String Theory
as
Drama Queen

Based on

*ES '14 Backdraft (+J. Polchinski unpublished)

*Work(s) in progress with M. Dodelson + S. Giddings; D. Marolf; L. McAllister, T. Bachlechner; G. Veneziano

previous work on potentially relevant stringy dynamics includes: Veneziano et al/ACV, Bachas, McAllister/Mitra, Susskind et al, Giddings et al, Lowe,...

Black Hole Thought Experiments:

Recent work on black holes (AMPS,...) showed an inconsistency in the hypothesis that low energy effective field theory applies near the horizon of an evaporating BH in the presence of late-time observers.

This has led to speculation about rather radical modification of quantum gravity, or bottom-up dynamical hypotheses (possibly violent or non-violent).

But we have to check the level of EFT breakdown in string theory, in the presence of the large relative boosts separating early matter and late observers. Non-adiabatic and string spreading effects can be significant in such processes in standard, perturbative string theory, potentially translating to `drama' for late observer.

In other words, while everyone else is busy reformulating non-perturbative physics by calculating entanglement, we are busy with papers from the '60s on tree level string amplitudes...

7.B.1 Nuclear Physics B10 (1969) 399-409. North-Holland Publ. Comp., Amsterdam

HIGH-ENERGY BEHAVIOUR OF THE BARDAKCI-RUEGG AMPLITUDE

A. BIAŁAS * and S. POKORSKI **
CERN - Geneva

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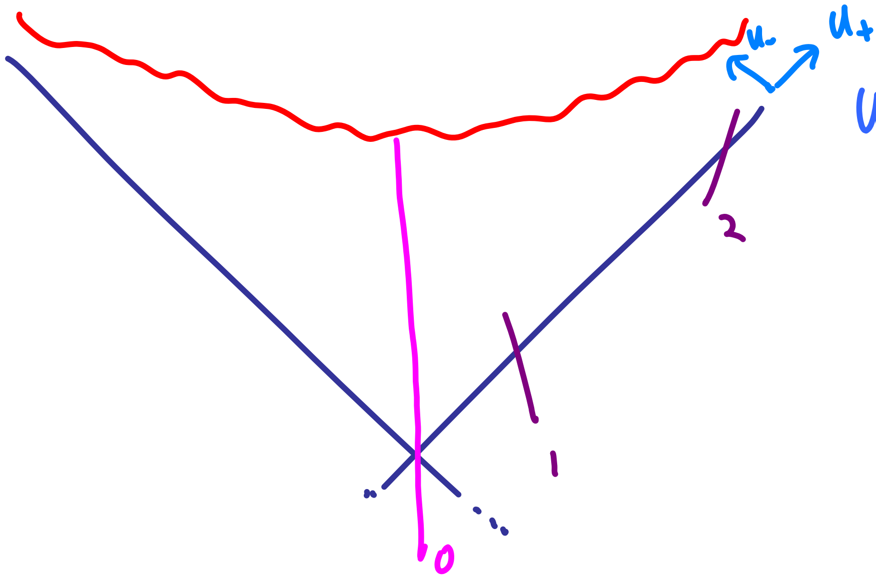
Abstract: The behaviour of the five-point function proposed by Bardakçi and Ruegg is discussed in the kinematical region of high-energy and small momentum transfers. Both single and double Regge limits are given explicitly in terms of the hypergeometric functions. When applied to the single-particle production at high energy, the formulae suggest a Regge exchange model in which the structure of the vertices is explicitly given.

BH trajectories

$$ds^2 = -\left(1-\frac{r_0}{r}\right)dt^2 + \frac{dr^2}{1-\frac{r_0}{r}} + r^2 d\Omega^2 + ds_\perp^2$$



$$u_\pm = r_0\sqrt{\frac{r}{r_0}-1}\; e^{\pm\frac{t}{2r_0}}$$

Send particles in with (modest) (Schwarzschild) energies E_1 & E_2.

