REVIEW:
THE SWAMPLAND PROGRAM

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REVIEW:
THE SWAMPLAND PROGRAM

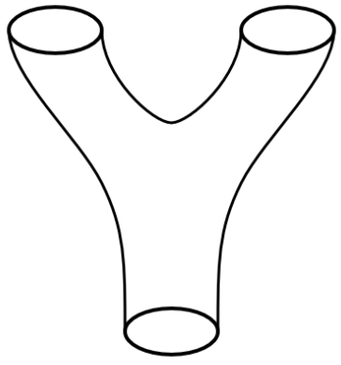
OUTLINE:

- Introduction & Motivation
- Overview of some "Swampland Conjectures"

LITERATURE:

- Eran Palti,
  "The Swampland: Introduction and Review,"
  arXiv:1903.06239.
- Irene Valenzuela et al.,
  "Lectures on the Swampland Program in String Compactifications,"
  arXiv:2102.01111.

STRING THEORY



➤ String Theory:

Consistent Theory of

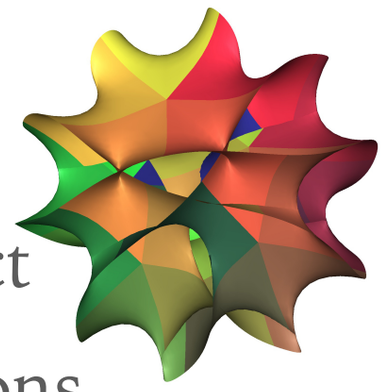
Quantum Gravity

➤ Caveat:

Mathematical Consistency → 10 spacetime dimensions

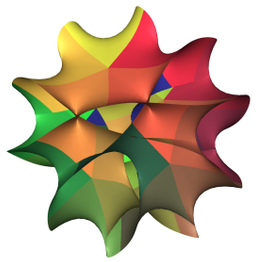
➤ Compactification:

4D physics from 10D string theory ← 6 small + compact "internal" dimensions



STRING THEORY LANDSCAPE

Compactification geometry:



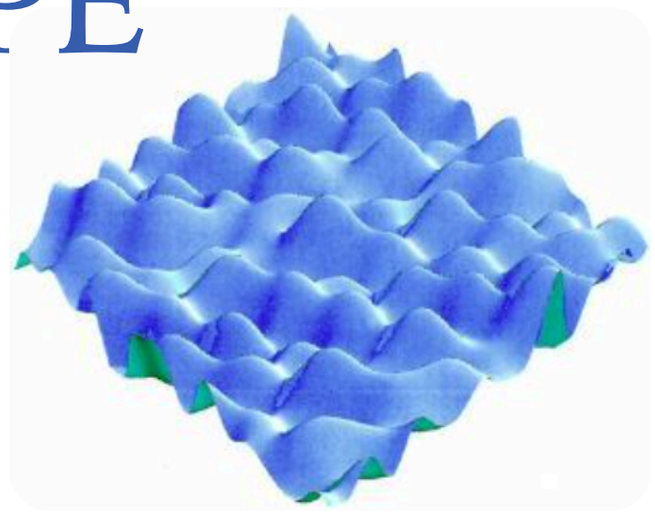
many possible choices

(e.g. Calabi-Yau geometries)

→ each has different 4D physics

➜ $\mathcal{O}(10^{500})$ string theory vacua & effective 4D models

THE LANDSCAPE



PREDICTIONS FROM THE LANDSCAPE?

- Problem:

Which vacuum do we live in?

- Realistic string theory vacua:
  - Standard model gauge group + matter
  - Dark energy: Small, positive cosmological constant
  - Dark matter
  - Inflation
  - Supersymmetry breaking
  - etc.

How to find such vacua?

Predictability?

Do they exist at all?

Anthropic principle?

STRING INSPIRED MODEL BUILDING

- Idea: try to solve these problems individually!

- Combine characteristic features of string compactifications (e.g. susy, extra-dimensions, …) in 4d-EFT language

Hope: Enormous size of the Landscape → High probability that a given "string inspired" model exists!

