New Developments in Particle Theory

Matt Reece

Leinweber Institute for Theoretical Physics at Harvard

Harvard University

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Not-So-New Developments

GRAND UNIFIED MODELS WITH AN AUTOMATIC PECCEI–QUINN SYMMETRY*

Howard M. GEORGI, Lawrence J. HALL[1] and Mark B. WISE[2]

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

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We construct a grand unified model with an automatic Peccei–Quinn symmetry. The resulting axion is invisible because the symmetry is broken at the unification scale.

Global symmetries are unpopular these days. The approximate global symmetries of the sixties, SU(3), SU(3)×SU(3), SU(6), etc., are no longer seen as fundamental [1]. They are understood in terms of the underlying dynamics of QCD. The separate lepton numbers and even the once sacrosanct global symmetry of baryon number are presumed to be violated. A global symmetry is no longer seen as an attractive simplifying property of a theory. Instead, it often seems to be an *ad hoc* extra constraint. But, some global symmetries are better than others. Baryon number

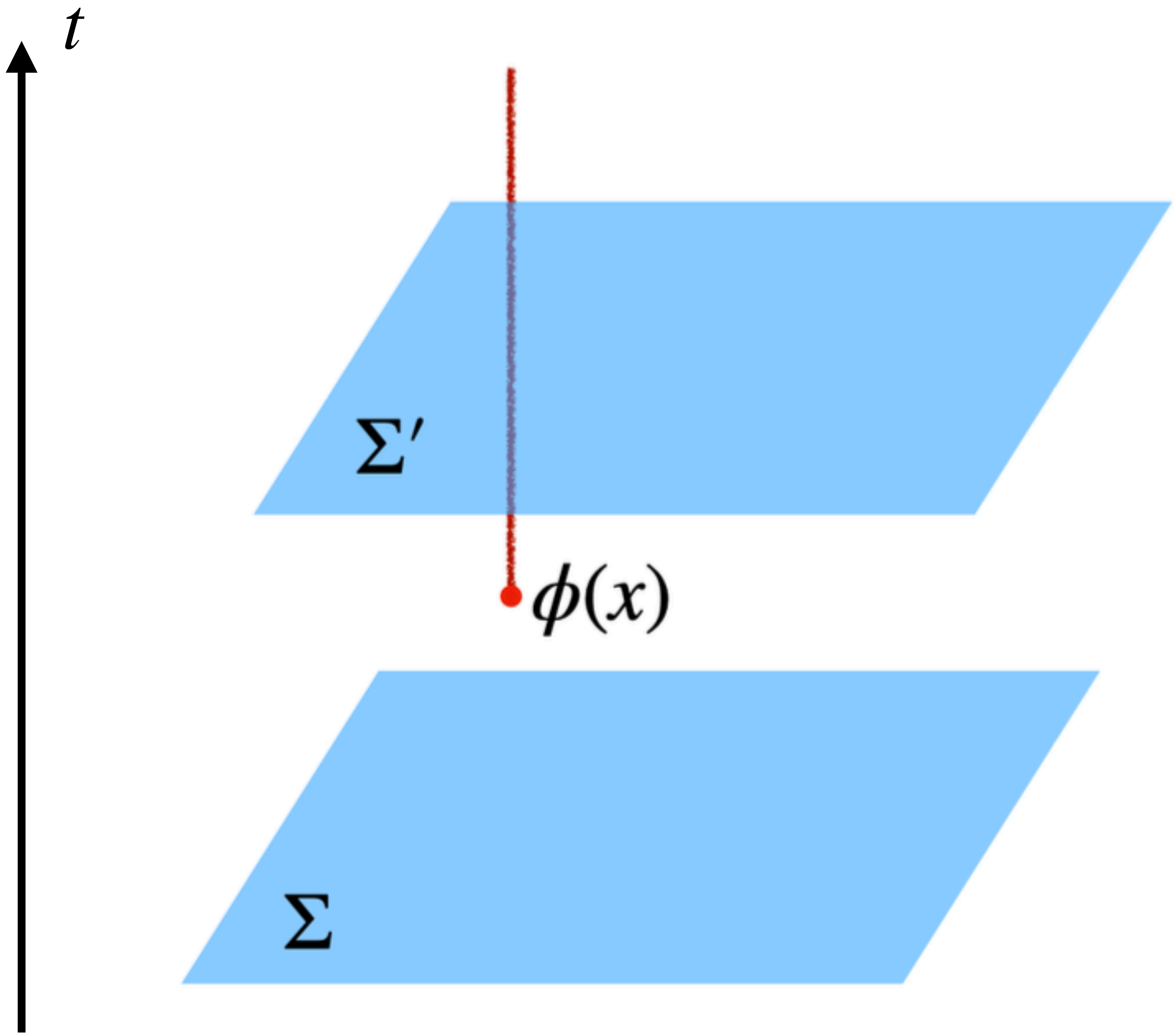
This Talk

“New developments in particle theory” is a huge topic.
I will just scratch the surface of two topics:

- The discovery of many new global symmetries in QFT.
- The absence of global symmetries in quantum gravity.

These two developments are in some tension with each other, and this tension is productive: it can point to places to look for new physics, and sometimes even makes quantitative predictions.

Symmetries and Conservation Laws



Current conservation:

$$\partial^\mu j_\mu = 0$$

Charge:

$$Q = \int d^3x\, j^0$$

U(1) family of unitary operators:

$$U(\alpha, t) = \exp\left(\mathrm{i}\alpha \int d^3x\, j^0(t, x)\right)$$

Emmy Noether

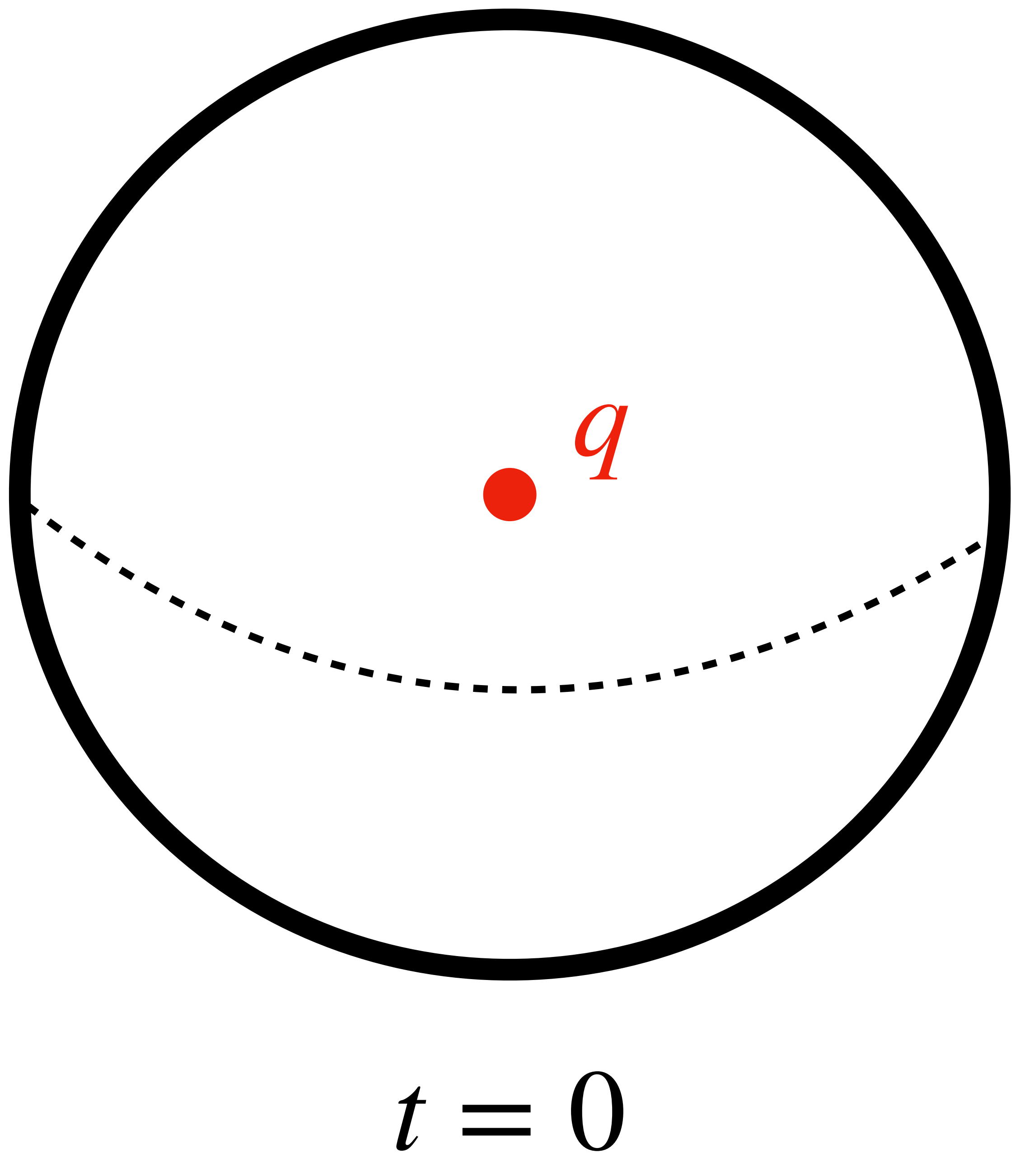
Gauging a (would-be) Global Symmetry

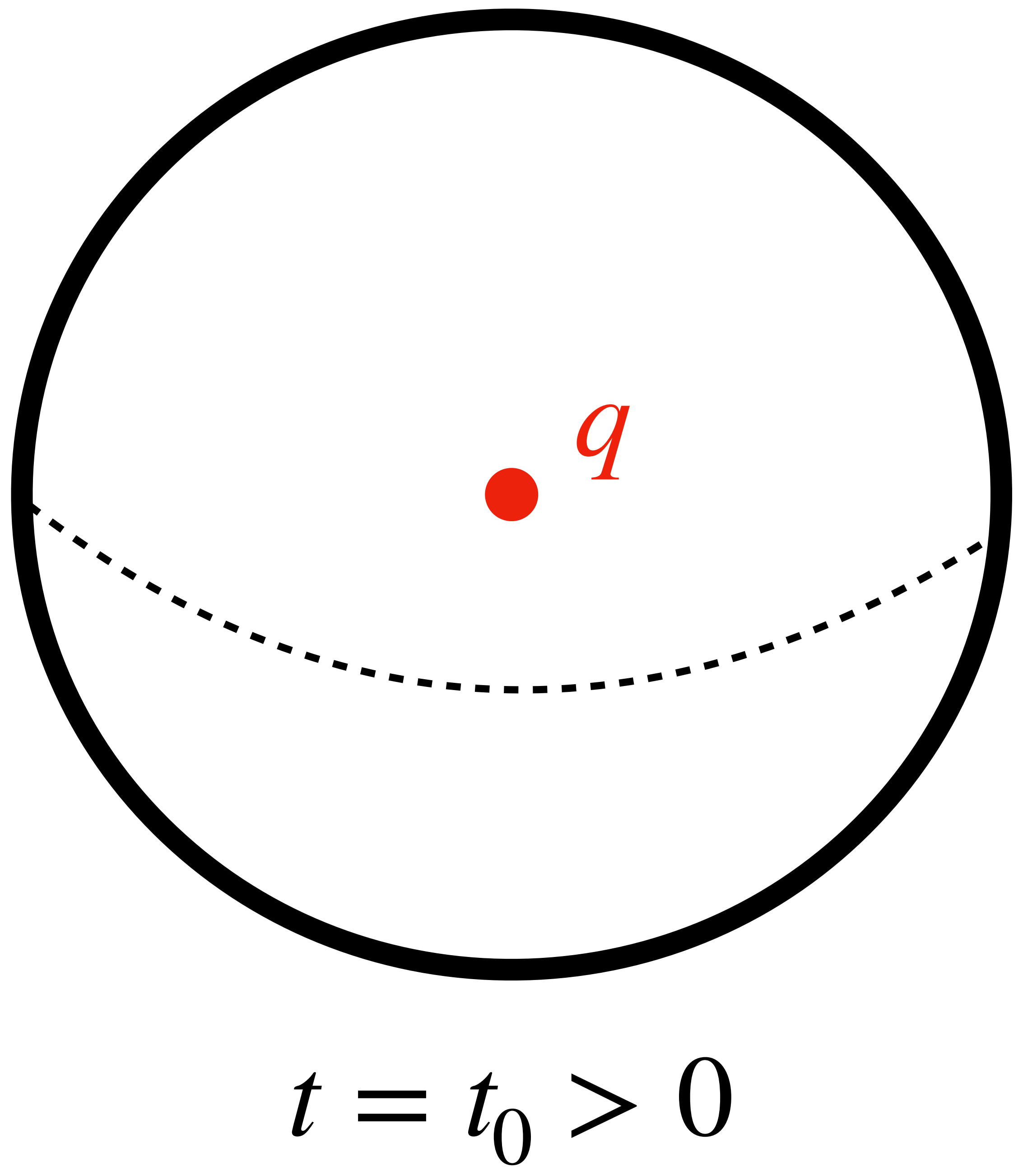
In electromagnetism, we *gauge* a would-be conserved current: $\int d^4x \, eA_\mu j^\mu$.

We obtain Maxwell's equations: $\partial^\nu F_{\mu\nu} = ej_\mu$.

