What is String Theory?

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What is the question about?

We conventionally view that

- string is a massive, tensile, **extended** continuum object
- string excitation contains infinitely many normal modes
- relativistic string contains Regge spectrum $M^2 = \alpha' J$
- relativistic string exhibits diffeo + weyl gauge invariances
- string exhibits T-duality and DFT gauge invariance

In this talk, I challenge all of these and argue for the case:

- string behaves a tensile but pointlike object
- excitation consists of **finitely** many states
- spectra comprise of α'-corrected DFT contents
- exhibits T-duality and DFT gauge invariance

Based on

- Kanghoon Lee, SJR, Alejandro Rosabal, to appear
- cf. Rosabal's talk at Banff (January, 2017)

Amazing connections

This question brings together seemingly unrelated ideas

- **DFT**
- massive gravity
- CHY scattering equation
- ambitwistor string
- tensionless string; Gross-Mende limit
- Pauli-Villar & Lee-Wick quantization
- eternal black hole & thermofield double

A Ph.D. Student Project (I): Calculable & Predictable?

$$
\begin{aligned}
I \;=\; & \int \mathrm{d}^4 x \, \Big[\frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\psi)^2 + \frac{1}{2} g^2 \phi^4 (\partial\phi)^2 + \frac{1}{2}\lambda^2 \psi^4 (\partial\psi)^2 \\
+ \; & \frac{1}{2}(\ln 2)^2 \kappa^2 \left(\frac{1}{7}\phi^4\psi^7(\partial\phi) + \frac{1}{5}\phi^5\psi^6(\partial\psi)\right)^2 + \frac{1}{2}\zeta^2(7) h^2 \psi^{16}(\partial\psi)^2 \\
+ \; & \frac{1}{2}(\ln 3)^2 \eta^2 \left(\frac{1}{9}\phi^9\psi^4(\partial\psi) + \frac{1}{5}\phi^8\psi^5(\partial\phi)\right)^2 + \frac{1}{2}\zeta^2(4) \sigma^2 \phi^{14}(\partial\phi)^2 \\
+ \; & \frac{1}{3} g (\partial\phi)(\partial\phi^3) + \frac{1}{2}\lambda(\partial\psi)(\partial\psi^2) + [\zeta(7) h \psi^8 + \zeta(4)\sigma\phi^7](\partial\phi\partial\psi) \\
+ \; & \frac{\ln 2}{35}\kappa(\partial\phi)\partial(\phi^5\psi^7) + \frac{\zeta(7)}{27} g h \partial(\phi^3)\partial(\psi^9) + \frac{\ln 2}{105} g\kappa \partial(\phi^3)\partial(\phi^5\psi^7) \\
+ \; & \frac{\ln 3}{45}\eta(\partial\psi)\partial(\phi^9\psi^5) + \frac{\zeta(4)}{16}\lambda\sigma\partial(\psi^2)\partial(\phi^8) + \frac{\ln 3}{90}\lambda\eta\partial(\psi^2)\partial(\psi^5\phi^9) \\
+ \; & \frac{\ln 2\,\zeta(7)}{315} h\kappa \partial(\phi^9)\partial(\phi^5\psi^7) + \frac{\ln 3\,\zeta(4)}{360}\sigma\eta\partial(\phi^8)\partial(\phi^9\psi^5) \\
+ \; & \text{(add extra if needed)}
\end{aligned}
$$

Secret code to Einstein gravity

$$
\begin{aligned}
I_{\text{gravity}} &= \frac{1}{16\pi G_N}\int \mathrm{d}^4x\sqrt{-g}R(g) + \text{(Gibbons-Hawking)} \\
&= \int \mathrm{d}^4x\left[(\partial h)^2 + h(\partial h)^2 + h^2(\partial h)^2 + \cdots\right]
\end{aligned}
$$

In particular,

$$\boxed{\text{Divergence at } \ell\text{-loop} = \ell(d-2)+2,}$$

independent of the number of external lines.

