



Time: the hidden dimension



Parameter to describe evolution and transformation

Orfeu Bertolami

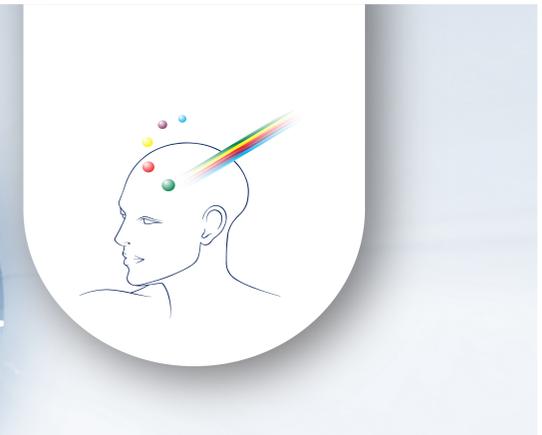
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13th SYMPOSIUM OF BIAL FOUNDATION
BEHIND AND BEYOND THE BRAIN
Aquém e Além do Cérebro
The mystery of time

Casa do Médico - Porto
April 6 to 9, 2022



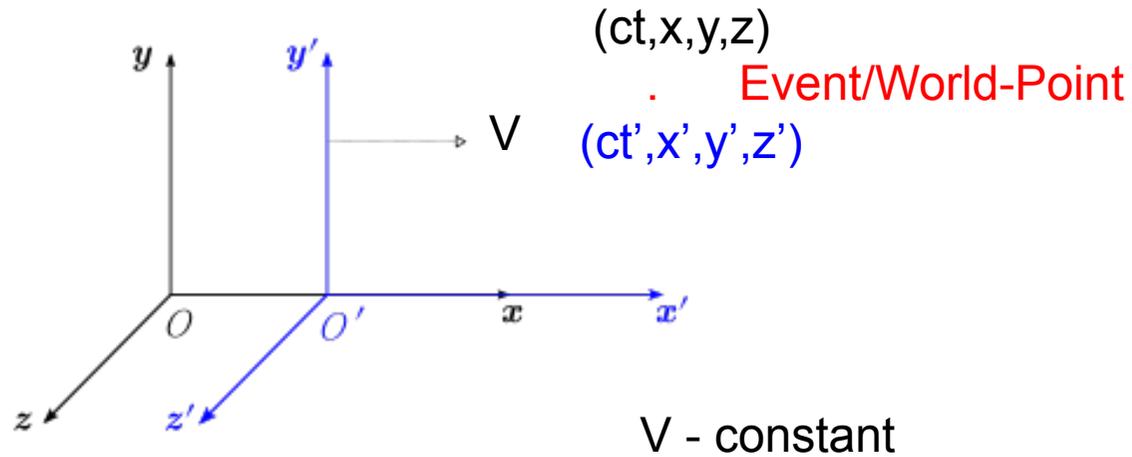
Understanding the origin and nature of time (space-time)

- **Space-Time of Special and General Relativity**
- **Arrows of Time:**
 - **Complex systems & Emergent properties**
 - **Time crystals**
 - **Fundamental systems & Discrete symmetries**
- **Emergent Space-Time?**
- **Closed time-like curves (Wormholes): Time Machines**
 - **Paradoxes & Putative Solutions**
- **Gravitational Entropy**
- **Block Universe**
- **Specious Present**
- **Some Tentative Conclusions**



See: **The Adventures of Spacetime, O.B.** in “Relativity and the Dimensionality of the World” (2006)
The Mystical formula and the mystery of Khronos, O.B. in “Minkowski Spacetime: A Hundred Years Later” (2008)
Time and Causation, O.B.& Lobo in NeuroQuantol. 7, 1-15 (2009)

Special Relativity (1905)



$$x' = \gamma(x - Vt)$$

$$y' = y$$

$$z' = z$$

$$\longrightarrow t' = \gamma(t - Vx/c^2)$$

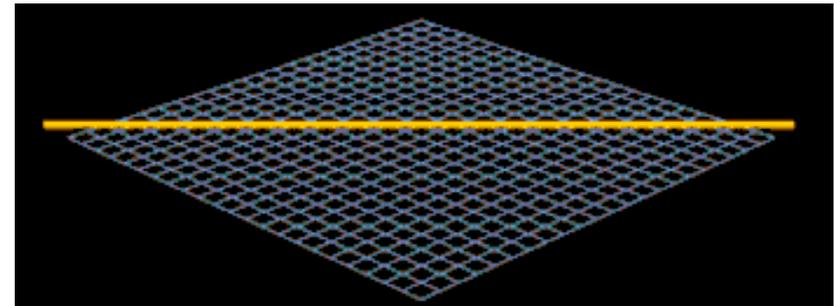
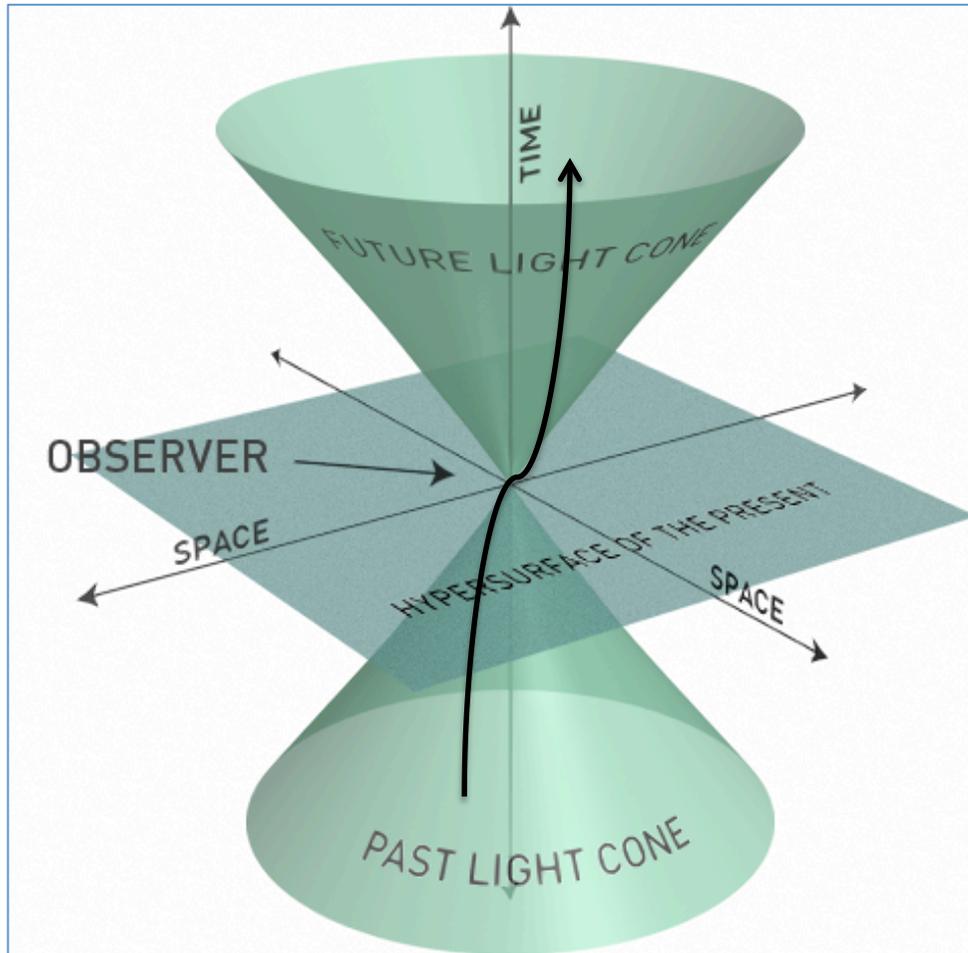
$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{V}{c}\right)^2}}$$

