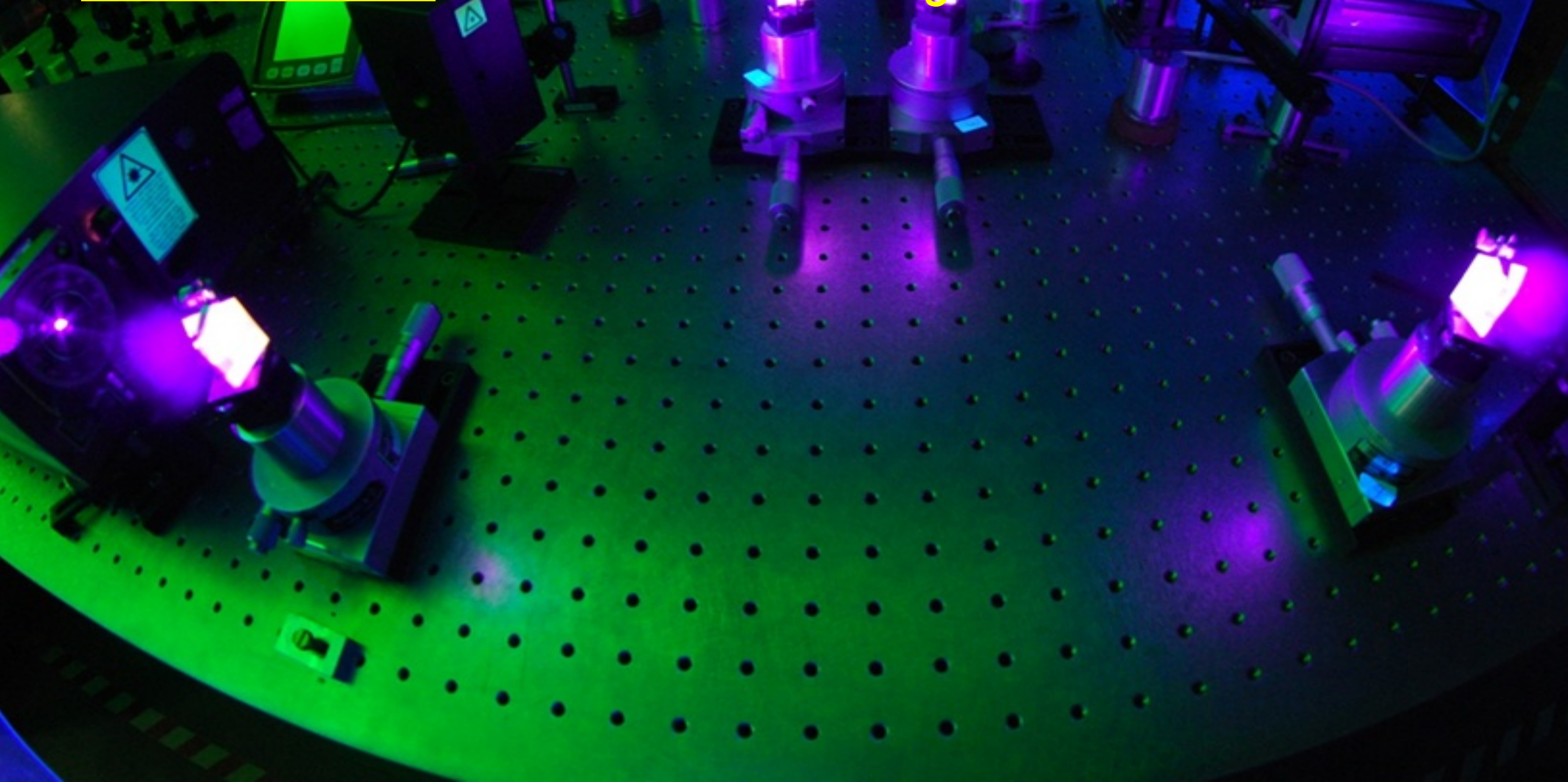
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

"Time" replaced by quantum correlations: experimental visualization

E. V. Moreva G. Brida M. Gramegna L. Maccone M. Genovese



The Time Machine Factory

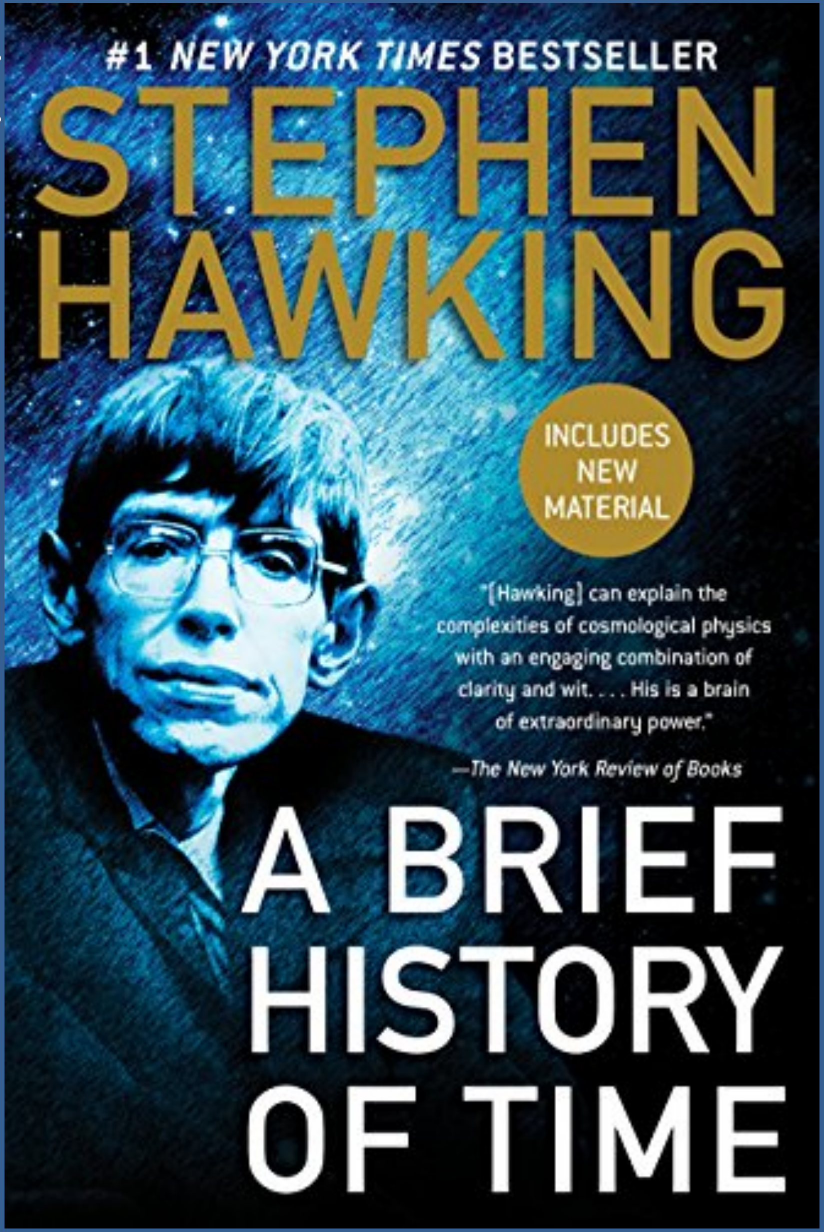
Introduction

…Today scientists describe the universe in terms of two basic partial theories – the general theory of relativity and quantum mechanics.

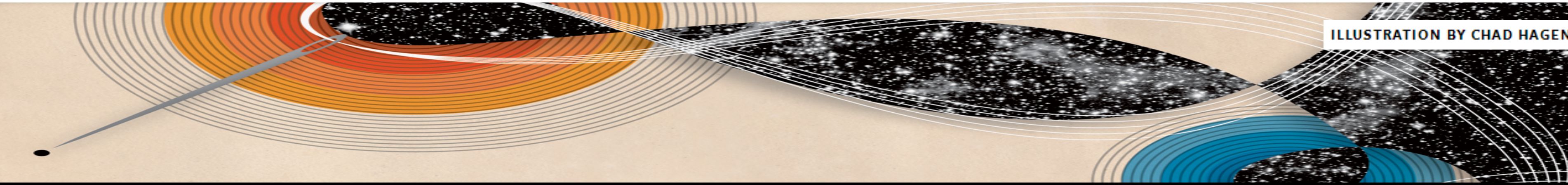
The general theory of relativity describes the force of gravity and the large-scale structure of the universe, that is, the structure on scales from only a few miles to as large as a million million million million miles, the size of the observable universe.

