The Swampland and Particle Physics

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Outline

- No Global Symmetries and Completeness Hypothesis
- Parity Symmetry in Quantum Gravity
- Weak Gravity Conjecture and Axion Strings
- Axions in Quantum Gravity

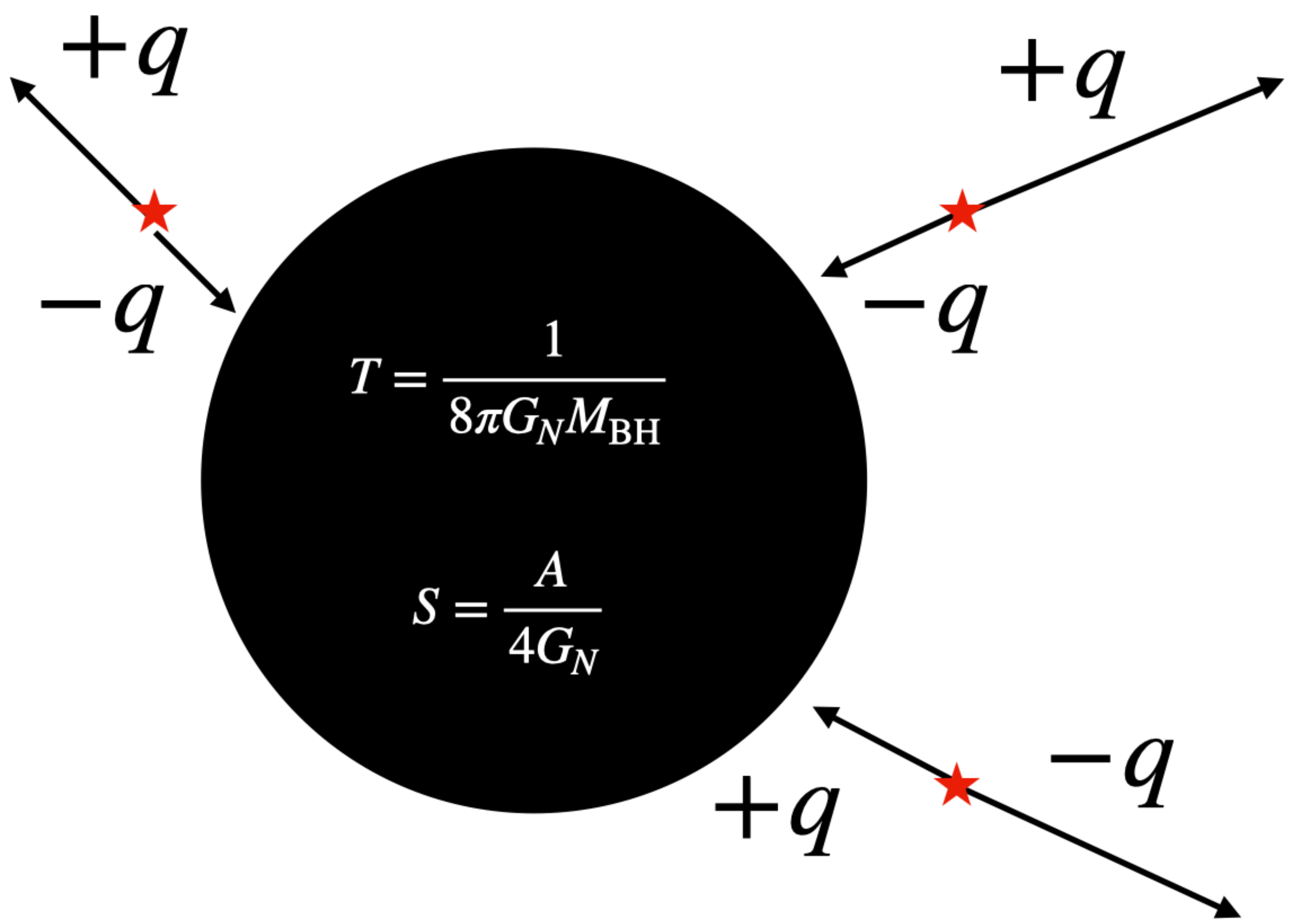
No Global Symmetries, Completeness Hypothesis

(Heidenreich, McNamara, Montero, MR, Rudelius, Valenzuela arXiv:2104.07036)

No Global Symmetries

(Wheeler; Hawking; Zeldovich; Banks, Dixon; Banks, Seiberg; Harlow, Ooguri; rapidly growing list of others….)

One big idea behind multiple things that I will discuss in this talk is that consistent theories of quantum gravity have **no global symmetries.** At the UV cutoff scale, not even ***approximate*** global symmetries.



Hawking radiation:

Random thermal emission of global charge.

Modern argument: Banks, Seiberg 2010

Generalized Global Symmetries Example: Symmetries in Free U(1) Gauge Theory

In free Maxwell theory, we have no electric or magnetic sources, so

$$\mathrm{d}(\star F) = 0$$

Closed (d–2)-form current
$\Longrightarrow$ **Global 1-form symmetry**

$$\mathrm{d}F = 0$$

Closed 2-form current
$\Longrightarrow$ **Global ($d-3$)-form symmetry**

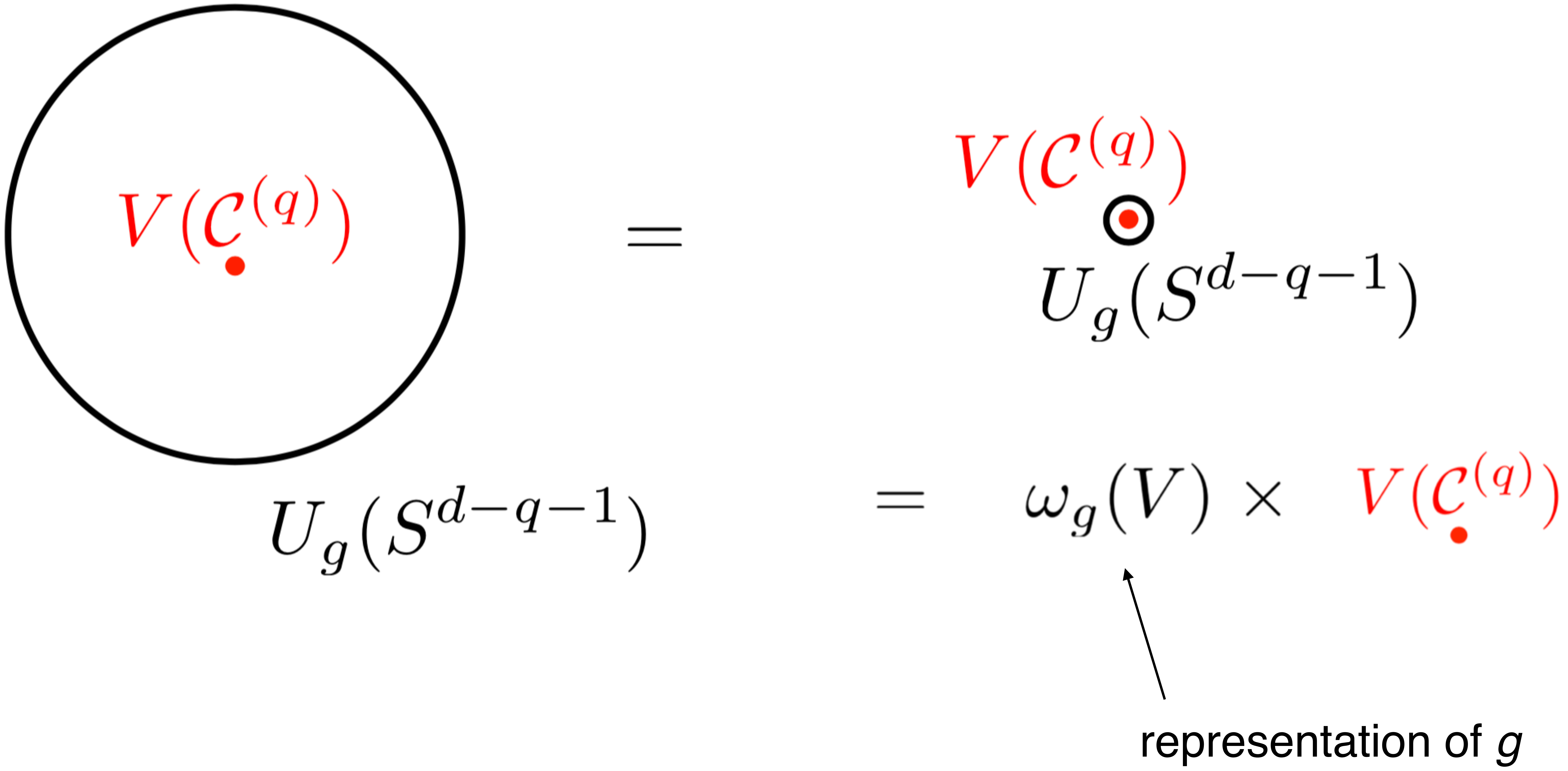
The quantization of fluxes means that these are both U(1) symmetries.
In 4d, they are both *1-form* global symmetries.

- **Electric symmetry, current $\star F$, charged objects are *Wilson loops*.**
- **Magnetic symmetry, current *F*, charged objects are *'t Hooft loops*.**

The symmetries basically *count* Wilson or 't Hooft loops.

Symmetry Operators Measure Charges

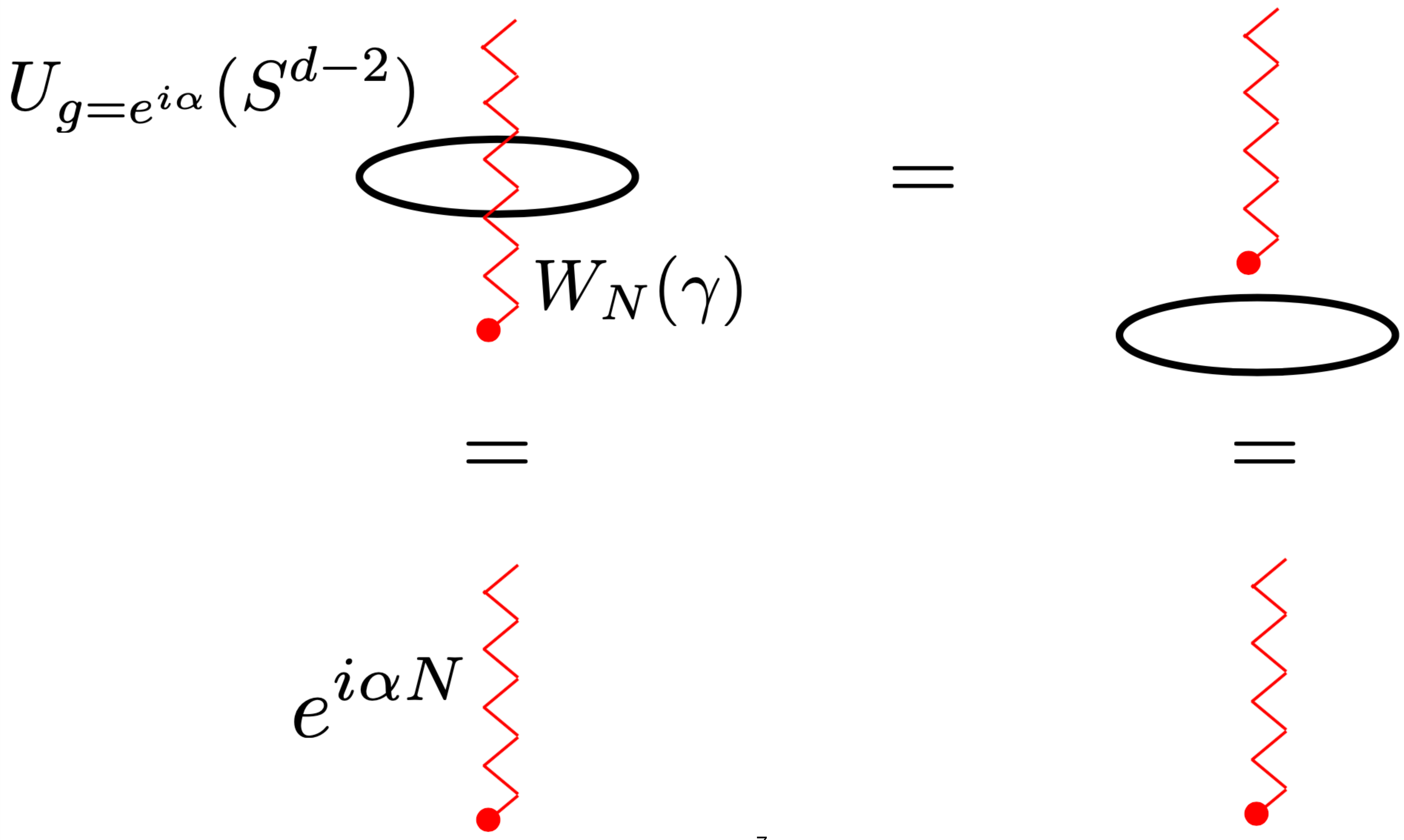
(Figure from a nice talk by Tom Rudelius at the 2019 Madrid workshop “Navigating the Swampland”)



Conservation law $\Longrightarrow$ *topological* operator

Endability vs. Topological

Linking a surface operator with an *endable* Wilson loop makes it *not topological*, and vice versa



