# Black holes, high-energy scattering, and locality

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UCSB and CERN

4th International Sakharov Conference

# There has been much discussion of the BH information paradox.

Message #1:

Message #2:

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Message #1:

Take it seriously!

Message #2:

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Message #1:

Take it seriously!

Message #2:

Can it teach us something about quantum-mechanical gravity?

My current viewpoint: this could play an important guiding role, analogous for example to the instability paradox in going beyond the classical model of the atom

arXiv:0705.2197

# The paradox:

## Hawking, 1974

What happens to information that falls into a black hole?

Emitted in evaporation: locality forbids

Destroyed: violent energy nonconservation

Preserved (remnant): infinite production instability

# The paradox: a conflict between

Lorentz/diff invariance (macroscopic)

Quantum mechanics

Locality (macroscopic)

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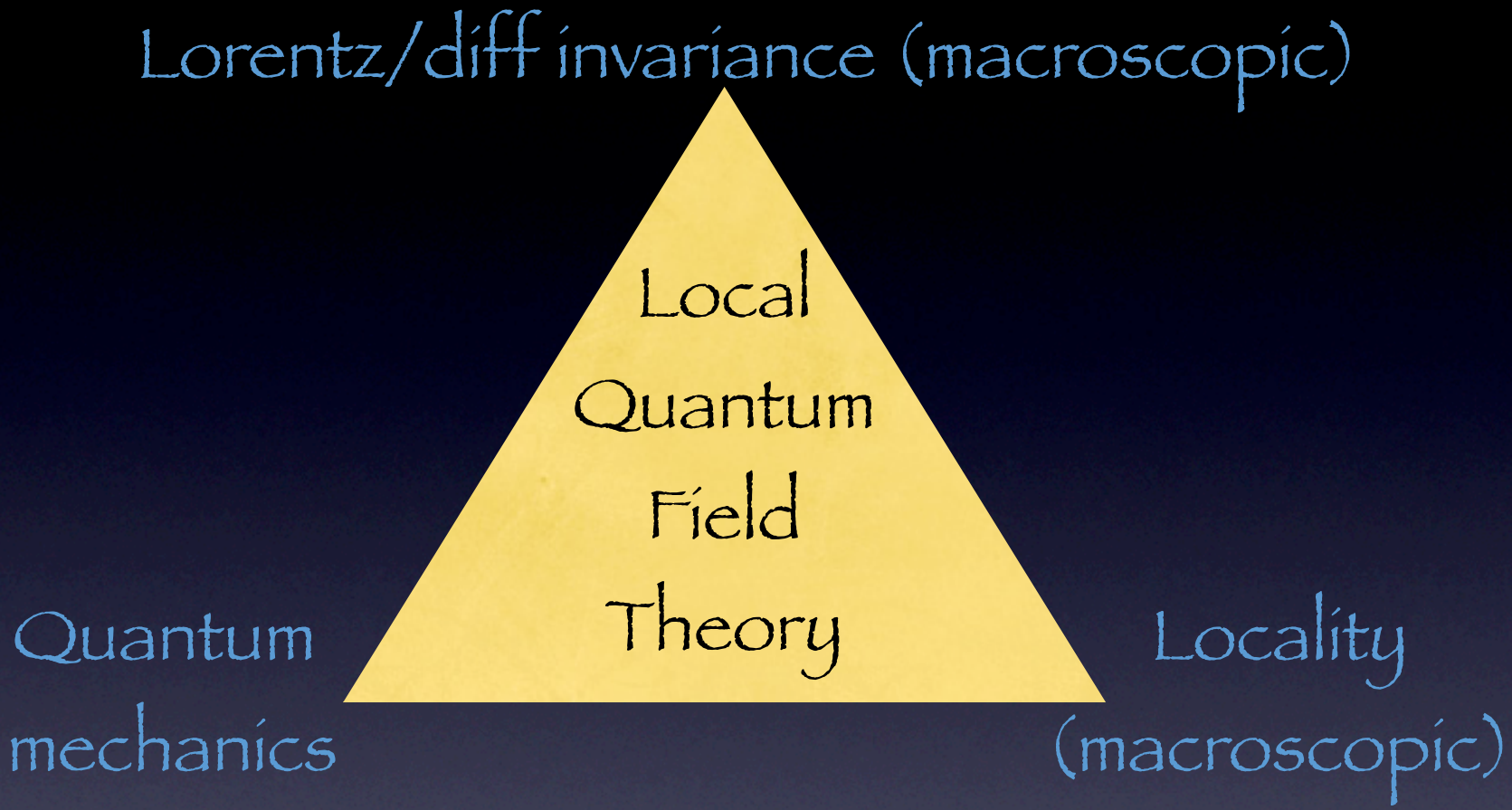

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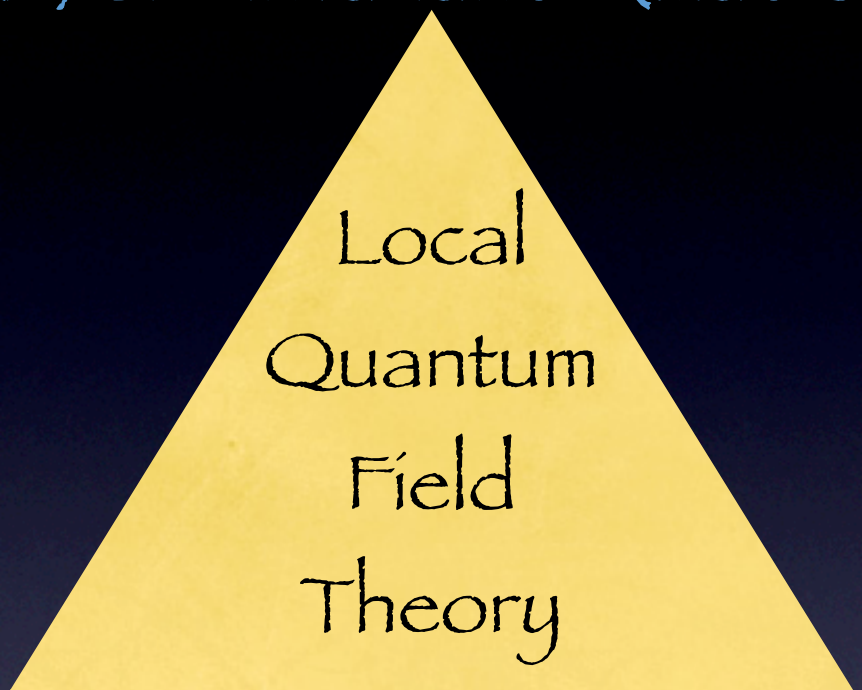


Quantum mechanics

Locality (macroscopic)

Working assumptions:

1) QM -- hard to consistently modify

2) LI -- hard to modify (symm of S-matrix)

# A growing sense: modify locality (at least)

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proposals:

historical order

- "Quantum foam"
- String extendedness
- Horizon scale nonlocality

(SBG, hep-th/9203059)

- Holographic principle;

AdS/CFT

...

These are different, and not entirely complete pictures.

Need a more precise characterization:

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1) Where does locality break down?
   parametrize correspondence boundary

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Need a more precise characterization:

1) Where does locality break down?
parametrize correspondence boundary

2) What is the mechanism?

3) What physical/mathematical framework replaces QFT, and how might locality emerge from it in familiar contexts?

