Strings, gravity, and nonlocality

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Based on:

hep-th/0604072;
hep-th/0703116;
arXiv:0705.1816, w. Gross and Maharana;
arXiv:0705.2197

Cosmology, strings, and phenomenology
Nordita, Stockholm

A plausible viewpoint:

the black hole information paradox is of comparable importance to the paradox of the classical instability of matter

Why a paradox?

Apparently must abandon a cherished principle of physics:

- unitarity and energy conservation (QM violated)
- stability (remnants)
- macroscopic locality (information escapes)

...widespread belief

But, if nonlocality:

1) What is the mechanism

2) How is Hawking's argument evaded

3) Where does GR+local QFT fail?

- what is the correspondence limit for new physics?

Some existing proposals for the correspondence limit:

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

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

modified dispersion: $p < M_p$

} 1 particle

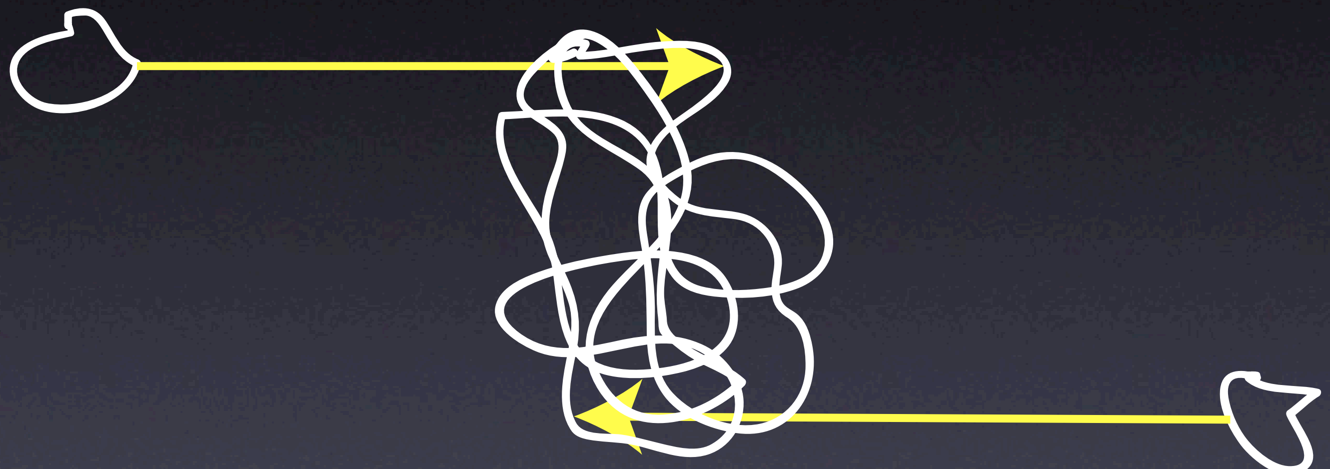
holographic (information) bounds: $S \leq A/4G_N$ multiparticle

Will explore some issues that seem to shed some light on these questions.

Begin with: The role of strings

If there is nonlocality in string theory, would expect to find evidence of it in high-energy scattering.

Does string extendedness provide the mechanism for nonlocality?



What does this have to do w/BH formation?

(Does it prevent? Or is this BH formation?)

(Q's: Strominger, Gross, ...;

string spreading - Susskind)

Long strings? $L \sim E/M_s^2$

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

(Veneziano, Gross)

($\longleftrightarrow$ nonlocality)

(Proposed app. to BH info: LPSTU)

Let's investigate ...

Begin w/tree-level amplitude: high E

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

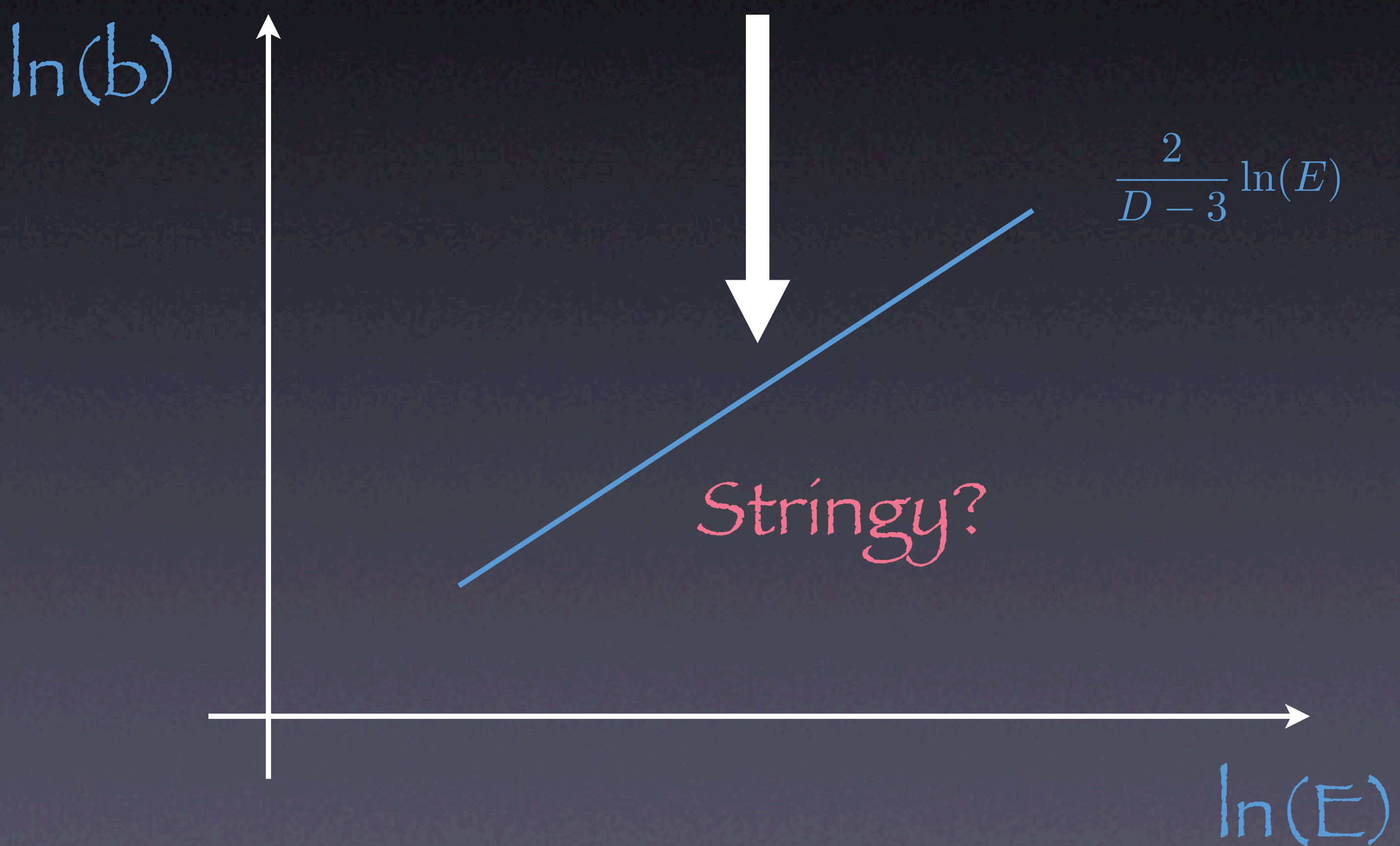
vs.

