Title: A strategy for progress in particle physics

Speakers: Isabel Garcia Garcia

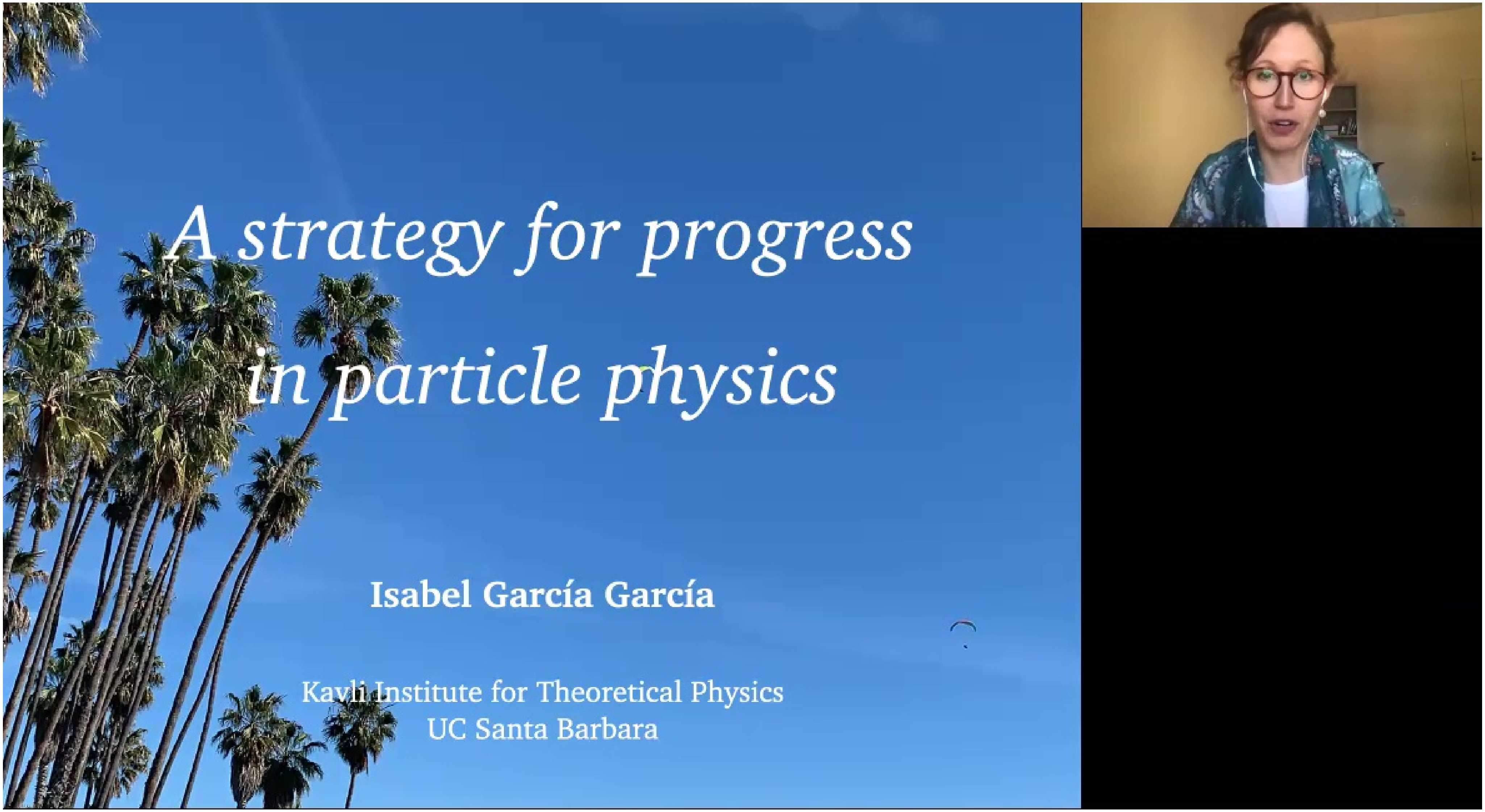
Series: Particle Physics

Date: March 12, 2021 - 1:00 PM

URL: http://pirsa.org/21030019

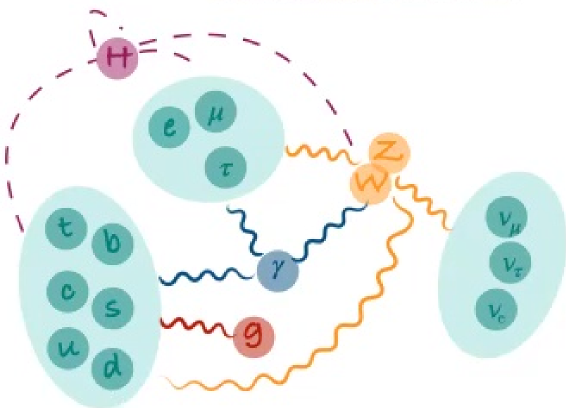
Abstract: From dark matter to the strong CP problem to the dynamics behind the weak scale, a variety of observations make for a compelling case that the Standard Model is an incomplete description of subatomic physics. Yet none of these puzzles provides unambiguous guidance on how we should proceed to find what comes next.

I will argue that this state of affairs calls for a multi-directional strategy in our quest for physics Beyond-the-Standard-Model. Only a combination of new theoretical developments and original ideas, confronted with the vast array of experiments at our disposal, will provide us with the big picture we need to move beyond.


A strategy for progress
in particle physics
Isabel García García
Kavli Institute for Theoretical Physics
UC Santa Barbara

Where are we?

