Black holes, high-energy scattering, and locality

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Based on:

hep-th/0604072;
hep-th/0703116;
arXiv:0705.1816, w/ Gross and Maharana;
arXiv:0705.2197; arXiv:0711:0757
arXiv:0711.5012, w/ Srednicki
WIP w/ M. Gary; D. Marolf; D. Trancanelli, J. Penedones

Any theory of quantum gravity must confront:

- The problem of high-energy scattering
- The mysteries of black holes

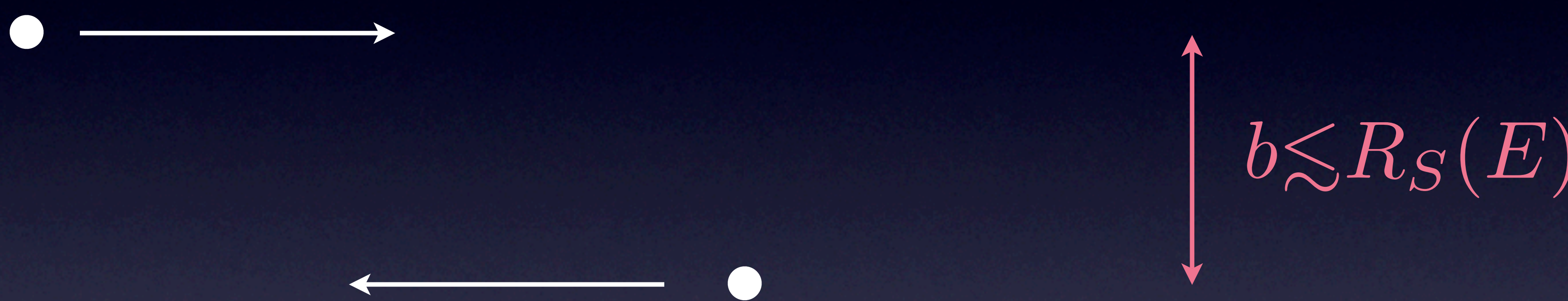
(These nonperturbative questions also related to those of cosmology)

These come into particularly sharp focus through the information paradox

My current viewpoint: this could play a key guiding role, analogous for example to the instability paradox in the classical model of the atom

Quick refresher (scattering formulation):

Consider an ultraplanckian collision:

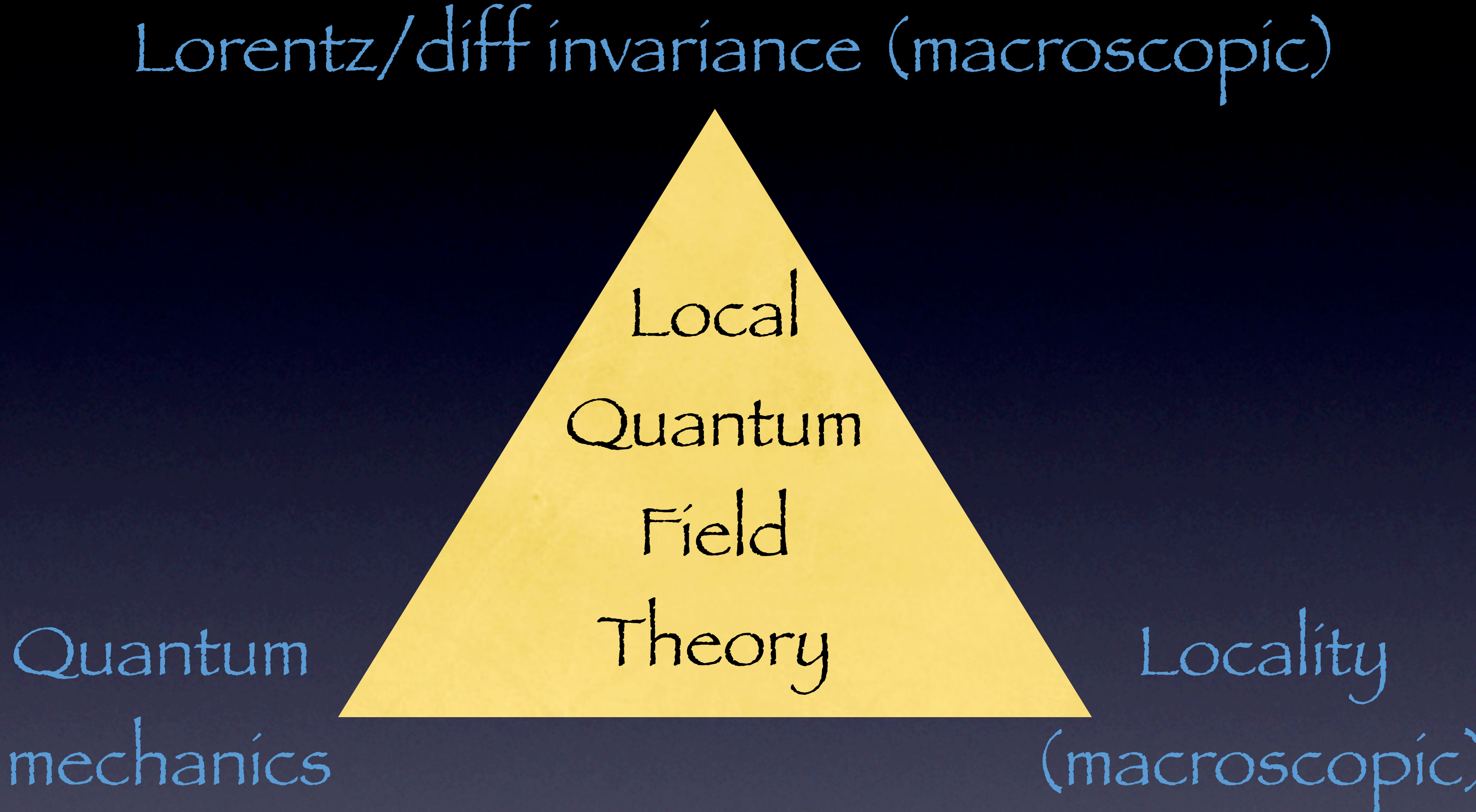


What is the state at late times?

