What Price Causality?

After Bell, how much must we give up to recover a satisfying relativistic causal principle?

The greatest mystery in science?

- **Locality** = "things do not go faster than *c*" = "no superluminal influence."

Bell: *"Now it is precisely in cleaning up intuitive ideas that one is likely to throw the baby out with the bathwater. So the next step should be **viewed with the utmost suspicion**…"*

- Bell's local causality is a conjunction of **relativistic causal structure** with a **Principle of Common Cause** (PCC).
- Many reasons to preserve some PCC-like idea in physics: causal explanation; new theories; why no signalling?
- Is there a way to preserve locality while evading Bell's argument that this conflicts with QM? **Implicit assumptions? Unnecessarily strong definition??**

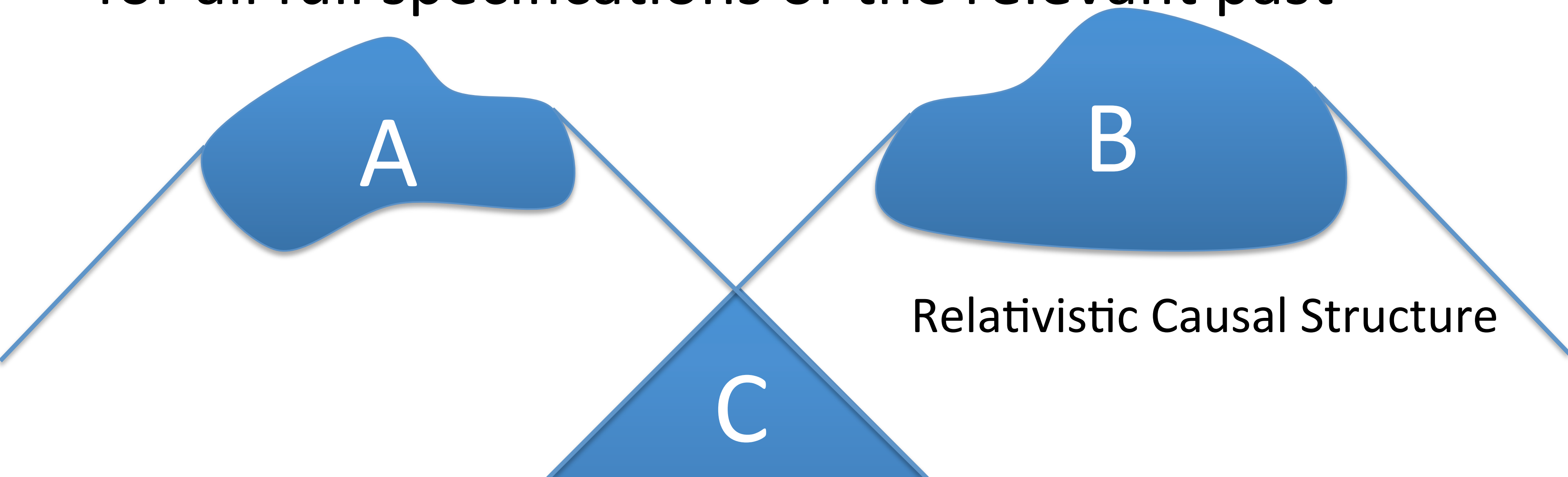
The PCC

If $P(A)P(B) \neq P(A \cap B)$

Then A→B, B→A or A←{C}→B

$$P(A|C)P(B|C) = P(A \cap B|C)$$

for all full specifications of the relevant past



Two clear responses to Bell

"Okay, then I will give up on relativity."

Natural for…

- deBroglie-Bohm Pilot waves
- Nelson-style mechanics

"Okay, then I will give up on the PCC."

Natural for…

- Operational QM
- Collapse theories
- Decoherent histories
- Anything relativistic

Are other responses possible?

Bell's theorem shows that:
QM is inconsistent with local theories?

- NOBSENED Hidden variable
- Separable
- Free settings
- Joe lives in London
- NOBSENED Counterfactually definite
- NOBSENED Realistic
- Non-relational
- Pro-causal

Bluff your way in causation

"The philosophical treatment on the subject of causality extends over millennia. In the Western philosophical tradition, discussion stretches back at least to Aristotle, and the topic remains a staple in contemporary philosophy."

- Task: find way to avoid all this reading.
- Result: "uncontroversial" requirements for a decent locality principle:
  - Locality **must** imply no-signalling.
  - Writing post-cards **must** be deemed local.
  - Super-luminal comets **must** be deemed non-local.
  - Locality **must** be robust under conditioning on past events (at least some of them!)
  - Locality **must** not be too vague.

