A Swampland Review for Cosmologists

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CERN

IFT UAM-CSIC

String-Cosmo day

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Swampland program

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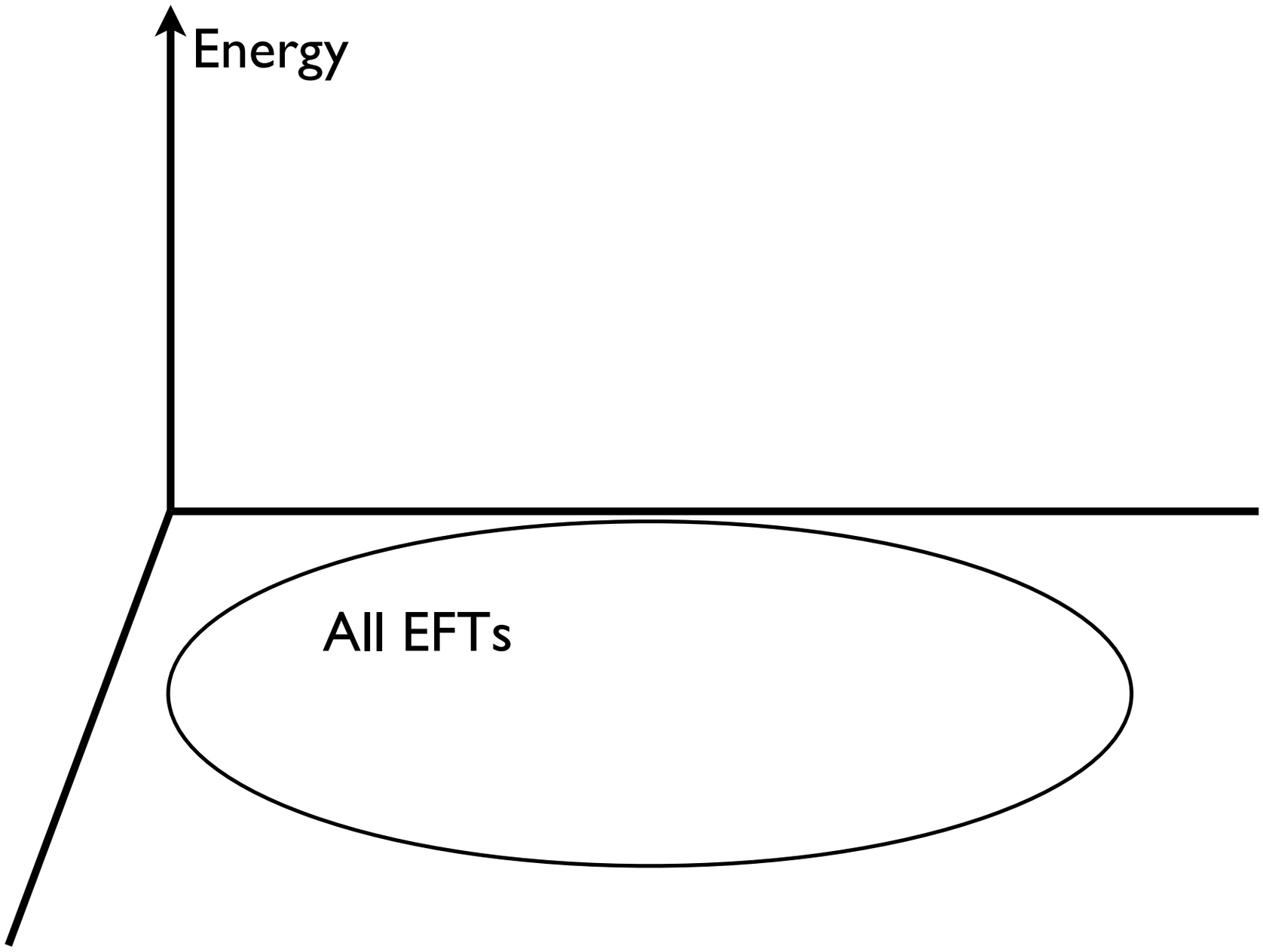
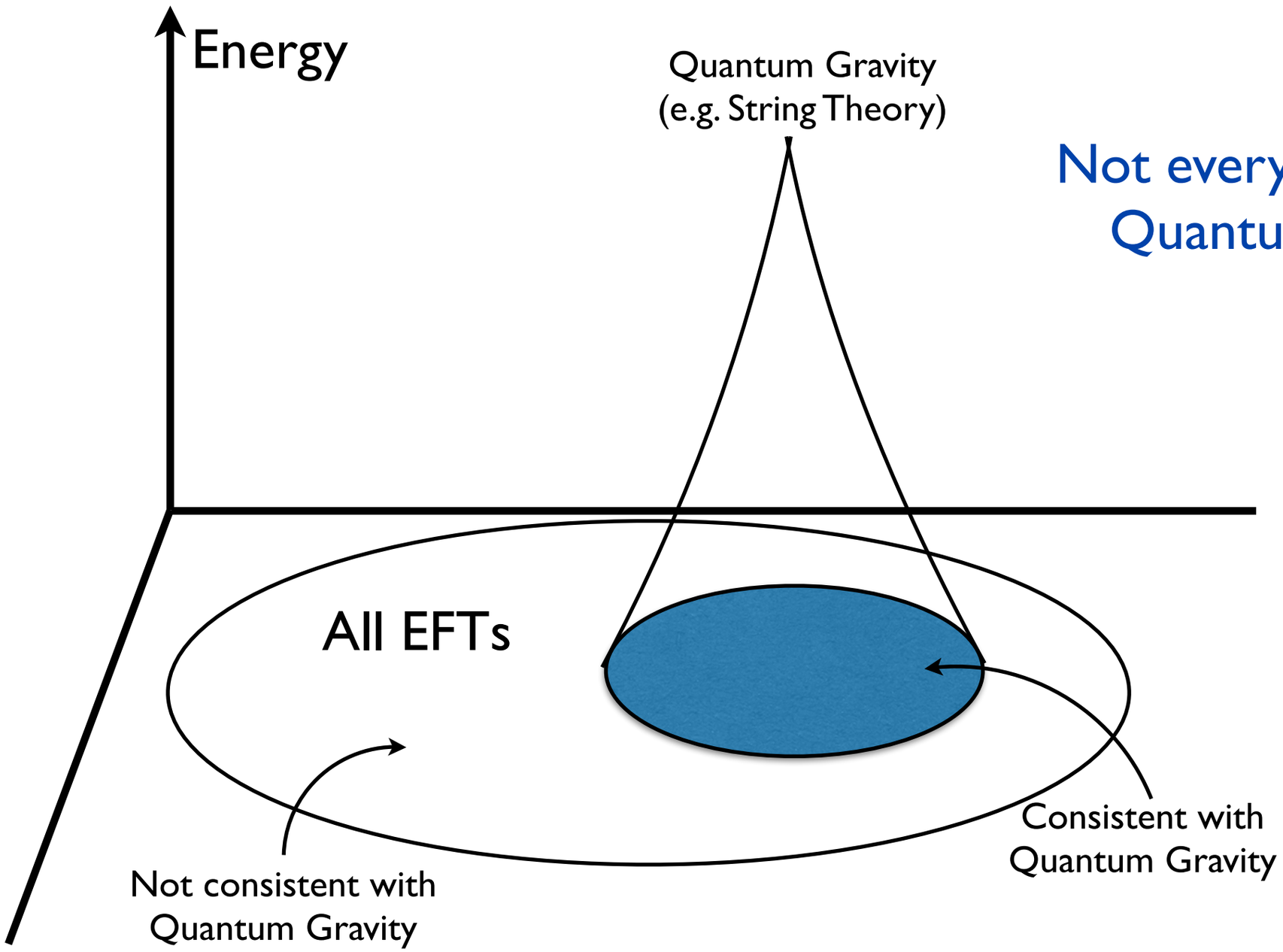
What is the quantum gravity cut-off?


Energy
All EFTs



Not everything goes in Quantum Gravity!

Swampland Lectures/Reviews:
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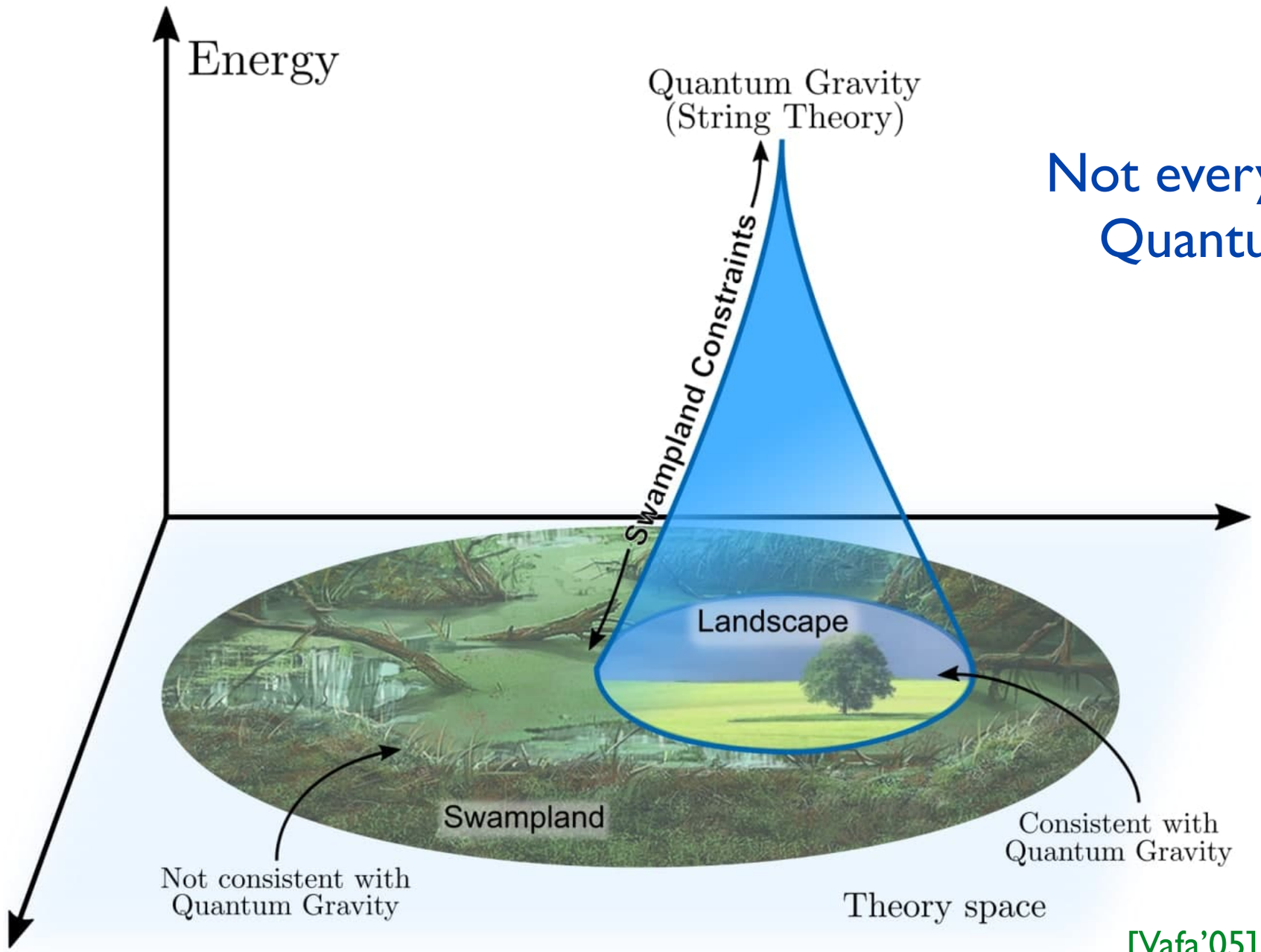

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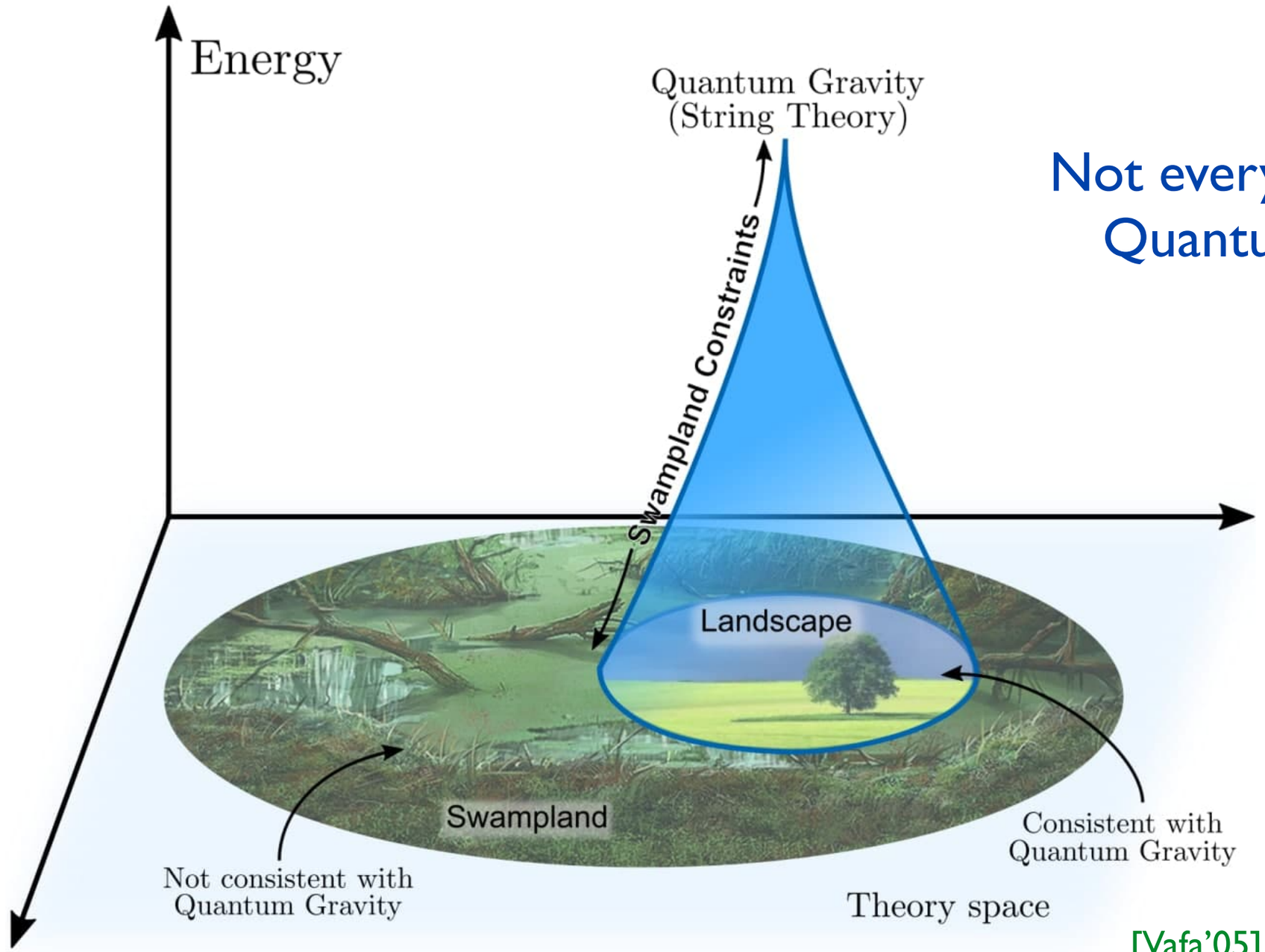

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Swampland:

Apparently consistent (anomaly-free) quantum effective field theories that cannot be UV completed in quantum gravity

Swampland program

Goal: Determine the constraints that an effective theory must satisfy to be consistent with quantum gravity

What distinguishes the landscape from the swampland?

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→ Universal UV imprint of quantum gravity at low energies

(New approach to connect string theory/quantum gravity to our world)

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Potential phenomenological implications:

New guiding principles to construct BSM models of Particle Physics and Cosmology

Failure of EFT expectations

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"What seems natural from UV perspective, might look unnatural from the IR perspective"

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Can we bring new insights to solve naturalness issues in our universe?

Swampland conjectures

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Identify pattern
(swampland conjecture)

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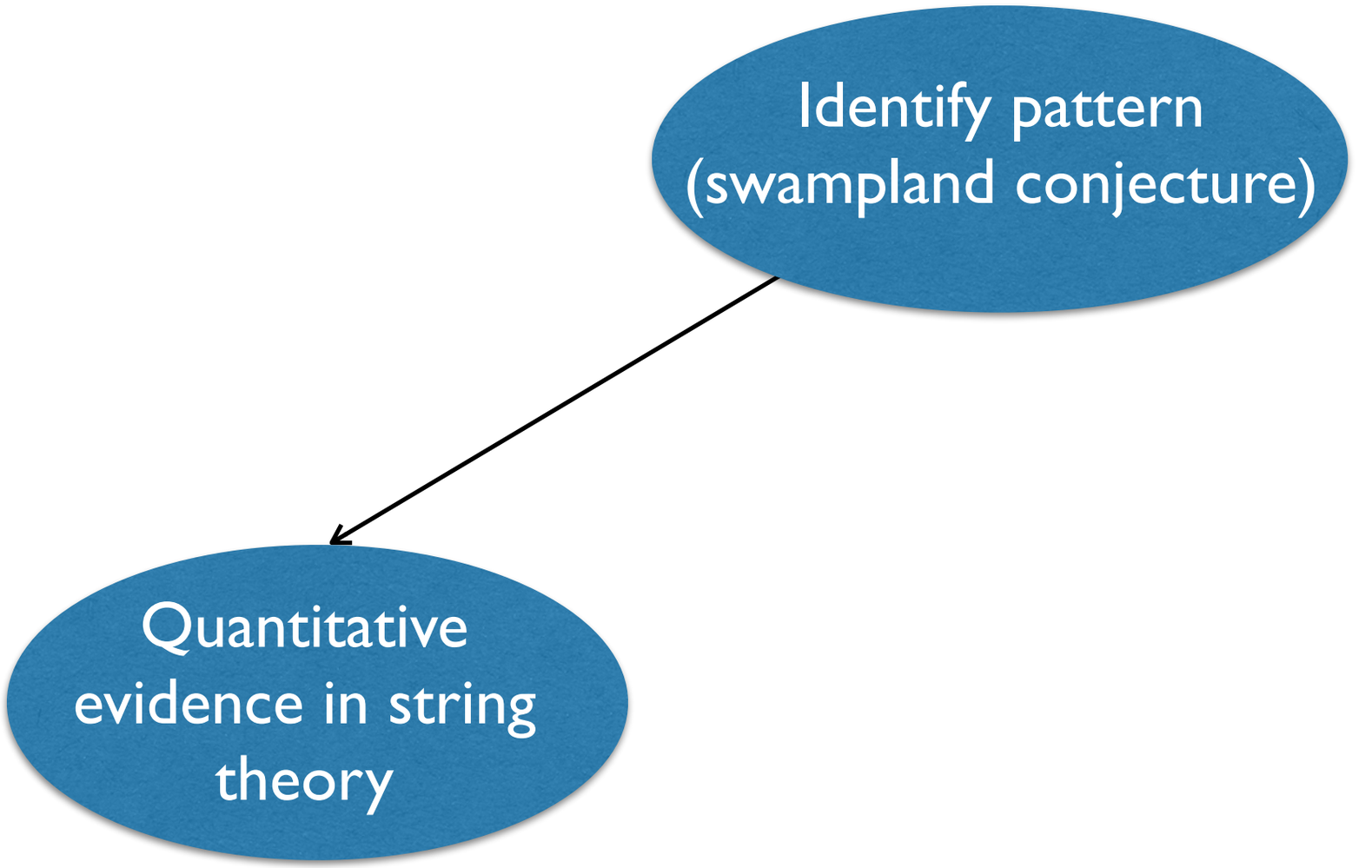

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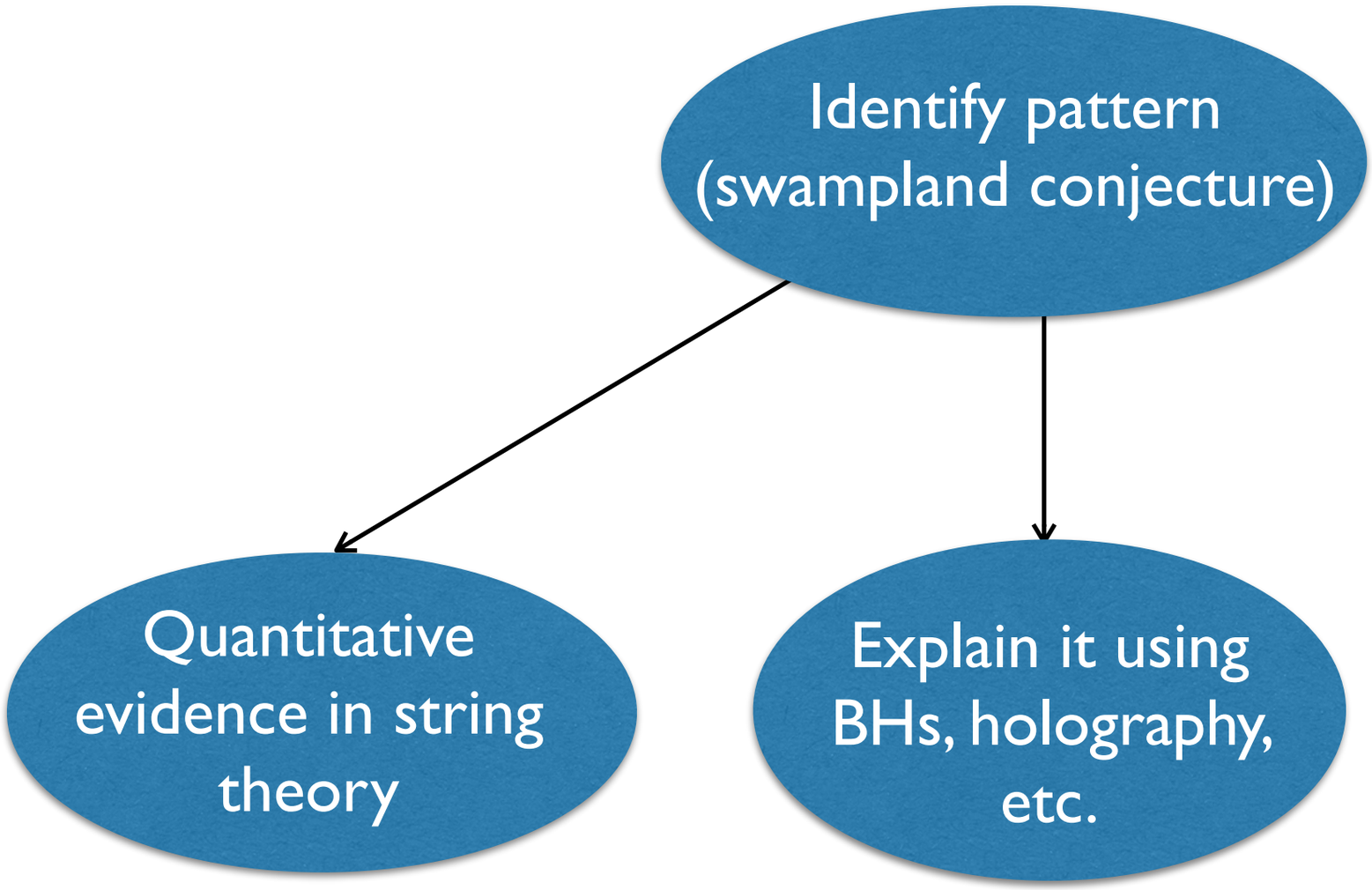

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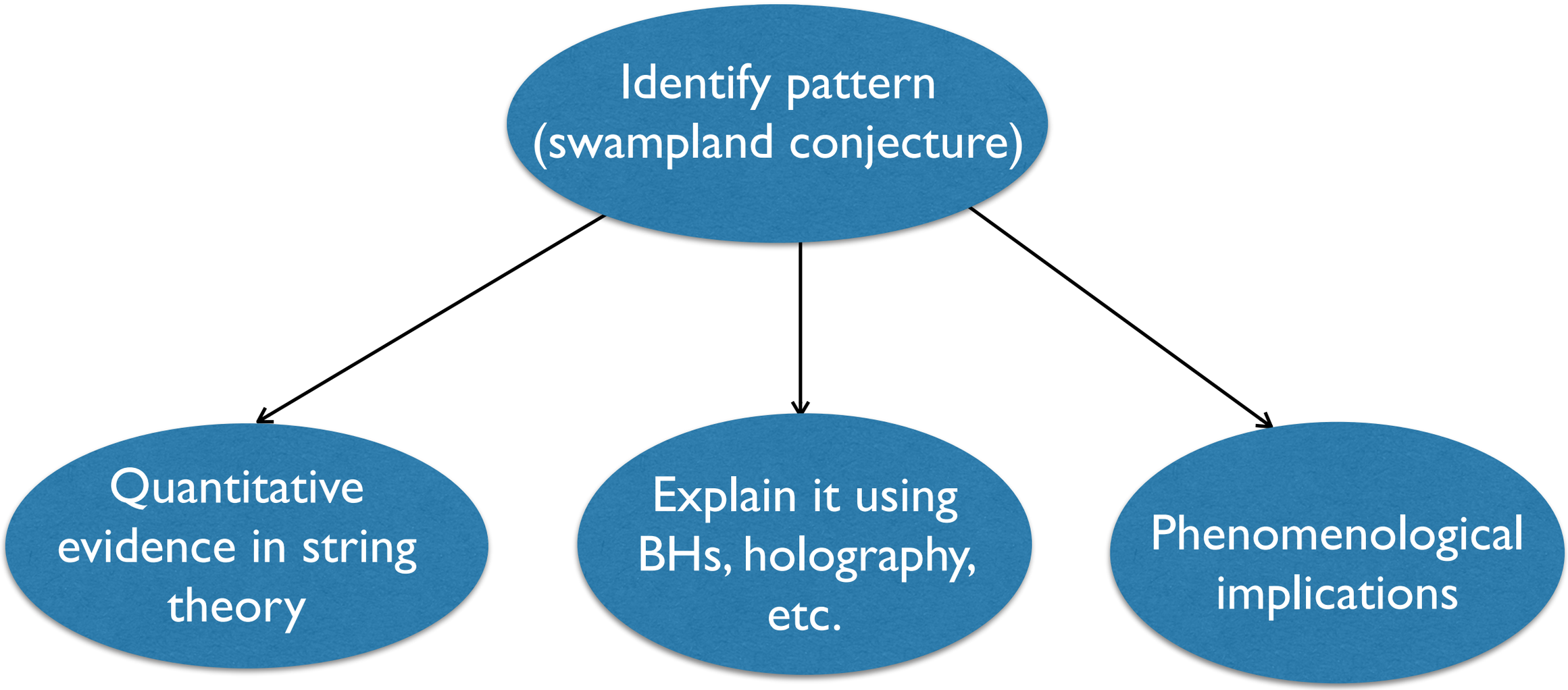

Swampland conjectures

Completeness hypothesis

No global symmetries

Weak Gravity Conjecture

Distance Conjecture

Swampland conjectures

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Cobordism conjecture

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Distance Conjecture

...