Usual picture: black hole forms; Hawking radiates

Outcome	Principle(s) violated
Mixed state	QM; E conserv
Remnant	Stability
Pure state "Hawking radiation"	Locality-macroscopic
No BH, or no HR	Lorentz/Diff invc;QM

The paradox: a conflict between



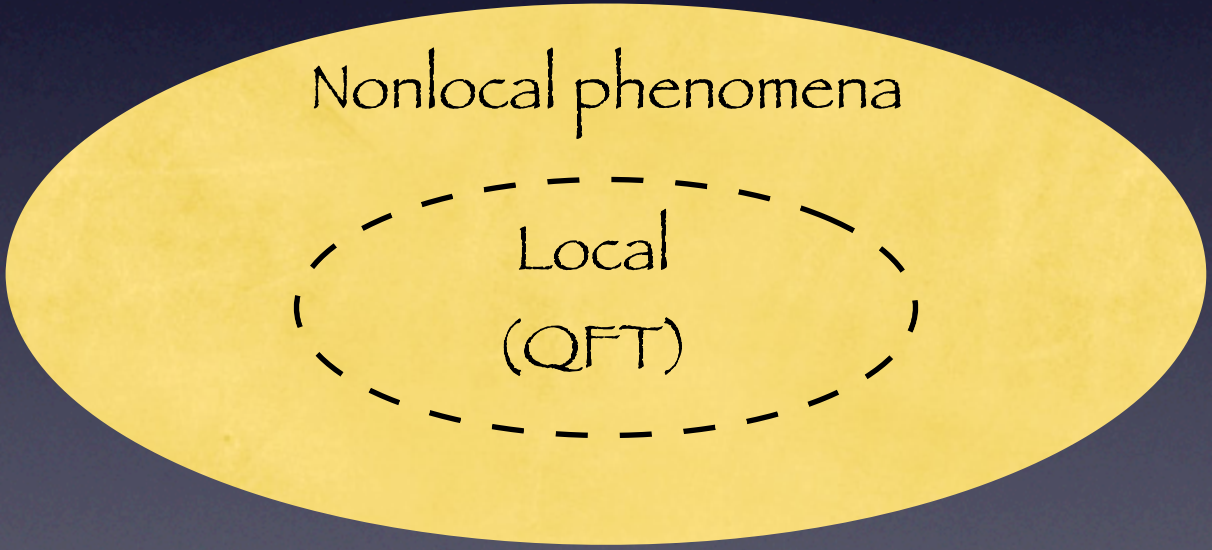
My working assumptions: 1) Quantum Mechanics

2) Lorentz Invariance

If locality breaks down, some questions:

1) What are relevant criteria for breakdown

2) What is the "correspondence boundary"?



Some possible proposals for a correspondence boundary:

planckian curvature: $\mathcal{R} < M_P^2$

string uncertainty principle: $\Delta X \geq \frac{1}{\Delta p} + \alpha' \Delta p$
(Veneziano/Gross)

modified dispersion: $p < M_p$

$\Bigg\}$ 1 particle

holographic (information) bounds: $S \leq A/4G_N$

multiparticle

3) What is the mechanism for breakdown?

extendedness of strings (branes ...)?

something else?

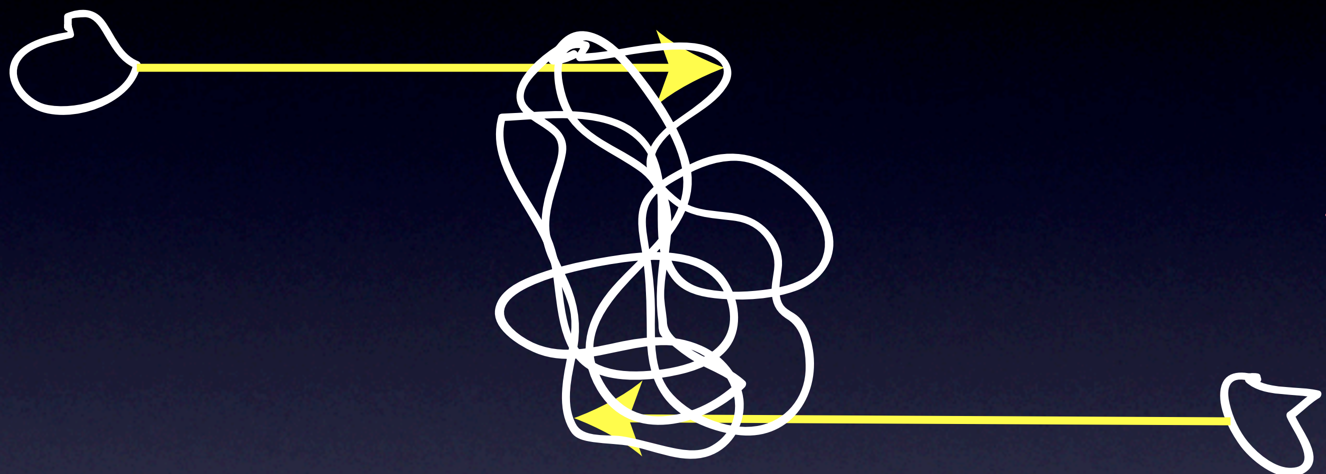
These questions are clearly related.

Can probe them by studying high-energy scattering

(There's a related story more closely based on observables, etc.)

E.g. is the basic mechanism string extendedness?

Possible picture in HE scatt:



Long strings

$L \sim E/M_s^2$

$\leftrightarrow$ String uncertainty principle $\Delta X \geq \frac{1}{\Delta p} + \alpha' \Delta p$

(Veneziano, Gross)

($\longleftrightarrow$ nonlocality)

(Proposed app. to BH info: LPSTU)

What does this have to do w/BH formation?

Does it prevent? (Strominger, Gross)

Or is this BH formation? (~Susskind)

Let's investigate ...

Begin w/tree-level amplitude: high E

$$\mathcal{A}_0^{\rm string}(s,t) \propto g_s^2 \frac{\Gamma(-t/8)}{\Gamma(1+t/8)} s^{2+t/4} e^{2-t/4}$$

vs.

