Sliding Towers, Dualities and the Species Scale

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In collaboration with Etheredge, Heidenreich, McNamara, Rudelius and Ruiz 2306.16440

Castellano and Ruiz 23xx.xxxx

String Phenomenology 2023, Daejeon, South Korea

We are entering an era of precision in the Swampland Program

- **No global symmetries** Heckman, Bhardwaj, Wang, Leedom

  Concrete predictions for new non-susy branes Dierigl

  Classification of the highly (non)SUSY landscape / string universality

  Graña, Parra de Freitas, Fraiman, Koga, Loges, Delgado, Rajaguru

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- **Distance Conjecture** Herráez, Castellano, Cribiori, Melotti, Minino, Petri, Calderón-Infante, Terada, Collazuol, Ruiz, Alvarez-Garcia

Sharper definition and beginning of global classification of limits/dualities

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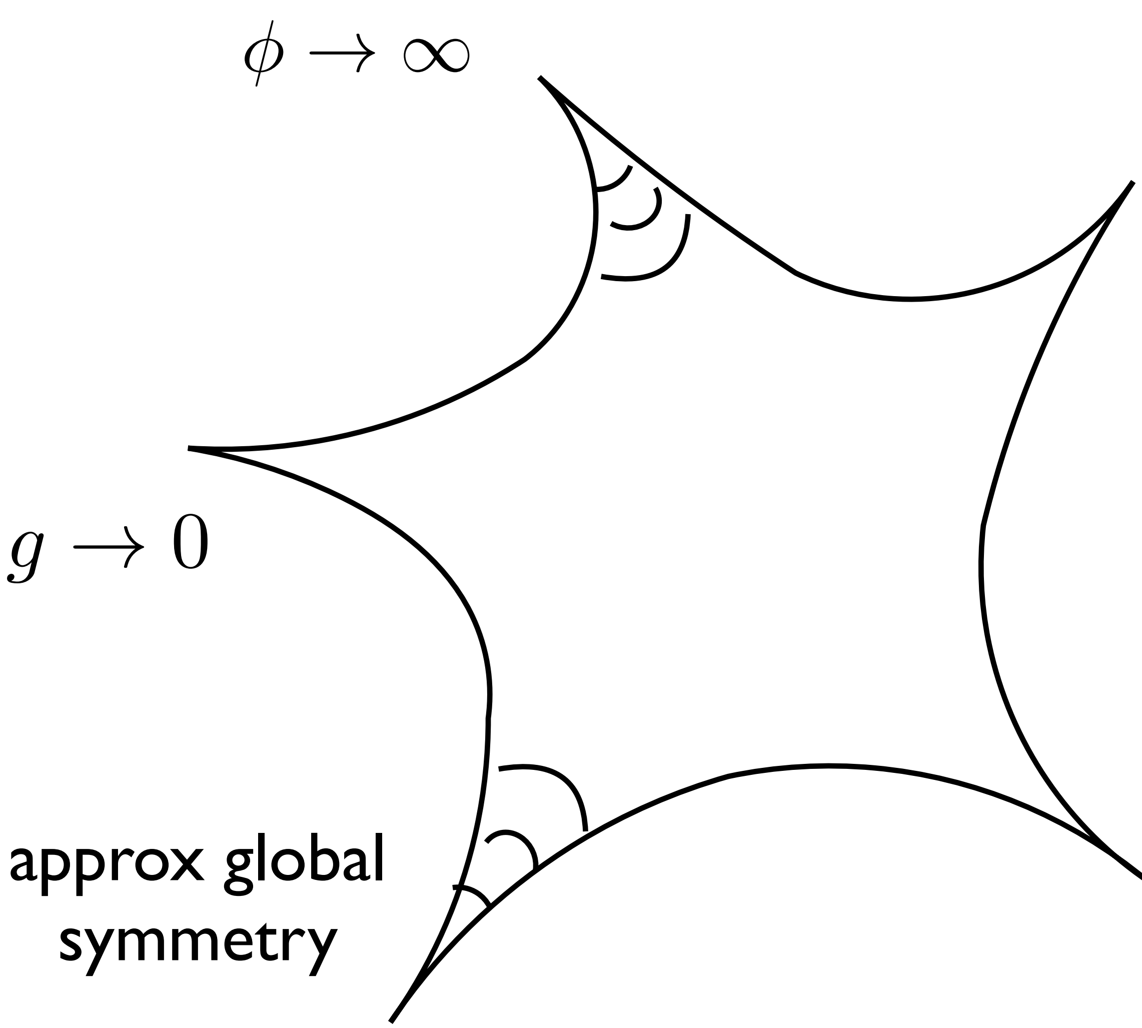
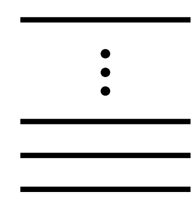


The cut-off goes to zero asymptotically:



infinite tower of states

$$\Lambda = \frac{M_p}{N^{1/(d-2)}} \to 0$$

(species scale cut-off)

[Ooguri-Vafa'06]

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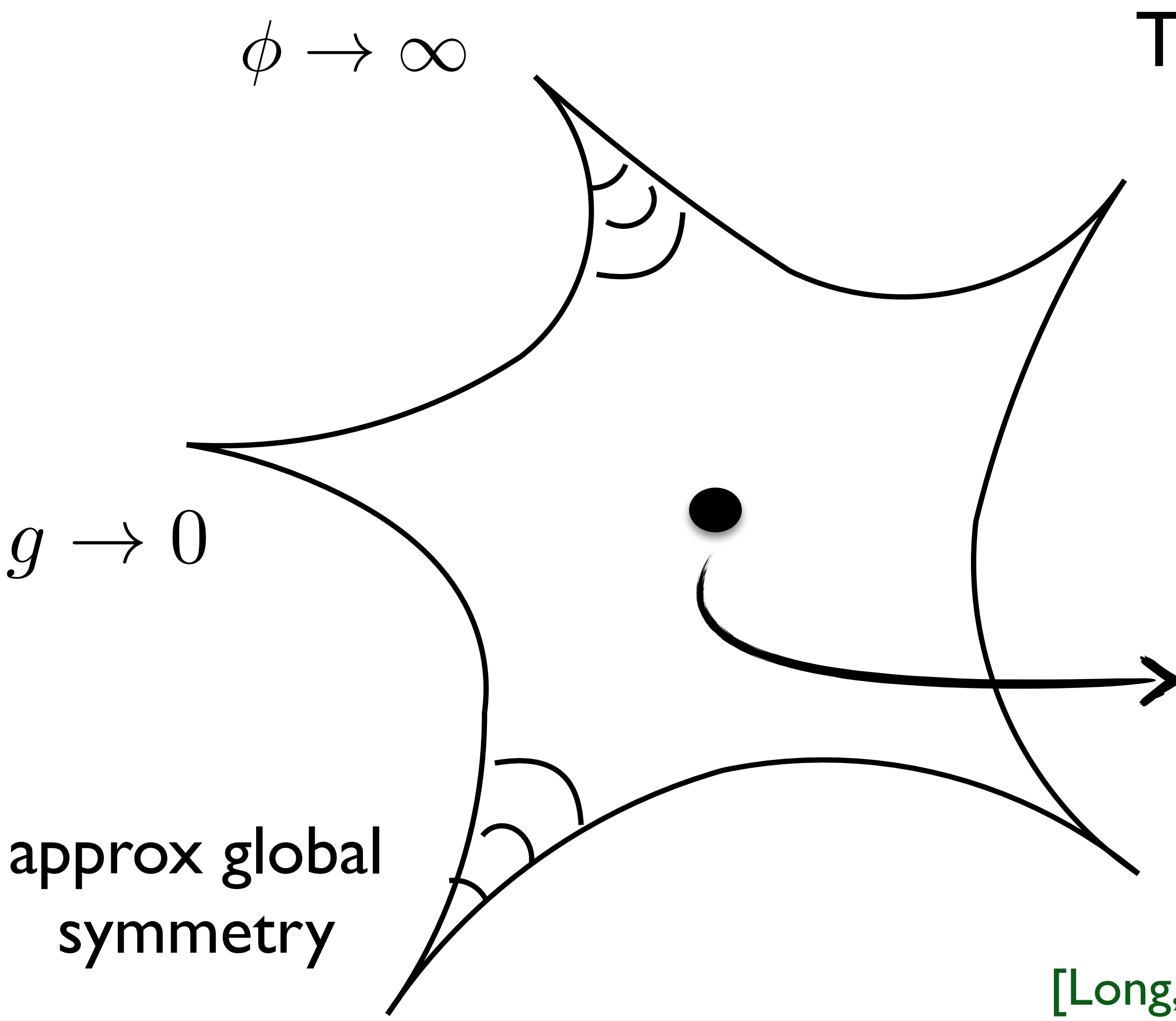

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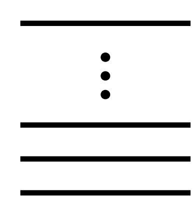

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Desert point: maximum Λ

$$\Lambda_{\max} \sim \mathcal{O}(1/N^a) M_p$$

Max's talk

[Long,Montero,Vafa,IV'21][van de Heisteeg,Vafa,Wiesner,Wu'22-23]

Distance Conjecture [Ooguri-Vafa'06]

Infinite tower of states $m \sim e^{-\alpha\Delta\phi}$ as $\Delta\phi \to \infty$ (geodesic distance)

Plethora of works testing and characterizing the towers in string compactifications: [Grimm,Palti,IV'18] [Lee,Lerche,Weigand'19] …

Álvarez-García, Andriot, Antoniadis, Basile, Baume, Bedroya, Angius, Benakli, Blasio, Blumenhagen, Brandenberger, Huertas, Buratti, Calderón-Infante, Castellano, Collazuol, Collins, Cota, Cremonini, Cribiori, Dalianis, Delgado, Dierigl, Etheredge, Farakos, Fierro Freitas, Gnecci, Gonzalo, Graña, Grimm, Hamada, Heidenreich, Herráez, Horer, Ibáñez, Jafferis, Kehagias, Lanza, Lee, Lerche, Li, Long, Lust, Marchesano, Mavromatos, McNamara, Melotti, Mininno, Montella, Montero, Morittu, Ooguri, Palti, Parra Petri, Bastian, Quirant, Rajaguru, Raman, Reece, Riet, Rudelius, Ruiz, Scalisi, Schlechter, Seo, Shiu, Stout, Tarazi, Tonioni, Tran, Tringas, Uranga, Van de Heisteeg, Vafa, Valenzuela, Weigand, Wiesner, Wrase, Wu, Xu, Yau...

→ learning a lot about asymptotic geometry in string theory

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$\Rightarrow$ learning a lot about asymptotic geometry in string theory

A lot of casuistics….

- what general lessons can we extract from it?
- what is the final sharp definition?
- can we classify all possibilities?

Distance Conjecture

What is the nature of the tower and the value of the exponential rate?

Emergent String Conjecture [Lee,Lerche,Weigand'19]

- ❖ Tower of Kaluza-Klein modes

- ❖ Tower of oscillator modes of a perturbative string

Sharpened Distance Conjecture: $\alpha \geq \frac{1}{\sqrt{d-2}}$ [Etheredge et al'22]

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  [Perlmutter,Rastelli,Vafa,IV'20]

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  [Perlmutter,Rastelli,Vafa,IV'20] see Jose Calderon-Infante's talk

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Distance Conjecture

What is the UV completion above the species scale cut-off?
What is the quantum gravity theory that we reach asymptotically?

Knowing only the leading tower is not enough

(the species scale is determined by all light towers)

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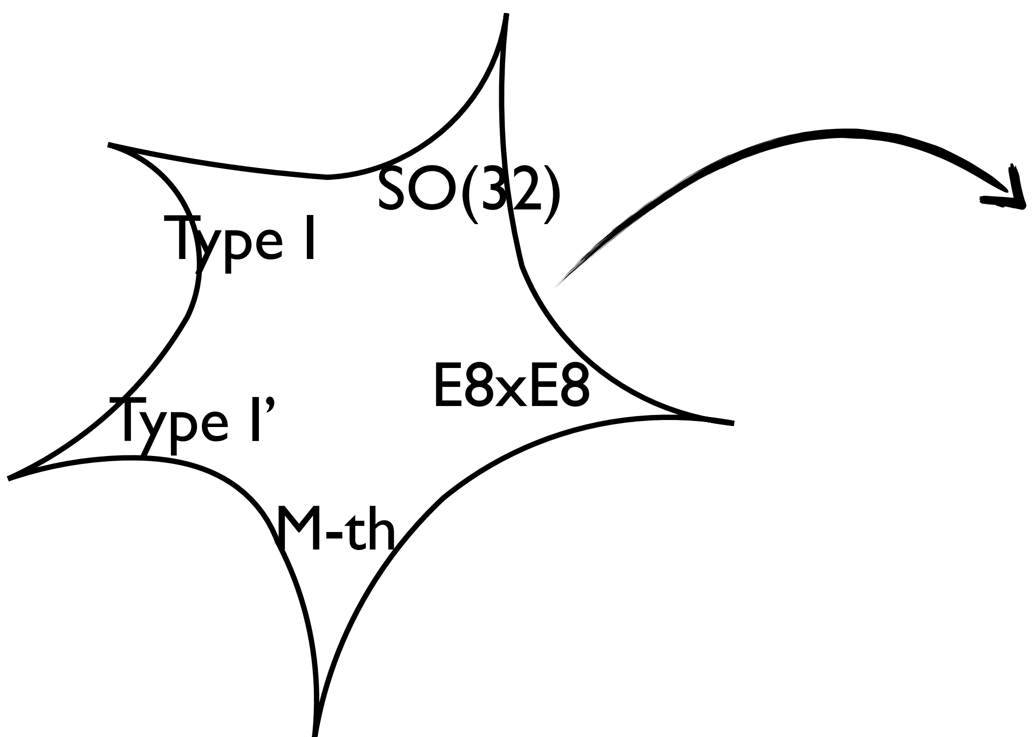
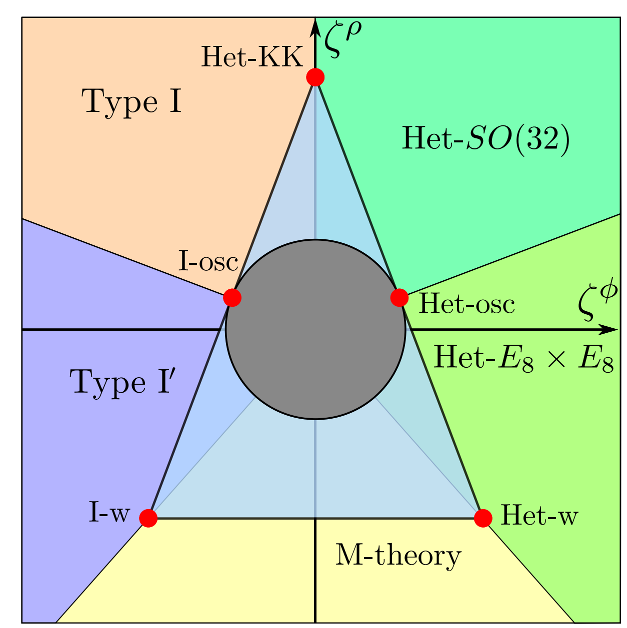
Are there rules constraining how to globally combine the different limits?
What are the possible duality perturbative frames that a theory can have?

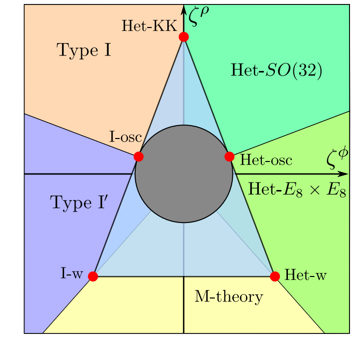
Ben’s talk





In this talk:

1) Distance Conjecture as a convex hull SWGC condition



Test in the case of decompactifications to running solutions

(explicit computation of the non-BPS KK mass)

Exponential rate change as we move in the moduli space but still $\alpha \geq \frac{1}{\sqrt{d-2}}$

[Etheredge,Heidenreich,McNamara,Rudelius,Ruiz,IV'23]

2) Universal pattern between the leading tower of states and the cut-off

$$\frac{\vec{\nabla} m}{m} \cdot \underbrace{\frac{\vec{\nabla} N}{N}}_{\text{number of species}} = -1 \quad \Rightarrow \quad \frac{\vec{\nabla} m}{m} \cdot \underbrace{\frac{\vec{\nabla} \Lambda}{\Lambda}}_{\text{species scale}} = \frac{1}{d-2}$$

It constrains structure of the tower and implies $\alpha \geq \frac{1}{\sqrt{d-2}}$

[Castellano,Ruiz'IV'ongoing]

1) Sliding Towers and Running Decompactifications

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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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: $\alpha = \vec{\zeta} \cdot \hat{\tau}$

exponential rate of the tower

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 $\dfrac{\vec{\nabla} m}{m}$ of light towers remains outside ball of radius α_0

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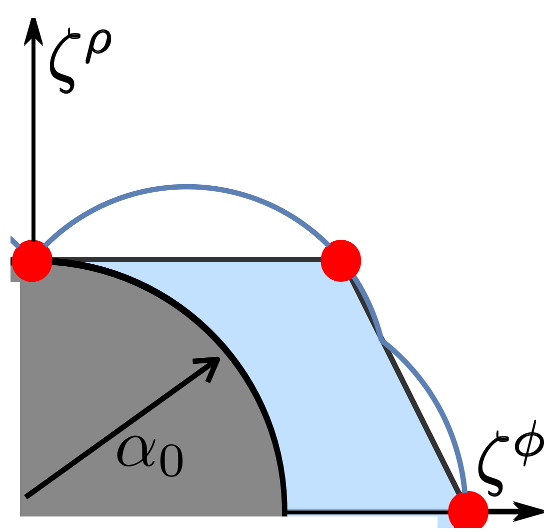

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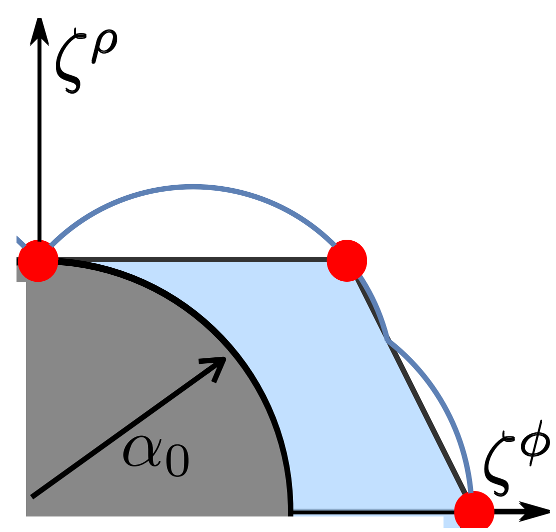

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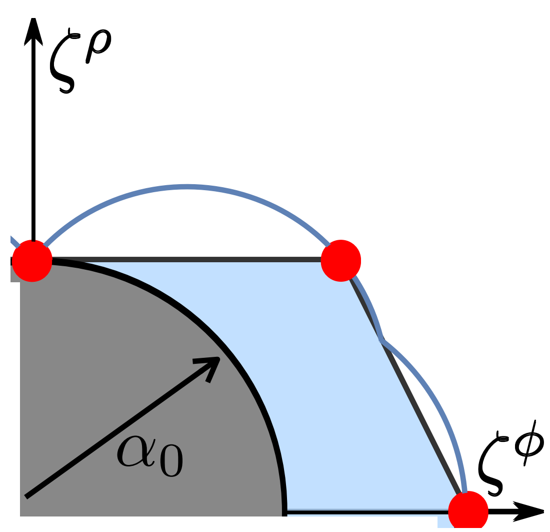

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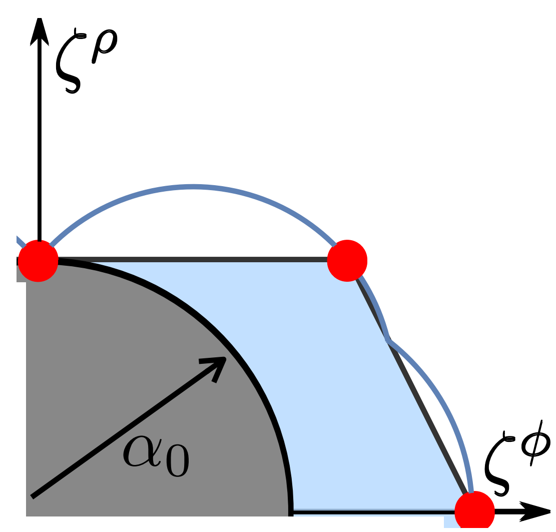

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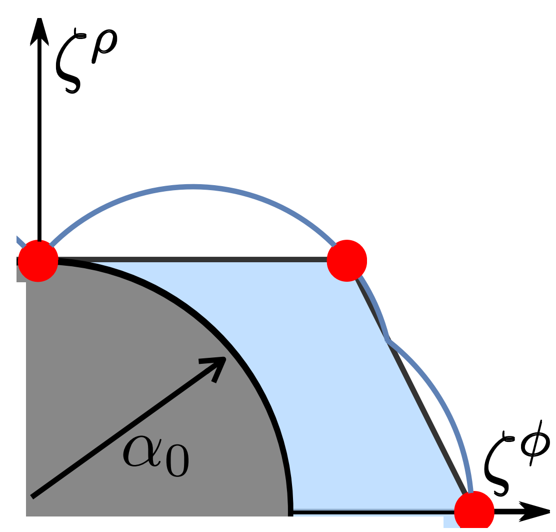

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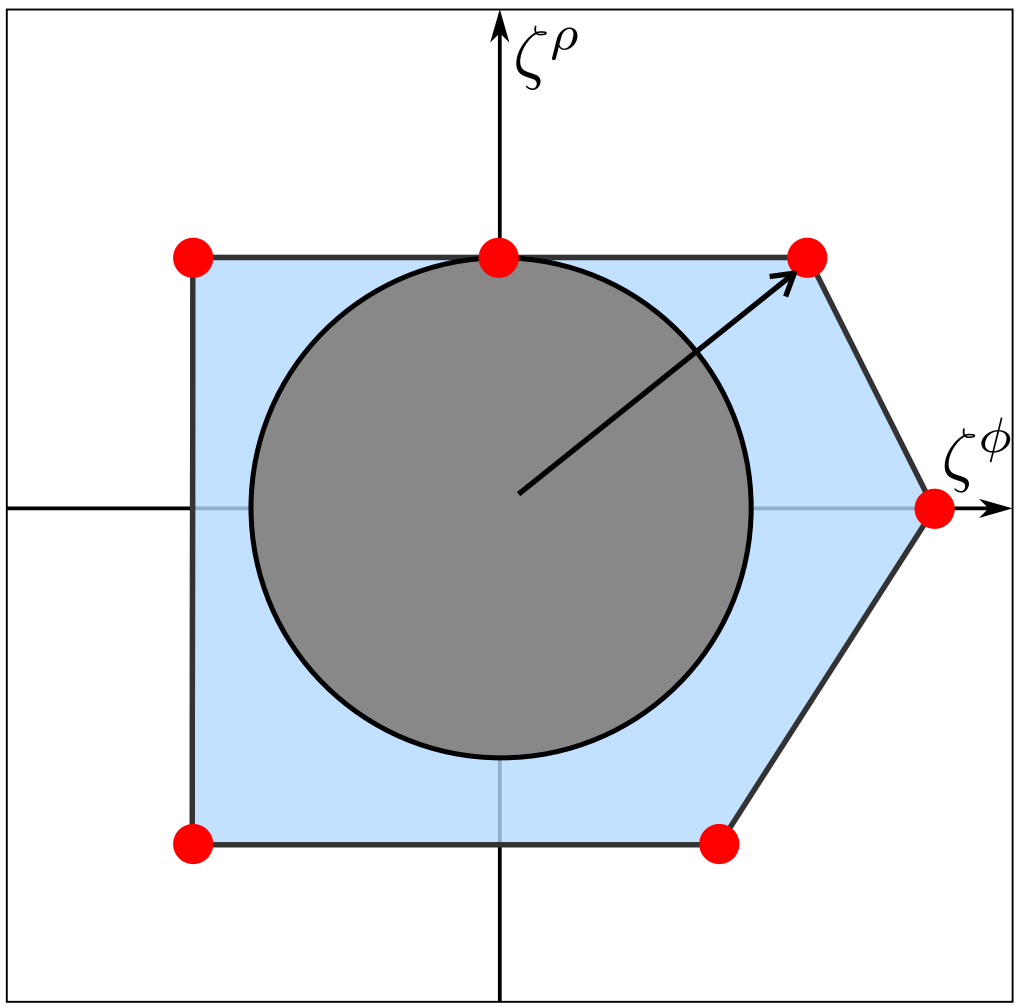
...does it?

