Utrecht University

STRINGS AT THE END OF THE SWAMPLAND

Stefano Lanza

based on arXiv: ***2104.05726***
with ***Fernando Marchesano, Luca Martucci, Irene Valenzuela***

Cortona Young ~ June 10, 2021

Plan of the Talk

- Introduction:
  the Swampland Program

- Swampland distance conjecture:
  infinite field distances and EFT inconsistencies

- A novel perspective:
  Axionic strings as tools to explore the moduli space

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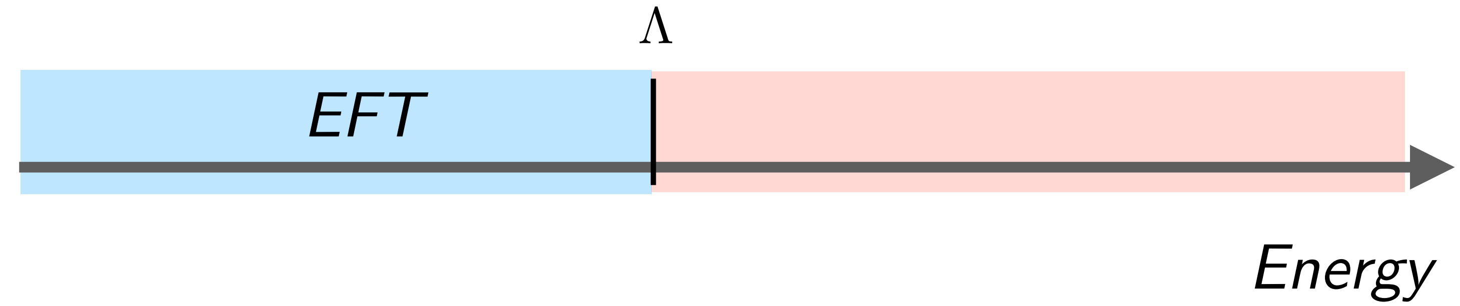
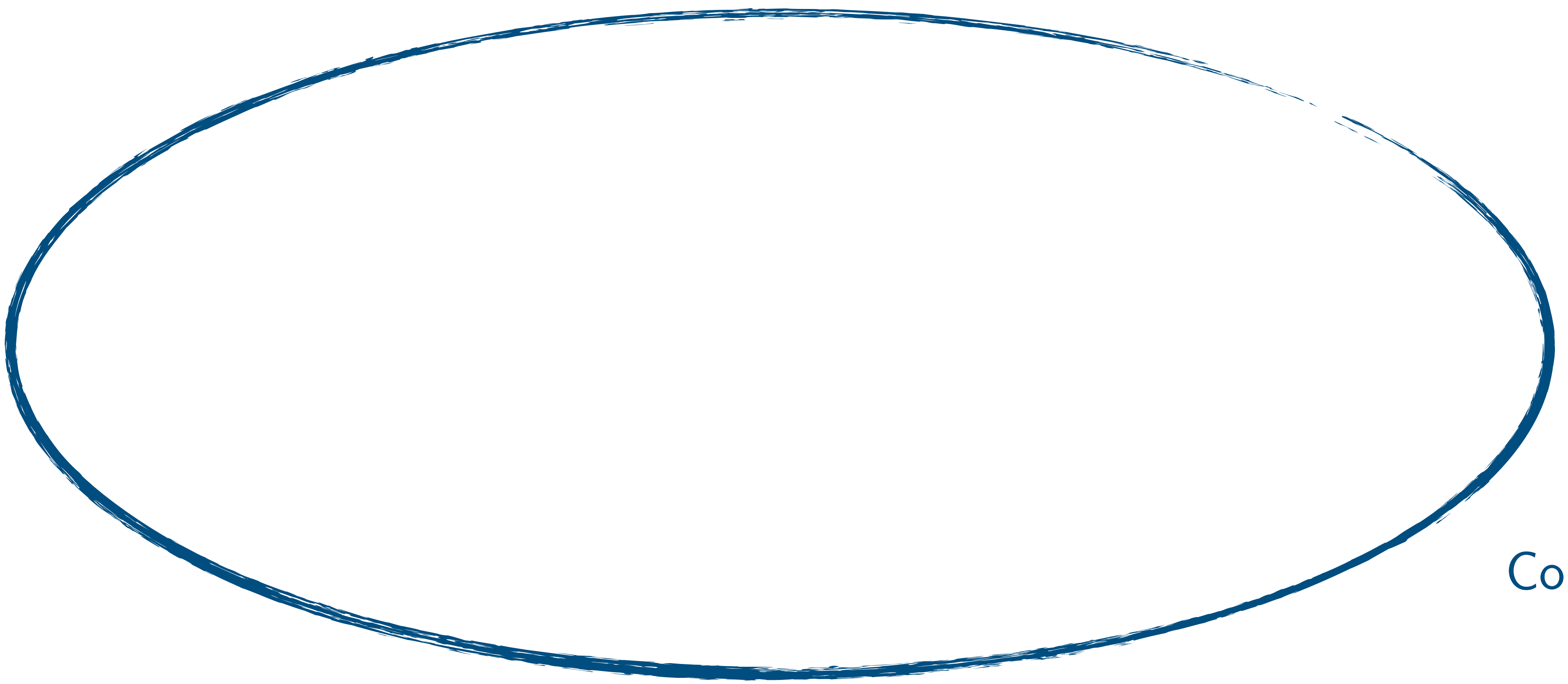
Including Gravity in EFTs

Consistent
Quantum Field Theory
+
Gravity

EFT, valid up to the cutoff Λ





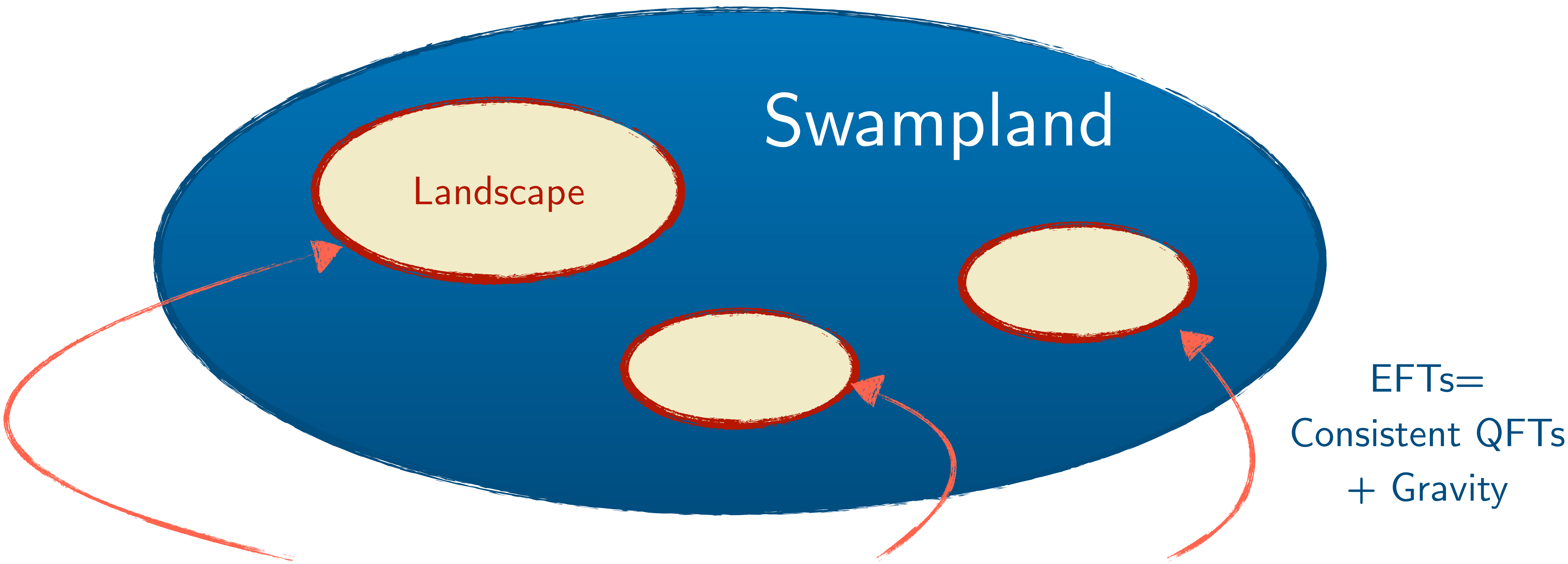
EFTs=
Consistent QFTs
+ Gravity

Can the EFT be embedded into a proper quantum theory of gravity?
Or: Does the EFT have a quantum gravity origin?