Standard Model

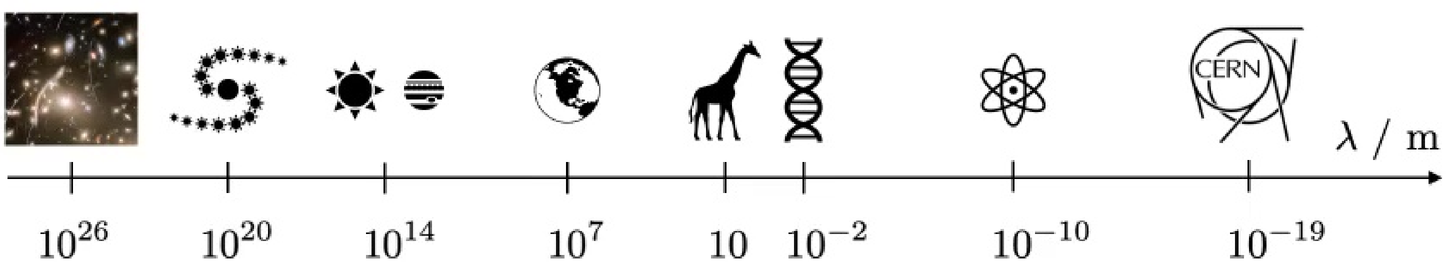


$$SU(3) \times SU(2) \times U(1)$$

General Relativity

$$G_{\mu\nu} = \frac{1}{M_{Pl}^2} 8\pi T_{\mu\nu}$$

" geometry = matter "



Why go beyond?

The Standard Model is an incomplete description of subatomic physics

- Dark Matter 
- Neutrino masses
- Matter/anti-matter asymmetry
- Strong CP problem:

  Need for a very special boundary condition on $SU(3)$ vacuum angle, $\bar{\theta} \lesssim 10^{-10}$, to accommodate the absence of neutron EDM

- Weak scale dynamics:

$$SU(2) \times U(1) \xrightarrow{\langle |H|^2 \rangle \neq 0} U(1)_{\text{EM}} \quad \text{with} \quad \frac{\langle |H|^2 \rangle}{M_{Pl}^2} \sim 10^{-32}$$

etc...

What next?

There are a variety of observations that together make for a compelling argument that the Standard Model is incomplete

Challenge: provide solutions that can be experimentally probed

- Hard, long-standing problems
- Compelling case in favor of physics Beyond-the-Standard-Model, but no unambiguous hint of what to expect

My talk

What I think is a right strategy in our attempt to discover the theory that underlies the Standard Model

① Revisit old assumptions in light of theoretical developments

weak scale dynamics

② Exploring connections between puzzles to find the guidance we currently lack

dark matter

③ Find all ways to test our ideas

strong CP

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Revisit

old

assumptions

Effective Field Theory

'EFT paradigm' underlies most prior work on these puzzles

for good reasons!

EFT is a framework to organize a theory in terms of energy scales

Decoupling: The behaviour of a physical system in the infrared (IR) is largely independent of its features in the ultraviolet (UV)

Wilson, Kadanoff, 1970s

e.g. universality in 2nd order phase transitions

An EFT is only valid up to some finite energy scale Λ — beyond, it needs to be 'UV-completed' into a more fundamental theory

details of UV-completion not important at energies $E \ll \Lambda$

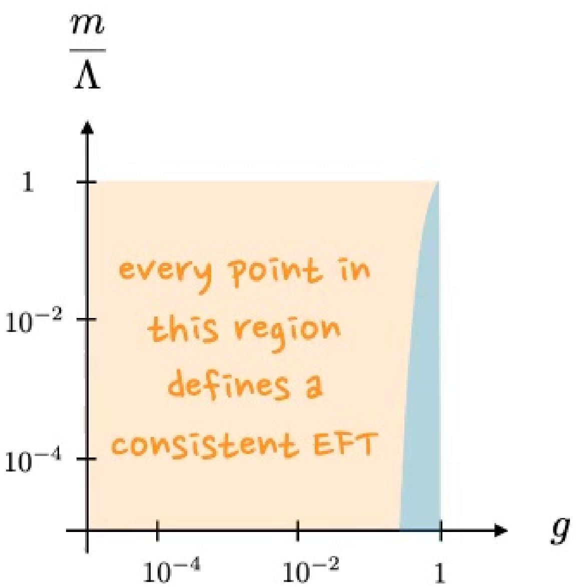
Effective Field Theory

e.g. QED with a single fermion ψ with mass m and charge g :

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\gamma^{\mu}\partial_{\mu}\psi + gA_{\mu}\bar{\psi}\gamma^{\mu}\psi - m\bar{\psi}\psi + \underbrace{\sum_i \frac{\mathcal{O}^{(i)}_{4+n}}{\Lambda^n}}_{\text{irrelevant}}$$

parameters of the EFT

irrelevant



Effect of irrelevant operators

$$\sim \left(\frac{E_{\rm IR}}{\Lambda}\right)^n \ll 1 \quad \text{for} \quad E_{\rm IR} \ll \Lambda$$

UV effects decouple from IR dynamics

Effective Field Theory

What about a *scalar* field?

$$\mathcal{L} = |\partial\Phi|^2 - m_\Phi^2|\Phi|^2 - \lambda|\Phi|^4 + \sum_i \frac{\mathcal{O}_{4+n}^{(i)}}{\Lambda^n}$$

parameters of the EFT

e.g. mass scale of new particles that couple to Φ

However… $\delta|m_\Phi^2| \sim \alpha \left(\frac{\Lambda}{4\pi}\right)^2 \times \text{logs}$

mass-squared of a scalar field quadratically sensitive to UV mass scales!

