The String Landscape and Quantum Gravity Conjectures

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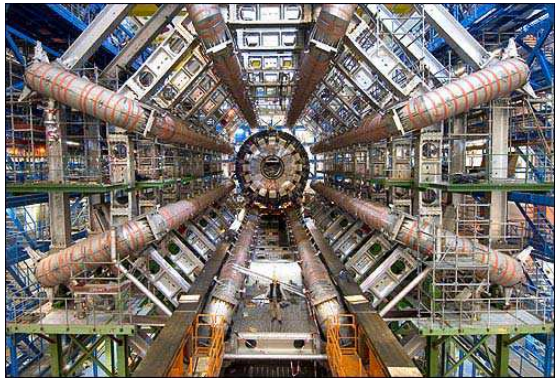
KPS Particles and Fields Division Meeting@IBS

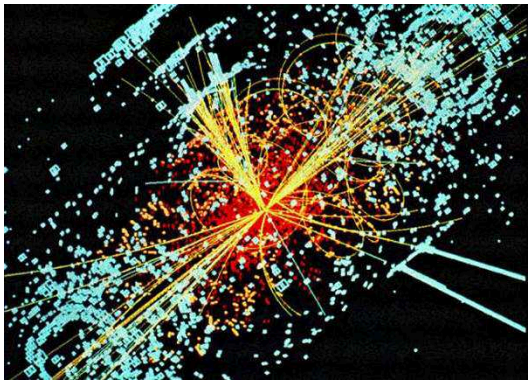
19-Dec-2024

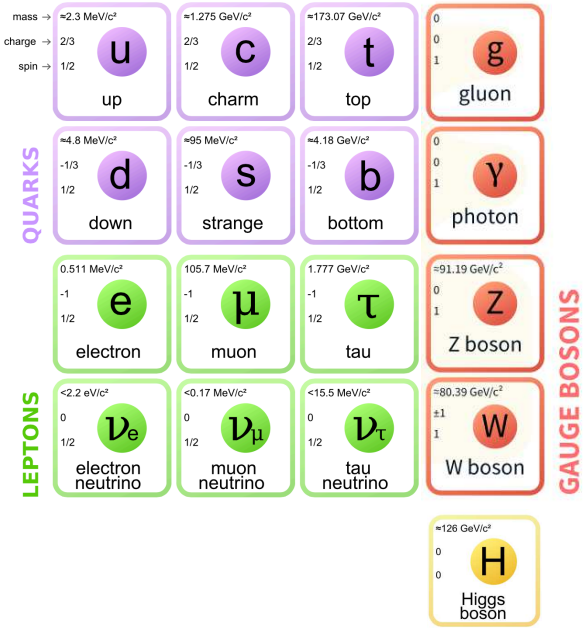
Particle Phenomenology

A Successful Description in Quantum Field Theory

- **The Standard Model (SM) of Particle Physics** [... '67]
  - A particular model in the **Quantum Field Theory** (QFT) framework
    - observed fundamental **matter particles**
    - three of the four fundamental **forces** (***EM***, ***weak*** and ***strong***)
  - The Higgs particle discovered at CERN **as predicted**!







Success: Theoretical computations consistent with many observations to a great precision

Beyond the SM/QFT

Quantum Gravity and String Theory

- **A Fundamental Trouble**
  - **Gravity** does not fit to the SM

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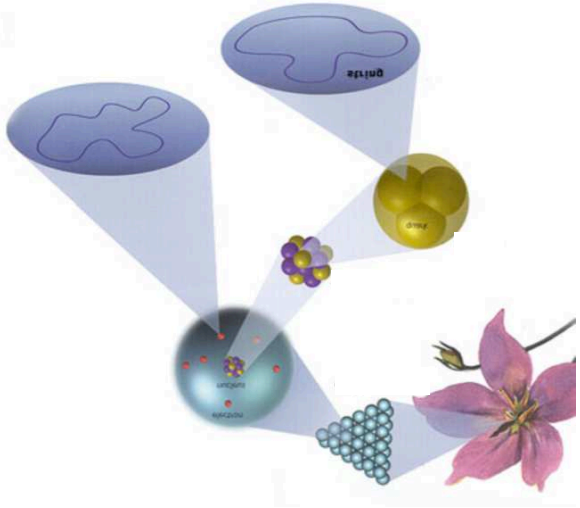

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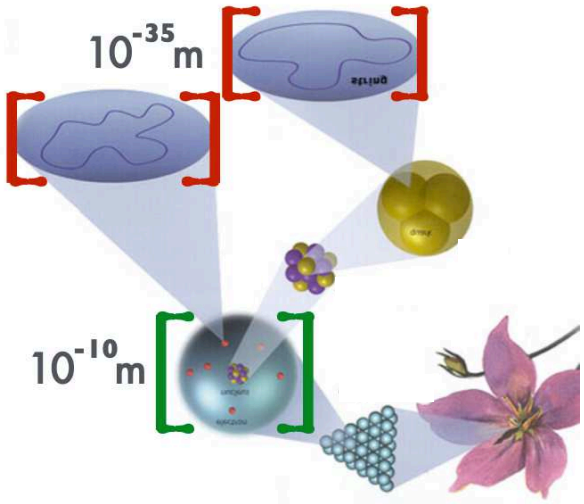

Low-energy description w/ **Fields**

Ultra-Violet Physics

Effective Physics

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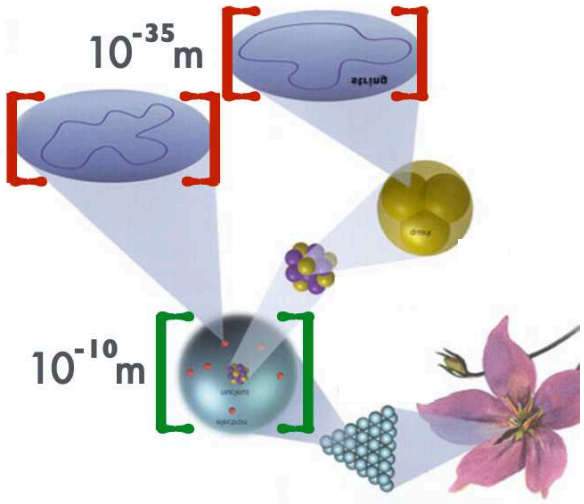

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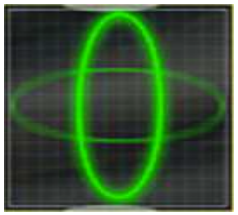

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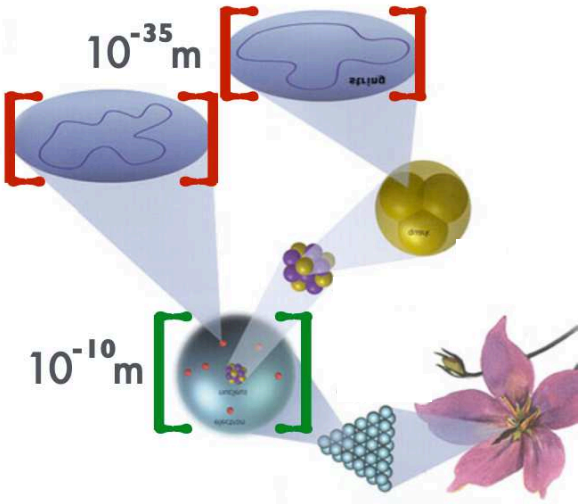

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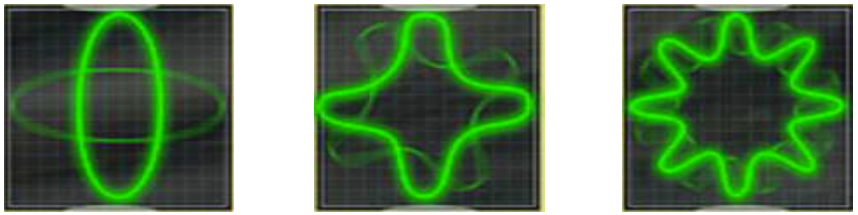

2. Different particle species = different modes

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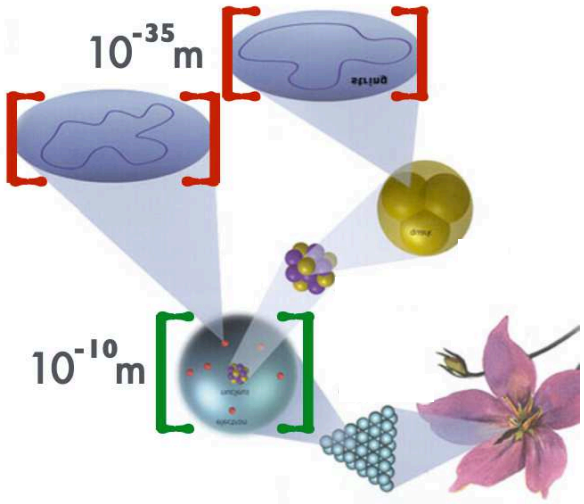

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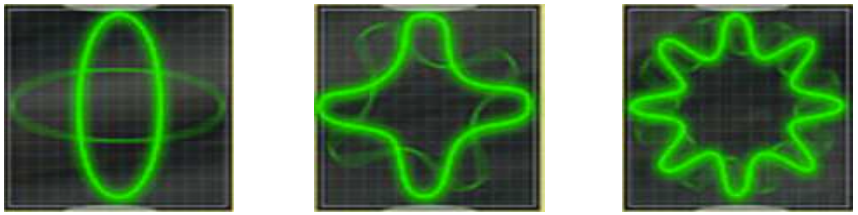

2. Different particle species = different modes

3. Graviton as a universal mode

Quantum gravity is ***consistent*** (and ***compulsory***)

String Phenomenology

Towards Realistic String EFTs

- **String Phenomenology**
  - Pursue a realistic low-energy effective QFT model of string theory
    - observed Standard-Model *particle physics* & *cosmology*

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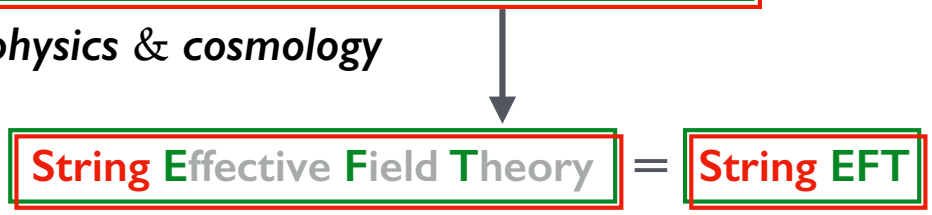

