Strings and Fields 2019

String Regge trajectory on de Sitter space and implications to inflation

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Outline

- **Naïve Expectation from Flat Space**
- **Regge Trajectory in dS**
- **High Energy Scattering**
- **Summary**

dS in String Theory

- **Maldacena-Nunez no-go theorem**
- **KKLT evades the no-go theorem**
- **Non-perturbative effects**

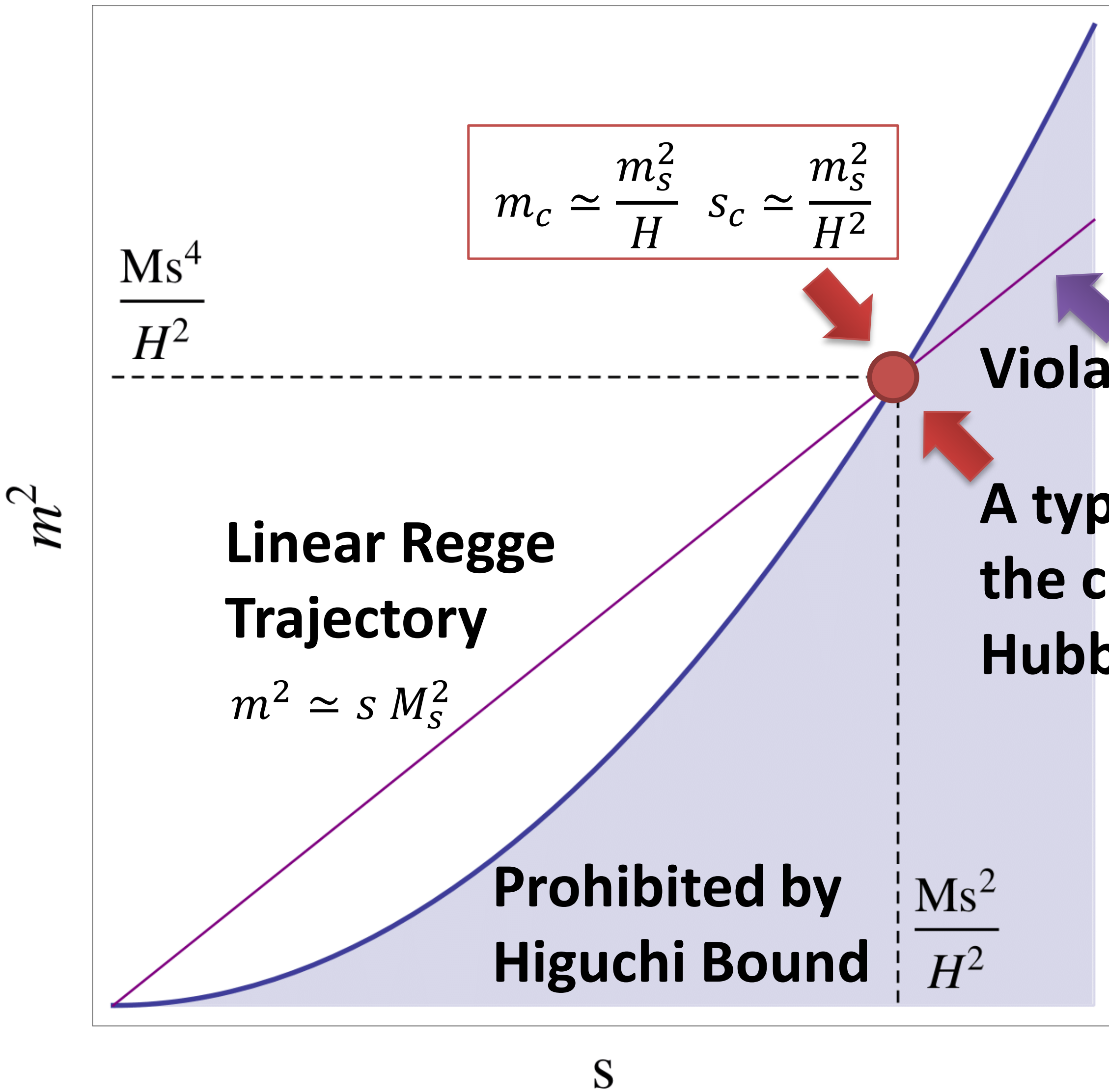
Can we have a consistent world-sheet theory on de Sitter space?