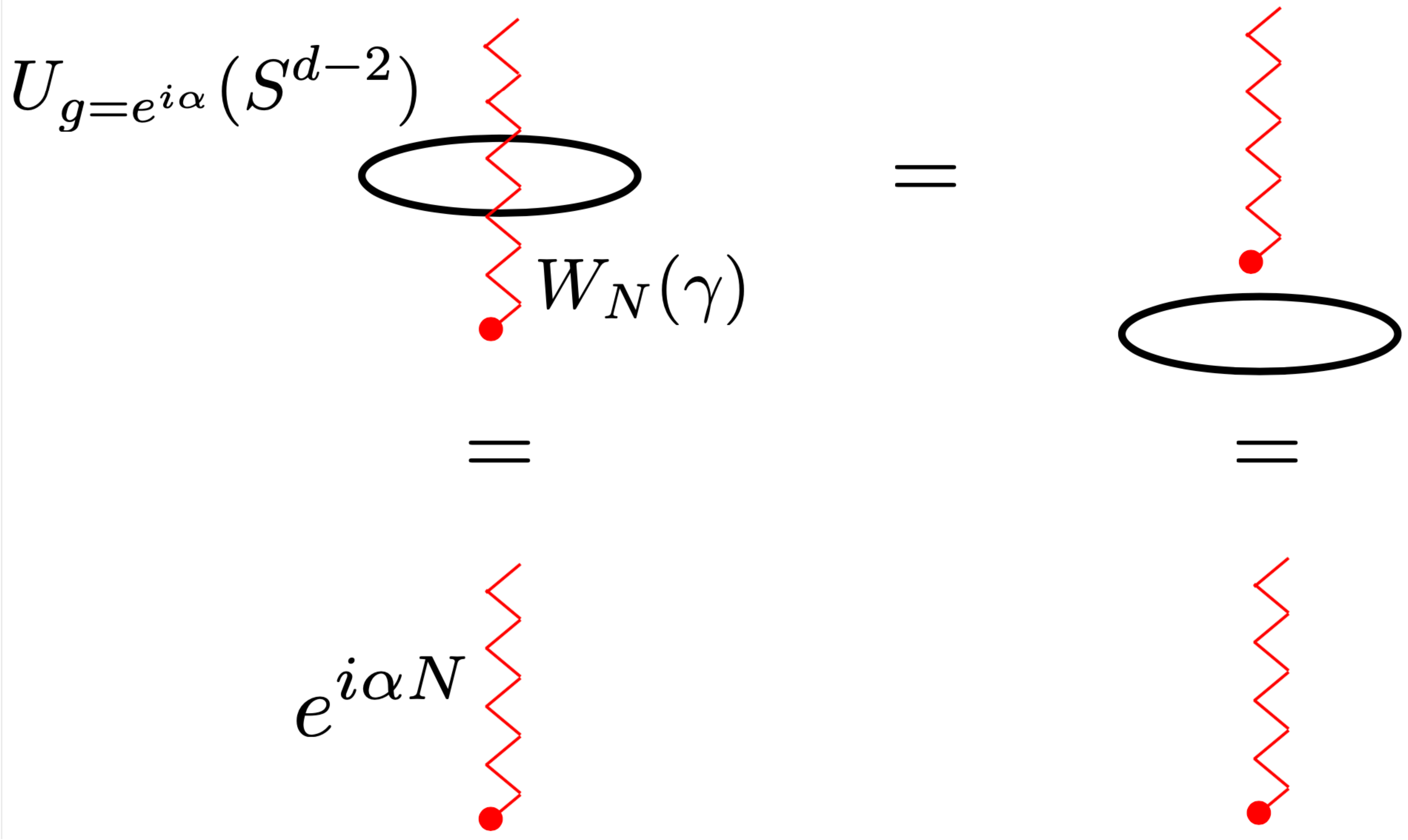
Complete spectrum of charged particles $\Longleftrightarrow$ absence of global symmetries

$$\mathrm{d}(\star F) = J$$

Wilson operators can end on local operators that create charged particles.

No longer a topologically invariant flux.

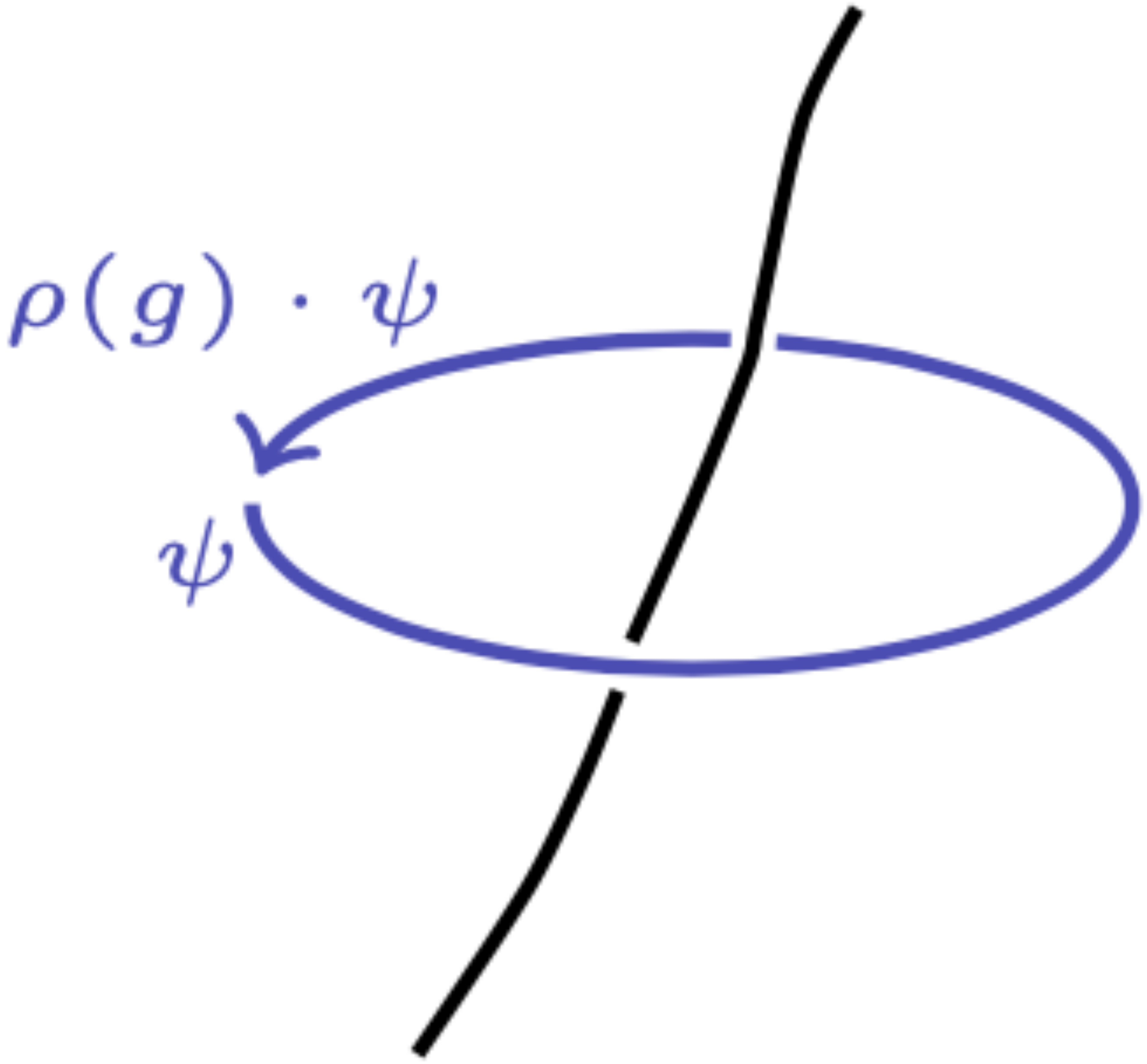
Charged particles break the *1-form symmetry*'s conservation law
(while gauging a *0-form symmetry* with current *J*)



Wilson lines can *end* $\Longleftrightarrow$ 1-form electric symmetry is *explicitly broken*.

Generalization to **all representations** of **any compact gauge group**: Rudelius, Shao '20; Heidenreich, McNamara, Montero, MR, Rudelius, Valenzuela '21

Discrete Gauge Symmetry and Vortices



Codimension-2 vortex (**cosmic string**, in 4d) inserts a "twist" (gauge transformation). Induces an **Aharonov-Bohm phase** on charged particles that circle it.

Static objects (gauge bundles).
In gauge theory, also **dynamical** object.
Boundary condition in the path integral: sum over gauge fields with fixed holonomy.

Quantum gravity: **dynamical vortices** exist to avoid $(d-2)$-form generalized symmetry generated by Wilson lines.

A Wrinkle in the Story

For U(1) gauge theory, we had:
All Wilson lines can end $\Longleftrightarrow$ States of any electric charge exist $\Longleftrightarrow$ No 1-form electric symmetry.

The last equivalence is **false** in general gauge theory.

Harlow, Ooguri ’18, counterexample: S_4 gauge theory can have no 1-form symmetry even with an incomplete spectrum

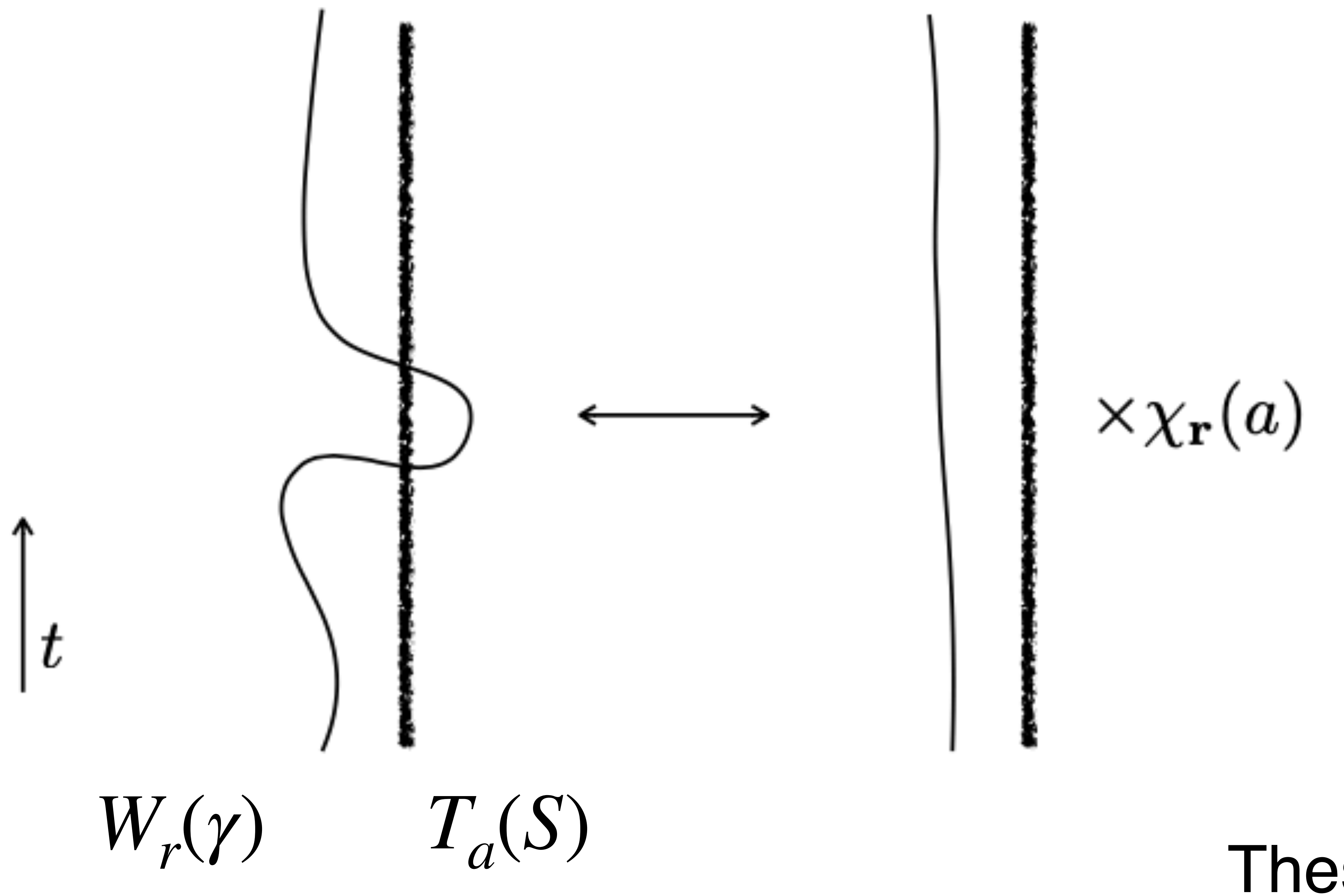
Rudelius and Shao ’20 proposed a corrected statement (proved for finite groups):
All Wilson lines can end $\Longleftrightarrow$ States in any representation exist $\Longleftrightarrow$ **No topological Gukov-Witten operators.**

“Topological Gukov-Witten operators” are an ***even more general*** notion of symmetry: a “non-invertible symmetry.”

What is a Gukov-Witten Operator?

Surface Operators that Produce Generalized Aharonov-Bohm Effects

Generalize the $\exp\left(i\alpha\int_{M^{(2)}}\frac{1}{e^2}\star F\right)$ 1-form symmetry operators we saw for $U(1)$



A Gukov-Witten operator lives on a codimension 2 surface and is labeled by a ***conjugacy class*** $a=[g]$ of elements of the gauge group G.

In words: a Gukov-Witten operator inserts a ***static, probe "magnetic flux tube"*** that produces an ***Aharonov-Bohm phase*** for charged matter.

These **either** end on (improperly quantized) 't Hooft lines or on operators creating **dynamical vortices.**

The General Story: Complete Spectrum

In arXiv:2104.07036, we proved two general claims:

Claim 1: All Wilson lines can end $\Longleftrightarrow$ States in any representation exist $\Longleftrightarrow$ No topological Gukov-Witten operators.

Claim 2: All Gukov-Witten operators can end $\Longleftrightarrow$ All possible vortex states exist $\Longleftrightarrow$ No topological Wilson line operators.

We believe that quantum gravity theories should have **no topological operators**—they are all "morally" a kind of symmetry.

Therefore, quantum gravity theories should have states in all representations, not only for ordinary particles, but for ***vortices.*** In 4d, these are also called ***cosmic strings***!

