Weak Gravity Conjecture and Phenomenological Implications

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refs:

1810.03637 w/Y. Hamada, G. Shiu

1802.04287 w/S. Andriolo, D. Junghans, G. Shiu

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Weak Gravity Conjecture

in quantum gravity,

$\exists$ a charged state satisfying

$$g^2 q^2 \geq \frac{m^2}{2M_{\rm Pl}^2}$$

for each U(1) gauge force

[ArkaniHamed-Motl-Nicolis-Vafa 06']

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∃ a charged state satisfying

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[ArkaniHamed-Motl-Nicolis-Vafa 06']

Weak Gravity Conjecture

in quantum gravity,

$\exists$ a charged state satisfying

$$g^2 q^2 \geq \frac{m^2}{2M_{\rm Pl}^2} \xrightarrow{M_{\rm Pl}\to\infty} 0$$

for each U(1) gauge force

[ArkaniHamed-Motl-Nicolis-Vafa 06']

- in QED, electron trivially satisfies the bound:

$$10^{-2} \sim g^2 q^2 \geq \frac{m^2}{2M_{\rm Pl}^2} \sim 10^{-44}$$

- generalization to axion (0-form gauge field):

$$\frac{f}{M_{\rm Pl}} \cdot S_{\rm inst} \leq 1$$

relevant to inflation, dark matter, quintessence, …

- neutrino mass from higher form WGC [Ooguri-Vafa '17]

very interesting if it is true

in [Hamada-TN-Shiu '18] we demonstrated

existence of a charged black hole satisfying

$$g^2 q^2 > \frac{m^2}{2M_{\rm Pl}^2}$$

follows from unitarity & causality

in a wide class of theories

(ex. stingy setups w/dilaton or moduli stabilized below M_s)

plan

1. Introduction: Landscape & Swampland

2. Weak Gravity Conjecture

3. WGC from unitarity and causality

4. Summary and prospects

1. Landscape & Swampland

various QFT models w/quantum gravity

ex. for particle physics and cosmology

QFT 1

QFT 2

QFT 3

QFT 4

Landscape : string theory has infinitely many vacua!

shape of extra dimensions, brane configurations, …

string theory

= generator of QFT models w/quantum gravity

Q. every QFT model is realized in string theory?

A. NO!!!

no global symmetry in string theory

continuous symmetries in string theory are gauged!

- world sheet theory analysis [Banks-Dixon '88, ···]

  conserved current $J \to$ gauge boson vertex op. $Je^{ik\cdot X}$

- if we assume AdS/CFT ···

conserved current J^μ in CFT $\rightleftarrows$ gauge field A_M in AdS

- BH thought experiments

holographic proof including discrete symmetries

[Harlow-Ooguri 18']

in this way,

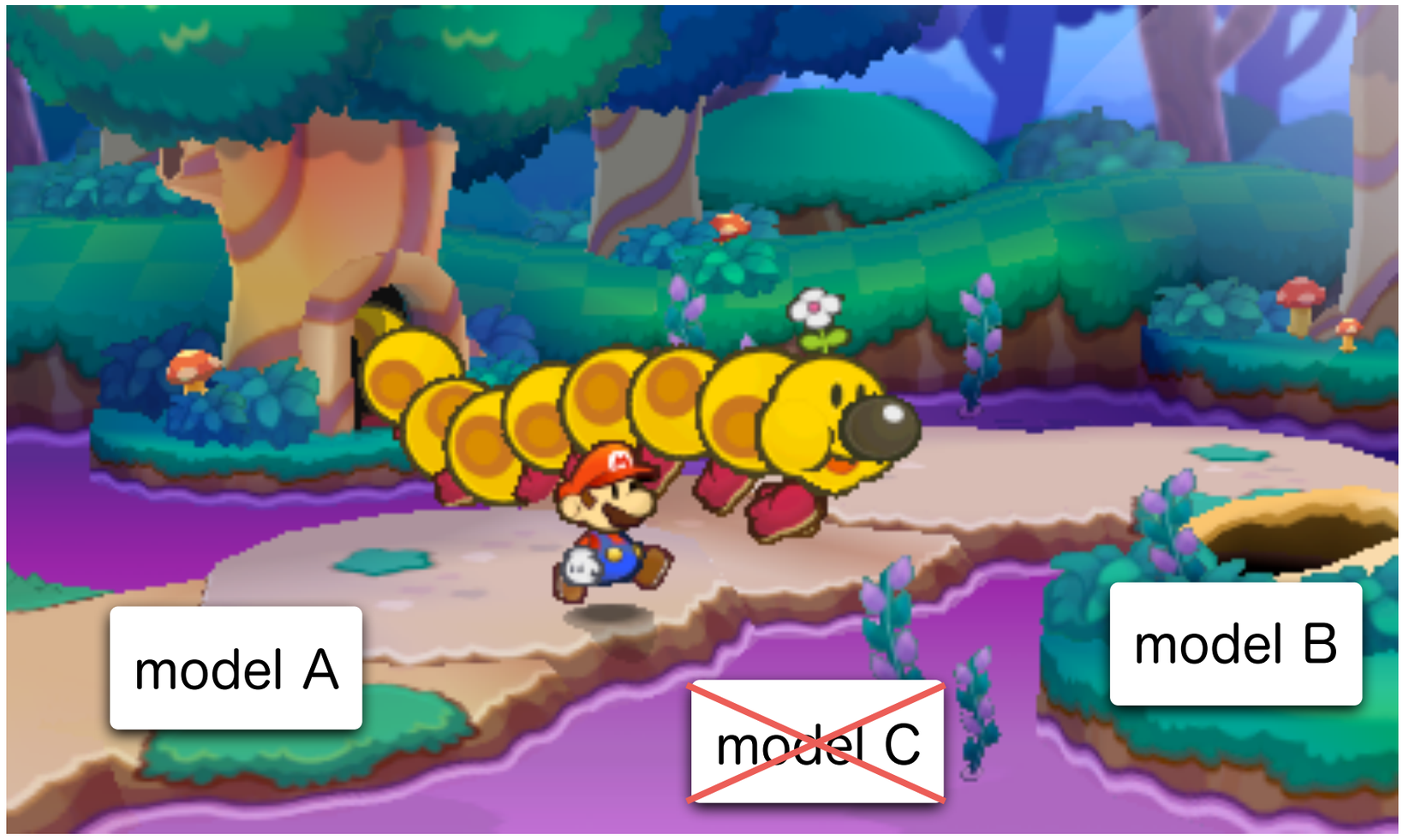
nontrivial constraints on symmetry & matter contents

in string theory (quantum gravity in more general)

→ Landscape & Swampland [Vafa '05, Ooguri-Vafa '06]