Laws of Physics Invariant

Space-Time Arena of Events Special Relativity & General Relativity

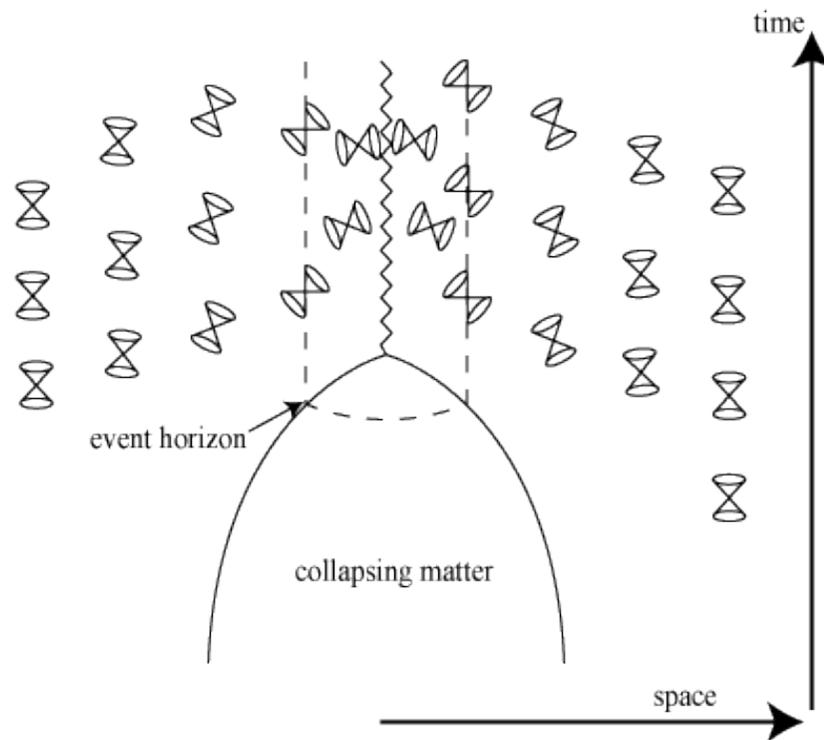
- **Space + Time = Space-time**
- **Continuum (till at about 10^{-20} m)**
- 10^{-15} s < Δt < 13.8×10^9 years
- **4 dimensions (3 space + 1 time) (at least)**
- **Coordinates: (ct, x, y, z) c = 300 000 km/s – speed of light in vacuum**
- **Admits a causal structure (global in the absence of matter-energy (Special Relativity), local in the presence of matter-energy (General Relativity))**

Causal Structure of Space-Time

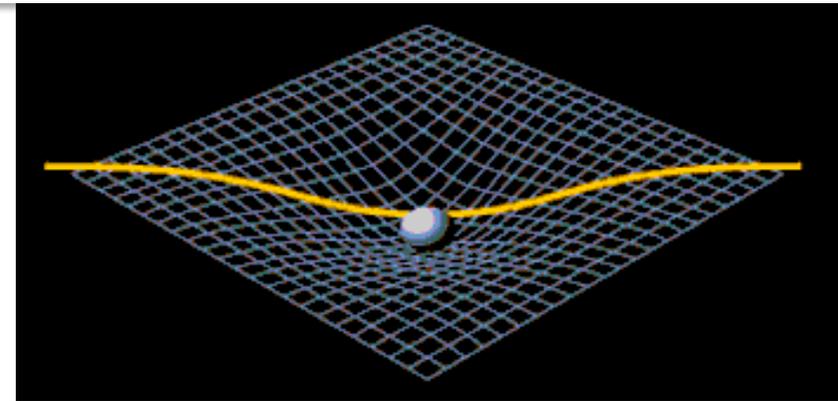


**Absence of matter-energy:
Global Space-Time Structure**

Causal Structure of Space-Time



**Presence of matter-energy:
Locally Curved Space-Time
Structure** Einstein 1915



General Relativity (GR)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Arthur Eddington
(1882-1944)

The Nature of the Physical World
(1928)

Arrow of Time

- 1. It is vividly recognized by consciousness.**
- 2. It is equally insisted on us by our reasoning faculty, which tells us that a reversal of the arrow would render the external world nonsensical.**
- 3. It makes no appearance in physical science except in the study of organization of a number of individuals.**

Physics

Thermodynamics (Entropy)

Cosmological Expansion (Gravity)

Quantum Mechanics (collapse of the wave function – decoherence)

