A Swampland Tour

from photon masses to axion physics

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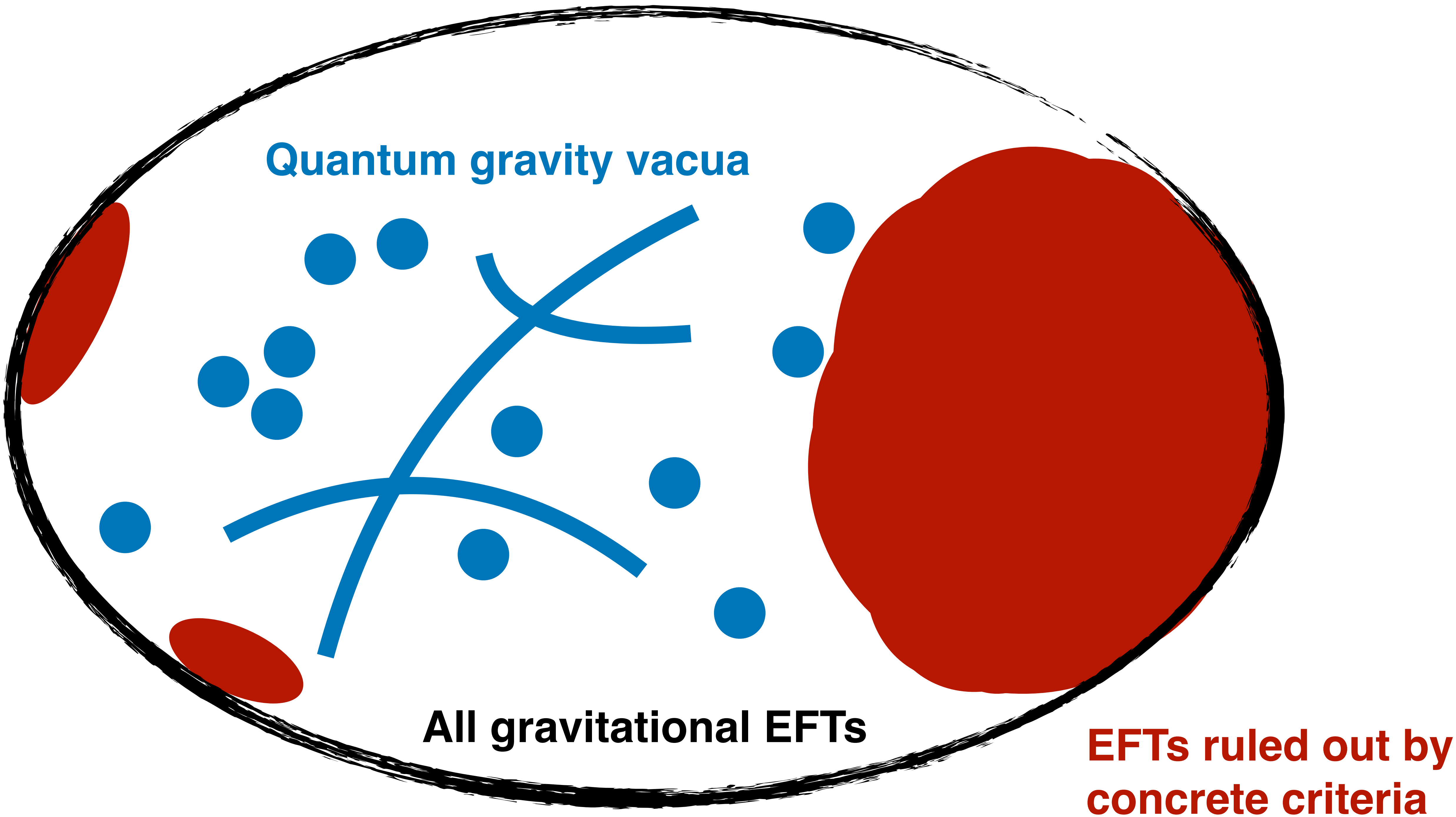
1. **The Swampland Program and the Weak Gravity Conjecture**

2. Photon Masses and the Swampland

3. Chern-Weil Global Symmetries and the Necessity of Axions

The Landscape vs. The Swampland



The Swampland is the complement of the Landscape.
Our goal is to characterize it. Many suggestions.

Hopes for phenomenology

String theorists can build quantum gravity theories in several ways: heterotic string constructions, Type II models, F-theory models, M-theory on G_2 manifolds…

These share common features that are relevant for phenomenology:

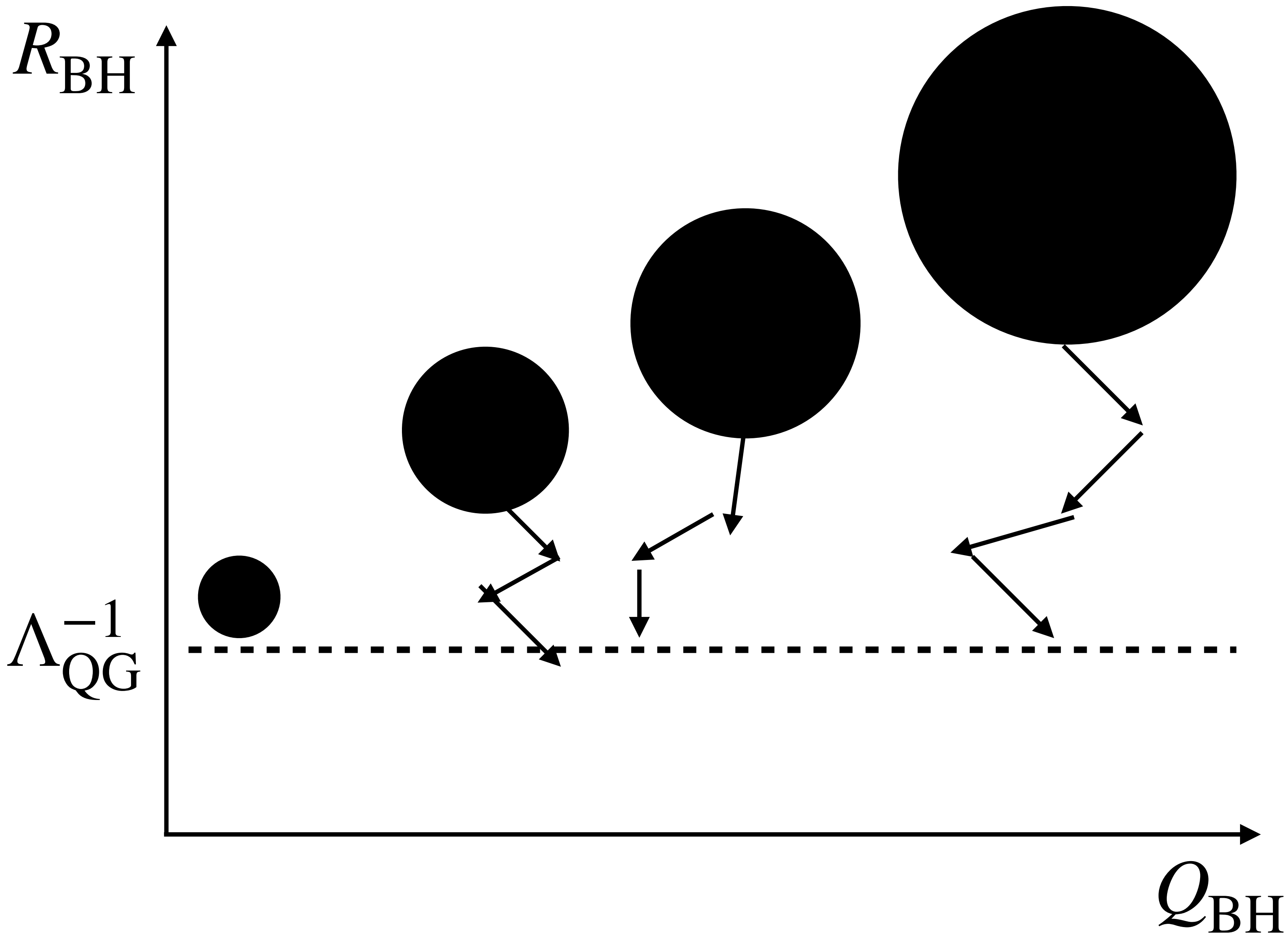
- **Axions exist** with couplings to $\mathrm{tr}(F \wedge F)$, obtaining mass only from instanton effects
- **No very light Stückelberg photon masses** (only with low cutoff)
- Chiral matter comes in **small reps** (generally 2-index) of gauge groups
- Scalar potentials are not flat over ranges >> the Planck scale
- Scalar moduli exist with couplings to $\mathrm{tr}(F_{\mu\nu}F^{\mu\nu})$
- …

