Title: What does relativity tells us about quantum theory?

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Abstract: Spacelike separated classical interventions make us to rethink what is quantum and what is classical. Quantum Lorentz transformations show that identification of subsystems is a tricky business, ditto entropy, entanglement and thermodynamic quantities. Resolution of information loss problem in black hole physics is tied to a construction of a theory of quantized gravity.

What does relativity tell us about quantum theory ?

Daniel Terno

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AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Credo

[and disclosure of the conflict of interests]

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1. I believe that the phenomena to which quantum theory applies may be appropriately described in an "*as if*" realism, where facts, whether observed or not, are assumed to exist and constitute the cornerstones of the theory. It should not be taken for granted that the notion of "fact" is synonymous with "macroscopic change".

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3. Wave functions are real ... because it is useful to include in our theories

   S. Weinberg, Dreams of a Final Theory, 1993

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Minimalist program

Core data: probabilistic structure of quantum theory as revealed in calculations of measurable quantities

Instrumental states

Going beyond: not necessarily "getting lost in wastelands of metaphysics" (Born), but a mental exercise that is subject to the consistency constraints.

Motivation:
(i) personal tastes and prejudices
(ii) hope for a better theory

- ✓ Instrumental
- ✓ Epistemic
- ✓ Ontic
- ✓ Nominalisitic

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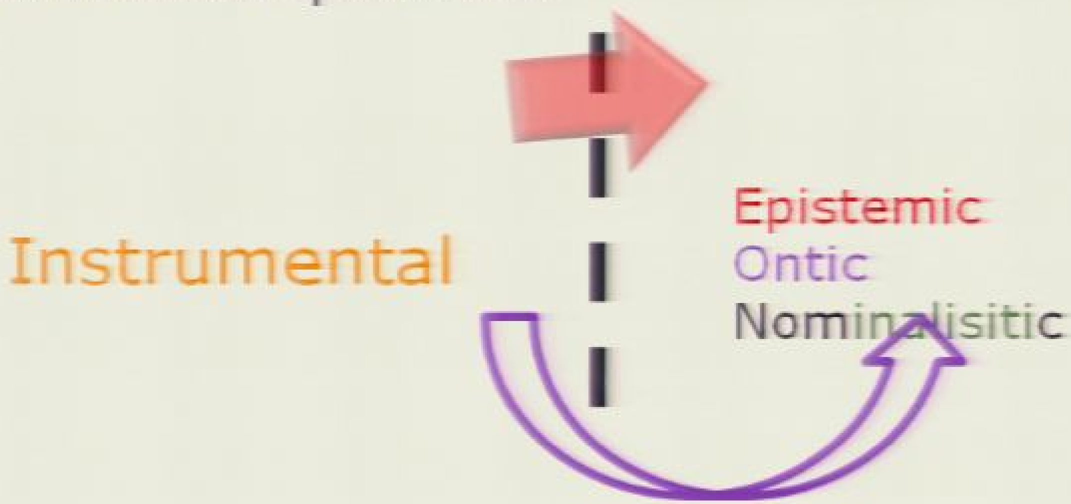

Going beyond

Core data: probabilistic structure of quantum theory as revealed in calculations of measurable quantities

Criteria:

Consistency
Simplicity

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Existence ?
If yes, uniqueness?

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I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses;' for whatever is not deduced from the phenomena is to be called a hypothesis, and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy.

Newton to Hooke (15 February 1676)

Modes of application:

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Special relativity

- Causality constraints: restrictions on quantum operations
- Absence of transformation laws for states outside common light cones of the interventions

Model: point-like quantum systems, point-like classical interventions, SR

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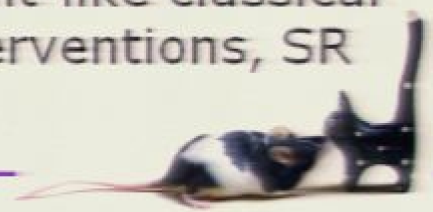

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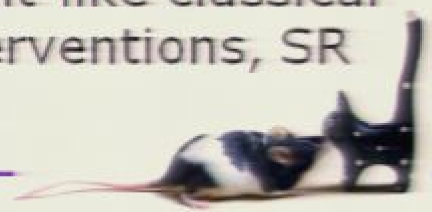

Special relativity

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Quantum field theory [flat spacetime]

- Fuzziness in identification of systems and their components
- Non-sharpness of localization
- Pervasiveness of entanglement

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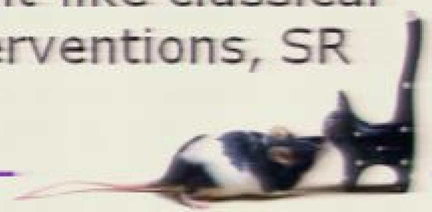

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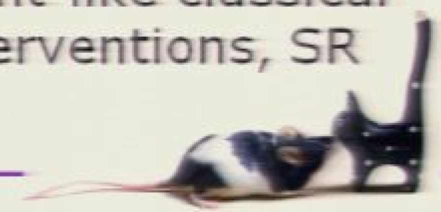

Quantum field theory [flat spacetime]

- Fuzziness in identification of systems and their components
- Non-sharpness of localization
- Pervasiveness of entanglement

Holography [whatever reason]

- Limits on the effective number of states

$$S \propto A$$

Modes of application:

$$H|\Psi\rangle = 0$$
$$[O, C] = 0$$

Quantum gravity

- Absence of time
- Non-local observables

(a) The same problems as in GR / other constrained theories
(b) Answer: relational observables

- Wave function of the Universe

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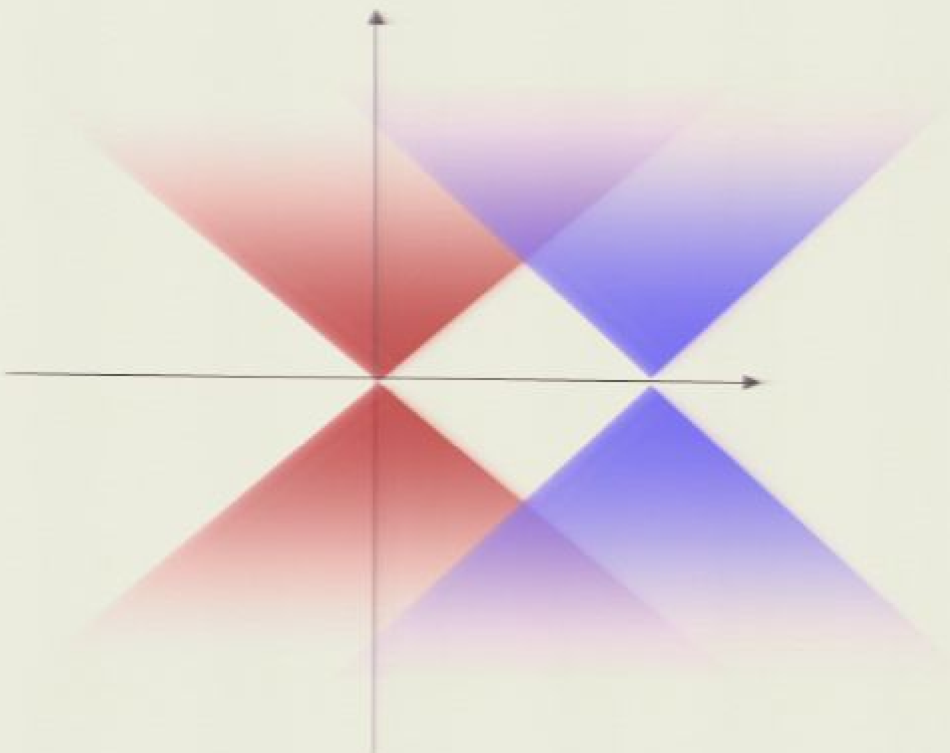
Closed time-like loops

