LQG & The Many Faces of Black Holes

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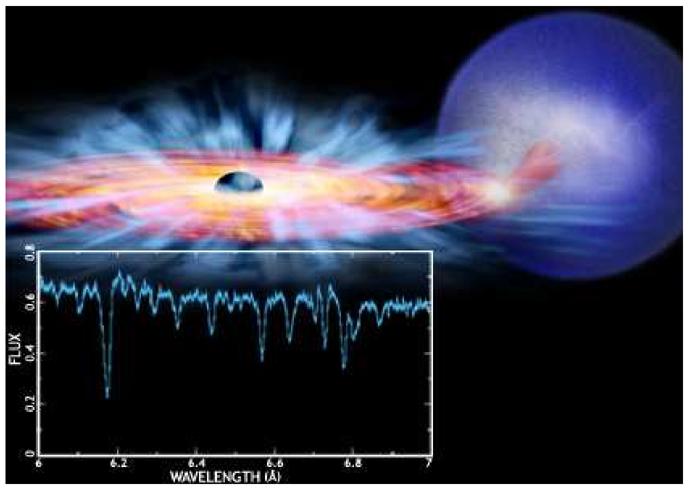
• Black holes are widely recognized as the engines that drive the most energetic phenomena in astrophysics. But they have also been the engines behind some of the most unexpected and fascinating advances in fundamental physics over the last three decades.

• Specifically, black holes have had profound impact on the conceptual fabric of general relativity, quantum theory and statistical mechanics. They provide the most concrete hint on the nature of quantum gravity. That's why they continue to be fascinating, intriguing and vexing in fundamental physics.

• Goal of the Talk:

A short overview of where we stand, and
What the most interesting open issues are.
Hope this will provide a scientific setting
for the workshop.



Unforeseen properties of Black Hole horizons

General Relativity & Thermodynamics are related! Black holes of GR are subject to three laws. First discovered for event horizons. (Bardeen, Carter, Hawking).

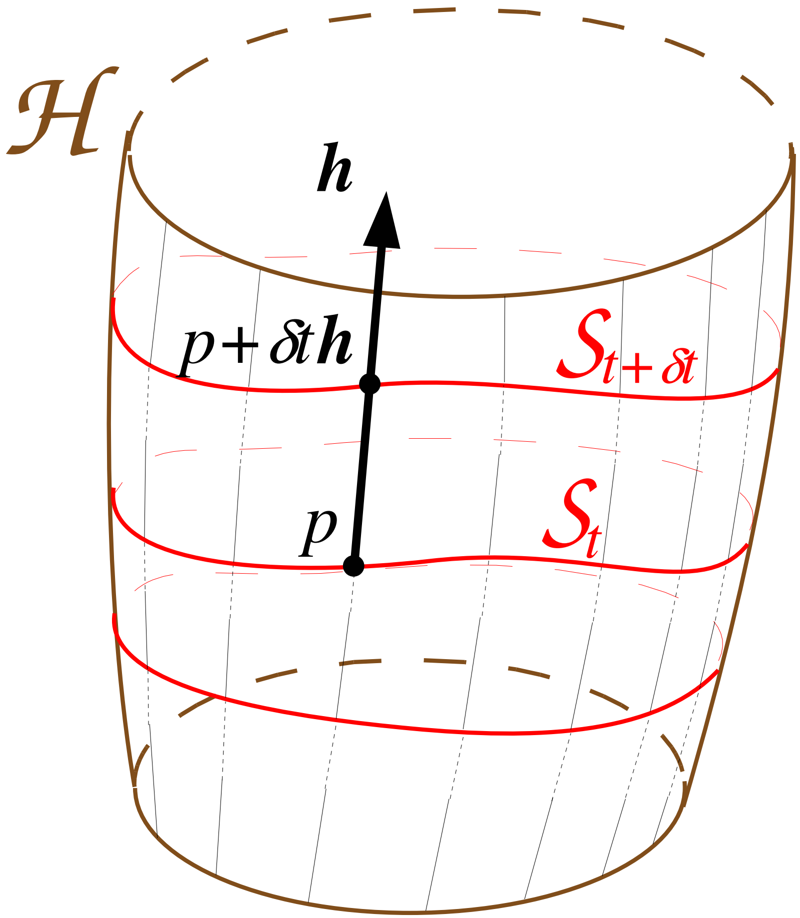
But event horizons have severe limitations.

