New Cosmological Background with Dynamical String Tension & String Field Theory

A Conceptual Trip about Cosmology and String Theory

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Outline

- The background: Geodesically complete cosmological spacetime; Local scale invariance naturally predicts a Cyclic Universe:
  $$\text{Bang} \overset{\text{expand,contract}}{\longrightarrow} \text{Crunch} \rightarrow \overset{\text{brief period } G_N<0}{\textit{Antigravity}} \rightarrow \text{Bang} \rightarrow \text{etc}$$
- How this is formulated in String Theory - Dynamical string tension (that can flip sign, just like G_N can!).
- How can String Field Theory help answer non-perturbative questions at the Big Bang (where string theory matters the most) now with new ingredients that play a crucial role at the Beginning!

Space-time Weyl symmetry disccused mainly at the classical level, some quantum understood.

Collaborators:

I.B.: 0804.1585, I.B + S.H. Chen: 0811.2510, 1004.0752

I.B.+ S.H. Chen + N. Turok: 1105.3606

I.B. + S.H. Chen + P. Steinhardt + N. Turok: 1112.2470, 1207.1940

I.B. : 1109.5872, 1209.1068

I.B. + P. Steinhardt + N. Turok: 1307.1848, 1307.8106, 1312.0739, 1407.0992

Weyl Symmetry & Geodesically Complete Cosmology

- String theory is not scale invariant, has a fundamental length, the string tension $T = (2\pi\alpha')^{-1}$, related to the gravitational constant.
- General Relativity + Standard Model can be lifted to a Weyl invariant version without any fundamental scales. All scales emerge from dimensionless constants combined with Weyl gauge fixing and vevs of fields (G_{grav}, v_{EW}, M_{Higgs}, M_{DM}, Λ_{DE}, $M_{q,l}$)
- There are new patches of field space that are missing in the standard approach to GR+SM. The Weyl invariant formalism reveals the additional field space (thrown away in usual Einstein frame which is geodesically incomplete). The gravitational constant changes sign in the new patches (antigravity).
- Cosmology in GR+SM with Weyl symmetry is geodesically complete, and very interesting (antigravity patch just before Big Bang, some initial conditions predicted). Explicit solutions show that generically geodesics go smoothly through big bang or big crunch singularities.
- How to do this in string theory & answer some open questions in QG?

Weyl Symmetric GR+SM (no dimensionful constants)

The SM without the Higgs mass is **globally scale invariant**. The electroweak scale, Higgs mass, the gravitational constant, dark energy, etc., ALL emerge from the same source in a **locally scale invariant** SM+GR (IB+Steinhardt+Turok, arXiv:1307.1848)

$$\mathcal{L}(x) = \sqrt{-g}\left[\begin{array}{c} L_{\text{SM}}\left(\begin{array}{c}\text{quarks,leptons,gauge bosons,darkmatter,}\nu_R\\ \text{Yukawa couplings to H,not to }\phi\text{ except for }\nu_R\end{array}\right)\\ +g^{\mu\nu}\left(\frac{1}{2}\partial_\mu\phi\partial_\nu\phi - D_\mu H^\dagger D_\nu H\right)\\ -\left(\frac{\lambda}{4}\left(H^\dagger H - \omega^2\phi^2\right)^2 + \frac{\lambda'}{4}\phi^4\right)\\ +\frac{1}{12}\left(\phi^2 - 2H^\dagger H\right)R(g)\end{array}\right]$$

- Conformally coupled scalars: $\left\{\begin{array}{l} H\text{=electroweak Higgs doublet}\\ \phi\text{= ``compensator'', relative } (-) \text{ sign is required}\end{array}\right.$

$$g_{\mu\nu} \rightarrow \Omega^{-2}g_{\mu\nu},\ \begin{array}{c}\phi\rightarrow\Omega\phi\\ H\rightarrow\Omega H\end{array},\ \psi_{q,l}\rightarrow\Omega^{3/2}\psi_{q,l},\ A_\mu^{\gamma,W,Z,g}\ \text{unchanged}$$

