Can the Weak Gravity Conjecture Rule Out Effective Field Theories?

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Conference on “The Weak Gravity Conjecture and Cosmology” at IFT UAM-CSIC

Based on arXiv:1412.3457 and arXiv:1604.XXXX with Anton de la Fuente and Raman Sundrum

Outline

- Intro: Why EFT and WGC?
- Review: Forms of the WGC and bottom-up motivations
- Example: Higgsing to generate violation of WGC at low energies
  - Extremal black hole decay?
  - Magnetic monopoles?
- Revisiting Extranatural Inflation: Minimality + WGC makes predictions
- Proposed "ultimate" WGC: Bound on cutoff is logarithmic in the gauge coupling?

The Weak Gravity Conjecture and Cosmology

The Weak Gravity Conjecture and Cosmology

Many different claims under this name, with two basic classes of arguments:

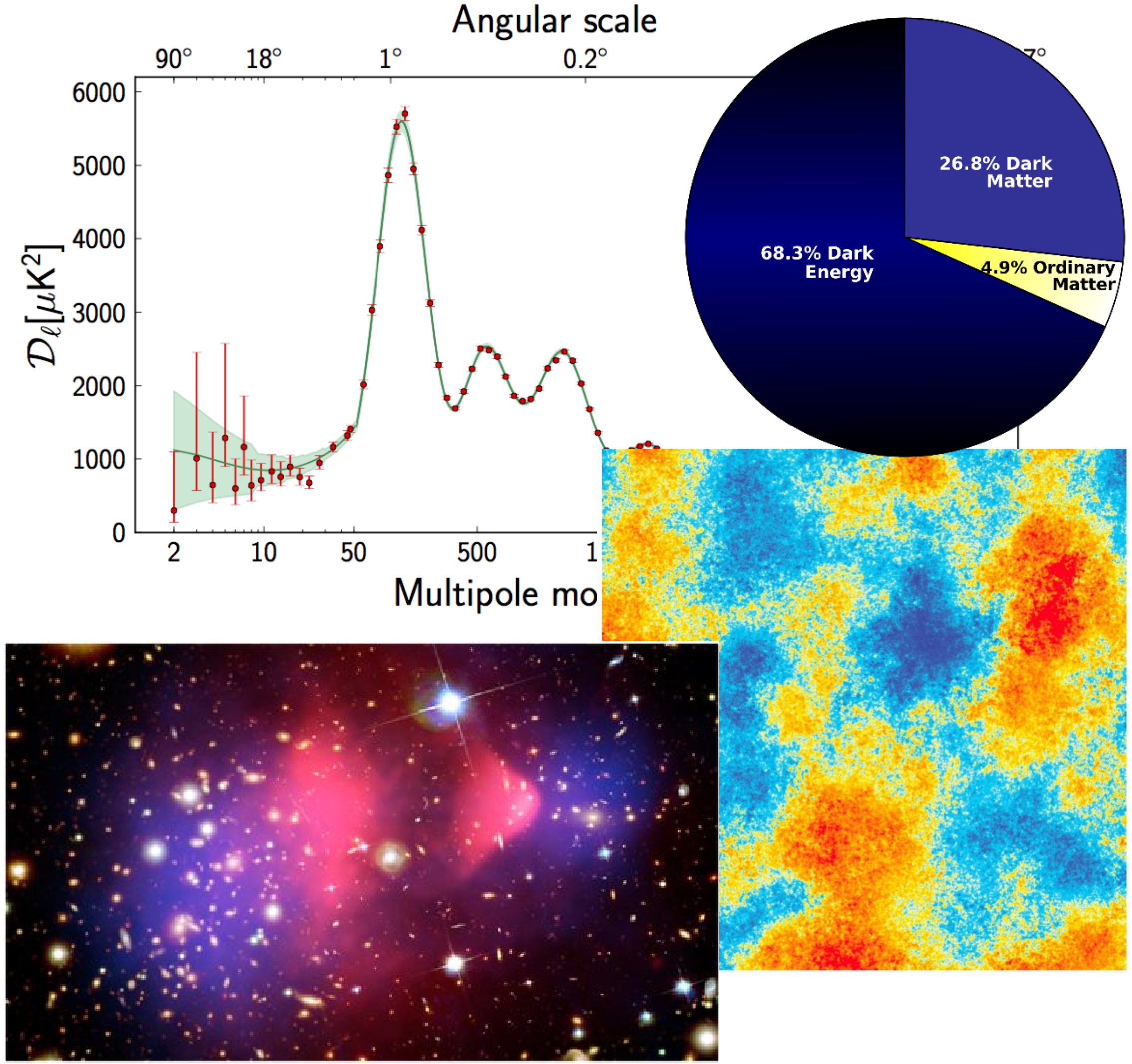
- “Top-down”: Explore candidate QG theories (e.g. examples string theory examples or emergent gauge fields) and check that constraints are satisfied. Can’t be exhaustive, only “looking under the lamppost.”

- “Bottom-up”: Argue from universal, low-energy features of theories with gauge fields + gravity: charged black holes

The Weak Gravity Conjecture and Cosmology

Many open questions about the role of new physics to explain:

- Inflation / Primordial density fluctuations
- Dark matter
- Dark energy (dynamical?)
- Hierarchy problem ("cosmological relaxation")



Effective Field Theory

The conventional wisdom:

“You don’t need to know atomic physics to cook spaghetti”

Effective Field Theory

The conventional wisdom:

describe low-energy physics

quantum gravity

"You don't need to know ~~atomic physics~~ to ~~cook spaghetti~~"

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EFT: Describe systems at low energy, with UV effects suppressed by decoupling and/or symmetry. Allows us to efficiently explore the space of models and their possible predictions

Challenged by the "swampland" program: Perhaps certain naïvely valid EFTs *cannot possibly* be completed into quantum gravity?

The question for phenomenology: Should the WGC be a veto on EFT models?

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I’ll argue that this would not be consistent, as theories which satisfy the WGC can still give rise to low-energy EFTs which violate it.

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I’ll argue that this would not be consistent, as theories which satisfy the WGC can still give rise to low-energy EFTs which violate it.

However, the model-building required to achieve this could have important consequences for observation.

The Many Faces of the Weak Gravity Conjecture

“Electric form”: Constraint on the spectrum of charged particles. $m < qM_{\mathrm{pl}}$-- for at least one particle? The lightest particle? All possible charges?

“Magnetic form”: Upper bound on the cutoff of effective field theory $\Lambda < eM_{\mathrm{pl}}$where e is the unit of charge

“0-form” WGC: Constraint on instanton contributions to axion potentials, by analogy/extrapolation from electric form

The Electric WGC and Extremal Black Hole Decay

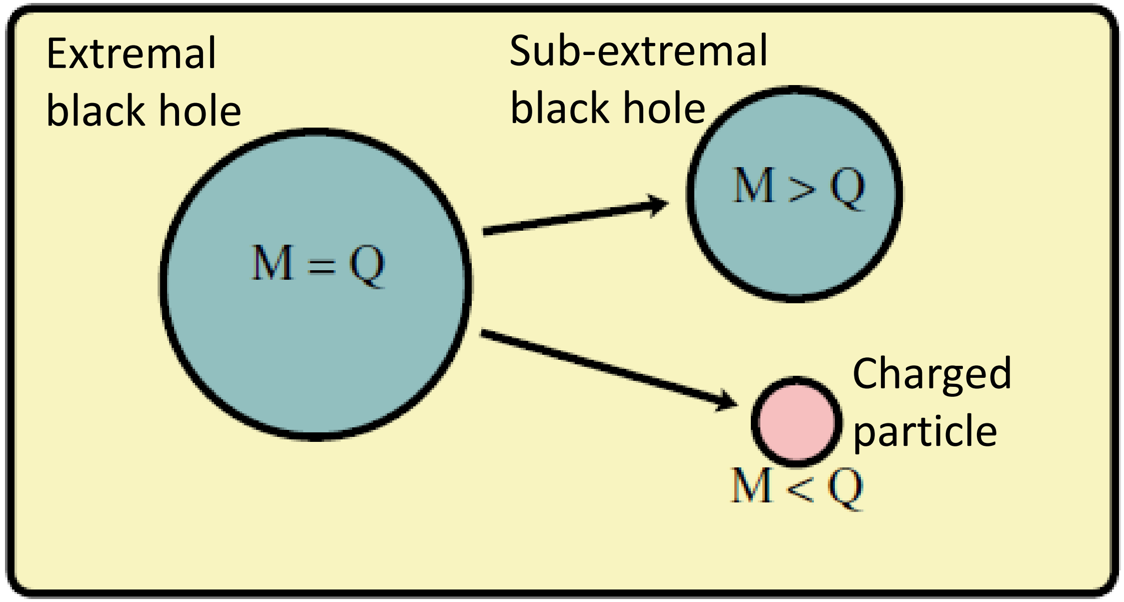


Figure from Arkani-Hamed, Motl, Nicolis, Vafa hep-th/0601001

Unless there are states with $M < Q$, extremal black hole are stable

Same problems as remnants? Not really, since due to charge quantization there are a finite number of states below any given mass

Black hole decay guaranteed by higher-order corrections?