In the Rindler region, they have relative boost

$$\Delta\eta = \eta_2^{(0)} - \eta_1^{(0)} + \overbrace{\frac{\Delta t}{2r_0}}^{\text{late-time}}$$

$\approx$ large boost

near-horizon rapidity relative to $\mathcal{O}_0$

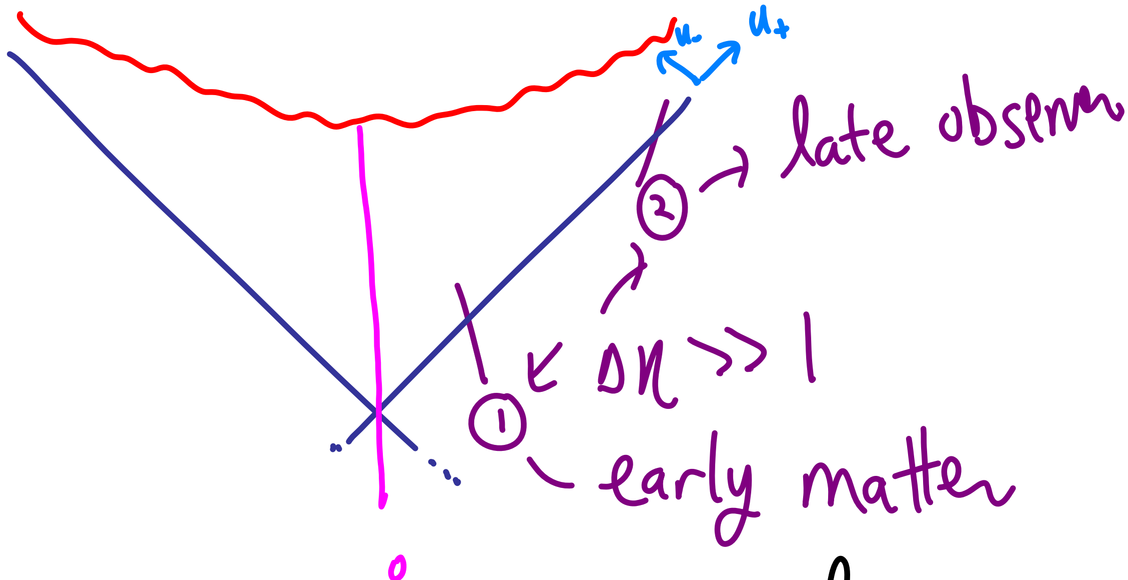
Specifically, at horizon crossing

$$\left.\frac{dU_+}{dU_-}\right|_h = e^{2\eta^{(0)}} \; ; \quad U_+\Big|_h = 2r_0\sqrt{e}\,\frac{E}{m}\,e^{\eta^{(0)}}$$

$$\eta^{(0)} = \frac{k}{2}\left((k^2+3)\tan^{-1}k + k\right) \quad (E<m)$$

$$k = \sqrt{\frac{R}{r_0} - 1}\,, \qquad R = \frac{r_0}{1-\frac{E^2}{m}}$$

$$\eta^{(0)} = \frac{t_0}{2r_0} - \frac{1}{2}\sqrt{\frac{\rho}{r_0}+1}\left(\sqrt{1+\frac{\rho}{r_0}} + \left(2-\frac{\rho}{r_0}\right)\tan^{-1}\sqrt{1+\frac{\rho}{r_0}}\right) - \frac{1}{2}\log\frac{r_0}{\rho}\,, \quad \rho = \frac{r_0}{\frac{E^2}{m^2}-1} \quad (E>m)$$



· In near-horizon region, the large relative boost is a large Minkowski energy

· EFT does not know its own limit

☆ $\alpha' R \ll 1$ not (obviously) enough for EFT

· Question: can boost enhanced string effects $\Rightarrow$ breakdown of EFT catalyzed by late observer ② in presence of ① ?

I) Open string production b/w D-branes

II) Longitudinal string spreading effects

Boost-enhanced string dynamics

1) Open string production b/w relativistic D-branes

Bachas
McAllister - Mitra
ES ...