$|m_\Phi^2| \ll \Lambda^2$ requires

- either $\alpha \ll 1$
- or UV value of m_Φ^2 finely adjusted
- or symmetry that forbids corrections to m_Φ^2

an EFT with a light scalar field is a special (and exciting!) situation

The Weak Scale

the standard Model appears to be an EFT with a light scalar field…!

$$\langle |H|^2 \rangle = \frac{|m_H^2|}{2\lambda} \equiv v^2 \sim (174 \text{ GeV})^2 \qquad \frac{v^2}{M_{Pl}^2} \sim 10^{-32} \ll 1$$

Options:

- Nothing above the weak scale interacts with the Standard Model

  hard given the various puzzles, especially the need for dynamical spontaneous symmetry breaking

- UV parameters highly fine-tuned
- The Standard Model breaks down at scales $\sim 4\pi v \sim \text{few} \times \text{TeV}$, and UV-completion introduces additional symmetry

  starting assumption of vast majority of the work on the dynamics behind the weak scale in the last 40+ years

The Swampland Program

The rules of EFT might need to be extended in a gravitational theory

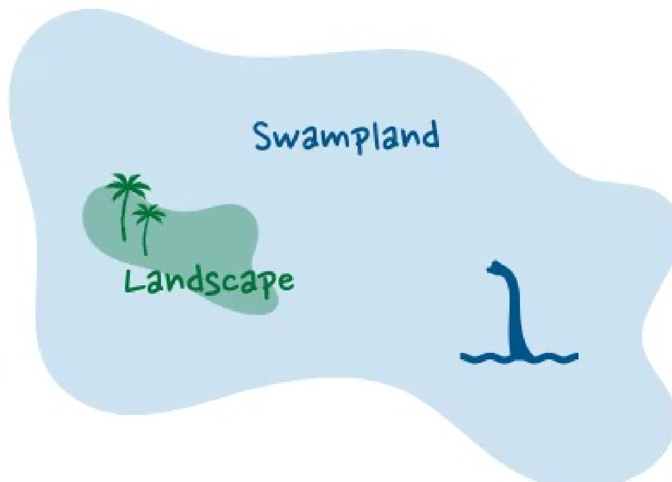
- Basic idea: Not all EFTs remain consistent when coupled to gravity

Vafa 2005

intuition from string theory + black hole thought experiments

- Goal: Identify conditions for landscape 'membership'

- Hope: Powerful discriminator as applied to EFTs in the far infrared



The Swampland Program

- No global symmetries — *Zeldovich, 1976*
- 'Completeness hypothesis' — *Polchinski, 2004*
- Charge quantization — *Banks, Seiberg, 2010*
- Weak Gravity Conjecture — *Arkani-Hamed, Motl, Nicolis, Vafa, 2006*

etc...

Most Swampland conditions remain conjectural, with few exceptions

Harlow, Ooguri, 2018

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Can the Swampland Program inform our quest Beyond-the-Standard-Model?

The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa, 2006

In any EFT that descends from a theory of quantum gravity,
gravity must be the weakest force

e.g. in a theory with gravity + electromagnetism: $F_{\text{grav}} \lesssim F_{\text{EM}}$

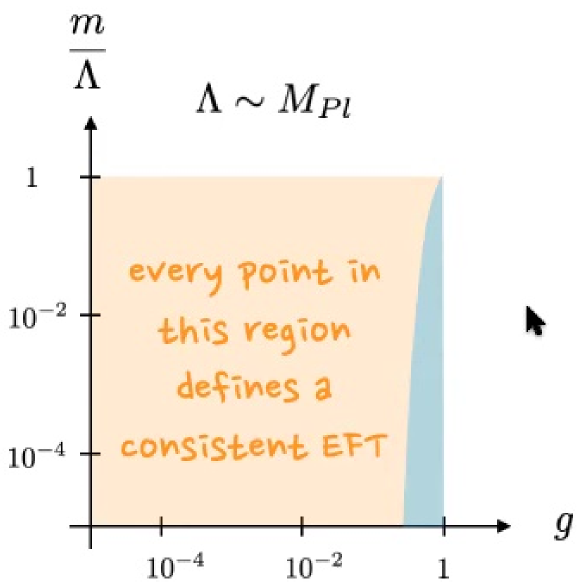
$$G_N \frac{m^2}{r^2} \lesssim \frac{g^2}{r^2} \qquad \Rightarrow \qquad m \lesssim \frac{g}{\sqrt{G_N}} = g M_{Pl}$$

bound disappears when we turn off gravity, i.e. $G_N \longrightarrow 0$

Motivation from black hole thought experiments
+ absence of counterexamples in string theory

EFT in the Swampland

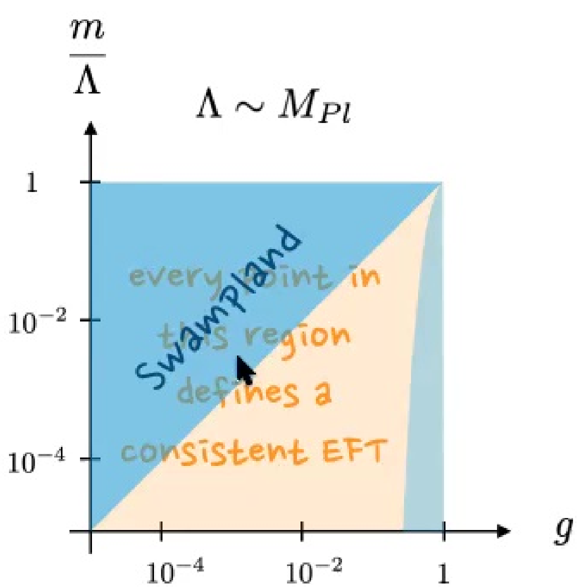
<u>In practice</u>: QED + massive fermion + gravity