First, they are too global. A smooth change in space-time geometry in a small neighborhood of singularity can shift them drastically and even make them disappear! (Hajicek).

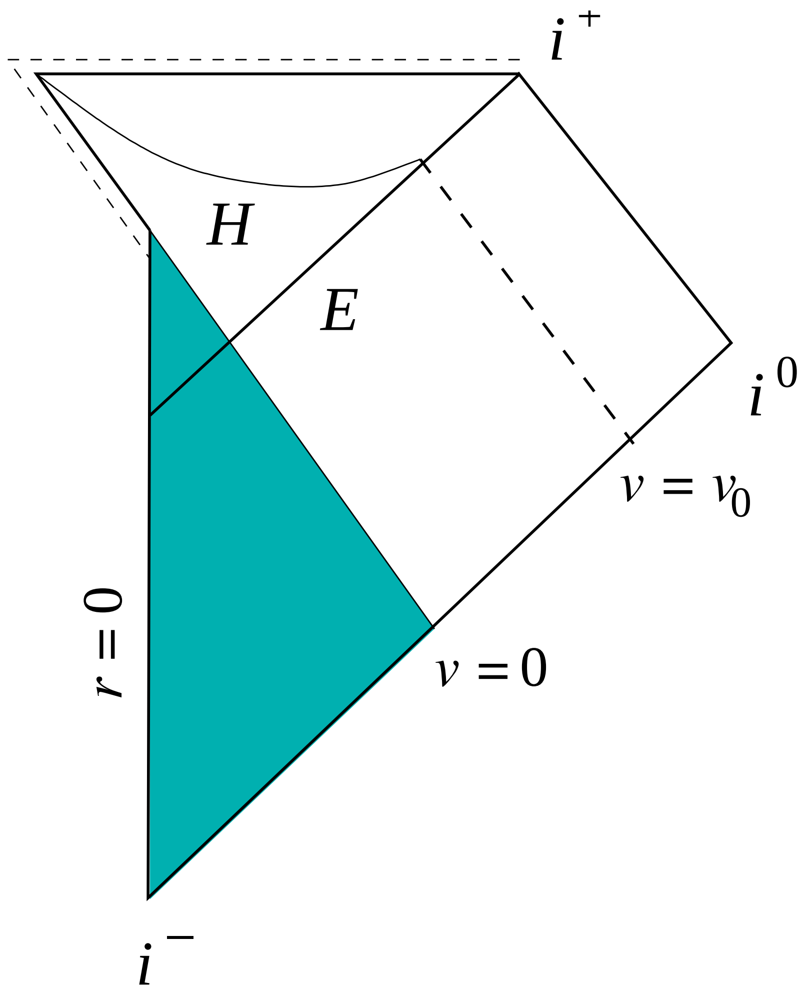
Second, they are teleological: They can grow *in anticipation* of matter that may fall in the future. There may be an event horizon forming and growing in this very room in anticipation of a collpase in the center of our galaxy a million years from today. (Concrete example: Vaidya meric).

Replacement: Quasi-local horizons (Isolated & Dynamical.)

Quasi-local horizons



(a) $\mathcal{H}$ obtained by stacking MTSs S_t



(b) Vaidya space-time

Unforeseen properties of Black Hole horizons

• BH thermodynamics was extended for more realistic situations through isolated and dynamical horizons (AA, Krishnan, Beetle, Booth, Fairhurst, Hayward, Liko, Lewandowski,....).

i) Surface gravity κ is constant on $\mathcal{H}$, if the BH is in equilibrium (isolated horizon), even when $\mathcal{H}$ is non-spherical! ($\kappa \;\sim g$ on earth's surface)

ii) If a BH makes a transition from an equilibrium state to a nearby equilibrium state, the mass M of the BH, the area a of $\mathcal{H}$, and κ, are related by

$$\delta M = \frac{\kappa}{8\pi G}\,\delta a + \delta[\text{Work done on the BH}]$$

iii) If matter satisfies 'energy conditions', the area a of $\mathcal{H}$ cannot decrease. The increase in area (of a dynamical horizon $\mathcal{H}$) is directly governed by the amount of energy and angular momentum falling across it (matter and gravitational waves).