$m_W = \phi(t)$

$= \dot\phi t$ (b/f backreaction)

$$\omega(t)^2 = \dot\phi^2 t^2 + \vec{k}^2 + b_\perp^2$$

↳ For this t-dependent QFT problem

$$\langle N_{\text{created particles}} \rangle = |\beta|^2 = e^{-\frac{\pi(\vec{k}^2 + b_\perp^2/\alpha'^2)}{\dot\phi}}$$

The correct answer in string theory is

$$|\beta|^2 = e^{\frac{-\pi\left(\vec{k}^2 + b_\perp^2/\alpha'^2 + n_{osc}\right)}{\Delta\eta/\alpha'}}$$

where again $\Delta\eta$ = relative rapidity

$$(\tanh\eta = v)$$

- Using 1st quantized saddle point methods, reproduce this precisely & can generalize to BH trajectories:

1st quantized worldline description of particle production:

We want $\dfrac{\langle out | a_{out}^2 | in \rangle}{\langle out | in \rangle}$

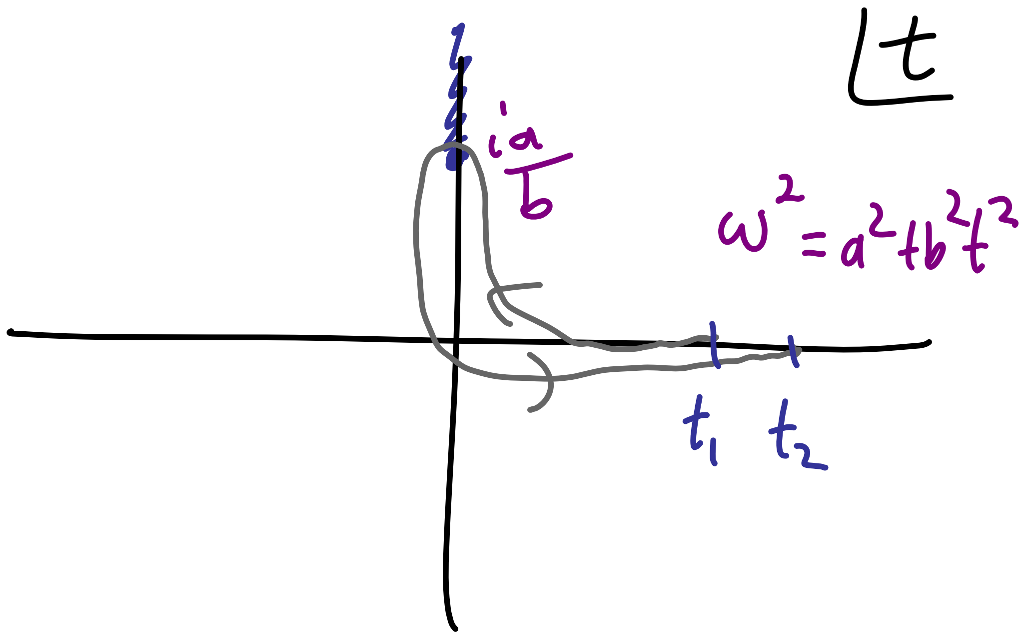
$$= \int_0^\infty dr \int Dt \Big|_{t_1}^{t_2} e^{\left\{-\frac{i}{2}\int_0^r dr' \left(\dot{t}^2 + m(t)^2 + \vec{k}^2\right)\right\}}$$

over an appropriate contour.

Constraint : $\dot{t}^2 = \omega^2(t) = m^2(t) + \vec{k}^2$

$\Rightarrow$ a contour that turns around at t_* must satisfy $\omega(t_*) = 0$

The appropriate contour is



$$S \to -\frac{b}{2}\left(t_1^2 + t_2^2\right) - \frac{a^2}{2b} \ln \frac{4b^2 t_1 t_2}{a^2} + i\frac{\pi a^2}{2b}$$

$$\Rightarrow \quad |\beta|^2 = e^{-\frac{\pi a^2}{b}}$$

(the standard answer)

Real-time estimates

$e^{-\frac{\omega^2}{\dot{\omega}}}$ estimates the level of non-adiabaticity

(minimal $\frac{\omega^2}{\dot{\omega}}$ at $|t| \sim \frac{a}{b}$ in above problem; more generally we can shut off $\dot{\omega}$ at some smaller $|t|$.)