(D noncmpct dims)

$$\mathcal{A}_0^{\rm grav}(s,t) \propto G_D \frac{s^2}{t}$$

- No evidence for long string effects:

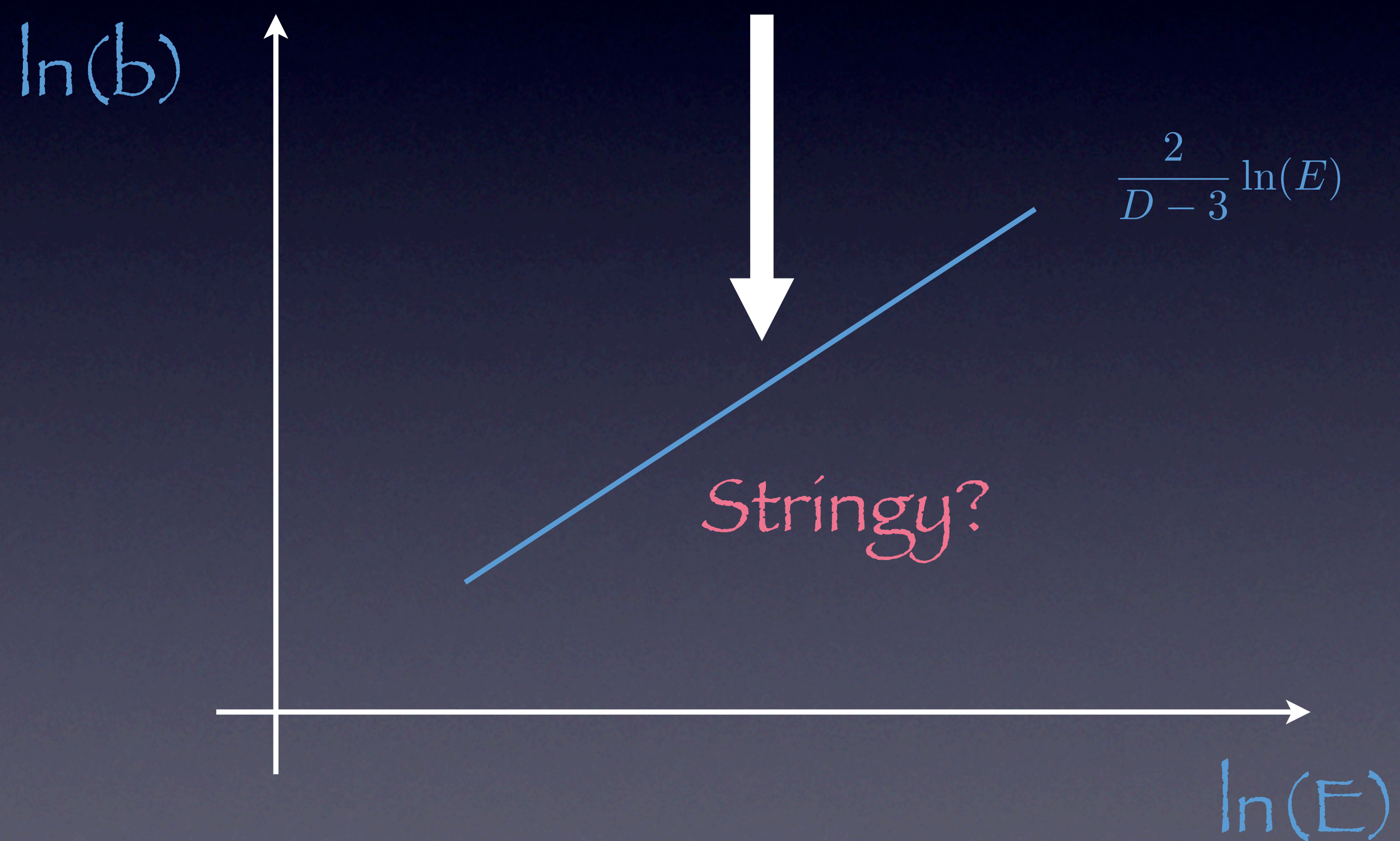
$$b \sim E \;\; \leftrightarrow \;\; t \sim E^{-2(D-5)}$$