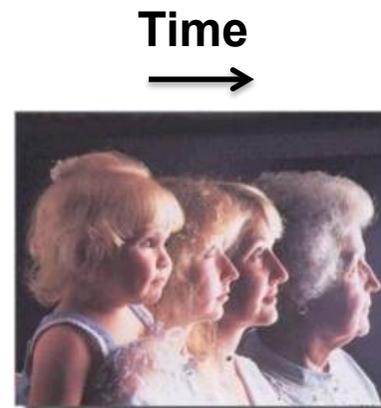
Arrows of Time



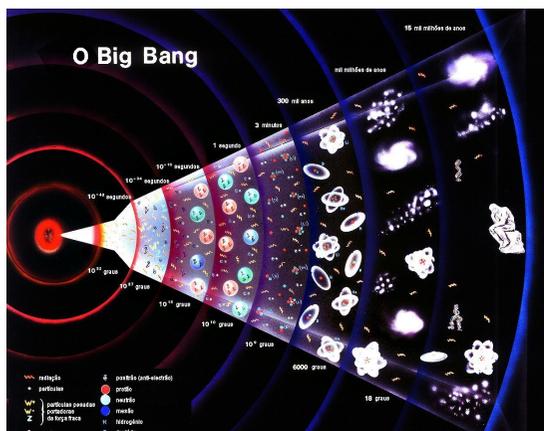
→
Time



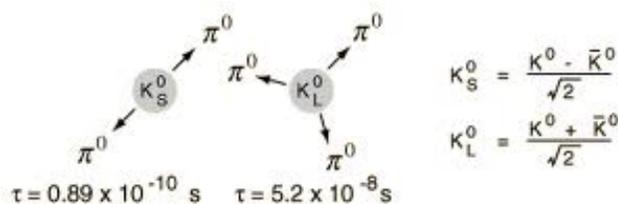
→
Entropy -- Time



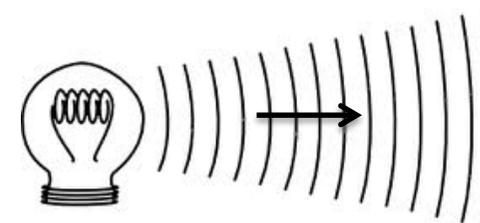
←
Memory – Historicalness



→
Time
(Birth of Space-time)
(Gravitational collapse)



CP violation → T violation
(CPT Theorem)



Electromagnetic radiation

Is there a correlation among these arrows of time?

Irreversibility Complex Systems

Macroscopically: energy dissipation

Microscopically: growth of the available states

Thermodynamics – Statistical Mechanics

Irreversibility is not a fundamental property



Temperature and Irreversibility are emergent properties



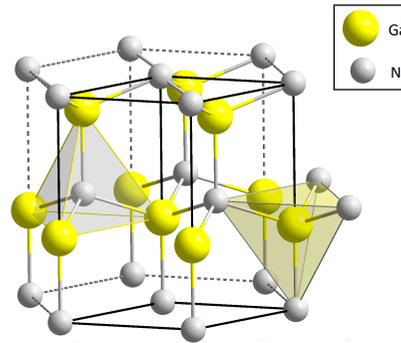
Arrow of time



Is time a fundamental or an emergent property?

Time Crystals

Crystal in space – configuration of atoms that repeat itself periodically in space (unchanged in time)



Time crystal – a quantum system in its lowest-energy whose particles are in repetitive motion, e.g. periodical spin flips. They possess “motion without energy”, being resistant to entropy [Wilczek 2012]

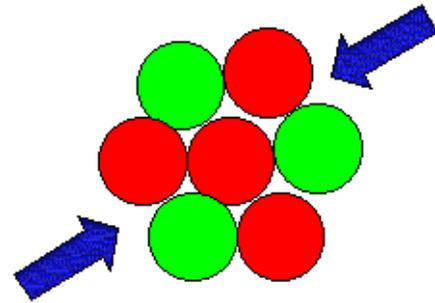
Time crystals break time-translation symmetry and show repeated patterns in time even if the laws of the system are invariant by time translations. Their existence is contested by some authors [Bruno 2013, Watanabe & Oshikawa 2015]

There are claims it was experimentally created:

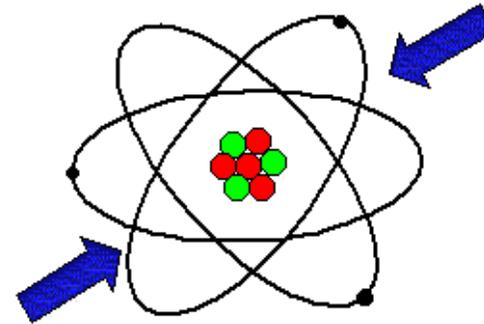
- 1. Chain of 1D interacting ytterbium-171 ions [Zhang et al. 2017]**
- 2. Quantum processor [Ippoliti & Quintana 2021]**

**Irreversibility
Fundamental Systems
(Elementary Particles)**

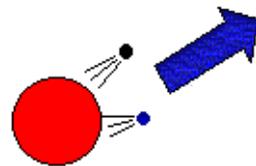
Four Fundamental Interactions of Nature



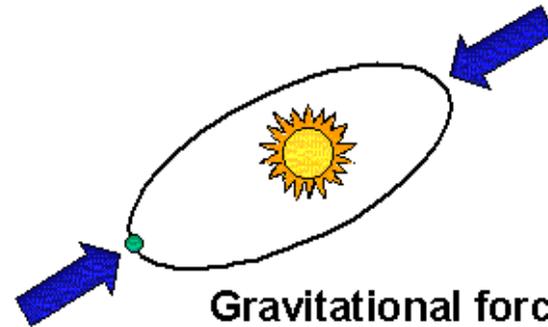
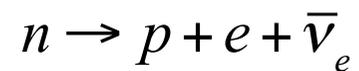
**Strong force
binds the nucleus**



**Electromagnetic
force binds atoms**



**Weak force in
radioactive decay**

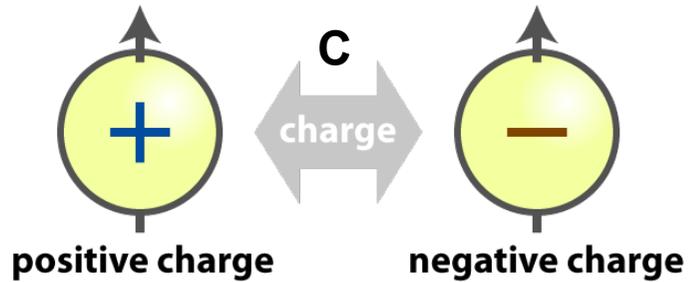


**Gravitational force
binds the solar system**

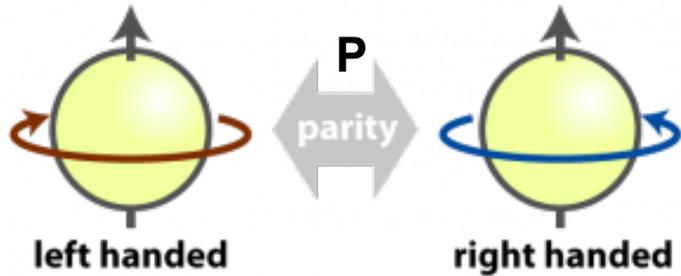
Phenomenological Features Fundamental Interactions

Force	Strength	Range (m)
strong	1	10^{-15}
electromagnetic	$1/137$	infinite
weak	10^{-6}	10^{-18}
gravity	6×10^{-39}	infinite

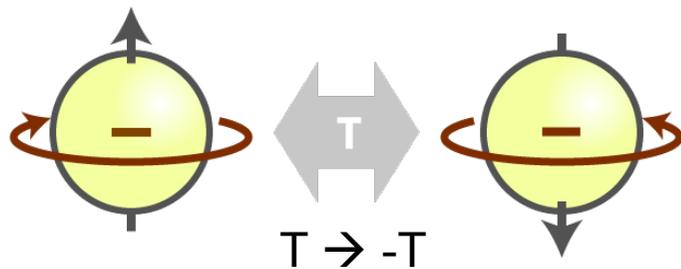
Discrete Symmetries: Symmetries of Nature?



