Measurement-based, Lorentz-covariant Bohmian trajectories of multiple photons

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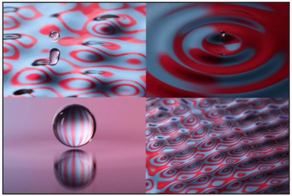
Bohmian mechanics[1] **(de Broglie-Bohm/pilot wave theory)**[2]

- Deterministic, nonlocal, hidden-variable theory
  - $\psi(x,t) \Rightarrow$ guiding potential $\Rightarrow$ particle dynamics $\Leftrightarrow$ velocity field
- $\rho(x,t) = |\psi(x,t)|^2$ is the density of particle trajectories



[1] David Bohm Phys. Rev. 85, 166 (1952)

[2] Most surveys report that $\sim 0 - 2\%$ of physicists prefer Bohmian mechanics over other interpretations

Nonrelativistic Bohmian mechanics and weak values

Wiseman: Connection between weak values and Bohmian-type velocity field of nonrelativistic particles,[3]

$$V(x,t) = \frac{{}_{\langle x|}\langle \hat{p}_w \rangle_{|\psi(t)\rangle}}{m} \Leftrightarrow \frac{j(x,t)}{\rho(x,t)}$$

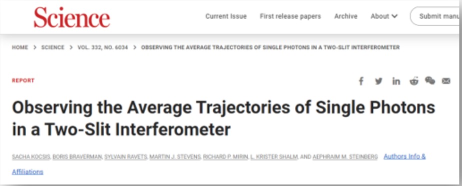
Weakly measure $\hat{p}_x$, strong measurement reveals system to be in $|x\rangle$ i.e. particle at (x,t).

Weak value definition:[4] first-order term for weak interaction between system and pointer

$${}_{\langle x|}\langle \hat{p}_w \rangle_{|\psi(t)\rangle} = \mathrm{Re} \frac{\langle x|\hat{p}_w|\psi(t)\rangle}{\langle x|\psi(t)\rangle}$$

[3] Wiseman, New J. Phys. **9** 165 (2007)
[4] Aharanov, Albert, and Vaidman, PRL **60** 1351 (1988)

NONRELATIVISTIC BOHMIAN TRAJECTORIES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REPORT

Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer

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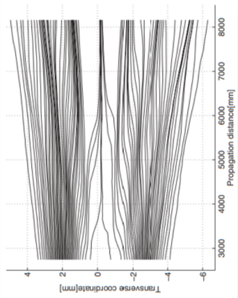

Figure 1: Nonrelativistic Bohmian trajectories in a double-slit interferometer, Kocsis et. al. Science, **332** 6034 (2011)


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ARTICLE

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Check for updates

Relativistic Bohmian trajectories of photons via weak measurements

Joshua Foo [1✉], Estelle Asmodelle [1], Austin P. Lund [1,2] & Timothy C. Ralph [1✉]

Lorentz covariant Bohmian mechanics

We extended Wiseman's formalism to relativistic regimes!

$$V(x,t) = \frac{\mathrm{d}x}{\mathrm{d}\tau}\frac{\mathrm{d}\tau}{\mathrm{d}t} = \frac{p}{E} \Rightarrow \frac{{}_{\langle x|}\langle \hat{p}_w \rangle_{|\psi(t)\rangle}}{{}_{\langle x|}\langle \hat{H}_w \rangle_{|\psi(t)\rangle}} \Leftrightarrow \frac{j_{\mathrm{KG}}(x,t)}{\rho_{\mathrm{KG}}(x,t)}$$

Trajectories satisfy **relativistic velocity addition** and **quantum-mechanical continuity**. Optics limit $\Rightarrow \rho_{\mathrm{KG}}(x,t) \geq 0$.

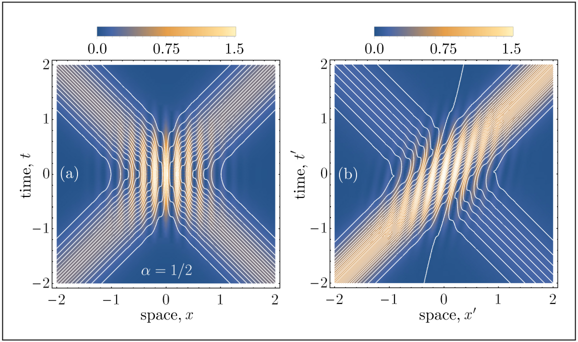


Figure 2: Photon trajectories. J. Foo, E. Asmodelle, A.P. Lund, T.C. Ralph, *Nature Comms.* **13** 4002 (2022).