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

- No evidence for long strings;
- But significant modifications for $t \sim -1$

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

e.g. $t \sim -1 \Leftrightarrow b \sim E^{2/D-3}$ (D noncmpct dims)

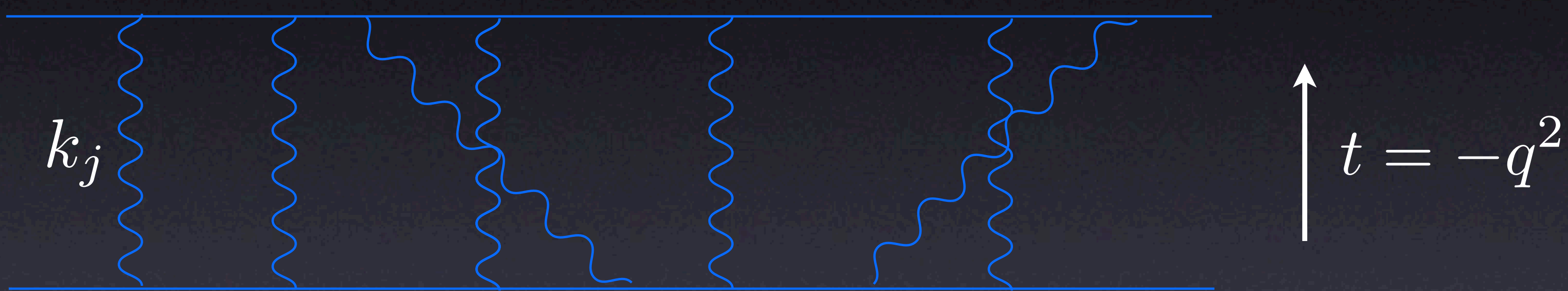


Fix E -- lower b

To check, compare loops:

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

Ultrahigh-E: Eikonal



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

$$\prod_{j=1}^{N+1} \frac{E^{2-\alpha' k_j^2}}{k_j^2}$$

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

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

Thus at large N, string corrections get smaller

Which N dominates?

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

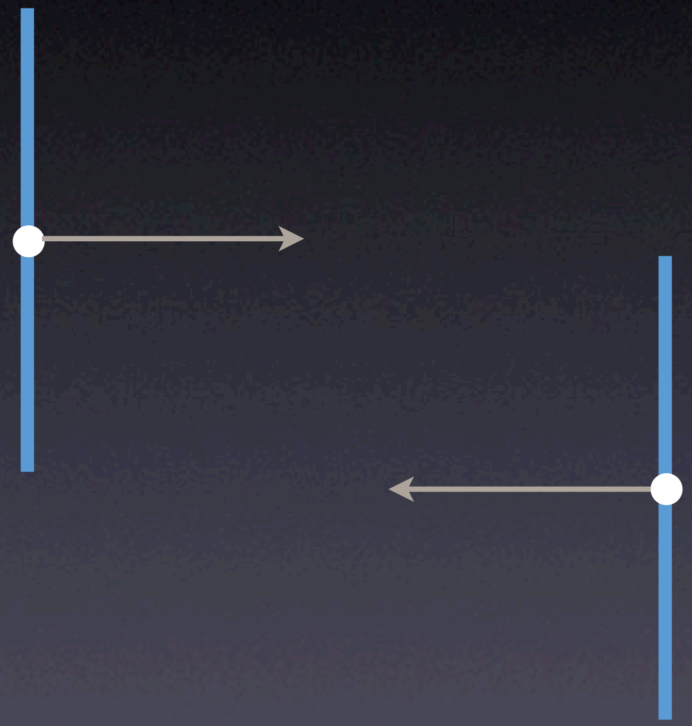
$\Leftrightarrow$ Dominant N: $\quad N \sim \frac{G_D E^2}{b^{D-4}}\;;$

