Title: A Pilot Wave(s) Theory of Exclusively Local Beables

Date: Sep 28, 2009 03:00 PM

URL: http://pirsa.org/09090086

Abstract: After reframing the question of the status of the quantum state in terms of J.S. Bell's "beables", I will sketch out a new theory which -- though nonlocal in the sense required by Bell's theorem -- posits exclusively local beables. This is a theory, in particular, in which the quantum mechanical wave function plays no role whatsoever -- i.e., a theory according to which nothing corresponding to the wave function actually exists. It provides, therefore, a concrete example of how the wave function might be regarded as (at best) "epistemic".

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...and the status of the quantum state therein

Related paper: arXiv:0909.4553

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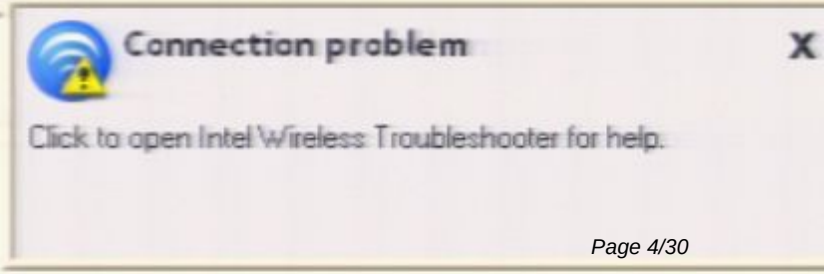

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Outline

- Background thoughts
- Motivation for a Pilot-Wave TELB
- P-W TELB: a foothold
- An actual (but somewhat ridiculous) P-W TELB
- The big picture
- Questions

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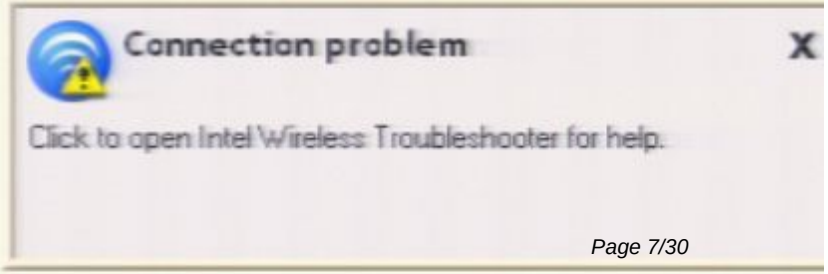

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The big question:

- What is the status of ψ ? Does it refer (directly) to something real, or only to our knowledge, or something else entirely?

- Important point: the question is not: "What's the status of ψ – epistemic, or ontic?" … but rather, or at least first: what's the status of ψ for some particular candidate theory. (And separately – probably later – which theory do we think is *true*?)
  - subsidiary question we'll need to return to: what's a theory?

- Spekkens/Harrigan classification: ψ-ontic vs. ψ-epistemic theories…

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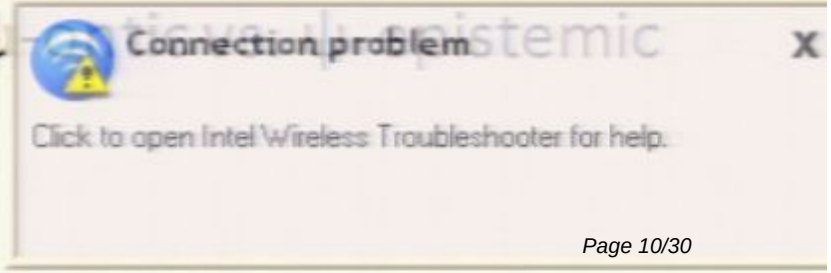

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Some background thoughts/concerns

1. The terminology "ψ-epistemic" may group together theories (or people or worldviews) which are fundamentally different. Consider some apparent examples of each type of theory:
   - Ψ-ontic: dBB, GRWm, GRWf, MWI, …
   - Ψ-epistemic: Copenhagen (?), Quantum Bayesianism, Ballentine's Statistical Interpretation, …

   - The ψ-ontic theories/people are "realist" about the wave function / quantum state.
   - The ψ-epistemic theories/people are "anti-realist" about the wave function / quantum state… but also (in various ways, explicitly or implicitly) anti-realist about the micro-world in general. At least, it is never too clear what (if anything) is being posited *instead* of ψ as the ontology for the theory.