- Higuchi bound in de Sitter space
- Modification of Regge trajectories

Higuchi Bound

- A unitarity bound on the mass of higher-spin particles in de Sitter space
- $m^2 \geq s(s-1)H^2$ for bosons
- $m^2 \geq s^2\, H^2$ for fermions
- Particles with masses violating the Higuchi bound contain helicity modes with a negative norm $\rightarrow$ Prohibited by unitarity

Linear Regge Trajectory Violates the Bound



Violates the Bound

A typical length of the string at the critical value is near the Hubble horizon scale

$$l \sim \frac{m_c}{M_s}\, l_s \sim H^{-1}$$

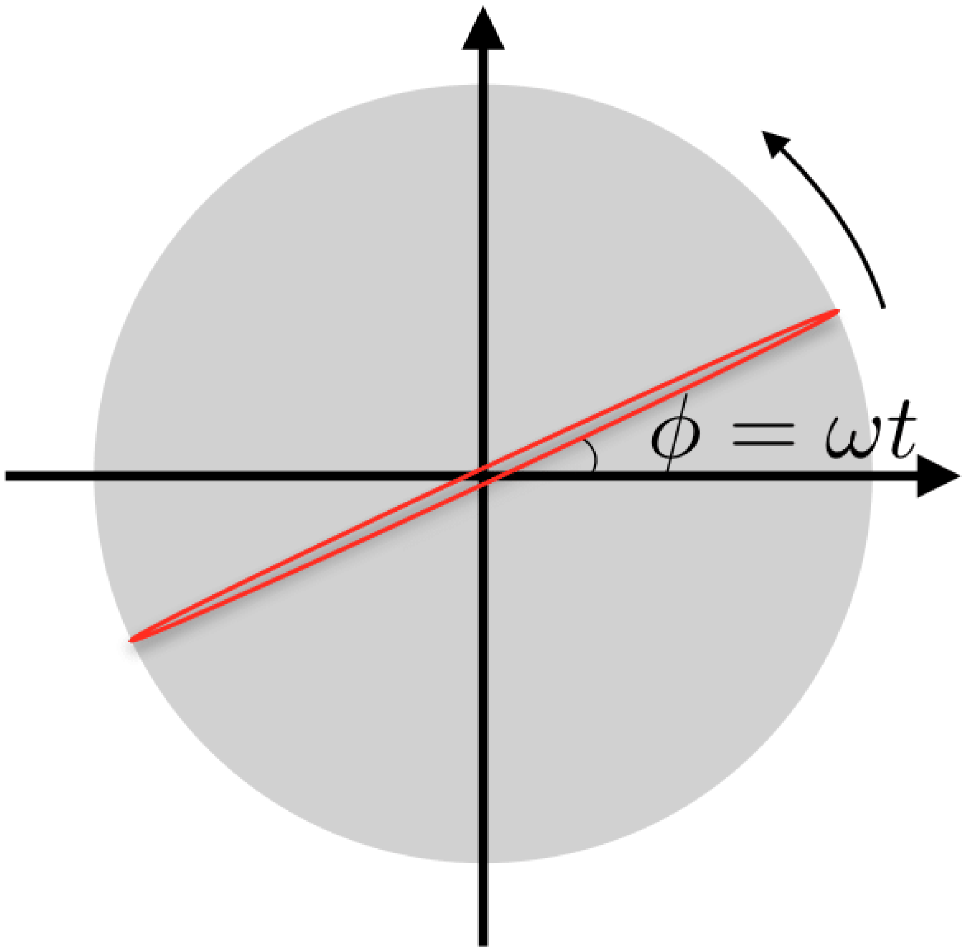
$$l_s \sim 1/M_s$$

See also Lust, Palti 19

How the Regge Trajectory is modified in dS?

Rotating Folded String in Flat Space

- Centrifugal Force
- String Tension
- Balance of the two forces requires the boundary have the speed of light