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)



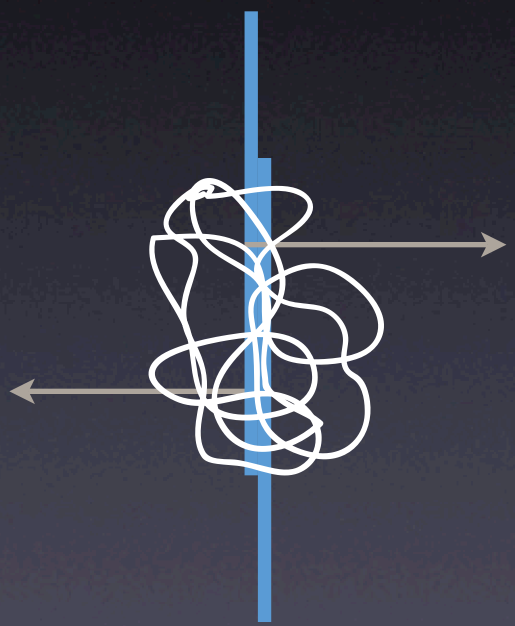
Black hole formation?

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

Indeed, unexcited (elastic) amplitude, near Schwarzschild radius:

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

So:



??

No black hole??

Info carried away?

(Veneziano, 2004)

But - intuition: string only "spread out" "after" collision??

However, string spreading is a notoriously fuzzy concept...

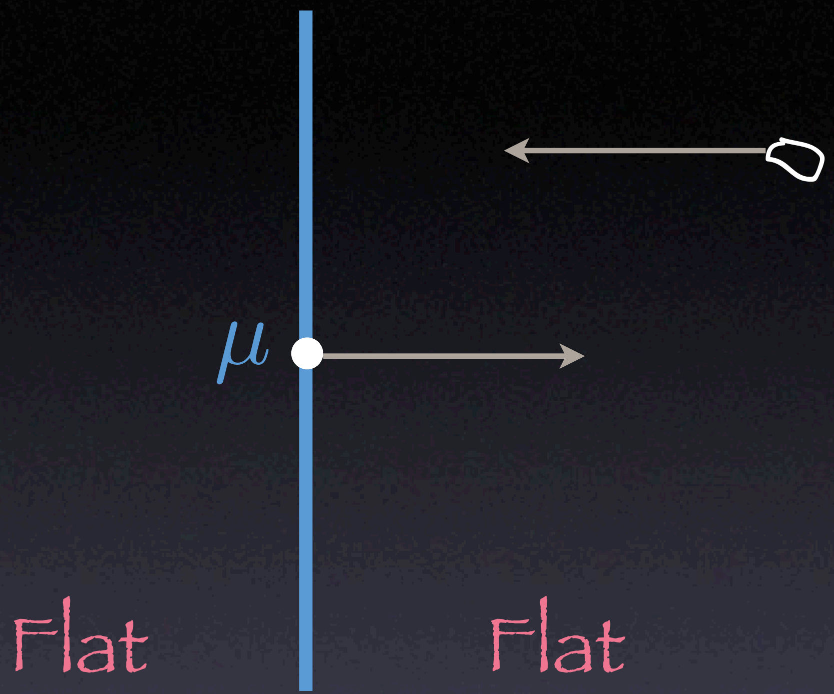
Where is the string?

Karliner, Klebanov, Susskind: it depends

“low resolution” “high resolution”

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

A test:



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

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

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

Scattering in a plane-wave metric:

de Vega and Sanchez; Horowitz and Steif

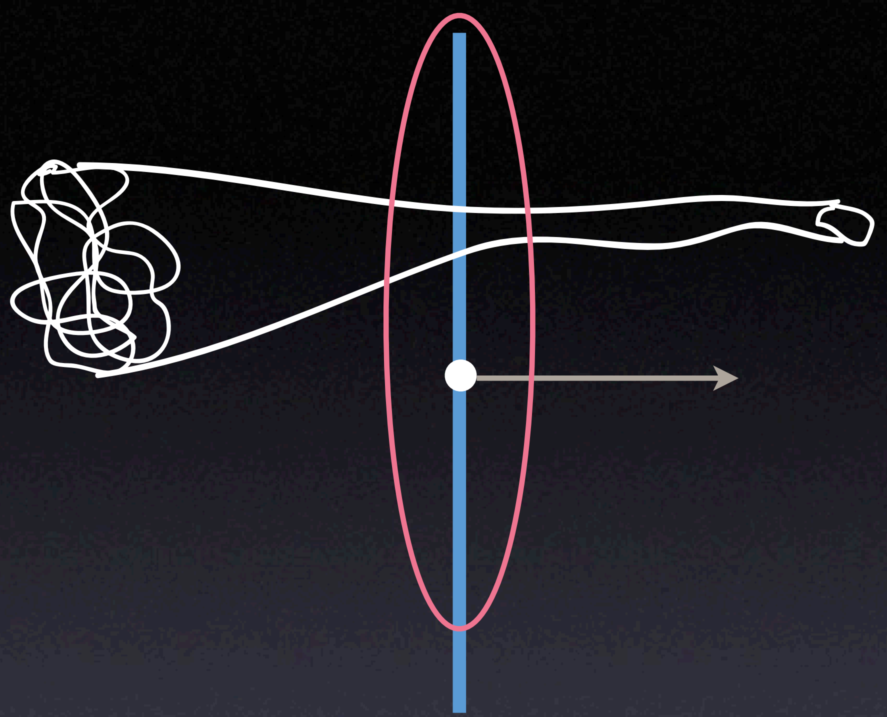
Light cone quantization

Compute for incoming unexcited string:

$$\langle \hat{X}^i_\epsilon(\tau,\sigma)\hat{X}^i_\epsilon(\tau,\sigma)\rangle$$

