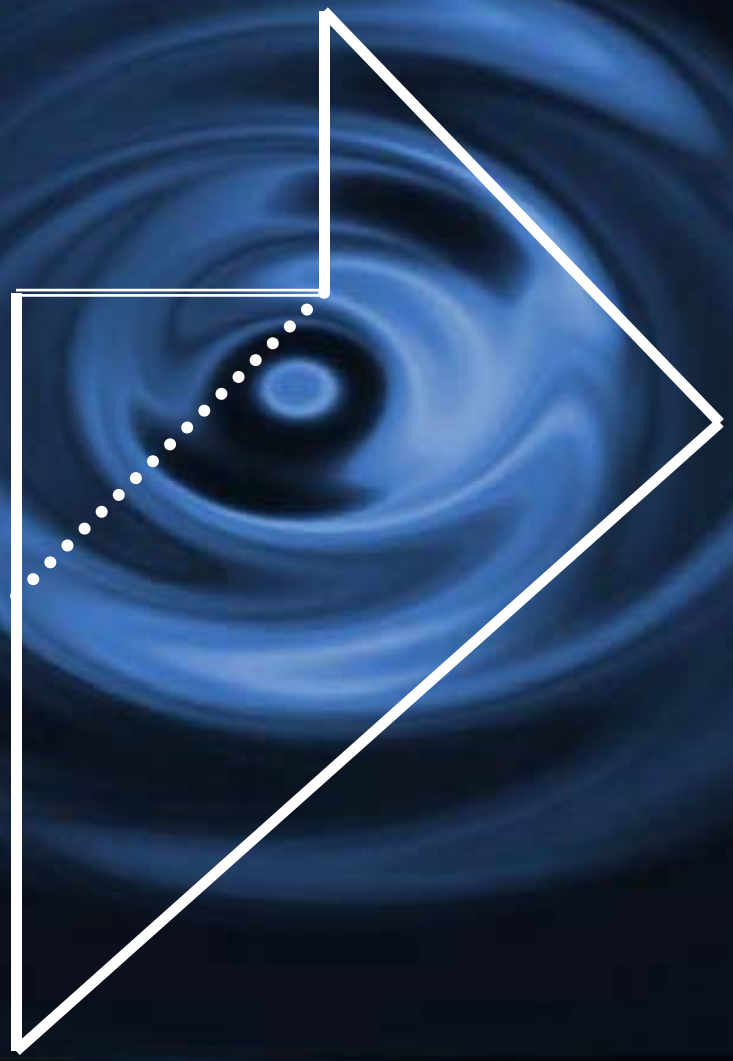
Quantum Black Holes:

What have we learned ?
Open problems.

Erik Verlinde

University of Amsterdam

Information paradox: Hawkings argument



Information paradox.

- Proposed "solutions": information loss
- remnants
- information comes out: stored in correlations (*)

- (*) now believed by most people.

Unitary Evolution

- Holds for every theory with a microscopic dual description (AdS/CFT)
- Can one prove unitarity in flat space? Directly, or do we need a dual theory.

What is wrong with Hawkings argument?

- Large red shifts near horizon?
- Quantum gravity effects at singularity?
- Are locality or causality violated?

What is wrong with Hawkings argument?

The argument is based on QFT in curved space and uses the notion that a quantum state lives on a Cauchy slice and satisfies local factorization rules.

This is just plain wrong for a situation that involves infinite red of bleu shifts in combination with gravity.

Does the singularity play a role?

- Conveyer belt: acausal information flow.
- Special final state: “bleeching”.
- Or does everything happen at the horizon? (*)

Black Hole Complementarity

- Region behind the horizon does not exist for the outside observer.
- RULE: there are no “Meta-observers” (‘t Hooft).

A meta-observer is someone who has information about causally disconnected regions.

Black Hole Complementarity

- Horizon = "hot membrane" for outside observer.
- Horizon = normal space time for infalling observer.

Observer Complementarity

RULES:

- Always state questions from the point of view of one particular observer.
- Never ask questions that involve two causally disconnected observers.

CLAIM: All information paradoxes are solved.

Observer Complementarity

- Every observer needs to describe physics only inside his own causal patch.
- Applies to black holes, cosmology, or flat space.
- Causally disconnected regions do not exist from the point of view of the observer.
- Horizons are described by “hot membranes”.

How does information come out?

- Information gets stored on “hot membrane” near the horizon.
- As the black hole evaporates its gets emitted true unitary evolution.
- The membrane and the “thermal” radiation remain in a pure state.

“LIKE A BURNING PIECE OF COAL”

Infalling observers.

- How to describe them? Is there a dual formulation too?
- How does it relate to the one for the asymptotic observer?
- What happens at the singularity?

Infalling observers.

Expectation:

Infalling observers can only be described as a non-isolated quantum system in terms of mixed states.