After canonical transformation

$$\begin{aligned} \Phi &= \phi + \frac{g}{3}\phi^3 + \frac{\zeta(7)}{9}h\psi^9 + \frac{\ln 2}{35}\kappa\phi^5\psi^7 \\ \Psi &= \psi + \frac{\lambda}{2}\psi^2 + \frac{\zeta(4)}{8}\sigma\phi^8 + \frac{\ln 3}{45}\eta\phi^9\psi^5, \end{aligned}$$

the theory is **FREE**:

$$\boxed{I_{\text{student}} = \frac{1}{2}(\partial\Phi)^2 + \frac{1}{2}(\partial\Psi)^2}$$

Ward identities:

$$\frac{Z_{\phi^3}}{Z_\phi} = \frac{Z_{\psi^9}}{Z_{\phi^3}} = \frac{Z_{\phi^5\psi^7}}{Z_{\psi^9}} = 1, \qquad \frac{Z_{\psi^2}}{Z_\psi} = \frac{Z_{\phi^8}}{Z_{\psi^2}} = \frac{Z_{\phi^9\psi^5}}{Z_{\phi^8}} = 1$$

[5]

Student Project (II): Calculable and Predictable?

O(N) nonlinear sigma model:

$$I = \int \mathrm{d}^4x \sum_{a,b=1}^{N-1} G_{ab}(\phi)\partial\phi^a\partial\phi^b, \qquad G_{ab} = \delta_{ab} + \frac{\phi_a\phi_b}{F^2 - \phi^2}$$

The model has two-derivative, non-polynomial interactions. At tree level, it behaves badly at real energy scales above $\sim 4\pi F$. At loop level, it behaves badly at virtuality above $\sim 4\pi F$.

To get better UV behavior, one must append the model with additional degrees of freedom at the threshold scale $\sim 4\pi F$. This UV completion is done by adding a Higgs field σ as the N-th component, replacing the scale $4\pi F$:

$$\boxed{I = \int \mathrm{d}^4x \sum_{A=1}^{N} \partial\Phi_A\partial\Phi_A + \frac{\lambda}{4}(\sum_{A=1}^{N} \Phi_A\Phi_A - F^2/\lambda)^2}$$

Maxim from Student Project

To attain better high-energy behavior and renormalizability, calculability and hence predictability of a theory framework:

Enlarge field degrees of freedom

Choose Variables Smartly

Enlarge gauge symmetries

Quantum Theory of Gravity

- string theory constructed as a theory of quantum gravity
- Prohibitively complicated, so ”divide & conquer”
- couplings, kinematical asymptotics, gauge symmetries

Starting from Einstein gravity, take pathway to string theory via

(1) (g, b, ϕ) supergravity = infinite tension, low-energy limit

(2) $(g_2, g_3, \cdots)$ higher-spin = zero tension, high-energy limit

(3) double field theory = unified gauge symmetry limit

Roadmap for Higgs Hunt

String Theory

$\Uparrow$

A Pathway ?

$\Uparrow$

Einstein Gravity

Pathway through Double Field Theory (DFT)

Einstein gravity	$\subset$ Double Field Theory	$\subset$ String Theory
$\mathit{Diff}(\mathrm{M}_D)$ $\subset$	$\mathit{Generalized}\ \ \mathit{Diff}(\mathrm{M}_D)$ $\subset$	G_{string}

[Question]

How (much) is high-energy behavior improved?

