A Universal Pattern at Infinite Field Distance

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In collaboration with Etheredge, Heidenreich, McNamara, Rudelius and Ruiz: 2306.16440 and ongoing
Castellano and Ruiz: 23xx.xxxx
Montero: 23xx.xxxx

Strings 2023, Perimeter, July 2023

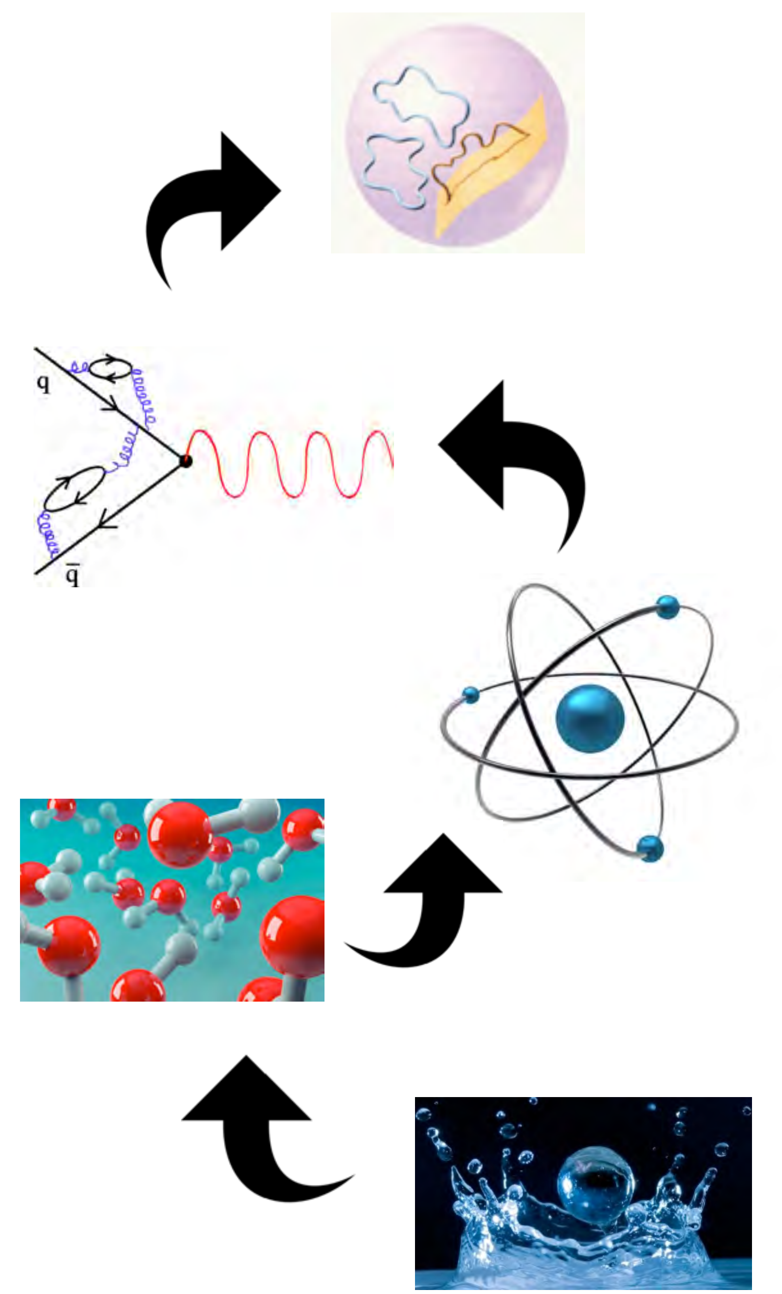
Given an Effective Field Theory (EFT) coupled to Einstein gravity,

Energy

Quantum Gravity

cut-off scale Λ

EFT coupled to classical gravity



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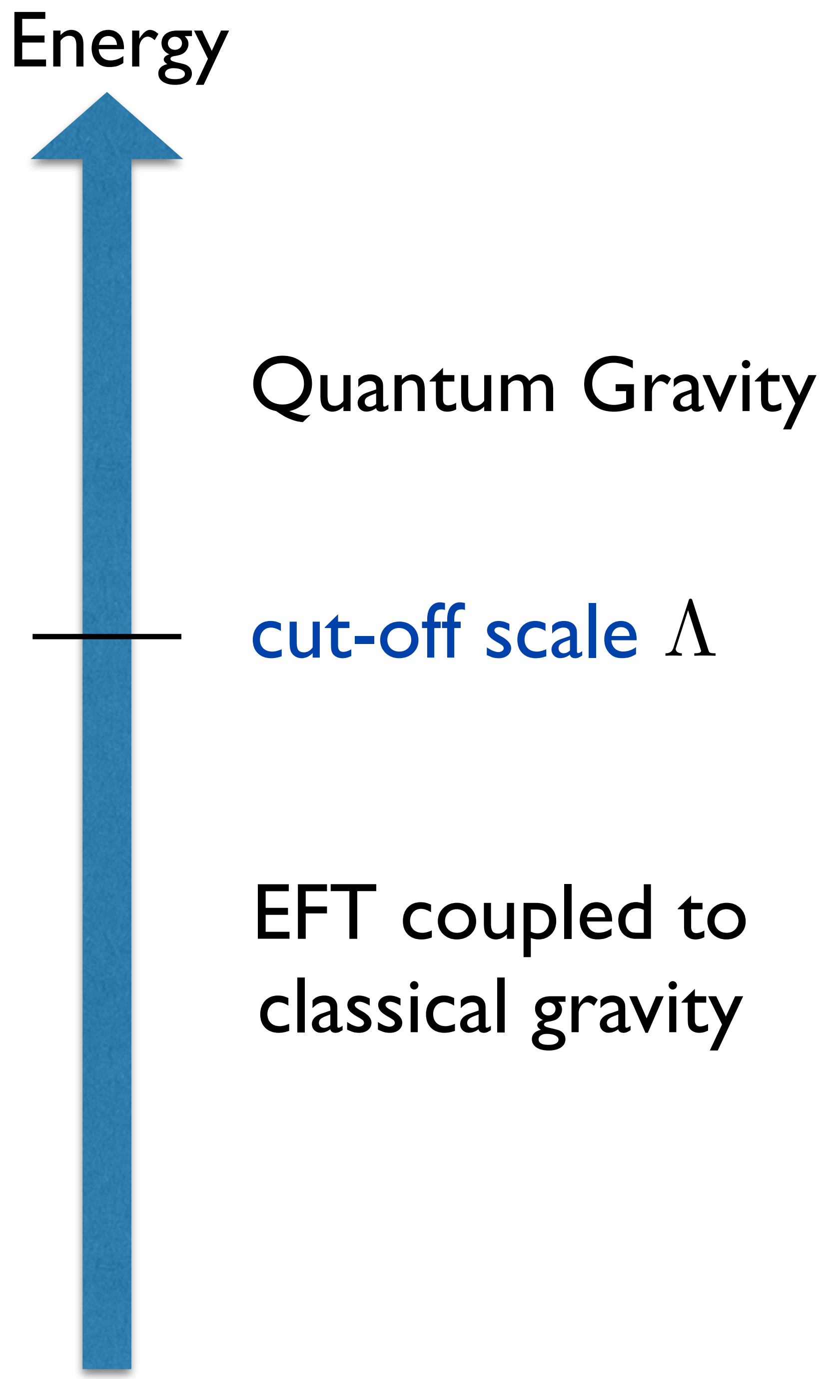

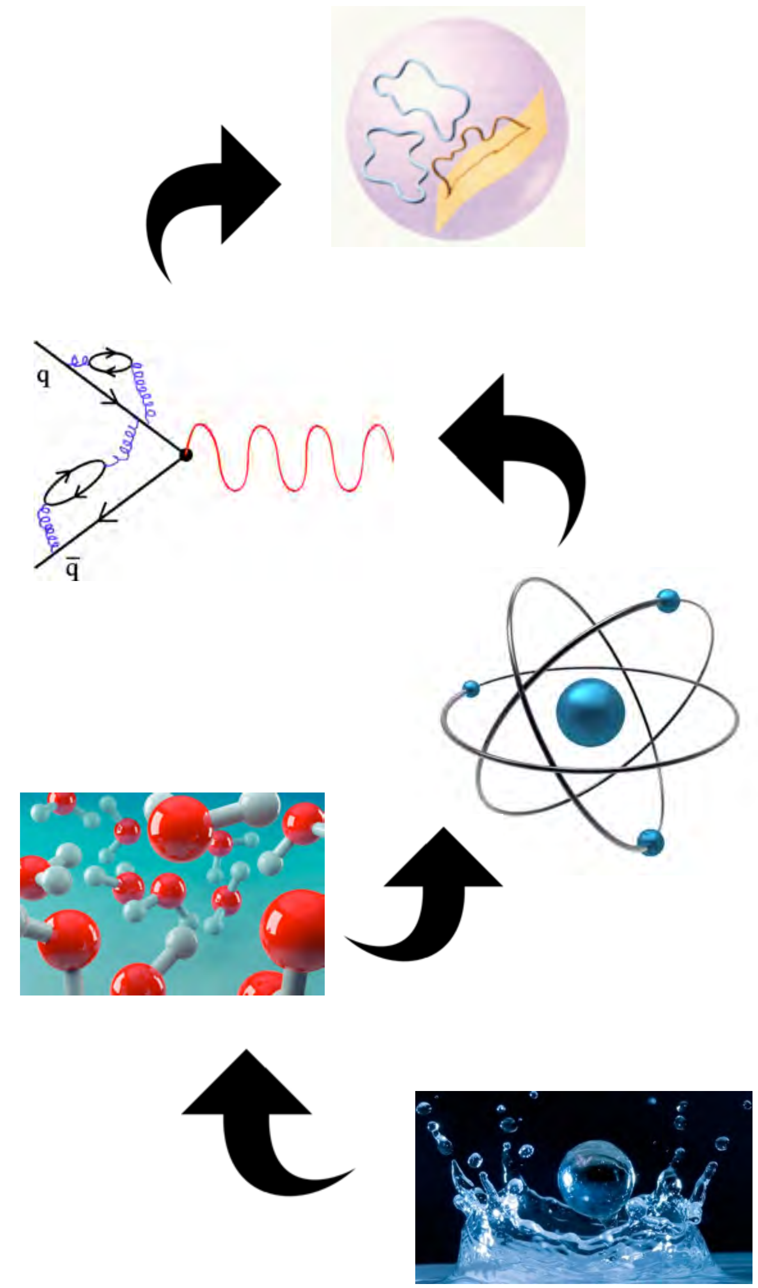

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Is it M_p ?

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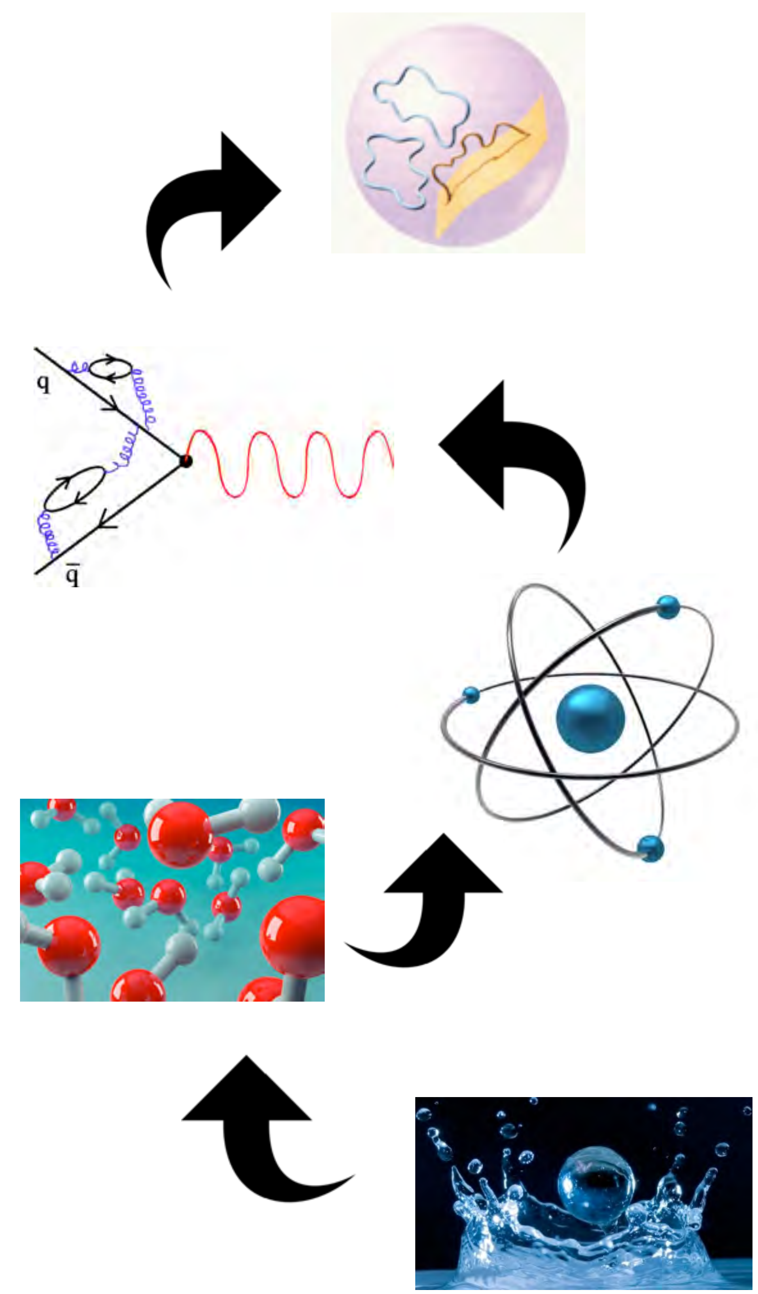

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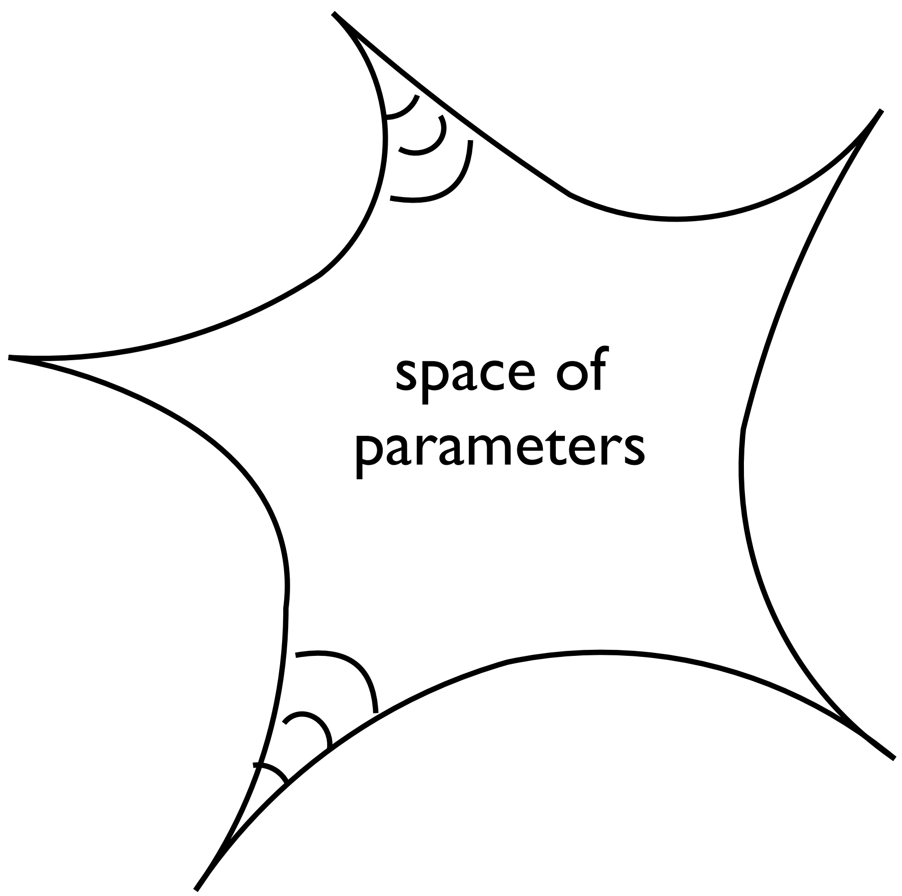
String Theory data / Swampland considerations imply a cut-off $\Lambda < M_p$
(for certain regions of the space of EFT parameters)



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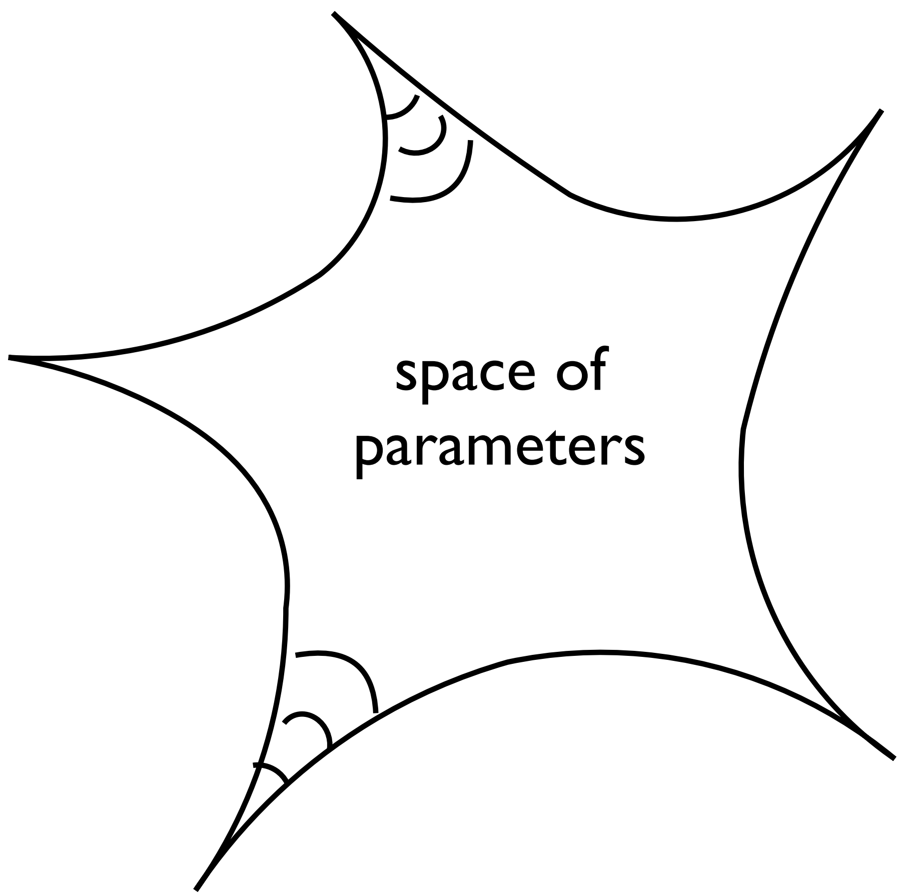

In String Theory:

EFT parameters are given by vacuum expectation values of scalar fields

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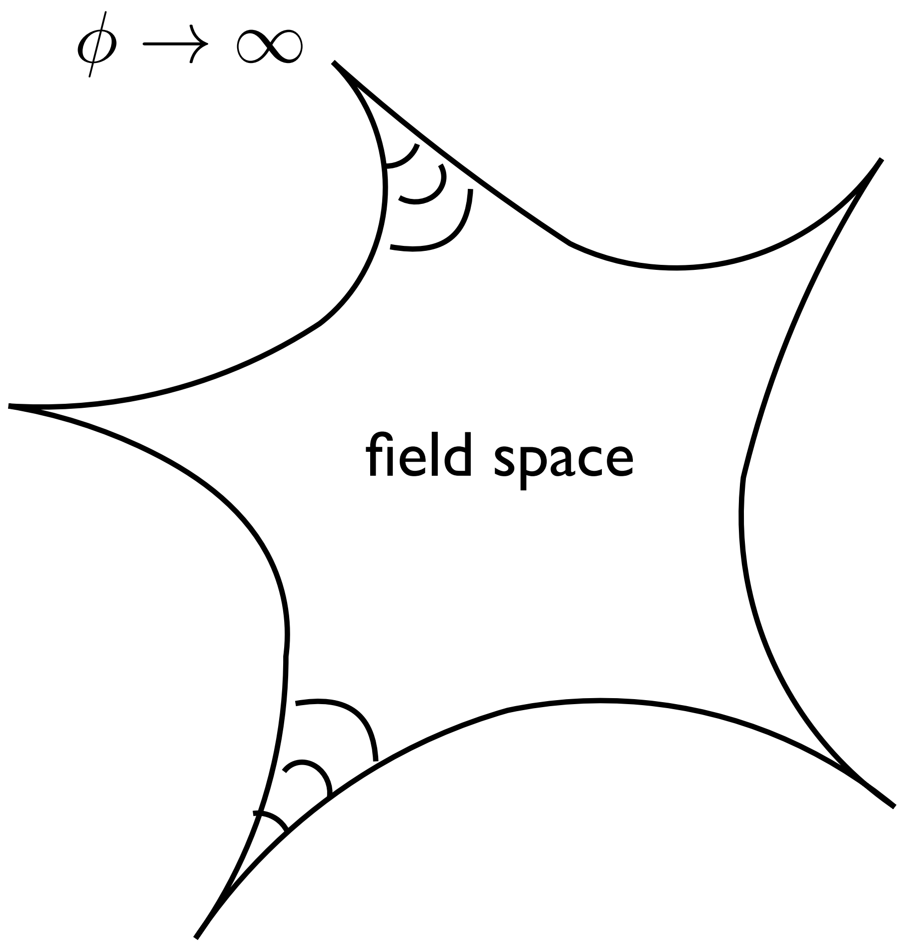

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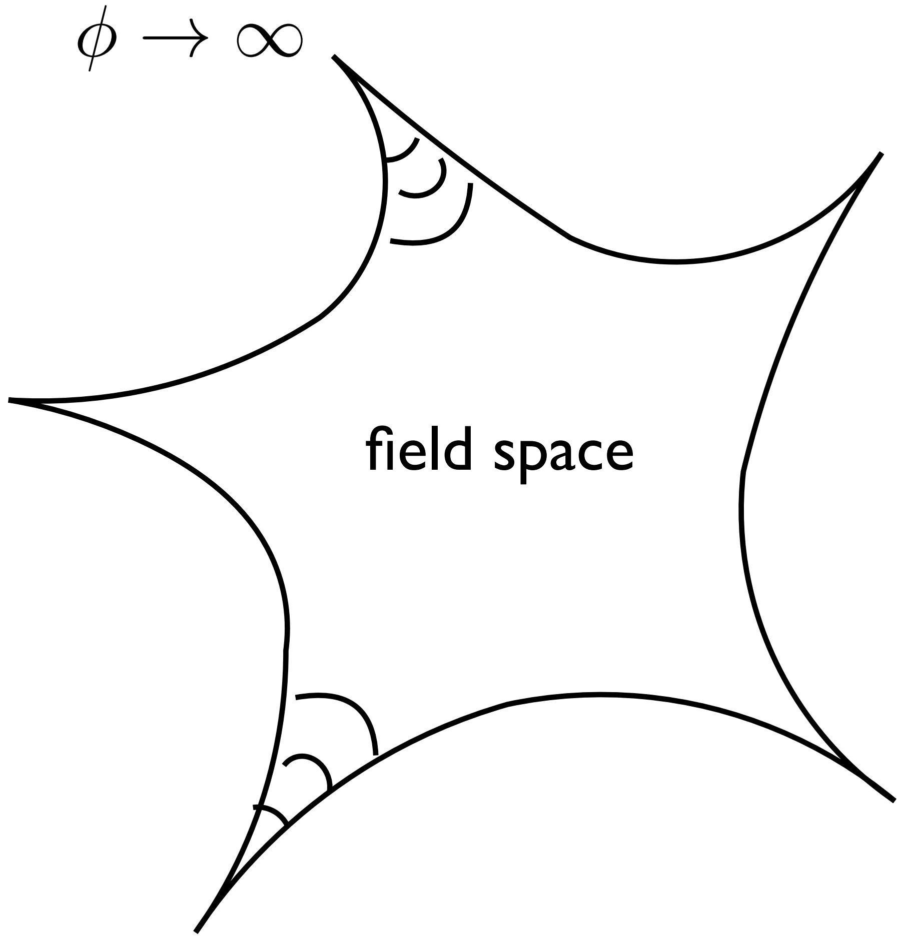

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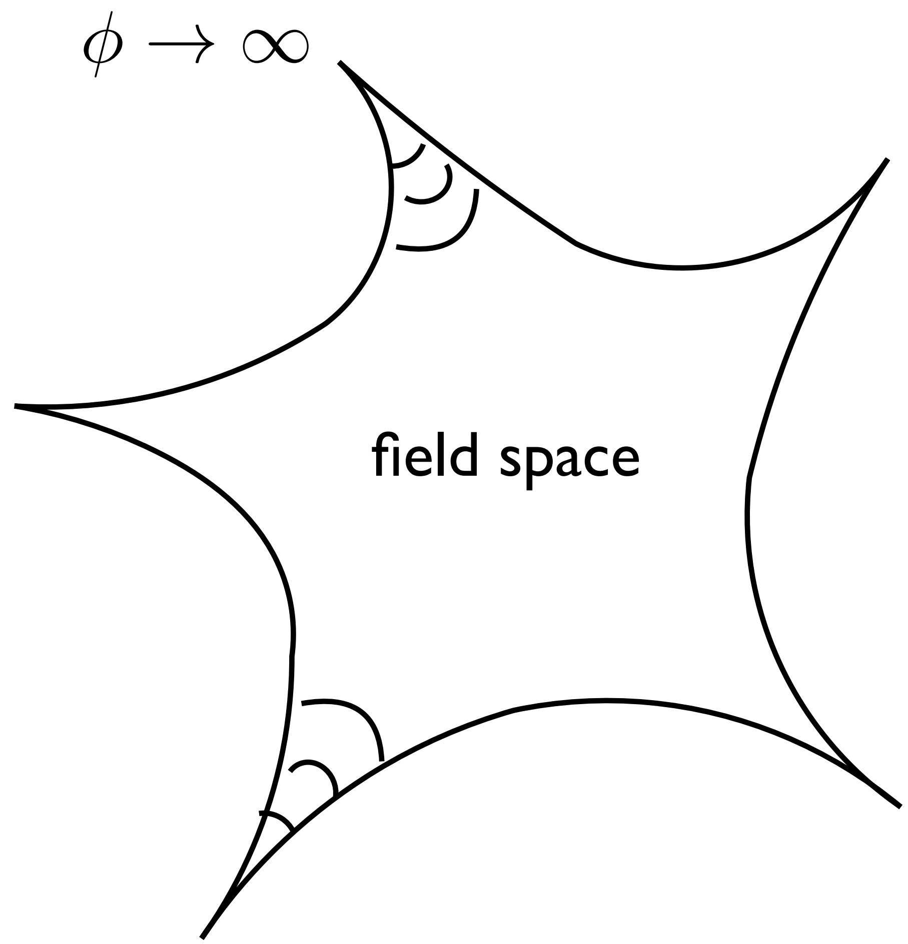

