Title: Can reality depend on the observer? Lessons from QBism and Relational Quantum Mechanics (RQM)

Speakers:

Series: Quantum Foundations

Date: October 08, 2021 - 2:00 PM

URL: https://pirsa.org/21100017

Abstract: There are many different interpretations of quantum mechanics. Among them, QBism and Rovelli's Relational Quantum Mechanics (RQM) are special because they both propose that reality itself is produced relative to "observers". For QBism, observers are defined as rational decision-making "agents", while in RQM any physical system can be an observer. But both interpretations agree that reality is shaped by what happens when observers encounter the world external to themselves. In this talk I will try to understand what these interpretations imply for the ongoing problem of defining an ontological model of quantum mechanics.

Can reality depend on the observer? Lessons from QBism and Relational Quantum Mechanics (RQM)

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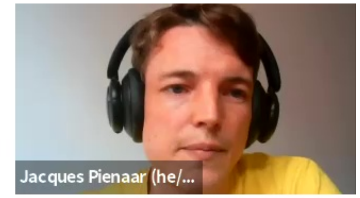
Overview:

- **QBism** and Rovelli's **Relational Quantum Mechanics** (RQM) are interpretations of quantum mechanics notable for saying that **facts** are relative to **observers**.
- I recently wrote some papers about QBism and RQM (arXiv:2108.13977, arXiv:2107.00670). Rovelli & Di Biagio wrote a reply (arXiv:2110.03610).
- But those papers do not discuss **locality**.
- Today I will argue two main points:
- (1) if space-time is treated as an effectively classical background, then both **QBism and RQM are explicitly local** with respect to this background.
- (2) However, both QBism and RQM imply that space-time must ultimately be treated quantum mechanically. When we do this, we find that the concept of **"locality" is not well-defined in general.**
- Hence QBism and RQM admit of ontological models that are as "local" as possible, granted the quantum nature of space-time.

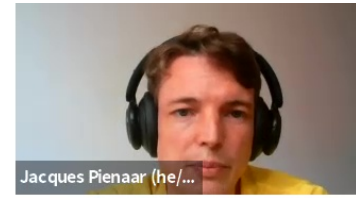
Fact relativity in **QBism**:



- "**fact/event**" = measurement outcome
- "**observer**" = decision-making agent
- **Basic postulate:** a **measurement outcome** is a *personal experience* of the **agent** who performs the measurement.
- What the **agent** experiences really happens for them (that is, it constitutes an element of reality *relative to them*).
- I will allow that the same element of reality can be experienced by several agents, but this is strictly optional.
- **Therefore:** the **facts/events** of QBism (**measurement outcomes**) are relative to the **observers** of QBism (**agents**).

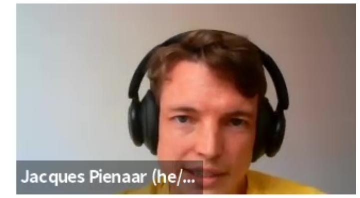
Fact relativity in RQM:

- "**fact/event**" = a natural **quantum event** that occurs when any two physical systems interact
- "**observer**" = any designated **physical system**
- **Basic postulate:** a **quantum event** happens *relative to the systems involved in the physical interaction*, either one of which can be designated as the **observer** of that event
- The **quantum events** correspond to elements of reality, but events for one observer may not be events for another.
- The same element of reality can be a quantum event relative to several observing systems.
- **Therefore:** the **facts/events** of RQM (**quantum events**) are relative to the **observers** of RQM (**interacting systems**).



Time orientation and free actions:

- In both RQM and QBism, the observer has an associated time orientation from their "past" to their "future";
- Operationally, some **events** can be considered as **free actions** relative to a given **observer**;
- A **free action** is necessarily independent of events outside its future light-cone;
- In QBism, **free actions** are the voluntary actions of free-willed **agents**;
- In RQM, they are simply **quantum events** that happen to be independent of any events in the past of the **observing system.**



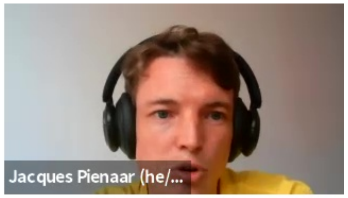
Three "layers" of a physical theory

- **Operational:** Deals with probabilities **P(x|a)** to observe outcomes **x** after performing actions **a** (eg. preparations, transformations, and measurements).
- *Purpose:* Apply the theory to laboratory practices and observations.

- **Mathematical:** Expresses the theory in terms of abstract mathematical structure that streamlines calculations. Eg vectors in Hilbert spaces, C*-algebras, etc.
- *Purpose:* Bring rigor and precision to the theory, do calculations with it.

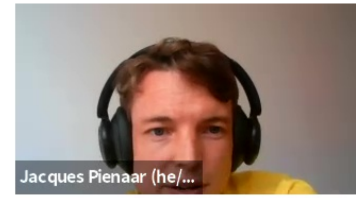
- **Ontological:** Formally represents the "elements of reality" and rules governing their behaviour.
- *Purpose:* explain the features of the other two layers by translating them into a "metaphysical worldview" of the universe and our place in it.

Three layers of "locality":



- **Non-signaling: (operational)** Observations **y** cannot be affected by actions **a** performed outside its past light-cone. (Formally, we must have $\mathbf{P(y|a) = P(y)}$).
- **Formalism locality (mathematical):** Calculations pertaining to any region of space-time employ only mathematical objects associated with that region. *Example:* when doing calculations in a region of space-time **R** using algebraic quantum field theory, you only need to use the field algebra defined in the region **R**.
- **Ontological locality:** An element of reality **e** *(not necessarily observable)* cannot be affected by actions **a** performed outside its past light-cone.

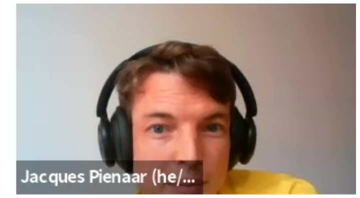
"Locality" in QBism:



- Here is how QBism uses **relative facts** to justify **ontological locality**:

> What the usual story overlooks is that the coming into existence of a particular measurement outcome is valid only for the agent experiencing that outcome. [. . .] Although each [agent] experiences an outcome to their own measurement, they can experience an outcome to the measurement undertaken by the other only when they receive the other's report. Each of them applies quantum mechanics in the only way in which it can be applied, to account for the correlations in two measurement outcomes registered in his or her own individual experience. And as noted above, **experiences of a single agent are necessarily time-like separated**. The issue of non-locality simply does not arise.

