On Semi-Classical Gravity as Effective Field Theory and the Information-Loss Paradox

Erik Curiel

Munich Center For Mathematical Philosophy
Ludwig-Maximilians-Universität

Black Hole Initiative
Harvard University

Smithsonian Astrophysical Observatory
Radio and Geoastronomy Division

erik@strangebeautiful.com

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Outline

Quantum Field Theory on Curved Spacetime and Semi-Classical Gravity. . .

. . . And Their Discontents

Most Especially the Information-Loss Paradox

So What? It's Just an Effective Field Theory

Concluding Unscientific Postscript

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general relativity: best theory #1

- valid from middling to largest spatial and temporal scales, and from near-perfect vacuum to super-dense matter
- dynamical spacetime geometry
- no quantum effects
- extreme causal weirdness, seemingly inconsistent with quantum mechanics

quantum field theory: best theory #2

- valid for meso-molecular (and smaller) matter at smallest spatial and temporal scales, and for highest and lowest energies
- static, flat spacetime geometry
- no gravity (*n.b.*: this doesn't follow from previous, *e.g.*, "soft gravitons")
- extreme quantum weirdness, seemingly inconsistent with general relativity (*n.b.*: *not* necessarily entanglement)

quantum field theory on curved spacetime

perhaps surprising to learn that there is a consistent, rigorous theory of quantum fields on relativistic spacetimes (algebraic or axiomatic):

1. fixed background classical spacetime geometry
2. non-interacting quantum fields propagating as "test matter"—"free fields"

(also standard canonical and Lagrangian formulations, but they're *messy* and raise yet more mathematical and physical problems; some results known in algebraic framework for interacting quantum fields in lower dimensions, but nothing of interest)

but freedom is scary. . .

semi-classical gravity (SCG)

shackle the fields to curvature with "back-reaction"
$\Rightarrow$ semi-classical Einstein field equation (SCEFE)

$$G_{ab} = 8\pi \langle \hat{T}_{ab} \rangle$$

classical Einstein tensor =
expectation value of stress-energy tensor as quantum operator

no completely rigorous mathematical theory, only standard formulations (Lagrangian, S-matrix, path integral, canonical, Hamiltonian-Jacobi, . . .), perturbative warts, non-renormalizability, and all

fundamental question:

How does the sober, rigorous and precise Apollonian convocation of classical Lorentzian geometry and the exuberantly inexact and informal Dionysian fandango of quantum field theory come into mutually fruitful contact, so as to give the joy of material content to the former and the restrained discipline of consistent structure to the latter?

especially urgent in light of:

1. theories are *prima facie* in severe tension, if not inconsistent (GR's causal weirdness, QFT's quantum weirdness)[1]
2. yet black hole thermodynamics (BHT) is most widely accepted, deeply trusted set of purely theoretical propositions in physics, seen as best guide to quantum gravity (QG)—*all with no empirical access*, much less support
3. ⇒ investigations necessarily speculative in a way unusual even in theoretical physics
4. ⇒ technically sophisticated physical questions inextricable from subtle philosophical considerations spanning ontology, epistemology, and methodology, again in a way unusual even in theoretical physics
5. ⇒ why do we trust it?!!!

[1] at root of many problems: quantum theory is fundamentally linear, general relativity is non-linear

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The Problem of the Regime of Applicability

The regime of applicability of effective field theories (EFTs) is normally circumscribed by energy scales, or spatial and temporal scales; in this case, however, the most severe circumscription is imposed by the coherence of the state of the quantum field.

[sketch example of Earth, bomb, and Moon]

The Problem of Semi-Classical Coupling

What justification, if any, can there be for the form of the SCEFE? Why should classical geometry couple to the expectation value of $\hat{T}_{ab}$ in semi-classical approximation?