Example: free settings is **part** of locality

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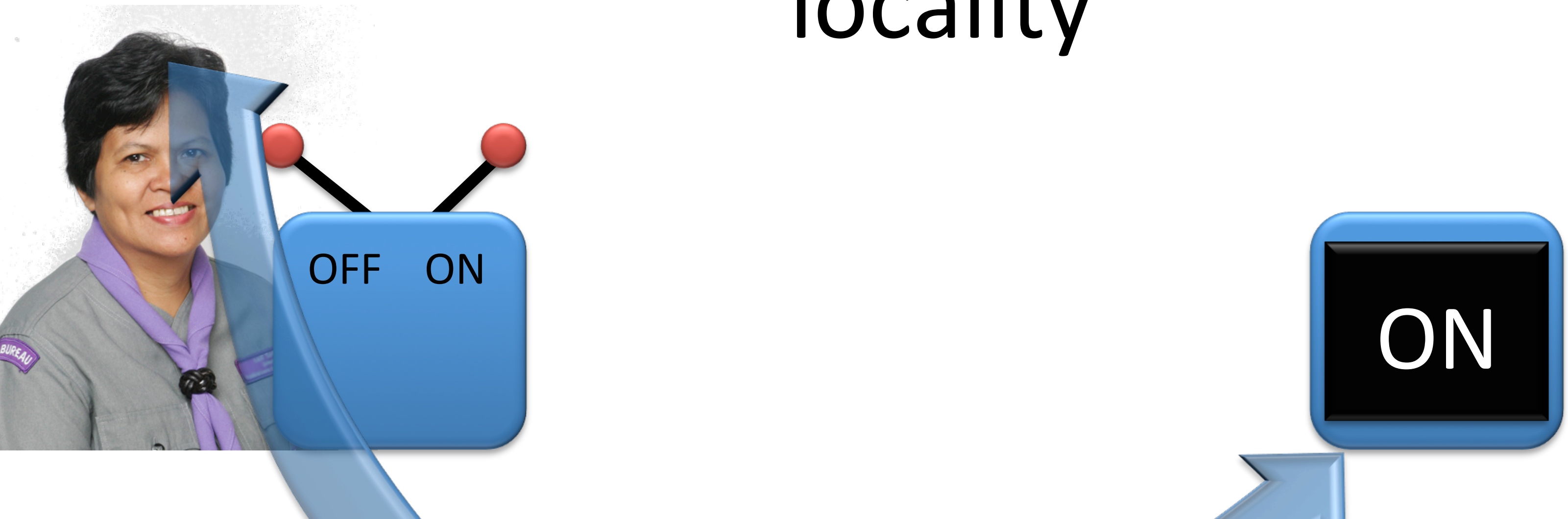


"without such freedom I would not know how to formulate *any* idea of local causality, even the modest human one [signaling]." (J. S. Bell p.61).

Conspiraton

Formalising Local Beables

Events $A, B, \ldots$ are subsets of a history space Ω. There is a probability measure μ on the Boolean algebra of events.

Regions $\mathcal{A}, \mathcal{B}, \ldots$ are subsets of a (weakly causal) spacetime $\mathcal{M}$.

A subalgebra $\Sigma(\mathcal{A})$ of events is associated to each region, such that:

$$\bigcap_i \Sigma(\mathcal{A}_i) = \Sigma(\bigcap_i \mathcal{A}),$$

$$\Sigma(\emptyset) = \{\emptyset, \Omega\},$$

A **full specification** of a region $\mathcal{A}$ is an event F such that

$$F \subset A \text{ or } F \subset \bar{A} \quad \forall\, A \in \Sigma(\mathcal{A})$$

Separability vs. locality?

"[**Separability**] is a fundamental ontological principle which… asserts that the contents of any two regions of spacetime separated by a nonvanishing spatiotemporal interval constitute separable physical systems, in the sense that (1) each possesses its own, distinct physical state, and (2) the joint state of the two systems is wholly determined by these separate states." -- Howard

"We might… all along have been testing not simply local hidden variable theories, but separable, local hidden variable theories." -- Howard

"Our unhesitating acceptance of relativistic causal theories... involves an assumption so basic to the thinking of most of us that we are not even aware that we are making it…" -- Teller

"[each system in a Bell experiment] does not possess independent properties of its own…" -- Redhead

"[i]f two systems are not separable, then there can be no interaction between them, because they are not really *two* systems at all." -- Howard

