Broken Symmetry Clues for Fundamental Physics

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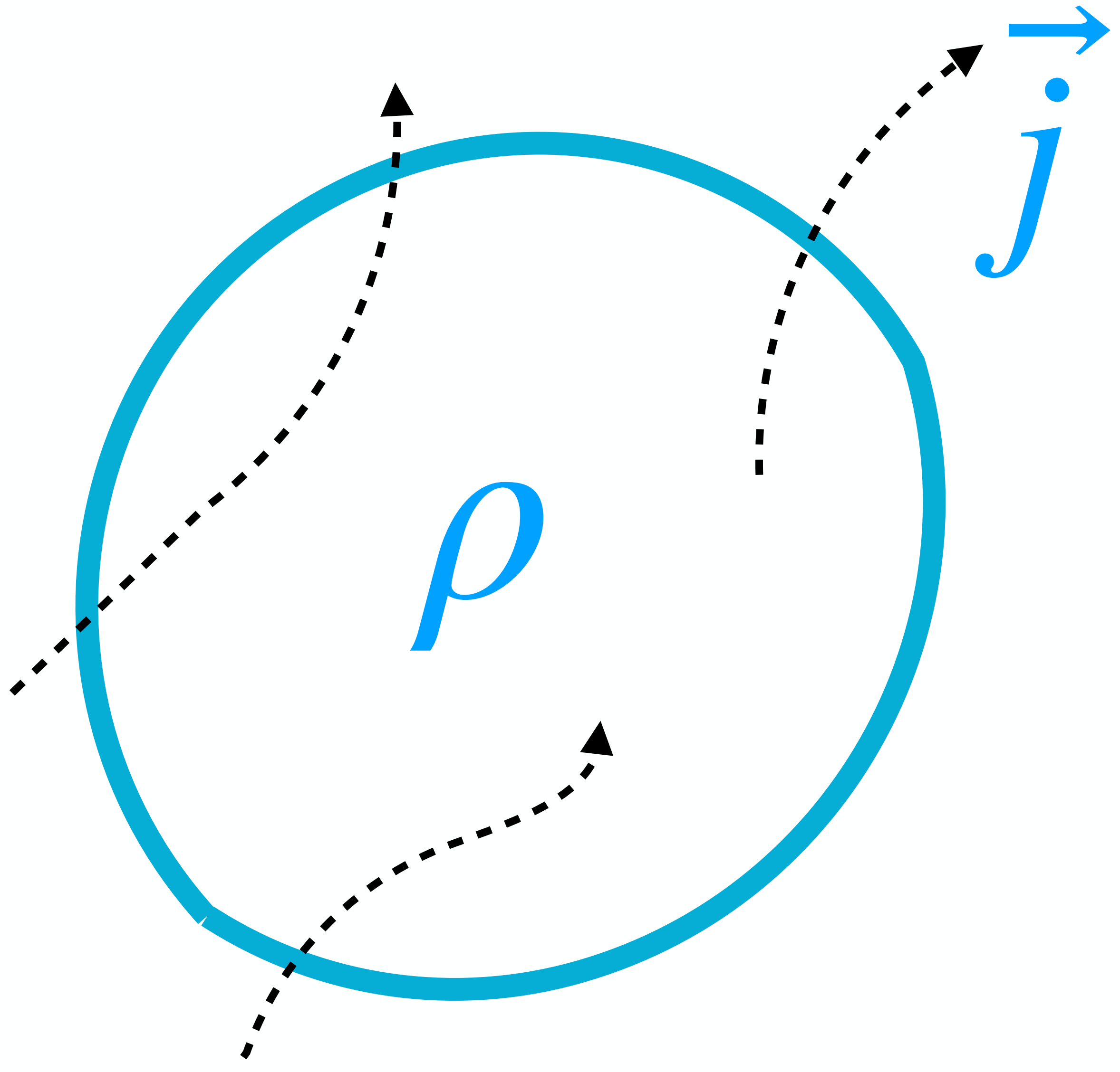
Overview

- Symmetries are a powerful organizing principle in physics
- Quantum gravitational theories are thought to have no global symmetries
- Many of the most exciting experiments in fundamental physics are searching for small violation of global symmetries
- How good an approximate symmetry can quantum gravity allow?
- *Axions* as a target for experiment to make contact with these ideas

Conservation Laws and Local Currents

Change in conserved quantity in a region = - flux of quantity escaping the surface of the region,

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = -\oint \vec{\Phi} \cdot \mathrm{d}\vec{S}$$



Local form: ***continuity equation*** relating density to current: $\frac{\partial \rho(t, \vec{x})}{\partial t} = -\vec{\nabla} \cdot \vec{j}(t, \vec{x})$

Package the charge density and current into a 4-vector: $j^{\mu} = (\rho, \vec{j})$, with $\partial_{\mu} j^{\mu} = 0$

Noether's Theorem

A continuous global symmetry in a field theory gives rise to a ***conserved current***.

Consider field variation that *would be* a symmetry if ϵ is constant: $\phi(x) \mapsto \phi(x) + \epsilon(x)\xi(x)$.

Then the action doesn't change if ϵ constant:

$S[\phi] \mapsto S[\phi] + \int d^D x\, j_\mu(x) \partial^\mu \epsilon(x)$, for some $j_\mu(x)$.

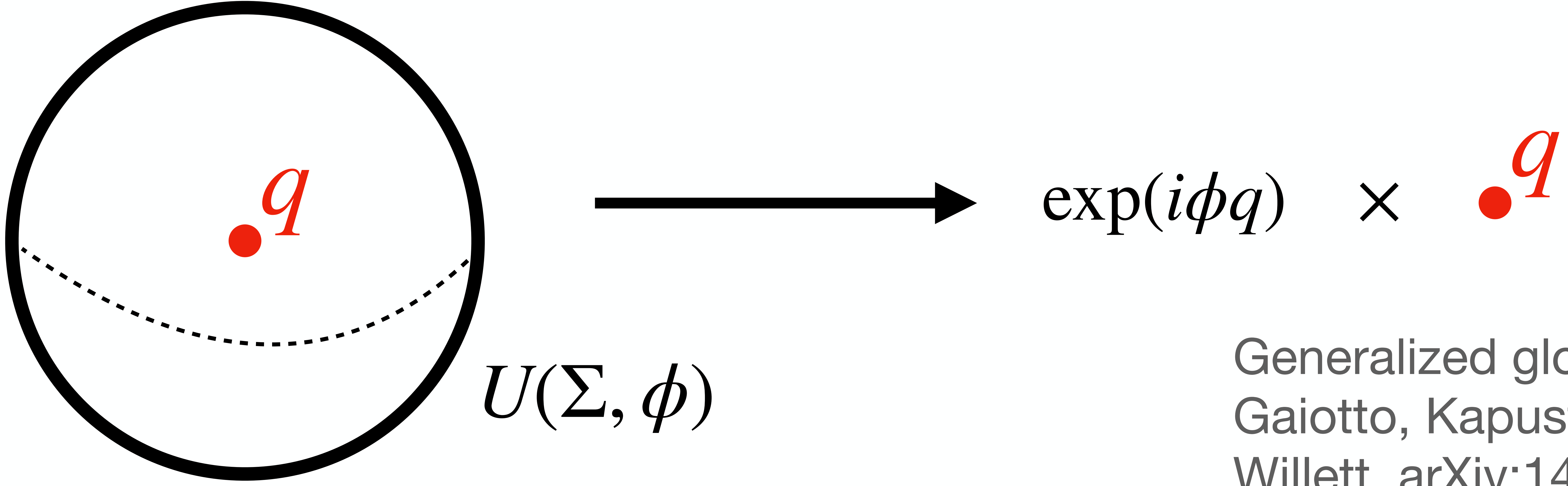
Now, impose the *equation of motion*: $\delta S = 0$ for *any* variation, including this one $\Rightarrow$ $\partial_\mu j^\mu = 0$

Emmy Noether

Quantum Symmetry Operators

The charge is given by $Q = \int d^3x\, j^0(x)$. More generally: integral over slice Σ of spacetime, $Q(\Sigma) = \int_\Sigma \star j$.

In the quantum theory, $U(\Sigma, \phi) = \exp(i\phi \int_\Sigma \star j)$ is a **family of operators.**



Generalized global symmetries: Gaiotto, Kapustin, Seiberg, Willett, arXiv:1412.5148

Gauging a Global Charge

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

$A_\mu = (\phi, \overrightarrow{A})$ $F_{\mu\nu} = \partial_{[\mu} A_{\nu]}$ $F_{0i} \sim E_i$ $F_{ij} \sim \epsilon_{ijk} B_k$

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

Now the charge density is a total derivative, so our charge **vanishes** and all would-be charge operators are trivial!

$$Q = \int_\Sigma \star j = \int_\Sigma \mathrm{d}(\star F) = 0$$

“Gauss Law Constraint”

Global Symmetry vs. Gauge “Symmetry”

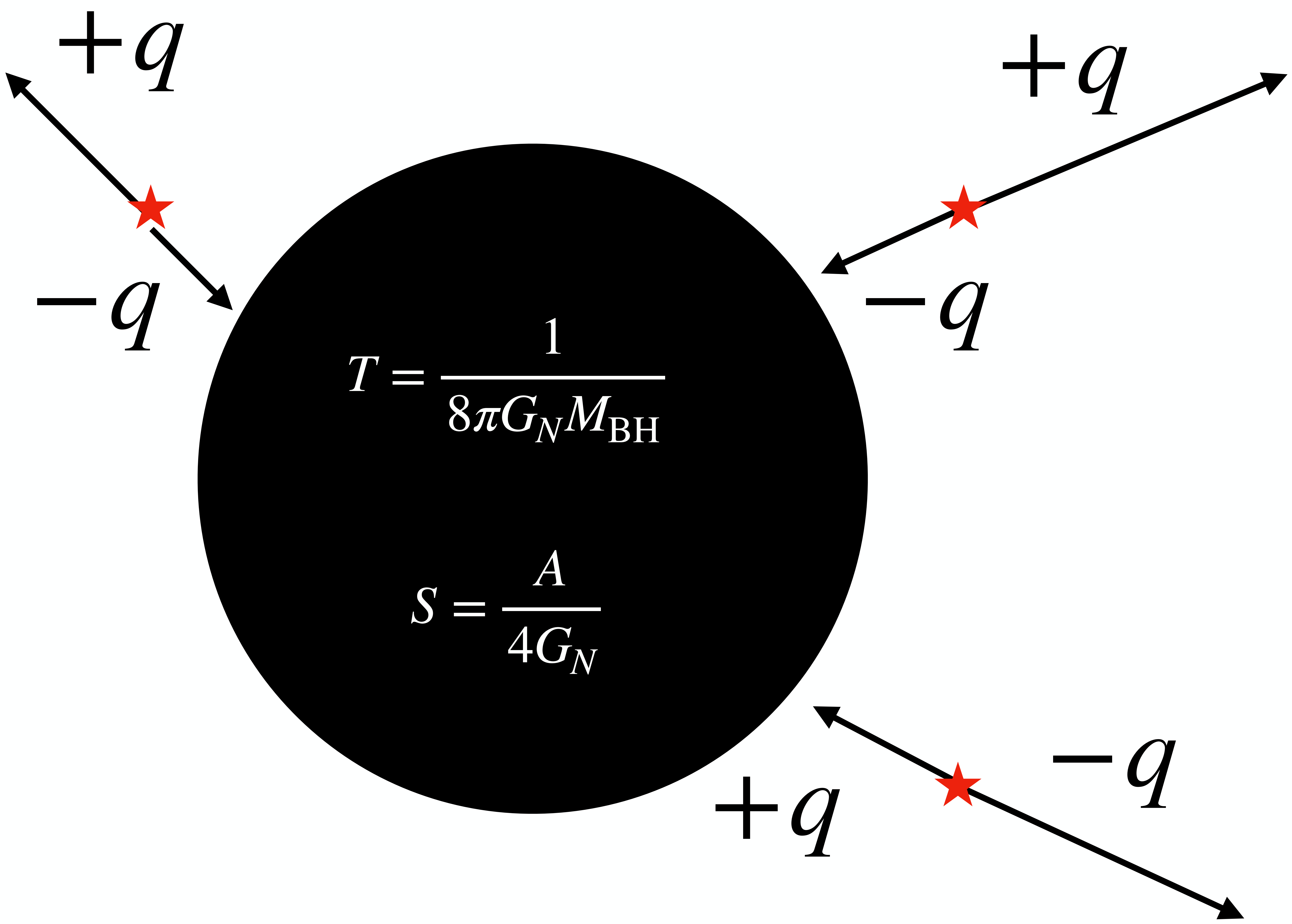
Global symmetry:

- States can have net charge.
- Symmetry operators exist. Topological: measure charge they link with.
- 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.

Black Holes Destroy Global Charges



$$T = \frac{1}{8\pi G_N M_{\mathrm{BH}}}$$

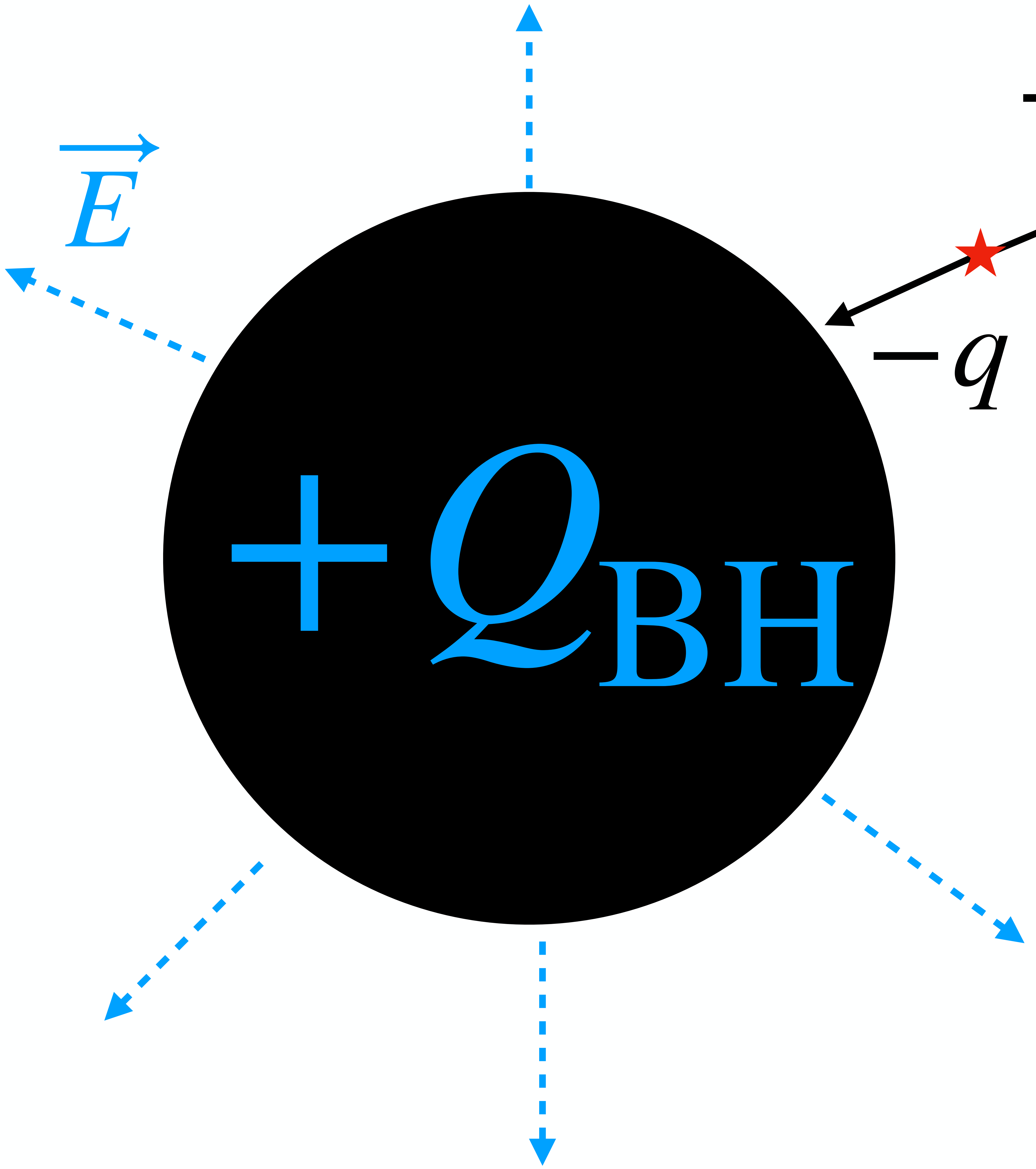
$$S = \frac{A}{4G_N}$$

Stephen Hawking

Random thermal emission of global charge.

Modern argument: Banks, Seiberg 2010

Black Holes and Gauge Charge



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

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

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

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

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

Key Lesson for Quantum Gravitational Theories

There are no global symmetries,
only gauge symmetries.

Gauge symmetries are not symmetries.

