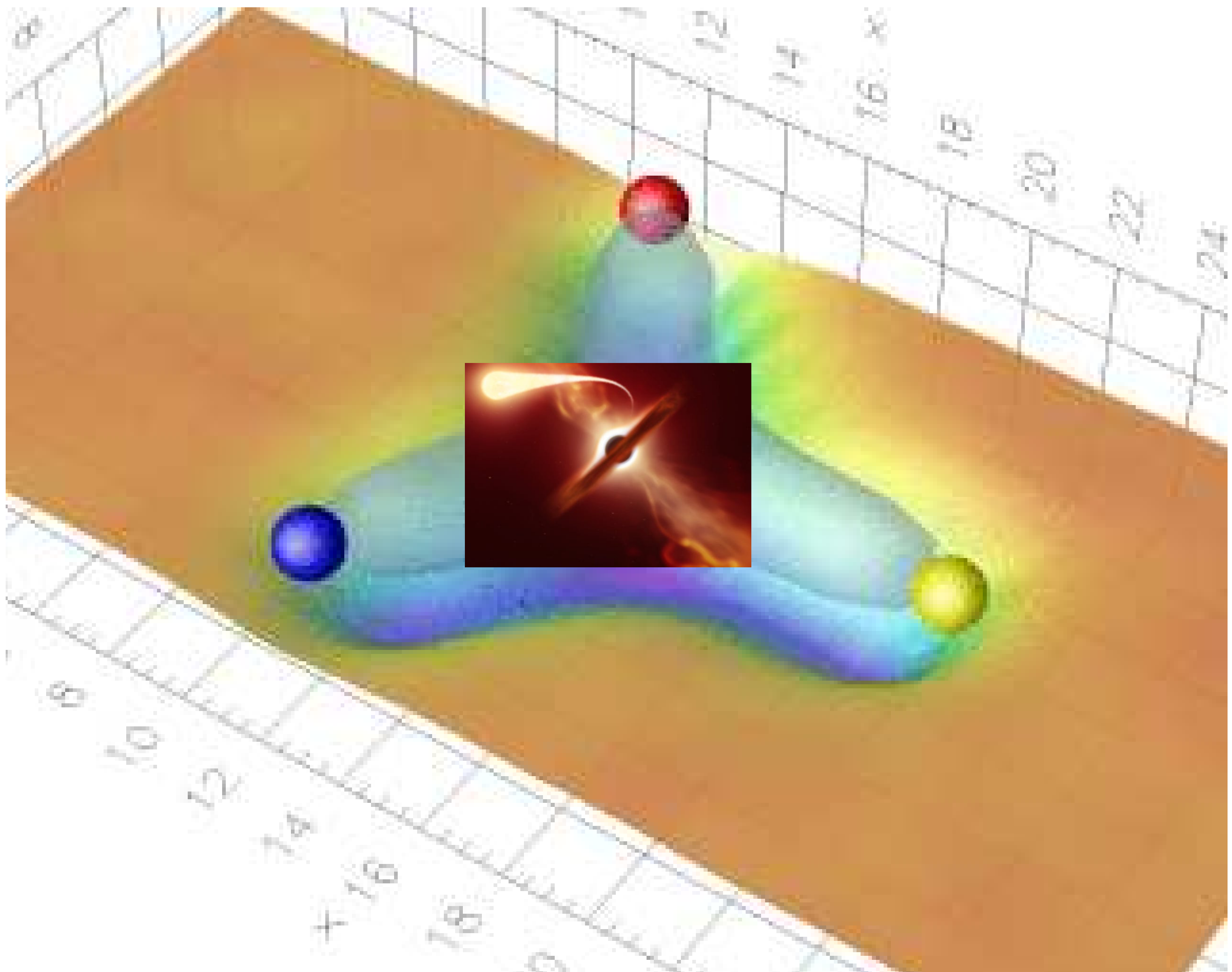
UV meets IR on the string worldsheet

Sergei Dubovsky
CCPP (NYU)



This talk is a mix of a review of well-known facts
and personal questions/confusions/hallucinations.
Apologies for the absence of refs.

