Emergence of Infinite Field Distances, Weak Coupling and the Swampland

Irene Valenzuela

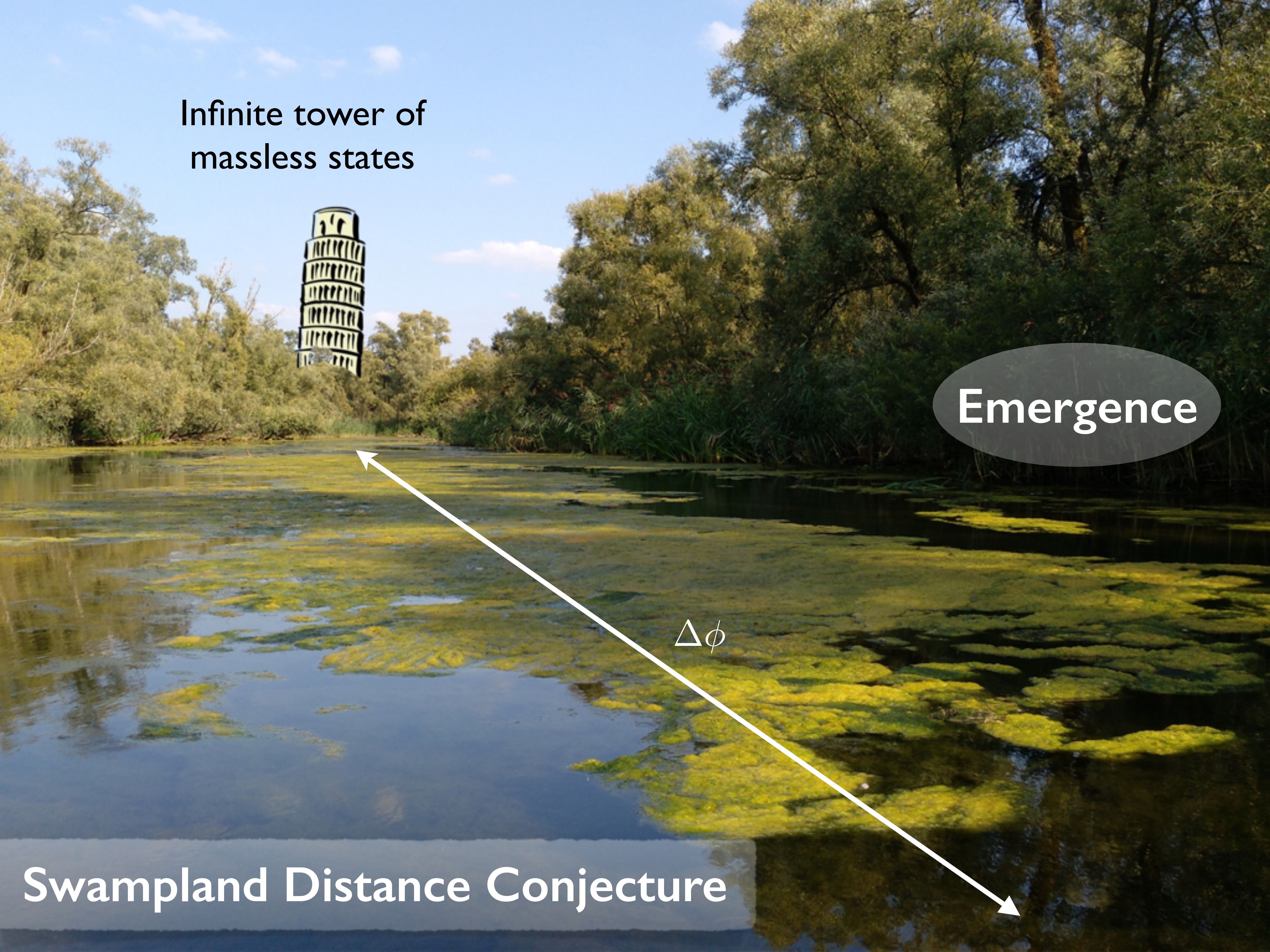
Utrecht University

Universiteit Utrecht

Grimm, Palti, IV [arXiv:1802.08264 [hep-th]]

Corvilain, Grimm, IV (to appear)

Vistas over the Swampland, IFT (Madrid), September 2018


Infinite tower of
massless states
Emergence
$\Delta\phi$
Swampland Distance Conjecture

Swampland Distance Conjecture

I. Relation to dualities, emergence and global symmetries

II. Explicit realisations in string theory

Swampland Distance Conjecture [Ooguri-Vafa'06]

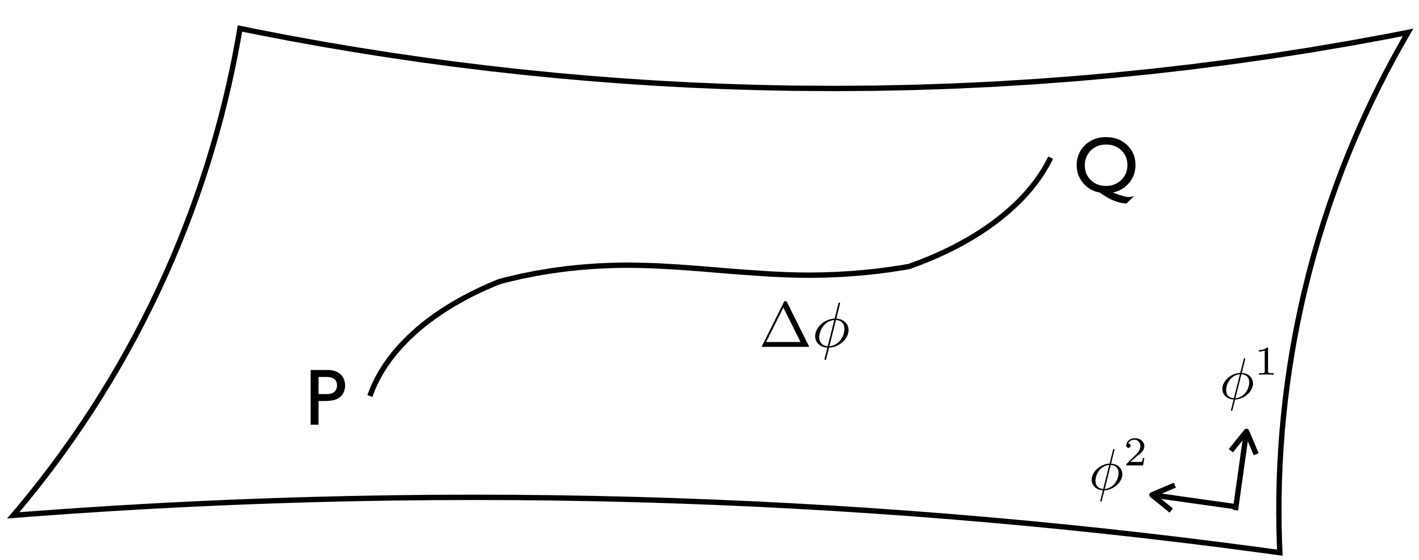
An effective theory is valid only for a finite scalar field variation $\Delta\phi$

because an infinite tower of states become exponentially light

$$m \sim m_0 e^{-\lambda\Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

Consider the moduli space of an effective theory:

$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j$ → scalar manifold



$\Delta\phi =$ geodesic distance between P and Q

$$m(P) \lesssim m(Q)e^{-\lambda\Delta\phi}$$

Swampland Distance Conjecture [Ooguri-Vafa'06]

An effective theory is valid only for a finite scalar field variation $\Delta\phi$

because an infinite tower of states become exponentially light

$$m \sim m_0 e^{-\lambda\Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

This signals the breakdown of the effective theory:

$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \, \exp(-\lambda\Delta\phi)$$

Swampland Distance Conjecture

Phenomenological implications: (to appear with Marco Scalisi)

It gives an upper bound on the scalar field range described by any effective field theory with finite cut-off

$$\Delta\phi \lesssim \frac{1}{\lambda}\log\left(\frac{M_p}{\Lambda}\right)$$

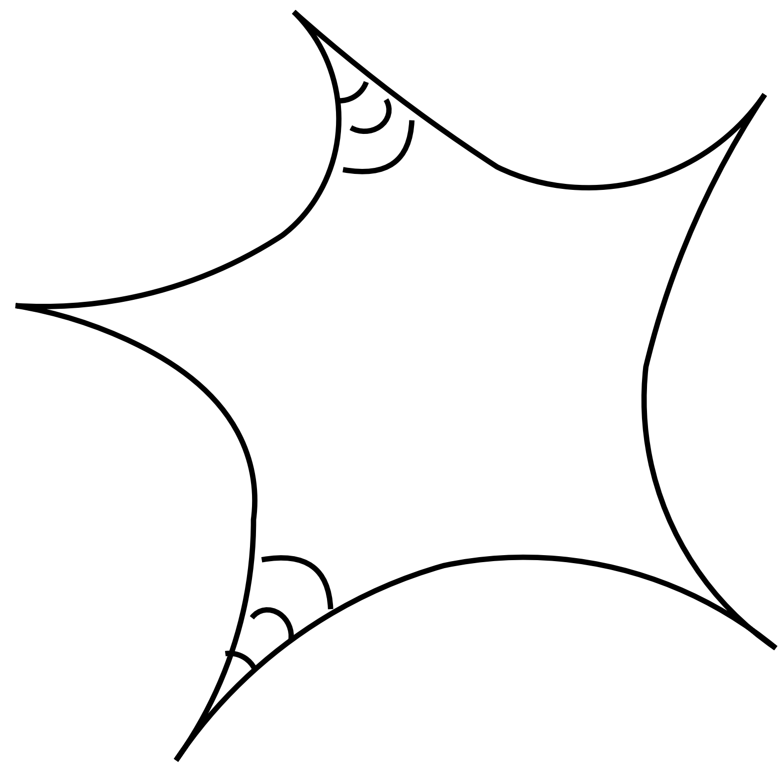
- **Large field inflation**
- **Cosmological relaxation of the EW scale**

