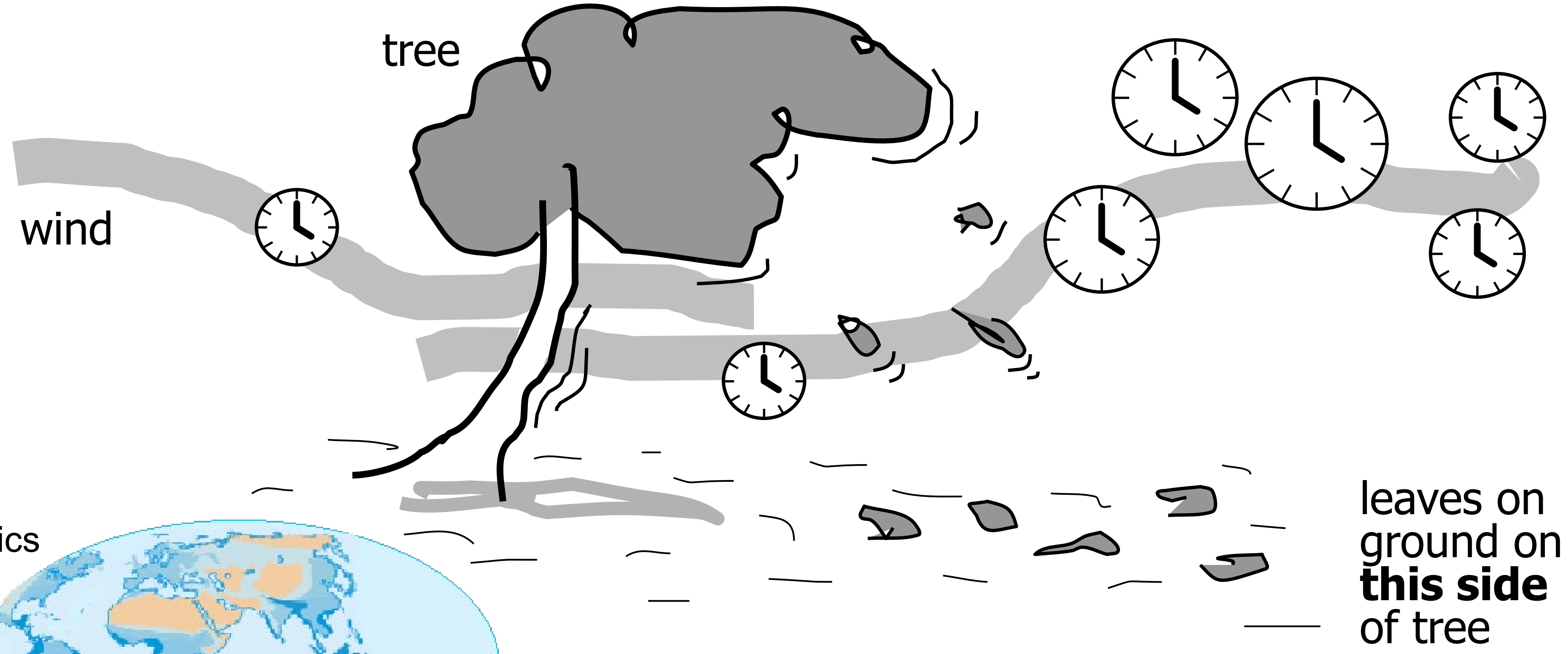
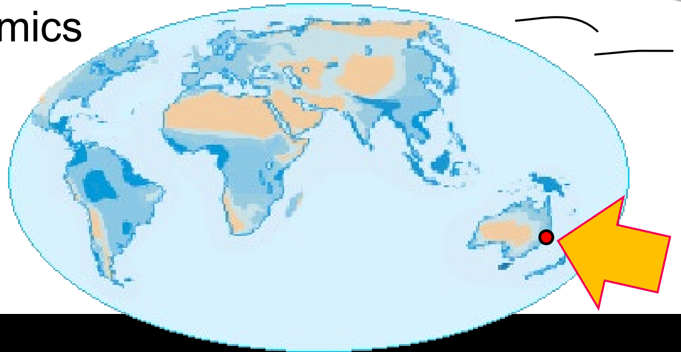
The quantum theory of time: from formalism to experimental test



Toshio Croucher
Joan Vaccaro
Centre for Quantum Dynamics
Griffith University
Brisbane
Australia



Griffith UNIVERSITY

Vaccaro, *Proc. R. Soc. A* **472**, 20150670 (2016)

Quantum asymmetry between time and space

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FEATURE 1 February 2017

One time or another: Our best 5 theories of the fourth dimension

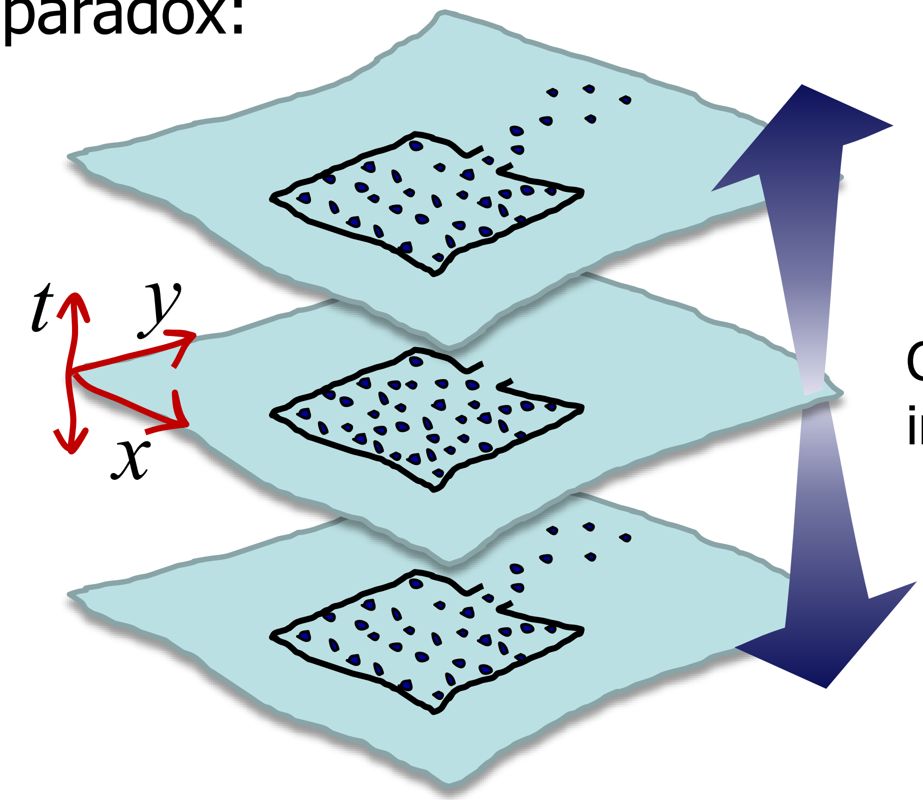
What is time and why does time flow? Is it just an illusion? Answering these questions is still one of physics' greatest challenges

Anthony Harvie/Getty

By Anil Ananthaswamy

Entropy & matter anomalies

Recall Loschmidt's paradox:



Evolving "upwards" in time:
– **entropy increases**.

Consider a gas with N, T, P, & V known, in a container that has a leak.

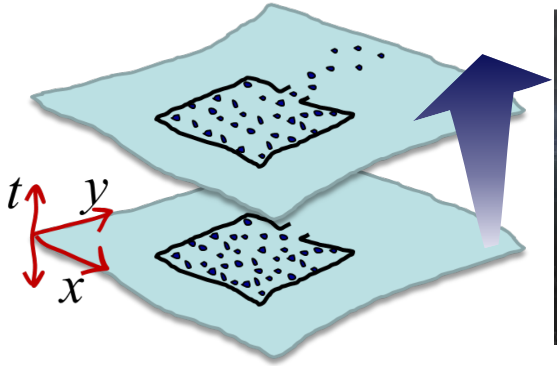
Evolving "downwards" in time:
– **entropy increases**.

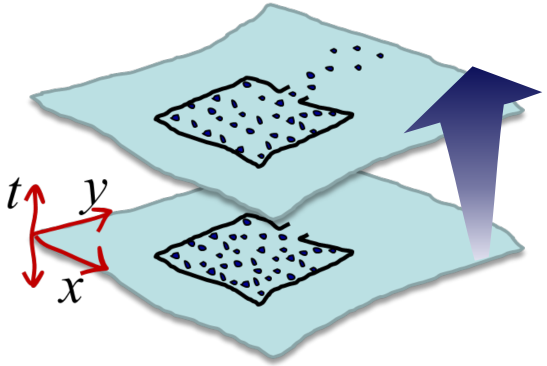
Symmetry is due to **time symmetric dynamical laws.**

We take entropy increase as **evidence** of the "direction of time evolution" or "direction of time" for short.

