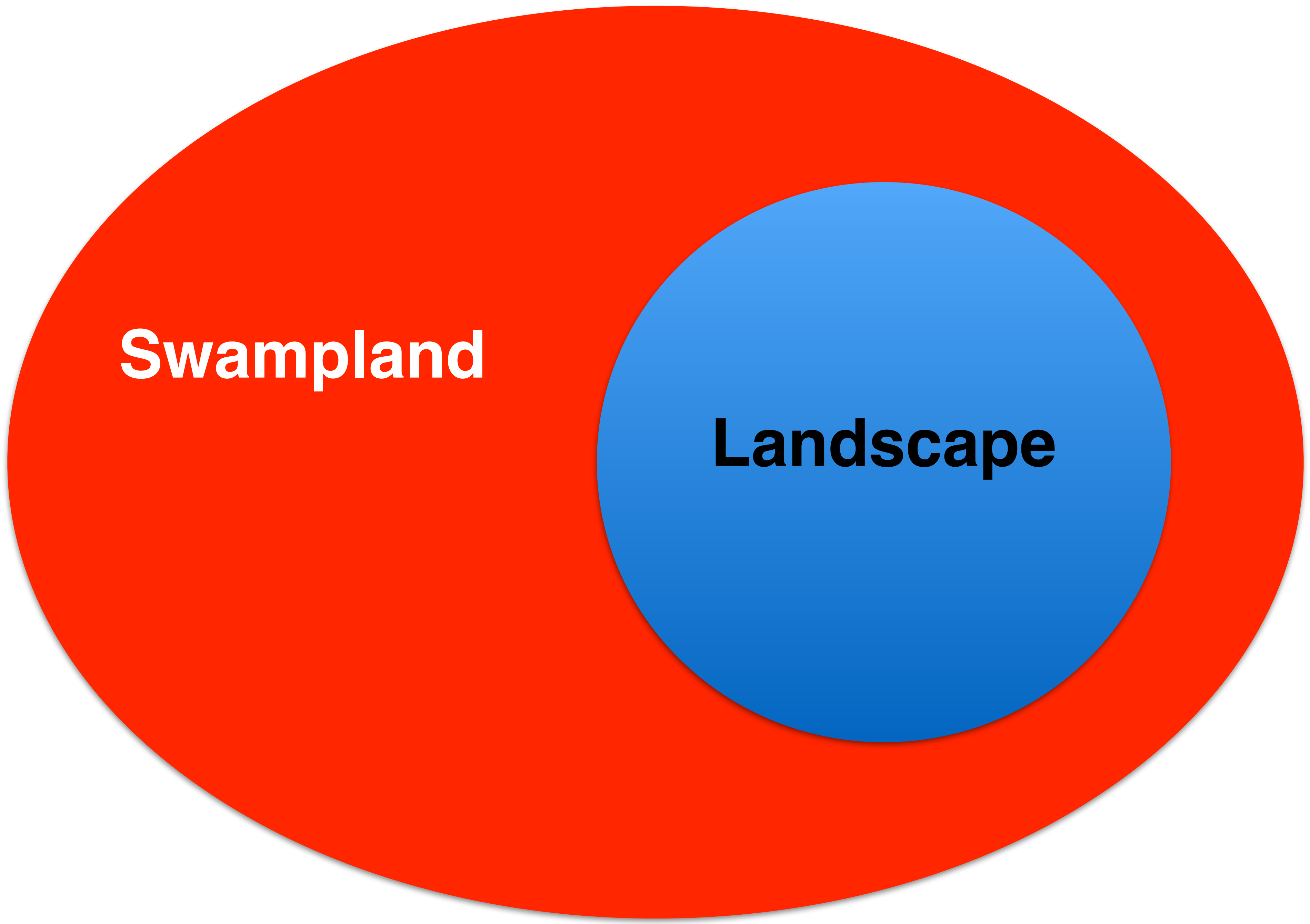
Quantum Gravity and the Swampland

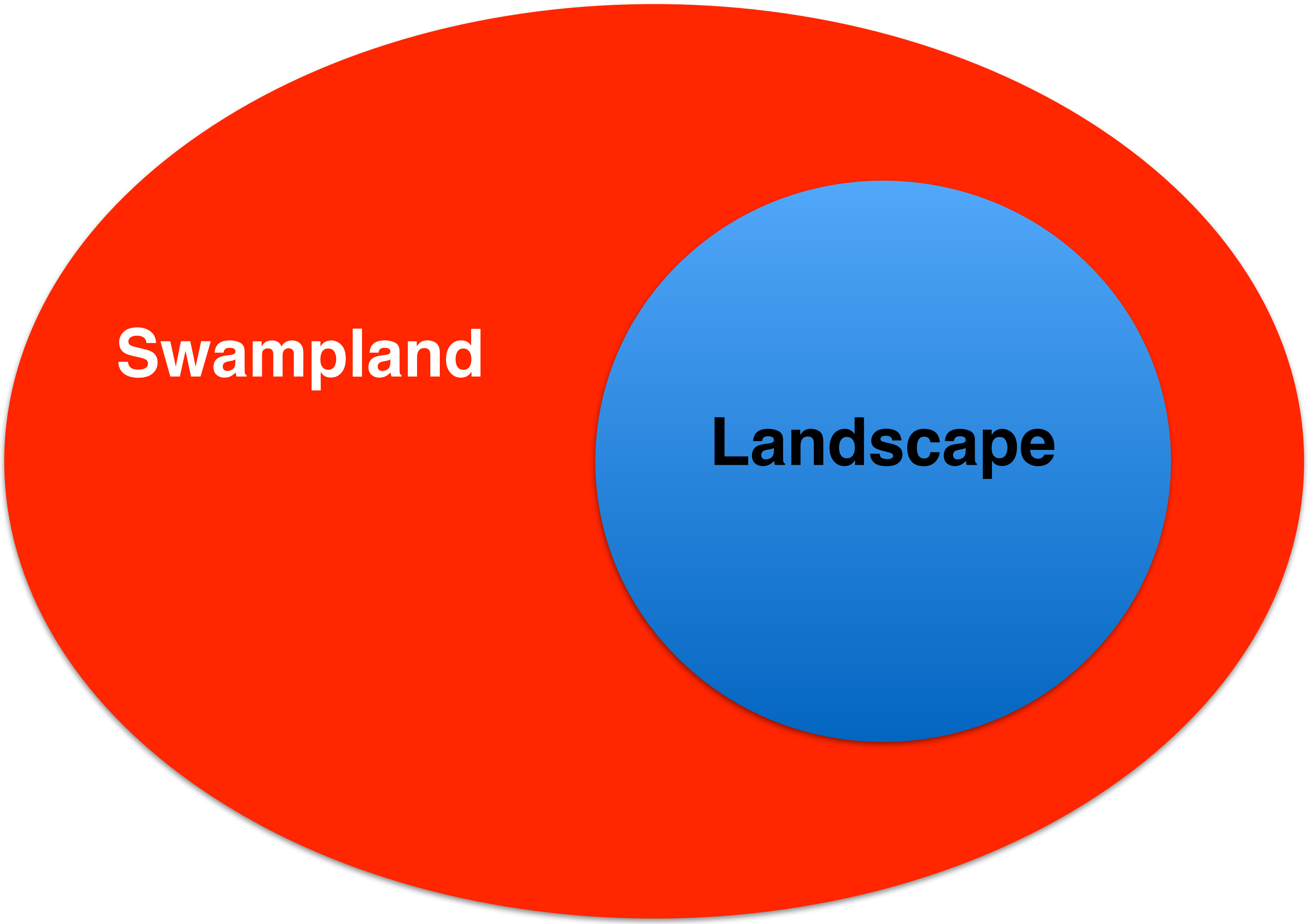
Gary Shiu
University of Wisconsin-Madison

Landscape vs Swampland

Landscape vs Swampland



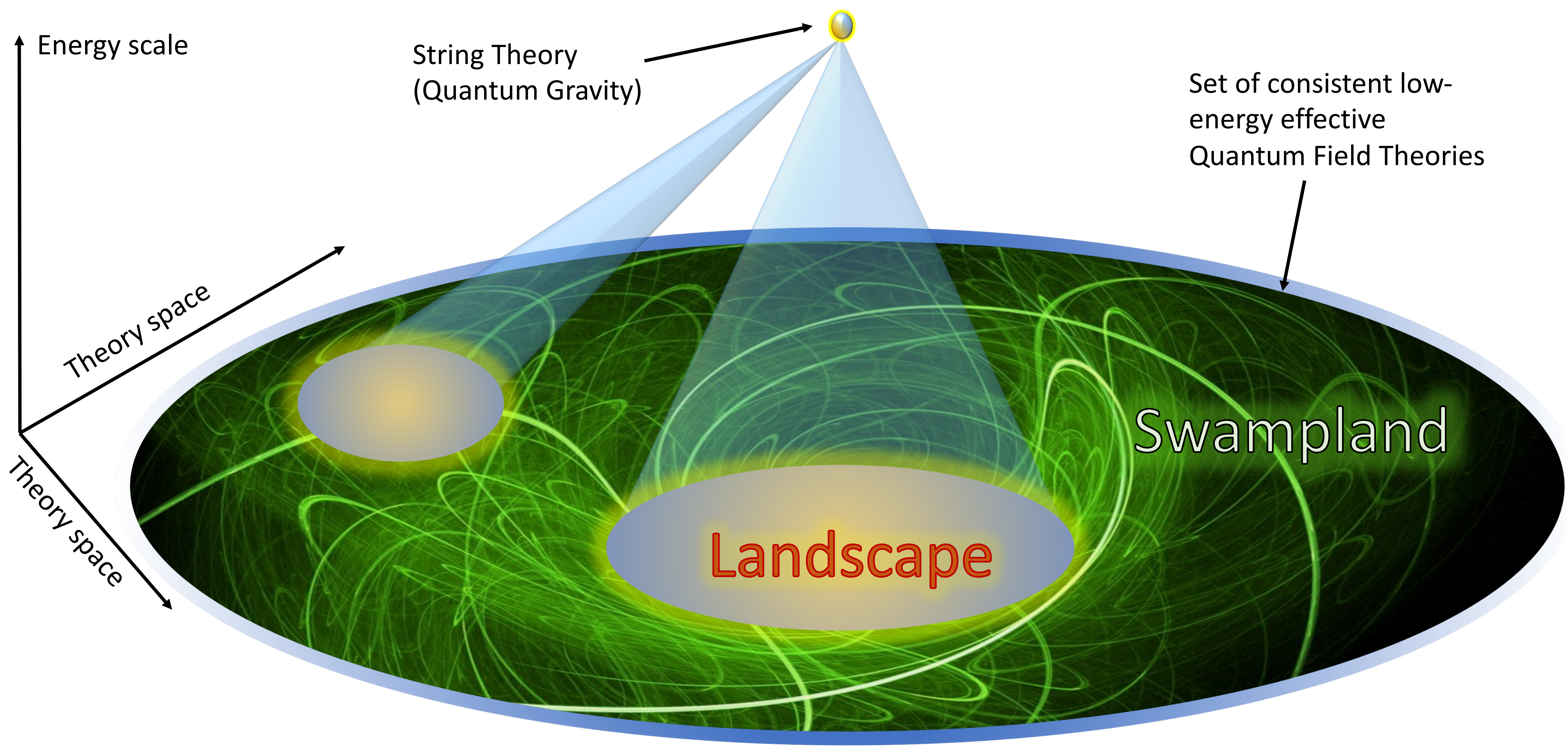
Landscape vs Swampland



We refer to the space of quantum field theories which are incompatible with quantum gravity as the ***swampland***. **[Vafa, ’05]; [Ooguri, Vafa, ’06]**