WKB ok for large $N_{species}$

($\frac{\omega^2}{\dot{\omega}} \gg 1$ ok)

Generalization to String theory

w/ tension $\mu(t)^2 = a^2 + b^2 t^2$

Production of circular string:

$$S = \frac{1}{2}\int d\tau\, d\sigma\, \mu(t)\left(-\dot{t}^2 + t'^2 + \dot{X}^2 - X'^2\right)$$

$$= \pi \int d\tau\, \mu(t)\left(-\dot{t}^2 + \dot{x}^2 + \dot{r}^2 - r^2\right)$$

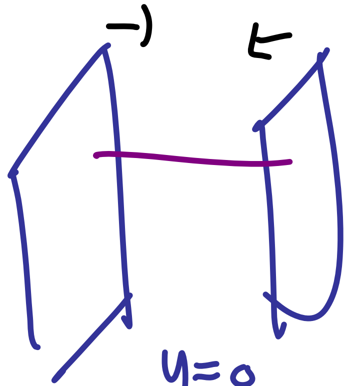
$\dot{r} \ll r$ frozen regime $\left(\frac{\dot{\mu}}{\mu} \gg \frac{\dot{r}}{r}\right)$

solve constraint →

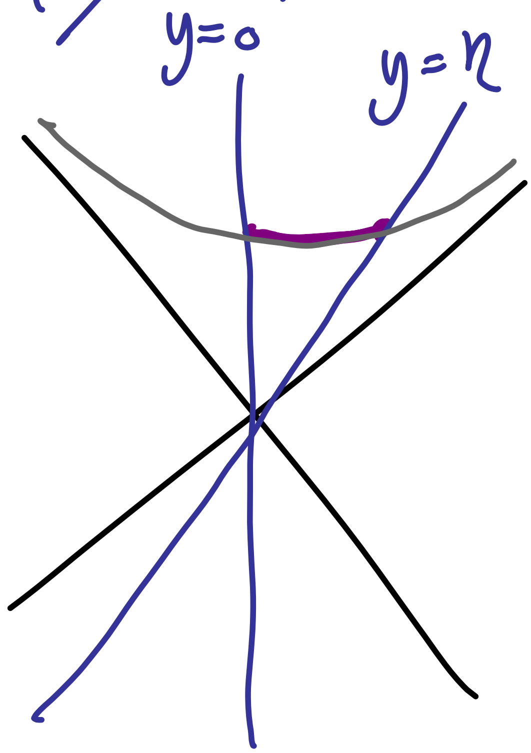
$$\langle N_k \rangle \sim e^{-\frac{\pi^2 r a^2}{b} + \frac{\vec{k}^2}{4br}}$$

agrees w/ Hamiltonian WKB treatment

Senatore, ES, Zaldarriaga



open string production



Milne coords

$$ds^2 = -dT^2 + T^2 dy^2$$

string symmetric embedding

$$T(\sigma,\tau) = T(\tau)$$

$$Y(\sigma,\tau) = \eta \frac{\sigma}{\pi}$$

saddle pt w/in this ansatz will be saddle pt

This gives action

$$S = \int \frac{dT}{\alpha'} \dot{T} = \int \frac{dT}{\alpha'} \sqrt{T^2 \eta^2 + b_\perp^2}$$

