Bell, Wigner, causal reasoning, and interpretations

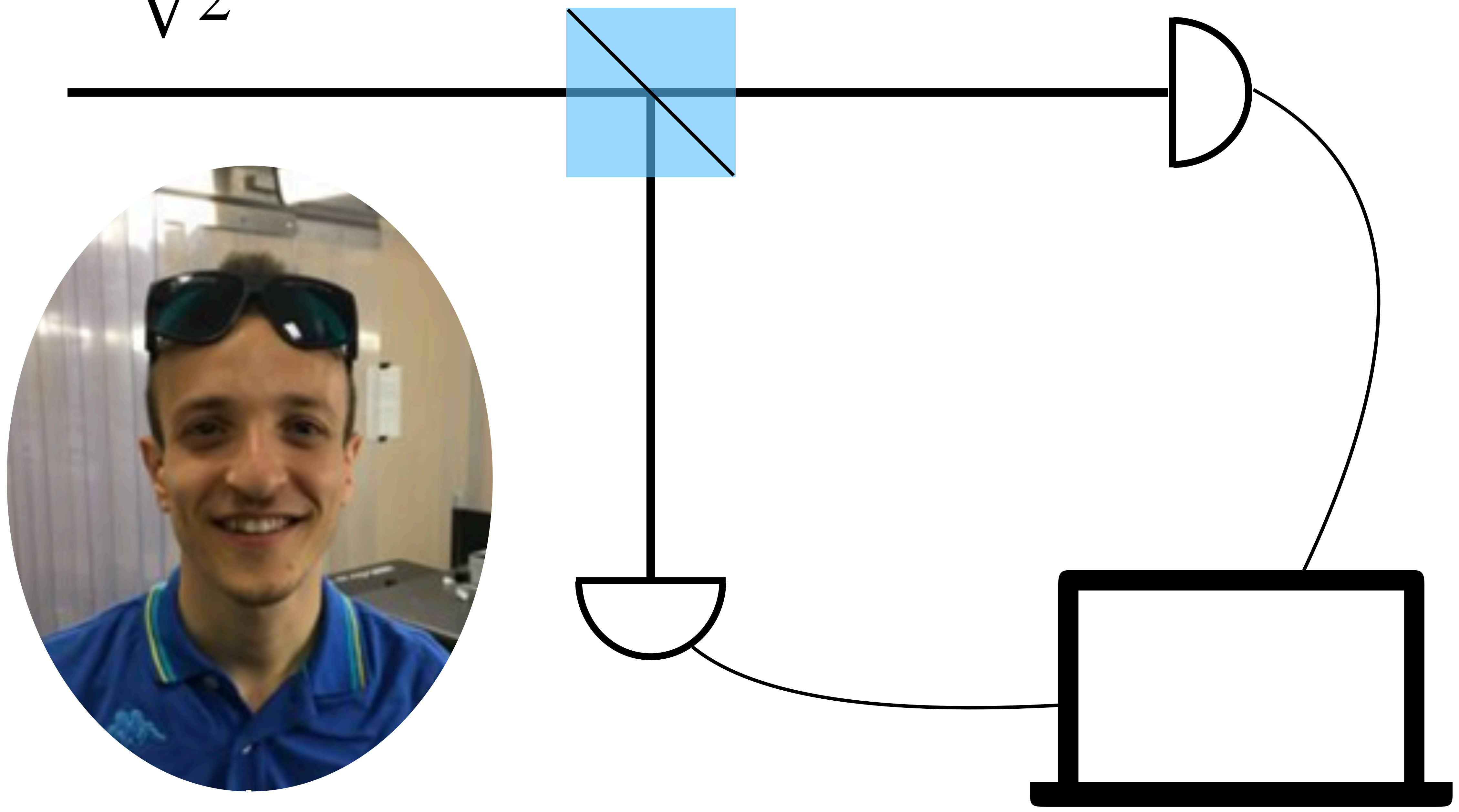
Andrea Di Biagio www.patternsthatabide.xyz

QISS Virtual Seminar 2025-06-19

Bell, Wigner

friends

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$



Bell, Wigner

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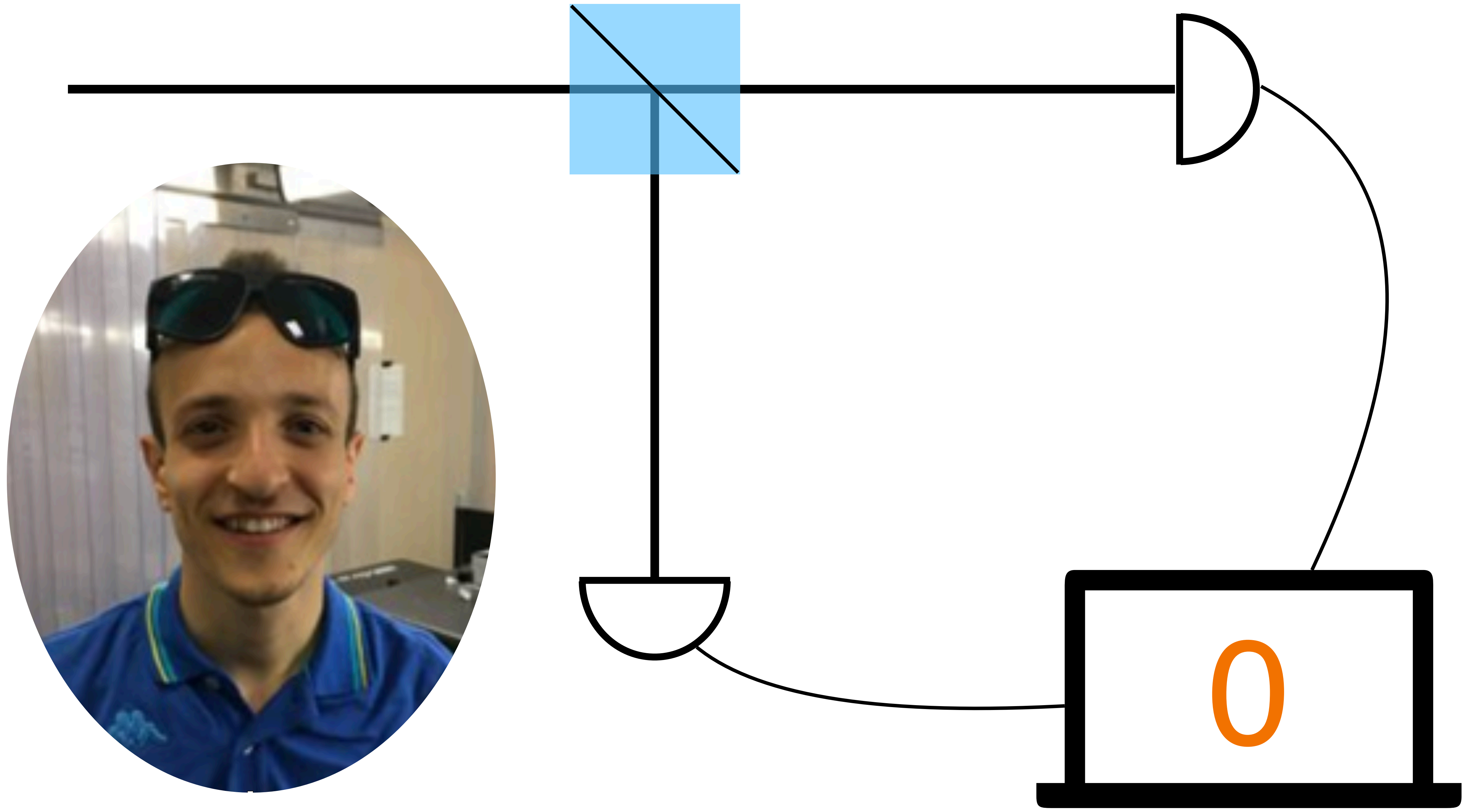

Bell, Wigner

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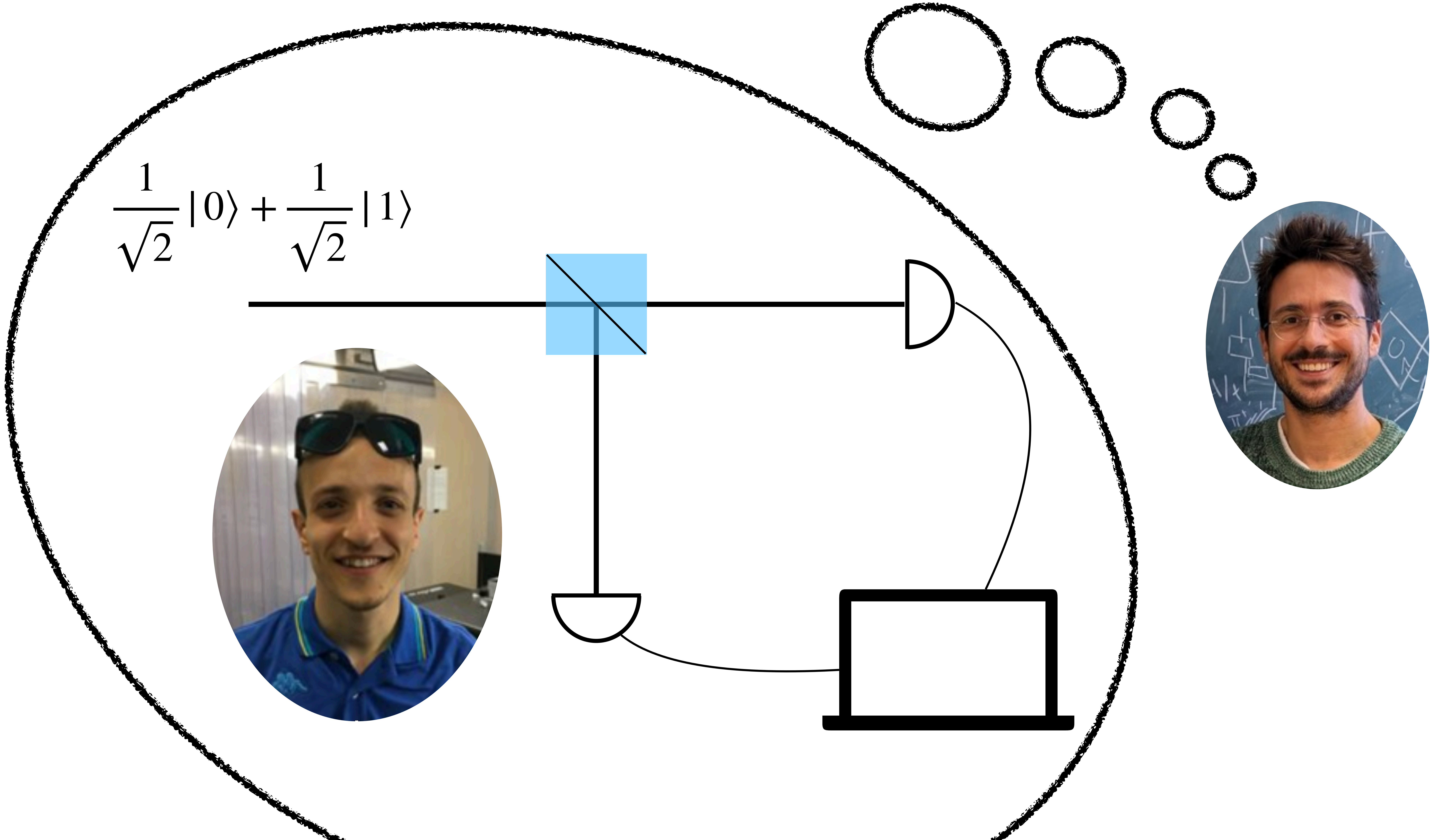
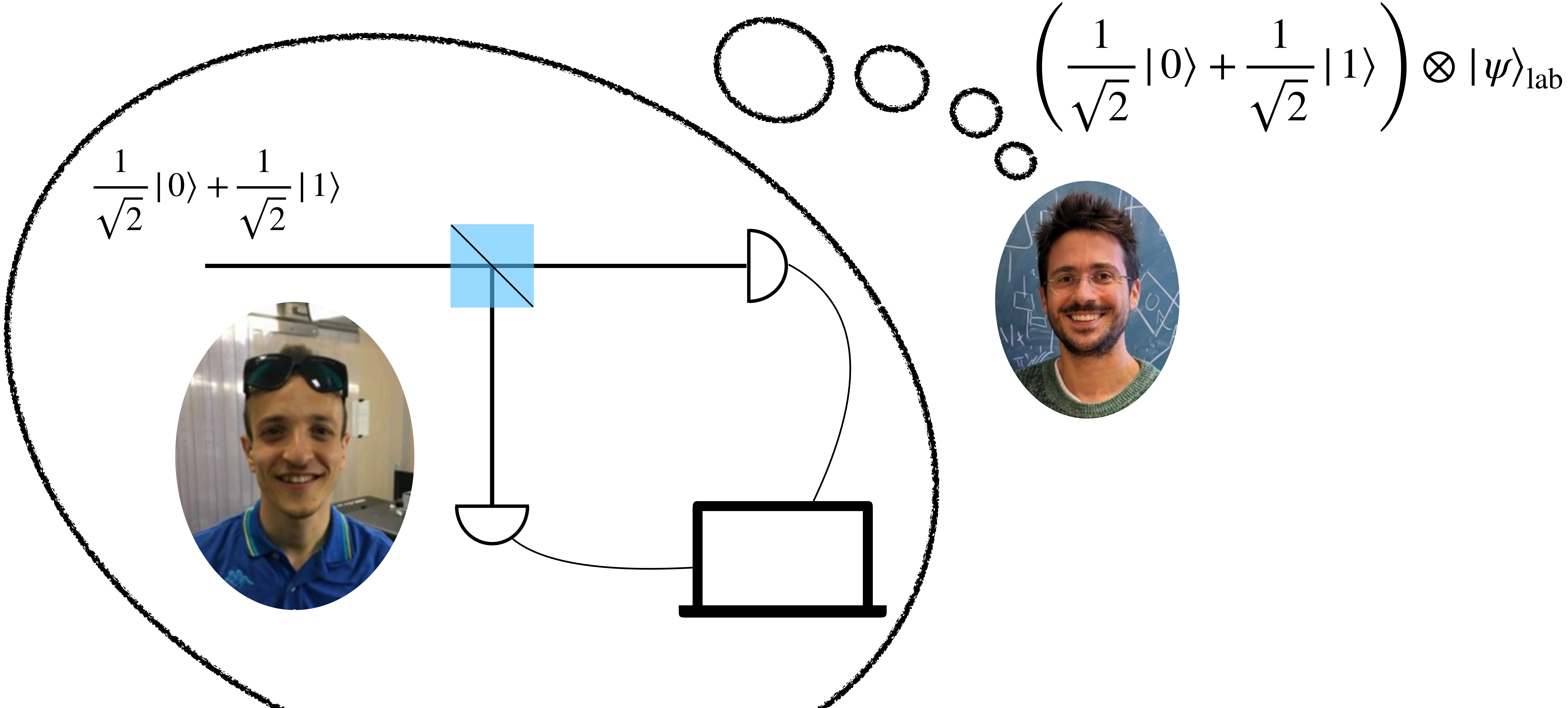


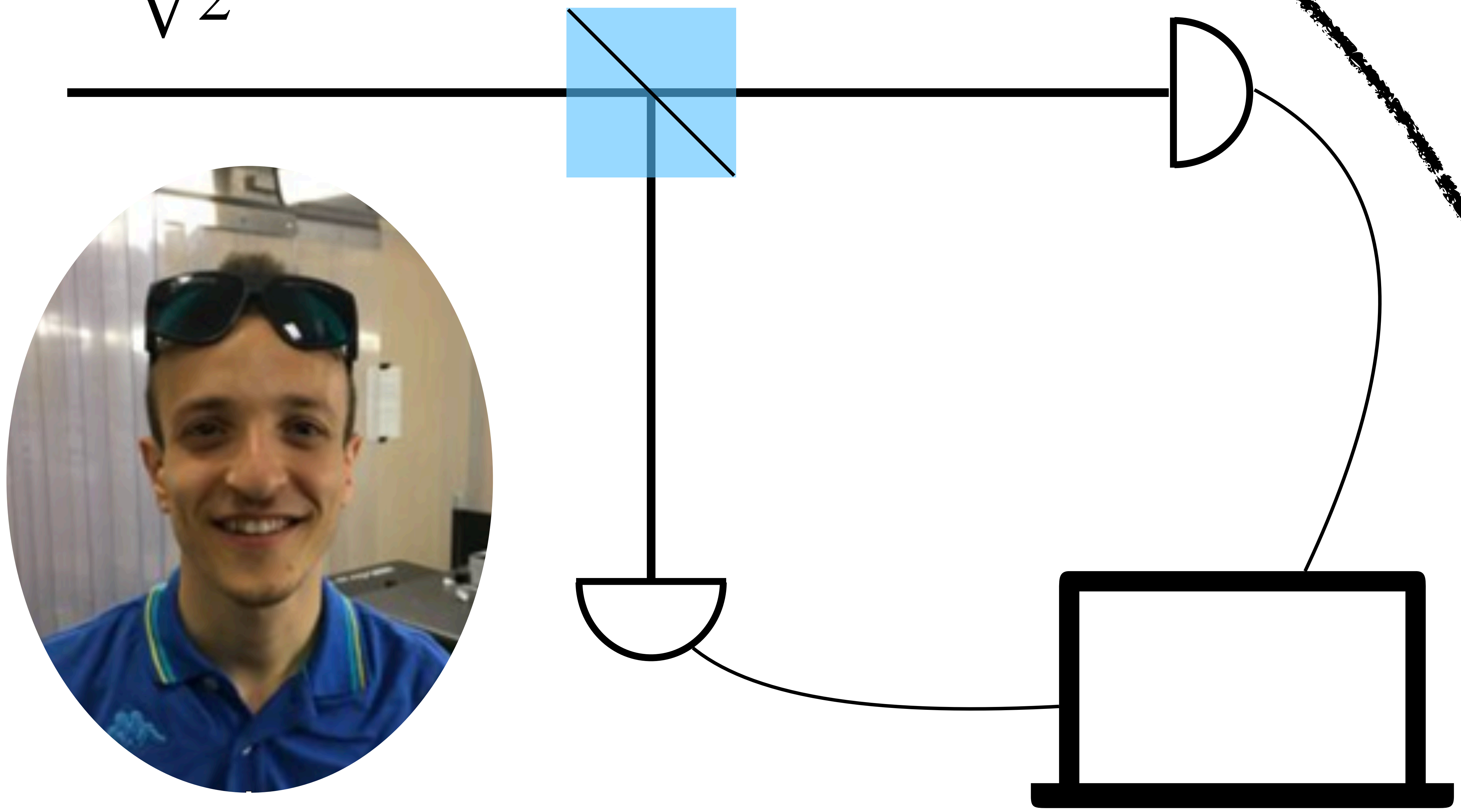
friends


$\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right) \otimes |\psi\rangle_{\text{lab}}$
$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$

friends

$$\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right) \otimes |\psi\rangle_{\text{lab}}$$

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$



$$\frac{1}{\sqrt{2}}|0\rangle|\psi_0\rangle_{\text{lab}} + \frac{1}{\sqrt{2}}|1\rangle|\psi_1\rangle_{\text{lab}}$$

Bell, Wigner

friends

Wigner's friend

is Emanuele really in a superposition?

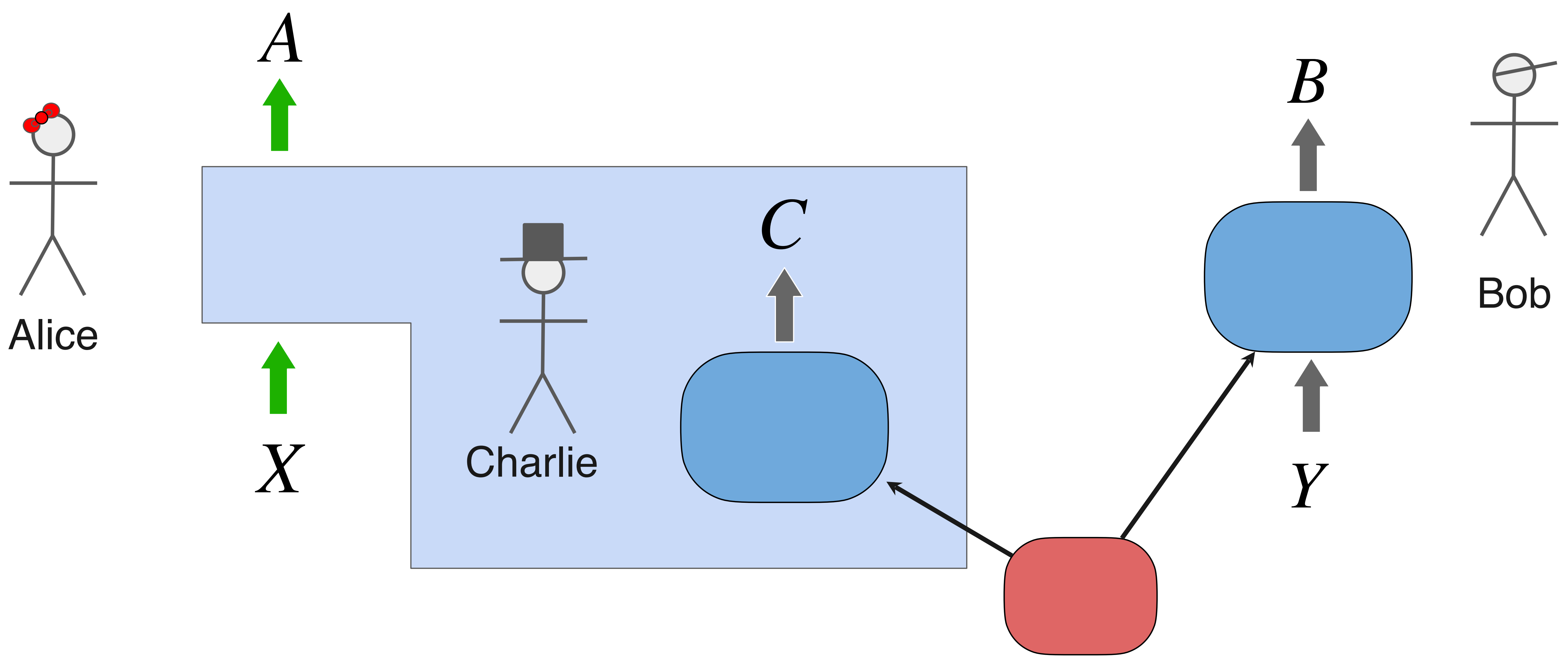
whenever I look in the lab, I see him in a definite state

it *must* just be a matter of lacking information, not a real superposition... *right*?

a problem with the quantum description

similar situation as with EPR... quantum theory said the outcomes were random, but there was a local hidden variable model for the the EPR correlations

extended Wigner's friend scenario



violations of certain inequalities in conflict with intuitive metaphysical assumptions

A No-Go Theorem for Observer-Independent Facts
by Časlav Brukner [1,2]
Entropy **2018**, *20*(5), 350; https://doi.org/10.3390/e20050350

extended Wigner's friend

other theorems

PAPER • OPEN ACCESS

A possibilistic no-go theorem on the Wigner's friend paradox

Marwan Haddara and Eric G Cavalcanti

New Journal of Physics, Volume 25, September 2023

A "thoughtful" Local Friendliness no-go theorem: a prospective experiment with new assumptions to suit

Howard M. Wiseman[1,2], Eric G. Cavalcanti[3], and Eleanor G. Rieffel[4]

Doi: https://doi.org/10.22331/q-2023-09-14-1112

Citation: Quantum 7, 1112 (2023).

arXiv:2209.03940 (quant-ph)

[Submitted on 8 Sep 2022]

A no-go theorem for absolute observed events without inequalities or modal logic

Nick Ormrod, Jonathan Barrett

QUANTUM MECHANICS

Facts are relative

Časlav Brukner

Nature Physics **16**, 1172–1174 (2020)

Home › Foundations of Physics › Article

When Greenberger, Horne and Zeilinger Meet Wigner's Friend

Open access | Published: 27 June 2022

Volume 52, article number 68, (2022) Cite this article

Gijs Leegwater

Article | Open access | Published: 18 September 2018

Quantum theory cannot consistently describe the use of itself

Daniela Frauchiger & Renato Renner

Nature Communications **9**, Article number: 3711 (2018)

arXiv:2308.16220 (quant-ph)

[Submitted on 30 Aug 2023]

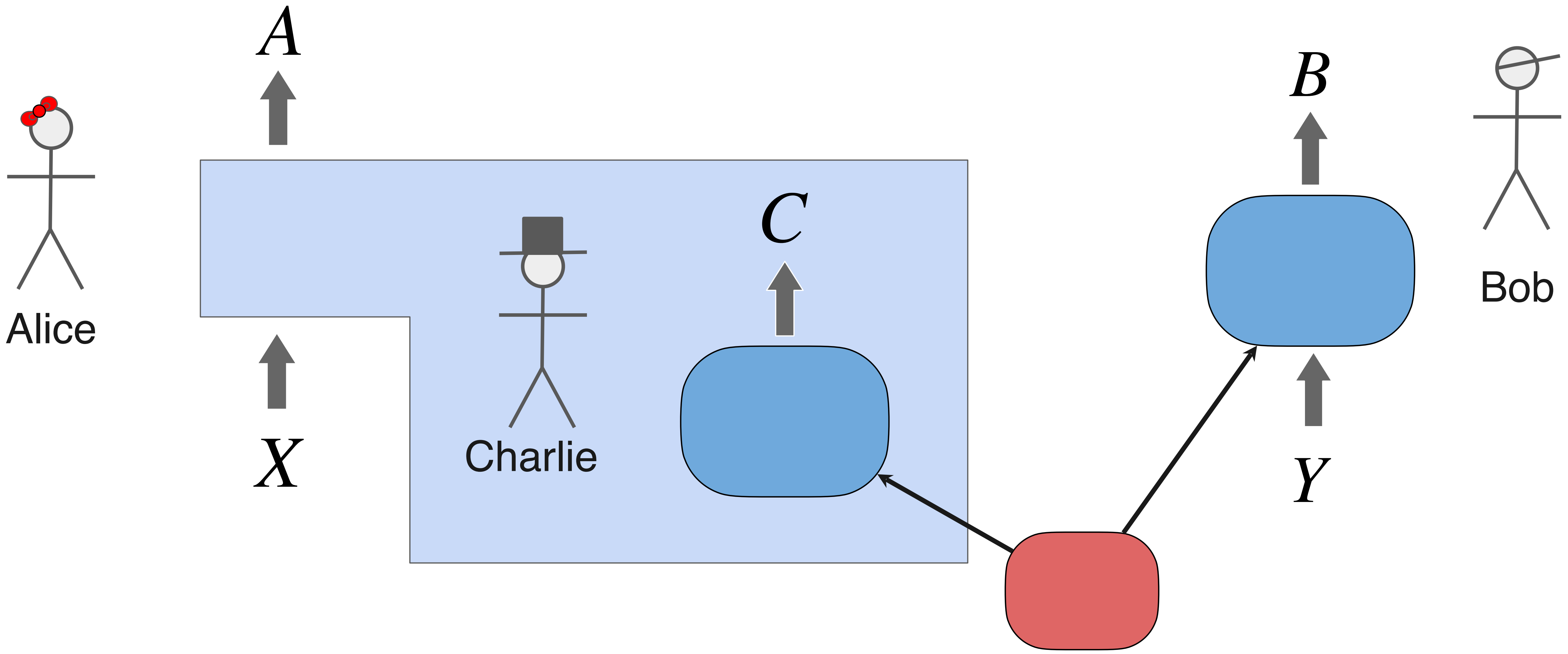
A review and analysis of six extended Wigner's friend arguments

David Schmid, Yìlè Yīng, Matthew Leifer

plan

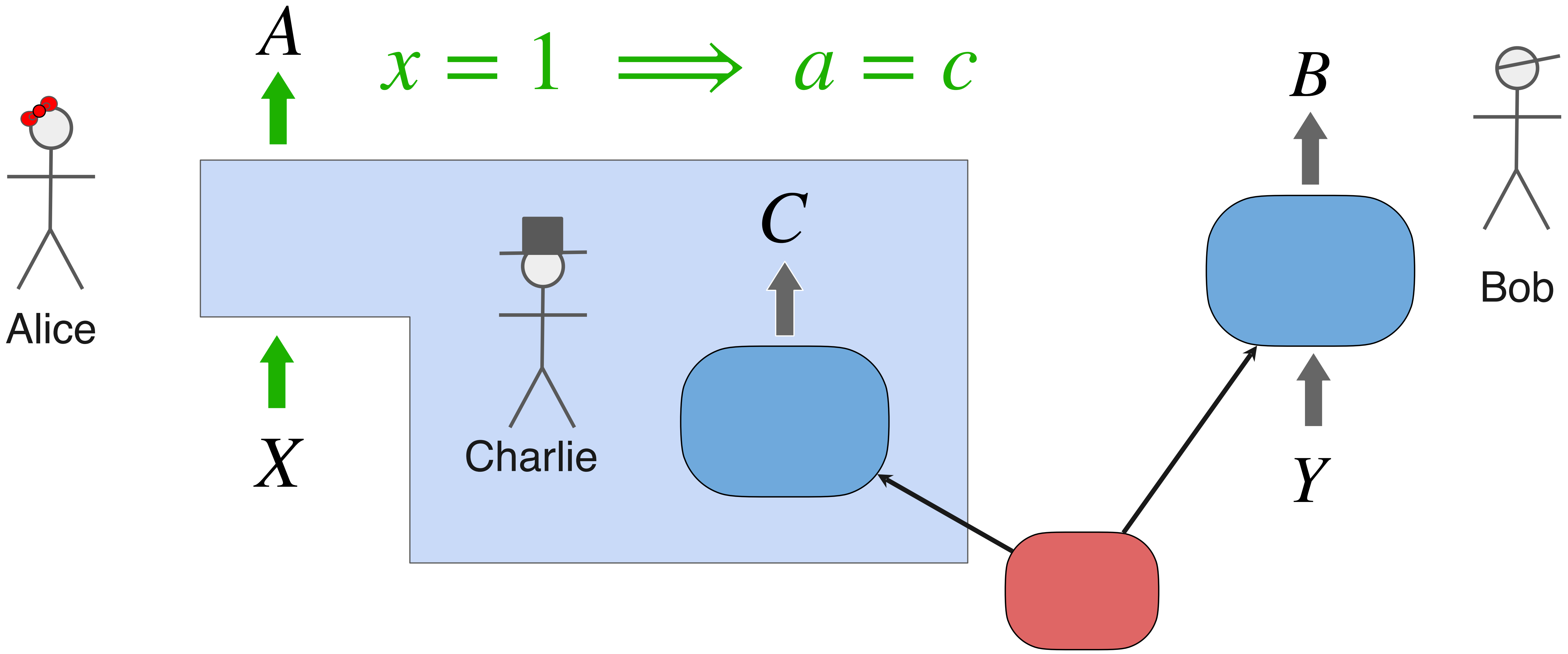
- local friendliness theorem
- constraints on interpretations: relation to Bell
- causal modelling
  - classical causal modelling cannot explain Bell inequality violations
  - solution: (post) quantum causal modelling
  - causal modelling cannot explain LF inequality violations

extended Wigner's friend scenario



$$f(ab\,|\,xy)$$

extended Wigner's friend scenario

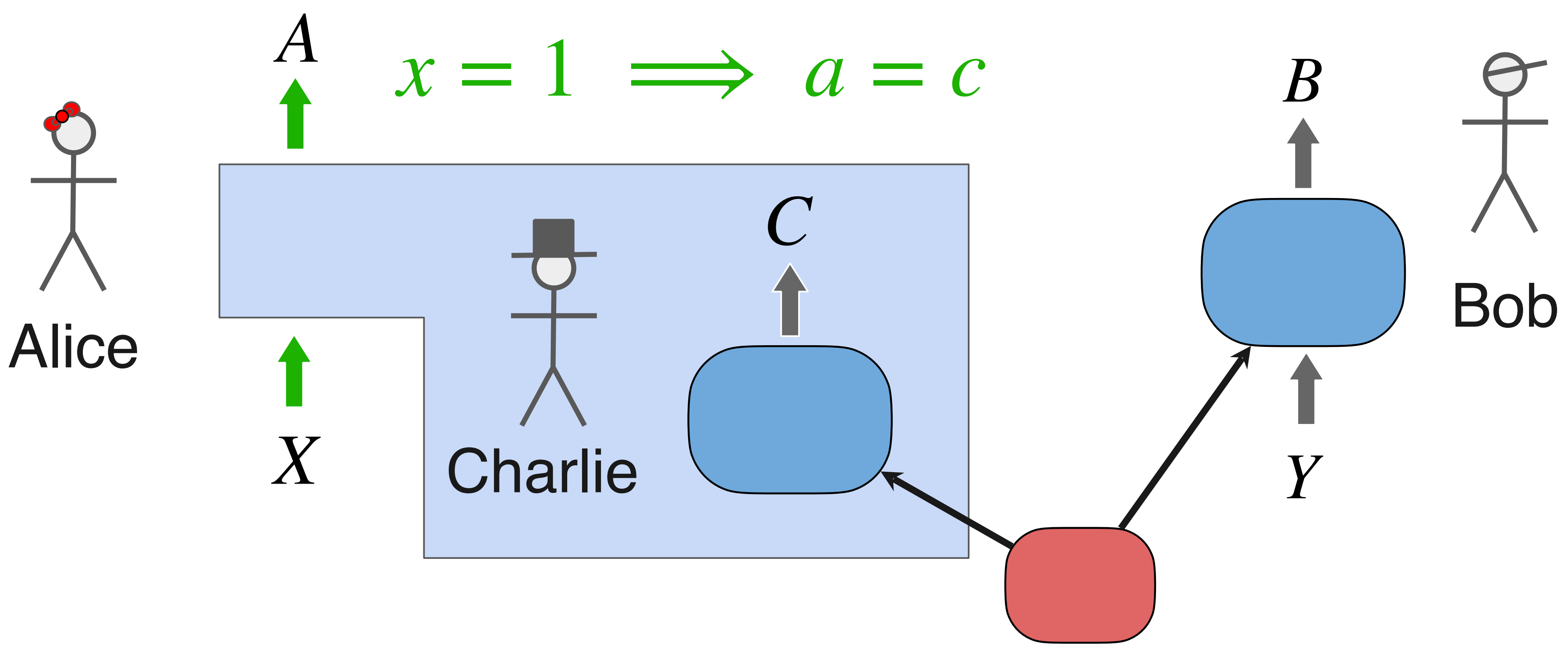


$$f(ab\,|\,xy)$$

$$f(abc\,|\,x=1,y)$$

Bell, Wigner

LF no-go theorem



Article | Published: 17 August 2020

A strong no-go theorem on the Wigner's friend paradox

Kok-Wei Bong, Aníbal Utreras-Alarcón, Farzad Ghafari, Yeong-Cherng Liang, Nora Tischler, Eric G. Cavalcanti, Geoff J. Pryde & Howard M. Wiseman