Are there deep principles behind these, or are the common features just because we only know simple examples of QG theories?

Many are related to a principle of **no global symmetries**.

No global symmetries: continuous case

Idea with a long history (Hawking for black hole evaporation; Banks & Dixon in perturbative string theory).



Black hole Hawking evaporation would lead to infinite entropy in finite mass range.

Banks, Seiberg ’10

Earlier work includes Georgi, Hall, Wise ’81; Kamionkowski, March-Russell ’92; Holman, Hsu, Kephart, Kolb, Watkins, Widrow ’92; Kallosh, Linde, Linde, Susskind ’95; …

No global symmetries: general case

It is believed that quantum gravity allows **no global symmetries**, including **discrete** and **p-form** global symmetries.

In the asymptotically AdS context, this has been argued by Harlow and Ooguri (1810.05337/8).

They define a global symmetry carefully to involve a "**splittability**" condition that avoids various pathological counterexamples.

Then, the non-existence of global symmetries in the AdS bulk follows from an argument using entanglement wedge reconstruction.

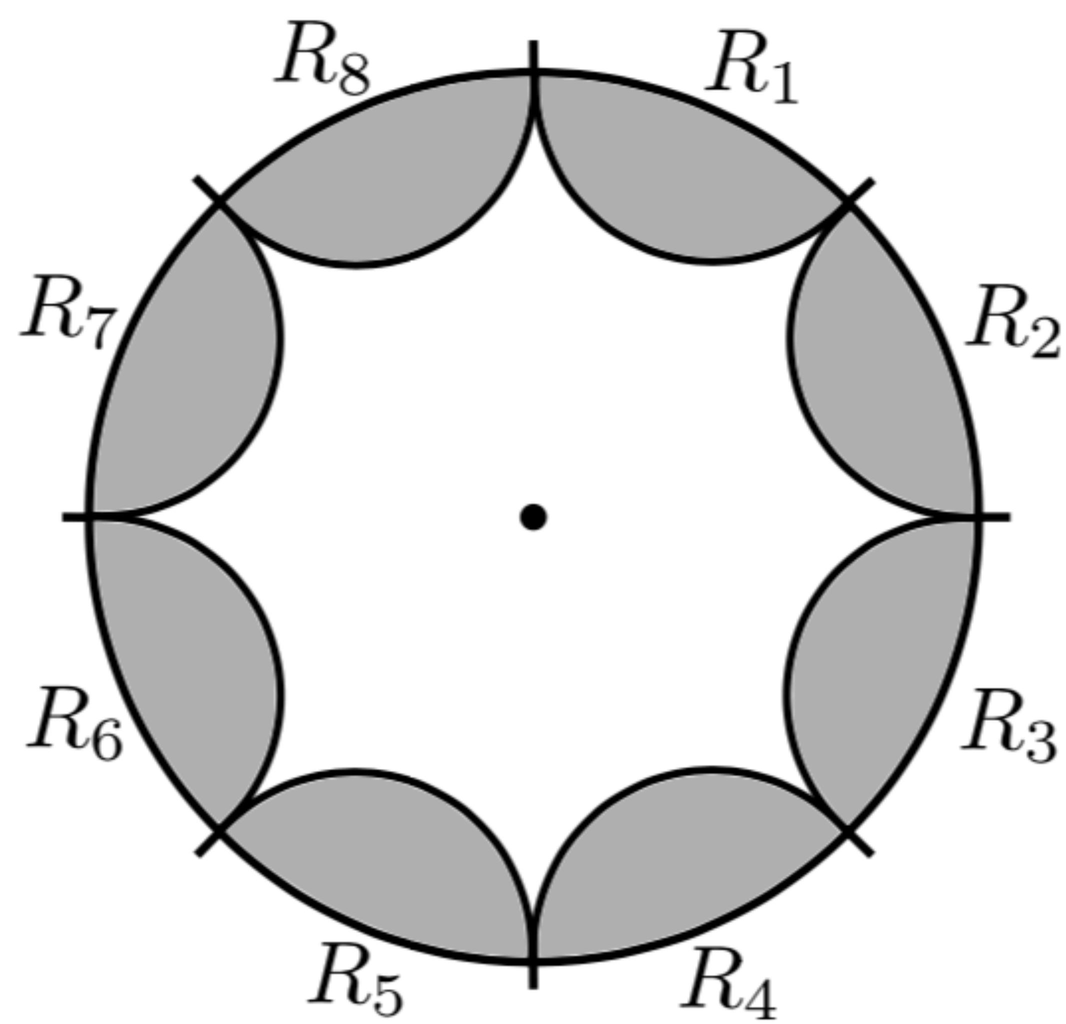


Fig. from 1810.05337 [Harlow/Ooguri]

What is the WGC? (Weak Gravity Conjecture)