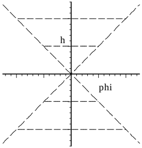
Without last term, only global scale symm., and problem massless Goldstone boson

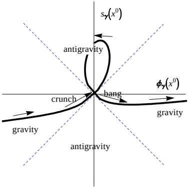
- NOT "fake" : there are field patches missing in “Einstein gauge” - crucial for **geodesical completion!**

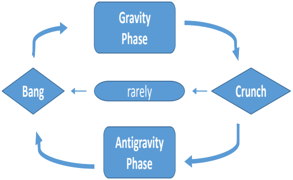
Sign of Eff Grav const : Gravity - Antigravity Transition

$$H = \begin{pmatrix} 0 \\ h/\sqrt{2} \end{pmatrix}, \quad \frac{1}{12}(\phi^2 - \overbrace{2H^\dagger H}^{h^2})R(g),$$

- Also SUGRA (1-Kähler potential), same generic conclusion missed before.
- Sign changes dynamically **generically**, but only at singularity (Eff grav const $= \infty$). It is **temporary**, quickly comes back to gravity.







- Weyl symm is **prediction of deeper gauge symmetry**: Phase space gauge symm requires 4+2 dims (2T-physics) to describe ALL gauge invariant physics in 3+1 dims. Weyl symm in 3+1 is reparametrization in extra 1+1 dims.

Low Energy Effective String Theory

- Worldsheet action

$$S_{string} = -\frac{1}{4\pi\alpha'}\int d^2\sigma \left[\begin{array}{c} \left(\sqrt{-h}h^{ab}G_{\mu\nu}(X) + \varepsilon^{ab}B_{\mu\nu}(X)\right)\partial_a X^\mu \partial_b X^\nu \\ -\alpha'\sqrt{-h}R^{(2)}(h)\,\Phi(X) + \cdots \end{array} \right]$$

- **Perturbative** worldsheet conformal invariance imposes equations on $\left(G_{\mu\nu}, B_{\mu\nu}, \Phi, \cdots\right)$. These are derivable from low energy action

$$S_{eff} = \frac{1}{2\kappa_d^2}\int d^d x \sqrt{-G} e^{-2\Phi}\left\{R(G) + 4(\partial\Phi)^2 - \frac{1}{12}H^2 - \frac{d-26}{3\alpha'} + \cdots\right\}$$
$$H_{\mu\nu\lambda} \equiv \partial_{[\lambda}B_{\mu\nu]}, \quad \kappa_d^2 \equiv (2\alpha')^{(d-2)/2} \sim (length)^{(d-2)}$$

- Not scale invariant. Introduce one more scalar field (compensator) to reformulate it as a locally scale invariant theory. Result is non-trivial.

General Weyl Invariant Low En. Eff. String Field Theory

$g_{\mu\nu},\ b_{\mu\nu},\ \phi^i=(\phi,s,\cdots)$, others suppressed. Note $(U,C_{ij},V,T)(\phi^i)$.

$$\mathcal{L}(x)=\sqrt{-g}\left\{\begin{array}{c}\frac{d-2}{8(d-1)}U\left(\phi^k\right)\left[R(g)-\frac{1}{12}H^2\left(b,\phi^k\right)\right]\\ -\frac{1}{2}C_{ij}\left(\phi^k\right)g^{\mu\nu}\partial_\mu\phi^i\partial_\nu\phi^j-V\left(\phi^k\right)\end{array}\right\}$$

$$H_{\mu\nu\lambda}\left(b,\phi^k\right)\equiv\partial_{[\lambda}b_{\mu\nu]}+T\left(\phi^k\right)^{-1}b_{[\mu\nu}\partial_{\lambda]}T\left(\phi^k\right)$$

- Local symmetries

  1) $\delta_\Lambda b_{\mu\nu}=\partial_{[\mu}\Lambda_{\nu]}+T\left(\phi^k\right)^{-1}\Lambda_{[\nu}\partial_{\mu]}T\left(\phi^k\right),\ \delta_\Lambda H_{\mu\nu\lambda}=0$ any $T(\phi)$

