



Implications of Local Friendliness violation to quantum causality

Eric G. Cavalcanti

Causality in a quantum world
Anacapri, 19 September 2019



Australian Government
Australian Research Council



arXiv:1907.05607

Testing the reality of Wigner's friend's experience

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Centre for Quantum Dynamics, Griffith University, Gold Coast, QLD 4222, Australia*

arXiv:1909.05434

Classical causal models cannot faithfully explain Bell nonlocality or Kochen-Specker contextuality in arbitrary scenarios

J. C. Pearl* and E. G. Cavalcanti[†]

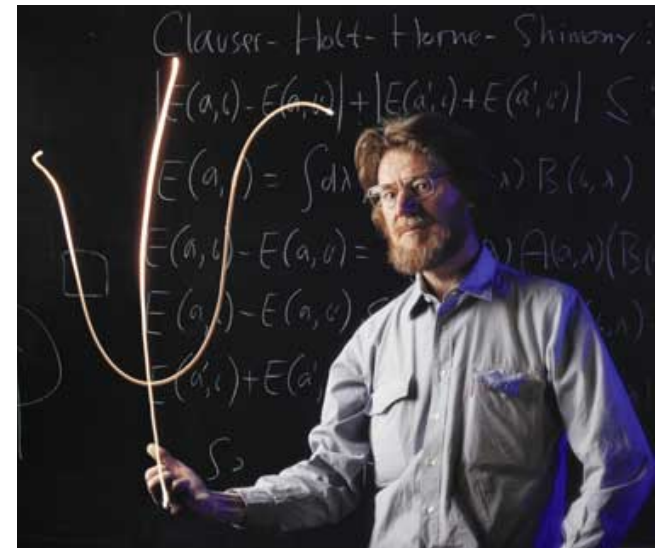
Centre for Quantum Dynamics, Griffith University, Gold Coast, QLD 4222, Australia

(Dated: September 13, 2019)

“For me then this is the real problem with quantum theory: the apparently essential conflict between any **sharp formulation** [of quantum theory] and fundamental relativity...

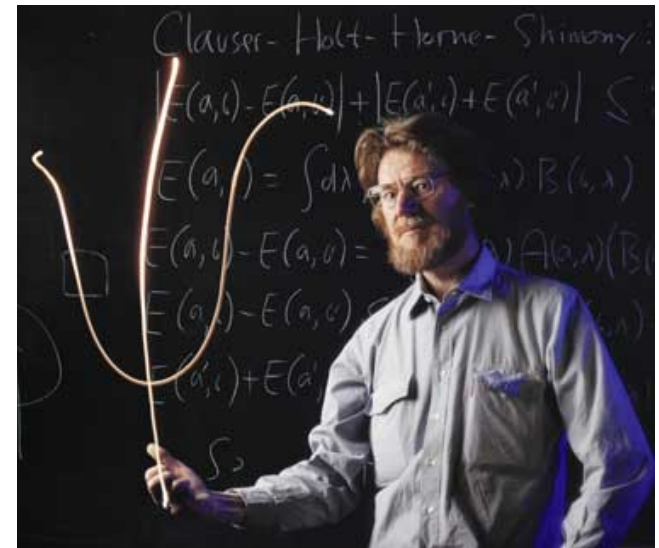
It may be that a real synthesis of quantum and relativity theories requires not just technical developments but radical conceptual renewal.”

J.S. Bell (1986)



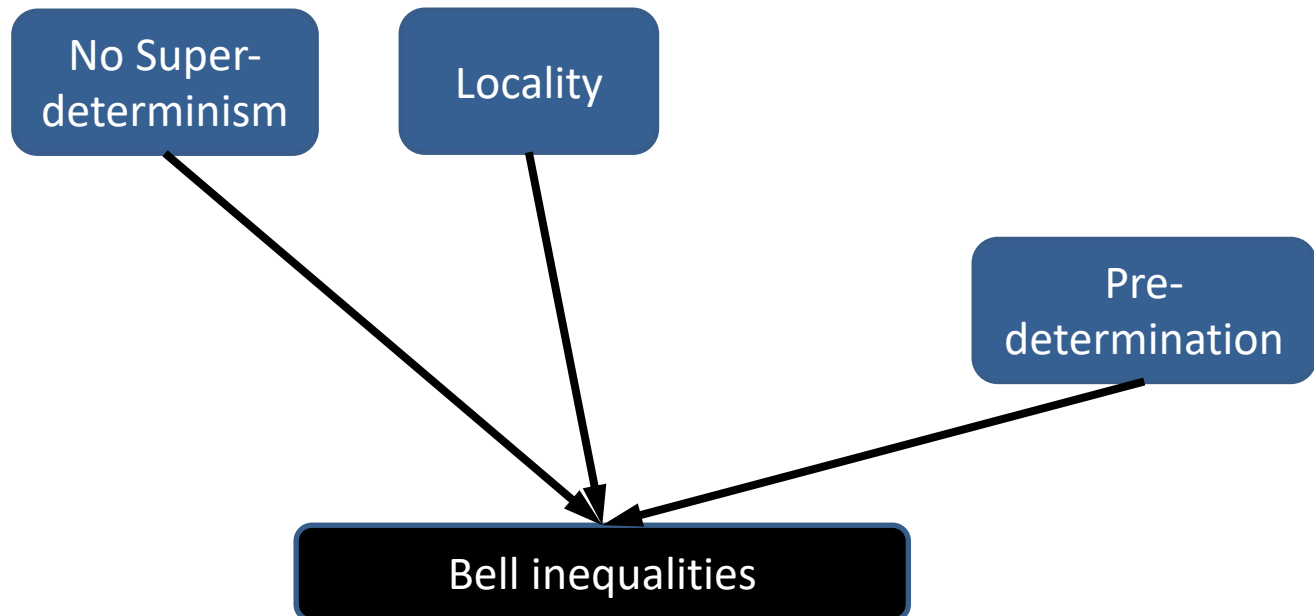
“Do we then have to fall back on “no signalling faster than light” as the expression of the fundamental causal structure of contemporary theoretical physics? That is hard for me to accept. For one thing we have **lost the idea that correlations can be explained, or at least this idea awaits reformulation**”.

– J.S. Bell, “La Nouvelle Cuisine” (1990)



H.M. Wiseman & EGC (2017) “Causarum Investigatio and the Two Bell’s Theorems of John Bell”.
In R. Bertlmann & A. Zeilinger (Eds.), *Quantum [Un]Speakables II*, arXiv:1503.06413

Bell’s 1964 theorem: Quantum phenomena violate the conjunction of No Superdeterminism, Locality, and Predetermination.



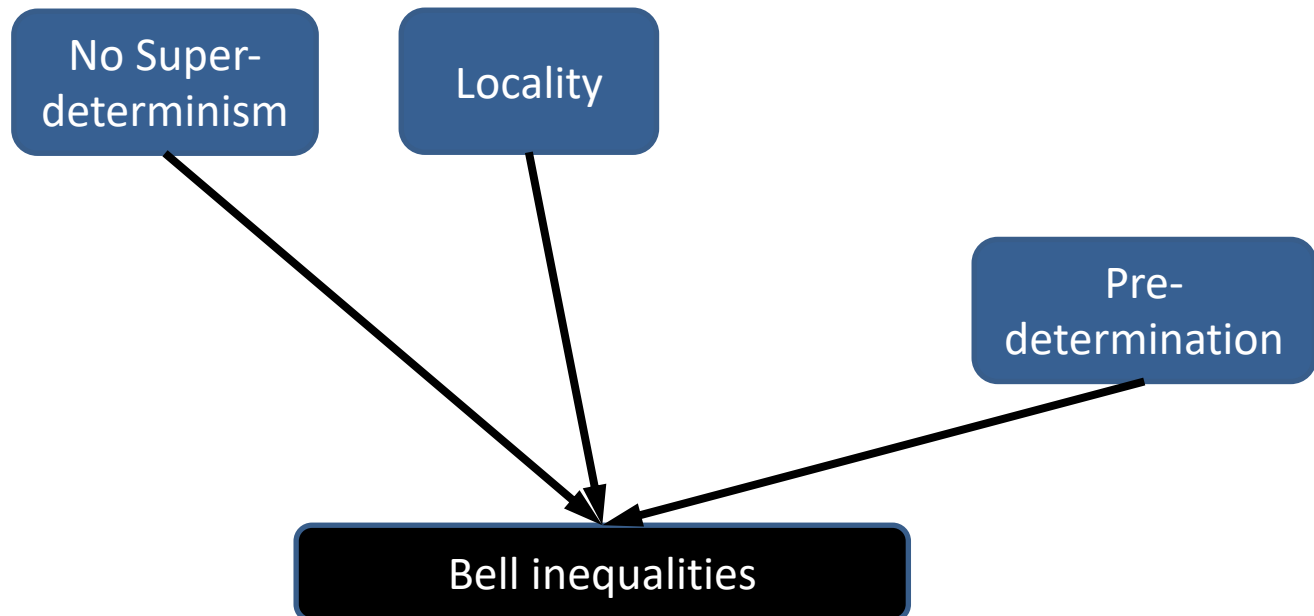
Bell's 1964 theorem

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Locality (“Parameter Independence”): The probability of an observable event A is independent of a space-like-separated intervention Y , even if it is already conditioned on other events not in the future light-cone of Y .

Predetermination: Any observable event A is determined by a sufficient specification of its CAUSES.

No Superdeterminism: Any set of events on a space-like hypersurface is uncorrelated with any set of interventions subsequent to that SLH.



Absolute
events

Minkowski
Space-time

Temporal
order

Causal arrow

Absolute events (“Macroreality”, “Observer-Independent Facts”): Observed events have absolute (rather than relative) existence.

Minkowski Space-time: Concepts such as space-like separation, light-cones, etc., are well defined in ordinary laboratory situations.

Temporal Order: For any event A , there is a space-like hypersurface containing A that separates events in the PAST of A from events that have A in their PAST.

Causal Arrow: Any CAUSE of an event is in its PAST.

