Quantum Gravity and the Swampland

Gary Shiu
University of Wisconsin-Madison

String Theory and Data Science

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University of Wisconsin-Madison

- Persistent Homology and Non-Gaussianity”, A. Cole, GS, JCAP **1803**, 025 (2018) [arXiv: 1712.08159 [astro-ph.CO]].
- “Topological Data Analysis for the String Landscape”, A. Cole, GS, JHEP **1903**, 054 (2019) [arXiv: 1812.06960 [hep-th]].
- “Searching the Landscape of Flux Vacua with Genetic Algorithms,” A. Cole, A. Schachner, GS, arXiv:1907.10072 [hep-th], to appear in JHEP.

Quantum Field Theory Meets Gravity

- Initial excitement in string theory was not only that it offers a framework for QFT and gravity to meet but also due to its sense of **uniqueness**.
- Anomaly cancellation **[Green, Schwarz, '84]**: E_8 x E_8, SO(32), $U(1)^{496}$ and E_8 x $U(1)^{248}$ gauge groups, the former 2 are realized by the **heterotic string** **[Gross, Harvey, Martinec, Rohm,'85].**
- **Calabi-Yau compactification** **[Candelas, Horowitz, Strominger, Witten, '85]:**

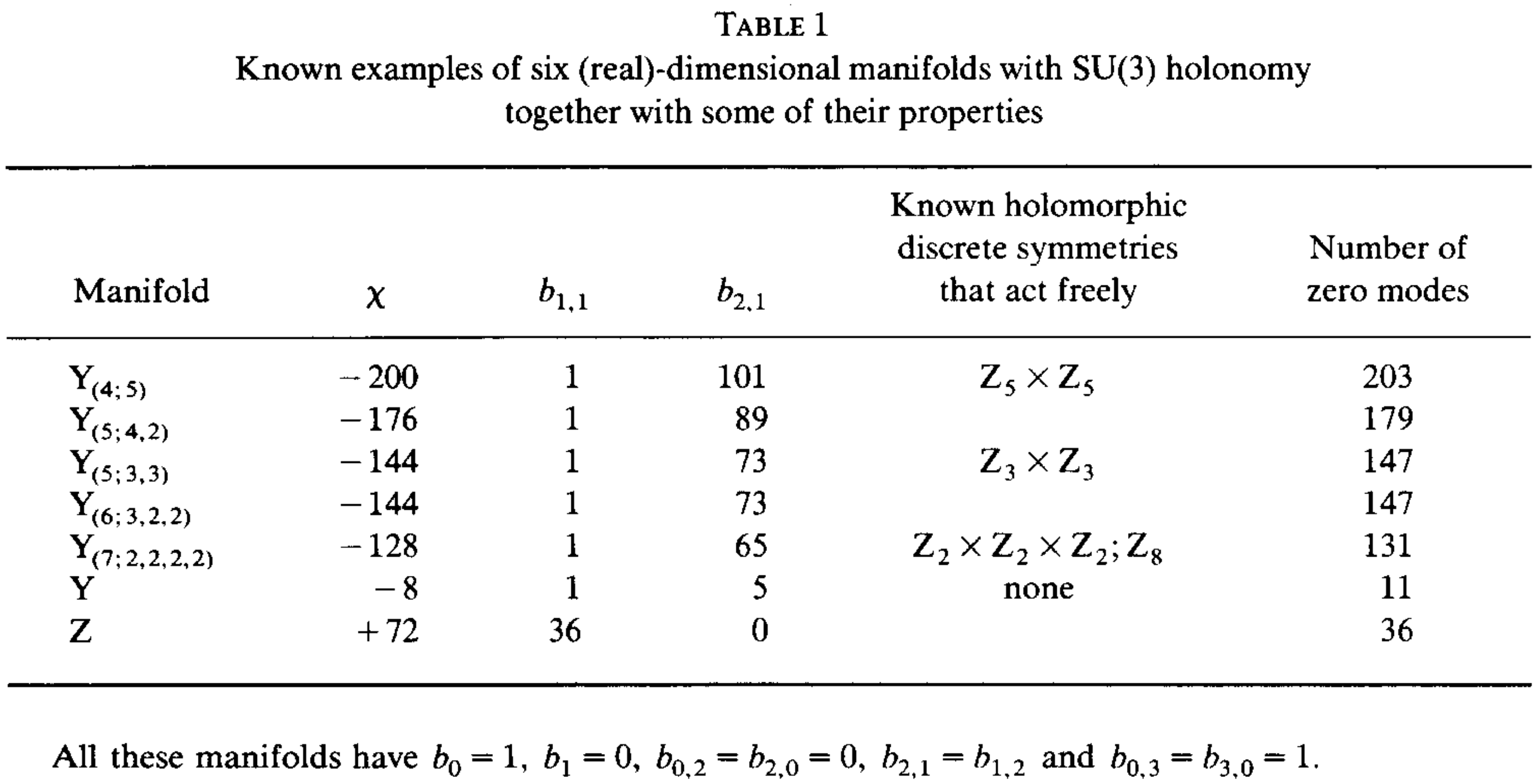


TABLE 1
Known examples of six (real)-dimensional manifolds with SU(3) holonomy
together with some of their properties

Manifold	χ	$b_{1,1}$	$b_{2,1}$	Known holomorphic discrete symmetries that act freely	Number of zero modes
$Y_{(4;5)}$	-200	1	101	$Z_5 \times Z_5$	203
$Y_{(5;4,2)}$	-176	1	89		179
$Y_{(5;3,3)}$	-144	1	73	$Z_3 \times Z_3$	147
$Y_{(6;3,2,2)}$	-144	1	73		147
$Y_{(7;2,2,2,2)}$	-128	1	65	$Z_2 \times Z_2 \times Z_2; Z_8$	131
Y	-8	1	5	none	11
Z	$+72$	36	0		36

All these manifolds have $b_0 = 1$, $b_1 = 0$, $b_{0,2} = b_{2,0} = 0$, $b_{2,1} = b_{1,2}$ and $b_{0,3} = b_{3,0} = 1$.

String Theory Landscape

String Theory Landscape

String Theory Landscape

$10^{272,000}$ "vacua"

[Taylor, Wang, '15]

10^{500} "vacua"

[Douglas '03]

Landscape vs Swampland

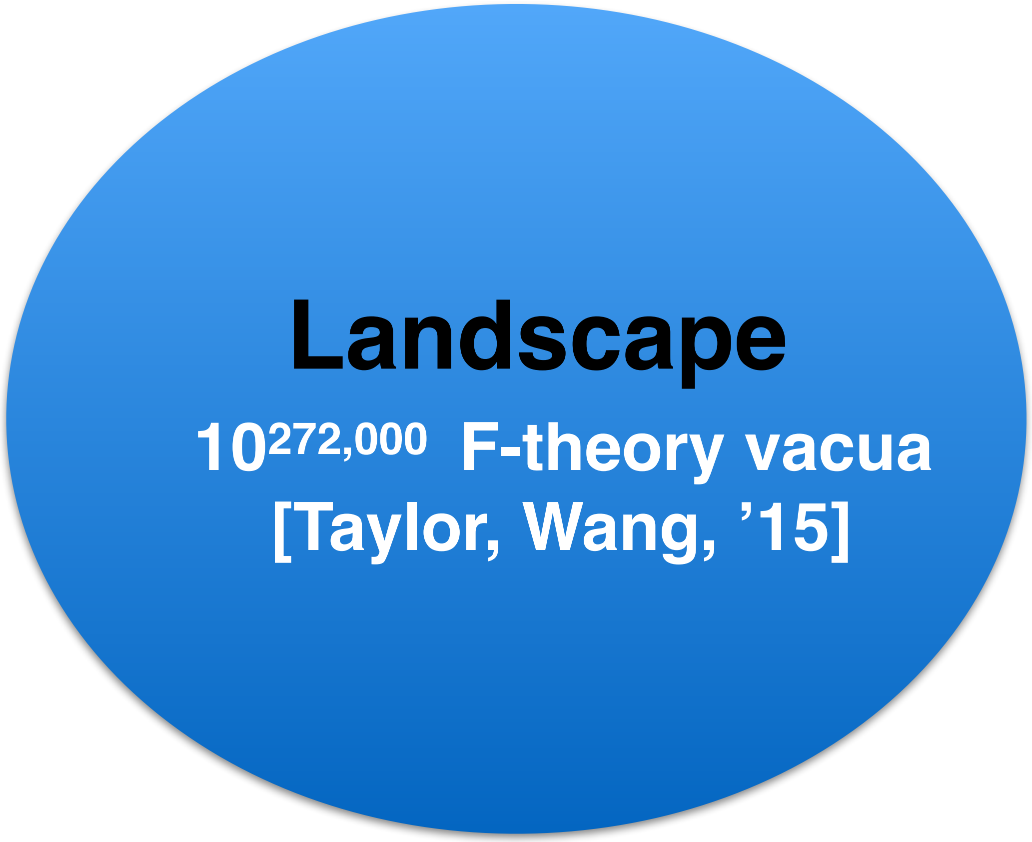
Landscape

Landscape vs Swampland

Landscape

10^{500} IIB flux vacua
[Douglas, '03]

