The Emergent String Conjecture and Universal Properties in Quantum Gravity

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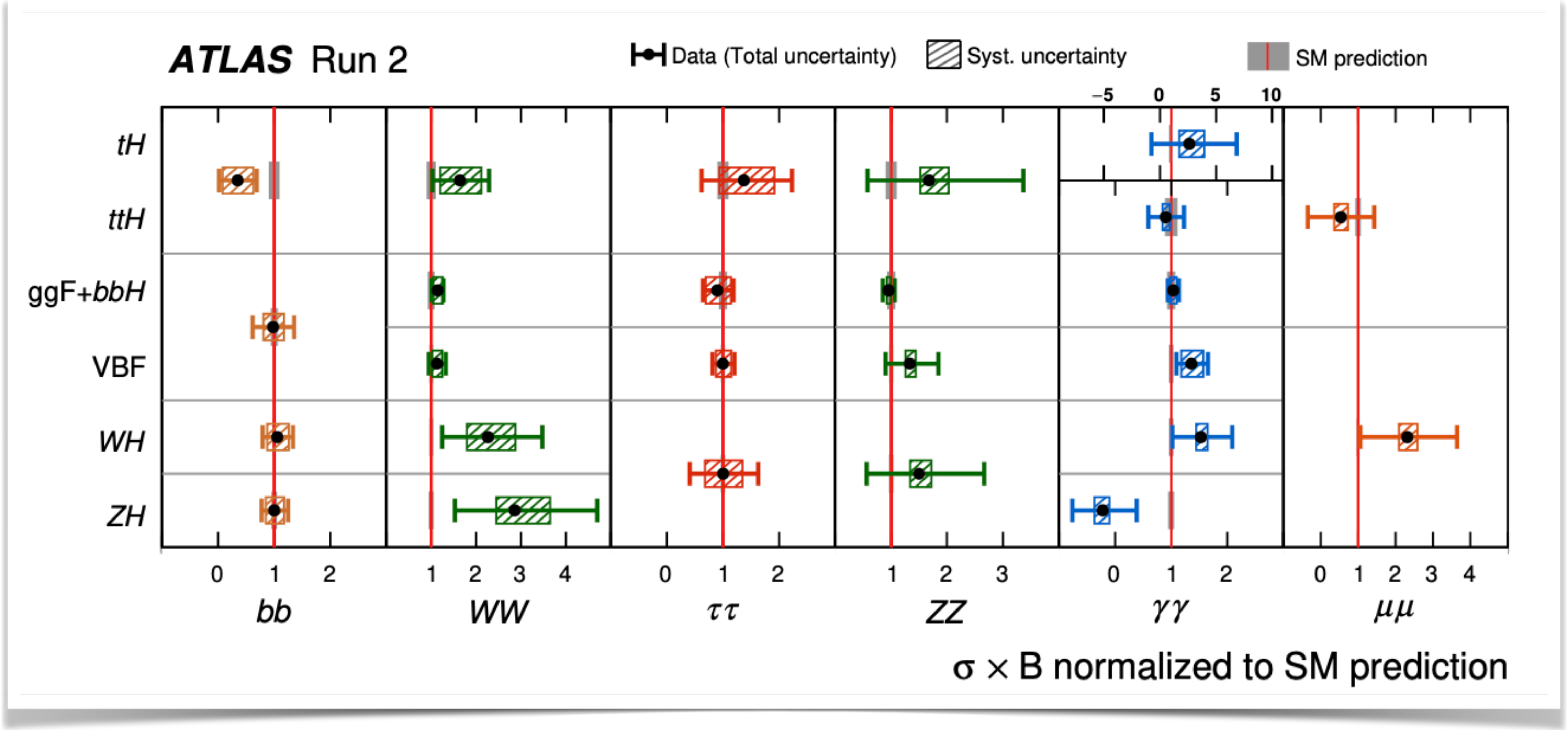
Motivation

Fundamental physics is experiencing extraordinary times:

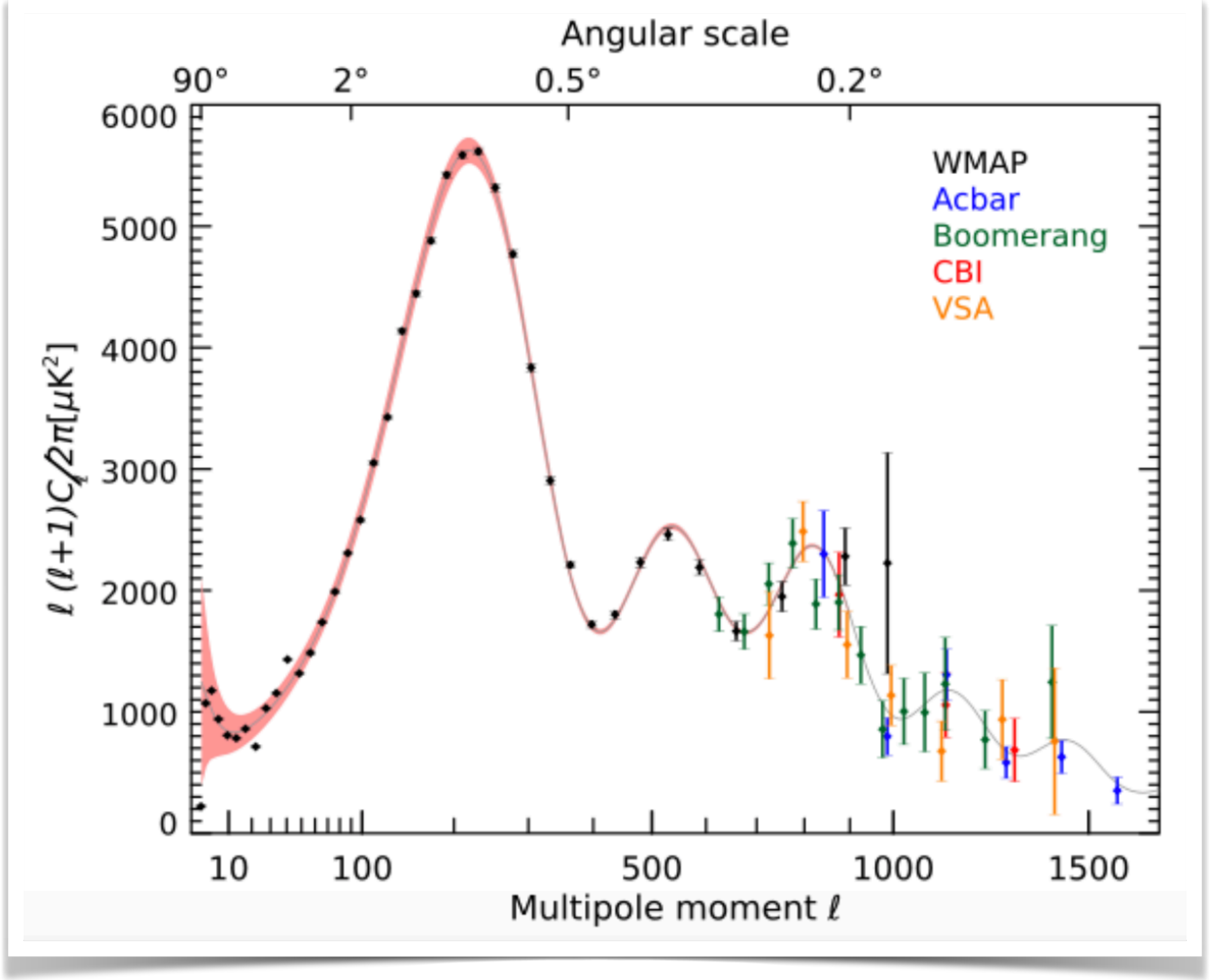
Triumphant success of

Standard Model of Particle Physics



ATLAS, 2207.00092

Standard Model of Cosmology (ΛCDM)



Motivation

Fundamental physics is experiencing extraordinary times:

Triumphant success of

Standard Model of Particle Physics

Quantum field theory/ Quantum gauge theory

Standard Model of Cosmology (ΛCDM)

Classical General Relativity

microscopic scales

astronomical/ cosmological scales

Length scales

Motivation

Fundamental physics is experiencing extraordinary times:

Deep theoretical and conceptual challenges

What is the reason for
matter-antimatter asymmetry?

Why are there hierarchical
couplings in the SM?

?

Nature of Dark Matter?

Origin of cosmic acceleration?
Nature of Dark Energy?
What explains its scale?

Reason for hierarchy between
electroweak scale and Planck scale?
Why is gravity to so weak?

Motivation

Key conceptual question: **How to describe gravity as a quantum theory?**

$$S_{\mathrm{EH}} = \frac{1}{2\kappa_4^2}\int_{\mathbb{R}^{1,3}} \sqrt{-g}\,R + \ldots$$

Dimensionful Coupling:

$$\kappa_4 = \frac{1}{M_{\mathrm{Planck}}} = (8\pi G_N)^{1/2}$$

Quantum gravity as theory of spin-2 fields is not perturbatively renormalisable.

naively - more later!

$\Longrightarrow$ **Effective field theory** valid at energies below **cutoff** $\Lambda_{\mathrm{QG}} \sim M_{\mathrm{Planck}} \sim 10^{19}\,\mathrm{GeV}$

Among the technical problems: **UV divergences in gravity**

Motivation

Top down approach to Quantum Gravity : **String Theory** as currently best developed candidate

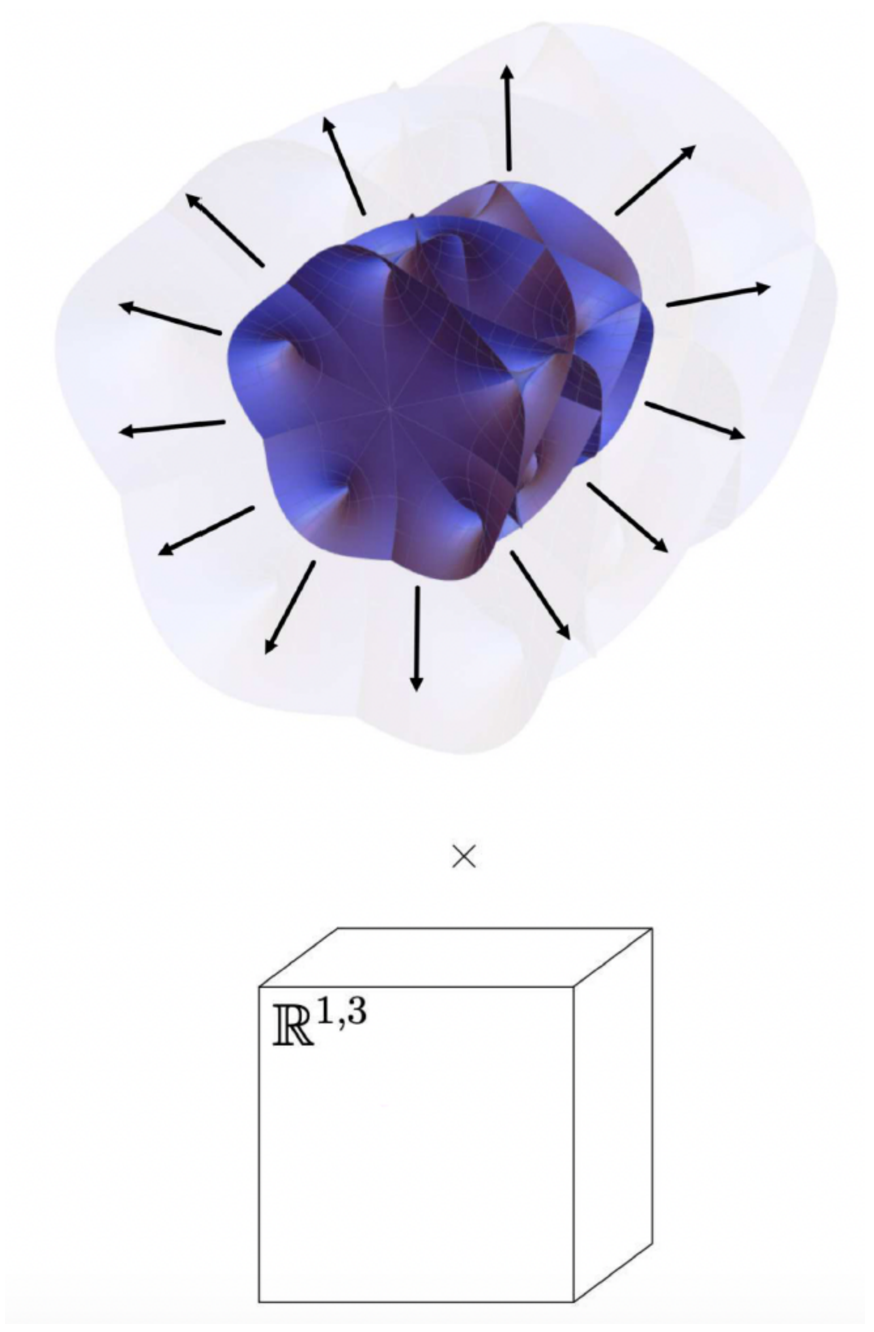
✓ Reproduces at low energies gauge theory and classical Einstein gravity

✓ Perturbatively free of ultra-violet divergences

✓ Unique as a theory up to dualities: no free parameters

✓ Study of its rich vacuum structure in lower dimensions makes contact with frontiers in modern geometry

$\Longrightarrow$ String compactifications may provide UV completion for particle physics and cosmological evolution of the Universe.



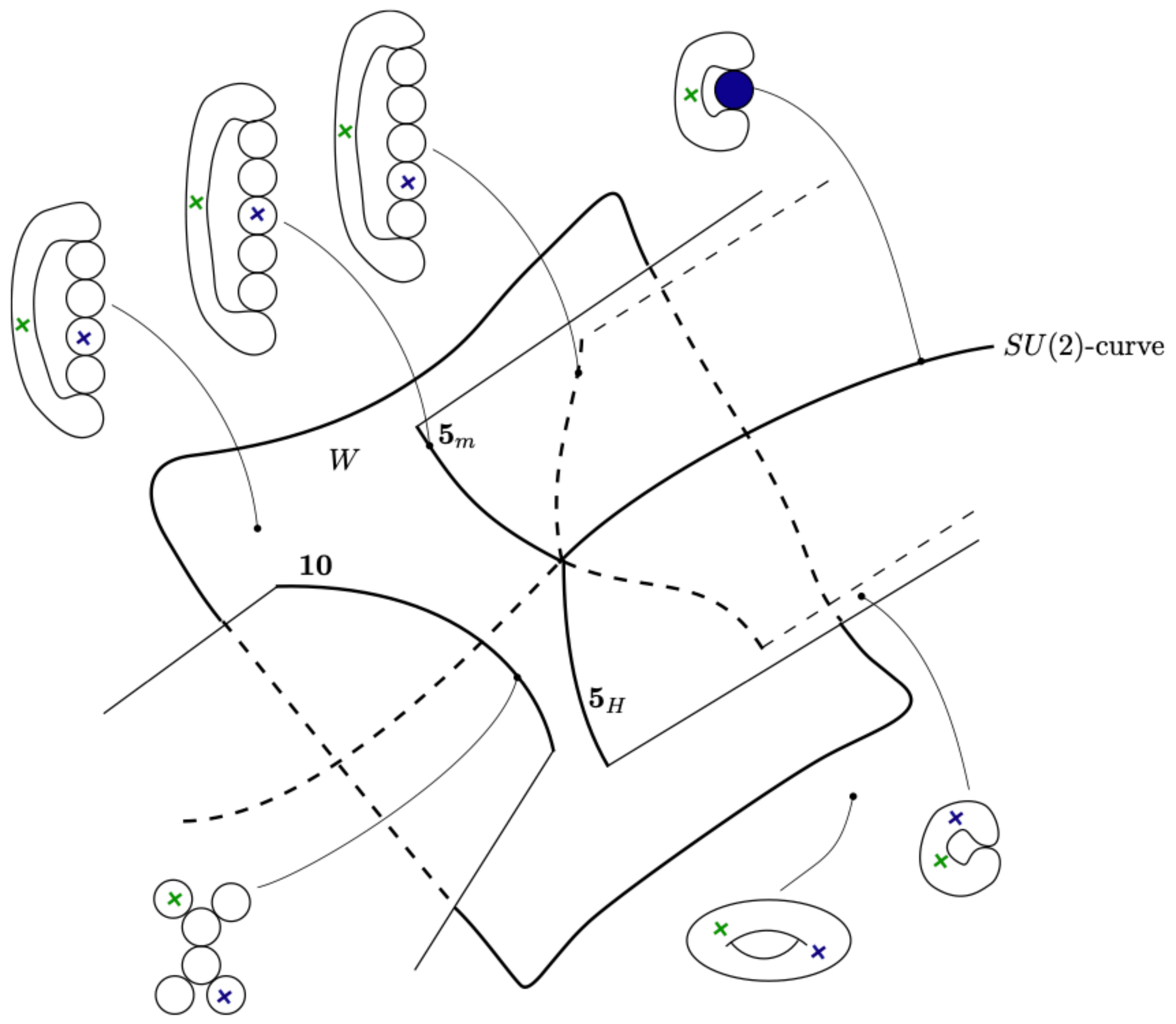
Motivation

Goal: Development of new stringy mechanisms to address challenges in particle physics and cosmology

- Generation of hierarchically small couplings via stringy instantons
  - ➡ new effects not based on strong gauge dynamics
  - ➡ Applications e.g. to neutrino masses

[Blumenhagen,Cvetic,TW'06] [Ibanez,Uranga'06]

- Development of F-theory as a non-perturbative framework for string compactifications:
  - ➡ including new ideas for Grand Unified Theories (GUTs)
  - ➡ along with developing technology in algebraic geometry



[Krause,Mayrhofer,TW'11]

Motivation

Bottom up approach: Can we identify general principles which a theory with a UV completion as a QG theory must satisfy?