   ➢ In Bell's terminology, ψ-ontic vs. ψ-epistemic seems to divide theories that posit unambiguous beables (including ψ) from those which refuse – on some kind of principle – to posit beables *at all*.

My interest is in theories that are anti-realist about ψ, but realist in general (even about little stuff) and so (like dBB, GRW, MWI, etc.) posit a clear and unambiguous slate of beables… which just happens not to include ψ.

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Concern #2:

- From this realist standpoint, classifying a theory as "ψ-epistemic" is very odd.
  - It would seem to mean: according to the theory, the wave function ψ somehow captures or contains *information* about, but does not directly describe, whatever *is* physically real. But then it should be possible to formulate the theory without ever even *mentioning* ψ – which, after all, according to the theory, doesn't really *exist*.

- But then, it's funny to classify it as "ψ-epistemic"...
  - Is modern, post-Lavoisier chemistry "phlogiston-epistemic"?
  - Is modern celestial mechanics "epicycle-epistemic"?
  - Is relativity theory "ether-epistemic"?

- Recommendation: instead of classifying by the status of one particular proprietary object (which may or may not exist according to different theories), we should instead classify physical theories based on *what they say exists* – what their *beables* are.
  - Thus, we have theories according to which ψ is a beable... and theories according to which only *other* things exist, i.e., theories according to which ψ doesn't exist, i.e., is nothing. That it may still serve some practical (epistemic) purpose for human theorists to think about ψ – even if it doesn't exist – seems to be of (at best) secondary importance.

Concern #3:

- The particular criterion proposed by Spekkens & Harrigan for deciding whether (for a given candidate theory) ψ really exists (or is instead merely epistemic) seems problematic to me. It says: if the ontic state (*openly* posited by a theory) uniquely determines a ψ, then ψ is also ontic.
  - Generally: anything that is uniquely defined by stuff that's real, is also real.
- So…
  - The center of mass point for a system is part of the ontology?
  - The phase space point (and so phase space?) is part of the ontology?
  - The field you get by subtracting the magnetic field three inches to the left (of a given point) from the electric field three inches to the right (of that point) is part of the ontology?
  - Both the "mass field" (m) and "flashes" (f) are already part of the ontology for "bare GRW"

- I would propose instead the following sufficient condition for "ontic status": if you can't formulate the theory without X, then X is ontic for that theory.
  - Particle positions are ontic for (Newtonian) classical physics
  - Electromagnetic potentials might not be ontic (because you can formulate classical electromagnetism in terms of the fields, instead) but they might be ontic (because you can formulate the theory in terms of them, too), etc.

Upshot:

- Lots of theories are formulated in terms of ψ, so there are lots of (very different!) theories to contemplate in which ψ is ontic. The interesting question (to me) is: can you formulate a theory (that is somehow empirically equivalent to QM, or – in the spirit of GRW – close enough FAPP) in which ψ simply doesn't appear?

- For such a theory (and, I think, only for such a theory) would it be possible to suggest that ψ is not among the beables, i.e., that ψ doesn't exist, isn't ontic, is "merely epistemic", or whatever.

  - I simply don't care about whether or not ψ then turns out to be uniquely defined by the beables, or not.

- Various people have suggested things in this direction, but none of them (to my knowledge) has a plausible ontology. What I want to propose is a new (actually old but long-forgotten) direction in which to search for more plausible theories of this sort.

However:

- The motivation for the kind of theory I'm interested in is not just to construct an example of a theory for which ψ is non-ontic (and which has a plausible ontology).
- Rather, for me, the motivation is *just*: to construct a theory which has a plausible ontology. For me, this implies finding a theory in which ψ isn't ontic, because I just don't know how to understand what it would mean for ψ to *be*. In Bell's terminology, it's a non-local beable – at best, some kind of physically real field on an abstract / high-dimensional space.
- My attitude about where we should get beliefs about "plausible ontology"...
  - Bell: "Is it not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave?" (6 possible worlds)
  - But... a wave that "propagates not in 3-space but in 3N-space"?! (QM for cosmologists)
- So for me the "fantasy theory" is a believable Pilot-Wave Theory of Exclusively Local Beables
  - Pilot-Wave, because to me that's the ontology that seems (far and away) most natural in an abductive, pre-theoretical sense
  - TELB, because the waves that do the piloting will only have this status if they are local beables