SWAMPLAND CONJECTURES

Only some them are embedded within a **quantum gravity completion:**

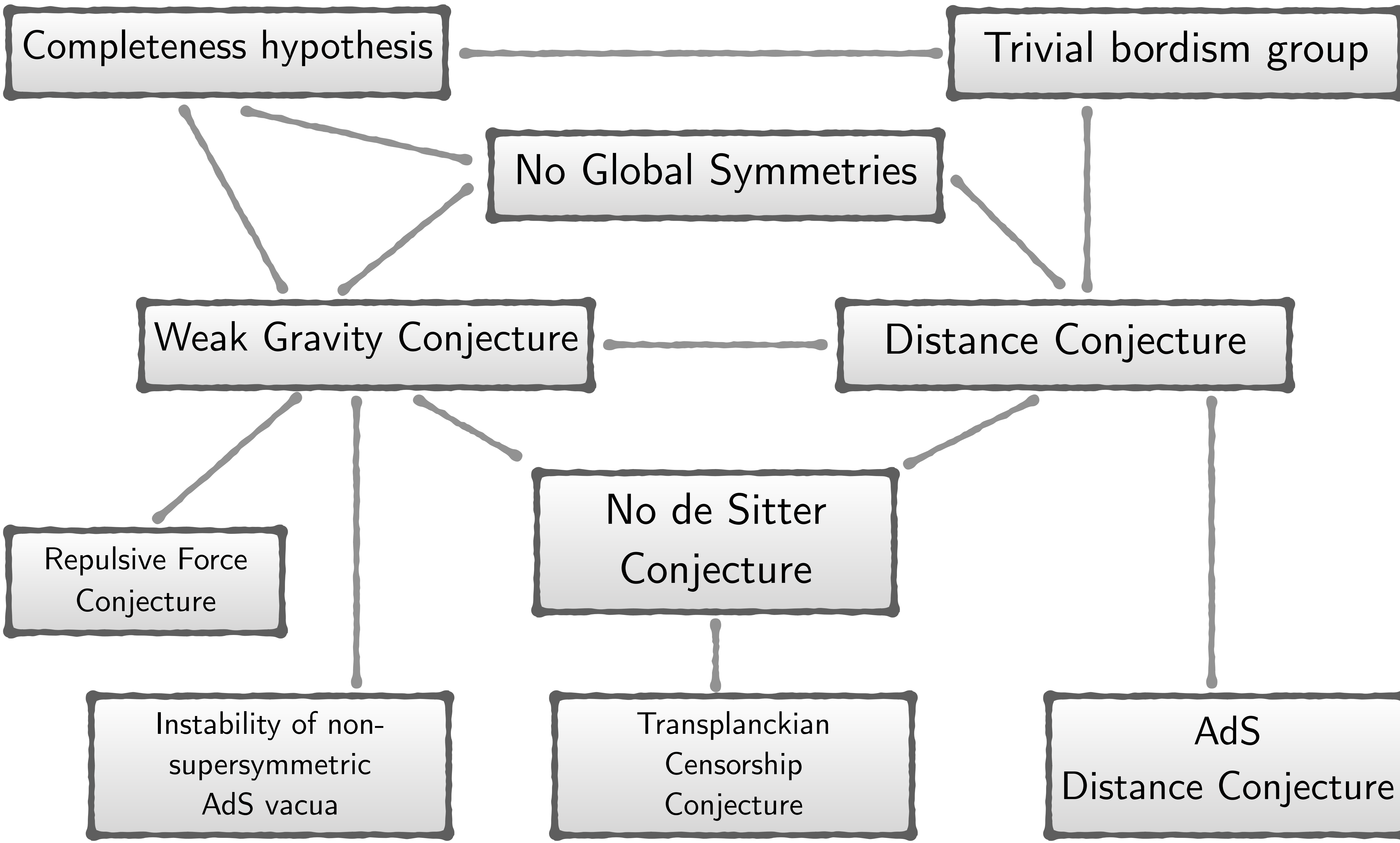
Landscape: consistent EFTs that admit a Quantum Gravity completion



The **Swampland program** aims at identifying the **borders** via "***Swampland Conjectures***"

The Web of Swampland Conjectures

Many consistency criteria, named ***Swampland Conjectures***, have been identified:



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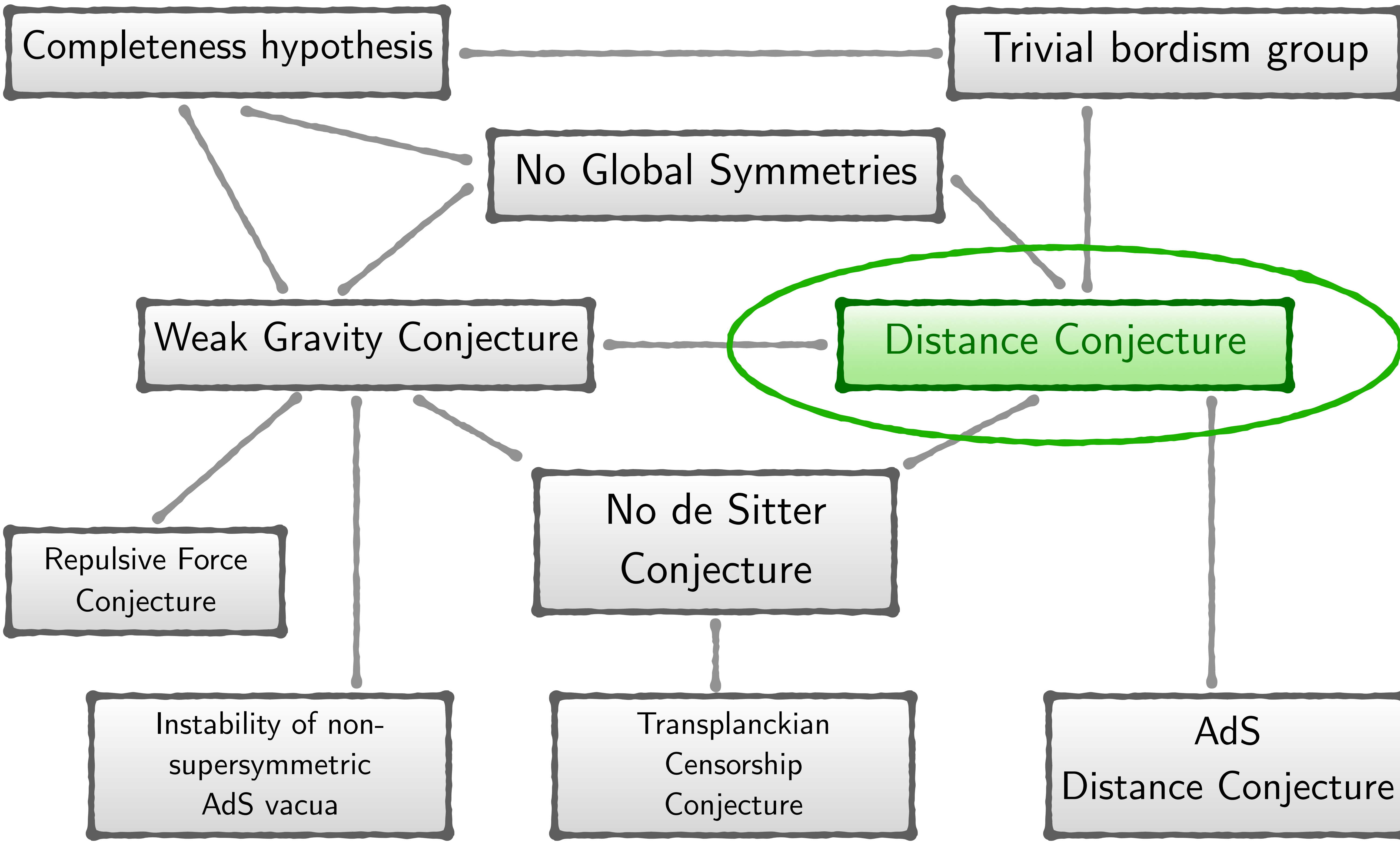


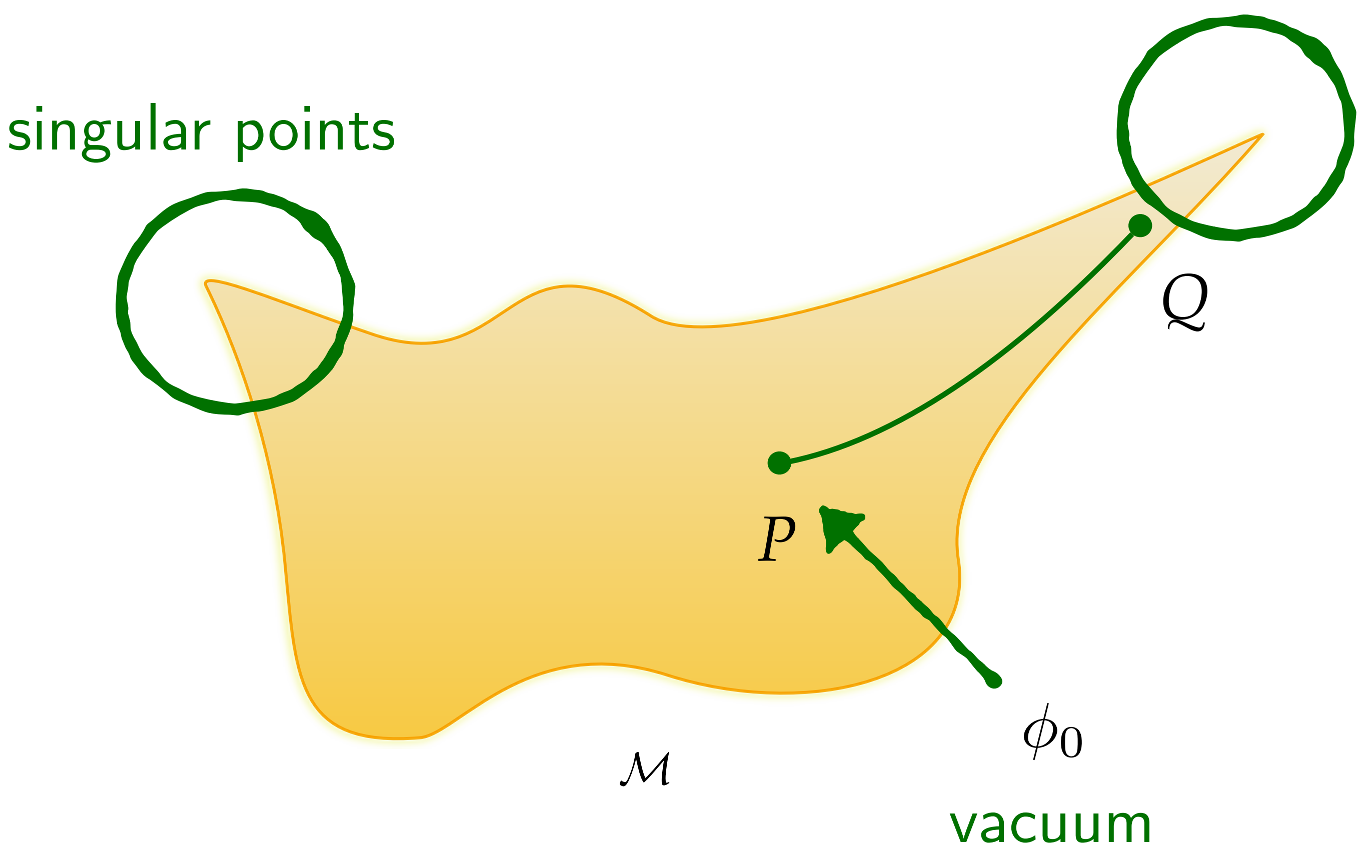
The Swampland Distance Conjecture

Singularities and Infinite Field Distances

Consider a generic d-dimensional EFT, valid up to the cutoff Λ:

$$S_d = \int \left(\frac{1}{2} R - \mathcal{G}_{ij}(\phi) \partial\phi^i \cdot \partial\phi^j + \dots \right) * 1$$

where ϕ^i span the manifold $\mathcal{M}$ and $\mathcal{G}_{ij}(\phi)$ is the field space metric.



