Non-Lorentzian Holography and Near-BPS Physics in String Theory

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Based on 2410.17074, W.I.P. w/ Neil Lambert (see also 2401.14955, 2405.06552)
2502.07969 w/ Neil Lambert & Eric Bergshoeff

Motivation

Would like to understand string theory non-perturbatively: this is famously hard!

No accepted microscopic formulation, though many proposals (e.g. string field theory, large-N BFSS, holography, etc.)

Could argue we're trying to do too much at once: plethora of non-perturbative dynamical *relativistic* objects, need to account for their production and interactions

Analogy from 20^{th} century:

Classical Relativistic Dynamics $\overset{?}{\Longrightarrow}$ Quantum Relativistic Dynamics

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Analogy from 20th century:

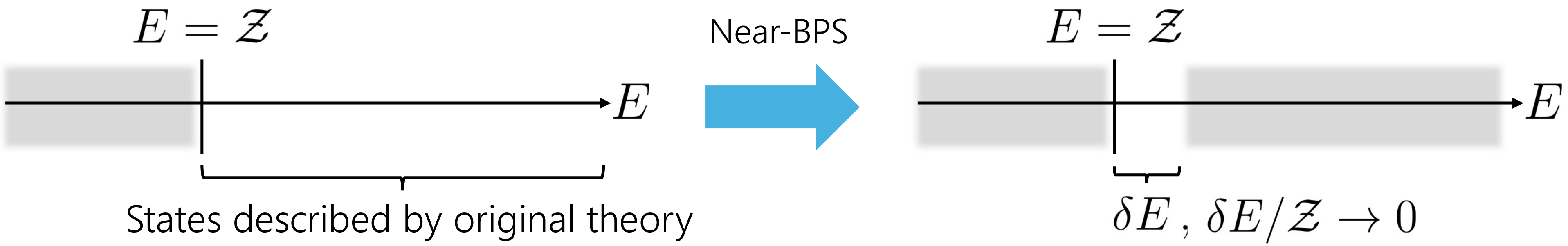
Classical Relativistic Dynamics $\Longrightarrow$ Quantum *Non-Relativistic* Dynamics $\Longrightarrow$ Relativistic QFT

BPS Decoupling Limits

Goal: Find self-contained corners of string theory built whose dynamics is governed by a single type of brane

Idea: Isolate states near BPS bound,

Harmark, Orselli '14



Infinitesimal excitations above bound → fixed number of branes

Physically corresponds to considering *non-Lorentzian* BPS branes

Warm Up: Free Scalar Field

To get a feel for these limits, let's consider a free complex scalar field:

$$S = -\frac{1}{2}\int d^{d+1}x\sqrt{-g}\left(g^{\mu\nu}\partial_\mu\bar{\varphi}\partial_\nu\varphi + M^2\bar{\varphi}\varphi\right)$$

To project onto low energy states we must consider the long-timescale limit, i.e. we work on

$$g = c^2\left(-c^2\,\cancel{dt^2 + dx^i dx^i}\right)$$

Deformation parameter, not 'physical' speed of light

and take $c \to \infty$ limit. Problem: As it stands, this kills all dynamics!

Solution is well known: couple theory to a background U(1) field and rescale,

$$\varphi = \sqrt{c}\,\phi\ ,\ \ A = c\,dt$$

Warm Up: Free Scalar Field

The action is then

$$S = \frac{1}{2}\int dt d^d x \Big(c^{-2}\partial_0\bar{\phi}\partial_0\phi + 2iq\bar{\phi}\partial_0\phi - \partial_i\bar{\phi}\partial_i\phi \\ - (M^2 - q^2)c^2\bar{\phi}\phi \Big)$$

Introduces divergent term that cancels if we take extremal limit,

$$M = q$$

Key point: In order to take a non-Lorentzian limit of particles, we must

1. Rescale the underlying geometry to define a static particle worldline and transverse directions
2. Couple to an extremal U(1) field to cancel off divergent rest energy

