

## What is Quantum Space Time?

How to do quantum field theory without space time?

How can we decode quantum space time: observables and their algebra

What are IR and what are UV observables?

## Perturbative Quantum Field Theory



## Quantum gravity



Space time points do not exist.

Need to be reconstructed (approximately).

# Example: Gauge invariant observables and entanglement (between regions) 

Diffeomorphism invariant characterization of space-time regions?


This problem already occurs for (Abelian) gauge theories: Entanglement entropy is ambiguous. [Cassini et al] Suggestion: Entanglement definition should be based on splitting of observable algebras.
[see also Giddings]
Problem is much more pronounced with diffeomorphism symmetry.

Question: Can we obtain "local" field observables from gauge invariant observable algebra?

## Quantum gravity aim:

## Construct (generalized) Hilbert space supporting diffeomorphism invariant excitations and operators to extract quantum geometry.

This Hilbert space carries a representation of the diffeomorphism invariant algebra of observables.

## Gauge invariant observables

## covariant



Functionals of space time metric and other fields invariant under space time diffeomorphisms.

Dirac observables:
Functionals of phase space variables (weakly) commuting with spatial diffeomorphism and Hamiltonian constraints. Hence are 'constants of motion'.
[C.Torre 90s:]
Need to include spatial derivatives of infinitely high order.
(Except Poincare charges.
There are no further hidden symmetries.)

## Fake problems hiding interesting problems



Clocks are part of the system, rest evolves in relation to them:

No perfect clocks?
Interesting conclusions can be drawn from that!

Do we need to add such (aether) clocks?
[Jacobson, ..., (Brown-) Kuchar, Giesel et al, Husain,... ]

Quantum fluctuations with clock time going backwards?

Do we need generalization of s.a.
operators (to POVMs)? [Fredenhagen et al]
Additional uncertainty relation
[Aharanov-Unruh, G-M-H, BD-T ]
Observables can be matched to each other. [BD 05]

Differences on a global level?

Real problem: quantization requires control over global features in phase space and space time.

## Relational / Complete observables

Relational observables (complete observables)

## Example:

Where is the particle at that moment in time when the clock $T$ shows value $\tau$ ?


Relational observables (complete observables) with many constraints / field theories
Example:
What is the value of field at point on the hypersurface where clocks $T_{I}(\sigma)$ show values $\tau_{I}(\sigma)$.


## The <br> gravitational measurement problem



## Relational / Complete observables

## Example:

What is the value of field at point on the hypersurface where clocks $T_{I}(\sigma)$ show values $\tau_{I}(\sigma)$.
[BD 04]
Expression as a series (solves the theory):
weakly commuting constraints:
$\tilde{C}_{K}(\sigma)=\int\left(A^{-{ }^{-4} j}{ }_{K}\left(\sigma, \sigma^{\prime}\right) C_{j}\left(\sigma^{\prime}\right) d \sigma^{\prime}, \quad A_{j}^{K}\left(\sigma, \sigma^{\prime}\right):=\left\{T^{K}(\sigma), C_{j}\left(\sigma^{\prime}\right)\right\}\right.$
$\left.f[\tau] \simeq \sum_{r=0}^{\infty} \frac{1}{r!} \int\left\{\cdots\left\{f, \tilde{C}_{K_{1}\left(\sigma_{1}\right)}\right\}, \cdots\right\} \tilde{C}_{K_{r}\left(\sigma_{r}\right)}\right\}$

$$
\begin{gathered}
\left(\tau^{K_{1}}-T^{K_{1}}\right)_{\left(\sigma_{1}\right)} \cdots\left(\tau^{K_{r}}-T^{K_{r}}\right)_{\left(\sigma_{r}\right)} d \sigma_{1} \ldots d \sigma_{r} \\
\text { clock values } \\
\text { clock fields }
\end{gathered}
$$

