Title: An experiment to test the discreteness of time

Speakers: Pierre Martin-Dussaud

Series: Quantum Gravity

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Abstract: Time at the Planck scale is an unexplored physical regime. It is widely believed that probing Planck time will remain for long an impossible task. Yet, we propose an experiment to test the discreteness of time at the Planck scale and show that it is not far removed from current technological capabilities.

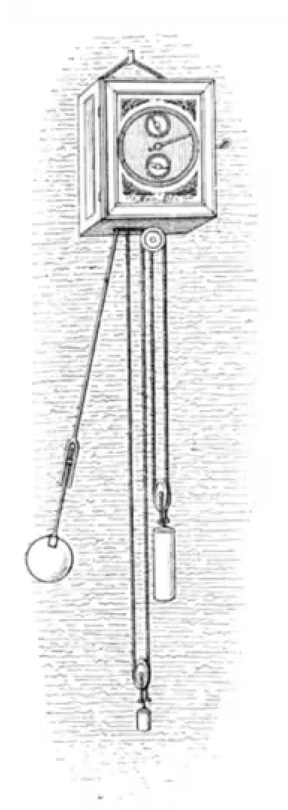
An experiment to test the discreteness of time

QG seminar
Perimeter Institute

Pierre Martin-Dussaud
from Langolen (France)
WWI Armistice Day 2021

arXiv: 2007.08431
in collaboration with Marios Christodoulou and Andrea Di Biagio

QISS THE QUANTUM INFORMATION STRUCTURE OF SPACETIME PennState BRCP



1656: Pendulum clock
(by Huygens)

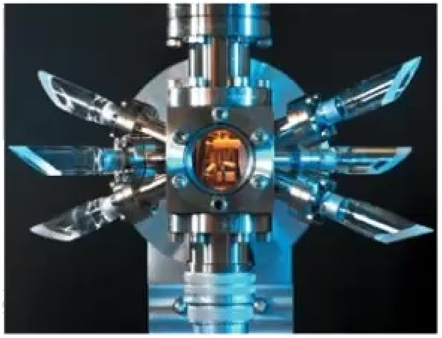
$1\,s$

Measuring Time

Good clock: stable periodic motion

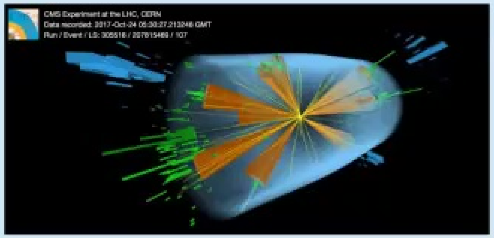
1927: Quartz clock

$10^{-4}\,s$



2018: Optical clock
(with Strontium)

$10^{-15}\,s$



Top quark lifetime

$10^{-25}\,s$

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Planck Time

Can we probe it?

$$t_P \stackrel{\text{def}}{=} \sqrt{\frac{\hbar G}{c^5}} \approx 10^{-44}\ \text{s}$$

Probing quantum gravity regime?

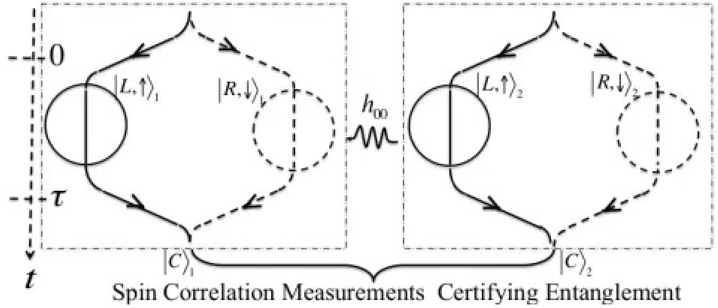
High-energy physics: astronomical size accelerator?

