Quantum Gravity Conjectures and their Realisation in String Theory

- 1808.05958, 1810.05169, 1901.08065, 1910.01135
  w/ Seung-Joo Lee and Wolfgang Lerche
- 2005.10837
  w/ Seung-Joo Lee, Wolfgang Lerche and Guglielmo Lockhart
- 2011.00024
  w/ Daniel Kläwer, Seung-Joo Lee and Max Wiesner

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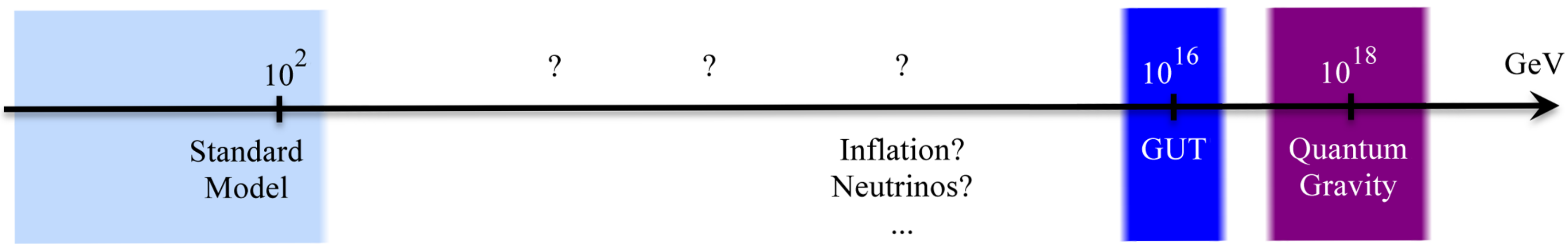
The Need for Quantum Gravity

Effective field theory is the way to describe physics below a cutoff.

Prominent example: Standard Model of Particle Physics

- In fantastic agreement with precision tests comparing to observations
- Known to be incomplete: **Quantisation of Gravity**



- Gravity as perturbative QFT non-renormalisable
- Breakdown expected at least at M_{Pl}

Standard Model: Effective theory searching for a UV completion including quantum gravity

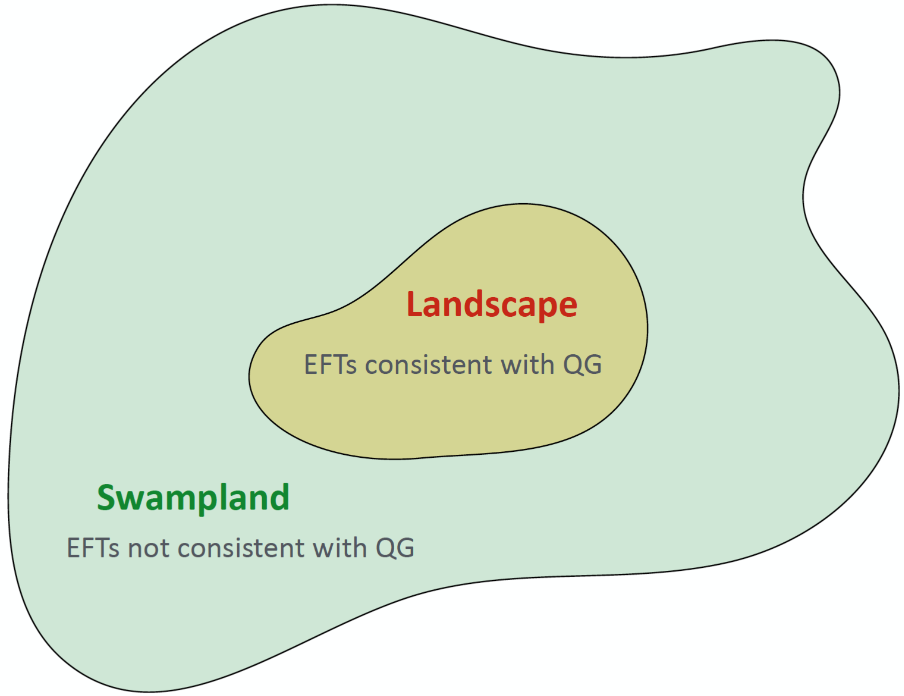
Quantum Gravity Conjectures

Which EFT can be coupled to a fundamental theory of QG?

Swampland of inconsistent EFTs

$\leftrightarrow$

Landscape of consistent QGs



Swampland Conjectures of general scope, but not sharply proven.

String theory as a framework for QG allows to test explicit conjectures.

- Quantitative check of swampland conjectures and sharper formulation
- **Which mathematical structure underlies the conjectures?**

Some QG Conjectures ($d \geq 4$)

1. No Global Symmetries: [Banks,Dixon'88], [Banks,Seiberg'11], [Harlow,Ooguri'18]
   There exist no exact global symmetries in presence of gravity.

2. Completeness Conjecture: [Polchinski'03]
   The full charge/weight lattice is populated by physical states.

3. Weak Gravity Conjecture: [Arkani-Hamed,Motl,Nicolis,Vafa'06]
   There exist 'super-extremal' charged particles with

$$\frac{\mathfrak{q}^2 g_{\rm YM}^2}{m^2}\Big|_{\rm state} \overset{!}{\geq} \frac{Q^2 g_{\rm YM}^2}{M^2}\Big|_{\rm B.H.} \geq \frac{\#}{M_{\rm Pl}^2}$$

   Tower of WGC states [Heidenreich,Reece,Rudelius'15'16] [Montero,Shiu,Soler'16]

   $\Rightarrow$ **New physics at tower scale:** $m \sim g_{\rm YM} M_{\rm Pl}$

   cf. **Species scale** $\Lambda \sim \frac{1}{\sqrt{N}} M_{\rm Pl}$ [Dvali,Gabadadze,Kolanovic,Nitti '01]
   [Grimm,Palti,Venezuela'18]

Some QG Conjectures ($d \geq 4$)

1. No Global Symmetries
2. Completeness Conjecture
3. Weak Gravity Conjecture
4. Swampland Distance Conjecture: [Ooguri,Vafa'06]
   Infinite tower of states becomes massless at infinite distance in moduli space:

$$m(\phi) = m_0\, e^{-c\frac{\Delta\phi}{M_{\rm Pl}}} \qquad c = \mathcal{O}(1)$$

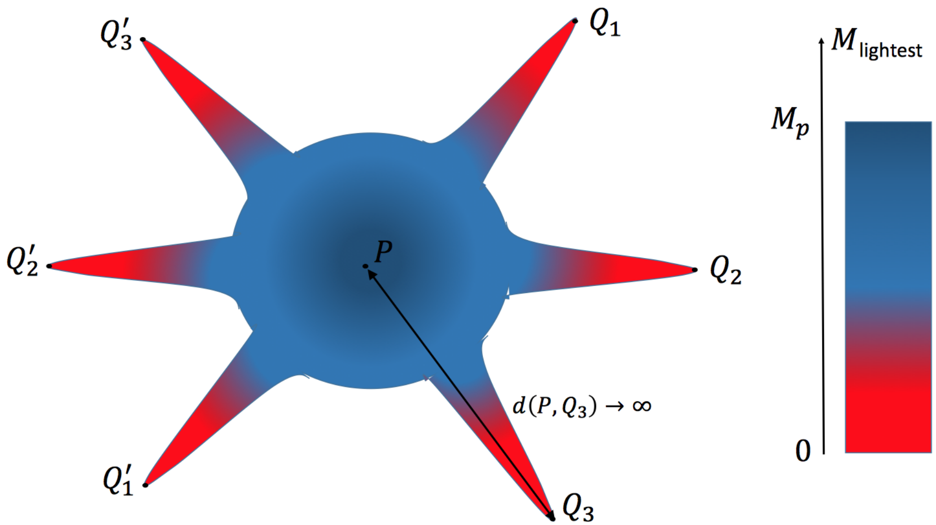


Image: Palti,1903.06239

Quantum Gravity Conjectures

Many more conjectures developed in recent years, e.g.