Thank you to people who were thinking with me about these topics:

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Raphael Flauger
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Guzman Hernandez-Chifflet
Mehrdad Mirbabayi

Where do UV and IR meet each other?

✳UV Meets the IR: Effective Field Theory Bounds from QFT to String Theory

suggests the date happens in the IR: UV descends down to establish the commandments for the IR

✳Can it be another way around?

IR principles determine what happens in the UV

In QFT we are used to set the rules of the game (microscopic d.o.f.’s and their fundamental interactions) in the UV and work out the rest from there

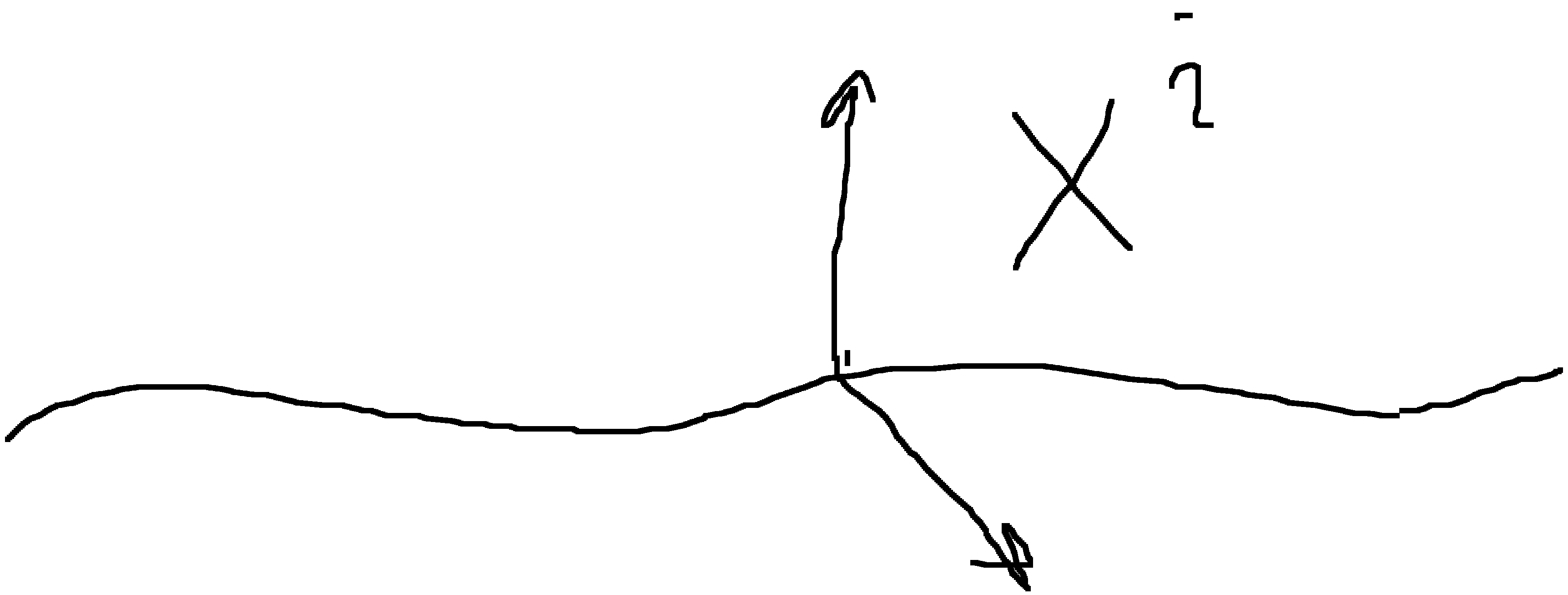
Gravity apparently changes this—we don’t need a Planck scale LHC to deduce what happens in transplanckian collisions—we know the answer: Black Holes form and evaporate