Now the charge density is a total derivative (on-shell), so our charge **vanishes**: $Q = \int d^3x \, j^0 = 0$ (**"Gauss law constraint"**). Symmetry operators are trivial! $U(\alpha, t) = \exp\left(\mathrm{i}\alpha \int d^3x \, j^0(t,x)\right) = 1$

Flux as a Conserved Charge in Pure U(1) Gauge Theory

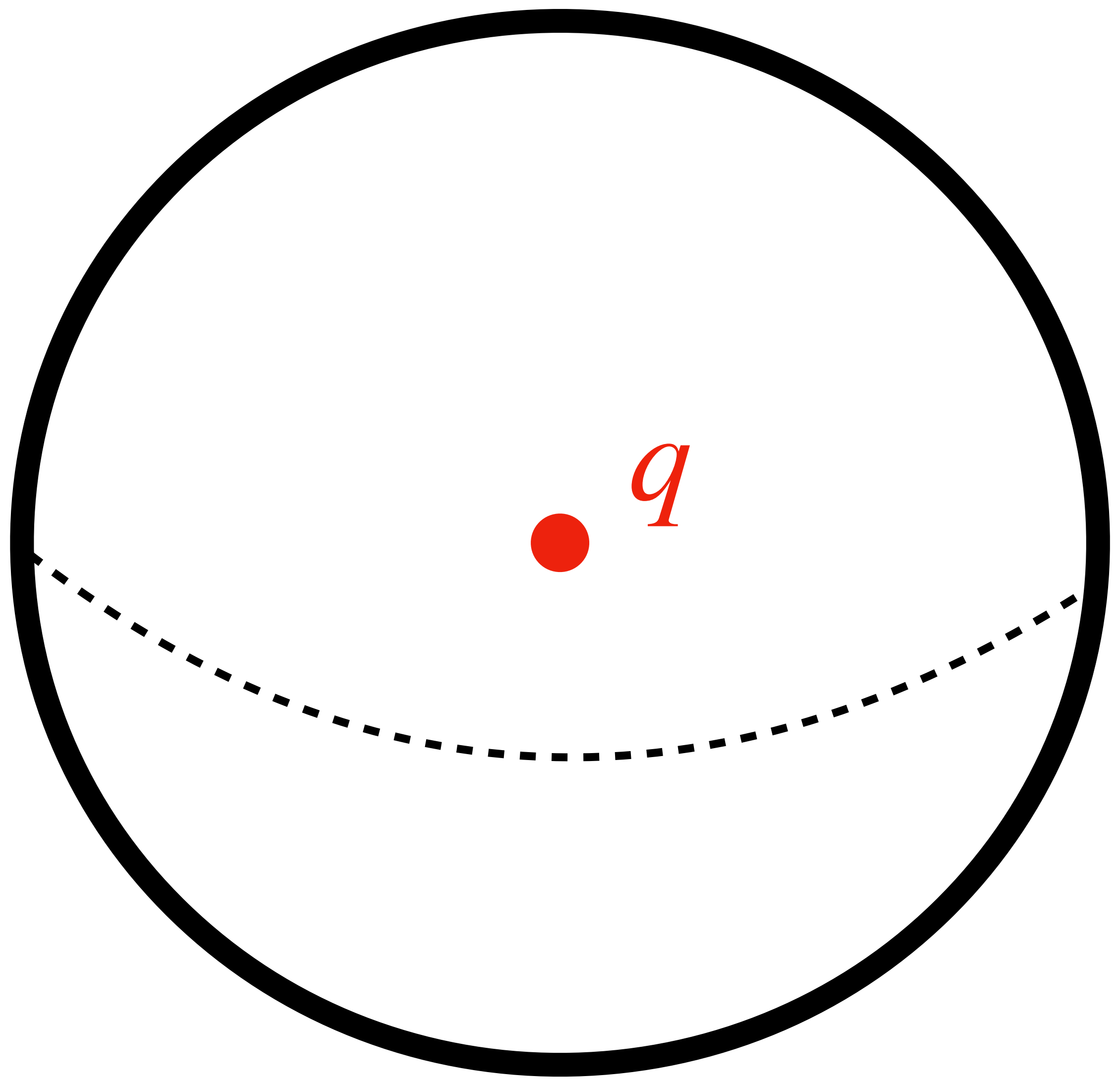




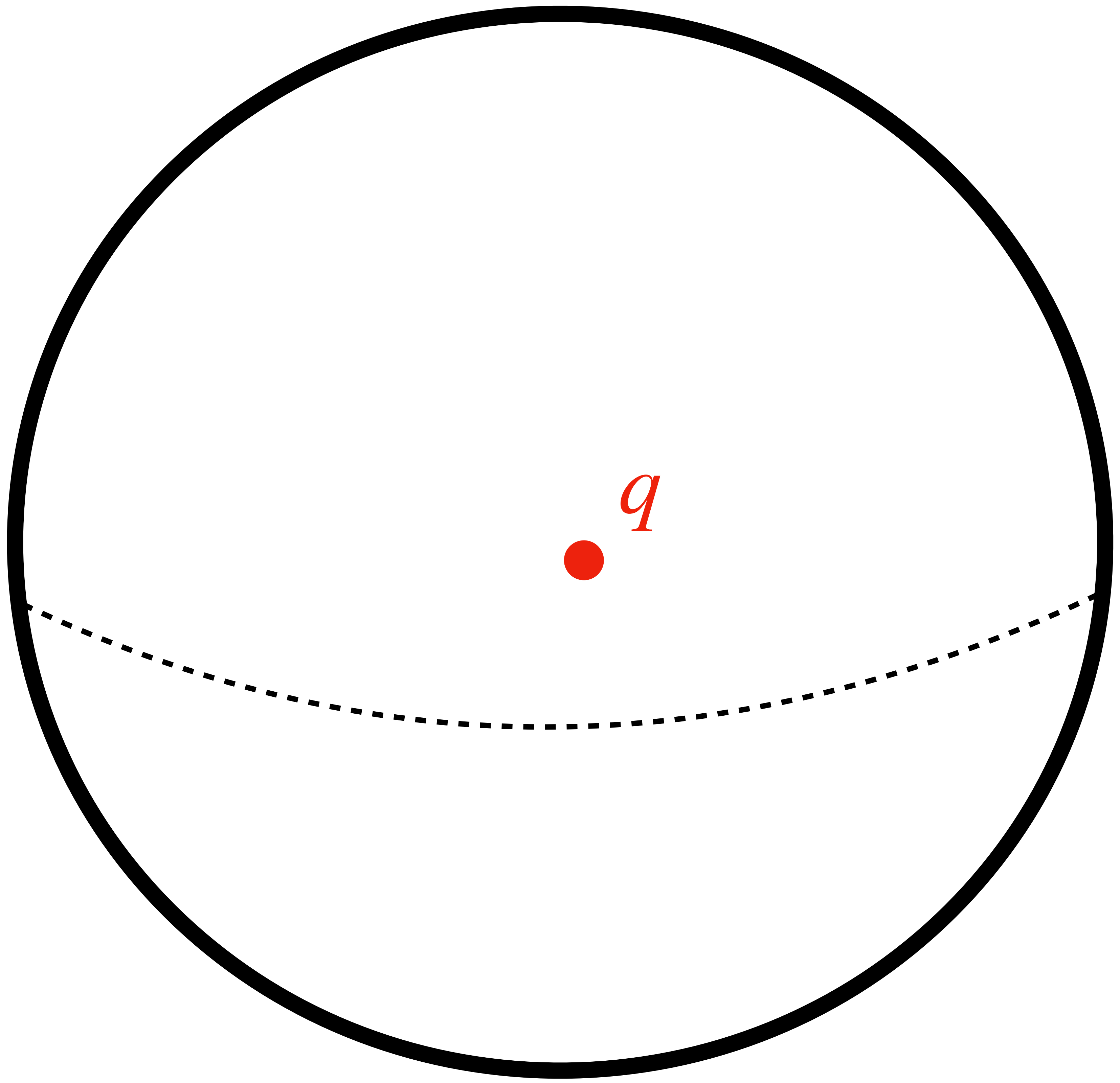
Electric or magnetic flux of a *probe* particle (Wilson line) is conserved in time.
Integrate over a **2-dimensional surface**, not all space: **"1-form symmetry."**

Gaiotto, Kapustin, Seiberg, Willett '14

Flux as a Conserved Charge in Pure U(1) Gauge Theory



radius r



radius $R > r$

Electric or magnetic flux of a *probe* particle (Wilson line) is conserved *in space* as well (topological).