More systematic approach:

Which consistent (e.g. anomaly free) EFTs can be realized in the String Theory Landscape?

Maybe all?
Answer: No! → *Swampland Program!*

THE SWAMPLAND IDEA

Constraints on Effective Field Theories (EFTs)
that can be consistently obtained from
String Theory

Landscape: EFTs with a String Theory origin

Swampland: seemingly consistent EFTs
that do not arise from String Theory

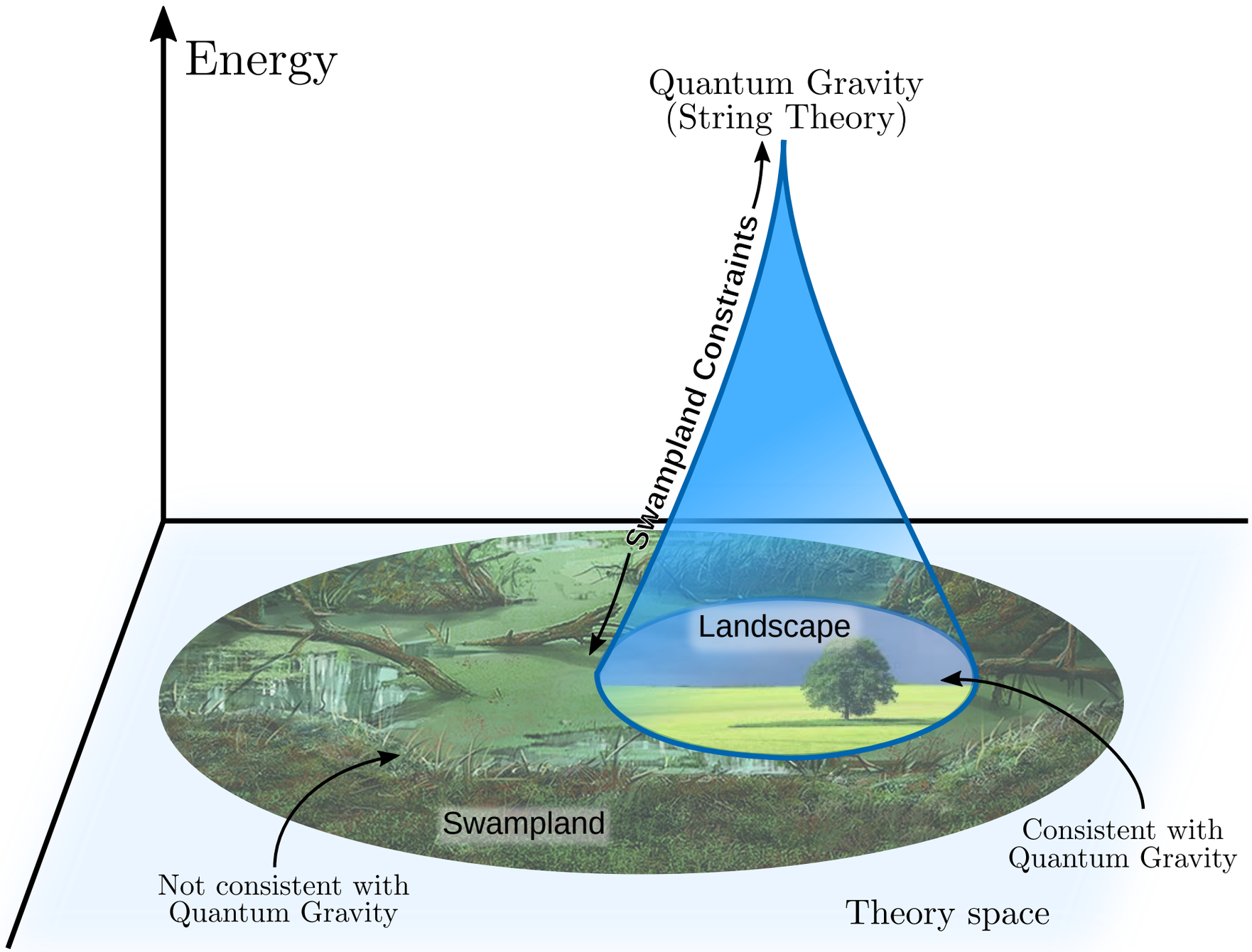
THE SWAMPLAND IDEA

Constraints on Effective Field Theories (EFTs)
that can be UV completed to
Quantum Gravity