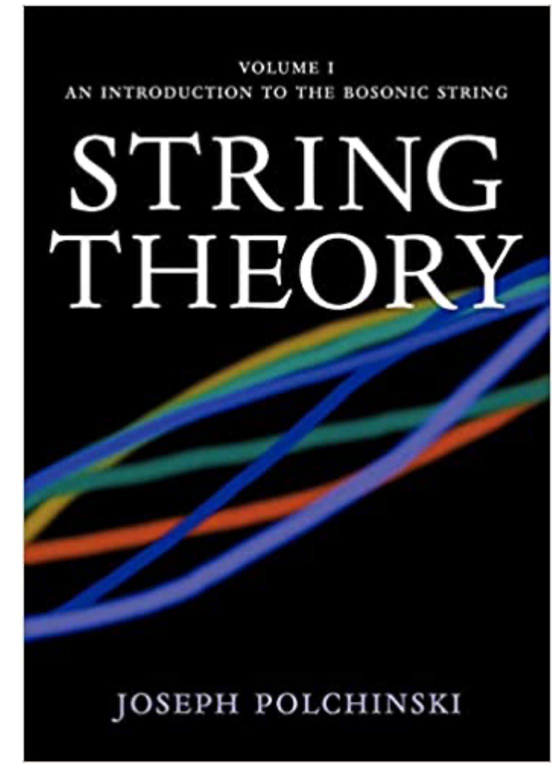
The very same process precludes one from defining local observables suggesting that the notion of subplanckian microscopic d.o.f. is moot

Remarkably, we are learning now that semiclassical gravitational path integral is smart enough to know that Hawking evaporation is a unitary process

The simplest toy system illustrating how starting from the IR one can deduce the rest:

A single long free critical (super)string





Classical Nambu-Goto action describes an integrable classical system with the time delay given by

$$\Delta t = \ell_s^2 E$$

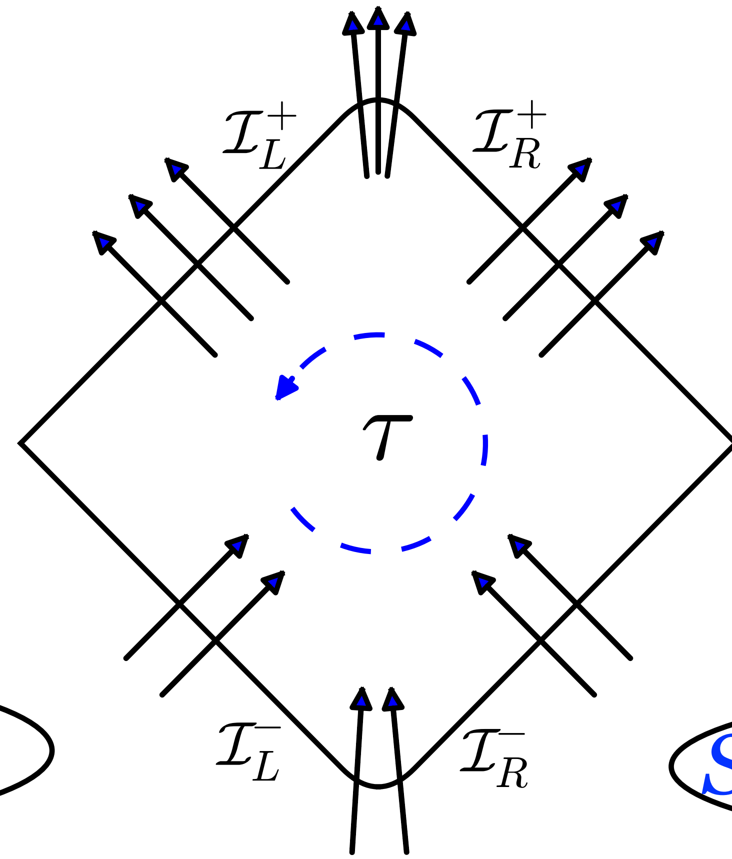
Enforcing this classical (~IR) geometrical principle as an exact quantum statement one would write a phase shift of the form

$$e^{2i\delta(s)} = e^{is\ell_s^2/4}$$

This is indeed the correct worldsheet S-matrix of a critical string

Describes (an integrable) model of 2d gravity with ℓ_s playing the role of the Planck length