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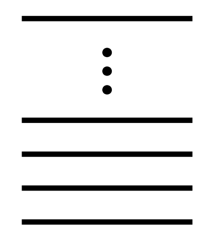

infinite tower of states → $\Lambda \to 0$

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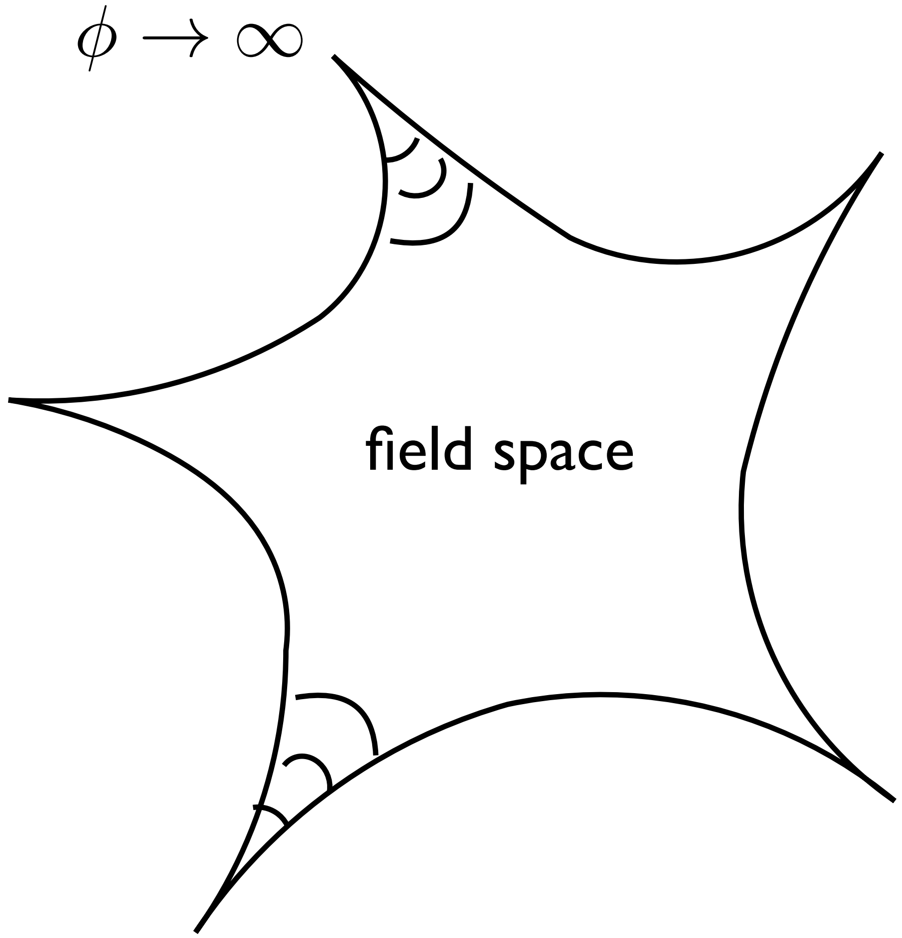

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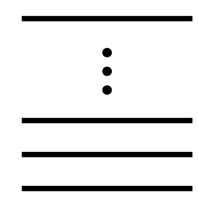

$\Lambda \to 0$

Swampland/quantum gravity constraint:

Distance Conjecture [Ooguri-Vafa'06]

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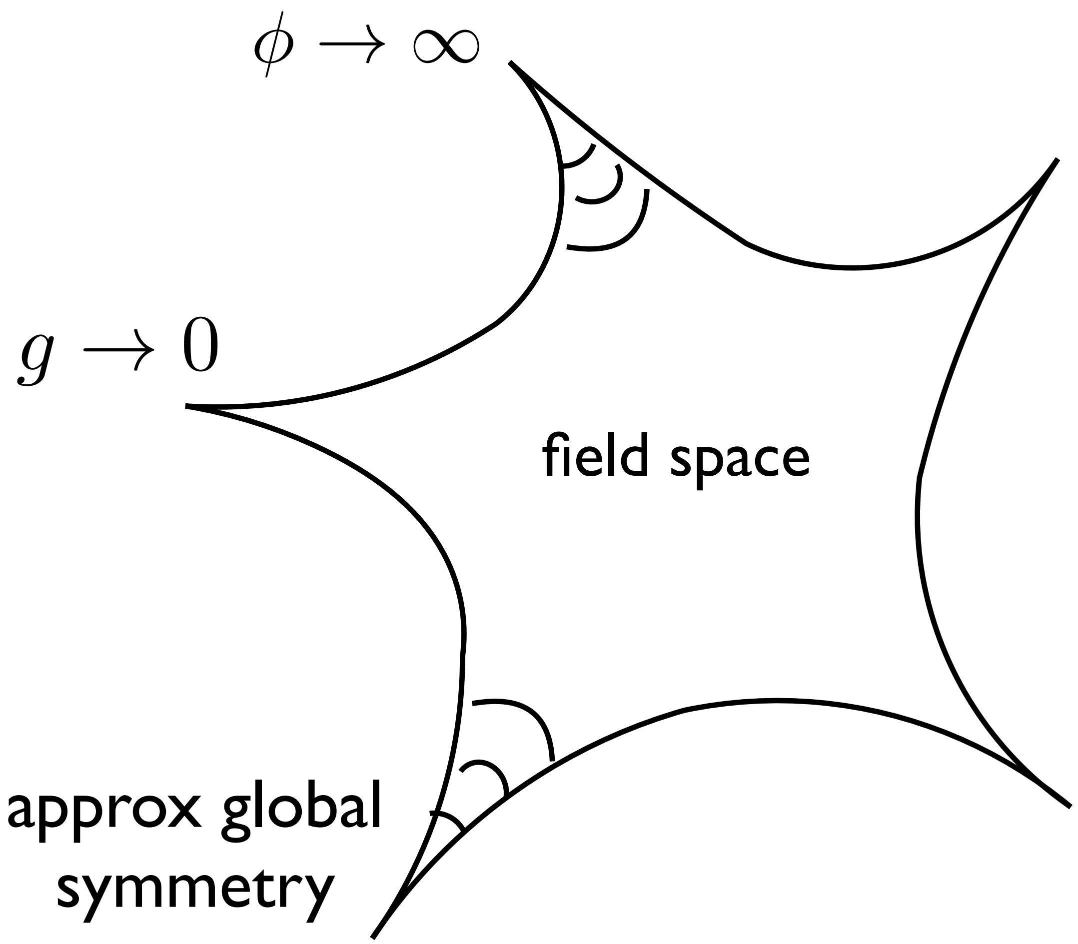

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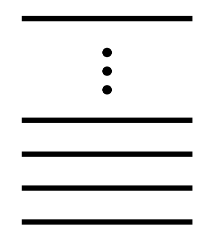

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From EFT perspective, these are e.g. weak coupling limits for gauge theories, approximate global symmetry limits, … $\Lambda \ll M_p$

Outline

1) Review of Distance Conjecture and drop-off of QG cut-off

2) Universal pattern underlying all known string theory examples

➡ To sharpen the conjecture and provide a quantitative bound on the mass of the tower

3) Beyond moduli spaces: Implications for accelerated expansion and AdS scale separation

➡ Non-perturbative test of DGKT AdS scale separated proposal

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Given an EFT coupled to gravity, with a moduli space parametrized by the vacuum expectation value of some scalar fields:

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m(P) \sim m(Q)e^{-\alpha\Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

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

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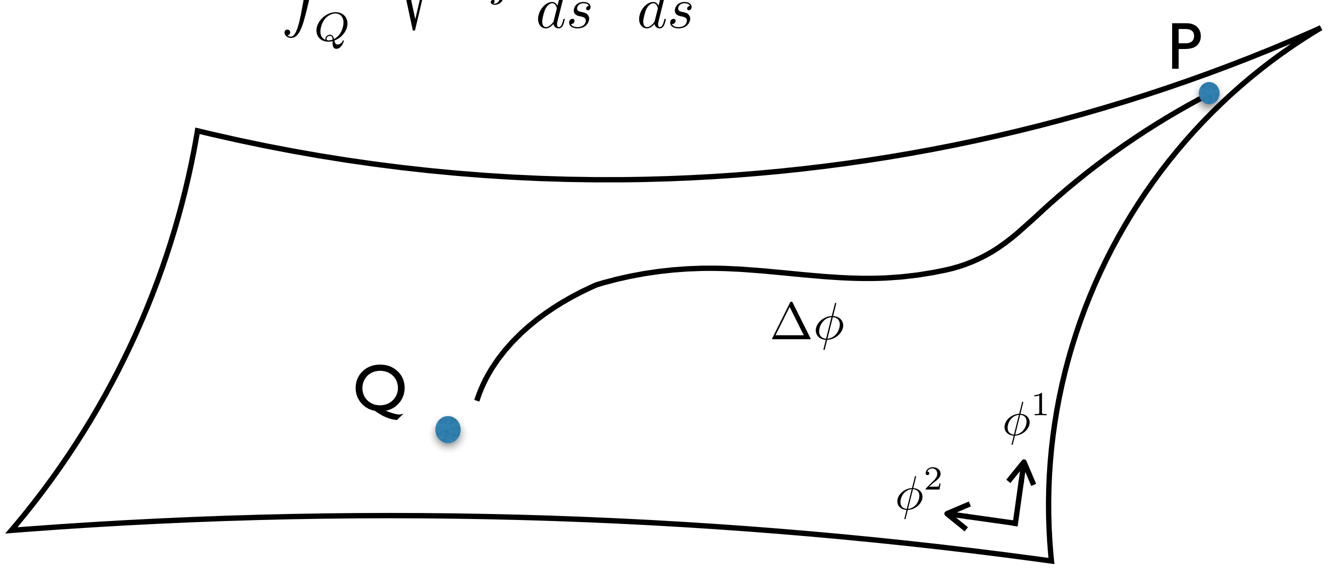

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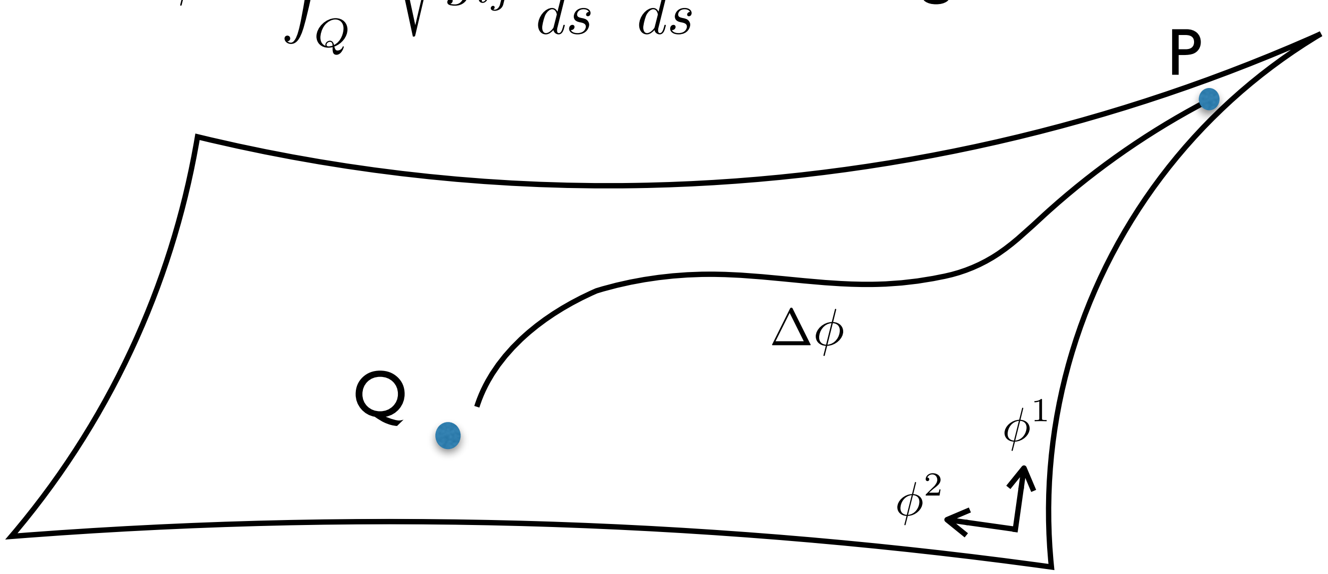

For example:

- Kaluza-Klein towers as $R \to \infty$
- winding modes as $R \to 0$
- string modes as $g_s \to 0$

Distance Conjecture

The tower signals a drastic breakdown of the effective theory at:

Quantum Gravity (QG) cut-off scale Λ

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- The QG cut-off is the string scale in an weak coupling string limit

$$\Lambda \simeq M_{\rm str} \ll M_{\rm pl,d}$$

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In general, it is also known as the species scale $\Lambda = \frac{M_p}{N^{1/d-2}}$ [Arkani-Hamed et al'05] [Dvali'07]

$N = \int^{\Lambda} \rho(m) dm$ (number of single-particle states weakly coupled to gravity)

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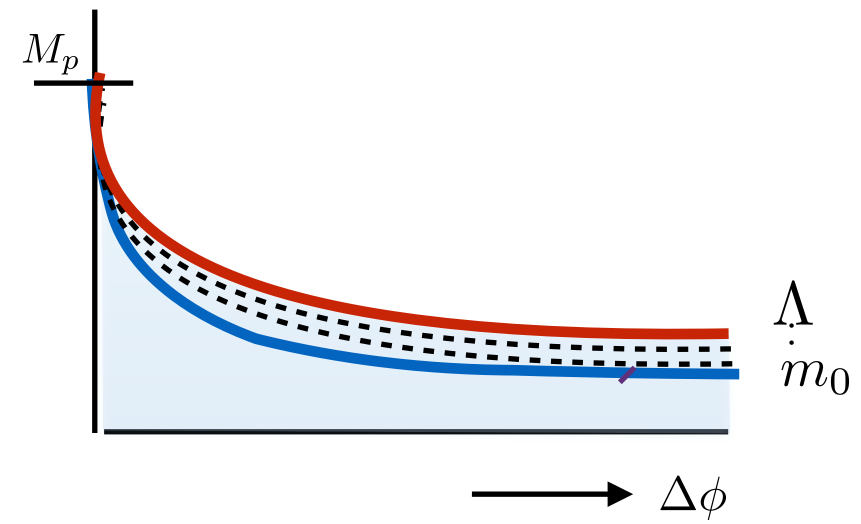
In the presence of a tower of states $m \sim m_0 \exp(-\alpha\Delta\phi)$:

$$\Lambda \sim M_p \exp(-\lambda\Delta\phi)$$

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



Evidence

❖ **Plethora of works testing the conjecture in string theory compactifications to flat space:**

(M-theory and Heterotic toroidal comp., F-theory and IIB on Calabi-Yau's, M-theory on G2, Type IIA orientifolds, non-SUSY heterotic…)

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- **AdS_{d+1}/CFT_d** All known infinite distance limits in the conformal manifold (for d>2) contain towers of higher spin operators decaying exponentially with the Zamolodchikov distance

→ CFT Distance Conjecture [Perlmutter,Rastelli,Vafa,IV'21] [Baume,Calderon-Infante'21]

(part of the conjecture recently proven using CFT techniques in [Baume,Calderon-Infante'23])

Evidence

What general lessons can we extract from this?

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Wish List

❖ Provide a bottom-up rationale beyond string theory examples

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❖ Sharpen the conjecture to provide:

- The nature of the tower $m \sim m_0 \exp(-\alpha \Delta\phi) \quad \alpha \sim \mathcal{O}(1)$
- The minimal possible value for the exponential mass decay rate α
- The quantum gravity theory that emerges at infinite distance above $\Lambda_{\rm QG}$

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(i.e. $G^{\phi^i \phi^j} \frac{\partial_{\phi^i} m}{m} \frac{\partial_{\phi^j} \Lambda}{\Lambda} = \frac{1}{d-2}$)

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m → mass of the leading (lightest) tower of states

Λ → quantum gravity cut-off

$d =$ space-time dimension

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Independently of the nature of the tower, the type of infinite distance limit, or the compactification manifold…

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In terms of the number of species: " lightest = less dense "

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} N}{N} = -1$$

$$N = \int^{\Lambda} \rho(m) dm \quad \text{with} \quad \Lambda \sim \frac{1}{N^{1/(d-2)}}$$

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The pattern implies a sharp lower bound for the exponential rate of the leading tower:

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$$\alpha_{min} = \left| \frac{\vec{\nabla} m}{m} \right| \geq \frac{1}{\sqrt{d-2}}$$

$m \sim m_0 \exp(-\alpha \Delta\phi)$

It reproduces the proposed bound in [Etheredge,Heidenreich,Kaya,Qiu,Rudelius'22]

which is consistent with the Emergent String proposal of [Lee,Lerche,Weigand'19]

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Fixing the $\mathcal{O}(1)$ factors:

➡ Sharp upper bound on asymptotic field range: $\Delta\phi \leq \frac{1}{\alpha_{\min}} \log\left(\frac{M_p}{\Lambda}\right)$

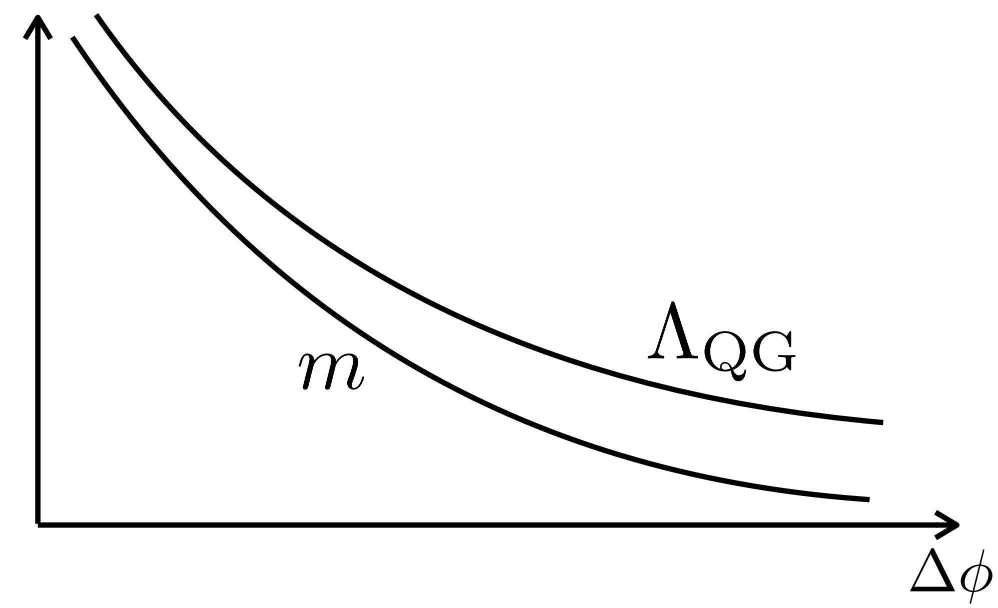
This should surprise you. Why?

Mass of the tower:

$$m \sim m_0 \exp(-\alpha \Delta\phi)$$

Quantum Gravity cut-off:

$$\Lambda_{\rm QG} \sim m^\gamma \sim M_p \exp(-\lambda \Delta\phi)$$



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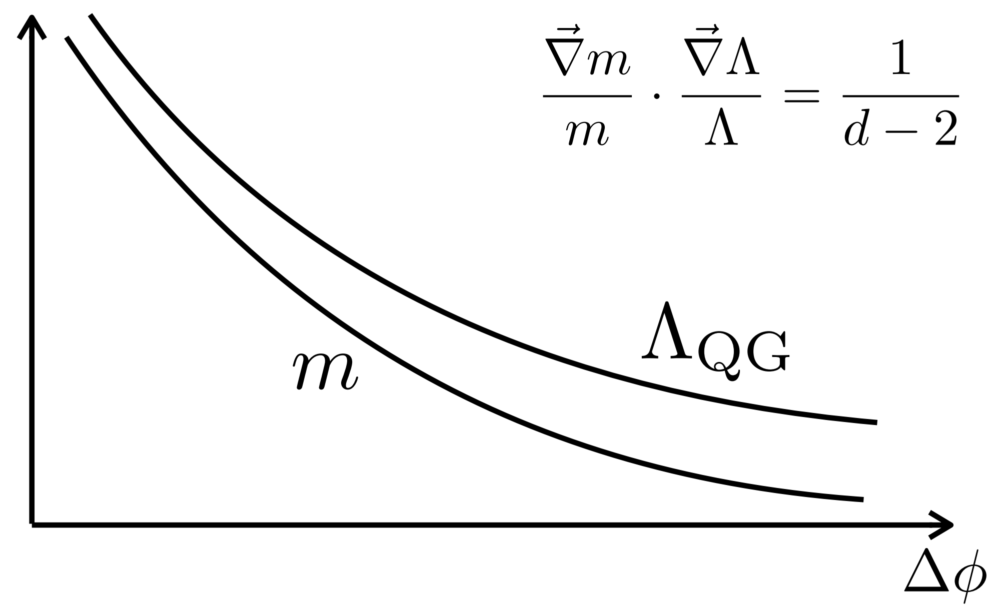

1)The structure/density of the towers of states fixes γ

We find that γ is related to the exponential decay rate α

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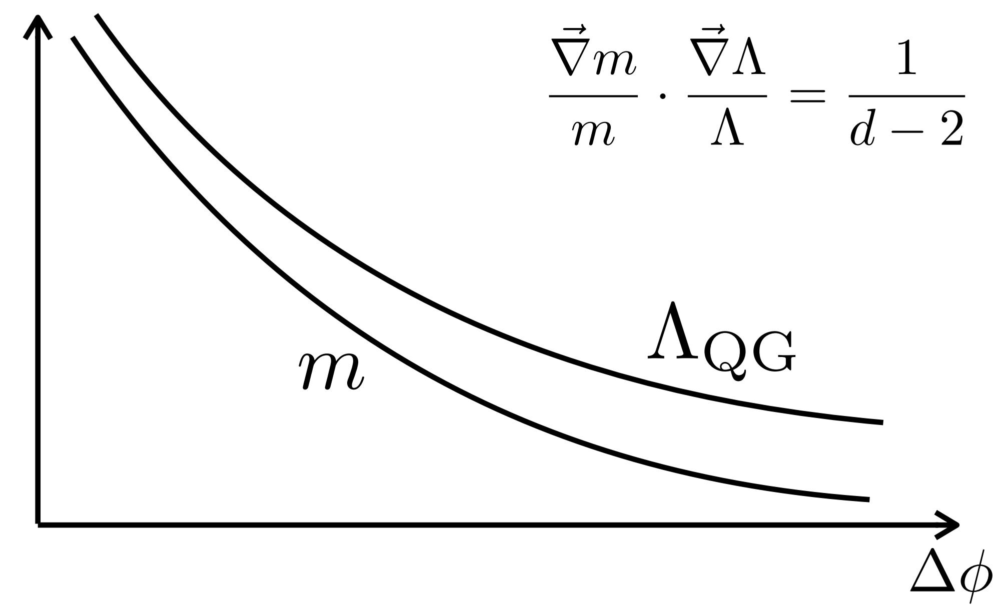

1)The structure/density of the towers of states fixes γ

We find that γ is related to the exponential decay rate α

Kaluza-Klein tower

String tower

This should surprise you. Why?