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

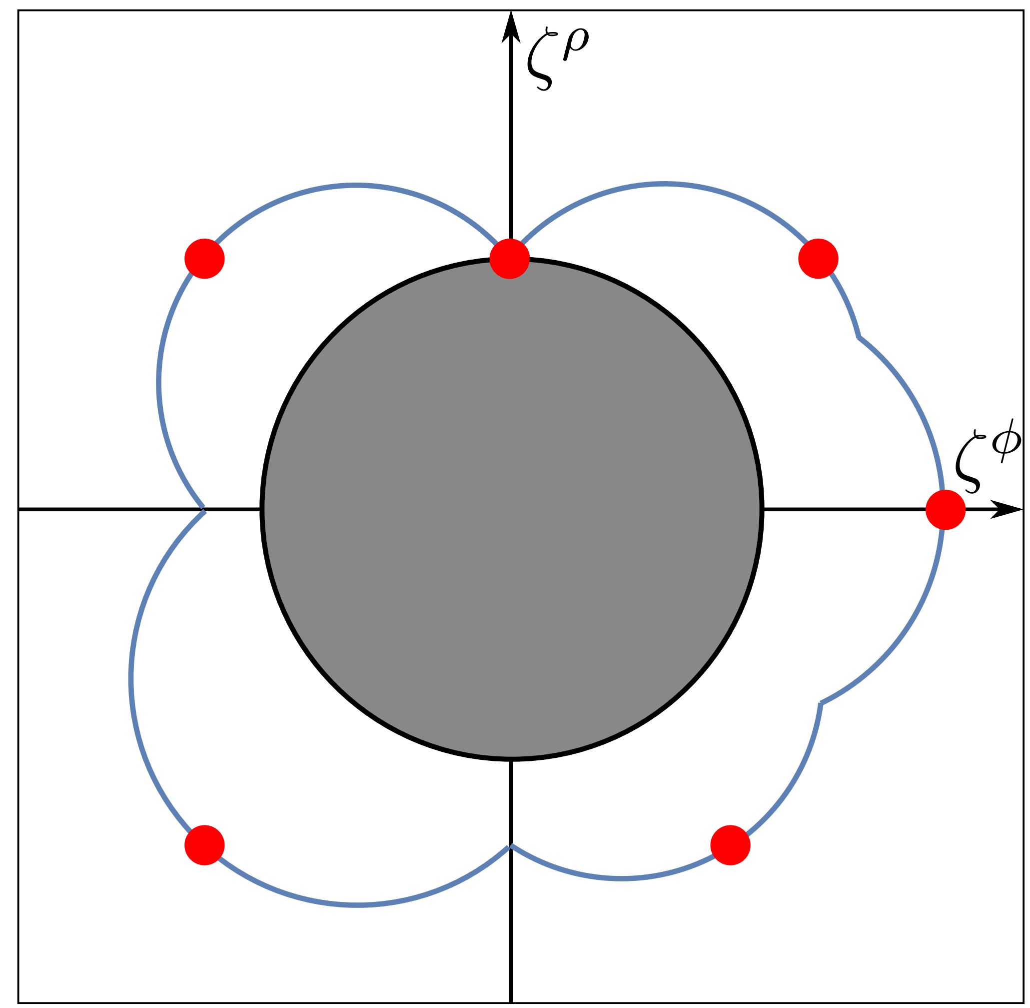
Let us check these ideas in 9 dimensional theories with 16 supercharges

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

SWGC plot



Max-alpha plot



decompactification to running solutions

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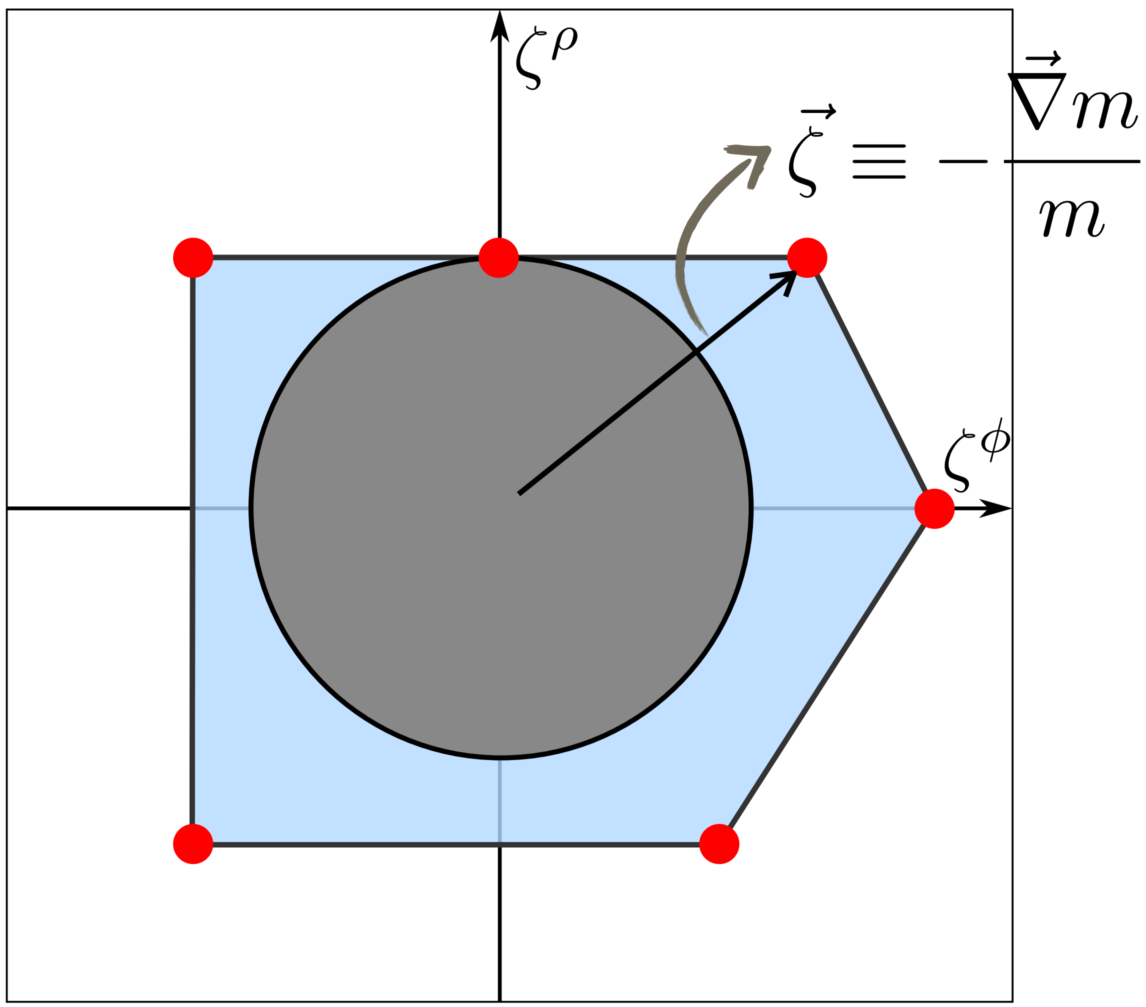

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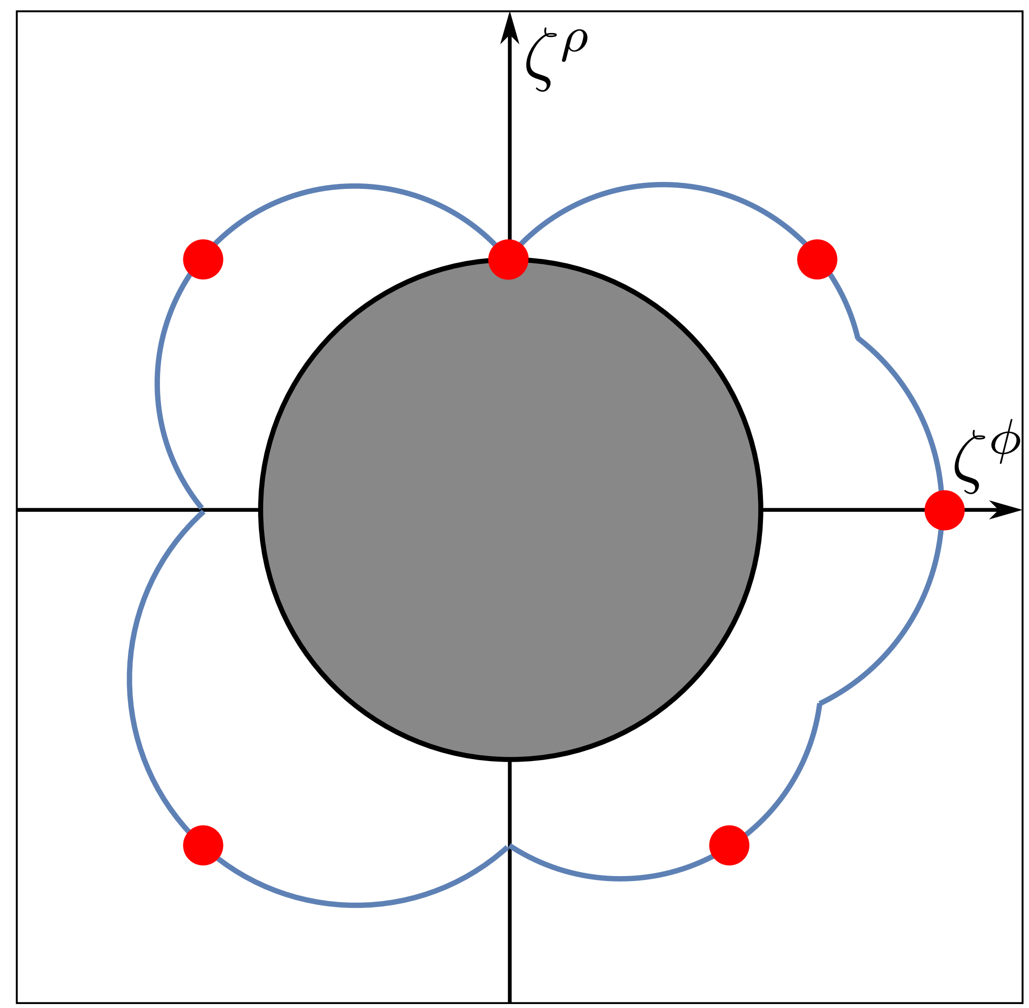

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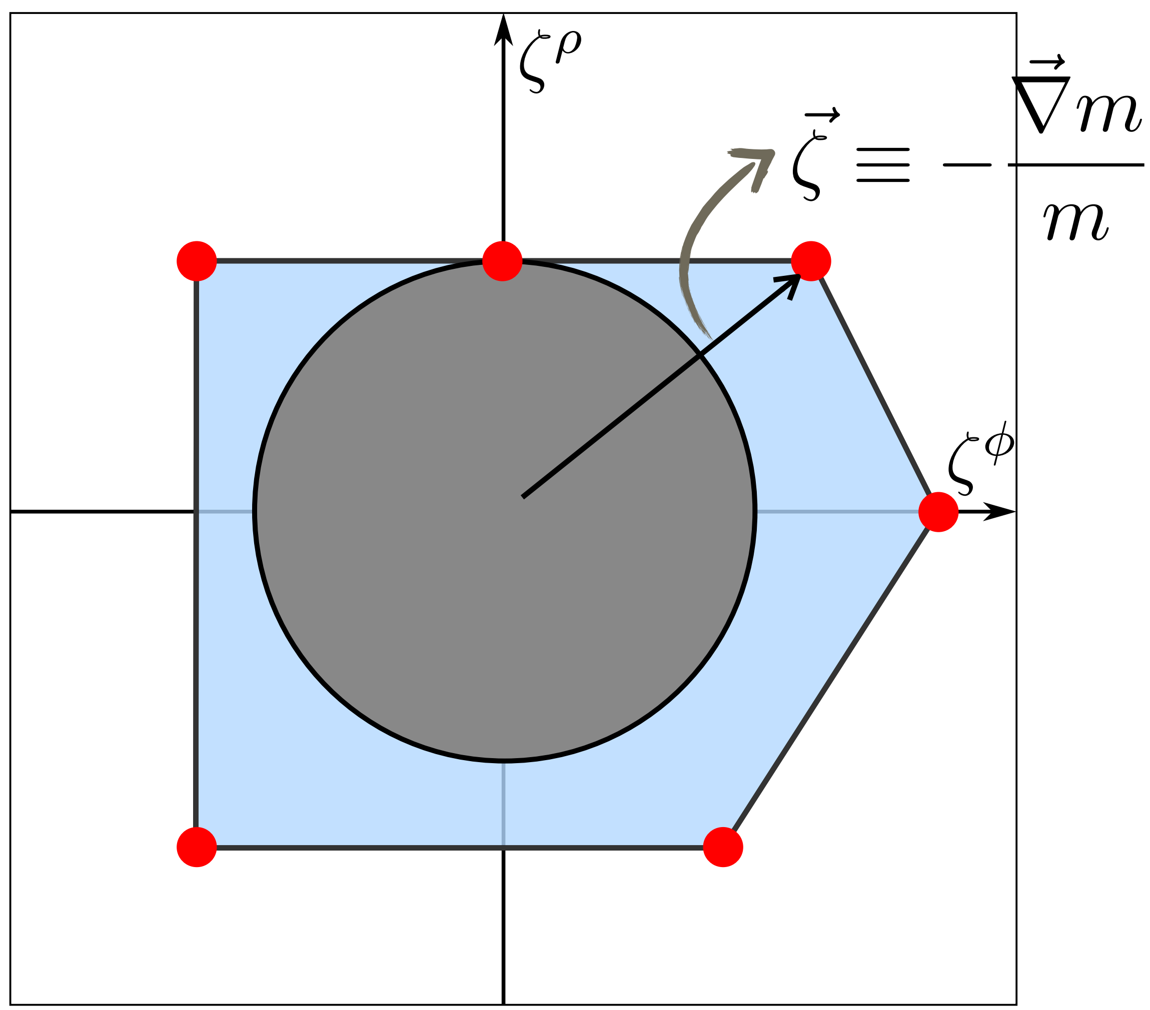

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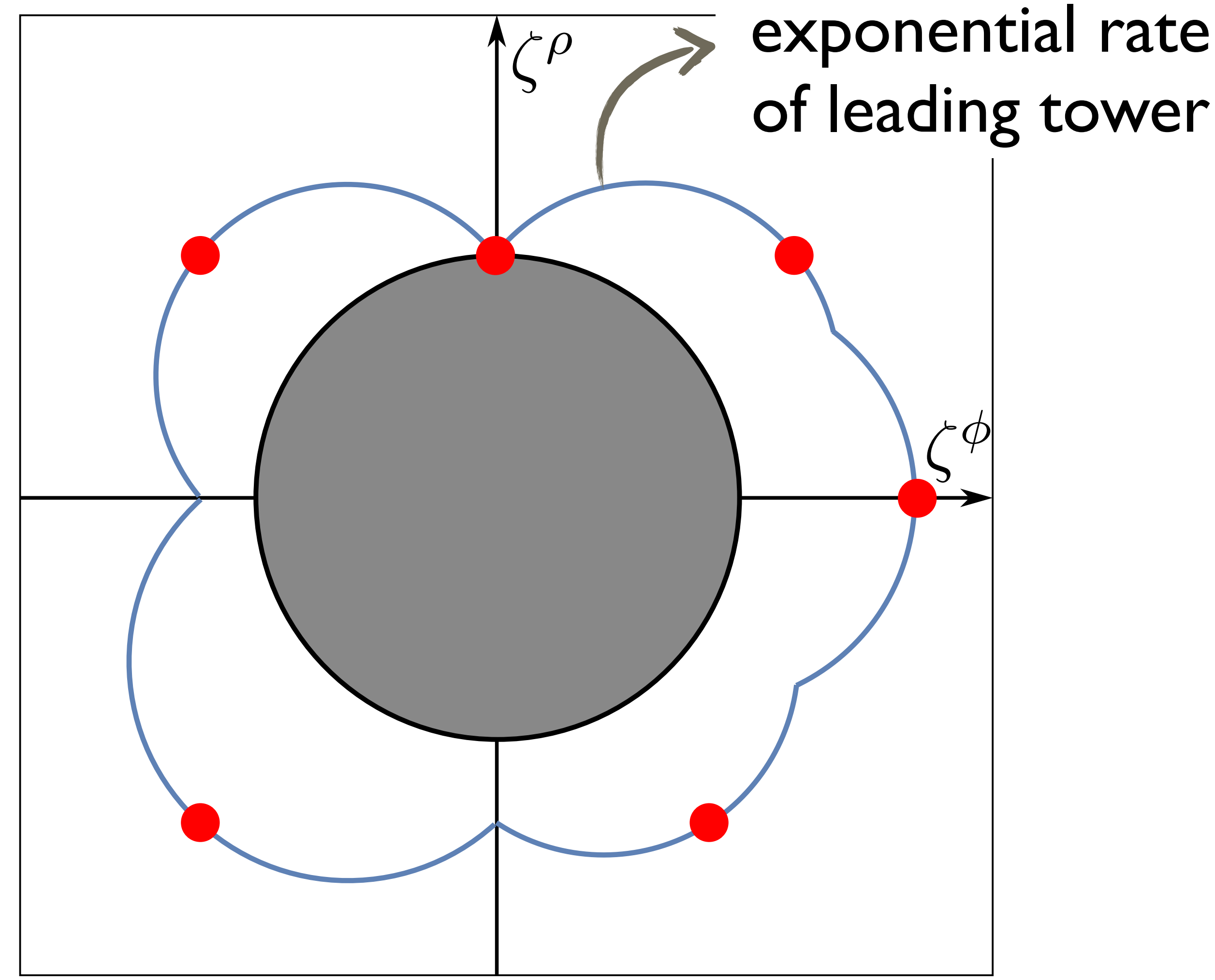

decompactification to running solutions

Heterotic on 9d

Consider a circle compactification of heterotic string theory with a fixed value of the Wilson Lines and axions set to zero

SO(16)xSO(16) SO(32) E8xE8

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string coupling

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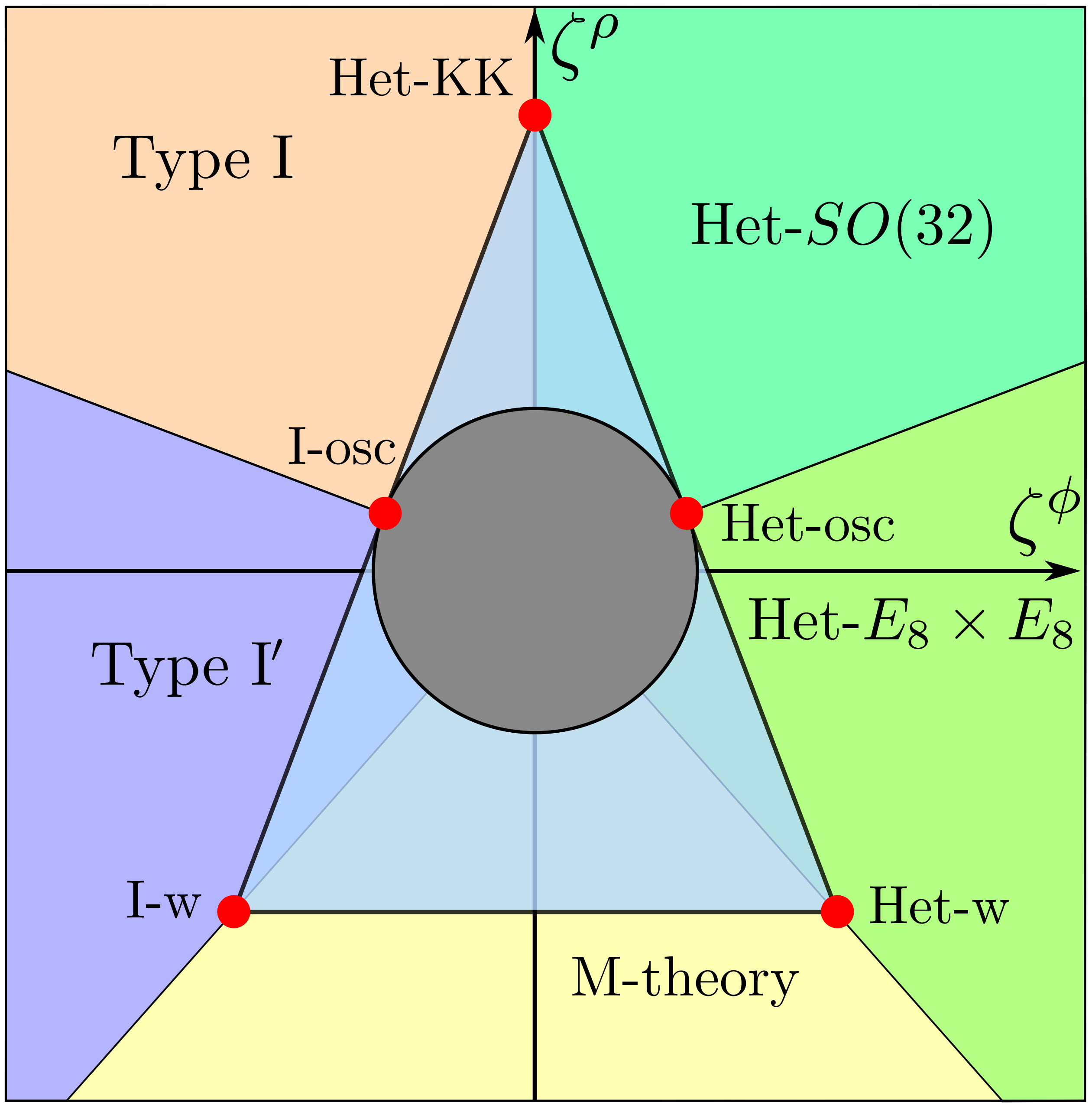
We can compute the scalar charge-to-mass ratio vectors of the the towers of states:

$$\vec{\zeta} \equiv -\frac{\vec{\nabla} m}{m} = \left(-\frac{\partial_\phi m}{m}, -\frac{\partial_\rho m}{m}\right) = (\zeta_\phi, \zeta_\rho)$$