Gravitational dressing of a general 2d QFT



"dressed" *S*-matrix

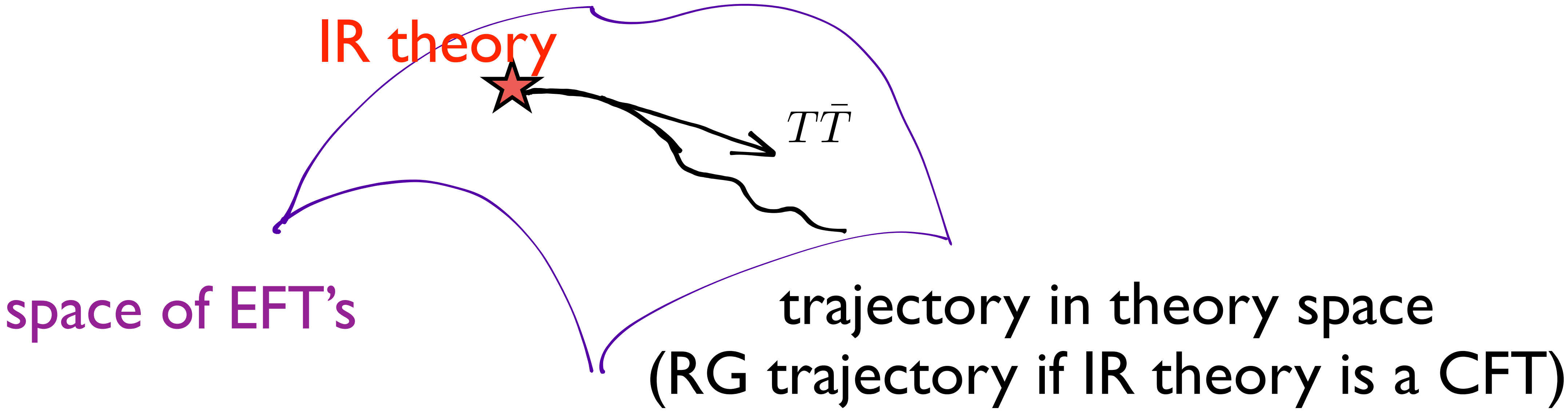
S-matrix of *any* 2D QFT

$$\hat{S}_n(p_i) = e^{i\ell^2/4 \sum_{i<j} p_i * p_j} S_n(p_i)$$

$$p_i * p_j = \epsilon_{\alpha\beta} p_i^\alpha p_j^\beta$$

Challenges the hierarchy problem

Gravitational dressing = $T\bar{T}$ deformation



$$T\bar{T} \equiv \frac{1}{2}\left(T_{\alpha\beta}T^{\alpha\beta} - T_{\alpha}^{\alpha 2}\right)$$

IR seed theory fully determines the UV

Gravitational dressing indeed describes a theory of gravity

$$Z_{JT} = \int \frac{\mathcal{D}e\mathcal{D}X}{V_{diff}} e^{-\frac{\Lambda}{2}\int \epsilon^{\alpha\beta}\epsilon_{ab}(\partial_\alpha X^a - e^a_\alpha)(\partial_\beta X^b - e^b_\beta))} Z_0(g_{\alpha\beta})$$