Geodesic distance between the points P and Q:

$$\mathrm{d}(P,Q) = \int_\gamma \sqrt{\mathcal{G}_{ij}(\phi)\dot{\phi}^i \dot{\phi}^j}\, \mathrm{d}\sigma$$

Some singular points are located at infinite distance

$$\mathrm{d}(P,Q) \to \infty$$

THE SWAMPLAND DISTANCE CONJECTURE

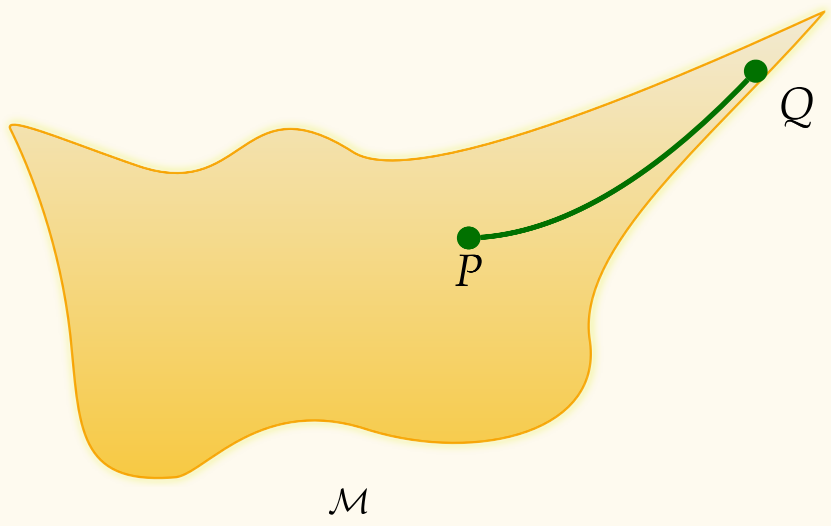
[Ooguri, Vafa, 2006]

The **Swampland Distance Conjecture** states that, in any EFT consistent with quantum gravity:

∃ an infinite tower of states that becomes exponentially light at *any* infinite field distance limit. Namely:

$$M(Q) \sim M(P) e^{-\lambda \, \mathrm{d}(P,Q)}$$

in terms of the geodesic distance $\mathrm{d}(P,Q)$ and with λ an *O(1)*-parameter.



<u>*Example:*</u> Consider a 10D string theory compactified over an S^1.
In 9D, a modulus ρ, the *radion*, is present

$$S_9 = \int \left(\frac{1}{2} R + \frac{1}{2\rho^2} \partial\rho \cdot \partial\rho + \dots \right)$$

The distance conjecture is realized towards decompactification limits:

$\rho \to \infty$ at $d(\rho_0, \rho) \to \infty$ ⟶ ∃ Infinite tower of KK modes $m^2_{\mathrm{KK}} \sim \frac{n}{\rho^2} \sim m^2_{\mathrm{KK},0} e^{-2\mathrm{d}(P,P_0)}$

THE SWAMPLAND DISTANCE CONJECTURE

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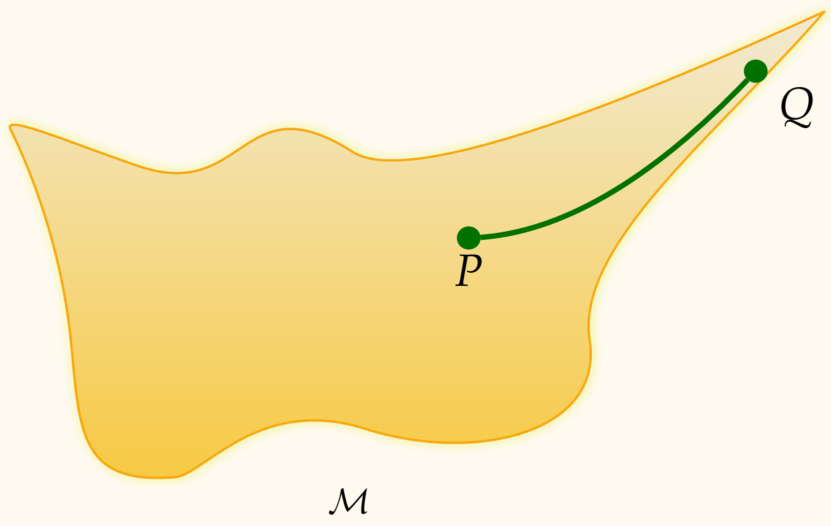

Many top-down arguments support the conjecture:

- Tower of D3-particles in general *N=2* settings
  [Grimm, Li, Palti, Valenzuela 2018-2020]
- Emergent string conjecture
  [Lee, Lerche, Weigand 2019]
- Towers of strings and membranes
  [Font, Herraez, Ibanez 2019]
- ...

THE SWAMPLAND DISTANCE CONJECTURE

[Ooguri, Vafa, 2006]

The **Swampland Distance Conjecture** states that, in any EFT consistent with quantum gravity:

$\exists$ an infinite tower of states that becomes exponentially light at *any* infinite field distance limit. Namely:

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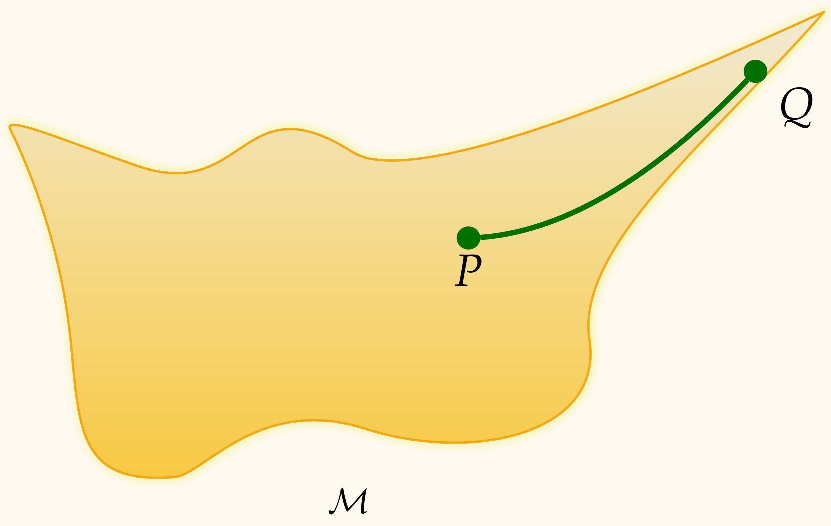


How can the Distance Conjecture be realized at the EFT level?

Or:

Is there a mechanism which drives the fields to the field space boundary?

a Novel Perspective:
introducing Axionic Strings

Axionic Strings

Focus on 4D EFTs. The objects that realize the Distance Conjecture at the EFT level are

Fundamental Axionic Strings

Their distinguishing features are:

- ***strict* codimension two**;
- electrically coupled to gauge two-forms via:

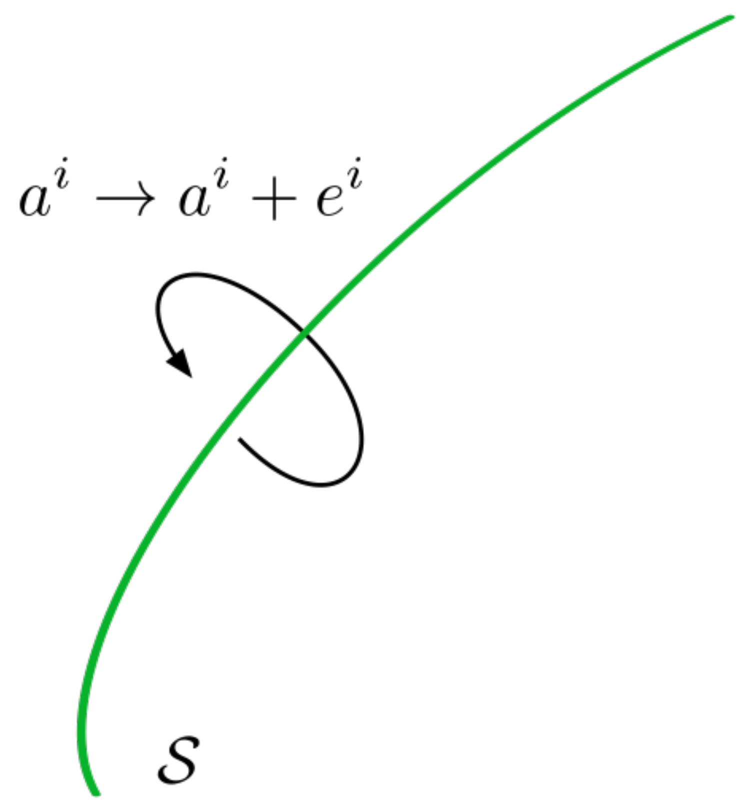
$$e^i \int_{\mathcal{S}} \mathcal{B}_{2\,i}$$

- magnetically coupled to the dual axions, such that, encircling the string:

$$a^i \to a^i + e^i$$

- they are semiclassical, i.e. within an EFT with cutoff Λ,

$$\mathcal{T}_{\rm str} \gtrsim \Lambda^2$$



Axionic Strings

Focus on 4D EFTs. The objects that realize the Distance Conjecture at the EFT level are

Fundamental Axionic Strings

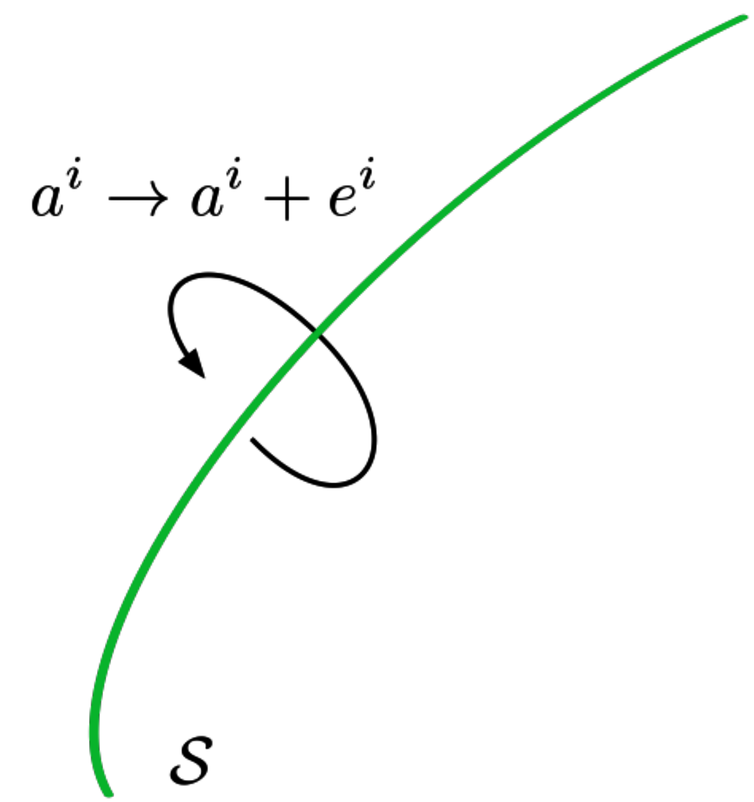
Axionic strings can be included in EFTs as unresolved, semiclassical objects via the action

Nambu-Goto term *Chern-Simons term*

$$S_{\rm str} = -\int_{\mathcal{S}} \mathrm{d}^2\xi\sqrt{-h}\,\mathcal{T}_{\rm str} + e^i\int_{\mathcal{S}} \mathcal{B}_{2\,i}$$

String tension (field dependent)

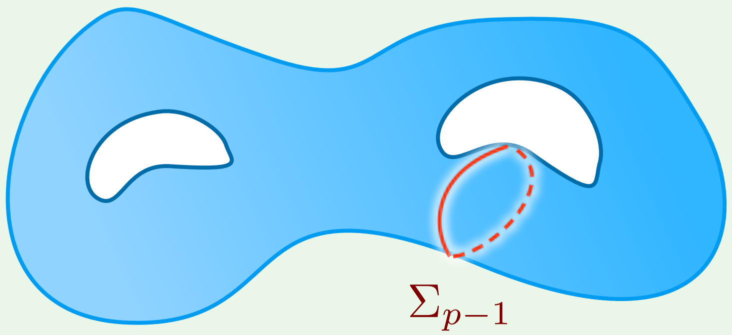
Electric charges/axion windings



AXIONIC STRINGS: WHAT ARE THEY?