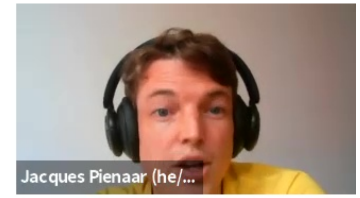
"Locality" in RQM:



- And here is how RQM uses **relative facts** to justify **ontological locality**:

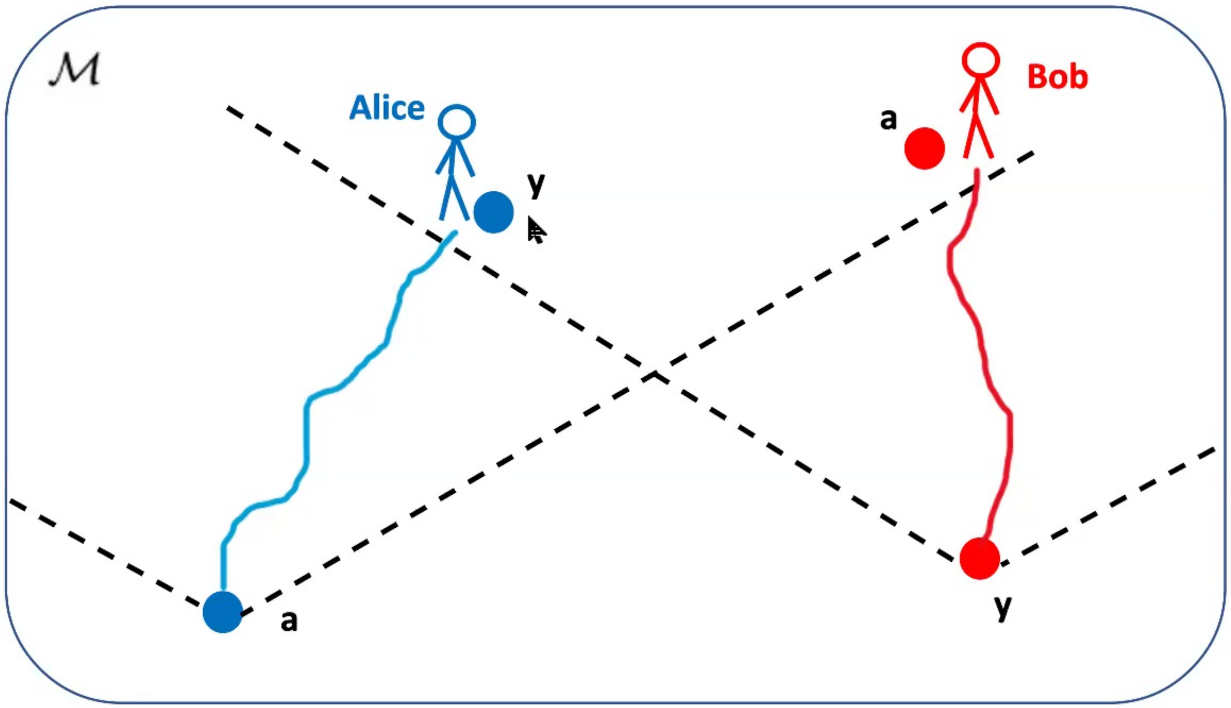
> [I]f one sticks to a particular observer, a relational beable is nothing but a quantum event. It will not be as absolute as Bell would have expected, because talking about 'quantum events' still requires us to first fix a reference observer, but a beable can still be conceived as an 'element of reality with respect to the reference observer'. Now, **given a reference observer O, the only physically meaningful beables lie in the past cone of O.** Indeed for O, it is a matter of metaphysical faith to attribute an existence to events beyond the scope of its practical experience (future or space-like separated events), but it is a matter of experimental facts to attribute an existence to events in its past cone.

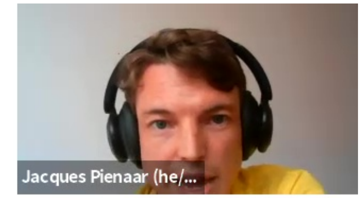
"Locality" in QBism and RQM



- Both are making the same argument using different words. What they are saying boils down to:

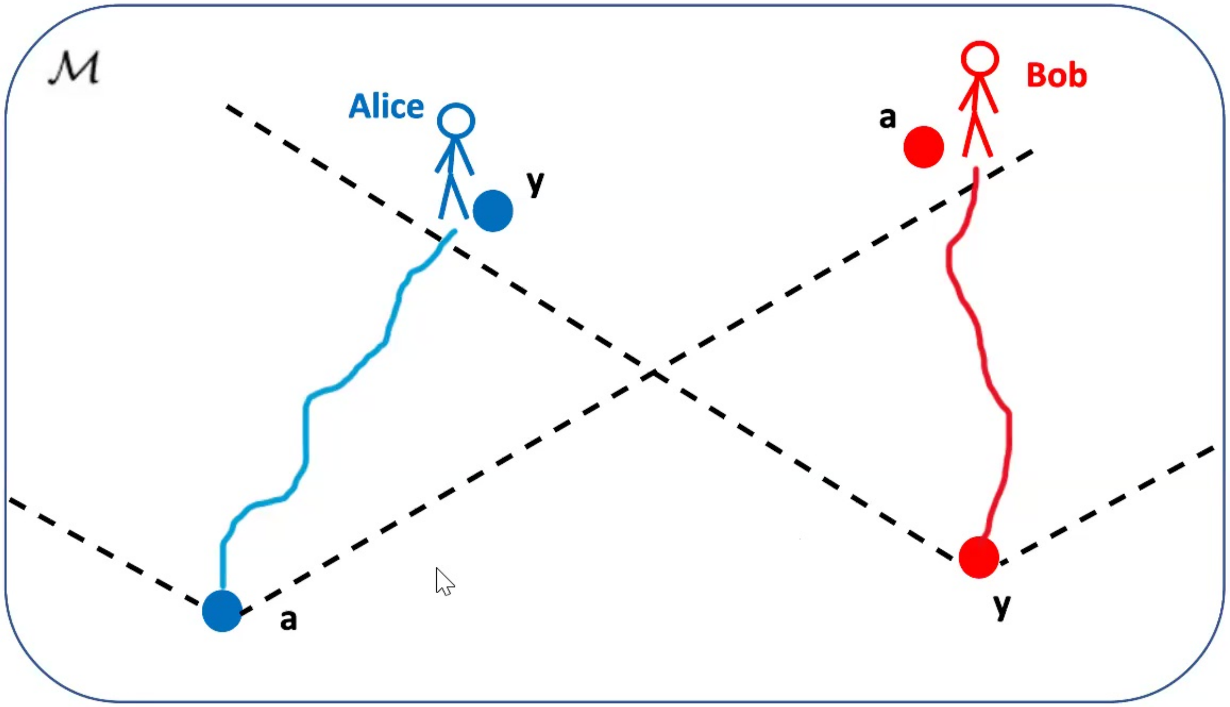
- (1) Locality must be understood relative to a given observer (say Alice);
- (2) According to **relative facts**, relative to Alice, Bob's measurement outcome **y** only becomes an element of reality when Alice observes it;
- (3) Since she follows a time-like trajectory through space-time, she can only observe **y** in the time-like future of her action **a**;
- (4) Therefore, relative to Alice, the outcome **y** is always necessarily in the time-like future of her action **a**, so **ontological locality** is upheld relative to Alice, regardless of the correlations between **a** and **y**.