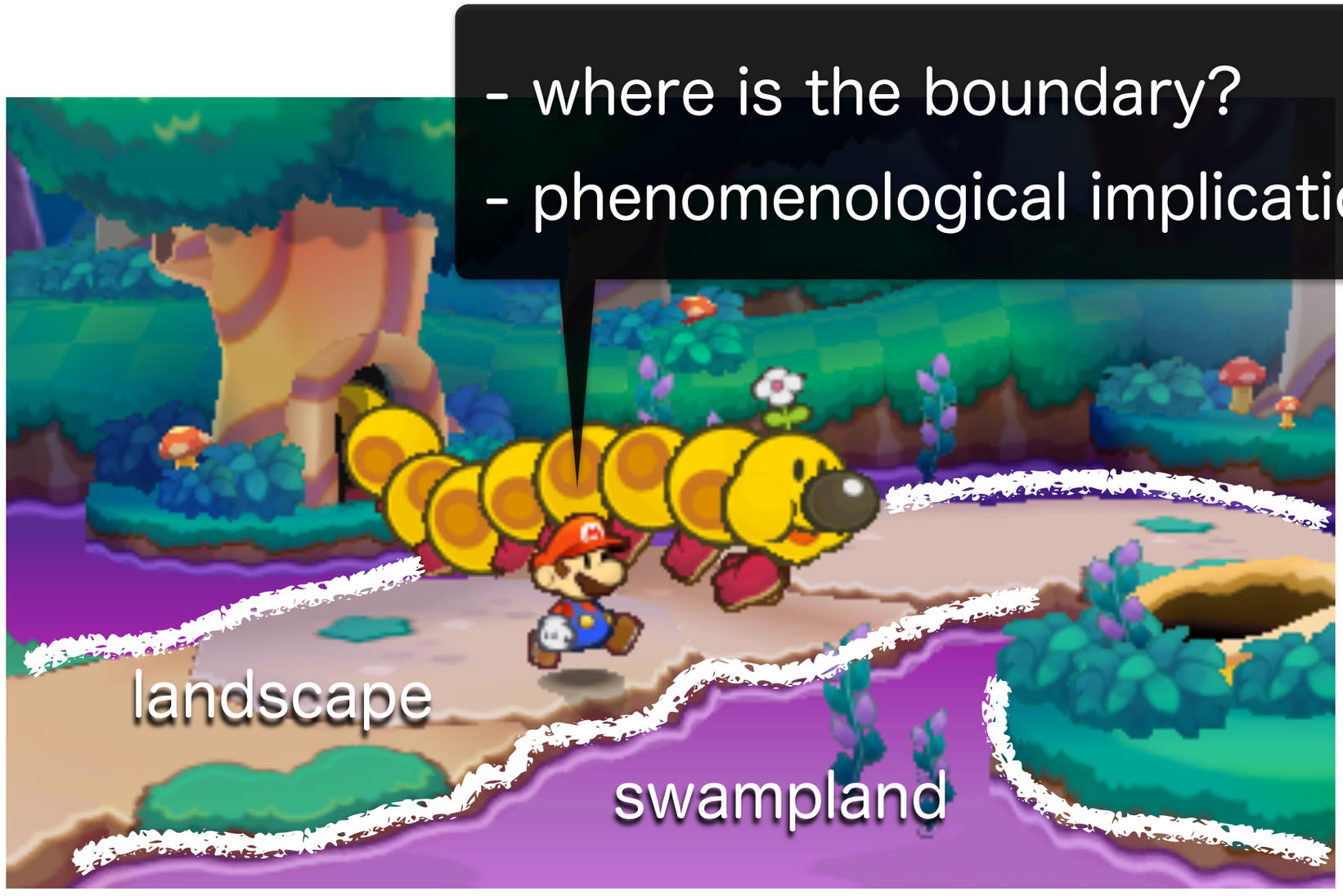
landscape：

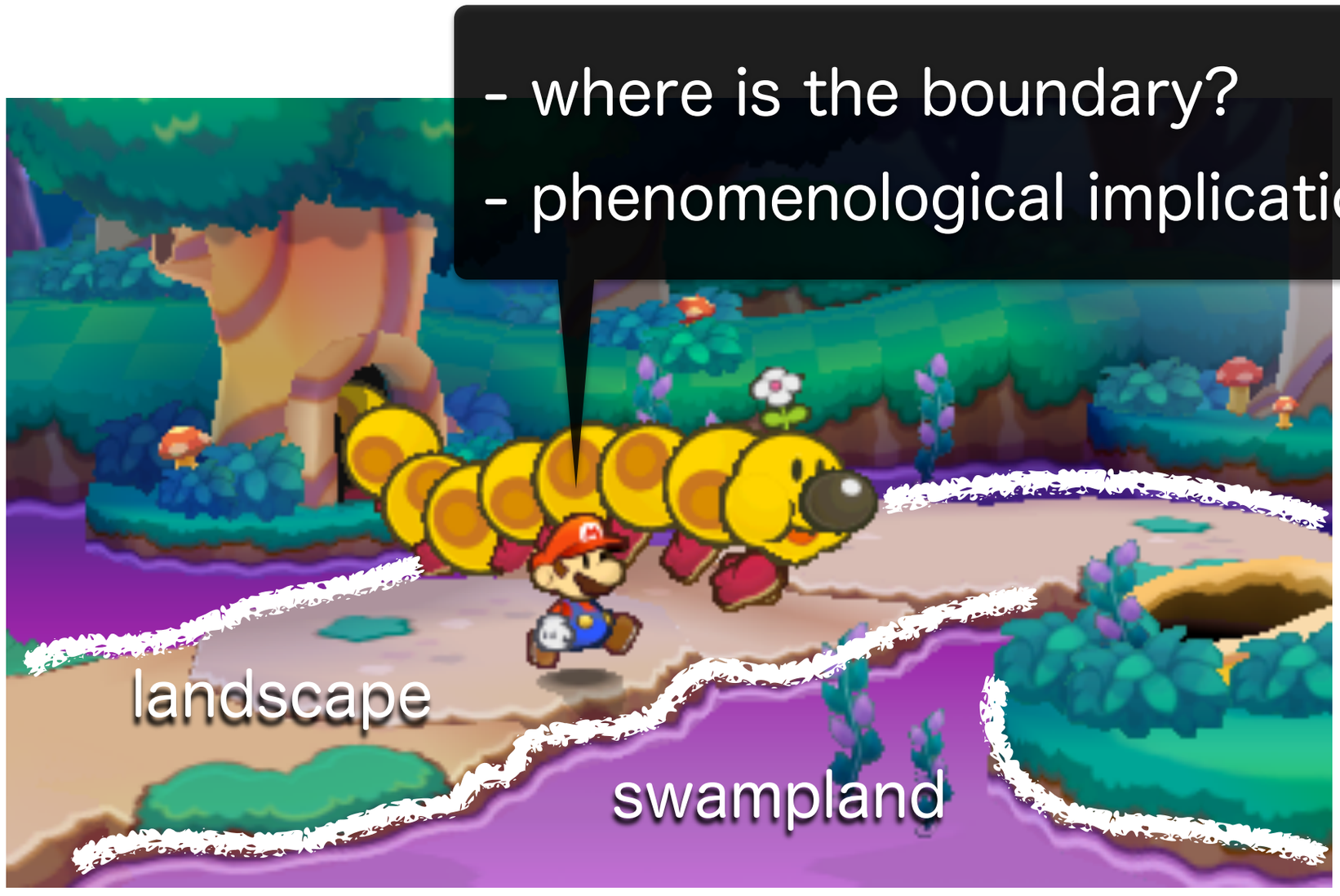
QFT models consistent w/quantum gravity



swampland：

apparently consistent, but not UV completable when coupled to gravity

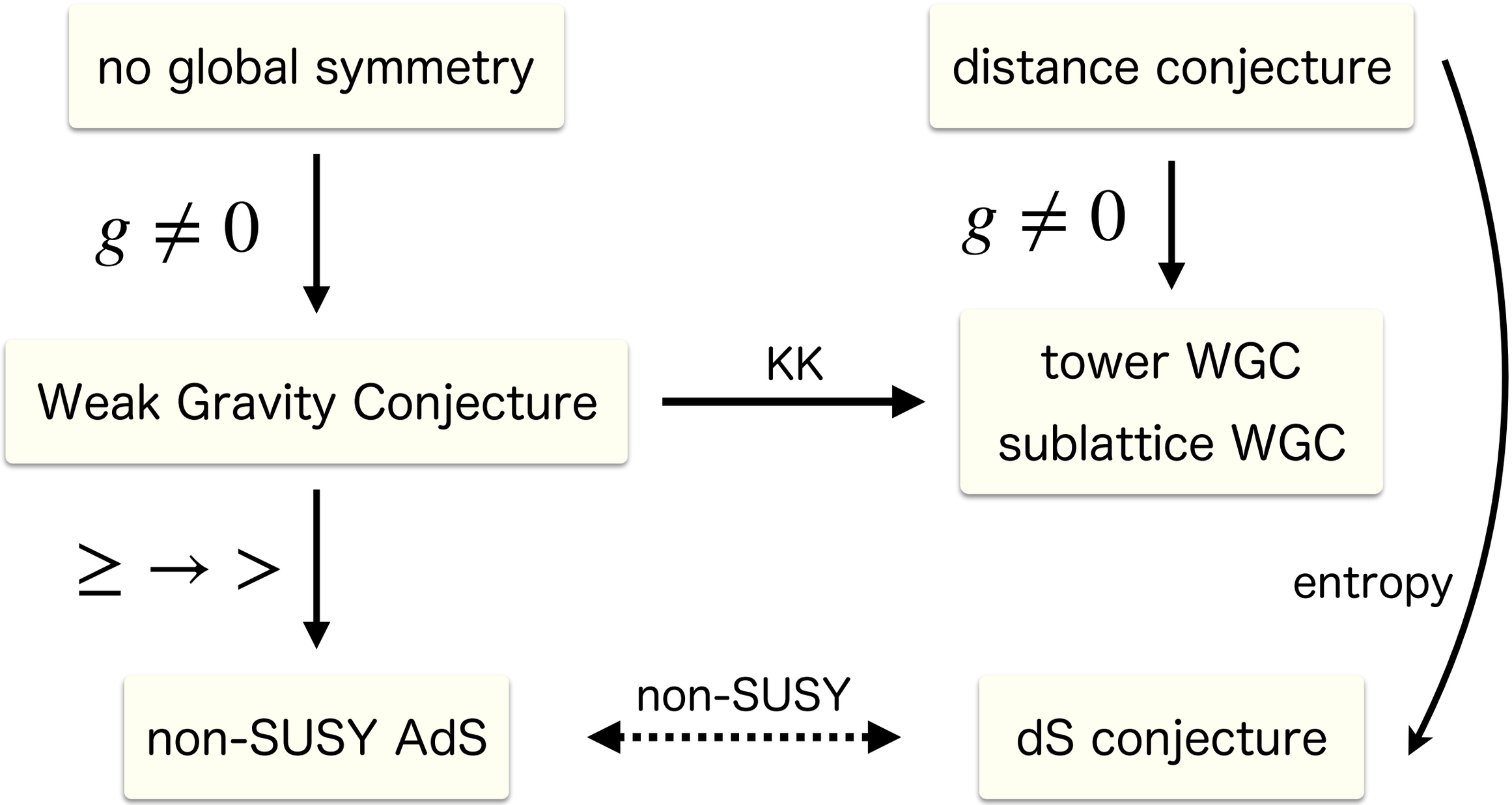

- where is the boundary?
- phenomenological implications?
landscape
swampland



Weak Gravity Conjecture [Arkani-Hamed et al 06']