- But significant modifications for

$$t \sim -1$$

To investigate: (s,t) $\longrightarrow$ (E,b) $\quad E \ggg M_P$

e.g. $\quad t \sim -1 \Leftrightarrow b \sim E^{2/D-3}$

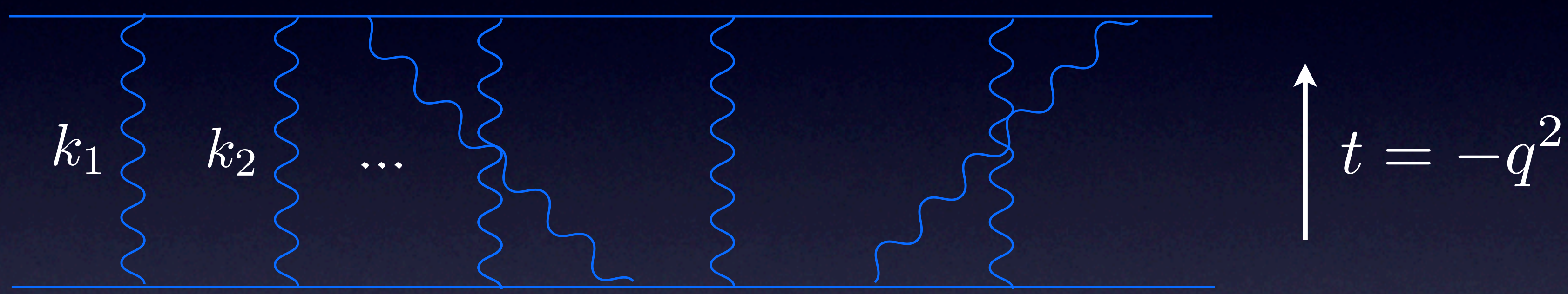


Fix E -- lower b

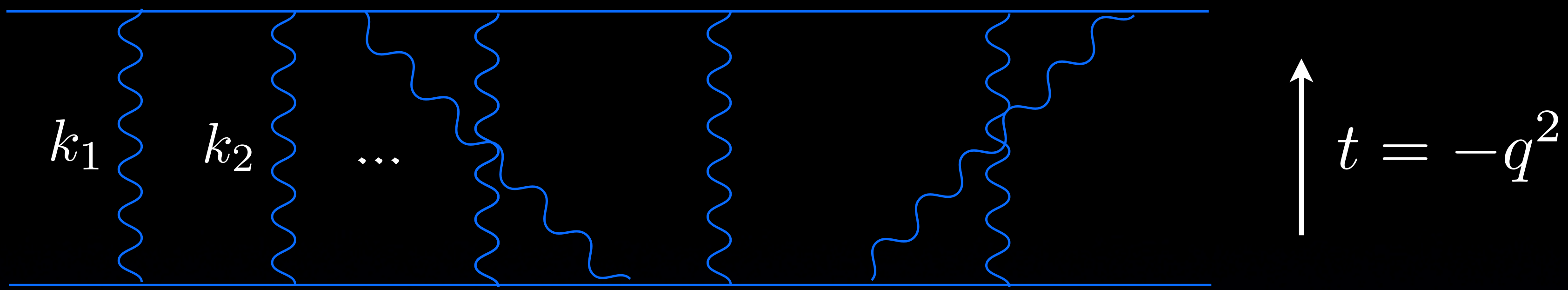
To check, include loops:

(Following Amati, Ciafaloni, Veneziano; Muzinich-Soldate; SBG, Gross, Maharana)

Ultrahigh-E, large b: ladders - eikonal



$$i\mathcal{A}_N^{\rm string} = \frac{2s}{(N+1)!}\int \left[\prod_{j=1}^{N+1} \frac{d^{D-2}k_j}{(2\pi)^{D-2}} \frac{i\mathcal{A}_0^{\rm string}(s,-k_j^2)}{2s}\right](2\pi)^{D-2}\delta^{D-2}\left(\sum_j k_j - q_\perp\right)$$



Features:

At given loop order, N:

1) $k_j \approx q/(N+1)$

2) $E^{-\alpha' q^2/(N+1)}$

Thus at large N, string corrections small

Which N dominates?

Can sum diagrams - eikonal series:

$$iA_{\rm eik}(s,t) = 2s\int d^{D-2}\mathbf{b}e^{-iq_\perp\cdot\mathbf{b}}(e^{i\chi(b)}-1)$$

with $\quad \chi(b) \sim G_D \frac{E^2}{b^{D-4}}$

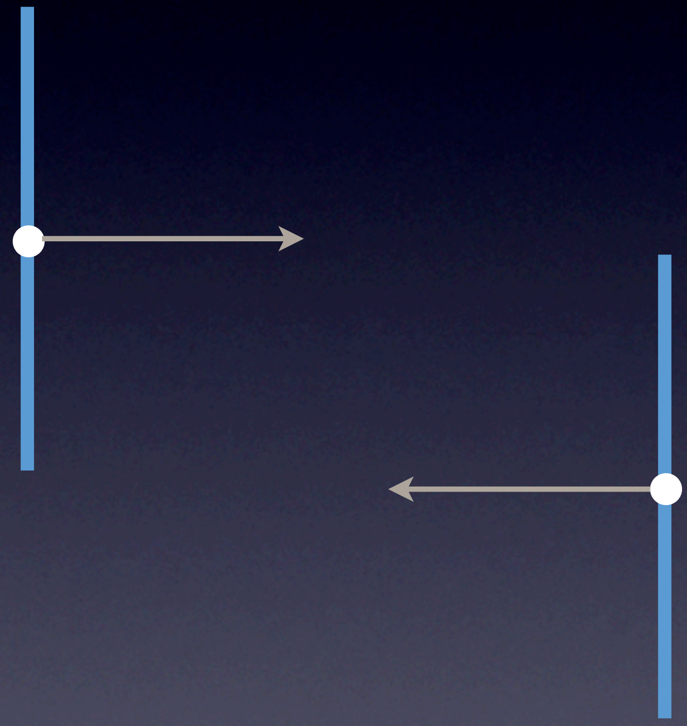
$\Leftrightarrow$ Dominant N: $\quad N \sim \frac{G_D E^2}{b^{D-4}}$;

At $t \sim -1$: $\quad N \sim (G_D E^2)^{\frac{1}{D-3}}$

$\therefore$ Large loop order dominates.

Eikonal ⟷ classical scattering

Two Aichelburg-Sexl shocks (ACV: checks)



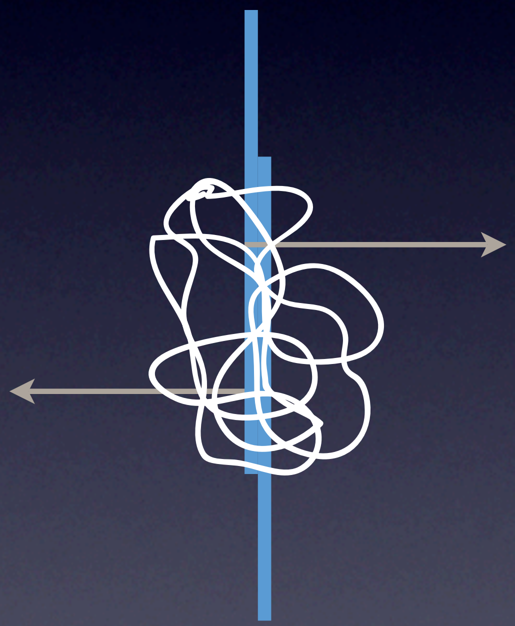
Black hole formation?

But - another effect: can excite strings - "diffractive excitation" (ACV)

Indeed, unexcited (elastic) amplitude, near Schwarzschild impact parameter:

$$\mathcal{A}_{el} \sim \exp\left\{-E^{(D-4)/(D-3)}\right\} \qquad !!$$

So:



??

No black hole??

Info carried away?

(Veneziano, 2004)

But there is a contrary intuition: string only "spreads out" "after" collision??

String spreading is a notoriously fuzzy concept, and requires some care

Where is the string?