Proton Decay: An Old "Naturalness" Puzzle

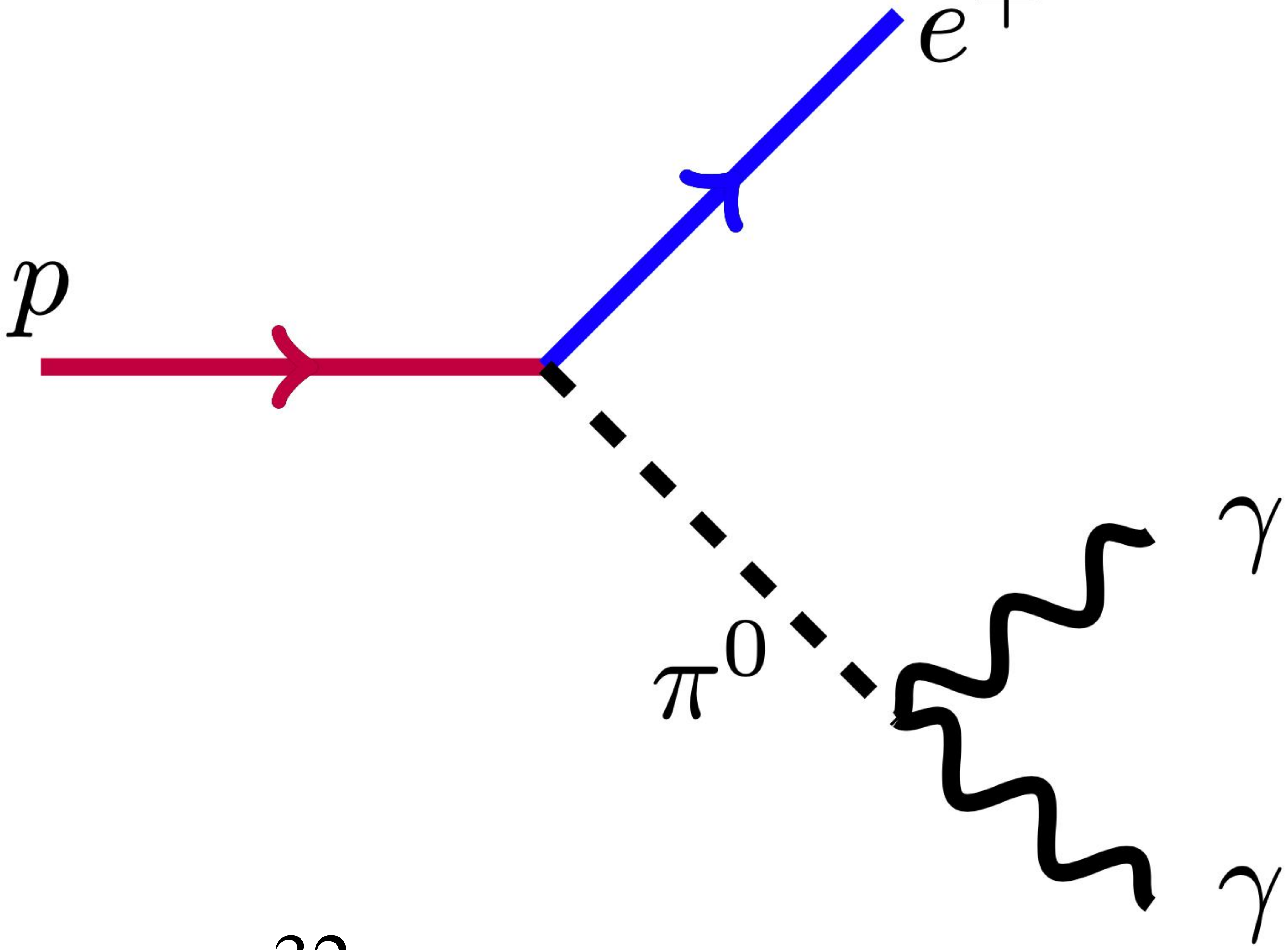
Charge, spin, kinematics all allow proton decay:

$$p \to e^+\pi^0, \qquad p \to K^+\bar{\nu}_e$$

Dimensionless interaction strength y_p:

$$\mathscr{L}_{\rm dec} = y_p p e^- \pi^0 + {\rm h.c.}$$

$$\tau_p \sim \frac{8\pi}{y_p^2 m_p} \sim \frac{10^{-23}\,{\rm sec}}{y_p^2}$$

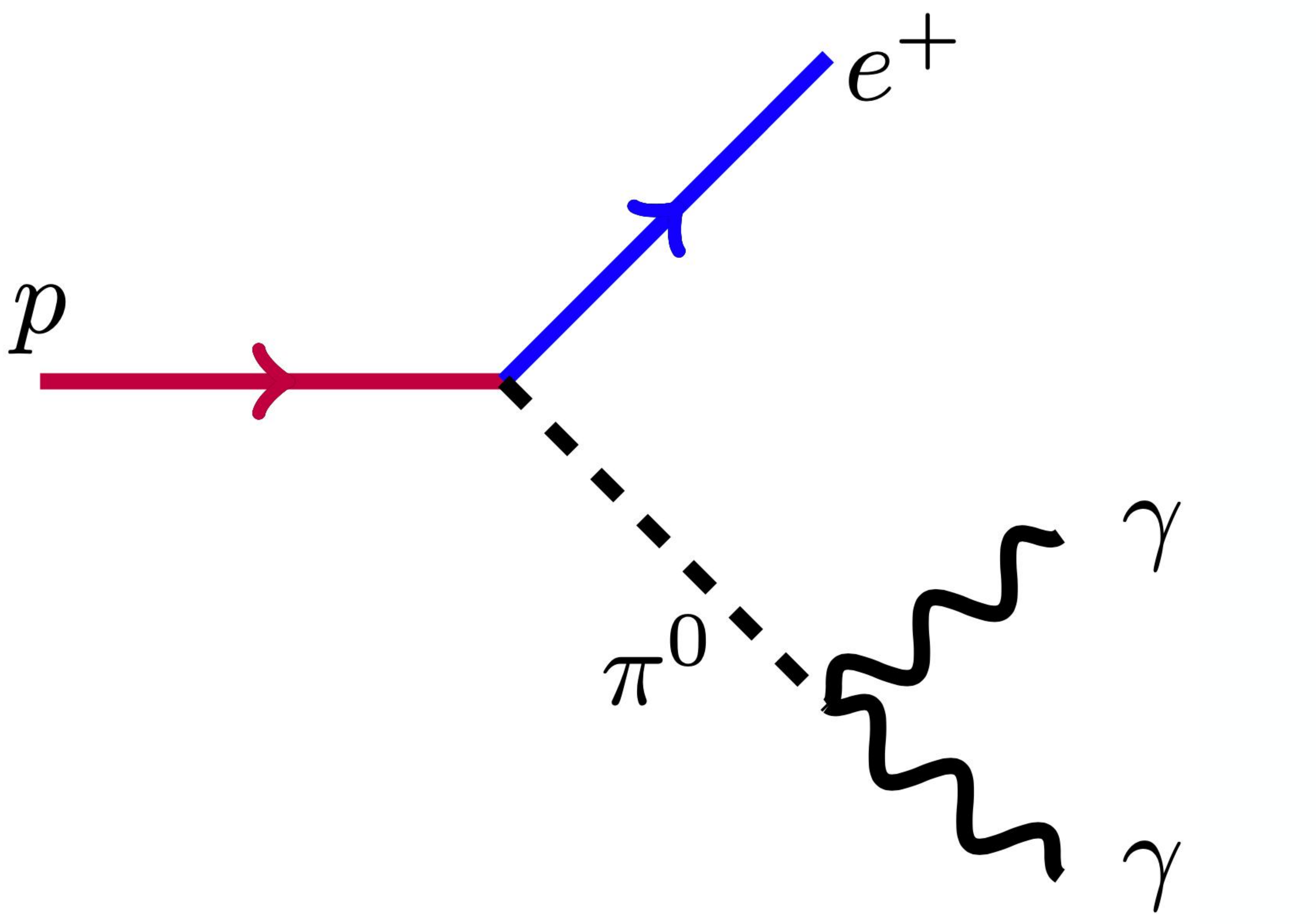


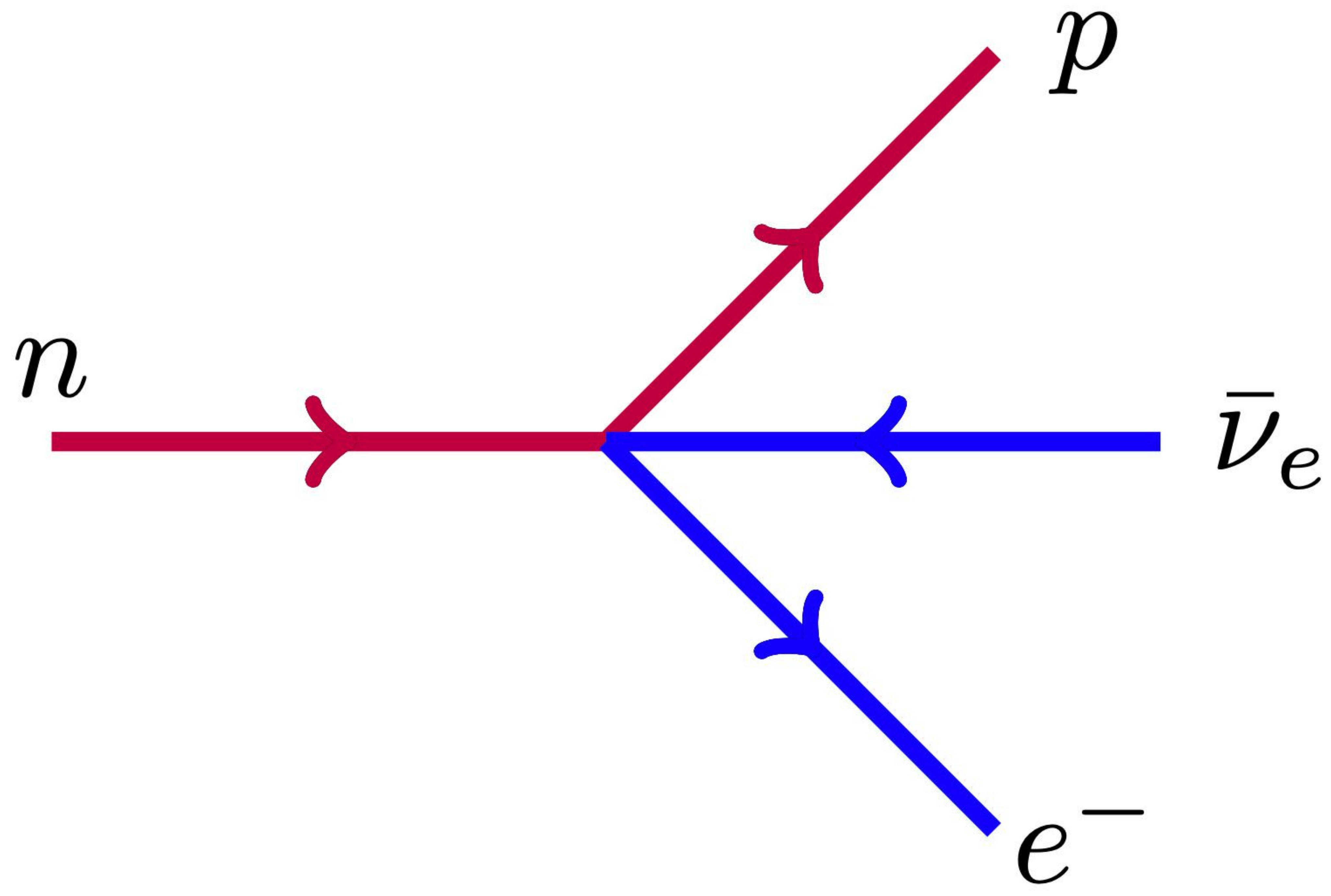
Experiment: $\tau_p \gtrsim 10^{34}\,{\rm yrs} \;\Rightarrow\; y_p \lesssim 10^{-32}$**!** **Why so small?**

Proton Decay: A Symmetry?

Baryon number: $B(p) = B(n) = +1$;

Lepton number: $L(e^-) = -L(e^+) = -L(\bar{\nu}_e) = +1$





Proton decay: forbidden! Symmetry violating

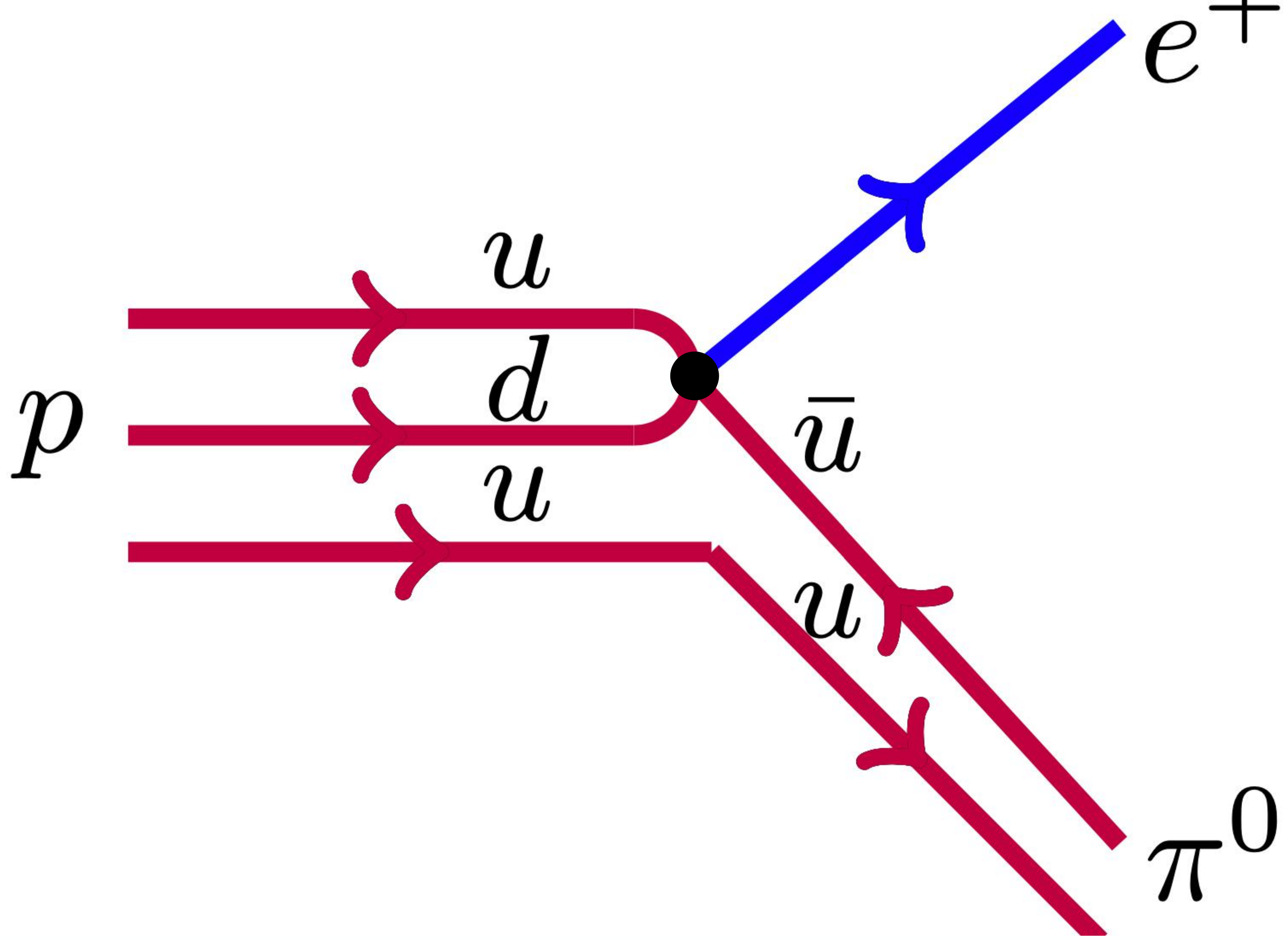
Beta decay: allowed!

Proton Compositeness: No Symmetry?

Turns out: **We don’t need any fundamental symmetry!**

The proton is not an elementary particle! Actually three quarks.

Zoom in to see what the more fundamental interaction looks like:



$$\mathscr{L}_{\text{dec}} = \frac{1}{M_{\text{dec}}^2} uude^- + \text{h.c.}$$

quark/hadron “matching”:

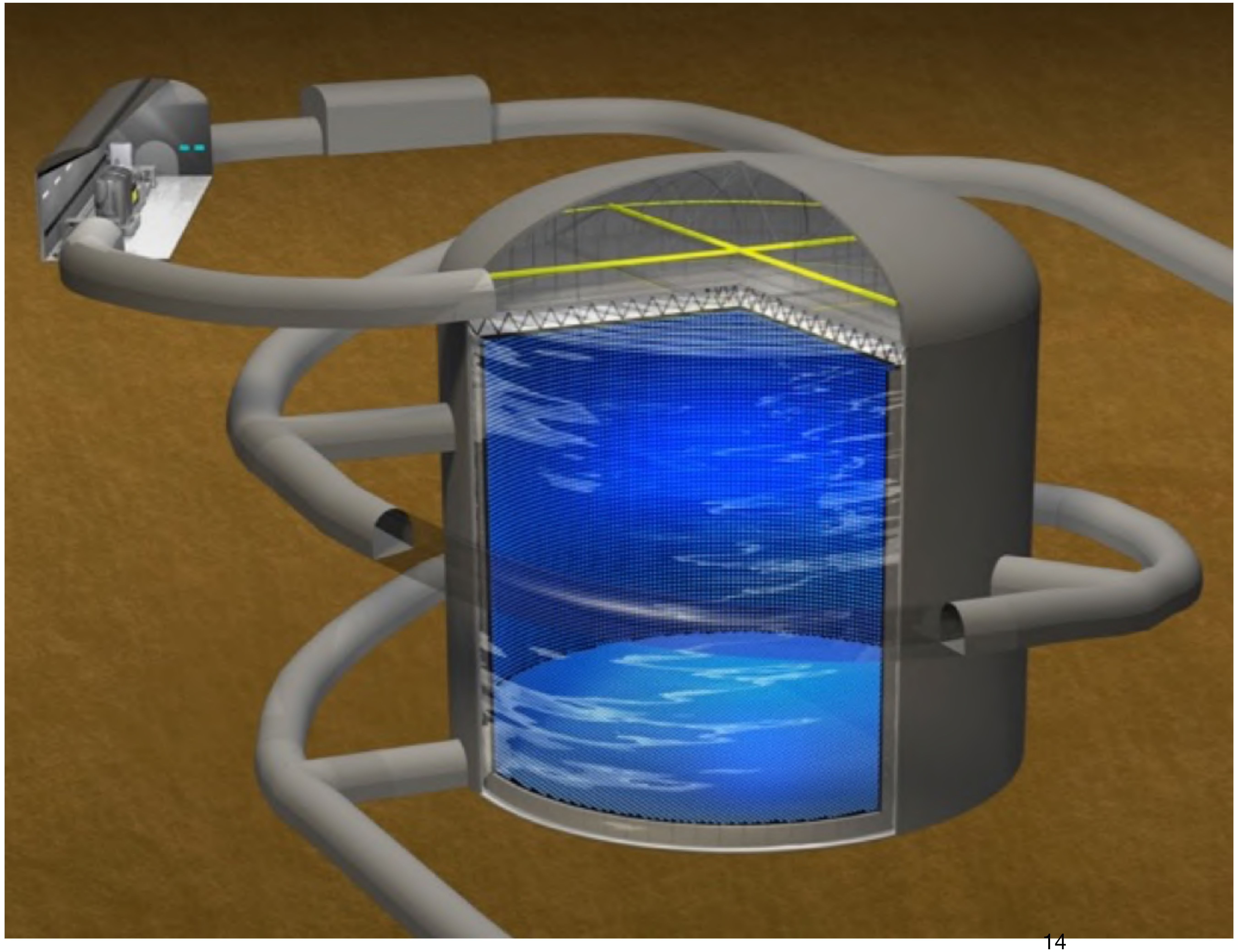
$$y_p \sim \frac{\Lambda_{\text{QCD}}^2}{M_{\text{dec}}^2}, \quad \Lambda_{\text{QCD}} \sim 300\,\text{MeV}$$

$$y_p \lesssim 10^{-32} \;\Rightarrow\; M_{\text{dec}} \gtrsim 10^{15}\,\text{GeV}$$

***Accidental* symmetry!**

Hyper-Kamiokande

A Next-Generation Proton Decay Search



~200 kton water,
40k photodetectors

Sensitive to lifetime
$\tau(p \to e^+\pi^0) \approx 10^{35}$ yrs
(~10x Super-K sensitivity)