is a conjectured criterion defining the boundary

web of swampland conjectures



web of swampland conjectures

rigorous

useless

no global symmetry

$g \neq 0$

Weak Gravity Conjecture

KK

tower WGC

sublattice WGC

$\geq \to >$

non-SUSY AdS

non-SUSY

dS conjecture

distance conjecture

$g \neq 0$

entropy

skeptical

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credit: Hirosi Ooguri

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plan

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2. Weak Gravity Conjecture

[ArkaniHamed-Motl-Nicolis-Vafa 06’]

no global symmetry in QG:

a) approximate global symmetry

b) ∃ gauge boson


well understood (there is even a proof!)


phenomenologically useless

a) sym. breaking can be very very tiny

b) gauge coupling can be very very tiny

motivation:

generalize the no global symmetry criterion

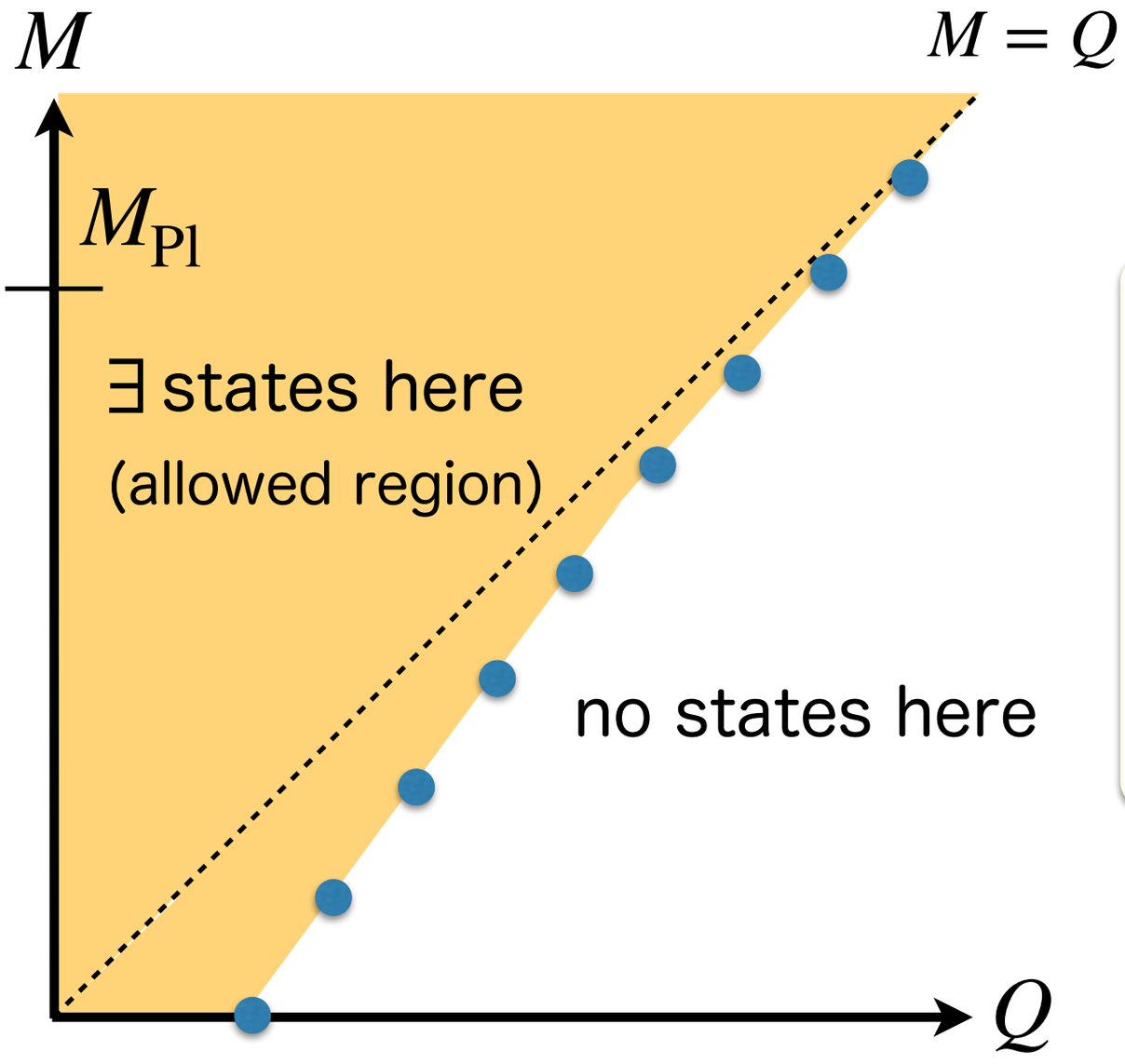
in a phenomenologically useful way

$$g^2 q^2 \geq \frac{m^2}{2M_{\rm Pl}^2}$$

Q. any insight from string theory?

typical string spectrum

ex. heterotic string compactified on tori w/generic Wilson lines



1. a tower of states w/ $M \leq Q$

2. $M \leq Q$ is saturated for $M \gg M_{\rm Pl}$

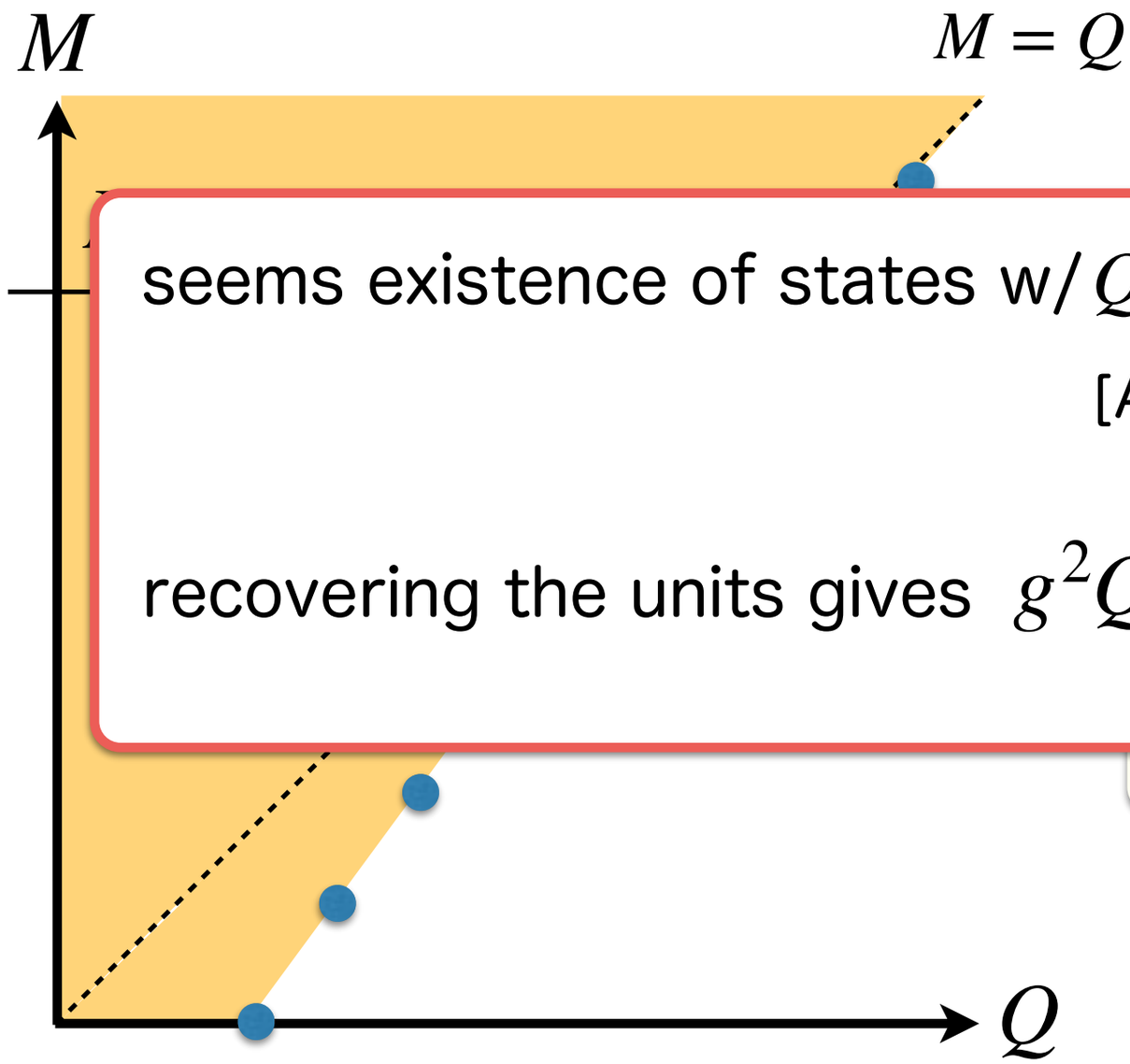
   cf. heavy string ⇆ BH

   ['t Hooft, Susskind, Sen, ⋯]

in the unit $M = Q$ for large extremal BHs

typical string spectrum

ex. heterotic string compactified on tori w/generic Wilson lines



seems existence of states w/ $Q \geq M$ is common in string theory

[ArkaniHamed-Motl-Nicolis-Vafa 06', ⋯]

recovering the units gives $g^2 Q^2 \geq \dfrac{M^2}{2M_{\rm Pl}^2}$

in the unit $M = Q$ for large extremal BHs

to motivate this bound in more general contexts,