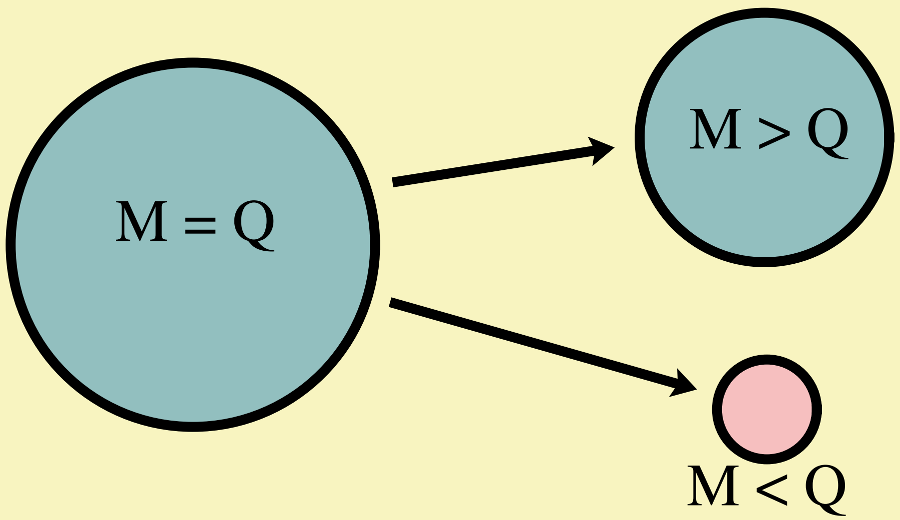


Fig. from AMNV

Arkani-Hamed, Motl, Nicolis, Vafa ("**AMNV**") hep-th/0601001

Particle exists with M<Q (superextremal).

Extremal BHs can shed charge.

Repulsive Force Conjecture:

A charged particle exists which is (long-range) **self-repulsive**. Gauge repulsion overcomes gravitational attraction.

Distinct conjectures when massless scalars exist.

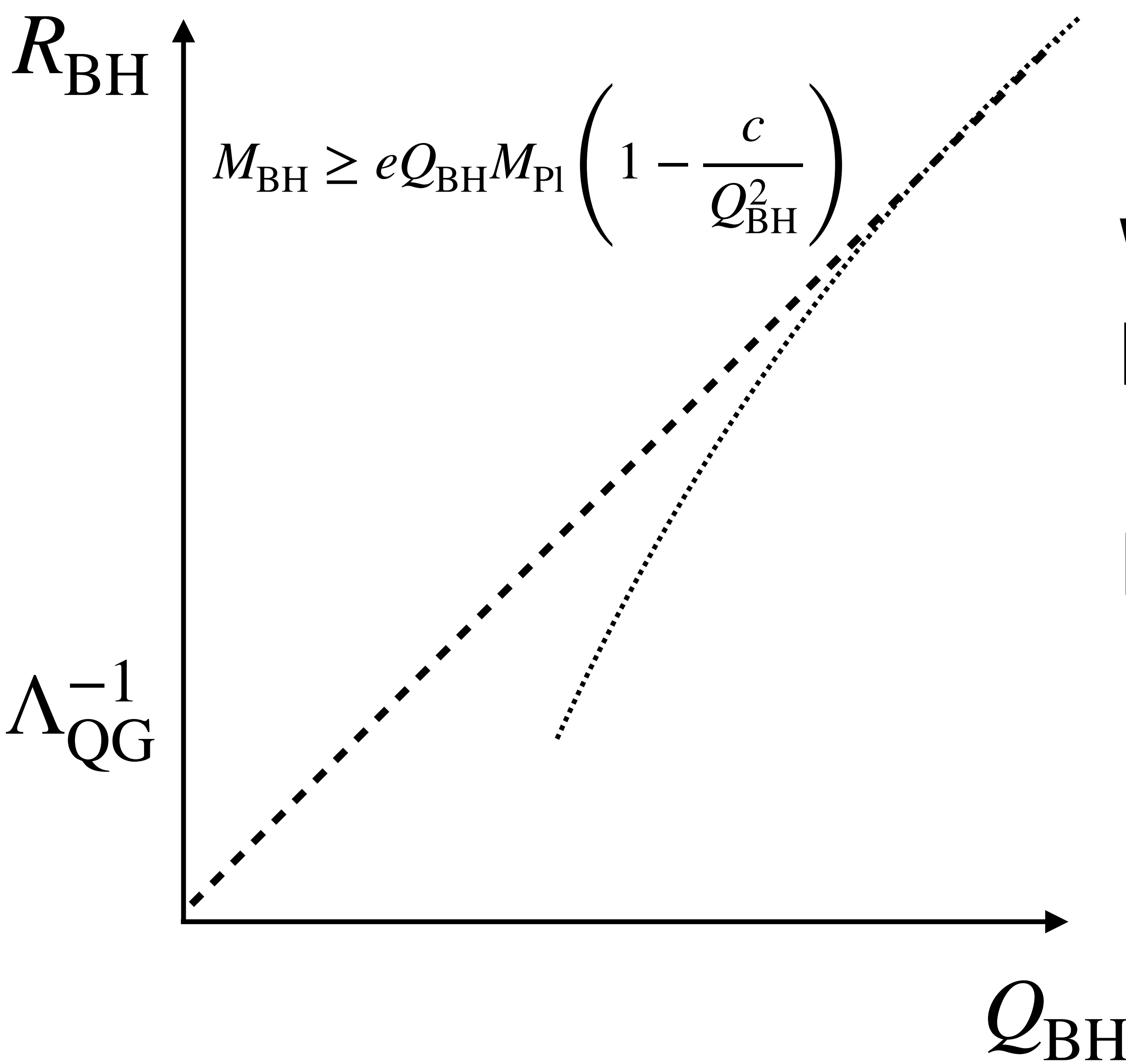
Palti '17; Lee, Lerche, Weigand '18; Heidenreich, MR, Rudelius '19

Is the minimal WGC obeyed by black holes?

Go beyond the 2-derivative action:

$$c_1(F_{\mu\nu}^2)^2 + c_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\sigma}F^{\sigma\mu} + c_3 R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} + c_4 R_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

AMNV; Kats, Motl, Padi ’06



WGC obeyed by big black holes with small corrections!