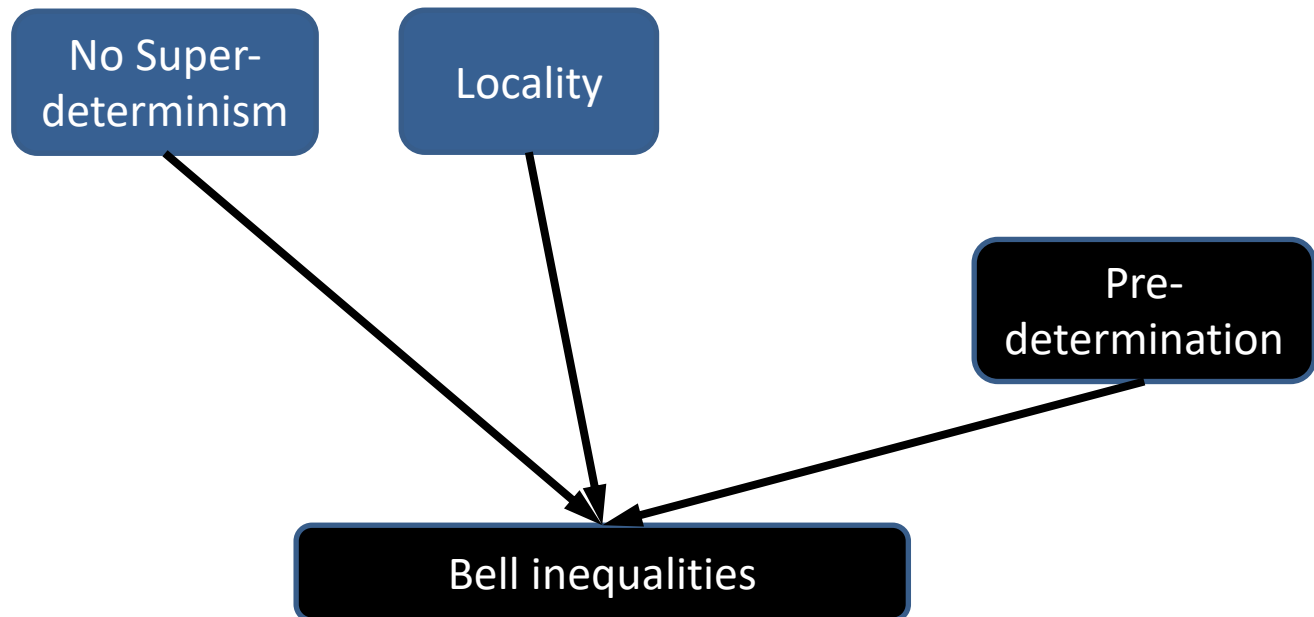
No Super-
determinism

Locality

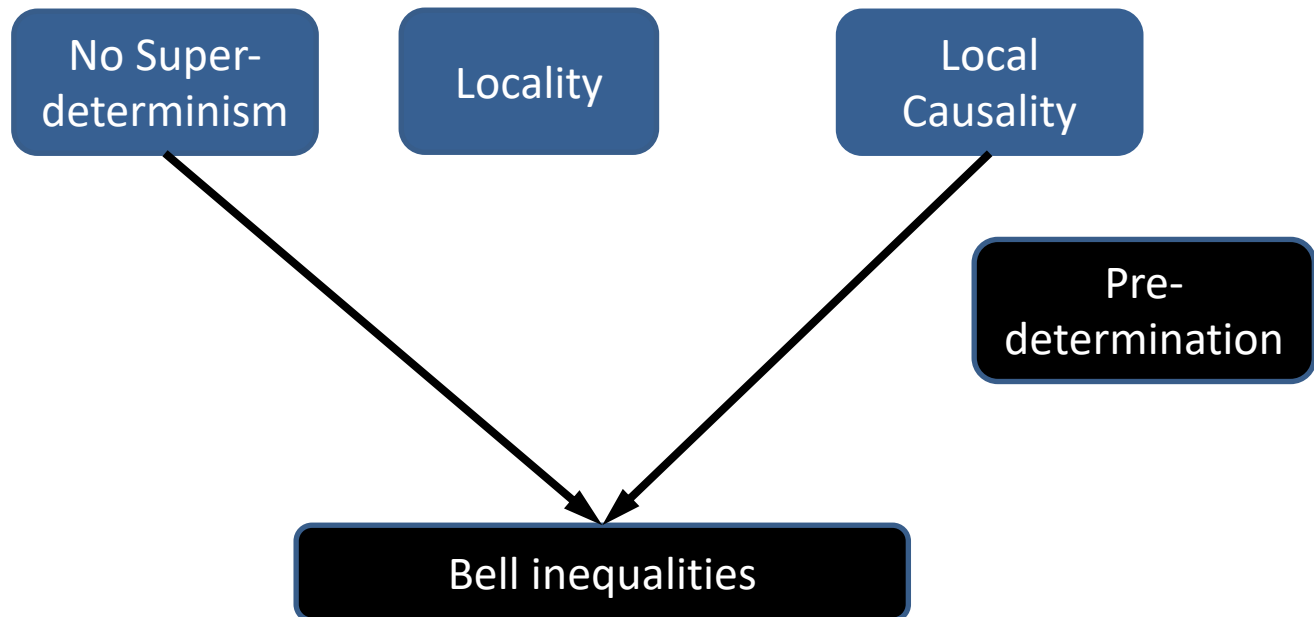
Pre-
determination

Bell inequalities

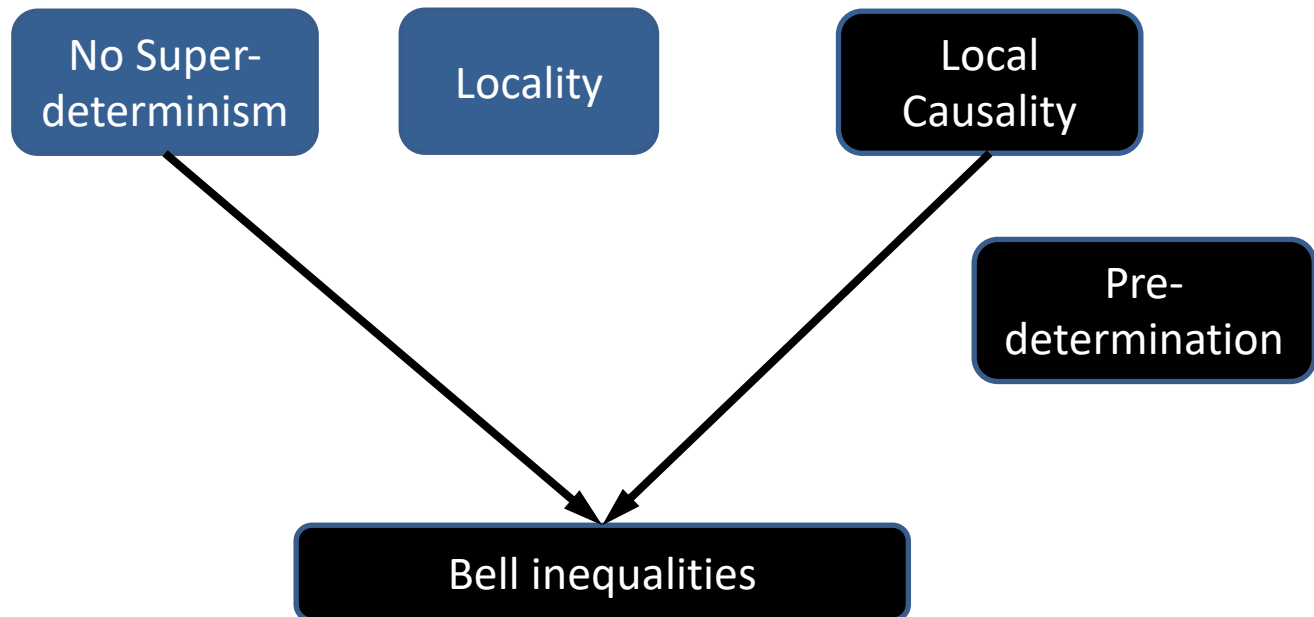
Give up predetermination?



Bell's 1976 theorem: Quantum phenomena violate the conjunction of No Superdeterminism and Local Causality.



Bell's 1976 theorem: Quantum phenomena violate the conjunction of No Superdeterminism and Local Causality.

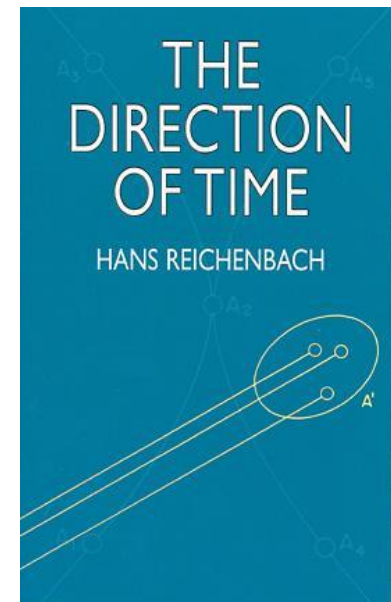


Causal explanation

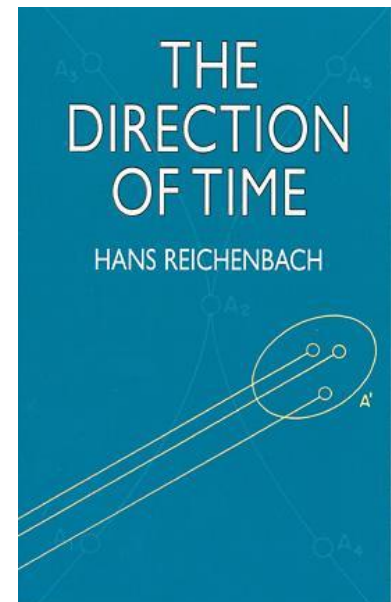
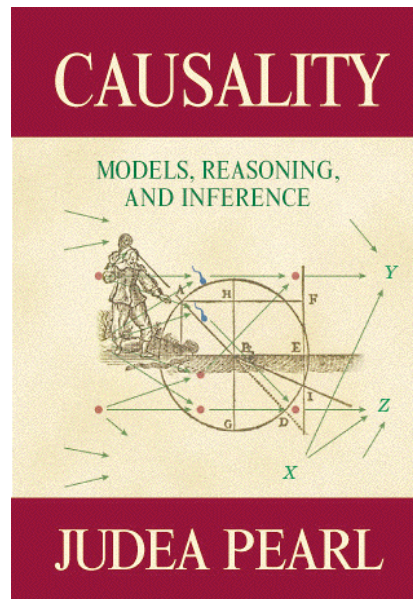
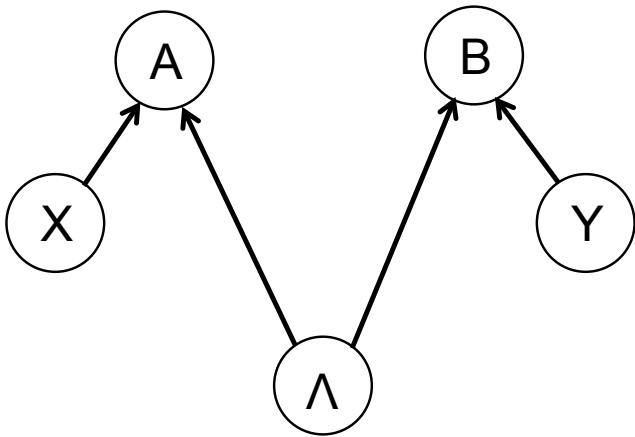
Reichenbach's Principle of Common Cause (1956): If two sets of events A and B are correlated, and no event in either is a CAUSE of any event in the other, then they have a set of common CAUSES C , such that conditioning on C eliminates the correlation.