Quantum mechanics, on the other hand, deals with phenomena on extremely small scales, such as a millionth of a millionth of an inch. Unfortunately, however, these two theories are known to be inconsistent with each other – they cannot both be correct.

One of the major endeavours in physics today is the search for a new theory that will incorporate them both – a quantum theory of gravity.



Introduction



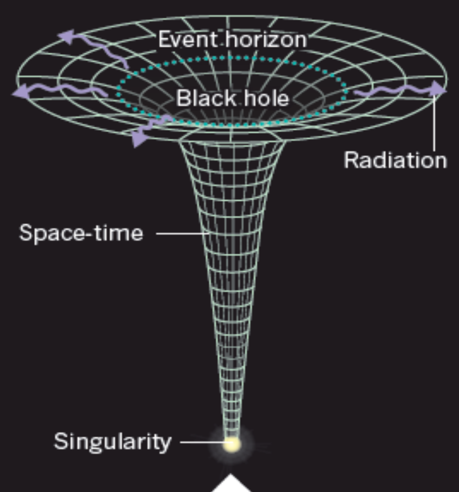
..there are a number of proposed quantum gravity theories. Currently, there is still no complete and consistent quantum theory of gravity, and the candidate models still need to overcome major formal and conceptual problems. They also face the common problem that there is no way to put quantum gravity predictions to experimental tests....

THE FABRIC OF REALITY

If space and time are not fundamental, then what is? Theoretical physicists are exploring several possible answers.

One clue

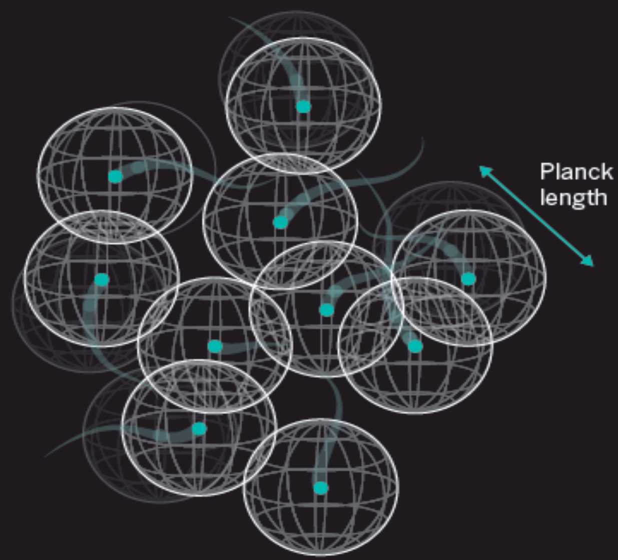
Quantum effects in the gravitational field of a black hole cause it to radiate energy as if it were hot, implying a deep connection between quantum theory, gravity and thermodynamics — the science of heat.



The black hole's mass is concentrated at a singularity of infinite curvature.

1. Gravity as thermodynamics

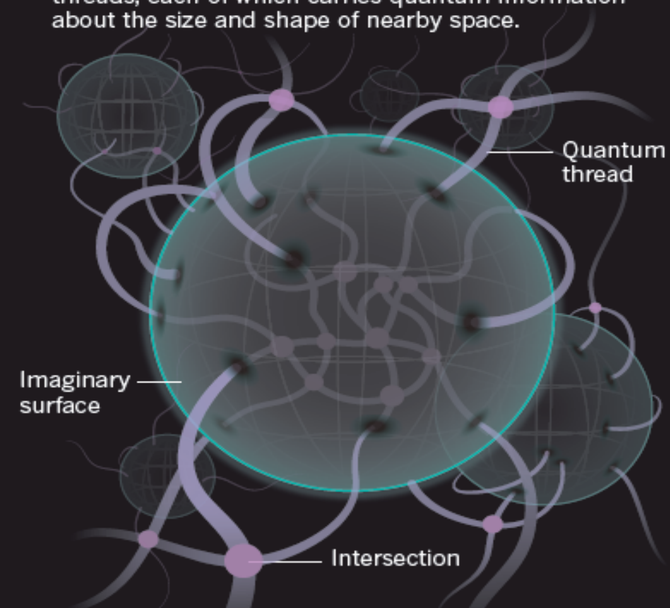
The equations of gravity can actually be derived from thermodynamics, without reference to space-time curvature.



This suggests that gravity on a macroscopic scale is just an average of the behaviour of some still-unknown 'atoms' of space-time.

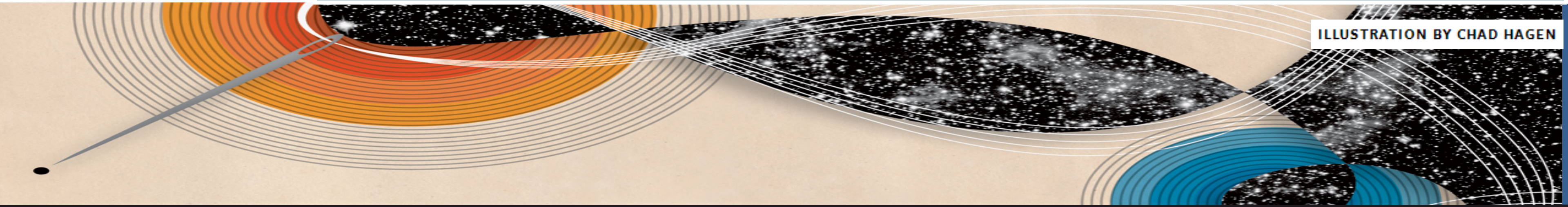
2. Loop quantum gravity

The Universe is a network of intersecting quantum threads, each of which carries quantum information about the size and shape of nearby space.



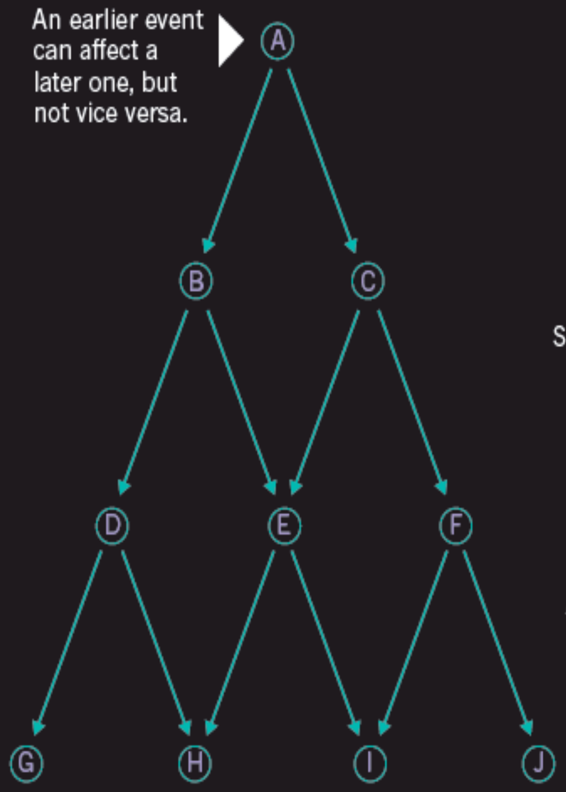
Imagine drawing a closed surface anywhere in the network. Its volume is determined by the intersections it encloses; its area by the number of threads that pierce it.

Introduction



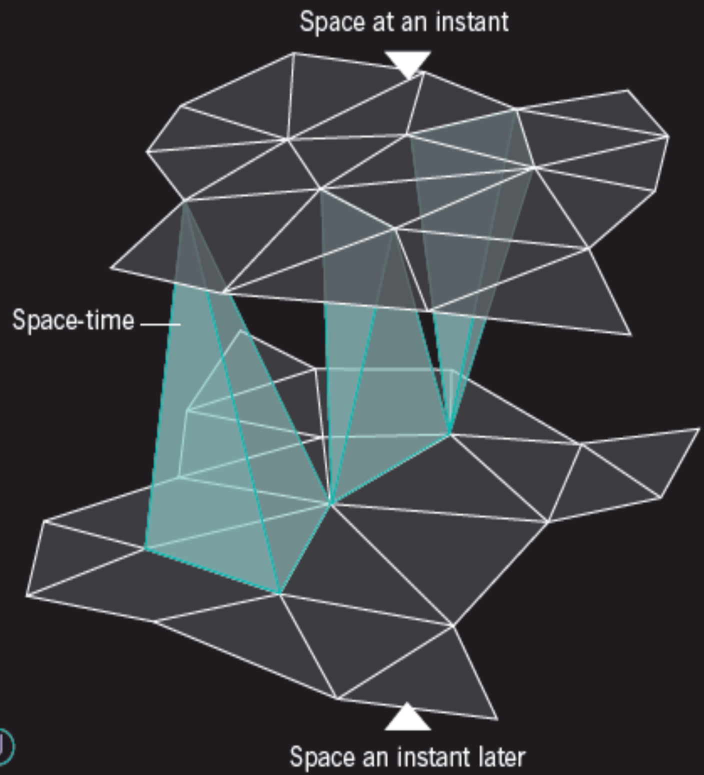
3. Causal sets

The building blocks of space-time are point-like 'events' that form an ever-expanding network linked by causality.



