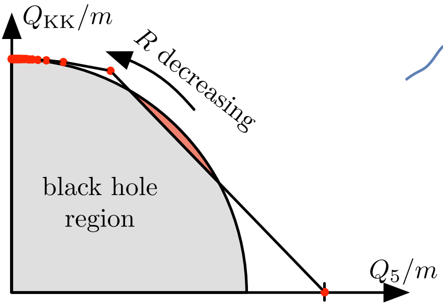
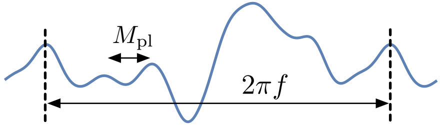
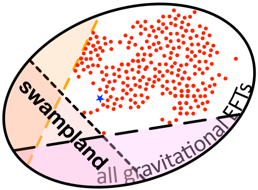
The Weak Gravity Conjecture:
from Quantum Gravity to the Real World







Ben Heidenreich
UMassAmherst | Physics

DESY Colloquium, May 31, 2022

I. The Landscape and the Swampland

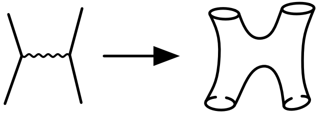
Quantum Mechanics + Gravity = ?

$$\Delta x \Delta p = \frac{\hbar}{2} \qquad G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

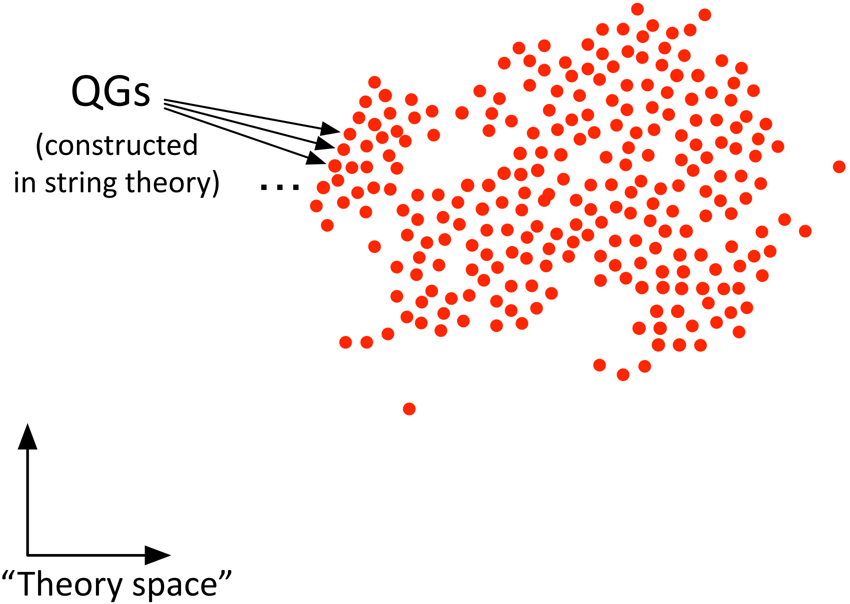
Yet to be understood from 1st principles

…but

String theory provides many **indirect**, exquisitely detailed insights



Insight #1: There are **many** QG theories



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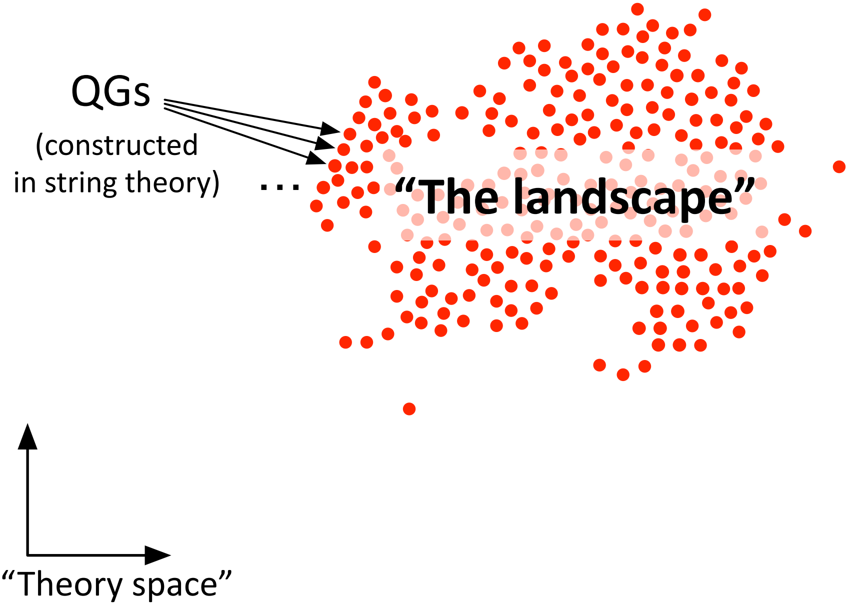

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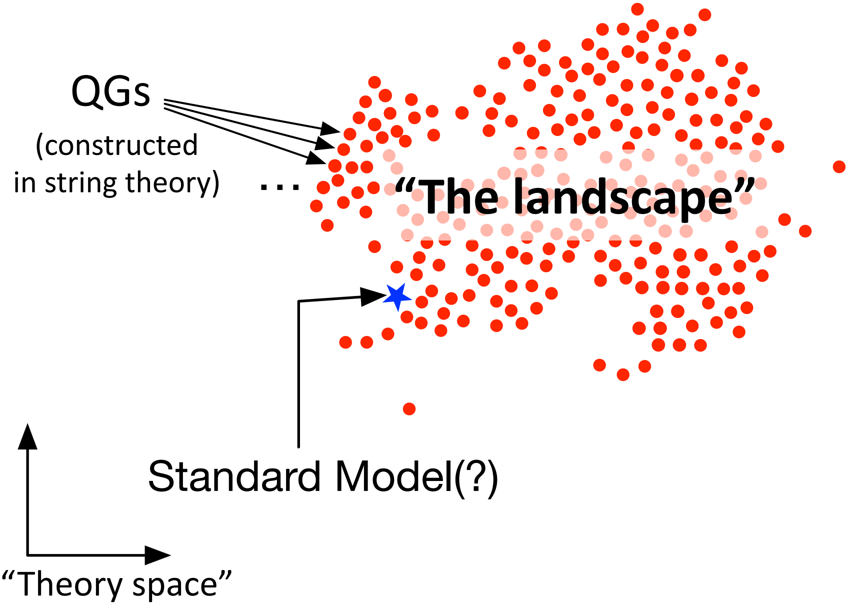
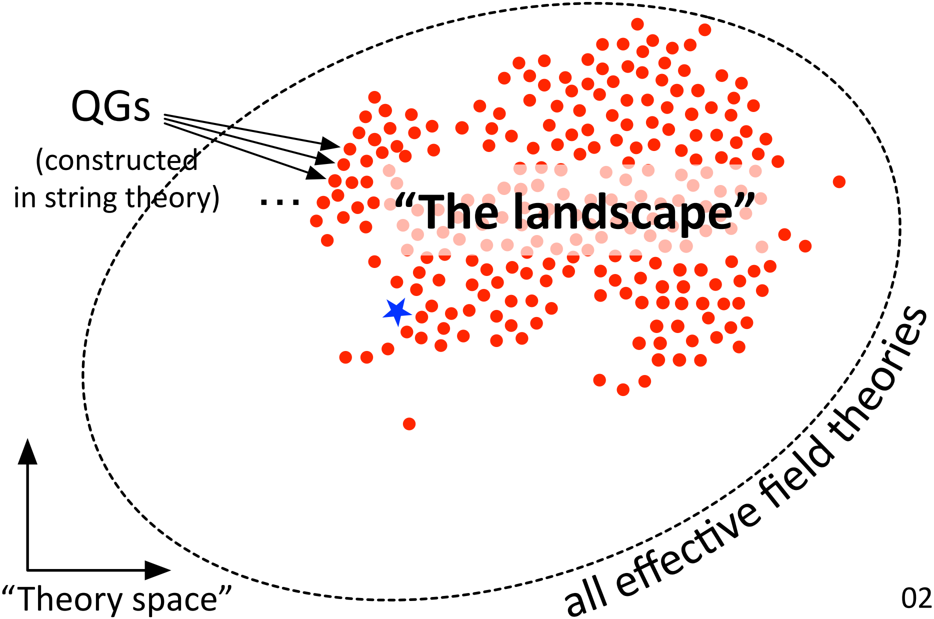


Insight #2: …but not everything goes



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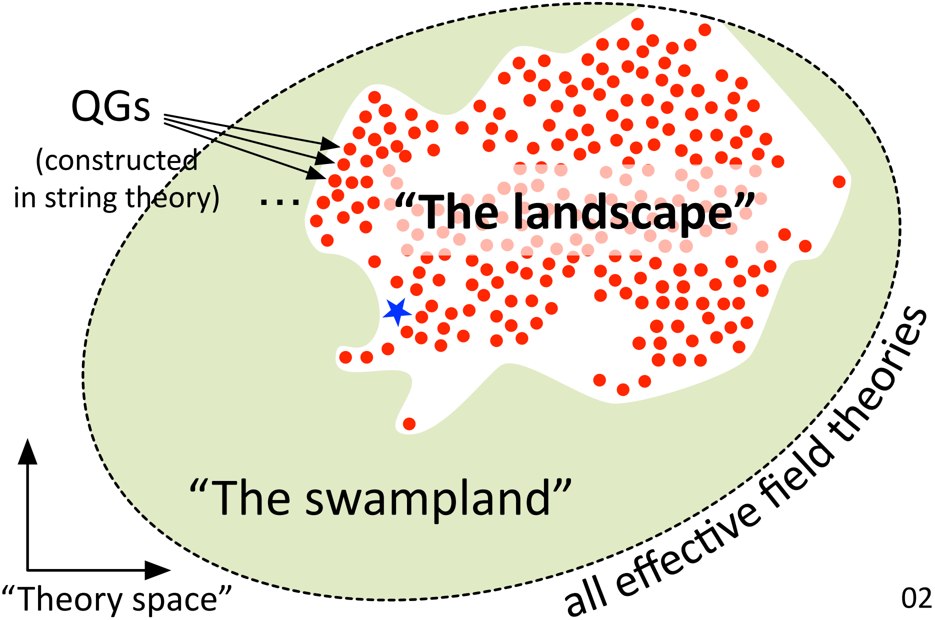

