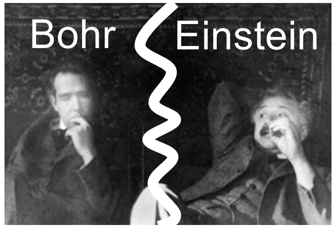
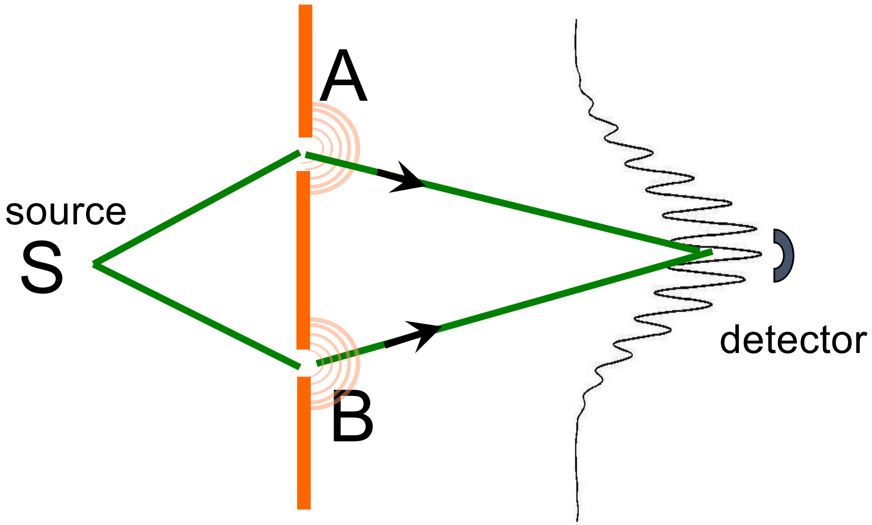
Le lien entre l'interprétation causale (de Broglie-Bohm) et l'interprétation relationelle (Rovelli)

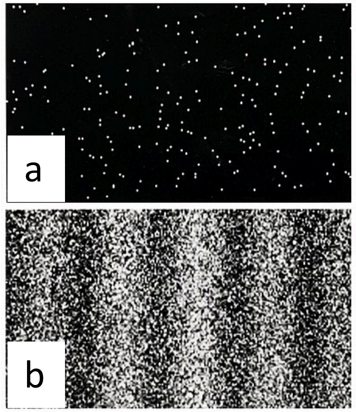
Pouvons nous reconcilier de Broglie et Heisenberg sans magie quantique?

Aurélien Drezet, Institut Néel, CNRS, Grenoble

The fundamental issue: Wave-particle dualism







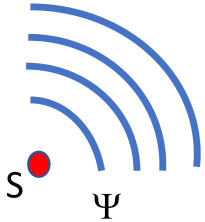
Tonomura et al. (1989)

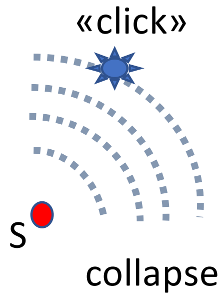
This point is of great logical consequence, since it is only the circumstance that we are presented with a choice of either tracing the path of a particle or observing interference effects, which allows us to escape from the paradoxical necessity of concluding that the behaviour of an electron or a photon should depend on the presence of a slit in the diaphragm through which it could be proved not to pass.

BOHR (1949)

Heisenberg/von Neumann wave function collapse/projection

Einstein's Measurement paradox!!