Hans Reichenbach

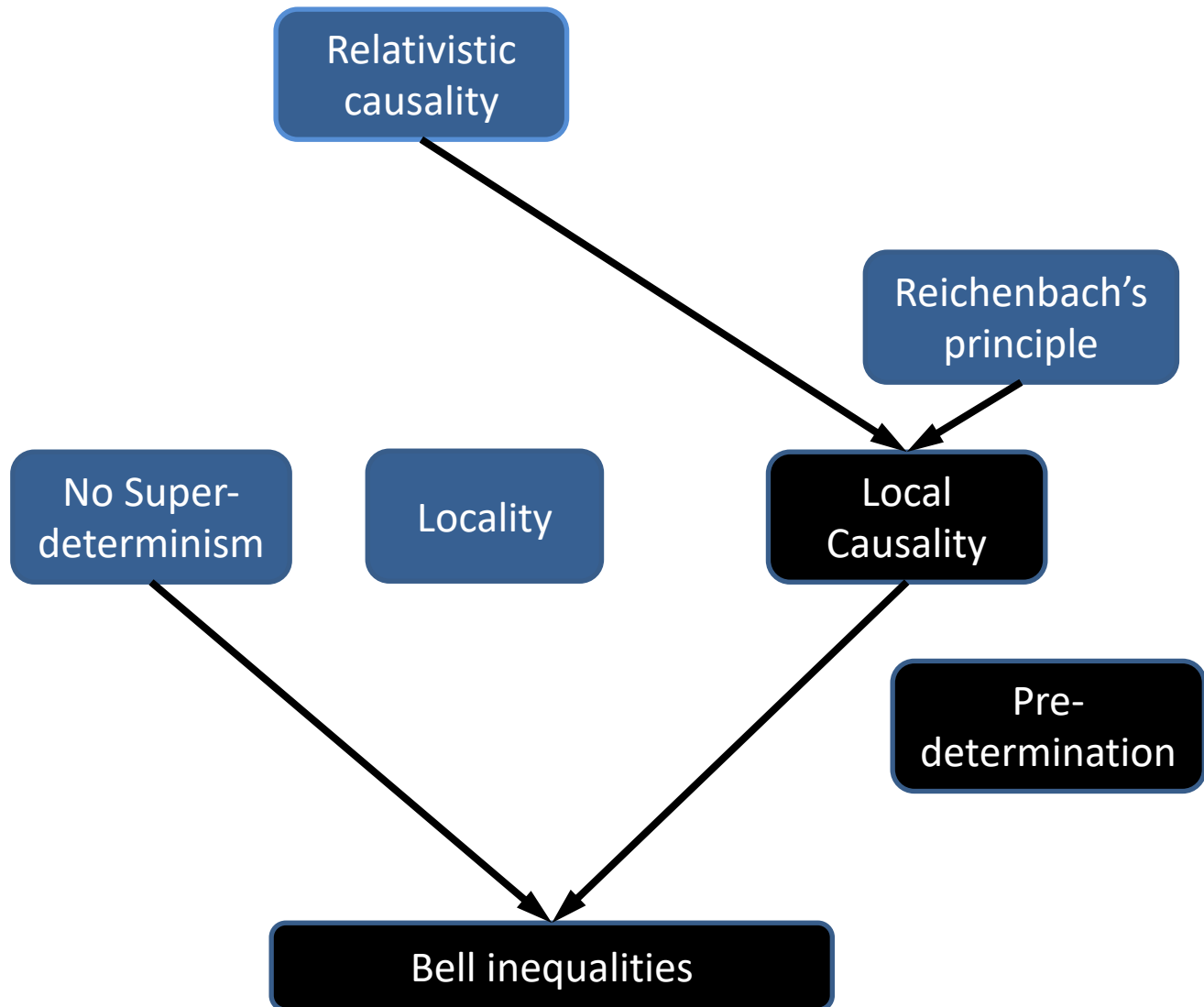


Causal models



Causal Markov Condition → Reichenbach's Principle

Relativistic Causality: The PAST is the past light-cone.



Give up relativistic causality?

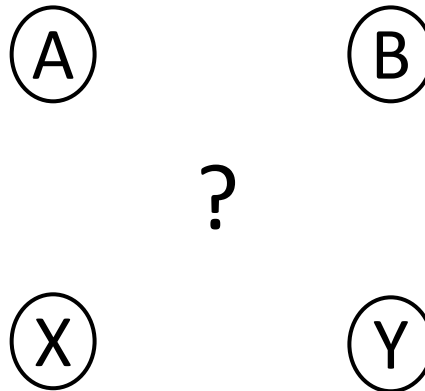
- E.g. Bohmian mechanics
 - violates, at a fundamentally hidden level, apparent operational symmetries.
- I.e., violates

Leibniz's Principle of the Identity of Indiscernibles* (Einstein's methodological principle):

Empirically indistinguishable scenarios should be represented by ontologically identical models.

*Spekkens, arXiv:1909.04628 (2019)

- Could there be a quantum theory that, despite violating relativistic causality, satisfies Leibniz's principle and Reichenbach's principle?

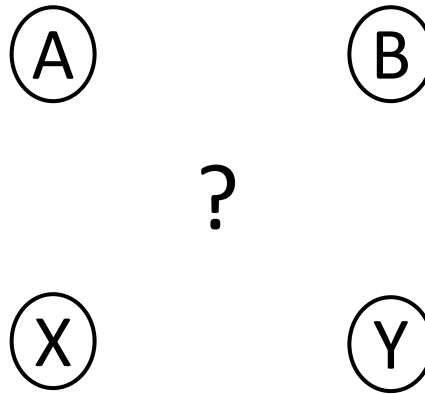


Leibniz's Principle \rightarrow Principle of No Fine-Tuning

- **No fine-tuning** (Faithfulness): Every conditional independence between variables must arise as a consequence of the causal graph and not due to special choices of causal-statistical parameters.

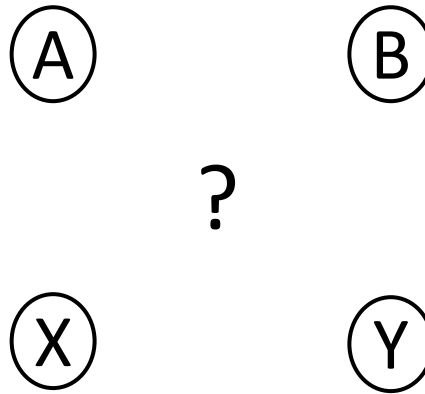
$$(X \perp Y | Z) \Rightarrow (X \perp Y | Z)_d$$

Finely tuned Bells



Wood and Spekkens, NJP **17**, 33002 (2015):

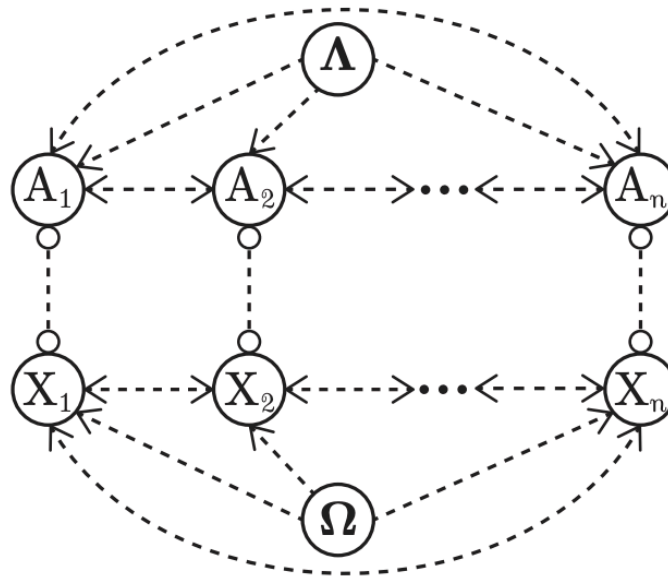
No classical causal model can explain all instances of bipartite Bell nonlocality without fine-tuning.



EGC, Phys. Rev. X 8, 021018 (2018):

No classical causal model can explain bipartite Bell nonlocality or Kochen-Specker contextuality in scenarios with two measurements per context without fine-tuning.