SO(16)xSO(16) slice



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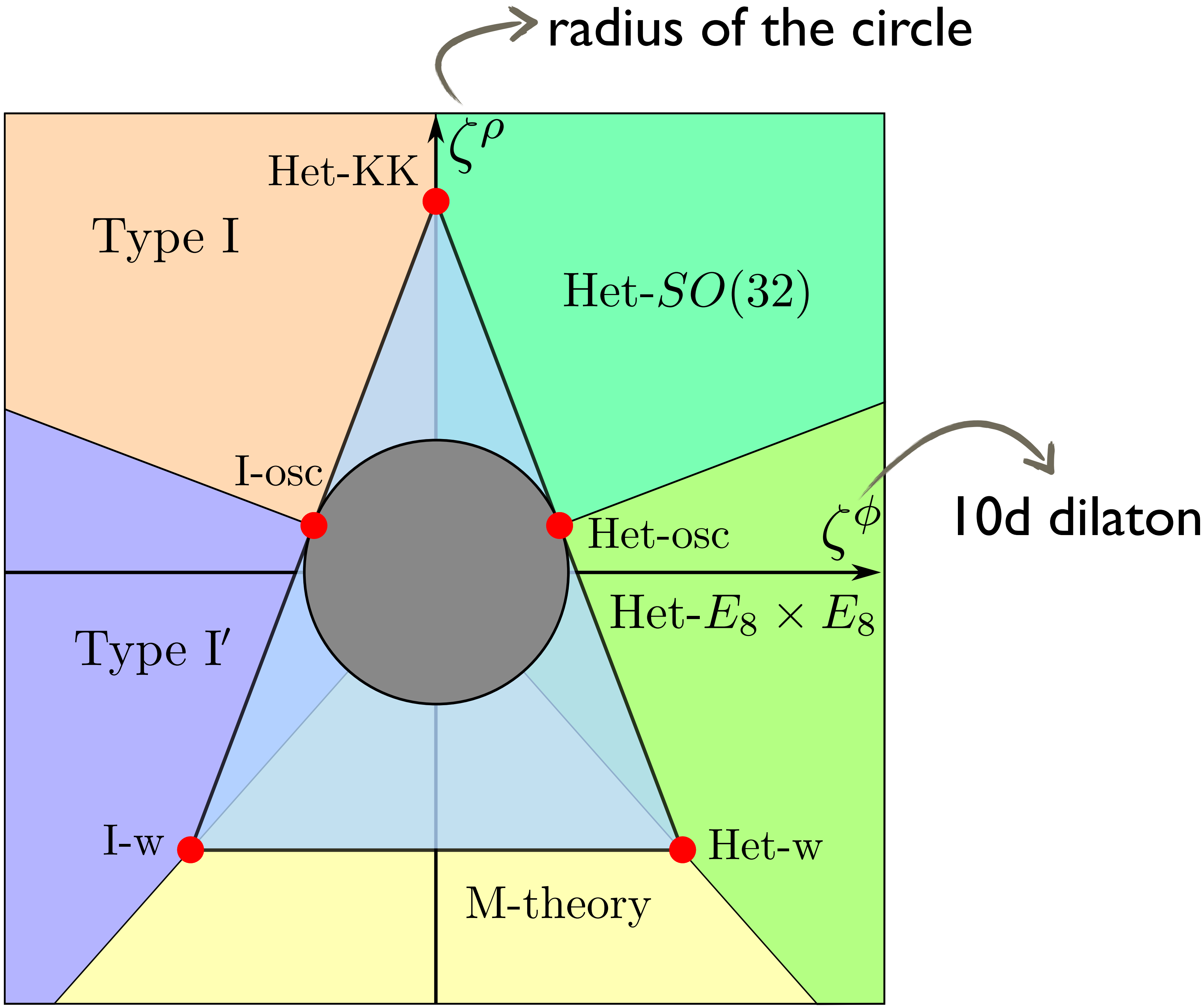

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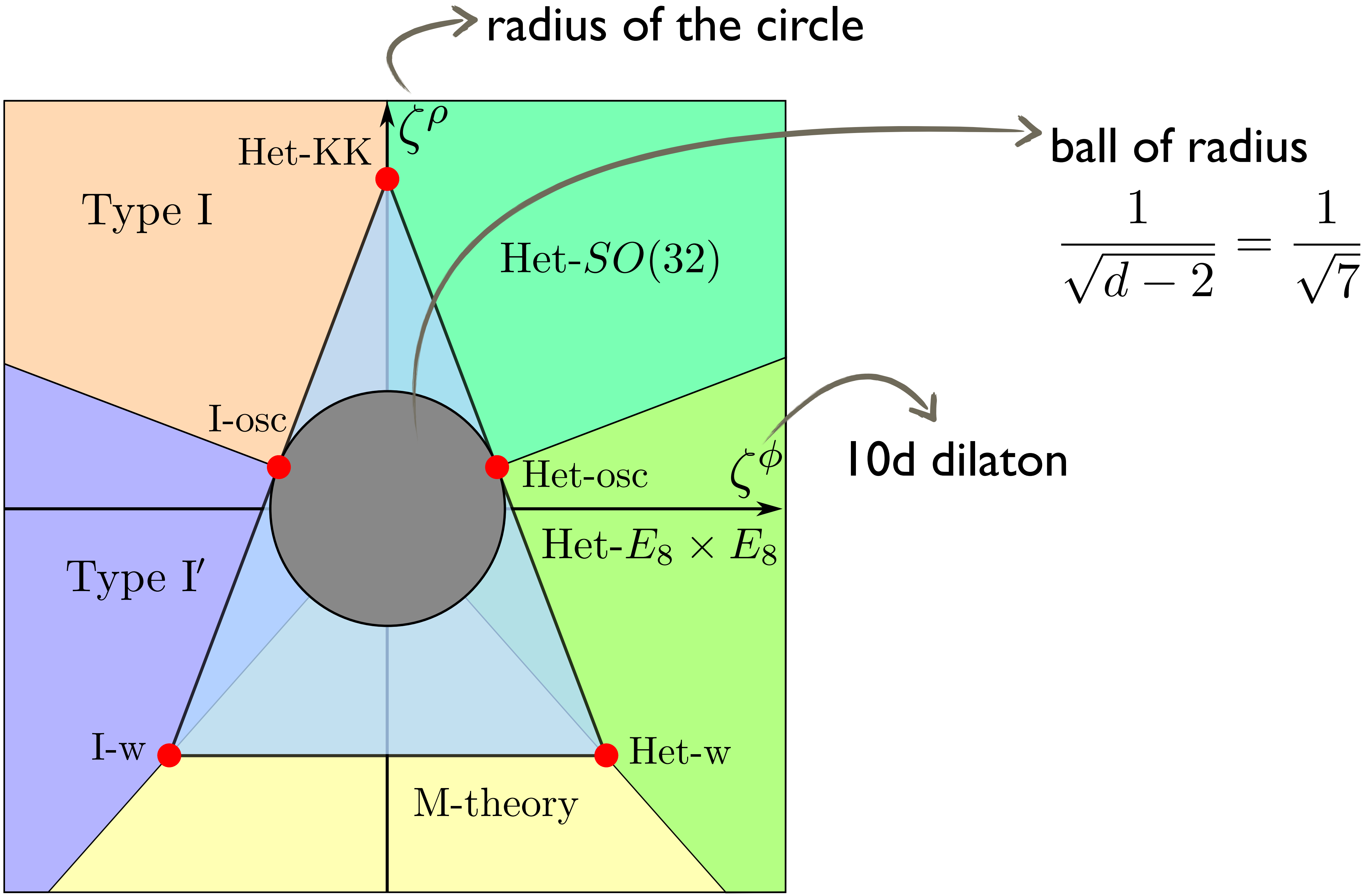

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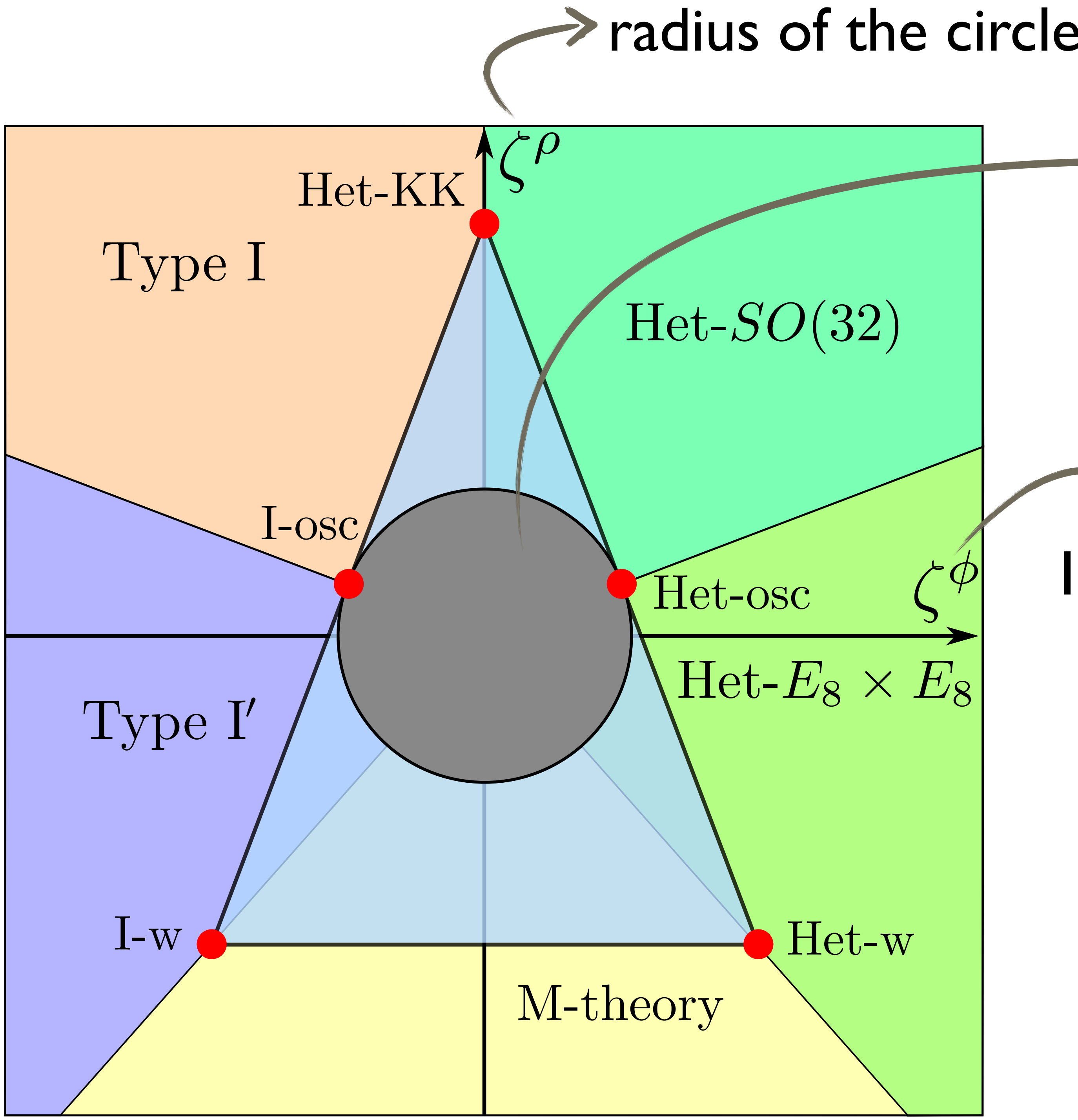

ball of radius

$$\frac{1}{\sqrt{d-2}} = \frac{1}{\sqrt{7}}$$

10d dilaton

Convex Hull SWGC satisfied

$$\left| \frac{\vec{\nabla} m}{m} \right| \geq \frac{1}{\sqrt{7}}$$

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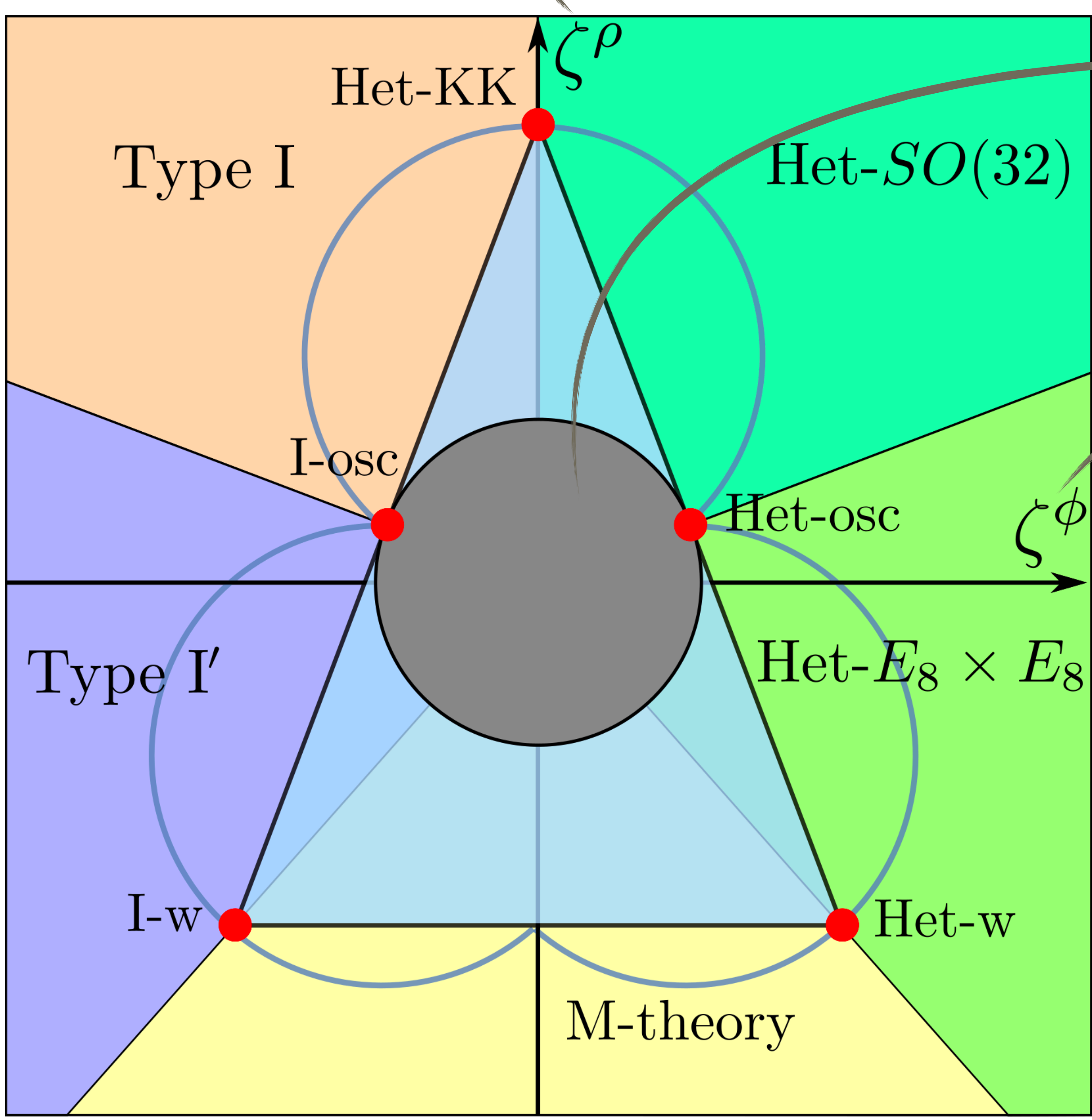

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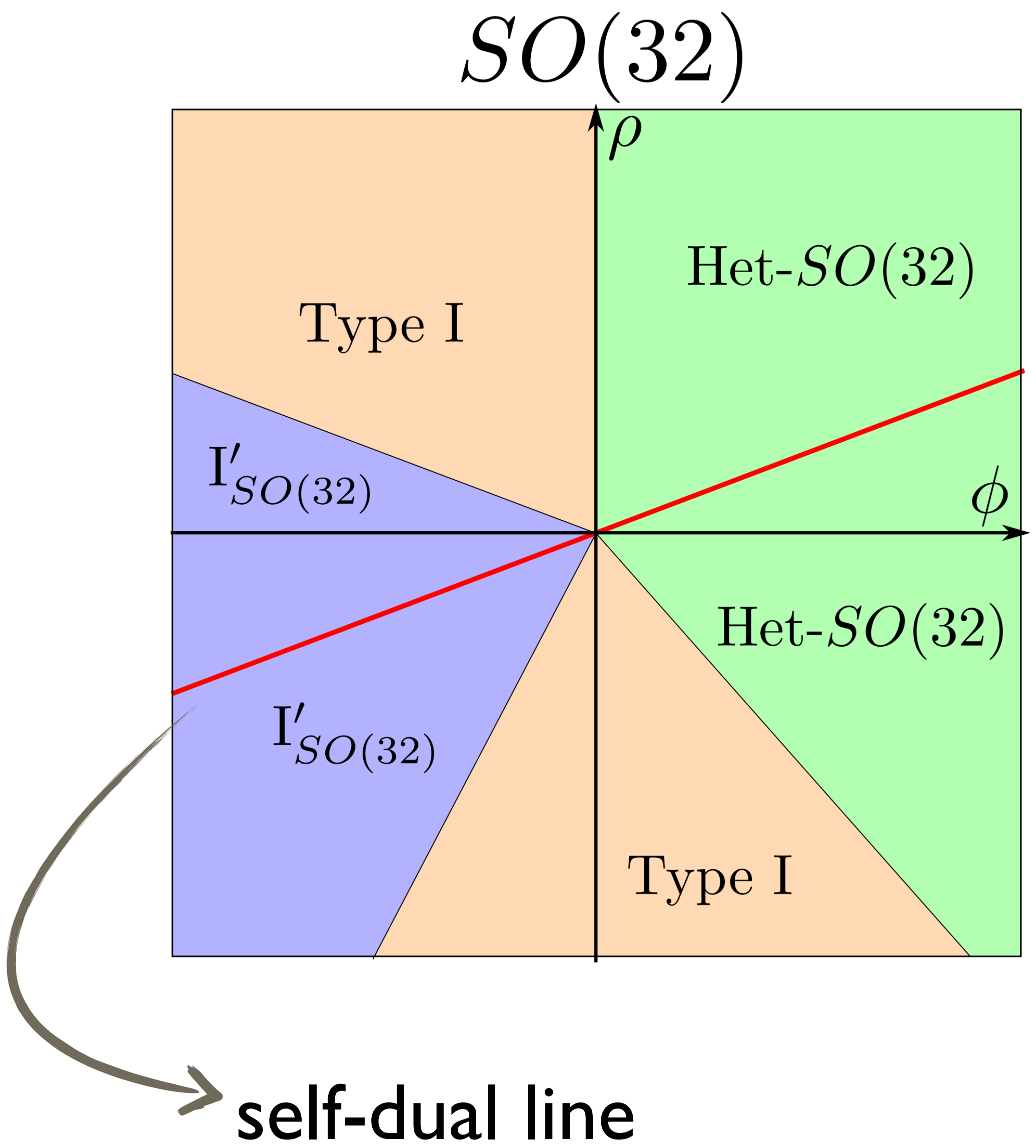
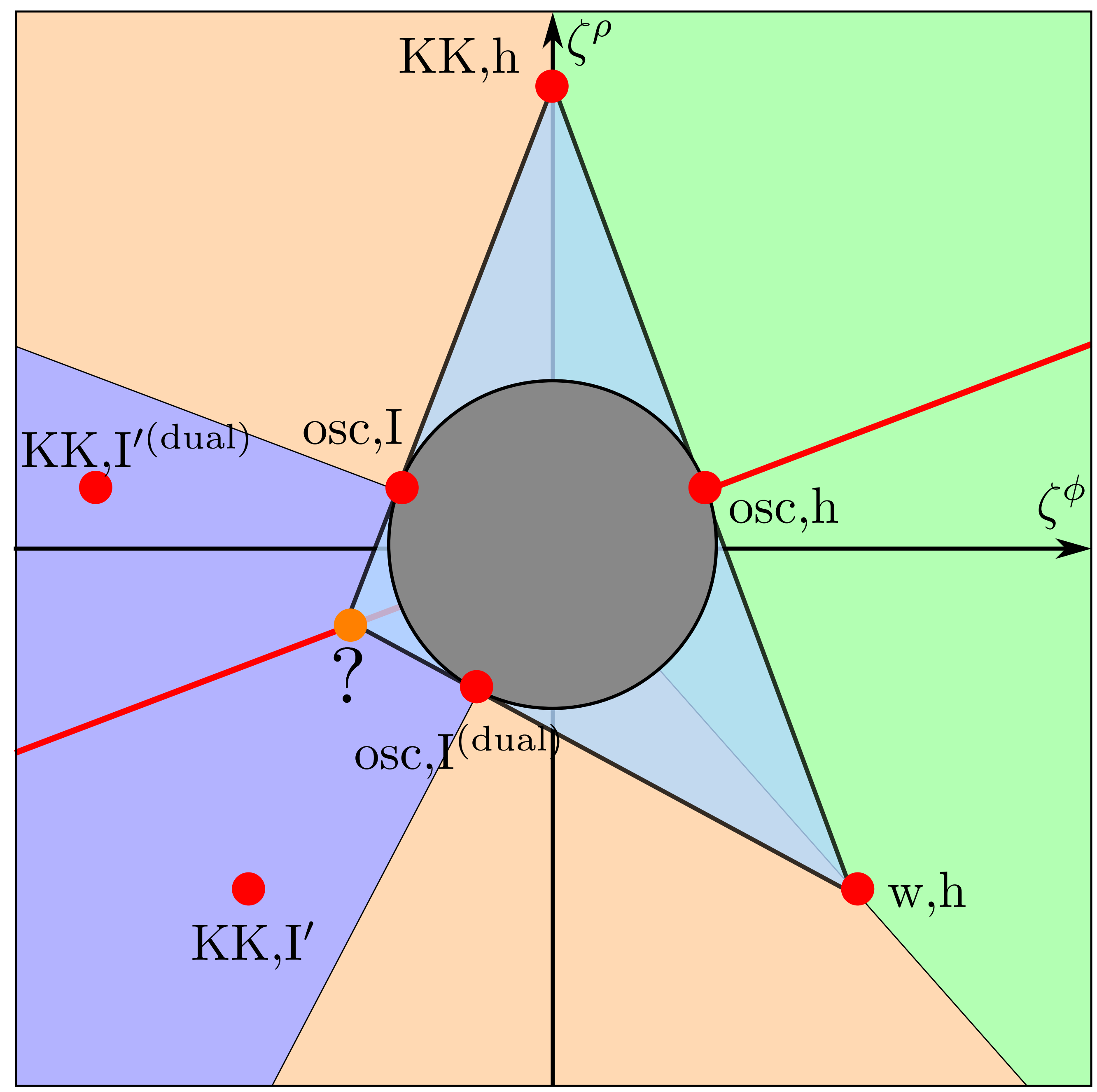
10d dilaton