Formalising Separability

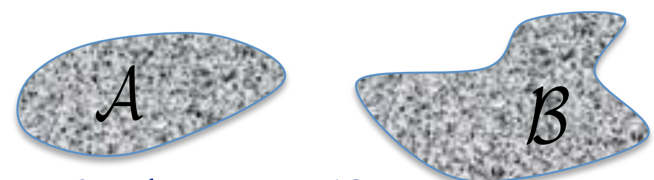
A subalgebra $\Sigma(\mathcal{A})$ of events is associated to each region, and:

$$\bigcap_i \Sigma(\mathcal{A}_i) = \Sigma(\bigcap_i \mathcal{A}), \quad \Sigma(\emptyset) = \{\emptyset, \Omega\},$$

A **full specification** of a region $\mathcal{A}$ is an event F such that

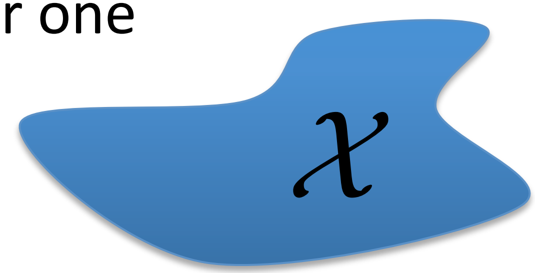
$$F \subset A \text{ or } F \subset \bar{A} \quad \forall\, A \in \Sigma(\mathcal{A})$$

Now we can define **separability**:



If A and B are full specifications of $\mathcal{A}$ and $\mathcal{B}$, then $A \cap B$ is a full specification of $\mathcal{A} \cup \mathcal{B}$.

This is **stronger** than just local beables, *e.g.* for one nontrivial event in a region:

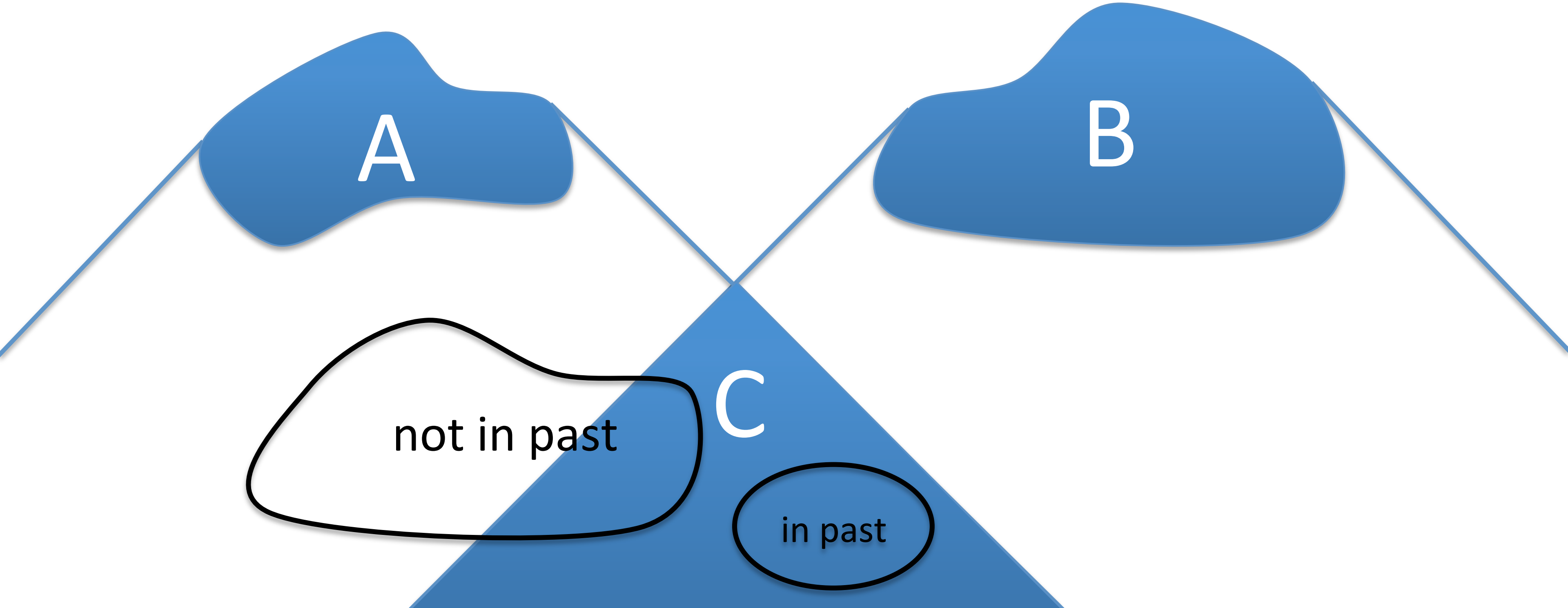


$$\Sigma(\mathcal{X}) = \Sigma(\mathcal{M}) = \{\emptyset, \bar{X}, X, \Omega\}$$