BPS Decoupling Limits of D-Branes

We now do the same in string theory. However, can't arbitrarily couple objects to background fields: need extremality w.r.t. a physical U(1) field, i.e. need to work with BPS branes. Consider Dp-brane with action (ignoring B-field)

$$S_p = -T_p \int d^{p+1}\xi \, e^{-\phi} \sqrt{-\det\left(P[G] + 2\pi\alpha' F\right)} + T_p \int C_{p+1}$$

Aim: after gauge-fixing, want to recover the usual low-energy D-brane action

$$\Phi^I = 2\pi\alpha' X^I$$

$$S_p \to -\frac{(2\pi\alpha')^2 T_p}{2} \int d^{p+1}x \left(\partial_a \Phi^I \partial^a \Phi^I + \frac{1}{2} F_{ab} F^{ab}\right)$$

Need to rewrite fields in a $SO(1,p) \times SO(9-p)$-invariant way that automatically deals with divergent terms and leads to action above!

BPS Decoupling Limits of D-Branes

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After some inspiration, we find

$$g_{10} = c^2 \eta_{p+1} + c^{-2} \delta_{9-p} \ , \ \ \phi = (p-3) \ln c \ , \ \ C_{p+1} = c^{p+1} \varepsilon_{p+1}$$

Observation: This is equivalent to the D-brane's supergravity solution with harmonic function $\mathcal{H}_p = c^{-4}$

However! String theory is a theory of gravity: need to extend this to curved geometries. For metric, this is

$$\tau_{\mu\rho} \mathcal{E}^{\rho\nu} = 0 \longleftarrow \begin{aligned} g_{\mu\nu} &= c^2 \boxed{\tau_{\mu\nu}} + c^{-2} \boxed{\mathcal{E}_{\mu\nu}} \,, \\ g^{\mu\nu} &= c^2 \boxed{\mathcal{E}^{\mu\nu}} + c^{-2} \boxed{\tau^{\mu\nu}} \end{aligned} \longrightarrow \text{Projective inverses}$$

Dp-Brane Newton Cartan Geometry

Generalisation to Any BPS Brane

This gives us a recipe for a near-BPS limit of any brane in string/M-theory:

1. Take supergravity solution, replace harmonic function with a negative power of c
2. Promote metric components to brane-like Newton Cartan fields, write divergent form-fields in terms of volume forms
3. Allow additional finite dilaton (if in 10d) and form-field terms

Example: M2 and M5-branes in 11d,

M2-brane Limit:

$$g_{11} = c^2\tau_3 + c^{-1}\mathcal{E}_8 \ ,$$
$$C_3 = -c^3\varepsilon_3 + c_3$$

M5-brane Limit:

$$g_{11} = c^2\tau_6 + c^{-4}\mathcal{E}_5 \ ,$$
$$C_6 = c^6\varepsilon_6 + c_6$$

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Non-Lorentzian Supergravity

Want to understand the physics of these limits! First step: look at long wavelength approximation, i.e. underlying supergravity theory

Limit can be taken at level of action or equations of motion: for consistency, we need both to agree*

Let's be explicit: example we'll study is M5-brane limit of 11d supergravity,

$$S_{11} = \frac{1}{2\kappa_{11}^2}\int d^{11}x\sqrt{-g}\,R(g) - \frac{1}{4\kappa_{11}^2}\int\left(F_4\wedge *F_4 - \frac{1}{3}C_3\wedge F_4\wedge F_4\right)$$

Expectation: Gravitational and gauge forces balanced for BPS states, so *small* universally attractive force for states infinitesimally above bound → Newtonian-esque gravity! Should find a form of Poisson equation