Regge Trajectory on de Sitter

- Static coordinate of de Sitter space

$$ds^2 = R^2\left[-(1-r^2)dt^2 + \frac{dr^2}{1-r^2} + r^2 d\Omega_2^2\right]$$

- Change the variable $r = \sin\rho$

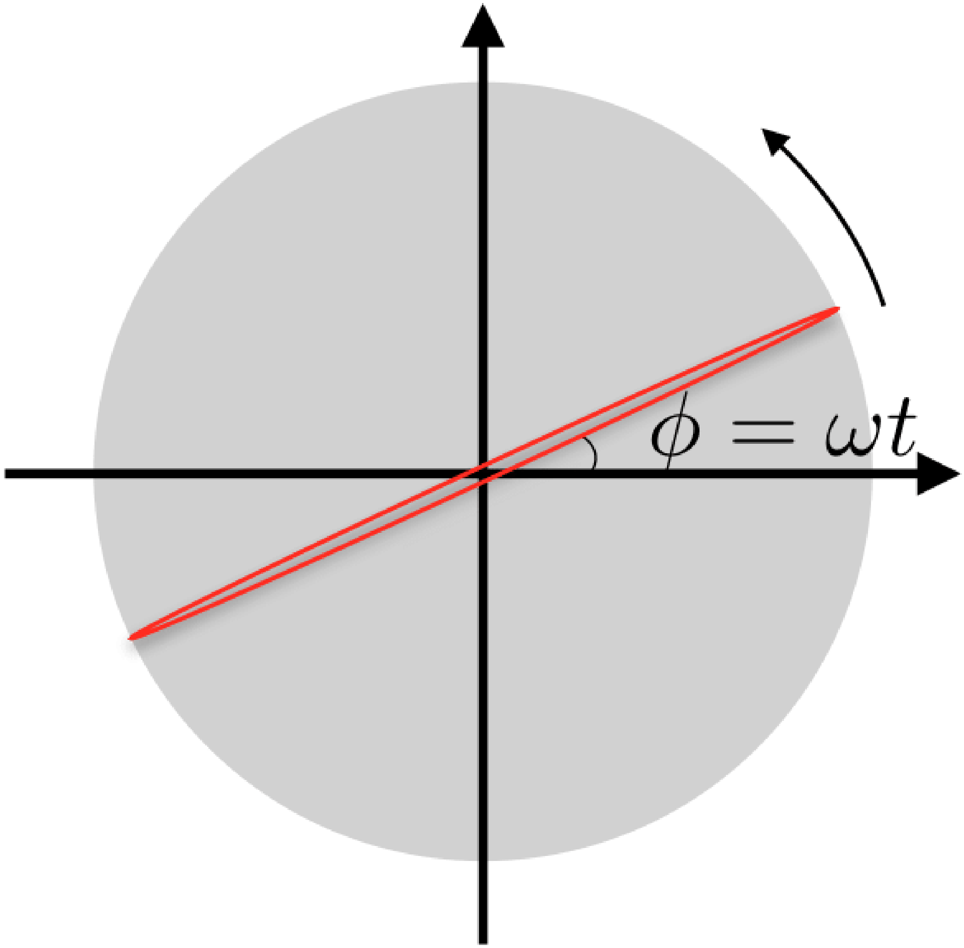
$$ds^2 = R^2[-\cos^2\rho dt^2 + d\rho^2 + \sin^2\rho d\Omega_2^2]$$

- Wick Rotation $\rho \to -i\rho \quad t \to it \quad R^2 \to -R^2$
- In this way we obtain the global coordinate on anti-de Sitter space

See also de Vega-Egusquiza '96 Gubser-Klevanov-Polyakov '02 for AdS

Rotating Folded String in dS Space

- Centrifugal Force
- String Tension
- Hubble Expansion
- Boundaries have the speed of light



Semiclassical Rotating String

- $\phi = \omega t$ **See also de Vega-Egusquiza '96**
- The string Lagrangian (Nambu-Goto)

$$L = -4\frac{R^2}{2\pi\alpha'}\int_0^{\rho_0} d\rho\sqrt{\cos^2\rho - \omega^2\sin^2\rho}$$