Landscape vs Swampland

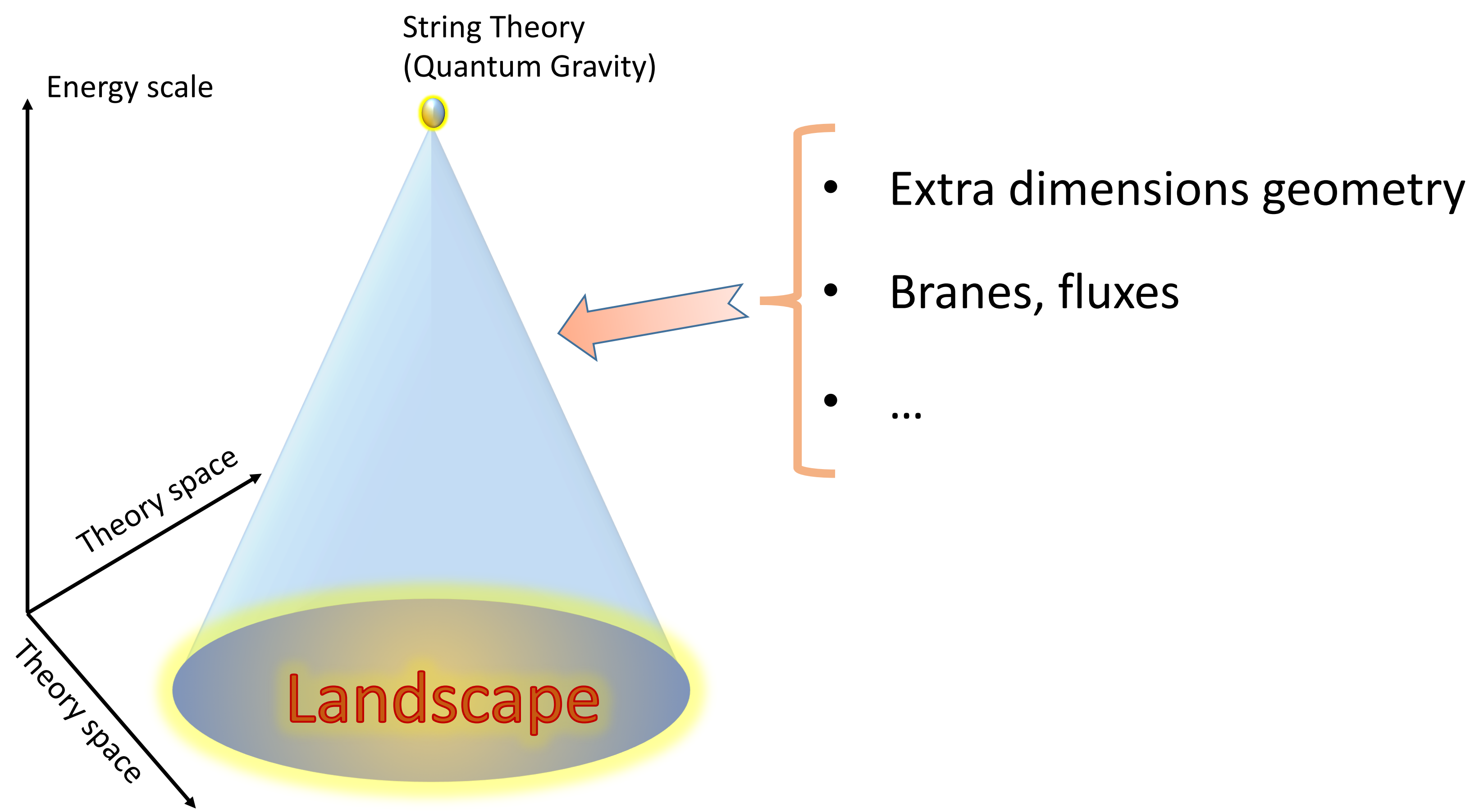
The Swampland program is about extracting possible universal predictions from string theory, and the rules governing them.



String Theory and the Swampland

The primary challenges include:

- No complete definition of String Theory — how can we be sure?



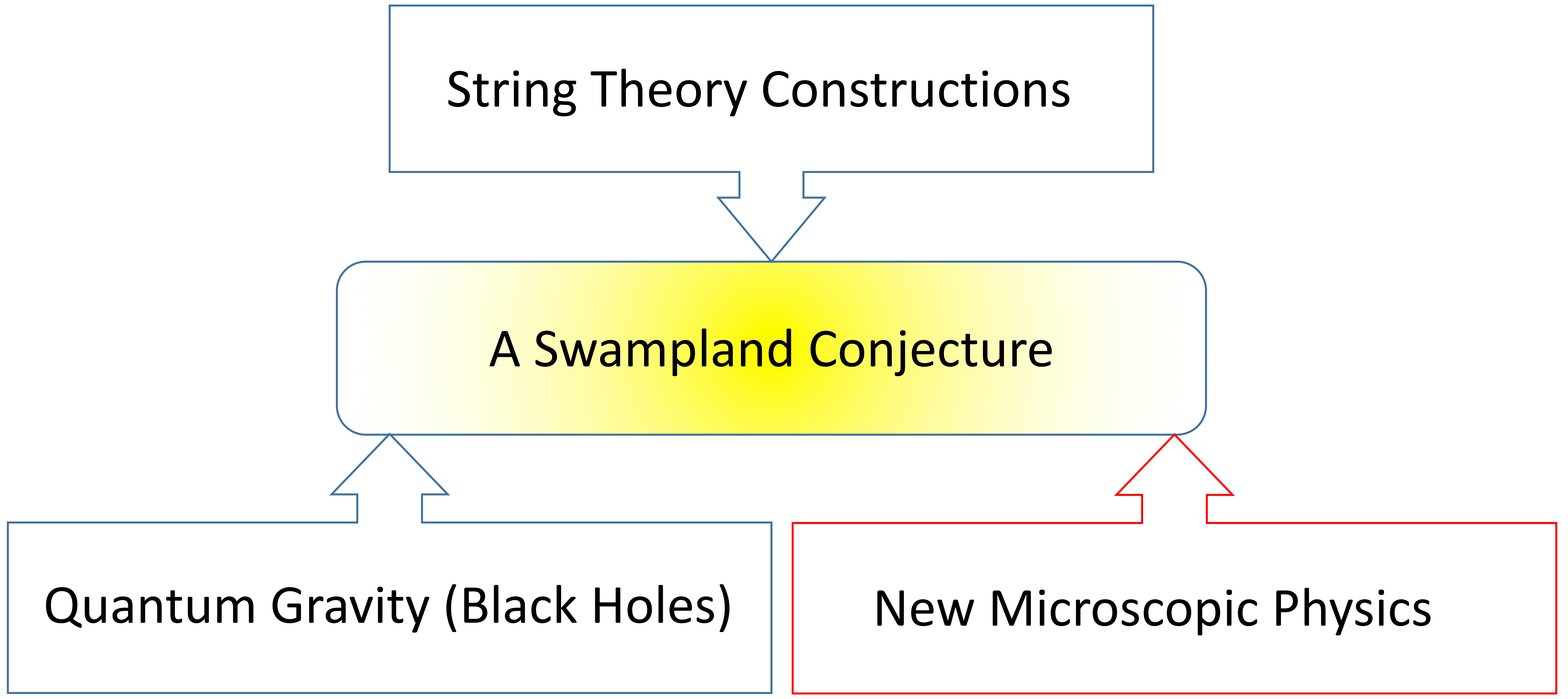
- String theory constructions live on a spectrum, where to draw the line?

"String Constructed"
+ quantum corrections under control

"String Inspired"

String Theory and the Swampland

To make progress, we combine inputs from different fronts:



Based mainly on two recent papers:

Y. Hamada, T. Noumi and GS,
"Weak Gravity Conjecture from Unitarity and Causality", arXiv:1810.03637

Yuta Hamada **Toshifumi Noumi**

Hirosi Ooguri **Eran Palti** **Cumrun Vafa**

H. Ooguri, E. Palti, GS and C. Vafa
"Distance and de Sitter Conjectures on the Swampland", arXiv:1810.05506

Touch upon earlier work with:


J. Brown


W. Cottrell


P. Soler


M. Montero


Y. Hamada

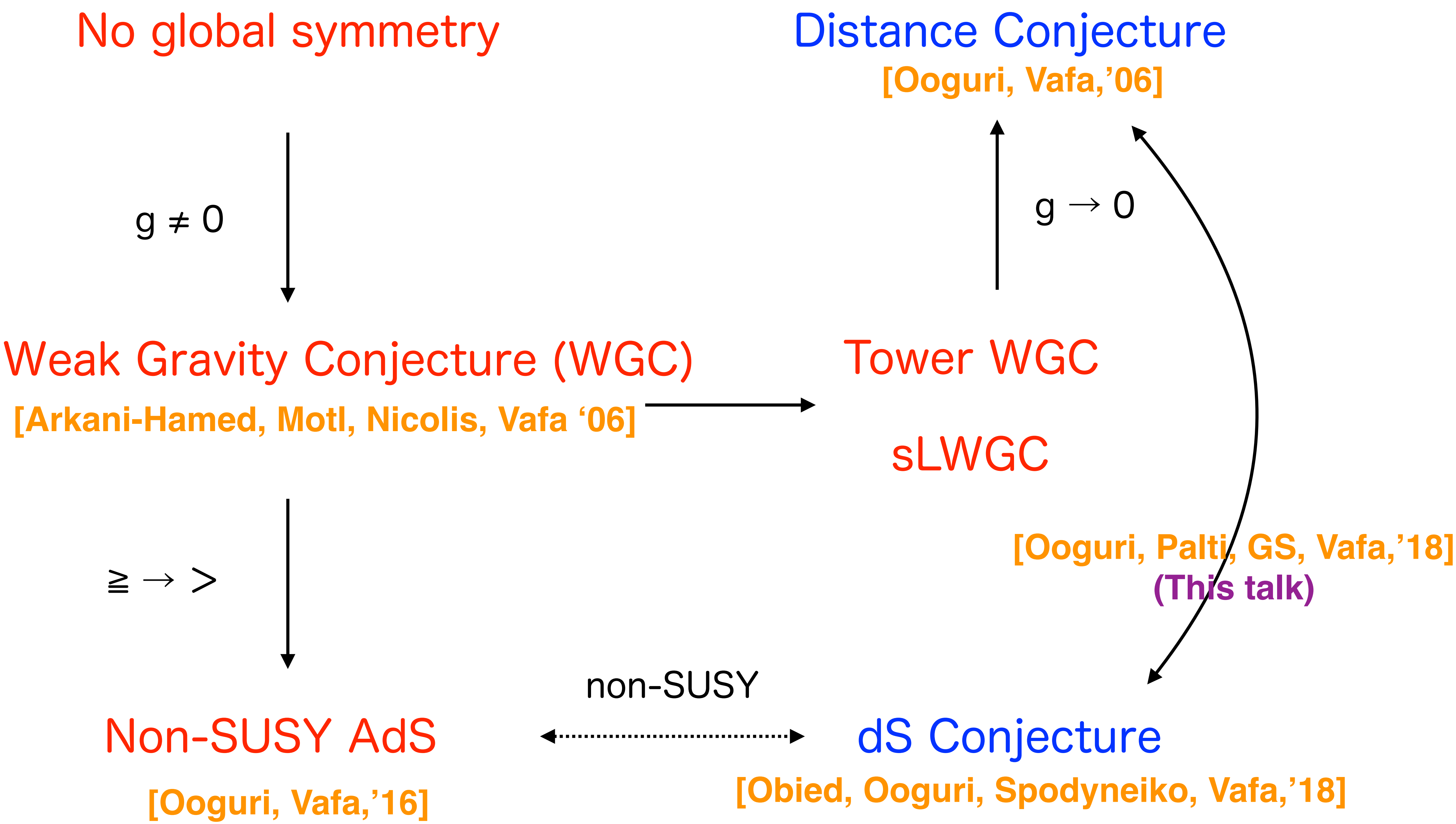

S. Andriolo


D.Junghans


T. Noumi

J. Brown, W. Cottrell, GS, P. Soler, JHEP **1510**, 023 (2015), JHEP **1604**, 017 (2016), JHEP **1610** 025 (2016).
M. Montero, GS and P. Soler, JHEP **1610** 159 (2016).
W. Cottrell, GS and P. Soler, arXiv:1611.06270 [hep-th].
Y. Hamada and GS, JHEP **1711**, 043 (2017).
S. Andriolo, D. Junghans, T. Noumi and GS, Fortsch.Phys. 66 (2018) no.5, 1800020.

Web of Conjectures



Quantum Gravity and Global Symmetries

QG and Global Symmetries

- **Global symmetries** are expected to be violated by gravity:

- **No hair theorem:** Hawking radiation is insensitive to Q.
  - ➡ Infinite number of states (remnants) with $m \lesssim M_p$
  - ➡ Violation of entropy bounds. At finite temperature (e.g. in Rindler space), the density of states blows up. **Susskind '95**

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

- In (perturbative) string theory, all symmetries are gauged **[Banks, Dixon '88].**

- There is a recent proof using holography **[Harlow, Ooguri, '18].**

- Many phenomenological ramifications, e.g., mini-charged DM comes with a new massless gauge boson **[GS, Soler, Ye, '13].**

The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa ‘06

The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa '06

- The conjecture:

"Gravity is the Weakest Force"

- For every long range gauge field there exists a particle of charge q and mass m, s.t.

$$\frac{q}{m} M_P \geq \text{``1''}$$

- Seems to hold for all known string theory models.

The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa '06

- The conjecture:

"Gravity is the Weakest Force"

- For every long range gauge field there exists a particle of charge q and mass m, s.t.

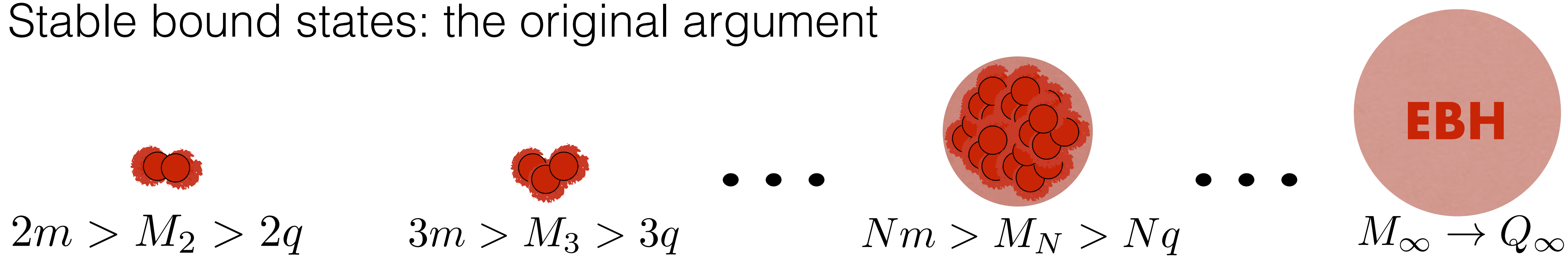
$$\frac{q}{m} M_P \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}} M_P$$

- Seems to hold for all known string theory models.

The Weak Gravity Conjecture

- Take U(1) gauge theory and a scalar with $m > q\,M_p$

- Stable bound states: the original argument



- All these BH states are **exactly stable**. In particular, large bound states (charged black holes) do not Hawking radiate once they reach the extremal limit M=Q, equiv. T=0.

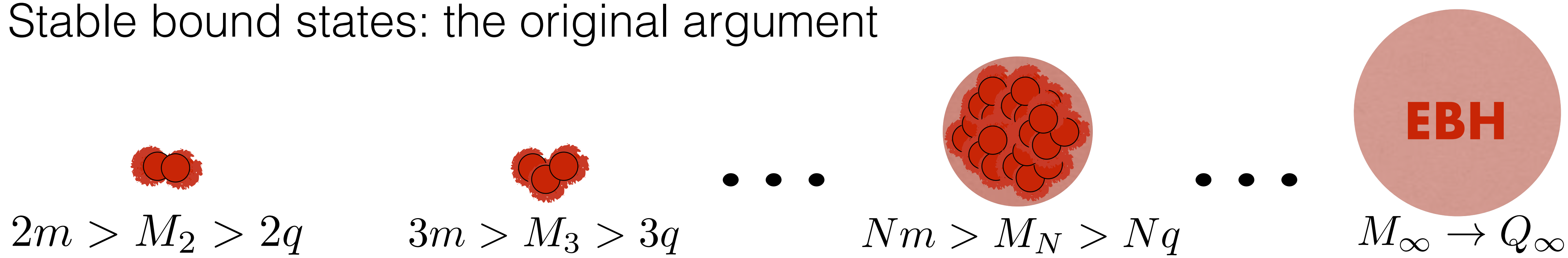
> "…there should not exist a large number of exactly stable objects (extremal black holes) whose stability is not protected by any symmetries."

Arkani-Hamed et al. '06

The Weak Gravity Conjecture

- Take U(1) gauge theory and a scalar with $m > q\, M_p$

- Stable bound states: the original argument



- All these BH states are **exactly stable**. In particular, large bound states (charged black holes) do not Hawking radiate once they reach the extremal limit M=Q, equiv. T=0.

- In order to avoid a large number of exactly stable states one must demand the existence of some particle with

$$\frac{q}{m} \geq \frac{Q_{ext}}{M_{ext}} = \frac{1}{M_p}$$

Evidences for the WGC

Evidences for the Weak Gravity Conjecture

Several lines of argument have been taken (so far):

- Holography [Nakayama, Nomura, ’15];[Harlow, ‘15];[Benjamin, Dyer, Fitzpatrick, Kachru, ‘16];[Montero, GS, Soler, ’16]
- Cosmic Censorship [Horowitz, Santos, Way, ’16];[Cottrell, GS, Soler, ’16];[Crisford, Horowitz, Santos, ’17]
- Entropy considerations [Cottrell, GS, Soler, ’16] [Fisher, Mogni, ’17]; [Cheung, Liu, Remmen, ’18];[Hamada, Noumi, GS, ‘18]
- IR Consistencies (unitarity & causality) [Cheung, Remmen, ’14] [Andriolo, Junghans, Noumi, GS,’18];[Hamada, Noumi, GS, ’18]