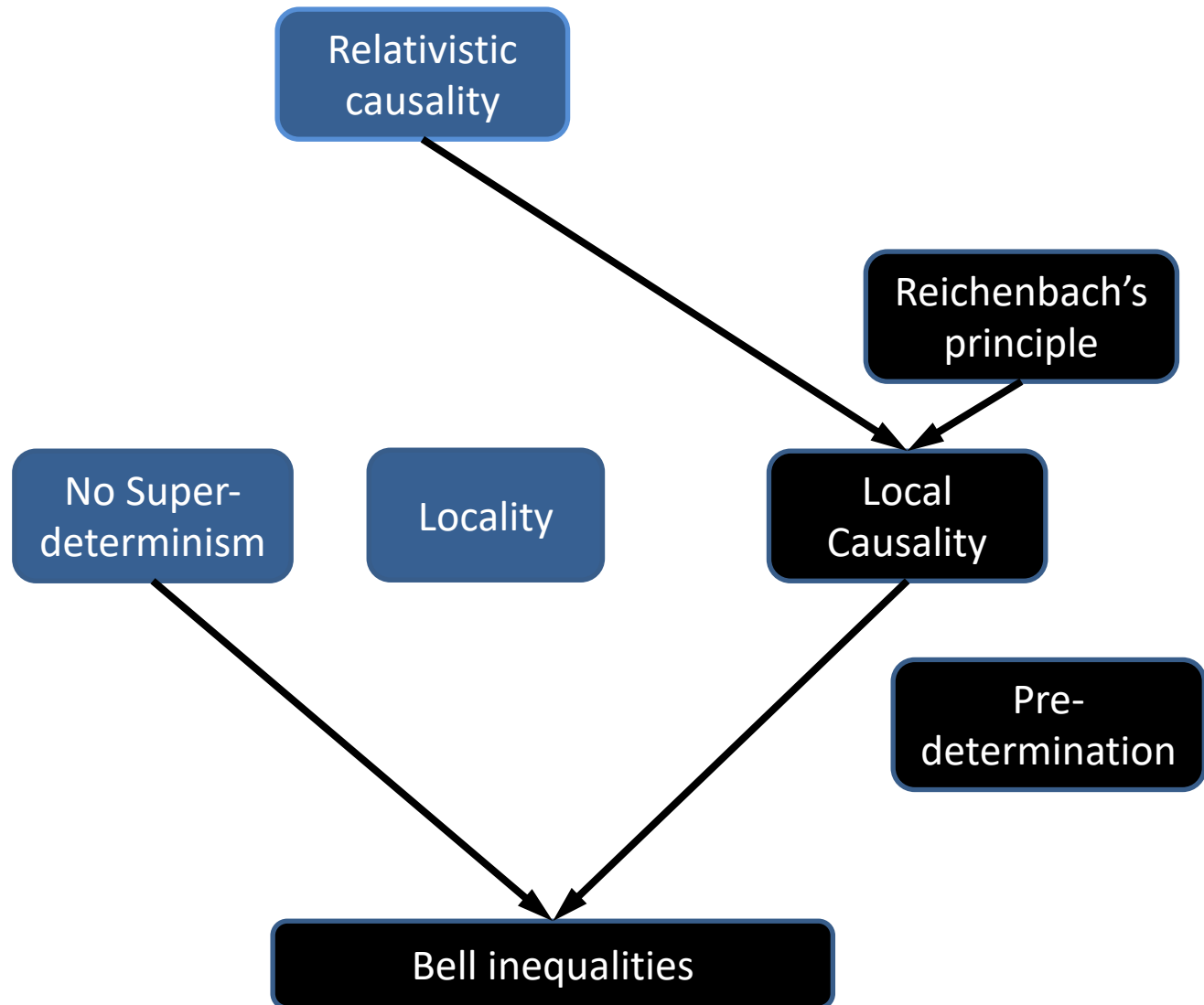
Arbitrary Bell-KS scenarios



J.C Pearl and EGC, arXiv:1909.05434 (2019):

No faithful classical causal model can explain Bell nonlocality or Kochen-Specker contextuality in arbitrary scenarios.

→ The only hope to *maintain* the Leibniz-Einstein methodological principle is to *reject Reichenbach's Principle*

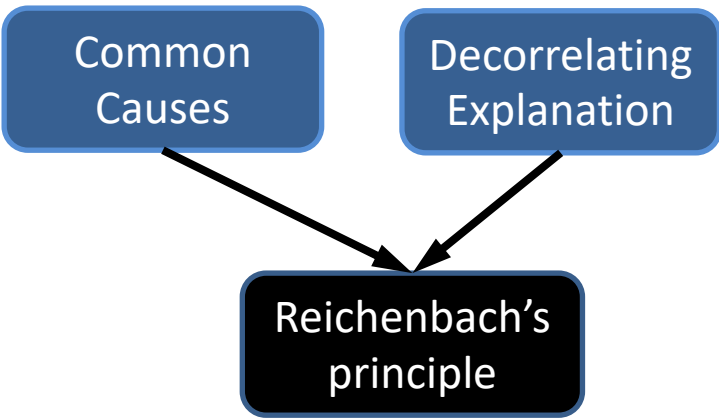


On modifications of Reichenbach’s principle of common cause in light of Bell’s theorem

Eric G Cavalcanti^{1,2} and Raymond Lal^{1,2}

¹ School of Physics, University of Sydney, NSW 2016, Australia

² Department of Computer Science, University of Oxford, Oxford OX1 3QD, UK



Principle of Common Cause: If two sets of events A and B are correlated, and no event in either is a CAUSE of any event in the other, then they have a set of common CAUSES C that EXPLAINS the correlation.

Principle Of Decorrelating Explanation: A set of CAUSES C, common to two sets of events A and B, EXPLAINS a correlation between them only if conditioning on C eliminates the correlation.

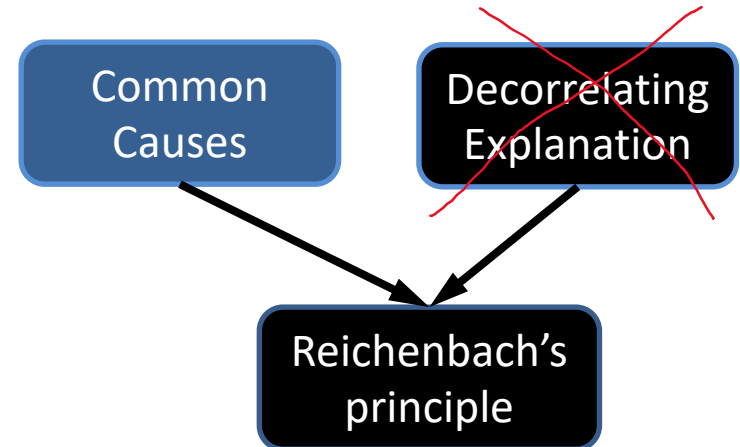
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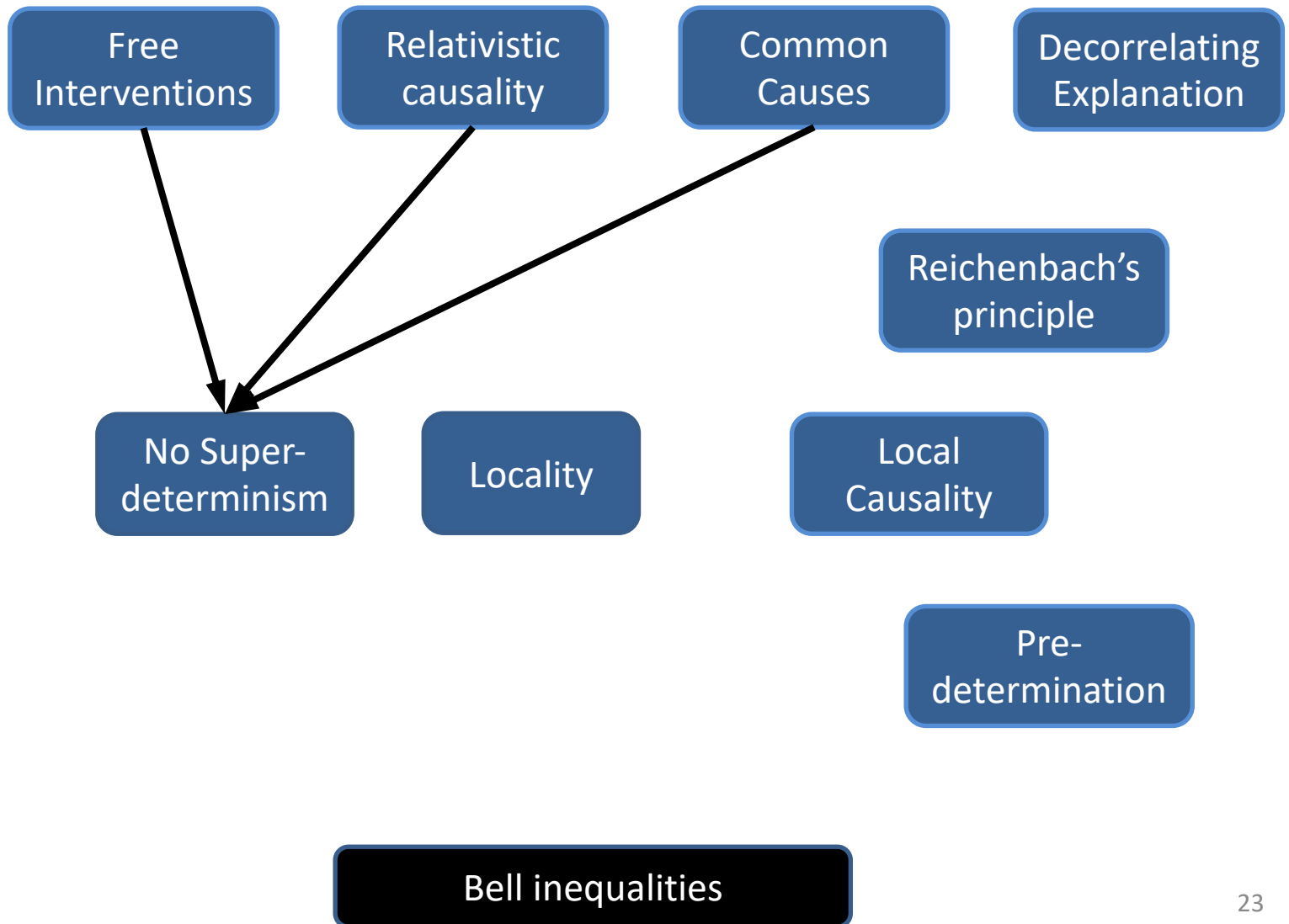
In the Leifer-Spekkens conditional states formalism:
Decorrelating explanation \rightarrow *Factorisation of channels*



