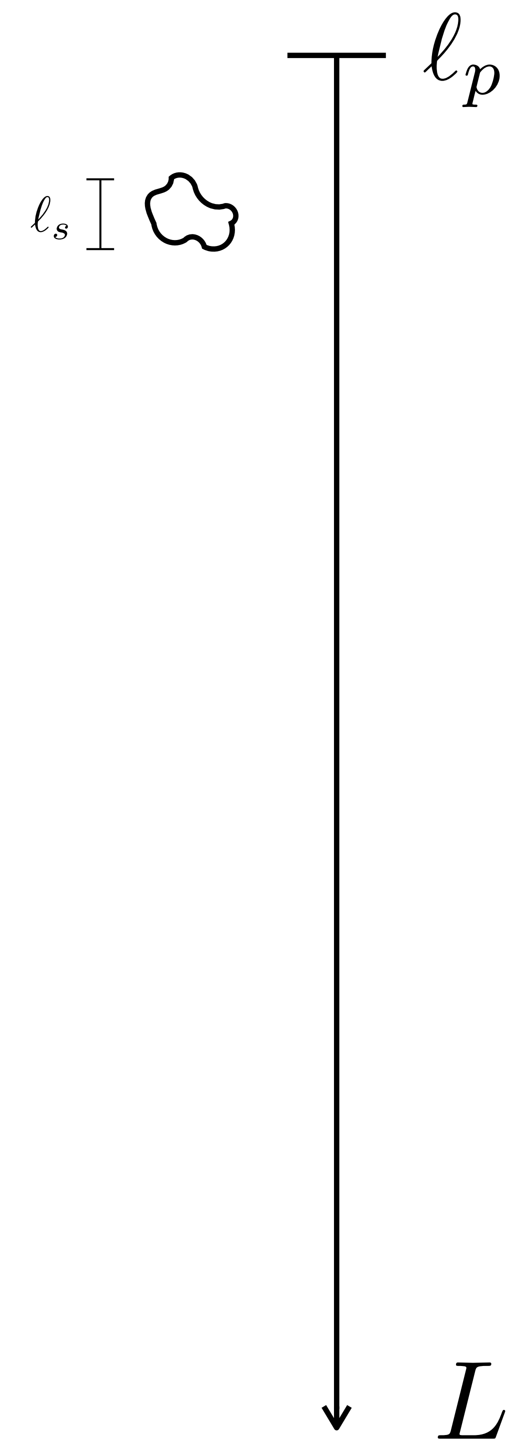
Swampland Conjectures

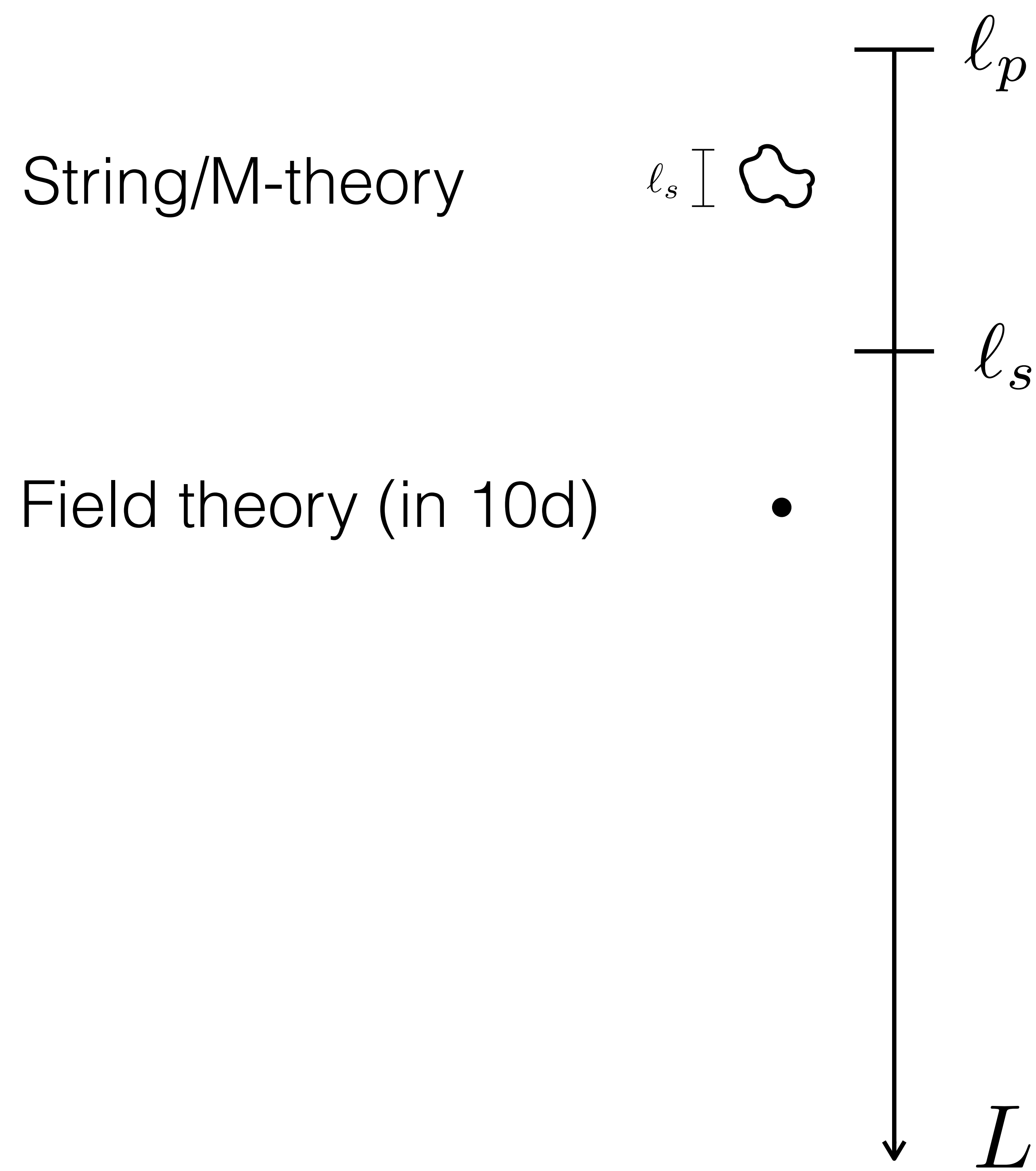
Pablo Soler - Heidelberg ITP

Strings and Fields ’19 - YITP Kyoto

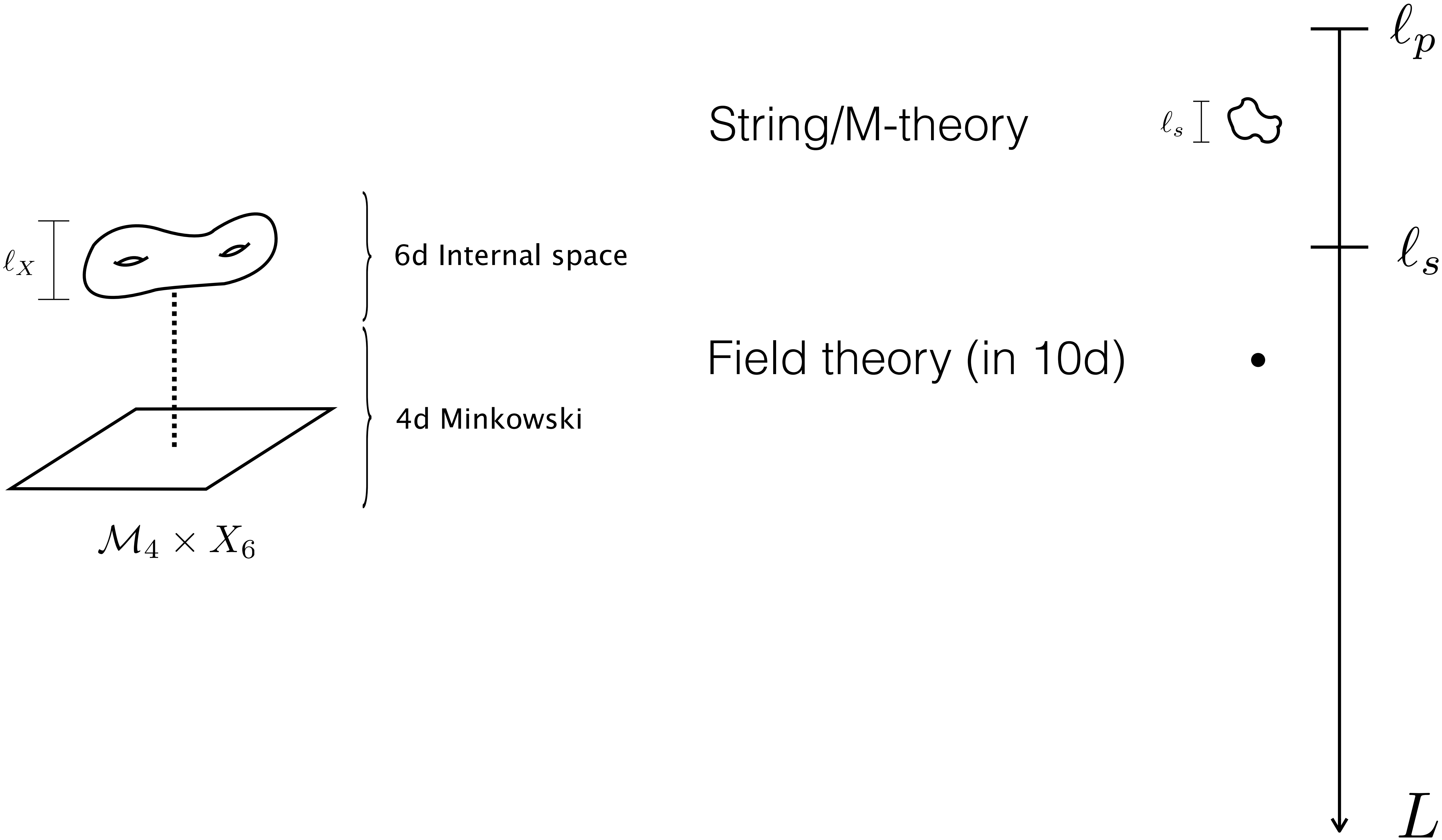
String phenomenology & the swampland

String/M-theory





String/M-theory
ℓ_s
Field theory (in 10d)
ℓ_p
ℓ_s
L



ℓ_X
6d Internal space
4d Minkowski
$\mathcal{M}_4 \times X_6$
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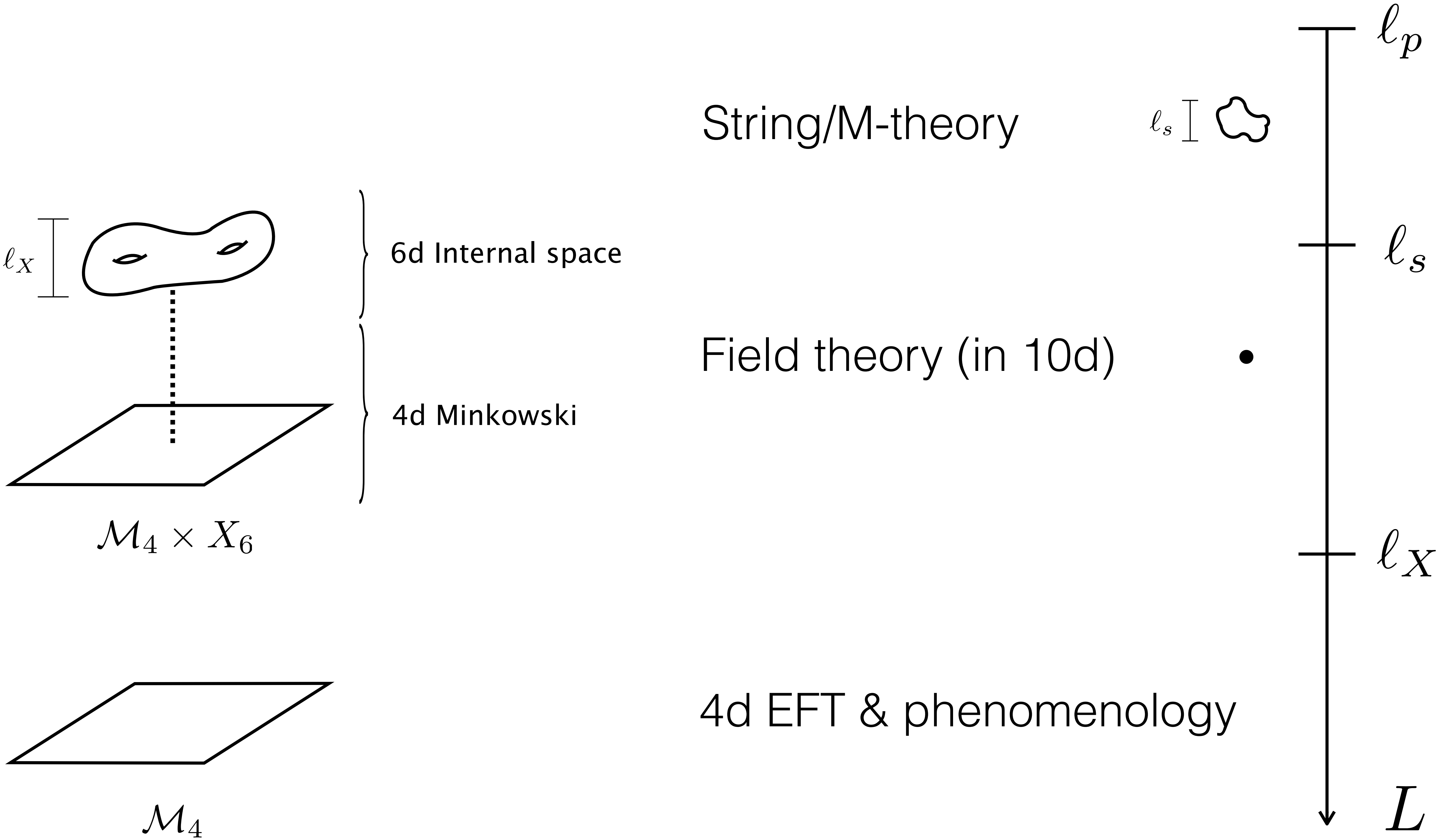

