Title: Time in quantum gravity.

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Collection/Series: Lee's Fest: Quantum Gravity and the Nature of Time

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Abstract:

In this talk, I will investigate the possibility of time being a fundamental physical entity in quantum gravity.

I will briefly review the different notions of time in classical and quantum mechanics and then focus on explaining the fundamental clash that exists between the notions of time in Quantum Field theory and general relativity. This clash, related to the so-called problem of time, is at the core of the fundamental difficulty of quantizing gravity. I will review how recent results in Quantum gravity allow a surprising resolution of this fundamental puzzle through the presence of a quantum anomaly, which promotes time to a fundamental quantum observable in quantum gravity.

Time in Quantum Gravity

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Lee's Fest
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Based on 2407.1132 and 2309.03932
with L. Ciambelli and R. Leigh
WIP with J. Kirklin

Time in Quantum mechanics

Does time exists as a fundamental physical object ?

Time has many layers and the answer depends on the physical framework we are in. Rovelli ‘21

I will briefly review the notion of time in Quantum Mechanics and in General Relativity and in Quantum Field Theory to adresss the problem of time Quantum Gravity and its resolution.

Time in Quantum mechanics

In classical Newtonian time and special relativistic physics time appears as external parameter as the Newtonian time and proper time.

Isham '92

In Quantum Mechanics time also appears as an external parameter.

Page-Wooters '83
Rovelli '91

However for a closed system there is no time. This can be resolved by resorting to relational observables and decomposing the total system into a system and a clock. Time can then be red through the entanglement of the system with the clock.

Pauli '58
Unruh-Wald '89

For physical clocks The time operator cannot be defined as an hermitian operator. It exists as a Projective Operator valued measure (POVM): Time possess a fundamental uncertainty $\langle \Delta T \rangle > 0$

Hoehn '19

Time in general relativity

In general relativity the generator of time translation is a constraint.
Physical observables are fundamentally non-local.

$$H = \int_\Sigma fC = 0$$

The dynamics of the theory can be expressed without any reference to time.

The presence of non-trivial asymptotics for spacetime can allow in some cases the definition of a parametric time. This time is conjugated to the asymptotic boundary time translation operator.

There are essentially three types: AdS spaces which admits a preferred asymptotic time variable. Asymptotically Flat (non-accelerating spaces) which admits a multifingered time (BMS) linked to memory. And Cosmological spaces (dS like) which do not admit any.

To summarize GR is timeless unless we live in AdS with specific boundary conditions.

Time in Quantum Field Theory (QFT)

In QFT Time is the foundation of the Hilbert space.
The construction of the vaccuum $|0\rangle$ which defines Fock space requires a split between positive and negative frequency with respect to a given time.

Different choice of times $t \to t' = F(t, x)$ related to each other by diffeomorphism

leads to different vaccua $|0\rangle \to |F\rangle$

Torre Varadarajan '97
Ciambelli, LF, Leigh 24

The corresponding Hilbert spaces $\mathcal{H} \to \mathcal{H}_F$ are unitarily inequivalent when $d > 2$ and F is not a conformal transformation

This means that $\langle F|G\rangle = 0$ when $F^{-1}G$ is non trivial

The Hilbert space containing all vaccua is non-separable and Minkowski vaccum is superselected

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Diffeomorphism symmetry is maximaly broken by QFT down to Poincaré.

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Good news for Flat space QFT: There is a unique vaccuum and a prefered class of times the special relativistic ones. bad news for Unitarity and quantum gravity
Fundamental tension between QFT and GR.

Time in Loop Quantum Gravity (LQG)

In LQG the emphasis is on strong background independence

This means that we look for a formulation where observable are gauge invariant

$$[C,O]=0$$

And time reparametrisation $F=\exp(f\partial_t)$ is trivially represented

$$|F\rangle = e^{i\int_\Sigma fC}|0\rangle = |0\rangle$$

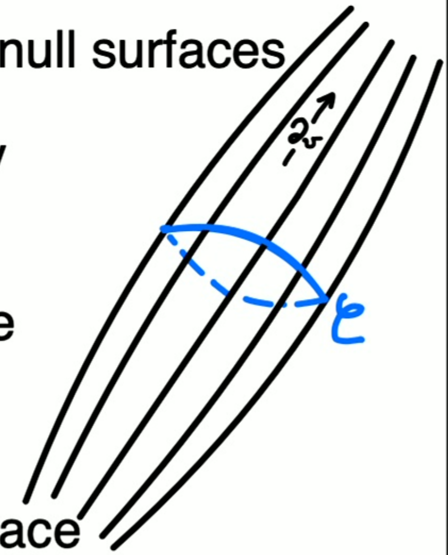
This is a timeless formulation: Gauge invariant operators can be constructed as relational observables, but time doesnt fundamentally or parametrically exists.