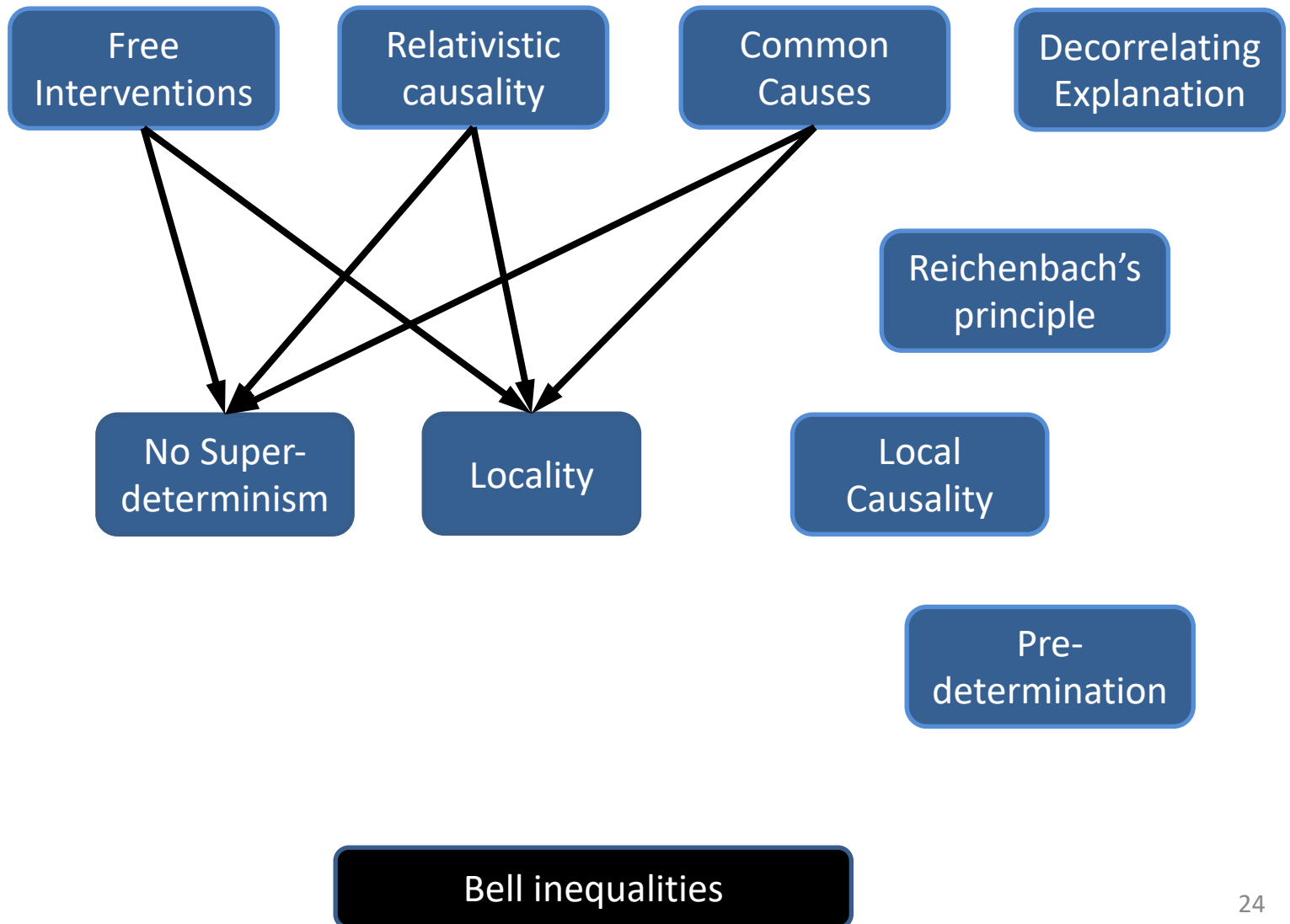
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Free Interventions: An intervention has no relevant CAUSES.



Free Interventions: An intervention has no relevant CAUSES.



Absolute
events

Minkowski
Space-time

Temporal
order

Causal arrow

Free
Interventions

Relativistic
causality

Common
Causes

Decorrelating
Explanation

No Super-
determinism

Locality

Local
Causality

Reichenbach's
principle

Pre-
determination

Bell inequalities

Quantum causal models

Leifer and Spekkens, Phys. Rev. A 88, 052130 (2013), arXiv:1107.5849

Wood and Spekkens, New Journal of Physics, 17 (2015), arXiv:1208.4119

Cavalcanti and Lal, J. Phys. A 47, 424018 (2014), arXiv:1311.6852

Fritz, T. Comm. Math. Phys., 341, 391–434 (2016), arXiv:1404.4812

Henson, Lal and Pusey (HLP), New J. Phys. 16, 113043 (2014), arXiv:1405.2572

Pienaar and Brukner (PB), New J. Phys. 17, 073020 (2015), arXiv:1406.0430

Chaves, Majenz and Gross, Nat. Commun. 6, 5766 (2015), arXiv:1407.3800

Costa, Shrapnel, New J. Phys. 18 063032 (2016), arXiv:1512.07106

Allen, Barrett, Horsman, Lee and Spekkens, Phys. Rev. X 7, 031021 (2017), arXiv:1609.09487

Barrett, Lorenz, Oreshkov, arXiv:1906.10726

- Significant steps towards a causal explanation of quantum correlations

→ Resolution of the “easy problem” of Bell?

The Bell still rings

“More importantly, the “no signalling” notion rests on concepts which are desperately vague . . . The assertion that “we cannot signal faster than light” immediately provokes the question: “Who do we think we are?” - J.S. Bell , “La Nouvelle Cuisine” (1990)



The Bell still rings

*“More importantly, the **“no signalling”** notion rests on concepts which are desperately vague . . . The assertion that “we cannot signal faster than light” immediately provokes the question: “Who do we think we are?” - J.S. Bell , “La Nouvelle Cuisine” (1990)*

- The “Hard Problem” of Bell = the Measurement Problem
- Do quantum causal models resolve the measurement problem?

E. G. Cavalcanti, “Bell’s theorem and the measurement problem: reducing two mysteries to one?”, J. Phys. Conf. Ser. 701, 12002 (2016).



Wigner's Friend paradox

- Intuition pump for the Measurement Problem



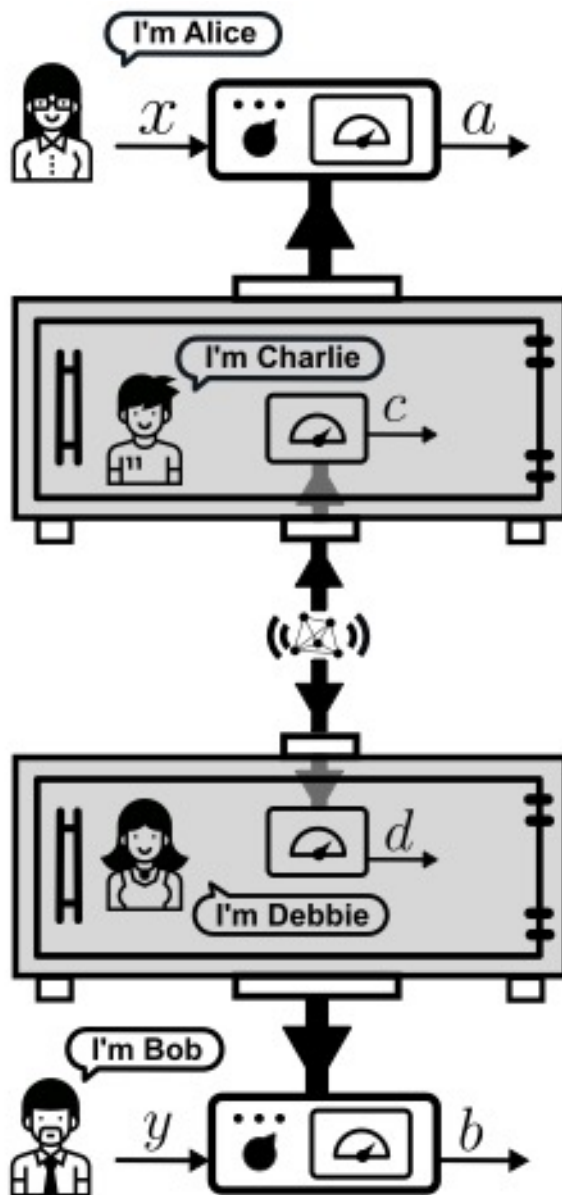
Eugene Wigner, 1962

Wigner's Friend paradox



Eugene Wigner, 1962

- Intuition pump for the Measurement Problem
- Some recent results:
 - Frauchiger & Renner, Nat. Comm. 9, 3711 (2018).
→ not theory-independent
 - Our work is based on:
Caslav Brukner,
Entropy 20, 350, (2018).



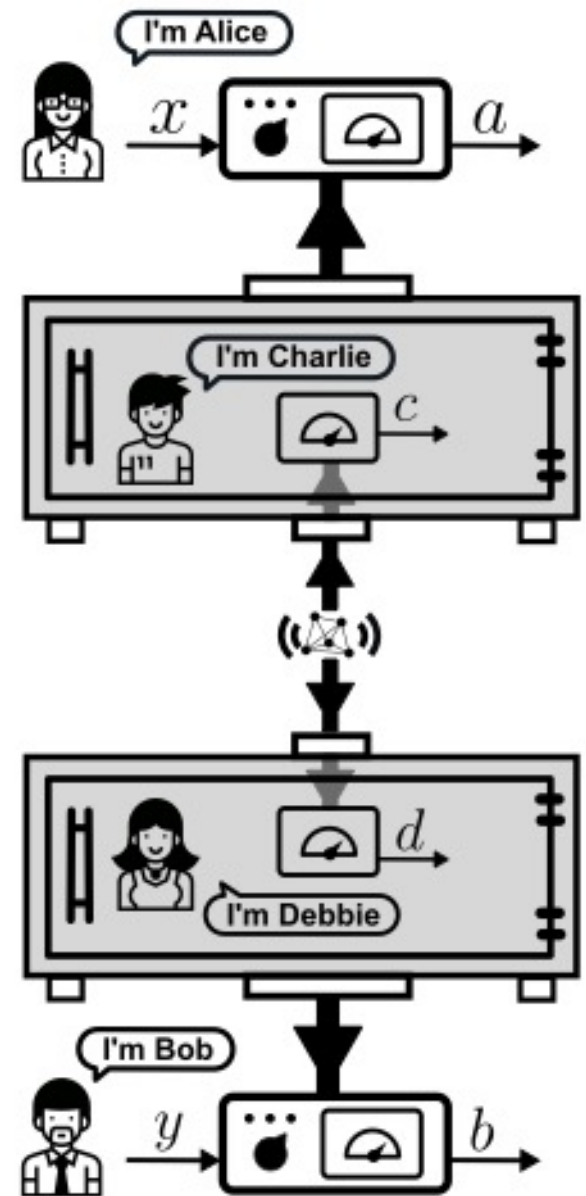
*Kok-Wei Bong *et al*, "Testing the reality of Wigner's friend's experience", arXiv:1907.05607

We* call “**Local Friendliness**” the conjunction of (following Brukner):

1. **Locality.**
2. **Freedom of choice**
(No super-determinism).
3. **Observer-independent facts**
(Absolute events).