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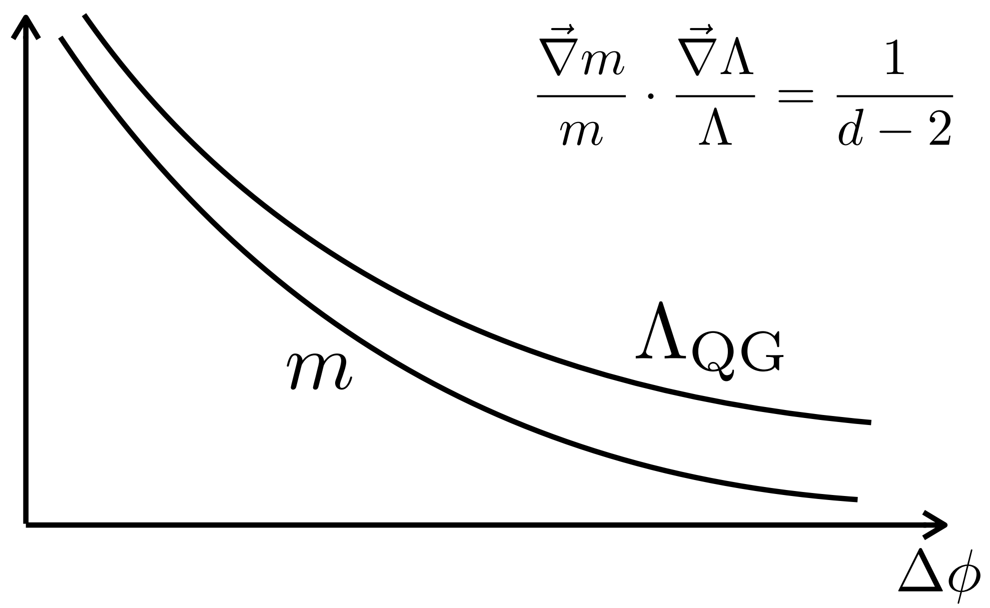

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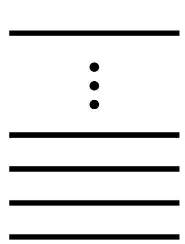

$$m_k = k\, m_{\rm KK}$$

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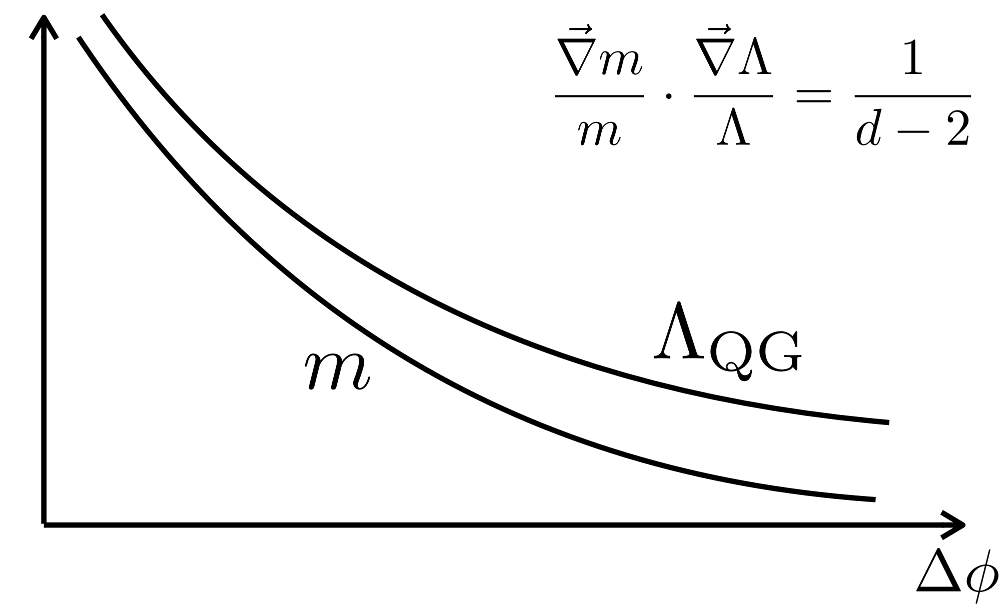

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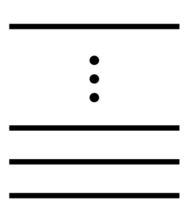

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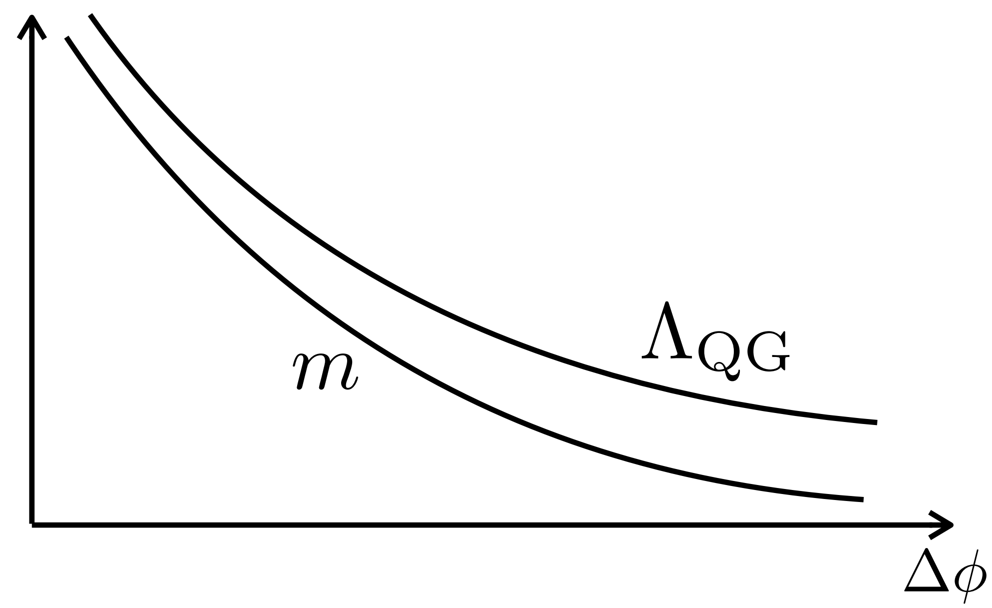

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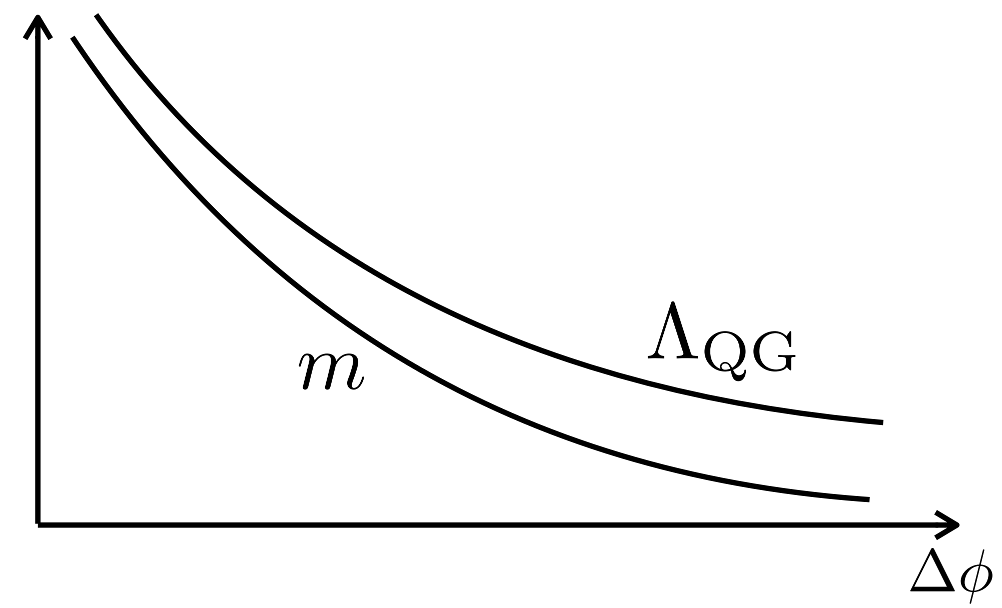

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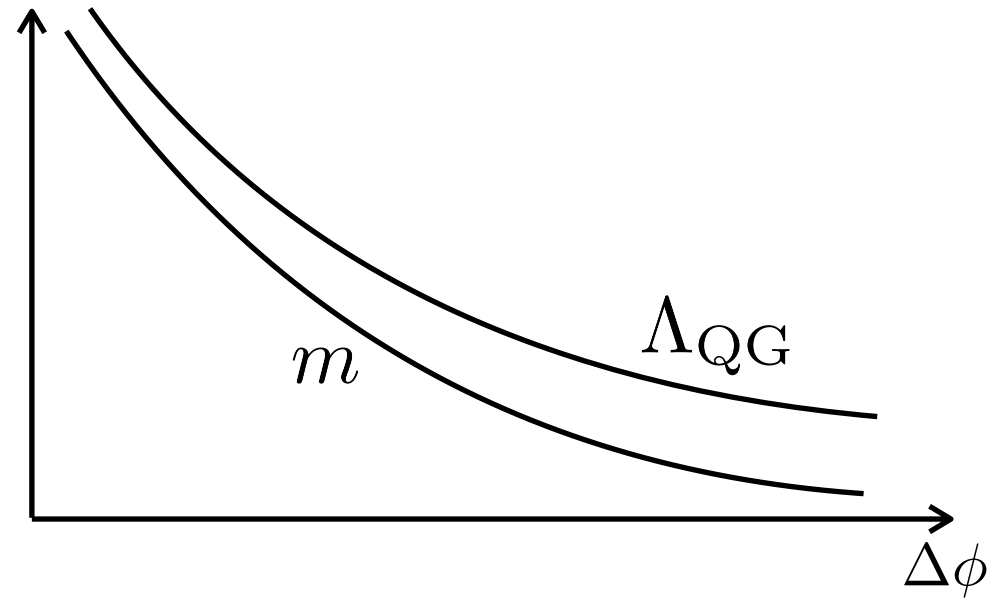

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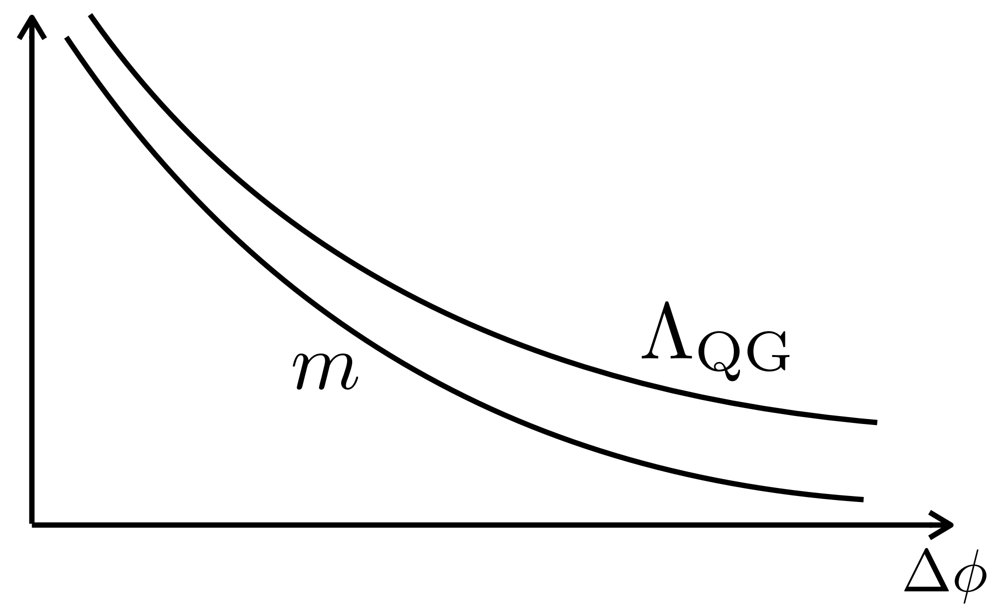

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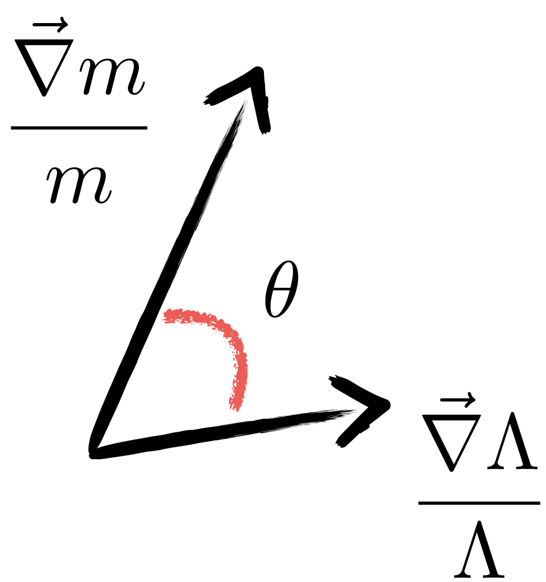

How??

The angle between them is always such that the pattern gets satisfied

Example 1:

Example 2:

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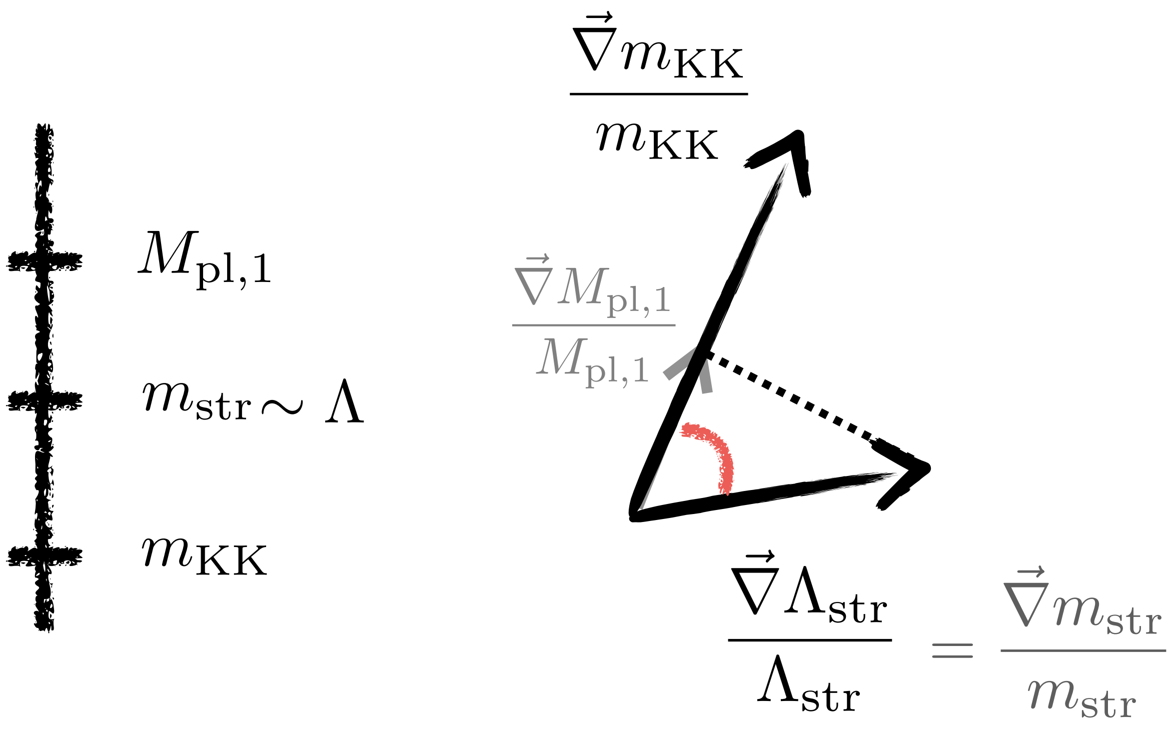

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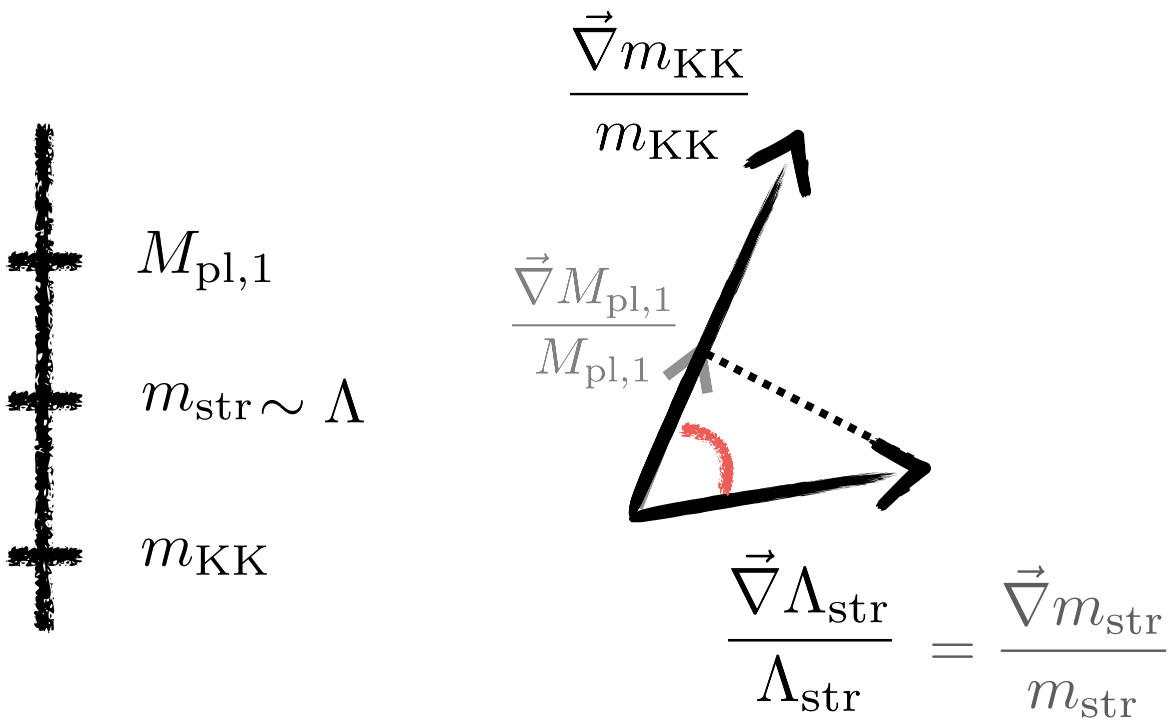

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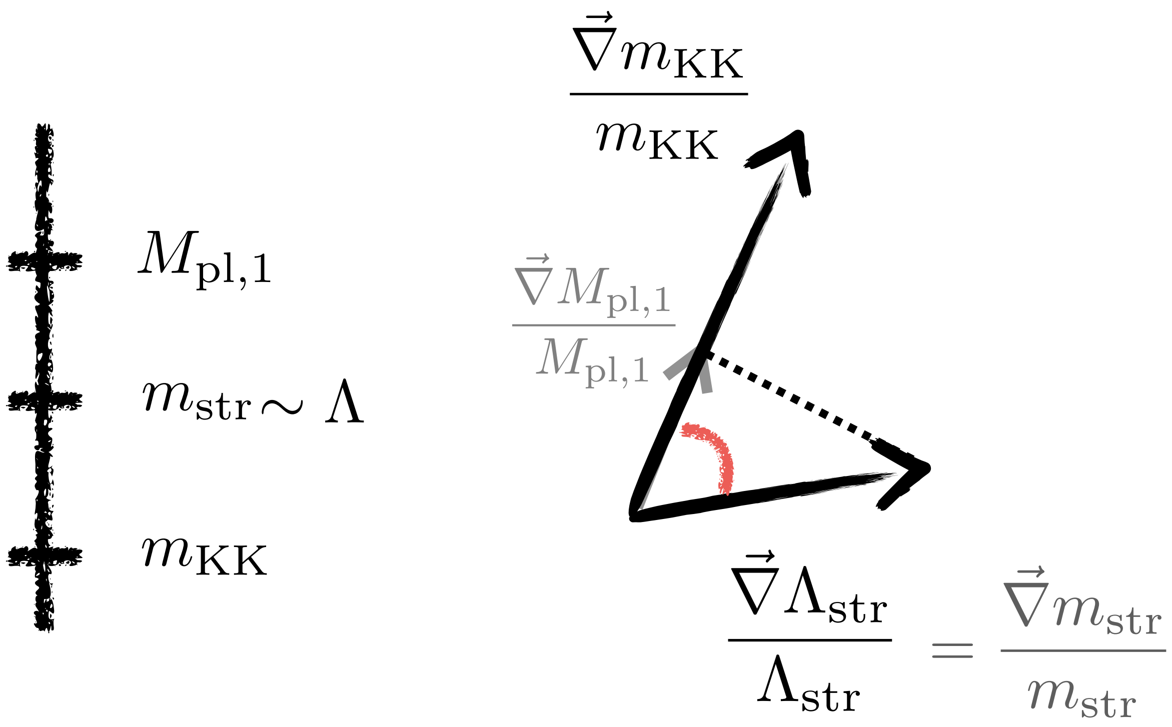

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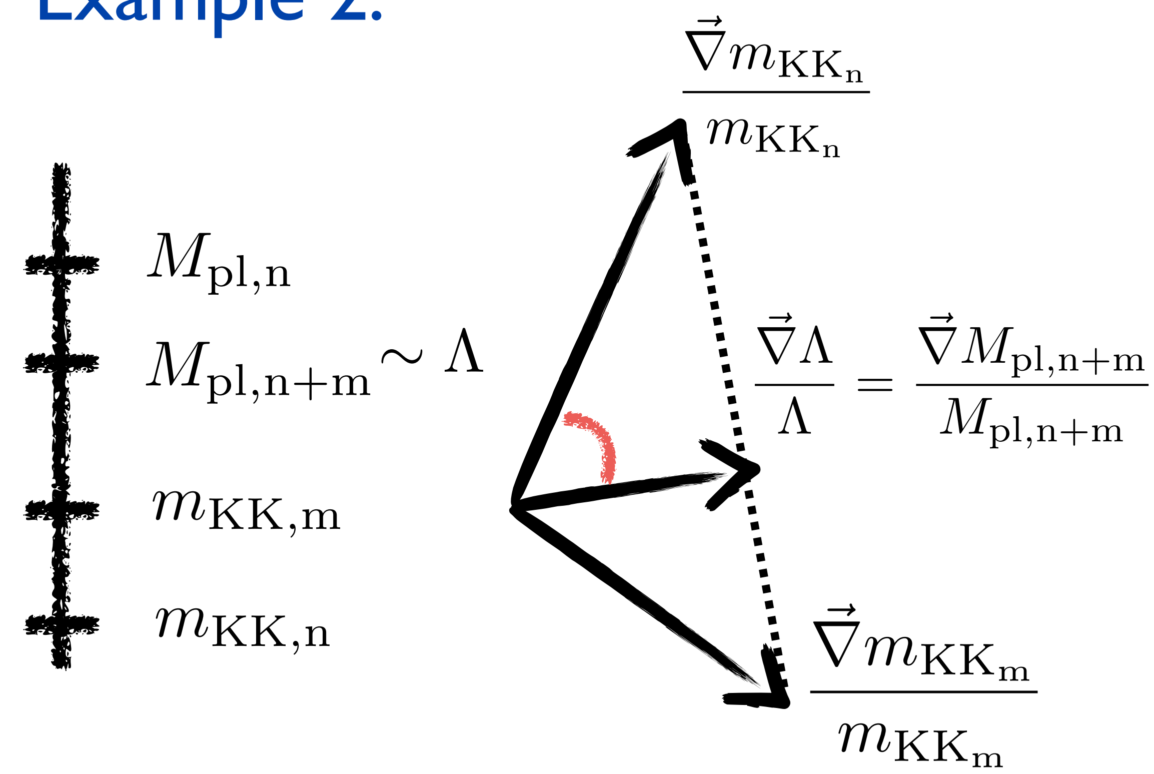

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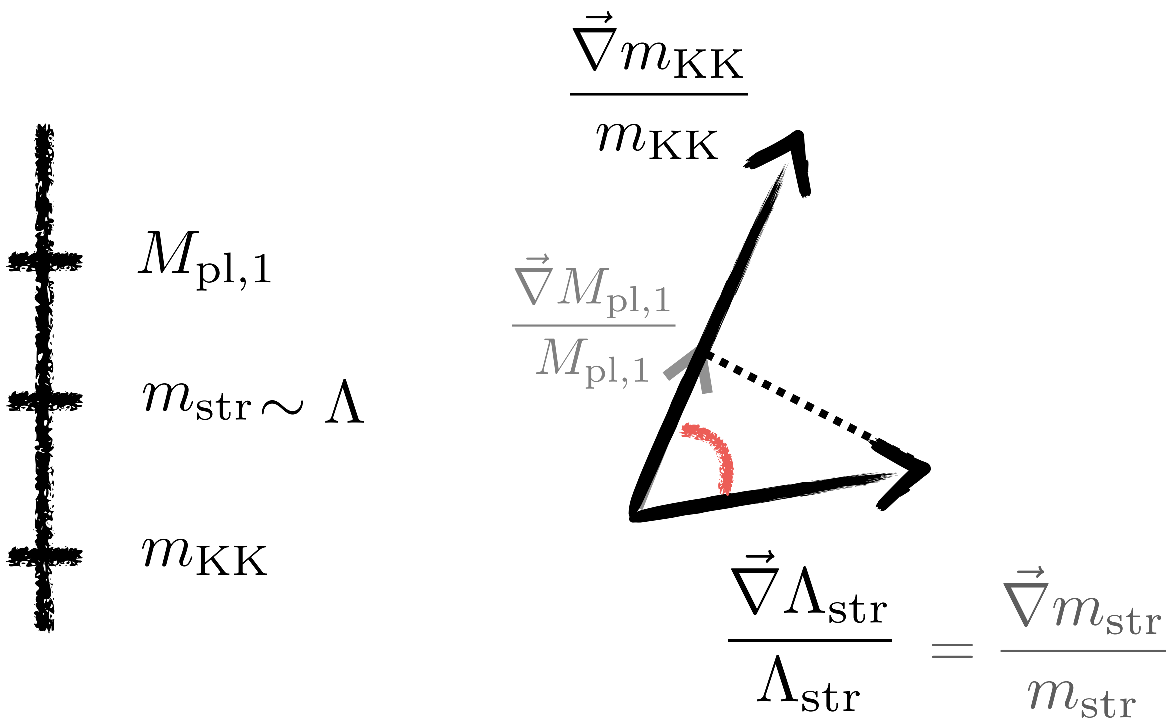