Empirical evidence:

all space and time has a consistent direction of entropy increase:





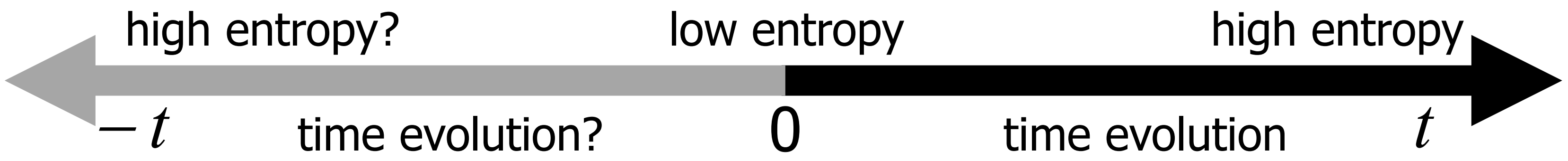
effects

direction of **entropy increase**

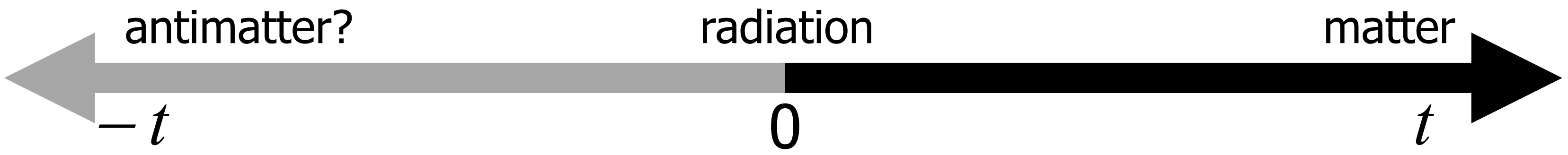
direction of **time evolution**

causes

From Loschmidt's paradox, expect symmetry in time:



Similarly, expect symmetry in matter and antimatter:

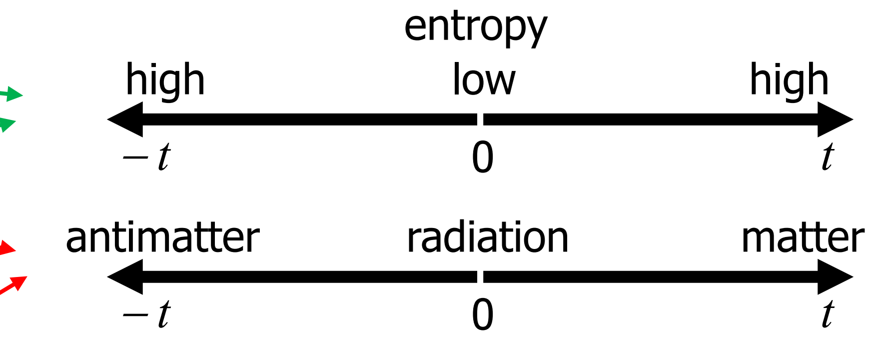


There is no external reference for the direction of time.
So the universe must be **time symmetric overall**.

These are the **entropy** and **matter-antimatter anomalies**.

Proposed resolutions:

- 2004 Carrol & Chen hep-th/0410270
- 2011 Vaccaro Found Phys **41,** 1596
- 2014 Barbour, Koslowski & Mercati Phys Rev Lett **113** 181101 (2014)
- 2018 Boyle, Finn & Turok Phys Rev Lett **121** 251301 (2018)



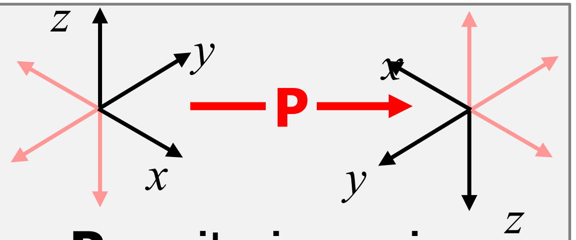
T violation anomaly

Recall the discrete symmetries:

$p \;\; n \;\; K^0$, $e^- \;\; \nu \;\; B^0$ —**C**→ $\bar{p} \;\; \bar{n} \;\; \bar{K}^0$, $e^+ \;\; \bar{\nu} \;\; \bar{B}^0$

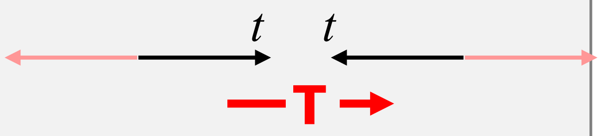
C charge conjugation

particle $\leftrightarrow$ antiparticle



P parity inversion

$x \leftrightarrow -x$
$y \leftrightarrow -y$
$z \leftrightarrow -z$



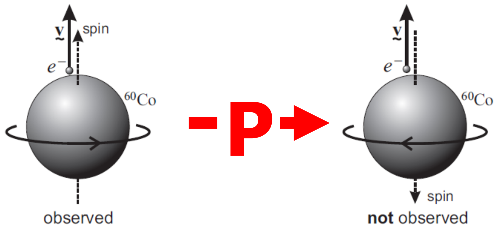
T time reversal

$t \;\leftrightarrow\; -t$

History:

P violation Lee & Yang 1956

β⁻ decay in ^{60}Co



Wu's experiment

CP violation Cronin & Fitch 1964

K^0 decay

$$K_L^0 \rightarrow \pi^+\pi^-$$

$$\underbrace{(K_-^0}_{CP=-1} + \underbrace{\epsilon K_+^0)}_{CP=+1} \neq \underbrace{\pi^+\pi^-}_{CP=+1}$$

T violation BarBar, SLAC 2012

B^0 decay

—**T**→

$$\bar{B}^0 \rightarrow B_- \;\neq\; B_- \rightarrow \bar{B}^0$$

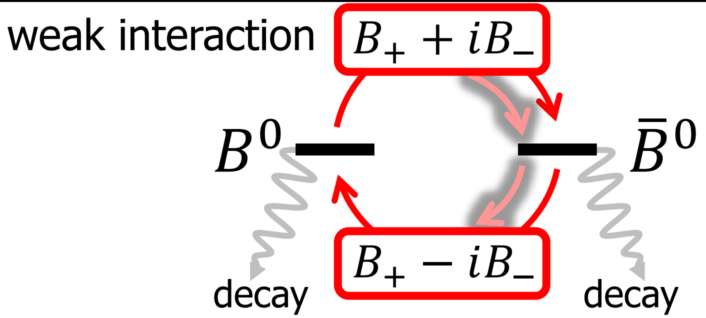
T violation in B⁰ system

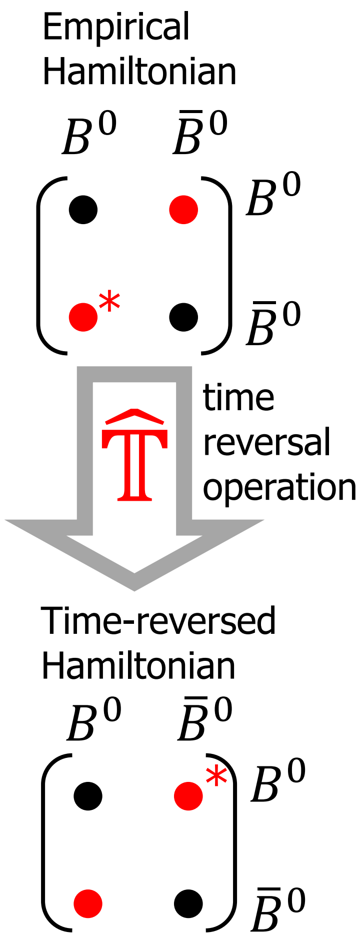
Experiment: BarBar Collaboration, SLAC, Stanford University