Implications for Cosmic Strings

Discrete gauge symmetries require “twist strings” in 4d

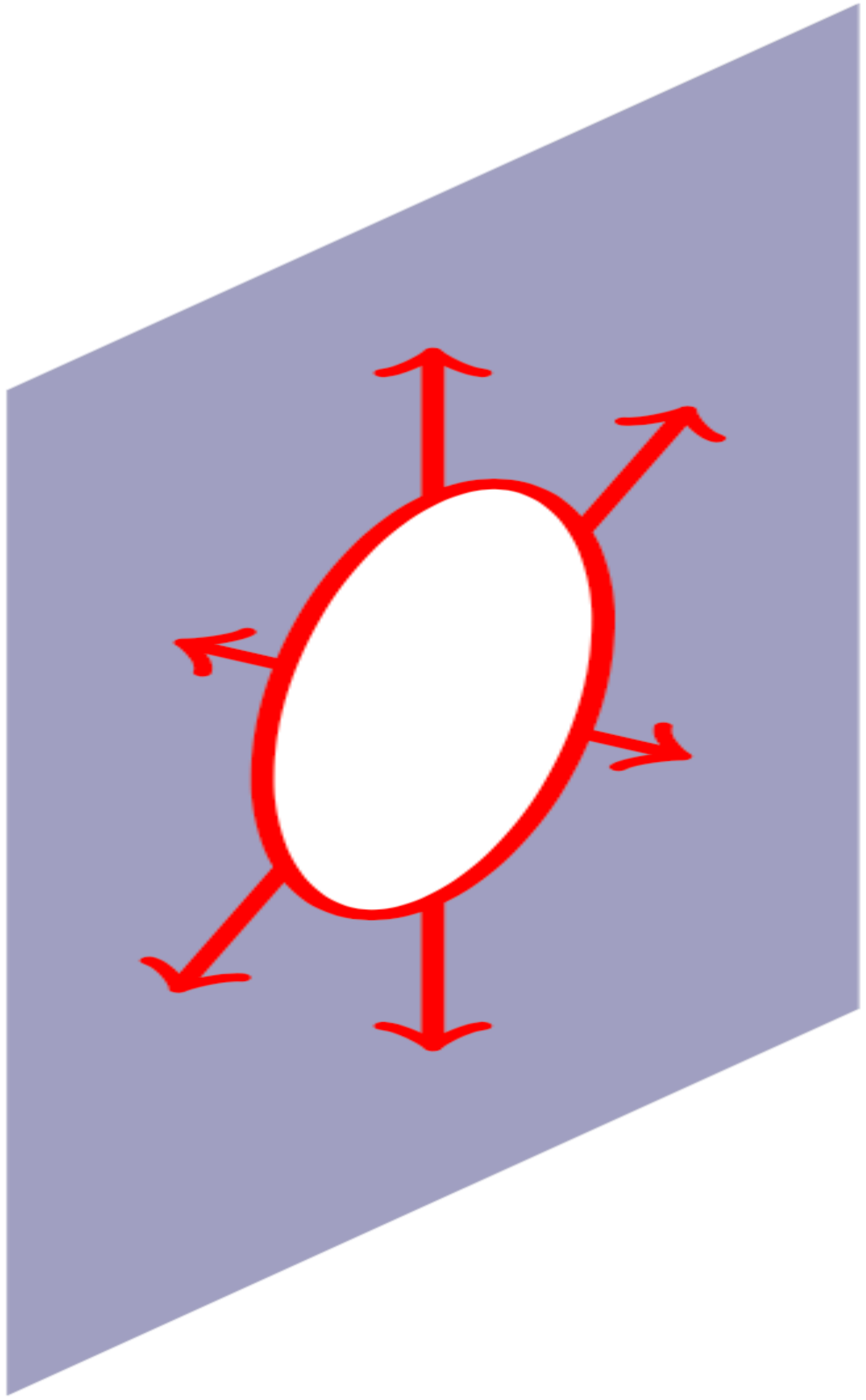
- Particles carrying $\mathbb{Z}_N$ charge: acquire Aharonov-Bohm phases around $\mathbb{Z}_N$ Krauss-Wilczek strings. Examples: **discrete *R*-symmetries, discrete symmetries to solve axion quality problem** should come with associated cosmic strings.

- Gauged finite groups: spontaneous symmetry breaking in cosmology produces **domain walls**, but these **can always be destroyed by loops of twist strings** that eat up the domain wall. (Though in general, this may be exponentially suppressed and ineffective.)

- Charge conjugation symmetries: always accompanied by “**Alice strings**.”

- Permutation symmetries, like an exact (but spontaneously broken) $\mathbb{Z}_2$ Twin Symmetry, should be associated to $\mathbb{Z}_2$ **Twin strings**; circulating around a string turns a Standard Model particle into a Twin particle. (These bound Twin domain walls.)

Dynamical Vortices Destabilize Domain Walls



Domain walls can end on vortices.

Two cosmological mechanisms:

1. Cosmic string network forms; DWs later form ending on the strings, network tears itself apart.

2. Cosmic strings nucleate holes in DWs that grow and eat up the DW. (Trickier—tunneling process, exponentially suppressed.)

Parity Symmetry in Quantum Gravity

(McNamara, MR arXiv:2212.00039)

Parity is a Spacetime Symmetry

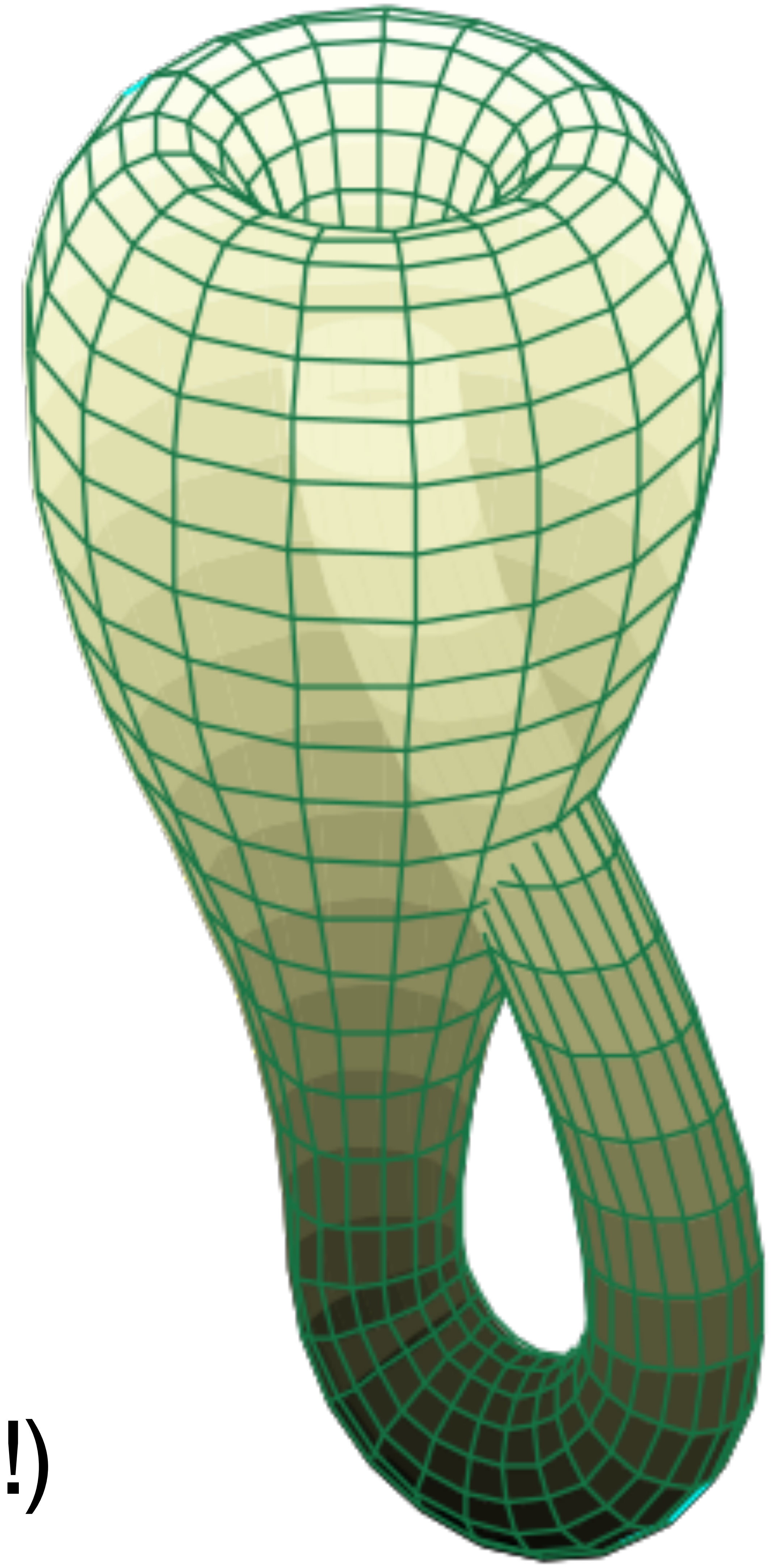
Parity/CP are orientation-reversing spacetime symmetries, $(t, \vec{x}) \mapsto (t, -\vec{x})$ in Minkowski space.

But that's nonsense on a general spacetime: what is $-\vec{x}$, anyway?

Right way to think about this (well-known):

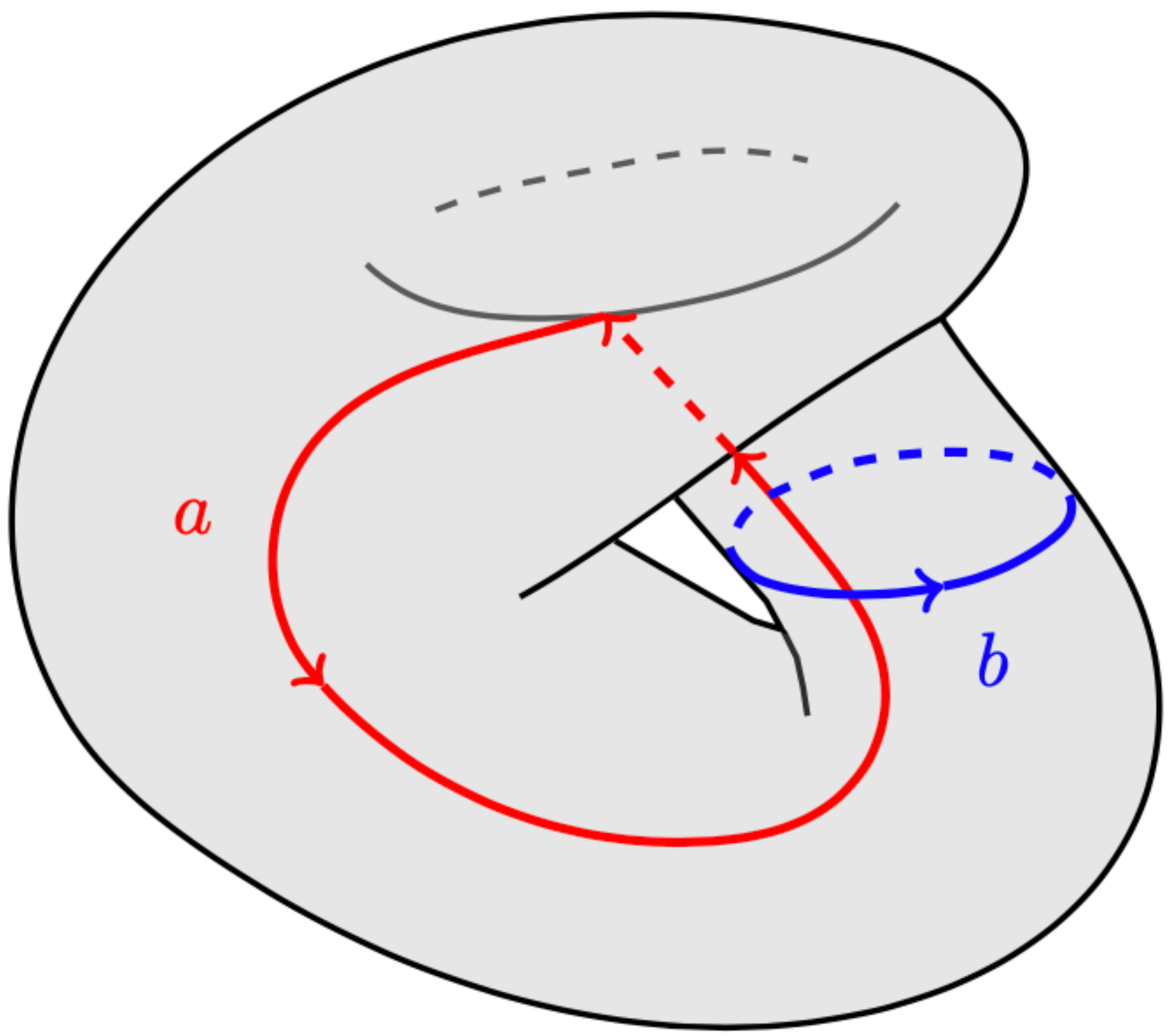
A theory with parity symmetry is a theory that makes sense when defined on non-orientable manifolds.

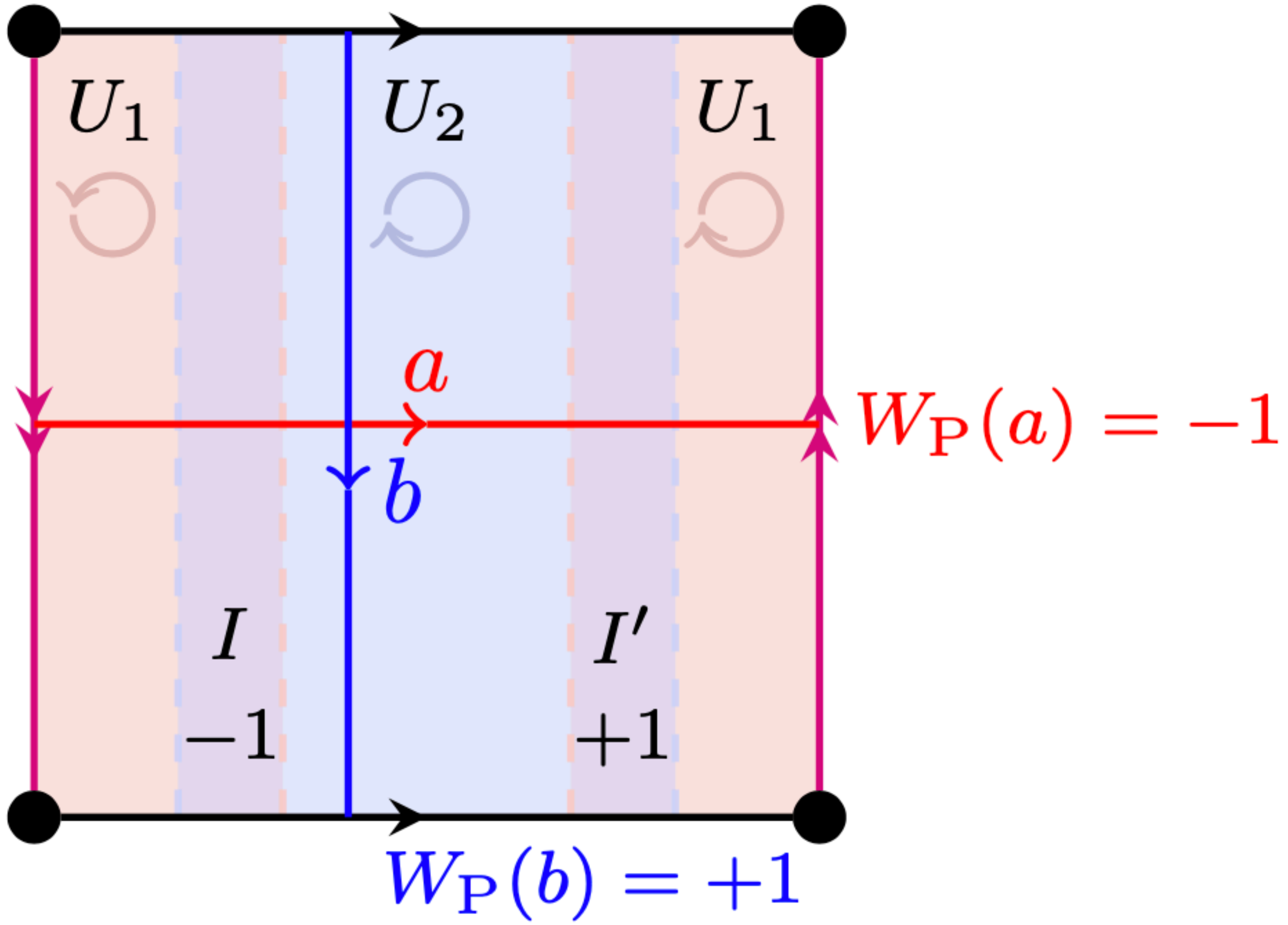
Global: fixed spacetime; gauge: sum over spacetimes (QG!)