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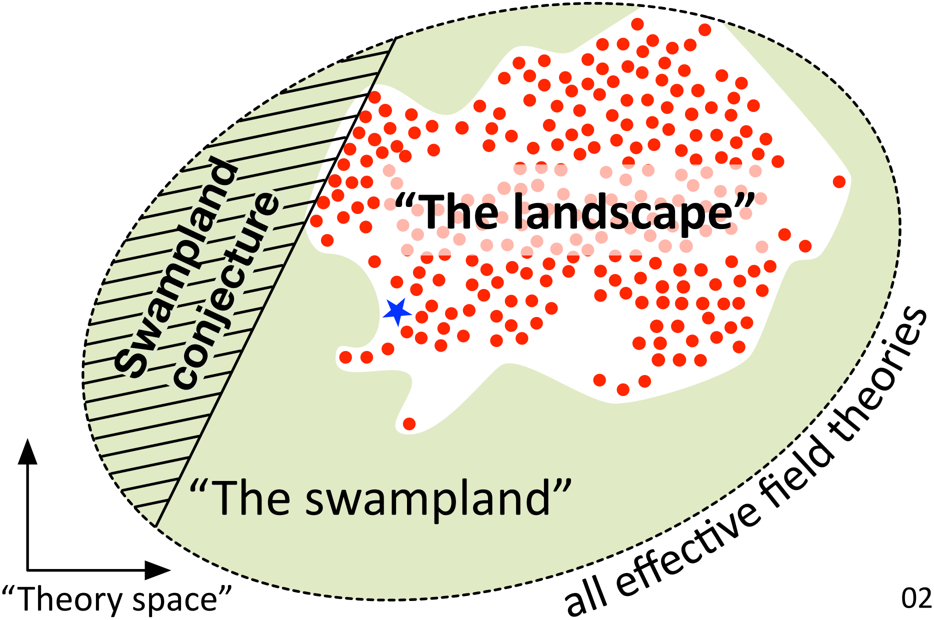
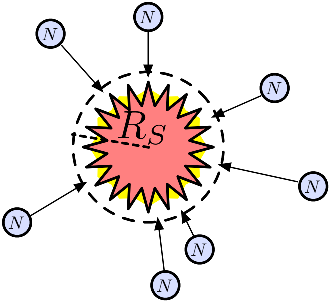


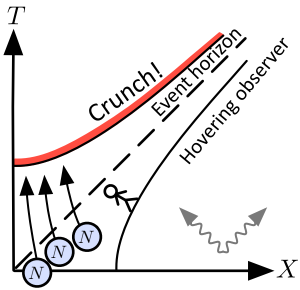
Ex: "Theorem"

Quantum gravities cannot have global symmetries (e.g., baryon number)

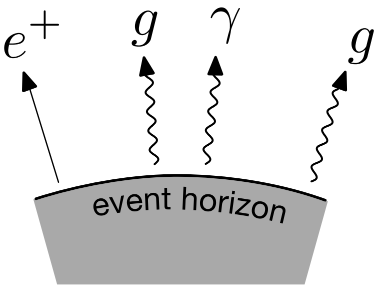
"Proof"

Create a black hole by colliding baryons





Quantum black holes **glow**



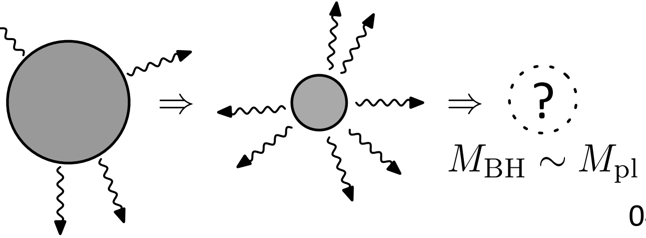
$$k_B T = \frac{\hbar c^3}{8\pi G M}$$

Hawking temperature

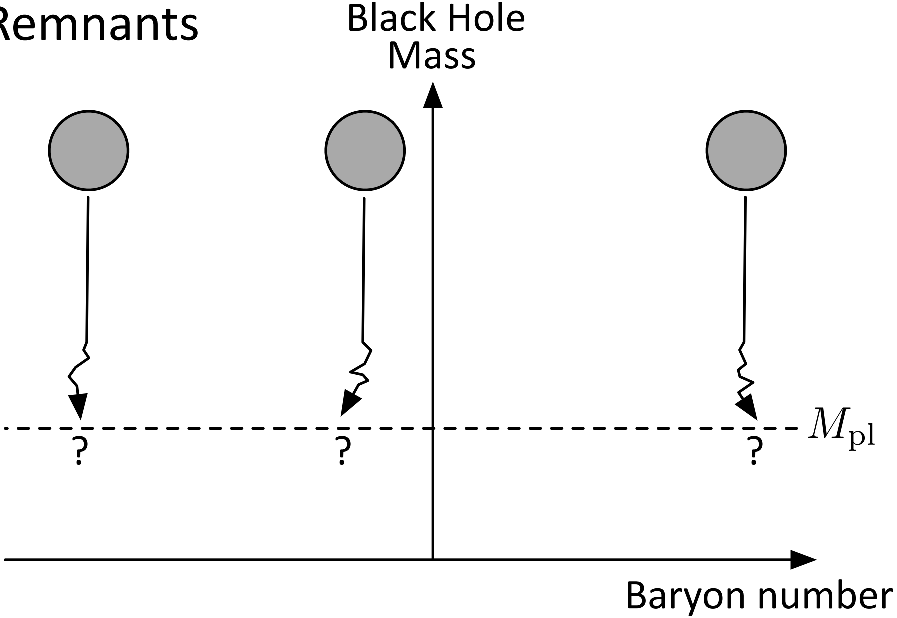
$$S = \frac{k_B c^3}{4\hbar G} A_{\text{Horizon}}$$

Bekenstein-Hawking entropy

Over time, they **evaporate**:



Remnants



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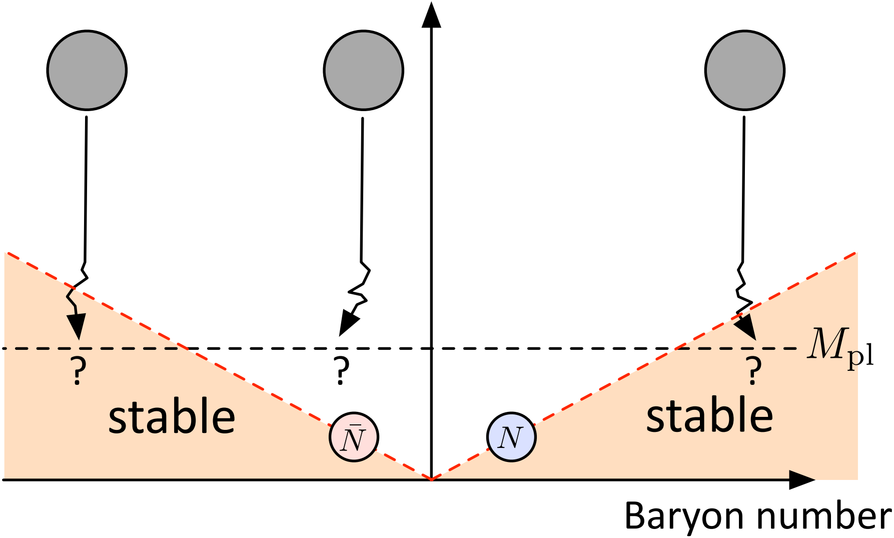
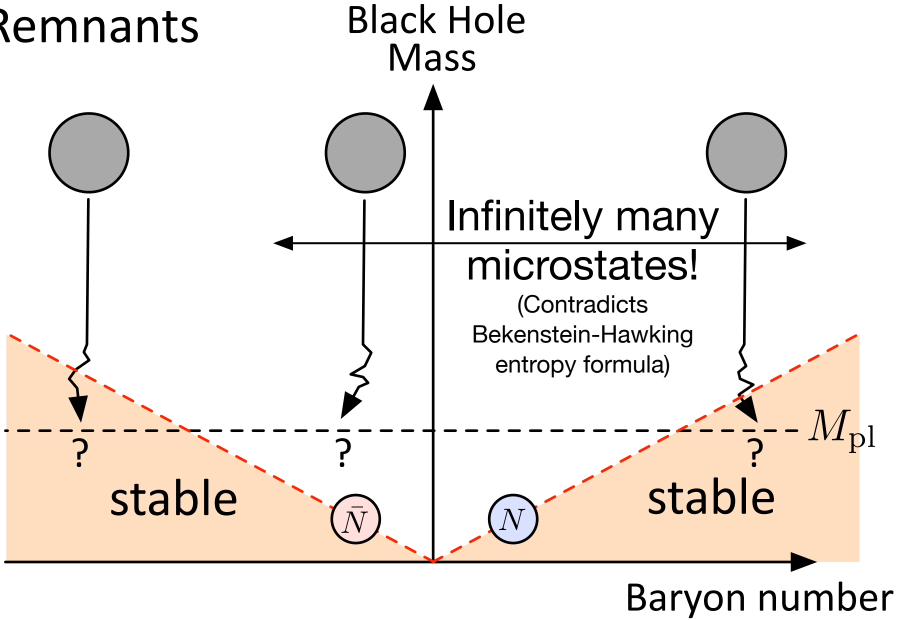

Black Hole Mass
?
?
?
M_{pl}
stable
stable
$\bar{N}$
N
Baryon number

Remnants



Black Hole
Mass
Infinitely many
microstates!
(Contradicts
Bekenstein-Hawking
entropy formula)
$M_{\rm pl}$
?
?
?
stable
stable
$\bar{N}$
N
Baryon number

Baryon number is violated!

e.g., $\mathcal{L}_{\text{eff}} \sim \frac{1}{M_{\text{pl}}^2} uude$

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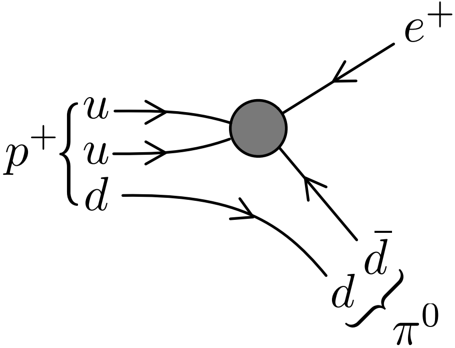
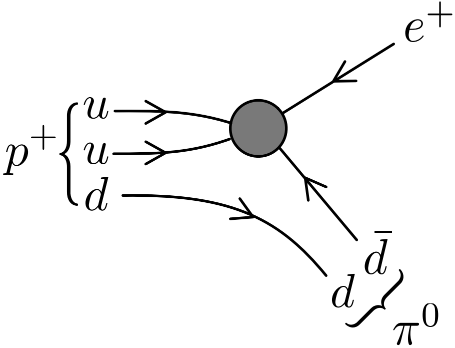


…proton decays!

Baryon number is violated!

e.g., $\mathcal{L}_{\mathrm{eff}} \sim \dfrac{1}{M_{\mathrm{pl}}^2} uude$



$\tau_{\mathrm{pred}} \sim 10^{45}$ yrs

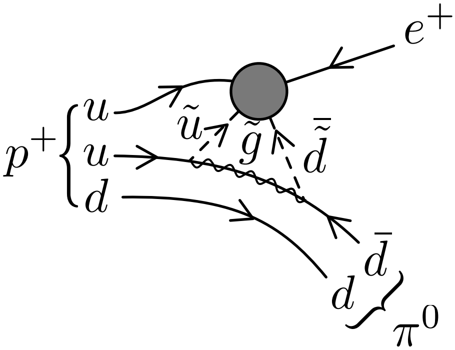
versus

$\tau_{\mathrm{obs}} \gtrsim 10^{34}$ yrs

…proton decays!

