Approaches to Quantum Gravity

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■ Opening remarks

- Gravity, as we know it, is described by Einstein GR which may be viewed as
  - relativistic extension of Newtonian gravity, or as
  - extension of special relativity to generic non-inertial observers.
- Einstein GR
  - is based on equivalence principle,
  - relates gravity to the fabric of spacetime,
  - may be viewed as a classical field theory, like Maxwell's theory.
  - The dynamical field in GR is the metric of spacetime.

- Unlike Maxwell theory,
  - Einstein equation is highly non-linear,
  - everything couples to gravity.
- GR is a diffeomorphism invariant theory.
- GR is background independent.
- It is a mathematically beautiful theory and has been successful with all current observations/experiments.
- Despite the successes, GR has some theoretical shortcomings....

Plan of the talk

- Main theoretical issues of GR
- Quantum theory and GR, exploring ideas
- Alternative approaches
- Different schools of thought
- Resolutions each school of thought offers

▶ Main theoretical issues of GR

(I) GR solutions are generically singular. Singularities,

- may be of different type like black hole, or cosmological Big Bang;
- can form in gravitational collapse, starting from ordinary matter;
- may be hidden behind a horizon or be naked.
- Horizon is a surface in spacetime across which two-sided (causal) communication is not possible.
- *Cosmic censorship conjecture* (**Penrose**) has been put forward to remedy this problem.

(II) GR allows Closed Time-like Curves (CTC).

- Presence of CTCs puts causality into trouble.

- If we have CTCs we can build time machines.

- *Chronology protection conjecture* (**Hawking**) has been put forward to remedy this problem.

- A ultimate theory of gravity is expected not to allow for CTCs.

(III) Non-renormalizability of GR

- is revealed applying standard quantization of field theories to GR, around a flat or arbitrary given background.

- *Effective, dimensionless coupling of gravity* is $G_N E^2$.

- This yields to non-renormalizable *UV divergences*.

- *Is this really a problem?* Should we quantize gravity?

- *Strong coupling issues:*

  In path integral G_N and $\hbar$ appear in the combination $1/(\hbar G_N)$

(IV) Black hole thermodynamics & microstates:

- Presence of *horizons* brings intriguing and unexpected features.

- Black holes and closedness of the Universe as a thermodynamical system, necessitates associating *entropy* to black holes to save laws of thermodynamics (**Bekenstein**).

- *Where does this entropy come from?*

- Do black holes have microstates? a stat.mech description?!

- Can this stat.mech. description be realized/described within GR?

(V) Black hole information problem:

- Quantizing a field theory on background of a classical GR solution, leads to Hawking-radiation.

- Semi-classical approximation in Hawking's computation remains valid up until black hole horizon becomes Planckian size.

- Black holes can emit their mass and energy and hence evaporate.

- Process of formation and evaporation of black holes is not governed by laws of QM.

One may start with a pure initial state and end up with the mixed thermal state, this is not a unitary process.

- Resolution to this problem may be possible in a theory of *Quantum Gravity* (QGr), e.g. *if* QGr has specific features not shared by standard non-gravitational Quantum Field Theories (QFT),
  - features such as holographic scaling and/or nonlocality;
  - or finite number of degrees of freedom at any given cutoff scale.

(VI) Spacetime metric vs Heisenberg uncertainty.

- Notion of distances in space or time are
  - subject to quantum uncertainty, but also
  - are measured precisely by the metric of spacetime.

- So either QM or GR should be compromised at some *short distance level*, or

- spacetime metric has quantum fluctuations, like any other quantum field, i.e. at short distances we deal with a *spacetime foam*, rather than a continuum spacetime.

(VII) Cosmological Constant problems.

- There are two cosmological constant problems:
  - *Theoretical:* Zero point energy in quantum theory and gravity?! (*technical naturalness issue*).
  - *Observational:* if we are now in an accelerated expanding Universe which is caused by Dark Energy (DE), and if DE is modeled by a cosmological constant, why is it so tiny compared to any other scale in our current physics. *(parametric naturalness).*
- There is also Dark Matter. But, as many others, I think DM is not a QGr problem, it is primarily a particle physics problem.
- Whether cosmological constant (and not DE) is a real problem to QGr is open to debate.

♦ Quantum theory & GR, exploring ideas

There seems to be

- a conflict between quantum theory and Einstein GR, or
- resolution of some problems in GR may need quantum theory.

Possible alternatives:

- Gravity is inherently classical and should not be quantized at all?!
- Gravity is inherently quantum and GR may be "coarse-grained" description of an underlying microscopic/quantum system.