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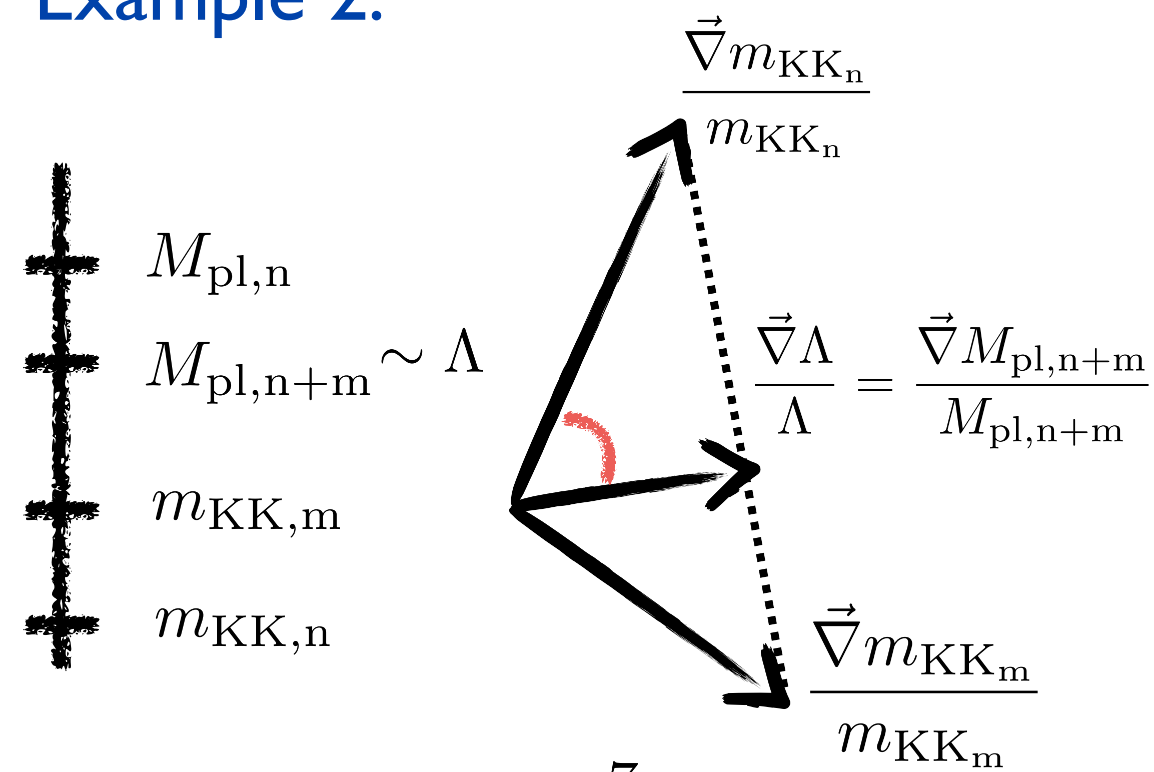

e.g. M-theory on $\mathbb{T}^7$

Leading tower: $m_{\rm KK_1}$

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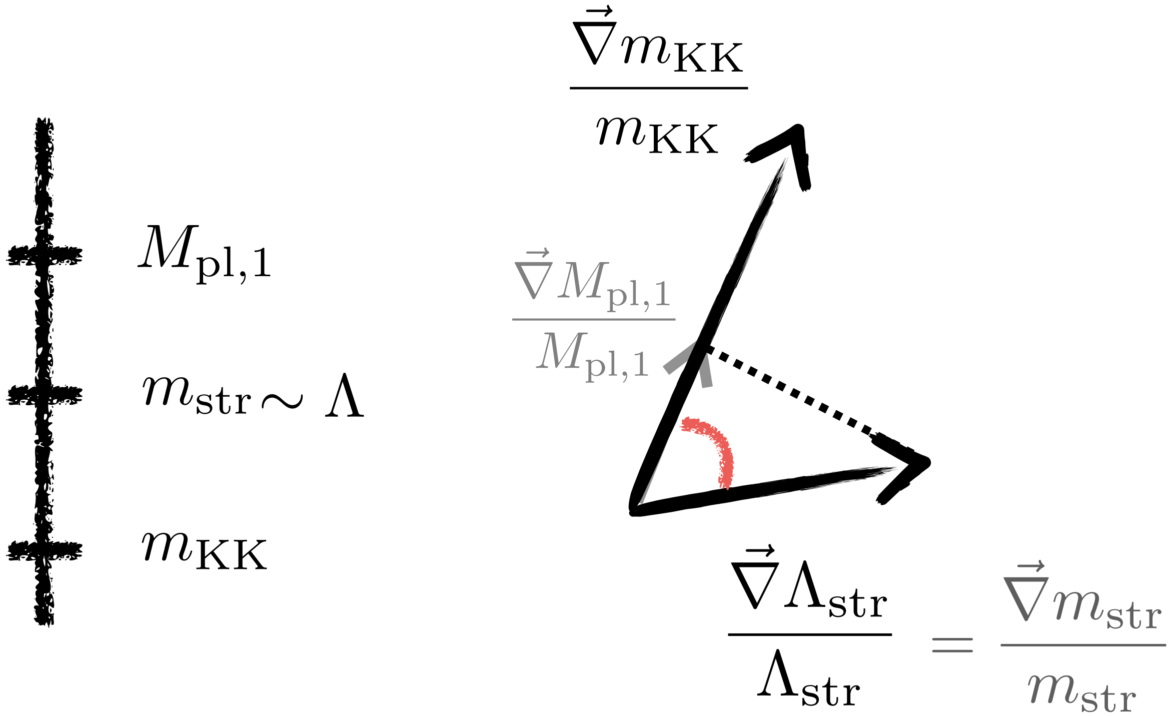

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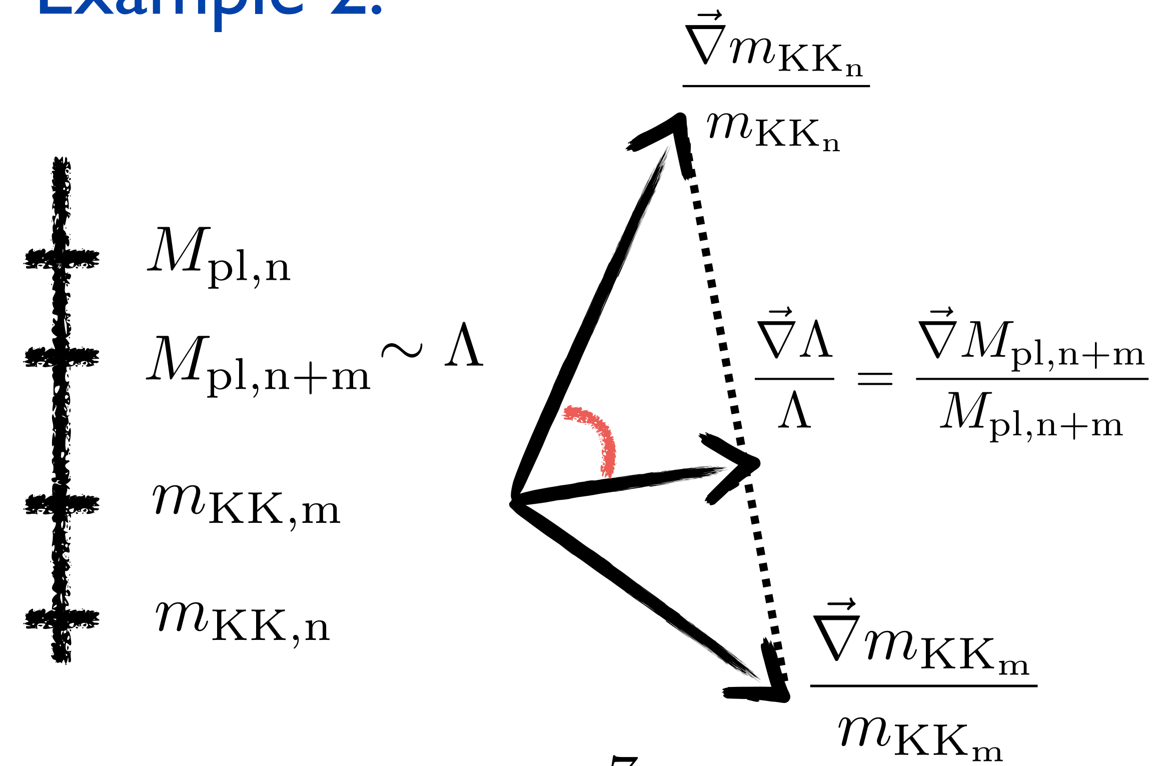

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Even if the leading tower is the same (e.g. a KK tower of one extra dimension), the quantum gravity cut-off can be different depending on the subleading towers

Subleading towers matter!

Evidence for the Pattern

See Ignacio Ruiz's poster

We check it in string theory examples:

- 32 (and 16) supercharges: M-theory on (orientifold) toroidal compactifications
- 8 supercharges: Type II and M-theory Calabi-Yau compactifications
- 4d N=1 theories from heterotic, F-theory, Type II…

It is related to continuity of the exponential rate of the leading tower as we move in moduli space [Castellano,Ruiz,IV'ongoing]

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Open question: can we find a bottom-up argument?

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} N}{N} = -1$$

constrains the variation (with the moduli) of the mass and the density of states

Maybe black hole/entropy bounds?

Taxonomy of infinite distance limits

It can be used to determine the angle between different light towers and **how different infinite distance limits fit together**

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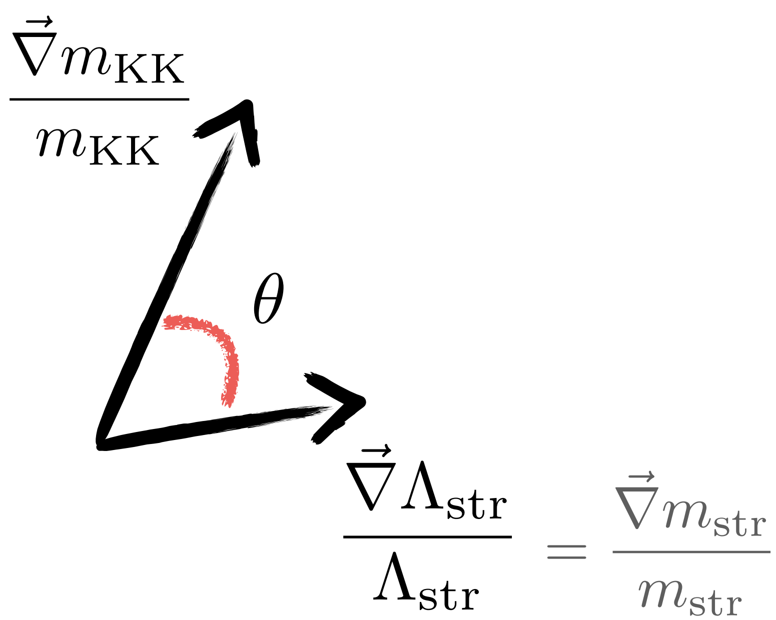
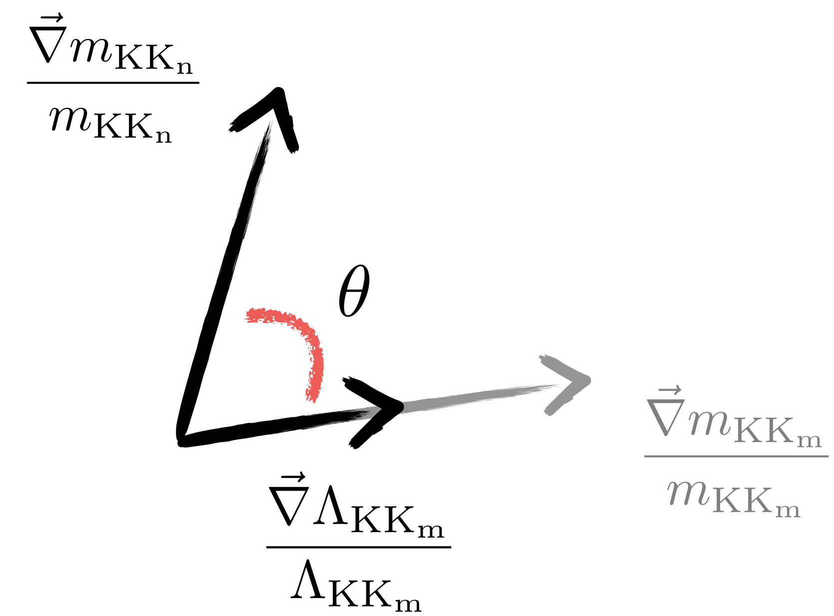
Angle between KK and string towers:



$$\cos\theta(\mathrm{KK}_n, \mathrm{str}) = \sqrt{\frac{n}{n+d-2}}$$

n → number of dimensions decompactifying

Angle between different KK towers:



$$\cos\theta(\mathrm{KK}_n, \mathrm{KK}_m) = \sqrt{\frac{nm}{(n+d-2)(m+d-2)}}$$

[Etheredge, Heidenreich, McNamara, Rudelius, Ruiz, IV'ongoing]

(These angles can also be derived if assuming that we have only KK and string towers)

Taxonomy of infinite distance limits

Example: Consider a moduli space with a flat metric

Different asymptotic regimes are characterized by different leading towers of states, but the sum of all of the angles must be:

$$\sum \theta_i = 2\pi$$

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$$\swarrow \qquad \searrow$$

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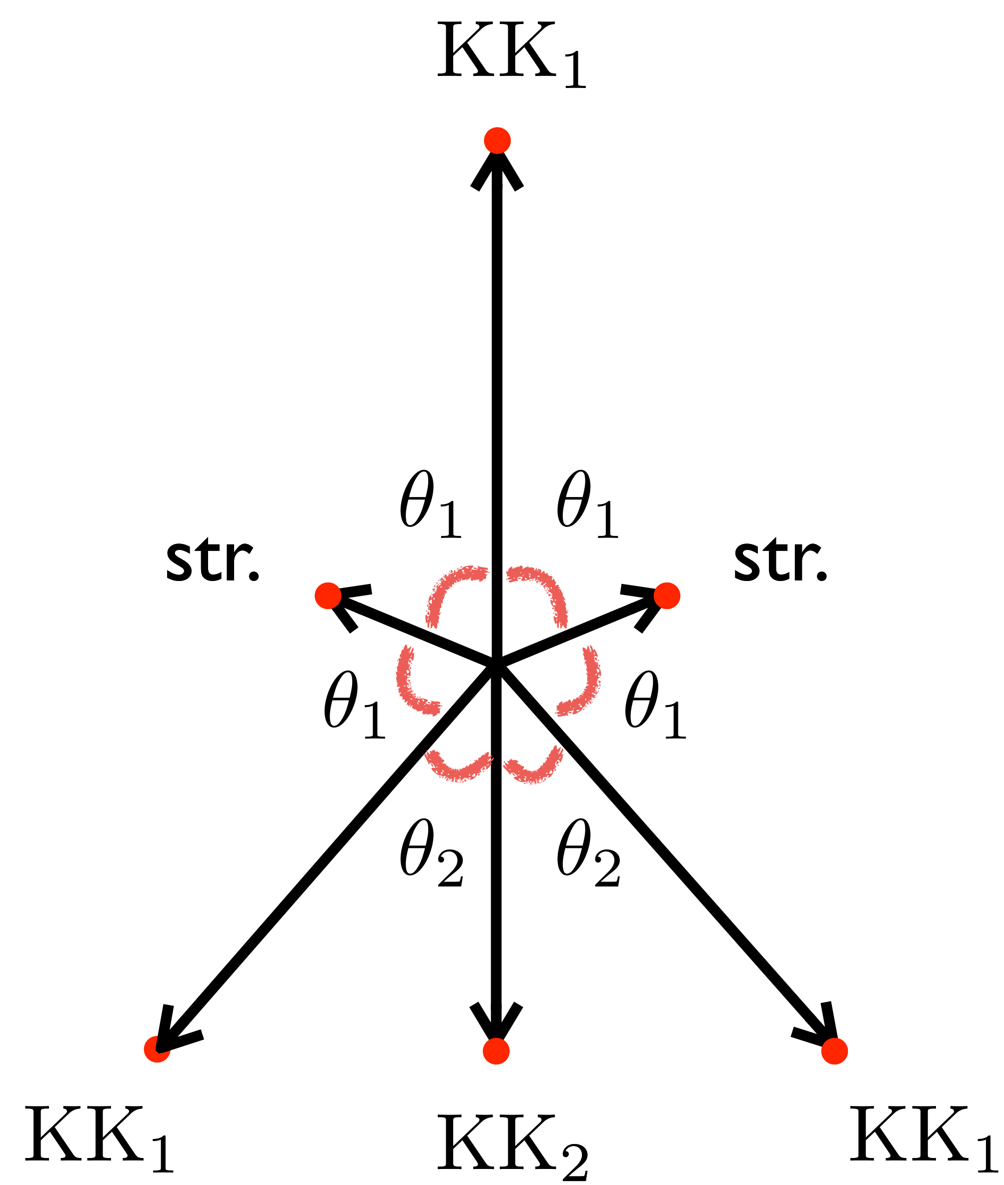

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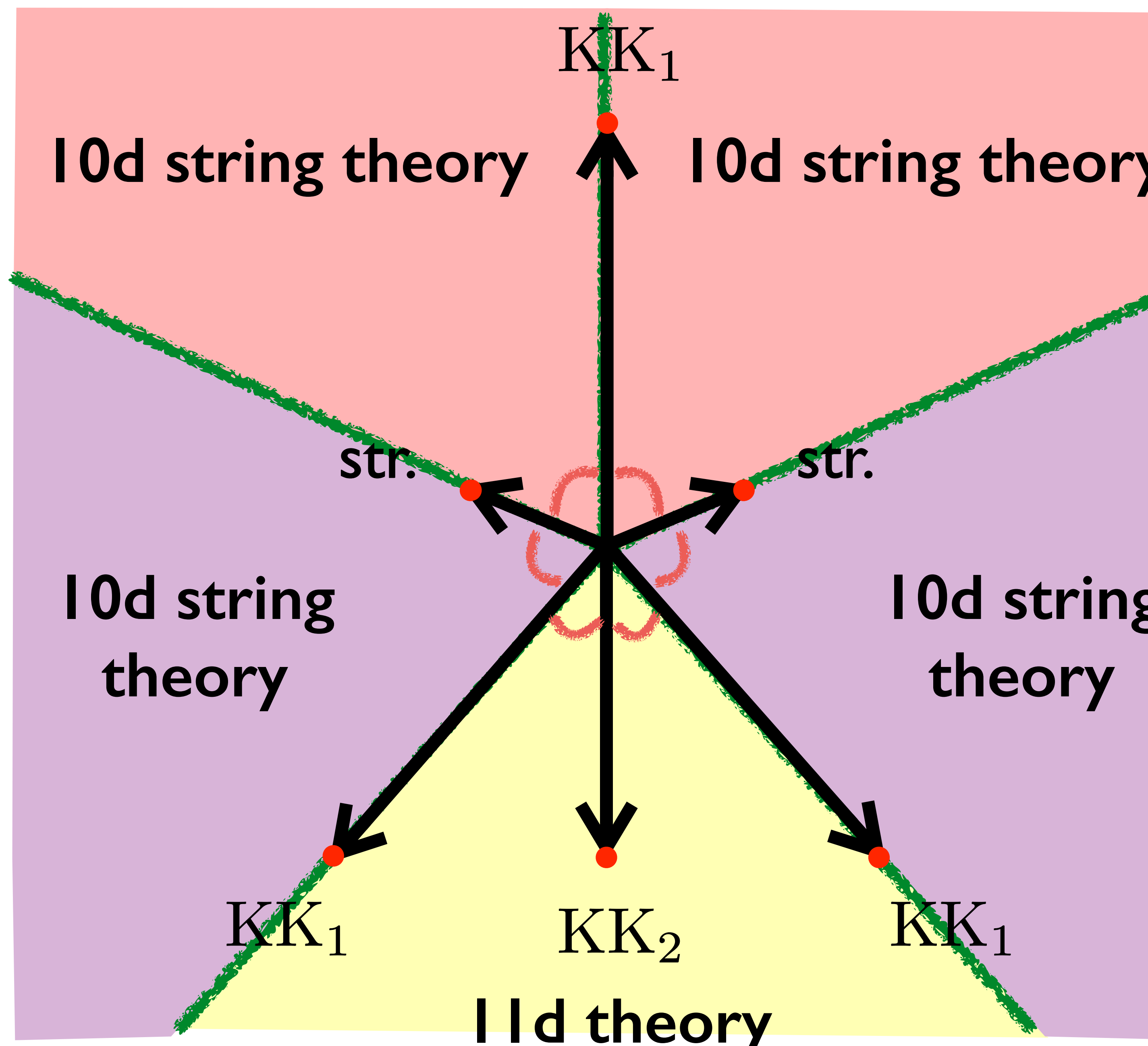

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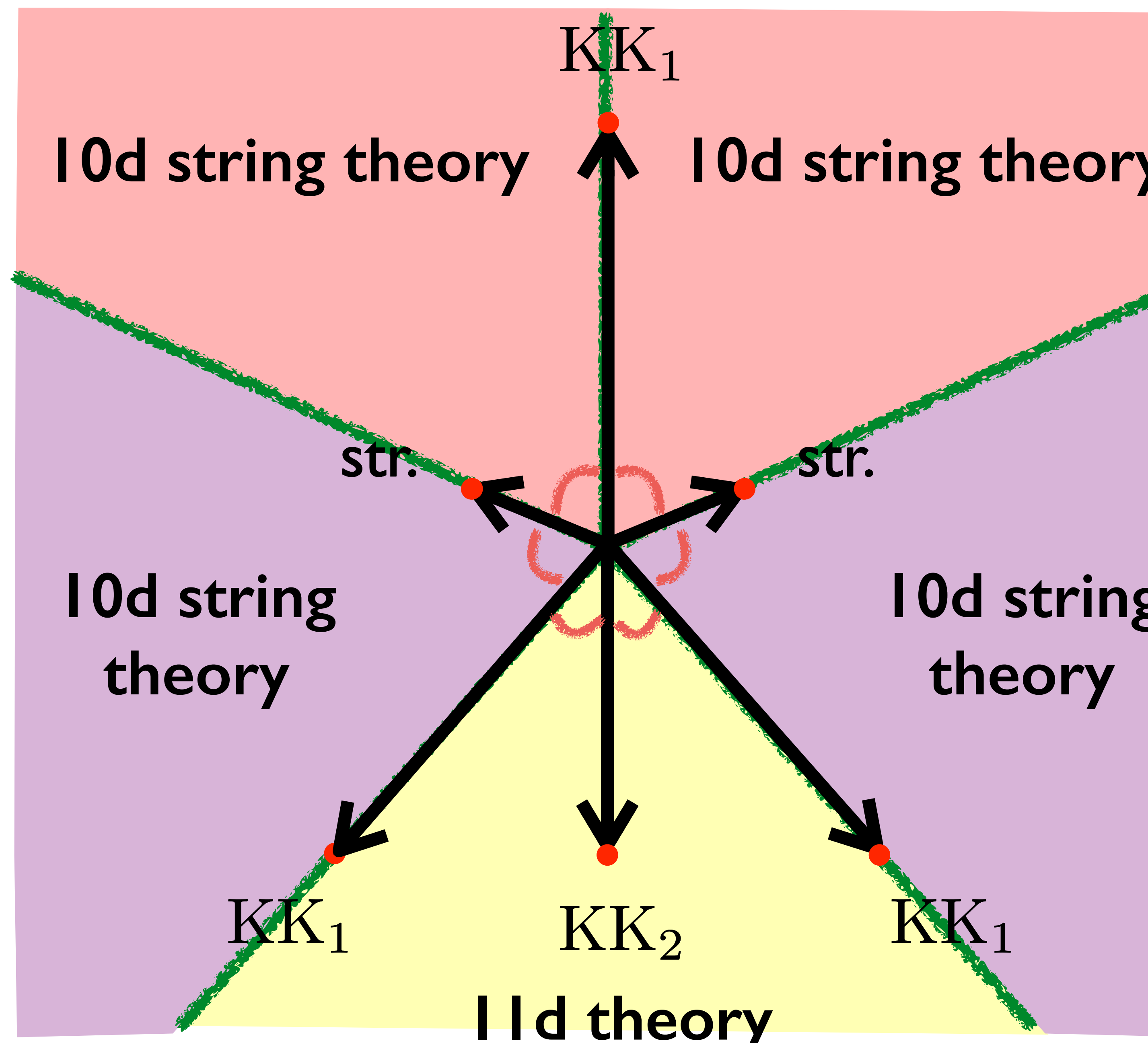

