Black Holes
and
Their Unresolved Issues

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Gravity, a Universal Attraction

- Gravity in standard viewpoint is a force.

- In the modern view it is not a force, it is related to the fabric of spacetime.

- According to Einstein GR, which is based on

the Equivalence Principle

- There always exists an observer, the free fall observer, where gravity is not seen;

- *free particles follow geodesic paths*.

- Gravity is at work at very large and very short distances.

- Within GR notion of time and dynamics needs to be revisited.

Black Holes in Classical GR

- Historically, what became to be called a *black hole* was the first solution to Einstein GR, constructed by Karl Schwarzchild in 1916.

- The name was given by John Wheeler.

- It took sometime to understand properties of this solution and accept it as something noteworthy, not to dismiss.

- As we understand it now, a black hole
  - has an event horizon;
  - has usually a singularity;
  - the singularity is expected to be sitting behind the horizon;
  - has usually (not always) a Killing horizon.

Event horizon is a light-like surface which

- divides the spacetime into two causally disconnected regions;

- At a given time one is either inside horizon or outside of it;

- It is like a one-way membrane, one can pass through it but cannot get back.

- Observers at the other sides of the horizon do not have a two-way causal contact. One can only send OR receive signals but not both.

Gravitational Collapse

- If pressure (repulsion of particles) in a lump of matter is not large enough to withstand their gravitational attraction, nothing prevents *gravitational collapse*.

- This can happen in astrophysical objects like stars if they are in certain range of mass (and other characteristic parameters).

- When a closed trapped surface is formed, formation of a black hole is inevitable.

- Black holes can form dynamically through a process which can be completely described within Einstein GR.

- Black hole is the end point of the dynamics for such stars within Einstein GR.

Black Holes in Sky

- Observed stellar mass black holes have mass range $few - 70\ M_\odot$.

- These black holes
  - have their own life and dynamics *within the galactic environment*.
  - *eat up* whatever they can find around and grow in time.

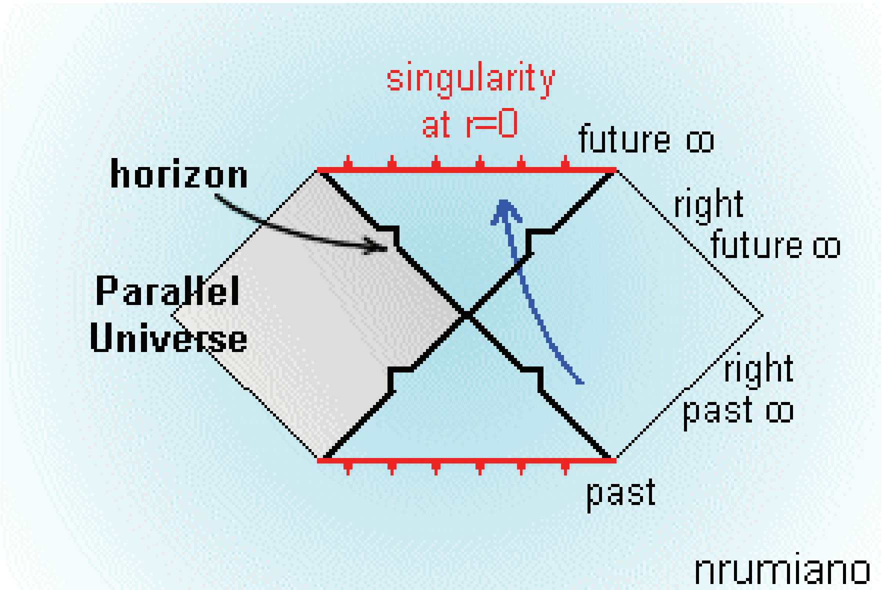
- At the galactic centers we usually find a supermassive black hole, with a mass range $10^6 - 10^{10}\ M_\odot$.

- These black holes influence the galactic dynamics around them.

- Stellar mass or supermassive black holes are generically recognized by the accretion disk of their food, which usually emit X-ray, or possibly through gravitational lensing.