Einstein on ψ-as-nonlocal-beable

Einstein on Schrödinger's introduction of the ψ-field on configuration space:

- "Schrödinger's works are wonderful – but even so one nevertheless hardly comes closer to a real understanding. The field in a many-dimensional coordinate space does not smell like something real." (June 18, 1926, to Ehrenfest)
- "The method of Schrödinger seems indeed more correctly conceived than that of Heisenberg, and yet it is hard to place a function in coordinate space and view it as an equivalent for a motion. But if one could succeed in doing something similar in four-dimensional space, then it would be more satisfying." (June 22, to Lorentz)
- "Of the new attempts to obtain a deeper formulation of the quantum laws, that by Schrödinger pleases me most. If only the undulatory fields introduced there could be transplanted from the n-dimensional coordinate space to the 3 or 4 dimensional!" (August 21, to Sommerfeld)
- "Schrödinger is, in the beginning, very captivating. But the waves in n-dimensional coordinate space are indigestible..." (August 28, to Ehrenfest)

...probably explains his coolness to de Broglie's and Bohm's P-W theories!

Pilot-Wave TELB: a foothold?

- Hence, dBB might seem like the last place to start if you want to find a TELB.
  - e.g., Bell: "Note that in this compound [wave-and-particle(s)] dynamical system the wave is supposed to be just as 'real' and 'objective' as say the fields of classical Maxwell theory – although its action on the particles ... is rather original. *No one can understand this theory until he is willing to think of ψ as a real objective field rather than just a 'probability amplitude'. Even though it propagates not in 3-space but in 3N-space.*" (QM for cosmologists)

- Nevertheless, this theory provides a natural starting point for the attempt to construct a TELB, because the actual particle positions in the theory allow one to construct "one particle wave functions" (CWFs) which live on physical space:

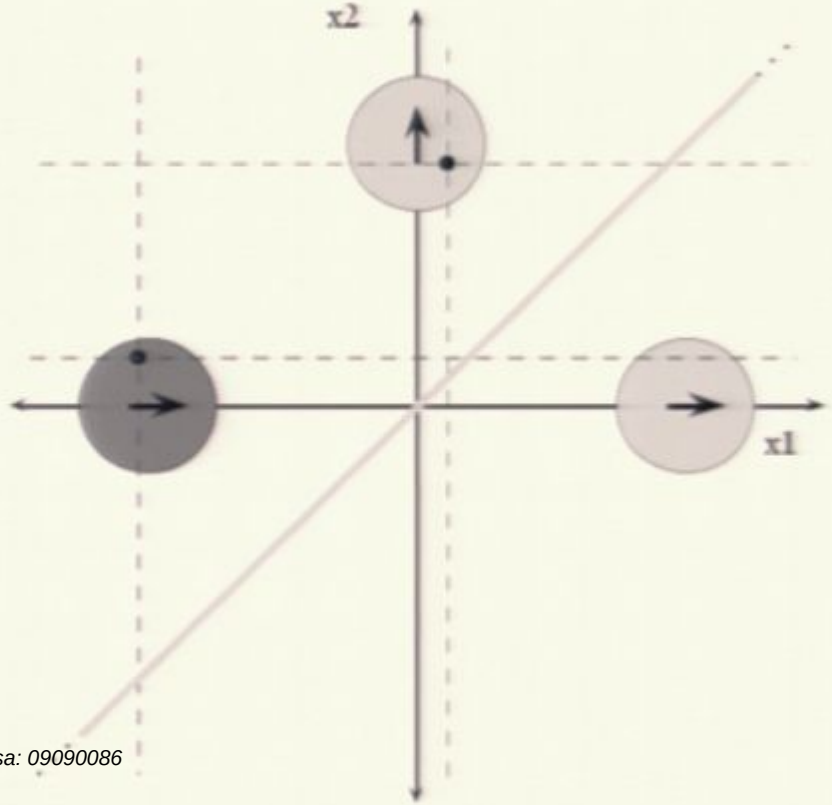
$$\psi_1(x,t) = \psi(x1,x2,t)\,|_{x1 = x,\ x2 = X2(t)}$$

- The usual pilot-wave "guidance formula" for each individual particle can be written in terms of just its CWF.

- So one is naturally led to contemplate a pilot-wave theory in which the CWFs (for all particles) – but not the configuration-space WF – are beables. Such a theory would replace the one function on 3N-space with N functions on 3-space... just what "everybody was trying to do" in the late 20s. (Eckart via Heilbron via Wessels)

Why CWFs alone are inadequate

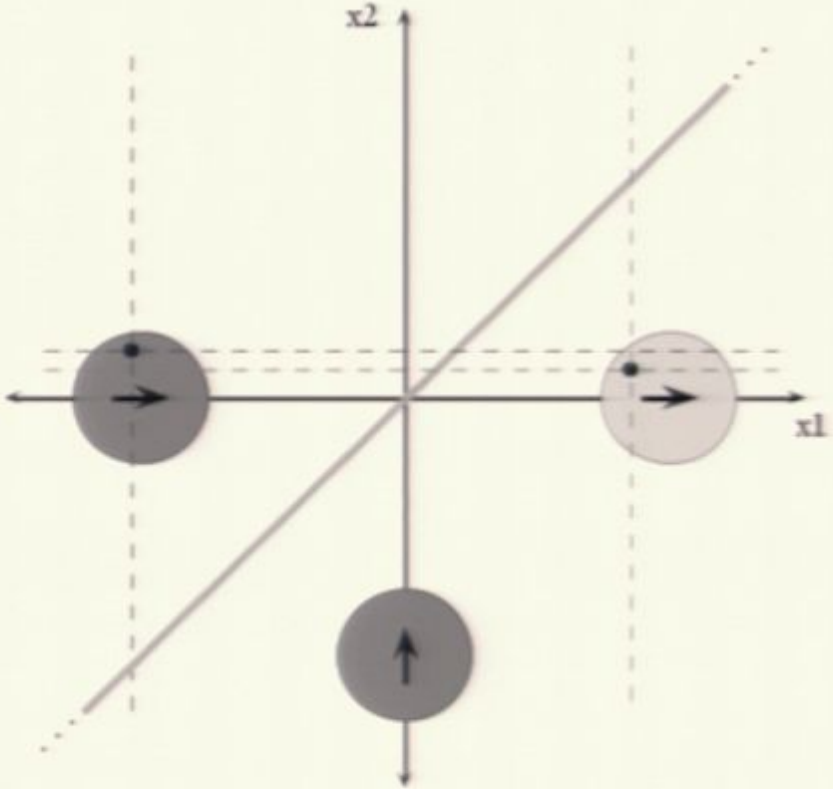
- Suppose two particles with a short-range interaction move in 1-D, so the configuration space is 2-D. Consider the scattering experiment pictured here in the 2-D configuration space:



- For some initial conditions, particle 1 will tunnel through particle 2; for others, there will be a collision and particle 1 will end up at rest.
- Before – and then again after – the interaction, the CWFs for each particle are the familiar one-particle wave functions we'd naturally associate with a particle in such a state... without any additional "collapse postulates"!
- But the proper dynamics for the particles cannot be reproduced with just particles and CWFs.

Why not?

- Consider the alternative (note: entangled!) initial condition represented in this picture:



- Dynamics is very different: now particle 1 is guaranteed to "tunnel through" particle 2.
- But the initial particle positions and CWFs can be identical.
- Lesson: CWFs necessarily fail to capture information about entanglement, which is dynamically relevant. So the CWFs (and particle positions) alone are insufficient beables to define a theory that is dynamically equivalent to ordinary, configuration-space pilot-wave theory (which we know is empirically adequate).

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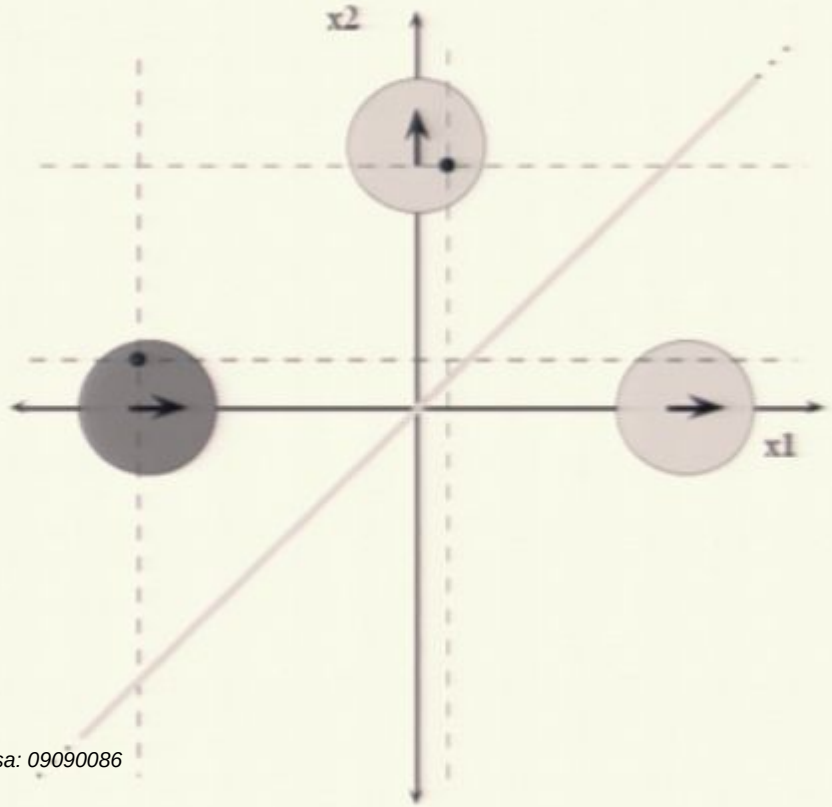

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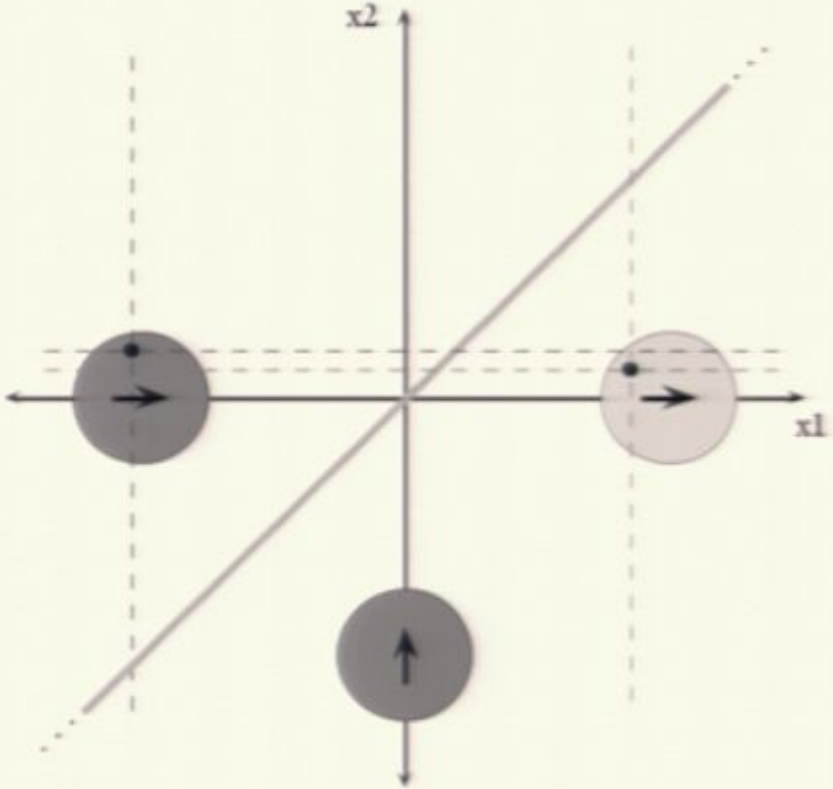

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Formally:

- How does, e.g., the CWF of particle 1 evolve in time?