***p*-branes wrapped on internal (p-1)-cycles**

Internal *(p-1)*-cycle



External 2-dim. string

Vortices solutions in Goldstone models

Break global symmetry → **axion** = Goldstone → vortex solution/"***global string***"

[Nielsen, Olesen, Vilenkin, Reece,...]

Cosmic strings

Phase breaking during inflation → Two-dimensional defects/"***cosmic strings***"

[Kibble, Vilenkin,...]

Axionic Strings in N=1 Supergravity

- Consider a set of chiral multiplets Φ^i is

$$\phi^i = a^i + \mathrm{i}s^i$$

axions

saxions

with the Kähler potential

$$K(\phi, \bar{\phi}) \equiv K(s)$$

Invariant under axionic shifts

$$a^i \to a^i + c^i \,, \qquad c^i \in \mathbb{R}$$

- The bosonic components of an *N=1* supersymmetric action of a set of chiral multiplets Φ^i is

$$S = \int M_{\mathrm{P}}^2 \left(\frac{1}{2} R - 2\mathcal{G}_{ij} \partial s^i \cdot \partial s^j - 2\mathcal{G}_{ij} \partial a^i \cdot \partial a^j \right) * 1$$

with the field space metric

$$\mathcal{G}_{ij}(s) = \frac{1}{2} \frac{\partial^2 K}{\partial s^i \partial s^j}$$

Axionic Strings in $N=1$ Supergravity

Dualize the chiral multiplets Φ^i to linear multiplets L_i:

saxions	s^i $\longleftrightarrow$	dual saxions	$\ell_i = -\frac{1}{2}\frac{\partial K}{\partial s^i}$
axions (gauge 0-forms)	a^i $\longleftrightarrow$	gauge 2-forms	$\mathcal{H}_{3i} = \mathrm{d}\mathcal{B}_{2i} = \frac{1}{2}\frac{\partial^2 K}{\partial s^i\,\partial s^j} * \mathrm{d}a^j$

- The dual action expressed in terms of a set of linear multiplets is:

$$S = \frac{1}{2}\int\left(M_\mathrm{P}^2\, R * 1 - M_\mathrm{P}^2\,\mathcal{G}^{ij}\mathrm{d}\ell_i \wedge *\mathrm{d}\ell_j - \frac{1}{M_\mathrm{P}^2}\mathcal{G}^{ij}\mathcal{H}_{3\,i} \wedge *\mathcal{H}_{3\,j}\right)$$

- ...to which we can couple a BPS string

$$S_\mathrm{str} = -\int_\mathcal{S} \mathrm{d}^2\xi\sqrt{-h}\,\mathcal{T}_\mathrm{str} + e^i\int_\mathcal{S}\mathcal{B}_{2\,i}$$

The string tension is fully fixed by supersymmetry

$$\mathcal{T}_\mathrm{str} = M_\mathrm{P}^2 e^i \ell_i(s) = -\frac{1}{2}M_\mathrm{P}^2 e^i\frac{\partial K}{\partial s^i}$$

[SL, Marchesano, Martucci, Sorokin, 2019]

AXIONIC STRINGS IN $N=1$ SUPERGRAVITY

Dualize the chiral multiplets Φ^i to linear multiplets L_i:

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- ...to which we can couple a BPS string

$$S_{\mathrm{str}} = -\int_{\mathcal{S}} \mathrm{d}^2\xi \sqrt{-h}\, \mathcal{T}_{\mathrm{str}} + e^i \int_{\mathcal{S}} \mathcal{B}_{2\,i}$$

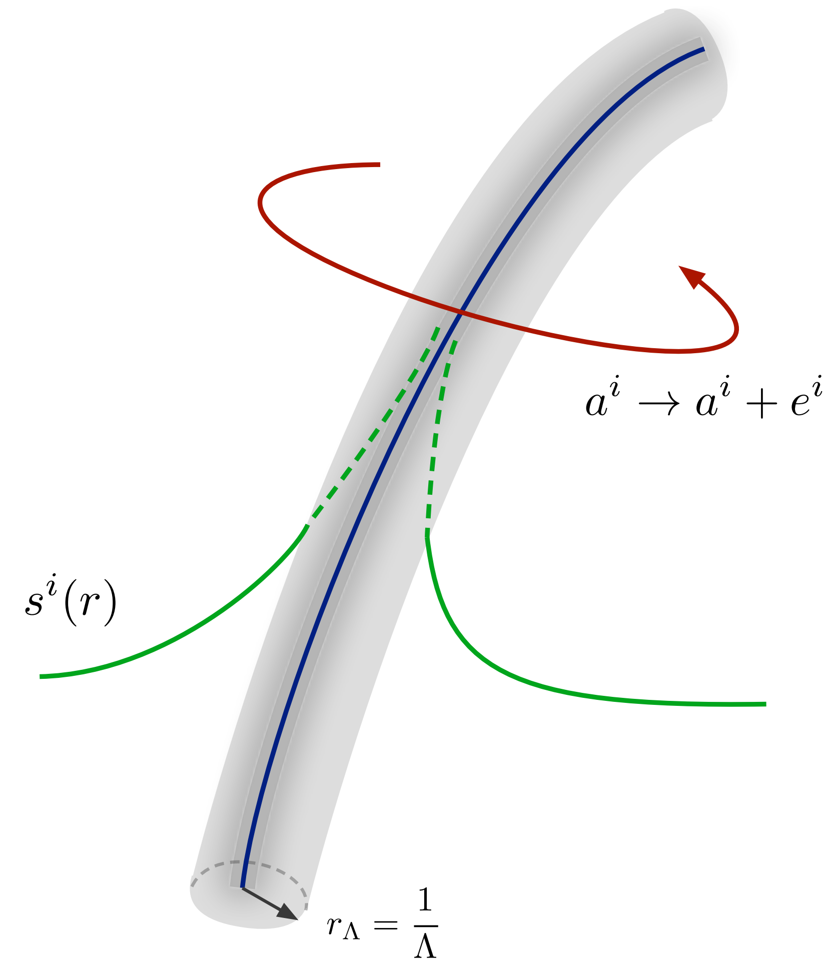
Solve the equations of motion of bulk + string

$\Rightarrow$ **String backreaction**

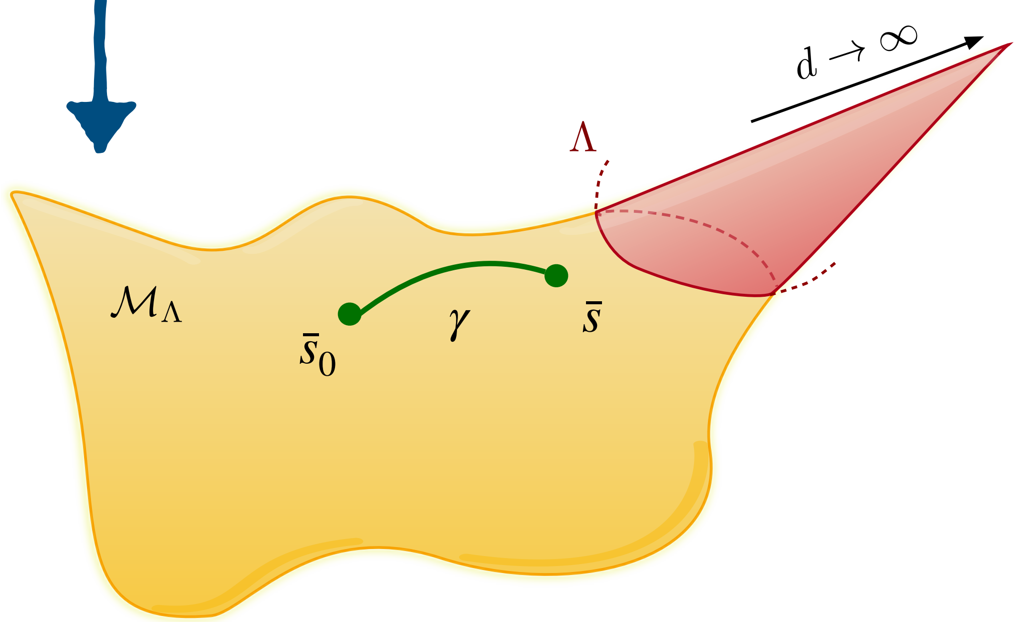
Interpreting the String Backreaction

- The backreaction of the string onto the fields is

$$s(r) = s_0 - \frac{e}{2\pi} \log \frac{r}{r_0}\,, \qquad a = \frac{\theta}{2\pi}\, e + \text{const}$$



maps to trajectories in the moduli space



We can explore the moduli space via the string backreaction

$$\gamma_{\mathbf{e}} \equiv \{\bar{\boldsymbol{t}} = \bar{\boldsymbol{a}}_0 + \mathrm{i}\bar{\boldsymbol{s}}(\sigma)\} \subset \mathcal{M}\,, \qquad \bar{\boldsymbol{s}}(\sigma) = \bar{\boldsymbol{s}}_0 + \sigma\mathbf{e}\,, \qquad \bar{\boldsymbol{a}}_0, \bar{\boldsymbol{s}}_0 = \text{const.}$$