they employed the following working hypothesis:

every BH has to decay unless protected by symmetry

BHs in Einstein-Maxwell theory

1) non-extremal BH: $g|Q| < M/\sqrt{2}M_{\rm Pl}$

emit Hawking radiation ($T \neq 0$) to decay; unstable

2) extremal BH: $g|Q| = M/\sqrt{2}M_{\rm Pl}$

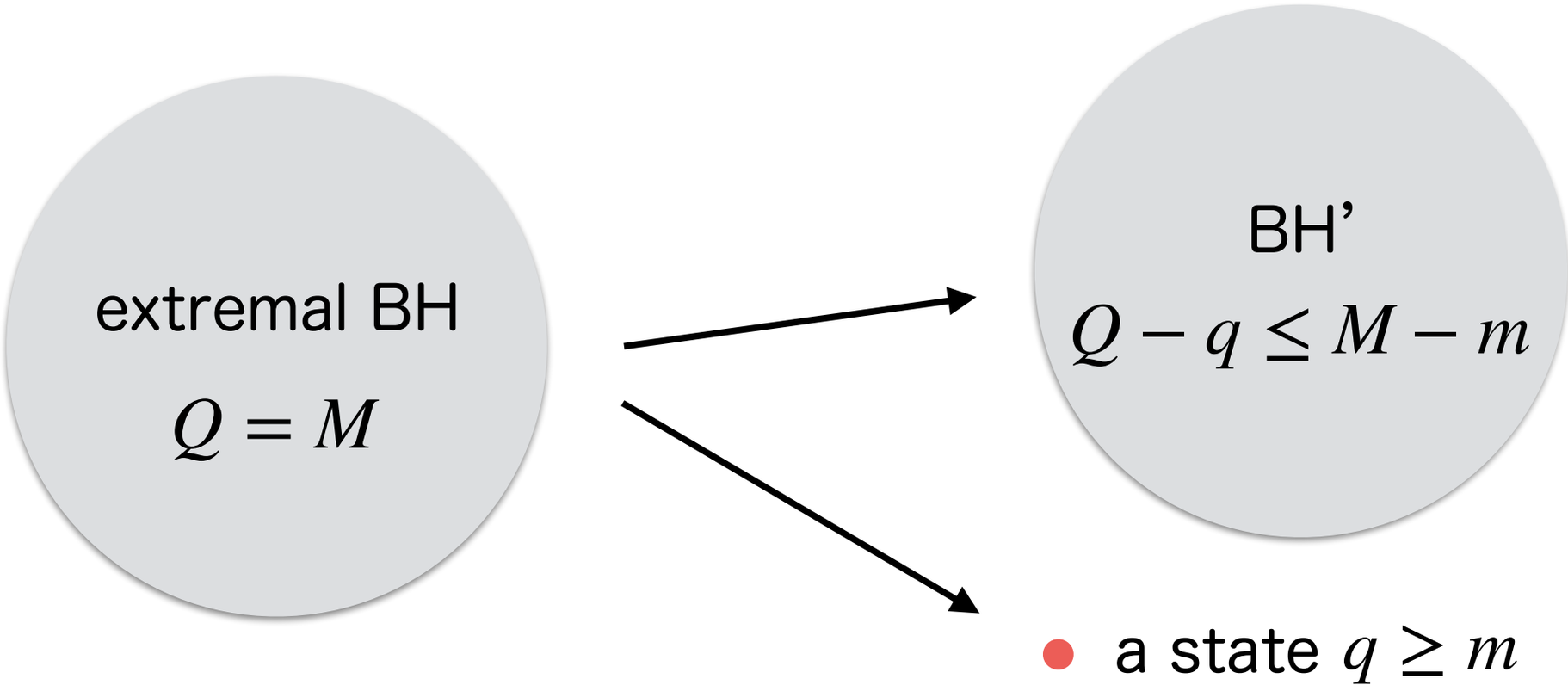
no Hawking radiation ($T = 0$)

$\rightarrow$ stable unless $\exists$ some other decay mechanism

※ $g|Q| > M/\sqrt{2}M_{\rm Pl}$: naked singularity (cf. cosmic censorship)

Weak Gravity Conjecture

[ArkaniHamed-Motl-Nicolis-Vafa 06']



- extremal BH has a decay channel

- the BH' after decay has no naked singularity

$\rightarrow \exists$ a charged state satisfying $q \geq m$

in the unit $Q_{\text{ext}} = M_{\text{ext}}$ for simplicity

Weak Gravity Conjecture

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for each U(1) gauge force

[ArkaniHamed-Motl-Nicolis-Vafa 06']

Weak Gravity Conjecture

in quantum gravity,

$\exists$ a charged state satisfying

$$0 \xleftarrow{g \to 0} g^2 q^2 \geq \frac{m^2}{2M_{\rm Pl}^2}$$

for each U(1) gauge force

[ArkaniHamed-Motl-Nicolis-Vafa 06']

generalization to p-form gauge fields

black brane has to decay

→ upper bound on tension of p-dim object $T \lesssim (g^2 M_{\rm Pl}^{D-2})^{1/2}$

※ if we think of axion as a 0-form gauge field

upper bound on axion decay constant: $S_{\rm inst} \cdot \dfrac{f}{M_{\rm Pl}} \lesssim 1$

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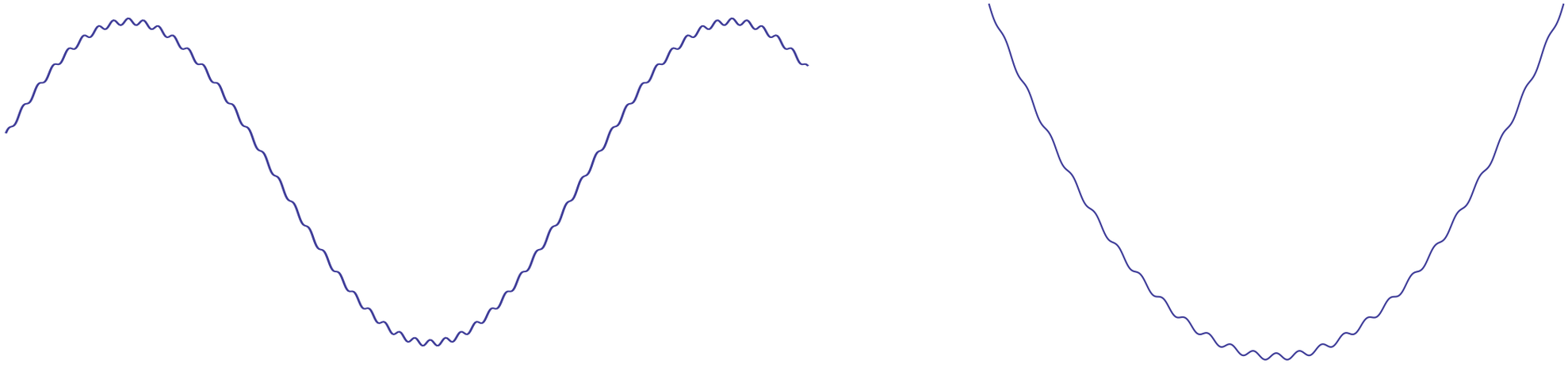

prediction about axion inflation:

oscillating features in CMB powerspecturm in large field inflation

driven by axion (ex. natural inflation, axion monodromy)