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Key Terminology

String Effective Field Theory = String EFT

- **Dimension of the Spacetime**
  - Strings *must* probe a 10-dim'l spacetime for consistency
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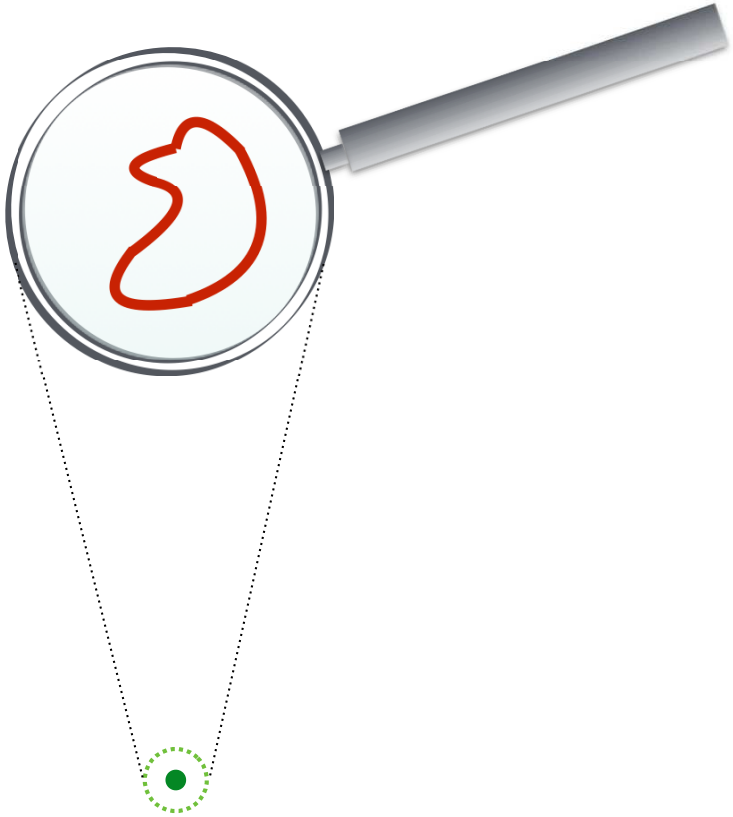
  - Compactifications

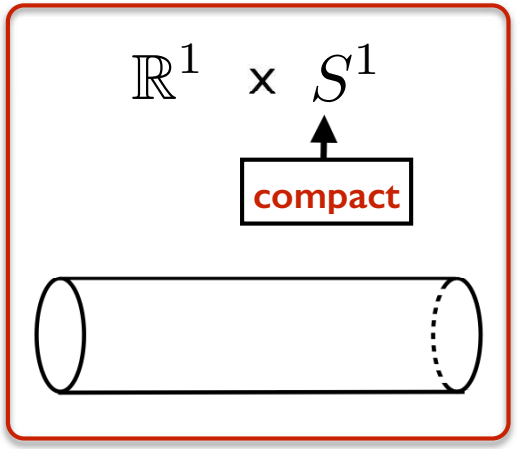
Compactifications: the Idea

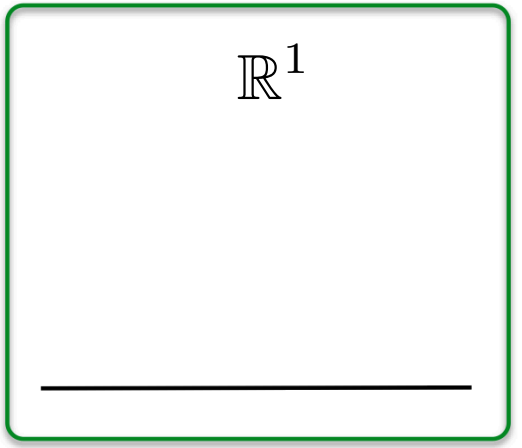
From 2d to 1d



Energy

$\mathbb{R}^1 \times S^1$ probed with **High Energy**





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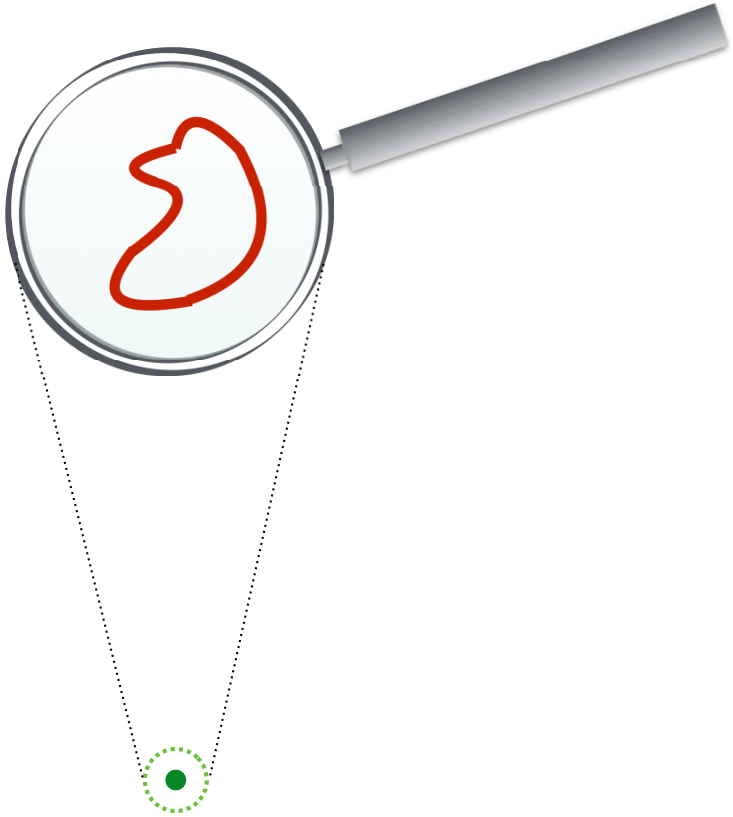
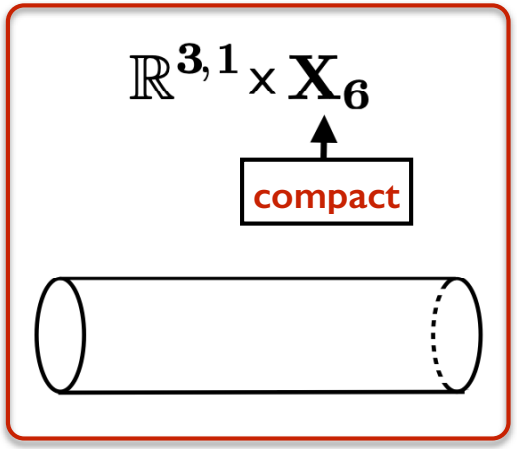


Energy

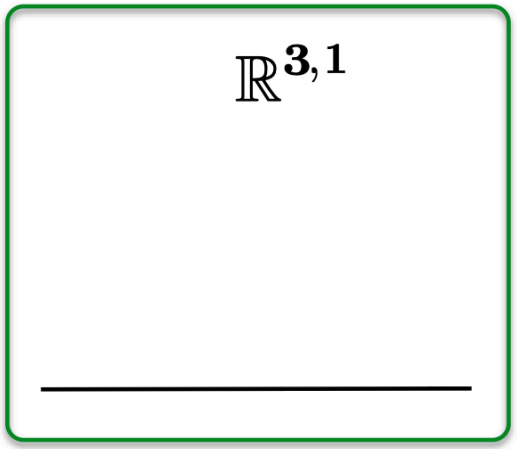
Spacetime probed with **High Energy**

$\mathbb{R}^{3,1} \times \mathbf{X_6}$

compact



$\mathbb{R}^{3,1}$



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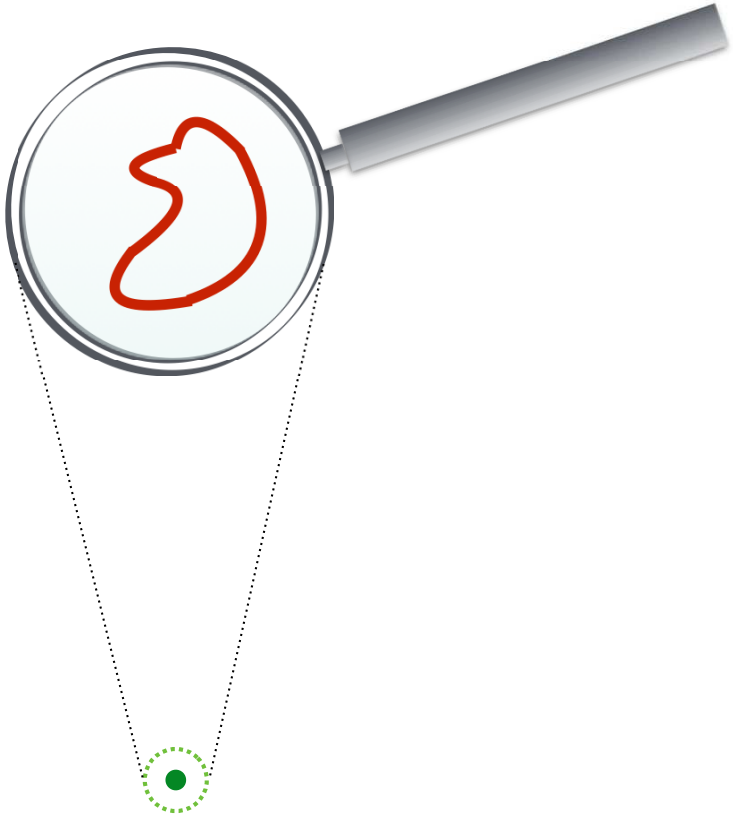

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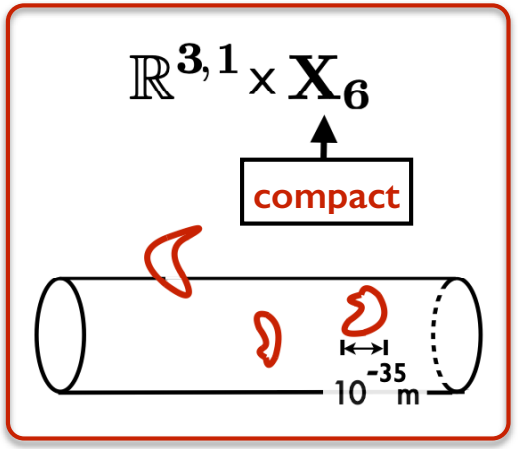