- expectation values standardly represent averages of possible experimental outcomes
- does the SCEFE assume that classical geometry effectively acts as a "continual measurement probe" of the quantum field?
- Ehrenfest Theorem irrelevant: we're not talking about "classical evolution of expectation value", but rather how the *quantum field operator* evolves *in a quantum way* when coupled to classical geometry

mostly, I think, the thought is that this is justified because the same techniques are used to "derive" the SCEFE as, say, to derive the semi-classical treatment of phonons and their coupling to classical fluid "background":

1. expansion in power series of coupling constants
2. saddle-point approximation
3. truncation to first order
4. ...
5. $\Rightarrow$ coupling mediated by expectation values of relevant "thermodynamical" quantum observables

(still doesn't address the problem of the regime of applicability)

Finally: Hawking radiation is not generated by micro-degrees of freedom of the event horizon...

Hawking radiation is not blackbody radiation!

The Temperature Decoupling Problem

Why should we believe the thermal temperature of Hawking radiation is the temperature of the black hole, when it is not generated by micro-degrees of freedom of the event horizon?

- one needs further assumptions to bring these two *prima facie* disparate phenomena—the dynamics of the horizon on the one hand, and those of the external quantum field on the other—into explicit and harmonious relation with each other
- only then can one conclude that the temperature of the thermalized quantum radiation is a sound proxy for the temperature of the black hole itself as determined by the dynamics of (presumably) its very own micro-degrees of freedom
- but it is exactly the lack of such bridging principles that, as we will see, calls into question the importance of the information-loss paradox

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information-loss paradox (standard)

quantum field in curved spacetime with black hole:

- dynamical evolution from pure state to mixed ("thermal") state
- $\Rightarrow$ violation of unitarity

information-loss paradox (Page-time problem)

- treat black hole as statistical-mechanical system of quantum degrees of freedom
- then emitted blackbody radiation will eventually no longer be thermal—must be entanglement between early- and late-time quanta
- but SCG says Hawking radiation is thermal
- $\Rightarrow$ contradiction

The arguments in favor of loss of unitarity in black-hole evaporation are strong—why all the fuss about it in the case of black-hole evaporation, but not in standard treatments of other quantum fields in an effective field theory formalism (and, for that matter, in the case of measurements in standard quantum theory)?

Correlatively, why do physicists feel confident that an effect predicted by what is manifestly an effective-field theoretic calculation—evaporation due to emission of Hawking radiation—can be trusted to reveal features of an underlying fundamental theory of quantum gravity?

The Cascade Problem

1. For standard Information-Loss Paradox, why assume failure of unitarity at semi-classical level automatically cascades down to failure of unitarity at level of more fundamental theory of quantum gravity?
2. For Page-Time problem, why assume seeming irreconcilability of statistical mechanical and quantum mechanical treatments of black hole automatically cascades down to failure at level of more fundamental theory of quantum gravity?

here is one plausible answer:

- in the case of black-hole evaporation, there is an articulated dynamical mechanism that directly yields violation of unitarity
- this is in clear opposition to the case of standard effective-field theoretic calculations, in which violation of unitarity is manifestly an artifact of the mathematical manipulations used to make calculations tractable, not reflecting or representing anything physical
- also, it happens at arbitrarily low energies, where one does *not* expect the "high-energy modes" one ignores in SCG to be non-negligible

moreover...

- the failure of unitarity follows from the geometry of the classical spacetime background rather than the dynamics of the quantum field itself
- in particular, it is global features of the large-scale structure of such spacetimes that are responsible for the failure of unitarity
- one can plausibly expect, moreover, that such global features should be insensitive to any effects due to a theory of quantum gravity near the evaporation point, since those effects are appropiately localized in a small spacetime region (a recent theorem of Lesourd makes this precise)

THUS: the onset of “new physics” here is heralded by complexity in the causal structure of spacetime—high *entropy*—not by the *energy* of “gravitational phenomena”

SCG is just an EFT—why get fussed about problems in an EFT?