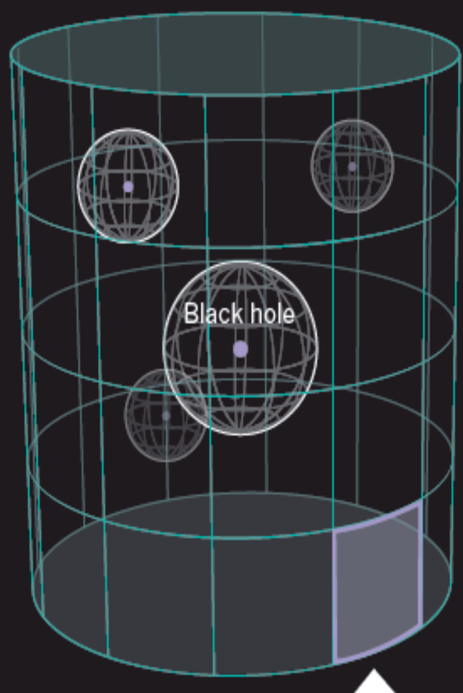
4. Causal dynamical triangulations

Computer simulations approximate the fundamental quantum reality as tiny polygonal shapes, which obey quantum rules as they spontaneously self-assemble into larger patches of space-time.



5. Holograpy

A three-dimensional (3D) universe contains black holes and strings governed solely by gravity, whereas its 2D boundary contains ordinary particles governed solely by standard quantum-field theory.



Anything happening in the 3D interior can be described as a process on the 2D boundary, and vice versa.

Introduction

not depending of the theory, the good candidate should give answer on some questions….

- ✓ *Are principles of the quantum mechanics and general relativity correct or should be modificated?*
- ✓ *What happens in singularities of general relativity?*
- ✓ *How to give description of nature at all scales ?*
- ✓ ***What is Time?***

Wheeler-De Witt equation *(1967) - canonical quantization of the general relativity*

$$\boxed{\mathcal{H}_{tot}|\Psi\rangle = 0}$$

…the Time disappears and the Quantum Cosmos doesn't evolve…

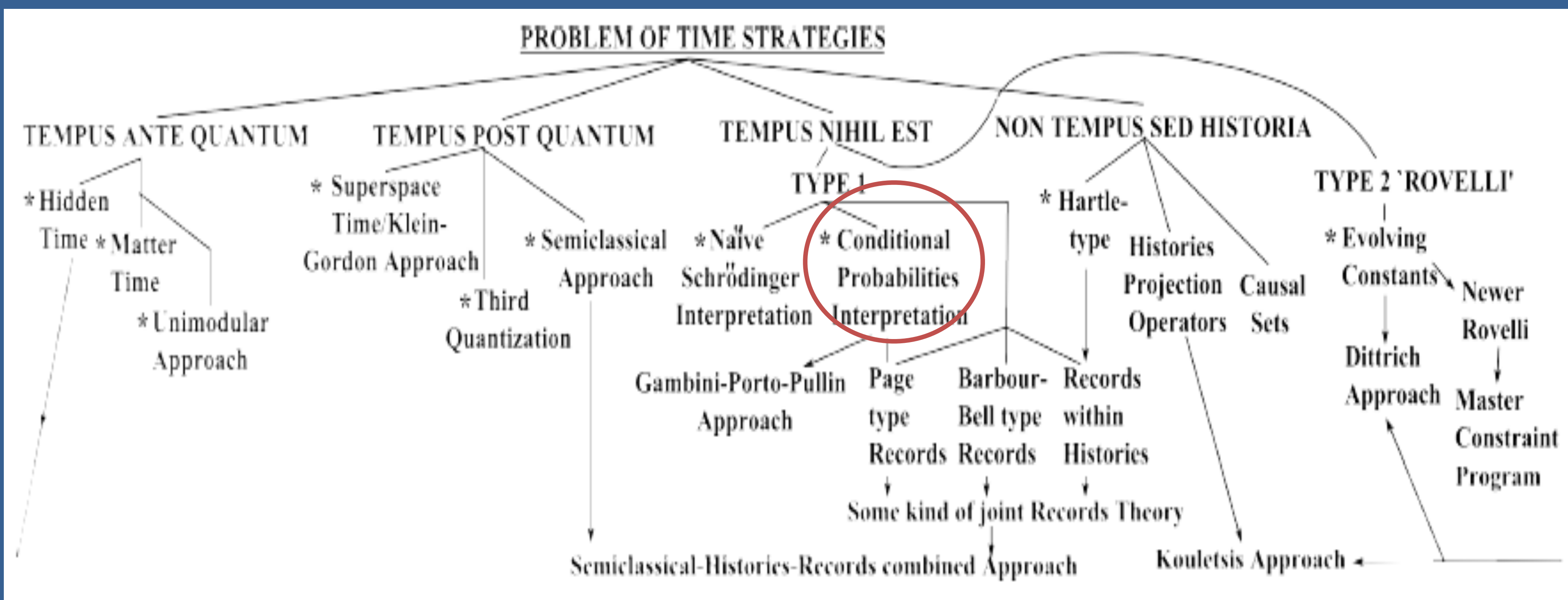
It clashes with our everyday experience of an evolving world….

The problem of time in quantum grav

THE PROBLEM OF TIME IN QUANTUM GRAVITY

Edward Anderson*

DAMTP, Cambridge, U.K.
and
Departamento de Física Teórica, Universidad Autonoma de Madrid.



Edward Anderson, arXiv:1009.2157 [gr-qc]

The problem of time in quantum grav

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

Classical parameter…

…for a fully consistent theory we need a quantum description!

How to define time?

Time – "what is shown on a clock"

⇩

How to define clock?

⇩

Clock – an quantum system

⇩

Degree of freedom

⇩

Time

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

The problem of time in quantum grav

PHYSICAL REVIEW D VOLUME 27, NUMBER 12 15 JUNE 1983

Evolution without evolution: Dynamics described by stationary observables

Don N. Page* and William K. Wootters†

International Journal of Theoretical Physics, Vol. 23, No. 8, 1984

"Time" Replaced by Quantum Correlations[1]

William K. Wootters

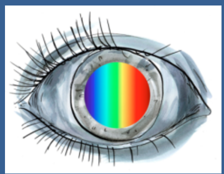
Department of Physics and Astronomy, Williams College, Williamstown, Massachusetts 01267

Received August 5, 1983

Time is a quantum degree of freedom, *evolution emerges via correlations (entanglement) between this quantum degree of freedom and the rest of the system. It exists only for internal observer. Any external observer outside sees a static, unchanging universe, just as the Wheeler-DeWitt equation predicts...*

The PaW Formalism

Model of the isolated Universe



"super - observer" mode

The staticity of the global system

"observer" mode

*The flow of time consists in the entanglement between the quantum degree of freedom of **time** and the rest and recover from the conditional measurements*