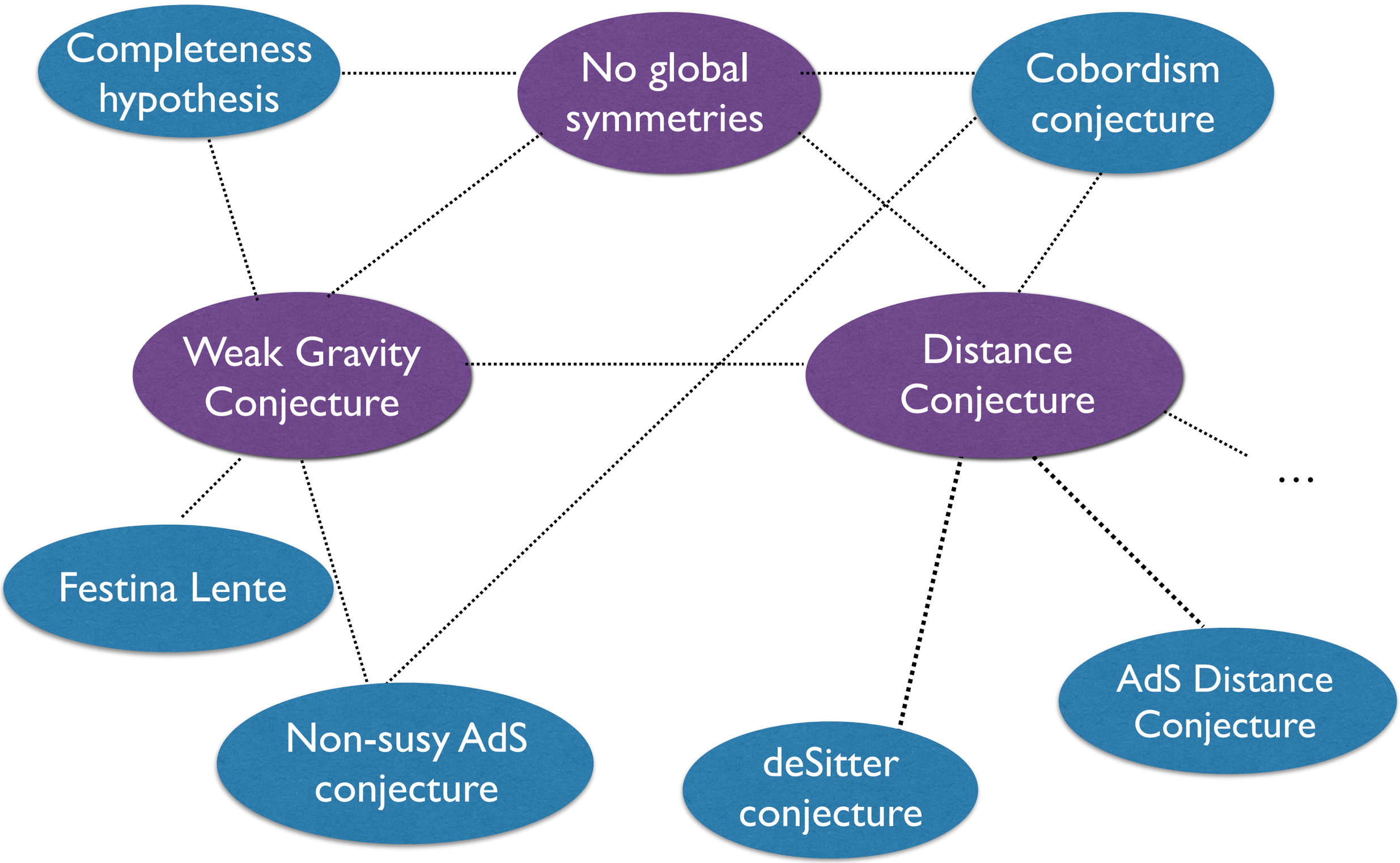
Festina Lente

Non-susy AdS conjecture

deSitter conjecture

AdS Distance Conjecture

Swampland conjectures



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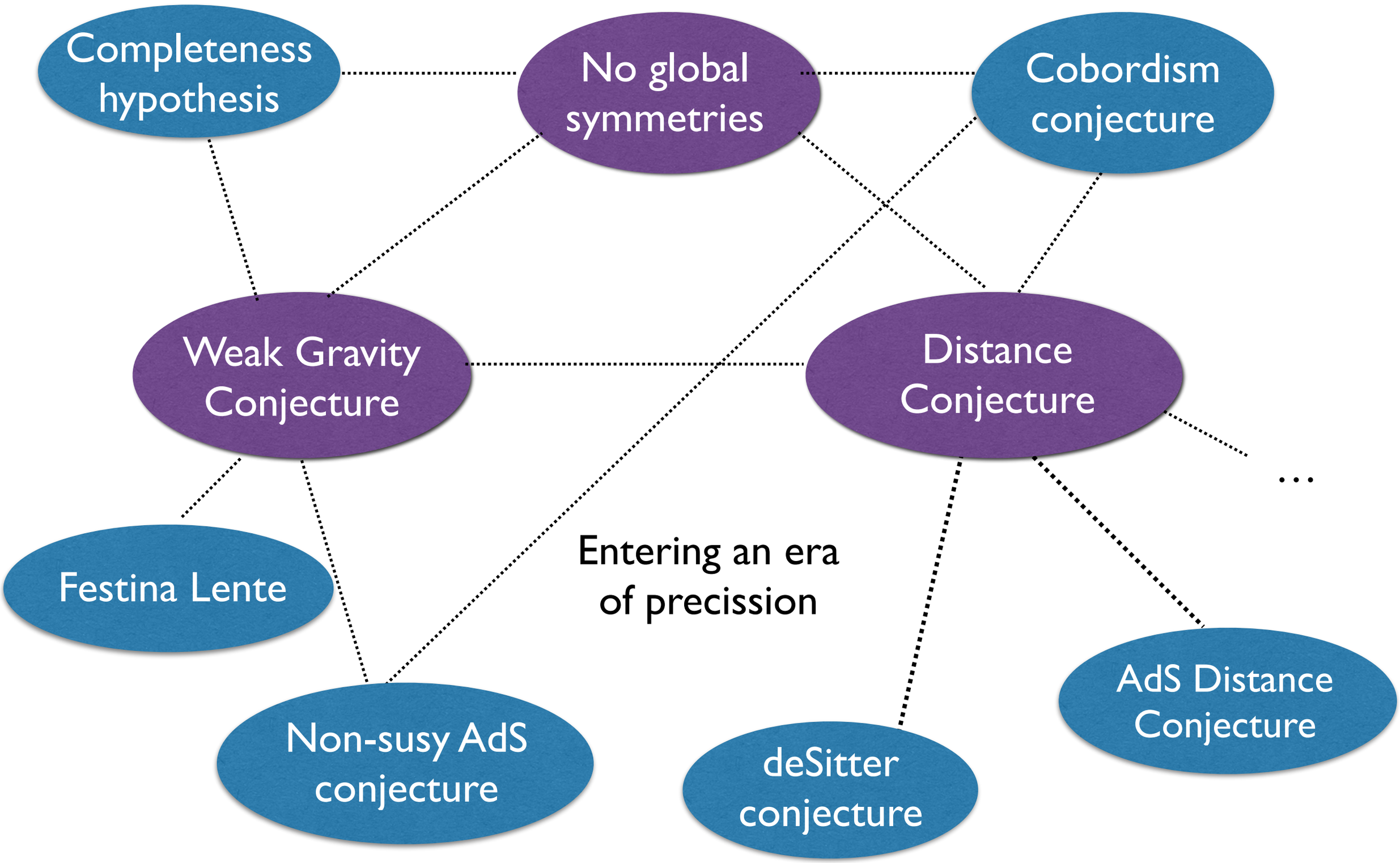
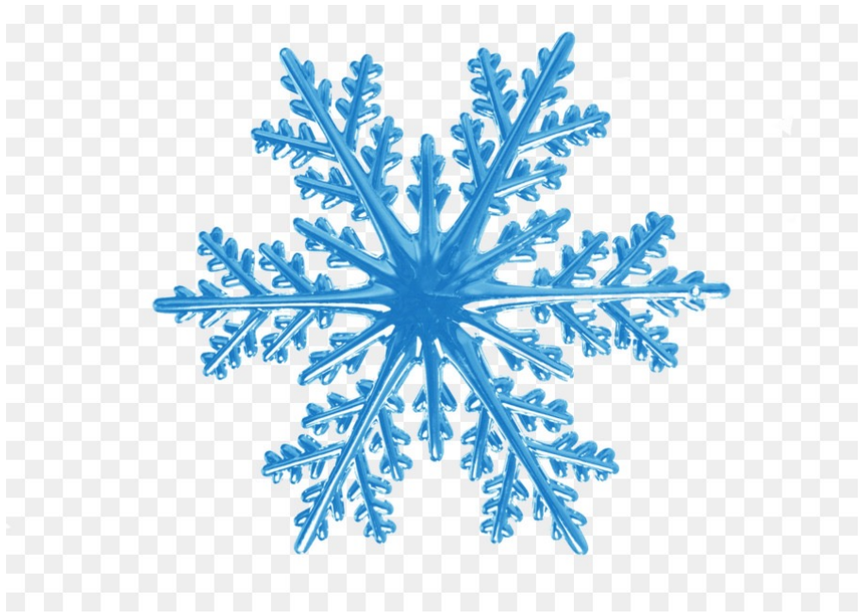


Swampland conjectures

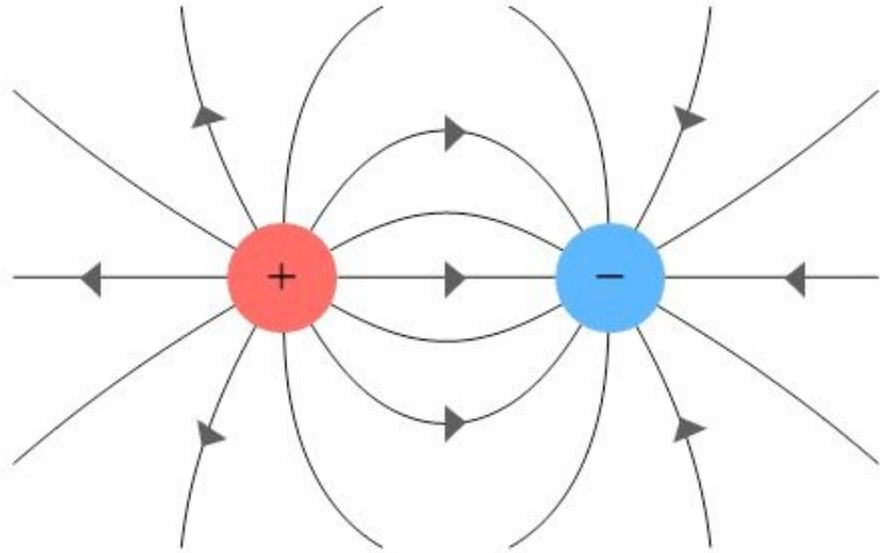
No global symmetries

Symmetries

Rotational symmetry



Electric charge



Angular momentum

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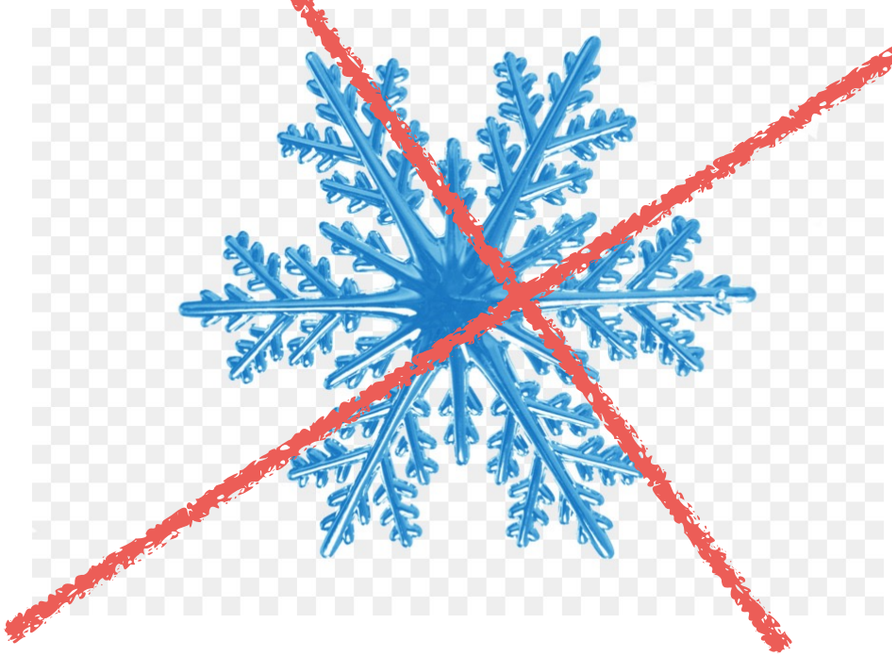

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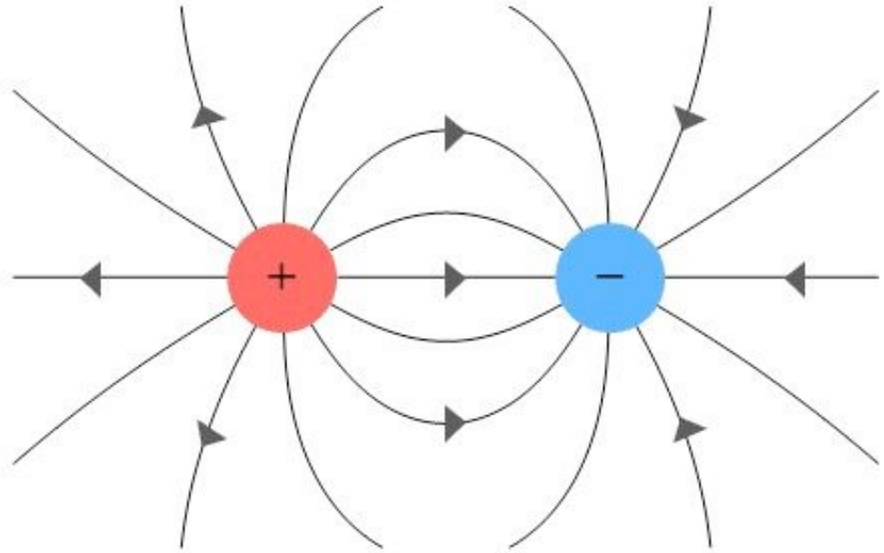

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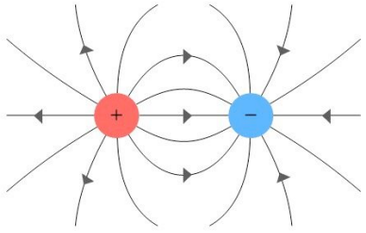

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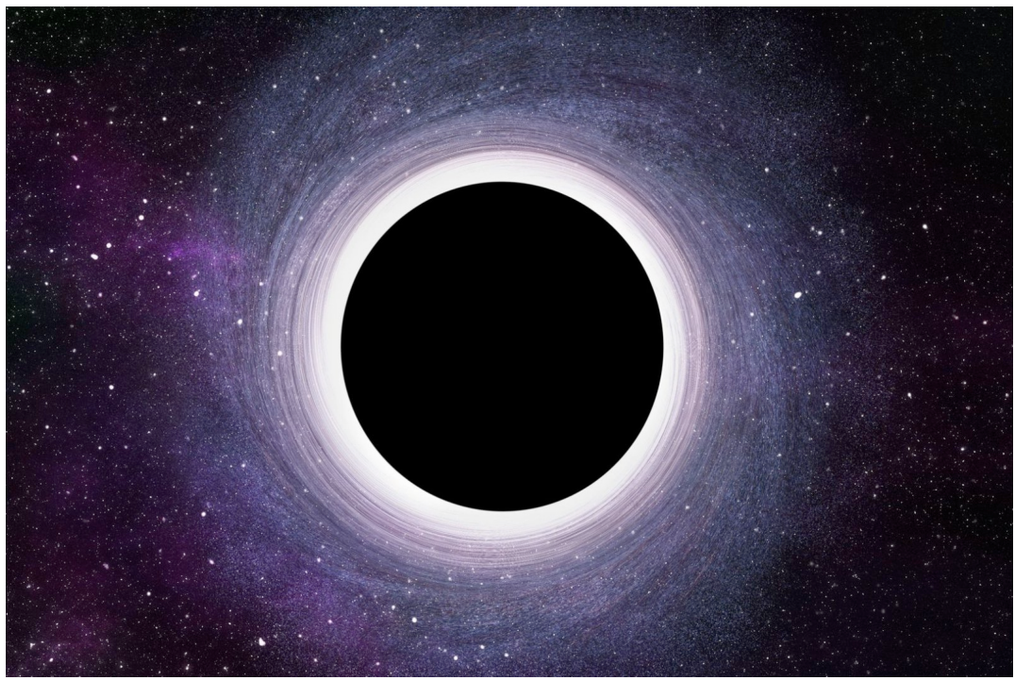
They are broken in quantum gravity

No global symmetries conjecture

Heuristic motivation from black holes:



Black holes have finite entropy

("how many different ways lead to the same black hole exterior")

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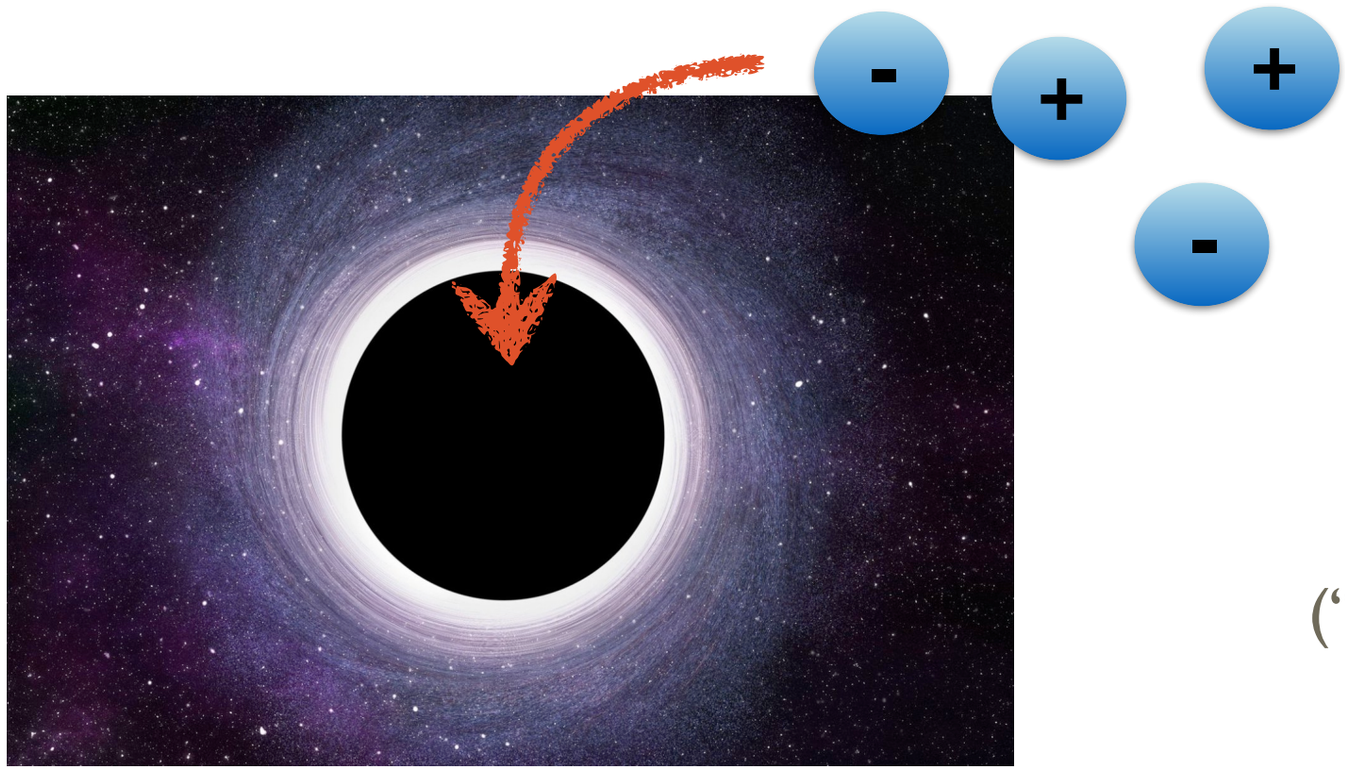

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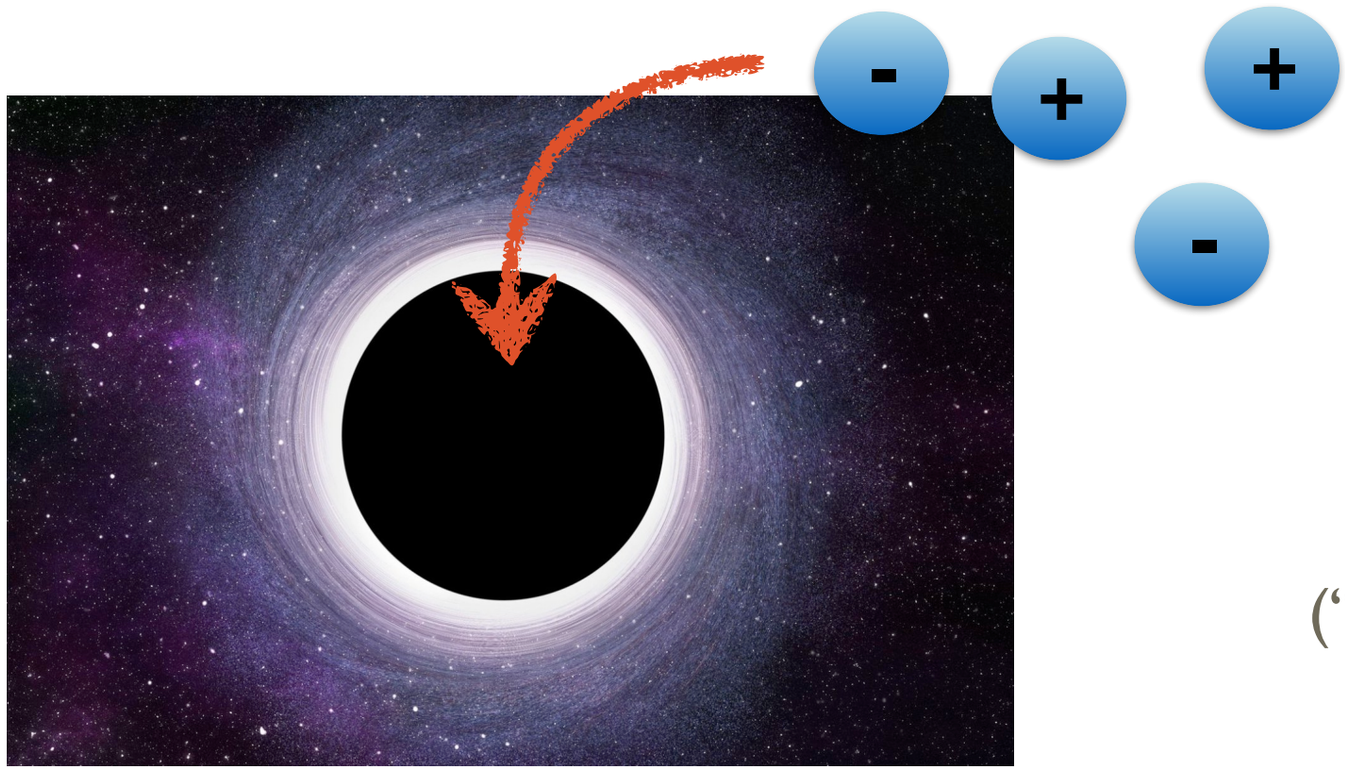