Can be used to
o) show that these observables are indeed (weakly) commuting with all constraints
a) prove properties of these observables: for example space time commutators
b) develop approximation scheme around
b2) symmetry reduced sectors, e.g. cosmology

## Complete observables, gauge fixings, deparametrization, ...

Complete observable framework
[BD 04]
matches (including symplectic structure, time evolution) and generalizes

- (gauge invariant extension of) (a family of) gauge fixings [Henneaux - Teitelboim book]
- deparametrization / reduced phase space (which assumes perfect clocks) [Kuchar, ...]
- allows intrinsic, extrinsic, non-local, geodesic, GPS $[$ [ewandowski'et li] clocks, use of cosmological time ...
- gives clock time generating function:'physical Hamiltonian' (requires choice of clock momenta)
- can also deal with partially gauge invariant / recurrent clocks
- allows reconstruction of full space time (also lapse and shift)


## Recover LQFT observables

Good clocks around a background? Here Minkowski space.

- Expand constraints in metric perturbations. Define everything up to Nth's order in perturbations
- Find clocks conjugated to (linear part of) constraints: defines ADM gauge [ADM]
- Leads to 'maximally' Cartesian coordinates (globally).

Don's remarks about harmonic gauge
$T_{I}(\sigma)=\Delta^{-1}$ (linear comb. of L and T modes of $q_{a b}$ and $\left.\pi^{a b}\right)$

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    non-local - but
to lowest order perfect clocks
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Allows reconstruction of space time points: appear as labels of gauge invariant observables.

Remark:

## Space time algebra of observables

[BD,Tambornino 06]

Couple (free) scalar field. Consider (Poisson bracket) commutator:

$$
\begin{aligned}
&\left\{{ }^{[2]} F_{\left[\phi\left(\sigma_{1}\right) ; T\right]}\left(t_{1}\right),{ }^{[2]} F_{\left[\phi\left(\sigma_{2}\right) ; T\right]}(0)\right\}=-\gamma S_{g r}\left(t_{1}, \sigma_{1} ; 0, \sigma_{2}\right)+O(2) \\
& \text { gravitationally dressed scalar field propagator/ Greens function: }
\end{aligned}
$$

$S_{g r}\left(t, \sigma ; 0, \sigma^{\prime}\right):=S\left(t, \sigma ; 0, \sigma^{\prime}\right)+$ space time integral over term linear in graviton field (can be explicitly written down in terms of propagators of scalar and graviton field)
I) Recover standard (LQFT) commutators to lowest order.
2) Gravitational dressing (describing light cone fluctuations away from background) to higher order.

## Space time algebra of observables

Use four scalar fields as clocks. 'Observe' a fifths scalar field.


Poisson commute if spatially separated with respect to space time metric encoded by phase space point.

## Space time algebra of observables

Use four scalar fields as clocks. 'Observe’ a fifths scalar field.

$$
\left\{\Psi(\sigma), C\left(\sigma^{\prime}\right)\right\} \sim \Pi(\sigma) \delta\left(\sigma, \sigma^{\prime}\right)
$$

For standard model matter. Quality of clocks depends on clock momenta.

[BD,Tambornino 06]

Very much related:
[Giddings, Hartle, Marolf 05: two point function in covariant quantization]

- bound on space time resolution: (super) holographic bound on number of degrees of freedom
[Aharanov-Unruh: just the free particle]
- additionally uncertainty relation for time of arrival operator (time can go backwards)

$$
F_{q}(\tau)=q+\frac{p_{q}}{m}(\tau-t) \quad F_{q}(\rho)=t+\frac{m}{p_{q}}(\rho-q)
$$

## Linear vs quadratic clock momenta in

## the constraints

... makes a huge difference.
Exercise: quantize (free) particle using 'position' as a clock.