• Striking similarity with the laws of thermodynamics: (a multiple of) κ plays the role of temperature, and (a multiple of) a of entropy! (Bekenstein) These laws hold even for hairy black holes, black holes with matter rings which distort the isolated horizon, ... New relations between solitons and colored black holes in Einstein-Yang-Mills-Higgs. theory; ...

Black hole Horizons and Thermodynamics

• However the analogy remained formal. Simple dimensional considerations $\Rightarrow$ cannot construct temperature from κ nor entropy from a in classical GR, i.e. with only G and c at one's disposal.
(Throughout, Boltzmann constant K set to 1.)

• Dramatic Change: Hawking's discovery that BHs radiate quantum mechanically as though they are black bodies at temperature $T = \hbar\kappa/2\pi$. From first law, one is led to assign entropy $S = a/4G\hbar = a/4\ell_{\mathrm{Pl}}^2$ to the horizon.

• The three pillars of fundamental physics, Quantum Mechanics, General Relativity and Statistical mechanics, unexpectedly brought together!

Entropy: Challenge to Quantum Gravity

• First law of BH Mechanics + Hawking's discovery that $T_{\rm BH} = \kappa\hbar/2\pi \;\; \Rightarrow$ for isolated horizons, $S_{\rm BH} = a_{\rm hor}/4\ell_{\rm Pl}^2$

• Entropy: Why is the entropy proportional to area? For a $M_\odot$ black hole, we must have $\exp 10^{76}$ micro-states, a HUGE number even by standards of statistical mechanics. Where do these micro-states come from?

For gas in box, the microstates come from molecules; for a ferromagnet, from Heisenberg spins; Black hole ?
Cannot be gravitons: gravitational fields stationary.

• To answer these questions, must go beyond the classical space-time approximation used in the Hawking effect. Must take into account the quantum nature of gravity.

• LQG and string theory provide distinct approaches. Attractive features but neither completely satisfactory. In Loop Quantum Gravity, this entropy arises from the huge number of microstates of the quantum horizon geometry. 'Atoms' of geometry itself!