Bell locality is fine without separability

$$P(A|C)P(B|C) = P(A \cap B|C)$$

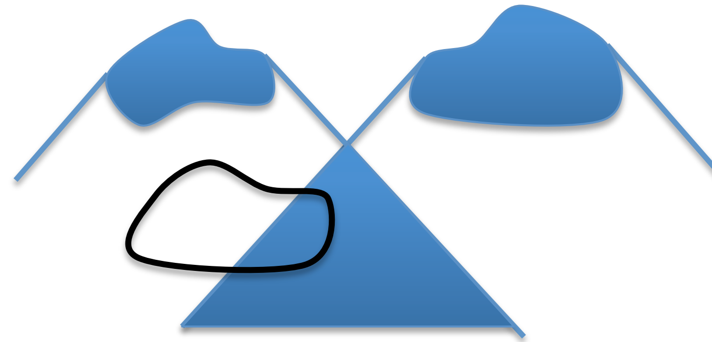
for all full specifications of the relevant past. So there might be non-separable events. So what?



Non-separability as inspiration to weaken Bell's assumptions?

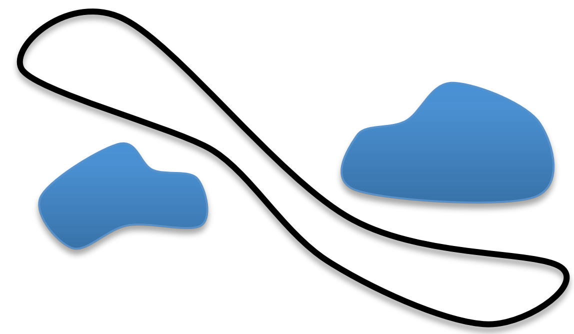
Causes partially outside lightcones?

DOES NOT HELP



Causes and effects partially outside lightcones?

SUPERLUMINAL SIGNALS



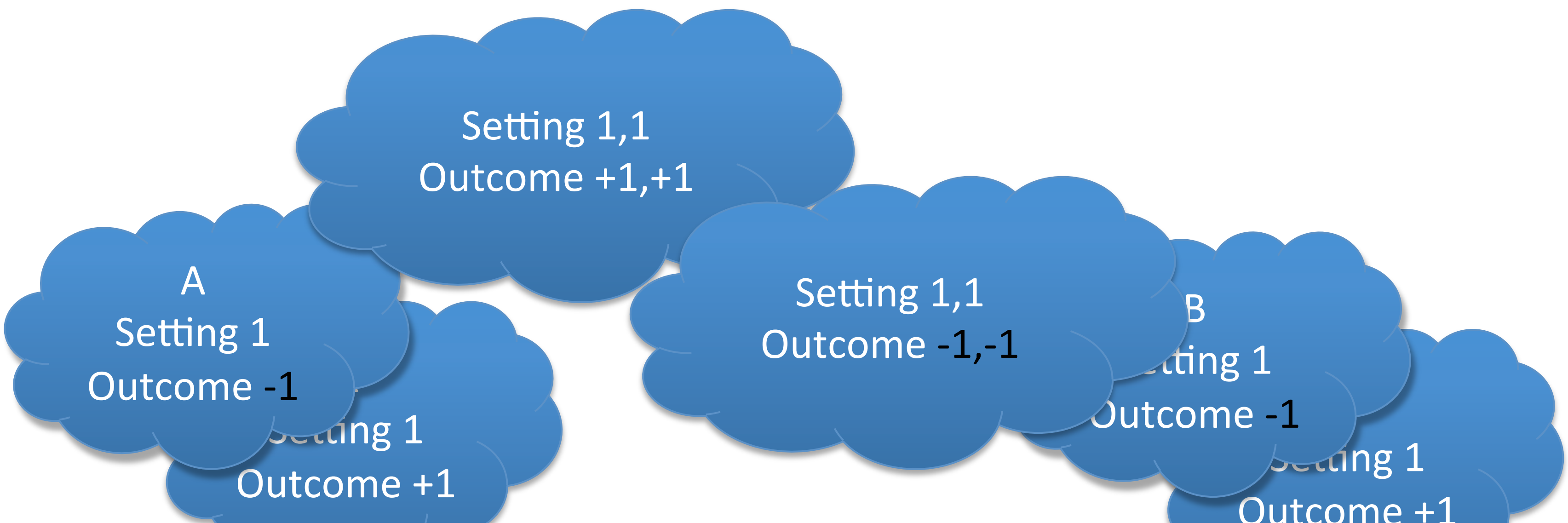
Operational events not localised in the wings?

SUPERLUMINAL SIGNALS

AND IT'S JUST SILLY

Saved by many worlds?