  2) Weyl : $\left(g_{\mu\nu},b_{\mu\nu}\right)\rightarrow\Omega^{-\frac{4}{d-2}}\left(g_{\mu\nu},b_{\mu\nu}\right),\ \phi^i\rightarrow\Omega\phi^i$

- a) Homogenous: $U\left(\Omega\phi^i\right)=\Omega^2U\left(\phi^i\right),\ C_{ij}\left(\Omega\phi^i\right)=C_{ij}\left(\phi^i\right)$
  $T\left(\Omega\phi^k\right)=\Omega^{\frac{4}{d-2}}T\left(\phi^k\right),\ V\left(\Omega\phi^i\right)=\Omega^{\frac{2d}{d-2}}V\left(\phi^i\right)$

  b) Homothety: $\partial_{\phi^i}U=-2C_{ij}\phi^j,\ C_{ij}\phi^i\phi^j=-U.$
- Then $H_{\mu\nu\lambda}\left(\Omega^{-\frac{4}{d-2}}b,\Omega\phi^k\right)=\Omega^{-\frac{4}{d-2}}H_{\mu\nu\lambda}\left(b,\phi^k\right)$, for homogeneous T.
  Lagrangian transforms into a total derivative, is Weyl invariant.
- General solutions for (U,C_{ij},V,T) in (1008.1540),(1307.1848),(1407.0992). Some freedom !!

Most general $C_{ij} = A^2(\phi^i)\,\eta_{ij}$ conformally flat $\Rightarrow U = \phi^2 - s^2,\ C_{ij} = \eta_{ij}$

two conform scalars ϕ, s

$$\frac{\mathcal{L}(x)}{\sqrt{-g}} = \left[\begin{array}{c} \frac{d-2}{8(d-1)}\left(\phi^2 - s^2\right)\left(R(g) - \frac{1}{12}H^2(b,\phi,s)\right) \\ +\frac{1}{2}\partial\phi\cdot\partial\phi - \frac{1}{2}\partial s\cdot\partial s - V(\phi,s) \end{array} \right]$$

- Compare to $\mathcal{L}_{eff}^{string}$, choose **s-gauge** to determine $\phi_s(\Phi)$ and $s_s(\Phi)$

s-gauge: **positive !!** (gravity sector) $\frac{d-2}{8(d-1)}\left(\phi_s^2 - s_s^2\right) = \frac{e^{-2\Phi}}{2\kappa_d^2},\ g^s_{\mu\nu} = G_{\mu\nu},\ b^s_{\mu\nu} = B_{\mu\nu}$

$$\phi_s = \pm\sqrt{\frac{4(d-1)}{(d-2)}}\frac{e^{-\Phi}}{\kappa_d}\cosh\frac{\Phi}{\sqrt{d-1}},\quad s_s = \pm\sqrt{\frac{4(d-1)}{(d-2)}}\frac{e^{-\Phi}}{\kappa_d}\sinh\frac{\Phi}{\sqrt{d-1}}\quad \text{or } s\to -s$$

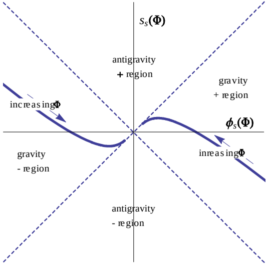
$$H_{\mu\nu\lambda} = \partial_{[\lambda}B_{\mu\nu]} \rightarrow \text{constant } T \text{ in s-gauge}\quad T(\phi_s, s_s) = \frac{1}{2\pi\alpha'},\ V(\phi_s, s_s) = \frac{d-26}{3\alpha'}\frac{e^{-2\Phi}}{2\kappa_d^2}$$

- **Homogeneity**: T, V unique before gauge fixing, **gravity sector** $|\phi| \geq |s|$

$$\underset{\textbf{dynamical tension}}{T(\phi,s)} = \left(\frac{d-2}{4(d-1)}\right)^{\frac{2}{d-2}}(\phi+s)^{2\frac{1+\sqrt{d-1}}{d-2}}(\phi-s)^{2\frac{1-\sqrt{d-1}}{d-2}}\quad \text{or } s\to -s$$

$$V(\phi,s) = \frac{(d-26)(d-2)}{12(d-1)}T(\phi,s)\left|\phi^2 - s^2\right|\quad \text{or } \phi^2 = s^2$$