Minimal WGC is **very weak.**

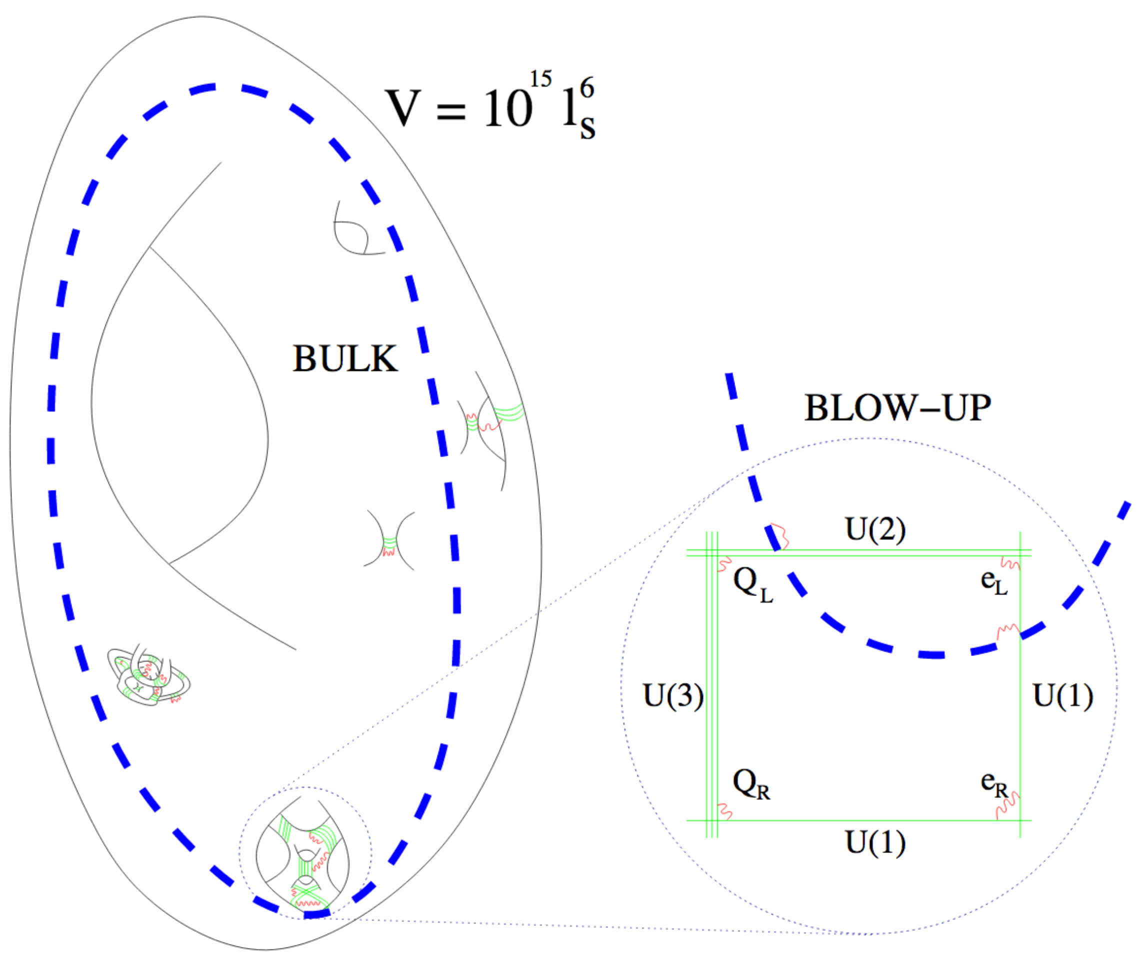
(Cheung, Remmen ’18; Hamada, Noumi, Shiu ’18; Bellazzini, Lewandowski, Serra ’19; Mirbabayi ’19; Charles, ’19; Arkani-Hamed, Huang, Liu, to appear)

Scalar Field Distances in QG

We now turn to a less famous, but possibly more useful, conjecture: the Ooguri-Vafa '06 "Distance Conjecture."

Background: in string theory (as well as many examples in Kaluza-Klein theory), couplings are not *fixed numbers*, but rather ***VEVs of scalar fields***, such as the dilaton, a radion, or more general ***moduli***, e.g.:

$$\frac{1}{g^2} \sim \frac{\langle\phi\rangle}{M_{\rm Pl}}$$



Small couplings $\Longleftrightarrow$ large volumes $\Longleftrightarrow$ large VEVs

Fig. from Burgess, Conlon, Hung, Kom, Maharana, Quevedo '08

Swampland Distance Conjecture

Ooguri and Vafa observed some features common to moduli spaces (scalar fields) in known string theories:

- Points at infinite distance $d(\phi) \to \infty$ exist
- Moving a large distance $d(\phi)$ from a fixed point in moduli space, an infinite tower of modes becomes light with masses trending as $\exp(-\alpha\, d(\phi)/M_{Pl})$
- The constant α is $O(1)$ in known examples

(See their paper for slightly more precise statements.)

Example: Kaluza-Klein theory

For intuition, keep in mind the classic KK theory, with an extra dimension of radius *R*.

$$\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}\mathscr{R}_4 - \frac{1}{2}(\partial\phi)^2 - \frac{1}{4e_{\rm KK}^2}e^{\alpha\phi}F_{\mu\nu}^2\right]$$

gravity radion U(1) gauge field

$$e_{\rm KK}^2 = \frac{2}{R^2 M_{\rm Pl}^2}$$ large radius $\Longleftrightarrow$ small gauge coupling

$$m_n = \frac{n}{R} = \frac{n e_{\rm KK}}{\sqrt{2}}M_{\rm Pl}$$ *infinite tower of* KK mode masses proportional to gauge coupling

$$R \propto e^{\sqrt{3}\phi/(2M_{\rm Pl})}$$ radius *exponential* in canonically normalized radion (field space distance)

Tower Weak Gravity Conjectures

The WGC tells us to expect a low UV cutoff at small e.

In known QG theories, the way this works is that the $e \to 0$ limit is precisely an infinite-distance limit in moduli space, just like the Kaluza-Klein example.

This motivates a stronger **Tower WGC:**

There are infinitely many charged particles of *different* charges q_i , *each of which* obeys the bound

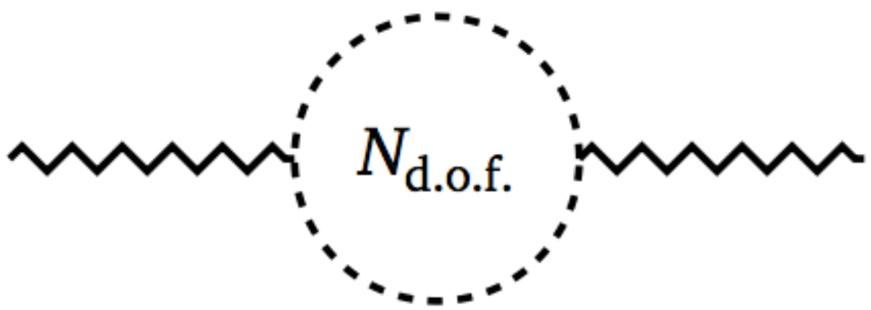
$$m_i \leq e q_i M_{\mathrm{Pl}}\,.$$

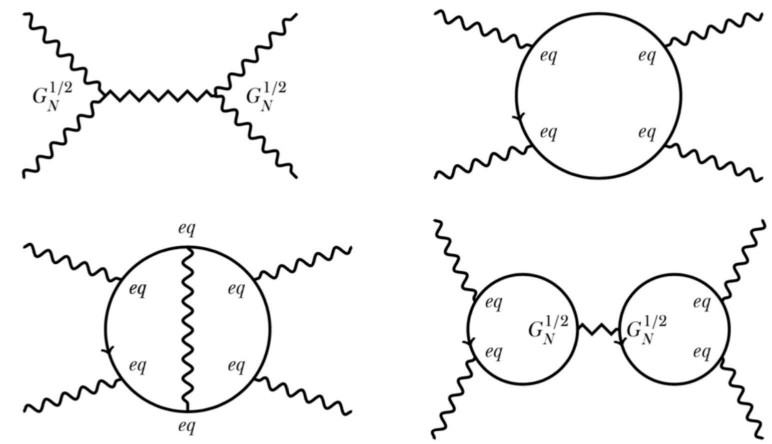
Stronger **Sublattice WGC (sLWGC)**: take the charges to lie in a sublattice (of the same dimension as full charge lattice).