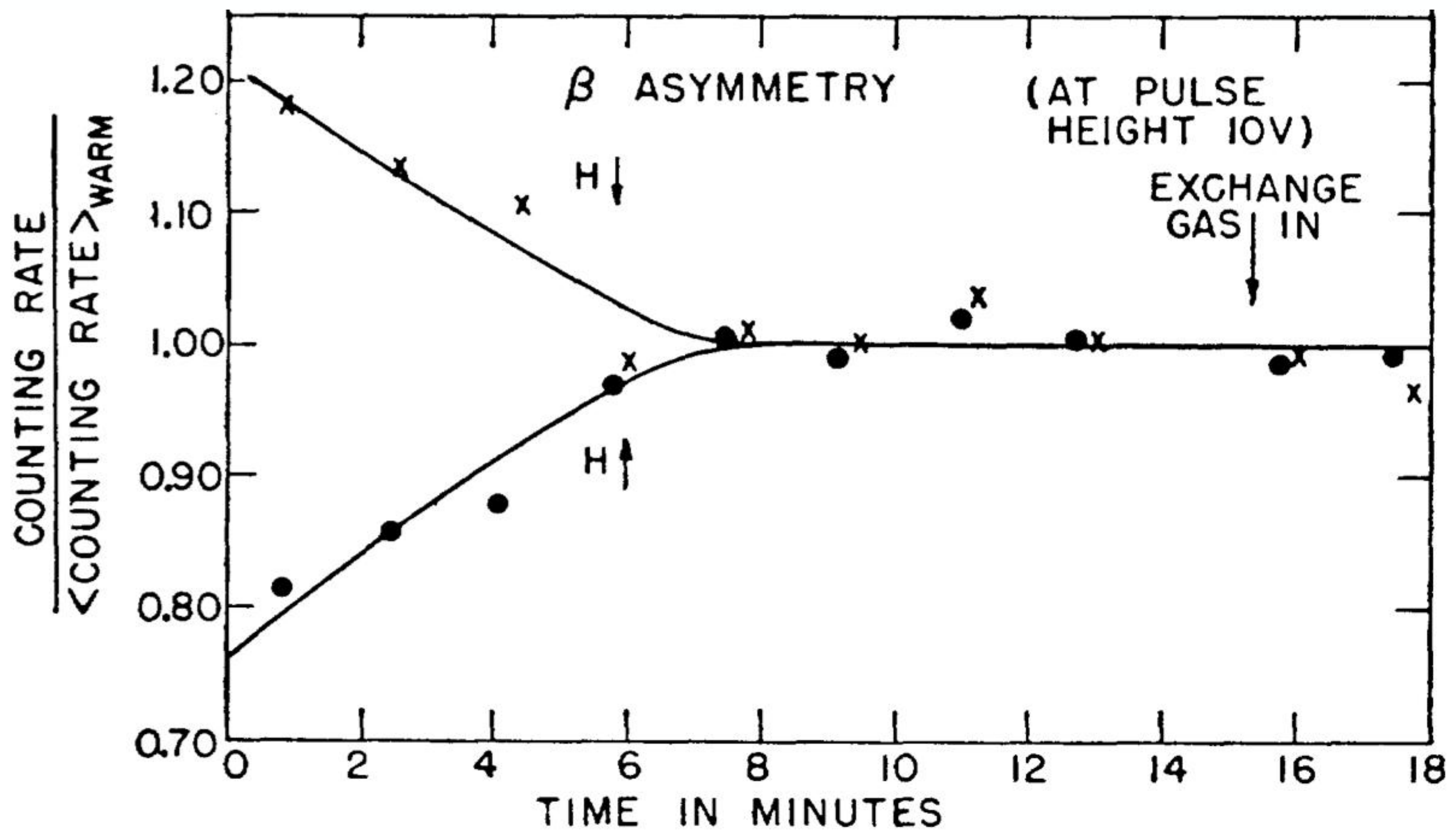
(after ~10yrs running)

Parity As Accidental Symmetry

At low energies, the laws of nature appear *parity-symmetric.* Fundamentally, they are **not at all!**

The particle spectrum of the Standard Model is **chiral:** particles have an intrinsic handedness.

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + e^{+} + \bar{\nu}_e + 2\gamma$$



We now know the **Higgs mechanism** leaves behind an *accidentally* parity-symmetric theory.

Chien-Shiung Wu

TD Lee, CN Yang

T-Symmetry Violation

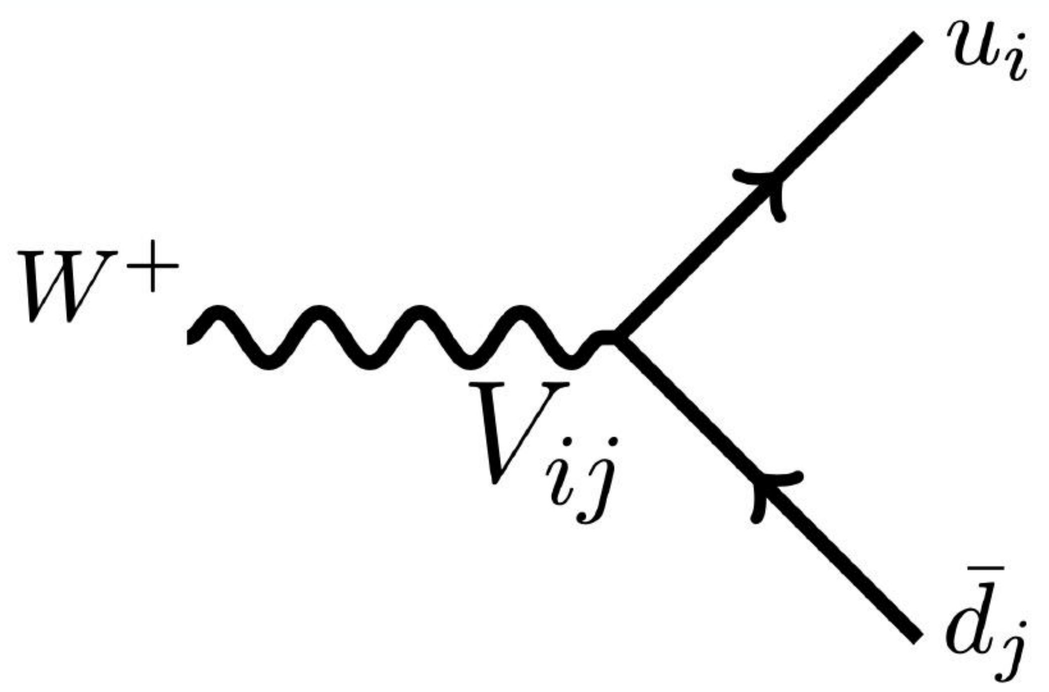
Recall from quantum mechanics that **time reversal** is an **anti-linear** operator: it complex conjugates whatever it acts on.

This means that T-violating effects show up whenever there is a **complex phase in the Lagrangian** that can't be eliminated with a field redefinition.

CPT is a good symmetry of any relativistic quantum field theory, so T-symmetry ⇔ CP symmetry.

Will often talk about **CP symmetry**.

CP Violation in the Standard Model



3 generations (families) of up/down quark “flavors”:

up/charm/top and *down/strange/bottom*

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{bmatrix}.$$

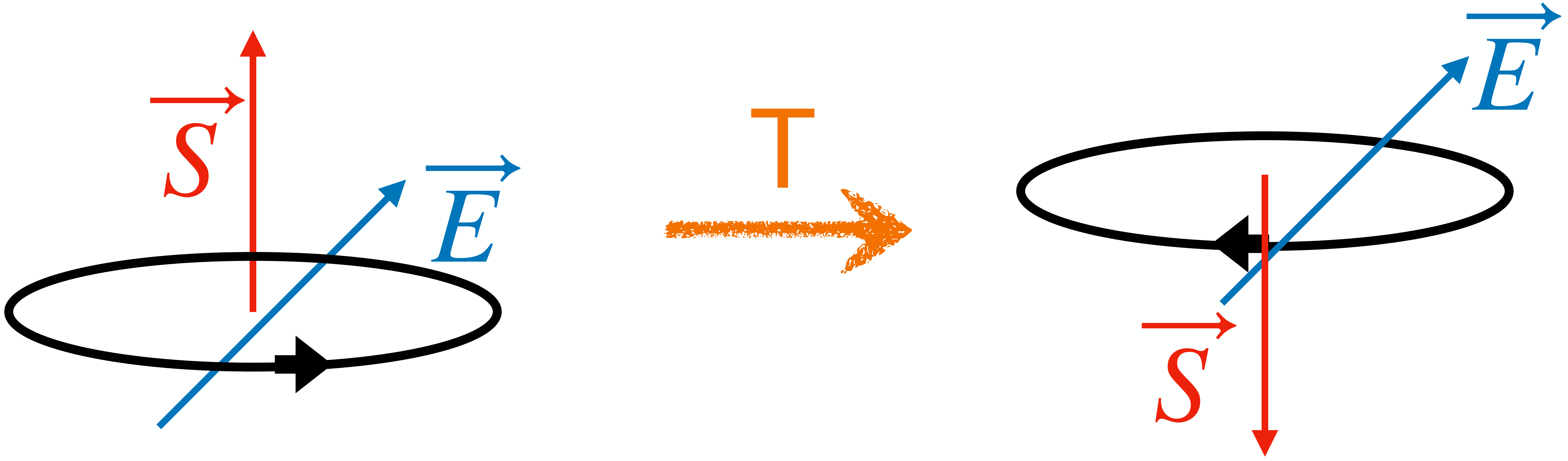
Makoto Kobayashi, Toshihide Maskawa

CP / time reversal **badly broken:** $\delta_{13} \approx 1.2$.

But accompanied by small parameters, e.g., $\theta_{13} \approx 3 \times 10^{-3}$.

Electric Dipole Moments (EDMs)

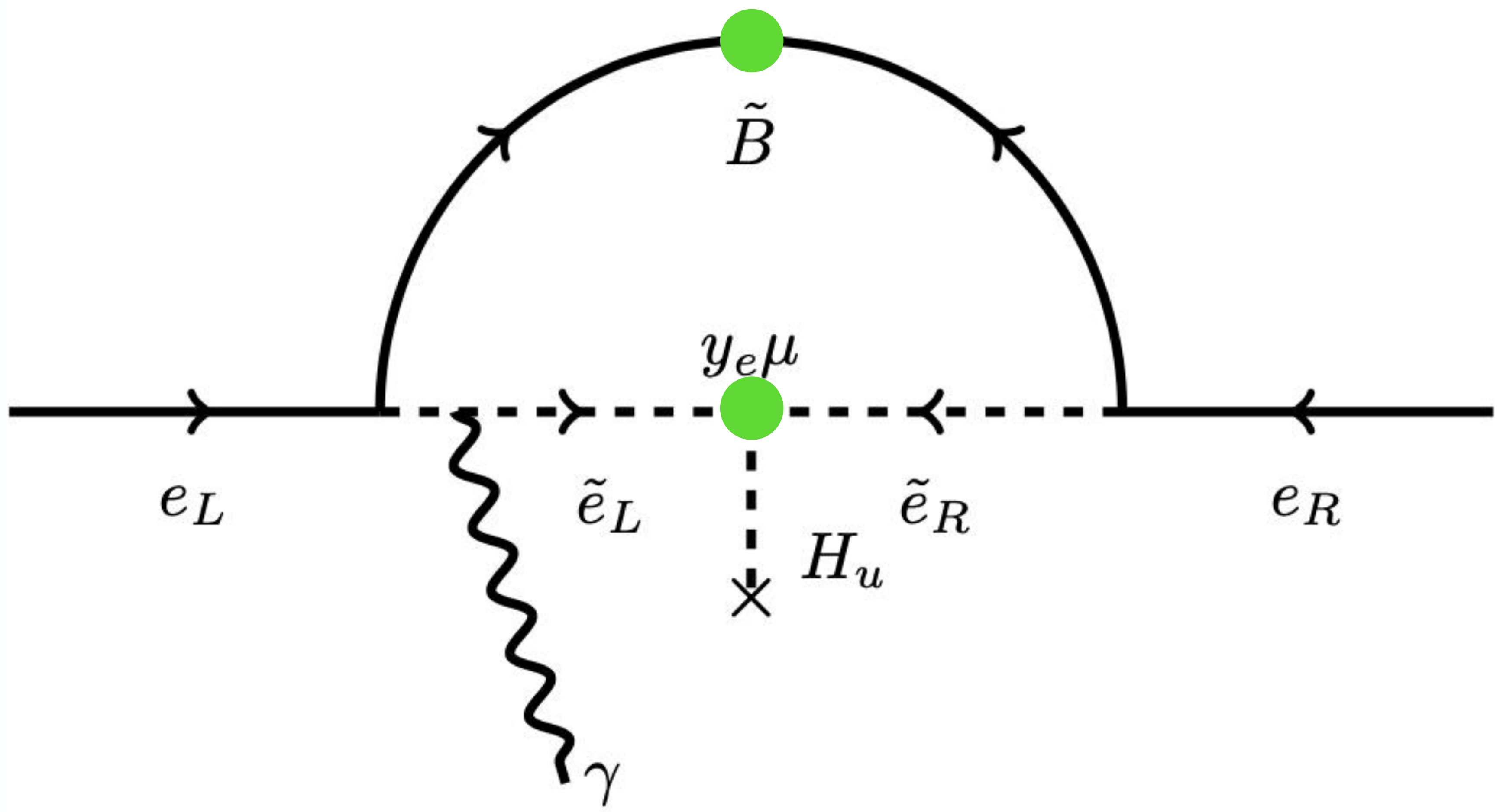
$\vec{d} = d\frac{\vec{S}}{S}$ $H_{\text{EDM}} = -\vec{d}\cdot\vec{E} \propto \vec{S}\cdot\vec{E}$ **Odd under time-reversal!**

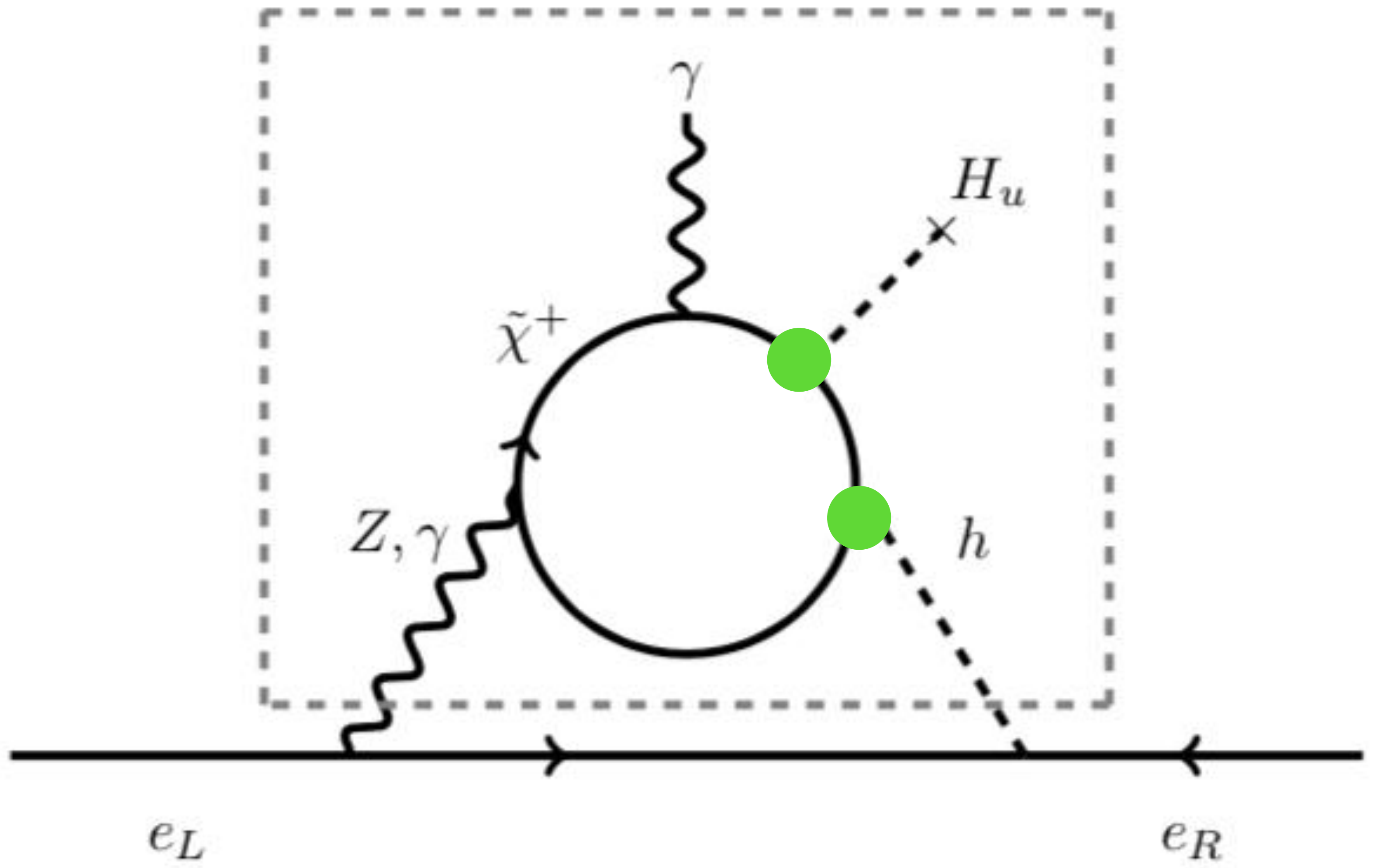


Electric dipole moments of leptons and hadrons provide a powerful probe of **T-violating** or, equivalently, **CP-violating** fundamental physics.

EDMs from New Physics

Look for terms allowing an invariant, **complex coefficient to appear in the Lagrangian**.



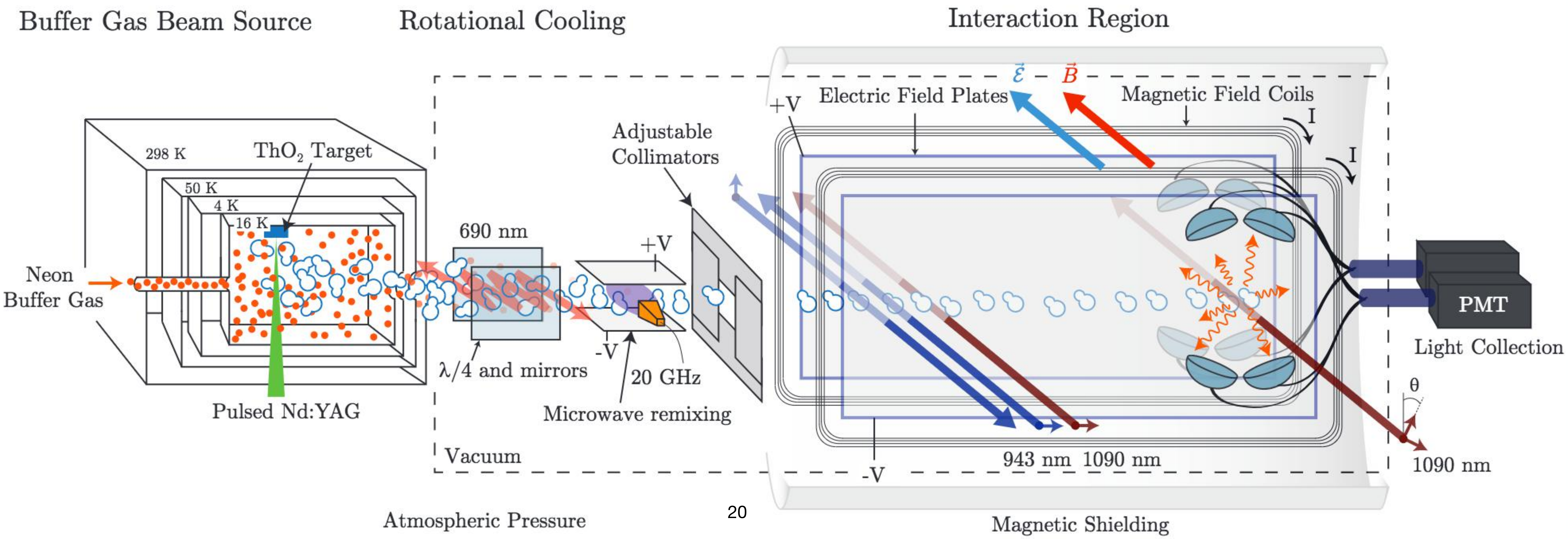


Generic expectation for new physics!