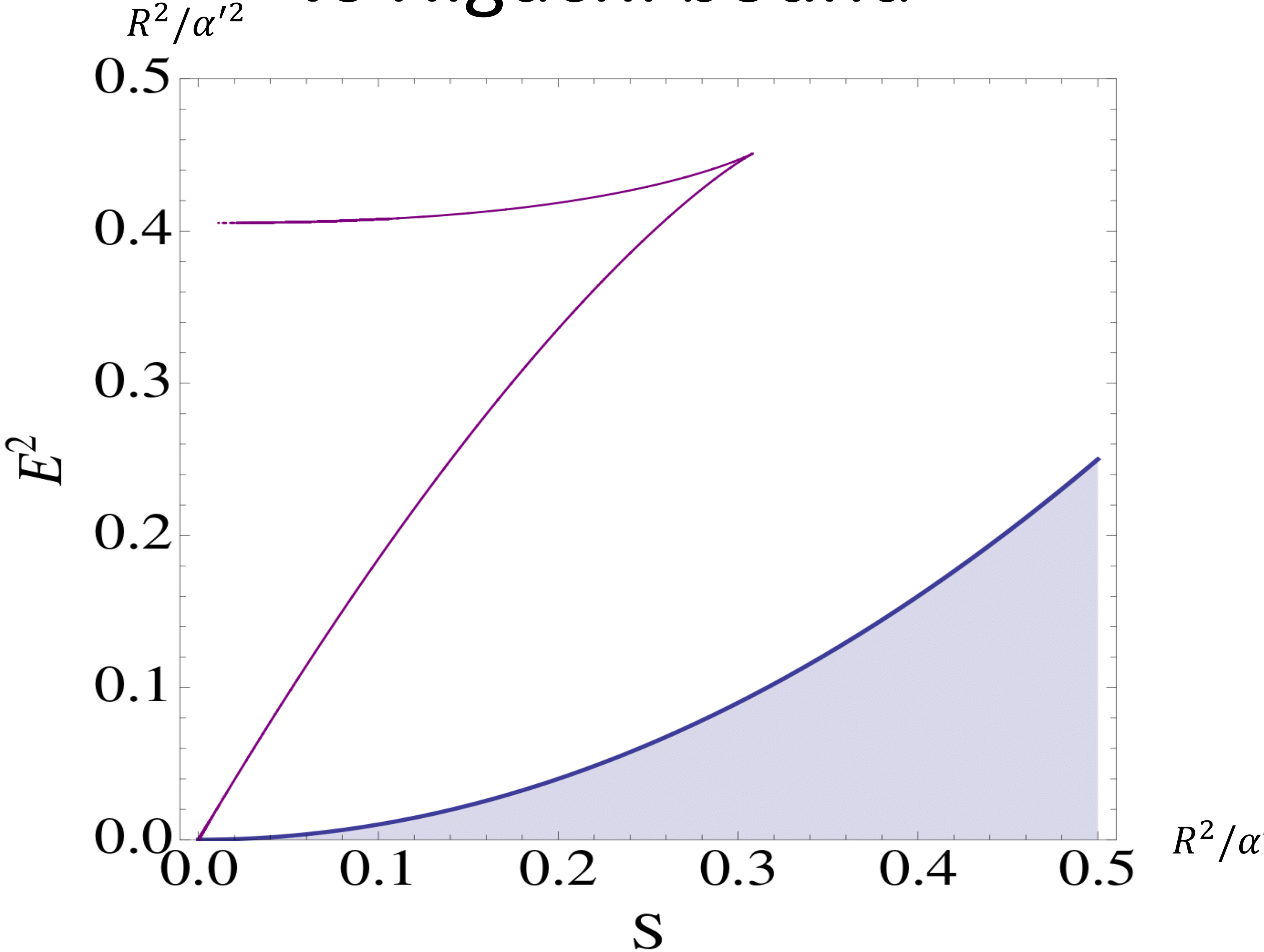
- String Energy

$$E = -4\frac{R^2}{2\pi\alpha'}\int_0^{\rho_0} \frac{d\rho\cos^2\rho}{\sqrt{\cos^2\rho - \omega^2\sin^2\rho}}$$