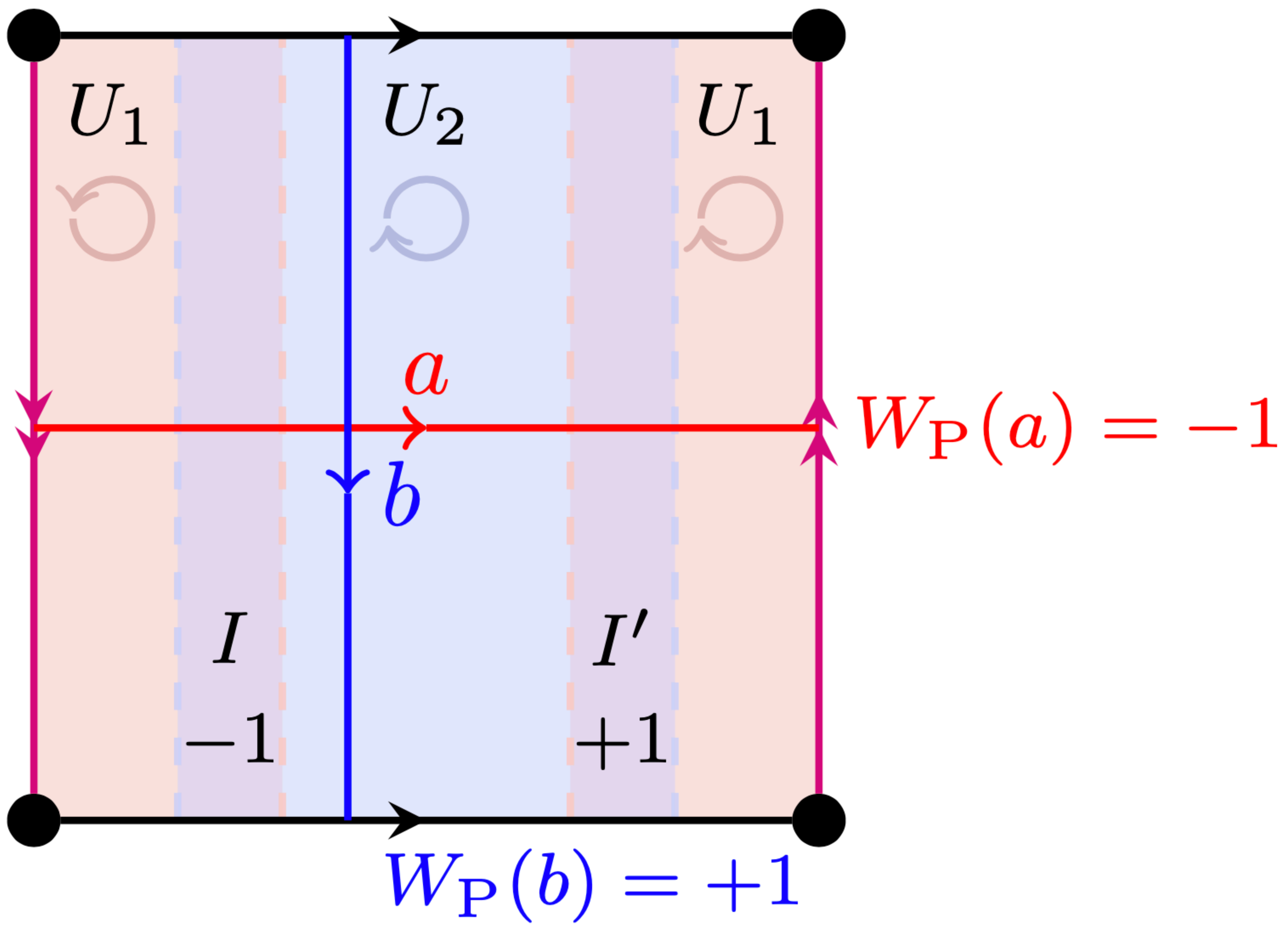
Klein Bottle as Background Gauge Field for Parity Symmetry

Parity as a **global $\mathbb{Z}_2^{\mathrm{P}}$ symmetry**: a parity background gauge field is fixed by a choice of background manifold. $\mathbb{Z}_2^{\mathrm{P}}$ **"composite gauge field" holonomies completely determined by topology of spacetime.**





Parity Transition Functions for $\mathbb{Z}_2^{\mathrm{P}}$



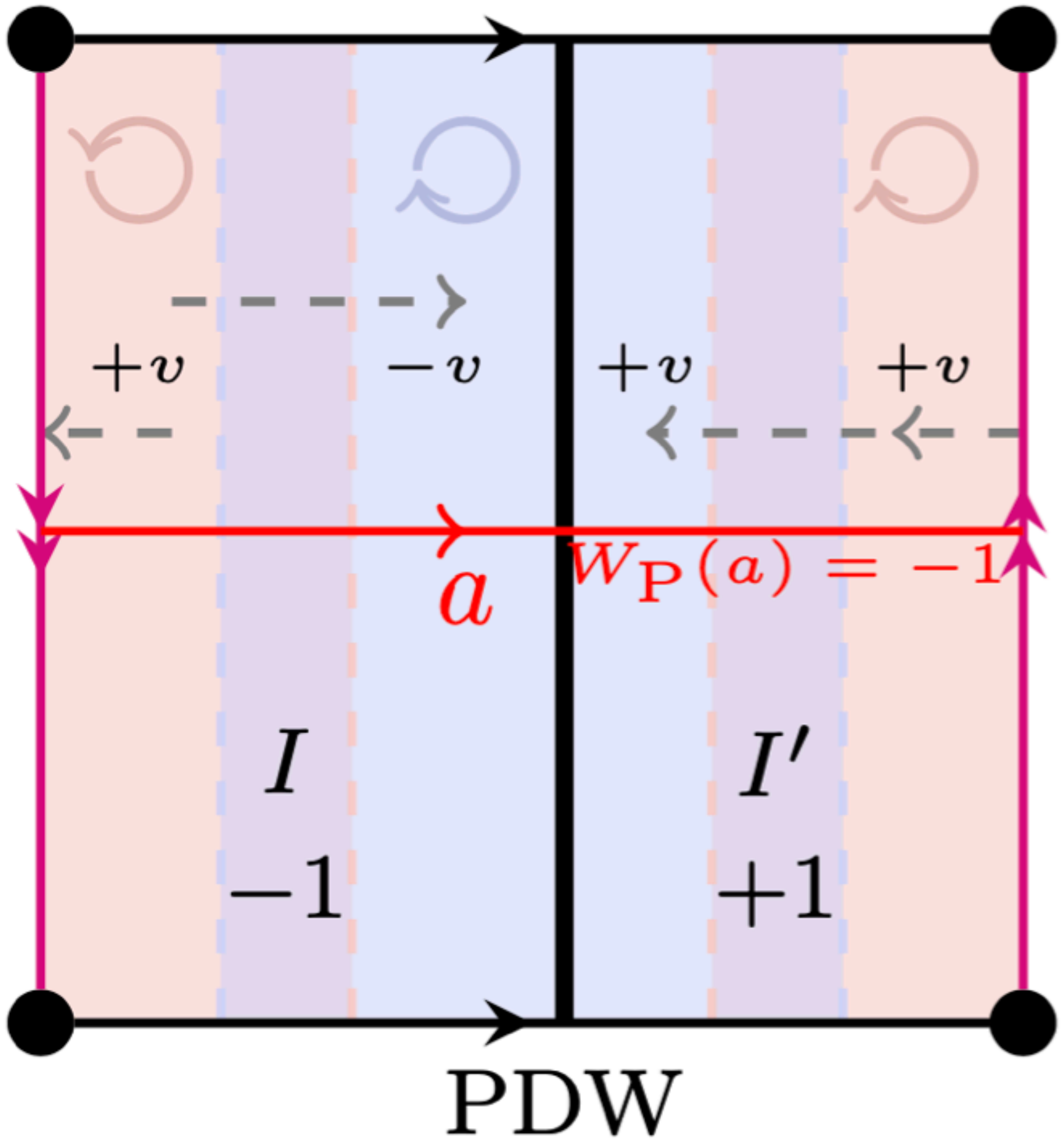
Work in different coordinate patches, have gluing rules on overlaps.

Pseudotensors (e.g., pseudoscalars) pick up an extra minus sign when moving from a patch with one orientation to a patch with the opposite orientation.

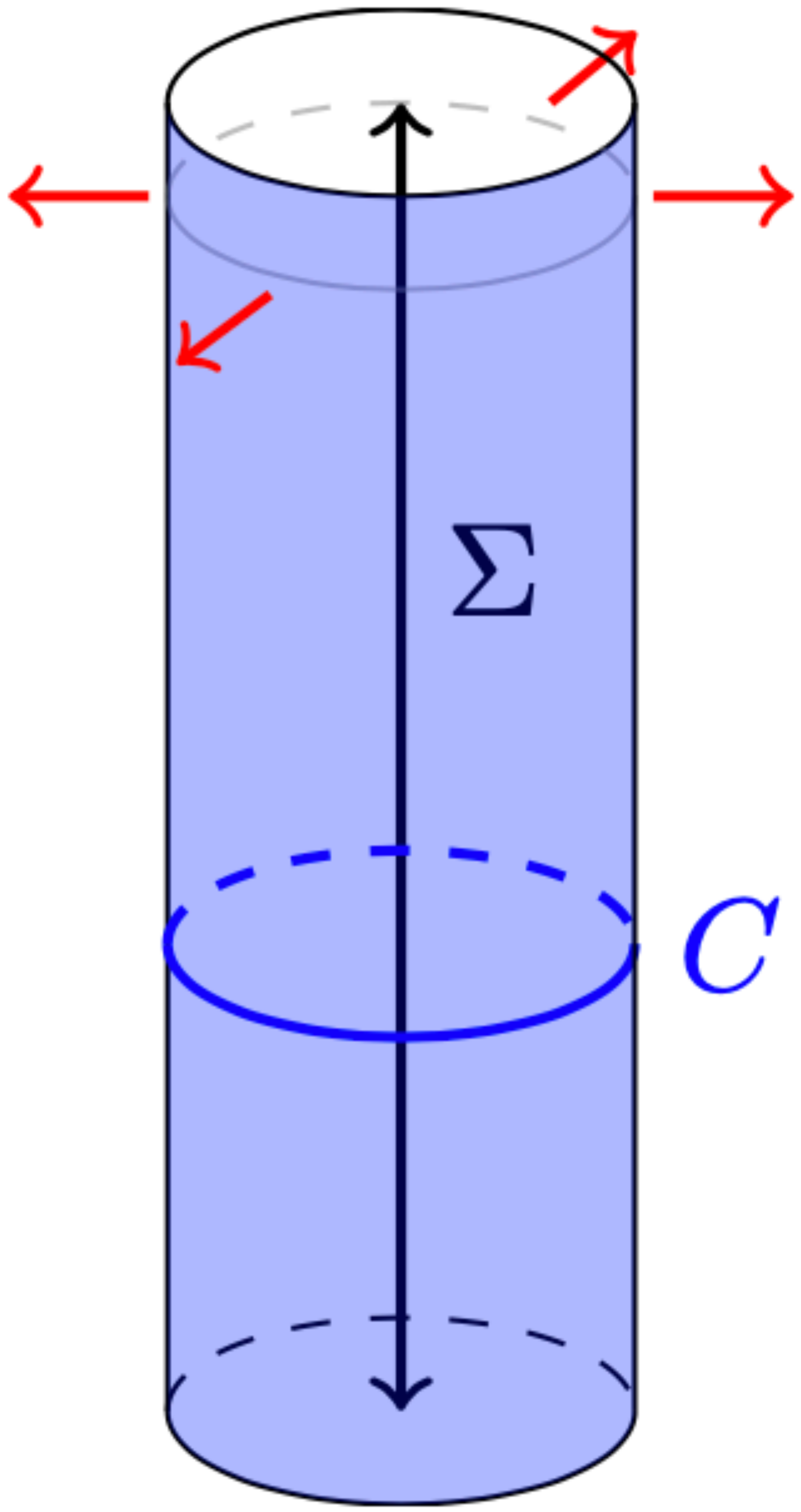
Extend to fermions, CP rather than P, etc., in the obvious way.

Domain Walls for Global Parity are Stable

A **non-orientable manifold** does not admit a nowhere-zero pseudoscalar field. **Domain walls exist and are stable as a consequence of topology.** DW decay would have to *change* topology.



Absence of Parity Vortex



A "parity vortex" would be a codimension-2 boundary condition in the (semiclassical) QG path integral.