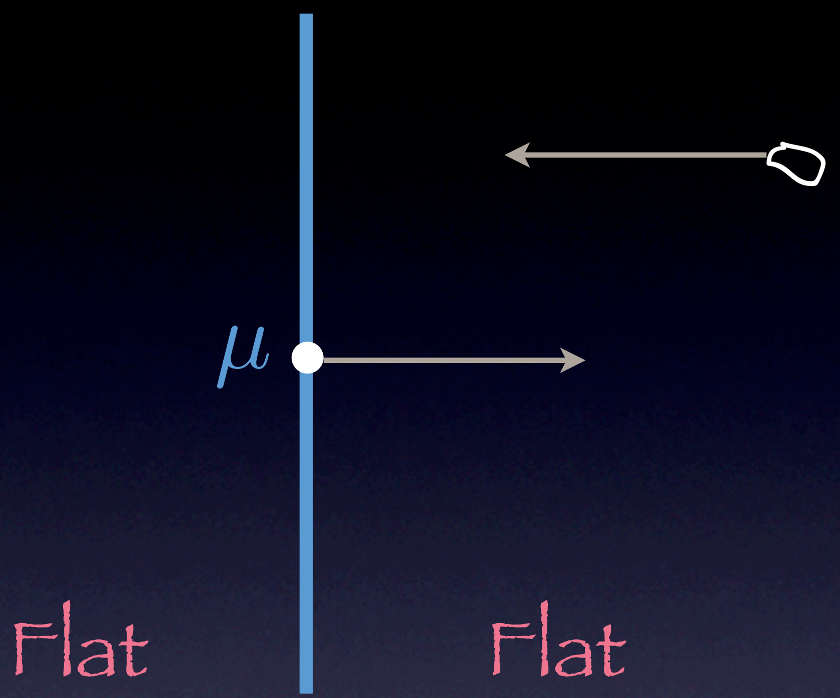
Karliner, Klebanov, Susskind: it depends

"low resolution"

"high resolution"

So: need to check for process in question ...

A test:

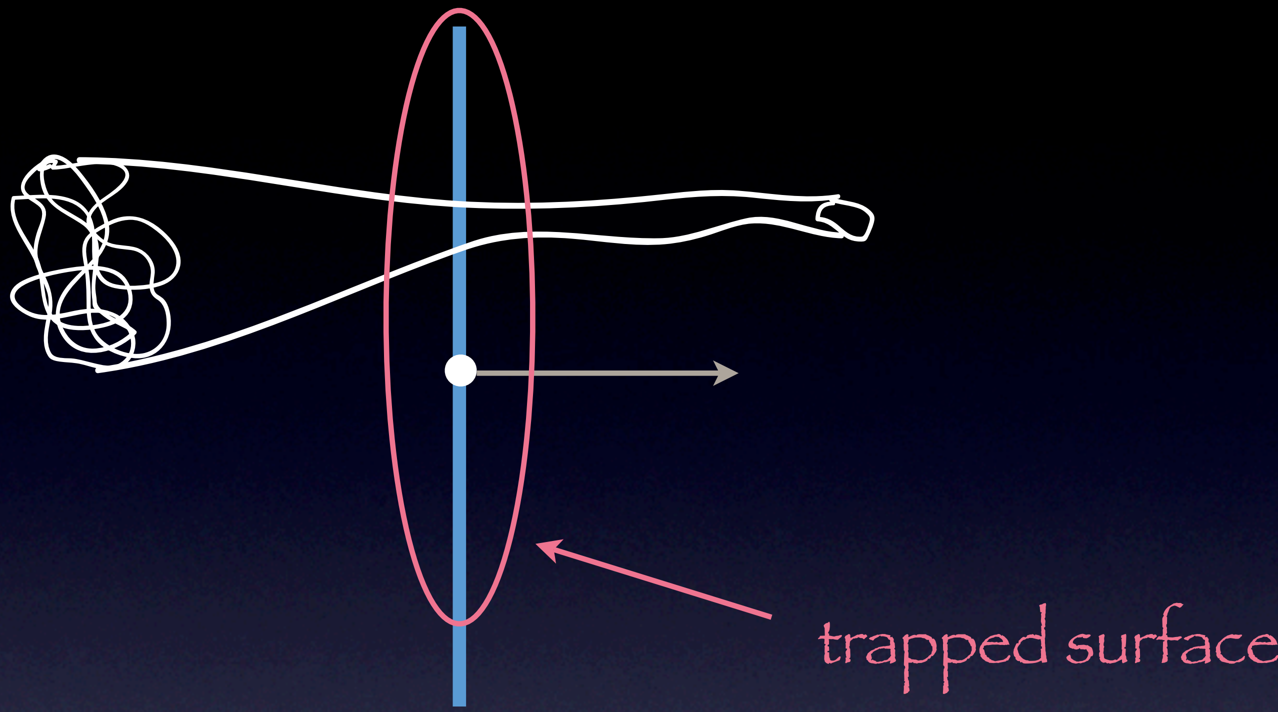


$$ds^2 = -du dv + dx^i dx^i + \Phi(\rho)\delta(u) du^2$$

$$\Phi(\rho) = -8G\mu \ln\rho \quad , \quad D = 4$$

$$\Phi(\rho) = \frac{16\pi G\mu}{\Omega_{D-3}(D-4)\rho^{D-4}} \quad , \quad D > 4$$

Find:



Indeed, origin of effect is "tidal string excitation"

$$(\Delta X)^2 \sim |\ln \epsilon| + \left[\frac{G_D E^2}{b^{D-2}}\tau\right]^2 |\ln \tau| \qquad \epsilon \ll \tau$$