Gaiotto, Kapustin, Seiberg, Willett ’14

Electric Flux (Non-)Conservation, in Equations

Flux conservation is associated with a conserved current, but it has *two* (antisymmetric) indices:

Electric flux conservation: current is $\frac{1}{e}F_{\mu\nu}$,

conservation is Maxwell's equation: $\partial^\mu F_{\mu\nu} = 0$,

broken by **dynamical** electric charges: $\partial^\mu F_{\mu\nu} = ej_\nu$.

Gaiotto, Kapustin, Seiberg, Willett '14

Magnetic Flux (Non-)Conservation, in Equations

Flux conservation is associated with a conserved current, but it has *two* (antisymmetric) indices:

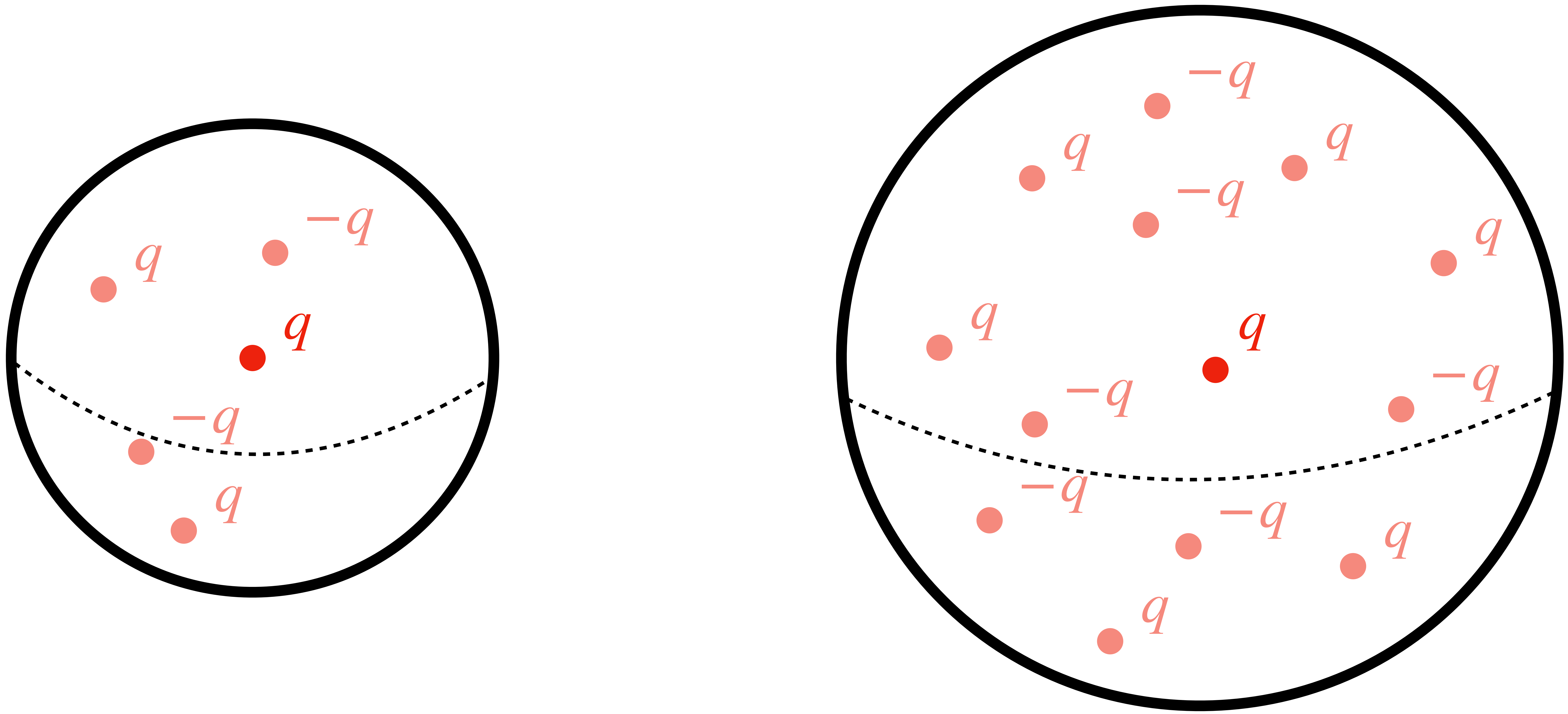
Magnetic flux conservation: current is $\frac{e}{2\pi}\widetilde{F}_{\mu\nu} = \frac{e}{4\pi}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$,

conservation is Bianchi identity: $\partial^\mu \widetilde{F}_{\mu\nu} = 0$,

broken by **dynamical** magnetic monopoles: $\partial^\mu \widetilde{F}_{\mu\nu} = \frac{2\pi}{e} j_\nu^{\mathrm{mag}}$.

Gaiotto, Kapustin, Seiberg, Willett ’14

Flux as a Non-Conserved Charge in QED



The topological property breaks down when there are dynamical charges, because of *screening*: the coupling runs.

Gaiotto, Kapustin, Seiberg, Willett ’14
Córdova, Ohmori, Rudelius ’22

Global Symmetry vs. Gauge "Symmetry"

Global symmetry:

- States can have net charge.
- Symmetry operators exist. Topological: measure charge they surround.
- Symmetry turns one state into a different state.

Gauge "symmetry":

- Gauss law: no net charge.
- Symmetry operators trivialized.
- Different gauges are *redundant descriptions* of a single state.

Types of generalized symmetries

Higher form symmetries: electric and magnetic flux are examples. Symmetry charge of a p-form symmetry comes from integrating over $(d-p-1)$ spatial dimensions. (Gaiotto, Kapustin, Seiberg, Willett ’14)

Higher group symmetries: multiple symmetries that “mix” with each other: current algebras like $\partial^\mu j_\mu(x) j_\nu(y) = \frac{\kappa}{2\pi} \partial^\lambda \delta(x-y) J_{\lambda\nu}(y)$.

(Córdova, Dumitrescu, Intriligator ’18; Brennan, Córdova ’20)

Non-invertible symmetries: associated with topological operators that are *not unitary*. More general algebraic structure than groups. (in 4d: Heidenreich, McNamara, Montero, MR, Rudelius, Valenzuela ’21; Kaidi, Ohmori, Zheng ’21; Córdova, Ohmori ’22; Choi, Lam, Shao, ’22)