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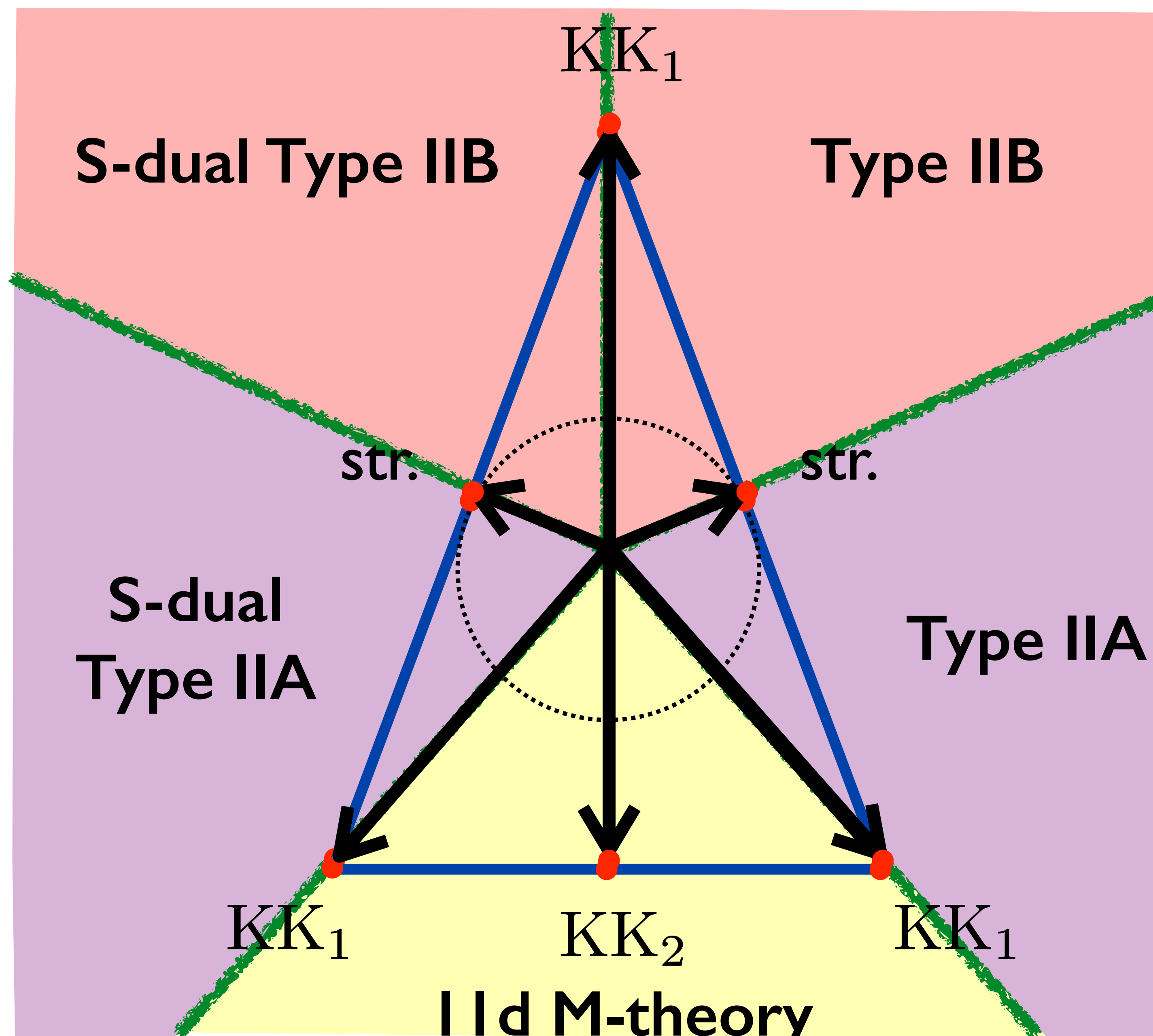
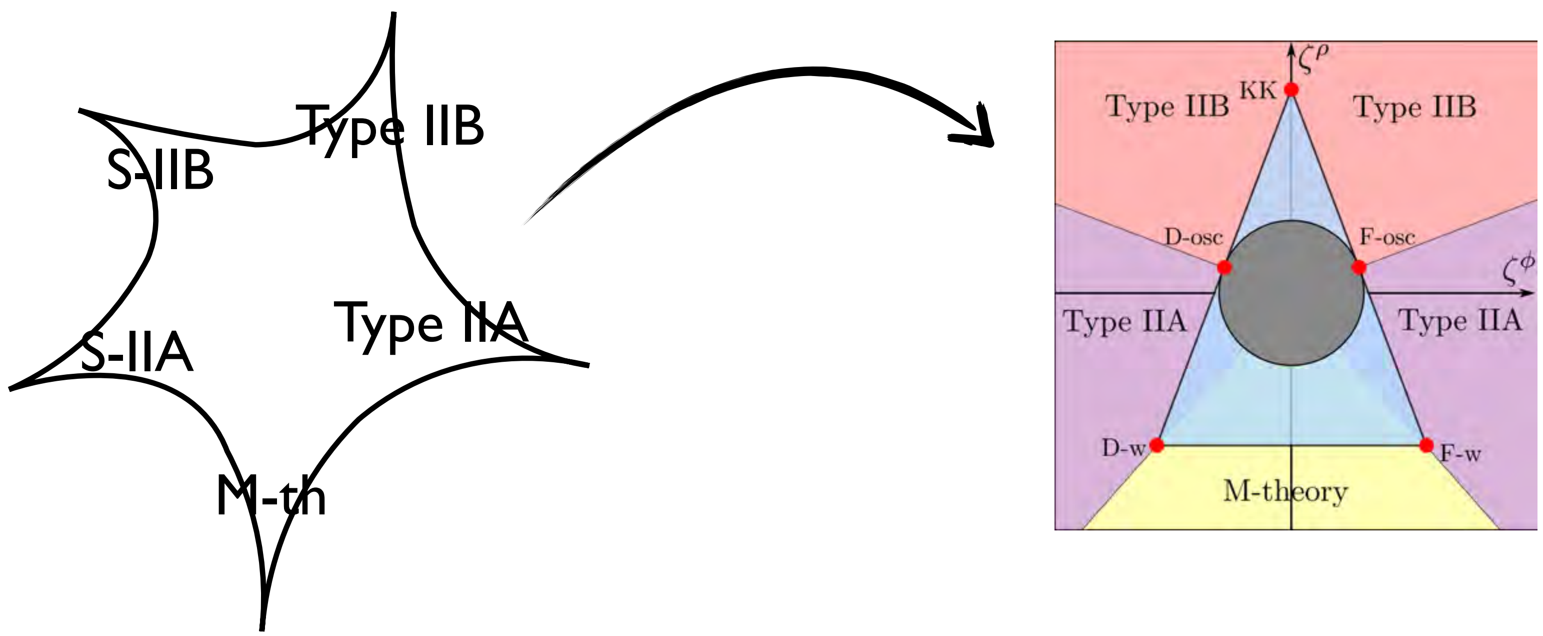


Taxonomy of infinite distance limits

We can characterize the different dualities of the moduli space in terms of a particular polytope (the convex hull of the towers)



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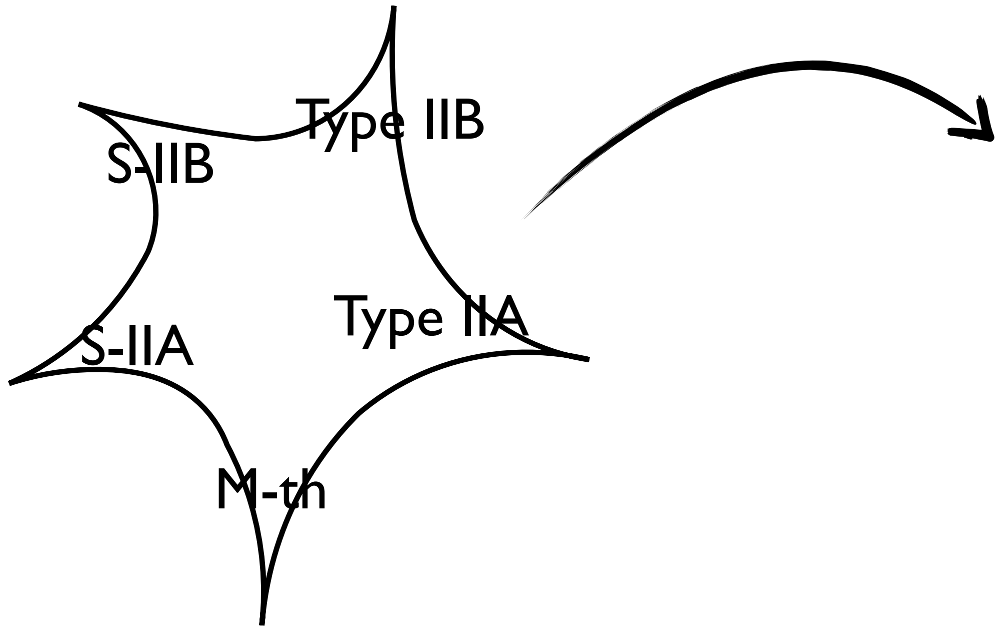
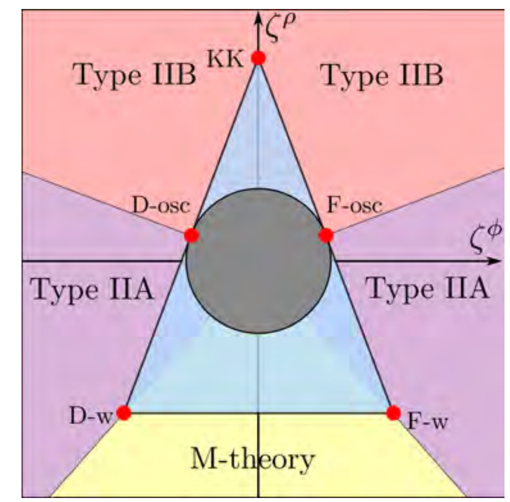
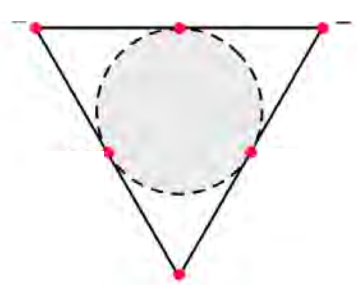


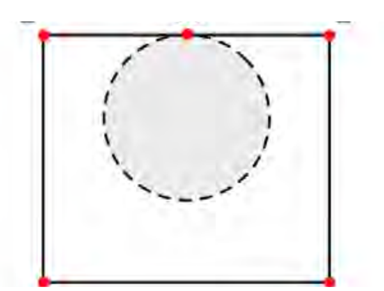


Can we classify all possibilities from bottom-up?

See Muldrow Etheredge's poster

In d=8:





[Etheredge,Heidenreich,McNamara, Rudelius,Ruiz,IV'ongoing]

⋮

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For lower SUSY setups: necessary to understand rules of jumping of states

(the convex hull can change as we move in moduli space)

Outline

1) Review of Distance Conjecture and drop-off of QG cut-off

2) Universal pattern underlying all known string theory examples

➡ To sharpen the conjecture and provide a quantitative bound on the mass of the tower

3) Beyond moduli spaces: Implications for accelerated expansion and AdS scale separation

➡ Non-perturbative test of DGKT AdS scale separated proposal

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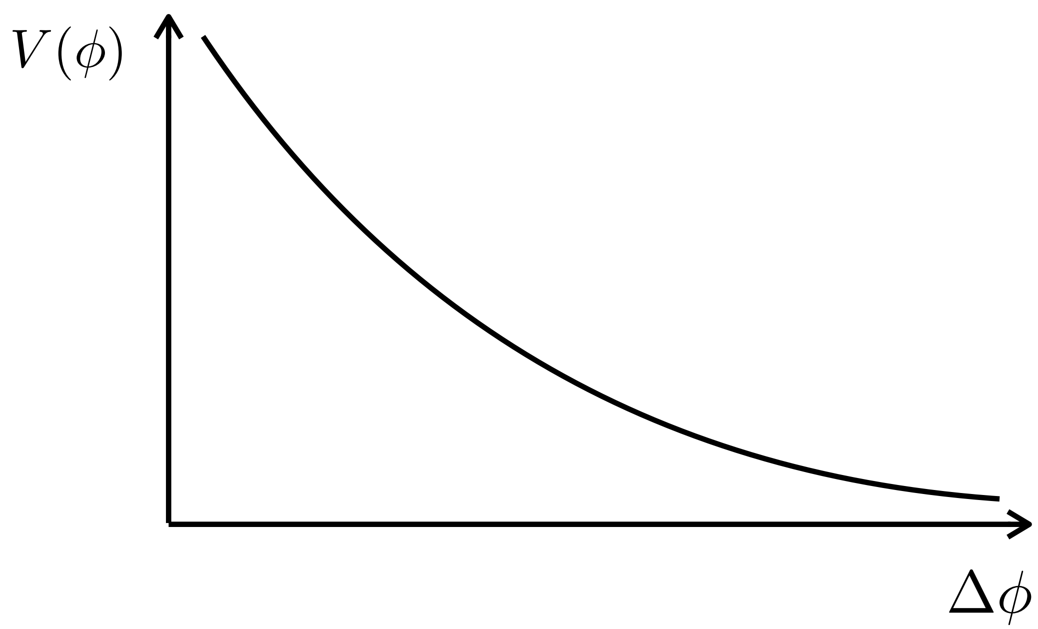
Beyond Moduli Spaces

What happens in the presence of a potential?

If the infinite distance limit is not obstructed, there are two typical scenarios:

Positive runaway

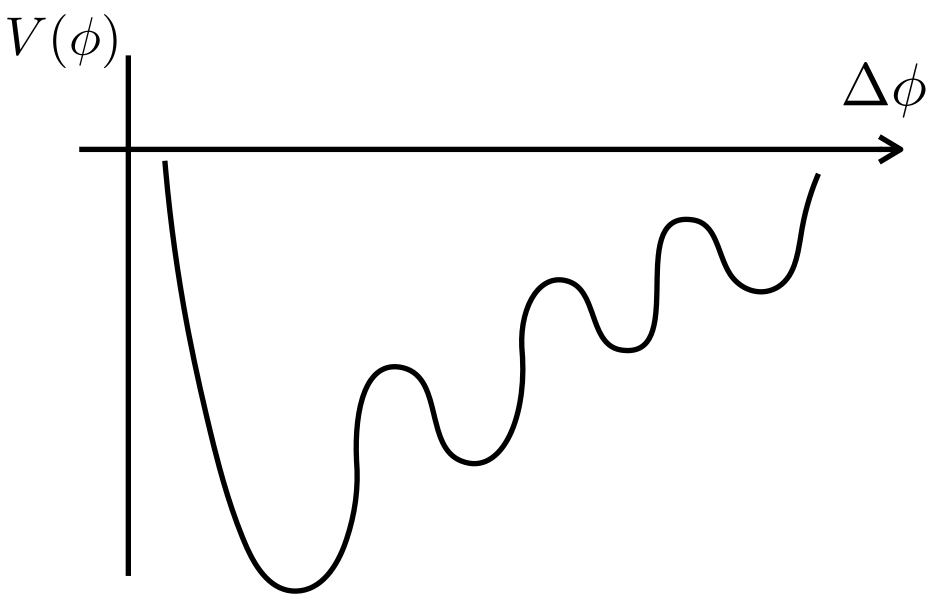


$$V_0 \sim m_{\text{tower}}^{\gamma}$$

[Ooguri et al'18]

Accelerated expansion?

Family of AdS vacua



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[Luest,Palti,Vafa'19]

AdS scale separation?

(also important for Dark Dimension scenario, Cumrun's talk)

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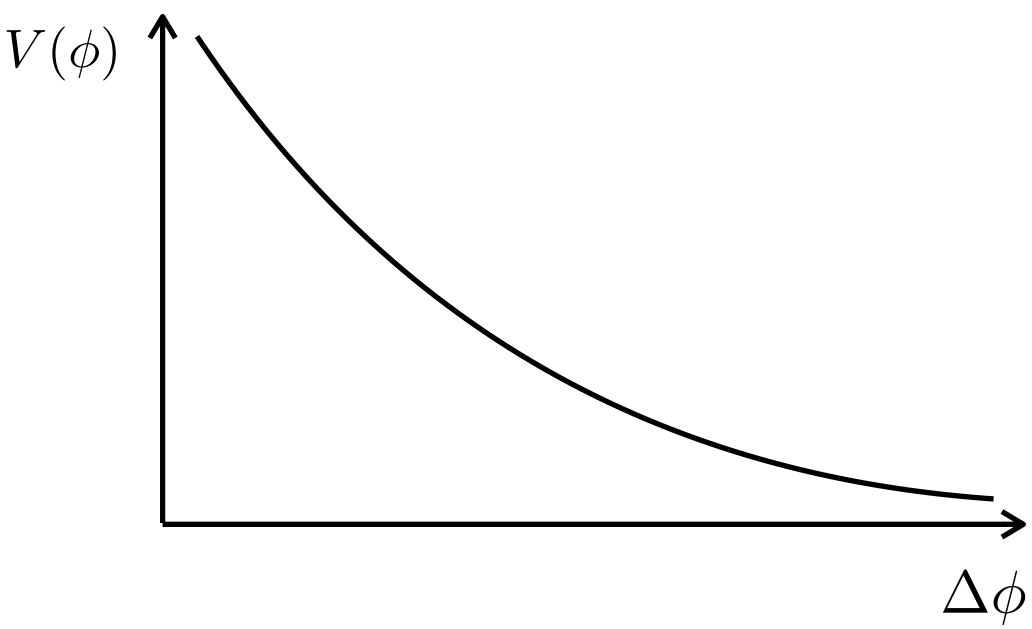

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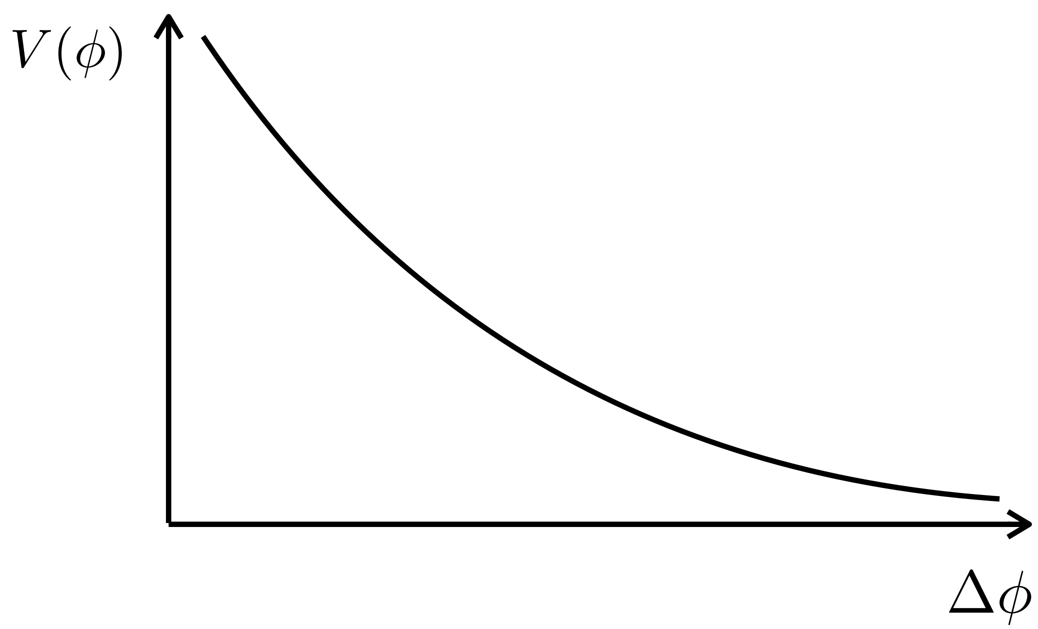

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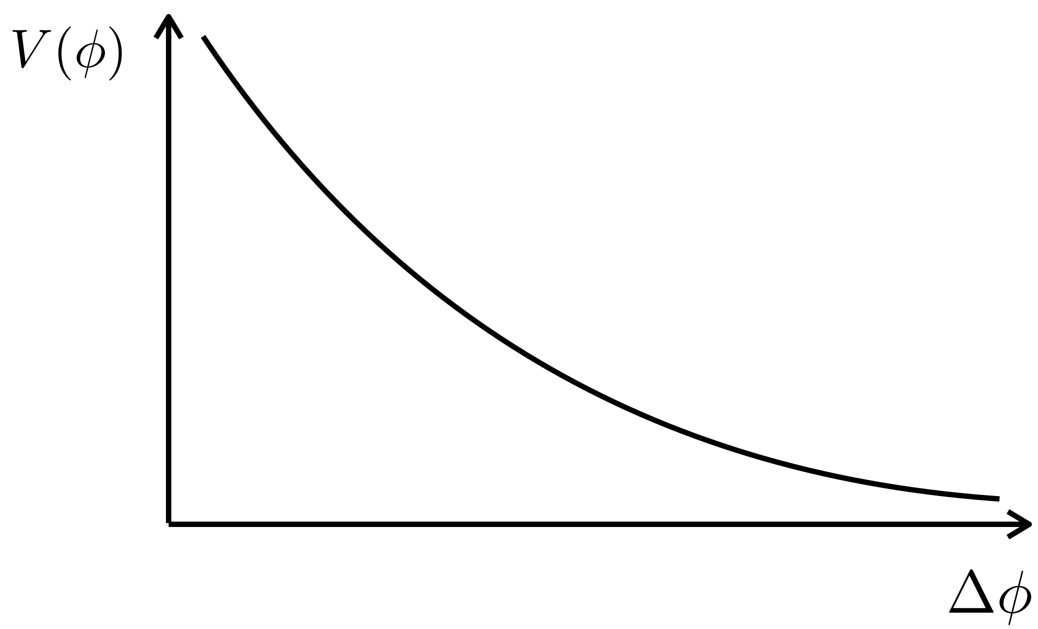

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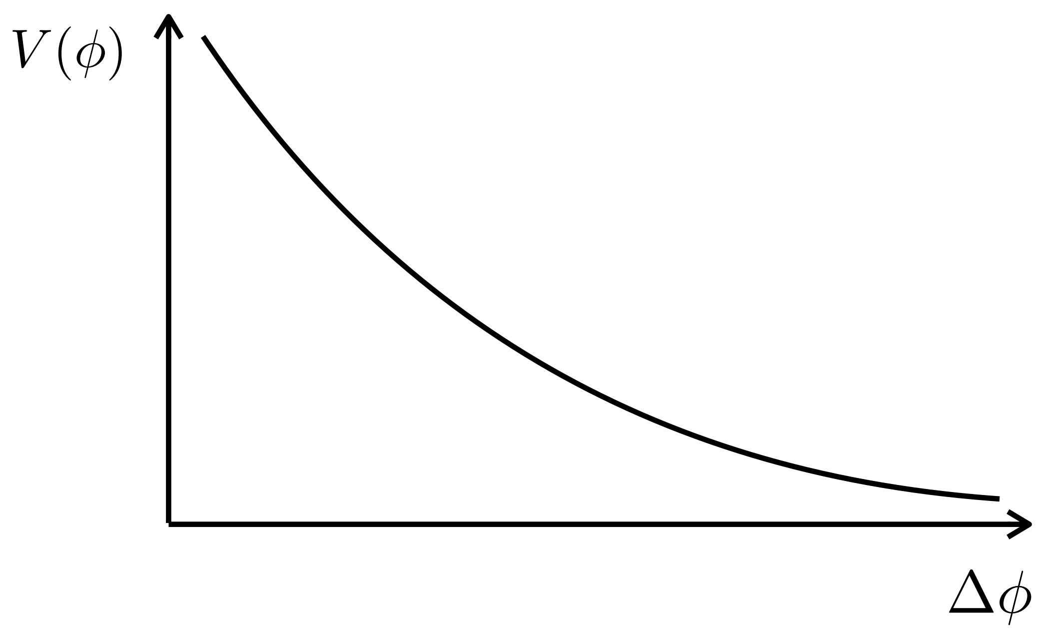

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Why is it so difficult to have small $\left|\frac{\vec{\nabla} V_0}{V_0}\right|$?

If the tower contains higher spin fields,

Higuchi bound implies $\gamma \geq 2$ [Montero,Vafa,IV'22] [Rudelius'22]

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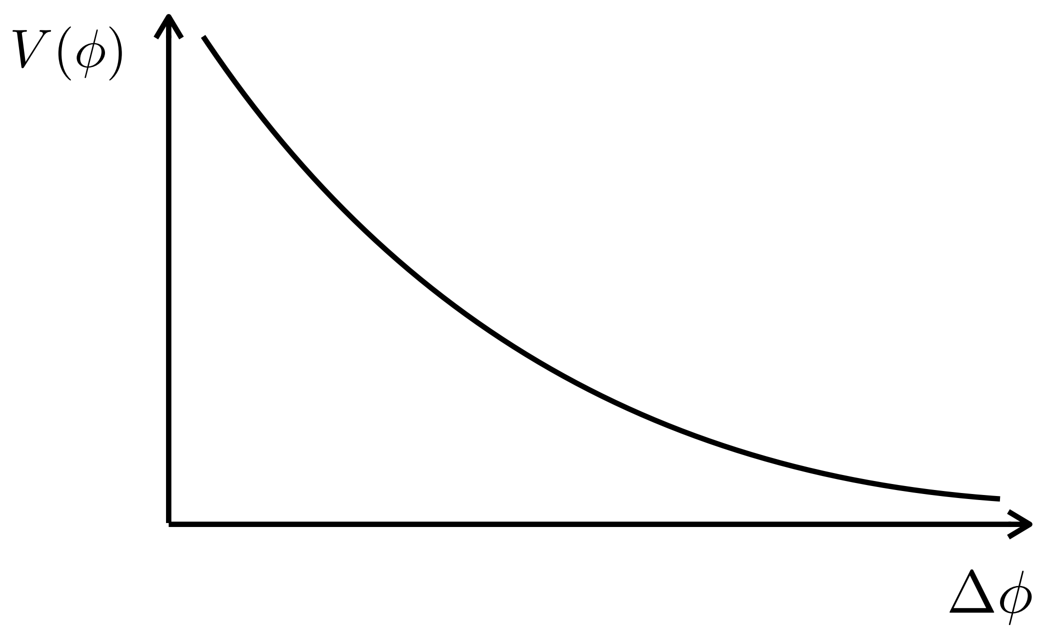

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[Li,Grimm,IV'19][Valeixo et al'20] [Andriot et al'20-22] [Cicoli et al'21-22] [Calderon-Infante et al'22] [Shiu,Tonioni'23] [Cremonini et al'23]…

↪ we evade previous no-go's for accel. exp. but still, no explicit examples

Why is it so difficult to have small $\left|\frac{\vec{\nabla} V_0}{V_0}\right|$?

If the tower contains higher spin fields,

Higuchi bound implies $\gamma \geq 2$ [Montero,Vafa,IV'22] [Rudelius'22]

which combined with $\left|\frac{\vec{\nabla} m}{m}\right| \geq \frac{1}{\sqrt{d-2}}$

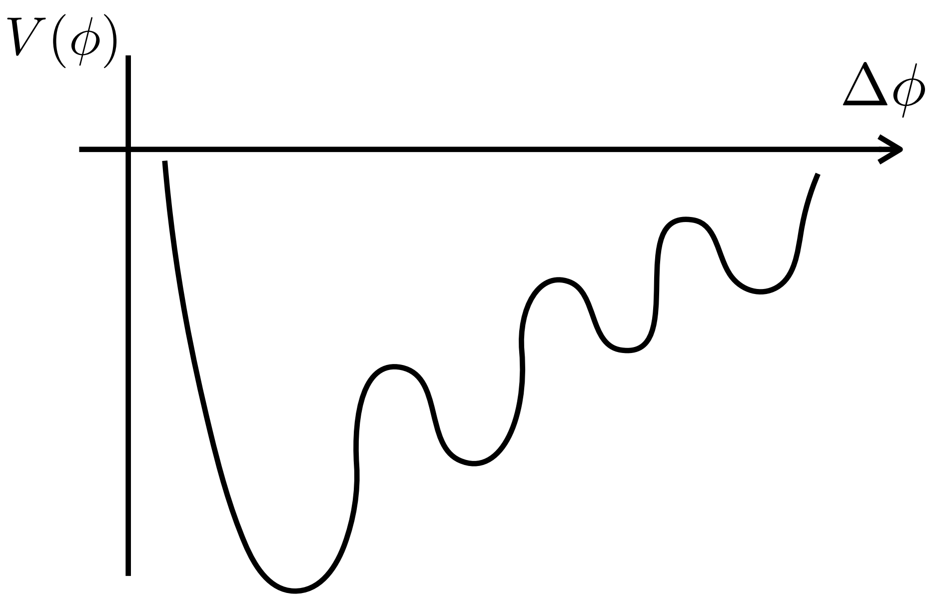
implies $\left|\frac{\vec{\nabla} V_0}{V_0}\right| \geq \frac{2}{\sqrt{d-2}}$ (no asymptotic accelerated expansion)

[Bedroya,Vafa'19] [Rudelius'22]

Beyond Moduli Spaces

What happens in the presence of a potential?