- String Spin

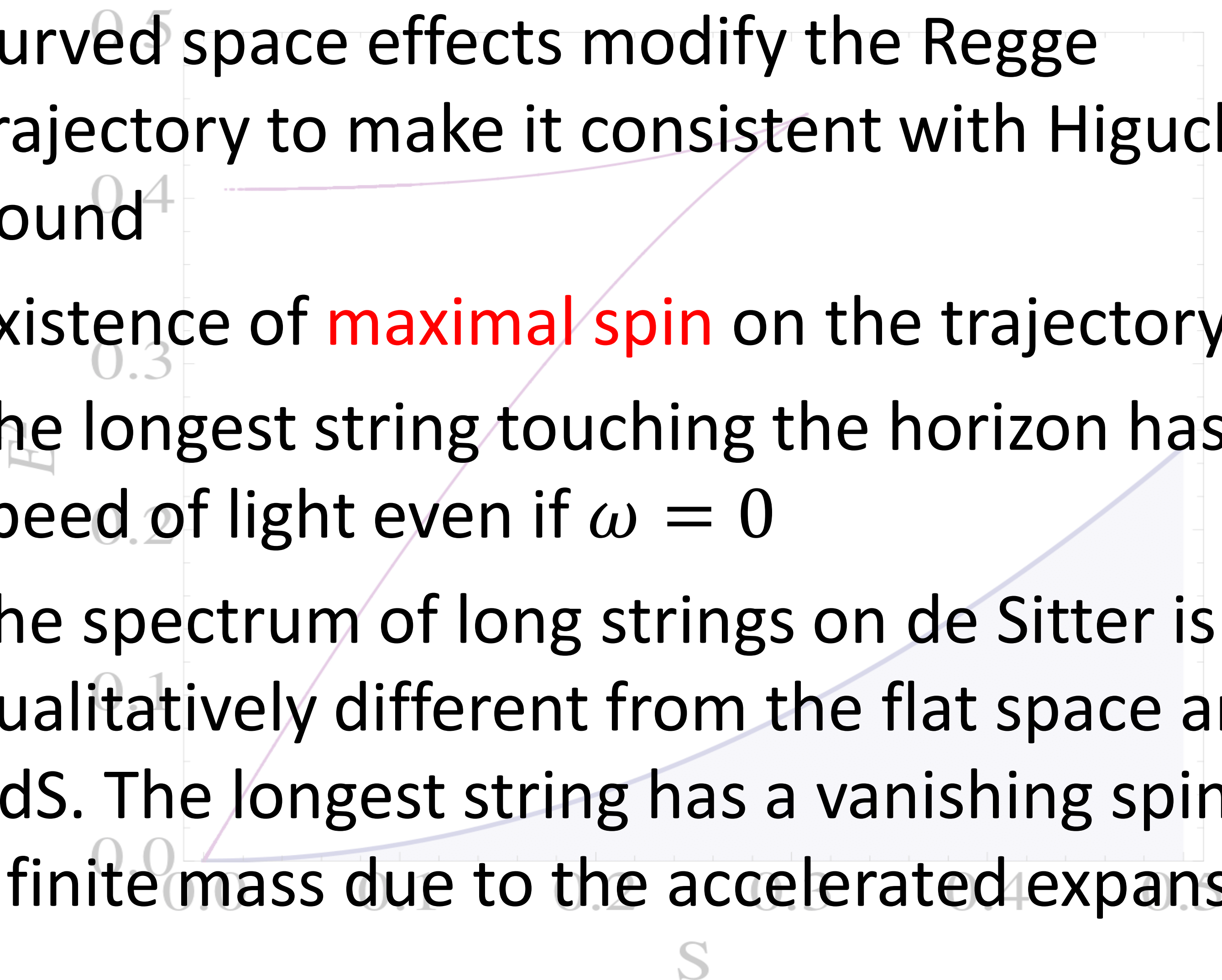
$$S = -4\frac{R^2}{2\pi\alpha'}\int_0^{\rho_0} \frac{d\rho\,\omega\sin^2\rho}{\sqrt{\cos^2\rho - \omega^2\sin^2\rho}}$$

