Beyond the Planck scale

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The Planck Scale -- XXV Max Born Symposium

Suggestion: focus on the Planck scale may be misleading

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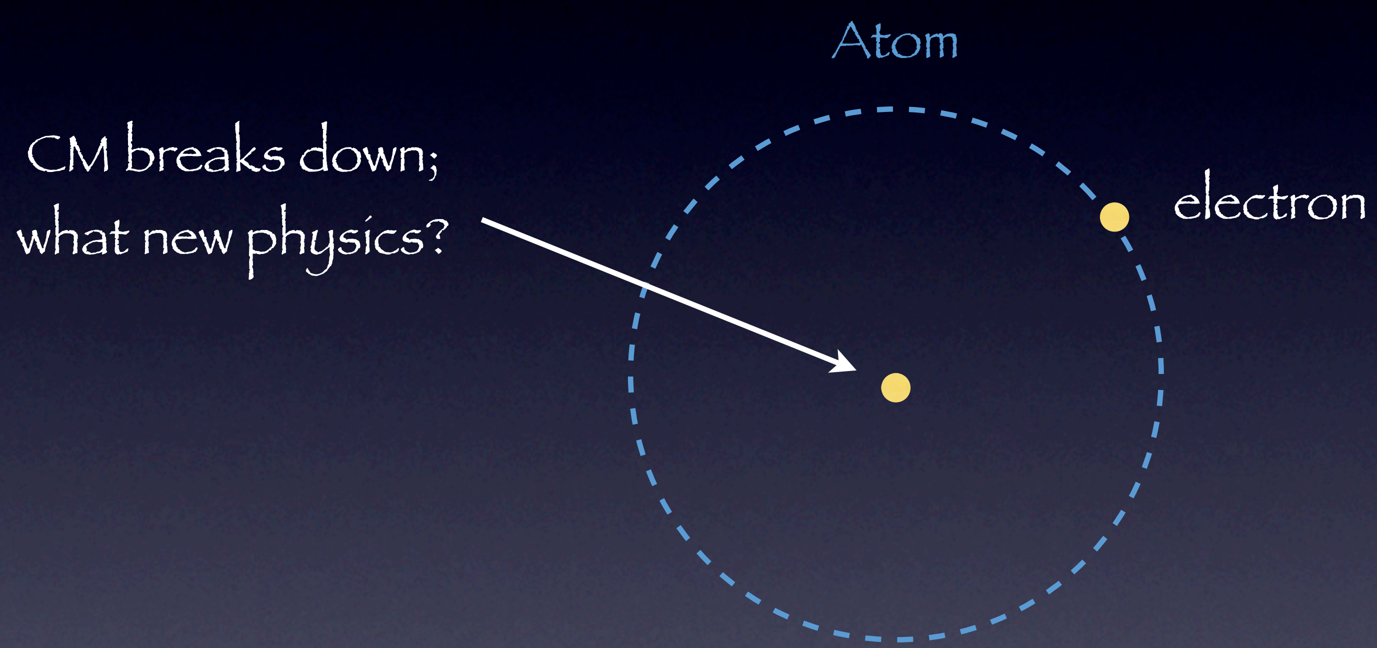
possible theoretical analogy: "classical instability paradox"



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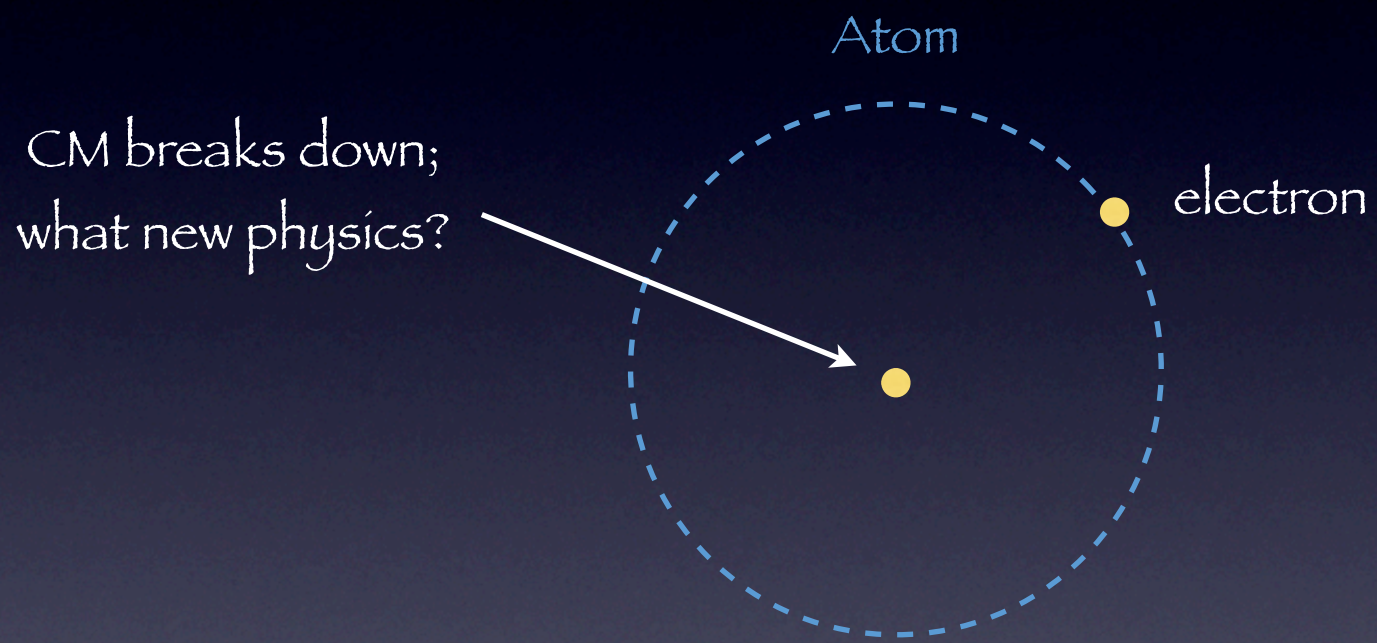

Experiment guided the resolution:
1) a different scale (a_0) 2) new principles (QM)

Plan:

1) Review arguments

(If you see a better alternative, tell me)

2) Summarize some ongoing work on the problem

A complete theory of quantum gravity should describe (or avoid) ultraplanckian collisions

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e^-

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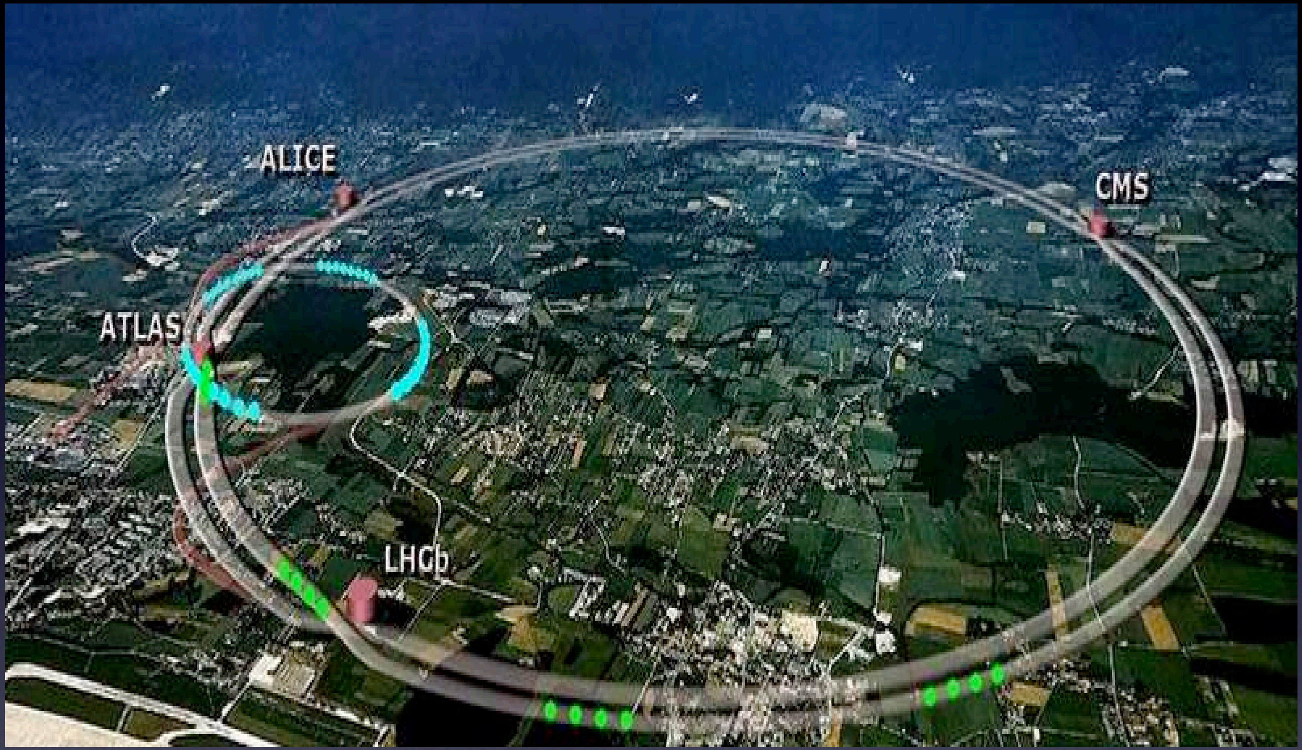
Just need: 1) Lorentz invariance