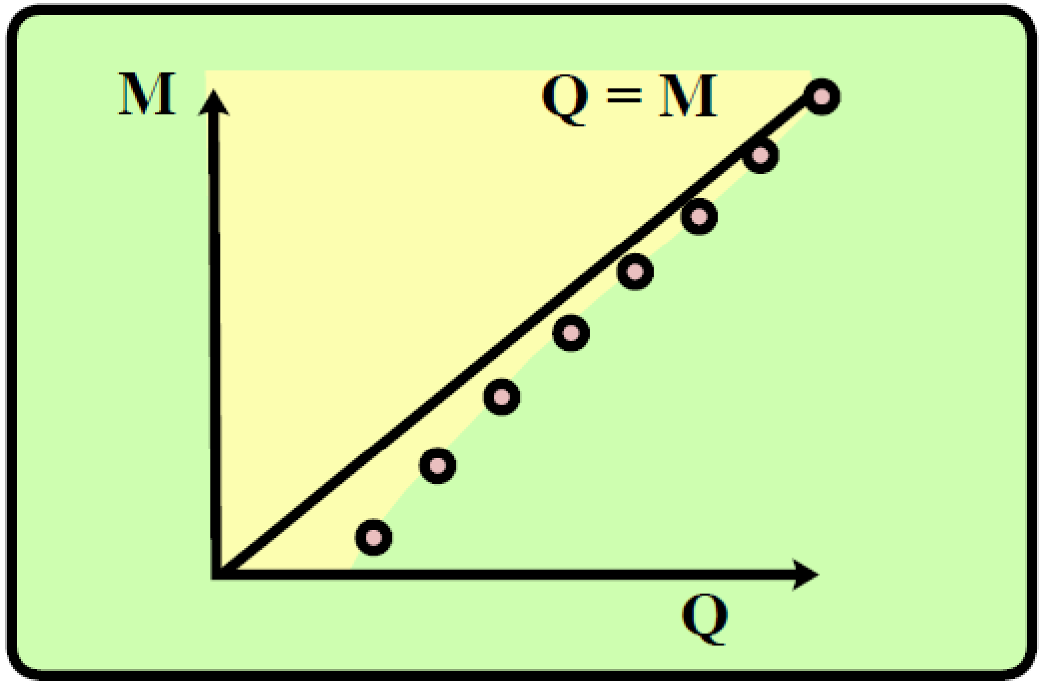


Figure from Arkani-Hamed, Motl, Nicolis, Vafa hep-th/0601001

Kats, Motl, Padi hep-th/0606100:
Within gauge+gravity EFT, nonrenormalizable terms such as $|F^{\mu\nu}|^4$ always shift extremal bound so that $M < Q$ for light black holes

→ All black holes can decay regardless of particle spectrum!

Forms of the Electric WGC

Just assume for now: extremal black holes must be able to decay into elementary charged particles.

Motivates "minimal" WGC: there exists *some* particle with $m < qM_{\mathrm{pl}}$

Other forms have been proposed in the literature

- "Strong" WGC: $m < qM_{\mathrm{pl}}$ for the *lightest* charged particle
- "Unit-charge" WGC: $m < qM_{\mathrm{pl}}$ for a particle of *minimal* charge
  - Related to "Lattice" WGC: For every allowed *q* there exists a state with $m < qM_{\mathrm{pl}}$

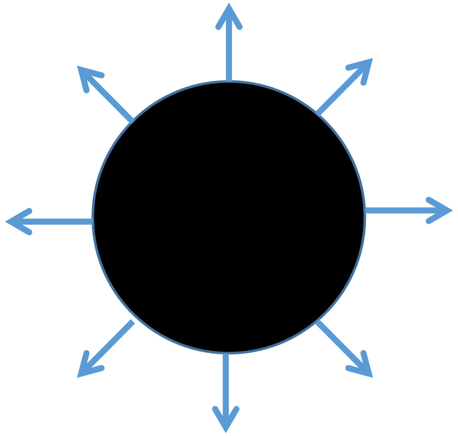
The Magnetic WGC

U(1) gauge groups must be compact (quantized charge), otherwise there is an exactly conserved global symmetry (e.g. Banks, Seiberg 1011.5120). Therefore there exist magnetic BH solutions.

Minimal (extremal) magnetic BH is in EFT control and has finite entropy:

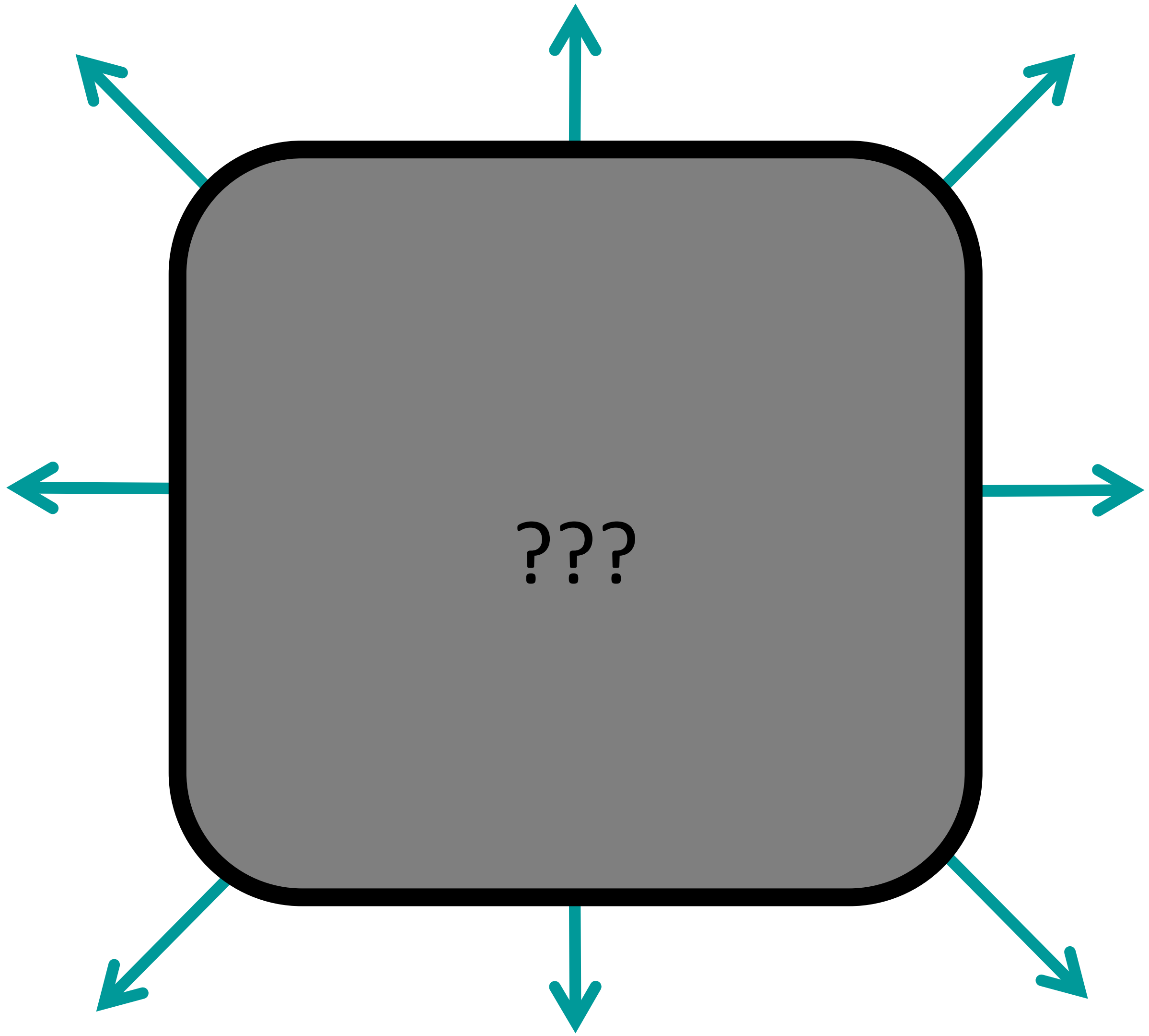
$$M \sim Q_{\mathrm{mag}} M_{\mathrm{pl}} = \frac{2\pi}{e} M_{\mathrm{pl}}$$

$$S \sim 1/e^2$$



$$Q_{\mathrm{mag}} = \frac{2\pi n}{e}$$

de la Fuente, PS, Sundrum (2014)



We have a black box with *large entropy* and an *exactly conserved charge*. “Usual” assumption is that the box contains “constituents” (possibly tightly bound) giving rise to the charge.