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6d Internal space
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4d EFT & phenomenology
ℓ_p
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ℓ_X
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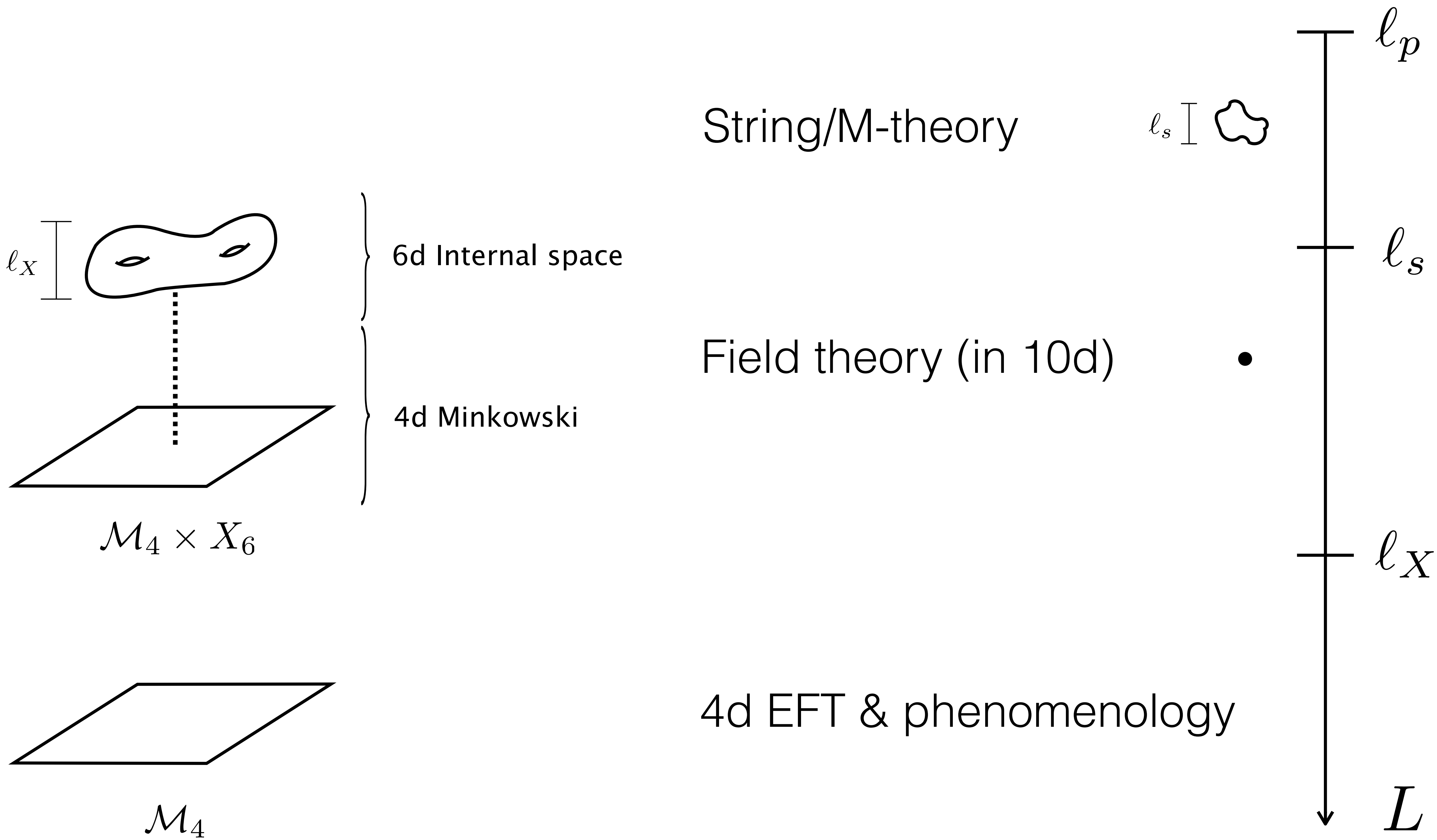

String phenomenology explores compactification spaces X_{6d} that reproduce the SM and interesting BSM scenarios.

String Pheno and the Swampland

- String theory admits a vast number $\gtrsim 10^{500}$ of 4d solutions: “the string landscape”

Douglas ‘03

- Two main traditional approaches to string phenomenology:
  - What is ***generic***? Axions, moduli,…
  - What is ***possible***? The SM, low energy ~~SUSY~~, …
- Recently, a novel perspective has emerged:
  - What is ***impossible***? “The swampland”

Vafa ’05; Ooguri, Vafa ’06;……
See Palti ’19 for a review

String Pheno and the Swampland

- String theory admits a vast number $\gtrsim 10^{272000}$ of 4d solutions: "the string landscape"

Braun, Watari '15; Taylor, Wang '15

- Two main traditional approaches to string phenomenology:
  - What is ***generic***? Axions, moduli,…
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String Pheno and the Swampland

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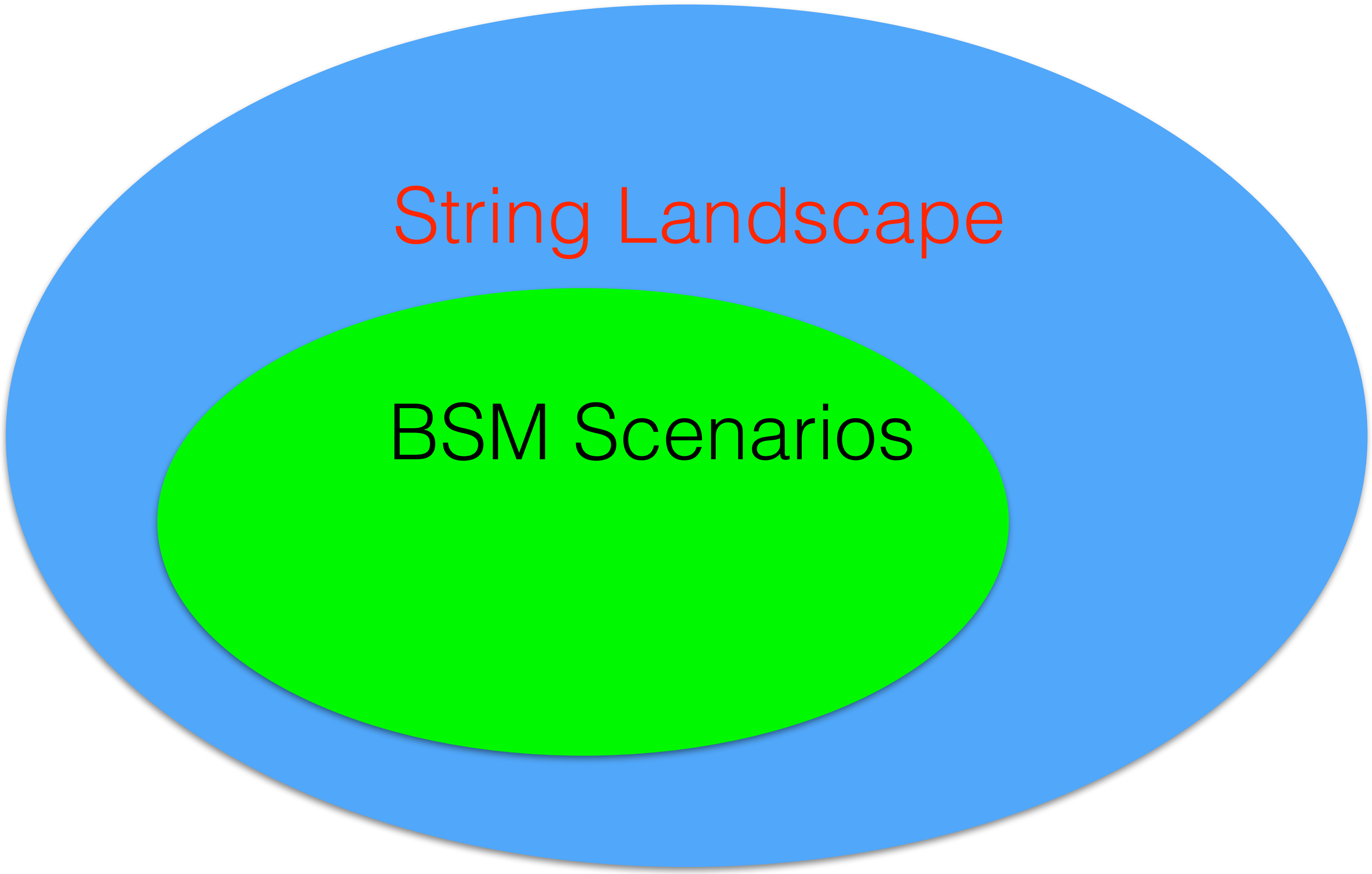
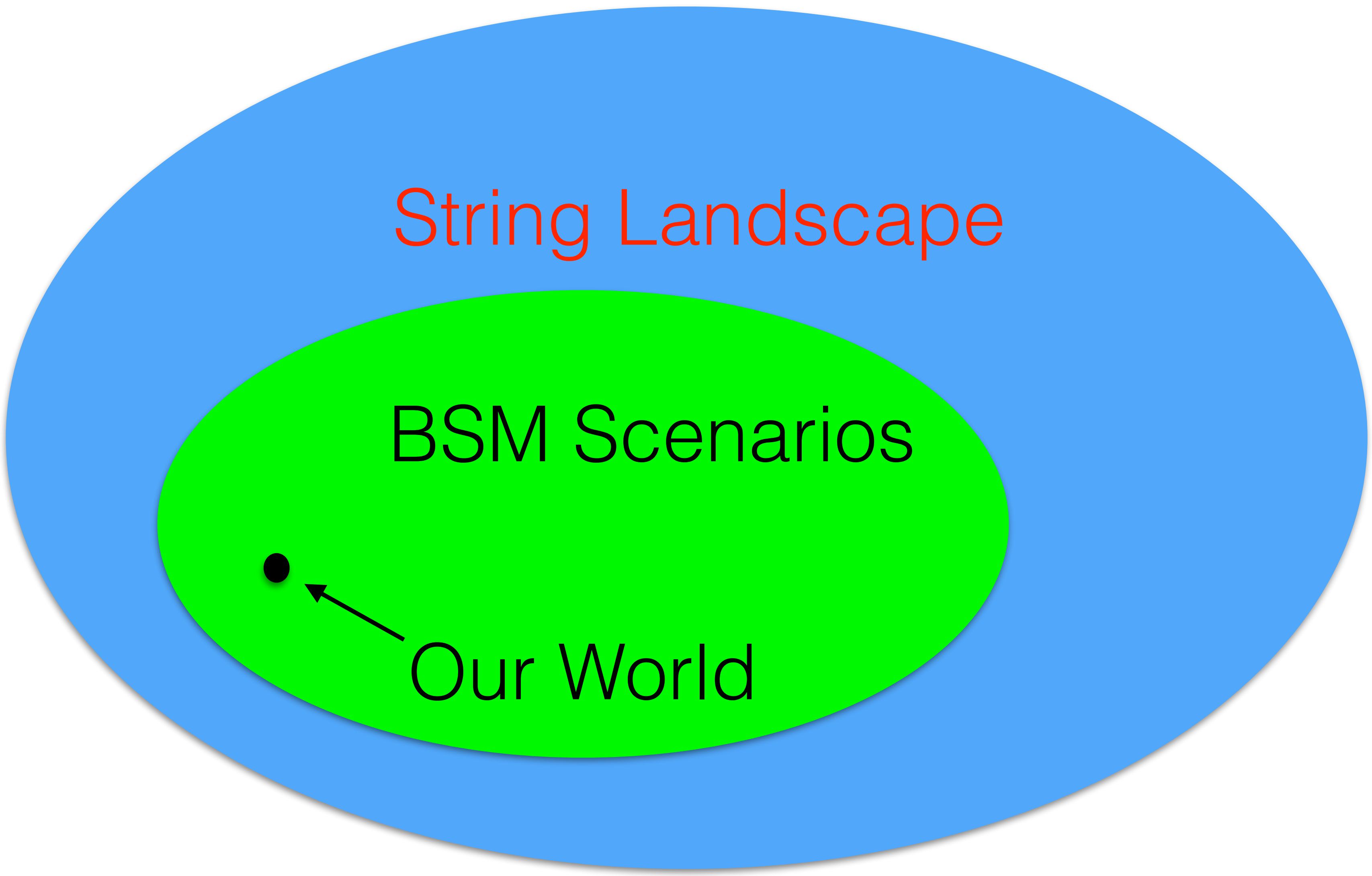
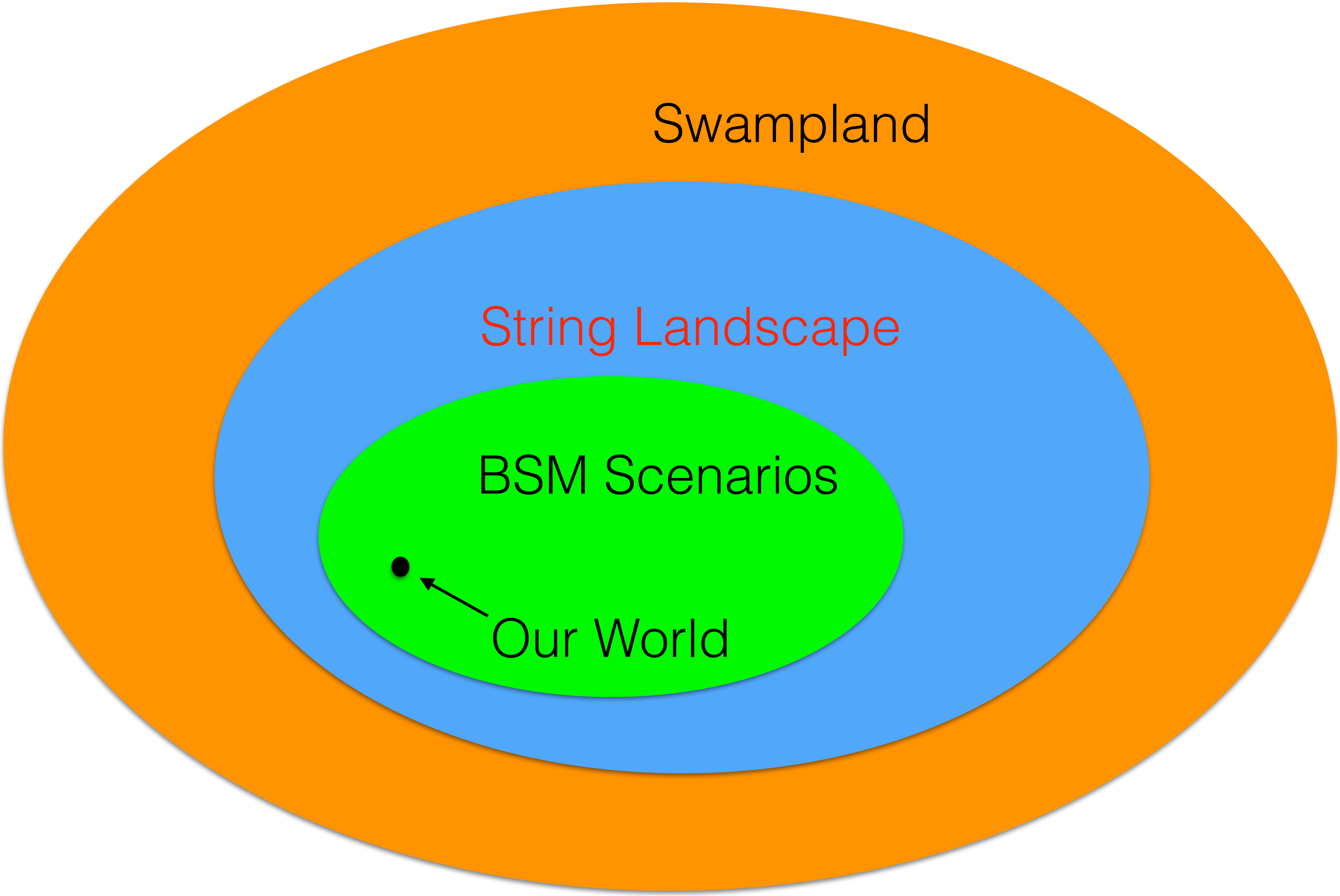


