Title: Measuring Quantum Discreteness of Time in the Lab with Gravity Entanglement Interference

Speakers: Carlo Rovelli

Collection: Quantizing Time

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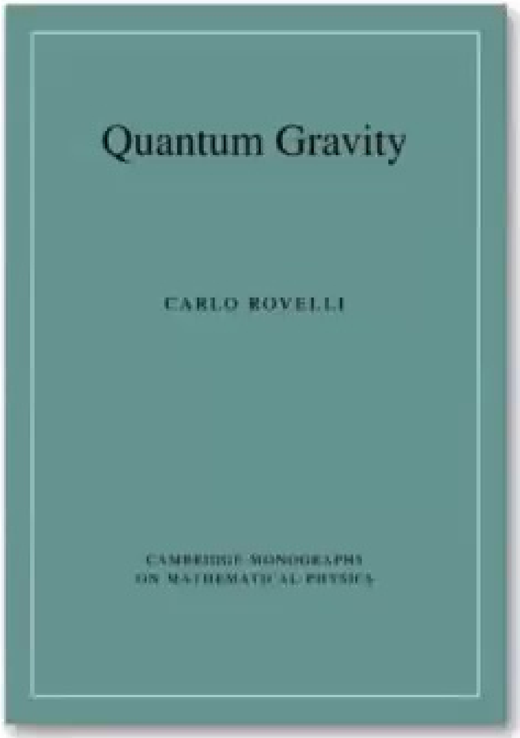
Abstract: The concrete perspective of using interference to measure Gravity Induced Entanglement in the lab is a very exciting development for quantum gravity. While the measurements considered so far only test the nonrelativistic regime, the same technique might allow access to genuine relativistic quantum effects. Among these, there might be the possibility of direct detection of time quantum discreteness.

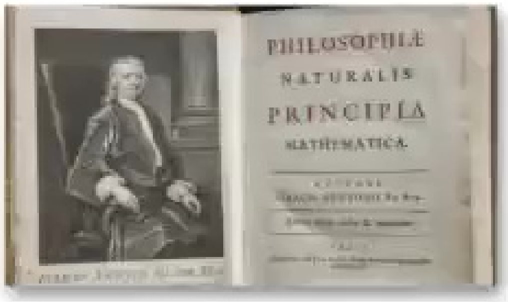
Time in quantum gravity

Carlo Rovelli



Quantum Gravity
CR
Cambridge UP 2004

Time



Traditional notion of time:

Any way of counting successions of events happening (day, night, day,…)

Remains the same in quantum gravity!

Newtonian time used in physics:

An entity flowing independent from anythings else,
which can (always imprecisely) measured by clocks

Changes in quantum gravity!

Pre-relativistic formulation of evolution

Physical variables $q_n(T)$ evolve with respect to the time variable T

Physical variables $q_n(T)$ evolve with respect to the time variable T

$$\frac{dq_n(T)}{dT} = \{H, q_n(T)\}$$

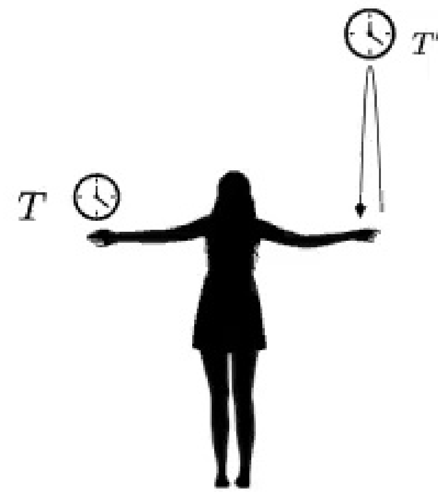
Measuring apparata measure variables

Clocks measure the time variable

This logic **does not work** in (general) relativistic physics

Time in general relativity

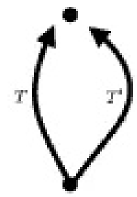
"The difficulty for developing general relativity was to struggle with the meaning of the coordinates"



Coordinates in non general relativistic field theories T :
distances and time intervals measured by rods and clocks.

Coordinates in general relativistic field theories $t \in (\vec{x}, t) = x$:
no measurable meaning at all.

