S-matrix `data' & Horizon Drama

with M. Dodelson (2 papers to appear)

+ discussions with S. Giddings

'14 (D-branes) E.S.

I. Intro
- Black Hole as accelerator
- string spreading   Susskind '94, Brower Polchinski Strassler Tan '06

II. Longitudinal Nonlocality in tree-level string amplitudes

III. Breakdown of EFT in Black Holes

Black Holes: conflict between EFT and Quantum Mechanics

... Hawking ... Mathur ... AMPS ...

↓

single observer can see the conflict

→ Check level of violations of EFT in string theory, with

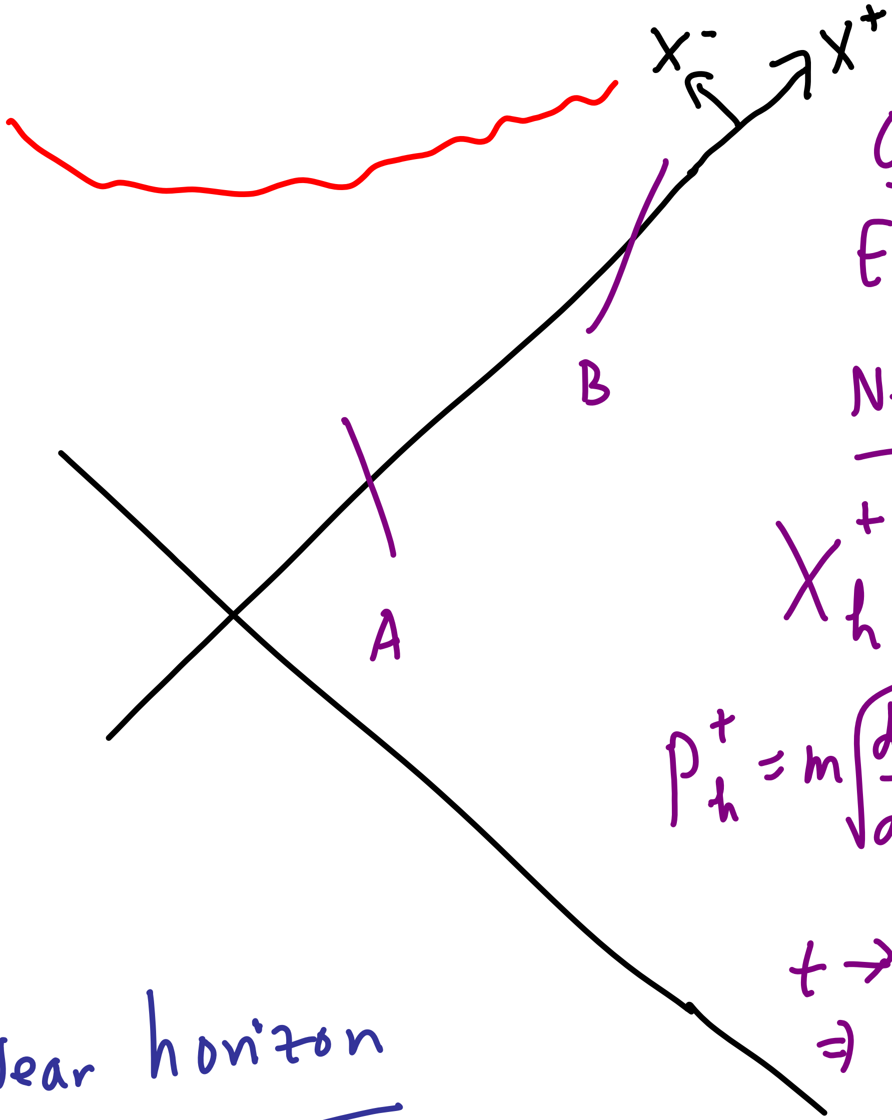
late infaller (+ early matter)

detector, e.g. string

string

*Despite $\alpha' R<<1$, these
early & late trajectories have huge
relative boost, i.e. huge C.M. energy
in the near-horizon (Rindler) region

$$ds^2 = -\frac{2r_s}{r} e^{1-\frac{r}{r_s}} dX^+ dX^- + r^2 d\Omega^2$$



Outside :

E, m fixed

Near Horizon :

$$X^+_h = 2r_s\sqrt{e}\,\frac{E}{m}\,e^{\eta}$$

$$p^+_h = m\sqrt{\frac{dX^+}{dX^-}}\Bigg|_h = m e^{\eta}$$

$$t \to t + \Delta t$$

$$\Rightarrow \eta \to \eta + \frac{\Delta t}{2r_s}$$

Near horizon

- $S \sim 2p^+_{B,h}\, p^-_{A,h} \sim e^{\frac{\Delta t}{2r_s}} m^2$
- $X^+_B - X^+_A \propto p^+_B \propto e^{\frac{\Delta t}{2r_0}}$

Near horizon: huge Energy, but separated along X^+.