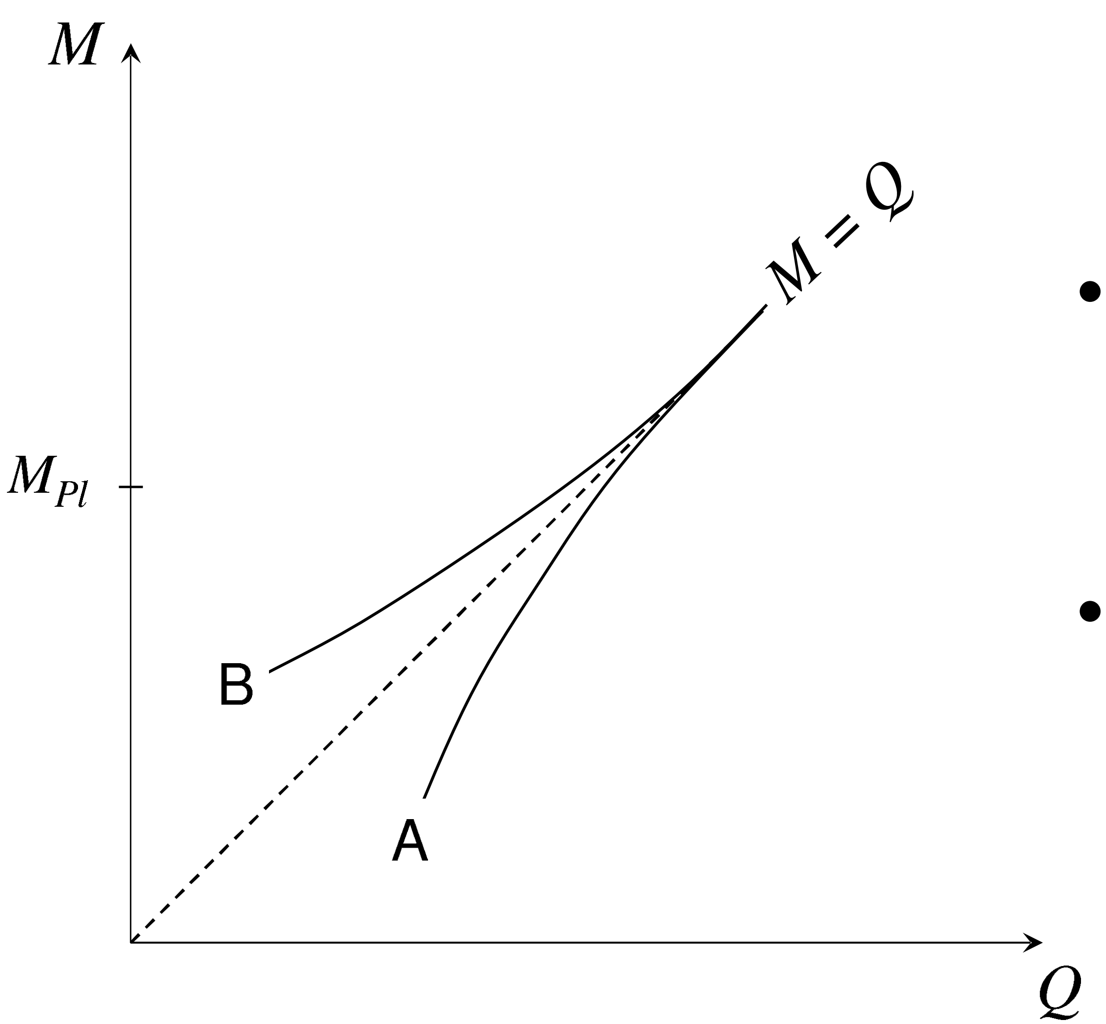
Evidences for *stronger* versions of the WGC:

- Consistencies with T-duality [Brown, Cottrell, GS, Soler, ‘15] and dimensional reduction [Heidenreich, Reece, Rudelius ’15].
- Modular invariance + charge quantization suggest a **sub-lattice WGC** [Montero, GS, Soler, ‘16] (see also [Heidenreich, Reece, Rudelius ’16])

WGC and Blackholes

Extremality of Blackholes

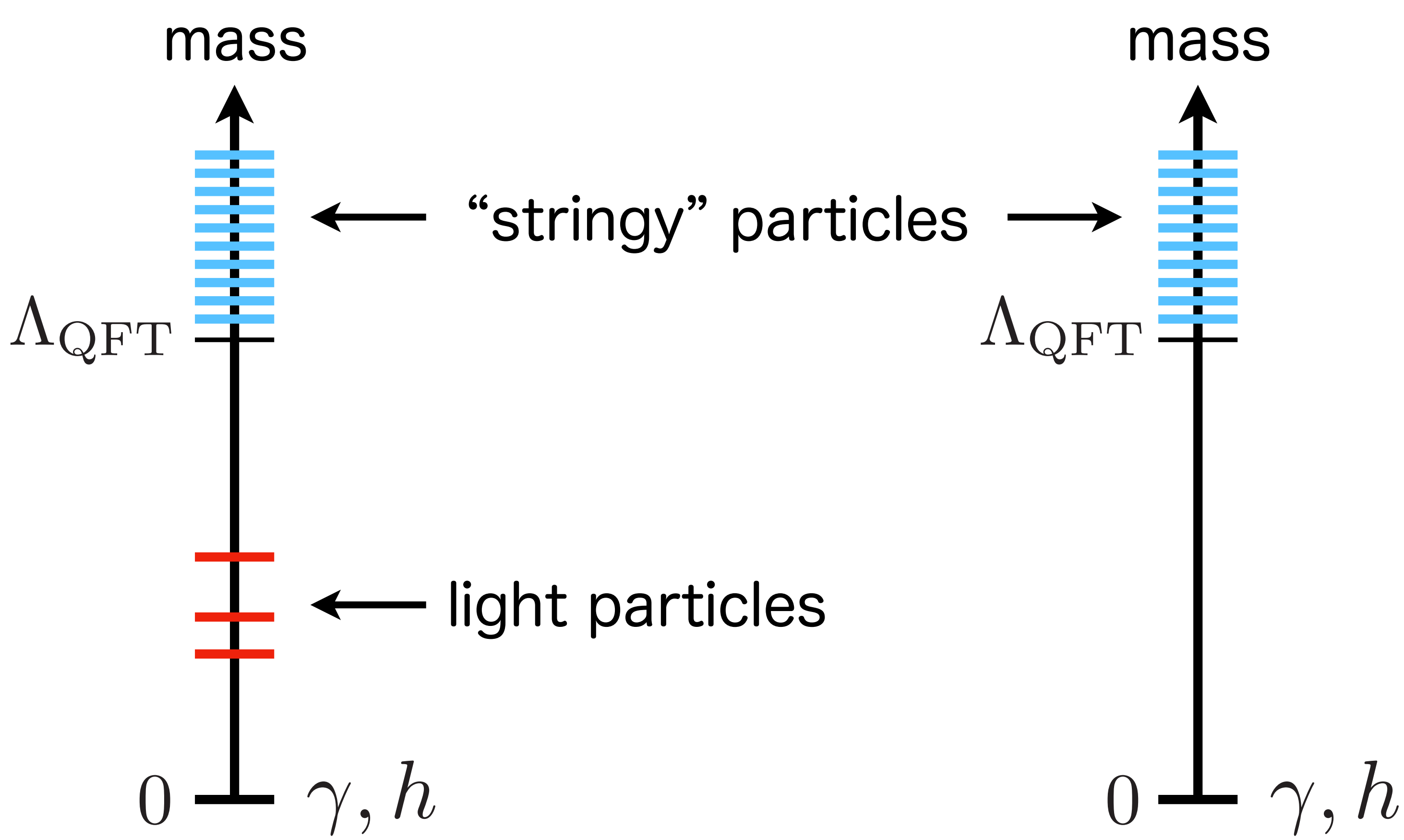
- The mild form of the WGC requires only ***some*** state for an extremal BH to decay to.
- **Can an extremal BH satisfy the WGC?**



- Higher derivative corrections can make extremal BHs lighter than the **classical bound** Q=M
- Demonstrated to be the case for 4D heterotic extremal BHs. **[Kats, Motl, Padi, '06]**
- We showed that this behavior (A) follows from unitarity (at least for some classes of theories). **[Hamada, Noumi, GS]**

WGC from Unitarity and Causality

- We assume a ***weakly coupled UV completion*** at scale Λ_{QFT}. Our proof for the strict WGC bound applies to at least two classes of theories:



- Theories with ***light*** (compared with Λ_{QFT})***, neutral i) parity-even scalars*** (e.g., dilaton, moduli), or **ii) spin ≥ 2 particles**

- ***UV completion*** where the photon & the graviton are accompanied by different sets of Regge states (as in open string theory).

Higher Derivative Corrections

- In the IR, the BH dynamics is described by an EFT of the photon and the graviton.
- In D=4, the general effective action up to 4-derivative operators (assume parity invariance for simplicity):

$$S = \int d^4x \sqrt{-g} \left[\frac{2M_{\rm Pl}^2}{4} R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \Delta\mathcal{L} \right]$$

where $$\begin{aligned} \Delta\mathcal{L} = \; & c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + c_3 R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} \\ & + c_4 R F_{\mu\nu} F^{\mu\nu} + c_5 R_{\mu\nu} F^{\mu\rho} F^{\nu}{}_{\rho} + c_6 R_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma} \\ & + c_7 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + c_8 F_{\mu\nu} F^{\nu\rho} F_{\rho\sigma} F^{\sigma\mu}. \end{aligned}$$

Higher Derivative Corrections

- In the IR, the BH dynamics is described by an EFT of the photon and the graviton.
- In D=4, the general effective action up to 4-derivative operators (assume parity invariance for simplicity):

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

by field redefinition. Here, $W^{\mu\nu\rho\sigma}$ is the **Weyl tensor:**

$$R_{\mu\nu\rho\sigma} = W_{\mu\nu\rho\sigma} + \frac{1}{2}\left(g_{\mu[\rho}R_{\sigma]\nu} - g_{\nu[\rho}R_{\sigma]\mu}\right) - \frac{1}{3}Rg_{\mu[\rho}g_{\sigma]\nu}$$

Extremality Condition

- The higher derivative operators modify the BH solutions, so the charge-to-mass ratio of an extremal BH is corrected:

$$z = \frac{\sqrt{2} M_{\mathrm{Pl}} |Q|}{M} = 1 + \frac{2}{5} \frac{(4\pi)^2}{Q^2} (2\alpha_1 - \alpha_3)$$

[Kats, Motl, Padi, '06]

applicable when the BH is sufficiently heavy: $M^2 \sim Q^2 M_{\mathrm{Pl}}^2 \gg \alpha_i M_{\mathrm{Pl}}^2$

because extremal BHs in Einstein-Maxwell theory satisfy:

$$R \sim M_{\mathrm{Pl}}^4 / M^2 \text{ and } F^2 \sim M_{\mathrm{Pl}}^6 / M^2$$

- Proving the WGC (mild form) amounts to showing:

$$2\alpha_1 - \alpha_3 \geq 0 \, .$$

so large extremal BHs can decay into smaller extremal BHs.

Sketch of the Proof

[Hamada, Noumi, GS]

- We first show that for the aforementioned theories, **causality** implies

$$|\alpha_1| \gg |\alpha_3|$$

- The helicity amplitudes $\mathcal{M}$ (1^+, 2^+, 3^{+2}) & $\mathcal{M}$ (1^-, 2^-, 3^{-2}) induced by α_3 lead to causality violation at the energy scale: $E \sim M_{\rm Pl}/\sqrt{\alpha_3}$

- Moreover, an infinite tower of massive higher spin particles with

$$m \gtrsim M_{Pl}/\sqrt{\alpha_3}$$

(just like string theory!) is required to UV complete the EFT at tree-level **[Camanho, Edelstein, Maldacena, Zhibodev].**

- This infinite tower is also confirmed by a holographic derivation using the conformal bootstrap approach **[Li, Melzer, and Poland].**

- If there are light fields or different Regge towers, α_3 is **subdominant** compared with the causality preserving terms α_1 and α_2.

