Cosmic Acceleration as Quantum Gravity Phenomenology

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The #1 Question in Cosmology

Quantum Gravity

Questions for Cosmology

- Why is the universe expanding at an accelerated rate?
- Why did cosmic acceleration begin shortly after the onset of structure formation?
- Can both questions be addressed simultaneously?
- Will the answer tell us something about quantum gravity, or vice versa?

Cosmic Acceleration = Cosmic Constant?

- 1998/99 Type Ia Supernovae rock our world
- Einstein's greatest blunder is now our only hope? (Lambda-Wan Kenobi …)
- Einstein's equation with Lambda:

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Adding a constant leaves a lot of questions unanswered …
- The problems may intersect, but they are not the same!

The Old, The New and the Coincidence

1. The measured value of the Cosmological Constant is 120 orders of magnitude too small
2. The value of the Cosmological constant isn't zero!
3. Coincidence problem: structure formation and dark energy dominance happened around the same time

The Vacuum is a Problem

- Defining vacuum in general relativity seems trivial
- Defining vacuum in QFT seems doable
- Connecting those vacuums turns out to be completely non-trivial/impossible to do!
- Maybe this is a quantum gravity problem (In the Spirit of Waterloo's motto: Why not?)

Only known solution: Landscape +Anthropics

Quantum Gravities

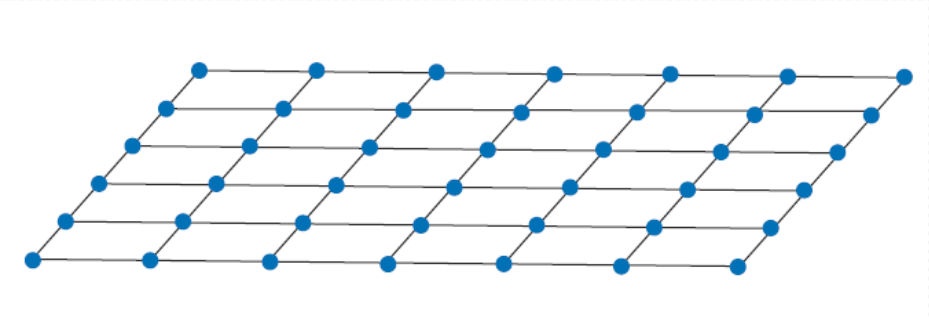
- String Theories/M-Theory

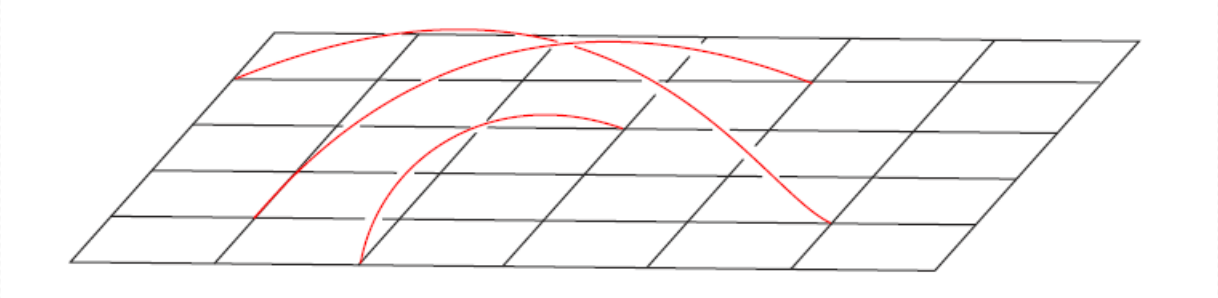
- Loop Quantum Gravity (canonical Quantization)
- Spin Foams (path integral LQG)
- Causal Sets (partial ordering Construction)
- Causal Dynamical Triangulations

Spacetime is fundamentally discrete! Or emergent. Or Something. We're not sure.

The Microscopic Picture

- Consider a weave or a lattice





(Markopoulou and Smolin 2007 , gr-qc:0702044)

- Extrapolation to large scales?

Non-Locality & Cosmology

- Quantum gravities where spacetime is emergent
- Quantum microscopic structure → Microscopic non-locality
- Survives coarse-graining to macroscopic (cosmological) scales?

Main Assumptions

1. The distribution of non-local connections can only depend on the scale factor and the Planck scale.
2. All non-local links have connections in the present comoving volume (for simplicity)
3. The distribution is otherwise random. There are no correlations between the ends of the links.
4. The time dependence of the distribution is given by a power law, with a scale factor of p.

Energetics

- Total Hamiltonian:

$$H^{matter} = H^{local} + H^{NL}$$

- In continuous limit:

$$H^{NL} = -\frac{\epsilon}{l_{Pl}} \frac{N_0}{a_0^p} \left(\int_a d^3x \sqrt{q} \right)^{\frac{p}{3}} \langle \sigma \rangle_a \cdot \langle \sigma \rangle_a$$

- Effective stress-energy tensor, assuming p=3.

$$T^{ab} = \frac{1}{\sqrt{-g}} \frac{\delta S^{NL}}{\delta g_{ab}} = -g^{ab} m^4 \langle \sigma \rangle_a^2$$

Non-Local Links & Lambda

$$T^{ab} = -g^{ab} V(\langle\sigma\rangle_a)$$

$$V(\langle\sigma\rangle_a) = -m^4 \langle\sigma(x_I)\rangle_a^2.$$

$$m^4 = \frac{N_0}{2 l_{Pl} a_0^3} = \frac{10^{-120}}{l_{Pl}^4}$$

$$N^{NL}(\text{now}) = 10^{-120} \left(\frac{a_{now}}{l_{Pl}}\right)^3 \approx 10^{60}$$

$$\frac{\Lambda}{G} \approx \frac{10^{-120}}{l_{Pl}^4}$$

Challenges

- No successful coarse graining mechanism
- Better understand whether proton decay is a problem?
- What is the microscopic nature of the links?

- Is there a unique observational signature???

What it all means.

- Cosmic acceleration provides a playground for the imagination
- What will background-independent quantum gravity look like?
- What might a quantum gravity resolution to it look like?
- Pesky cosmological constant problems?

In theory . . .

- Quantum gravity will solve the coincidence problem and help us reformulate the old and new cosmological constant problems.

- So, maybe cosmology is just another branch of quantum gravity . . . Or rather, cosmology *is* quantum gravity phenomenology!