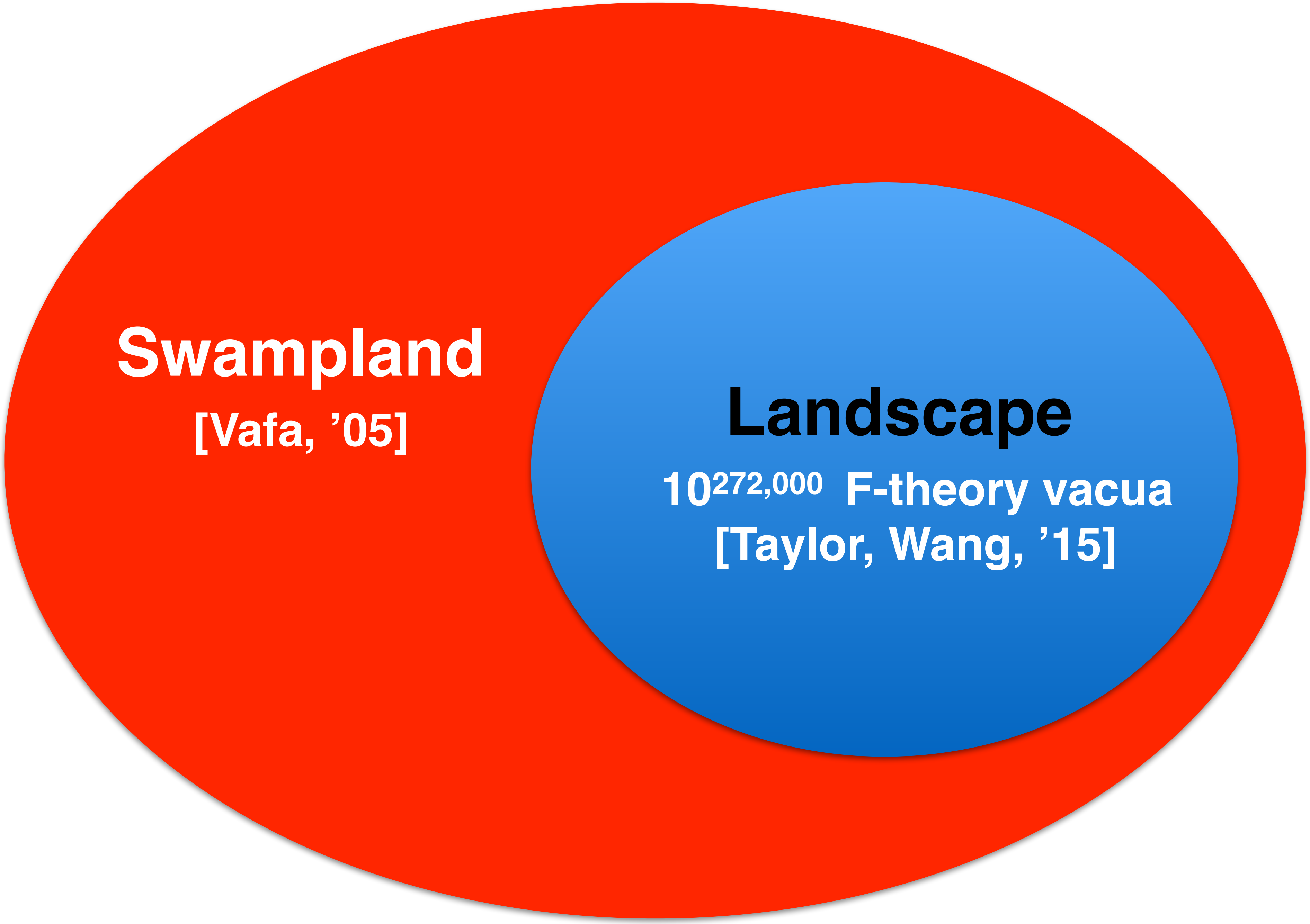
Landscape vs Swampland



Landscape

$10^{272,000}$ F-theory vacua
[Taylor, Wang, ’15]

Landscape vs Swampland



Swampland

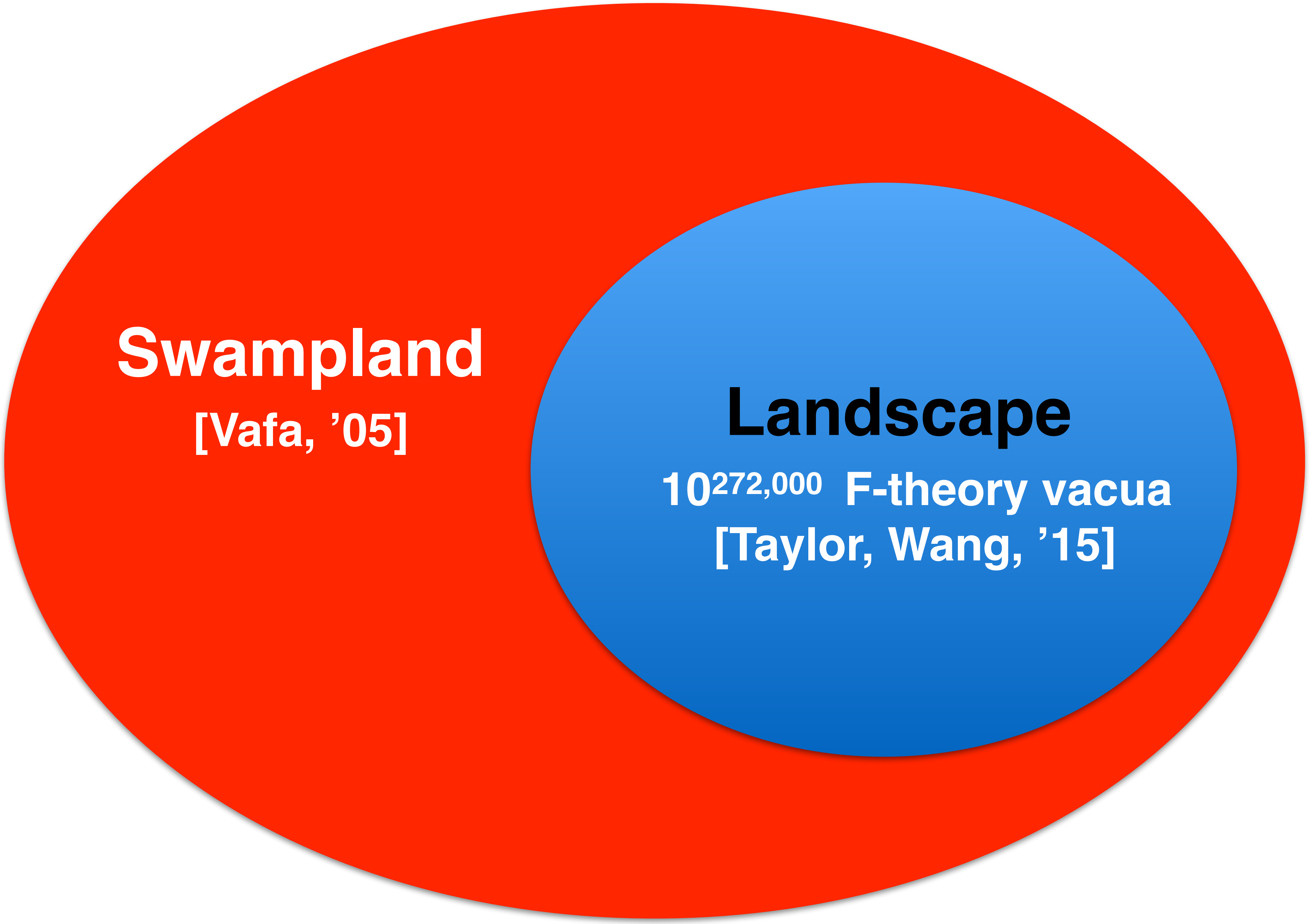
[Vafa, ’05]

Landscape

$10^{272,000}$ F-theory vacua

[Taylor, Wang, ’15]

Landscape vs Swampland



Swampland

[Vafa, ’05]

Landscape

$10^{272,000}$ F-theory vacua

[Taylor, Wang, ’15]

What properties delineate the landscape from the swampland?

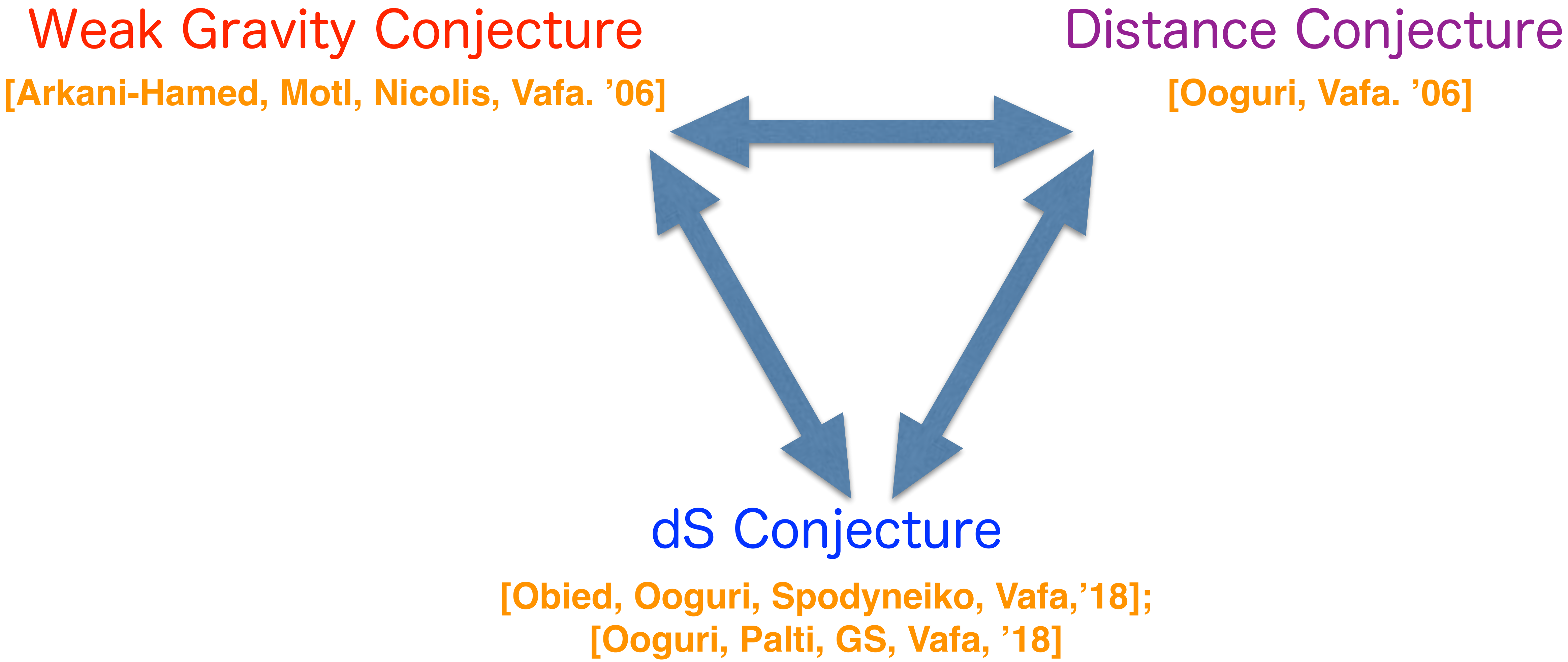
What are the phenomenological implications?