2) very weak notion of locality

(LI violation might postpone...)

In TeV-scale gravity models, even

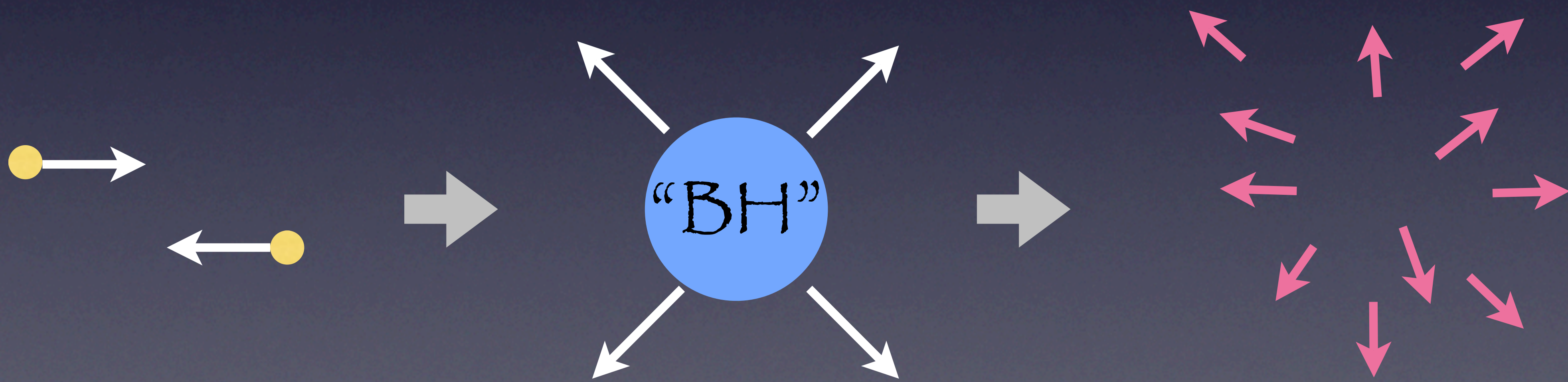


at LHC!

(A review: arXiv:0709.1107)

$E \gg M_p$: dynamics

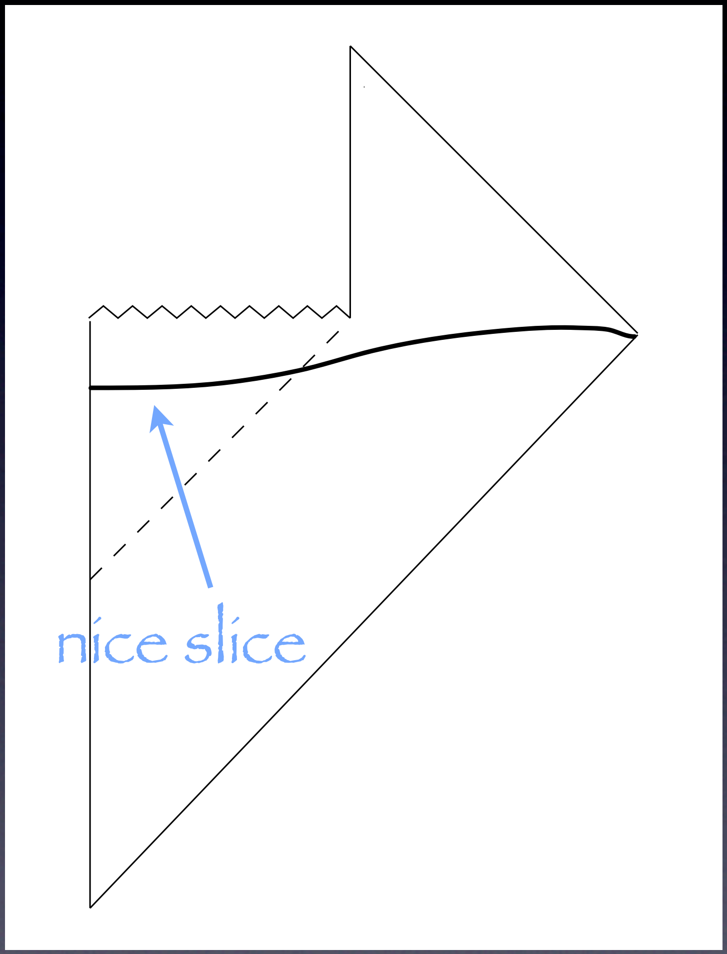
- Control impact parameter b -- wavepackets
- Large E: $\sim$ semiclassical picture
- Classically, produce black hole, + radiation
- Quantum corrections: Hawking radiation



(Indeed, ~~LI~~ doesn’t avoid, if form BHs other ways)

So, confront information paradox:

Hawking, updated: nice slice argument



Locality:

$$|\psi_{NS}\rangle \Rightarrow \rho_{out} = \mathrm{Tr}_{in}|\psi_{NS}\rangle\langle\psi_{NS}|$$

$$S_{BH} = -\mathrm{Tr}\left(\rho_{out} \ln \rho_{out}\right) \sim A_{BH}$$

$\therefore$ information lost

(Hawking, 1976)

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Such breakdown of QM $\Rightarrow$ Massive E nonconservation

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Such breakdown of QM $\Rightarrow$ Massive E nonconservation

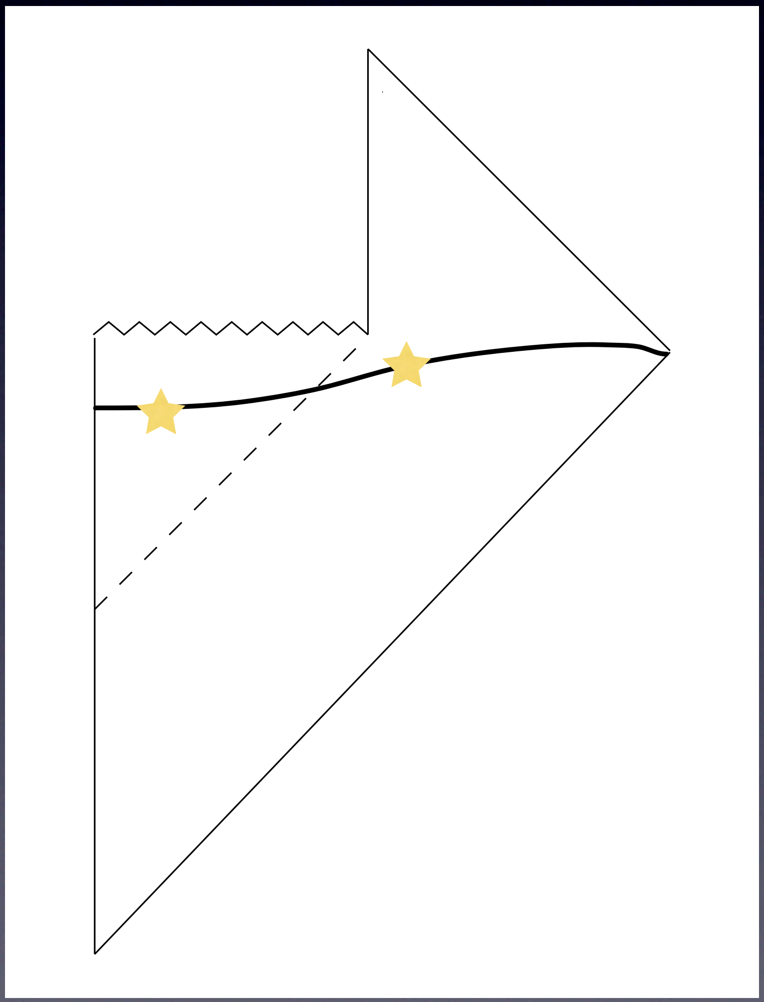
$\therefore$ Let's try to keep unitarity!