Parametric plots $(\phi_s(\Phi), s_s(\Phi))$ in **s-gauge, gravity region** $|\phi| \geq |s|$

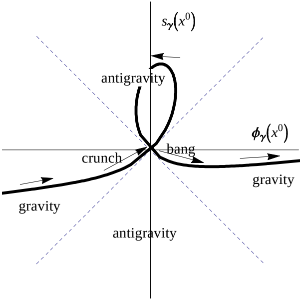


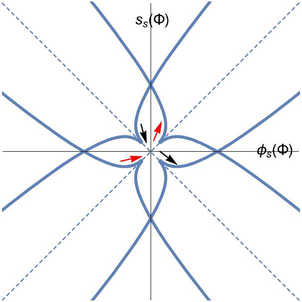
- The origin corresponds to $\Phi = +\infty$, far left/right ends $\Phi = -\infty$.
- Each quadrant of field space (ϕ, s) in the s-gauge is geodesically incomplete. In nicer gauges, geodesically complete solutions of the eqs of motion, as a function of **conformal time**, generically cross to antigravity regions $|s| \geq |\phi|$ at the origin, where $s/\phi = \pm 1$. **This crossing is gauge invariant**.
- Other gauges, $\phi = \Omega\phi_s(\Phi)$, $s = \Omega s_s(\Phi)$. Some gauge invariants:

$$\frac{s}{\phi},\ \left(\sqrt{-g}\right)^{\frac{d-2}{2d}}\phi,\ \left(\sqrt{-g}\right)^{\frac{d-2}{2d}}s,\ |T(\phi,s)|^{-\frac{d-2}{4}}\phi,\ |T(\phi,s)|^{-\frac{d-2}{4}}s,\ \text{etc.}$$

Other curves in (ϕ, s) plane: behavior near the origin is universal.

Missing branches in s-gauge and geodesic completeness





Geodes complete soln. in γ-gauge, $\det g_\gamma = 1$, scale $a_\gamma(\tau) = 1$, time idependent. Anisotropy & radiation main time dependent effects near 0.

$$\frac{s_\gamma(\tau)}{\phi_\gamma(\tau)} = \frac{s_s(\Phi(\tau))}{\phi_s(\Phi(\tau))} \longrightarrow \Phi(\tau)$$

s-gauge all branches of $\phi_s(\Phi(x^0))$, $s_s(\Phi(x^0))$. sign $(\phi^2 - s^2)$ is gauge invariant, change of sign of a solution as a function of space-time is gauge invariant.

Geodesically Complete Eff. String Theory at Low E

- Extend all fields to all quadrants: $g_{\mu\nu},\ b_{\mu\nu},\ \phi^i = (\phi, s)$, + others

$$\underset{\phi,s}{\overset{\text{two}}{\text{conform scalars}}}\ \frac{\mathcal{L}(x)}{\sqrt{-g}} = \left[\begin{array}{c} \frac{d-2}{8(d-1)}\left(\phi^2 - s^2\right)\left(R(g) - \frac{1}{12}H^2(b,\phi,s)\right) \\ +\frac{1}{2}\partial\phi\cdot\partial\phi - \frac{1}{2}\partial s\cdot\partial s - V(\phi,s) + \cdots \end{array} \right]$$

$$H_{\mu\nu\lambda}(b,\phi,s) = \partial_{[\lambda} b_{\mu\nu]} + T(\phi,s)^{-1}\, b_{[\mu\nu}\partial_{\lambda]} T(\phi,s)$$

$$\text{Reflection symm} \quad : \quad \phi \leftrightarrow s,\ \begin{array}{c} g_{\mu\nu} \to -g_{\mu\nu} \\ b_{\mu\nu} \to -b_{\mu\nu} \end{array},\ \ \underset{Tg_{\mu\nu},\ Tb_{\mu\nu}\ \text{invariants}}{T(\phi,s) = -T(s,\phi)}$$

- **Generic** classical cosmological solutions are cyclic (including anisotropy & radiation):
  Bang $\longrightarrow$Expand$\longrightarrow$Contract$\longrightarrow$Crunch$\longrightarrow$Antigravity$\longrightarrow$Bang , repeats indefinetily ...
  Some initial conditions fixed uniquely (an attractor at the singularity).
- **Classical geodesics** sail smoothly through the cosmological singularity. Info goes trhough.
- Mechanism for entropy production during antigravity cycle.(a perpetual motion machine).