SWAMPLAND: **coined by [Vafa'05]**

Effective field theories consistent as QFTs, but with no UV completion as a quantum gravity

$\Longleftrightarrow$

LANDSCAPE:

Effective field theories arising as low-energy limit of fully consistent quantum gravity

Infinite set of theories
$\Longrightarrow$ *Limited predictive power*

Hope: Finite set of theories
$\Longrightarrow$ *Improved predictive power*

Motivation

Arguments oftentimes conjectural in full generality and based on insights on black hole physics

Quantitative tests possible in string theory, e.g. based on properties (quantum) geometry of compactifications

$\Longrightarrow$ connection to mathematics and even predictions for mathematics (see later)

Motivation

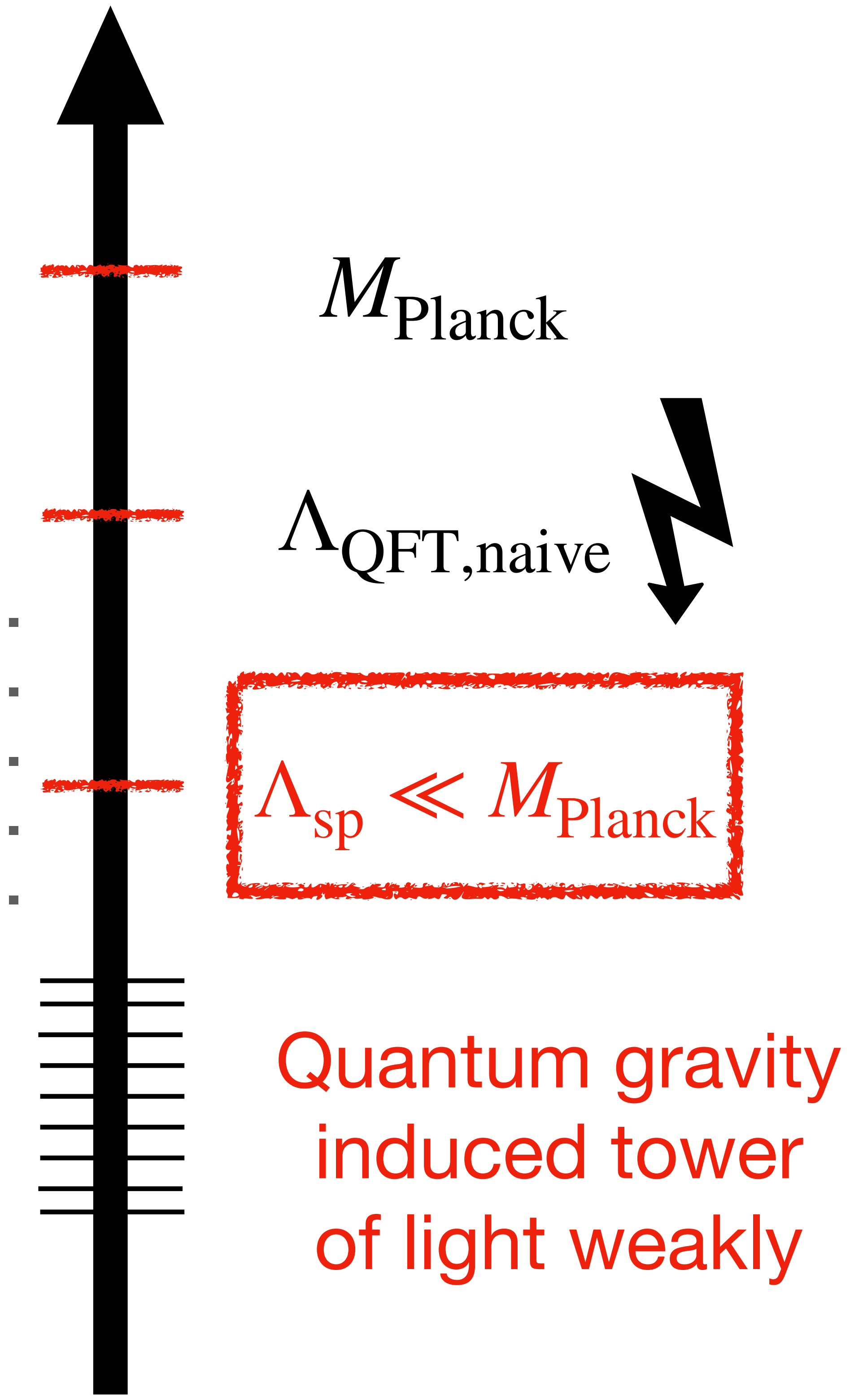
Two key types of observations:

1) Gravity can cease to be described as a *weakly coupled local QFT* parametrically below M_{Planck}:

Species scale $\Lambda_{\text{sp}} \sim N^{-\frac{1}{d-2}} M_{\text{Planck}}$

[Dvali'07] [Dvali,Redi'07] [Dvali,Gomez'08] …

[Harvard group '22-23] [Madrid group '22-23] [MPI groups '22-'24]



- N: number of light weakly coupled particle species enforced by QG
- If $N \gg 1$: $\Lambda_{\text{sp}} \ll M_{\text{Planck}}$
- Example:

  $\Lambda_{\text{sp}} \sim g_{U(1)} M_{\text{Planck}}$ for certain weakly coupled $U(1)$ - see later

When is $\Lambda_{\text{sp}} \ll M_{\text{Planck}}$ and what does this mean for the physical theory?

Motivation

TEASER

Two key types of observations:

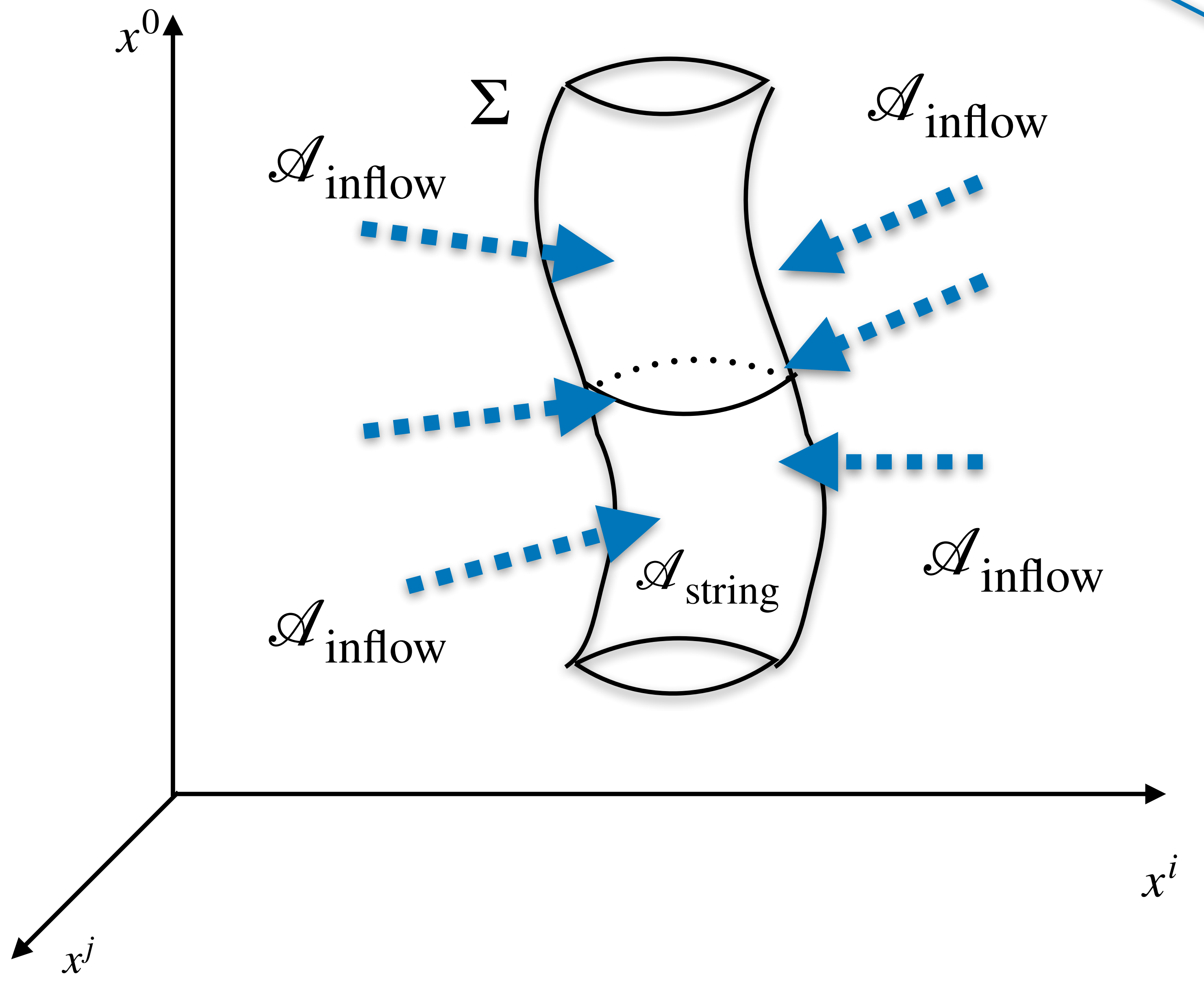
2) Principle of charge completeness in QG

$\Longrightarrow$ higher-dimensional physical objects

$\Longrightarrow$ additional consistency conditions

$\boxed{\Longrightarrow \text{ Finiteness and positivity}}$

More details later!



$$\boxed{\mathscr{A}_{\text{inflow}} = \mathscr{A}_{\text{string}}}$$

Part I:

Emergent String Conjecture

Main question of this talk

Which types of quantum gravity theories are possible?

Or at least asymptotically, at parametrically weak coupling?

Conjecture:

[Lee,Lerche,TW'19]

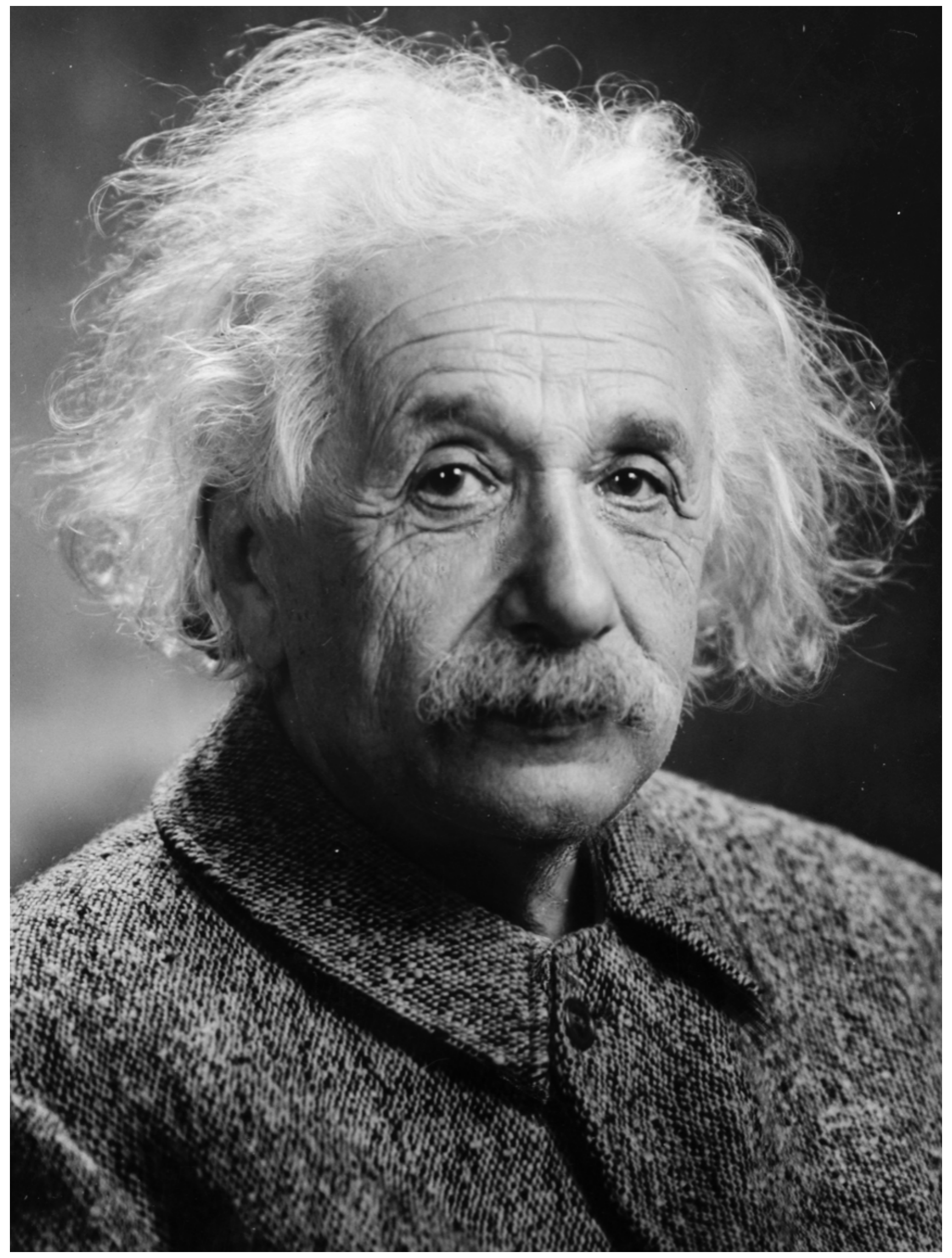
(Almost) Universal behaviour at infinite distance in moduli space of a quantum gravity theory (in asymptotically Minkowski, $d \geq 4$)

No coupling constants in QG

Conjecture: *In a theory of quantum gravity in d > 2 dimensions, all dimensionless couplings are dynamical.*

"Concerning such [dimensionless constants] I would like to state a theorem which at present cannot be based upon anything more than upon a faith in the simplicity of nature:
there are no arbitrary constants of this kind. ..."