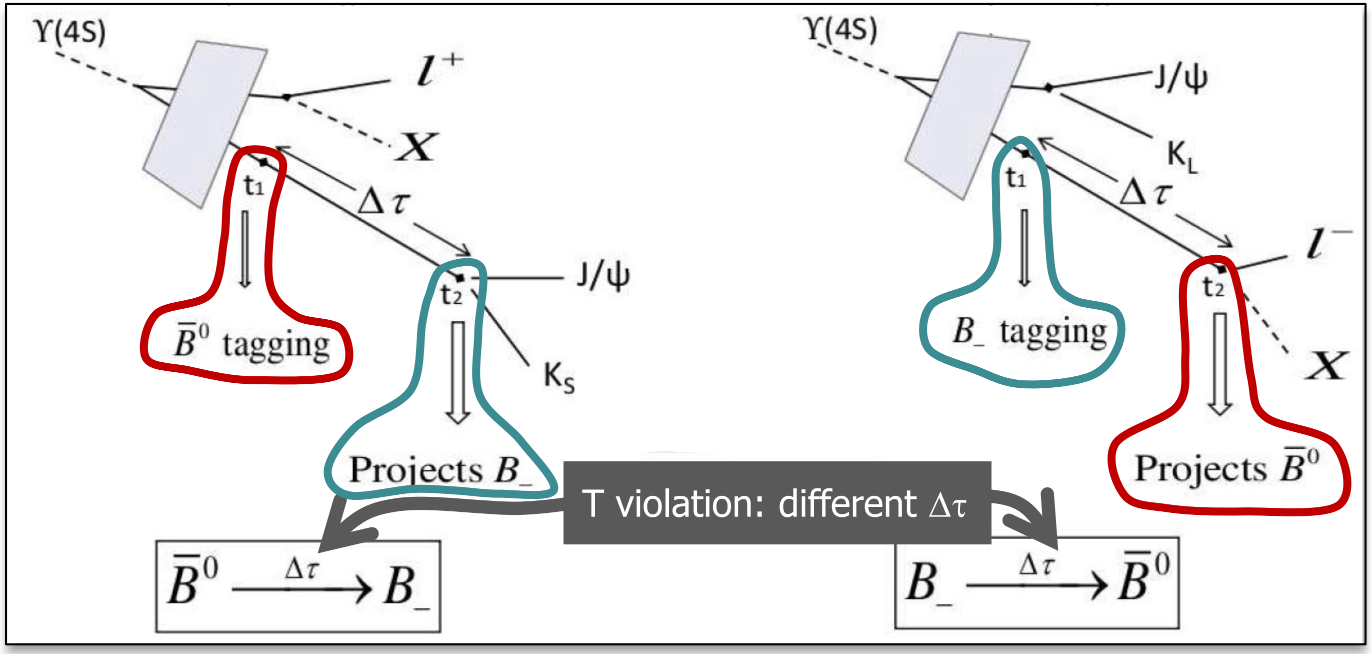
J. P. Lees et al., Phys. Rev. Lett. 109, 211801 (2012).

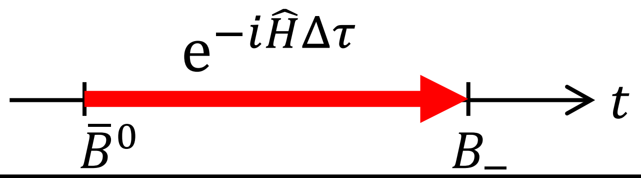
Detailed description:

Bernabeu et al, JETP Lett. 2012, 64 (2012).









T violation implies **2 Hamiltonians** and 2 dynamics – one for each direction of time.

Physical theory needs to account for **both Hamiltonians.**

Conventional physical theories have a **single version of the Hamiltonian** and the time evolution it describes (into the future, by default).

This is the **T violation anomaly**

Proposed resolution:
The quantum theory of time

Phil. Tras. A **376**, 20170316 (2018).

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Opinion piece

The quantum theory of time, the block universe, and human experience

Joan A. Vaccaro

Centre for Quantum Dynamics, Griffith University, Nathan 4111, Australia

JAV, 0000-0003-4576-9545

2018 The
block universe,
Trans. R. Soc. A
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molecular

Advances in our understanding of the physical universe have dramatically affected how we view ourselves. Right at the core of all modern thinking about the universe is the assumption that dynamics is an elemental feature that exists without question. However, ongoing research into the quantum nature of time is challenging this view: my recently introduced quantum theory of time suggests that dynamics may be a phenomenological consequence of a fundamental violation of time reversal symmetry. I show here that there is consistency between the new theory and the block universe view. I also discuss the new theory in relation to the human experience of existing in the present moment, able to reflect on the past and contemplate a future that is yet to happen.

arXiv: 1605.01965

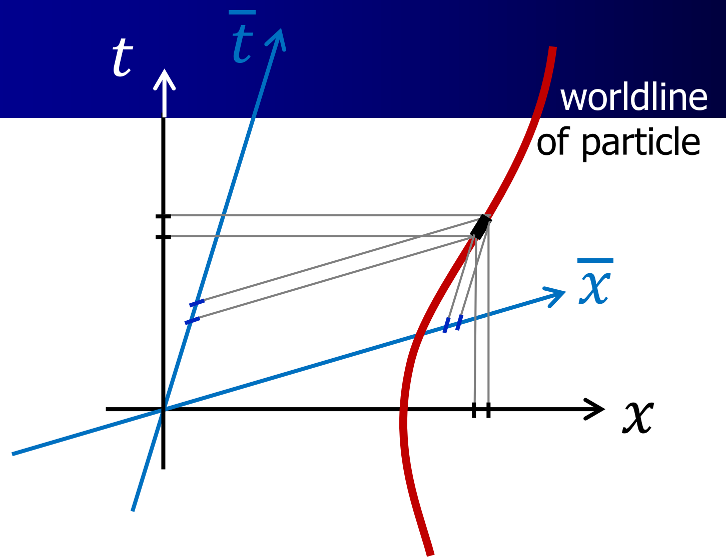
Chapter 15
An Anomaly in Space and Time and the Origin of Dynamics

Joan A. Vaccaro

Abstract The Hamiltonian defines the dynamical properties of the universe. Evidence from particle physics shows that there is a different version of the Hamiltonian for each direction of time. As there is no physical basis for the universe to be asymmetric in time, both versions must operate equally. However, conventional physical theories accommodate only one version of the Hamiltonian and one direction of time. This represents an unexplained anomaly in conventional physics and calls for a reworking of the concepts of time and space. Here I explain how the anomaly can be resolved by allowing dynamics to emerge phenomenologically. The resolution offers a picture of time and space that lies below our everyday experience, and one in which their differences are epiphenomenal rather than elemental.

Invited Chapter in book:
S. Wuppuluri, G. Ghirardi Eds,
"Space, Time and the Limits of Human Understanding"
(Springer International, 2016) 185-201

Quantum theory of time



Space-time background itself:

- **space** and **time** are essentially **interconvertible**

$$ds^2 = dt^2 - dx^2 - dy^2 - dz^2$$
$$= d\bar{t}^2 - d\bar{x}^2 - d\bar{y}^2 - d\bar{z}^2$$

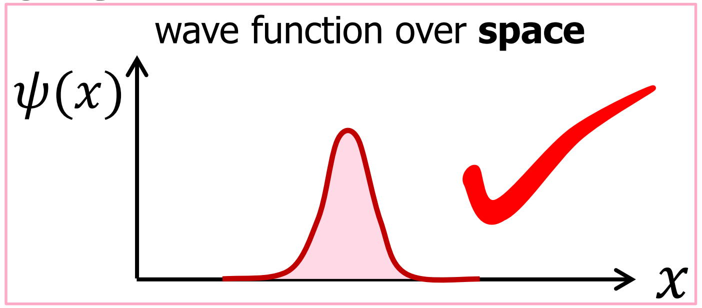
Things on space-time background:

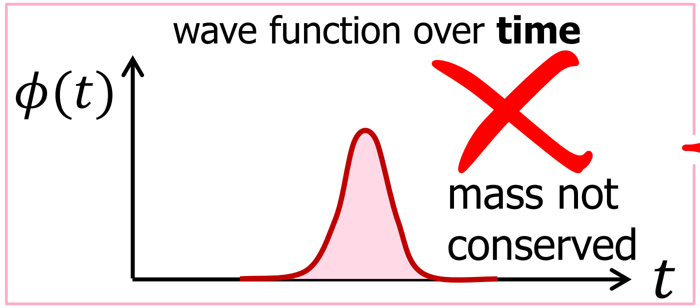
Dynamics (relativistic, quantum, classical):
- defines translations over **time** but not **space**.

Conservation laws (energy, momentum, lepton #,...):
- apply over **time** but not over **space**.