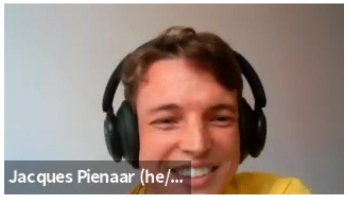




a = Alice does something (eg pulls a lever)

y= Bob observes something (eg detector click).

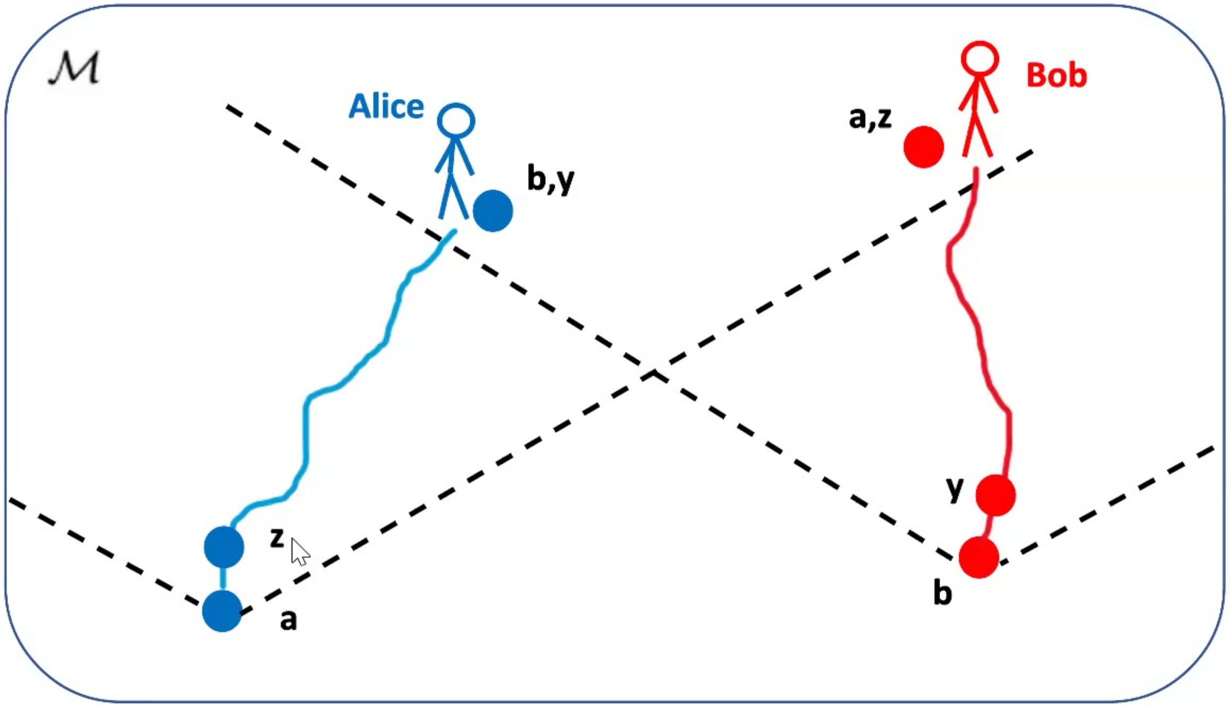


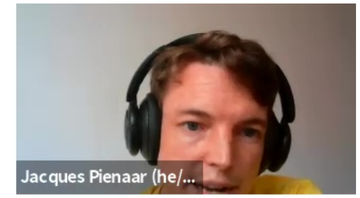


a = Alice does something (eg pulls a lever)

y= Bob observes something (eg detector click).

(5) For Bob, the action **a** occurs when he learns of it from Alice, hence it lies in the time-like future of his observation of **y**. He can therefore explain any correlations between them by assuming that **y** and **a** have a common cause, or even that **y** causes **a.** (Hence Bob disagrees with Alice about whether **a** is a free action, but such disagreement is allowed in QBism and RQM.)



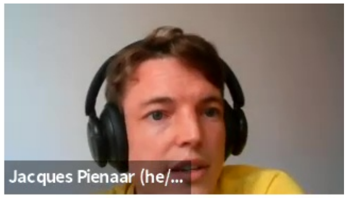


a = Alice does something (eg pulls a lever)

y= Bob observes something (eg detector click).

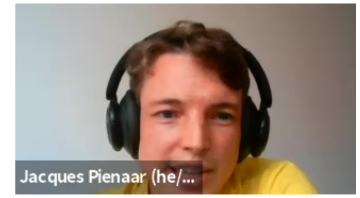
(Bell experiment).
Relative to Alice, **b,z,y** are in the causal future of her action **a**; while relative to Bob, **a,z,y** are in the causal future of his action **b**.

Objections to locality in RQM and QBism



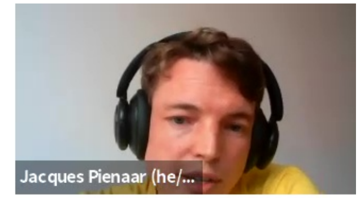
- **Objection 1:** Even granted the events **a** and **y** are time-like separated for Alice (and so are the events **b** and **z**, relative to Bob) they still need to explain the Bell inequality violations in the joint statistics **P(y z|a b)**. How do they do that?
- **Objection 2:** Since the argument applies to any correlations between **a** and **y**, it seems like it would also work for correlations that signal across arbitrary space-like separations between Alice and Bob. But that means it cannot explain why quantum theory is **operationally non-signaling.** (Cavalcanti, arXiv:2008:05100)
- **Objection 3:** The argument presupposes that Alice and Bob are embedded in a well-defined background space-time. But if distances and times are also the outcomes of quantum mechanical measurements, how can this assumption be justified? (JP, arXiv:1807.06457)