# Possible analogy from history:

# "classical instability paradox"

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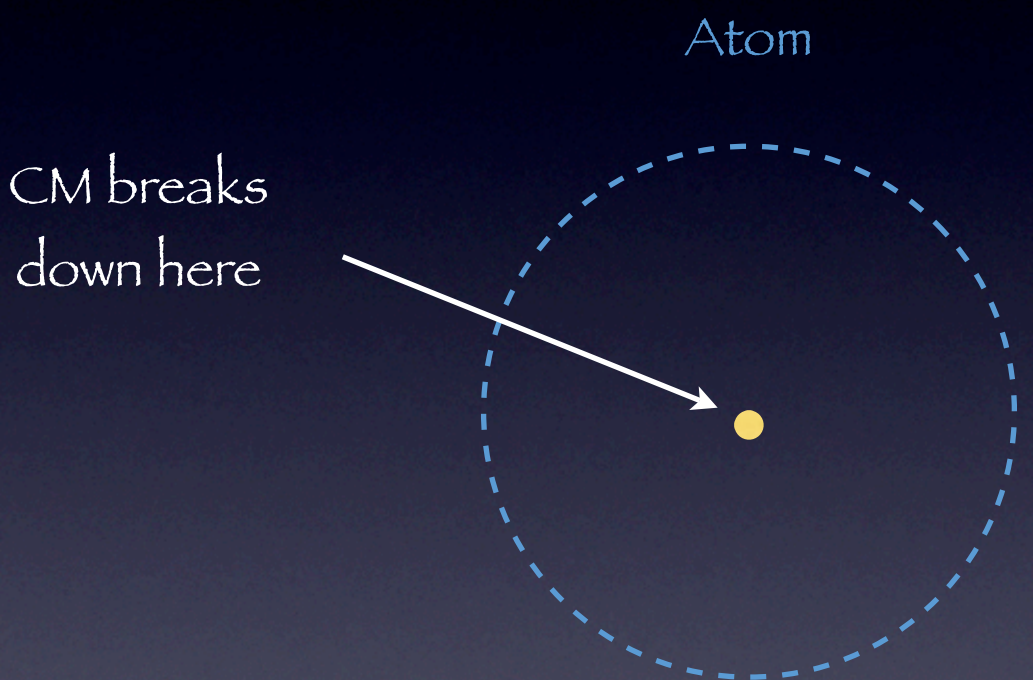

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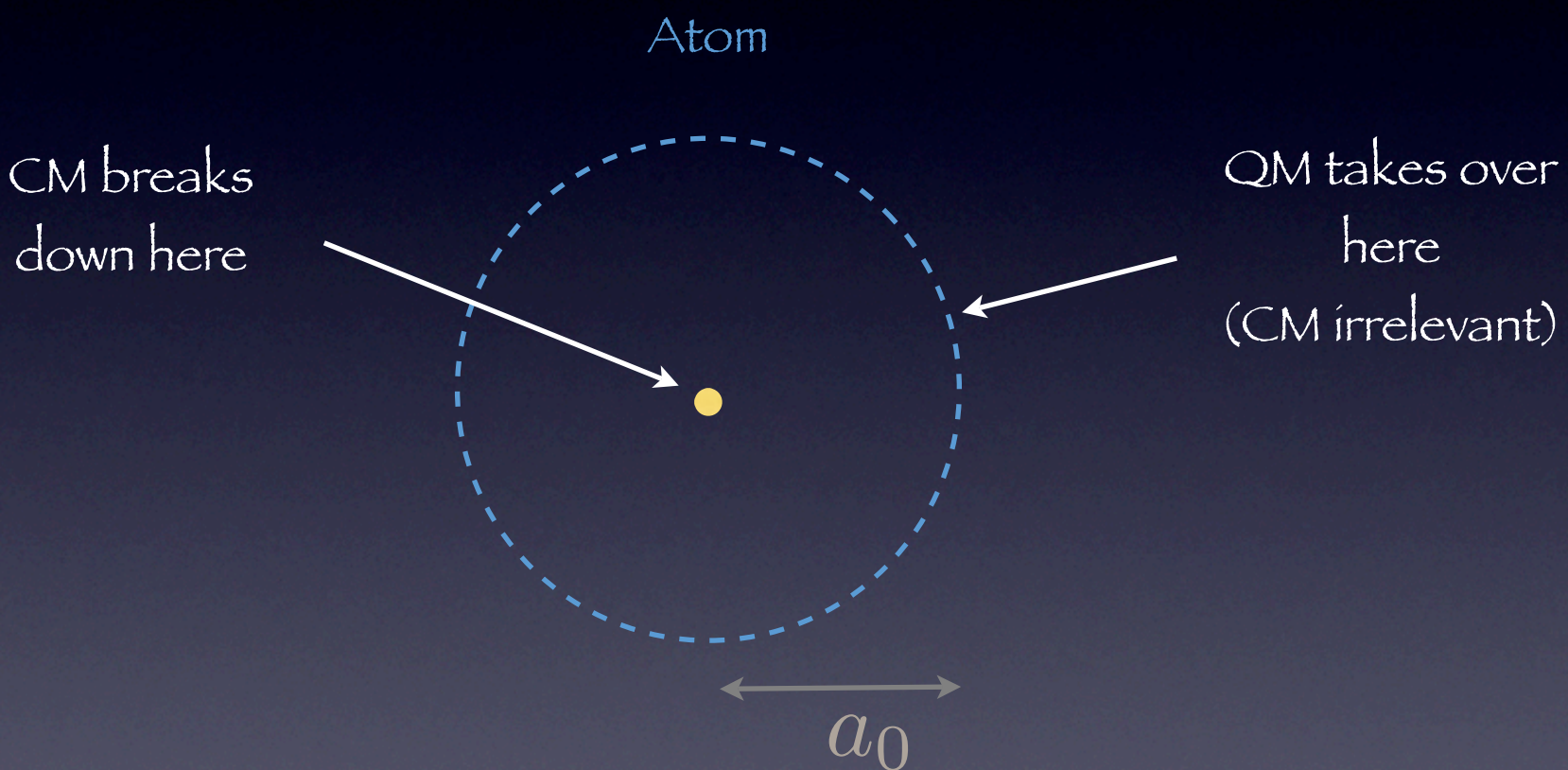



(big surprise: new principles at $a_0 \gg r_N$ )

# Breakdown of classical mechanics:

1) Where fails: $\Delta x \Delta p = 1$ ~~(phase space)~~

(correspondence boundary)