Background independence = $\langle F|G\rangle = 1$ = problem of time

The LQG vaccum cannot be connected to the Fock vaccua:
Profound divide between Non perturbative QG and QFT.

Time in Quantum Gravity (QG)

In our work we looked at a canonical formulation of gravity along null surfaces



Remarkably the geometry of null surface is Carrollian. The theory becomes ultralocal: Operators along different null rays factorises

Moreover the gravitational constraints projected along null surface can be solved non-pertubatively. $f(v,\sigma)\partial_v$
The Raychaudhuri one generates null time reparametrisation

We proposed a quantization of constraint compatible with Fock space representation of matter and graviational radiation

The constraint algebra develops a central charge c where $c \propto N$

N= # of points on the codimension 2 cut

$N = \infty$ in QFT, N is finite in QG

Raychudhuri constraint

$$C = \partial_v \Omega - \mu \partial_v \Omega + \Omega({\sigma_a}^b {\sigma_b}^a + 8\pi G (\partial_v \phi)^2)$$

spin 0 Ω Area form Pure geometry/Newton Fundamental QRF

spin 2 ${\sigma_a}^b$ Shear Graviton

matter ϕ $\langle \partial_v \phi(1) \partial_v \phi(2) \rangle = \frac{\delta(1,2)}{(u_1 - u_2 + i\epsilon)^2}$ Ultralocality

The constraint is a balance equation between 3 stress tensors $C = T_0 + T_2 + T_{\rm mat} = 0$

$$[C_f, C_g] = C_{[f,g]_{\rm dW}} + c \int_N (f''g' - g''f')$$

$$C_f = \int_N fC$$

$$[f,g]_{\rm dW} = fg' - gf'$$

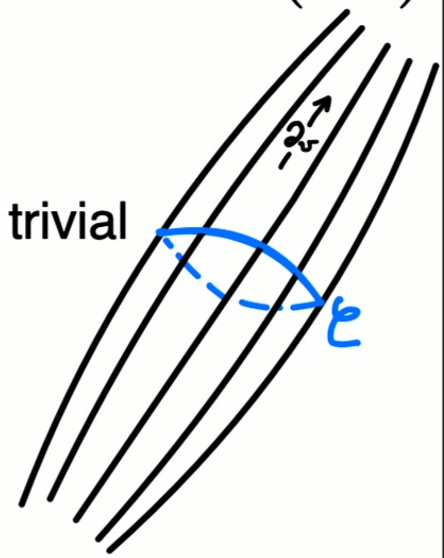
Central charge comming fron double commutators

Time in Quantum Gravity

$F \in \mathrm{Diff}(M)$

Fundamental QG postulate: c is finite in Quantum gravity

since c is proportional to # of points on the 2 d cuts
This is compatible with area quantization however it allows a non trivial representation of time reparametrisation



Kirklin, LF 25

We find that

$$\langle F|G\rangle = e^{-cS(F^{-1}G)}$$

$\mathrm{Re}(S) > 0$

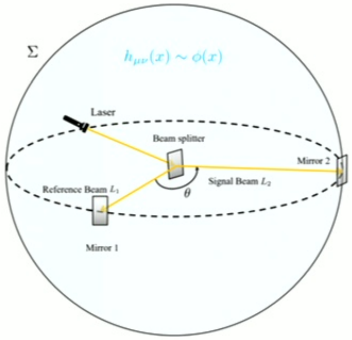
Classical limit	$c \to 0$	$\langle F\|G\rangle \to 1$	Strong Background independence
QFT limit	$c \to \infty$	$\langle F\|G\rangle \to 0$	Symmetry breaking
QG	c finite	$\langle \Delta F\rangle^2 \propto c\,\mathrm{tr}(\partial^2 S)$	Fundamental time fluctuation

Conclusion

The presence of a central charge in the constraint algebra reconcile background independence(BI) and Fock quantization.
It allows a resolution of the problem of time: Time is a fundamental object

The key is to demand a weaker version of BI: Observables are gauge invariant (commute with C) and diffeomorphism transformations are unitarily (but not trivially) represented on the QG Hilbert space

$$\langle F|G\rangle = e^{-cS(F^{-1}G)}$$



Amelino-Camelia 16
Zurek et al 21-25
Oberfrank, LF 25

The knowledge of the action S implies a new phenomenology:
Time Fluctuations in interferometry experiments