Title: An experiment to detect the Discreteness of time

Speakers: Marios Christodoulou

Collection: Quantizing Time

Date: June 18, 2021 - 11:00 AM

URL: http://pirsa.org/21060117

Abstract: To this date no empirical evidence contradicts general relativity. In particular, there is no experimental proof a quantum theory of gravity is needed. Surprisingly, it appears likely that the first such evidence would come from experiments that involve non relativistic matter and extremely weak gravitational fields. The conceptual key for this is the Planck mass, a mesoscopic mass scale, and how it relates with what remains of general relativity in the Newtonian limit: time dilation. Indeed, current technological capabilities can amplify differences in time dilation superposition that are much smaller than the smallest time interval that can be measured by an atomic clock. Inspired from recent proposals to detect non--classicality of the gravitational field, we devise and examine the feasibility of an experiment that could detect a granularity of time at the Planck scale.

6:22 PM Fri 18 Jun 100%

An experiment to test the discreteness of time

Marios Christodoulou

University of Vienna

Based on scipost.org/submissions/2007.08431v2,
with **Andrea Di Biagio** and **Pierre Martin-Dussaud.**

which was a follow up to
On the Possibility of Experimental Detection of the Discreteness of Time,
Frontiers in Physics 10.3389/fphy.2020.00207,
with **Carlo Rovelli.**

(see Carlo's talk last week at ICTP-SAIFR youtu.be/cPFj78YwIN4 for the latter)

1 / 8

If proper time deviates from what predicted by GR at the Planck timescale, how difficult is this to detect?

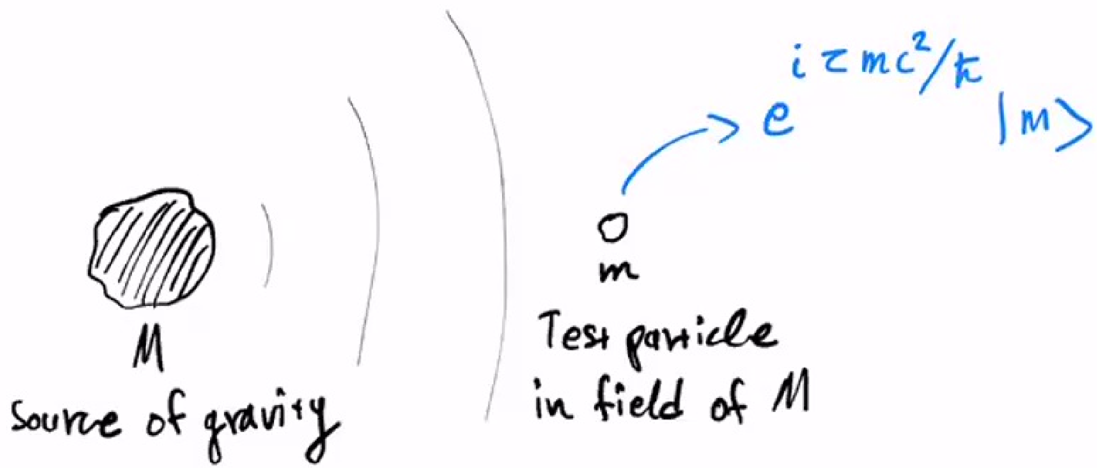
- Main result: the difficulty is comparable to detecting gravity mediated entanglement growth. We will see this with a specific hypothesis of there being a fundamental Planckian period of time.

- A negative outcome also very interesting, it would confirm that the proper time of general relativity is valid up to the Planck time $(10^{-44}s)$.

- More imminently, **an easier version of the experiment could be done perhaps even with current laboratory setups. This would still put direct bounds on the continuous behaviour of proper time at unprecedented precision.** For example, relaxing requirements by 10 orders of magnitude, the continuity of time can be tested at 10^{-34} seconds, way above the precision of clock measurements.

- The reason there remains a clear scientific interest in easier versions of the experiment (as opposed to detecting gravity mediated entanglement) is because this is a quantitative task, as opposed to a qualitative task such as witnessing or not entanglement production which can only happen once a certain scale is reached. This provides additional strong motivation for making intermediate steps in experimental capabilities.

Premise: the `intrinsic quantum clock' of quantum evolution is proper time.



Our premise is that quantum evolution goes with proper time. This is the 'Quantum Gravity assumption' needed to then test if proper time deviates from general relativity at small timescales.