Baryon number is violated!

vs. $\mathcal{L}_{\rm eff} \sim \dfrac{1}{M_{\rm pl}} u\tilde{u}\tilde{d}e$ (MSSM)



$\tau_{\rm pred} \sim 10^{20}$ yrs

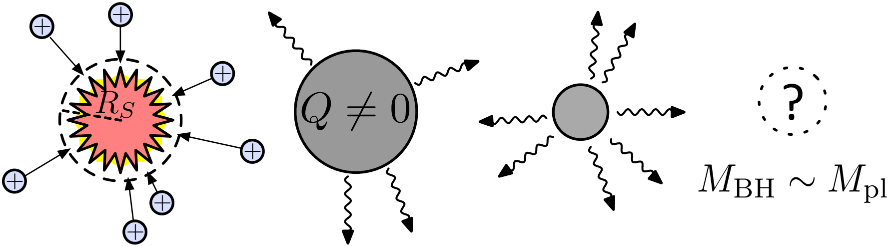
versus

$\tau_{\rm obs} \gtrsim 10^{34}$ yrs!

…proton decays **too rapidly**!

Charged remnants?

What if the symmetry is gauged (coupled to a long range force) rather than global?



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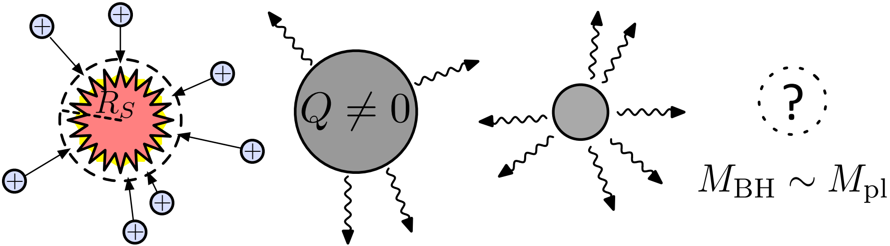
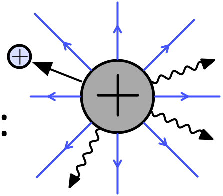
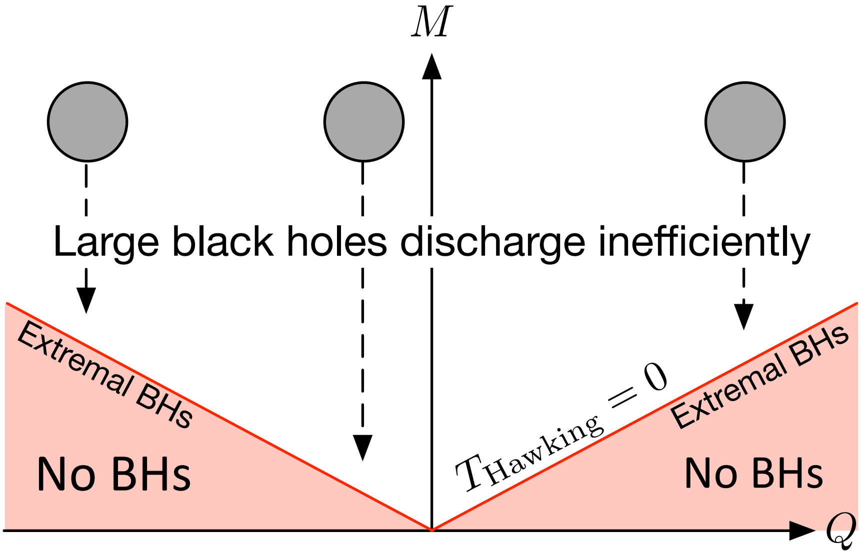


Now there is an electric field:



(Too much charge destroys the horizon)

Charged remnants?



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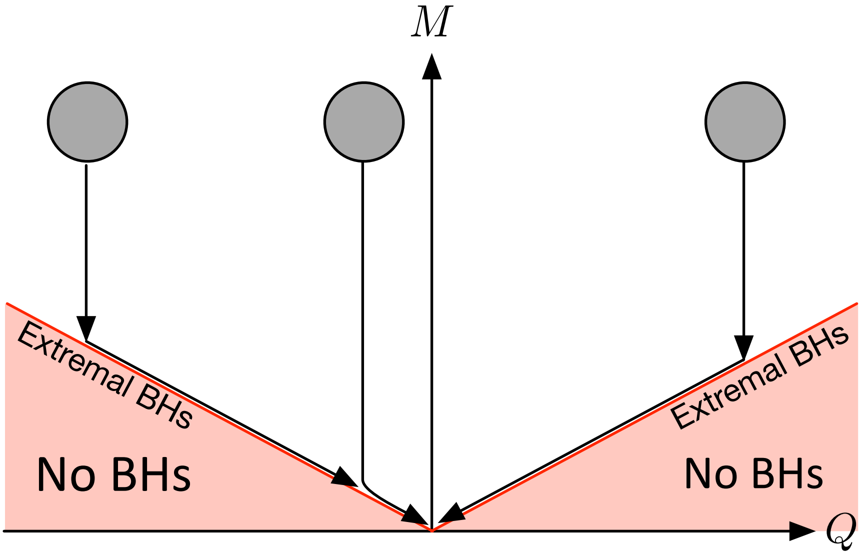

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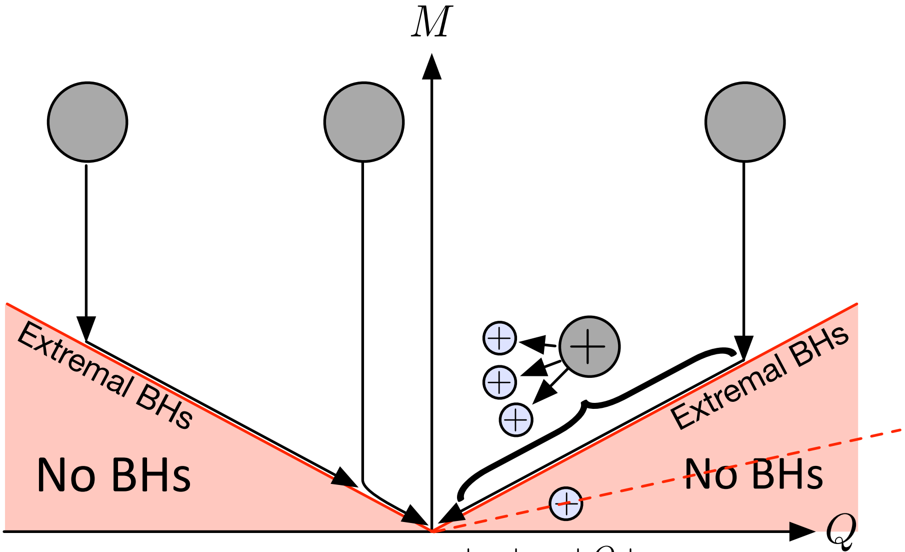

Only possible when $\left|\frac{q}{m}\right| \geq \left|\frac{Q}{M}\right|_{\text{ext BH}}$

The Weak Gravity Conjecture (WGC)

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

There is a charged particle with

$$\left|\frac{q}{m}\right| \geq \left|\frac{Q}{M}\right|_{\mathrm{ext\ BH}}$$

(Otherwise would have charged remnants)

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(Otherwise would have charged remnants)

“Gravity is the weakest force!”

$|F_{\text{Coulomb}}| \geq |F_{\text{Newton}}|$ for identical pair

The Weak Gravity Conjecture (WGC)

e.g., for electromagnetic forces

$$\frac{e^2}{4\pi} \sim \frac{\hbar c}{137} \gg G m_e^2 \sim 10^{-45}\,\hbar c$$ easily satisfied!

The Weak Gravity Conjecture (WGC)

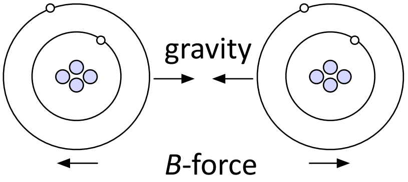
e.g., for electromagnetic forces

$$\frac{e^2}{4\pi} \sim \frac{\hbar c}{137} \gg G m_e^2 \sim 10^{-45}\,\hbar c$$ easily satisfied!

but for a "fifth force" such as *B* (really *B*-*L*)

$$\frac{Q_N^2}{4\pi} \ll G m_N^2 \sim 10^{-38}\,\hbar c$$

not satisfied (by nucleons)!



II. The Weak Gravity Conjecture

The Magnetic WGC (AMNV ’06)

No (generalized) global symmetries

$$\Big\Downarrow$$

(e.g., 2104.07036
& earlier “folk theorem”)

Magnetic monopoles exist!

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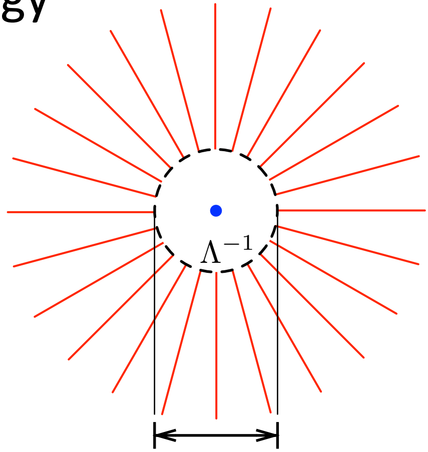
WGC for magnetic charge requires

$$\left|\frac{q_{\mathrm{mag}}}{m}\right| \geq \left|\frac{Q_{\mathrm{mag}}}{M}\right|_{\mathrm{ext\ BH}}$$

The Magnetic WGC (AMNV '06)

Monopole self-energy

$$m \gtrsim \frac{q_{\rm mag}^2}{e^2}\Lambda$$



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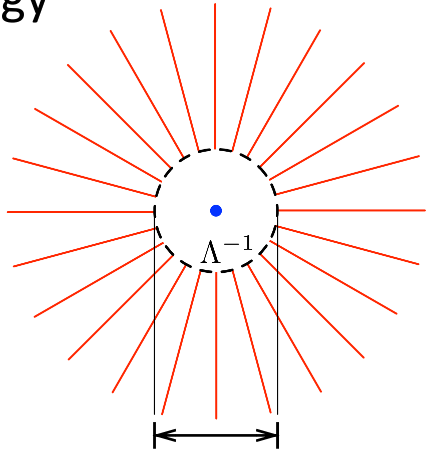
WGC

$$m < \sqrt{2}\,\frac{q_{\rm mag}}{e}M_{\rm pl}$$

$$\Longrightarrow \boxed{\Lambda \lesssim e M_{\rm pl}}$$



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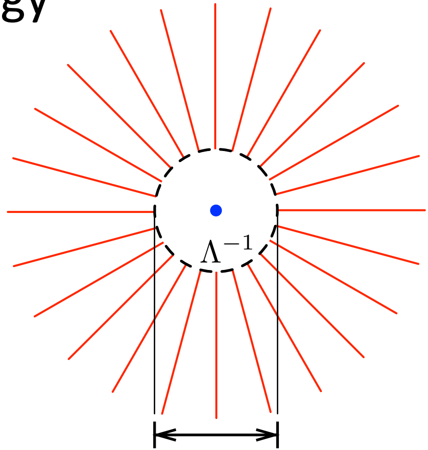
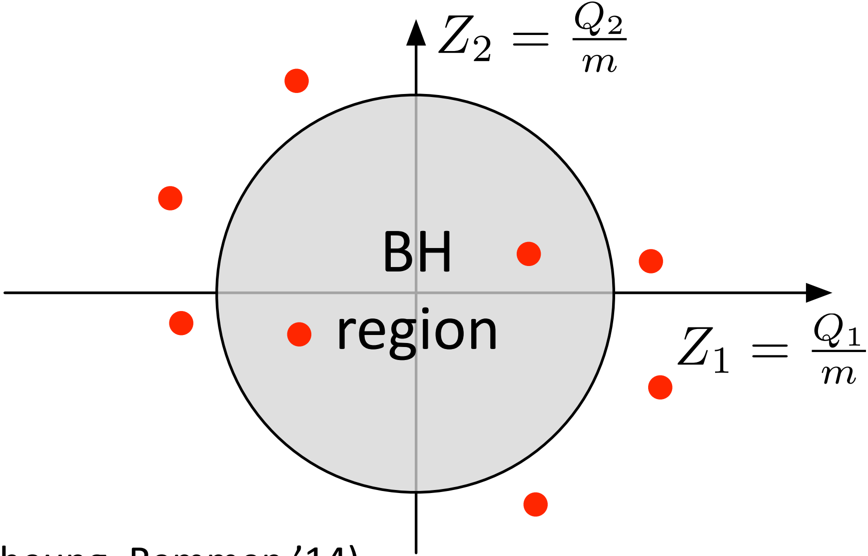


What happens at new physics scale Λ?