[Note] DFT as a proxy for the MAXIM

DFT - Spacetime Description

- start with T-duality symmetry of strings
- treat momentum, winding on equal footing: $(x^m, \tilde{x}_m) := X^M$

$$\mathcal{M}_D \otimes \tilde{\mathcal{M}}_D \longrightarrow \hat{\mathcal{M}}_{(D,D)} \longrightarrow \overline{\mathcal{M}}_D / O(D, D, \mathbb{Z})$$

$$\partial_A \partial^A \Phi(X) \simeq 0, \qquad \partial_A \Phi(X) \partial^A \Psi(X) \simeq 0.$$

- $(g, b, \phi)_D \to (g, b, \phi)_{(D,D)}$, then project down to $\overline{\mathcal{M}}_D$
- combine Diff(g) and G(b) with O(D,D) covariance

$$\boxed{G_{\mathrm{DFT}} = \mathit{GenDiff}(\hat{\mathcal{M}}_D); \quad \mathit{GenDiff}(\hat{\mathcal{M}}_D) \gg \mathit{Diff}(\mathcal{M}_D)}$$

- DFT endows unified gauge invariance of massless string modes (g, b, ϕ) at the apparent expense of manifest locality

DFT – Worldsheet Description

- $x(z,\bar{z}) = x_L(z) + x_R(\bar{z})$; $\tilde{x}(z,\bar{z}) = x_L(z) - x_R(\bar{z})$
- T-dualty

$$x_L \to x_L, \qquad x_R \to -x_R$$

  is the origin of O(D,D) signature of $X^M = (x,\tilde{x})$
- Level-matching condition leads to the section constraints

$$(L_0 - \bar{L}_0)|\Phi\rangle = 0 \quad \to \quad \partial^2\Phi = 0, \quad \partial_A\Phi\partial^A\Psi = 0$$

- $G_{\mathrm{DFT}} = \mathit{GenDiff}(\hat{\mathcal{M}}_D)$ arises from closed SFT gauge algebra, which receives α'-corrections after $O(D,D)$ non-covariant field and parameter redefinitions

DFT at Leading Order in α'

- Fields $(g, b, \phi) \to (\mathcal{M}_{MN} = \mathcal{E}_M \cdot \mathcal{E}_N, d)$ smart choice of variables
- O(D,D) invariant metric and O(D,D) covariant background

$$\mathcal{J} = \begin{pmatrix} 0 & \mathbb{I} \\ \mathbb{I} & 0 \end{pmatrix}; \qquad \mathcal{H} =< \mathcal{M} >$$

- At leading-order in α', $\mathcal{M}$ is constrained cf. O(N) nonlinear sigma model

$$\mathcal{M}^2 = \mathcal{J}; \qquad \mathcal{H} = \begin{pmatrix} g^{-1} & -g^{-1}b \\ bg^{-1} & g - bg^{-1}b \end{pmatrix}$$

$$\begin{aligned} S_0 &= \int e^{-2d}\mathcal{R}(\mathcal{E}) + \oint e^{-2d}\mathcal{L}_{\mathrm{GH}}(\mathcal{E}) \quad \text{subject to} \quad \mathcal{M}^2 = \mathcal{J} \\ \mathcal{R} &:= \mathcal{M}\partial\mathcal{M}\partial\mathcal{M} + \partial\partial\mathcal{M} + \mathcal{M}\partial d\partial d + \partial\mathcal{M}\partial d + \partial\mathcal{E}\partial\mathcal{E}\mathcal{M} \end{aligned}$$

- The action is uniquely fixed by G_{DFT}! enlarged gauge symmetry
- Unfortunately, the constraint $\mathcal{M}^2 = \mathcal{J}$, puts the weak field expansion of $\mathcal{M}$ as $g = \eta + h$ and $g^{-1} = \eta + h + h^2 + \cdots$ non-polynomial.