Landscape: EFTs with a Quantum Gravity UV completion

Swampland: seemingly consistent EFTs
that do not arise from Quantum Gravity

SWAMPLAND & LANDSCAPE



(taken from [van Beest, Calderón-Infante, Mirfendereski, Valenzuela '21])

SWAMPLAND CONJECTURES

Constraints that determine which
Effective Field Theories allow for a
String Theory or Quantum Gravity
UV-completion

How to obtain Swampland Conjectures?

Top-Down: Inspection of known String Theory examples.

Bottom-Up: Consistency arguments from semi-classical black holes.

SOME SWAMPLAND CONJECTURES

NO GLOBAL SYMMETRIES

[Banks, Dixon '88]
[Banks, Seiberg '10]

Conjecture:

There are no exact global symmetries in Quantum Gravity.

→ All symmetries must be only approximate or gauged!

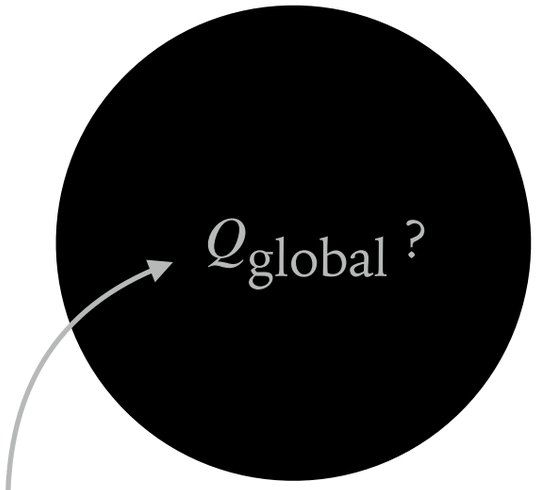
Motivation:

"No-hair theorem"

Properties of black-holes detectable from the outside:

- Mass
- angular momentum
- gauge (!) charge

Black hole:



global charge:
arbitrary + invisible

→ infinite entropy?!