Yes!



No!
Violated in weak interaction decays



No!
Violated in weak interaction decays

Emergent Space-Time?

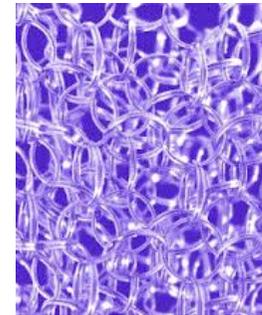
Is space-time derivable from more fundamental entities?

Pregeometry

String theory/M-theory

Loop Quantum Gravity: space-time is a weaving of Planck size fundamental loops

Hořava-Lifshitz Gravity: space and time are different at high energies



Zen and the Art of Space-Time Manufacturing, O.B., arXiv: 1303.2381 [gr-qc]
What if ... General Relativity is not the theory? O.B., arXiv: 1112.2048 [gr-qc]

Emergent Spacetime

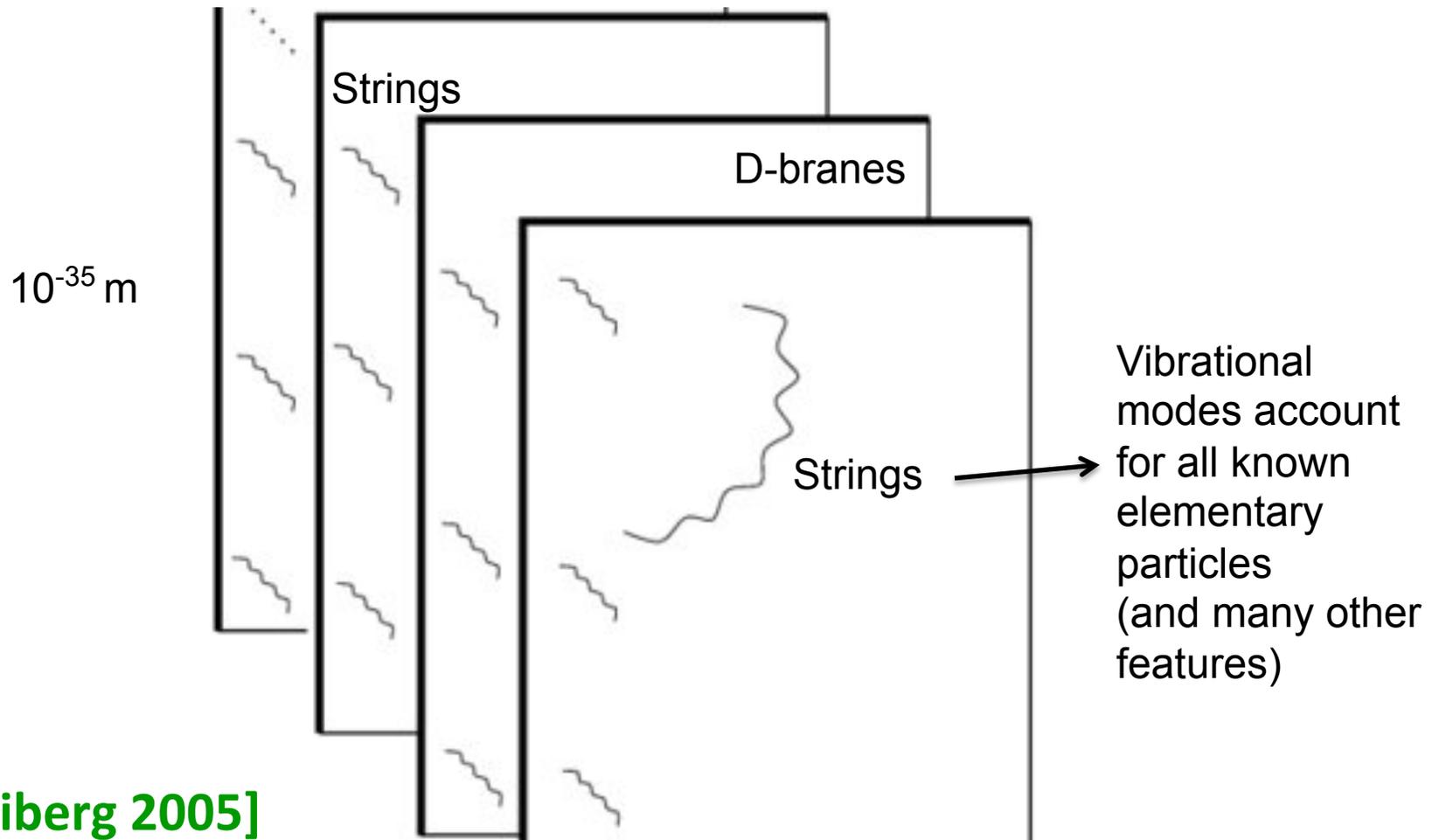
XXIIIrd Solvay Conference in Physics

December, 2005

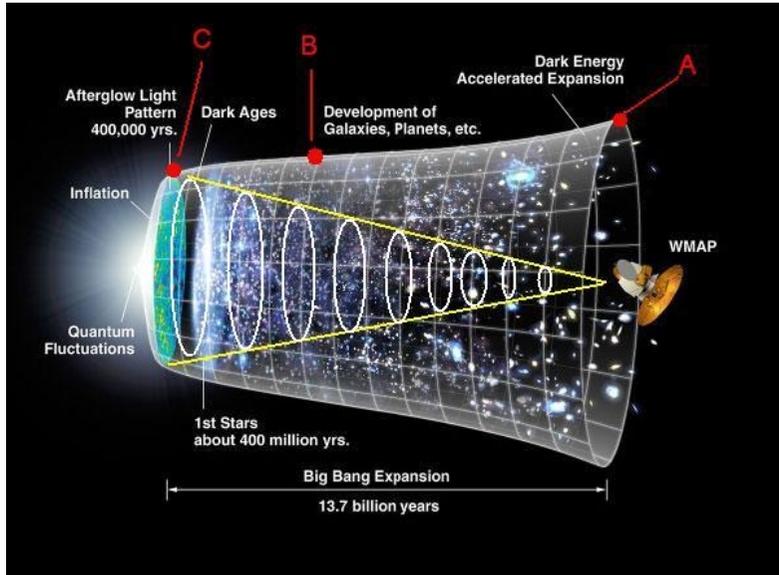
Nathan Seiberg

arXiv:hep-th/0601234

Space arise from a stack of D-branes



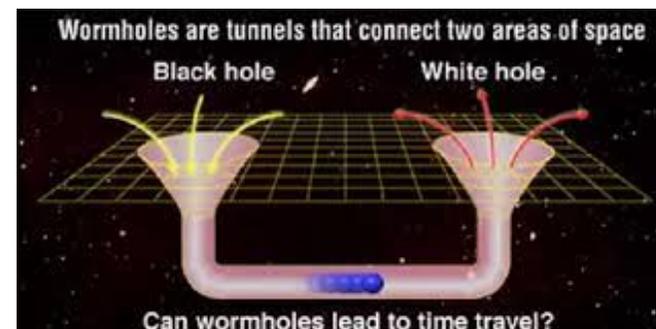
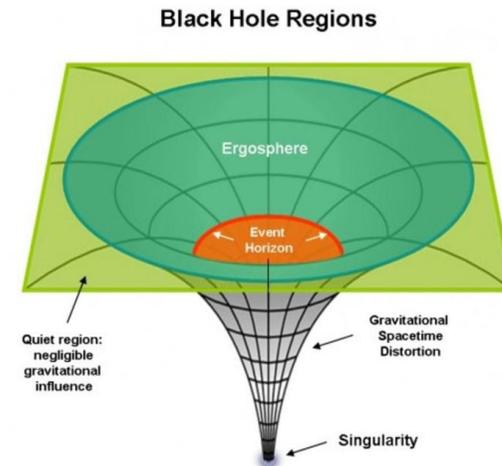
What about gravity?



Universe is expanding and observationally, it seems it will remain expanding. But, in principle, it could contract.

Gravitational attraction can turn a star in a black hole.

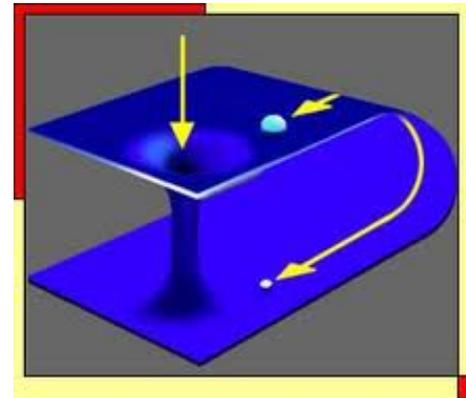
But, in principle, Einstein-Rosen bridges can connect black holes to white holes ...



Wormhole geometry

[Morris, Thorne 1998]

“Wormholes in Spacetime and their use for Interstellar Travel: a tool for teaching General Relativity”



[Morris, Thorne, Yurtsever 1988]

“Wormholes, Time Machines and the Weak Energy Condition”

Time Machine Solutions

Wormhole time machine sols. $\xrightarrow{\text{GR}}$ Negative Energy!

Non-minimally coupled theories of gravity \longrightarrow Positive energy

[Lobo, Oliveira 2011; O.B., Ferreira 2012]

$$S = \int \left[\frac{1}{2} f_1(R) + f_2(R) L_m \right] \sqrt{-g} d^4 x \quad [\text{O.B., Böhmer, Harko, Lobo 2007}]$$