String Pheno and the Swampland



String Pheno and the Swampland



String Pheno and the Swampland

- What properties distinguish landscape and swampland?

  Swampland conjectures

- How do we test them?

  String tests

  Quantum gravity (black hole) arguments

- What are the implications for phenomenology? Are there BSM proposals that live in the swampland?

Outline

- No Global Symmetries
- **The Weak Gravity Conjecture**
  - **Axion-WGC and axion inflation**
- The non-SUSY AdS conjecture
- **The swampland distance conjecture**
- **The no de-Sitter conjecture**
- The AdS distance conjecture

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rigorous

speculative

Disclaimer

Many of the ideas in this talk are still quite speculative and controversial

Quantum Gravity and Global Symmetries

QG and Global Symmetries

- **Global symmetries** are expected to be violated in QG:

- **No hair theorem:** Hawking radiation is insensitive to Q.
  - ➡ Infinite number of states (remnants) with $m \lesssim M_p$
  - ➡ Breakdown of EFT (e.g. at finite temperature the density of states blows up)

Susskind '95

- **Swampland conjecture**: theories with exact global symmetries are not UV-completable.

- Proven in (perturbative) string theory and in AdS/CFT.

Banks, Dixon '88; Harlow, Ooguri '18

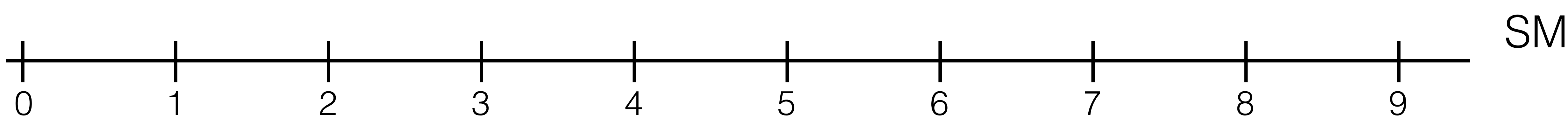
QG and Global Symmetries

- **Pheno application:** mini-charged Dark Matter

What if Dark Matter was not electrically neutral?

$$\mathcal{L} = -\frac{1}{4e} F_{\mu\nu} F^{\mu\nu} + A_\mu \left(J^\mu_{\rm SM} + \epsilon \, J^\mu_{\rm DM} \right)$$

- Mini-charge: $\varepsilon \ll 1$
- The SM charges are quantized (in units of e). DM charges are proportional to $\epsilon \, e$
- Imagine ϵ is irrational: charges are **not quantized.**



QG and Global Symmetries

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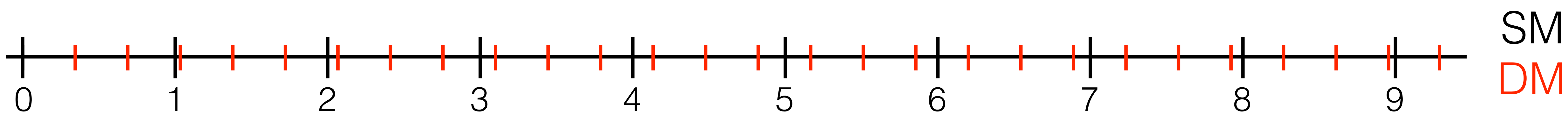
$$\mathcal{L} = -\frac{1}{4e} F_{\mu\nu} F^{\mu\nu} + A_\mu \left(J^\mu_{\rm SM} + \epsilon \, J^\mu_{\rm DM} \right)$$

- Mini-charge: $\varepsilon << 1$
- The SM charges are quantized (in units of e). DM charges are proportional to $\epsilon \, e$
- Imagine ϵ is irrational: charges are **not quantized.**



QG and Global Symmetries

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- Problem: the theory contains an **exact global symm.**

- Gauge symmetry:

$$\begin{aligned} A_\mu &\to A_\mu + e\, \partial_\mu \alpha \\ \Psi_{\rm SM} &\to e^{i\alpha}\, \Psi_{\rm SM} \\ \Psi_{\rm DM} &\to e^{i\epsilon\alpha}\, \Psi_{\rm DM} \end{aligned}$$

- Global symmetry:

$$\begin{aligned} A_\mu &\to A_\mu \\ \Psi_{\rm SM} &\to \Psi_{\rm SM} \\ \Psi_{\rm DM} &\to e^{i\beta}\, \Psi_{\rm DM} \end{aligned}$$

Every gauge invariant operator, is invariant under global β-transformations

Banks, Seiberg '10

QG and Global Symmetries

- **Pheno application:** mini-charged Dark Matter

What if Dark Matter was not electrically neutral?

$$\mathcal{L} = -\frac{1}{4e} F_{\mu\nu} F^{\mu\nu} + A_\mu \left(J^\mu_{\rm SM} + \epsilon\, J^\mu_{\rm DM} \right)$$

- Conclusion: simplest minicharged DM models $\in$ **Swampland**
- Possible ways out:
  - Small **rational** charges: $\epsilon \in \mathbb{Q}$ Unnatural
  - Gauge extra global symmetry $\Longrightarrow$ **New massless gauge boson**

$$\mathcal{L} = -\frac{1}{4e} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4\tilde{e}} \tilde{F}_{\mu\nu} \tilde{F}^{\mu\nu} + A_\mu \left(J^\mu_{\rm SM} + \epsilon\, J^\mu_{\rm DM} \right) + \tilde{A}_\mu\, J^\mu_{\rm DM}$$

Holdom ’86; Shiu, PS, Ye ‘13

The Weak Gravity Conjecture

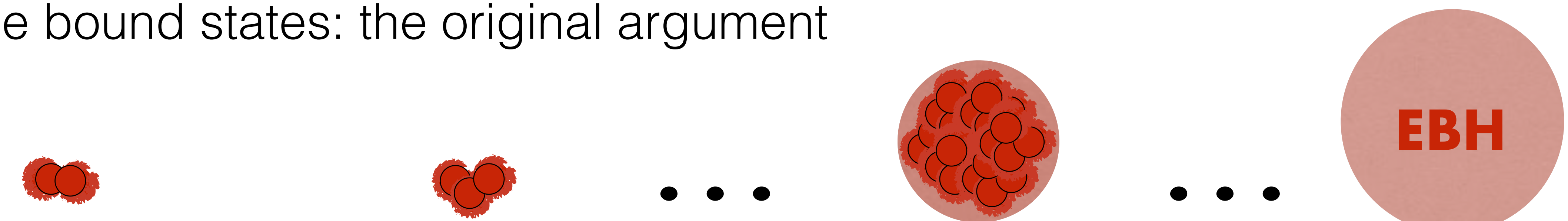
The Weak Gravity Conjecture

- We have argued that global symmetries are in conflict with Quantum Gravity
- Gauge symmetry at g=0 $\Rightarrow$ Global symmetry
  - It is not unreasonable to expect problems for gauge theories in the weak coupling limit: g -> 0
- When do things go wrong? How? …

The Weak Gravity Conjecture

- Take U(1) gauge theory with only one charged field with $m > q\, M_p$

- Stable bound states: the original argument



$2m > M_2 > 2q$ $\quad$ $3m > M_3 > 3q$ $\quad \cdots \quad$ $Nm > M_N > Nq$ $\quad \cdots \quad$ $M_\infty \to Q_\infty$