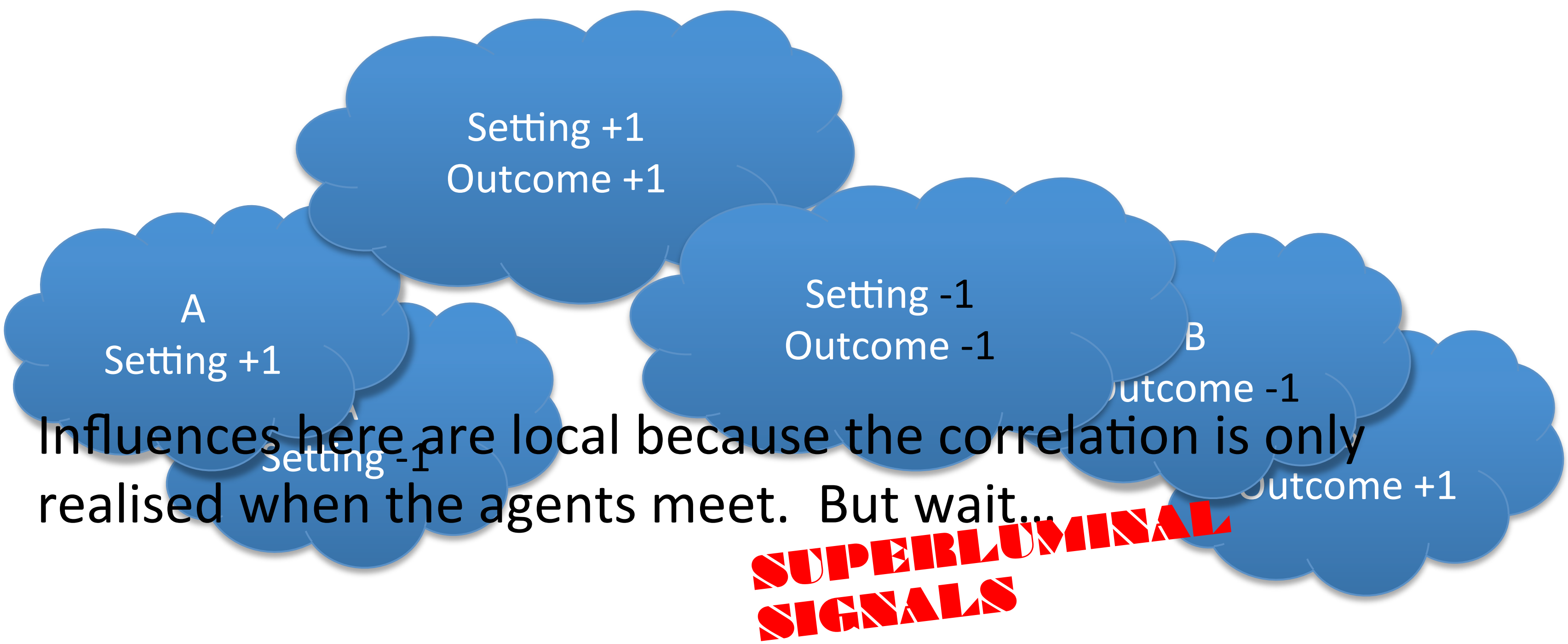
Your measurement result is only true in one branch. For **you**, the measurement result in the distant wing is **indefinite**.



Influences here are local because the correlation is only realised when the agents meet.