EFT:

- an explicitly approximative representation of phenomena using only degrees of freedom relevant for its characteristic scales (energy, length, time, . . . —generically "UV modes")
- UV modes "integrated out"—-*e.g.*, incorporated into "coupling constants" mediating effective interactions at the relevant scale
- example: coefficient of friction in treatment of dissipative motion in Newtonian mechanics, encoding "averaged effect of inter-molecular electrostatic interactions"
- breakdown is expected to herald "new physics"

so let's look more closely at how treating SCG as EFT may bear on the problems I've raised

SCG as EFT

that the geometry is treated classically, *viz.*, with no internal or micro (quantum?) degrees of freedom, suggests (at least) 2 ways to treat as EFT:

1. classical geometry is a coarse-grained environment that quantum field couples to $\Rightarrow$ *prima facie* can reasonably expect Lindblad-evolution (non-unitary) for the quantum field characteristic of an open system, from other standard cases

2. $\mathcal{TBD}$ gravitational degrees of freedom "integrated out" of coupling with quantum field $\Rightarrow$ *prima facie* can reasonably expect (for the most part) unitary evolution, from other standard cases

coarse-graining

- treat "gravity" as free statistical-mechanical system (with micro-degrees of freedom presumably properties of some possibly perturbative quantum gravitational states), then coarse-grain
- curvature is then macro-property that external systems couple with (like temperature and pressure for gases)
- loss of unitarity comes about for reasons similar to why we expect loss of retrodictability for classical systems interacting with dissipative coarse-grained or effectively integrated systems—they wipe out information about initial conditions (*e.g.*, box sliding down incline with friction)
- possible relation to "gravity from thermodynamics" programs of Jacobson and Padmanabhan?

coarse-graining virtues (clarifying conceptual muddles?) and demerits (raising new difficulties):

1. hints for origin of thermodynamical character of BHs (and more general pure gravitational systems) when external quantum effects taken into account?
2. hints for way to explain that BHs (and more general pure gravitational systems) obey thermodynamical relations in *classical* GR, at least formally: any theory of gravity at the classical level *must* recapitulate (at least formally) such thermodynamical behavior as a minimal criterion of adequacy
3. possible problem—not clear why following seems to be ruled out: that general relativity could be adequate in some regimes in which seeming thermodynamical nature of gravity is irrelevant (*e.g.*, Solar System, gravitational waves, cosmology), without also being adequate in those regimes in which thermodynamical character of gravity *is* relevant (*e.g.*, BHs)
4. seems to dissolve the Information-Loss Paradox: may show why loss of unitarity at semi-classical level need not imply anything about dynamics at more fundamental levels

coarse-graining virtues and demerits, cont.:

5. indeed, retaining of predictability with loss of retrodictability is exactly what one has in BH evaporation (I can tell you exactly what mixed state this pure state will evolve into, but not what pure state it came from once it's there), and exactly what one expects from such coarse-graining
6. may still provide guidance to quantum gravity: look for gravitational micro-degrees of freedom whose statistics give the kind of coarse-grained environment required, both for manifesting thermodynamical behavior of BHs and for coupling to $\langle \hat{T}_{ab} \rangle$
7. problem: *really* hard to see how this could *explain* coupling to $\langle \hat{T}_{ab} \rangle$
8. problem: *really* hard to see how this could explain coherence of quantum-field state as condition on adequacy of approximation

integrating out

- we treat quantum field's degrees of freedom as coupling with something like "perturbative quantum gravitational degrees of freedom"
- then integrate out from the interaction the $\mathfrak{TBD}$ gravitational degrees of freedom as in the standard EFT framework in particle physics
- coupling can't be with "fundamental quantum gravity" degrees of freedom, because we don't expect those to couple with gross macroscopic (relatively speaking) matter

integrating-out virtues (clarifying conceptual muddles?) and demerits (raising new difficulties):

1. hard to see how to characterize "$\mathfrak{TBD}$":
   - **1.a** can't be "UV" because gravitational field *has no* high-energy modes in relevant cases (at least as compared to energies of possible modes of quantum field)
   - **1.b** can't be "IR", because we want "arbitrarily close to" Minkowski spacetime as a possibility
   - **1.c** only possibility left seems to be something like "low entropy" modes (compared to characteristic entropy of the standard quantum field states), since it is effectively high gravitational entropy that characterizes the relevant cases
   - **1.d** but this is severely non-standard form of EFT, and difficult to see how to implement
2. *prima facie*, no relief from Information-Loss Paradox: standard EFTs can in principle violate unitarity, but only when dynamics "tries to probe integrated-out phase space regions" (*i.e.*, when coupling energies become large); but that is not BH evaporation, at least not for big BHs with effectively flat curvature and infinitesimal Hawking temperature

integrating-out virtues and demerits, cont.:

3. if low entropy modes integrated out, there may be relief: it is exactly those modes that quantum field degrees of freedom are trying to probe, if one assumes a form of coupling in which mode-by-mode interaction is governed by respective entropies, not respective energies
4. but no such coupling is known for any other types of field, and it would seem impossible to govern such a coupling with a Hamiltonian (energy doesn't govern dynamics, and quantum entropy is not a self-adjoint operator nor is it obvious how to make it one)
5. because $\mathfrak{TBD}$ modes are integrated out from the *interaction*, there is some hope of explaining the coupling of G_{ab} to $\langle \hat{T}_{ab} \rangle$
6. difficult to see why coherence of quantum-field state should be restriction on adequacy of semi-classical approximation

the Page-time problem:

- argument assumes BH micro-degrees of freedom in statistical-mechanical treatment are entangled with Hawking radiation
- Hawking radiation is a "macroscopic" phenomenon (relative, presumably, to fundamental QG)
- $\Rightarrow$ BH micro-degrees of freedom, presumably, are of the form that the EFT integrates out or coarse-grains over (otherwise, it's hard to understand how SCG can be framework for BHT)
- $\Rightarrow$ one may be justified in treating Page-time problem as no more nor less paradoxical, with regard to fundamental theory, as the standard Information-Loss Paradox (*pace* Wallace), since those degrees of freedom are *ex hypothesi* not fundamental

my sense is that, at this level of discussion, coarse-graining wins on virtues and demerits—but one really needs to work through all the virtues and demerits in detail to verify them as such (which I have not done)

if one were decisively argued to be superior, what would it tell us about conceptual structure of SCG, and its standing as a viable, possibly fruitful physical framework?

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recall the story told to justify the form of the SCEFE, that its derivation (and subsequent form) mirrors that of other semi-classical phenomena but in the other contexts, because of all the background knowledge we have about the solid-state/fluid systems (*e.g.*), including both theoretical and empirical/experimental justifications, we know:

- what the representation in the power-series means physically
- what the individual terms in the power-series mean physically
- what the saddle-point approximation means physically (including understanding its regime of applicability)
- what truncating to first-order means, including again its regime
- ...

because of all that, we have epistemic warrant for using the semi-classical phonon model (both for claiming that we understand it, and for claiming that it is a good model in the circumscribed regime)

we have epistemic warrant for using it as the basis for further knowledge claims that *ipso facto* already have some confirmatory support in virtue of being derived from the well entrenched, well understood semi-classical phonon model

- we want to use the SCEFE as the basis for arguments whose conclusions we want to have confidence in—we want, essentially, to use it as part of an evidential network to buttress the assertability of claims in BHT (*inter alia*)
- but we have none of the entrenched background in SCG
- we must be careful in trying to use SCG to draw fundamental lessons!

- I am not saying that we shouldn't use it as the grounds for *speculative* investigation
- I am rather saying that we should be more critical, more skeptical, and more modest in our understanding of the epistemic warrant we have for it...
- ... both with regard to our understanding of it, and with regard to our confidence in using it as the ground for further investigation
- we should be clearer on our epistemic state with regard to it

A Knight of Faith? Or a Lost Soul?

- Is there a consistent picture of spacetime geometry, matter, and their interaction in this framework?
- Can such a problematic framework give good results, and, if so, how?
- Why have faith in results from a framework with such manifest, serious, unresolved problems?
- How to make progress in important parts of theoretical physics if one doesn't have faith?

Make the Leap of the Absurd?
or
Remain a Skeptic and Be Damned?

I Tentatively Recommend...

Socratic Irony

a dialectical process of moving from skepticism to faith, and back again, as our epistemic circumstances evolve under constant questioning, knowing that we do not know