(Tower WGC: Andriolo, Junghans, Noumi, Shiu ’18; Sublattice WGC: Heidenreich, Reece, Rudelius ’15/’16)

Tower and Sublattice WGCs

Substantial evidence that in string theory, weak coupling always emerges by integrating out loops of many degrees of freedom:





Stronger (Tower/Sublattice) version of the WGC: **infinitely many particles** in the weakly-coupled EFT below the Planck scale **each** obey the WGC.

(Tower WGC: Andriolo, Junghans, Noumi, Shiu ’18; Heidenreich, MR, Rudelius ’19;
Sublattice WGC: Heidenreich, MR, Rudelius ’15/’16; Montero, Shiu, Soler ’16;
String evidence: Grimm, Palti, Valenzuela ’18; Lee, Lerche, Weigand ’18/’19; Corvilain, Grimm, Valenzuela ’18; Grimm, Ruehle, van de Heisteeg ’19; Grimm, Li, Valenzuela ’19; Gendler, Valenzuela ’20)

One of the sharpest formulations (“String Emergence”):
weak coupling always arises as either a **decompactification limit** (many light KK modes) or a **tensionless string limit** (many light string modes).

(Lee, Lerche, Weigand ’19)

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M. Reece, 1808.09966

Does the photon have a mass?

Do any of you believe that the photon mass is nonzero?

If so, why do you think so?

If not, what's your best counterargument?

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If so, why do you think so?

If not, what's your best counterargument?

If not:

"Gauge invariance" is not a convincing answer.

"Embedding in SU(5)" is better, but assumes a lot about the UV of our universe.

Photon masses

Recall: gauge invariance is needed for a theory with a massless photon; the *redundancy* $\epsilon_\mu \to \epsilon_\mu + \alpha p_\mu$ is needed to leave just the two physical helicity states.

The Proca Lagrangian which just adds a mass $m_\gamma^2 A_\mu A^\mu/2$ is perfectly healthy, and describes a massive gauge field with 3 propagating degrees of freedom.

We can even introduce a "gauge invariance" with the Stückelberg trick, $f_\theta^2(\partial_\mu\theta - eA_\mu)^2/2$ where under a gauge transformation $A_\mu \mapsto A_\mu + (1/e)\partial_\mu\alpha,\ \theta \mapsto \theta + \alpha$.

In EFT, photon masses are perfectly innocent. (Unlike massive nonabelian gauge fields or gravitons—scattering amplitudes of longitudinal modes blow up.)

Does the photon have a mass?

From Sidney Coleman's Lectures on QFT:

No matter how small μ is, this is a system with three degrees of freedom. Everyone says the photon is massless. But suppose the photon had a mass of 10^{-23} of the electron's. This would be a very hard thing to determine experimentally. Some people say, "No, absolutely not! It would be trivial to detect experimentally because we know the real massless photon has only two degrees of freedom; polarized light and so on. If we took a hot oven and let things come to thermal equilibrium, because the walls are emitting and absorbing photons, we wouldn't get the Planck Law, but instead $\frac{3}{2}$ times the Planck Law." This is *garbage*. The amplitude for the oven walls to radiate a helicity zero photon, according to this current, goes to *zero* in the limit as $\mu/|\mathbf{k}| \to 0$. At every stage in the limiting process there are indeed three degrees of freedom just as you'd expect from a theory of massive vector mesons. But as $\mu/|\mathbf{k}| \to 0$, the amplitude for emitting the third photon goes to zero. If the photon mass is small enough, it will require twenty trillion years for that oven to reach thermal equilibrium![13]

Discussed by Bass & Schrödinger, 1955

Variety of experimental bounds. Conceptually simplest: purely kinematic bound from Fast Radio Bursts.

$$m_\gamma \lesssim 10^{-14}\,\mathrm{eV}$$

(Wu et al. 1602.07835, Bonetti et al. 1602.09135, 1701.03097)

Conclusion?

Just like neutrino masses turned out to be nonzero, and the cosmological constant turned out to be nonzero, and most of us believe the QCD theta angle will turn out to be nonzero…

The photon mass could also be nonzero. We should keep trying to measure it.

Conclusion?

Just like neutrino masses turned out to be nonzero, and the cosmological constant turned out to be nonzero, and most of us believe the QCD theta angle will turn out to be nonzero…

The photon mass could also be nonzero. We should keep trying to measure it.

Not Quite.

While I certainly do believe we should keep subjecting it to experimental tests, I think the photon mass is exactly zero—and that *quantum gravity* (& experimental input) can help us see what EFT does not.

Stückelberg masses

Consider a *Stückelberg* photon mass, introducing a Goldstone boson that shifts:

$$\frac{1}{2}f^2(\partial_\mu\theta - e\hat{A}_\mu)^2$$

This is a good example of a *technically natural* small mass parameter,

$$m_\gamma = ef$$

One general lesson of the Swampland program is to be wary of things that are “technically” natural but not explained in terms of underlying dynamics.

Stückelberg in the Swampland

In string theory, such masses are ubiquitous. SUSY implies that a radial mode exists. Distinguishing feature is the kinetic term:

$$K(\Phi, \Phi^\dagger, V) = -M^2 \log(\Phi + \Phi^\dagger - cV)$$

The point of zero photon mass lies at infinite distance,

$$\operatorname{Re}\Phi \to \infty, \quad m_V \sim \frac{M^2}{(\Phi + \Phi^\dagger)^2}$$