The photon metric

nonrelativistic dynamics $\longrightarrow$ relativistic dynamics

guiding potential $\longrightarrow$ guiding metric

Alcubierre (photon) metric

"Warp drive" solution in GR:

$$\mathrm{d}s^2 = -(1 - v_s^2)\mathrm{d}t^2 - 2v_s\mathrm{d}x\mathrm{d}t + \mathrm{d}x^2$$

Define $v_s = (|V(x,t)| - 1)\,\mathrm{sgn}(V(x,t))$ then the speed of light according to faraway observers is

$$c = v_s + \mathrm{sgn}(V(x,t)) = V(x,t).$$

Multiple photons?

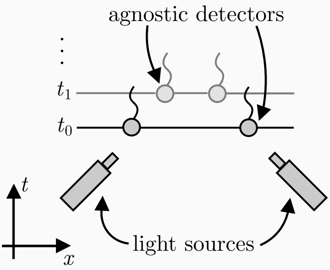
Weak value description of relativistic trajectories for multiple interacting photons?

$$\text{velocity}\Big|_{\mathrm{WV}} \underset{???}{=} \text{velocity}\Big|_{\mathrm{KG}}$$

Constructing two-photon velocity fields

Operational approach

- Initially separable state of the two photons
- Agnostic detectors
- Weak value velocities constructed from detector measurements



Constructing two-photon velocity fields

Multiparticle Klein-Gordon Approach

- Relativistic Klein-Gordon wavefunctions
- Symmetrise in spacetime

$$\psi(t_1, x_1, t_2, x_2) = \psi_1(t_1, x_1)\psi_2(t_2, x_2) + \psi_1(t_2, x_2)\psi_2(t_1, x_1)$$

- Evaluate velocity fields along a single timeslice

$$V_i(t_1, x_1, t_2, x_2) = \left.\frac{j_i(t_1, x_1, t_2, x_2)}{\rho_i(t_1, x_1, t_2, x_2)}\right|_{t_1=t_2=t}$$

where $i = 1, 2$ identifies the particle

They yield the same result!

$$\text{velocity}\Big|_{\text{WV}} = \text{velocity}\Big|_{\text{KG}}$$

Relativistic Two-Photon Interaction

Photons exhibit **nonclassical interference** due to their **indistinguishability** $\Rightarrow$ photon-bunching.

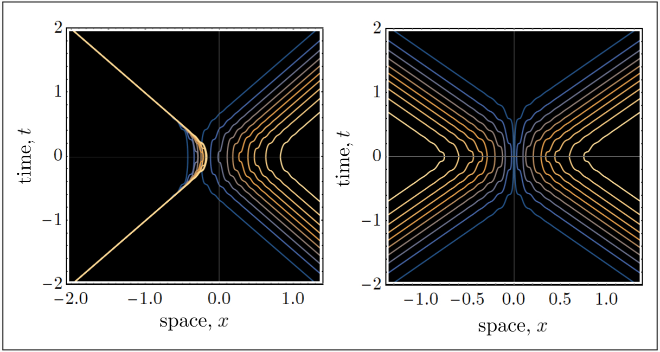


Figure 3: Bohmian trajectories for two indistinguishable photons. Colours indicate pairs of photons.

Continuity

Quantum-mechanical continuity: density of trajectories matches quantum-mechanical density ρ_{KG}, holds for all time.