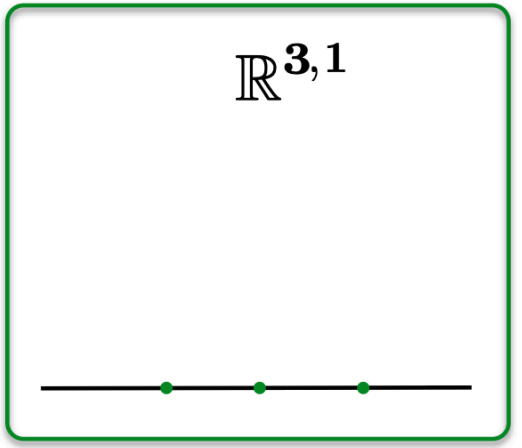

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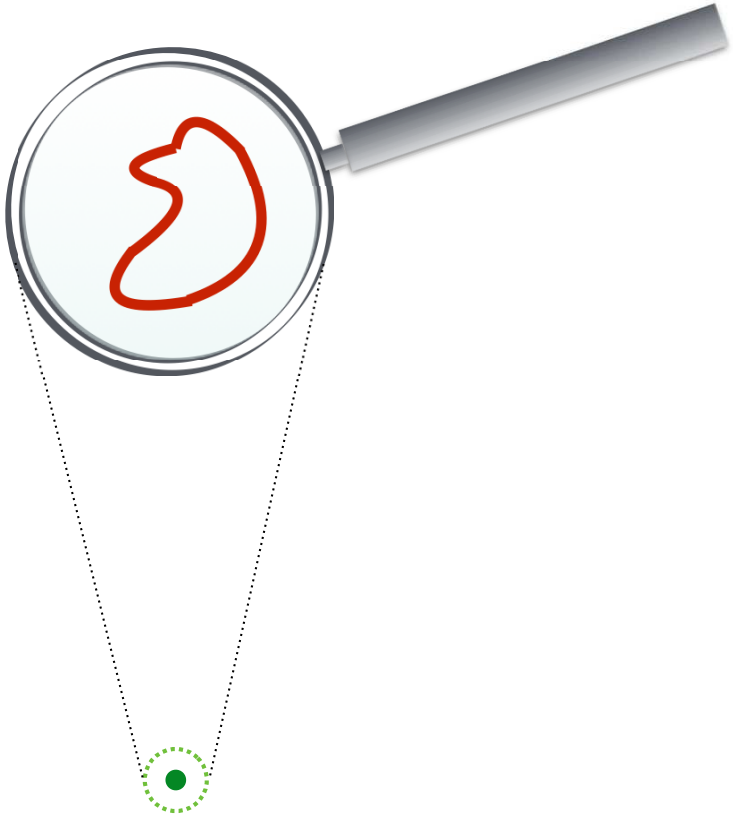

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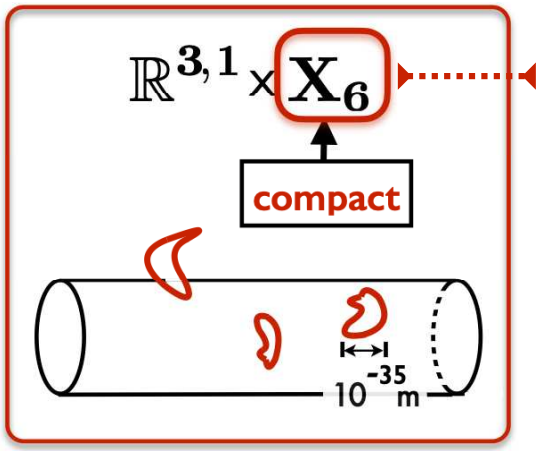

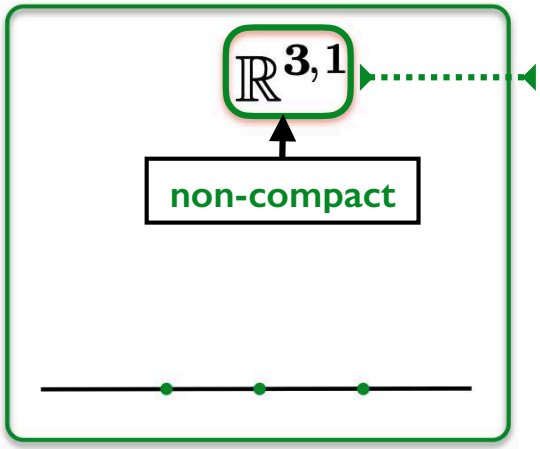

Spacetime probed with **Low Energy**

Effective 4-dim'l Theory

Physics via Geometry

- **Effective Physics of String Theory**

a **choice** for the **geometry** of the **internal 6-dim'l space**

a **String EFT** in the **external 4-dim'l spacetime**

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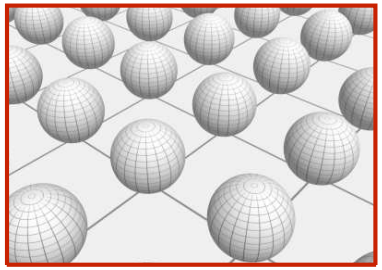
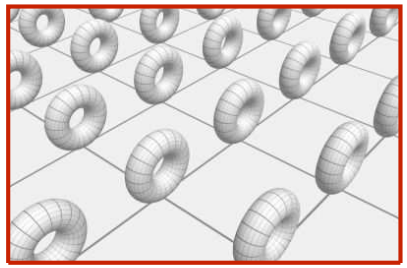
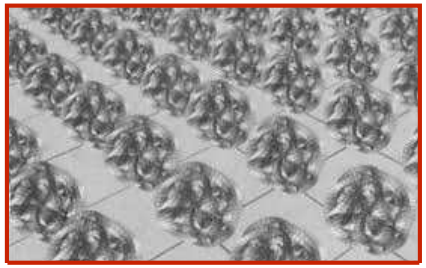


Internal Geometry 1



Internal Geometry 2



Internal Geometry 3

. . .

String EFT 1

String EFT 2

String EFT 3

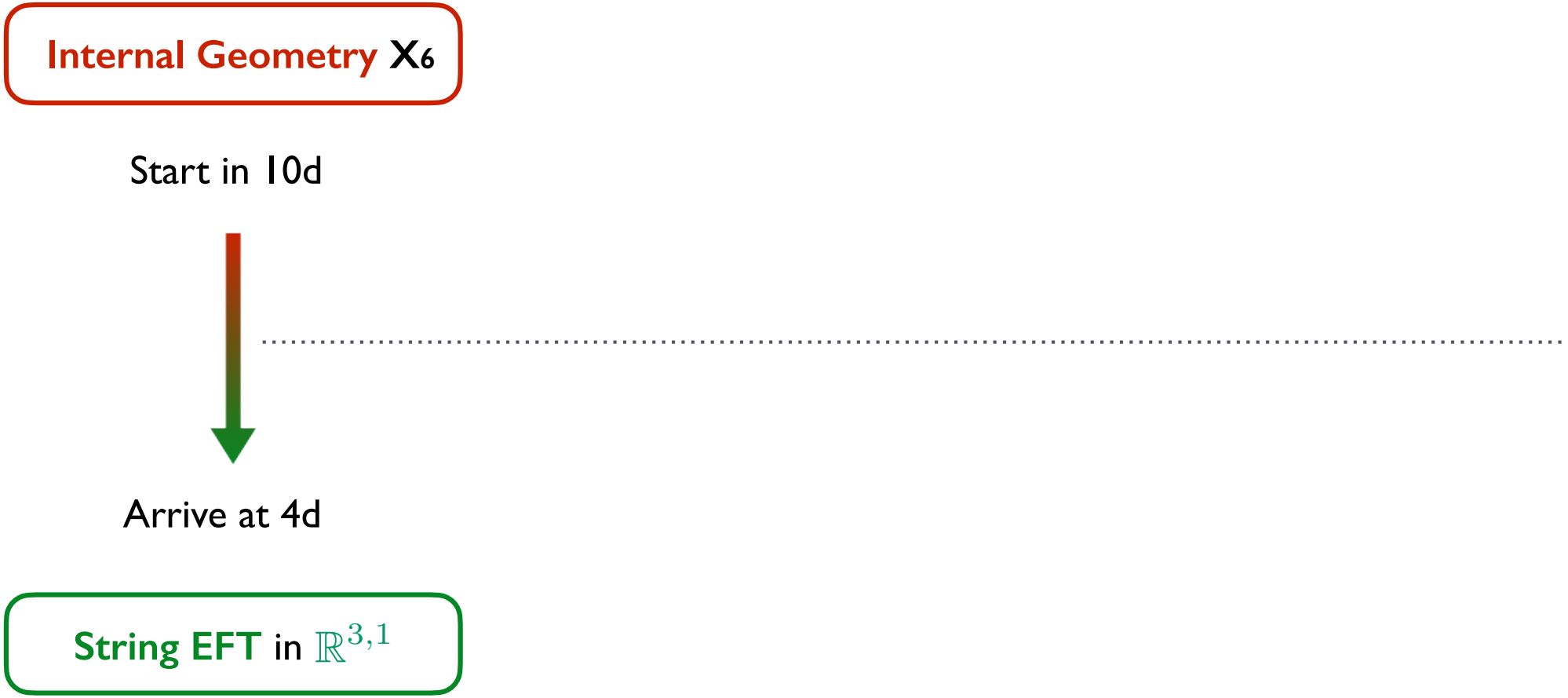
. . .

a **String EFT** in the **external 4-dim'l spacetime**

Constraints on String Geometry

Consistency and Phenomenology

- **Constraining the Geometry**



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Internal Geometry X_6 Which internal spaces X_6 are **allowed by strings**?

Start in 10d

Arrive at 4d

String EFT in $\mathbb{R}^{3,1}$

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$$0 = \nabla_M \epsilon - \frac{1}{4}\mathbf{H}_M \epsilon \ ,$$

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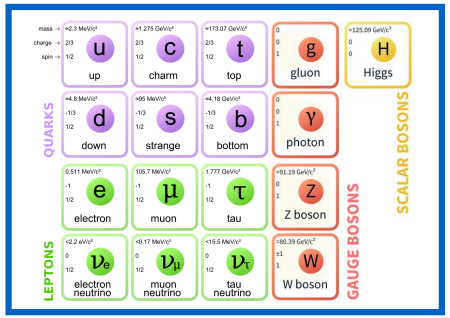

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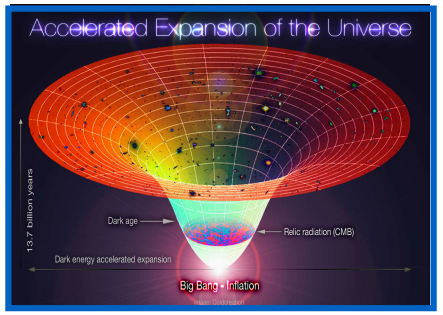

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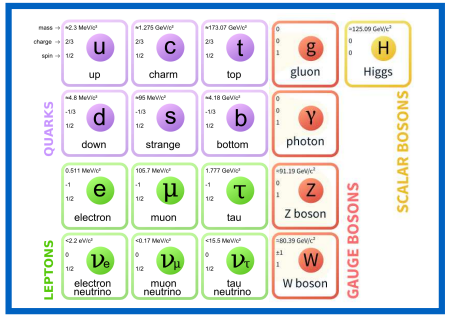

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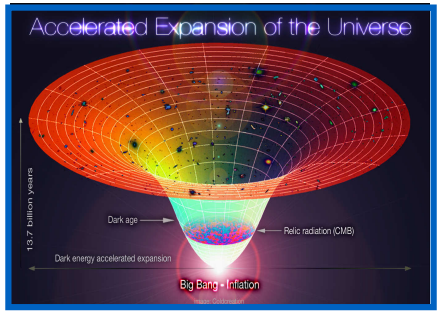

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X better be a "**flat**" space

⟷ *cf. supersymmetry*

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X better be a Calabi-Yau space

cf. supersymmetry

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Hints on New Physics ?