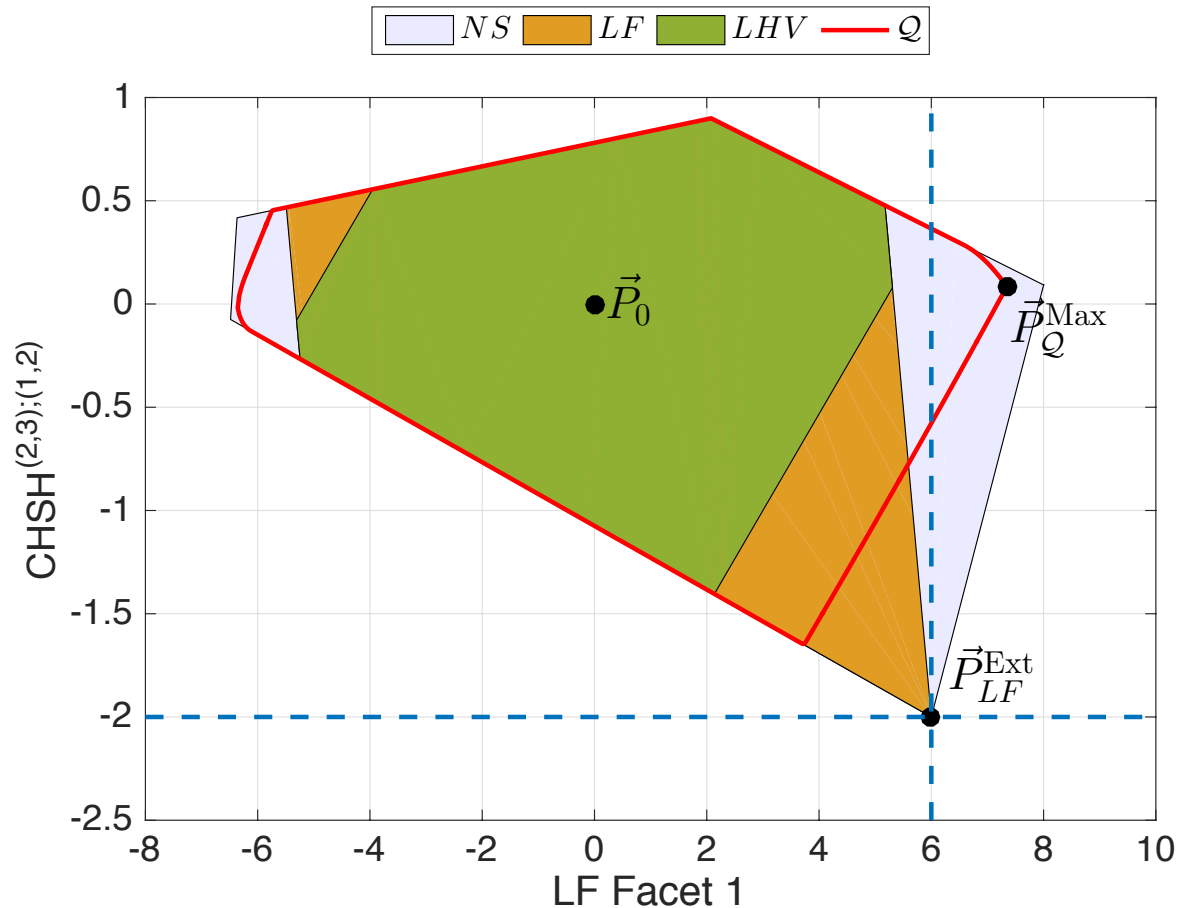
From these we derive “LF inequalities”, as constraints on $P(a,b|x,y)$.

- *LF inequalities can in principle be violated by quantum mechanics.*

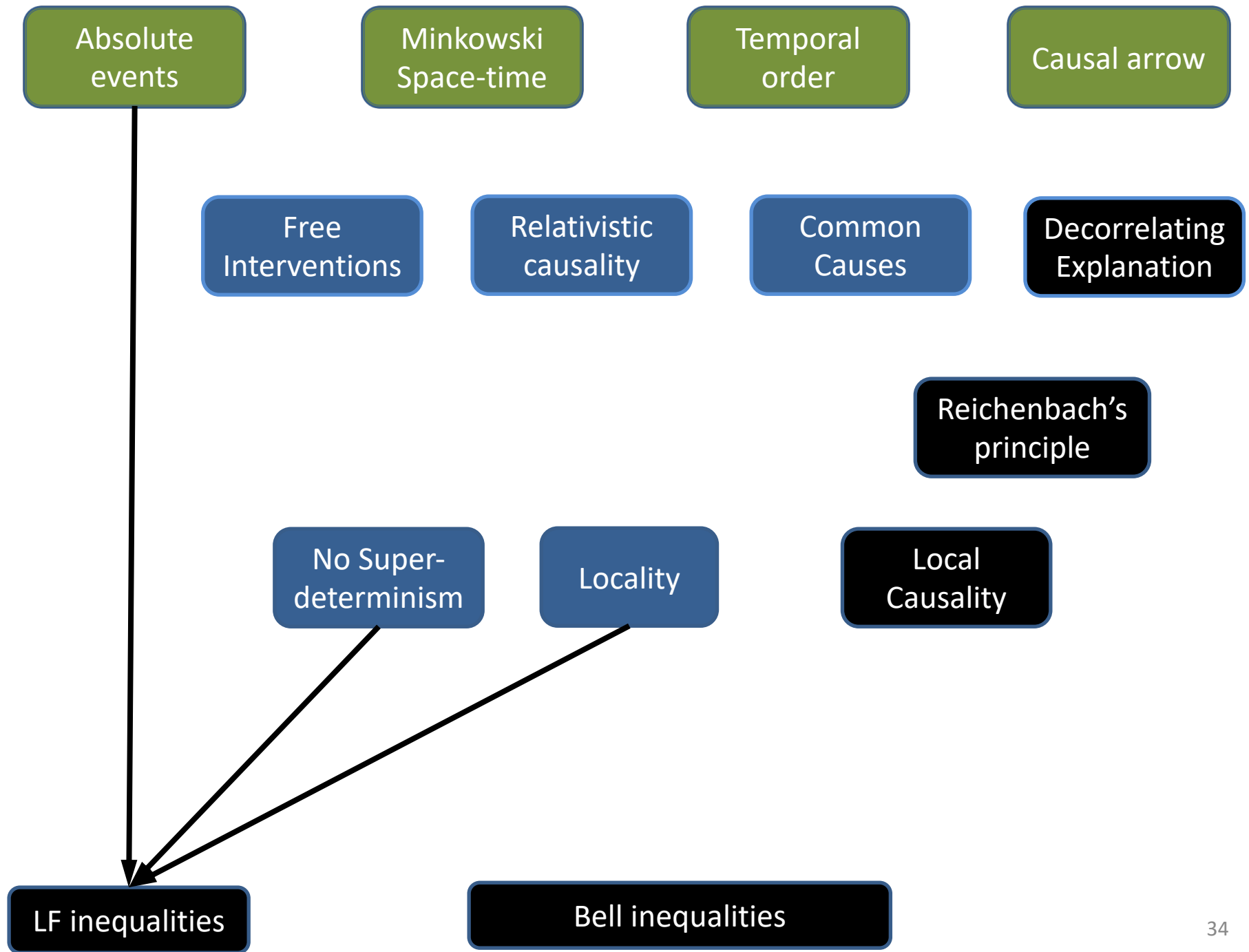


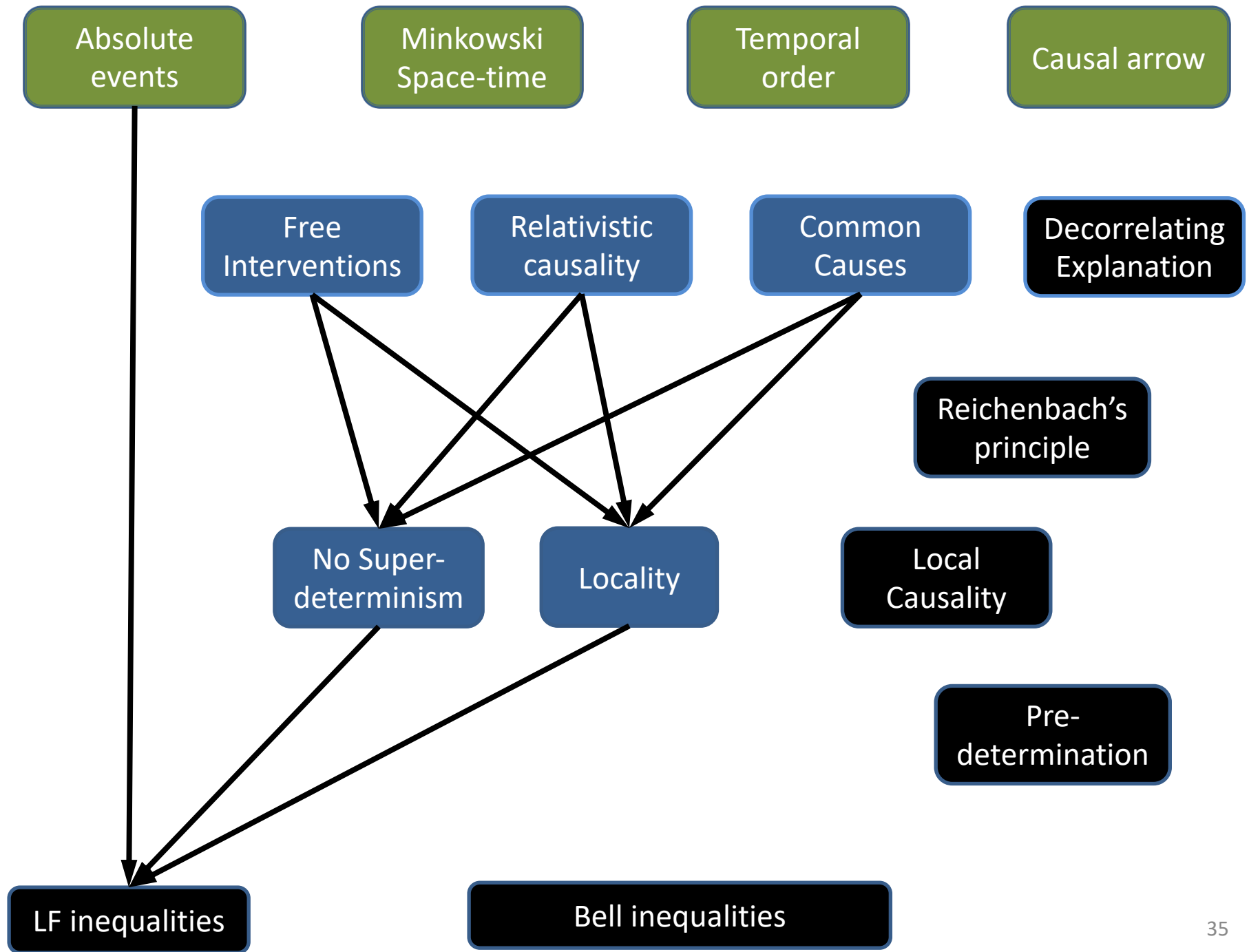
*Kok-Wei Bong *et al*, “Testing the reality of Wigner's friend's experience”, arXiv:1907.05607

Local Friendliness polytope strictly contains LHV polytope



Strictly Stronger than Bell's theorem





Absolute
events

Local Agency: The only relevant events correlated with an intervention are in its future light cone.