Objections to locality in RQM and QBism

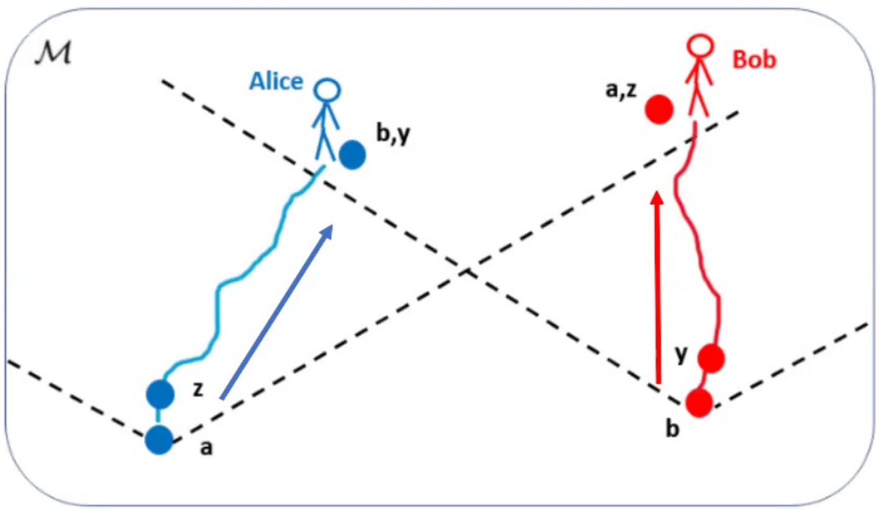


- **Objection 1:** How to explain the Bell inequality violations?
- *Details:*
- When Alice and Bob measure two parts of an entangled system, there is no-signalling in the correlations **P(y z|a b)**.
- Any *causal model* that faithfully explains the no-signalling must not say that **a** causes **y** or that **b** causes **z** (principle of **no fine-tuning**).
- Furthermore, Reichenbach's principle of **decorrelating explanation** says that correlations due to common causes must disappear when we condition on the common causes.
- Together, this implies Bell inequalities on **P(y z|a b)**. (This is the causal version of Bell's theorem). (Wood & Spekkens 2012, arXiv:1208.4119)

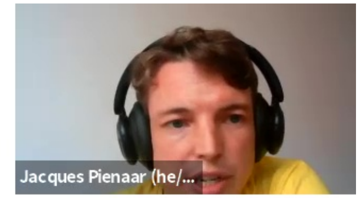
Objections to locality in RQM and QBism



- **Objection 1:** How to explain the Bell inequality violations?
- **Answer1:** Reject **no fine-tuning** and allow non-signaling causal relations to exist. For instance, Alice can explain the Bell inequality violations by assuming that her action **a** influences Bob's outcome **y**. Conversely, Bob can explain it by assuming that his action **b** influences Alice's outcome **z**. Such influences will necessarily follow time-like trajectories relative to each observer.

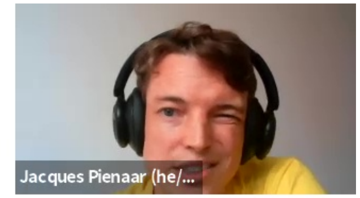


Objections to locality in RQM and QBism



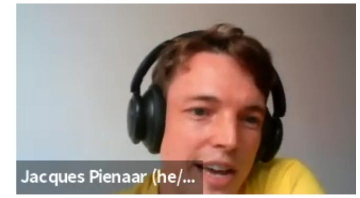
- **Objection 1:** How to explain the Bell inequality violations?
- **Answer2 (preferred):** Reject **decorrelating explanation.** It is normally justified by assuming that correlations can be modeled in terms of underlying stochastic hidden variables. Since both QBism and RQM reject hidden variables, nothing compels them to accept this principle. (See Wiseman & Cavalcanti, arXiv:1503.06413)
- This creates a new problem: how to explain the bounds on quantum correlations (eg Tsirelson's bound)?
- RQM and QBism both have programs to derive the Hilbert space formalism from information theoretic axioms, which would indirectly explain the bounds on quantum correlations.

Objections to locality in RQM and QBism



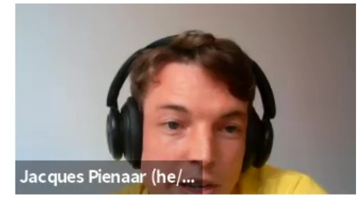
- ~~**Objection 1:** Even granted the events **a** and **y** are time-like separated for Alice (and so is Bob's action **b** with outcome **z**, relative to Bob) they still need to explain the Bell inequality violations in the joint statistics **P(y z|a b)**.~~ How do they do that? A: They have ways.
- **Objection 2:** Since the argument applies to any correlations between **a** and **y**, it seems like it would also work for correlations that signal across arbitrary space-like separations between Alice and Bob. But that means it cannot explain why quantum theory is **operationally non-signaling**.
- **Objection 3:** The argument presupposes that Alice and Bob are embedded in a well-defined background space-time. But if distances and times are also the outcomes of quantum mechanical measurements, how can this assumption be justified?

Objections to locality in RQM and QBism



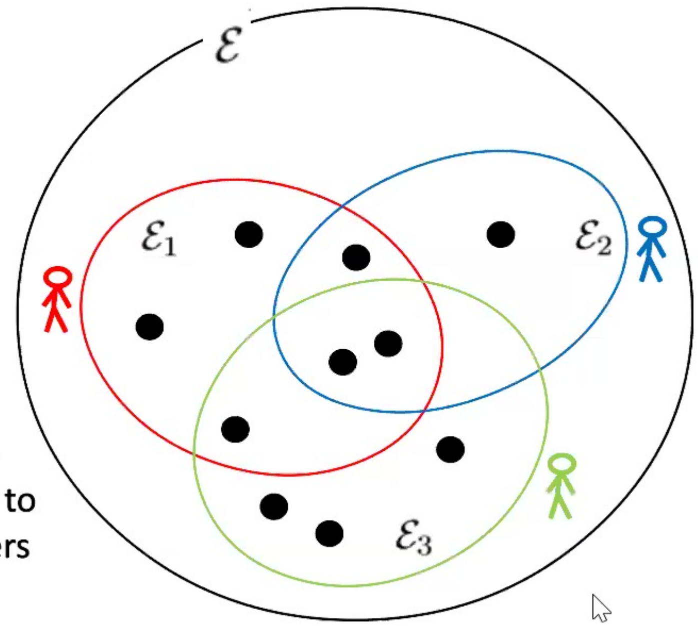
- **Objection 2:** How to explain **no-signaling**?
- Details:
- Instantaneous signaling seems to be compatible with the ontology of relative facts:
- No matter what correlations between **a** and **y**, no matter how far apart they are in space, Alice can claim that **a** is the cause of **y**, and Bob can claim that **y** is the cause of **a**, without violating **ontological locality**. *Or so it seems.*
- Let us make this objection precise using a formal ontological model that respects the principle of **relative facts**.