Extra force in $f(R)$ modified theories of gravity, O.B., Böhmer, Harko, Lobo, Phys. Rev. D 75, 104016 (2007)

Traversable Wormholes and Time Machines in non-minimally coupled curvature-matter $f(R)$ theories, O.B., Ferreira, Phys. Rev. D 85, 104050 (2012)

Time travel paradoxes

- **The killing of an ancestor paradox** → **Serious threat to Causality**

- **Predestination paradox**

A time traveller attempting to alter his/her past, intentionally or not, would only be fulfilling his/her role in creating history as we know it, not changing it. That is, the time-traveller's knowledge of its own history already includes future travels to the past.

- **Creation of information paradox**

Time traveller from the future conveys the secret of time travelling to a researcher, who in turn publishes it. Later, the researcher travels back in time and convey the secret to his/her younger person. Hence, the information has appeared from “nowhere”.

Putative Solutions

Novikov's self-consistent principle [Novikov 1990]

CTCs might exist, but that they cannot entail any type of causality violation or time paradox

It assumes either that there is only one timeline or that alternative timelines (such as in the Many-Worlds Interpretation of Quantum Mechanics) are not accessible

Hawking's chronology protection conjecture [Hawking 1992]

“It seems that there is a Chronology Protection Agency which prevents the appearance of CTCs so to make the universe safe for historians”

Emergent Gravity Solution [O.B. 2012]

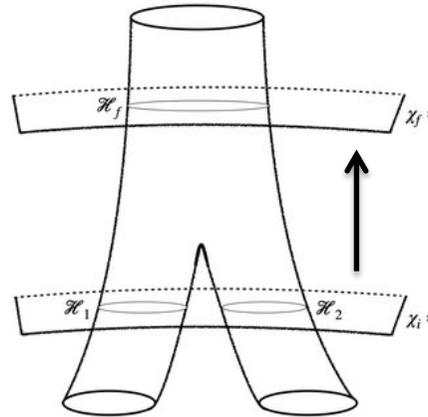
CTCs do not exist as they require conditions which in the context of GR are unphysical

Gravitational Entropy

Bekenstein - Hawking (1971-1972)
Black Hole Entropy:

$$S = \frac{k_B c^3}{4\hbar G} A = \frac{2\pi k_B G}{\hbar c} M^2$$

Hawking theorem
(1971)



$$T_H = \frac{\hbar c^3}{4k_B GM}$$

Hawking temperature
(1974)