Distance Conjecture satisfied

$$\alpha \geq \frac{1}{\sqrt{7}}$$

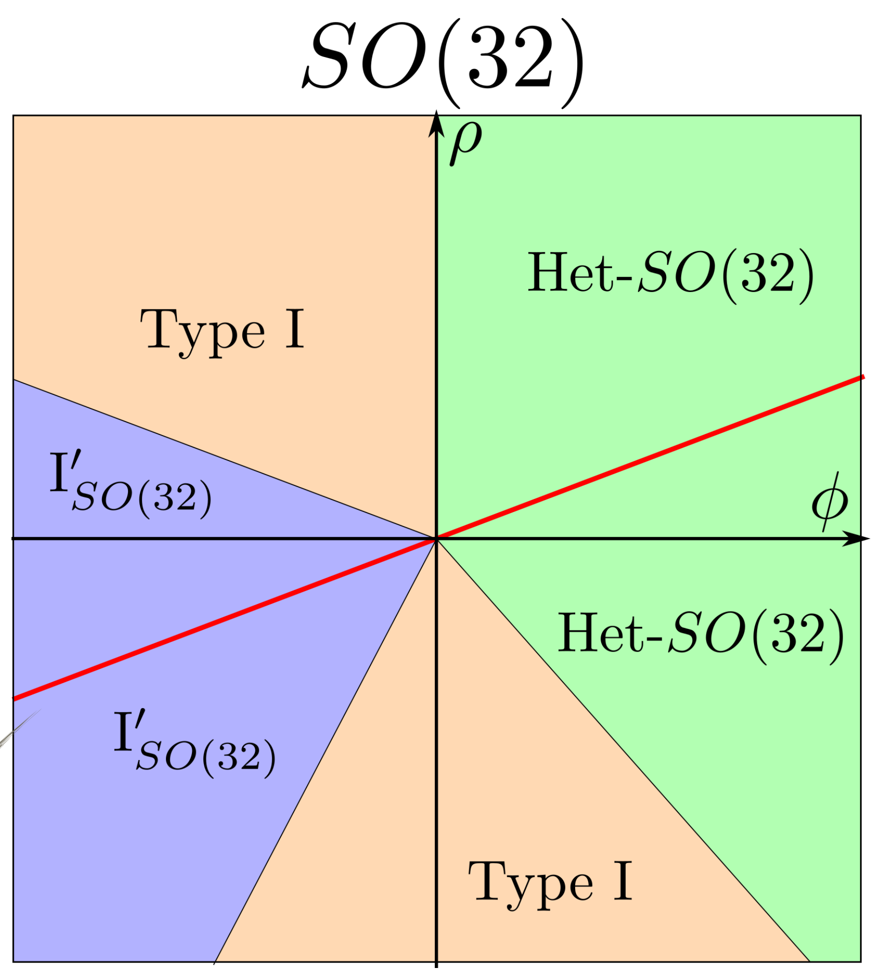
SO(32) slice



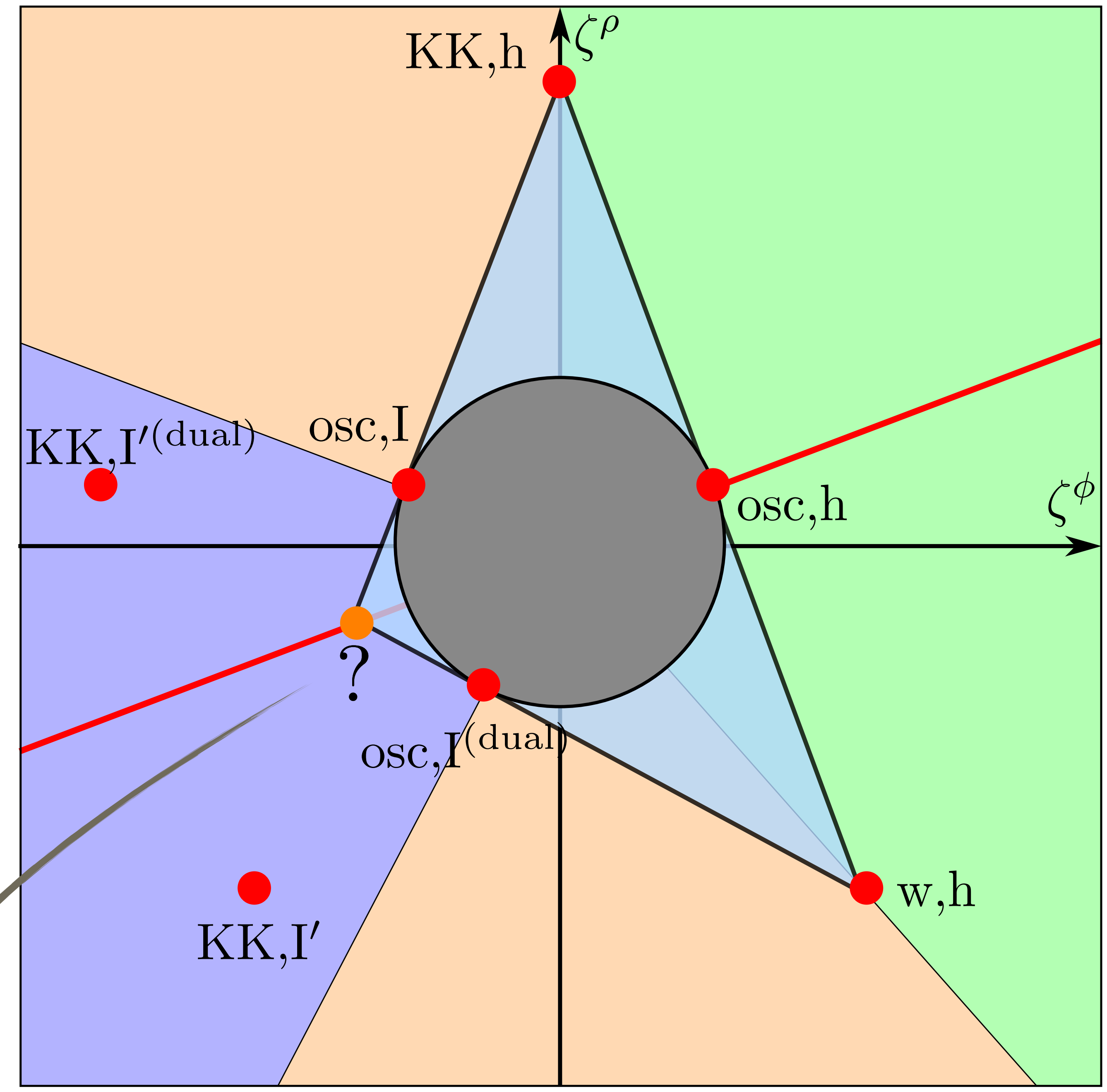


$\vec{\zeta}$

SO(32) slice



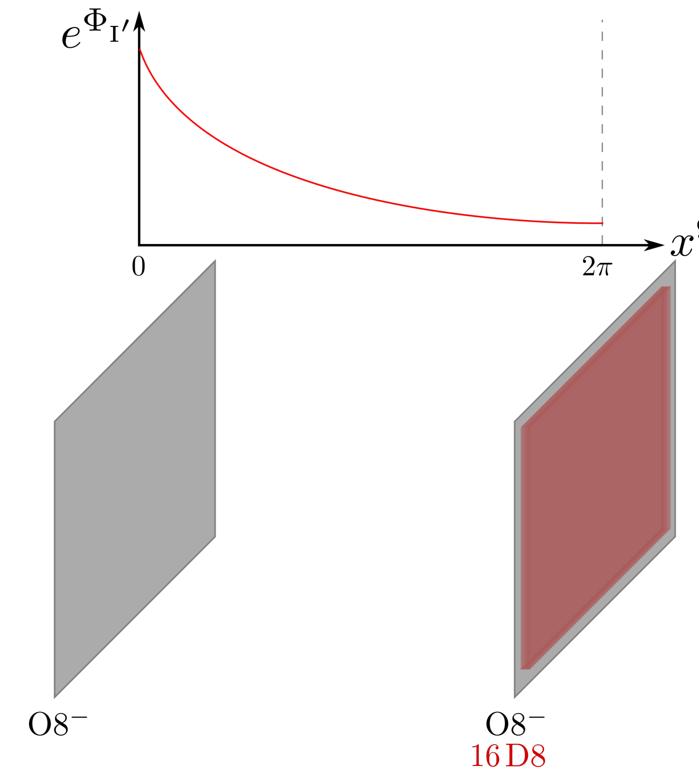
self-dual line



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

SO(32) slice

Type I' on an interval with two orientifolds and 16 D8 on top of one of them



see Ignacio Ruiz's talk

Warped metric: $\Omega(x^9) = C z(x^9)^{-1/6}$

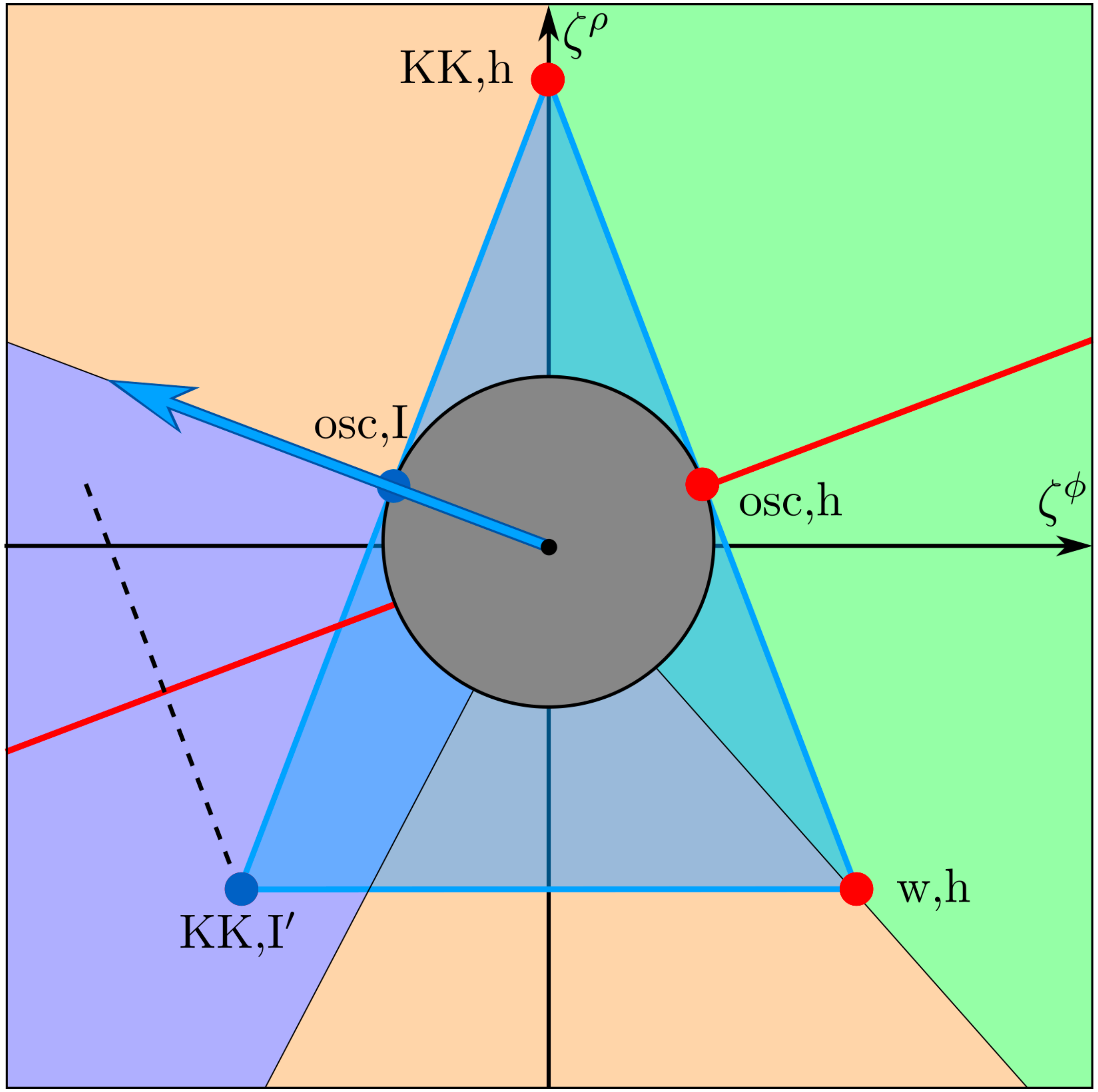
Running dilaton: $e^{\Phi_{\mathrm{I}'}(x^9)} = z(x^9)^{-5/6}$

$$z_{SO(32)}(x^9) = \sqrt{\frac{180}{41}(\alpha'_{\mathrm{I}'})^2 \mu_8 C(B+8x^9)}$$

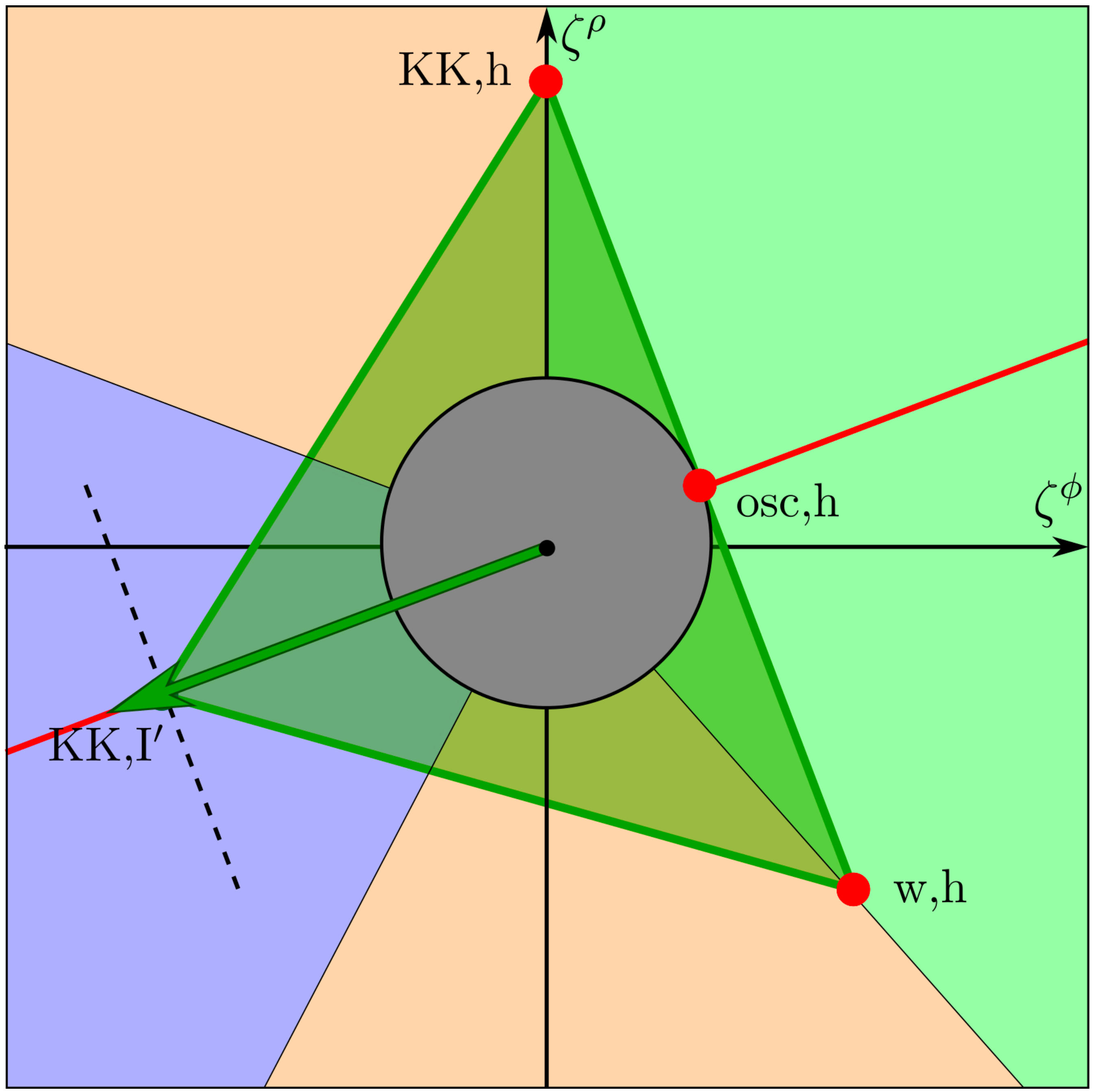
We perform the dimensional reduction and compute the Kaluza-Klein mass:

$$m_{\mathrm{KK,I}'} = \left(\int_0^{2\pi} dx^9 \hat{\Omega}^8 e^{-2\hat{\Phi}_{\mathrm{I}'}}\right)^{-1/7} M_{\mathrm{Pl};9}$$

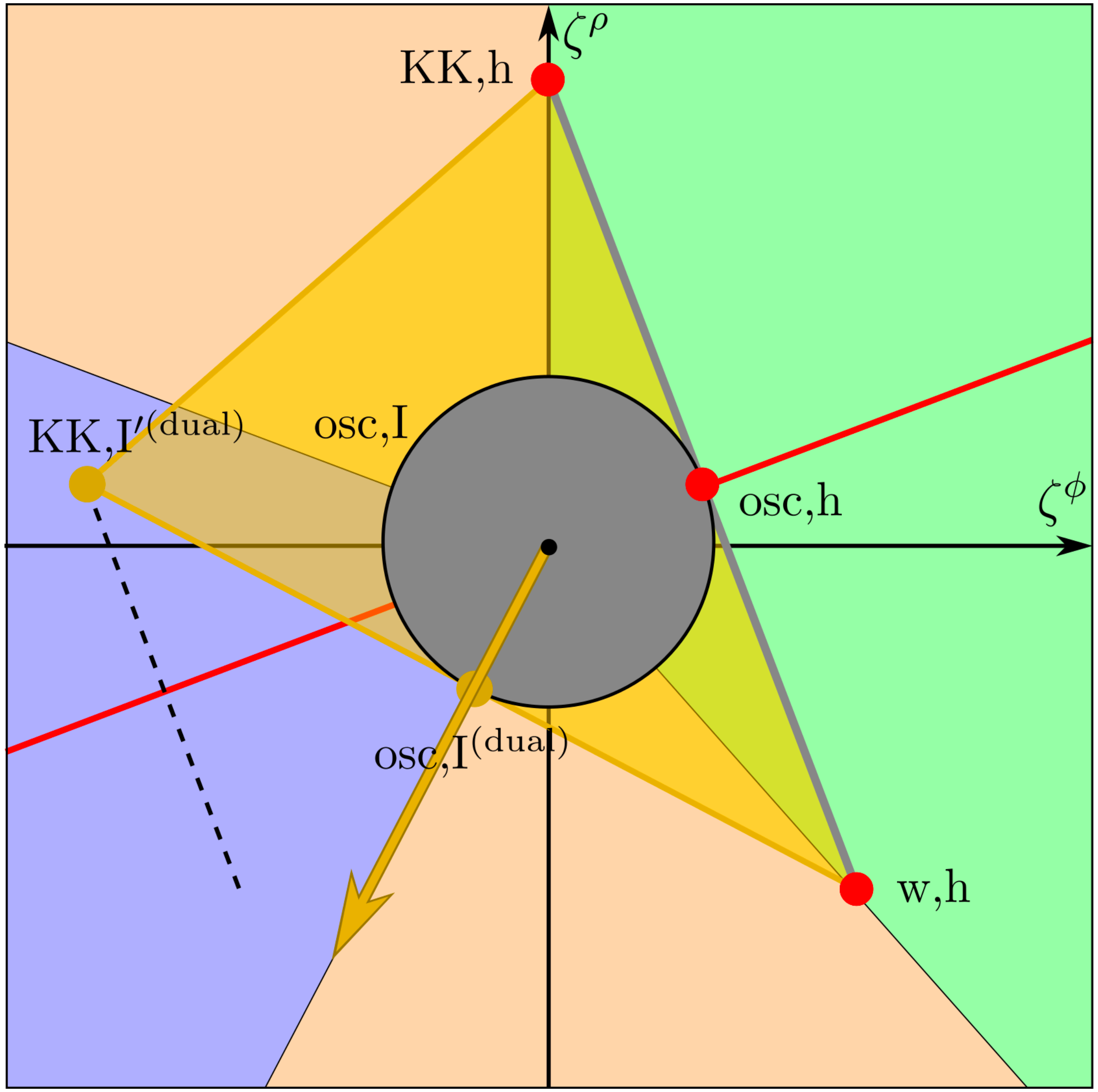
$$\vec{\zeta}_{\mathrm{KK,I}'} = \left(-\frac{3}{2}\left[\frac{2}{\sqrt{1-e^{-4\phi_B}}}+1\right]^{-1}, \frac{5}{2\sqrt{7}}\right) \neq \text{const.}$$