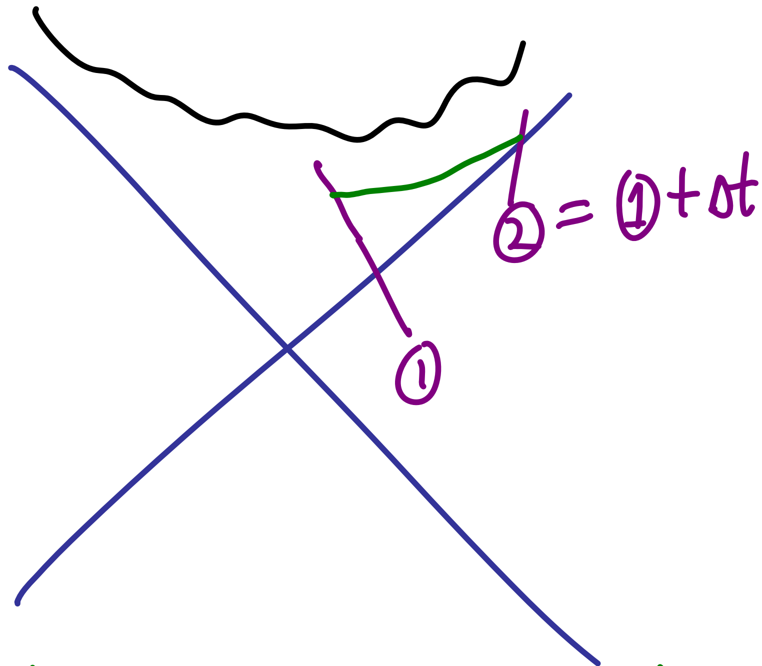
Same structure as before, giving

$$\mathrm{Im}\, S = \frac{\pi b_\perp^2}{2 \eta \alpha'}$$

rapidity, not velocity

(reproduces Bachas ✓)

BH



Again have symmetric embedding

$$t = t(\tau) + \Delta t \frac{\sigma}{\pi}, \quad r = r(\tau), \quad X_\perp = b_\perp \frac{\sigma}{\pi}$$

$$S = -\frac{1}{\alpha'} \int d\tau\, d\sigma \sqrt{-\det G_{MN}\, \partial_\alpha X^M \partial_\beta X^N}$$

$\underline{E < m}$: • full trajectories collided in past, exact saddle point →

$$\operatorname{Im} S = \frac{\pi b_\perp^2 R^2}{\alpha' r_0 \Delta t} = \frac{\pi b_\perp^2 R^2}{2 r_0^2 \eta}$$

BH

$E<m$: • finite time estimates

$$S = \int \frac{d\hat{\tau}}{\tau'} \underbrace{\sqrt{b_\perp^2 + \Delta t^2\left(\frac{E^2}{m^2} - 1 + \frac{r_0}{r}\right)}}_{\equiv \hat{\omega}}$$

$\hat{\tau}$ = proper time along ②

$$\frac{\hat{\omega}^2}{\frac{d\hat{\omega}}{d\hat{\tau}}}$$ combined with Hagedorn density leads to large effect for $E \ll m$

• $\frac{\omega^2}{\dot{\omega}}$ large in Painlevé time for $E \gg m$

- Adiabatic for BTZ & hyperbolic BH moduli space D-branes, and for dS static patch

- Future: additional stringy effects from
    - asymmetric trajectories Bachlechner/McAllister
    - Bremsstrahlung
    - higher dim'l brane production
    - spreading effects: ...

2) String spreading (Susskind)

Work in light-cone gauge in D dimensions (we can consider $D = D_{crit}$ or linear dilaton, $\Phi = V_\mu X^\mu$ with $V^2 = \frac{26-D}{6\alpha'}$

$$X^+ = p^+ \tau + x^+$$

Constraint:

$$\partial_\pm X^- \partial_\pm X^+ = V_\mu \partial_\pm^2 X^\mu + \frac{1}{2}(\partial_\pm X^i)^2$$

$$X^\mu = x^\mu + p^\mu \tau + i\sqrt{\frac{\alpha'}{2}} \sum \frac{\alpha_n}{n} e^{-in(\tau+\sigma)} + \cdots$$

solve for X^-.

$$\Rightarrow \alpha^-_n = \frac{L^\perp_n + V_i(-in)\alpha^i_n}{p^+ + inV_-}$$

where $L^+_n \sim \sum_{n'} \alpha^i_{n'} \alpha^i_{n-n'}$

$$\Rightarrow \left\langle (X^- - x^-)^2 \right\rangle = \left\langle \sum_{n,n'} \left[\frac{\alpha^-_n}{n}, \frac{\alpha^-_{n'}}{n'} \right] \right\rangle$$

$$= \left\langle \sum_{n,n'} \frac{\left(\overbrace{\left[\frac{L^\perp_n}{n}, \frac{L^\perp_{n'}}{n'} \right]}^{\dots + \frac{(D-2)}{12} n^3 \delta_{n+n'}} - V^2 nn' \overbrace{\left[\frac{\alpha^i_n}{n}, \frac{\alpha^i_{n'}}{n'} \right]}^{n\delta_{n+n'}/nn'} \right)}{(p^+ + inV_-)(p^+ + in'V_-)} \right\rangle$$

$$\Rightarrow \langle (\Delta X^-)^2 \rangle \sim \sum_n \frac{2n\,\delta_{n+n'}}{p^{+2} + n^2 V_-^2}$$

- e.g. for spatial (or 0) linear dilaton $(V_-=0)$ * we have a prediction

$$\langle \Delta X^{-2} \rangle \sim \frac{n_{max}^2}{p^{+2}}$$

(* otherwise, linear dilaton softens spreading)

where n_{max} is a cutoff on the mode sum, related to the lt cone time resolution of the detector.