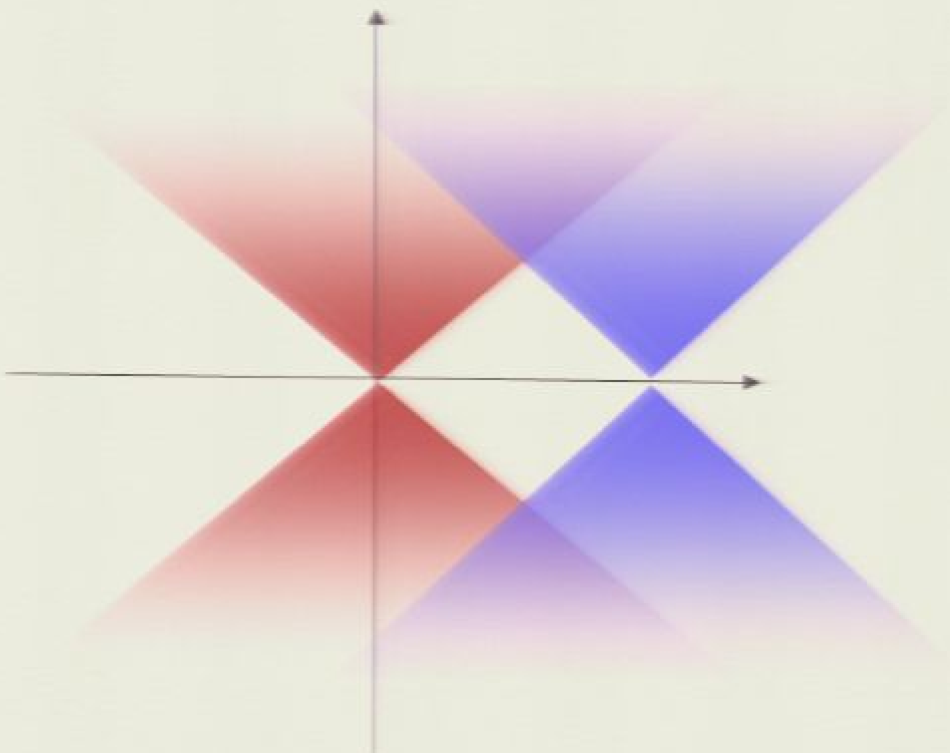
Spacelike interventions
Lorentz transformations

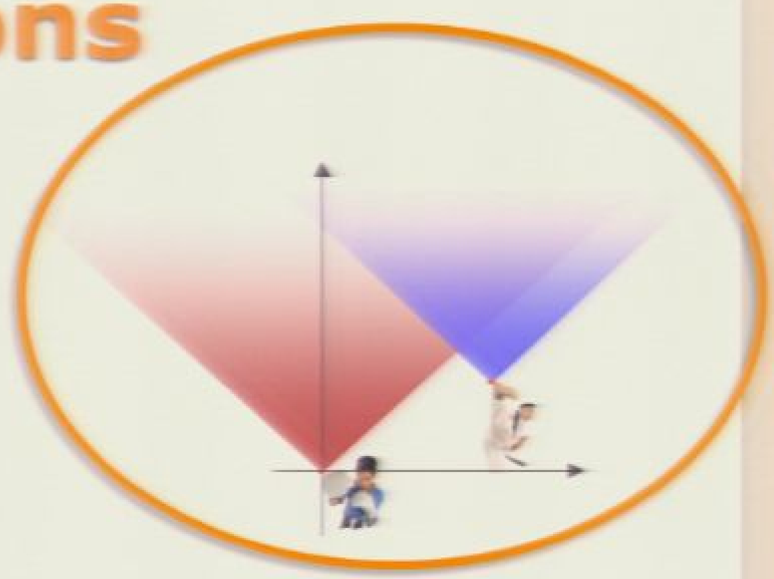
Special Relativity

Classical interventions



Classical interventions





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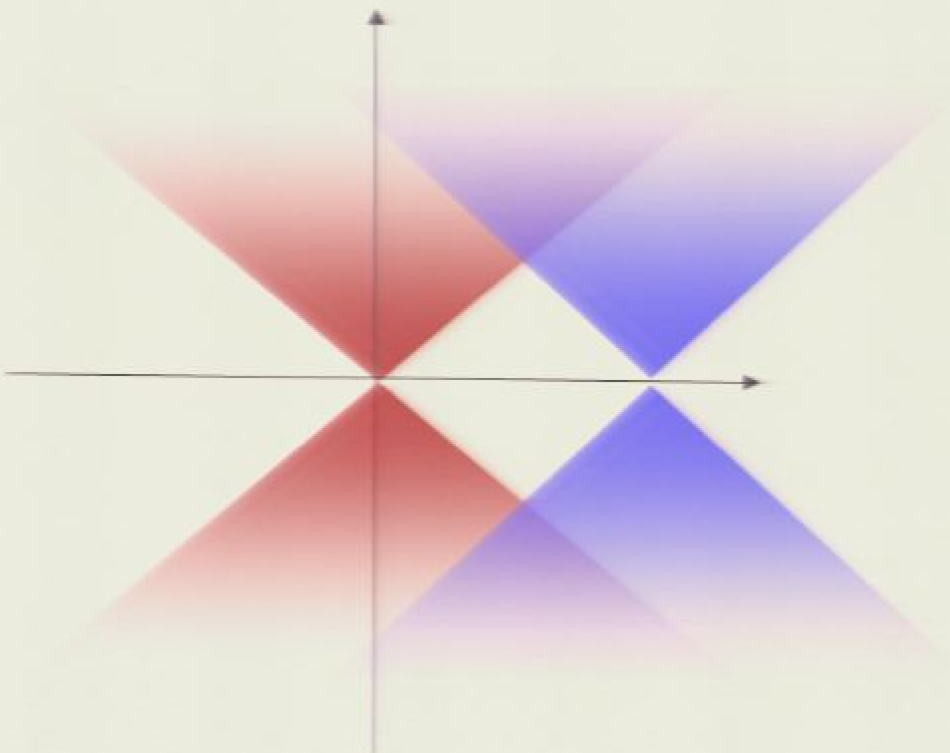

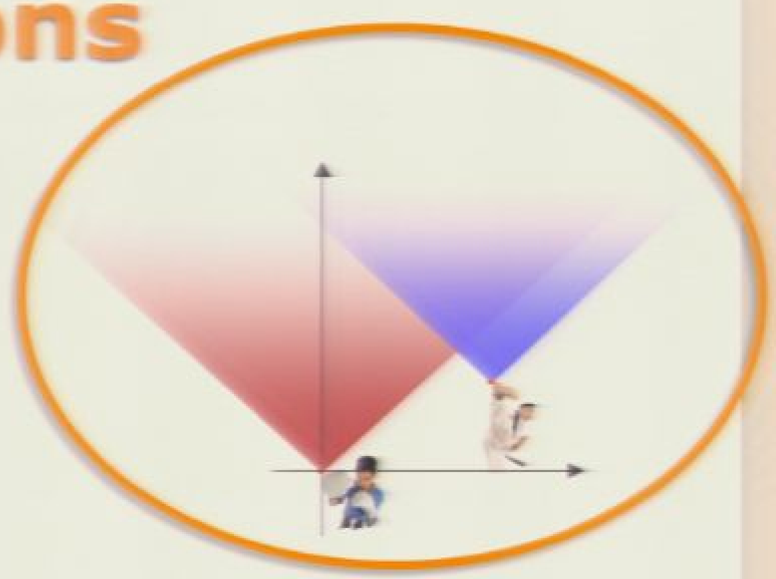

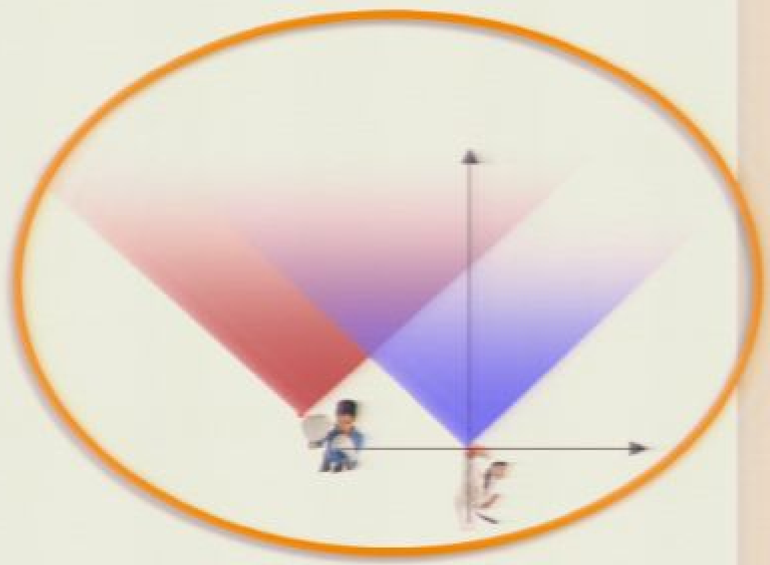

Initial state: $|\sigma_z = 1\rangle_A |\sigma_z = 1\rangle_B$
[appropriate unitary modifications @ Alice & Bob]

One particular history:

$$|\sigma_y = 1\rangle_A |\sigma_x = -1\rangle_B$$

Measurements happen: $t=0$ in the local frames

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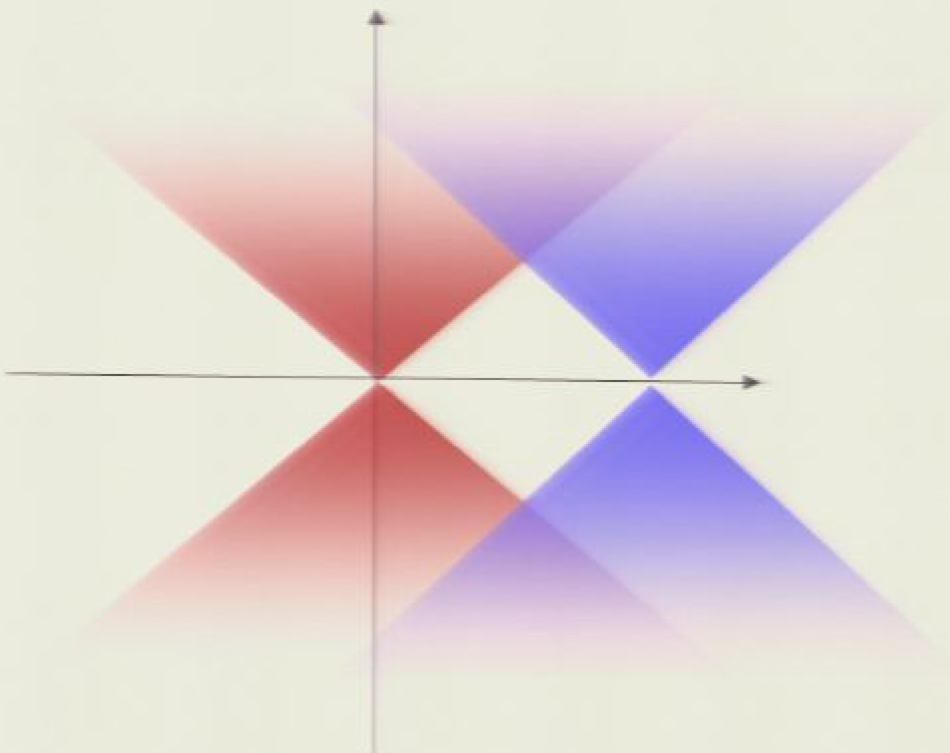

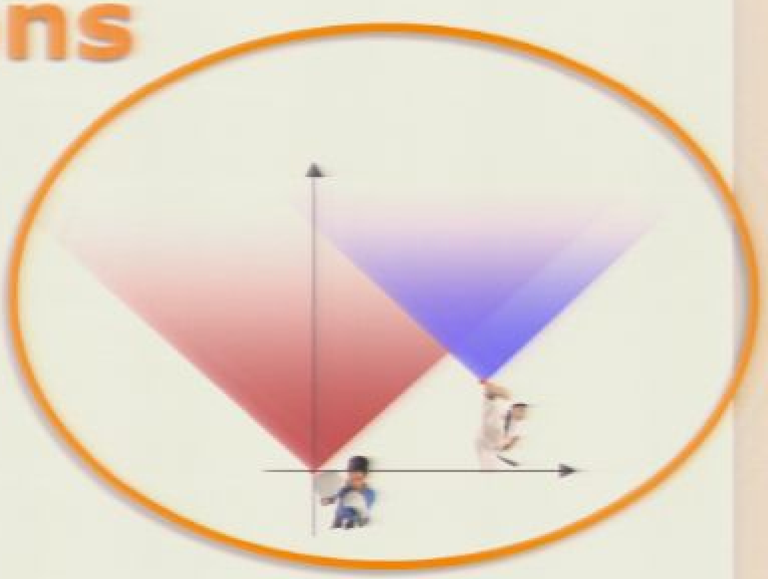

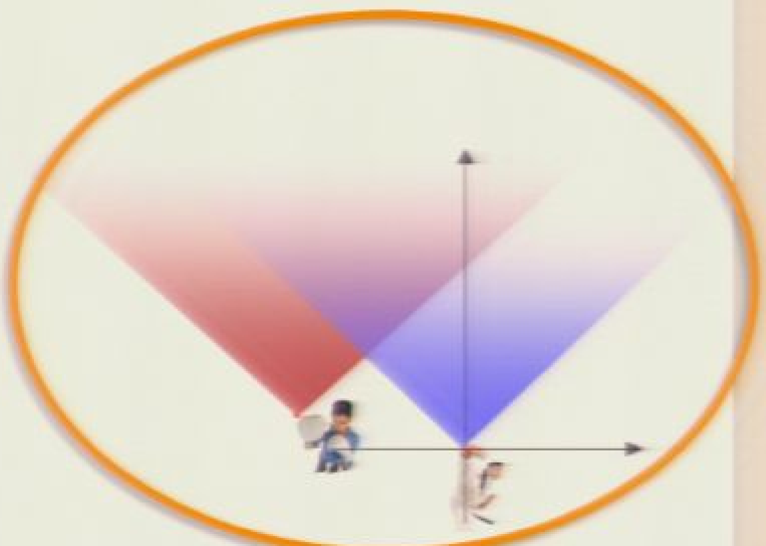

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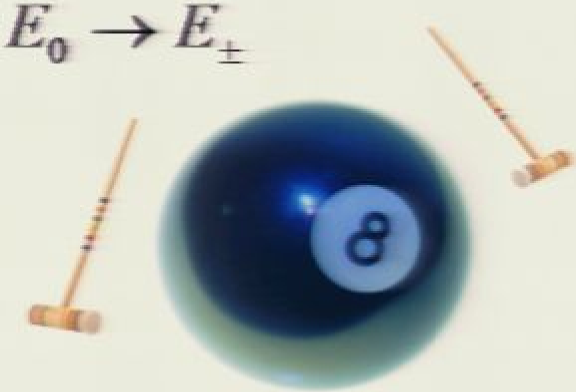
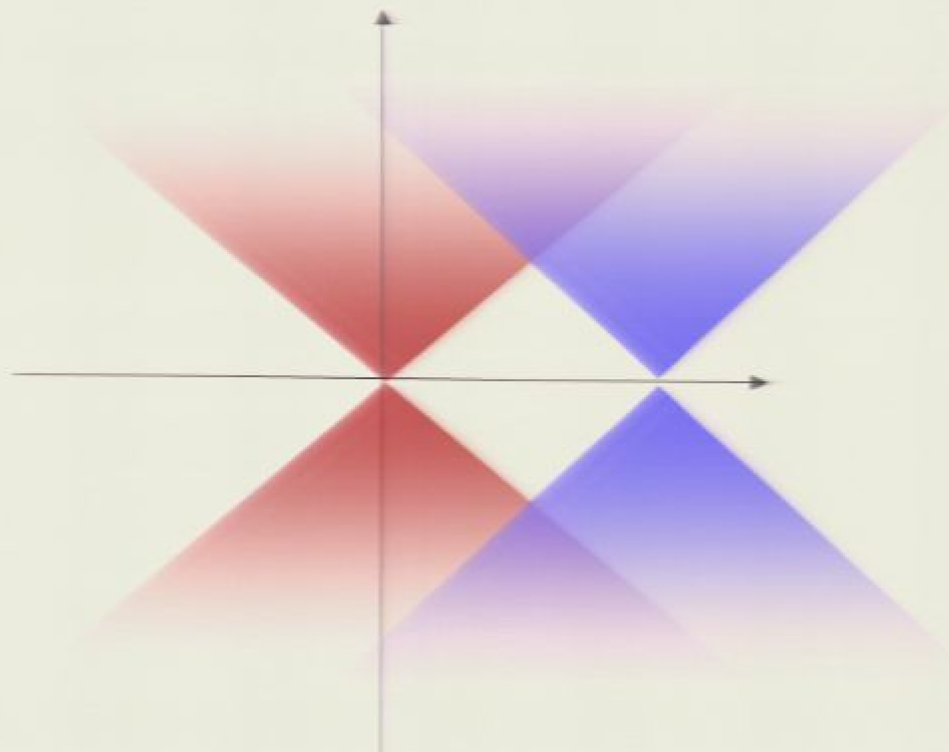
Classical particles

$E_0 \rightarrow E_{\pm}$



Liouville functions



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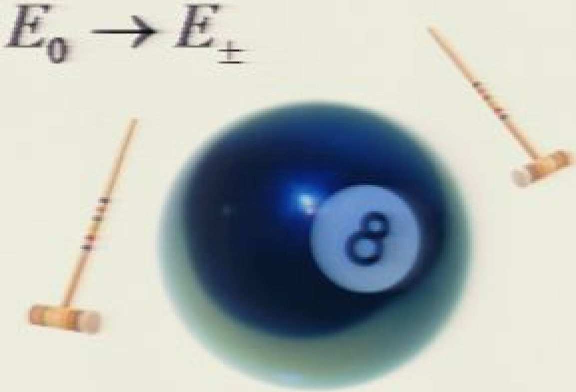

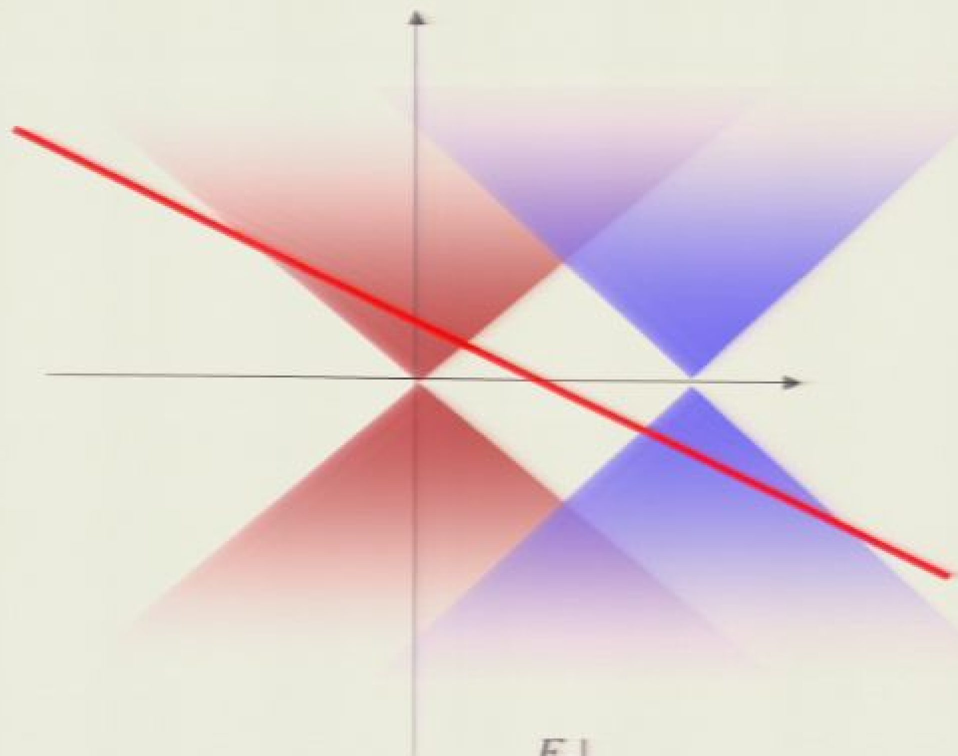

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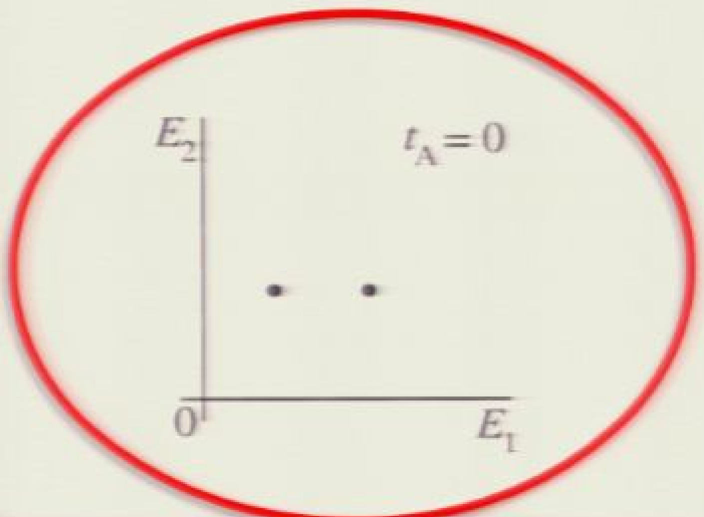

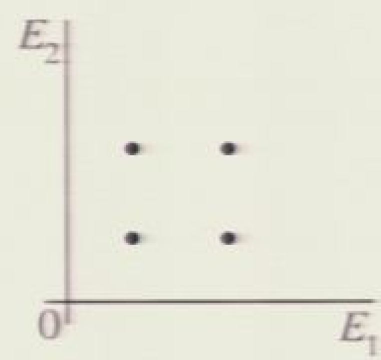

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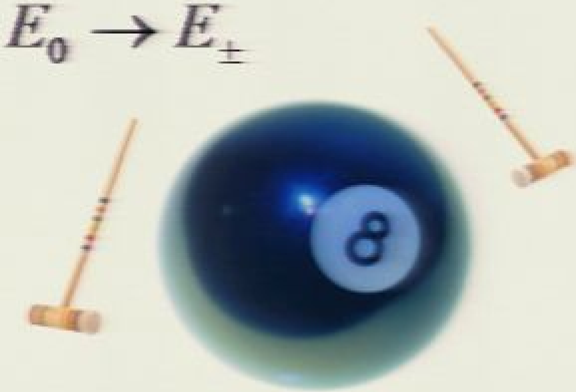

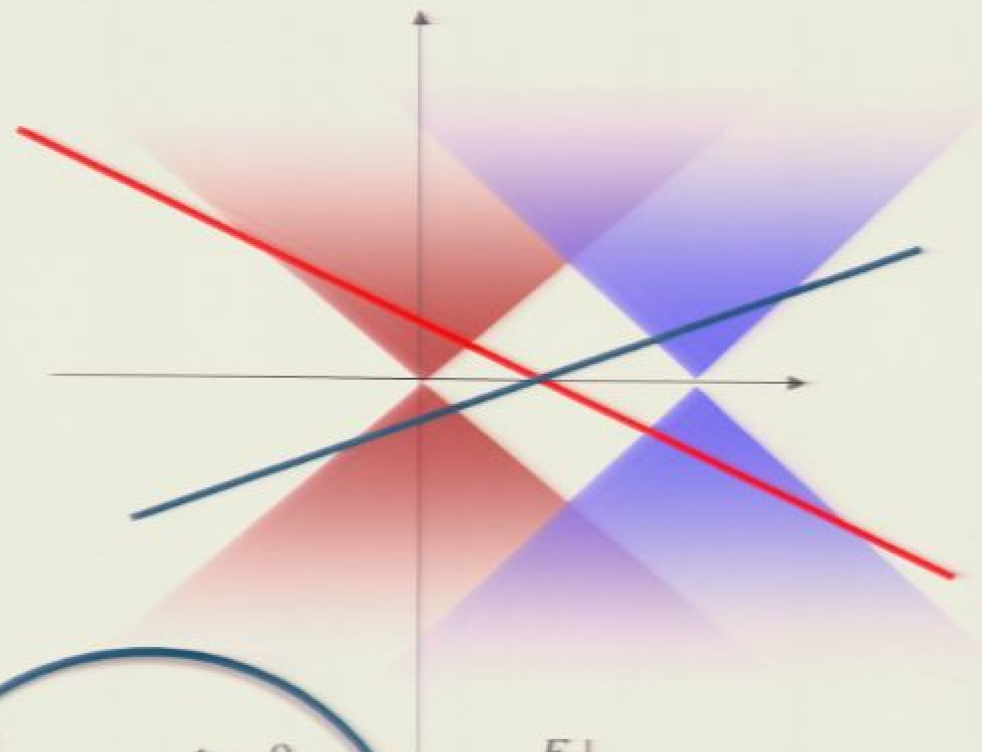

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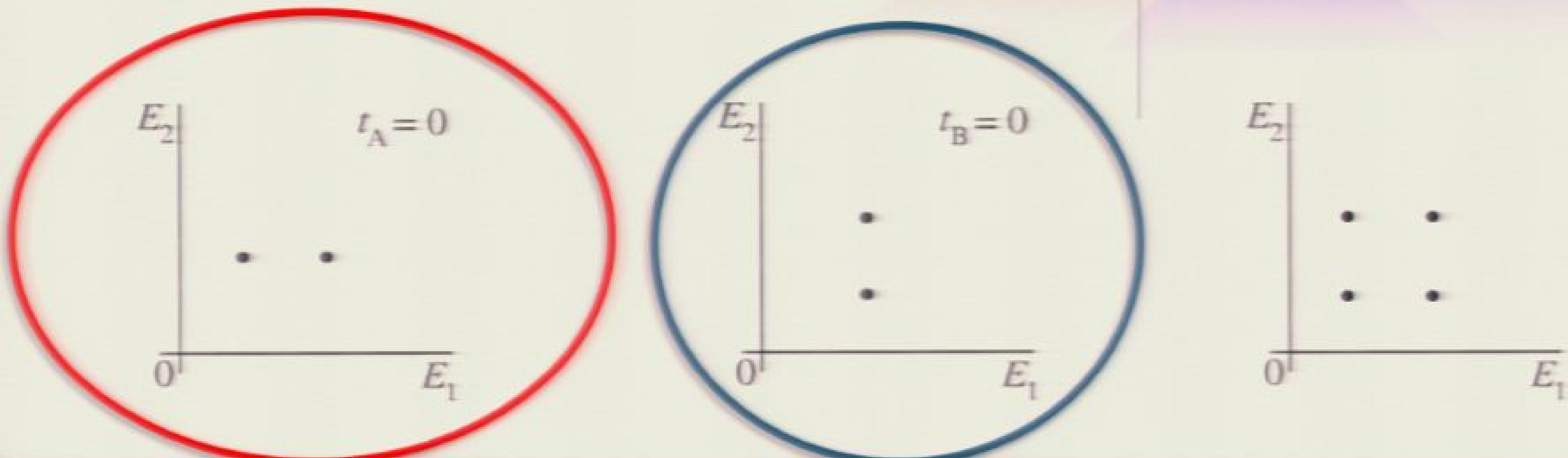

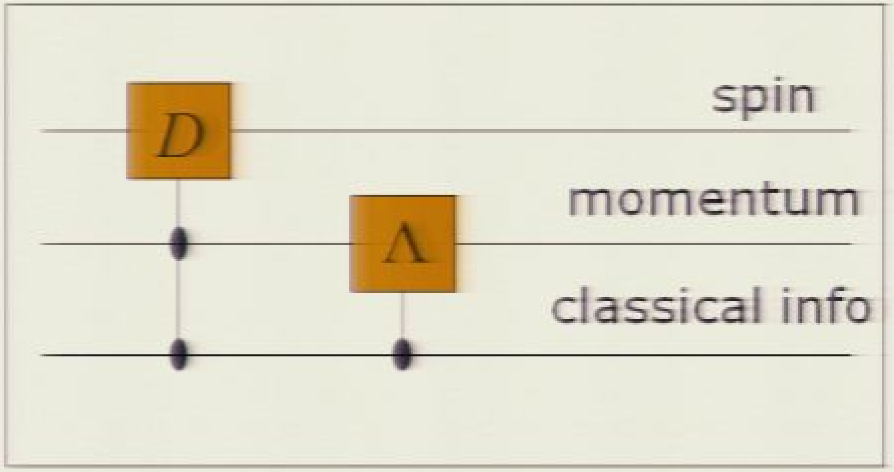

$$U(\Lambda)|p,\sigma\rangle = \sum_{\xi} D_{\xi\sigma}[W(\Lambda,p)]|\Lambda p,\xi\rangle$$

Massive particles

$k_S = (m,0,0,0)$

$\sigma = \text{spin} = \pm\frac{1}{2}$

$W \in \mathrm{SO}(3)$

$D = e^{i\boldsymbol{\sigma}\cdot\hat{\mathbf{n}}\theta_W/2}$

Photons

$k_S = (1,0,0,1)$

$\sigma = \text{helicity}$

$W = S(\alpha,\beta)R_z(\varphi) \in \mathrm{E}(2)$

$D_{\xi\sigma} = e^{i\sigma\varphi}\delta_{\xi\sigma}$

Quantum Lorentz transforms

- One-particle states

$$\langle p,\sigma|q,\zeta\rangle=(2\pi)^3(2p^0)\delta^{(3)}(\mathbf{p}-\mathbf{q})$$

$$|\Psi\rangle=\sum_\sigma\int d\mu(p)\psi_\sigma(p)|p,\sigma\rangle \qquad d\mu(p)=\frac{d^3\mathbf{p}}{2p^0(2\pi)^3}$$

$$\langle\Psi|\Phi\rangle=\int d\mu(p)\psi^*_\sigma(p)\phi^\sigma(p)$$

- Reduced density matrix $\rho_{\sigma\xi}=\int d\mu(p)\psi_\sigma(p)\psi^*_\xi(p)$

Peres and DRT, Rev. Mod. Phys. **76**, 93 (2004)

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- Partial trace is not Lorentz covariant

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- Partial trace is not Lorentz covariant
- Spin entropy is not Lorentz invariant
- Distinguishability depends on motion

Peres and DRT, Rev. Mod. Phys. **76**, 93 (2004)

- Pure spin, nearly at rest at Alice's..

$$\psi(p) = N\chi e^{-\mathbf{p}^2/2\Delta^2}, \quad \Delta/m << 1$$

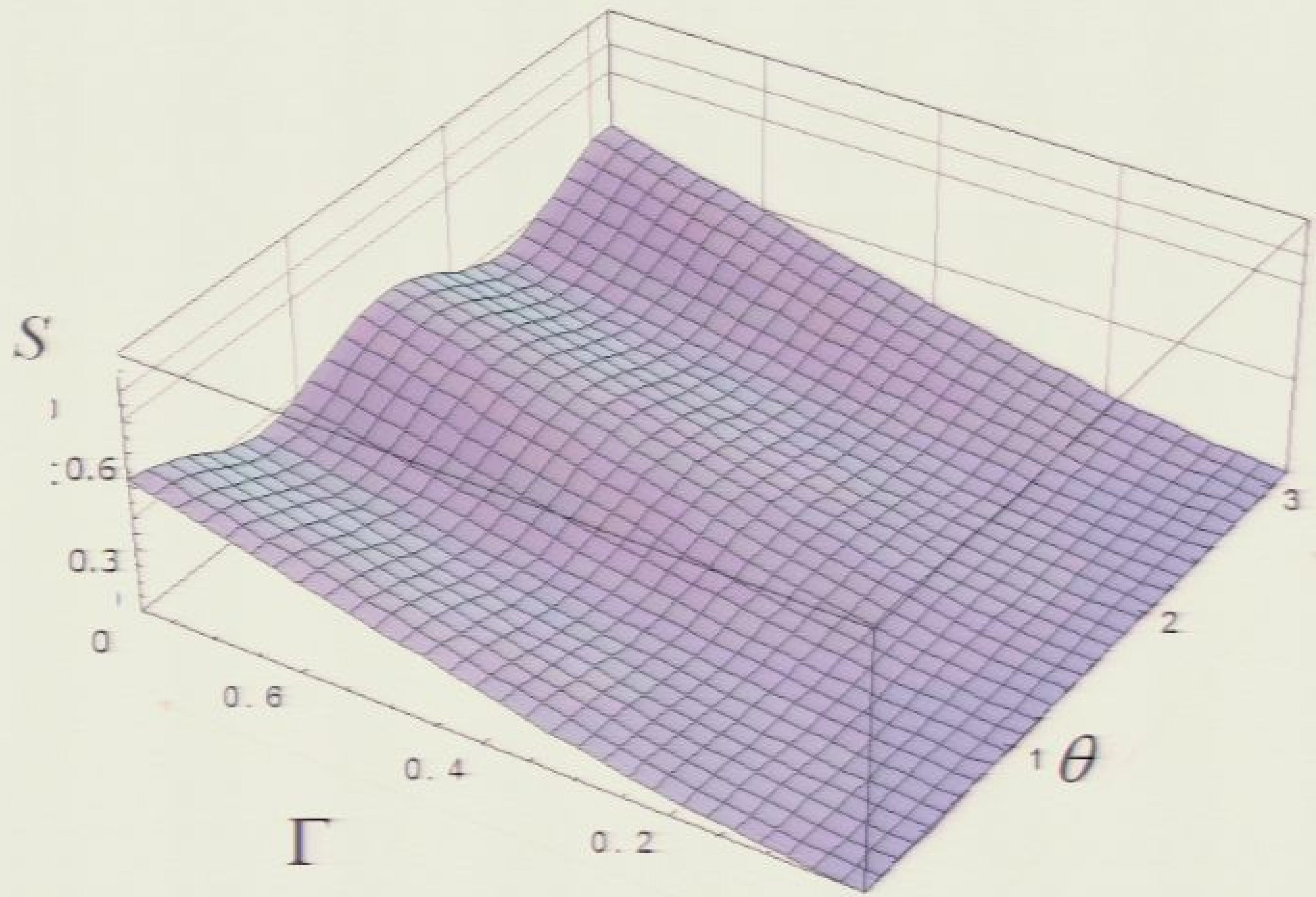
$$\chi_A = \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix} \quad \rho_A = \chi\chi^\dagger = \begin{pmatrix} s^2 & sc \\ sc & c^2 \end{pmatrix}$$

- Bob is moving with v along z-axis

$$\rho_B = \begin{pmatrix} s^2(1-\Gamma^2/4)+c^2\Gamma^2/4 & sc(1-\Gamma^2/4) \\ sc(1-\Gamma^2/4) & c^2(1-\Gamma^2/4)+s^2\Gamma^2/4 \end{pmatrix}$$

$$\Gamma = \frac{1-\sqrt{1-v^2}}{v}\frac{\Delta}{m}$$

- Entropy= degree of entanglement >0



Reeh-Schlieder theorem
Epstein-Glaser-Jaffe theorem
Reduced state property

QFT: restrictions and opportunities

Language

- Basic formalism of QInfo:
  POVM & CP dynamics works with everything

- General (algebraic) QFT
  - algebras of (quasi)(local) operators with CCR/ACR
  - states
  - Hilbert space(s)

$A(O)$

In more detail...

- *Examples*

$$\hat{\phi}(x) = \int d\mu(p)[e^{-ip\cdot x}\hat{a}^\dagger + e^{ip\cdot x}\hat{a}] \to \hat{\phi}(f) = \int dx \hat{\phi}(x) f(x)$$

$$\hat{T}_{\mu\nu}(x) \to \hat{T}_{\mu\nu}(f)$$

Local: f has a bounded support
Quasi-local: f has exponentially decaying tails

Theorems

- Reeh-Schlieder theorem

The set of states generated from the vacuum by the (polynomial) algebra of operators in any bounded region, is dense in the Hilbert space of all field states.

Meaning: there are local operators which, applied to the vacuum, produce a state that is arbitrarily close to any arbitrary state

- Epstein-Glaser-Jaffe theorem

$\hat{Q}(x) \lhd$ field

$|\Omega\rangle \lhd$ vacuum

$|\Psi\rangle \lhd$ any state

$$\forall |\Psi\rangle : \ \langle\Psi|\hat{Q}(x)|\Psi\rangle \geq 0, \ \ \langle\Omega|\hat{Q}(x)|\Omega\rangle = 0$$

- Corollary: no local operator annihilates the vacuum

Meaning: detectors must have dark counts

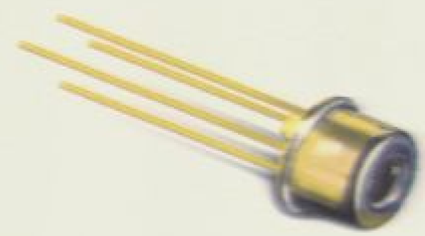
- POVMs [that are built from local operators] are not resolutions of identity

Why? $X_1 \cup X_2 \cup \ldots \cup X_n = X$

$$\hat{E}(X) = \hat{1} \Rightarrow \sum_i p_i(\Omega) = \langle \Omega | \hat{E}(\bigcup_{i=1}^{n} X_i) | \Omega \rangle = 1$$

always fires...

Meaning: useful detectors have non-zero chance to fail



- Localization POVM is not local

Why? $\bigcup_{i=1}^{\infty} I_i = \mathcal{M}$

translational invariance

$$\langle\Omega|\hat{E}(I)|\Omega\rangle = \langle\Omega|\hat{U}(x)\hat{E}(I)\hat{U}^{\dagger}(x)|\Omega\rangle = \varepsilon > 0$$

pick up enough disjoint bins

$$\langle\Omega|\hat{E}(\bigcup_{i=1}^{n} I_i)|\Omega\rangle = n\varepsilon > 1$$

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- Localization POVM is not quasi-local

- Localization POVM is not local

Why? $$\bigcup_{i=1}^{\infty} I_i = \mathcal{M}$$

translational invariance

$$\langle\Omega|\hat{E}(I)|\Omega\rangle = \langle\Omega|\hat{U}(x)\hat{E}(I)\hat{U}^{\dagger}(x)|\Omega\rangle = \varepsilon > 0$$

pick up enough disjoint bins

$$\langle\Omega|\hat{E}(\bigcup_{i=1}^{n} I_i)|\Omega\rangle = n\varepsilon > 1$$

- Localization POVM is not quasi-local

- Space-time events can be defined only by non-local procedures

- Corollary: any entangled state can be approximated by acting locally on the vacuum state

$$|\Psi\rangle \approx \hat{A}_\Psi(O)|\Omega\rangle$$

- Clustering property: $\hat{A},\hat{B} \in A(O):$

$$\langle\Omega|\hat{A}\hat{B}_{\mathbf{x}}|\Omega\rangle = \langle\Omega|\hat{A}|\Omega\rangle\langle\Omega|\hat{B}_{\mathbf{x}}|\Omega\rangle + \int\sum\langle\Omega|\hat{A}|\Psi\rangle\langle\Psi|\hat{B}_{\mathbf{x}}|\Omega\rangle$$
$$\xrightarrow{\mathbf{x}\to\infty} \langle\Omega|\hat{A}|\Omega\rangle\langle\Omega|\hat{B}_{\mathbf{x}}|\Omega\rangle$$

Meaning: states created by local operations looks almost like a vacuum with respect to measurements in distant causally unconnected regions.

- Vacuum is entangled

$\hat{A} \in A(O_1), \hat{B} \in A(O_2)$ $\quad \left| \langle \Omega | \hat{A}\hat{B} | \Omega \rangle - \langle \Omega | \hat{A} | \Omega \rangle \langle \Omega | \hat{B} | \Omega \rangle \right| > 0$

$\propto 1/|\mathbf{x}|^2$  $\propto e^{-m|\mathbf{x}|}$ 

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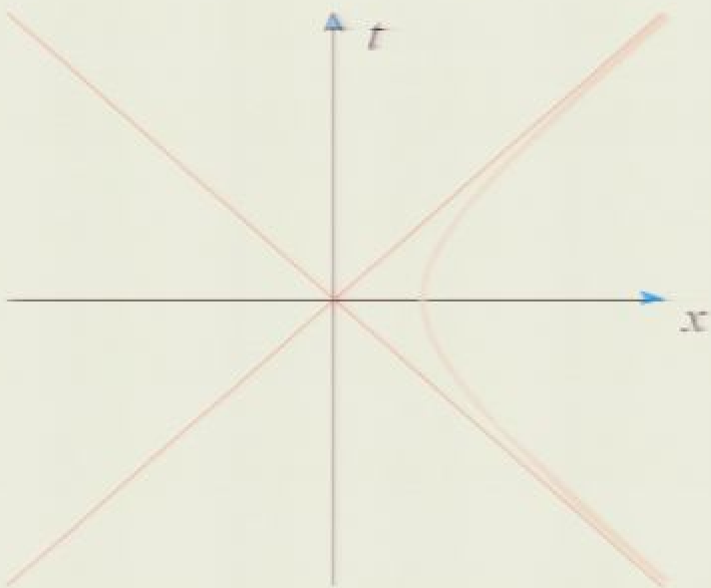
Accelerated detector



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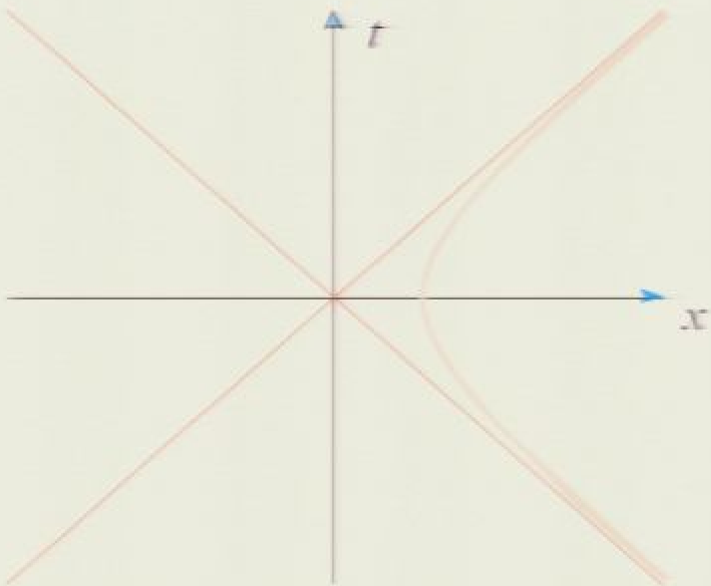
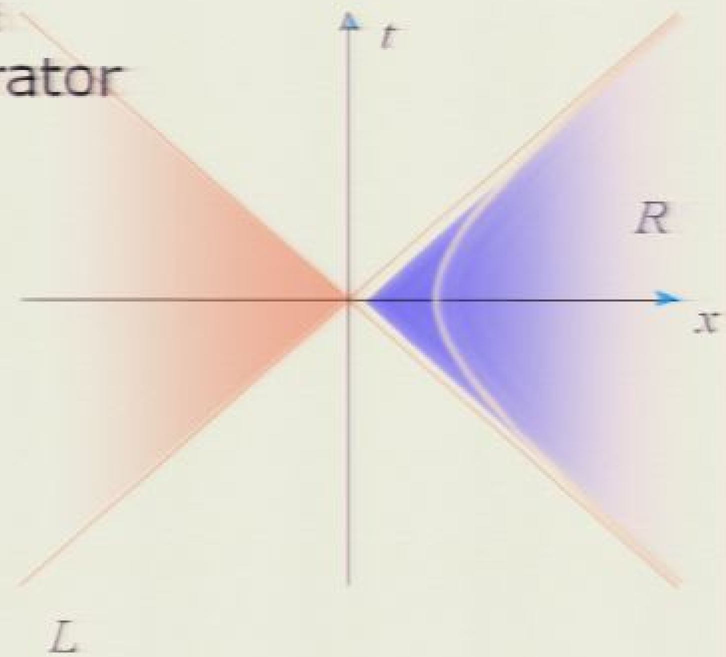
Accelerated detector



Rate: as if in the bath with

$$T = \frac{\hbar a}{2\pi c k_B}$$

- Local partial trace [corresponding to a region of space] is not a trace class operator



  - Rindler coordinates

Step 1: a uniformly accelerated Bob, with a proper acceleration a whose asymptotic trajectory is $t \sim x$

$$t = \frac{1}{a}\sinh a\eta,\ x = \frac{1}{a}\cosh a\eta$$

Step 2: new coordinates for the wedge

$$t = \frac{e^{a\xi}}{a}\sinh a\eta,\ x = \frac{e^{a\xi}}{a}\cosh a\eta \qquad -\infty < \eta, \xi < \infty$$

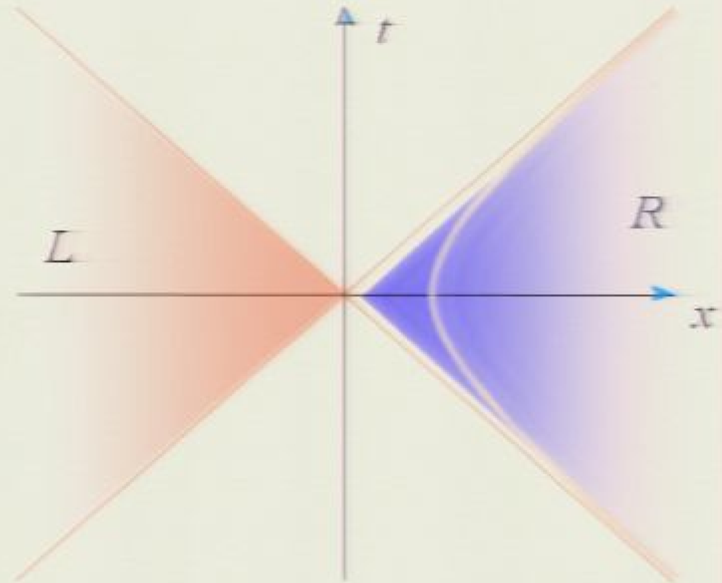
Step 3: new coordinates for the wedge II

- Quantization in Rindler coordinates

Bogoluybov transformation applied to vacuum [a formal unitary]

$$U|\Omega\rangle = \prod_{\omega}\sum_{n=0}^{\infty}\exp(-n\pi\omega/a)|n_{\omega}\rangle_{L}|n_{\omega}\rangle_{R}$$

Minkowski vacuum looks like a squeezed state



Reduced density operator [not a trace class operator]

$$\rho_{R}^{\Omega} = \prod_{\omega}\sum_{n=0}^{\infty}\exp(-\pi\omega n_{i}/a)Z^{-1}|n_{\omega}\rangle\langle n_{\omega}|$$

$$Z^{-1} = \left(\sum_{n} e^{-n\pi\omega/a}\right)^{-1} = (1-e^{-\pi\omega/a})$$

Black hole dynamics laws
Hawking radiation
Unitary evolution

Black holes & unitarity

PHILOSOPHICAL

TRANSACTIONS,

OF THE

ROYAL SOCIETY

OF

LONDON.

VOL. LXXIV. For the Year 1784.

PART I.

LONDON,

SOLD BY LOCKYER DAVIS, AND PETER ELMSLY,
PRINTERS TO THE ROYAL SOCIETY.
MDCCLXXXIV.

16. Hence, according to article 10, if the semi-diameter of a sphære of the same density with the sun were to exceed that of the sun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its surface a greater velocity than that of light, and consequently, supposing light to be attracted by the same force in proportion to its vis inertiæ, with other bodies, all light emitted from such a body would be made to return towards it, by its own proper gravity.

17. But if the semi-
sity with the sun, was
that of the sun, thoug
such a body, would n
always suffer some dimi
magnitude of the said sp
tion may be easily foun
to represent the semi-di
the semi-diameter of t
from what has been she
ference between the sq
be always proportional
after it has suffered all
from this cause; and c
whole velocity of light
above, will be the dim
diminution of the veloc
account of it's gravitat
what less than a 495.c
would have had if no
the square of 497 being
the diminution of the

VII. *On the Means of discovering the Distance, Magnitude, &c. of the Fixed Stars, in consequence of the Diminution of the Velocity of their Light, in case such a Diminution should be found to take place in any of them, and such other Data should be procured from Observations, as would be farther necessary for that Purpose. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendish, *Esq. F. R. S. and A. S.*

Read November 27, 1783.

DEAR SIR, Thornhill, May 26, 1783.

THE method, which I mentioned to you when I was last in London, by which it might perhaps be possible to find the distance, magnitude, and weight of some of the fixed stars, by means of the diminution of the velocity of their light, occurred to me soon after I wrote what is mentioned by Dr. PRIESTLEY in his History of Optics, concerning the diminution of the velocity of light in consequence of the attraction of the sun; but the extreme difficulty, and perhaps impossibility, of procuring the other data necessary for this purpose appeared to me to be such objections against the scheme, when I first thought of it, that I gave it then no farther consideration. As some late observations, however, begin to give us a little more chance of procuring some at least of these data, I thought it would not be amiss, that astronomers should be apprized of the method, I propose (which, as far as I know, has

F 2

- Schwarzschild metric

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = (1-2M/r)dt^2 - (1-2M/r)^{-1} dr^2 - r^2 d\Omega^2$$

Proper time of a stationary observer $d\tau = \sqrt{(1-2M/r)}dt$

Gravitational radius = event horizon $r_g = 2M$

Physical singularity $r = 0$

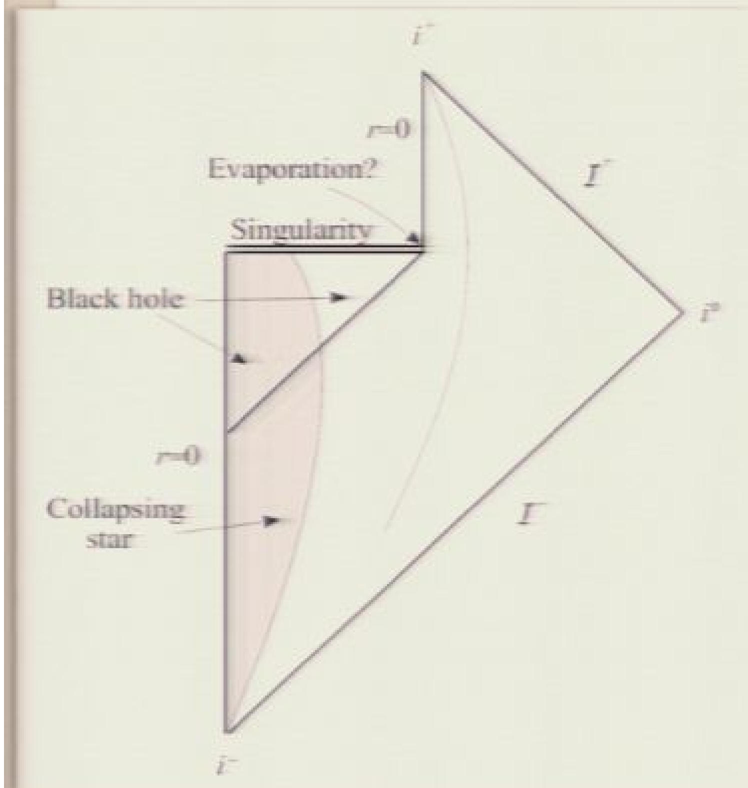
Surface gravity: the force per unit mass as measured at infinity, to keep the observer stationary just outside the horizon $\kappa = 1/4M$

Basic quantities

- 0^{th} law: surface gravity is constant on the horizon
- 1^{st} law: $dM = \frac{\kappa}{8\pi} dA + \omega_H dJ$
- 2^{nd} law: $dA \geq 0$
- Bekenstein-Hawking entropy $S_{BH} = Ac^3 / 4G\hbar$
- Quantum effects: Hawking radiation
  - Black body temperature $T = \frac{\kappa}{2\pi} \frac{\hbar c^3}{G k_B}$
  - Evaporation $\dot{M} \propto -T^4 A \propto M^{-2}$

$$M = (1 - t/t_E)^{1/3} M_0, \; t_E = a M_0^3$$

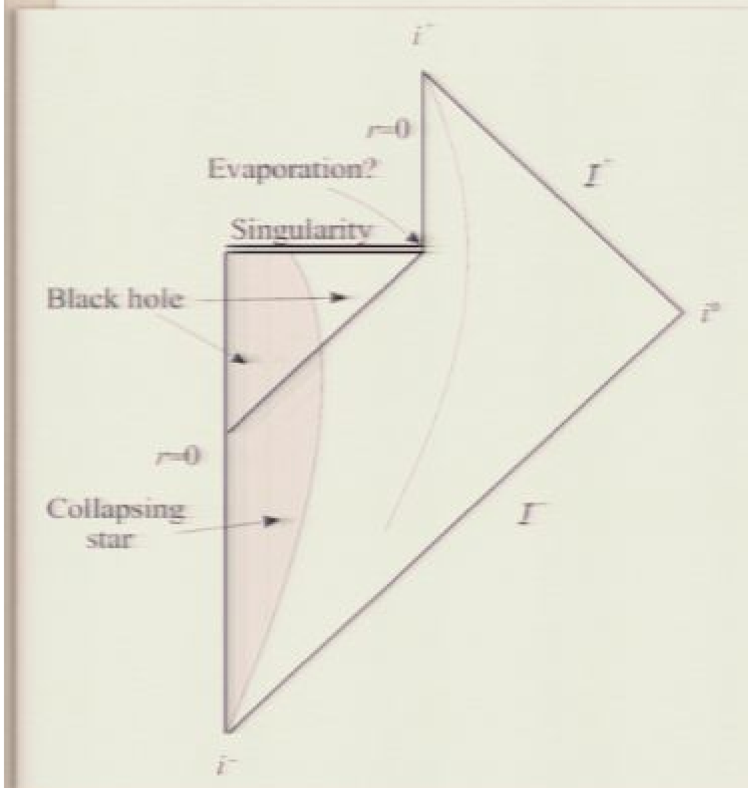
Basic physics



$$|\phi\rangle\langle\phi| \rightarrow \$|\phi\rangle\langle\phi|$$ pure to mixed

Black hole evaporates via the Hawking process within a finite time. If the correlations between the inside and outside of the black hole are not restored during the evaporation process, then by the time that the black hole has evaporated, an initial pure state will have evolved to a mixed state, i.e., "*information*" will have been lost.

Wald, Liv. Rev. Rel (2001)



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Wald, Liv. Rev. Rel (2001)

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Succesful QG theory: no info loss

Evolution of matter = evolution of an open system

$$|\Psi\rangle_{\rm in} \approx |\psi\rangle_{\rm grav} |\phi\rangle_{\rm mat}$$

$$|\Psi\rangle_{\rm out} \approx U |\Psi\rangle_{\rm in}$$

$$\rho_{\rm mat} = {\rm tr}_{\rm grav} |\Psi\rangle\langle\Psi|$$

Matter entropy =degree of entanglement

DRT, arXive/0909.4143
Husain and DRT, arXive/0903.1471

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Matter entropy =degree of entanglement

DRT, arXive/0909.4143
Husain and DRT, arXive/0903.1471

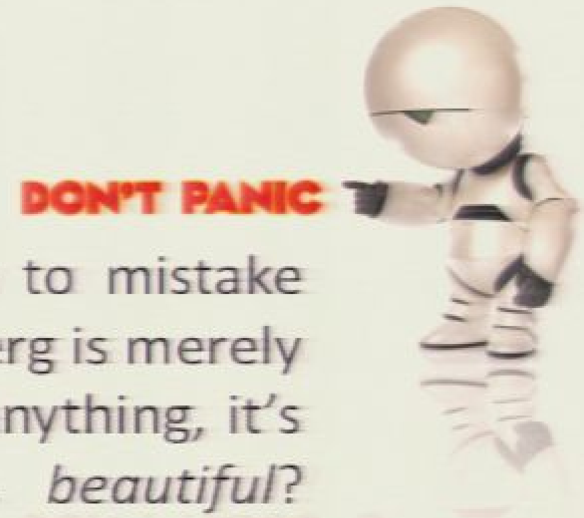
Summary

- Identity is fuzzy
- Constituents are approximate
- Locality is unsharp
- Interventions destroy transformations
- Some weirdness is classical
- Black holes do not destroy information

or strings, loops, and foams are wrong

Rushdie – Adams interpretation of QT

Rushdie – Adams interpretation of QT



In an age of great uncertainties it is easy to mistake science for banality, to believe that Heisenberg is merely saying, gee, guys, we just can't be sure of anything, it's so darn *uncertain*, but isn't that, like, *beautiful*? Whereas actually he's telling us the exact opposite: that if you know what you're doing you can pin down the exact quantum of uncertainty in any experiment, any process. To knowledge and mystery we can now ascribe percentage points. A principle of uncertainty is also a measure of certainty. It's not a lament about shifting sands but a gauge of the solidity of the ground.

Salman Rushdie, *The ground beneath her feet*

Rushdie – Adams interpretation of QT

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Click to add notes

Theorems

- Reeh-Schlieder theorem

The set of states generated from the vacuum by the (polynomial) algebra of operators in any bounded region, is dense in the Hilbert space of all field states.

Meaning: there are local operators which, applied to the vacuum, produce a state that is arbitrarily close to any arbitrary state

- Epstein-Glaser-Jaffe theorem

$\hat{Q}(x) \triangleleft$ field

$|\Omega\rangle \triangleleft$ vacuum

$|\Psi\rangle \triangleleft$ any state

$$\forall|\Psi\rangle: \ \langle\Psi|\hat{Q}(x)|\Psi\rangle \geq 0, \quad \langle\Omega|\hat{Q}(x)|\Omega\rangle = 0$$

Click to add notes