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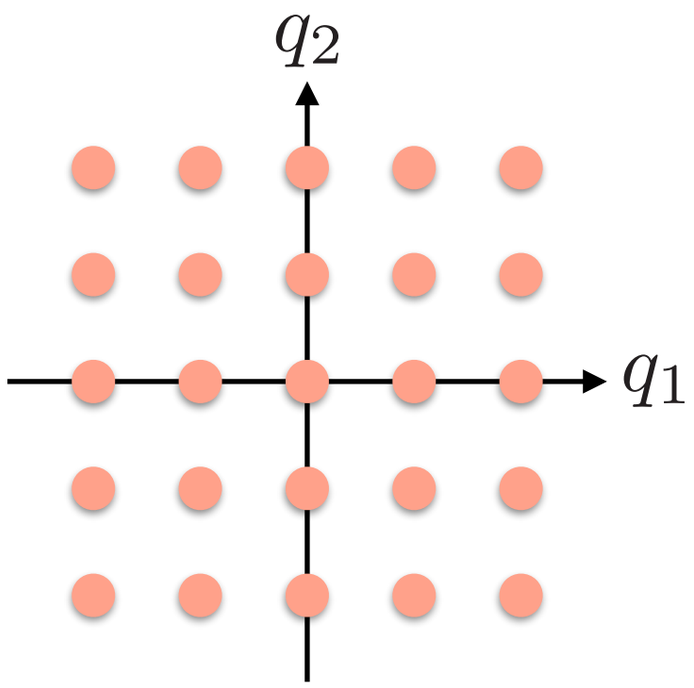
Tower/(sub)Lattice Weak Gravity Conjecture

[Heidenreich et al '15 & '16, Montero et al '16, Andriolo-Junghans-TN-Shiu '18]



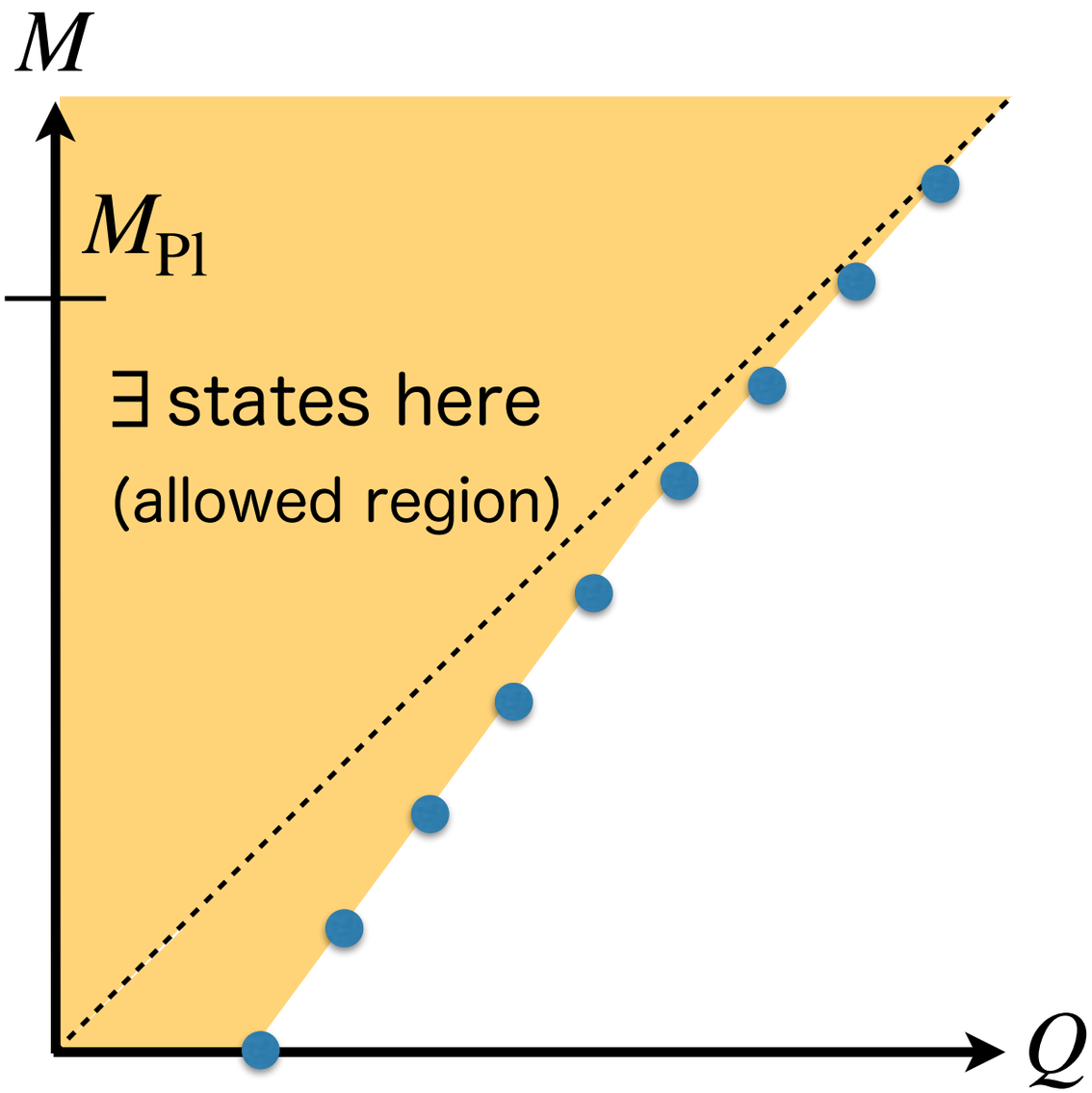
∃ a tower/lattice of charged states w/ $|\vec{q}| \geq m$

- BH argument + KK reduction [Heidenreich et al '15]
- positivity + KK reduction [Andriolo-Junghans-TN-Shiu '18]
- modular invariance [Heidenreich et al '16, Montero et al '16]

3. WGC from unitarity and causality

[Hamada-TN-Shiu ’18]

Q. How generic this picture is?



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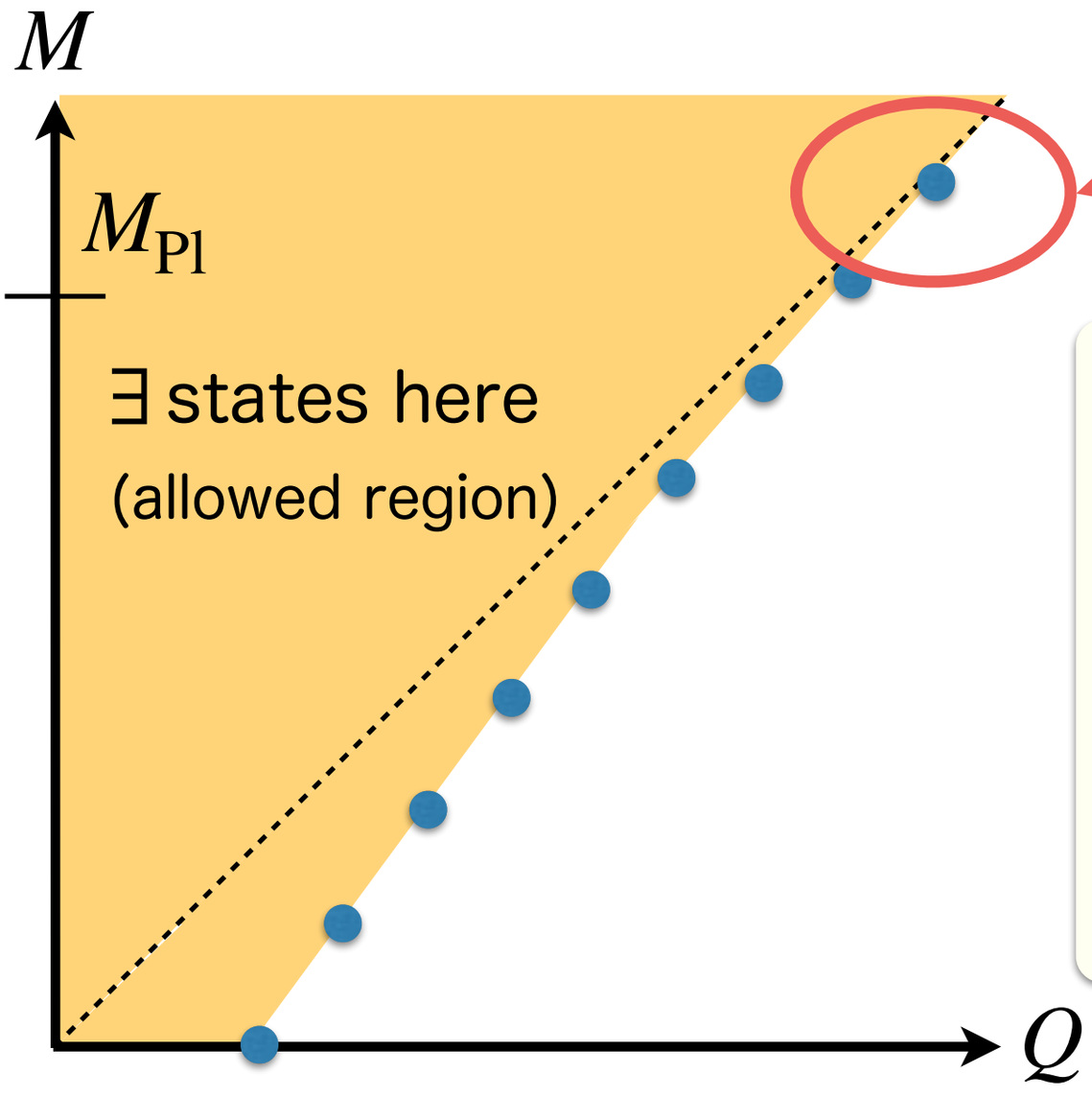