Could model detector as generalized Unruh detector w/ D. Marolf ...

Let us take the detector d to be a string of mass m_d. Let us quantize it also in the l.c. gauge.

$$\tau_d = X^+ / p_d^+ = \tau \, p^+ / p_d^+$$

Its mode expansion is

$$X^\perp = i\sqrt{\frac{\alpha'}{2}} \sum_{n=0} \frac{\alpha^\perp_{n,d}}{n} e^{in(\tau_d + \cdots)} + \cdots$$

with some oscillator(s) turned on up to a level $N_d \sim M_d^2 \alpha'$.

n_d is intrinsic frequency of the detector string with respect to τ_d.

$$n_{max} \sim \frac{1}{\Delta \tau} \sim \frac{1}{\Delta \tau_d} \times \frac{p^+}{p_d^+}$$

$$n_{max} \sim n_d \frac{p^+}{p_d^+}$$

$$\boxed{n_{max} \sim (m_d^2 \alpha') \overbrace{\frac{p^+}{p_d^+}}^{e^{\Delta \eta}}}$$

The idea (Susskind '90s) is that the string is always infinitely spread, but usually nobody has resolution to see it. ☆ BH generates a large relative boost which endows late observer with fine resolution:

(If a string spreads in a forest ... ?)

Kinematics

- Comparing

$$\Delta U_t \Big|_{\text{trajectories}} \quad \alpha \quad \Delta U_t \Big|_{\substack{\text{long.}\\ \text{spreading}}}$$

gives effect ('drama') for

$$\frac{m_d^2 \alpha'}{2\sqrt{e}\, m_{string}\, r_0} \geq \frac{E_d}{m_d}$$

• Is the longitudinal spreading meaningful? Checking in S-matrix:

o) Transverse spreading manifest in Regge 4-pt functions

$$A \sim (-s)^{t\alpha' + \alpha(0)}$$

$\Leftrightarrow$ support out to $b_\perp \sim \sqrt{\alpha' \log s\alpha'}$

*) Longitudinal Spreading
(in progress)

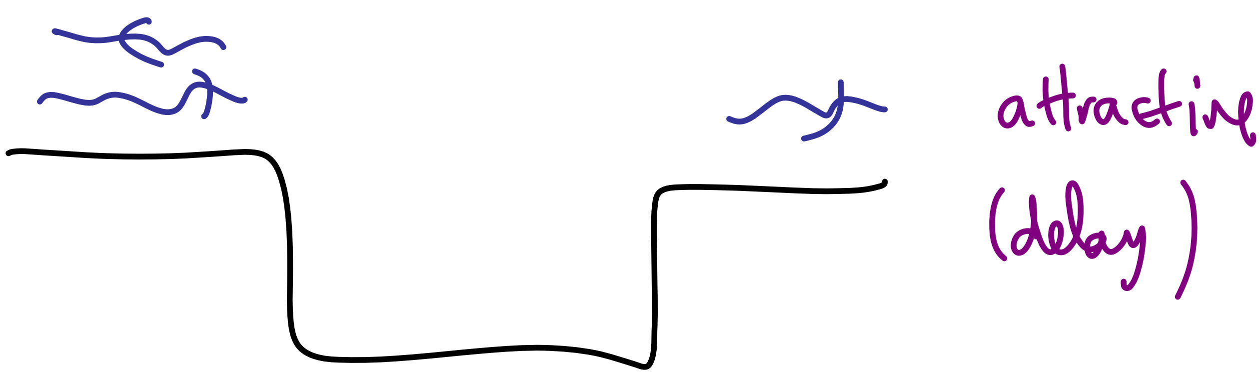
- Consider high-p_t amplitudes to track finite-time physics