2) Mechanism: wave behavior of matter

classical phase space $\longrightarrow$ quantum wavefunction

3) Framework: Hilbert space; Schrodinger/ Heisenberg mechanics

# Some possible proposals for a correspondence boundary for gravity:

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

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

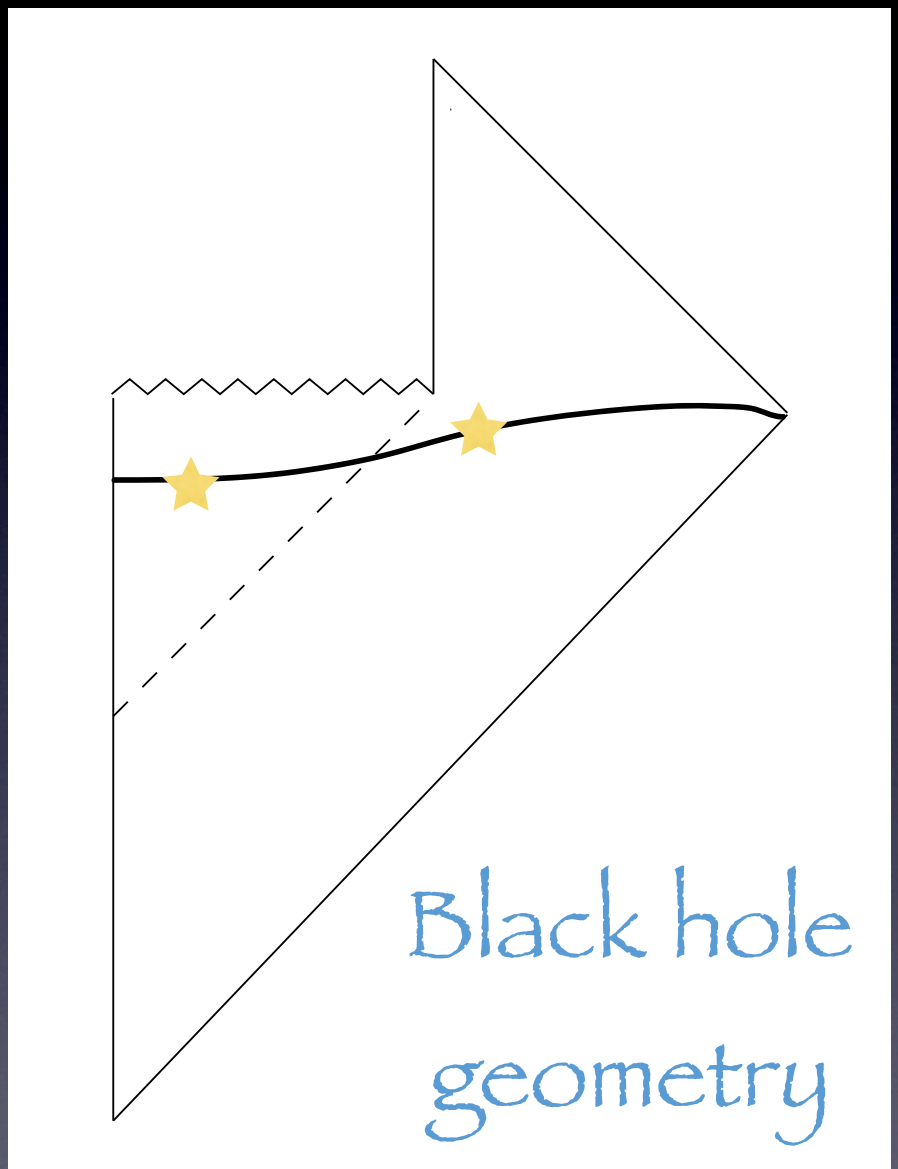
modified dispersion: $p < M_p$

} 1 particle

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

multiparticle

# A hint from the "inside" perspective:



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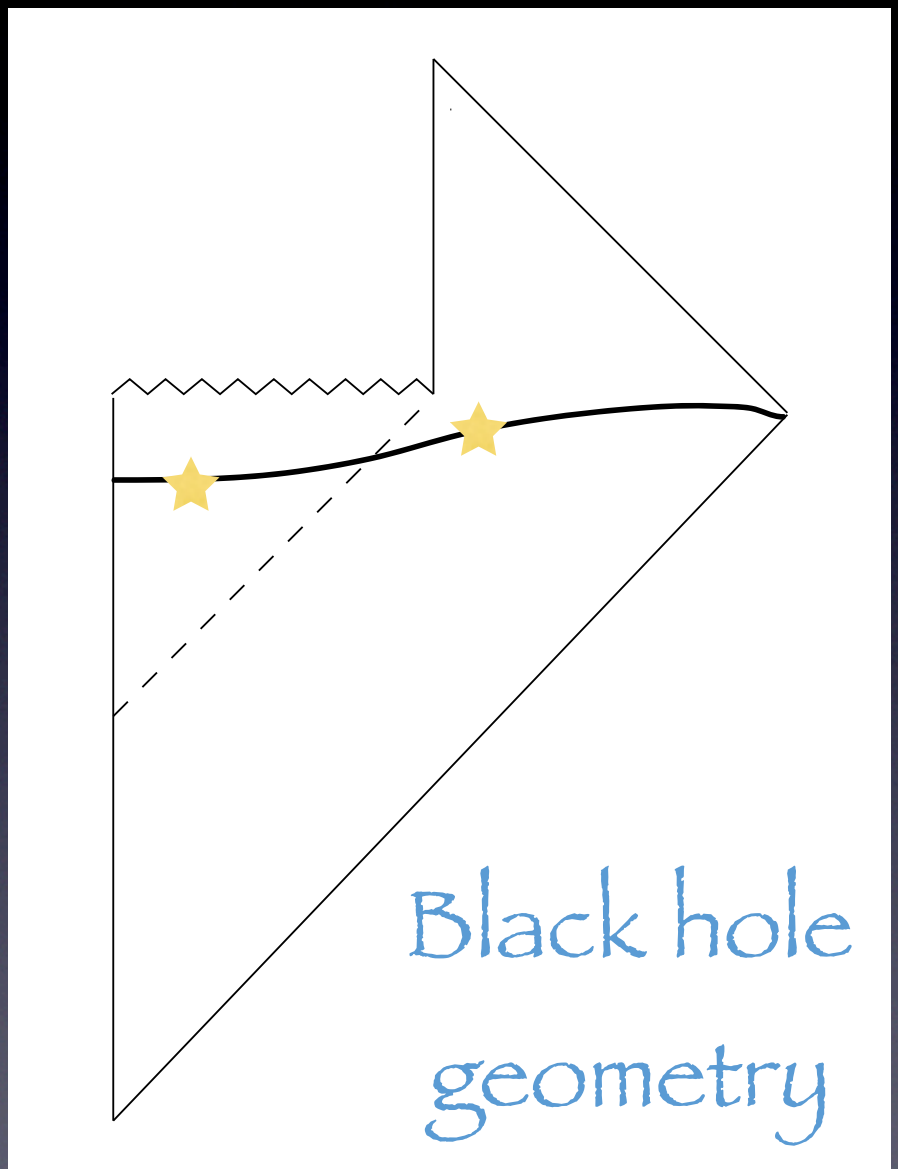
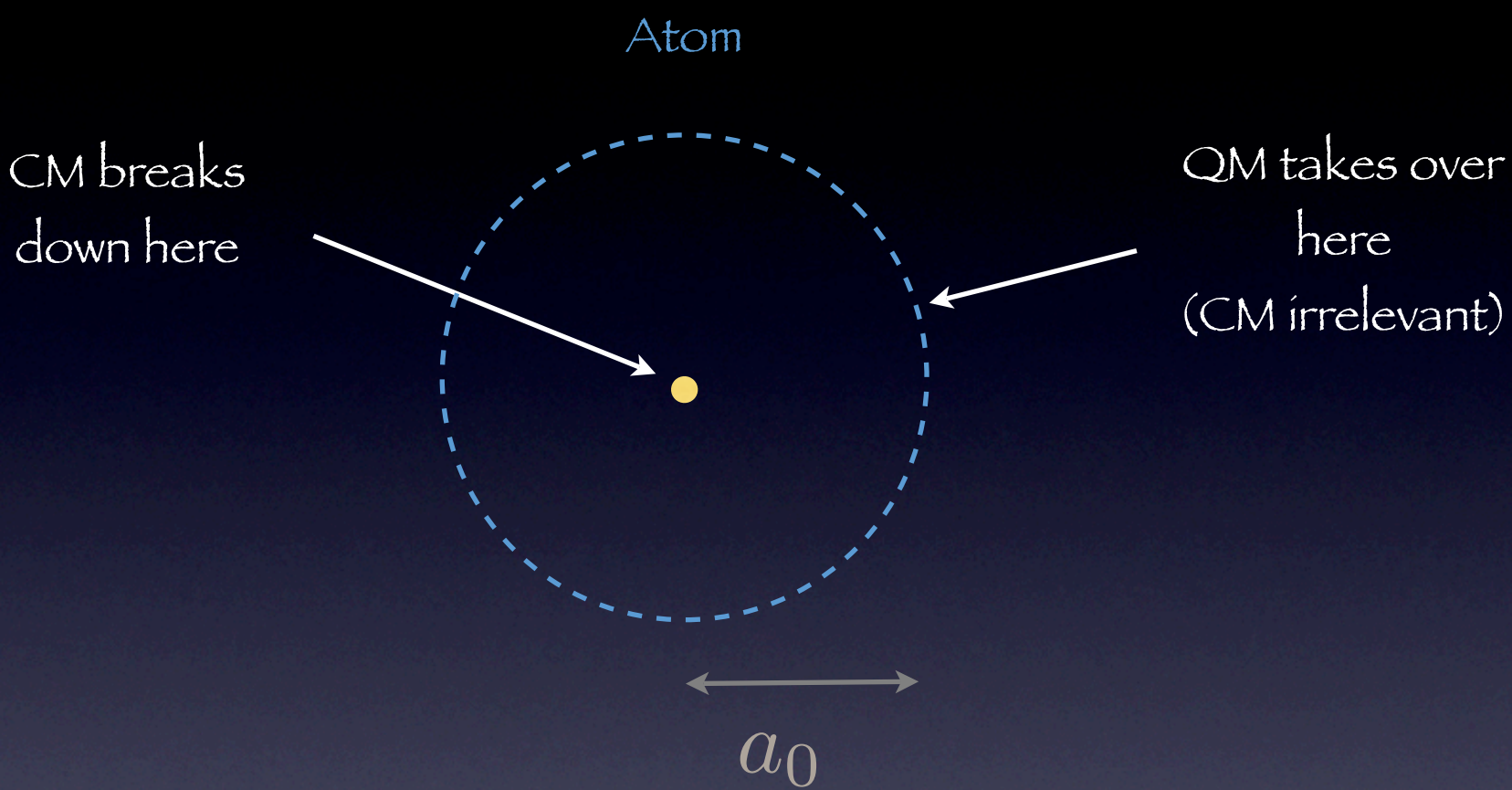