} treat as a **phenomenological**

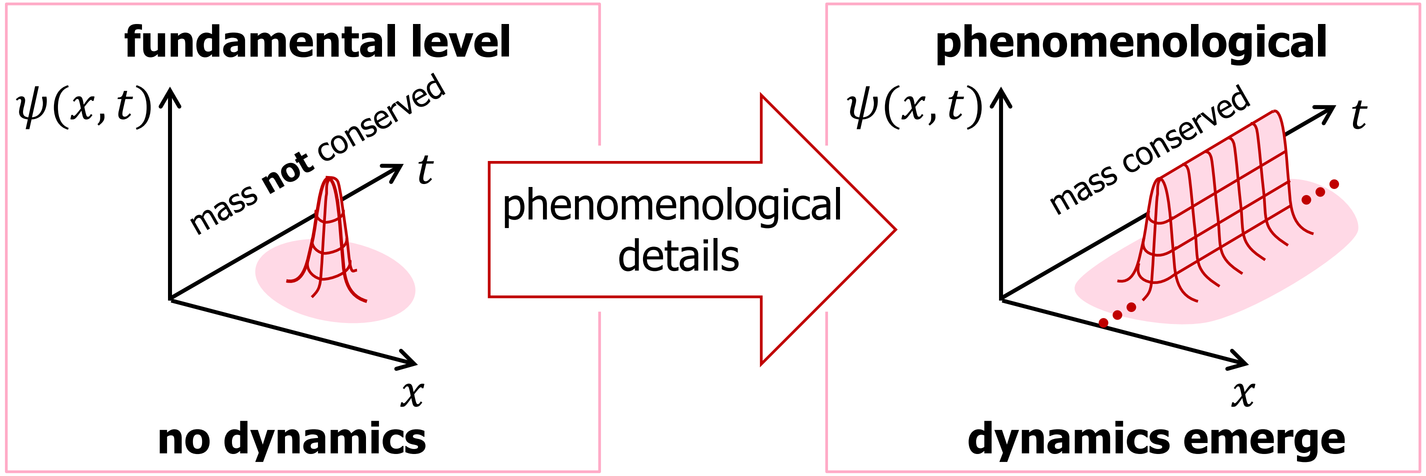
e.g. **Quantum Mechanics**:





{ **why not this?**

The idea is this:



Need to look at **phenomenology** of generators of **translations** in space and time:

- the **Hamiltonian** generates translations in **time**

$$e^{+i\hat{\mathbb{T}}\hat{H}\hat{\mathbb{T}}^{-1}t} \qquad e^{-i\hat{H}t} \qquad t$$

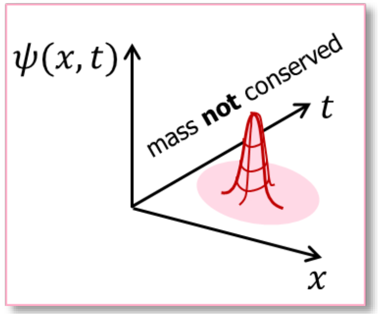
- the **momentum** operator generates translations in **space**

$$e^{+i\hat{P}x} \qquad e^{-i\hat{P}x} \qquad x$$

C,P,T discrete symmetries are violated by the <u>Hamiltonian</u> only!

Four principles

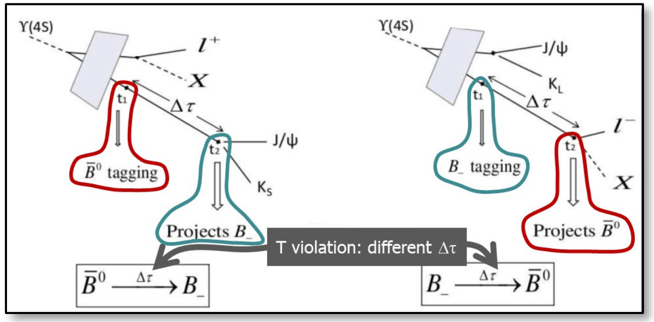
Vaccaro, *Phil. Trans. Roy. Soc. A* **376**, 20170316 (2018).



1. States have same construction in time and space

Retain the symmetry of the space time background

2. Time evolution is directional



$\hat{H}_F \equiv \hat{H},\qquad e^{-i\hat{H}_F\delta t}\qquad$ "forwards"

$\hat{H}_B \equiv \hat{\mathbb{T}}\hat{H}\hat{\mathbb{T}}^{-1},\qquad e^{i\hat{H}_B\delta t}\qquad$ "backwards"

time evolution
physical dynamics $\equiv$ **causality**

"backwards" $e^{i\hat{H}_B\delta t}$ ← → $e^{-i\hat{H}_F\delta t}$ "forwards"

t

$e^{-i\hat{H}_B\delta t}$ $\qquad$ $e^{i\hat{H}_F\delta t}$

mathematical inverses $\equiv$ **rewind**

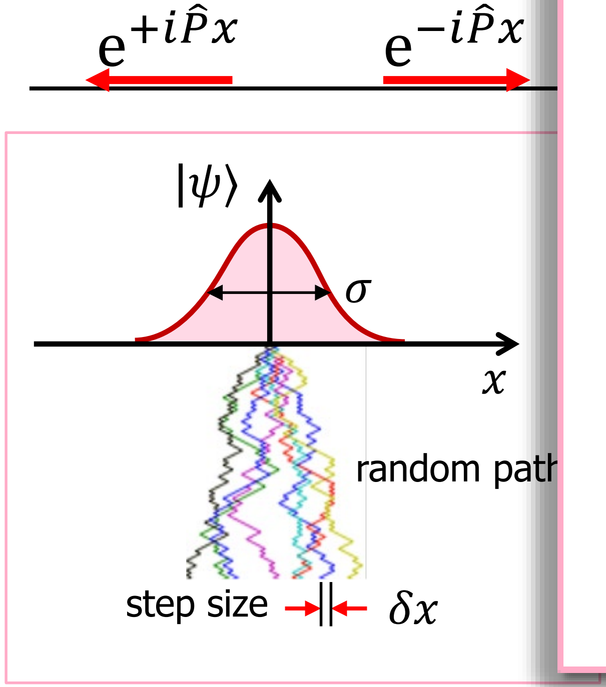
3. Fundamental resolution limit

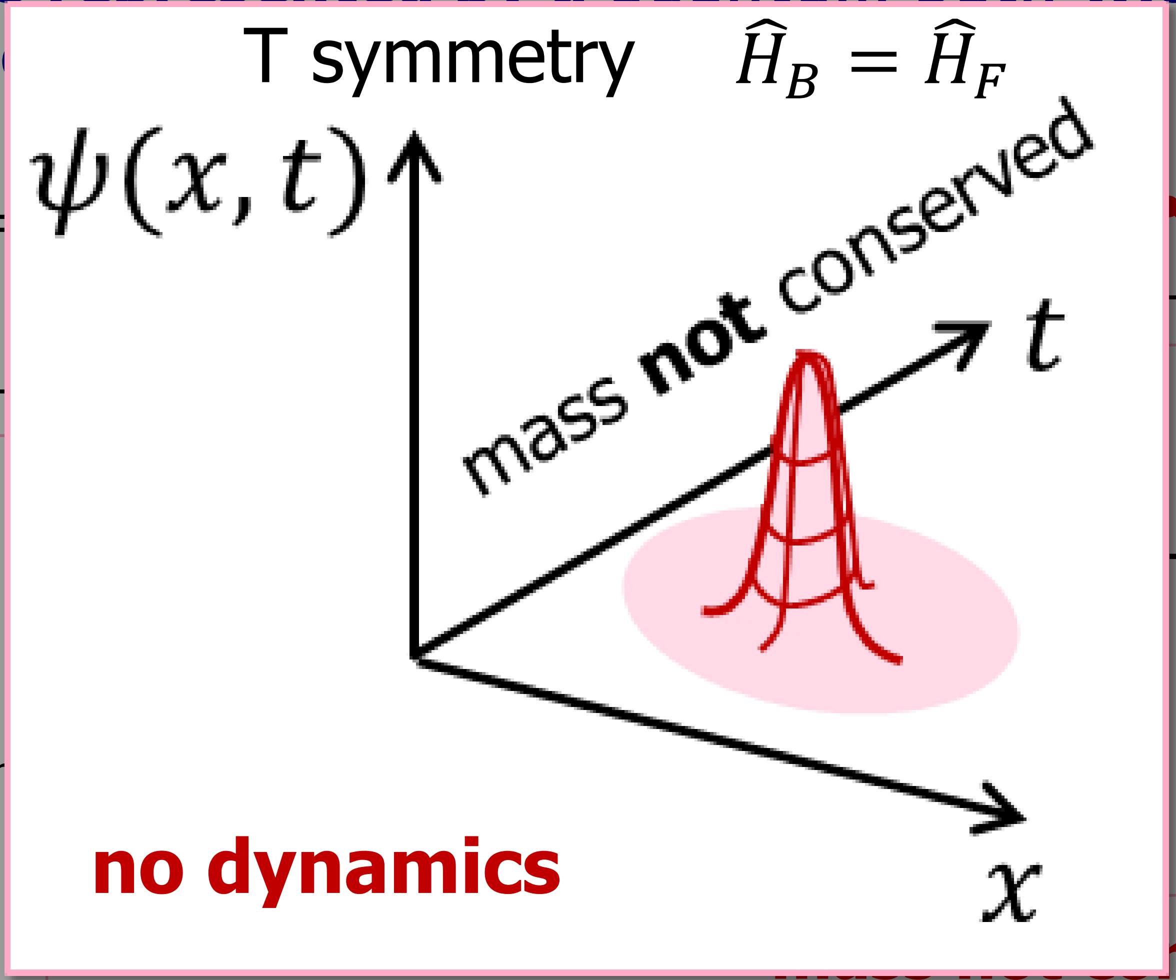
E.g. Planck scale, or other limit (the actual limit is not important)