Non-Lorentzian Supergravity

At level of action: must use metric/vielbein and 3-form as variables, so only possible structure respecting 5-brane symmetries is to leave 3-form unscaled,

$$E_\mu^M = \{c\,\tau_\mu^A, c^{-2} e_\mu^a\}\ ,\ \ C_3 = c_3$$

Plugging decomposition into action, find divergent terms:

$$S_{11} = c^{12} S_2 + c^6 S_1 + S_0 + O(c^{-6})$$

Fortunately, after rearranging divergent pieces are squares,

$$S_{1,2} = -\int d^{11}x\, \Omega\, \mathcal{C}_{1,2}^2$$

Measure formed from $\{\tau_\mu^A, e_\mu^a\}$

Non-Lorentzian Supergravity

Can then regulate these terms using Hubbard-Stratonovich fields,

$$c^{2\alpha} \int d^{11}x \, \Omega \, \mathcal{C}_{1,2}^2 \Rightarrow \int d^{11}x \, \Omega \Big(2\lambda_{1,2} \cdot \mathcal{C}_{1,2} - c^{-2\alpha} \lambda_{1,2}^2 \Big)$$

Non-Lorentzian Supergravity

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$$c^{2\alpha}\int d^{11}x\,\Omega\,\mathcal{C}_{1,2}^2 \Rightarrow \int d^{11}x\,\Omega\Big(2\lambda_{1,2}\cdot\mathcal{C}_{1,2} - \cancel{c^{-2\alpha}\lambda_{1,2}^2}\Big)$$

Impose constraints on theory: for the M5-brane limit, we have

$$f_{abcd} = 0\ ,$$

$$(d\tau^A)_{ab} = \frac{1}{6}\epsilon_{abcde}f^{cdeA}$$

Obstruction to 'absolute' 5-brane foliation

Had to add additional fields to the description here – is this consistent with e.o.m. expansion? (Will come back to this!)

Non-Lorentzian Supergravity

Add this to finite part of the action to get well-defined theory, but no Poisson equation: what's going wrong?

Answer: additional gauge symmetry emerges after limit! Local dilatation symmetry,

Morally equivalent to local rescaling of c

$$\tau^A \to e^{\omega(x)}\tau^A \ , \ \ e^a \to e^{-2\omega(x)}e^a$$

Noether's 2nd theorem: implies additional relation between e.o.m.,

$$2e^\mu_a \mathbb{E}^a_\mu + \tau_\mu^A \mathbb{E}_A^\mu = 0$$

Fewer e.o.m. than relativistic theory, so must proceed via equations of motion: projection of leading order e.o.m. vanishes, so can go to subleading order to find additional scalar equation

Non-Lorentzian Supergravity

Easiest to handle e.o.m. expansion by introducing on-shell dual field,

$$G_7 = dC_6 - \frac{1}{2} C_3 \wedge F_4 \Rightarrow G_7 = *F_4$$

Strategy: Project equations along all combinations of τ^A and e^a, and extract leading terms

When applied to the duality relation, recover constraints imposed by HS fields! Also able to identify these with finite components of 7-form g_7

Now look at Einstein equation: find expected cancellation, with subleading equation

$$\nabla_\mu \left(e_a^\mu g_a \right) + 2(d\tau^A)_{aA}\, g_a = \text{geom.} + \text{flux}$$

$g_a \propto \epsilon^{ABCDEF} g_{aABCDEF}$

5-brane Poisson equation!

Non-Lorentzian Brane Solutions

Can construct solutions by inserting deformation parameter in relativistic solutions and taking limit

How can we ensure that we get something sensible after limit? Answer: Arrange M5-brane limit and backreacting brane in ¼-BPS configuration

Example: M2-brane,

$$g_{11} = \mathcal{H}_5^{-1/3}\Big(\mathcal{H}^{-2/3}\eta_2 + \mathcal{H}^{1/3}d\sigma^I d\sigma^I\Big) + \mathcal{H}_5^{2/3}\Big(\mathcal{H}^{-2/3}dx^2 + \mathcal{H}^{1/3}dX^M dX^M\Big)$$

$$C_3 = \big(\mathcal{H}^{-1} - 1\big)dt^0 \wedge dt^1 \wedge dx$$

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Example: M2-brane,

$$g_{11} = c^2\Big(\mathcal{H}^{-2/3}\eta_2 + \mathcal{H}^{1/3}\overbrace{d\sigma^I d\sigma^I}^{\text{Take this to be } T^4\text{, smear M2-branes}}\Big) + c^{-4}\Big(\mathcal{H}^{-2/3}dx^2 + \mathcal{H}^{1/3}dX^M dX^M\Big)$$