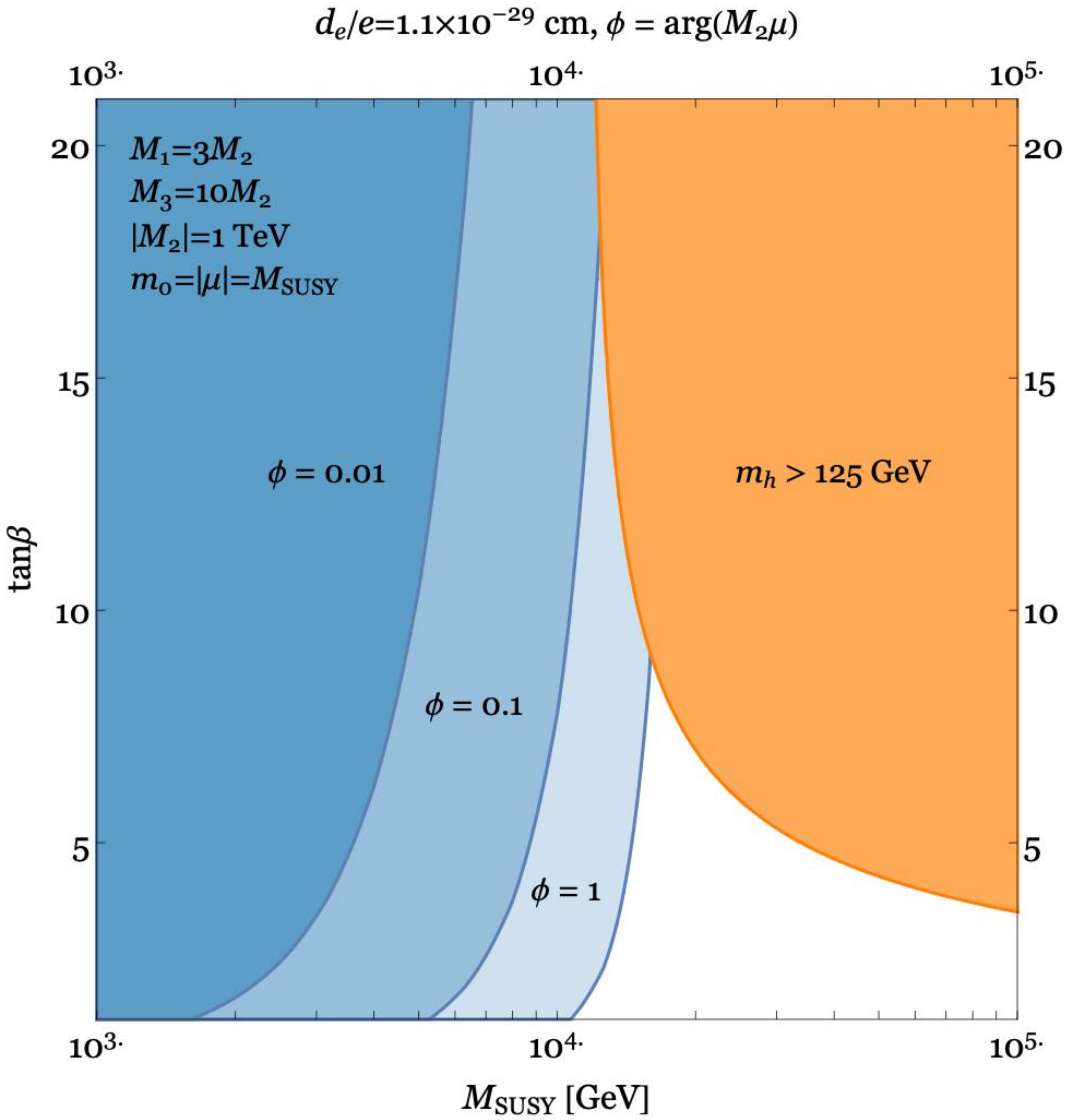
Electron Electric Dipole Moment

Recent dramatic progress in AMO physics.

ACME 2 (source: electronedm.org) DeMille, Doyle, Gabrielse and collaborators. New result in 2018: $|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}$

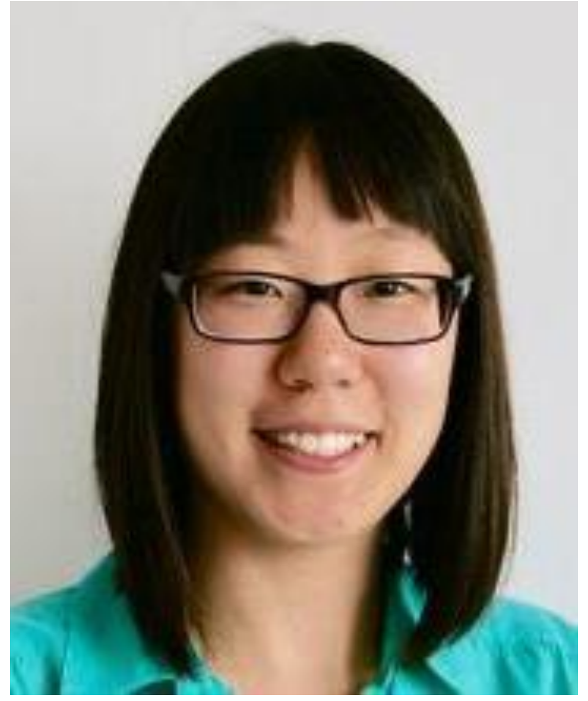
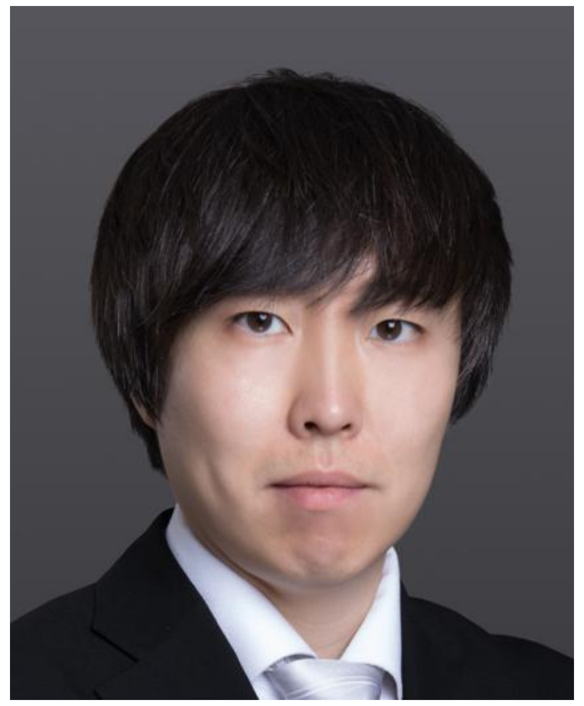


Electron EDM versus New Physics



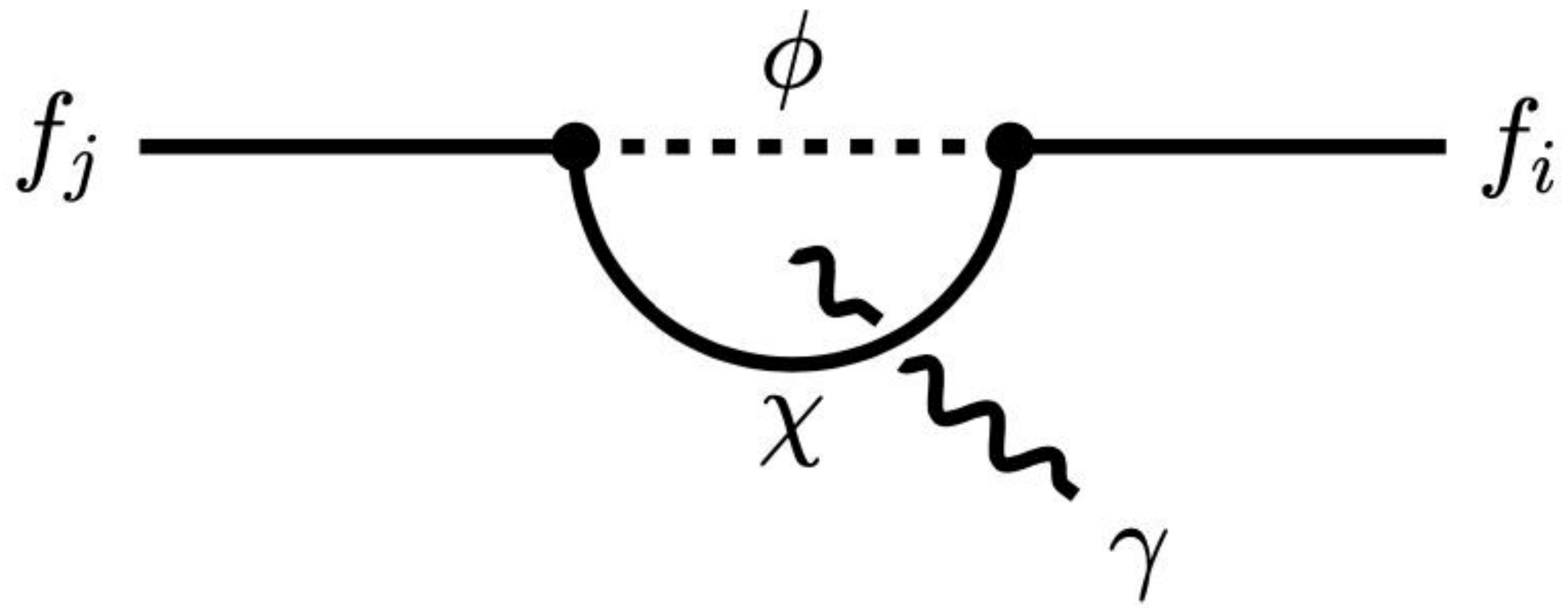
Assume CP is **not at all** a symmetry: all complex phases $O(1)$.

New physics like supersymmetry excluded to masses $\sim 20\,\mathrm{TeV}$!


(arXiv:1810.07736: Cari Cesarotti, Qianshu Lu, Yuichiro Nakai, Aditya Parikh, MR)

Lepton Dipole Family

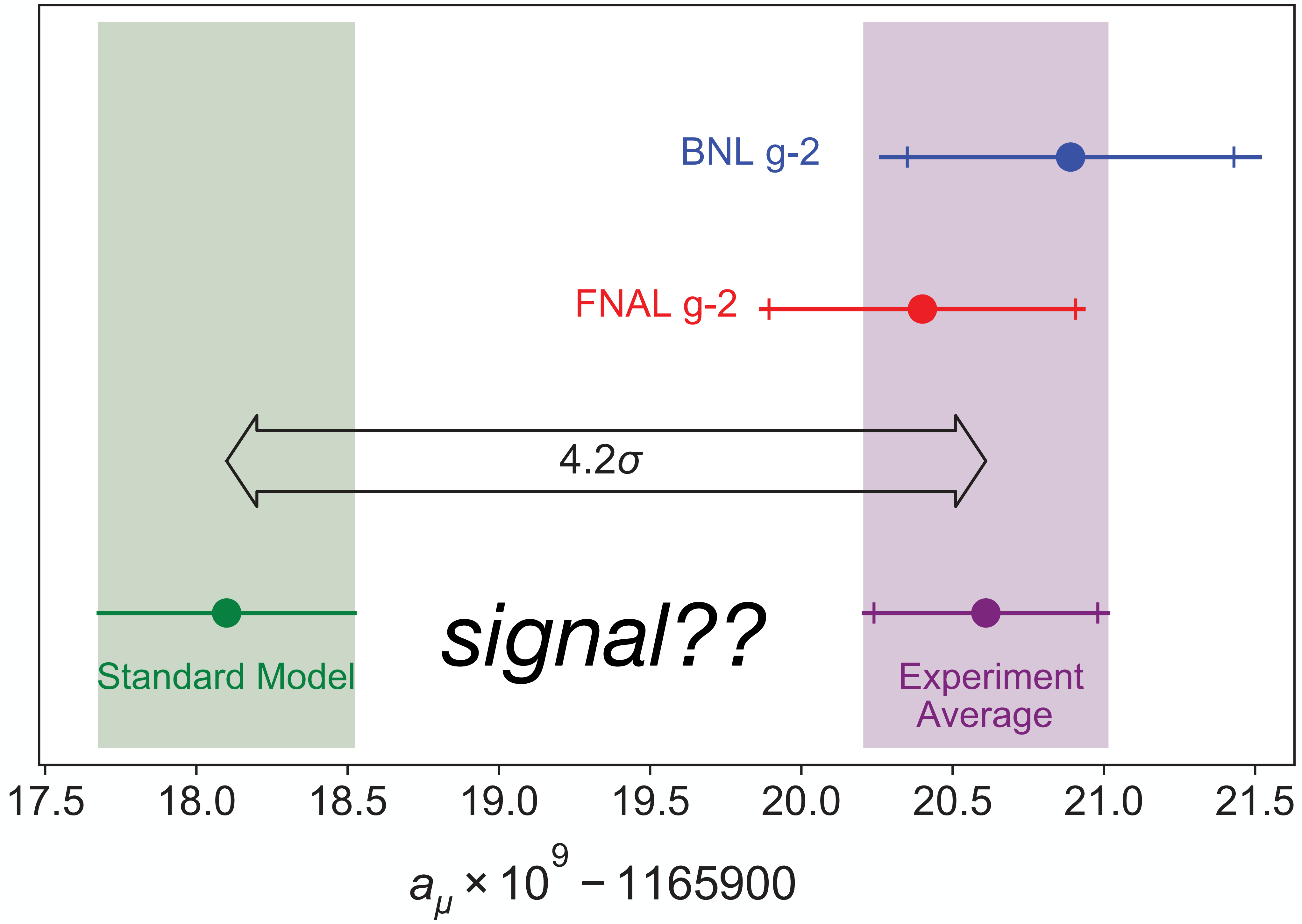


Charged lepton flavor violation:

$$\mathrm{Br}(\mu \to e\gamma) \lesssim 4 \times 10^{-13}$$

(MEG experiment)

Fermilab muon $g-2$



Magnetic dipole moment,
not T-violating

Electron EDM:

$$|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}$$

Correlating Flavor and CP Symmetries

Yossi Nir, Riccardo Rattazzi, 1996

Idea: the only CP violation we've seen in nature so far is *correlated* with flavor symmetry violation (in the CKM matrix).

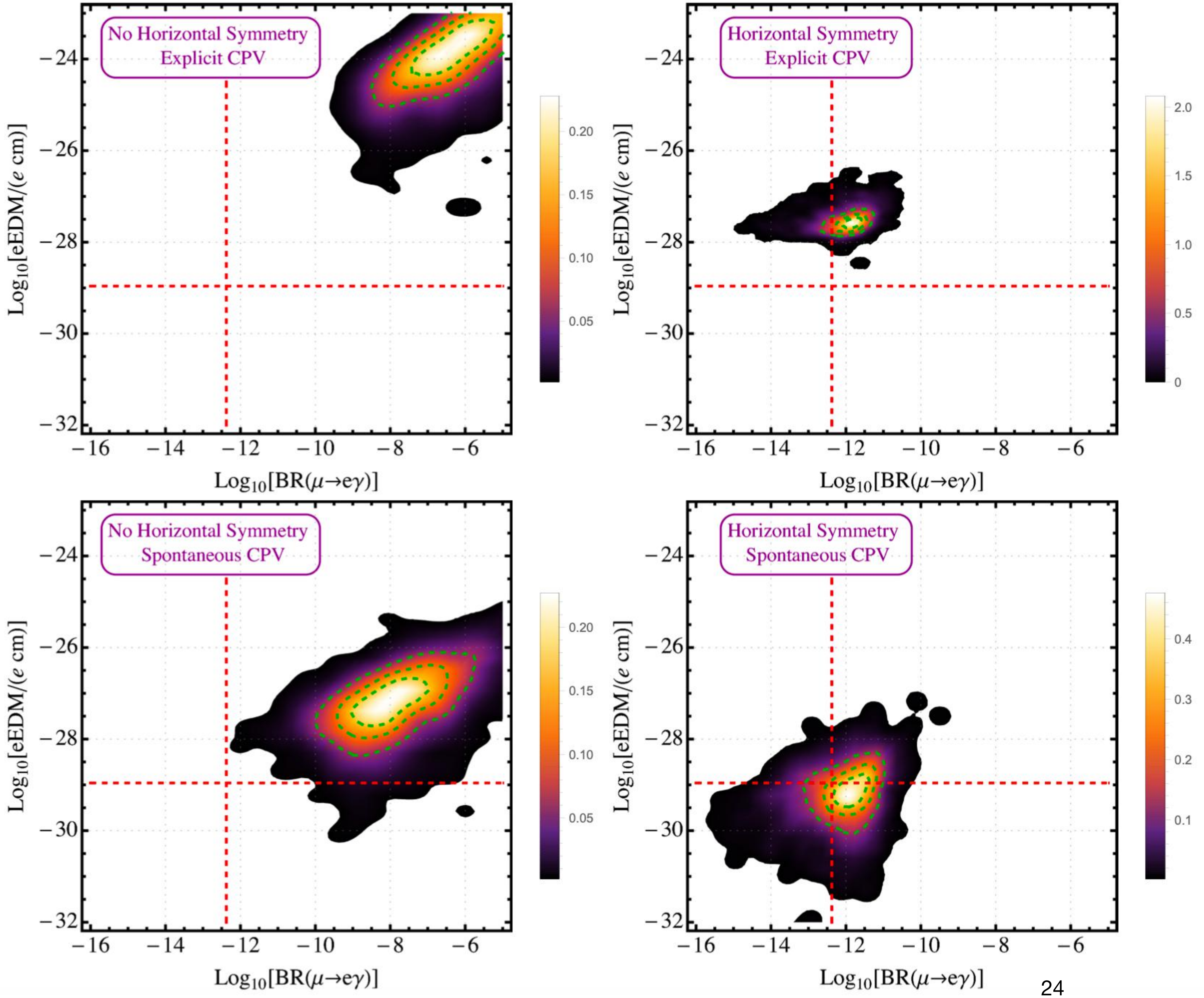
What if: **CP is a fundamental symmetry, spontaneously broken in a way that *also* breaks flavor?**

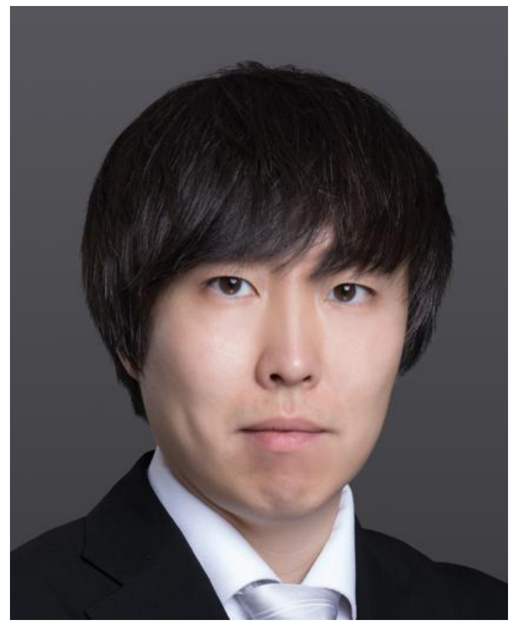
Prediction:

CP and flavor violation might always come hand-in-hand.