WGC w/ multiple photons



(Cheung, Remmen '14)

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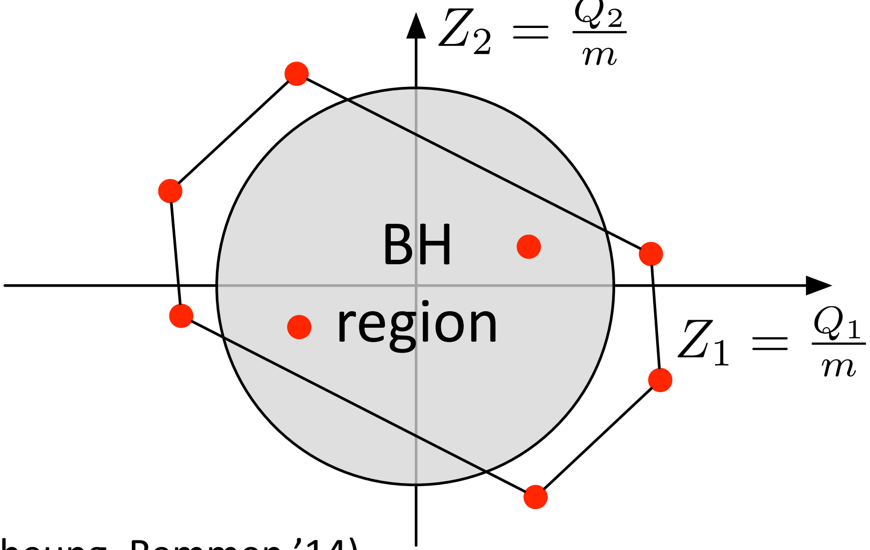

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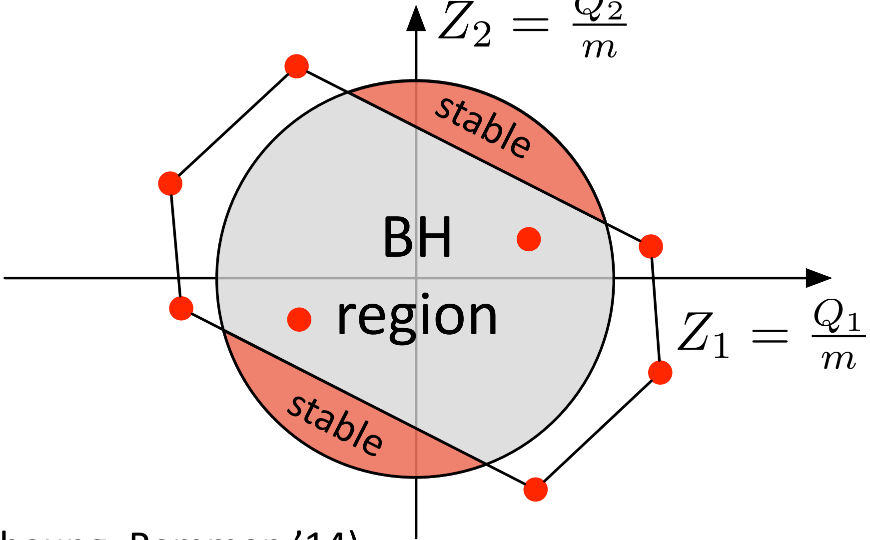
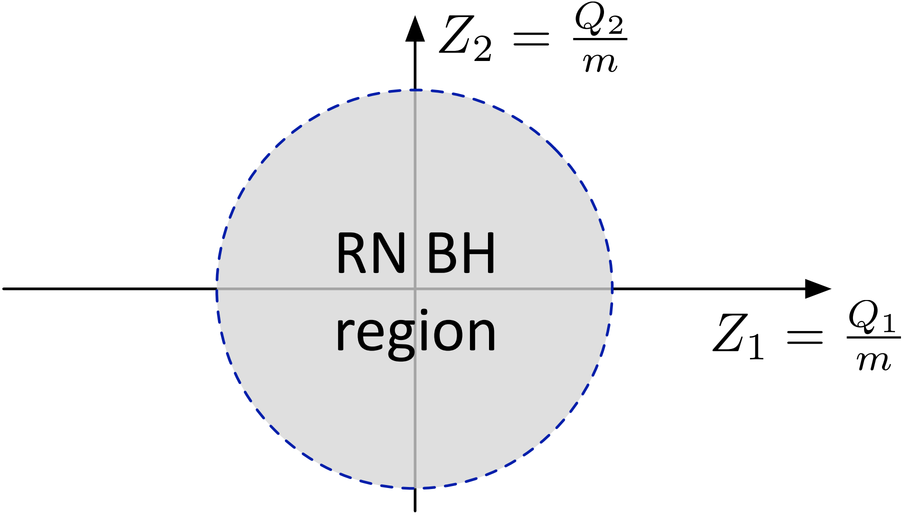


(Cheung, Remmen '14)

The WGC with Moduli

BH, Reece Rudelius '15



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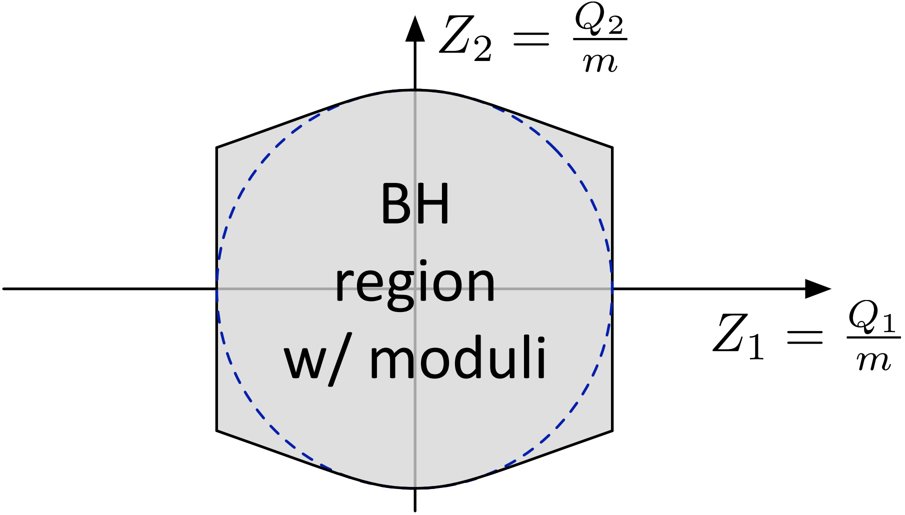
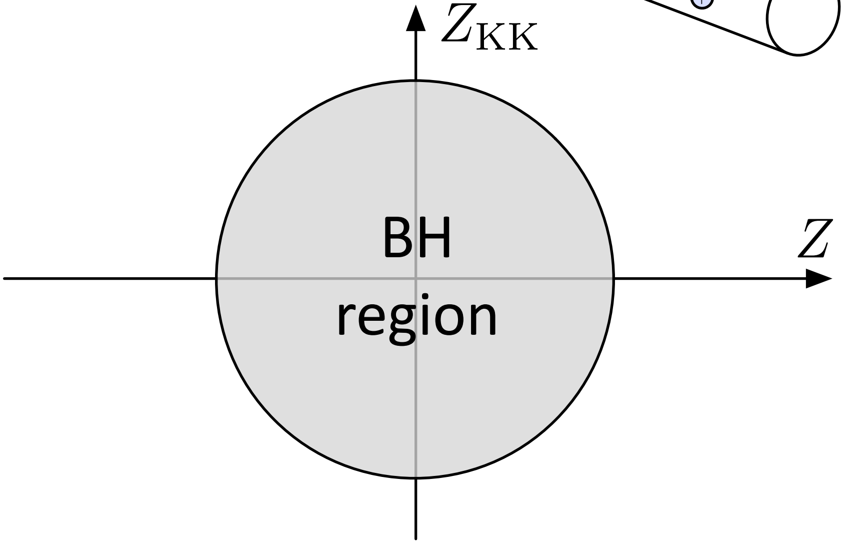
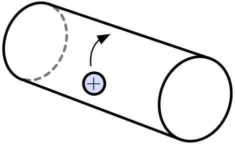


Ex. from Alim, BH, Rudelius, 2108.08309

Circle compactification





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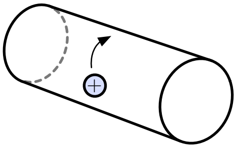

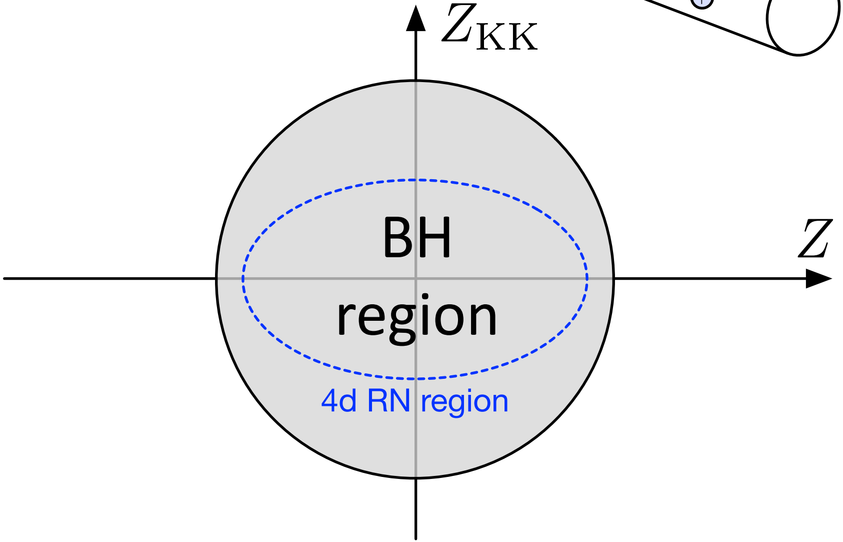

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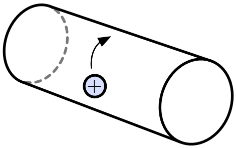
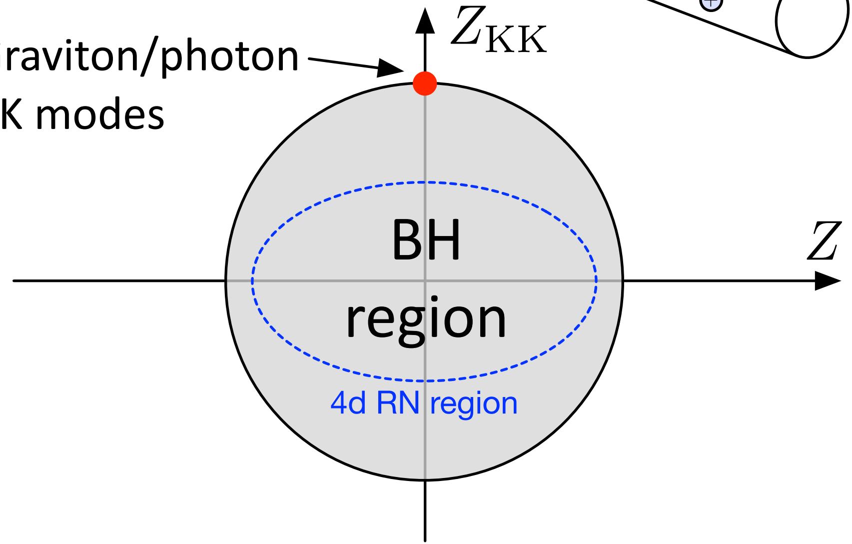