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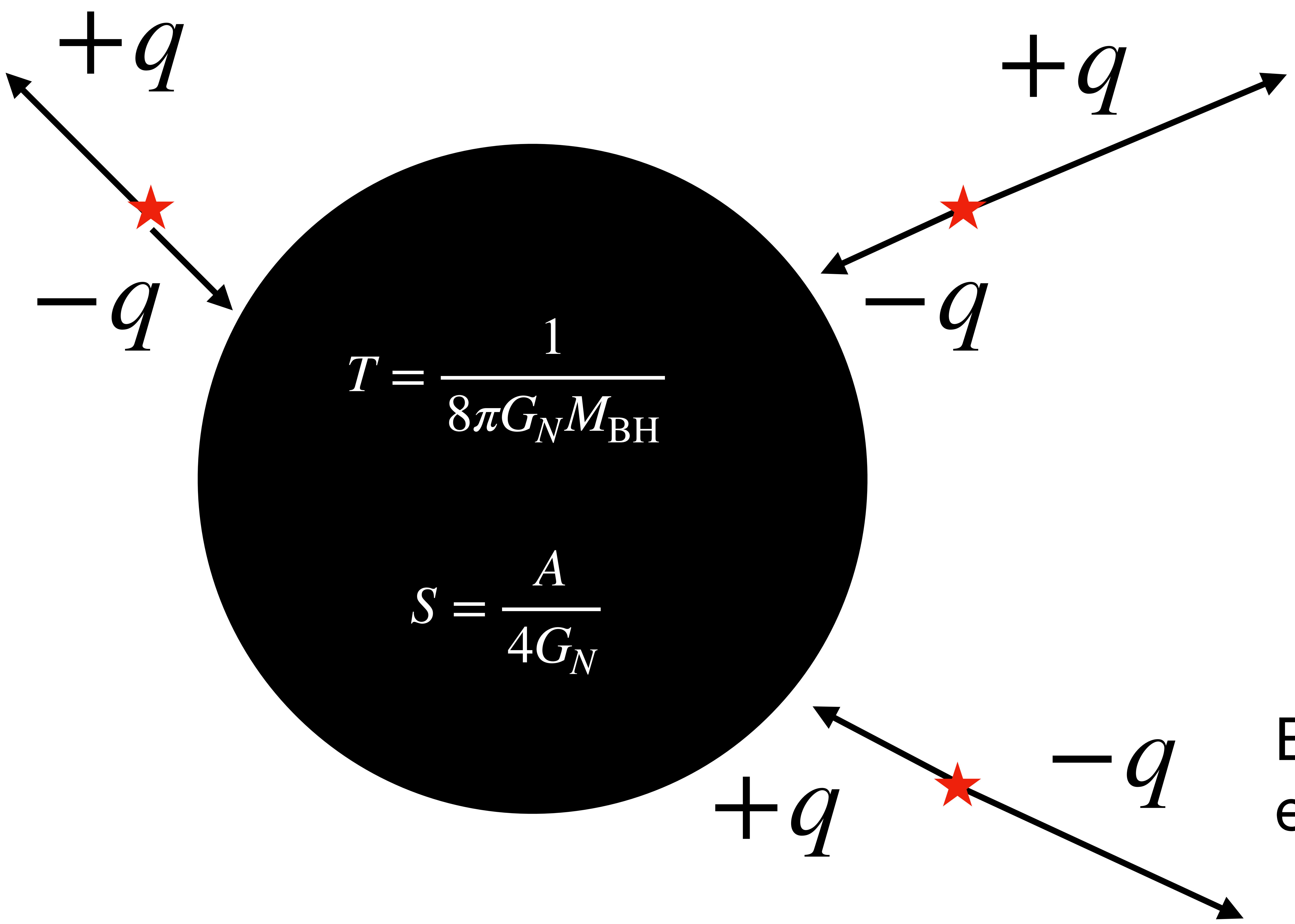
The latter two lead to nontrivially, potentially phenomenologically useful “emergence constraints” on symmetry-breaking scales.

No Global Symmetries in Quantum Gravity

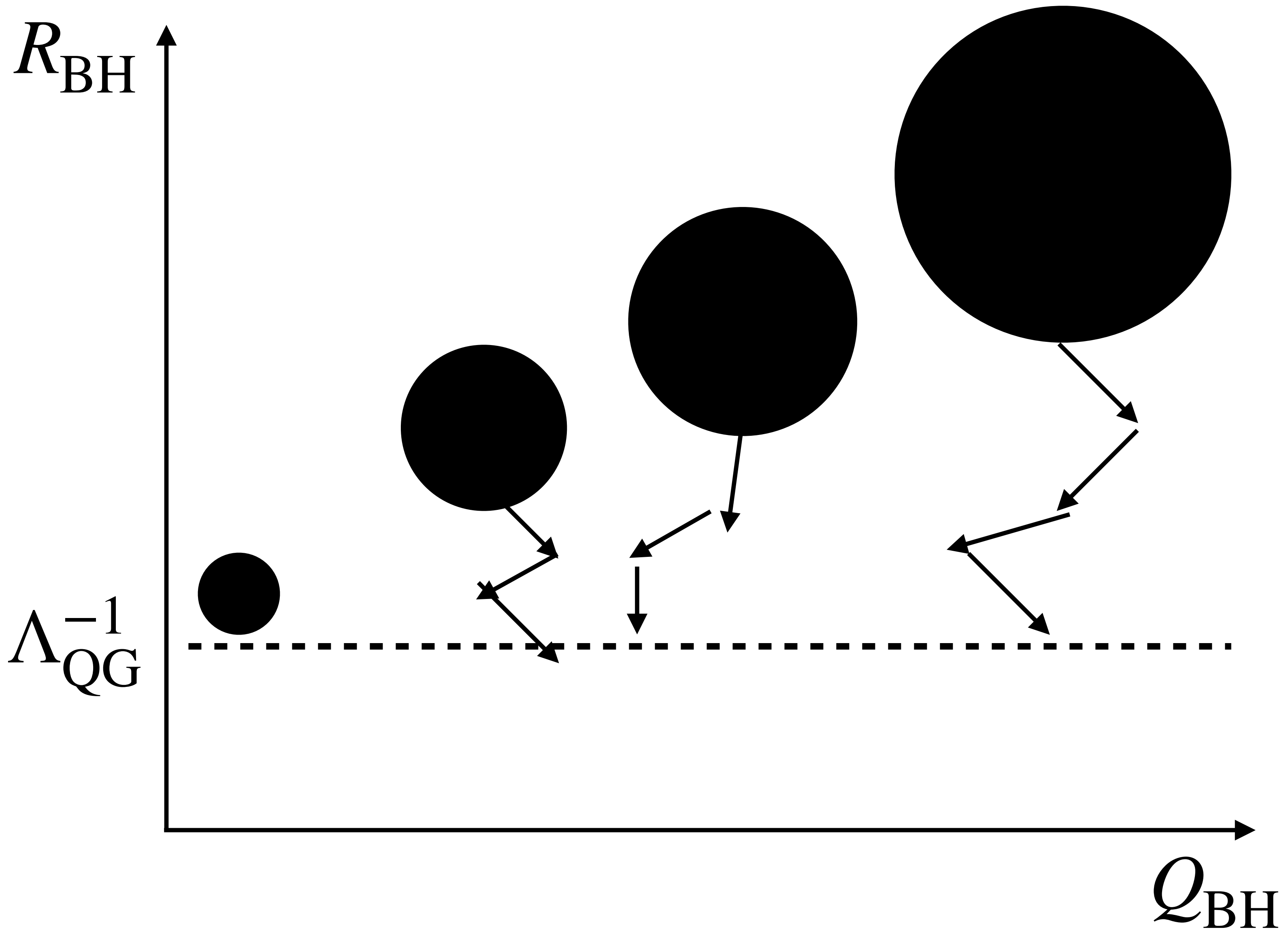


Stephen Hawking

Black holes have random thermal emission of global charge.