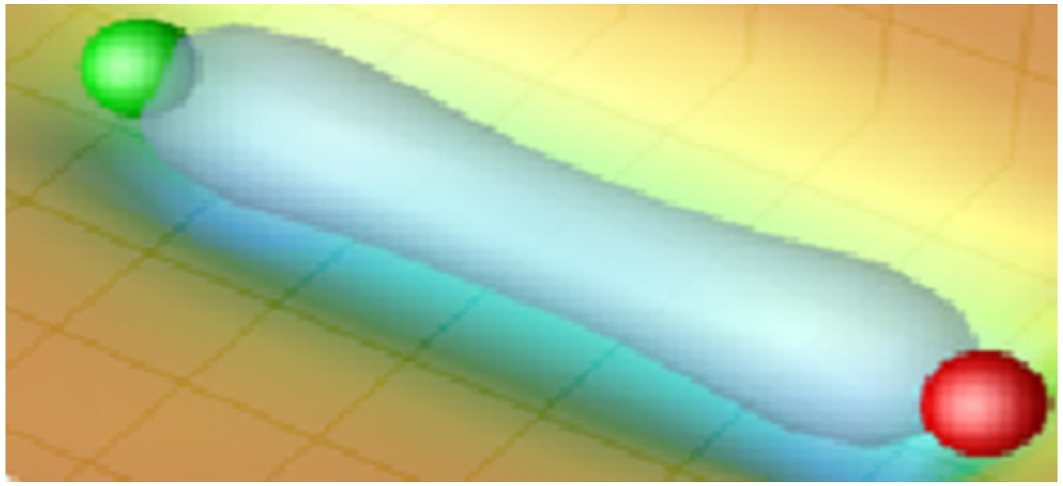
The role of gravity here is to introduce dynamical "clocks and rods" X's (aka relational observables; also very similar to target space coordinates for a string)

No "new physics"/d.o.f.'s in the UV. Gravitational scattering comes about from stretching of the space-time as a result of using these dynamical clocks and rods.

As a curiosity, positive Λ theory provides an example of a UV completion of the "wrong sign" superluminal theories

Are there other theories with similar UV behavior hopefully, with more rich dynamics ?

Yes, there is a large class of physically interesting and poorly understood theories. All what one needs to do is to replace a critical string with a confining one.