Even limiting the scope to my own work, there is time only for a “slice” of the swampland program in this talk:

- **Branes and the Swampland** **[Kim, GS, Vafa, ’19]**
- **Weak Gravity Conjecture (WGC):**
  - WGC, Black Hole Entropy, & Modular Invariance **[Aalsma, Cole, GS, ’19]**
  - Black hole thermodynamics and the WGC **[Loges, Noumi, GS, ’19]**
  - WGC from Unitarity and Causality **[Hamada, Noumi, GS, ’18]**
  - Tower WGC **[Andriolo, Junghans, Noumi, GS, ’18]**
  - WGC and holography → Sublattice WGC **[Montero, GS, Soler, ’16]**
  - Constraints on (large field) inflation **[Brown, Cottrell, GS, Soler, ’15, ’16]**
- **AdS instability conjecture and Particle Physics** **[Hamada, GS, ’17]**
- **de Sitter in String Theory**
  - Refined de Sitter Conjecture **[Ooguri, Palti, GS, Vafa, ’18]**
  - 10d description of KKLT **[Hamada, Hebecker, GS, Soler, ’18, ’19]**

Swampland Criteria

There are varying degrees of understanding for different swampland criteria and their interconnections:



Weak Gravity Conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa. ’06]

Distance Conjecture

[Ooguri, Vafa. ’06]

dS Conjecture

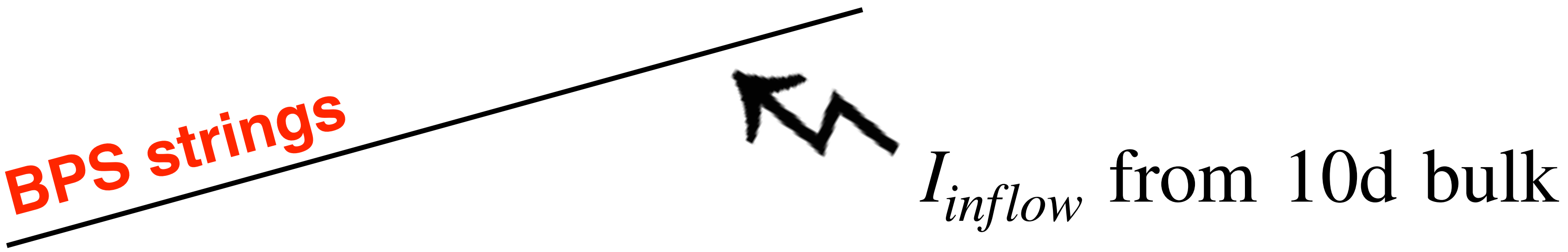
[Obied, Ooguri, Spodyneiko, Vafa,’18];
[Ooguri, Palti, GS, Vafa, ’18]

These criteria do not follow from purely low-energy EFT considerations. Why are they necessary for consistency of quantum gravitational theories?

Branes and the Swampland

[Kim, GS, Vafa, ’19]

- Completeness of spectrum of charged branes **[Polchinski ’03], [Banks, Seiberg, ’10]:** use them to probe consistency of EFTs coupled to gravity.
- Consider e.g., a BPS string:



- The string action is not invariant under a gauge transformation of the 2-form B_2 to which it couples → **anomaly inflow.**
- In a consistent theory, these anomalies must be cancelled by the anomalies coming from the dofs in a **unitary** worldsheet theory.

Branes and the Swampland

[Kim, GS, Vafa, '19]

- First consider N=(1,0) SUGRA theories in 10d & 6d as gauge and gravitational anomaly cancellations severely limit the possibilities.
- We illustrate the power of this approach with just a few examples and with only **string probes** but we expect this program of using **brane probes** to understand swampland criteria has wider applicabilities.
- We showed the 10d anomaly-free theories with $E_8 \times U(1)^{248}$ and $U(1)^{496}$ gauge groups (which have no string realizations) are in the swampland.
- Infinite families of anomaly-free 6d theories **[Kumar, Morrison, Taylor, '10]** with unbounded gauge group rank, or unbounded number of tensors or matter in exotic representations. We showed that **unitarity of current algebra on string probes** can rule out some of these infinite families.
- Our method was recently used to bound the # of abelian gauge group factors in 6d gravitational theories with minimal SUSY **[Lee, Weigand].**

Quantum Gravity and Global Symmetries

Quantum Gravity 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];** recently revisited using holography **[Harlow, Ooguri, '18].**

- Many phenomenological ramifications, e.g., milli-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"

- This is a scale-dependent statement, but as we'll see, the WGC comes with a UV cutoff Λ (magnetic WGC).
- For every long range gauge field there exists a particle of charge q and mass m, s.t.

$$\frac{q}{m} M_P \geq \text{“1”}$$

- This implies an extremal BH can decay.
- Applying the WGC to magnetically charged states imply:

$$q_{mag} \sim 1/g, \quad m_{mag} \sim \Lambda/g^2 \quad \Rightarrow \quad \Lambda \lesssim g(\Lambda) M_P$$

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

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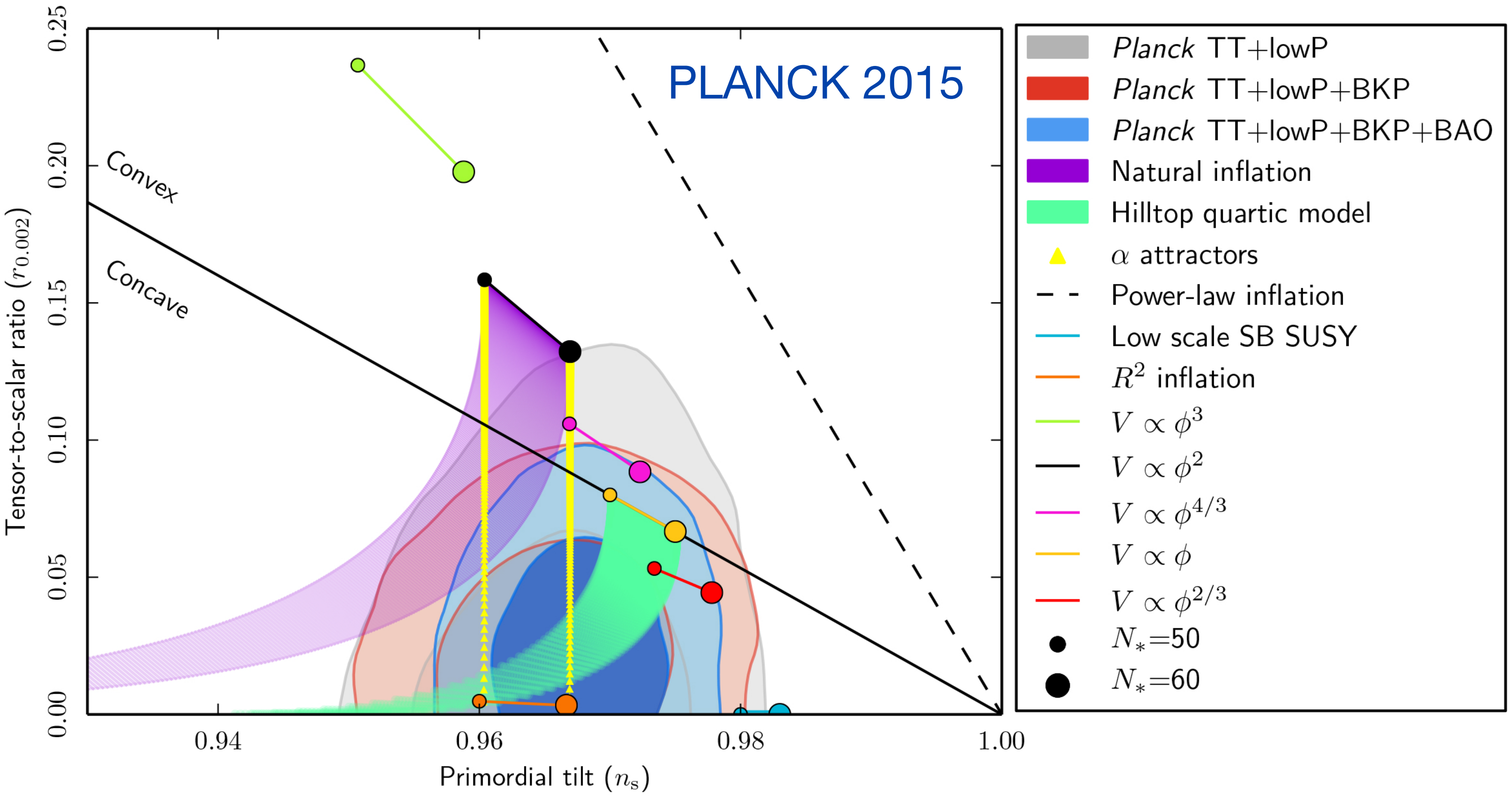
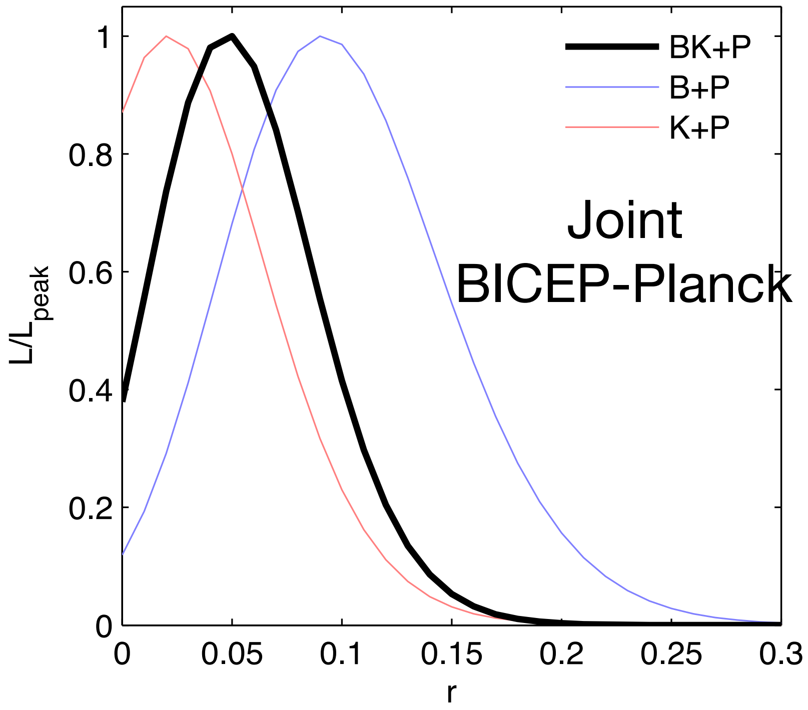
WGC and Inflation

Primordial Gravitational Waves





Many experiments including BICEP/KECK, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD, … can potentially detect primordial B-mode at the sensitivity r~10^{-2}.

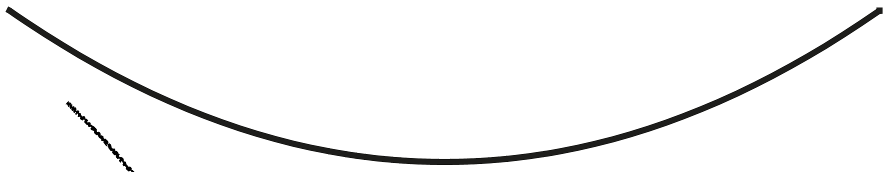
Further experiments, such as CMB-S4, PIXIE, LiteBIRD, DECIGO, Ali, .. may improve further the sensitivity to eventually reach r ~ 10^{-3}.