ζ^{ρ}
KK,h
osc,I
osc,h
ζ^{ϕ}
w,h
KK,I′

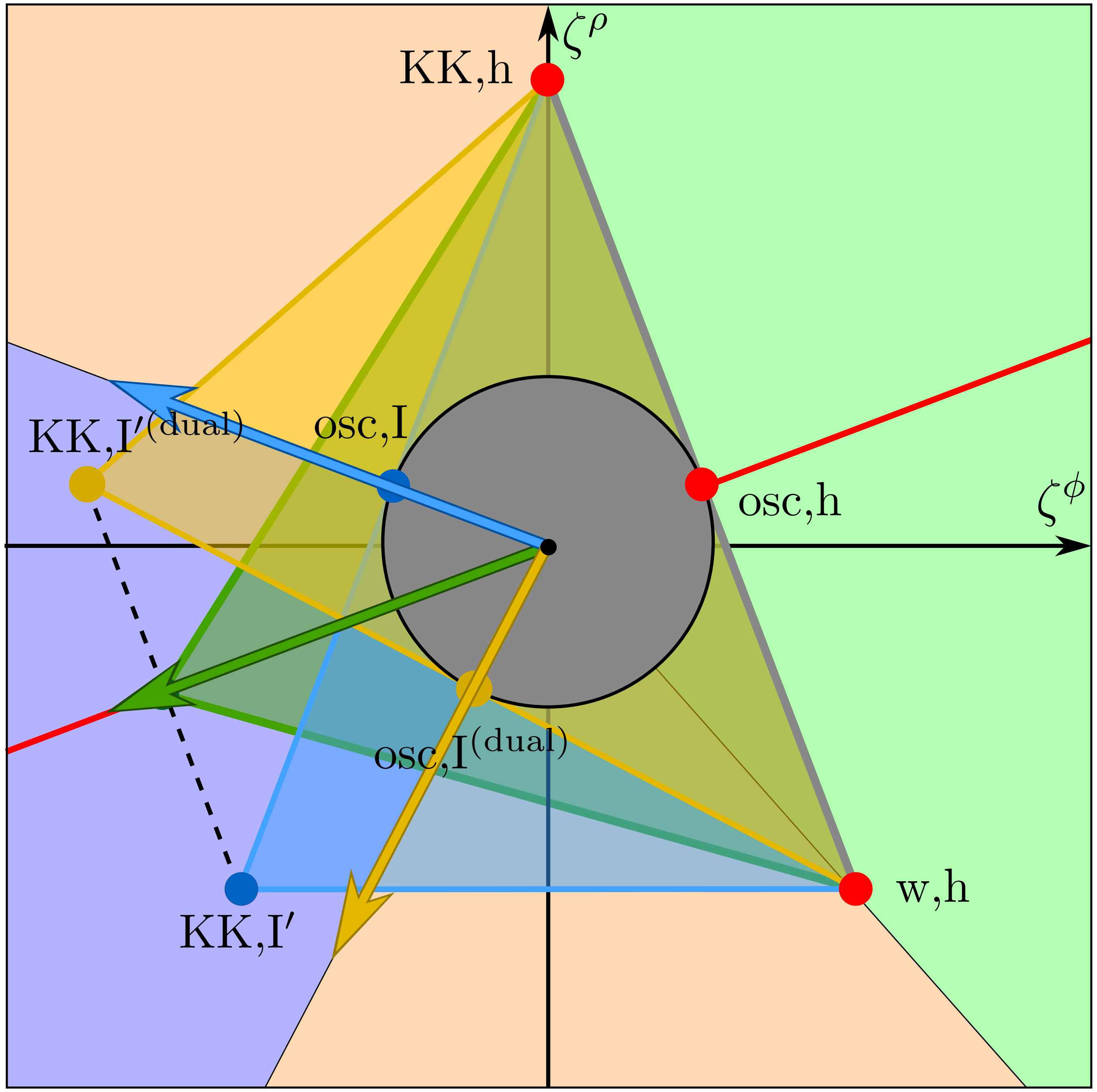


ζ^ρ
KK,h
osc,h
ζ^ϕ
KK,I$'$
w,h



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

SO(32) slice



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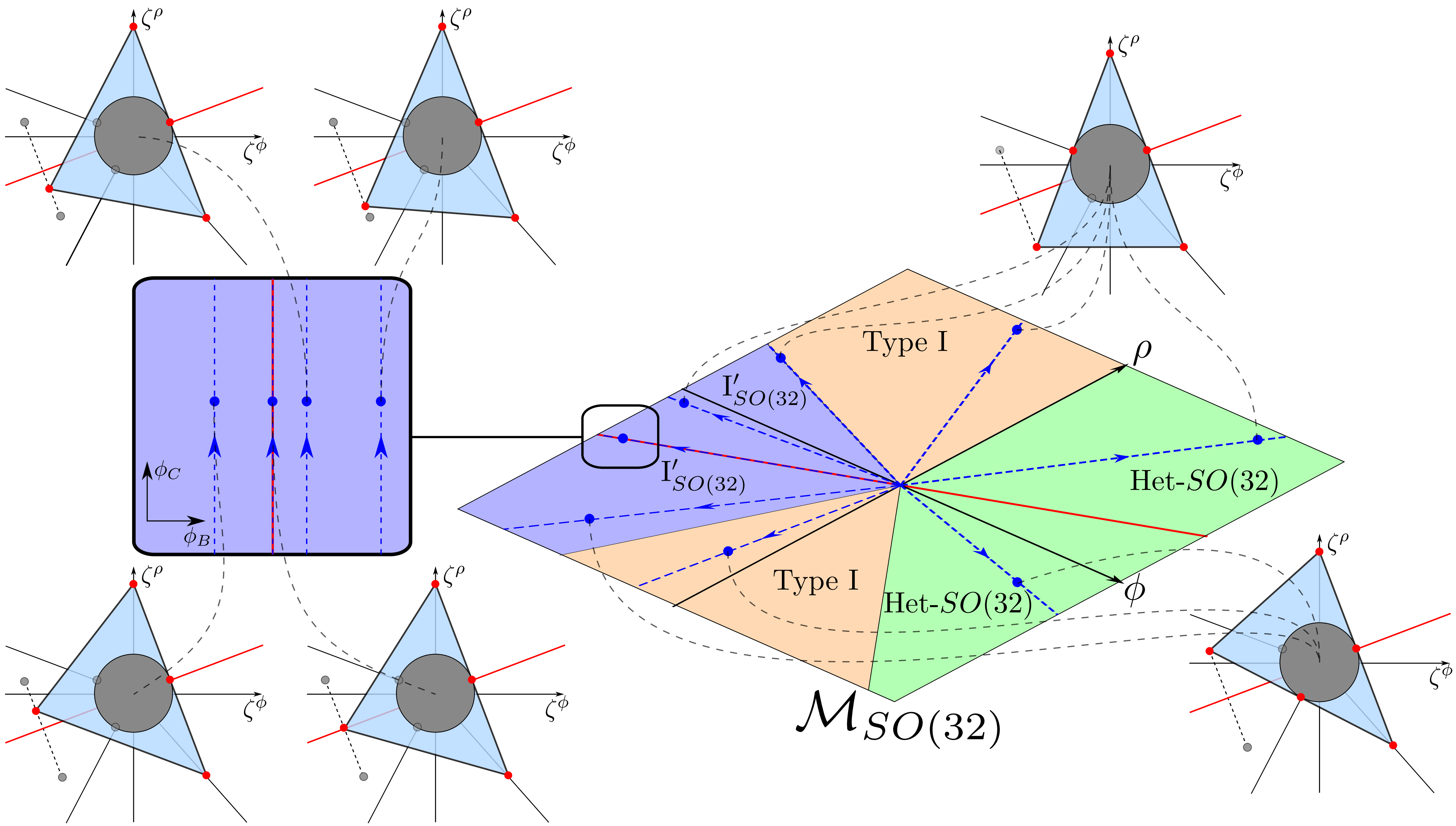
w,h
$\text{KK,I}'$

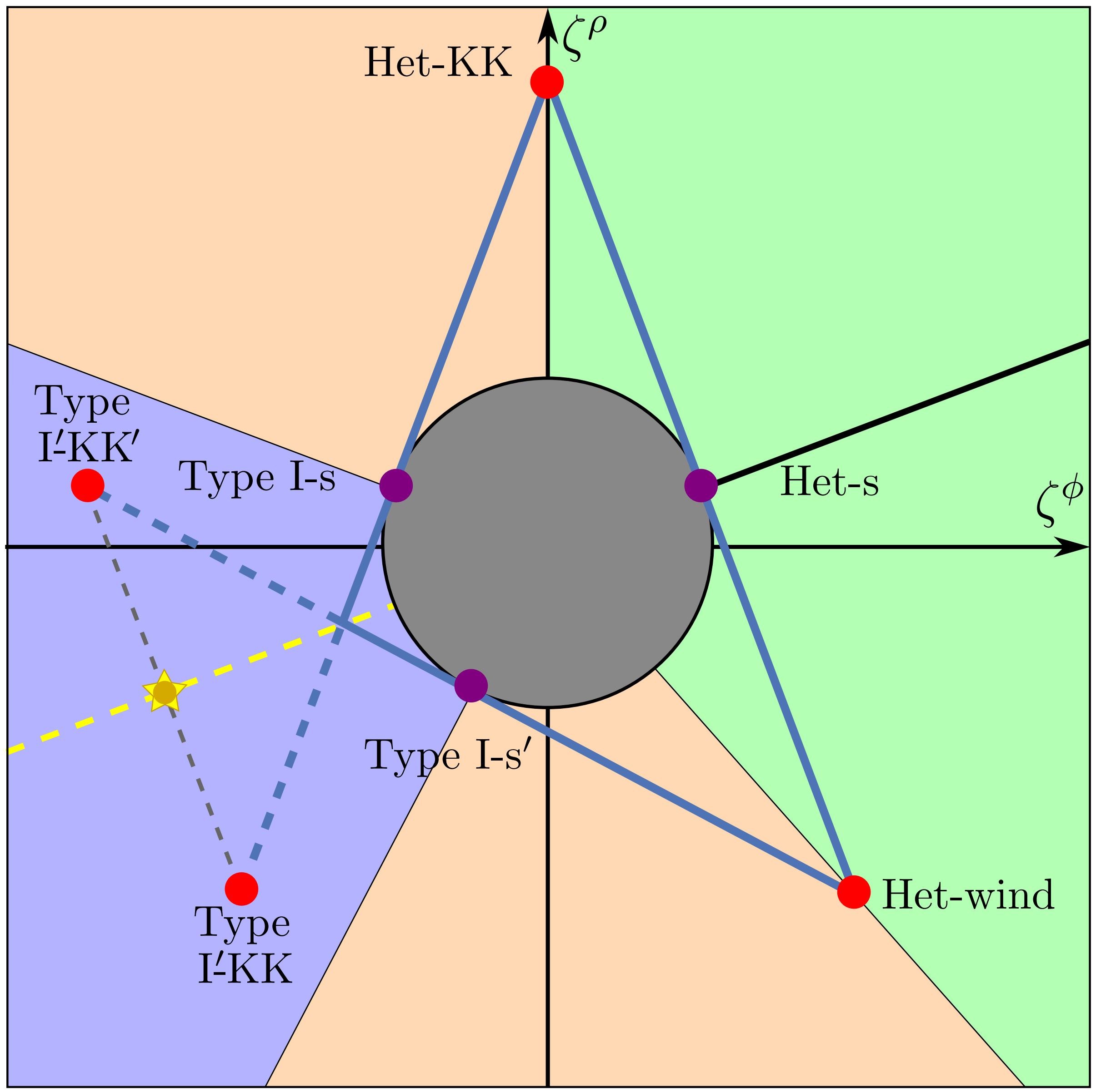
SO(32) slice



The $\vec{\zeta}$-vector of the towers change as a function of the impact parameter but not of the asymptotic direction

SO(32) slice

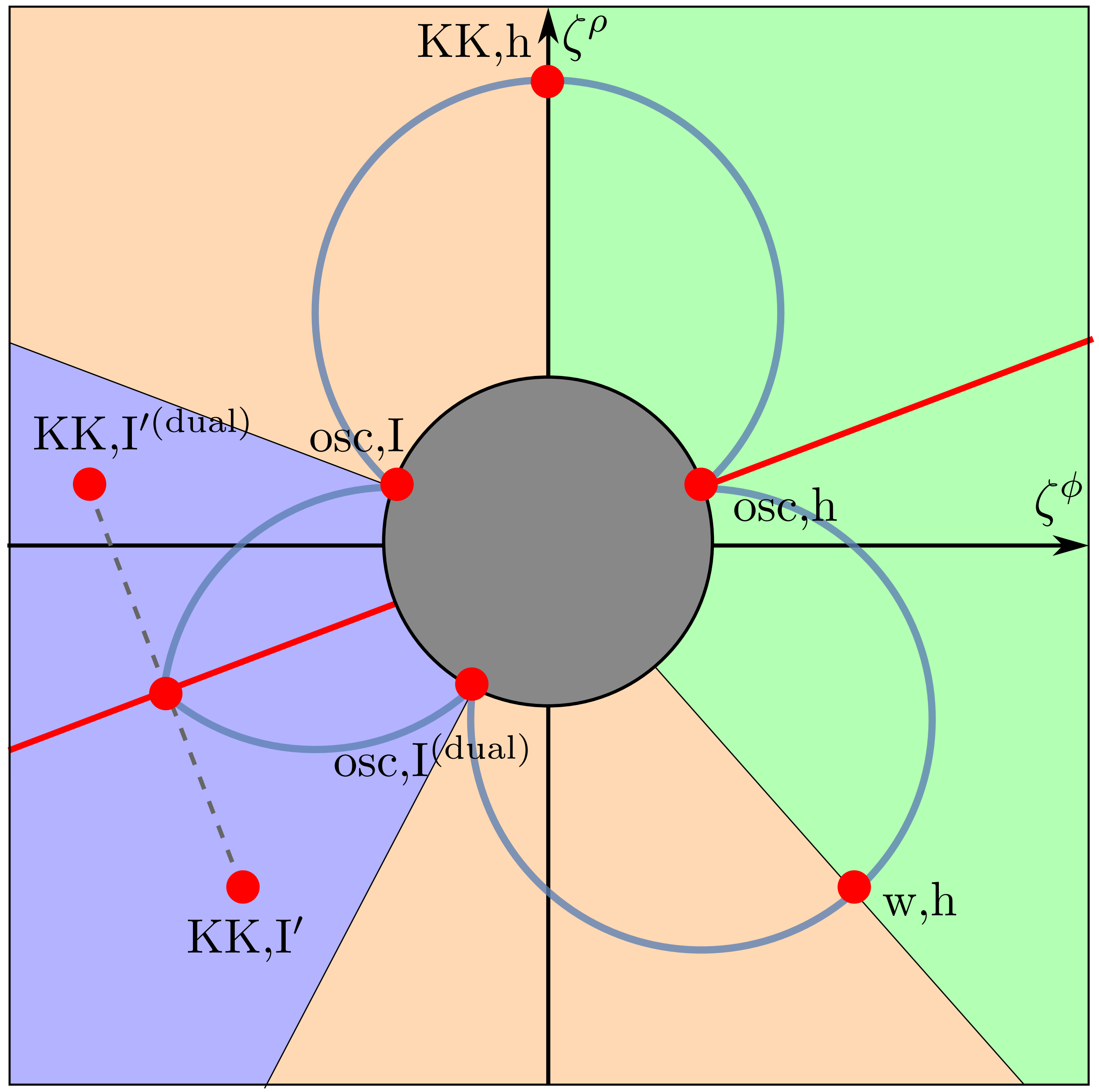
Convex Hull Distance Conjecture:



We plot only the part of the convex hull of the light towers in each asymptotic regime

In each asymptotic regime we can still reformulate the Distance Conjecture as a convex hull SWGC condition,
but they do not glue into a single convex hull since there can be branch cuts

SO(32) slice



Exponential rate of KK modes along self-dual line is $\dfrac{5}{2\sqrt{7}} \leq \sqrt{\dfrac{d+n-2}{n(d-2)}} = \sqrt{\dfrac{8}{7}}$

SO(32) slice

Results:

- ❖ Convex Hull SWGC is satisfied (at every point) with

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

- ❖ Sharpened Distance Conjecture is satisfied as $\alpha \geq \dfrac{1}{\sqrt{d-2}}$

- ❖ Convex Hull Distance Conjecture satisfied at every asymptotic region, but not globally

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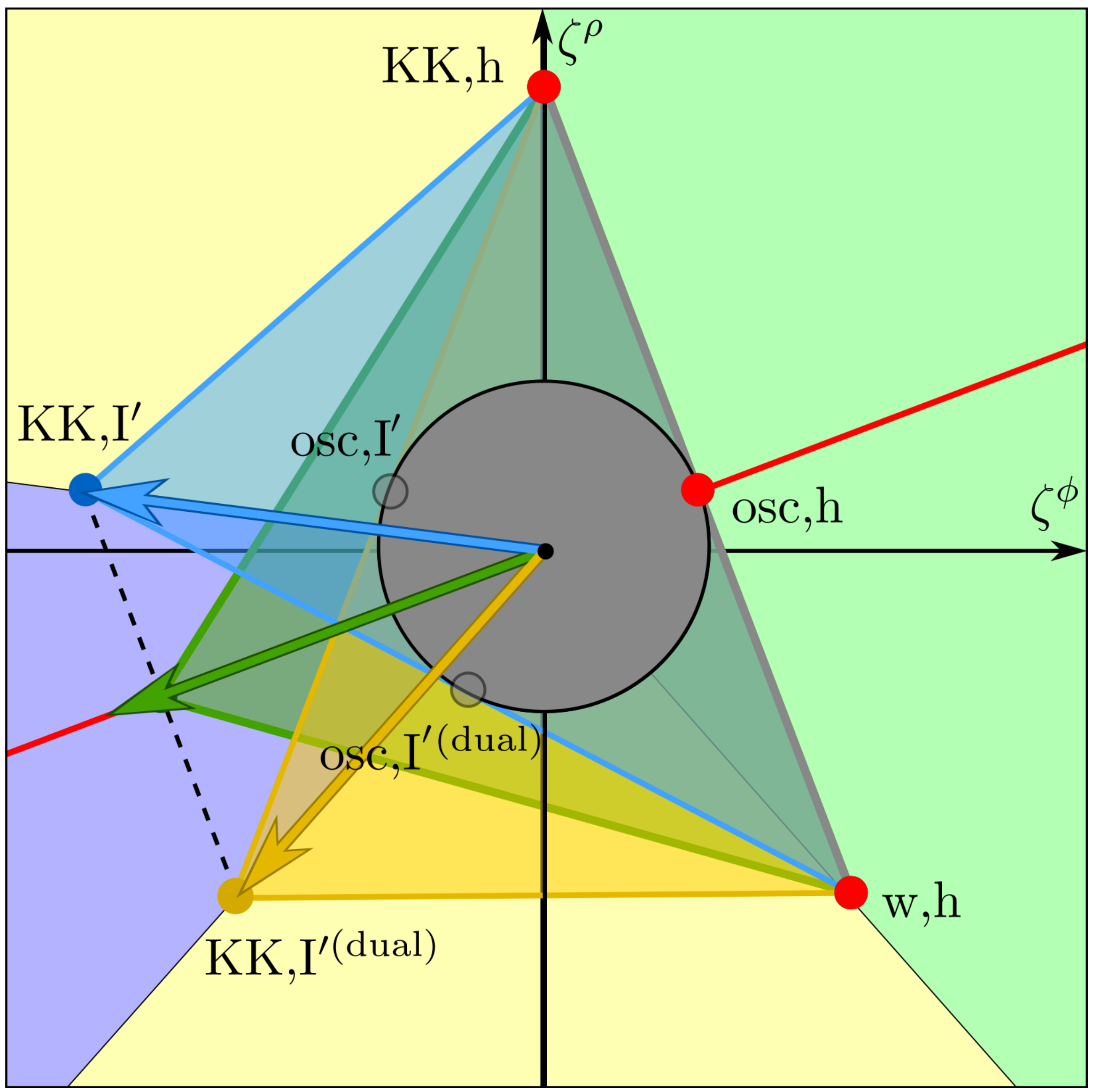
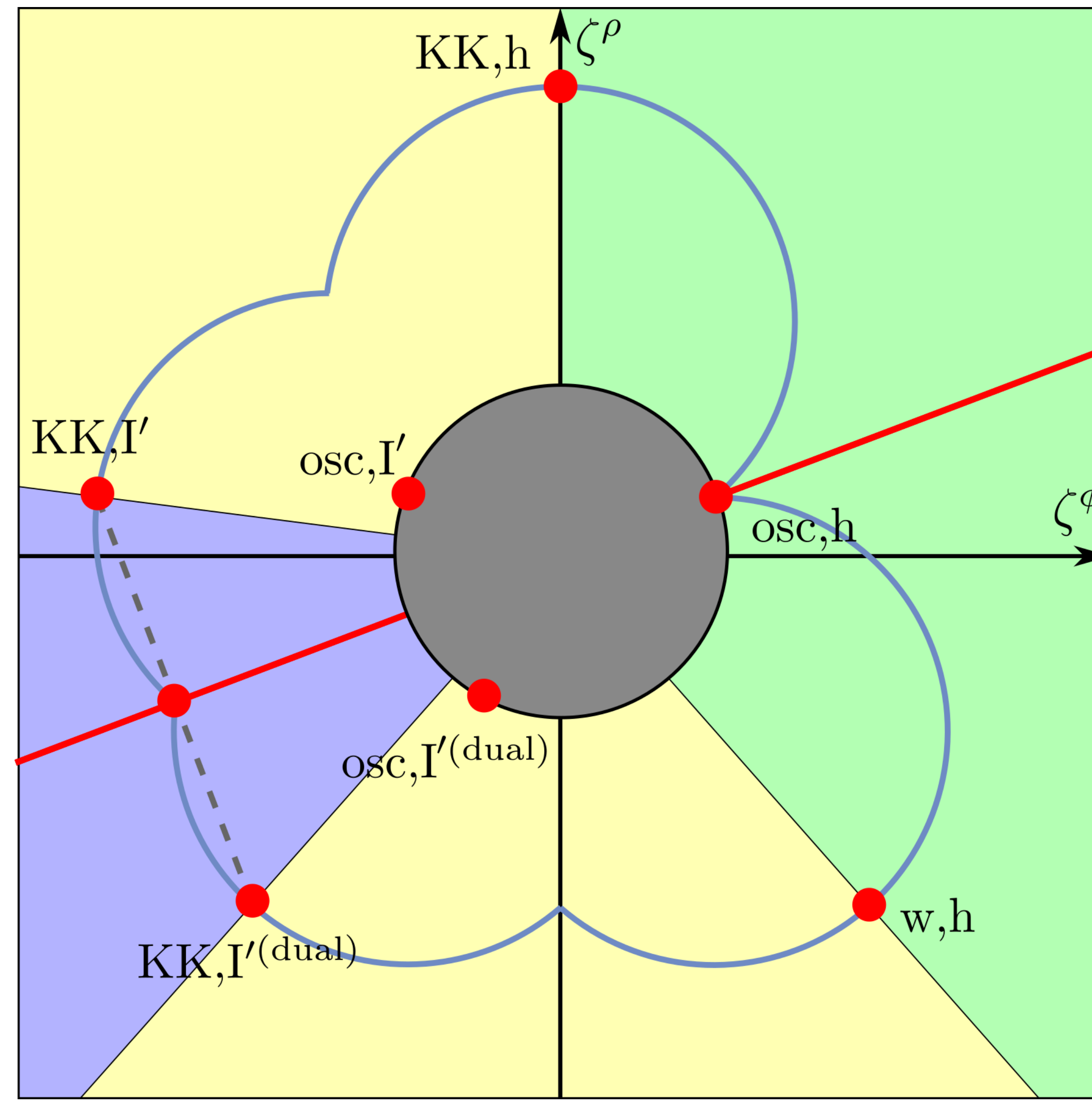
Everything thanks to the jumping of $\dfrac{\vec{\nabla} m}{m}$ as a function of asymptotic direction

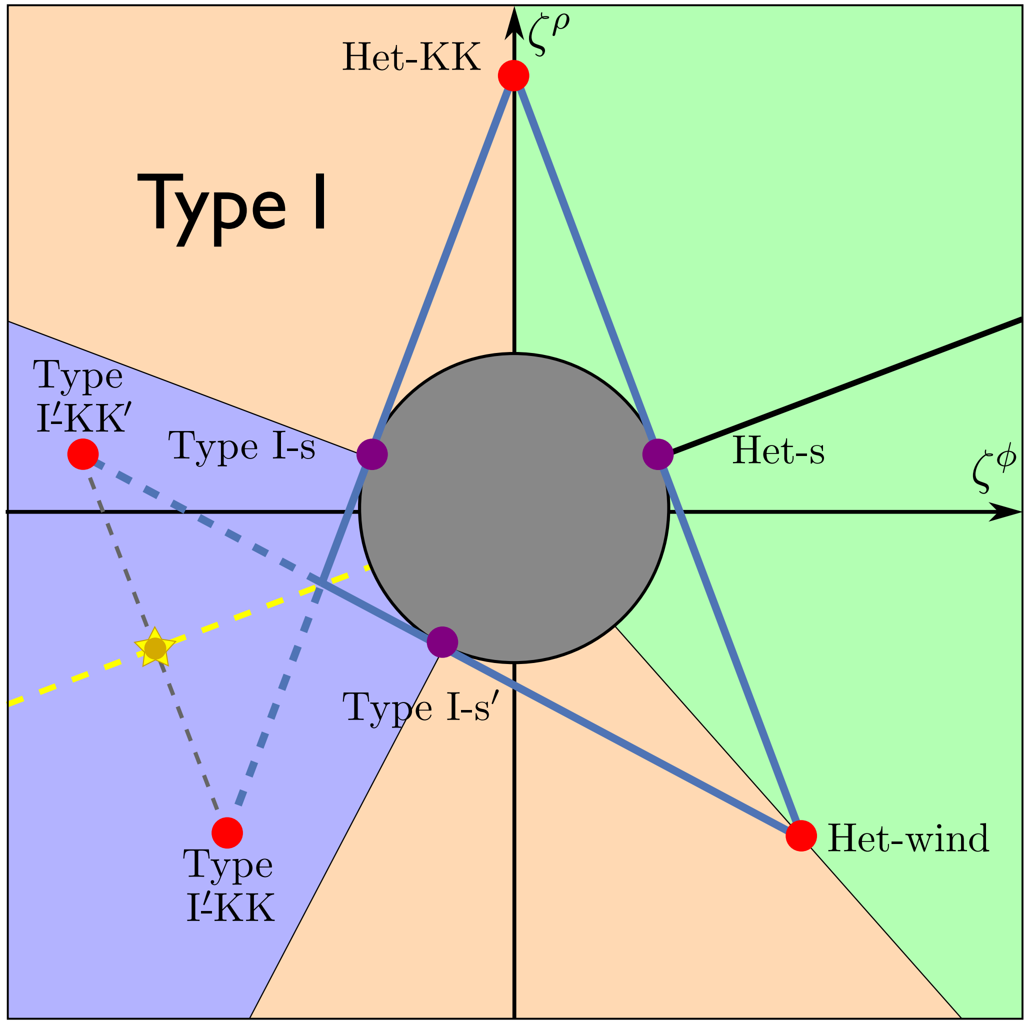
E8xE8 slice





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

SO(32) slice



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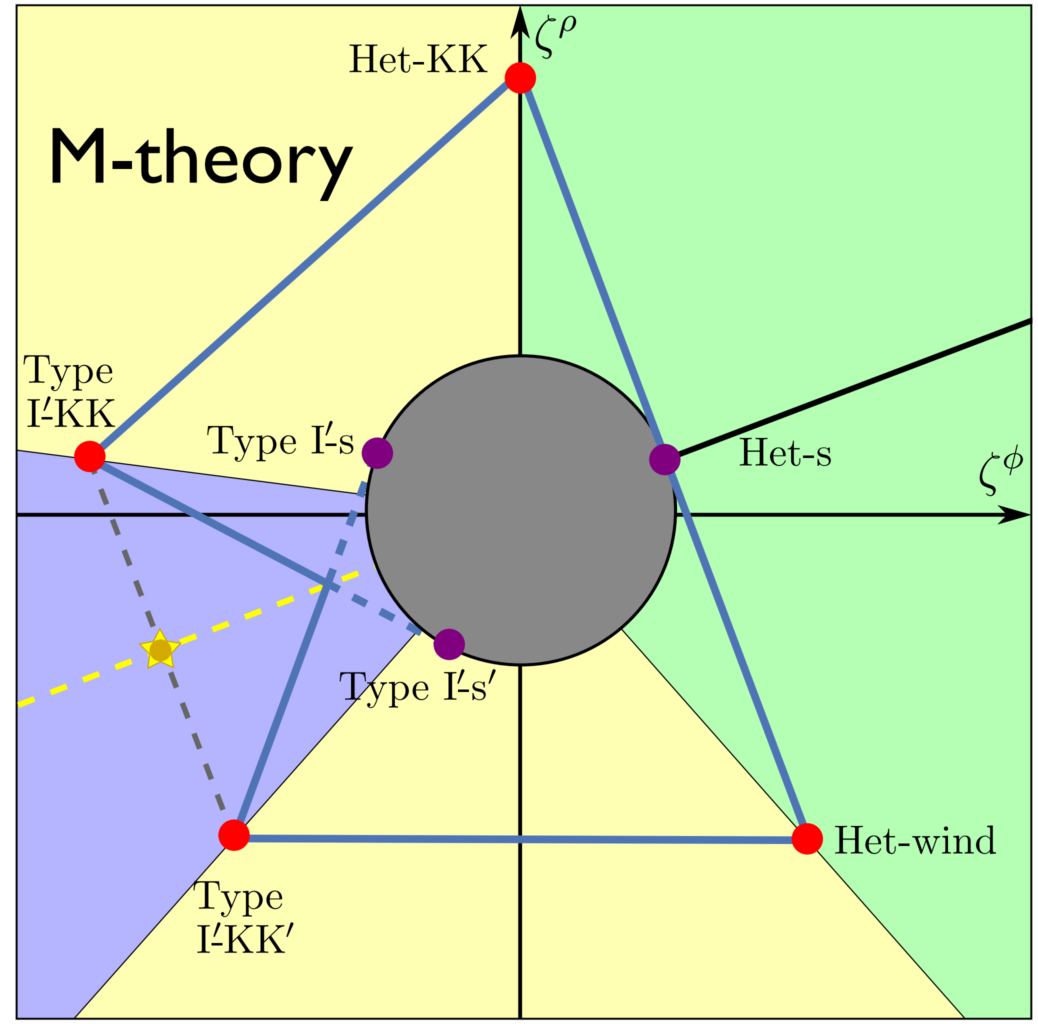