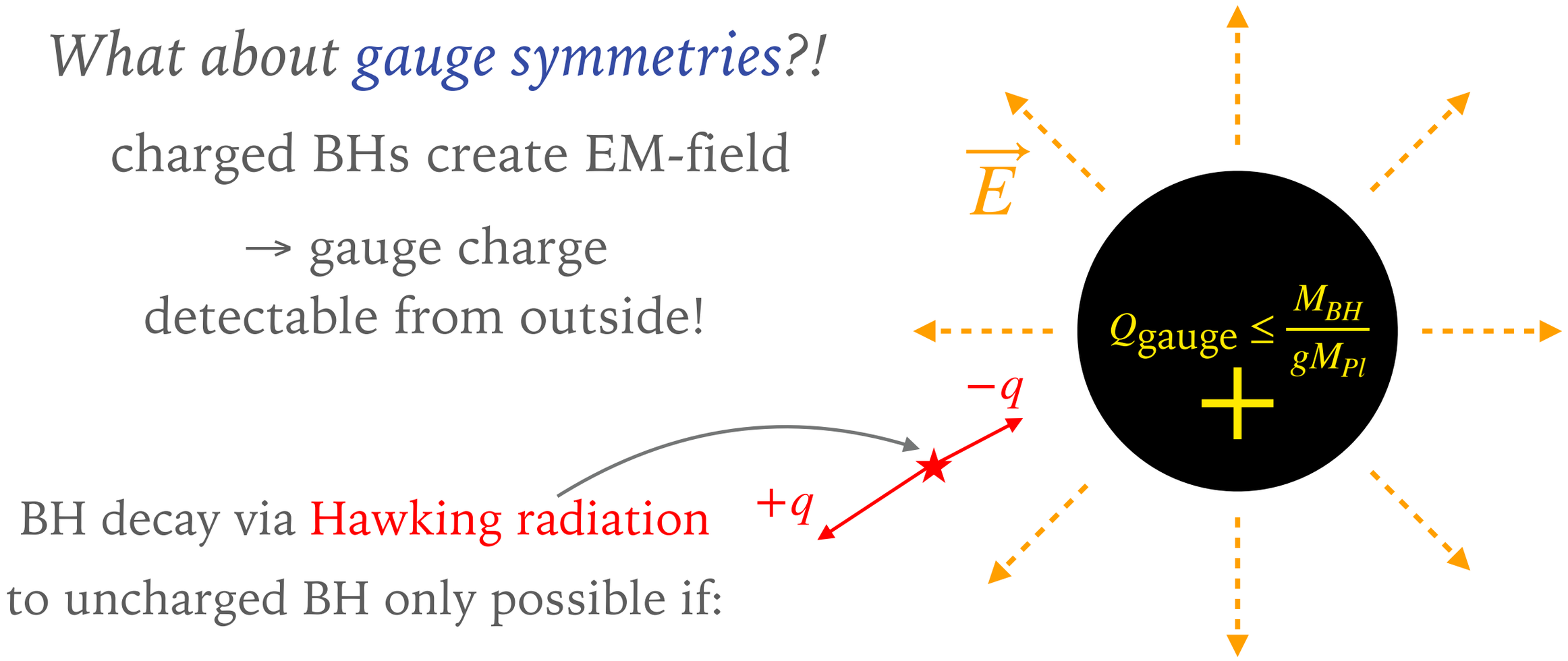
THE WEAK GRAVITY CONJECTURE

[Arkani-Hamed, Motl, Nicolis, Vafa '06]

What about gauge symmetries?!

charged BHs create EM-field

→ gauge charge
detectable from outside!



BH decay via Hawking radiation
to uncharged BH only possible if:

Weak Gravity Conjecture:

There exists at least one state with a charge to mass ratio

$$\frac{|q|}{m} \geq \frac{1}{g\, M_{Pl}} \,.$$

MAGNETIC WEAK GRAVITY CONJECTURE

[Arkani-Hamed, Motl, Nicolis, Vafa '06]

Can we recover a global symmetry from a gauge symmetry by sending

$$g \to 0 \qquad ?$$

Apply the Weak Gravity Conjecture to magnetic monopoles:

mass of a monopole (instanton) in EFT:

$\exists$ monopole with: $\quad m_{mag} \lesssim g_{mag} M_{pl} \sim \dfrac{M_{Pl}}{g_{el}}$ $\qquad\qquad$ $m_{mag} \sim \dfrac{\Lambda_{EFT}}{g_{el}^2}$

Magnetic Weak Gravity Conjecture:

> The cut-off scale of the EFT is bounded by
> $$\Lambda_{EFT} \leq g M_{Pl} \, .$$

$\Rightarrow g \to 0$ is not possible!

COUPLING CONSTANTS AND SCALAR FIELDS

[Ooguri, Vafa '06]

String theory:

dynamical gauge couplings: VEVs of scalar fields:

$$g \sim e^{-\langle\phi\rangle}$$

Conjecture:

There are no dimensionless coupling constants in Quantum Gravity.