Calabi-Yau Space, Conceptually

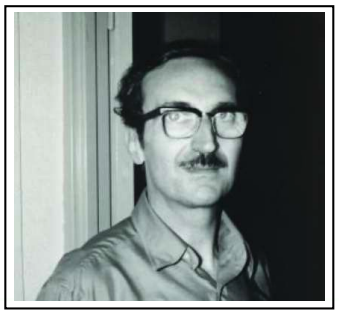
Maths v.s. Physics

[1950s]

Maths

"Flat" Geometry

Calabi



Yau

Calabi-Yau Space, Conceptually

Maths v.s. Physics

[1950s]

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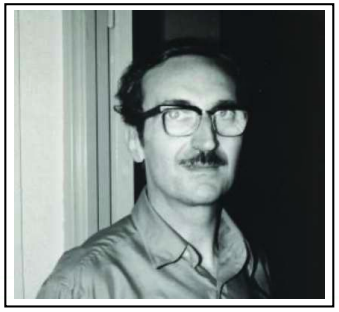

Yau

Calabi-Yau **geometry** is characterized via a simple **topological criterion**

Calabi-Yau Space, Conceptually

Maths v.s. Physics

[1950s]

Maths

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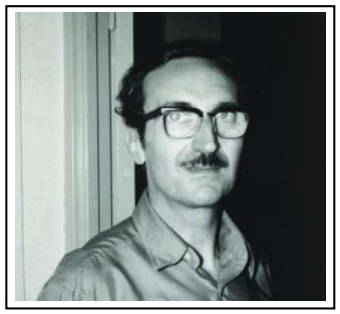


Yau

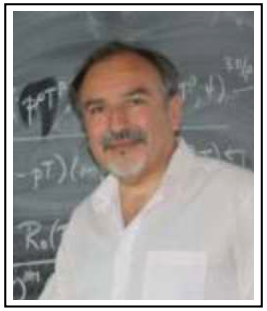
Calabi-Yau **geometry** is characterized via a simple **topological criterion** and turns out to be a legitimate internal space allowed by strings!

[1985]

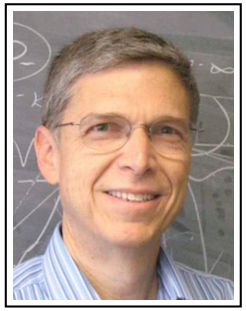
Physics

Sol. to string EOMs (string vacuum)

Candelas

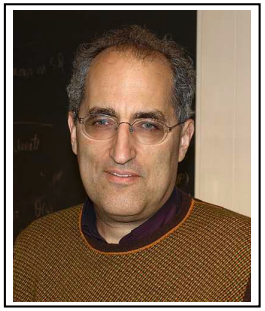


Horowitz



Strominger

Witten



Calabi-Yau Space, Practically

Does there exist an example of such a flat geometry?

Calabi-Yau Space, Practically

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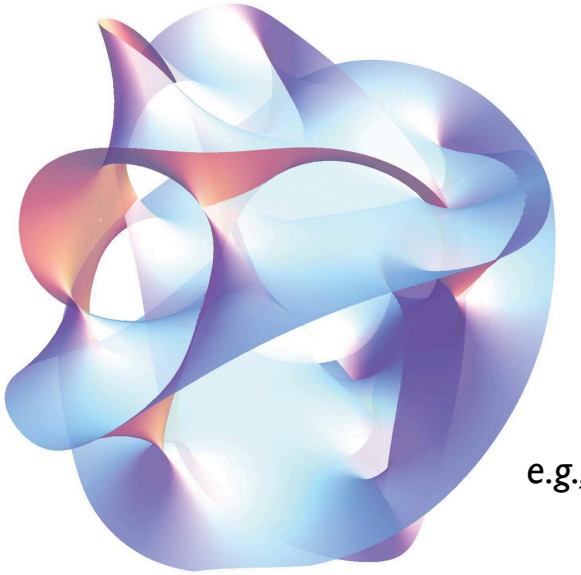
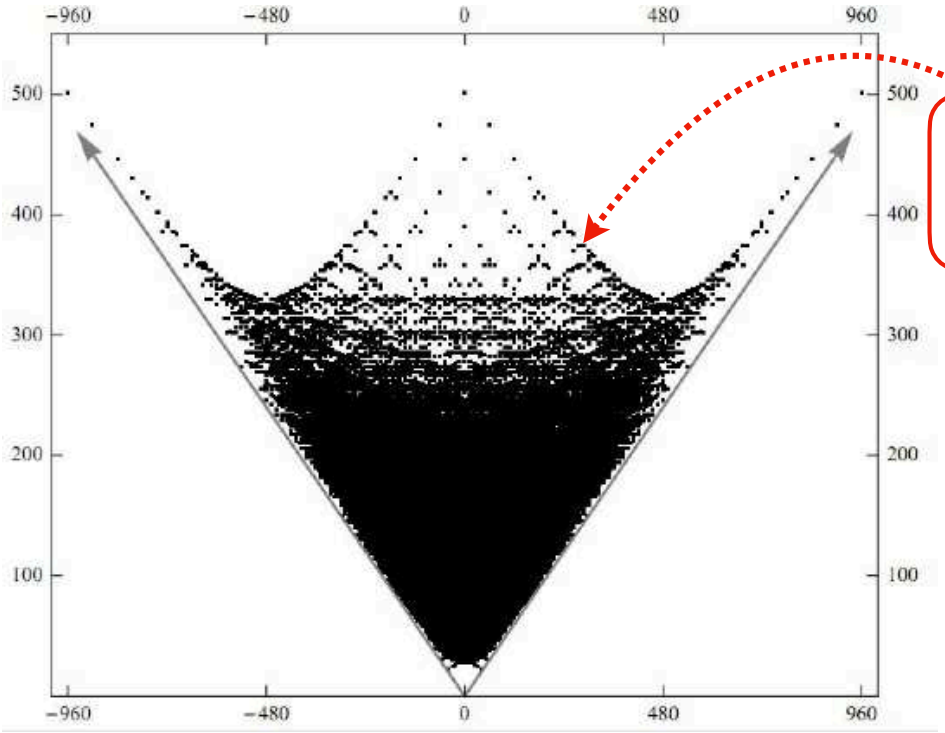


e.g., the Quintic

Yes

Calabi-Yau Space, Practically

Can one find any other flat geometries?



each dot representing a distinct Calabi-Yau space

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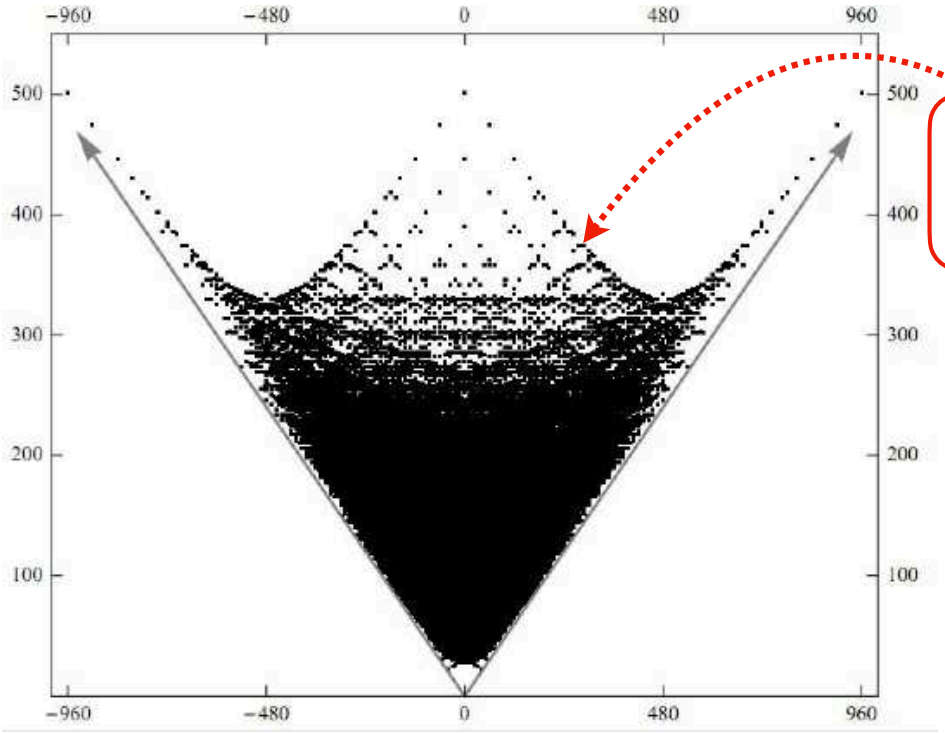

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- A Big Data of 6-dim'l Calabi-Yau spaces via algebraic geometry

  [Green, Hubsch '87], [Candelas, Dale, Lutken, Schimmrigk '88], [Candelas, Lynker, Schimmrigk '90], [Kreuzer, Skarke '02], …