Graviton/photon
KK modes



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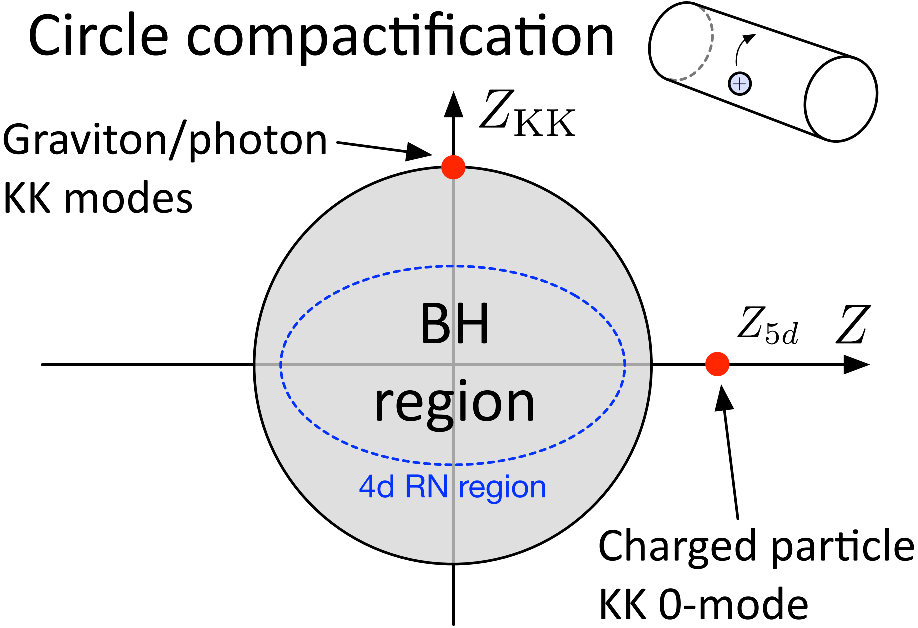

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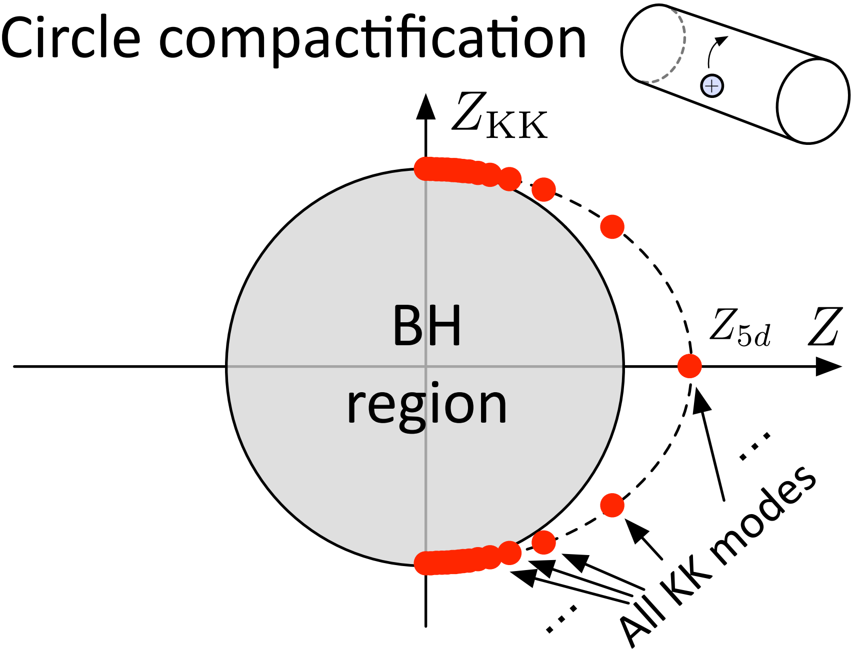
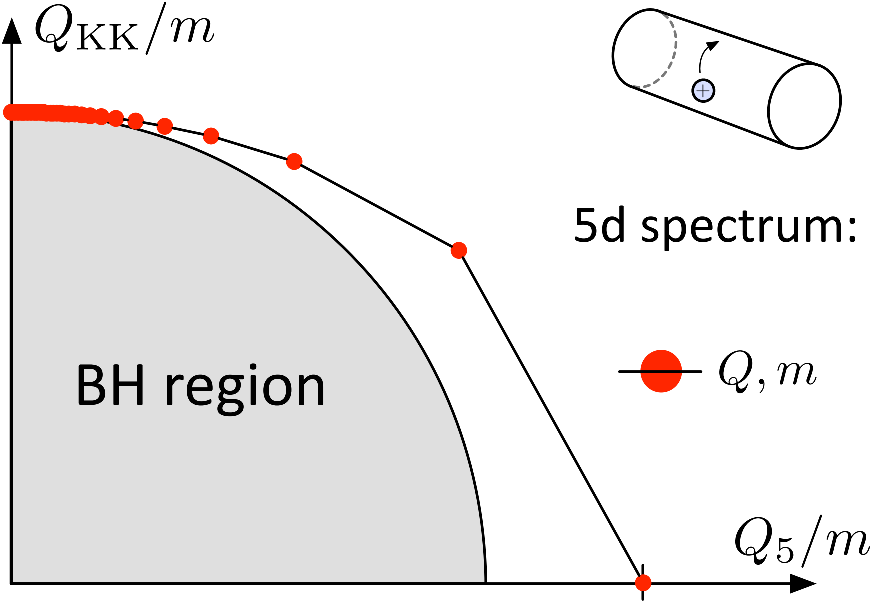
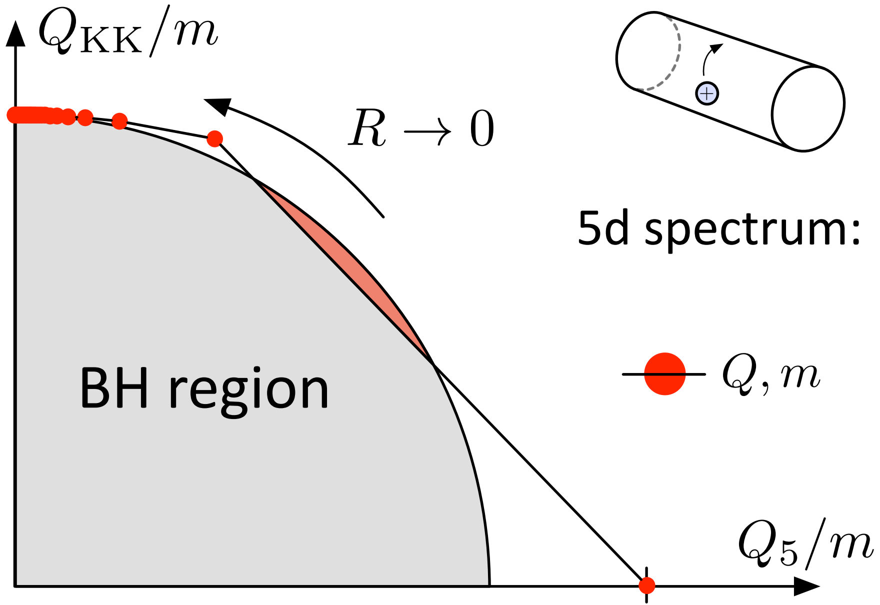
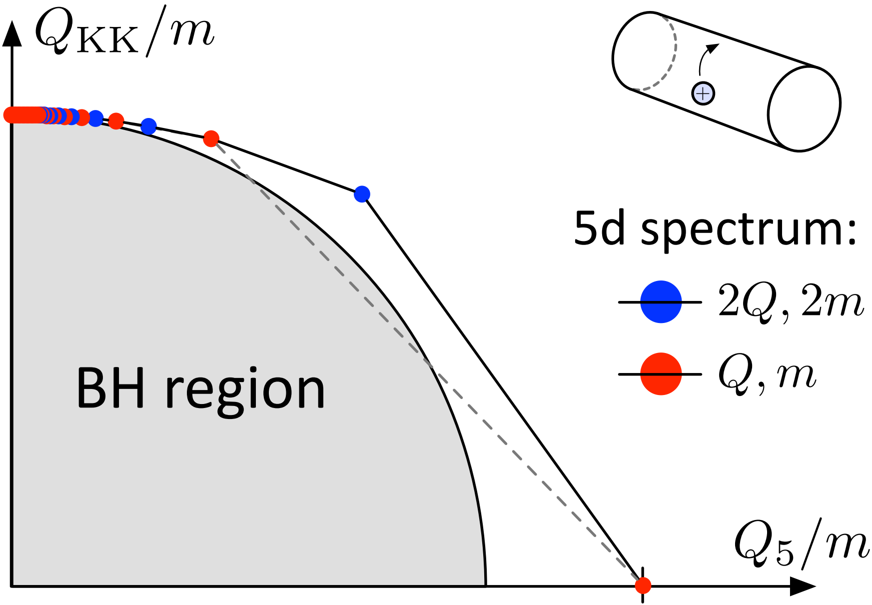


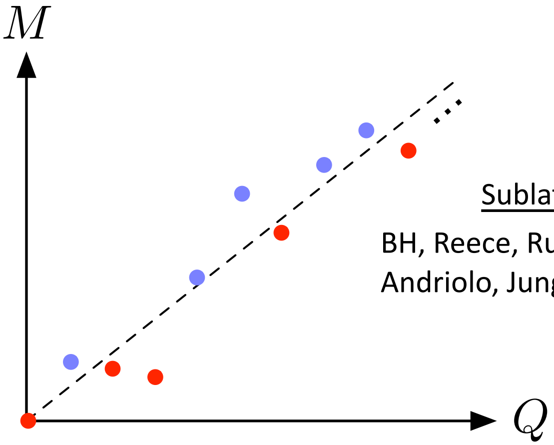

Q_{KK}/m
5d spectrum:
Q, m
BH region
Q_5/m



Q_{KK}/m
$R \to 0$
5d spectrum:
Q, m
BH region
Q_5/m


Q_{KK}/m
5d spectrum:
$2Q, 2m$
Q, m
BH region
Q_5/m

WGC$_{d-1}$ requires superextremal resonances of arbitrarily large charge!