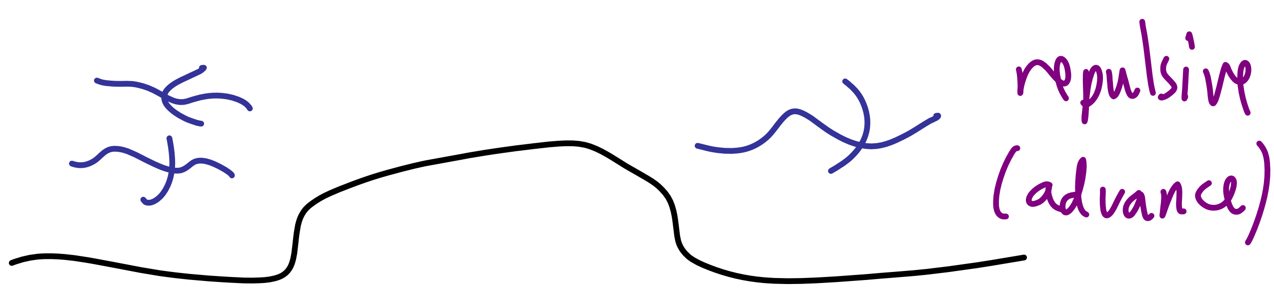
- Probe via time delay/advance, (S. Giddings)

interpreting geometrically & in terms of parameters

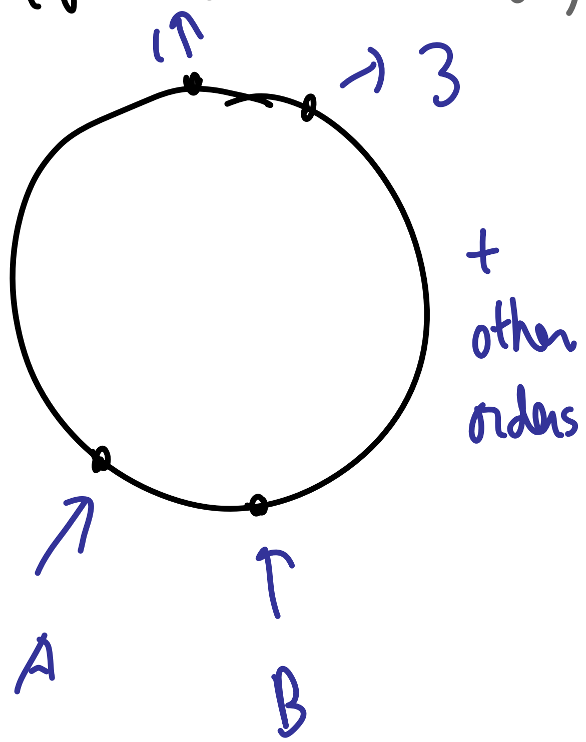
$\left(g_s,\ D,\ \frac{t}{s},\ \ldots\right)$

Roughly, scattering effectively extended objects could lead to Time delay or advance like in Q.M.