Nature Physics **16**, 1199–1205 (2020) | Cite this article

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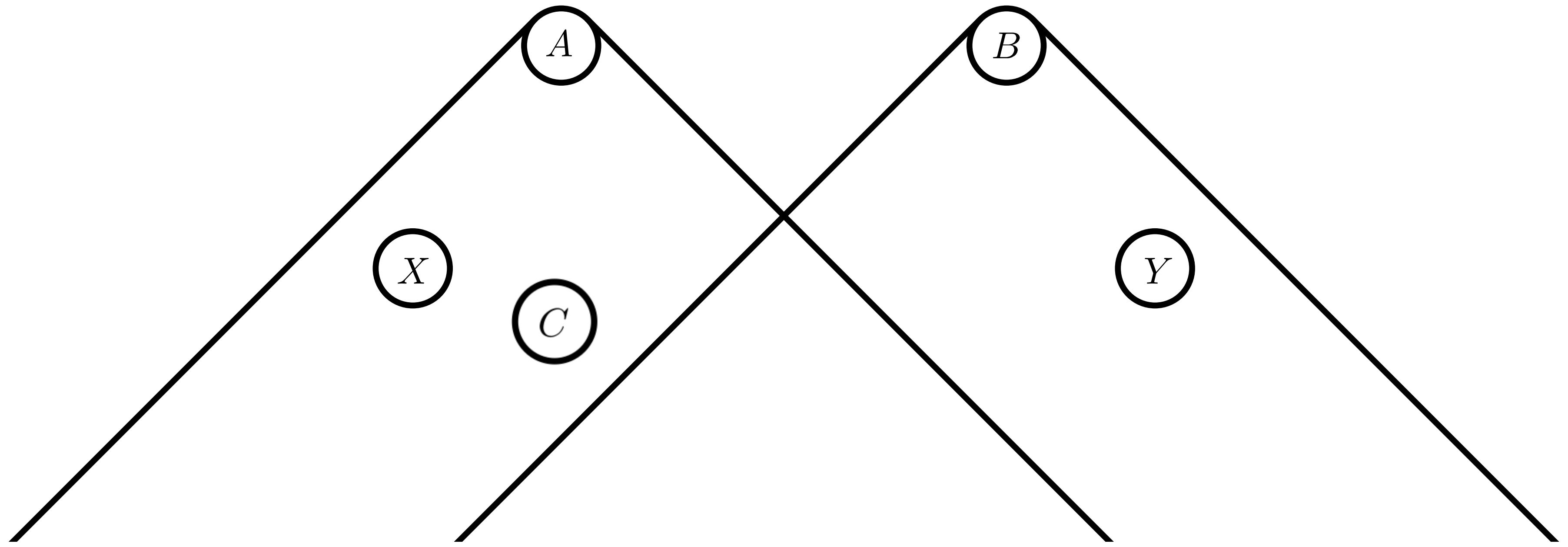

$$f(ab\,|\,xy) = \sum_c p(abc\,|\,xy)$$

$$p(a = c\,|\,x = 1) = 1$$

$$p(c\,|\,xy) = p(c)$$

$$p(a\,|\,cxy) = p(a\,|\,cx)$$

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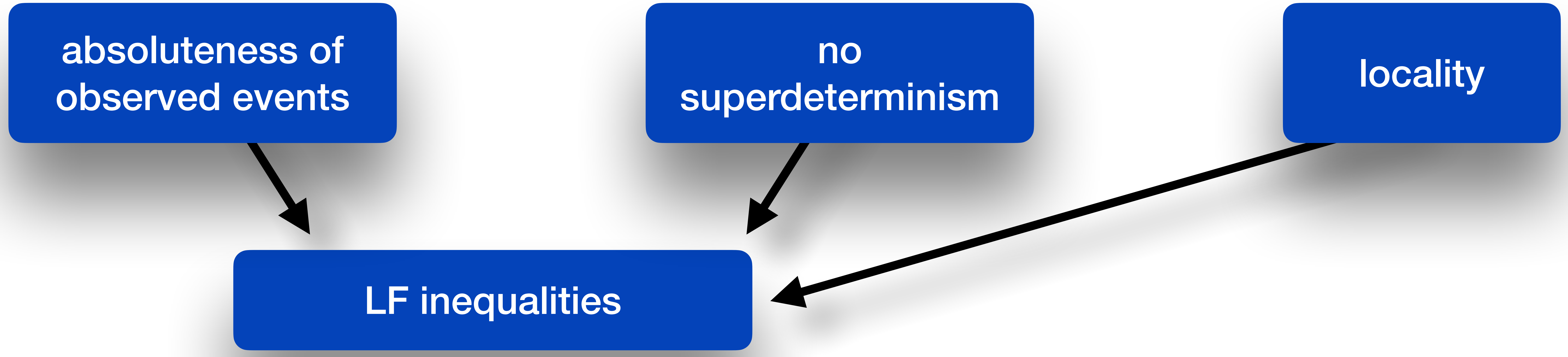
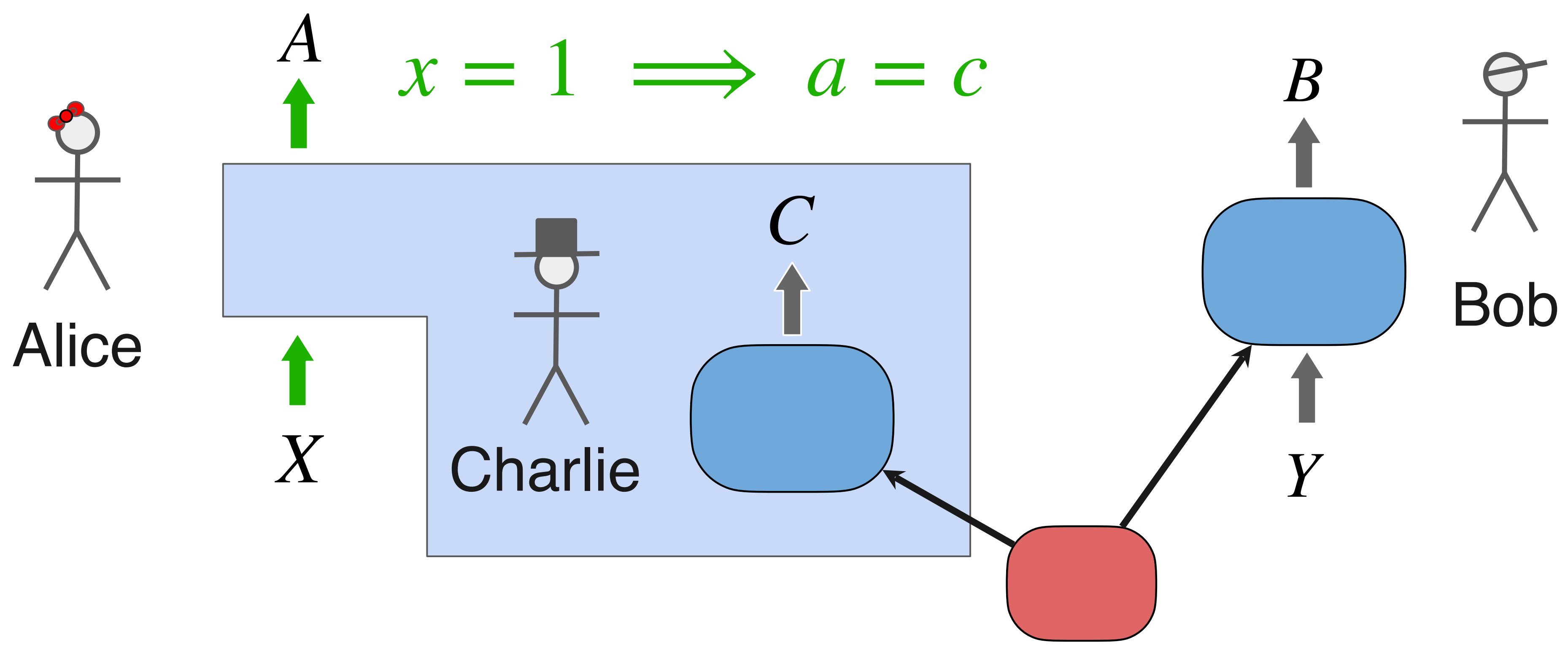


Bell, Wigner

LF no-go theorem



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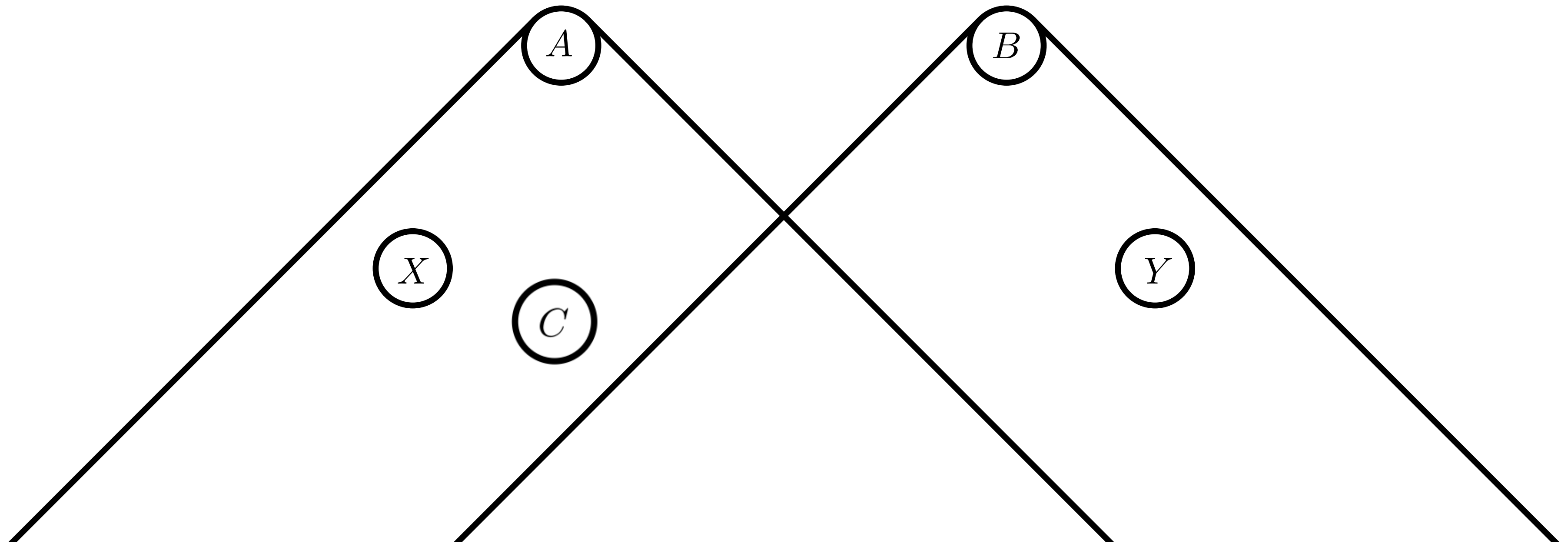

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absoluteness of observed events

no superdeterminism

locality

LF inequalities

incompatible with QM!

if observers can be treated as quantum systems

closing remarks

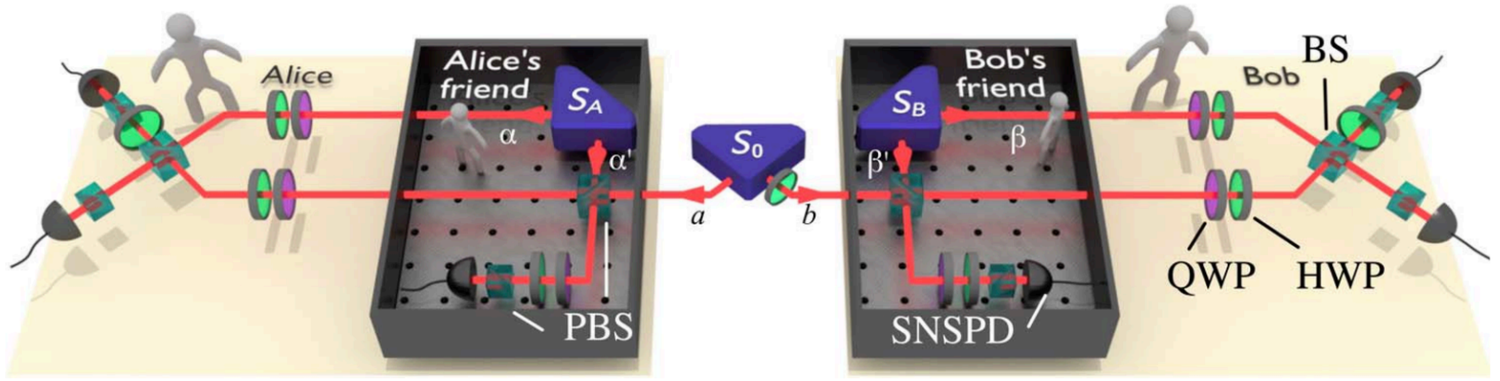
experimental realisations

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Experimental test of local observer independence

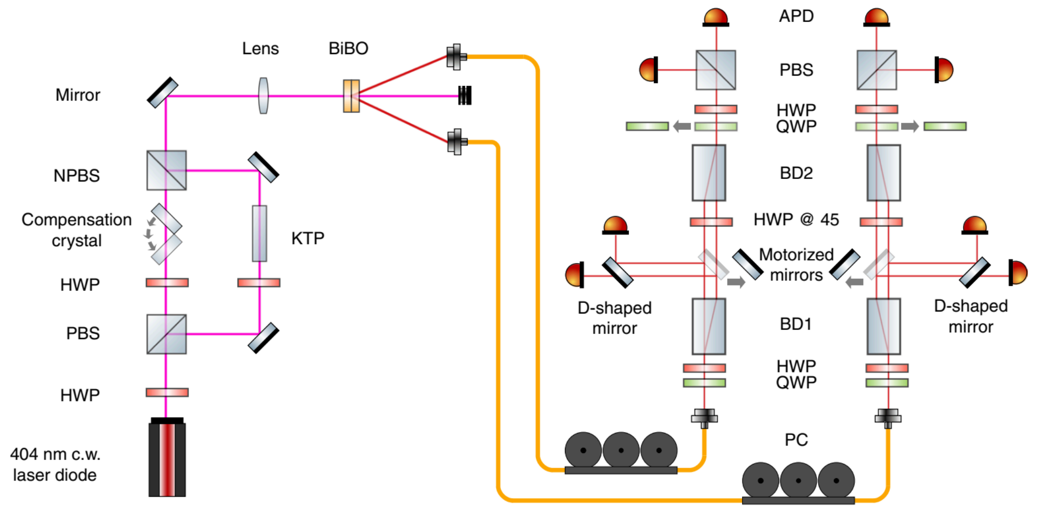
Massimiliano Proietti[1], Alexander Pickston[1], Francesco Graffitti[1], Peter Barrow[1], Dmytro Kundys[1], Cyril Branciard[2], Martin Ringbauer[1,3], Alessandro Fedrizzi[1]*



nature physics
ARTICLES
https://doi.org/10.1038/s41567-020-0990-x
Check for updates

A strong no-go theorem on the Wigner's friend paradox

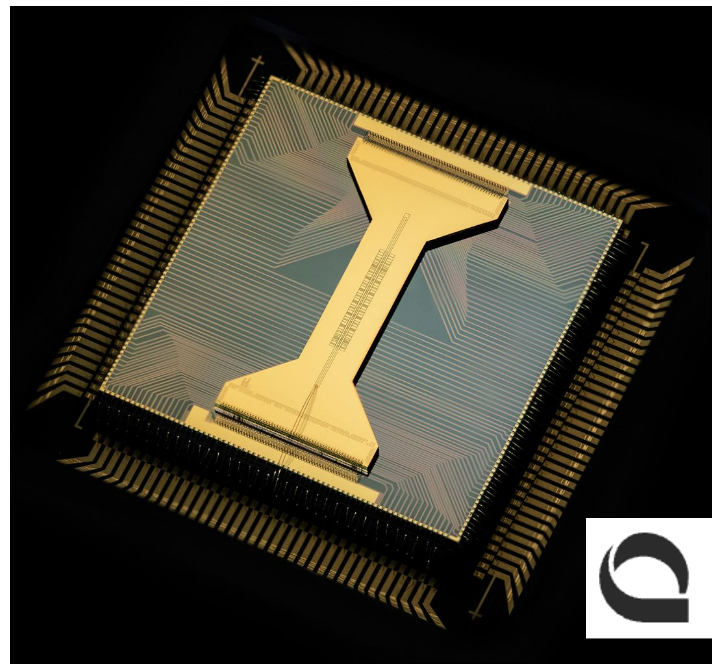
Kok-Wei Bong[1,4], Aníbal Utreras-Alarcón[1,4], Farzad Ghafari[1], Yeong-Cherng Liang[2], Nora Tischler[1], Eric G. Cavalcanti[3], Geoff J. Pryde[1] and Howard M. Wiseman[1]



arXiv:2409.15302 (quant-ph)
[Submitted on 4 Sep 2024 (v1), last revised 3 Jun 2025 (this version, v2)]

Towards violations of Local Friendliness with quantum computers

William J. Zeng, Farrokh Labib, Vincent Russo



16 qubits

QUANTINUUM

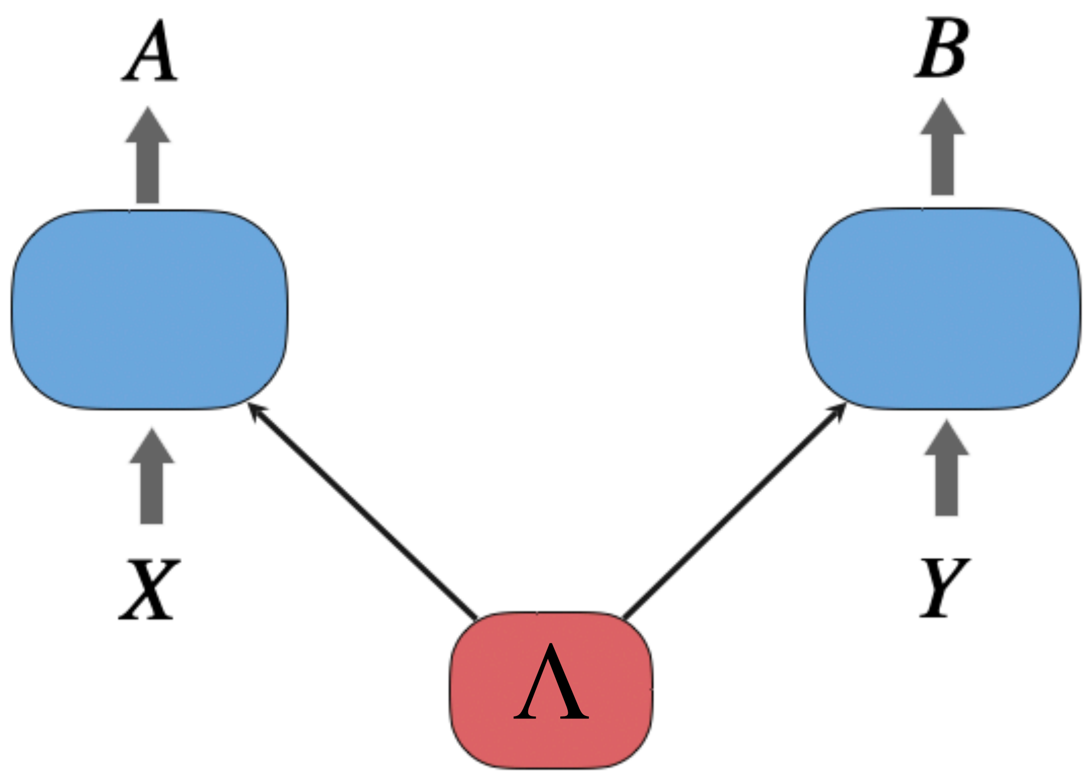
photonic qubit | human level AI | human animal

16 qubits | cat

increasingly credible friend

metaphysics roadmap

Bell's theorem



$$f(ab\,|\,xy) \;=\; \sum_{\lambda} p(ab\,|\,xy\lambda)p(\lambda\,|\,xy)$$

$$p(a\,|\,\lambda xy) = p(a\,|\,\lambda x)$$
$$p(b\,|\,\lambda xy) = p(y\,|\,\lambda y)$$

locality

$$p(ab\,|\,xy\lambda) \in \{0,1\}$$

pre-determination

Bell inequalities

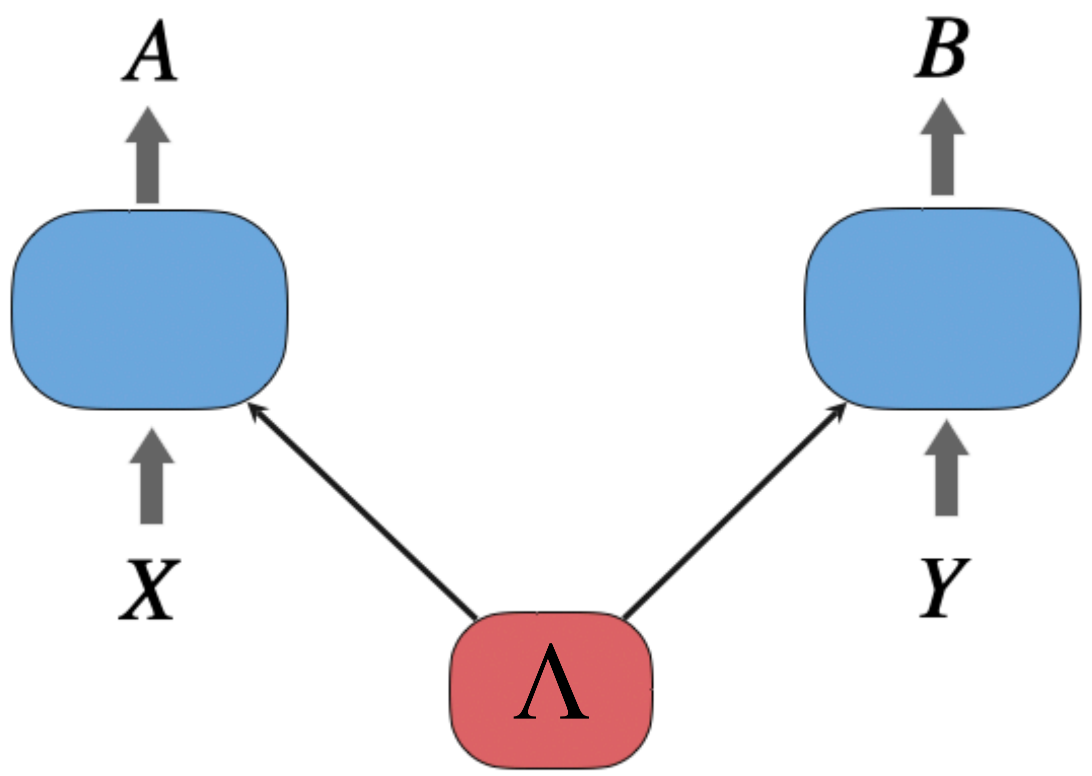
$$p(\lambda\,|\,xy) = p(\lambda)$$

no superdeterminism

Bell 1964

[1] Wiseman and Cavalcanti (2015) Causarum Investigatio and the Two Bell's Theorems of John Bell, Quantum [Un]speakables II
[2] Cavalcanti and Wiseman (2021) Implications of Local Friendliness violations for quantum causality, Entropy 23, 8

Bell's theorem



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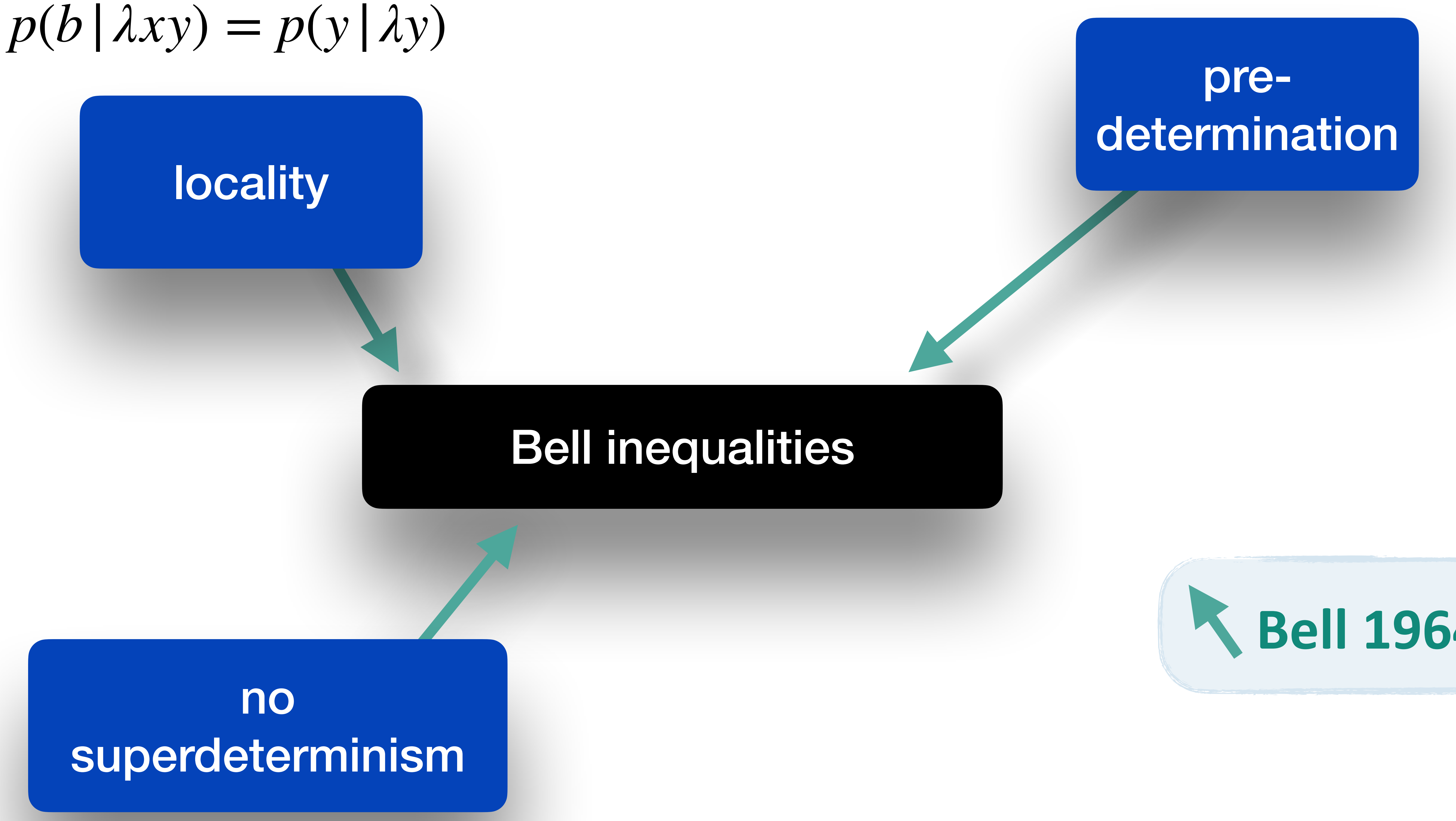

$$p(\lambda|xy) = p(\lambda)$$

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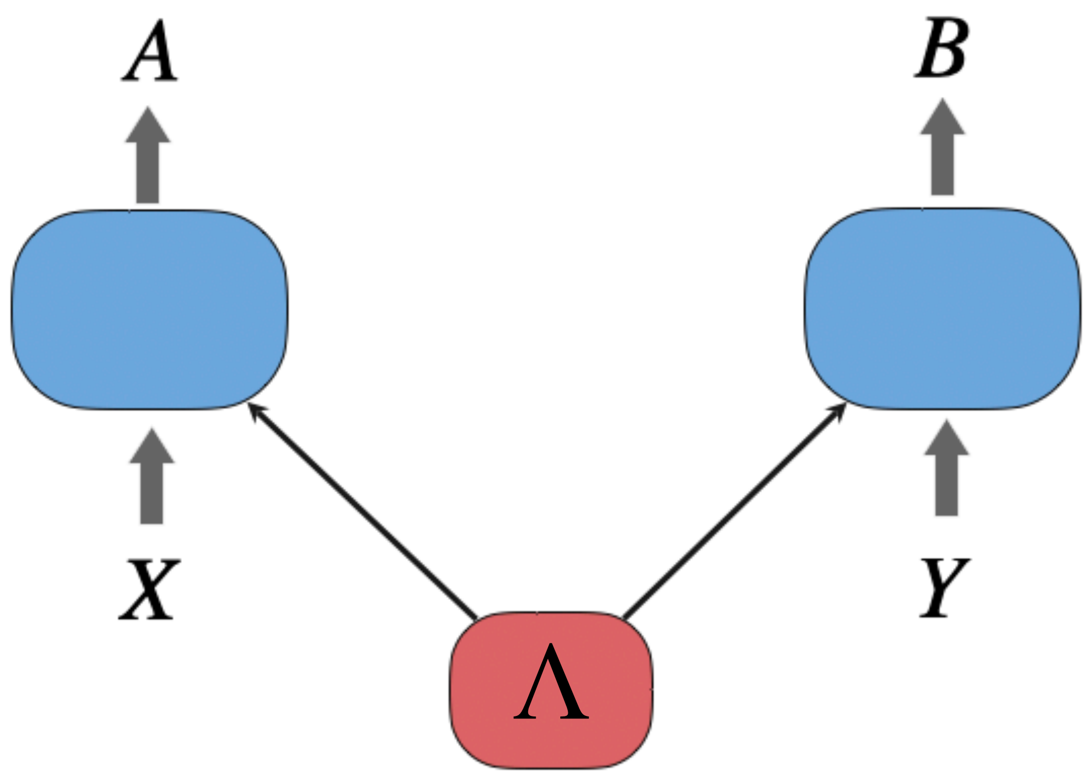