What happens in the limit

$\phi \to \pm\infty$ *?!*

Expectation from Weak Gravity Conjecture:

Breakdown of the EFT:

$\Lambda_{EFT} \to 0$

INFINITE DISTANCE CONJECTURE

[Ooguri, Vafa '06]

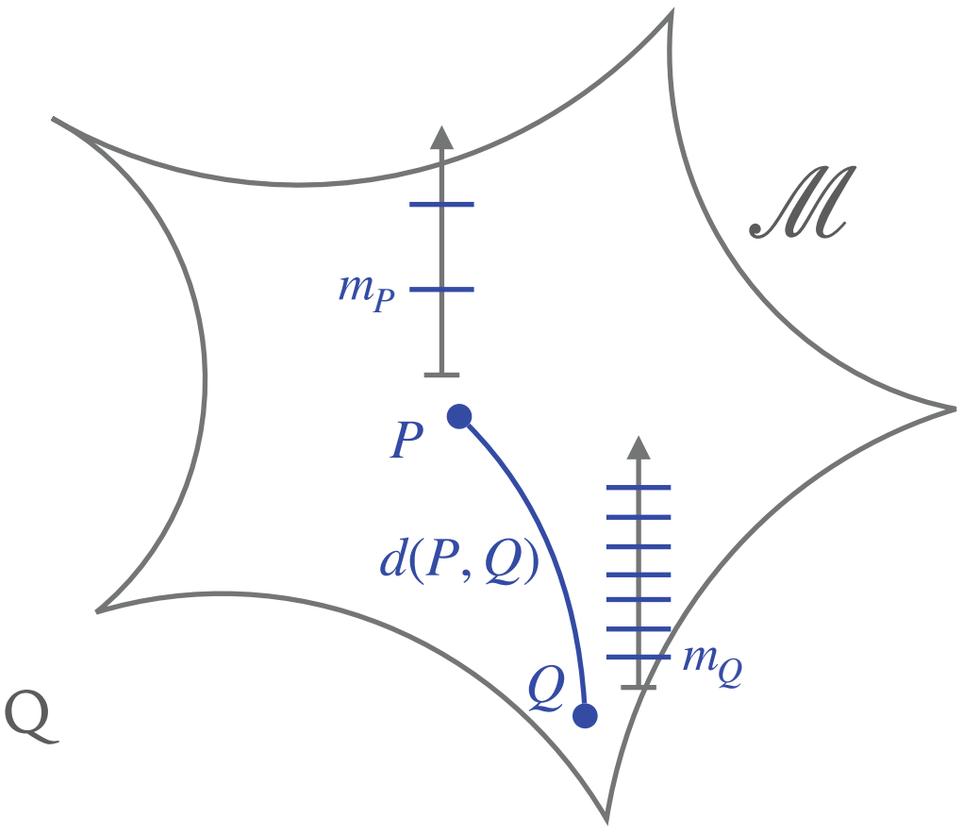
σ-model Lagrangian:

$$\mathscr{L} \supset - g_{ij}(\phi)\partial_\mu \phi^i \partial^\mu \phi^j$$

g_{ij}: metric on $\mathscr{M}$

ϕ^i: coordinates on $\mathscr{M}$

Scalar field space / Moduli space:



use g_{ij} to define distances:

$d(P,Q)$: geodesic distance between P and Q

Infinite Distance Conjecture:

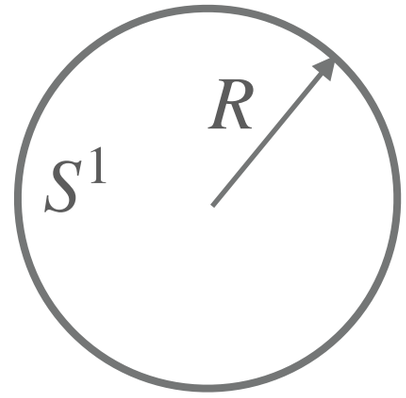
There is an infinite tower of states that becomes exponentially light at any infinite field distance limit

$$m_Q \sim m_P\, e^{-\lambda\, d(P,Q)} \quad \text{for} \quad d(P,Q) \to \infty$$

INFINITE DISTANCES AND COMPACTIFICATION

- Example: Kaluza-Klein Theory on a circle

$$M_d = M_{d-1} \times S^1$$



- Tower of Kaluza-Klein modes:

$$m_n \sim \frac{n}{R} \sim n\, e^{-\alpha\phi} \qquad n \in \mathbb{Z}$$

radius R:
scalar field in lower dim. theory

canonically normalized field ϕ:
$R \sim \log \phi$

infinite distance limit:

$R \to \infty$ → (d-1)-dim. EFT breaks down → gets replaced by d-dim. EFT

NO SCALE SEPARATION

[D. Lüst, Palti, Vafa '19]

Infinite Distance Conjecture: Asymptotic limits in scalar field space!