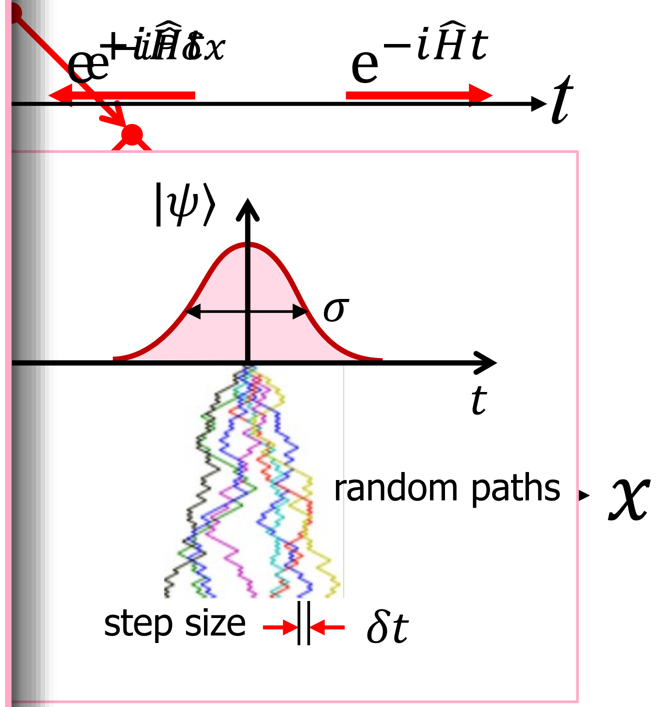
4. A state is represented by a *quantum path* with step sizes bel

Space:

$|\psi\rangle_N =$







nserved, no dynamics

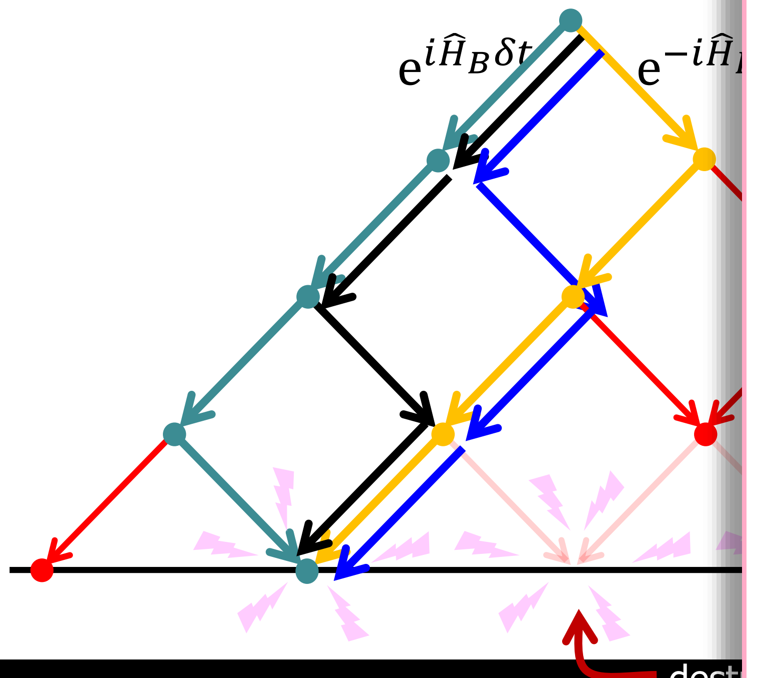
T violation

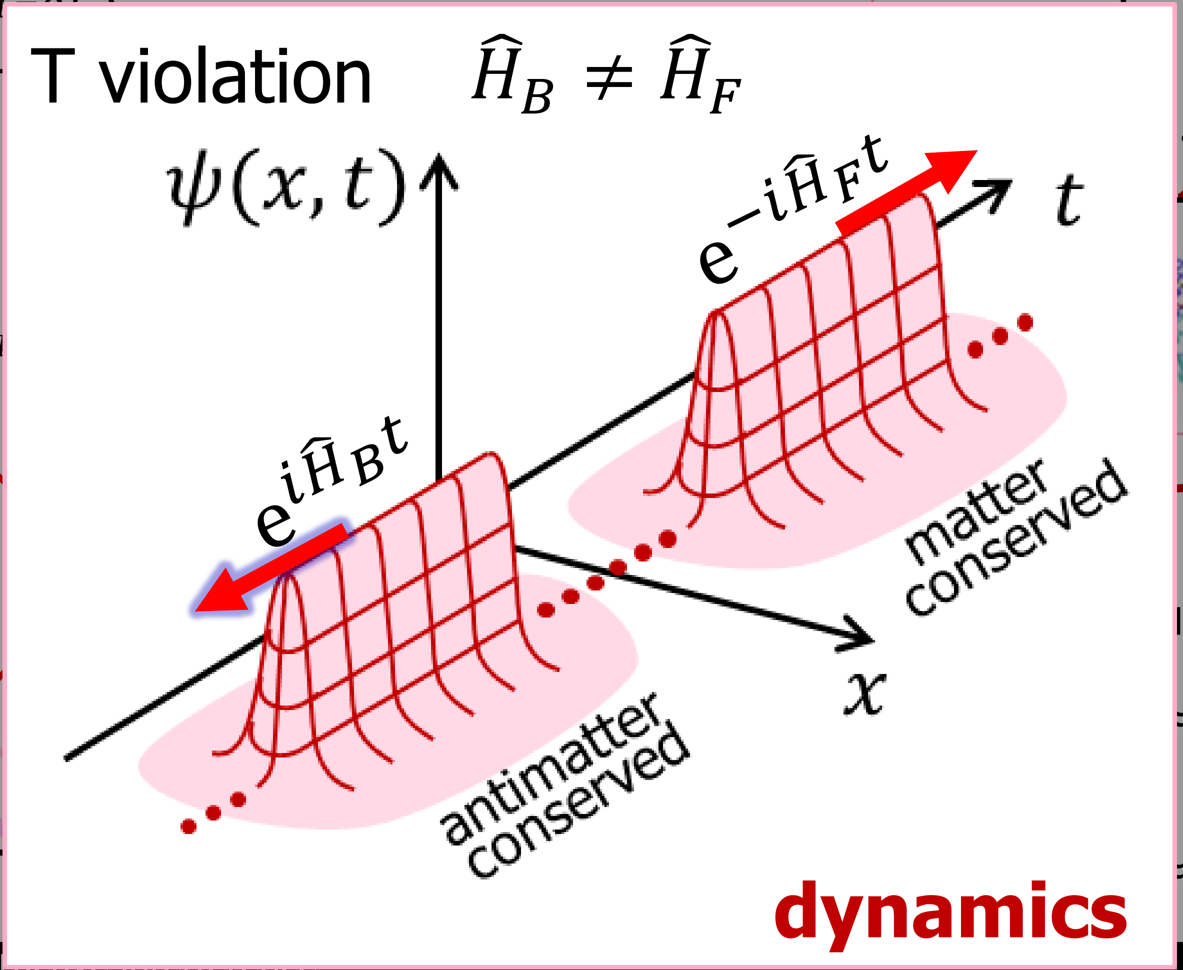
$$\left[\hat{H}_B, \hat{H}_F\right] = i\lambda\hat{\mathbb{I}}$$

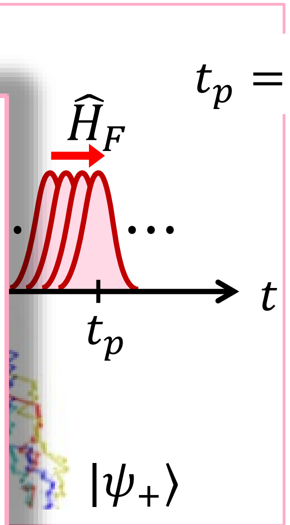
Get **interference** between different paths to the same point in time.

$$|\psi\rangle_N = \left(\frac{e^{i\hat{H}_B\delta t} + e^{-i\hat{H}_F\delta t}}{2}\right)^N$$

$$\delta t = \frac{\sigma_T}{\sqrt{N}}$$







$$t_p = \frac{2\pi\sqrt{n}}{\sigma\lambda}$$

ations

$\approx -i\hat{H}_F\,|\psi_+(t)\rangle$

$\approx -i\hat{H}_B\,|\psi_-(t)\rangle$

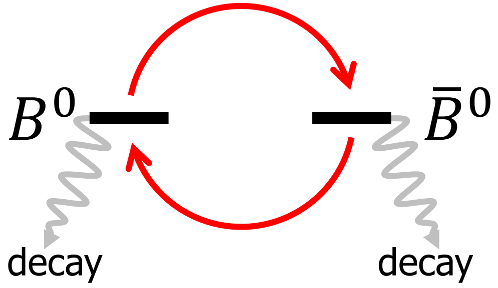
Sources of T violation

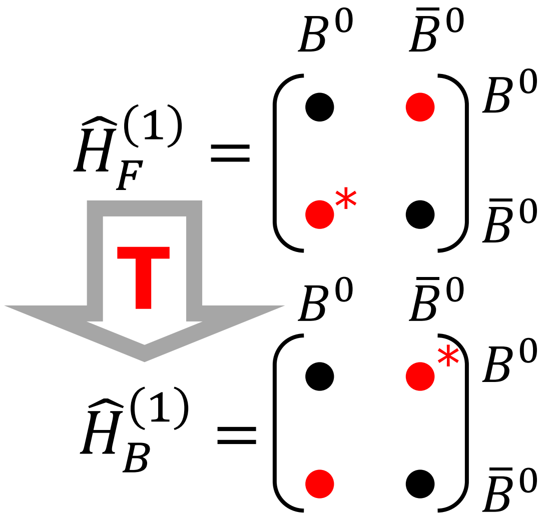
Croucher & Vaccaro, in preparation (2019)