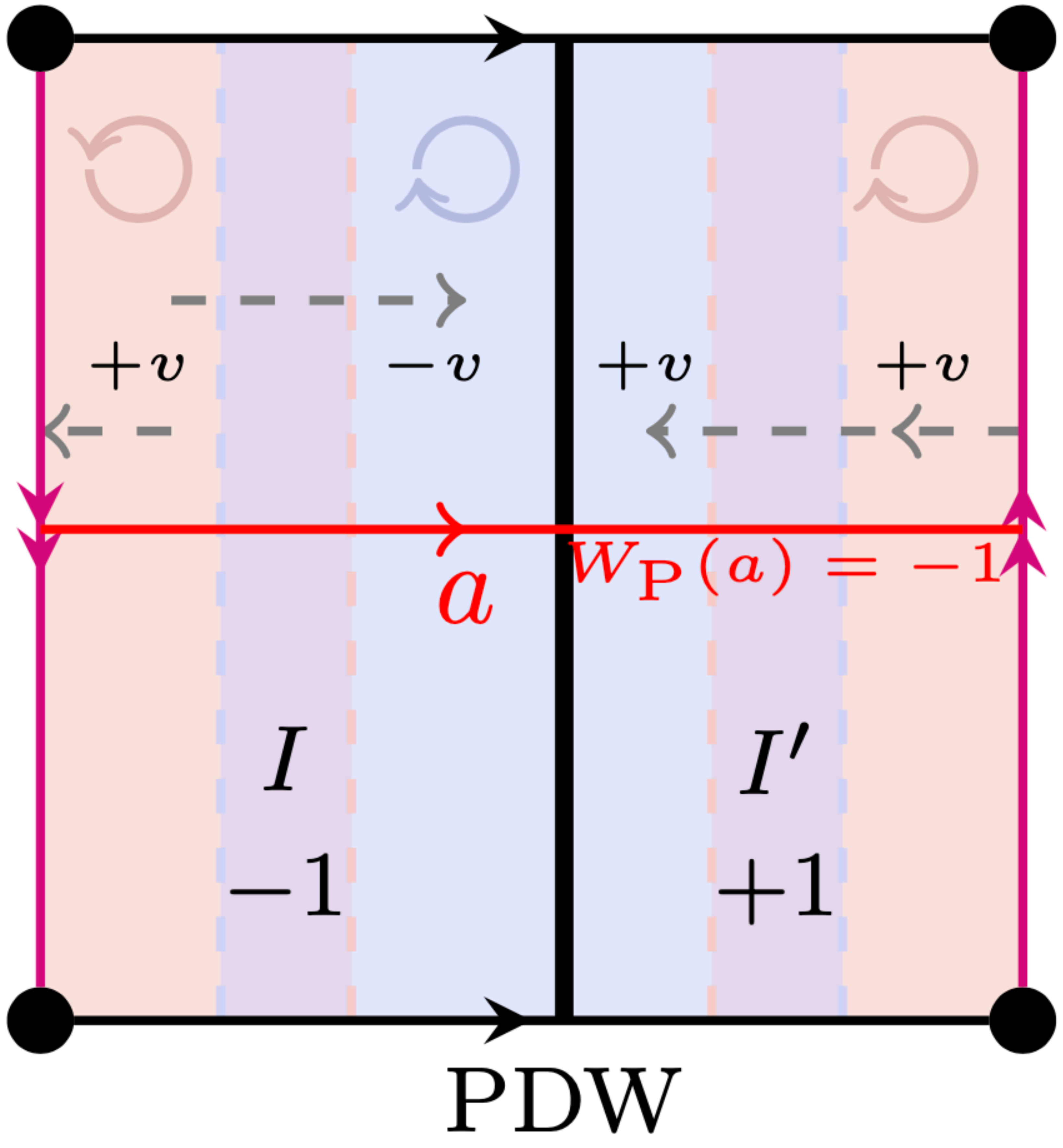
Sum over spacetimes X, $\partial X = \Sigma \times C$, with **fixed** Σ; want parity Wilson line $W_P(C) = -1$. But all closed 1-manifolds are orientable! No such b.c. exists.

An *even* number of DWs ends on any codimension-2 object.

Parity vortices cannot exist.

Stability of Parity Domain Walls

If a domain wall is exactly stable, we expect they are protected by a **charge** under some symmetry. What is this charge?



As explained in the Klein bottle example, a cycle with $W_P(C) = -1$ $(+1)$ intersects an odd (even) number of DWs.

Thus $W_P(C)$ **is** a symmetry operator for a $(d-2)$-form symmetry $\mathbb{Z}_2^{\mathrm{PDW}}$.

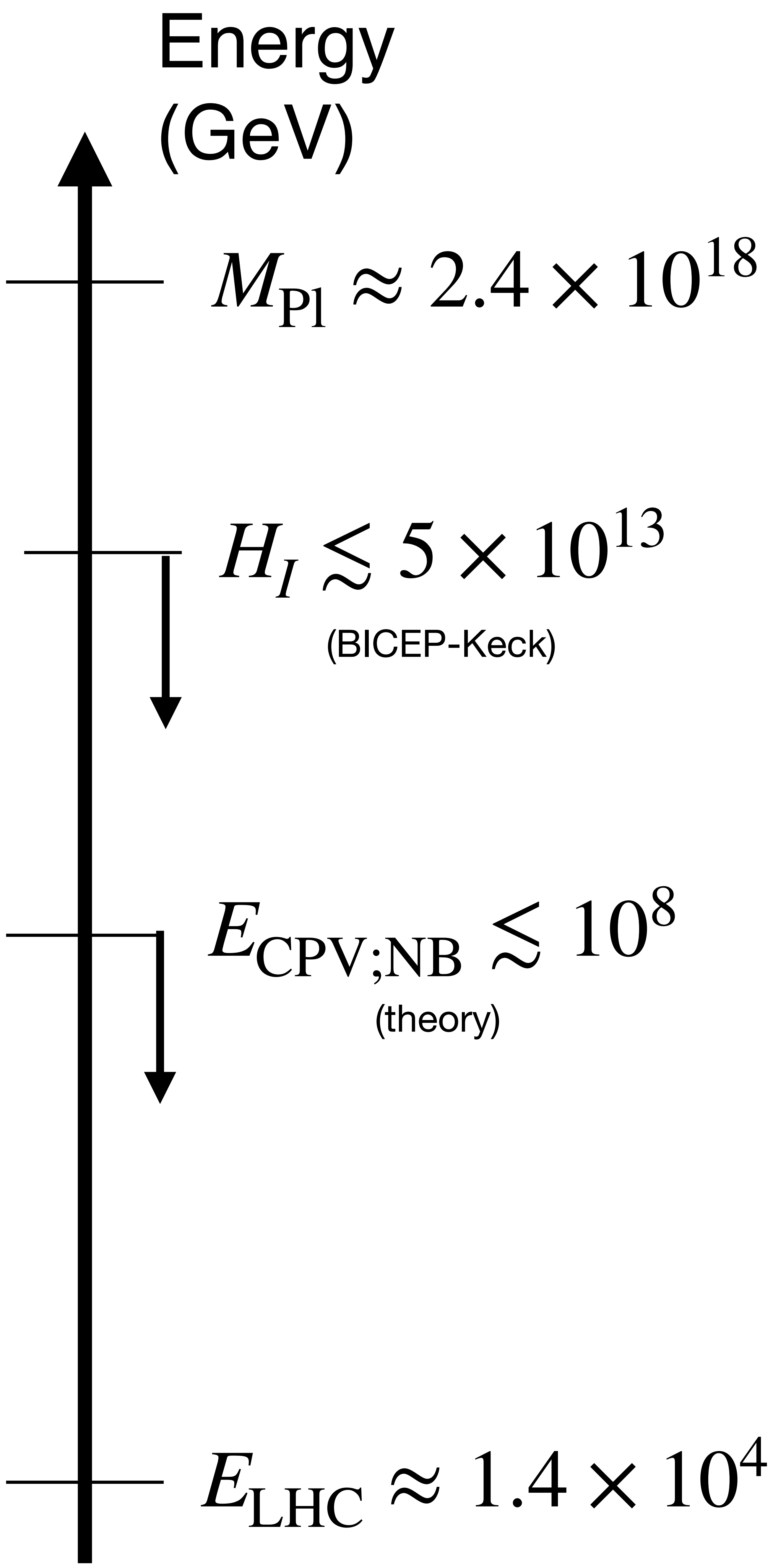
However, this is a **gauge** symmetry in QG. (Details in paper.)

Spontaneous CP Violation

Cosmological CP-violating phase transition produces **stable domain walls**.

These must be inflated away, so we need inflation to end **after** the phase transition: $H_I \lesssim E_{\rm CPV}$.

In many models this is an *extremely* strong constraint! Nelson-Barr wants $E_{\rm CPV} \lesssim 10^8\,{\rm GeV}$.
(Choi, Kaplan, Nelson '92; Dine, Draper '15)
(Ameliorated in more complex, chiral models: Valenti, Vecchi 2106.09108; Asadi, Homiller, Lu, Reece 2212.03882)



Sequestered CP Violation

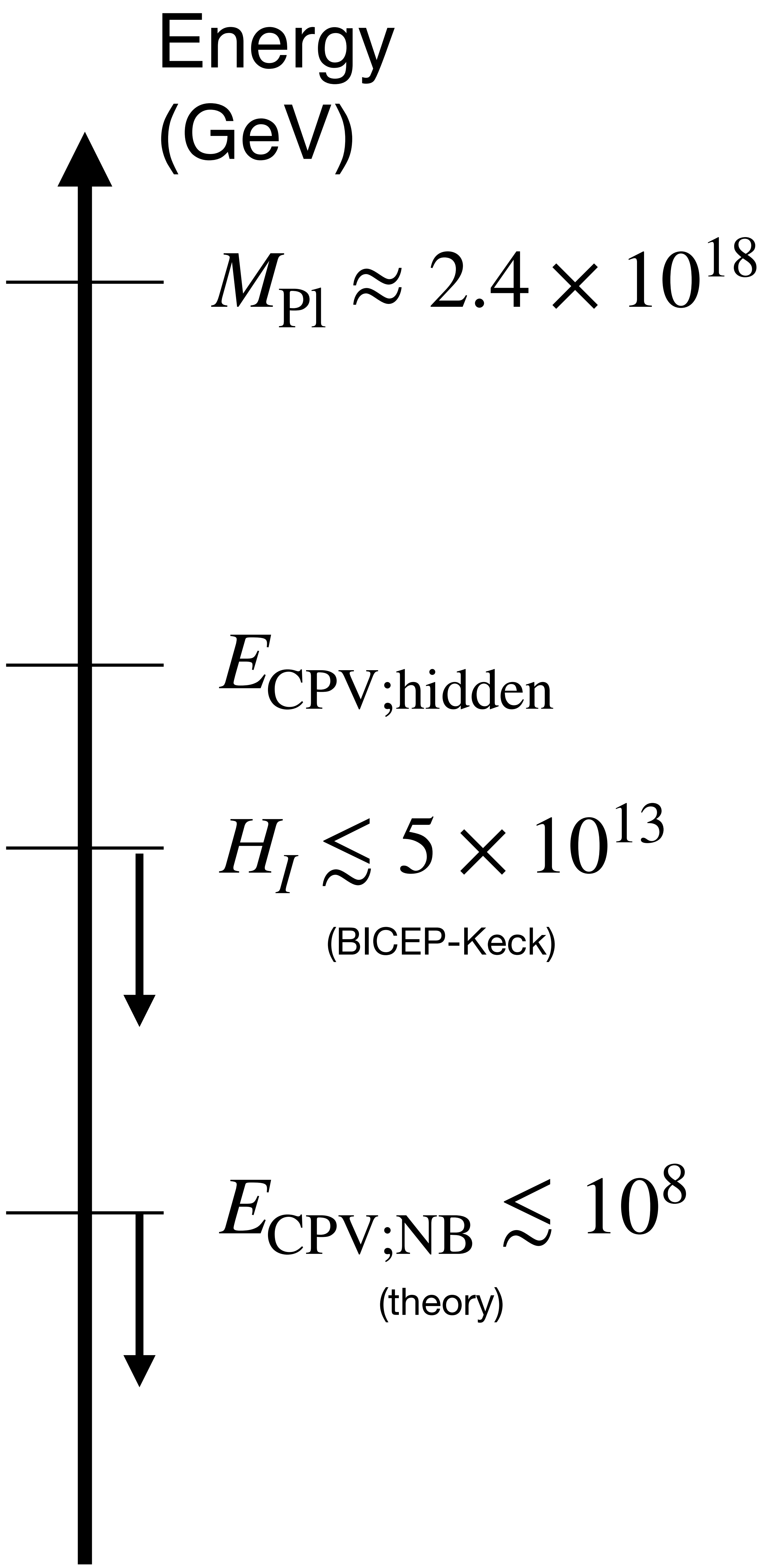
Challenge for model-building:

Break CP in a sequestered hidden sector; inflate away the stable domain walls.

Subsequently, small hidden/visible interactions make *effective* explicit CPV. (Similar to existing models, but not just "write down Planck-suppressed operators.")

Then visible sector CPV gives *unstable* domain walls.

Solve tensions in model, predict grav. wave signals?