Info storage in remnants? Infinite species

Infinite production instabilities

(See e.g. hep-th/9310101, hep-th/9412159)

So, keeping Lorentz invariance and quantum mechanics apparently tells us to revisit locality:



On scale :

$$R_S \propto (G_D M)^{1/(D-3)}$$

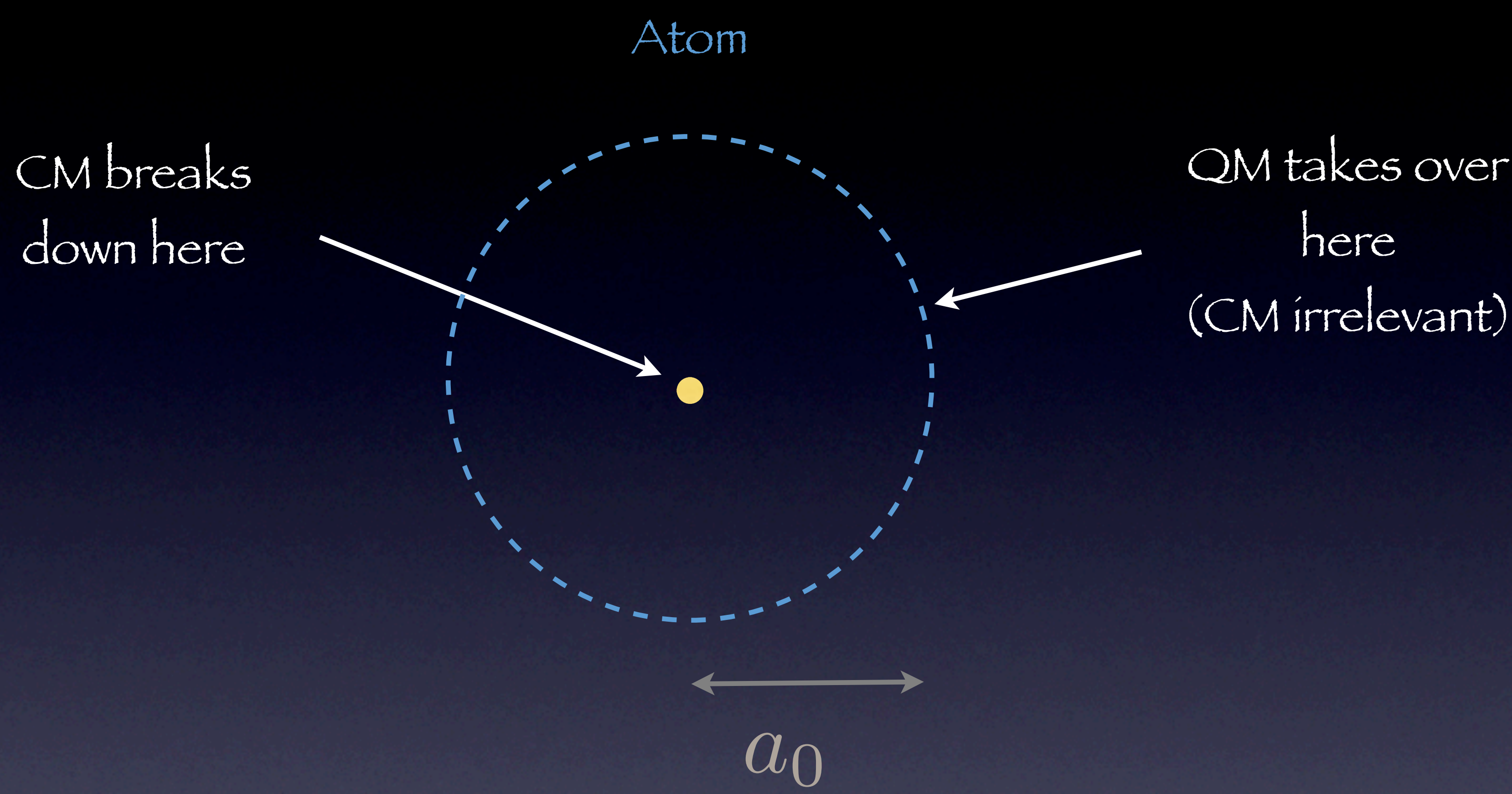
$$>>> l_p$$

By a time:

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

(Page, hep-th/9306083)

The atomic analogy:



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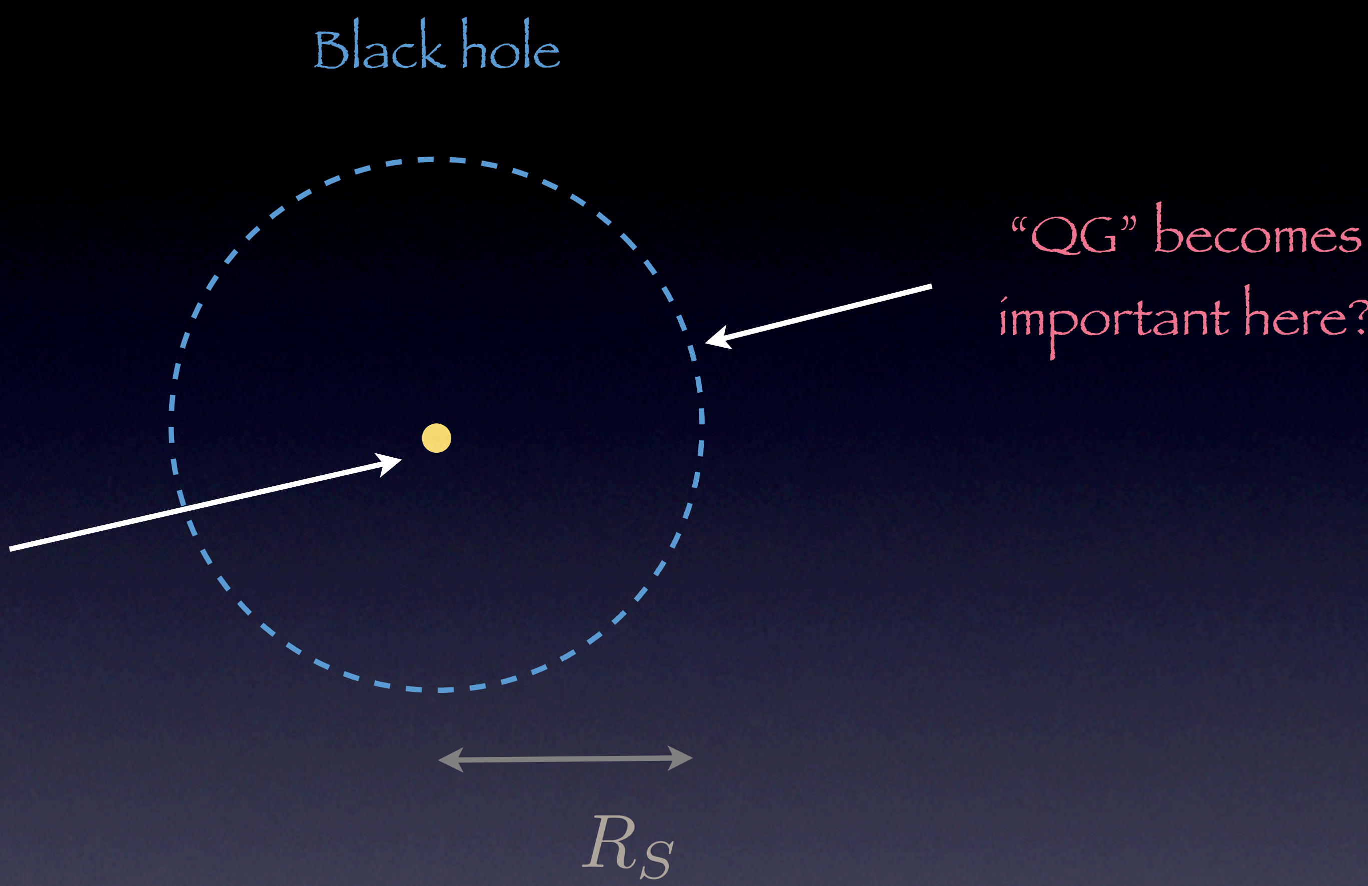


Suggestion: take literally -- new principles at R_S

What does string theory say?