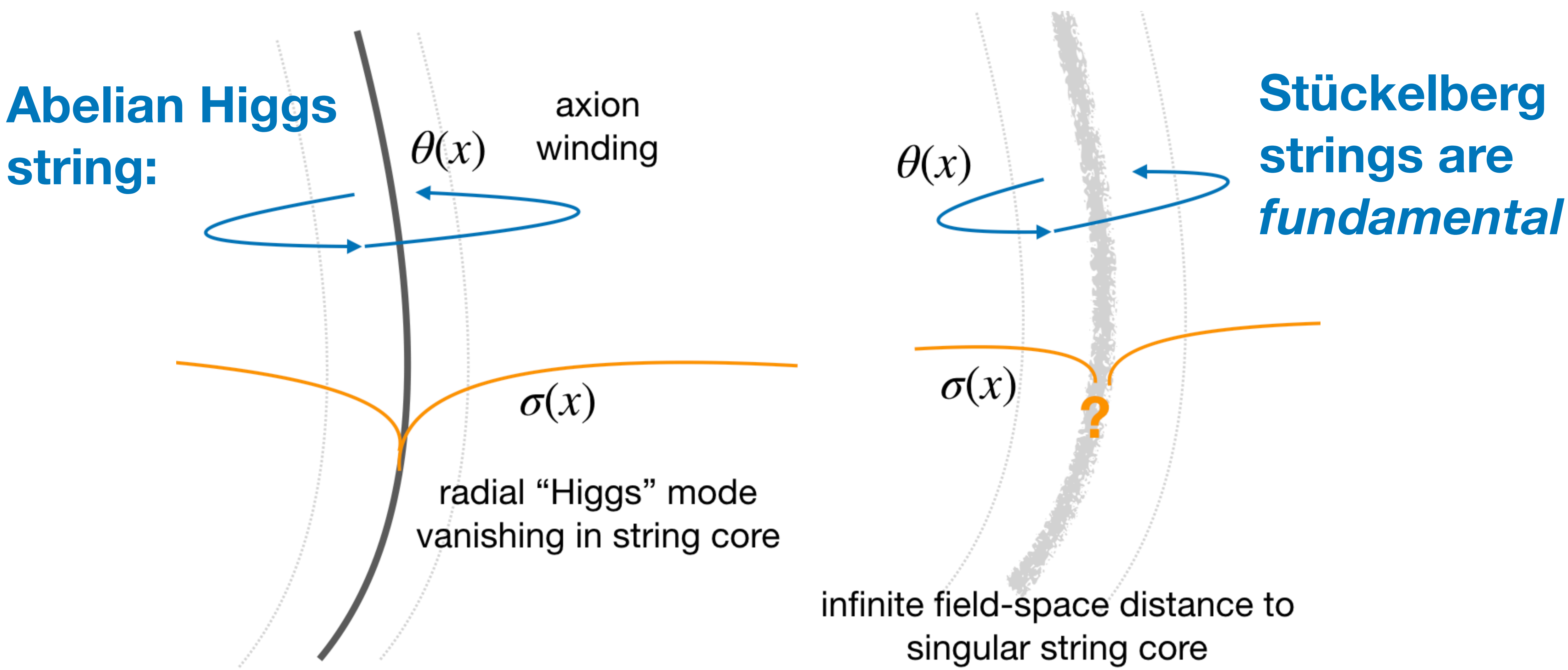
The ***Swampland Distance Conjecture*** then tells us to expect that small m_V comes at the cost of a tower of light modes, and a low UV cutoff.

Stückelberg vs the WGC

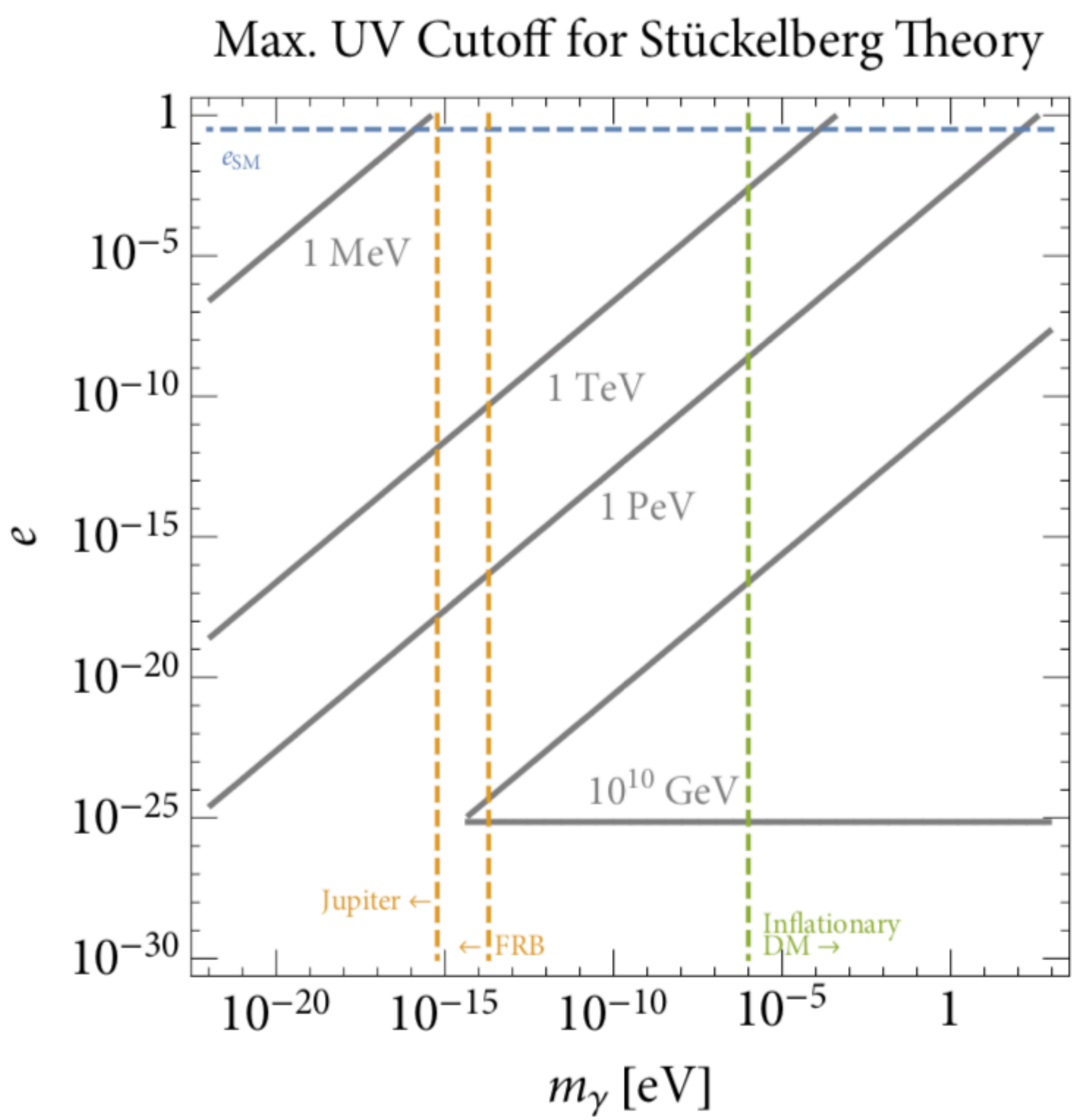
Dualize the eaten Goldstone boson to a 2-form gauge field B:

$$\epsilon^{\mu\nu\rho\lambda}\partial_{[\mu}B_{\nu\rho]} = f^2\partial^\lambda\theta$$

Now apply the **WGC** to the B-field: charged strings exist with tension $T \lesssim f\, M_{\rm Pl}$. (see Hebecker, Soler ’17)



Ultraviolet cutoffs on Stückelberg photons



$$m_\gamma = ef$$

$e \to 0 : A_\mu$ weakly coupled

$f \to 0 : B_{\mu\nu}$ weakly coupled

$$\Lambda_{QG} \lesssim \min(e^{1/3} M_{Pl}, \sqrt{m_\gamma M_{Pl}/e})$$

species bound for sLWGC $(e \to 0)$

tension of string $(f \to 0)$

MR, ’18

the “inflationary DM” line is dark photon dark matter produced by inflationary fluctuations: Graham, Mardon, Rajendran 2015

Can the photon have a mass?