Weak Gravity Conjecture and Axion Strings

(Heidenreich, MR, Rudelius arXiv:2108.11383)

Weak Gravity Conjecture (WGC)

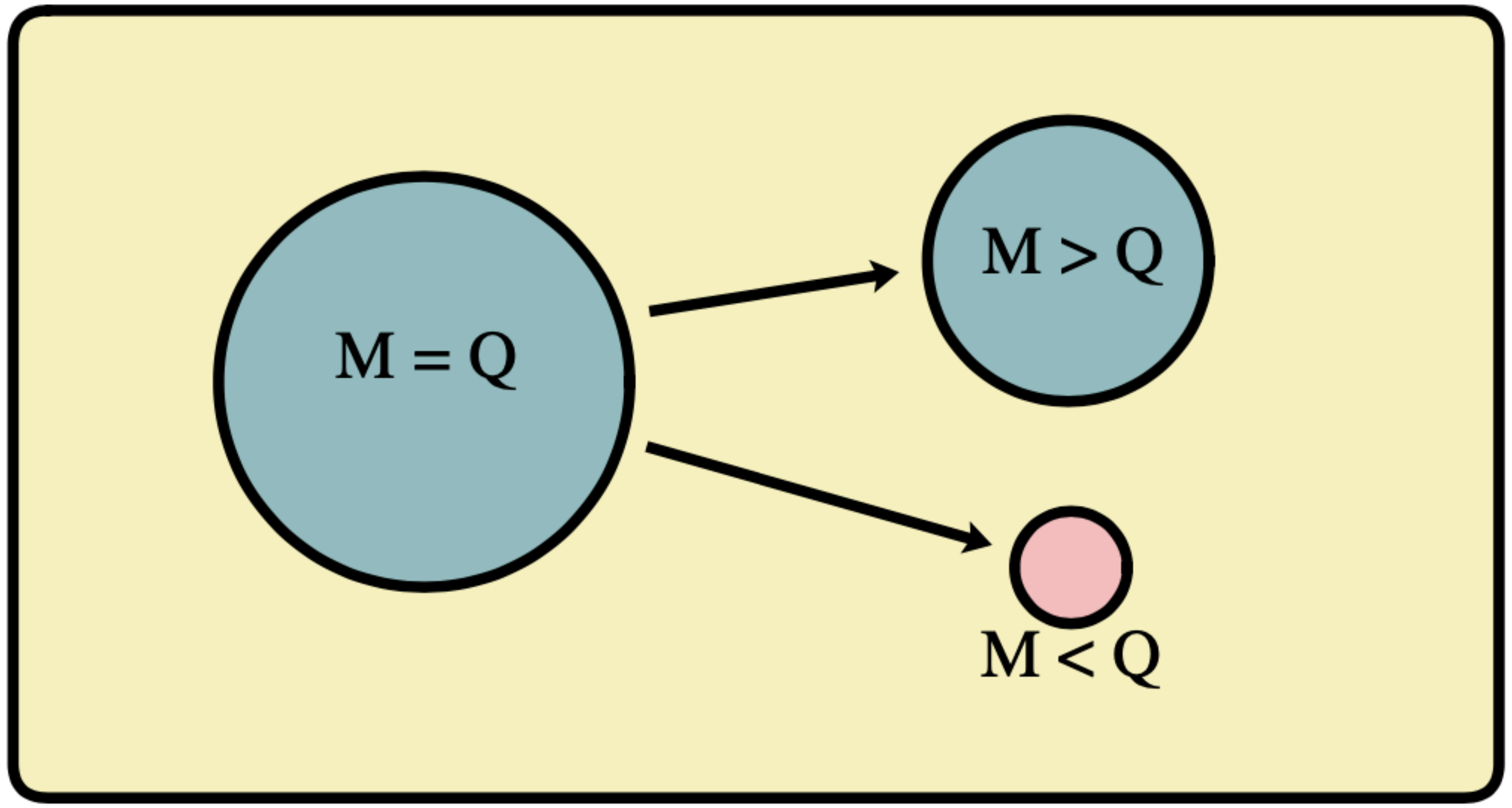
Exists electrically charged object with:

$$m < \sqrt{2}eqM_{\rm Pl}$$

Electric/Magnetic duality
⇒ exists magnetically charged object with:

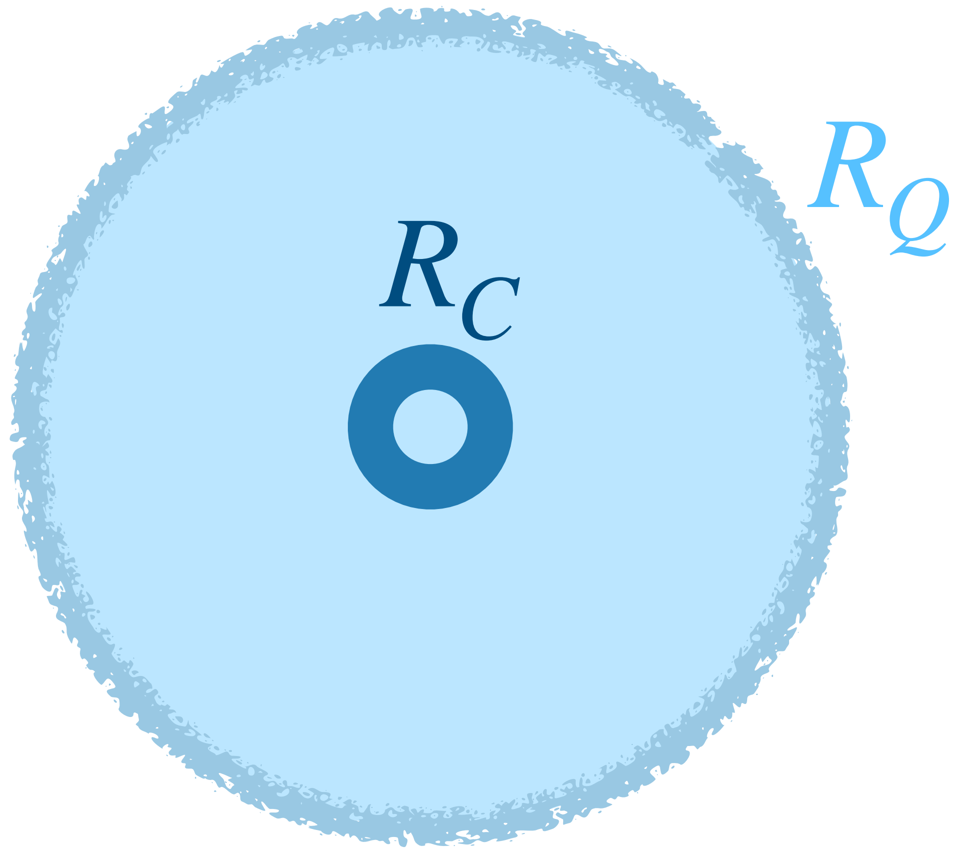
$$m_{\rm mag} < \sqrt{2}\frac{2\pi}{e}q_{\rm mag}M_{\rm Pl}$$

hep-th/0601001, Arkani-Hamed, Motl, Nicolis, Vafa

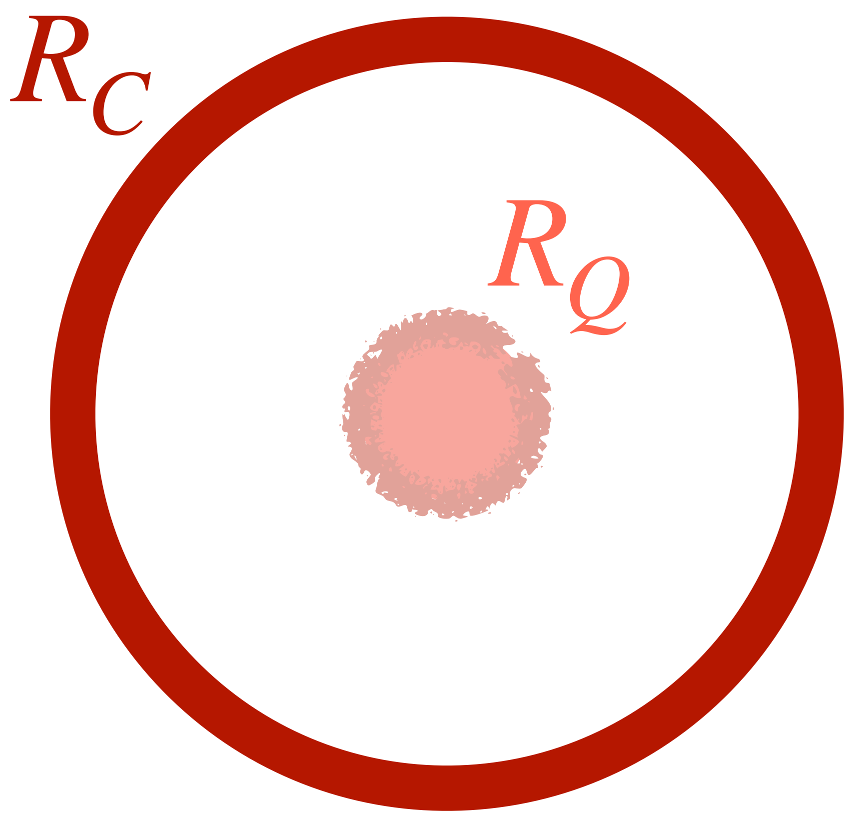


Necessary condition for discharge of extremal black holes.

Electric vs. Magnetic Charged Objects



$$\vec{E} \leftrightarrow \vec{B},\ e \leftrightarrow \frac{2\pi}{e}$$



$$\frac{R_Q}{R_C} = \frac{1}{\alpha} \gg 1$$

$$\frac{R_Q}{R_C} = 4\alpha \ll 1$$

The classical radius R_C of a magnetic monopole serves as a *cutoff*:
must have new physics at shorter distances.

Magnetic WGC: Quantum Gravity Fights Weak Coupling

hep-th/0601001, Arkani-Hamed, Motl, Nicolis, Vafa

The WGC applied to a magnetically charged object tells us:

$$m_{\rm mag} < \sqrt{2}\frac{2\pi}{e} q_{\rm mag} M_{\rm Pl}$$

We can rewrite this in terms of the object's classical radius:

$$R_{C;{\rm mag}} > \frac{q_{\rm mag}}{2\sqrt{2} e M_{\rm Pl}}$$

Interpreted as an *energy cutoff*: new physics must appear at

$$\Lambda = R_{C;{\rm mag}}^{-1} \lesssim e M_{\rm Pl}$$

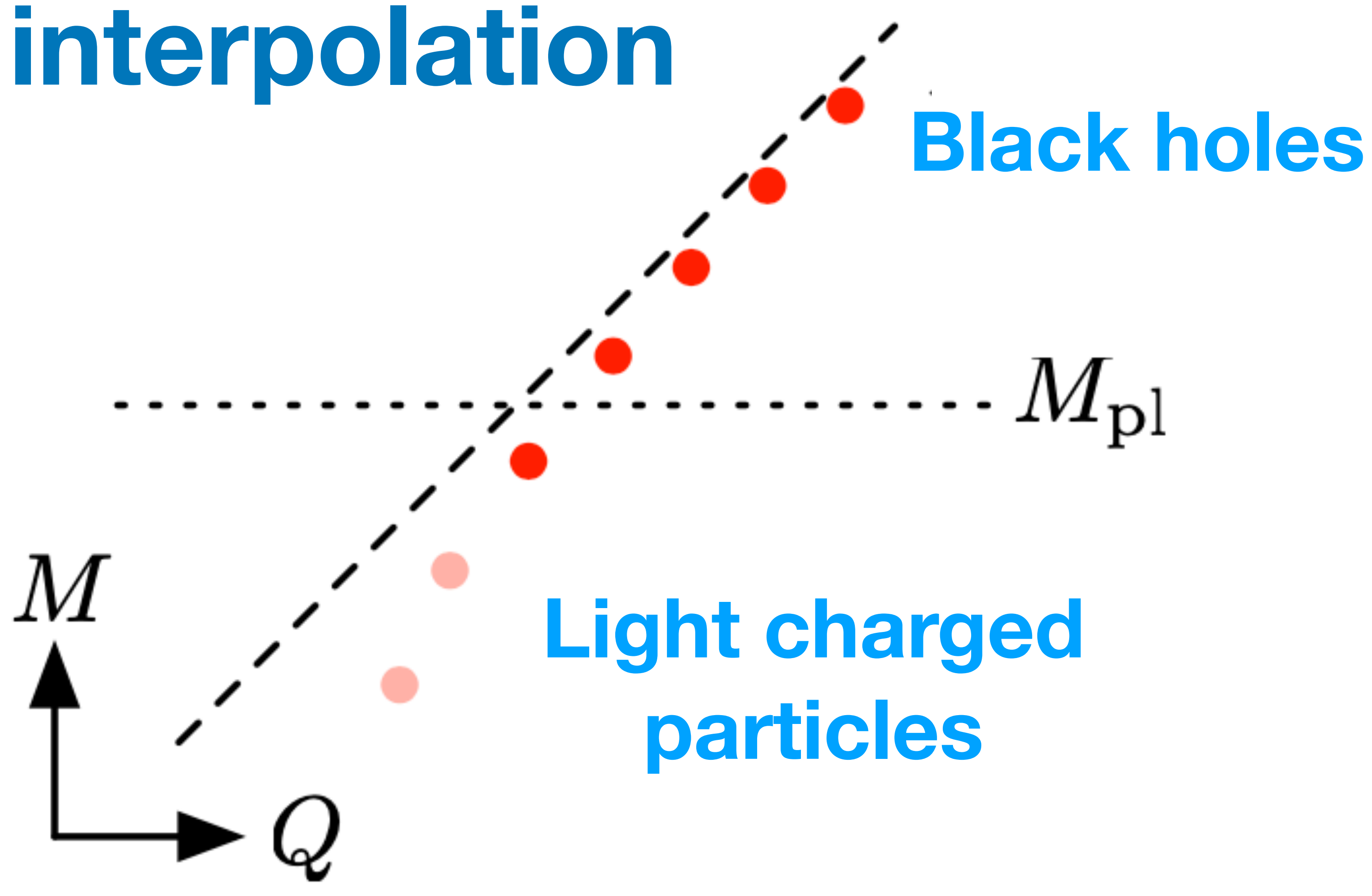
Tower Weak Gravity Conjecture

$\Lambda \lesssim eM_{\rm Pl}$ is our cutoff energy. But what happens there?

Internal consistency under dimensional reduction / examples:

There is always an infinite *tower* of charged particles of different charge q, *each of which* obeys the bound $m < \sqrt{2}eqM_{\rm Pl}$.