No Global Symmetries in Quantum Gravity

How do we know the black hole won't carry some "remnant" information about its symmetry charge?
Modern arguments:



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

Banks, Seiberg '10

splittability and entanglement wedge reconstruction

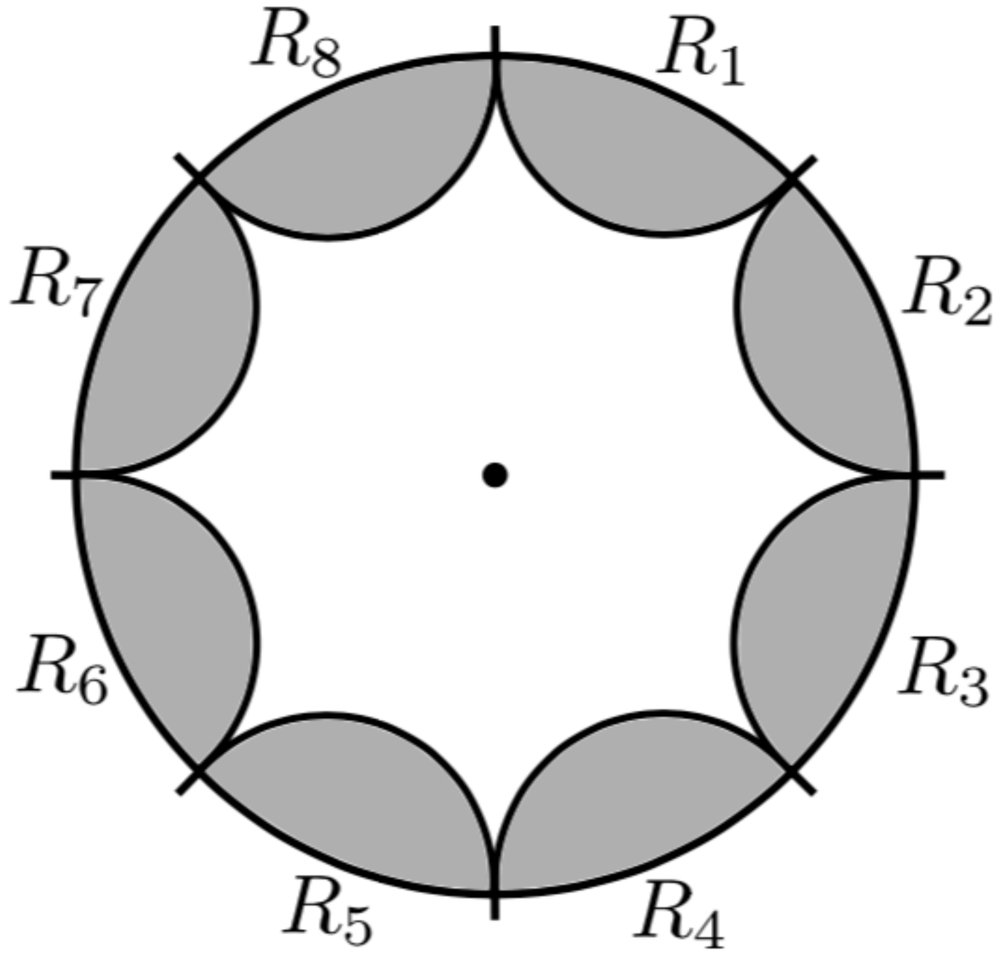
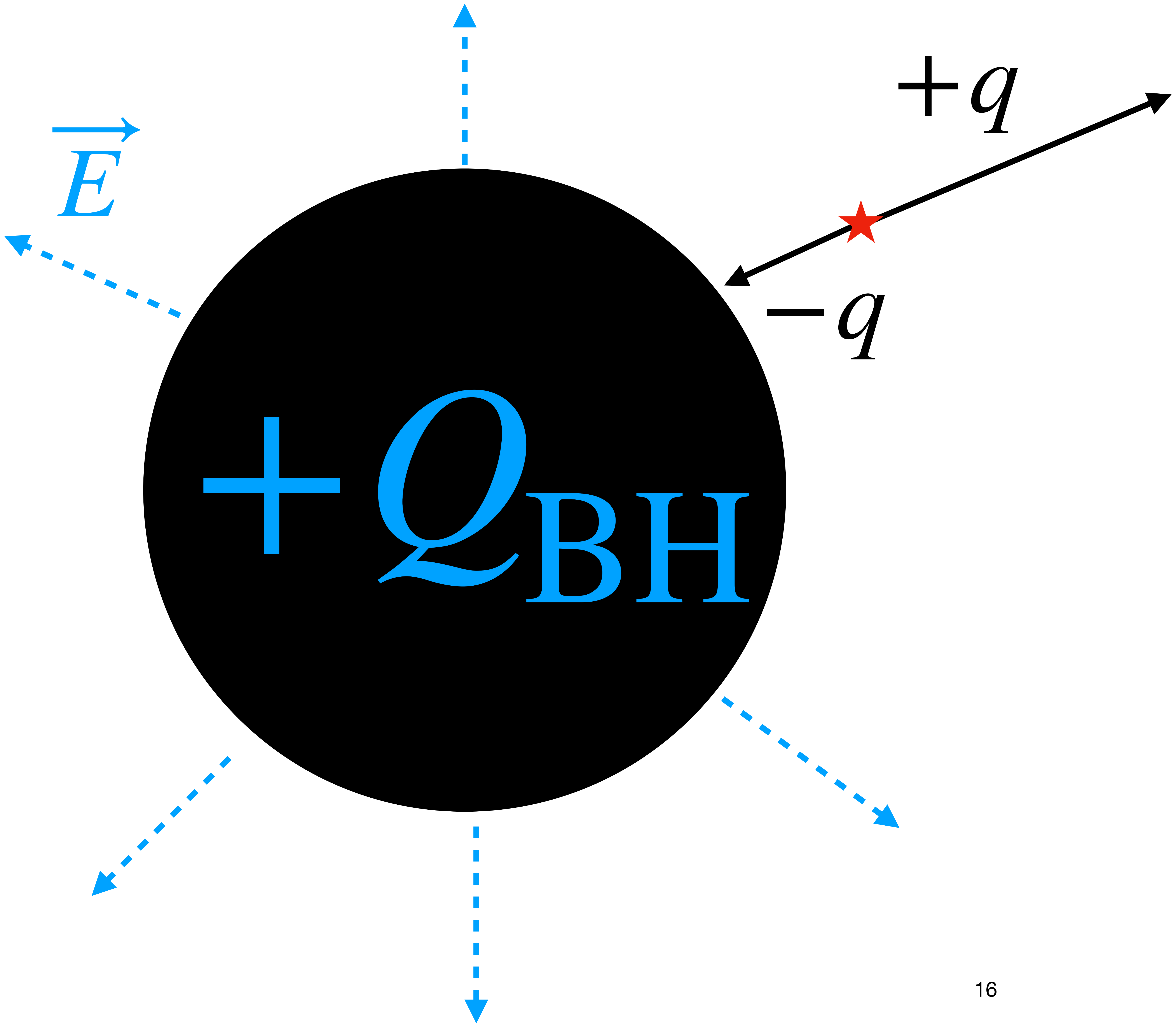


Fig. from 1810.05337 [Harlow/Ooguri]

More recent activity: Nomura '19; Harlow, Shaghoulian '20; Chen, Lin '20; Hsin, Iliesiu, Yang '20; Yonekura '20; Bah, Jefferson, Roumpedakis, Waddleton '24; …

Black Holes and Gauge Charge



Measurable $\vec{E}$ field outside BH: **preferential discharge**, if light charged particles exist.

$$\mu \propto Q_{\mathrm{BH}}$$

$\vec{E}$ field contributes to BH energy: **extremality bound**

$$M_{\mathrm{BH}} \geq \sqrt{2} e Q_{\mathrm{BH}} M_{\mathrm{Pl}}$$

$$\left(M_{\mathrm{Pl}} = \sqrt{\frac{1}{8\pi G_N}}\right)$$

Key Lesson for Quantum Gravitational Theories

**There are no global symmetries,
only gauge symmetries.**

Gauge symmetries are not symmetries.