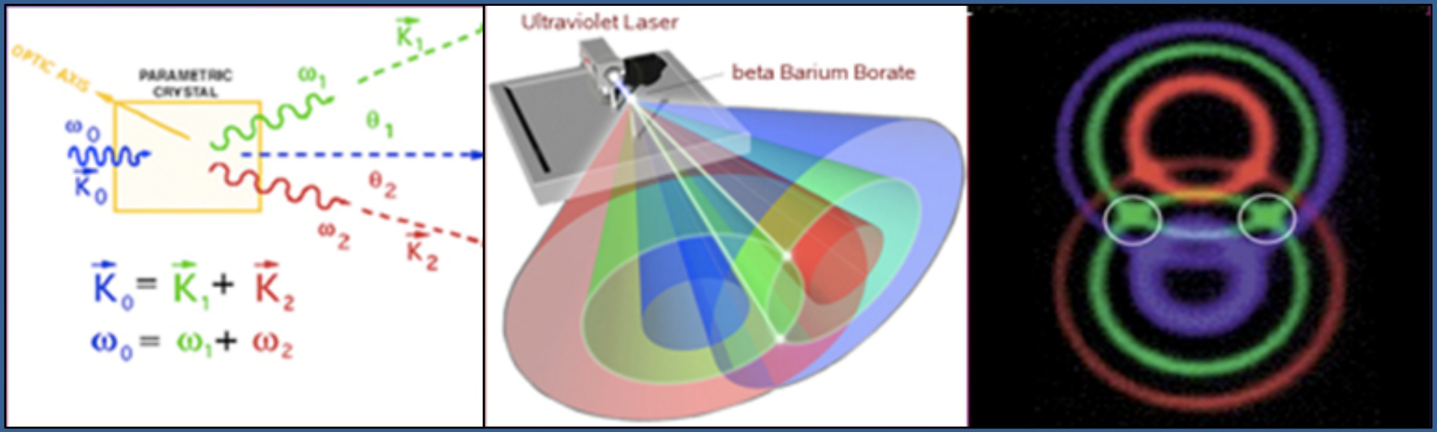
The PaW formalism

- *Time represents a dynamical degree of freedom connected to some quantum system (Experiment 1)*
- *Time degree of freedom as an abstract purification space (Experiment 2)*

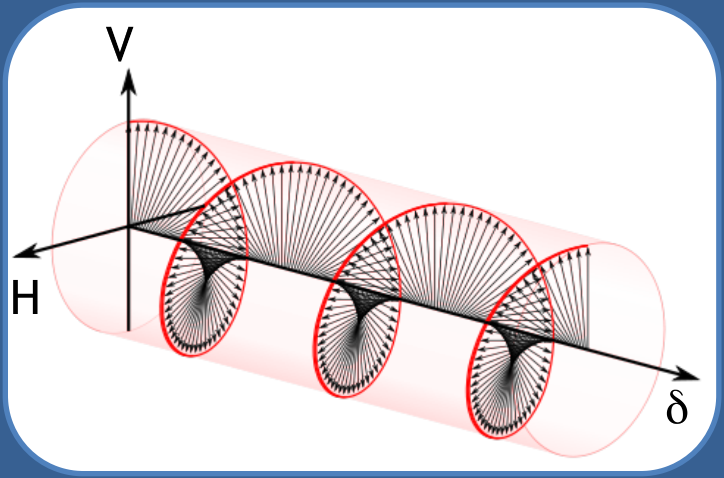
The PaW Mechanisms: approach I

How to create the small Universe?

$$|\Psi\rangle \longrightarrow |\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_c|V\rangle_r - |V\rangle_c|H\rangle_r\right)$$



How to introduce the "flow of time"?



The polarization of both photons evolves in the birefringent quartz plates as:

$$|V\rangle \rightarrow |V\rangle \cos\delta + i\,|H\rangle \sin\delta.$$

δ *: material's optical thickness*

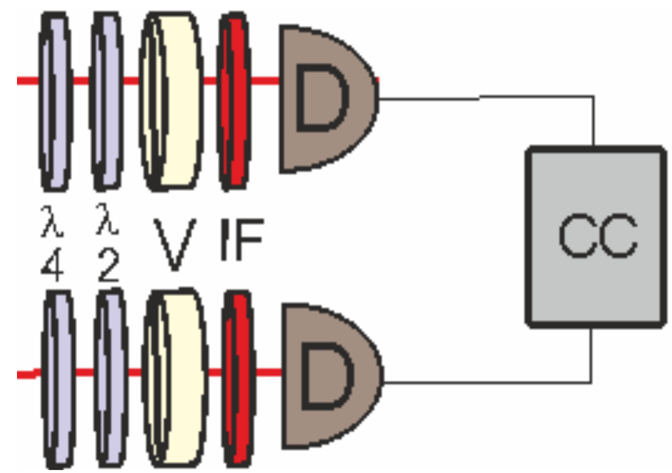
How to reconstruct the state of the Universe?

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_c|V\rangle_r - |V\rangle_c|H\rangle_r\right)$$

Two-photon polarization state → four-dimensional Hilbert space

Quantum state reconstruction (quantum tomography) - *set of projective measurements (16) realized with polarization filters consisting of a sequence of quarter- and half-wave plates and a polarization prism which transmits vertical polarization (V).*

$$K_4 \equiv (K_2)_1 \otimes (K_2)_2 = \begin{pmatrix} A & E & F & G \\ E^* & B & I & K \\ F^* & I^* & C & L \\ G^* & K^* & L^* & D \end{pmatrix} \rightarrow \rho = |\Psi\rangle\langle\Psi|$$



$$A = \langle a_1^+ a_2^+ a_1 a_2 \rangle = |c_1|^2, B = \langle a_1^+ b_2^+ a_1 b_2 \rangle = |c_2|^2,$$

$$C = \langle b_1^+ a_2^+ b_1 a_2 \rangle = |c_3|^2, D = \langle b_1^+ b_2^+ b_1 b_2 \rangle = |c_4|^2$$

$$E = \langle a_1^+ a_2^+ a_1 b_2 \rangle = c_1^* c_2, F = \langle a_1^+ a_2^+ b_1 a_2 \rangle = c_1^* c_3, G = \langle a_1^+ a_2^+ b_1 b_2 \rangle c_1^* c_4,$$

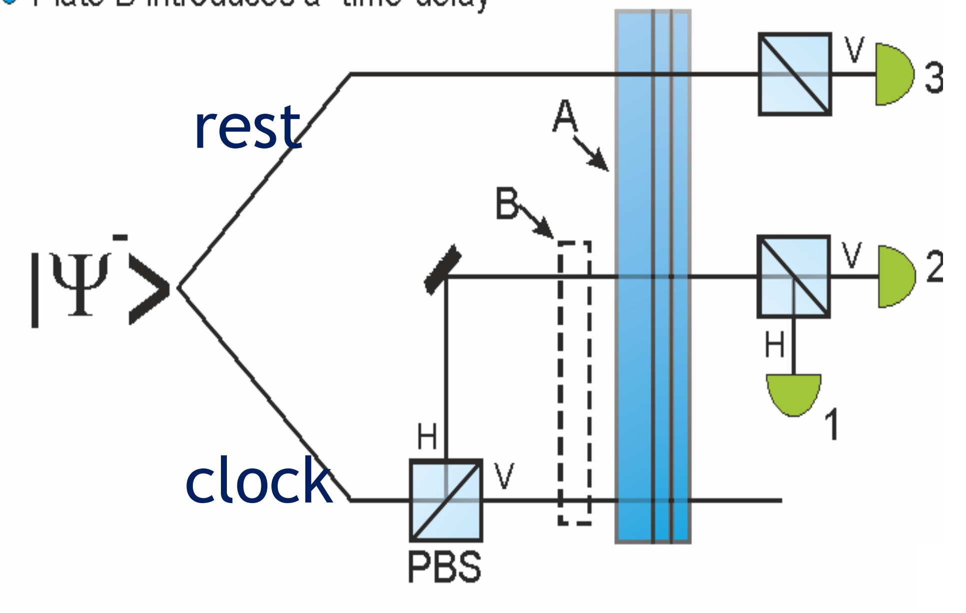
$$I = \langle a_1^+ b_2^+ b_1 a_2 \rangle = c_2^* c_3, K = \langle a_1^+ b_2^+ b_1 b_2 \rangle = c_2^* c_4, L = \langle b_1^+ a_2^+ b_1 b_2 \rangle = c_3^* c_4$$

ρout : *final state after its evolution through the plates*

$$\boxed{Fidelity = \left(Tr\sqrt{\rho_{teor}^{1/2}\rho_{exp}\rho_{teor}^{1/2}}\right)^2}$$

Approach I: observer mode

- Plate A provides time evolution of the state
- Plate B introduces a “time”delay