(Non-abelian case: tower of different irreps)



2015-2017: Ben Heidenreich, MR, Tom Rudelius

(related: Montero, Shiu, Soler ’16; Andriolo, Junghans, Noumi, Shiu ’18)

p-Form Weak Gravity Conjecture

General (p-form) case: $-\frac{1}{4e_p^2}F^2_{\mu_1\cdots\mu_{p+1}}$, exists a charged $(p-1)$-brane with tension

$$T_p \lesssim e_p q M_{\mathrm{Pl}}$$

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

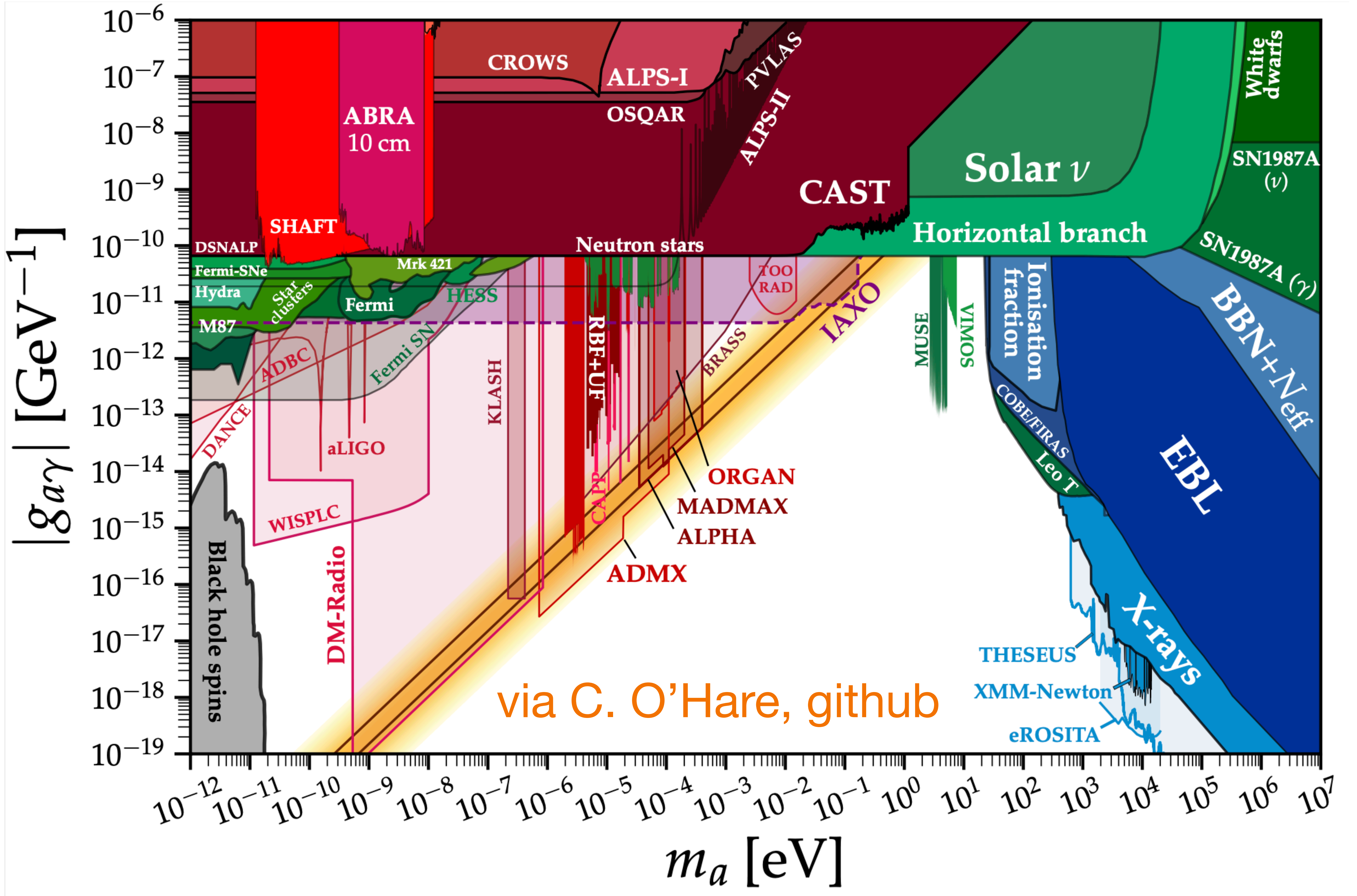
$$S \lesssim \frac{q}{f_a}M_{\mathrm{Pl}}$$

Axions and the WGC

Axion as "0-form gauge field": $S_{\text{inst}} \lesssim \frac{1}{f_a} M_{\text{Pl}}$.

Given $\theta \, \text{tr}(F \wedge F)$,
S_{inst} from usual QCD instantons:

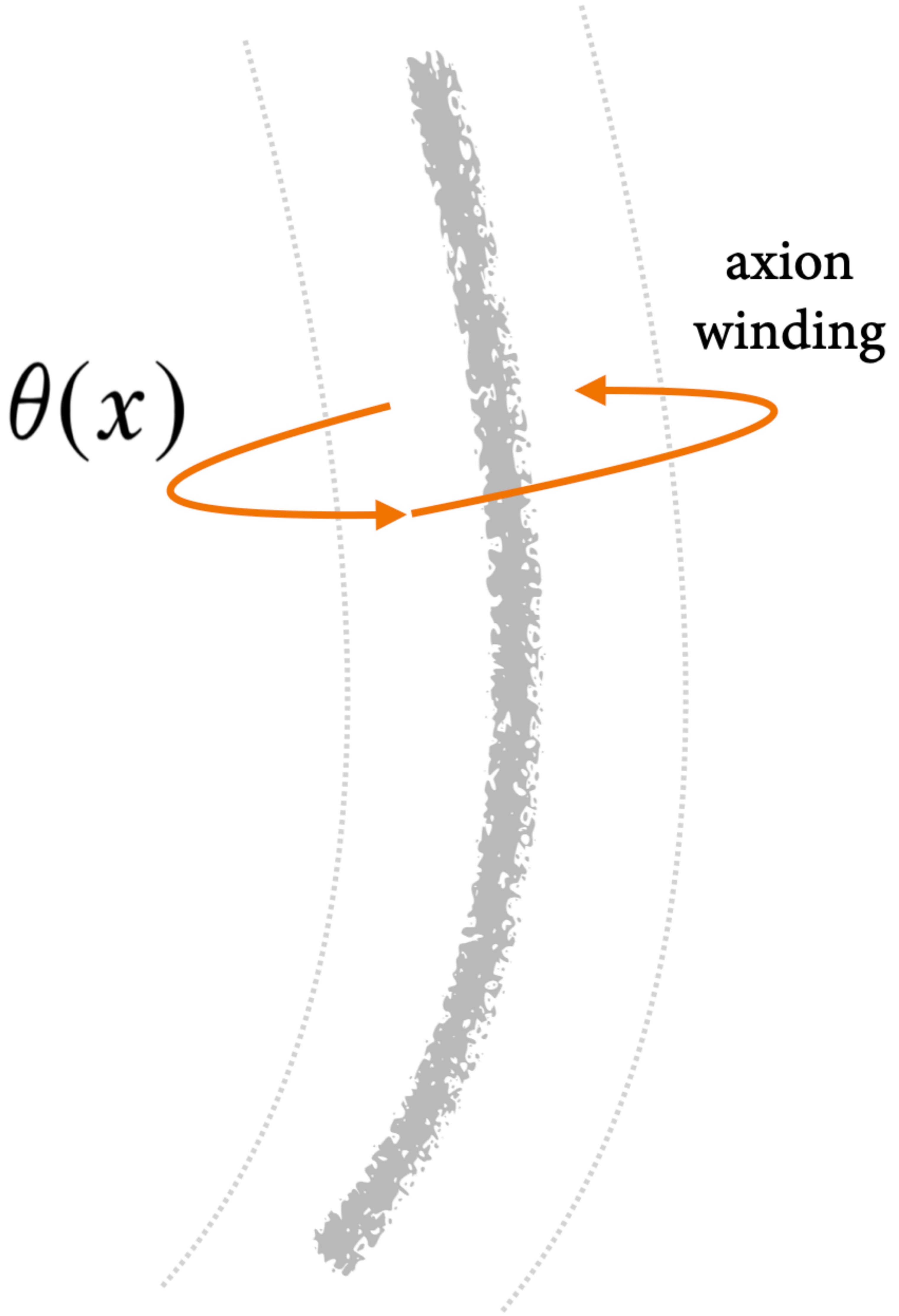
$$f_a \lesssim \frac{g^2}{8\pi^2} M_{\text{Pl}}$$



Nontrivial phenomenological prediction!
QCD axion with $f_a \lesssim 1.5 \times 10^{16}\,\text{GeV}$.

Axion Strings

arXiv:2108.11383 Ben Heidenreich, MR, Tom Rudelius



Assume $\theta F \wedge F$ coupling.

4d axion has a "magnetic dual" 2-form B-field: $\partial^\mu \theta \sim \epsilon^{\mu\nu\rho\sigma}\partial_{[\nu}B_{\rho\sigma]}$

Magnetic axion WGC: string tension

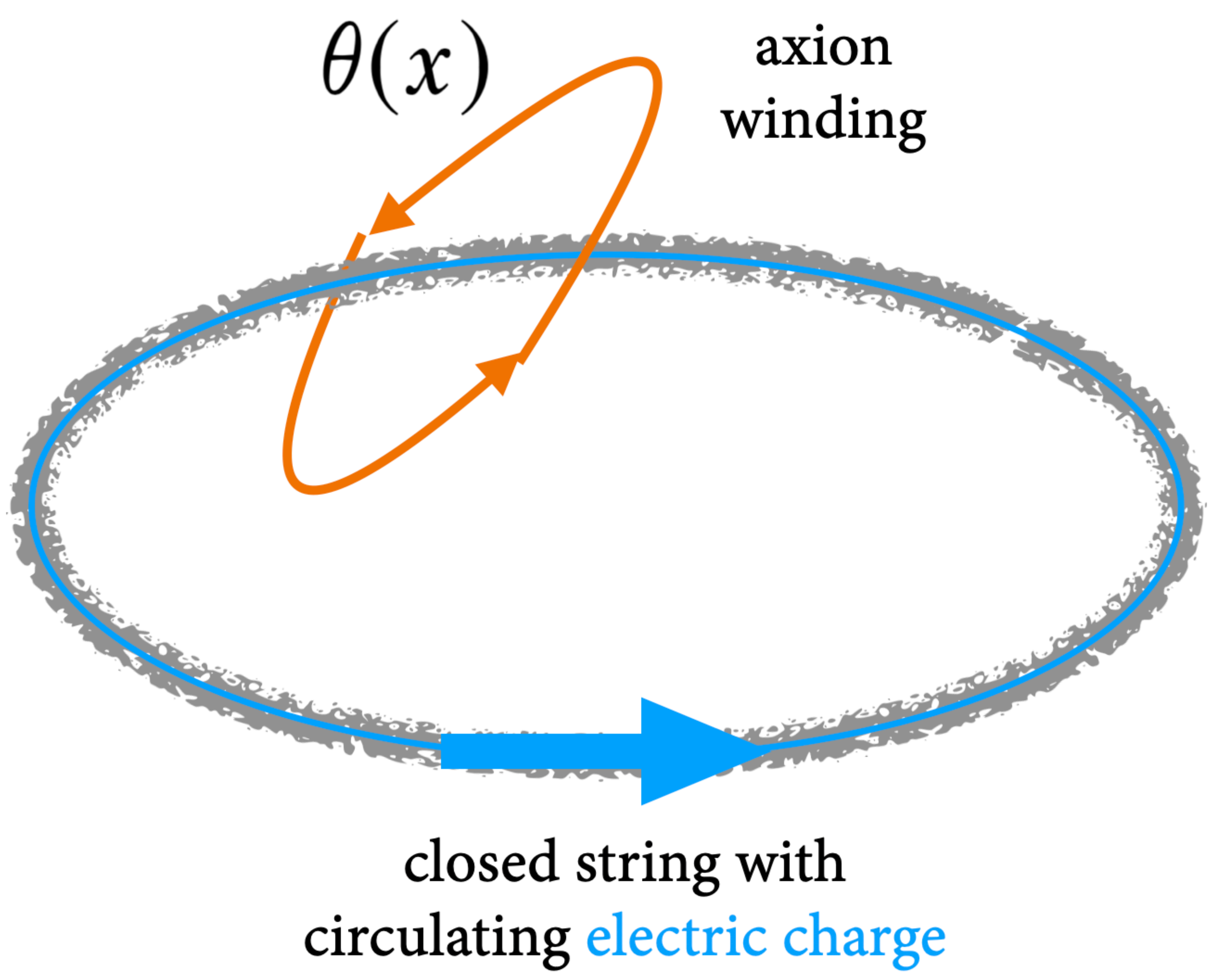
$$T \lesssim 2\pi f_a M_{\mathrm{Pl}} \lesssim \frac{g^2}{4\pi} M_{\mathrm{Pl}}^2$$

String excitations $M_{\mathrm{string}} \lesssim g M_{\mathrm{Pl}}$

— at the ordinary *gauge field's* WGC scale!

Tower WGC Modes from Axion Strings

arXiv:2108.11383 Ben Heidenreich, MR, Tom Rudelius



String excitations $M_{\text{string}} \lesssim g M_{\text{Pl}}$.

In fact, these can can carry A gauge charge!

“**Anomaly inflow**” (Callan, Harvey 1985)

$\theta F \wedge F$ interaction $\Rightarrow$ nontrivial gauge invariance, $A \mapsto A + \mathrm{d}\lambda, B \mapsto B + \frac{1}{4\pi}\lambda F$.

Charged modes on string cancel the λF.

Tower WGC automatic, via axion physics!

Also abelian case: monopole-loop instantons

(Fan, Fraser, MR, Stout arXiv:2105.09950)

Phenomenological Implications

Fundamental axion strings for WGC tower ⇒ **breakdown of local QFT**

$\theta F \wedge F$ interaction ⇒ QFT breaks down by $M_{\text{string}} \lesssim g M_{\text{Pl}}$.

E.g., no massless $B - L$ gauge boson allowed to have $\theta F \wedge F$, as $g \lesssim 10^{-24} \Rightarrow \Lambda_{\text{QG}} \lesssim \text{keV}$.

Relates to "Emergent String Conjecture": Lee, Lerche, Weigand 2018/19:

Only *known* weak-coupling limits in QG are KK modes or low-tension strings. Could there be others? Bottom-up arguments?

Axions in Quantum Gravity

(Heidenreich, McNamara, Montero, MR, Rudelius, Valenzuela
arXiv:2012.00009; work in progress)

Ubiquitous Axion: Lamppost or Principle?

Moduli and axions are ubiquitous in string theory compactifications. But is this an accident, or are they there for a reason?

$$\frac{1}{2}f^2(\partial\theta)^2 + \frac{\theta}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad \partial^\mu(f^2\partial_\mu\theta) = \frac{1}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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instanton number density

$$\frac{1}{2}f^2(\partial\theta)^2 + \frac{\theta}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad \partial^\mu(f^2\partial_\mu\theta) = \frac{1}{16\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

The axion causes a would-be "conserved quantity" (instanton number) to vanish: integral of a total derivative.

Axions as Gauge Fields

(Heidenreich, McNamara, Montero, MR, Rudelius, Valenzuela '20)

The job of the axion in quantum gravity is to *eliminate* a Chern-Weil symmetry with current $\mathrm{tr}(F \wedge F)$ by *gauging* it.

In higher dimensions, this is a genuine *p*-form symmetry. In 4d, it is a "**(-1)-form U(1) symmetry**." Need to understand these better!