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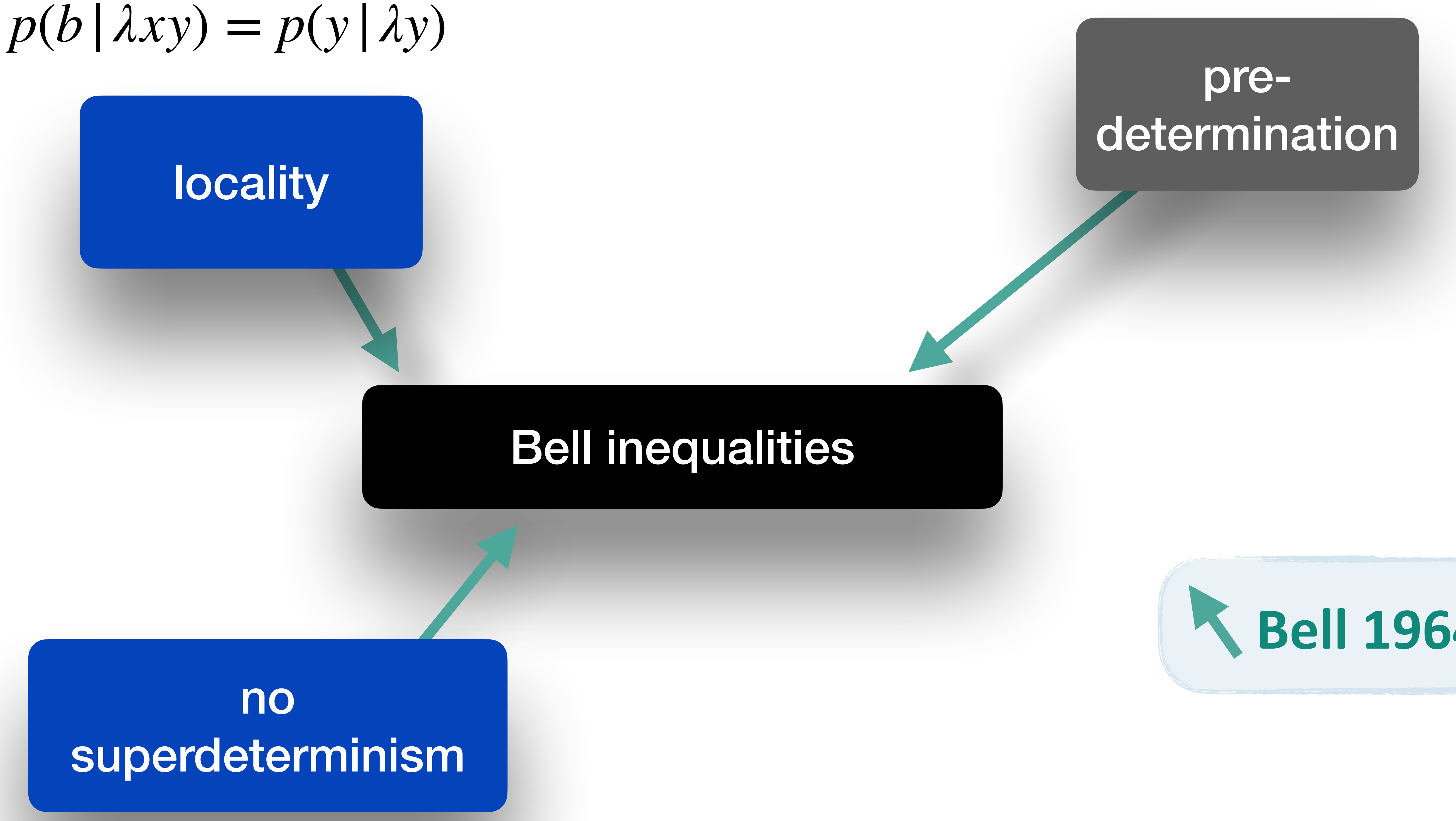

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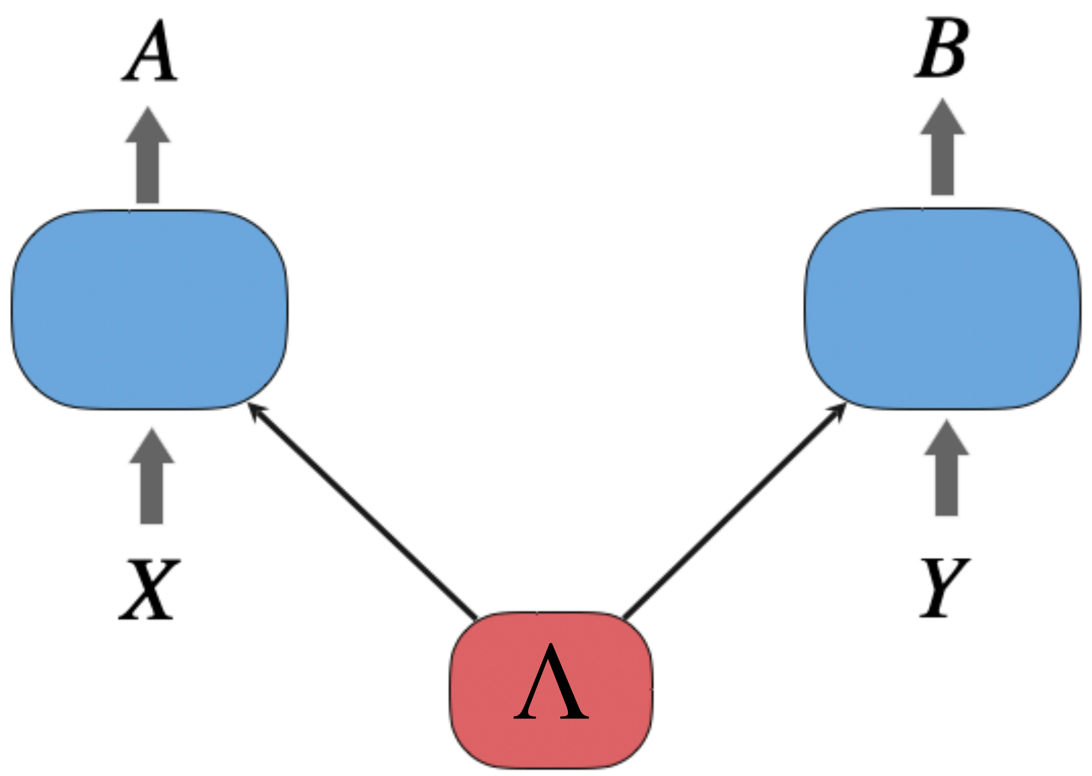
Bell's second theorem



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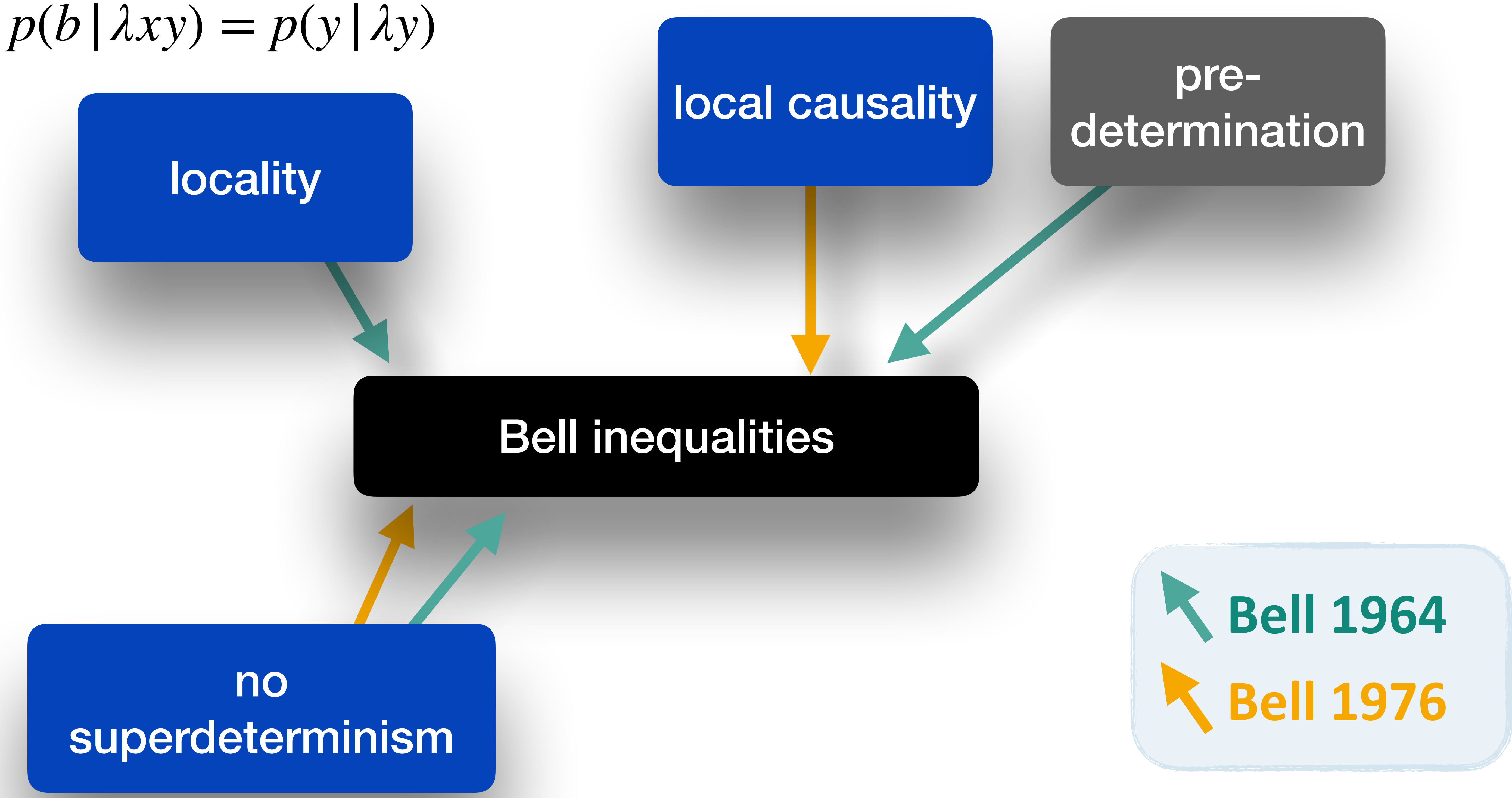

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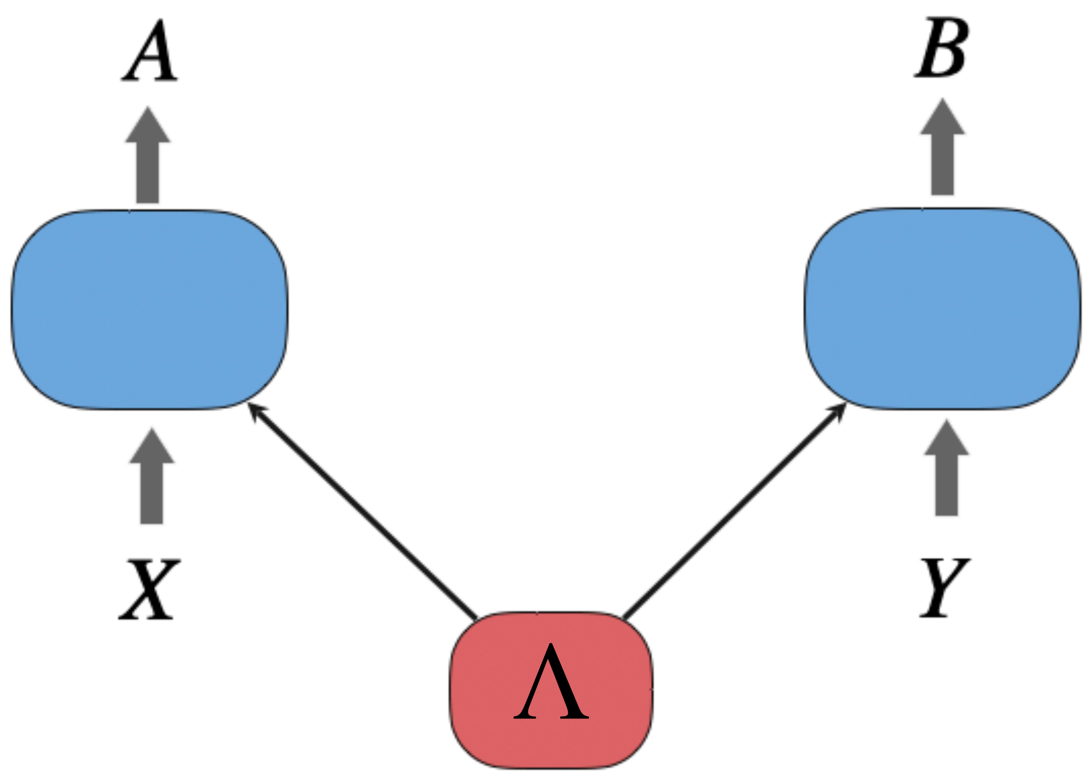

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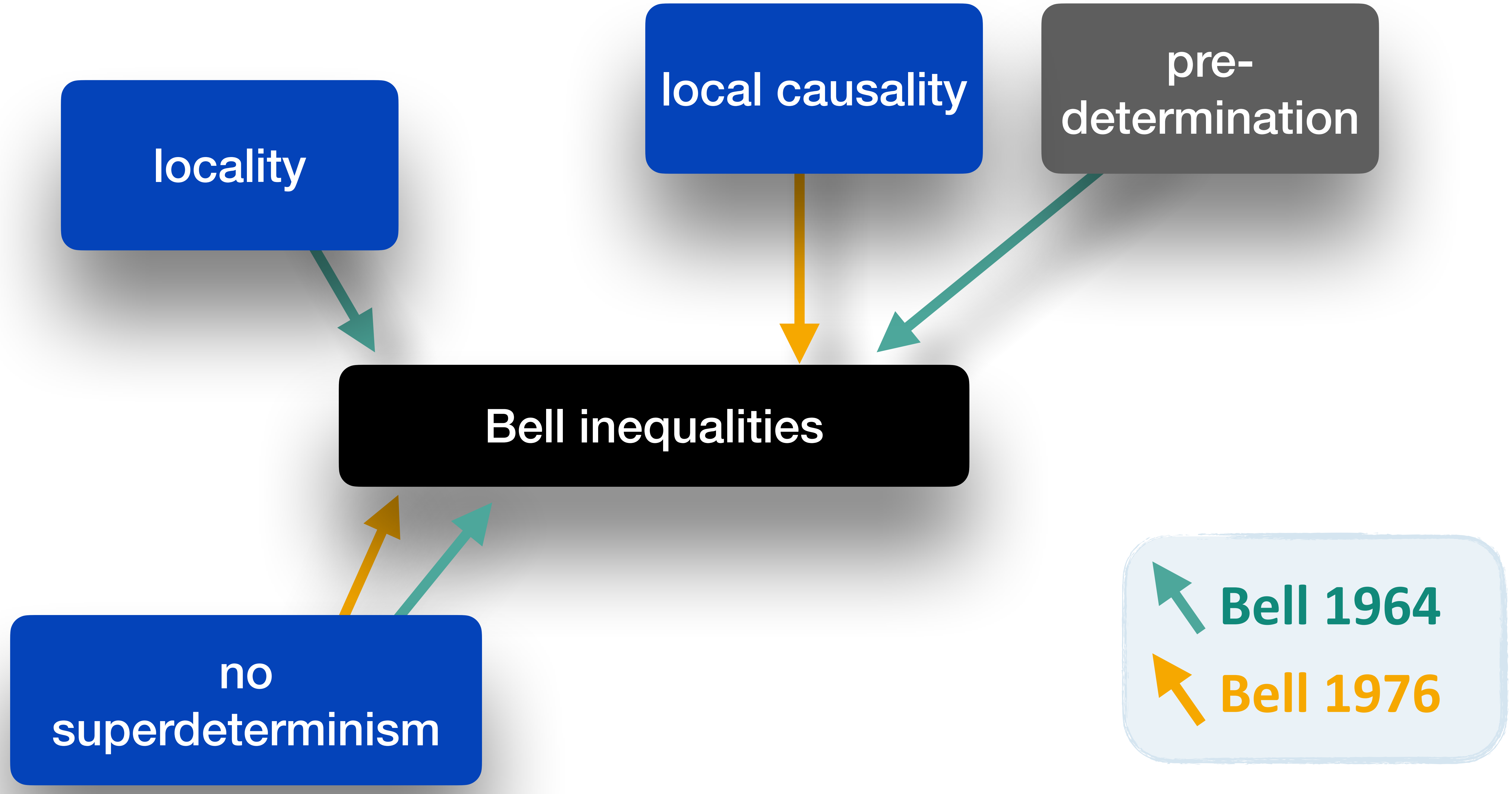

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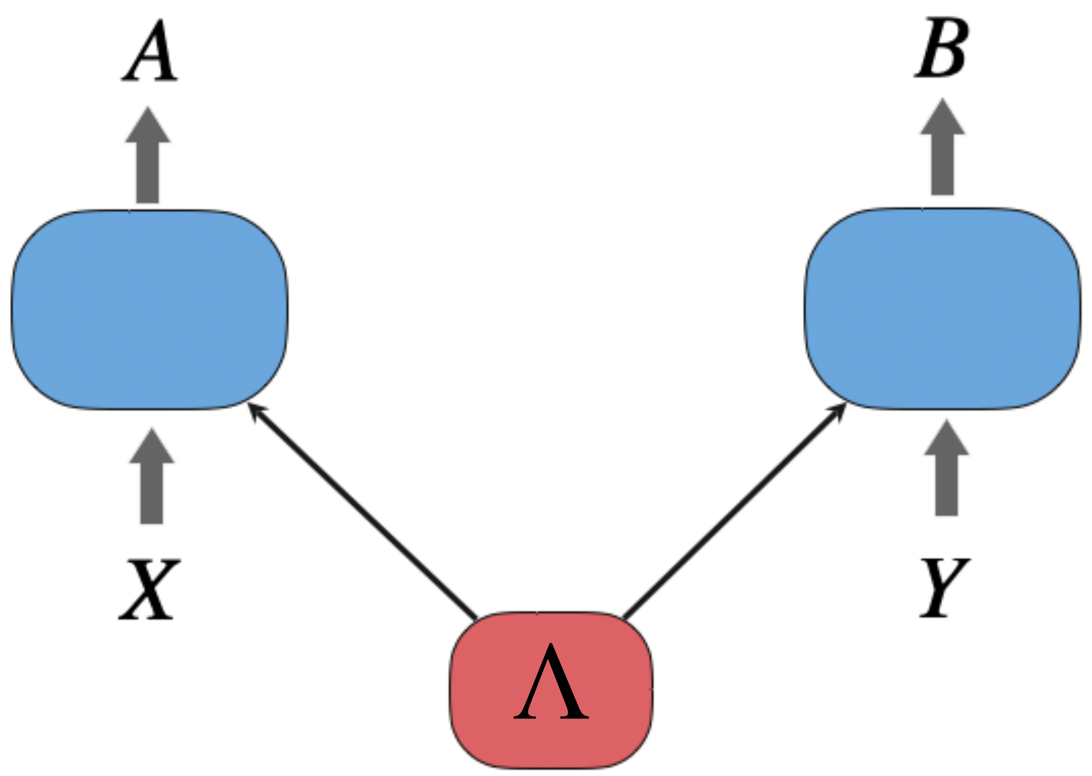
metaphysical assumptions

Bell's second theorem



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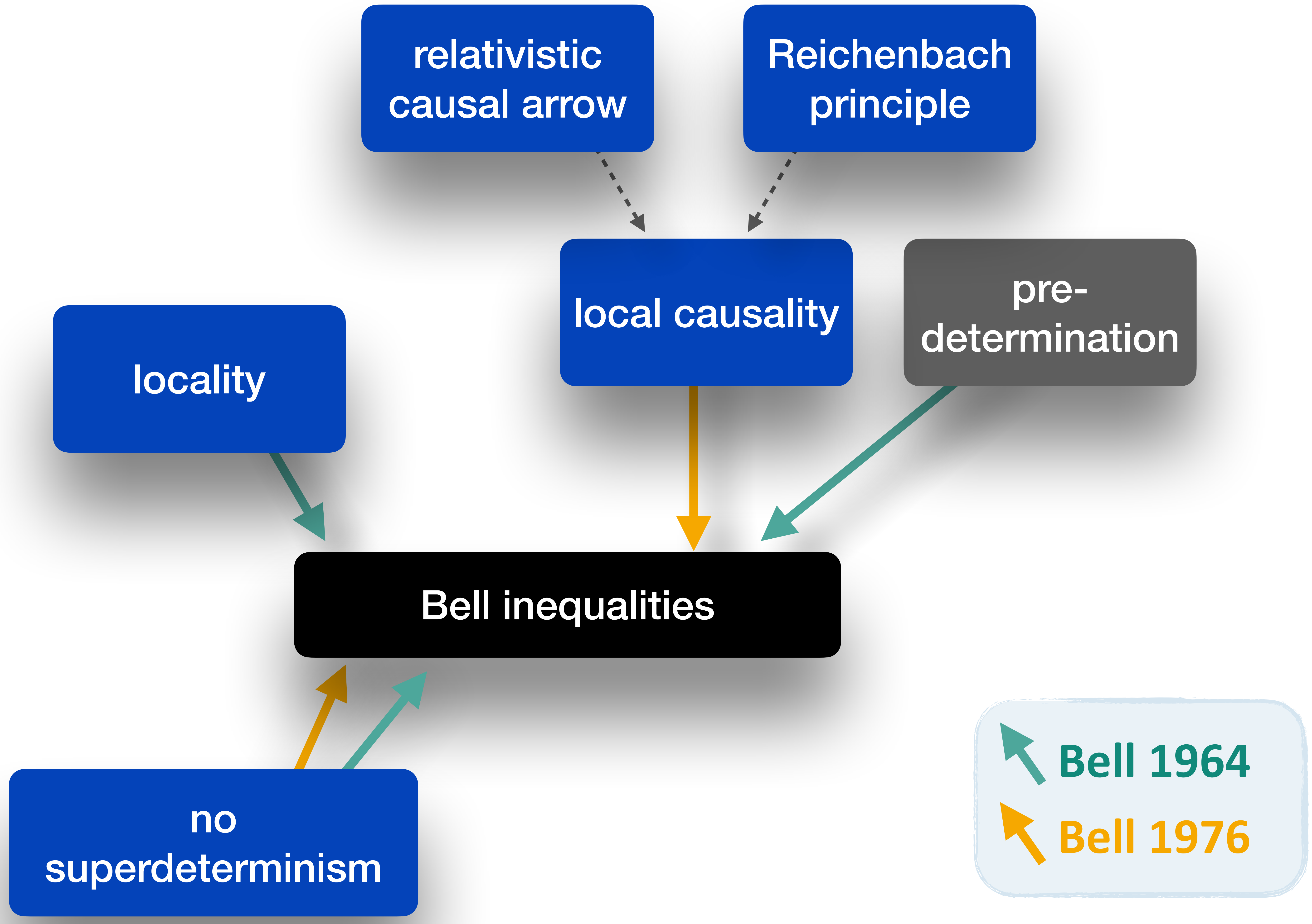

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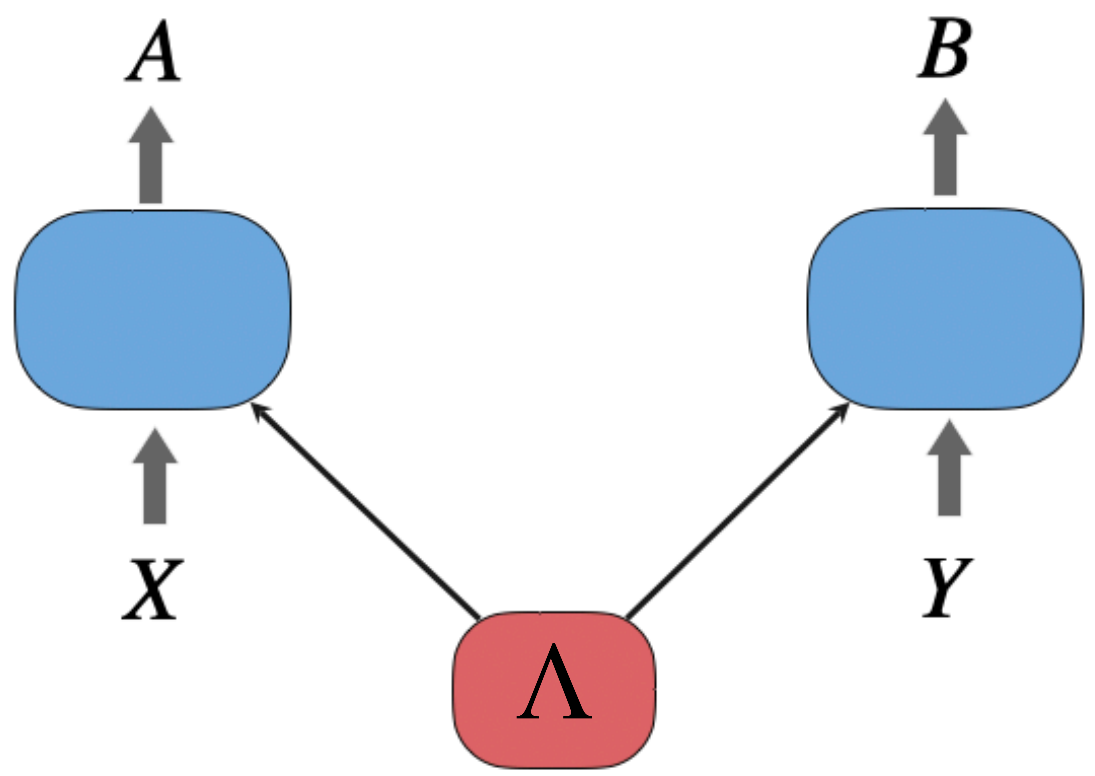

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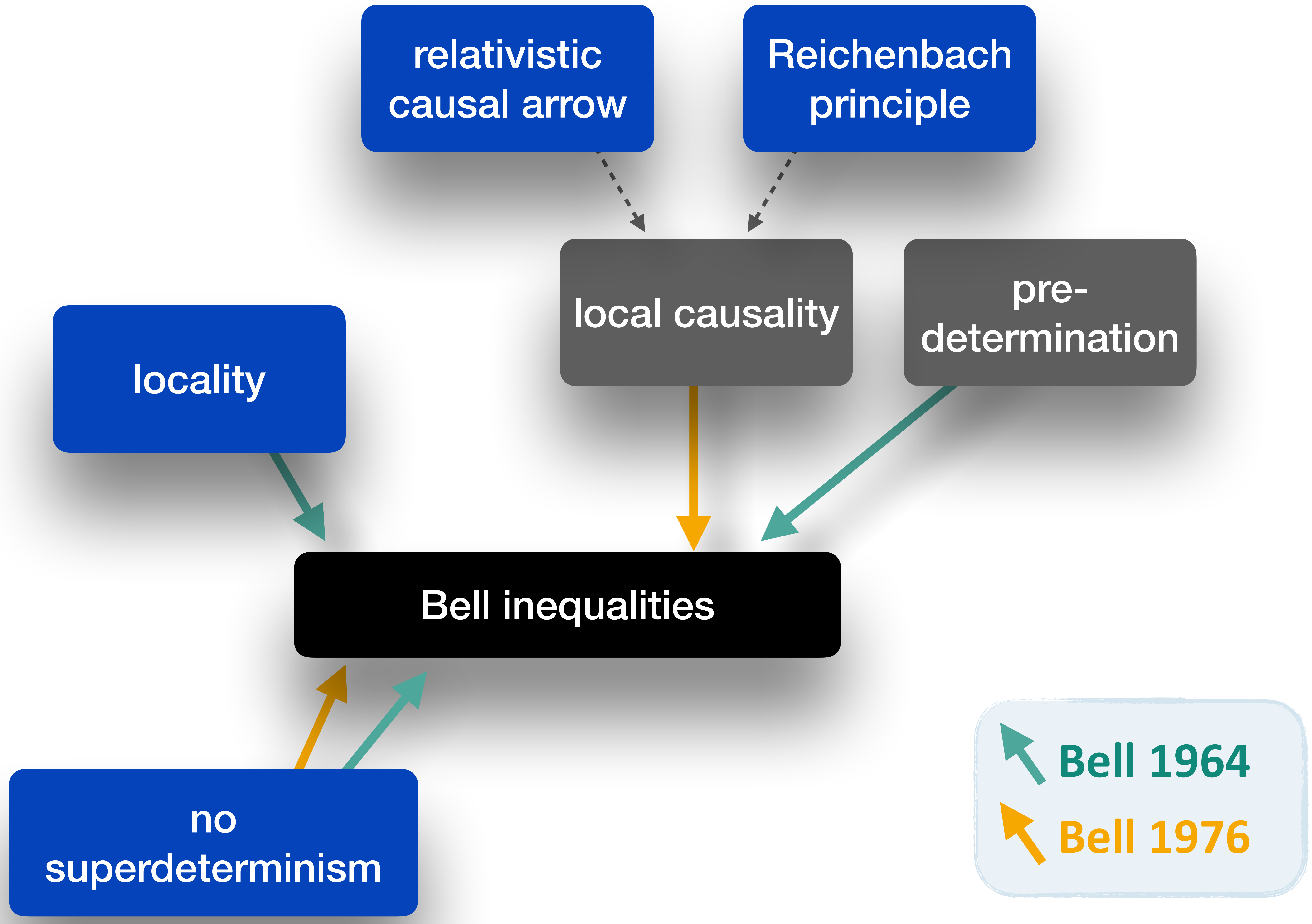

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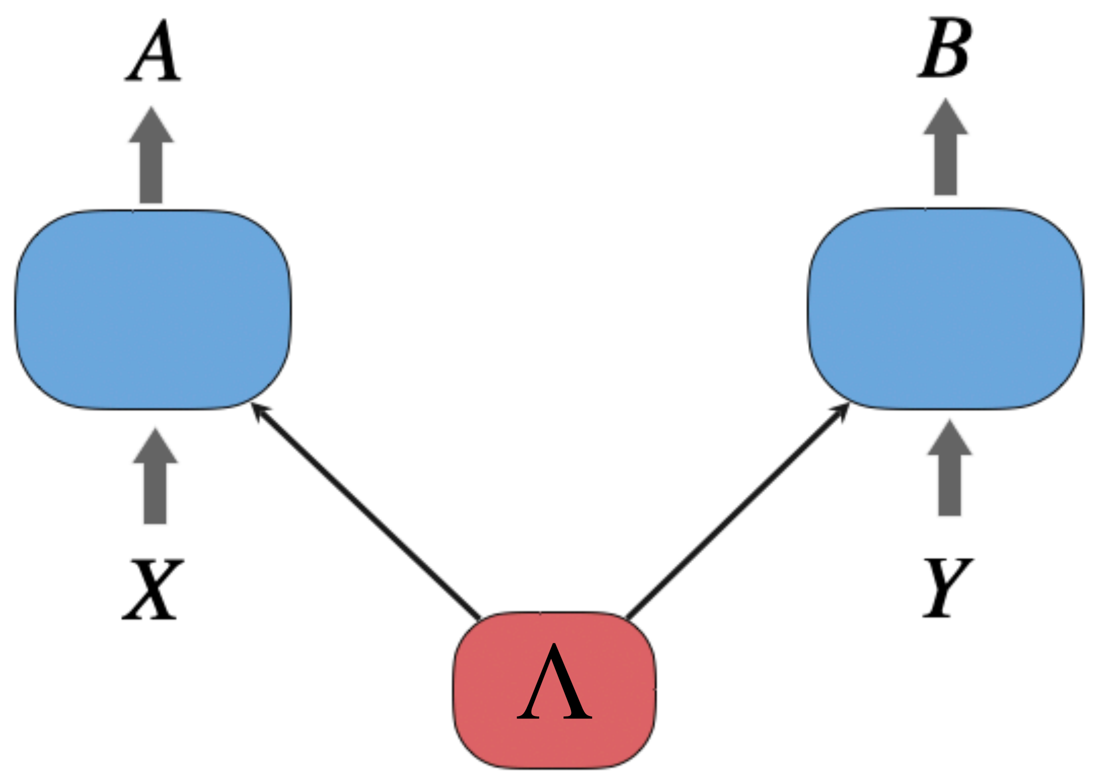