An ontological model for relative facts

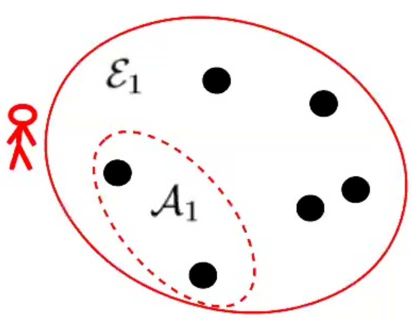


Definition: A **perspectival ontological model** (POM) consists of a set of observers $\{O_i\}$, a set of events $\{E_k\}$, and for each observer O_i the following elements are defined:

- A subset $\mathcal{E}_i \subseteq \mathcal{E}$ representing the events that happen relative to that observer;
- A subset $\mathcal{A}_i \subseteq \mathcal{E}_i$ representing events that happen which are also 'free actions' relative to that observer;
- a mapping $\mathcal{C}_i : \mathcal{E}_i \mapsto \mathcal{M}$ from the events $\mathcal{E}_i$ onto Minkowski spacetime $\mathcal{M}$, such that $\mathcal{C}_O(e)$ represents the space-time co-ordinates where event $e \in \mathcal{E}_i$ happens relative to O_i;
- a set of rules constraining how the observer O_i should assign probabilities $P_i(\mathcal{E}_i)$ to their events.

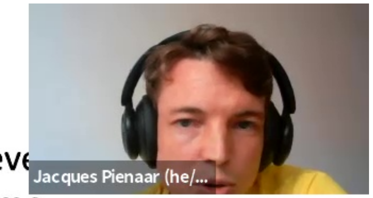


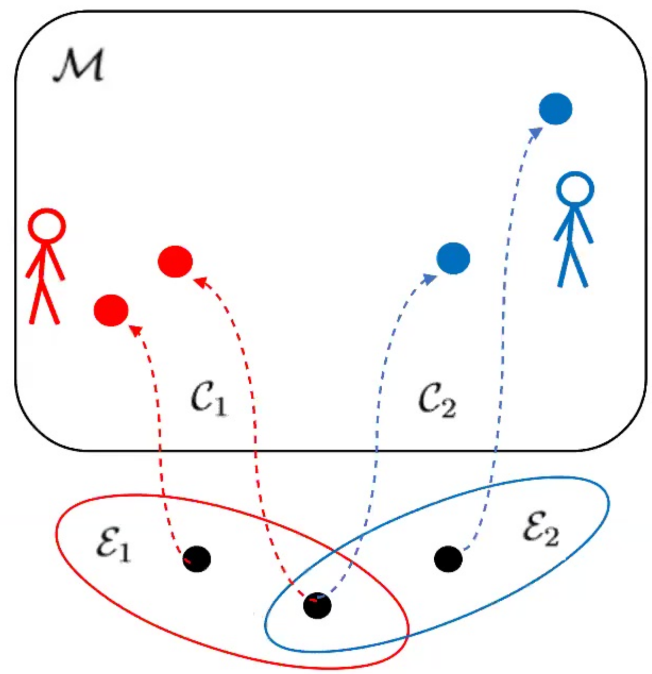
Events happen relative to observers



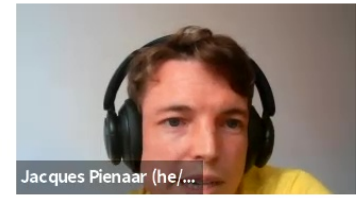
Each observer has their own \`free actions'

Observers map their eve into different space-time points within the same background manifold.



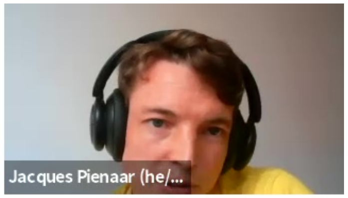


An ontological model for relative facts



- **Note1:** Assumes that all observers map out their own trajectories on a single "map" of space-time, eg. using a co-ordinated protocol of clocks and light pulses. **Hence no observer is considered to be in a superposition of different space-time locations relative to the others**.
- (Wigner and his friend might disagree about whether an atom's spin has a definite value, but we assume they agree on where they and the atom are in space-time).
- **Note2:** In accordance with **relative facts**, the same event can occur at different space-time locations relative to different observers, *hence its space-time co-ordinates are not uniquely defined in the ontology*.

Locality in a perspectival ontological mod



- **Problem:** which space-time co-ordinates of a given event to use in our definition of "locality"?

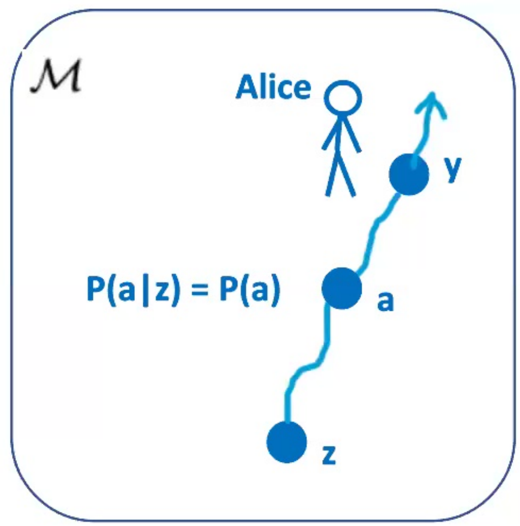
- **Option 1:** Define "locality" for each observer separately, using the co-ordinates that represent when the events occur for that observer (**perspectival locality**);

- **Option 2:** Define "locality" relative to a collective protocol for assigning a single co-ordinate to each event (**global locality**).

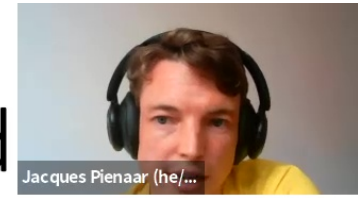
Locality in a perspectival ontological mod

Jacques Pienaar (he/...

Perspectival locality: A POM satisfies perspectival locality if for every observer O_i:
(i) the co-ordinates of any $e \in \mathcal{E}_i$ relative to O_i lie along the world-line of O_i;
(ii) the probability of any free action $a \in \mathcal{A}_i$ is prescribed to be independent of events in the past of a.

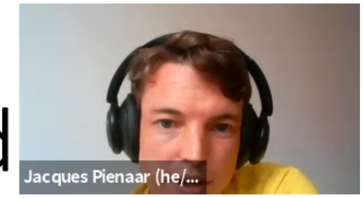


Locality in a perspectival ontological mod

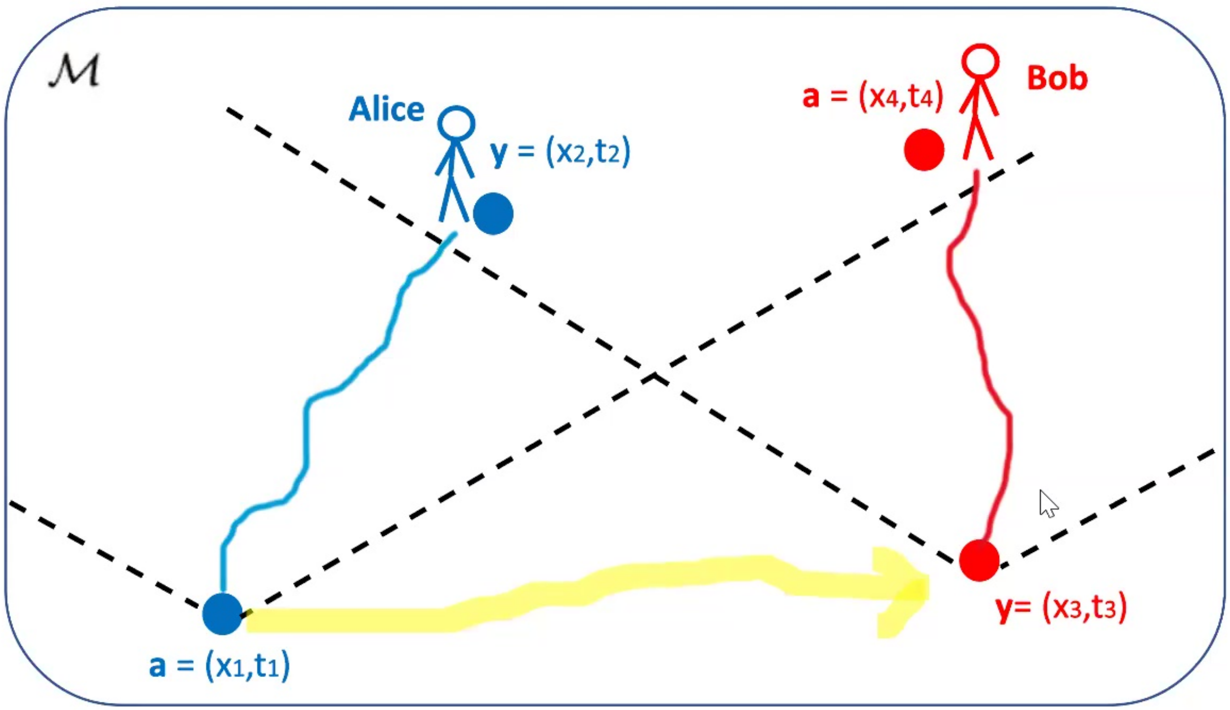


- **Result 1:** The principle of **relative facts** together with **free actions** implies **perspectival locality**:
- As QBism and RQM argue, events only happen relative to an observer when the observer encounters them, hence along its world-line;
- The defintion of **free actions** in RQM and QBism requires the observer's world line to be oriented, such that the actions are independent of events in their **past.**
- **Conclusion 1:** A POM for QBism/RQM must be **perspectivally local**.

Locality in a perspectival ontological mod

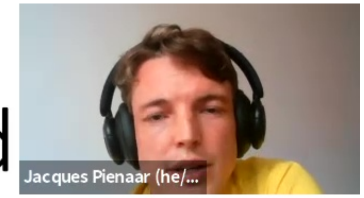


- **Result 2:** A POM that is **perspectivally local** is still compatible with **instantaneous signaling**.



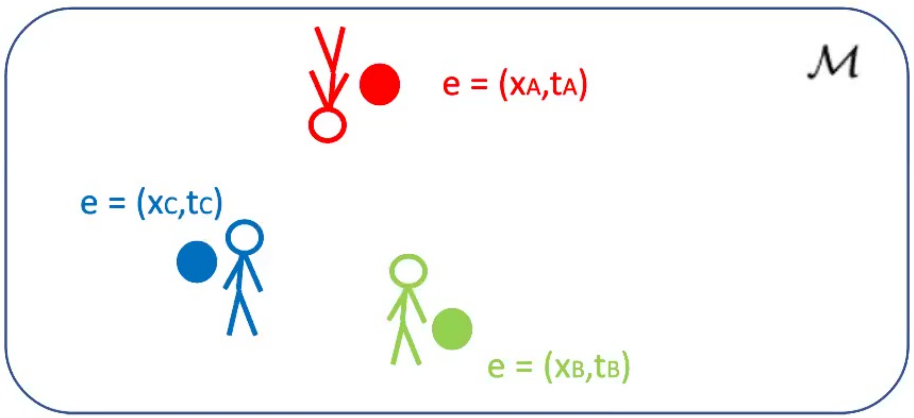
(Because even for **events** which are space-like separated *between* observers, **perspectival locality** guarantees that, relative to each observer, these events will occur at co-ordinates located along the observer's own time-like world-line).

Locality in a perspectival ontological mod

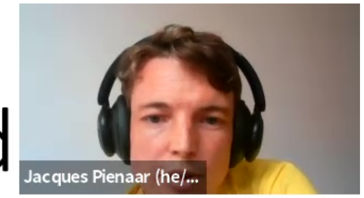


Option 2: Define 'locality' relative to a collective protocol for assigning a single co-ordinate to each event (**global locality**).

Problem: Each event $e \in \mathcal{E}$ happens relative to some subset of observers, call them $\{O_A, O_B, O_C, \ldots\} \subseteq \{O_i\}$. For each observer, the same event e happens at different co-o$\mathcal{M}$inates, say $(x_A, t_A), (x_B, t_B), \ldots$. *We need a protocol that unambiguously assigns a single 'global' co-ordinate to e.*



