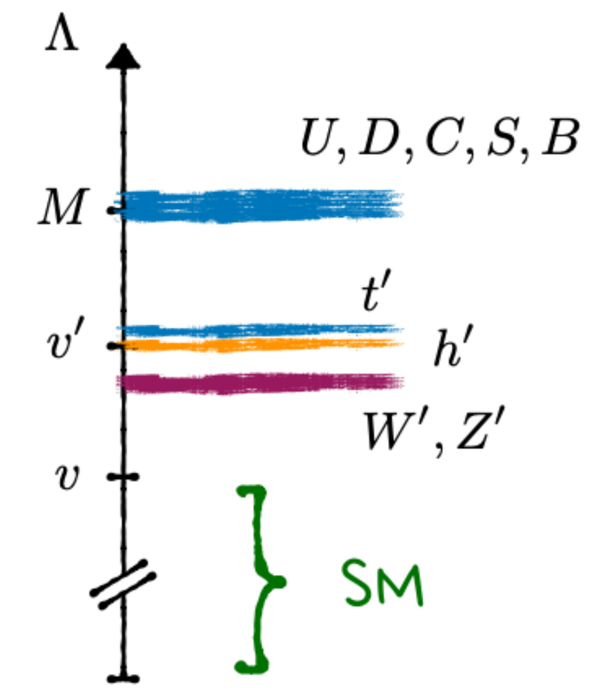
The Universal Seesaw Mechanism

A bound on M is set by generating the b quark mass via the seesaw mechanism ($M \gg v, v'$):

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

Mirror quarks are then heavy due to large M → allows for lower parity breaking scale $v' \implies$ **lower fine-tuning**.

We then have a least-tuned mass spectrum



We treat the top quark separately due to its large mass.

Collider Bounds

We can constrain the parity-breaking scale most strongly via direct probes on exotic gauge bosons:

$$m_{W'} \simeq \frac{gv'}{2} \gtrsim 6\ \mathrm{TeV} \Longrightarrow v' \simeq 18\ \mathrm{TeV}$$

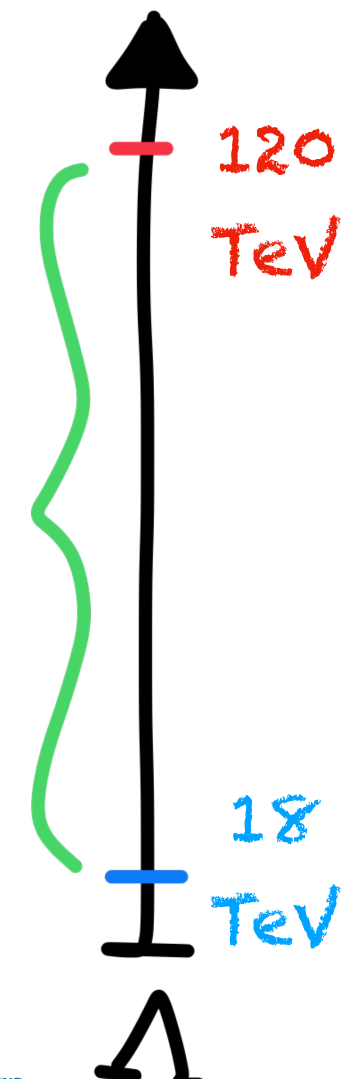
Gives a tuning $\Delta^{-1} \sim 10^{-3}$ (1 part in 10^3)

A 100 TeV collider like the FCC-hh should be sensitive to W' and Z' as heavy as 40 TeV, or $v' \simeq 120$ TeV

This covers much of the "most natural" parameter space.

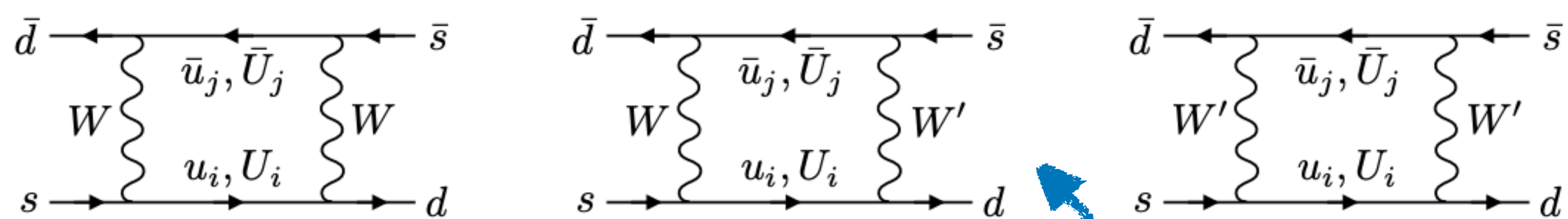
A "non-observation" $\Longrightarrow$ tuning to $\Delta^{-1} \sim 10^{-5}$ (1 part in 10^5)