The problem

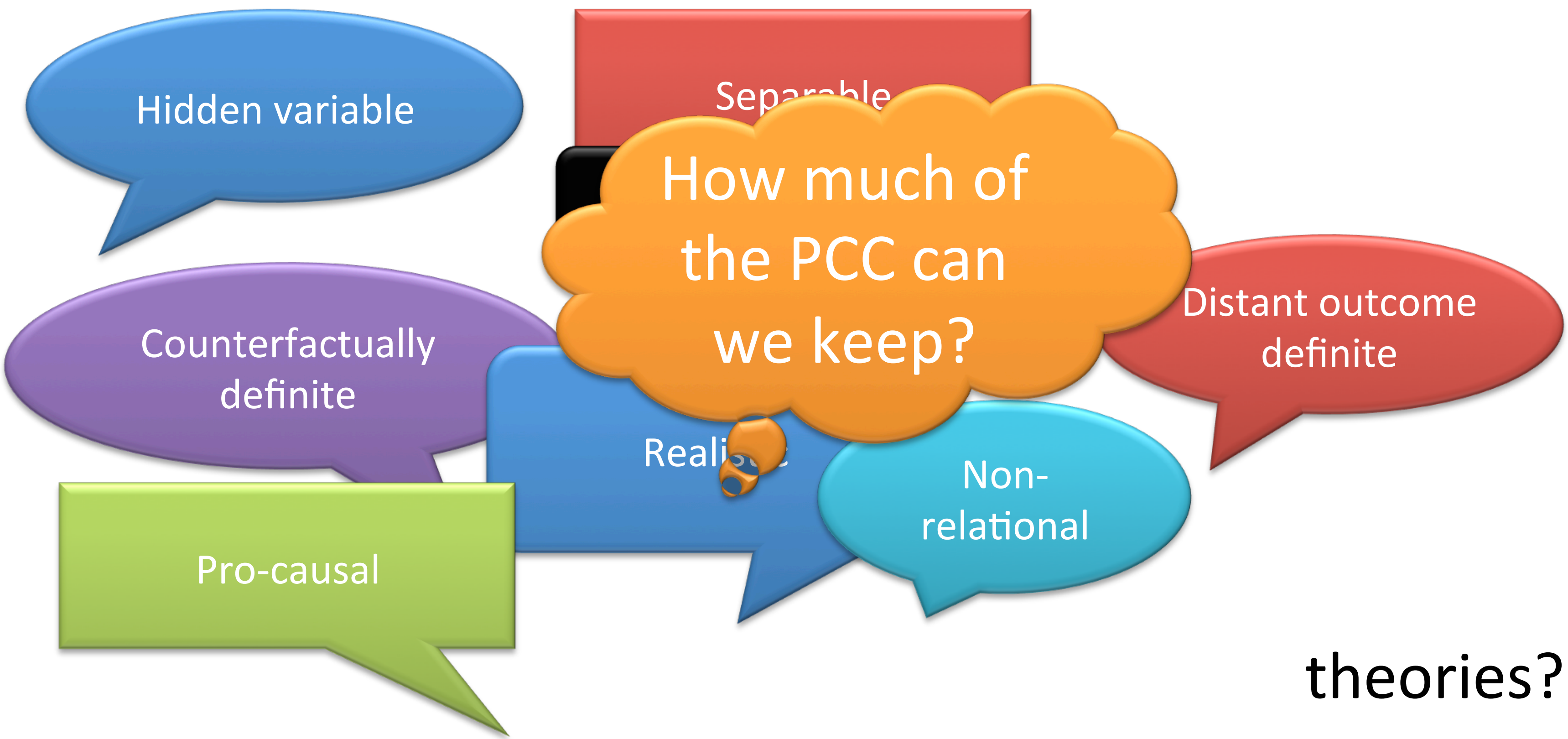
Your setting is true in one branch. For **you,** the measurement result in the distant wing is **indefinite**.



Influences here are local because the correlation is only realised when the agents meet. But wait…

Are other responses possible?