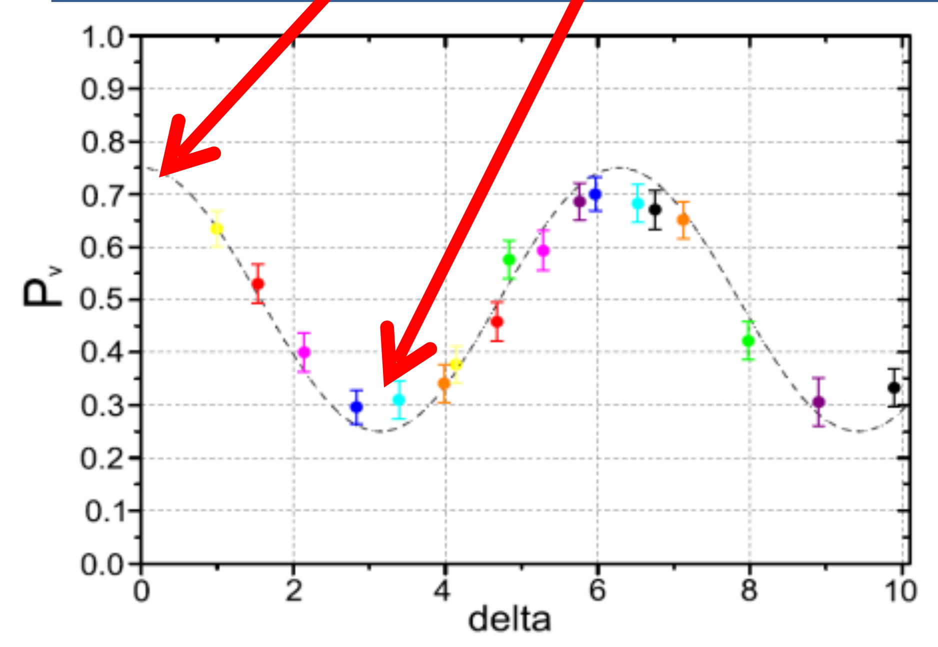
The Clock photon polarization has a dial with only two values:

$|H\rangle$, clicked D1, corresponding to ***time***

$|V\rangle$ clicked D2,corresponding to ***time t =***

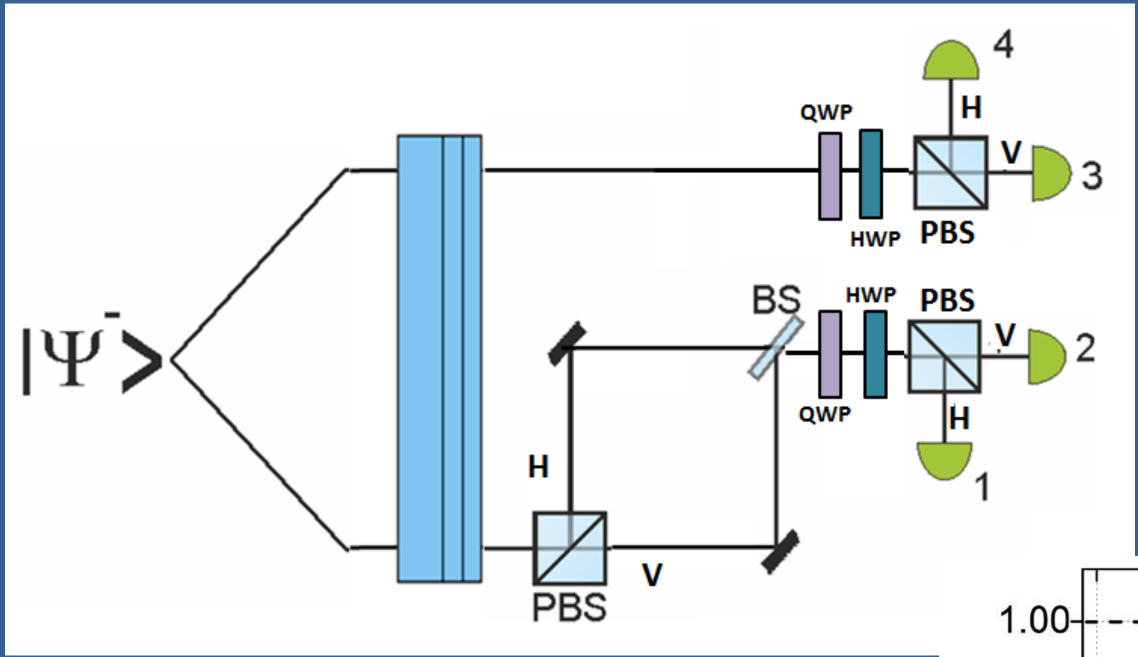
t2 − t1 = π/2ω

$p(t_1) = P_{3|1}$ $p(t_2) = P_{3|2}$



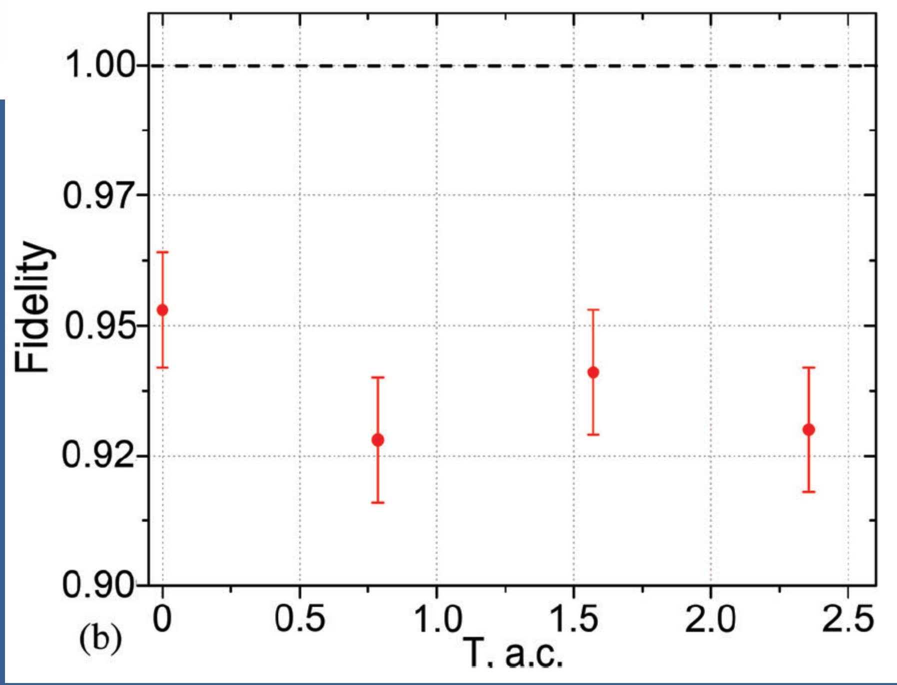
- ✓ *To obtain a more interesting clock a τ dependence is introduced by varying time delays to the clock photon (plates of variable thickness B)*
- ✓ *In this way he obtains a sequence of time-dependent values for the conditional probability*

Approach I: super- observer mode



The ***super-observed mode*** *is employed to prove that the* ***global state is static*** *respect to abstract coordinate time*

$$\left|\Psi^{-}\right\rangle_{teor}=\frac{1}{\sqrt{2}}\left(\left|H_1V_2\right\rangle-\left|V_1H_2\right\rangle\right)$$



The fact that the fidelity is constant and close to one (up to experimental imperfections) al different coordinate times proves that the ***global entangled state is static****.*

Approach 2: Theory

PHYSICAL REVIEW D 92, 045033 (2015)

Quantum time

Vittorio Giovannetti,[1] Seth Lloyd,[2] and Lorenzo Maccone[3]

✓ *consider a Hilbert space:* $\mathfrak{H} := \mathcal{H}_T \otimes \mathcal{H}_S$

✓ *Constraint operator of the model:* $\hat{\mathbb{J}} := \hbar\hat{\Omega} \otimes 1\!\!1_S + 1\!\!1_T \otimes \hat{H}_S$

✓ *Global state of system plus clock:* $|\Psi\rangle\rangle = \int dt |t\rangle_T \otimes |\psi(t)\rangle_S$

$\hat{\mathbb{J}}|\Psi\rangle\rangle = 0$ - *Wheeler-DeWitt equation*

✓ *Conditional state at time t*

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle_S = \hat{H}_S|\psi(t)\rangle_S$$