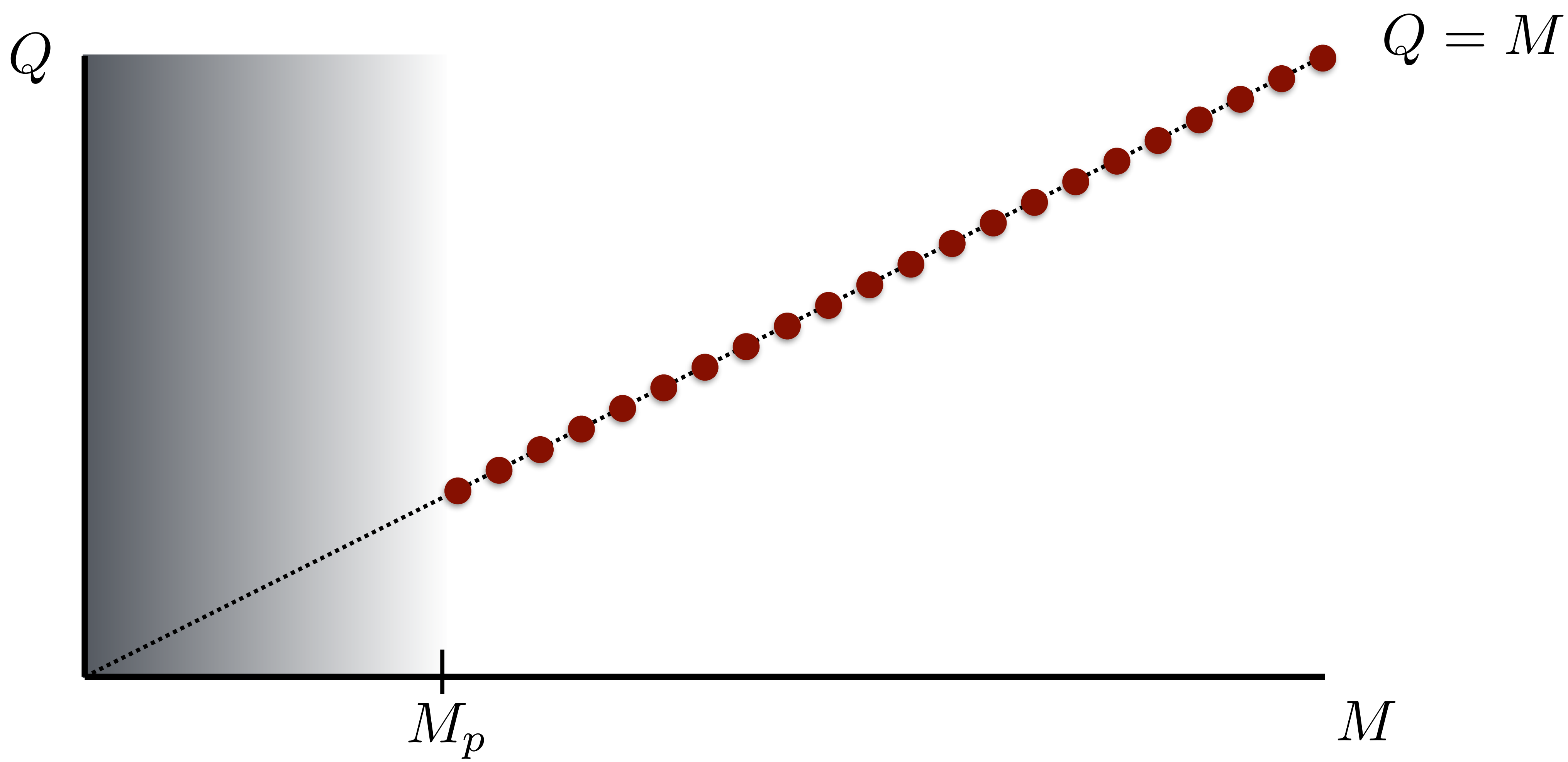
- All these states are **exactly stable**

- These *may* be problematic*****: in order to avoid them, one postulates the existence of some particle with