Albert Einstein, 1949



No coupling constants in QG

Conjecture: *In a theory of quantum gravity in d > 2 dimensions, all dimensionless couplings are dynamical.*

Example 1: This underlies the idea of solving the strong CP problem via an axion.

$$\underbrace{\theta}_{\text{constant parameter}} \int_{\mathbb{R}^{1,3}} F(x) \wedge F(x) \quad \longrightarrow \quad \int_{\mathbb{R}^{1,3}} \underbrace{a(x)}_{\text{dynamical field}} \, F(x) \wedge F(x)$$

No coupling constants in QG

Conjecture: *In a theory of quantum gravity in d > 2 dimensions, all dimensionless couplings are dynamical.*

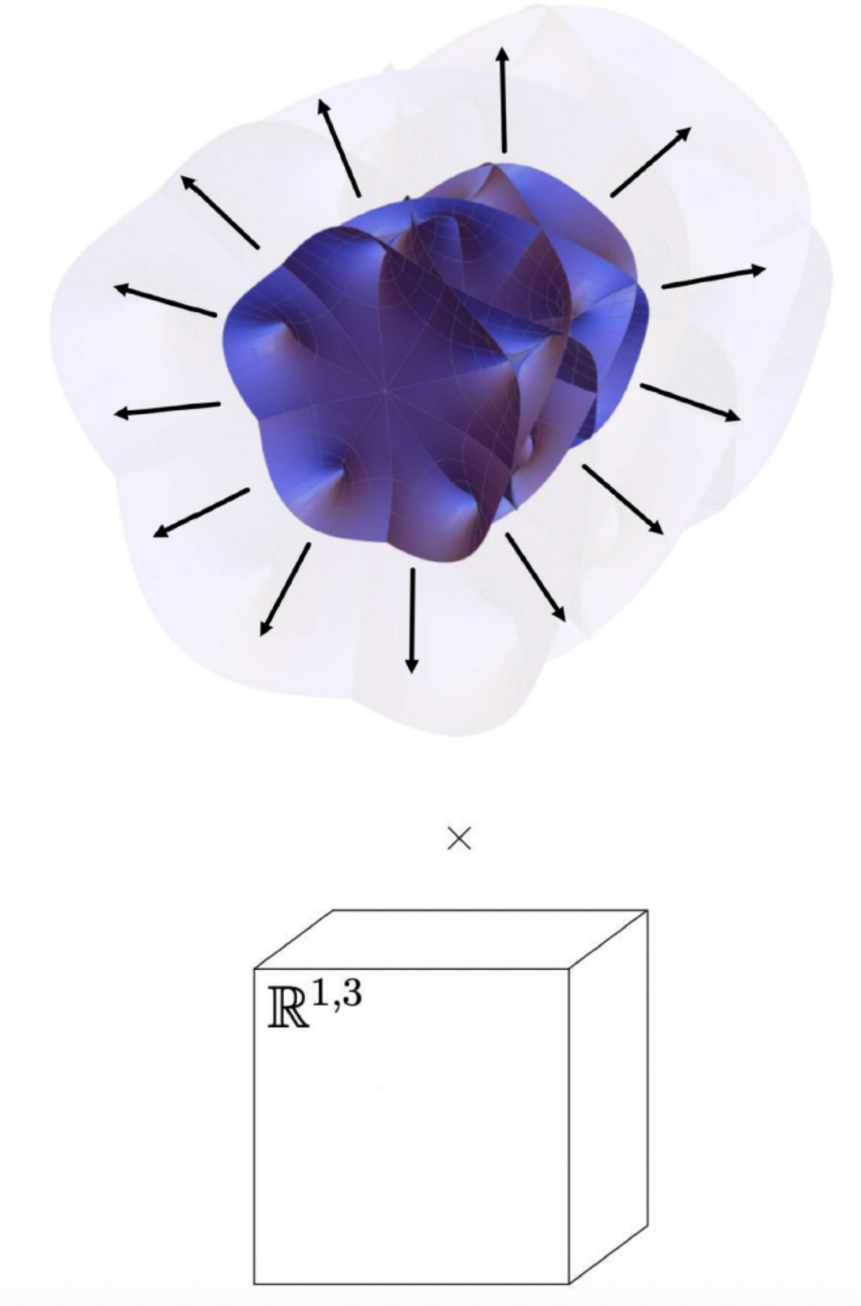
Example 2: In string theory all dimensionless couplings are set by vacuum expectation values of dynamical scalar fields = moduli

$$S = \int \frac{1}{2g^2(\varphi)} F^2 + \ldots + G_{ij}(\varphi)\, \partial_\mu \varphi^i\, \partial^\mu \varphi^j$$

coupling

dynamical scalar fields

metric on the moduli space



In geometric compactifications: moduli = fluctuations of spacetime metric along extra dimensions

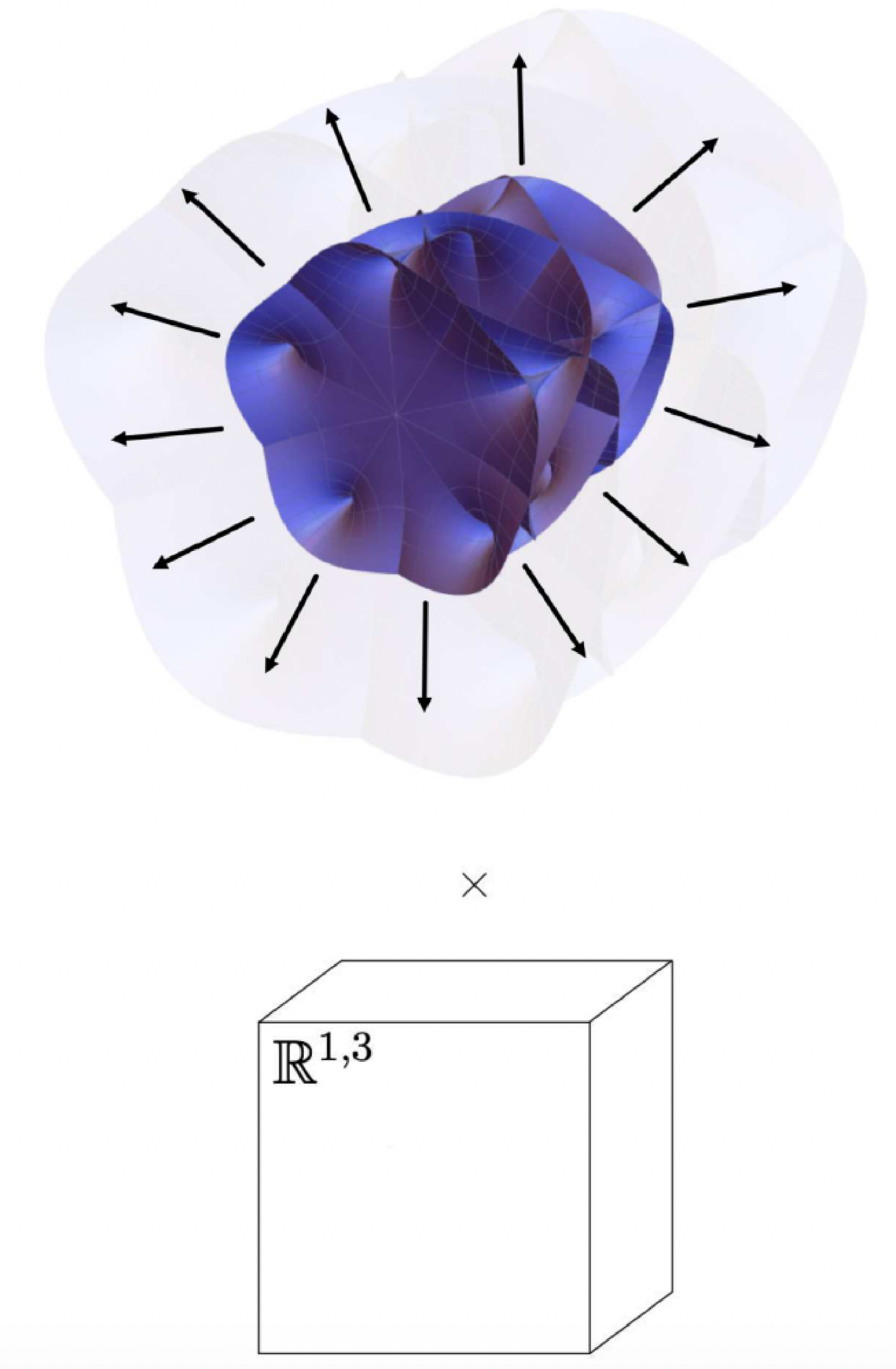
No coupling constants in QG

Conjecture: *In a theory of quantum gravity in d > 2 dimensions, all dimensionless couplings are dynamical.*

Example 2: In string theory all dimensionless couplings are set by vacuum expectation values of dynamical scalar fields = moduli

$$g_i = \langle \varphi_i \rangle$$

In geometric compactifications:
moduli = fluctuations of metric along extra dimensions



Space of physical couplings $\Longleftarrow$ $\boxed{\text{Moduli space}}$ $\Longrightarrow$ Shape and size of extra dimensions

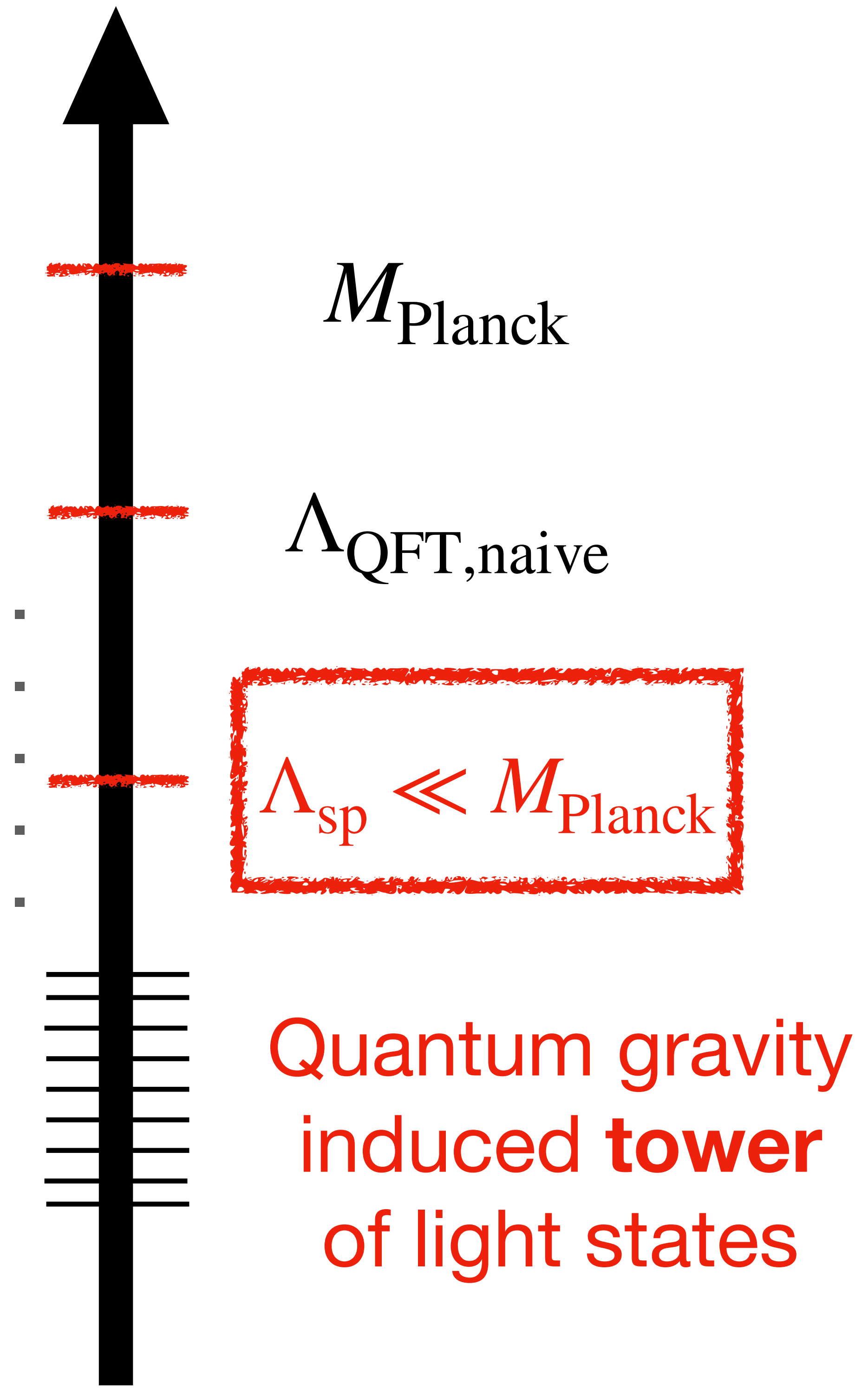
Swampland Distance Conjecture

Swampland Distance Conjecture

[Ooguri,Vafa'06]

- If a quantum gravity moduli space is non-empty, it is non-compact.
- **At infinite distance** in moduli space (w.r.t. natural metric $G_{ij}(\varphi)$) the effective field theory breaks down:

An **infinite tower** of weakly coupled states becomes **light.**



geodesic distance

$$\boxed{M_Q = M_P \exp\left(-\alpha \frac{d_{PQ}}{M_{\text{Pl}}}\right) \to 0}$$

In particular: This happens at asymptotically weak coupling $g \to 0$!

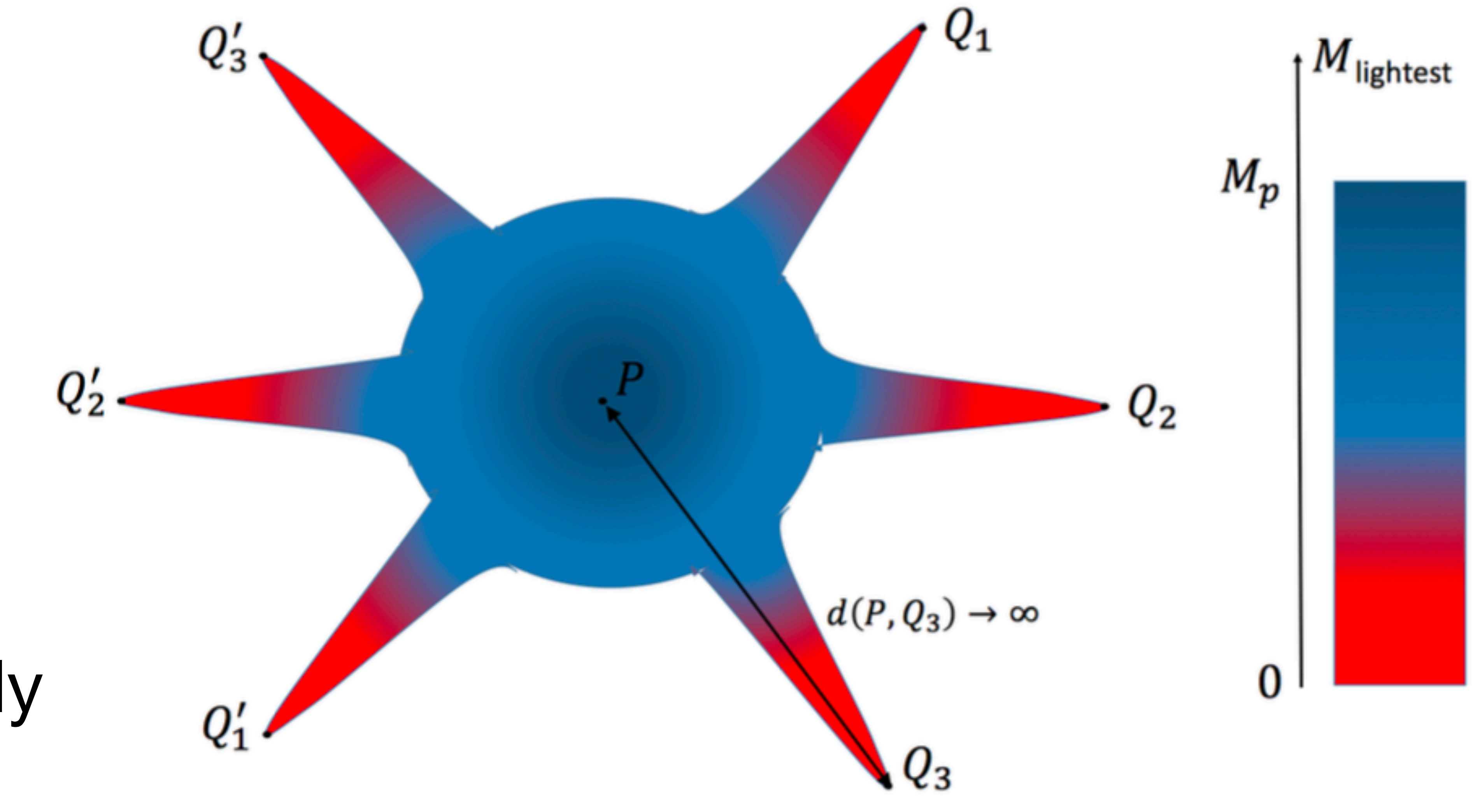
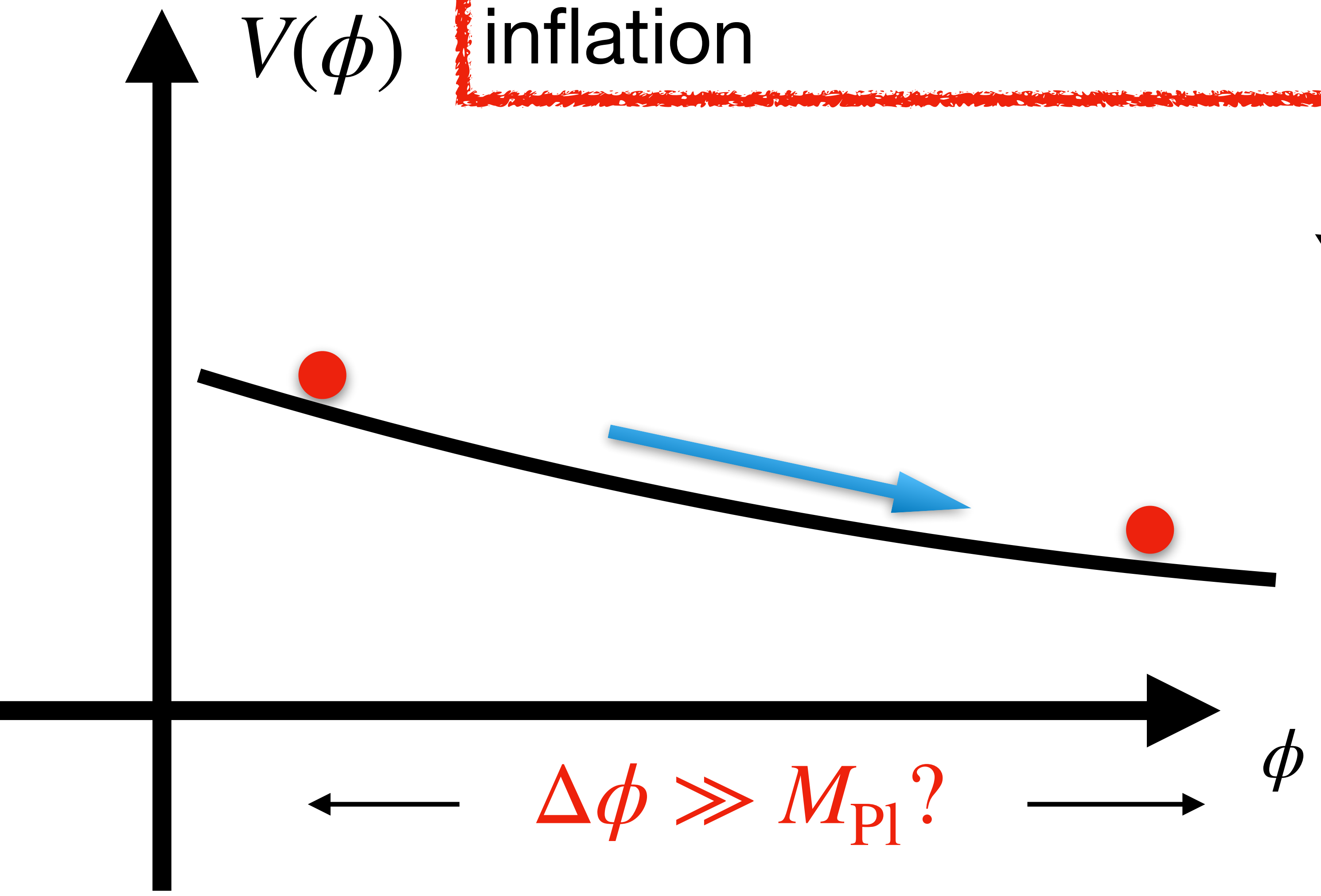