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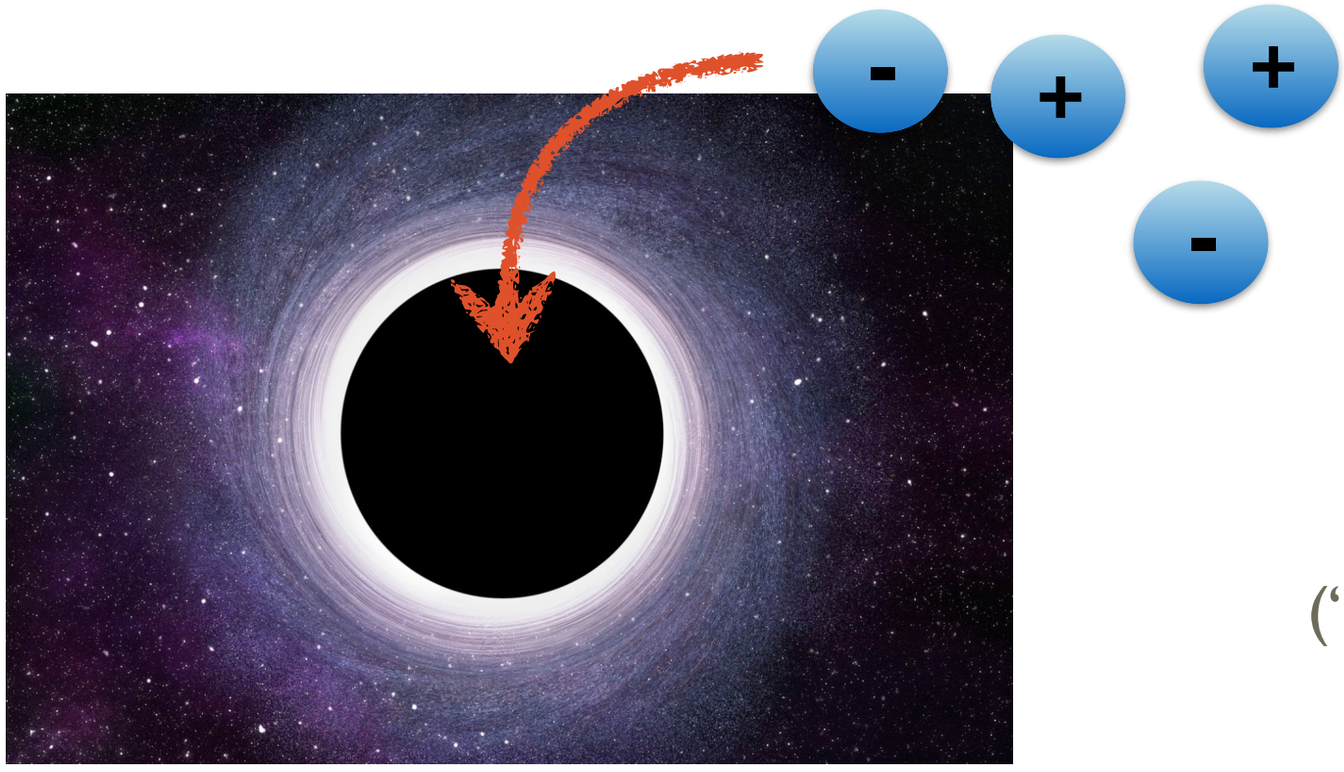

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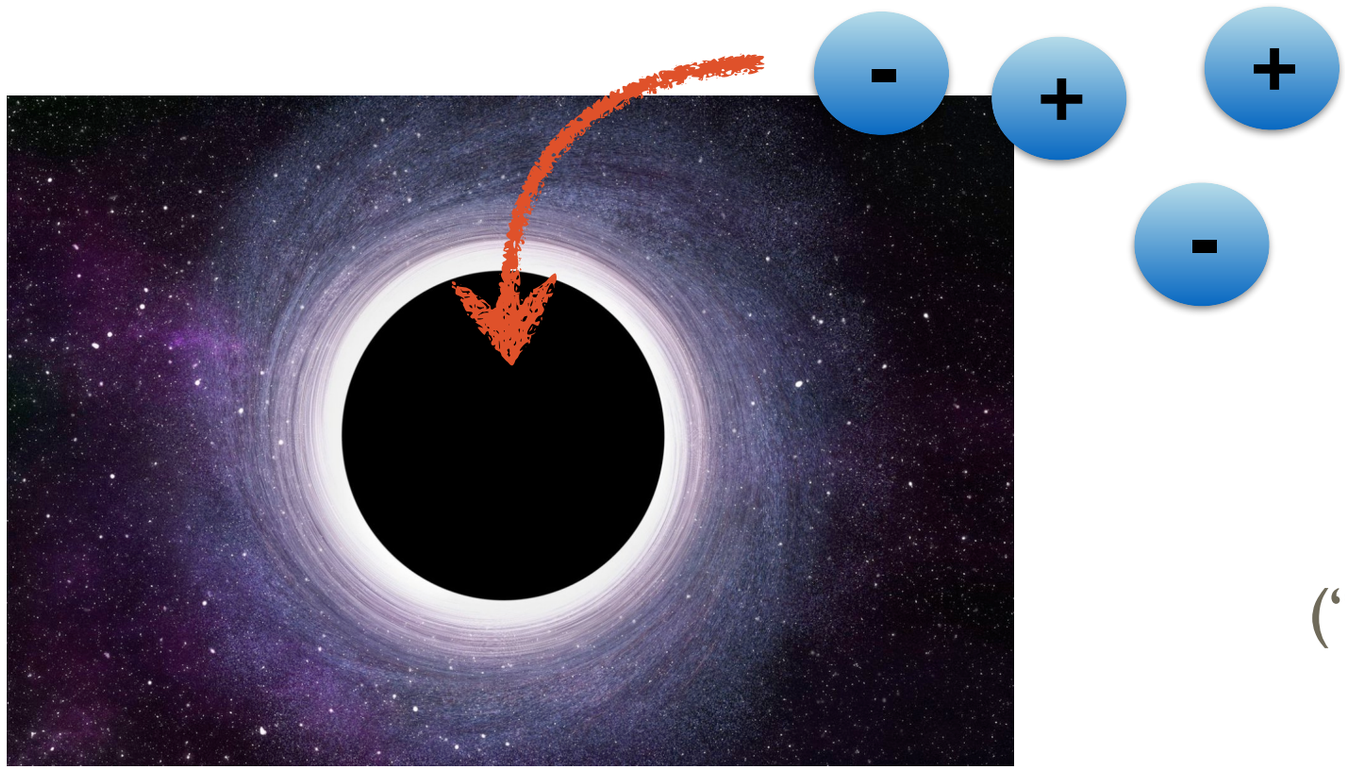

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→ Infinite entropy contradiction!

No global symmetries conjecture

Global symmetries cannot be exact in quantum gravity
(unless they are gauged)

[Banks-Dixon'88] [Horowitz,Strominger,…] [Susskind] [Banks,Seiberg'11]

Evidence:

- Proof in perturbative string theory [Polchinski's book]
- Proof in AdS/CFT [Harlow,Ooguri '18]
- Correlation to unitary black hole evaporation (and topology changing processes) [Harlow,Shaghoulian '20] [Chen,Lin '20] [Hsin et al '20] [Yonekura '20] [Bah,Chen,Maldacena'22]

Global symmetries are not well defined in quantum gravity as the topology itself fluctuates

Swampland conjectures

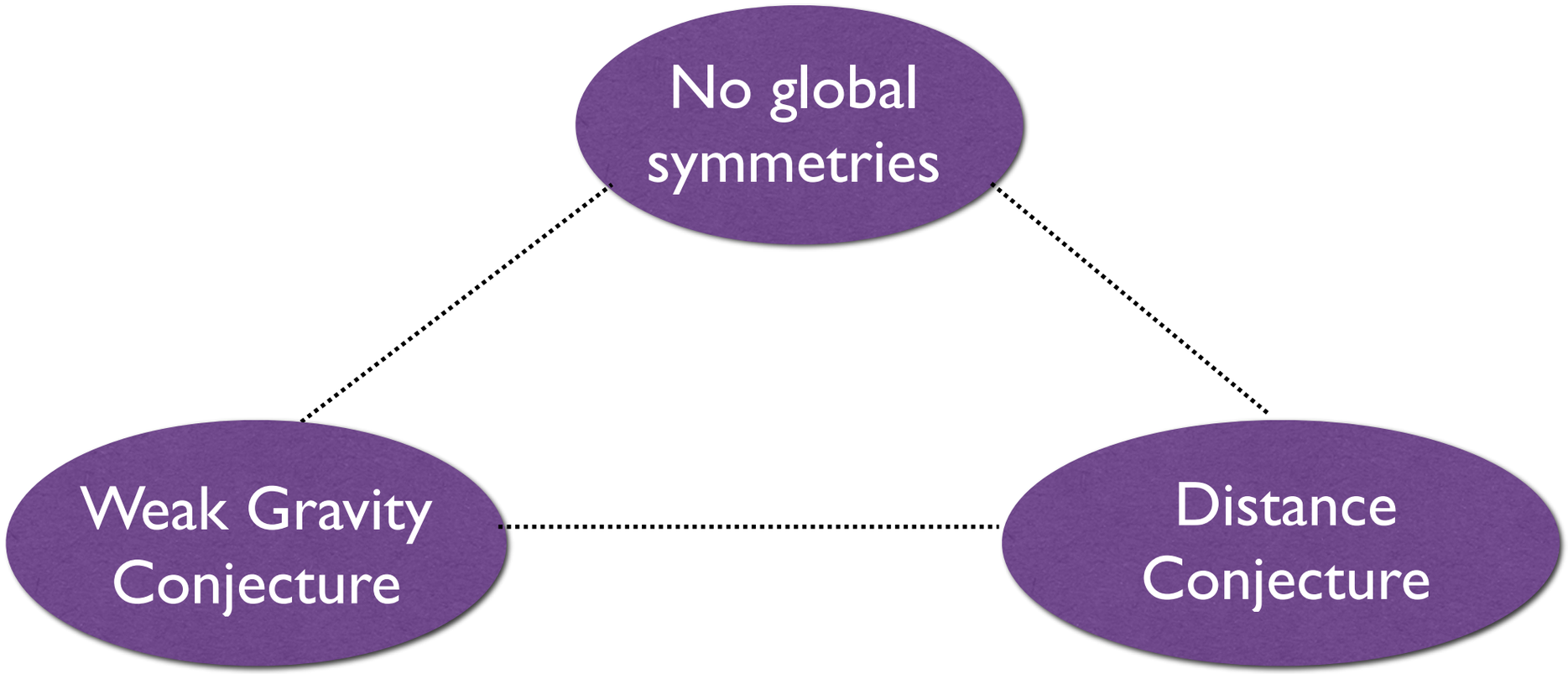
No global symmetries

Open questions:

How much are the symmetries broken?

Or if they are gauged, how small can the gauge coupling be?

Swampland conjectures



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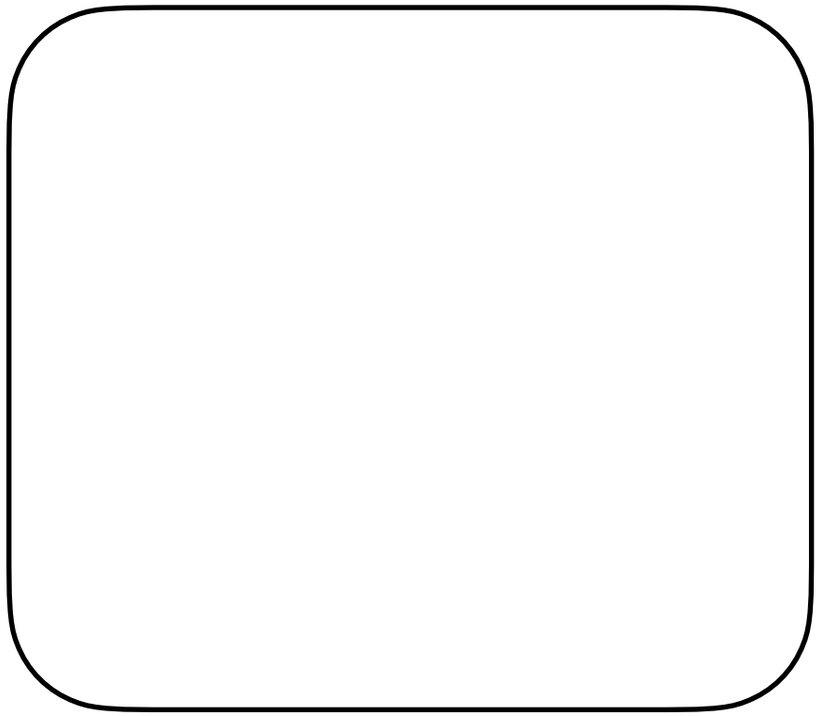

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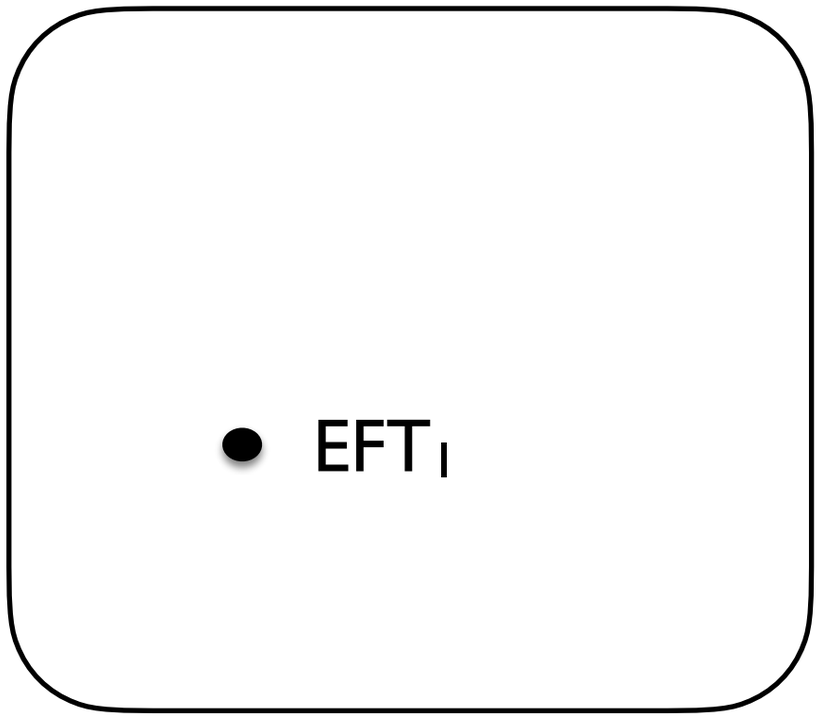

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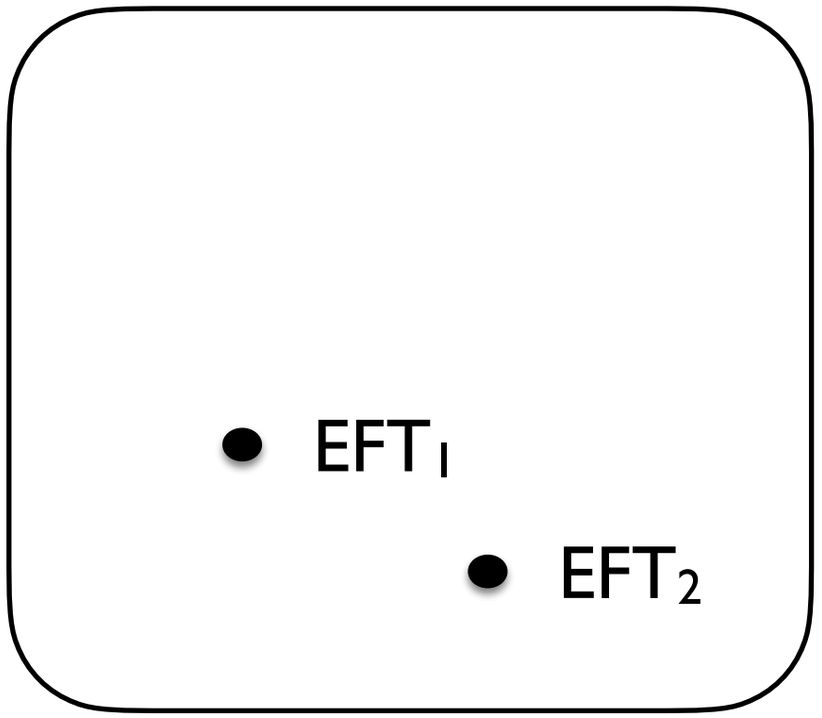

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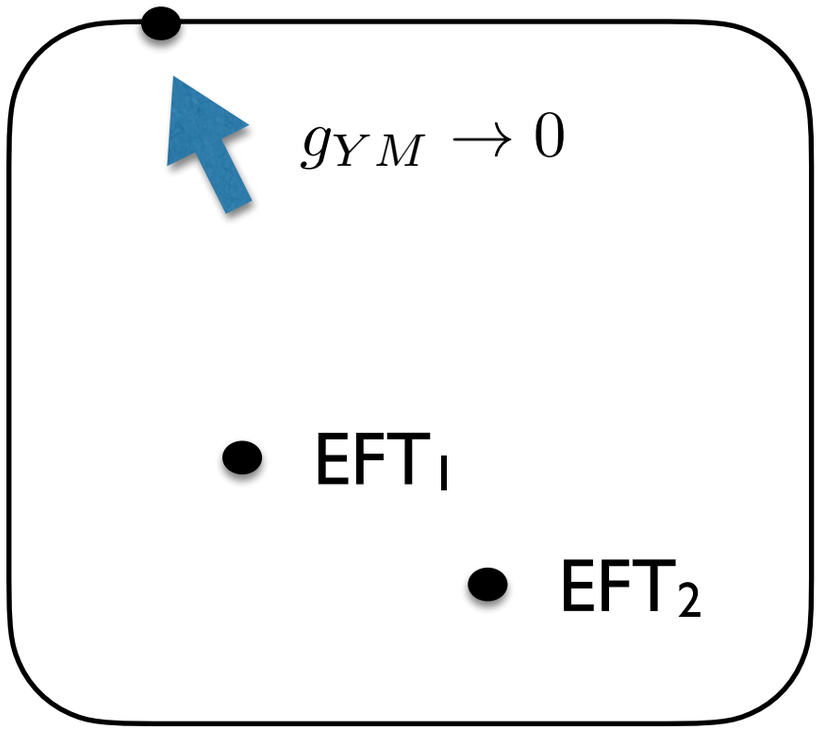

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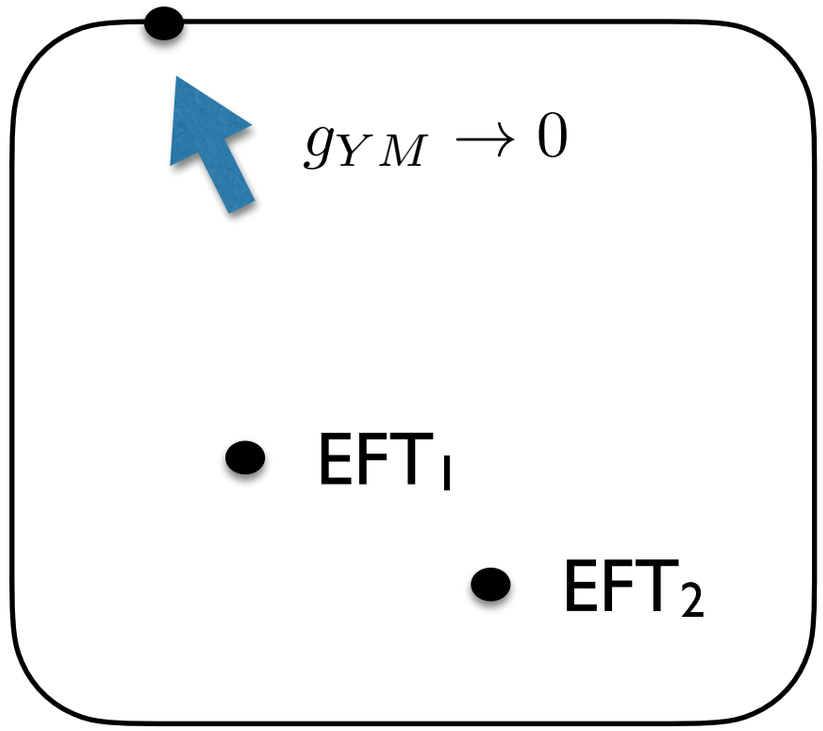

Assume some global symmetry can be restored in a continuous way at some special points of the parameter space

e.g. by sending gauge coupling $g_{YM} \to 0$
we restore a U(1) global symmetry

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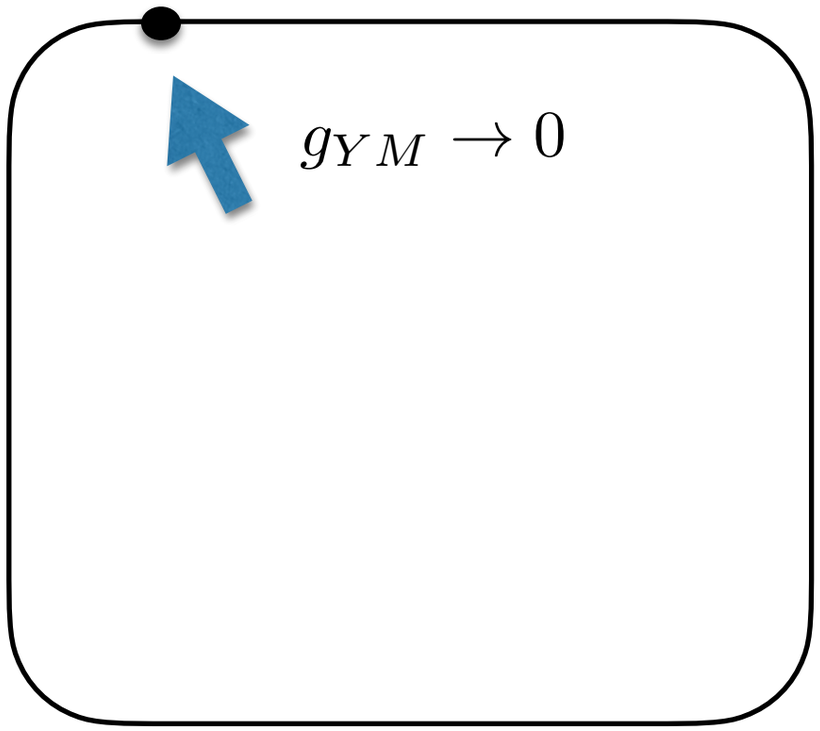

String Theory has no free parameters:

All masses/couplings are given by vacuum expectation values of scalar fields that fix the size/shape of extra dimensions

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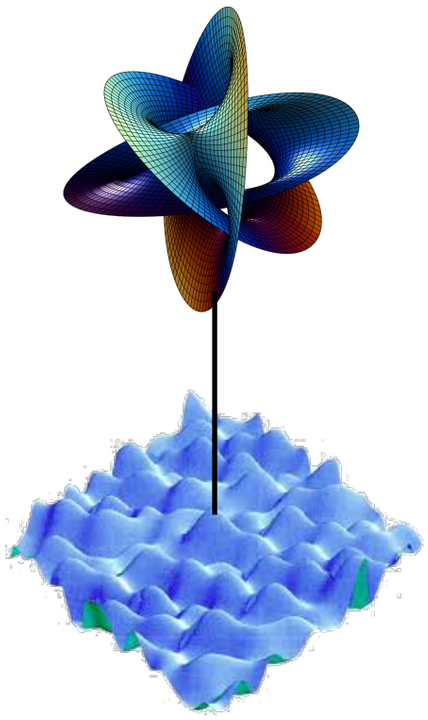

Approximate global symmetries

Parameter space:

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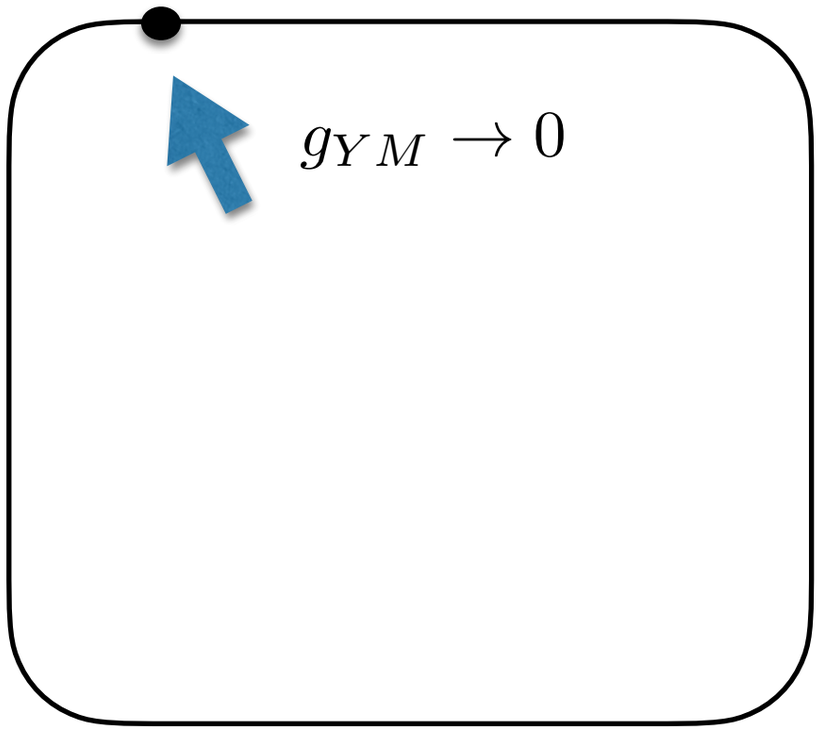
Scalar field space
in String Theory

$$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j$$

↳ field metric



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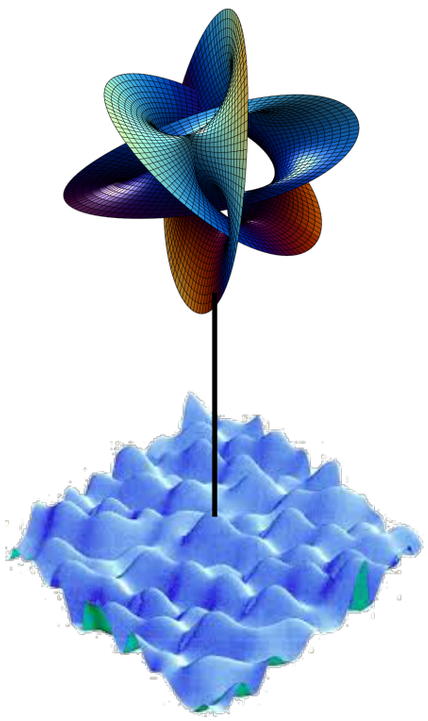

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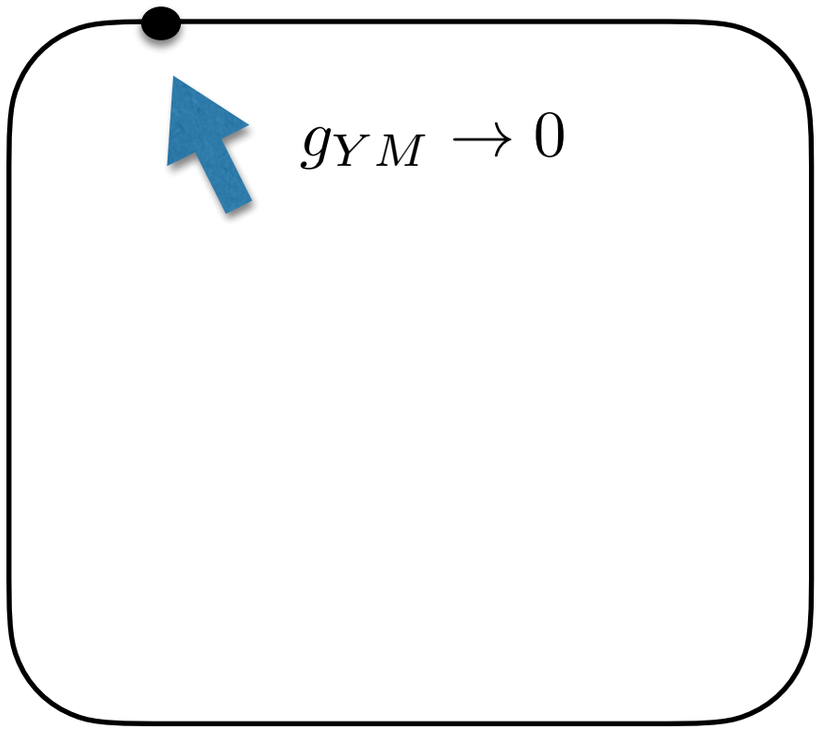

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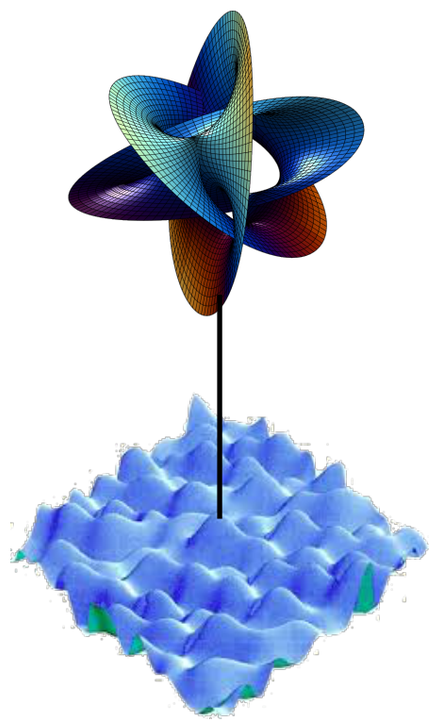

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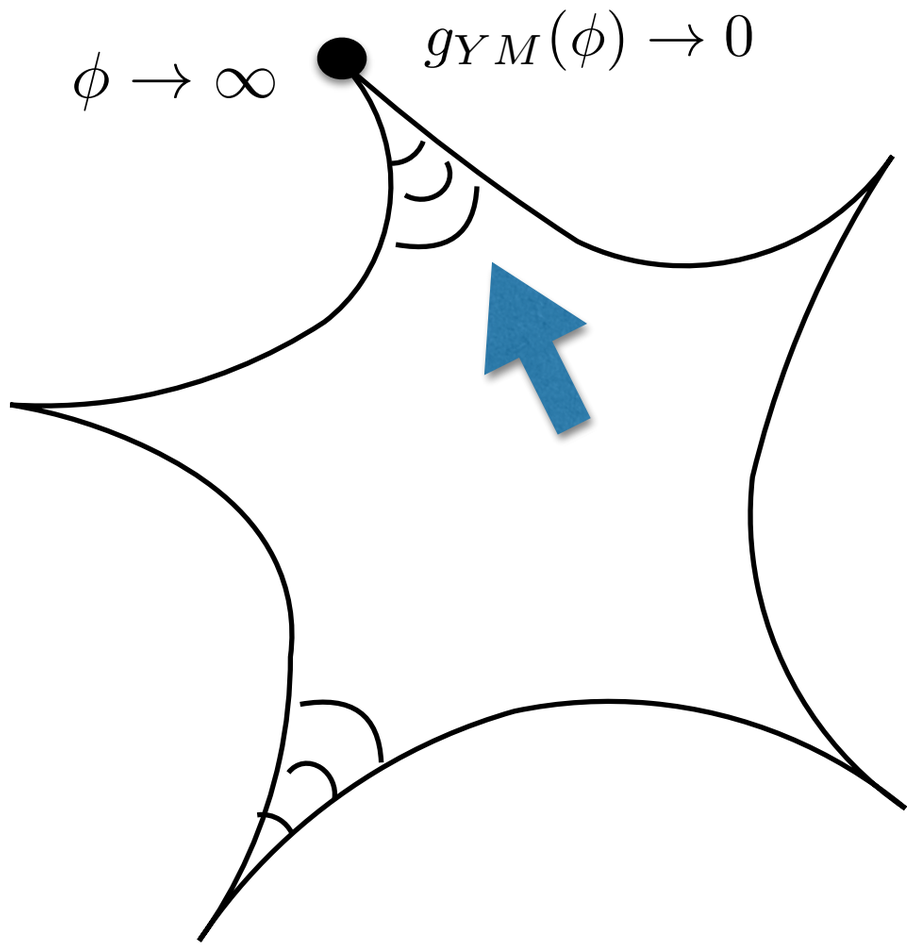

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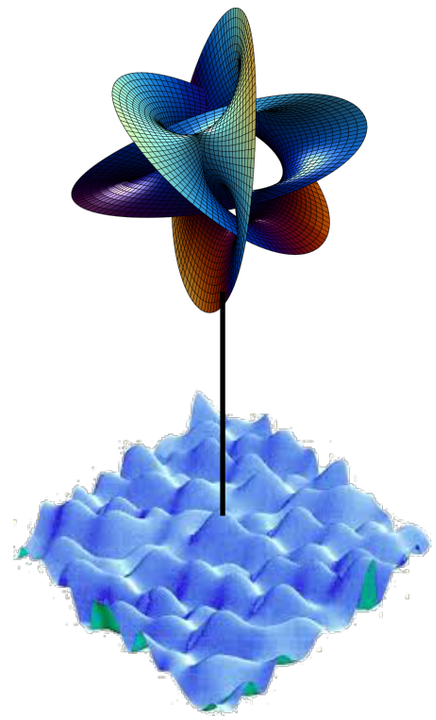

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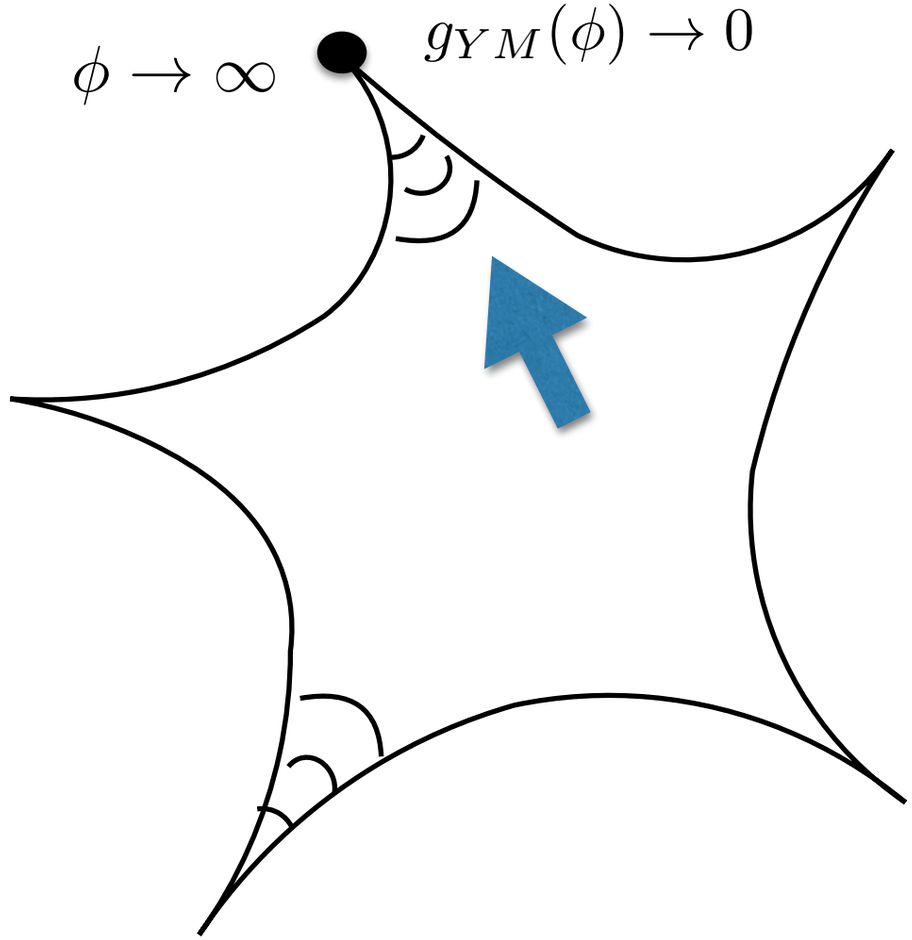

approx global
symmetry

Global symmetries not allowed in quantum gravity → They can only be restored at infinite field distance (asymptotic limits)

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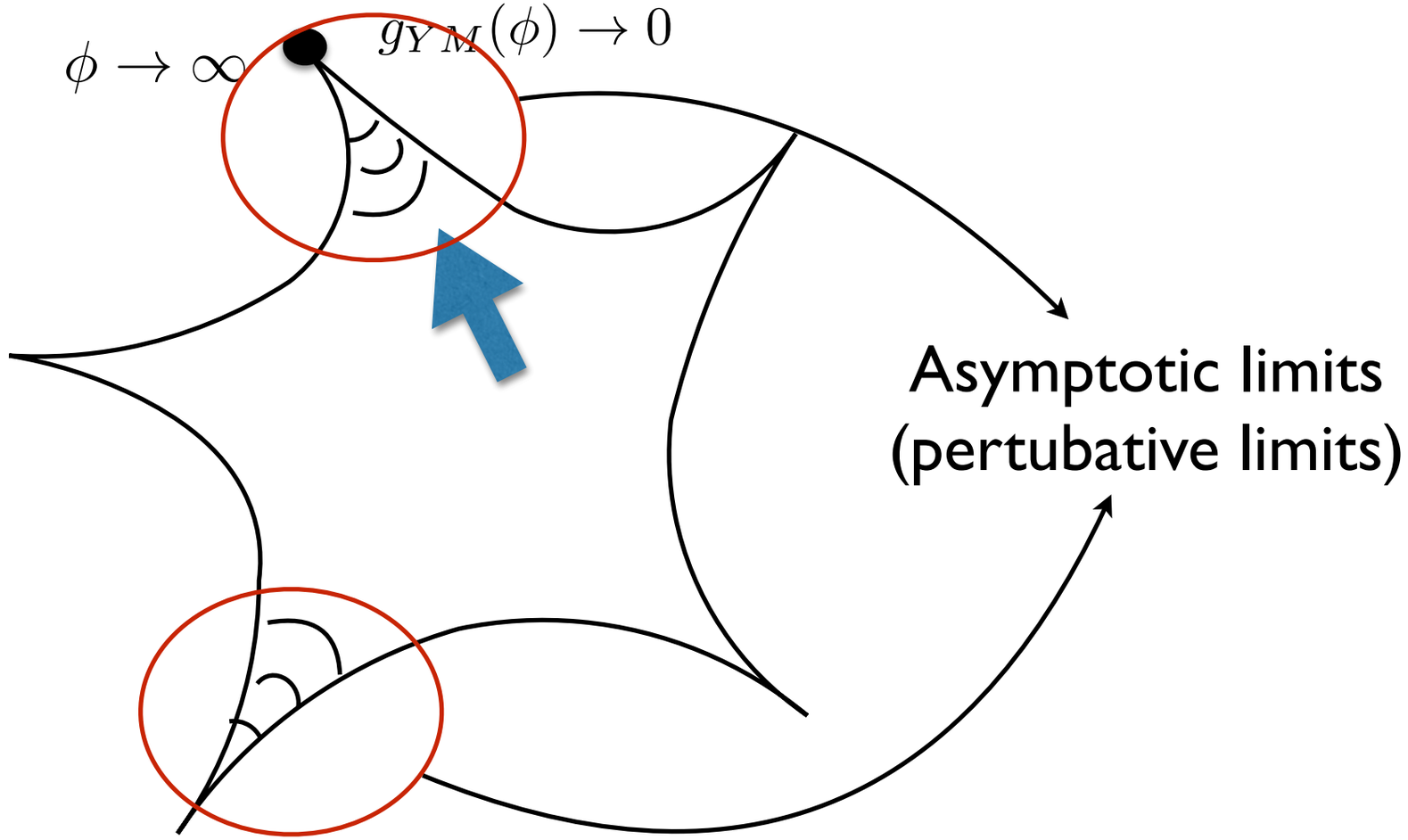

approx global symmetry

Examples: large volume, weak coupling…

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Asymptotic limits

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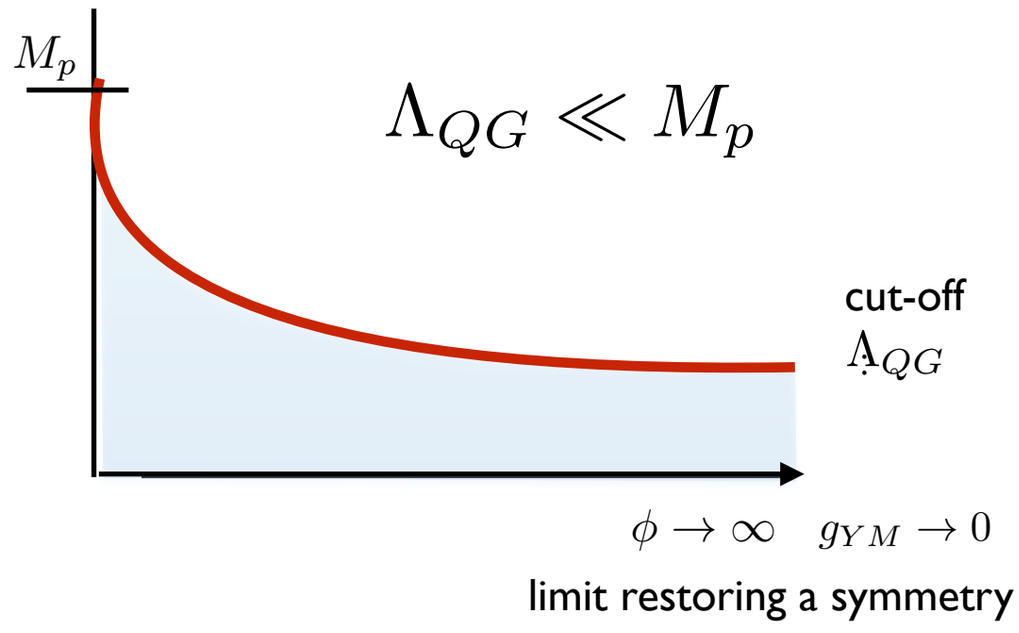

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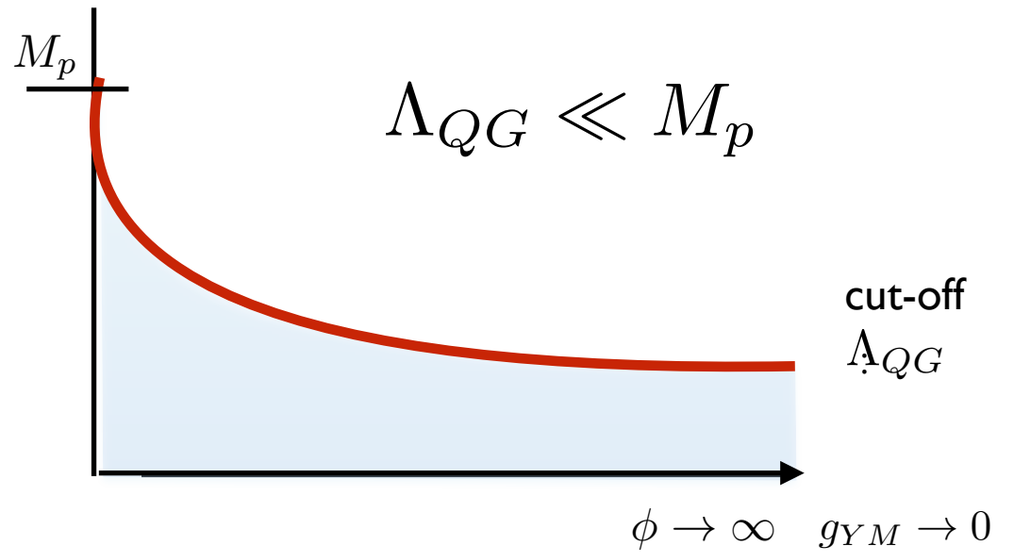
How? Does this happens in a **universal way** in string theory?



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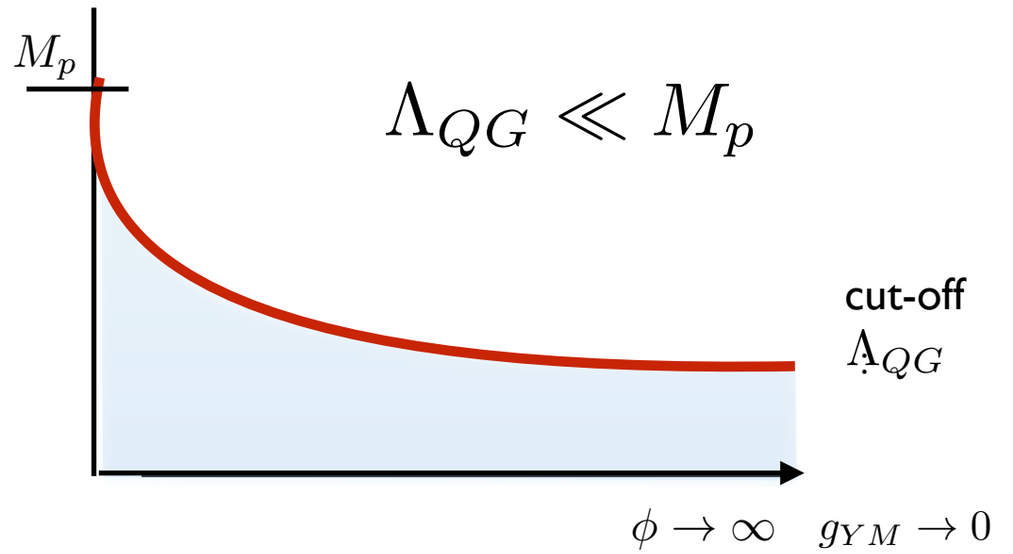

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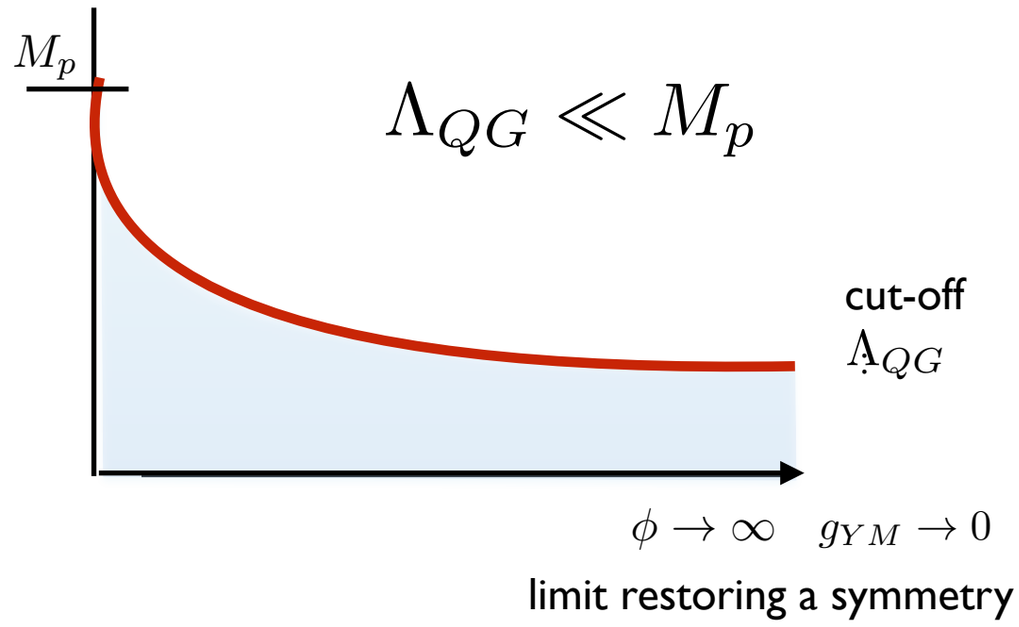


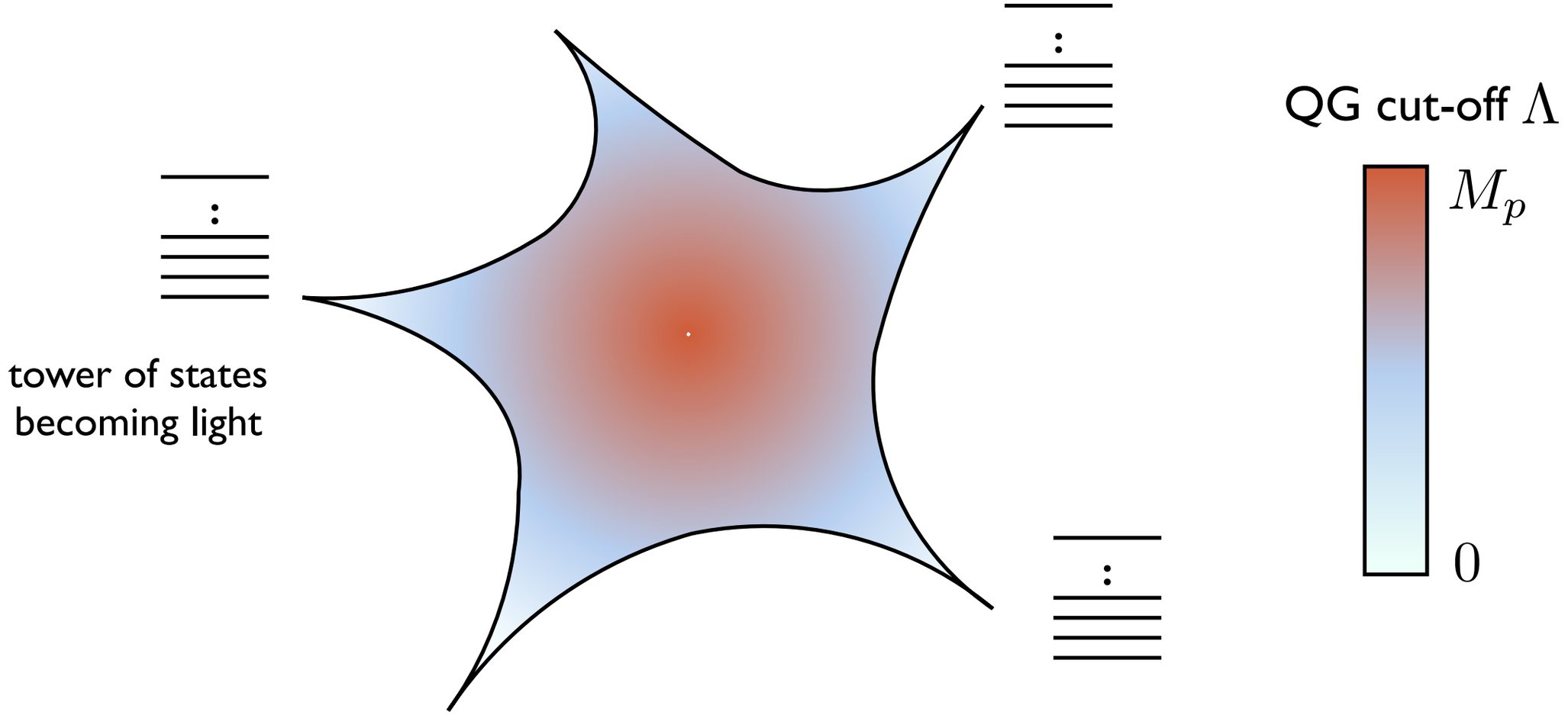
tower of states

There is new light physics that forces the cut-off to go to zero

and acts as a censorship mechanism to restore global symmetries.