$\boxed{\text{Colliders are a viable way to probe these solutions}}$



Flavor Constraints

Usual meson mixing one-loop diagrams now include contributions from mirror gauge bosons. Largest contributions to the FCNC at one-loop from kaons:



Largest individual contribution from WW' diagram with u or c quarks

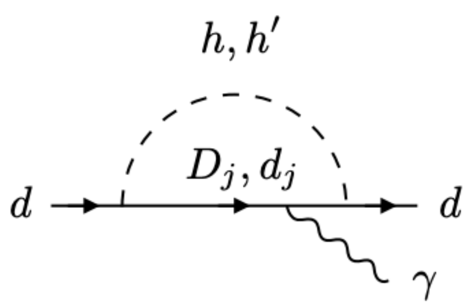
Leading corrections to kaon mixing parameters are:

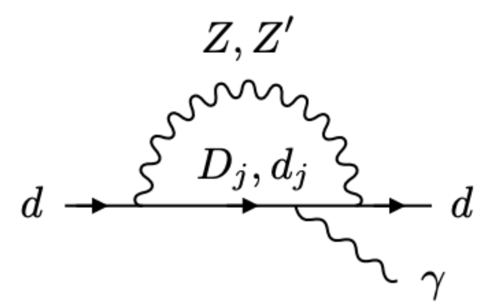
$$(\Delta m_K)_{u,c} \approx -6 \cdot 10^{-16}\ \mathrm{GeV} \left(\frac{6\mathrm{TeV}}{m_{W'}}\right)^2, \ |\epsilon_K|_{u,c} \approx 7 \cdot 10^{-5} \left(\frac{6\mathrm{TeV}}{m_{W'}}\right)^2$$

Results are consistent with current bounds on kaon mixing

Neutron Electric Dipole Moments

Breaking parity $\Longrightarrow$ can radiatively generate EDMs. In the case of **softly-broken parity**:





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

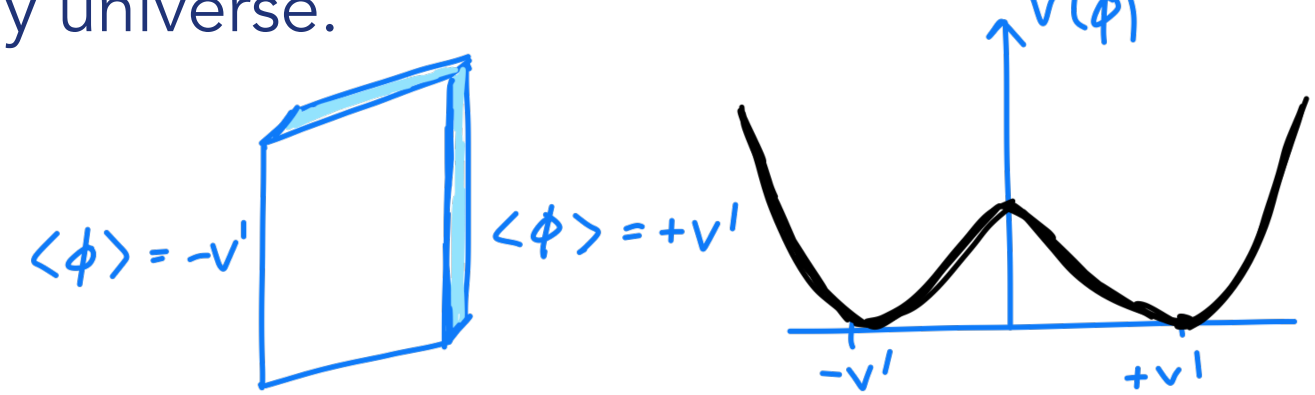
For parity as a **global symmetry**, an EDM can be generated via higher-dimensional operators that explicitly violate P:

$$\mathscr{L} \supset \frac{1}{M_{pl}}[(\alpha_u)_{ij}(H'Q'_i)(HQ_i) + (\alpha_d)_{ij}(H'^{\dagger}Q'_i)(H^{\dagger}Q_i)],\ v' \lesssim \frac{20\text{ TeV}}{|\alpha|}\left(\frac{\bar{\theta}}{10^{-10}}\right)$$

$\boxed{\bar{\theta} \text{ contribution accessible to near-future EDM experiments}}$

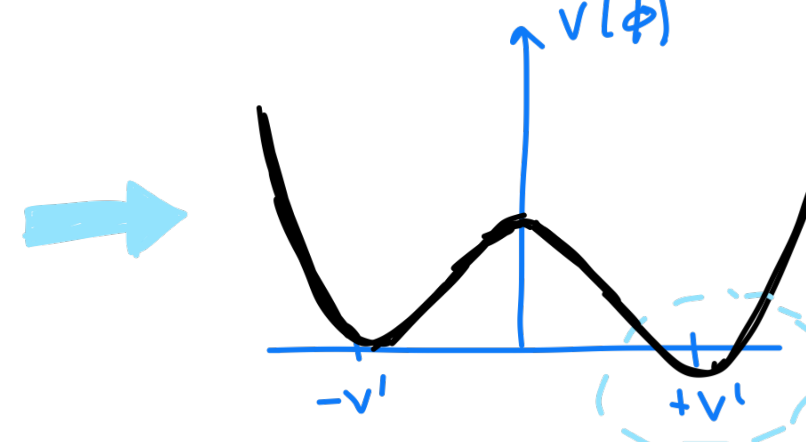
Breaking of P by Gravity

Spontaneous breaking of a discrete symmetry $\Longrightarrow$ network of domain walls in early universe.