Where $\hat{X}^i_\epsilon(\tau,\sigma)$ is deviation from CM of string, w/world sheet regulator ϵ

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

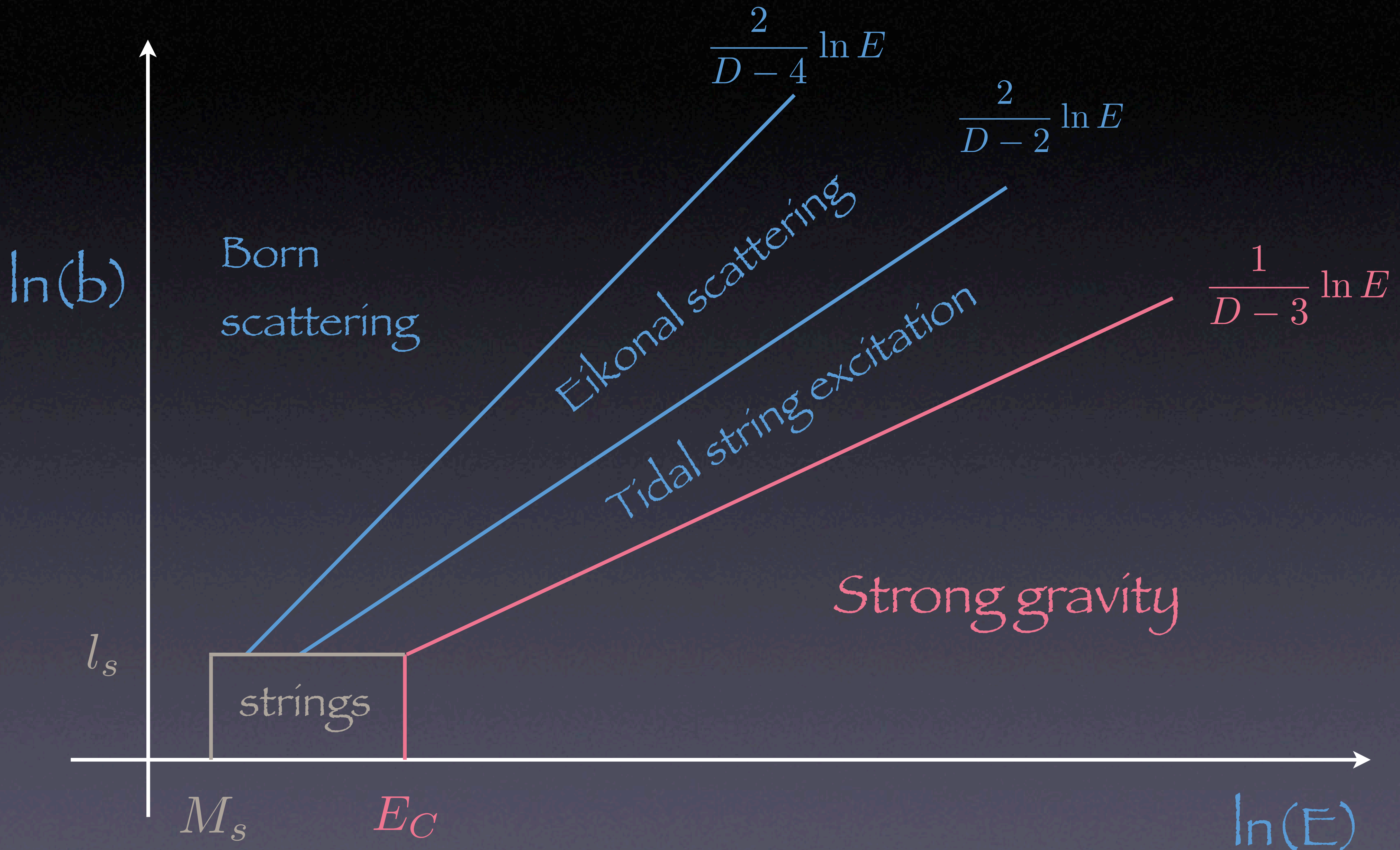
Thus:

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

What conclusions can we draw?

1. No evidence string effects prevent BH formation

Suggested "phase diagram:"



Moreover:

BH formation corresponds to breakdown of the gravitational loop expansion:

$$1 \quad + \quad \mathcal{O}(R_S/b)$$

In what sense is string theory a complete theory of quantum gravity?

2. No obvious precise notion of locality

Local QFT bounds

$$\sigma_T \leq c(\ln E)^{D-2}$$

Froissart

$$|\mathcal{A}_{el}(s,t)| \geq e^{-f(\theta) E \ln E}$$

Cerulus-Martin

Strong gravity/ black hole regime:

$$\sigma_T(E) \sim [R_S(E)]^{D-2} \sim E^{\frac{D-2}{D-3}}$$

$$\mathcal{A}_{el}(s,t) \sim e^{-S_{BH}}$$

$$\sim e^{-E R_S(E)} \sim e^{-E^{(D-2)/(D-3)}}$$

3. Scattering appears dominated by strong gravitational effects; this suggests that any nonlocality would have its origin in gravitational dynamics (as opposed to, e.g., string extendeness)

side comment: perhaps unitarity is a deeper issue than renormalizability in quantum gravity (compare EW physics); BH info paradox suggests it can be respected at the price of locality

4. Suggested correspondence boundary

where does GR+LQFT break down?