Gauging or Breaking

Given an EFT with an apparent global symmetry, quantum gravity allows us only two options: the symmetry must be **gauged** or **explicitly broken**. Gauging often has dramatic low-energy effects, while breaking may be subtle.

Example: the magnetic flux symmetry with current $\frac{e}{2\pi}\widetilde{F}_{\mu\nu}$.

How can we eliminate it?

1. **Gauge it**: add a two-index antisymmetric tensor gauge field $B_{\mu\nu}$ with $B_{\mu\nu}\widetilde{F}^{\mu\nu}$ coupling. This **gives the photon a mass**! Not phenomenologically viable.

2. **Break it (explicitly)**: add dynamical magnetic monopoles, $\partial^\mu \widetilde{F}_{\mu\nu} = \frac{2\pi}{e} j_\nu^{\text{mag}}$.

Prediction: Magnetic Monopoles Exist

This example is instructive because it shows that **the principle of no global symmetries** in QG has a **direct real-world implication.**

Photon is massless ⇒ magnetic 1-form symmetry was not gauged.

Symmetry must be broken ⇒ magnetic monopoles exist.

The magnetic monopoles could be very heavy, so this is not immediately useful as a guide to experiment. But it is an important proof of principle.

Strategy:

1. Identify a symmetry.

2. Categorize ways to **gauge** or **break** it.

3. Understand which are possible in the real world.

Instanton Number as a Symmetry

In $d > 4$ spacetime dimensions, the **instanton number density** of a gauge theory is a U(1) conserved current: $\partial^{\mu_1}(\epsilon_{\mu_1\ldots\mu_d}F^{a\mu_2\mu_3}F^{a\mu_4\mu_5}) = 0.$

In quantum gravity there are only two options for this $(d-5)$-form symmetry.

- **Gauging:** a gauge field $C_{\mu_1\ldots\mu_{d-4}}$ can couple through a **Chern-Simons** term $\epsilon_{\mu_1\cdots\mu_d}C^{\mu_5\cdots\mu_d}F^{a\mu_1\mu_2}F^{a\mu_3\mu_4}$.
- **Breaking:** the conservation law can be broken by **magnetic monopoles** but an improved current can be constructed if they admit dyonic excitations.

This is one of many examples of “Chern-Weil” symmetries of gauge theories, which follow from the topology of the gauge group. (Heidenreich, McNamara, Montero, MR, Rudelius, Valenzuela ’20)

Why Axions Should Exist

In $d = 4$, instanton number is not quite a symmetry. But there is still a version of the two options:

In quantum gravity there are only two options for this $(d-5)$-form symmetry.

- **Gauging:** an **axion** field $\theta(x)$ can couple through a **Chern-Simons** term $\theta F^a_{\mu\nu}\widetilde{F}^{a\mu\nu}$, which leads to a "Gauss law constraint" $\int F\widetilde{F} = f^2 \int \partial^\mu \partial_\mu \theta = 0.$

- **Breaking**: a **magnetic monopole** without dyonic excitations cannot be coupled to an axion due to the **Witten effect.** θ angle *frozen*.

In theories with light, minimally charged fermions, the latter option is impossible. In the string landscape, **we always find axions in such theories**.

(Heidenreich, McNamara, Montero, MR, Rudelius, Valenzuela '20; MR to appear '26)

Weak Gravity Conjecture

(Arkani-Hamed, Motl, Nicolis, Vafa ’06)

So far we talked about *existence* arguments. The WGC is more quantitative. Given a U(1) gauge theory, must exist electric particles with

$$m \leq \sqrt{2} e M_{\rm Pl}$$

and magnetic with

$$m_{\rm M} \leq \sqrt{2} \frac{2\pi}{e} M_{\rm Pl} \,.$$

By analogy (or dimensional reduction),

axion (0-form) case: $\frac{1}{2} f_a^2 (\partial_\mu \theta)^2$, exists a charged **instanton** with action

$$S \lesssim \frac{q}{f_a} M_{\rm Pl}$$

The Axion Weak Gravity Conjecture

Axion as "0-form gauge field": $S_{\text{inst}} \lesssim \frac{1}{f_a} M_{\text{Pl}}$. (Arkani-Hamed, Motl, Nicolis, Vafa '06)