***Conjecture*:** There must also be a fundamental (zero entropy) magnetic monopole in the spectrum to explain these black holes

Magnetic monopole cannot be pointlike; its size defines a cutoff length scale $1/\Lambda$

Mass of monopole (magnetic self-energy) is

$$M_{\text{monopole}} \sim \int d^3x B^2 \sim \frac{\Lambda}{e^2}$$

Require Schwarzschild radius to be less than $1/\Lambda$:

$$\frac{\Lambda}{e^2 M_{\text{pl}}^2} \lesssim \frac{1}{\Lambda} \rightarrow \boxed{\Lambda \lesssim e M_{\text{pl}}}$$

Argument based on decay of extremal black holes

"Minimal" electric WGC:
$m < qM_{\mathrm{pl}}$ for some particle

Does ***not*** constrain low-energy EFT

No apparent argument from black hole physics

"Strong" electric WGC:
$m < qM_{\mathrm{pl}}$ for lightest charged particle

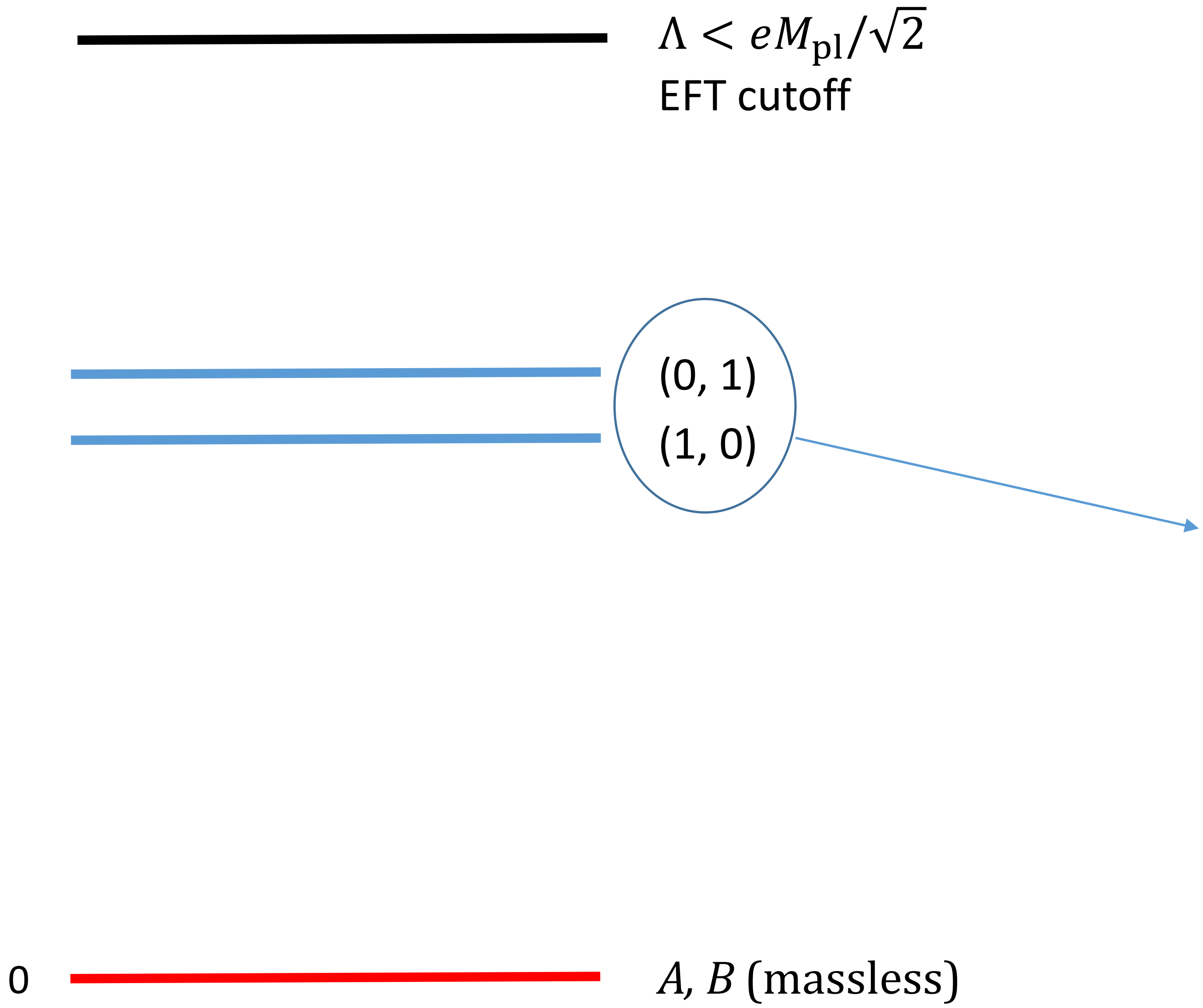
"Unit charge"/"Lattice" WGC:
$m < qM_{\mathrm{pl}}$ for minimally charged particle

Increasingly strong constraints on low-energy EFT

Argument based on origin of magnetic black hole charge

Magnetic WGC:
Field theory cutoff at $\Lambda < eM_{\mathrm{pl}}$

Violating the WGC in Low-Energy EFT



Example model:

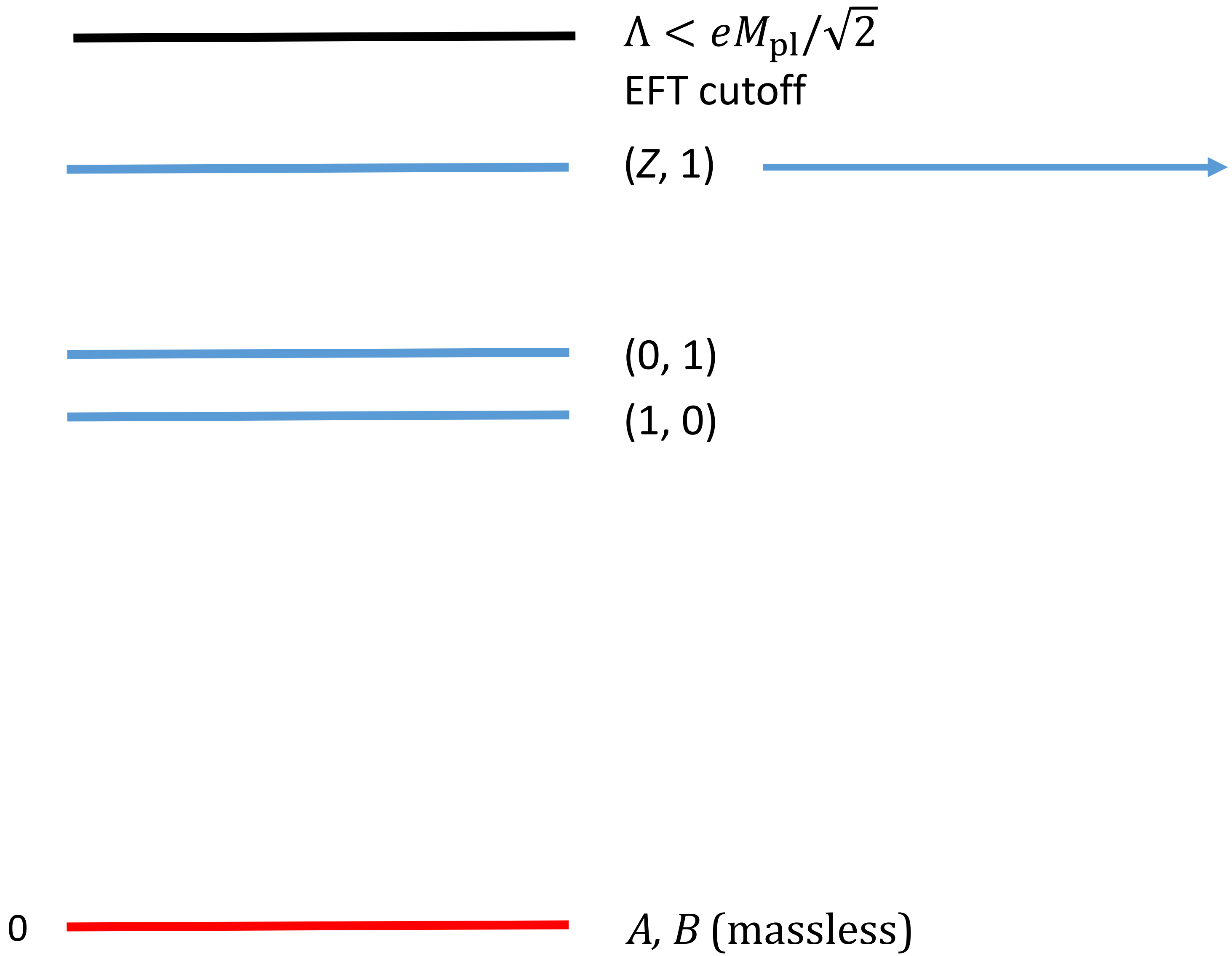
$$U(1)_A \times U(1)_B$$

Two $U(1)$'s A and B, with same gauge coupling e (for simplicity)

Charges under (A, B)