Low-energy experiment: gravity-mediated entanglement

Bose et al. 1707.06050
Marletto & Vedral 1707.06036

$$m_P \stackrel{\text{def}}{=} \sqrt{\frac{\hbar c}{G}} \approx 2 \times 10^{-8}\ \text{kg}.$$

1. Two particles, each sent through a Stern-Gerlach
2. They interact only through the gravitational field.
3. Entanglement is created only if gravity is non-classical.



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Experimental setup

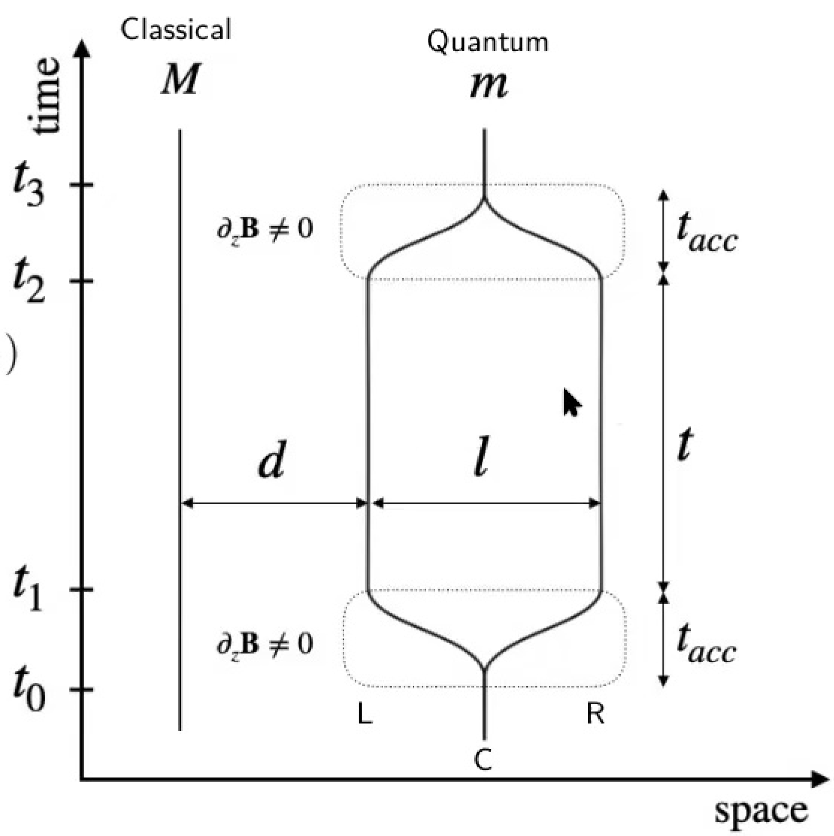
$$\delta\phi = \frac{GMmt}{\hbar}\frac{l}{d(d+l)}$$

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

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

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

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

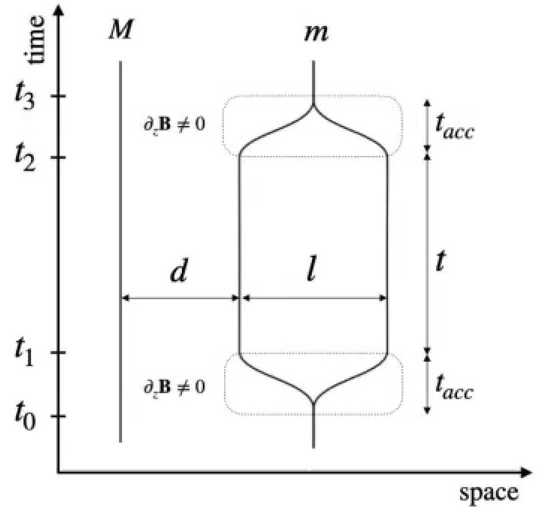


Hypothesis & Strategy

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

Measure in the diagonal basis $|\pm i\rangle \overset{\text{def}}{=} \frac{1}{\sqrt{2}}\left(|\uparrow\rangle \pm i\,|\downarrow\rangle\right)$

$$P_+ = \frac{1}{2} + \frac{1}{2}\sin(\delta\phi) = \frac{1}{2} + \frac{1}{2}\sin\left(\frac{m}{m_P}\frac{t}{\beta}\right)$$



$$\delta\phi = m\,\delta\tau \qquad \boxed{\delta\tau = \frac{t}{\beta}t_P} \qquad \beta \overset{\text{def}}{=} \frac{d(d+l)c^2}{GMl}t_P$$