$$C_3 = \big(\mathcal{H}^{-1} - 1\big)dt^0 \wedge dt^1 \wedge dx$$

Harmonic function for solution is

$$\mathcal{H} = 1 + \frac{R^2}{r^2}$$

Non-Lorentzian Brane Solutions

Smearing ensures c-independence of M2-brane flux,

$$N_{M2} \propto \int_{S^3_\infty \times T^4} *F_4$$

Taking near-horizon limit and using local dilatation,

$$\tau_6 = \boxed{\frac{r^2}{R^2}\eta_2} + d\sigma^I d\sigma^I \ , \ \mathcal{E}_5 = dx^2 + \boxed{\frac{R^2}{r^2}dr^2} + R^2 g_{S^3}$$

Non-Lorentzian
analogue of AdS_3

Same idea holds in general: get well-defined brane solution (i.e. finite flux) if we start with a ¼-BPS intersecting brane set-up and smear over coordinates in $\mathcal{T}$ transverse to backreacting brane

Beyond Supergravity?

Seen that limits lead to well-defined theories of Newtonian-like gravity in the IR: can we go beyond this and take limit of full QG theory?

Best understood case is non-relativistic string limit: underlying (bosonic) string theory is Gomis-Ooguri string, i.e. left+right moving $\beta\gamma$ system + D-2 transverse scalars on flat background

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Two perspectives,

1. Compute scattering amplitudes in flat background – done explicitly at tree-level and one-loop, UV-finite results
2. Couple worldsheet to background fields (i.e. turn on marginal deformations) and compute beta functions – at one-loop, agree with NRST limit of supergravity (including Poisson equation)

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UV completion of non-Lorentzian gravity

Beyond Supergravity?

Can go further: near-BPS limits obey usual string theory dualities, so applying in sequence gives

$$\boxed{\text{NRST limit of IIB}} \xRightarrow{\text{S-duality}} \boxed{\text{D1-brane limit of IIB}} \xRightarrow{\text{T-duality}} \cdots \xRightarrow{\text{T-duality}} \boxed{\text{Dp-brane limit of IIA/B}}$$

Claim: All near-BPS limits of string/M-theory lead to UV-complete theories of non-Lorentzian quantum gravity

Microscopic dynamics given by interacting near-BPS (i.e. low energy) branes: understood in various cases, e.g. Dp-brane limits on a flat background theory are described by U(N) (p+1)-dim. MSYM

Aside: How Does AdS/CFT Fit Into This?

So far we've said nothing about the most famous example of a decoupling limit – the duality between $\mathcal{N} = 4$ SYM and string theory on $AdS_5 \times S^5$. Can we understand this from our discussion so far?

Consider the IIB supergravity solution,

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$$g_{10} = \frac{r^2}{R^2}\eta_4 + \frac{R^2}{r^2}\delta_6 \ , \ C_4 = \frac{r^4}{R^4}\varepsilon_4$$

Defining a 'holographically-running speed of light' $\tilde{c}(r) = r/R$, this is

$$g_{10} = \tilde{c}^2\eta_4 + \tilde{c}^{-2}\delta_6 \ , \ C_4 = \tilde{c}^4\varepsilon_4$$

$r \to \infty \Rightarrow \tilde{c} \to \infty \Rightarrow$ D3-brane limit at asymptotic boundary

Novel perspective on why low-energy brane QFT appears at boundary!

Non-Lorentzian Holography

How can we probe properties of limits? Use holography,

$$\begin{tikzcd} \text{(Lorentzian) QG on NH Brane Geometry} \arrow[r, Leftrightarrow, "\text{Dual!}"] \arrow[d, Rightarrow] & \text{Brane Worldvolume QFT at Conformal Boundary} \arrow[d, Rightarrow] \\ \text{p-brane Limit of QG on NH Geometry} \arrow[r, Leftrightarrow, "\text{Dual?}"] & \text{p-brane Limit of Brane Worldvolume QFT} \end{tikzcd}$$

If we believe holography holds at quantum level, both sides should match!

