Title: Observables and (no) time in quantum gravity

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Abstract: I will explain the special requirements that observables have to satisfy in quantum gravity and how this affects deeply the notion of time. I will furthermore explore how the search for observables in classical gravity can inform the construction of a quantum theory of gravity.

Quantum reference systems: Where foundations meets gravity

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Observables and (no) time in quantum gravity

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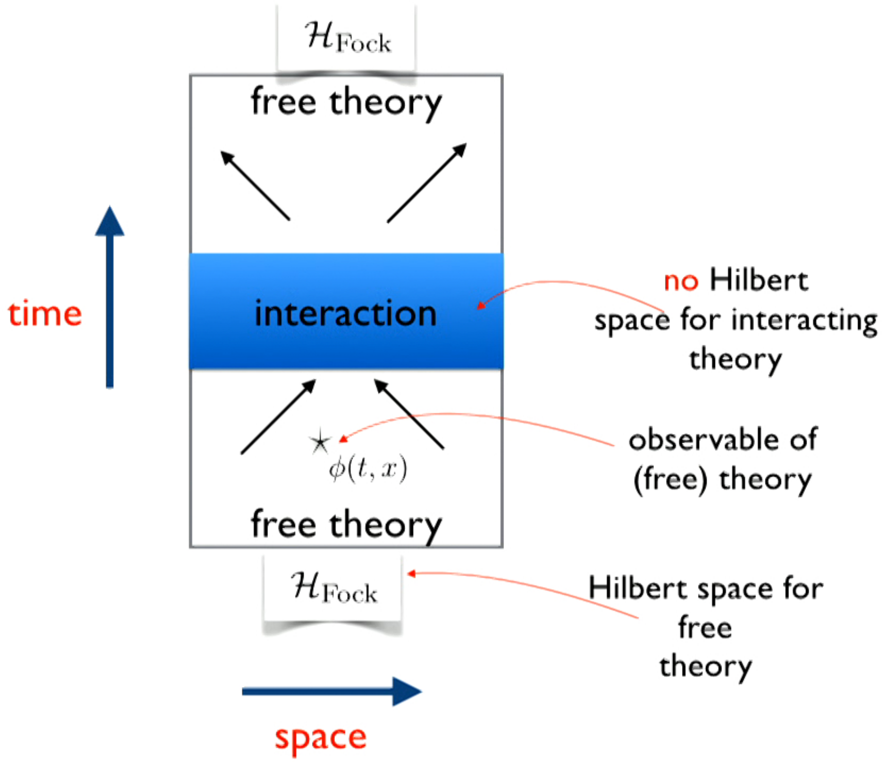
How to measure
Quantum Space Time?

Observables in (quantum) gravity

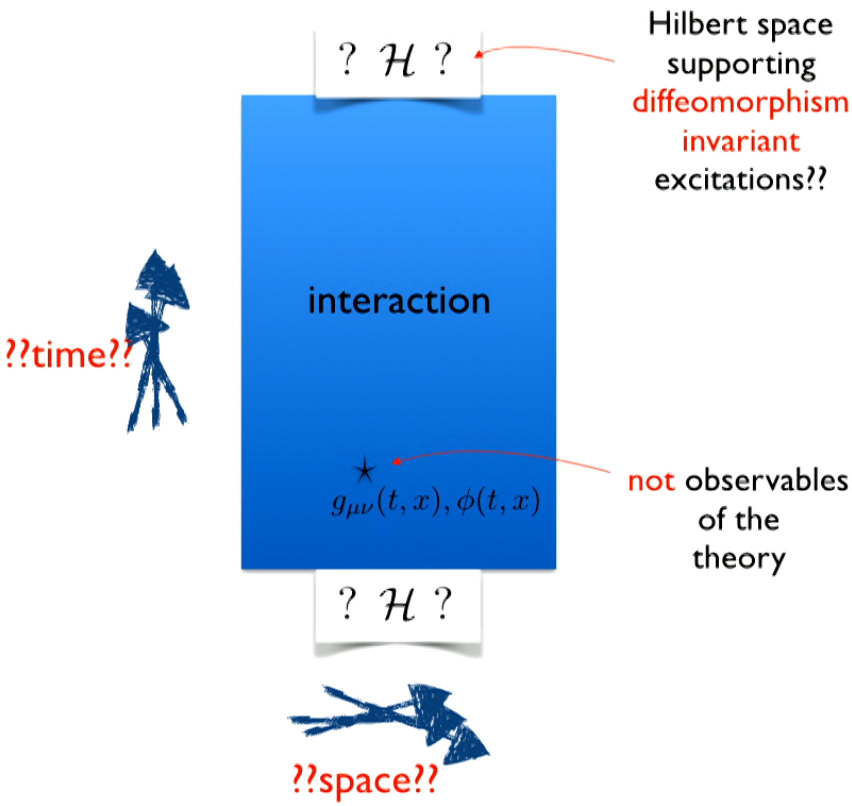
(Perturbative) Quantum Field Theory



Perturbative quantum gravity fails: non-renormalizable.

