BLACK HOLE ENTROPY

Since Bekenstein: coarse-grained entropy, associated to all possible ways the black hole would have formed.

At this stage it's clear that black holes are really thermodynamics systems, but: what is the meaning of this entropy in terms of statistical mechanics? Which are the microstates and how do we count them?

- What is the mechanism that makes S_{BH} a universal function?
- Why is S_{BH} non-extensive?
- What are the black hole microstates and where are they located?
- Are there corrections to S_{BH}? Do we need to go beyond semiclassics?

It's expected a final theory of quantum gravity to answer this.

Meanwhile, several approaches addressing above questions. Two categories:

- Associate S_{BH} with quantum fields
- Associate S_{BH} with fundamental states

⇒ All of them recover Bekenstein entropy ⇒ problem of Universality

- Bekenstein entropy as entanglement entropy
- Thermal entropy of Unruh radiation
- Quantum gravitational statistical mechanics – $\mathcal{H}$ of quantum gravity
- Entropy as Noether charge
- ....

BLACK HOLE PUZZLES

- The temperature of the black hole : 10^{-8} K
  Nothing that cold in reel world! As it emits Hawking radiation. By the time it has reached Plank mass : 10^{32} K!
- Lifetime of a black hole (Page'76)

$$\tau_{BH} \sim 10^{71} \left(\frac{M}{M_\odot} \right)^3 \text{ sec.}$$

Solar-mass black : $\tau \sim 10^{53}$ times the age of the universe

- Transplanckian problem : It refers to the appearance of quantities beyond the Planck scale. Then we cannot trust the semiclassical approximation.
  A wave packet received by an observer at infinity can be traced back to the horizon, and it is blueshifted exponentially (with respect to Killing time). That gives rise to the appearance of arbitrary high frequencies

Blue-shift factor : $e^{\kappa_H t_{BH}}$

$\kappa_H = \frac{1}{4m}$ surface gravity of initial black hole

$t_{BH} = 5120\pi \left(\frac{m}{m_p} \right)^3 t_p$ lifetime evaporating black hole

→ Planck mass & time

↓ times typical frequencies Hawking radiation, of order κ_H

Solar-mass black hole : $\kappa_H \sim 10^{-39} w_p$, $t_{BH} \sim 10^{118} t_p$

$w_{max} \sim \kappa_H e^{\kappa_H t_{BH}} \sim 10^{10^{75}} w_p$

- **The information loss**: As the black hole radiates energy, it shrinks, until it is gone. As every bit of information that went into the black hole would be permanently hidden from the outside world. When there is not bh anymore, where the information go? [Classical picture of 'no hair']

Hawking radiation is thermal → No way of convey the vast amount of information hidden by that entropy

Standard picture: Consider a shell of quantum matter in a pure state collapsing to form a black hole, that then evaporates completely via Hawking radiation

Initial pure state ⟶ final mixed (thermal) state

But unitarity requires that pure state evolves to pure state

We can think on term of von Neumann entropy (as a measure of lack of information), this prosses has led to an unallowed loss of information.

We have lost predictability: Having the final state we cannot determine which was the original initial state.

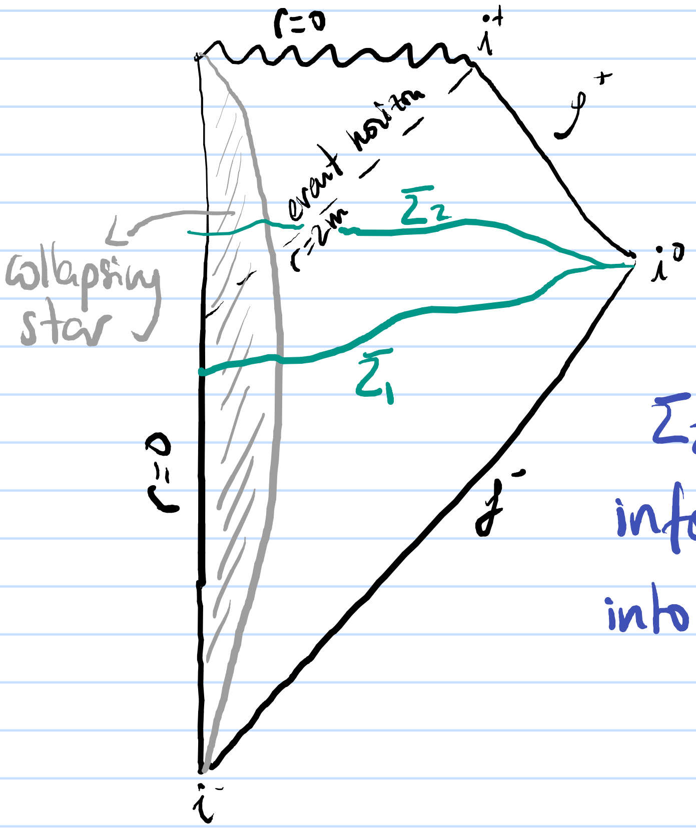
Hidden assumption:

- No long-lived remnants
- No residue of singularity
- Pure thermal radiation
- Close system
- No "exotic matter"
- Locality + Lorentz invariance
- Unitarity

One way of conveying the essence of the information loss paradox:

We assume collapse and that a singularity forms, with an associated event horizon. Both of which dissapear when the black hole fully evaporates, leaving behind a spacetime with a Minkowski causel structure. The problem is then obvious if we think in terms of Cauchy surfaces.