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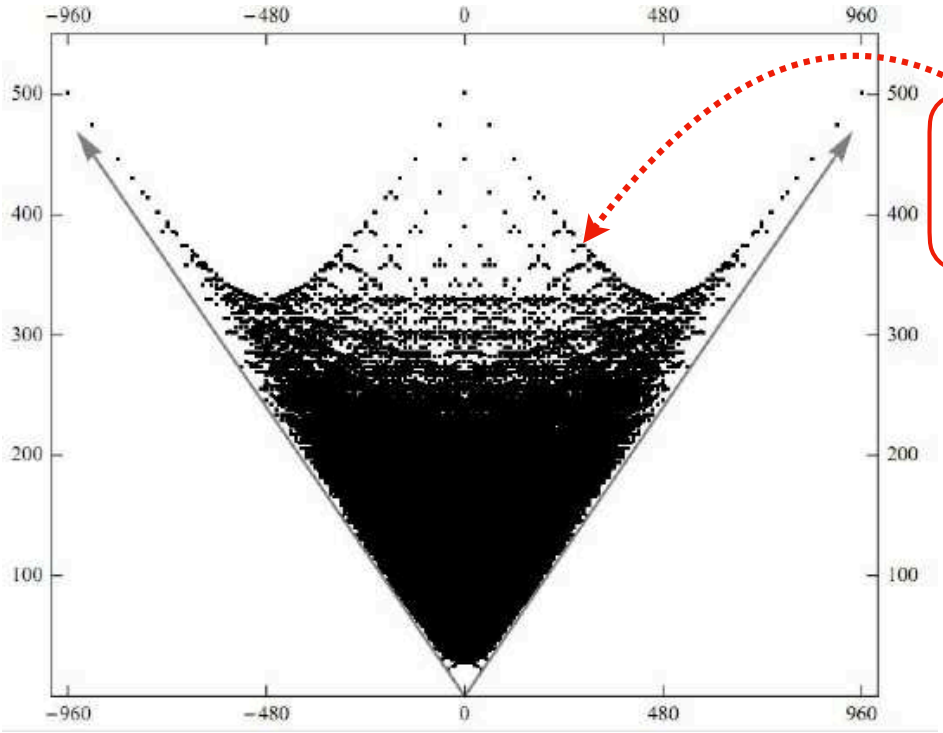

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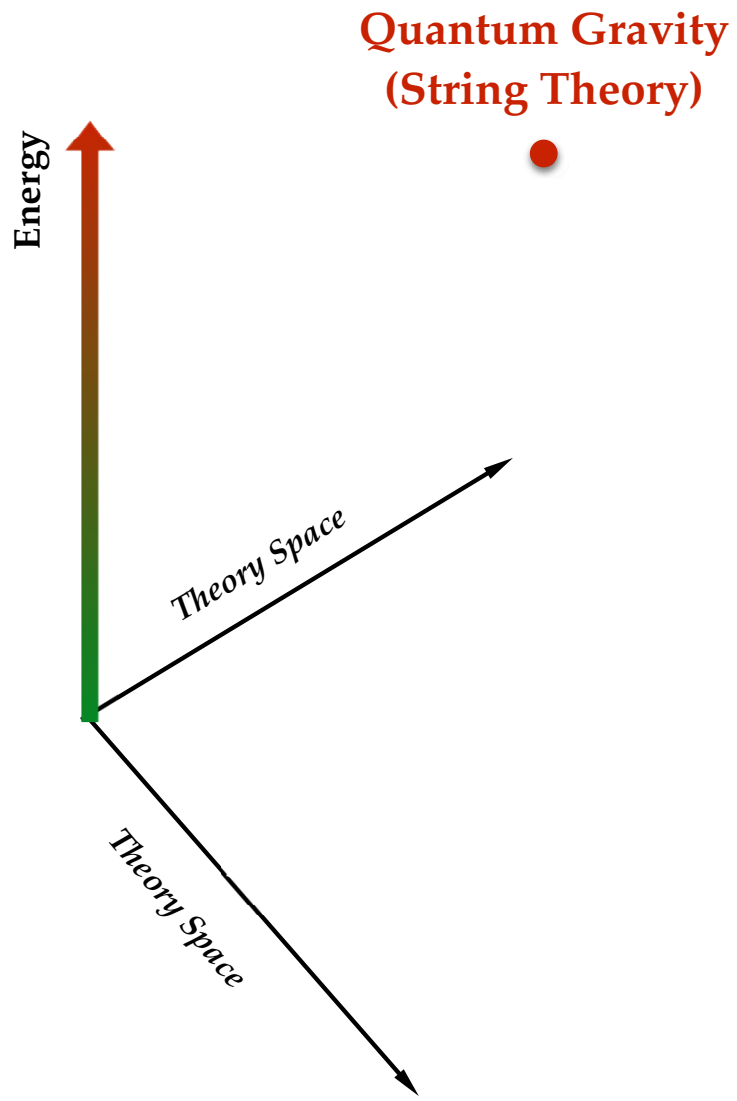
- Estimated to have over 10^{400} spaces [Chandra, Constantin, Fraser-Taliente, Harvey, Lukas '23]

A Plethora of String EFTs

The String Landscape

- **String Theory**
  - *Unique* at *high* energy



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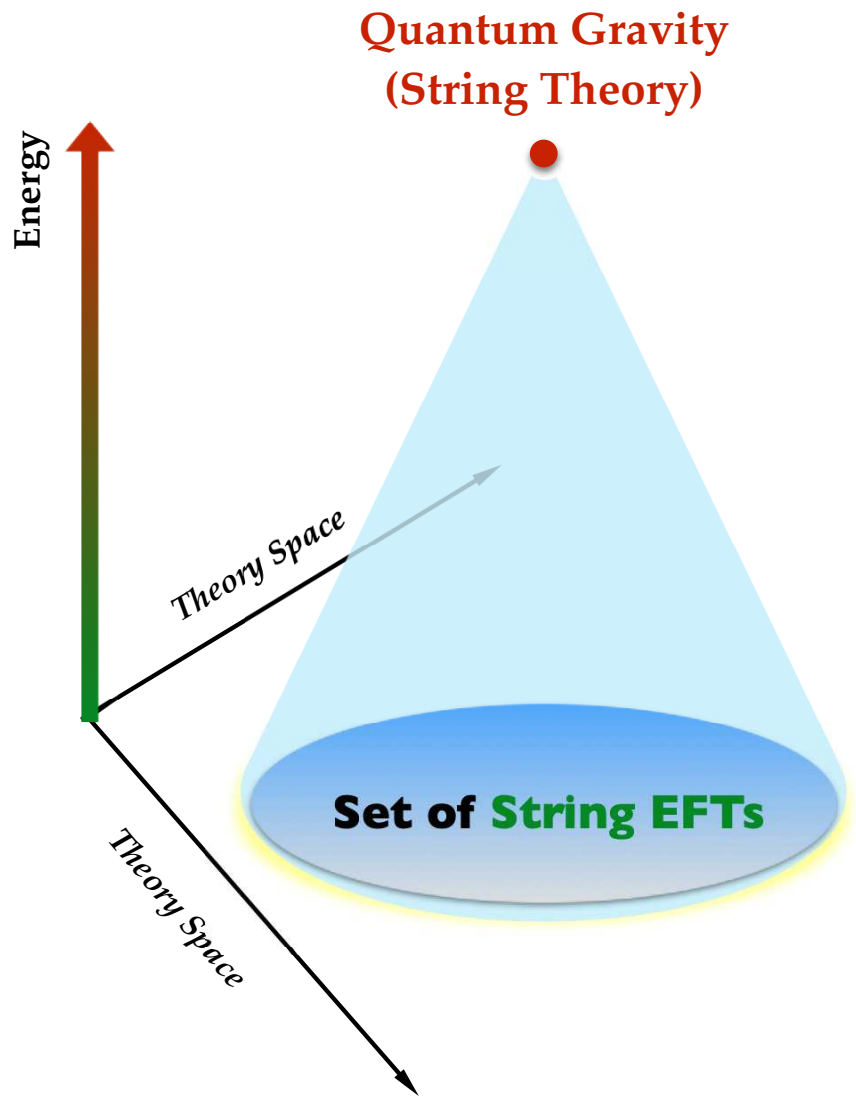

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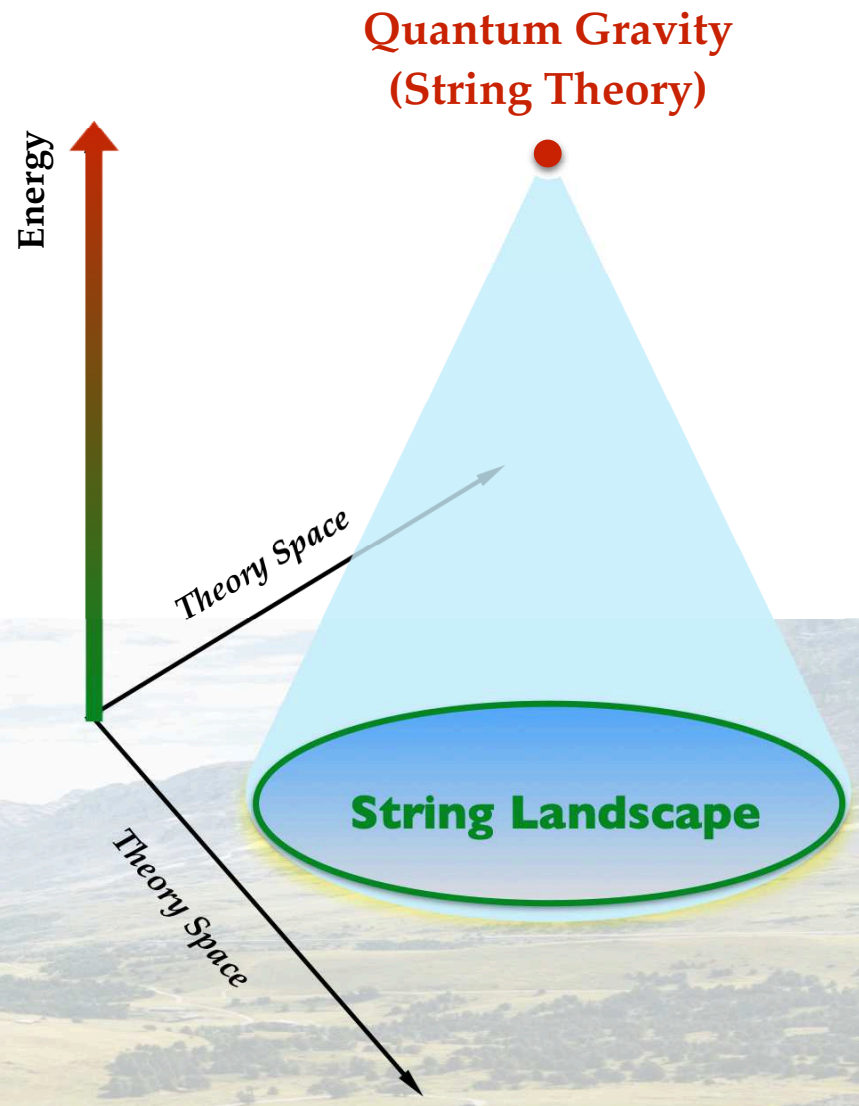