And does not answer crucial questions (eg big bang).

Quantum gravity



Space time coordinates have no physical significance. Need to implement diffeomorphisms invariance. This avoids assigning unphysical quantum fluctuations to choice of coordinates.

Observables

- diffeomorphism symmetry (coordinate transformation) is a gauge symmetry of general relativity

- include time translations, which are therefore gauge symmetries

- physical observables should be gauge invariant, hence

  physical observables should be constant in 'time'

- this argument leads to the the nebulous

  (naive) "problem of time" or "frozen time formalism"

(Naive) solution: Relational observables [Einstein, Bergmann, Kuchar, Rovelli, BD ...]

"Position of particle"   is not an observable.

"Position of particle at 5pm (on Philipp's clock)" is an observable. This allows a notion of evolution with respect to Philipp's clock.

There is also a notion of (physical) Hamiltonian that evolves Philipp and the rest of the universe (but not his clock).

So no "problem of time"?

Actual problems:

A. In the canonical formalism observables are pre- or post-dictions.

Need to solve dynamics of the theory. [But can be done in principle and perturbatively: BD 2004-07]

B. Good clocks?   Existence of (smooth and well defined) observables on all of phase space.

So far: have not found perfect clocks, which are 'natural'.

This has interesting consequences for the structure of the theory.

The problem of clocks

With clocks we determine time and without perfect clocks

we do not have a canonical notion of time.

But such a notion of time is a crucial ingredient in quantum theory:

- unitary evolution
- wave function collapse
- Hamiltonian and energy
- vacuum

…depend on choice of time and therefore clocks.

Good and bad clocks

Geometrical clocks

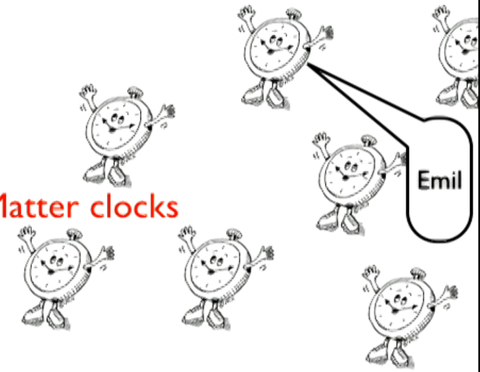
- no additional matter required
- usually quite non-local
- can choose clocks that are

  perfect around e.g. Minkowski:

  allow to describe QFT limit [BD, Tambornino 2006]
- can describe fluctuations of light cones

  [BD, Tambornino 2006]

Matter clocks



- Unnatural matter: aether, dust, …
- Allows for ‘perfect’ clocks but unrealistic for quantum gravity regime

- Relativistic matter: scalar fields
- bound on resolution

  [Giddings, Hartle-Marolf 2004;

  BD, Tambornino 2006]

Relativistic vs unrealistic clocks

Kinetic energy ~ (Momentum)^2 vs (Momentum)

This makes a big difference for properties of relational observables!

Example: Time of arrival operator.

Hamiltonian

$$C = p_t + \frac{p_q^2}{2m}$$

Position at a certain time

$$F_q(\tau) \;=\; q + \frac{p_q}{m}(\tau - t)$$

Time at a certain position

$$F_t(\rho) = t + \frac{m}{p_q}(\rho - q)$$

Cannot turned (without additional input) into a self-adjoint operator.

[Aharonov, Unruh et al: additional uncertainty relation]

Two-point function of scalar field relative to (four) clock scalars

[BD, Tambornino 2006]

$$\{\phi(\Psi), \phi(\Psi+\epsilon)\} = G(\Psi, \Psi+\epsilon)\left(1 + \frac{\text{Energy}(\phi)}{\text{Energy}(\Psi)}\right)$$

encode 'free' dynamics

Green's function on fixed background

Resolution limit for degrees of freedom points depending on energy of clocks.

Similar: for two-point function in path integral approach [Giddings, Hartle, Marolf 2005]

Forming of black holes leads to strong bound on number of dof's [Giddings, Hartle, Marolf 2005]

Existence of black holes: no perfect clocks?

Changing clocks

Clocks that are only used throughout parts of a trajectory: fashionables. [Bojowald, Hoehn et al. 2010]

Changing clocks: effects similar to non-unitary evolution.

No time:

Global aspects

Universes without good clocks

Universe evolving completely periodically:

(According to canonical quantization program) there is no observable 'counting' the cycles.

A time on a chosen clock is always referring to infinitely many moments.

But all of these moments are physically indistinguishable.

What happens if we are in a chaotic regime?