The space time picture is approximate and breaks down at the singularity.

Infalling observers.

There is no description of infalling observers in term of pure quantum states.

Bekenstein-Hawking formula

- Reproduced microscopically for extremal case.
- Can one reproduce it for generic black hole?
- Is there an explanation why S= A/4G?

The BH entropy formula

It is a generic result (like thermo and hydrodynamics)

It holds for every sensible microscopic theory with the right properties to contain gravity.

The BH entropy formula

Newton's constant is not a true fundamental constant of nature, but an effective "phenomenological" parameter characterizing the number of fundamental d.o.f.
(like the central charge for a CFT).

The BH entropy formula

Eventually will be derived by showing that entropy behaves like an area in an emergent space-time.

- D-branes: states in "dual" weak coupling non-BH phase => strong coupling BH states.
- Unclear "where states live". Counting confirms BH-entropy but does not explain or derive it.

- No other checks (loop QG, pure gravity, ...)

Black hole entropy can not be explained from a purely (super-)gravitational theory

Does “Quantum Gravity” exist?

- Is there a fundamental complete unitary theory that uses (dynamical) space time in its fundamental formulation?
- Closed string theory or LQG?

There does not exist a complete microscopic theory that is formulated in terms of a dynamical space-time.

“quantum gravity”

Fuzzball program

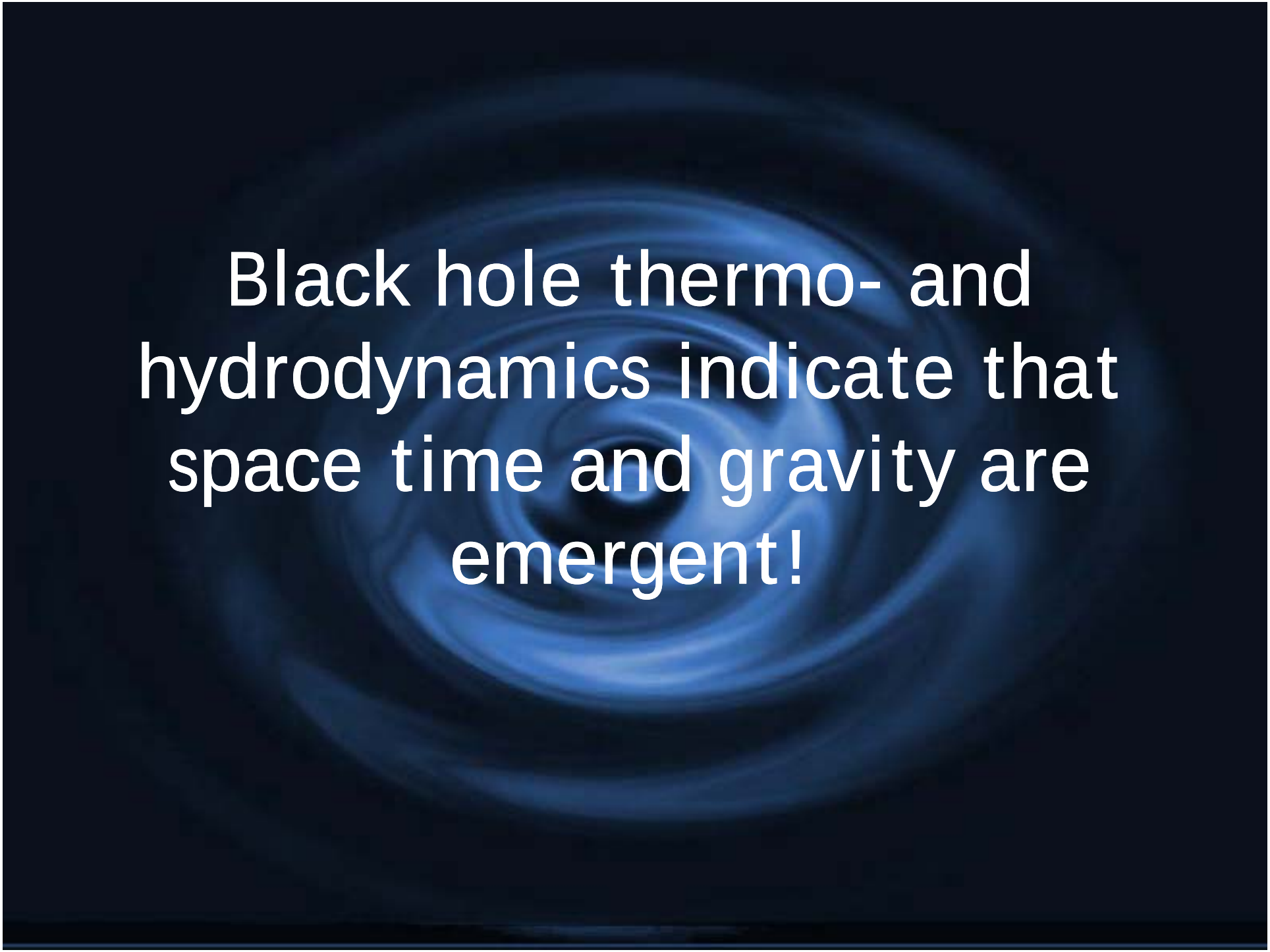
- Do quantum states correspond to classical geometries?
- Can pure states correspond to black holes, or is a black hole always a mixed state (thermal)?
- Is there a version of the "fuzzball" program that could be right?