String Spreading

- Susskind '94
- Brown Polchinski Strassler Tan '06

Light Cone gauge $X^- \sim p^- \tau$,

Constraint determines X^+ in terms of $X^\perp$

$$\langle\psi|\left(X_\perp - x_\perp\right)^2|\psi\rangle = \sum_n^{n_{max}} \frac{1}{n} = \log\frac{n_{max}}{n_0} + \mathcal{O}\left(\frac{1}{n_{max}}\right)$$

$$\langle\psi|\left(X^+ - x^+\right)^2|\psi\rangle \cong \frac{1}{(p^-)^2}\sum^{n_{max}} n \cong \frac{n_{max}^2}{(p^-)^2}$$

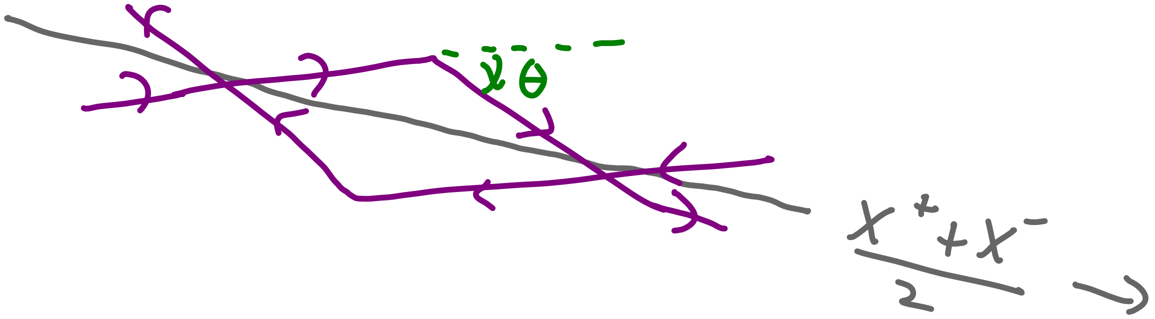
$n_{max} \leftrightarrow$ light cone time resolution :

- Apparent asymmetry between $X_\perp$ and $X^\pm$ directions?

No: the RMS longitudinal spreading is detectable for

$X^\pm \approx$ direction of relative motion

More precisely: Brick Wall frame



respects time-reversal symmetry

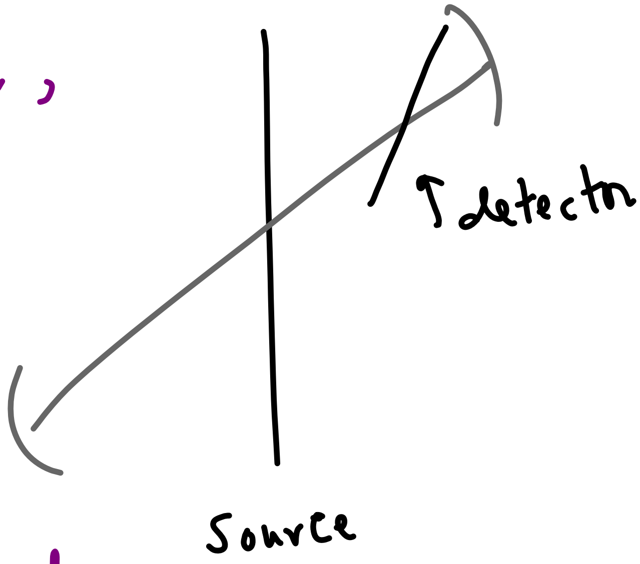
Light cone time resolution:

$$\Delta X^- \sim \frac{1}{P^+_{\text{detector}}} \qquad \eta_{max} \sim \frac{g'}{\Delta\tau} \qquad \tau \sim \frac{X^-}{P_s^-}$$

$$\Rightarrow \eta_{max} \sim P_s^- P_d^+$$

$$\left(\text{for } t \sim -k_\perp^2 \sim O\left(\frac{1}{g'}\right) \right)$$

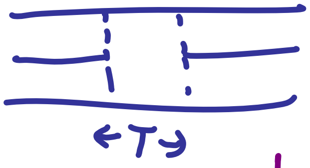
More generally,



Measurement degrades as ↑ $P_\perp$: conservatively

$$\Delta X^- \sim \frac{P_\perp^2 + m^2}{P^+_{\text{det}}}, \qquad \eta_{max} \sim \frac{P_s^- P_d^+}{P_\perp^2 + m^2}$$

☆ This physical idea is confirmed explicitly in BPST '06 calculation of 4-point Regge amplitude in light-cone gauge.