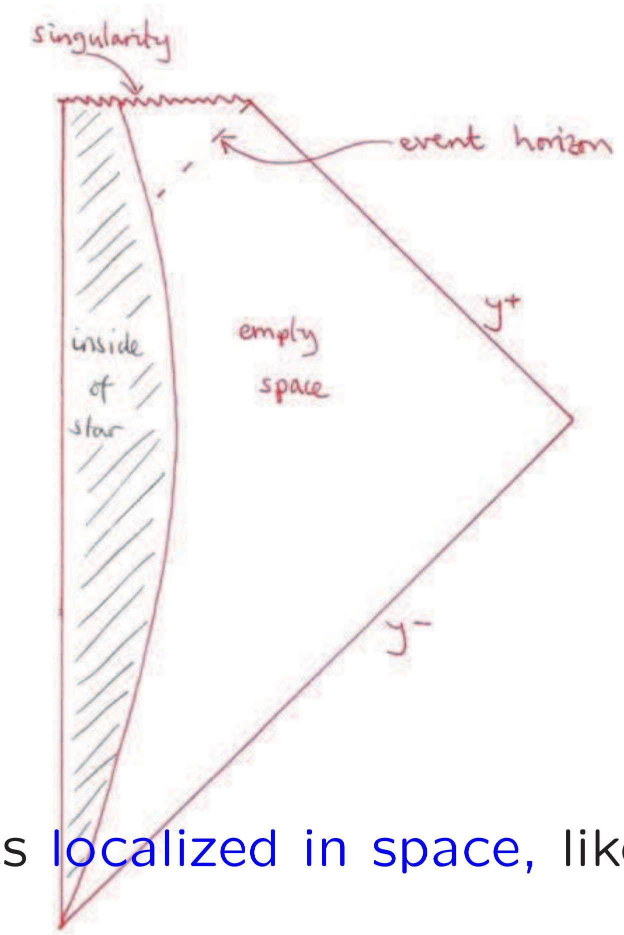
Causal Structure of Black Hole

- is encoded in the Penrose-Carter diagram.



- Sch'd black hole depicted above is a time-symmetric object; it is an eternal black hole. Above shows a (white + black) hole.

Real black holes are a result of gravitational collapse are not eternal:



Black holes are objects localized in space, like a "dense star."

Before the horizon forms, the collapsing matter falls behind the trapped surface (which is not depicted here).

Equivalence Principle and Black Holes

- Equivalence principle:

  All information must be available to all observers.

- Free fall observers can't communicate after horizon crossing.

- So,

  - Either, all the physical information is only contained in observers which remain in one side of horizon (who are in causal contact), or

  - equivalence principle should be revised.

Black Hole as Thermodynamical Systems

- Early 1970's was a time of rapid, big and deep developments in physics of black holes:

- Black holes in many respects are like "holes" and not walls in spacetime.

- A Universe with a black hole in it, is an open system.

- In the presence of black holes, not only few particles systems, but also many particle thermodynamical systems, are also open.

- As in other places in physics we'd like to deal with closed systems. One may then ask:

Shall we close the system by "adding black hole itself" to the system?

Black Holes Have Entropy

- J. Bekenstein [1972,1973]: Yes. One can close the system thermodynamically if a black hole also behaves like a thermodynamical system, in particular if it has an entropy.

- Entropy of black hole should be proportional to its horizon area A_H. Specifically:

$$S \propto \frac{A_H}{G_N}$$

- We also know that black holes are specified by their mass M, angular momenta J_i and possibly electric or magentic charges Q_a.

Do black holes, besides energy and conserved charges and entropy, show other characteristics of generic thermodynamical systems?

Classical Laws of Black Hole Mechanics

- Bardeen-Carter-Hawking [1973]:

  Black holes are indeed governed by four laws, paralleling laws of thermodynamics.

- **Zeroth Law:** Surface gravity κ, the gravitational force (acceleration) for an observer sitting at the horizon, behaves like temperature.

$$\kappa = \frac{G_N M}{R_H^2}, \qquad R_H = 2G_N M\,.$$

  Horizon is like a "equi-potential" surface.