- *Schrödinger equation*

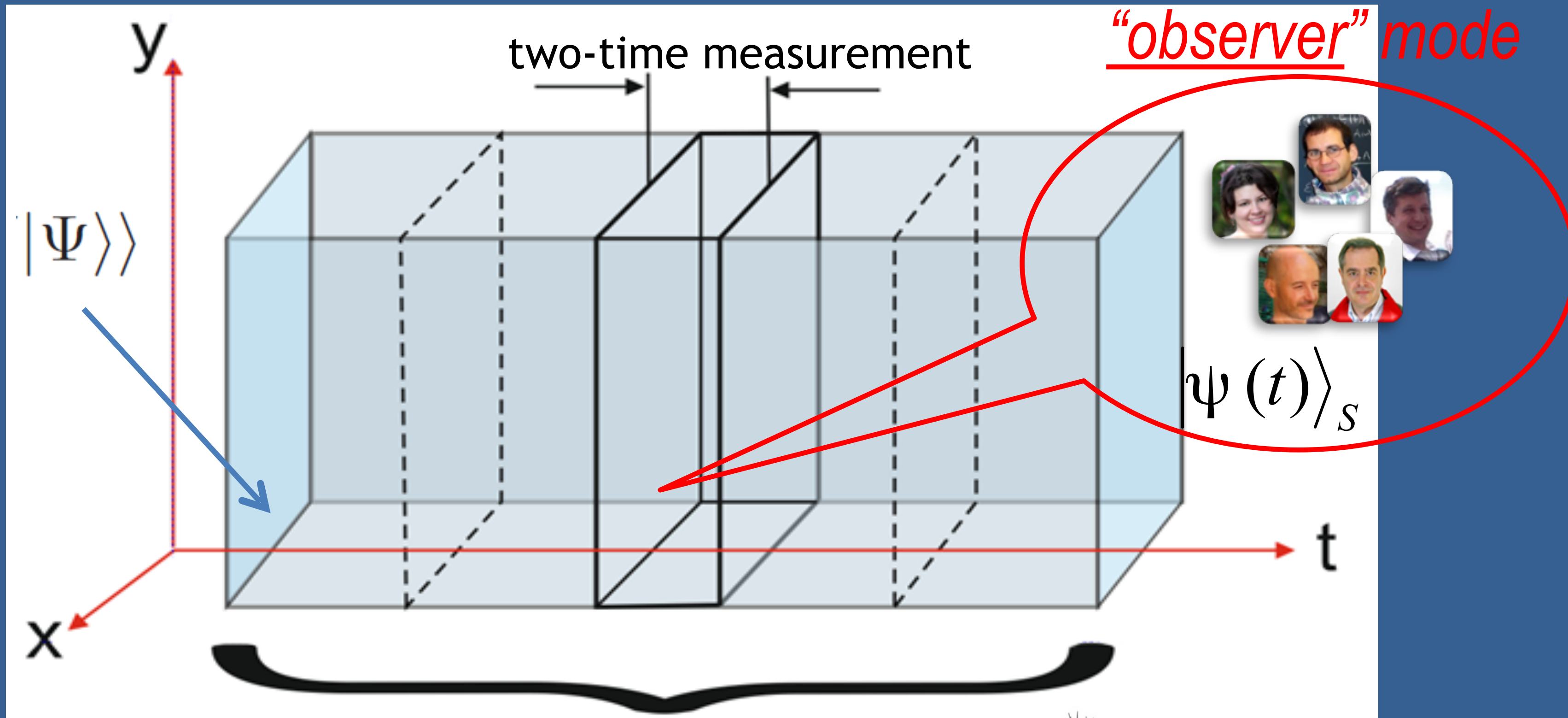
Approach 2: Theory

$\mathcal{H}_T \otimes \mathcal{H}_S$

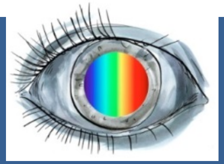
expand space

X,Y – Hilbert space of the system,

t – Hilbert space of the clock system



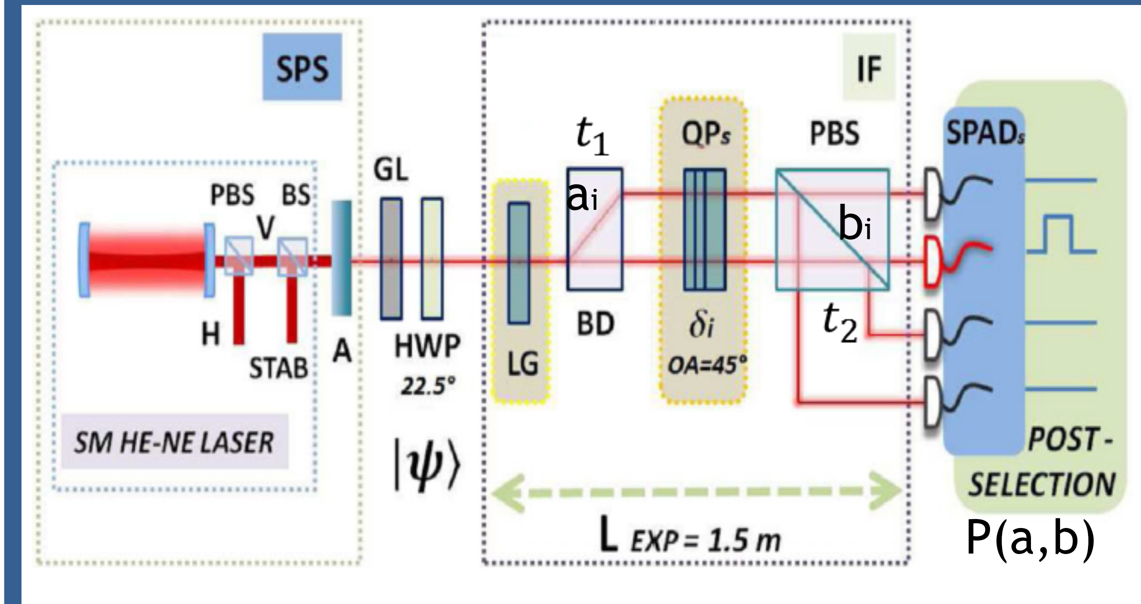
"super-observer" mode



"Super-observer" mode – *time-independent state*

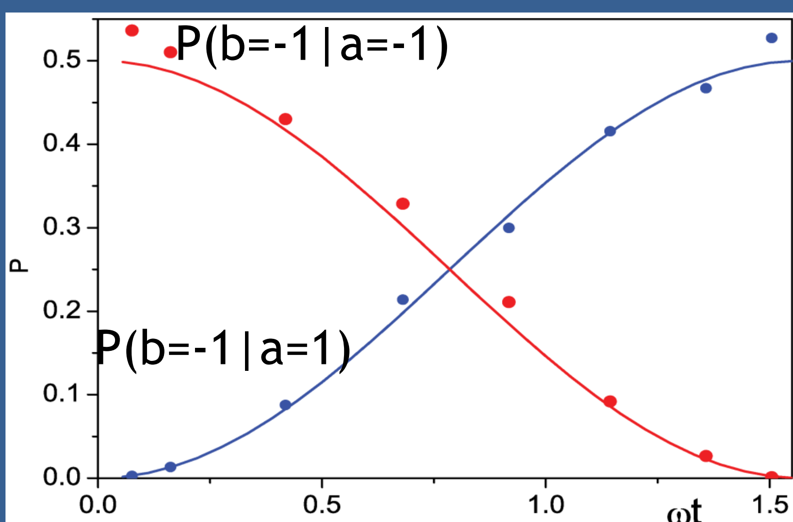
Observer mode – evolution is reconstructed through the two-time measurements