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- Approaching the string core

$$s \to \infty$$

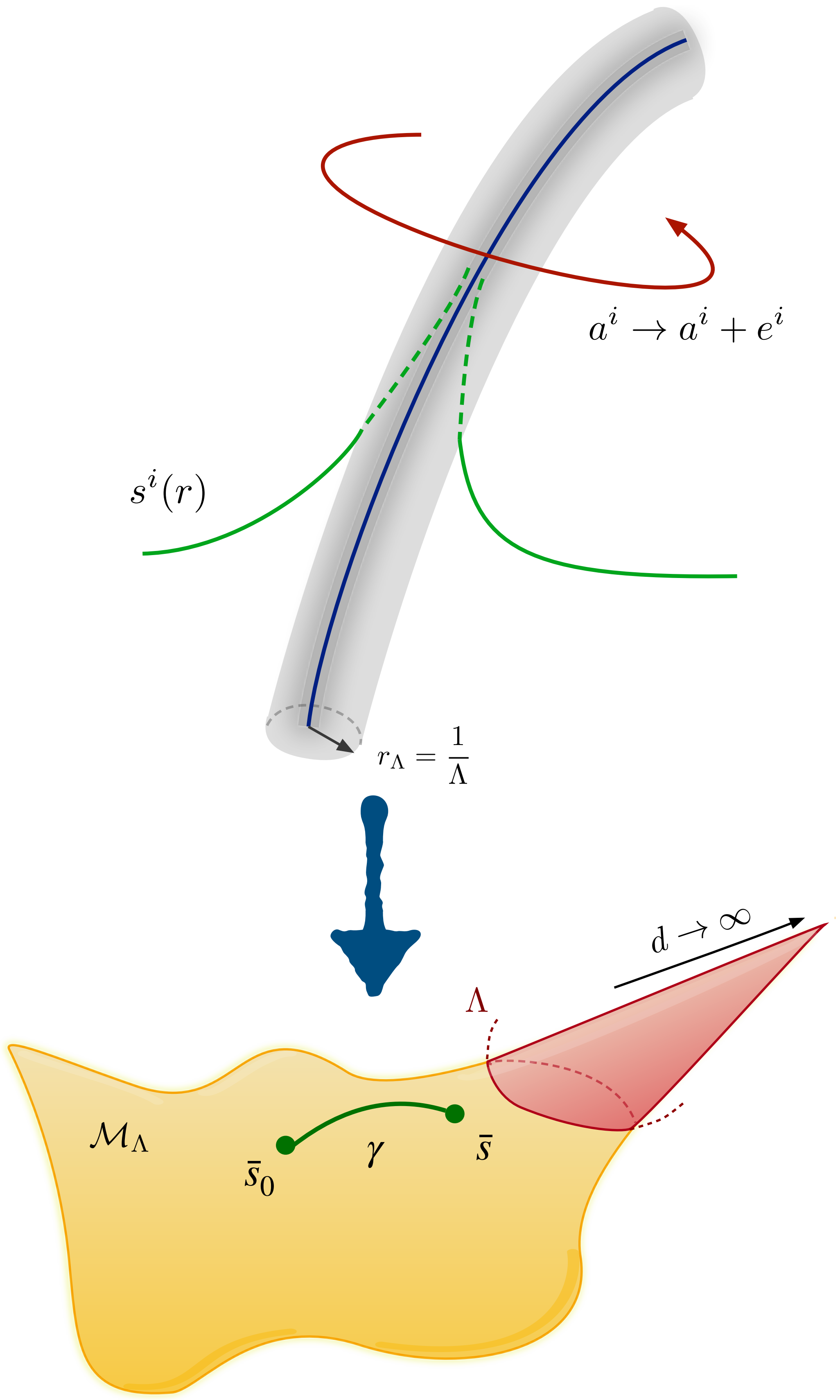
For Kähler potentials such as

$$K = -n\log s$$

these are infinite field distance limits

$$\mathrm{d}(s, s_0) \to \infty$$

Infinite distances reached toward the core



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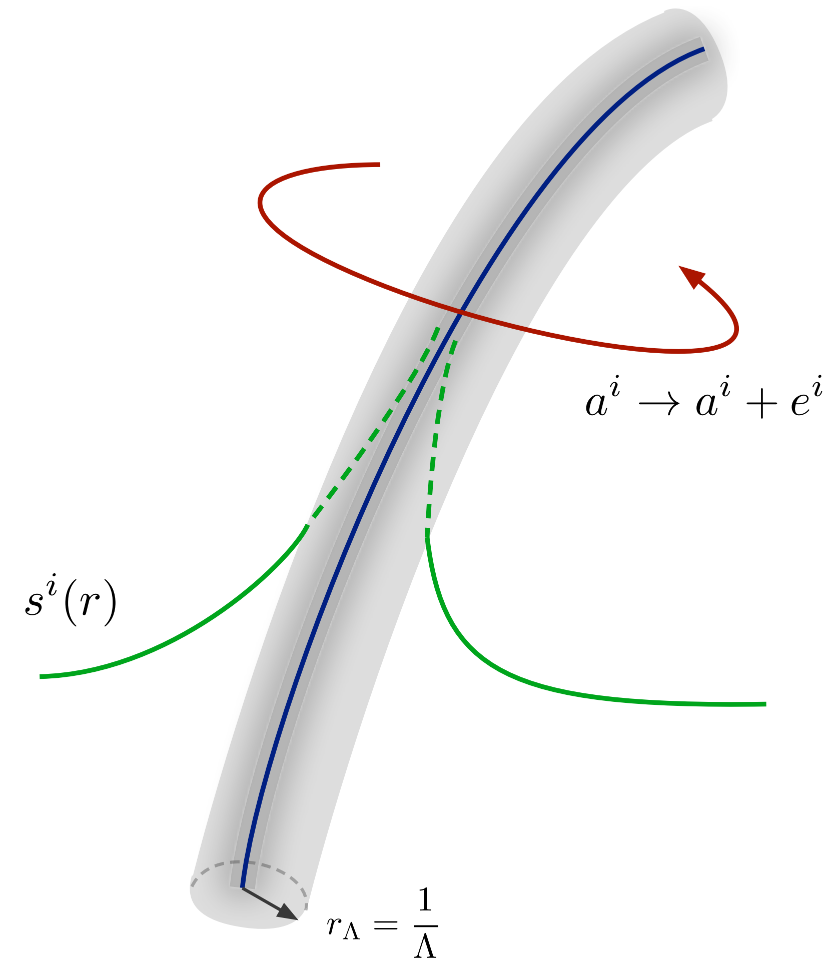


- Approaching the string core, the string appears tensionless

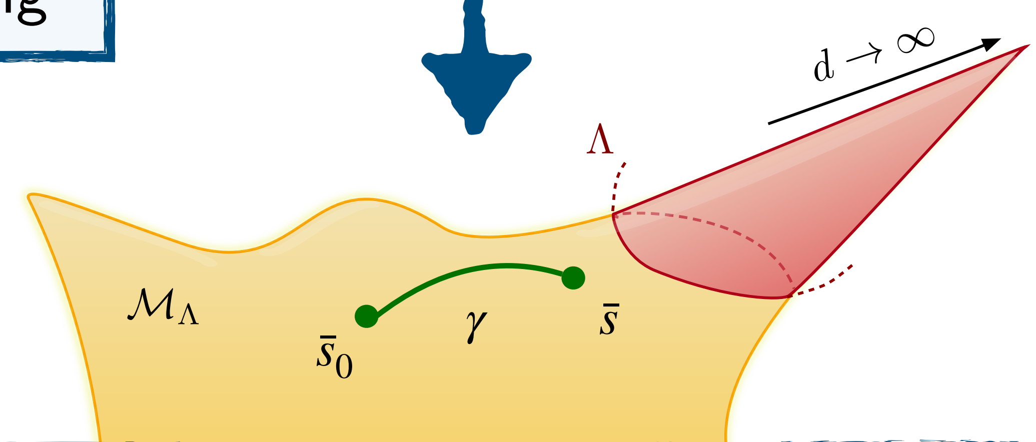
$$\mathcal{T}_{\text{str}} = M_{\text{P}}^2 e\,\ell(r) = \frac{M_{\text{P}}^2 e\,n}{2s_0 - \frac{e}{\pi}\log\frac{r}{r_0}} \xrightarrow{r\to 0} 0$$

Define the energy scale $\Lambda = r^{-1}$
Consider the string tension as EFT coupling

- ...and we regard the backreaction as an **RG flow**

[Polchinski et al., 2015, Goldberger, Wise, 2001]

$$\mathcal{T}_{\text{str}}^{\text{eff}}(\Lambda) = \frac{\mathcal{T}_{\text{str}}^{0}}{1 + \frac{\mathcal{T}_{\text{str}}^{0}}{2\pi M_{\text{P}}^2}\log(\Lambda r_0)}$$



Changing energy scales, following the RG flow, different, distant regions can be explored

Weak coupling closer to the string!