Free
Interventions

Relativistic
causality

Common
Causes

Decorrelating
Explanation

Reichenbach's
principle

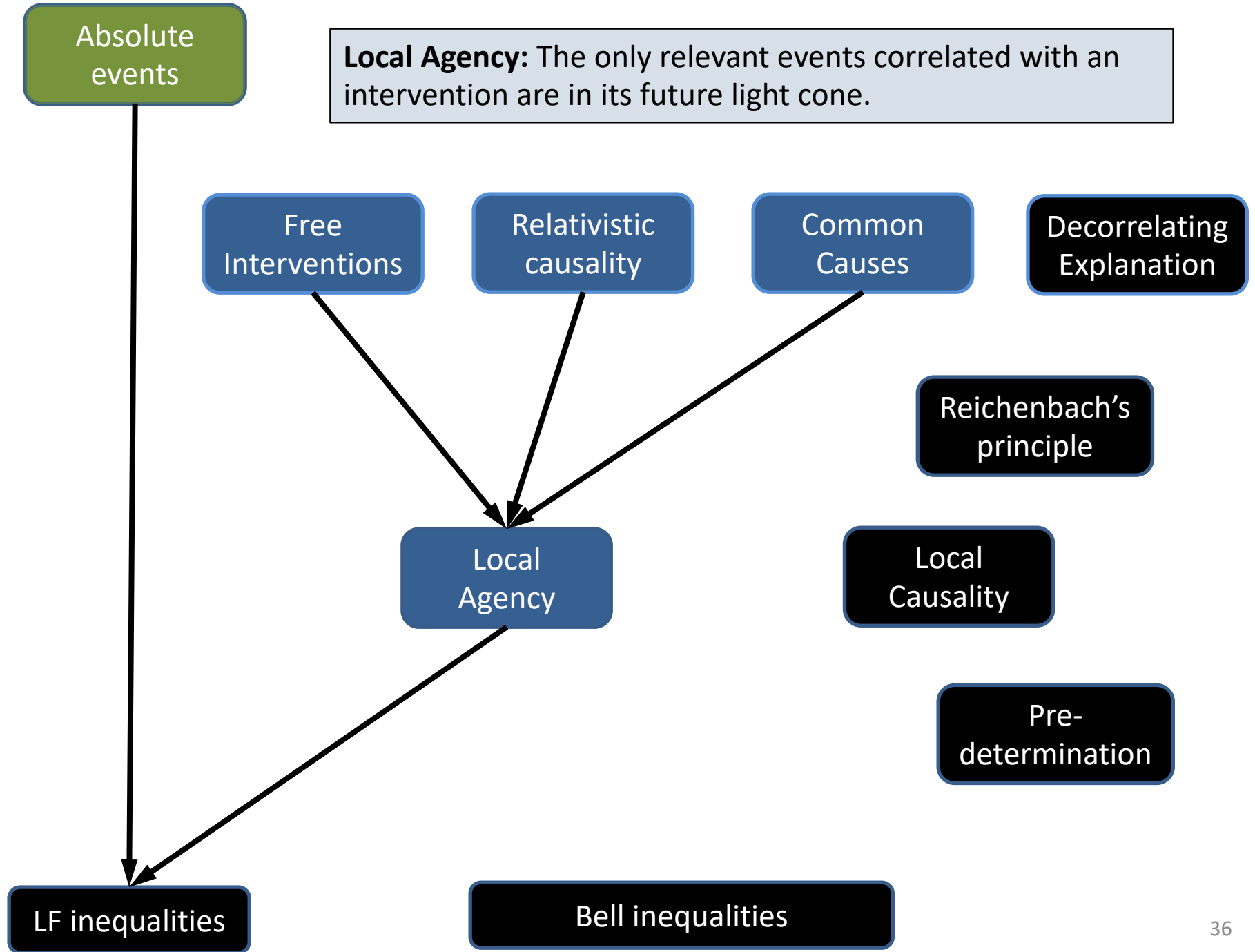
Local
Causality

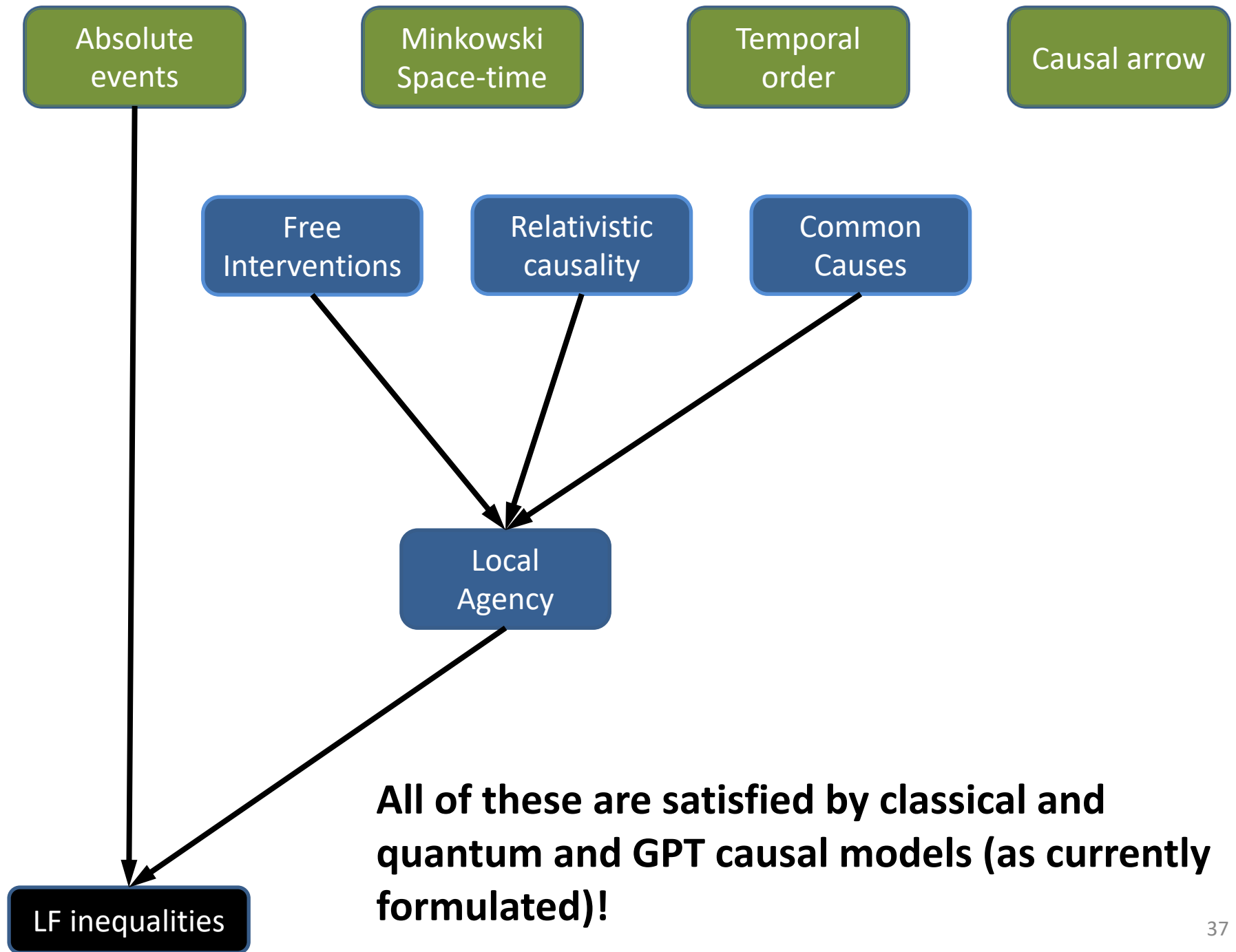
Pre-
determination

Local
Agency

LF inequalities

Bell inequalities

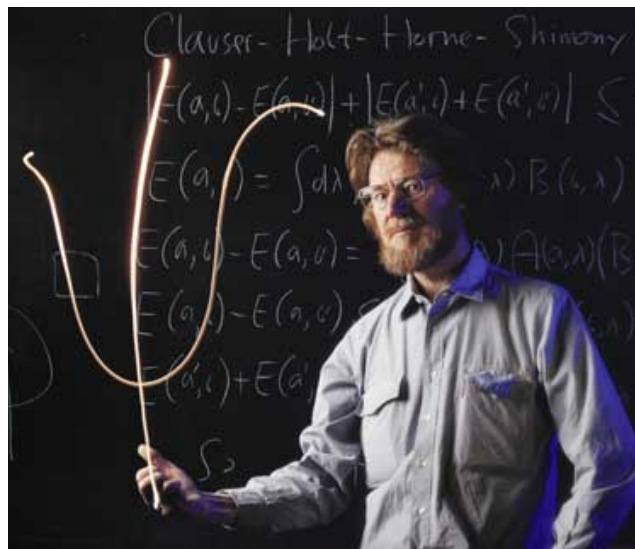




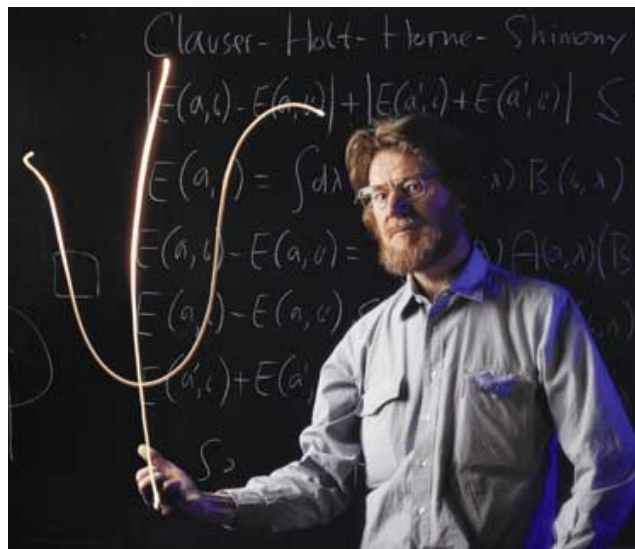
Implications for Quantum Causality?