Suppress EDMs **(to a *predictable* extent)**, keep CKM phase.

Gauged Flavor and CP Symmetries



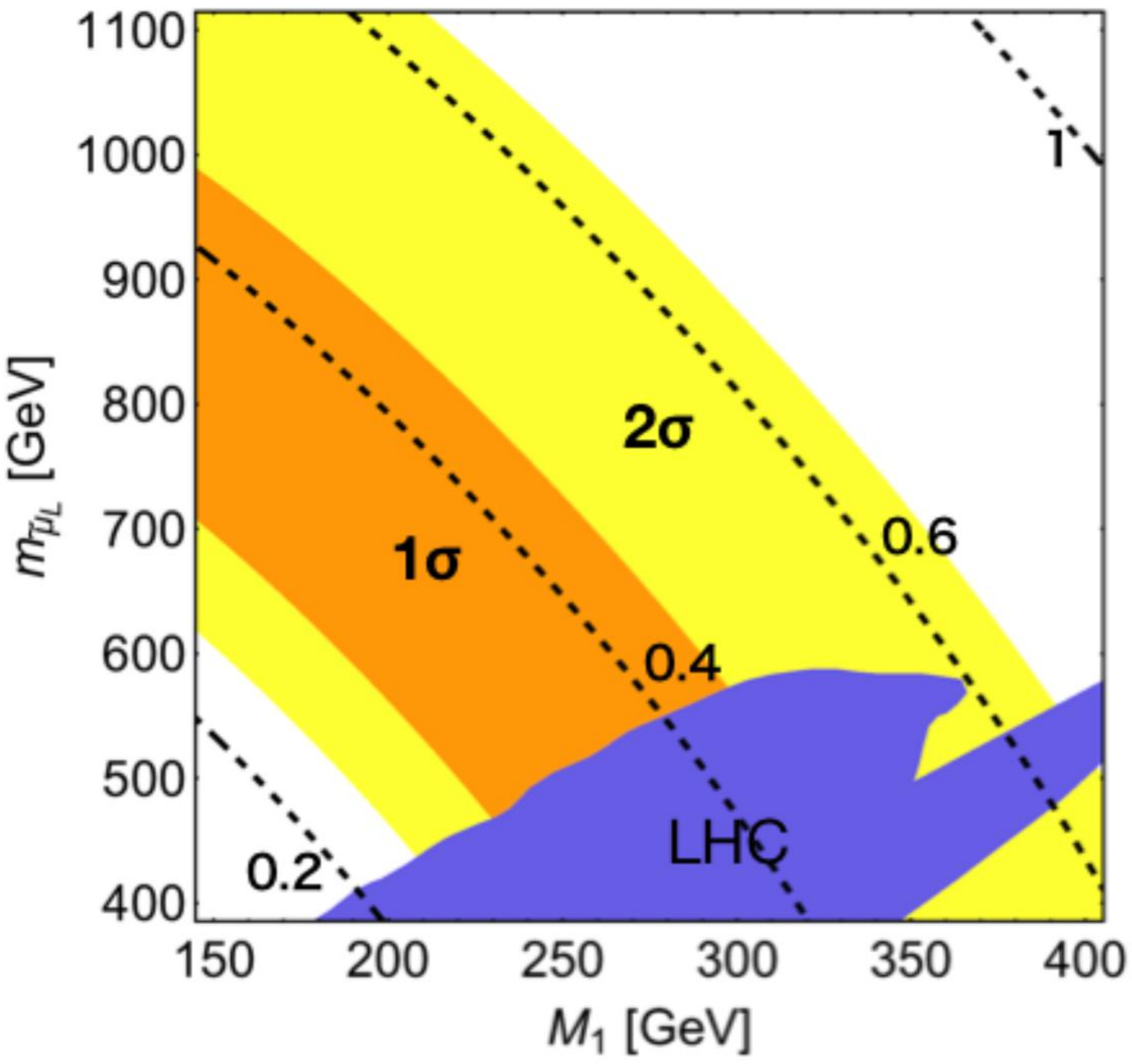


Extend to lepton sector; fit neutrino mixing textures

Correlate, suppress electron EDM and $\mu \to e\gamma$ signals

(arXiv:2104.02679: Pouya Asadi, Daniel Aloni, Yuichiro Nakai, MR, Motoo Suzuki)

Flavor & CP Symmetries and Muon $g-2$



$U(1) \times U(1)$ Flavor Symmetry Model

Key:

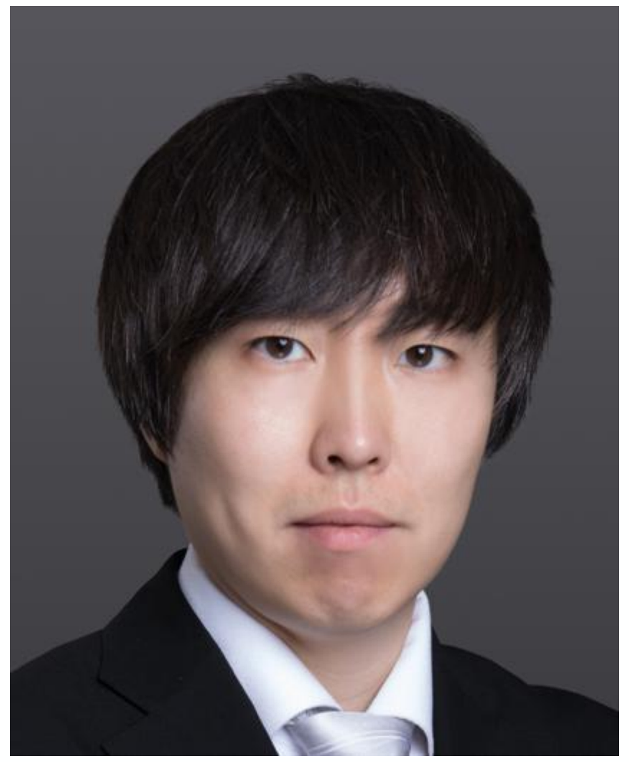
Muon g-2 preferred

LHC excluded

Dashed Lines:

Predict Electron EDM = 10^{-30} *e* cm visible at next-gen experiments!

if operator has 0.2, 0.4, 0.6, 1 coefficient



(arXiv:2107.10268: Yuichiro Nakai, MR, Motoo Suzuki)

Time Reversal from the Theta Term in QED

Under time reversal, $\overrightarrow{E} \mapsto \overrightarrow{E}, \overrightarrow{B} \mapsto -\overrightarrow{B}$.
(Consider $\overrightarrow{E}$ from static charge, $\overrightarrow{B}$ from circulating current.)

So a term $\overrightarrow{E} \cdot \overrightarrow{B}$ in the Hamiltonian violates time reversal symmetry.

Lagrangian:

$$\frac{\theta}{32\pi^2}\int d^4x\, \epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = \frac{\theta}{8\pi^2}\int F \wedge F = \frac{\theta}{8\pi^2}\int \mathrm{d}(\mathrm{A} \wedge \mathrm{dA})\,.$$

Total derivative! No physical effect?

The Witten Effect


Edward Witten, 1979

Add the time-reversal odd term in the action: $\frac{\theta}{8\pi^2}\int F \wedge F$

Then, derive the modified Maxwell equations.

Electric Gauss's law: $\nabla \cdot \mathbf{E} + \boxed{\frac{e^2}{4\pi^2}\theta(\nabla \cdot \mathbf{B})} = 0$

Consider a magnetic monopole, which sources **B** $\Rightarrow$ $\boxed{\frac{Q_E}{e} = -\frac{\theta}{2\pi}}$

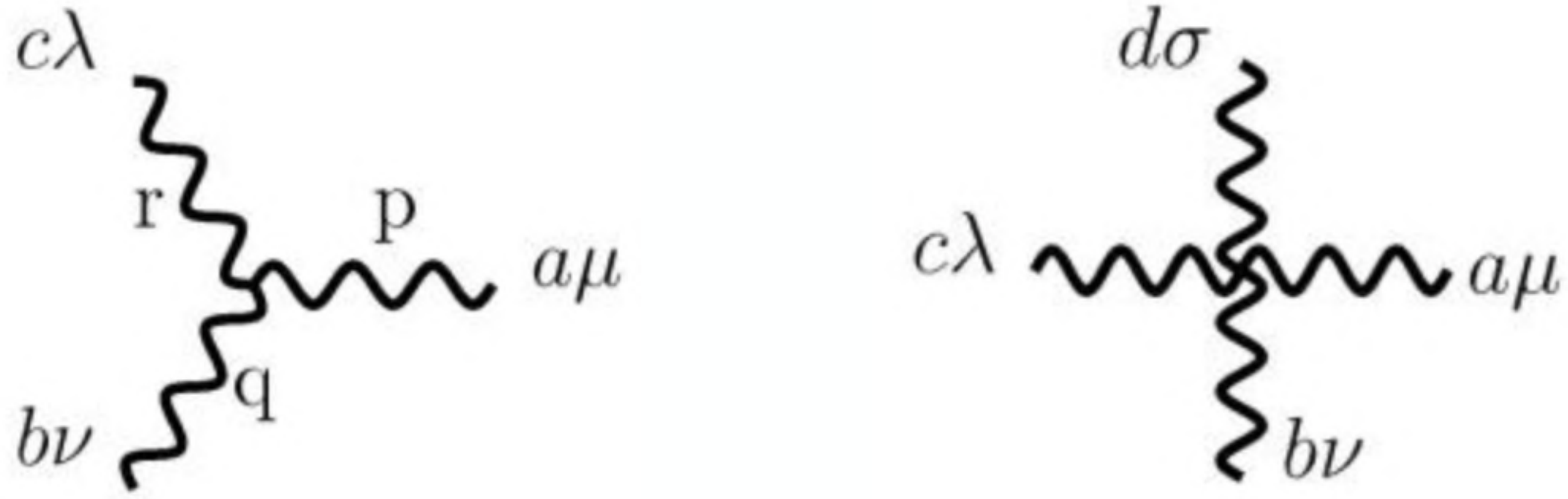
Magnetic monopole acquires an electric charge!

Magnetic monopole provides boundary condition allowing effect. We haven't seen one (yet), so no experimental probe of this T-violating effect.

QCD and Its Theta Term

The structure of the **strong interactions** in the Standard Model is a **non-abelian gauge theory, QCD**. Field strengths $F^a_{\mu\nu}, \quad a = 1,\ldots 8,$ where $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + \sum_{b,c} f^{abc} A^b_\mu A^c_\nu$.

Gluons self-interact:



$\theta \cong \theta + 2\pi$ term can be added. T-violating term, still a total derivative.

$$\frac{\theta}{64\pi^2}\int d^4x\,\epsilon_{\mu\nu\rho\sigma}F^{a\mu\nu}F^{a\rho\sigma} = \frac{\theta}{8\pi^2}\int \mathrm{tr}(F\wedge F) = \frac{\theta}{8\pi^2}\int \mathrm{d}(\mathrm{A}\wedge \mathrm{dA} + \frac{2}{3}\mathrm{A}\wedge\mathrm{A}\wedge\mathrm{A})\,.$$

Instantons

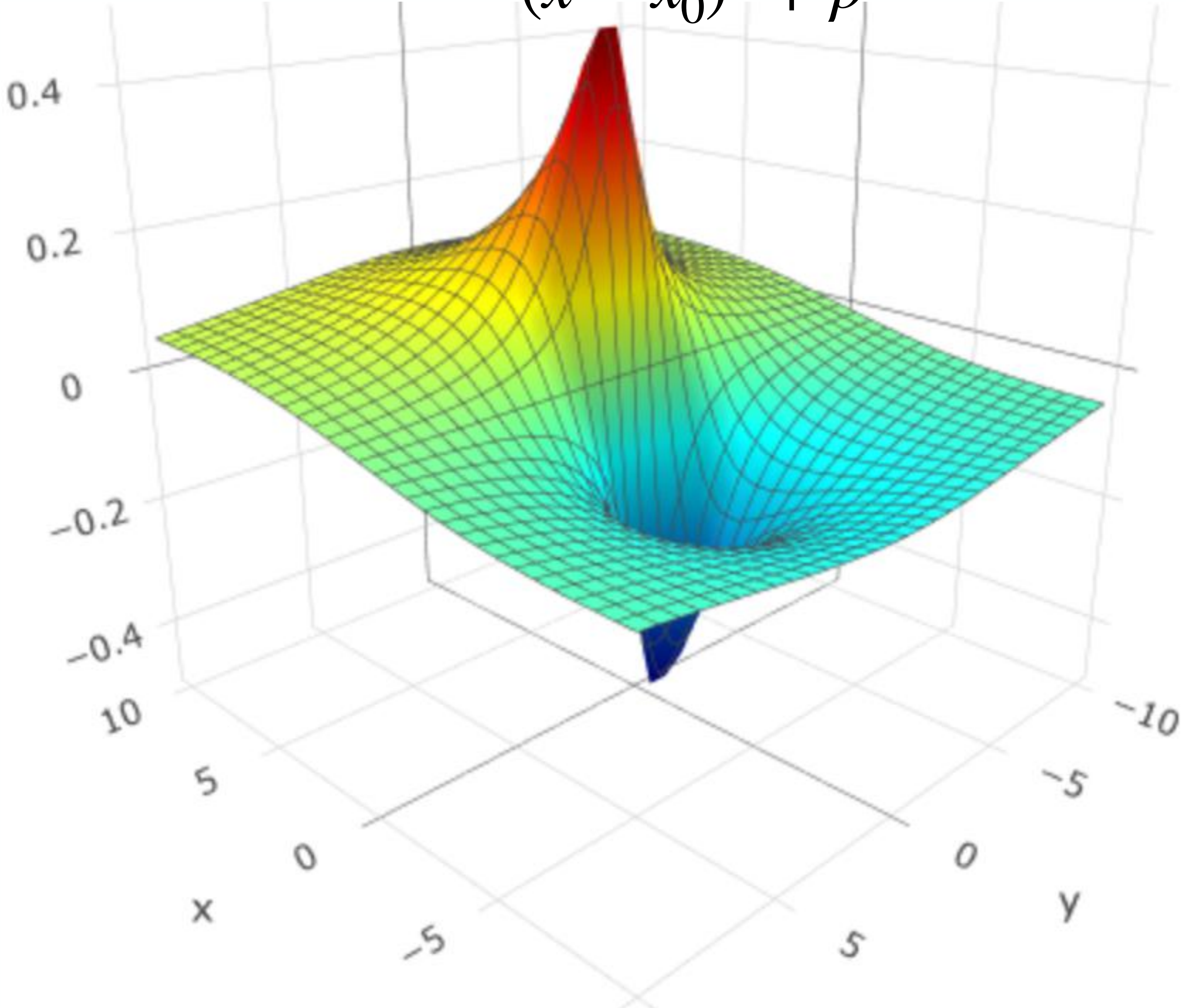
In QCD, don't need a new object to detect the θ term.

It has an effect via *classical Euclidean solutions* called "instantons": localized in spacetime.

Action: $S = \dfrac{8\pi^2}{g^2}$

Decay as $A \sim 1/r$, slowly enough to have boundary effect.

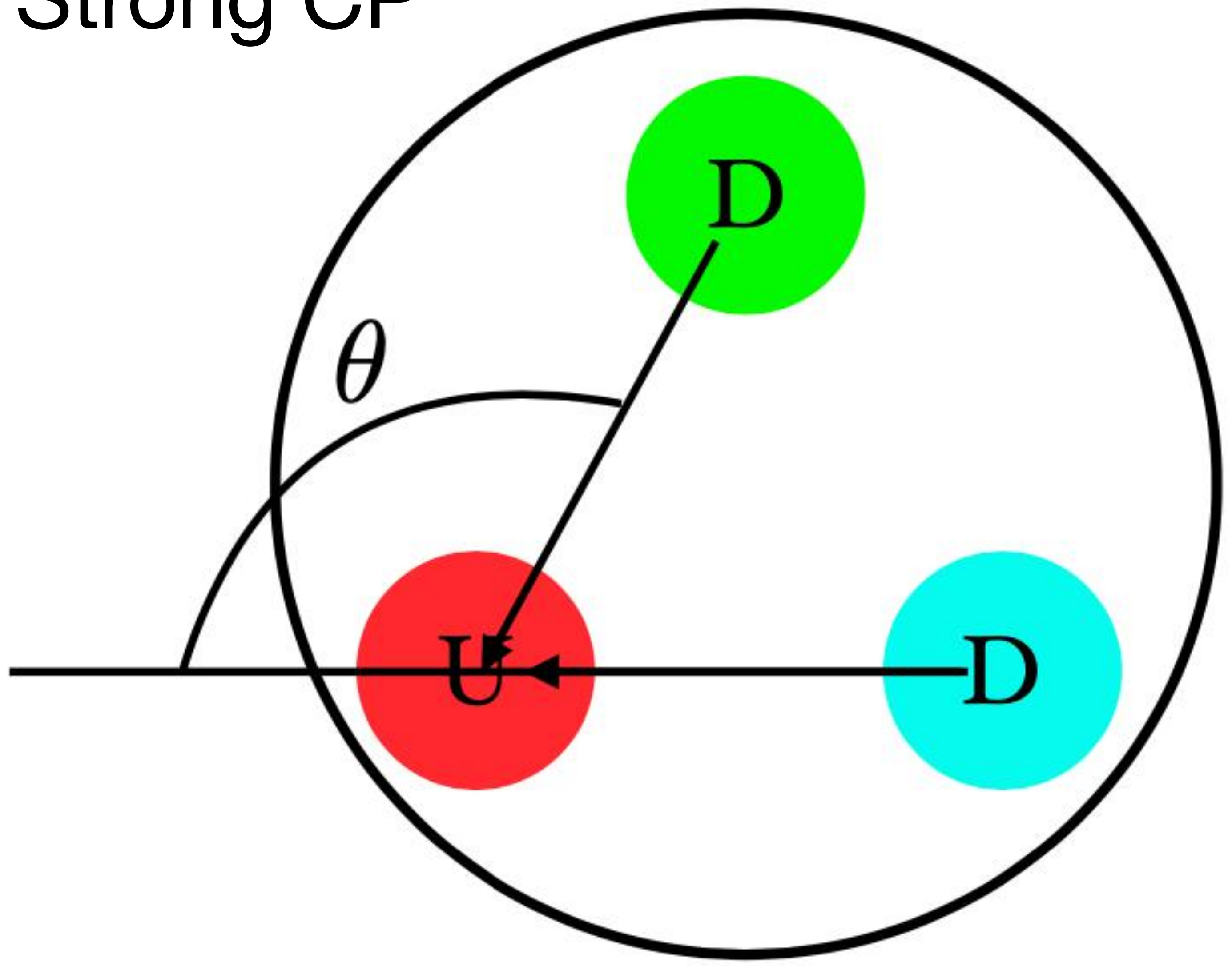
$$A_\mu^a = 2\eta_{a\mu\nu}\frac{(x-x_0)_\nu}{(x-x_0)^2+\rho^2}$$



$\dfrac{1}{8\pi^2}\mathrm{tr}(F\wedge F)$ is "instanton density"

Strong CP Problem

Fig. from Anson Hook, TASI Lectures on Strong CP



QCD becomes strongly interacting at low energies, binding quarks and gluons into hadrons.

This gives nonperturbative effects a chance to play a big role. Should be able to measure θ.

