Hunting for potential quantum gravity signatures in gravitational waves

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Outline

- Introduction
- Echoes from "QG modified horizons" and various problems
- Bouncing models in black holes and potential echoes
- Potential signatures from fuzzballs
- Potential EM counterparts in firewalls
- Summary

Fundamental problems in black hole physics: **central singularity**, and **"information loss paradox."** **Conservative** as well as **radical** ideas for solutions in quantum gravity. GW astronomy opens a new window to test/rule out quantum gravity theories.

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A conservative solution: GR replaced near Planck scale by its quantum avatar, such as Loop Quantum Gravity (LQG), which resolves the singularity. Negligible low curvature effects. Since singularity acts as a sink of information, its absence can resolve the "paradox." Pure states starting from past null infinity can evolve to pure states at future null infinity **(Ashtekar, Bojowald (05)).** Explicit demonstration for 2-D black holes **(Ashtekar, Taveras, Varadarajan (08)).**

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Growing body of evidence in last decade that LQG resolves various cosmological singularities **(Ashtekar, Corichi, Pawlowski, PS, .. (06-..)).**

Central singularity for Schwarzschild spacetime recently resolved. Quantum geometry leads to universally bounded curvature scalars. GR recovered in low curvature regimes **(Ashtekar, Olmedo, PS (18)).**

Some radical ideas

Fuzzball proposal: In higher dimensional supergravity theories, given a black hole with entropy S one can find e^S non-singular, horizonless solutions which asymptotically appear as a black hole but result in a non-trivial structure at horizon scale. Black hole to be viewed as an average over the fuzzball solutions. A fuzzball surface closer in description to that of a planet than a black hole.
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Firewall proposal: Two standard assumptions to solve "information loss paradox": Hawking radiation is in the pure state, and information carried by radiation emitted near horizon with low energy effective field theory valid beyond some microscopic distance from horizon, contradict the statement that in-falling observers encounter nothing at the horizon. Conventional view of no drama at the horizon does not hold. Rather, in-falling observers burn up at the horizon. **(Almheiri, Marolf, Polchinski, Sully (13))**

Potential echoes from exotic compact objects

Exotic compact objects, such as highly spining boson stars, mimicking standard black holes at large distances but differing in near horizon regime, can result in potential signatures in late time ringdown waveform **(Cardoso, Franzin, Hoper, Palenzuela, Pani, ... (16-...)).**

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Radiation partially trapped between two peaks in curvature potential: surface and the photon sphere. Some of the energy is trasmitted away from the system in successive bounces in this cavity, resulting in a series of delayed echoes.

Reflection coefficient of the surface and its location, determine the amplitude of echo signals and their time separation.

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Idea imported to QG inspired scenario: Motivated by fuzzball and firewall paradigms, black hole horizon is replaced by a partially reflective surface at a Planck length distance outside the would-be horizon **(Abedi, Dykar, Afshordi (16))**

Claims of evidence of echoes and rebuttal

Abedi, Dykar, Afshordi (16-18) Crude phenomenological GW template.

- 2.5 σ evidence in GW150914, LVT151012 and GW151226
- 4.2 σ evidence in GW170817 neutron star merger

Conklin, Holdom, Ren (17): $\sim 3\sigma$ evidence for GW151226, GW170104, GW170608, GW170814 and GW170817. But no evidence of echoes in GW150914 and LVT151012.

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Ashton, Birnholtz, Cabero, Capano, Dent, Krishnan, Meadors, Nielsen, Nitz, Westerweck (16,18): Echo template parameters depend on mass and spin of final BH. Echo claims used one initial waveform to generate all echo templates instead of using initial waveform corresponding to different sets of echo parameters for different events. Claimed echoes of LVT151012 have higher SNR than GW150914, while peak of LVT151012 much lower than GW150914.

Improved template search finds no evidence of echoes. Reduced significance consistent with noise.

Similar results by **Nielsen, Capano, Birnholtz, Westerweck (18).**

Some more problems with echo claims

Price, Khanna (17)

In a sequence of echoes, shape of the first burst quite different from later echoes. Contradicts one of the main assumptions in echo claims. Later and later echoes do not approach a ringing at a quasi-normal mode frequency.