At leading-order in α', the DFT achieves enormously enlarged gauge symmetry G_{DFT}, but the field variables are still not smart

DFT at leading order in $\alpha' \simeq$ Einstein gravity

DFT at Next Order in α'

- Metaphor: Nonlinear to Linear O(N) model with Higgs
- At next order, DFT miraculously manages to achieve this:

$$
\begin{aligned}
S_1 &= \int e^{-2D}\Big[\big(\mathcal{M} - \frac{1}{3}\mathcal{M}^3\big) \\
&+ \alpha'\big((\mathcal{M}^2 - 1)\mathcal{M}\partial\partial D + \mathcal{M}\partial\mathcal{M}\partial\mathcal{M} + \mathcal{M}\partial\partial D\big) \\
&+ O(\alpha'^2\partial^4) + O(\alpha'^3\partial^6)\Big]
\end{aligned}
$$

- Enlarged gauge symmetry remains the same, G_{DFT}
- $\mathcal{M}$ is no longer constrained; $\mathcal{S}_1$ is polynomial in fields
- The action is uniquely determined by G_{DFT}
- No other possible counter-terms up to this order

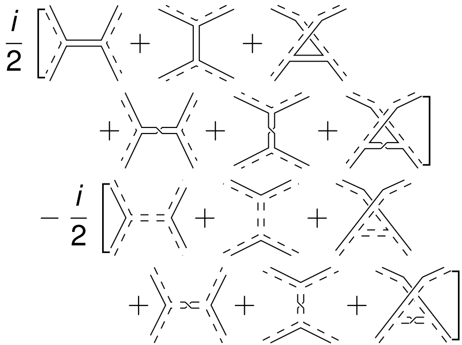
- What are the "Higgs" modes?
- Is high-energy behavior improved?

Higgs modes?

- $\mathcal{M}$ is no longer constrained
- S_0 contains ∂^2 terms, S_1 contains up to ∂^6 terms.
- $\mathcal{M} \simeq (g, b, \phi) \oplus (m, \bar{m})_{(mn)}$ from weak field expansion
- By O(D,D) field redefinition, only ∂^2 terms are relevant

$$\alpha' \Box m - 4m = \mathcal{L}(\mathcal{M}, m, \bar{m}) = h^T h + \cdots$$
$$\alpha' \Box \bar{m} + 4\bar{m} = \bar{\mathcal{L}}(\mathcal{M}, m, \bar{m}) = h\, h^T + \cdots$$

- It can be viewed as quiver matrix theory associated with double spin-Lorentz symmetry O(D)$\otimes$O(D). The $m, \bar{m}$ fields are symmetric, the (h, b) is bi-fundamental. It admits large-D expansion.



Higgs Modes?

Extra fields $(m, \bar{m})$ are the "Higgs" fields with features:

- $\mathcal{M}$ is no longer constrained; extra DOFs = $m, \bar{m}$
- $m_{0i}, \bar{m}_{0i}$ are non-dynamical fields cf. not Lagrage multiplier
- negative norm, akin to Pauli-Villar and Lee-Wick

  Boulware+Gross
- $m^2 = \pm 4/\alpha'$; this precise massive pair is needed upon integrating out $m, \bar{m}$ to cancel ∂^0 terms for $\mathcal{M}$ absent in S_0

  cf. Hohm, Nasser, Zwiebach

Can we get the DFT at finite α' as some new kind of string theory itself, not just as a low-energy truncation of it?

New Quantization

On the worldsheet, the classical string is parity symmetric and Lorentz invariant. Upon quantization, it is therefore natural to choose the vacuum parity symmetric and Lorentz invariant.

$$X(z,\bar{z}) = X_R(z) + X_L(\bar{z})$$

$$X_R(z) = \frac{1}{2}X - \frac{i}{4}\alpha' P \log(z) + \sum_{n\neq 0} \frac{1}{n}\alpha_n z^n$$

$$X_L(\bar{z}) = \frac{1}{2}X - \frac{i}{4}\alpha' P \log(\bar{z}) + \sum_{n\neq 0} \frac{1}{n}\bar{\alpha}_n \bar{z}^n$$

We shall quantize the string in canonical quantization method.