(see Ralph's talk)

Evidence: based on particular examples in string theory compactifications

[Ooguri,Vafa'06] [Baume,Palti'16] [I.V.,'16] [Bielleman,Ibanez,Pedro,I.V.,Wieck'16] [Blumenhagen,I.V.,Wolf'17] [Hebecker,Henkenjohann,Witkowski'17] [Cicoli,Ciupke,Mayhrofer,Shukla'18][Blumenhagen et al.'18]

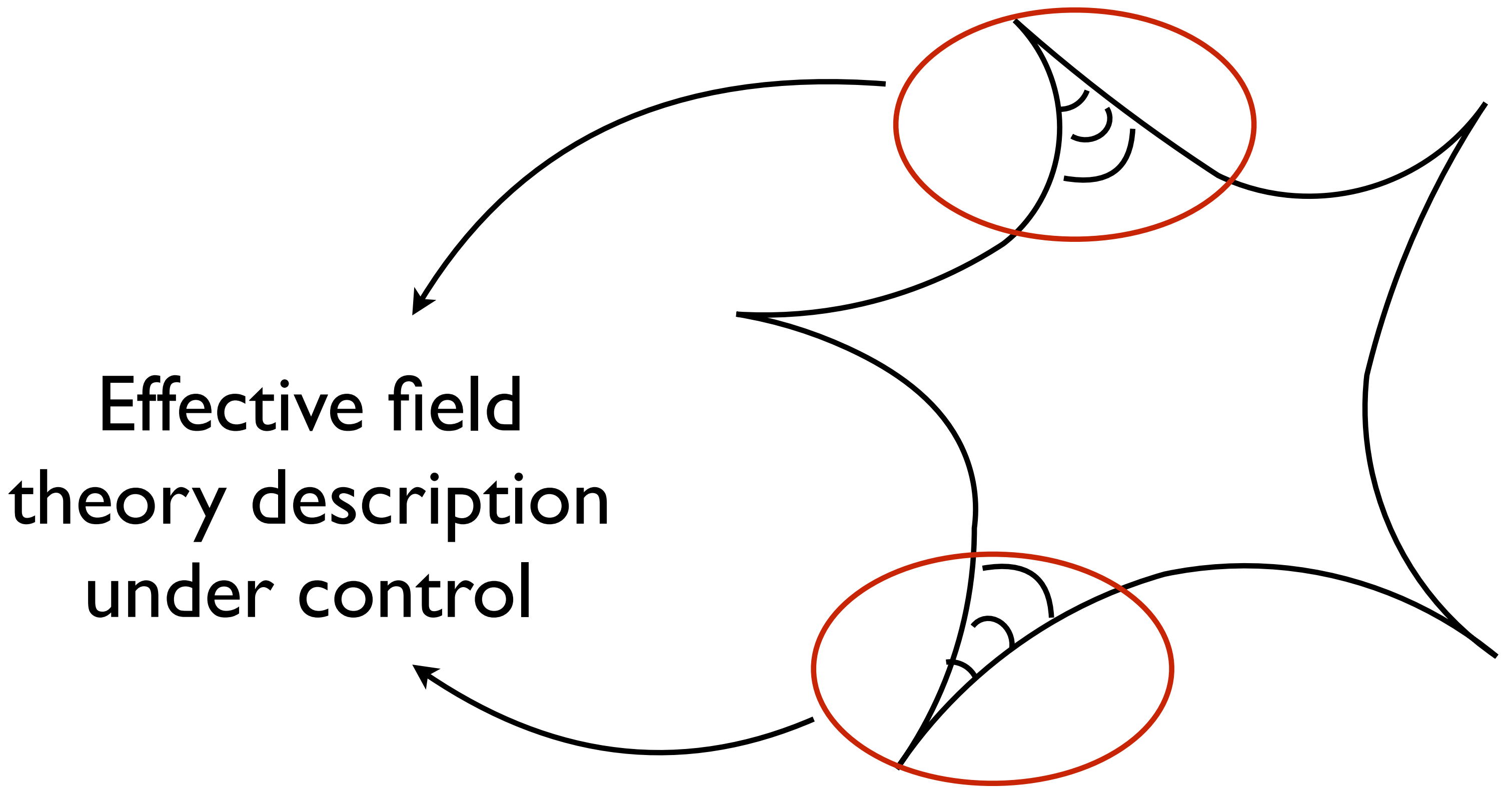
SDC and Dualities



Infinite geodesic distances can occur only if approaching a singularity/boundary of the moduli space

➡ New massless degrees of freedom appear

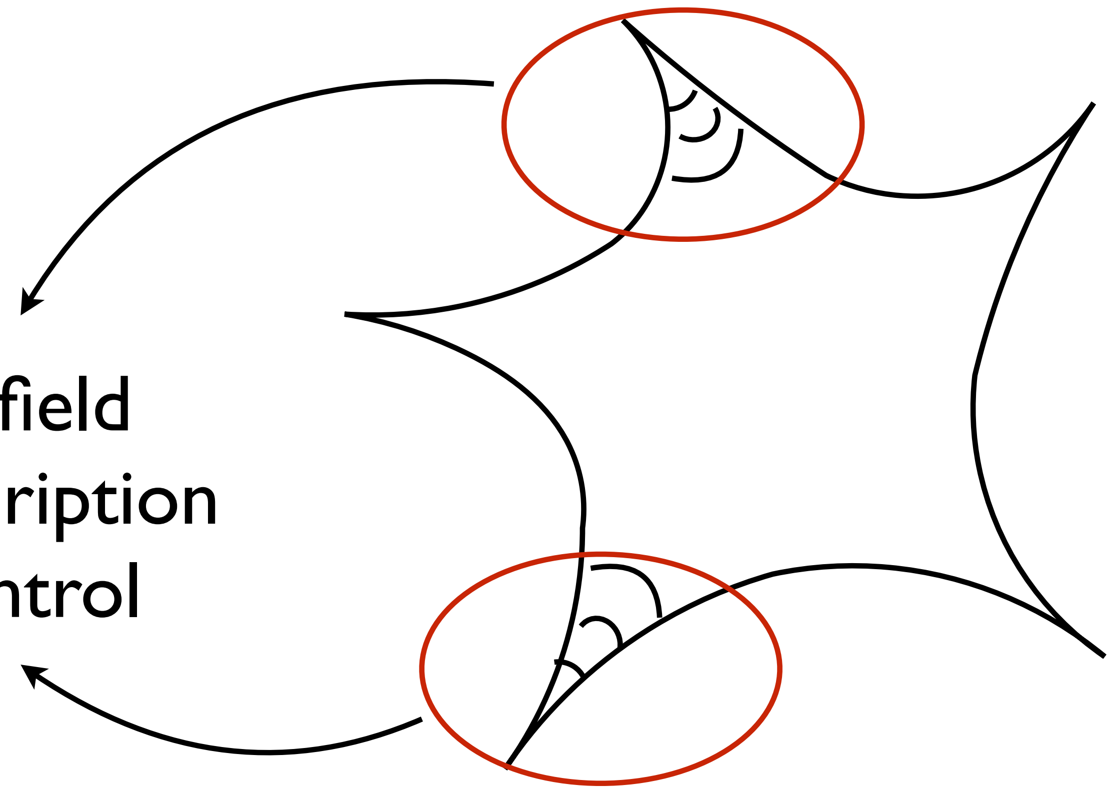
SDC and Dualities



Infinite geodesic distances can occur only if approaching a singularity/boundary of the moduli space

→ New massless degrees of freedom appear

SDC and Dualities

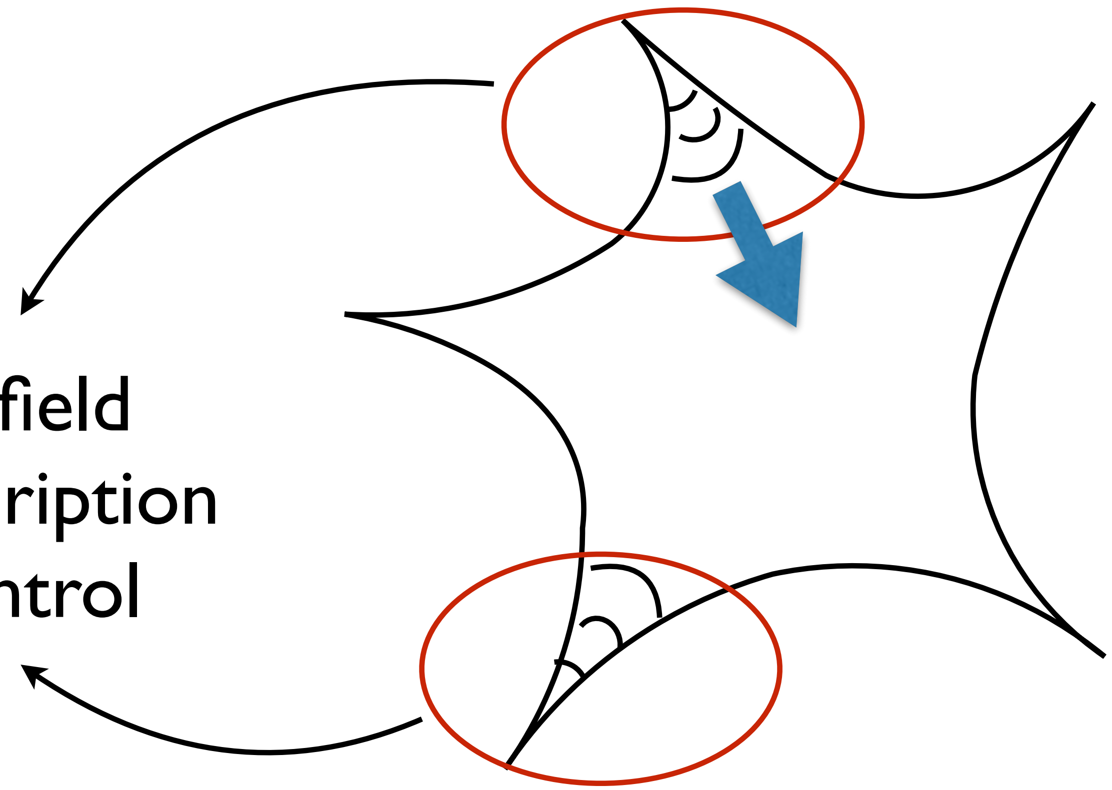


Effective field theory description under control

Infinite distance loci: special limits where a weakly coupled description arises

(weakly coupled gauge theory, global symmetries…)