this asymptotic behavior (of BHs)

follows from unitarity & causality

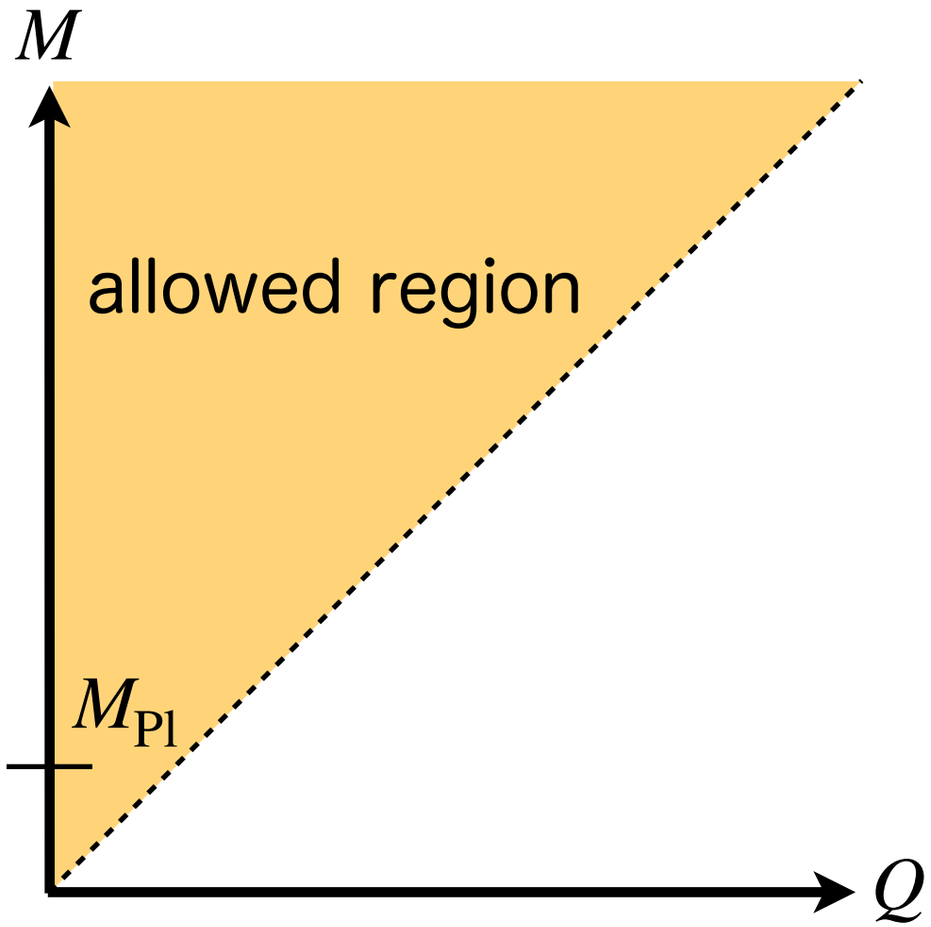
in a wide class of theories

[Hamada-TN-Shiu '18]

※ existence proof of (mild) WGC

let us consider spectrum of charged BHs

in Einstein-Maxwell theory + higher derivative corrections



allowed region:

∃ event horizon to hide singularity

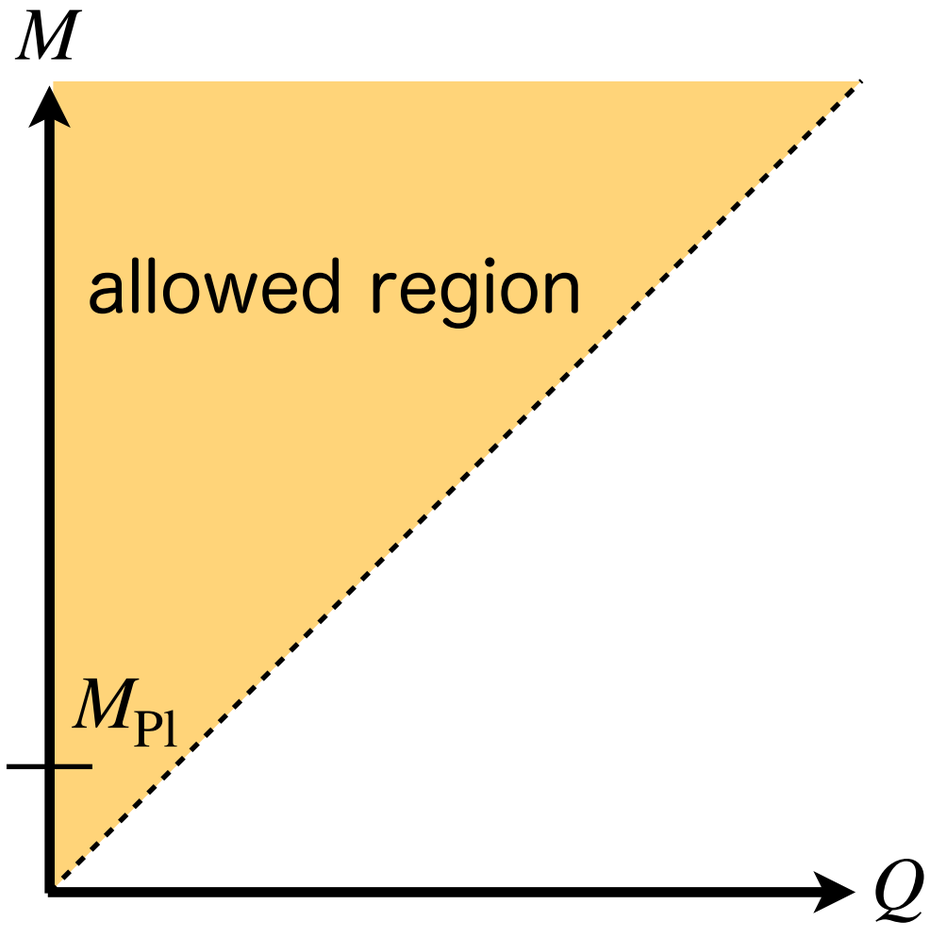
(required by cosmic censorship)

in the Einstein-Maxwell theory,

absence of naked singularity requires the extremal bound:

$$\frac{|Q|}{M} \leq 1$$ ← opposite to the WGC bound

※ work in the unit $2M_{\rm Pl}^2 = 1,\ g = 1$ in the following



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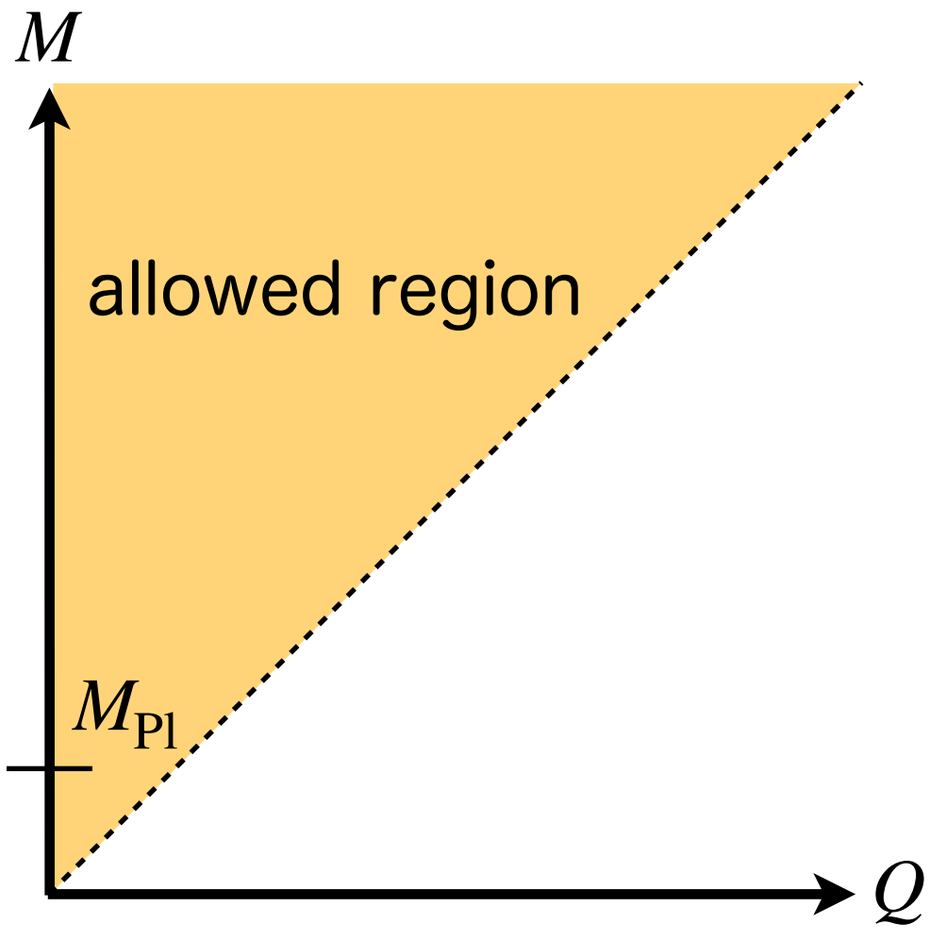
higher derivative corrections to Einstein-Maxwell theory

$$S = \int d^4x\sqrt{-g}\Big[\frac{1}{4}R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \alpha_1(F_{\mu\nu}F^{\mu\nu})^2 + \alpha_2(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2 + \alpha_3 F_{\mu\nu}F_{\rho\sigma}W^{\mu\nu\rho\sigma} + \cdots\Big]$$

※ work in the unit $2M_{\rm Pl}^2 = 1,\ g = 1$ in the following

※ higher order terms are negligible for heavy BHs

$$F^2 \sim R \sim 1/M^2$$



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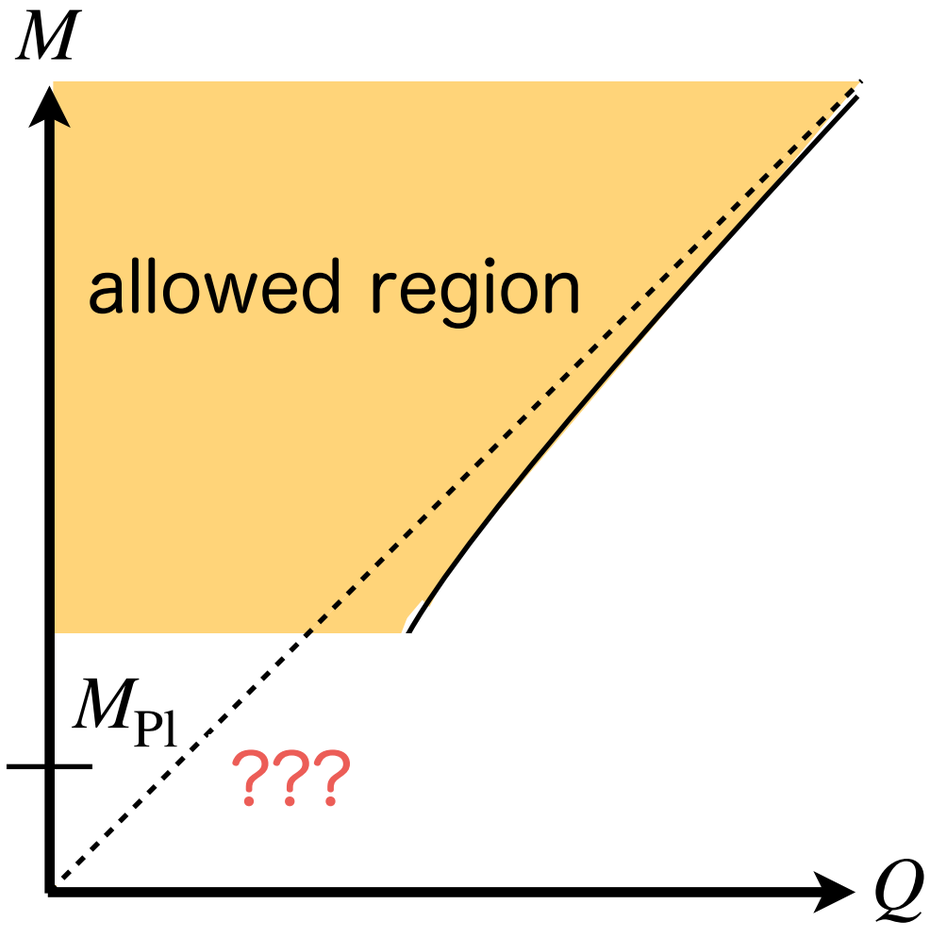
→ modify BH solutions and horizon structure [Kats-Motl-Padi '06]

no naked singularity if $\dfrac{|Q|}{M} \leq 1 + \dfrac{2}{5}\dfrac{(4\pi)^2}{Q^2}(2\alpha_1 - \alpha_3) + \mathcal{O}(1/Q^4)$



BHs with $|Q| > M$ are allowed

iff $2\alpha_1 - \alpha_3 > 0$

higher derivative corrections to Einstein-Maxwell theory

$$S = \int d^4x\sqrt{-g}\Big[\frac{1}{4}R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \alpha_1(F_{\mu\nu}F^{\mu\nu})^2 + \alpha_2(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2 + \alpha_3 F_{\mu\nu}F_{\rho\sigma}W^{\mu\nu\rho\sigma} + \cdots\Big]$$

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our task is now to prove $2\alpha_1 - \alpha_3 > 0$

our following proof applies to

a) theories w/ light neutral particles such as dilaton and moduli

b) theories w/ light charged particles

c) open string theory

(photon and graviton are accompanied by different Regge states)

※ here light means lighter than “string scale”

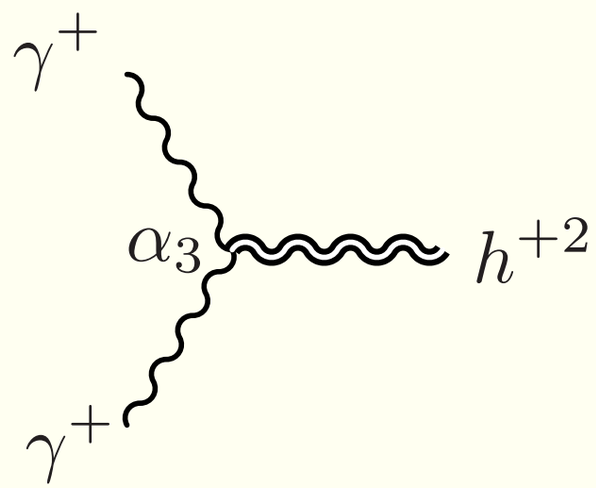
WGC from unitarity and causality

[Hamada-TN-Shiu '18]

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{4}R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \alpha_1(F_{\mu\nu}F^{\mu\nu})^2 \right.$$
$$\left. +\alpha_2(F_{\mu\nu}\widetilde{F}^{\mu\nu})^2 + \alpha_3 F_{\mu\nu}F_{\rho\sigma}W^{\mu\nu\rho\sigma} + \cdots\right]$$

① α_3 is highly constrained by symmetry causality

$\text{SUSY: } \alpha_3 = 0, \ \text{non-SUSY: } |\alpha_1|, |\alpha_2| \gg |\alpha_3|$



causality constraint

[cf. Camanho-Edelstein-Maldacena-Zhiboedov '14]

WGC from unitarity and causality

[Hamada-TN-Shiu '18]