Conventional quantization proceeds with the commutation relations where the quantized oscillators obey

$$
\begin{aligned}
&[X^\mu, P^\nu] = i\eta^{\mu\nu} \\
&[a_m^\mu, a_n^\nu] = m\delta_{m+n,0}\eta^{\mu\nu} \\
&[\bar{a}_m^\mu, \bar{a}_n^\nu] = m\delta_{m+n,0}\eta^{\mu\nu}.
\end{aligned}
$$

and the choice of vacuum $|0\rangle = |0_0\rangle \otimes |0_R\rangle \otimes |0_L\rangle$:

$$
P|0_0\rangle = 0, \quad a_n|0_R\rangle = 0, \quad \bar{a}_n|0_L\rangle = 0 \quad (n = 1, 2, 3, \cdots)
$$

viz.

$$
|0_0\rangle \in \mathrm{Kre}(P), \quad |0_L\rangle \in \mathrm{Ker}(a_n), \quad |0_R\rangle \in \mathrm{Ker}(\bar{a}_n).
$$

The dual vacuum $\langle 0| = (0\rangle)^\dagger$ is 1-to-1 with the vacuum $|0\rangle$ if and only if the vacuum state is normalizable.

New quantization proceeds with the commutation relations where the quantized oscillators obey the same commutation relations

$$
\begin{aligned}
&[X^\mu, P^\nu] = i\eta^{\mu\nu} \\
&[a^\mu_m, a^\nu_n] = m\delta_{m+n,0}\eta^{\mu\nu} \\
&[\bar{a}^\mu_m, \bar{a}^\nu_n] = m\delta_{m+n,0}\eta^{\mu\nu}.
\end{aligned}
$$

but the choice of vacuum is specified by

$$
P|0_0\rangle = 0, \quad a_n|0_R\rangle = 0, \quad \langle 0_L|\bar{a}_n = 0 \quad (n = 1, 2, 3, \cdots)
$$

viz.

$$
|0_0\rangle \in \mathrm{Kre}(P), \quad |0_L\rangle \in \mathrm{Ker}(a_n), \quad \langle 0_R| \in \mathrm{coKer}(\bar{a}_n).
$$

This choice of vacuum is meaningful only if the vacuum state is not normalizable.

Consequences

With the new choice of vacuum in L-sector,

- creation and annihilation operators are interchanged

$$[a, a^\dagger] = +1, \qquad [\bar{a}, \bar{a}^\dagger] = -1$$

  The L-vacuum obeying $\langle 0|a = 0$ is non-normalizable as its wave function is exponentially growing. This is reminiscent of Lee-Wick prescription to quantize ghost system.

- time-ordering is opposite between L and R sectors. This is reminiscent of time evolution in thermofield double. One can view L sector as therm-double of R sector at $T = -\infty$.
- the string correlator becomes

$$\langle X^\mu(z_i, \bar{z}_i) X^\nu(z_j, \bar{z}_j)\rangle = -\frac{\alpha'}{4}\eta^{\mu\nu} \log \frac{(z_i - z_j)}{(\bar{z}_i - \bar{z}_j)}$$

Virasoro constraints

The Virasoro operators of the system are

$$L_0 = \frac{1}{2}P^2 + \mathbf{N} - a, \qquad \bar{L}_0 = \frac{1}{2}P^2 - \bar{\mathbf{N}} - \bar{a}$$

where

$$\mathbf{N} = \sum_{n=1}^{\infty} \alpha_{-n}\alpha_n, \qquad \bar{\mathbf{N}} = -\sum_{n=1}^{\infty} \bar{\alpha}_n\bar{\alpha}_{-n}.$$

The level-matching condition and mass-shell condition are

$$\mathbf{N} + \bar{\mathbf{N}} = a - \bar{a}, \quad M^2 = \frac{4}{\alpha'}(\mathbf{N} - a) = \frac{4}{\alpha'}(-\bar{\mathbf{N}} - \bar{a}).$$

where $a = 1$, $\bar{a} = -1$.
We also have gauge conditions

$$L_m|\text{phys}\rangle = 0, \quad \langle\text{phys}|\bar{L}_m = 0, \qquad (m > 0)$$