B-mode and UV Sensitivity

A detection at the targeted level implies that the inflaton potential is nearly flat over a **super-Planckian** field range:

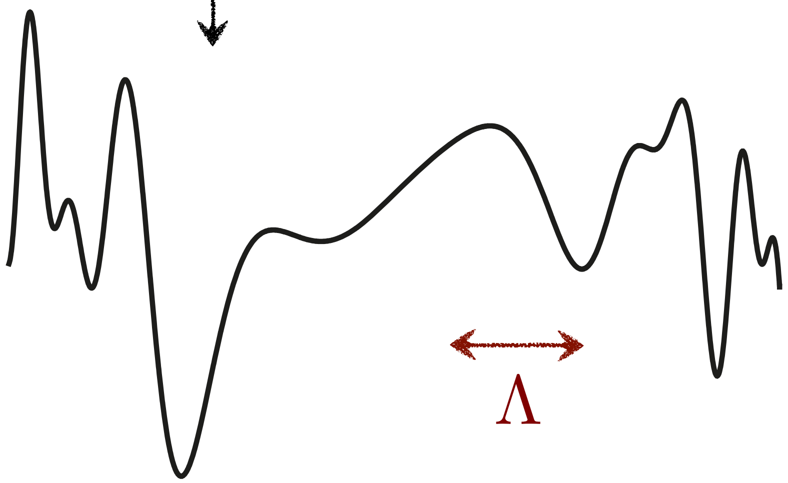
$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

Lyth '96



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

$$\Big\downarrow \; c_i \sim \mathcal{O}(1)$$



"Large field inflation" are highly **sensitive to UV physics**

Axions and ALPs

The QCD axion [Wilczek, ’78]; [Weinberg, ’78] was introduced in the context of the Pecci-Quinn mechanism and the strong CP problem.

An axion enjoys a **perturbative shift symmetry.**

String theory has many **higher-dimensional form-fields**:

e.g.

$$F = \mathrm{d}A$$

3-form flux

2-form gauge potential:

gauge symmetry: $A \rightarrow A + \mathrm{d}\Lambda$

Integrating the 2-form over a 2-cycle gives an ***axion-like particle* (ALP)**:

$$a(x) \equiv \int_{\Sigma_2} A$$

The gauge symmetry becomes a **shift symmetry,** that is broken by non-perturbative (instanton) effects**.**

WGC and Axions

- Consider a U(1) gauge theory in 5d, and compactify on S to 4d. Upon dimensional reduction: $A_M(x, x_4) \to (A_\mu(x), \phi(x))$

$$S = \int d^5x \, \frac{-1}{4g_5^2} F_{MN}F^{MN} \quad \longrightarrow \quad \int d^4x \left(\frac{-1}{4g_4^2} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi \right)$$

- The gauge symmetry leads to an axion shift symmetry $\phi = \phi + c$

- Topologically non-trivial Euclidean configurations (instantons) with charged fields wrapping the 5d circle generate a potential

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

$$S_{inst} = 2\pi R m_5$$
$$f^{-1} = q_5\sqrt{2\pi R}$$

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

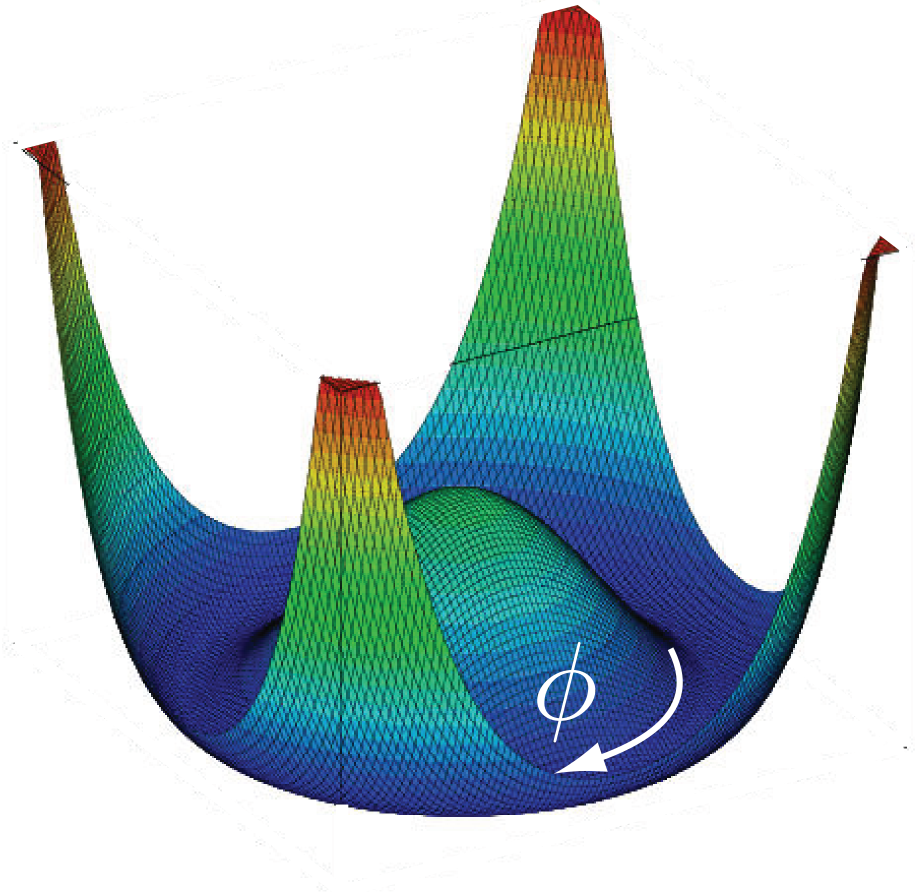
$$\boxed{f \cdot S_{inst} \leq M_p}$$

More generally, using duality:
Brown, Cottrell, GS, Soler, '15

Axions & Large Field Inflation

Natural Inflation [Freese, Frieman, Olinto]

Pseudo-Nambu-Goldstone bosons are natural inflaton candidates.



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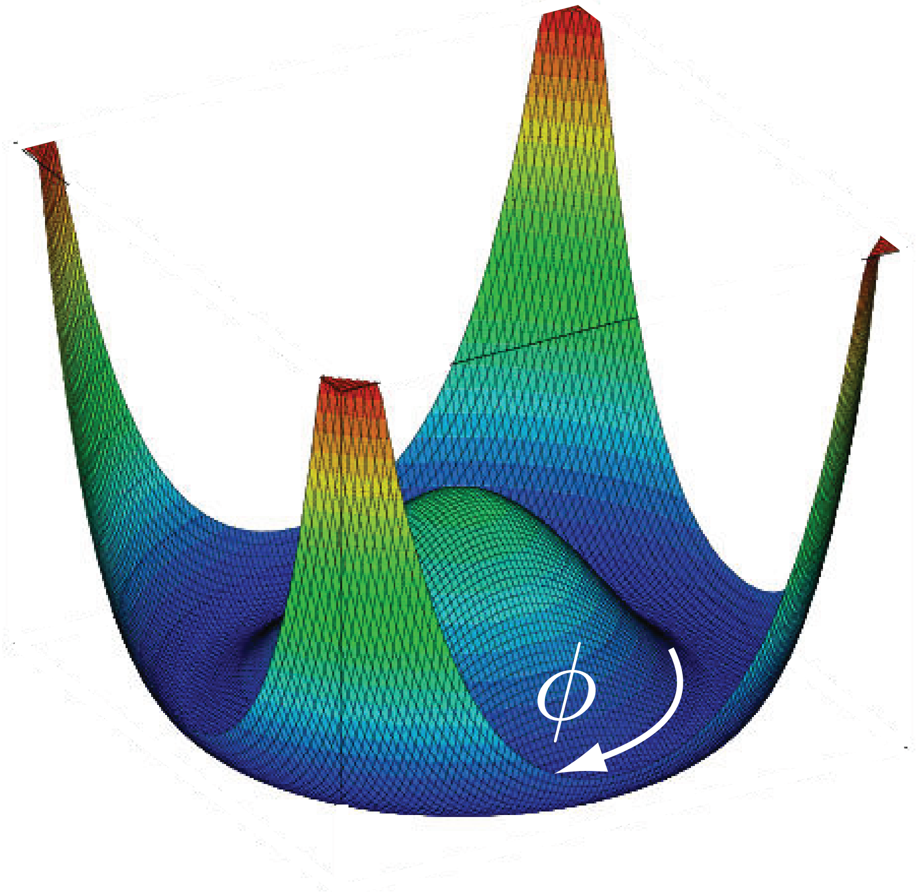
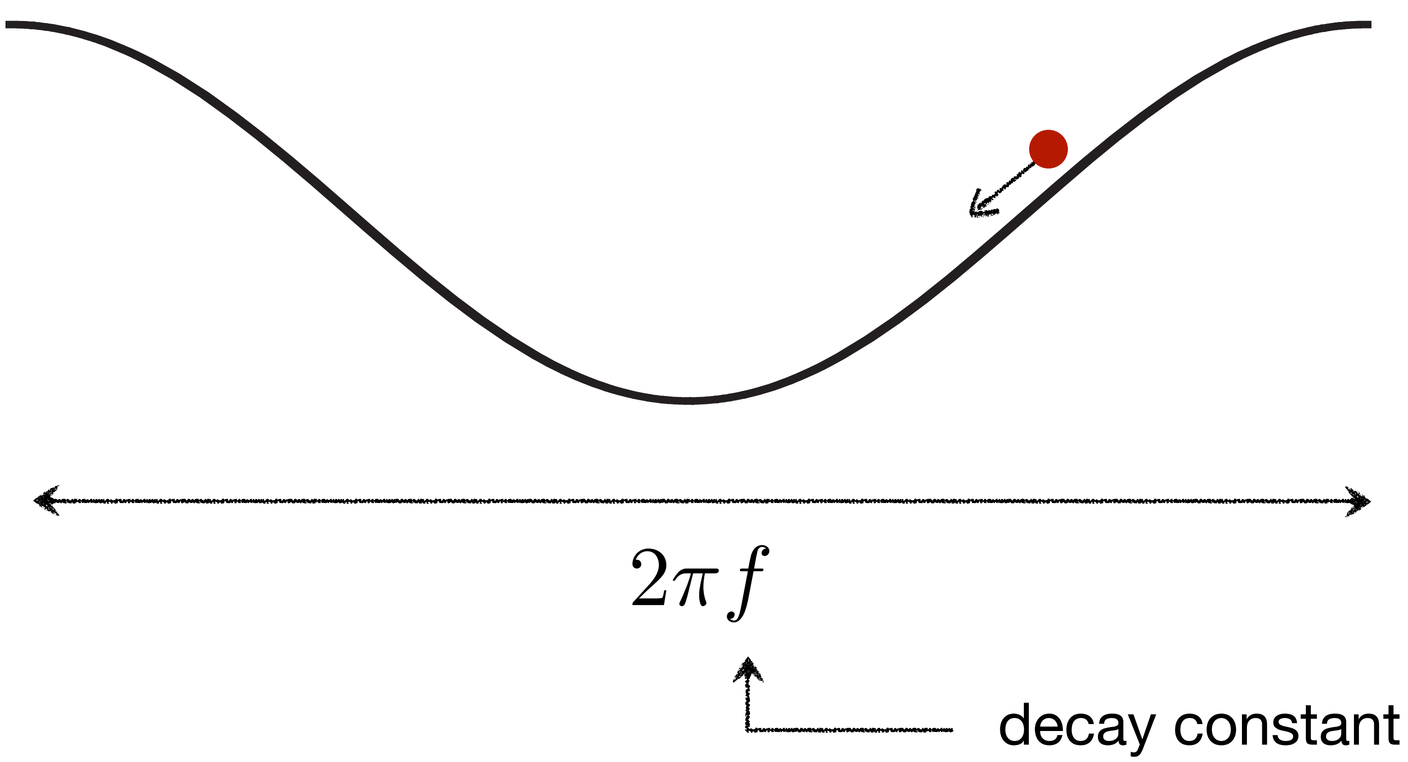