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

(min uncertainty wavepackets)

good description for $|x-y|^{D-3} > G|p+q|$

where $G \sim G_{Newton}$

"the locality bound"

(extends off shell?)

Other versions of the locality bound:

Measurement limit: $\Delta t(\Delta x)^{D-3} \geq G\hbar$

N-particle: $\phi_{x_1,p_1} \cdots \phi_{x_N,p_N}|0\rangle$

not good for $\mathrm{Max}|x_i - x_j|^{D-3} < G|\sum_i P_i|$

de Sitter: see SBG and Marolf, arXiv:0705.1178

Suggestion: perhaps these are special cases of a broader "nonlocality principle," stating that the nonperturbative physics that unitarizes gravity in domains where gravitational perturbation theory fails is nonlocal

Of course, we have other hints of nonlocality:

Possible indicators of nonlocality:

hints from AdS/CFT & holographic beliefs

(though don't yet fully address issues)

formulation of approx. local ("proto-local") observables, w/ limitations

SBG, Marolf, and Hartle, hep-th/0512200

SBG and M. Gary, hep-th/0612191

conundrums of cosmology (eternal inflation/ landscape; Boltzmann brains, etc.) and likely breakdown of GR+LQFT

Arkani-Hamed et al, arXiv:0704.1814

SBG hep-th/0703116; SBG and Marolf, arXiv:0705.1178

Returning to the original problem:

How is the information paradox resolved?

Logical possibilities:

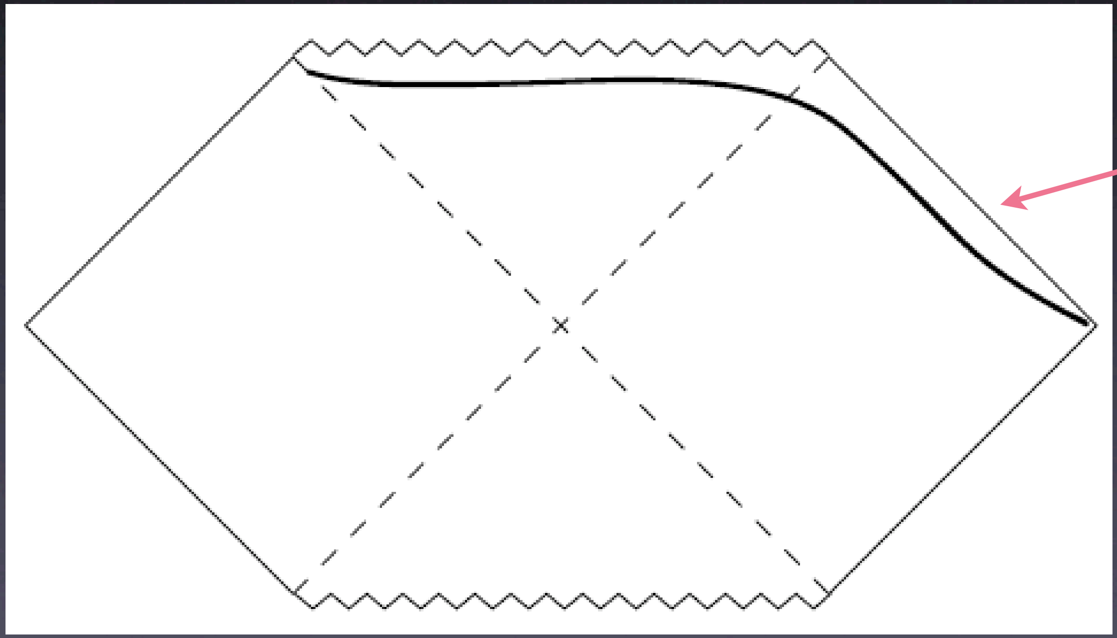
A. Compare classical - quantum, the H atom: classical physics doesn't break down at r_{atom}, it is replaced

B. Actual breakdown of semiclassical gravity

evidence for B...

Hawking's calculation (w/ updates):

$$\Delta I = S \quad \leftarrow \rho \quad \leftarrow |\psi\rangle \quad \leftarrow |\psi\rangle_{NS}$$



"nice slice"

Can we justify this in a reliable approximation?

leading contribution - perturbative expansion in

$$1/M_P$$

(fix $M_P^{-2}M$)

$\longleftrightarrow$ QFT in semiclassical background (matter: ϕ)