Image: Palti,1903.06239

Constrains parametrically large field excursion/ inflation



Swampland Distance Conjecture

Asymptotic no deSitter Conjecture
[Ooguri,Palti,Shiu,Vafa'18]

$\Longleftrightarrow$ at best quasi de Sitter complementary to earlier arguments in [Dvali,Gomez'13/14]

AdS Distance Conjecture: tower of $m \sim \Lambda^{-a}$
[Lüst,Palti,Vafa'19]

CFT Distance Conjecture
[Baume,Calderon-Infante'20]
[Perlmutter,Rastelli,Vafa,Valenzuela'20]
[Baume,Calderon-Infante'23]
[Ooguri,Wang'24]

Gravitino mass Conjecture
[Cribiori,Lüst,Scalisi'21]
[Castellano,Font,HerraezIbanez'21]

Asymptotics of Quantum Gravities

What is the **nature of the asymptotic gravity theory**?

- ➡ Is it a known theory?
- ➡ Or is it a mess with infinitely many massless states defying a sensible EFT?
- ➡ Can one discover new theories in this way, similar to behaviour at strong coupling at finite distance?

What is the **nature of the asymptotic tower of light states,** up to duality?

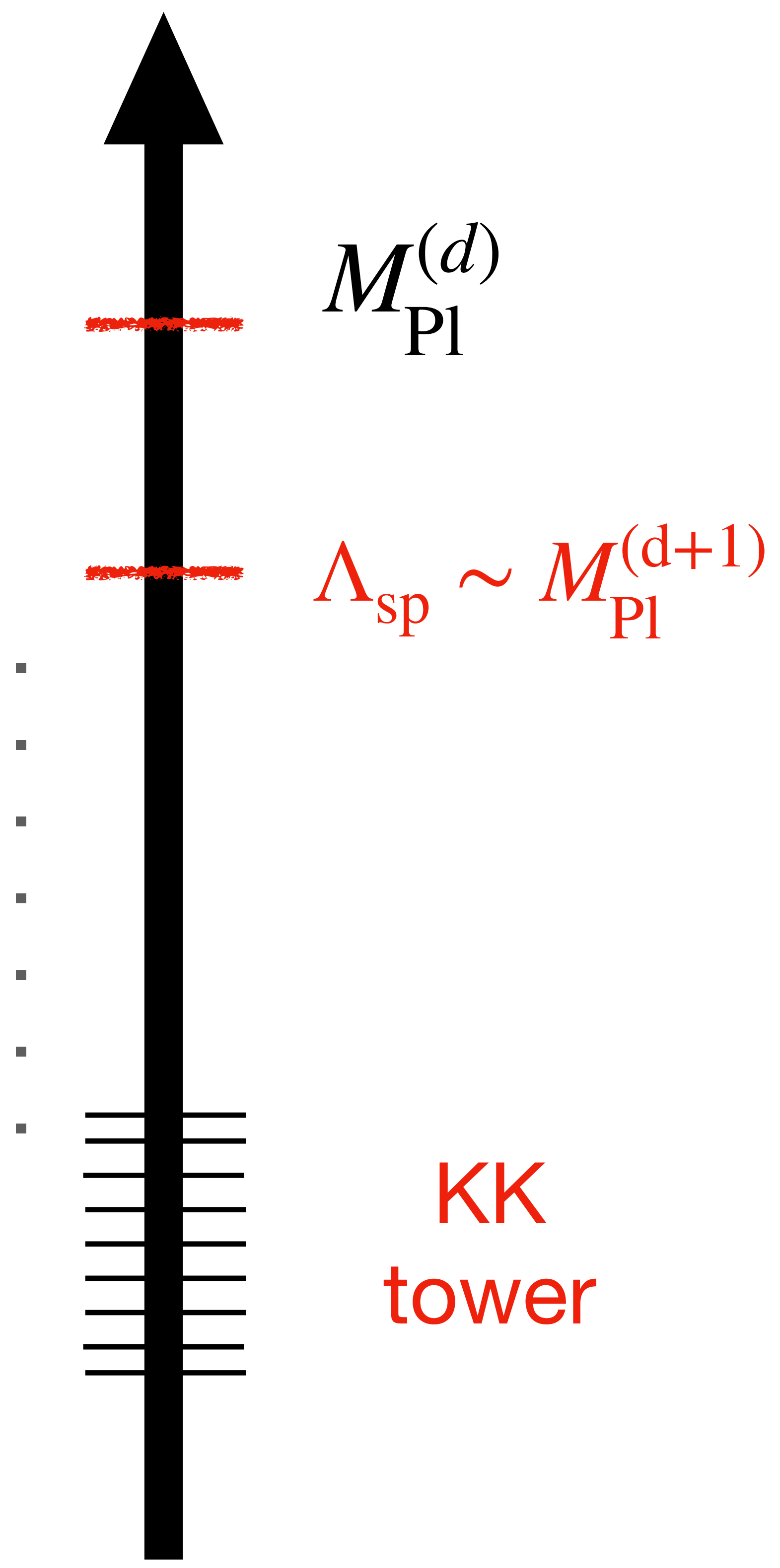
What is the **species scale**?

What is the **exponential vanishing rate α in $M \sim M_0 e^{-\alpha \frac{\Delta}{M_{\rm Pl}}}$** ?
needed for practical applications e.g. to cosmological evolution

Emergent String Conjecture

[Lee,Lerche,TW'19]

Consider a quantum gravity theory in $d \geq 4$ dimensions, asymptotically Minkowski.
Every infinite distance limit in the moduli space (if existent) is one of 2 types:



Decompactification limit :

- One or several extra dimensions decompactify.

- Leading tower: KK modes

↓

Higher-dimensional theory

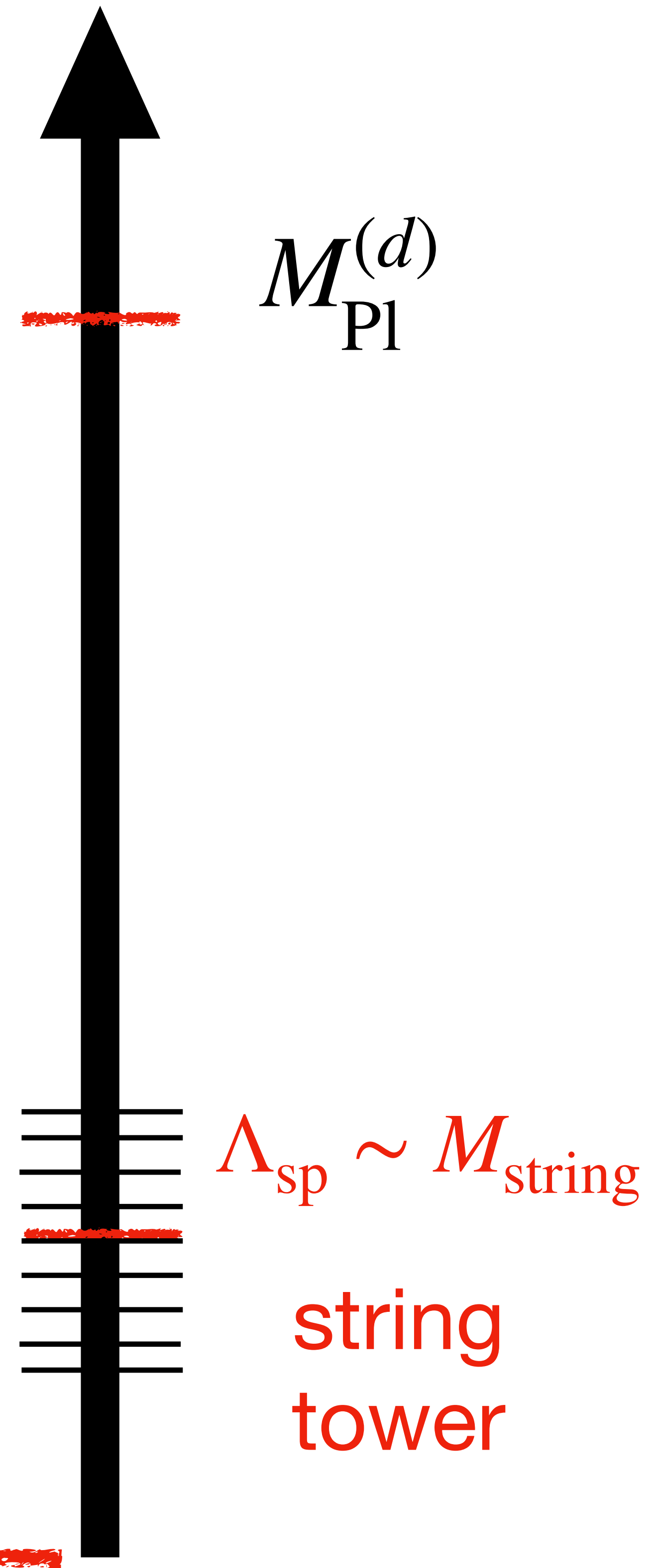
Emergent String Limit:

- A *unique* critical string becomes asymptotically tensionless w.r.t. Planck scale and weakly coupled.

- Leading tower: String excitations accompanied by tower KK modes at same scale (unless $d = 10$)

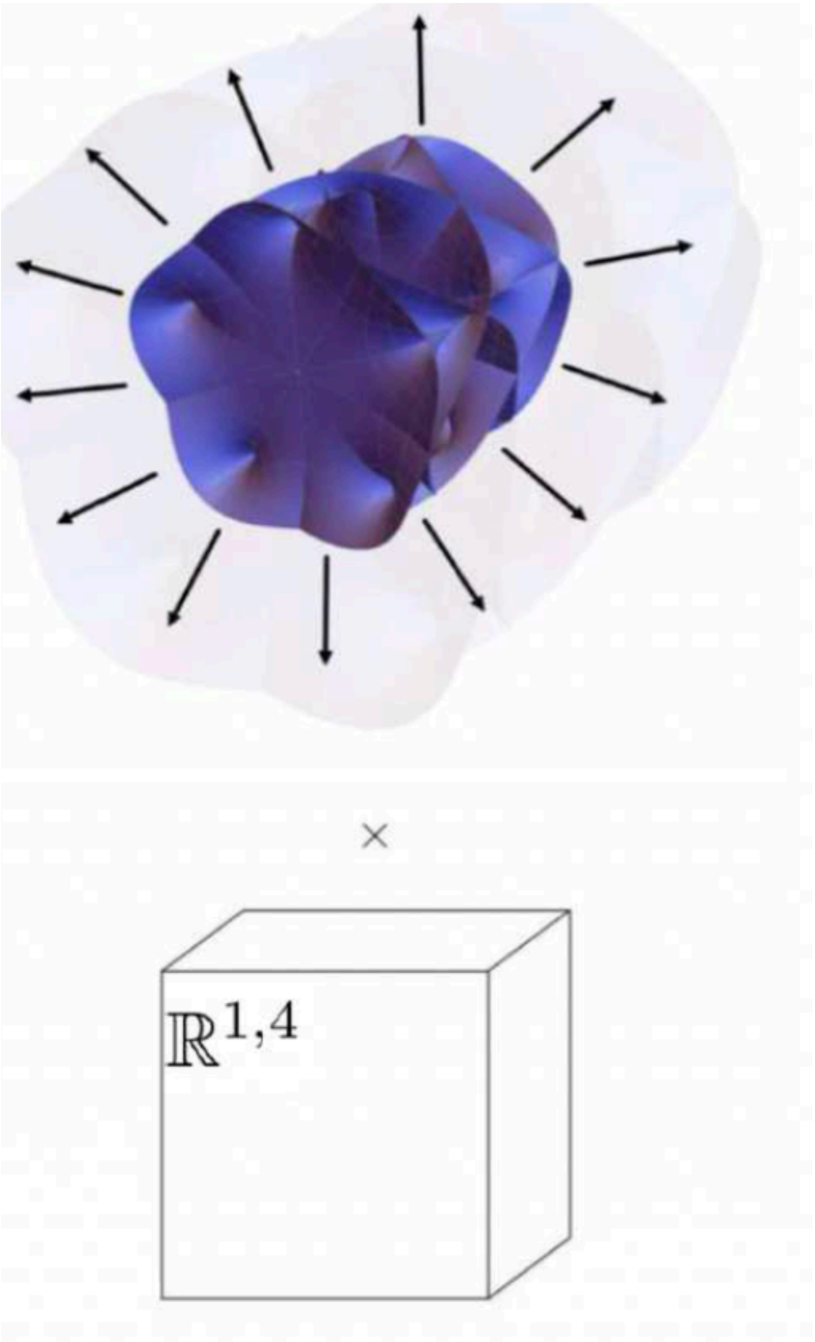
↓

Weakly coupled string theory in same dimension



Evidence

M-Theory on Calabi-Yau 3-fold



M-theory on $\mathbb{R}^{1,4} \times X_3$ $\Longrightarrow$ 5d $N = 1$ supergravity

Physics:
Parametrises the gauge couplings $\longleftarrow$ **Vector multiplet moduli space** $\longrightarrow$ **Geometry of X_3:**
Volumes of curves on X_3 at fixed total volume $\mathscr{V}_{X_3}$

$$S = \int \frac{1}{2g^2(\varphi)} F^2 + \ldots + G_{ij}(\varphi)\, \partial_\mu \varphi^i\, \partial^\mu \varphi^j$$

$\varphi^i \leftrightarrow \mathscr{V}_{C_i}$ $\longleftarrow$ complex curves on X_3

Wanted: Mathematics and physics of **infinite distance limits at fixed $\mathscr{V}_{X_3} = 1$:**

taking some curve volumes $\mathscr{V}_C \to \infty$ at fixed overall volume $\mathscr{V}_{X_3}$

M-Theory on Calabi-Yau 3-fold

Wanted: taking some curve volumes $\mathscr{V}_C \to \infty$ at fixed overall volume $\mathscr{V}_{X_3}$