EFT in the Swampland

In practice: QED + massive fermion + gravity

Weak Gravity Conjecture $\Rightarrow$ region $m \gtrsim g M_{Pl}$ belongs in the Swampland



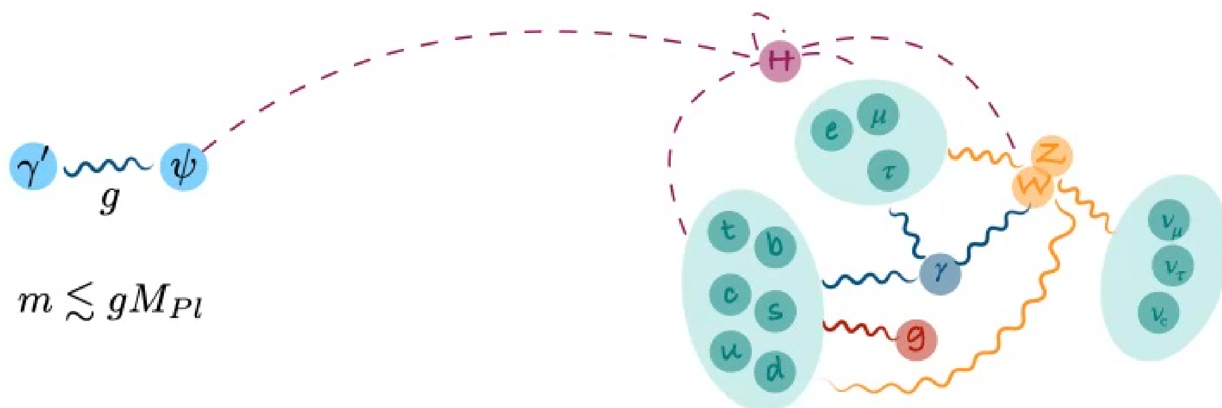
Swampland considerations can impose significant extra restrictions not accessible within the EFT alone

The Weak Scale from Weak Gravity

JHEP 1909 (2019) 081

IGG in collaboration with N Craig, and S Koren

The Weak Gravity Conjecture can be behind the large ratio between the weak scale and the Planck scale



$m \lesssim g M_{Pl}$

<u>Requirements</u>: new (very weak) extra force + new charged state that gets some of its mass from electroweak symmetry breaking (i.e. the Higgs vev)

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Toy model:

$$\mathcal{L} \supset -y\Phi\bar{\psi}_R\psi_L + \text{h.c.} \quad \Rightarrow \quad \mathcal{L} \supset -m\bar{\psi}\psi$$

$$\langle|\Phi|^2\rangle = v^2 \neq 0 \qquad\qquad m = yv$$

$$m \lesssim gM_{Pl} \quad \Rightarrow \quad \frac{v}{M_{Pl}} \lesssim \frac{g}{y}$$

largely insensitive to the UV

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largely insensitive to the UV

- Need $g \lesssim 10^{-16}$ for the weak scale

addresses the hierarchy problem by violating the expectations of EFT

- Attempts to implement this idea with the symmetries and field content of the Standard Model fail *Cheung, Remmen, 2014*

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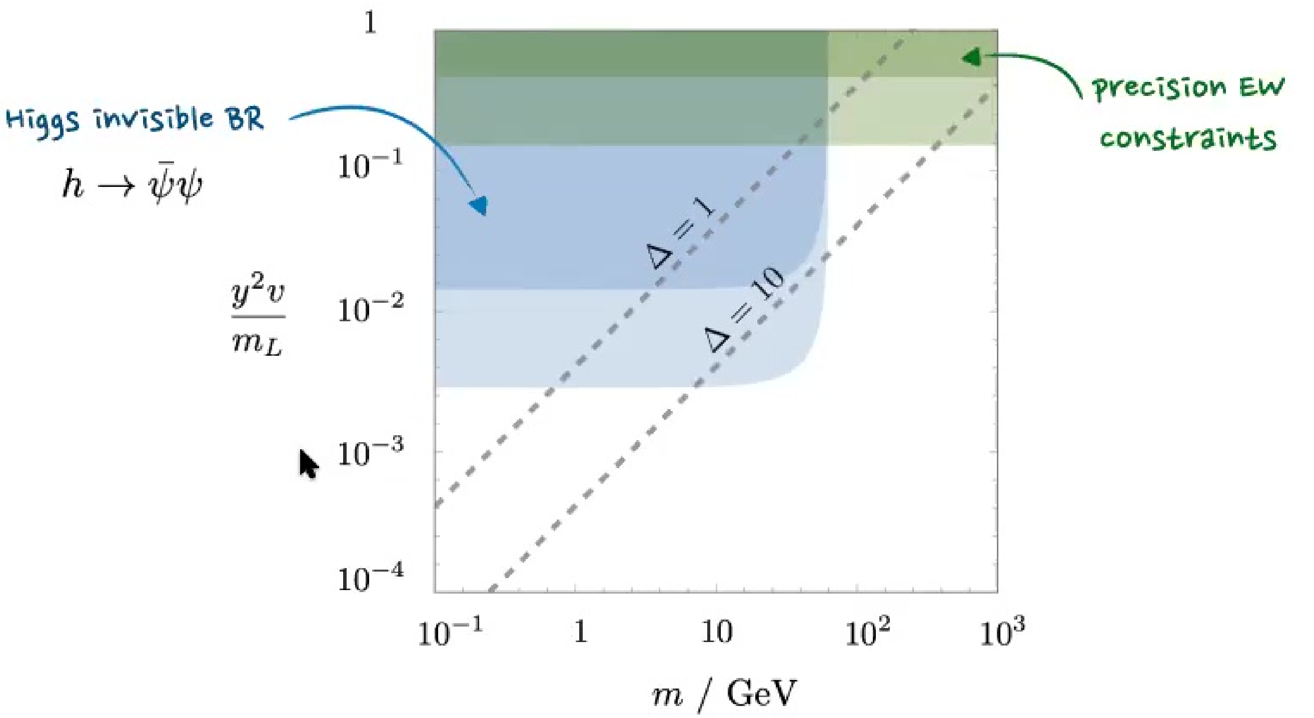
New interactions with the Higgs $\Rightarrow$ experimental signatures at colliders