Can derive: **Neutron electric dipole moment:** $d_n \sim \theta \times 10^{-16}\, e\, \mathrm{cm}$

Recent ultracold neutron measurement at Paul Scherrer Institute:

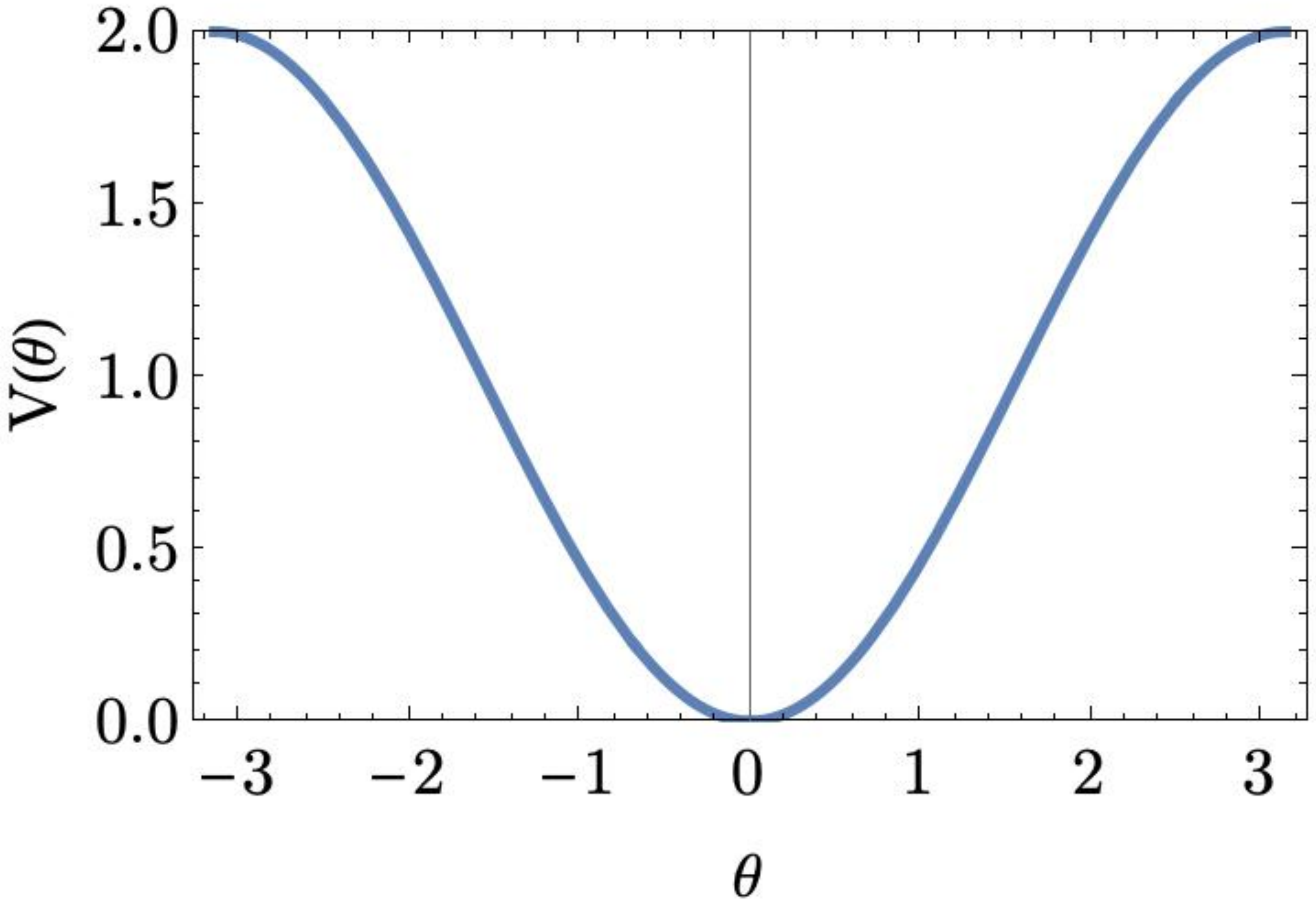
$|d_n| \leq 1.8 \times 10^{-26}\, e\, \mathrm{cm}$

So: $|\theta| \lesssim 10^{-10}$. **But why!? CP is not a symmetry of nature!**

Axions

Promote θ to a **dynamical field,** $\theta(x)$, interacting with gluons.

$$\mathscr{L} = \frac{1}{2} f_a^2 (\partial\theta)^2 + \frac{1}{32\pi^2} \theta(x) F^a_{\mu\nu} \tilde{F}^{a\mu\nu}(x)$$



Strong dynamics ⇒

Axion relaxes to CP-conserving value.

$$m_a \sim \frac{m_\pi f_\pi}{f_a} \sim \frac{10^{-5}\,\mathrm{eV}}{f_a/(10^{12}\,\mathrm{GeV})}$$

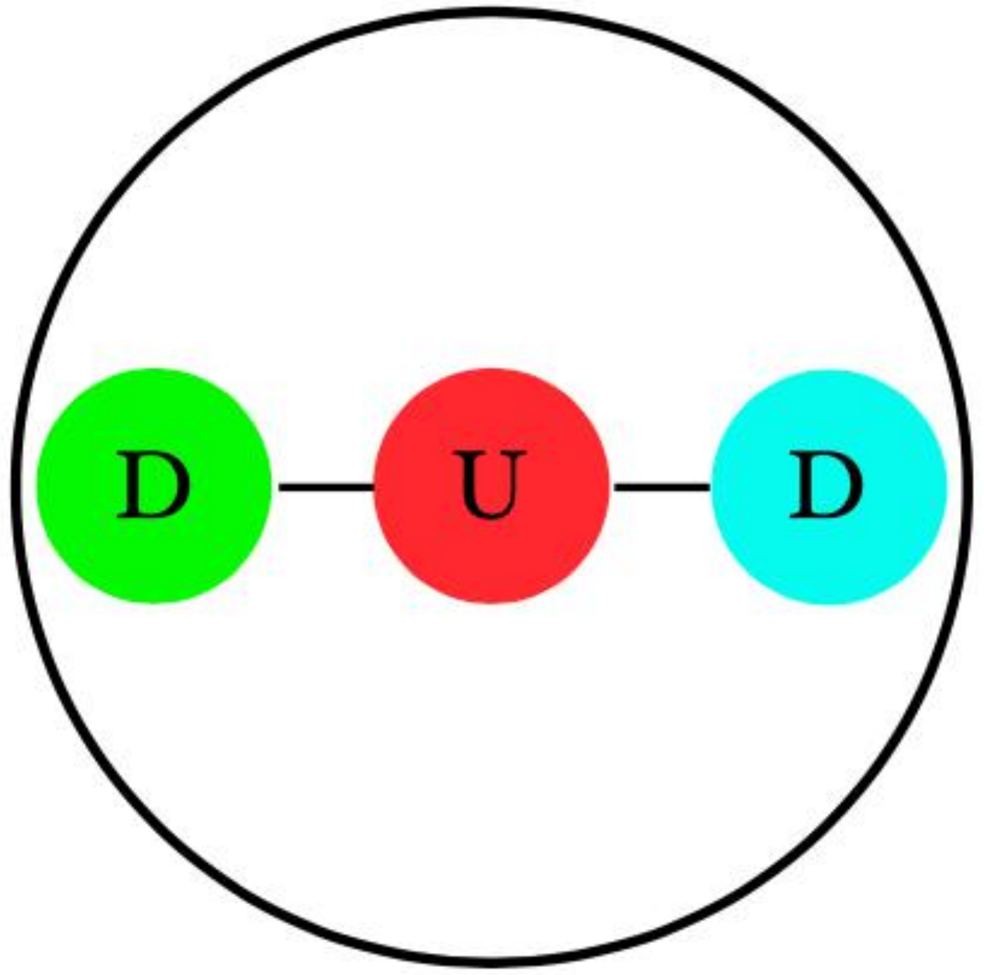
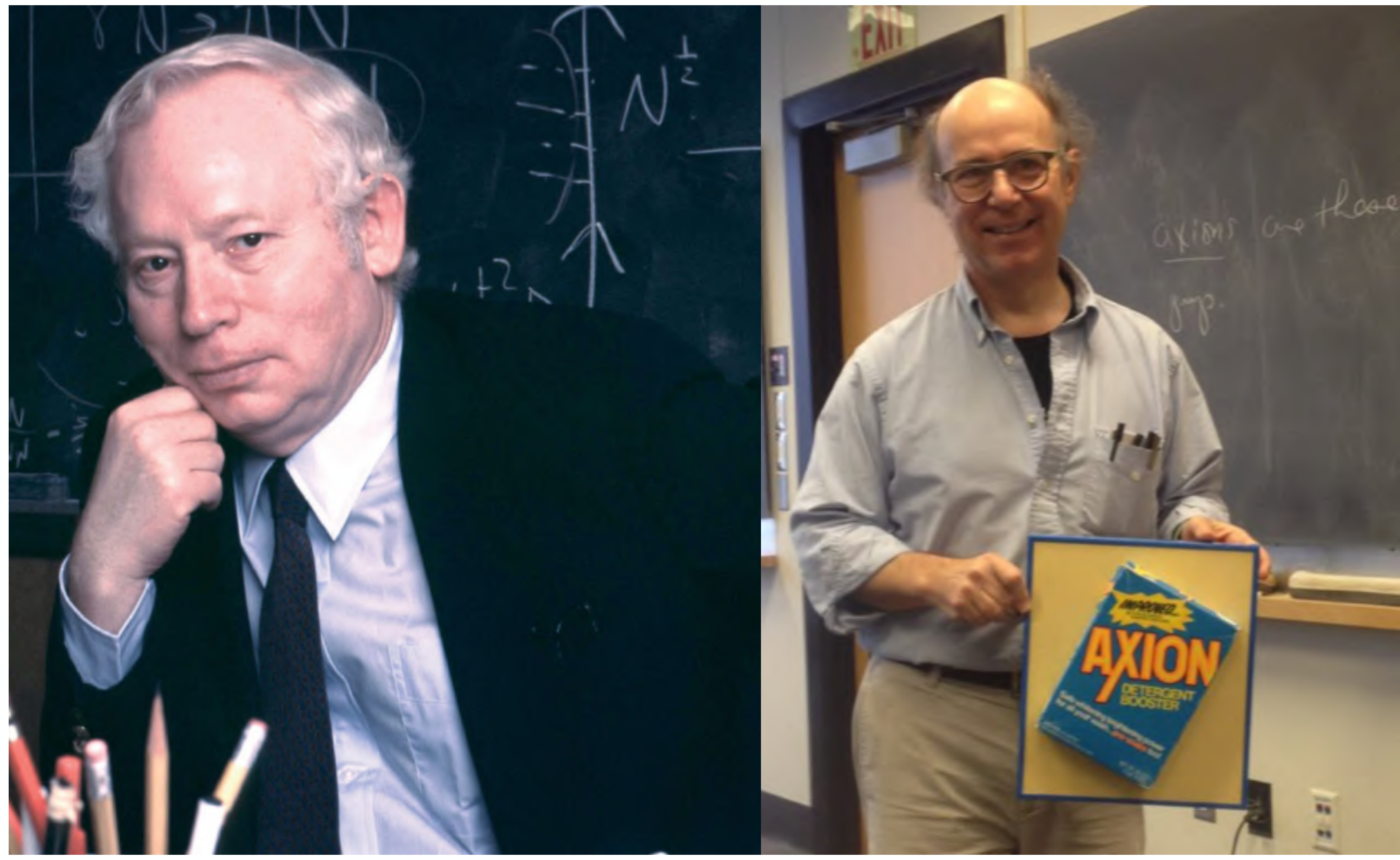


Fig. from Anson Hook, TASI Lectures on Strong CP

Roberto Peccei, Helen Quinn
(photo: Ryan Schude, Quanta Magazine)

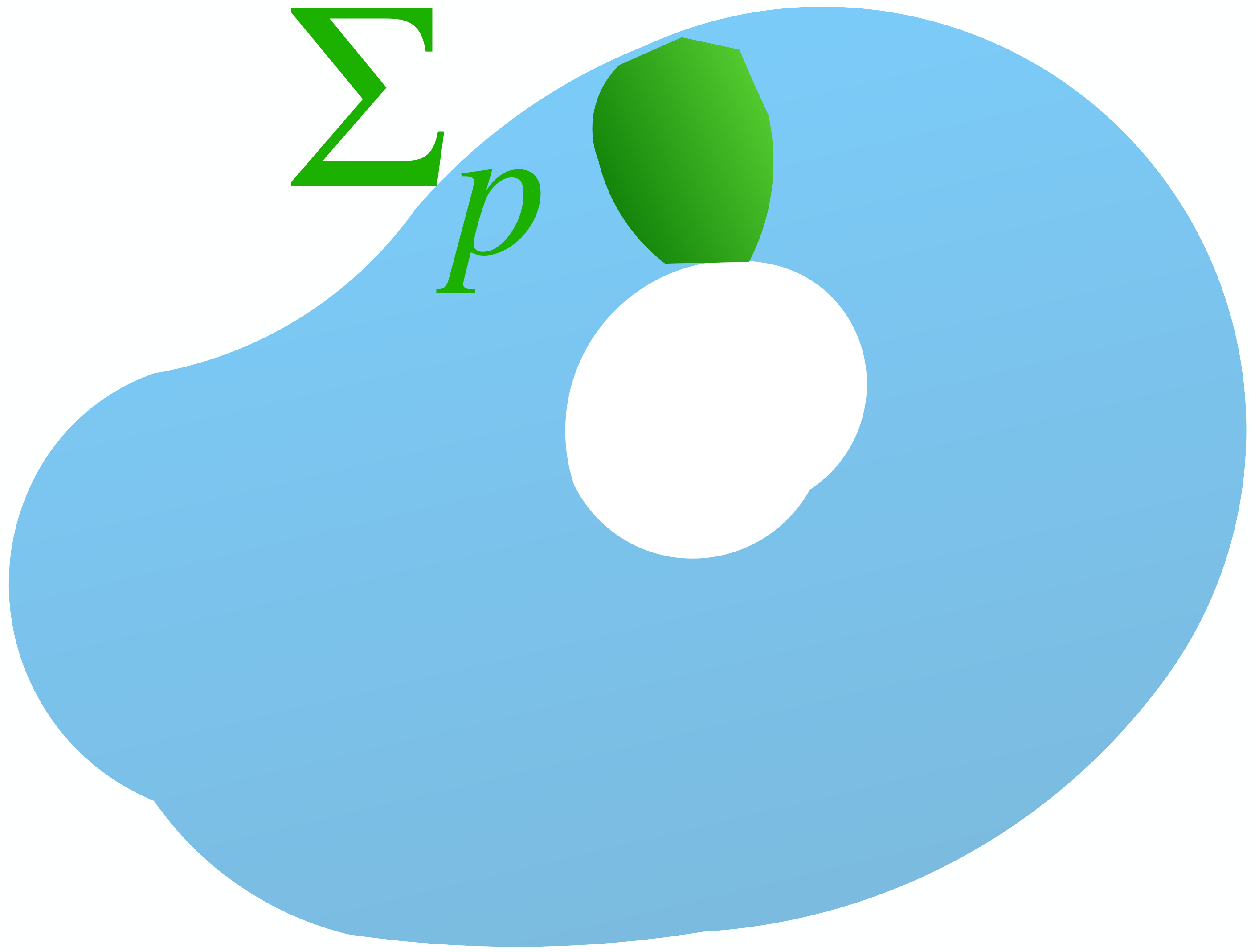


Steven Weinberg, Frank Wilczek

The Ubiquitous Axion: Lamppost or Principle?

There is a large ***Landscape*** of known, consistent quantum gravity theories containing gauge fields. (String compactifications.)

Almost always couple to axions via $\theta \, \mathrm{tr}(F \wedge F)$ interactions!



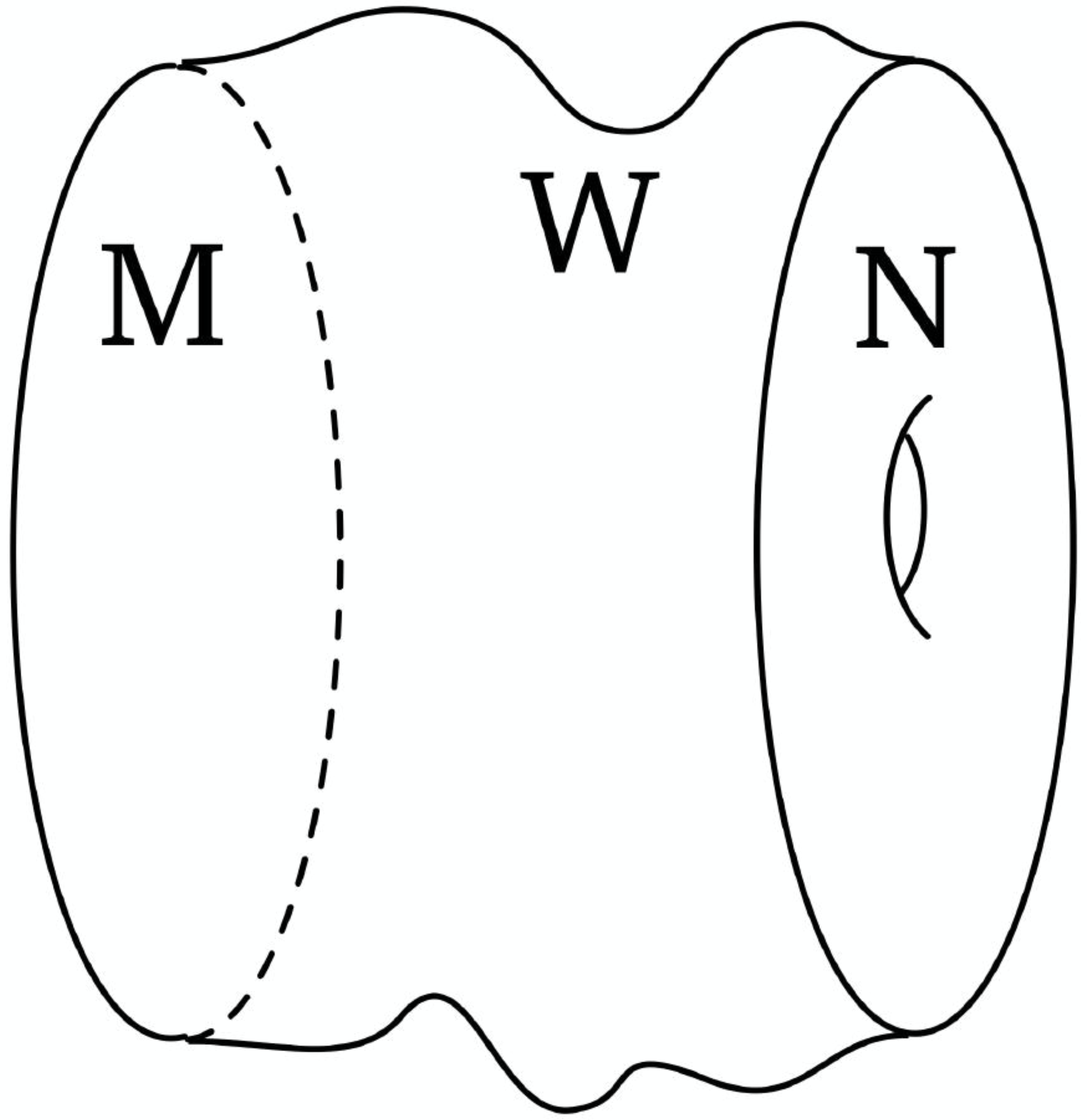
Often higher-dimensional gauge fields C_p with Chern-Simons couplings $C_p \wedge \mathrm{tr}(F \wedge F)$, and $\theta = \int_{\Sigma_p} C_p$.