Intuition: X_3 **must become very anisotropic**

Locally: $X_3 \simeq F \times B$ $\qquad \mathscr{V}_F \to 0 \qquad \mathscr{V}_B \to \infty$

$$\mathscr{V}_{X_3} \sim \mathscr{V}_F \times \mathscr{V}_B \sim \text{const}$$

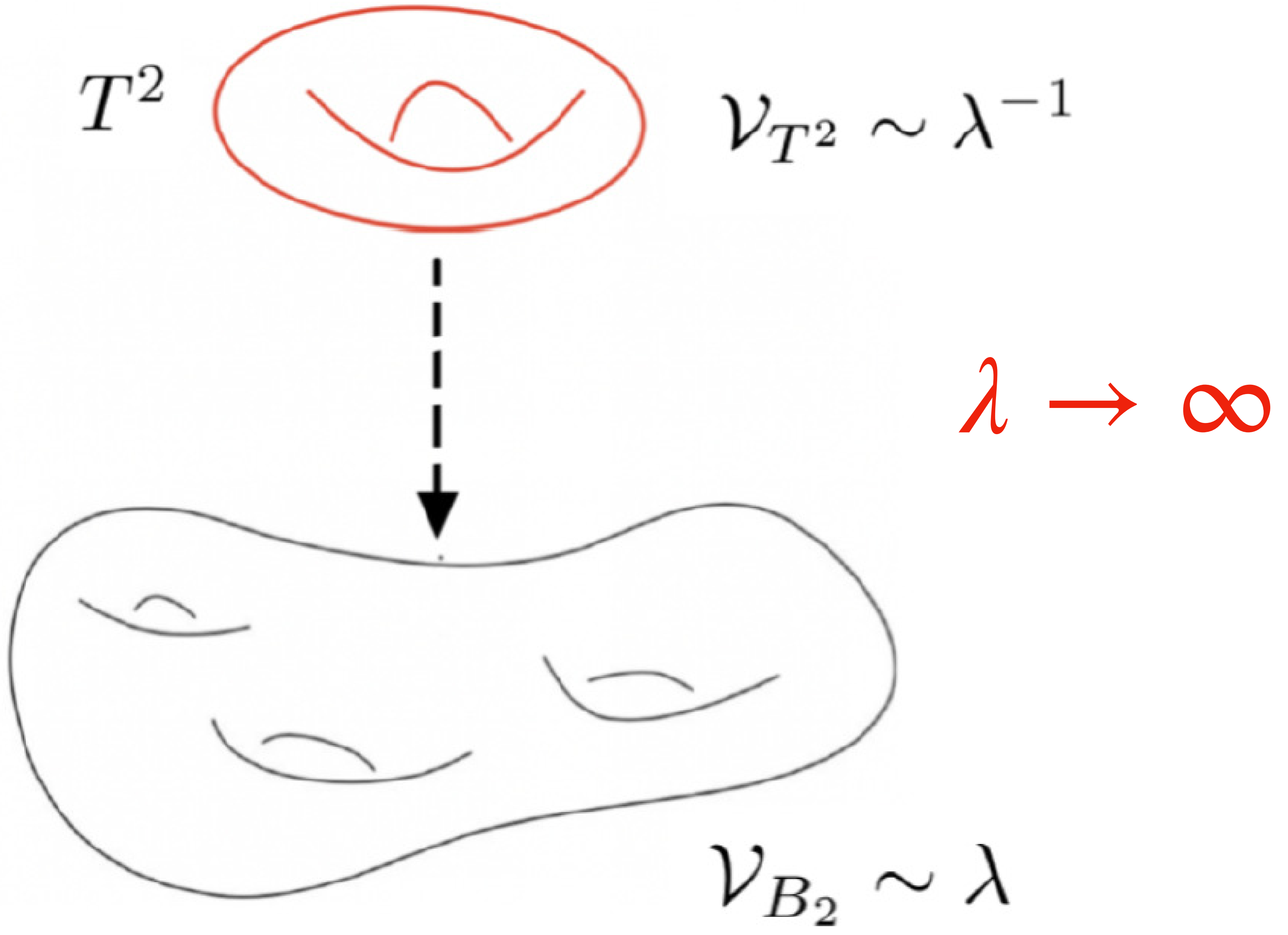
Globally: X_3 has structure of a **fibration**, with *small fiber* F

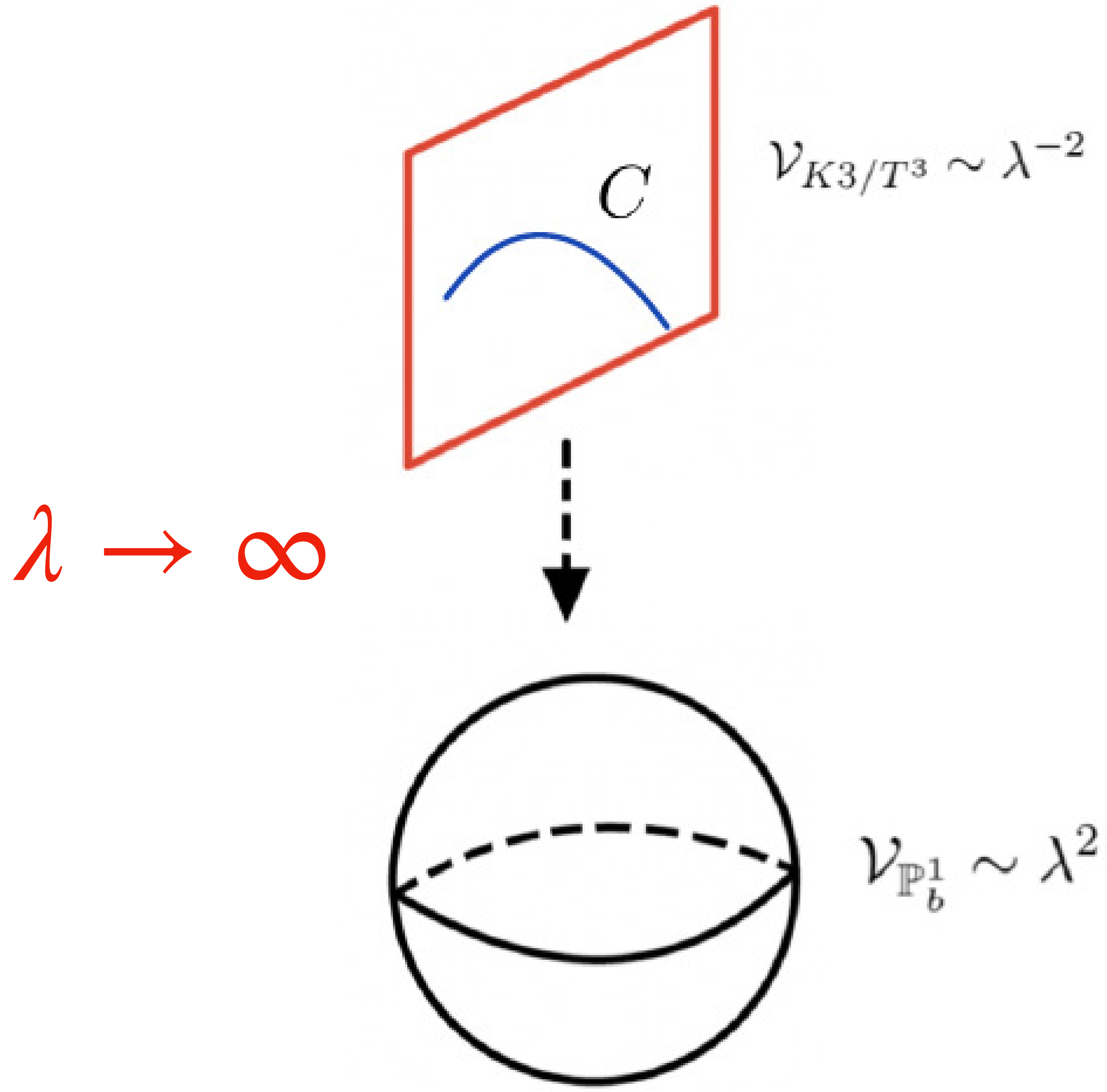
M-Theory on Calabi-Yau 3-fold

Result of **systematic geometric classification**: [Lee,Lerche,TW'19 (1)(2)(3)]

In every such infinite distance limit in classical Kähler moduli space there is a **unique fiber shrinking at the fastest rate,** with two possibilities:

Case 1: T^2 Limit

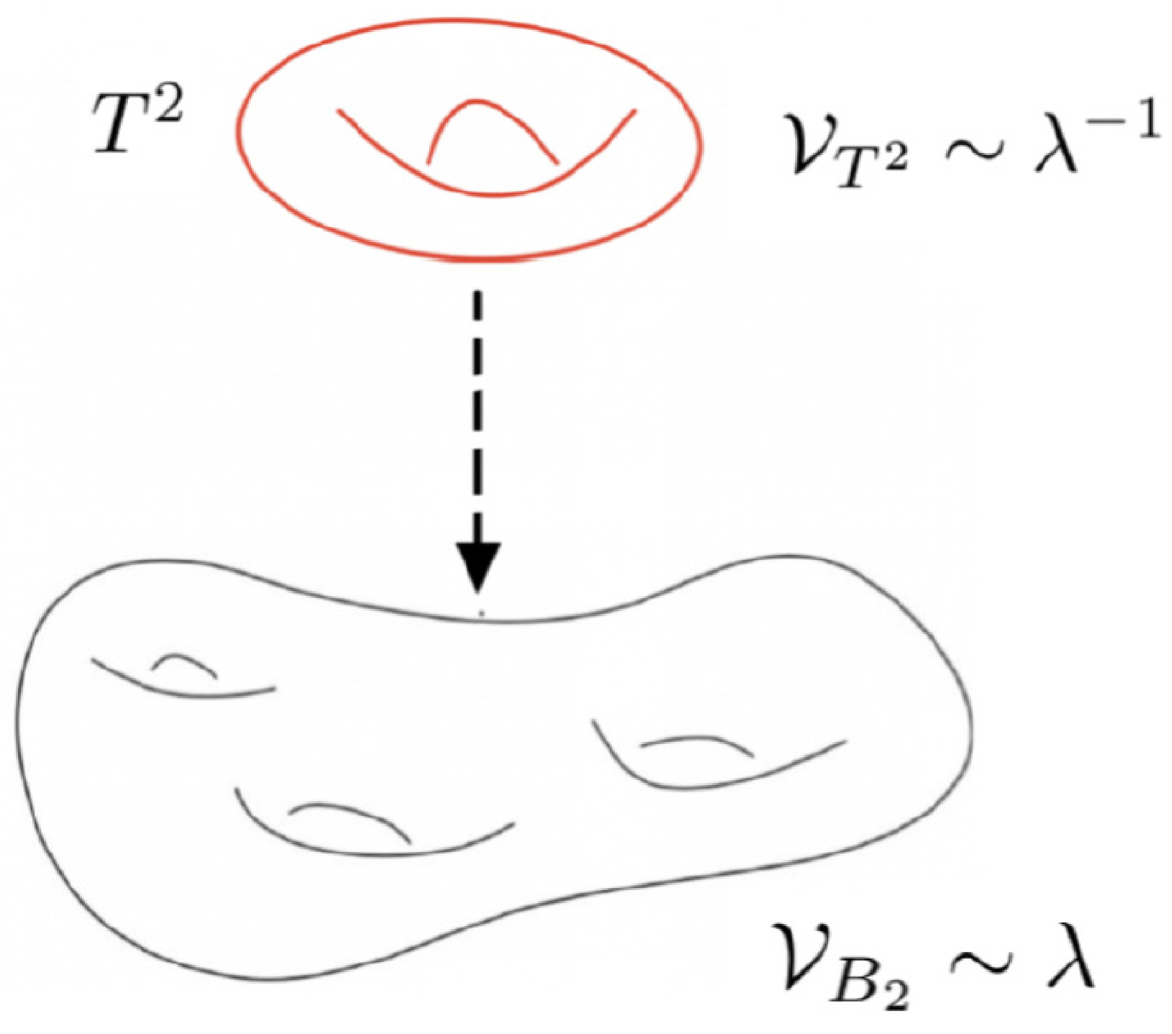




Case 2: K3 / T^4 Limit

M-Theory on Calabi-Yau 3-fold

Case 1: T^2 **Limit**



$\lambda \to \infty$

M2-brane wrapped n-times on T^2

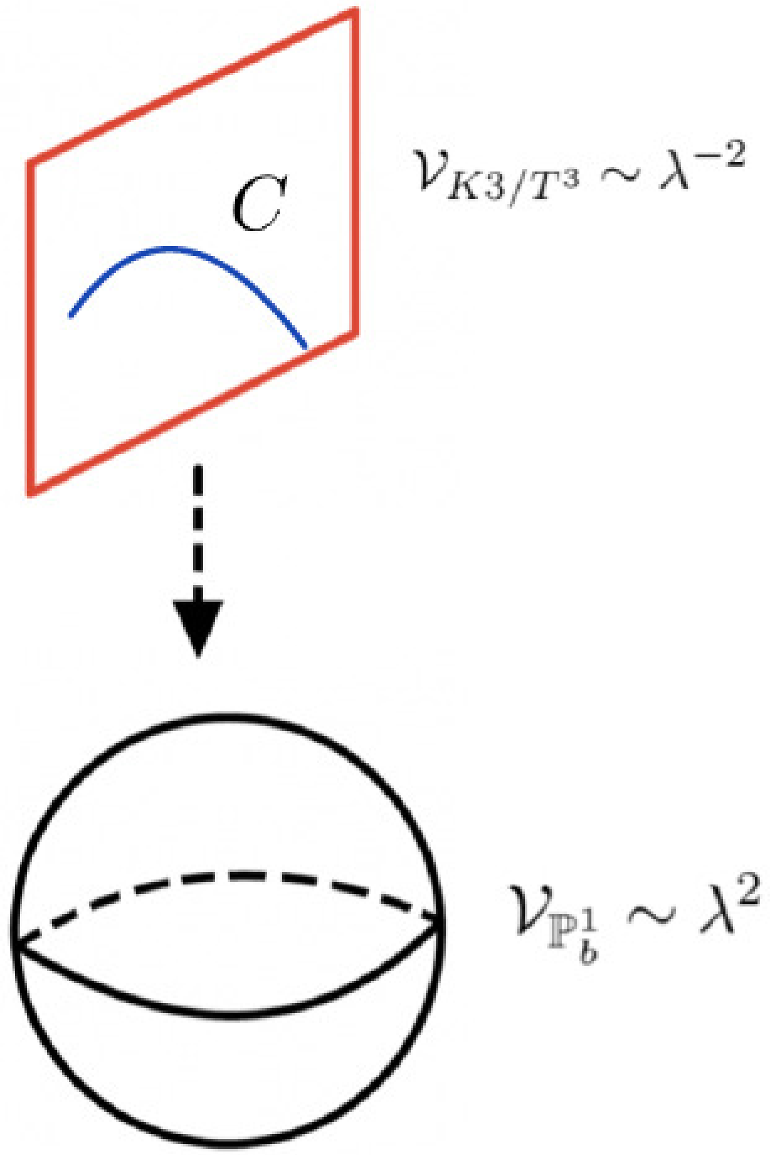
KK-like tower of light particles:

$$\frac{M_n}{M_{\rm Pl}} \sim n\mathscr{V}_{T^2} \to 0$$

Decompactification limit

here: 5d → 6d

$\lambda \to \infty$



Case 2: **K3 /** T^4 **Limit**

M5-brane wrapped once on $K3/T^4$

Tower of string excitations!

Light critical string!

$$\frac{M_n}{M_{\rm Pl}} \sim \sqrt{n}\mathscr{V}_{K3/T4} \to 0$$

Emergent String limit

Three potential pitfalls

Caveat 1: Emergent strings are critical strings.

✓ guaranteed by properties of fiber as K3 or T^4 surface in geometry!

Caveat 2: Emergent strings are always unique.

✓ guaranteed by explicit geometric realisation of limits

✓ avoids potential inconsistencies

Caveat 3: Emergent strings are always accompanied by a KK tower.