SDC and Dualities



Effective field theory description under control

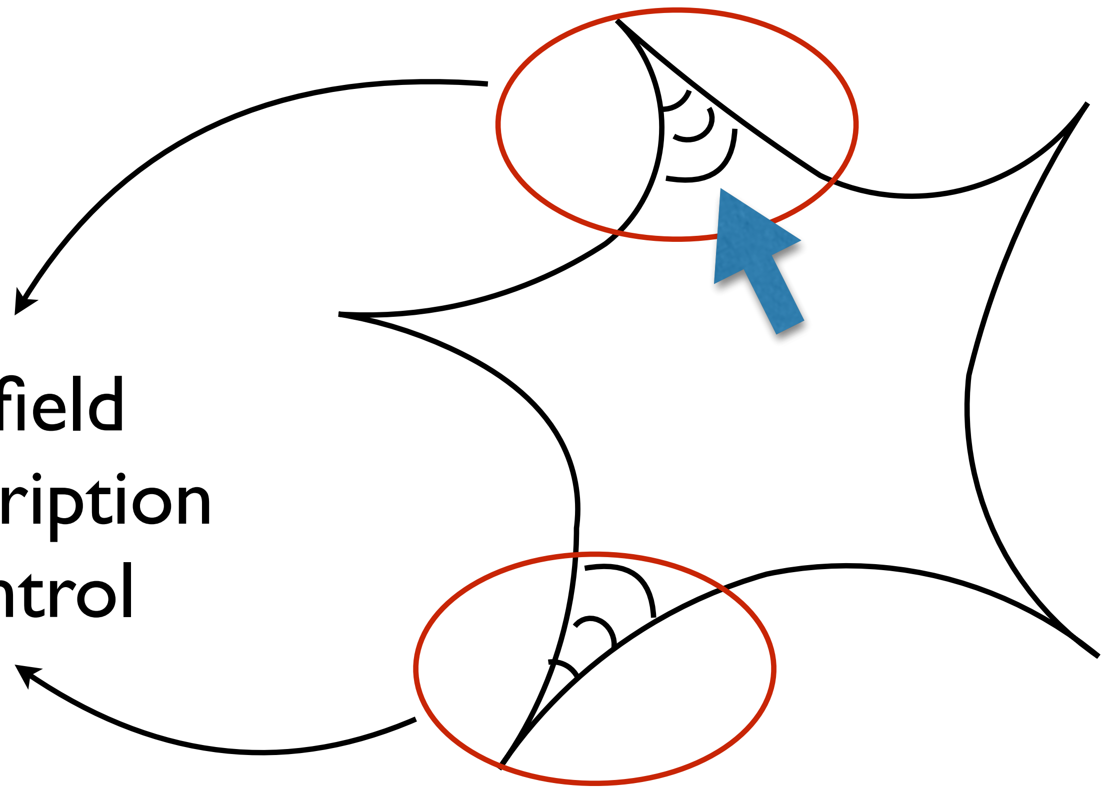
It breaks down when going to the bulk

(instanton,quantum corrections,etc.)

Infinite distance loci: special limits where a weakly coupled description arises

(weakly coupled gauge theory, global symmetries…)

SDC and Dualities



Effective field theory description under control

It breaks down when approaching the boundary

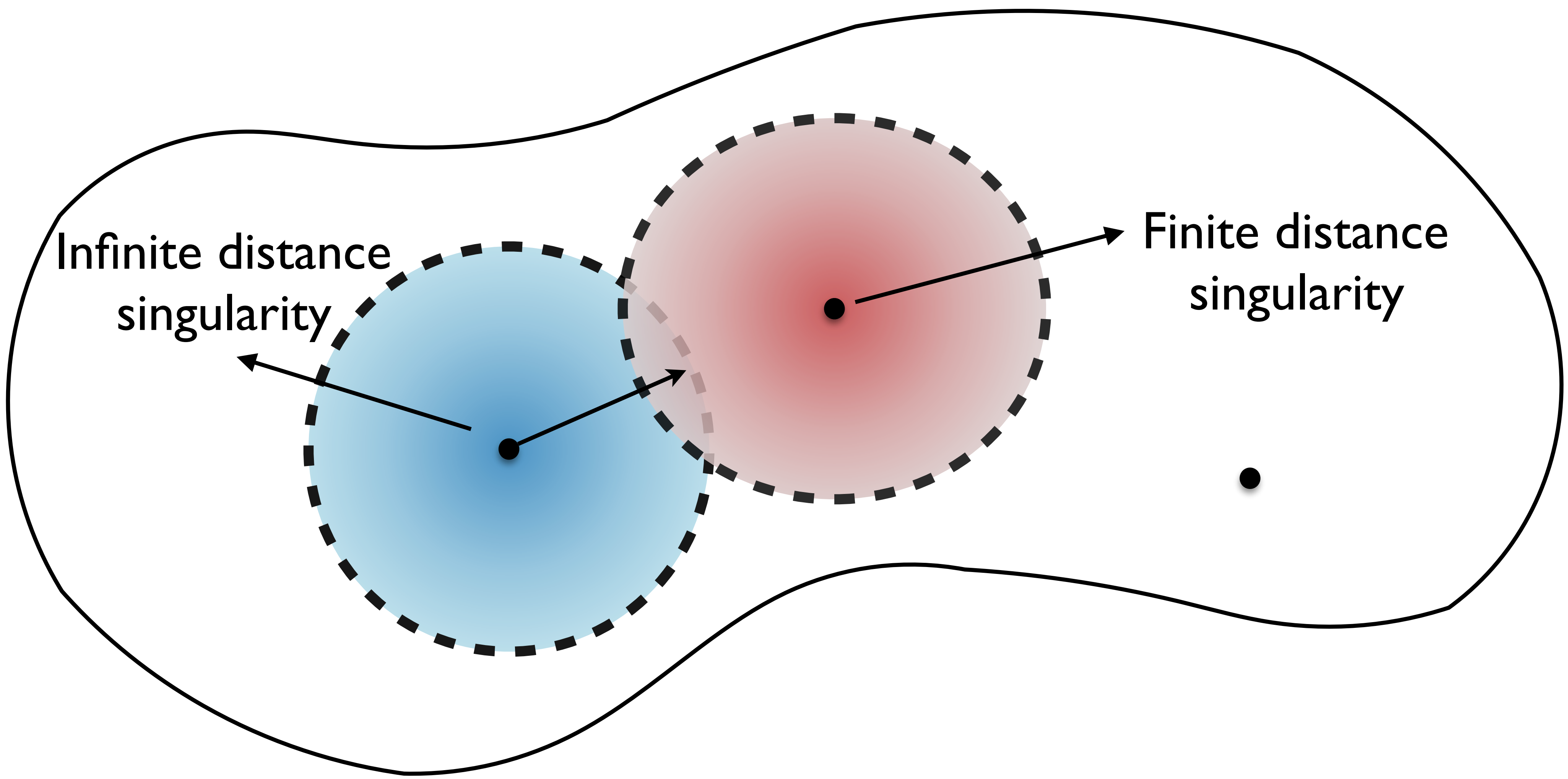
(Infinite massless tower = QG effect)

Infinite distance loci: special limits where a weakly coupled description arises (weakly coupled gauge theory, global symmetries…)

SDC, WGC… = Quantum Gravity Obstruction to restore global symmetries

SDC vs EFT validity

Moduli space of a string compactification:

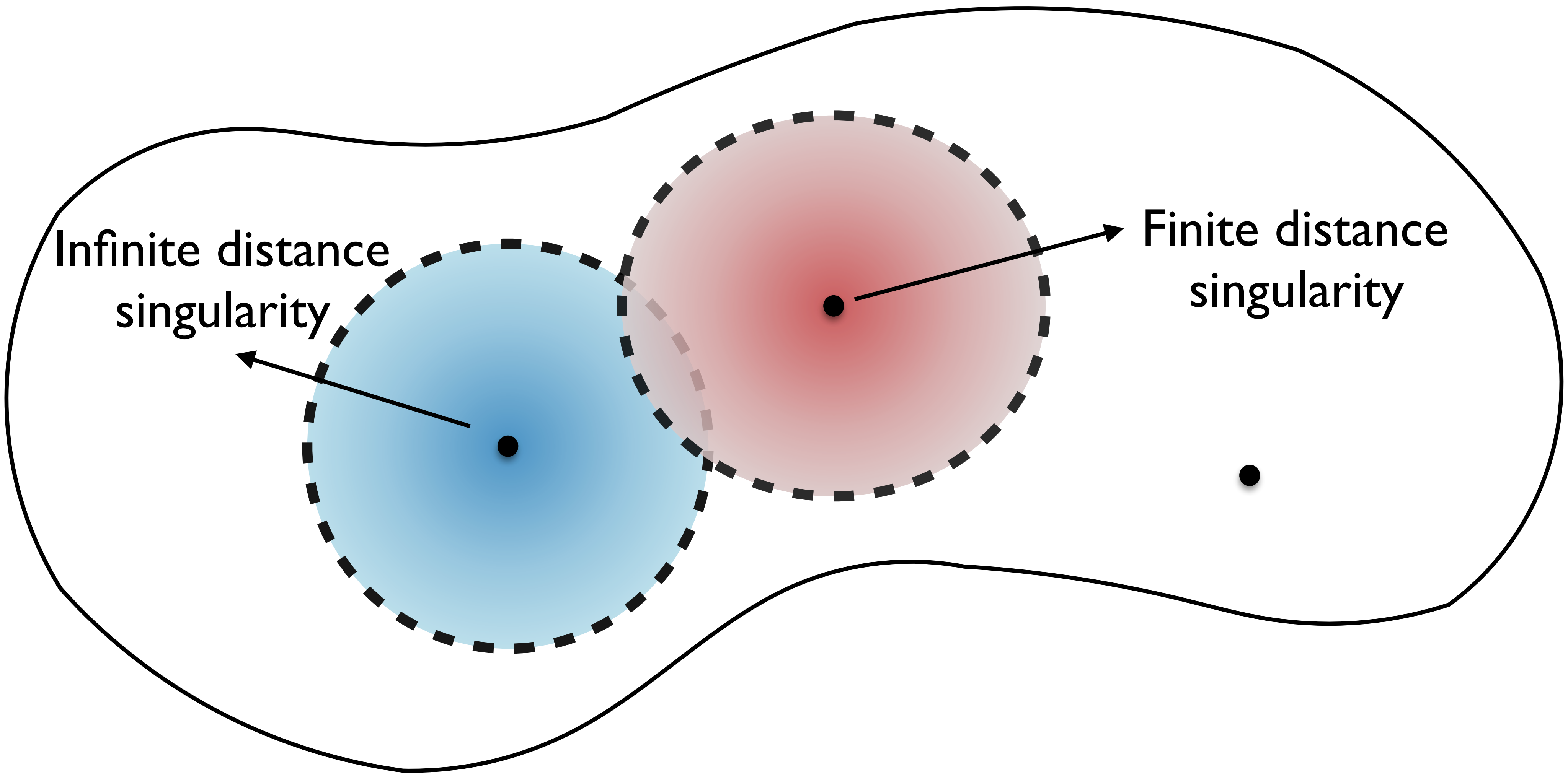


Two types:

- Infinite distance singularities: any trajectory approaching P has infinite length
- Finite distance singularities: at least one trajectory approaching P has finite length

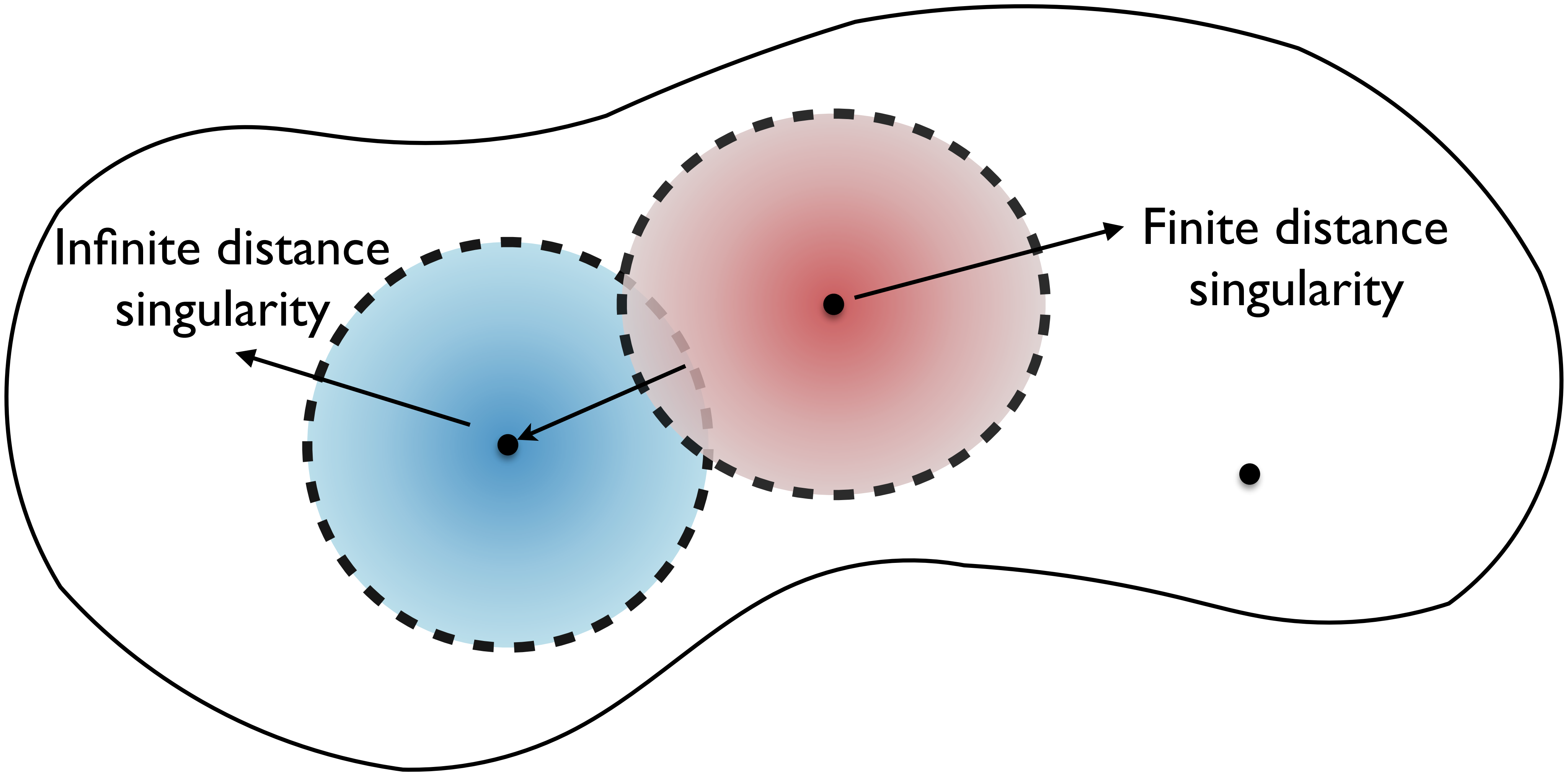
SDC vs EFT validity

Moduli space of a string compactification:



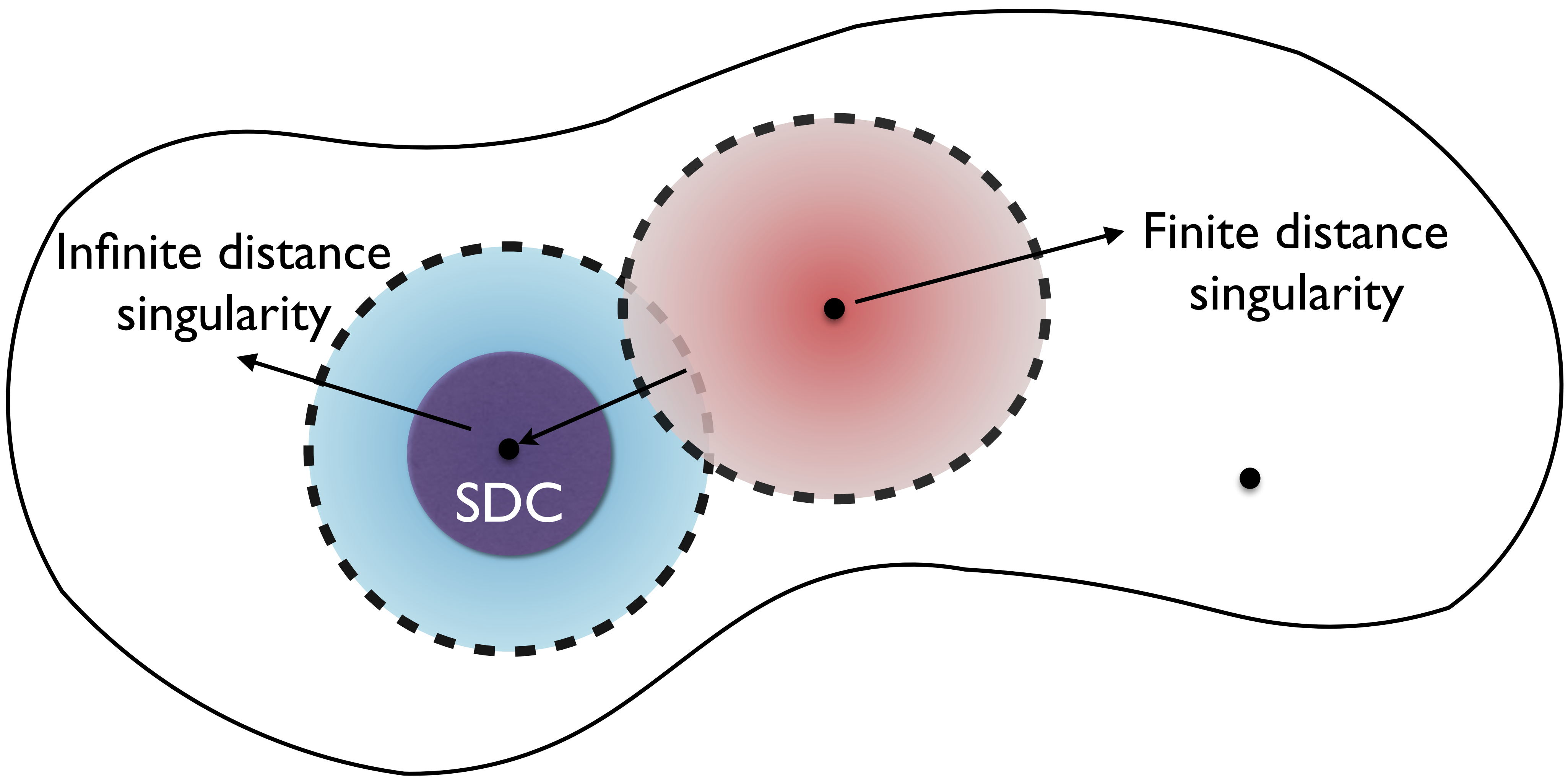
SDC vs EFT validity

Moduli space of a string compactification:



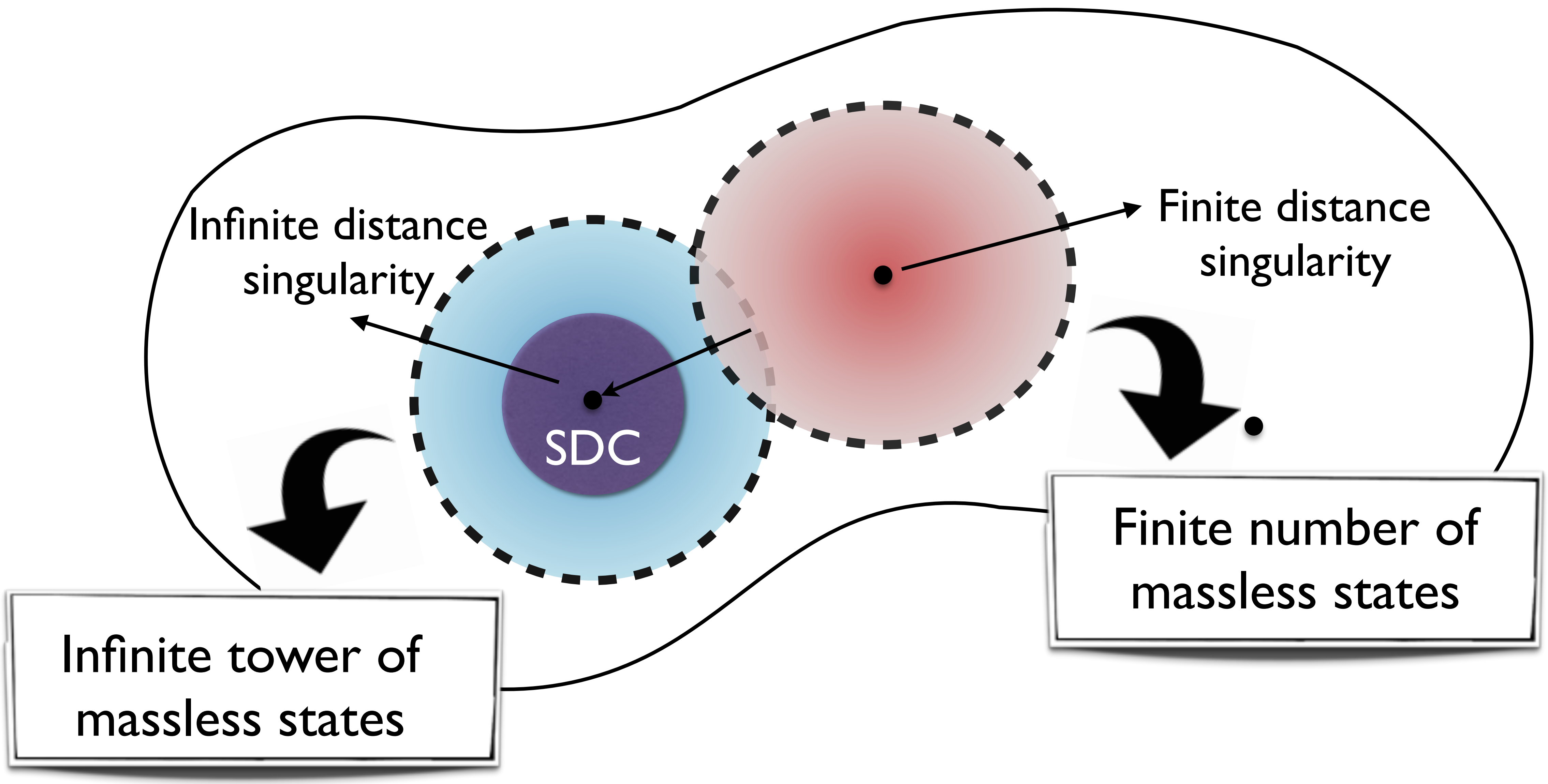
SDC vs EFT validity

Moduli space of a string compactification:



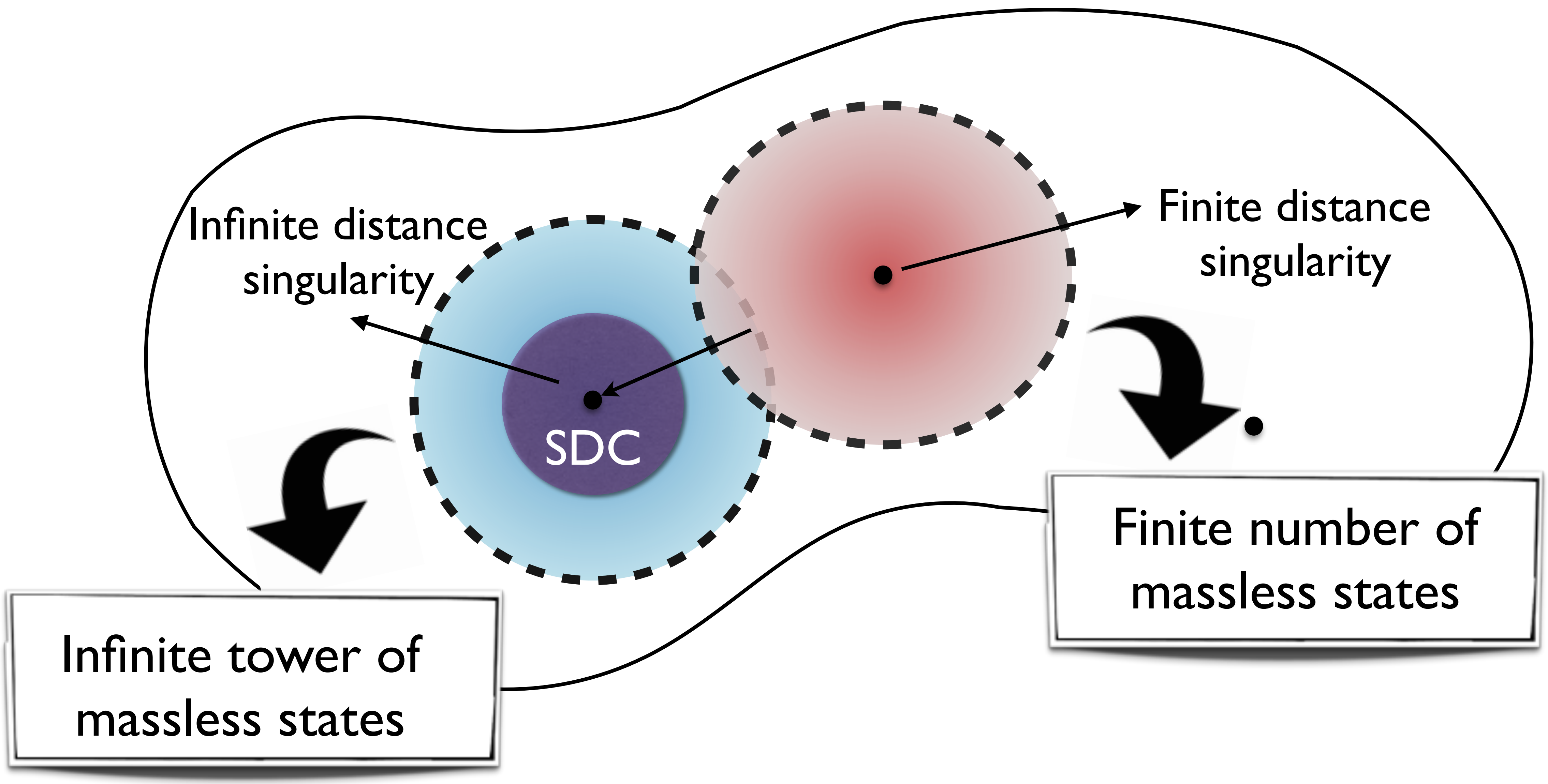
SDC vs EFT validity

Moduli space of a string compactification:



SDC vs EFT validity

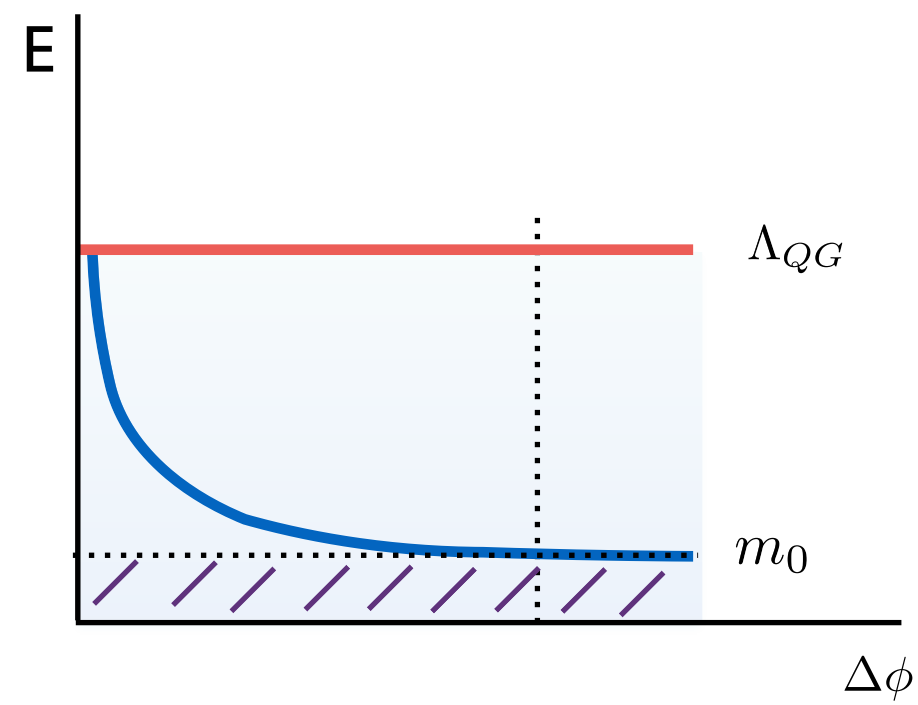
Moduli space of a string compactification:



Quantum gravity cut-off goes to zero: drastic change of the EFT (dual theory)

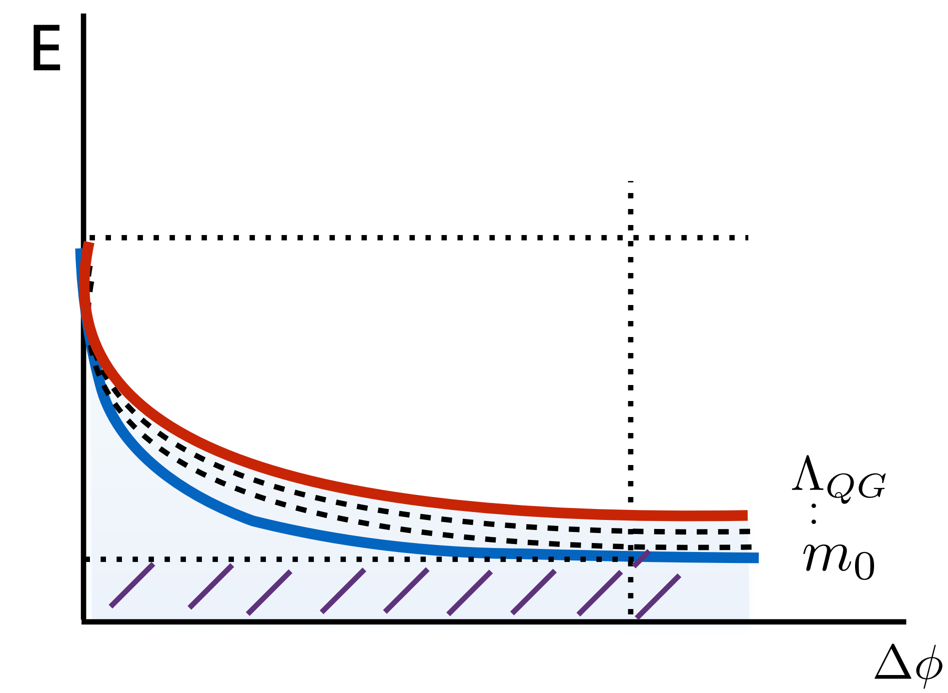
SDC vs EFT validity

Finite distance singularity:



(one field becoming massless)

Infinite distance singularity:



(infinitely many becoming massless)

Quantum gravity cut-off goes to zero: drastic change of the EFT (dual theory)

Global symmetries

SDC as a Quantum Gravity obstruction to restore global symmetries

SDC = Magnetic Scalar WGC

- Magnetic version:

WGC: $\Lambda < g M_p$ If $g \to 0$ global symmetry is restored

How small can the gauge coupling be?

SDC: $\Lambda \sim M_p \exp(-\lambda \Delta\phi)$ If $\Delta\phi \to \infty$ global symmetry is restored

How large can the field variation be?

- Electric version:

$$\underbrace{g^{ij}\,(\partial_i m)\,(\partial_j m)}_{\text{charge}}\, M_p^2 \geq \underbrace{m^2}_{\text{mass}}$$

→ satisfied for long distance if mass is exponential in ϕ [Palti'17]

Emergence

Infinite distance and weak coupling emerge from quantum corrections of integrating out an infinite tower of states!

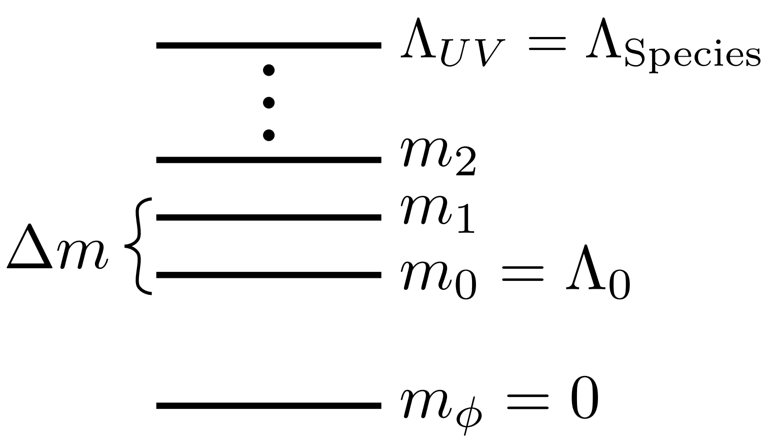
	SDC →	
Infinite distance		Infinite states (specific structure)★
	← Emergence	
	?	

Grimm, Palti, IV [arXiv:1802.08264 [hep-th]]
(see also [Heidenreich,Reece,Rudelius'18])

★ Infinite tower of stable states (different species) satisfying:

$$g^{ij}\frac{\partial_{\phi_i} m \partial_{\phi_j} m}{m^2} \geq 1 \quad \text{when} \quad \phi \to \infty \qquad \text{(Scalar WGC!)}$$

Emergence of the infinite field distance



- Original theory:

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial\phi)^2}_{\text{light field}} + \sum_{i=1}^{N}\left[\frac{1}{2}(\partial h_i)^2 + \underbrace{\frac{1}{2}m_i\,(\phi)^2\,h_i^2}_{\text{tower of massive fields}}\right]$$

tower of massive fields $\longrightarrow$ integrate them out!

$$m_k = m_0 + k\Delta m$$

- Quantum correction to the field metric for ϕ :

$$\delta g_{\phi\phi} \propto \sum_{k=1}^{N}(\partial_\phi m_k)^2$$

Consider $m_k(\phi_1) = 0$

Proper field distance: $d(\phi_1, \phi_2) \simeq \int_{\phi_1}^{\phi_2}\sqrt{\sum_{k=1}^{N}(\partial_\phi m_k)^2}$ always finite if N is finite

How to perform the infinite sum $N \to \infty$ as we approach ϕ_1 ?

Emergence of the infinite field distance

$\Lambda_{UV} = \Lambda_{\text{Species}}$

$\vdots$

m_2

$\Delta m \{$ m_1, $m_0 = \Lambda_0$

$m_\phi = 0$

UV cut-off = Species bound

$$\Lambda_{UV} = \frac{M_p}{\sqrt{N}}$$ [Dvali'07]

$\hookrightarrow$ number of species below Λ_{UV}

- We have to integrate out the tower of particles up to the UV cut-off of the original theory!

$$N = \frac{\Lambda_{UV}}{\Delta m(\phi)} \rightarrow$$

$\downarrow$ tower gets compressed

$$\Lambda_{UV}(\phi) \sim \Delta m(\phi)^{1/3}$$

Field dependent UV cut-off!

At the singularity: $\Delta m(\phi) \to 0$ $\quad \begin{cases} \Lambda_{UV} \to 0 \\ N \to \infty \end{cases}$

Emergence of the infinite field distance

$\Lambda_{UV} = \Lambda_{\text{Species}}$

$\vdots$

m_2

$\Delta m \left\{ \begin{array}{l} m_1 \\ m_0 = \Lambda_0 \end{array} \right.$

$m_\phi = 0$

UV cut-off = Species bound

$$\Lambda_{UV} = \frac{M_p}{\sqrt{N}}$$ [Dvali'07]

↳ number of species below Λ_{UV}

- Quantum correction to the field metric for ϕ

$$\delta g_{\phi\phi} \propto \sum_{k=1}^{N} (\partial_\phi m_k)^2 \sim \left(\frac{\partial_\phi \Delta m}{\Delta m}\right)^2$$

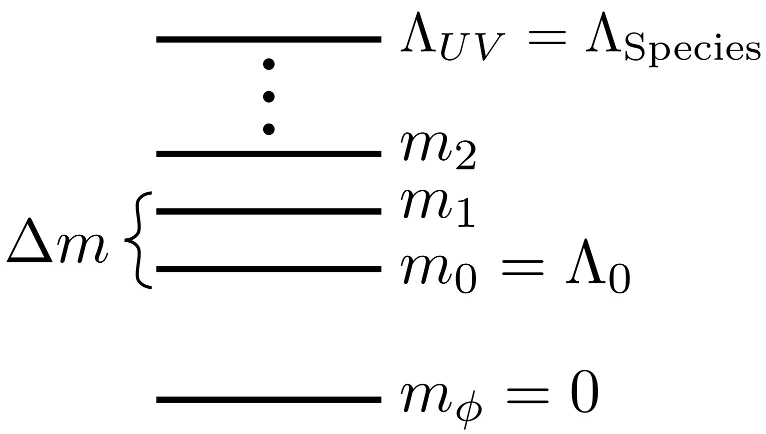
$$d(\phi_1, \phi_2) \simeq \int_{\phi_1}^{\phi_2} \sqrt{\delta g_{\phi\phi}} \sim \log\left(\frac{\Delta m(\phi_2)}{\Delta m(\phi_1)}\right)$$

Universal exponential mass behaviour!