Difference of proper time between the two branches

Christodoulou & Rovelli 1808.05842

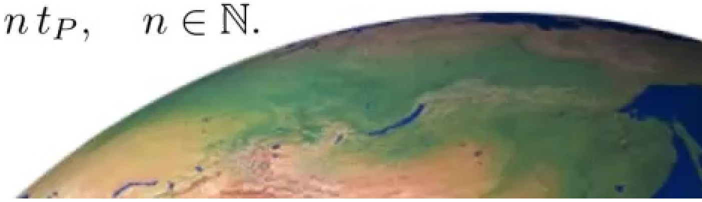
Colella et al. 1975

Hypothesis:

Time is flowing step by step.

Planck time is the fundamental period.

$$\delta\tau = n\,t_P, \quad n \in \mathbb{N}.$$



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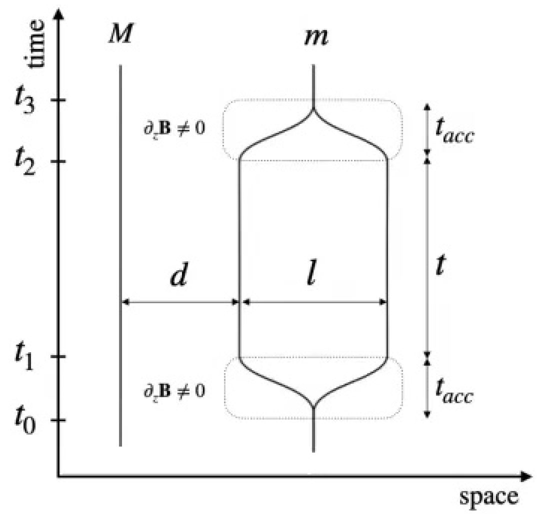

$$\boxed{\delta\tau = \left\lfloor\frac{t}{\beta}\right\rfloor t_P.}$$

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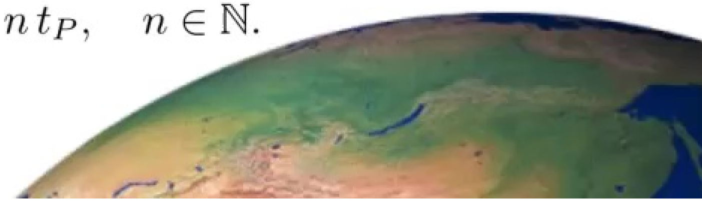

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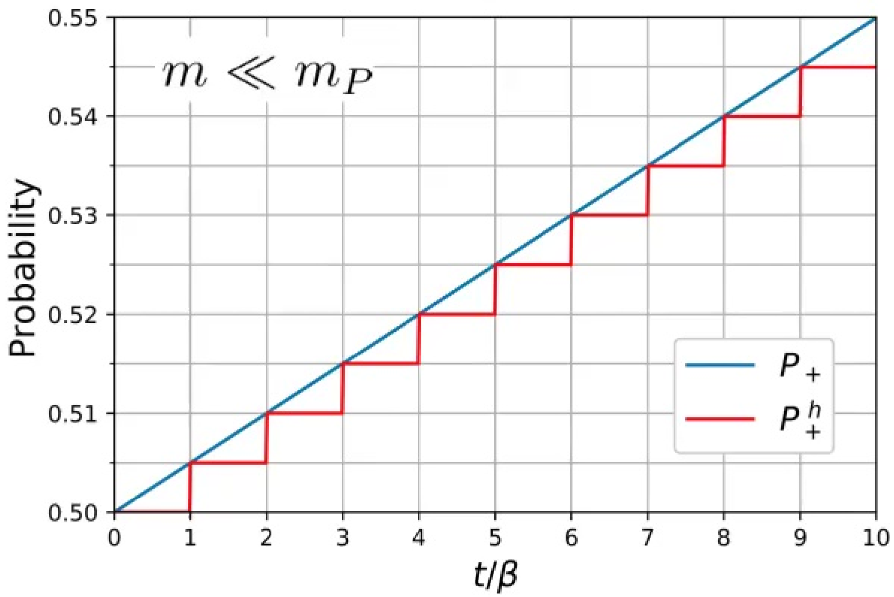