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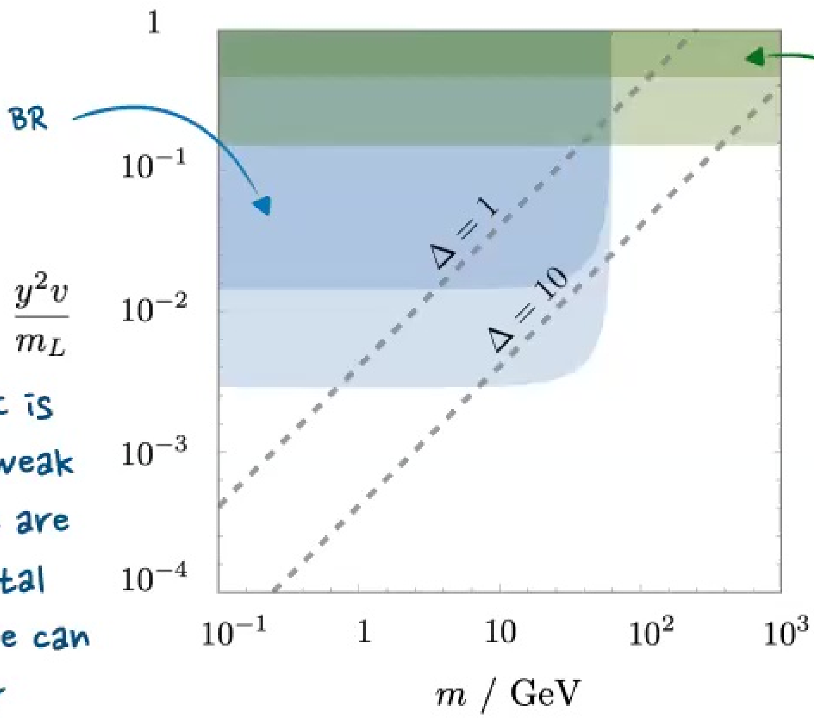
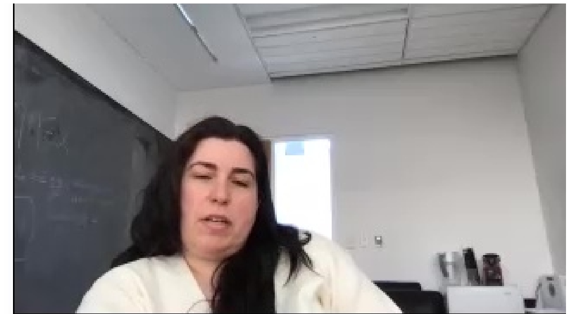
Higgs invisible BR

$h \to \bar{\psi}\psi$



precision EW constraints

if the WGC is behind the weak scale, there are experimental signatures we can look for



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New interactions with the Higgs $\Rightarrow$ experimental signatures at colliders

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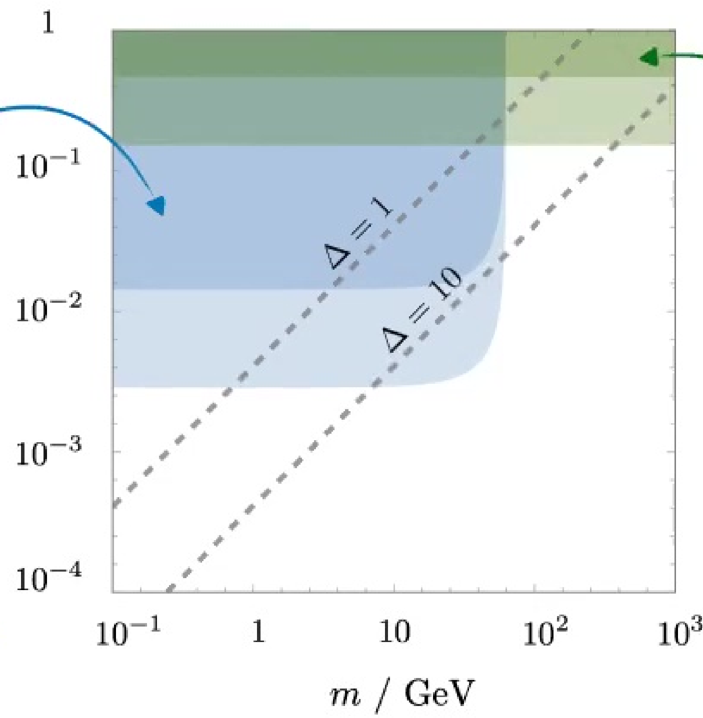
$h \to \bar{\psi}\psi$