nonlocality needed
on scale $\sim R_S$ ?

# The atomic analogy:



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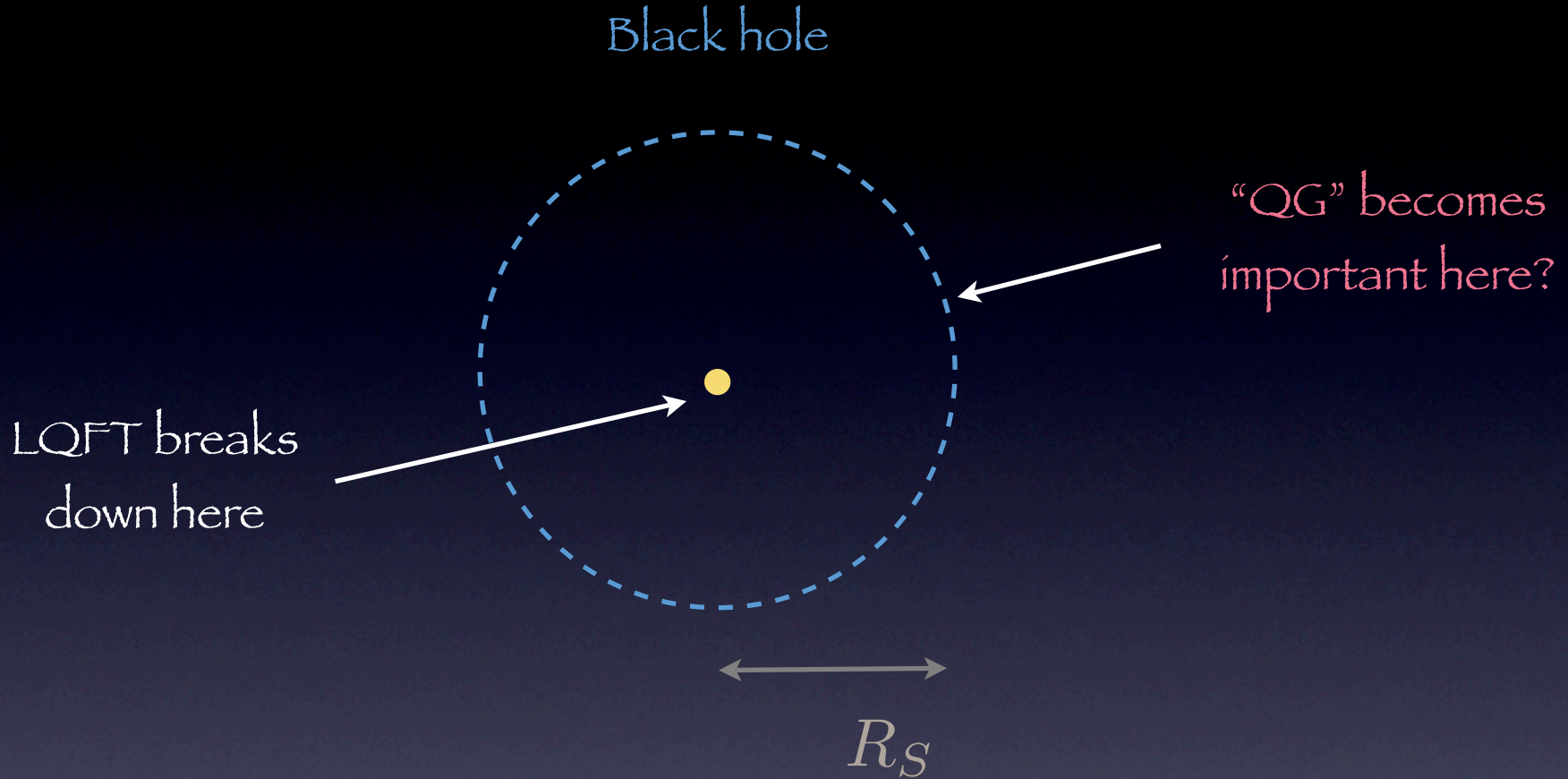


Will suggest: take more literally: new principles at $R_S$

# Probes of locality:

- local observables
- high-energy scattering

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- local observables

- high-energy scattering

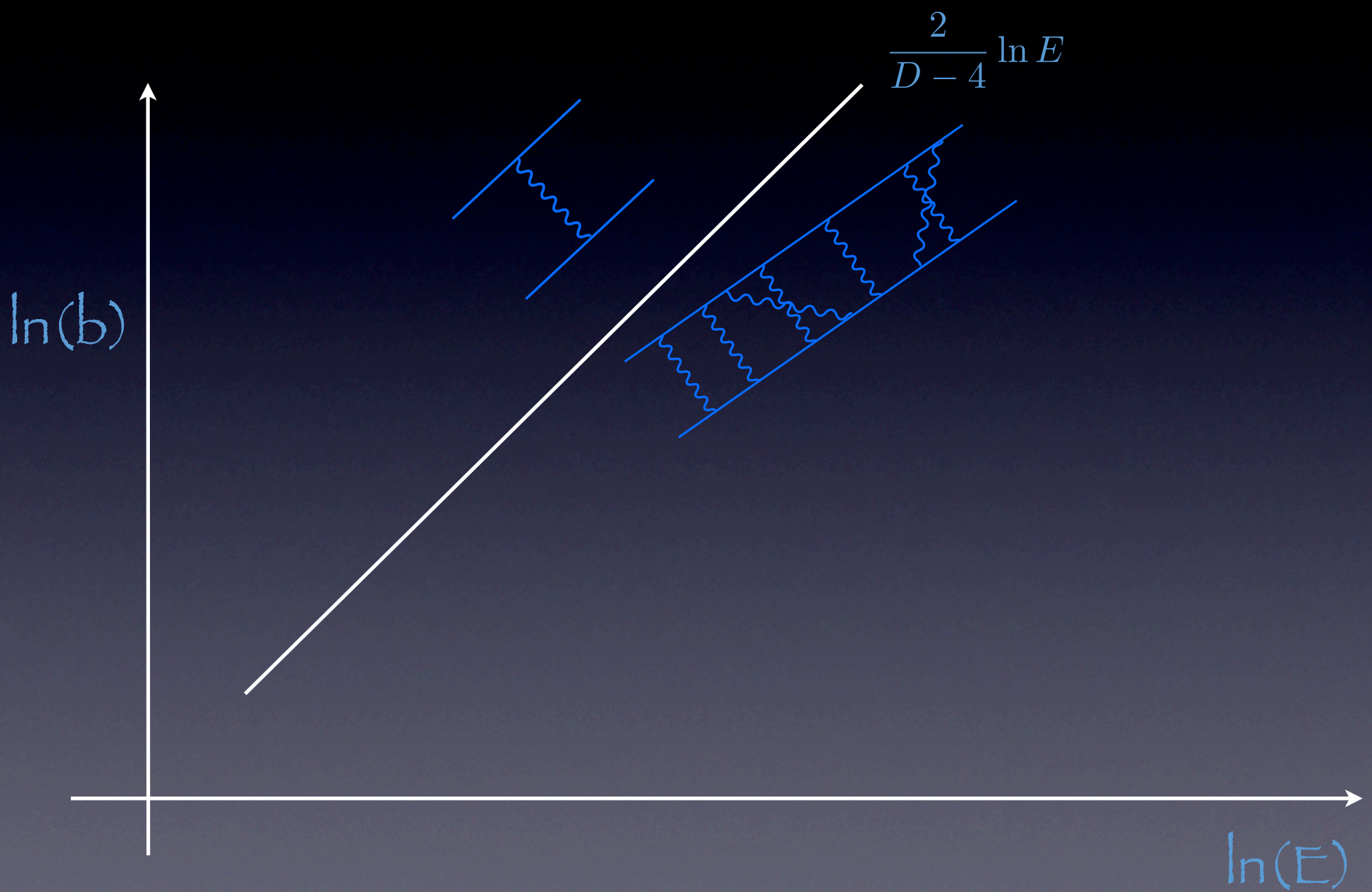
where does present framework break down?