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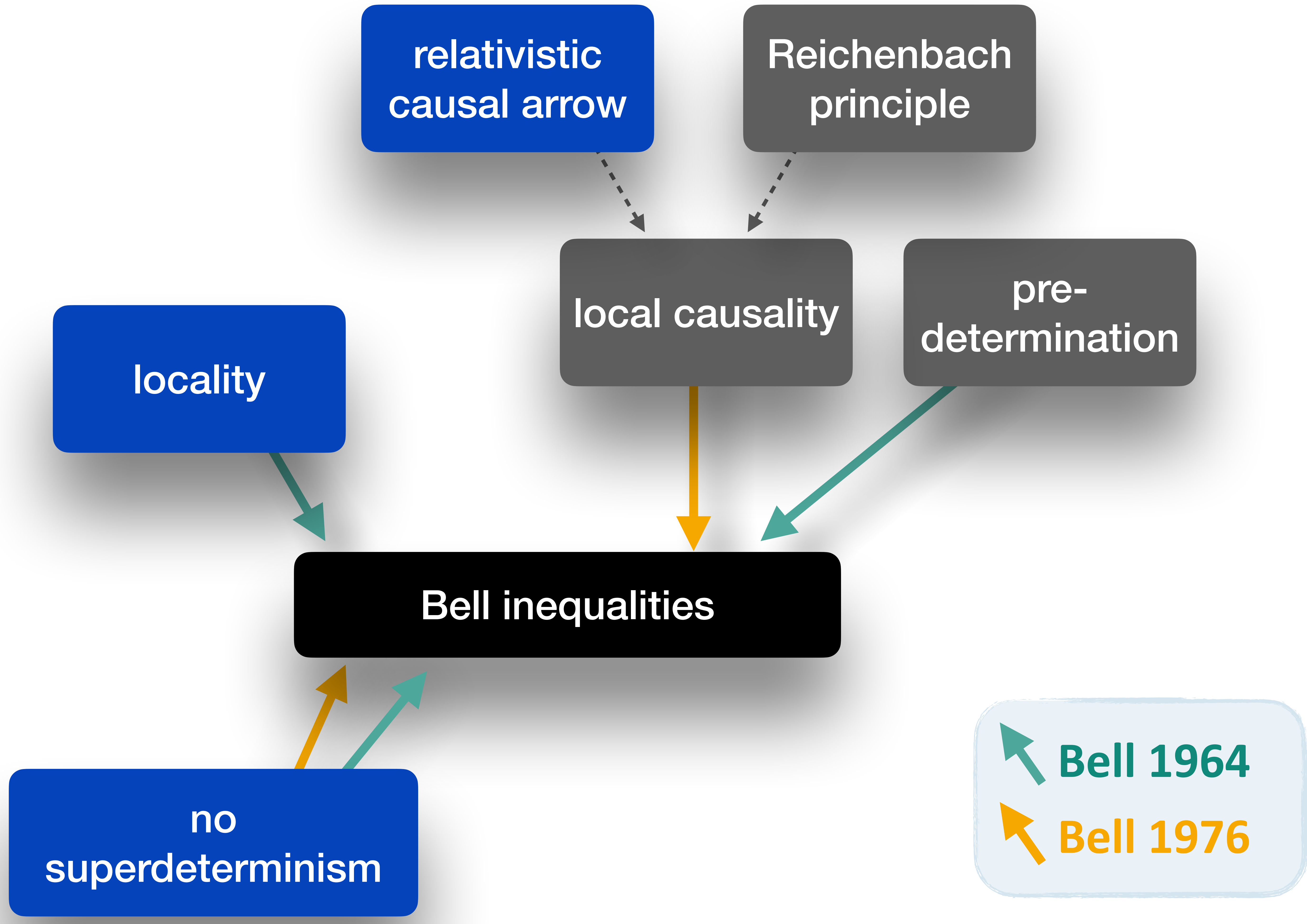

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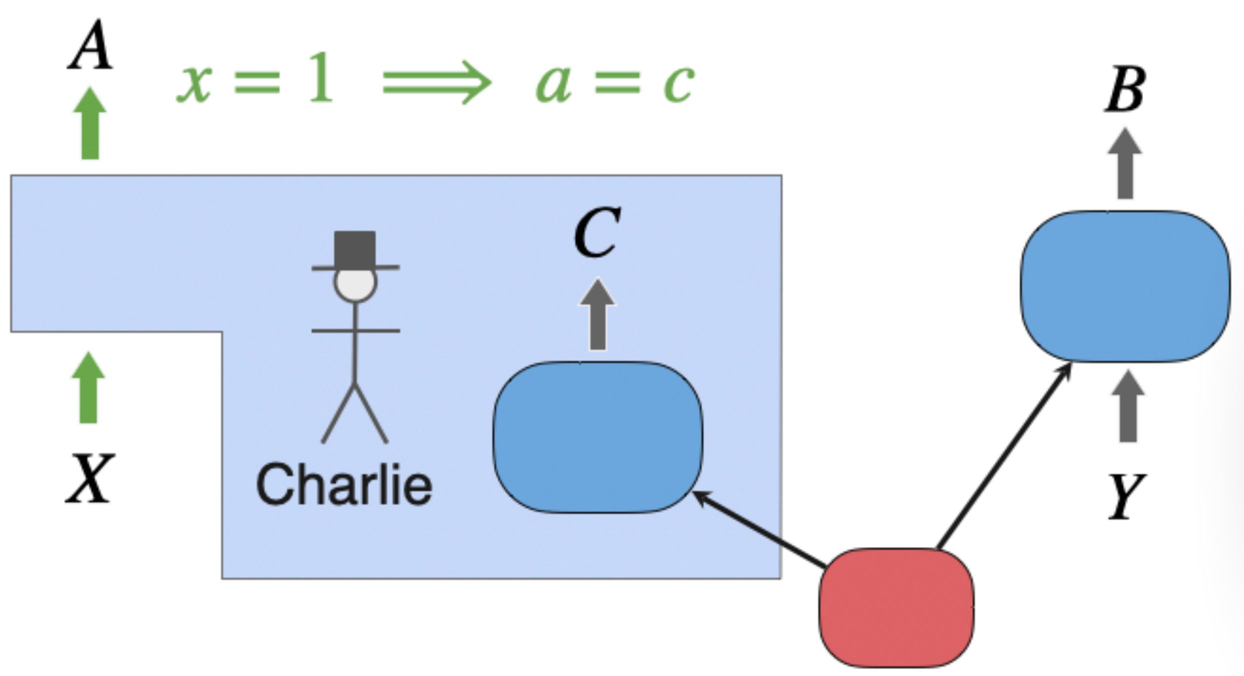

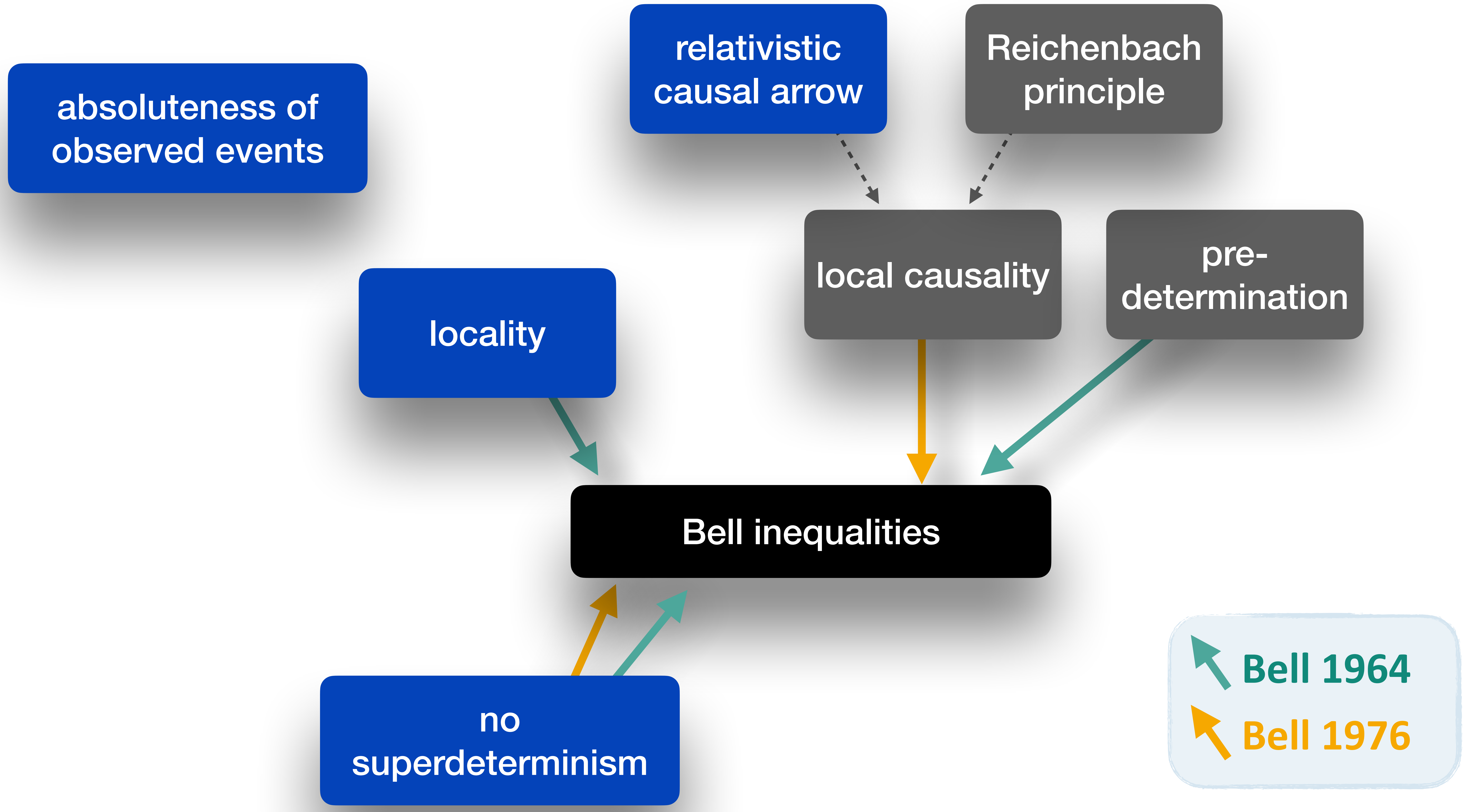

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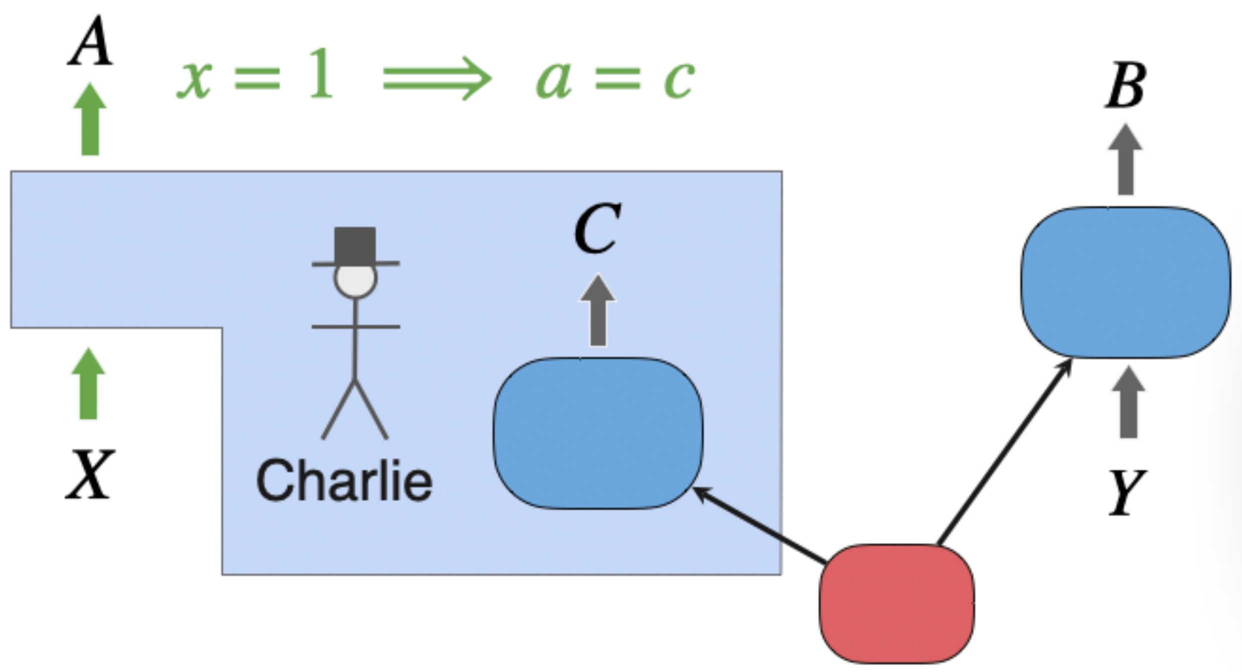

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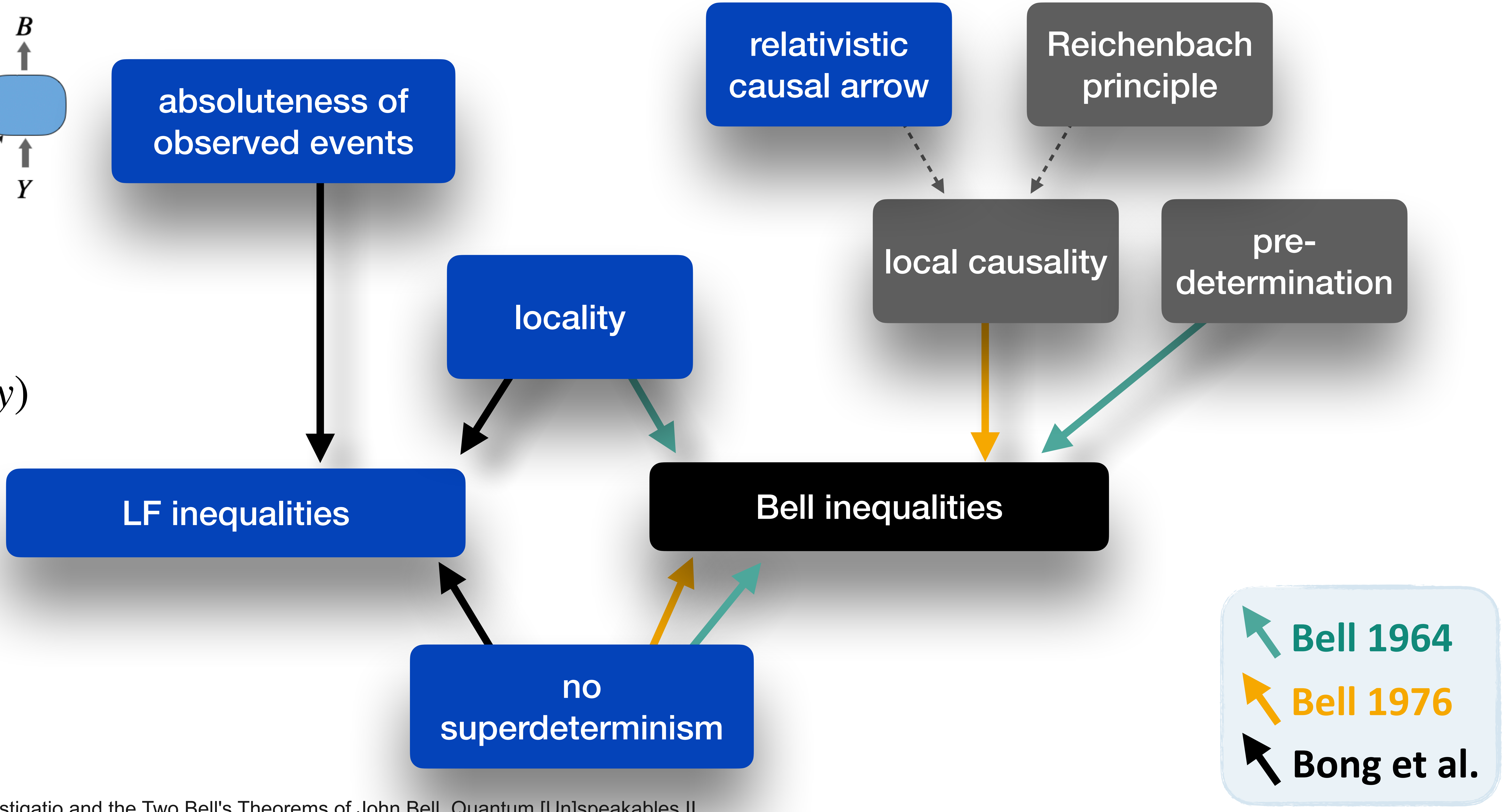

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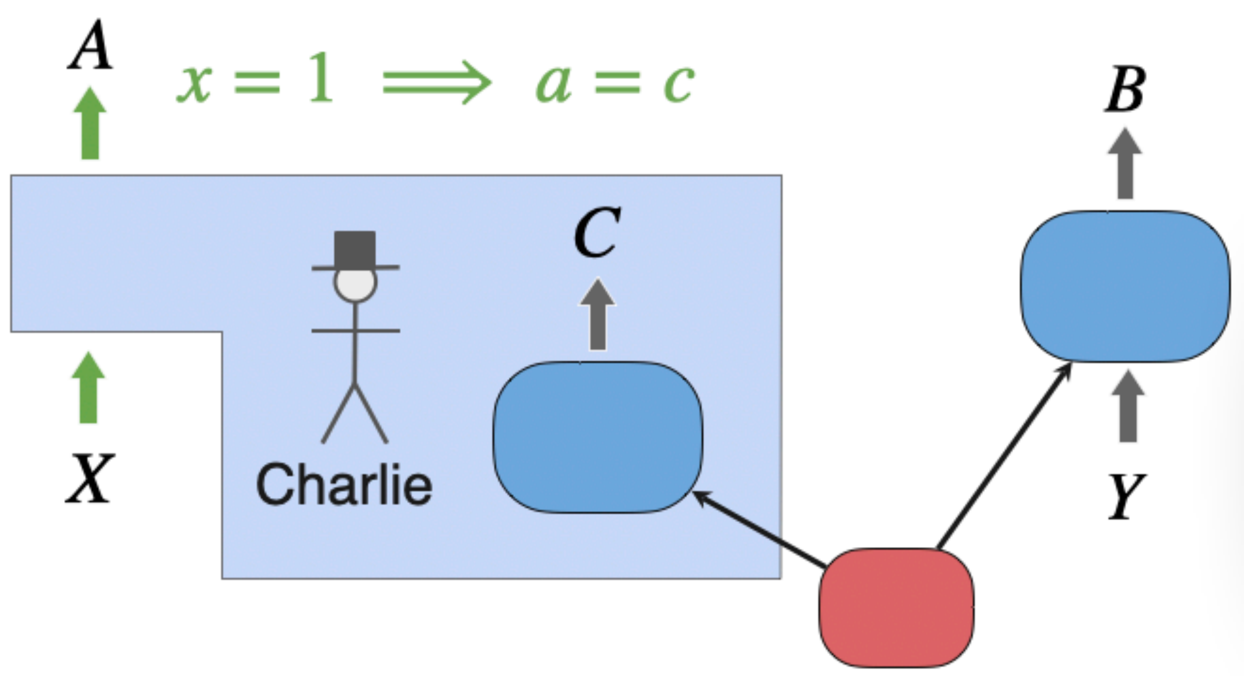

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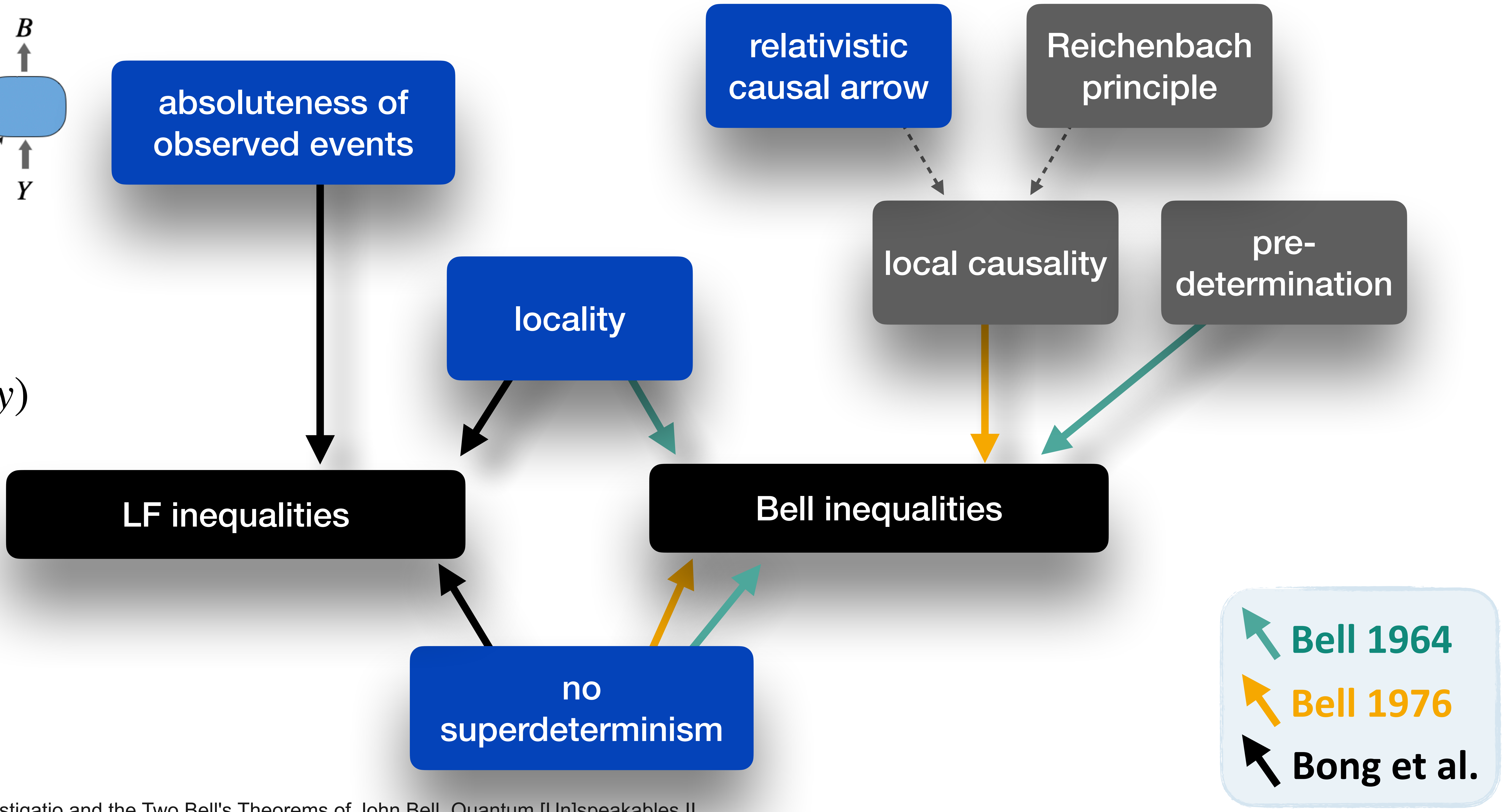

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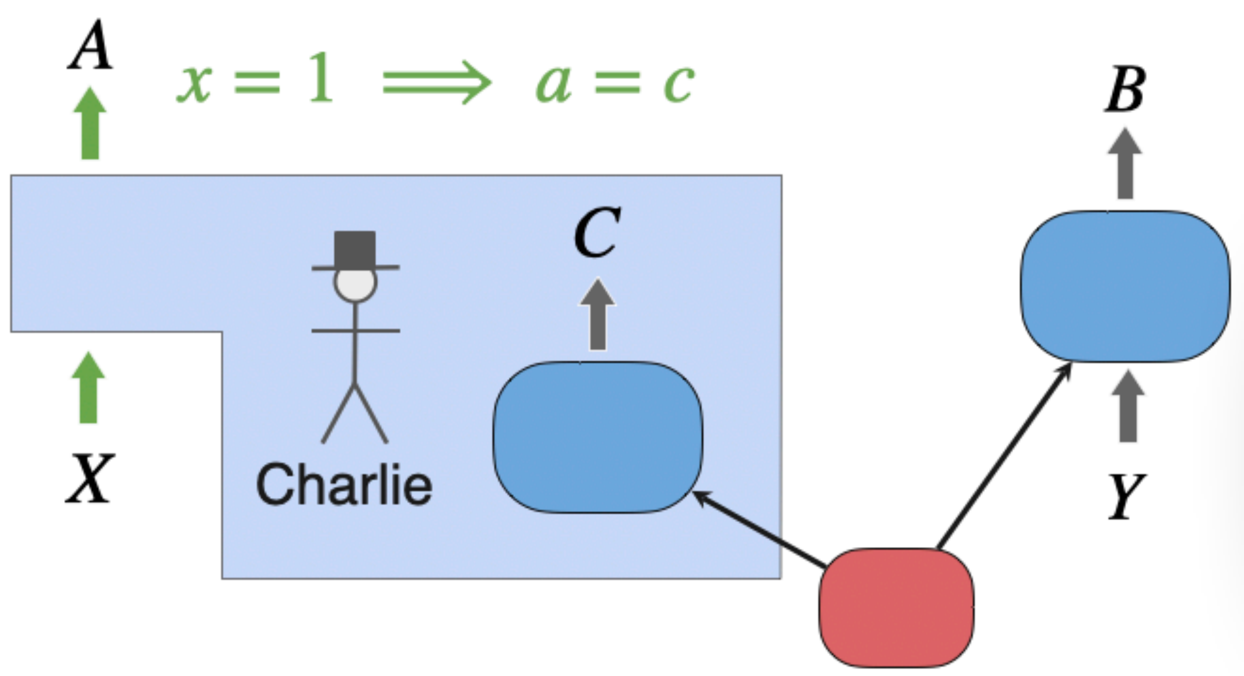

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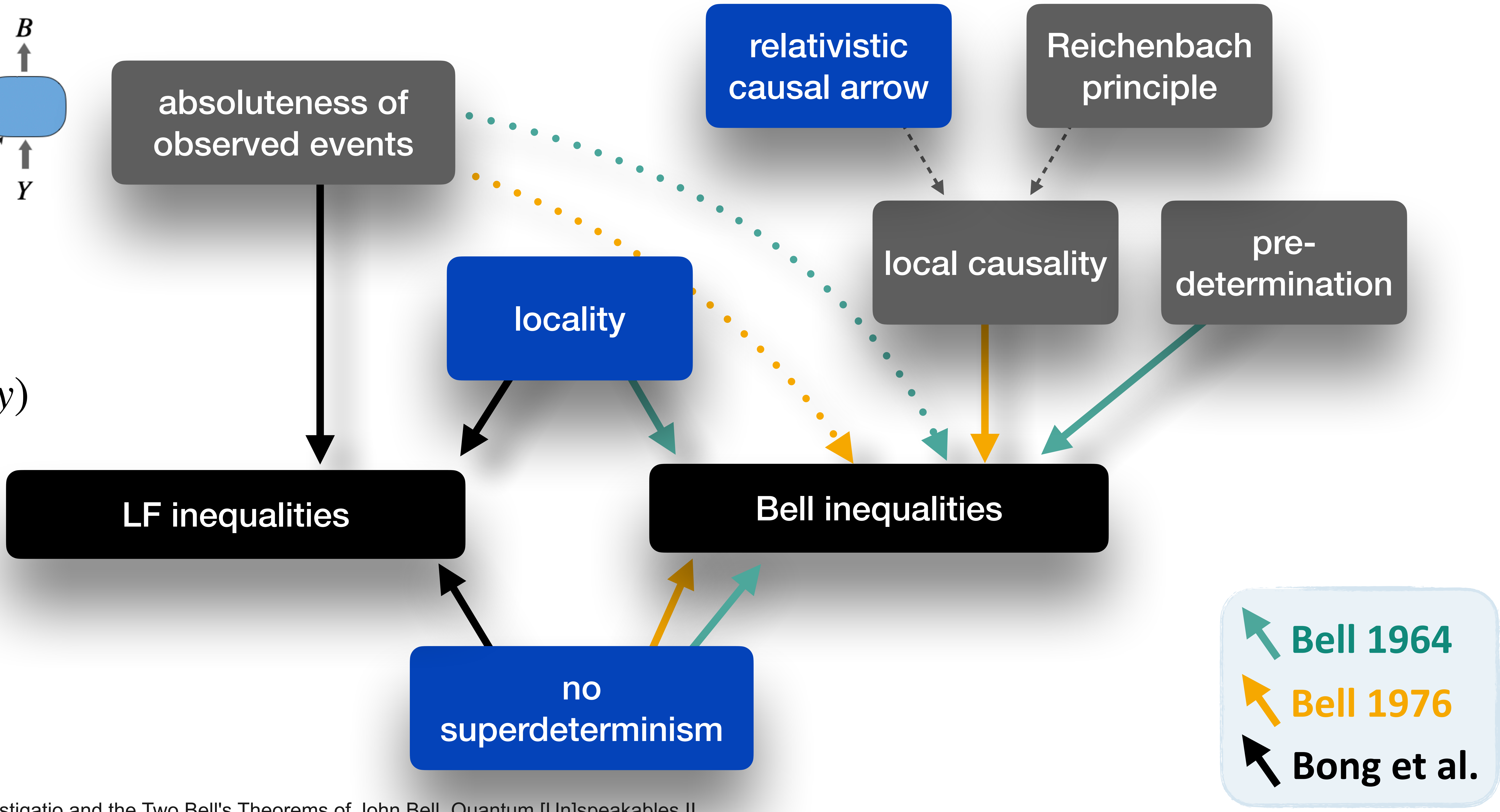

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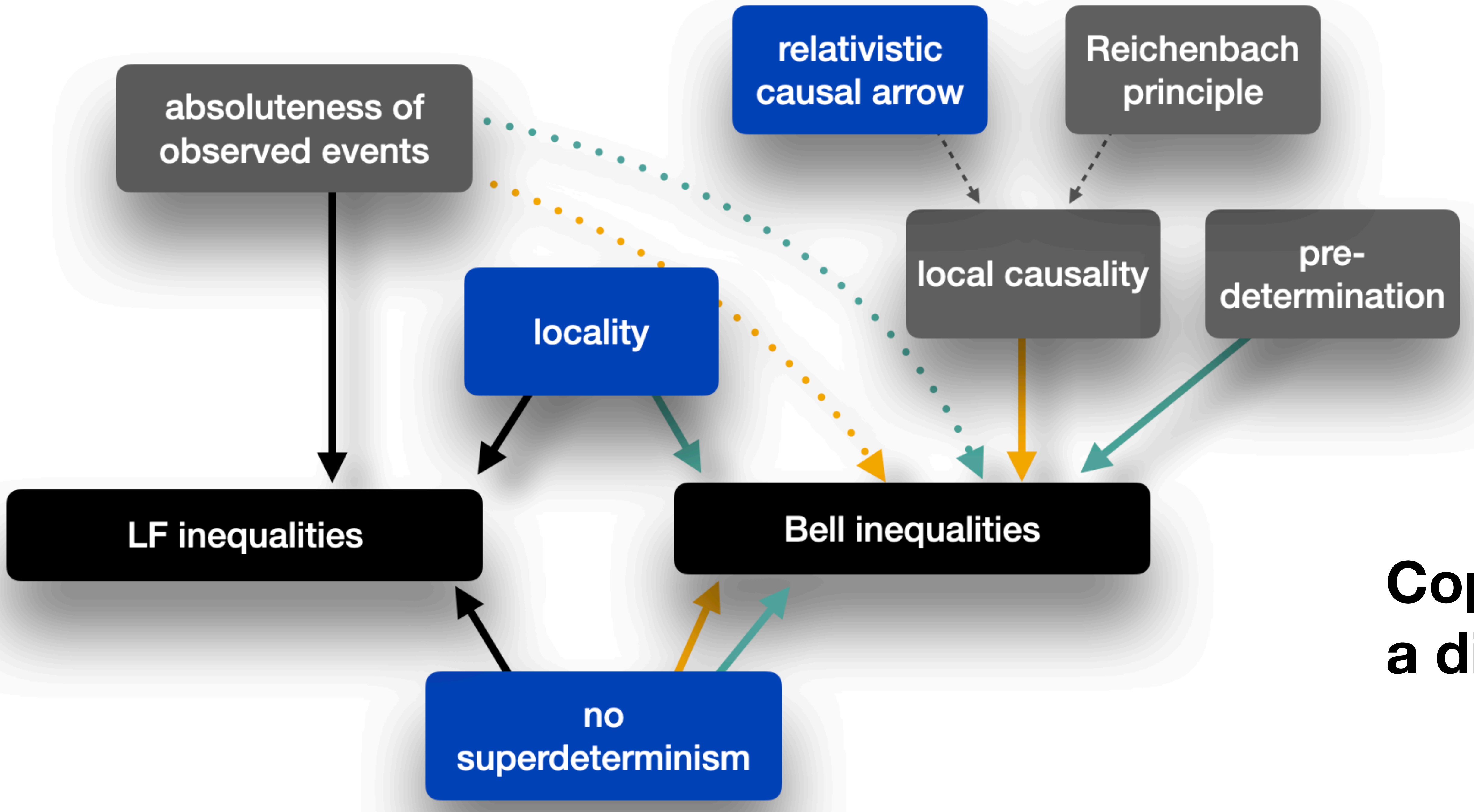
implications for interpretations



interpretations resolving all theorems by dropping the same assumption:
- pilot wave theory (aka Bohmian mechanics)
- superdeterministic models
- Everettian QM (aka many worlds)

Copenagen(ish) interpretations forced to drop a different assumption in each theorem

"no-interpretation" interpretation not good anymore
$\Longrightarrow$ need to talk about what happens to different observers

alternatively, modify QM: spontaneous collapse, observers / consciousness fundamental

remarks

- EWF stands to WF like Bell stands to EPR
- observations of friend play the role of the hidden variables of Bell
- violations of LF inequalities already happened, but for small systems
- what is a good friend? ---> theory of observation
- letting go of absoluteness of observed events:
  - what does it mean? how does it happen?
  - assumption in Bell, revise?