  For a supermassive black hole

$$\frac{\kappa}{g_{Earth}} \sim 1 - 100$$

- **First Law:** black holes and their environment can exchange energy and entropy but their variations always satisfy

$$\frac{\kappa}{2\pi}\delta S = \delta M - \sum_i \Omega_i \delta J_i + \sum_a \Phi_a \delta Q_a$$

Ω_i is horizon angular velocity and

Φ_a is horizon electric potential.

- **Second Law:** In processes involving a black hole of entropy S_{BH} and another system of entropy S_{other}, entropy never decreases and also

  in the process of merger of black holes the final black hole has a larger entropy than the sum of the original ones.

- **Third Law:** Extremal black holes, black holes of vanishing surface gravity, do not form under gravitational collapse (in a finite time).

Is this just an analogy or is there anything deeper?!

Is black hole a “real” thermodynamical system?

Semiclassical Aspects of Black Holes

- Adding quantum (semi-classical) effects Hawking [1974, 1975] showed that

Black holes do radiate a black-body radiation at temperature

$$T_H = \hbar \, \frac{\kappa}{2\pi}.$$

- Horizon is not a "one-way membrane" at quantum level, it is a permeable surface allowing *thermal radiation* to leak out.

- For a Sch'd black hole $T_H \sim (G_N M)^{-1}$, the bigger the black hole, the cooler it is.

$$T_H\Big|_{Solar Mass BH} \sim 10^{-17}\ K\,, \qquad T_H\Big|_{Supermassive BH} \sim 10^{-26}\ K\,,$$

- **Hawking:** the radiation seen by the observer at infinity is actually emitted by the collapsing matter, after the formation of closed trapped surface, before the horizon is formed.

Semiclassical Aspects of Black Holes

- **Hawking:** Hawking-radiation is a messenger of the turbulent times of collapse, and the radiation undergoes a very large redshift to reach the observer at infinity.

- Eternal black holes do not Hawking-radiate.

- Extremal black hole do not Hawking radiate.

- Black holes radiate off all kinds of charges they have; i.e. mass, angular momenta and possibly electric charges.

- Black hole radiation comprises a thermodynamical system adiabatically detached from the black hole.

- In the usual semiclassical treatment,
  - backreaction effects of the Hawking radiation on the black hole remains small,
  - approximations in Hawking's computation remain valid and,
  - nothing prevents a black hole from shedding all its mass and complete evaporation.

Black Hole Microstates and the Entropy

- Thermodynamical systems usually have underlying stat.mech. systems, where the dynamics is reversible and unitary.

- Moreover, noting

  - universality of the Bekenstein-Hawking entropy and thermodynamics picture and,

  - the universality of gravity theory and its interactions,

- it is natural to relate these two universal descriptions.

- Therefore, unitary stat.mech. system should be uniquely specified by the gravity theory the black hole is a solution to.

Black Hole Microstates and the Entropy

- How to model or to identify this stat.mech. system?!

- At zeroth order, one would like to do microstate counting, not a detailed knowledge of the microscopic system.

- String theory, as a model for QGr., is the only known example providing a setup for microstate counting, and in some cases identifying the underlying stat.mech. system.

- String theory has been successful for supersymmetric black holes which are extremal, and do not Hawking-radiate.

- String theory, so far, has not been successful (except special cases, namely D1D5P-system) in dealing with generic non-extremal black holes.

- The other contender, loop quantum gravity, has not appeared so successful in this ground.

But, we usually think that there is a semi-classical level between thermodynamics and microscopic system; e.g. recall theory of elasticity or spin-waves.

Do we need to go all the way to Q.Gr. level to have a better understanding of thermodynamics of black holes and their evolution?

Is there a semi-classical framework?

Semiclassical Black Holes and Equivalence Principle

- Equivalence Principle:

  at classical level gravity may always be **locally** replaced by acceleration.