Bell's theorem shows that:
QM is inconsistent with local

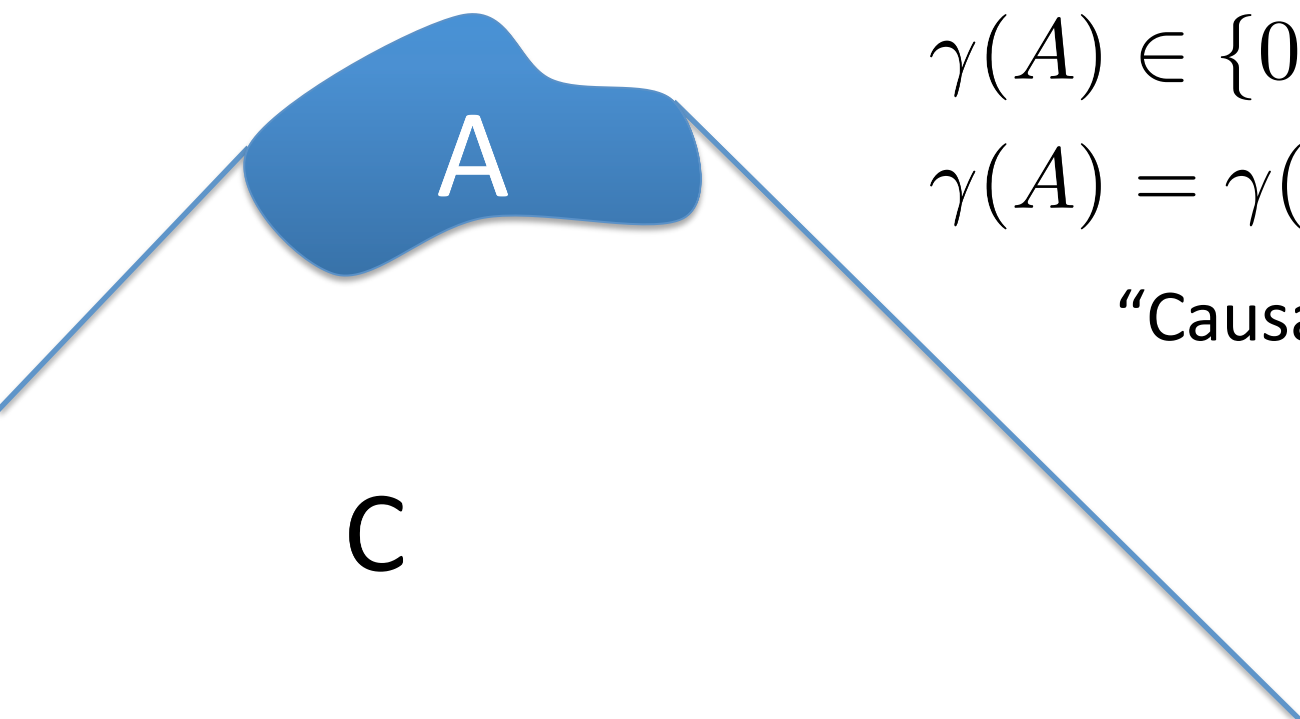


theories?

Einstein Locality

A strong locality condition:

For any event A, there is an event C to its past that has the same truth value for all dynamically allowed histories.



$$\gamma(A) \in \{0, 1\}$$

$$\gamma(A) = \gamma(C) \quad \forall\, \gamma \subset \Theta$$

"Causal antecedent"

A third option

“A happens”: $\gamma(A) = 1$

“A does not happen”: $\gamma(A) = 0$

“It is not definite that A happened”:

$$\gamma(A) = 1/2$$

New wriggle room: **It is no longer clear what constitutes a correlation or a cause.**

If definiteness is just another ontological property like the others (colour, mass etc.) this makes no difference.

But there are other possibilities.

What can’t we change?

This still demands a causal explanation.

What *can* we change?

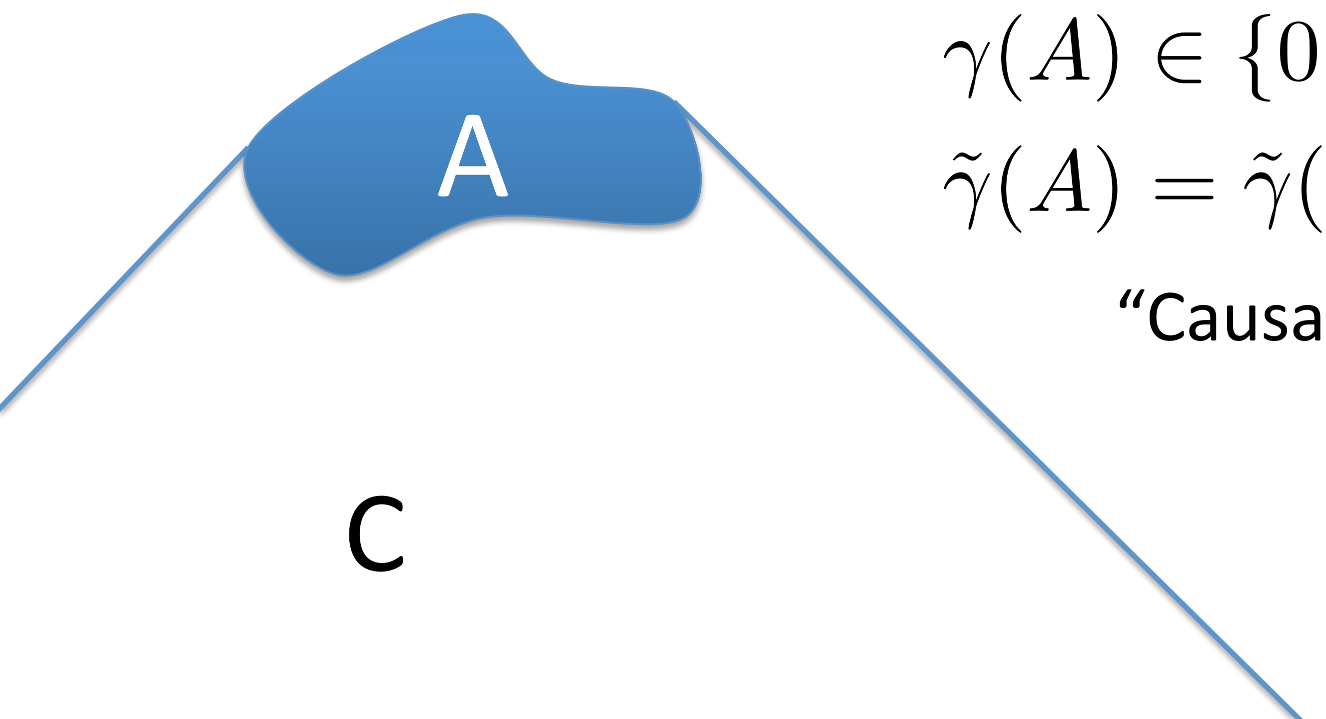
But what about this?