in brick wall frame: $p_{\perp r} \sim \frac{k_\perp}{2}$, $m \simeq 0$

$$\underbrace{\sum_{n=1}^{\infty} \frac{1}{n + \frac{n^2 T}{2\alpha' p_s^-}}}_{\text{Appears in BPST Calculation}} \underset{\substack{\uparrow \\ \text{on the nose}}}{=} \sum_{n=1}^{n_{max}} \frac{1}{n} = \log \frac{n_{max}}{n_0} + \mathcal{O}\left(\frac{1}{n_{max}}\right)$$

with $T \sim \frac{k_\perp^2}{p_d^+ + p_s^+} \simeq \frac{k_\perp^2}{p_d^+}$

Let us take as given the transverse spreading

$$\Delta X_\perp \sim \sqrt{\alpha'} \log n_{max}$$

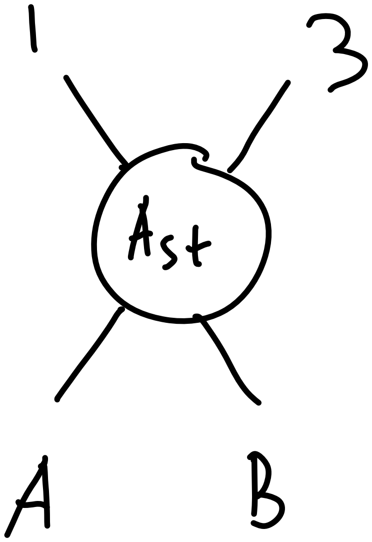
$$\sim \sqrt{\alpha'} \log S\alpha'$$

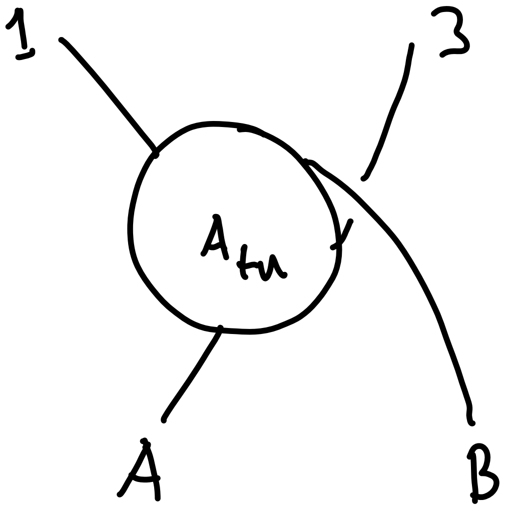
- Can be seen from impact parameter transform in forward scattering
- well-established in BPST

Given that, we find features of tree-level string amplitudes that require longitudinal nonlocality to explain.

4pt)

Veneziano

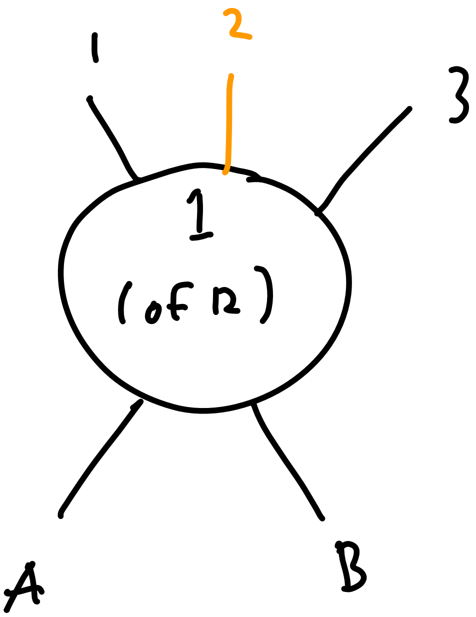


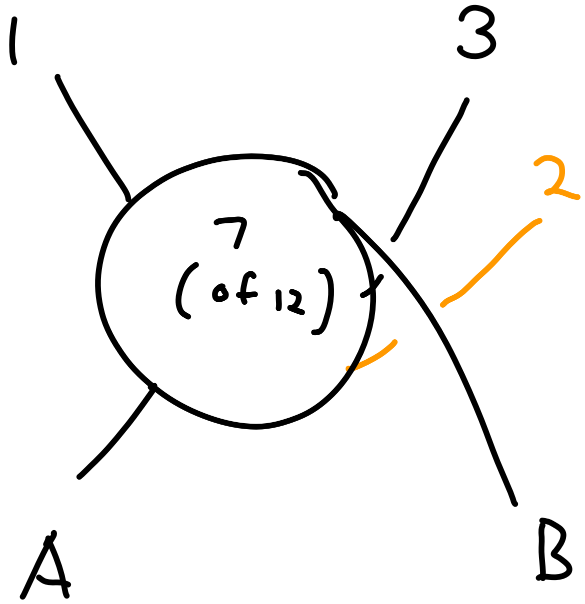


5pt)