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- Quantum questions: instabilities during antigravity (unitarity OK, but negative E states for grav).
- The study of the gravity/antigravity transition as well as the study of the physics during antigravity needs a reliable theory of quantum gravity $\longrightarrow$ string theory!
- However string theory is not scale invariant. Need a **space-time Weyl symmetric** reformulation of string theory that is consistent with the Weyl invariant framework of low energy effective string theory.
- Need a dynamical string tension to replace $(2\pi\alpha')^{-1}$. The obvious candidate is $T(\phi, s)$ since it reduces to $(2\pi\alpha')^{-1}$ in the string gauge, $\phi \longrightarrow \phi_s(\Phi)$ and $s \longrightarrow s_s(\Phi)$.

String theory w/ dynamical string tension and Weyl symm

Replace tension $(2\pi\alpha')^{-1} \to T(\phi, s)$ and dilaton $\Phi \to \Phi(\phi, s)$

$$S = \int d^2\sigma \left[\begin{array}{c} -\frac{1}{2} T(\phi(X), s(X)) \left(\sqrt{-h} h^{ab} g_{\mu\nu}(X) + \varepsilon^{ab} b_{\mu\nu}(X) \right) \partial_a X^\mu \partial_b X^\nu \\ + \frac{\sqrt{d-1}}{16\pi} \sqrt{-h} R^{(2)}(h) \ln \left(\frac{\phi(X)+s(X)}{\phi(X)-s(X)} \right)^2 + O\left(\frac{1}{T}\right) \end{array} \right]$$

$X^\mu(\tau, \sigma)$ is the string coordinate. Becomes the usual theory in the s-gauge.

- Symmetries of background include: (1) space-time Weyl, (2) Reflection.
- Quantum conformal symmetry, perturbative up to order α' $\left(\text{i.e.}\, T^{-1}\right)$ requires $\left(\phi, s, g_{\mu\nu}, b_{\mu\nu}\right)$ to satisfy the eoms of the Weyl invariant low energy string theory. Any solution of low energy theory (eg our generic cosmological solution as function of $X^0(\tau, \sigma)$) provides a background consistent with quantum conformal invariance.
- Desirable to find conformally exact backgrounds that are also Weyl invariant.
- Now $T(\phi(X), s(X))$ can change sign !!! Much to explore!!!

4D String in Geodesically Complete Cosmo. Background

Insert generic cosmological solution of worldsheet quantum conformal symmetry in γ-**gauge**

$$Tg_{\mu\nu}dx^{\mu}dx^{\nu} = T\left(\phi_{\gamma}, s_{\gamma}\right) \overset{a_{\gamma}=1}{a_{\gamma}^{2}} \left(\begin{array}{c} -\left(dx^{0}\right)^{2} + e^{2\left(\alpha_1+\sqrt{3}\alpha_2\right)}\left(dx^{1}\right)^{2} \\ +e^{2\left(\alpha_1-\sqrt{3}\alpha_2\right)}\left(dx^{2}\right)^{2} + e^{-4\alpha_1}\left(dx^{3}\right)^{2} \end{array} \right)$$

$$T\left(\phi_{\gamma}, s_{\gamma}\right) = \frac{1}{6}\left(\phi_{\gamma}^{2} - s_{\gamma}^{2}\right)\left|\frac{\phi_{\gamma}+s_{\gamma}}{\phi_{\gamma}-s_{\gamma}}\right|^{\sqrt{3}}, \quad \text{note} \quad T\overset{\gamma\text{-gauge}}{\left(\phi_{\gamma}, s_{\gamma}\right)} \overset{s\text{-gauge}}{=} \left(a_{s}^{2}/2\pi\alpha'\right)$$