origin of important corrections?

(bear in mind: possible surprises; classical physicist would have never guessed $a_0$ )

Lessons - Amati, Ciafaloni, Veneziano;
't Hooft; SBG, Gross, Maharana; ...

consider strings, or
more generally



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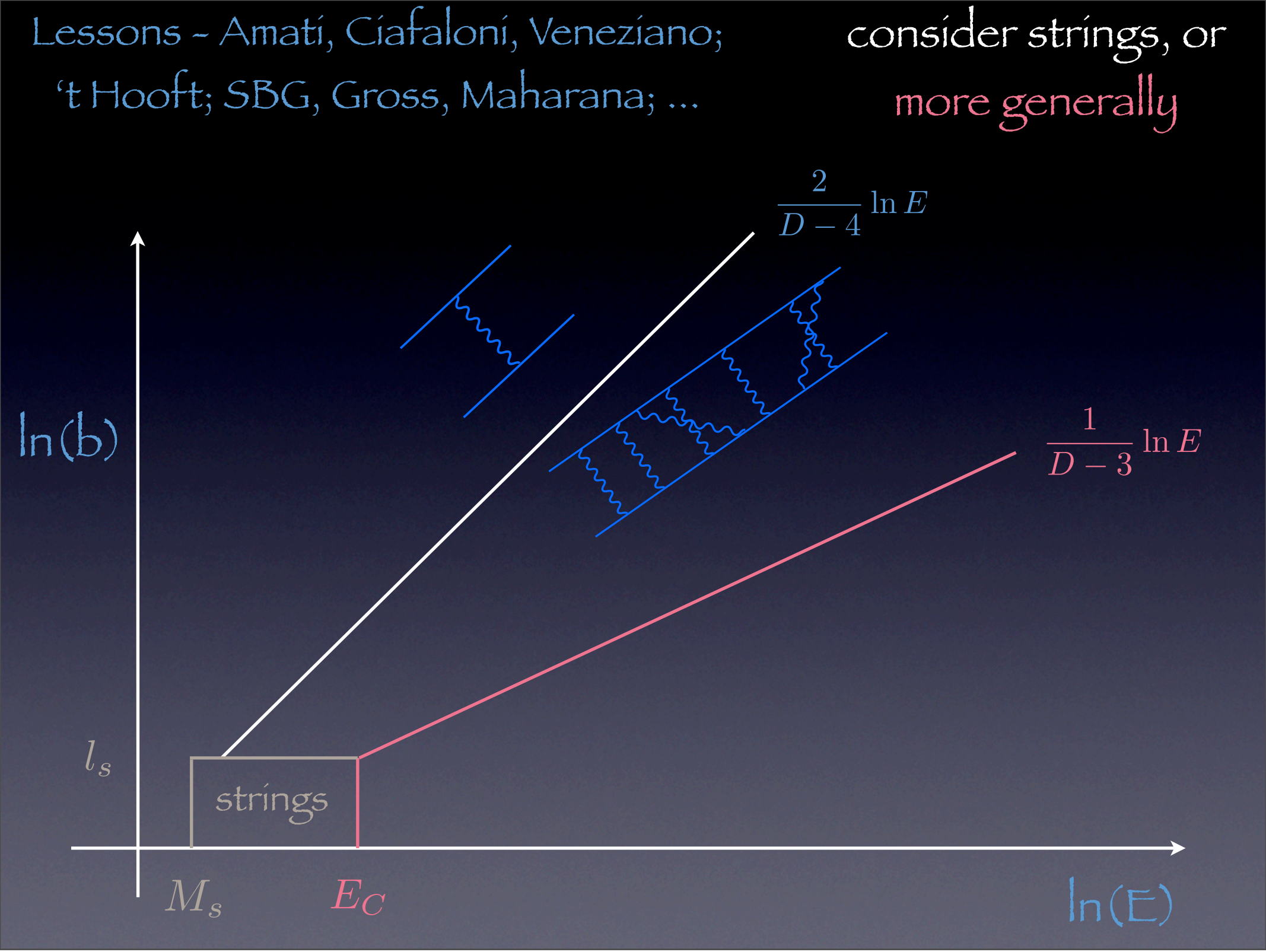