Bardakci - Ruegg

Bialas - Pokorski

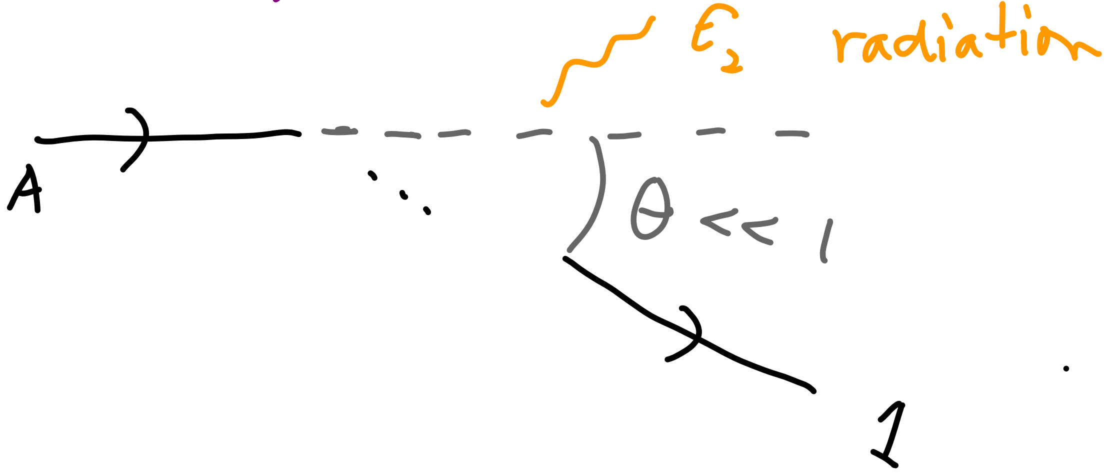




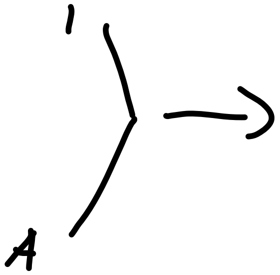
S-matrix 'data' analysis

- Work in Regge or double Regge

$$E\theta_1, E_2 << E$$

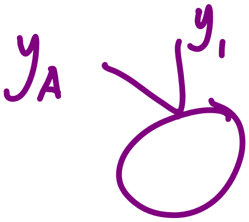


(0) Reproduce standard 'Reggeon' description



→ Reggeon carrying $k_\perp$ momentum transfer

from



$y_A \to y_1$ in amplitude

(1) Keep track of phases in amplitudes

$$A \sim e^{i\delta(k_I \cdot k_J)}\, \hat{A}_{slow}$$

in tractable regime, and

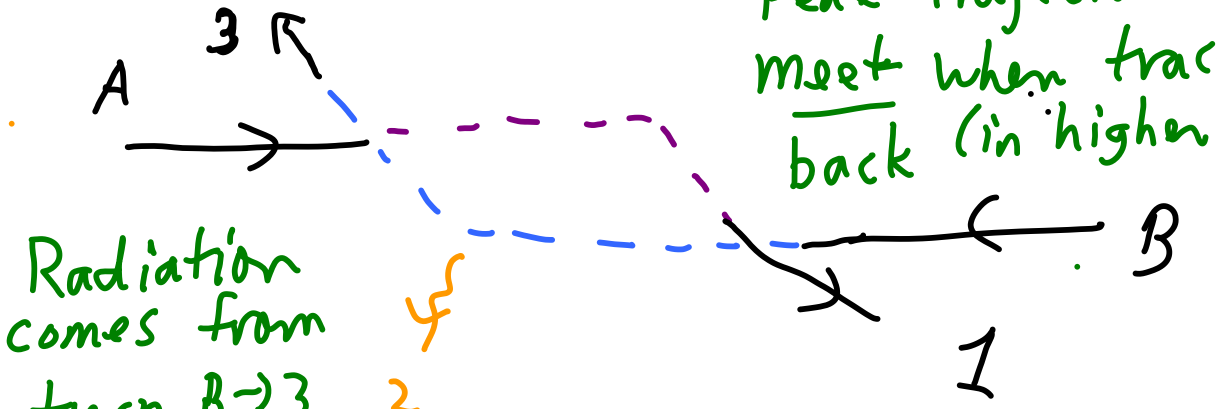
(2) convolve with wavepackets to determine peak trajectories

$\cup$

peak impact parameter b_{AB}

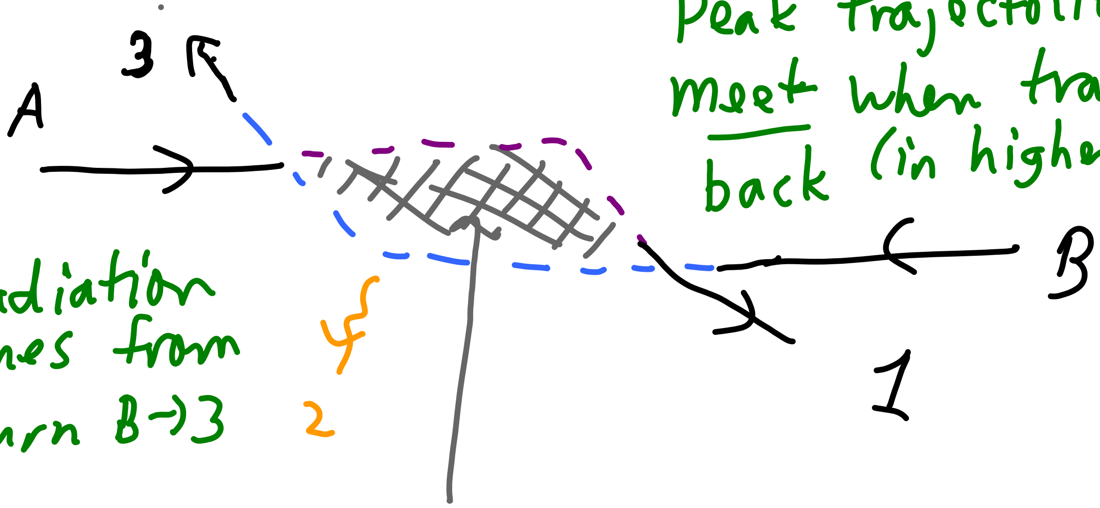
time delays/advances $T_{1,2,3}$

☆ fit nontrivially with $A \to 1$, $B \to 3$, including expected Bremsstrahlung



Peak trajectories meet when traced back (in higher D)