Locality in a perspectival ontological mod

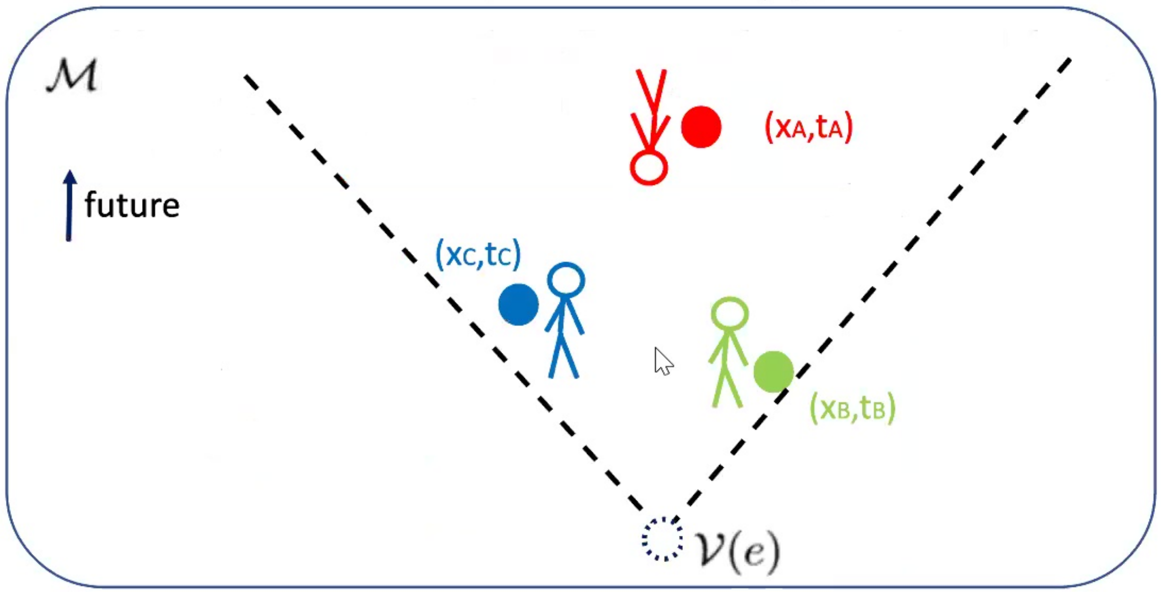


Global co-ordinate protocol:

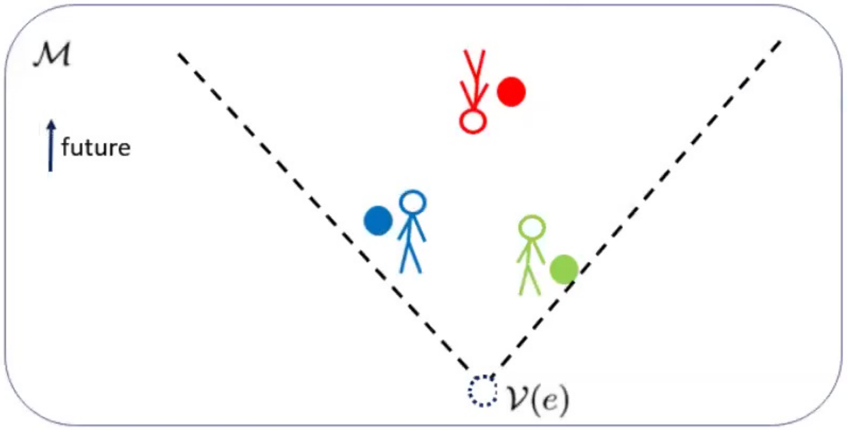
(1) Fix a 'global' convention for the past-future orientation of $\mathcal{M}$;

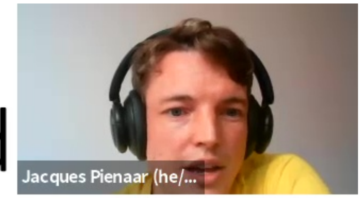
(2) Consider the 'tightest' future-oriented light-cone that encloses the co-ordinates $(x_A, t_A), (x_B, t_B), \ldots$ assigned to e by all observers for which e is an event;

(3) Define the **global co-ordinate** of e, denoted $\mathcal{V}(e)$, as the vertex of this light-cone.



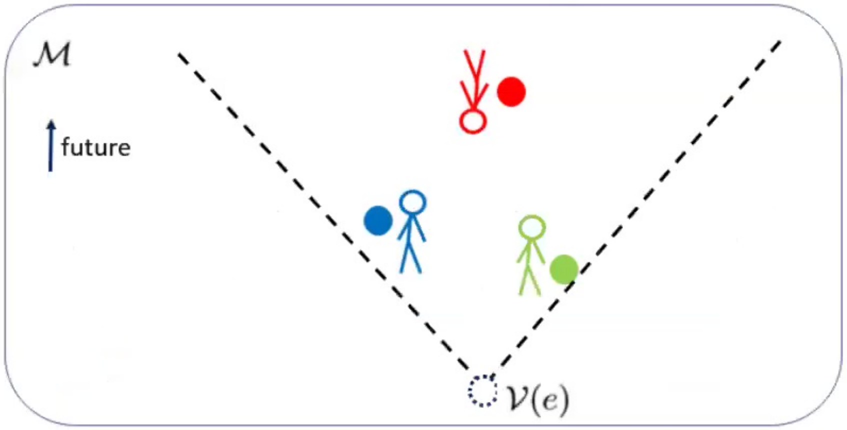
Locality in a perspectival ontological mod





- **Note1:** The global co-ordinate of *e* is an *abstract* co-ordinate: it need not correspond to a location where *e* actually happens relative to any observer;
- **Note2:** We assume all observers know which co-ordinates the other observers assign to *e,* hence using the above protocol they will all calculate the same global co-ordinates of *e*.
- **Note 3:** The choice of `global' orientation of space-time is just a convention that defines the protocol; a priori we do not assume that the observers' personal orientations line up with it (or with each other)!

Locality in a perspectival ontological mod



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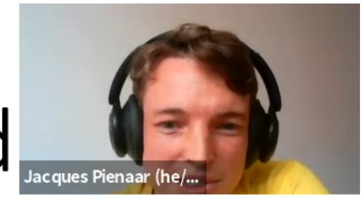

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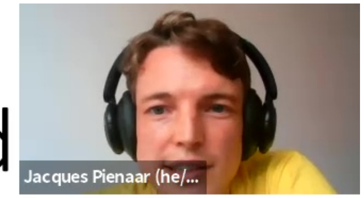
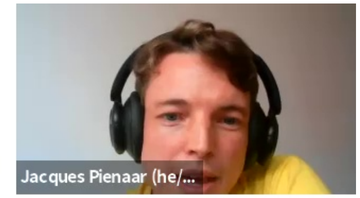


Global locality: A POM satisfies global locality if the following conditions are met relative to every observer O_i:
(1) The global co-ordinates $\mathcal{V}(e)$ of any event $e \in \mathcal{E}_i$ is independent of all free actions whose global co-ordinates lie outside the past light-cone of $\mathcal{V}(e)$;
(2) Every 'free action' $a \in \mathcal{A}_i$ is statistically independent of all events whose invariant co-ordinates lie outside the future light-cone of $\mathcal{V}(a)$.

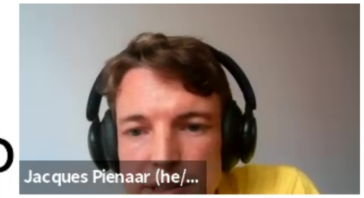
- **Result 3:** If a POM satisfies **global locality**, then all observer's personal past-future orientations line up with the global orientation;

- **Result 4:** If a POM satisfies **perspectival locality** and **global locality**, then it must be **non-signaling**.