Is it a generic prediction, or an accident of our current abilities?

Cobordism Conjecture: No Labels in QG

One way to think about an ordinary symmetry is that there is a **label** we can assign to a *state* — its charge — which cannot be altered by continuous variations of the state.

Extend to labels on regions of different dimension, even all spacetime.
In quantum gravity, everything deformable to everything else.



Example: **instanton number** is a label attached to gauge field configurations in spacetime. Quantum gravity should forbid this, somehow.

arXiv:1909.10355, Jake McNamara, Cumrun Vafa

Axions Remove Instanton Number Label

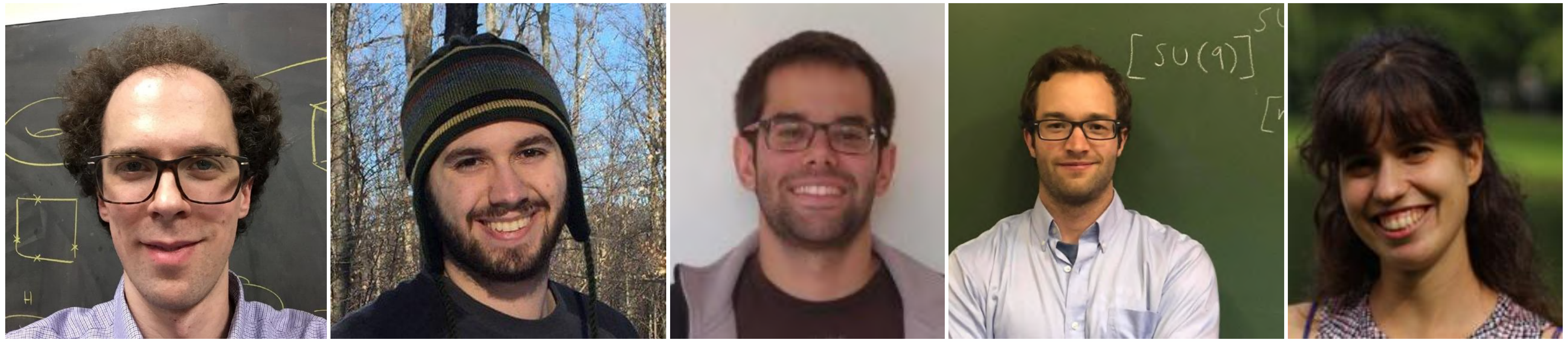
The axion has a job to do in QG:

instanton number density

$$\frac{1}{2} f_a^2 (\partial\theta)^2 + \frac{\theta}{32\pi^2} F^a_{\mu\nu}\tilde{F}^{a\mu\nu} \quad \Rightarrow \quad \partial^\mu (f_a^2 \partial_\mu \theta) = \boxed{\frac{1}{32\pi^2} F^a_{\mu\nu}\tilde{F}^{a\mu\nu}}$$

Gauss law constraint! Axion causes would-be invariant in spacetime (instanton number) to vanish: integral of total derivative.

But this is very qualitative! Can we guide experiments more?



arXiv:2012.00009, Ben Heidenreich, Jake McNamara, Miguel Montero, MR, Tom Rudelius, Irene Valenzuela

Weak Gravity Conjecture (WGC)

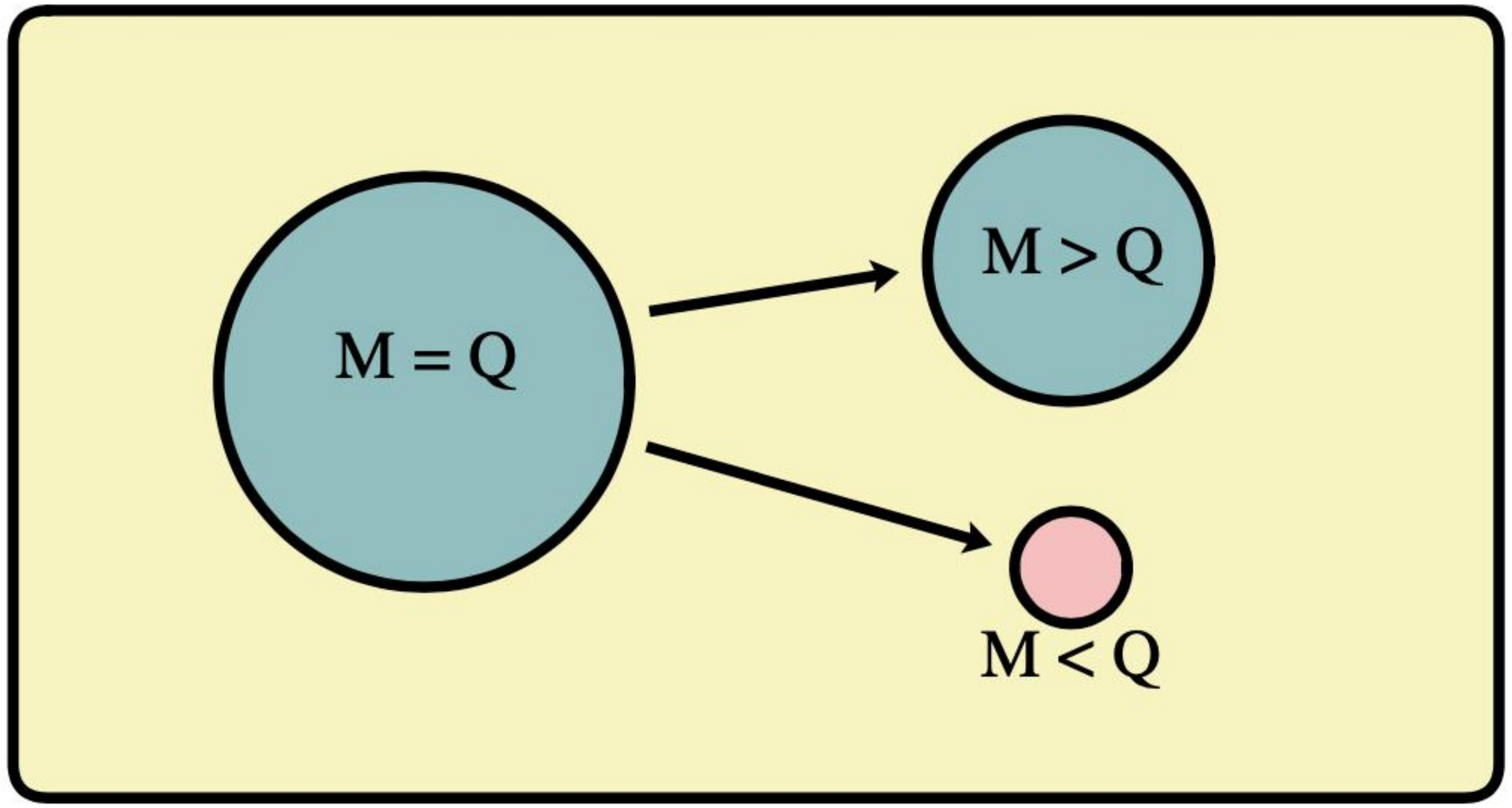
Exists electrically charged object with:

$$m < \sqrt{2} e q M_{\rm Pl}$$

Electric/Magnetic duality
⇒ exists magnetically charged object with:

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

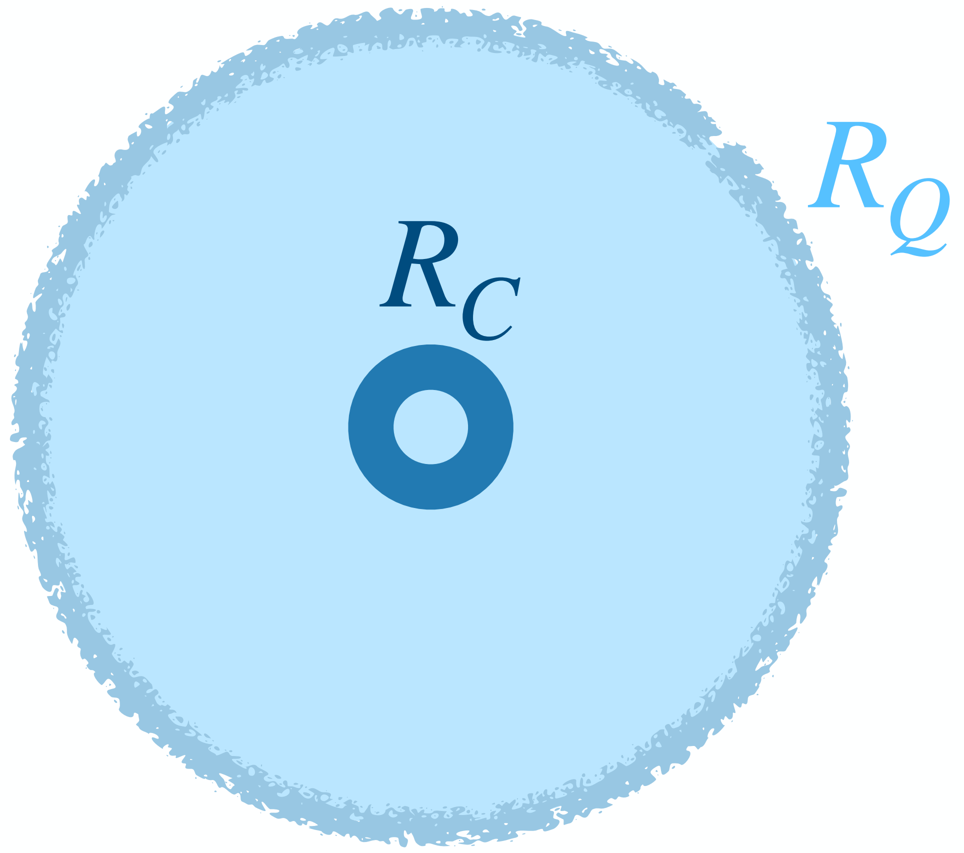
hep-th/0601001, Arkani-Hamed, Motl, Nicolis, Vafa



Necessary condition for discharge of extremal black holes.

Classical vs. Compton Radius of an Object

Electron *classical* radius R_C: integrate energy stored in electric field, down to radius R_C, equals the electron mass.



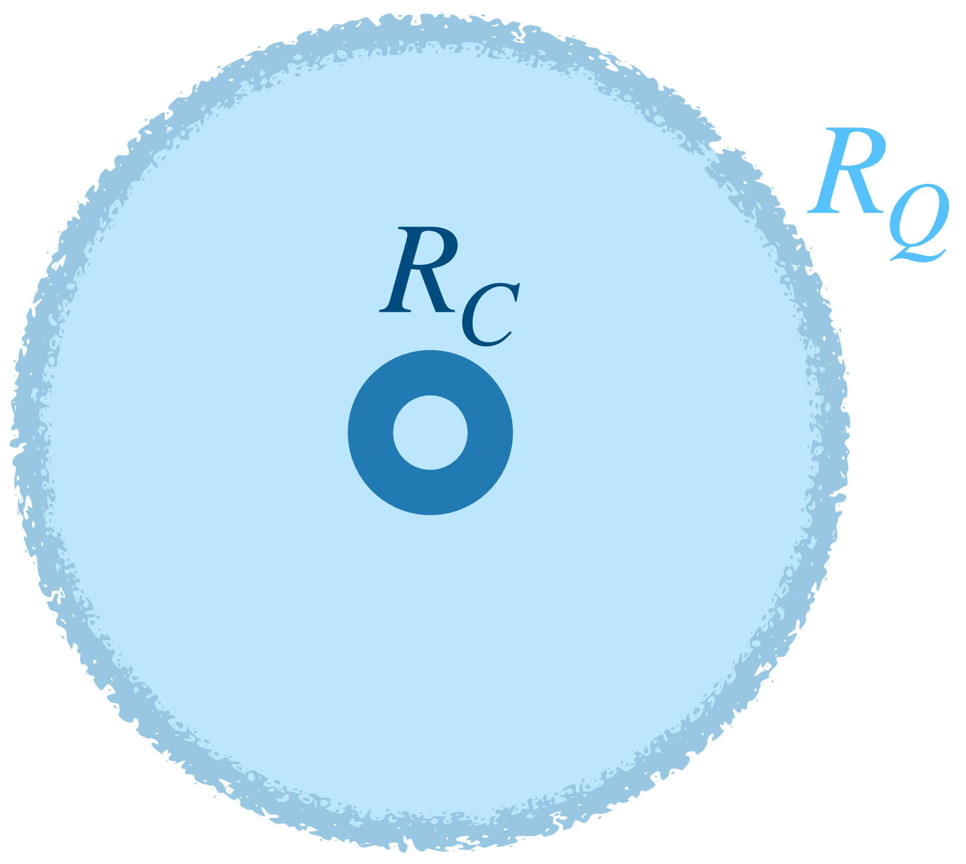
Linearly divergent integral:

$$\int_{R_C}^{\infty} r^2 \mathrm{d}r \mathrm{d}\Omega \left(\frac{e}{r^2}\right)^2 = \frac{4\pi e^2}{R_C} = m_e c^2 . \qquad R_C = \frac{e^2}{4\pi m_e c^2}$$

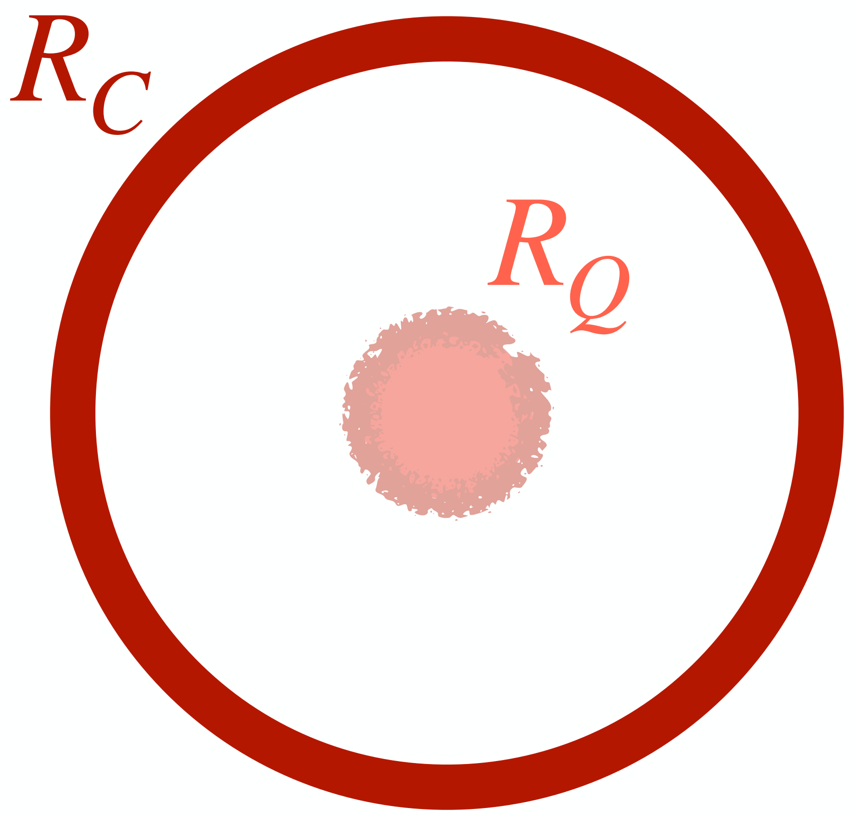
Classical "self-energy" puzzle.

Electron *Compton* radius $R_Q = \dfrac{\hbar}{m_e c}$: at this length scale, quantum effects of virtual electron/positron pairs "screen" the charge.

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

The WGC applied to a magnetically charged object tells us:

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

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

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

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

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

Monopoles That Aren't Black Holes

Aside from the *classical* and *Compton* radii, another important radius in quantum gravity is the *Schwarzschild* radius, $R_S = 2G_N M$.

If $R_S > R_C$, then the monopole *is* a black hole. Suppose that some "elementary" monopole should exist which is *not* a black hole. Then:

$$R_C = \frac{\pi}{e^2 m_{\mathrm{M}}} > R_S = \frac{m_{\mathrm{M}}}{4\pi M_{\mathrm{Pl}}^2} \quad \Rightarrow \quad m_{\mathrm{M}} < \frac{2\pi}{e} M_{\mathrm{Pl}}\,.$$

$$\Rightarrow \quad \Lambda = R_C^{-1} \lesssim e M_{\mathrm{Pl}}\,.$$

Same conclusion, no explicit appeal to WGC!

arXiv:1412.3457, de la Fuente, Saraswat, Sundrum

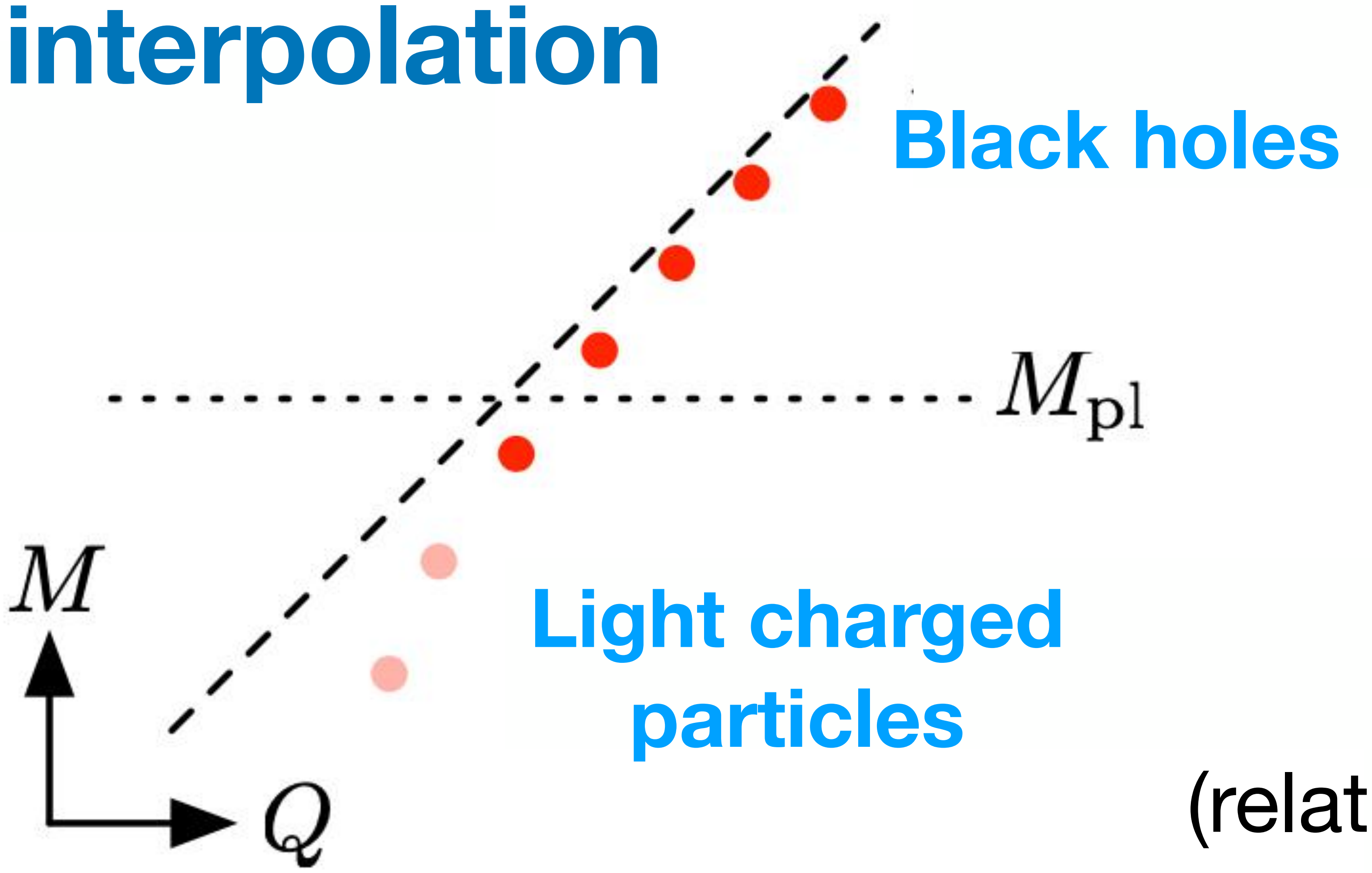
Tower Weak Gravity Conjecture

$\Lambda \lesssim e M_{\rm Pl}$ 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 $m < \sqrt{2} e q M_{\rm Pl}$.