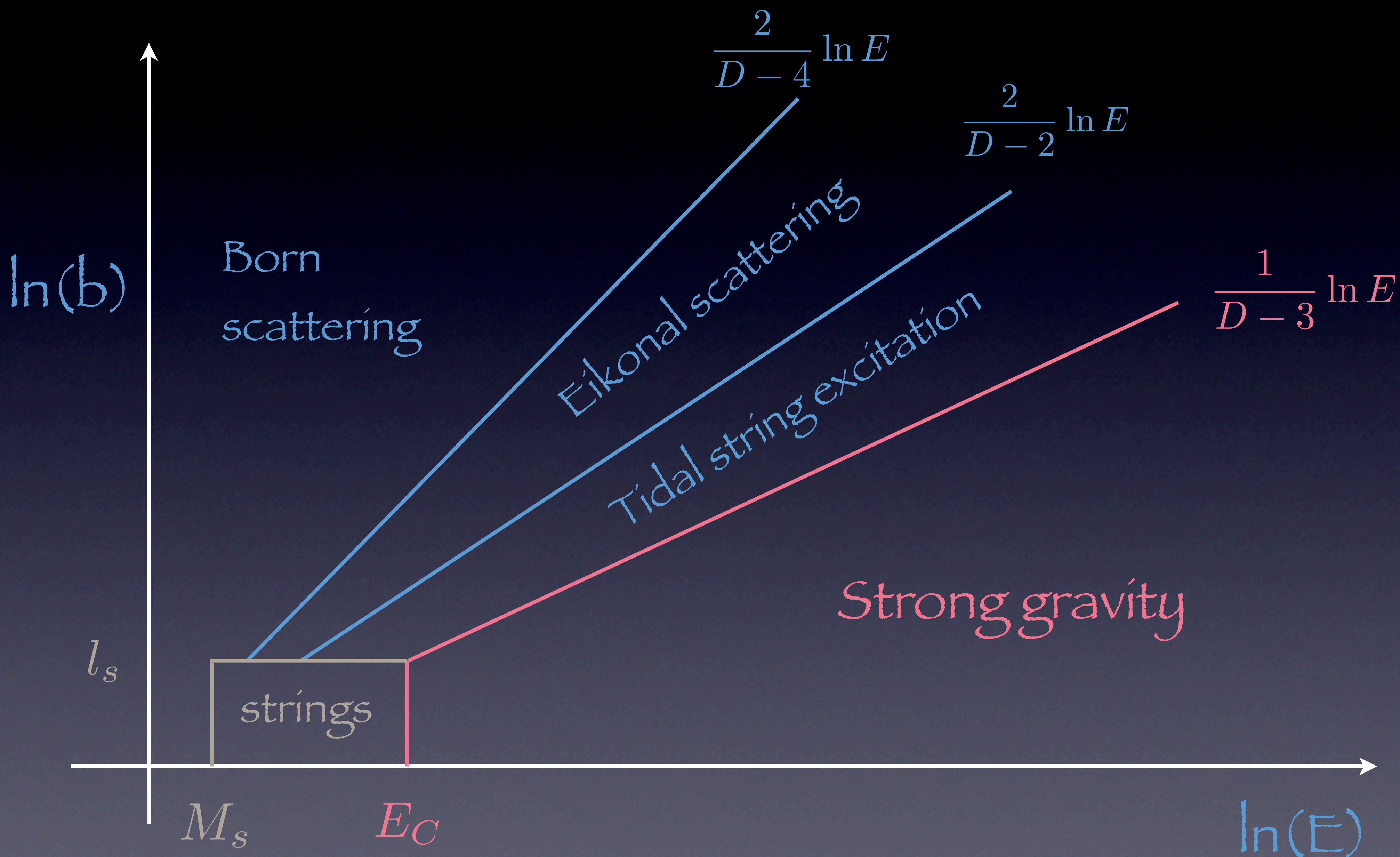
For small tau: inside trapped surface

Thus:

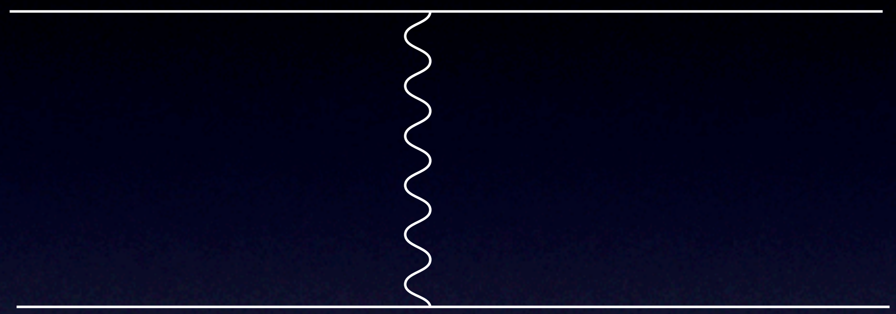
- String appears to behave ~locally during collision
- Trapped surface (aka black hole) appears to safely form

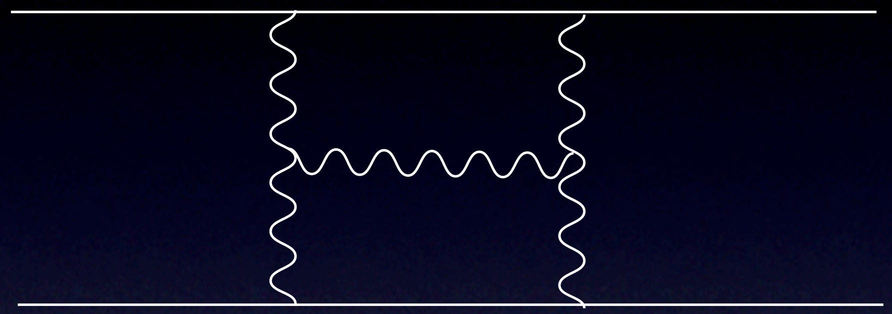
What conclusions can we draw?

1. A suggested "phase diagram:"



2. Perturbation thy apparently breaks down





$$1 \qquad + \qquad \mathcal{O}\left[(R_S(E)/b)^{2(D-3)}\right]$$

...not short distance

This seems a challenge to calculability
in any theory of quantum gravity

3. Nonlocality/mechanism: no fundamental role for string extendedness has emerged

A. Assuming scattering is finite and unitary:

unitarization apparently via intrinsically nonperturbative gravitational effects?