Asymptotic Towers of States

Quantum gravitational effects become significant at a scale $\Lambda_{QG} \ll M_p$ due to towers of states becoming light as approaching the boundaries



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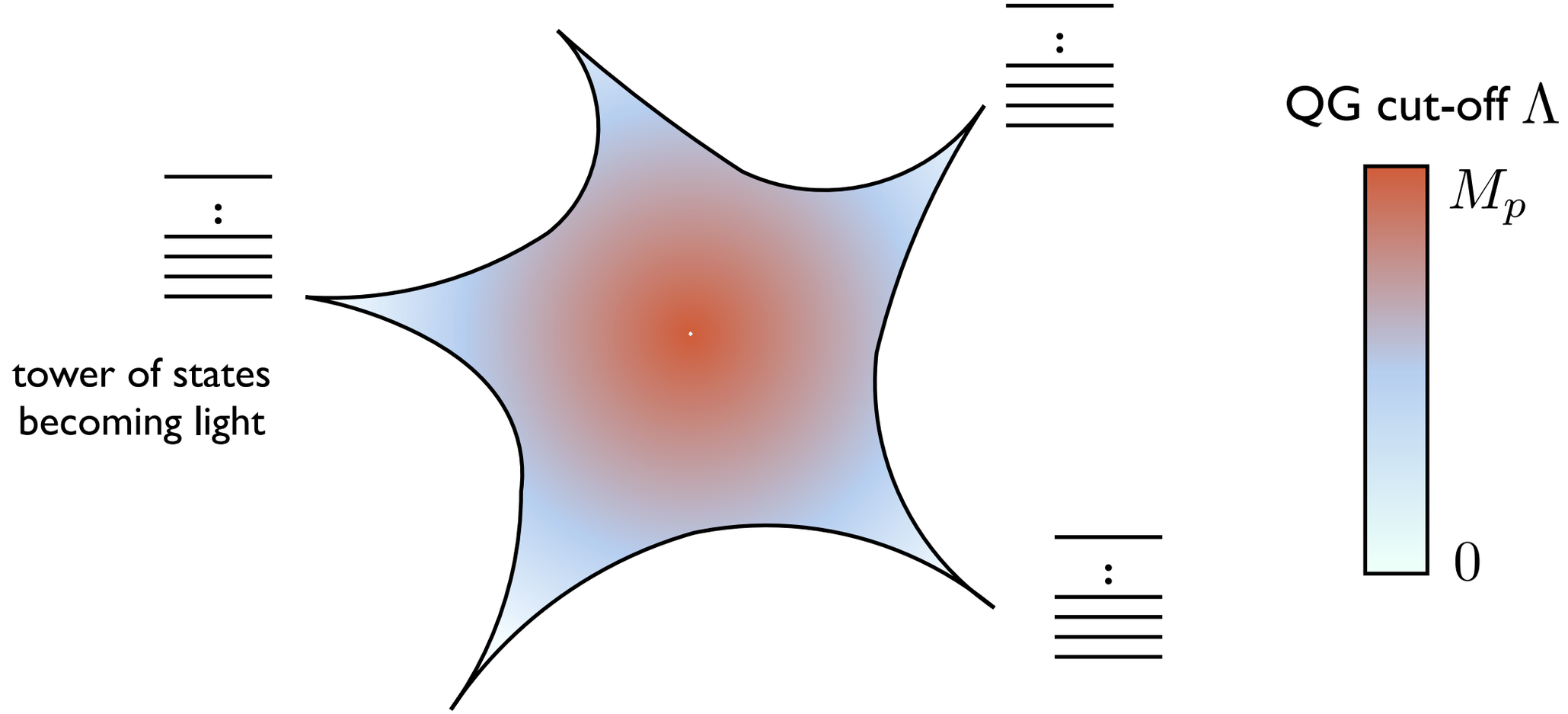
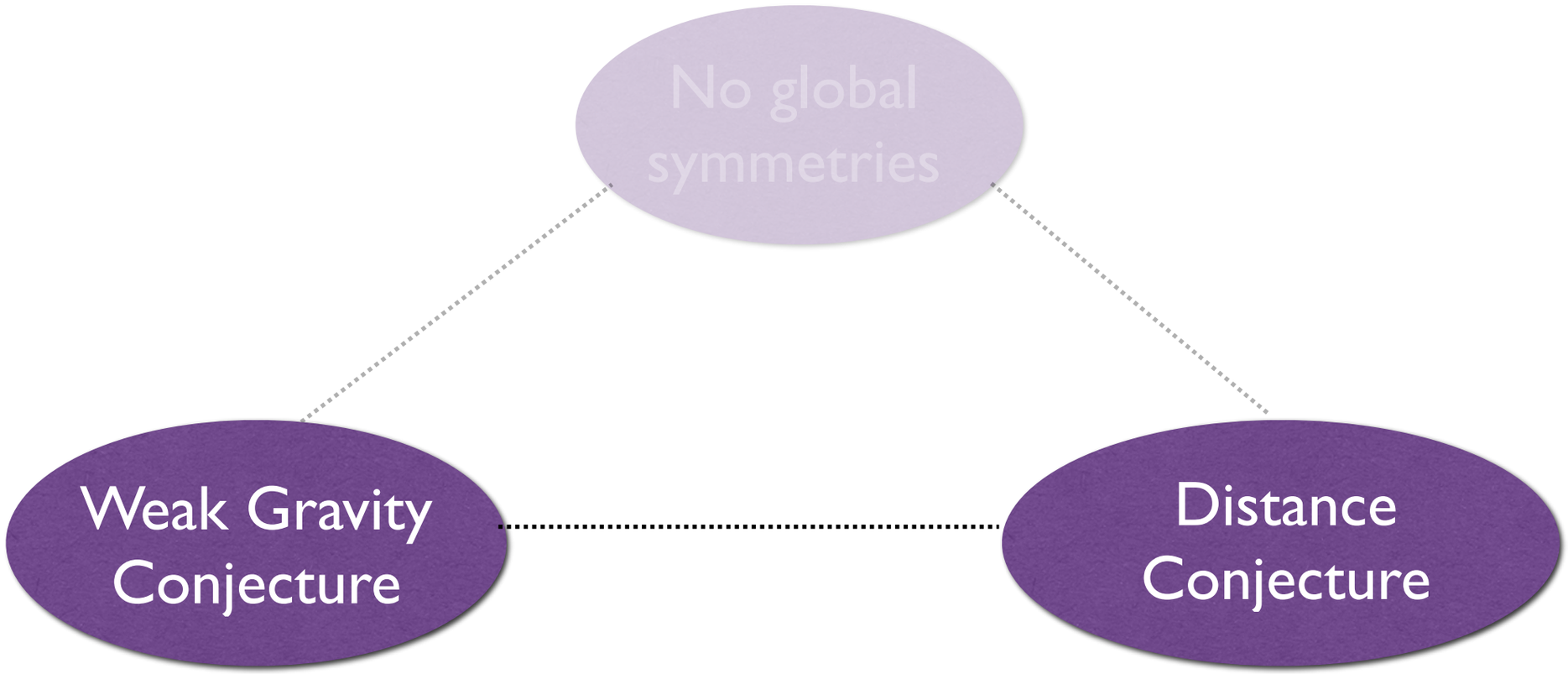
Goal: Determine the quantum gravity cut-off at which the EFT breaks down in terms of EFT data that quantifies how close we are to the boundaries (e.g. the value of a gauge coupling, the scalar field range…)



Swampland conjectures



They quantify how approximate global symmetries can be by specifying the concrete behaviour of this tower of states

Distance Conjecture

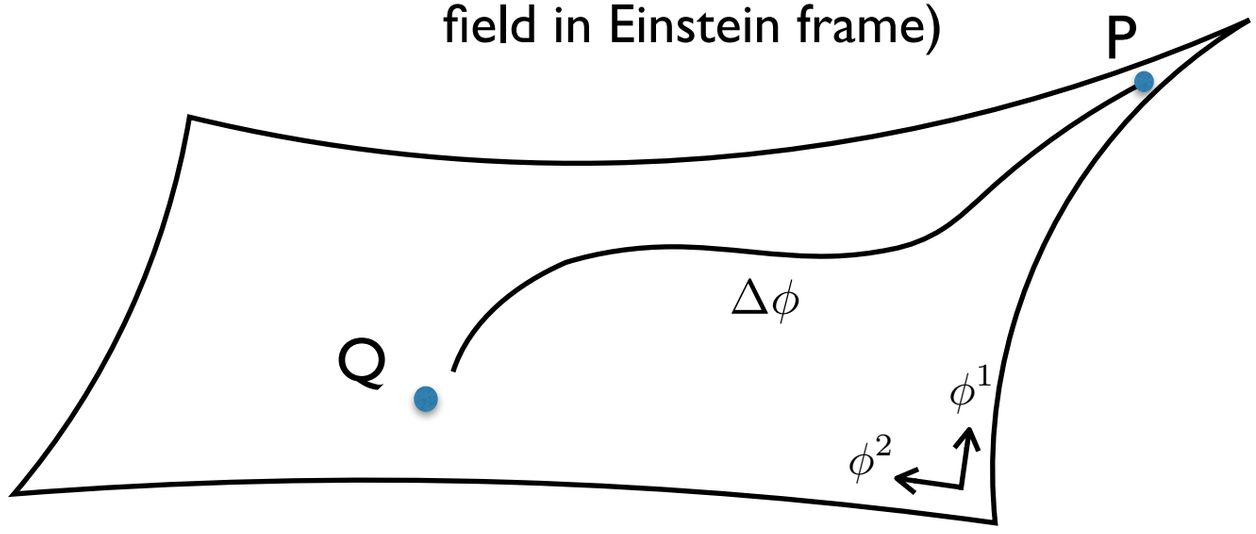
Given an EFT coupled to gravity, with a moduli space parametrized by the vacuum expectation value of some scalar fields:

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m \sim m_0 e^{-\alpha \Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$ [Ooguri-Vafa'06]

$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j$ → scalar manifold (moduli space)

$$\Delta\phi = \int_Q^P \sqrt{g_{ij}\frac{d\phi^i}{ds}\frac{d\phi^j}{ds}}ds \equiv \text{geodesic distance}$$ (canonically normalised scalar field in Einstein frame)



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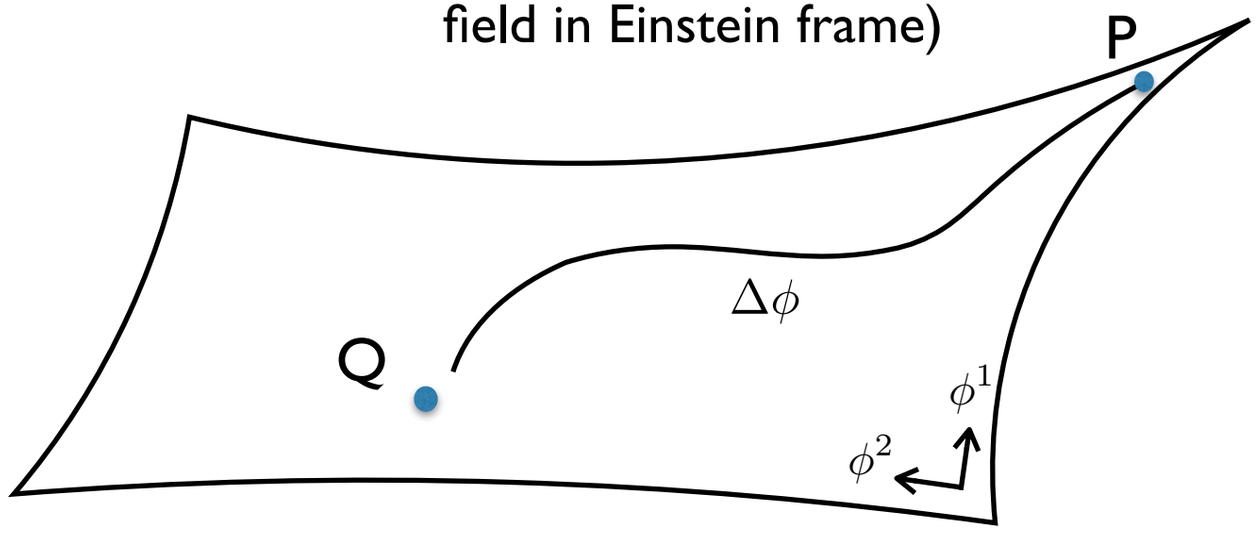
For example:

- Kaluza-Klein towers as $R \to \infty$
- winding modes as $R \to 0$
- string modes as $g_s \to 0$



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Evidence:

- Plethora of quantitative tests in string theory

  [Grimm, Palti, IV'18] [Grimm,Palti,Li'18] [Gendler,IV'20] [Lee,Lerche,Weigand'.I.8-21] [Corvilain, Grimm, IV'18] [Baume,Marchesano,Wiesner'19] [Lanza,Marchesano,Martucci, IV'20-21] [Klaewer,Lee,Weigand,Wiesner'22] …

- Bottom-up arguments based on black hole physics / entropy bounds

  [Hamada,Montero,Vafa, IV'21] [Cribiori et al'22]

- Tests in AdS/CFT [Perlmutter,Rastelli,Vafa,IV'21] [Calderon-Infante et al'23]

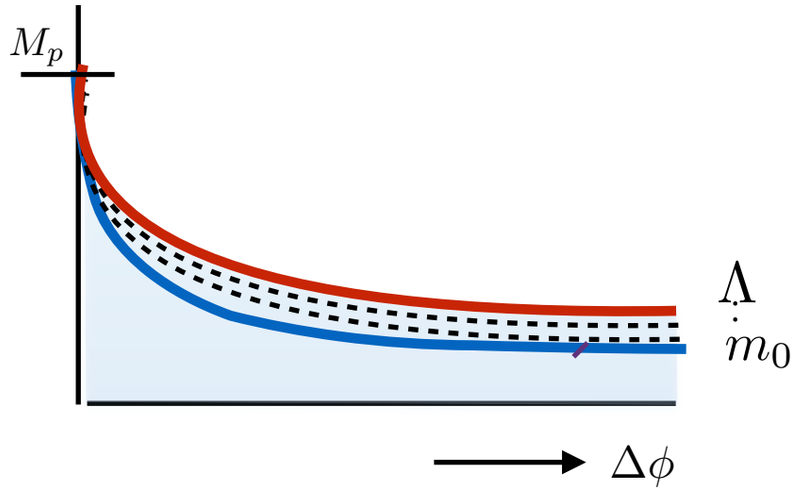
  [Baume,Calderon-Infante'21-23]

Phenomenological Implications

This tower signals the quantum gravity breakdown of the effective theory:

$$\Lambda \sim M_p \exp(-\lambda \Delta\phi)$$

$$\Delta\phi \lesssim \frac{1}{\lambda} \log\left(\frac{M_p}{\Lambda}\right)$$



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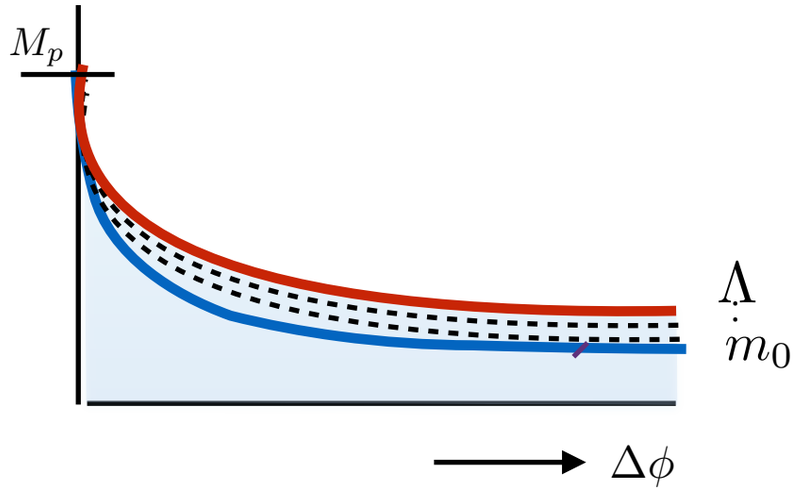

Maximum scalar field range* that can be accommodated in a given EFT as a function of the Quantum Gravity cut-off

*Caveats to be discussed later

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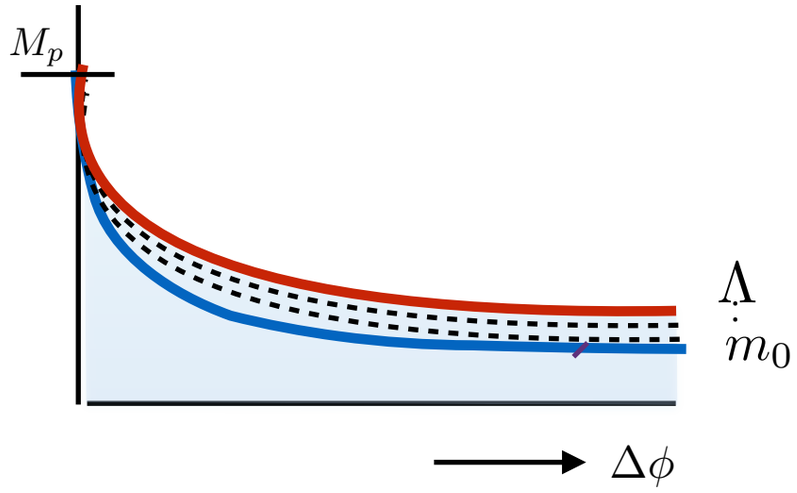

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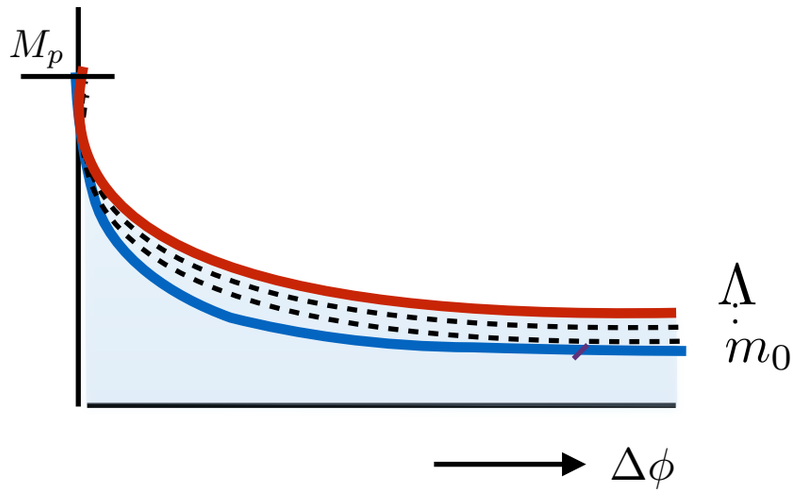

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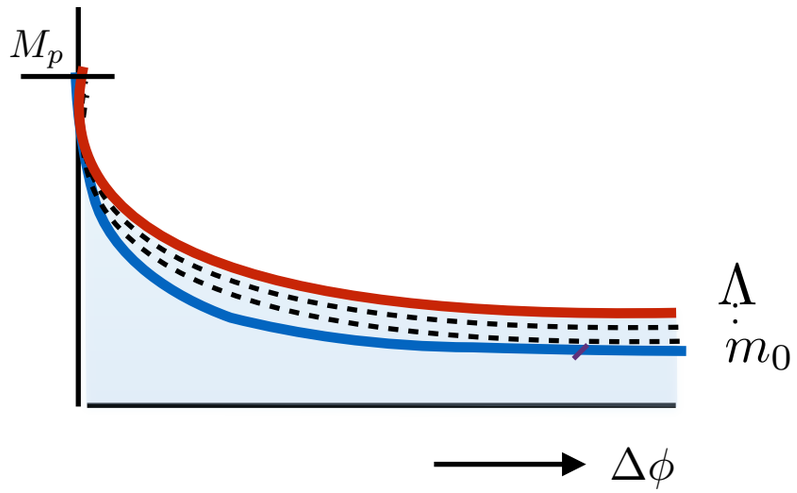
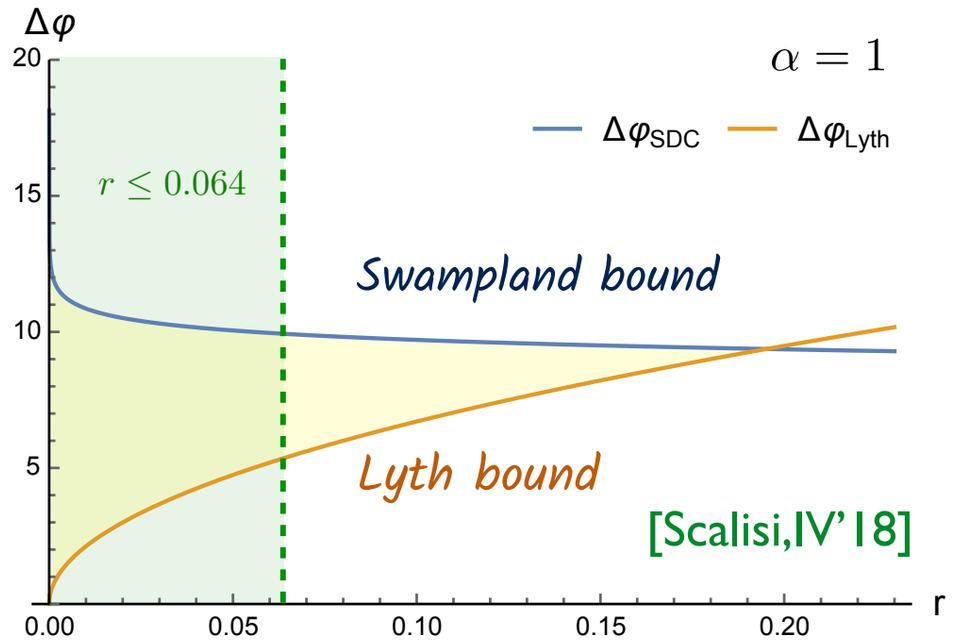


Example: Constraints on single field inflation

$$\Delta\phi \leq \frac{1}{\alpha} \log \frac{M_p}{H} \qquad = \frac{1}{\alpha} \log \sqrt{\frac{2}{\pi^2 A_s r}}$$

$$H \leq \Lambda$$



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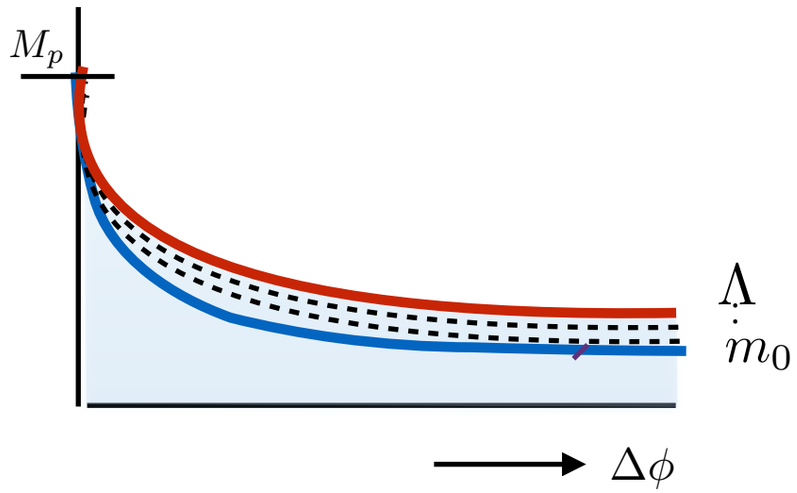

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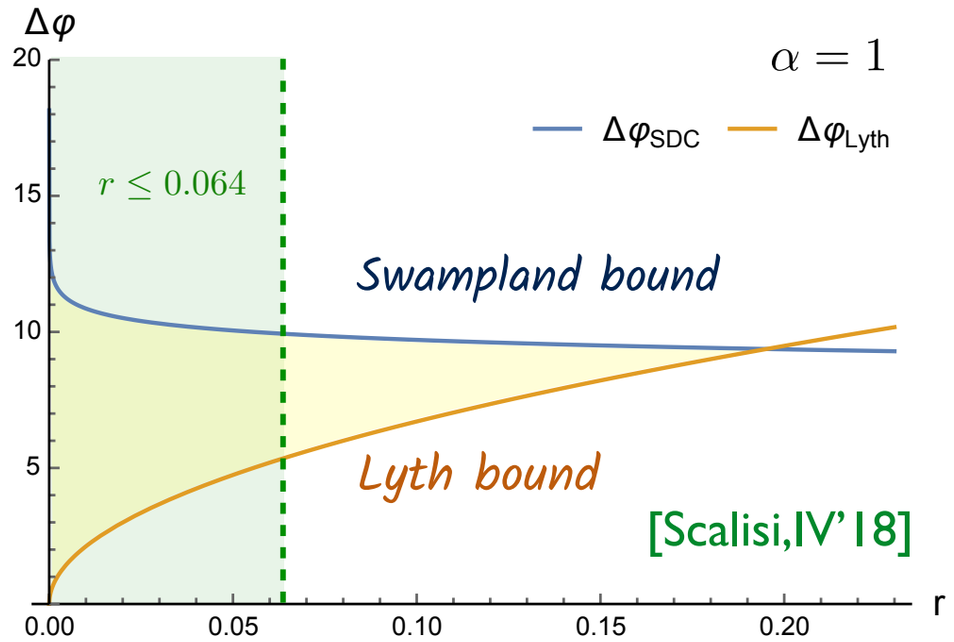
Large field inflation is not ruled out, but can be highly constrained



Cosmological signatures of the tower?