Sketch of the Proof

[Hamada, Noumi, GS]

- The forward limit t→0 of γγ scattering for the aforementioned theories:

$$\mathscr{M}^{1234}(s) = \sum_n \left[\frac{g_{h_1 h_2 n} g_{\bar{h}_3 \bar{h}_4 n}}{m_n^2 - s} P^{1234}_{\mathbf{s}_n}(1) + \frac{g_{h_1 h_4 n} g_{\bar{h}_3 \bar{h}_2 n}}{m_n^2 + s} P^{1432}_{\mathbf{s}_n}(1) \right] + \text{analytic}$$

Spinning polynomials

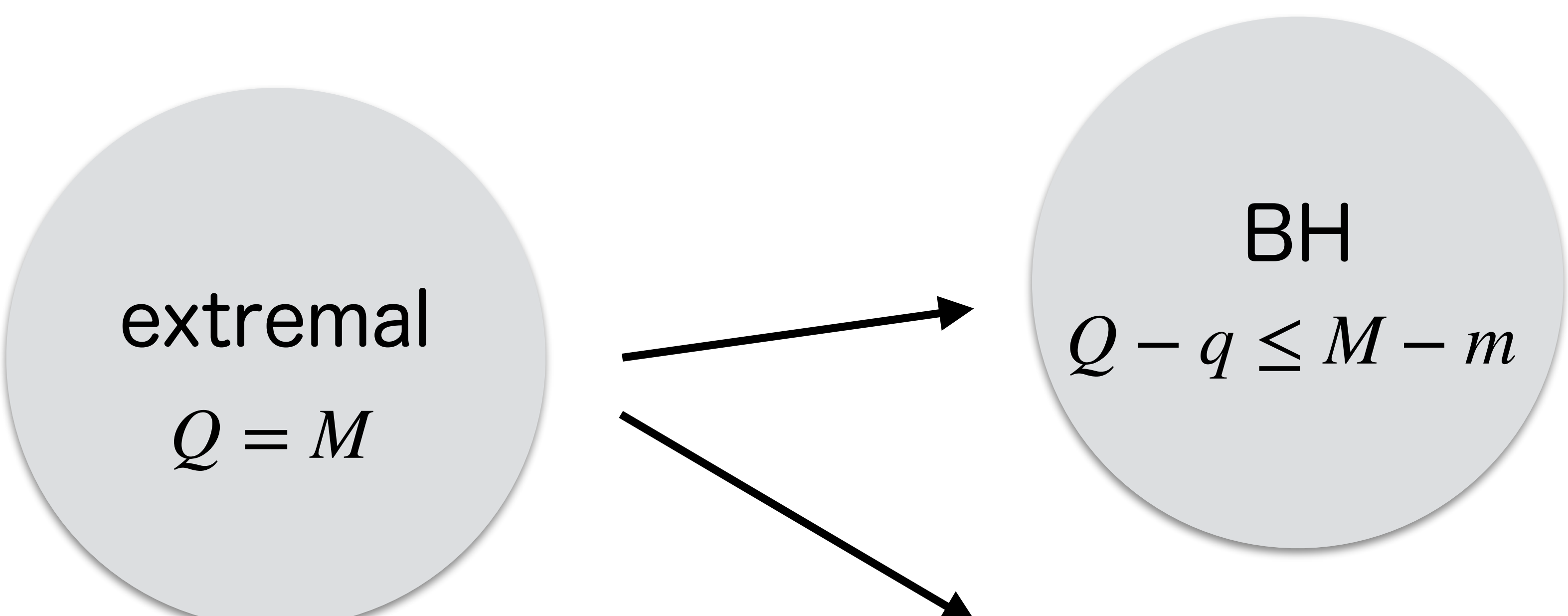
[Arkani-Hamed, Huang, Huang, '17]

Froissart bound $a_n + b_n s$

- The higher derivative operator parametrized by α_1 leads to:

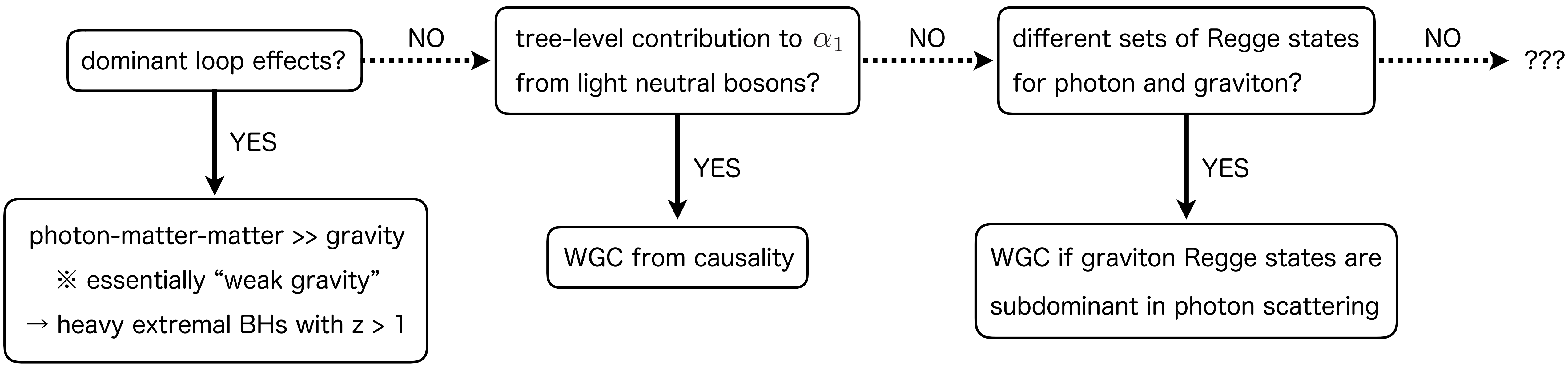
$$\alpha_1 (F_{\mu\nu} F^{\mu\mu})^2 \quad \Rightarrow \quad \mathscr{M} \sim \alpha_1 s^2$$

Unitarity ⇒ $\alpha_1 > 0$



- a state $q \geq m$ **can be an extremal BH!**

Summarizing the Unitarity Constraints



- Theories not covered by our proof are those with one type of Regge states (e.g., heterotic string) & no light bosons below M_S.
- If the WGC follows from field theoretical consistencies alone, it won't be a swampland condition!
- Nonetheless, explicit calculations of scattering amplitudes give $\alpha_1>0$ and $\alpha_2>0$. Moreover, $\alpha_3=0$ because of SUSY.

Swampland, Duality, & de Sitter Entropy

de Sitter vacua in String Theory

- Observation of accelerating universe poses the dark energy puzzle. Simplest explanation is that we are living in a metastable dS vacuum.

- Despite heroic efforts (e.g., **[Silverstein]; [KKLT]; [LVS]**), ***explicit, controlled*** de Sitter vacua seem difficult to construct.

- Attempts to find simpler de Sitter vacua run into potentials with too steep a gradient or tachyonic directions

  [Hertzberg, Kachru, Taylor, Tegmark];[Silverstein];[Haque, GS, Underwood, Van Riet];[Flauger, Paban, Robbins, Wrase];[Caviezel, Koerber, Kors, Lust, Wrase, Zagermann];[Danielsson, Haque, GS, Van Riet];[Danielsson, Haque, Koerber, GS, Van Riet, Wrase]; [GS, Sumitomo];[Danielsson, Haque, Van Riet, Wrase]; …

- This state of affairs motivated **[Obied, Ooguri, Spodyneiko, Vafa]** to conjecture:

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \qquad c \sim \mathcal{O}(1) > 0$$

- Could there be some general physics underlying this behavior?

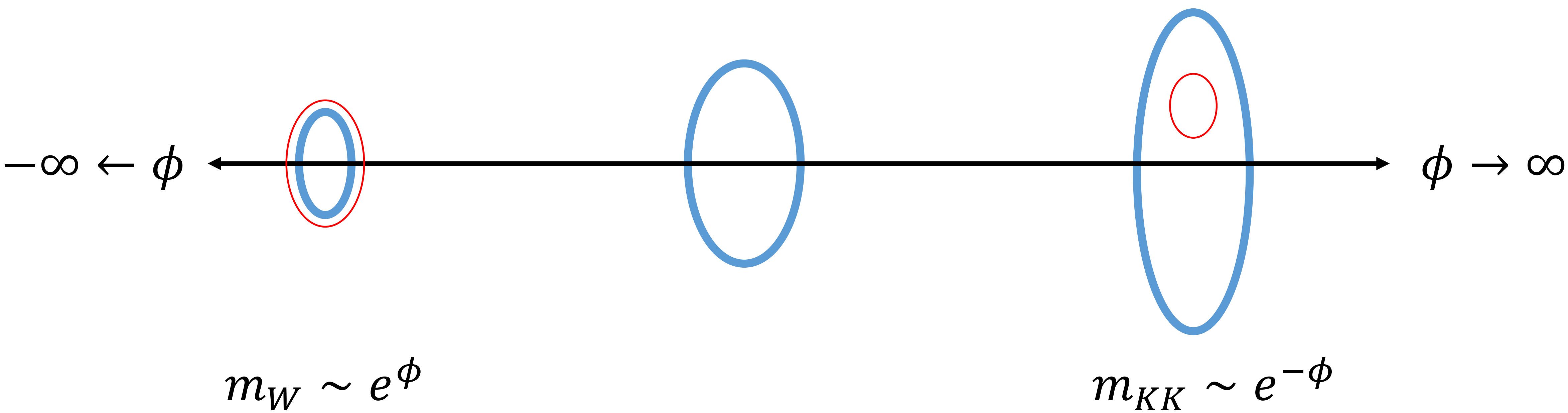
Swampland Distance Conjecture

- Approaching any infinite distance locus in moduli space, there is an infinite tower of states which becomes exponentially light:

$$m_{\text{tower}} \sim e^{-a\phi} \quad \text{for} \quad \phi \to \infty$$

[Ooguri, Vafa, '06]

- Simple example: compactification on a circle



- This conjecture has passed some non-trivial tests (at least for theories with 8 supercharges) **[Cecotti,'15];[Grimm,Palti, Valenzuela,'18]; [Lee, Lerche, Weigand,'18]**

Swampland Distance Conjecture

- While there are open questions **[Landete, GS];[Hebecker, Henkenjohann, Witkowski]** regarding what is $\Delta\phi$ at the onset of this exponential behavior:

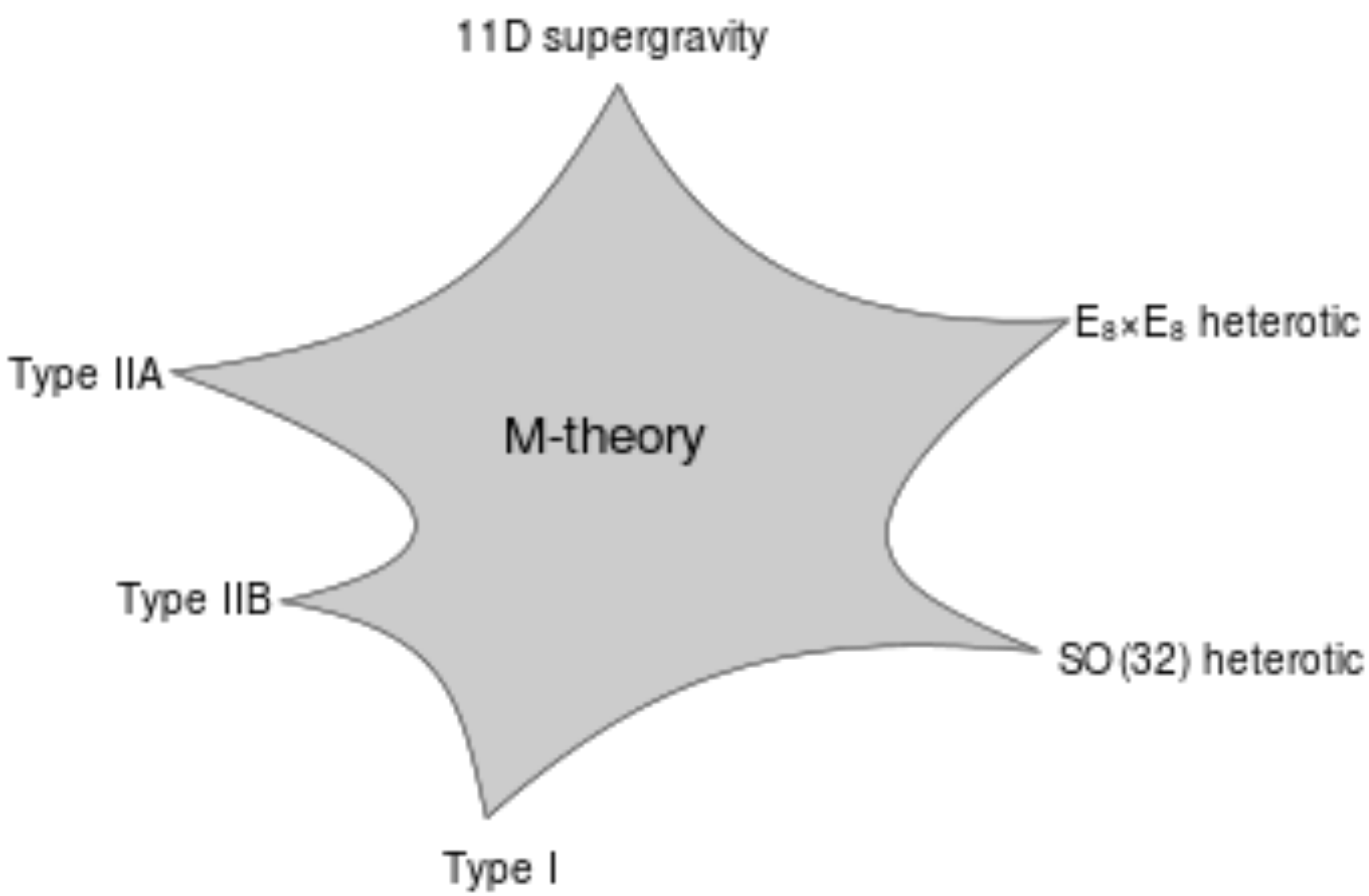
$$m_{\text{tower}} \sim e^{-a\phi} \quad \text{for} \quad \phi \to \infty$$

  and the notion of distance in the presence of a potential V(ϕ), such subtleties do not affect the proposed universal behavior at $\phi \to \infty$.

- The infinite distance regime is where we will use this conjecture for our entropy argument.

Swampland Distance Conjecture & Duality

- The underlying motivation for this conjecture is **duality**: at large distance, there is a dual description in terms of the light states.



Couplings in string theory are scalar fields

$$\text{Weak Coupling } g \to 0 \quad \Leftrightarrow \quad \text{Large distance } \phi \to \infty$$

Swampland Distance Conjecture & Duality

- We interpret the Swampland Distance Conjecture as:

Any weakly coupled region in string theory should have a dual description in terms of the tower of light states.

- We argued how this tower of states may provide a dual description of the potential V(ϕ)>0 and the associated entropy.

de Sitter Entropy

- The Gibbons-Hawking entropy of de Sitter space:

$$S_{\mathrm{GH}} = R^2 = 1/\Lambda$$

- This entropy has been interpreted in terms of:

$$\dim \mathcal{H} = e^{1/\Lambda}$$

in an observer's causal domain **[Banks];[Witten].**

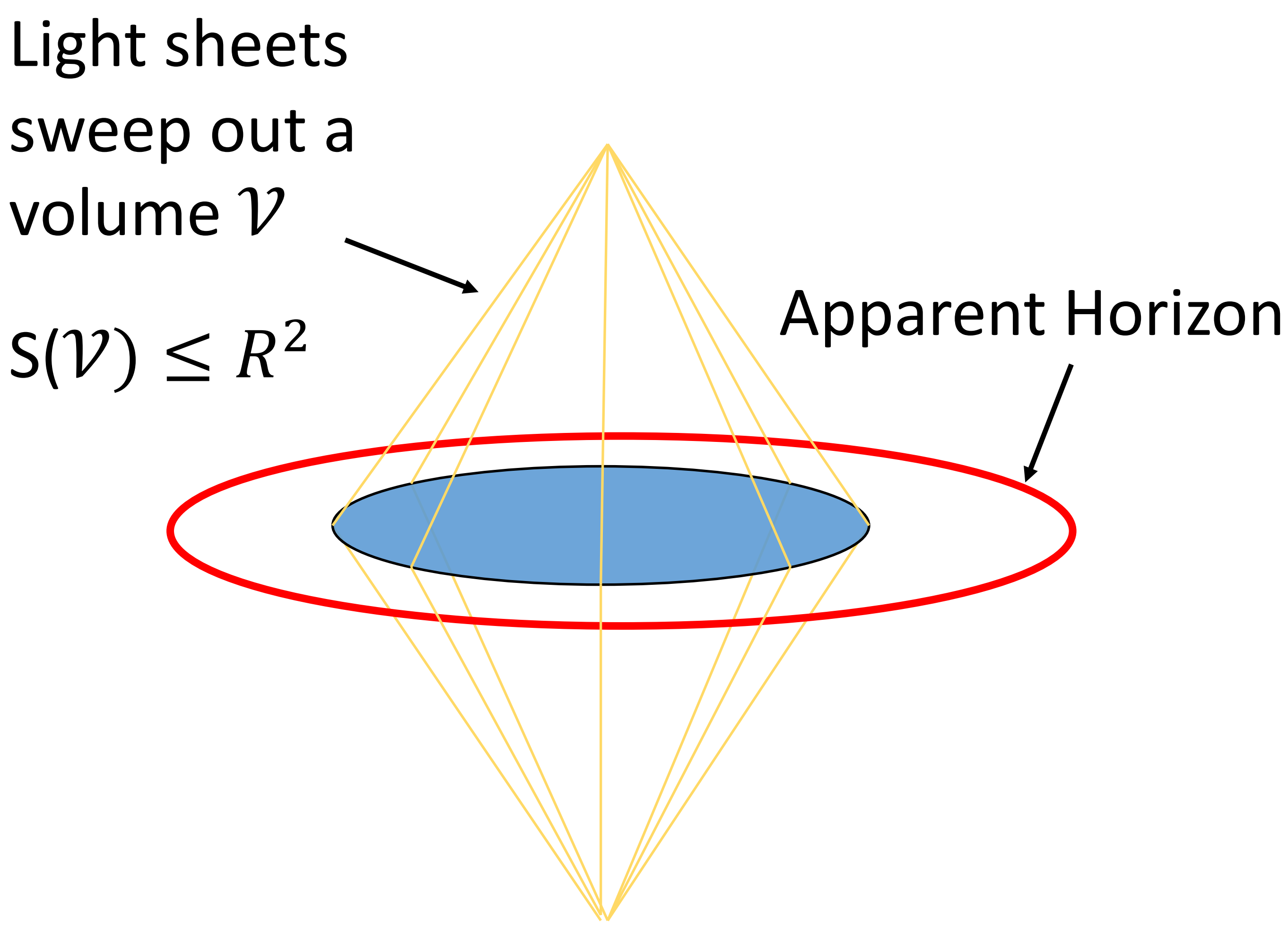
- Instead of Λ, we have $V(\phi)>0$. If $V(\phi)$ has a local minimum, we have a long-lived metastable de Sitter vacuum, and S_{GH} is meaningful.