(renormalizability vs. unitarity)

B. This dynamics is apparently not local.

Proposal: "nonlocality principle:" the nonperturbative physics that unitarizes gravity in regimes where gravitational perturbation theory fails is nonlocal

4. Suggested correspondence boundary:

where does GR+LQFT break down?

Example of basic configuration of QFT+GR

2 part Fock sp.: $\phi_{x,p}\phi_{y,q}|0\rangle$

(min uncertainty wavepackets)

description apparently fails unless $|x-y|^{D-3} > G|p+q|$

where $G \sim G_{Newton}$

Proposal: "the locality bound"

(extends off shell?)

Sharper tests of locality?

How does this relate to BH info?

Does NP string theory address?

What about cosmology?

...

Material for a few talks ... will just overview

Criteria for locality, and breakdown

1. Derivable from local QFT

2. $[\mathcal{O}_1(x), \mathcal{O}_2(y)] = 0 \ , \ (x-y)^2 > 0$

3. Bounds/analyticity: Froissart; Cerulus-Martin; polynomial boundedness ...

2. $[\mathcal{O}_1(x), \mathcal{O}_2(y)] = 0 \ , \ \ (x-y)^2 > 0$

- There are no local gauge invariant observables in gravity. (Diffeos!)
- One can construct gauge invariant "proto-local" observables that approximately reduce to local observables in certain states (SBG, Marolf, and Hartle hep-th/0512200; Gary and SBG, hep-th/0612191).
- However, in situations characterized by the locality bound (and generalizations), one encounters obstacles to such a reduction.
- Thus this criterion for locality apparently is only approximate and appears to break down in situations of interest.

3. Bounds/analyticity: Froissart; Cerulus-Martin; polynomial boundedness ...

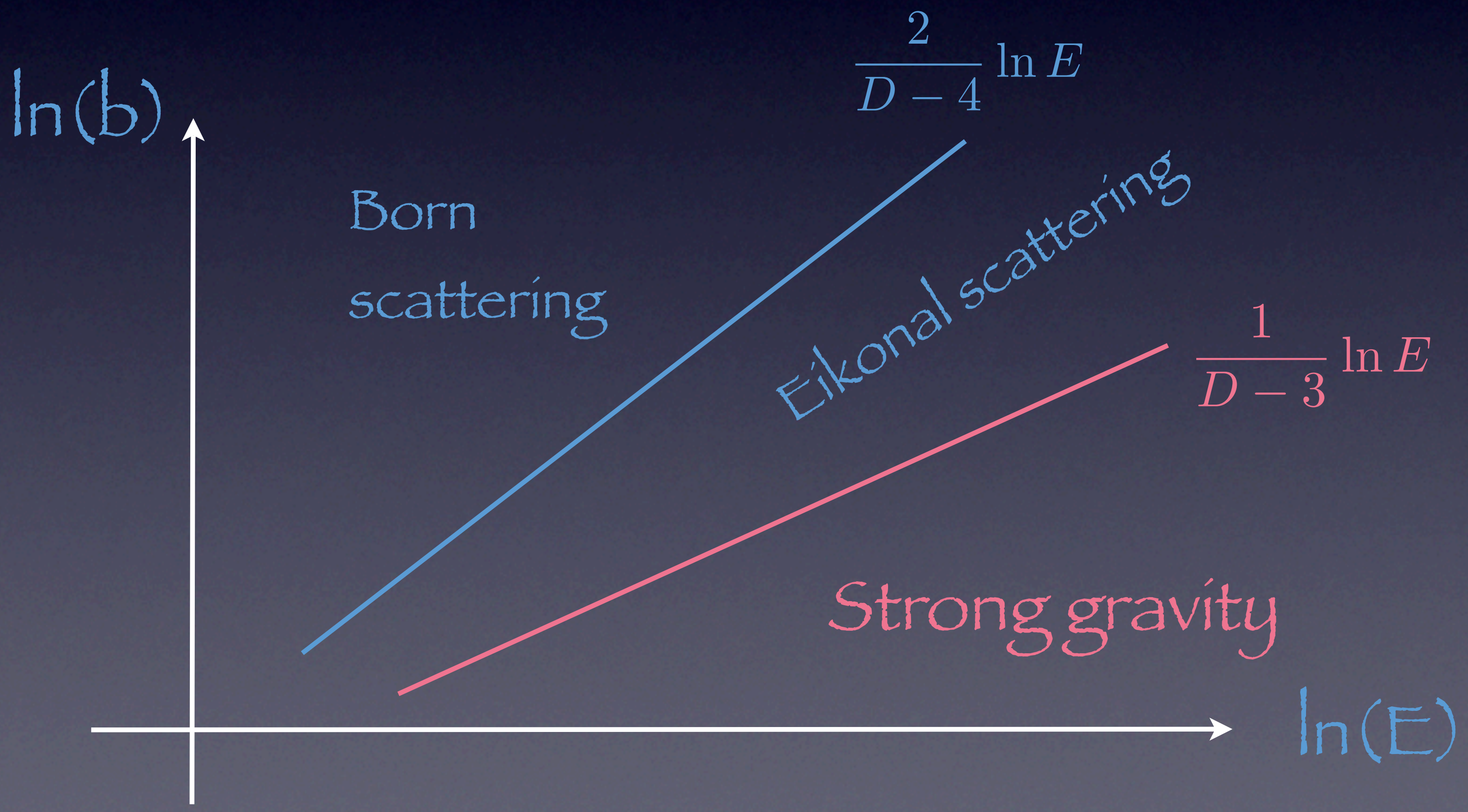
What general properties of gravitational amplitudes can we infer?