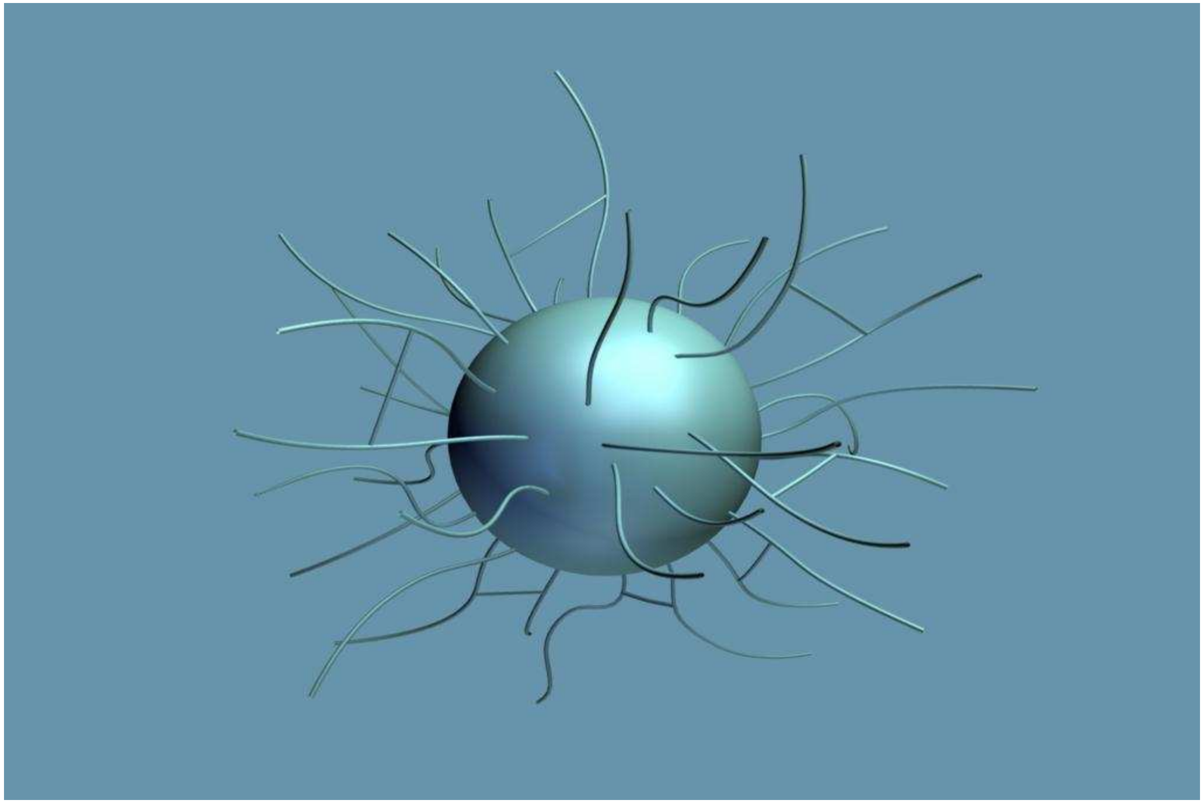
Quantum Horizon Geometry & Entropy

• Heuristics: Wheeler's It from Bit
Divide the horizon into elementary cells, each carrying area $\ell_{\rm Pl}^2$.
Assign to each cell a 'Bit' i.e. 2 states.
Then, # of cells $n \sim a_o/\ell_{\rm Pl}^2$; No of states $\mathcal{N} \sim 2^n$;
$S_{\rm hor} \sim \ln \mathcal{N} \sim n \ln 2 \sim a_o/\ell_{\rm Pl}^2$. Thus, $S_{\rm hor} \propto a_o/\ell_{\rm Pl}^2$.

• Argument made rigorous in quantum geometry. Many inaccuracies of the heuristic argument have to be overcome: Calculation has to know that the surface is black hole horizon; What is a quantum horizon? Isolated horizon boundary condition made into an operator equation. Quanta of area not $\ell_{\rm Pl}^2$ but $4\pi\gamma\,\sqrt{j(j+)}\,\ell_{\rm Pl}^2$.

• Interesting mathematical structures $\mathrm{U}(1)$ and $\mathrm{SU}(2)$ Chern-Simons theory; CFTs; non-commutative torus, quantum $\mathrm{U}(1)$, mapping class group, issues in number theory...(AA, Baez, Corichi, Krasnov; AA, Engle, Van Den Broeck; Borja-Fernandez, Diaz-Polo; Domagala, Lewandowski; Meissner; Ghosh, Mitra; Sahlmann; Corichi et al; Barbero, Villasenor, ...)

Quantum Horizon



Continuum only an approximation. At Planck scale, fundamental excitations of bulk geometry 1-dimensional, polymer-like. Each quantum thread pierces the horizon $\mathcal{H}$ and deposits a quantum of area on $\mathcal{H}$. Quantum geometry of $\mathcal{H}$ described by the $\mathrm{U}(1)$ Chern-Simons theory.

Entropy: Salient features

- Start with isolated horizons. Ensemble defined using geometric, diffeomorphism invariant multipoles. Global stationarity not necessary.

By contrast in string theory one focuses on event horizons of globally stationary space-times.

- Calculation naturally encompasses physically realistic horizons with rotation, distortion, multipoles; mathematically interesting horizons with color change for which uniqueness theorems fail; & cosmological horizons.

By contrast in string theory, detailed calculations only for extremal, stationary BHs.

- Detailed picture of the quantum horizon geometry. Quantum Gauss-Bonnet theorem. What is counted is its micro-states. Degrees of freedom that can interact with the exterior.

By contrast in string theory one counts states of a system in flat space and argues by non-renormalization theorems, that BH has the same number of states.

- A precise notion of a quantum horizon through an operator equation. Highly non-trivial & surprising element: Eigenvalues of unrelated operators in two distinct theories have to agree exactly!

Entropy: Salient features

• BI-parameter ambiguity inherited from quantum geometry. Value comes from an algebraic equation. Lack of physical understanding. Would be better if it were derived independently of BHs.