What about infinite distances in space-time metric space?

Conjecture:

> Consider (A)dS space-time with cosmological constant Λ.
> In the infinite distance limit $\Lambda \to 0$ there is an infinite tower of massive states with masses
>
> $$m \sim |\Lambda|^{\alpha} \, .$$

Origin of the tower:

KK-modes of internal space!

→ Internal and external space have comparable scales!

→ "No Scale Separation"

String Theory:
well-tested for SUSY AdS!

Recent proposal for dS: $\Lambda \approx 10^{-122} M_{Pl}^2$
$\Rightarrow$ *Extra dimension of size* $l \sim \Lambda^{\frac{1}{4}} \sim 10^{-6}\,\mathrm{m}$

[Montero, Vafa, Valenzuela '22]

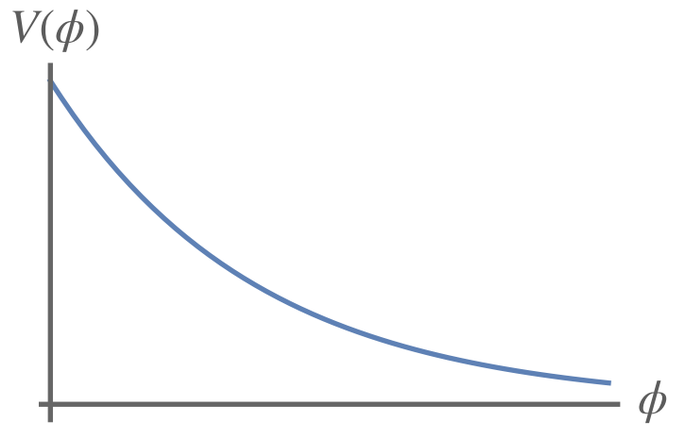
DE SITTER CONJECTURE

[Obied, Ooguri, Spodyneiko, Vafa '18]

Asymptotic limits in field space play a special role!

What about the scalar potential?

In string theory: $V(\phi) \sim e^{-\alpha\phi}$ for $\phi \to \infty$



Conjecture:

The potential always satisfies the bound

$$|\nabla V| \geq \alpha V$$

for some constant $\alpha \sim \mathcal{O}(1)$

Consequence: No (asymptotic) de Sitter vacua!

(minimum: $\partial_i V = 0$; de Sitter: $V > 0$)

Also in interior of field space?

We don't know!

TRANS-PLANKIAN CENSORSHIP CONJECTURE [Bedroya, Vafa '19]

Conjecture:

> Sub-Planckian quantum fluctuations
> always remain quantum.

More precise formulation:

Consider an expanding phase of an FLRW universe.
The initial and final scale factors a_i and a_f satisfy:

$$\underbrace{\frac{a_f}{a_i}}\ell_{Pl} < \frac{1}{H_f}$$

Planck-length

size of an originally Planck-scale fluctuation after expansion

final Hubble parameter → *larger fluctuations become classical*

TRANS-PLANKIAN CENSORSHIP CONJECTURE (2) [Bedroya, Vafa '19]

Consequence of the TCC:

- de Sitter minima possible but unstable

Lifetime: $$T \lesssim \frac{1}{H} \log \frac{M_{pl}}{H}$$

(for our Universe: $T \approx 10^{12}$ years)