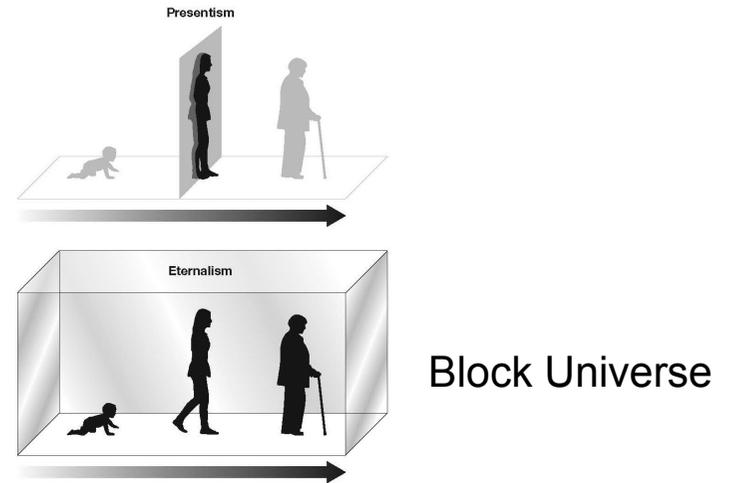
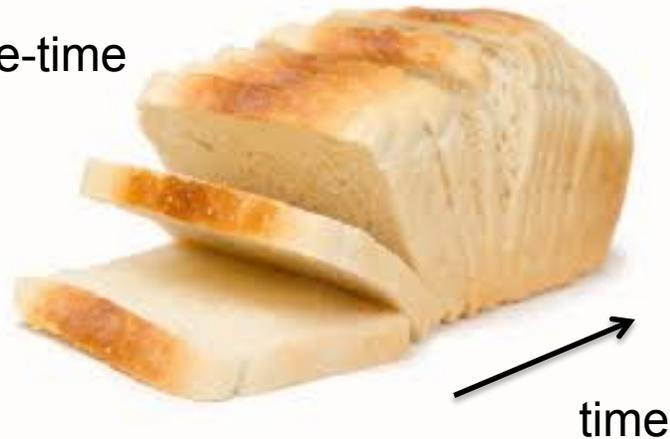
Penrose Weyl tensor hypothesis (1979): $S \sim$ Weyl tensor \leftarrow clumpiness

Vacuum entropy? \longrightarrow Cosmological Constant Problem [O.B. 2021]

Inflation, phase transitions and the cosmological constant, O.B., Gen. Rel. & Grav. 53,11 (2021)

Eternalism or give me a Block Universe

Space-time



Common sense objection: past is gone, present is fleeting, future is not there yet ...

Causality in a Block Universe:

[Broad 1923, McTaggart 1927, ...]

1. Events are causally related;
2. Causal relation is time asymmetric: effects are not yet real at the time of their cause;
3. Event A causes B (is earlier than) ~ an event simultaneous to A causes some event simultaneous to B;
4. Universe is a growing Block

Strong physical objections: time asymmetry and irreversibility

[Elitzur, Dolev 2003, Ellis 2006, Cortês, Smolin 2014, ...]

Specious Present I

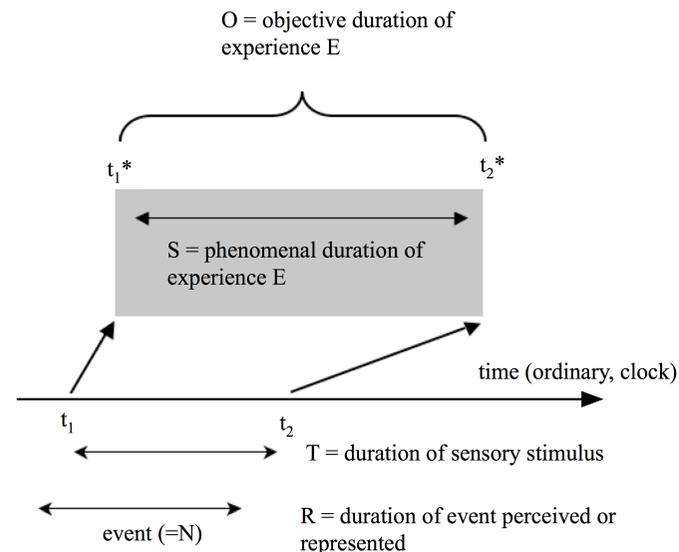
“The relation of experience to time has not been profoundly studied. Its objects are given as being of the present, but the part of time referred to by the datum is a very different thing from the conterminous of the past and future which philosophy denotes by the name Present. The present to which the datum refers is really a part of the past—a recent past—delusively given as being a time that intervenes between the past and the future. Let it be named **the specious present**, and let the past, that is given as being the past, be known as the obvious past.”

Anonymous (E. Robert Kelly), *The Alternative: A Study in Psychology*. London 1882.

[William James 1893, Edmund Husserl 1893-1917, ...]

$$\Delta T_{PP} < 125 \text{ ms}$$

$$\Delta T_{PF} < 45 \text{ ms}$$



Specious Present II

$$\Delta T_{PP} < 125 \text{ ms}$$

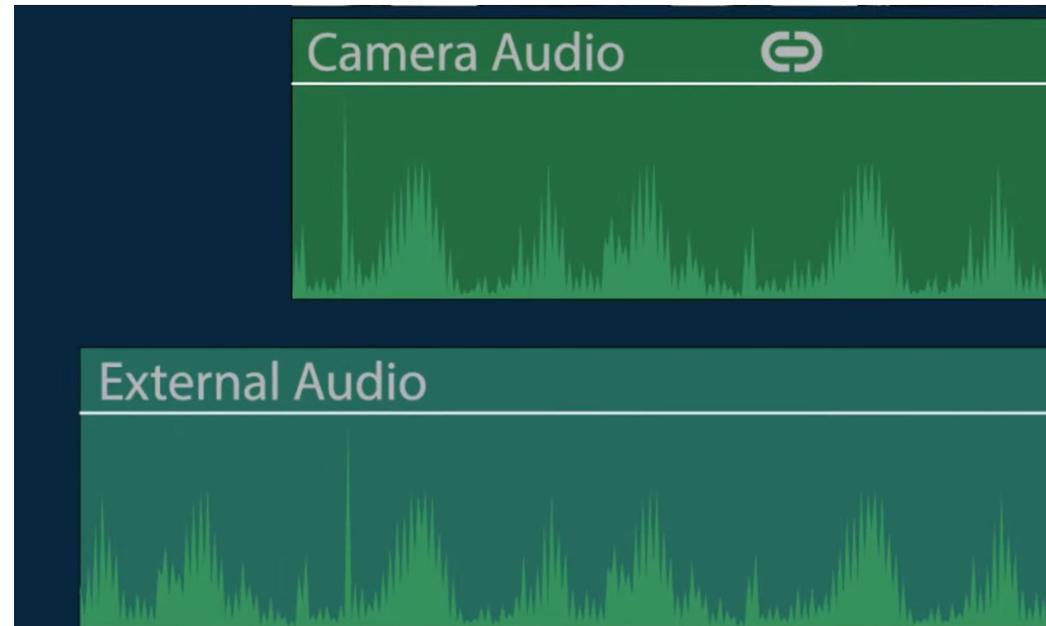
$$\Delta T_{PF} < 45 \text{ ms}$$



Time asymmetry!