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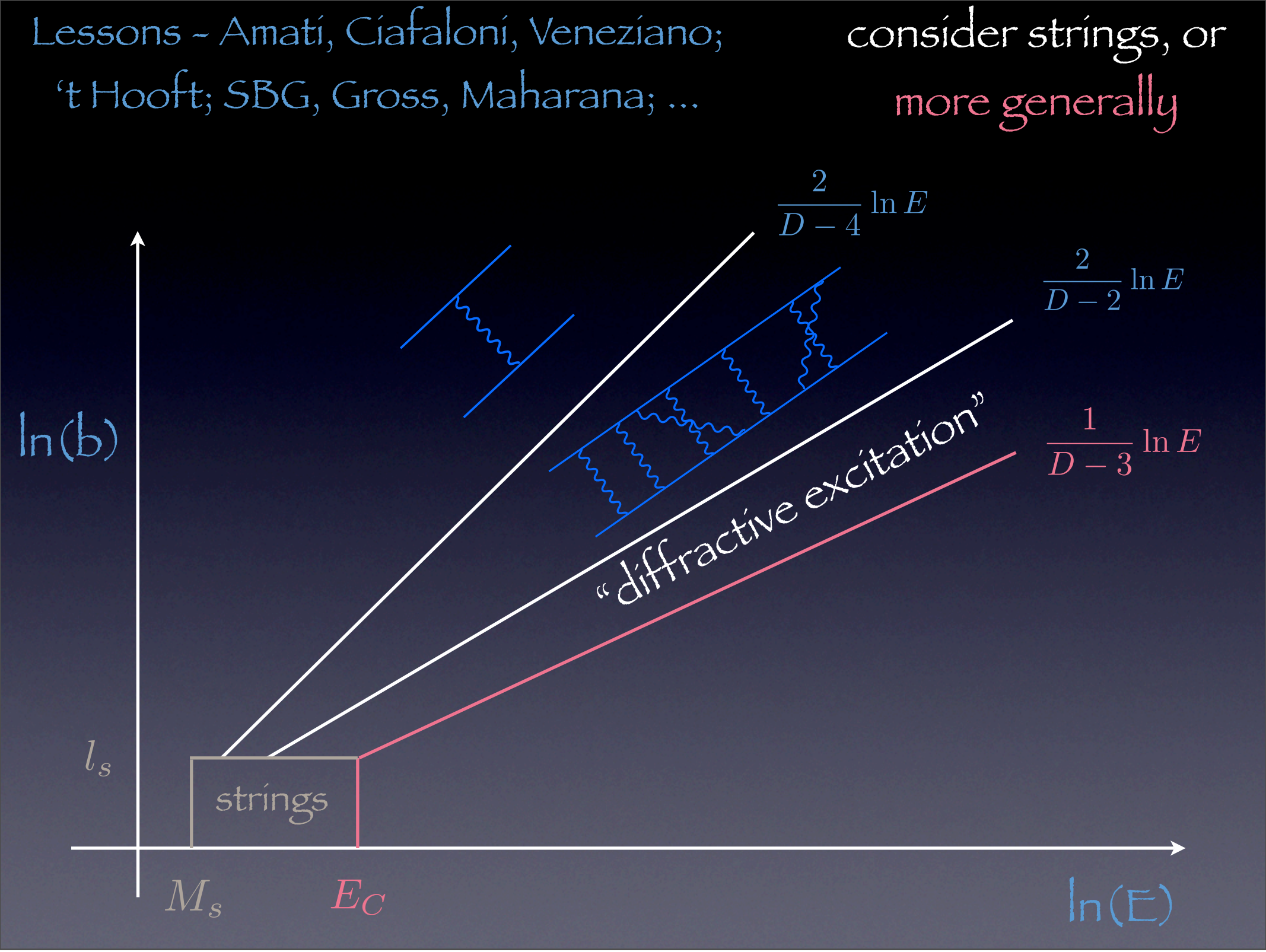
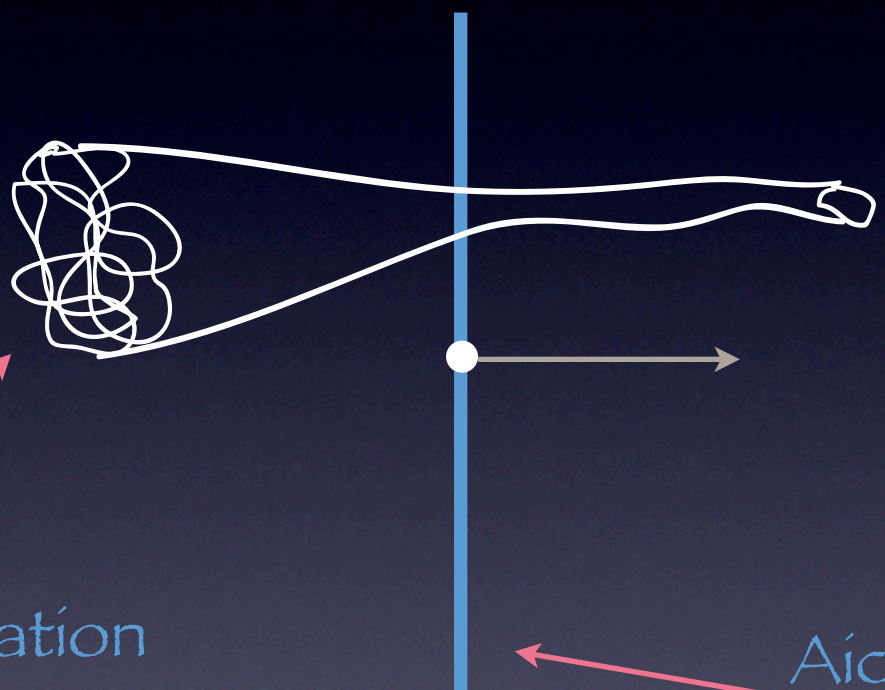


# Q1: understand diffractive excitation

Picture:

hep-th/0604072;
arXiv:0705.1816 w/ Gross and Maharana



asymptotic excitation

Aichelburg-Sexl

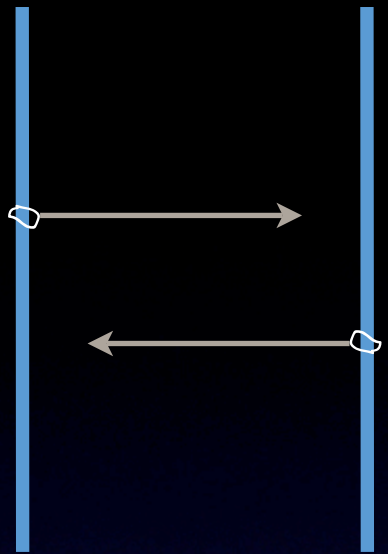
"tidal excitation"

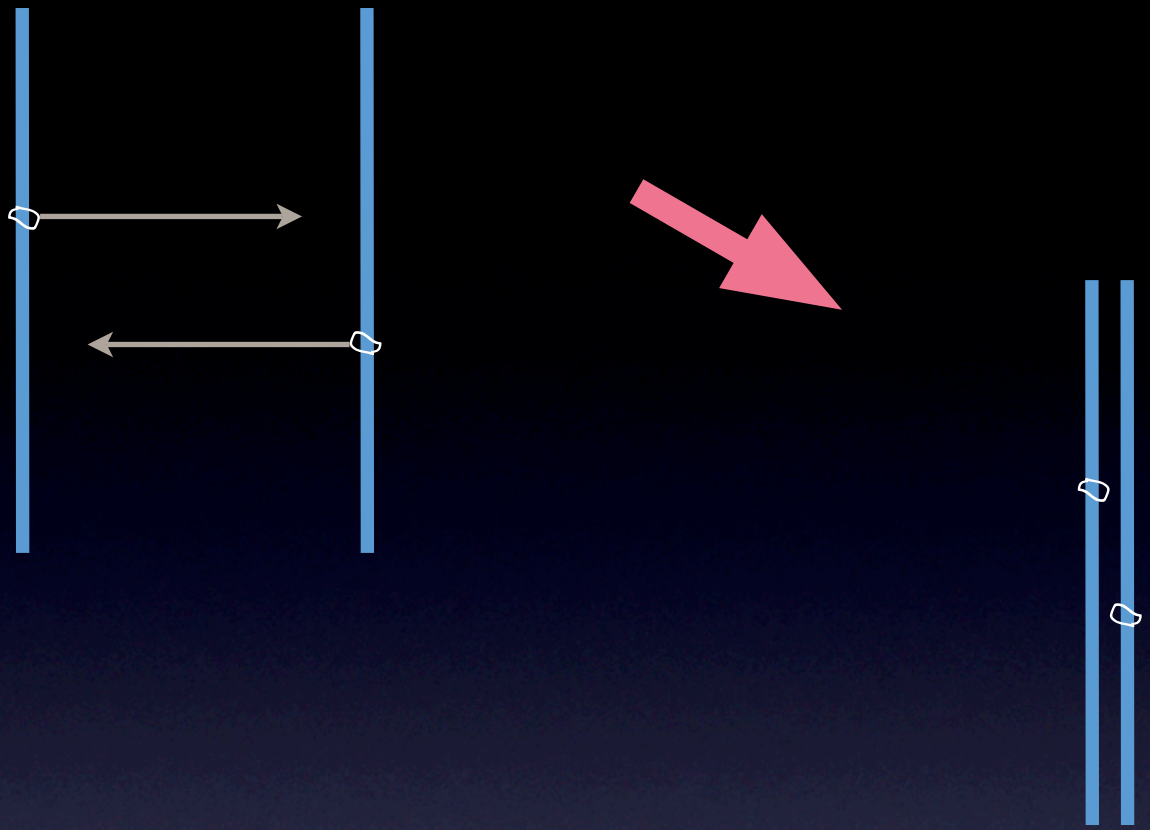
# Q2: what happens at $b \sim R_S(E)$ ?

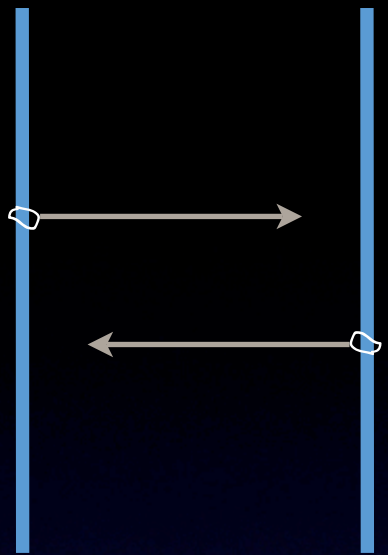
## A) stringy effects?