Leading Regge trajectory vs Higuchi bound

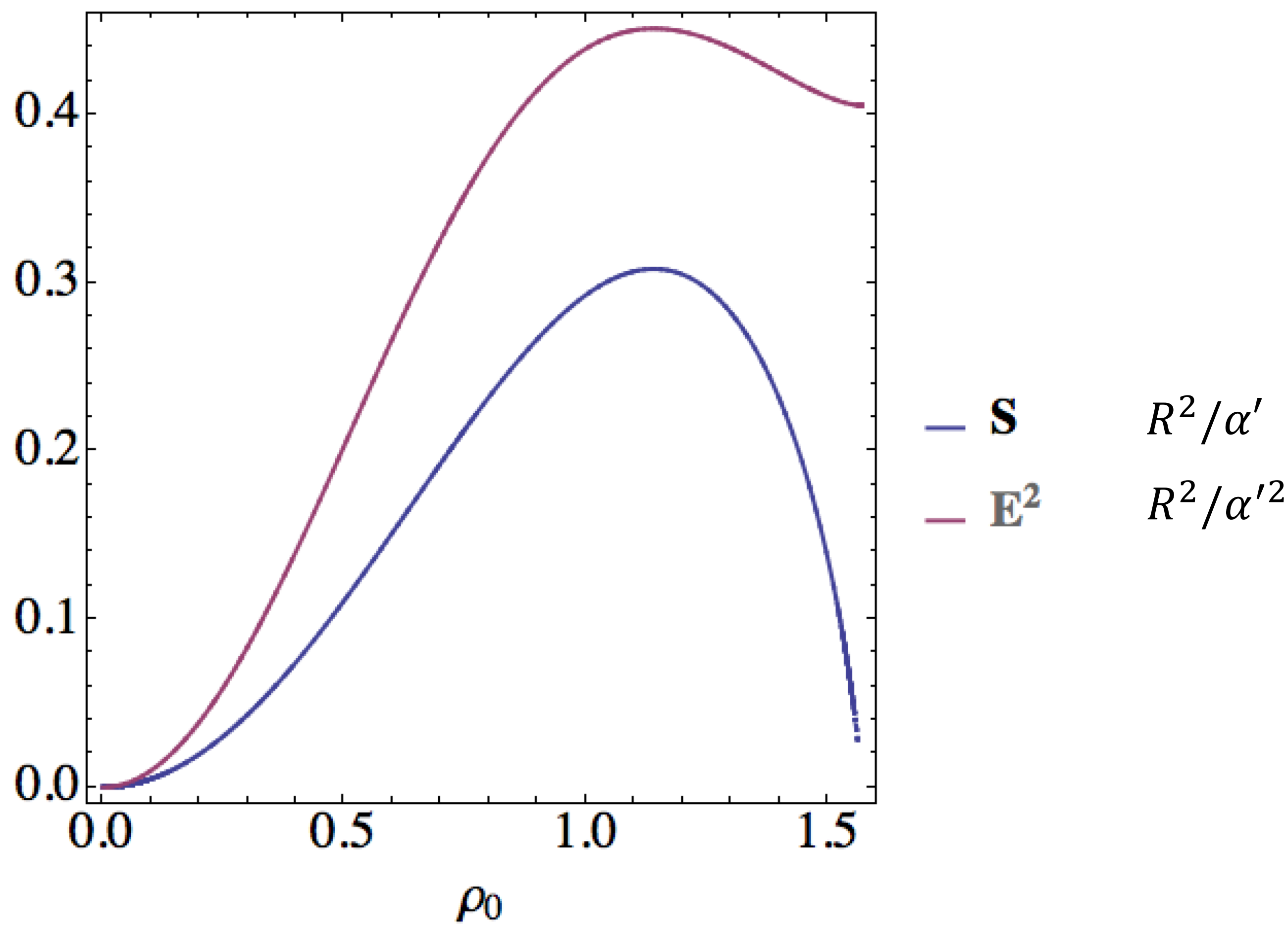


Leading Regge trajectory vs Higuchi bound

- Curved space effects modify the Regge Trajectory to make it consistent with Higuchi bound
- Existence of maximal spin on the trajectory
- The longest string touching the horizon has a speed of light even if $\omega = 0$
- The spectrum of long strings on de Sitter is qualitatively different from the flat space and AdS. The longest string has a vanishing spin and a finite mass due to the accelerated expansion



Energy Spin Relation



Short Strings

$$\rho_0 \simeq \omega^{-1}$$

- The energy and spin are the same as the flat space ones

$$E \simeq \frac{R}{\alpha'}\rho_0, \quad S \simeq \frac{R^2}{2\alpha'}\rho_0^2$$

- Linear Regge trajectory

$$E^2 \simeq \frac{2}{\alpha'}S$$

Long Strings

- Touching the horizon $\rho_0 \to \frac{\pi}{2}$
- $\omega \to 0$

$$\rho_0 \simeq \pi/2 - \omega$$

- Spacetime curvature is not negligible

$$E \simeq \frac{2R}{\pi\alpha'}, \quad S \simeq -\frac{2R^2}{\pi\alpha'}\omega \ln \omega$$

High Energy Scattering

- In string theory, existence of an infinite higher spin tower (the Regge tower) is crucial to make mild the high-energy behavior of scattering amplitudes and to UV complete gravity in a weakly coupled regime
- Existence of a maximum spin in the Regge trajectory makes it nontrivial to maintain the mildness of high-energy scattering

Two Possibilities

- UV completion by the leading Regge trajectory
- UV completion by multiple Regge trajectories

UV completion: leading Regge trajectory

- In order to UV complete gravity in a weakly coupled regime, we would need sufficiently many higher-spin states from the string scale up to near the Planck scale.