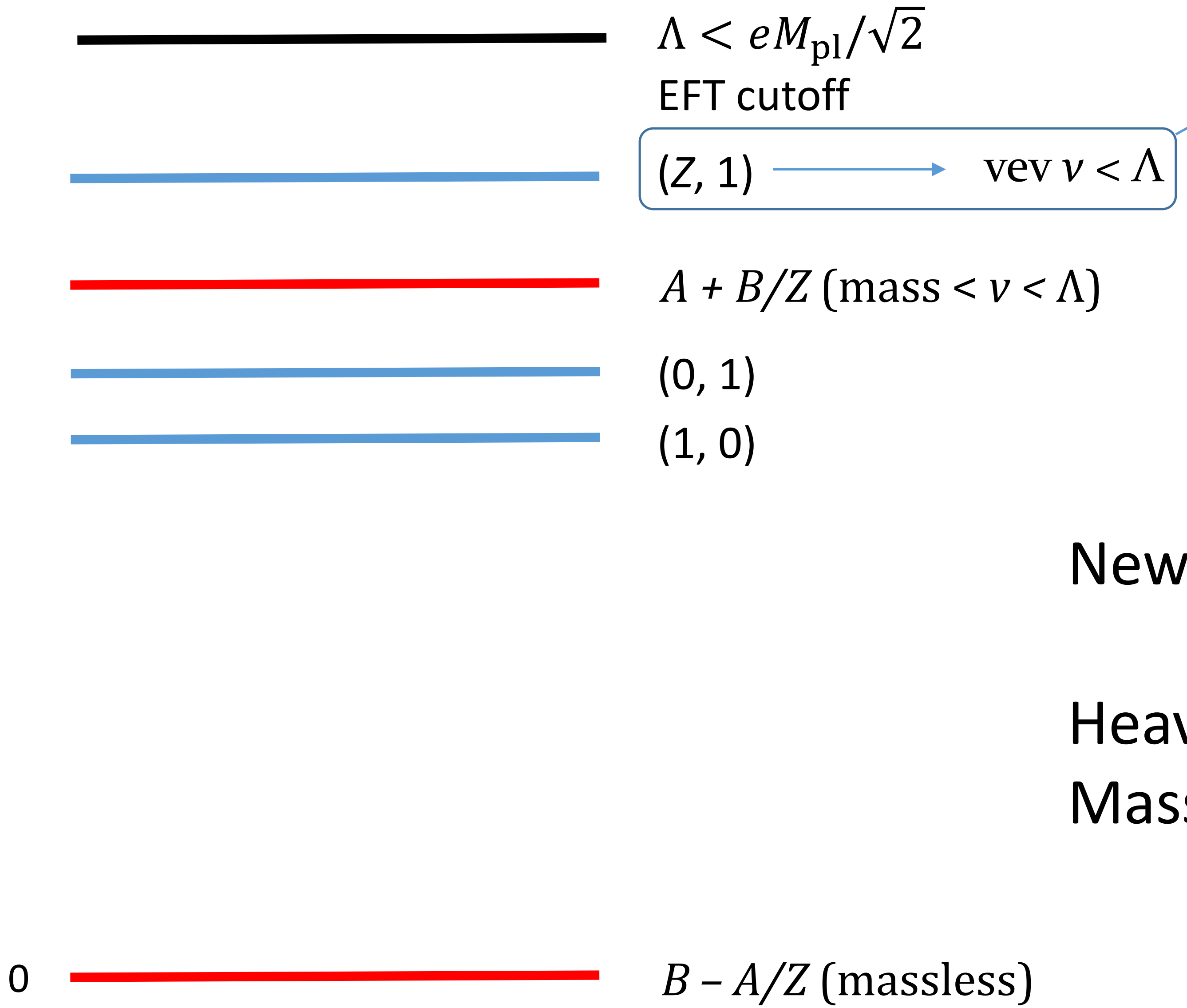
Satisfies all forms of the WGC discussed here

Violating the WGC in Low-Energy EFT



Now add a scalar with these charges under (A, B). Still satisfies all WGCs including strong, unit-charge etc.

Violating the WGC in Low-Energy EFT



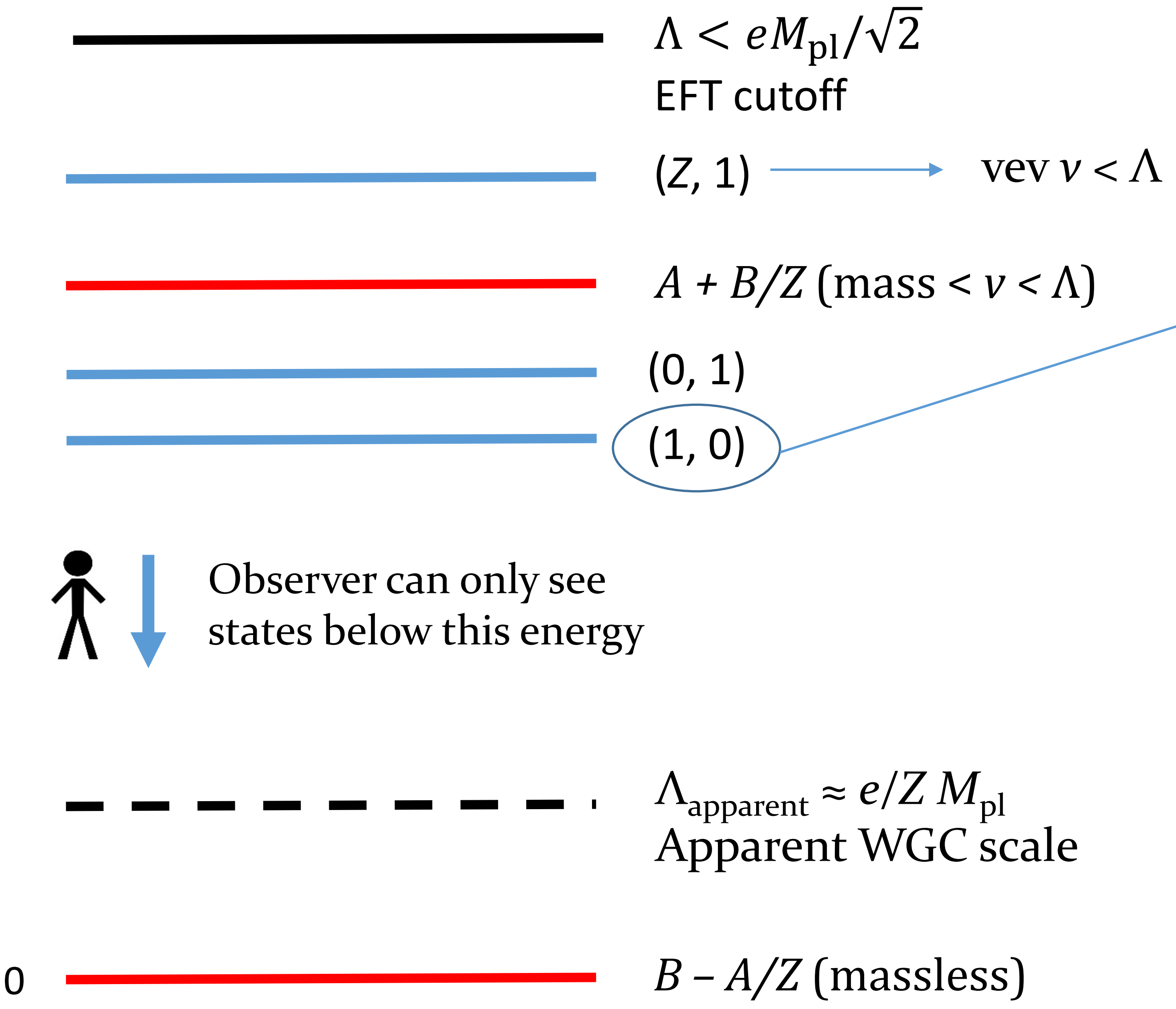
Now consider a Higgs phase in which this scalar gets a vev.

Consider $Z \gg 1$, but keep $Ze < 1$ for perturbativity

New mass basis for gauge fields:

Heavy: $A + B/Z$ with mass $(Ze)v < \Lambda$
Massless: $B - A/Z$

Violating the WGC in Low-Energy EFT

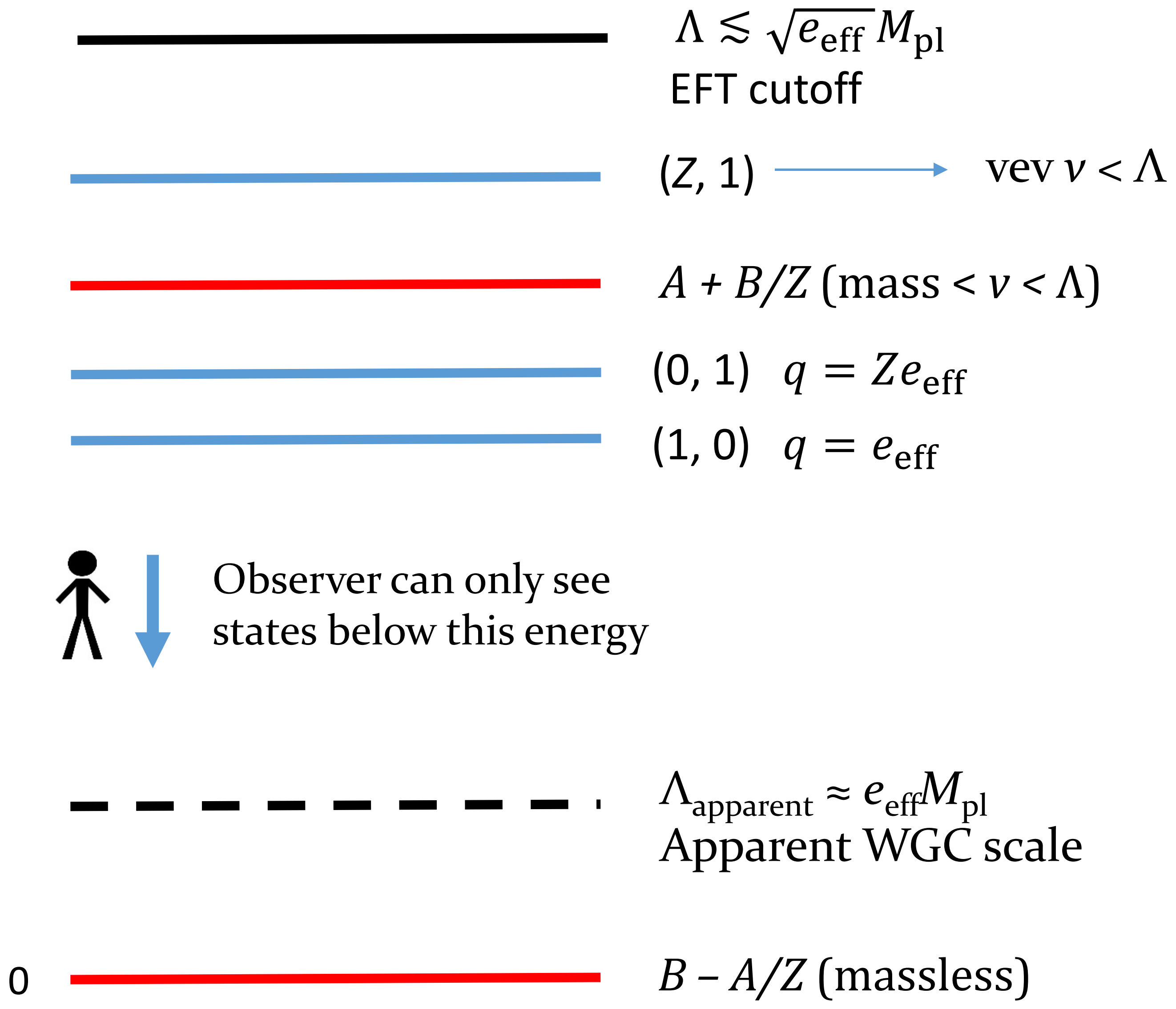


Under the massless field $B - A/Z$, particles can have charge e/Z

Low-energy observer sees massless $U(1)$ with charge quantum $e_{\text{eff}} = e/Z$

But *no charged particles or EFT cutoff* below the "WGC scale" $\Lambda_{\text{apparent}} = e/Z\; M_{\text{pl}}$!

Violating the WGC in Low-Energy EFT



Because $Ze < 1$ to ensure perturbativity, we have the bound $e_{\text{eff}} = e/Z > e^2$

In terms of the low-energy gauge coupling e_{eff}, the actual cutoff is at $\Lambda \lesssim \sqrt{e_{\text{eff}}} M_{\text{pl}}$

Argument based on decay of extremal black holes

OK

"Minimal" electric WGC:
$m < qM_{\mathrm{pl}}$ for some particle

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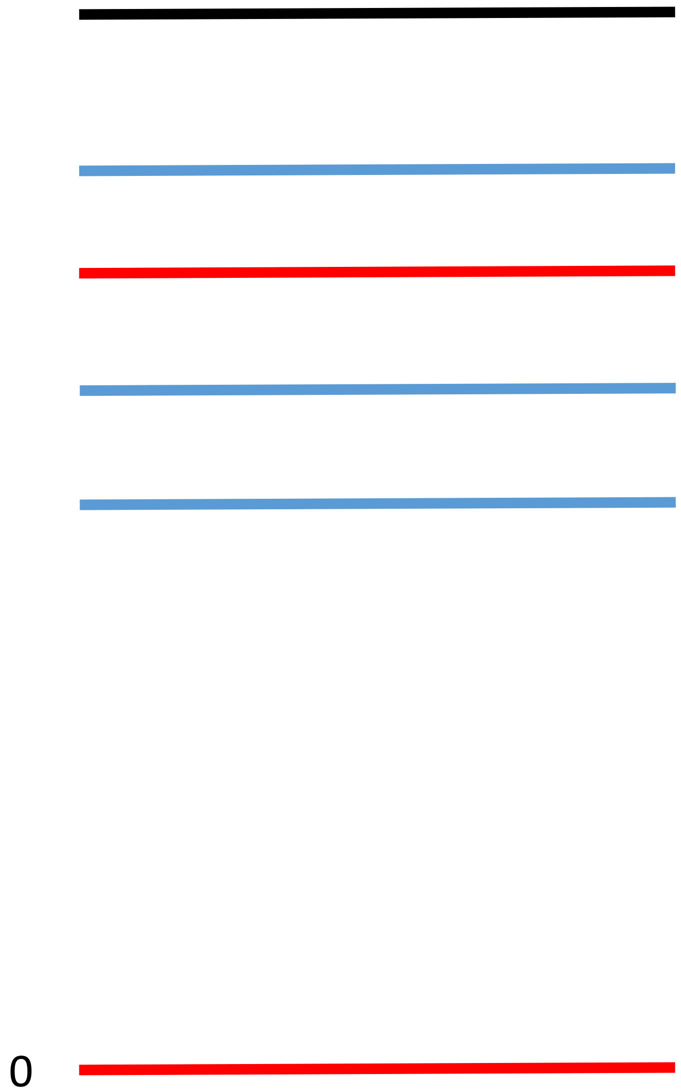
~~Magnetic WGC:~~
~~Field theory cutoff at $\Lambda < eM_{\mathrm{pl}}$~~

What Happened to the Electric WGC?



$\Lambda < eM_{\mathrm{pl}}/\sqrt{2}$
EFT cutoff

$(Z, 1)$ $q_{\mathrm{eff}} = 0$

$(0, 1)$ $q_{\mathrm{eff}} = e > m/M_{\mathrm{pl}}$

$(1, 0)$ $q_{\mathrm{eff}} = e/Z < m/M_{\mathrm{pl}}$

$B - A/Z$ (massless)

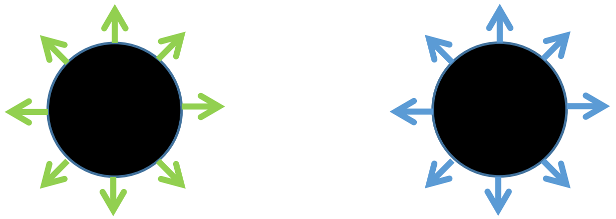
Charged black holes still have two-body decays, losing *Z* units of the *e/Z* charge quantum

Can check that every black hole with size greater than the true WGC cutoff Λ^{-1} can decay *completely* into the charged particles

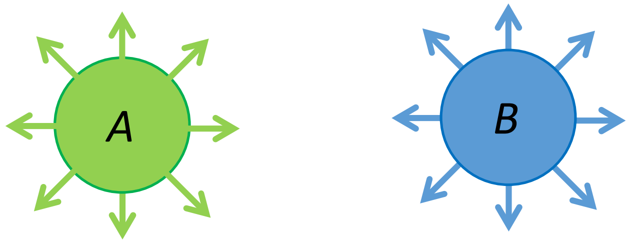
What Happened to the Magnetic WGC?

In the Coulomb phase:

BHs exist with magnetic charge $2\pi/e$ under A and B

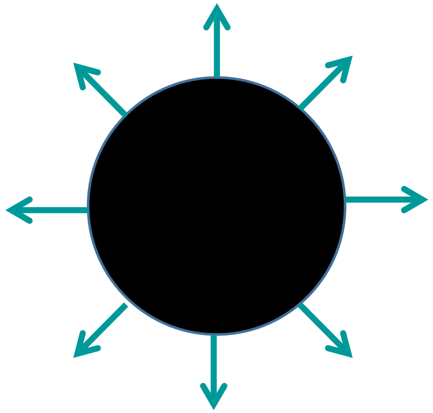


We demanded that there also exist monopoles which are not black holes



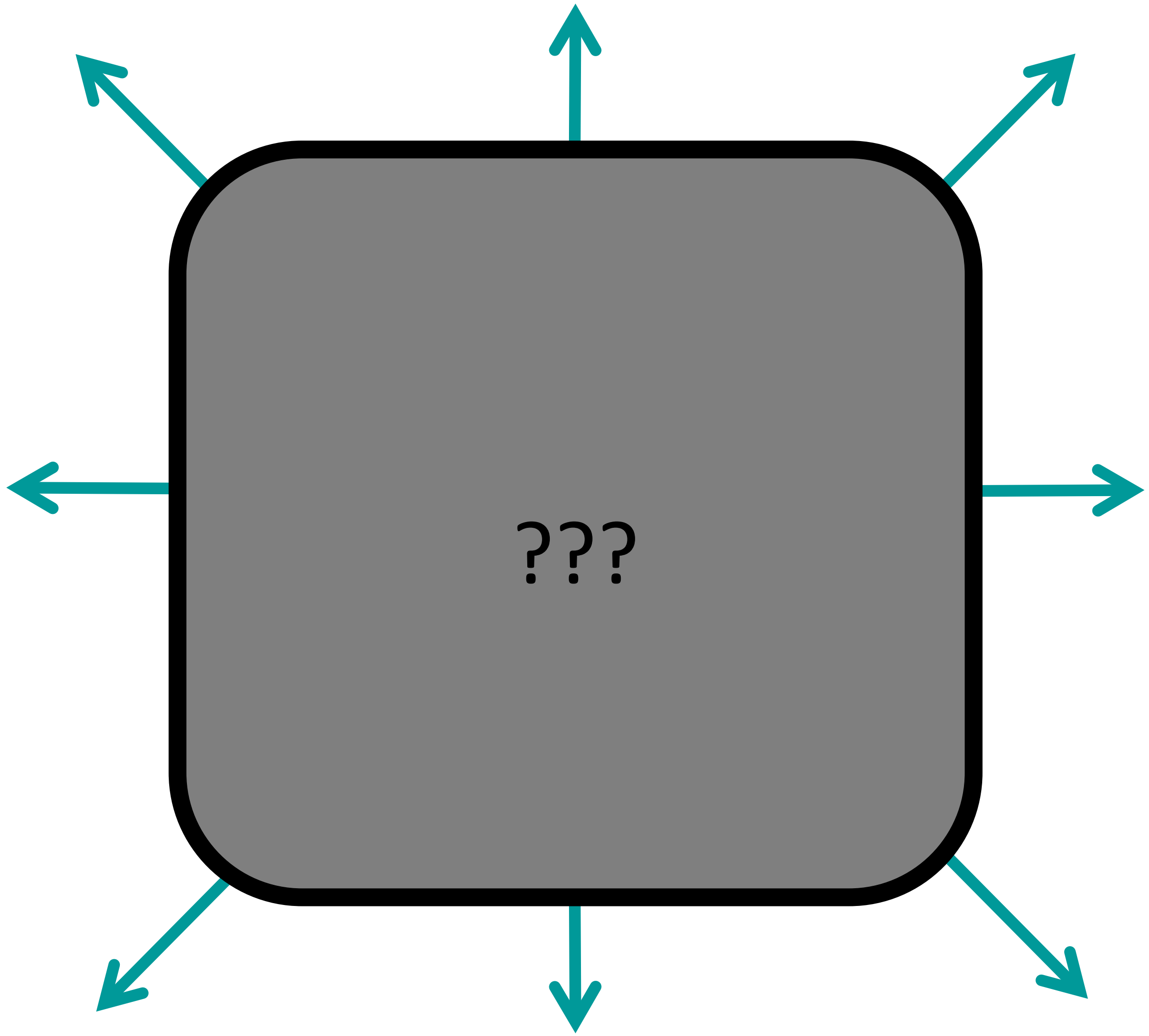
In the Higgs phase:

BHs now carry a magnetic charge in units of $2\pi Z/e$



Original A and B monopoles are confined!
No *finite-energy* monopole that is not a black hole

de la Fuente, PS, Sundrum (2014)



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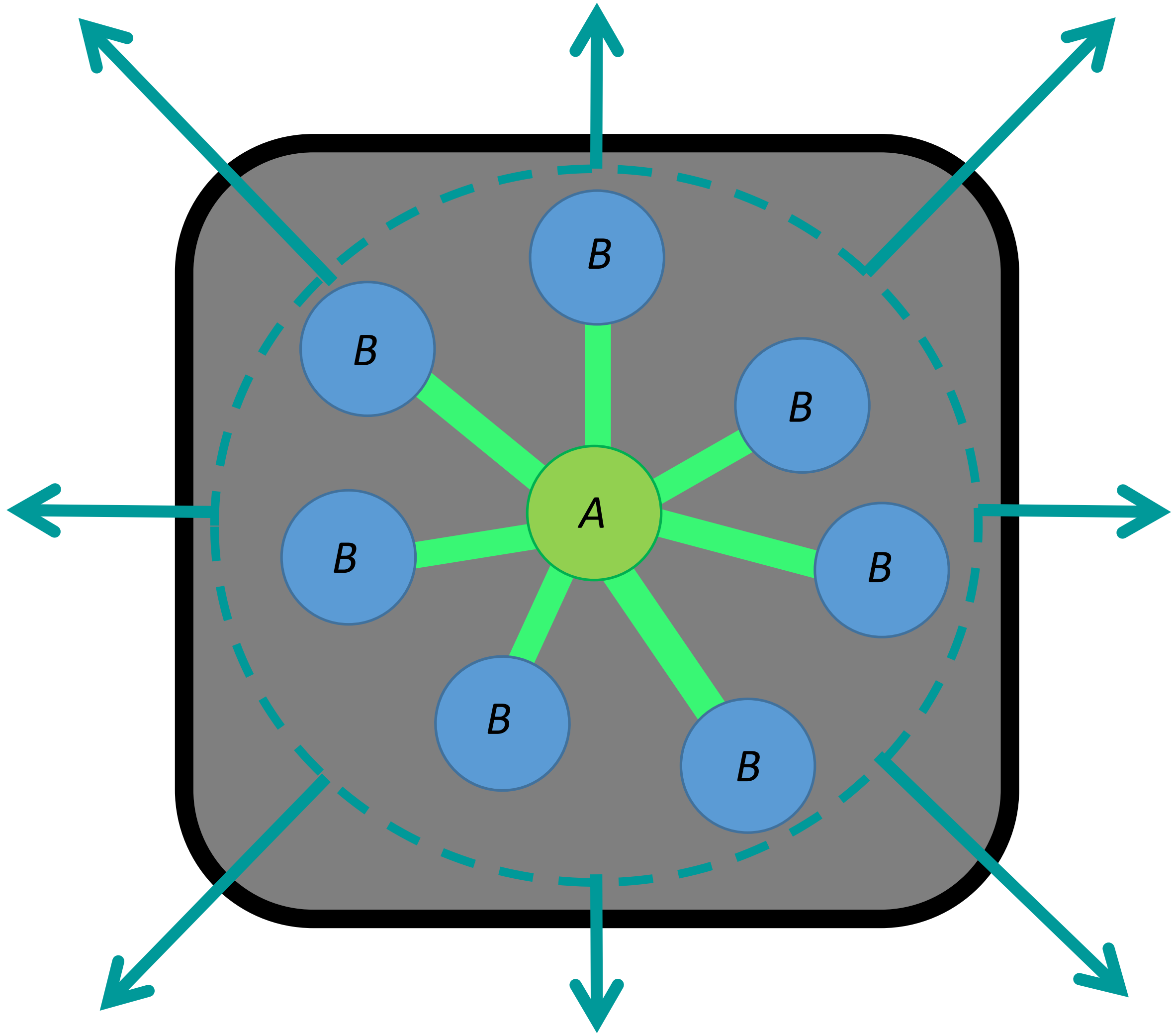

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A black hole's magnetic charge can arises from *confined* constituents

No longer mysterious why net magnetic charge can only exist in high-entropy configurations

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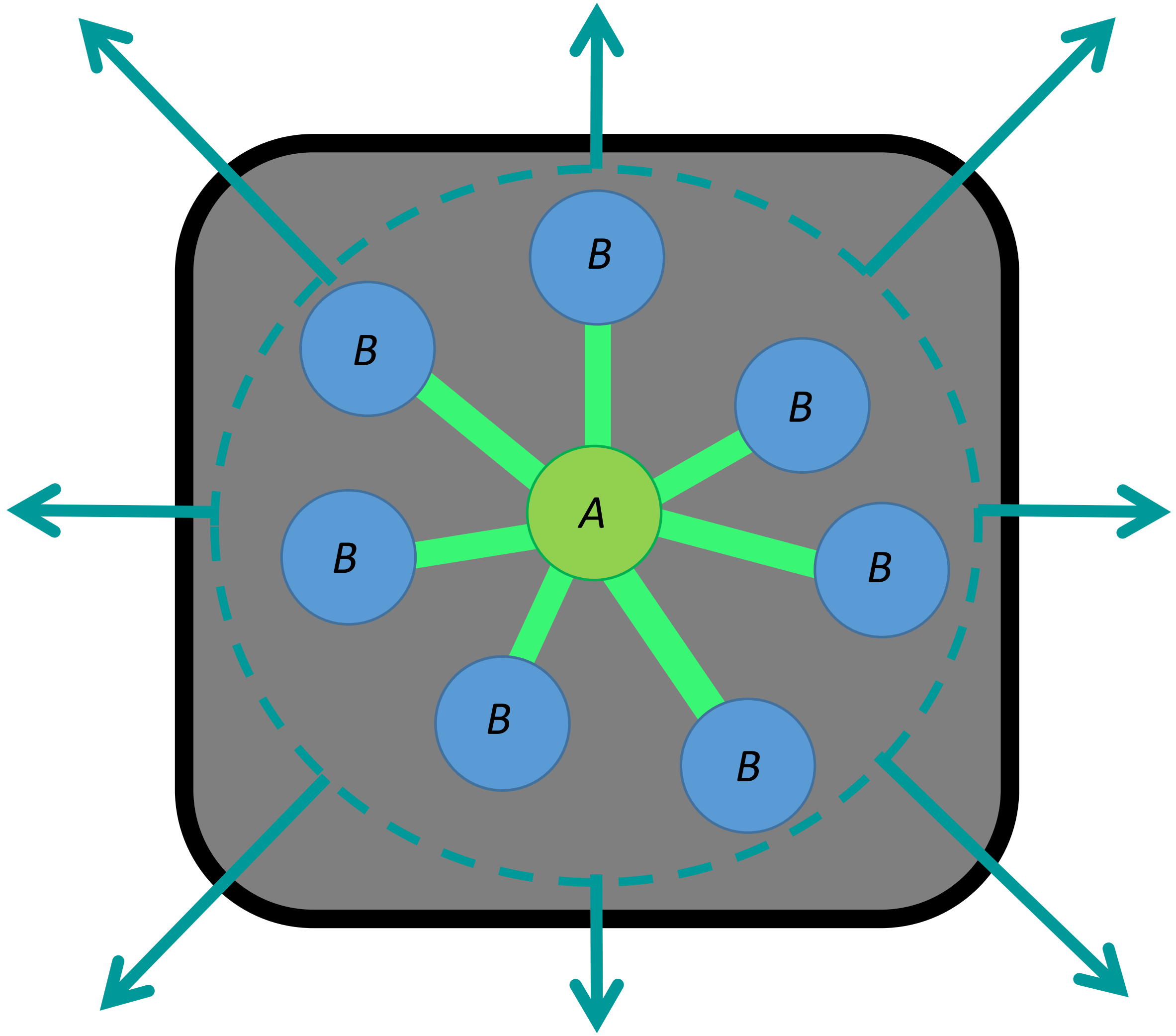
~~de la Fuente, PS, Sundrum~~ (2014)