Single limit of string theory on curved background vs double limit on flat background

Non-Lorentzian Holography

Focus on D-brane decoupling limits. Consider Dq-brane limit of Dp-brane,

$$\begin{array}{c}\text{String Theory on}\\\text{Flat Background}\end{array} \xrightarrow{\text{Dp-Brane Limit}} \begin{array}{c}\text{(p+1)-dim.}\\\text{U(N) MSYM}\end{array} \xrightarrow{\text{Dq-Brane Limit}} \begin{array}{c}\text{Dq-brane limit}\\\text{of } \mathrm{MSYM}_{p+1}\end{array}$$

First takes us to near-BPS Dp-branes, second takes us to near-BPS Dq-branes *within* near-BPS Dp-branes: in other words, taking both localises us onto near-BPS Dp-Dq bound states

Can consider reversing limits: physically should pick out same bound-state dynamics, so can propose the equality

$$\begin{array}{c}\text{Dq-brane limit}\\\text{of } \mathrm{MSYM}_{p+1}\end{array} = \begin{array}{c}\text{Dp-brane limit}\\\text{of } \mathrm{MSYM}_{q+1}\end{array}$$

Example: D0-D4 Bound States

Start with D0-D4 states: take D4-brane limit first. Worldvolume QFT on D4-branes is 5d $\mathcal{N} = 2$ SYM,

$$S_{D4} = -\frac{1}{4g^2}\mathrm{tr}\int d^5x\left(F_{\mu\nu}F^{\mu\nu} - 2D_\mu Y^M D^\mu Y^M + [Y^M, Y^N]^2\right)$$

Need to translate D0-brane limit of flat background into QFT scaling:

Decomposition of Metric		$\{t, x^i\} \to \{c\,t, c^{-1}x^i\}\ ,\ Y^M \to c^{-1}Y^M$
Dilaton Scaling	$\Longrightarrow$	$g^2 \to c^{-3}g^2$
Divergent 1-form Field		$\Delta S_{D4} = \frac{c^4}{2g^2}\mathrm{tr}\int dt \wedge F \wedge F$

Example: D0-D4 Bound States

Substituting into action gives

$$S_{D4} = \frac{1}{2g^2}\mathrm{tr}\int dt d^4x \Big(\underbrace{-\frac{c^4}{2}(F - *F)^2}_{\text{Divergent Squared Term!}} + F_{0i}F_{0i} - D_iY^M D_iY^M \Big)$$

As in supergravity limit, tame with Hubbard-Stratonovich transformation: imposes YM instanton equation

$$F = *F$$

YM kinetic term reduces to moduli space kinetic term

Hyper-Kähler metric on moduli space

$$\mathrm{tr}\int dt d^4x\, F_{0i}F_{0i} = \int dt\, g_{\alpha\beta}(m)\dot{m}^\alpha \dot{m}^\beta$$

(Supersymmetric) QM on Instanton Moduli Space

Example: D0-D4 Bound States

Now look at supergravity solution: using method discussed earlier, find

$$g_{10} = -c^2\mathcal{H}^{-1/2}dt^2 + c^{-2}\Big(\mathcal{H}^{-1/2}dx^i dx^i + \mathcal{H}^{1/2}dY^M dY^M\Big)$$

$$e^{\phi} = c^{-3}\mathcal{H}^{-1/4}\ ,\ C_1 = c^4 dt\ ,\ C_5 = (\mathcal{H}^{-1} - 1)dt \wedge dx^1 \wedge \ldots \wedge dx^4$$

for D4-brane in terms of harmonic function

$$\mathcal{H} = 1 + \frac{R^3}{r^3}$$

As it stands, this is messy: however, D0-brane theory has local dilatation symmetry which we can use to trivialise dilaton,

$$c \rightarrow c\,\mathcal{H}^{-1/12}$$

Example: D0-D4 Bound States

Applying this to solution and taking near-horizon limit gives

$$g_{10} = -c^2 \boxed{\frac{r^2}{R^2} dt^2} + c^{-2} \left(\boxed{\frac{r}{R} dx^i dx^i} + \boxed{\frac{R^2}{r^2} dr^2} + R^2 g_{S^3} \right)$$

