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”

CM breaks down; what new physics?

Atom

electron
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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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The reason:

$e^-$

Boost to $E \gg M_p$
A complete theory of quantum gravity should describe (or avoid) ultraplanckian collisions.

The reason:

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:

\[ |\psi_{NS}\rangle \Rightarrow \rho_{out} = \text{Tr}_{in} |\psi_{NS}\rangle \langle \psi_{NS}| \]

\[ S_{BH} = -\text{Tr} (\rho_{out} \ln \rho_{out}) \sim A_{BH} \]

\[ \therefore \text{information lost} \]

(Hawking, 1976)
The problem is, QM is remarkably robust:

Banks, Peskin, Susskind (1984):

Such breakdown of QM $\Rightarrow$ Massive Energy 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:

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

On scale:

$$\ggggg l_p$$

By a time:

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

(Page, hep-th/9306083)
The atomic analogy:

CM breaks down here

Atom

QM takes over here (CM irrelevant)

$\alpha_0$
The atomic analogy:

Black hole

LQFT breaks down here

“QG” becomes important here?

Suggestion: take literally -- new principles at $R_s$
What does string theory say?

Hints (?) at a solution:

Idea: “holography:”

\[ D\text{-dim. grav} \equiv (D-1) \text{ non-grav unitary thy} \]

(AdS/CFT)

addresses nonrenormalizibility
extendedness/nonlocality
microstate counting, etc.

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

\[ \frac{1}{2} \left( \frac{R_S(E)}{b} \right)^{2(D-3)} \]

(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
     - 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 \( \rightarrow \) quantum wavefunction

3) Framework: Hilbert space; Schrödinger/Heisenberg mechanics
Some possible proposals for a correspondence boundary for gravity:

- Planckian curvature:
  \[ R < M_P^2 \]

- String uncertainty principle:
  \[ \Delta X \geq \frac{1}{\Delta p} + \alpha' \Delta p \]

- Modified dispersion:
  \[ p < M_p \]

- Holographic (information) bounds:
  \[ S \leq \frac{A}{4G_N} \]

\[ \{ \text{1 particle} \}

\[ \{ \text{multiparticle} \]
<table>
<thead>
<tr>
<th>Dynamical descriptor</th>
<th>Validity</th>
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<tr>
<td>$x(t), p(t)$</td>
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**dynamical descript.**

**validity**

**CM:**

\[ x(t), p(t) \]

\[ \Delta x \Delta p > 1 \]

**QFT + GR:**

\[ \phi_{x,p} \phi_{y,q} |0\rangle \]

(min uncertainty wavepackets)
dynamical descript.  

CM: \( x(t) , p(t) \)  

QFT + GR: \( \phi_{x,p} \phi_{y,q} |0\rangle \)  
(mín uncertainty wavepackets)  

validity  

\( \Delta x \Delta p > 1 \)  

\( |x - y|^{D-3} > G|p + q| \)
dynamical descriptor.

CM: $x(t), p(t)$

validity

$\Delta x \Delta p > 1$

QFT + GR:

$\phi_{x,p} \phi_{y,q} |0\rangle$

(min uncertainty wavepackets)

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

"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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- high-energy scattering
Asymptotically flat space:

The gravitational S-matrix

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

e.g: locality $\leftrightarrow$ polynomiality?

SBG and Srednicki arXiv:0711.5012
SBG and Porto, WIP
2 → 2 scattering: PW expansion:

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

\[ \nu = \frac{D - 3}{2} \]

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

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

\[ \beta_l \approx \frac{S(E, l)}{4} \] (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?

(relating: 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:

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

Diff invariance $\Rightarrow$ None in gravity!
Likely resolution: Relational approach:

“proto-local observables”
see: SBG, Marolf, Hartle;
Gary & SBG: 2d, concrete

Basic idea:

\[ O = \int d^4x \sqrt{-g} B(x)O(x) \]
\[ \langle B(x) \rangle = b(x) \]

for appropriate background: \[ \langle O \rangle \approx O(x_0) \]

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: 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 $\tau_{Page} \sim R_SS_{BH}$

(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,

  \[ \tau \sim R_{dS} S_{dS} \]

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 > $R^4_{dS} e^{S_{dS}}$

- 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 $\gg l_P$

“unitarity restored at price of locality”
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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 (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 excitement
Q1: understand diffractive excitation

Picture:

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

asymptotic excitation

“Aichelburg-Sexl

“tidal excitation”
Trapped surface
Trapped surface

Black hole

Different timescales

No role for extendedness?
Phase diagram
consider strings, or more generally

\[ \frac{2}{D-4} \ln E \]
consider strings, or
more generally

\[ \frac{2}{D-4} \ln E \]

\[ \frac{1}{D-3} \ln E \]
consider strings, or more generally.
\[ \ln(E) \]

\[ \ln(b) \]

\[ \text{Born scattering} \]

\[ \frac{2}{D-4} \ln E \]

\[ \frac{2}{D-2} \ln E \]

\[ \frac{1}{D-3} \ln E \]

\[ \text{Eikonal scattering} \]

\[ \text{Tidal string excitation} \]

\[ \text{Strong gravity} \]

\[ \ln(E) \]

\[ M_s \quad E_C \]

\[ \ln(b) \]

\[ l_s \]

\[ \text{strings} \]}
Locality bd
Other versions of the locality bound:
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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 \[ \max |x_i - x_j|^{D-3} < G|\sum_i P_i| \]
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de Sitter: see SBG and Marolf, arXiv:0705.1178