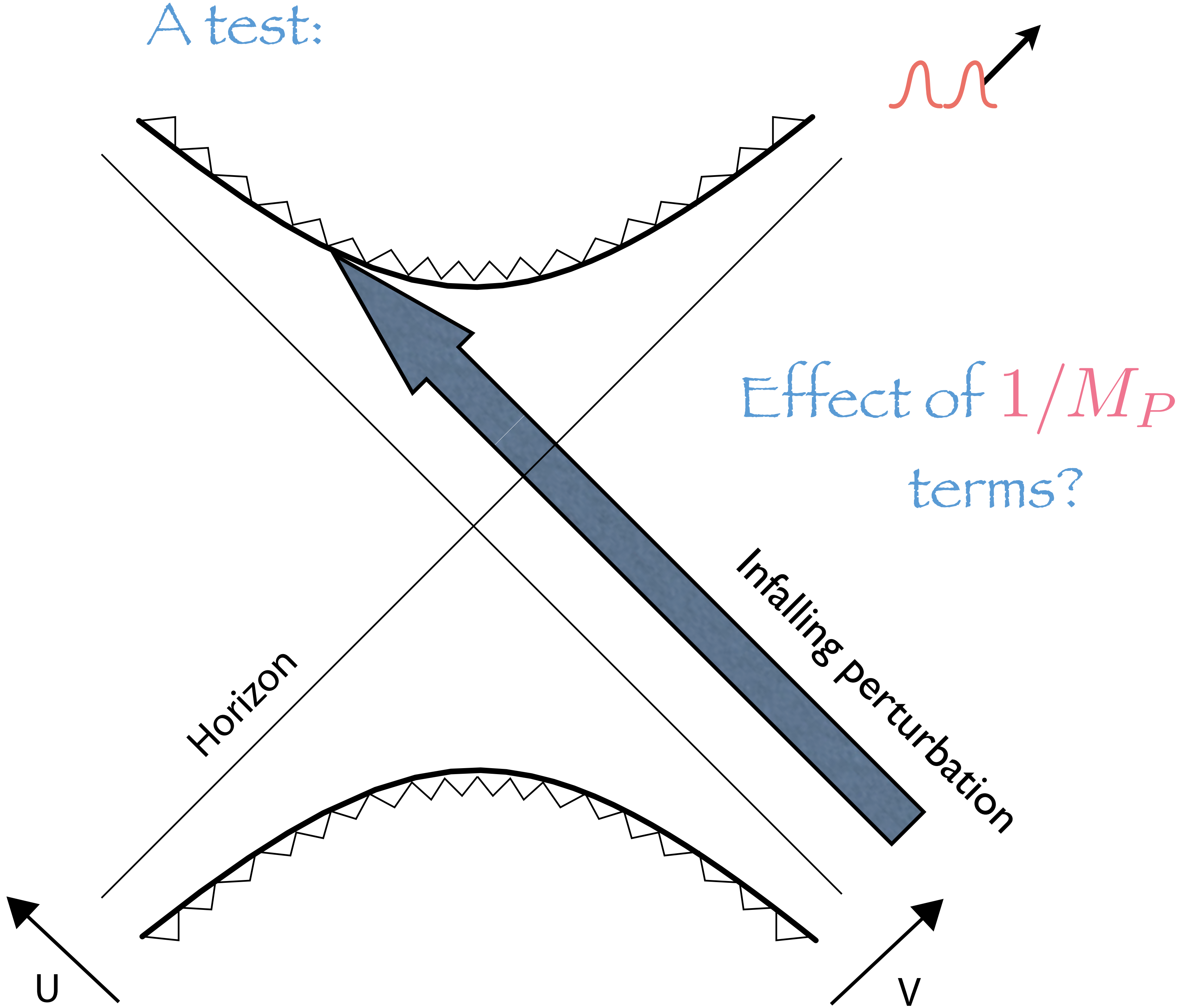
$$|\Psi\rangle \sim \int_{\Psi_{in}} \mathcal{D}h\mathcal{D}\phi e^{iS}$$

$$g_{\mu\nu} = g^0_{\mu\nu} + M_P^{-1} h_{\mu\nu}$$

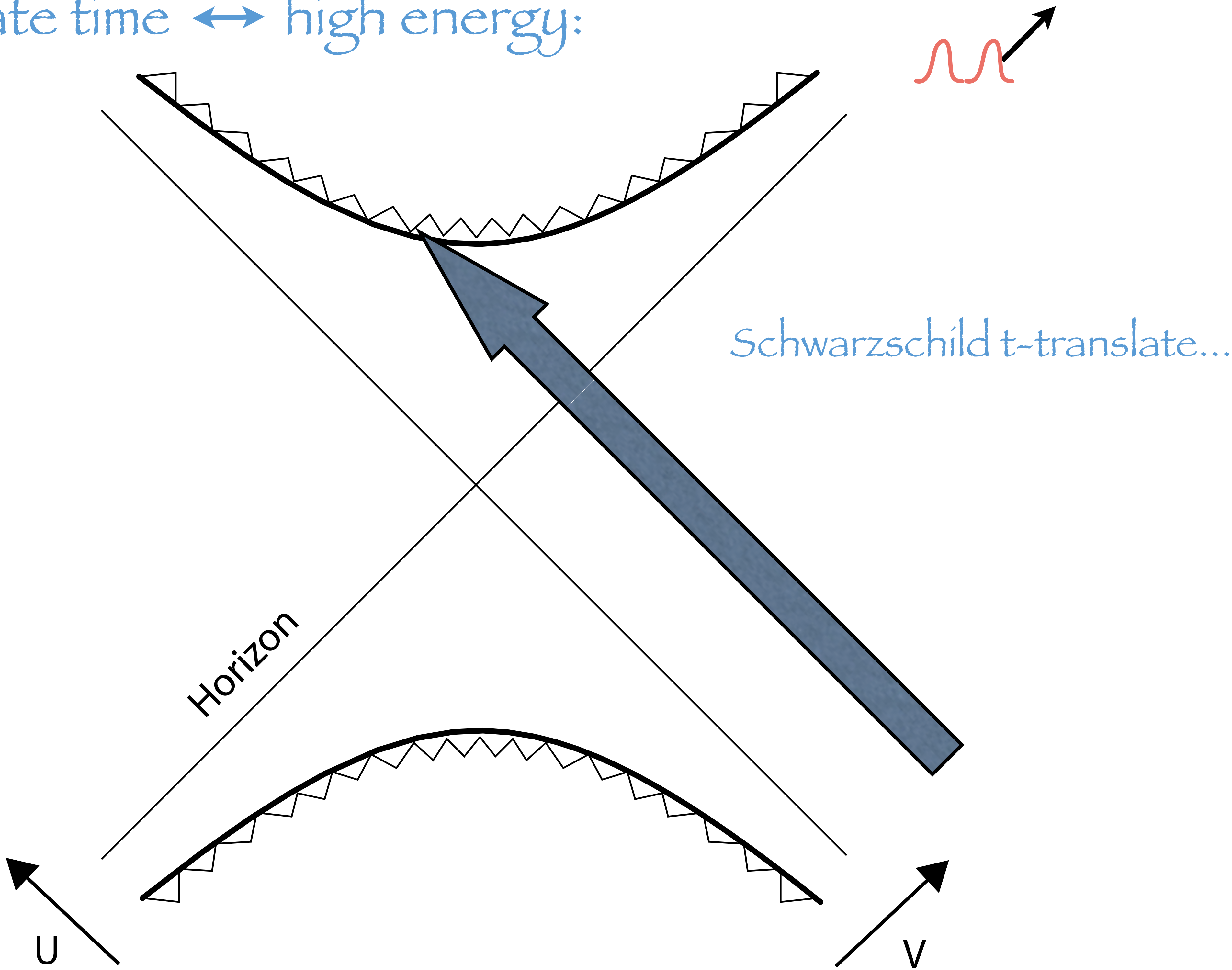
$$S \sim \int d^4x \sqrt{-g_0} \Big\{ -(\nabla_0\phi)^2 + h\Delta^0_L h$$ semiclassical