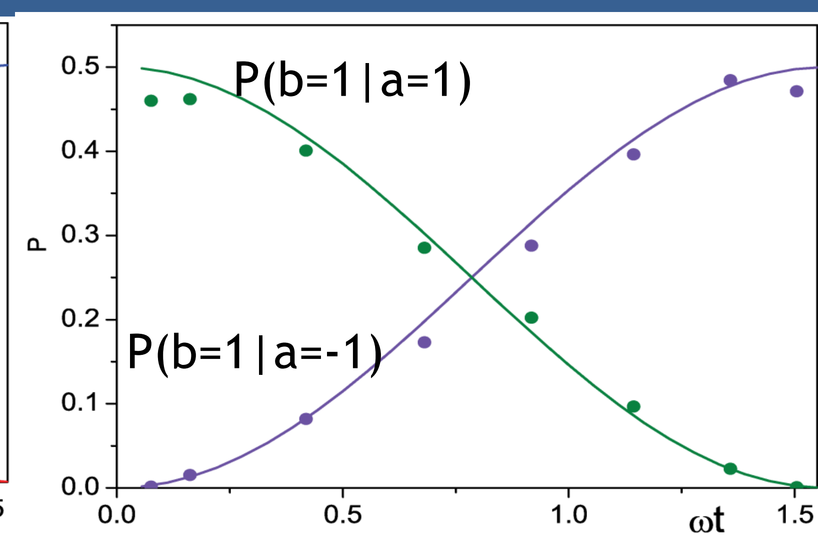
Experimental setup: observer mode

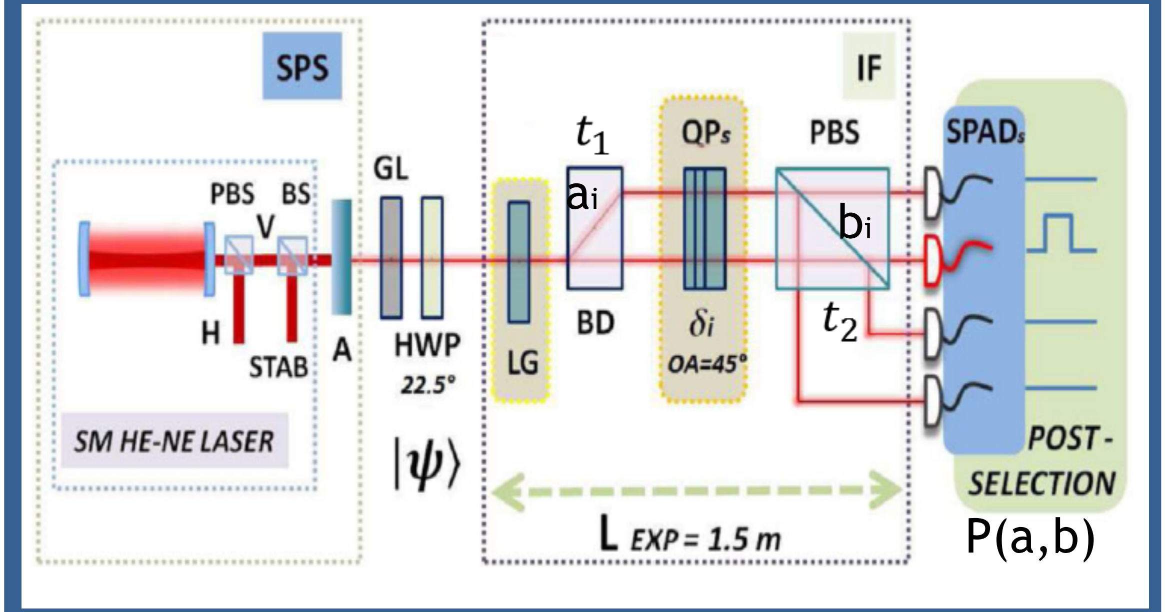


Experimental conditions

SPS- *narrow-band attenuated He-Ne laser*
System –*photon's polarization*
Clock - *photon's position/ time of arrival*
Clock must be in superposition of all relevant times - >
"flow of time" - *birefringent quartz plates*



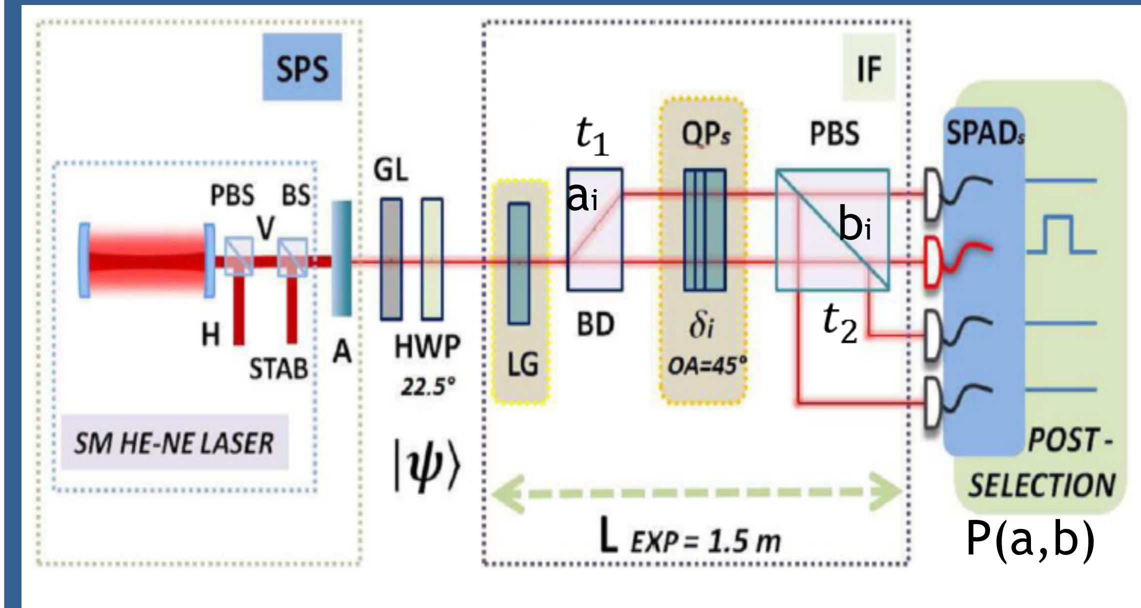




Experimental conditions

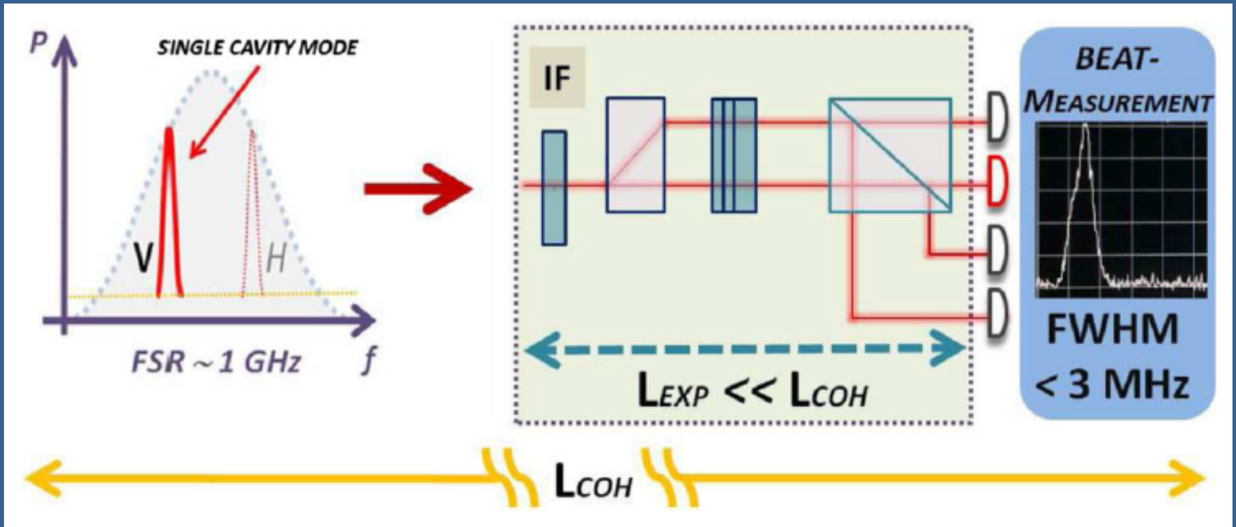
SPS- *narrow-band attenuated He-Ne laser*
System –*photon's polarization*
Clock - *photon's position/time of arrival*
Clock must be in superposition of all relevant times - >
"flow of time" - *birefringent quartz plates*

Experimental setup: super-observer m



Experimental conditions

SPS- *narrow-band attenuated He-Ne laser*
System -*photon's polarization*
Clock - *photon's position/time of arrival*
Clock must be in superposition of all relevant times - >
"flow of time" - *birefringent quartz plates*



Control that global system is time independent (control the coherence length)

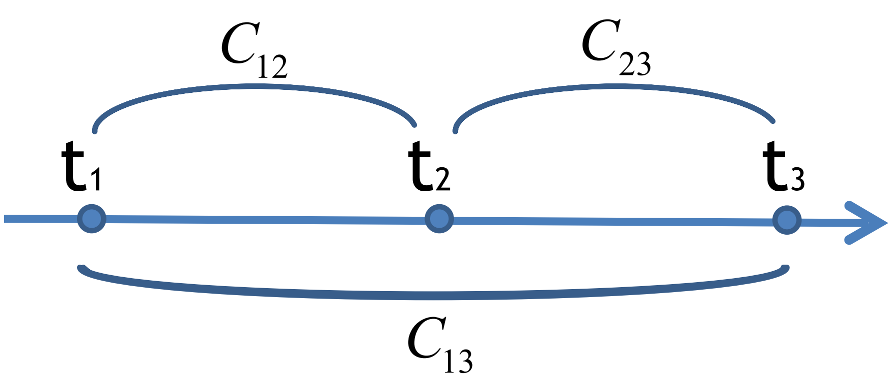
Leggett-Garg inequality and PaW mechanism

LGI is analog of spatial Bell's inequality, but involves correlations of measurements on a system at different times.