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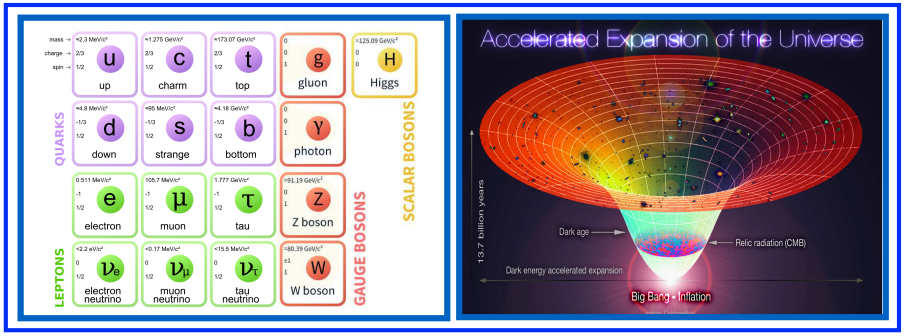

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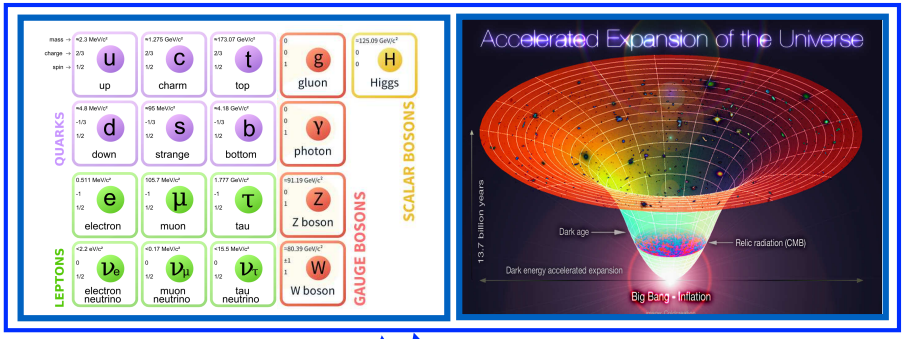

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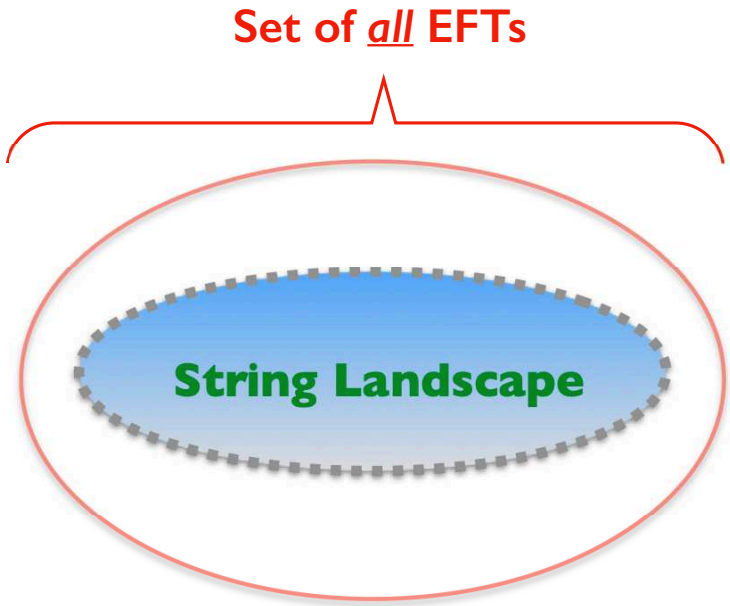

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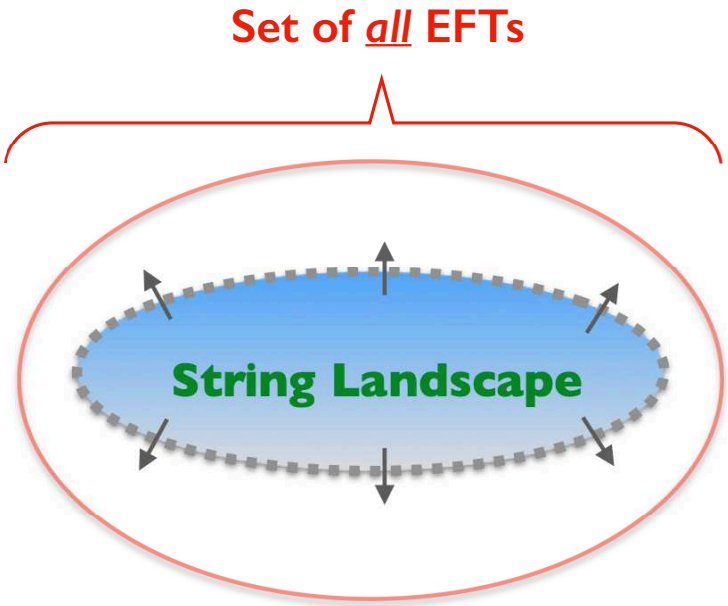

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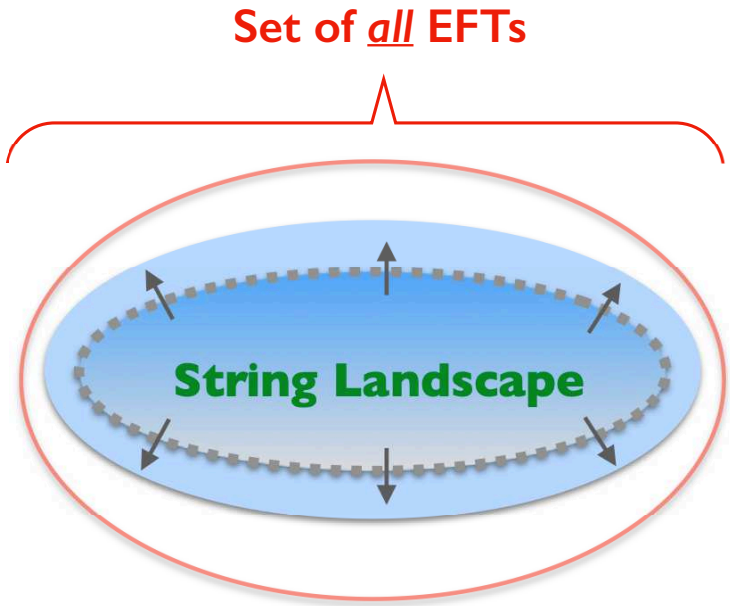

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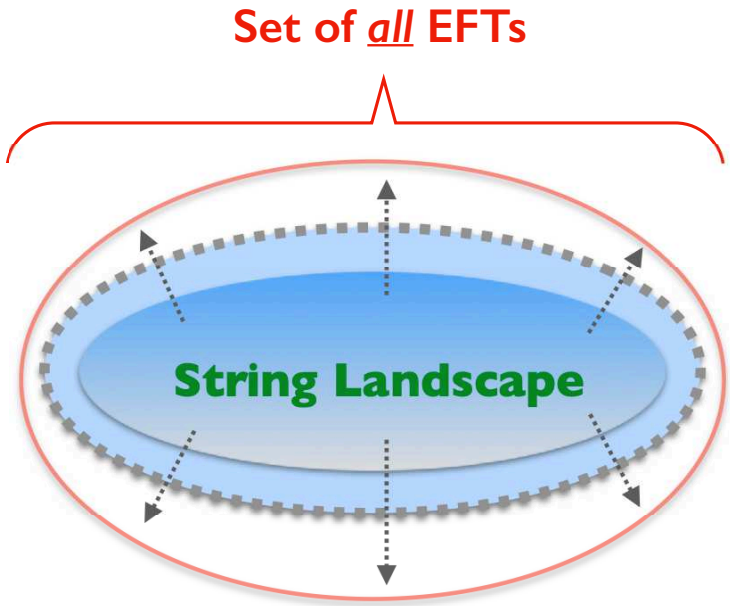

Universal Aspect of the String Landscape

Geometrical Constraints on Physics

- **Boundary of the String Landscape and Beyond**
  - Division of the set of QFT models with gravity
    - String Landscape (String EFTs) $\subset$ Landscape (EFTs w/ a UV-completion)
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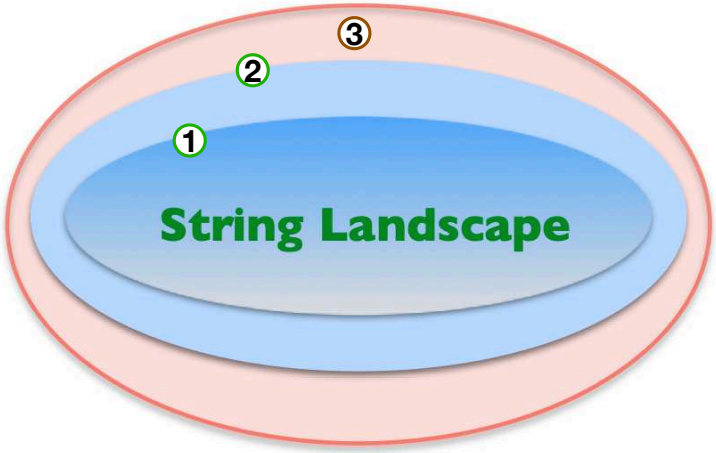

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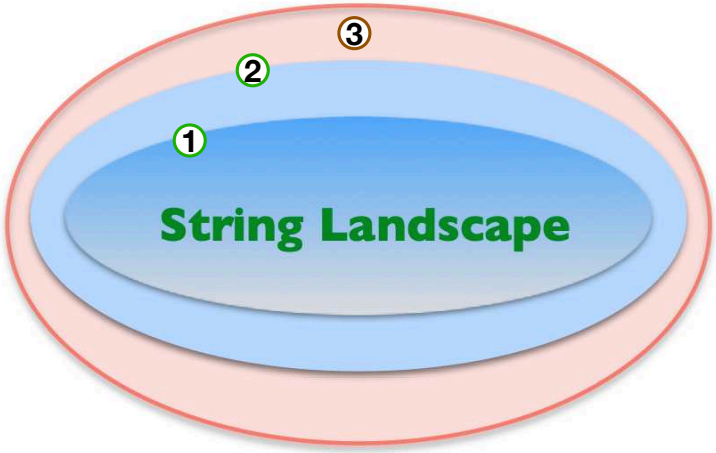