Spectrum

The states that obey Virasoro constraints are

$\hat{N}$	$\hat{\bar{N}}$	M^2	state	gauge condition	norm
1	1	0	$\epsilon_{\mu\nu}\alpha^{\mu}_{-1}\bar{\alpha}^{\nu}_{1}\|0,k\rangle$	$k^{\mu}\epsilon_{\mu\nu} = k^{\nu}\epsilon_{\mu\nu} = 0$	1
2	0	$\frac{4}{\alpha'}$	$m_{\mu\nu}\alpha^{\mu}_{-1}\alpha^{\nu}_{-1}\|0,k\rangle$	$k^{\mu}m_{\mu\nu} = m_{\mu}{}^{\mu} = 0$	-1
0	2	$-\frac{4}{\alpha'}$	$\bar{m}_{\mu\nu}\bar{\alpha}^{\mu}_{1}\bar{\alpha}^{\nu}_{1}\|0,k\rangle$	$k^{\mu}\bar{m}_{\mu\nu} = \bar{m}_{\mu}{}^{\mu} = 0$	-1

The massive states are Pauli-Fierz spin-2 fields but they obey the Virasoro gauge conditions

$$k^{\mu}m_{\mu\nu} = m^{\mu}_{\mu} = 0, \quad k^{\mu}\bar{m}_{\mu\nu} = \bar{m}^{\mu}_{\mu} = 0.$$

This is precisely the spectrum of ′-corrected DFT!
(cf. HSZ and HNZ: overlooked the Virasoro gauge conditions)

Superstring Counterpart

If repeat our quantization for superstring theory, we find

- heterotic string: N=1 string supergravity + ONE massive spin-2 ghost of mass-squared $\pm 4/\alpha'$
- type II string: N=2 string supergravity, no ghosts

Further Analysis (1)

We computed 4-point scattering amplitudes of massless string gravity states, and found the following remarkable properties

- a rational function of s, t, u – field theory
- manifestly s, t, u invariant
- factorization to a sum of three-point scattering amplitudes of the spectrum
- $\alpha' \to 0$ limit: reduces to string gravity system (leading order DFT)
- $\alpha' \to \infty$ limit: interacting three spin-2 system (some are ghosts, so evades no-go theorem)

Analysis (2)

We computed the one-loop partition function (cosmological constant) and found the following properties

- NOT modular invariant
- divergent at UV
- for supersymmetric system (type II), partially finite at UV (in fact, 0)

High-Energy Behavior (I)

- 4-point (h, b) amplitudes

cf. Huag, Siegel, Yuan; Huang's talk

$$A_4^{\mathrm{DFT}}(s,t,u) \sim \left(1 + \frac{su}{s^2 - 4/\alpha'^2} + \cdots\right) A_4^{\mathrm{grav}}(s,t,u)$$

- KLT kernel

$$A_4^{\mathrm{DFT}} = A_4^{\mathrm{chiral}}(+\eta) K_{\mathrm{DFT}} \bar{A}_4^{\mathrm{chiral}}(-\eta)$$

where

$$K_{\mathrm{DFT}} = \left(1 + \frac{su}{s^2 - 4/\alpha'^2} + \cdots\right) K_{\mathrm{grav}}$$

- For such soft UV behavior, both ”negative-norms” and ”precise mass-squared spectrum $\alpha' m^2 = \pm 4$ are crucial

High Energy Behavior (II)

- BCFW factorization viewed as soft-collinear scattering

  Arkani-Hamed+Kaplan
- At large z, enhanced spin symmetry governs the leading behavior
- For leading DFT, the same as Einstein gravity cf. Boels+Hurst
- For $O(\alpha')$ DFT, BCFT asymptotics gets more convergent

$$A_4^{\mathrm{DFT}}(-,-;\pm,\pm) \to \underbrace{\left(\frac{1}{z} + \cdots\right)}_{\mathrm{DFT}} \cdot \frac{1}{z^s}\bigg|_{s=2}$$