$\frac{y^2 v}{m_L}$



precision EW constraints

if the WGC is behind the weak scale, there are experimental signatures we can look for

However... real tell-tale sign that the WGC is at play: WGC particle charged under extremely weak gauge force

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Explore connections between puzzles

Dark Matter & Weak Gravity

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A WGC explanation of the weak scale comes with a stabilizing symmetry: lightest particle charged under the new $U(1)$ is stable $\Rightarrow$ dark matter

- The dark matter is charged under a *very* weak, long-range force

- It behaves like a plasma: *collective effects* dominate over $2 \to 2$ scattering, and can be important at large scales

e.g. scale of galaxy clusters

Ackerman, Buckley, Carroll, Kamionkowski, 2008

Mardon, 2016

Dark Matter & Weak Gravity

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IGG in collaboration with N Craig, and S Koren

- For us, timescale for instabilities is set by the plasma frequency:

$$m \lesssim g M_{Pl}$$

$$\omega_p = \sqrt{\frac{g^2 \rho}{m^2}} \gtrsim \frac{\sqrt{\rho}}{M_{Pl}}$$

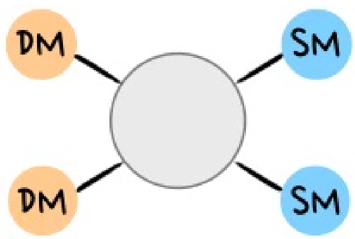
$$\omega_p^{-1} \lesssim 10^{15}\ \mathrm{s}\ \left(\frac{0.04\ \mathrm{GeV\ cm^{-3}}}{\rho}\right)^{1/2}$$

cf. timescale for cluster collision $\tau \sim 1\ \mathrm{Gyr} \sim 10^{16}\ \mathrm{s}$

complementary signatures that we can look for!

Dark Matter & the Weak Scale

Dark matter candidates are a common occurrence in theories
of the weak scale with additional symmetries and field content

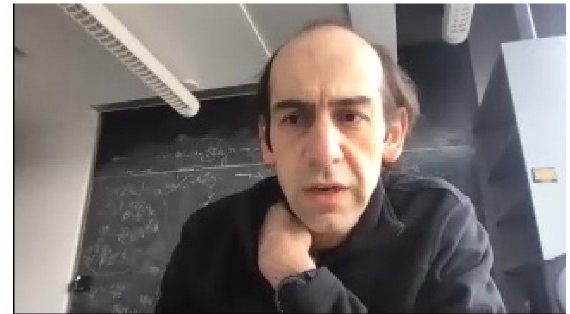


e.g. WIMPs with relic abundance set by *freeze-out*

Zeldovich, 1965

Zeldovich, Okun, Pikelner, 1965

Lee, Weinberg, 1977



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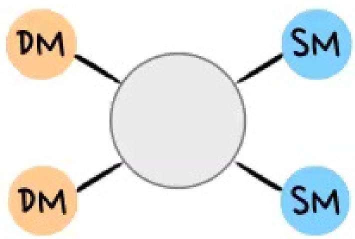

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Lee, Weinberg, 1977

e.g. models of dark matter in theories of "Neutral Naturalness", including Asymmetric Dark Matter

Phys.Rev.Lett. 115 (2015) no.12, 121801
***IGG** in collaboration with R Lasenby, and J March-Russell*

Phys.Rev.D 92 (2015) no.5, 055034
***IGG** in collaboration with R Lasenby, and J March-Russell*

3

Find all ways to test our ideas

The QCD vacuum angle

Standard Model gauge group is $SU(3) \times SU(2) \times U(1)$

$$\pi_3\left(SU(3)\right) = \mathbb{Z}$$

no vacuum angles

$\Rightarrow$ an additional angular parameter — the *QCD vacuum angle* $\bar{\theta}$ — is necessary to specify the vacuum of the theory

in principle, could take any value between 0 and 2π

$\bar{\theta}$ 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:

$$d_n \sim 10^{-16}\ \bar{\theta}\ e \cdot \text{cm}$$

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

The strong CP problem

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

$$\mathcal{L} \supset \frac{\theta_s \alpha_s}{4\pi} G\tilde{G} \quad \longleftarrow \quad \longrightarrow \quad \theta_q = \arg\det \mathcal{M}_q$$

A 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

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<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

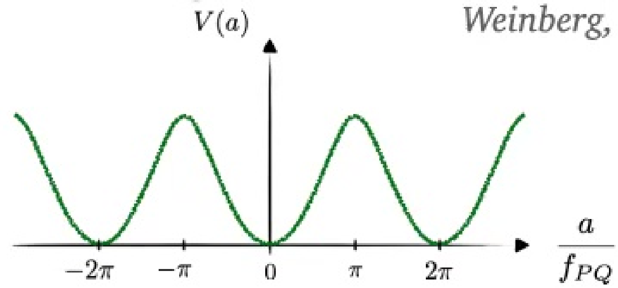
$\bar{\theta}$ promoted to dynamical field, the axion, which a pseudo-Nambu-Goldstone boson of a spontaneously broken $U(1)_{PQ}$ global symmetry, which must also be broken explicitly by QCD