$$+ \frac{h}{M_P}\left[T^\phi_{\mu\nu} + (\nabla h)^2\right] \cdots \Big\}$$ $\frac{1}{M_P^n}$ terms

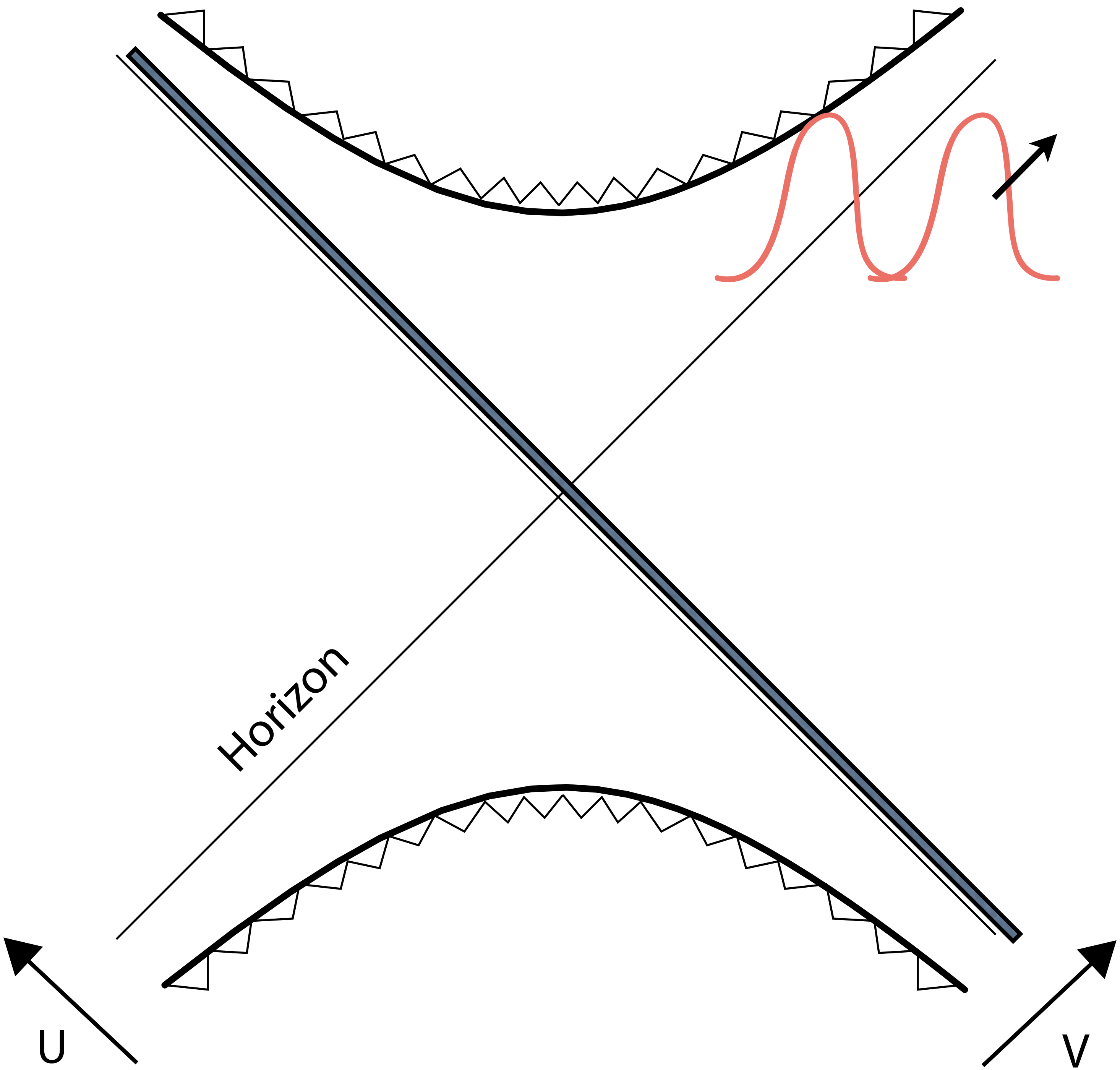
IMPORTANT?