Clocks measure proper time $$T = \int_\gamma \sqrt{g_{ab}(x)\ dx^a dx^b}$$



These fact of nature are incompatible with

$$\frac{dq_n(T)}{dT} = \{H, q_n(T)\}$$

Measuring apparata measure variables

Clocks measure the time variable

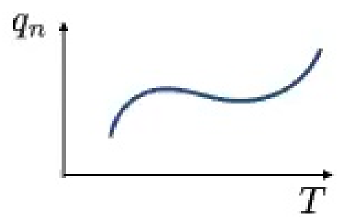
Physical variables $q_n(T)$ evolve with respect to the time variable T .

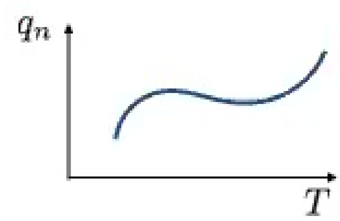
Physical variables $q_n, T, T'...$ evolve with respect to one another .

Generalize the formalism

Variables	q_n
Time	T
Evolution	$q_n = q_n(T)$
Equations	$\dfrac{dq_n(T)}{dT} = \{H, q_n\}$

Partial observables	$q^i = (q_n, T, T', T'', \ldots)$
Evolution	$Q(q^i) = 0$
Equations	$\{C, Q(q^i)\} = 0$





$$C = p_T + H$$

$$Q_n = q_n - q_n(T) = 0$$

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→

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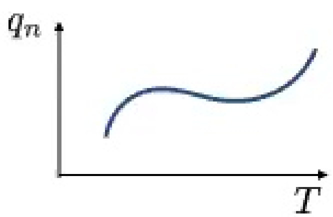
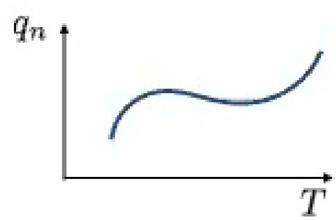




$$C = p_T + H$$
$$Q_n = q_n - q_n(T) = 0$$

Relativistic dynamics is not “frozen”!

It is simply described in a different (and more general) language.

Generalize the formalism

Observables q_n on $\mathcal{H}$

Time T

Evolution $q_n = q_n(T)$

Equations $\frac{dq_n(T)}{dT} = \frac{i}{\hbar}[H, q_n]$

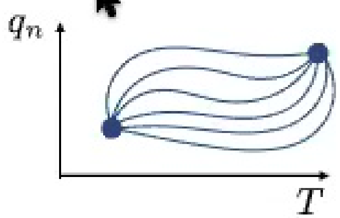
$$i\hbar\frac{\partial\psi}{\partial T} = H\psi$$

Partial observables $q^i = (q_n, T, T', T'', ...)$ on $\mathcal{K}$

Evolution $f(q^i) = 0$

Equations $[C, Q(q^i)] = 0$

$C\psi = 0$ Wheeler de Witt equation



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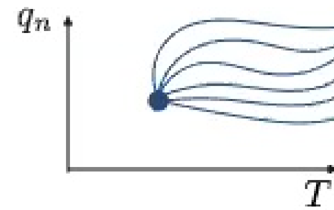


General covariant transition amplitudes

$$C = p_T + H$$
$$q^i = (x, t)$$
$$\psi(x,t) \in \mathcal{K}$$

Partial observables q^i on $\mathcal{K}$

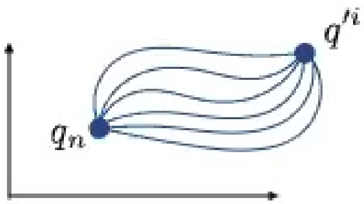
$C\psi = 0$ defines $\mathcal{H}$

$P = \mathcal{K} \to \mathcal{H}$

$$W(x't', x\,t) = \langle x't'|P|x,t\rangle = \langle x'|e^{iH(t'-y)}|x\rangle$$

$q^i|\mathbf{q^i}\rangle = \mathbf{q^i}|\mathbf{q^i}\rangle$

$W(\mathbf{q'^i}, \mathbf{q^i}) = \langle q'^i|P|q^i\rangle$



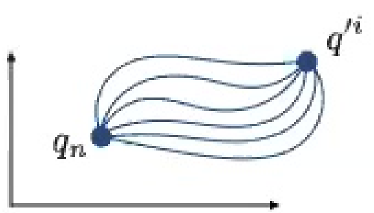
Application to general relativity (formal)

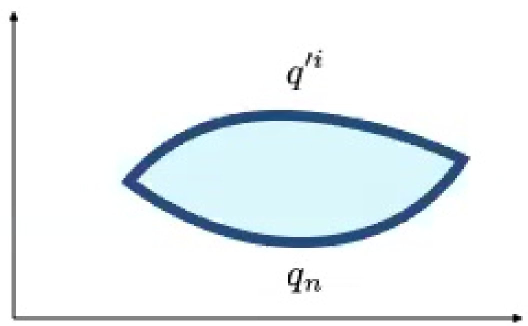
Partial observables $q_{ab}(\vec{x})$ on $\mathcal{K}$