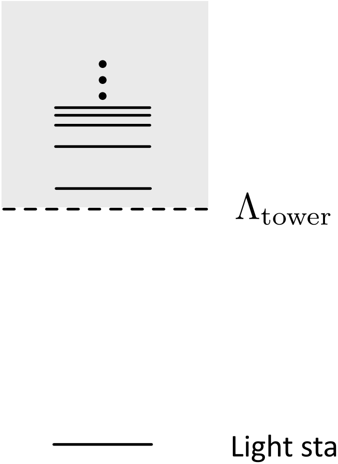


<u>Sublattice / Tower WGC</u>

BH, Reece, Rudelius, '15, '19

Andriolo, Junghans, Noumi, Shiu '18

sL/TWGC versus magnetic WGC



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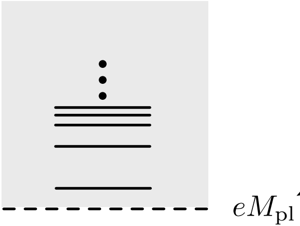
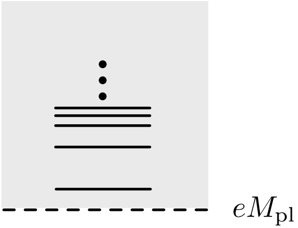
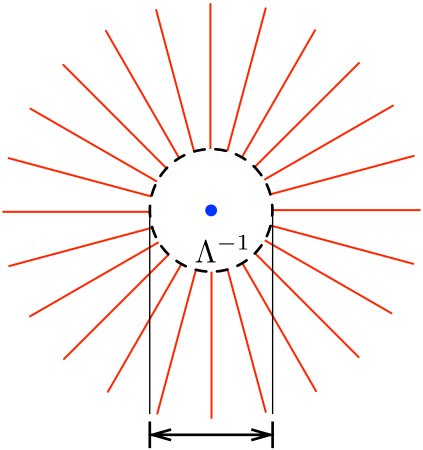


Assuming tower starts at
$q \simeq O(1)$

Light states

sL/TWGC versus magnetic WGC

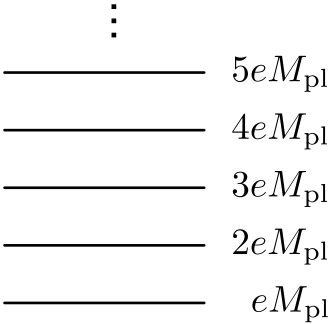


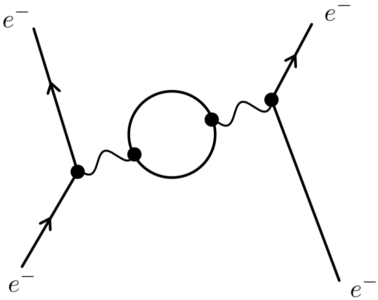


Light states

Tower provides required new physics!

Emergence

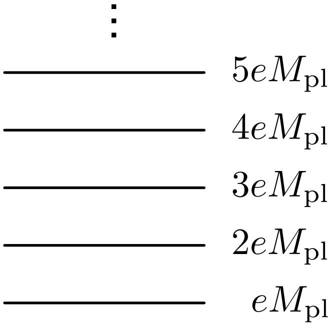


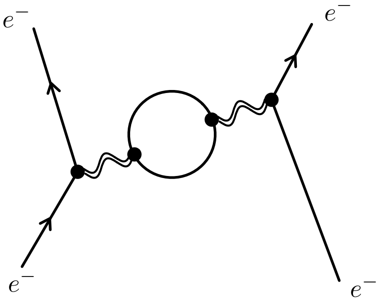


Loops of tower resonances renormalize elementary charge

$$e \to \infty \text{ as } \Lambda \to e_{\rm IR}^{1/3} M_{\rm pl}$$

Emergence

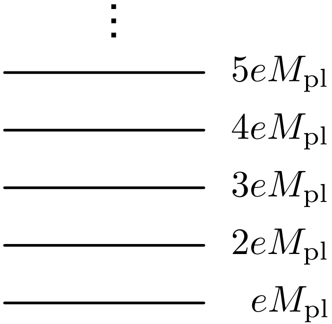


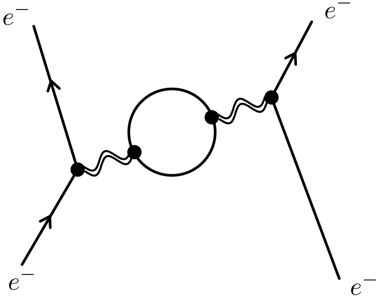


Gravitational interactions also get stronger

$$M_{\text{pl}} \to M_{\text{pl}}/\sqrt{N} \quad \text{for } N \text{ light species}$$

Emergence





These scales match!

$$M_{\mathrm{pl}}/\sqrt{N} \simeq e_{\mathrm{IR}}^{1/3} M_{\mathrm{pl}}$$

Emergence

Gravity and electromagnetism both become highly non-linear at

$$\Lambda_{\mathrm{QG}} \simeq e_{\mathrm{IR}}^{1/3} M_{\mathrm{pl}}$$

Emergence

Gravity and electromagnetism both become highly non-linear at

$$\Lambda_{\rm QG} \simeq e_{\rm IR}^{1/3} M_{\rm pl}$$

Expectation: notion of spacetime breaks down at length scale $\ell_{\rm QG} = \hbar c / \Lambda_{\rm QG}$

Spacetime concepts, like local (gauge) symmetries must disappear above this scale. They "emerge" for $\ell \gg \ell_{\rm QG}$, due to screening effects of the tower of resonances.

Emergence

Conversely, if gravity and electromagnetism both become highly non-linear at a common scale "Λ_{QG}" then the WGC (approximately) follows!

Emergence implies the WGC!

Harlow '15

BH, Reece, Rudelius '17

Emergence

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Emergence implies the WGC!

Harlow '15
BH, Reece, Rudelius '17

e.g., Kaluza-Klein theory:

$$e_{\mathrm{KK}}^{1/3} M_4 = \sqrt{2}\pi^{1/3} M_5$$

$$\Longrightarrow \Lambda_{\mathrm{QG}} \simeq M_5!$$

The WGC in string theory

Very often true in string theory:

<u>Lattice Weak Gravity Conjecture:</u>

$\forall Q \in \Gamma, \exists$ a superextremal charged particle with charge Q

BH, Reece, Rudelius, '15

The WGC in string theory

Very often true in string theory:

Not always! BH, Reece Rudelius, '16

<u>Lattice Weak Gravity ~~Conjecture:~~</u>

$\forall Q \in \Gamma, \exists$ a superextremal charged particle with charge Q

BH, Reece, Rudelius, '15

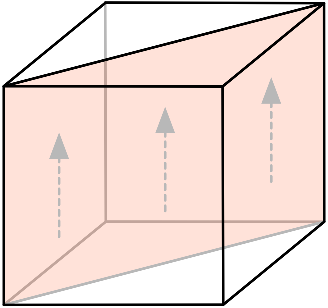
Counterexample to LWGC

KK theory on $T^2/(\mathbb{Z}_2 \times \mathbb{Z}_2')$

$$\mathbb{Z}_2 : \theta_{1,2} \to \theta_{1,2} + \pi$$

$$\mathbb{Z}_2' : \theta_1 \to -\theta_1, \theta_3 \to \theta_3 + \pi$$

smooth
(fixed pt free)
orbifold!



conserved

$$\mathbb{Z}_2 : \phi_{n_1 n_2 n_3} \to (-1)^{n_1+n_2} \phi_{n_1 n_2 n_3}$$

not conserved!

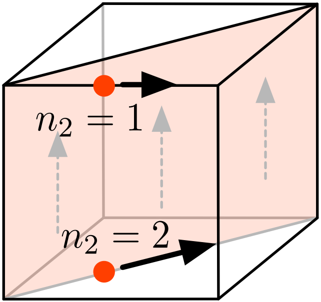
conserved

$$\mathbb{Z}_2 : \phi_{n_1 n_2 n_3} \to (-1)^{n_1+n_2} \phi_{n_1 n_2 n_3}$$

not conserved!

$$m^2 = \frac{n_1^2}{R_1^2} + \frac{n_2^2}{R_2^2} + \frac{n_3^2}{R_3^2} > \frac{n_2^2}{R_2^2} + \frac{n_3^2}{R_3^2}$$

for $n_2 \in 2\mathbb{Z} + 1$



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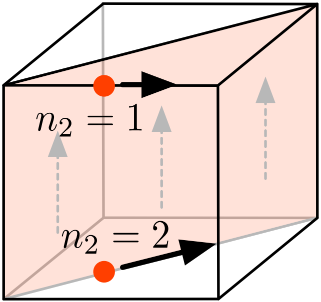


<u>Open question:</u>

Is there some organizing principle to LWGC violation?

The WGC in string theory

tree-level*

Always true in string theory:

sub

<u>Lattice Weak Gravity Conjecture:</u>

$\exists$ a finite-index sublattice $\Gamma_0 \subseteq \Gamma$ s.t. $\forall Q \in \Gamma_0, \exists$ a superextremal charged particle with charge Q

BH, Reece, Rudelius, '16

*In the electric NSNS sector

Proof via modular invariance

(BH, Reece, Rudelius ’16; Montero, Shiu, Soler ’16; BH, Lotito 2207.xxxxx)