For the two-state system an observable ***Q(t)*** *takes values* ***±1***

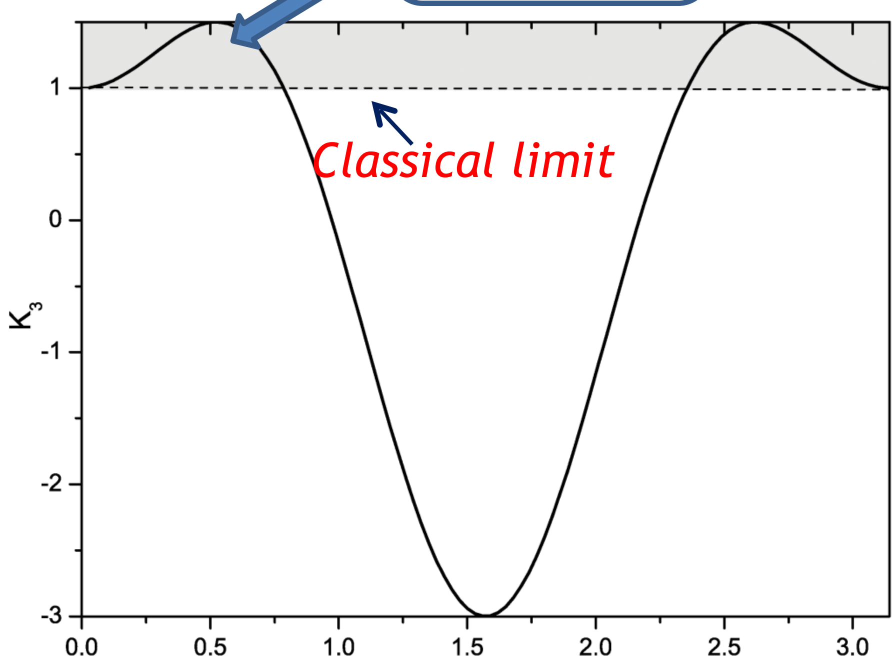
two-time correlation functions: $C_{ij} = \langle Q(t_i) Q(t_j) \rangle$

$$C_{ij} = \sum_{Q_i, Q_j = \pm 1} Q_i Q_j P_{ij}(Q_i, Q_j)$$

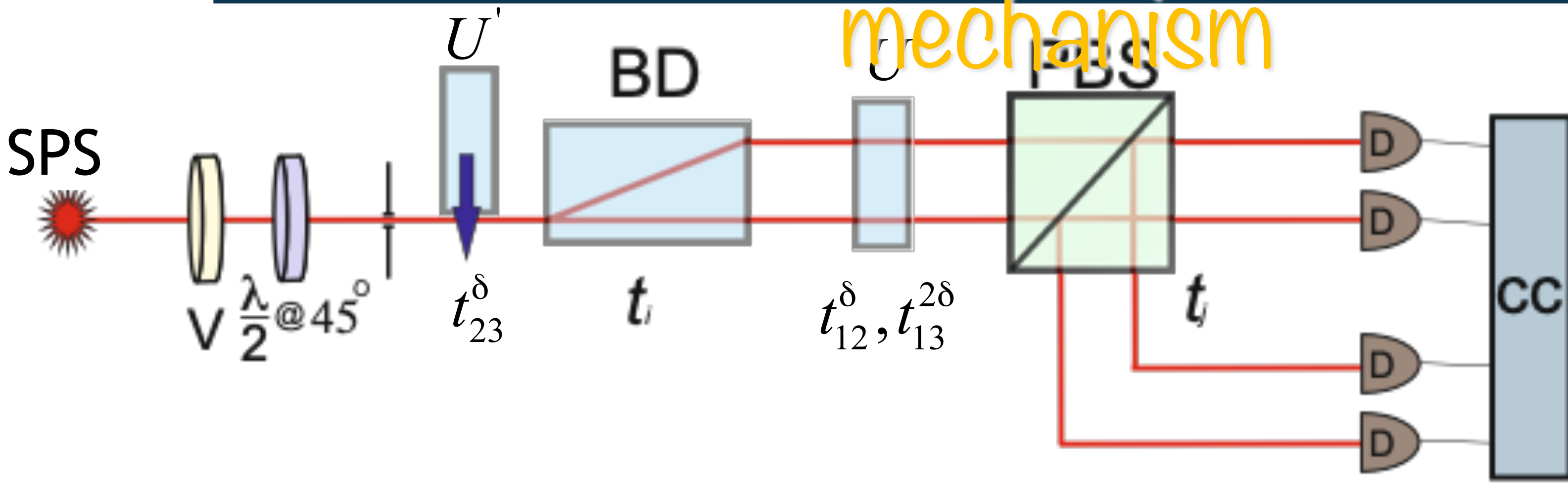


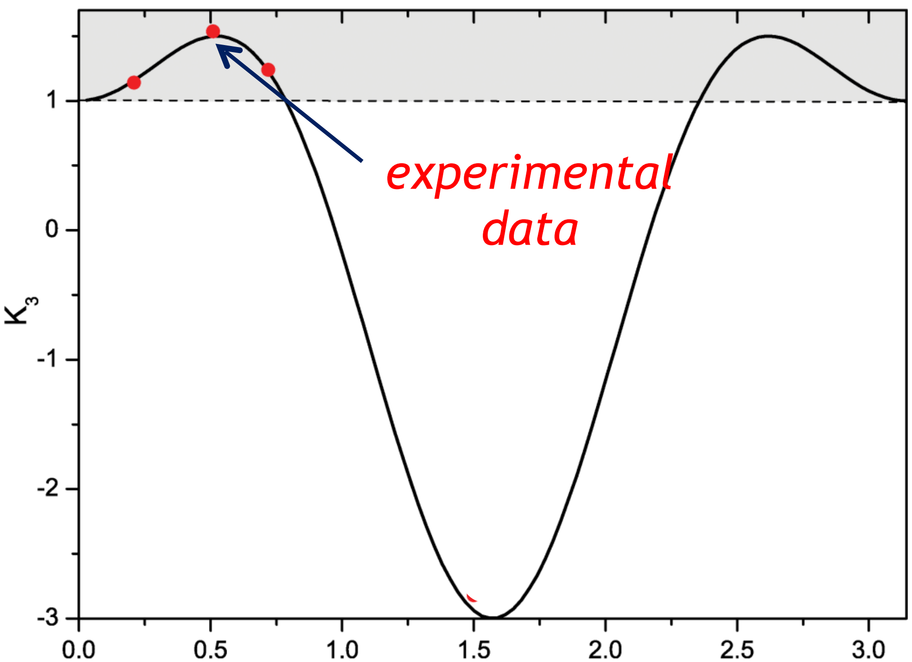
$$\boxed{K_3 \equiv C_{12} + C_{23} - C_{13} \leq 1}$$

$K_3^{\max} = 3/2$
at $t\omega = \pi/6$



Leggett-Garg inequality and PaW mechanism





We should measure values:

$$C(t_1,t_2),\ C(t_1,t_3),\ C(t_2,t_3),$$

$$\Delta t_{12} = \Delta t_{23} = \Delta t_{13}/2 \Rightarrow U = U'$$

δ	Theory	Experiment	
0.2	1.159	1.138±0.004	~35 s.d.
0.5	1.499	1.534±0.018	~30 s.d.
0.7	1.282	1.238±0.012	~20 s.d.

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Conclusions

- ✓ *The experimental illustration of two different approaches of Page and Wootters mechanism of quantum description of time had been done*
- ✓ *The PaW mechanism gives conventional quantum mechanic description of* ***evolution in observer mode*** *though the conditional probabilities and at the same time operates with a global,* ***time independent*** *state in super-observer mode.*
- ✓ *We have shown that Page and Wootters experiment with quantum time from the "internal" observer point of view clearly demonstrates a violation of the classical limits imposed by the Leggett-Garg inequality*

References: **Phys. Rev. A 89, 052122, (2014)**
Phys. Rev. D 96, 102005, (2017)