Radiation comes from turn B→3



Peak trajectories meet when traced back (in higher D)

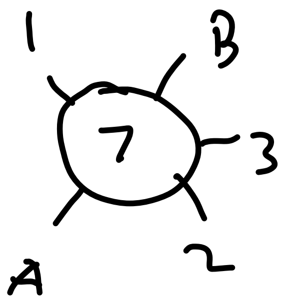
Radiation comes from turn B→3

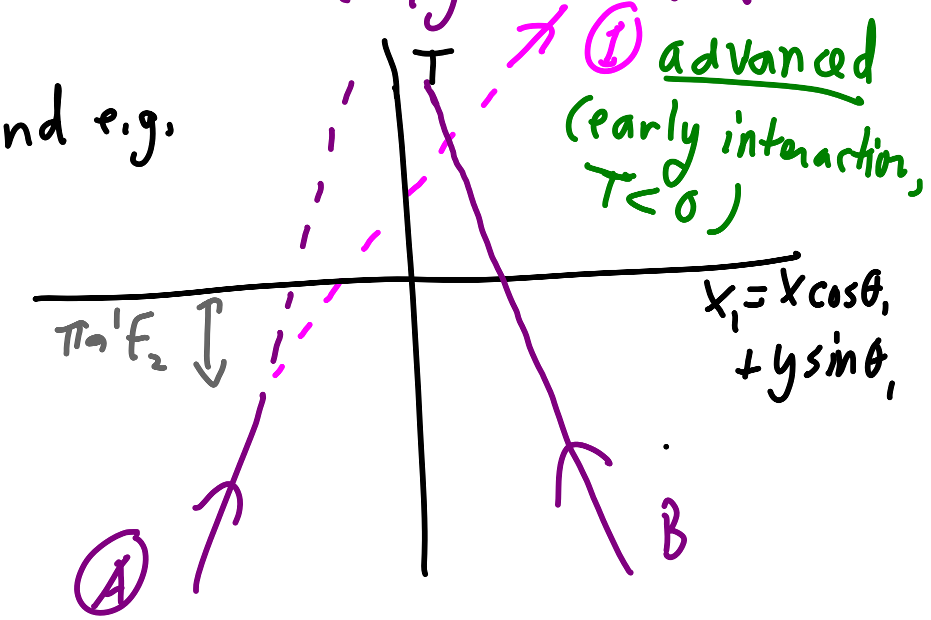
(3) Explicit & simple string solutions for intermediate s-channel states ↔ imag. parts

✡ quantitative agreement with peak b & T

(4) use causality and limited ⊥ spreading to isolate longitudinal effects

find e.g.





advanced (early interaction, $T<0$)

2 Main examples: 4point:

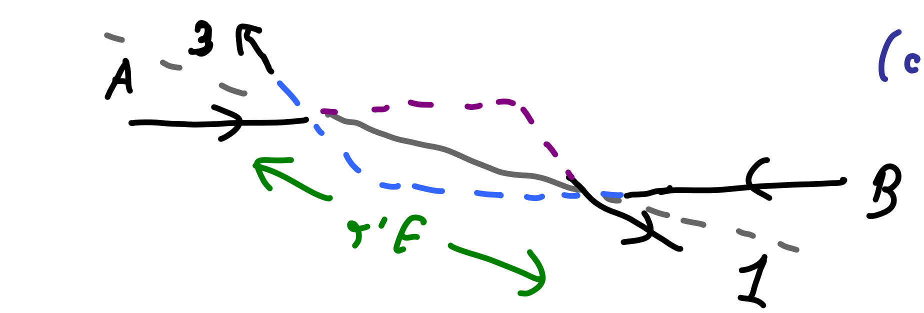
$$\sim g_0^2\,\Gamma(-1-\alpha' t)(\alpha' s)^{1+\alpha' t}\,e^{-i\pi t}+\cdots$$

← phase

→ Peak trajectories

- $b_{AB} = -2\pi\alpha' E\sin\theta_1$ $\neq 0$!

$$T_1 = 2\pi\alpha' E(1-\cos\theta_1) \underbrace{\simeq \pi E\theta_1^2\alpha'}_{\text{time delay (cf attractive potential)}}$$