Mesons $K^0, \bar{K}^0 \quad B^0, \bar{B}^0$

Particle and antiparticle mixing:

weak interaction





Branco, Silva & Lavoura *CP Violation* (1999)

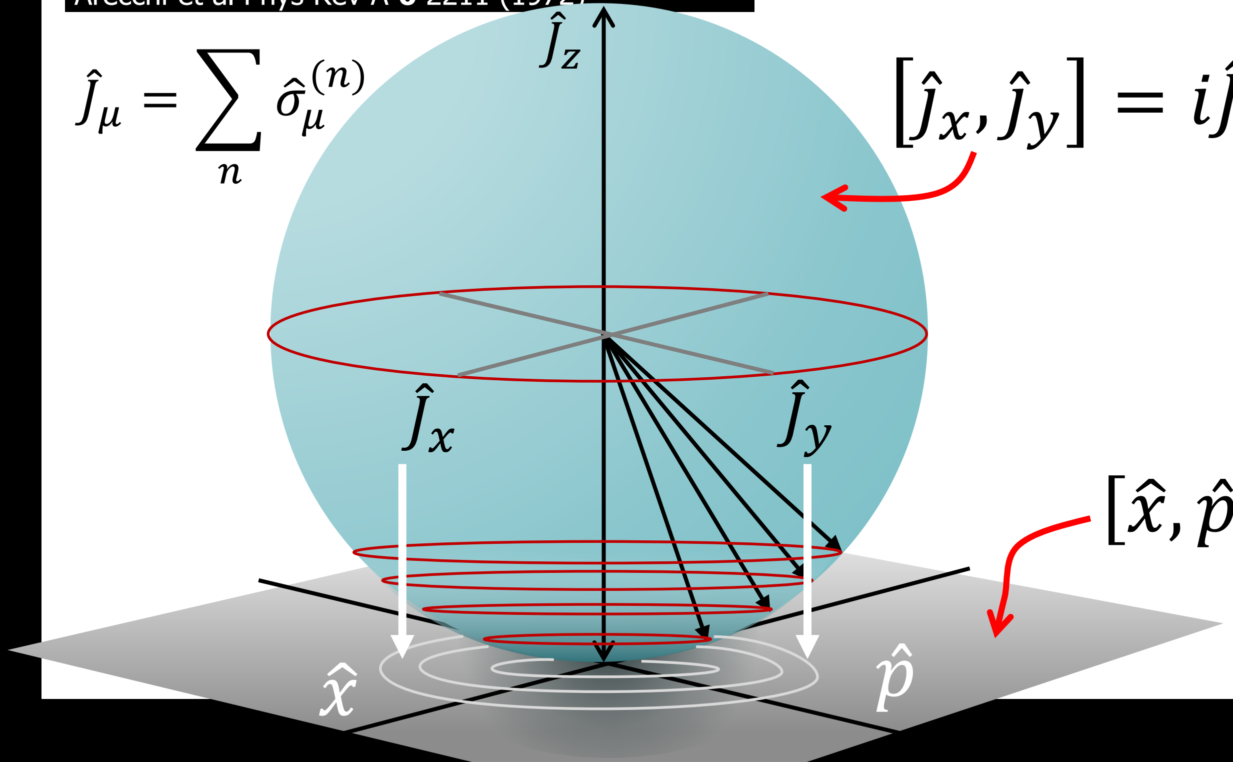
Many particles
→ group contraction
→ harmonic oscillator:

$\hat{J}_- \rightarrow \hat{a}$
$\hat{J}_+ \rightarrow \hat{a}^\dagger$

Inonu & Wigner P Natl Acad Sci USA **39** 510 (1953)
Arecchi et al Phys Rev A **6** 2211 (1972)

$$\hat{J}_\mu = \sum_n \hat{\sigma}_\mu^{(n)}$$

$$[\hat{J}_x, \hat{J}_y] = i\hat{J}_z$$



$$[\hat{x}, \hat{p}] = i\hat{\mathbb{I}}$$

$$\hat{H}_F^{(N)} = \omega \hat{a}^\dagger \hat{a} + \sqrt{N}\boldsymbol{\alpha}\hat{a} + \sqrt{N}\boldsymbol{\alpha}^*\hat{a}^\dagger$$
$$\hat{H}_F^{(N)} = \omega \hat{a}^\dagger \hat{a} + \sqrt{N}\boldsymbol{\alpha}^*\hat{a} + \sqrt{N}\boldsymbol{\alpha}\hat{a}^\dagger$$

$$\left[\hat{H}_F^{(N)}, \hat{H}_B^{(N)}\right]_{N \gg \omega} \approx i\, N|\boldsymbol{\alpha}|^2 \hat{\mathbb{I}}$$

Neutrinos

Nunokawa Prog. Part. Nucl. Phys. **60** 338 (2008)

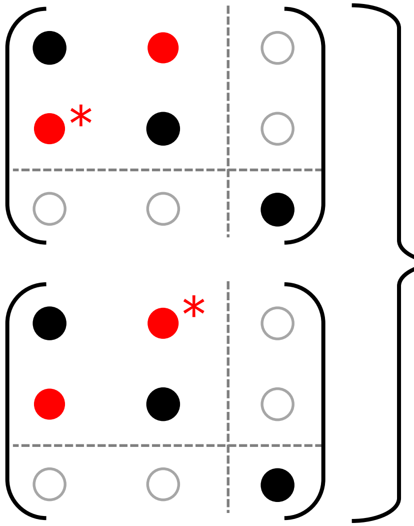
Suspected of violating CP and T symmetries

Flavour mixing:

$$\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \hat{H}^{(1)}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

In rotated Flavour basis:

$\hat{H}_F^{(1)} =$, $\hat{H}_B^{(1)} =$



2D subspace is just like mesons

$$\left[\hat{H}_F^{(N)}, \hat{H}_B^{(N)}\right]_{N\gg 1} \approx i\, N|\alpha|^2\hat{\mathbb{I}}$$

Higgs-like scalar field

Branco *et al., Phys Rep.,* **516**, 1 (2012)

Spontaneous symmetry breaking:

CP & T violation arises in 2 or more doublet models

Explicit symmetry breaking in scalar field:

$$\hat{\mathcal{H}} = \hat{\pi}^2 + \left(\nabla\hat{\phi}\right)^2 + m^2\hat{\phi}^2 + \boldsymbol{a}\hat{\phi} + \boldsymbol{b}\hat{\pi}$$

zero momentum mode

$$\hat{H}_{0F} = m\hat{a}_0^\dagger\hat{a}_0 + \boldsymbol{\alpha}\hat{a}_0 + \boldsymbol{\alpha}^*\hat{a}_0^\dagger$$

$$\hat{H}_{0B} = m\hat{a}_0^\dagger\hat{a}_0 + \boldsymbol{\alpha}^*\hat{a}_0 + \boldsymbol{\alpha}\hat{a}_0^\dagger$$

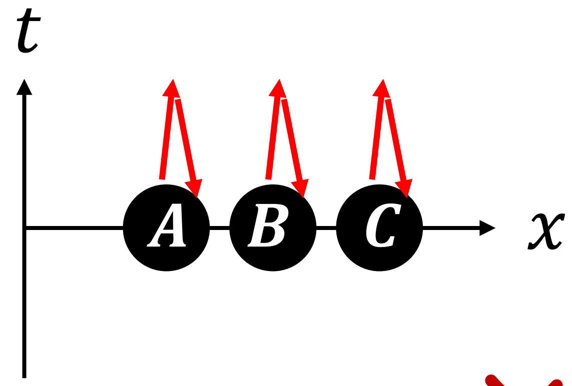
$$\left[\hat{H}_{0F}, \hat{H}_{0B}\right]_{|\alpha|\gg m} \approx i\,|\boldsymbol{\alpha}|^2\hat{\mathbb{I}}$$

Experimental test

Vaccaro, in preparation (2019)