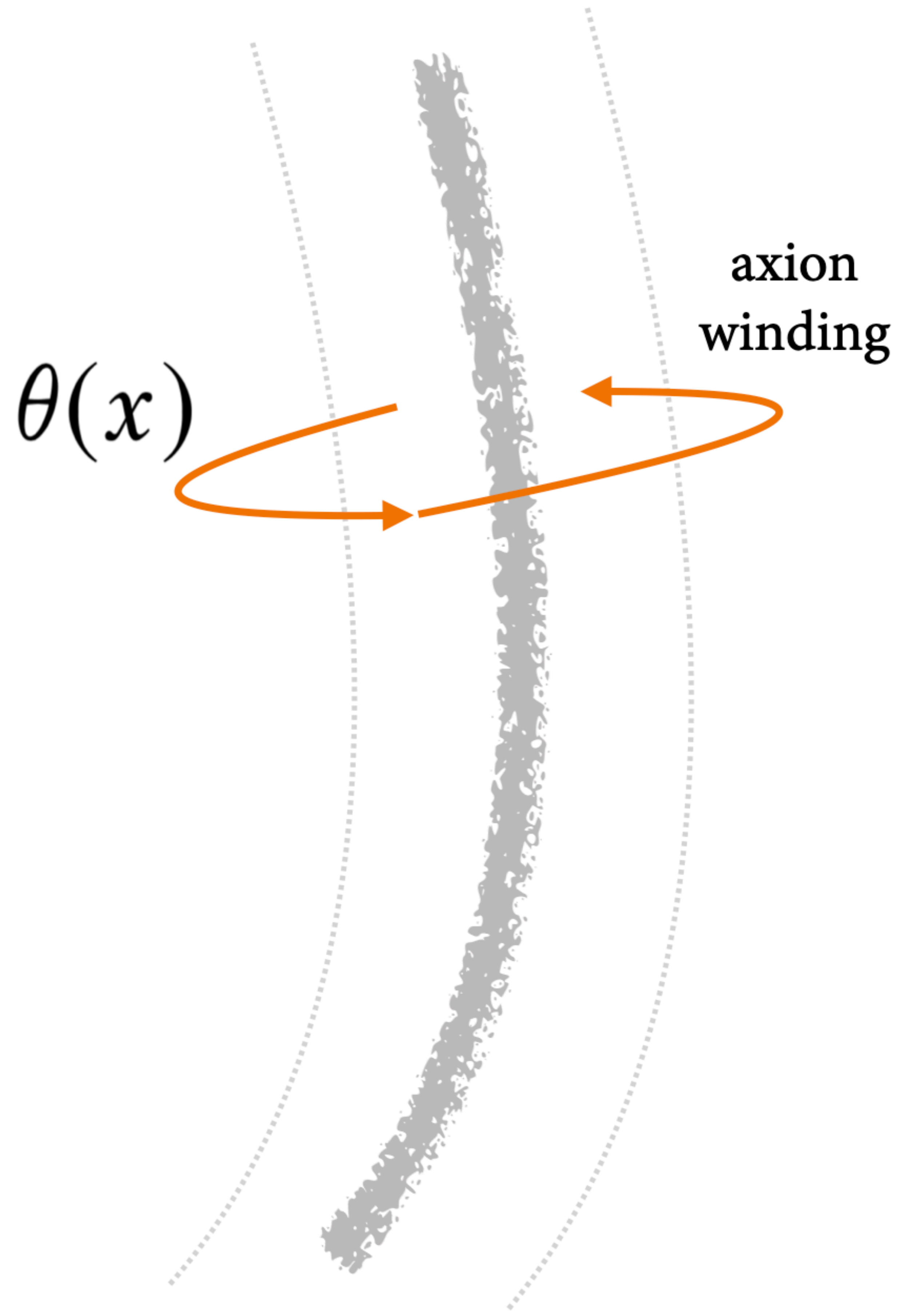
Axions in string theory often just *are* zero modes of higher dimensional gauge fields.

$$\tau(x) = \frac{1}{2\pi}\theta(x) + 4\pi \mathrm{i} S(x), \quad \theta = \int_{\Sigma_p} C_p, \quad S \sim \mathrm{Vol}(\Sigma_p)$$

Chern-Simons: $\theta F^{\mu\nu}\tilde{F}_{\mu\nu}$ from $\int C_p \wedge F \wedge F$

Interpreting the Axion Decay Constant

Standard discussion: 4d model (e.g., KSVZ) with potential $V(\phi)$ spontaneously breaking $U(1)_{PQ}$.



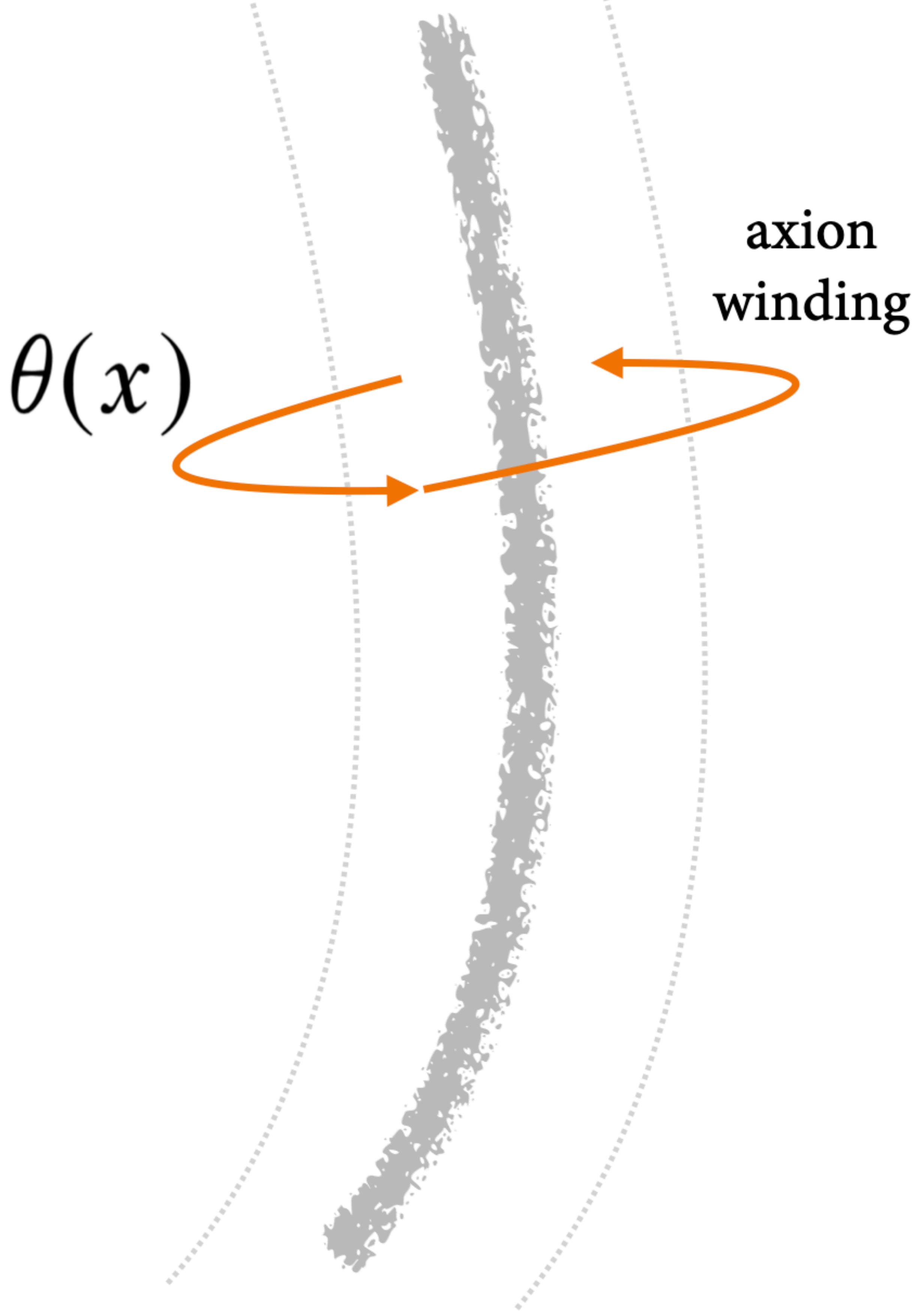
PQ breaking after inflation: **solitonic** cosmic string network produced during phase transition, affects relic abundance of axion DM.

Measuring f: learn about high-scale 4d physics, constraints on inflation (axion isocurvature), etc.

Well-developed story.

Interpreting the Axion Decay Constant

Axions from extra-dimensional gauge fields: no 4d PQ phase transition, ***fundamental*** strings (no $f \to 0$ at finite distance in field space).



Necessarily “pre-inflation” axion!

Expect f to be related to fundamental scales.

Generic expectation: a discovery of an axion with, e.g., $f \sim 10^{12}\,\mathrm{GeV}$ — well below the Planck scale — indicates **large internal dimensions** and a low UV cutoff.

Interpreting the Axion Decay Constant

Various arguments (WGC, SDC / Scalar WGC, specific string constructions) suggest useful parametric relations.

e.g.: IIB, SM on D7 branes, axion from C_4, $8\pi^2/g^2$ = 4-cycle volume (τ), **axion strings are D3 branes** wrapped on intersecting 2-cycle with tension $\propto t$.
Leading order relationship:

$$M_{\rm Pl}^2 t^I = \frac{\partial^2 K}{\partial \tau_I \partial \tau_J} \tau_J \mathscr{V}$$

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$$M_{\rm Pl}^2 t^I = \frac{\partial^2 K}{\partial \tau_I \partial \tau_J} \tau_J \mathscr{V}$$

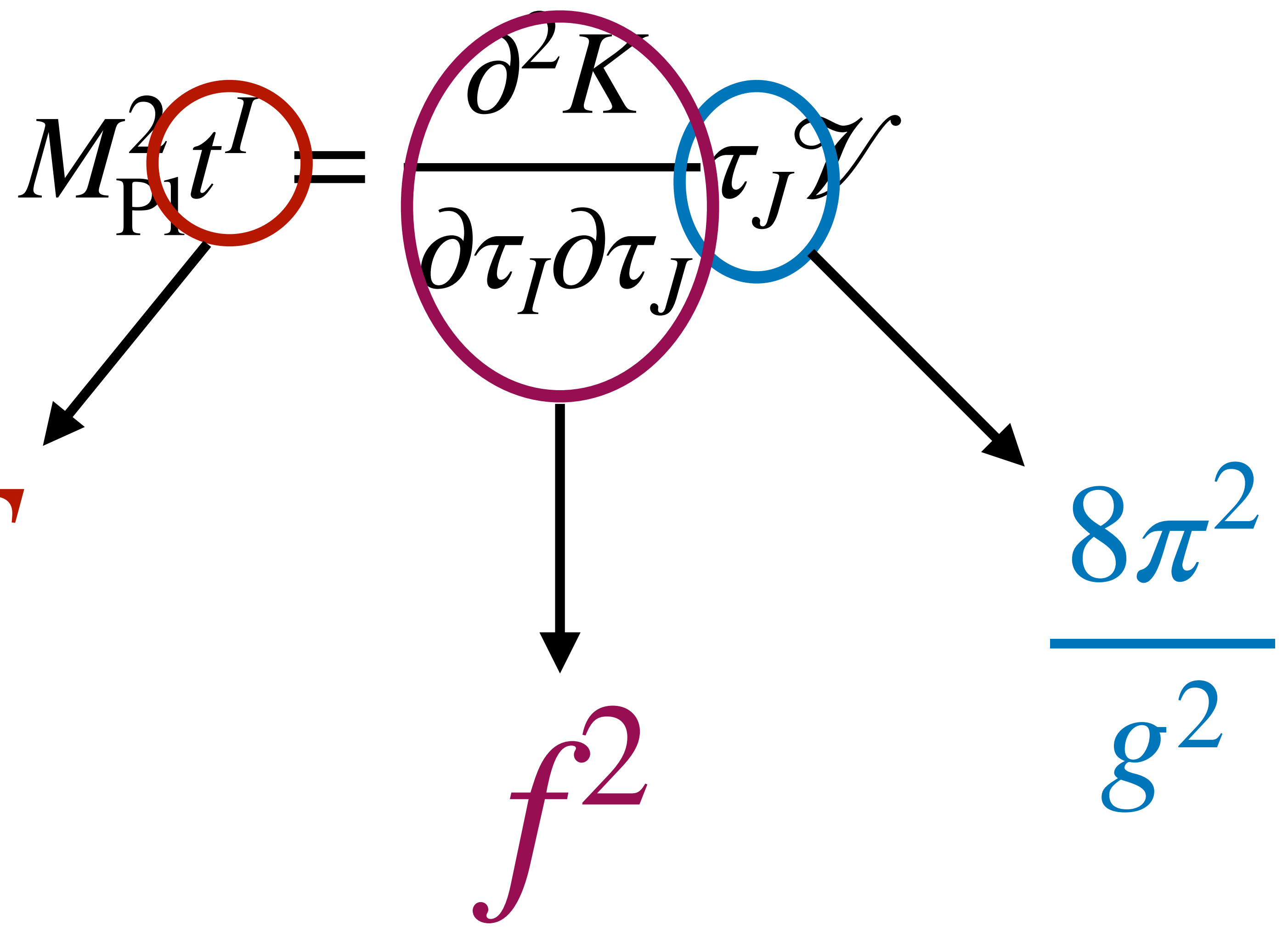
T

f^2

$\frac{8\pi^2}{g^2}$

(in string units, where the other factor $M_{\rm Pl}^2/\mathscr{V}$ is 1)

Interpreting the Axion Decay Constant



which suggests $T \sim 2\pi \frac{8\pi^2}{g^2} f^2 \lesssim 2\pi f M_{\rm Pl}$ (obeying naive magnetic axion WGC), saturated only when naive electric axion WGC $f \sim M_{\rm Pl}/S_{\rm inst} = \frac{g^2}{8\pi^2} M_{\rm Pl}$ is saturated.

Low $f \Longrightarrow$ low-tension string $\Longrightarrow$ low QG cutoff.

Axion Summary

Conventional axion theories (KSVZ, DFSZ):

f is a normal 4d scale; cosmic strings in low-energy QFT; severe axion quality problem

***Axions from higher-dimensional gauge fields (e.g., closed string axions)*:**

f close to the fundamental QG scale; cosmic strings are fundamental objects (F-strings, wrapped D-branes); mild axion quality problem

Very different paradigms, differences not usually emphasized in pheno discussions of “axiverse.”

Can we experimentally distinguish?

Conclusions

Conclusions

"No global symmetries": very strong statement when we consider generalized symmetries, Chern-Weil symmetries, non-invertible symmetries, (-1)-form symmetries, ….

Completeness hypothesis: exotic cosmic strings, other interesting objects

Parity symmetry: QG has stable parity domain walls; constraint for Nelson-Barr

Weak Gravity Conjecture: most powerful in "Tower WGC" form, relation to axion strings. Stronger hypotheses (Emergent String Conjecture) clarify (next talk!)

Axions in quantum gravity: ubiquitous. *Gauge* instanton number. f as fundamental scale. Can we prove that axions *must* exist for consistency?