Leads to possible **domain wall problem** in which the universe's energy density is dominated by domain walls.

Luckily...quantum gravity violates global symmetries $\Longrightarrow$ degeneracy will be broken



This leads to the **formation of gravitational waves** following a network collapse time: $t_{coll.} \sim \dfrac{\sigma}{\delta V} \sim \dfrac{\sqrt{\kappa_\phi} M_{Pl}}{\epsilon v_\phi^2}$

Gravitational Wave Signals

Resulting gravitational waves will have a strength:

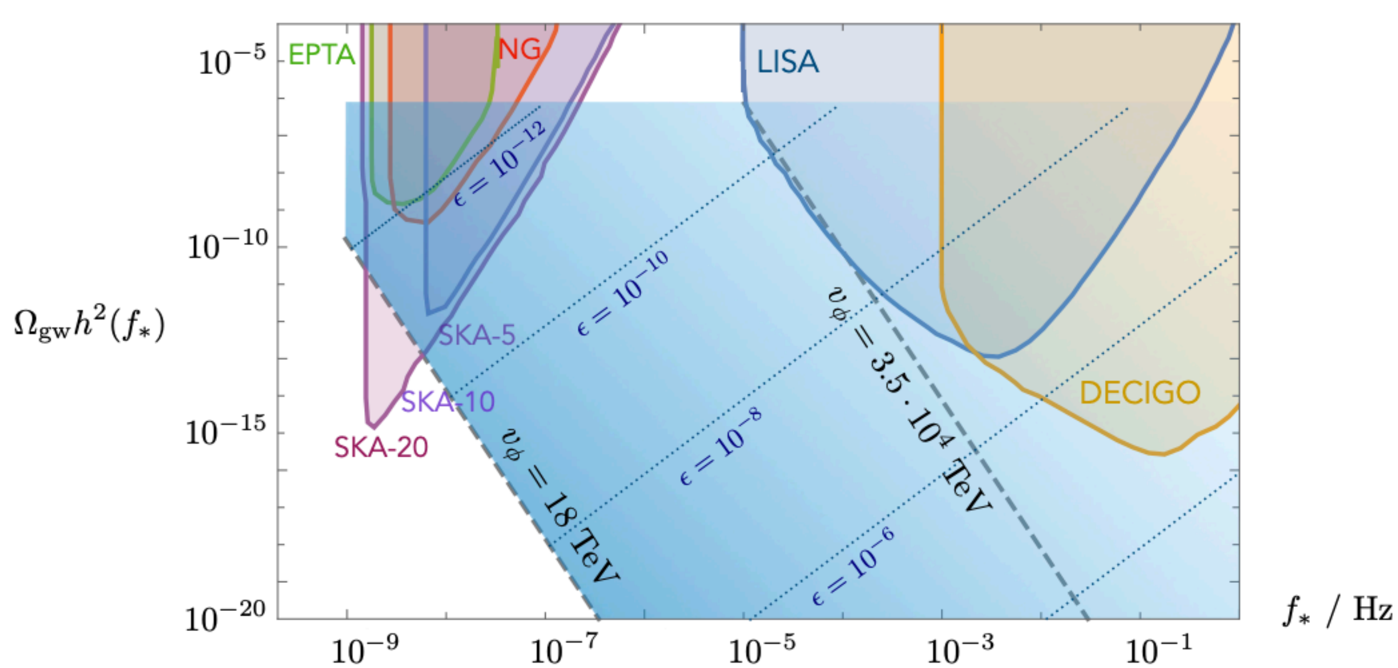
$$\rho_{gw} \sim G_N \sigma^2$$

And a peak frequency:

$$f_* \sim 10^{-9}\ \text{Hz}\left(\frac{v_\phi}{18\ \text{TeV}}\right)\left(\frac{\epsilon}{10^{-12}}\right)^{1/2}\left(\frac{1}{\kappa_\phi}\right)^{1/4}$$

Smaller amount of symmetry breaking $\epsilon \implies$ later time for collapse $\implies$ stronger signal and lower frequency.

For low tuning, want to be close to the left dashed line



Blue region corresponds to possible peaks of stochastic background

Conclusions

Many compelling reasons to consider parity solutions:

1. Easier to make these models compatible with a gravitational UV-completion than other solutions.

2. A high parity-breaking scale would induce heavy mirror quark masses, explaining why we have not detected them.

3. A **testable** class of solutions to the strong CP problem, accessible to future colliders, EDM experiments, and gravitational wave observatories.

Thank You!