Family of AdS vacua



$$V_0 \sim m_{\text{tower}}^{\gamma}$$

AdS scale separation if

$$\gamma \geq 2$$

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Known holographic SUSY examples have

$$\gamma = 2$$

(no scale separation between AdS length and internal dimensions)

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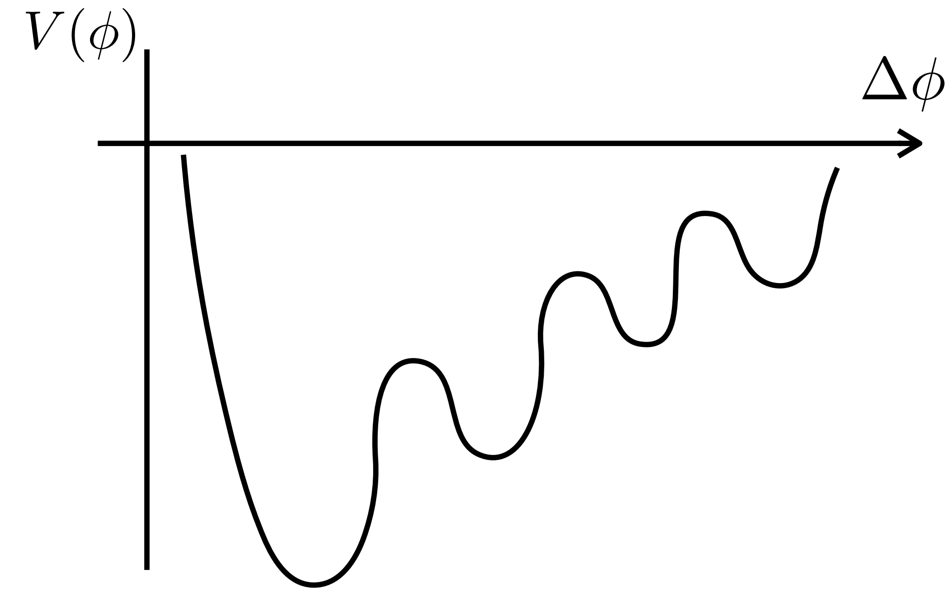

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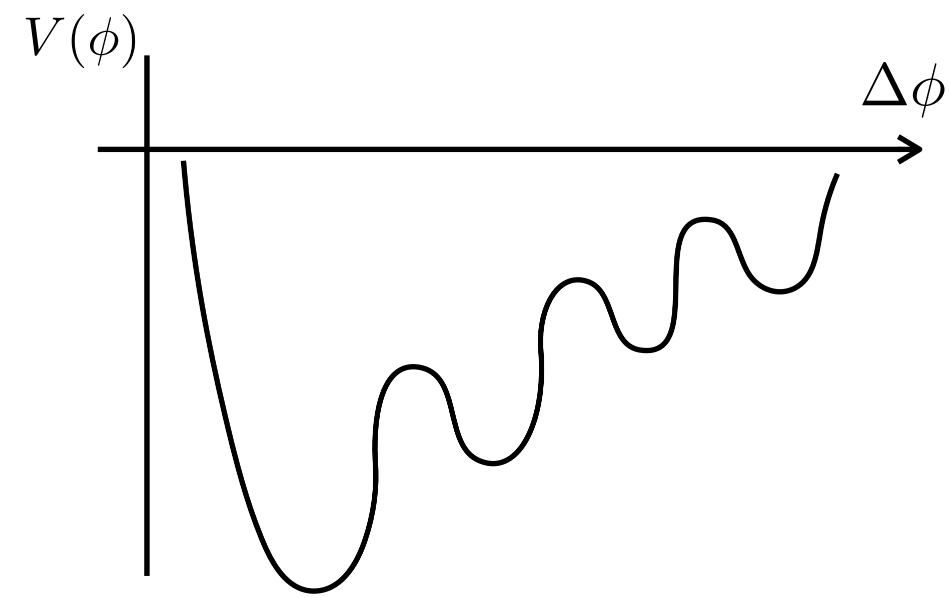

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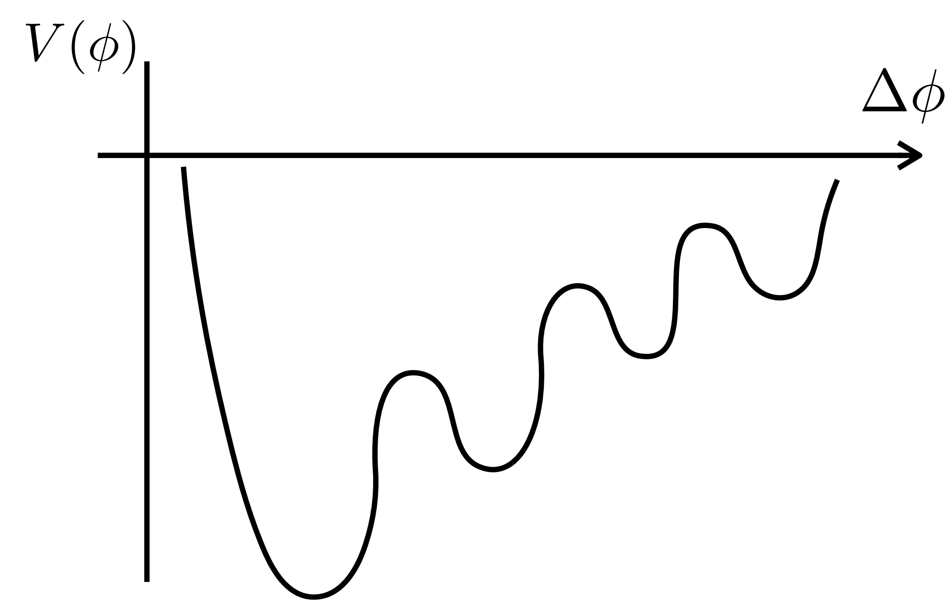

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No explicit 10d uplift

New results regarding consistency of the vacuum
[Montero,Valenzuela 'ongoing]

DGKT vacuum

[De Wolfe, Giddings, Kachru, Taylor '05]

4d N=1 AdS vacuum arising from compactifying massive Type IIA on a CY3 with O6-planes and fluxes for

$$F_0, F_4, H_3 \quad \rightarrow \quad \text{AdS4xCY3}$$

There is one **unconstrained flux** that does not appear on the tadpole:

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By solving the 4d eoms, one finds a family of AdS vacua with

$$V_0 \sim N^{9/2}$$

$$m_{\mathrm{KK}}^{-2} \sim L_{\mathrm{KK}}^2 \sim N^{7/2} \quad \rightarrow \quad \left(\frac{\ell_{AdS}}{L_{KK}}\right)^2 \sim N$$

So this solution is **scale-separated** in the large N limit.

DGKT vacuum

The consistency of the solution is not clear because we only solved **4d equations of motion** (zero mode of 10d eoms on CY3)

Lot of recent progress, everything seems fine so far, but no conclusive answer.

[Andriot, Apers, Casas, Castellano, Collins, Cribiori, Dall'Agata, De Luca, Emelin, Farakos, Graña, Herraez, Hoter, Ibañez, Junghans, Lust (x2), Marchesano, Marconnet, Montella, Morittu, Ning, Palti, Plauschinn, Prieto, Quirant, Revello, Shiu, Shukla, Tomasiello, Tonioni, Toulikas, Tringas, Tsimpis, Vafa, Van Hemelryck, Van Riet, Walcher, Wiesner, Wrasse, Xu, Yau, Zatti,…]

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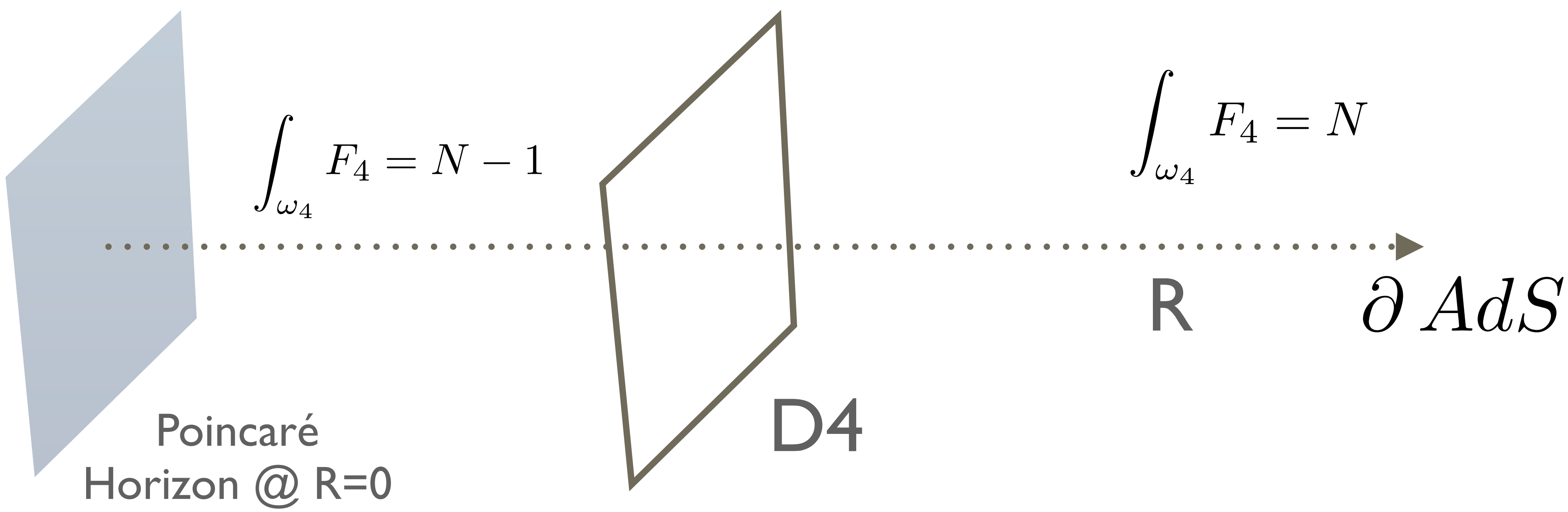
We will assume everything is OK, and study the fate of branes on DGKT vacuum, to perform a non-perturbative consistency check

[Montero, Valenzuela 'ongoing]

Test of DGKT vacuum

Consider a D4-brane wrarpping a holomorphic 2-cycle dual to the large N flux

$$\int_{\omega_4} F_4 = N$$



In principle, it is **BPS**, so the position of the brane is a modulus

(see also [Aharony,Antebi,Berkooz '08])

Test of DGKT vacuum

However, at low energies the worldvolume theory is $3d\,\mathcal{N}=1$

This is so little SUSY that there are no protected quantities

The superpotential can receive corrections (unless there is a parity symmetry)

[Gaiotto-Komargodski-Wu '18]

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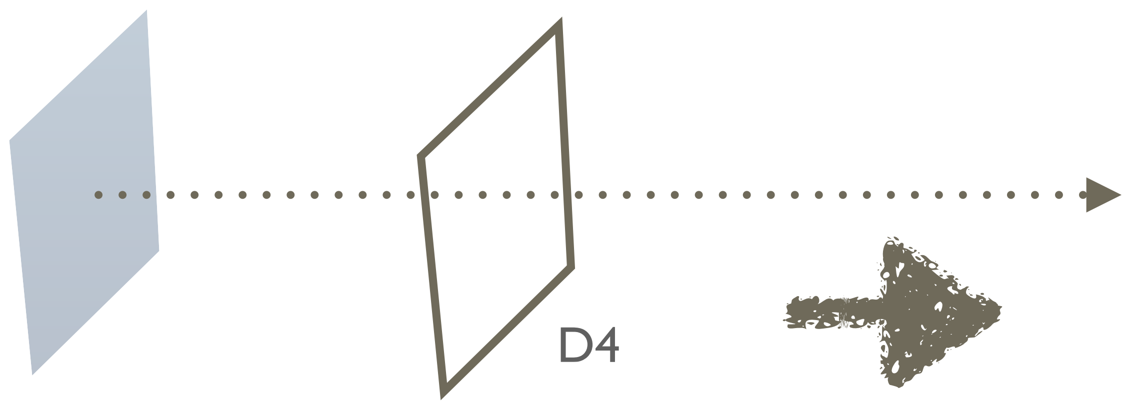
→ the position of D4 is not a modulus

(it feels an attractive force)

Test of DGKT vacuum

The result is in tension with the Weak Gravity Conjecture (WGC)

According to the WGC, a non-BPS brane should be repulsive



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➡ No SUSY AdS scale-separated vacuum

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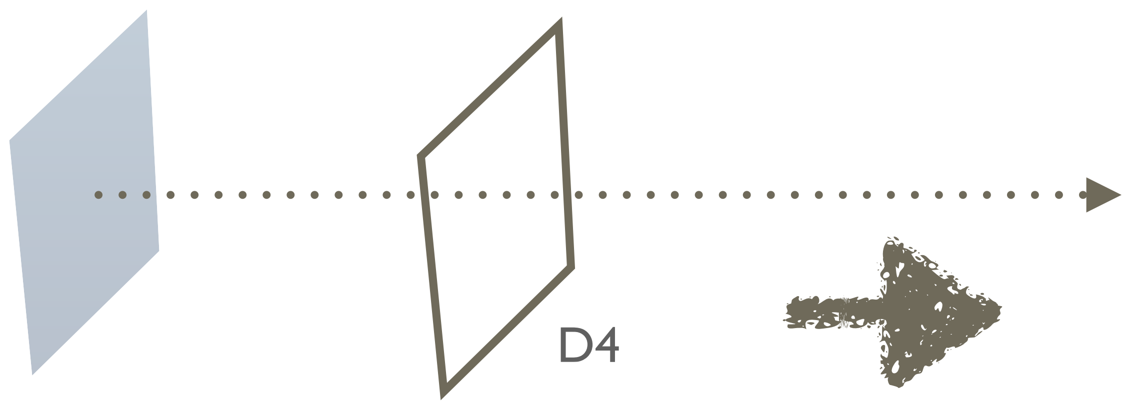

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→ No SUSY AdS scale-separated vacuum

Ongoing work!

We are exploring the implications of this clash between DGKT vacuum and the WGC for membranes

[Montero, Valenzuela 'ongoing]

Stay tuned

Conclusions

❖ We are entering an era of precision in the Swampland program

Fix all "order one" factors $m \sim m_0 \exp(-\alpha\Delta\phi)$ $\Lambda \sim M_p \exp(-\lambda\Delta\phi)$

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- It provides a quantitative bound for the exponential rate of the tower

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} \Lambda}{\Lambda} = \frac{1}{d-2} \quad \Rightarrow \quad \alpha \geq \frac{1}{\sqrt{d-2}}$$

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❖ We perform a non-perturbative check of DGKT and the result is in tension with the Weak Gravity Conjecture

Thank you!

back-up slides

Scalar WGC

Can we reformulate the Distance Conjecture as a sharp local condition that the spectra of the theory must satisfy at a given point of the moduli space?

(in analogy to the Weak Gravity Conjecture $\frac{Q}{m} \geq \gamma_{\rm BH}$) *

* The Distance Conjecture (a drop-off of the cut-off) resembles the "magnetic version" of the WGC, is there an analogous "electric version" for the Distance Conjecture?

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Attempt: **Scalar Weak Gravity Conjecture (SWGC)** [Palti'16]

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Notice! Moduli (massless scalars) induce Yukawa scalar forces:

$$\mathcal{L} \supset M^2(\phi)\chi^2 \simeq 2M\partial_\phi M\,\phi\chi^2 + \ldots$$

modulus — *scalar charge*

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scalar charge-to-mass ratios: $\vec{\zeta} \equiv -\frac{\vec{\nabla} m}{m}$

If applied to towers of states decaying exponentially: $\alpha = \vec{\zeta} \cdot \hat{\tau}$

(α: exponential rate of the tower; $\hat{\tau}$: unit tangent geodesic vector)

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Convex Hull Distance Conjecture

The Distance Conjecture can be formulated as a convex hull SWGC applied to towers: [Calderon-Infante,Uranga,IV'20]

Distance conjecture with exponential rate $\alpha \geq \alpha_0$ ⟺ convex hull of $\frac{\vec{\nabla} m}{m}$ of light towers remains outside ball of radius α_0

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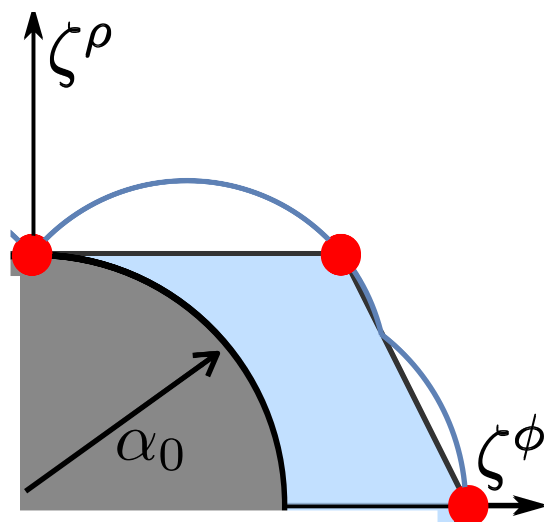

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[Etheredge et al'22]

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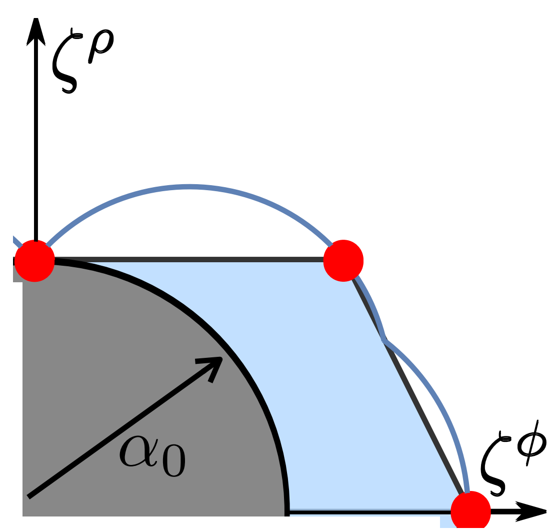

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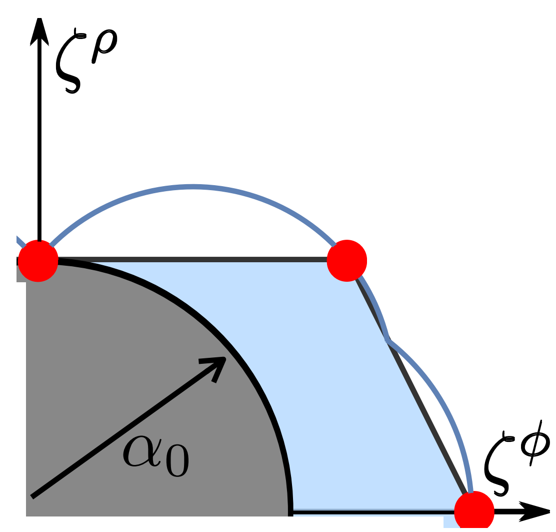

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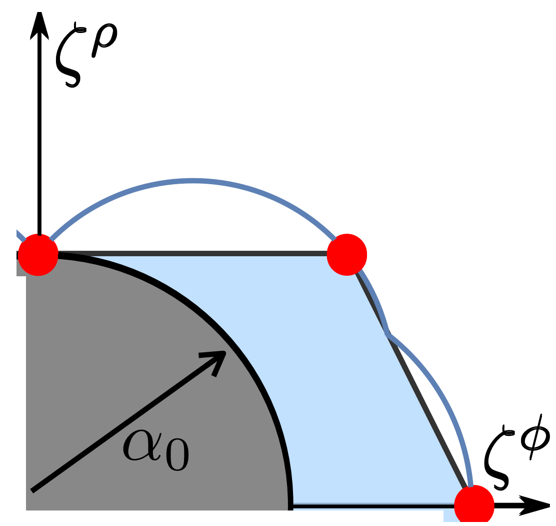

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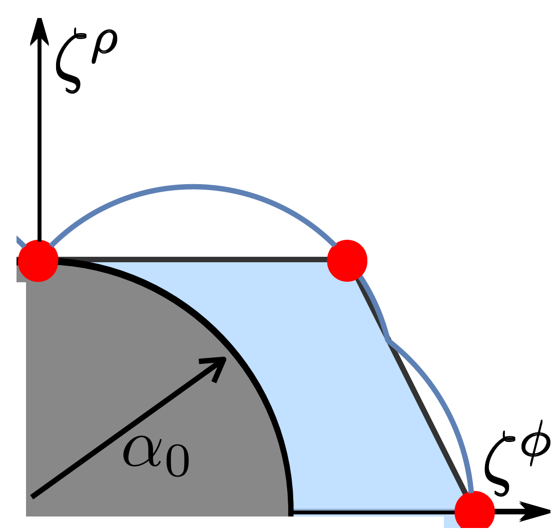

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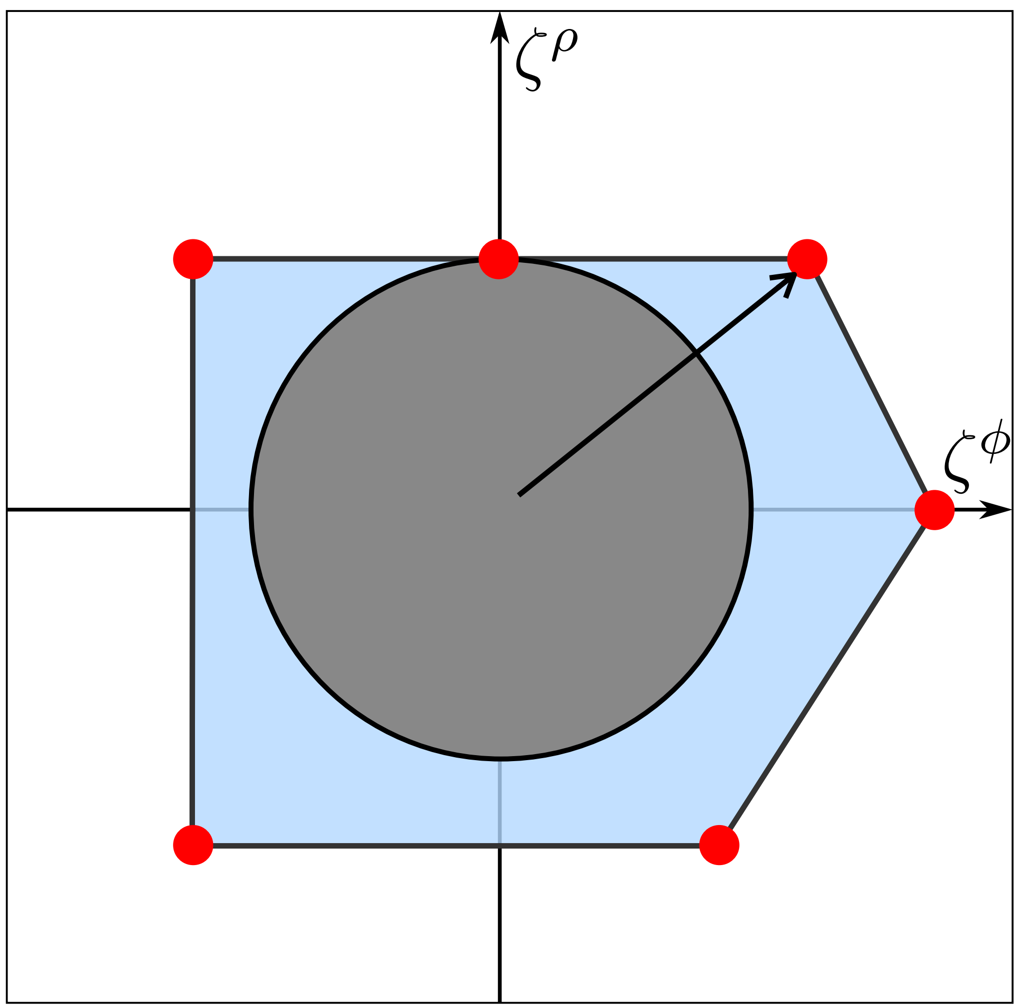
...does it?