- asymptotically ($\phi \to \infty$):

$$\frac{|\nabla V|}{V} \geq \frac{2}{\sqrt{(d-1)(d-2)}} = \sqrt{\frac{2}{3}}$$

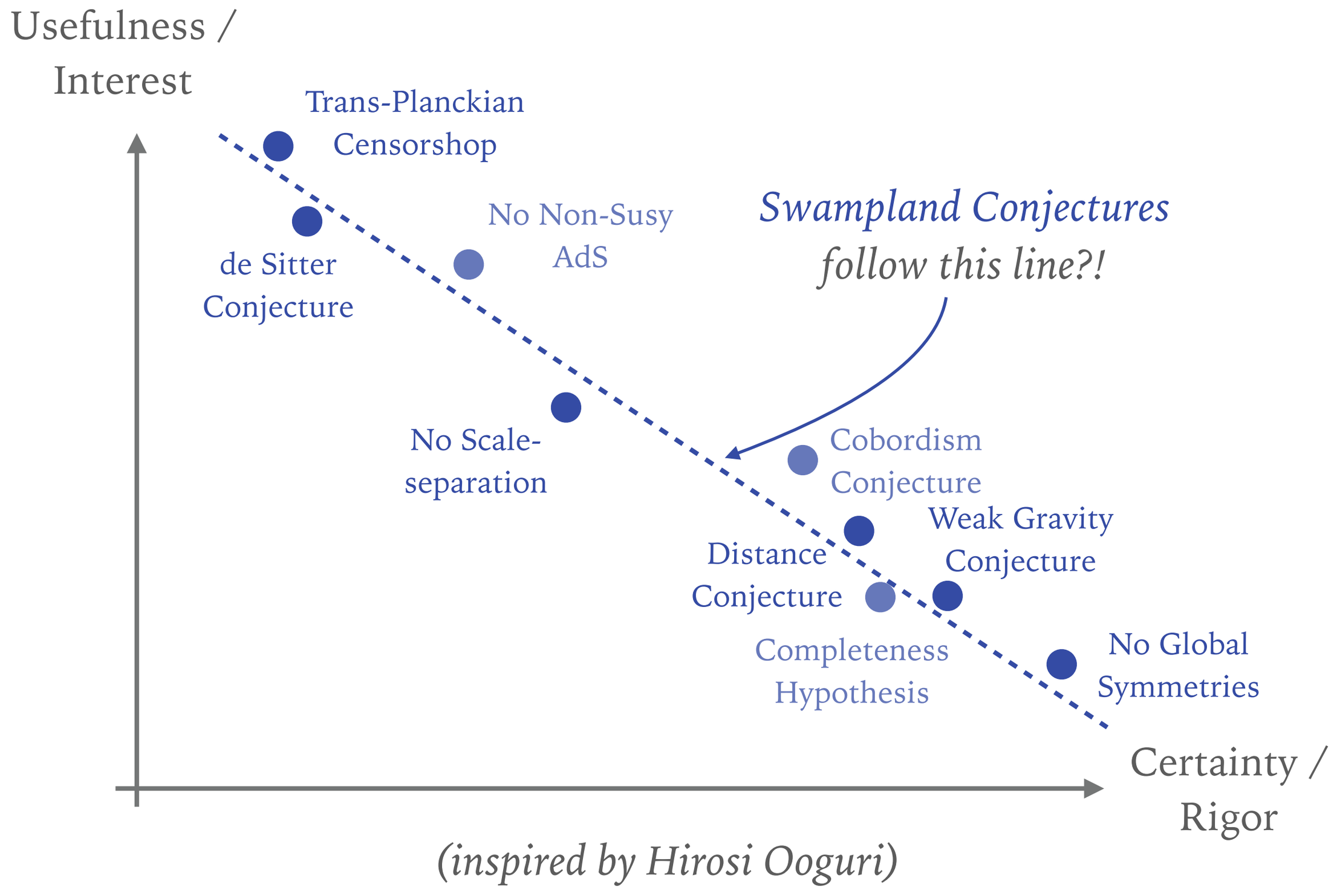
$d = 4$

mild tension with single exponential quintessence

→ reduces to dS conjecture

But: weaker in the interior of field space!

LANDSCAPE OF SWAMPLAND CONJECTURE



(inspired by Hirosi Ooguri)

THANK YOU!