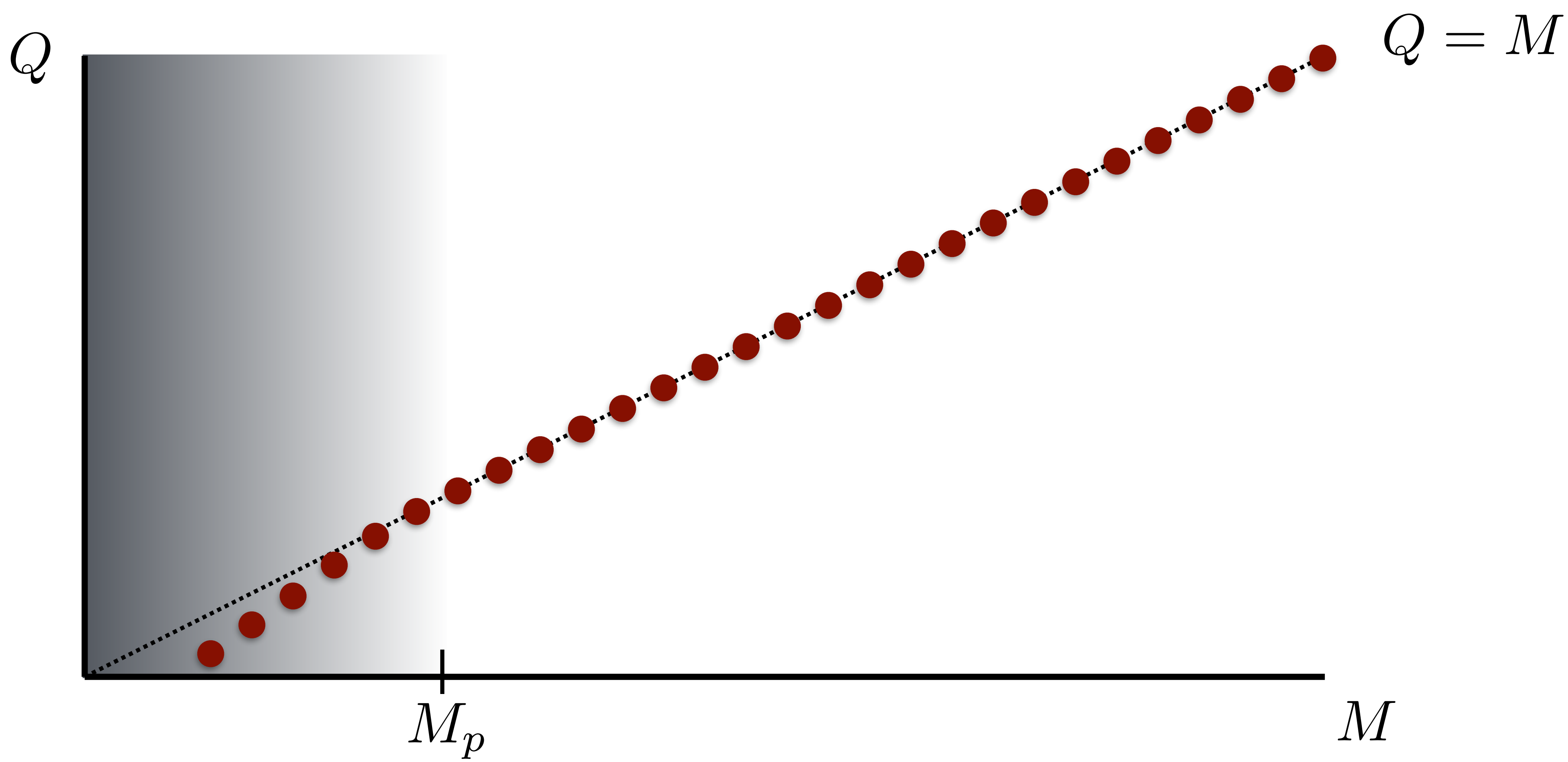
$$q\, M_p \geq m$$

"Gravity is the weakest force": Arkani-Hamed, Motl, Nicolis, Vafa '06

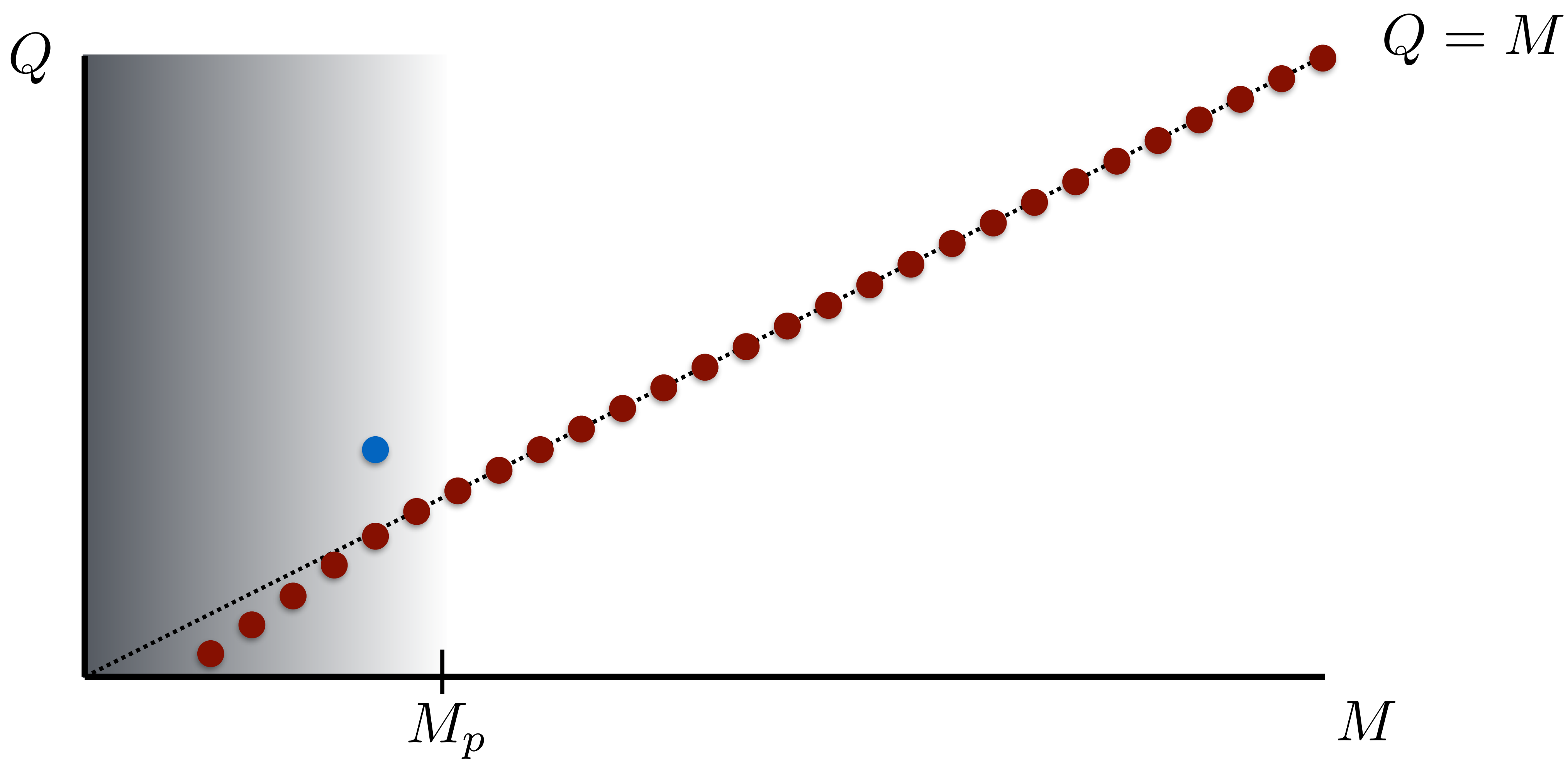
The Weak Gravity Conjecture



The Weak Gravity Conjecture

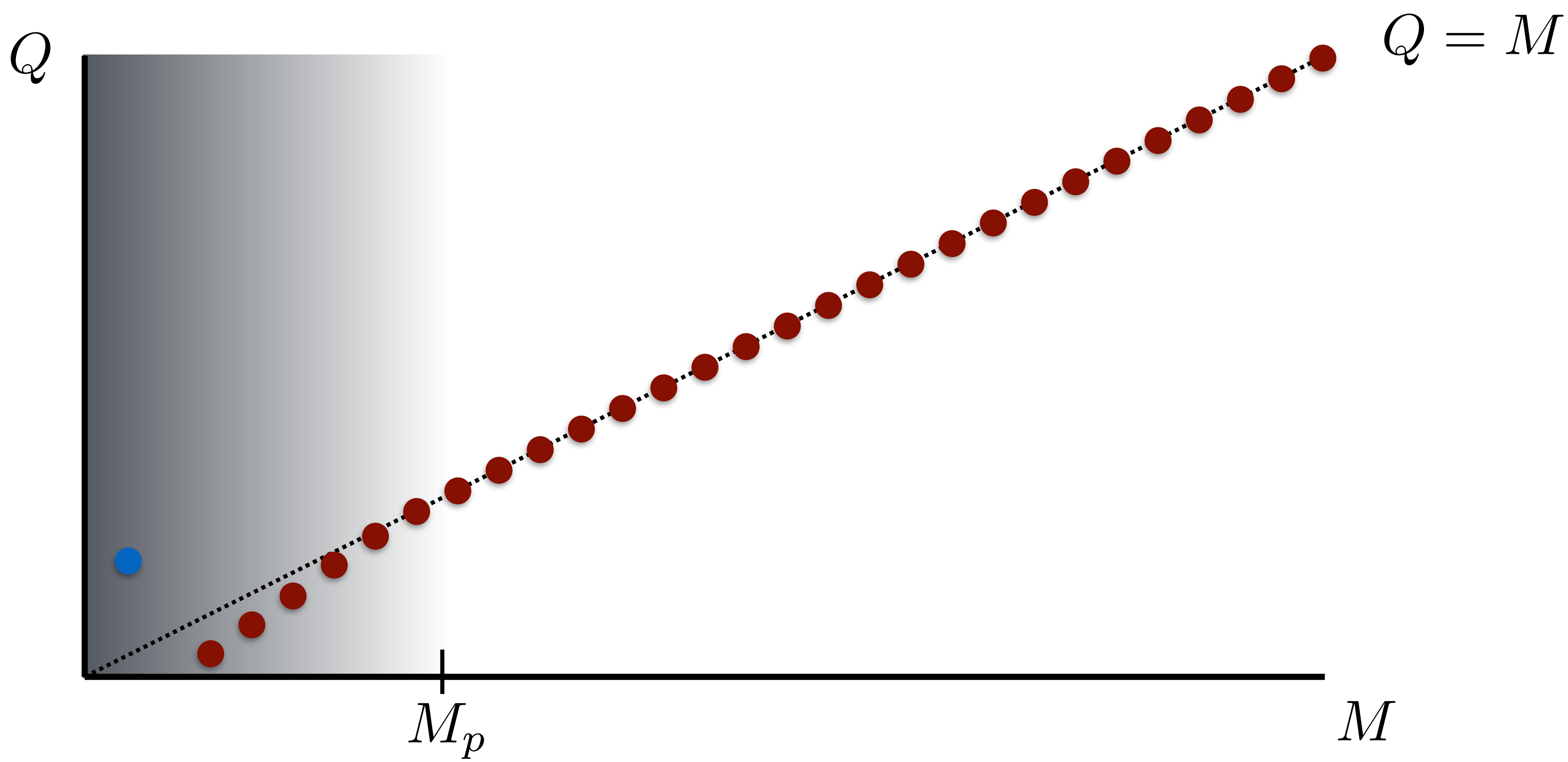


The Weak Gravity Conjecture



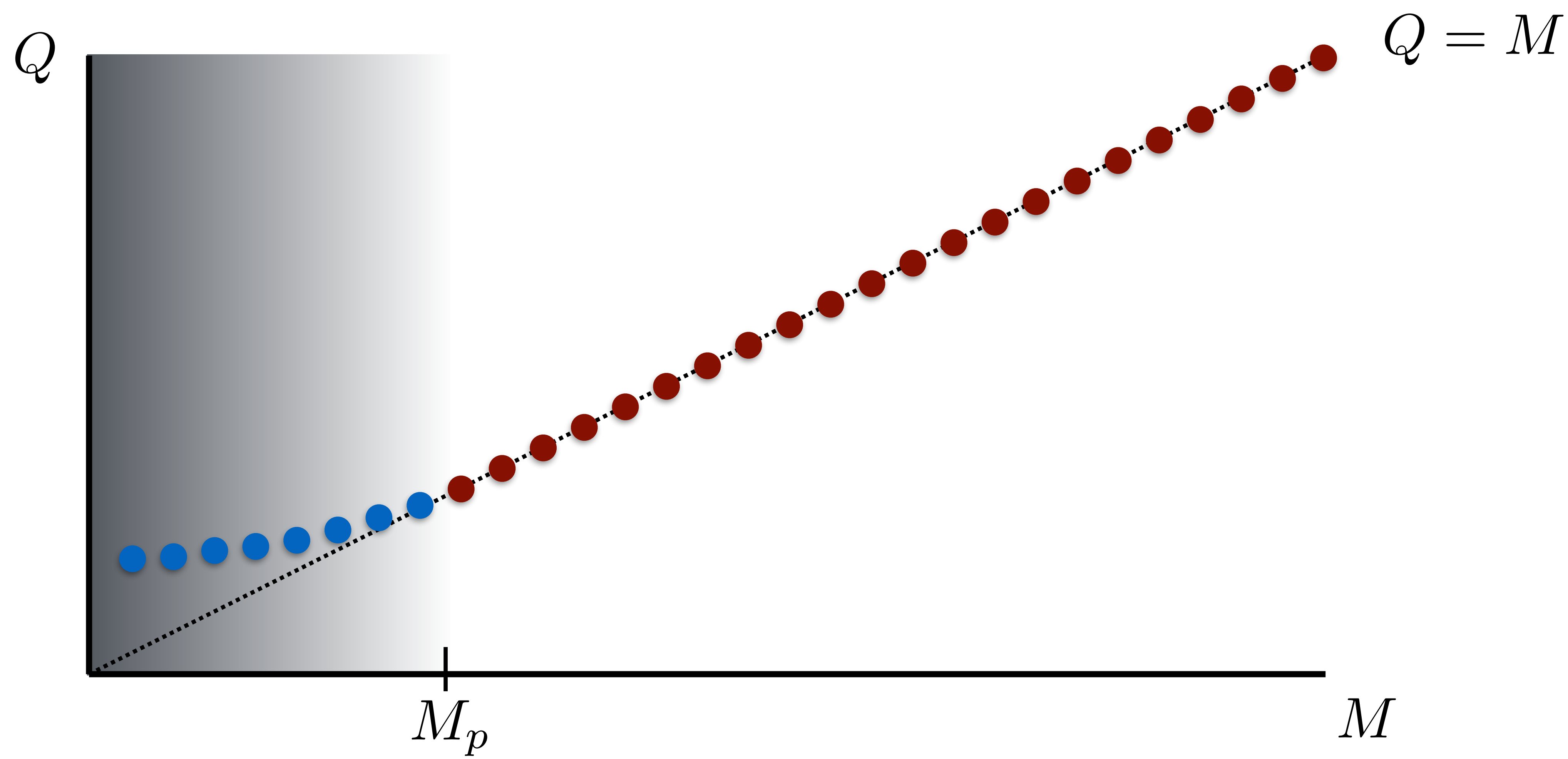
- "Mild" - WGC (does not constrain low energy EFT)

The Weak Gravity Conjecture



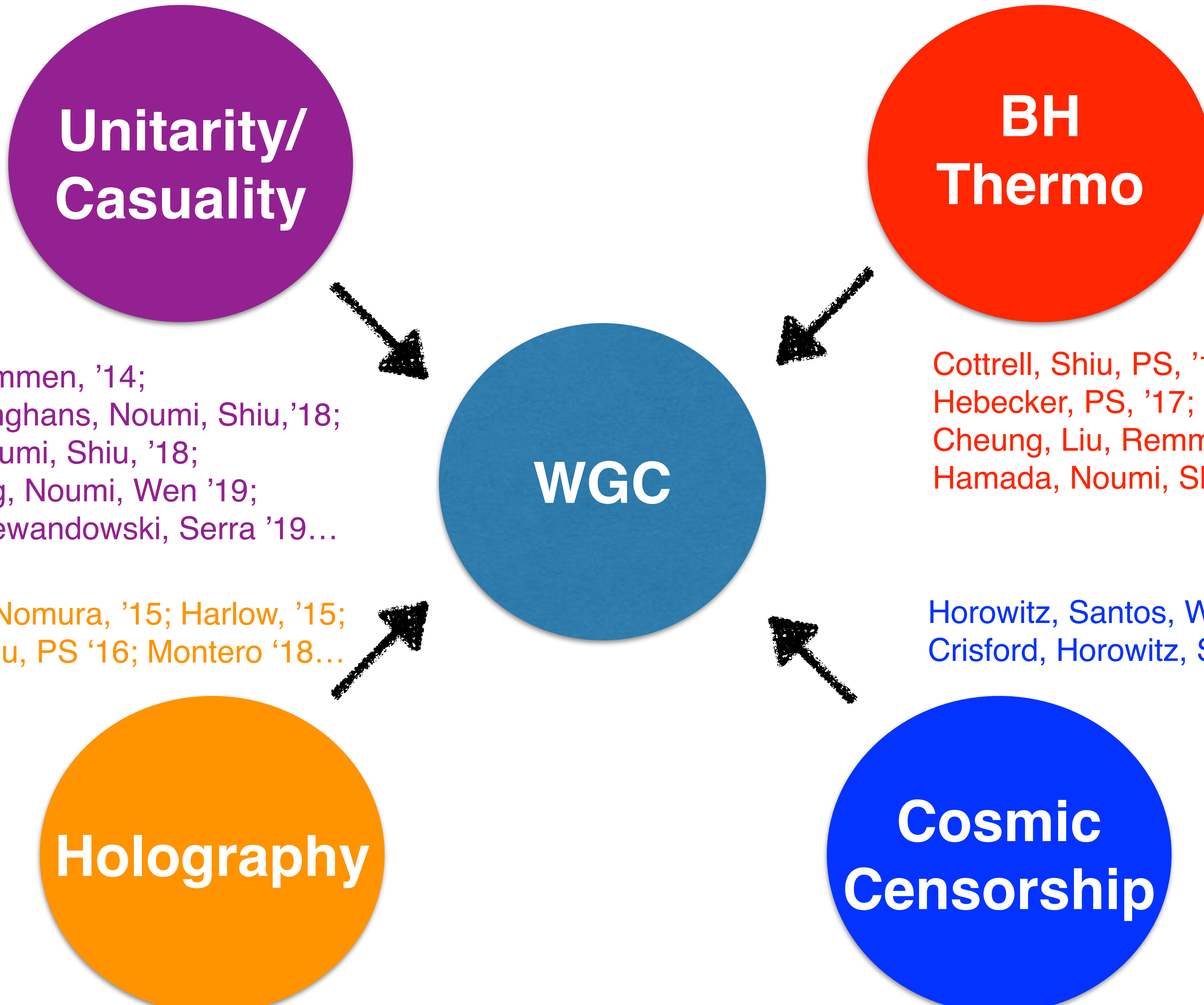
- “Strong” - WGC (important pheno implications)

The Weak Gravity Conjecture



- String theory seems to satisfy stronger versions of the WGC ("sub-lattice or tower WGC")

Evidence for the WGC



Cheung, Remmen, ’14;
Andriolo, Junghans, Noumi, Shiu,’18;
Hamada, Noumi, Shiu, ’18;
Chen, Huang, Noumi, Wen ’19;
Bellazzini, Lewandowski, Serra ’19…

Cottrell, Shiu, PS, ’16;
Hebecker, PS, ’17;
Cheung, Liu, Remmen, ’18, ‘19;
Hamada, Noumi, Shiu, ’18; …

Nakayama, Nomura, ’15; Harlow, ’15;
Montero, Shiu, PS ‘16; Montero ‘18…

Horowitz, Santos, Way, ’16;
Crisford, Horowitz, Santos, ’17; …

The WGC for axions

WGC and axions

- U(1) gauge theory in 5d compactified on a circle to 4d:

	5d theory		4d theory
Fields	$A_M(x, x_4)$	$\longrightarrow$	$(A_\mu(x), \phi(x))$
Action	$S = \int d^5x \, \frac{-1}{4g_5^2} F_{MN} F^{MN}$	$\longrightarrow$	$\int d^4x \left(\frac{-1}{4g_4^2} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi \right)$
Symmetries	$A_M \sim A_M + \partial_M \lambda$	$\longrightarrow$	$A_\mu \sim A_\mu + \partial_\mu \lambda \, , \; \phi \sim \phi + c$

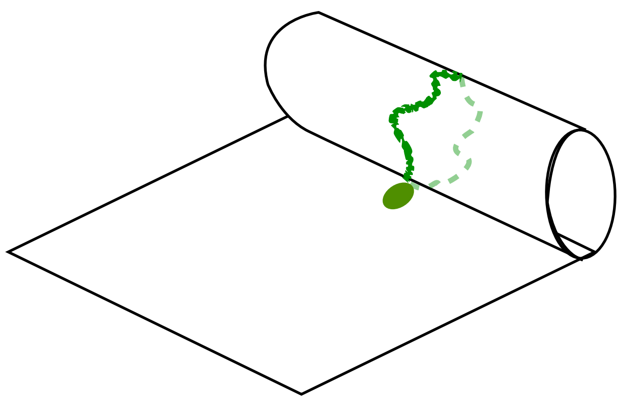
ϕ is an axion

How is V(ϕ) generated?

