What does high-energy scattering teach us about the quantum physics of gravity?

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2009 Corfu workshop on Quantum Gravity and Quantum Geometry

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1) Any candidate theory of quantum gravity should describe this regime, at least in principle. (E.g. could put on big computer.)

2) Generally high-energy scattering probes the most fundamental structure of a theory.

3) Such scattering encounters a deep conceptual paradox, driving at the heart of the conflict between general relativity and quantum mechanics.

4) Reasons 2 and 3 suggest that its study may point the way to new principles critical to understanding the quantum mechanics of gravity.

5) If we're very lucky, it could be studied at the LHC.

Plan of talk: bird's eye overview of this and related issues

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The reason:

e^-

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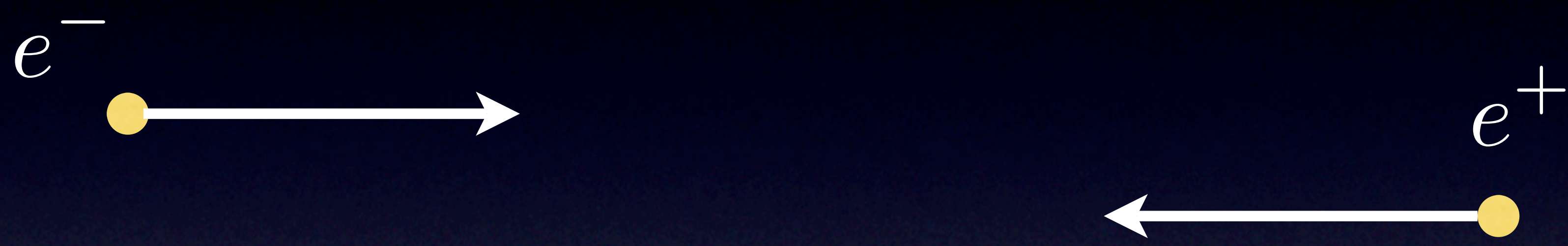


Boost to $E \gg M_p$

Just need: 1) Lorentz invariance

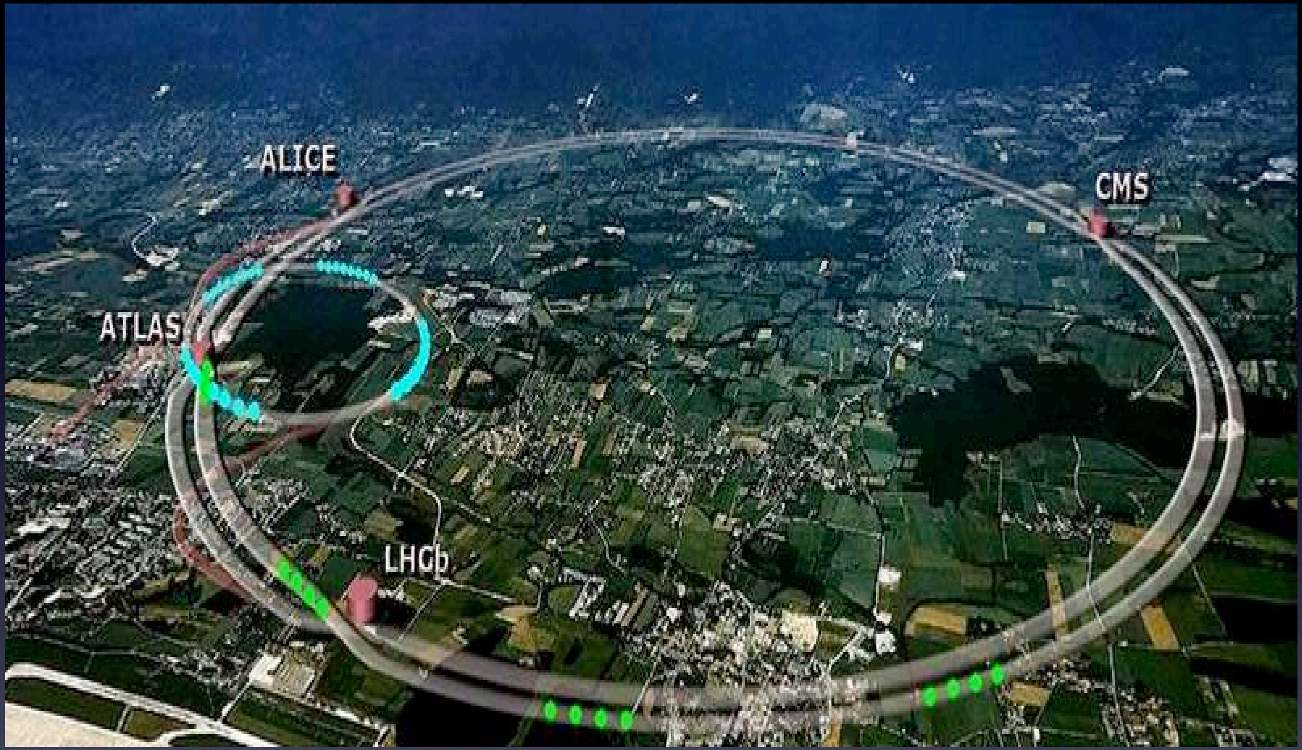
2) very weak notion of locality

Indeed, nature provides us with observed cosmic accelerators (presumably AGN) reaching already up to

$$\sim 10^{12}\, GeV$$

Moreover, ...

In extra dimensional scenarios yielding TeV-scale gravity, even



at LHC!

(A review: arXiv:0709.1107)

LI violation might alter this story, but:

- hard to violate such symmetry a small amount

- stringent constraints

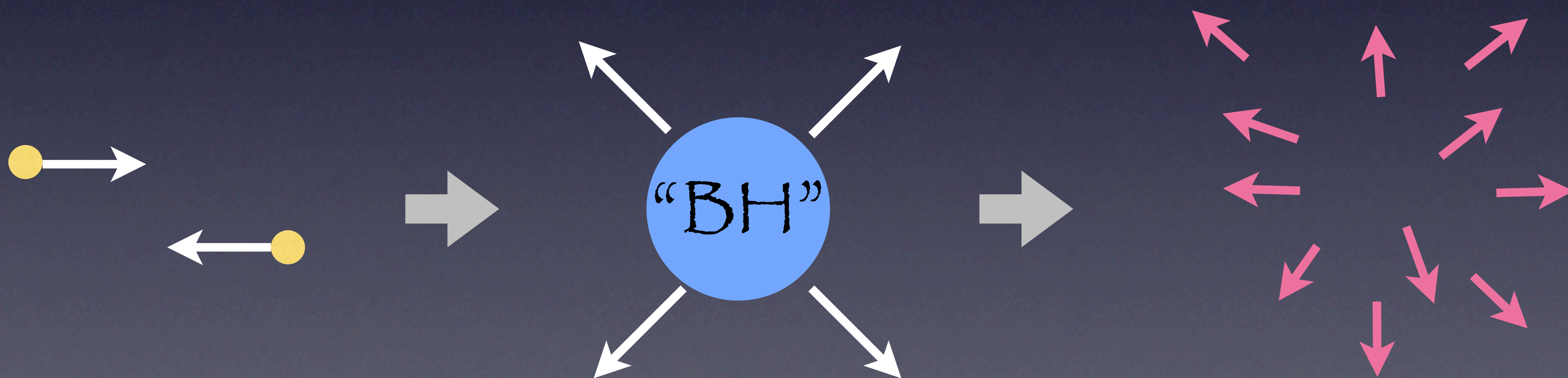
- potentially alters basic properties of black holes

- still find the problem of black holes and evaporation in more complicated contexts

$\Rightarrow$ won't consider

$E \gg M_p$: 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)

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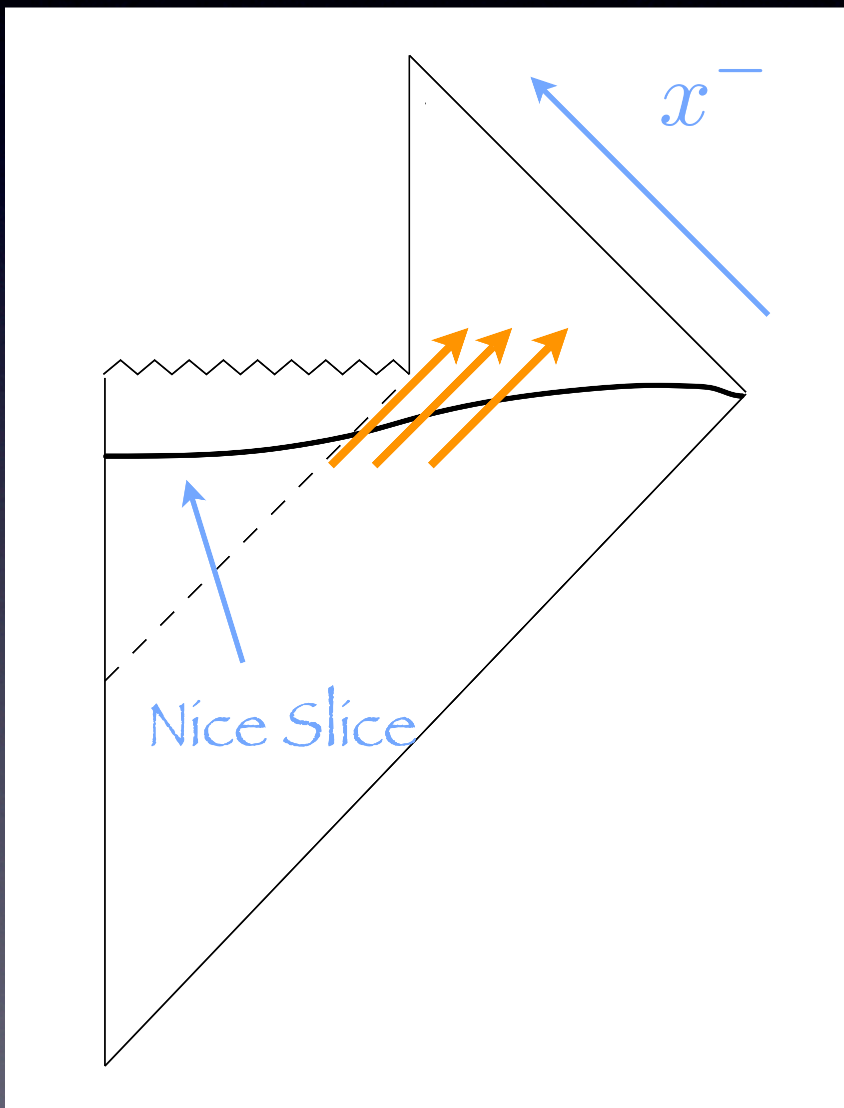
Lightening review:

Hawking, updated: nice slice argument



Locality:

$$|\psi_{NS}\rangle \Rightarrow \rho_{HR} \sim \mathrm{Tr}_{in}|\psi_{NS}\rangle\langle\psi_{NS}|$$

$$S_{HR}(x^-) \sim -\mathrm{Tr}\,(\rho_{HR} \ln \rho_{HR})$$

Increases to $\sim A_{BH}$

$\therefore$ information lost

(Hawking, 1976)

The problem is, QM is remarkably robust:

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Basic idea: transmitting info requires energy

$\therefore$ loss of info violates energy conservation

$\therefore$ such virtual effects

$\Rightarrow$ Massive E nonconservation

$T \sim M_p$, in this room

So: let's try to keep unitary evolution!

If information isn't lost, maybe it's left behind: in remnants?

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But: begin w/ arbitrarily large black hole

$\Rightarrow$ infinite species $M \sim M_p$

$\Rightarrow$ Infinite production instabilities

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

The “paradox:” a conflict between

Lorentz/diff invariance (macroscopic)

Quantum mechanics

Locality (macroscopic)

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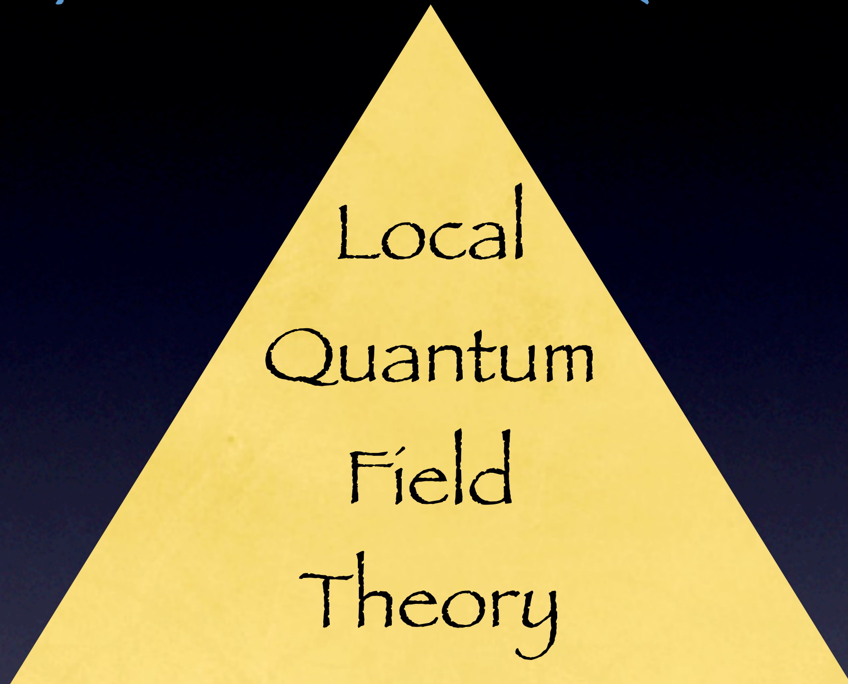
Lorentz/diff invariance (macroscopic)



Quantum mechanics

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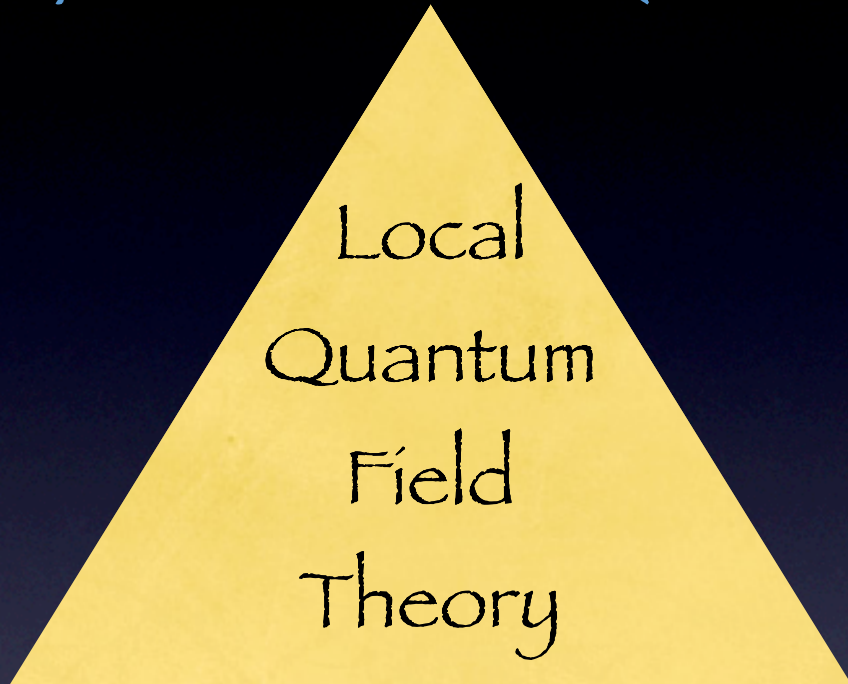


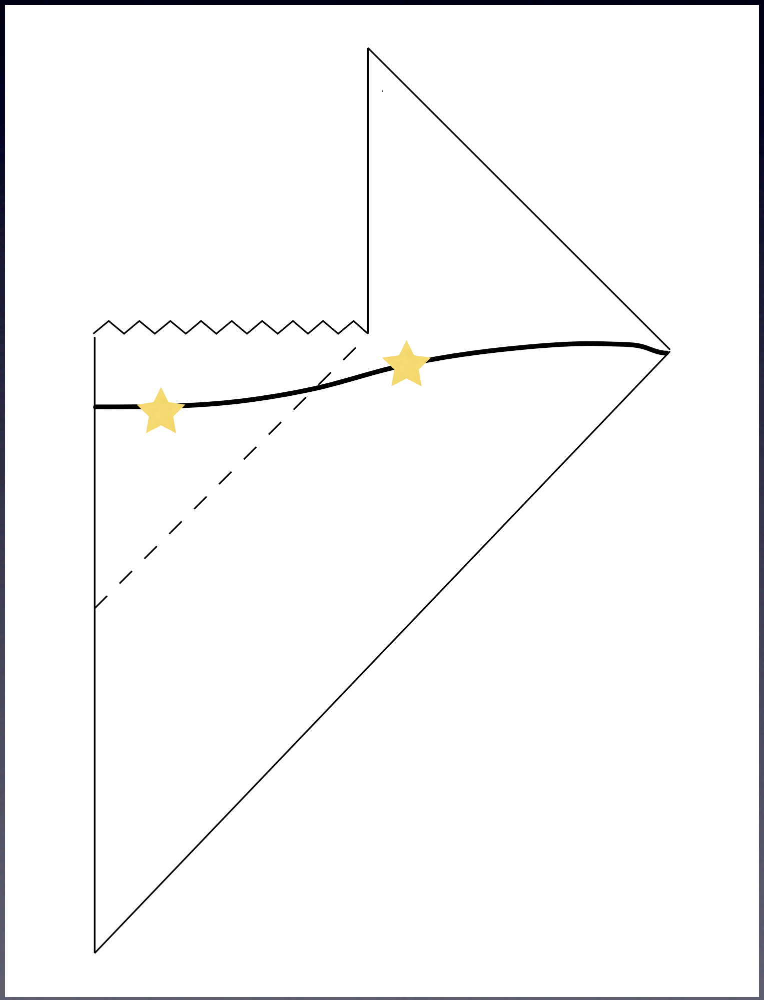
Quantum mechanics

Locality (macroscopic)

QM, LI -- can't see how to modify, respecting consistency and observation

A weak point: locality?

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



On scale :

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

$$>>> l_p$$

A parable from "plasmaworld"

Consider an advanced civilization of plasma-beings:

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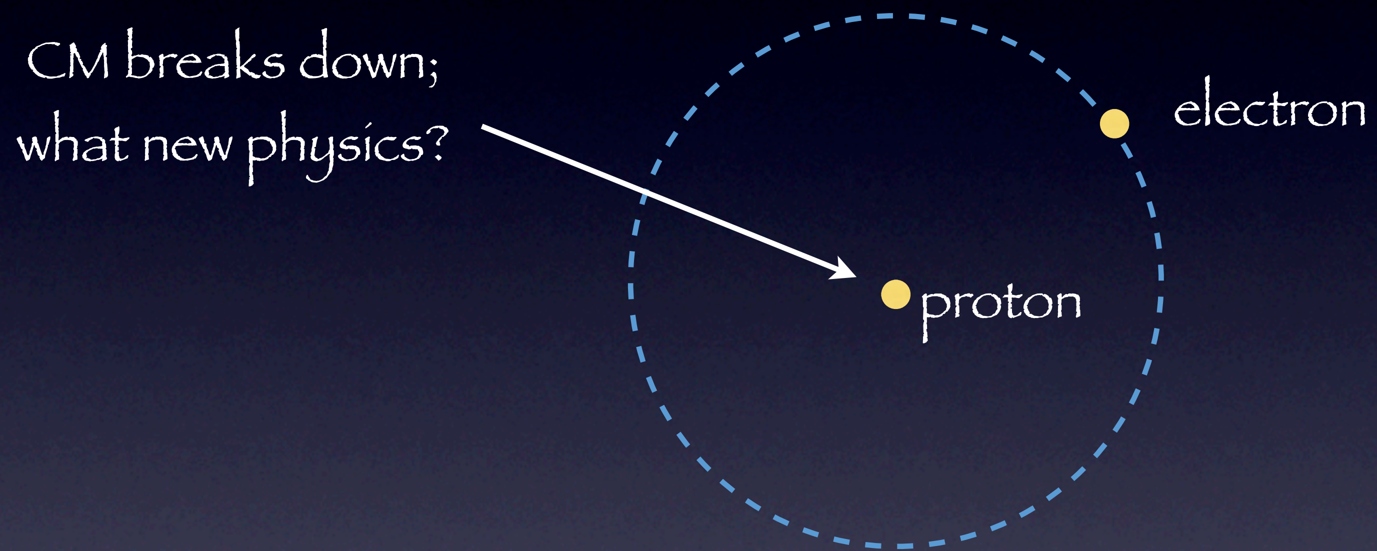
Consider an advanced civilization of plasma-beings:

- They have never seen a hydrogen atom
- they know well classical mechanics and electrodynamics
- their science advances to the discovery of electrons and protons
- their theorists discover a theoretical breakdown of physics:

In the hypothetical world, outside the plasma-

the UV singularity problem:



... their theorists then spend the next 50 years trying to modify classical physics at scales $r \sim r_{proton}$ to resolve the problem

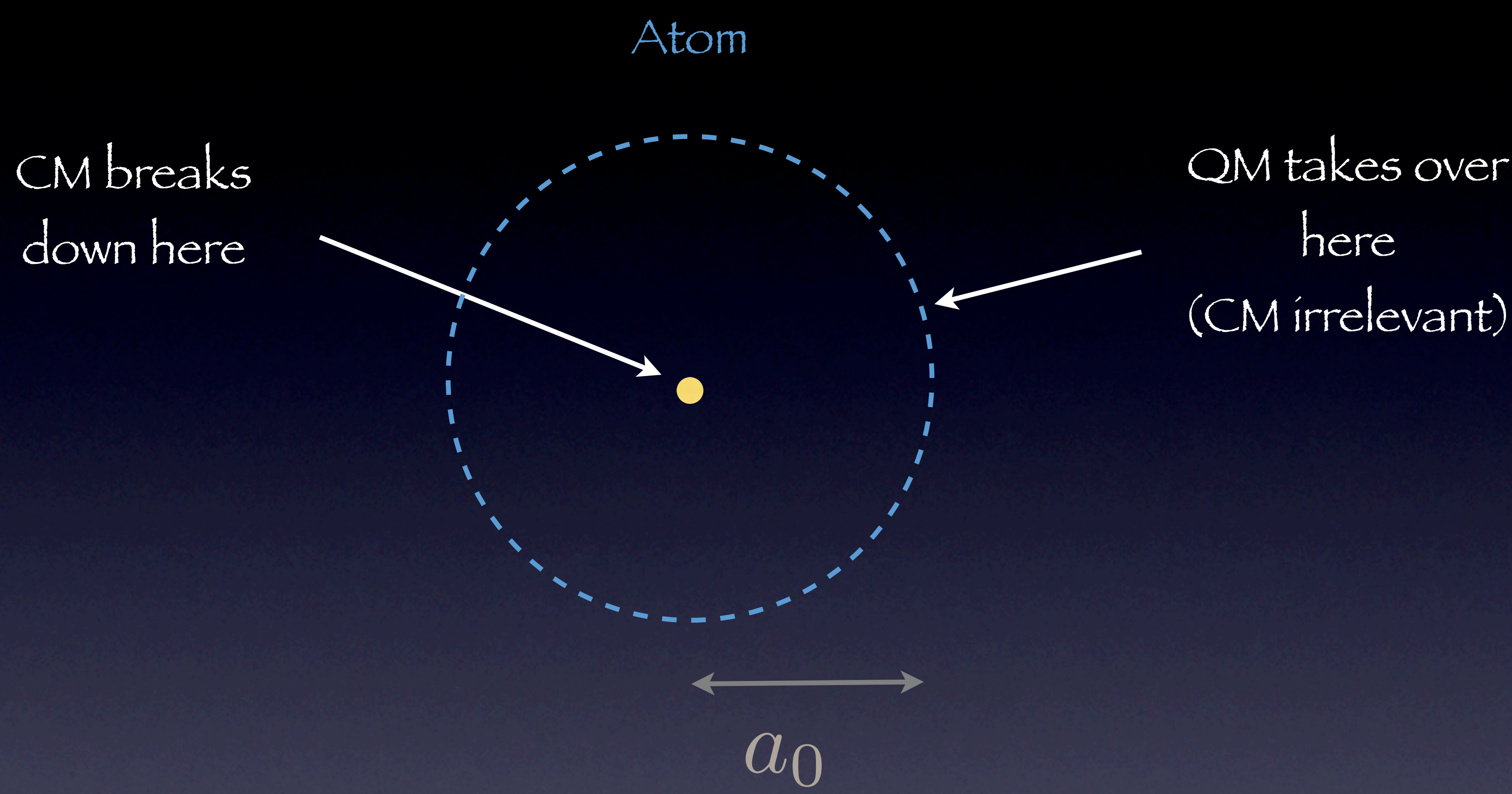
This is absolutely wrong!

In our "cold" world, resolution guided directly by experiment:

1) a different scale (a_0)

2) new principles (QM)

Are we in an analogous situation?



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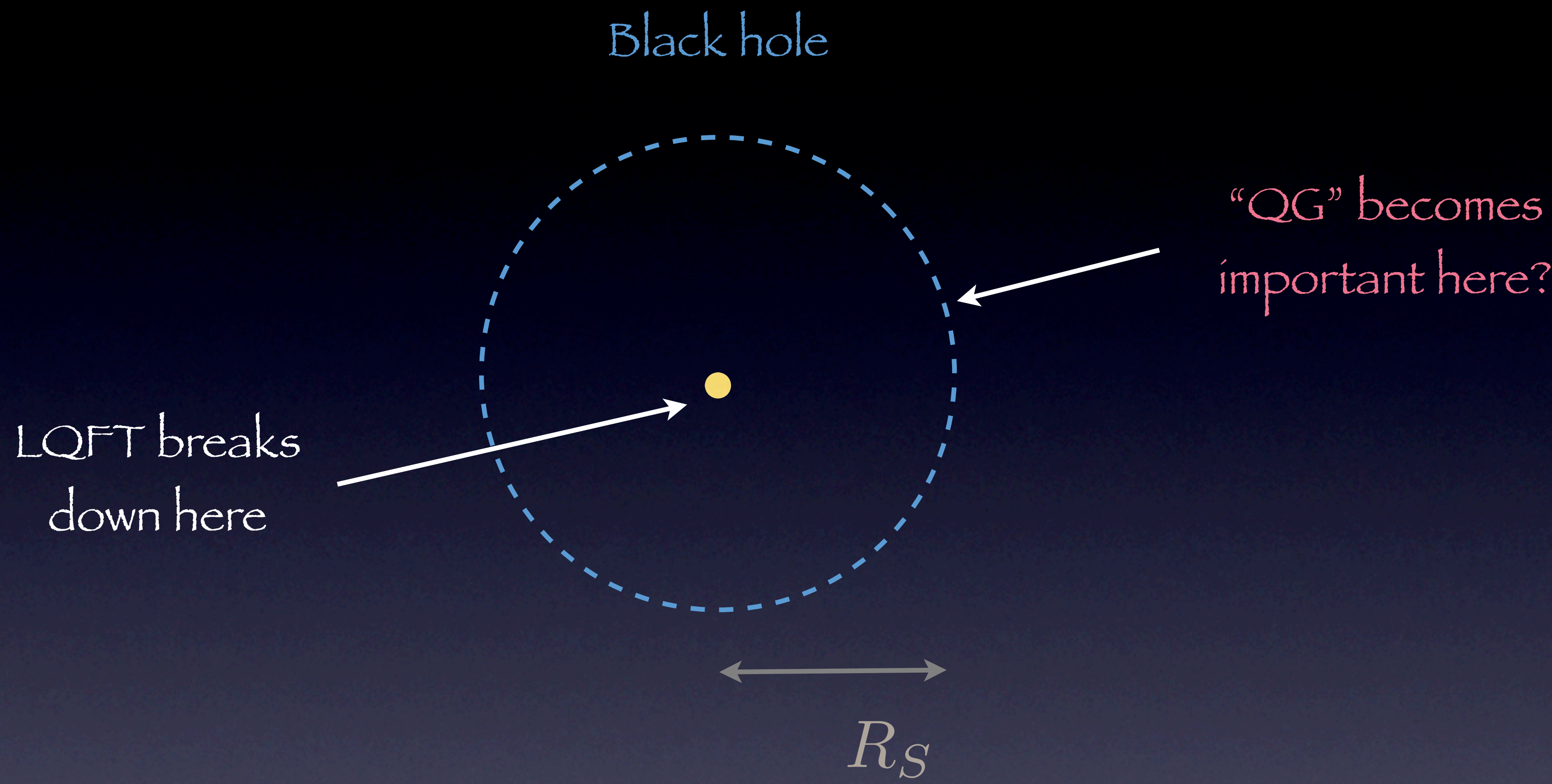

Suggestion: take literally -- new principles at R_S

What do the dominant quantum gravity paradigms say?

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LQG: working to recover the familiar world of (~) Minkowski space, multi-particle perturbations, and their scattering

String theory:

Hints (?) at a solution:

addresses nonrenormaliziblity

extendedness/nonlocality

microstate counting, etc.

Idea: "holography:"

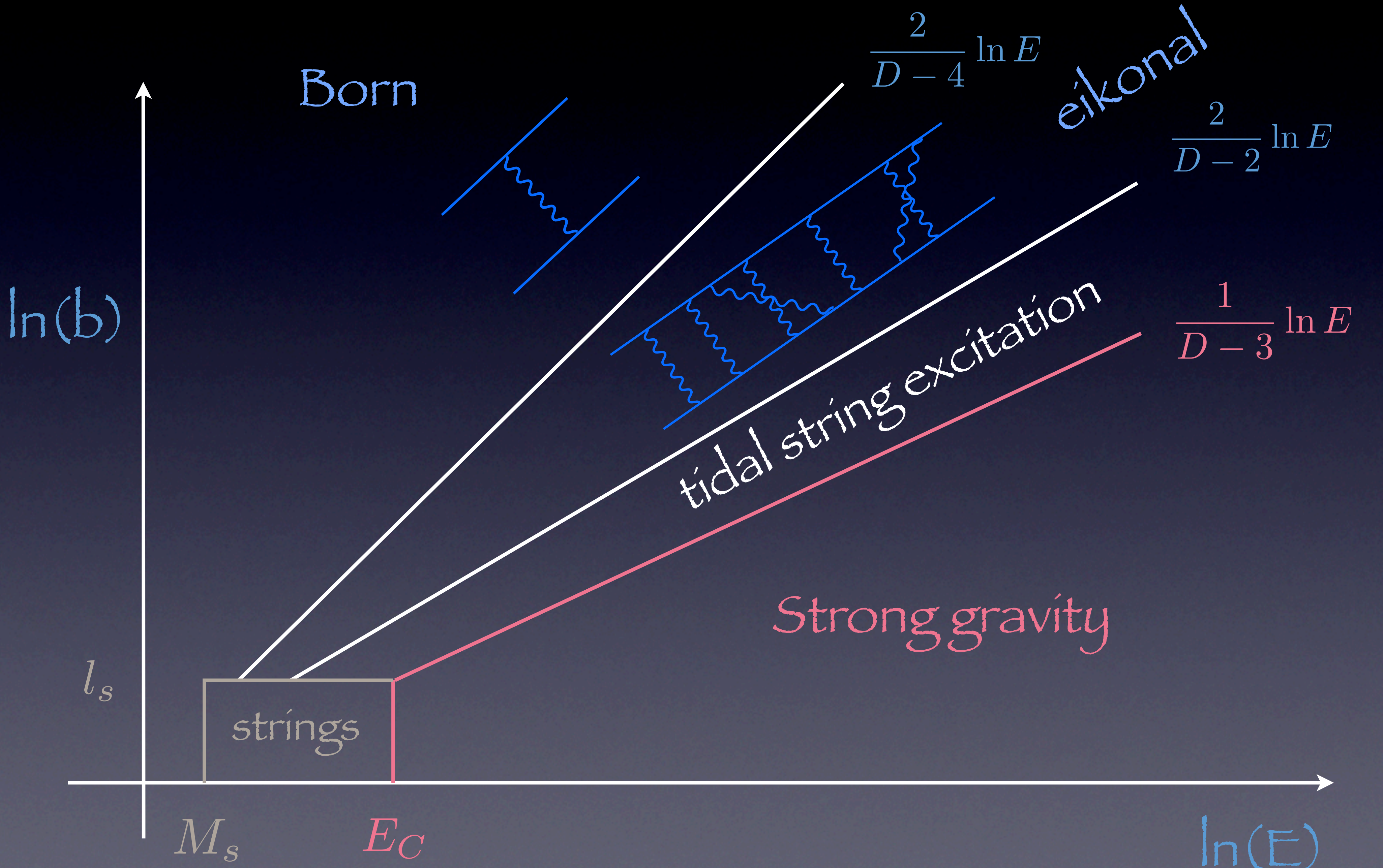
D-dim. grav $\equiv$ (D-1) non-grav unitary thy

(AdS/CFT)

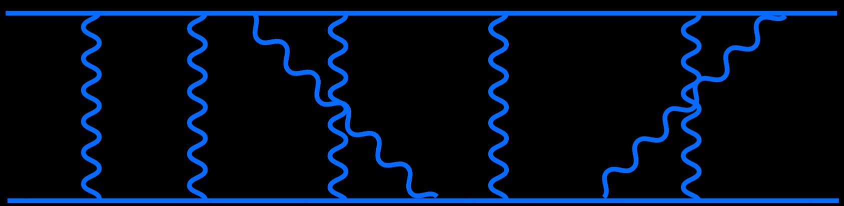
But ...

1) No apparent role for string extendedness

SBG, hep-th/0604072; SBG, Gross, Maharana, arXiv:0705.1816



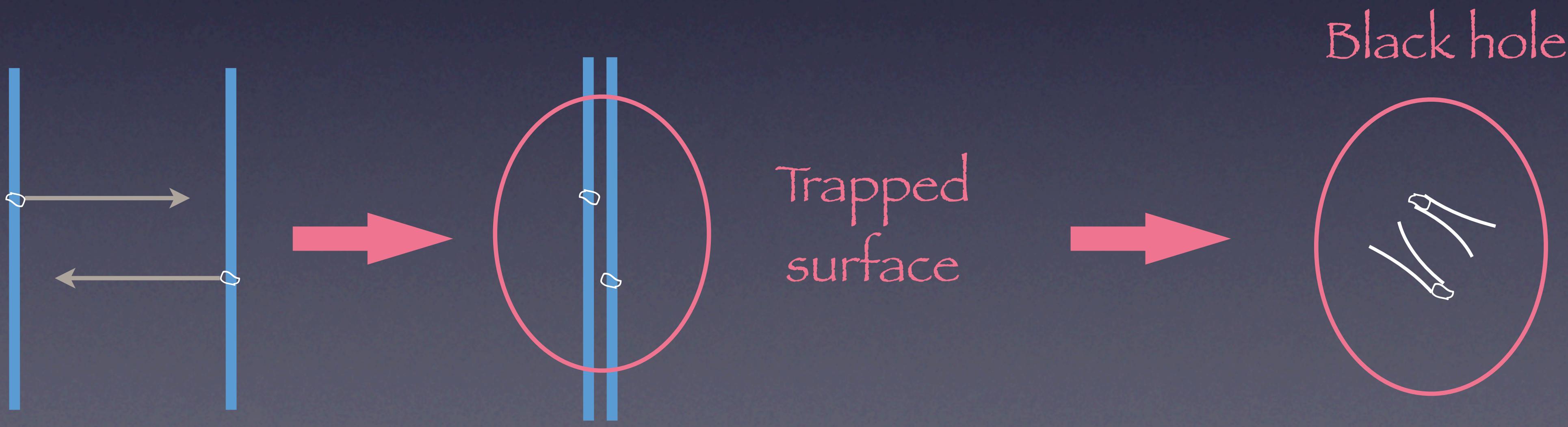
Eikonal regime:



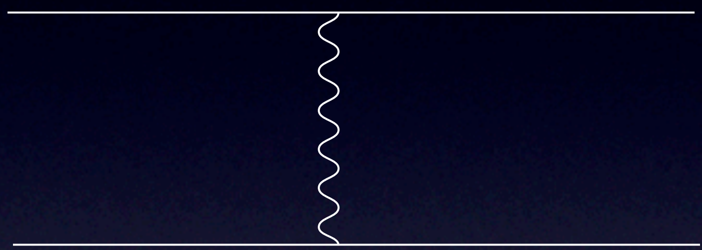
many soft exchanges:

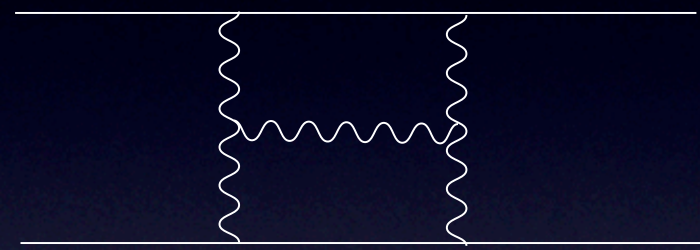
(expectation: same dynamics obscures possible would-be UV fixed point ?)

Tidal excitation: 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) Nonperturbative 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 proposed theories ultimately answer these questions, can we see outlines of the answers?

Whether proposed theories ultimately answer these questions, can we see outlines of the answers?

- We see strong indications for new effects at scales $\sim R_S(E)$

- Nonperturbative gravity (distinct from, e.g. string extendedness?)

- Good indications: breakdown of locality

Reasons to question locality, at $\sim R_S(E)$:

- information paradox
- growth of size in scattering

$$\theta_c \sim \left[\frac{R_S(E)}{b}\right]^{D-3}$$

indicates gravitational growth of object (though not nonperturbative regime)

black holes: 2 body $\quad b \sim R_S(E)$

connection to "nonpolynomiality"

- lack of local observables

approximately local observables fail in same regime

Search for clues - a basic set of questions:

1) Where does local QFT fail? Correspondence boundary

2) What is the mechanism?

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

Some previous 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: $p < M_p$

} 1 particle

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

multiparticle

Compare CM/QM

	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)

Specifically, compare 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	?

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- local observables

- polynomial behavior of HE scattering

Indeed, independently interesting problem:

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

(asymptotic Minkowski space)

The gravitational S-matrix

e.g: locality $\longleftrightarrow$ polynomiality?

SBG and Srednicki arXiv:0711.5012

SBG and Porto, WIP

$2 \rightarrow 2$ 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" (cosmology, black hole)
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:

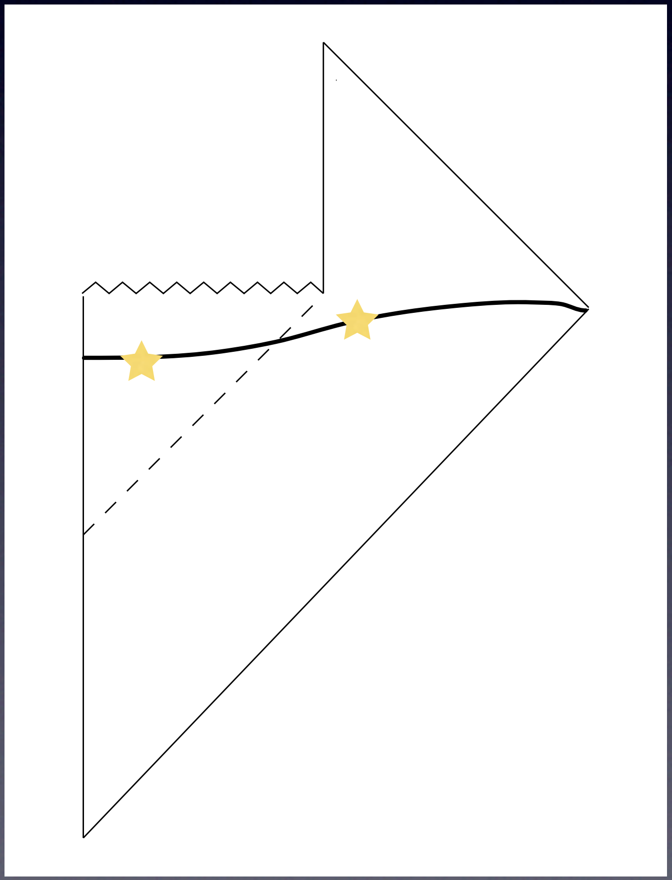
- localization only approximate
- must include background/observer

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_{HR} requires fine-grained, local $|\psi\rangle_{NS}$



Two potential obstacles:

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

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

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

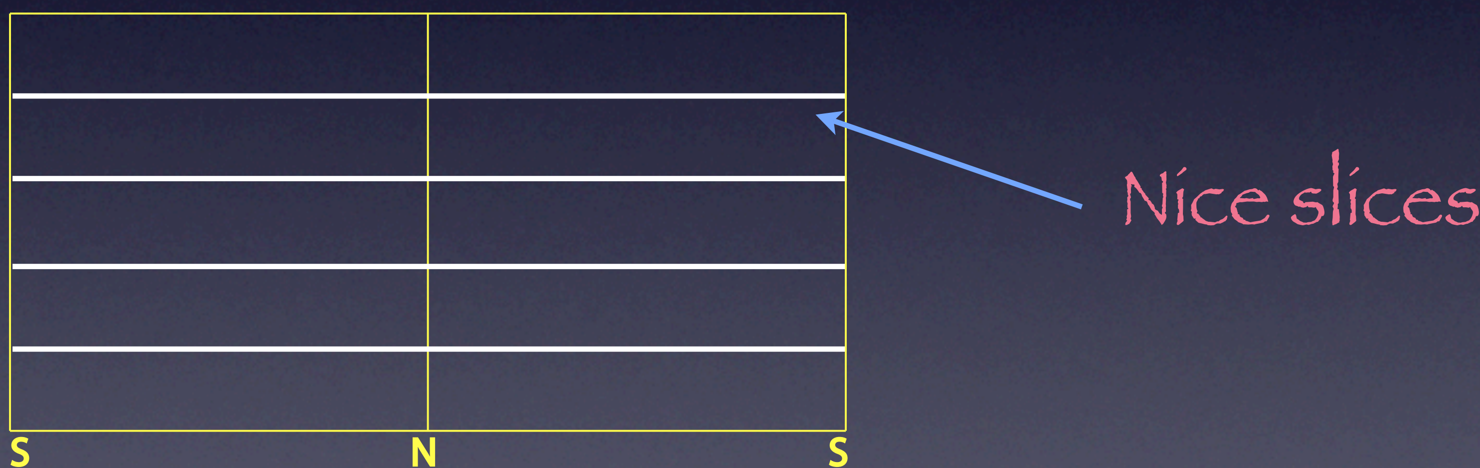
(literal CM/QM analogy may be another out...)

- 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 this set of considerations to 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 $\gg l_P$, in certain circumstances

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How to make more concrete 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 Hartle's "generalized QM"

arXiv:0711.0757

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!

This, plus relevant gedanken experiments:

guides to such a "Non-Local (but Nearly-Local) Mechanics"?