Hints(?) at a solution:

- addresses nonrenormalizibility
- extendedness/nonlocality
- microstate counting, etc.

Idea: "holography:"

D-dim. grav $\equiv$ (D-1) non-grav unitary thy

(AdS/CFT)

But ...

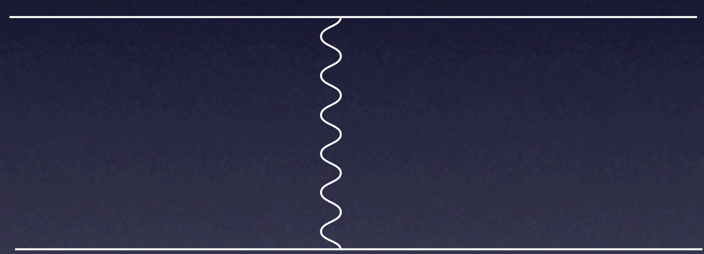
1) No apparent role for string extendedness

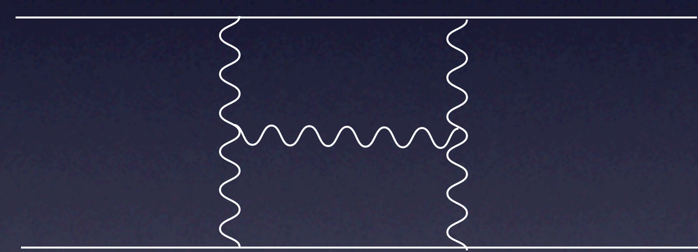
SBG, hep-th/0604072

SBG, Gross, Maharana, arXiv:0705.1816

"different time scales"

2) The problem appears intrinsically nonperturbative





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

(unitarity a more critical issue than renormalizability ?)

3) Microstate counting: not far from BPS

(Schwarzschild)

4) Holographic "duals" don't clearly contain sufficient information

- A test: recover the flat space S-matrix

Limited progress: Gary, SBG, Penedones arXiv:0903.4437

Potential obstacles: Gary, SBG arXiv:0904.3544

- No understanding of ~ local observables

(And such strong holography seems possibly overoptimistic)

Whether or not strings the solution ...

Questions to answer:

1) Where does local QFT fail? Correspondence boundary

what is wrong with nice slice argument?

2) What is the mechanism?

how does it preserve unitarity?

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

how to preserve consistency/causality?

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

modified dispersion: $p < M_p$

$\Big\}$ 1 particle

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

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

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$\boxed{\text{“locality bound”}}$

(generalizations: N-particle; dS)

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

Correspondingly, mechanism:

"delocalization w.r.t. semiclassical geometry, intrinsic to unitary dynamics of nonperturbative gravity"

~ "nonlocality principle"

contrast with: extended strings (or branes)

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

How do we probe/quantify locality?

- local observables

- high-energy scattering

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Asymptotically flat space:

The gravitational S-matrix

Investigate general properties of scattering, consistent with unitary quantum evolution, basic features of gravity

e.g: locality $\longleftrightarrow$ polynomiality?

SBG and Srednicki arXiv:0711.5012

SBG and Porto, WIP

$2 \to 2$ scattering: PW expansion:

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

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

A. Can infer features of δ_l, β_l in "weak gravity" regime (large impact param. -- Born, eikonal)

B. Ansatz for BH region $l \lesssim ER_S(E) = L$

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

(Bekenstein-Hawking entropy - approx. thermal description)

Features:

- significant indications, amplitudes not polynomial:

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

plausibly associated w/ lack of usual locality?

(related: viol. of Froissart, eg $\sigma_{BH} \sim [R_S(E)]^{D-2}$)

- interesting constraints from crossing

(not "too" nonlocal)

This is "outside" (asymptotic) viewpoint. To discuss "inside," need local observables

Indeed, locality - QFT:

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

Diff invariance $\Rightarrow$ None in gravity!

Likely resolution: Relational approach:

"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

But: - localization only approximate

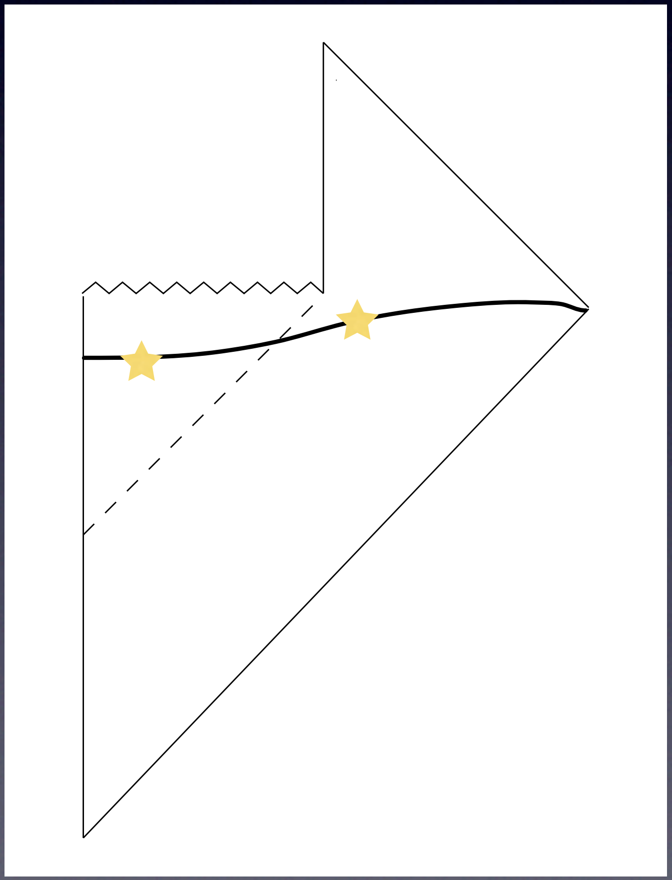
- must include background/observer

In the inside perspective, can find flaw in nice slice argument, and see where Hawking went wrong?

Some thoughts:

hep-th/0606146

Sharp computation of S_{BH} requires fine-grained, local $|\psi\rangle_{NS}$



Two potential obstacles:

1) observ. background $\Rightarrow$ large mods. to $|\psi\rangle_{NS}$

2) backreaction of fluctuations $\Rightarrow$ large mods. to $|\psi\rangle_{NS}$

Both by $\tau_{Page} \sim R_S S_{BH}$

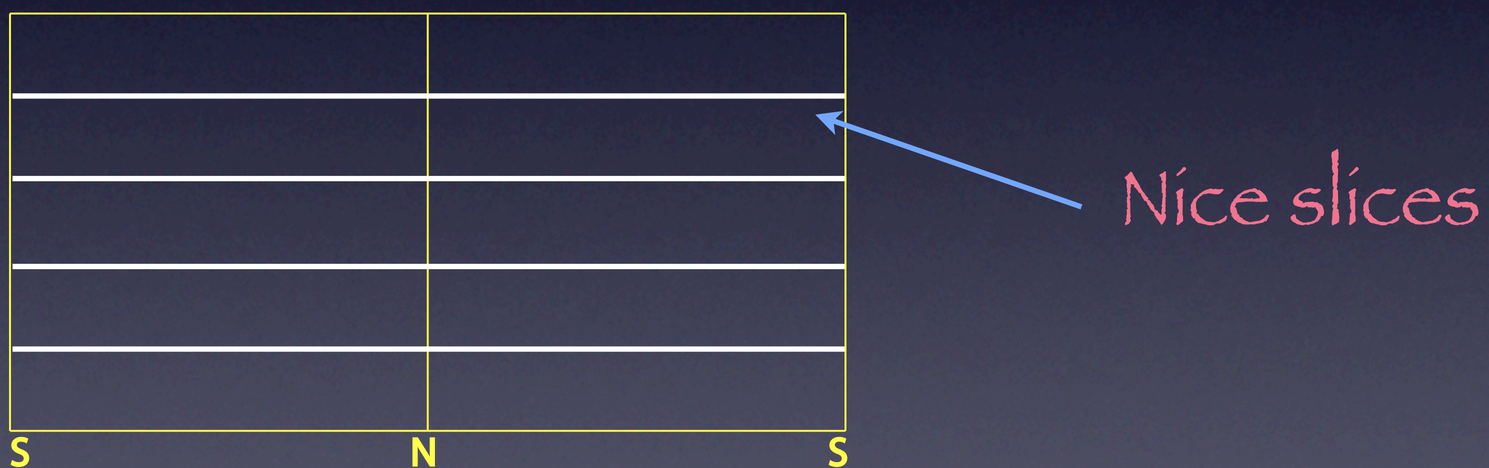
(literal CM/QM analogy may be another out...)