- Bill Unruh [1976]:

  at semi-classical level, vacuum state of an observer with acceleration a is a thermal state at temperature

$$T_{Unruh} = \hbar a.$$

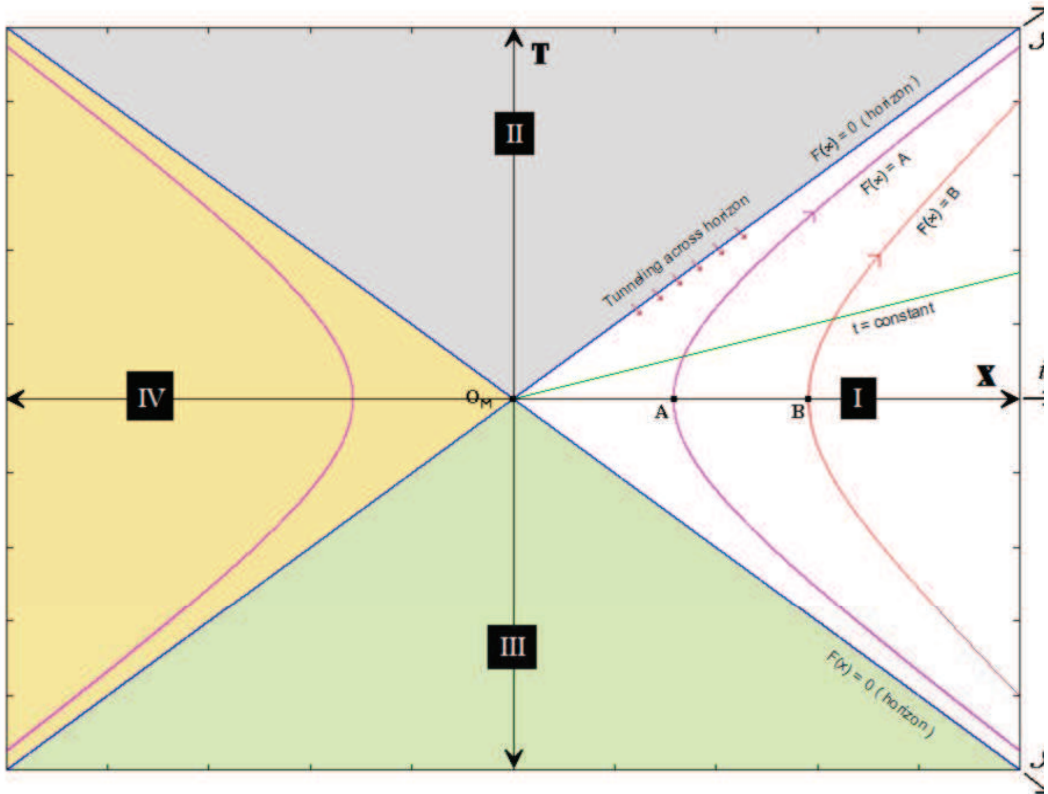
- T_{Unruh} equals Hawking temperature for a black hole, with $\kappa = a$.

- Unruh's work suggests the possibility of equivalence principle at semi-classical level:

  - Acceleration leads to thermal effects.

  - Rindler space has a Killing (but not an event) horizon.

In other words: a quantum field theory on flat Minkowski space is equivalent to the same QFT in a non-zero temperature on Rindler wedge.



Rindler vacuum from the Minkowski theory viewpoint is a thermally entangled state of states in causally disconnected regions I and IV.

Semiclassical Black Holes and Equivalence Principle

- Together with Bekenstein's result, previous discussions motivate the idea that

Thermodynamic description of a black hole has something to do with its horizon, and not the interior.