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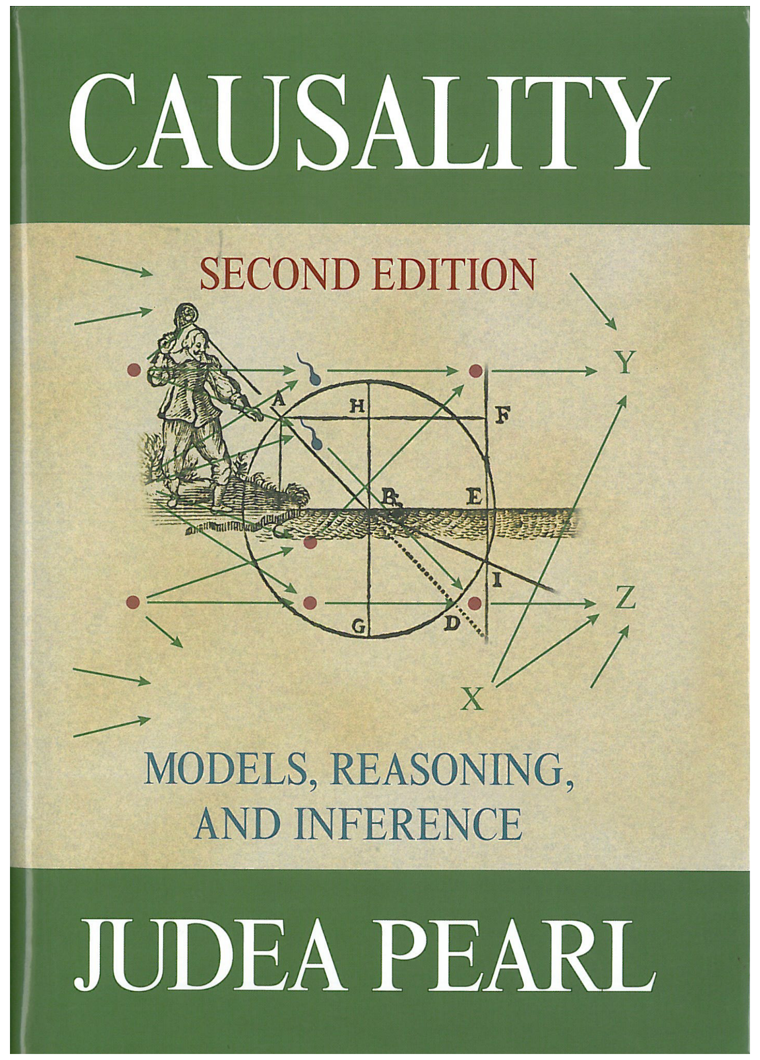
Bell and classical causal models

classical causal modelling



causal explanation

causal structure

+

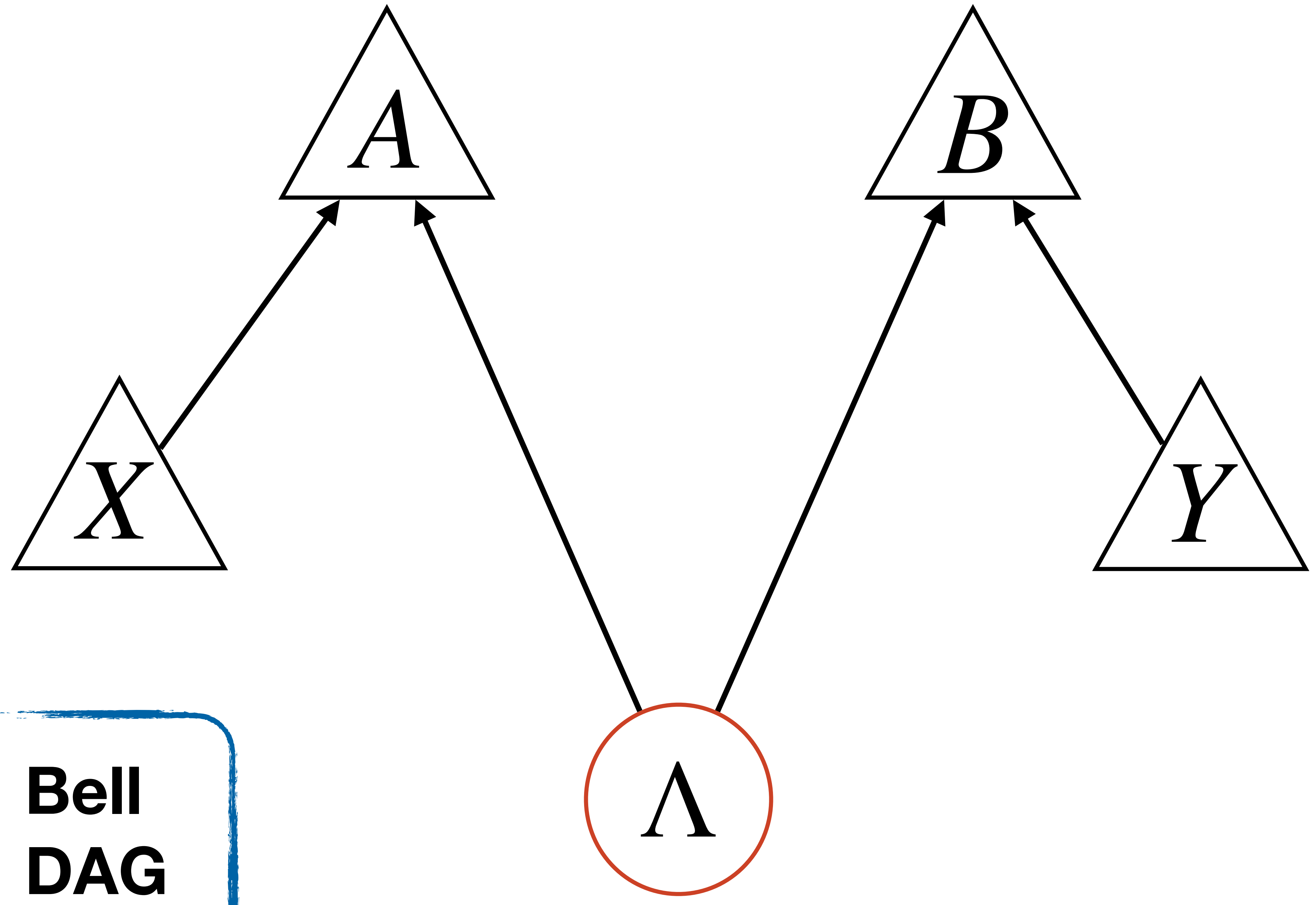
compatible probability distribution

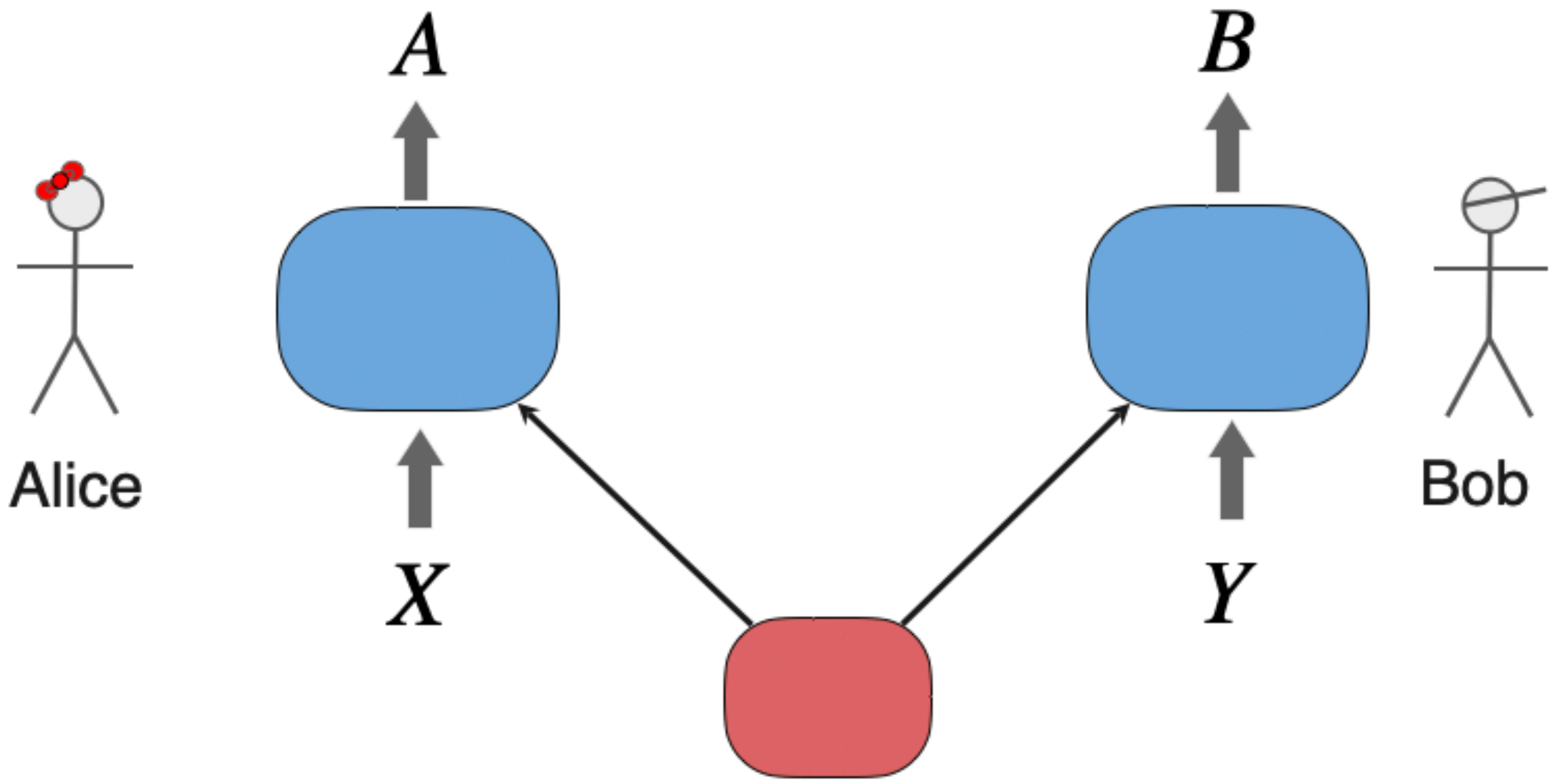
causal structure = a directed acyclic graph (DAG) (cause and effect relations)

compatibility = Markov conditions ≈ variables depend only on direct causes

used in medicine, economics, epidemiology, sociology, AI, etc…

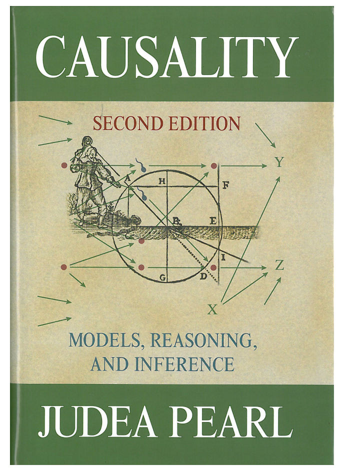
Bell DAG





$A \perp Y | X$

$B \perp X | Y$



Bell DAG

$$p(abxy) = \sum_{\lambda} p(a|x\lambda)p(b|y\lambda)p(x)p(y)p(\lambda)$$

Markov condition

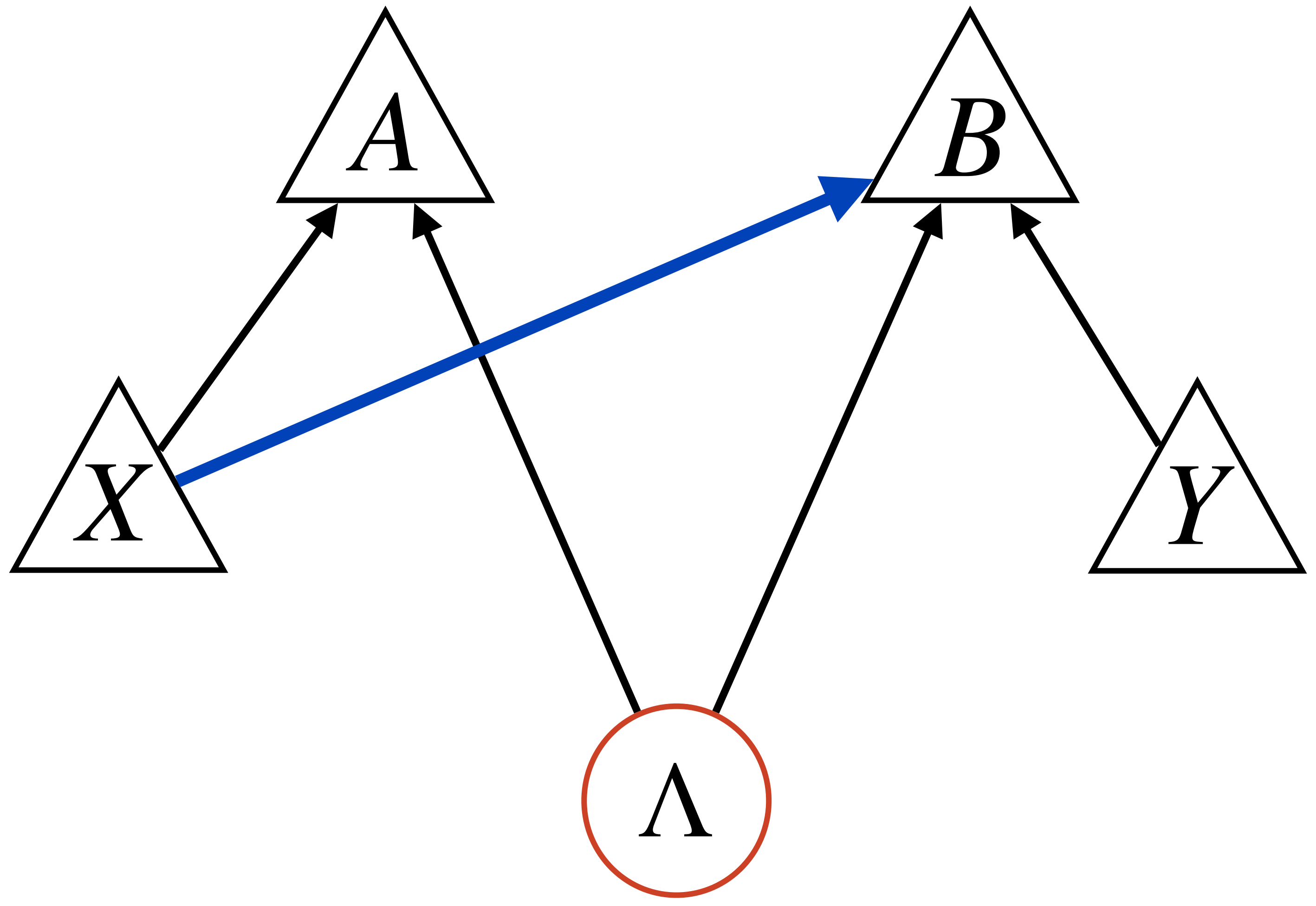
$\swarrow$ $A \perp Y | X$

$\Downarrow$ $B \perp X | Y$

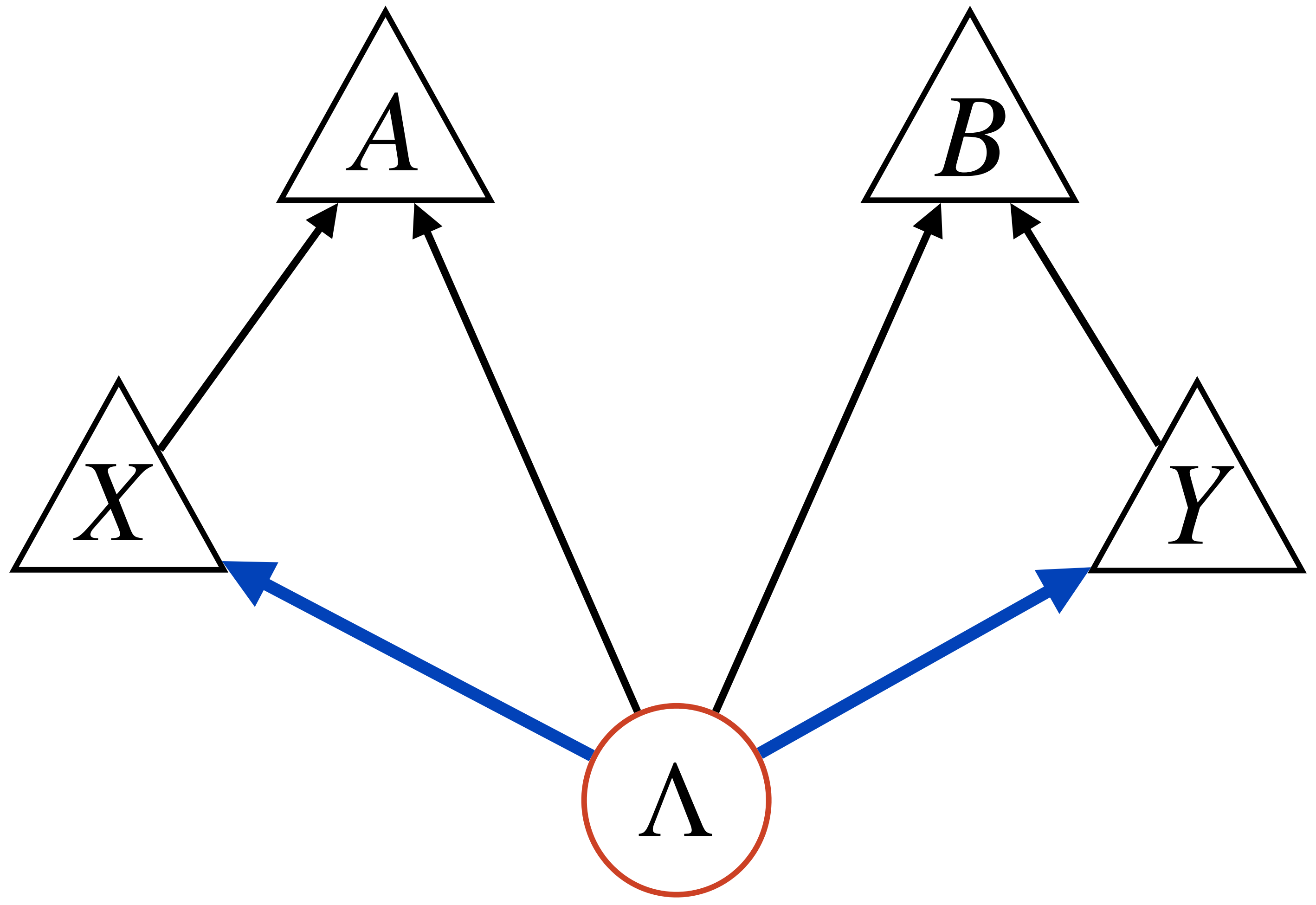
$\searrow$ **Bell Inequalities**

alternative causal models

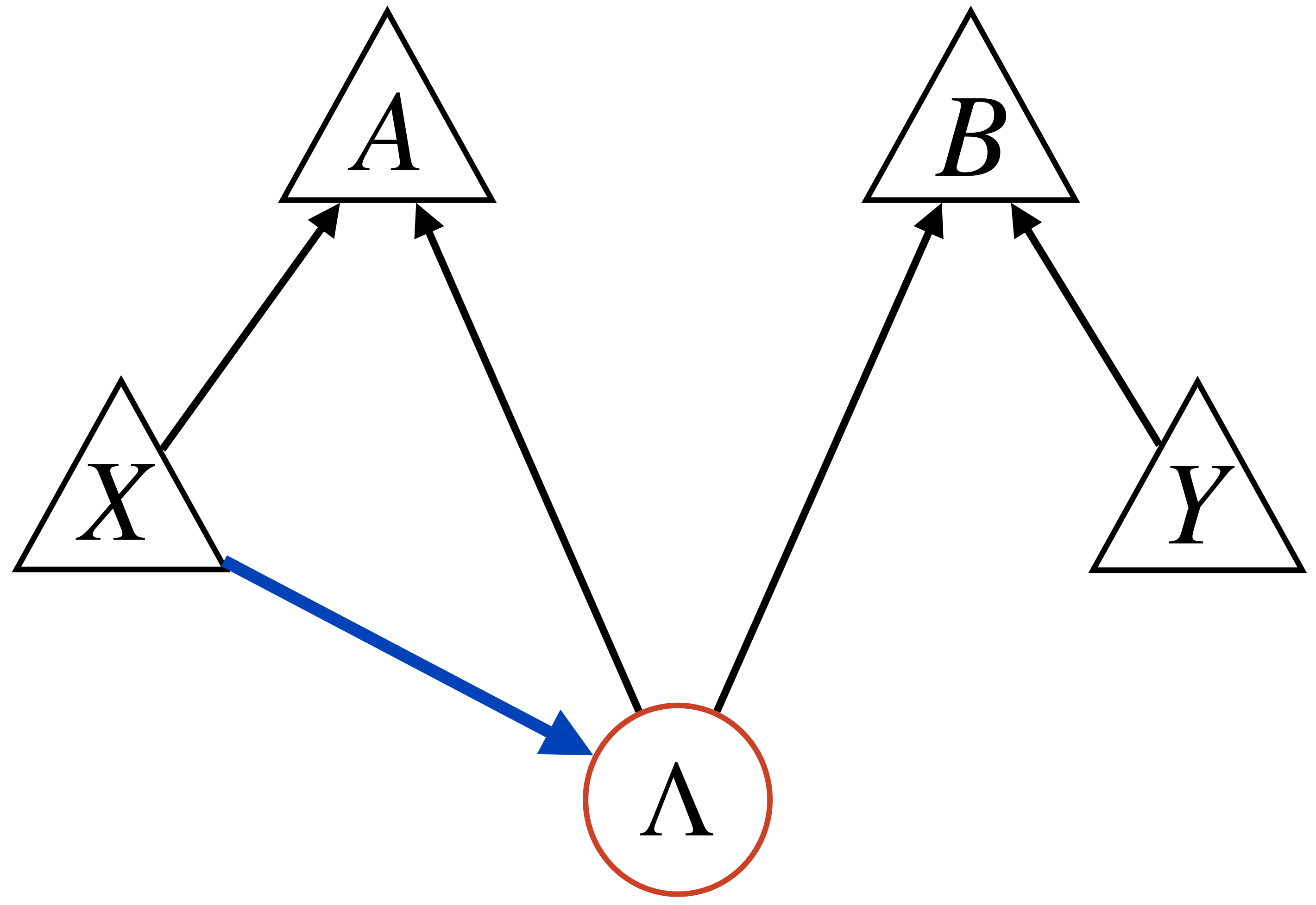
superluminal causation



superdeterminism



retrocausality



compatible with Bell inequality violations... <u>BUT</u> in tension with Bell's assumptions (of course)

<u>AND ALSO</u> *finetuned* explanations

no finetuning principle

$$A \perp B \mid C \quad \Longleftrightarrow \quad A \perp_d B \mid C$$

no finetuning principle

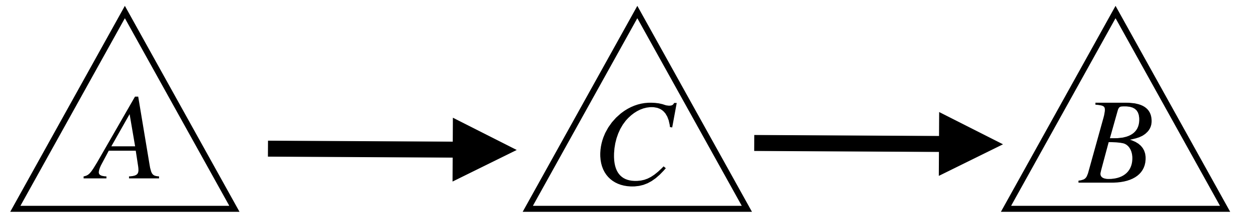
every statistical independence in the data is implied by the causal structure