Interpreting the String Backreaction

- The backreaction of the string onto the fields is

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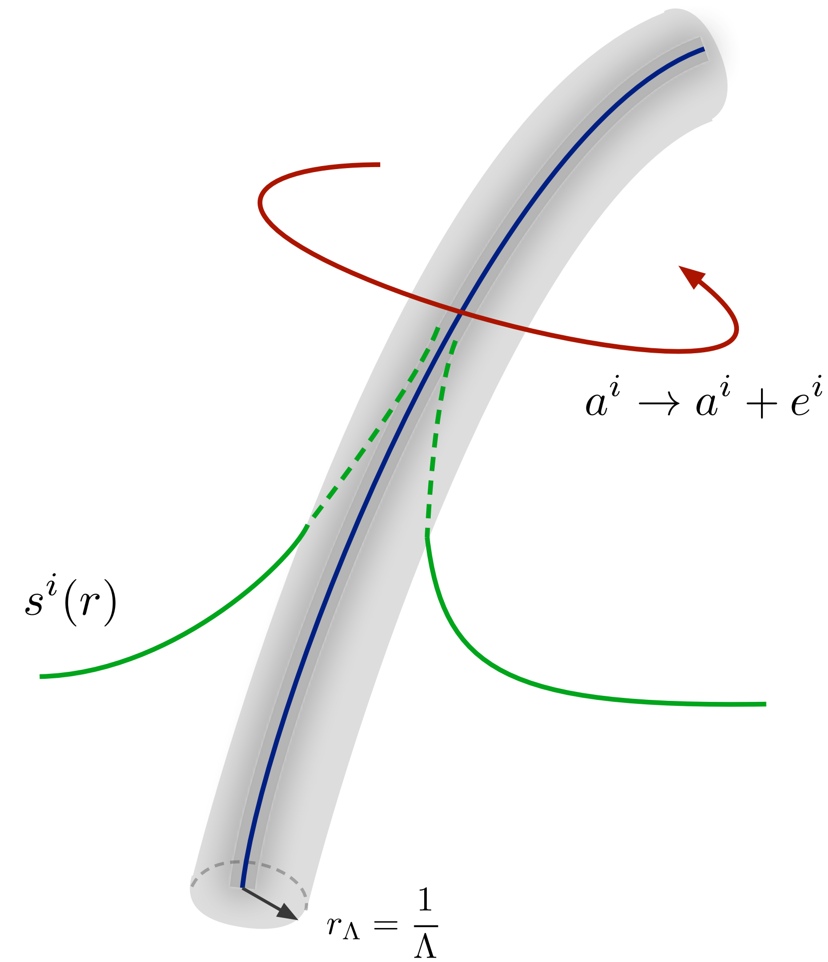
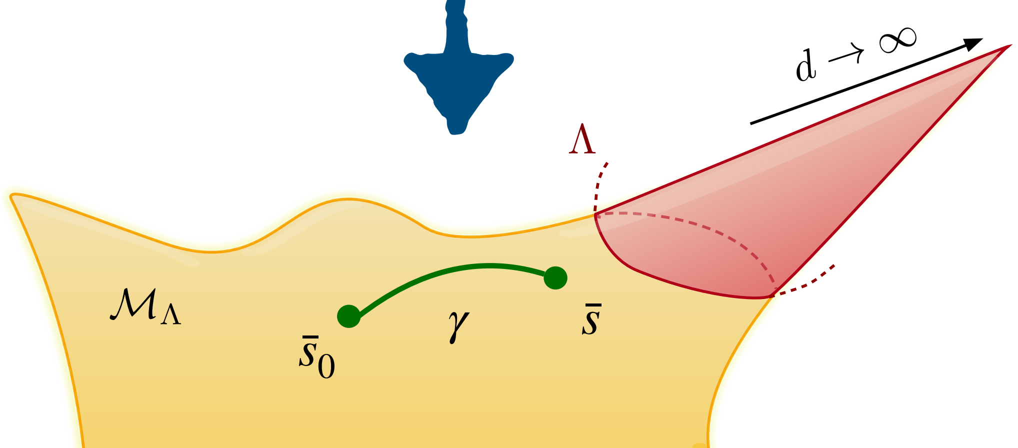


As the string becomes tensionless, an <u>infinite tower of states</u> appears

$$m \sim \mathcal{T}_{\rm str}^{1/2} \sim (\mathcal{T}^0_{\rm str})^{1/2}\exp\left(-\frac{\gamma}{2}\mathrm{d}(s,s_0)\right) \to 0$$

with $\gamma = \mathcal{Q}_{\rm str}/\mathcal{T}_{\rm str}$ *and* $\mathcal{Q}_{\rm str} = \mathcal{G}_{ij}e^i e^j$



The EFT breaks down approaching the string!

Interpreting the String Backreaction

- The backreaction of the string onto the fields is

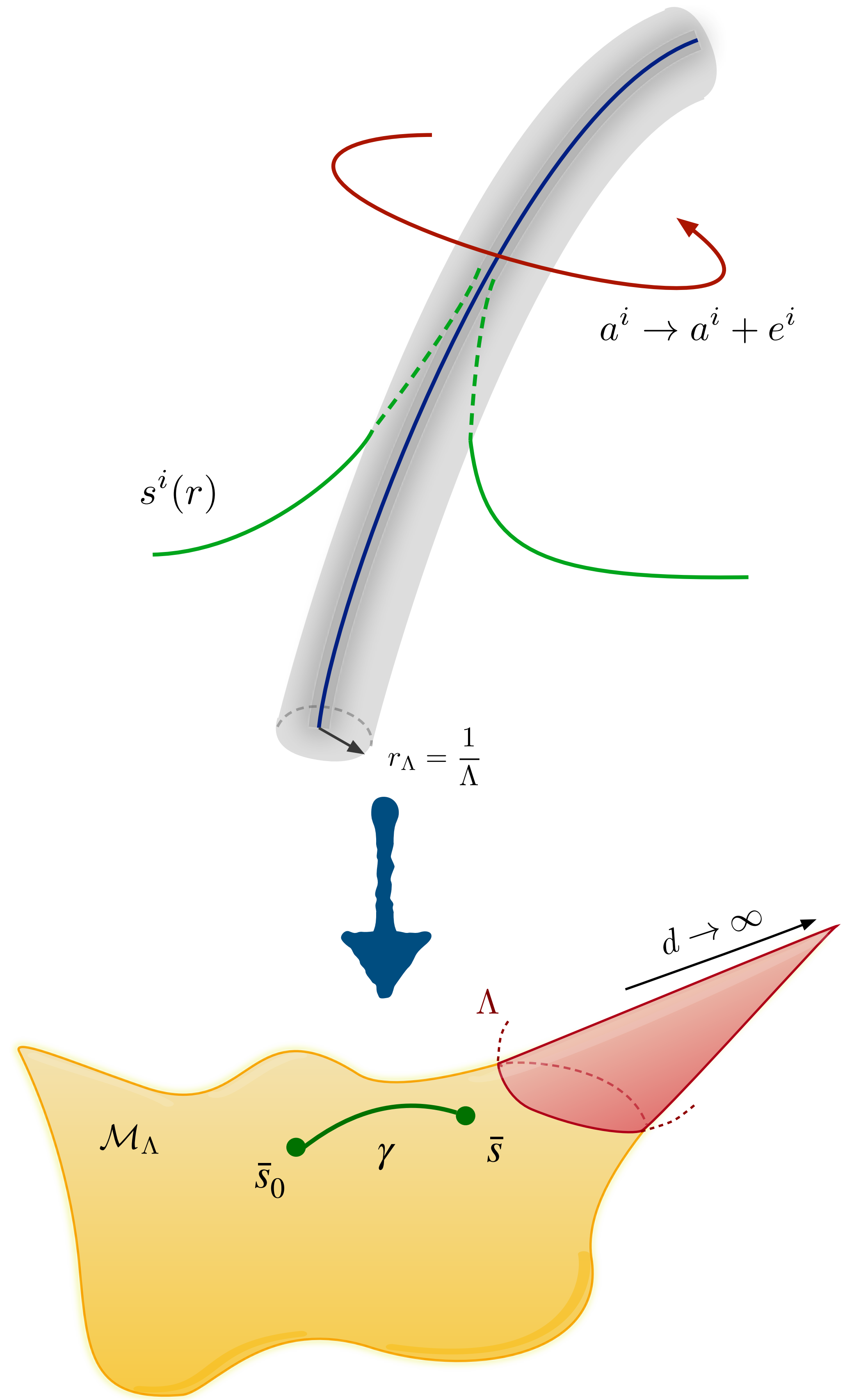
$$s(r) = s_0 - \frac{e}{2\pi}\log\frac{r}{r_0}\,, \qquad a = \frac{\theta}{2\pi}\,e + \text{const}$$

Approaching the string core, or moving along the **RG flow**

- Boundaries of moduli space reached
- Infinite field distances
- Infinite tower of massless states

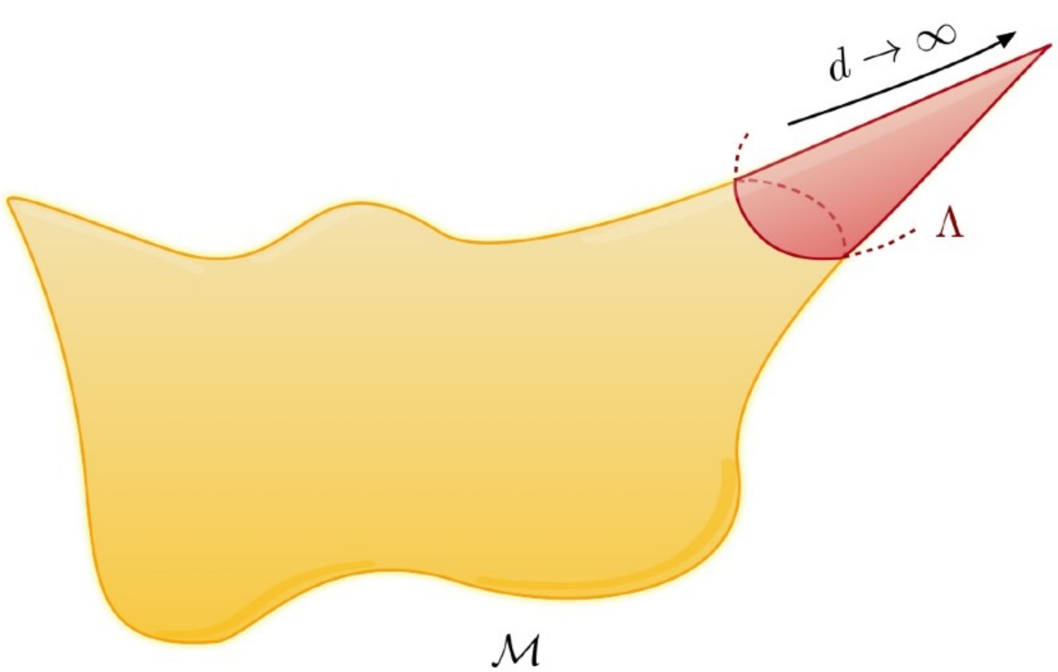
$$m \sim \mathcal{T}_{\text{str}}^{1/2} \sim (\mathcal{T}_{\text{str}}^{0})^{1/2}\exp\left(-\frac{\gamma}{2}\mathrm{d}(s,s_0)\right) \to 0$$

We are realising
the distance conjecture at the EFT level!

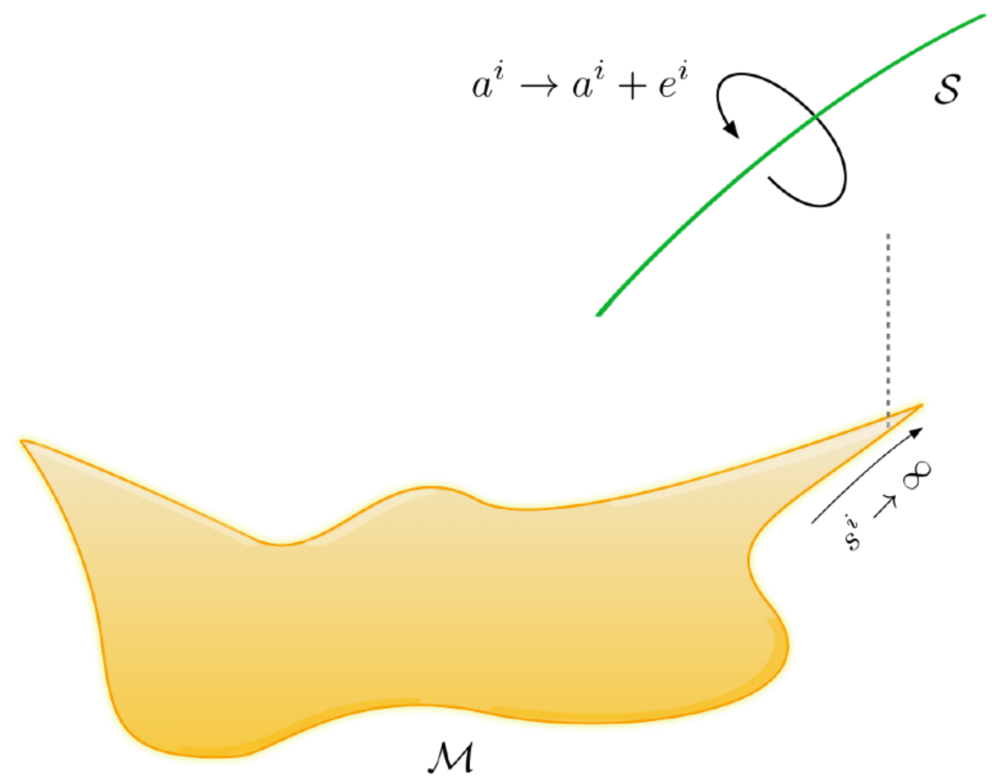


THE DISTANT AXIONIC STRING CONJECTURE

Distant Axionic String Conjecture (DASC):
All infinite distance limits of a 4d EFT can be realised as an RG flow endpoint of a fundamental axionic string.



RG Flow
$\Rightarrow$ Increase Λ
$\Rightarrow$ Infinite distances



For finite cutoff Λ, the moduli space is only partially explorable.

Infinite field distances are explorable via the string RG flow.

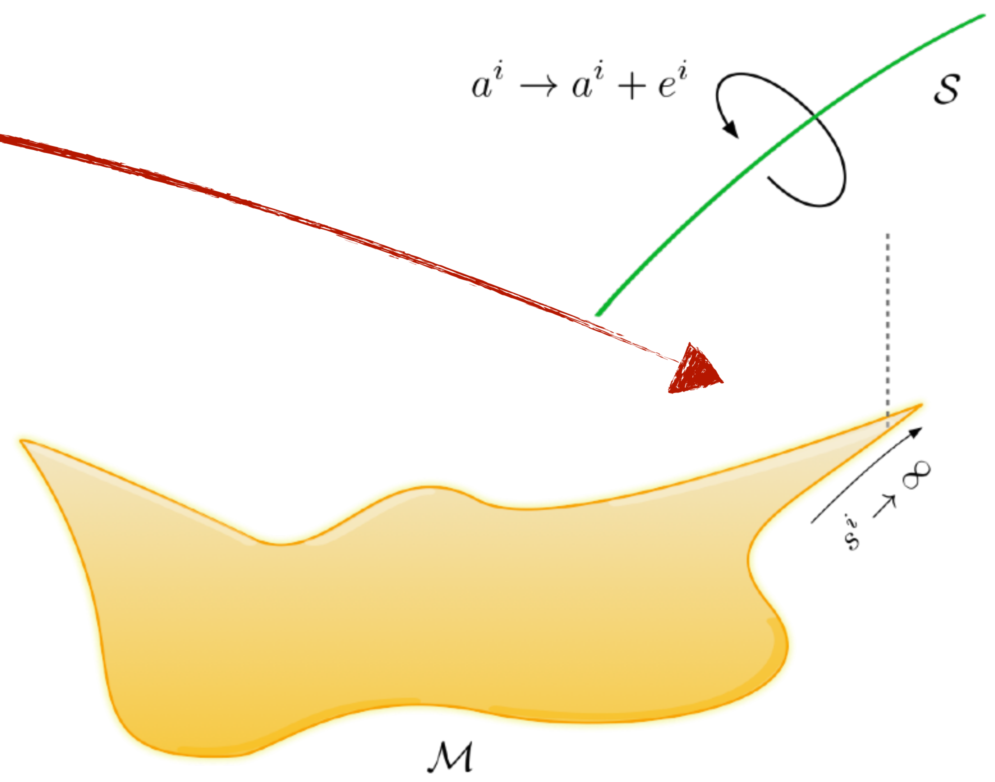
THE DISTANT AXIONIC STRING CONJECTURE

Distant Axionic String Conjecture (DASC):
All infinite distance limits of a 4d EFT can be realised as an RG flow endpoint of a fundamental axionic string.

Infinite tower of states becomes massless

⇒ EFT breaking down

In Stringy EFTs:
KK/winding modes, D0 branes, ...
(see SL, Marchesano, Martucci, Valenzuela '21 for the detailed analysis)



Infinite field distances are explorable via the string RG flow.

THE DISTANT AXIONIC STRING CONJECTURE

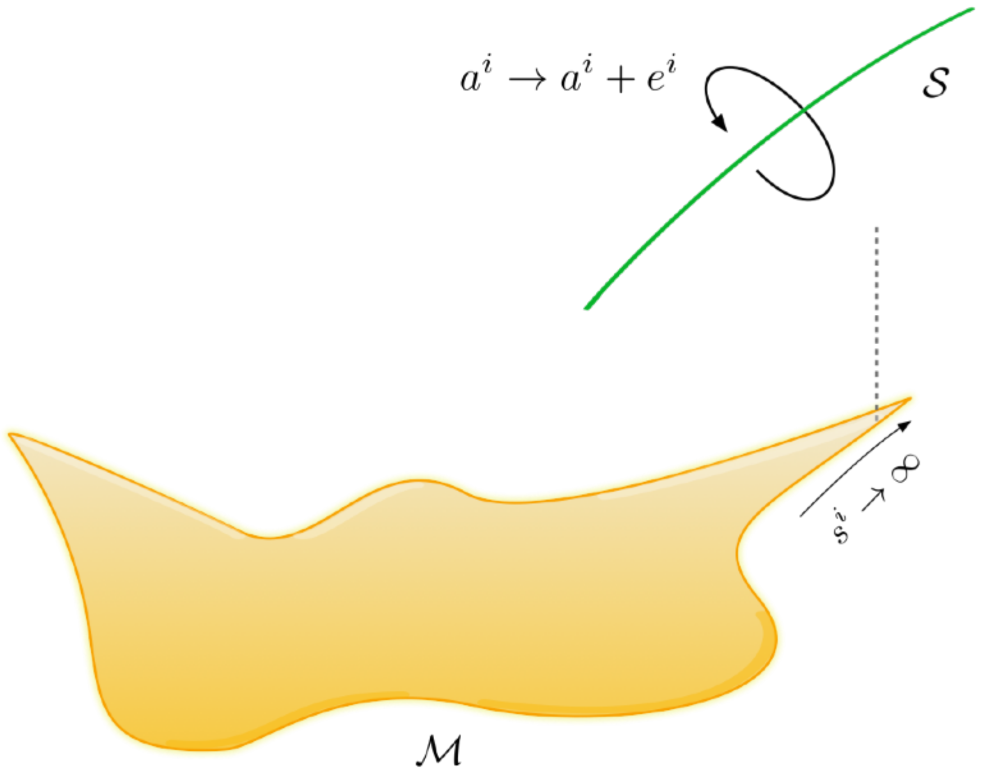
Distant Axionic String Conjecture (DASC):
All infinite distance limits of a 4d EFT can be realised as an RG flow endpoint of a fundamental axionic string.

Supported by:

Cut-off Asymptotics:
Along an asymptotic limit specified by the RG flow of an EFT string, its tension goes to zero. The maximal EFT cut-off m_* then scales like:

$$m_*^2 \simeq M_{\rm P}^2 A \left(\frac{\mathcal{T}_{\rm str}}{M_{\rm P}^2}\right)^w$$

with the scaling weight $w \in \mathbb{N}$.
(In stringy EFTs $w = 1,2,3$)



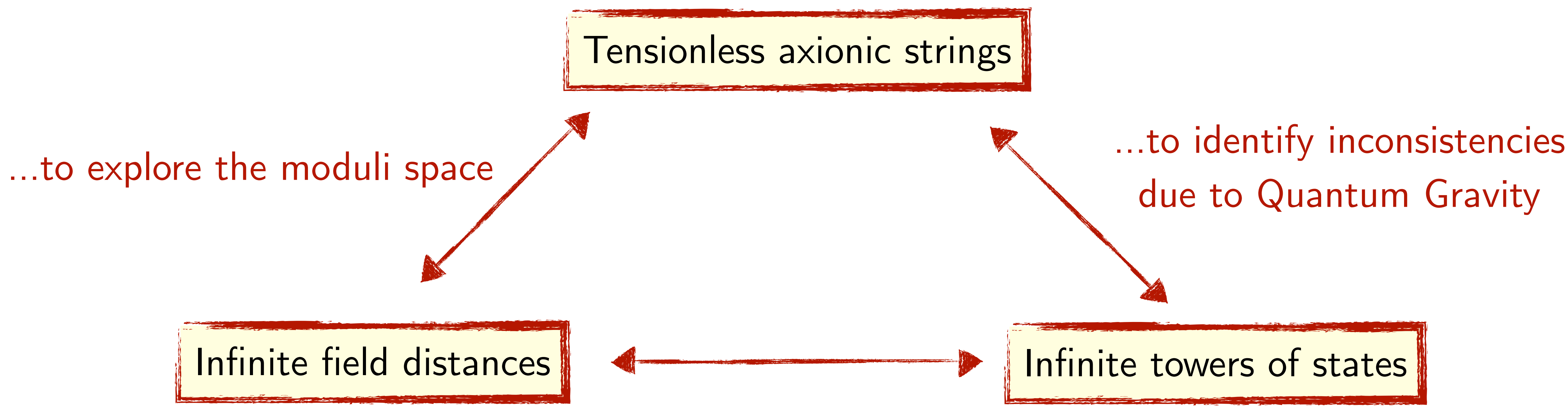
Infinite field distances are explorable via the string RG flow.