Charged matter $\longrightarrow$ Charged matter + **Instantons**

ALPs in string theory: a toy model

- Consider a 5d particle with mass ‘m_5’ and charge ‘q_5’ whose (Euclidean) worldline wraps the compact dimension



- This particle sources the axion and is localized to a point in 4d spacetime, i.e. it is an **instanton**:

$$V(\phi) \sim e^{-S_{inst}} \cos\left(\frac{\phi}{f}\right)$$

$$S_{inst} = 2\pi R m_5$$
$$f = q_5\sqrt{2\pi R}$$

- The 5d WGC for charged particles $m_5 < q_5 M_{p,5d}^3$ translates into:

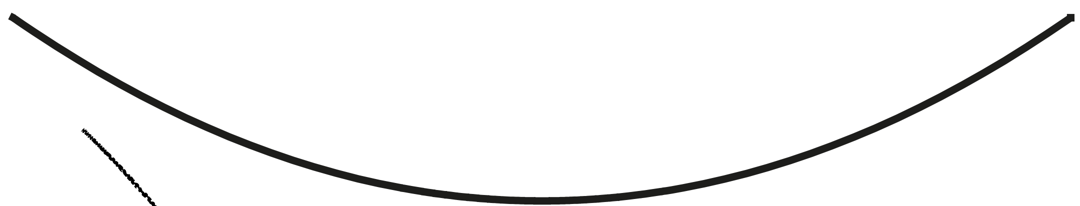
$$f \cdot S_{inst} \leq M_p$$

Phenomenological application:

Axion inflation

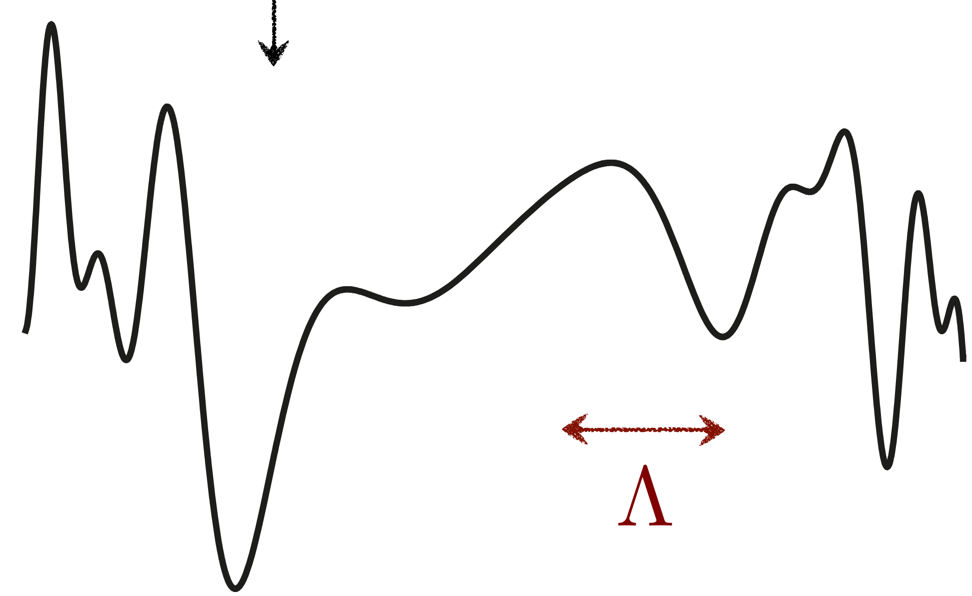
WGC and axion inflation

UV sensitivity of large field inflation: $\Delta\phi > M_P$



$$\mathcal{L}_{\text{eff}}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\left(1 + \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}} + \cdots\right)$$

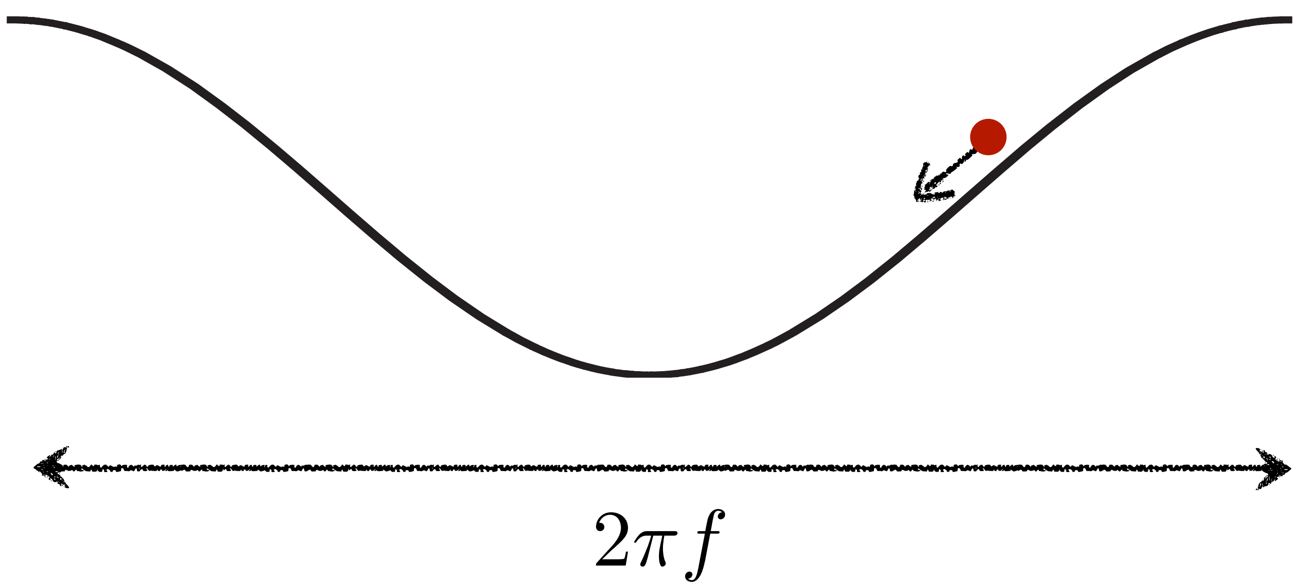
$c_i \sim \mathcal{O}(1)$



WGC and axion inflation

- Inflation with axions:

$$V(\phi) \propto e^{-S_{inst}}\left[1-\cos\left(\frac{\phi}{f}\right)\right]+\sum_{k>1} e^{-kS_{inst}}\left[1-\cos\left(\frac{k\phi}{f}\right)\right]$$



- Simplest natural inflation: slow roll and pert. control

$$f > M_p\,,\quad e^{-S_{inst}} \ll 1 \quad\Longrightarrow\quad \boxed{f\cdot S_{inst} > M_p}$$

Non-SUSY AdS conjecture

Non-SUSY AdS conjecture

- Extremal branes contain AdS_p (x S) factors in their near horizon geometries supported by flux

- The WGC implies that such backgrounds must be unstable against emission of super-extremal WGC-states.

    - WGC corollary: non-SUSY AdS spaces supported by flux are unstable

- This conclusion lead [Ooguri, Vafa '16] to conjecture

    - **Non-SUSY AdS conjecture:** any non-SUSY AdS space must exhibit some instability

- This would have important implications for non-SUSY AdS/CFT and under further assumptions for particle (neutrino) physics

Ibanez, Martin-Lozano, Valenzuela '17; Hamada, Shiu '17; Gonzalo, (Herraez), Ibanez '18

The swampland distance conjecture

Swampland distance conjecture

- String compactifications contain numerous scalar fields (moduli) whose vev control the couplings of the theory.

- Consider a circle compactification to d-dimensions of perturbative string theory (M_p=1)

  - Canonically normalized radius modulus ϕ is $R \sim e^{\beta\phi}$ with β~O(1)

  - Moving in moduli ϕ-space changes the spectrum of the theory

KK modes: $$M_k^2 \sim \left(\frac{k}{R}\right)^2 \left(\frac{1}{R}\right)^{\frac{2}{d-2}} \sim k^2 e^{-\alpha\phi}$$

Winding modes: $$M_w^2 \sim (wR)^2 R^{\frac{2}{d-2}} \sim w^2 e^{\alpha\phi}$$ $(\alpha \sim \mathcal{O}(1))$

- Both at large ($\phi \to \infty$) and small ($\phi \to -\infty$) radius there is an infinite tower of states that becomes exponentially light

Swampland distance conjecture

- Such behaviour is very generic in string theory, leading to

Swampland Distance Conjecture: given two points ‘p’ and ‘q’ in moduli space separated by a distance $d_{p,q} \gg M_p$ there exists an infinite tower of states with mass scale

$$M(q) < M(p) e^{-\alpha \frac{d_{p,q}}{M_p}}$$

with $\alpha \sim \mathcal{O}(1)$

Ooguri, Vafa ‘16

Swampland distance conjecture

- Remarks
  - The swampland distance conjecture has been confirmed extensively in asymptotic limits of moduli space $d \to \infty$

    Grimm, Palti, Valenzuela ’18; Grimm, Li, Palti ’18, Corvilain, Grimm, Valenzuela ’18; Blumenhagen, Kläwer, Schlechter, Wolf ’18; Hebecker, Junghans, Schachner ’18; Joshi, Klemm ’19; Lee, Lerche, Weigand ’19;…

  - The tower of light states is expected to arise already when $d \gtrsim M_p$
  - It is expected to hold in the presence of a potential V(ϕ)

  } “Refined distance conjecture”

  Baume, Palti ’16; Klaewer, Palti ’16

- If correct, EFT cannot be trusted upon trans-Planckian displacements of scalar fields
  - Would strongly constrain models of large field inflation

Ongoing debate

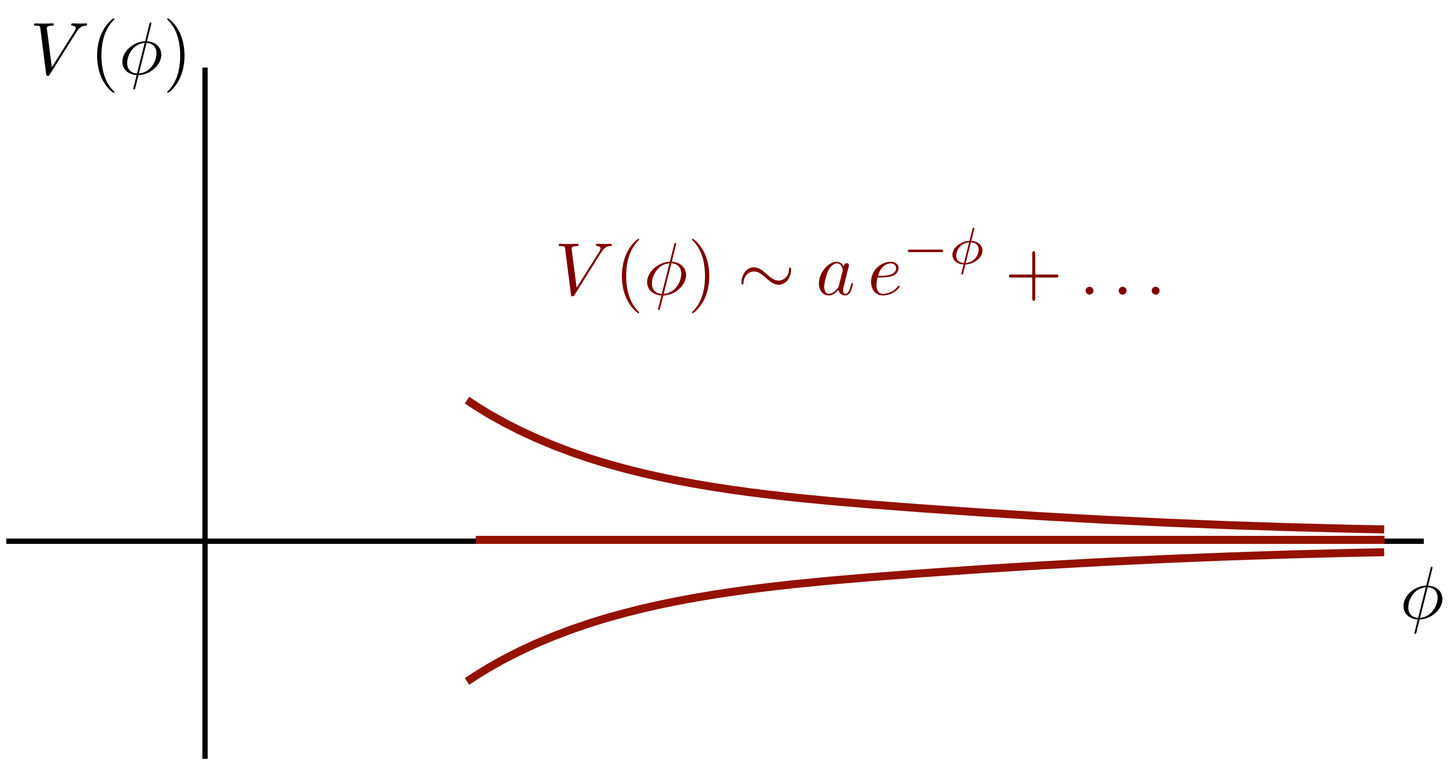
dS vacua and the swampland

dS and the swampland

- It is notoriously difficult to obtain string dS vacua.
- The difficulty can be traced back to the **Dine-Seiberg problem**:

  In string theory, there are no free parameters: coupling constants are vevs of scalar fields (moduli), e.g. $g_s = e^{-\phi}$

  At weak coupling ($\phi \to \infty$), vacuum energy vanishes



- V>0: runaway (quintessence?)
- V=0: flat (massless ϕ)
- V<0: roll to strong coupling