The choice: no longer demand that the PCC covers this kind of thing.

Einstein Locality with indefiniteness

For any event A, there is an event C to its past that has the same truth value for all dynamically allowed histories.

Things that we know are definite.



$$\gamma(A) \in \{0, 1, 1/2\}$$

$$\tilde{\gamma}(A) = \tilde{\gamma}(C) \quad \forall\, \gamma \subset \Theta$$

“Causal antecedent”

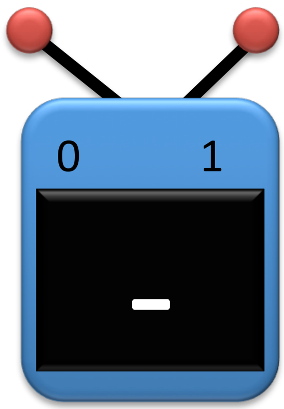
Superluminal signalling?

If the decay is definite, this is not allowed because it is against freedom of settings.

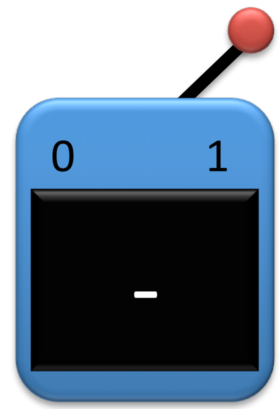
If the decay is indefinite, it cannot be the causal antecedent of the output.

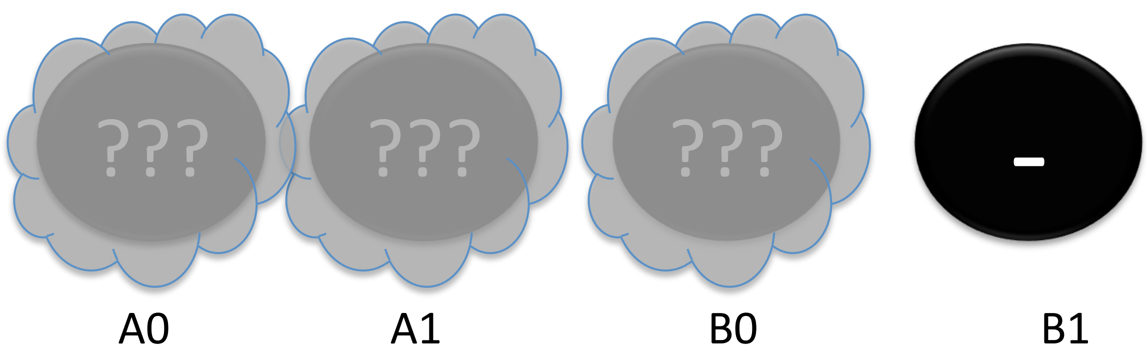
Conspiraton

The EPRB experiment



All non-signaling correlations are allowed





Three responses to Bell?

"Okay, then I will give up on relativity."

Natural for…

- deBroglie-Bohm Pilot waves
- Nelson-style mechanics

"Okay, then I will give up on the PCC…"

Natural for…

- Operational QM
- Collapse theories
- Decoherent histories

"But keep a remnant of the PCC."

Natural for…

???

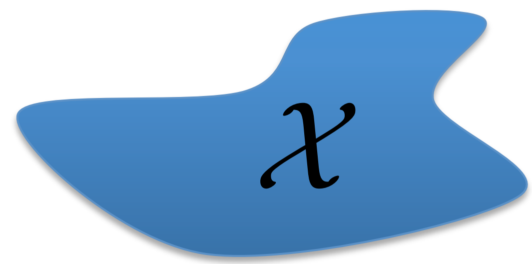
Conclusions

- The is no cheap way to avoid the conclusion that Bell's theorem undermines any viable relativistically causal theory.
- Instead of giving up on the PCC altogether, we can keep a powerful remnant of it.
- The possibilities opened up by this (interpreting, building toy models, bounding QM correlations) remain unexplored.

Localised events are fine without separability

$$\Sigma(\mathcal{X}) = \Sigma(\mathcal{M}) = \{\emptyset, \bar{X}, X, \Omega\}$$

Others trivial.



Non-separable but has localised events.

$$\bigcap_i \Sigma(\mathcal{A}_i) = \Sigma(\bigcap_i \mathcal{A}),$$

$$\Sigma(\emptyset) = \{\emptyset, \Omega\},$$