Phenomenological Implications

Caveats to be better understood at the theoretical level in order to give precise phenomenological implications:

1) What is the value of the exponential rate? Is there a lower bound?

$$m \sim m_0 e^{-\alpha \Delta\phi} \quad \Rightarrow \quad \Delta\phi \lesssim \frac{1}{\lambda} \log\left(\frac{M_p}{\Lambda}\right)$$

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$$\alpha_{min} = \left|\frac{\vec{\nabla} m}{m}\right| \geq \frac{1}{\sqrt{d-2}}$$ [Etheredge et al'22]

[Lee et al'19]

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} \Lambda}{\Lambda} = \frac{1}{d-2}$$ [Castellano et al'23]

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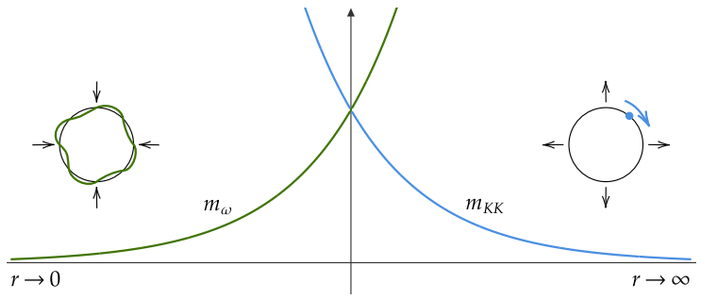
2) When does the exponential behaviour of the masses kick in?



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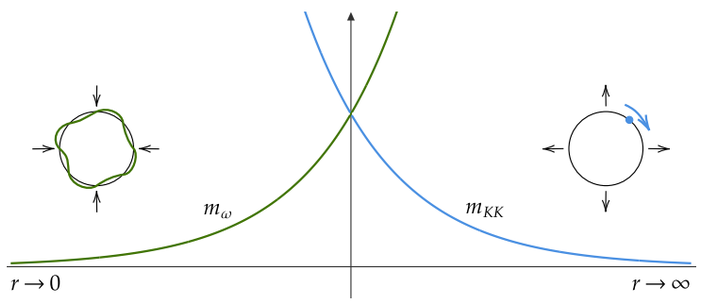


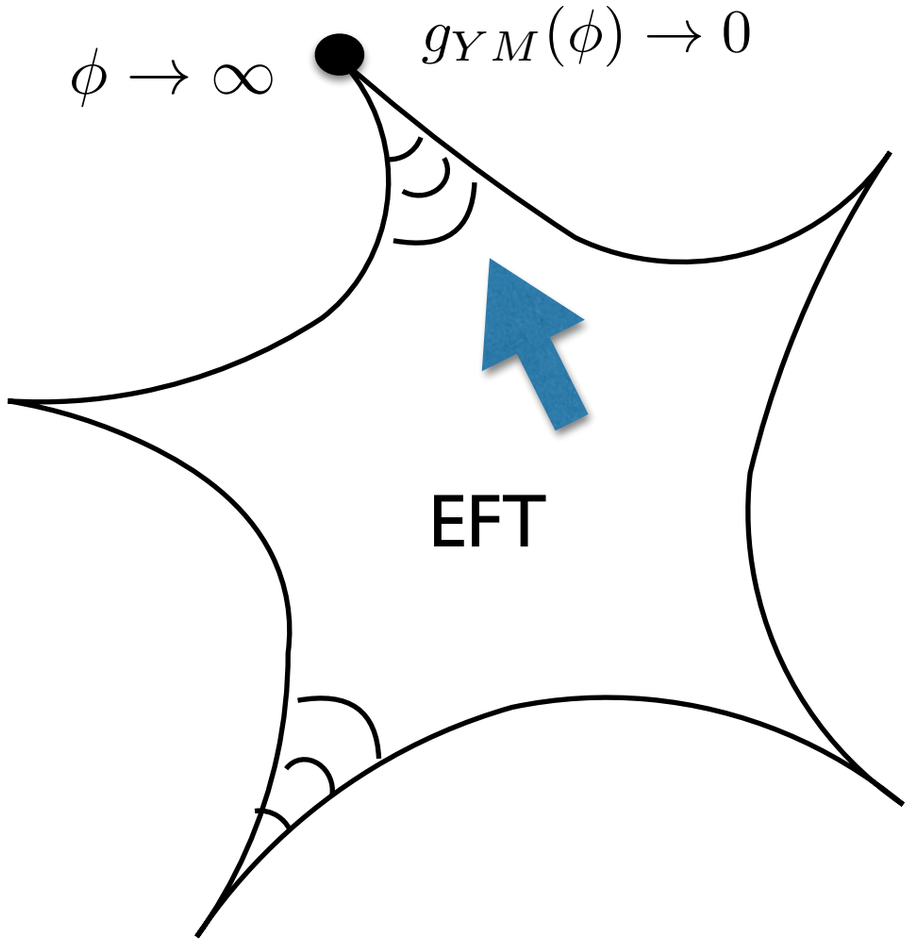
[Long et al'21]

[van de Heisteeg et al'22-23]

3) This is a bound on geodesic distances, that must be read from the kinetic term of the scalars. What about non-geodesic trajectories? (related to constraints on the potential)

[Calderon-Infante et al'20] [Freigang et al'23]…

How does the tower/cut-off behaves in terms of EFT data?



For weak coupling limits:

$\exists$ tower of states satisfying the Weak Gravity Conjecture

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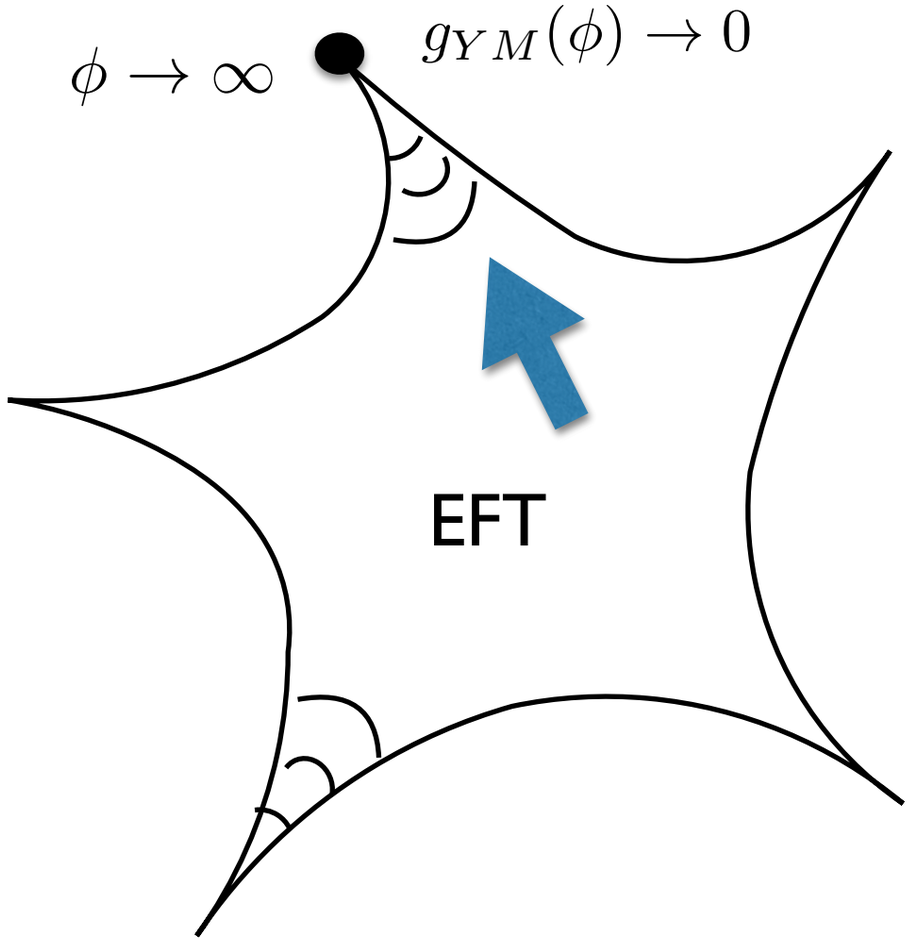

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➡ EFT breaks down at $\Lambda \lesssim g_{\rm YM}^{p} M_p$

with $1/3 \leq p \leq 1$

Lower bound on gauge coupling!

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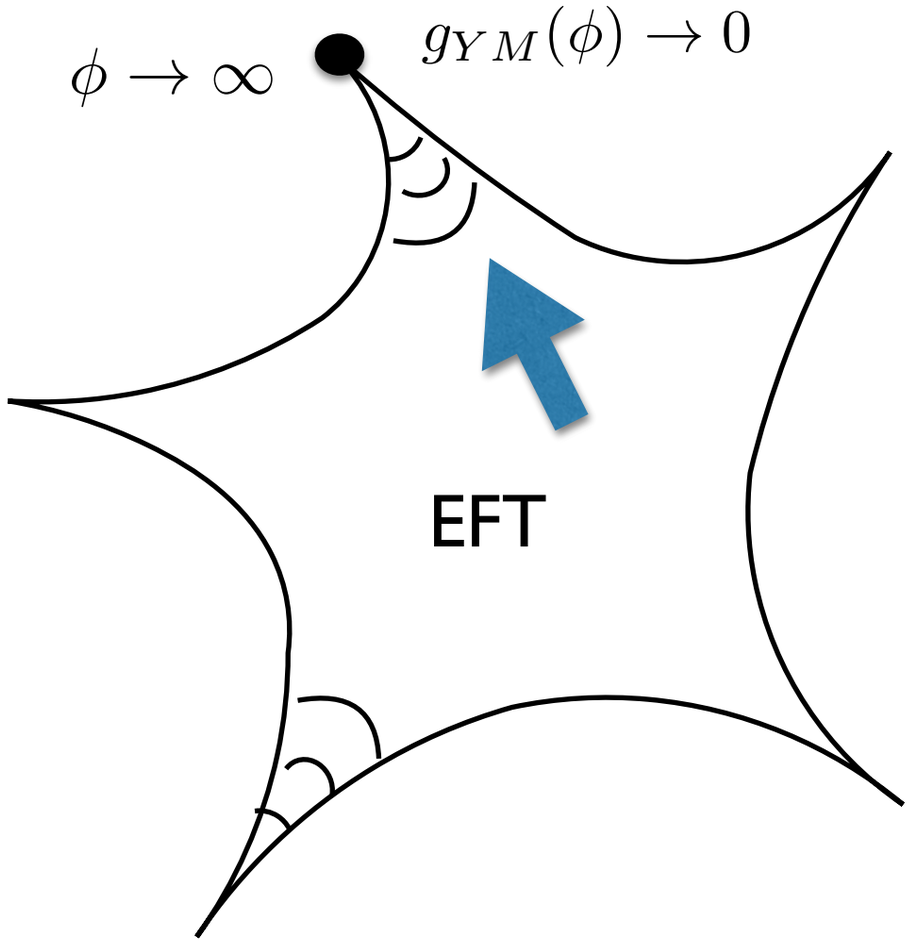

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Weak Gravity Conjecture

Weak Gravity conjecture: [Arkani-Hamed et al'06]

Given a gauge theory coupled to gravity, there must exist an electrically charged state with:

$\mathcal{O}(1)$ *factor (extremality bound of the black holes)*

mass $m \leq \gamma_{\rm BH} Q M_p$ *electric charge*

$$Q = q\, g_{\rm YM}$$

quantized charge *gauge coupling*

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review: [Harlow et al'22]

If $g_{\rm YM} \ll 1$ there is a tower of states satisfying the WGC

[Montero et al.'16][Heidenreich et al.'15-16][Andriolo et al'18][Gendler,IV'20]

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quantized charge *gauge coupling*

Festina Lente: [Montero et al'19]

Given a gauge theory coupled to gravity in dS space, all particles must satisfy:

$$m^2 \geq \sqrt{6}\, g H M_p$$ to allow BHs to evaporate back to dS

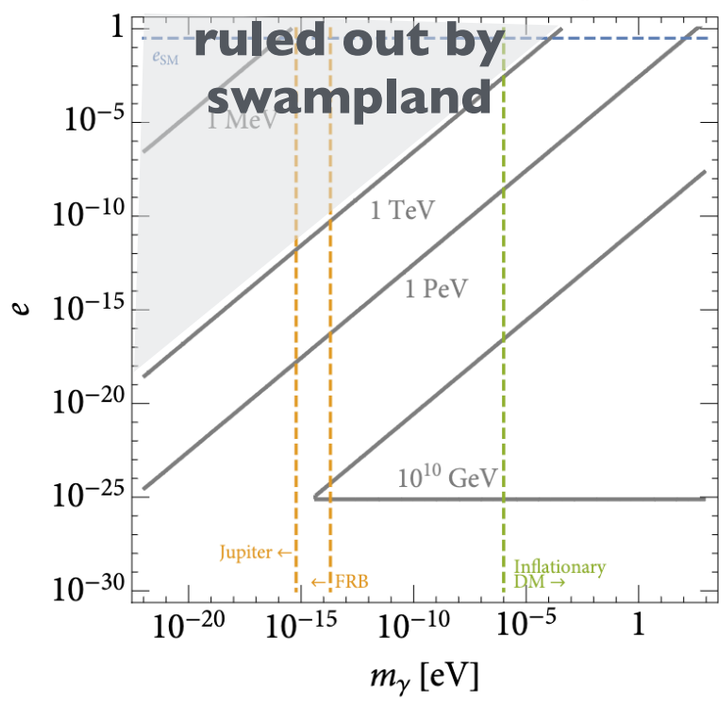
Motivated by a similar reasoning than the WGC for BHs in dS space

Phenomenological implications

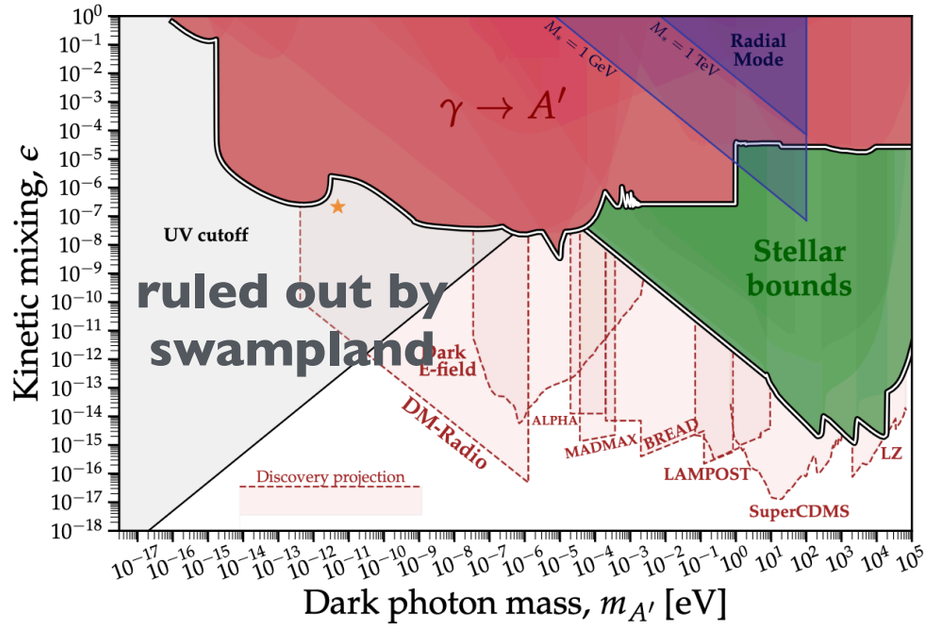
Constraints on dark photons for dark matter:

The quantum gravity cut-off becomes $\Lambda_{QG} \ll M_p$

for weakly coupled or very light dark photons



[Reece'18]



[Montero,Muñoz,Obied'22]

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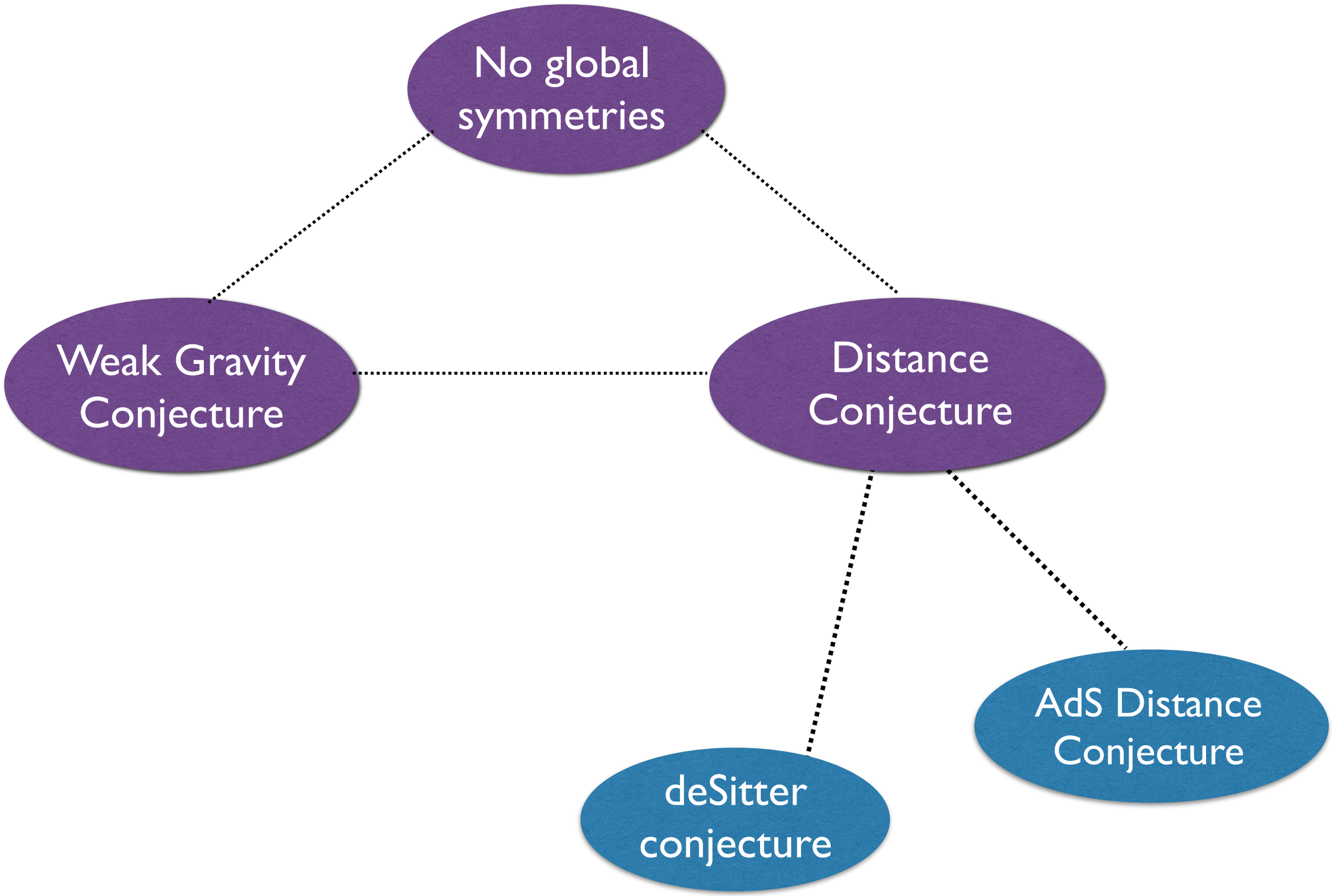
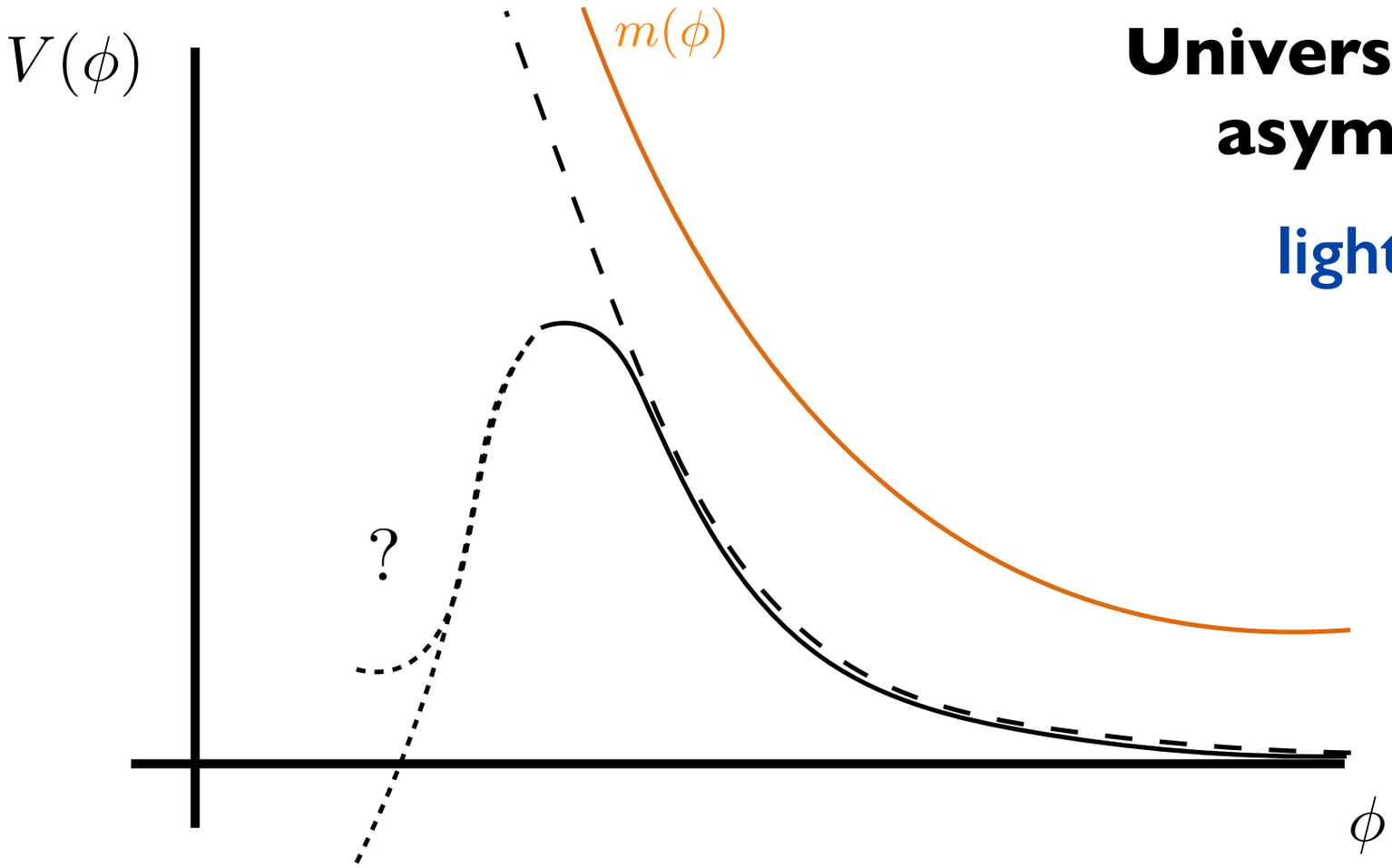