In particular: $\Delta m \sim \phi^{-n} \longrightarrow \delta g_{\phi\phi} \sim \dfrac{n}{\phi^2}$ ➡ $\left\{ \begin{array}{l} d(\phi_1, \phi_2) \sim n \log\left(\dfrac{\phi_2}{\phi_1}\right) \to \infty \\ m \sim \exp\left(-\dfrac{1}{n} d(\phi_1, \phi_2)\right) \end{array} \right.$

Emergence: $\delta g_{\phi\phi} \sim g_{\phi\phi}$ if $g^{\phi\phi} (\partial_\phi \Delta m)^2 \sim \Delta m^2$ (Scalar WGC for an infinite tower)

Emergence of the infinite field distance



UV cut-off = Species bound

$$\Lambda_{UV} = \frac{M_p}{\sqrt{N}}$$ [Dvali'07]

↳ number of species below Λ_{UV}

- UV cut-off decreases exponentially fast in the proper field distance

$$\Lambda_{UV} \sim M_p \, e^{-\frac{1}{n} d(\phi_1, \phi_2)}$$

SDC! ✓

Emergence of the weak gauge coupling

$$\Lambda_{UV} = \Lambda_{\text{Species}}$$
$$\vdots$$
$$m_2$$
$$\Delta m \begin{cases} m_1 \\ m_0 = \Lambda_0 \end{cases}$$
$$m_\phi = 0$$

- **Original theory:**

U(1) gauge field theory + tower of charged massive fields

- **Quantum correction to the gauge coupling:**

$$\frac{1}{g_{IR}^2} = \frac{1}{g_{UV}^2} - \sum_k^N \left(\frac{8q_k^2}{3\pi^2} \log \frac{\Lambda_{UV}}{m_k} \right) \begin{cases} \dfrac{1}{g_{IR}^2} \propto \log m_0 & \text{for single field (logarithmic running)} \\[2ex] \dfrac{1}{g_{IR}^2} \propto \dfrac{1}{\Delta m^2} & \text{for infinite tower (power law!)} \end{cases}$$

$g \to 0$ as a power law on m if an infinite tower of states are integrated out up to the species bound

Emergence from integrating out the states

Infinite distance and weak coupling emerge from integrating out an infinite tower of states!

Grimm, Palti, IV [arXiv:1802.08264 [hep-th]]

Can this be a general feature for any stringy moduli space?

These limits correspond to restoring a continuous global symmetry, so global symmetries would also be emergent from integrating out infinitely many states!

(emergence is continuous)

$$\Lambda_{UV} = \frac{M_p}{\sqrt{S}} \longrightarrow 0 \quad \text{when} \quad S \to \infty \quad \text{unless} \quad M_p \to \infty$$

Global symmetries only possible if gravity decouples

Swampland Distance Conjecture

II. Explicit realisations in string theory:

- Complex structure moduli space of Type IIB CY compactifications

- Kahler moduli space in M/F-theory

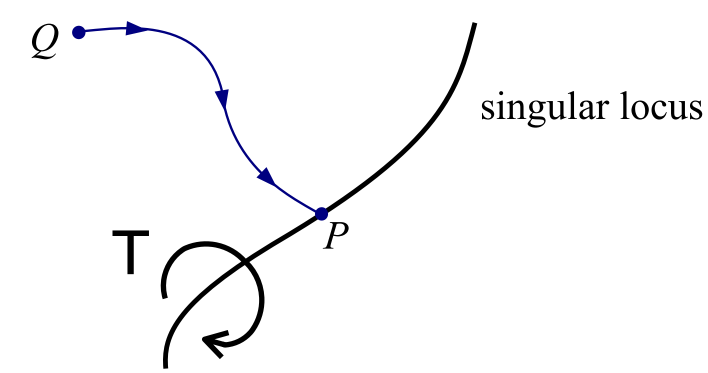
Grimm, Palti, IV [arXiv:1802.08264 [hep-th]]

Complex structure moduli space of IIB CY compactifications

(4d N=2 string theory moduli space preserving special Kahler geometry)

Massless BPS states (wrapping D3-branes) arise at the singularities

Candidates for SDC tower!



Aim: Identify infinite tower of exponentially massless BPS states at any infinite distance singularity

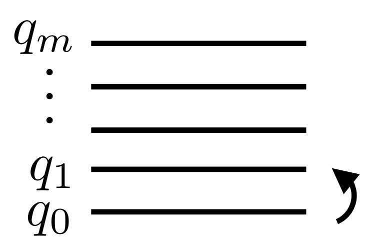
Key ingredient: **Monodromy** transformation T around the singular locus

Infinite distances - Infinite states

1) Infinite distances occur only if monodromy is of infinite order

2) Monodromy can be used to populate an infinite orbit of BPS states

Only the tower (but not individual states) need to be invariant under T



$$q_m = T^m q \qquad m \in \mathbb{Z}$$

If T is of infinite order ➡ Starting with one state, we generate infinitely many!

3) Monodromy is enhanced to a continuous transformation at the singularity

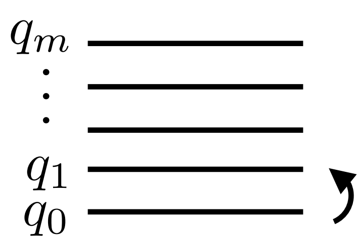
Appearance of an axion enjoying a would-be continuous global shift symmetry

Infinite distances - Infinite states

1) Infinite distances occur only if monodromy is of infinite order

2) Monodromy can be used to populate an infinite orbit of BPS states

Only the tower (but not individual states) need to be invariant under T



$$q_m = T^m q \qquad m \in \mathbb{Z}$$

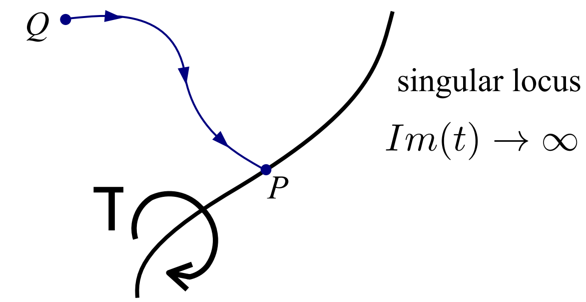
If T is of infinite order → Starting with one state, we generate infinitely many!

3) Monodromy is enhanced to a continuous transformation at the singularity

Appearance of an axion enjoying a would-be continuous global shift symmetry

Nilpotent orbit theorem

It gives a universal local expression for physical quantities near infinite distance singularities!



Nilpotent matrix $N = \log T \quad \left(N^d a_0 \neq 0\,,\; N^{d+1} a_0 = 0 \right)$

[Schmid'73]

Periods of the (D,0)-form: $\Pi(t,\eta) = \exp(tN)\, a_0(\eta) \,+\, \mathcal{O}(e^{2\pi i t}, \eta)$

- Field space metric: $g_{t\bar{t}} = \dfrac{d}{\mathrm{Im}(t)^2} + \dots$
- Central charge of BPS states: $Z = e^K q \cdot \Pi$

$$\frac{M_q(P)}{M_q(Q)} \simeq \exp\left(-\frac{1}{\sqrt{2d}}\, d_\gamma(P,Q)\right)$$

- Power law growth of gauge kinetic function

Universal local form of the metric gives rise to the exponential mass behaviour and the infinite field distance

Infinite monodromy charge orbit

Swampland Distance Conjecture holds if there is:

Infinite massless monodromy charge orbit at the singularity

$$\exists\, q \quad \text{s.t.} \quad q^T N^j a_0 = 0\,, \quad j \geq d/2 \quad \text{(Massless)}$$

$$Nq \neq 0 \quad \text{(Infinite orbit)}$$

Tool: mathematical machinery of mixed hodge structure

[Deligne][Schmid][Cattani,Kaplan,Schmid][Kerr,Pearlstein,Robles'17]

Points that belong to:

- A single singular divisor ✓ [Grimm,Palti,IV.'18]
- Intersection of multiple singular divisors, general expression for charge orbit

[Grimm,Palti,Li] in progress

Valid for any CY!

Emergence from integrating out the states

These moduli spaces are 'quantum in nature' → geometry incorporates information about integrating out BPS states

Famous example: Conifold singularity [Strominger'95]

One-loop corrections from integrating out the tower of BPS states

→ matches geometric result for field metric and gauge coupling

Counting of BPS states via crossing marginal walls of instability implies an exponential growth of stable states as we approach the singularity

→ consistent with species bound

(number of species = number BPS states)

Swampland Distance Conjecture

- Complex structure moduli space of Type IIB CY compactifications
- Kahler moduli space in M/F-theory

Corvilain, Grimm, IV (to appear)

Kaluza-Klein compactification

Circle reduction:

- KK tower $m_k = \frac{n}{R} \to 0$ as $R \to \infty$

- Species bound = Planck mass of higher dimensional theory

$$\Lambda_{QG} \simeq \left(\frac{M_{\rm p,D}^{D-2}}{R} \right)^{\frac{1}{D-1}} \sim M_{\rm p,D+1} \to 0 \quad \text{as} \quad R \to \infty$$

(if we insist on keeping $M_{p,D}$ finite)

- Quantum corrections to field metric: $\delta g_{RR} \sim \frac{M_{p,D}^{D-2}}{R^2}$

$\longrightarrow$ infinite field distance and exponential mass behaviour

M/F-theory duality in 5d/6d

5d M-theory compactification on CY_3 :

- Rich structure of infinite distance singular loci at large volume:

  Classification in terms of monodromy properties

  $\longrightarrow$ completely specified by intersection numbers

- Identification of infinite tower of states:

  Infinite monodromy orbit at certain large volume limits $\Longleftrightarrow$ KK tower of 6d F-theory on a circle

Many things to explore…

(see also Timo's talk, [Lee,Lerche,Weigand'18])

Summary

Swampland Distance Conjecture:

✓ Test in the complex structure moduli space of CY IIB compactifications

- Infinite order monodromy as generator of the infinite tower
- Emergence of infinite field distance and weak coupling from integrating out infinitely many fields

Is this general?