✓ never find new critical string of purely d<10 dimensional type

✓ often guaranteed only due to quantum corrections to moduli space

[Baume,Marchesano,Wiesner'20] [Kläwer,Lee,TW,Wiesner'20] [Alvarez-Garcia,Kläwer,TW'21]

Bottom-up arguments

Evidence presented so far is top-down, starting from string or M-theory and via dualities

Recent arguments constrain possible light weakly coupled towers from bottom-up

- using species entropy **[Basile, Lüst, Montella'23] [Herraez,Lüst,Masias,Scalisi'24]**
- using black hole thermodynamics **[Bedroya, Mishra, Wiesner'24]**

These results indeed suggest:

Possible towers are

- KK-towers, or
- or towers with exponential degeneracy (string-like behaviour)

ESC and positivity in supergravity

Which properties must a supergravity theory obey to comply with the Emergent String Conjecture? **[Kaufmann,Lanza,TW in progress]**

Preliminary results:

Positivity of topological couplings key to guarantee uniqueness of emergent strings and absence of pathological limits

Example:
5d N=1 SUGRA

$$S = \int_{\mathbb{R}^{1,4}} \frac{M_{\mathrm{Pl}}^3}{2}\sqrt{-g}\, R + f_{IJ}\, F^I \wedge *F^J + \frac{1}{6} C_{IJK}\, A^I \wedge F^J \wedge F^K + \ldots$$

Positivity $C_{IJK} \geq 0$ seems required

Some consequences

Weak Gravity Conjecture

[Arkani-Hamed,Motl,Nicolas,Vafa'05]

A U(1) gauge theory coupled to quantum gravity must possess **some**

super-extremal state with

$$\boxed{\frac{g_{\mathrm{U(1)}}\, q}{m} \geq \frac{g_{\mathrm{U(1)}}\, Q_{\mathrm{BH,ext.}}}{M_{\mathrm{BH,ext.}}}}$$

required super-extremal state

Extremal charged black hole sets largest charge-to-mass ratio of all black hole

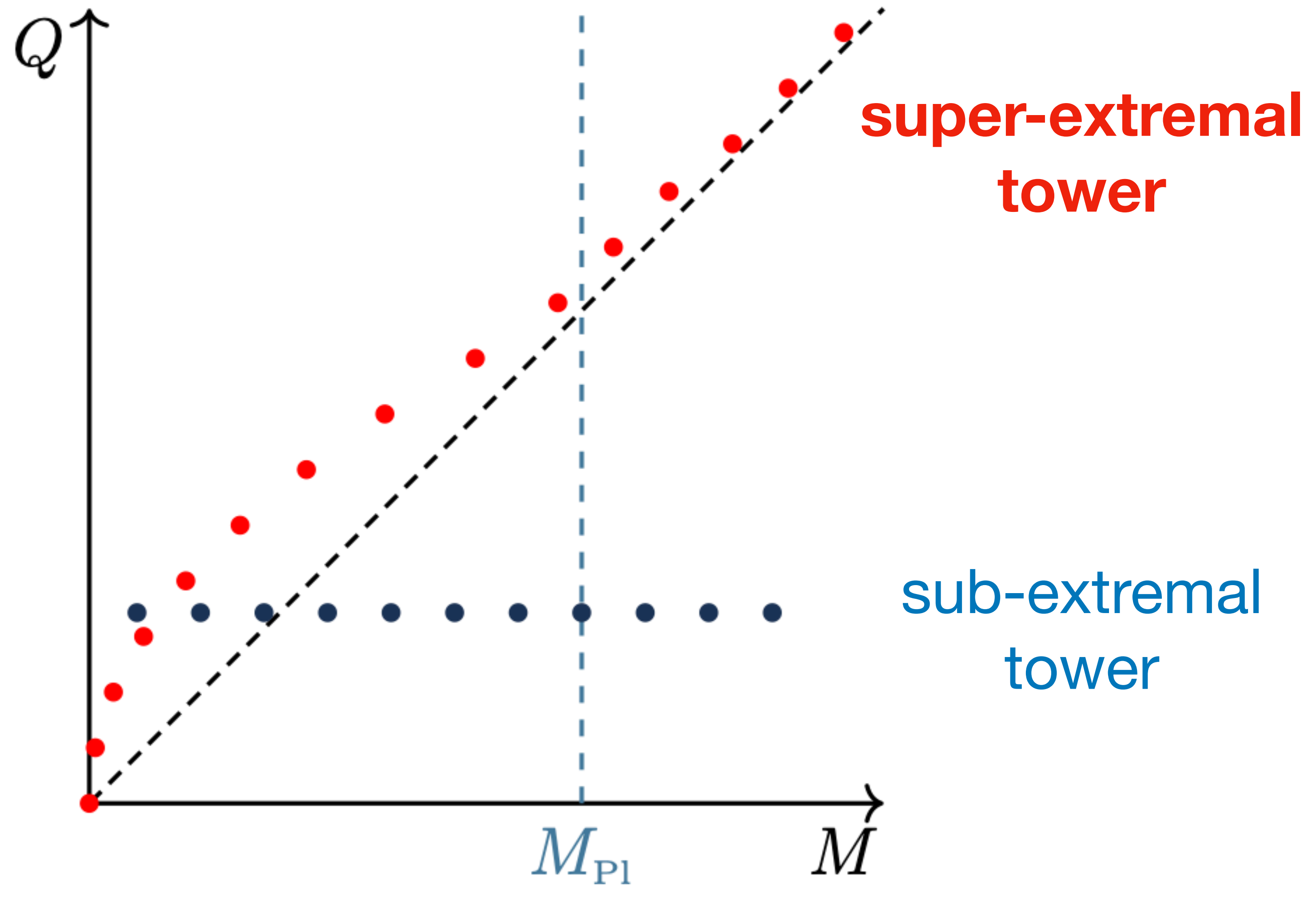
Arguments a priori heuristic (every black hole should be able to decay)

In asymptotically weak coupling limits:

[Cota,Mininno,TW,Wiesner'23]

Consistency under circle reduction requires a **tower of super-extremal states**

[Heidenreich,Reece,Rudelius'15] [Montero,Shiu,Soler'16][Andriolo,Junghans,Noumi,Shiu'18]



The Asymptotic Tower Weak Gravity Conjecture …

… follows from the Emergent String Conjecture!

- Asymptotic weak coupling limits are infinite distance limits in moduli space.
- The only weakly coupled gauge groups are therefore:

Kaluza-Klein U(1) gauge groups → Kaluza-Klein tower

Perturbative gauge groups from (heterotic) string theory → Perturbative string excitation tower

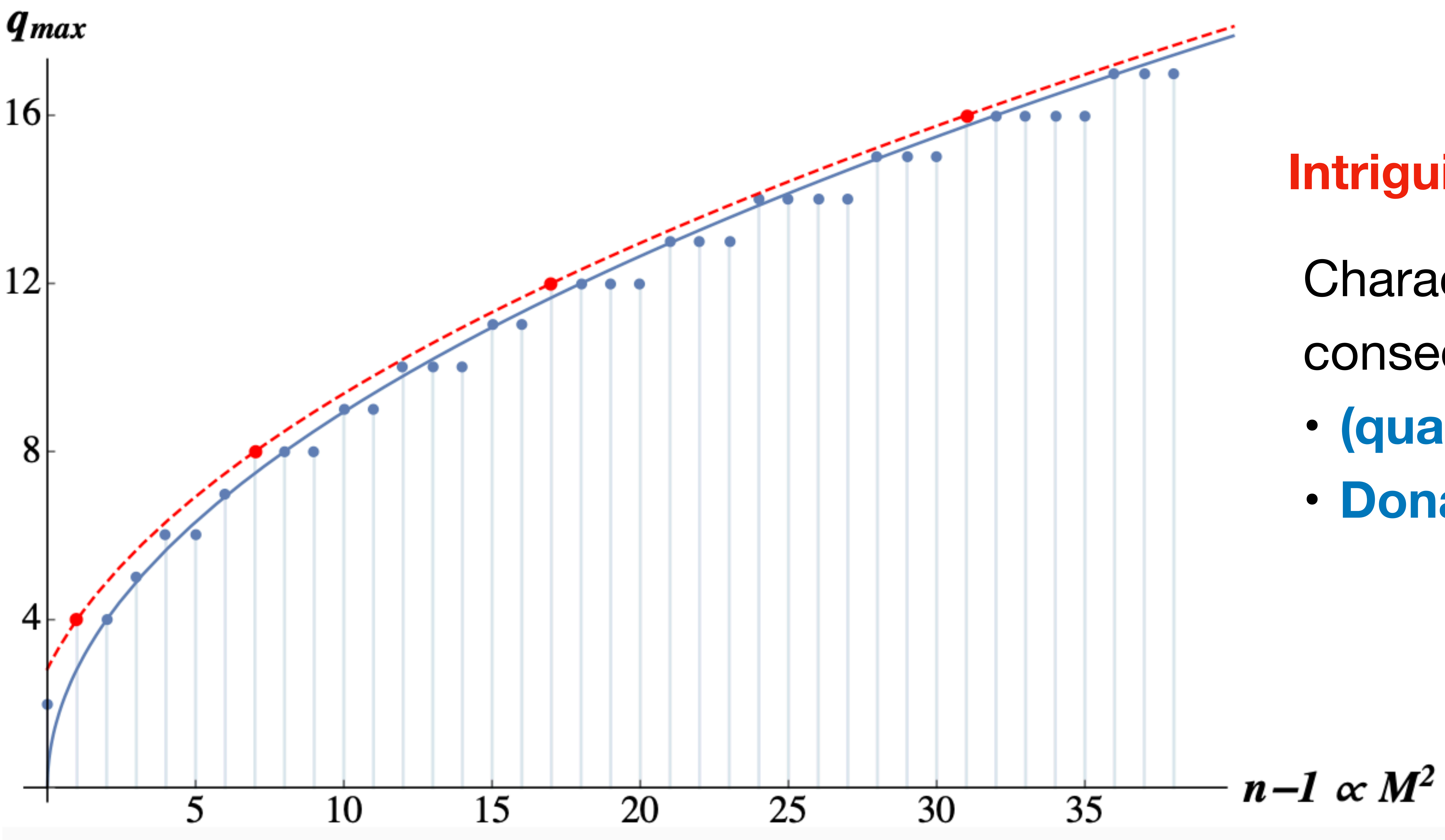
✔

Both include a tower of super-extremal states!

$$\frac{g_{\mathrm{U}(1)}\, q}{m} \geq \frac{g_{\mathrm{U}(1)}\, Q_{\mathrm{BH,ext.}}}{M_{\mathrm{BH,ext.}}}$$

Detailed analysis:

- F-theory: [Lee,Lerche,TW'18-20] [Lee,Lerche,Lockhart,TW'20] [Kläwer,Lee,TW,Wiesner'21]
- M-theory: [Cota,Mininno,TW,Wiesner'22-23]



taken from [Lee,Lerche,TW'18]

Intriguing connection to mathematics:

Characteristic behaviour is a consequence of **modular properties** of

- **(quasi-)Jacobi forms** (6d/4d), or of
- **Donaldson-Thomas invariants** (5d/4d)

Detailed analysis:

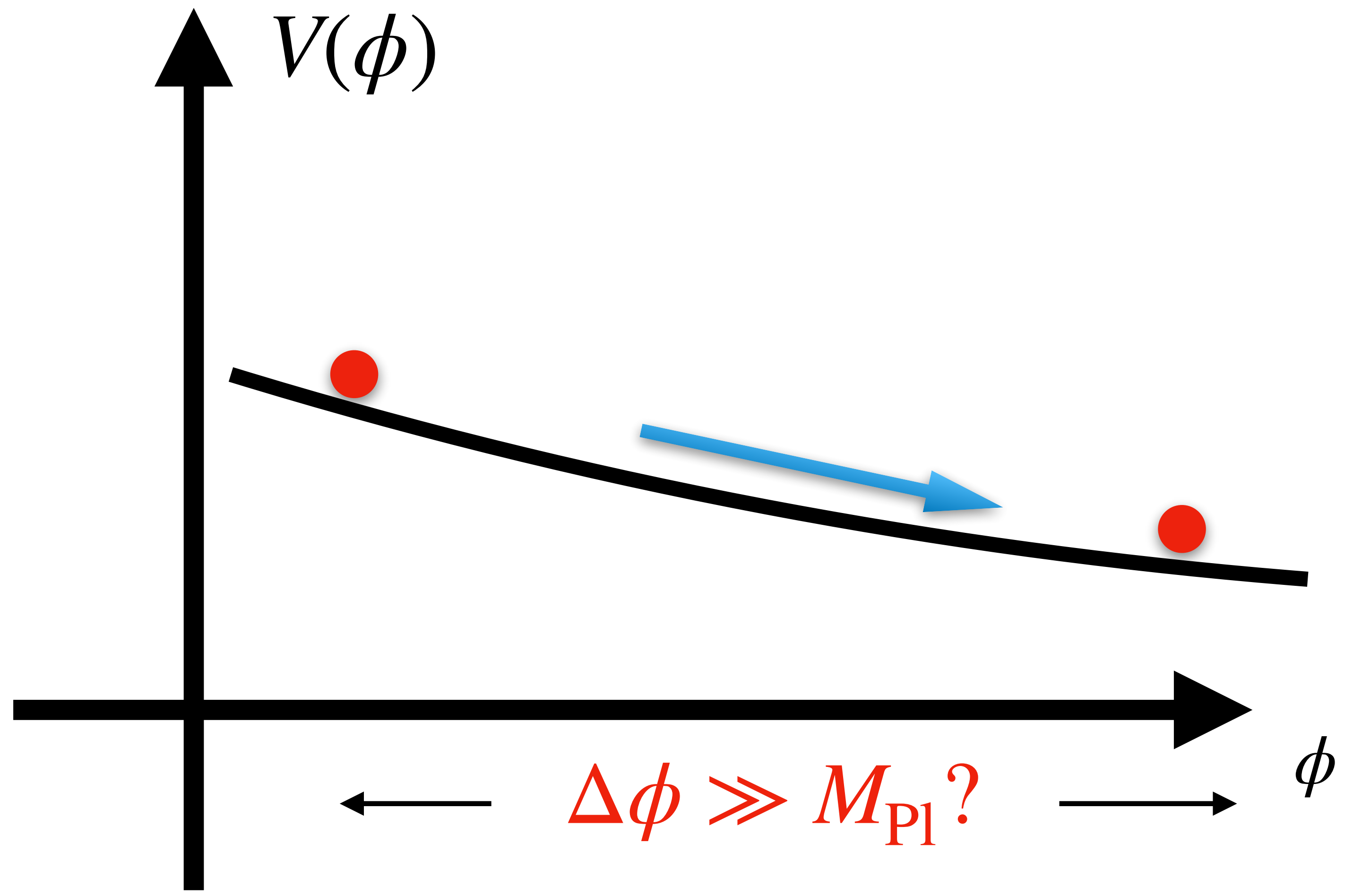
- F-theory: **[Lee,Lerche,TW'18-20]**
  [Lee,Lerche,Lockhart,TW'20]
  [Kläwer,Lee,TW,Wiesner'21]
- M-theory: **[Cota,Mininno,TW,Wiesner [22-23]**
  + work in progress

Refined SDC and Emergent Strings

Exponential scaling behaviour:

$$M_Q = M_P \exp\left(-\alpha \frac{d_{PQ}}{M_{\rm Pl}}\right) \to 0$$

for light towers
at infinite distance in moduli space



Crucial for applications e.g. to cosmology:

How small can decay rate α become?

Emergent String Conjecture implies:

$$\boxed{\alpha \geq \frac{1}{\sqrt{d-2}}}$$

Emergent String Limit: $M_s = M_{\rm Pl} e^{-\frac{1}{\sqrt{d-2}}\hat{\phi}}$

Decompactification Limit: $m_{\rm KK} \sim e^{-\sqrt{\frac{D-2}{(D-d)(d-2)}}\hat{\rho}}$

[Etheredge, Heidenreich,Kaya,Qiu,Rudelius '22]
[Agmon,Dedroya,Kang,Vafa'22]

Dark Dimension Scenario

Speculative! Scenario!

Interpretation of $\Lambda \sim 10^{-122} M_{\text{Pl}}^4$:

[Montero,Vafa,Valenzuela '22]
[Lüst,Palti,Vafa '19]

Our universe is at very far distance in a (pseudo-)moduli space

$$m_{\text{tower}} \sim |\Lambda|^{1/4} \sim \mathcal{O}(eV)$$

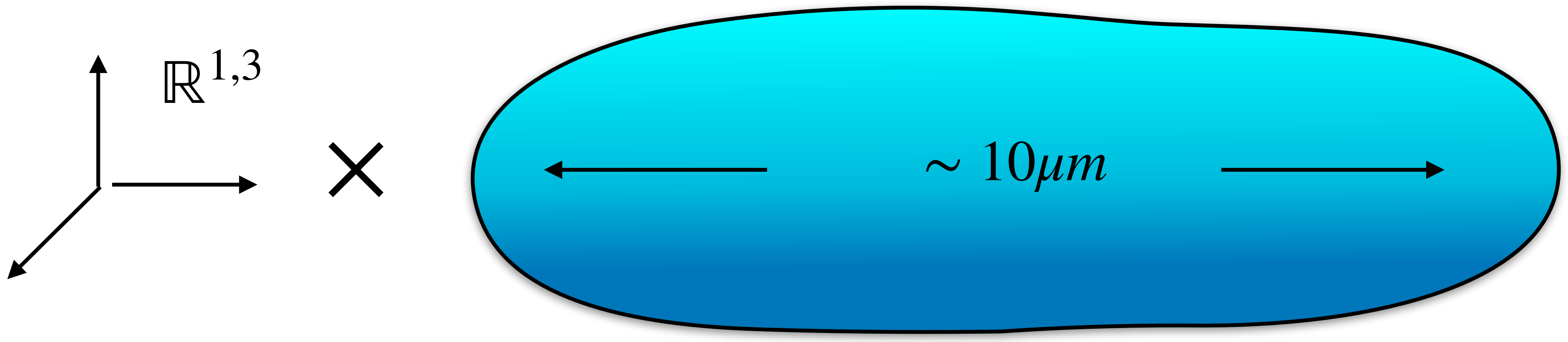
What is the nature of the tower?