Is our brain causally wired or it got, through evolution, adapted to better cope with sensory data?





Some Tentative Conclusions

- Reality is an “effective model” that incorporates the properties of the lower levels of the description arising from the fundamental theories of Physics [molecular (10^{-8}m), atomic (10^{-10}m), nuclear (10^{-15}m), elementary particles (10^{-20}m), ... , quantum gravity (10^{-35}m)]
- Unlike temperature, time and its arrow seem to be fundamental entities, not derivable from any other. If so CTCs (Close Timelike Curves) should not be admissible.
- General Relativity is most likely an effective model. We do not know specifically from which fundamental theory, and as such, CTCs and thus causality violations, should not exist **[O.B. 2012]**
- Does gravity has an associated entropy? Likewise black holes? What is the role of the Weyl tensor? Should one assign an entropy to the vacuum?
- A veto for CTCs must arise from Quantum Gravity, which has to be incorporated into the associated effective theories. If so CTCs should be forbidden by a symmetry or by a set of symmetries still to be identified

Muito Obrigado!

Thank you!

Grazie mille!

Merci beaucoup!

!Muchas gracias!

Vielen Danke!

谢谢你!

תודה רבה!

The Dry Salvages

... "Fare forward, travellers! Not escaping from the past
Into indifferent lives, or into any future;
You are not the same people who left that station
Or who will arrive at any terminus,
While the narrowing rails slide together behind you;
And on the deck of the drumming liner
Watching the furrow that widens behind you,
You shall not think 'the past is finished'
Or 'the future is before us' ...

Fare forward, you who think that you are voyaging;
You are not those who saw the harbour
Receding, or those who will disembark.
Here between the hither and the farther shore
While time is withdrawn, consider the future
And the past with an equal mind ...

But fare forward, voyagers." ...

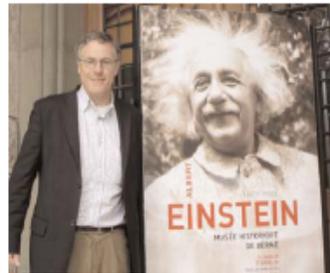
T.S. Eliot (1941)

See also:

O Universo é o livro de todas as escolhas cósmicas, o registo de todos os acontecimentos que cinzelam o corpo do cosmos. Cosmos em contínuo estado de transformação, global e local, que é o nosso porto de abrigo e o oceano das indagações cósmicas da civilização humana.

Uma narrativa sobre a história do Universo é necessariamente uma história das ideias, descobertas e técnicas que conduziram ao estágio actual do conhecimento científico sobre o Universo. Assim, o Livro das Escolhas Cósmicas é também um relato do esforço da humanidade para entender o cosmos, dos mitos da criação à revolução científica, desta às descobertas da radiação cósmica de fundo e da aceleração da expansão do Universo. Descobertas estas que conduziram ao desenvolvimento das ideias mais recentes sobre a origem e evolução do Universo tais como os mundos-membrana, a inflação, a matéria escura, a energia escura e que convivem com objectos e ocorrências igualmente extraordinárias como os buracos negros, os núcleos activos de galáxias, as explosões de raios gama, etc.

Orfeu Bertolami nasceu em São Paulo, Brasil, em 1959. Licenciado em Física pela Universidade de São Paulo em 1980, obteve o mestrado no Instituto de Física Teórica em São Paulo em 1983, o Grau Avançado em Matemática na Universidade de Cambridge em 1984 e o doutoramento em física teórica na Universidade de Oxford em 1987.



Desenvolveu actividades de investigação no Institut für Theoretische Physik em Heidelberg, na Alemanha, no Centro Europeu de Investigação Nuclear (CERN) em Genebra, na secção de Turim do Istituto Nazionale de Fisica Nucleare e na Universidade de Nova Iorque. É Professor Associado no Departamento de Física do Instituto Superior Técnico, onde leciona desde 1991. Obteve a Agregação pela Universidade Técnica de Lisboa em 1996.

Publicou mais de 130 artigos científicos, em livros, jornais, actas de conferências e revistas especializadas nas áreas da astrofísica, cosmologia, gravitação quântica e em teorias de cordas. Já apresentou cerca de duas dezenas de palestras convidadas em conferências internacionais e quase duas centenas de seminários especializados em universidades e centros de investigação na Europa, na Rússia, na Coreia, no Japão, no Brasil, na Argentina e nos Estados Unidos. Tem participado em actividades de divulgação apresentando dezenas de palestras sobre temas como a unificação das interacções fundamentais, o Big Bang, explosões de raios gama, a origem da vida no Universo, ciência e literatura, a vida e a obra de Albert Einstein, entre outros.

Foi galardoado com o terceiro prémio da Gravity Research Foundation dos Estados Unidos em 1999 e com o Prémio União Latina de Ciência em 2001. Colabora em projectos europeus de estudo da física da matéria escura e da energia escura, com a Agência Espacial Europeia e com o Jet Propulsion Laboratory da NASA na Califórnia.