This contains the essential information to derive the "quantum gravity resolution" / UV completion

(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

2) A Pattern between the Towers and the Species Scale

The Pattern

Universal pattern between the leading tower of states and the species scale cut-off

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At every point of the asymptotic regime:

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

(i.e. $G^{ij} \dfrac{\partial_i m}{m} \dfrac{\partial_j N}{N} = -1$)

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metric in field space

mass of the leading (lightest) tower of states

number of species

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

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" lightest = less dense "

Independently of number of dimensions, nature of the tower, etc.

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It implies a lower bound for the exponential rate of the leading tower that reproduces the sharpened Distance Conjecture

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We check it in string theory examples:

- Toroidal M-theory compactifications (maximal sugra)
- 8 supercharges: 4d N=2 vector and hypermultiplets
- 4d N=1 theories

Maximal supergravity

For a single modulus and a single tower:

According to Emergent String Conjecture, the leading tower is:

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- Kaluza-Klein tower: $m_{\rm KK} \sim \exp\left(-\alpha_{\rm KK}\phi\right)$, $\alpha_{\rm KK} = \sqrt{\frac{d+n-2}{n(d-2)}}$

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It is satisfied that $\dfrac{\vec{\nabla} m}{m} \cdot \dfrac{\vec{\nabla}\Lambda}{\Lambda} = \dfrac{1}{d-2}$

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The species scale has information about all light towers and it is not necessarily associated to the leading one

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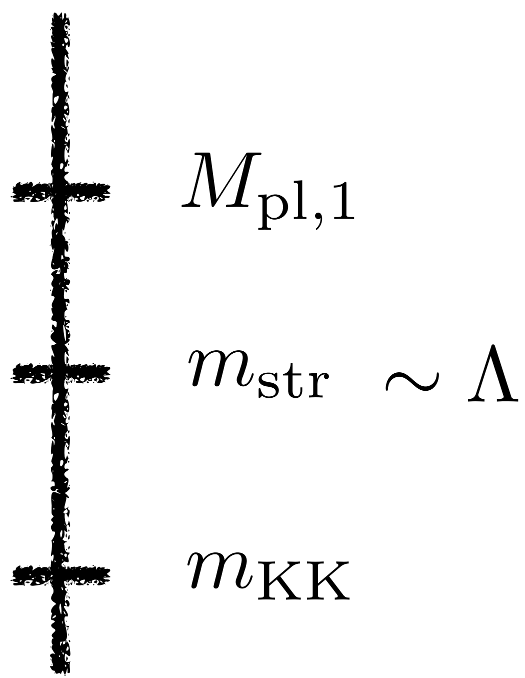

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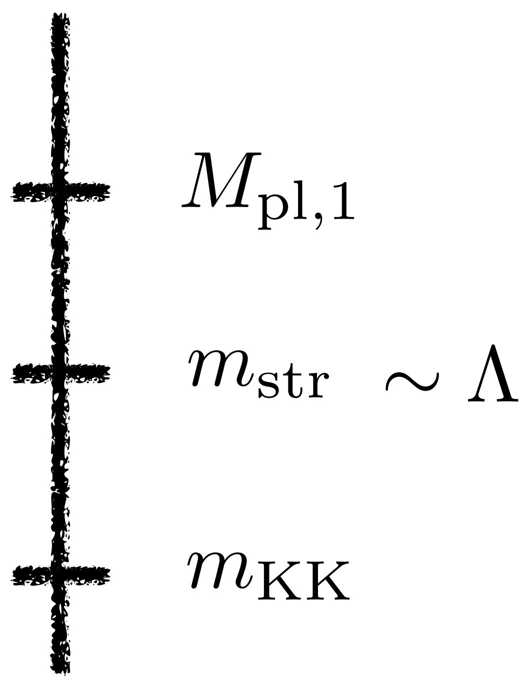

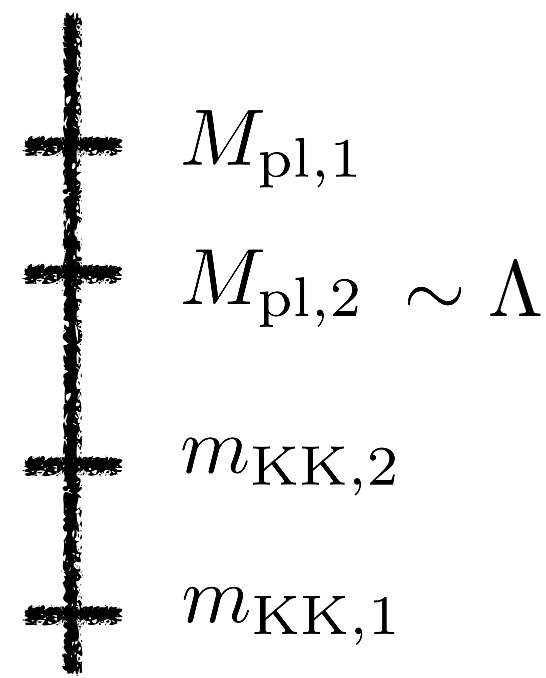

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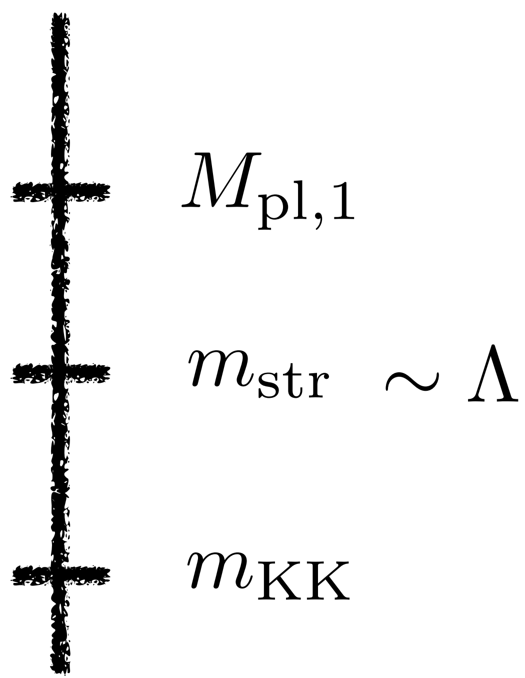

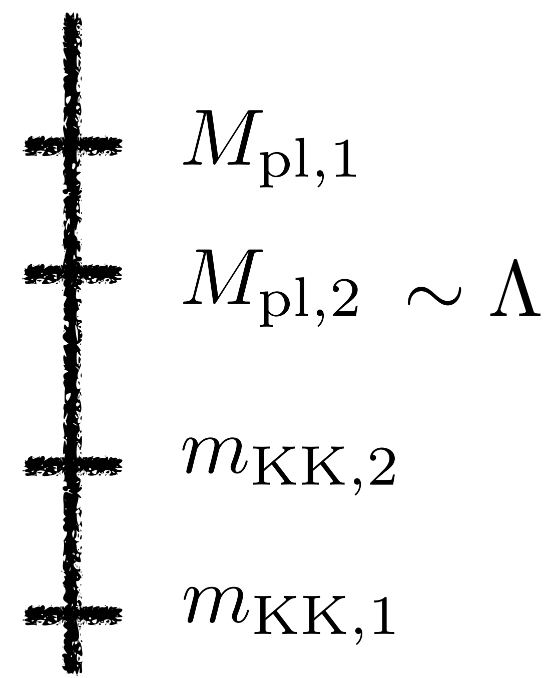

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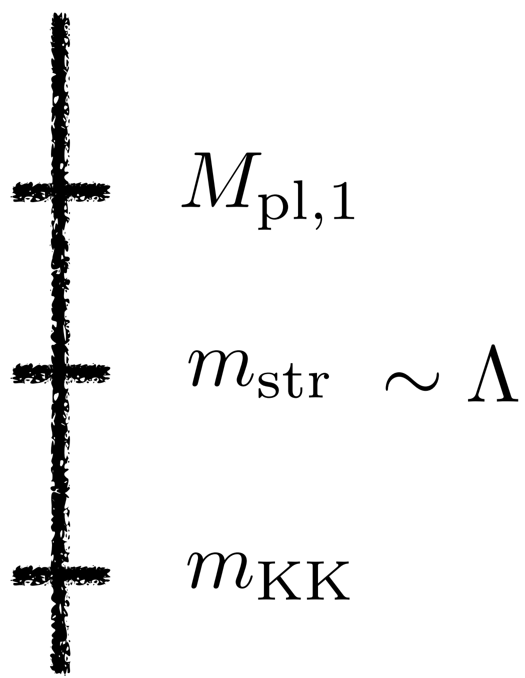

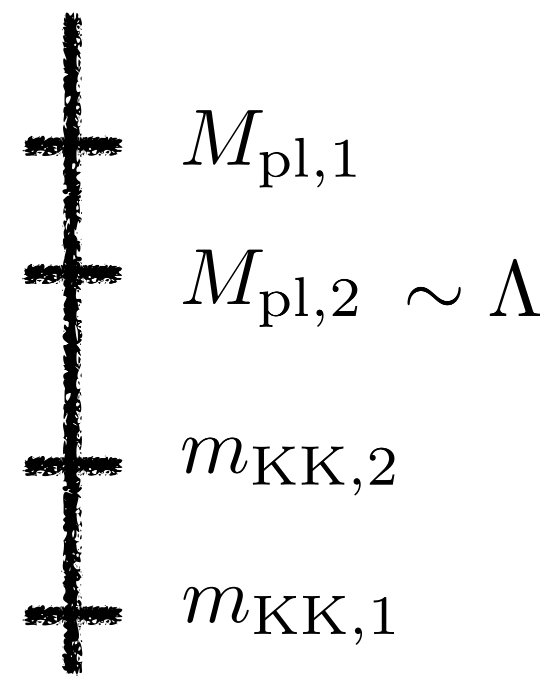

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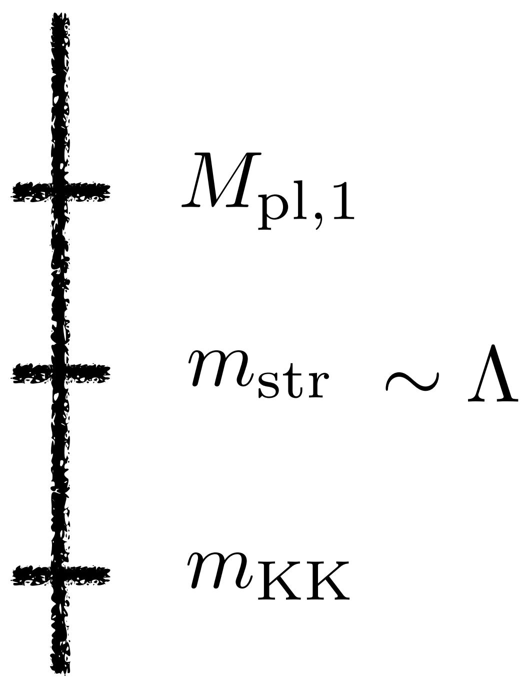

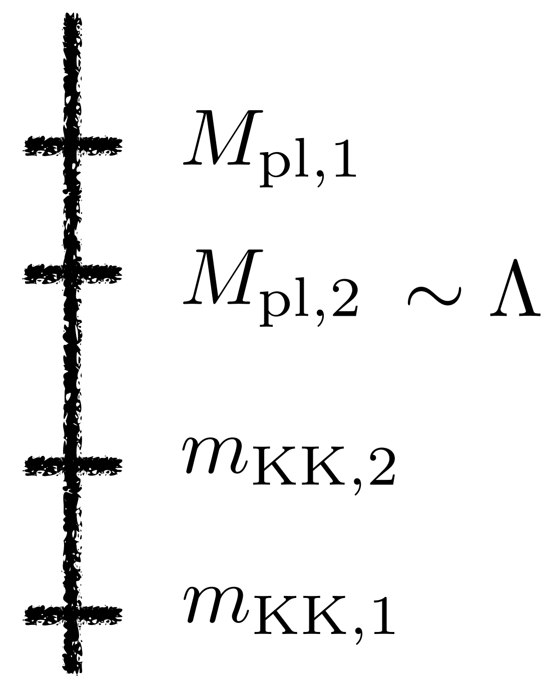

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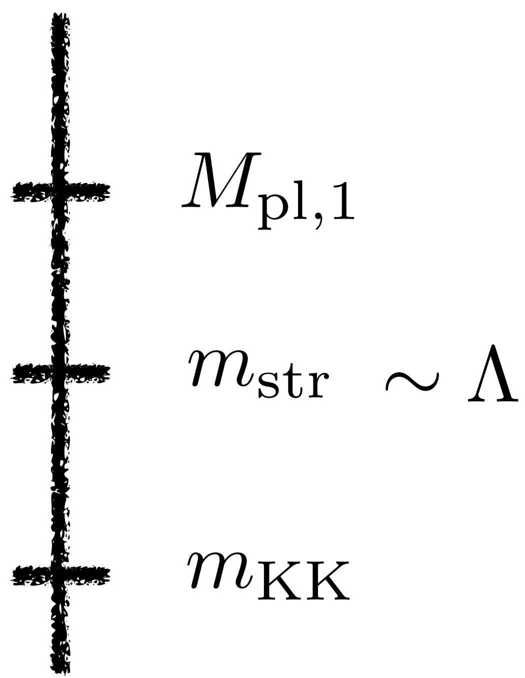
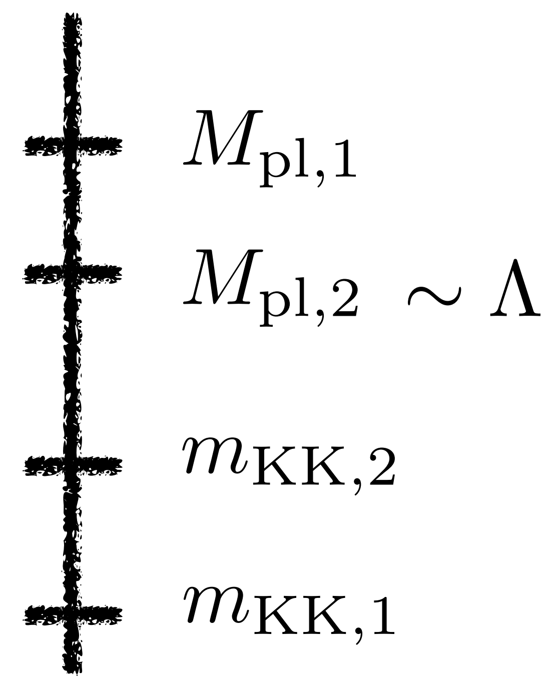


Why?



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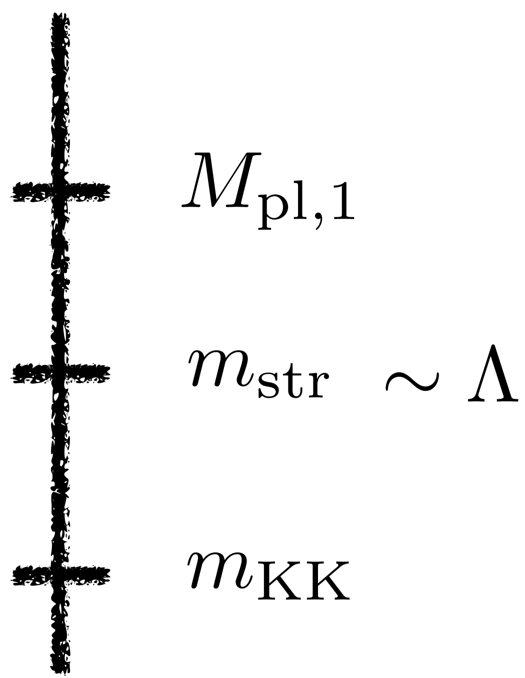

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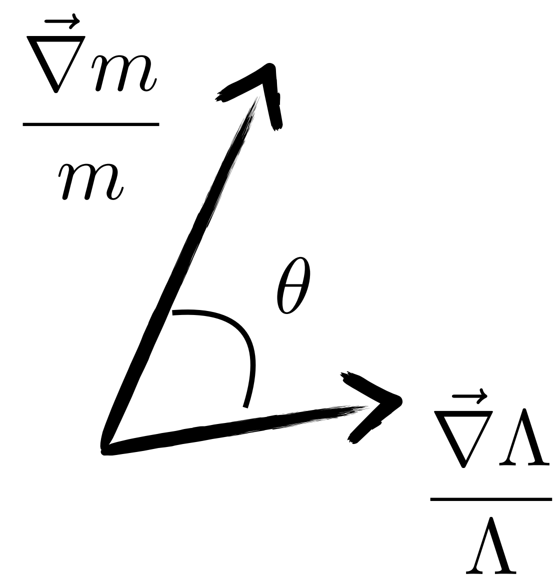

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The angle between them is always such that the pattern gets satisfied

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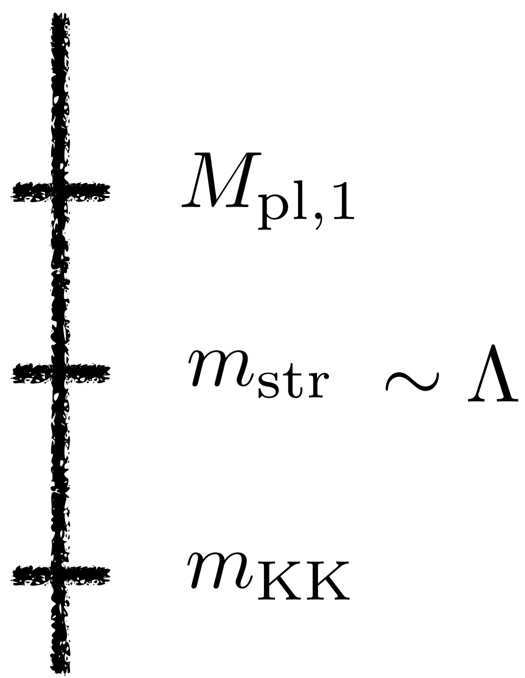

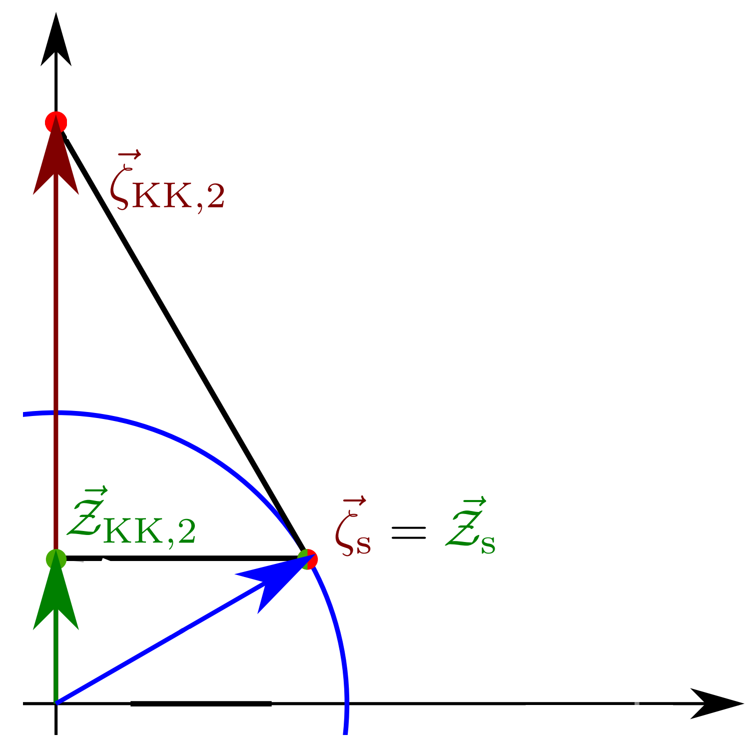

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[Calderon-Infante et al'23]