6:27 PM Fri 18 Jun

Experimental setup

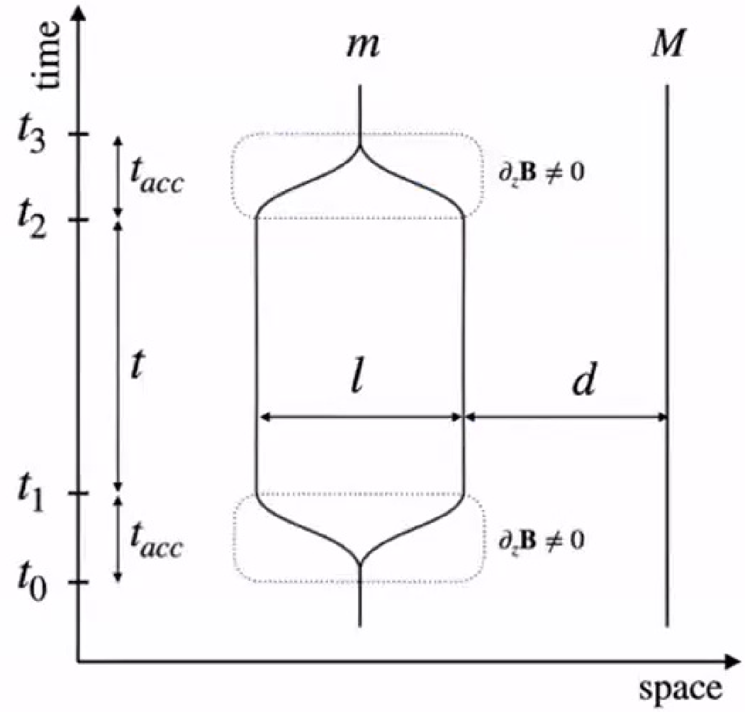
$$\delta\tau = \tau_L - \tau_R \qquad \delta\phi = \frac{\delta\tau}{t_P}\frac{m}{m_P}$$

$$|\psi_3\rangle = \frac{1}{\sqrt{2}}|C\rangle\left(|\uparrow\rangle + e^{i\delta\phi}|\downarrow\rangle\right)$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}(e^{i\phi_L}|L\uparrow\rangle + e^{i\phi_R}|R\downarrow\rangle)$$

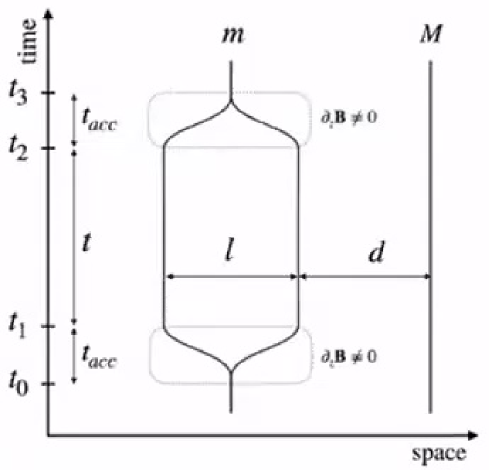
$$|\psi_1\rangle = \frac{1}{\sqrt{2}}(|L\uparrow\rangle + |R\downarrow\rangle)$$

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}|C\rangle\left(|\uparrow\rangle + |\downarrow\rangle\right)$$



Notice the conceptual similarity with the COW experiment where M was earth. Perhaps counterintuitively, to probe a possible QG regime here we want a *tiny weak* mass source M instead: because we want to measure the *tiny time dilation difference* $\delta\tau$ between the two branches due to M.

Experimental setup



$$\delta\phi = \frac{m}{m_P}\frac{\delta\tau}{t_P}$$

$$\Delta p_+ < \frac{m}{m_P}$$

$$\delta\tau = \frac{t}{\beta}t_P \qquad \beta = \frac{d(d+l)c^2}{GMl}t_P$$

- Prepare z-axis superposition ($\uparrow\downarrow$), measure along y-axis basis $|\pm i\rangle$.
- Plot experimental probability distribution $p_+(m, M, d, l, t) = \frac{N_+}{N}$ against a varying experimental parameter, where N_+ is how many times we find $|+i\rangle$
- Compare with theoretical prediction from GR+QM $P_+(m, M, d, l, t) = \frac{1}{2} + \frac{1}{2}\sin\delta\phi$
- Now, assume there is a fundamental period of proper time so that it only takes values as multiples of Planck time. Then we would also have that $\delta\tau = n\, t_p$ which gives a different distribution P_+^h .
- Question: what are the experimental parameters required to distinguish between P_+ and P_+^h with this experiment?