Non-Lorentzian AdS–like spacetime

$$C_5 = \frac{r^3}{R^3} dt \wedge dx^1 \wedge \ldots \wedge dx^4$$

Possesses an emergent z=2 Lifshitz scaling symmetry,

$$t \to \lambda^2 t \ , \ \ x^i \to \lambda x^i \ , \ \ r \to \lambda^{-2} r$$

Actually enhances to full Schrödinger symmetry

Same symmetry emerges after limit in gauge theory description due to presence of homothetic killing vector on moduli space

Example: D1-D3 Bound States

Can do the same with T-dual setup: D1-D3 bound states. Can either take limit starting from $\mathcal{N}=4$ or dimensionally reduce D0-D4 action

Find SQM on the moduli space of BPS monopole equations,

$$F_{ij} = \epsilon_{ijk} D_k X$$

which require $\langle X \rangle \neq 0$ to have non-trivial solutions: corresponds to monopole mass scale

Physically corresponds to D3-brane separation: monopoles are D1-branes stretched across interval hep-th/9608163

Conformal symmetry of $\mathcal{N}=4$ broken by VEV: also seen in dual supergravity solution

Non-Relativistic Strings and Galilean YM

D-brane limits interesting, but hard to quantise: in gauge theory description have Lagrange multipliers, and in moduli space description need explicit understanding of metric

Look for limit in which dynamics arise from perturbative QFT states: a good choice is to look at non-relativistic string limit of D-brane QFT,

D0 limit of D4 Instantons	$\xRightarrow{\text{T-duality}}$	D1 limit of D3 BPS Monopoles	$\xRightarrow{\text{S-duality}}$	F1 limit of D3 W-Bosons

QFT limit goes through using same steps as before: novelty here is that transverse scalars split into two groupings and B-field induces shift of connection,

$$\{X, Y^M\} \to \{cX, Y^M\}\ ,\ A_0 \to A_0 + c^2 X$$

Non-Relativistic Strings and Galilean YM

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Resulting theory is Galilean Yang-Mills,

$$S_{GYM} = \frac{1}{2g^2}\mathrm{tr}\int dtd^px\Big((D_0X)^2 - 2D_iXF_{0i} - \frac{1}{2}F_{ij}F_{ij} - 2iD_0Y^M[X,Y^M] - D_iY^MD_iY^M + \frac{1}{2}[Y^M,Y^N]^2\Big)$$

How do we see dynamics? Restrict to SU(2) theory and work on Coulomb branch, $\langle X\rangle = v\sigma^3/2$. Expanding other scalars as

$$Y^A = y^A\sigma^3/\sqrt{2} + \omega^A\sigma^+ + \bar{\omega}^A\sigma^-$$

gives quadratic terms

$$S_{quad.} = \int dtd^px\Big(\underbrace{2iv\,\bar{\omega}^A\partial_0\omega^A - \partial_i\bar{\omega}^A\partial_i\omega^A}_{\text{Non-relativistic particle of mass } M=v} - \frac{1}{2}\overbrace{\partial_iy^A\partial_iy^A}^{\text{Non-Dynamical Field}}\Big)$$

Non-Relativistic Strings and Galilean YM

General structure of theory:

- Galilean electrodynamics + real scalars with only spatial derivatives (i.e. abelian limit of GYM action)
- Massive charged non-relativistic particles
- Fermions (give supersymmetric theory)

Interesting case is $p = 2$, describing low-energy physics of a D2-brane in NRST: observe Schrödinger symmetry, with scaling

VEV Preserved!

$$\{t, x^i\} \to \{\lambda^2 t, \lambda x^i\}\ ,\ \boxed{X \to X}\ ,\ Y^M \to \lambda^{-1} Y^M$$

Same symmetries observed in near-horizon limit of D2-brane on transverse circle in NRST: does this persist once quantum effects included?