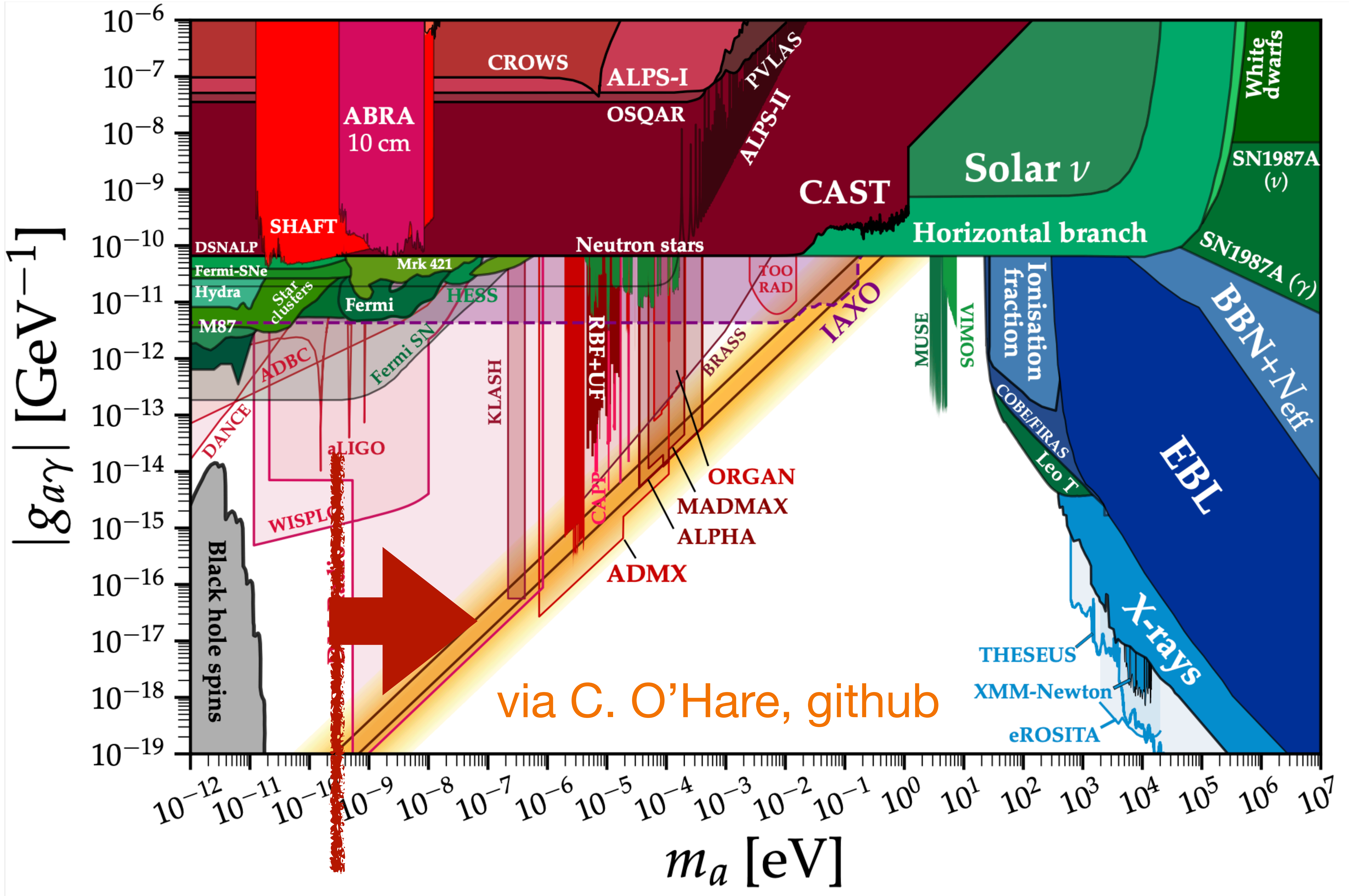
Given $\theta\, \text{tr}(F \wedge F)$,

S_{inst} from usual QCD instantons:

$$f_a \lesssim \frac{g^2}{8\pi^2} M_{\text{Pl}}$$

Nontrivial phenomenological prediction!

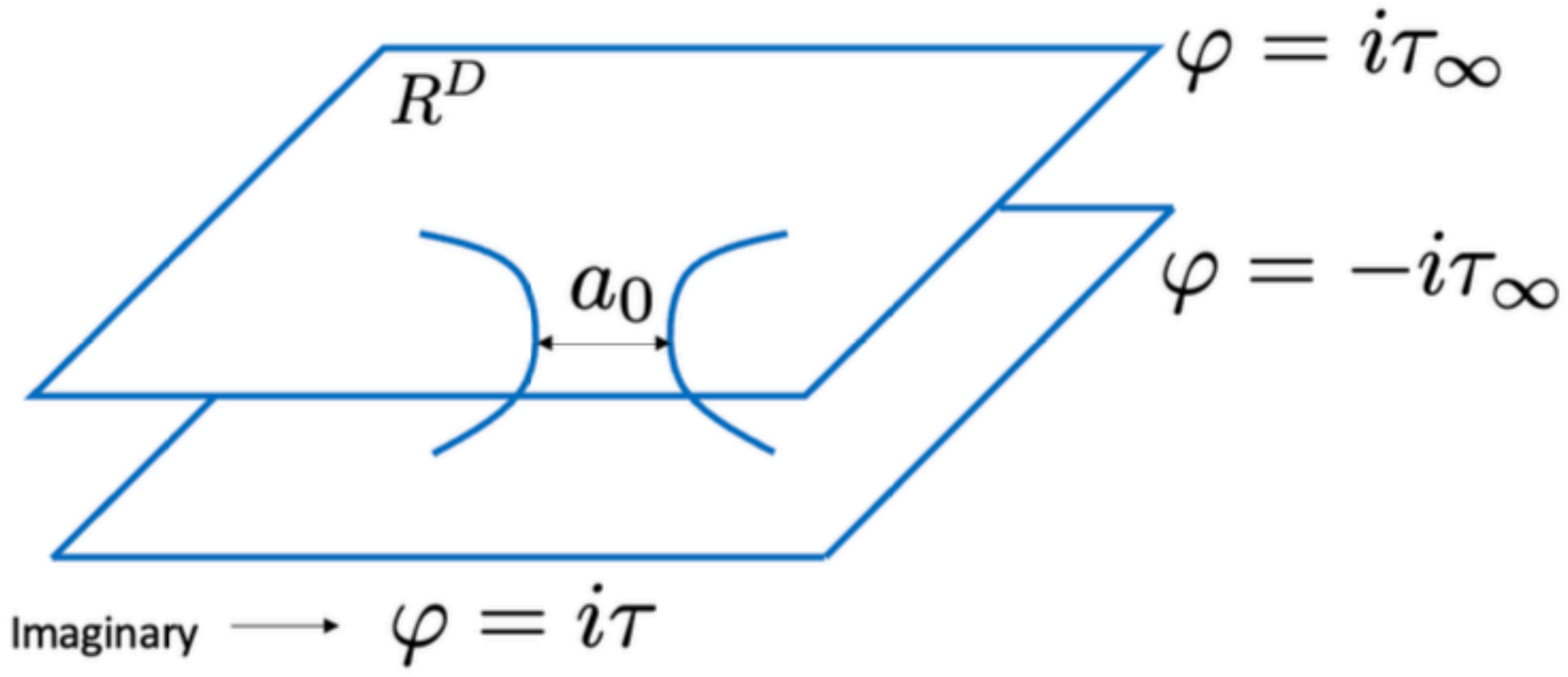
QCD axion with $f_a \lesssim 2 \times 10^{16}\,\text{GeV}$.



The Imaginary Distance Bound

A *very* new theoretical development (last week!):

Di Ubaldo, Iliesiu, Lin, Yan 2605.06305; Maldacena, Maloney, McPeak 2605.05336



Massless scalar fields coupled to gravity admit Euclidean “wormhole” solutions with *imaginary* asymptotic field values.

(Giddings & Strominger, 1988)

These lead to pathologies (e.g., negative norm states) unless an *imaginary distance bound* is obeyed:

$$\mathrm{Im}\,\Delta\phi \le \pi\sqrt{\frac{D-1}{D-2}}M_{\mathrm{Pl}}\,.$$

The Imaginary Distance Bound

The imaginary distance bound

$$\mathrm{Im}\,\Delta\phi \le \pi\sqrt{\frac{D-1}{D-2}}M_{\mathrm{Pl}}$$

Di Ubaldo, Iliesiu, Lin, Yan 2605.06305;
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requires some new physics to modify free scalar + GR.

In particular, **the shift symmetry of the massless scalar should be broken**.

This leads to a ***quantitative*** **axion WGC**:

$$f \le \frac{\pi}{2}\sqrt{\frac{3}{2}}\frac{M_{\mathrm{Pl}}}{S_{\mathrm{inst}}} \lesssim 7\times 10^{16}\,\mathrm{GeV}$$

This is both interesting for experiment and nontrivially consistent with examples in string theory. The IDB is also connected to the ordinary WGC by compactification.

Summary

In recent years, we have learned that:

- Gauge theories have many previously unknown *global* symmetries
- These lead to constraints on symmetry breaking scales in QFT ("emergence")
- In quantum gravity, global symmetries must be gauged or broken
- Related arguments suggest that a QCD axion should exist

The key work ahead of us is to refine these arguments and make them more *quantitative*.

There is significant recent progress in this direction.

Thank you!