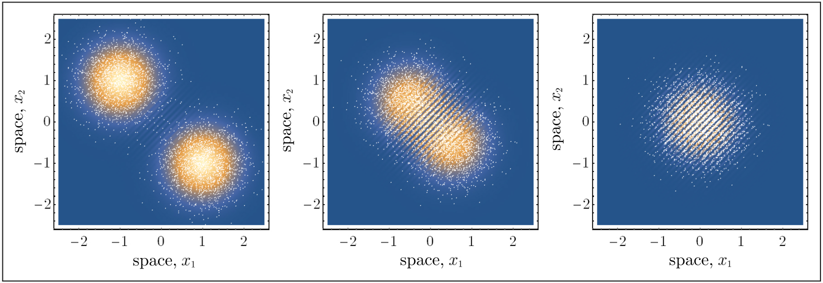


Figure 4: Randomly sampled initial conditions, demonstrating continuity of trajectories.

Lorentz Boosts

Lorentz boost: $x \mapsto \gamma(x - vt)$ and $t \mapsto \gamma(t - vx)$.

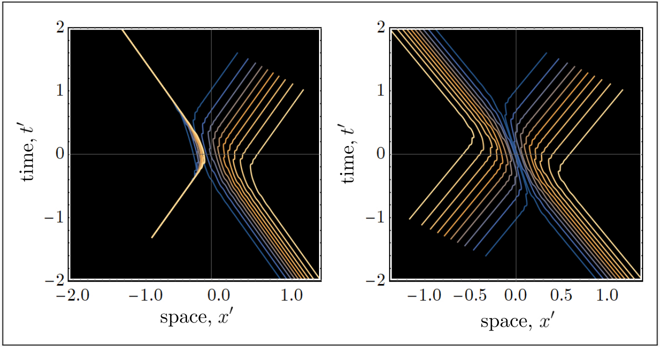


Figure 5: Boosted trajectories. J. Foo, A.P. Lund, T.C. Ralph, *arXiv:23...*

Conclusions

Extended WV Bohmian framework to relativistic multiparticle interactions

- **Grounding** two-photon Bohmian trajectories in **weak values**

This gives us hope that our approach extends to:

- Entangling interactions
- Trajectories in curved space/gravitational potentials
- Particle production and annihilation processes

Email **jfoobles@gmail.com** for questions, suggestions, collaboration! Twitter: (at)jfoobles

Life in a Bohmian Universe

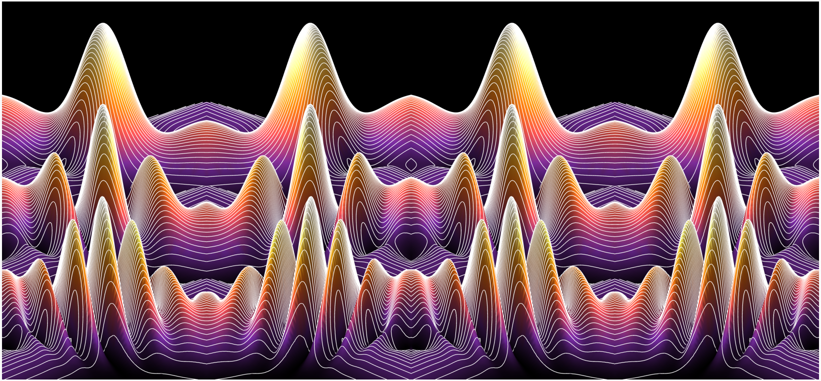


Figure 6: Front cover of the CQC2T annual report. *Life in a Bohmian universe*, J. Foo.

PHOTONS ARE LIKE BASKETBALLS

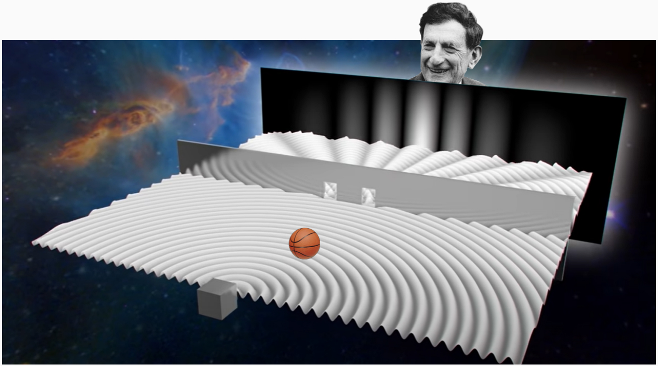


Figure 7: 3-Minute Thesis slide, J. Foo.