Peccei, Quinn, 1977
Wilczek, 1978
Weinberg, 1978

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. $\bar{\theta} = 0$

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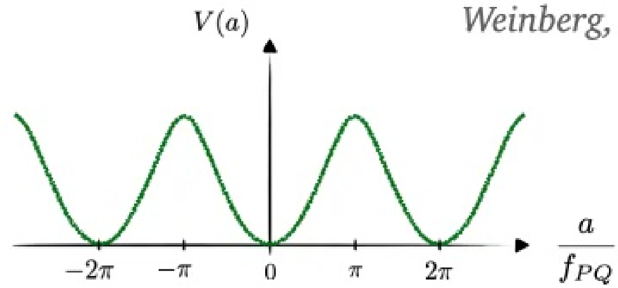

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huge experimental effort to probe the axion paradigm

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

* However… *

Quantum gravity violates global symmetries

the most well-established conjecture in the swampland program

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

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

axion solution in tension with "no global symmetries" in quantum gravity

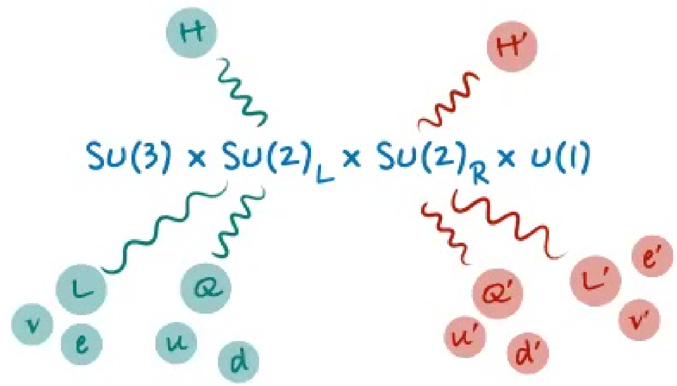
motivates considering alternative solutions to the strong CP problem

Parity solutions to strong CP

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

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

Babu, Mohapatra, 1990
Barr, Chang, Senjanovic, 1991



"Generalized" parity = ordinary parity + interchange of fields in the Standard Model and mirror sectors

Crucially, $\bar{\theta}$ remains odd under generalized parity (we'll just call it parity)

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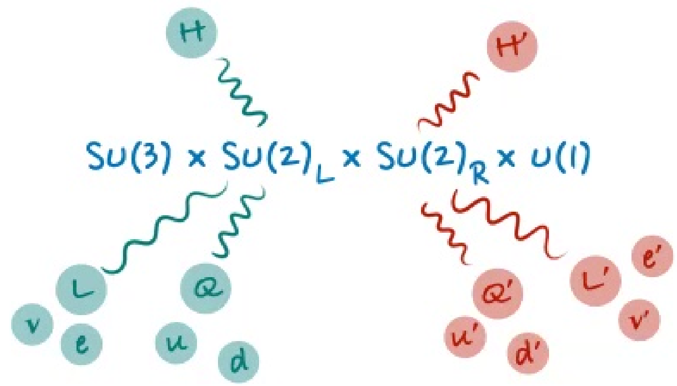


"Generalized" parity = ordinary parity + interchange of fields in the Standard Model and mirror sectors

Crucially, $\bar{\theta}$ remains odd under generalized parity (we'll just call it parity)

parity must be spontaneously broken, so that "mirror" particles are heavy

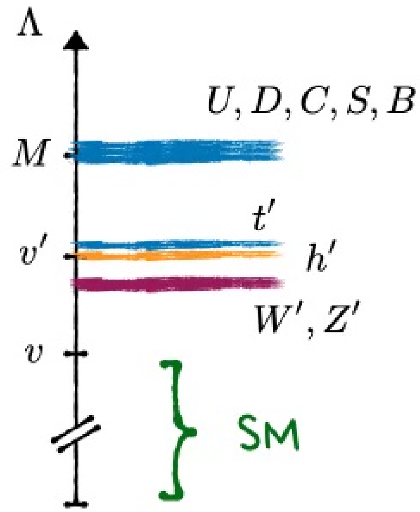
To solve strong CP: $\Delta^{-1} \sim \frac{v^2}{v'^2} \gtrsim 10^{-10} \quad \Rightarrow \quad v' \lesssim 10^7$ GeV

P not PQ

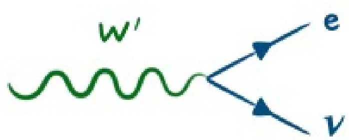
e-Print: 2012.13416

IGG in collaboration with N Craig, G Koszegi, and A McCune

Parity breaking scale may be as low as ~ 18 TeV if Standard Model fermions masses are realized through the "see-saw" mechanism



Leading constraint from direct production of exotic gauge bosons at LHC



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

$$\Rightarrow \quad v' \gtrsim 18 \text{ TeV}$$

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

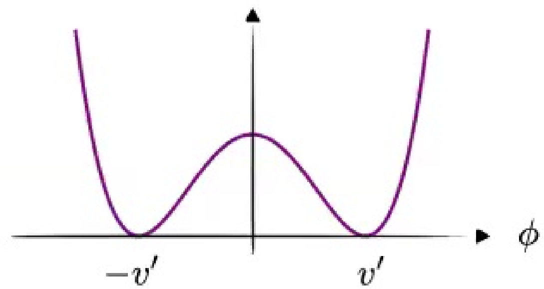
Domain Walls

e-Print: 2012.13416

IGG in collaboration with N Craig, G Koszegi, and A McCune

Spontaneous breaking of parity: $\phi \overset{P}{\longleftrightarrow} -\phi$

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

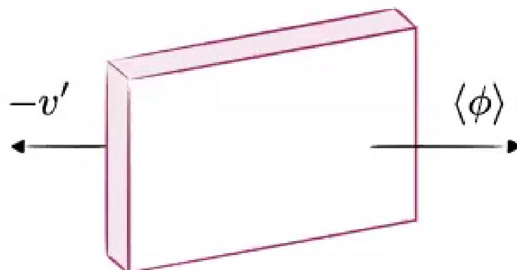


Spontaneously broken discrete symmetry

$\Rightarrow$ domain wall solutions

topologically stable
(if global)