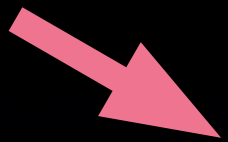
Debates/discussions with
Gross (and others);

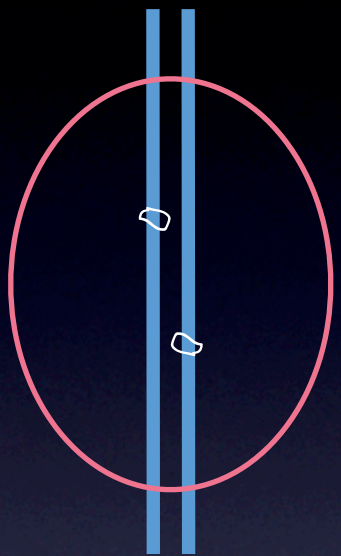
Our discussion converged in writing
GGM:



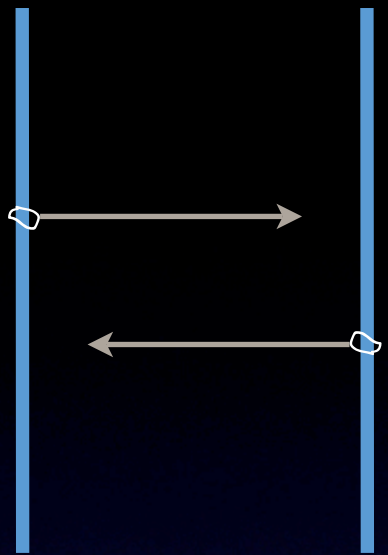


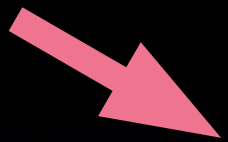


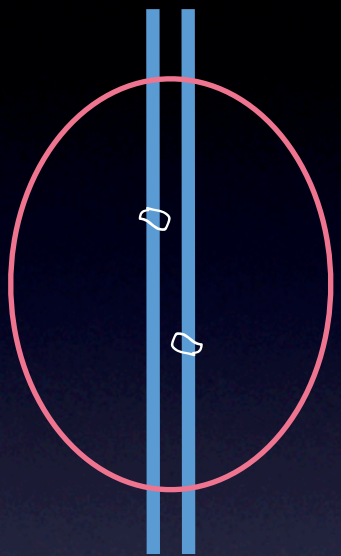




Trapped surface







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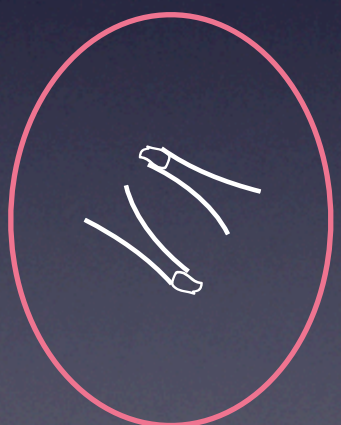

Black hole

Different timescales

No role for extendedness?

# B) What effects are relevant?

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

- Perturbation thy apparently breaks down

- This divergence is not short distance

- Renormalizability (or order-by-order finiteness) doesn't resolve it!

(Indication: unitarity is perhaps a more fundamental issue than renormalizability in gravity?)

This suggests some proposals:

# 1) Proposed correspondence boundary

(or piece thereof)

| | dynamical descript. | validity |
|---|---|---|
| CM: | $x(t)\,,\,p(t)$ | $\Delta x \Delta p > 1$ |

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"locality bound"

(generalizations: N-particle; dS)

SBG & Lippert;
hep-th/0605196;
hep-th/0606146

# 2) Proposed mechanism

## nonperturbative gravity: delocalization

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nonperturbative gravity: delocalization

e.g. isn't obviously: extended strings (or branes)

(correspondingly, clear distinction between "string uncertainty principle" and the locality bound)

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

# How else to probe these ideas?

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## Parameterize our ignorance:

## The S-matrix

General properties of scattering, consistent with unitary quantum evolution, basic properties of gravity

e.g: locality $\longleftrightarrow$ polynomiality?

SBG and Srednicki;

SBG and Porto, WIP

# $2 \to 2$ scattering:

- for large enough D, eliminate IR divs in pert. theory.

- so, conjecture amplitudes are well defined in full theory: $T(s,t)$

# PW expansion:

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

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

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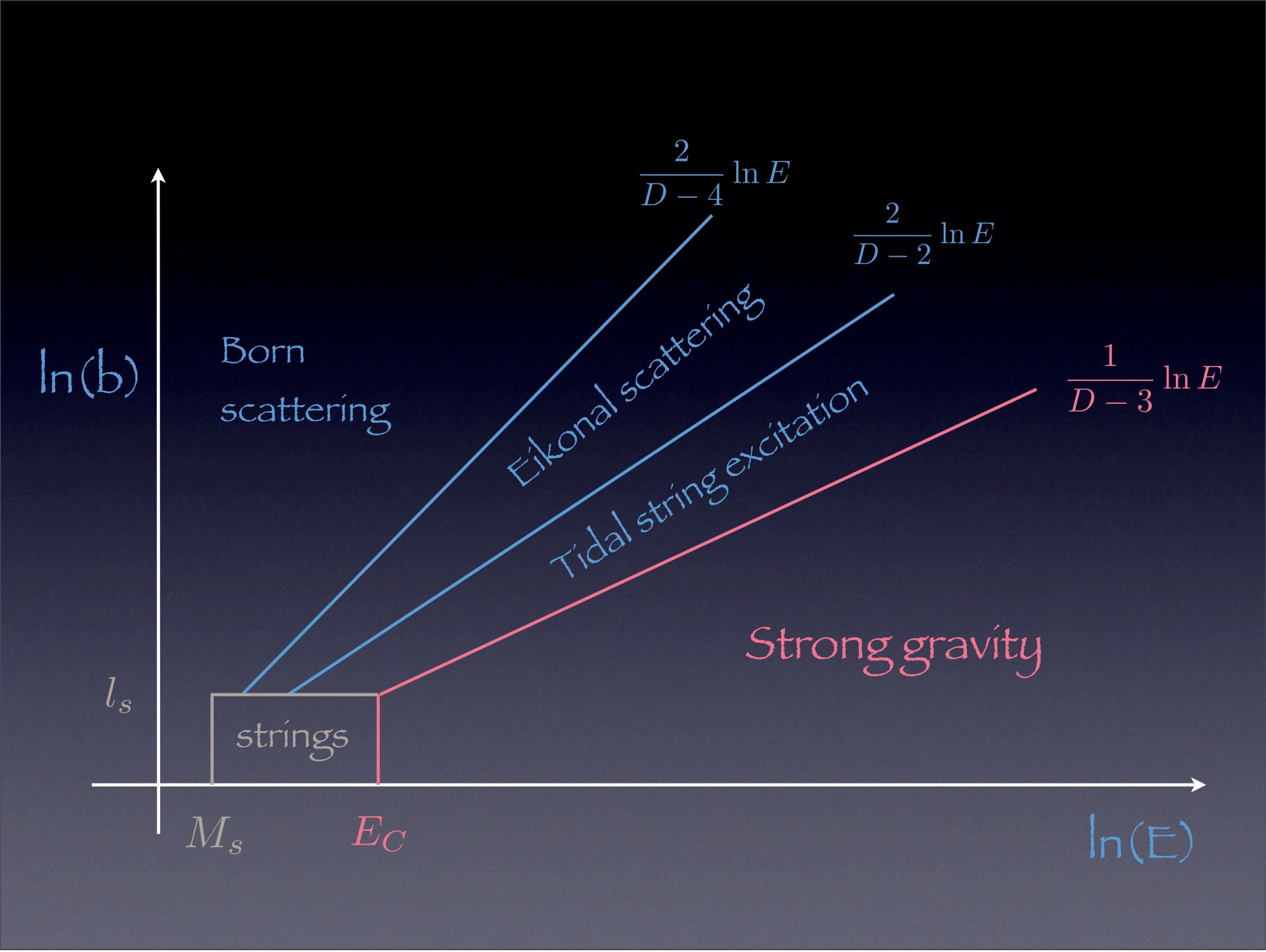
Some features:

A. Understand Born, eikonal regions

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

$\beta_l =$ "unimportant"

(though model dependent)


$\frac{2}{D-4}\ln E$
$\frac{2}{D-2}\ln E$
$\frac{1}{D-3}\ln E$
ln(b)
Born scattering
Eikonal scattering
Tidal string excitation
Strong gravity
$l_s$
strings
$M_s$
$E_C$
ln(E)

## B. Ansatz for BH region

$$l \lesssim E R_S(E) = L$$

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

(Bekenstein-Hawking entropy -- expected if approx. thermal description)

(likewise, Ansatz (modified) for real part

$$\delta_l(E) \sim \pi S(E,l)$$

- though not critical for following observations?)

## Features:

- both absorptive and eikonal amplitudes violate Froissart; e.g.

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

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- related point, amplitudes not polynomial:

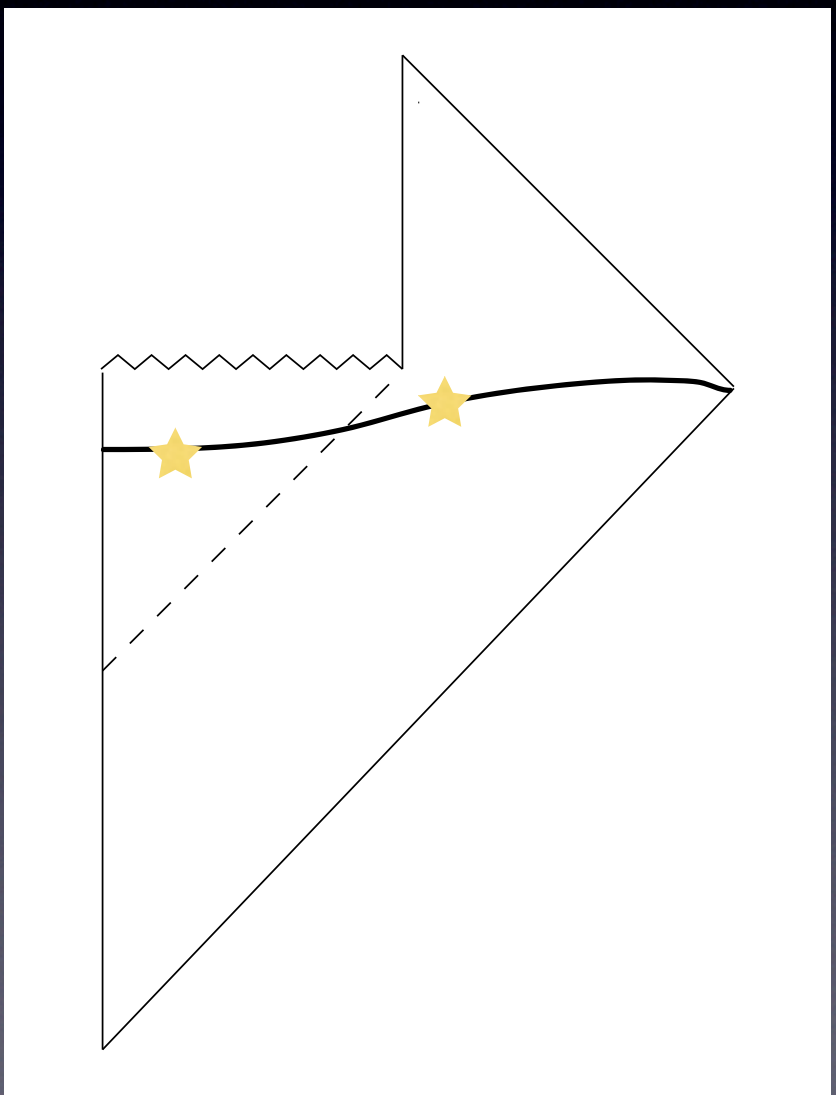
$$T(s,t) \sim e^{s^\alpha t^\beta}$$

plausibly associated w/ lack of usual locality?

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

# Another way to probe these ideas:

# Where did Hawking go wrong?



"Nice slice argument"

inside viewpoint

apparently require
nonlocality on scale $\sim R_S$

A) perhaps the correct theory simply doesn't accurately describe the collection of nice slice states, just as quantum mechanics doesn't accurately describe phase space at $\Delta x \Delta p < 1$

(though, expect approx. description of infalling obs.)

B) See breakdown of QFT+GR on nice slices

some evidence: (hep-th/0703116)

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ii) Quantization on nice slices: fluctuations and large backreaction

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ii) Quantization on nice slices: fluctuations and large backreaction

both by: $t \sim R_S S_{BH}$

# More precise investigation:

Need to understand (~) local observers/observables

(diff. invariance: no exact local observables)

... also for cosmology!

# Relational approach (Thursday talk):

## "proto-local observables"

see: SBG, Marolf, Hartle;

Gary & SBG: 2d, concrete

Basic idea: $\mathcal{O} = \int d^4x \sqrt{-g} B(x) O(x)$

$\langle B(x) \rangle = b(x)$

for appropriate background: $\langle \mathcal{O} \rangle \approx O(x_0)$

localization relative to background

- exploring in cosmological contexts

e.g. dS: SBG & Marolf and WIP

- localization only approximate

- e.g.: fail to reproduce local obs. when locality bd. violated

- thus, fits with the notion that usual notion of locality is not exact in gravity

# Other ways to proceed?

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## perturbative ~~string~~ theory

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perturbative ~~string~~ theory

non-perturbative?

AdS/CFT or Matrix: dual theories

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## Are strings the answer?

perturbative ~~string~~ theory

non-perturbative?

## AdS/CFT or Matrix: dual theories

## Warmup: can extract the flat-space S-matrix?

arXiv:0903.4437 w/ Gary & Penedones: Some success (plane wave lim.)

arXiv:0904.3544 w/ Gary: Some apparent limitations

(another talk...)

## How can string theory address these questions?

# More generally:

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A highly non-trivial set of conditions to satisfy!

Might this help guide us to such a "Non-Local (but Nearly-Local) Mechanics"?

## Approaches:

1) Better understanding of properties of S-matrix

(WIP w/ Porto)

2) Investigate other general aspects of theory

e.g. one small piece: generalize QM sufficiently to not require spacetime input

a very modest suggestion in this direction:

arXiv:0711.0757: ~ generalization of S-matrix framework; apply to cosmology, etc.

relational/proto-local observables

...

# What should we conclude?

1) Multiple considerations (HE scattering; observables; BH information, ...) suggest modification of conventional notion of locality - at long distances.

possible slogan:

"unitarity restored at the price of locality"

(though the nonlocality may be less radical than some aspects of holography?)

## 2) Mechanism:

- no obvious role for string extendedness

- non-perturbative gravity: not local by usual measures

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- no obvious role for string extendedness

- non-perturbative gravity: not local by usual measures

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

Likely not "quantum gravity" -- i.e. quantized version of geometry. too local, too classical, ...

Not yet clearly addressed in string theory

(important to understand if could be)

## 3) In what circumstances does locality fail?

modest proposals for part of "correspondence boundary" for such a "nonlocal (but "nearly-local) mechanics:"

locality bound, and other related bounds

## 4) General principles?

Very modest steps: properties of HE scattering; proto-local observables; appropriate generalization of QM

It is important to:

- ask the right questions
- discard superfluous constructs

Apparently non-trivial constraints: locality without locality, ...