Directly analogous to the θ ambiguity in YM (Gambini & Pullin; Mercuri et al). Robustness: Determined by the calculation for the spherical IH; then theory is fixed; same value works for all other IHs. Also, qualitative agreement with Cosmology, particularly the Bousso covariant entropy bound.

In the extremal case, string theory leads to the exact Bekenstein formula; no adjustments.In the AdS/CFT argument, the simple/clear calculation yields a wrong coefficient. Only qualitative arguments on to correct it.

• In LQG we start with the phase space of grav fields with an inner IH horizon boundary and then go to quantum theory. Should locate the quantum horizons in the quantum theory!

Entropy: Salient features

• So far, only qualitative understanding of Hawking evaporation. Need more: phenomenological models of a BH as an ensemble; more detailed arguments using atomic physics analogy, (along the lines of Dreyer, for example.) Recent analysis from number theory may help.

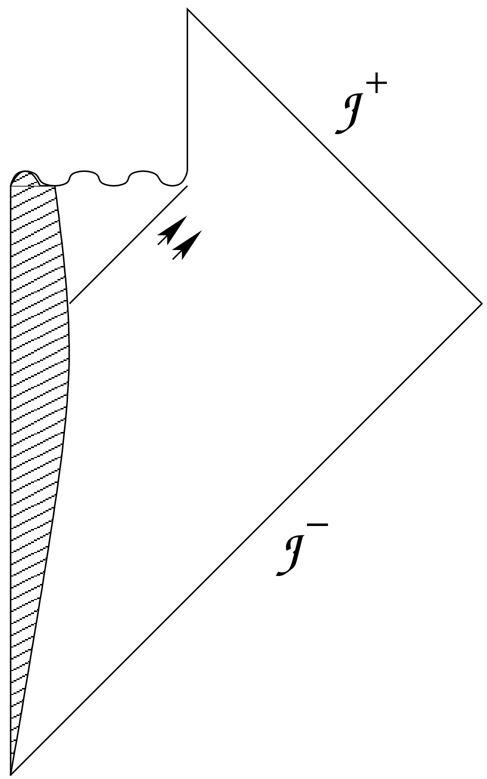
String theory: Compelling derivation of Hawking radiation for near-extremal BHs.

• An independent/simplified derivation in the extremal case? Any overlap with the string theory calculation? In both cases, horizon is a membrane; Gauge fields on the membrane play an important role; 1-d excitations pierce the membrane; the coefficient of the sub-leading logarithmic correction is the same; . . .

Next Challenge: Information loss!

• Hawking radiation: Quantum Field Theory in a fixed BH space-time. Energy conservation $\Rightarrow$ BH must loose mass and evaporate.

• Suppose BH was formed by a collapsing matter in a pure state. Hawking radiation is thermal. So when the BH is 'gone', we are left with a mixed state of maximum entropy (for the given energy). So, in BH formation and evaporation, pure states seem to evolve to mixed states. Process seems non-unitary; information is lost! Suggests: Basic structure of quantum mechanics has to be modified!!



• Where did the information go?? Although BH has evaporated, in Hawking's picture a singularity still remains. (The Cheshire cat disappears but the smile remains!) Acts as a sink of information.