- $b_{AB} \neq 0$ fits with longitudinal joining

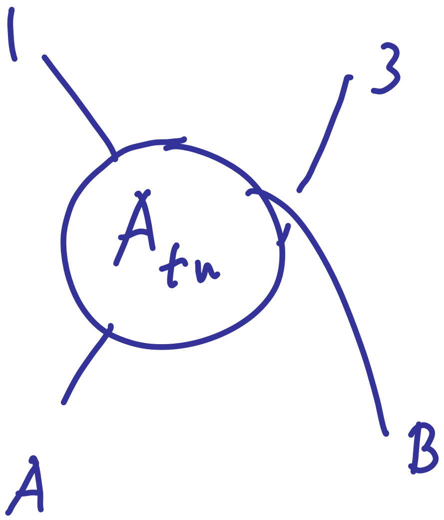
$$\rho(X^+) \sim e^{-\frac{X^{+2}}{E^2\alpha'^2}} \sim e^{-1}$$

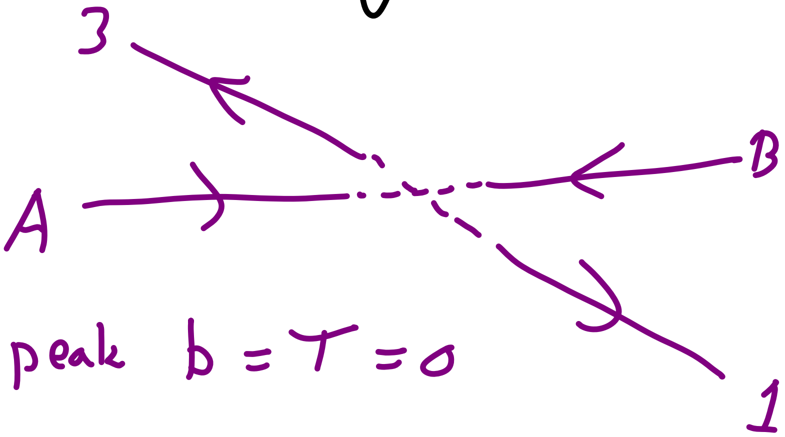
does not fit with ⊥ spreading-induced interaction: $\rho(X_\perp) \propto \mathrm{Exp}\left(-\frac{X_\perp^2}{\log s\alpha'}\right)$

would prefer $b=0$

- Intermediate string (yo yo) never fully $\perp_{(\text{kinks})}$

One of the 4 pt diagrams has zero time delay/advance





peak $b = T = 0$

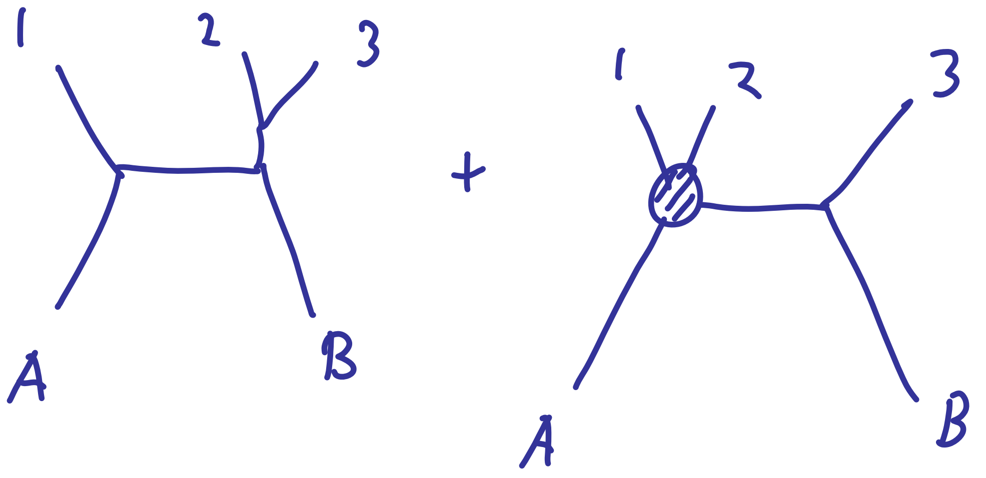
In this one, when we upgrade to 5 points we find time advance.

$$A_7 = \frac{g_0^2}{g'} \Gamma(1+K_{A1})\Gamma(1+K_{B3})\, e^{i\pi(K_{B3}-K_{A1})} \, |K_{23}|^{K_{A1}-K_{B3}}$$

$$\times K_{A3}^{-1-K_{A1}} \times U(1+K_{A1}, 1+K_{A1}-K_{B3}, K-i\varepsilon)$$