  Or gravity may be essentially a loop effect and Einstein GR may be a one-loop effective action...

- Modify quantum and make it compatible with GR?

▶ Hawking: In presence of gravity, quantum dynamics is not unitary and it need not be.

Gravity in presence of horizons forces *reduction of wavefunctions*.

▶ t' Hooft: Quantum theory is dissipative in its basic fundamental level (once we consider it on the whole Universe).

- Modify GR while accepting quantum theory?

- *Some different Proposals:*

  - QGr is like other QFTs, so it is described by a generally invariant action involving higher powers of Riemann curvature,

  - **Hořava-Lifshitz gravity**: Gravity at UV is not a Lorentzian theory; general covariance is an accidental/emergent IR symmetry.

  - Asymptotic Safety (**Weinberg**): GR has nontrivial IR & UV fixed points.

    Nonrenormalizability of GR is an artefact of making perturbative expansion around a point which is not an RG fixed point.

- Other possibilities.....
  - Quantum in QGr is as usual, but QGr is not a QFT?

    This viewpoint has many advocates, including string theorists.

    There are, however, many ways to go about this idea and formulate it....

Alternative approaches

- To solve either of the 7 issues listed, we need
  - deep understanding of the problem and,
  - ideas, some of which we briefly mentioned.
- Depending on the background and research tastes, there are different schools of thought.
- In each school, different problems in the set of 7 may be given different weights.
- Each idea is motivated by one or two of the above problems.

■ Three schools of thought

♦ GR school

- GR is the main framework. Standard QFT (on curved background) is also applicable.

- Features: Uniqueness and positivity theorems.

- Singularity and CTC problems are given more weight.

- Main questions: What is allowed by GR dynamics, what are appropriate initial and boundary conditions.

- Information paradox is a feature and not a problem.

♦ Quantum Spacetime school

- Main idea: QGr should be formulated on Quantum spacetime.

- Main question: Finding mathematical setups to replace differential and manifold geometry.

- QFT (in abstract and algebraic sense) provides the main framework.

- Spacetime foam problem is viewed more fundamental.

♦ HEP-TH and String theory school

- QFT and its gadget is the main tool.

- Nonrenormalizability problem, and then problems associated with black holes are given more weight.

- Feature: QGr is presumably not a QFT.

♦ Quantum spacetime school

- Mathematics (geometry and algebra) are the main tools.

- Spacetime foam problem, and then nonrenormalizability and next problems associated with black holes are given more weight.

- Feature: QGr starts with defining a notion of Quantum Spacetime.

♦ Quantum Information school

- Quantum Theory and especially Quantum Information measures are main concepts.

- Black hole information, spacetime foam and singularity problems are given more weight.

- Feature: Spacetime and diffeomorphism invariance are emergent notions, what is fundamental is **Hilbert space of Quantum Theories** and Quantum Inf. notions.

- This school is still emerging and has provoked many thoughts, ideas and projects.....

Disclaimers:

- The above four schools of thought are to my taste and choice.
- The border line between these schools of thought is not bold.
- There are some people residing on the borderlines.
- There could be other less “visible” schools of thought.

Next:

How does each school of thought perceive and handle the 7 problems?

▶ GR school & 7 problems

- Singularity problem:
  - Several uniqueness theorems.
  - Classification of singularities and energy conditions analysis.
  - cosmic censorship conjecture.
  - Big Bang singularity:
    Wheeler-De Witt equation & Hartle-Hawking wavefunction. Similar idea has been discussed for black holes Horowitz-Maldacena [2002].

- CTC problem
  - Chronology protection theorem (Hawking): CTC can only form in spacetimes with matter violating Weak Energy Condition. Backreaction avoids formation of CTC's.

- Black hole microstates & information problems
  - Either take this as a feature (Hawking before 2004 & Unruh, Wald, ...), or
  - No physical observer can see information loss, or
  - **Holographic principle** [Susskind & 't Hooft] and **black hole complementarity** proposal [Susskind].

- Spacetime foam problem: Use Wheeler-De Witt equation and wave-function of the Universe.

- Nonrenormalizability problem
  - I think, no good idea to handle this.
  - Reduce the problem to quantum mechanical one and not QFT.

- Dark Energy/cosmological constant problem
  - Unimodular gravity or "Squesterring the Cosm.Const."?!
  - No good resolution ....