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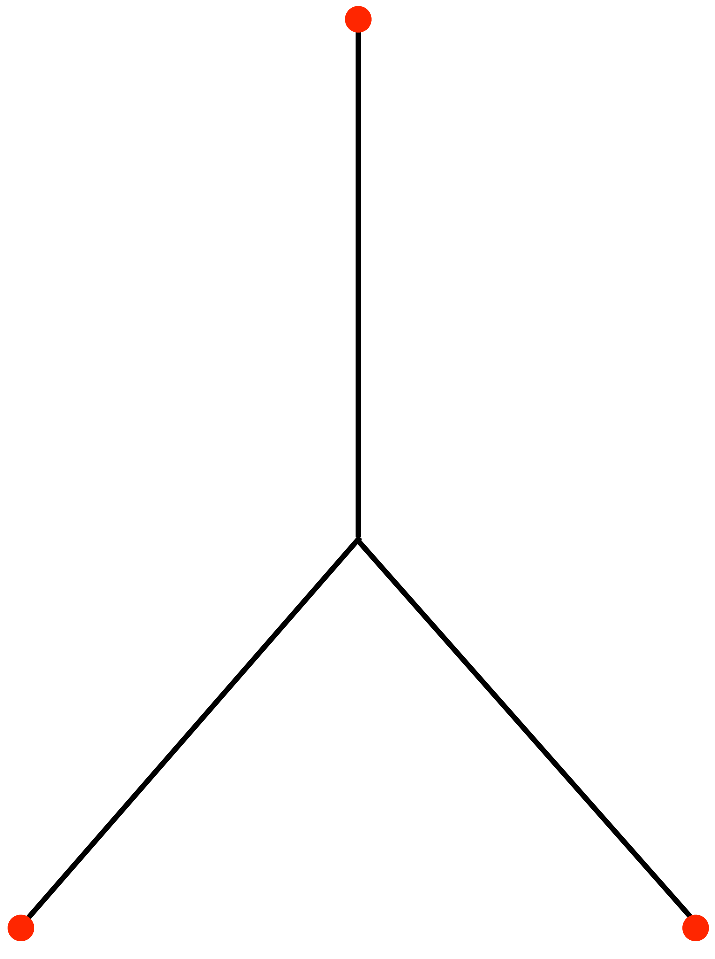
Species scale vector is perpendicular to the facets of the convex hull of the towers



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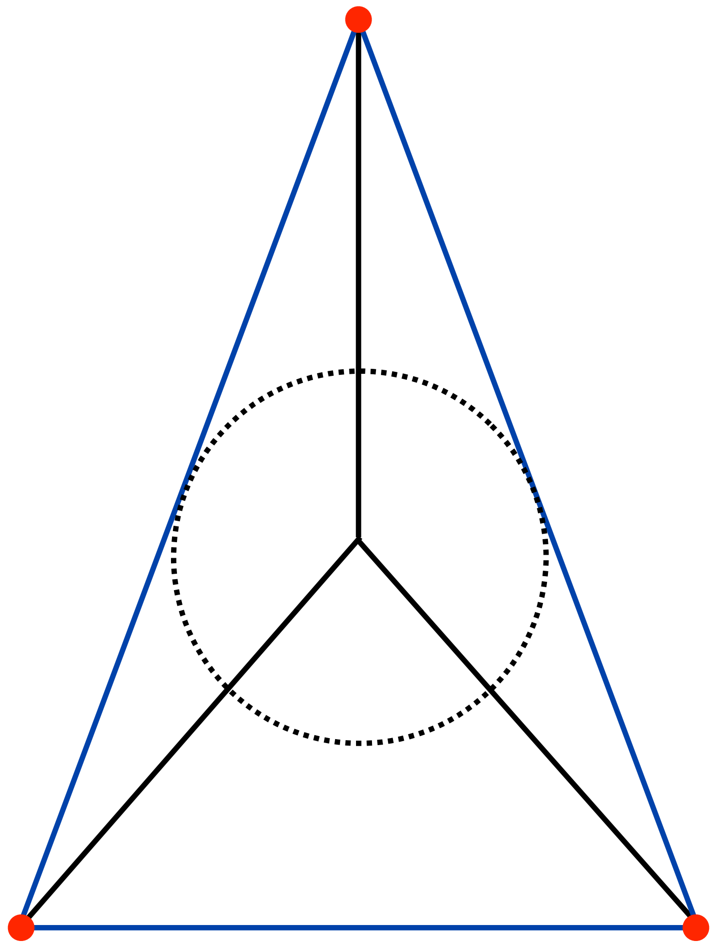

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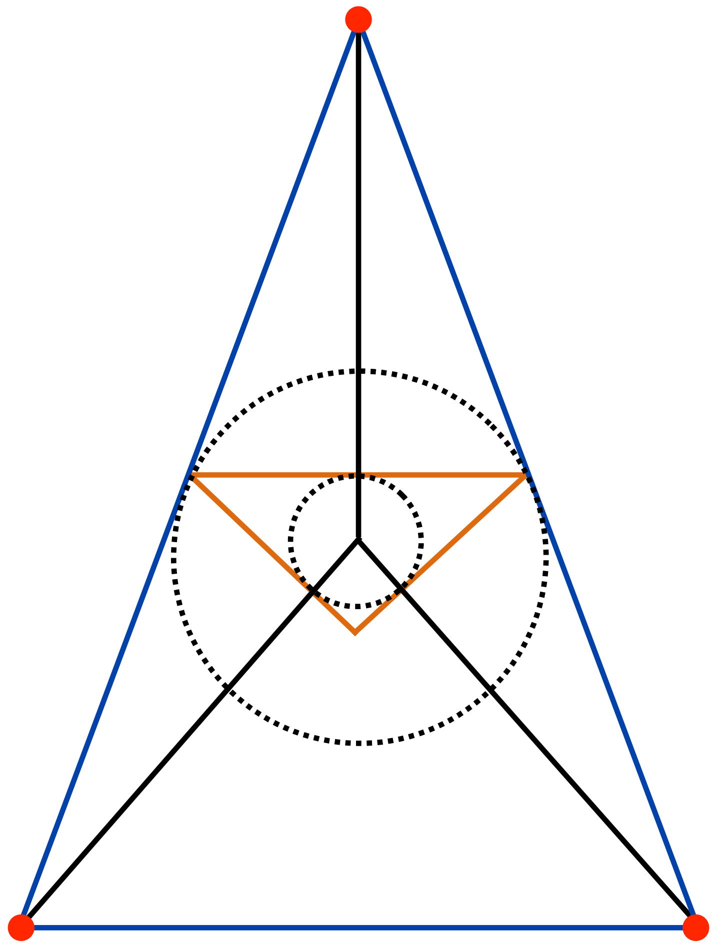

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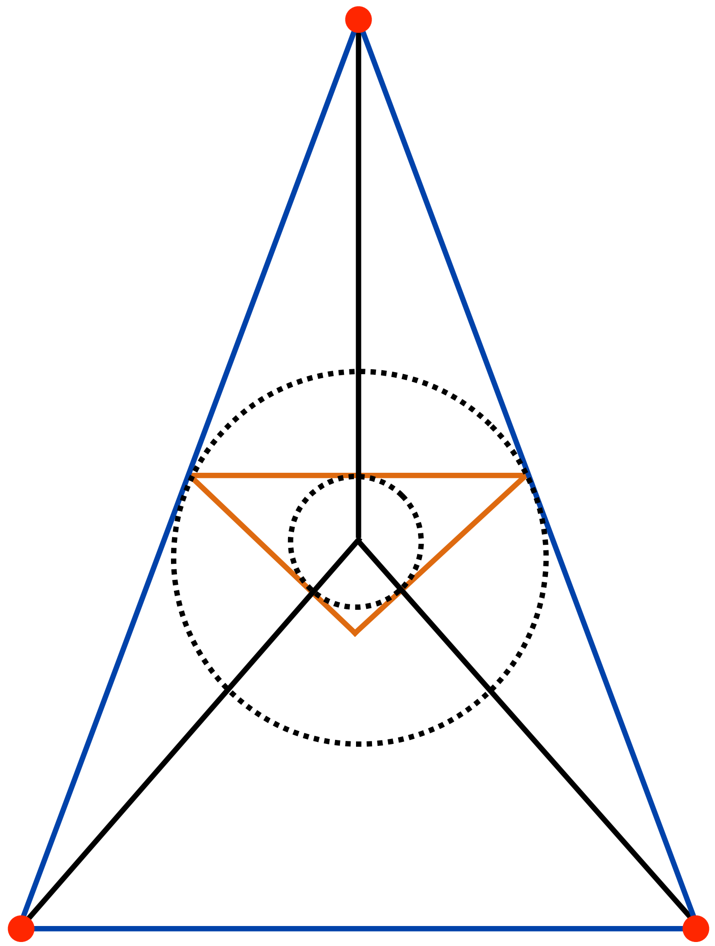

- Convex Hull for the towers

  [Calderon-Infante,Uranga,IV'20] [Etheredge et al'22-23]

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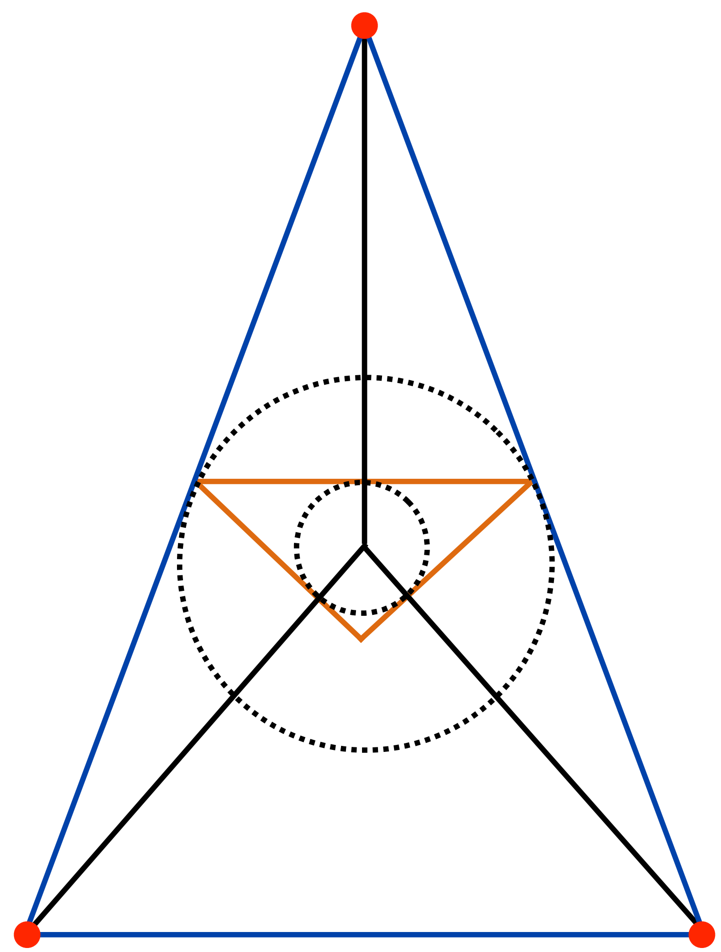

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- Convex Hull for the species scale

  [Calderon-Infante,Castellano,Herraez,Ibanez'23]

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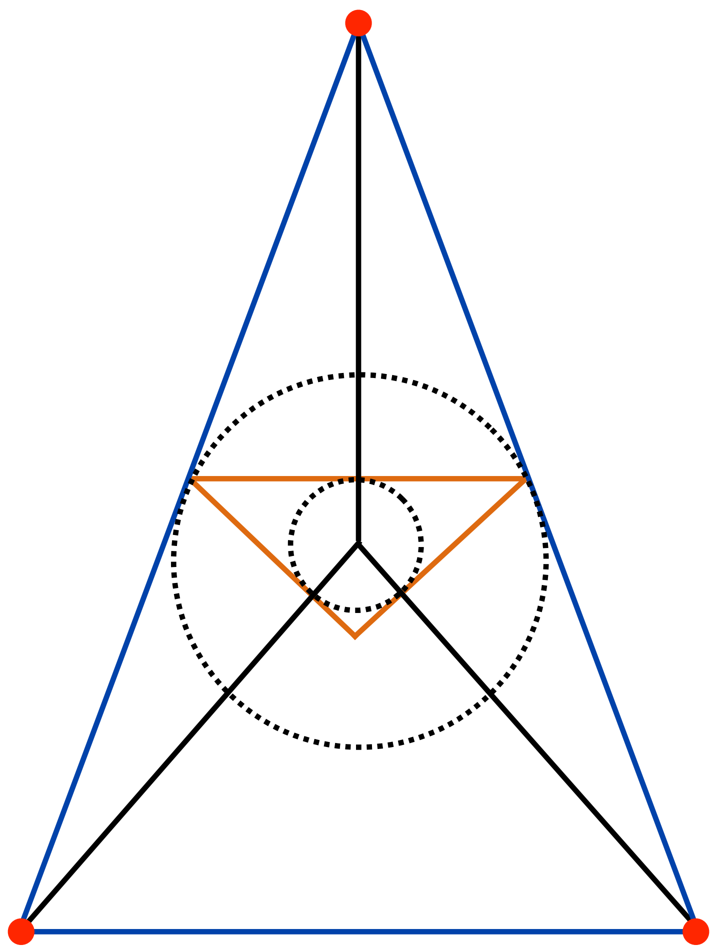

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  [Calderon-Infante,Castellano,Herraez,Ibanez'23]

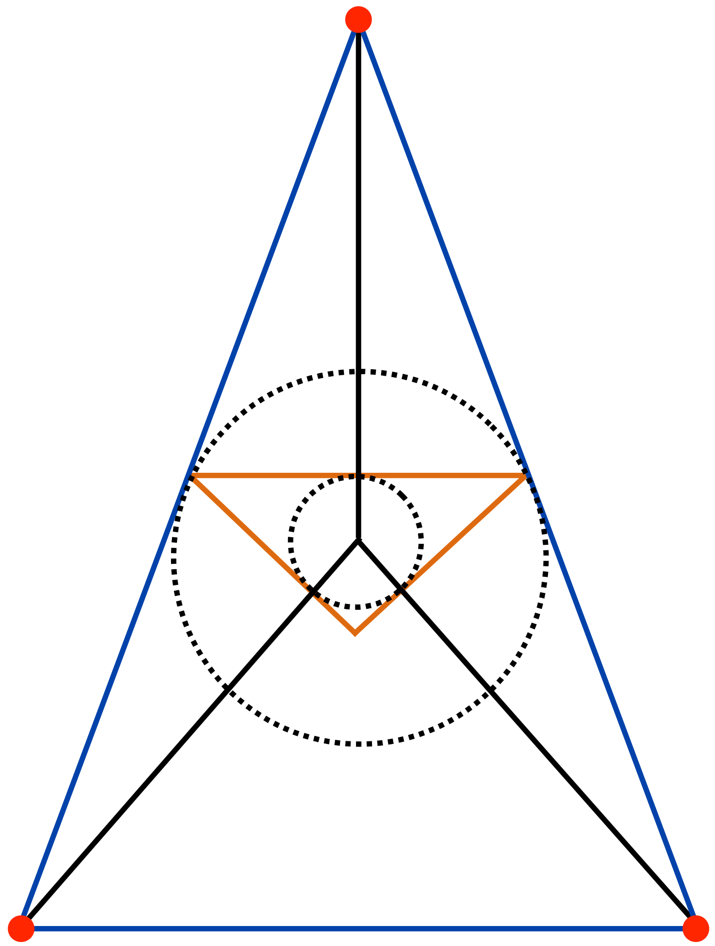
The two polytopes are dual to each other

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla} \Lambda}{\Lambda} = \frac{1}{d-2}$$

Species scale vector is perpendicular to the facets of the convex hull of the towers

Alberto's and Alvaro's talk

Luis's talk



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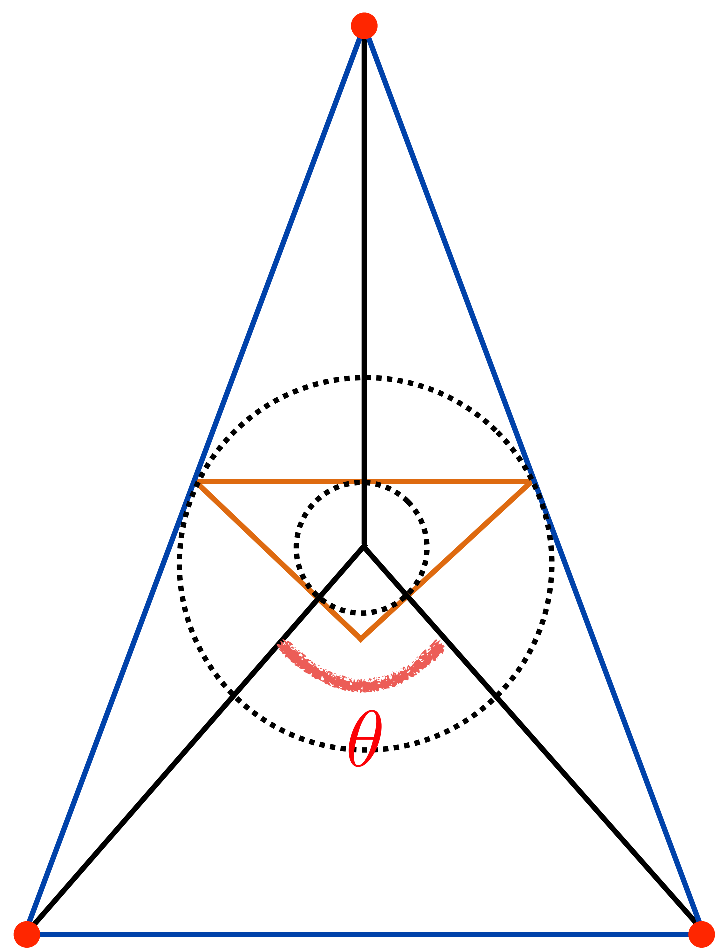

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It underlies the rules of taxonomy of infinite distance limits from Ben's talk

(it determines the angles between the different vectors of the towers)

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

Can we classify all possible limits from bottom-up?

We also check the pattern in setups with lower supersymmetry and it still holds

We provide examples with 16, 8 and 4 supercharges [Castellano,Ruiz,IV'ongoing]

e.g. it holds in all examples of EFT strings in 4d N=1 explored in [Lanza,Marchesano,Martucci,IV'21]

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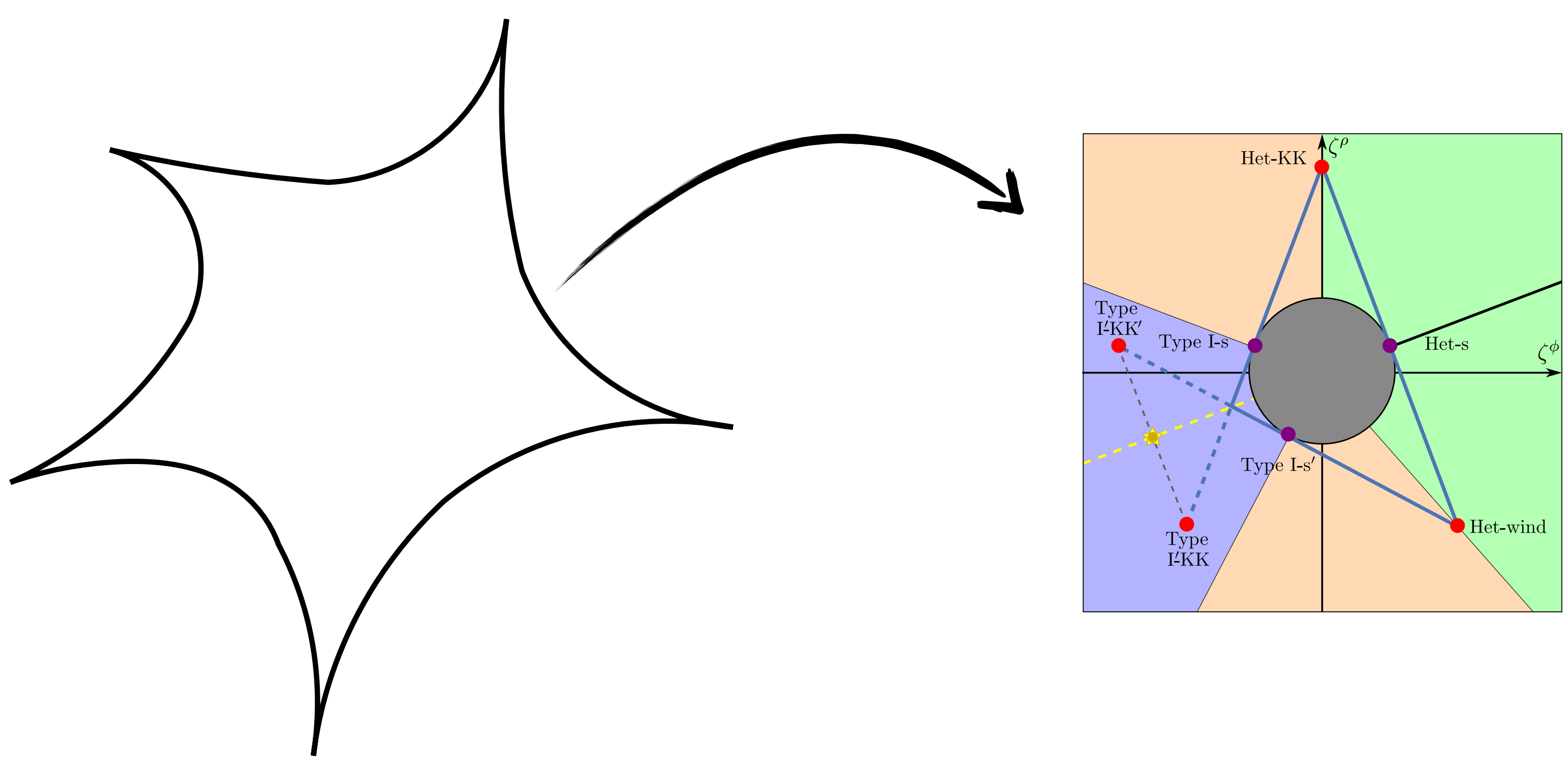
Promising avenue to extend the taxonomy of infinite distance limits to less supersymmetric setups?



Summary

1) The sharpened Distance Conjecture and convex hull SWGC are still satisfied in 9d string theories

- despite the variation of the exponential rate of non-BPS KK modes associated to decompactifiying to a running solution
- thanks to the fact that they "jump" as a function of asymptotic direction

Is this jumping a general feature of asymptotic limits?

2) We found a universal pattern between the leading tower of states and the species scale cut-off

Lamppost effect or bottom-up explanation?

It reproduces the sharpened lower bound for the exponential rate and certain rules about how to combine different limits

Thank you!

Online series of Swampland seminars / open mic discussions

on Mondays at 10:30 am ET (4:30 pm CET)

https://sites.google.com/view/swamplandseminars

Everybody is welcome! :)

back-up slides

CFT Distance conjecture

Consider AdS_{d+1}/CFT_d : bulk moduli space = conformal manifold

(marginal deformations)

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For $d \geq 3$: Tower of higher spin modes "CFT Distance conjecture"

(all known examples are free points $g_{YM} \to 0$)

$$\gamma_J \sim e^{-\alpha d(\tau,\tau')} \quad \text{as} \quad d(\tau,\tau') \to \infty$$

[Perlmutter,Rastelli,Vafa,IV'21]
[Baume,Calderon-Infante'21]

anomalous dimension

distance measured by Zamolodchikov metric

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Notice: No pure decompactification limit
(are all limits associated to tensionless strings?)

CFT Distance conjecture

central charge

Exponential rate: $$\boxed{\alpha = \sqrt{\frac{2c}{\mathrm{dim}G}}}$$ [Perlmutter,Rastelli,Vafa,IV'21]

gauge group getting free

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Exponential rate: $$\boxed{\alpha = \sqrt{\frac{2c}{\dim G}}} \quad \geq \frac{1}{\sqrt{3}} \text{ for 4d N=2}$$

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[Bhardwaj,Tachikawa'13]
[Razamat, Sabag, Zafrir'20]

For all possible 4d SCFTs with large N and simple gauge groups:

$$\alpha = \frac{1}{\sqrt{2}}, \sqrt{\frac{7}{12}}, \sqrt{\frac{2}{3}}$$

because of $\frac{a}{c} = \{1, \frac{13}{14}, \frac{7}{8}\}$

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- They satisfy bound $\alpha \geq \frac{1}{\sqrt{d-2}} = \frac{1}{\sqrt{3}}$ but do not saturate it (unlike in string perturbative limits in flat space)
- Funny coincidence: These factors coincide with what one would obtain for a KK tower decompactifying to 11, 9 and 8 dimensions.