For the SM photon, very simple kinematic bounds (from fast radio bursts) tell us

$$m_\gamma \lesssim 10^{-14}\ \mathrm{eV}$$

A mass at this scale leads to local EFT breaking down at low energies:

$$\Lambda_{\mathrm{QG}} \lesssim \sqrt{m_\gamma M_{\mathrm{Pl}}/e} \lesssim 10\ \mathrm{MeV}$$

So the SM photon can't have a Stückelberg mass.
Loophole is the unit of charge: suppose the electron charge is N, i.e. what we know as e is really $e_0 N$ for $N >> 1$.

We can push the UV cutoff above a TeV if $N \sim 10^{14}$.
(Or Higgs mechanism: Higgs is millicharged, similarly huge N.)

Does QG allow **enormous charge ratios** in light particles?

MR, '18

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work in preparation with Ben Heidenreich, Jake McNamara, Miguel Montero, Tom Rudelius, and Irene Valenzuela

Conservation laws and closed forms

Conserved current: $\partial_\mu j^\mu = 0$

Rewrite in terms of (d−1)-form $J = \star j$:

$$J_{\mu_1 \cdots \mu_{d-1}} = \varepsilon_{\mu_1 \cdots \mu_d} j^{\mu_d} \quad \text{and} \quad \partial_\mu j^\mu = 0 \quad \Rightarrow \quad \mathrm{d}J = 0.$$

Conserved currents $\Longleftrightarrow$ Closed forms (related by $\star$)

Total charge:

$$Q = \int \mathrm{d}^{d-1}x \, j^0 \quad \Leftrightarrow \quad Q = \int_{M_{d-1}} J$$

Gauging a conserved current:

$$A_\mu j^\mu \quad \Leftrightarrow \quad A \wedge J_{d-1}$$

Equation of motion:

$$\partial^\mu F_{\mu\nu} = j_\nu \quad \Leftrightarrow \quad \mathrm{d}(\star F) = J$$

A current is gauged when it is *exact*, not just *closed*.
Gauging removes currents from the cohomology.

Conservation of Chern-Weil currents

In an abelian gauge theory, if dF = 0 (no magnetic monopoles), then

$$\mathrm{d}(F \wedge F) = \mathrm{d}F \wedge F + F \wedge \mathrm{d}F = 0,$$

so F ∧ F is a conserved 4-form current, and generates a (*d* – 5)-form symmetry. It is broken if magnetic monopoles exist (but the story is not so simple—stay tuned).

A generalization is true in nonabelian gauge theories:

$$\begin{aligned}\mathrm{d}\,\mathrm{tr}(F \wedge F) &= \mathrm{tr}(\mathrm{d}F \wedge F + F \wedge \mathrm{d}F) \\ &= \mathrm{tr}\big((\mathrm{d}F + [A, F]) \wedge F + F \wedge (\mathrm{d}F + [A, F])\big) \\ &= \mathrm{tr}(\mathrm{d}_A F \wedge F + F \wedge \mathrm{d}_A F) = 0\end{aligned}$$

This is a lemma in the construction of the Chern-Weil homomorphism, an important step in the theory of characteristic classes.

Conservation of Chern-Weil currents

More generally, we have a family of conservation laws,

$$\mathrm{d}\,\mathrm{tr}\left(\bigwedge^k F\right) = 0$$

Here $\bigwedge^k F$ denotes $F \wedge F \wedge \ldots \wedge F$, with k copies of F.

These conservation laws all follow from the nonabelian Bianchi identity,

$$\mathrm{d}_A F \equiv \mathrm{d}F + [A, F] = 0$$

Each $(2k)$-form conserved current means there is a generalized $(d - 2k - 1)$-form global symmetry, which we call a ***Chern-Weil global symmetry***.

Chern-Weil global symmetries vs. quantum gravity?

Chern-Weil global symmetries are ubiquitous in gauge theories.
They are not easy to break, as they follow from the Bianchi identity.

In 4 dimensions, the current $\mathrm{tr}(F \wedge F)$ is a 4-form, so it is trivially conserved. Nonetheless, there is a sense in which it generates a U(1) global "(–1)-form symmetry," because it has quantized (integer) integrals (periods). The charge is **instanton number**.

In 5 dimensions, this becomes an honest 0-form global symmetry and instantons are particles that carry a conserved charge.

Quantum gravity cannot have global symmetries. How does it remove these apparent Chern-Weil global symmetries?

Chern-Weil meets ’t Hooft-Polyakov

Consider d-dimensional SU(2) gauge theory higgsed to U(1) with an adjoint VEV. This theory contains the semiclassical, ’t Hooft-Polyakov magnetic monopole, whose worldvolume has codimension 3.
(We consider $d \geq 4$; the case $d = 4$ is somewhat degenerate, but I think it does make sense.)

UV: $\mathrm{d}\,\mathrm{tr}(F \wedge F) = 0$ Conserved 4-form current

IR: $\mathrm{d}\,(F \wedge F) = 2\,J_{\mathrm{mag}} \wedge F$

Broken 4-form current, due to monopoles

So, it appears that the Higgsing process has eliminated the symmetry from our IR theory.

Dyons and ’t Hooft-Polyakov

However, the story is more interesting. The classical ’t Hooft-Polyakov monopole solution has **collective coordinates** or **zero modes**.

The obvious zero modes are translations. However, there is a less obvious one, corresponding to a global U(1) rotation. This is realized as a ***compact scalar boson*** σ living on the monopole worldvolume.

In the 4d case, σ is described by the QM of a particle on a circle, which has a spectrum labeled by integers. Exciting this particle above its ground state **transforms the monopole into a dyon**, and the integer is the electric charge. σ shifts under U(1) gauge transformations.

For $d > 4$, σ is still a compact scalar, described by a *QFT* on the monopole worldvolume.

[Julia, Zee ’75; Jackiw, ’76; Tomboulis, Woo ’76; Christ, Guth, Weinberg ’76]

Chern-Weil, Dyons, and 't Hooft-Polyakov

We can *gauge* the SU(2) Chern-Weil current by adding a (d – 4)-form gauge field C with a (Chern-Simons) coupling,

$$\frac{1}{8\pi^2} C \wedge \mathrm{tr}(\mathrm{F} \wedge \mathrm{F})\,.$$

After Higgsing, this coupling is inherited not only by the U(1) gauge field but by the theory on the monopole worldline:

$$C \wedge F \wedge F - C \wedge \mathrm{d}_A \sigma \wedge J_{\mathrm{mag}}$$

(I am not being careful about normalization of the terms here and subsequently)

You can think of J_{mag} as the delta functions that localize the latter coupling on the worldline. Thus, the existence of the monopole breaks the conservation law of $F \wedge F$, but it *preserves* another closed 4-form current,

$$\mathrm{d}\left[F \wedge F - \mathrm{d}_A \sigma \wedge J_{\mathrm{mag}}\right] = 0.$$

This current had to exist, or our gauging with *C* would have been inconsistent!