Emergent String Conjecture

- String Tower at $M_{\text{string}} = \mathcal{O}(eV)$ — **Excluded experimentally!** see however: **[Basile,Lüst'24]**
- Kaluza-Klein tower at $M_{\text{KK}} = \mathcal{O}(eV)$

1 mesoscopic extra dimension

- $R \sim 10\mu m$
- $\Lambda_{\text{species}} = 10^9 - 10^{10}\text{GeV} = M_{\text{Planck,5d}}$



Distinguish: **[Antoniadis,Arkani-Hamed,Dvali'98]**
Large extra dimension scenario
$M_{\text{Planck;higher}} \sim$ TeV

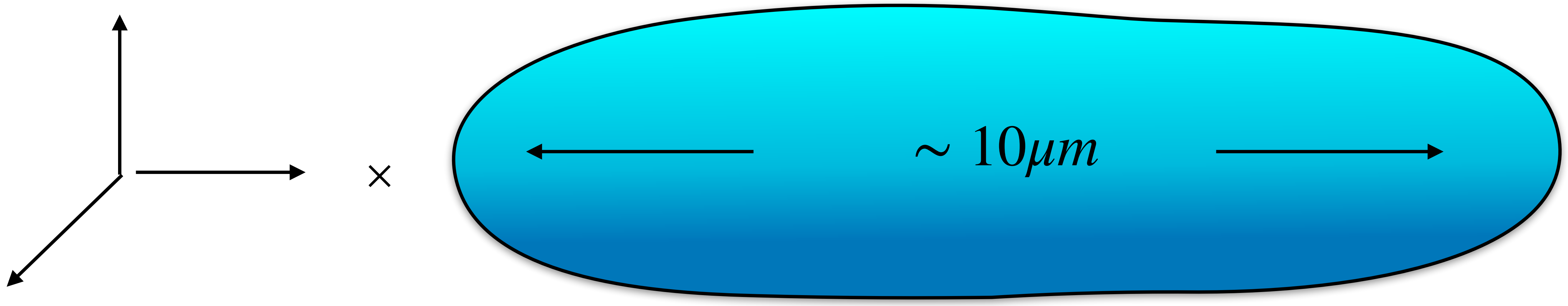
Explicit realisations: [Blumenhagen,Brinkmann,Makridou'22]

Dark Dimension Scenario

Speculative Scenario!

1 mesoscopic extra dimension

- $R \sim 10\mu m$
- $\Lambda_{\text{species}} = 10^9 - 10^{10}\text{GeV} = M_{\text{Planck,5d}}$



Potentially interesting connections to phenomenology, including, among others:

- Prospect to be ruled out/in by upcoming measurements of Newton's law at μm scale
- KK tower giving sterile right-handed neutrinos? cf. [Dienes et al.'98] [ArkaniHamed,Dimopoulos,Dvali,March-Russell'98] [Carena et al.'17]
- Dark Matter candidates: KK tower or 5d primordial black holes [Gonzalo,Montero,Obied,Vafa'22] [Achordoqui,Anoniadis,Lüst'22], ...
- GUTs at 10^{16} GeV *would* imply charged KK modes at $\mathcal{O}(1 - 10\text{TeV})$ [Heckman,Vafa,TW,Xu'24]

Part II:

Finiteness and positivity from probe arguments

Finiteness and positivity from probe branes

- What is the **maximal possible rank** of the gauge group in a quantum gravity theory?

Example: Is $SU(N)$ gauge theory, $N \to \infty$, consistent with gravity *in the same dimension*?

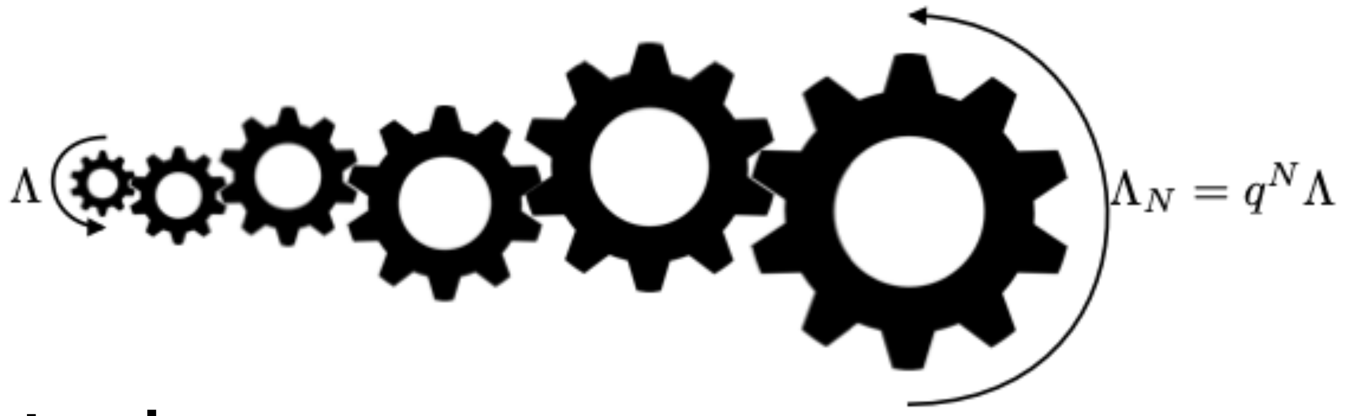
- What is the maximal possible light charged matter content or the **highest charge of light states**?

Example: Is a non-chiral U(1) gauge theory with massless matter charged with $q_1 = 1\,,\ q_2$ arbitrary ok in gravity?

- Which is the **structure of allowed couplings**?

Are all couplings compatible with symmetries allowed?

Not just of theoretical/academic interest:



Example: Bounds on charges and/or number of U(1) gauge factors would constrain proposals for producing hierarchies such as via clockwork mechanism

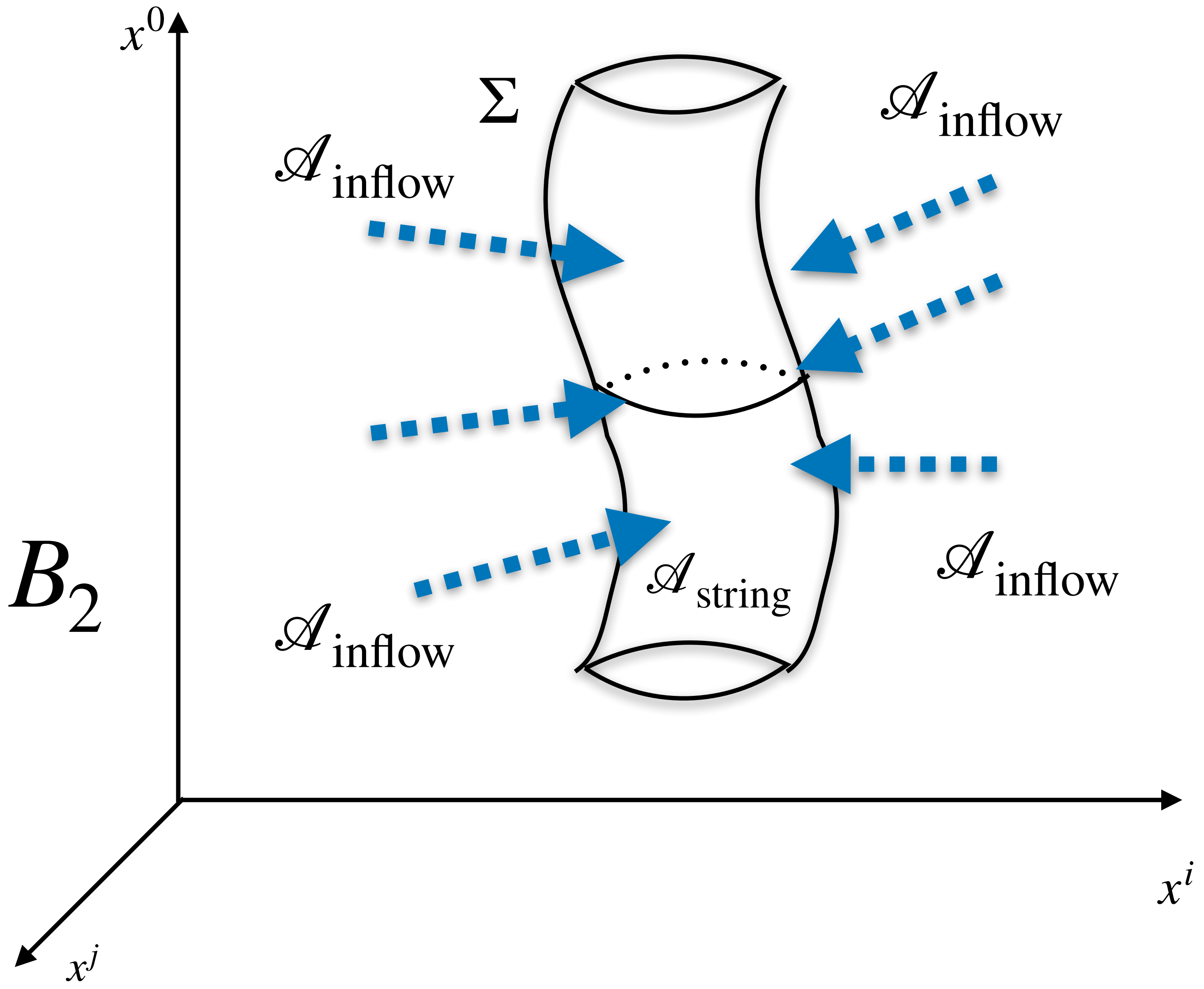
[Choi,Im'15]
[Kaplan,Rattazzi'15]
[Giduice,McCollough'16]
[Saraswat'16]
…

Finiteness and positivity from probe branes

Probe brane idea:

- QG may contain higher-dimensional objects.
- Consistency of their worldvolume theory $\Longrightarrow$ strong constraints

String-like source: $S_{int.} \sim \int_\Sigma B_2$



- Many theories contain 2-form gauge fields B_2.
  e.g. 4d N=1 SUGRA, asymptotically, 5d and 6d SUGRA
- In QG, these objects are assumed to be physical (Completeness Hypothesis). [Polchinski'03] [Banks,Seiberg'10]
- **Anomaly inflow** from bulk theory produces anomaly on string worldsheet. [Callan,Harvey'85]

Consistency of string (probe brane):

$$\boxed{\mathscr{A}_{\text{inflow}} = \mathscr{A}_{\text{string}}}$$

Information on bulk fields

Constrained by unitarity of worldsheet theory

$\longrightarrow$ **Consistency conditions on bulk theory**

Finiteness from probe branes

Bound on number of U(1) gauge factors in 6d N=(1,0) supergravities

$r_{\mathrm{U}(1)} \leq 22$ (with at least 1 tensor)

[Lee,TW'19]

Specialisation $\longrightarrow$ to F-theory

Bound on rank of Mordell-Weil group of rational sections of elliptic Calabi-Yau 3-folds

Current record: $r_{\max} = 10$

[Grassi, TW'21], [Elkies unpublished]

Quantum gravity prediction for algebraic geometry!

Positivity from probe branes

Bounds on higher order couplings in 4d N=1 supergravity

axionic partner of Gauss-Bonnet term

$$S = \int_{\mathbb{R}^{1,3}} \frac{M_{\rm Pl}^2}{2}\sqrt{-g}R - \frac{C}{96\pi}\int_{\mathbb{R}^{1,3}} a\,\mathrm{tr}R\wedge R + \dots$$

axion (part of chiral multiplets)

Bound from consistency of axionic strings: $C \in 3\mathbb{N}$ **[Martucci,Risso,TW'22]**

Caveat: proven for theories without a 5d origin

In particular: $C \geq 0$ and $r_G \leq 2C - 2$ in presence of gauge fields! C **bounds numbers of d.o.f.!** cf **[Dvali'24]**

Positivity built into quantum gravity!

Independent arguments for positivity of GB term include:

[Kallosh,Linde,Linde,Susskind'95] (wormholes)
[Cheung,Remmen'16] in d > 4 (unitarity)
[Aalsma,Shiu'22] (WGC)
[Ong'22] (d>4, AdS, holography)
[Dvali'24] (instanton effects)

Conclusions

Goal: Find **general principles in Quantum Gravity** -
complementary to top-down construction e.g. via string theory

Established in essentially all known non-perturbative string/M-theory compactifications

Emergent String Conjecture:
Universal behaviour of QG near boundaries of moduli space (weak coupling limits)

Recent/Ongoing:
Understanding from bottom-up

Weak Gravity Conjecture

Bounds on exponential decay rates (cosmology!)

More speculative:
Mesoscopic extra dimension?

Bounds on ranks of gauge groups
Open: Bounds on charges?

Probe brane arguments:
New constraints on QG

Hints on positivity of topological couplings

Extra Material

Further Evidence

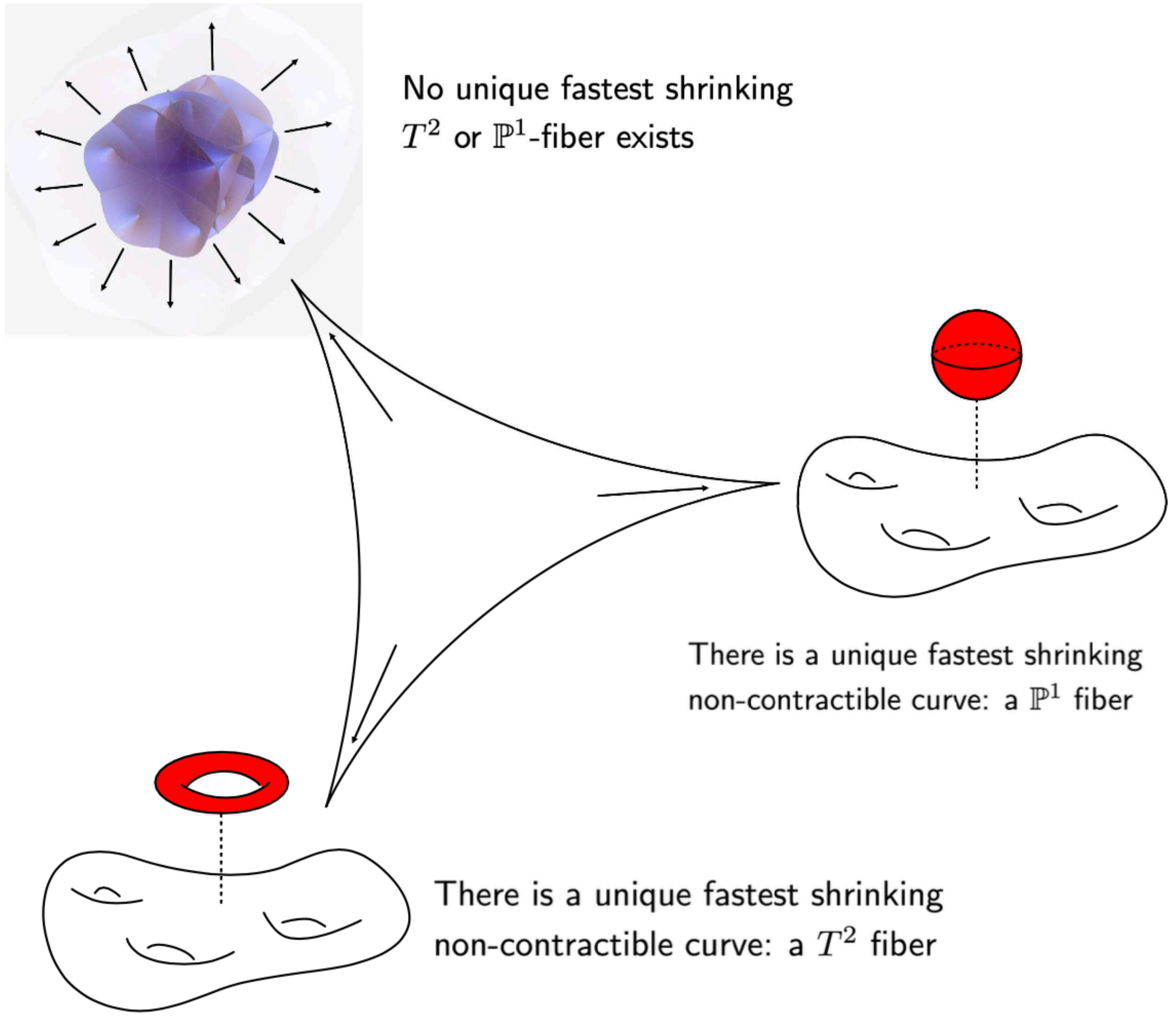
(Quantum) Kähler moduli spaces

F-theory on $\mathbb{R}^{1,5} \times Y_3$: 6d N=1 — Lee, Lerche, TW'18

F-theory on $\mathbb{R}^{1,3} \times Y_4$: 4d N=1 — Lee, Lerche, TW'19; Kläwer, Lee, TW, Wiesner'20