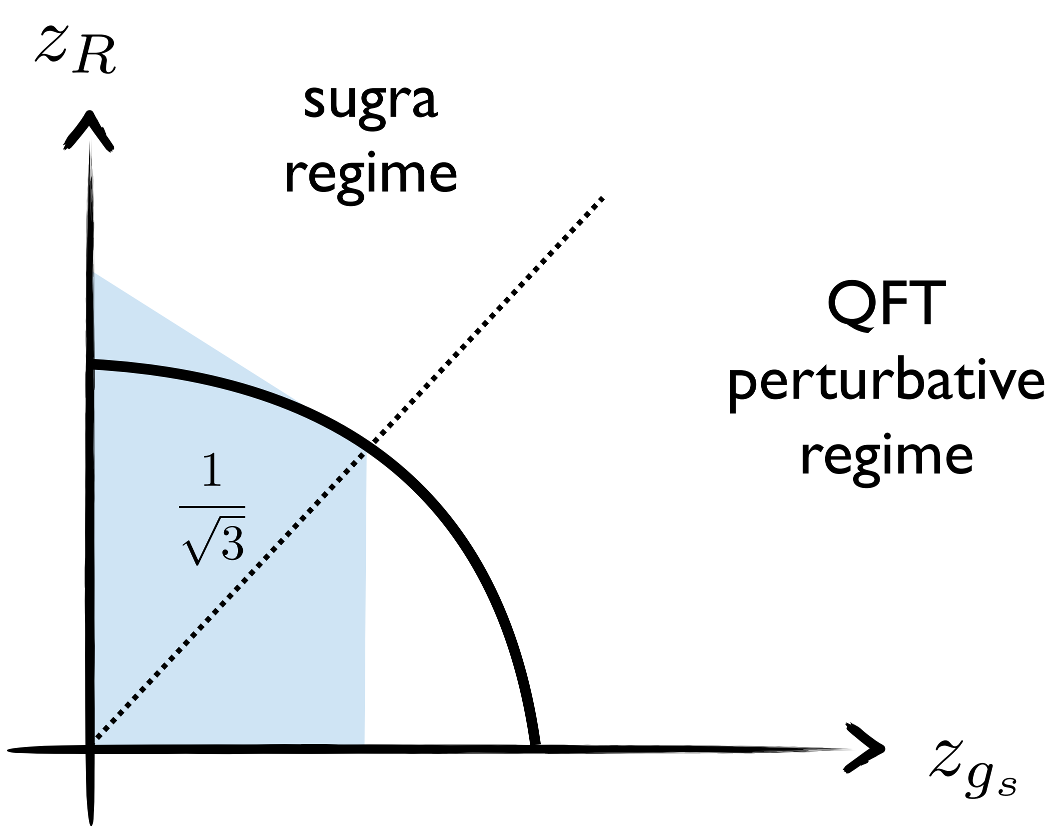
Example: $N=4$ SYM / $AdS_5 \times S^5$

$$R = M_{p,5}^{-1} N^{2/3}$$

String tension: $T_s = M_{p,5}^2\, g_s^{1/2} R^{-5/4}$

$$\lambda = g_{YM}^2 N$$

Let us check the convex hull Distance conjecture:



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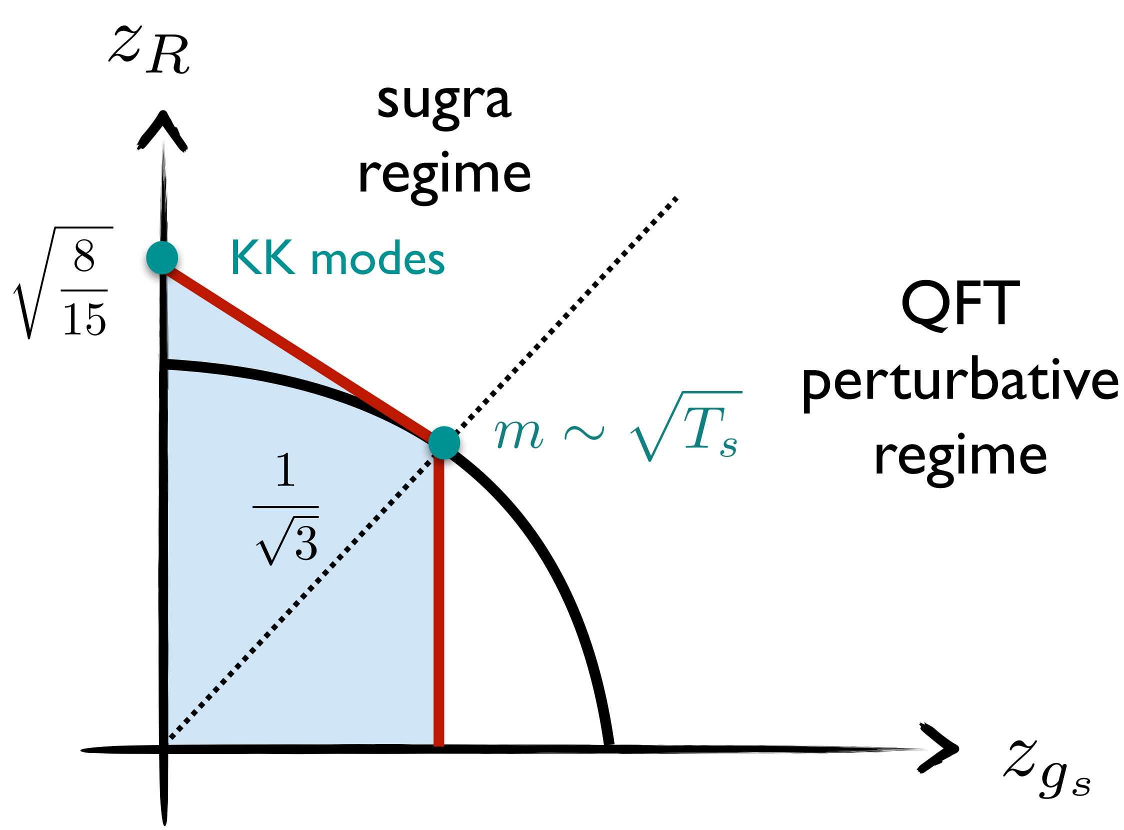

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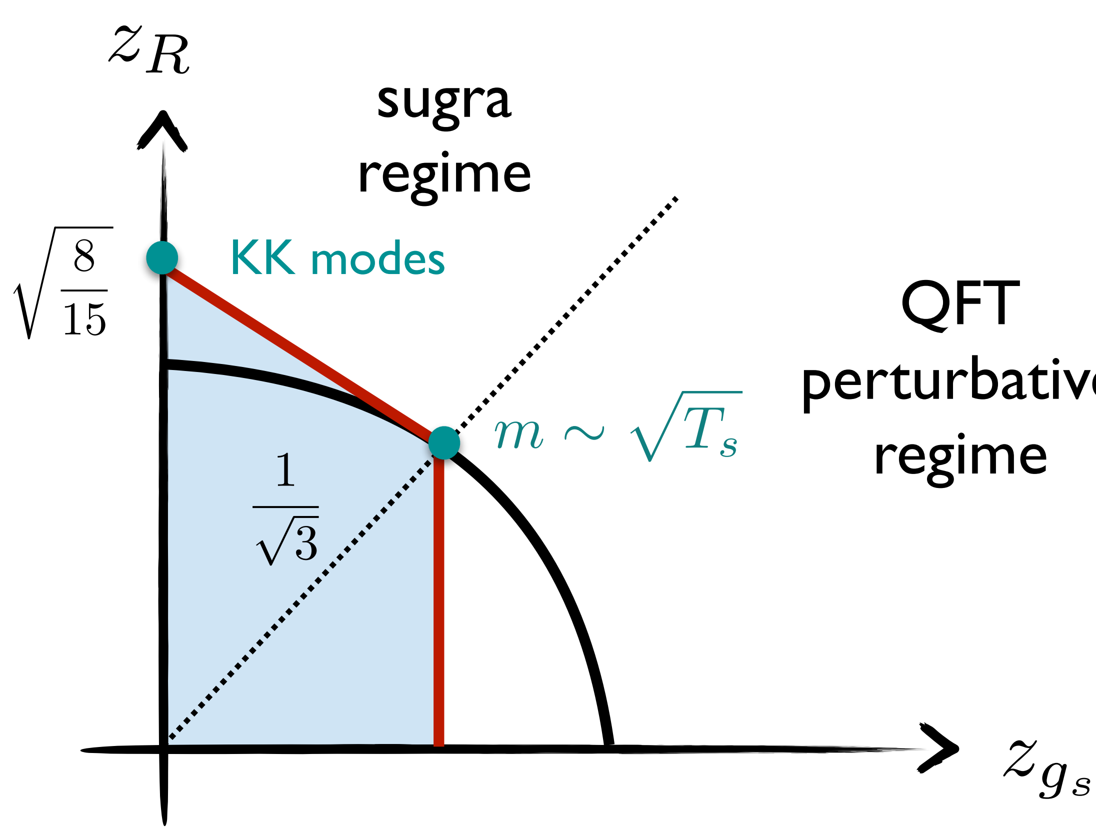

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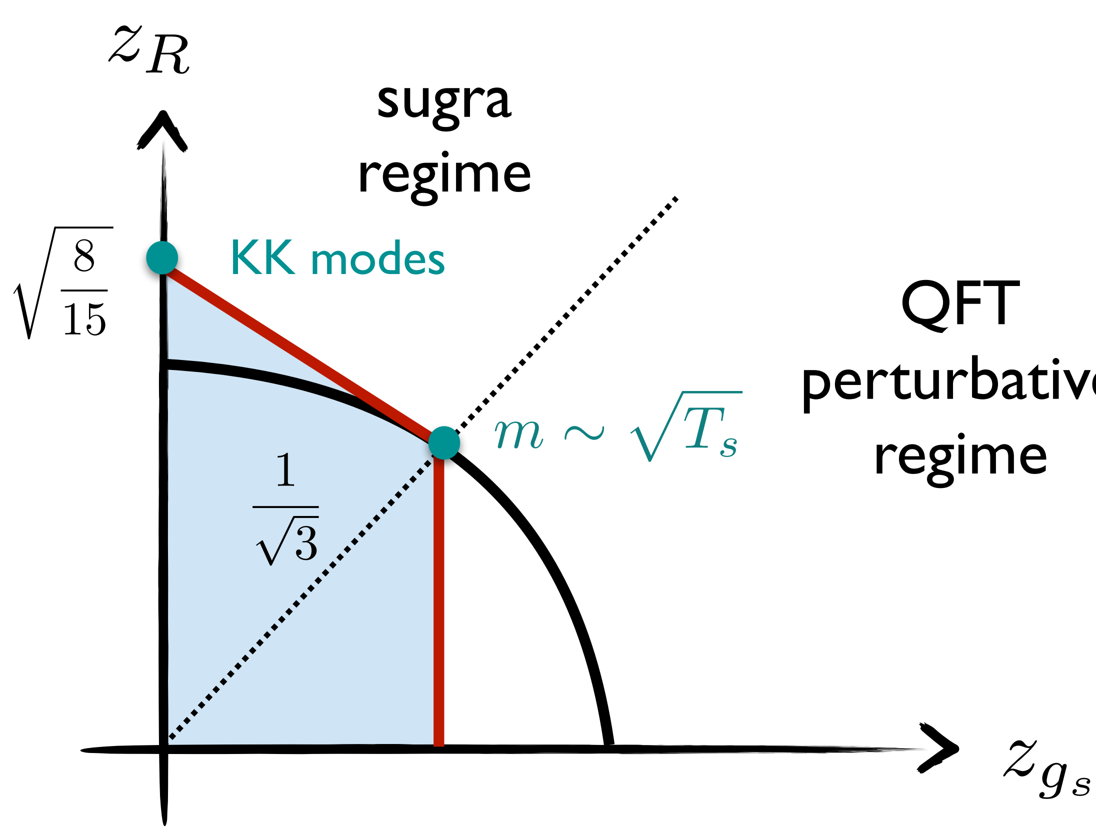

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This would violate Convex Hull Distance conjecture!

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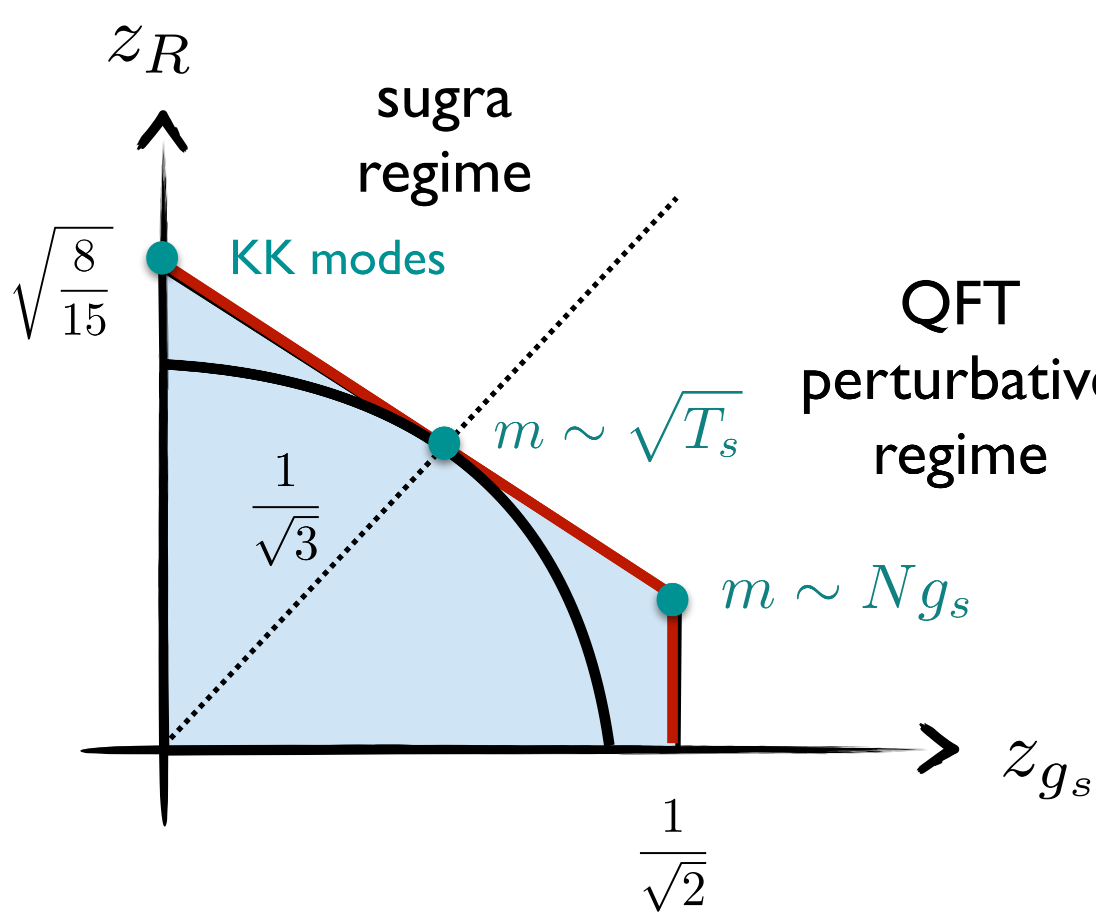

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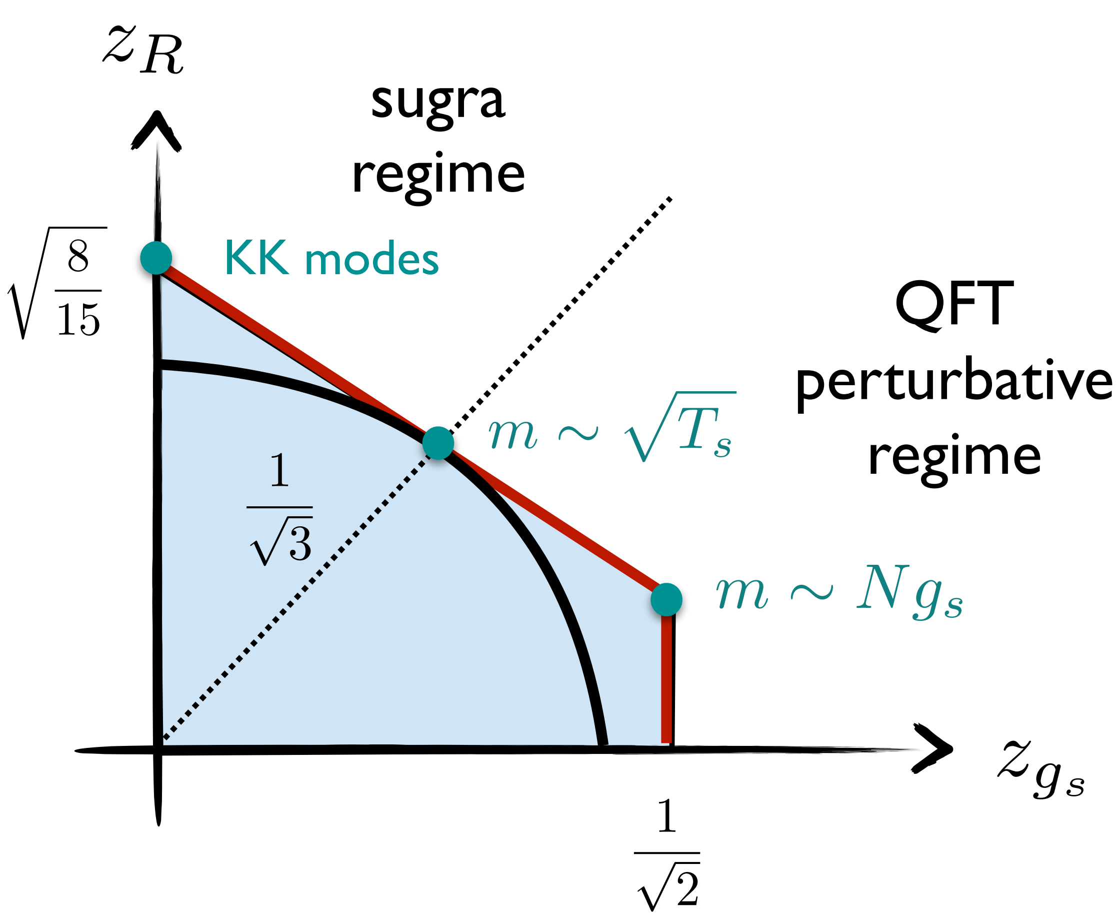

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$$\Rightarrow \quad \alpha = \frac{1}{\sqrt{2}}$$

N=2

G	Hypermultiplets	c	α
$SU(N)$	$2N$ fund	$\frac{1}{6}(2N^2-1)$	$\sqrt{\frac{2}{3}}$
$SU(N)$	1 asym, $N+2$ fund	$\frac{1}{24}(7N^2+3N-4)$	$\sqrt{\frac{7}{12}}$
$SU(N)$	2 asym, 4 fund	$\frac{1}{12}(3N^2+3N-2)$	$\frac{1}{\sqrt{2}}$
$SU(N)$	1 asym, $N-2$ fund	$\frac{1}{24}(7N^2-3N-4)$	$\sqrt{\frac{7}{12}}$
$SU(N)$	1 sym, 1 asym	$\frac{1}{12}(3N^2-2)$	$\frac{1}{\sqrt{2}}$
$USp(2N)$	$4N+4$ $\frac{1}{2}$ fund	$\frac{1}{2}N(1+2N)$	1
$USp(2N)$	1 asym, 4 fund	$\frac{1}{12}(6N^2+9N-2)$	$\frac{1}{\sqrt{2}}$
$SO(N)$	$N-2$ vect	$\frac{1}{12}N(2N-3)$	$\sqrt{\frac{2}{3}}$

N=1

G	Theory	c	α
$SU(N)$	Table 2, #1	$\frac{1}{24}(7N^2-5)$	$\sqrt{\frac{7}{12}}$
$SU(N)$	Table 2, #5	$\frac{1}{24}(6N^2+3N-5)$	$\frac{1}{\sqrt{2}}$
$SU(N)$	Table 3, #4	$\frac{1}{24}(7N^2-4)$	$\sqrt{\frac{7}{12}}$
$SU(N)$	Table 5, #4	$\frac{1}{24}(8N^2-3)$	$\sqrt{\frac{2}{3}}$
$USp(2N)$	Table 12, #1	$\frac{1}{24}(14N^2+15N-1)$	$\sqrt{\frac{7}{12}}$
$USp(2N)$	Table 13, #9	$\frac{1}{8}(4N^2+8N-1)$	$\frac{1}{\sqrt{2}}$
$USp(2N)$	Table 13, #10	$\frac{1}{24}(14N^2+21N-2)$	$\sqrt{\frac{7}{12}}$
$SO(N)$	Table 18, #1	$\frac{1}{48}(7N^2-21N-4)$	$\sqrt{\frac{7}{12}}$
$SO(N)$	Table 18, #2	$\frac{1}{48}(7N^2-15N-2)$	$\sqrt{\frac{7}{12}}$
$SO(N)$	Table 18, #3	$\frac{1}{24}(4N^2-9N-1)$	$\sqrt{\frac{2}{3}}$

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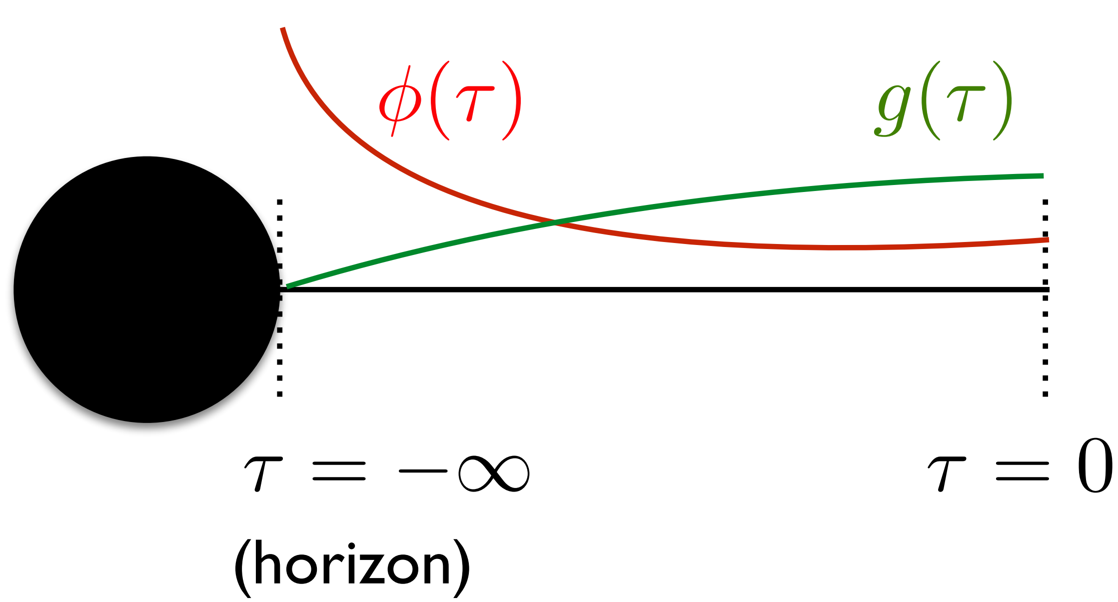
BH induces a running of the scalar field and gauge coupling as approaching the horizon leading to:



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 $A = L^2$

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

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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