d-separation

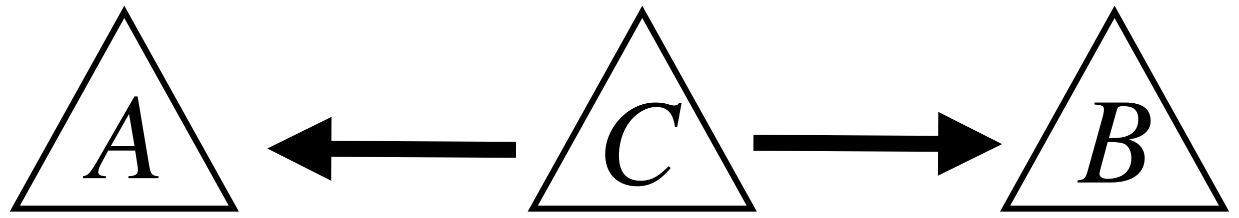
$$A \perp_d B \mid C$$

C d-separates A and B
if it ***blocks***
all paths from A and B

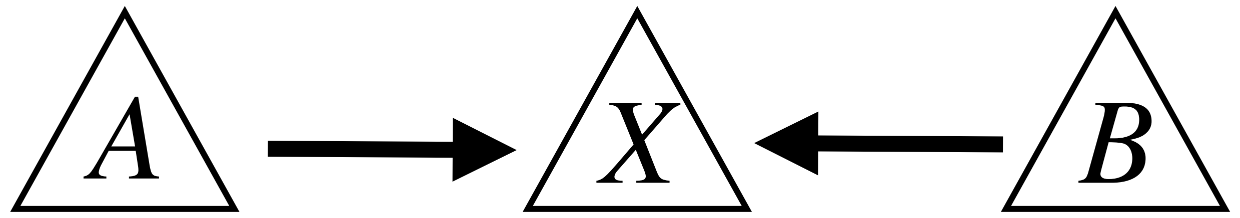
mediation



common cause



collider



$C \npreceq X$

no finetuning principle

data

$$A \perp B \mid C$$

A **and** B **are**
statistically independent given C

$$p(ab \mid c) = p(a \mid c)p(b \mid c)$$

Markov condition

$$\Longleftarrow$$

$$\not\Longrightarrow$$

model

$$A \perp_d B \mid C$$

A **and** B **are**
d***-separated by*** C

$$A \to C \to B \qquad A \leftarrow C \to B$$

$$A \xrightarrow{C \npreceq X} X \leftarrow B$$

no finetuning principle

data

$$A \perp B \mid C$$

A and B are

statistically independent given C

$$p(ab \mid c) = p(a \mid c)p(b \mid c)$$

no finetuning

$$\Longleftrightarrow$$

model

$$A \perp_d B \mid C$$

A and B are

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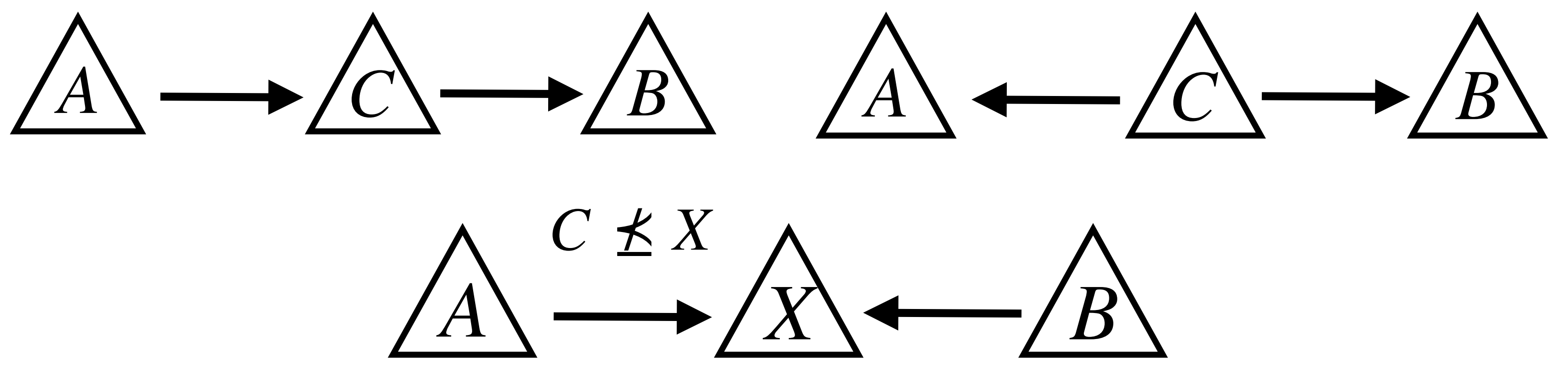
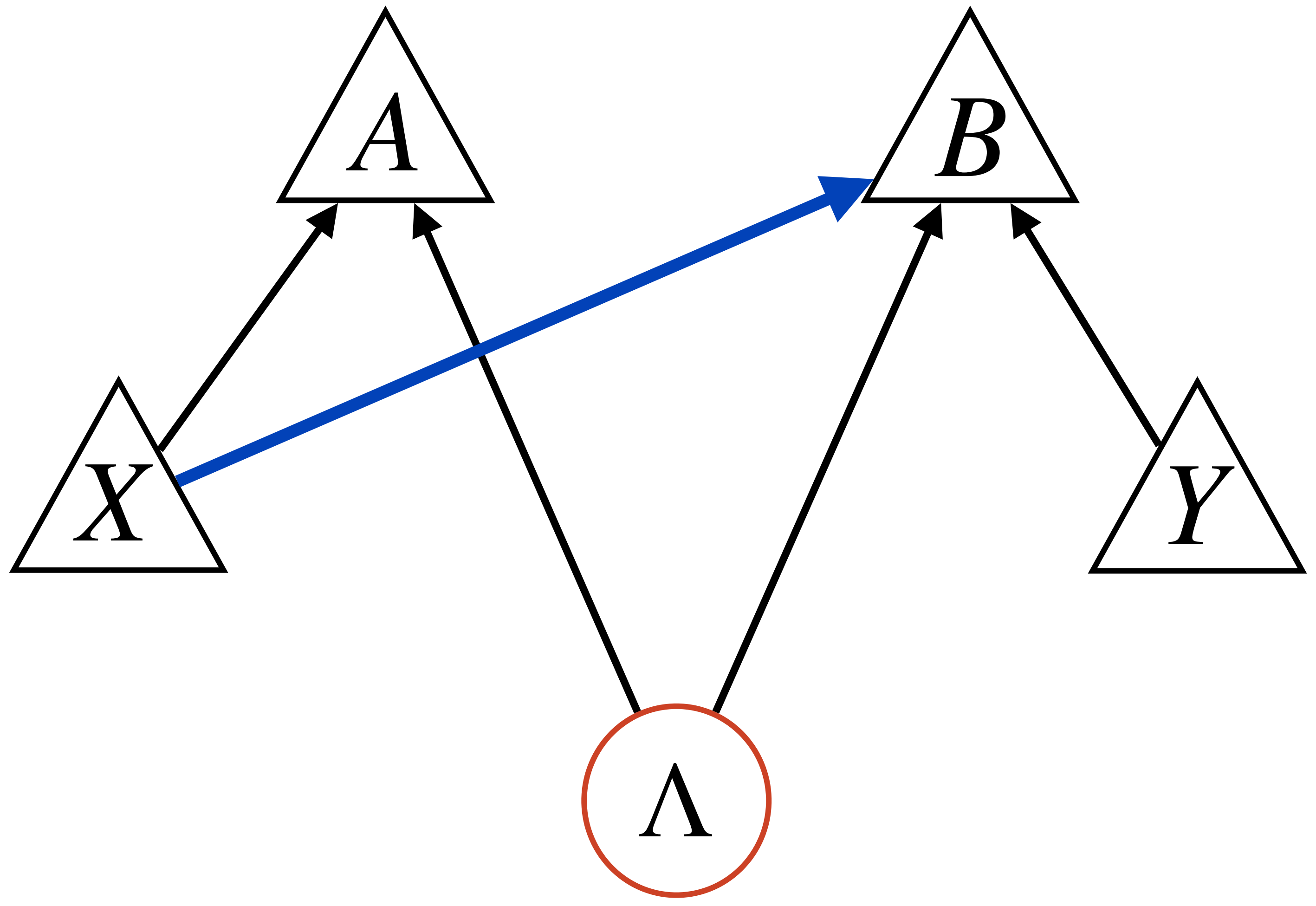
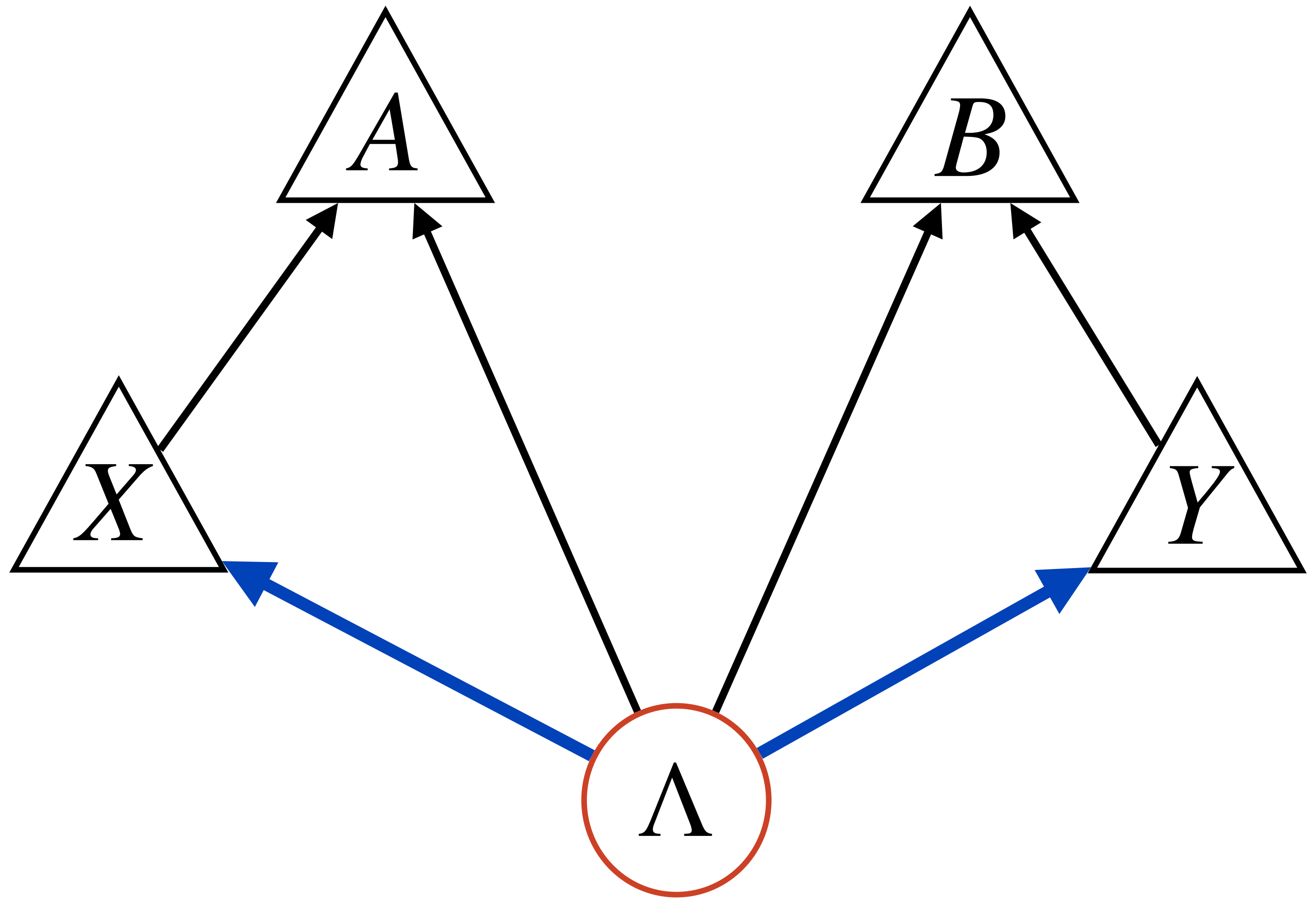


alternative causal models

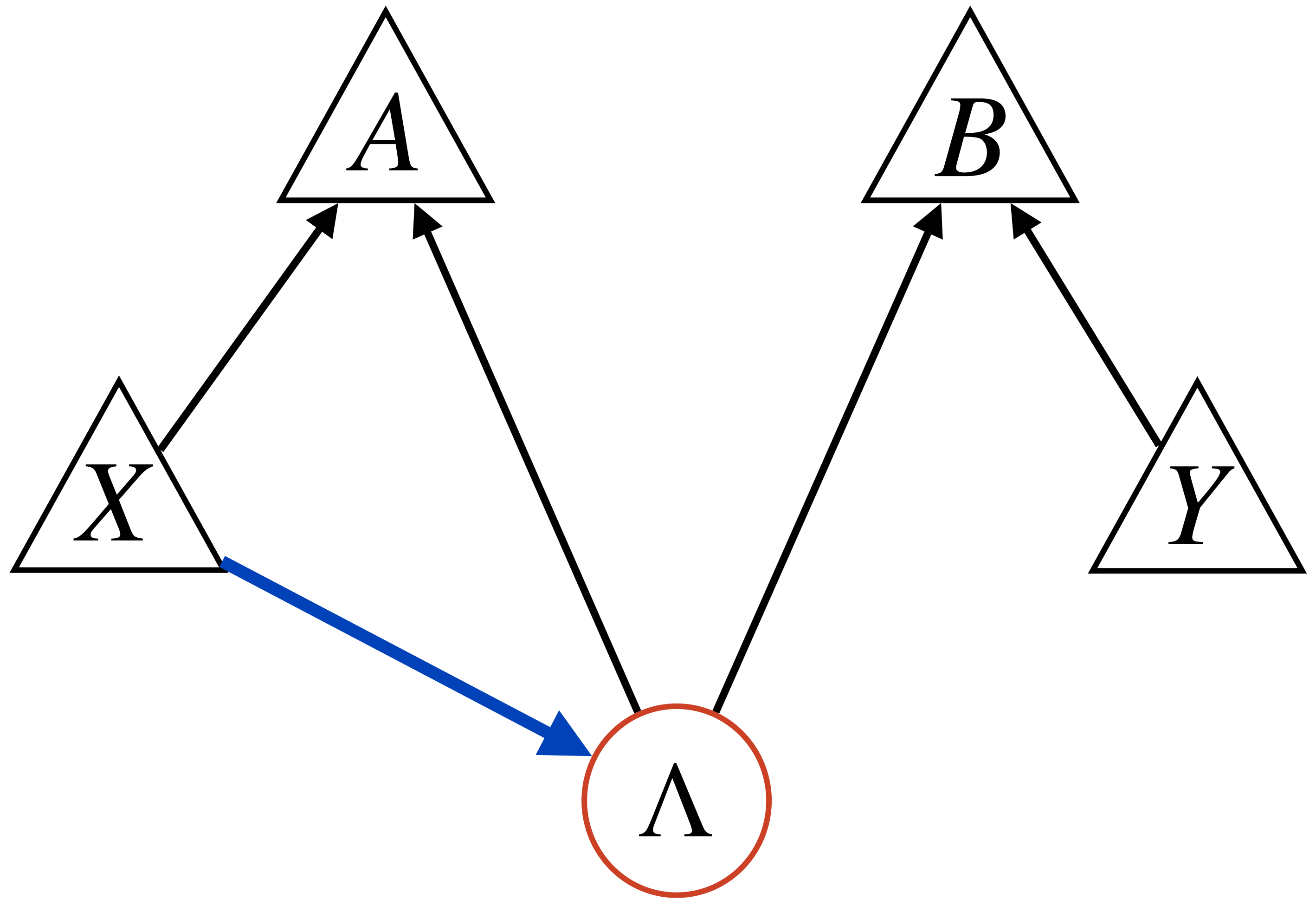
superluminal causation



superdeterminism



retrocausality



compatible with Bell inequality violations...

<u>BUT</u>

***finetuned* explanations** $B \not\perp_d X \mid Y$

requires more explanation

Wood-Spekkens theorem

PAPER • OPEN ACCESS

The lesson of causal discovery algorithms for quantum correlations: causal explanations of Bell-inequality violations require fine-tuning

Christopher J Wood and Robert W Spekkens

New Journal of Physics, Volume 17, March 2015

Citation Christopher J Wood and Robert W Spekkens 2015 *New J. Phys.* **17** 033002

DOI 10.1088/1367-2630/17/3/033002

all **classical causal models for Bell inequality violations are finetuned**

(no need for spacelike separation!)

$$A \perp Y | X \qquad B \perp X | Y$$

observations

no finetuning $\Longrightarrow$

$$A \perp_d Y | X \qquad B \perp_d X | Y$$

causal structure

Markov $\Longrightarrow$

Bell inequalities

observations

classical causal modelling Bell

Wood-Spekkens solution

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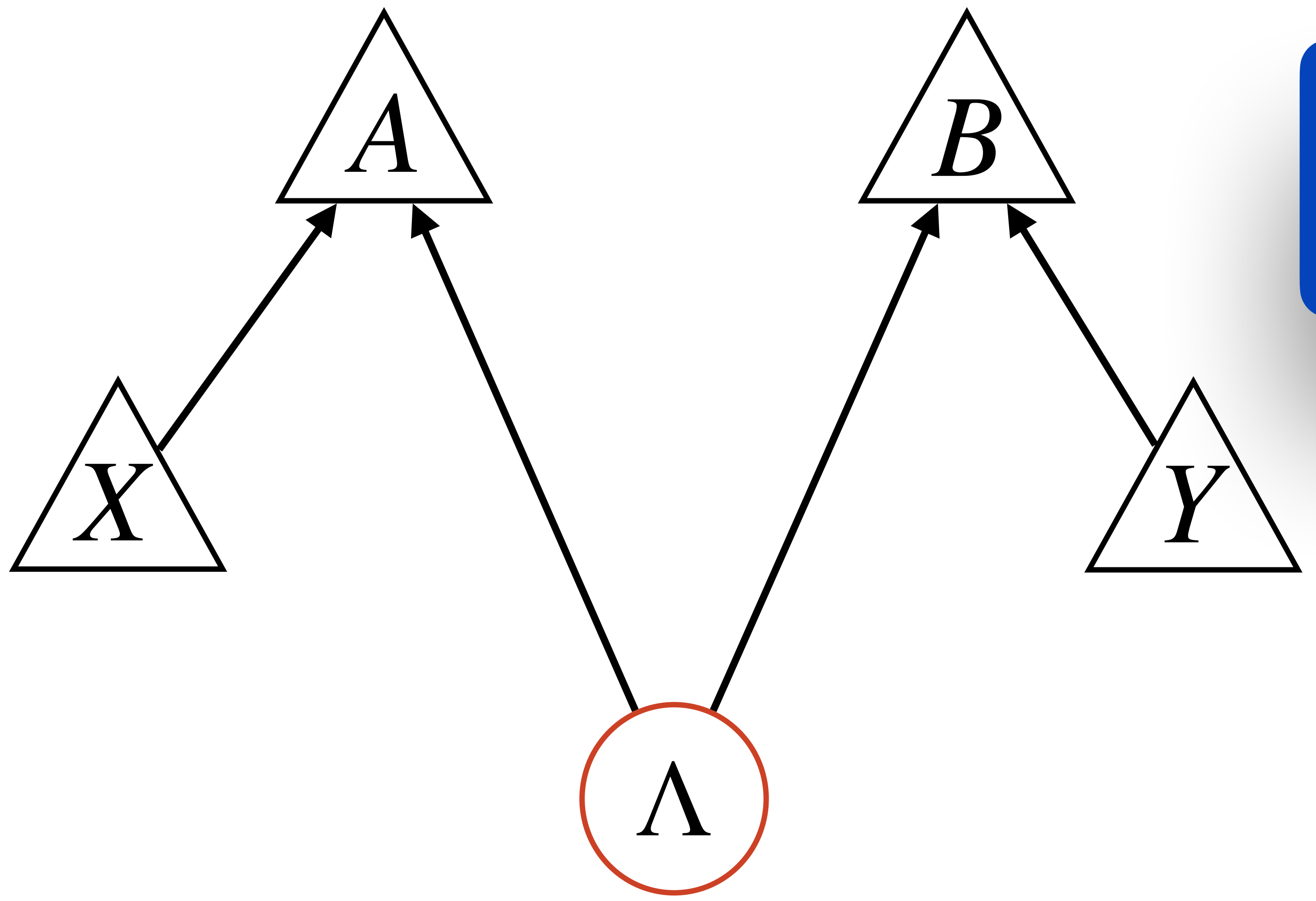
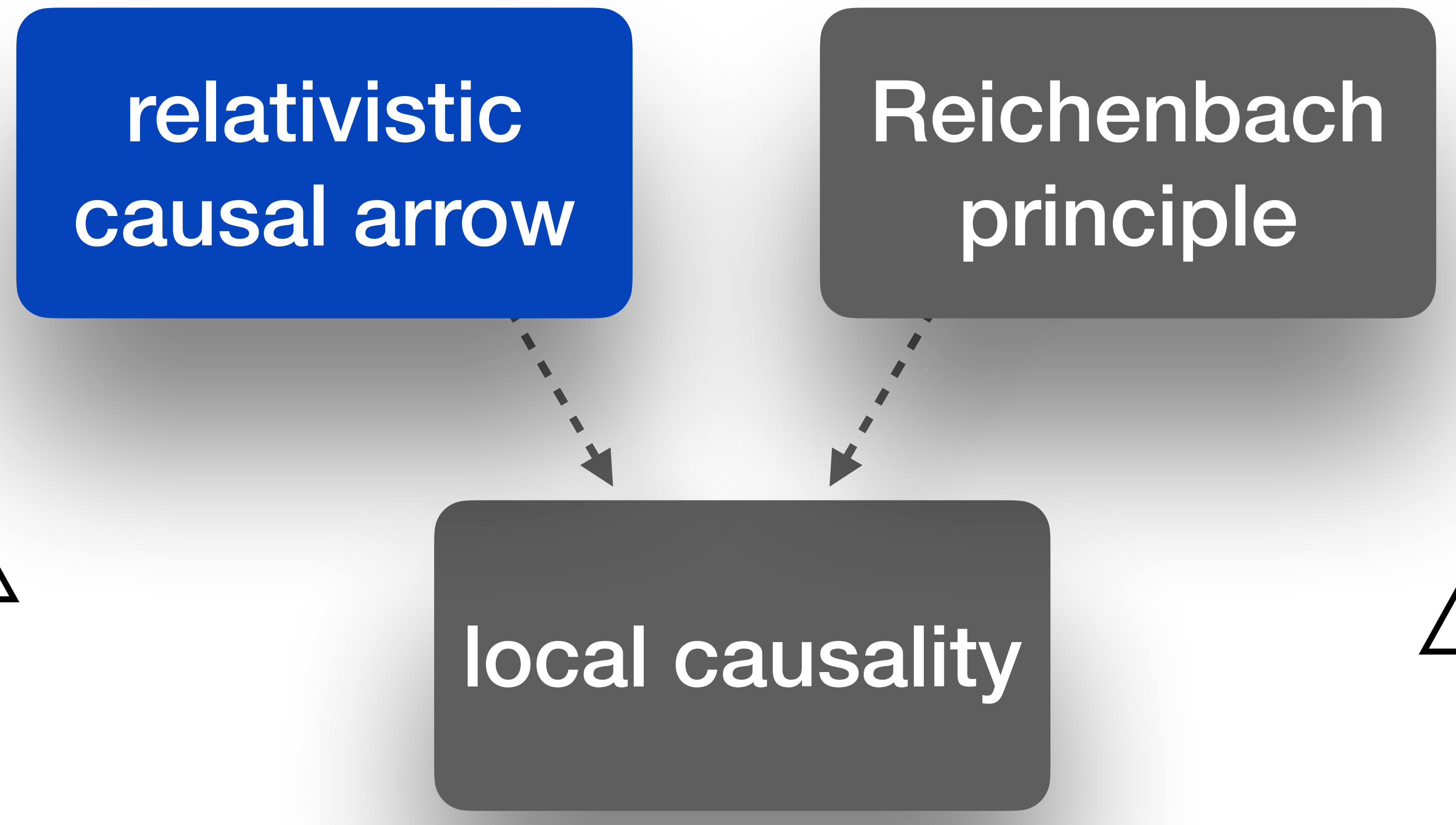
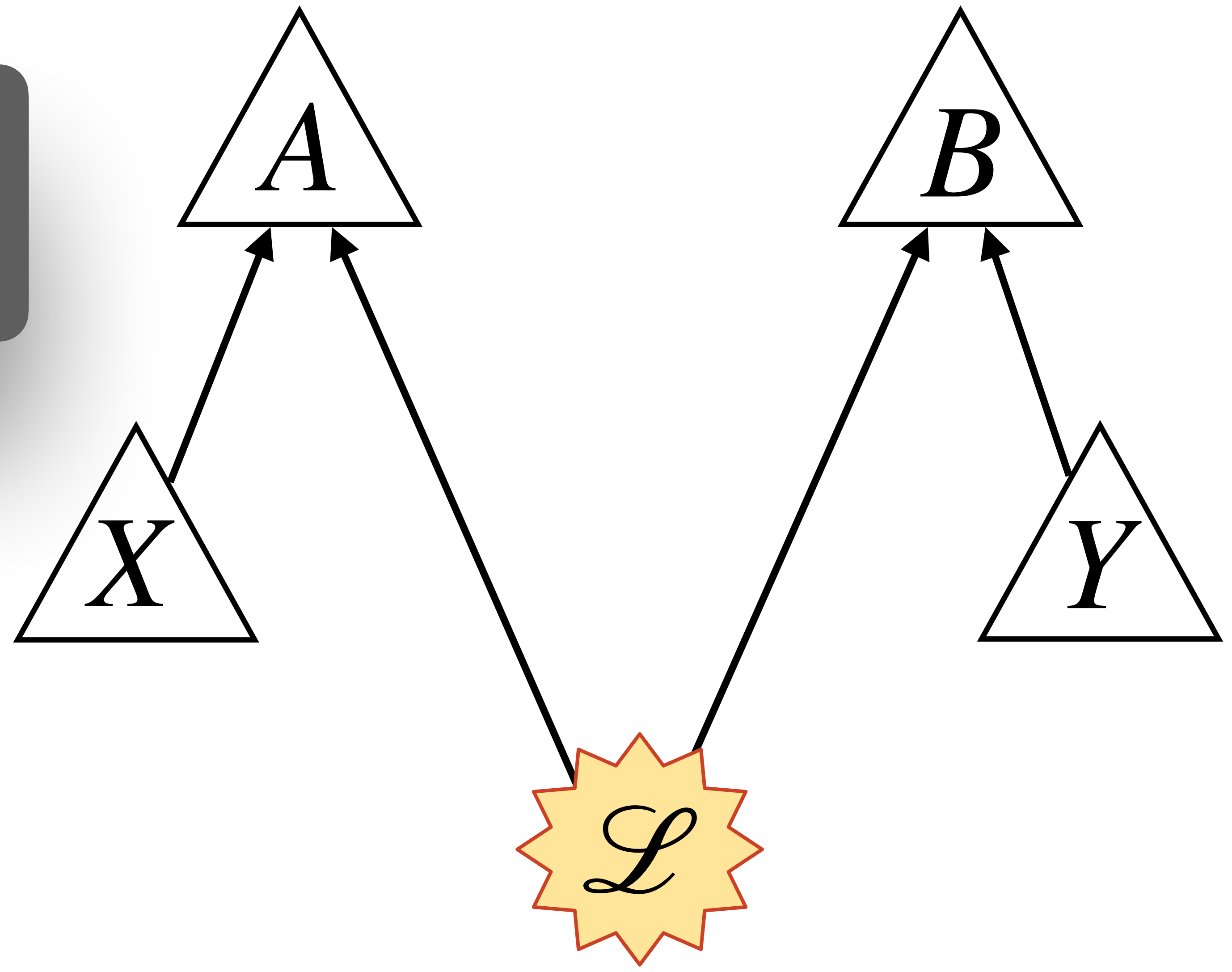
classical causal modelling





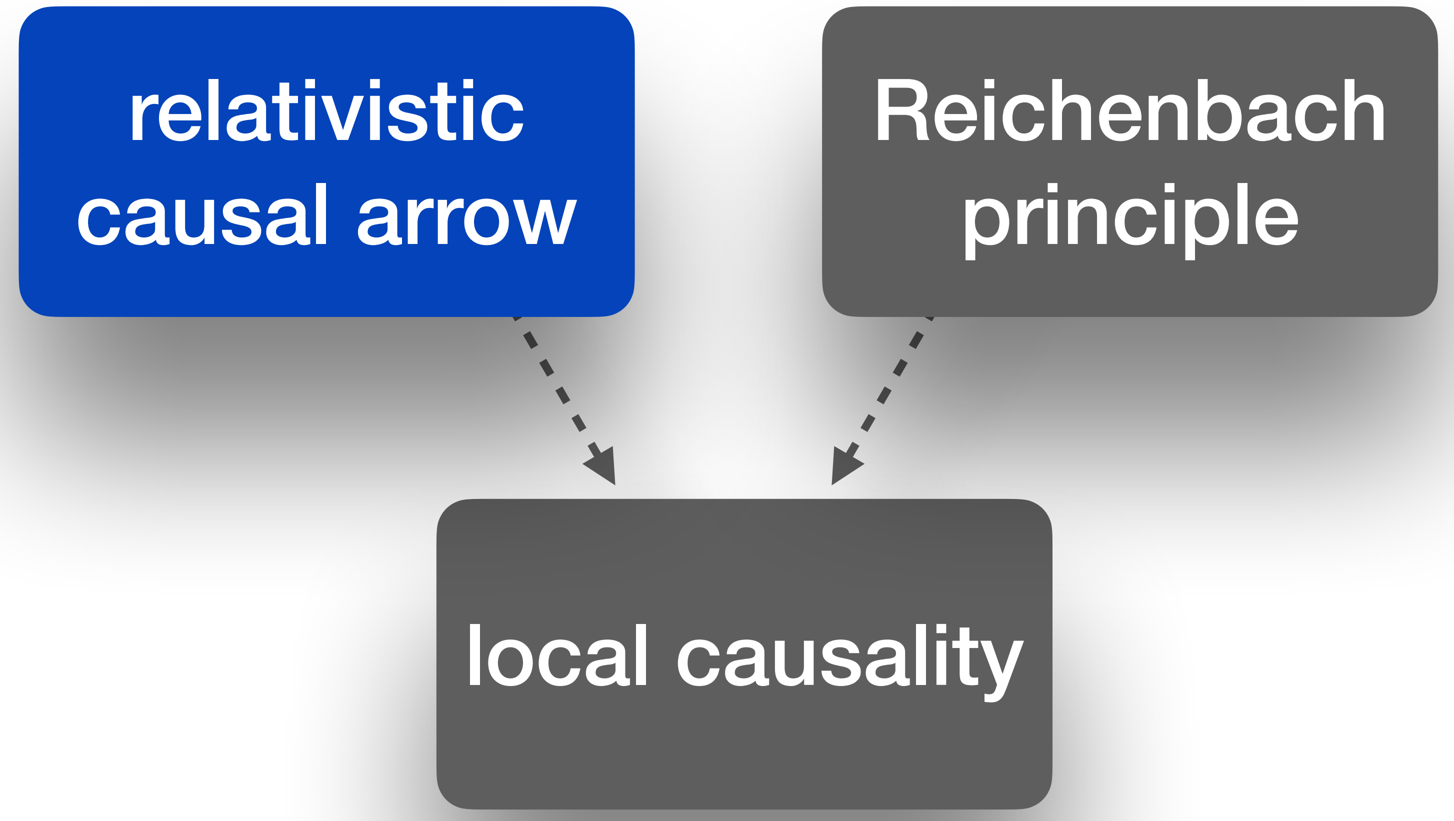
quantum causal modelling

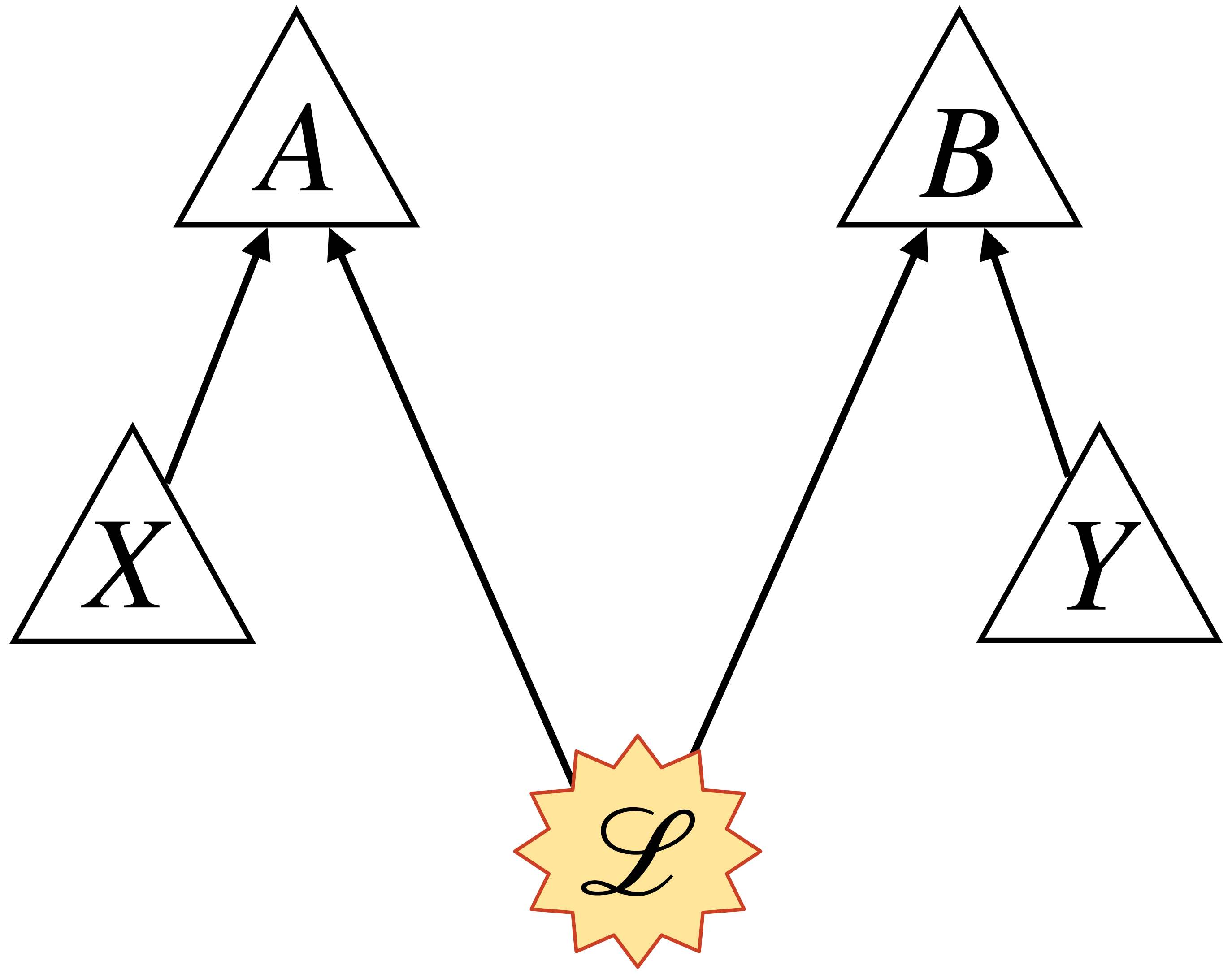


$$p(abxy) = \sum_{\lambda} p(a\,|\,x\lambda)p(b\,|\,y\lambda)p(x)p(y)p(\lambda)$$

$$p(abxy) = \mathrm{tr}\left[E_x^a E_y^b \rho_{\mathscr{L}}\right] p(x)p(y)$$

Wood-Spekkens solution





$\implies \quad A \perp Y | X$

$\implies \quad B \perp X | Y$

$\not\Longrightarrow$ **Bell inequalities**

$\implies$ **Tsirelson bound**

$$p(abxy) = \mathrm{tr}\left[E_x^a E_y^b \rho_{\mathscr{L}}\right] p(x)p(y)$$

Wigner and post-quantum causal models

Quantum

2024-09-26, volume 8, page 1485

Relating Wigner's Friend Scenarios to Nonclassical Causal Compatibility, Monogamy Relations, and Fine Tuning