Tree-level spectrum:

$$\frac{\alpha'}{4}m^2 = \frac{1}{2}Q_L^2 + T_L = \frac{1}{2}Q_R^2 + T_R$$

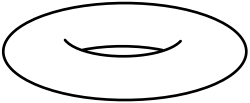
Partition function (torus 0-pt amplitude):

$$Z(\mu,\tau) = \mathrm{Tr}(q^{T+\frac{1}{2}Q^2}y^Q)$$

$$Z(\mu+\rho) = Z(\mu), \qquad \rho \in \Gamma^*$$

$$q = e^{2\pi i\tau}$$

$$y = e^{2\pi i\mu}$$



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Benjamin, Dyer, Fitzpatrick, Kachru ’16:

$$Z(\mu/\tau, -1/\tau) = e^{\pi i\frac{\mu^2}{\tau}}Z(\mu,\tau)$$

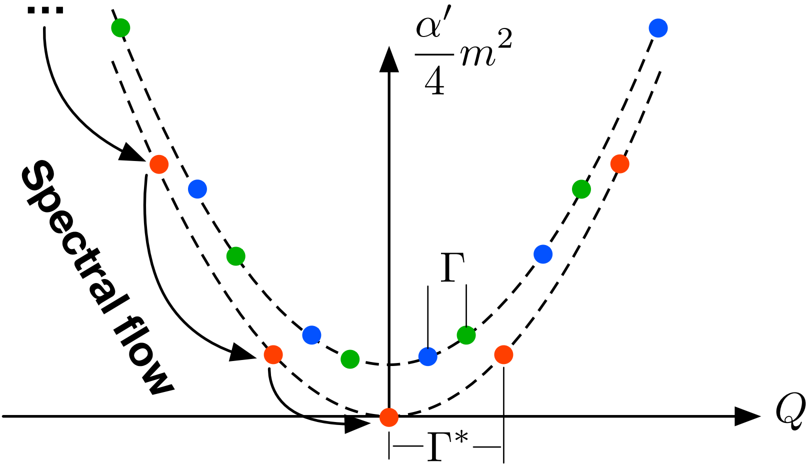
$$Z = \mathrm{Tr}(q^{T+\frac{1}{2}Q^2} y^Q)$$

$$= \mathrm{Tr}(q^{T+\frac{1}{2}(Q+k\rho)^2} y^{Q+k\rho})$$

Spectral flow

$$Z = \mathrm{Tr}\left(q^{T+\frac{1}{2}Q^2} y^Q\right)$$

$$= \mathrm{Tr}\left(q^{T+\frac{1}{2}(Q+k\rho)^2} y^{Q+k\rho}\right)$$



$$Z = \mathrm{Tr}\left(q^{T+\frac{1}{2}Q^2} y^Q\right)$$
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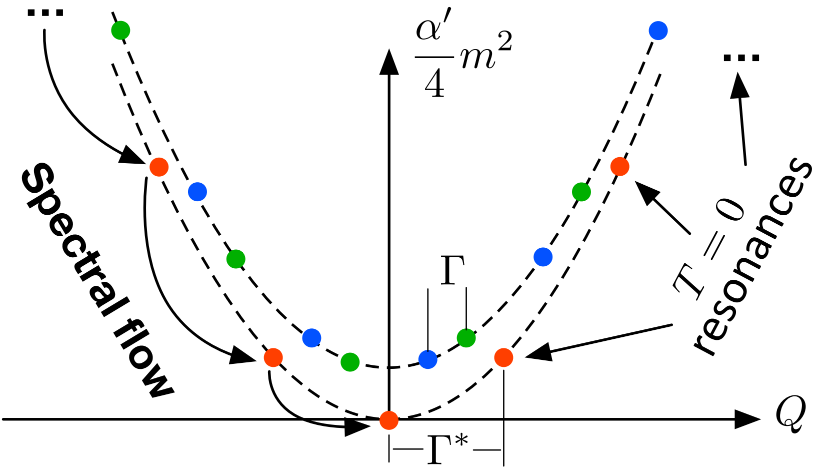

The extremality bound & the RFC

BH, Reece, Rudelius ’19; BH, Lotito 2207.xxxxx

Found a tower of resonances with:

$$\frac{\alpha'}{4}m^2 = \frac{1}{2}\max(Q_L^2, Q_R^2)$$

What is the relation to extremal BHs?

The extremality bound & the RFC

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Detour: "sublattice RFC"

$\exists$ a finite-index sublattice $\Gamma_0 \subseteq \Gamma$
s.t. $\forall Q \in \Gamma_0, \exists$ a **self-repulsive**
charged particle with charge Q

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Proved in tree-level ST

BH, Lotito 2207.xxxxx

The extremality bound & the RFC

BH, Reece, Rudelius ’19; BH, Lotito 2207.xxxxx

Found a tower of resonances with:

$$\frac{\alpha'}{4}m^2 = \frac{1}{2}\max(Q_L^2, Q_R^2) \qquad (*)$$

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BH, Lotito 2207.xxxxx

Proved in tree-level ST

…actually this proves **($*$)** is extremal

The extremality bound & the RFC

BH, Reece, Rudelius '19; BH, Lotito 2207.xxxxx

Found a tower of resonances with:

$$\frac{\alpha'}{4} m^2 = \frac{1}{2} \max(Q_L^2, Q_R^2) \qquad (*)$$

What is the relation to extremal BHs?

A particle that is self-repulsive throughout moduli space is superextremal

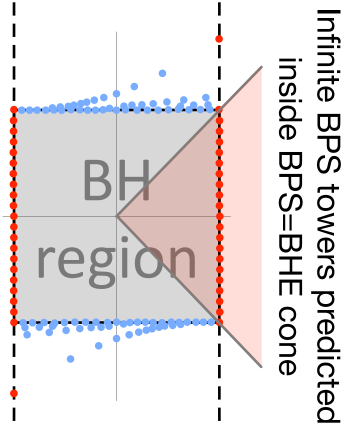
(BH, Reece, Rudelius '19)

(Harlow, BH, Reece, Rudelius 2201.08380)

Nonperturbative evidence via BPS states

Alim, BH, Rudelius 2108.08309
Gendler, BH, McAllister, Moritz, Rudelius 22xx.xxxxx

BPS prediction:



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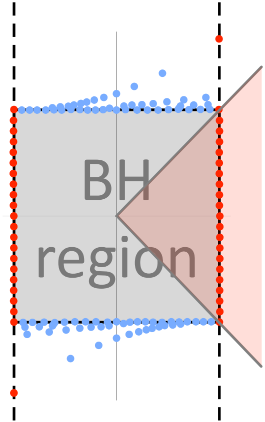
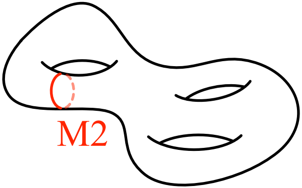


Infinite BPS towers predicted inside BPS=BHE cone



Genus 0 GV invariants:

$q_Y \setminus q_X$	0	1	2	3
0		640	10032	288384
1	64	6912	742784	75933184
2	0	14400	8271360	2445747712
3	0	6912	31344000	26556152064
4	0	640	48098560	130867460608
5	0	0	31344000	329212616704
6	0	0	8271360	445404149568
7	0	0	742784	329212616704
8	0	0	10032	130867460608
9	0	0	0	26556152064
10	0	0	0	2445747712
11	0	0	0	75933184
12	0	0	0	288384
13	0	0	0	0

$\tilde{X}$

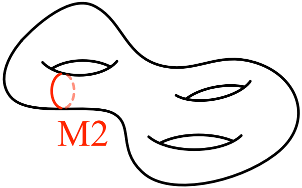
$\tilde{Y}$

BPS=BHE cone

Nonperturbative evidence via BPS states

Alim, BH, Rudelius 2108.08309

Gendler, BH, McAllister, Moritz, Rudelius 22xx.xxxxx



WGC

$\Downarrow$

Highly nontrivial predictions about CY geometry

Genus 0 GV invariants:

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0		640	10032	288384
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$\tilde{X}$

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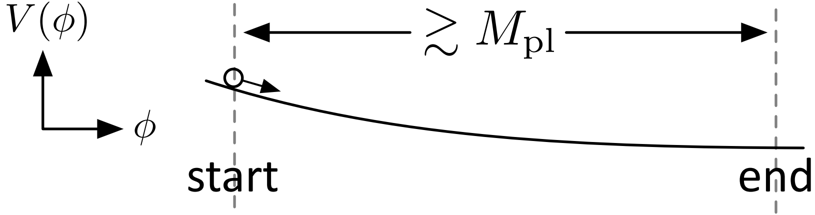
BPS=BHE cone

III. Axion Potentials & the WGC

Transplanckian scalars!?

Can a scalar field have a flat potential over a super-Planckian field range?



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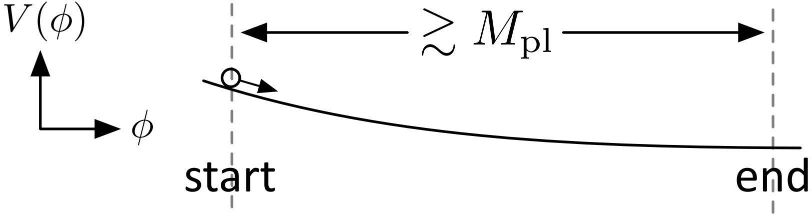
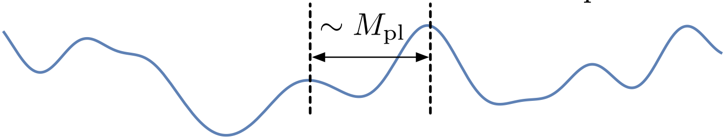


Generically **no**:

$$V_{\rm eff}(\phi) \sim V_0(\phi) + \phi^5/M_{\rm pl} + \phi^6/M_{\rm pl}^2 + \ldots$$



Axion loophole? $\phi \cong \phi + 2\pi f$

$$V_{\text{eff}}(\phi) \sim V_0(\phi) + \cancel{\phi^5/M_{\text{pl}}} + \ldots$$

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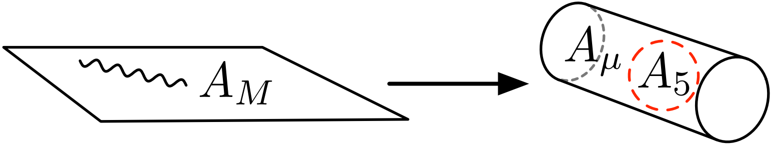
Example:

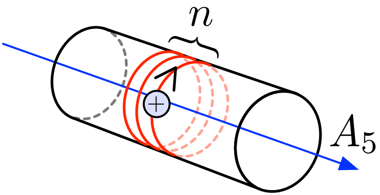


photon $\longrightarrow$ photon+axion

<u>typical in string theory</u>

Axion Potential

Casimir effect $\sum_{\text{species}} \sum_{n}$

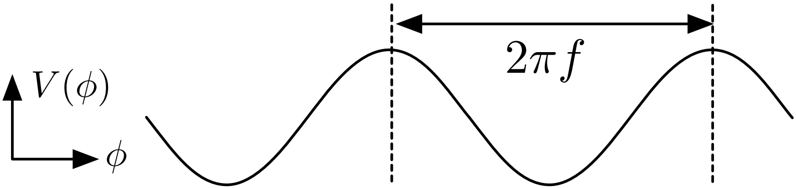


$$V = \sum_i c_i \underbrace{\cos(q_i \phi / f)}_{\text{Aharonov-Bohm phase}} e^{-2\pi R m_i} + \ldots$$

$(Q_i \propto q_i \in \mathbb{Z},\ A_5 \propto \phi)$

$$V = \sum_i c_i \cos(q_i \phi / f)\, e^{-2\pi R m_i} + \ldots$$

Suppose $m_1 \ll m_{i \neq 1}$, $q_1 = 1$



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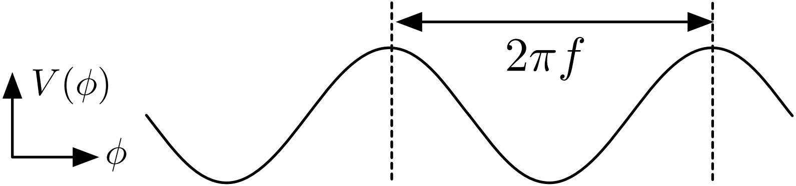

"Natural inflation" (Freese, Frieman, Olinto '90)

Needs $f \gtrsim 5\text{–}10\ M_{\mathrm{pl}}$ for successful inflation

$$V = \sum_i c_i \cos(q_i \phi / f)\, e^{-2\pi R m_i} + \ldots$$

(s)LWGC implies particles with

$$2\pi R m_i \lesssim \frac{M_{\rm pl}}{f} q_i \quad \text{for every} \quad q_i \in \mathbb{Z}$$