What if $\frac{\vec{\nabla} m}{m}$ change as we move in moduli space? This formulation can fail

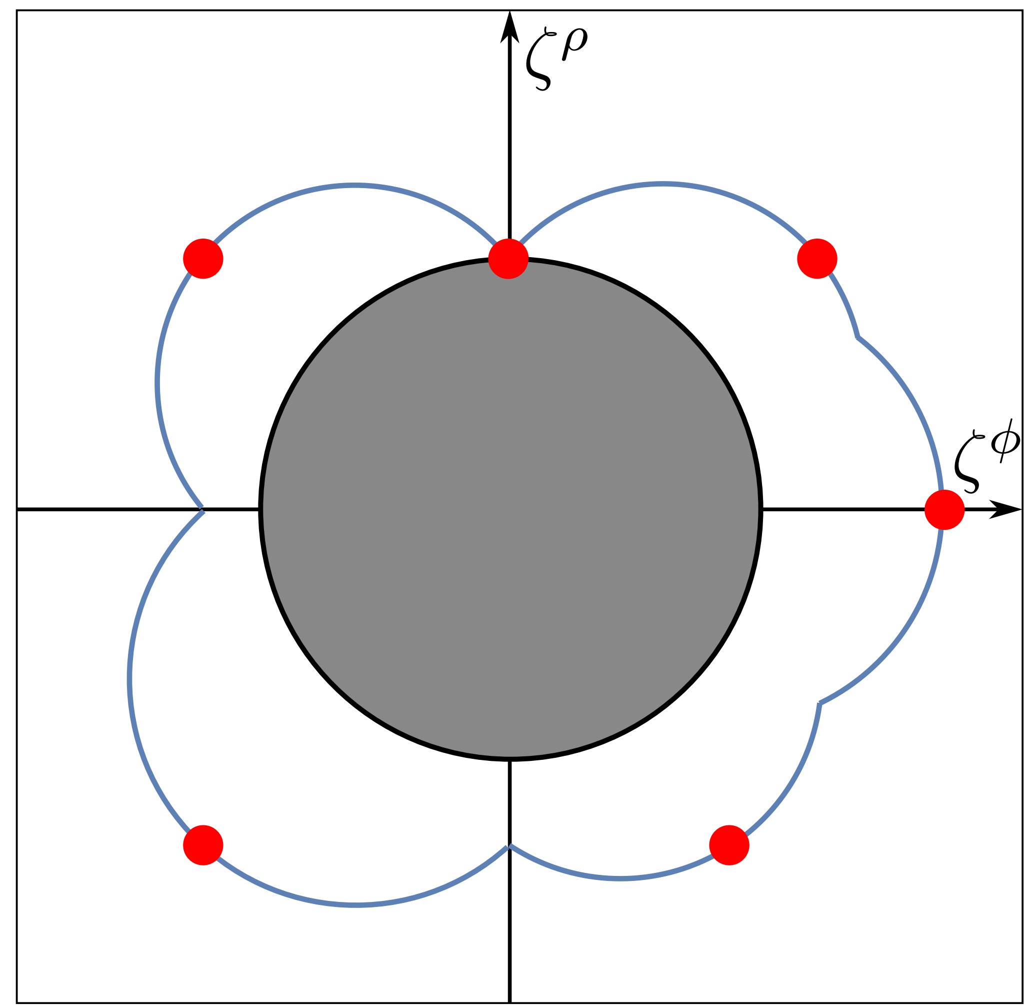
Let us check these ideas in 9 dimensional theories with 16 supercharges

(e.g. circle compactification of heterotic string theory)

SWGC plot



Max-alpha plot



➡ decompactification to running solutions

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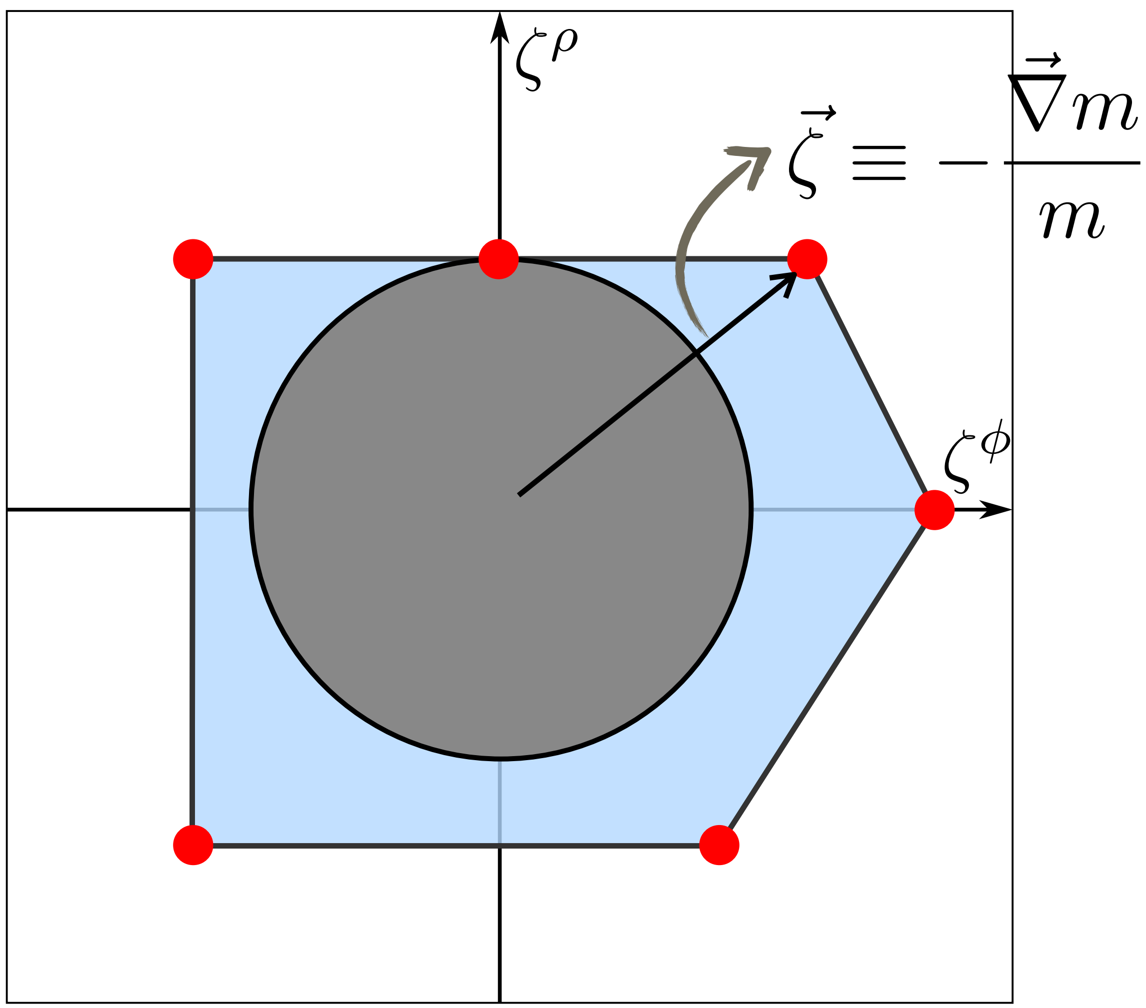

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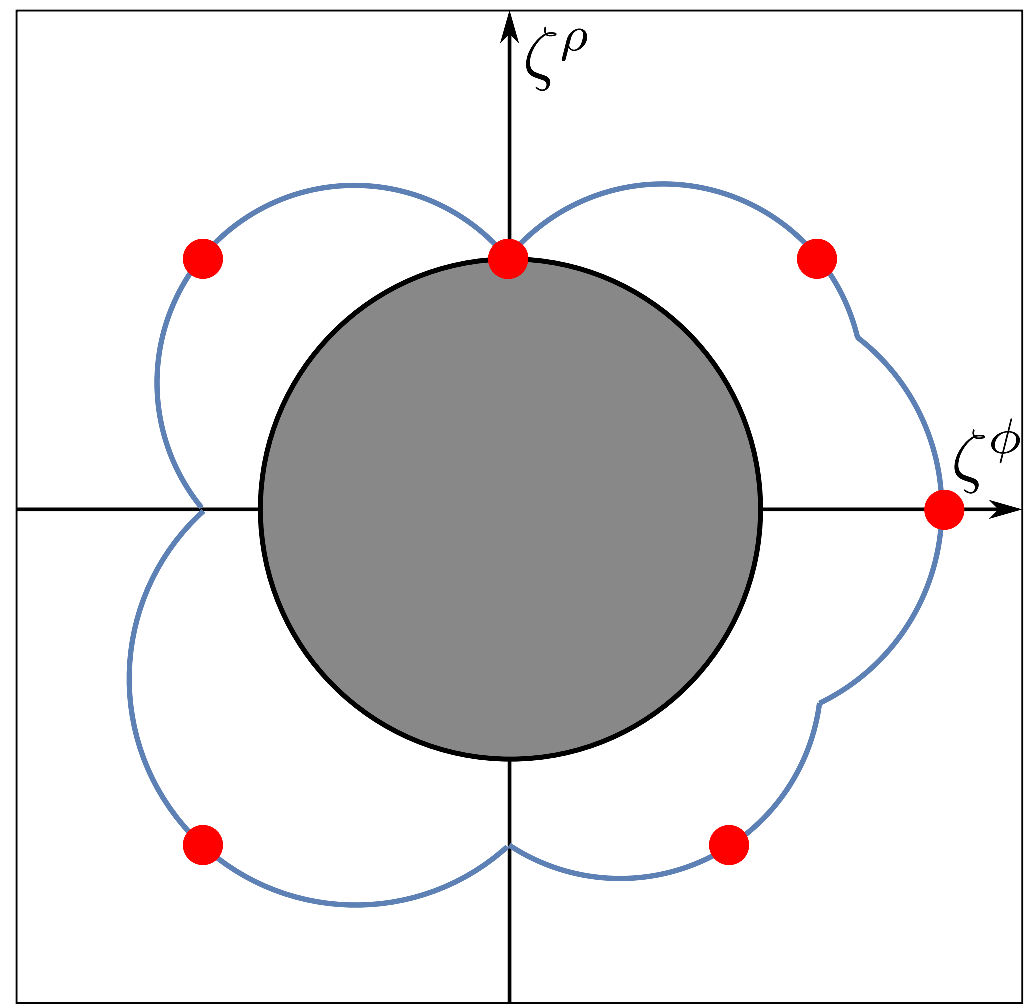

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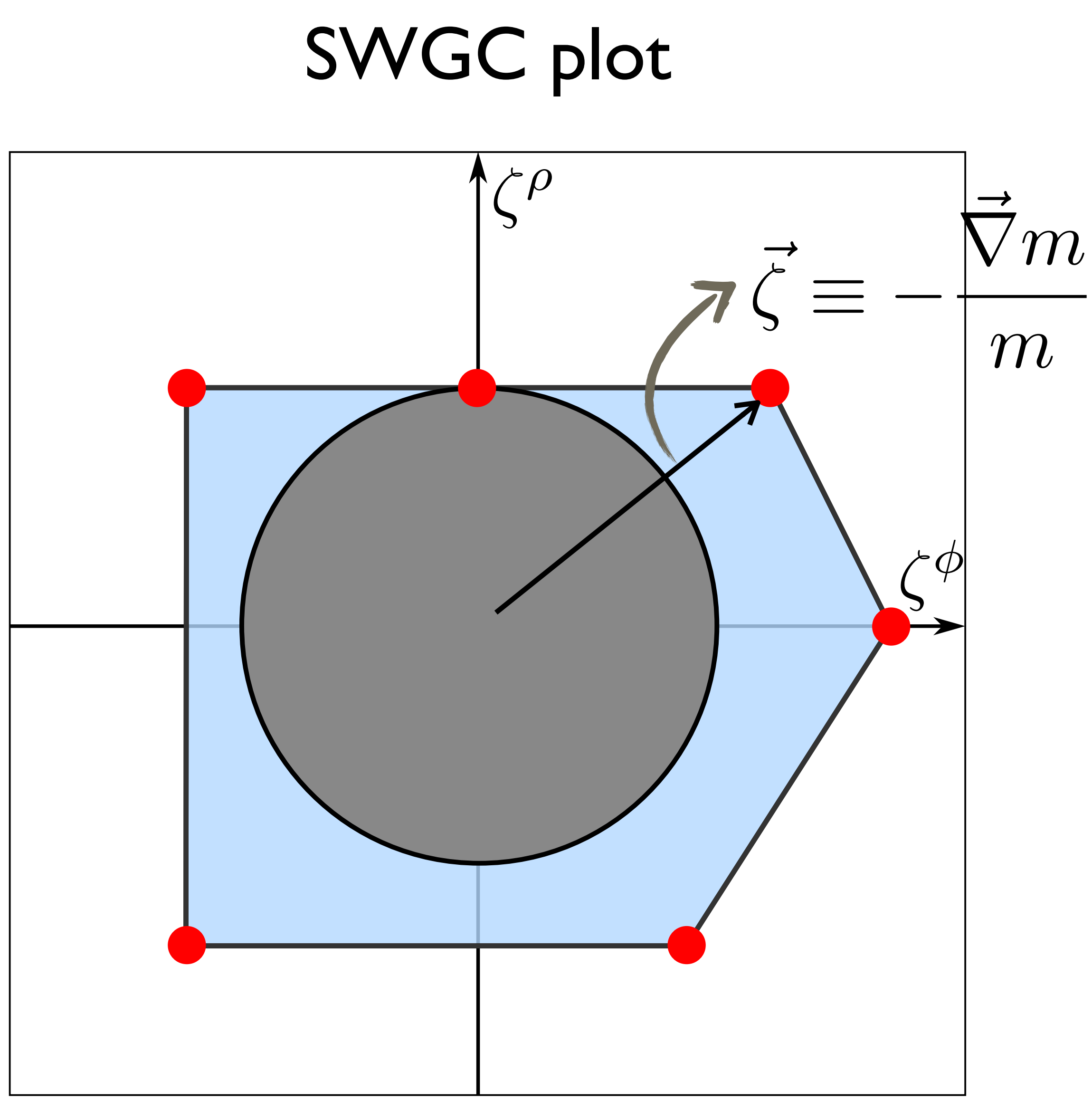
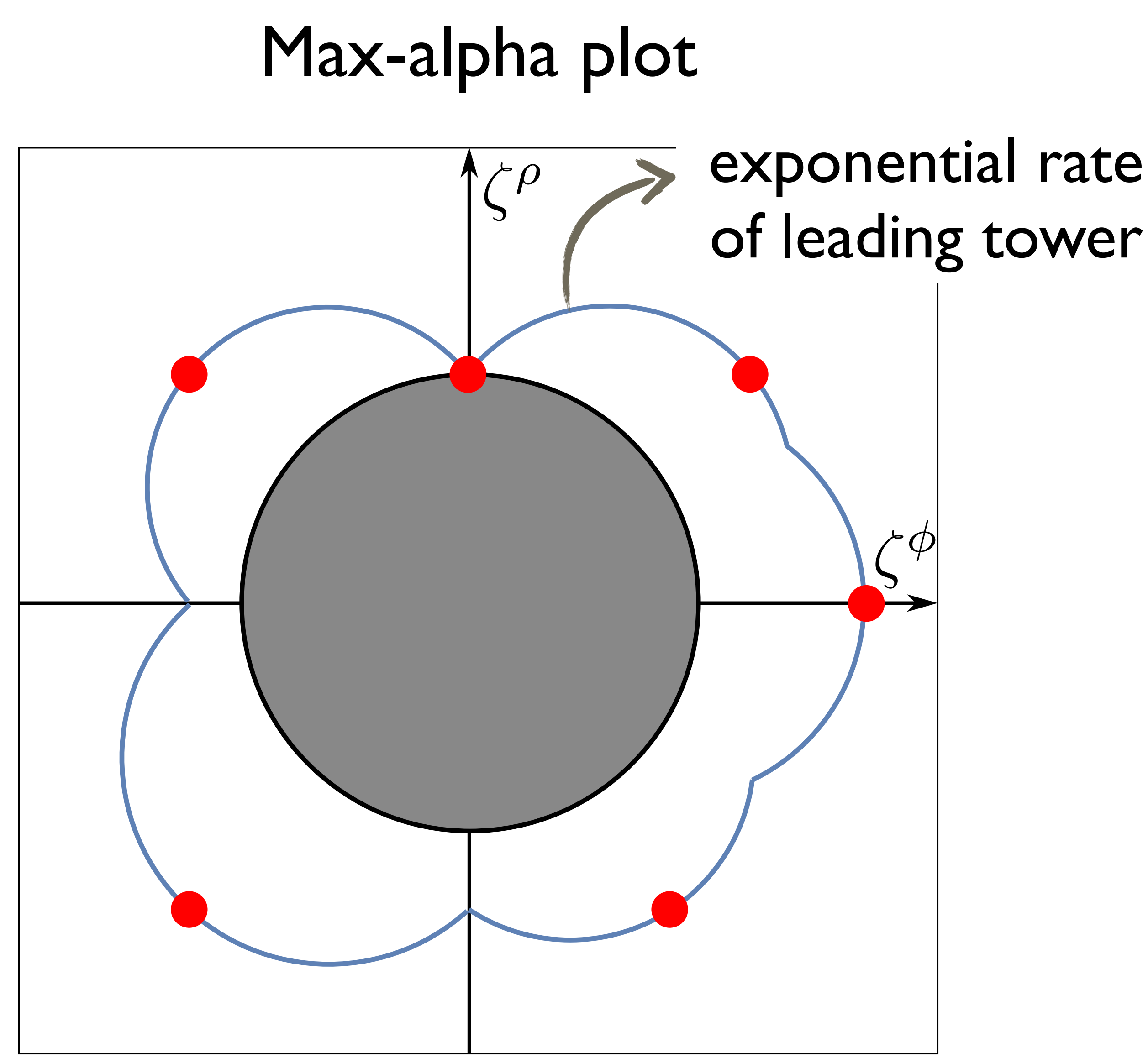
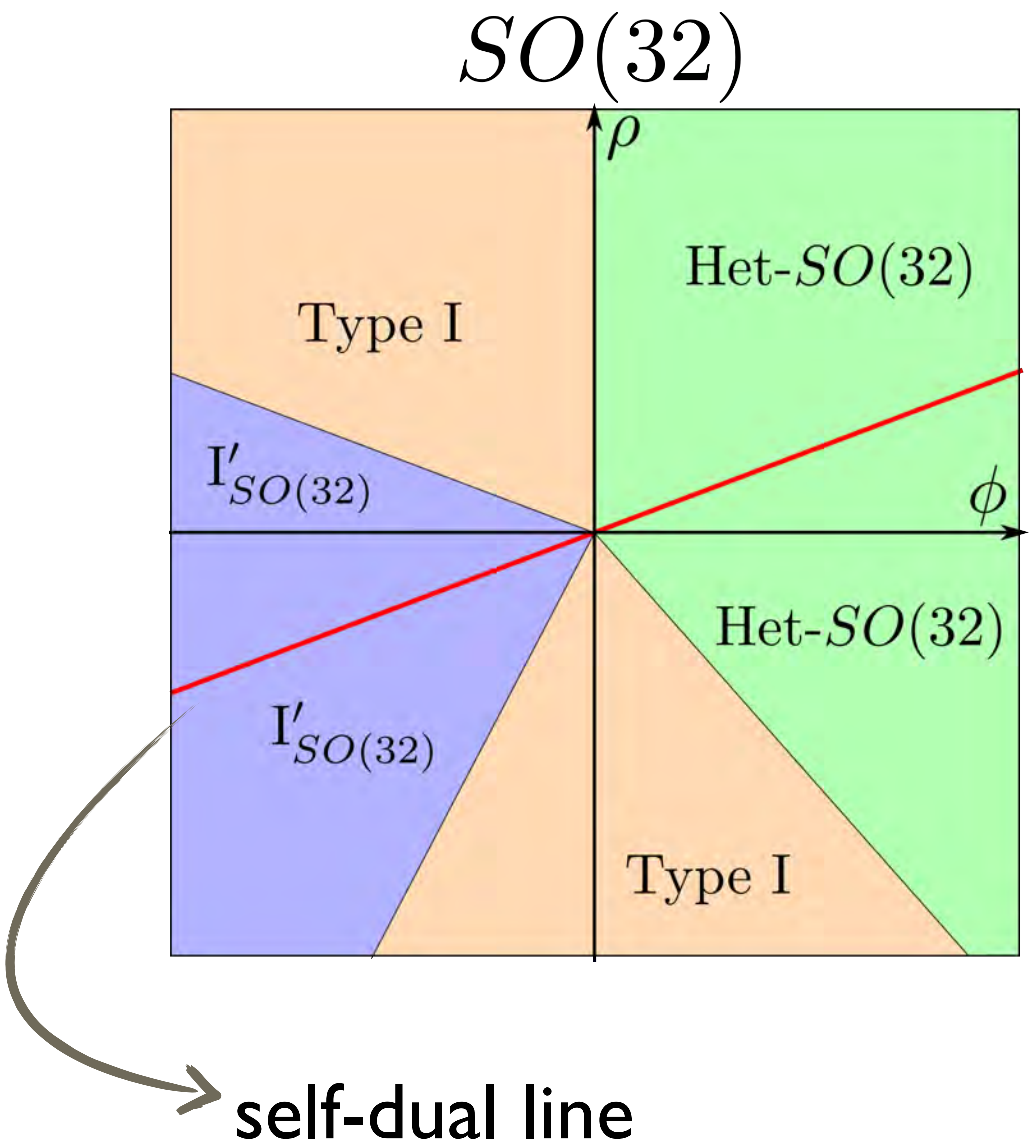
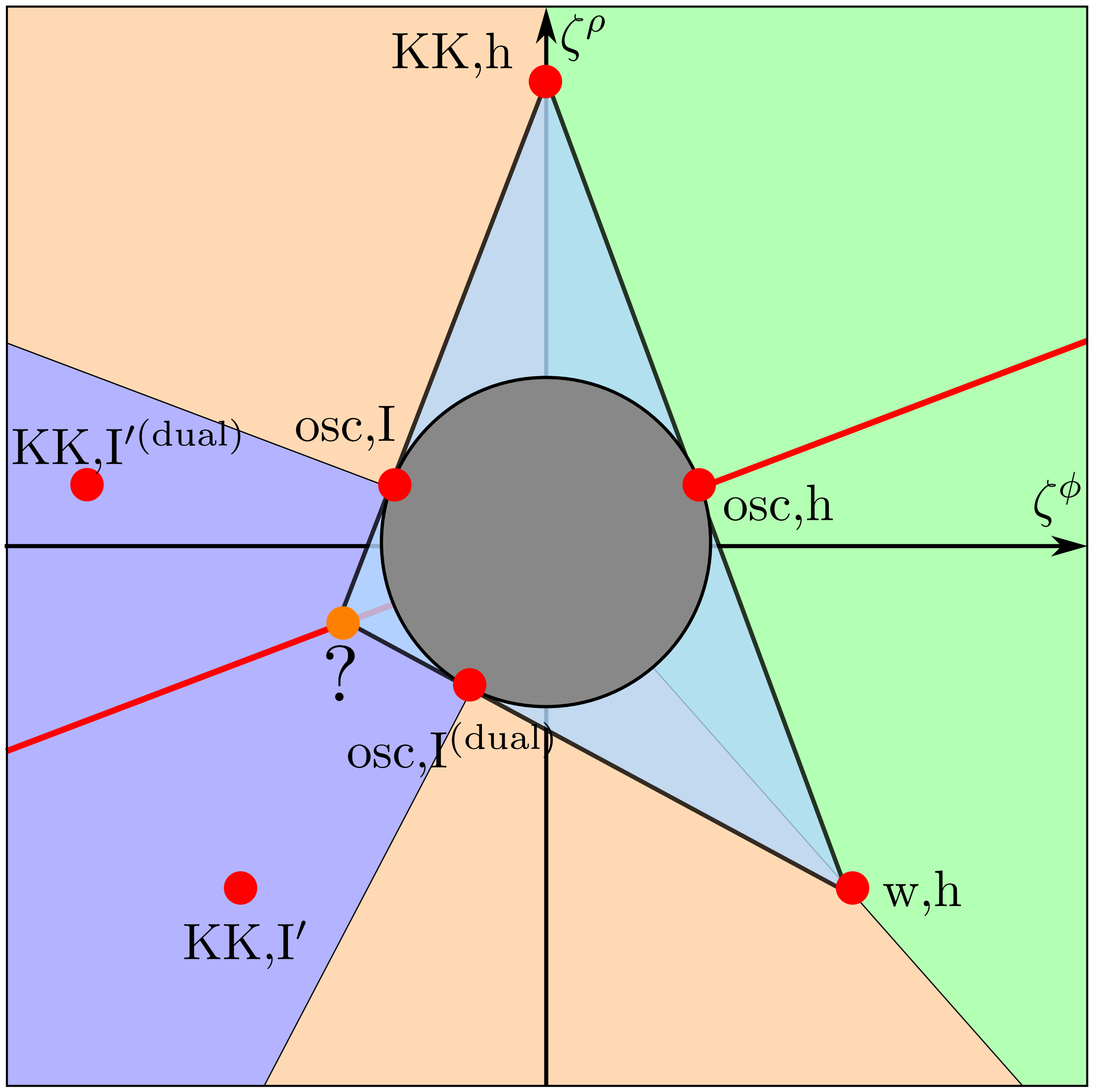