Including Quantum Effects

Perturbative structure very constrained due to first-order propagator, 2007.03033

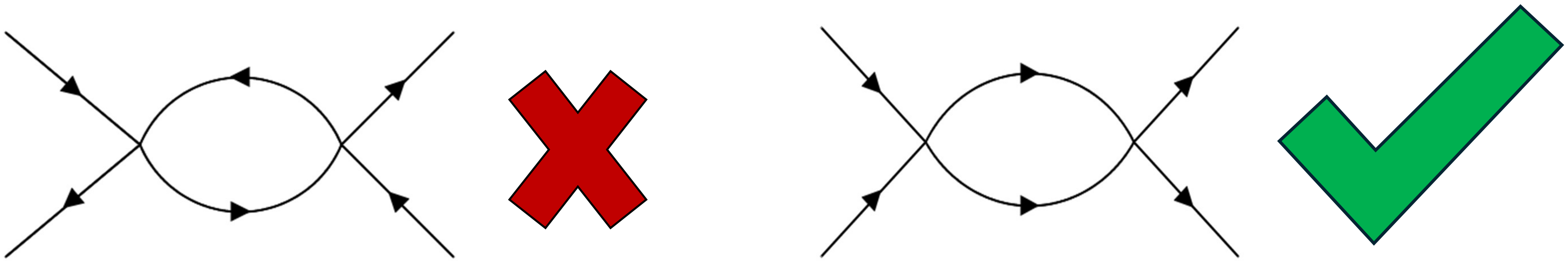
$$G(t,p) = \frac{\Theta(t)}{2v}\exp\left(\frac{ip^2}{2v}\right)$$

In particular, closed particle loops vanish:

$t_{N+1} = t_1$

$$\text{closed loop} \sim \prod_i \Theta(t_{i+1} - t_i) = 0$$

Even with loop energy insertions, can show that these diagrams can only contribute power-law divergences (which cancel via SUSY)



Including Quantum Effects

Two-point and three-point functions completely protected from log-divergences: however, for four-point functions find divergences, e.g.

$$\Gamma^{(4)}_{1-loop} = -\int \frac{d^3 p_i}{(2\pi)^3}\, \omega_1^A \omega_2^B \bar{\omega}_3^C \bar{\omega}_4^D \, V_{ABCD}(p_i)$$

$$V_{ABCD} = (\delta_{AB}\delta_{CD} - \delta_{AC}\delta_{BD}) \int \frac{d^2\tilde{p}}{(2\pi)^2} \frac{2}{v\tilde{p}^2} + \text{finite}$$

No divergences found in correlation functions involving y^A: need to add new terms in renormalisation! Obvious choices

$$[X, Y^A][X, Y^B][Y^A, Y^B] \ , \ ([X, Y^A][X, Y^B])^2$$

Must be able to do this while preserving SUSY: extremely constraining, seems to pick out a unique candidate one-parameter family of deformations

SUSY preserving? Conformal?

Conclusion and Future Directions

To sum up:

- For each BPS brane in string theory, we have an associated near-BPS limit
- Constructed the M5-brane limit of eleven-dimensional supergravity: saw that it possessed an emergent local scaling symmetry and Poisson equation, and showed how to construct brane solutions
- Took near-BPS limits of D-brane holographic pairs: on QFT side found dynamics reduced to motion on relevant soliton moduli space, with same symmetries as dual non-Lorentzian supergravity solution
- Started including quantum corrections using the example of supersymmetric Galilean Yang-Mills

Conclusion and Future Directions

What next?

GYM + NRST:

- Do we have a SUSY-preserving deformation that leaves the scalar four-point function UV-finite at one loop? Does this extend to the whole theory?
- What does the theory look like at the quantum level for a general gauge group? In particular, what happens at large-N?
- Can we construct the worldsheet dual in NRST and match observables on both sides?

Dp-Brane Limits:

- Can we construct full quantum dynamics from an intrinsically bulk perspective for arbitrary asymptotics?
- How does relativistic bulk structure emerge at large-N?

Thanks for listening!