Smooth interpolation



2015-2017: Ben Heidenreich, MR, Tom Rudelius

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

Axions and the WGC

The WGC generalizes to p-form gauge fields: tension $T_p \lesssim e_p M_{\mathrm{Pl}}$.

Axion as “0-form gauge field”: $S_{\mathrm{inst}} \lesssim \dfrac{1}{f_a} M_{\mathrm{Pl}}$.

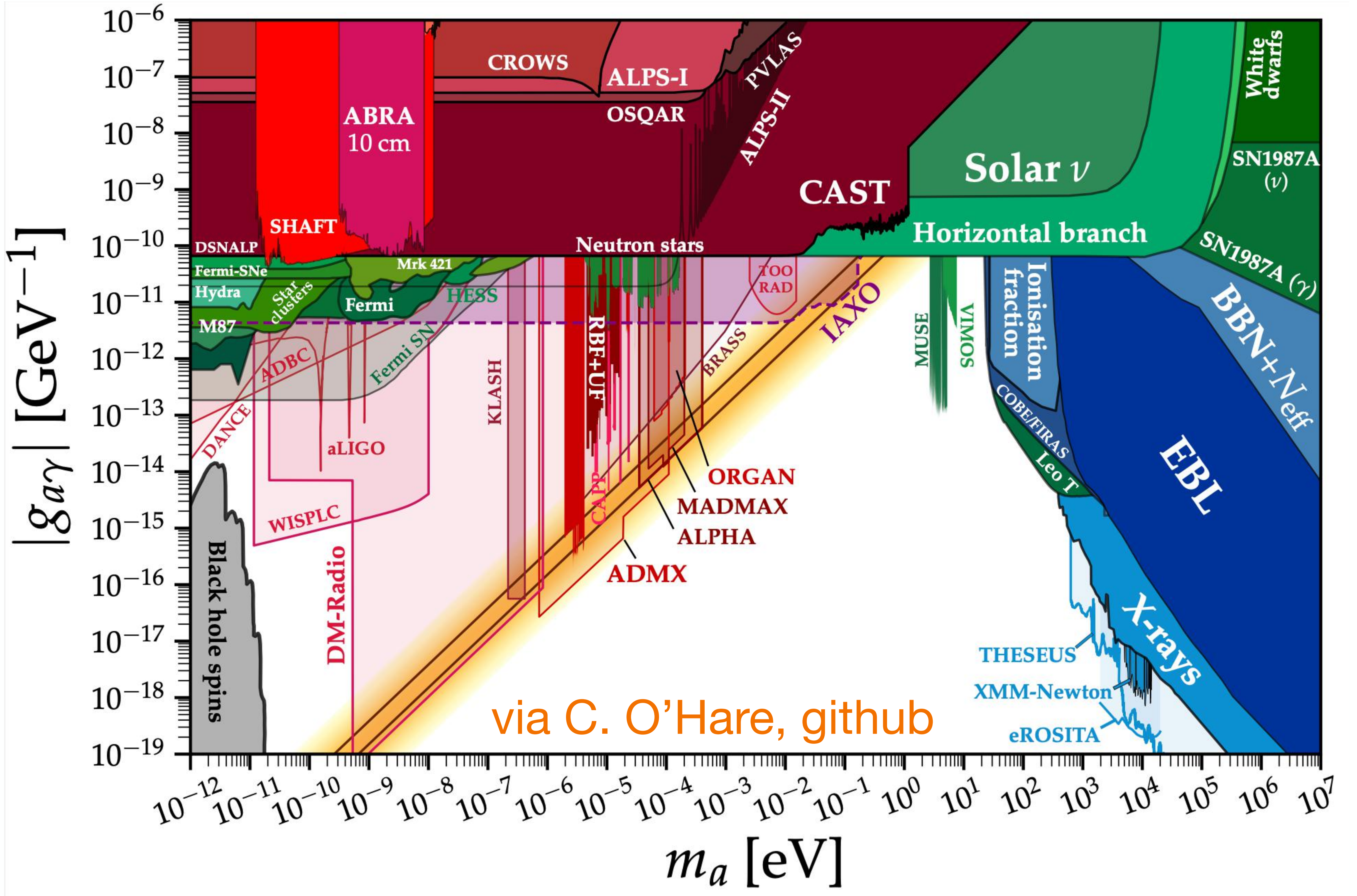
Given $\theta\, \mathrm{tr}(F \wedge F)$;

S_{inst} from usual QCD instantons:

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

Nontrivial phenomenological prediction!

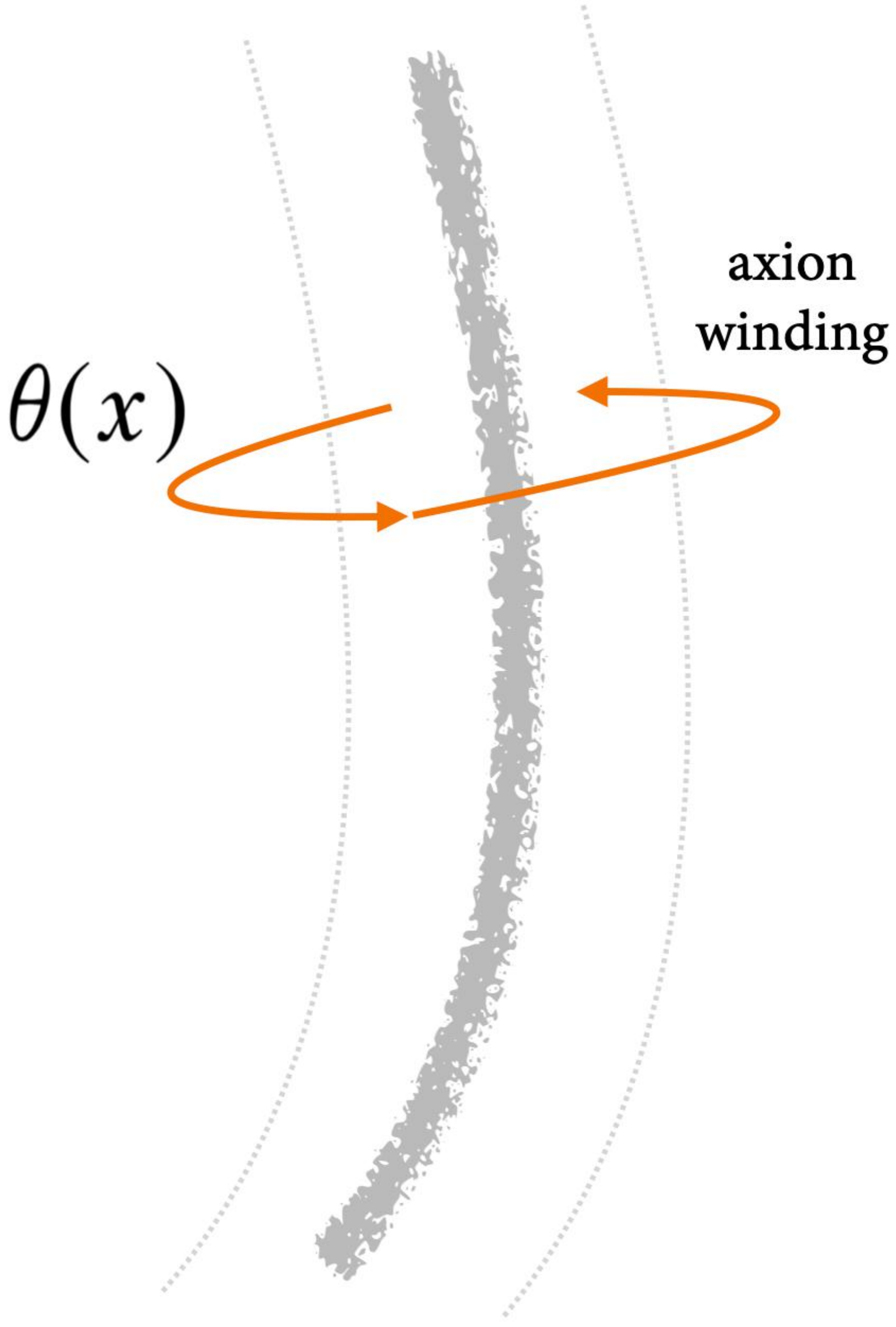
QCD axion with $f_a \lesssim 1.5 \times 10^{16}\,\mathrm{GeV}$.



via C. O’Hare, github

Axion Strings

arXiv:2108.11383 Ben Heidenreich, MR, Tom Rudelius



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

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

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

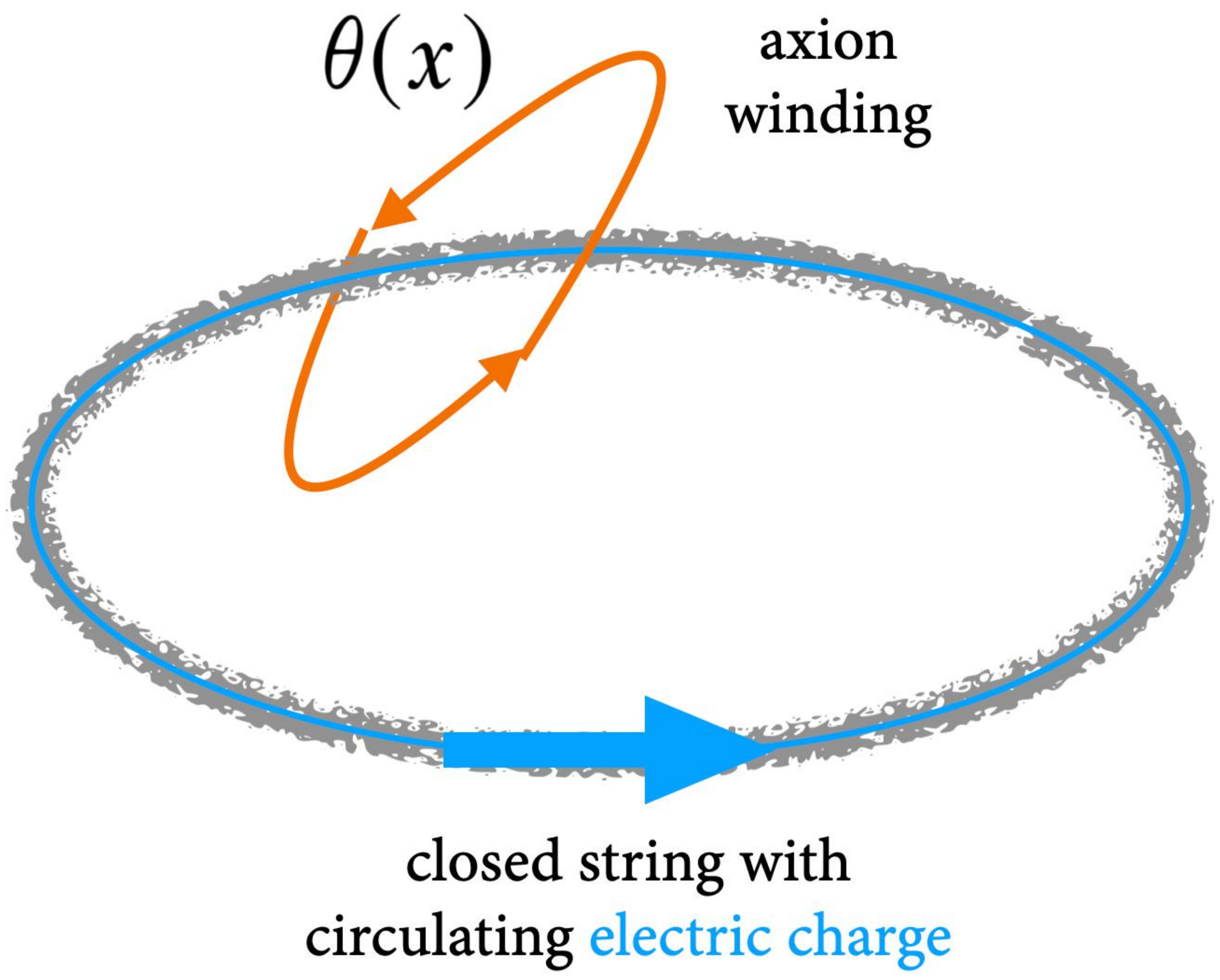
Consistent with black hole symmetry violation:

$$\exp(-8\pi^2/g^2) \gtrsim \exp(-8\pi^2 M_{\rm Pl}^2/\Lambda^2)$$

$$\Leftrightarrow \ \ \Lambda \lesssim g M_{\rm Pl}.$$

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 ⇒ 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!

What about abelian case? No instantons?

Axions and Magnetic Monopoles

Dyons: monopole with *n* units of electric charge, in θ (axion) background

$$m_D^2 = m_M^2 + m_\Delta^2 \left(n - \frac{\theta}{2\pi}\right)^2$$

baseline monopole mass

extra energy in electric field

θ-dependence from Witten effect

Particles with θ-dependent mass

$\Downarrow$

θ-dependent vacuum energy

(“Coleman-Weinberg potential”)

arXiv:2105.09950 JiJi Fan, Katie Fraser, MR, John Stout

Axion Potential from Virtual Monopoles

Tower of Dyons
Sum vacuum loops over *n*

Poisson
resummation

Winding of zero mode σ
Sum over winding ℓ

$$V_{\mathrm{eff}}(\theta) = -\frac{m_\Delta^4}{2(2\pi)^6}\sum_{\ell=1}^{\infty} \mathrm{e}^{-\ell S}\cos(\ell\theta)\left(\frac{3}{\ell^5}+\frac{3S}{\ell^4}+\frac{S^2}{\ell^3}\right), \quad S = \frac{2\pi m_{\mathrm{M}}}{m_\Delta}$$

$S \sim 1/e^2$; $S = 8\pi^2/g^2$ for critical ’t Hooft-Polyakov monopole!

New source of nonperturbative axion potential, from virtual magnetic monopoles. Any axion interacting with the photon is expected to acquire such a mass! *(Subtleties related to charged fermion mass-dependence currently under study.)*

arXiv:2105.09950 JiJi Fan, Katie Fraser, MR, John Stout

Conclusions

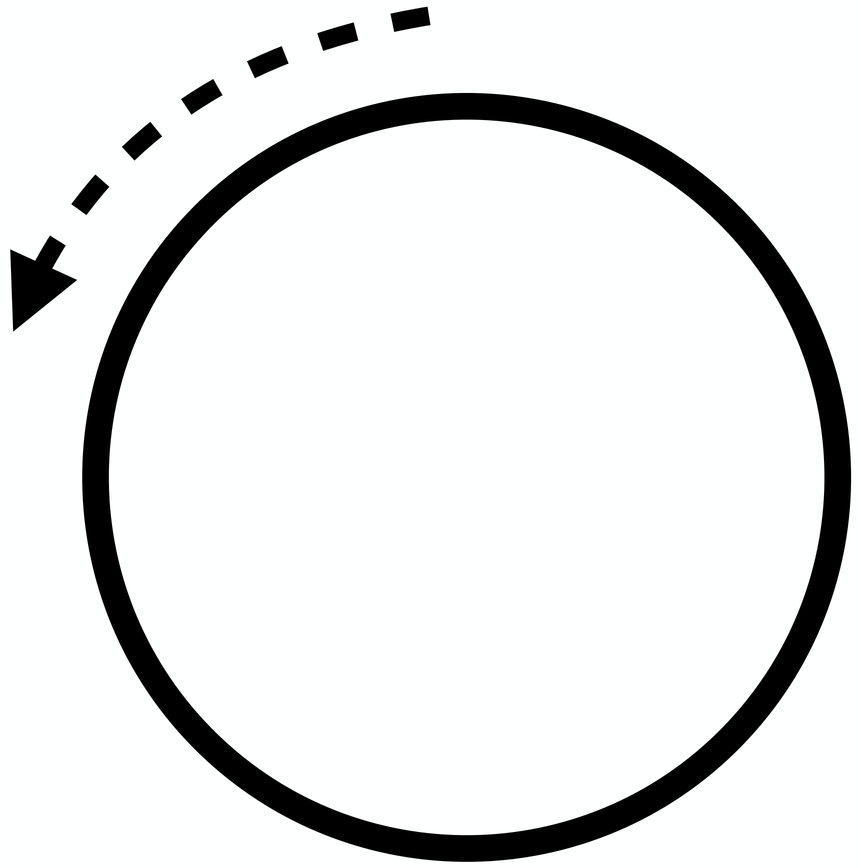
- Approximate global symmetries in the world around us: baryon number, lepton number, flavor symmetries, parity…. Even more *generalized* symmetries, like instanton number.
- Quantum gravity forbids symmetries. Whatever symmetries we see should be *approximate* symmetries enforced by underlying *gauge constraints*.
- Current, important experiments quantifying symmetry breaking: EDMs, $\mu \to e\gamma$, proton decay, axion searches. They can shed light on fundamental questions.
- Axion physics is an arena where quantitative statements about quantum gravity, like the Weak Gravity Conjecture, might find real-world tests.

Thanks for listening!

backup

Example: Kaluza-Klein Theory

A circular extra dimension gives a classic example of how to obtain a gauge charge within a gravitational theory.



Charge q = number of units of momentum around the circle.

$$\sqrt{-g}\left[\underset{\substack{\swarrow \\ \text{gravity}}}{\frac{M_{\text{Pl}}^2}{2}\mathscr{R}_4} - \underset{\substack{\downarrow \\ \text{radion}}}{\frac{1}{2}(\partial\phi)^2} - \underset{\substack{\searrow \\ \text{U(1) gauge field}}}{\frac{1}{4e_{\text{KK}}^2}\mathrm{e}^{\alpha\phi}F_{\mu\nu}^2}\right]$$

$$e_{\text{KK}}^2 = \frac{2}{R^2 M_{\text{Pl}}^2}$$

large radius ⟺ small gauge coupling

$$m_q = \frac{|q|}{R} = \frac{|q|\,e_{\text{KK}}}{\sqrt{2}}M_{\text{Pl}}$$

infinite tower of KK mode masses proportional to gauge coupling

$$M_{5d} \sim e_{\text{KK}}^{1/3} M_{\text{Pl}}$$

UV cutoff small as well