Yìlè Yīng

Marina Maciel Ansanelli

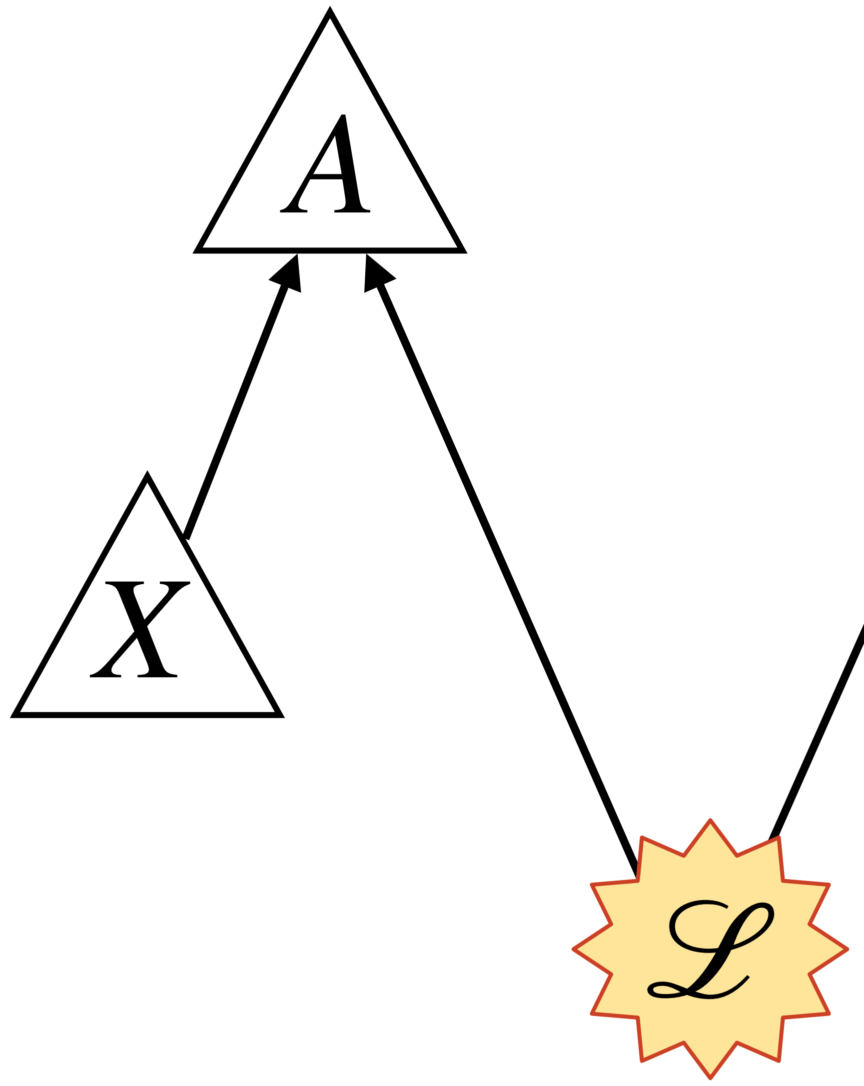
Elie Wolfe

David Schmid

Eric Gama Cavalcanti

post-quantum causal modelling

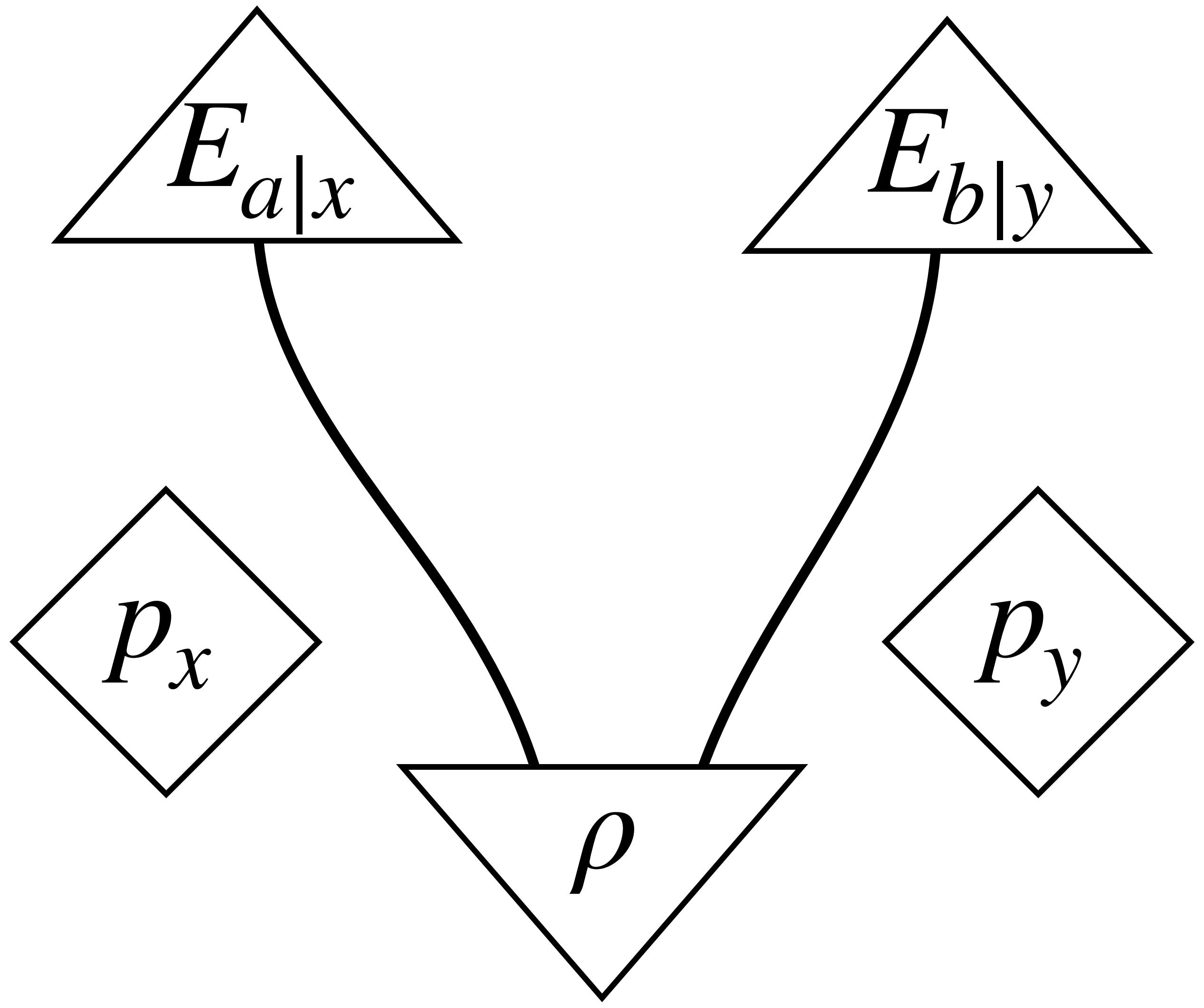
DAG



generalised Markov condition

$$\Longrightarrow$$

GPT circuit



A probability distribution over observed nodes, denoted as $P(\mathtt{obs}(\mathcal{G}))$, is GPT-compatible[19] with a given causal structure $\mathcal{G}$ if and only if it can be generated by a GPT in the way prescribed by $\mathcal{G}$, namely, if and only if there exists a GPT T such that:

- a system in T is associated to each edge that starts from a latent node in $\mathcal{G}$,
- for each latent node Y and for any value of its observed parents, denoted $\mathtt{Opa}(Y)$, there is a channel $\mathcal{C}_Y(\mathtt{opa}(Y))$ in T from the systems associated with latent-originating edges incoming to Y to the composite system associated with all edges outgoing from Y,
- for every value x of an observed node X, and for any value $\mathtt{opa}(X)$ of its observed parents $\mathtt{Opa}(X)$, there is an effect $\mathcal{E}_X(x|\mathtt{opa}(X))$ in T on the system composed of all systems associated with edges incoming in X, such that $\sum_x \mathcal{E}_X(x|\mathtt{opa}(X))$ is the unique deterministic effect on the systems associated to edges coming from latent nodes to X,
- $P(\mathtt{obs}(\mathcal{G}))$ is the probability obtained by wiring the various tests $\mathcal{E}_X(x|\mathtt{opa}(X))$ and channels $\mathcal{C}_Y(\mathtt{opa}(Y))$.

Note that the theory T may contain several system types, e.g., including also classical ones. According to these definitions above, an observed node with no latent parents is simply associated with a (conditional) probability distribution (a set of effects on the trivial system that sum to the unique deterministic effect on the trivial system), while a latent node with no latent parents is associated to a classically-controlled state over the relevant systems (i.e., a controlled deterministic channel from the trivial system).

$$p(abxy) = (E_{a|x} \otimes E_{b|y})[\rho]\ p(x)p(y)$$

PAPER · OPEN ACCESS

Theory-independent limits on correlations from generalized Bayesian networks

To cite this article: Joe Henson *et al* 2014 *New J. Phys.* **16** 113043

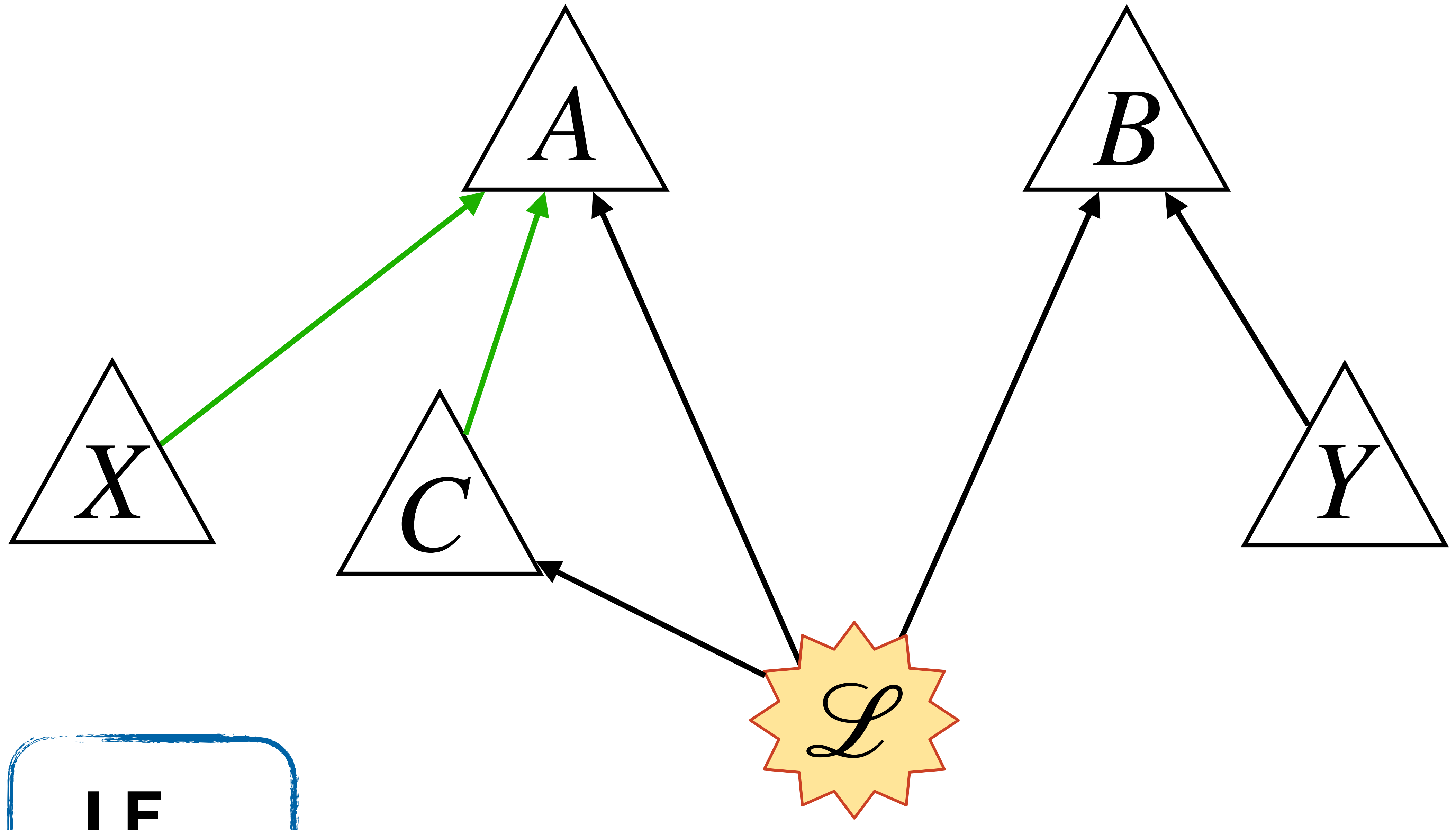
post-quantum causal modelling LF scenario