Data would look something like this

p_+ would first seem to corroborate P_+ but if the precision is not there actually this can not be decided from the data. As the precision begins to satisfy the inequalities we set out in the paper, only then can we say whether we are seeing P_+ or not.

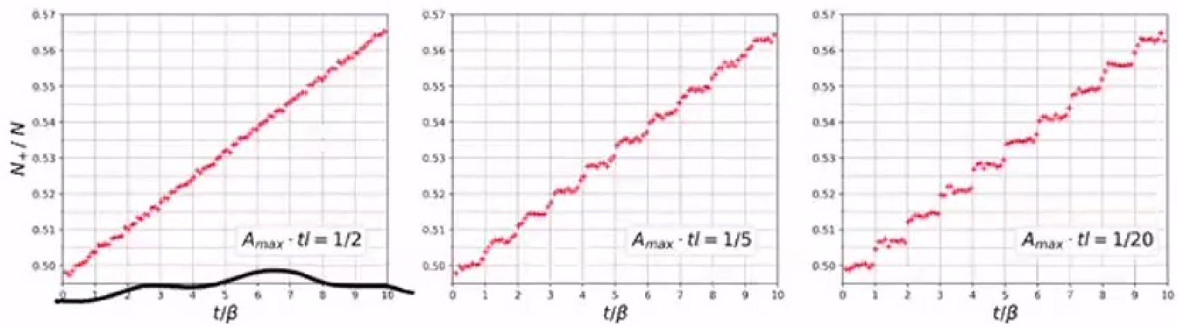
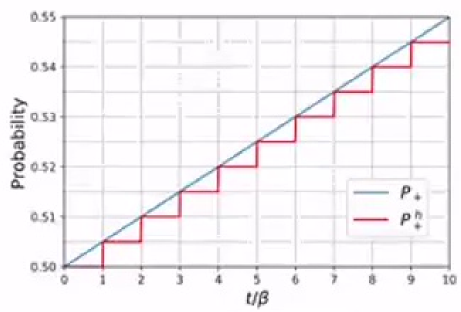


Figure 4: **Simulated data points with decreasing gravitational noise.** The data points are obtained in the same manner as those in figure 3, with the following difference. At each run, a value of A is picked uniformly at random from $[-A_{max}, A_{max}]$ and the quantity Alt is added to t/β before sampling the distribution. This procedure simulates the influence of a single mass moving uncontrollably while statistics are collected, see section IV C. The value of the parameters is as set in table I, while A_{max} is, from left to right, $1/(2tl)$, $1/(5tl)$ and $1/(20tl)$ in natural units. The discontinuities become visible only if the gravitational noise is reduced.

Theoretical probabilities P_+ and P_+^h :



Result

Parameter	Value	Uncertainty
m	3×10^{-10} kg	10^{-12} kg
M	3×10^{-9} kg	10^{-11} kg
t	10^{-1} s	10^{-4} s
l	10^{-7} m	10^{-9} m
d	$[17, 54]$ cm	10^{-2} cm
A	$\leq 4 \times 10^{-10}$ kg m^{-2}	
N_{dp}	100	
N	10^6	
T_{tot}	1 year	
n	$[0, 10]$	

$$\partial_z B \sim \mu_B B/\ell \sim 10^9 T/m \quad (B \sim 10^2 T)$$

$$P \sim 10^{-17} Pa$$

$$T < 4K$$

- Visibility of horizontal (probability axis) : $\Delta p_+ < \frac{m}{m_P} \sim \frac{1}{\sqrt{N}}$, main trade off with total duration of experiment (T_{tot}, N, N_{dp})
- Visibility of vertical axis (parameters): precision of experimental parameters, main trade off with cryogenic/decoherence requirements and gravitational noise
- Want t as small as possible, trade off with $\partial_z B \ (t_{acc})$
- Gravitational noise comparable to GME detection (extremely sensitive)
- Casimir ok as we want d large (makes it sensitive to smaller $\delta\tau$)
- Cryogenic requirements: $10^{-17} Pa$ and $T \leq 4K$ comparable to GME detection (extremely low pressure). Trade off between black body and imperfect vacuum effects

6:37 PM Fri 18 Jun

Some references

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- ***On the elementary electrical charge and the Avogadro constant, R. A. Millikan. Physical Review 2, 109 (1913)***

"...confirmed that the charges were all small integer multiples of a certain base value, which was found to be 1.5924(17)×10^{-19} C, about 0.6% difference from the currently accepted value of 1.602176634×10^{-19} C" (Wikipedia, Oil drop experiment)