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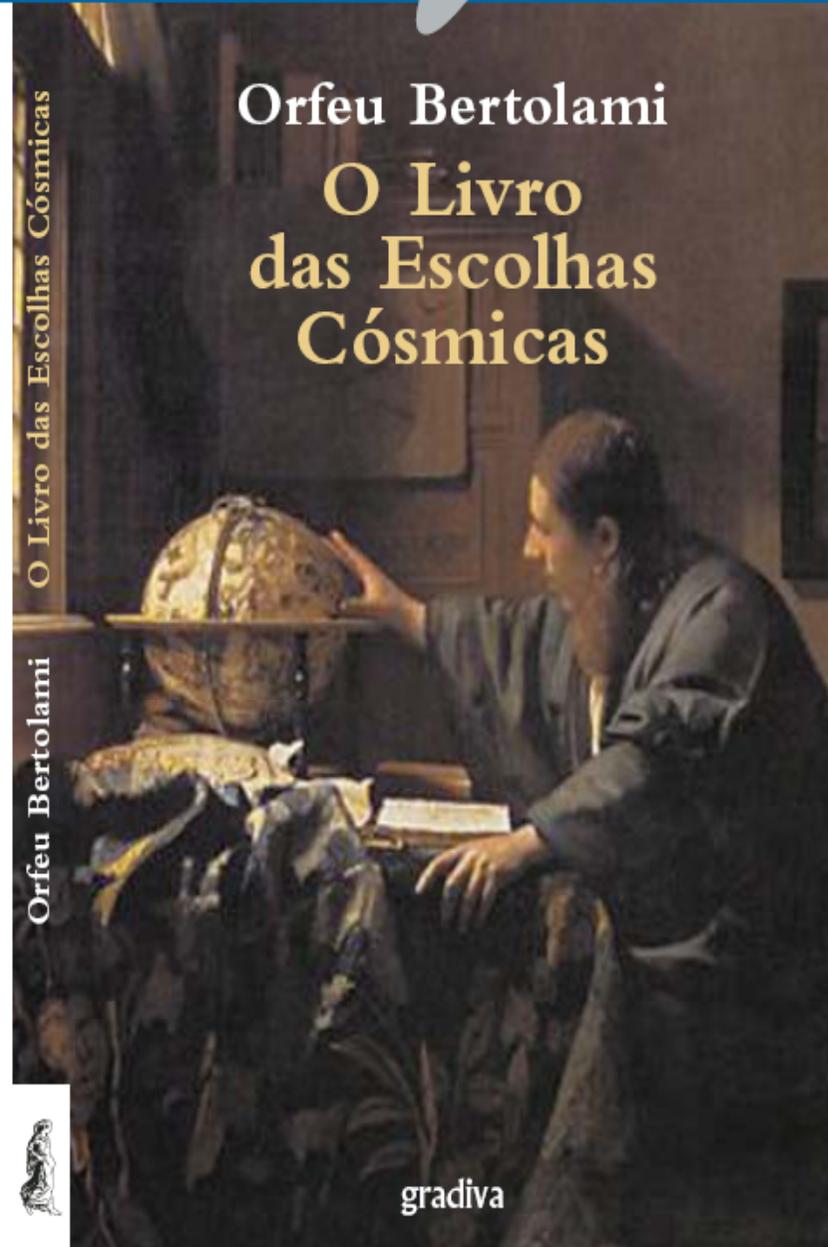
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O Livro das Escolhas Cósmicas

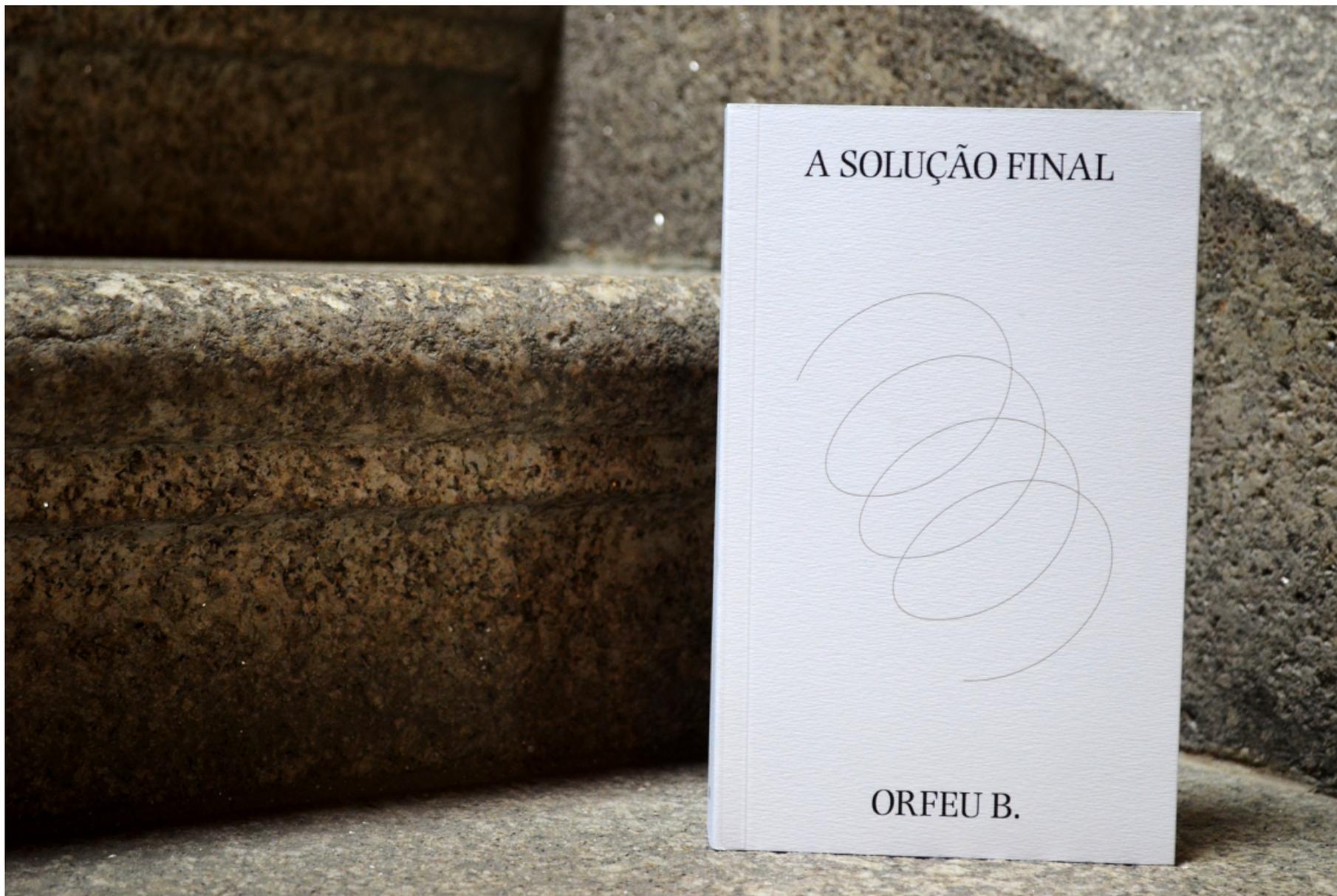
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See also:





Ruben Anselmo
Time is now