They satisfy a shift symmetry that is only broken by non-perturbative effects:



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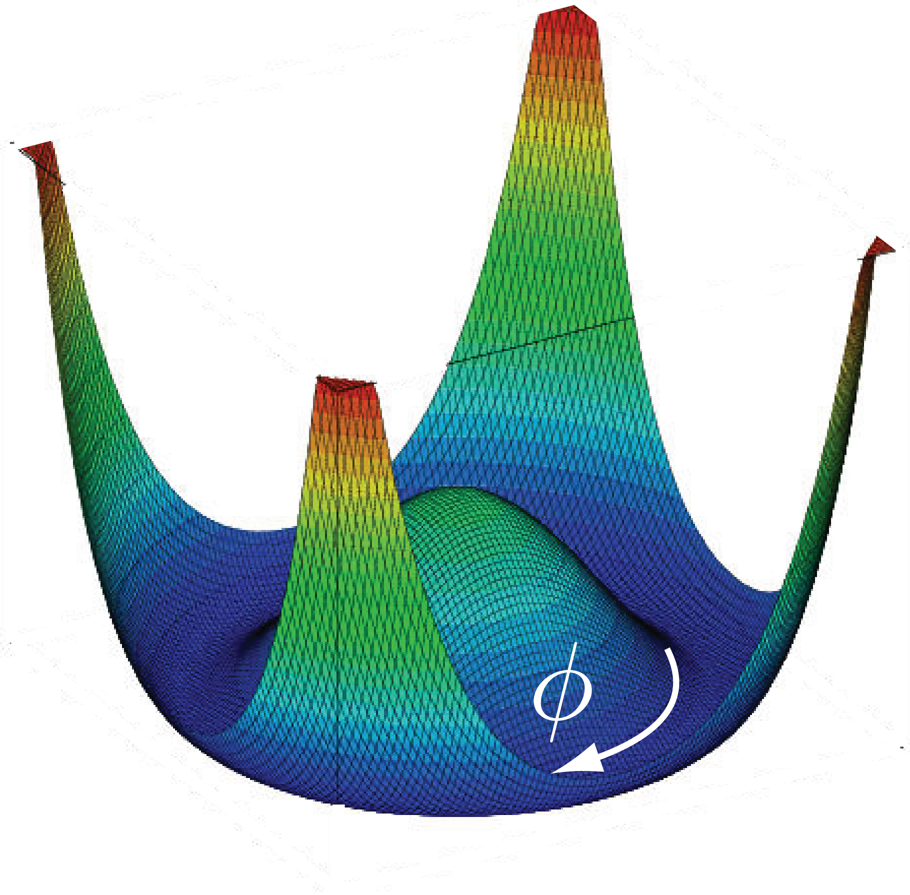

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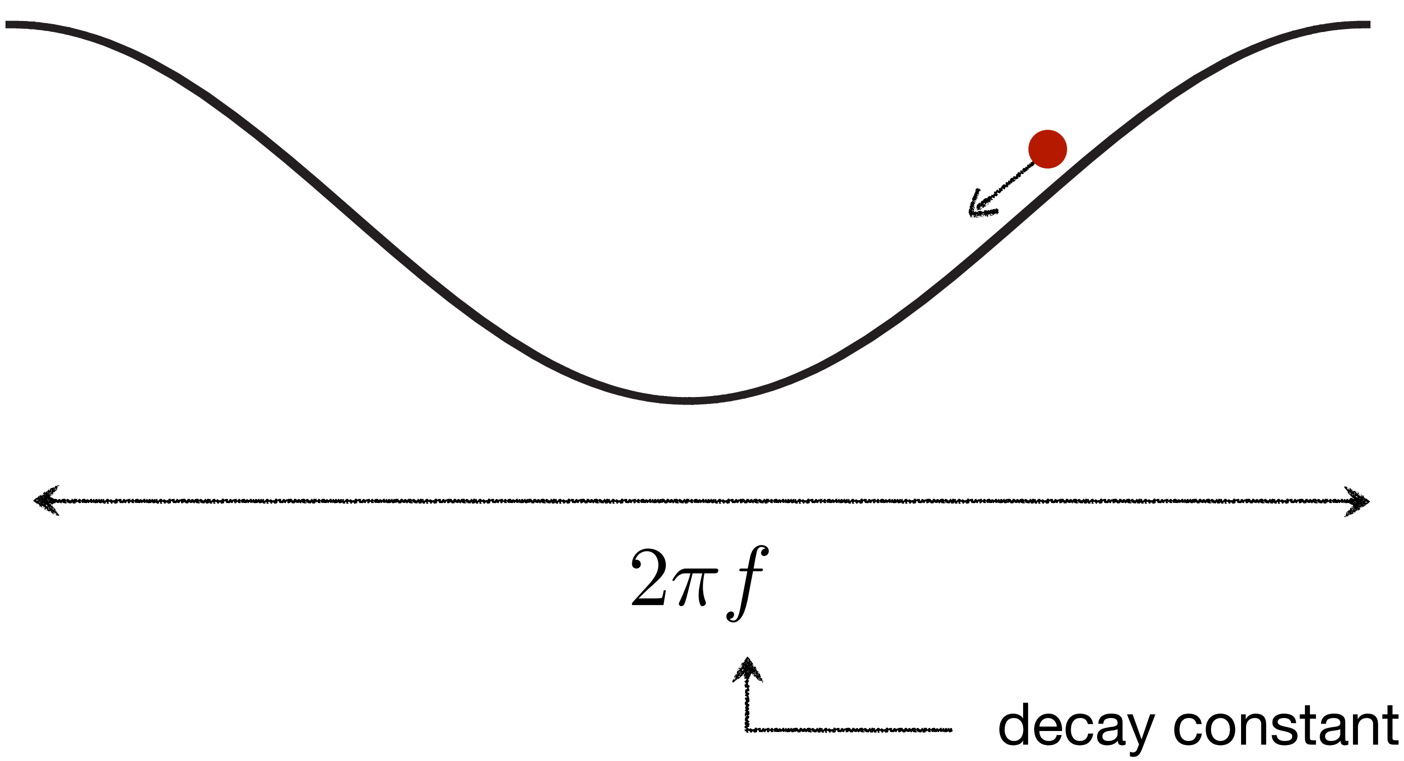

Slow roll: $f > M_P$

$$V(\phi) = 1 - \Lambda^{(1)} \cos\left(\frac{\phi}{f}\right) + \cancel{\sum_{k>1} \Lambda^{(k)} \left[1 - \cos\left(\frac{k\phi}{f}\right)\right]} \quad \text{if} \quad \frac{\Lambda^{(n+1)}}{\Lambda^{(n)}} \sim e^{-S_{\text{inst}}} << 1$$

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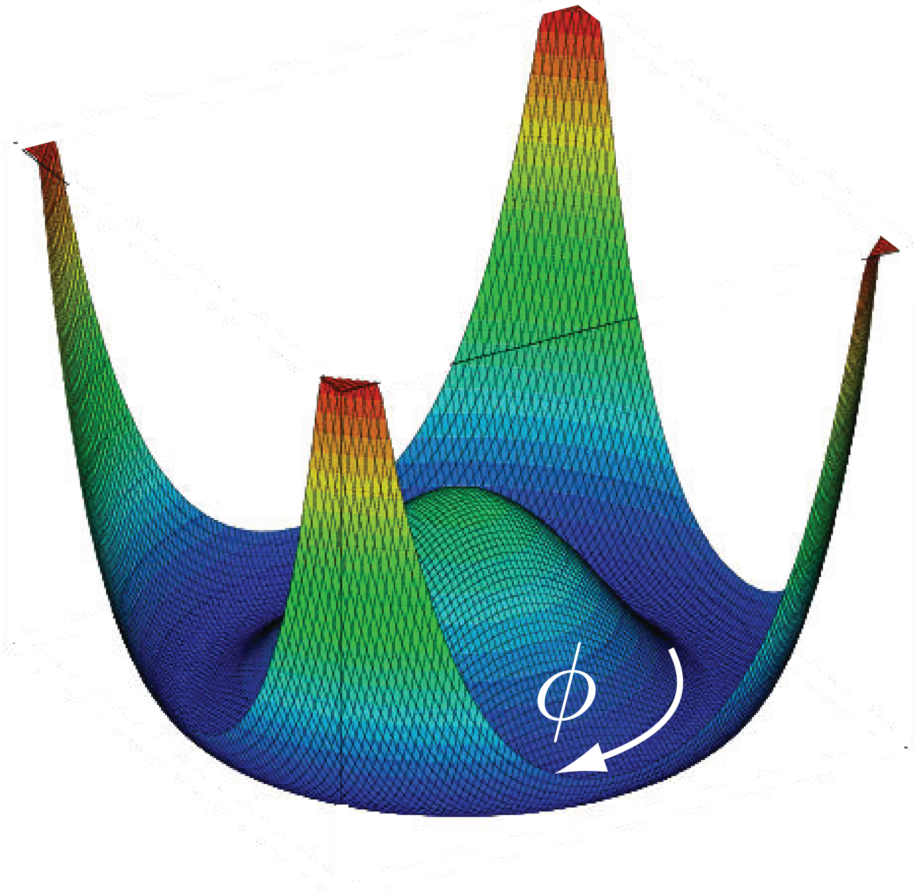