Asymptotic vacuum energy



Universal consequence of asymptotic regimes:

light tower of states

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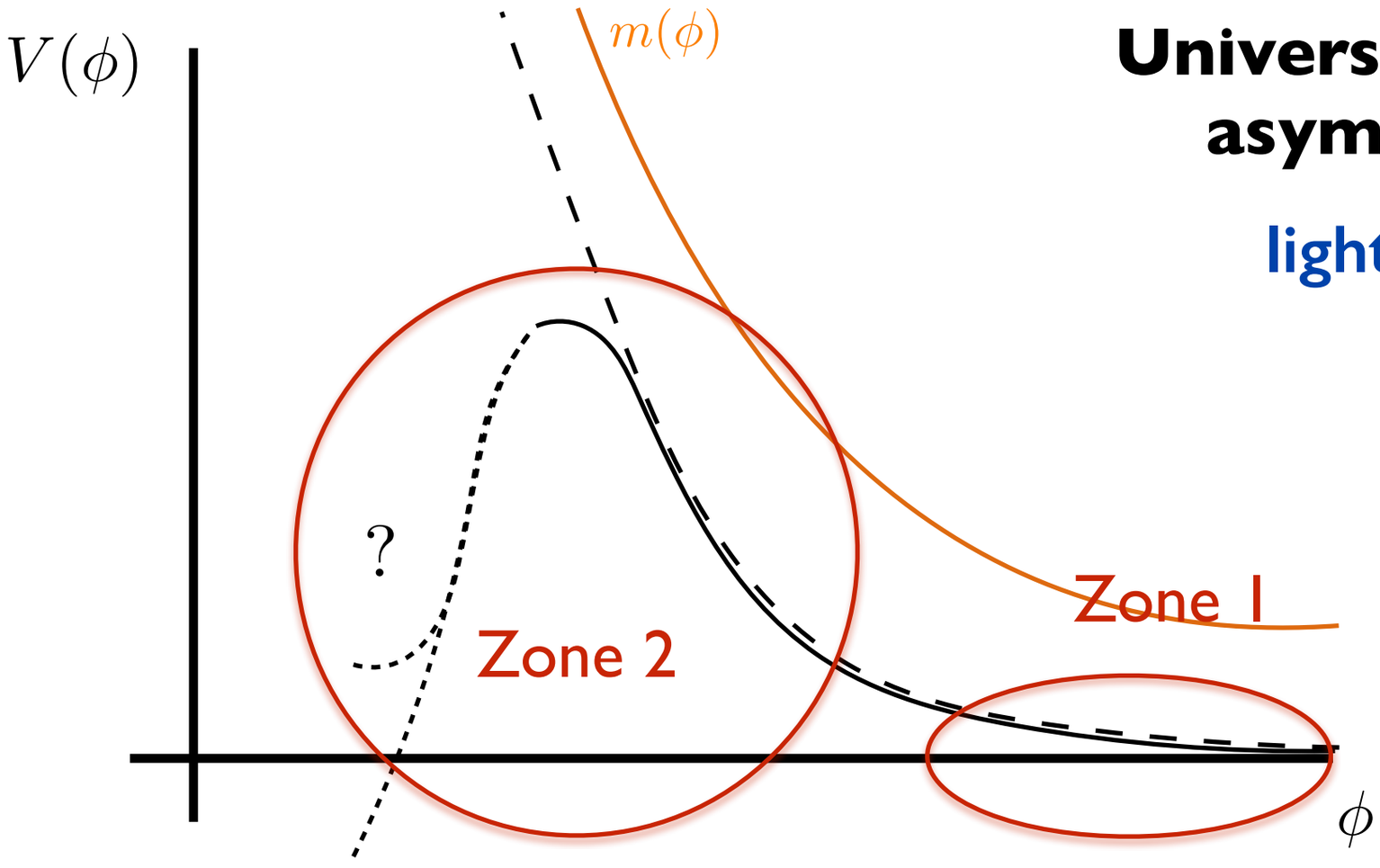

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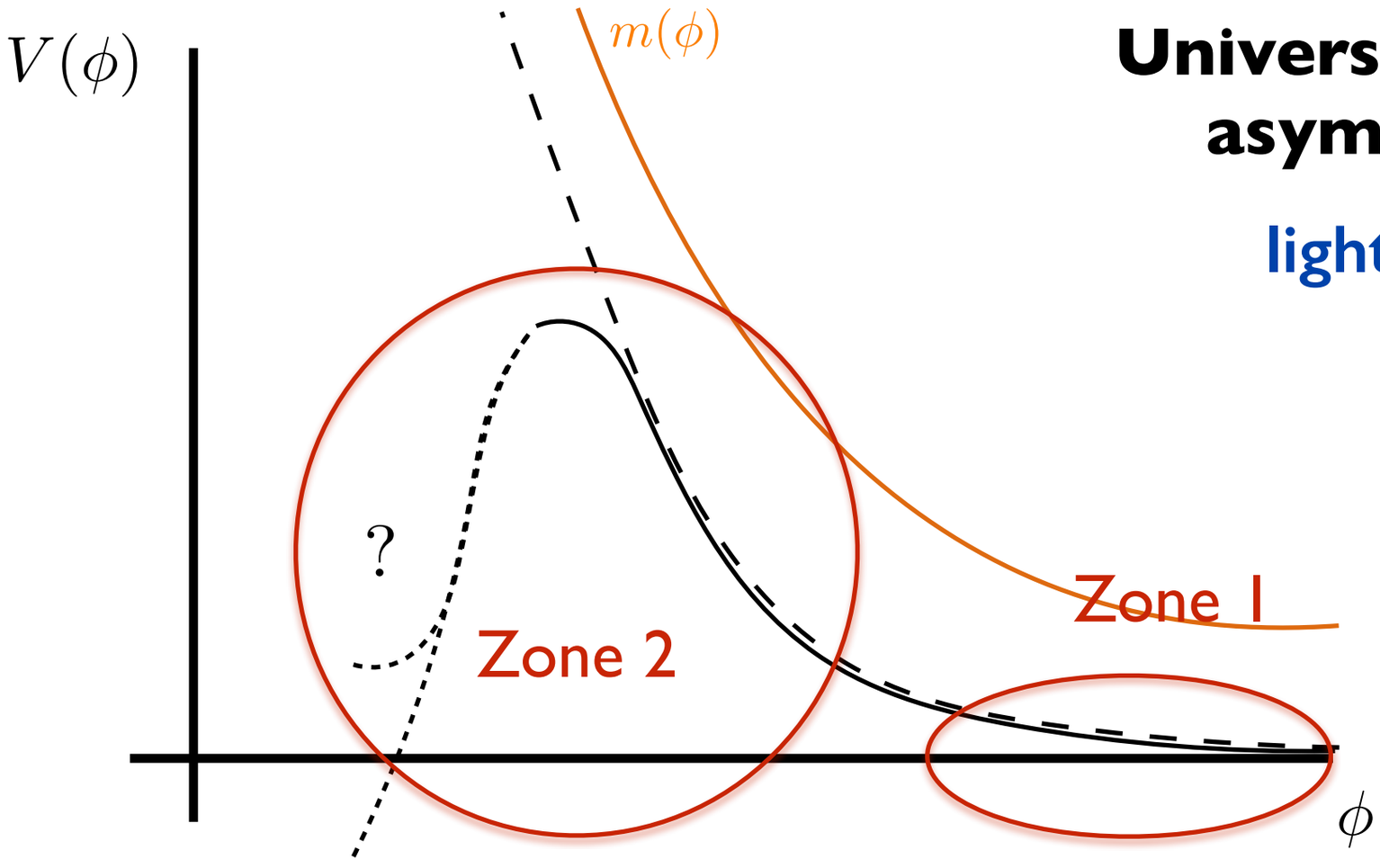

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How does the tower of states relates to the vacuum energy?

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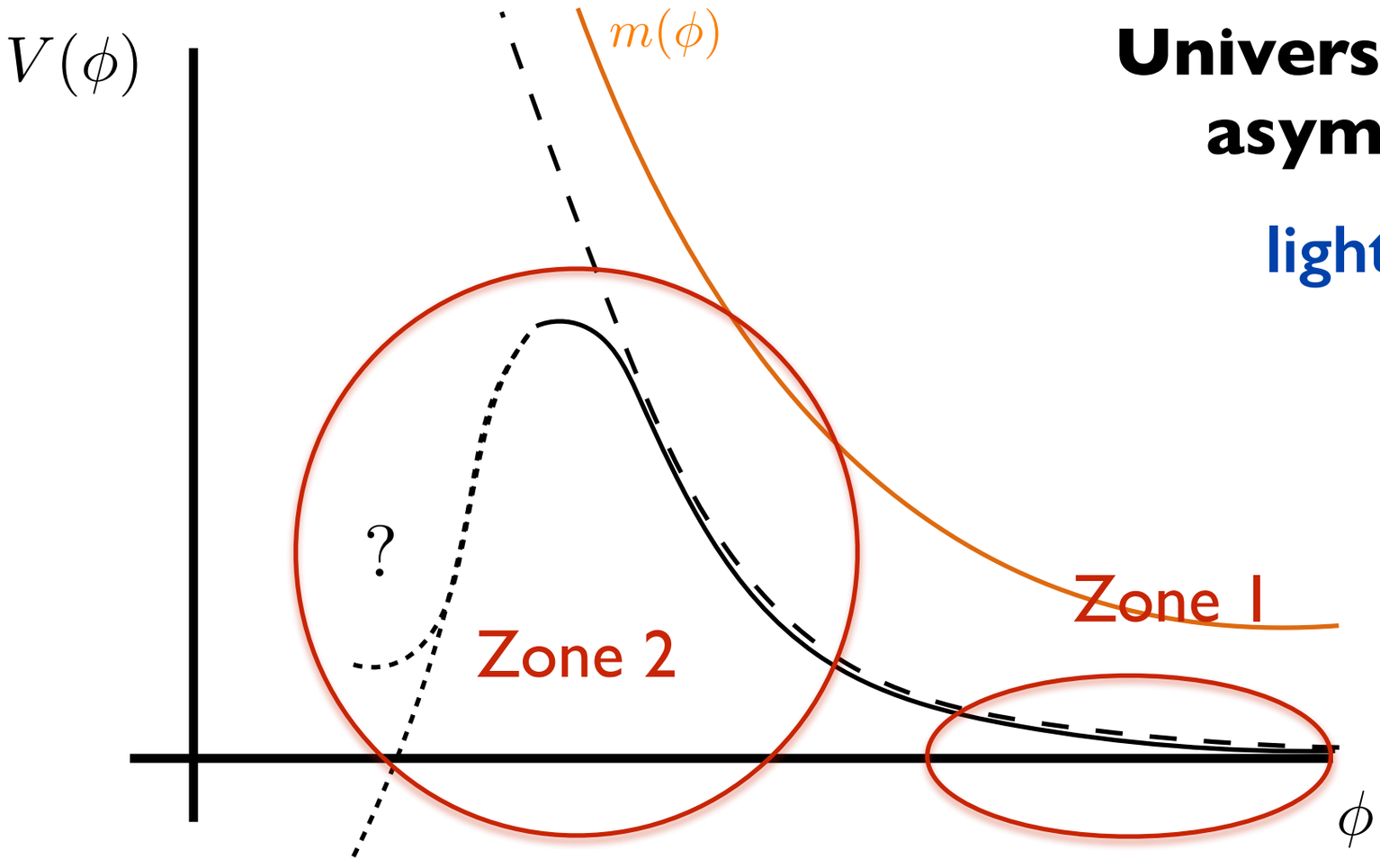

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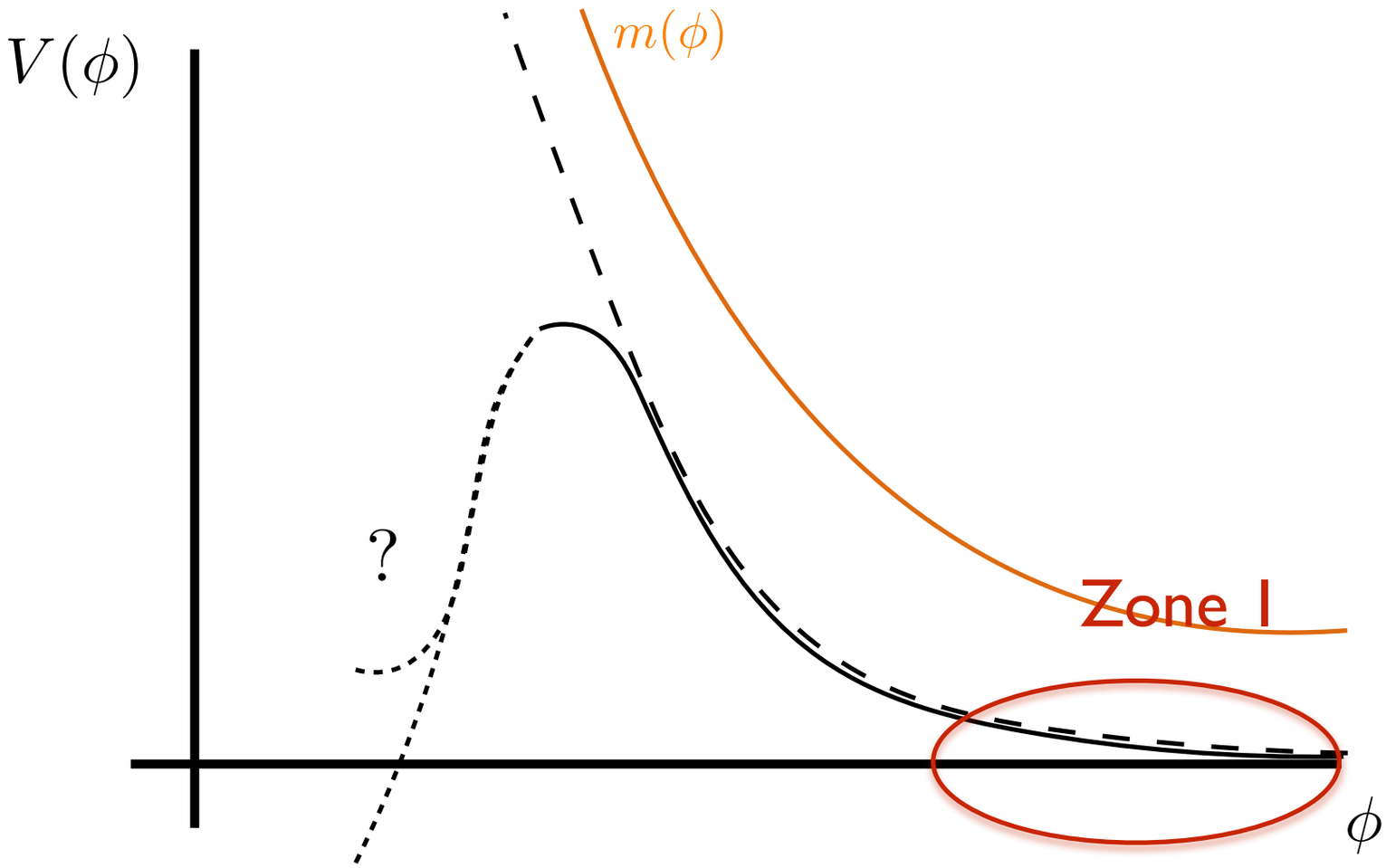
$$V_0 \sim m_{\text{tower}}^{\alpha} \quad \text{in Planck units,} \quad \text{as} \quad V_0 \to 0$$

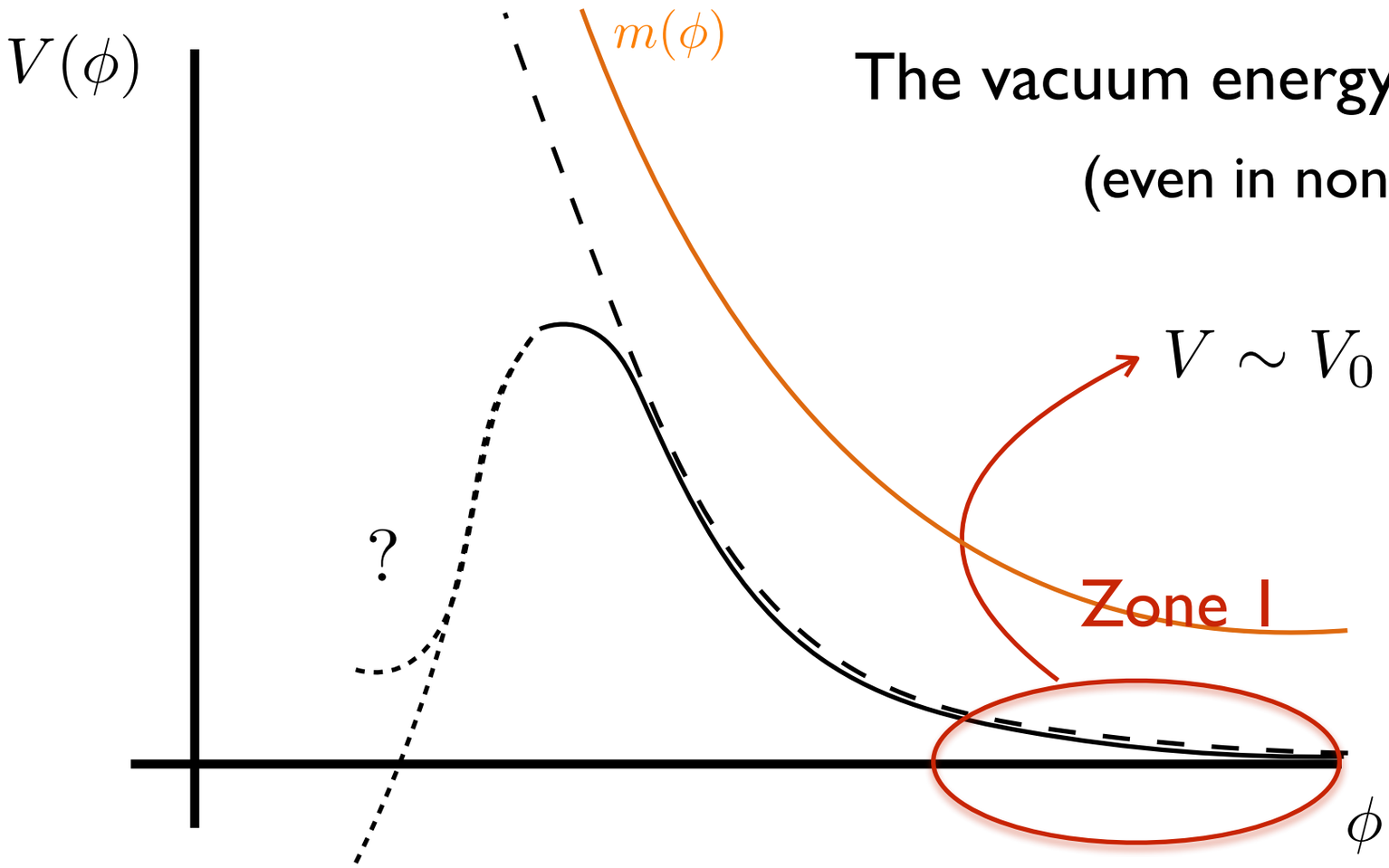
Asymptotic vacuum energy



What is the asymptotic behaviour of the potential?

Could the universe be accelerating forever?

Asymptotic vacuum energy



The vacuum energy goes to zero asymptotically

(even in non-SUSY string theories)

$$V \sim V_0 \exp(-\gamma\phi) \sim m^\alpha$$ in Planck units

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Asymptotic potential at parametric control

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Asymptotic deSitter conjecture: $\gamma = \dfrac{\nabla V}{V} \geq \mathcal{O}(1)$

[Ooguri,Palti,Shiu,Vafa'18]

- Swampland motivation: consequence of the light tower of states

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- Plethora of string theory evidence: [Wrase,Junghans,Andriot… '18-19] [Grimm et al'19]

(new no-go's for dS at parametric control)

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- Plethora of string theory evidence: [Wrase,Junghans,Andriot… '18-19] [Grimm et al'19]

(new no-go's for dS at parametric control)

What is γ ? Could it describe an accelerating cosmology?

Notice! If $\gamma \leq \dfrac{2}{\sqrt{d-2}}$ accelerated expansion à la quintessence

Asymptotic potential at parametric control

Asymptotically: $V \sim V_0 \exp(-\gamma\phi) \sim m^\alpha$ in Planck units

Asymptotic deSitter conjecture: $\gamma = \dfrac{\nabla V}{V} \geq \mathcal{O}(1)$

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Many recent checks in string theory (no clear no-go yet) [Li,Grimm,IV'19][Valeixo et al'20] [Andriot et al'20-22] [Cicoli et al'21-22] [Calderon-Infante et al'22] [Shiu,Tonioni'23] [Cremonini et al'23][Hebecker et al'23]…

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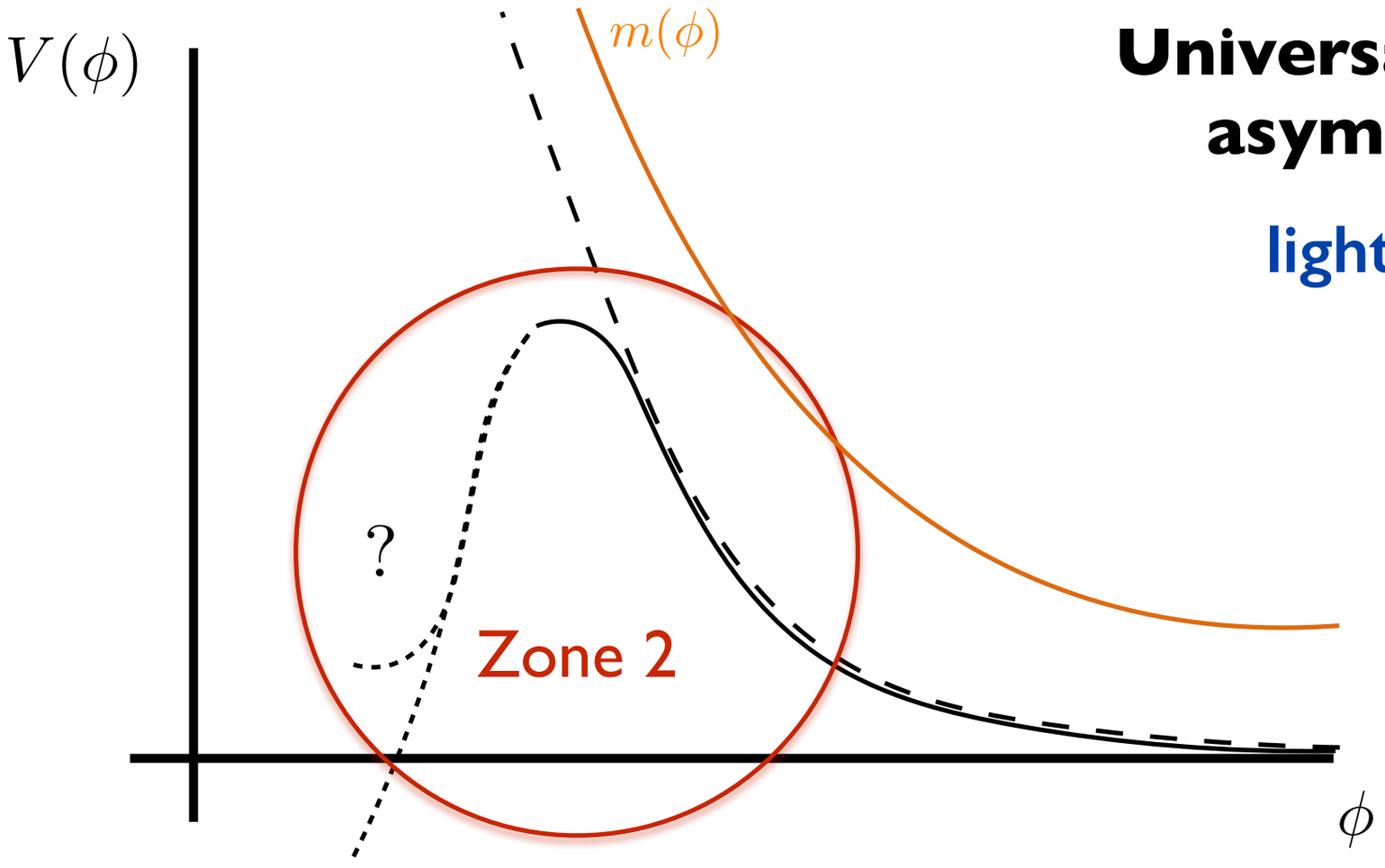
If the tower contains higher spin fields: $\alpha \geq 2$ (Higuchi bound)

$$\left|\frac{\vec{\nabla} m}{m}\right| \geq \frac{1}{\sqrt{d-2}} \quad \text{implies} \quad \left|\frac{\vec{\nabla} V_0}{V_0}\right| \geq \frac{2}{\sqrt{d-2}}$$

[Bedroya,Vafa'19] [Rudelius'22]

→ no accelerated expansion at parametrically late times

Asymptotic vacuum energy



Universal consequence of asymptotic regimes:

light tower of states

The behaviour of the potential becomes model-dependent

How does the tower of states relates to the vacuum energy?

$V_0 \sim m_{\text{tower}}^{\alpha}$ in Planck units, as $V_0 \to 0$

Relation with vacuum energy

$$V_0 \sim m_{\rm tower}^{\alpha} \quad \text{in Planck units,} \qquad \text{as} \quad V_0 \to 0$$

From string theory perspective: $V = V_{\rm tree} + V_{\rm loop} + \dots$

If the different terms compete to generate a vacuum, at the minimum one naturally still has: $V_0 = \lambda m^{\alpha}$

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- ☑ All known families of holographic AdS vacua (even DGKT)
- ☑ KKLT-like proposals for dS in string theory
- ☑ AdS/dS proposals using Casimir energies: $V_0 \sim m^d$

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From swampland perspective:

It can be motivated by generalising the conjecture to distances in the space of metric configurations (rather than only in moduli space):

Distance $\sim \log|V_0|$ *Flat space limit* $V_0 \to 0$ *is at infinite distance*

$$m \sim \exp(-\alpha\,\text{distance}) \sim \Lambda^{\alpha} \quad \text{as} \quad \Lambda \to 0$$

(AdS Distance Conjecture) [Luest,Palti,Vafa'19]

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No clear bottom-up explanation (indep. of string theory) yet

Our universe

Let me assume this relation and study its consequences

$$m \sim V_0^{1/\alpha} \to 0$$

Could it be the case of our universe?