→ decompactification to running solutions

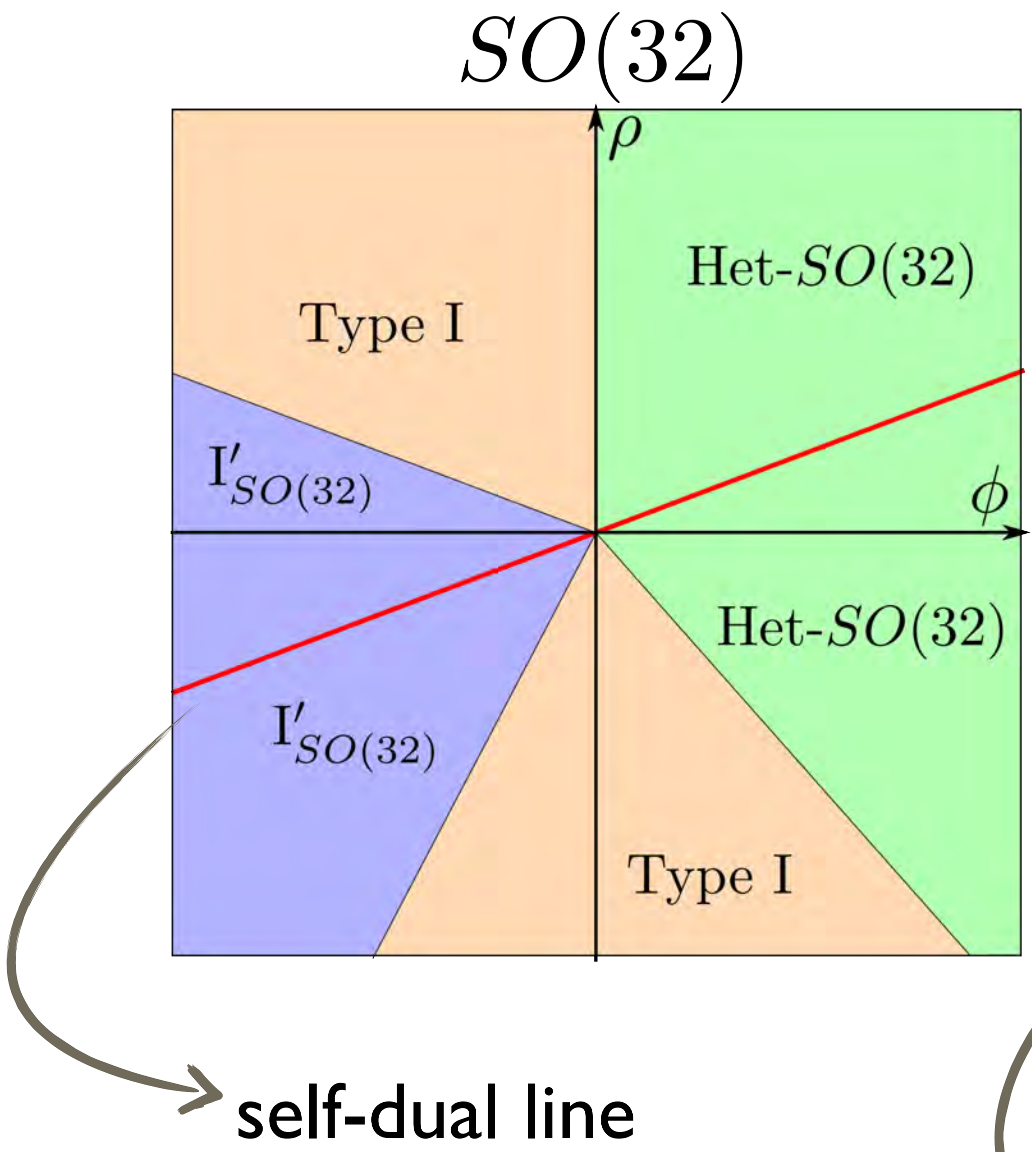
SO(32) slice

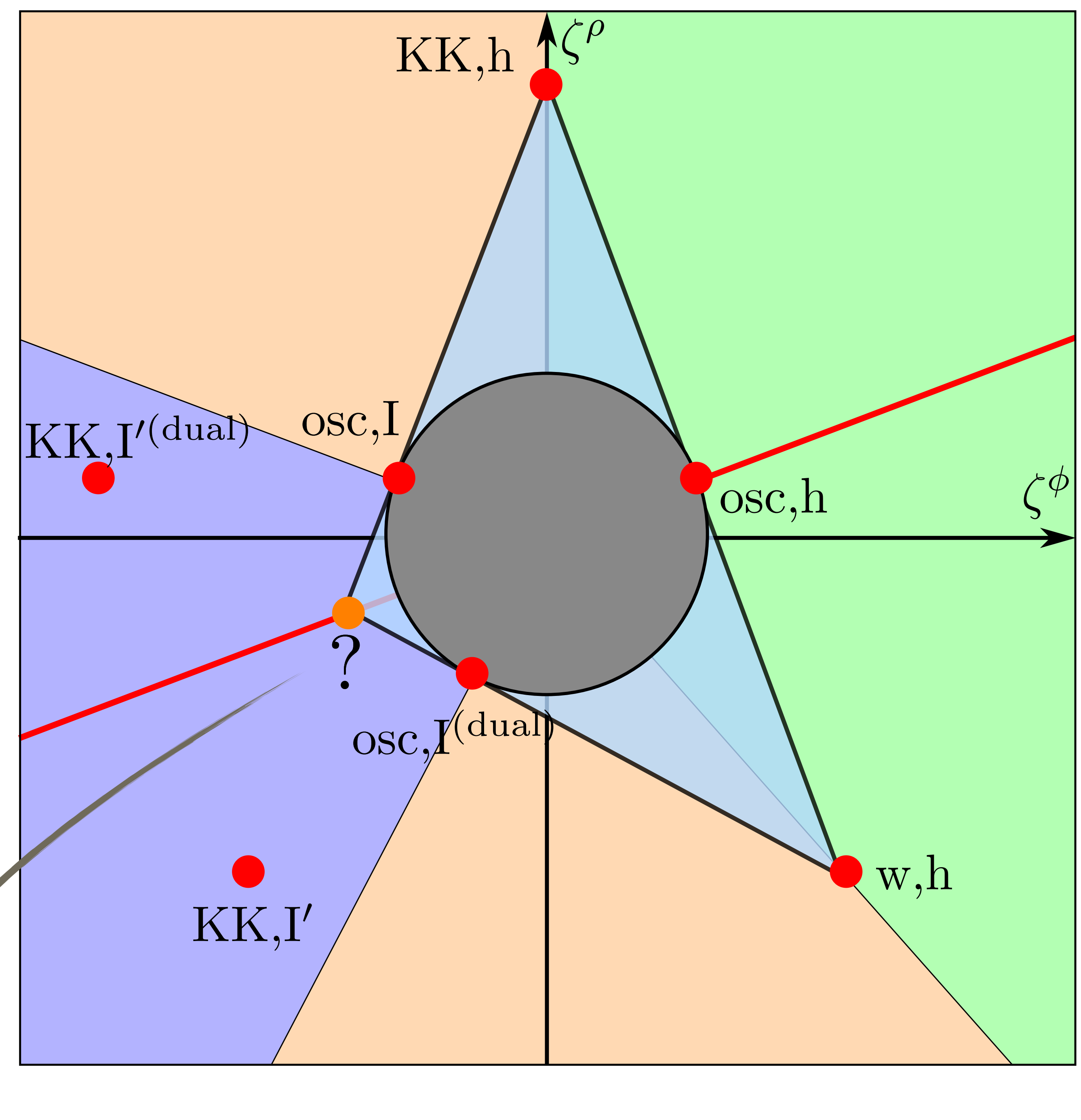




$\vec{\zeta}$

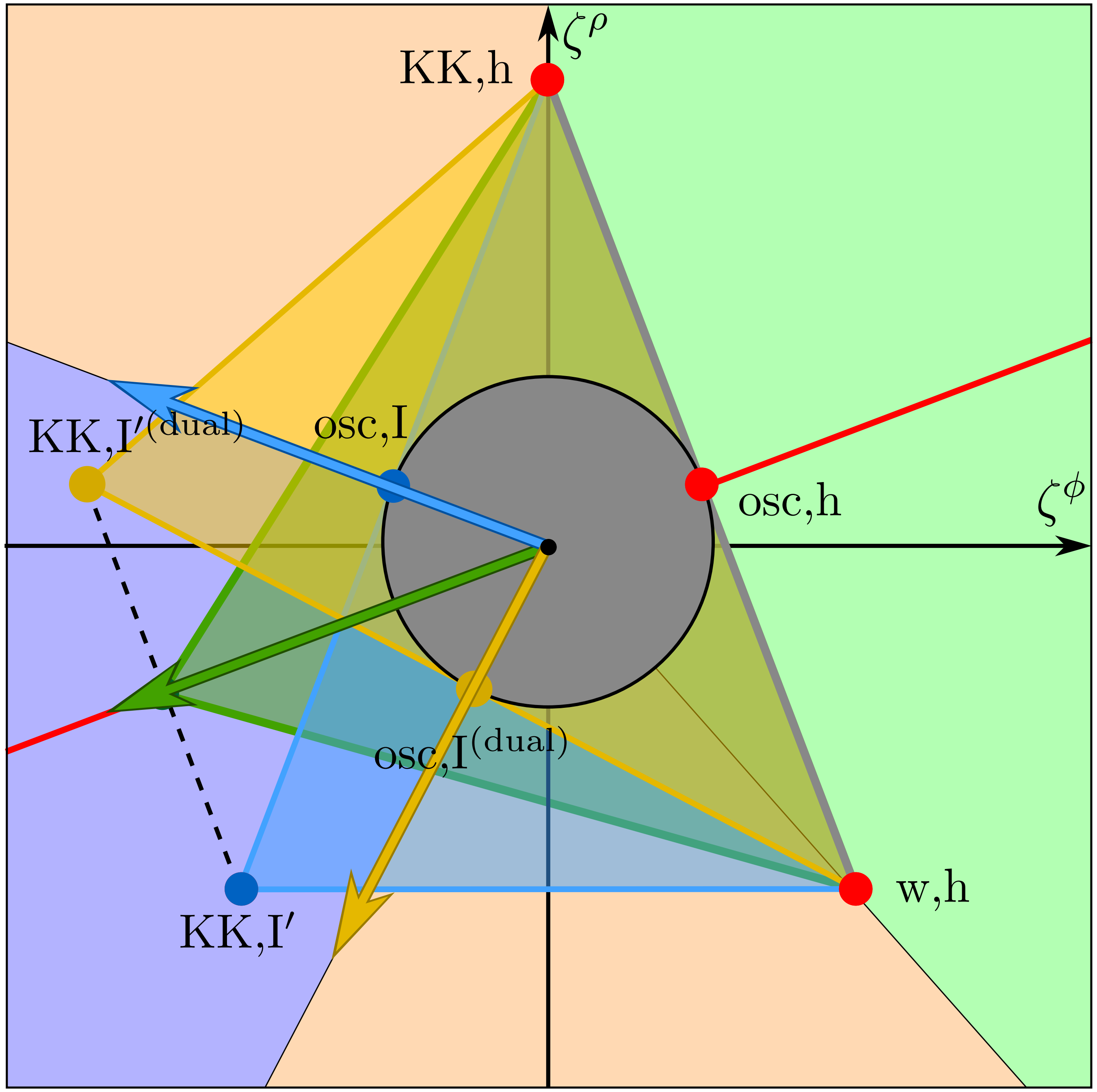
SO(32) slice





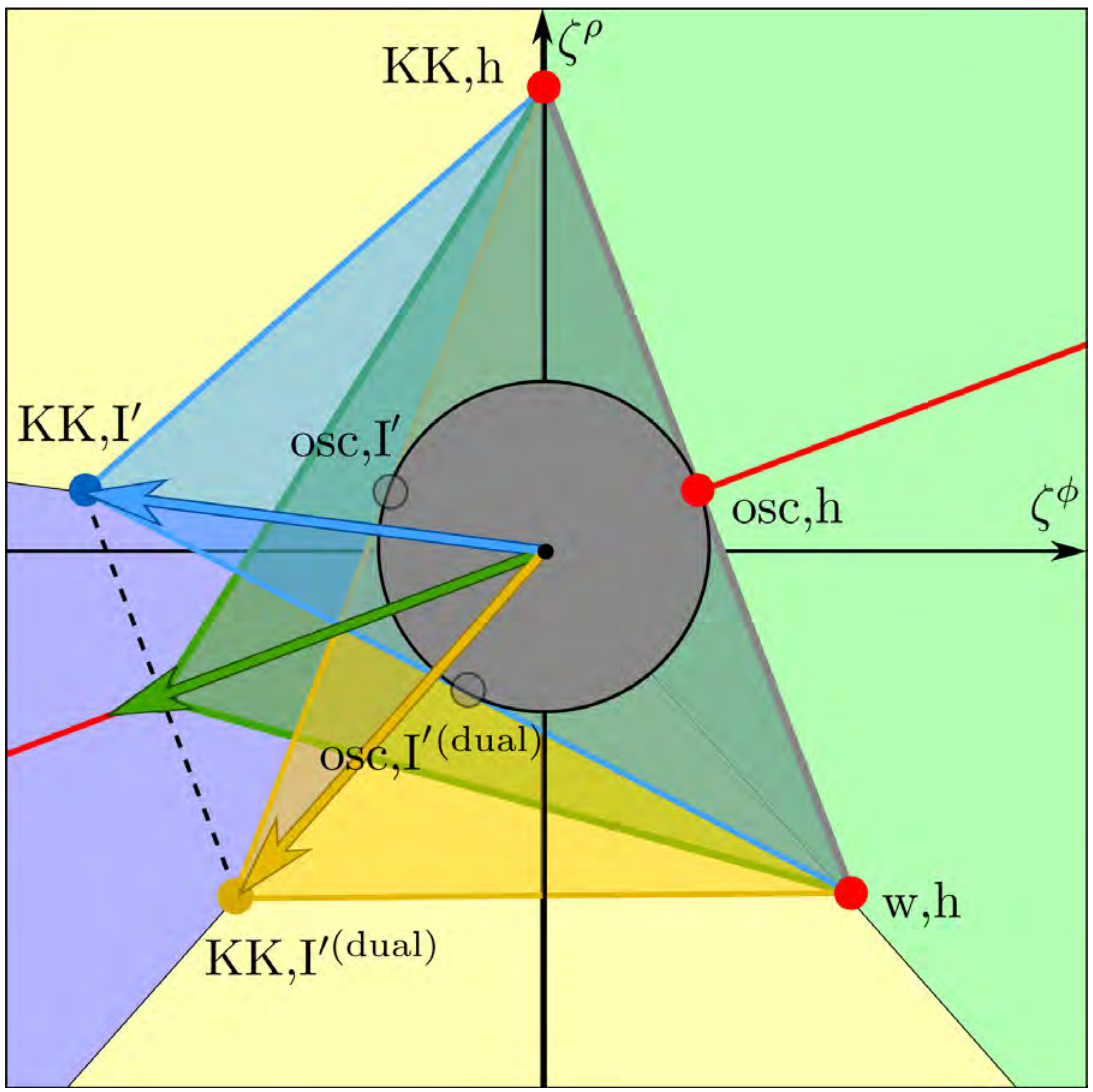
Nothing here, the $\vec{\zeta}$-vectors of the towers change as we move in the moudli space!

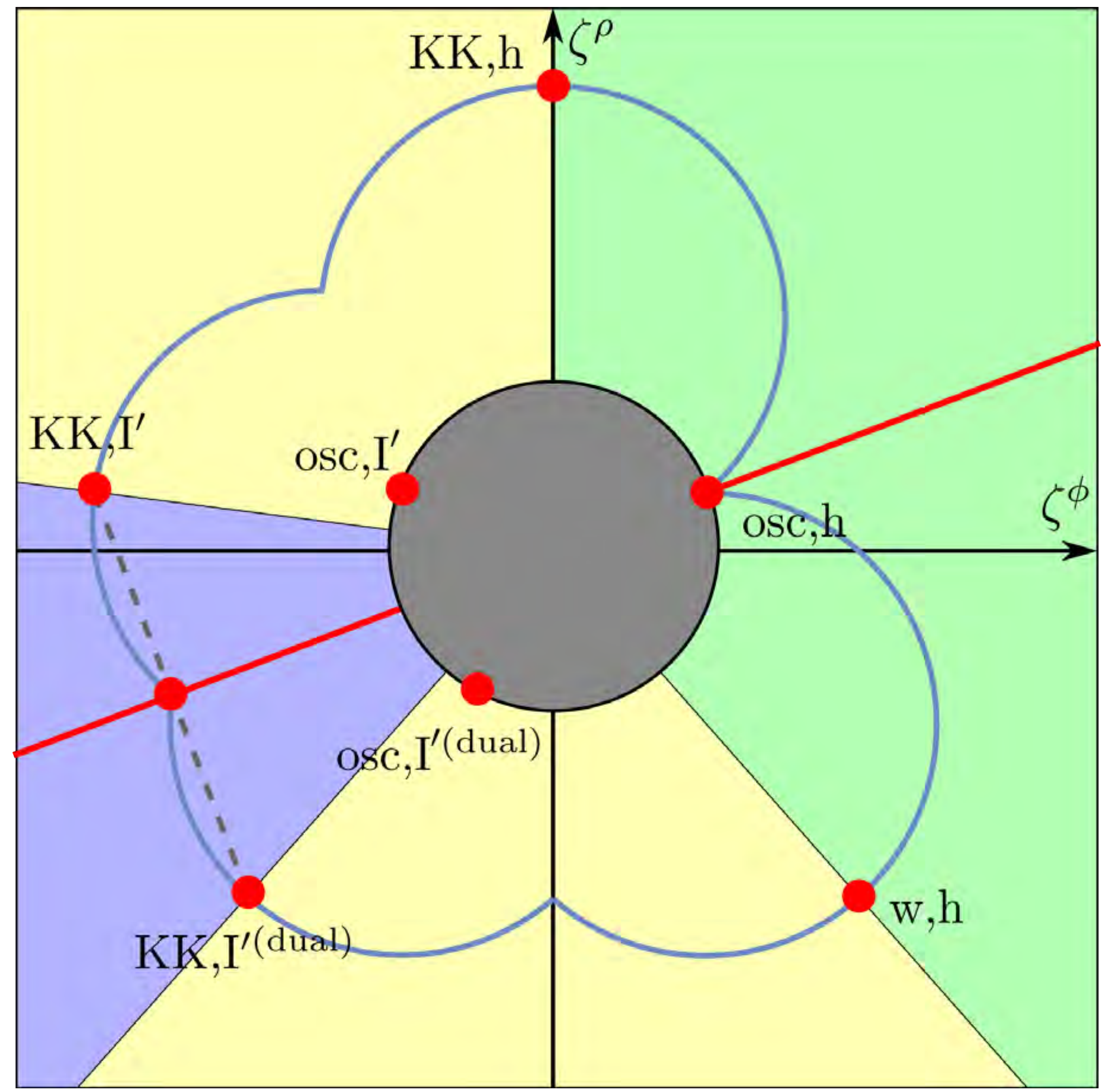
SO(32) slice



ζ^ρ
KK,h
ζ^ϕ
osc,h
osc,I
KK,I$'^{\mathrm{(dual)}}$
osc,I$^{\mathrm{(dual)}}$
w,h
KK,I$'$

E8xE8 slice

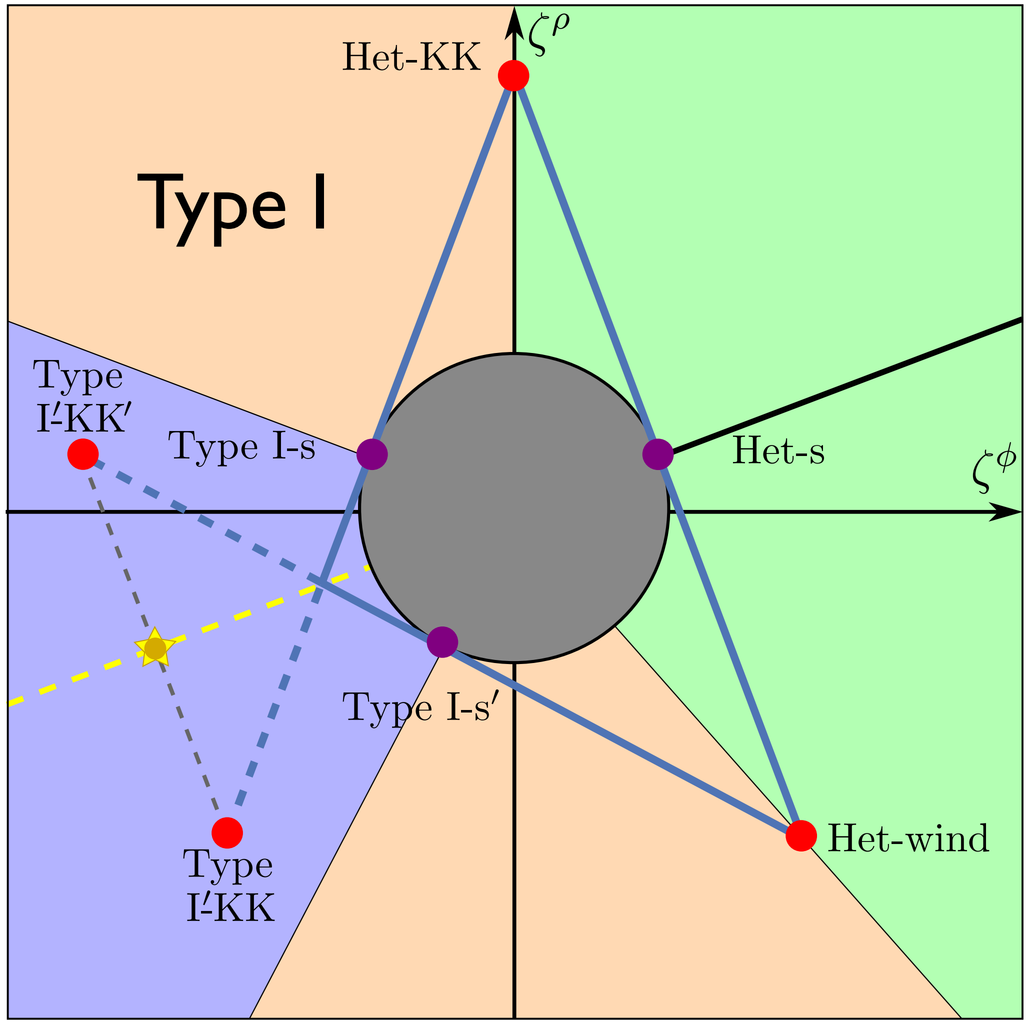


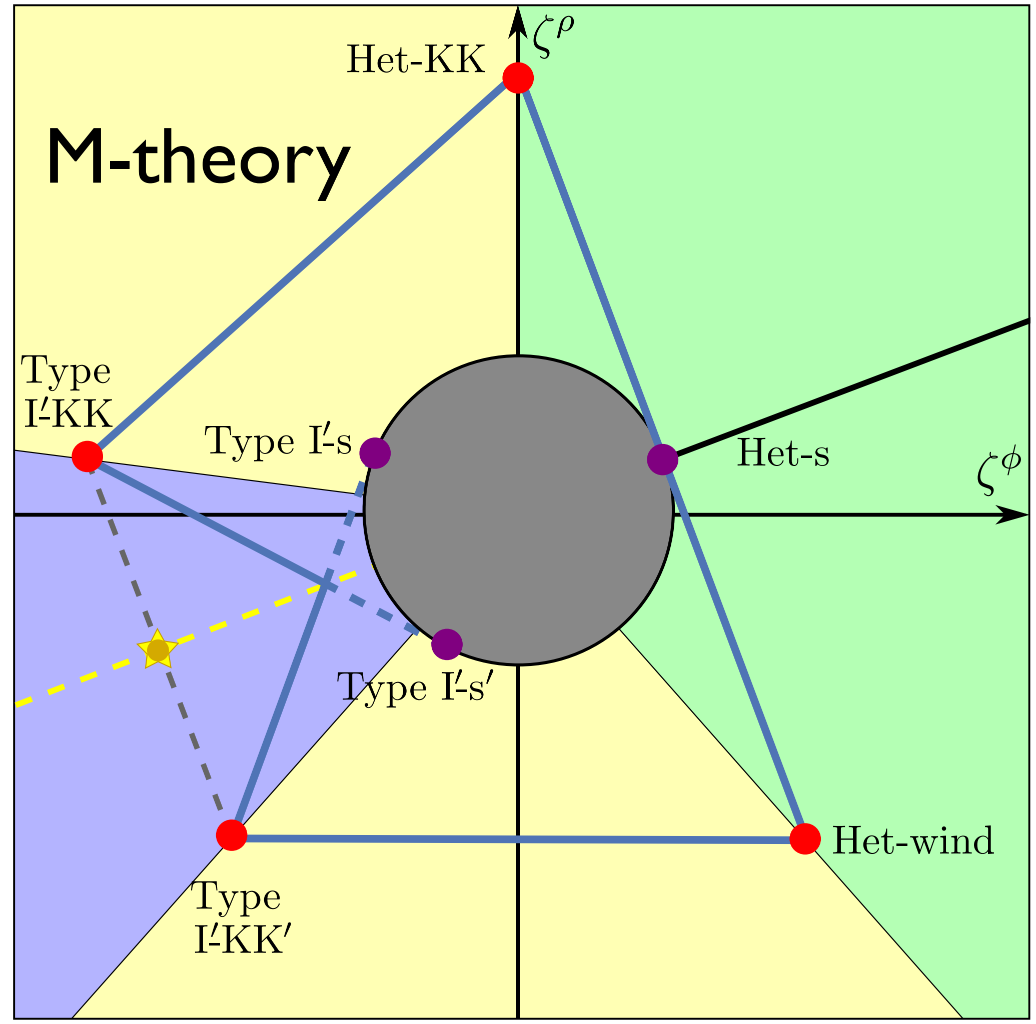


Jumping occurs in opposite direction than the SO(32) case

SO(32) slice

E8xE8 slice





This contains the essential information to derive the "quantum gravity resolution" / UV completion

(i.e. whether we reach an string theory, a higher dimensional theory, etc.)

(see also [Bedroya, Raman, Tarazi'23])

Each asymptotic region is associated to a concrete species scale

WGC and SDC from Entropy Bounds

Take Einstein-Maxwell-Dilaton theory:

$$S = \int d^4x\sqrt{-g}\left[R + 2|d\phi|^2 + \frac{1}{2g(\phi)^2}|F|^2\right] \quad \text{s.t.} \quad g(\phi) \to 0 \quad \text{as} \quad \phi \to \infty$$

There are electrically charged BH solutions with classical zero area (small BHs)

If $g(-\infty) \to 0$ then $A(-\infty) \to 0$: Small BH

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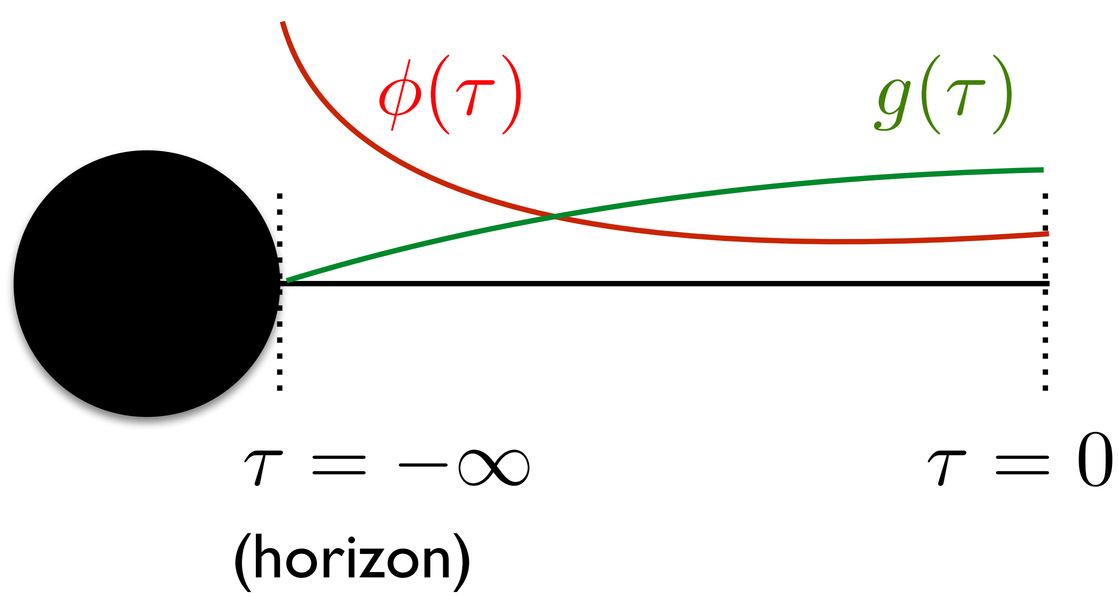
BH induces a running of the scalar field and gauge coupling as approaching the horizon leading to:



large field range!
small gauge coupling!

WGC and SDC from Entropy Bounds

Small BHs lead to a violation of the Bekenstein bound, unless the EFT cutoff decreases as dictated by the SDC / WGC

Entropy Bound:

A region of size L cannot have more entropy than a Schwarzschild black hole of the same area $A = L^2$

$$N_{\text{species}} = Q_{\max} \lesssim L^2 = A$$

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Entropy Bound: A region of size L cannot have more entropy than a Schwarzschild black hole of the same area $A = L^2$

$$N_{\text{species}} = Q_{\max} \lesssim L^2 = A$$

Using extremality condition and that EFT breaks down at $|d\phi|^2 \sim \Lambda^2$

$\Rightarrow$ $\Lambda \lesssim g$ in Planck units

due to an infinite tower of states