$$K_{IJ} \equiv 2g' k_I \cdot k_J \qquad K = \frac{K_{23}K_{A2}}{K_{A3}}$$

$A_7 \simeq$



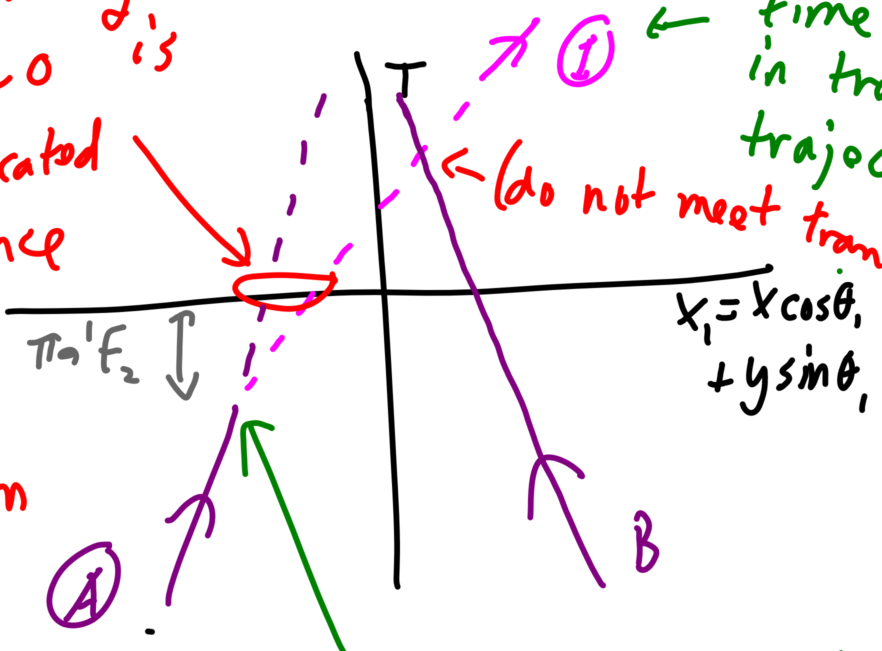
double Regge

In a concrete regime with $A_7 \simeq e^{i\pi(k_{B3}-k_{A1})}\hat{A}_{slow}$, peak trajectories, traced back, meet nontrivially such that

A → 1 <u>early</u> (before putative c.m. collision at $T=0$)

B → 3 late

as expected from standard Reggeon picture, and confirmed also by Bremsstrahlung e.g. projected to 1+1 dimensions



again purely transverse effect at $T \geq 0$ is contraindicated by absence of Gaussian suppression factor.

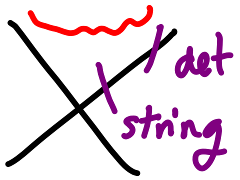
time advance in traced-back trajectory

(do not meet transversely)

meet in ∀ directions, early

In general, simple interpretation of amplitudes (tracing $A \to 1$, $B \to 3$ with explicit s-channel string creation) fits facts nontrivially, but requires longitudinal spreading given $\rho(x_\perp)$.

Horizon physics



- In Schwarzschild BH, find (including decays/secondary probes)

$$\Delta X^+ \sim p^+_{\text{detector}} \alpha' \Rightarrow \text{detectable}$$

spreading for $m_{det} > \frac{r_s}{\alpha'} \frac{E_{det}}{m}$

→ breakdown of EFT for late infalling detector given

$$m_{det} > \frac{r_s}{\alpha'} \qquad (m \sim E_s)$$

$$m_{det} > \frac{r_s^{\frac{1}{2}}}{\alpha'^{\frac{3}{4}}}$$

(dropped from R s.t. $\sqrt{\alpha'} \ll R - r_s \ll r_s$)

Remarks

- ✩ despite $R_g' \ll 1$, BH accelerates trajectories to generate large near-horizon relative boost
(Not simply Minkowski/Rindler dynamics)

- **Causal** (source string always spread, detector develops the required ΔX^- resolution via BH trajectories) but **nonlocal**

- Catalyzed by pair of probes (early matter + late infaller), not intrinsic to horizon alone.
cf observer-dependent horizons.

- relative boost sets in <u>outside</u> horizon; neither strict 'firewall' AMPS nor low-energy 'non violent nonlocality' Giddings but has elements of each.

  Also timescale $\Delta t \underset{\sim}{\gg} 2r_s$ short compared to Page time

- Observational tests ??

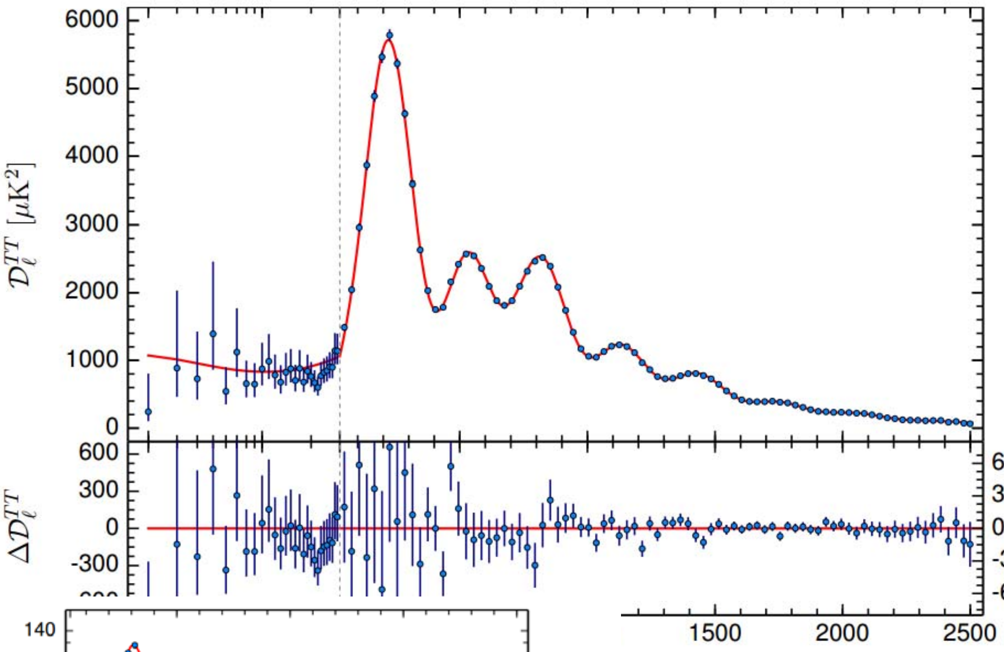
  - EHT imaging Kerr BH horizons (if control astro effects)
  - large m_{det} so far (for Schwarzschild)