$$\frac{d}{dt}[\psi(x,x_2,t)|_{x_2=X_2(t)}]=\frac{\partial\psi(x,x_2,t)}{\partial t}|_{x_2=X_2(t)}+\frac{dX_2(t)}{dt}\frac{\partial\psi(x,x_2,t)}{\partial x_2}|_{x_2=X_2(t)}$$

...and so...

$$i\hbar\frac{\partial\psi_1(x,t)}{\partial t}=-\frac{\hbar^2}{2m_1}\frac{\partial^2\psi_1(x,t)}{\partial x^2}+V[x,X_2(t),t]\,\psi_1(x,t)$$
$$-\frac{\hbar^2}{2m_2}\frac{\partial^2\psi(x,x_2,t)}{\partial x_2{}^2}|_{x_2=X_2(t)}$$
$$+i\hbar\frac{dX_2(t)}{dt}\frac{\partial\psi(x,x_2,t)}{\partial x_2}|_{x_2=X_2(t)}$$

The last two terms cannot be written in terms of any of the beables posited so far (particle positions and CWFs)...

...so posit some new ones!

- Namely:

$$\psi_1'(x,t) \equiv \frac{\partial \psi(x,x_2,t)}{\partial x_2}\Big|_{x_2=X_2(t)}$$

and

$$\psi_1''(x,t) \equiv \frac{\partial^2 \psi(x,x_2,t)}{\partial x_2^{\,2}}\Big|_{x_2=X_2(t)}$$

and so on.

- Then the stuff needed to define the time-evolution of the CWF is "in the ontology". Of course, the newly-posited fields will also evolve in time, and we can determine the time-evolution laws (needed to reproduce the particle trajectories of the configuration space theory) by playing the same game again.

A (contrived, trivial, ridiculous) Pilot-Wave(s) TELB

- Each "particle" consists of: a literal particle (with a definite position), a pilot-wave field, and an infinite number of "entanglement fields" obeying a dynamics that is contrived to reproduce, for the particle positions, the same trajectories one gets from ordinary, configuration-space pilot-wave theory.
- This is a TELB.
- Instead of replacing the one function on 3N-space with N functions on 3-space, we replace the one function on 3N space with a countable infinity of functions on 3-space.
- Presumably one could do better, e.g., find some way to define a finite number of fields on physical space that gives a FAPP "good enough" reproduction of the usual pilot-wave dynamics, and hence of the predictions of ordinary QM.
  - More efficient expansions, then truncate?
  - Different "field" beables?
  - Replace some beables with more complex dynamics?

The big picture:

- The "forgotten argument" for the pilot-wave ontology is that it provides (for the kinds of experiments, involving single particles, that made people create QM in the first place and which are still taught to all students as the evidentiary basis for QM) an extremely natural, simple, straightforward explanation.
- But, despite its many other virtues, the usual de Broglie – Bohm pilot-wave theory can't figure in such explanations. The only wave that really exists according to the theory is the "big" one – so it's impossible to say, for example, that "something goes through both slits and interferes and then pushes the particle toward places where the wave intensity is high."
- So what we should really want is a theory that starts with the ontology that allows us to make sense of such experiments (namely: N copies of particle-and-guiding-wave) – and then incorporates "entanglement" (either by positing additional beables, or more complicated dynamics, or both) – and does it in a believable way.
- The theory I sketched here isn't that. But maybe it can function as a gesture in the direction of a certain research program that I think is worth pursuing.

Questions and Comments:

- Despite my suggestions that the usual quantum state ψ isn't a beable – isn't ontic – for this "pilot wave(s) TELB", it comes out as ontic according to the Spekkens/Harrigan criterion. So maybe there's more to say about the status of ψ in this theory...
- Should one be bothered by nonlocal beables when one has anyway to include nonlocal dynamics? If not, why bother with this program of chopping up the big ψ into a bunch of little waves?
- Is a TELB with explicitly nonlocal dynamics more, or less, consistent with Special Relativity than a Lorentz invariant theory in which ψ is a beable (say, something like Tumulka's rGRWf)?
  - Earman's "pre-locality", etc.
- If one is "mildly embarrassed" about the non-local-beable status of ψ in ordinary Bohmian Mechanics (as I am), why not regard it as nomic instead?