Background fields, $\alpha_1, \alpha_2, \phi_{\gamma}, s_{\gamma}$, **unique** slns, functions of only $X^0(\tau,\sigma)$

$$T\left(X^{0}\right) = \frac{1}{3}\rho_{r}X^{0}(X^{0}-x_{c}^{0})\left(\frac{1}{2}\left|\frac{X^{0}}{l_{3}^{4}\rho_{r}(X^{0}-x_{c}^{0})}\right|^{p_3/p}\right)^{\sqrt{3}}, \quad \frac{\rho_{r}}{a^{4}(X^{0})} \ \text{radiation density (massless dofs)}$$

$Tg_{00}\left(X^{0}\right), Tg_{11}\left(X^{0}\right), Tg_{22}\left(X^{0}\right), Tg_{33}\left(X^{0}\right)$ all functions of $X^{0}(\tau,\sigma)$

$p \equiv \sqrt{p_1^2+p_2^2+p_3^2}, l_1, l_2, l_3$ are integration constants (all initial conditions)

These are smoothly evolving functions through the big bang singularity (when $X^0(\tau,\sigma)=0$) or big crunch singularity (when $X^0(\tau,\sigma) = x_c^0 \equiv -\frac{\sqrt{6}p}{\kappa\rho_r}$)

Timelike gauge, 4D string Hamiltonian & Dyn. Tension

- Gauge $X^0(\tau,\sigma)=\tau$. Background, $T\hat{g}_{\mu\nu}=T_\gamma\times diag\left(-1,e_1^2,e_2^2,e_3^2\right)$ (anisotropy)

  Solve Virasoro constraint
  $$\mathcal{H}(\tau,\sigma)=T(\tau)\left(\frac{e_j^2(\tau)\left(\partial_\sigma X^j\right)^2}{1-e_j^2(\tau)\left(\partial_\tau X^j\right)^2}\right)^{1/2},\quad P^i(\tau,\sigma)=\mathcal{H}e_i^2\partial_\tau X^i$$

- Hamiltonian in terms of canonical conjugates
  $$\mathcal{H}(\tau,\sigma)=T(\tau)\left(e_j^{-2}(\tau)(P_j)^2+T^2(\tau)e_j^2(\tau)\left(\partial_\sigma X^j\right)^2\right)^{1/2},\ H(\tau)=\int d\sigma\mathcal{H}(\tau,\sigma),\ \partial_\tau H(\tau)\neq 0.$$

- $X^i(\tau,\sigma)$ satisfy equations of motion and constraints
  $$-\partial_\tau\left(\mathcal{H}e_i^2\partial_\tau X^i\right)+\partial_\sigma\left(\frac{e_i^2}{\mathcal{H}}\partial_\sigma X^i\right)=0,\quad \partial_\sigma X\cdot P=0\ \text{ constraint}$$

  Classical solutions well behaved. Like particle geodesics sail through the singularities.

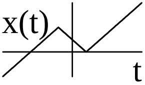
- Quantization and constraints
  $$\left[X^i(\tau,\sigma),P_j(\tau,\sigma')\right]=i\delta_j^i\delta(\sigma-\sigma'),\quad (:\partial_\sigma X\cdot P:)\,|phys\rangle=0.$$

  No negative norm states! E<0 states available TEMPORARILY $(\Delta\tau=\sqrt{6}p/\rho_r\kappa)$

Analogous simple example in QM - time dependent system

- A free particle with time dependent Hamiltonian $H = \varepsilon\left(|t| - \frac{\Delta}{2}\right) \times p^2/2m$

time	$t < -\frac{\Delta}{2}$	$-\frac{\Delta}{2} < t < \frac{\Delta}{2}$	$t > \frac{\Delta}{2}$
Eq. motion	$\dot{x} = p$	$\dot{x} = -p$	$\dot{x} = p$