- Even if V has a non-zero gradient, as long as $|\nabla V|/V < \sqrt{2}$, there is an **apparent horizon** with

$$R = \frac{1}{\sqrt{V}}$$

Bousso Bound

- Since the apparent horizon is always inside of a cosmic event horizon (if the latter exists), lightsheets emanating from it will close at caustics:



[Fischler, Susskind, '98];[Bousso, '99]

de Sitter Entropy

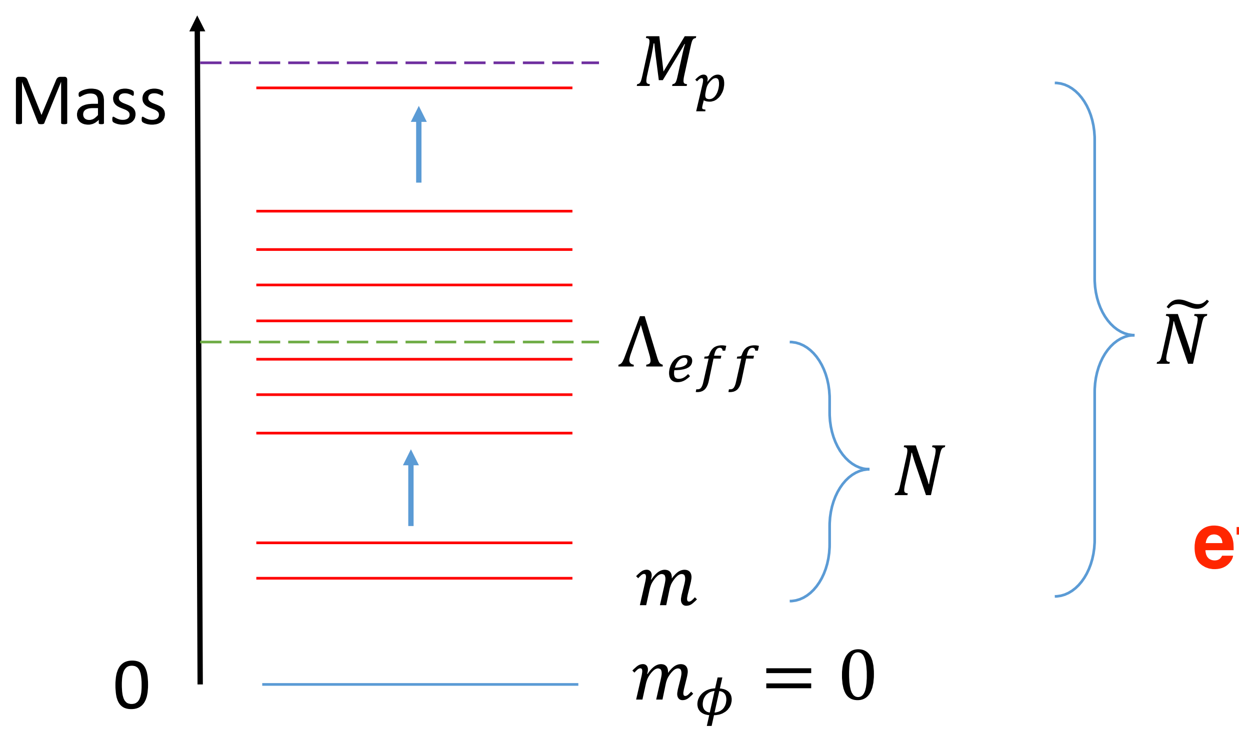
- This semi-classical picture is valid provided quantum fluctuations of ϕ are negligible.
- If the Hessian $\nabla_i \nabla_j V$ has a negative eigenvalue below $-c'/R^2$, with $c' \sim \mathcal{O}(1)$, the zero point fluctuations at horizon crossing becomes **tachyonic** $\Rightarrow$ semi-classical picture breaks down.
- If V is positive and satisfies:

$$|\nabla V| \leq \sqrt{2} \cdot V \quad \text{and} \quad \min(\nabla_i \nabla_j V) \geq -c' V$$

  there is an accelerating universe, and the entropy inside of its apparent horizon is bounded by R^2.
- The second inequality also ensures that the first inequality holds for at least one Hubble time.

Tower of States

- In the weak coupling regime, we have towers of light states with exponentially small masses.
- This should increase the entropy and influence how $V(\phi)$ behaves.



$$N(\phi) \sim n(\phi) e^{b\phi}$$

effective # of towers

b ≠ a in general

- We expect $n(\phi)$ to increase toward the weak coupling limit.

Entropy and Tower of States

- The entropy associated with the light states is a function of N and R:

$$S_{\text{tower}}(N, R)$$

- Since N, R ≫ 1, S_{tower} (N,R) should be dominated by a single term:

$$S_{\text{tower}}(N, R) \sim N^{\gamma} R^{\delta}$$

- The Bousso bound applied to the tower:

$$N^{\gamma} R^{\delta} \leq R^2$$

- Since the tower of states dominate the Hilbert space in the weak coupling regime, we expect them to saturate the Bousso bound:

$$V(\phi) \sim R^{-2} \sim N^{-\frac{2\gamma}{2-\delta}}$$

The Refined de Sitter Conjecture

- The gradient condition follows from the exponential behavior of N(ϕ)

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \qquad \text{with} \qquad c = \frac{2b\gamma}{2-\delta}$$

- A prerequisite for the notion of entropy is:

$$\min(\nabla_i \nabla_j V) \geq -c' V$$

- Our analysis naturally led to the **Refined de Sitter Conjecture:**

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \ , \quad \textbf{or} \quad \min(\nabla_i \nabla_j V) \leq -\frac{c'}{M_p^2} \cdot V$$

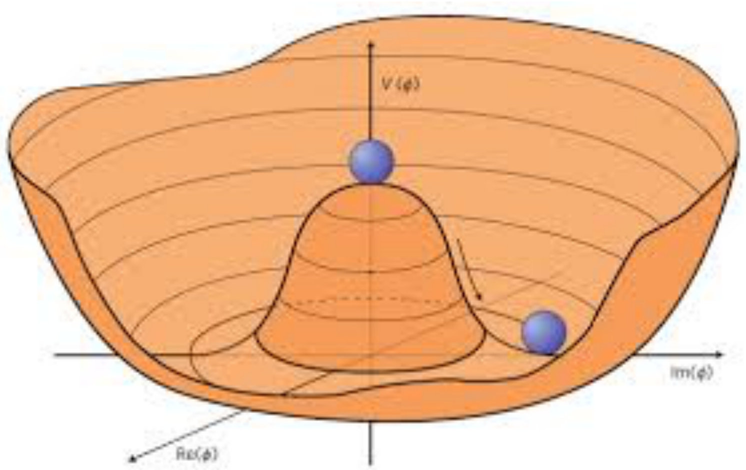
[Ooguri, Palti, GS, Vafa]

The Refined de Sitter Conjecture

- While not our motivation, our refined de Sitter conjecture can evade some counterexamples **[Denef, Hebecker, Wrase];[Conlon];[Murayama, Yamazaki, Yanagida]; [Choi, Chway,Shin];[Hamaguchi, Ibe, Moroi]** to the original de Sitter conjecture.

- The top of the Higgs potential:

$$|\nabla V| \sim \frac{10^{-55}}{M_{Pl}} V \quad \min(\nabla_i \nabla_j V) \sim -\frac{10^{35}}{M_{Pl}^2} V$$



- The top of the potential for the pion or QCD axion

$$\min(\nabla_i \nabla_j V) \sim -\frac{1}{f^2} V$$

The WGC for axions gives $f \leq M_{Pl}$

The Refined de Sitter Conjecture

[Ooguri, Palti, GS, Vafa]

Recall our assumptions:

- The Swampland Distance Conjecture holds for potentials
- In a weakly coupled regime where the tower is a dual description.
- In a quasi de Sitter setting (accelerating expansion with horizon)

$$\Rightarrow \quad |\nabla V| \geq \frac{c}{M_p} \cdot V \,, \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

Entropy Counting

- While the de Sitter conjecture is insensitive to the microstate counting, the cosmology depends on γ and δ.

- There is no known method to compute $S_{tower}(N,R)$ by enumerating all states in the Hilbert space of quantum gravity in a quasi-dS space.

- There are (at least) three types of states:

    - QFT states localized within the bulk of de Sitter
    - Black holes
    - States localized on the horizon

- We can count their subset when the low energy theory consists of N free particles, this can be regarded as a **lower bound** on $S_{tower}(N,R)$.

Entropy of Free Particles

- Consider a single free field with mass m in a box of size R, up to a maximum momentum k_{max}, the associated entropy and energy are:

$$S_{N=1} \sim (k_{\max} R)^3 \quad , \quad E_{N=1} \sim \omega \, (k_{\max} R)^3$$

- The maximum energy associated to these modes is:

$$E_{N=1} \sim k_{max} \left(k_{max} R\right)^3$$

- For such configuration to not collapse into a blackhole: $E_{N=1} < R$

$$k_{max} < R^{-\frac{1}{2}} \quad , \quad S_{\text{tower}} < R^{\frac{3}{2}}$$ **[Page'81];[Banks, '05]**

- Though this cannot saturate the Bousso bound, it may be possible with large N species of particles.

Entropy of a Tower of Free Particles

- Consider N species of such particles. To maximize the entropy, we can regard them to be in a thermal bath of a common temperature T.

$$S_N \sim N T^3 R^3 \ , \quad E_N \sim N T^4 R^3 \ .$$

- Not forming black holes implies:

$$T \leq N^{-\frac{1}{4}} R^{-\frac{1}{2}} \ , \quad S_N \sim N^{\frac{1}{4}} R^{\frac{3}{2}}$$

- S_N can saturate the Bousso bound for an extremely large number of species, with the minimum entropy assigned to each:

$$N \sim R^2 \quad T \sim \frac{1}{R} \quad S_1 \sim 1$$

- The low temperature and entropy per species means at borderline of thermodynamics, but can explicitly check by counting microstates.

Cosmological Implications

- While the de Sitter conjecture is insensitive to the O(1) values of γ and δ, the phenomenology is.
- How would these bounds apply to our universe, with $R \sim 10^{60}$?
- Consider an evenly spaced tower: $m_n \sim nm$ and a cutoff scale Λ_N below which there are N states contributing to the entropy:

$$N^{-\frac{1}{2}} < \Lambda_N < 1$$

- The tower of states have masses in the range: $R^{\frac{3(\delta-2)}{2\gamma}} < m < R^{\frac{\delta-2}{\gamma}}$
- For free particles, $\gamma = 1/4$, $\delta = 3/2$ give an unrealistic spectrum. If the entropy bound is saturated, our universe is not at parametrically weak coupling.
- Taking different values, $\gamma = 1$, $\delta = 7/4$ gives $N \sim 10^{15}$ and MeV<m<TeV.
- The mass of the tower is time-dependent as the quintessence field evolves and could lead to interesting pheno **[See e.g., Matsui, Takahashi, Yamada]**

Conclusions

Web of Conjectures

No global symmetry

↓ $g \neq 0$

Weak Gravity Conjecture (WGC)

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

→ Tower WGC

sLWGC

↓ $\geqq \to >$

Non-SUSY AdS

[Ooguri, Vafa,'16]

Web of Conjectures

No global symmetry

Distance Conjecture
[Ooguri, Vafa,'06]

↓ $g \neq 0$

Weak Gravity Conjecture (WGC)
[Arkani-Hamed, Motl, Nicolis, Vafa '06]

→ Tower WGC

sLWGC

↓ $\geqq \rightarrow >$

Non-SUSY AdS
[Ooguri, Vafa,'16]

Web of Conjectures

No global symmetry

Distance Conjecture

[Ooguri, Vafa,'06]

$g \neq 0$ $\downarrow$

Weak Gravity Conjecture (WGC)