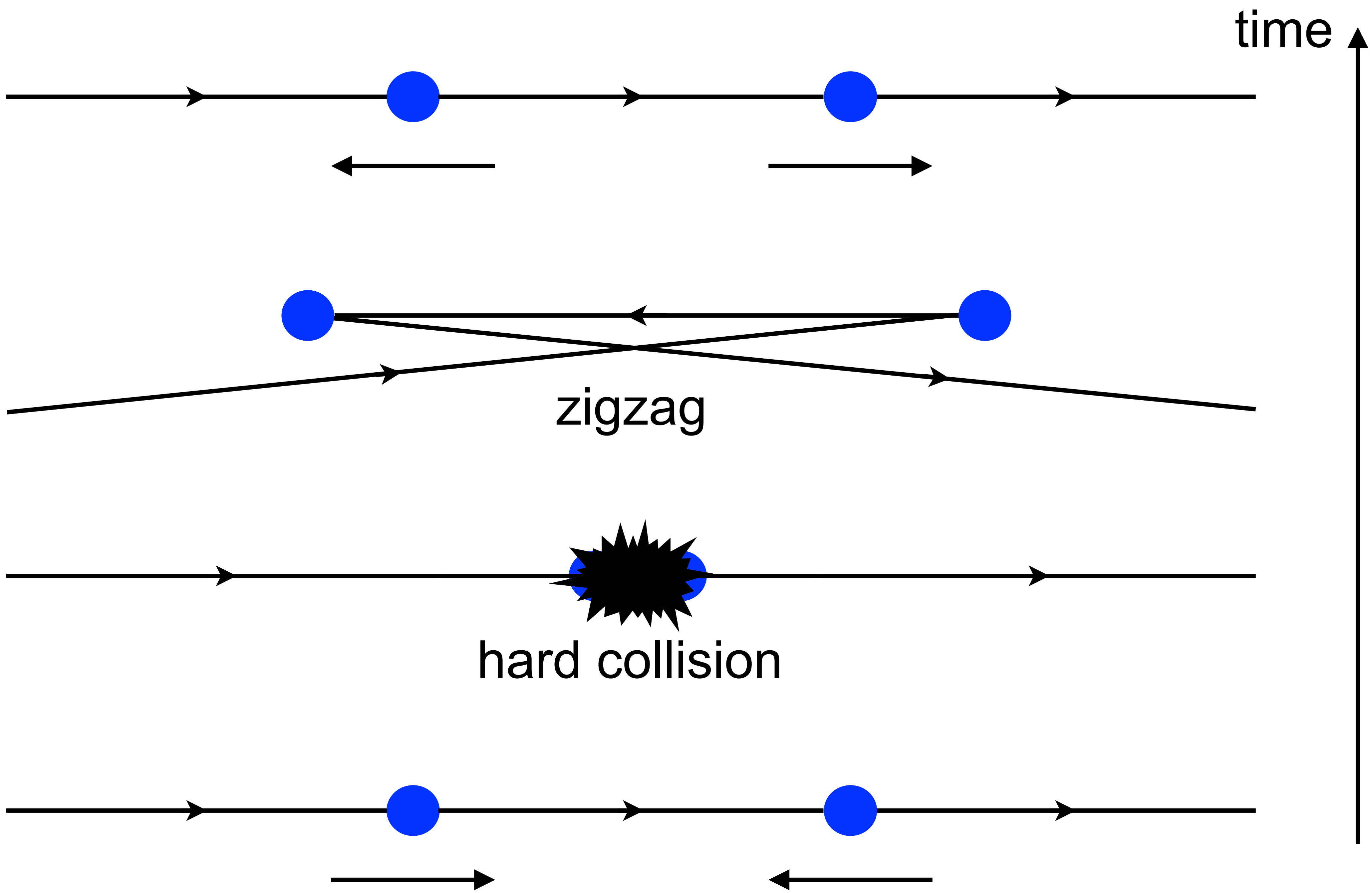


Consider confining QCD-like theories with adjoint matter (pure glue is the primary example), and take the planar 't Hooft limit.

Low-energy dynamics is still described by Nambu-Goto, but the full theory is in general non-integrable.

At first sight high-energy dynamics is completely disconnected from what happens in the IR now. The relevant degrees of freedom should be QCD partons.

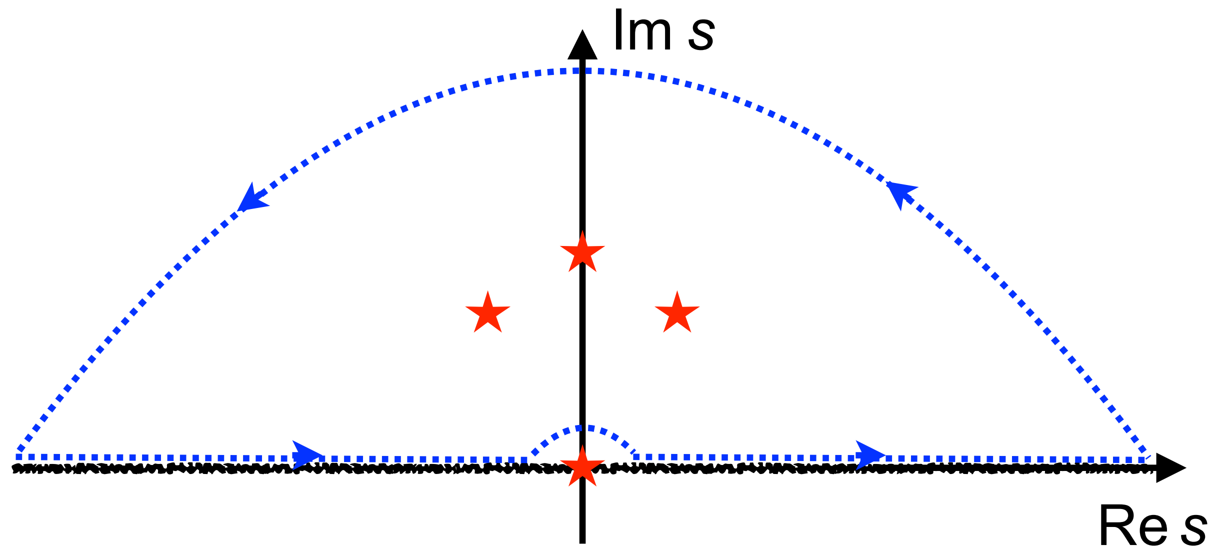
A Cartoon of High-Energy Worldsheet Scattering



Asymptotic Freedom+Confinement=UV Integrability

- Ultimate UV asymptotics is again dominated by semiclassical stretching of space-time (worldsheet)
- Interestingly, zigzag produces the same time delay as the low energy Nambu-Goto calculation
- However, the actual story appears to be more involved