- The mass $E_*{\sim}R/\alpha'{\sim}M_s^2/H$ of the maximum spin state in the leading Regge trajectory has to be bigger than the Planck scale $E_* > M_{pl}$

UV completion: leading Regge trajectory

- This condition implies an upper bound on the vacuum energy of inflation
$$V = 3M_{pl}^2 H^2 < M_s^4$$
- An upper bound on the tensor-to-scalar ratio
$$r = 0.01 \times \frac{V}{(10^{16} GeV)^4} < 0.01 \left(\frac{M_s}{10^{16} GeV}\right)^4$$
- M_{pl} can be the Planck scale in higher dimension, which makes the bound weaker

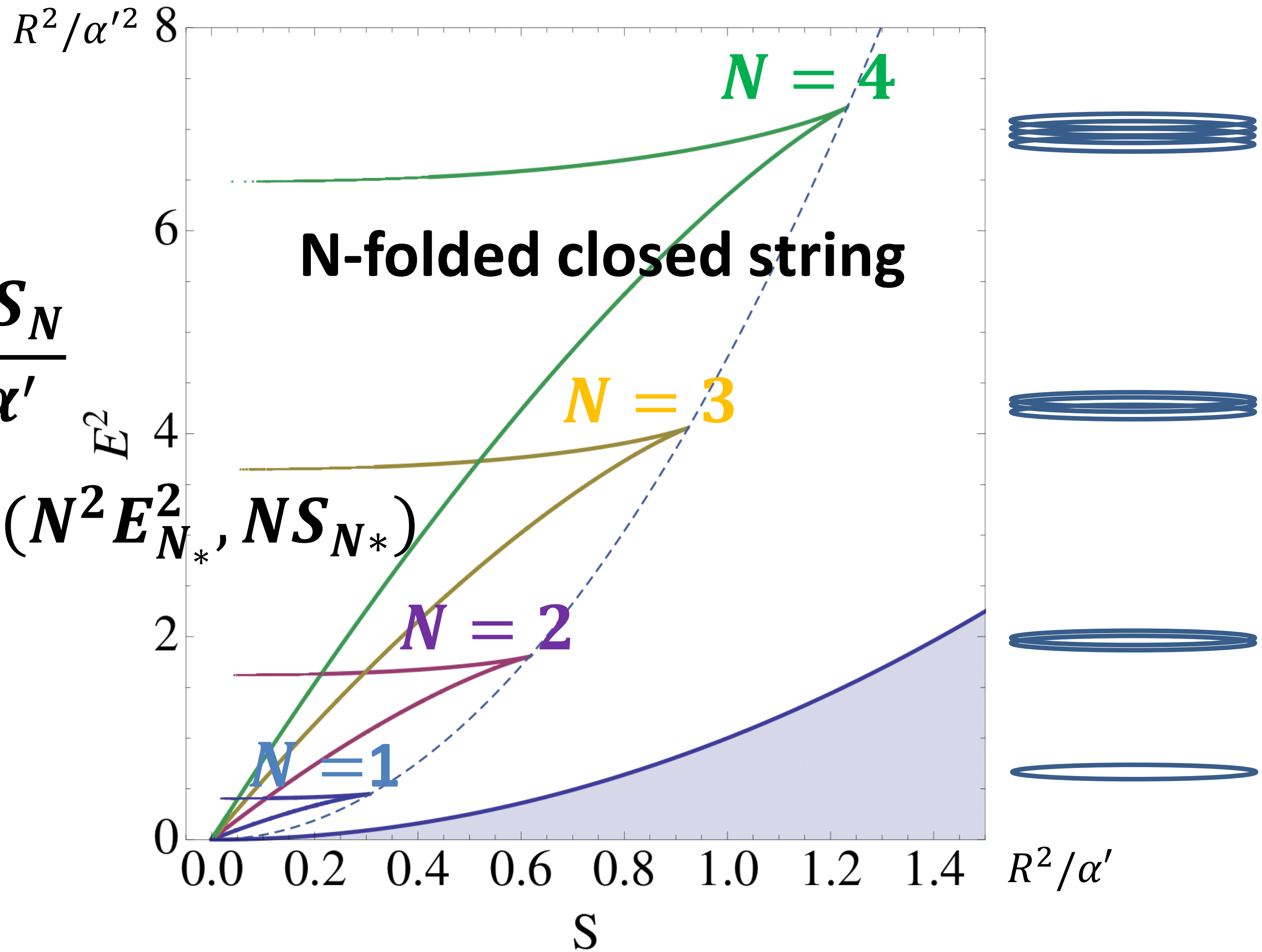
UV completion: multiple Regge trajectories

$$E_N = NE$$

$$S_N = NS$$

$$E_N^2 = N \times \frac{2S_N}{\alpha'}$$

$$(E_{N_*}^2, S_{N*}) = (N^2 E_{N_*}^2, NS_{N*})$$



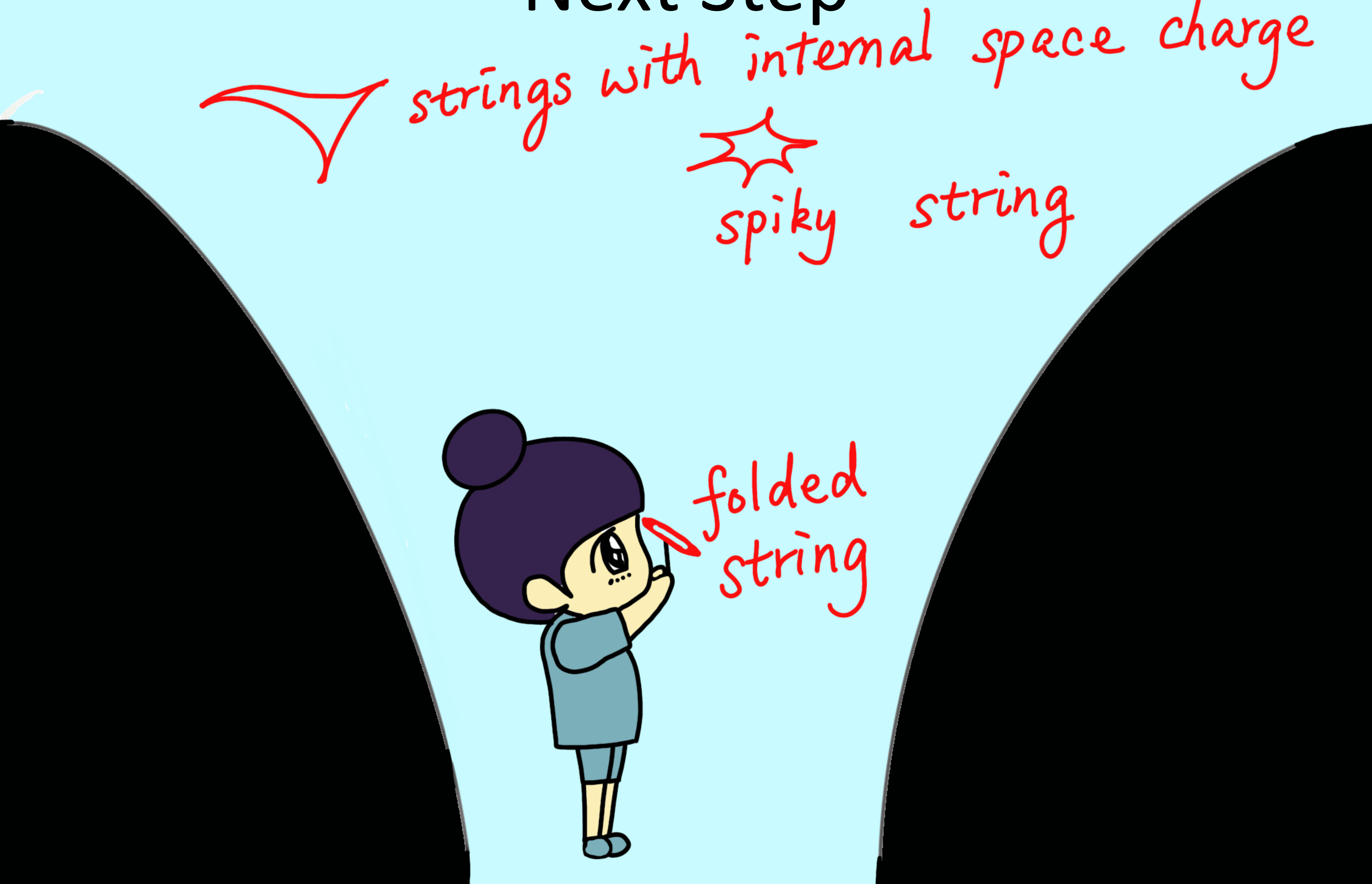
We don't know yet if scattering amplitudes are Reggeized.

Summary

- String Regge trajectory is modified in de Sitter space
- There exists a maximum spin for each trajectory
- Semiclassical string spectrum on de Sitter space is consistent with the Higuchi bound
- There may exist an upper bound on tensor to scalar ratio under some assumptions

$$r = 0.01 \times \frac{V}{(10^{16} GeV)^4} < 0.01 \left(\frac{M_S}{10^{16} GeV} \right)^4$$

Next Step


strings with internal space charge
spiky string
folded string

Thank you