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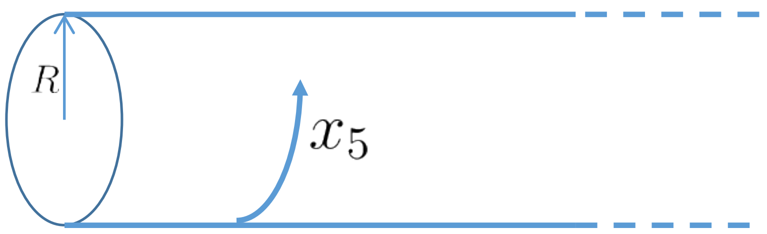
Review: Extranatural Inflation

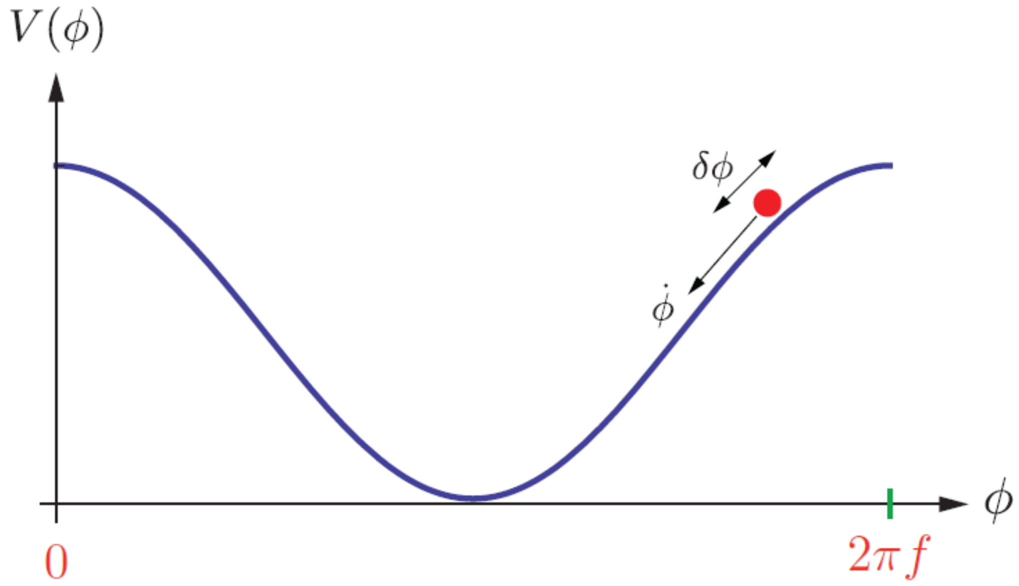
Arkani-Hamed, Cheng, Creminelli, Randall
hep-th/0301218

$U(1)$ gauge field in the bulk of an extra dimension S^1. Wilson loop gives a protected 4D field:



$$\phi \equiv \frac{1}{2\pi R} \oint_{S_1} dx^5 A_5 \Rightarrow V(\phi) \sim V_0 \cos \frac{\phi}{f}$$

+ small higher harmonics



$$\boxed{f = \frac{1}{2\pi R e}}$$

Can get arbitrarily large inflaton field range by taking $e \ll 1$

Extranatural Inflation and WGC

However, for control of the 5D EFT we should have $1/R < \Lambda$. Then

$$1/R < eM_{\rm pl} \quad \Longrightarrow \quad f \sim \frac{1}{eR} \lesssim M_{\rm pl}$$

But the "Higgsing trick" let's us write an EFT with a gauge coupling of g and no EFT cutoff until the scale $\Lambda \approx \sqrt{e}M_{pl}$. This allows

$$1/R < \sqrt{e}M_{\rm pl} \quad \Longrightarrow \quad f \lesssim M_{\rm pl}\left(M_{\rm pl}R\right)$$

Exactly analogous to bi-axion "alignment" scenario of 1412.3457, except instead of just integrating out a heavier axion, we integrate out the whole (5D) gauge field

Constraints on Inflationary Phenomenology

Same as for model in de la Fuente, PS, Sundrum (2014)

$$\mathcal{N}_{\text{e-folds}} \sim \frac{f_{\text{eff}}}{M_{\text{pl}}} \lesssim M_{\text{pl}} R$$

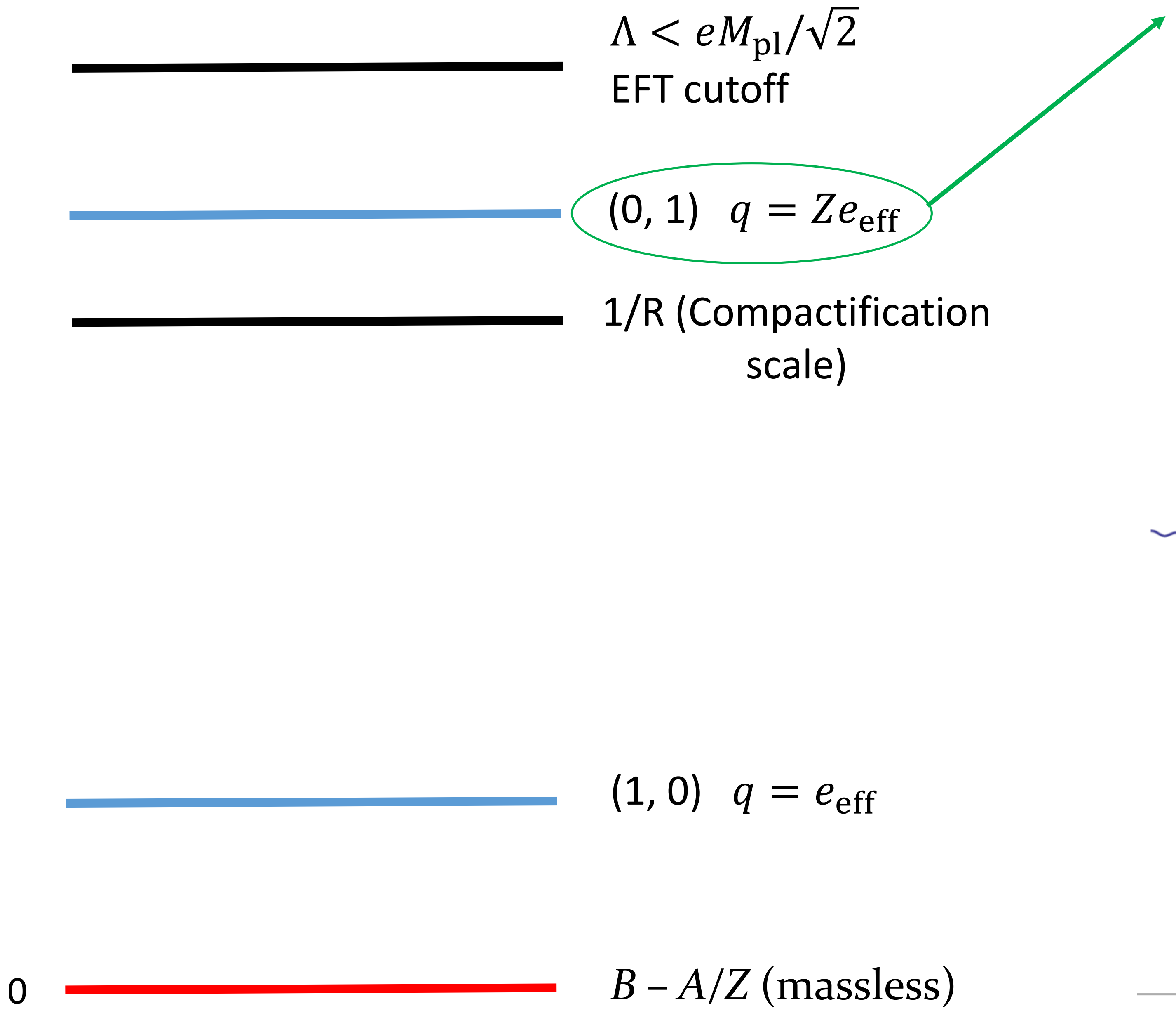
But $M_{\text{pl}} R$ also controls the Hubble scale, because $V \sim (1/R)^4$

$$H \sim \frac{\sqrt{V}}{M_{\text{pl}}} \sim M_{\text{pl}} \frac{1}{(M_{\text{pl}} R)^2} \lesssim \frac{M_{\text{pl}}}{\mathcal{N}^2_{\text{e-folds}}}$$