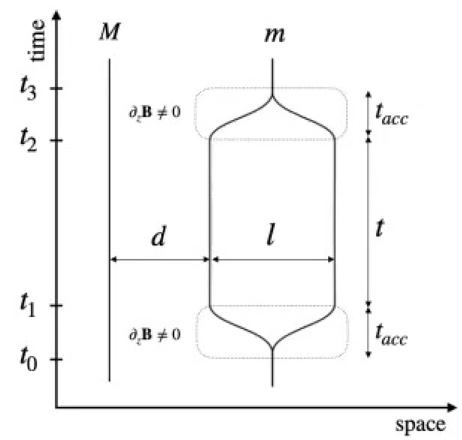

$$\beta \stackrel{\text{def}}{=} \frac{d(d+l)c^2}{GMl} t_P$$

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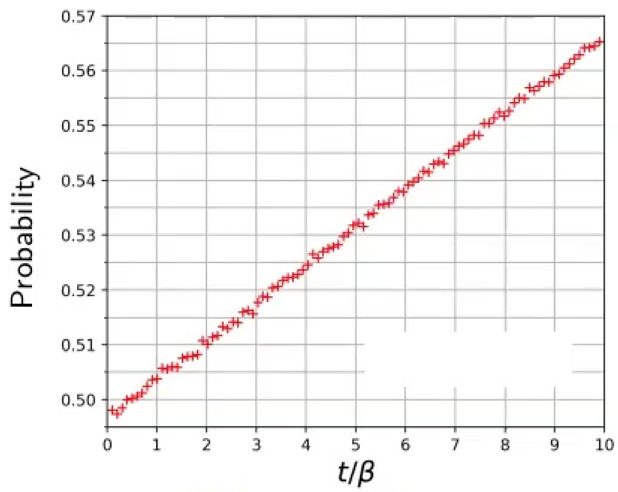
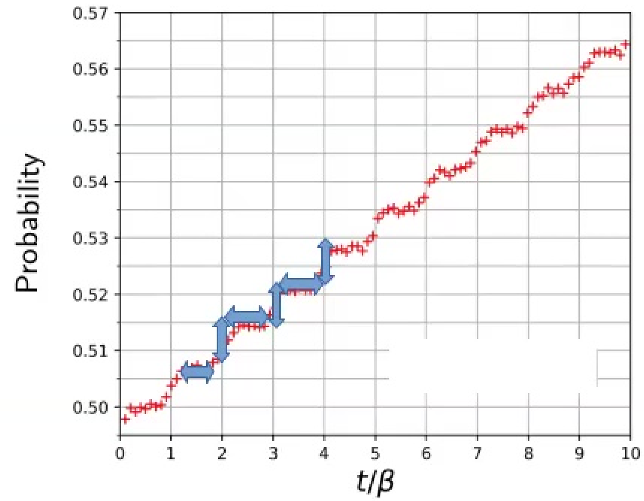
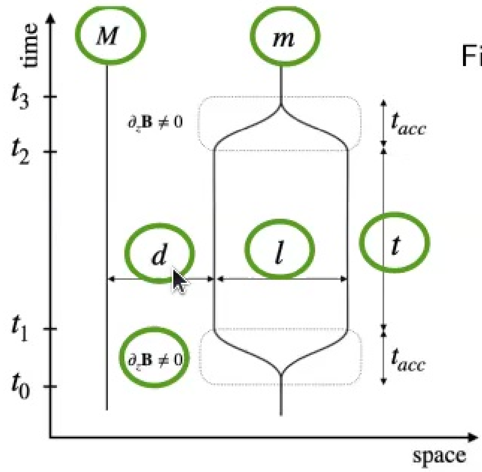
The blur of experiments