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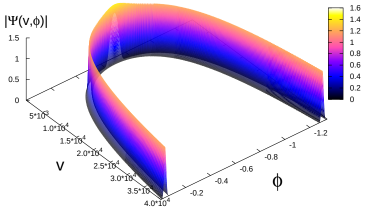
Barcelo, Carballo-Rubio, Garay (17)

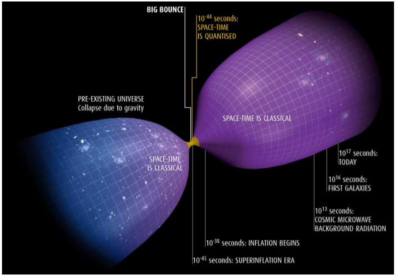
In-falling observers see a wall of concentrated energy only for old black holes. Black holes should have halved their area under Hawking evaporation. Firewalls do not form early enough after merger to cause echoes.

But, non-perturbative effects, of completely different origin, resolving singularities and propagating to horizons via bounce can lead to echoes.

Loop quantum gravity and bounce

Non-perturbative background independent quantization of GR. Geometry at quantum level predicted to be discrete. Spacetime atomized! For various isotropic and anistropic spacetimes, curvature scalars bounded, spacetime geodesically complete. Classical continuum spacetime emerges as an approximation at small spacetime curvature. Rich phenomenology **(Abhay's talk)**





New Scientist (Dec 2008) by A. Ananthaswamy

(Ashtekar, Pawlowski, PS, .. (06-..))

FLRW universe bounces at density $\rho = 3/8\pi G\Delta^2 \approx 0.41\rho_{\rm Pl}$. Δ, minimum area gap, fixed by black hole entropy calculations, and tightly constrained by CMB observations **(Ashtekar, Gupt (16))**

Time symmetric bounces in gravitational collapse

Barcelo, Carballo-Rubio, Garay, Jannes (14–..)

Very radical proposal partially inspired by non-singular bouncing cosmologies in LQG.

A time symmetric singularity free black hole connected to a white hole with a very short bouncing time: $\tau_b \propto M$
Contrast to black hole evaporation time $\tau_{evap} \propto M^3$.

Some qualitative similarities with Planck star proposal (inspired by bounce in LQG) yielding $\tau_b \propto M^2$ **(Haggard, Rovelli, Vidotto, ... (14–..))**

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Non-trivial modifications to causal structure in Planck regime where gravity is assumed to be diluted resulting in a Minkowskian type background. Propagation of a non-perturbative shock wave originating at Planck densities to region a little outside Schwarzschild radius. Thus, modifying light cone structure of GR even in regimes with small spacetime curvature.
(Qualitatively different picture from results so far in LQG).

Observational implications of time symmetric bounce

Collapsing matter produces a trapped region. As the collapsing matter reaches Planckian densities, it bounces out and subsequently causes trapped region to disappear.

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Vachaspati (16): Coalescence of black stars produce a delayed GRB following the GW signal which mimics that of black holes.

Potential signatures from fuzzballs

Hertog, Hartle (17) Consistent histories formalism used to understand probabilities in gravitational collapse in fuzzball formation.

Probability for coarse grained observables, such as mass, peaked on classical black hole solutions. But probability for fine grained observables, such as higher multipole moments, not peaked on average values. Near horizon observables in ringdown phase can potentially distinguish different fuzzball solutions.

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A given collapse history corresponds to one branching wavefunction undergoing a series of tunneling events which can lead to bursts of GW radiation.

Crude estimate for GW150914: $E_{GW} \sim 1.5 M_{\odot} c^2$

Detectable GW emission from tunneling transitions between different fuzzball solutions possible.

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The assumption that presence of such a firewall outside a black hole does not significantly affect the space-time metric seems problematic, backreaction necessary to be included. For a Planck density firewall of Planck length thickness, $M_F \sim M$.

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Abramowicz, Bulik, Ellis, Meissner, Wielgus (16)

Since $M_F \sim M$, a significant fraction of corresponding energy $M_F c^2$ may be released in firewall collision during merger and may result in an EM afterglow. Absence of powerful EM afterglows argued to constrain firewall paradigm.

Summary

- As CMB measurements provides a platform to test quantum gravity signatures in very early Universe, GW astronomy along with MMA can potentially test quantum gravity effects near black holes horizons.

- Phenomenological models inspired by ideas and results in QG proposed. Claimed to be observationally relevant. But, many gaps remain to be filled. Models so far very crude, based on many assumptions and lack various details.

- Qualitative features expected from some of the radical proposals might be soon under tight constraints. Whether some bold ideas in quantum gravity are viable in resolving central singularity and "information loss paradox" can be potentially answered in near future.