Spatial distribution – T symmetry case

$$\hat{\boldsymbol{H}}^2 = (\hat{H}_A + \hat{H}_B + \hat{H}_C)^2 \Rightarrow e^{-\frac{\hat{\boldsymbol{H}}^2\sigma^2}{2}} = \lim_{N\to\infty}\left(\frac{e^{\frac{i\hat{\boldsymbol{H}}\sigma}{\sqrt{N}}} + e^{-\frac{i\hat{\boldsymbol{H}}\sigma}{\sqrt{N}}}}{2}\right)^N \Rightarrow$$

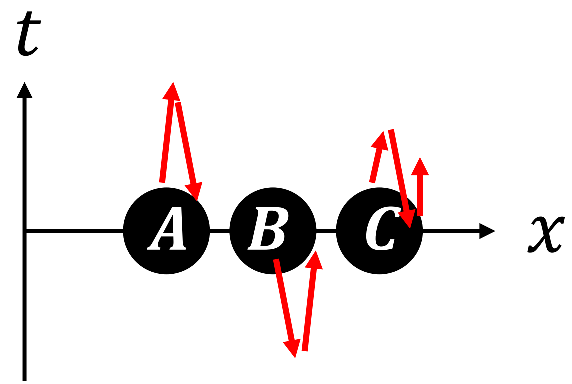


correlated fluctuations ✗

$$\hat{H}_A^2 + \hat{H}_B^2 + \hat{H}_C^2$$

$$\Rightarrow e^{-\frac{(\hat{H}_A{}^2 + \hat{H}_B{}^2 + \hat{H}_C{}^2)\sigma^2}{2}} = e^{-\frac{\hat{H}_A{}^2\sigma^2}{2}} e^{-\frac{\hat{H}_B{}^2\sigma^2}{2}} e^{-\frac{\hat{H}_C{}^2\sigma^2}{2}}$$

$$\left(\frac{e^{\frac{i\hat{\boldsymbol{H}}_A\sigma}{\sqrt{N}}} + e^{-\frac{i\hat{\boldsymbol{H}}_A\sigma}{\sqrt{N}}}}{2}\right)^N \left(\frac{e^{\frac{i\hat{\boldsymbol{H}}_B\sigma}{\sqrt{N}}} + e^{-\frac{i\hat{\boldsymbol{H}}_B\sigma}{\sqrt{N}}}}{2}\right)^N \left(\frac{e^{\frac{i\hat{\boldsymbol{H}}_C\sigma}{\sqrt{N}}} + e^{-\frac{i\hat{\boldsymbol{H}}_C\sigma}{\sqrt{N}}}}{2}\right)^N \Rightarrow$$



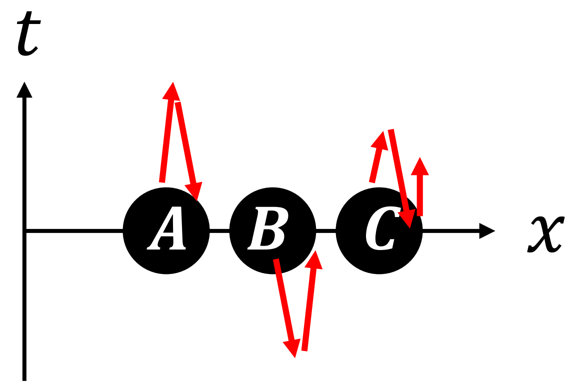
independent fluctuations
but no interactions ✗

$$\hat{H}_A^2 + \hat{H}_B^2 + \hat{H}_C^2 = \frac{1}{3}\left(\hat{H}_A + \hat{H}_B + \hat{H}_C\right)^2 + \frac{1}{3}\left(\hat{H}_A - \hat{H}_B\right)^2 + \frac{1}{3}\left(\hat{H}_B - \hat{H}_C\right)^2 + \frac{1}{3}\left(\hat{H}_A - \hat{H}_C\right)^2$$

$$\left(\frac{\mathrm{e}^{\frac{i\frac{1}{3}(\hat{\boldsymbol{H}}_A + \cdots)\sigma}{\sqrt{N}}} + \mathrm{e}^{-\frac{i\frac{1}{3}(\hat{\boldsymbol{H}}_A + \cdots)\sigma}{\sqrt{N}}}}{2}\right)^N \left(\frac{\mathrm{e}^{\frac{i\frac{1}{3}(\hat{\boldsymbol{H}}_A - \hat{\boldsymbol{H}}_B)\sigma}{\sqrt{N}}} + \mathrm{e}^{-\frac{i\frac{1}{3}(\hat{\boldsymbol{H}}_A - \hat{\boldsymbol{H}}_B)\sigma}{\sqrt{N}}}}{2}\right)^N \left(\frac{\mathrm{e}^{\frac{i\frac{1}{3}(\hat{\boldsymbol{H}}_B - \hat{\boldsymbol{H}}_C)\sigma}{\sqrt{N}}} + \mathrm{e}^{-\frac{i\frac{1}{3}(\hat{\boldsymbol{H}}\cdots}{}}}{2}\right.$$

allows interactions

allows independent fluctuations



independent fluctuations,
with interactions ✓

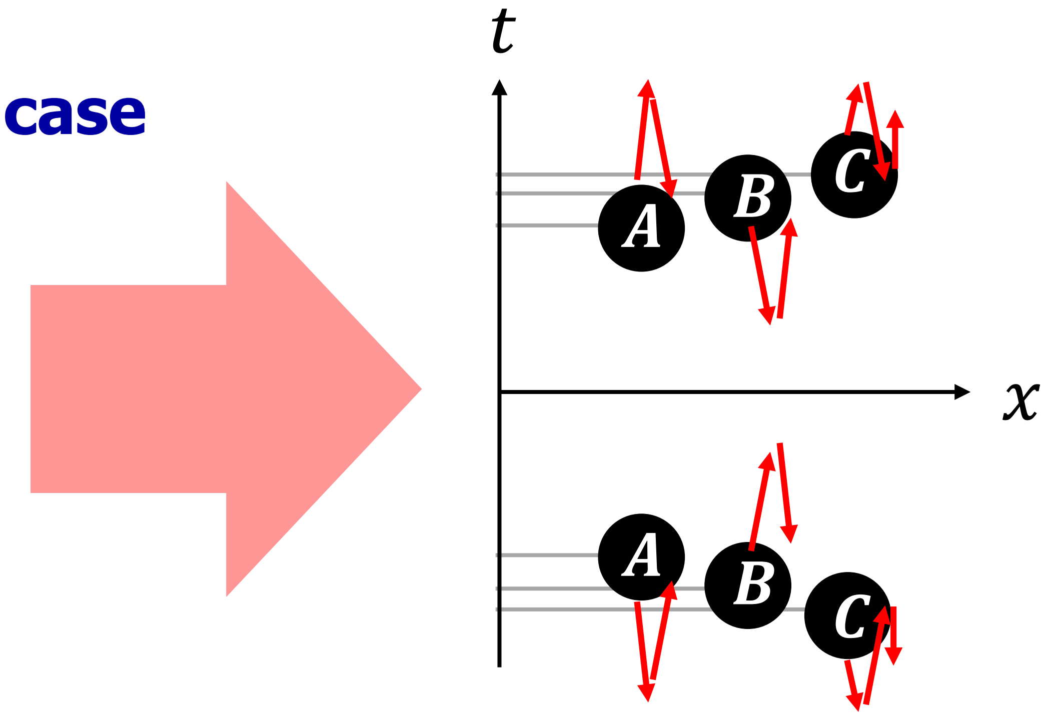
One last thing….