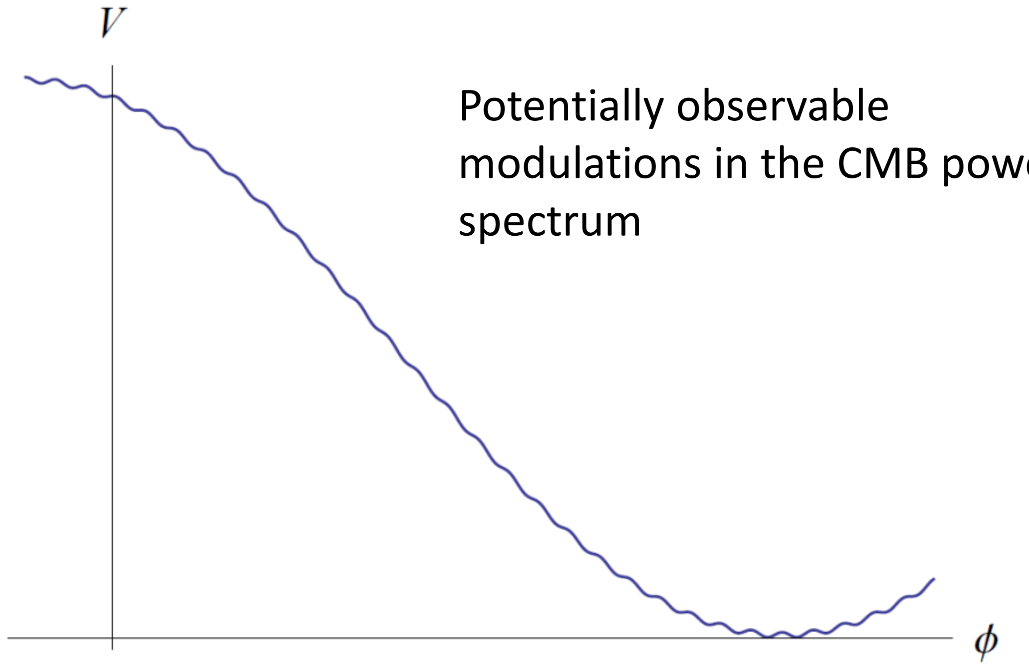
To fit the real world data we need

$$\frac{H}{M_{\text{pl}}} \sim 10^{-4} \qquad \mathcal{N}_{\text{e-folds}} \gtrsim 60$$

On the edge of the controlled parameter space…



In this model there *must* be an additional particle with Z units of charge. Fitting the observed data requires it to be not much heavier than $1/R$
→Significant contribution to the axion potential!



Potentially observable modulations in the CMB power spectrum

Iterating the Higgsing model can generate exponentially small effective gauge couplings in the IR

Gauge Sector: $U(1) \times U(1) \times U(1) \times U(1) \times \cdots$

All gauge couplings = *e*

Higgs Sector:

$$(Z, 1, 0, 0, ...)$$
$$(0, Z, 1, 0, ...)$$
$$(0, 0, Z, 1, ...)$$
$$\vdots$$

$$e_{\text{eff}} = e/Z^{N-1} \quad (Ze < 1)$$

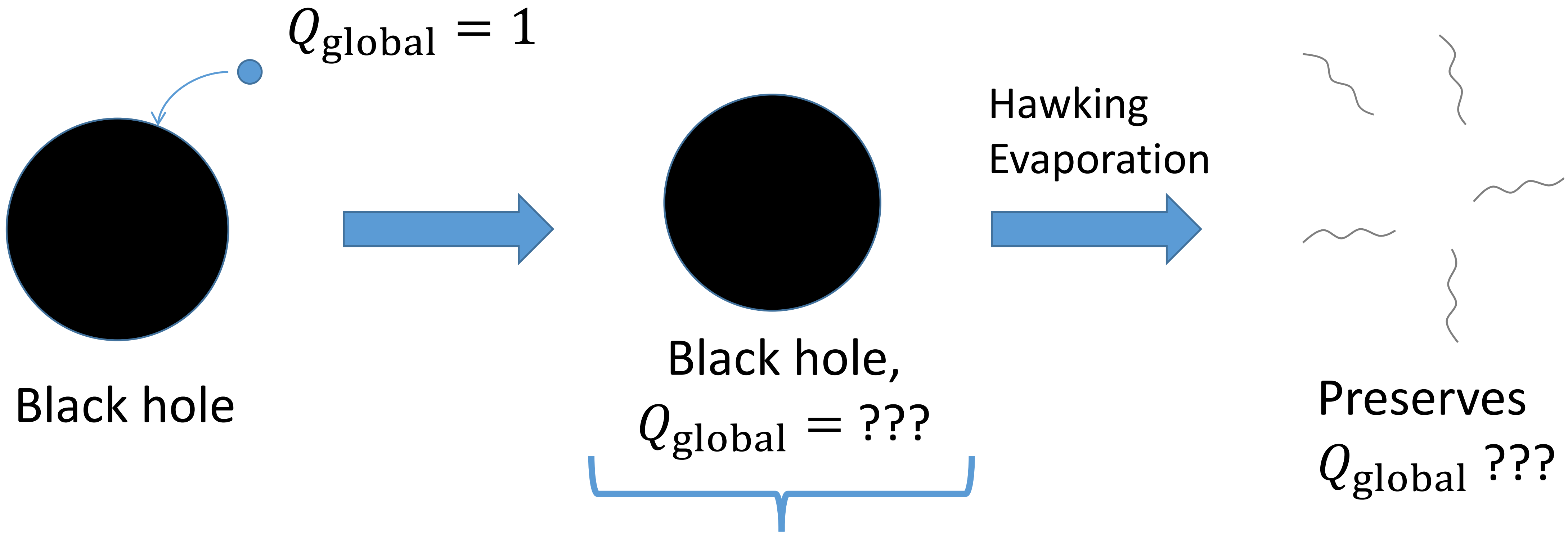
$$\Lambda \lesssim e M_{\text{pl}} \lesssim e_{\text{eff}}^{\frac{1}{N}} M_{\text{pl}}$$

Analogous to Choi, Kim, Yun (2014); Higaki, Takahashi (2014)

So the “tension” that led to a prediction of significant corrections to the potential can disappear in more complicated models

An Ultimate Weak Gravity Conjecture?

$g_{\text{eff}} = 0$ corresponds to an exact global symmetry, which is abhorred by quantum gravity!

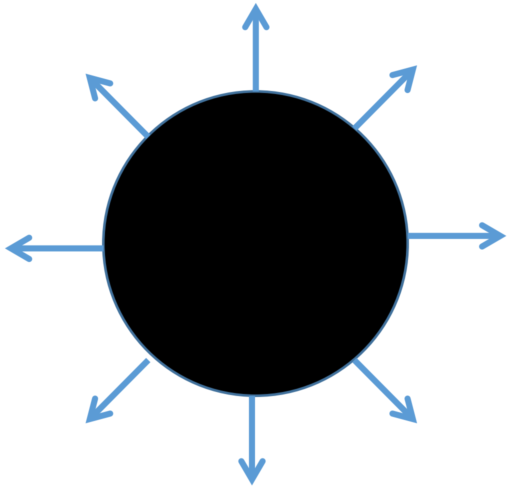


Black hole would hide arbitrary amount of global charge, in violation of entropy bound

An Ultimate Weak Gravity Conjecture?

A charged black hole must have enough entropy to account for the exactly conserved gauge charge:

$$e^S > Q/e_{\text{eff}}$$



Extremal:

$$Q \sim M \sim R$$

$$S \sim R^2$$

$$(M_{\text{pl}} = 1)$$

$$S > \log Q + \log \frac{1}{e_{\text{eff}}}$$

$$S \gtrsim \log \frac{1}{e_{\text{eff}}}$$

$$R \gtrsim \sqrt{\log \frac{1}{e_{\text{eff}}}}$$

Conclude that there is a cutoff on black hole physics:

$$\boxed{\Lambda \lesssim \left(\log \frac{1}{e_{\text{eff}}}\right)^{-1/2} M_{\text{pl}}}$$

An Ultimate Weak Gravity Conjecture?

We can raise the WGC cutoff by using a large number of fields *N*, but this can also *lower* the cutoff by renormalizing the Planck scale:

$$\Lambda \lesssim e_{\text{eff}}^{\frac{1}{N}} M_{\text{pl}} \qquad\qquad \Lambda \lesssim \frac{M_{\text{pl}}}{\sqrt{N}}$$

To get the highest possible cutoff for given e_{eff} we should choose N to optimize between these two constraints.

Solution: $$\boxed{\Lambda \lesssim \left(\log \frac{1}{e_{\text{eff}}}\right)^{-1/2} M_{\text{pl}}}$$

Consistent with bottom-up argument! ✓

Conclusions

- The Weak Gravity Conjecture cannot constrain low-energy EFT. A model which violates one of the WGCs can be completed at very high energies into a model which satisfies it.
- However, if we take the WGC as true in the UV, then generating WGC violation at low energies with a minimal model can have implications for phenomenology.
- Both top-down and bottom-up arguments do support an alternative form of the WGC that places exponentially weaker constraints on gauge couplings.