Chern-Weil and the Witten effect

In the 4d case, C is a **"0-form gauge field"**, which is to say, a periodic scalar boson—**an axion!**

$$\frac{1}{8\pi^2}\theta\,\mathrm{tr}(\mathrm{F}\wedge\mathrm{F})\,.$$

The localized coupling on the monopole worldline, that is, the familiar theta term of a particle on a circle in QM,

$$\theta\,\mathrm{d}_A\sigma$$

serves to implement the **Witten effect**: magnetic monopoles acquire an electric charge when a theta angle is turned on,

$$q_{\mathrm{el}} = q_{\mathrm{mag}}\frac{\theta}{2\pi}\,.$$

We see that this whole story fits together nicely: the Witten effect is essential in order to allow us to consistently gauge the Chern-Weil symmetry of the nonabelian theory.

Chern-Weil gauging on D-branes

In string theory, gauge fields can live on a stack of Dp-branes, which have a (p+1)-dimensional worldvolume. In these cases, we always find that the Chern-Weil current tr(F $\wedge$ F) is gauged by a closed string (p – 3)-form field:

$$C_{p-3} \wedge \mathrm{tr}(F \wedge F)$$

So far, so good. But this field actually propagates into the bulk, where it couples to lower-dimensional membranes, so a more complete story is:

$$C_{p-3} \wedge \left[\mathrm{tr}(F \wedge F) \wedge J_{Dp} + J_{D(p-4)}\right]$$

Where J_{Dq} is a (9 – q)-form (the number of delta functions needed to localize on the brane).

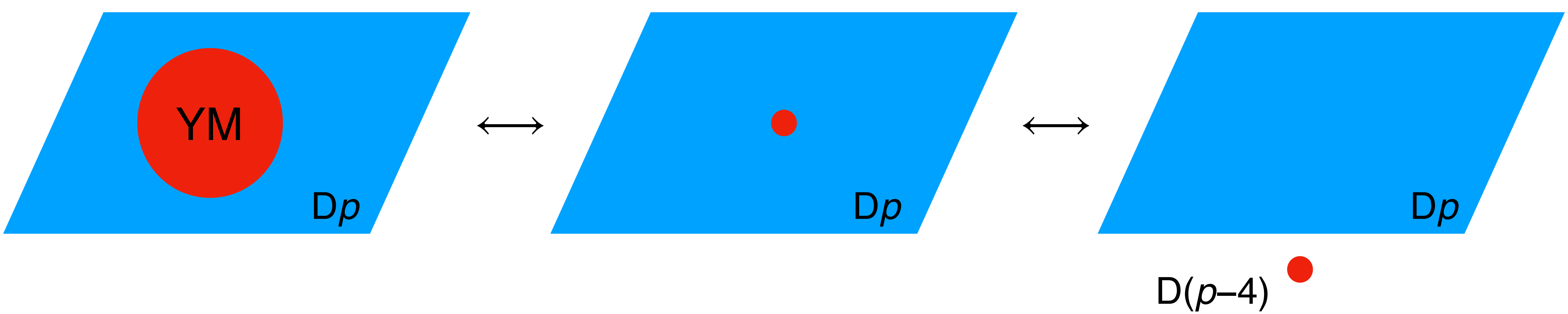
Chern-Weil gauging on D-branes

If the closed string gauge field $C_{p\text{-}3}$ is gauging the current in brackets,

$$C_{p-3} \wedge \left[\mathrm{tr}(F \wedge F) \wedge J_{Dp} + J_{D(p-4)} \right]$$

then **what happens to the other linear combination of these two conserved currents?**

The answer is a well-known effect in string theory: **zero-size Yang-Mills instantons on the D*p*-brane are *the same thing* as D(*p* – 4)-branes.** (Witten ’95; Douglas ’95; Green, Harvey, Moore ’96).



Chern-Weil and GUTs

Consider a nonabelian gauge group that is higgsed to a product group, as in the SM embedding in a GUT, for instance:

$$\mathrm{SU}(5) \to \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$$

The IR theory has more Chern-Weil currents than the UV theory. Some of these are “accidental”: selecting out SU(3) within SU(5) requires Higgs insertions, so the IR $\mathrm{tr}(F \wedge F)$ contains Higgses in the UV theory, and d(Higgs) is nonzero.

An IR theorist might overcount Chern-Weil symmetries and expect more gauge fields (or axions). However, there will always be at least one. This UV explicit breaking of IR Chern-Weil symmetries only happens for “unifiable” gauge groups.

Summary of examples

Once you start looking for Chern-Weil symmetries and mechanisms to remove them, you get a fresh perspective on many familiar phenomena.

Chern-Weil symmetries are ubiquitous in gauge theories. They are not easy to eliminate.

String theory removes many Chern-Weil symmetries by **gauging via Chern-Simons terms**. This might even be thought of as the reason why C-S terms are so generic in string theory.

Other symmetries are broken to the diagonal with another current through **intrinsically stringy UV effects**, e.g., turning YM instantons into branes.

[see also: “Chern-Simons pandemic”, Montero, Uranga, Valenzuela ’17]

Implications for axion physics

If SM gauge fields propagate in higher dimensions, the tr(F $\wedge$ F) terms are symmetry currents. Expect at least one combination to be gauged. Reducing to 4d, this gives an axionic coupling,

$$\frac{1}{8\pi^2}\theta \,\mathrm{tr}(\mathrm{F} \wedge \mathrm{F})\,.$$

to a *fundamental* axion (compact scalar).

Even in 4d, the notion of a U(1) (–1)-form global symmetry may be well-defined and require such couplings, though this is subtle.

String theory *examples* with axions coupling to tr(F $\wedge$ F) are common. Chern-Weil symmetry perspective sheds light on *why*—not just “looking under the lamp post.”

Implications for axion physics

A common concern about axions for solving strong CP is the **axion quality problem**: misaligned contributions to the potential could lead to strong CP violation.

$$\Lambda_{\mathrm{UV}}^4 \left[\mathrm{e}^{-S_{\mathrm{QCD}}+\mathrm{i}\theta} + \mathrm{e}^{-S_{\mathrm{other}}+\mathrm{i}\theta+\mathrm{i}\phi} + \mathrm{h.c.} \right]$$

If $\phi \neq 0$, need $S_{\mathrm{other}} \gg S_{\mathrm{QCD}}$.

The Chern-Weil perspective ameliorates this worry. Given two kinds of instantons, **either** we expect two independent axions, **or** the different kinds of instantons can be transformed into each other.

Suggests we only worry about gauge sectors **"unifiable"** with QCD.

Disclaimer: It's harder to dismiss a different sort of potential, from "axion monodromy"; more details to appear in our paper.

Conclusions

Some messages to take away

The original, minimal WGC is satisfied by (corrected) black holes themselves, and is too weak to be useful.

There is substantial evidence for stronger statements: at the **“Magnetic WGC” cutoff** $\Lambda \sim e M_{\rm Pl}$ a **tower of charged states** appears.

Such towers are ubiquitous and may be a universal way that quantum gravity prevents a too-good approximate global symmetry from arising:

Towers lead to a break down of theories with a **light Stückelberg photon mass.**

QFTs have **Chern-Weil symmetries** that must be broken. Often this is done with Chern-Simons couplings. **Suggestive of why axions are necessary in QG.**

Future: what does it mean for those to be “badly broken”?

Where are we and where are we going?