Dine, Seiberg '85

dS and the swampland

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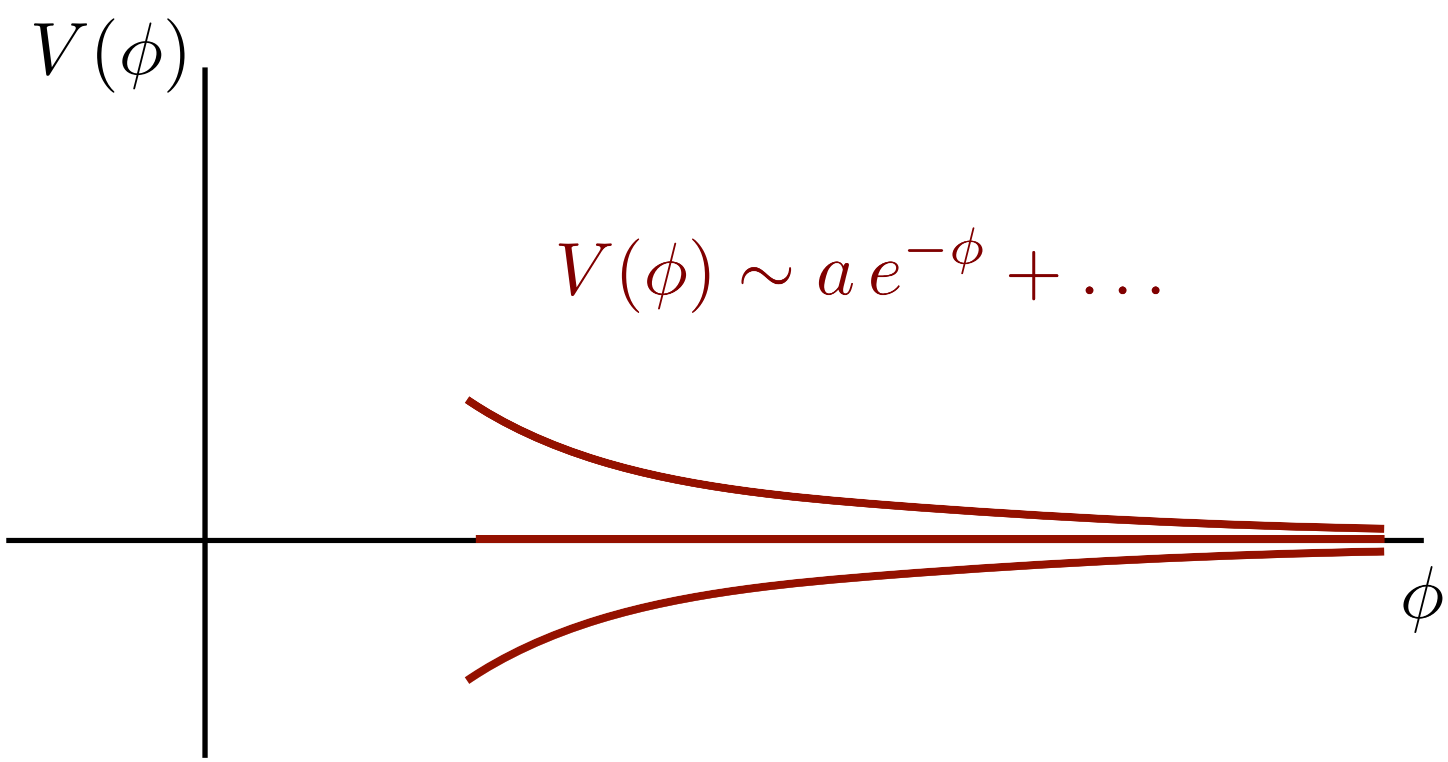


- No vacuum (either AdS, Mink, or dS) at **parametrically** weak coupling exists!

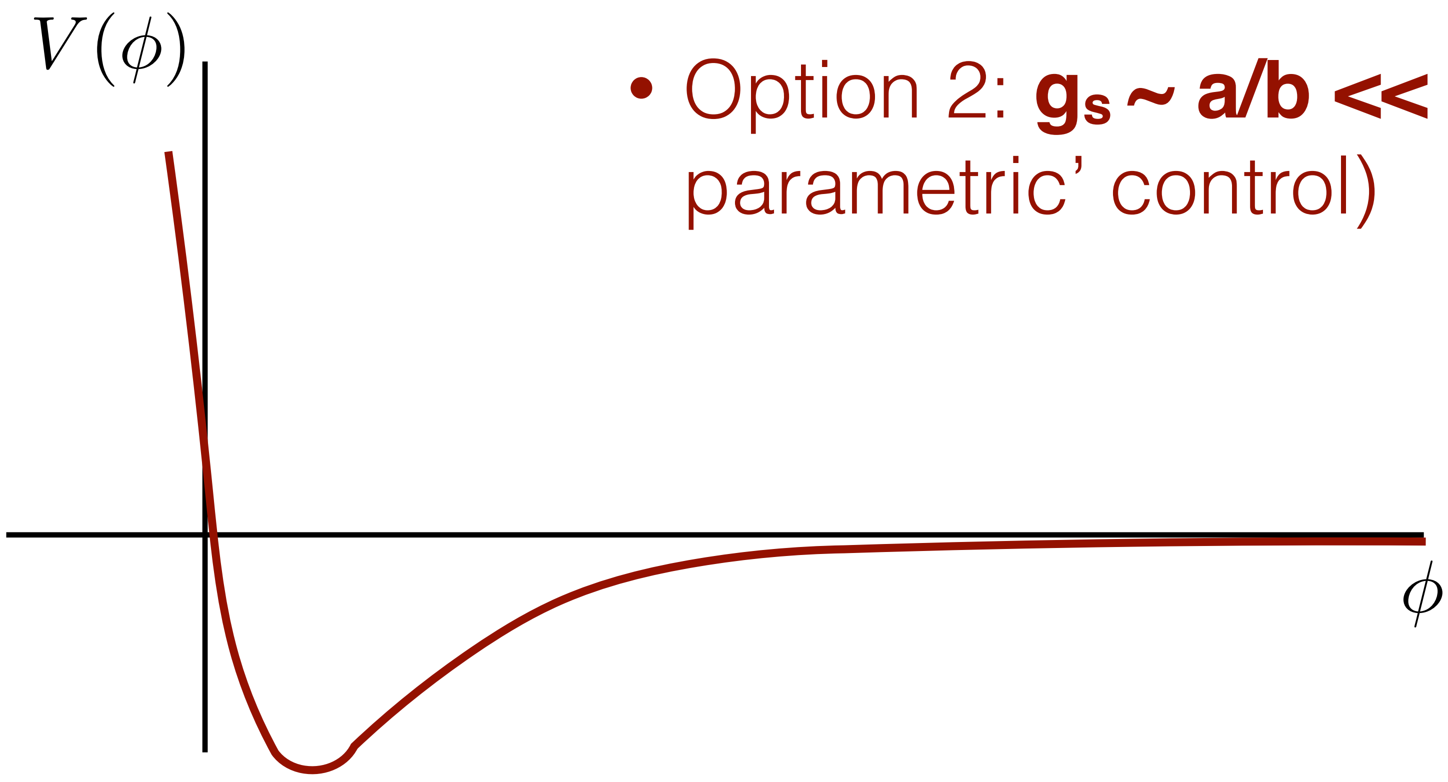
Dine, Seiberg '85

dS and the swampland

- To find a minimum, one needs higher order corrections in the potential, but then perturbativity is endangered

$$V(\phi) = -a\, e^{-\phi} + b\, e^{-2\phi} + \dots \qquad \Longrightarrow \qquad g_s = e^{-\phi_0} = \frac{a}{2b}$$

- Option 1: $g_s \sim a/b \sim 1$ strong coupling (no control)!
- Option 2: **$g_s \sim a/b << 1$** AdS at small coupling ('non-parametric' control)

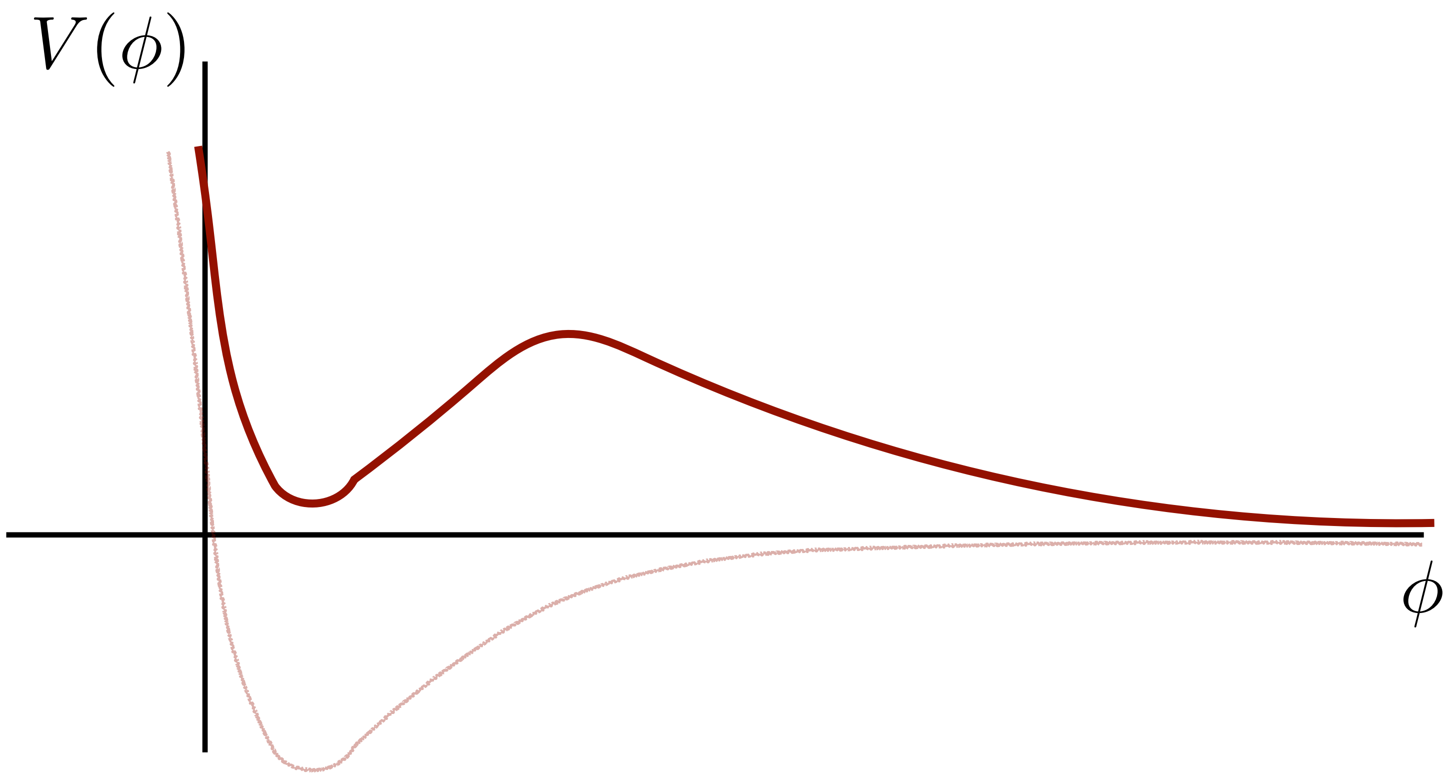


dS and the swampland

- To find a minimum, one needs higher order corrections in the potential, but then perturbativity is endangered

$$V(\phi) = a\, e^{-\phi} - b\, e^{-2\phi} + c\, e^{-3\phi} + \ldots$$

- With one more term, one can obtain potentials with dS minima at $g_s << 1$. Not ideal, but who said it should be?



Moduli stabilization and constructions of vacua (AdS or dS) exploit this mechanism

GKP '01, KKLT '03, LVS '05

dS and the swampland

- Recent suggestion: in every direction in moduli space, the potential must satisfy **asymptotically**

$$|\nabla V(\phi)| \geq \alpha V \qquad\qquad \alpha \sim \mathcal{O}(1)\,,\ \phi \to \infty$$

Obied, Ooguri, Spodyneiko, Vafa '18

This behaviour arises naturally in string theory, and is required asymptotically by the distance conjecture. Ooguri, Palti, Shiu, Vafa '18

- **De Sitter swampland conjecture:** this must hold (with minor qualifications) throughout moduli space, forbidding dS vacua.

dS vacua (KKLT, LVS)	vs.	dS swampland conjecture
Necessarily complicated Vacuum energy		Simple but speculative Quintessence

Lively ongoing debate

AdS distance conjecture

AdS distance conjecture

- The most rigorously stablished AdS solutions of string theory take the form $AdS_p \times X_q$, with the radius of AdS of the same order as the radius of X (as in AdS_5 x S^5)

  There is no gap between Λ and the massive KK states

  Λ -> 0 corresponds to Vol(X) -> ∞ . This is an infinite distance in moduli space, and comes with a tower of light states

- **AdS distance conjecture**

  Any theory of Quantum Gravity in AdS spacetime contains a tower of states with mass scale (M_p=1)

$$m \sim |\Lambda|^\alpha$$

($\alpha = 1/2$ in SUSY)

Lüst, Palti, Vafa '19

- This is in contrast with some proposed AdS string vacua

KKLT '03, DeWolfe et al. '05,...