Find a range of parameters compatible with the constraints:

- visibility on the vertical axis
- total time of the experiment
- visibility on the horizontal axis
- gravitational noise
- decoherence

$$\begin{cases} 10^2 \dfrac{N_{dp}\, t}{T_{tot}} < \left(\dfrac{m}{m_P}\right)^2 \\ U \dfrac{t}{\beta} < 10^{-1} \\ A\, l\, t < 5 \times 10^{-2} \dfrac{t_P\, m_P}{l_P} \end{cases}$$

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Intuitive understanding

for why it is possible

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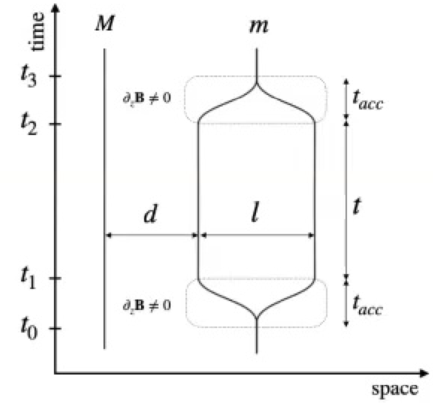
A set of viable parameters?

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

~ 10^{-2} m_P. In GME experiment: ~ 10^{-6} m_P

A bee 200m away



Pressure	10^{-17} Pa
Temperature	4 K

Most serious difficulty? Interstellar medium: 10^{-14} Pa

Bold conclusion: we can probe Planck time regime!

Cautious conclusion: probing Planck time may not be so impossible as we used to think

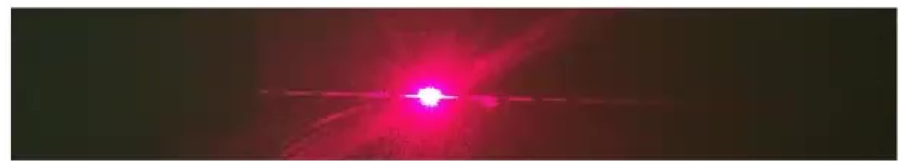
Intuitive understanding

for why it is possible

1. Gravity is weak!

Between the 2 bees, difference of proper time of 10^{-30}s !

2. Magnifying power of interferences



3. Leverage effect of fundamental constants

$$\delta\phi = \frac{GMmt}{\hbar}\frac{l}{d(d+l)}$$

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Intuitive understanding

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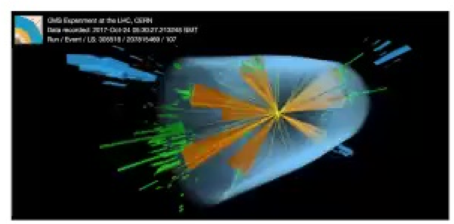
4. Leverage effect of statistics



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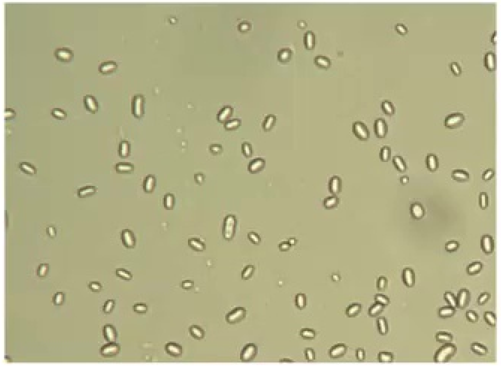
Historical examples

Probing a microscopic scale with many low-energy mesoscopic particles.