Conclusions

Conclusions and Future Outlook

With Axionic strings we can explore the moduli space

- They realise the Distance Conjecture at the EFT level;
- Their existence may be experimentally tested;
- They draw the correspondence among:



Some open questions:

- Extension to non-supersymmetric cases?
- Closer relations to other conjectures?
- Closer connections to Nielsen-Olesen strings or cosmic strings in literature?

Thank you!

Backup Slides

THE STRING BACKREACTION AS RG FLOW

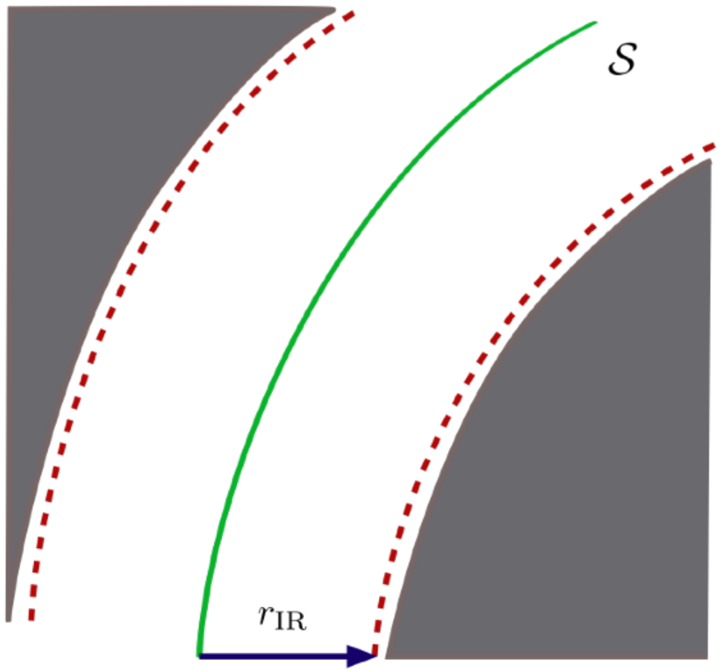
- The flow of the tension is

$$\mathcal{T}_{\rm str} = M_{\rm P}^2 e\,\ell(r) = \frac{e\,n\,M_{\rm P}^2}{2s_0 - \frac{e}{\pi}\log\frac{r}{r_0}}$$

which breaks down at a distance

$$r_{\rm IR} = r_0 \exp\left[\frac{n\pi\,M_P^2}{\mathcal{T}_{\rm str}(r_0)}\right]$$

In the limit $r \to 0$: $\quad \mathcal{T}_{\rm str} \to 0$



Define the energy scale $\Lambda = r^{-1}$
Consider the string tension as EFT coupling

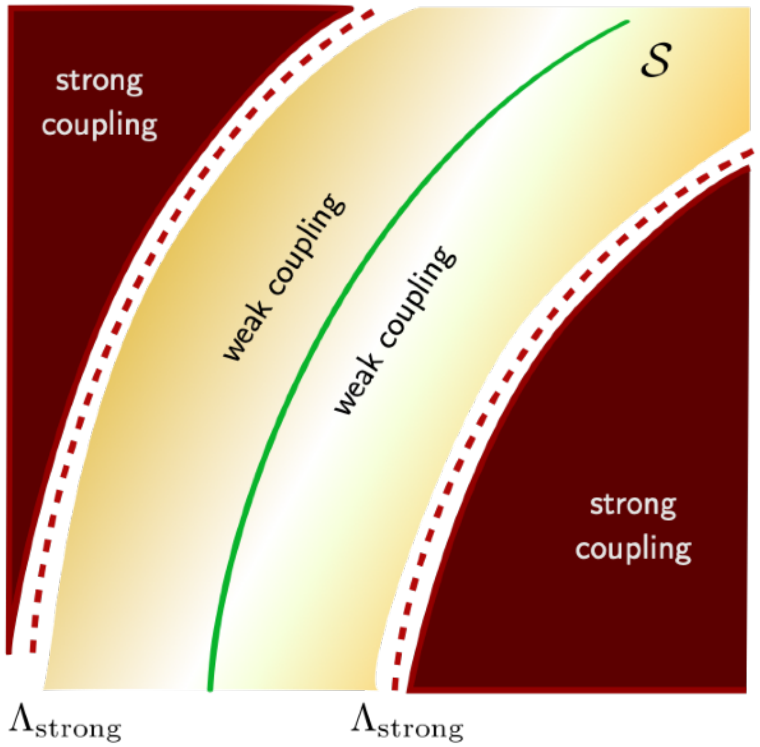
- We regard the profile of the tension as RG-flow of the tension

$$\mathcal{T}_{\rm str}^{\rm eff}(\Lambda) = \frac{\mathcal{T}_{\rm str}^0}{1 + \frac{\mathcal{T}_{\rm str}^0}{2\pi M_{\rm P}^2}\log(\Lambda r_0)}$$

and the EFT breaks at the strong coupling scale

$$\Lambda_{\rm strong} = \Lambda_0 \exp\left[-\frac{n\pi\,M_P^2}{\mathcal{T}_{\rm str}(\Lambda_0)}\right]$$

On the other hand, the limit $r \to 0$ corresponds to weak coupling.



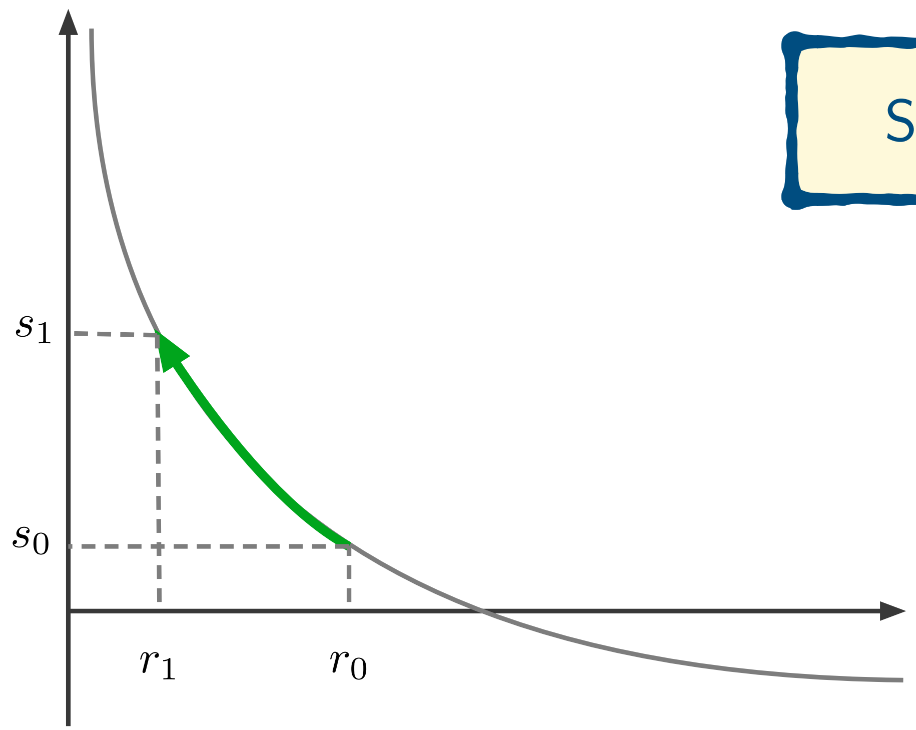
Exploring the Moduli Space via Strings

The string tension has the following symmetry

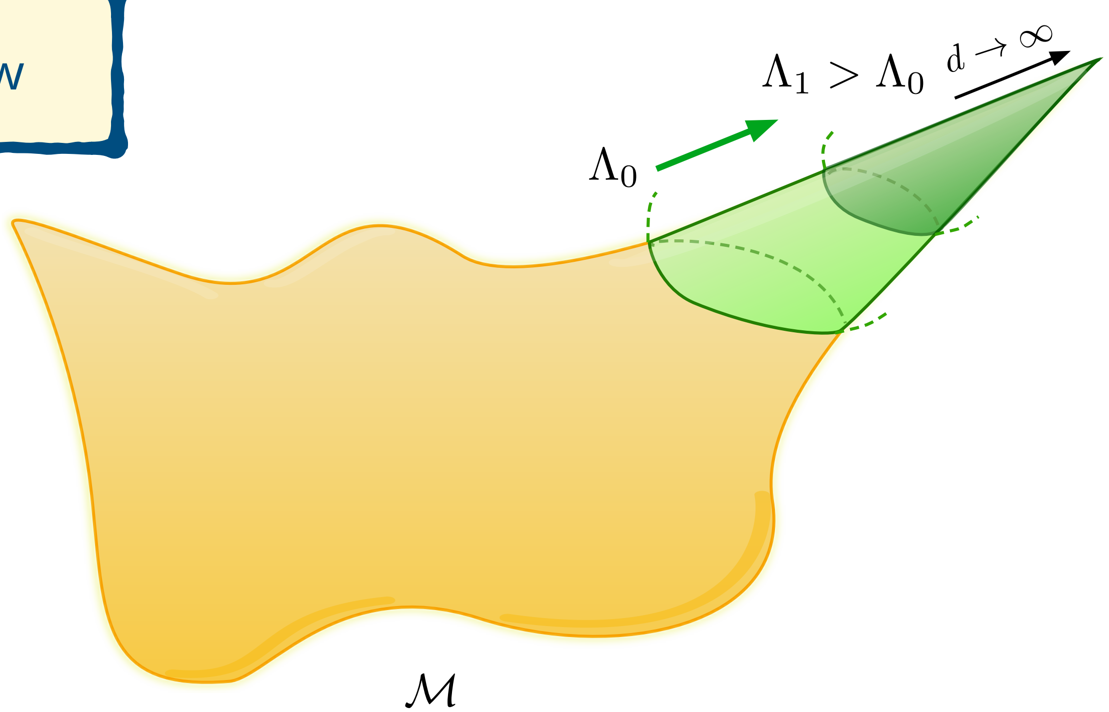
$$\mathcal{T}_{\mathbf{e}}(\Lambda e^{2\pi\sigma}, \bar{\boldsymbol{s}}) = \mathcal{T}_{\mathbf{e}}(\Lambda, \bar{\boldsymbol{s}} + \mathbf{e}\sigma)$$

that is, a change in the cutoff can be seen as a change in the field configuration

$$\bar{\boldsymbol{s}}_0 \to \bar{\boldsymbol{s}}(\sigma) = \bar{\boldsymbol{s}}_0 + \sigma\mathbf{e} \quad \Leftrightarrow \quad \Lambda \to \Lambda e^{2\pi\sigma}$$



String RG flow



Combining String RG flow + backreaction we can explore the moduli space via the axionic string solution!