- **LF inequalities not violated with “observers”?**
 - Empirical question → collapse models
- **Reject Free Interventions or Relativistic Causality?**
 - (Presumably) violates Leibniz-Einstein Principle
- **Reject Common Causes?**
 - How to make sense of causal explanation?
- **Reject Space-time, Temporal Order or Causal Arrow?**
 - Suggested by indefinite causal structure
 - But how exactly can that explain the violation of LF inequalities?
- **Reject Absolute Events?**
 - Does not obviously violate Leibniz-Einstein Principle
 - Independent reasons from quantum gravity
 - Reformulate other concepts with relational notions of “events”, “space-time”, etc?

We still need radical conceptual renewal.



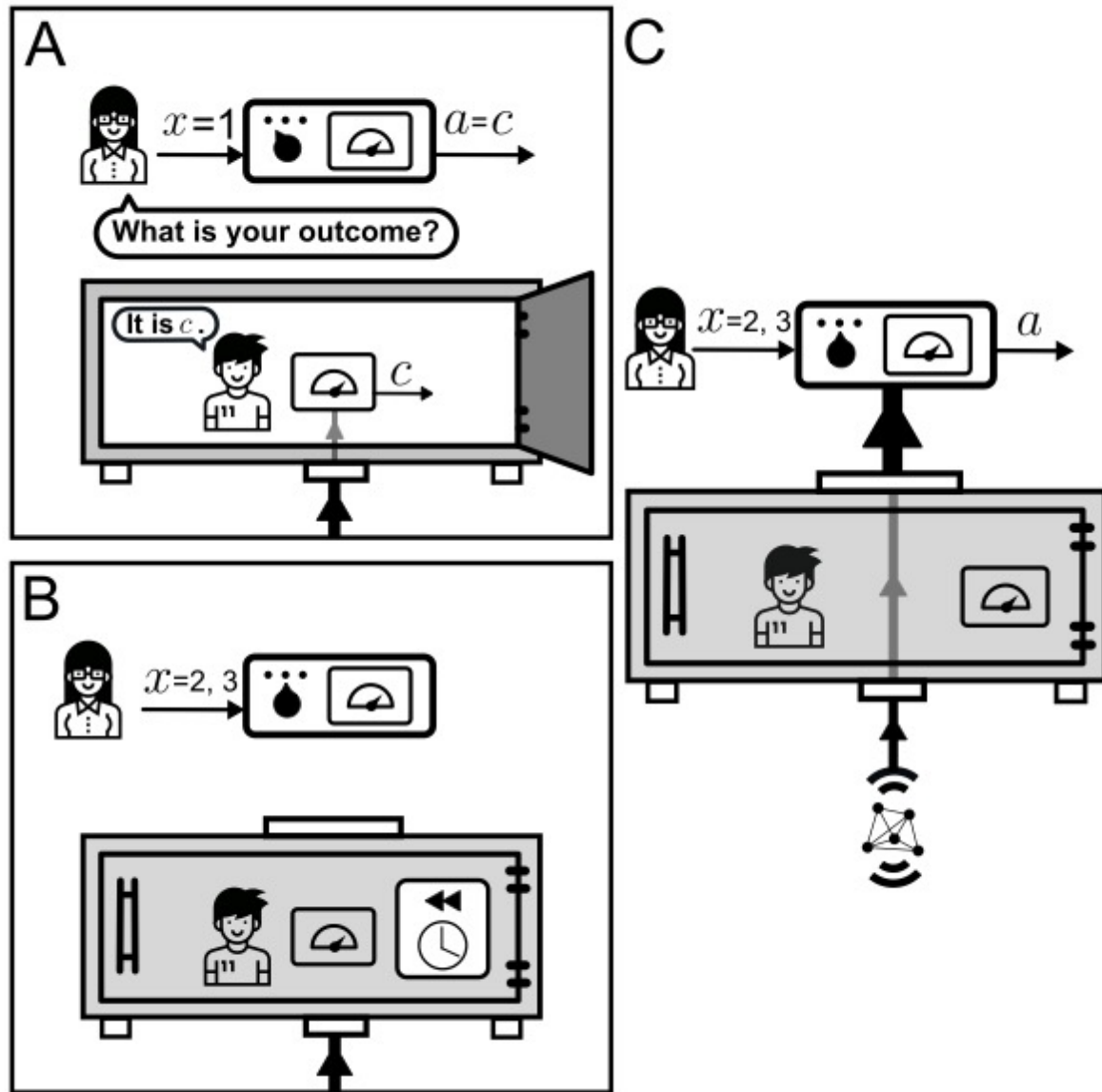
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Thank you

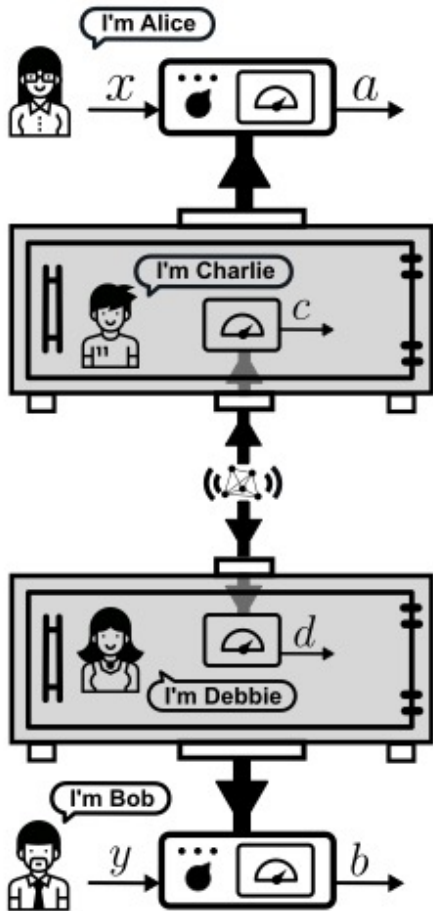
2-year Postdoctoral Research Fellow position available at Griffith University, Gold Coast campus





Kok-Wei Bong *et al*, "Testing the reality of Wigner's friend's experience", arXiv:1907.05607

Strictly stronger than Bell's theorem

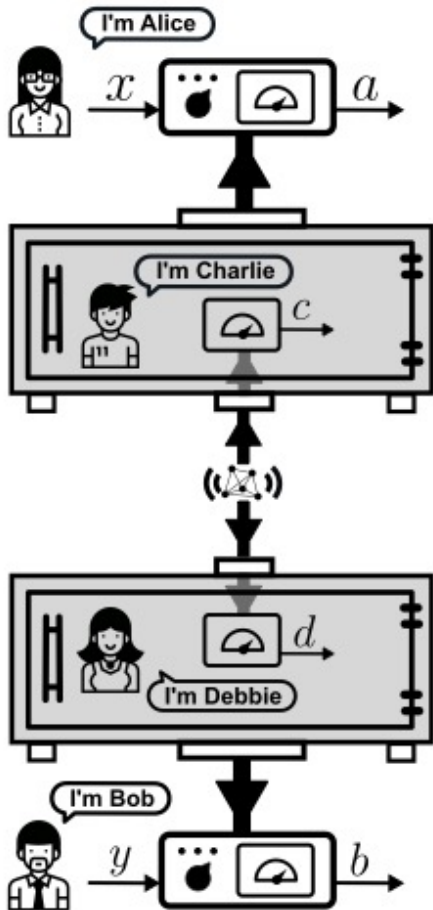


Observer-Independent Facts (Absolute events): *Any observed event exists absolutely, not relative to anything or anyone.*

$$\Rightarrow P(a, b|x, y) = \sum_{c, d} P(a, b, c, d|x, y)$$

- NOT “Unperformed experiments have results” but “**performed** experiments have **absolute** results”.

Strictly stronger than Bell's theorem



Locality (a.k.a Parameter Independence): *The probability of an observable event a is unchanged by conditioning on a space-like-separated free choice y , even if it is already conditioned on other events not in the future light-cone of y .*

$$\Rightarrow P(a|c, d, x, y) = P(a|c, d, x)$$

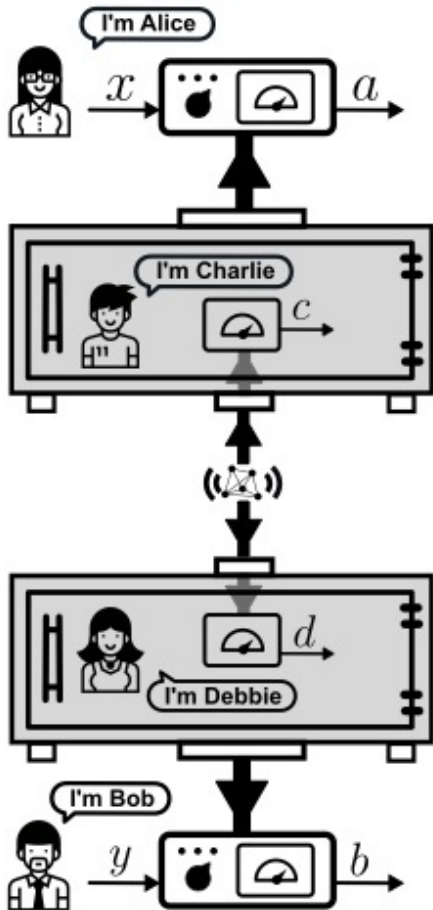
– NOT Bell's assumption of Local Causality:

$$P(a|b, c, d, x, y) = P(a|c, d, x)$$

– LC = Locality + Outcome Independence:

OI: $P(a|b, c, d, x, y) = P(a|c, d, x, y)$

Strictly stronger than Bell's theorem



Freedom of Choice (No super-determinism): *Any set of events on a space-like hypersurface is uncorrelated with any set of freely chosen actions subsequent to that space-like hypersurface.*

$$P(c, d|x, y) = P(c, d)$$

- Same meaning as in Bell's theorem

“Partially deterministic polytopes”

- After one of us (HMW) presented these results at a conference, it was brought to our attention that the LF polytopes had been previously studied under the name of “partially deterministic polytopes” [1].
- Information-theoretic interpretation:
 - The sets of phenomena for which randomness *cannot* be certified device-independently in the presence of a no-signaling adversary.

[1] Erik Woodhead, PhD thesis, Université libre de Bruxelles (2014).