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

$\longrightarrow$

Tower WGC

sLWGC

$\geqq \to >$ $\downarrow$

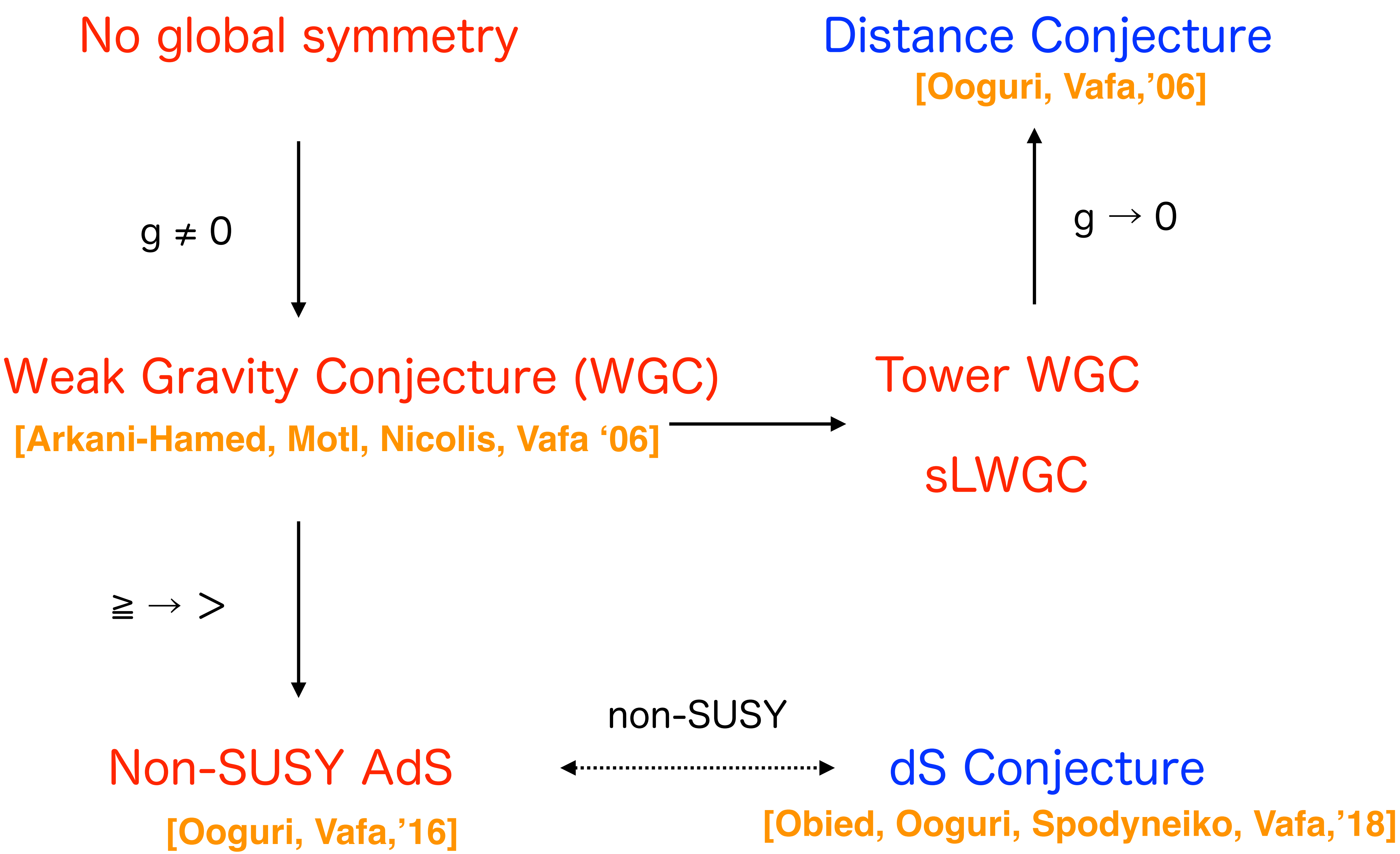
Non-SUSY AdS

[Ooguri, Vafa,'16]

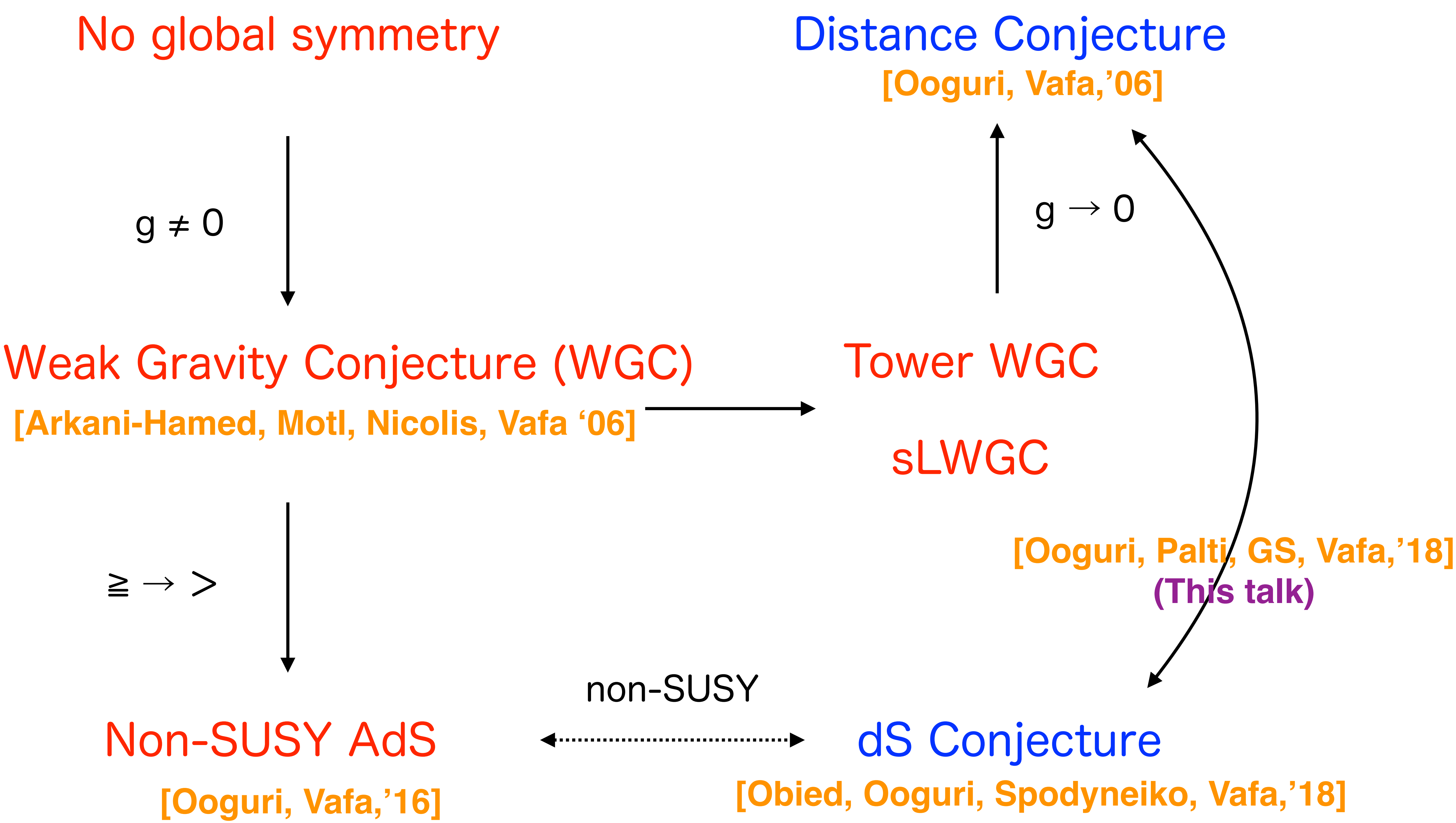
dS Conjecture

[Obied, Ooguri, Spodyneiko, Vafa,'18]

Web of Conjectures



Web of Conjectures



Conclusions

- A web of inter-related swampland conjectures with a variety of interesting applications in **cosmology** & **particle physics**.
- Ongoing global experimental effort in detecting inflationary gravity wave imprinted on CMB B-mode, targeting $r \sim 10^{-2}$ (or even 10^{-3})
- A detection at the targeted level would strongly suggest that the inflaton potential is nearly flat over a super-Planckian field range:

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

[Lyth, '96]

- The WGC has been used to argue that some large-field inflation models are in the swampland **[Brown, Cottrell, GS, Soler].** Models that evade this bound include:
  - Axion monodromy **[Silverstein, Westphal];[McAllister, Silverstein, Westphal]; [Marchesano, GS, Uranga];[Blumenhagen, Plauschinn];[Hebecker, Kraus, Witkowski].**
  - Multi-axion models using alignment **[Kim, Nilles, Peloso]** or clockwork **[Choi, Im]; [Kaplan, Rattazzi]**, ***but only w/ "spectator instantons"*** **[Brown,Cottrell,GS,Soler]**

Conclusions

- The dS conjecture naturally suggests the possibility that dark energy can be realized as a quintessence field, and can be tested experimentally by Euclid, DES, DESI, …
- The WGC for branes suggest that non-SUSY AdS vacua are unstable **[Ooguri, Vafa, '16]**. This AdS-instability conjecture has interesting consequences in particle physics **[Ibanez, Martin-Lozano, Valenzuela];[Hamada, GS].**
- We showed the WGC (mild form) for a wide class of theories, including generic string setups with dilation or moduli stabilized below M_S.
- We pointed out a connection between the distance conjecture and a refined version of the dS conjecture in any parametrically controlled regime of string theory.
- The refined de Sitter conjecture:

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \,, \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

turns out evade all counterexamples raised about scalar potential maxima.

Conclusions

- The dS conjecture naturally suggests the possibility that dark energy can be realized as a quintessence field, and can be tested experimentally by Euclid, DES, DESI, …
- The WGC for branes suggest that non-SUSY AdS vacua are unstable **[Ooguri, Vafa, '16]**. This AdS-instability conjecture has interesting consequences in particle physics **[Ibanez, Martin-Lozano, Valenzuela];[Hamada, GS].**
- We showed the WGC (mild form) for a wide class of theories, including generic string setups with dilation or moduli stabilized below M_S.
- We pointed out a connection between the distance conjecture and a refined version of the dS conjecture in any parametrically controlled regime of string theory.
- The refined de Sitter conjecture:

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \,, \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

turns out evade all counterexamples raised about scalar potential maxima.