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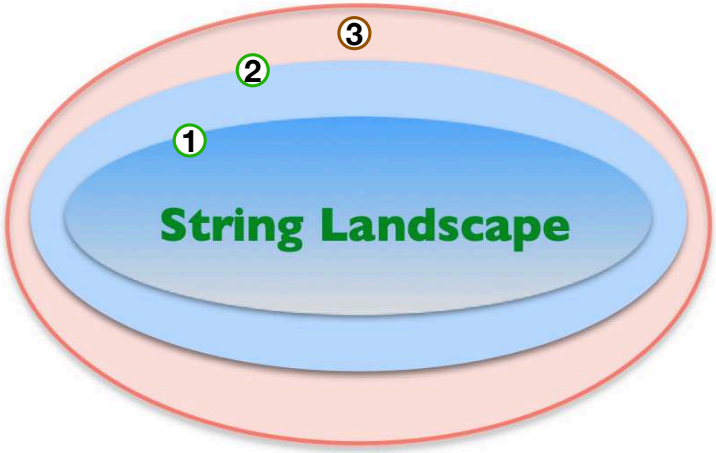

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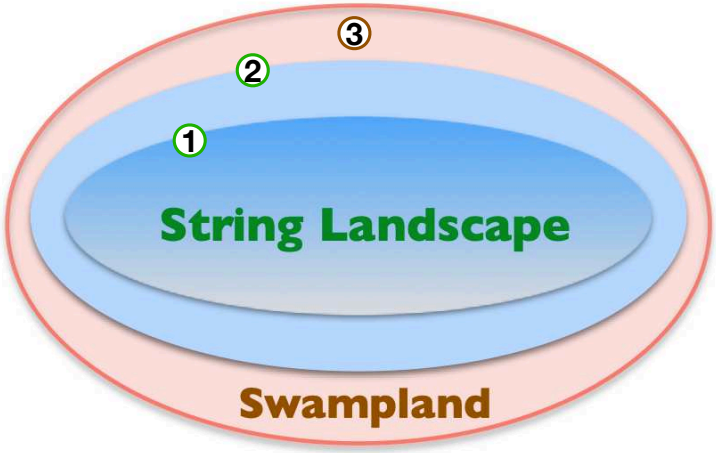

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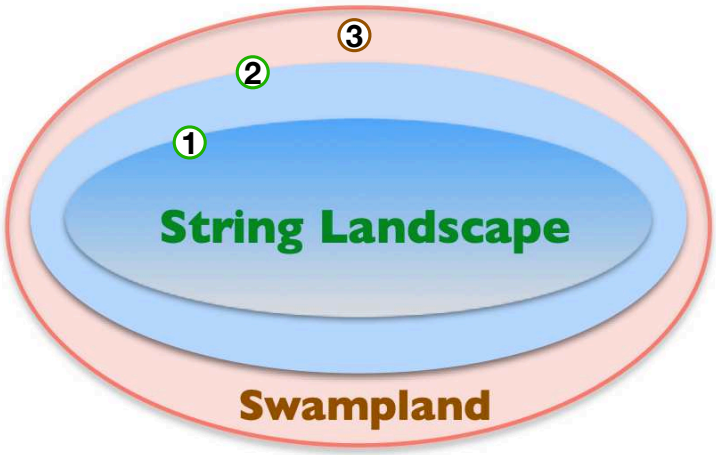

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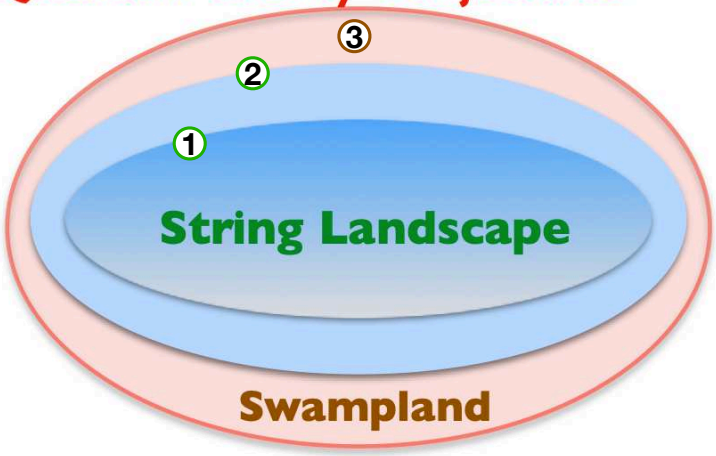

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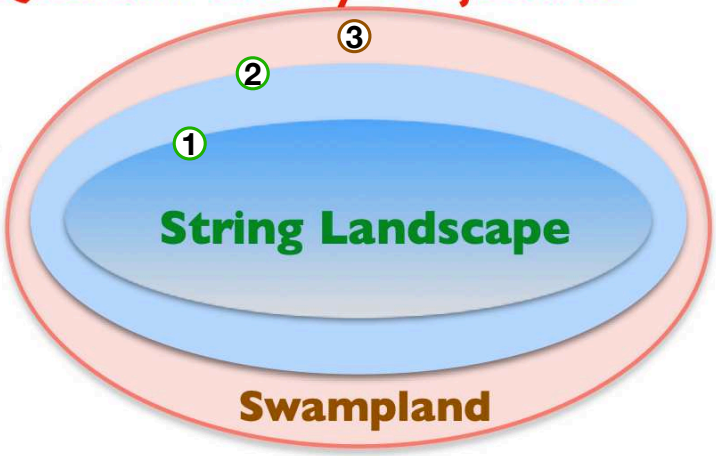

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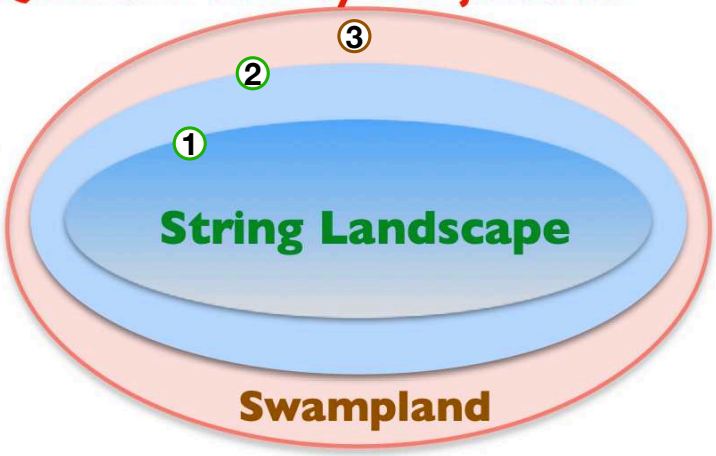

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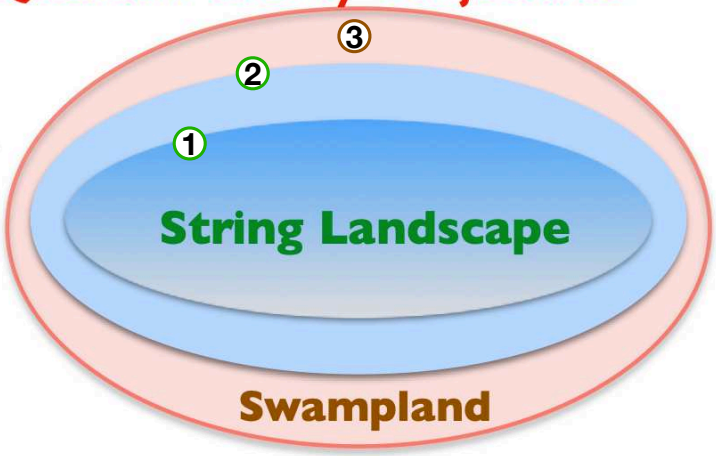

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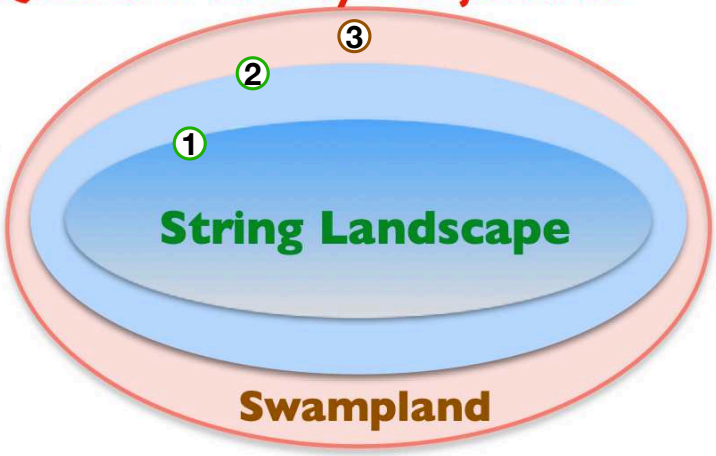

- **Geometrical Constraints on Physics**

"establish universal behaviors of the internal geometry to constrain the effective physics"

Weakness of Gravity

Verification for String EFTs at Weak U(1) Coupling

- **The Weak Gravity Conjecture(s)** [Arkani-Hamed, Motl, Nicolis, Vafa '06]; [Heidenreich, Reece, Rudelius '16-'17], [Montero, Shiu, Soler '16]

"The *gravitational* force is weaker than the *electric* force"

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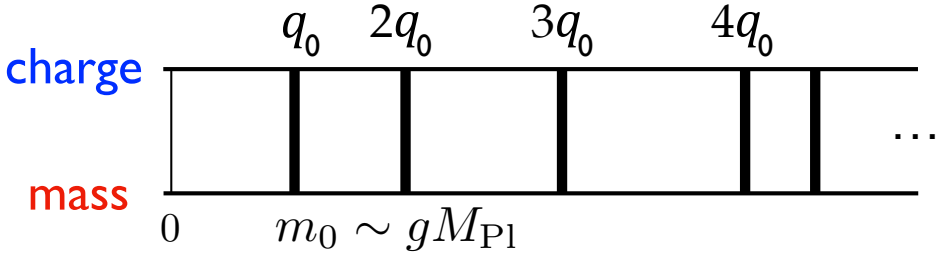

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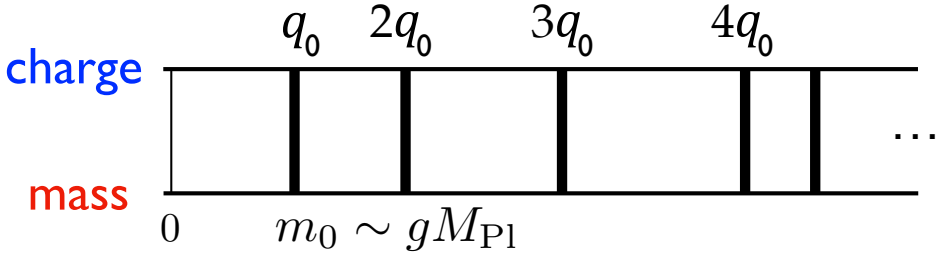