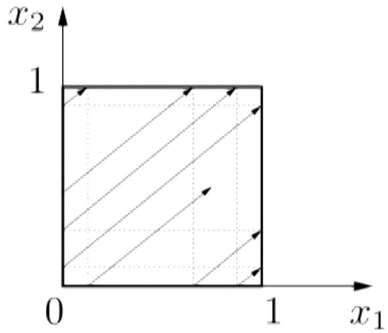
Clocks cannot differentiate between a priori distinguishable moments.

Example: FRW with massive scalar field shows chaotic behaviour.

Can chaos be observed in quantum gravity?

[BD, Hoehn, Koslowski 2015]

A simple model



Particle moving

on two-dimensional torus

$$C = \frac{p_1^2}{2m_1} + \frac{p_2^2}{2m_2} - E \approx 0.$$

Hamiltonian (constraint)

Particle trajectory is either periodic or fills torus densely.

There does not exist a smooth configuration observable distinguishing the orbits.

Can chaos be observed in quantum gravity?

[BD, Hoehn, Koslowski 2015]

Reduced phase space quantization fails:

There is no reduced phase space (with differentiable structure).

Standard (Dirac) quantization fails:

Too few solutions to the constraint in order to build semi-classical states.

Can chaos be observed in quantum gravity?

[BD, Hoehn, Koslowski 2015]

Is there anything that can be done?

There is a configuration observable, however it is nowhere differentiable.

To represent this observable in the quantum theory, we have to adjust the topology underlying the quantization to the non-smoothness of the observable.

We choose a discrete topology on the (configuration) torus —
corresponds to a Bohr compactification of momentum space.

Can chaos be observed in quantum gravity?

[BD, Hoehn, Koslowski 2015]

We choose a discrete topology on the (configuration) torus —

corresponds to a Bohr compactification of momentum space.

Leads to a sufficiently big physical Hilbert space carrying a representation of the configuration and momentum observable.

Bohr compactification has consequences on e.g. spectrum of observables: momenta are bounded.

Can chaos be observed in quantum gravity?

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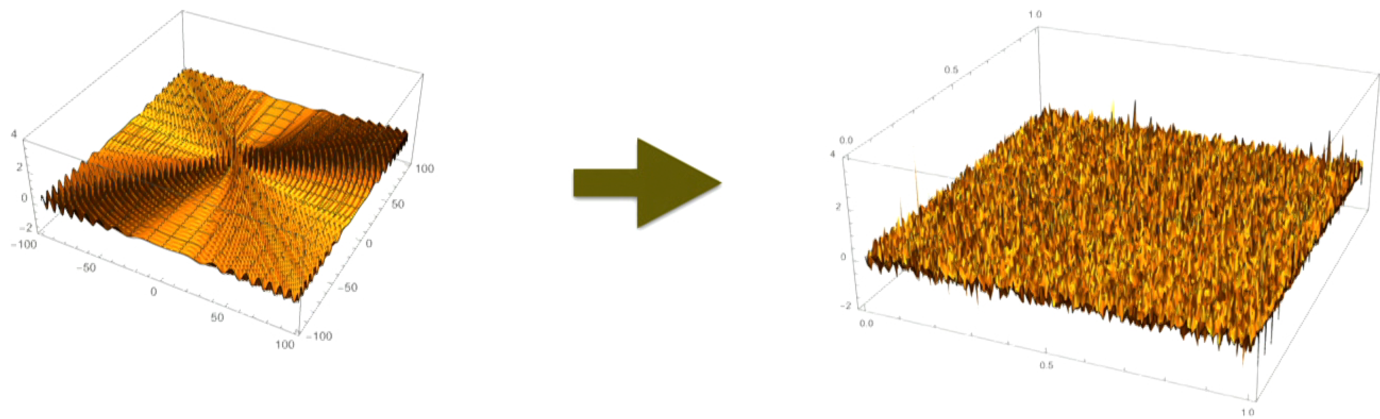
Physical wave functions look highly irregular due to wrapping around the torus:



Summary

In quantum gravity we have to use relational observables.

There might be no perfect choice for the reference system and therefore no canonical time.

The properties of observables, and therefore the properties of (quantum) space time do depend on choice of 'clocks'.

Properties of observables should inform the construction of quantum gravity theories.

Can chaos be observed in quantum gravity?

[BD, Hoehn, Koslowski 2015]

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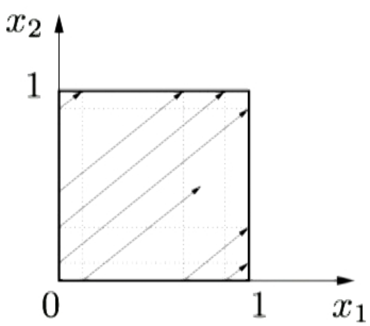

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