HOLOGRAPHY

- States can be represented in terms of d.o.f. on the horizon.
- Should that be a local FT?
- Non-local map from boundary to bulk?
- Extra coordinate "emerges", like scale in AdS/CFT. Is there a flat space analogue?

A unique microscopic theory?

- A theory of "quantum gravity", should contain d.o.f. to account for BH entropy.
- Counting of states for extremal black holes (with susy) in terms of D-brane d.o.f.
- Are the microscopic d.o.f. unique?
- Or are there other microscopic theories for which the BH formula holds?

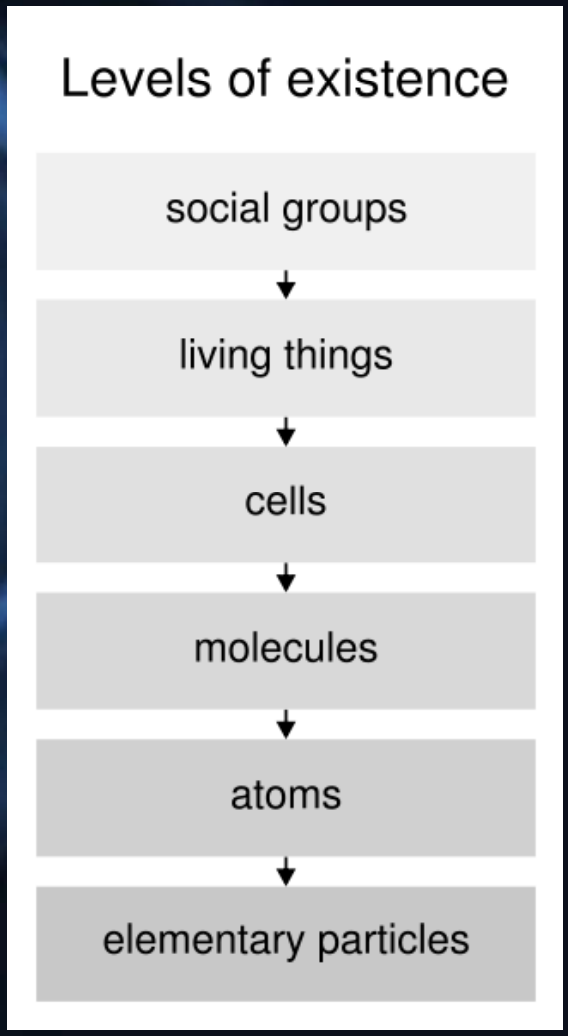

Black hole thermo- and hydrodynamics indicate that space time and gravity are emergent!

Strong Emergence

- new properties arise in a system that can not be directly derived from its components.

"The whole is greater than the sum of its parts."

"The system supervenes its components"



Weak Emergence

- new properties arise as a result of interactions at an elemental level.
- macroscopic system has an effective “mean field” description derived from a more “fundamental” microscopic theory.
- Examples: thermodynamics, hydrodynamics

Is Gravity Emergent?

- It is universal, independent of details!

But then:

- Even geometry is a derived concept.
- Its underlying microscopics is not derivable through "quantization" or "discretization"
- Such approaches are at best effective descriptions.

Derived concepts

- macroscopic, no “fundamental” meaning
- effective description of microscopics
- universal, independent of details
- underlying microscopics is not derivable through “quantization” or “discretization” of macroscopics

String Theory

most string theorist believe:

- it is the complete and final fundamental theory
- geometry is an important ingredient
- strings (or D-branes) represent the true microscopic degrees of freedom
- many vacua: compactifications that generically break supersymmetry (landscape)
- it leads to “holographic” dualities, like AdS-CFT

String Theory

Few (but some) string theorist believe:

- complete theory, but not the final one.
- space time geometry is a derived concept.
- gravity is emergent, possibly in the weak sense.
- strings are emergent, probably in the strong sense.
- the many vacua parametrize the universality classes =>landscape
- holography (AdS-CFT) is THE paradigm to understand the emergence of strings and gravity.

Todays “fundamental” theories are tomorrows “effective” ones.

It is “Turtles”

…

all the way down


THE END