1905: brownian motion of pollen grains to measure the size of atoms (Einstein)



1909: oil drop experiment to measure the elementary electric charge (Millikan)

Conclusion

- We propose an experiment to test an hypothesis about a possible granularity of time.

- We show that it is not too far removed from current technological capabilities.

Christodoulou, Di Biagio, Martin-Dussaud 2007.08431

A set of viable parameters?

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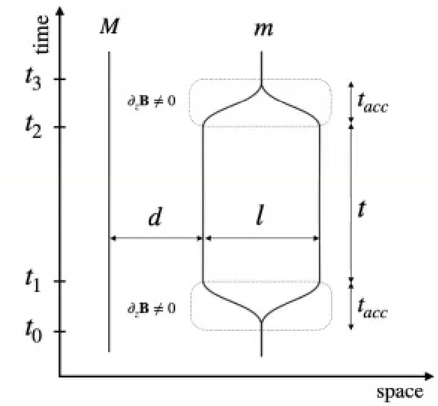

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Motivations and alternative hypotheses

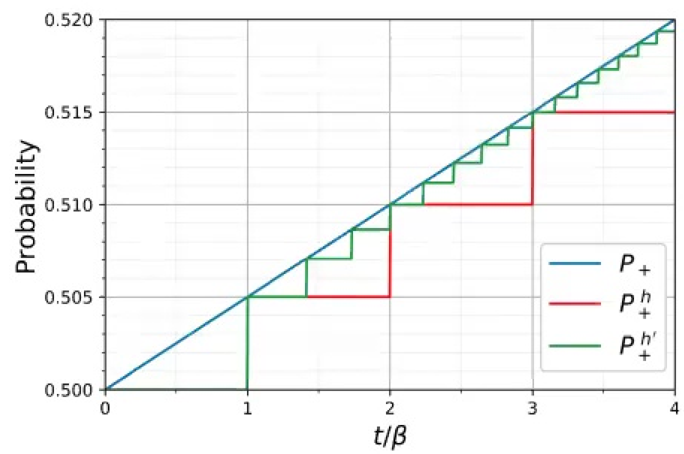
Time is flowing step by step.
Planck time is the fundamental period.

$$\delta\tau = n\, t_P, \quad n \in \mathbb{N}.$$

None of the main current theories predict such a behaviour.

Loop Quantum Gravity: discrete area $A_j = 8\pi\gamma l_P^2 \sqrt{j(j+1)}, \quad j \in \mathbb{N}/2$

Dimensional comparison: $\delta\tau = \sqrt{n}\, t_P$?



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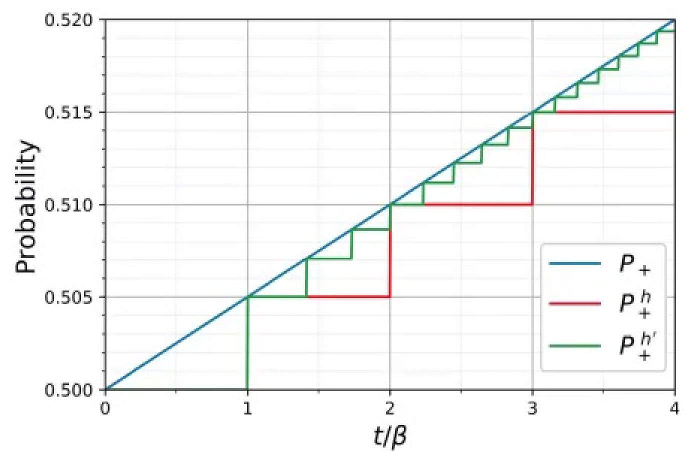
$$\tau = \sqrt{n}\,t_P \ ?$$

$$\delta\tau = \frac{n\,t_P}{N}$$



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