- General picture:
  - *Thermal description is a local feature, our local physics seems to be doing well at semi-classical level when we have horizons.*
  - Thermal state is an entangled state of states on the other sides of the horizon in the sapcetime sense, on a Penrose diagram, which are causally disconnected.
  - The von Neumann entropy of this entangled state is exactly equal to the Bekenstein entropy.

$$S_{von-Neumann} = S_{Bekenstein}$$

Black Hole Evaporation and Information Paradox

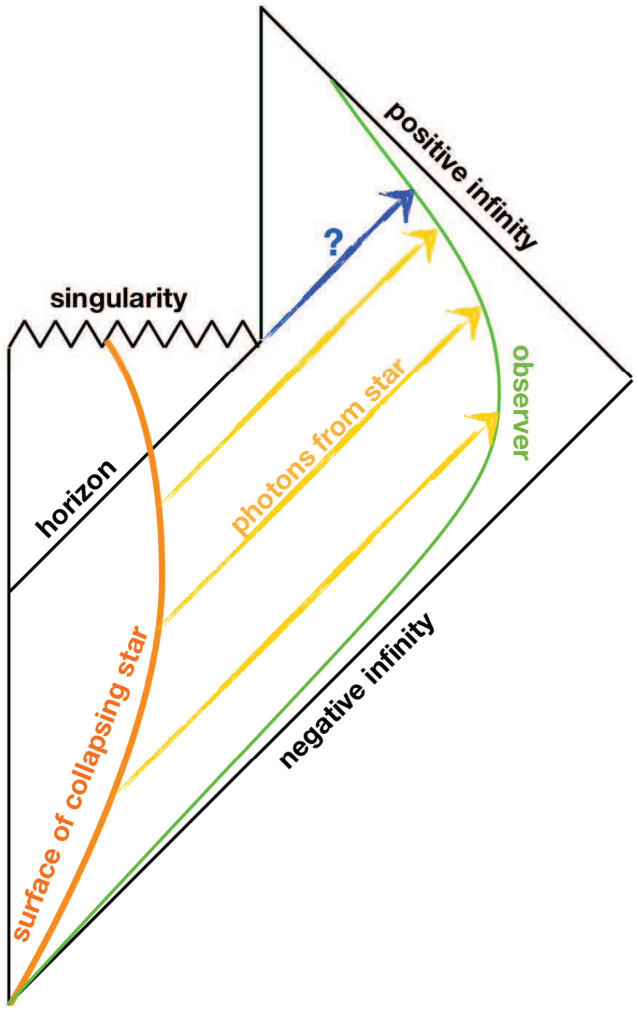
- Anything which passes through the horizon will eventually fall onto the singularity, basically moving out of our physical access (within semi-classical picture).

- In adiabatic regime and when back-reactions of Hawking radiation are small, the above picture is a trustable one if things which fall off into black hole are thermalized before reaching the singularity.

- When the amount of mass radiated off from black hole is comparable to its original mass this picture may need revisiting.

- Suppose that nothing stops black hole shedding off (almost) all its mass. What would then happen to the physical information about what went inside it to make up the black hole?

Black Hole Evaporation and Unitarity



Process of formation and evaporation of black holes, as depicted, happens through a black hole stage, and may not be a unitary evolution.

Black Hole Evaporation and Information Paradox

- If something stops black holes from complete evaporation, we could be safe; black hole remnants may store all the information, or,

- the Hawking radiation, especially in the last stages has a non-thermal tail. This non-thermality may be sourced in different ways and may become bigger and notable after a fraction of life-time of black hole.

- Is the information of the stuff went in extractable?

- Black hole complementarity may be invoked to answer such questions.

Black Hole Complementarity

- Black hole complementarity is a manifestation of equivalence principle at semi-classical level:

1. All the possible information about black hole is already stored in one side of the horizon;

2. The information behind the horizon is a copy of what is available to any outside observer;

3. This copy may arise from (maximal) thermal entanglement picture discussed;

4. The processes involving black holes, their formation and evaporation, are all describable by **local** and **unitary** semi-classical physics. No UV complition is needed until, perhaps the very last stages of complete evaporation.

Black Hole Complementarity

Black hole complementarity implies that

1. The observer sitting at infinity sees the Hawking radiation and associates an entropy to black hole.

2. The free fall observer does not see the Hawking radiation and when passing through the horizon s/he does not carry any extra information to the inside.

   NOTE: According to equivalence principle, free fall observer is supposed to see only a usual Minkowski space.

3. Thermodynamical properties of black holes can all be attributed to a region very close to, but outside the event horizon, the stretched horizon.