▶ HEP-TH school & 7 problems

- Nonrenormalizability problem
  - At Planck scale ($M_{pl} \sim 10^{19}$ GeV), QFT does not work,
  - particles and spacetime alike are states of "string theory".
  - Dealing with extended (string-like) objects, there is no sharp interaction points. This ameliorates the UV divergences.

- At low energies, $E \ll M_{pl}$ string theory reduces to standard QFT's.

- String theory is shown to be one-loop renormalizable.

- String theory inherently includes gravity.
- String theory has hence black holes as well as singular solutions.
- Singularity problem
  - Within string theory one cannot resolve distances, or squeeze energy or wavefunctions below the string scale.
  - In string theory, we do not have points with zero size.

- Singularity problem & string theory
  - This has very much remained at the level of idea and been shown to work by robust calculations only for orbifold singularities.
  - String theory has no clear idea for dealing with cosmological singularities.

- Black hole microstates & string theory
  - Black holes are thermodynamical limit of a stat. mech. microscopic system with many stringy microstates.
  - Black holes are "condensates" of strings or branes.

- Black hole microstates & string theory, cont'd.
  - Strominger & Vafa [1996] could successfully count (not identify) stringy microscopic system for certain black holes.
  - Compute supersymmetric indices for the BPS black holes. It contains information about microstate counting.
  - This is still an ongoing project, we are still awaiting statements on generic non-BPS black holes
  - There has been the fuzzball proposal [Samir Mathur]. The idea is that stringy (QGr) effects become important at scales much bigger than Planck/string scale. Horizon is region appearing due to coarse-graining and a black hole is a sum of horizonless smooth microstate geometries.

- Black hole information puzzle & string theory
  - Generically perturbative string theory is not a suitable setup for black hole information problem.
  - We need to be able to deal with string theory on time-dependent backgrounds. Not much direct results here....
- Spacetime foam & string theory
  - This is just what string theory says: no spacetime below what various probes of the theory can probe.
  - What we see depends on the probe we use.

- CTC problem & string theory: String theory does not add much.

- Dark Energy/cosmological constant
  - No clear resolution.
  - Resorting to anthropic reasoning.

- String Theory has a very deep, useful and powerful offspring:
  AdS/CFT

- AdS/CFT has been widely applied to the 7 problems.

▶ AdS/CFT & 7 problems:

- AdS/CFT maps a problem in (Q)Gr to a problem in a non-gravitating QFT, which resides in a lower dimension.
- Absence of CTC is tied to unitarity in the dual field theory picture.
- Formation of black holes (and horizons) to thermalization process in the gauge theory plasma.
- BH microstates are (yet to be identified) states in the gauge theory.
- Maldacena et al have shown how in principle unitarity of evolution of BH can be demonstrated for specific 2d BHs.
- Technically they have a proposal to recover the Page curve.

- Within AdS/CFT the “holographic direction” is emergent.

- One can try to construct spacetime through the codimension 1 slices and the information on them.

- Quantum information notions, tools and techniques has been developed within this setup to shed light on the spacetime structure and its relevance to black hole problems.

▶ Quantum Spacetime school & 7 problems

- There are many ideas around but neither is at a very mature level. These are ideas for modeling a quantum spacetime:
  - **Noncommutative Geometry**;
  - **Causal Dynamical Triangulation (CDT)**;
  - **Spin Foam and Loop Quantum Gravity**.
- These ideas can be very closely related to ideas from string theory or AdS/CFT.
- This is a fruitful and interesting line of research.

▶ Quantum Information school & 7 problems

- The idea is that spacetime is not a fundamental notion, unlike what we have in QFT.

- This is very timely, active and interesting line of research.

- Fundamental objects are **Hilbert space and the density matrix**; notions like spacetime (and quantum fields on it) and particle are derived notions.

- Notions like entanglement entropy, mutual/multipartite and relative information are thought relevant to reconstruct spacetime.

- Notions like complexity are thought to be relevant to notion of interactions (especially gravity).

- Black hole and any other spacetime is (should be) identified with a density matrix over a Hilbert space.

- Once we have such a density matrix, microstates and information problem are already answered.

- Usefulness of this approach relies on the ability to reconstruct a classical metric and spacetime as a particular limit of the density matrix which does not require the full knowledge of it.

- Tensor networks is one such idea to reconstruct spacetime.

- Notion of time and hence CTC in this setting are less clear ...

- These ideas are indeed very closely related to ideas from string theory or recent developments in AdS/CFT.

You are cordially invited to take part in this endeavor.

Thank You
For Your Attention