- Similar softer behavior for other polarizations

High Energy Behavior (III)

- vacuum amplitudes

cf. bosonic YM theory at d=26; Tseytlin, SJR

$$
\begin{aligned}
A_0 &= \int \mathrm{d}^4 p \left[\sum_{(h,b,d)} \log p^2 - \sum_{m,\bar{m}} \log(p^2 \pm 4) \right] \\
&\simeq \left[(d-2)^2 - 2 \cdot \frac{1}{2}(d-1)^2 + 2(d-1) + 1 \right] \Lambda^4 + \cdots
\end{aligned}
$$

- Subleading divergence uncancelled
- Radiative correction to Newton's constant non-vanishing from leading order

At higher-order in α', the DFT retained enormously enlarged gauge symmetry G_{DFT}, and also the "Higgs" modes that soften the high-energy behavior

DFT at higher order in $\alpha' \simeq$ UV improved gravity

cf. Higher-spin theory at higher loop order

Giombi, Klebanov, Tseytlin, Beccaria, ...

Remark on Indefinite Hilbert Space

- $m, \bar{m}$ are ghosts
- dynamical Pauli-Villar fields and Lee-Wick mechanism?

  Boulware, Gross; Grinstein, Wise
- If arising from a certain limit of string theory, then "how"?
- Could they be viewed as "effective" description of contribution of infinitely many positive-norm states?

$$2\sum_{s=1}^{\infty}\frac{+1}{p^2 \pm m^2} = \frac{2\zeta(0)}{p^2 \pm m^2} = \frac{-1}{p^2 \pm m^2}$$

Remarks for Ambitwistor Strings

- $O(\alpha')$ DFT was derived from chiral CFT and hence "chiral string" dynamics Hohm, Siegel, Zwiebach
- We derived this chiral string from conventional string after integrating out anti-chiral part and taking infinite tension limit; This fits nicely on "how" the spacetime signature changes between original and T-dual coordinates in DFT coordinates $X^M = (x, \tilde{x})$ see also Hai-Tang Yang

$$\boxed{\langle x^m(z,\bar{z})\tilde{x}^n(z,\bar{z})\rangle = \eta^{mn}\log\frac{z}{\bar{z}} = +\eta^{mn}\log z - \eta^{mn}\log\bar{z}}$$

- The signature change converts the standard KLT to closed string amplitude to DFT amplitude Huang, Siegel, Yuan
- Ambitwistor string approach to YM and gravity scattering amplitudes and explanation of CHY scattering equation

cf. Cachazo, He, Yuan; Casali, Tourkine

Remark on Little DFT

- LST enjoys T-duality symmetry Vafa et.al.; Hohenegger, Iqbal, SJR; Kim, Kim, Lee
- no ten-dimensional (g, b, ϕ)
- 5-brane worldvolume fields (a, b^+) + massive excitations
- manifest O(D,D) covariant description of (a, b^+) leads to doubled gauge theory with enlarged gauge symmetries

$$\boxed{\text{little DFT = double gauge theory}}$$

$$S_{\text{littleDFT}} = \int e^{-2d}\frac{1}{2}\text{Tr}\mathcal{F}^2(A), \qquad A_M \simeq (a, b^+)$$

- As a pathway for UV completing gauge theories to LST, explore high-energy behavior of the little DFT
- Expect to shed light to noncritical / QCD strings cf. Komargodski
- Tension between massive higher-spins from QCD (a) versus from abelian Higgs model (b^+)?

Thank You

For out of olde feldes, aas men seith,
Cometh al this newe corn fro yeer to yere;
And out of olde bokes, in good feith,
Cometh al this newe science that men lere.

Geoffrey Chaucer