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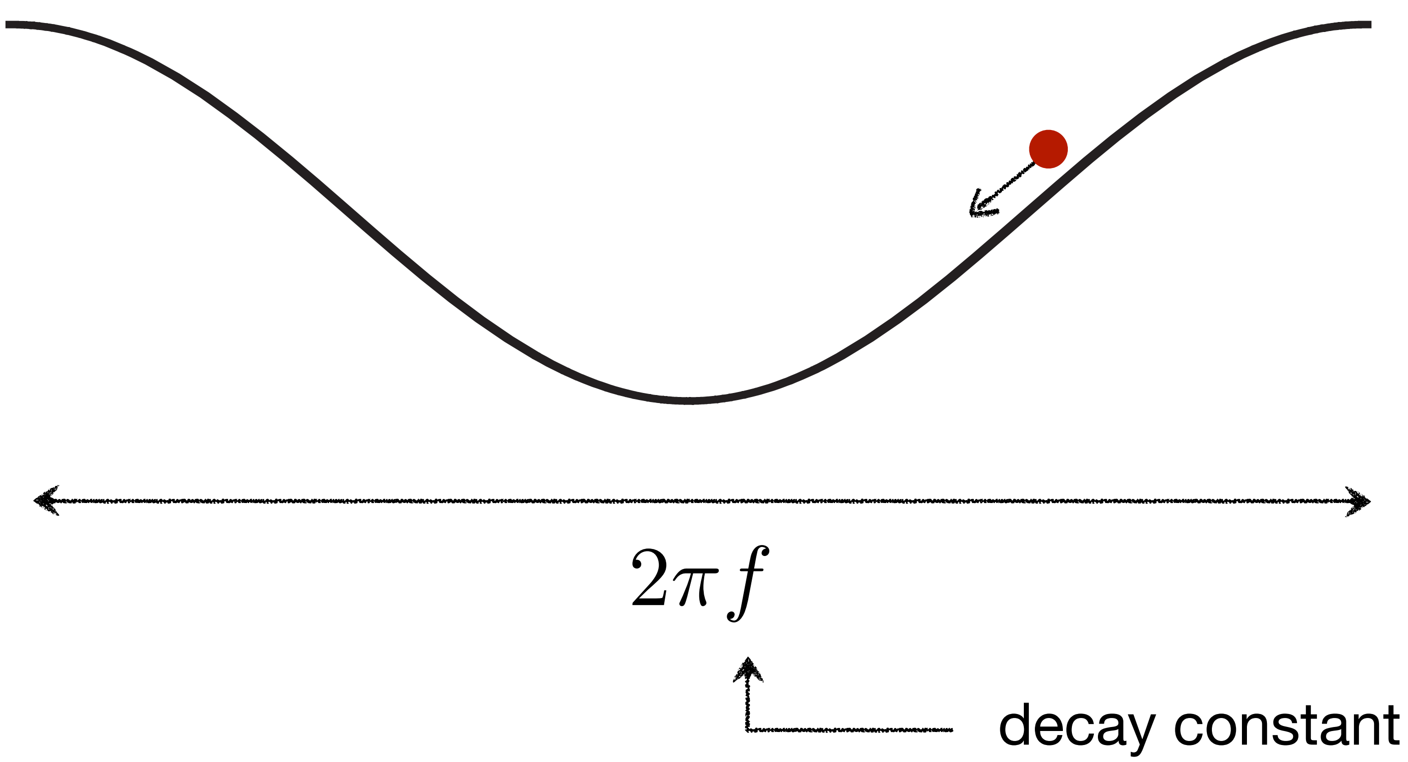

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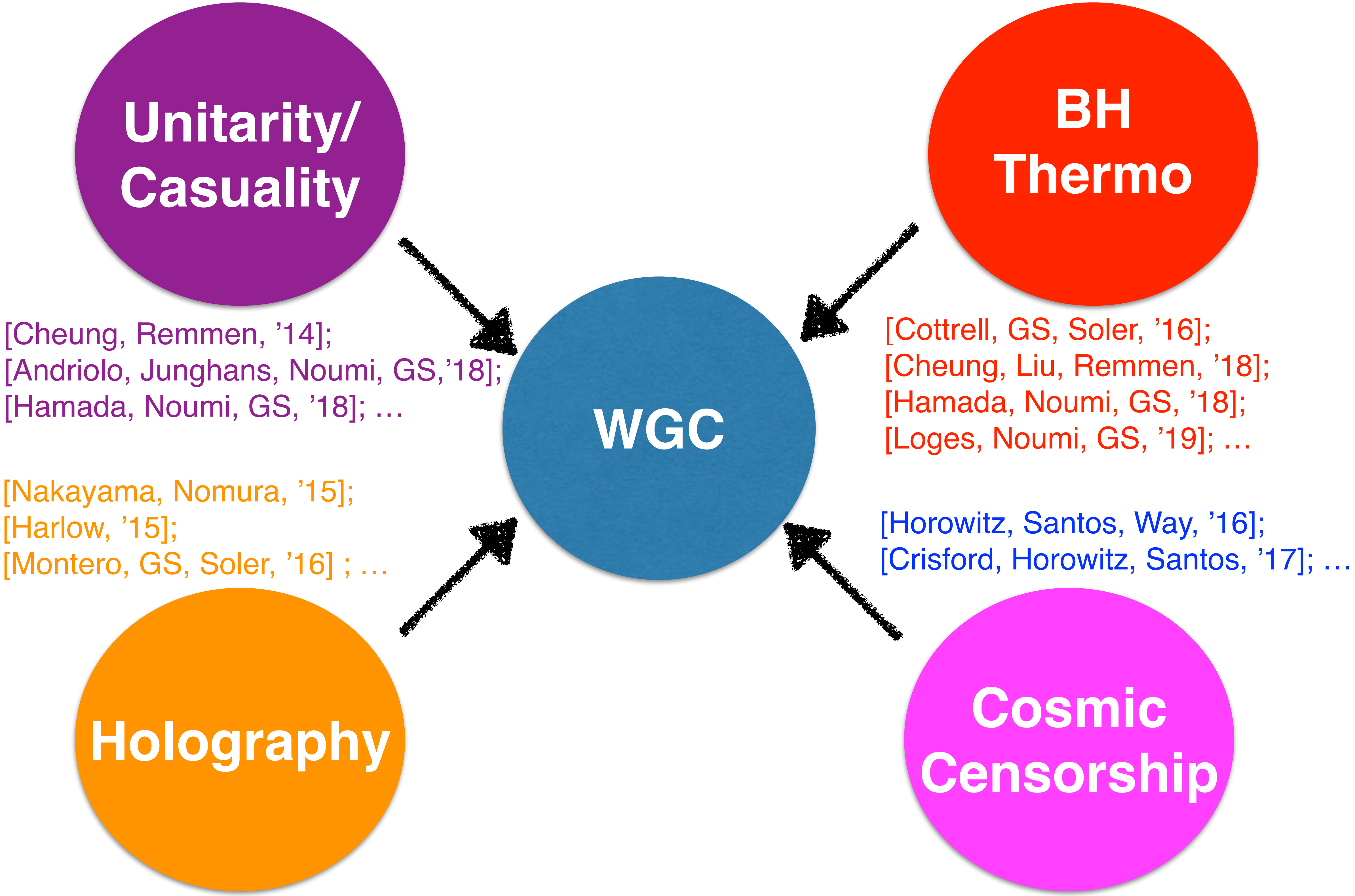
The WGC implies that these conditions cannot be *simultaneously* satisfied.

Evidence for the WGC



Unitarity/ Casuality

[Cheung, Remmen, ’14];
[Andriolo, Junghans, Noumi, GS,’18];
[Hamada, Noumi, GS, ’18]; …

BH Thermo

[Cottrell, GS, Soler, ’16];
[Cheung, Liu, Remmen, ’18];
[Hamada, Noumi, GS, ’18];
[Loges, Noumi, GS, ’19]; …

WGC

[Nakayama, Nomura, ’15];
[Harlow, ’15];
[Montero, GS, Soler, ’16] ; …

Holography

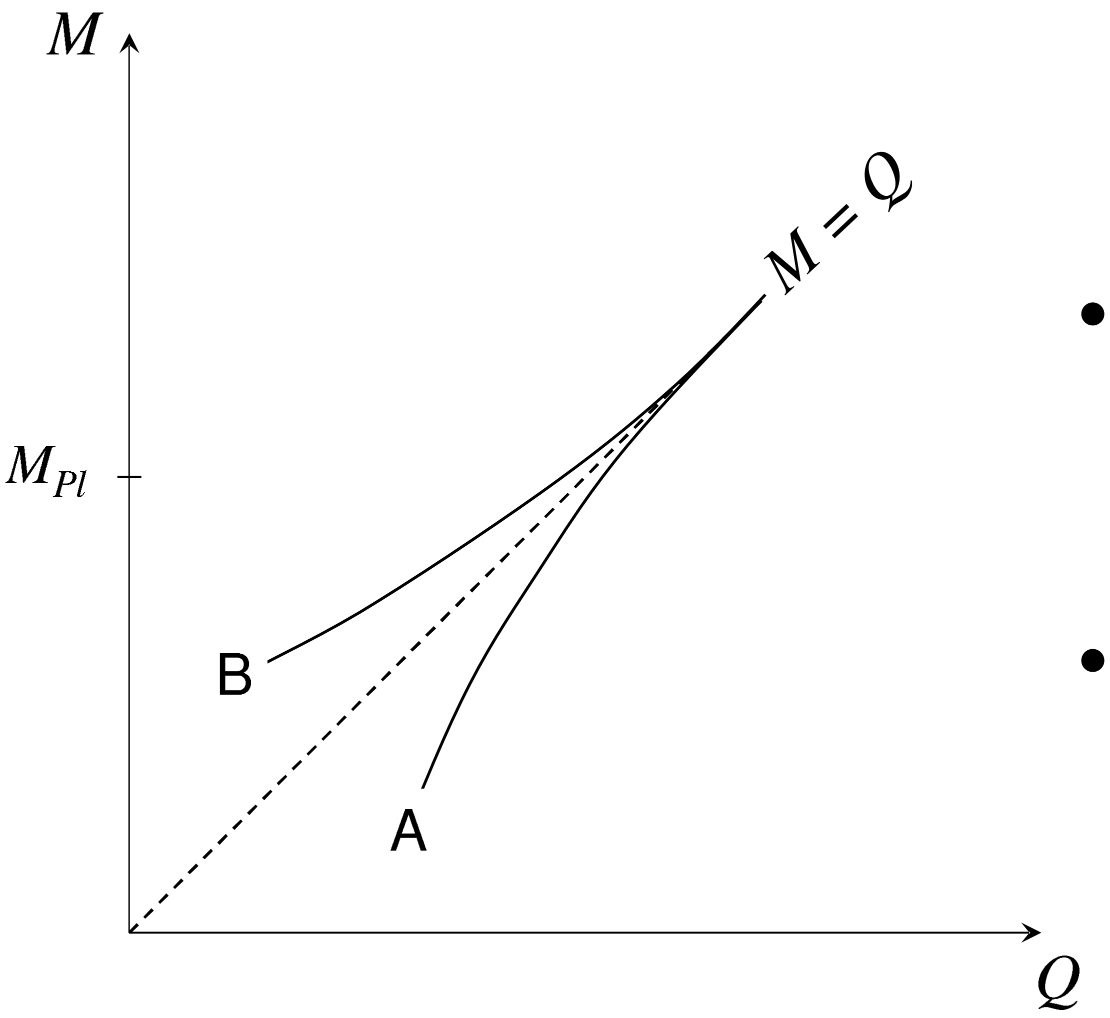
[Horowitz, Santos, Way, ’16];
[Crisford, Horowitz, Santos, ’17]; …

Cosmic Censorship

WGC and Black Holes

Extremality of Black Holes

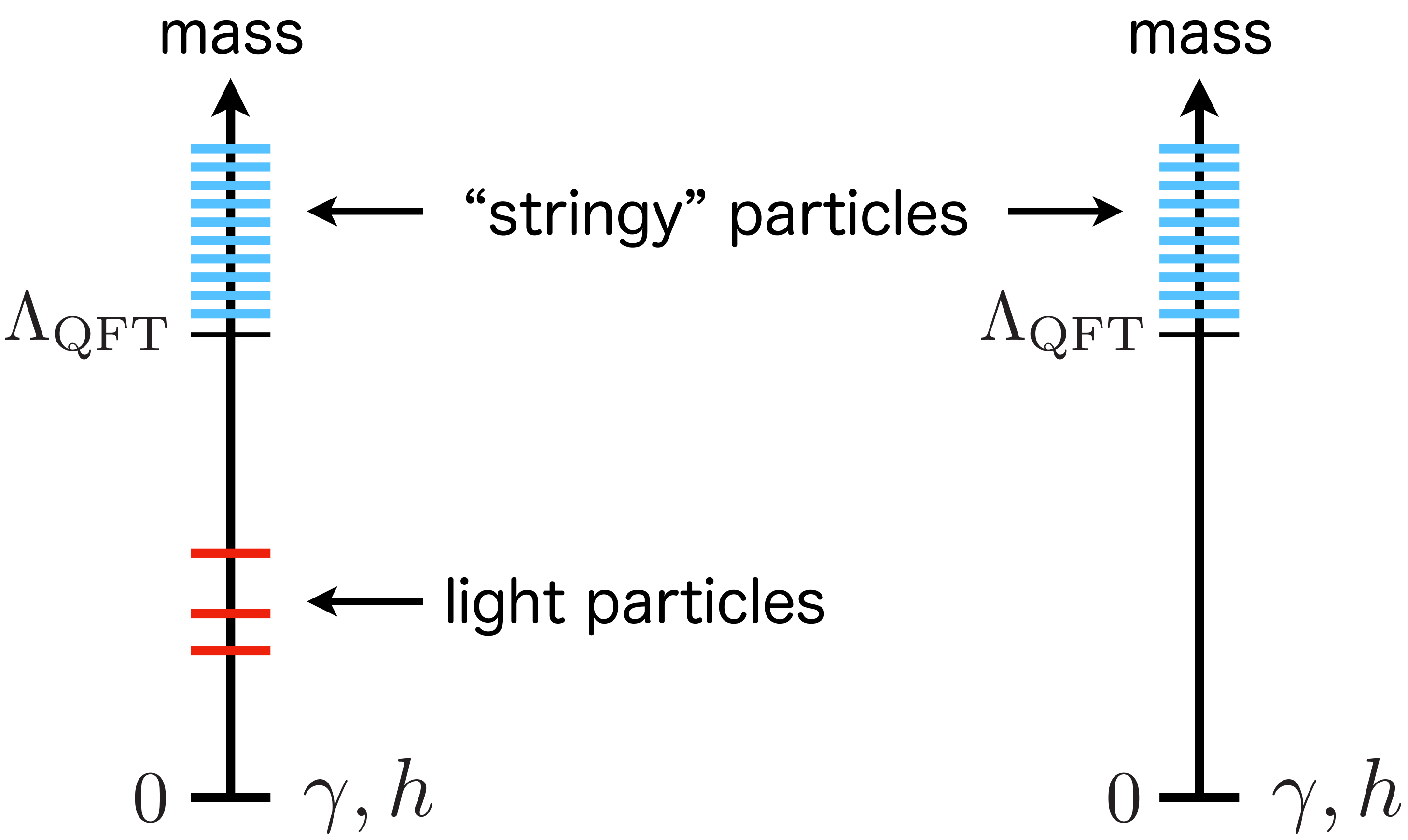
- The mild form of the WGC requires only ***some*** state for an extremal BH to decay to.
- **Can an extremal BH satisfy the WGC?**



- 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 photon & graviton.
- In D=4, the general effective action up to 4-derivative operators (assume parity invariance for simplicity):

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

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:

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

[Kats, Motl, Padi, '06]

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

because extremal BHs in Einstein-Maxwell theory satisfy:

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

- 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: Step 1

[Hamada, Noumi, GS]

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

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

because α_3 leads to causality violation and an infinite tower of massive higher spin states is required to UV complete the EFT at tree-level **[Camanho, Edelstein, Maldacena, Zhiboedov].**

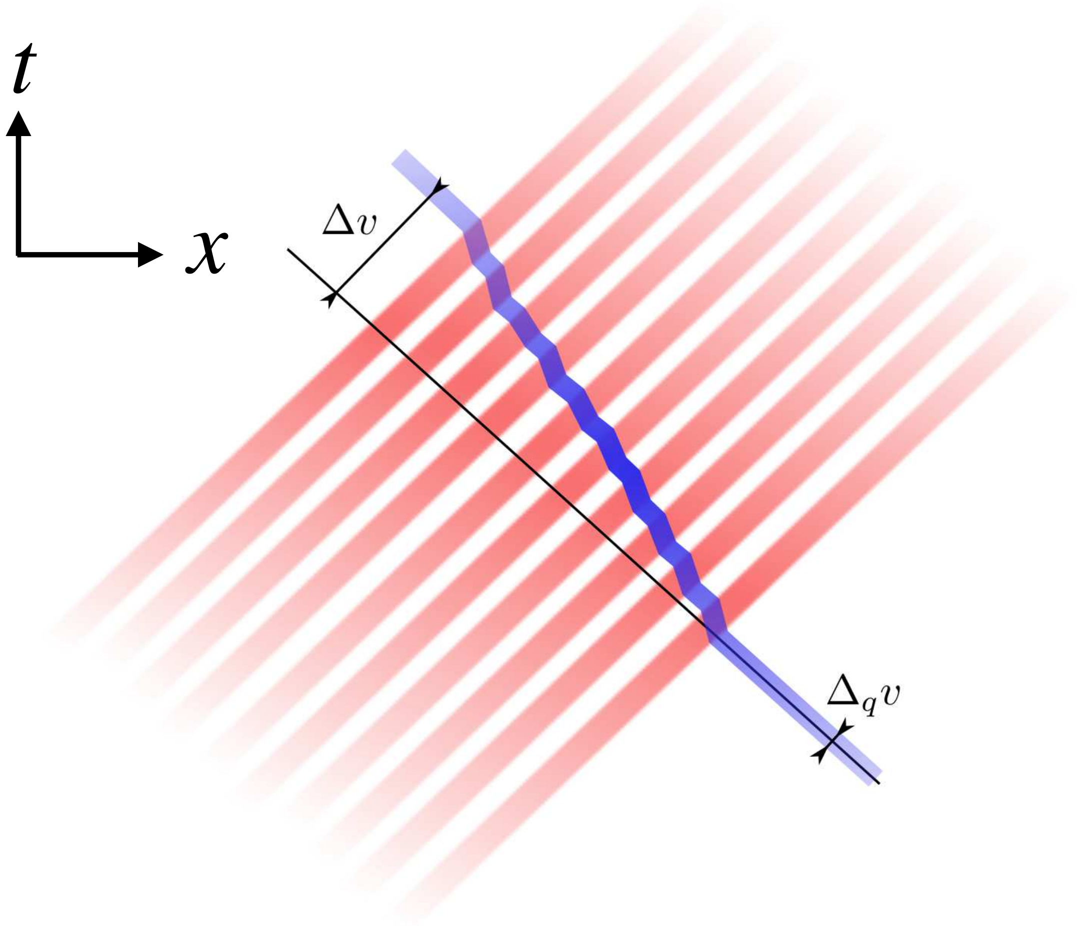


fig: Camanho et al ’14

phase shift of photon propagation:

$$\delta \sim s \left(\ln(L_{\rm IR}/b) \pm \frac{|\alpha_3|}{b^2} + \dots \right)$$

time delay in GR

helicity dependent phase shit

b : impact parameter $L_{\rm IR}$: IR cutoff

Sketch of the Proof: Step 1

[Hamada, Noumi, GS]

- **Time advancement** if $b^2 \ln(L/b) \ll |\alpha_3|$
- Phase shift generated by spin J is $\delta \sim s^{J-1}$. A finite # of higher spin particles does not help → infinite tower of higher spin states.
- **Causality violation** unless the scale $M_P/\alpha_3^{1/2}$ is above $\Lambda_{QFT.}$
- Integrating out light neutral scalars does not give significant contributions to α_3 and so $|\alpha_1| \gg |\alpha_3|$
- If there are different Regge towers as in theories with open strings:

$$\alpha_{1,2,3}^{\text{closed}} \sim \frac{M_{\text{Pl}}^2}{M_s^2} \quad \ll \quad \alpha_{1,2}^{\text{open}} \sim \frac{M_{\text{Pl}}^2}{g_s M_s^2} \,, \qquad g_{\text{open}} \sim \sqrt{g_s} \gg g_s$$

- 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: Step 2

[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

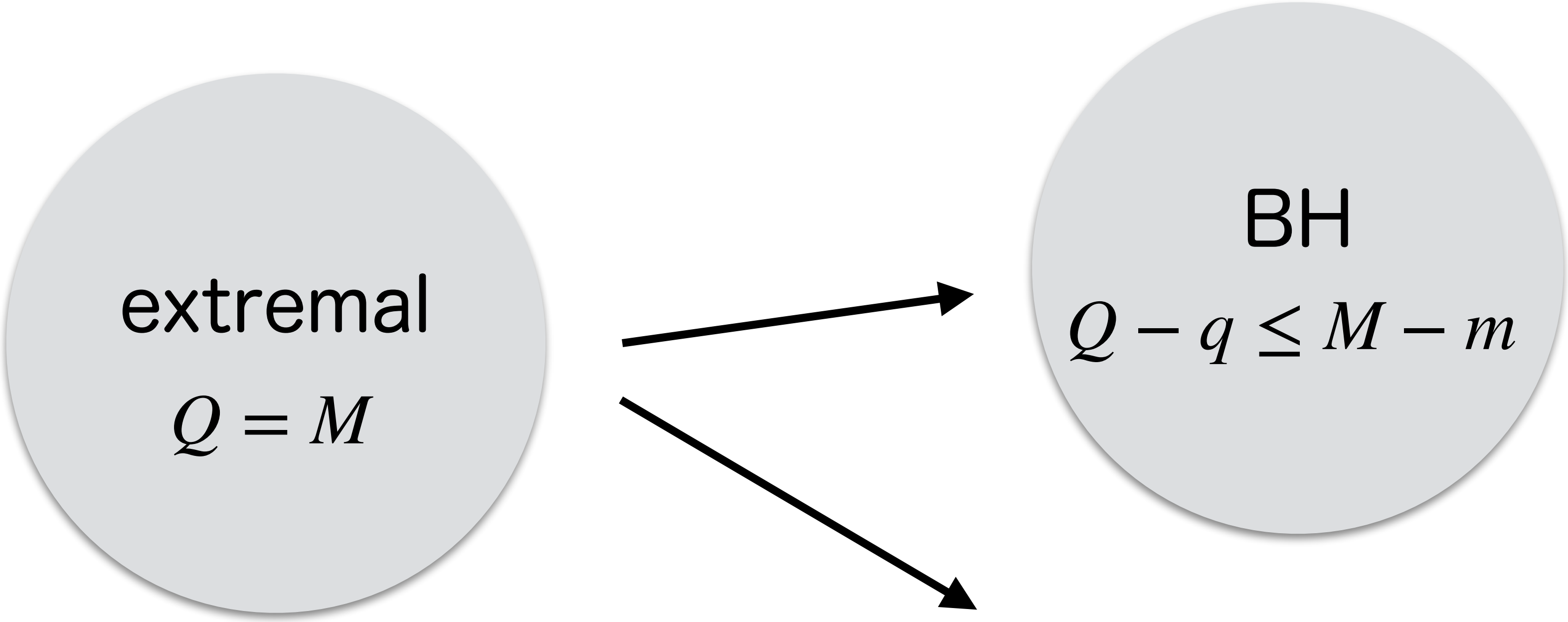
[Arkani-Hamed, Huang, Huang, '17]