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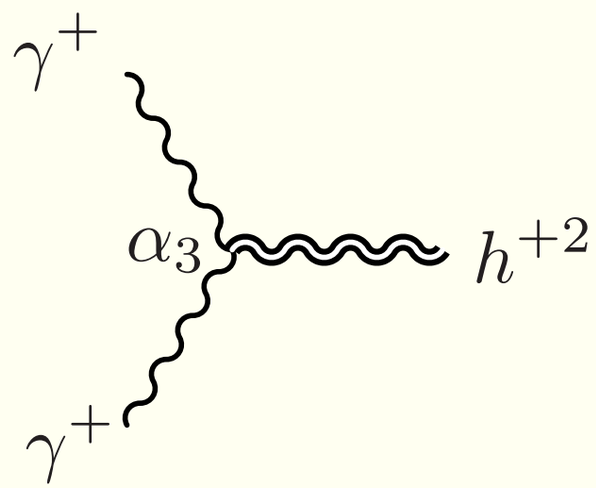


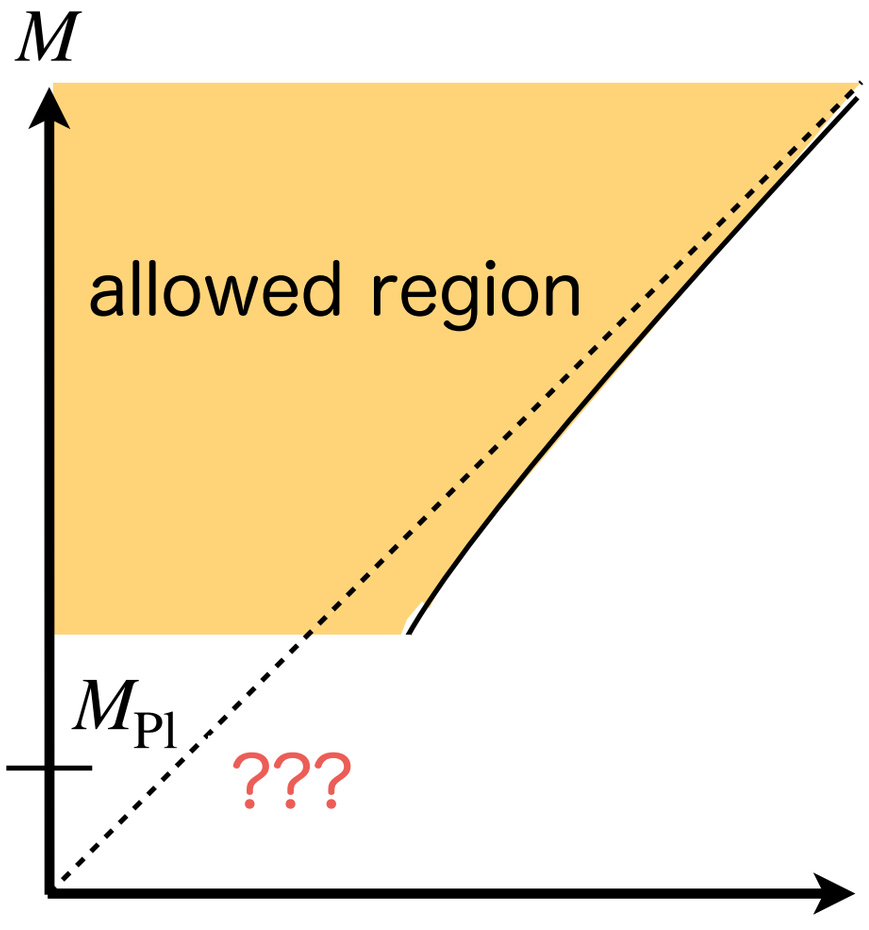
causality constraint

[cf. Camanho-Edelstein-Maldacena-Zhiboedov '14]

② sign of α_1 is constrained by unitarity

ex. dilaton coupling

$\frac{\phi}{f}F_{\mu\nu}F^{\mu\nu}$ → integrate out → effective int. $\frac{1}{2m^2f^2}(F_{\mu\nu}F^{\mu\nu})^2$



$$2\alpha_1 - \alpha_3 \simeq 2\alpha_1 > 0$$

causality unitarity

- existence proof of mild form of WGC

- evidence for the big picture behind stronger WGCs

$$\alpha_1 : (FF)^2, \quad \alpha_2 : (F\tilde{F})^2, \quad \alpha_3 : F^2W$$

Summary and prospects

Summary

as a consequence of unitarity & causality,

heavy charged BH satisfies the WGC bound

$$g^2 q^2 > \frac{m^2}{2M_{\rm Pl}^2}$$

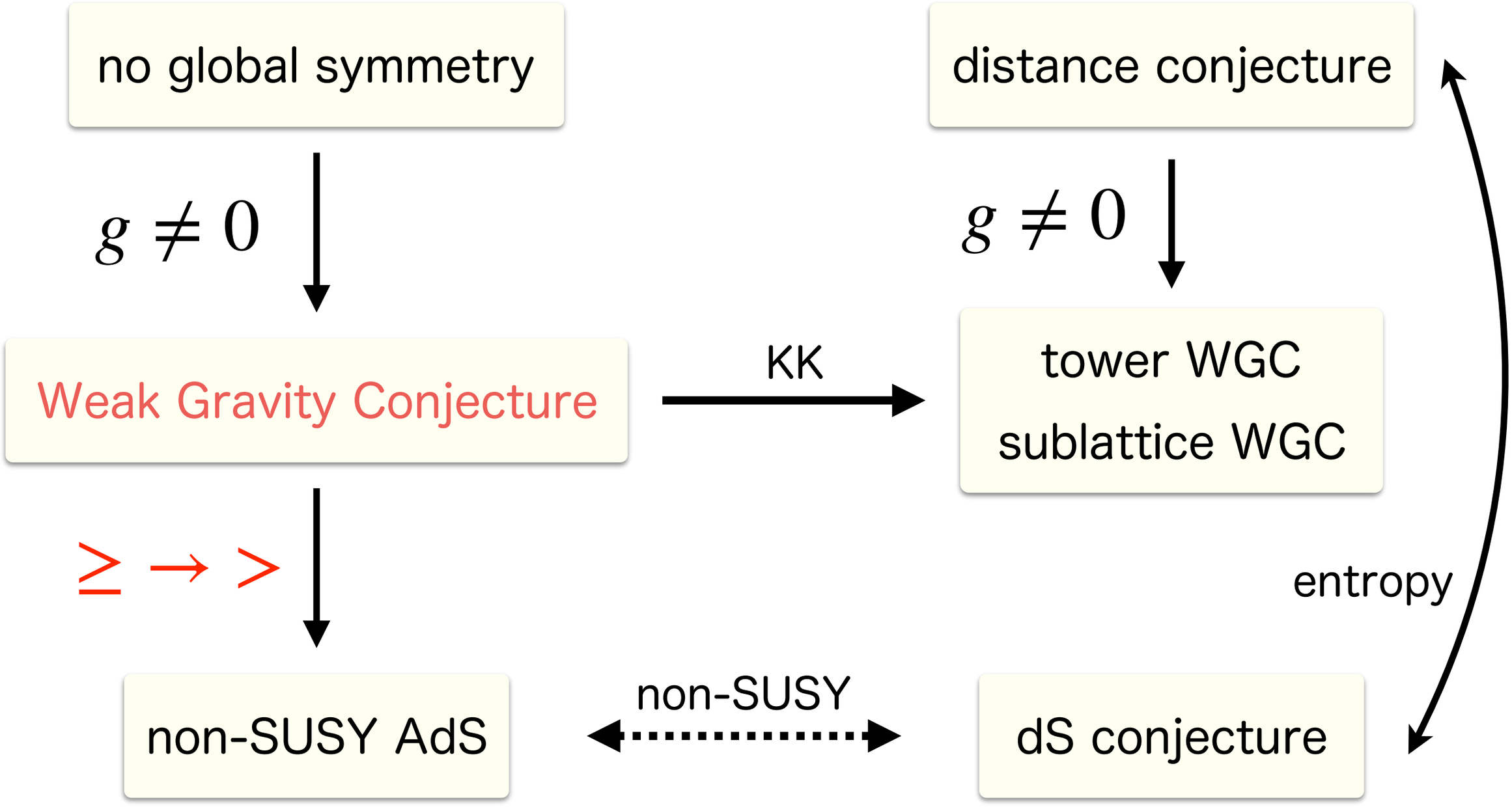
- in theories w/light neutral particles (ex. dilaton, moduli)

- in open string theory type UV completion

✔ extension to higher dimension, multiple U(1)'s

in progress: extension to WGC for axion, p-form etc

web of swampland conjectures



proof and implications of other conjectures!?

Thank you!