The quantum problem is the transition amplitude from an initial state $|x\rangle$ in the past to a final state $|x'\rangle$ in the future,

$$A_{fi} = \langle x'| e^{\frac{i}{\hbar} H_+ \frac{\Delta}{2}} e^{-\frac{i}{\hbar}\Delta H_-} e^{\frac{i}{\hbar} H_+ \frac{\Delta}{2}} |x\rangle = \int_{-\infty}^{+\infty} \frac{dp}{2\pi} e^{i\frac{p^2\Delta}{\hbar m} + ip(x'-x)}.$$

- Interacting particle with a potential, $H = \varepsilon\left(|t| - \Delta\right) \times p^2/2m + m\omega^2 x^2/2.$

time	$t < -\frac{\Delta}{2}$	$-\frac{\Delta}{2} < t < \frac{\Delta}{2}$	$t > \frac{\Delta}{2}$
Hamiltonian	$\left(\frac{p^2}{2m} + \frac{m\omega^2 x^2}{2}\right)$	$\left(-\frac{p^2}{2m} + \frac{m\omega^2 x^2}{2}\right)$	$\left(\frac{p^2}{2m} + \frac{m\omega^2 x^2}{2}\right)$

$|A_{fi}|^2$ for initial/final coherent states, $|z_i\rangle$ & $|z_f\rangle$,
or for initial/final eigenstates of $H_+ = \frac{p^2}{2m} + \frac{m\omega^2 x^2}{2}$, $|n_i\rangle$ & $|n_f\rangle$

$$|A(z_f, z_i)|^2 = \frac{e^{-|z_f|^2 - |z_i|^2 + \frac{2\,\mathrm{Re}(\bar{z}_f z_i)}{\cosh(\omega\Delta)}} e^{\tanh(\omega\Delta)\,\mathrm{Im}\left(\bar{z}_f^2 e^{-i\omega\Delta} + z_i^2 e^{i\omega\Delta}\right)}}{\cosh(\omega\Delta)}$$

String interactions and dynamics with dynamical tension

- String field theory, $Q = \int d\sigma \overbrace{\{c\,[\text{Stress Tensor}] + bc\partial c\}}^{\text{background fields, including tension } T(X)}$.

$$S_{open} = Tr\left[\frac{1}{2}AQA + \frac{g}{3}A \star A \star A\right], \text{ also } S_{closed}$$

- An example, a simple model: just like the quantum mechanics model, $T_{\pm\pm} = \varepsilon\left(\left|X^0(\tau,\sigma)\right| - \Delta\right)(\partial_\pm X)\cdot(\partial_\pm X)$. Without interactions ($g = 0$), free string solutions with matching boundary conditions at $\left|X^0(\tau,\sigma)\right| = \Delta$. With interactions ($g \neq 0$), it becomes more interesting, classical & quantum SFT.
- The temporarily negative tension $T\left(X^0\right)$ in Q is balanced by the interactions in determining properties of the interacting theory. Temporarily negative tension $T\left(X^0\right)$ is not a fundamental concern.
- Framework and basics OK. Many details yet to be worked out. Including new physical applications, especially non-perturbative effects.

Remarks

- To understand quantum gravity effects at gravity/antigravity transitions, we proposed to lift string theory to new space-time Weyl invariant version with a **dynamical tension**: 1407.0992
- The solution of the quantum worldsheet conformal symmetry that yielded the cosmological background $\phi_\gamma\left(X^0\right), s_\gamma\left(X^0\right), \alpha_1\left(X^0\right), \alpha_2\left(X^0\right)$, and the tension $T\left(X^0\right)$, with all initial conditions, is **unique and generic** (attractor mechanism: 1112.2470). Should be taken seriously in string th. and in cosmology.
- A cyclic universe with antigravity sector is a natural background in string theory.
- Conformally (worldsheet) exact bacgrounds with similar properties are desirable (WZW, gWZW, etc).
- Needed progress: more classical solns, more on quantum aspects of the single string, effects of interactions via SFT or other methods.
- Cosmic perturbations, data fitting, remains to be developed.
- Could same methods work for black holes, other geometries? Open.