$\langle\phi\rangle = -v'$



$\langle\phi\rangle = v'$

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

Domain Walls

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

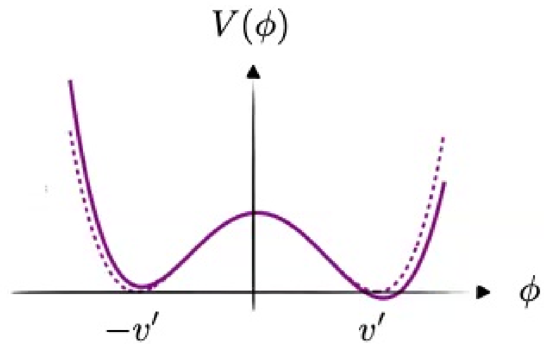
Zeldovich, Kobzarev, Okun, 1974

* However… *

Quantum gravity violates global symmetries

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

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



network of domain walls collapses, emitting gravitational radiation

Gravitational Waves

e-Print: 2012.13416

IGG in collaboration with N Craig, G Koszegi, and A McCune

Two main quantities characterize the resulting gravitational wave signal:

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

typical domain wall radius ← → network collapse

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

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 frequency, stronger signal (less redshift)

Gravitational Waves

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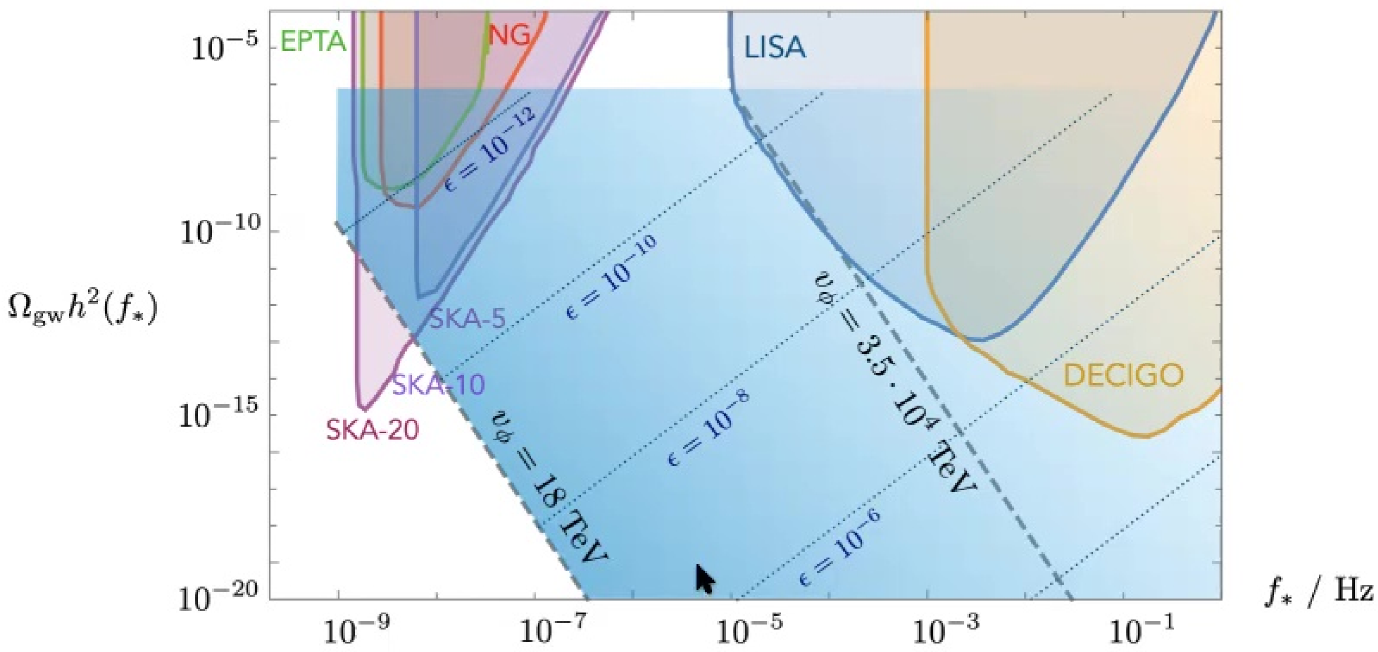

Gravity breaks P

e-Print: 2021.13416

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

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

$$\bar{\theta} \sim 10^5 \frac{v'}{2M_{Pl}} \qquad \Rightarrow \qquad v' \lesssim 20 \text{ TeV} \left(\frac{\bar{\theta}}{10^{-10}} \right)$$

<u>Just</u> consistent with lower bound from colliders $v' \gtrsim 18 \text{ TeV}$

P solution to strong CP + gravity violates all global symmetries

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

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a feature... not a bug!

Conclusions

A variety of problems in the Standard Model remain unsolved

Formal developments can provide us with a new perspective, in ways that can be experimentally pursued

Enormous diversity of experiments —- from colliders to dark matter detectors to gravitational wave observatories

Combination of theoretical and experimental developments will provide us with the breakthrough we need

* it is an exciting time to be working in particle physics*

Thank you!