4d N=1: quantum corrections shield pathological limits with

$$M_{\text{str.}} \ll M_{\text{KK}}$$

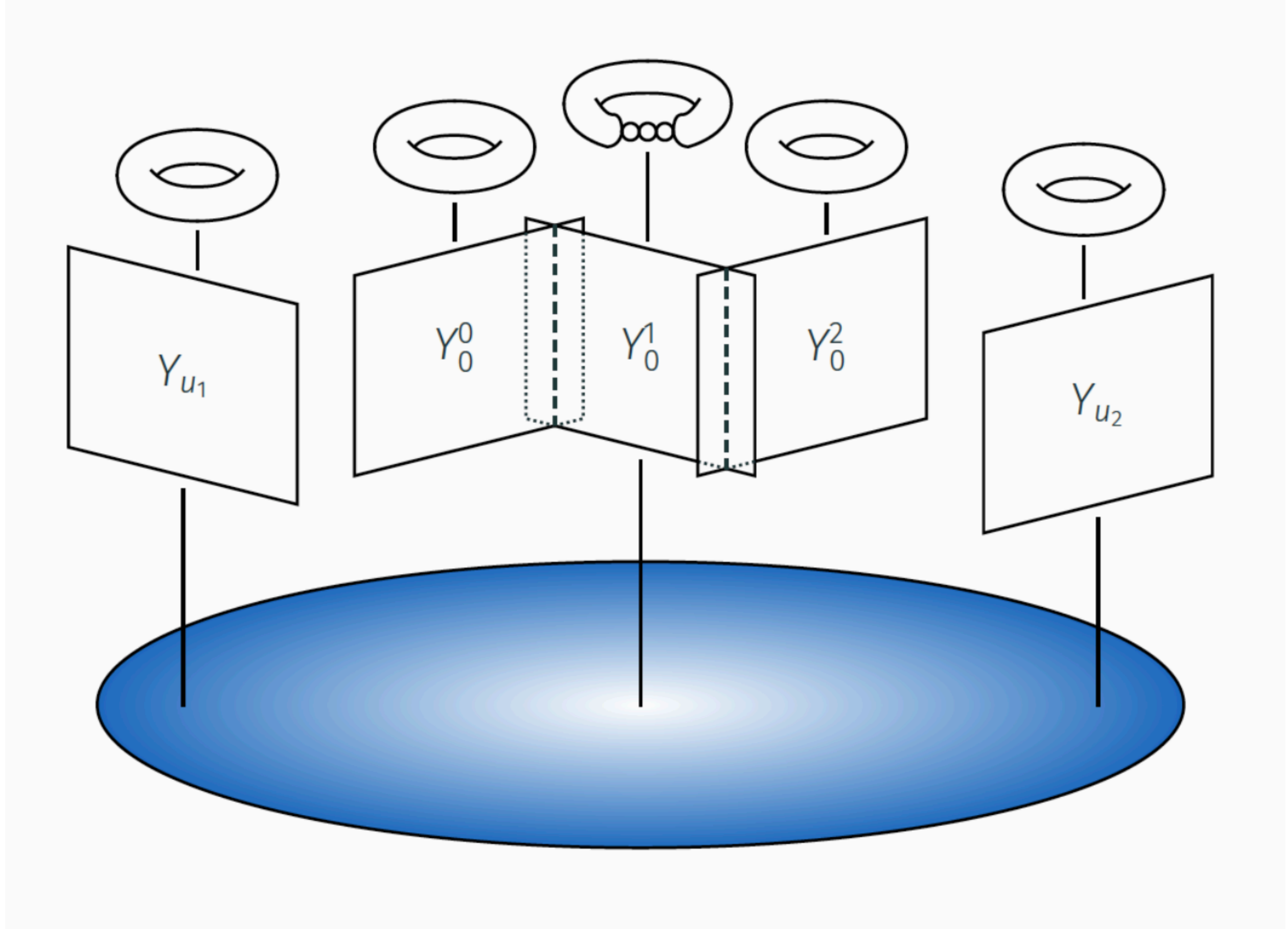


Complex structure moduli spaces

F-theory on $\mathbb{R}^{1,7} \times K3$: 8d N=1 — Lee,TW'21; Lee, Lerche, TW'21

F-theory on $\mathbb{R}^{1,5} \times Y_3$: 6d N=1 — Alvarez-Garcia,Lee,TW'23 (2x) + to appear

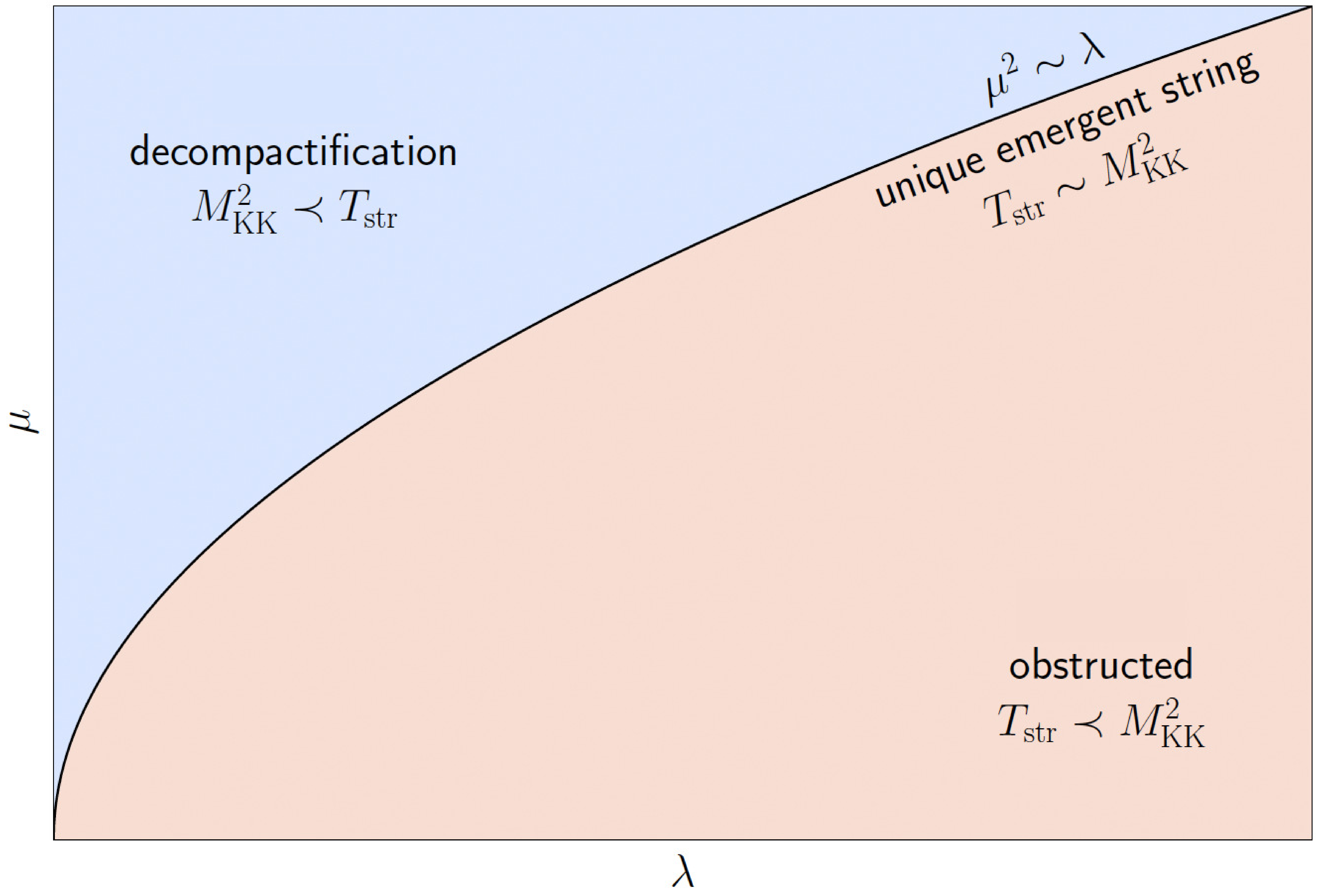
M-theory on $\mathbb{R}^{1,4} \times Y_3$: 5d N=1 — Alvarez-Garcia,Kläwer,TW'21



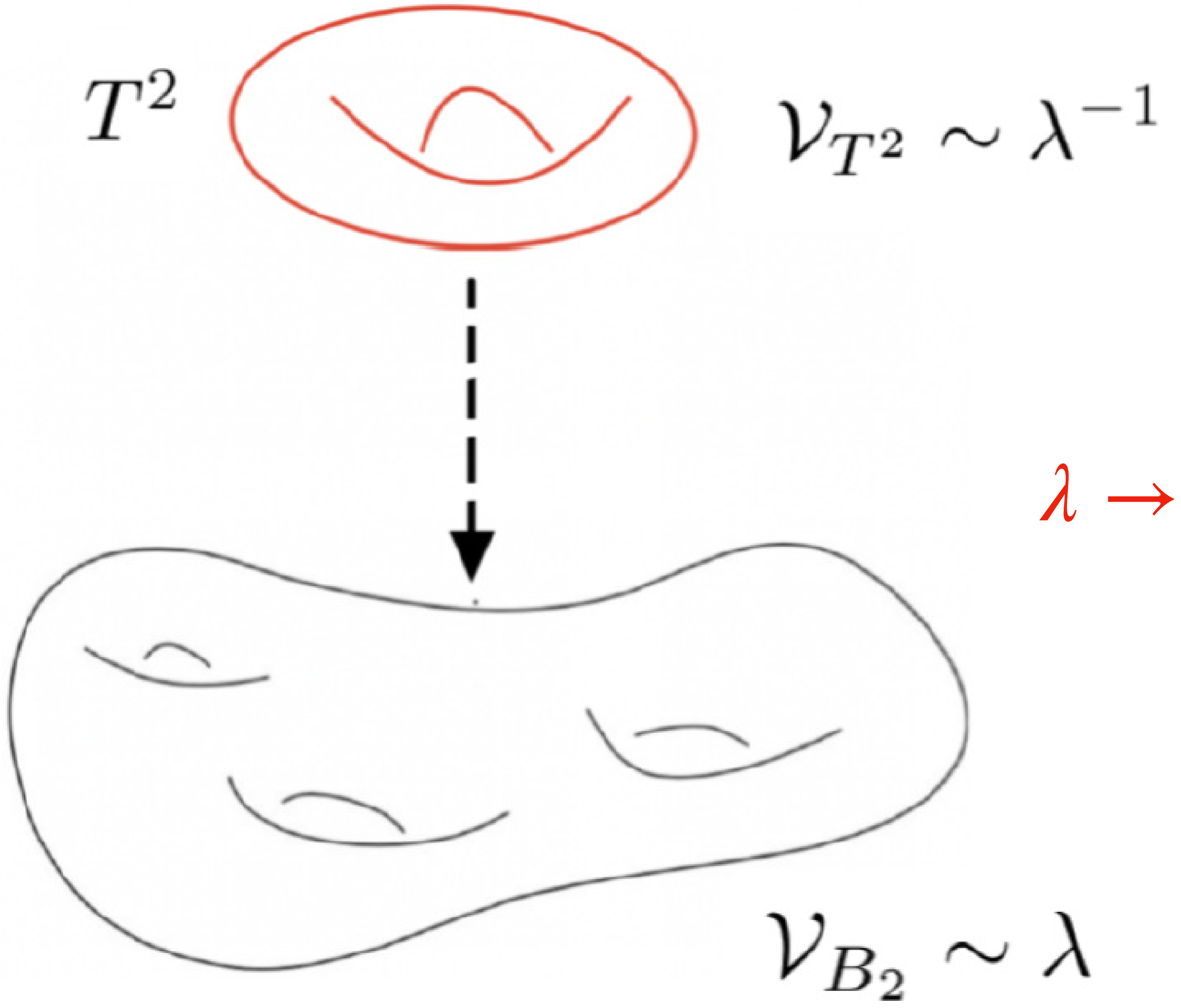
Three potential pitfalls

Caveat 3: Emergent strings always accompanied by KK tower

- ✓ never find new critical string of purely d<10 dimensional type
- ✓ often guaranteed only due to quantum corrections to moduli space [Baume,Marchesano,Wiesner'20] [Kläwer,Lee,TW,Wiesner'20] [Alvarez-Garcia,Kläwer,TW'21]



M-Theory on Calabi-Yau 3-fold



$\lambda \to \infty$

Leading tower:

Counted by GV invariants
$N_{g=0}(nT^2) = \chi(X_3)\ \forall n$

M2-brane wrapped n-times on torus fiber:

$$M_n^2 = n^2 M_0^2 \qquad M_0 = T_{\mathrm{M2}} \mathscr{V}_{T^2}$$

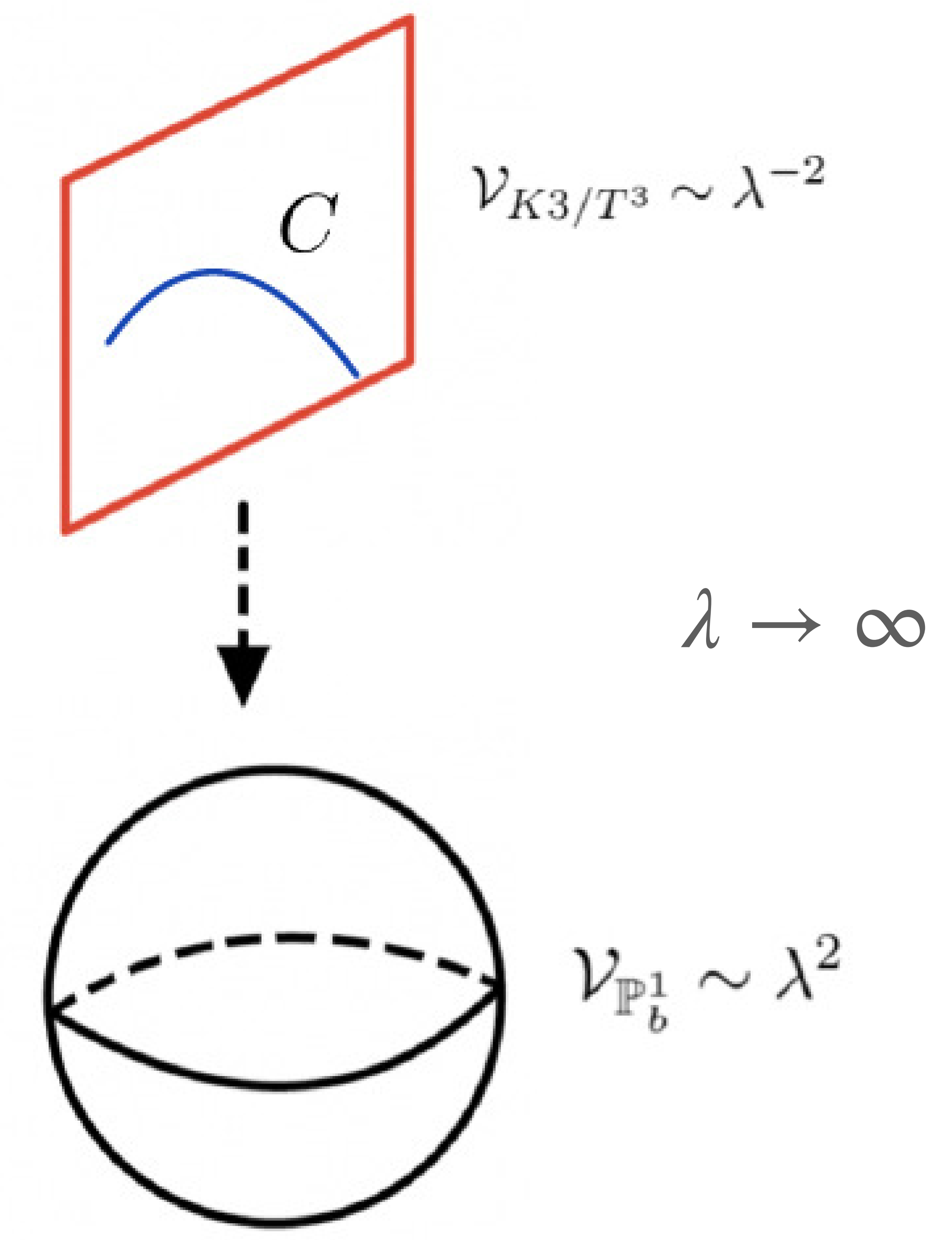
$\Longleftrightarrow$ Behaviour of KK tower for decompactification

$5d \to 6d$ (F-theory limit of M-theory)

in the well-known sense of [Vafa'96] [Witten'96]

$\Longrightarrow$ **Decompactification Limit** - but in a dual sense! ✓

M-Theory on Calabi-Yau 3-fold



M5 brane on $K3/T^4$:

Heterotic / Type II critical string in 5d
[Harvey, Strominger'95]

String tension:
$T_{\text{em}} \sim T_{\text{M5}} \mathscr{V}_{K3/T^4} \sim \lambda^{-2} \to 0$

Emergent string setting dual Heterotic / Type II Frame

2 leading towers ***at same scale***:

- String excitation tower: $M_n^2 \sim n\, T_{\text{em}}$
- Kaluza Klein towers:
  - SUGRA states from large base $\mathbb{P}^1$ $\quad M^2_{\text{KK},1} \sim \mathscr{V}^{-1}_{\mathbb{P}^1} \sim \lambda^{-2}$
  - M2-branes on curves $C \cdot_{\text{K3/T}^4} C \geq 0$ $\quad M^2_{\text{KK},2} \sim \mathscr{V}^2_C \sim \lambda^{-2}$

Emergent String Limit in 5d: heterotic / Type II ✓