- Apparent signals of perturbative breakdown; proposed resolution of information paradox

- Non-pert. completion would be required to describe information "relay"/ restore unitarity

but, a clue ...

- Interestingly, there are parallel arguments in dS,



suggesting LQFT incomplete after $\tau \sim R_{dS} S_{dS}$

(Likely related argument: Arkani-Hamed et al arXiv:0704.1814)

In general, expect similar considerations to possibly be important in cosmology

Work w/ Marolf on dS, etc. arXiv:0705.1178, and WIP x2

- More general limitations on local QFT for volumes > $R_{dS}^4 e^{S_{dS}}$

- Investigation of proto-local observables in dS

deal w/ constraints, linearization stability

- Measurement for protolocal observables

To sum up, should be probing limits of local quantum field theory description, likely on scales $\gg l_P$

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How to progress?

(~ How to invent QM w/out experiment?)

One small step: what is a general enough quantum-mechanical framework to incorporate these ideas?

More general than "generalized QM"

arXiv:0711.0757

Thought experiments, pursuing a consistent quantum description of

- high energy scattering
- observables
- cosmology

and eliminating superfluous concepts

How can we have a theory w/ features of gravity:

1) Consistent (~ causal)

2) Quantum mechanical

3) Nonlocal

4) Nearly-local

} essential tension

(i.e. behaves locally in usual low-energy circumstances)

A highly non-trivial set of conditions to satisfy!

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

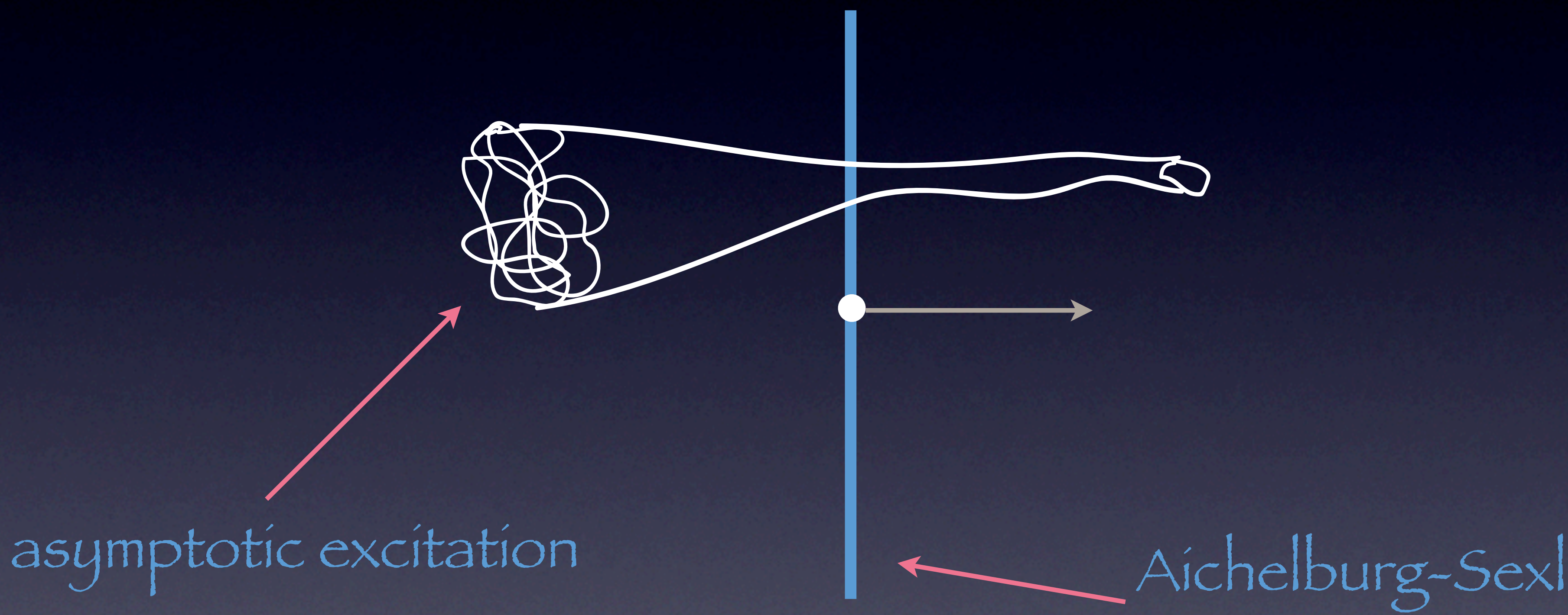
Backups

Tidal string excitation

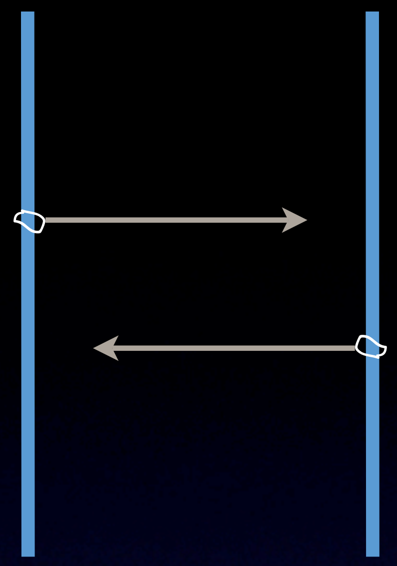
Q1: understand diffractive excitation

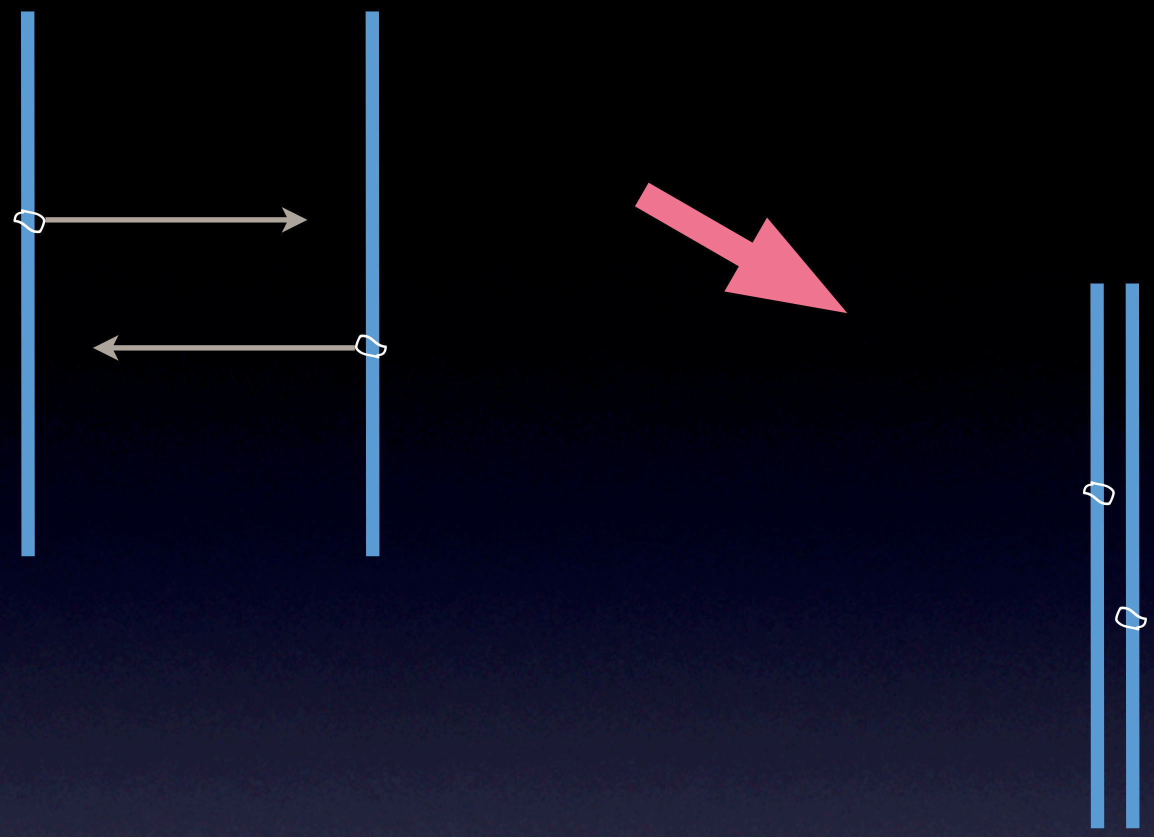
Picture:

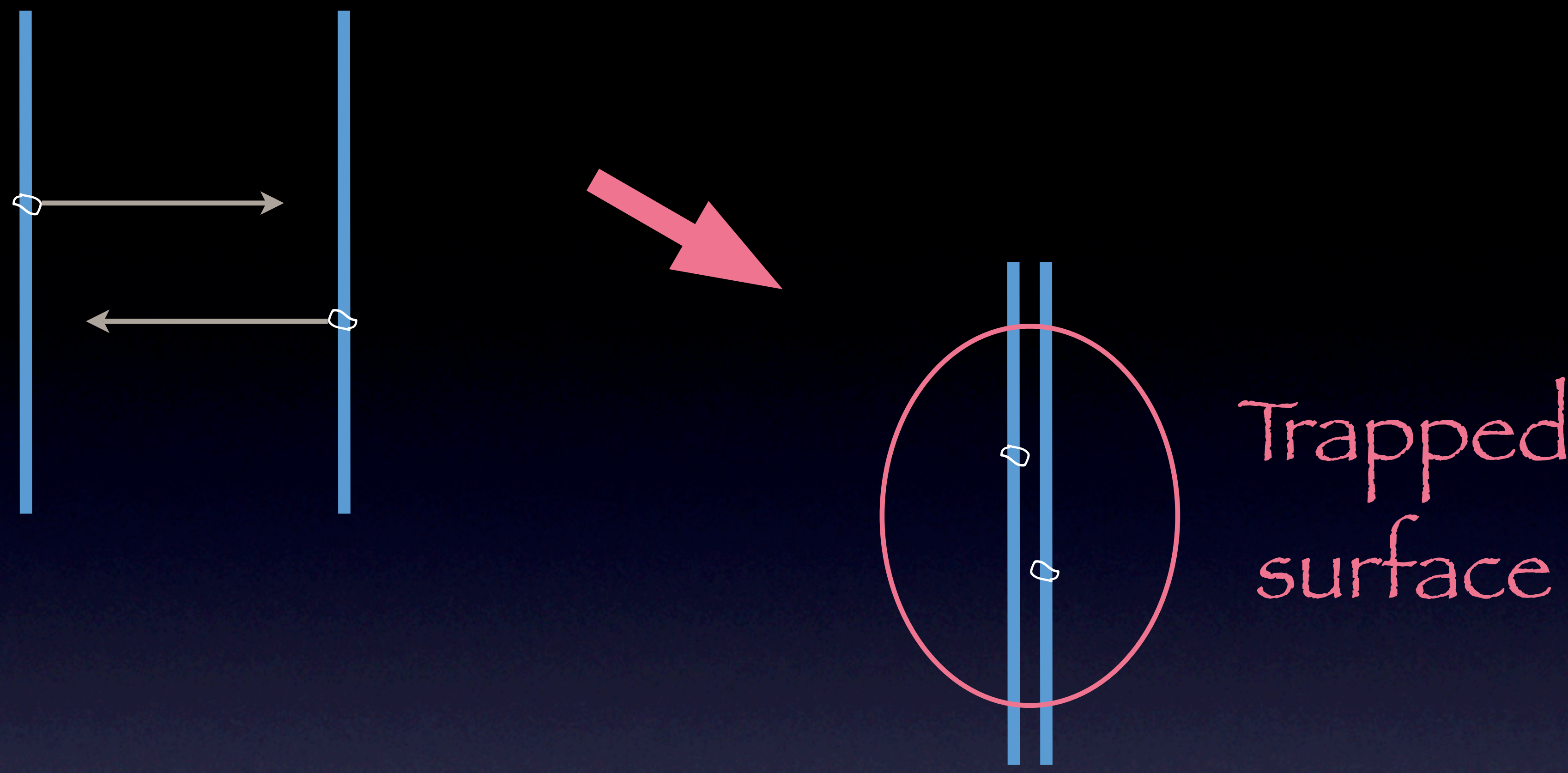
hep-th/0604072;
arXiv:0705.1816 w/ Gross and Maharana

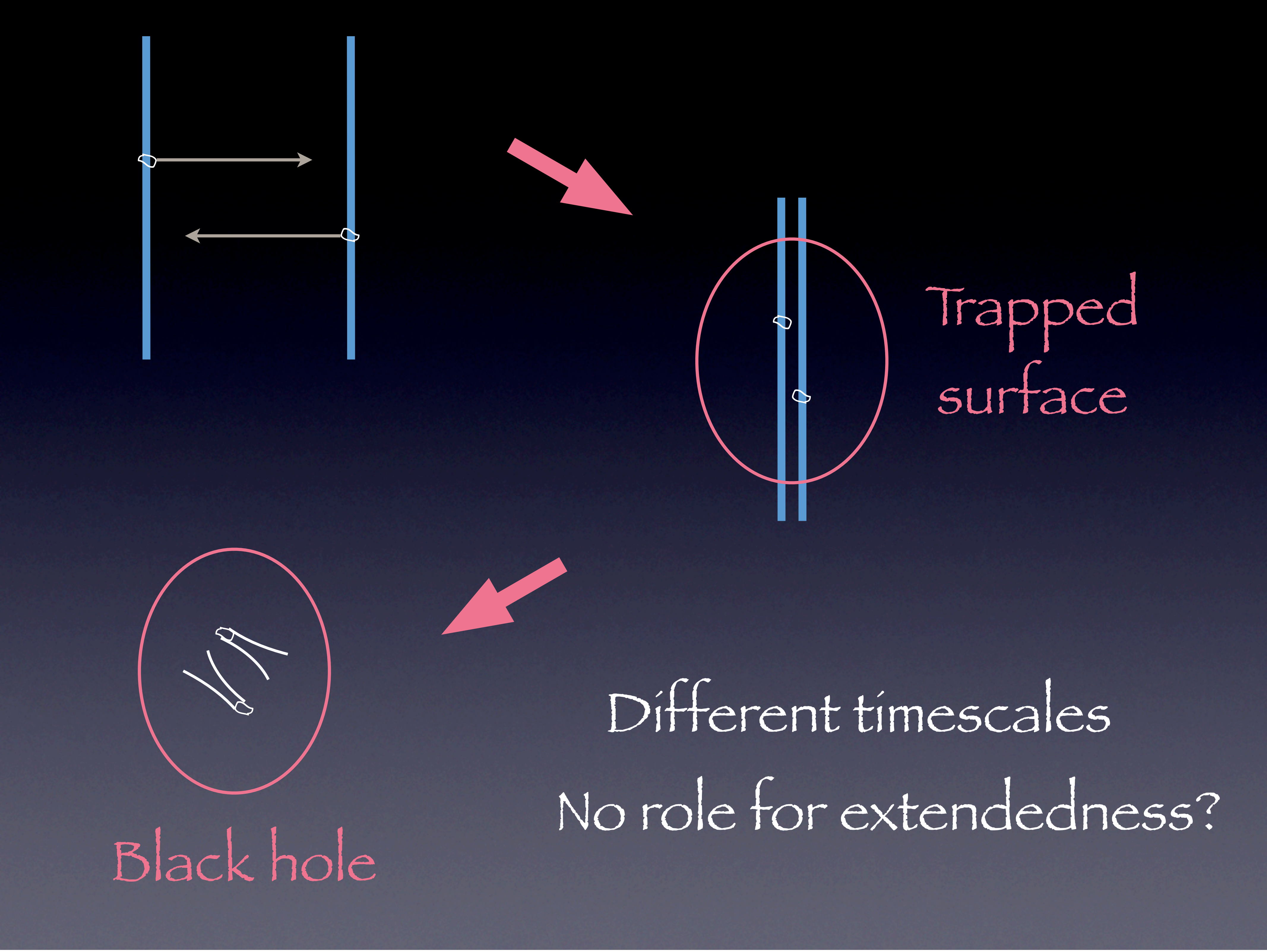


“tidal excitation”





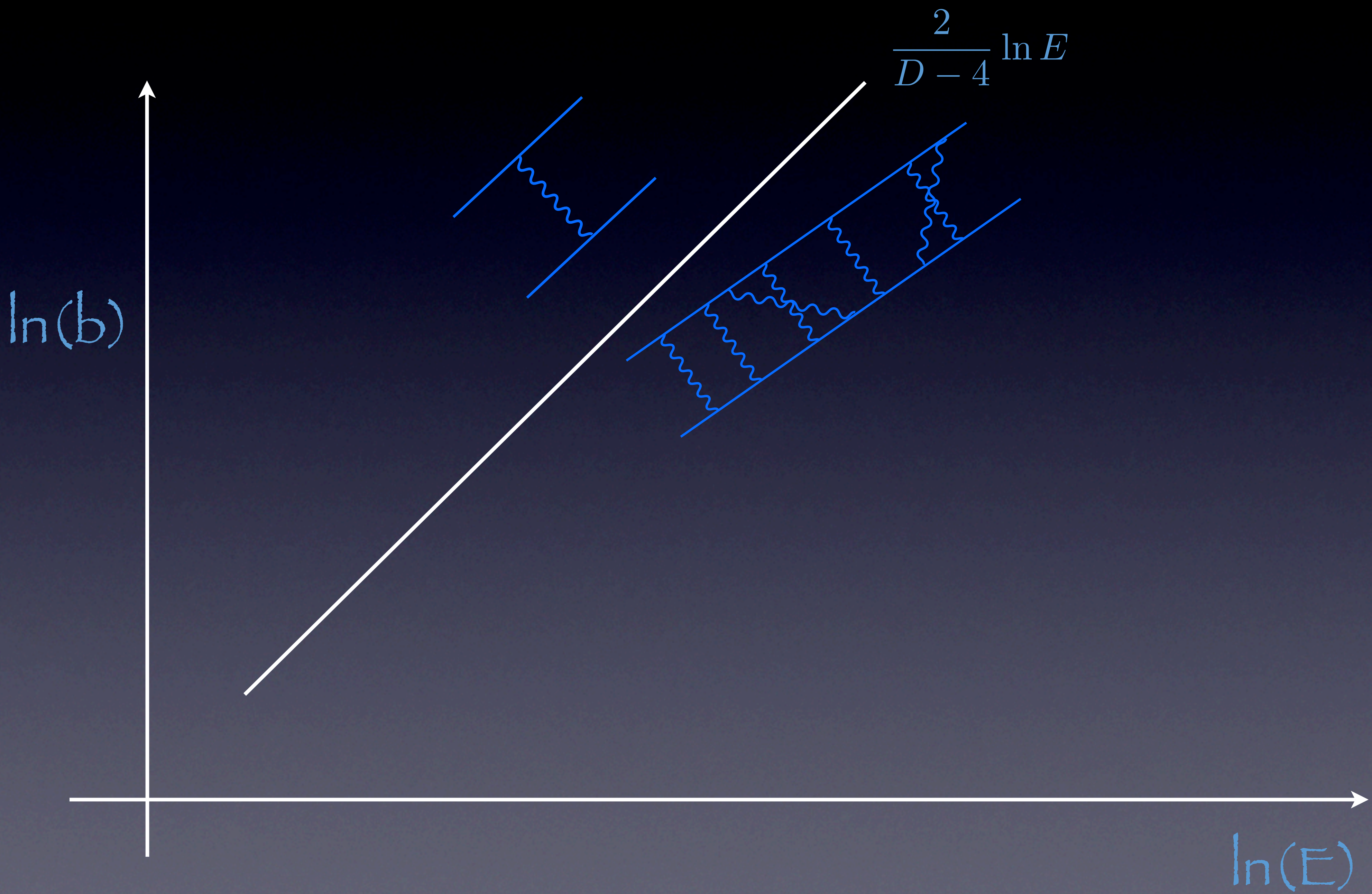

Trapped
surface


Trapped
surface
Black hole
Different timescales
No role for extendedness?

Phase diagram

consider strings, or

more generally



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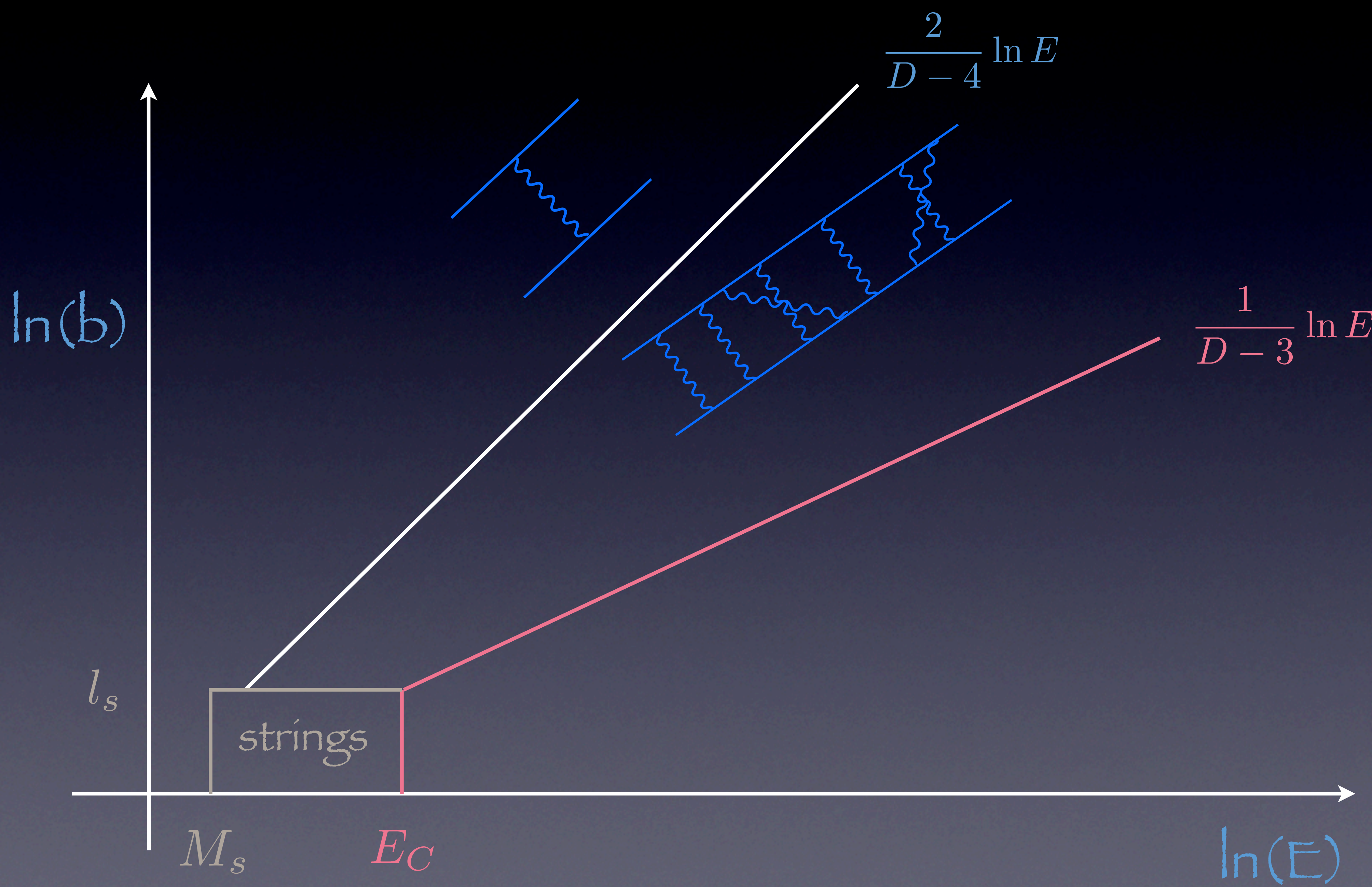

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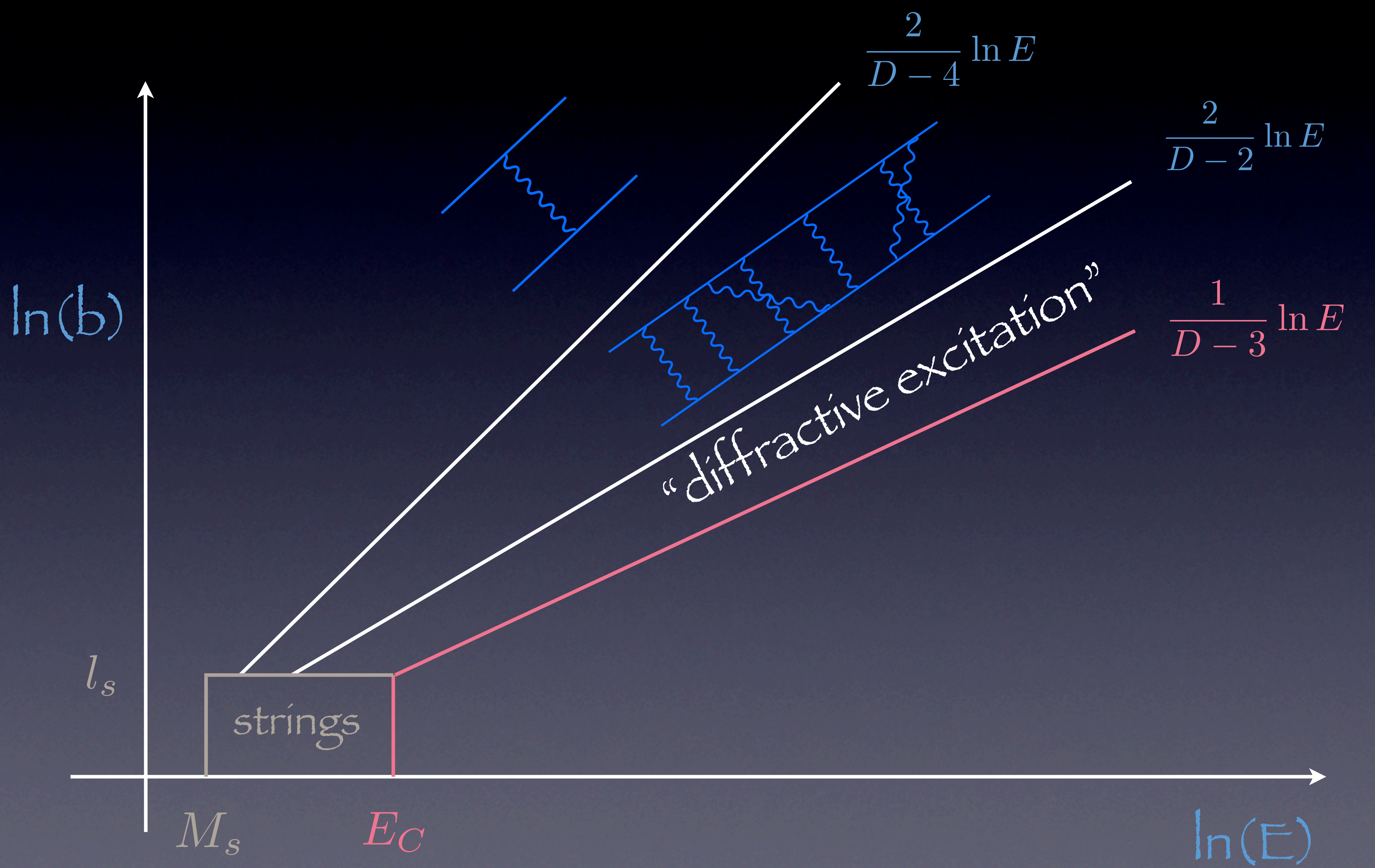

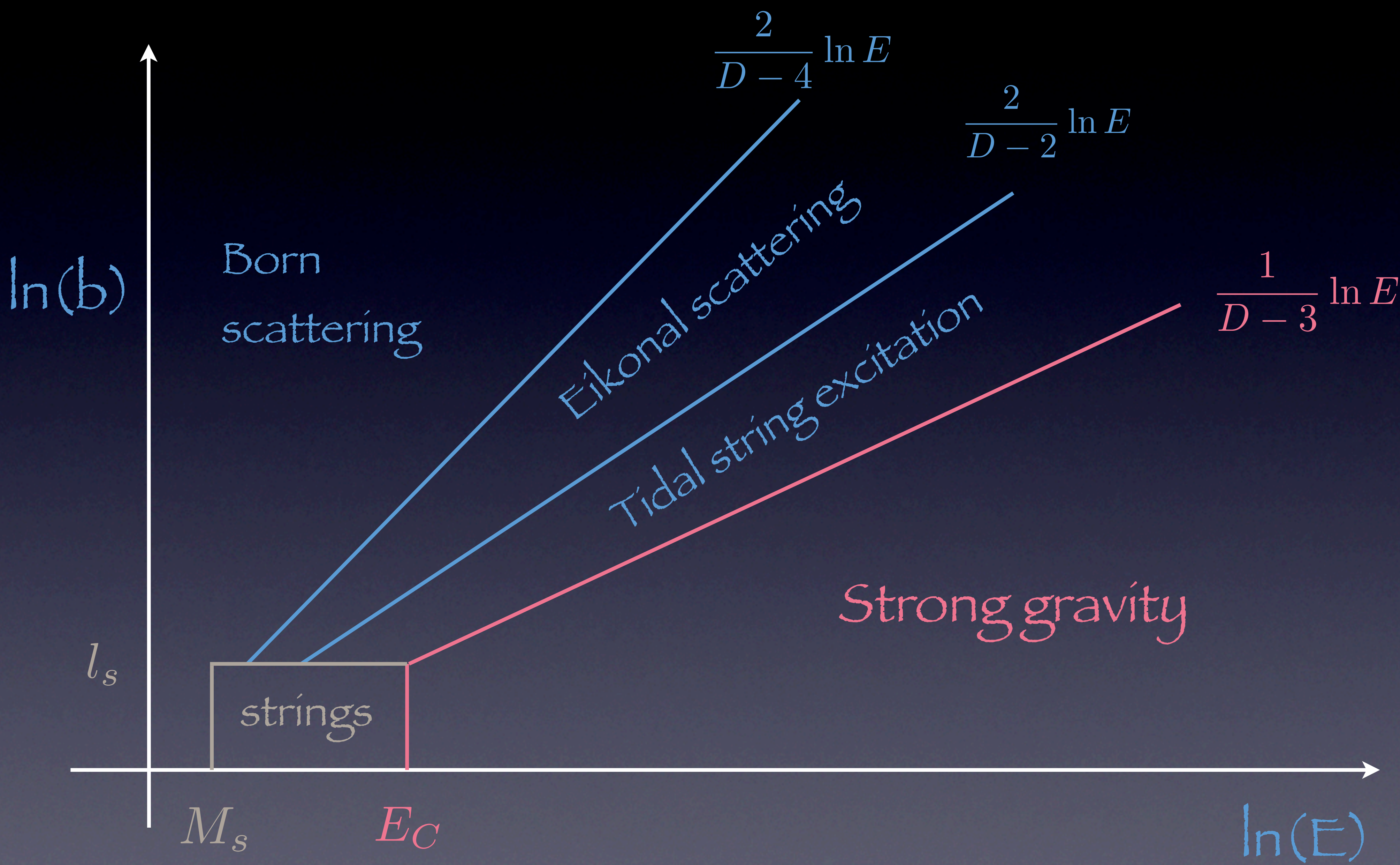

$\frac{2}{D-4} \ln E$
$\frac{2}{D-2} \ln E$
$\frac{1}{D-3} \ln E$
ln(b)
Born
scattering
Eikonal scattering
Tidal string excitation
Strong gravity
l_s
strings
M_s
E_C
ln(E)

Locality bd

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

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

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

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de Sitter: see SBG and Marolf, arXiv:0705.1178