4. Holographic Principle, that all the information in a d dimensional (quantum gravity) system is available on a $d-1$ dimensional space-time, is suggested by the black hole complementarity.

Summary of Black Hole Complementarity and stretched horizon setup

1. Temperature is understood through thermally entangled state (*a la* Unruh);

2. Entropy is the von Neumann entropy and;

3. Thermodynamical characteristics of black holes is associated with an arbitrary QFT residing on the stretched horizon. Quantum gravity effects are not essential to the thermodynamical behavior.

4. In this picture, perhaps unlike the lore (e.g. Wald's entropy formula), the entropy is not associated with the "classical geometry," but with the logarithm of number of microstates available at a given energy.

   Implicit in the above: states of this field theory have a discrete and countable spectrum.

Complementarity Under Strain

- To address the shortcomings of the complementarity picture, we need to view gravity or thermodynamical picture for black hole as the thermodynamic limit of an underlying unitary stat.mech. system.

- This stat.mech. system is supposed to have a unitary local QFT continuum limit.

- Identification of entropy as stated above suffers from species problem.

- S. Mathur: 1990's-2000's: Unitarity of formation-evaporation of black hole necessitates order one corrections to physics at the horizon, invalidating semi-classical description.

- Recently, this has been put in a more explicit setting:

Firewall controversy.

Firewall Controversy, a Challenge to Complementarity

- According to complementarity,
  - anything outside black hole is (thermally) entangled with anything outside;
  - Hawking-radiation is also thermally entangled with a similar state inside the horizon.

- When black hole radiates off half of its mass, after the so-called Page time, everything inside should be completely thermally entangled with the radiation outside.

- While Hawking-radiation is expected to continue as before.

Firewall Controversy, a Challenge to Complementarity

- Black hole still radiates stuff to the outside horizon region so that the two parts of the Hawking radiation are maximally (thermally) entangled with each other.

- The controversy appears because: there exists specially tuned in-falling observer which can access

  - not only both of the two parts of early and late Hawking radiation,

  - but also the part which is inside horizon.

  while all three are maximally entangled.

- This leads to a contradiction.

Firewall Controversy, a Challenge to Complementarity

- How to resolve it: Such an observer which can access all three parts cannot exist, or the in-falling observer should be prevented from accessing inside.

- That is to assume that after the Page time horizon is in fact becoming a firewall: a place with a concentration of energy momentum tensor.

- This is in tension with complementarity.

- Possible Resolutions?!
  - relax one (or some) of the requirements of complementarity (e.g. locality).
  - back reaction?!
  - Hawking-radiation is not maximally entangled?!
  - Inside horizon changes?!
  - Black hole singularity plays a role?!

Summary

- Black holes as classical solutions of GR and geometries with specific properties.

- Black holes have an event horizon which divides the spacetime into two causally disconnected parts.

- There is usually a singularity, which is hidden, censored, behind the horizon.

- Since things can fall into black holes, one should associate an entropy with them.

- This entropy has exactly the same meaning as the entropy in standard thermodynamical systems.

Summary

- Classical black holes may be viewed as macroscopic systems satisfying four laws, paralleling laws of thermodynamics.

- At semi-classical level black hole horizon is permeable and let's Hawking-radiation out.

- Hawking radiation is a black-body radiation at a temperature.

- Therefore, semi-classical black hole is indeed a thermodynamical system like any other.

- Thermal properties of black hole may be attributed to its horizon.

- To avoid information loss in the processes involving black holes one may invoke black hole complementarity:

  No extra information is inside horizon.

- Complementarity is in fact a manifestation of equivalence principle at semi-classical level.

- Complementarity implies that inside and outside horizon are (maximally) thermally entangled.

Concluding Remarks

- Hawking's analysis of the radiation can in principle continue beyond black holes half life, the Page time.

- Hawking radiation after the Page time is in principle accessible to a physical observer falling inside, leading to firewall controversy.

- This is a challenge to complementarity, which is a semiclassical statement of the equivalence principle.

- *The jury is still out*.

Thank you for your attention.