Specially design matter so that we have better / perfect clocks?
[Jacobson aether, ...., Rovelli-Brown-Kuchar dust, Thiemann et al, Husain,... ]

## But:

[Bondi: Can we accelerate clocks without bound? Louko et al I503 (due to Unruh effect): ideal clocks are fiction]

(Huge) Difference in epistemology (then ontology) of quantum gravity..

## What clocks to use?

- recover QFT on fixed background, cosmological perturbations: non-local, gravitational clocks
- keep causality: scalar field clocks: but have to fill space time with scalar field (gradients)
L. Hardy: Be-ables How about vacuum? Does Minkowski (qft vacuum) 'exist'?
- add specially designed matter: Changes General Relativity.
- GPS clocks
[Rovelli]
or都
using geodesics (for spatial diffeo-constraints)
[Lewandowski et al I503:
claim: observables commute on fixed spatial hypersurface.
In this case they should commute for space like separation.]


## Unitary time evolution?

- naive time evolution: frozen on physical states
- use clocks to reconstruct (relational) time evolution:

Is it unitary? ... Achievable (can be demanded) with perfect clocks.
[Bojowald-Hoehn-Tsobojan I0]

- change clocks if necessary: fashionables
- discuss dissipation effects due to non-perfect clocks


# Quantum Gravity Foundations: 

From UV to IR.

What is UV and IR in quantum gravity?

Should it be from IR to UV?

## Renormalization in a background independent framework <br> [BD I2, BD, Steinhaus I3, BD | 4] and observables

## What do we observe at 'different scales'?

- use: generalized boundary formalism [Oeck]]: In QG boundary can have any shape!
- dynamics are encoded in amplitude associated to boundary [Carlo's talk]

Microscopic details.


Boundary Hilbert space supporting higher complexity wave functions '(IR x) UV'

Macroscopic order parameters.

Renormalization ala Wilson:
Choose a way to coarse grain variables.


Boundary Hilbert space supporting only lower complexity wave functions
'IR'

Tensor-Network / MERA (Entanglement) renormalization: We are not free to choose how to coarse grain. (for the most effective description)

## What do we observe at ‘different scales’?



Construct an embedding of Hilbert spaces such that:


For the low energy wave functions
'UV' (: less relevant) $\longleftarrow$ (Algorithm-designing) problem: degrees of freedom decouple from
'IR' degrees of freedom.
Recursive definition.
defines (dynamically preferred) coarse graining of observables (including field redefinitions)
'IR' and 'UV' degrees of freedom should depend on dynamics of the system.

MERA
[Vidal]

## does not need to be AdS!

[Swingle: MERA and AdS/CFT]

## could describe a large class of boundary wave fcts

MERA: special and clever way (in order to cover local field theories) of constructing the embedding maps.

embedding of Hilbert spaces

## How to express the continuum dynamics

Boundary Hilbert space with low complexity wave functions
 boundary Hilbert spaces
 boundary
Hilbert spaces

Boundary Hilbert space with high complexity wave functions
initial discrete theory gives approximation


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A (complete) family of consistent amplitudes defines a complete theory* of quantum gravity.

* Corresponds to a complete renormalization trajectory,
with scale given by complexity parameter.
[BD NJP I2,
Amplitudes can be computed iteratively in an approximation (TNW) scheme.
BD, Steinhaus 13]
Least effort necessary for low complexity = homogeneous 'cosmology' configurations.


## What do we observe at 'different scales'?

More remarks:

- includes definition of (quantum gravity ) vacuum, related to no-boundary / Hartle-Hawking
- actual renormalization flow of coupling constants can be / needs to be extracted [BD 14]
- space time geometry only as emergent (low complexity) variables?
[Wen:Tensor-Networks allows transmutation between all kinds of fields,
spin foams / Iqg [BD, Ryan 08, Freidel-Speziale 09...]: generalized geometric configurations in 'UV']

How to design a theory so that space time geometry emerges as lower complexity descriptions?


Whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed.
[Einstein 1926]

## Happy I00th Birthday to GENERAL RELATIVITY!