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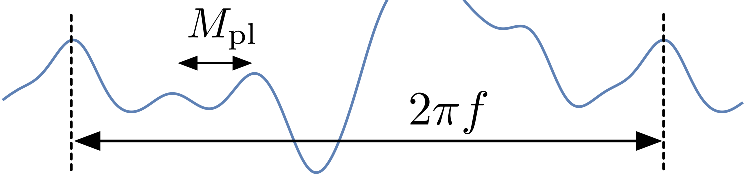
$\boxed{f \gtrsim M_{\rm pl}}$



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(s)LWGC implies particles with

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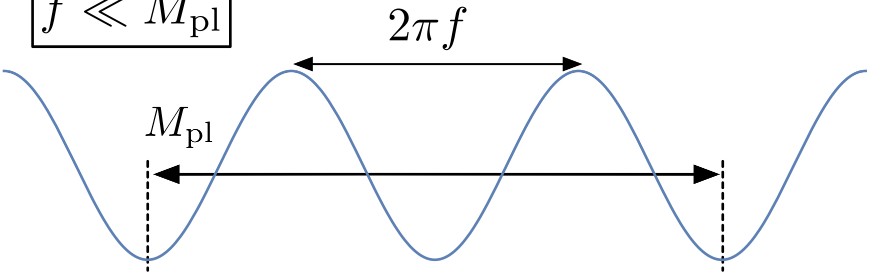
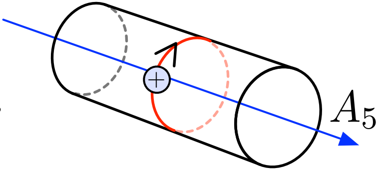
$$\boxed{f \ll M_{\rm pl}}$$



The generalized WGC

Charged worldline wrapped around circle generates an “instanton”

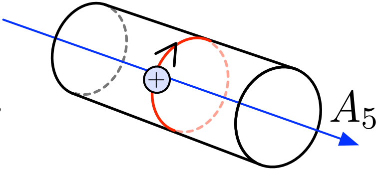


“Action” is

$$S = 2\pi R m \lesssim M_{\rm pl}/f$$

The generalized WGC

Charged worldline wrapped around circle generates an “instanton”



“Action” is

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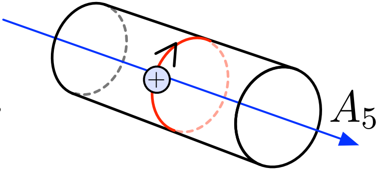
Tower of instanton corrections unsuppressed when $f \gtrsim M_{\rm pl}$

Generates harmonics in the potential, reducing effective field range!

The generalized WGC

Charged worldline wrapped around circle generates an "instanton"



"Action" is

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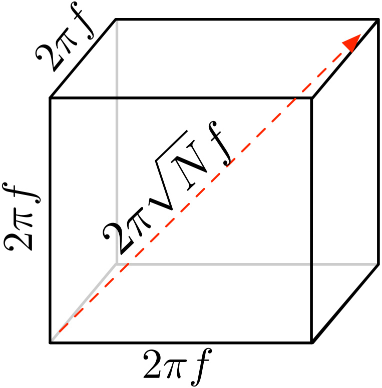
Tower of instanton corrections unsuppressed when $f \gtrsim M_{\rm pl}$

Generates harmonics in the potential, reducing effective field range!

ST: $f \lesssim M_{\rm pl}$ (Banks, Dine, Fox, Gorbatov '03)

1 axion: $f \lesssim M_{\rm pl}$ (Banks, Dine, Fox, Gorbatov '03)

$N \gg 1$ axions?



$$f_{\rm eff} = \sqrt{N} f$$

(Dimopoulos, Kachru, McGreevy, Wacker '05)

Random axion potentials

BH, Long, McAllister, Rudelius, Stout '19

$$\mathcal{L} = -\frac{1}{2}\delta_{ab}\,\partial_\mu\phi^a\,\partial^\mu\phi^b - \Lambda^4 \sum_{\mathbf{Q}\in\Gamma} Z_{\mathbf{Q}} \exp\left(i\mathbf{Q}\cdot\boldsymbol{\phi}\right)$$

$$\langle |Z_{\mathbf{Q}}|^2 \rangle = e^{-2\mu|\mathbf{Q}|}$$

Focusing on potential along a ray:

$$\sigma_n^2(\bar{\mathbf{e}}) = \sum_{\mathbf{Q}\in\Gamma}^{\mathbf{Q}\cdot\bar{\mathbf{e}}=n} e^{-2\mu|\mathbf{Q}|}$$

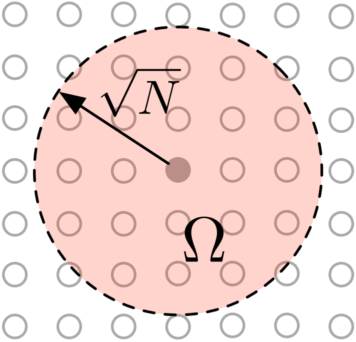
Using a continuum approximation

$$\mathrm{vol}\,\boldsymbol{\phi} \lesssim \mathrm{vol}\,D_N(2\mu)$$

Ball, not cube!

Random axion potentials

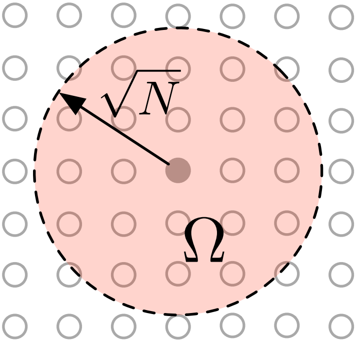
BH, Long, McAllister, Rudelius, Stout '19



Many instantons contribute!

Random axion potentials

BH, Long, McAllister, Rudelius, Stout '19



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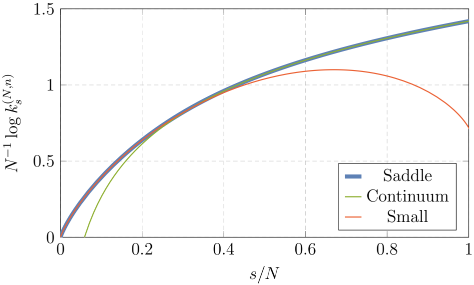
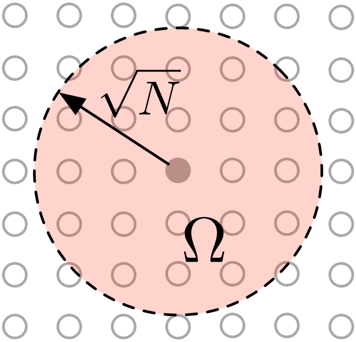


Better: saddle point analysis

Random axion potentials

BH, Long, McAllister, Rudelius, Stout '19



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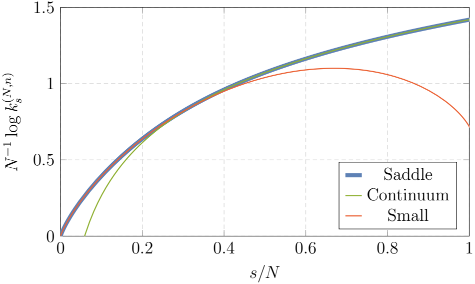
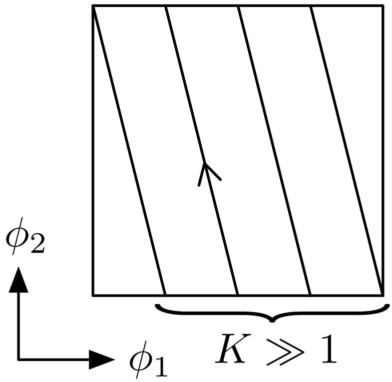


Better: saddle point analysis

Still find: $f_{\text{eff}} \lesssim M_{\text{pl}}$

Alignment (Kim, Nilles, Peloso '04)



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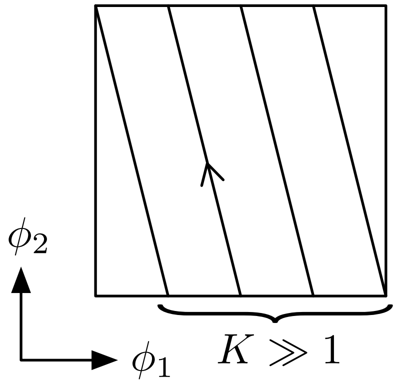
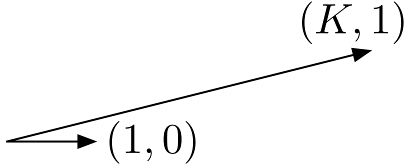
(Kim, Nilles, Peloso '04)



5d charge spectrum:



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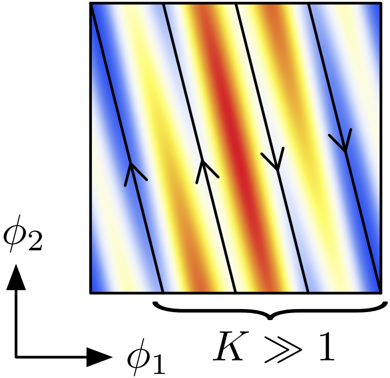
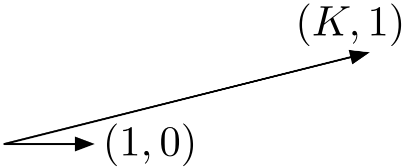


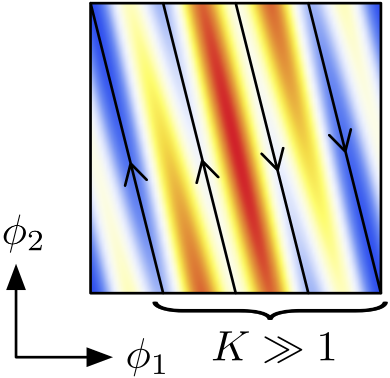
5d charge spectrum:



$$f_{\text{eff}} = \sqrt{K^2 + 1} f \simeq K f$$

Alignment

(Kim, Nilles, Peloso '04)



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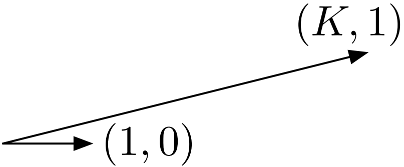

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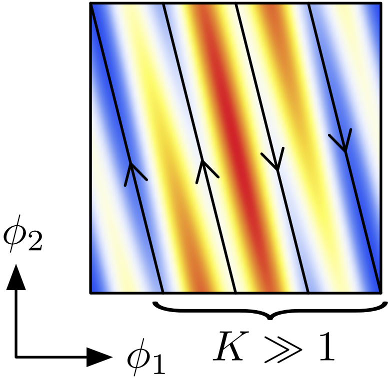

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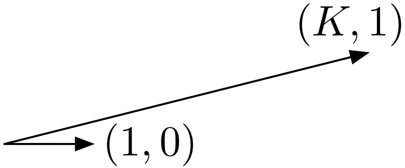

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Potential alternative: kinetic alignment

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…even though there is still much more to be learned about the WGC itself!