The value of σ needs to adjust locally to maintain minimum uncertainty in energy, thus

$$\left(\hat{H}_A + \hat{H}_B + \hat{H}_C\right)\sigma \mapsto \hat{H}_A\sigma_A + \hat{H}_B\sigma_B + \hat{H}_C\sigma_C$$

$$\left(\frac{e^{\frac{i\frac{1}{3}(\hat{H}_A\sigma_A+\cdots)}{\sqrt{N}}}+e^{-\frac{i\frac{1}{3}(\hat{H}_A\sigma_A+\cdots)}{\sqrt{N}}}}{2}\right)^N\left(\frac{e^{\frac{i\frac{1}{3}(\hat{H}_A\sigma_A-\hat{H}_B\sigma_B)}{\sqrt{N}}}+e^{-\frac{i\frac{1}{3}(\hat{H}_A\sigma_A-\hat{H}_B\sigma_B)}{\sqrt{N}}}}{2}\right)^N\left(\frac{e^{\frac{i\frac{1}{3}(\hat{H}_B\sigma_B-\hat{H}_C\boldsymbol{\sigma}+C}{\sqrt{N}}}}{}\right.$$

T violation case



independent fluctuations,
with interactions and **local effects**

Experimental test

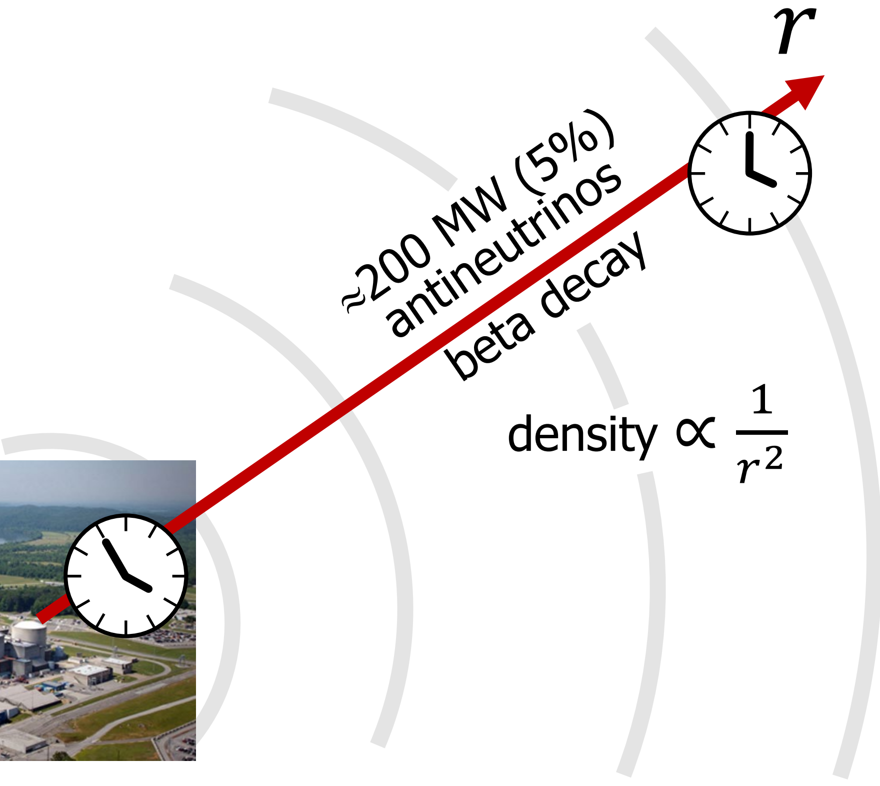
Local variation in T violation → local variation in clock time $t_c = \dfrac{2\pi\sqrt{N}}{\sigma_r}$

Antineutrinos

$$\sigma_r = i\langle\ [\hat{H}_B, \hat{H}_F]\ \rangle$$

$$\propto 1 + \Lambda\frac{1}{r^2}$$

Λ is the ratio of the strengths of the T violation due to the reactor neutrinos and the background processes at 1 m



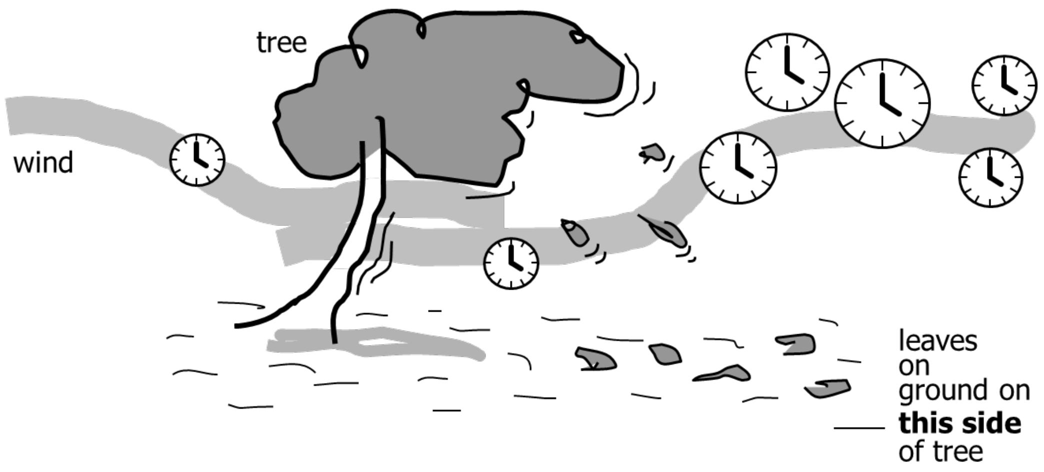
quantum clock dys-schronisation:

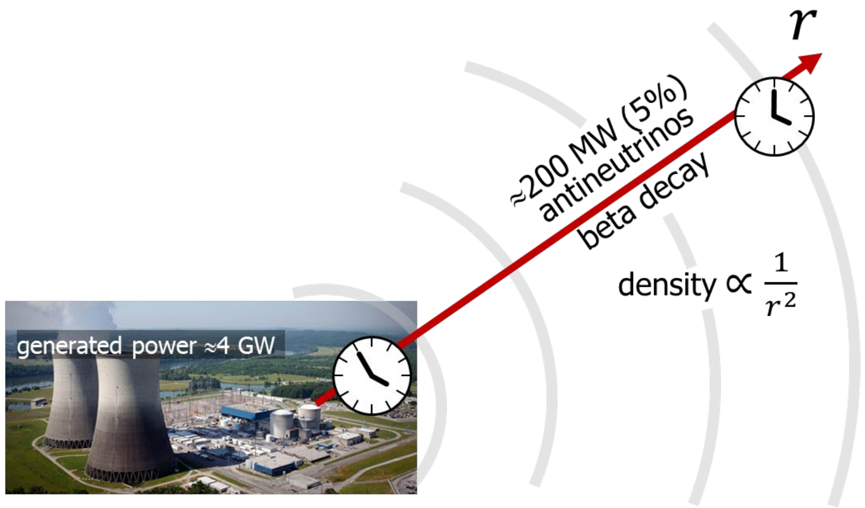
$$t_c(r) = \gamma_r t_c(1) \quad \text{where} \quad \gamma_r = 1 - \frac{\Lambda}{r^2}$$

Conclusion

Proc. Roy. Soc. A **472**, 20150670 (2016)
arXiv: 1605.01965 (book chapter)
Phil. Tras. A **376**, 20170316 (2018).

- Violations of discrete symmetries P, C & T are yet to be fully appreciated
- Generator of translations in time violates P, CP and T
- Proposed here as the **origin of dynamics and conservation laws**





Rare opportunity:
To formulate a well-posed question for Nature,
the answer of which could necessitate a *revision* of how we treat Time in physics

Lorentz covariant extension

QFT: Recall the Klein-Gordon equation for massive scalar field $\psi(x)$ $(+,-,-,-)$

$$\frac{\partial^2}{\partial x_\mu^2}\psi(x) = -m^2\psi(x) \qquad \text{mass shell:} \quad \omega_{\mathbf{k}}^2 = k^2 + m^2$$

Feynman's **off mass shell** theory for virtual (exchange) particle described by $\phi(x,\tau)$

Feynman, Phys. Rev. 80, 440 (1950) App. A
See also Fanchi, *Found. Phys*. **23**, 487 (1993)

$$i\frac{\partial}{\partial\tau}\phi(x,\tau) = -\frac{\partial^2}{\partial x_\mu^2}\phi(x,\tau)$$

where τ is "proper time" of the particle. Recover $\psi(x)$ by projection:

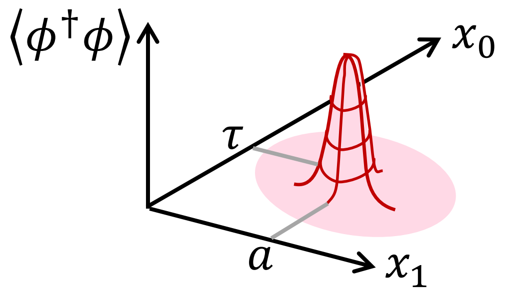
$$\psi(x) = \int_{-\infty}^{\infty} \exp\left(-im^2\tau\right)\phi(x,\tau)$$

picks out one mass component (frequency)

Here: $\phi^\dagger(x,\tau)$ creates single particle from vacuum centred on point $x = (\tau, a, b, c)$.

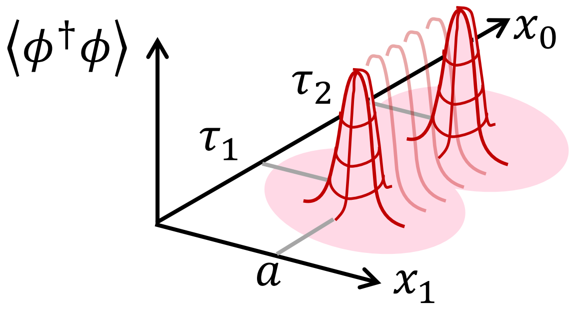
T symmetry

peak at $x_0 = \tau$



T violation

peaks at $x_0 = \tau_1, \tau_2, \ldots$



coarse graining fixes mass