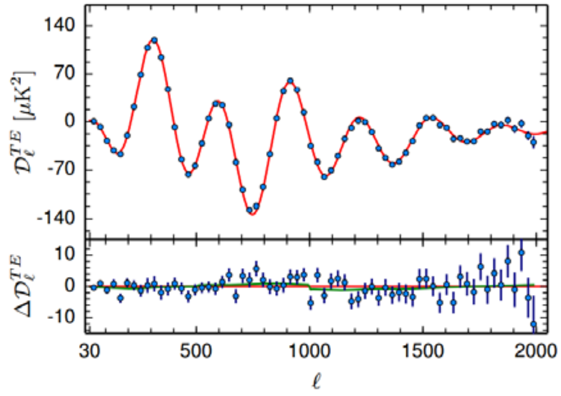
In general seems eminently reasonable (and conservative!) that string theory contains required dynamics

Cosmological Horizons?

observer-dependent
...

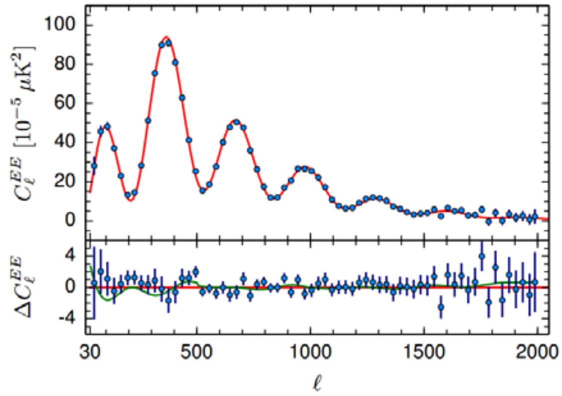
Planck Collaboration: Cosmological parameters





) we show the maximum likelihood frequency averaged
d with foreground and other nuisance parameters deter-
ıltipole range $2 \le \ell \le 29$, we plot the power spectrum
ɔver 94% of the sky. The best-fit base ΛCDM theoretical
anel. Residuals with respect to this model are shown in

Small perturbations from ΛCDM allowed (tensors, features/oscillations, non-Gaussianity), but wildly dramatic effects highly constrained



Cosmological horizons

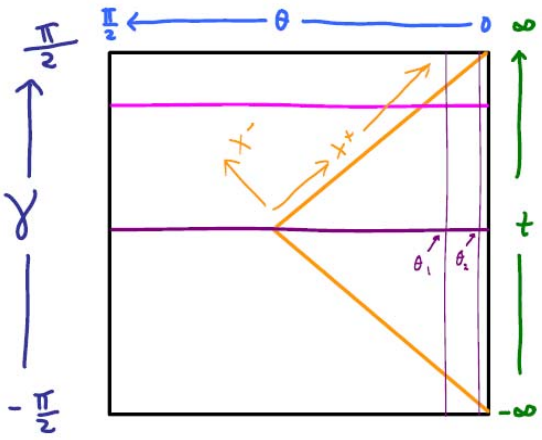


Figure 6: Trajectories 1 and 2 in the late de Sitter universe, as described in the text. For small values of the global spatial coordinate θ, the trajectories fall across the indicated observer horizon at a late global time, so that the spatial slices are nearly flat as in our observed universe. Within that regime, the hierarchy $\frac{\theta_2}{\theta_1} \ll 1$ leads to a large relative boost at the horizon, generated by the cosmological background.

- Late universe :
  - Δt of order L_{dS}
  - m_{det} huge

  $\Rightarrow$ not ruled out ✓

- Early U : $\forall$ data consistent with vacuum initial conditions during inflation

  $\Rightarrow$ no strings + detectors involved ✓

Future directions

- Other regimes of string and QG effects, e.g. single-Regge, 6-pt, ...
- background fields (linear dilaton, tachyon wall, AdS, electromagnetic flds, etc.) may further help tease out/test the longitudinal nonlocality
- Kerr BH : mass constraint on m_{det}?
- Implications for AMPS etc.
  - sensible dynamics for late 'drama'
  - Much less radical than violating Q.M.