- AdS Distance Conjecture [Lüst,Palti,Vafa '19]
- No dS Conjecture [Dvali,Gomez'13/14] [Obied,Ooguri,Spodyneiko,Vafa'18] [Palti,Shiu,Ooguri,Vafa'18], ...
- ...

Conjectures often based on heuristic arguments, but agree with complementary concrete ideas on QG.

Many successful tests in String Theory by numerous groups.

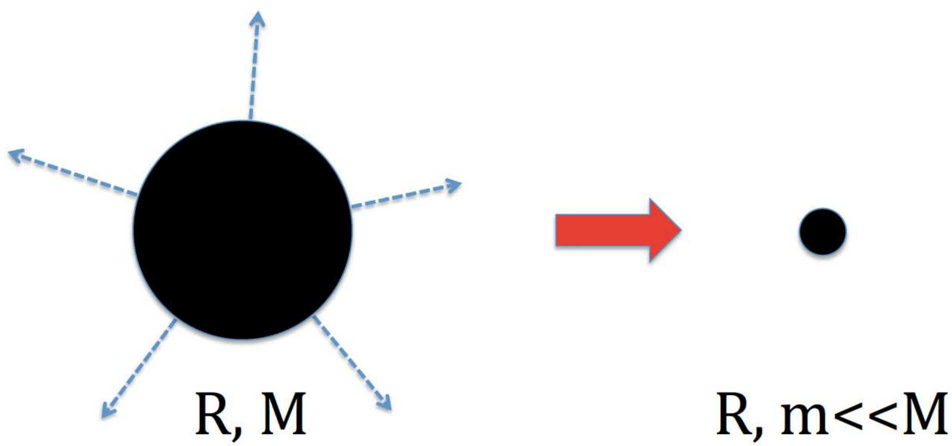
Quantum Gravity Conjectures

A priori based on *heuristic arguments* often related to black hole physics

Example: **No global symmetries**

Form a black hole of arbitrarily high representation R of G (continuous)

$\rightsquigarrow$ Hawking radiation does not change R since G is not gauged



$\rightsquigarrow$ BH reaches point where either

1. the BH entropy $S = \frac{\text{Area}}{4G}$ cannot account for high representation,
2. or where it becomes a charged remnant.

Quantum Gravity Conjectures

A priori based on *heuristic arguments* often related to black hole physics

Example: **Weak Gravity Conjecture**

'Charged black holes must be able to decay, at least for $g_{\rm YM}$ small'.

[AMNV'06]

$\Rightarrow \exists!$ 'super-extremal' state w.r.t. charged extremal black hole

$$\frac{q_k^2 g_{\rm YM}^2}{M_k^2}\Big|_{\rm state} \overset{!}{\geq} \frac{Q^2 g_{\rm YM}^2}{M^2}\Big|_{\rm B.H.} = \frac{\#}{M_{\rm Pl}^2}$$

Alternative viewpoint:

State with highest charge-to-mass ration must satisfy

$$\begin{aligned} |F_{\rm Coulomb}| &\geq |F_{\rm Grav}| \\ \frac{g_{\rm YM}^2 q_k^2}{M_k^2} &\overset{!}{\geq} \frac{1}{M_{\rm Pl}^2}\frac{d-3}{d-2} \end{aligned}$$

$\Longrightarrow$ No stable charged remnants

QG Conjectures in String Theory

1) Quantitative test of the conjectures in computational framework, especially in situations with minimal supersymmetry

2) Understand mathematical foundations of conjectures

3) Refine and unify conjectures

QG Conjectures in String Theory

1) Quantitative check of the conjectures in computational framework, especially in situations with minimal supersymmetry

This talk: **4d N=1 theories** (framework: F-theory on CY_4)

2) Understand mathematical foundations of conjectures

- Limits in Kähler moduli space
- Modular properties of arithmetic genus

3) Refine and unify conjectures

- Swampland Distance $\Longrightarrow$ Emergent String Conjecture
  If a QG theory can undergo an infinite distance limit in moduli space, it either decompactifies or a unique tensionless fundamental string emerges.
- WGC consequence of emergent light strings, with possibility of computing sub-leading corrections

Main Results

1) Evidence in favour of Emergent String Proposal

Classical Kähler Geometry $+$ Quantum corrections $\Longrightarrow$ Unique weakly coupled emergent string @ inf. distance (or decompactification)

2) Better understanding the Weak Gravity Conjecture

Emergent String Geometry $+$ Modularity $\Longrightarrow$ Weak Gravity Conjecture $+$ proposal for quantum corrections

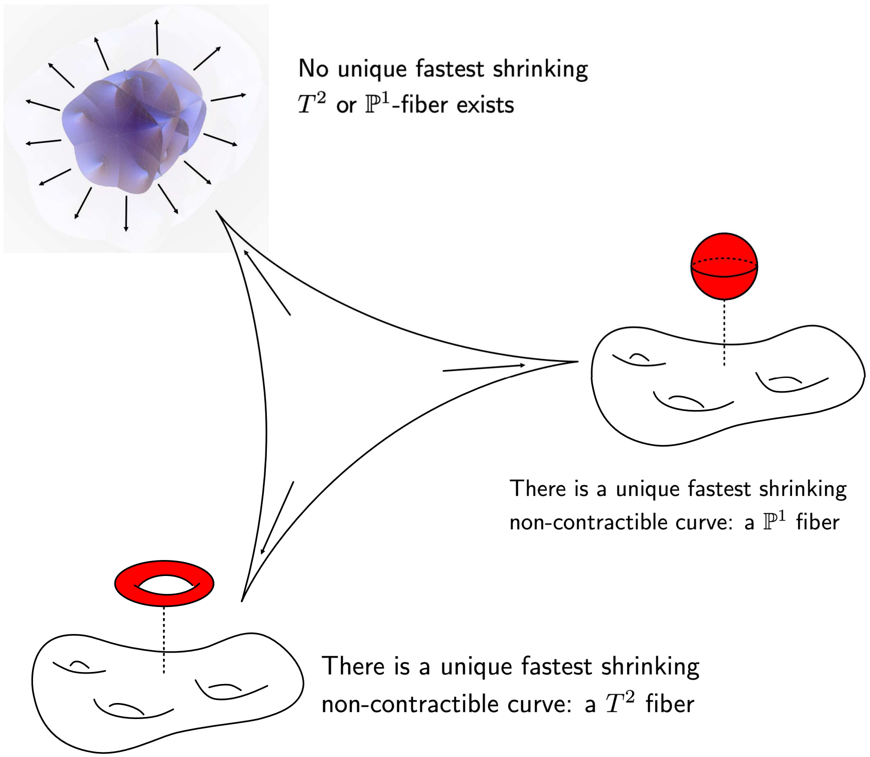
0) Introduction

1) Infinite Distance Limits - Classical

2) Infinite Distance Limits - Quantum Corrections

3) Weak Gravity Conjecture

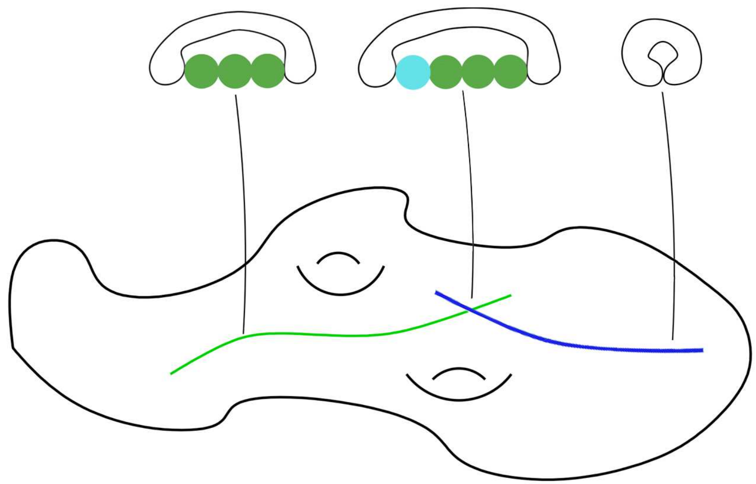
Part I: Infinite distance limits - Classical



[Lee,Lerche,TW'18/19] [Lee,Kläwer,TW,Wiesner'20]

F-theory in 4d

F-theory in 4d N=1 $\Longleftrightarrow$ Type IIB on $\mathbb{R}^{1,3} \times B_3$ with 7-branes



- B_3 = compact Kähler 3-fold
  $\Longrightarrow$ dynamical gravity
- 7-branes on complex surface $\mathbf{S} \subset B_3$
  $\Longrightarrow$ gauge symmetry
- Gauge fluxes on $\mathbf{S}$ required for chiral spectrum

Couplings: (IIB Einstein frame)

$$\frac{\mathbf{M_{Pl}^2}}{\mathbf{M_{IIB}^2}} = 4\pi \mathcal{V}_{\mathbf{B_3}} \qquad \frac{\mathbf{1}}{\mathbf{g_{YM}^2}} = \frac{\mathbf{1}}{\mathbf{2}\pi} \mathcal{V}_{\mathbf{S}}$$

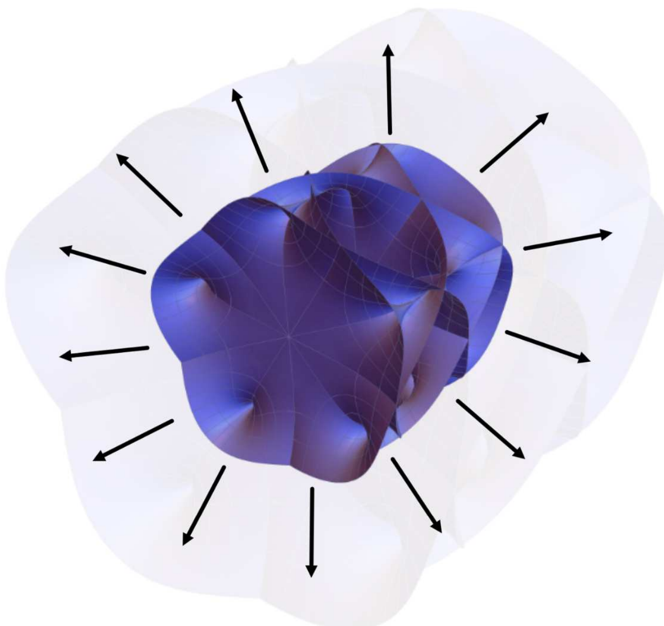
Infinite distance limits - Classical

Kähler 3-fold B_3 classical Kähler form $J = \sum_{i \in \mathcal{I}} T^i J_i \,,$ $T^i \geq 0$

$$\mathcal{V}_C = \int_C J \qquad \mathcal{V}_{\mathbf{S}} = \frac{1}{2} \int_{\mathbf{S}} J^2 \qquad \mathcal{V}_{B_3} = \frac{1}{3!} \int_{B_3} J^3$$

Infinite distance limit in classical Kähler moduli space:

- (some) $T^i \to \infty$ $\Rightarrow$ *generically*: $\mathcal{V}_{B_3} \sim \mu^3 \to \infty$



Infinite distance limits - Classical

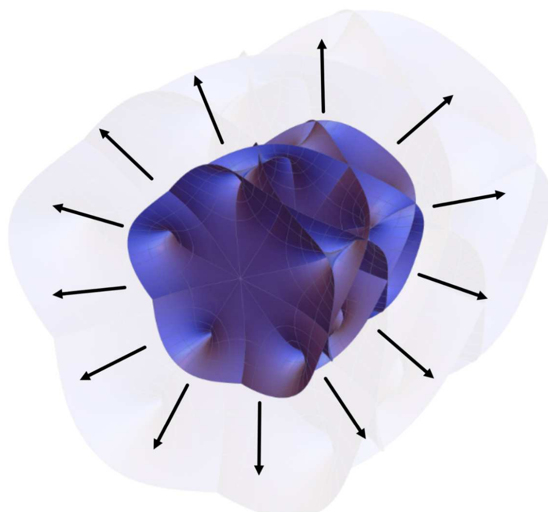
Kähler 3-fold B_3 classical Kähler form $J = \sum_{i\in\mathcal{I}} T^i J_i\,,$ $T^i \geq 0$

$$\mathcal{V}_{B_3} = \tfrac{1}{3!}\int_{B_3} J^3$$

Geometric infinite distance limit:

- (some) $T^i \to \infty$ $\Rightarrow$ generically: $\mathcal{V}_{B_3} \sim \mu^3 \to \infty$
- scale out μ: $J = \mu\, J' = \mu\,(\sum_{i\in\mathcal{I}} T'^i J_i)$ $\int_{B_3}(J')^3 =$ finite

If all T'^i finite:
$\mathcal{V}_{B_3} \sim \mu^3 \to \infty =$ homogenous decompactification



Tower of light Kaluza-Klein modes

$$\frac{M_{\rm KK}^2}{M_{\rm Pl}^2} \sim \frac{\mathcal{V}_{B_3}^{-1/3}}{\mathcal{V}_{B_3}} \sim \mu^{-4} \to 0$$

Infinite distance limits - Classical

Kähler 3-fold B_3 classical Kähler form $J = \sum_{i \in \mathcal{I}} T^i J_i \,, \qquad T^i \geq 0$

$$\mathcal{V}_{B_3} = \frac{1}{3!} \int_{B_3} J^3$$

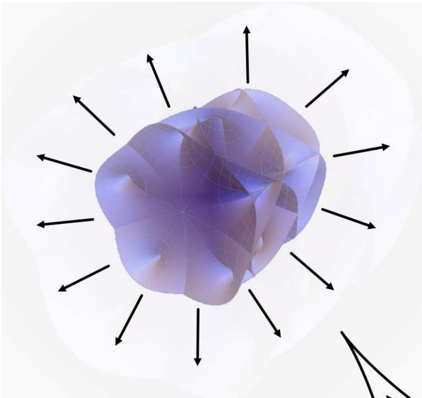
Geometric infinite distance limit:

- (some) $T^i \to \infty$ $\Rightarrow$ generically: $\mathcal{V}_{B_3} \sim \mu^3 \to \infty$
- scale out μ: $J = \mu \, J' = \mu \left(\sum_{i \in \mathcal{I}} T'^i J_i \right) \,, \quad \mathcal{V}'_{B_3} := \int_{B_3} (J')^3$ finite

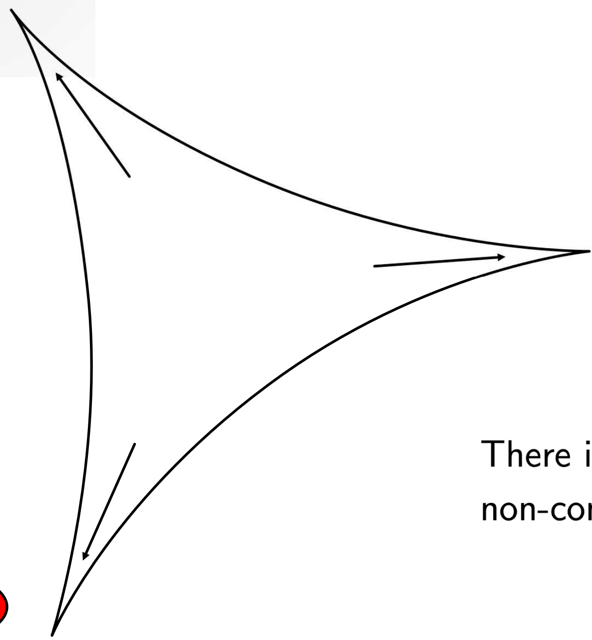
If all T'^i finite $\Longrightarrow$ no further inf. distance limit
All vanishing cycles contractible
Only weakly coupled tower: KK tower

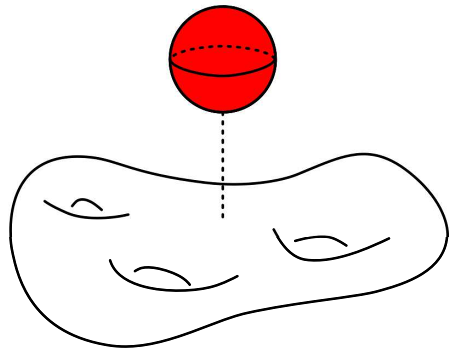
If some $T'^i \to \infty$ others to zero $\Longrightarrow$ residual infinite distance limit with
$\mathcal{V}'_{B_3} \sim \int_{B_3} (J')^3$ finite
non-contractible cycle shrinks w.r.t. J'

Infinite distance limits - Classical

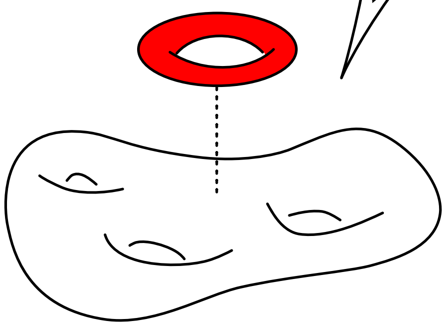


No unique fastest shrinking
T^2 or $\mathbb{P}^1$-fiber exists





There is a unique fastest shrinking
non-contractible curve: a $\mathbb{P}^1$ fiber

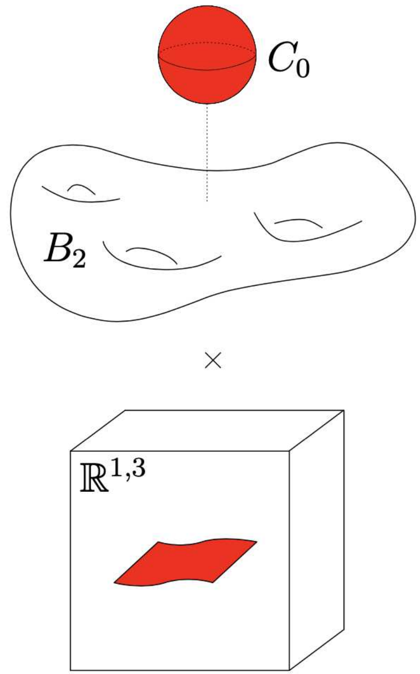


There is a unique fastest shrinking
non-contractible curve: a T^2 fiber

Infinite distance limits - Classical

Possibility 1):

There is a unique fastest shrinking non-contractible curve: a $\mathbb{P}^1$ fiber C_0



D3-brane on C_0:

fundamental heterotic string

$$J = \mu\Big(\lambda J_0 + \textstyle\sum_{\mu\in\mathcal{I}_1} \frac{a^\mu}{\lambda^2} J_\mu + \sum_{r\in\mathcal{I}_3} b'^r J_r\Big)$$

$$\frac{M^2_{\rm het}}{M^2_{\rm Pl}} \sim \frac{\mathcal{V}_{C_0}}{\mathcal{V}_{B_3}} \sim \mu^{-2}\lambda^{-2} \qquad \frac{M^2_{\rm KK}}{M^2_{\rm Pl}} \sim \mu^{-4}\lambda^{-1}$$

3 classical regimes:

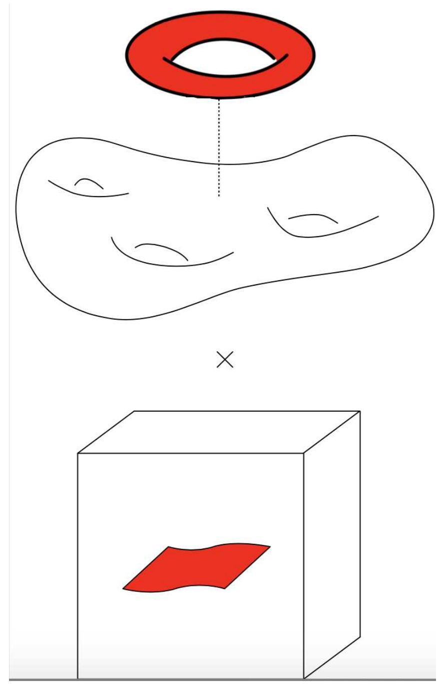
$\mu^2 \succ \lambda : \frac{M^2_{\rm KK}}{M^2_{\rm het}} \to 0$ — decompactification limit

$\mu^2 \sim \lambda : \frac{M^2_{\rm KK}}{M^2_{\rm het}} \sim 1$ — **4d emergent string limit**

$\mu^2 \prec \lambda: \frac{M^2_{\rm KK}}{M^2_{\rm het}} \to \infty$ — pathological (???)

Infinite distance limits - Classical

Possibility 2):
There is a unique fastest shrinking non-contractible curve: a T^2 fiber C_0



D3-brane on C_0:
fundamental Type II string

$$J = \mu\left(\lambda J_0 + \sum_{\mu \in \mathcal{I}_1} \frac{a^\mu}{\lambda^2} J_\mu + \sum_{r \in \mathcal{I}_3} b'^r J_r\right)$$

$$\frac{M_{\rm sol}^2}{M_{\rm Pl}^2} \sim \frac{\mathcal{V}_{C_0}}{\mathcal{V}_{B_3}} \sim \mu^{-2}\lambda^{-2} \qquad \frac{M_{\rm KK}^2}{M_{\rm Pl}^2} \sim \mu^{-4}\lambda^{-1}$$

3 classical regimes:

$\mu^2 \succ \lambda$: $\frac{M_{\rm KK}^2}{M_{\rm sol}^2} \to 0$ — decompactification limit

$\mu^2 \sim \lambda$: $\frac{M_{\rm KK}^2}{M_{\rm sol}^2} \sim 1$ — **4d emergent string limit**

$\mu^2 \prec \lambda$: $\frac{\hat{M}_{\rm KK}^2}{\hat{M}_{\rm sol}^2} \to 0$ — T-dual decompactification limit

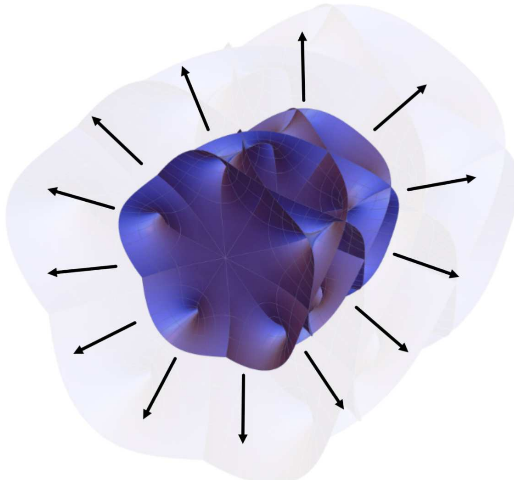
Infinite distance limits - Classical

Possibility 3):

No unique fastest shrinking T^2 or $\mathbb{P}^1$-fiber exists

Detailed analysis shows:

M_{KK} always leading parametrically compared to any other potential tower of weakly coupled particles



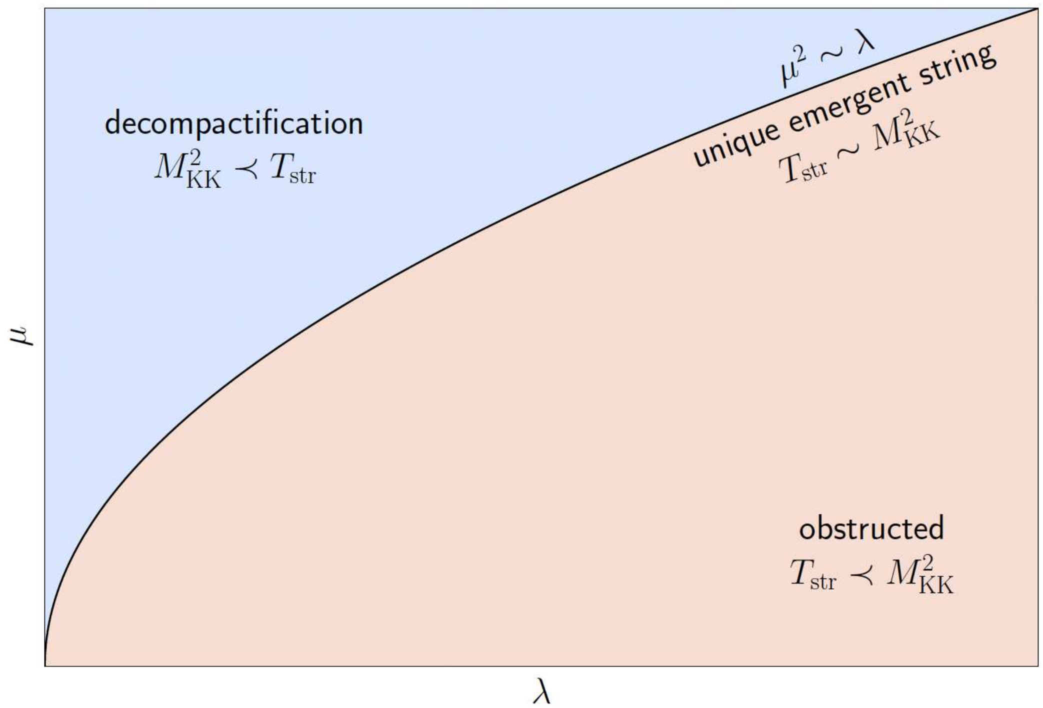
$\Longrightarrow$ **Decompactification limit**

Example:

Whenever have two compatible weakly coupled light strings, then KK tower dominates

Part II: Infinite distance limits

- Quantum Corrections



[Lee,Kläwer,TW,Wiesner'20]

Infinite distance limits - Quantum

Quantum corrections expected when cycles shrink

- Perturbative α' corrections:

$$K^F = -2\ln(\mathcal{V}^0_{B_3} + \mathcal{O}(\alpha'^2) + \mathcal{O}(\alpha')^3 + \ldots)$$

Leading order $\mathcal{O}((\alpha')^2)$ computed in F-theory by dim. reduction of higher-derivative terms of 11d M-theory and uplift to F-theory

[Grimm et al.'14-17][Weissenbacher'18-'20] [Conlon,Palti '09]

Schematic structure: 4d $N=1$ chiral coordinates corrected as

$$\mathrm{Re}T_\alpha \sim \mathrm{Re}T^{\mathrm{cl}}_\alpha \left(1 + \sum_i \frac{1}{\mathcal{V}_{D_i}}\right) \qquad \mathrm{Re}T^{\mathrm{cl}}_\alpha = \mathcal{V}^0_{D_\alpha} = \frac{1}{2}\int_{D_\alpha} J^2$$

- Non-perturbative corrections from D3-brane instantons: suppressed with divisor volume $e^{-S_{\mathrm{D3}}} \sim e^{-\mathcal{V}_D}$

Computational control requires: no shrinking divisors on B_3

Infinite distance limits - Quantum

Computational control requires: no shrinking divisors on B_3

Turns out: Smallest (non-contractible) divisor volume $\sim \frac{\mu^2}{\lambda}$

Apply to 3 classical regimes of $\mathbb{P}^1$ limits:

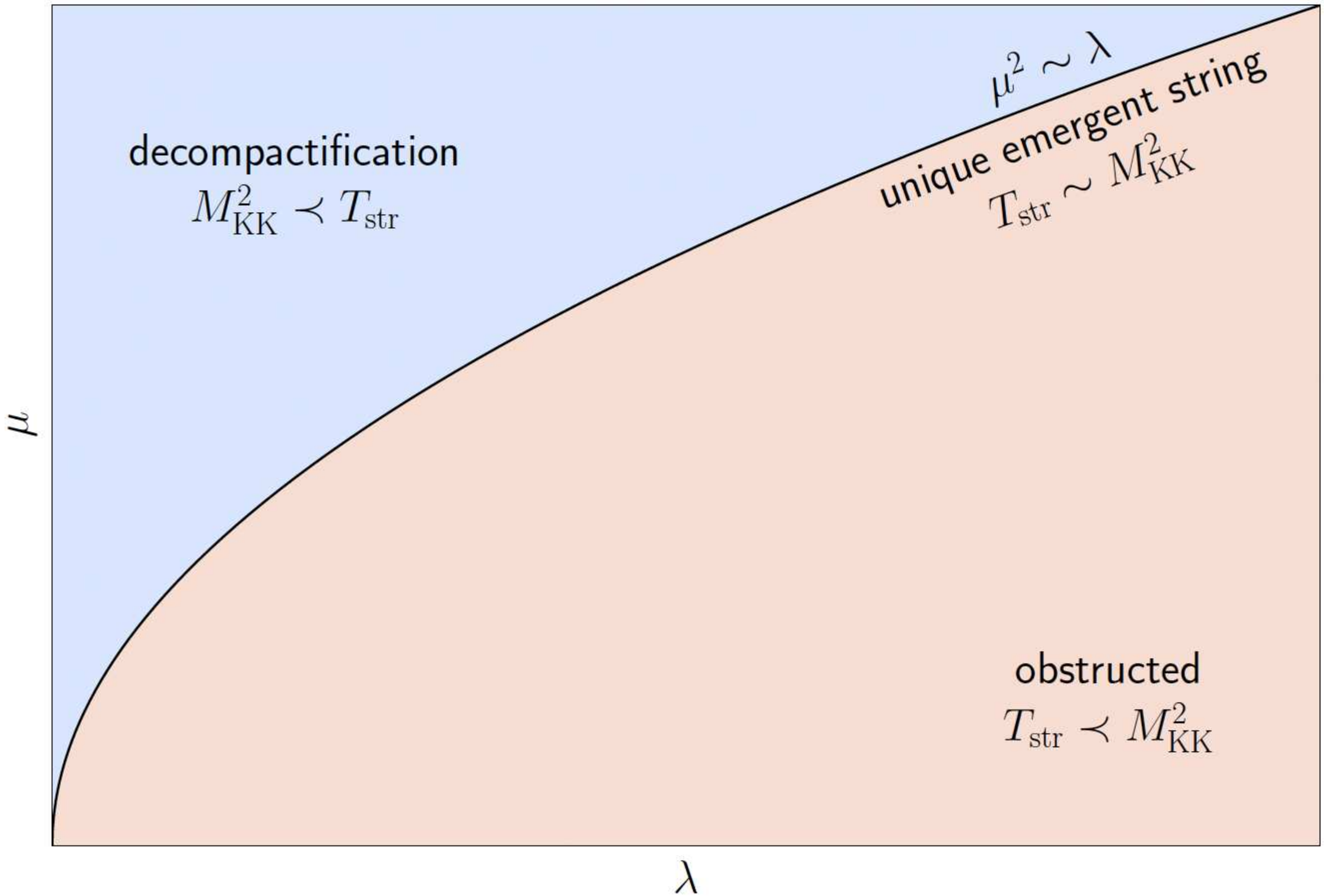
$\mu^2 \succ \lambda : \frac{M_{\mathrm{KK}}^2}{M_{\mathrm{het}}^2} \to 0$ decompactification limit

$\mu^2 \sim \lambda : \frac{M_{\mathrm{KK}}^2}{M_{\mathrm{het}}^2} \sim 1$ 4d emergent string limit

$\mu^2 \prec \lambda$: $\frac{M_{\mathrm{KK}}^2}{M_{\mathrm{het}}^2} \to \infty$ pathological (???) $\Rightarrow$ Obstructed by quantum corrections

Fate of 4d emergent string limit and decompactification limit depends on precise 'starting point' of limit (suitable values for a^μ and b'^r)
(presence of small contractible divisors - independent of λ and μ)

Infinite distance limits - Quantum



String Emergence

Proposal: [Lee,Lerche,TW'19]

String emergence at infinite distance

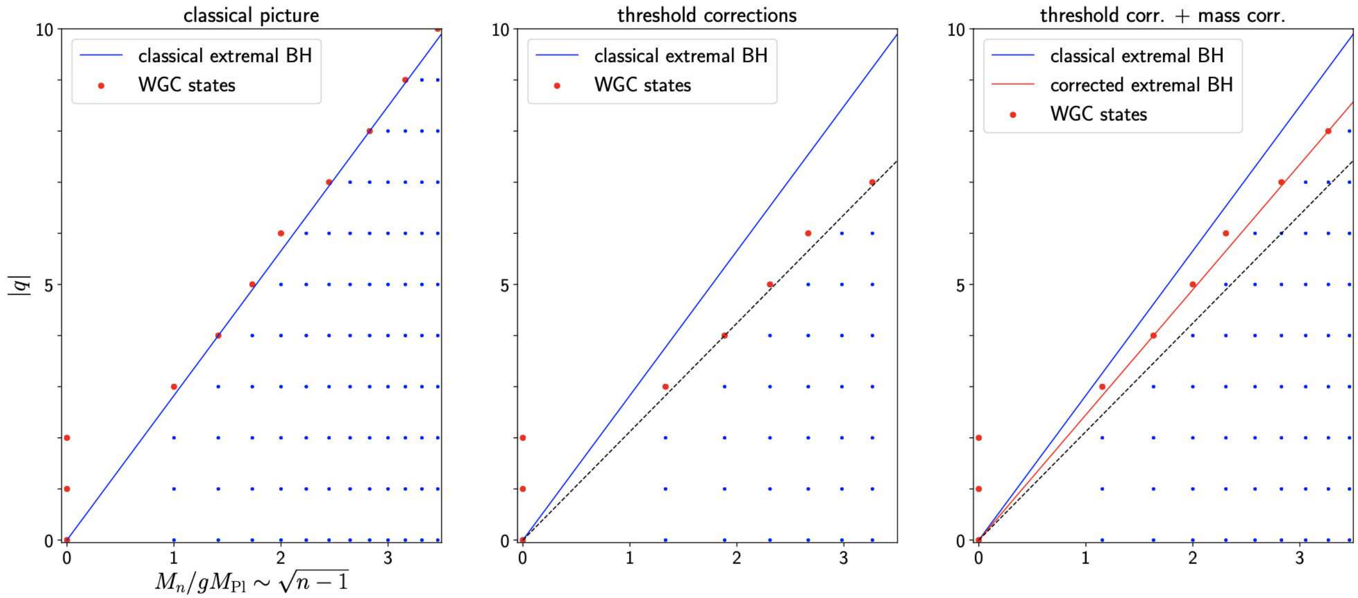
If a quantum gravity theory admits an infinite distance limit, then

- *either it reduces to a weakly coupled string theory*
  $\Rightarrow$ *infinite tower of string excitations*
- *or it decompactifies*
  $\Rightarrow$ *infinite tower of Kaluza-Klein excitations*

Confirmed in highly-non-trival (non-perturbative) setups:

Existence and uniqueness of emergent critical string $\Longleftrightarrow$ (Quantum) geometry of string compactification [Lee,Lerche,TW'19],[Baume,Marchesano,Wiesner'19], [Lee,Kläwer,TW,Wiesner'20]

Part III: Weak Gravity Conjecture
- including quantum corrections

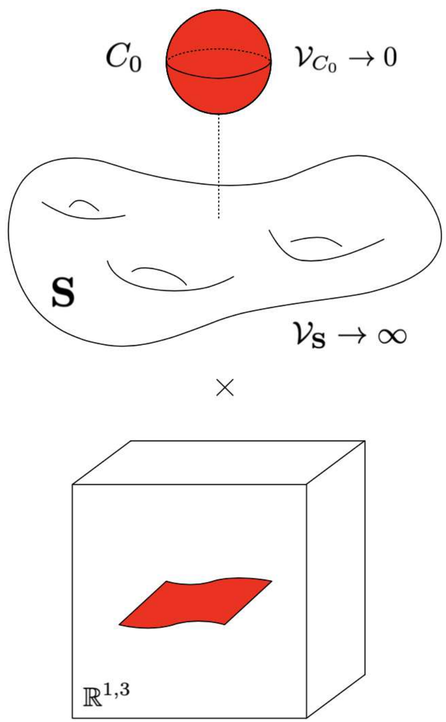


Weak Gravity Conjecture

Find the tower of states with $\frac{q_k^2 g_{\rm YM}^2}{M_k^2} \overset{!}{\geq} \frac{Q^2 g_{\rm YM}^2}{M^2}\Big|_{\rm BH}$

Weak coupling limit $g_{\rm YM} \to 0$ lies at infinite distance in moduli space (at least in type of compactifications considered here)

- Gauge group: 7-brane $\mathbb{R}^{1,3} \times \mathbf{S}$
- $\frac{1}{g_{\rm YM}^2} \sim \mathcal{V}_{\mathbf{S}} \to \infty$



$g_{\rm YM} \to 0$: **emergent heterotic string**

Weak Gravity Conjecture

$$\frac{q_k^2 g_{\rm YM}^2}{M_k^2}|_{\rm state} \overset{!}{\geq} \frac{Q^2 g_{\rm YM}^2}{M^2}|_{\rm B.H.}$$

First: Strict weak coupling limit $g_{\rm YM} \to 0$

Relevant black holes: Dilatonic Reissner-Nordström BH

[Heidenreich,Rudelius,Reece'15] [Lee,Lerche,TW'18/19]

- $S = \int \sqrt{-g}R + \frac{1}{2}d\phi \wedge *d\phi + \frac{1}{4g_{\rm YM}^2} e^{\sqrt{2}\phi} F_{\mu\nu}F^{\mu\nu}$

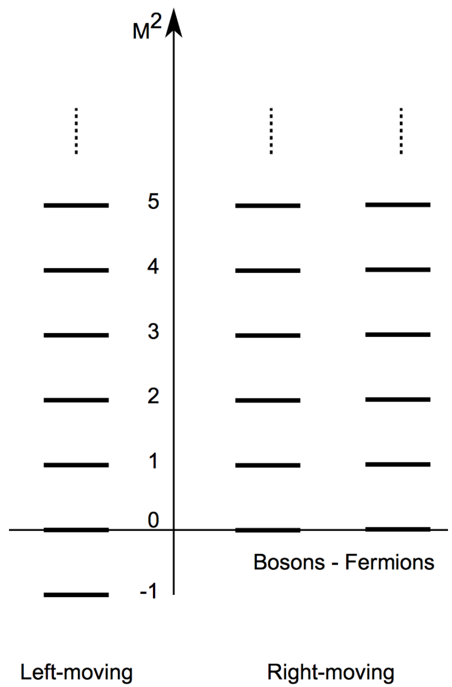
$$\Rightarrow \frac{g_{\rm YM}^2 Q^2}{M^2}|_{\rm BH} = \left(\frac{1}{2} + \frac{1}{2}\right)\frac{1}{M_{\rm Pl}^2}$$

Coincides with 'Repulsive-Force criterion' [Palti'17] [Lee,Kläwer,TW,Wiesner'20]

$$\begin{aligned} |F_{\rm Coulomb}| &\geq |F_{\rm Grav}| + |F_{\rm Yukawa}| \\ \frac{g_{\rm YM}^2 q_k^2}{M_k^2} &\overset{!}{\geq} \frac{1}{M_{\rm Pl}^2}\left(\frac{d-3}{d-2}|_{d=4} + \frac{1}{4}\frac{M_{\rm Pl}^4}{M_k^4} g^{rs}\partial_r\left(\frac{M_k^2}{M_{\rm Pl}^2}\right)\partial_s\left(\frac{M_k^2}{M_{\rm Pl}^2}\right)\right) \\ &= \frac{1}{M_{\rm Pl}^2}\left(\frac{1}{2} + \frac{1}{2}\right) \end{aligned}$$

Heterotic solitonic string

$\Longleftrightarrow$ tower of light states for $g_{\rm YM} \to 0$



Idea:

Tower of states =
excitation spectrum of
asymptotically light string

In strict weak coupling limit:

$$M_k^2 = 8\pi(n_k - 1)T_{\rm het} \qquad \frac{T_{\rm het}}{M_{\rm Pl}^2} = \frac{1}{2}\frac{\mathcal{V}_{C_0}}{\mathcal{V}_{B_3}}$$

Weak Gravity Conjecture

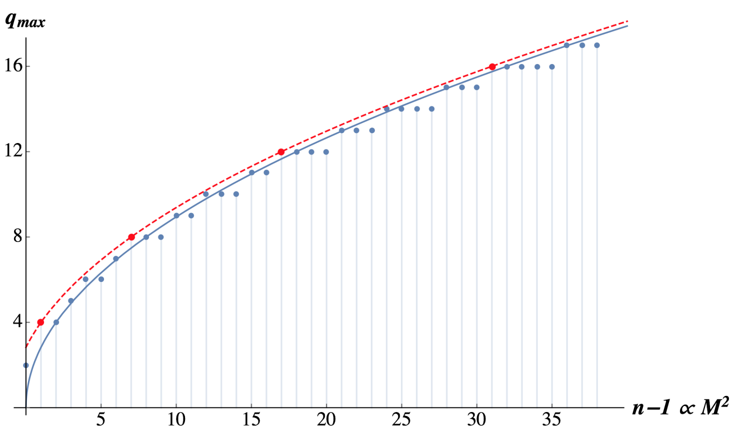
Wanted: States with highest ratio of q_k^2 to excitation level n_k

Index-like partition function: 4d N=1 heterotic string elliptic genus

$$Z(\tau, z) \equiv \mathrm{Tr}_R \left[(-1)^F F \, e^{2\pi i \tau H_L} \, \bar{e}^{-2\pi i \bar{\tau} H_R} \, e^{2\pi i z J} \right]$$

Computable via mirror symmetry on 4-folds with fluxes

[Mayr'96][Klemm,Cota,Schimannek'17] [Lee,Lerche,TW'19]



Distinguished modular properties (quasi-Jacobi forms):

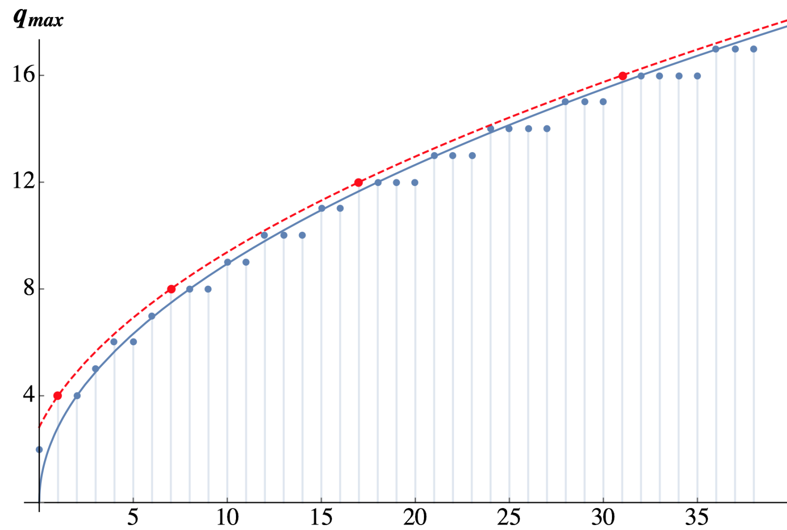
$$Z = Z_{-1,m}(\tau, z) + \partial_z Z_{-2,m}(\tau, z)$$

[Lee,Lerche,Lockhart,TW'20]

$\mathfrak{q}_k^2 = 4m \, n_k$ for $\mathfrak{q}_k = 2m \, k$ $\quad m = \frac{1}{2} C_0 \cdot \mathbf{S}$

Weak Gravity Conjecture

$\mathfrak{q}_k^2 = 4m\, n_k$ for $\mathfrak{q}_k = 2m\, k$



$$\frac{g_{\rm YM}^2 q_k^2}{M_k^2} \geq \frac{g_{\rm YM}^2}{4\pi} \frac{2m}{M_{\rm het}^2} = \frac{2m\mathcal{V}_{B_3}}{\mathcal{V}_{\mathbf{S}}\mathcal{V}_{C_0}} \frac{1}{M_{\rm Pl}^2}$$

$$g_{\rm YM}^2 = \frac{2\pi}{\mathcal{V}_{\mathbf{S}}}\,, \qquad M_{\rm het}^2 = 2\pi\mathcal{V}_{C_0}\,, \qquad M_{\rm Pl}^2 = (4\pi)\mathcal{V}_{B_3}$$

Find geometrically:

$$\frac{2m\mathcal{V}_{B_3}}{\mathcal{V}_{\mathbf{S}}\mathcal{V}_{C_0}} = 1 - \Delta \qquad \Delta \to 0 \qquad \text{as } g_{\rm YM}^2 \to 0$$

In strict limit $g_{\rm YM}^2 \to 0$ confirm for sublattice $\mathfrak{q}_k = 2m\, k$:

$$\frac{g_{\rm YM}^2 q_k^2}{M_k^2} \geq \frac{1}{M_{\rm Pl}^2}$$

Weak Gravity Conjecture

[Lee,Kläwer,TW,Wiesner'20]

$$\frac{g_{\rm YM}^2 q_k^2}{M_k^2} \geq \frac{2m\mathcal{V}_{B_3}}{\mathcal{V}_{\bf S}\mathcal{V}_{C_0}}\frac{1}{M_{\rm Pl}^2} = \frac{1}{M_{\rm Pl}^2}(1-\Delta+\dots)$$

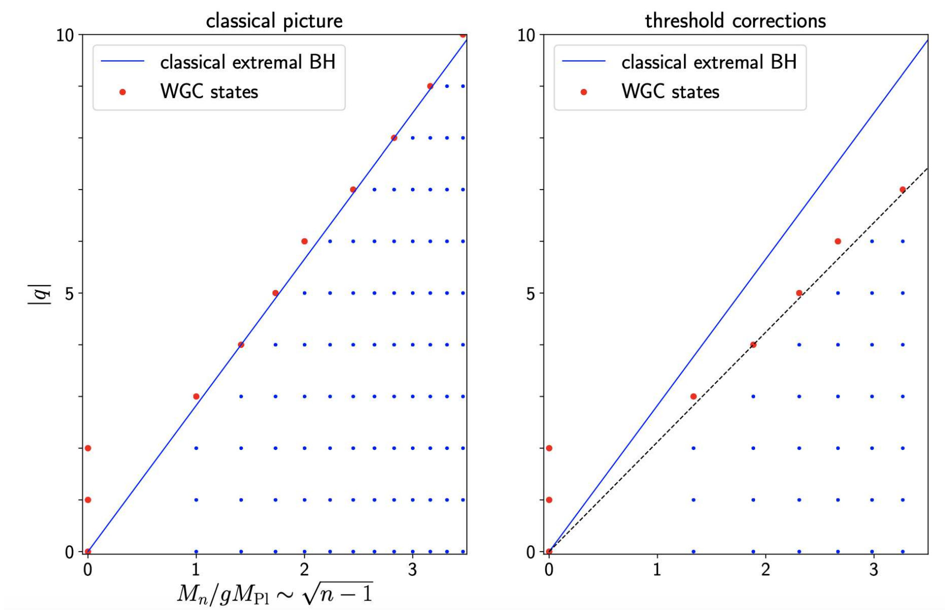
- Δ_0: classical geometric corrections away from strict limit
- Δ_1: $(\alpha')^2$ corrections

For dual het string:

$\Delta =$ 1-loop thresholds

at $M_{\rm het}$

Naively these destroy WGC relation.



Weak Gravity Conjecture

Proposal: [Lee,Kläwer,TW,Wiesner'20]

1-loop renormalisation to mass of string excitations

$$\frac{M_k^2}{M_{\rm Pl}^2} =: 8\pi(n_k - 1)\frac{M_{\rm het}^2}{M_{\rm Pl}^2}\,(1+\delta)$$

Changes both sides of WGC relation

$$\frac{g_{\rm YM}^2 q_k^2}{M_k^2} \overset{!}{\geq} \frac{1}{M_{\rm Pl}^2}\left(\frac{d-3}{d-2}|_{d=4} + \frac{1}{4}\frac{M_{\rm Pl}^4}{M_k^4} g^{rs}\partial_r\left(\frac{M_k^2}{M_{\rm Pl}^2}\right)\partial_s\left(\frac{M_k^2}{M_{\rm Pl}^2}\right)\right)$$

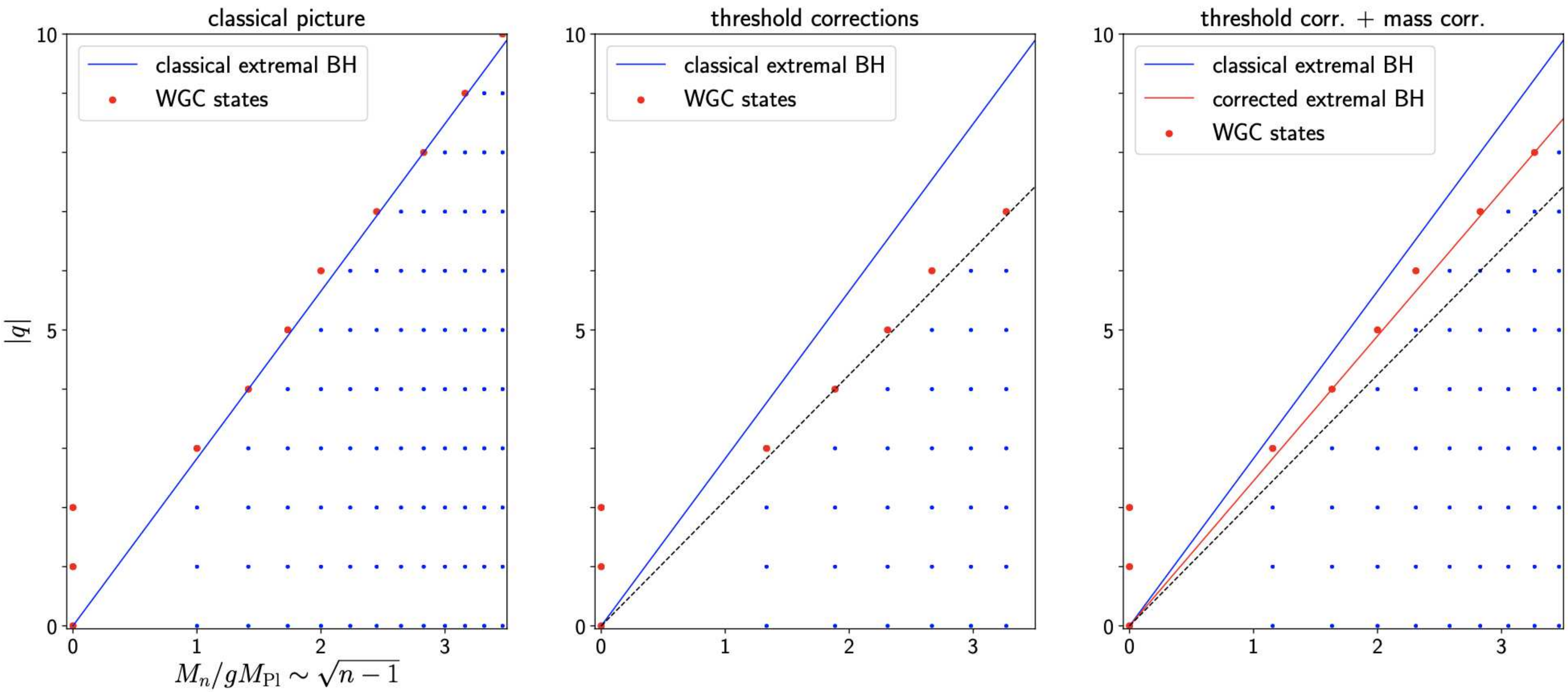
Determine δ by imposing WGC for states with $\mathfrak{q}_k^2 = 4m\,n_k$:

$$\delta = -\tfrac{1}{2}\Delta + \ldots$$

WGC relation at 1-loop : $$\frac{g_{\rm YM}^2 q_k^2}{M_k^2} \overset{!}{\geq} \frac{1}{M_{\rm Pl}^2}\left(1 - \frac{1}{2}\Delta\right)$$

Weak Gravity Conjecture

WGC relation at 1-loop : $$\frac{g_{\mathrm{YM}}^2 q_k^2}{M_k^2} \overset{!}{\geq} \frac{1}{M_{\mathrm{Pl}}^2}\left(1-\frac{1}{2}\Delta\right)$$



Open:

1) Derive mass renormalisation for string states

2) Compare with 1-loop corrected charge-to-mass of BHs

Conclusions

Quantum Gravity Conjectures in 4d string theory with N=1 SUSY

1) Swampland Distance Conjecture $\Longrightarrow$ Emergent String Conjecture

Equi-dimensional infinite distance limits are emergent string limits

- Classical Kähler geometry + quantum corrections
  $\Longrightarrow$ unique weakly coupled strings at infinite distance
- Confirmed even in setups without strings away from boundary
  How general is this really?

2) Weak Gravity Conjecture including loop-corrections

- Responsible mathematics: Modularity of elliptic genus
- Directions for future work:
  Proposal for mass renormalisation of string states
  Proposal for charge-to-mass ratio correction of extremal black holes

QG informs Model Building

1. **General constraints on gauge sector**

   WGC $\Rightarrow$ No pure Einstein-Yang-Mills

   Also violates cosmic censorship [Horowitz,Santos'17]

   WGC $\Rightarrow$ Constraints on hidden sectors, e.g. with $g_{\rm YM}^{\rm hidden} \ll 1$:

   '*Watch out for towers of light states.*'

2. **Early Universe Cosmology:**

   SDC: $m(\phi) = m_0\, e^{-c\frac{\Delta\phi}{M_{\rm Pl}}} \Longrightarrow$ for $\Delta\phi_{\rm infl} \gg M_{\rm Pl}$, EFT breaks down

   $\Longrightarrow$ constraints on large field inflation - c-dependent! [Scalisi,Valenzuela'18]

   e.g. no *parametrically* large tensor-to-scalar ratio r in

   single-field slow roll infl. however: [Achucarro,Palma'18]

3. **Late Universe Cosmology:** [Ooguri,Shiu,Palti,Vafa'18] cf. [Dvali,Gomez'13/14]

   Swampland Distance Conjecture $\Rightarrow$ No deSitter vacua for *asymptotic* field ranges