Summary

Swampland Distance Conjecture:

✓ Test in the complex structure moduli space of CY IIB compactifications

- Infinite order monodromy as generator of the infinite tower
- Emergence of infinite field distance and weak coupling from integrating out infinitely many fields

Is this general?

Thank you!

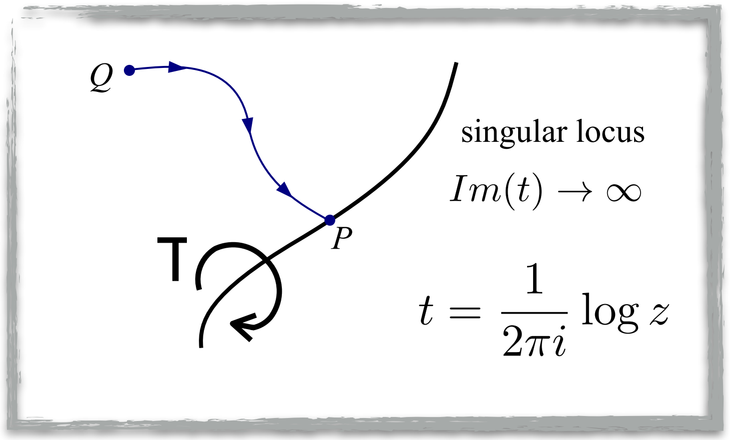
back-up slides

Nilpotent orbit theorem

- Distances given by: $d_\gamma(P,Q) = \int_\gamma \sqrt{g_{IJ}\dot{x}^I\dot{x}^J}ds$

$$g_{I\bar{J}} = \partial_{z^I}\partial_{\bar{z}^J}K$$

$$K = -\log\left(-i^D\int_{Y_D}\Omega\wedge\bar{\Omega}\right)$$



Nilpotent orbit theorem

- Distances given by: $d_\gamma(P,Q) = \int_\gamma \sqrt{g_{IJ}\dot{x}^I\dot{x}^J}ds$

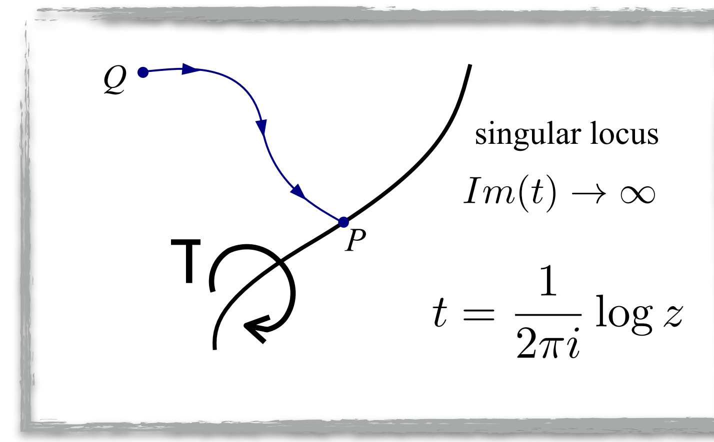
$$g_{I\bar{J}} = \partial_{z^I}\partial_{\bar{z}^J} K$$

$$K = -\log\left(-i^D \int_{Y_D} \Omega \wedge \bar{\Omega}\right)$$

- Periods of the (D,0)-form: $\Pi^{\mathcal{I}} = \int_{\Gamma_{\mathcal{I}}} \Omega$

transform under monodromy $\Pi(e^{2\pi i z}) = T \cdot \Pi(z)$

(remnant of higher dimensional gauge symmetries)



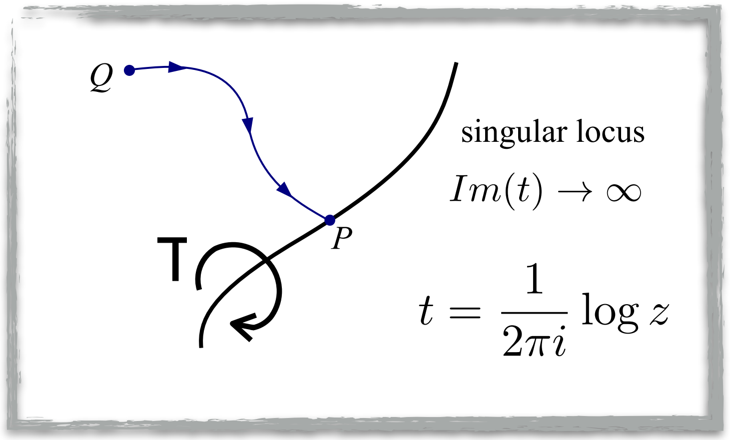
Nilpotent orbit theorem

- Distances given by: $d_\gamma(P,Q) = \int_\gamma \sqrt{g_{IJ}\dot{x}^I\dot{x}^J}ds$

$$g_{I\bar{J}} = \partial_{z^I}\partial_{\bar{z}^J}K$$

$$K = -\log\left(-i^D\int_{Y_D}\Omega\wedge\bar{\Omega}\right)$$

- Periods of the (D,0)-form: $\Pi^{\mathcal{I}} = \int_{\Gamma_{\mathcal{I}}}\Omega$



transform under monodromy $\Pi(e^{2\pi i z}) = T\cdot\Pi(z)$

(remnant of higher dimensional gauge symmetries)

- Define nilpotent matrix $N = \log T$ (only non-zero if monodromy T is of infinite order)

$(\text{no } k \text{ s.t. } T^k = T)$

Nilpotent orbit theorem

- Distances given by: $d_\gamma(P,Q) = \int_\gamma \sqrt{g_{IJ}\dot{x}^I \dot{x}^J}\, ds$

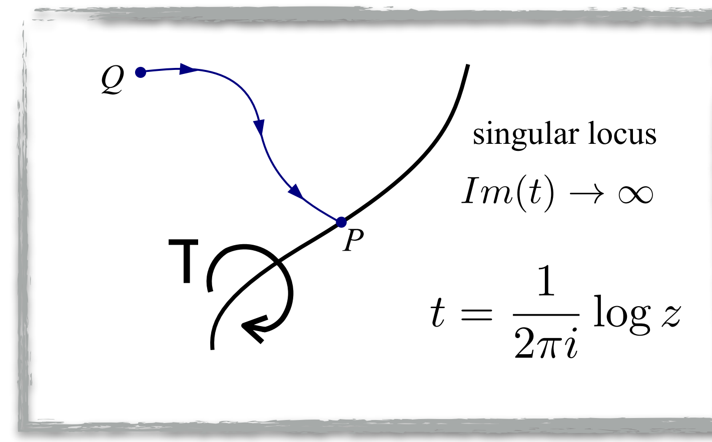
$$g_{I\bar{J}} = \partial_{z^I}\partial_{\bar{z}^J} K$$

$$K = -\log\left(-i^D \int_{Y_D} \Omega \wedge \bar{\Omega}\right)$$

- Periods of the (D,0)-form: $\Pi^{\mathcal{I}} = \int_{\Gamma_{\mathcal{I}}} \Omega$

  transform under monodromy $\Pi(e^{2\pi i z}) = T \cdot \Pi(z)$

  (remnant of higher dimensional gauge symmetries)



- Define nilpotent matrix $N = \log T$ (only non-zero if monodromy T is of infinite order)

  (no k s.t. $T^k = T$)

Nilpotent orbit theorem: [Schmid'73]

$$\Pi(t,\eta) = \exp(tN)\, a_0(\eta) + \mathcal{O}(e^{2\pi i t}, \eta)$$

$$g_{t\bar{t}} = \frac{d}{\mathrm{Im}(t)^2} + \ldots$$

It gives local expression for the periods near singular locus!

$$\Pi(t,\eta) = (1 + tN + \cdots + t^d N^d) a_0(\eta) + \mathcal{O}(e^{2\pi i t, \eta})$$

BPS states and stability

How many BPS states are when approaching singularity?

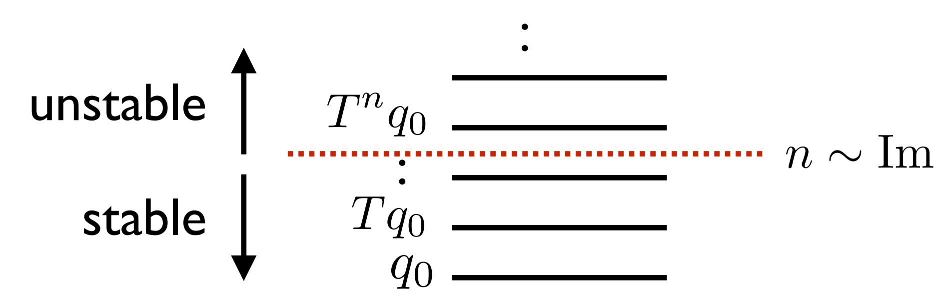
Do they cross a wall of marginal stability upon circling the monodromy locus?

Consider: $\mathbf{q}_C = \mathbf{q}_B + \mathbf{q}_{\bar{A}}$ $\Rightarrow$ $M_{\mathbf{q}_C} \leq M_{\mathbf{q}_B} + M_{\mathbf{q}_{\bar{A}}}$

Wall of marginal stability: $\varphi(B) - \varphi(A) = 1$ with $\varphi(A) = \frac{1}{\pi} \mathrm{Im} \log Z_{\mathbf{q}_A}$

Upon circling the monodromy locus n times:

$$\varphi_{\mathrm{I}} \to \varphi_{\mathrm{I}} - \frac{n}{\pi \mathrm{Im}\, t} + \mathcal{O}\left(\frac{1}{(\mathrm{Im}\ t)^2}\right)$$



Charge states $\mathbf{q} = T^n \mathbf{q}_0$ with $n \ll \mathrm{Im}\, t$ are stable (grade does not change)

(states higher up in the tower are unstable)

Number of BPS states: $n \sim \mathrm{Im}(t) \sim e^{d_\gamma(P,Q)}$

(grows when approaching the singularity and diverges there)