The issue of Information loss

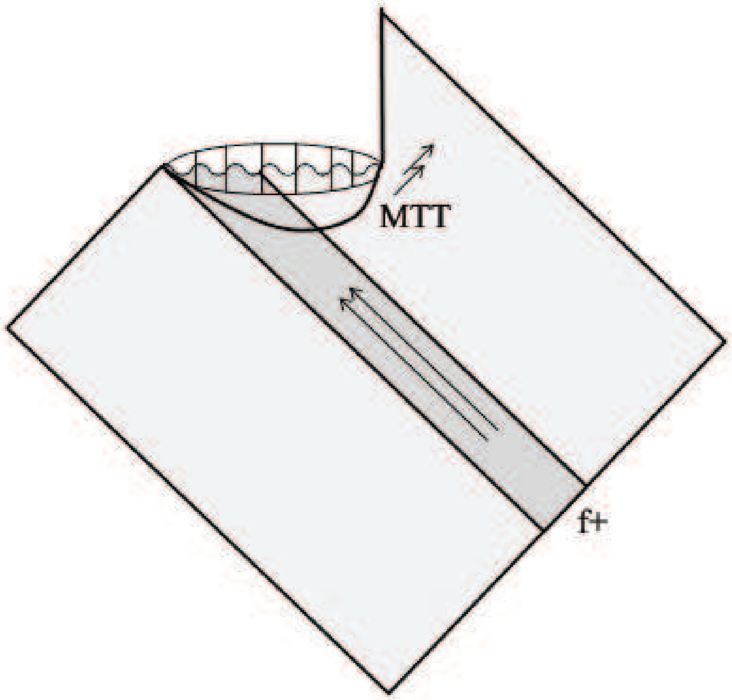
- If on the other hand the space-like singularity is resolved as in quantum cosmology brown (much circumstantial evidence from the BKL conjecture, singularity resolution in Bianchi models; first treatments of the Kontowski-Sachs model) then information has nowhere to hide.

A coherent paradigm for information recovery: future null infinity of the quantum space-time is much larger than than that of the classical space-time so that the S-matrix can be unitary. (AA & Bojowald).

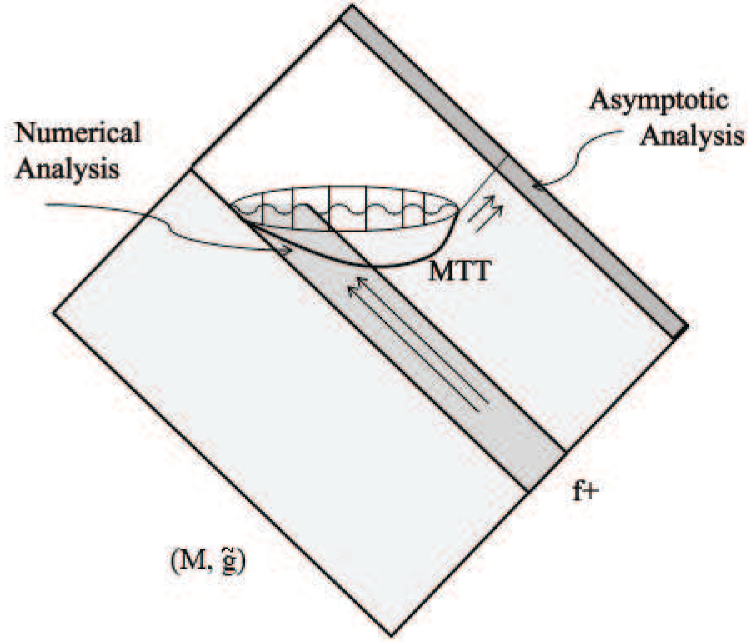
- Scenario has been developed in greater detail in 2-dimensional CGHS BHS which have many similarities with 4-d spherical BHs. (AA, Taveras & Varadarajan; Ori; Pretorius & Ramazanoglu)

- String theory appeals to AdS/CFT to say that the information must be recovered. But no direct understanding of how this happens. So, seems more like a postulate.

Quantum process: Older and the New descriptions



(c) Remnant singularity: sink of info



(d) No singularity & no info loss

There is no information loss because the quantum space-time is sufficiently larger than the classical one.

Open Issues

• How in detail does the information come out at scri-plus? Detailed comparison with the Hawking effect: Details of where and how the standard argument breaks down.

• What happens, in detail, in the interior? What happens at left scri-plus which is not a part of infinity in the full quantum space-time?

• What is the quantum geometry like in a neighborhood of the end-point of evaporation?

• Can the argument be generalized to 4-d? No longer have recourse to conformal invariance to simplify analysis.

• Does almost all incoming energy come out in the Hawking evaporation as in 2-d or does a sizable portion "bounce through" the quantum region?

• How exactly is the singularity resolved? All calculations to date have deep limitations. Is there a coherent theory what reduces to classical GR in the weak curvature region and yet resolve the singularity? Does it have controllable effective equations?

Workshop Program

- Thursday: Black Hole Entropy
- Friday: Information Loss and Singularity resolution
- Saturday: Ideas from outside LQG which may help us address the key open issues.