Objections to locality in RQM and QBism

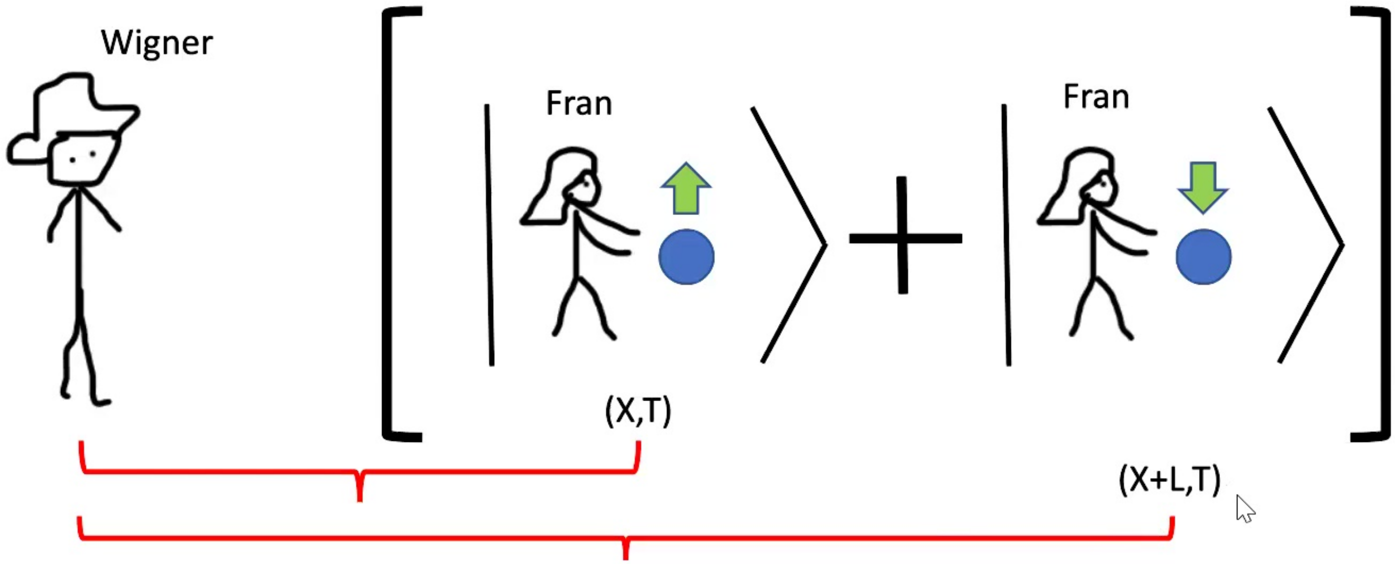


- **Objection 1:** Even granted the events **a** and **y** are time-like separated for Alice (and so is Bob's action **b** with outcome **z**, relative to Bob) they still need to explain the Bell inequality violations in the joint statistics **P(y z|a b)**. How do they do that? A: They have options.
- **Objection 2:** Since the argument applies to any correlations between **a** and **y**, it seems like it would also work for correlations that signal across arbitrary space-like separations between Alice and Bob. But that means it cannot explain why quantum theory is **operationally non-signaling**. A: They can, if we define locality as a perspectively and globally local POM.
- **Objection 3:** The argument presupposes that Alice and Bob are embedded in a well-defined background space-time. But if distances and times are also the outcomes of quantum mechanical measurements, how can this assumption be justified?

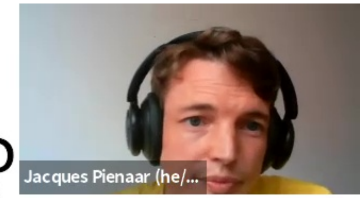


Locality without background space-time?

- **Objection 3:** If distances and times are also outcomes of quantum measurements, there is no well-defined backround space-time, hence no well-defined notion of "locality".

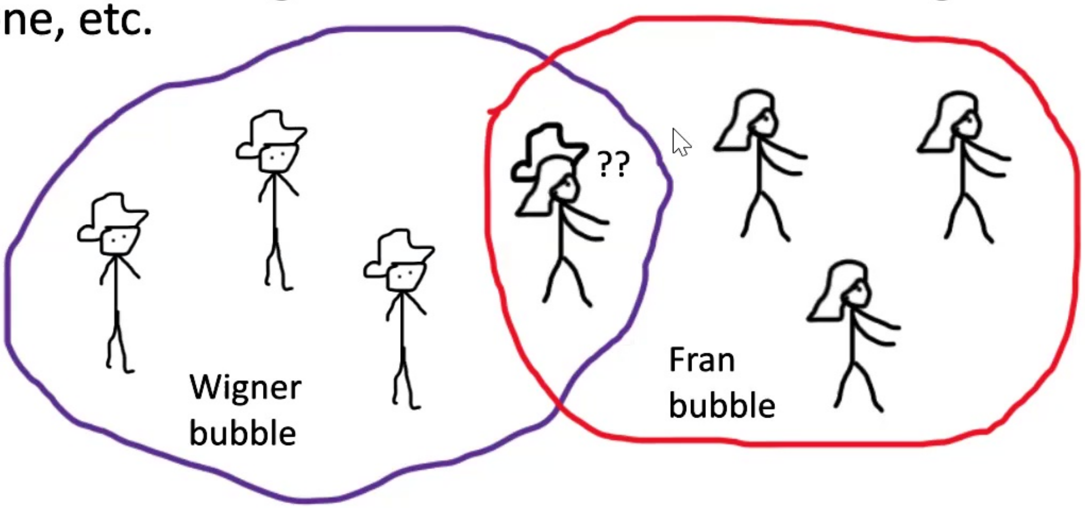


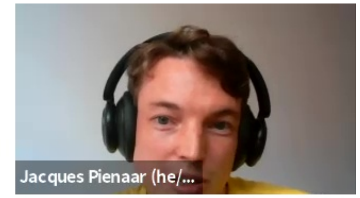
Wigner and Fran disagree about where Fran's world-line (hence light-cones, etc) are located!



Locality without background space-time?

- **Problem:** in general, we cannot assume that all observers use the same "space-time map" to locate themselves and their events.
- **Option:** Generalize defintion of POM to allow a "patchwork" space-time, in which only *subsets* of observers share the same space-time map.
- Within such a POM, locality is only defined *within* a given patch. Between patches, **we cannot say that the ontology is either local or non-local**: the terms are not meaningful because there is no unambiguous notion of world-line, light-cone, etc.





Conclusions:

- It is possible to define a framework of **perspectival ontological models** (POM) which are consistent with **relative facts**, and so can be consistent with QBism or RQM.
- Within POMs, we can give a mathematical definitions of locality that allow us to define *explicitly local* ontological models for QBism and RQM.
- Within this framework it is possible to explain Bell-inequality violations and non-signaling, without giving up on ontological locality.
- The big price, of course, is that **facts are relative** in this ontology.

Thank you!