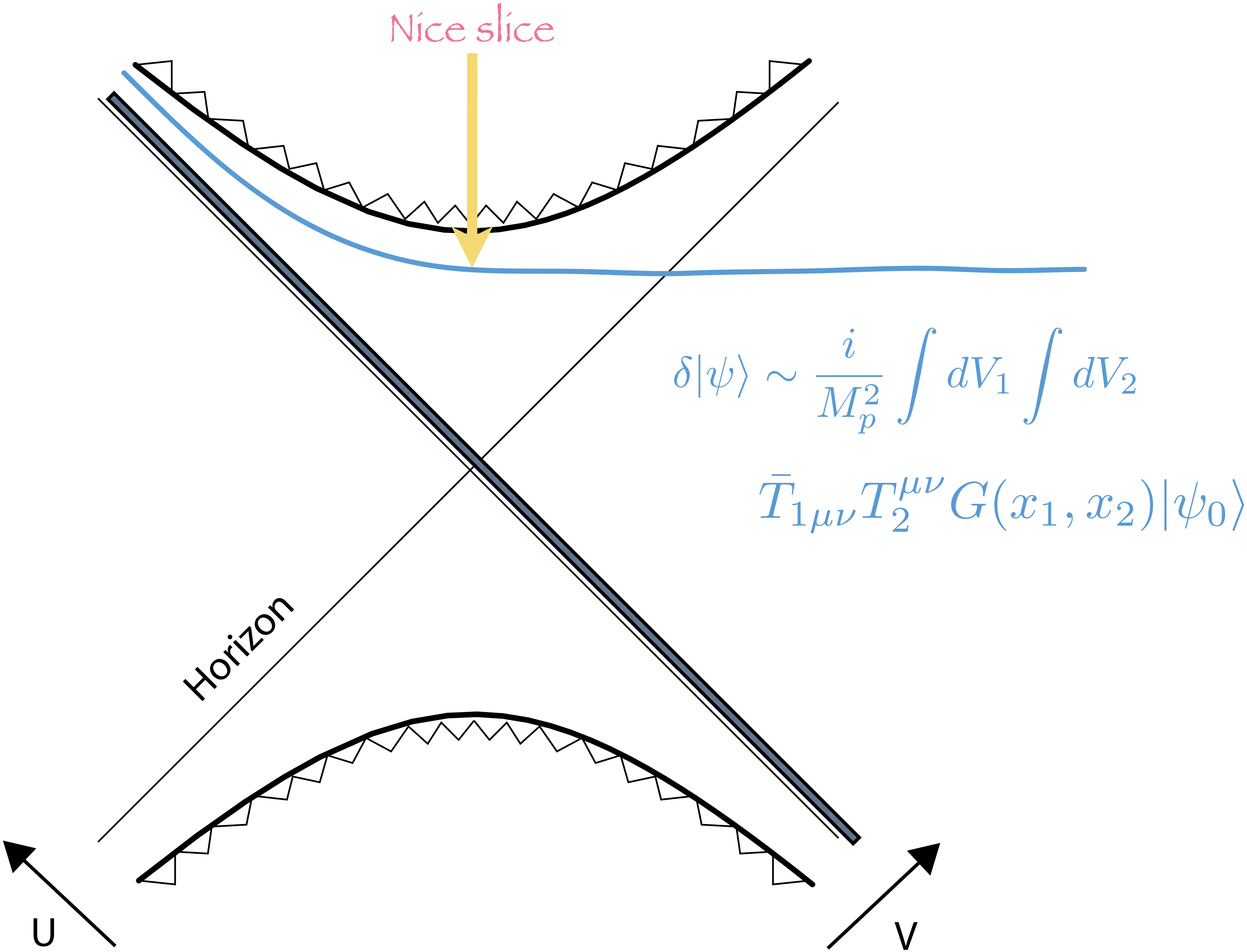

A test:
Effect of $1/M_P$ terms?
Infalling perturbation
Horizon
U
V

Late time ⟷ high energy:



Late time ⟷ high energy:





Nice slice
$\delta|\psi\rangle \sim \frac{i}{M_p^2}\int dV_1 \int dV_2$
$\bar{T}_{1\mu\nu}T_2^{\mu\nu}G(x_1,x_2)|\psi_0\rangle$
Horizon
U
V

w/ $1/M_P$ terms:

estimate $\mathcal{O}(1)$

change in the nice slice state

by the time $t \sim M^3$

Suggests breakdown of perturbation theory, at the required timescale (Page)

This leads to a proposal for how the information paradox is resolved:

1) Hawking's argument for information loss is not reliable; to accurately compute nice slice state need non-perturbative gravity (thus, no paradox)

2) The remaining information problem could be resolved if non-perturbative gravity has appropriate nonlocality

Could supply more details, but another talk ...

similar considerations suggest that perturbative treatment of dS breaks down at time scale

$$t \sim R^3$$

due to large fluctuations.

(possibly related to arguments of Arkani-Hamed et al)

Some conclusions:

- Pert. theory breaks down in HE scattering at sufficiently small b -- intrinsically gravitational
- No clear essential role for strings
- Possible intrinsically gravitational nonlocality?
- Pert thy apparently fails when computing ΔI
- Suggests: nonpert effects restore unitarity, at the price of locality?

What is needed:

the nonperturbative, and quite possibly nonlocal, dynamics

(Is it string theory??)

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	?
Schrodinger eqn	?

What is this "nonlocal mechanics"?