Let's consider D=3 pure glue giving rise to a theory of a single Goldstone boson on the worldsheet



Dispersion relation for the 2->2 S-matrix

$$\oint ds \frac{S_2'(s)}{s S_2(s)} = 2\pi i \sum_{zeros} \frac{1}{s} \ .$$

Assuming

$$S_2(s \to 0) \approx 1 + i\ell_{IR}^2 s/4 + \ldots$$

$$S_2(s \to \infty) \sim e^{i\ell_{UV}^2 s/4}$$

one arrives at

$$\ell_{IR}^2 - \ell_{UV}^2 = -\frac{4}{\pi}\int_0^\infty \frac{\log|S_2|^2}{s^2} + 8i\sum_{zeros}\frac{1}{s} \geq 0$$

particle production worldsheet resonances

Naively, in conflict with the geometrical picture:
UV time delay is not determined just by the IR tension

$$\ell_{IR}^2 - \ell_{UV}^2 = -\frac{4}{\pi}\int_0^\infty \frac{\log|S_2|^2}{s^2} + 8i\sum_{zeros}\frac{1}{s} \geq 0$$

particle production worldsheet resonances

- ✳In the absence of particle production excludes resonances. Indeed, $e^{\ell_s^2 s/4}$ is the only integrable phase shift compatible with target space Poincare symmetry.

- ✳May be compatible with the presence of particle production, if the latter is an extensive long time process (~Unruh type radiation). Although I'm confused whether 2->2 S-matrix is the right object to look at then.

- ✳Suggests the absence of resonances, in agreement with lattice data for D=3 pure glue. Puzzling more generally.

- ✳Feels one may learn more from this dispersion relation.

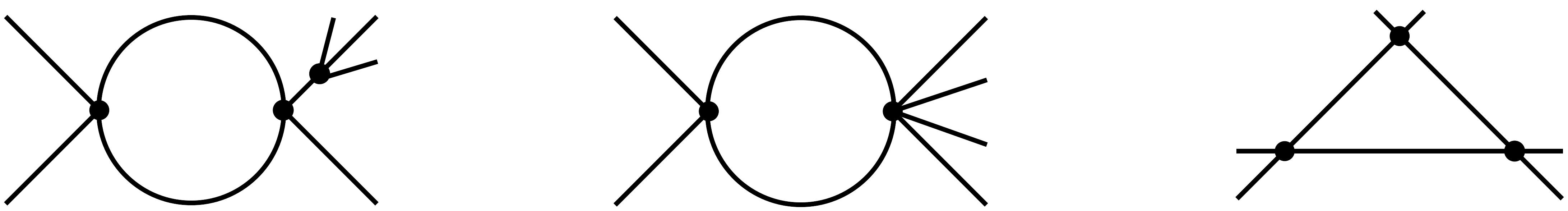
At D=4 we encounter a very puzzling instance of the UV/IR meeting

Two calculations in D=4 pure glue

UV: Leading log violation of scale invariance

$$\beta(\alpha_s) = -\frac{22}{24\pi} C_A \alpha_s^2$$

IR: Leading particle production on the worldsheet



Polchinski—Strominger generating functional for all one-loop amplitudes:

$$S_{PS} = -\frac{26-D}{48\pi}\int \partial_+\phi\partial_-\phi$$

$$\phi = -\frac{1}{2}\log\left(2 - \partial_+X^i\partial_-X^i + \frac{1}{8}(\partial_+X^i)^2(\partial_-X^i)^2\right)$$

$$26 - 4 = 22$$

Zeroth order sanity check: In the presence of adjoint (s)quarks

$$\beta(\alpha_s) = -\frac{22 - n_{sc} - 4n_f}{24\pi} C_A \alpha_s^2$$

matches the shift of the PS coefficient calculated neglecting the (s)quark masses

The project of the explanation is that the leading particle production is the factorized long time process (~zigzag Unruh radiation/~gluon splitting)

Suggests the positivity bound on the PS coefficient

Instead of conclusions: