*Reflections on space, time and their quantum nature, AEI, 27 Nov. 2012*

# Against the emergence of space-time

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# The claim

- against an *ontology* according to which four-dimensional physical space-time and entities located in space-time exist, but are not fundamental, emerging from a fundamental quantum reality that is not spatio-temporal
- EITHER four-dimensional physical space-time and entities located in space-time do not exist (and the task then is to explain why it appears to us as if we were living in a four-dimensional space-time)

  OR they do exist, and then they are, as things stand, fundamental (= not reducible to anything else)

# not against

- formal *descriptions* that *abstract from* four-dimensional space-time (= that abstract from something that there is)
- analogy: reduction of geometry to algebra

  ≠ spatial relations emerge from algebra

  = reduction of one *representation* of physical space to another *representation* of physical space
- analogy: Porphyrios: substance/ organism / mammal / barking → dog

  Darwin: theory of evolution applied to dogs

# not against

- space-time being discrete instead of continuous
- space-time developing out of basic elements, provided that these elements are spatio-temporal / four-dimensional (causal set theory, evolving block universe)
- space-time having more than four dimensions, provided that the theory explains how ordinary space-time is embedded in a higher-dimensional space and why we do not observe the additional dimensions (Kaluza-Klein theory, string theory)

# The argument

- Any quantum theory, by contrast to classical theories, runs into the problem of what the empirical content of the theory is: the formalism does not permit to establish a direct representational link with anything located in a physical space-time.
- This problem carries from quantum mechanics on to quantum field theories and theories of quantum gravity: there is nothing in these latter theories that permits to solve or to dispel that problem.
- → Any ontological claims (= any claims about what the world is like based on these theories) face the

# The measurement problem in QM
# Tim Maudlin (1995)

**A The wave-function of a system is *complete*, i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.**

**B The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).**

**C Measurements of, e.g., the spin of an electron always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up).**

# The problem of empirical content

- A and B → not C
- A and B: bare formalism of any quantum theory (quantum state of the universe defined on high-dimensional space)

® no empirical content, since the formalism does not yield statements about observable phenomena

- A and B → there is nothing of the sort of what we take to make up the empirical content of a theory: three-dimensional space or four-dimensional space-time with something located in it

# Carlo Rovelli
# Quantum gravity CUP 2004

"A weave is one of many quantum states that have a certain macroscopic property, and a very peculiar one, since it is a single element of the spin network basis. There is no reason for the physical state of space not to be in a generic state, and the *generic* quantum state that has this macroscopic property is not a weave state: it is a *quantum superposition* of weave states. Therefore it is reasonable to expect that at small scale, space is a quantum superposition of weave states. Therefore the picture of physical space suggested by canonical quantum gravity is not truly that of a small scale lattice, or as a T-shirt. Rather, it is a quantum probabilistic cloud of lattices."

# David Albert (1996)

"… it has been essential (…) to the project of quantum-mechanical *realism* (in *whatever* particular form it takes …) to learn to think of wave functions as physical objects *in and of themselves*. And of course the space those sorts of objects *live* in, and (therefore) the space *we* live in, the space in which any realistic understanding of quantum mechanics is necessarily going to depict the history of the world as *playing itself out* (…) is configuration space. And whatever impression we have to the contrary (whatever impression we have, say, of living in a three-dimensional space, or in a four-dimensional space-time) is somehow flatly illusory."

# Quantum state ontology: *only* Ψ

- "configuration space" misleading: no given configuration of anything that this space represents
- only entangled universal wave-function Ψ as field in high-dimensional space
- ® no empirical content
- ® no observable *physical* phenomena to be accounted for, because these do not exist
- ® *appearances* of physical phenomena in minds of persons to be accounted for
- many minds: radical ontological dualism; minds primitive & split universal wave-function
- many worlds: decoherence splits quantum state of the universe

# Emergence of space-time?

- theory of QG based on A and B
- fundamental reality that is not spatio-temporal
- four-dimensional, spatio-temporal reality emerging from this fundamental reality
- no emergence in temporal sense
- no emergence in causal sense
- In general, not intelligible how a quantum state existing in a high-dimensional space could lead to the coming into being of another space with something being localized in that other space.

# The situation

- either A and B → only fundamental reality that is not spatio-temporal, and no four-dimensional, spatio-temporal reality
- or C → quantum formalism to be amended such that either not complete (not A) or other dynamics (not B), this amendment to be carried on from QM to QFT and QG

→ Ψ *and* $X$ instead of *only* Ψ, $X$ all the way down

→ in all known proposals for (not A) or (not B) local beables (= four-dimensional, localized

# Textbook quantum mechanics

- $X$ = observable phenomena, macroscopic objects localized in space-time
- link from $\Psi$ to $X$ via algorithm to calculate probabilities for measurement outcomes (Born's rule) and correction of $\Psi$ by hand ("collapse")
- **incoherent:** no cut between quantum domain and classical domain; macroscopic objects composed of microscopic objects and developed out of microscopic objects during cosmic evolution

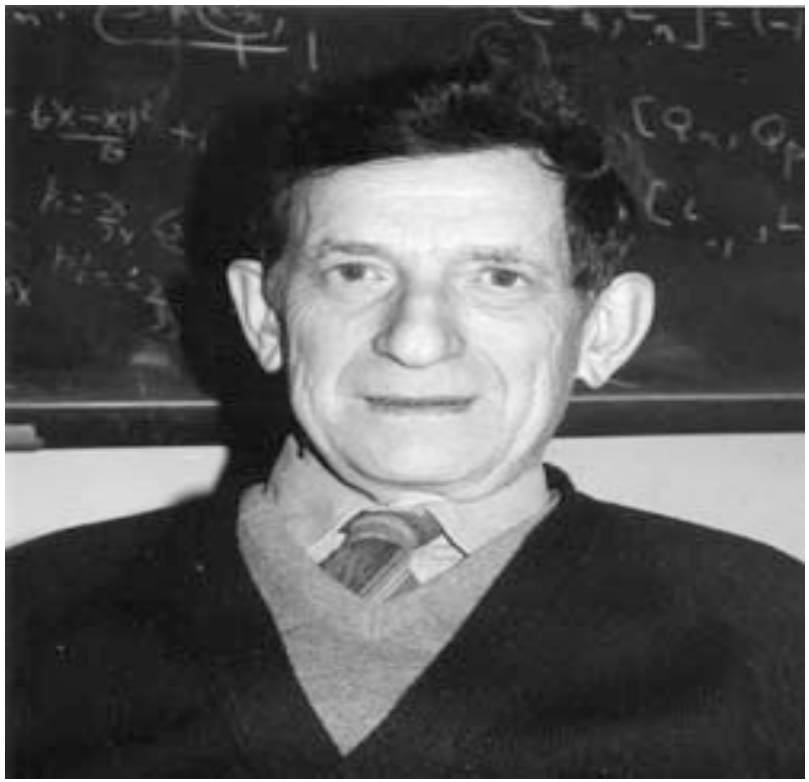
# Space-time ontology Ψ *and X*: particles

- macroscopic objects localized iff microscopic objects localized as well
- **common sense realism:** macroscopic objects localized independently of observation → **microscopic objects localized independently of observation**
- **classical mechanics:** macroscopic objects composed of particles
- **de Broglie (1928), Bohm (1952), Bell (1982):**

  particles localized when composing macroscopic objects iff they are *always* localized

® **position, trajectory**

# Space-time ontology Ψ *and X*: particles Bohmian mechanics



- *X* = localized particles
- Ψ = quantum state that fixes the velocity of the particles given their position
- **holism:** quantum state property of all the particles taken together, **velocity of any particle at *t* depends on position of all the other particles at *t***
- **ignorance of exact initial particle positions**
- ® **quantum probabilities**

# Space-time ontology $\Psi$ *and* $X$: Bell-Bohm QFT: particles

- law of the temporal evolution of the particles amended to make room for stochastic events of particle creation and annihilation
- empirical predictions of textbook QFT grounded in an ontology of particles

# Bohmian QG

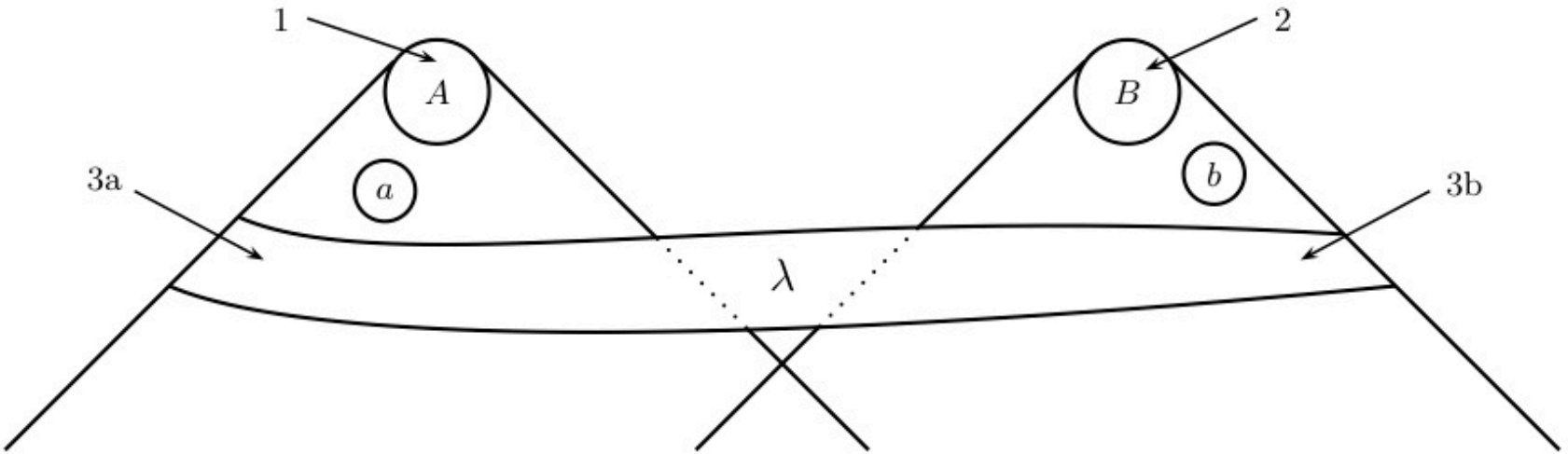
- **Wheeler-deWitt equation: universal, stationary wave-function**
- **law that is applied to initial conditions consisting in initial configuration of spatio-temporal, local beables (Planck-sized bits of matter and / or space) (= the additional ("hidden") variable which is the referent of the formalism)**
- **law yields transition from one configuration of local beables to next configuration, thereby generates temporal development (= builds up four-dimensional space-time)**
- **stationary wave-function implies problem of time iff ontology of type *only* Ψ (A and B) presupposed**
- **in Bohmian QG, timeless, stationary wave-function coherent, since wave-function is supposed to be the *law* that provides for transition from one configuration of local beables to next one**

# Ψ *and X*: other dynamics

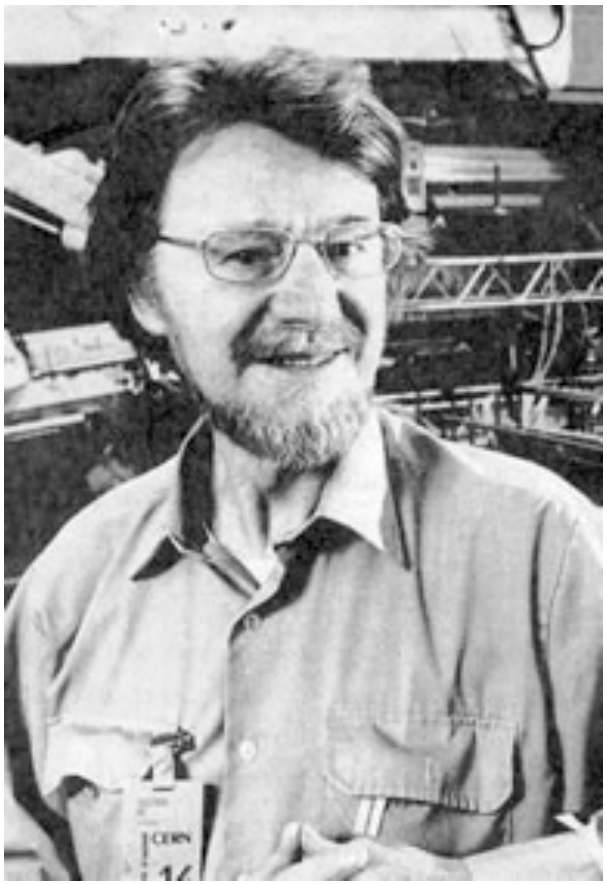
# Ghirardi, Rimini & Weber (1986)

- **GRW dynamics instead of Schrödinger dynamics:** dynamics with "collapse" of the wave-function
- no extension to QFT or QG known (as yet)
- **in any case, Ψ *and X*:** wave-function Ψ in configuration has the function to represent development of configurations of local beables in four-dimensional space-time
- **Ghirardi: *X* = density of stuff (mass density) in space-time**
- **Bell: *X* = flashes occurring at space-time points**

® four-dimensional space-time and entities located in it fundamental, quantum state Ψ = law for their development


1
2
A
B
3a
a
b
3b
λ

# Quantum non-locality
# Bell's theorem (1964)



- non-locality:

$$P_{a,b}(A \mid B, \lambda) \neq P_a(A \mid \lambda)$$

$$P_{a,b}(B \mid A, \lambda) \neq P_b(B \mid \lambda)$$

- applies also in QFT
- Bell (1984): "For me then this is the real problem with quantum theory: the apparently essential conflict between any sharp formulation and fundamental relativity. That is to say, we have an apparent incompatibility, at the deepest level, between the two fundamental pillars of contemporary theory."

# The non-locality problem

- **ontology of type *only* Ψ: no problem with relativity physics, since not realist about relativity physics: four-dimensional space-time with something located in it does not exist.**
- **ontology of type Ψ *and X*: Ψ law for temporal development of *X*, with *X* = entities in four-dimensional space-time**
- **realism about Ψ → real correlations between space-like separated entities A and B, in the sense that temporal development of A depends on temporal development of B (and *vice versa*)**
- **no Lorentz-invariance possible (otherwise, ontologically undetermined which A depends on which B)**
- **unique foliation of space-time into spatial hypersurfaces that are ordered in time**
- **no commitment to ether, distribution of mass in the universe may fix foliation of space-time (as in Bohmian QG)**

# Conclusion

- EITHER four-dimensional space-time and entities located in it do not exist
  - shift task of physics from accounting for empirical phenomena to accounting for the appearance of such phenomena to persons
- OR four-dimensional space-time and entities located in it are fundamental
  - no emergence of time or of space-time & quantum non-locality implies commitment to unique foliation of space-time