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 ⇒ $\alpha_1 > 0$



extremal

$Q = M$

BH

$Q - q \leq M - m$

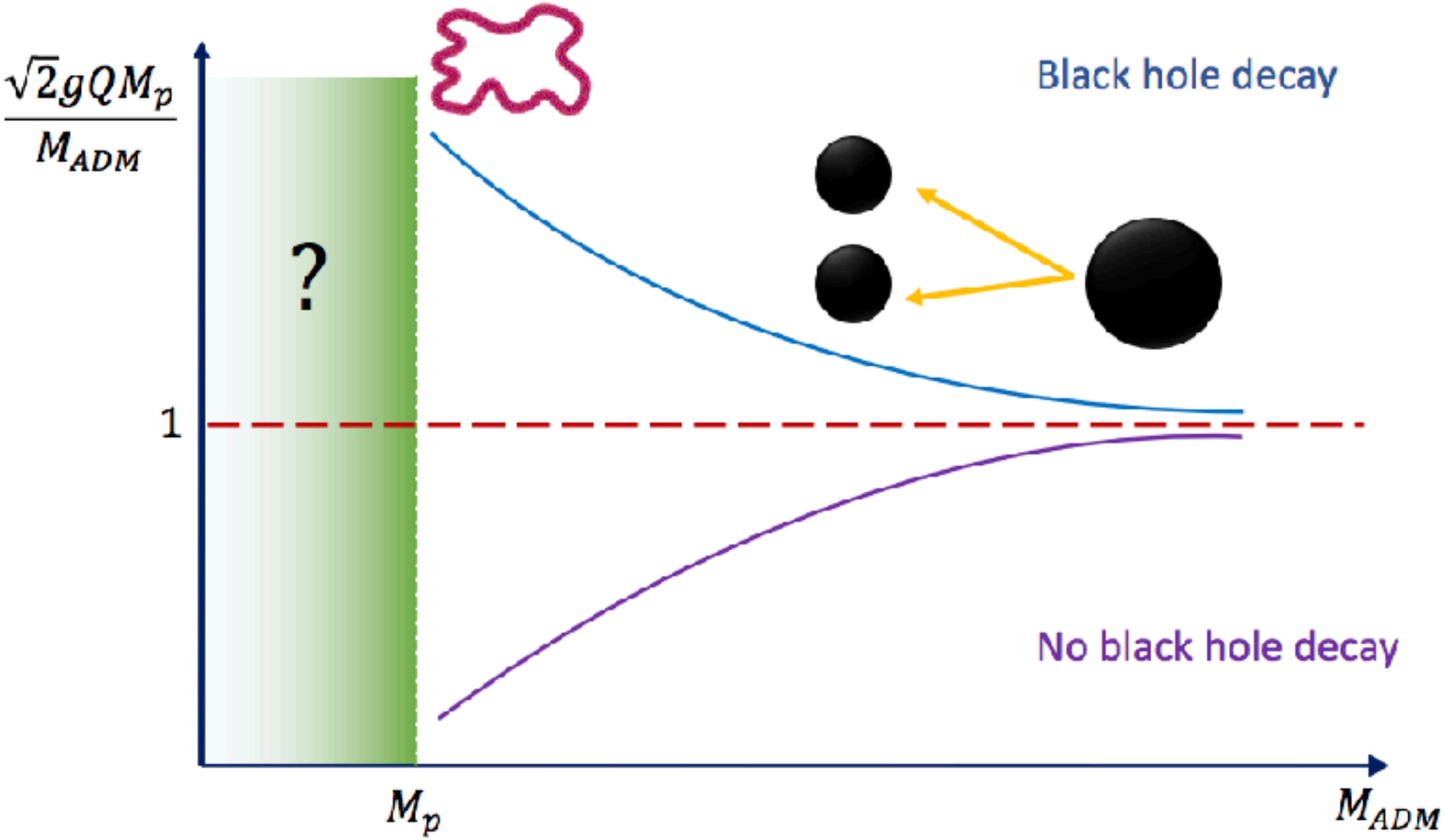
- a state $q \geq m$ **can be an extremal BH!**

WGC: Mild vs Strong

- Moreover, higher derivative corrections in WGC-satisfying theories increase the BH entropy as $z_{ext} > 1 \Leftrightarrow \Delta S > 0$ **[Hamada, Noumi, GS].**
- Similar results hold for **dilatonic, dyonic BHs** **[Loges, Noumi, GS].**
- **1-loop effects** of these higher derivative terms (dominated for asymptotically large BHs) increase z_{ext} **[Arkani-Hamed, Huang, Liu, unpublished];[Charles]** while for N=2 BPS BHs, z_{ext} remains 1.
- While the WGC can be satisfied by a very massive state, this mild form of the WGC seems rather toothless.
- For example, the 0-form version of the WGC can be satisfied by a large instanton action with negligible contribution to the potential (spectator instanton) **[Rudelius];[Brown, Cottrell, GS, Soler].**
- Several stronger forms of the WGC have been proposed: **Tower WGC** **[Andriolo, Junghans, Noumi, GS];[Lee, Lerche, Weigand]**: $m_i \leq e q_i M_{pl}$; **Sublattice WGC** **[Montero, GS, Soler];[Heidenreich, Reece, Rudelius].**

WGC and Modular Invariance

- In **[Aalsma, Cole, GS],** we argued that for extremal BHs with a near horizon AdS_3 geometry, we can use modular invariance and anomalies to infer that there is a tower of superextremal states interpolating between perturbative string states and BHs.



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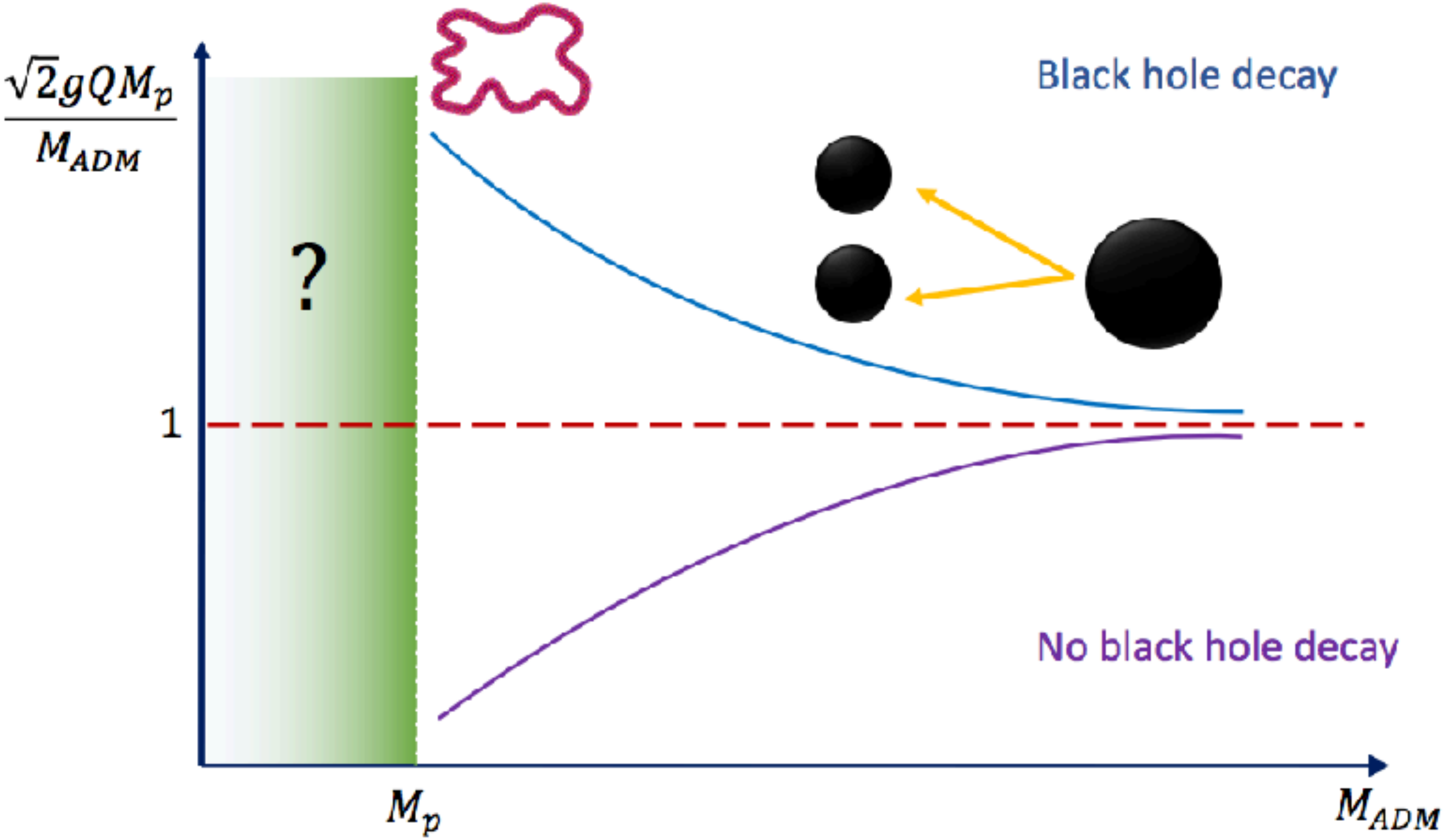

Summary

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- The Swampland program attempts to clarify the formulation, motivation and applications of several consistency criteria:
    - No global symmetries → Mini-charged DM. **[GS, Soler, Ye, ’13]**
    - Completeness conjecture → Low energy spectrum **[Kim, GS, Vafa, ’19]**
    - Weak Gravity Conjecture → Large field (natural) inflation, Fuzzy DM
    - Distance Conjecture → Axion monodromy inflation.
    - Instability of non-SUSY AdS Neutrino physics? **[Ooguri, Vafa, ’16]; [Ibanez, Martin-Lozano, Valenzuela, ’17];[Hamada, GS, ’17]**
    - No dS -> Inflation, CC, quintessence **[Obied, Ooguri, Spodyneiko, Vafa, ’18];[Ooguri, Palti, GS, Vafa, ’18]**
- Much remains to be done to fully understand the origin and consequences of these conjectures.