$C\psi = 0$ defines $\mathcal{H}$

$P = \mathcal{K} \to \mathcal{H} \qquad W(\mathbf{q'^i}, \mathbf{q^i}) = \langle q'^i | P | q^i \rangle$

$$W(q, q') \sim \int_{\partial g = (q, q')} dg \; e^{iS[g]}$$





Application to general relativity (non formal)

$\mathcal{H}$ Truncation: $\mathcal{H}_\Gamma \subset \mathcal{H}$ $\quad \mathcal{H}_\Gamma = L^2[SU(2)^L/SU(2)^N]_\Gamma$

q^i Operators: $\vec{E}_l = i l_p^2 \vec{L}_l$ $\quad L^i\psi(h) \equiv \frac{d}{dt}\psi(he^{t\tau_i})\Big|_{t=0}$

spin network
(nodes, links)

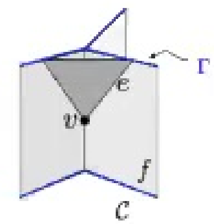
1995

$$\mathcal{W}_\mathcal{C} : \mathcal{H}_\Gamma \to \mathbb{C} \qquad \partial\mathcal{C} = \Gamma$$

Transition amplitudes $W_\mathcal{C}(h_l) = N_\mathcal{C} \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf})$

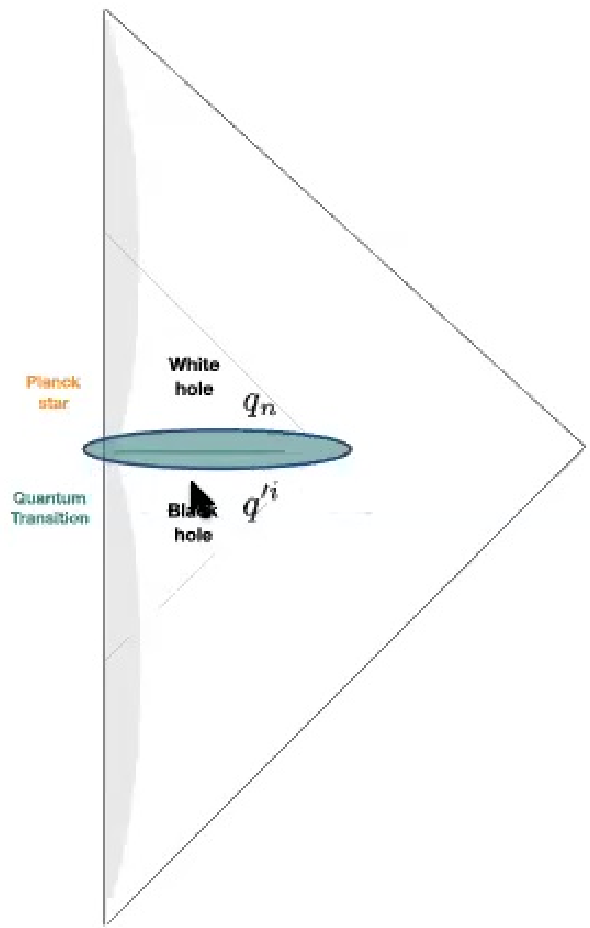
Vertex amplitude $A(h_{vf}) = \int_{SL(2,\mathbb{C})} dg'_e \prod_f \sum_j (2j+1)\; D^j_{mn}(h_{vf}) D^{\gamma(j+1)\,j}_{jmjn}(g_e g_{e'}^{-1})$

$$h_f = \prod_v h_{vf} \qquad\qquad W = \lim_{\mathcal{C}\to\infty} W_\mathcal{C}$$



spinfoam
(vertices, edges, faces)

2005



$$W(\mathbf{q}'^{\mathbf{i}}, \mathbf{q}^{\mathbf{i}}) = \langle q'^i | P | q^i \rangle$$

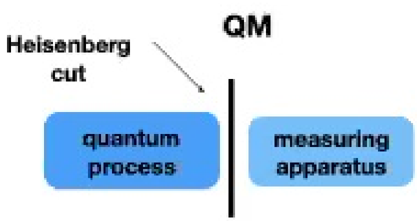
Issues:

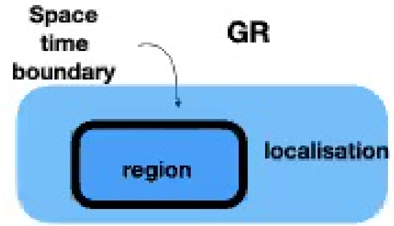
Where is the time variable?	Which time variable? (GR!)
Where are probabilities?	Probabilities is what the theory gives
Where is evolution, change?	The theory is about evolution, change
Is causal structure fixed?	No, not can obviously be in superpositions
Do we need quantum reference frames?	We do not need reference frames at all
Is the geometry locally flat?	Yes at large scales, at small scales it is fuzzy
Is there a “manifold”?	No.

Issues:

Where is the observation?

QG **Spacetime boundary = Heisenberg cut**



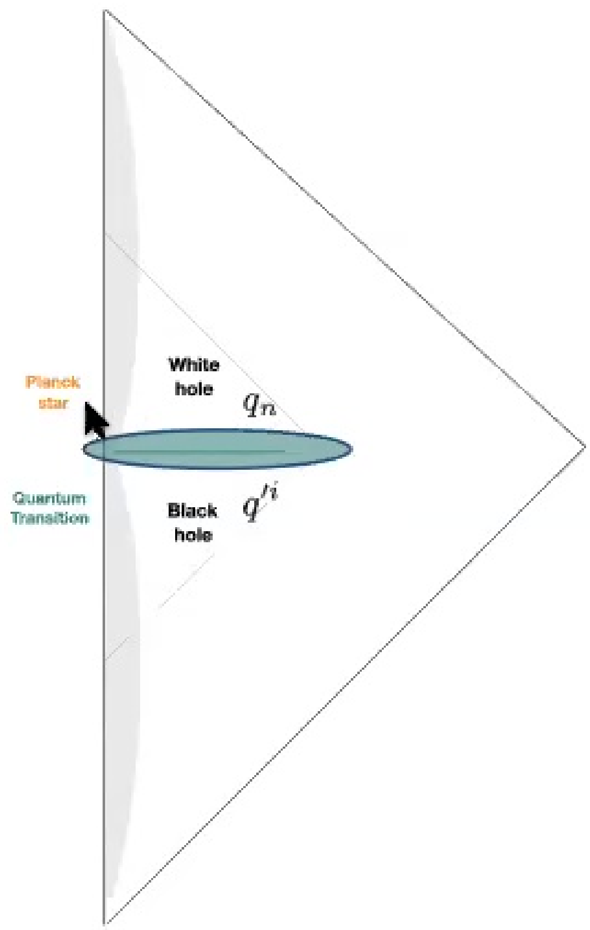


Does spacetime "emerge"?

In the same sense in which an electromagnetic wave "emerges" from photons,
namely as a standard classical approximation.

Is this dramatic?

No.



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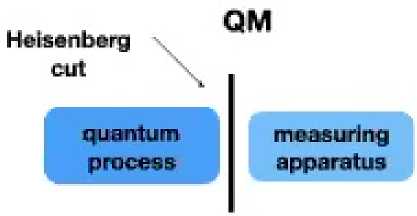

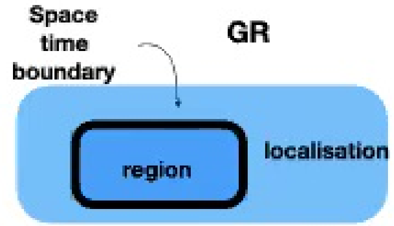

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So, what is "time":

- The name we give to the fact that events "happen":	Same in quantum gravity
- A way of counting (local sequences of events):	Exists in quantum gravity
- The reading of a clock:	As in GR: there are many cooks
- A complete ordering of events:	Does not exactly exist in Nature (SR)
- Minkowski spacetime:	Only approximately in QG
- Newtonian time:	Only an approximation
- Oriented time:	It is a macroscopic, statistical phenomenon Quantum gravity is not going to change this!

Quantum time?

Time variables are many, are measurable, are on the same footing as other variables.

There is nothing "frozen" in the Wheeler DeWit equation.
No need to invoke quantum theory to see time "emerge".

There is no mystery about "emergence of time"

Can we have superposition of "times"? Of course

Can time be fuzzy? Of course, it is a variable like others.

Can time be discrete? Of course, and the discreteness of time can be measurable!

See the talk of Marios Christodoulous !

Application to general relativity (formal)

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