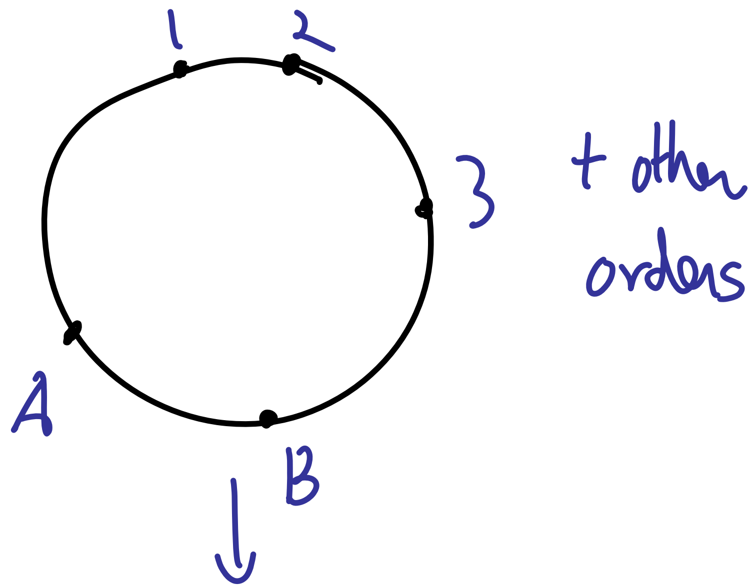




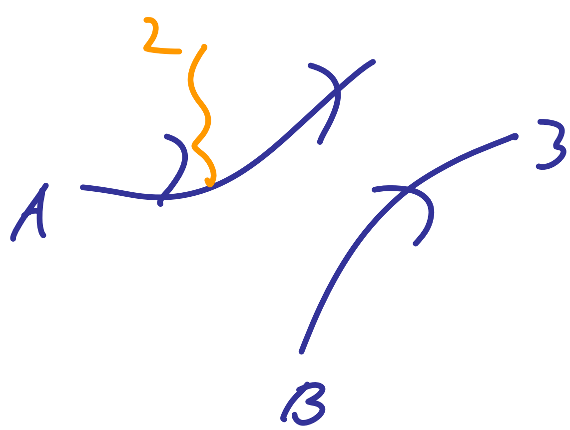
4pt (Veneziano)



5 pt {Bardaki-Ruegg, Bialis/Pokorski '69}



e.g. might expect Bremsstrahlung radiation



regardless of whether delay or advance at 4pt level

$$A_1 = \frac{\Gamma(-1-\alpha' s)\,\Gamma(-1-\alpha' t)}{\Gamma(-2-\alpha'(s+t))}$$

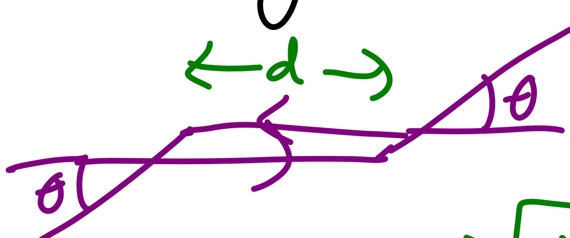
$$\sim \Gamma(-1-\alpha' t)\, e^{-i\pi t}\, (\alpha' s)^{1+\alpha' t}$$

Regge $\quad s \to \infty$

$\quad t \sim E^2\theta^2$ fixed

using Stirling's approx good for sufficiently large Im s

Convolving with wavepackets $\to$ time delay $\Delta T \sim E\theta^2$

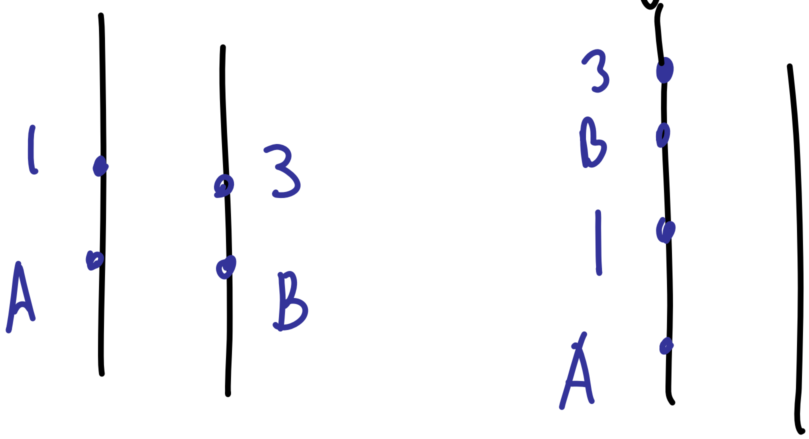


$$\Delta T \sim d(1-\cos\theta)$$

$$\sim E\theta^2\alpha'$$

$$\Rightarrow \boxed{d \sim E\alpha'} \sim \Delta X^-_{\text{Lenny}}$$

• Other orderings



etc.

give a variety of phases, some w/ advances & some delays

including some w/ larger phases ~ πs. still in progress...

Summary

from modest $E_{\text{Schwarzchild}}$

- BH generates large boost for late observer relative to early matter
- String theory has some boost-enhanced non-adiabatic and spreading effects which can generate some 'drama', catalyzed by the late observer
- We should be able to settle the status of longitudinal spreading, as part of determining brkdown of EFT in string theory