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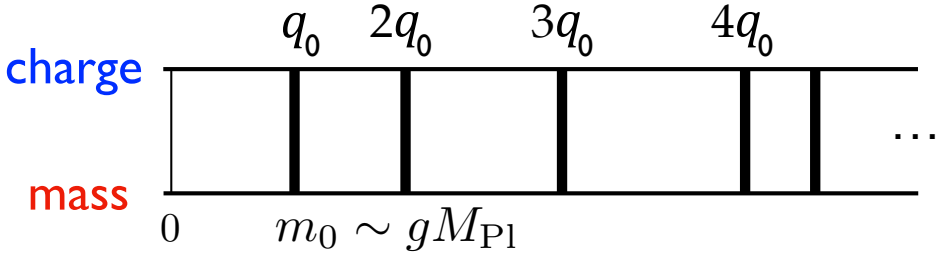

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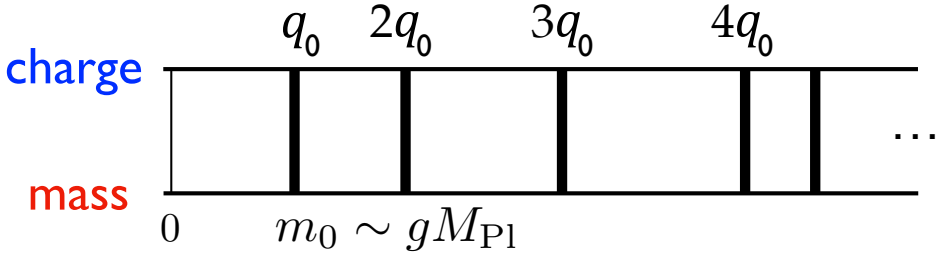

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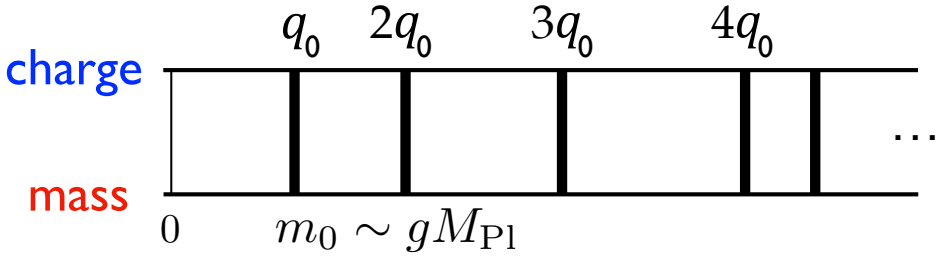

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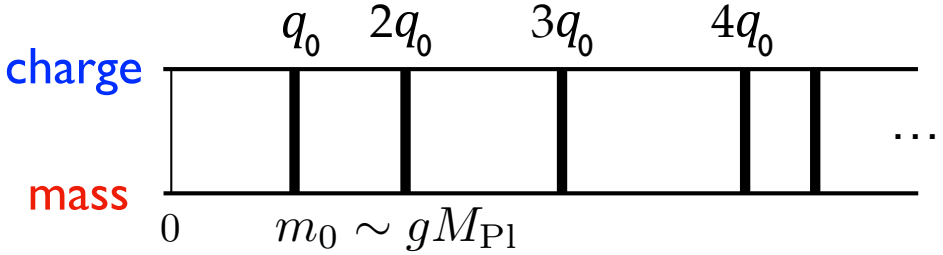

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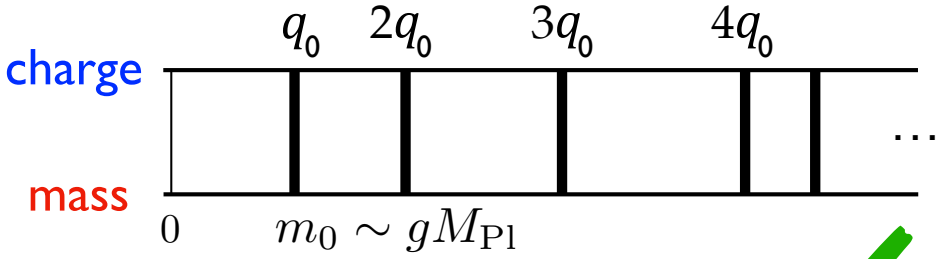

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- **Confirmation@** $g \ll 1$ [Klawer, S.-J.L., Weigand, Wiesner '20]

- A *universal geometric structure* assures that a light string emerges at weak coupling
- A symmetry of the string partition function leads to a *universal spectral pattern*
- The spectrum necessarily contains a tower/sublattice subject to the above inequality!

Weakness of Gravity

Verification for String EFTs at Weak U(1) Coupling

- **The Weak Gravity Conjecture(s)** [Arkani-Hamed, Motl, Nicolis, Vafa '06]; [Heidenreich, Reece, Rudelius '16-'17], [Montero, Shiu, Soler '16]

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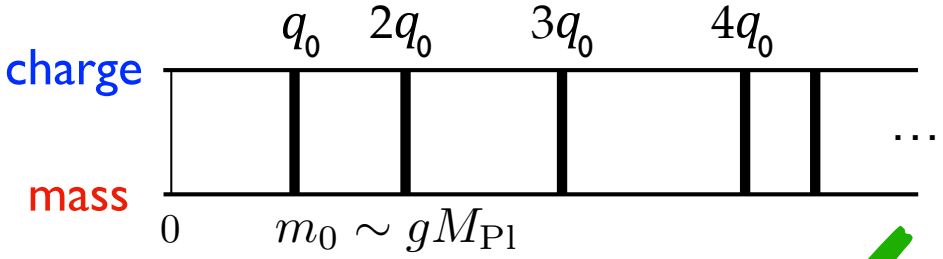

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F/M/IIA theory in 6/5/4d [S.-J.L., Lerche, Weigand '18-'20]

IIA/IIB hyper moduli in 4d [(Baume,) Marchesano, Wiesner '19]

M-theory in 4d [Xu '20]

F-theory in 4d

[S.-J.L., Lerche, Weigand '19], [Klawer, S.-J.L., Weigand, Wiesner '20]

Type II theory in 4d (closed)

[Grimm, Palti, Valenzuela '18], [Grimm, Li, Palti '18],

[Klemm, Joshi '19], [Grimm, Li, Valenzuela '19], …

F-theory in 8d (open) [S.-J.L., (Lerche,) Weigand '21]

F-theory in 6d (open) [Alvarez-Garcia, S.-J.L., Weigand '23]

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- Bottom-up intuitions e.g. in [Basile, Lust, Montella, '23], [Bedroya, Mishra, Wiesner, '24]
- Fruitful applications to particle physics, cosmology, pure geometry, …

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- Consistent EFTs of quantum gravity seem to exhibit certain universal features, known as **quantum gravity conjectures**.

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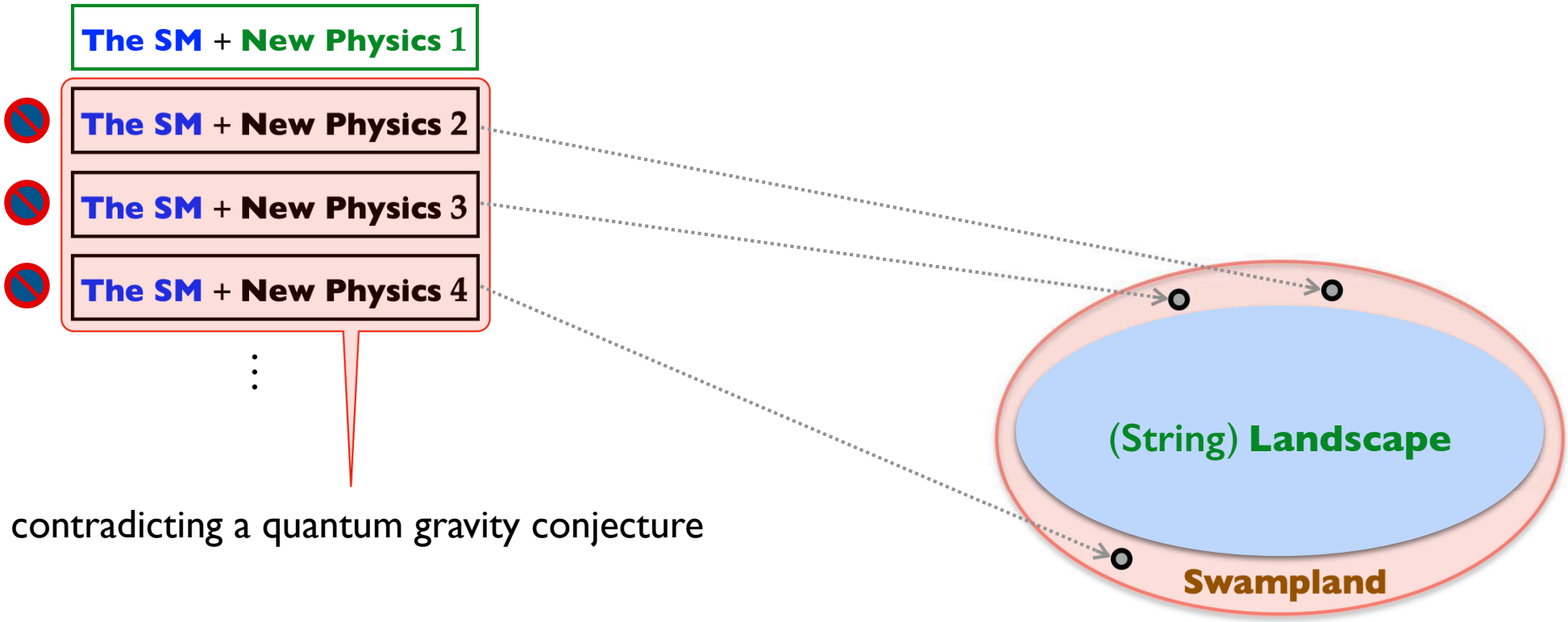
Thank You!

Connection to Phenomenology

Universal vs. Pheno Aspects

"The Swampland Program and the String Pheno Program are both in pursuit of a consistent theoretical model of **Our Universe!**"



contradicting a quantum gravity conjecture

Emergent String Conjecture

Potential Caveats

- **String Limits**
  - Could there arise ***multiple*** species of ***lightest strings***?
    - **No!** Universal patterns of asymptotic geometry support uniqueness

      [S.-J.L., Lerche, Weigand '18-'20]
  - Could ***higher-dim'l*** objects be lighter than the string?
    - **No!** Circumstantial evidence for quantum obstructions of potential membrane limits

      [Alvarez-Garcia, Klawer, Weigand '21]
- **Decompactification Limits**
  - Would the **Lorenz invariance** persist ***after the decompactification***?
    - **Not always!** **Defects** may arise in the "**brane moduli limits**"

      [Alvarez-Garcia, S.-J.L., Weigand '23]