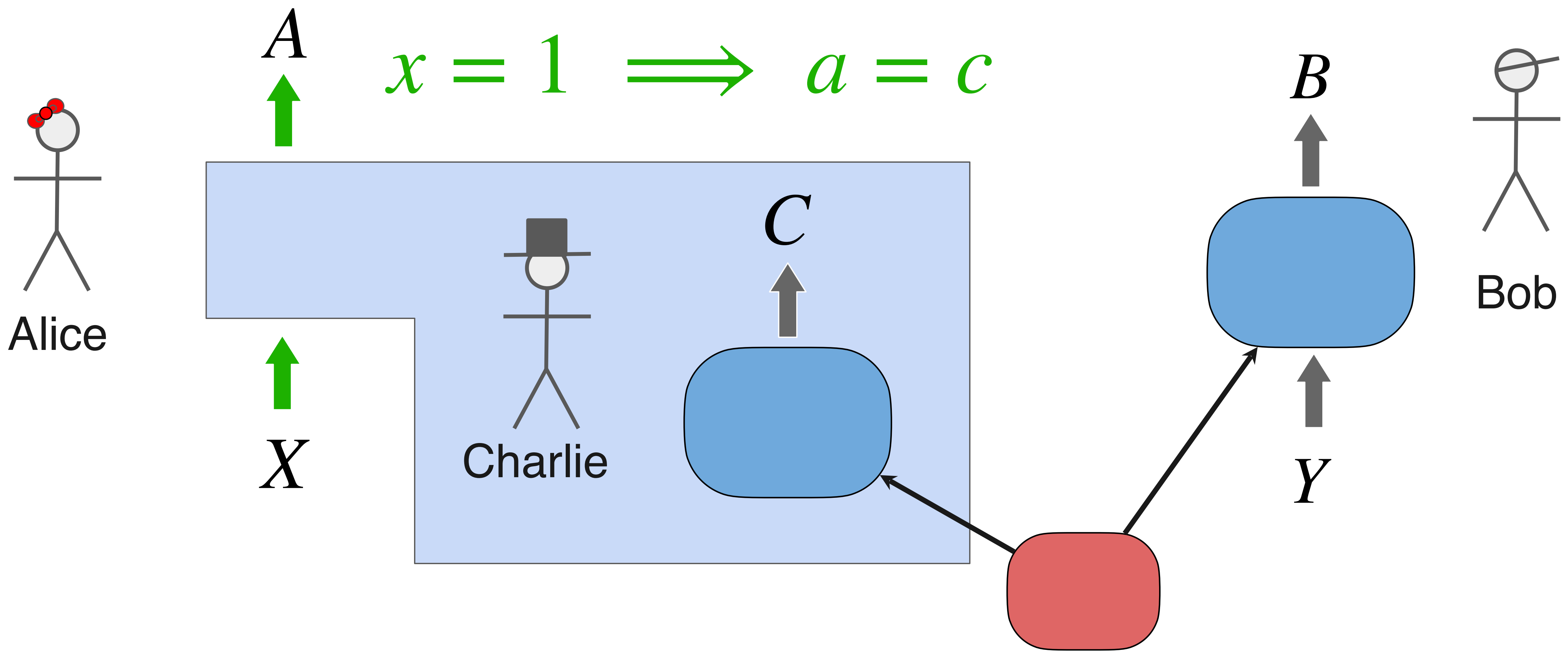
LF DAG

$A \perp Y | X$

$B \perp X | Y$

$C \perp Y | x = 1$

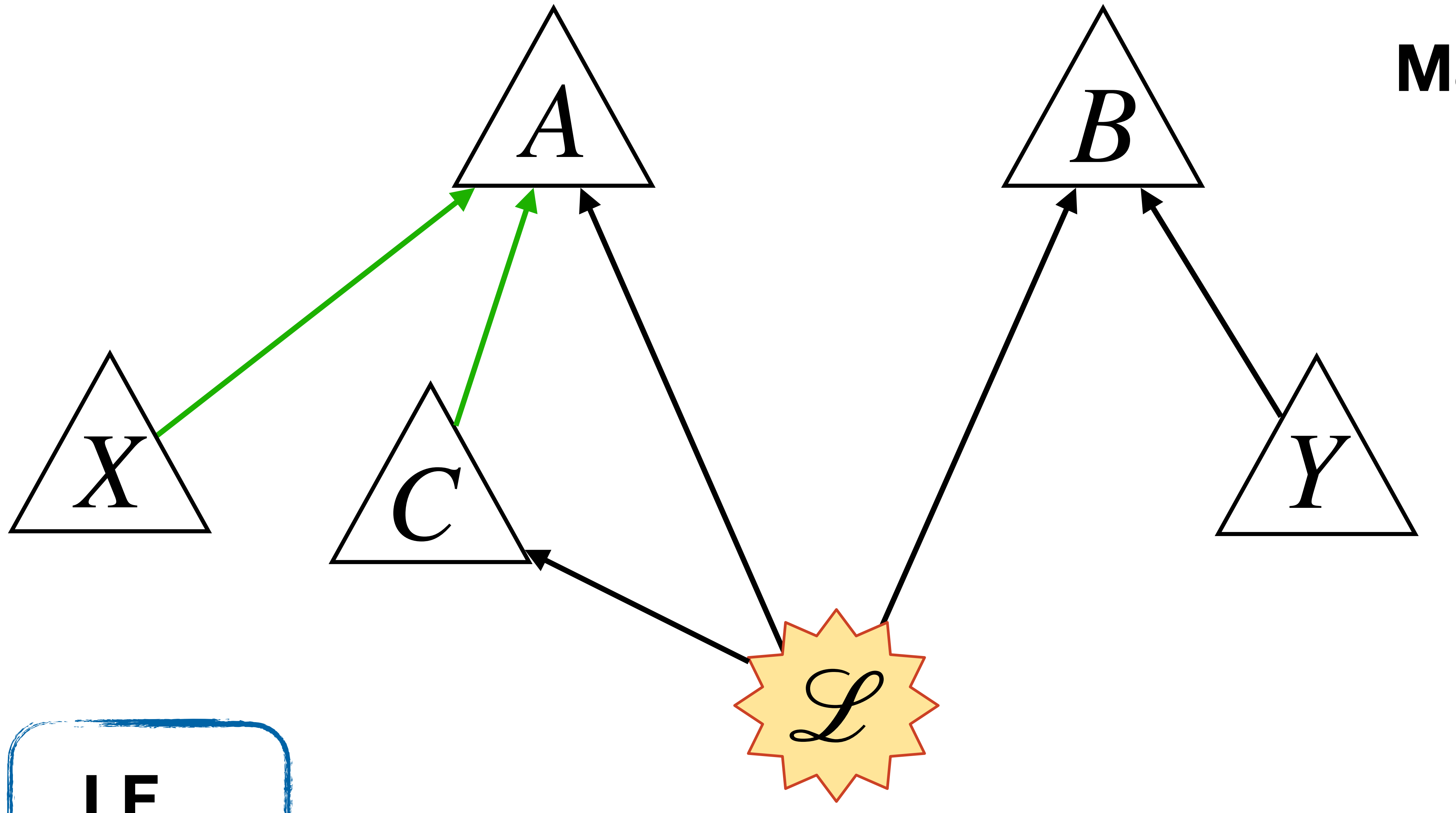




LF DAG

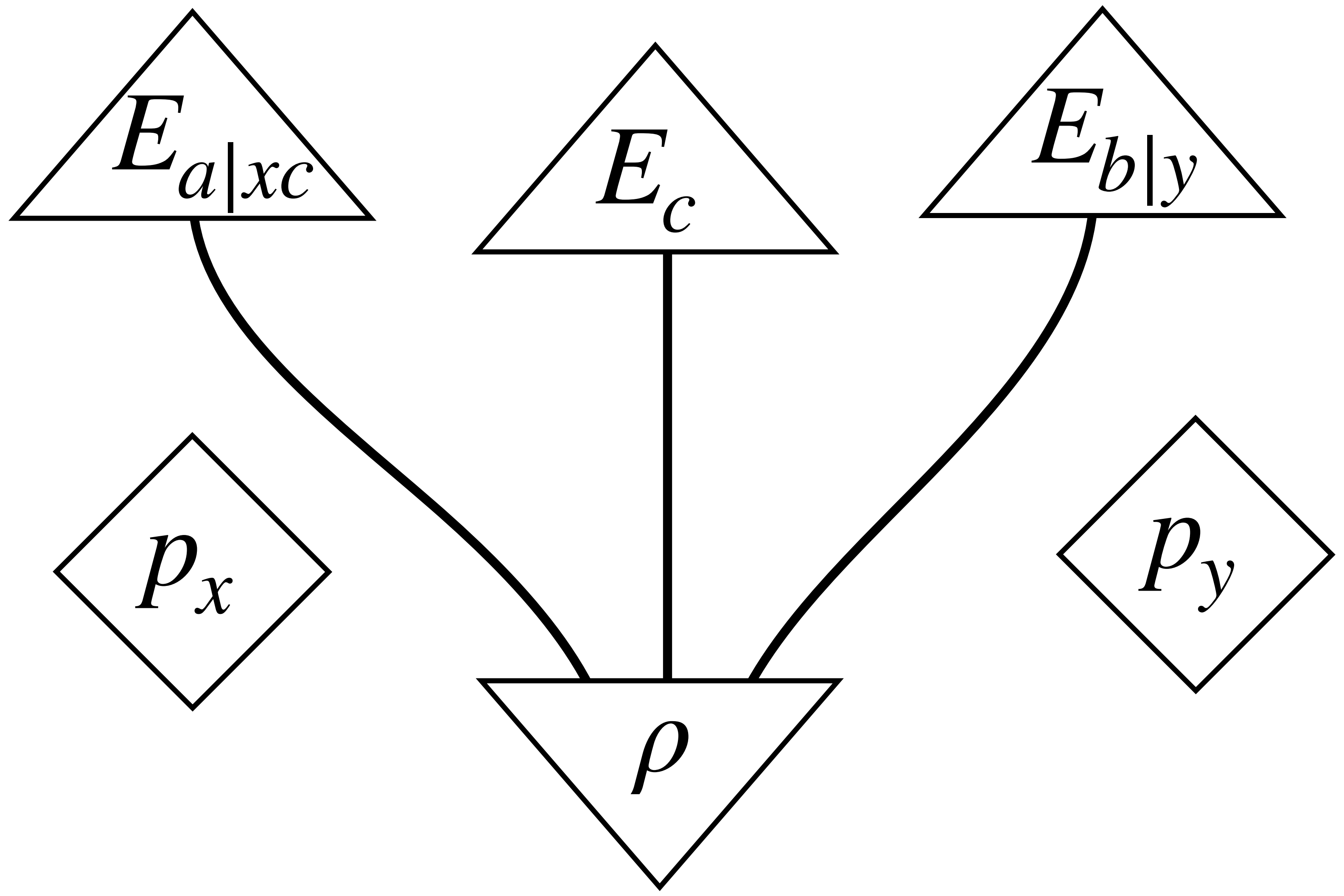
LF DAG

causal structure



generalised Markov condition

GPT circuit

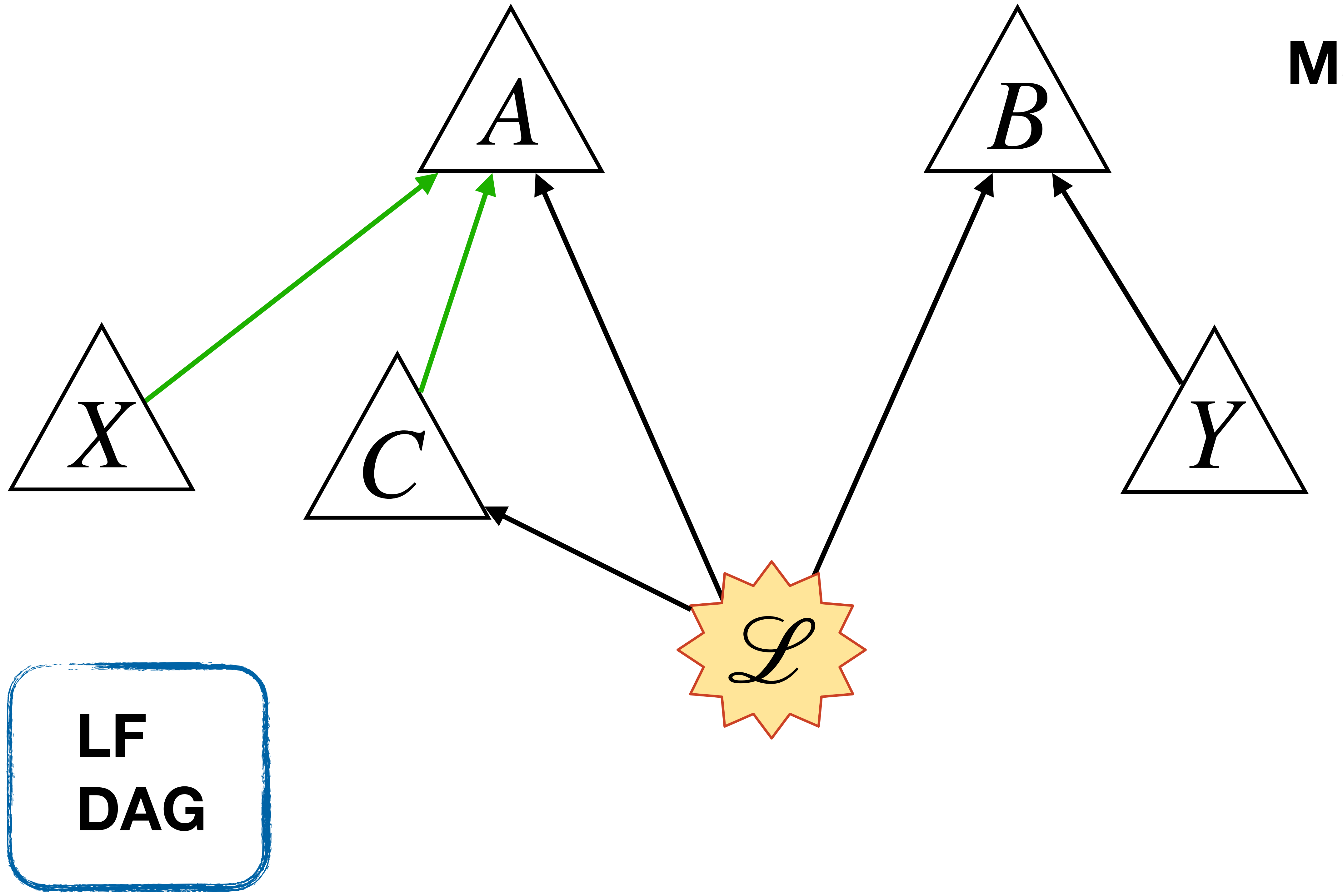


$$p(abxy) = \sum_c (E_{a|xc} \otimes E_c \otimes E_{b|y})[\rho]\ p(x)p(y)$$

LF DAG

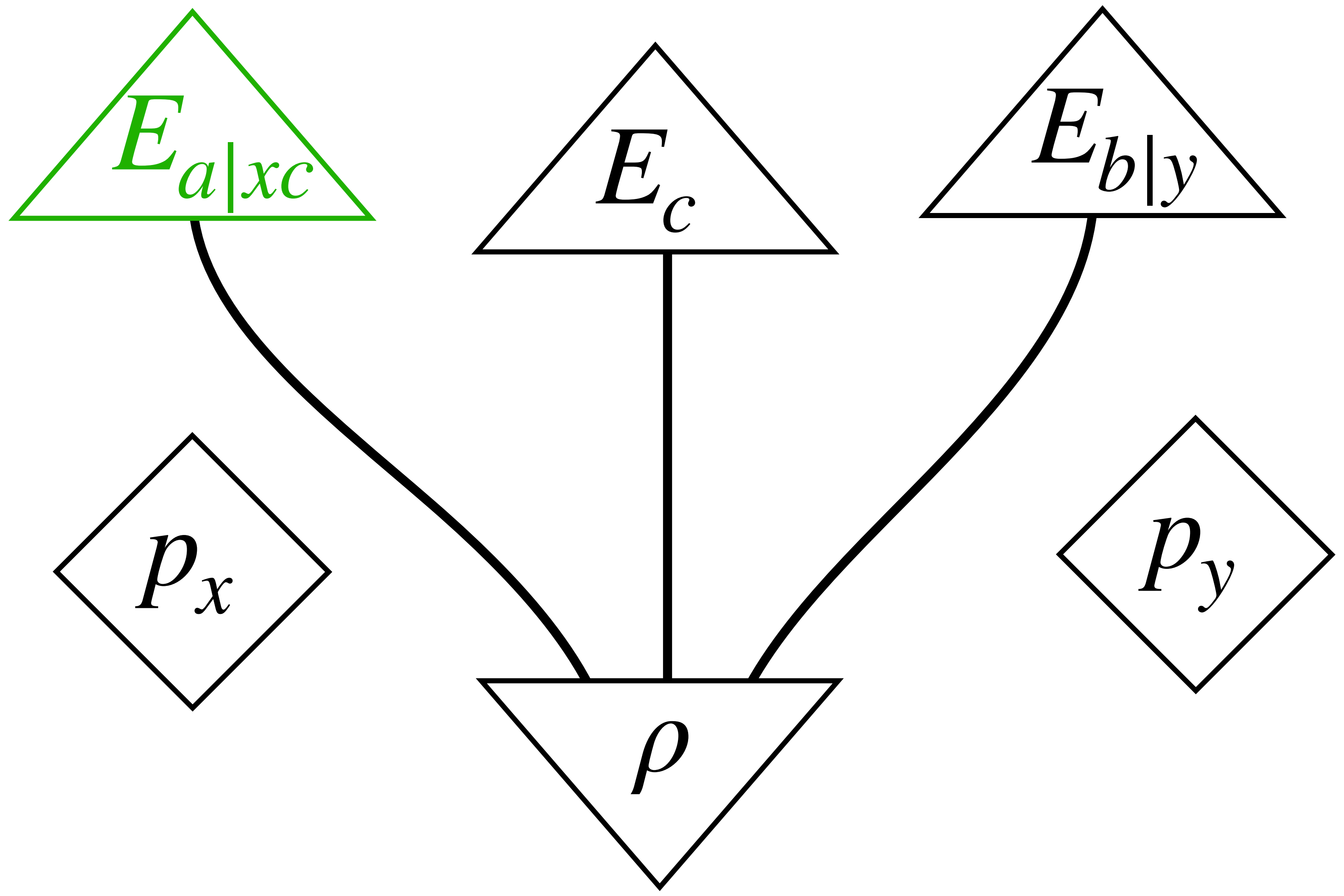
LF DAG

causal structure



generalised Markov condition

GPT circuit

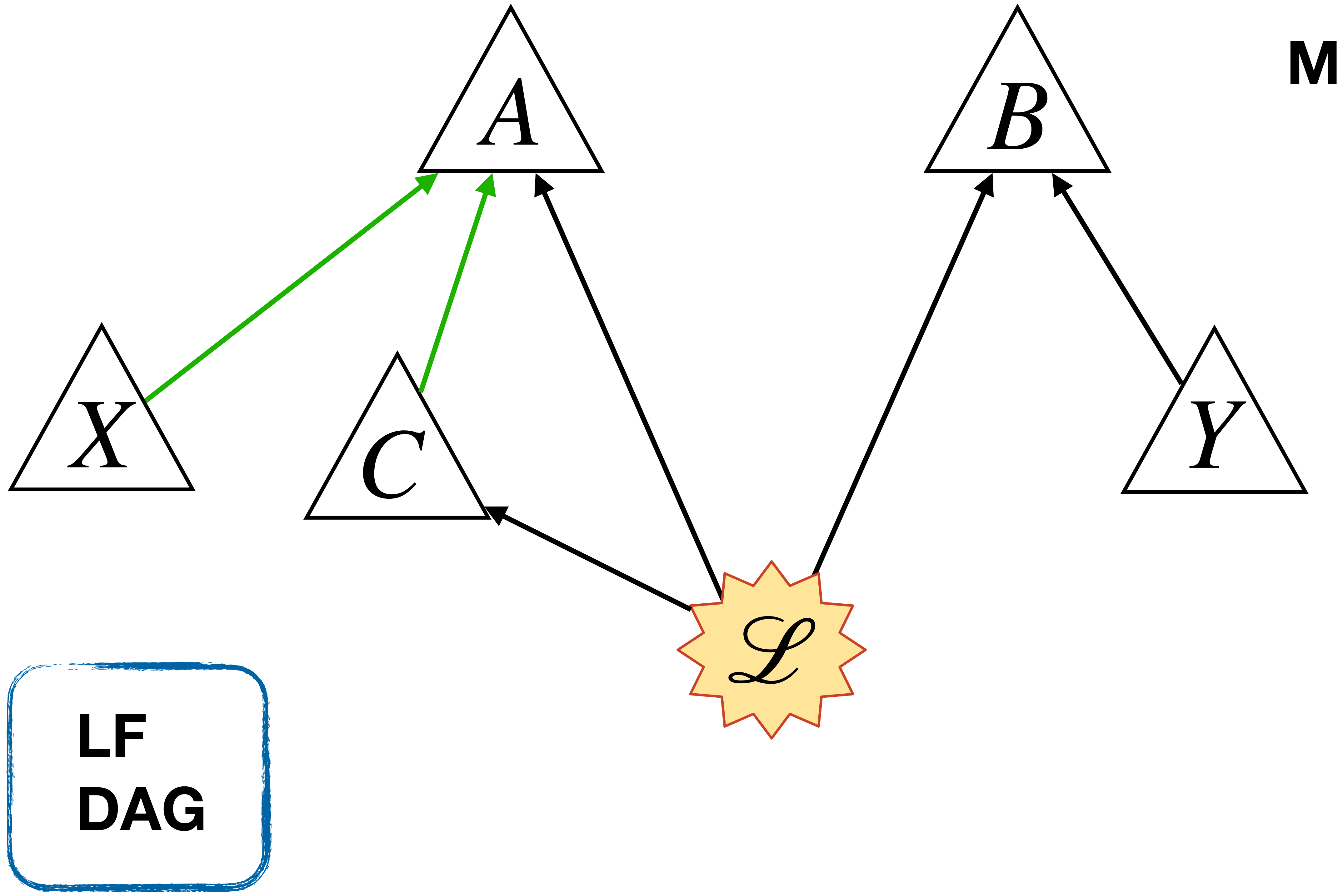


$$p(abxy) = \sum_c (E_{a|xc} \otimes E_c \otimes E_{b|y})[\rho]\ p(x)p(y)$$

$$E_{a|x=1,c} \propto \delta_{ac}$$

LF DAG no good

causal structure



generalised
Markov condition

GPT circuit

$$p(abxy) = \sum_c (E_{a|xc} \otimes E_c \otimes E_{b|y})[\rho]\ p(x)p(y)$$

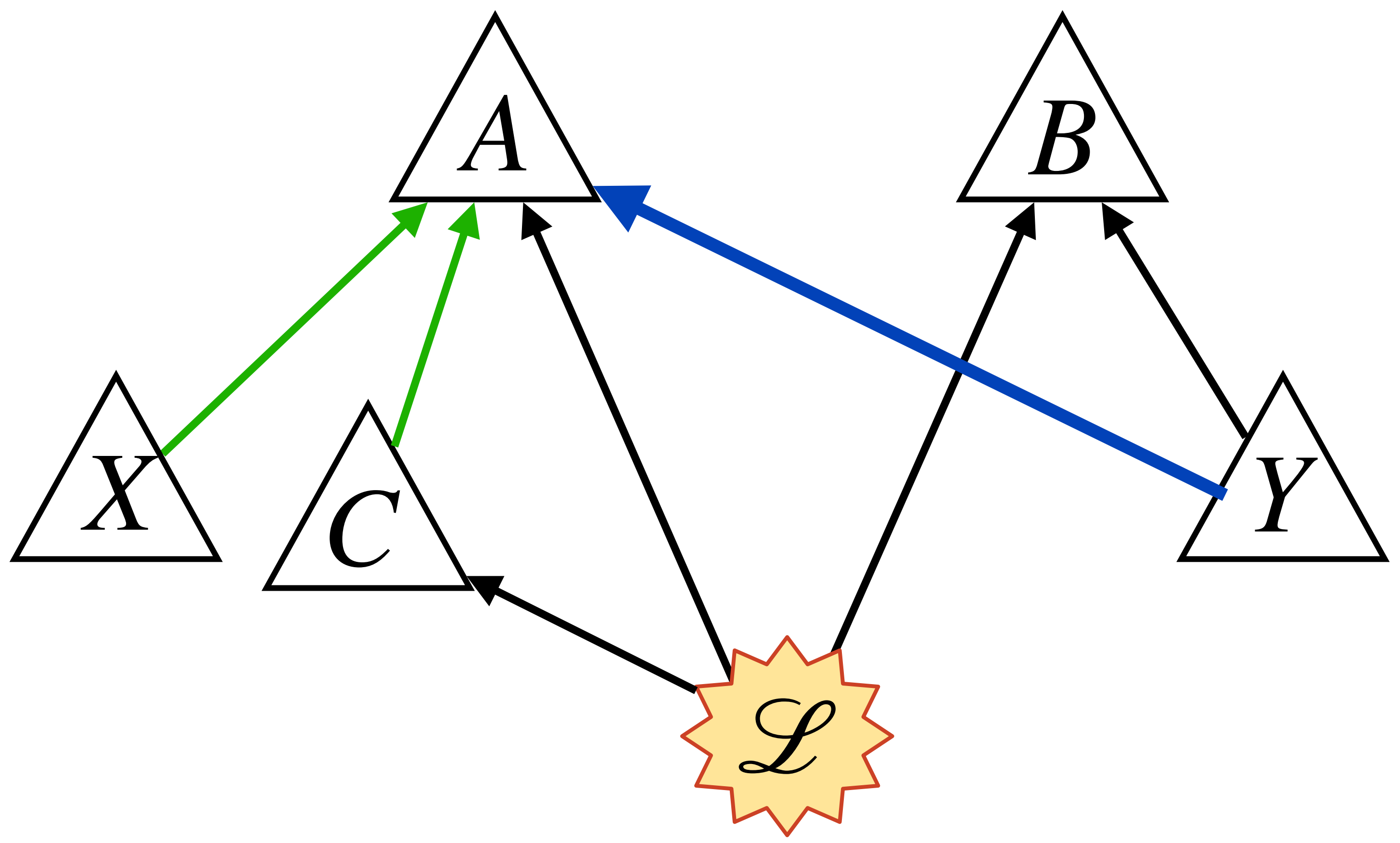
$$E_{a|x=1,c} \propto \delta_{ac}$$

$\Swarrow$ $\Downarrow$ $\Searrow$

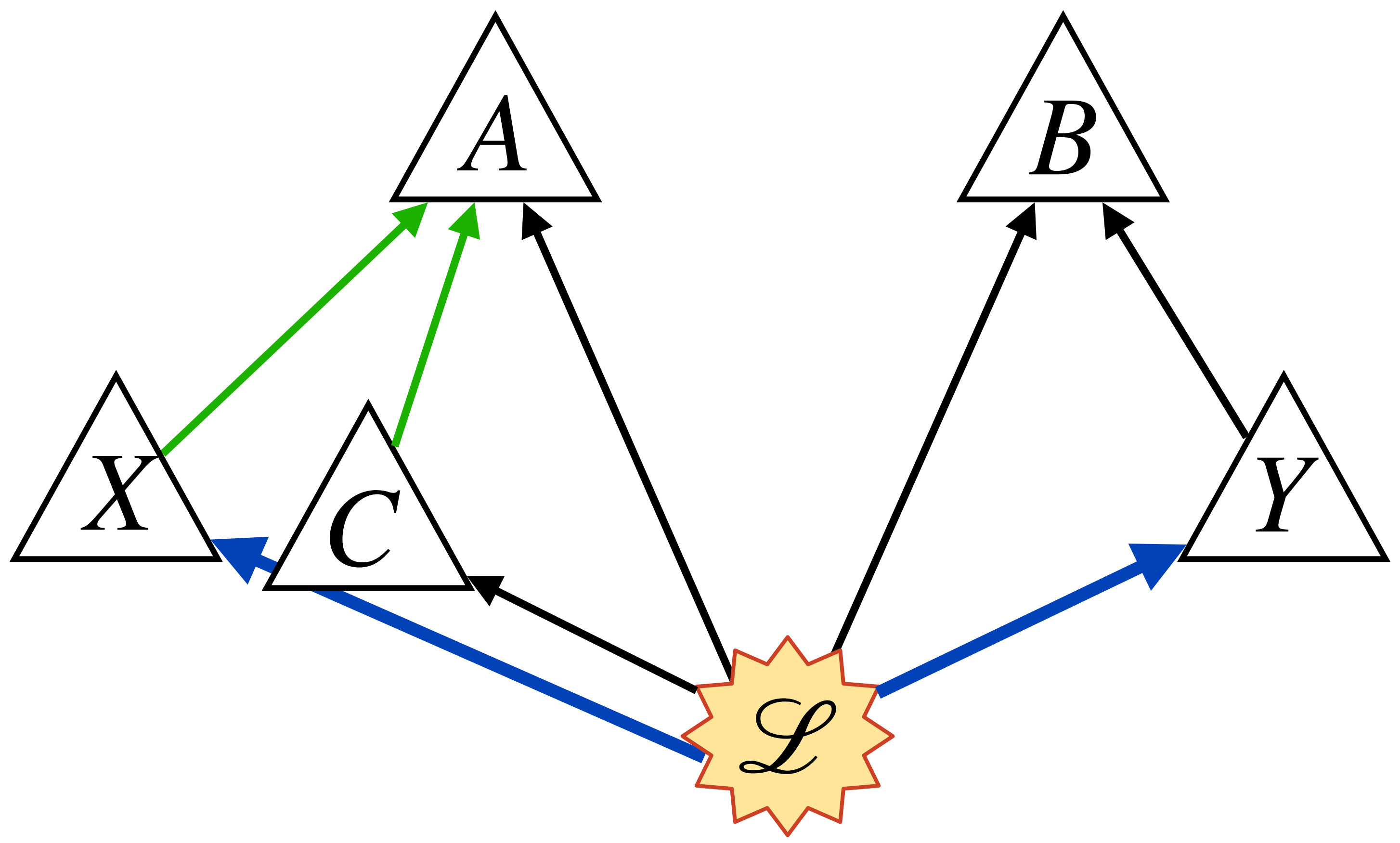
$A \perp Y | X$ $B \perp X | Y$ <u>**LF inequalities**</u>

alternative causal models

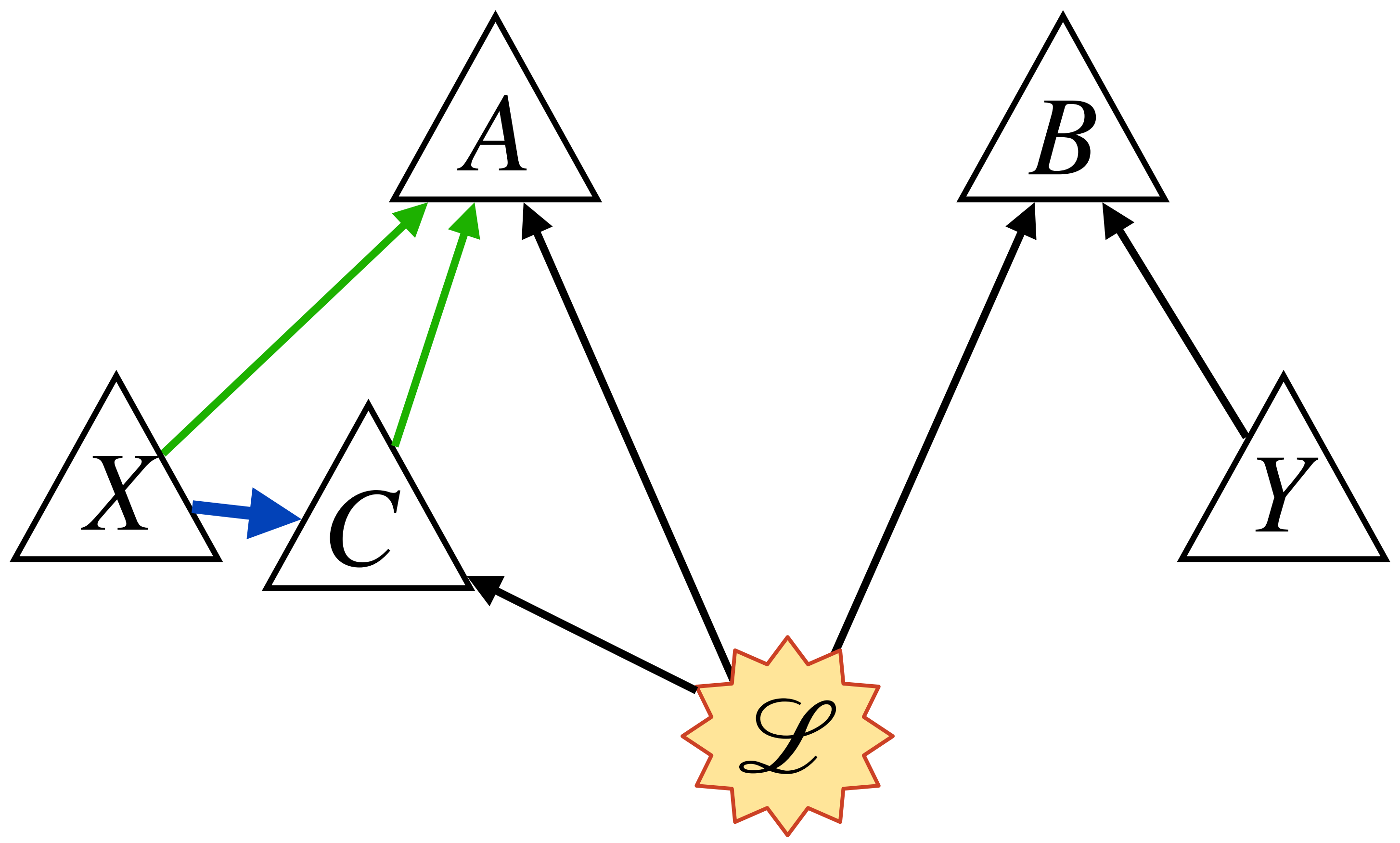
superluminal causation



superdeterminism



retrocausality



allow for LF inequality violations **BUT** in tension with LF assumptions (of course)

AND ALSO *finetuned* explanations

our theorem

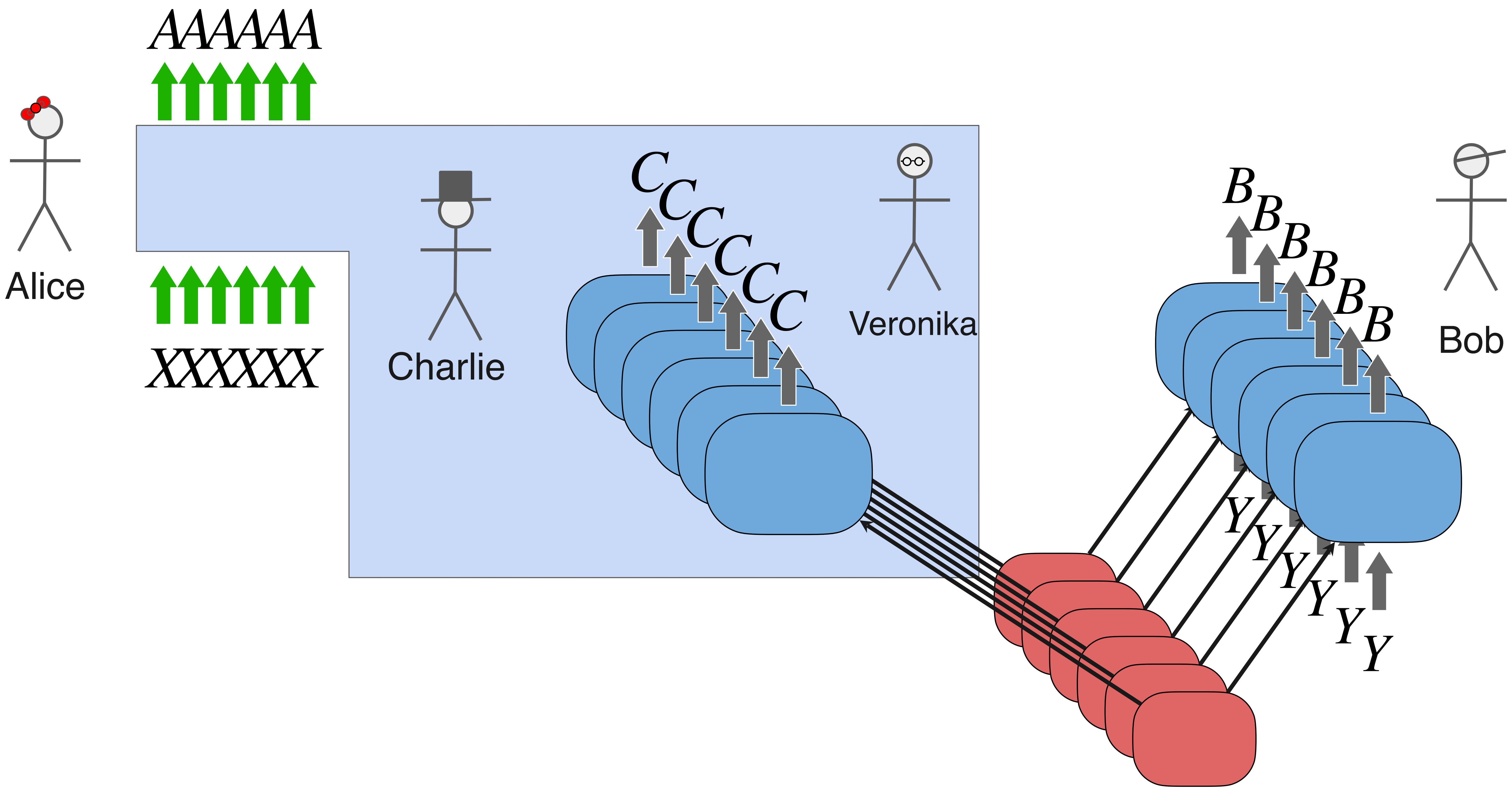
***all* GPT-causal models**
for LF inequality violations are finetuned

(no need for spacelike separation!)

observations		causal structure		observations
$A \perp Y \mid X$	no finetuning	$A \perp_d Y \mid X$	generalised Markov	LF inequalities
$B \perp X \mid Y$	$\Longrightarrow$	$B \perp_d X \mid Y$	$\Longrightarrow$	
$C \perp XY$		$C \perp_d XY$		

post-quantum causal modelling LF scenario

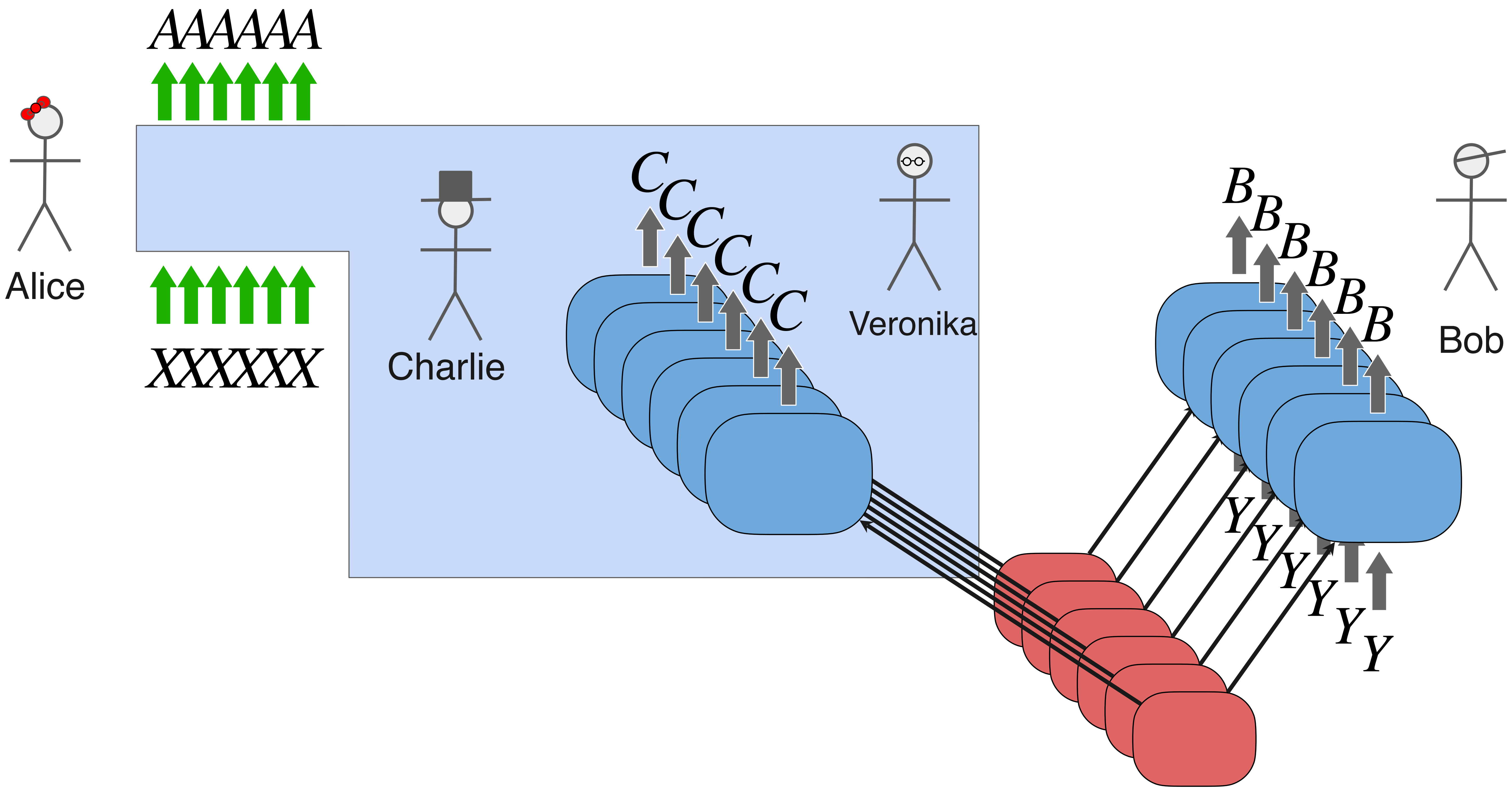
Veronika protocol



$C \perp XY \quad ?$

Veronika Bauman

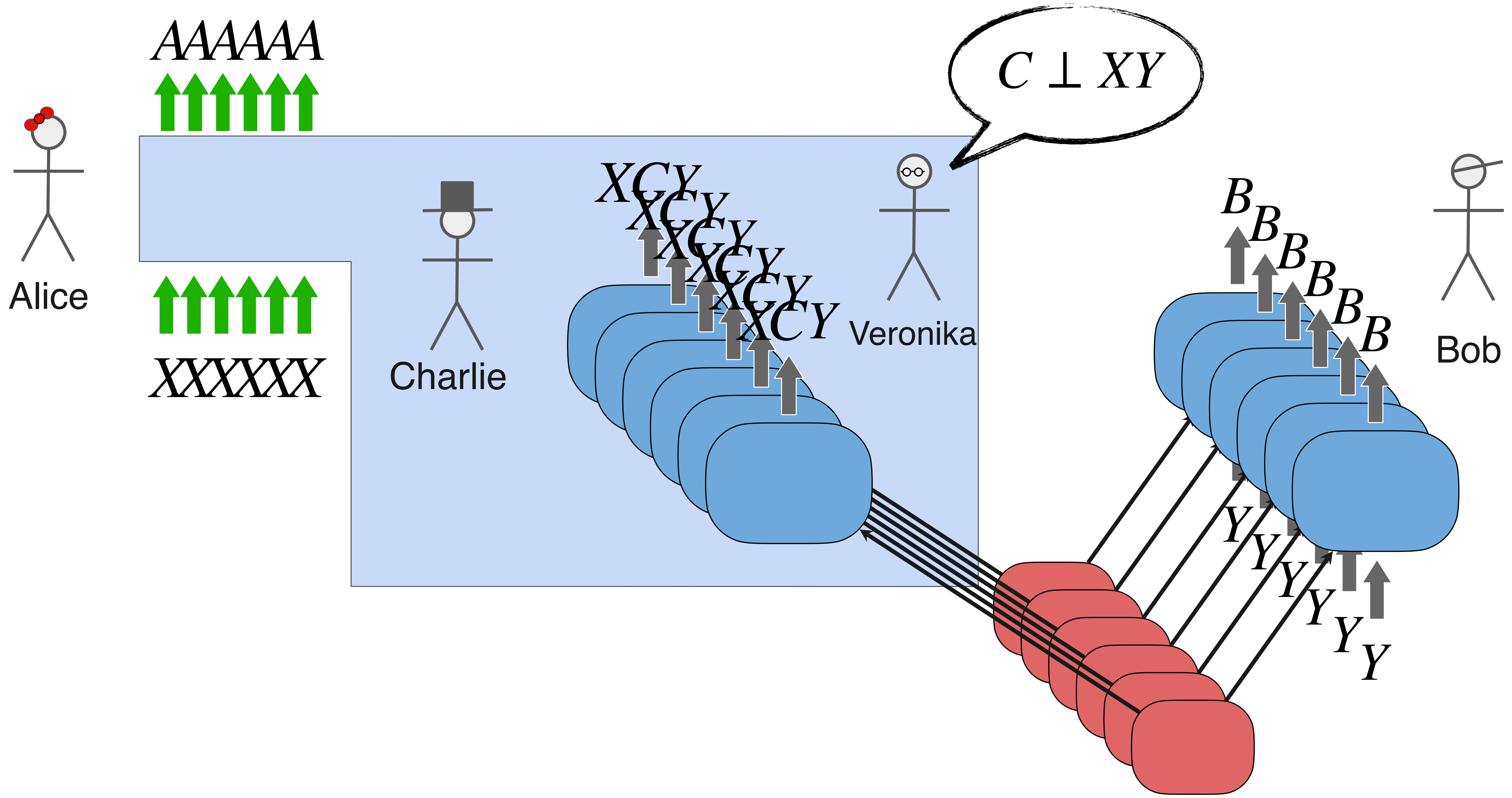
Veronika protocol



$C \perp XY \quad ?$

post-quantum causal modelling LF scenario

Veronika protocol



$C \perp XY$?

our theorem

***all* GPT-causal models**
for LF inequality violations are finetuned

(no need for spacelike separation!)

observations		causal structure		observations
$A \perp Y \mid X$	no finetuning	$A \perp_d Y \mid X$	generalised Markov	LF inequalities
$B \perp X \mid Y$	$\implies$	$B \perp_d X \mid Y$	$\implies$	
$C \perp XY$		$C \perp_d XY$		

our paper

Quantum
2024-09-26, volume 8, page 1485

Relating Wigner's Friend Scenarios to Nonclassical Causal Compatibility, Monogamy Relations, and Fine Tuning

- **LF inequalities as monogamy relations**
- **generalisation past GPT-causal models**
  - d**-sep causal models** $(A \perp_d B|C \implies A \perp B|C)$
  - **cyclic causal models**

Yìlè Yīng

Marina Maciel Ansanelli

Elie Wolfe

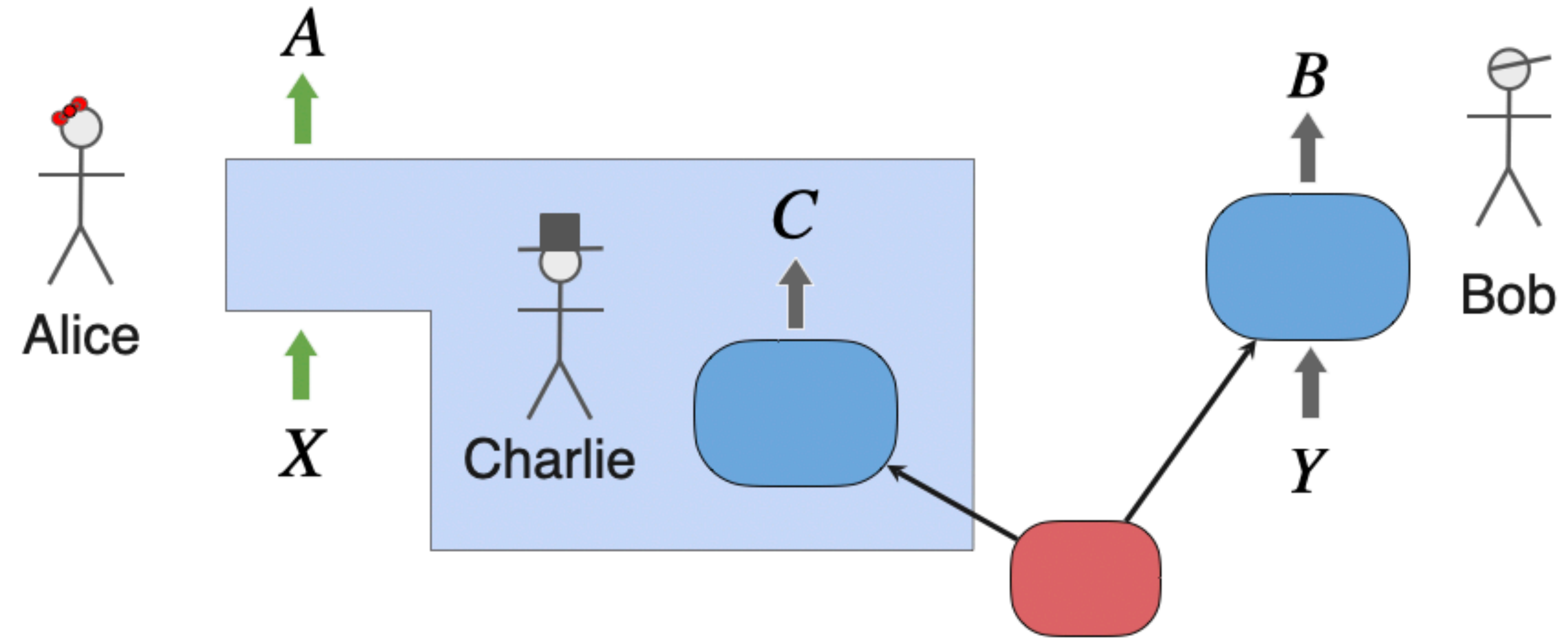
David Schmid

Eric Gama Cavalcanti

giving up
absoluteness of observed events?

giving up absoluteness of observed events

relative facts?



absoluteness of observed events

$$f(ab\,|\,xy) = \sum_c p(abc\,|\,xy)$$

$$p(a = c\,|\,x = 1) = 1$$

arXiv:2402.08727v2 (quant-ph)

[Submitted on 13 Feb 2024 (v1), last revised 20 Jan 2025 (this version, v2)]

On the significance of Wigner's Friend in contexts beyond quantum foundations

Caroline L. Jones, Markus P. Mueller

Open Access Editor's Choice Article

Parallel Lives: A Local-Realistic Interpretation of “Nonlocal” Boxes

by Gilles Brassard [1,2,*] and Paul Raymond-Robichaud [1,*]

Entropy **2019**, *21*(1), 87; https://doi.org/10.3390/e21010087

disturbance

$$p(a = c\,|\,x = 1) \neq 1$$

disturbing Charlie too much

relative facts

$$f(ab\,|\,xy) \neq \sum_c p(abc\,|\,xy)$$

$$p(a = c\,|\,x = 1) = 1$$

interference sign of relational facts

no sense to ask "what was the value of C ?" without actually asking Charlie

interference effects delete information

duplication

$$f(ab\,|\,xy) \neq \sum_c p(abc\,|\,xy)$$

two or more Charlies in the box, no way to unambiguously identify *the* value of C

LF violation due to interference of these two localised worlds thank you for listening

closing remarks

- **EWFS stands to WF like Bell stands to EPR**
- **EWFS even stronger challenge to causal modelling**
    - **is there a further generalisation?**
- **letting go of absoluteness of observed events: what does it mean, exactly?**
- **violations of LF inequalities already happened, but for small systems**
    - **what is a good friend?**
      ---> theory of observers