(0711.5012 w/ M. Srednicki)

E.g. study partial wave expansion of 2-2 scattering(IR: e.g. $D>6$)

$$T(s,t) = (const)E^{4-D} \sum_{l=0}^{\infty} (l+\nu) C_l^{\nu}(\cos\theta) \left[e^{2i\delta_l(s) - 2\beta_l(s)} - 1 \right]$$

$$\nu = \frac{D-3}{2}$$



Some features:

A. Understand Born, eikonal regions

e.g. $$\delta_l \approx [ER_S(E)]^{D-3}/l^{D-4}$$

$$\beta_l = \text{“unimportant”}$$

(though model dependent)

B. Ansatz for BH region

$$\beta_l \approx \frac{S(E,l)}{4}$$

apparent consequences:

- amplitudes apparently obey Cerulus-Martin (contrary to earlier expectations)

- absorptive amplitude violates Froissart

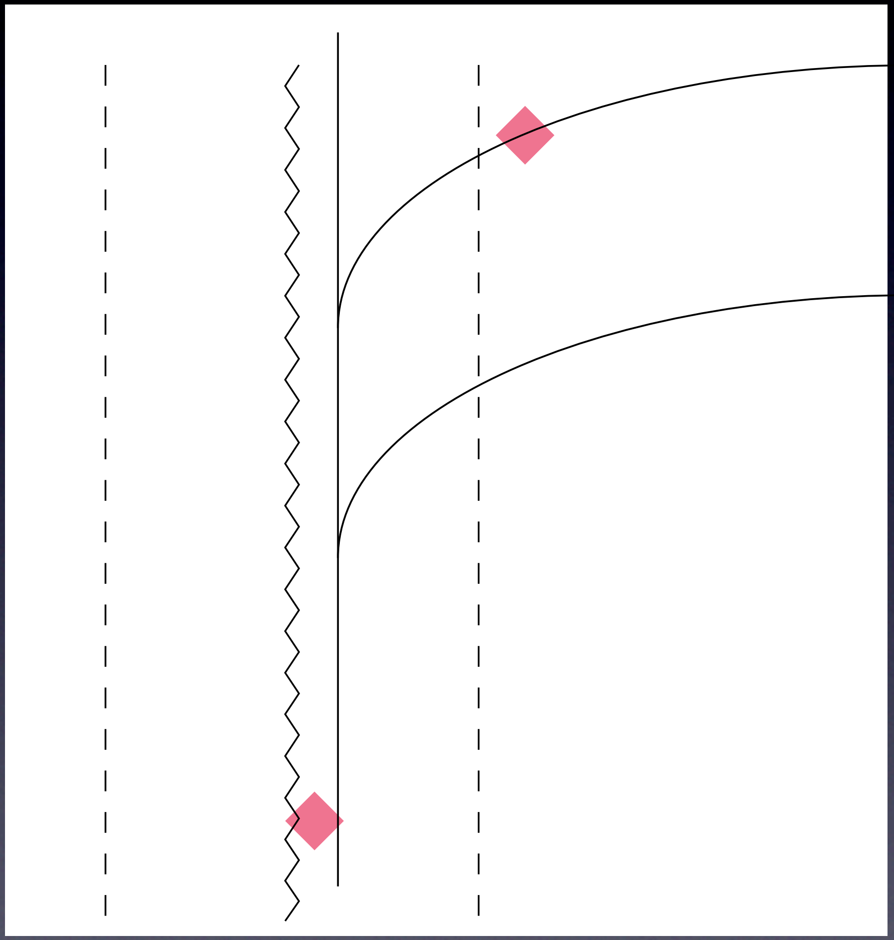
$$\sigma_{abs} \sim [R_S(E)]^{D-2}$$

- correspondingly, amplitudes not poly bdd:

$$T(s,t) \sim e^{R_S(E)\sqrt{t}}$$

(Not "local" by usual criterion)

What is missing in Hawking's argument for information loss?



proposal:

these non-perturbative, non-local effects become important by

$$T \sim R_S S_{BH}$$

(strong complementarity/ strong holography not needed?)

Some comments:

- there exists motivation for such effects, based on a) apparent breakdown of perturbation thy in nice slice quantization and b) limitations on observation of state. See hep-th/0703116

- but, a complete picture of how/why such physics enters and how it relays the information would require knowledge of this nonpert. dynamics ...

Can string theory address these problems?

Argued: not likely in perturbation theory

Commonly believed that one has complete nonpert descriptions of string theory

- AdS/CFT: need to extract flat space limit. Subtle. Concrete First test: can we see $1/q^2$ of Born regime? (WIP w/ M. Gary)

- Matrix thy: does it sidestep divergences of grav. pert thy? (WIP w/ D. Trancanelli)

Cosmology: de Sitter, etc.: a few brief comments

- if complementarity inessential in BHs, there should also be a global picture for dS.

- steps towards the formulation of such a picture: SBG and Marolf, arXiv:0705.1178 and WIP

- some features: finite number of pert. dS states not violating loc. bd.; no recurrences; relational observation

- apparent limitations to local QFT description of global picture by timescale $R_{dS}S_{dS}$: Boltzmann brain observers; large perturbative corrections ~BH case ... (longer times likely allowed in static patch picture)

- related constraints found in Arkani-Hamed et al [arXiv:0704.1814] picture of regulating dS: large fluctuations at time $\sim R_{dS}S_{dS}$

More general question: where does this leave us?

1) Locality implies quantum fields. So, if physics is not local, why should the degrees of freedom be (approximately) local fields?

String theory, LQG almost look too local!

2) What is a suitably general quantum mechanics to describe such a theory?

E.g. generalized QM: histories ~ local field configs

More general: "Universal QM"

hep-th/0711.0757

Summary

- several considerations (HE scattering; observables; BH information, ...) support breakdown of conventional locality: at macroscopic scales

- mechanism: no apparent role for string extendedness; rather nonperturbative gravity

- not clear how any existing model for QG addresses these issues?

- correspondence boundary for such a "nonlocal (or "nearly-local) mechanics:" locality bound, etc.

- such nonlocality should explain how info escapes black holes ("unitarity restored at the price of locality")

- related story for inflationary cosmology; potentially places limitations on regime of local QFT description

(might we expect corresponding limitations on eternally inflating landscape?)

Analogy to emergence of quantum mechanics, pre 1925

QM	? (NLM)
$\hbar$	$\hbar$, G
Hydrogen atom	Black hole
UV catastrophes	Information paradox, ...
Old quantization rules	Holographic princ; I=A/4
Uncertainty principle	Nonlocality principle (locality bound, ...)
(Noble gases)	(Extremal black holes)
Wave function	? (UQM states??)
Schrodinger eqn	?

What is this "non- (but nearly-) local mechanics"?