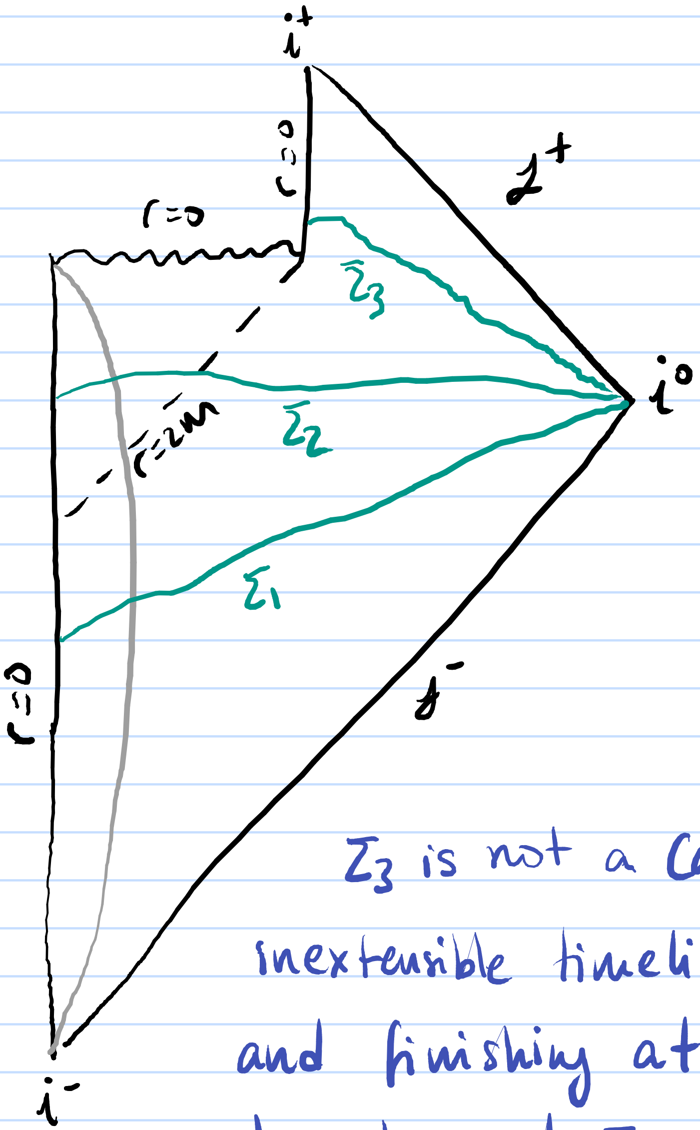
Collapse:



Σ_2 must contain all the information about what fell into the event horizon

Every inextensible timelike curve originated at $\mathscr{I}^-$ intersects Σ_1 (and Σ_2) exactly once.

Evaporation :



Σ_3 is not a Cauchy surface. Any inextensible timelike curve originated at $\mathcal{I}^-$ and finishing at the singularity, fails to intersect Σ_3.

Information present on Σ_1, Σ_2 is absent on Σ_3.

Then, Σ_1 to Σ_3 is a Cauchy to non-Cauchy transition $\Rightarrow$ cannot be retrodictable or unitary.

A broad picture of proposals

- Information hidden in the correlations:

Most pragmatic idea. The information is hidden in the Hawking radiation and it emerges with it.
Hawking calculations reveal no such correlation due to its semiclassical character.
[Full development next lecture]

- Remnants: Can the information be retained by a stable black hole remnant?

This Planck size remnant should be capable of carrying an arbitrary large amount of information
Which are their thermodynamic properties? Can they interact with the outside world?

- Information coming out in a final burst:

Radiation remains truly thermal down to the Planck size, where semiclassical approach breaks down and information starts to leak out encoded in correlations.
Arbitrary amount of information in a object of Planck mass that needs to be released
Also, final stage must take very long time, so same problem of stability than remnants.

- <u>Baby universes</u> : can information escape to another universe?
  Collapse induces nucleation of baby universe, causally disconnected from us (so information is completely inaccessible)
  Here the multiverse encompasses the quantum mechanical interactions of all universes classically disconnected.
  A 'superobserver' (capable of observing the state of the whole multiverse) would see no information lost.
- <u>Soft-hair</u> : Can the information be encoded in quantum hair?
  No-hair theorem is classical, but quantum analysis could reveal the existence of a soft hair (like BMS proposal)
- <u>Information loss</u> : What if we really lose information?
  Evolution is not unitary and information escapes to infinite, because of considering an open system (Wald & Unruh proposal)
- <u>No black holes</u> : What if a real black hole never forms in reality?
  In a collapse not a true event horizon or singularity forms, but a extremely compact object mimicking the black hole.
  (black stars, fuzzballs ...)