Further topics & Summary

Further topics

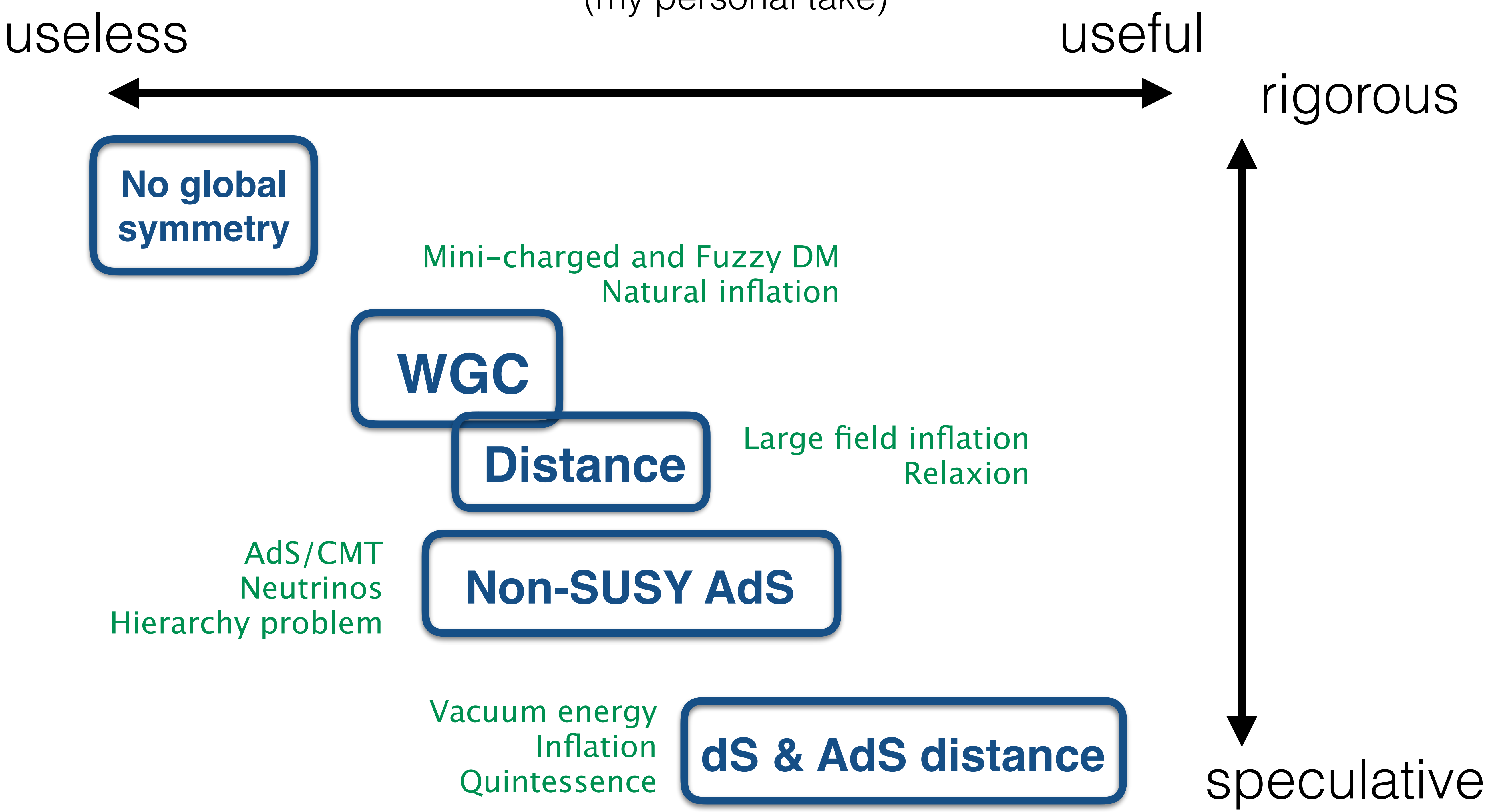
- Further swampland conjectures and refinements
  - Completeness in QG, moduli space conjectures, magnetic-WGC and (species) cutoffs, scalar-WGC, Stuckelberg conjectures…
- The emergence proposal and the swampland
- Phenomenological applications
  - Mini-charged & Fuzzy DM, natural inflation, axion monodromy and large field inflation, relaxion, cosmological constant and quintessence, massive gravity, neutrino physics, AdS/CMT…
- Swampland tests in quantum gravity and in string theory

See Palti '19 for many more details and references

The Ooguri chart

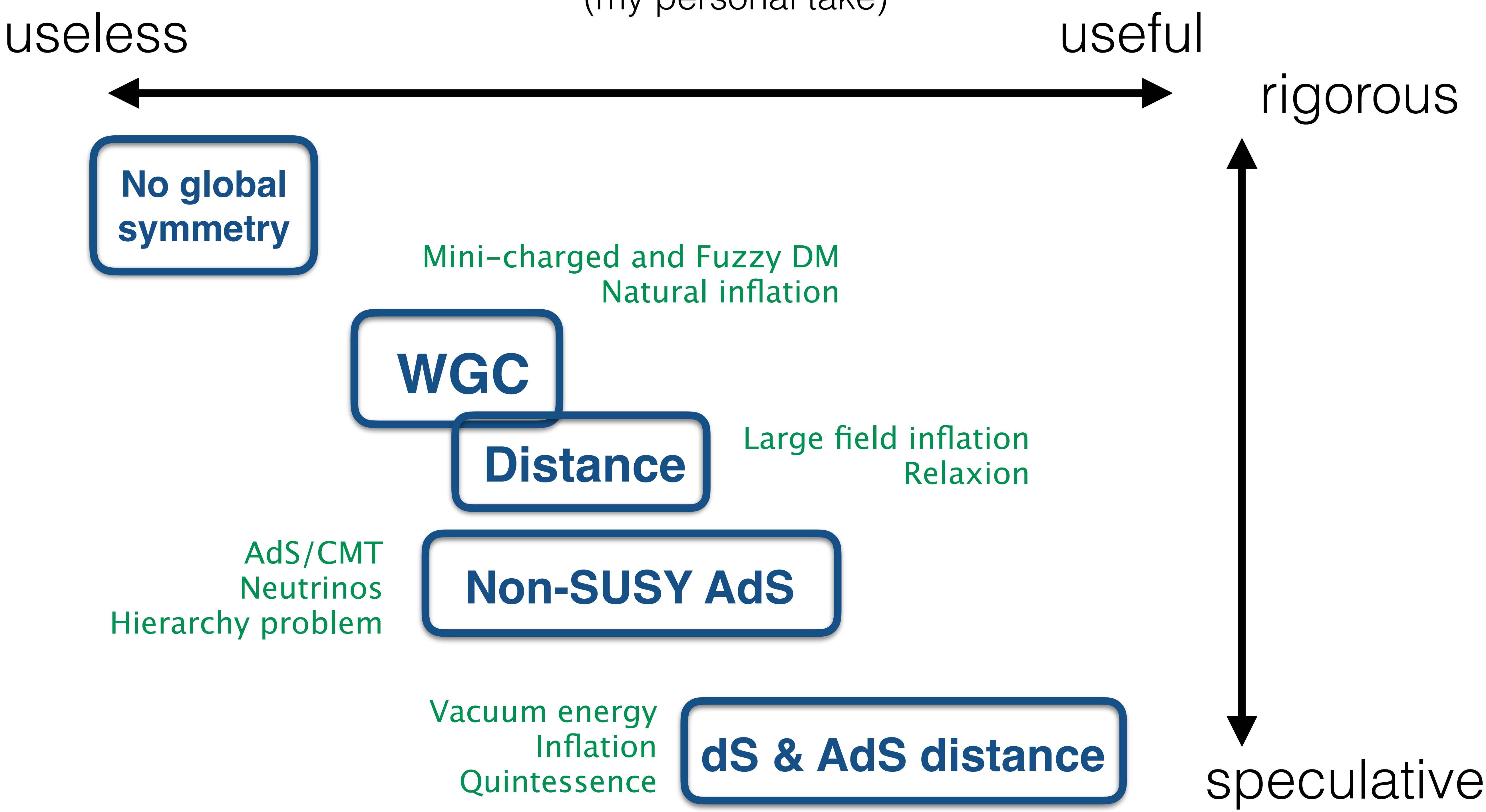
The Ooguri chart

(my personal take)



The Ooguri chart

(my personal take)



- Much work remains to be done to fully understand the origin and consequences of these conjectures.

Stay tuned!

The Ooguri chart

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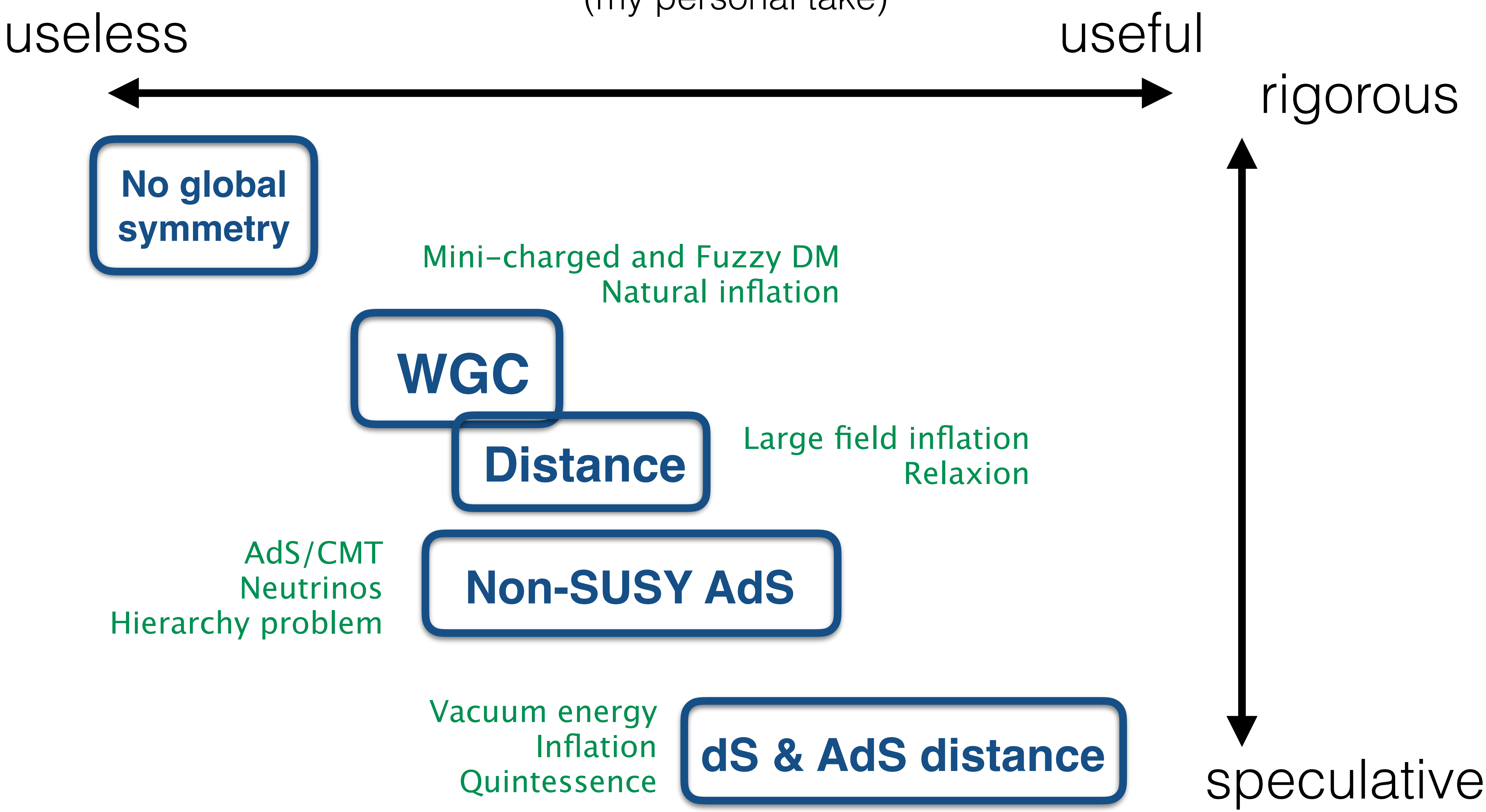
(my personal take)



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