[Montero,Vafa,IV'22]

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The smallness of our vacuum energy is not due to a huge fine-tuning of contributions in a landscape, but is a signal of being near an asymptotic limit where it naturally goes to zero

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Consequence:

But then, there should be a light tower of states whose mass is correlated to the cosmological constant

$$2 \leq \alpha \leq d \quad \Rightarrow \quad V^{1/2} \lesssim m \lesssim V^{1/4}$$

Higuchi bound

no fine-tuning

$d =$ space-time dimension

Experimental constraints

Is a tower with $V^{1/2} \lesssim m \lesssim V^{1/4}$

compatible with experimental constraints?

In our universe: $V^{1/4} \sim 2.31 \text{ meV}$

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Nature of the tower (according to string theory): [Lee,Lerche,Weigand'19]

- ~~String perturbative limit~~ *ruled out exp.*
- Decompactification of n extra dimensions

Experimental constraints:

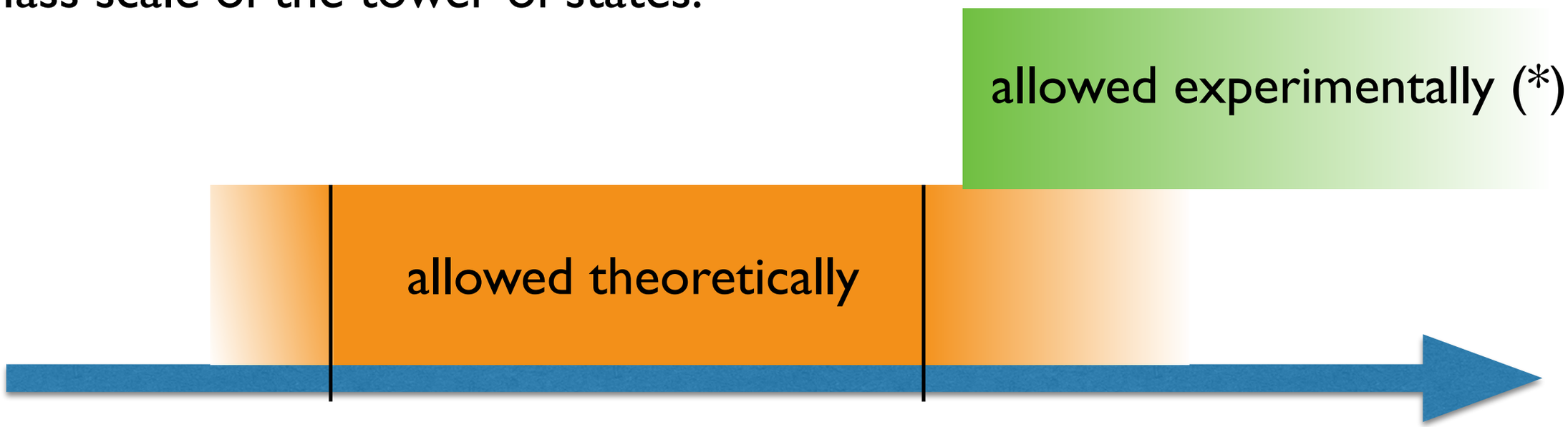
- Astrophysical bounds: $m^{-1} \leq 10^{-4}\,\mu m \quad (n=2)$ ~~$(n=2)$~~ *ruled out*

  [Hannestad and Raffelt '03] $m^{-1} \leq 44\,\mu m \quad (n=1)$

- Dev. from Newton's laws (n=1): $m^{-1} \leq 30\,\mu m$ [Lee et al '21]

Experimental constraints

Mass scale of the tower of states:



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Casimir contribution
(one loop quantum correction)

(*) astrophysical bounds and deviations from Newton's law

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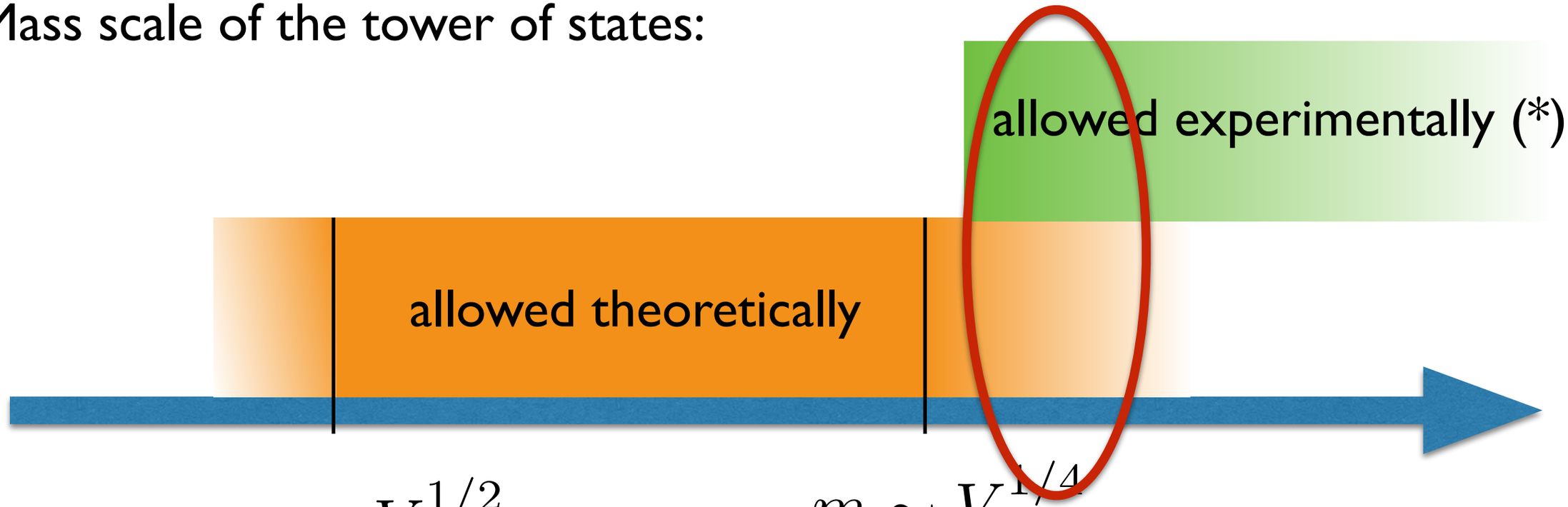

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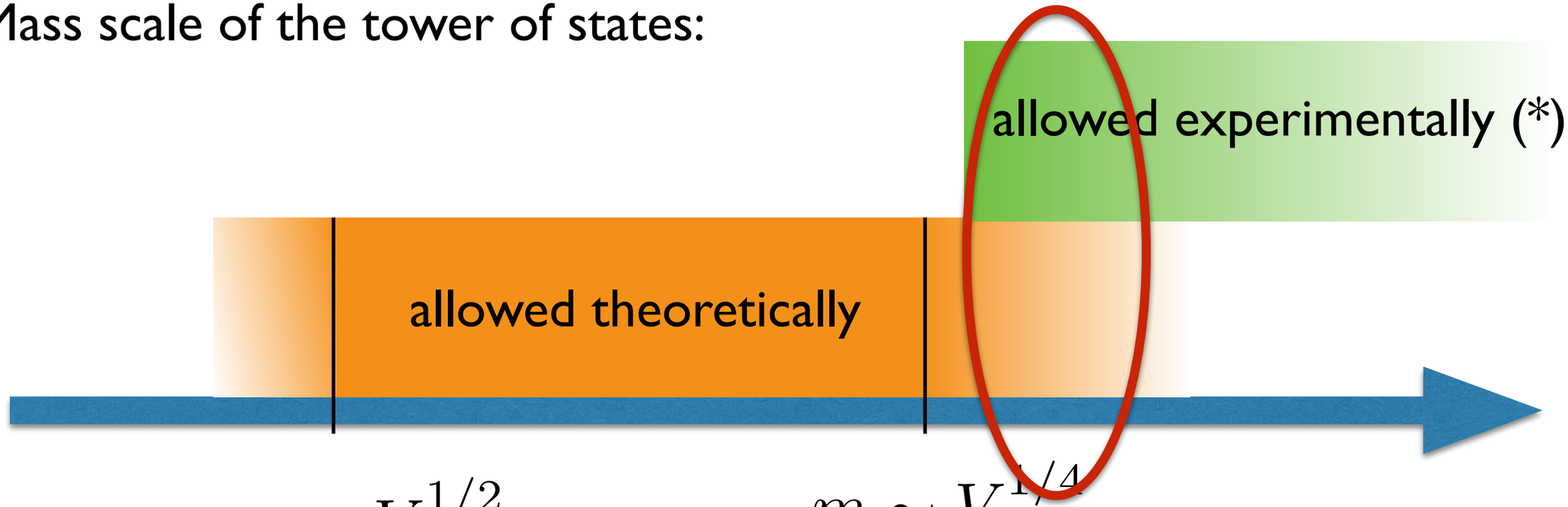

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Only n=1 (one large extra dimension) is marginally compatible!

Dark Dimension Scenario

If our universe lives near an infinite distance limit $V_0 \to 0$,

there should be a light tower of states of mass: (mod extra fine-tunings)

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(This tower also helps to avoid violation of the AdS Distance conjecture upon compactification of the Standard Model) [Gonzalo,Ibanez,IV'21]

Dark Dimension Scenario

[Arkani-Hamed,Dimopoulos, Dvali'98]

This scenario is an example of the Large Extra Dimension models (ADD)

although the scale is different than usual, since it was motivated by the smallness of the cosmological constant and not by the EW hierarchy problem:

QG cut-off: $\hat{M} \sim m^{1/3} M_P^{2/3} \sim 10^{10}\, GeV$

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Open challenges: We do not have a concrete string theory embedding including the SM!

It will be tested in future experiments that will improve the precision measurements on deviations from Newton's law

New ISLE at the Conrad Observatory

[Aspelmeyer,Adelberger,Shayeghi,Zito…]

Conclusions

- Consistency with Quantum Gravity can have important implications for our universe at energies much below the Planck scale.

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  → new towers of states become light yielding $\Lambda_{QG} \ll M_p$

- Swampland constraints motivated by string theory motivate an scenario in which the smallness of our vacuum energy is tied to the existence of one mesoscopic extra dimension of

  $l \sim 0.1 - 10 \mu m$ in our universe.

Thank you!

If you want to hear more about the Swampland program:

Online series of Swampland seminars / open mic discussions

on Mondays at 11:00 am ET (5:00 pm CET)

You can subscribe here: https://sites.google.com/view/swamplandseminars/

Everybody is welcome! :)

back-up slides

Approximate global symmetries,
Weakly coupled gauge theories,
Large field ranges…

…come at a price.

(Swampland) Distance Conjecture (SDC):

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m(P) \sim m(Q) e^{-\alpha \Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

(geodesic distance)

[Ooguri-Vafa'06]

[Arkani-Hamed et al'06]

Weak Gravity Conjecture (WGC):

Given a gauge theory, there must exist an electrically charged state with

$$\frac{Q}{M} \geq \left(\frac{Q}{M}\right)_{\text{extremal}} = \mathcal{O}(1)$$

Q=q g : charge
m : mass in Planck units

Strong version: *there is a sublattice/tower of superextremal states*

[Montero et al.'16][Heidenreich et al.'15-16][Andriolo et al'18]

UV cut-off goes to zero
due to new light states

$$\Lambda \sim g M_p$$

$$\Lambda \sim M_p \exp(-\alpha \Delta\phi)$$

Evidence for WGC and SDC

❖ String theory compactifications: Plethora of quantitative tests!

- Systematic approach according to the level of supersymmetry [Grimm, Palti, IV'18] [Grimm,Palti,Li'18]
- Interesting connections to mathematics [Lee,Lerche,Weigand'18-19] …

❖ AdS/CFT:

- WGC proven for AdS3 using modular invariance of the CFT [Heidenreich et al'16] [Montero et al'16]
- WGC from QI theorems and entanglement entropy [Montero'18]
- SDC formulated in terms of a CFT Distance conjecture [Perlmutter et al'20]

❖ Black hole arguments:

- WGC follows from requiring black holes to decay [Arkani-Hamed et al'06]
- WGC/SDC follows from entropy bounds associated to small BHs [Hamada et al'21]
- Connection between WGC and weak cosmic censorship [Crisford et al'17]

❖ Using positivity/unitarity bounds: lead to mild versions of the WGC

[Cheung et al'18][Hamada et al'18]…

WGC and SDC from Entropy Bounds

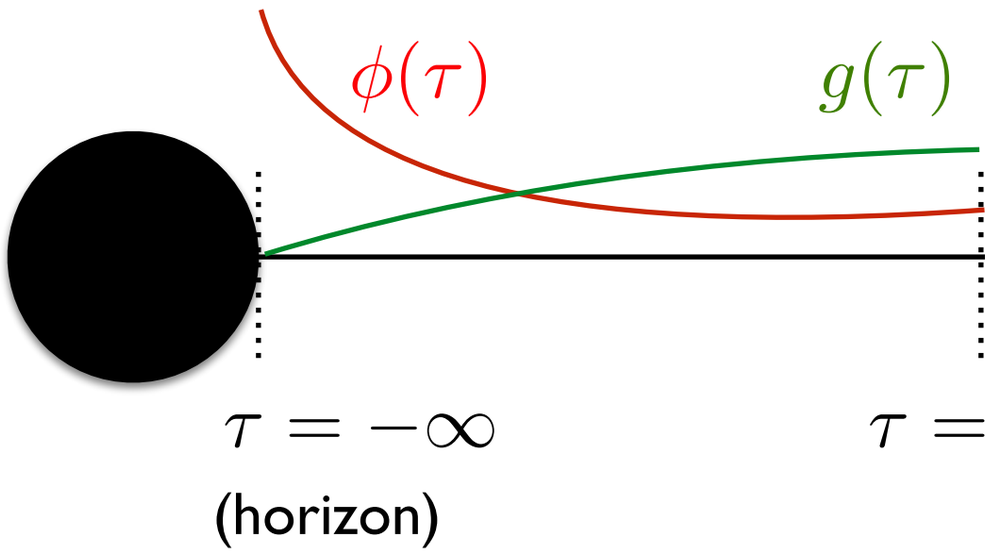
Take Einstein-Maxwell-Dilaton theory:

$$S = \int d^4x\sqrt{-g}\left[R + 2|d\phi|^2 + \frac{1}{2g(\phi)^2}|F|^2\right] \quad \text{s.t.} \quad g(\phi) \to 0 \quad \text{as} \quad \phi \to \infty$$

There are electrically charged BH solutions with classical zero area (small BHs)

If $g(-\infty) \to 0$ then $A(-\infty) \to 0$: Small BH

BH induces a running of the scalar field and gauge coupling as approaching the horizon leading to:



large field range!
small gauge coupling!

WGC and SDC from Entropy Bounds

Small BHs lead to a violation of the Bekenstein bound, unless the EFT cutoff decreases as dictated by the SDC / WGC

Entropy Bound:

A region of size L cannot have more entropy than a Schwarzschild black hole of the same area $A = L^2$

$$N_{\text{species}} = Q_{\max} \lesssim L^2 = A$$

Using extremality condition and that EFT breaks down at $|d\phi|^2 \sim \Lambda^2$

$\Lambda \lesssim g$ in Planck units

due to an infinite tower of states

Cobordism conjecture

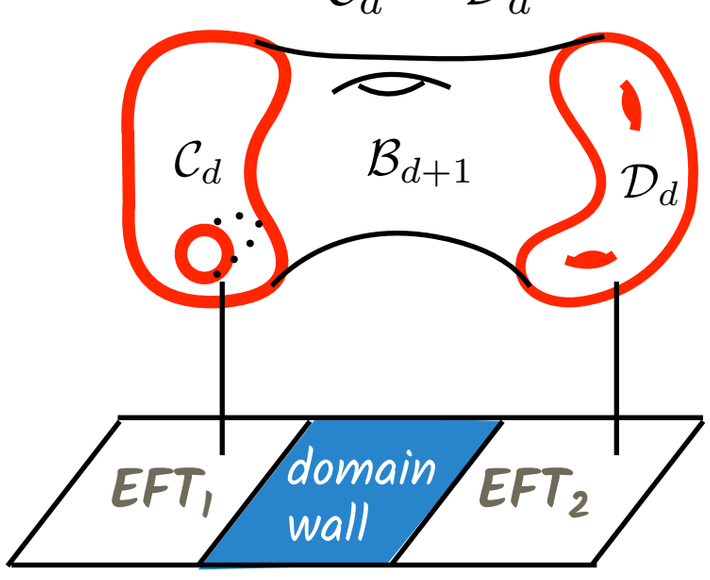
The cobordism group of a quantum gravity theory must be trivial:

$$\Omega_k^{QG} = 0$$ [McNamara,Vafa'19]

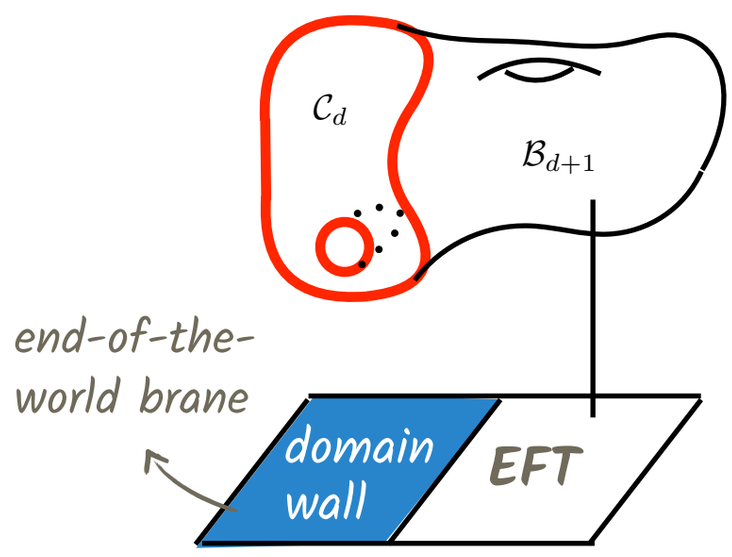
k : internal dimension
D : total dimension

to avoid a (D-k-1)-form global symmetry with charges $[M] \in \Omega_k^{QG}$

$\mathcal{C}_d \sim \mathcal{D}_d$



$C_d = \partial B_{d+1}$ *(trivial class)*



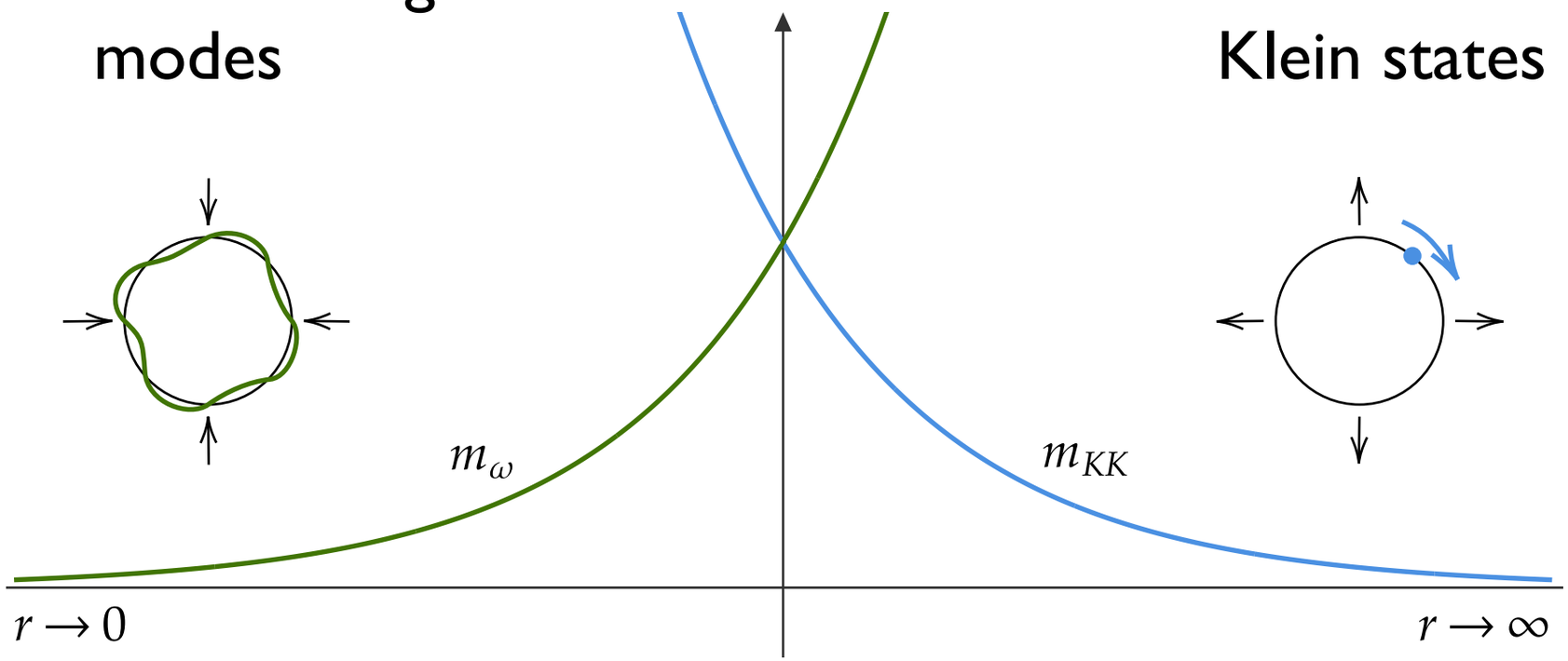
It implies all theories of same dimension are connected by finite energy domain walls, and predicts the existence of new defects in string theory!

Asymptotic Towers of States

Simplest example: Circle compactificaton of a string theory

Tower of winding modes

Tower of Kaluza-Klein states



Quantum gravity cut-off: $\Lambda \equiv M_{\mathrm{pl},d+1} = \dfrac{M_{\mathrm{pl},d}}{r} \to 0$ as $r \to \infty$

(same for T-dual theory as $r \to 0$)

Pattern

In all known string theory examples so far, it occurs that

$$V_0 \sim m_{\rm tower}^{\alpha} \quad \text{in Planck units,} \qquad \text{as} \quad V_0 \to 0$$

We can bound $2 \leq \alpha \leq d$ in quasi-dS space [Montero,Vafa,IV'22]

$\alpha \geq 2$: Higuchi bound: $m_{\rm tower} \geq H$ since the tower contains higher spin fields

$\alpha \leq d$: Even if tree level is small, there is at least a one-loop contribution:

$$V \sim m^d \quad \text{(if non-susy)}$$

$d =$ space-time dimension

Failure of IR EFT expectations

In all known string theory examples so far, it occurs that

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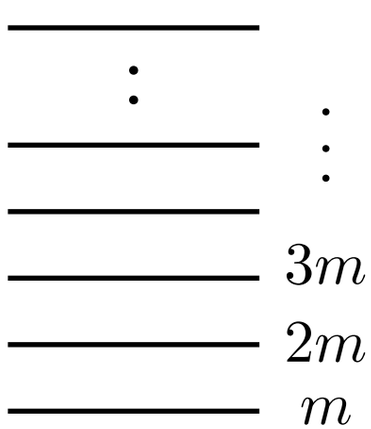


It is important to consider the contribution of the entire tower of states (vs a finite number of fields):

- If integrating out the infinite tower: (e.g. Casimir energies)

$$V_0 \sim m_1^d$$ first light state of the tower!

- If integrating a finite number of fields below a cut-off:

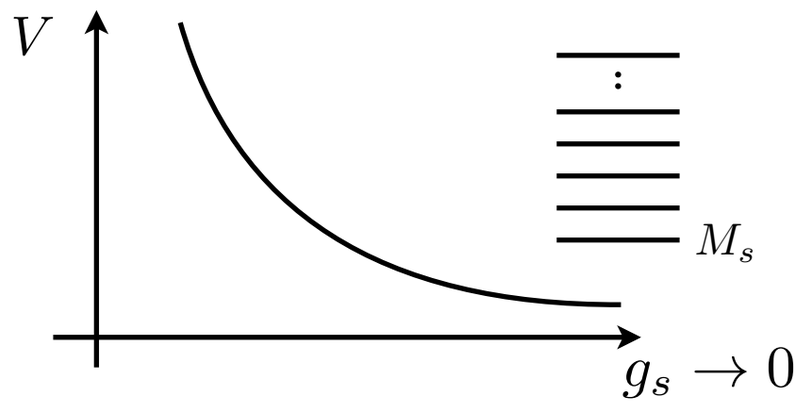
$$V_0 \sim m_{\rm heavy}^d$$ the heavy states dominate

Non-SUSY string theory example

SO(16)xSO(16) non-SUSY (tachyon-free) heterotic string theory:

Tower of string modes becoming light in the weak coupling limit, starting at

$$m_{\text{tower}} = M_s$$



Positive runaway on the dilaton

$V_{\text{tree}} = 0$ by conformal invariance

$$V_{\text{1-loop}} \sim -\sum_i (-1)^{F_i} \int_{\Lambda_{UV}^{-2}}^{\infty} \frac{ds}{s^6} \exp\left(-\frac{m_i^2 s}{2}\right) \quad \Rightarrow \quad V \sim m_{\text{tower}}^{10}$$

Contribution of massive string excitations is "cut-off" at Ms due to modular invariance (to avoid redundancy of counting the same states more than once)

More massive NS5-branes do not contribute either, they are composite objects