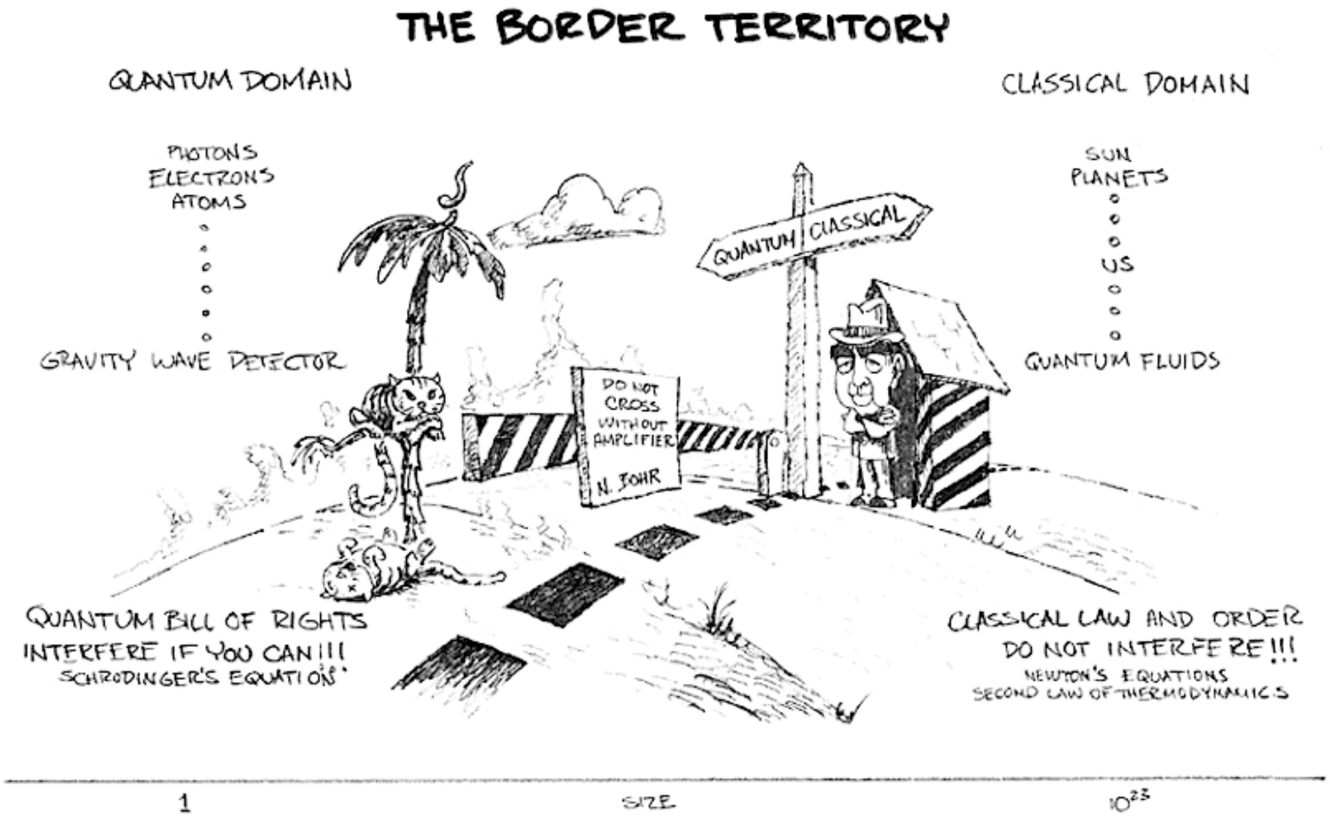




$$i\hbar\frac{d}{dt}|\Psi_t\rangle = \mathcal{H}|\Psi_t\rangle \qquad \langle\mathcal{A}\rangle = Tr[\mathcal{A}|\Psi\rangle\langle\Psi|]$$

- Wave function as a **catalog of potentiality**!
- **No trajectory**
- Genuine **randomness**
- **Measurement = actualization**

The Heisenberg "Cut" - The elusive shifty split

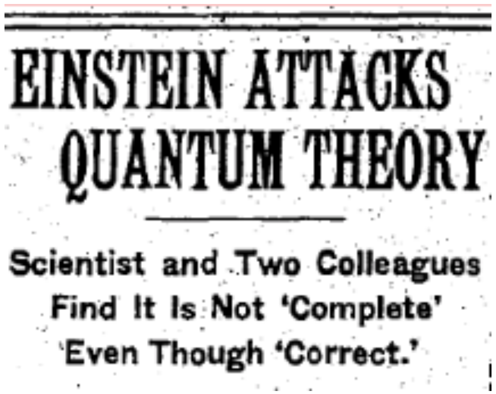


The **classical / quantum boundary** is vaguely defined and **decoherence** doesn't make the job !

Einstein - Against Bohr and quantum 'talmudism'

As for the Talmudist philosopher [Bohr], he couldn't care less about "reality", that scarecrow just good enough to frighten naive souls.
Einstein to Schrödinger (June 1935)

God doesn't play dice



EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

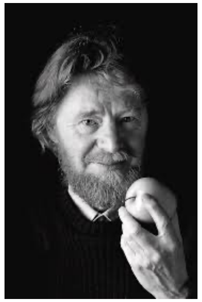
Is the moon there when nobody looks?

Randomness

Locality/completeness

Realism

John Bell - Against 'measurement'



Einstein said **that it is theory which decides what is 'observable'.**

I think he was right - 'observation' is a complicated and theory-laden business. Then that notion should not appear in the *formulation* of fundamental theory.

Information? Whose information? Information about *what?*

An alternative path:
The pilot wave theory
de Broglie (1927) - Bohm (1952)

DE BROGLIE

BOHM

Copenhagen-magic

Pilot wave-determinism

The core of the dBB model

$$i\partial_t \Psi(x,t) = -\frac{\Delta}{2m}\Psi(x,t) + V(x,t)\Psi(x,t)$$

$$\Psi(x,t) = a(x,t)e^{iS(x,t)}$$

Particle velocity:
(guidance law)

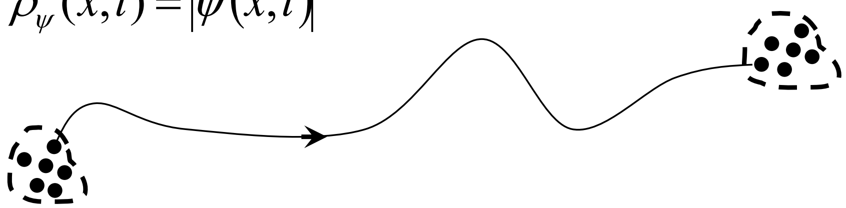
$$\vec{v}_\psi(x(t),t) = \vec{\nabla} S(x(t),t)/m$$

dBB-Newton law:

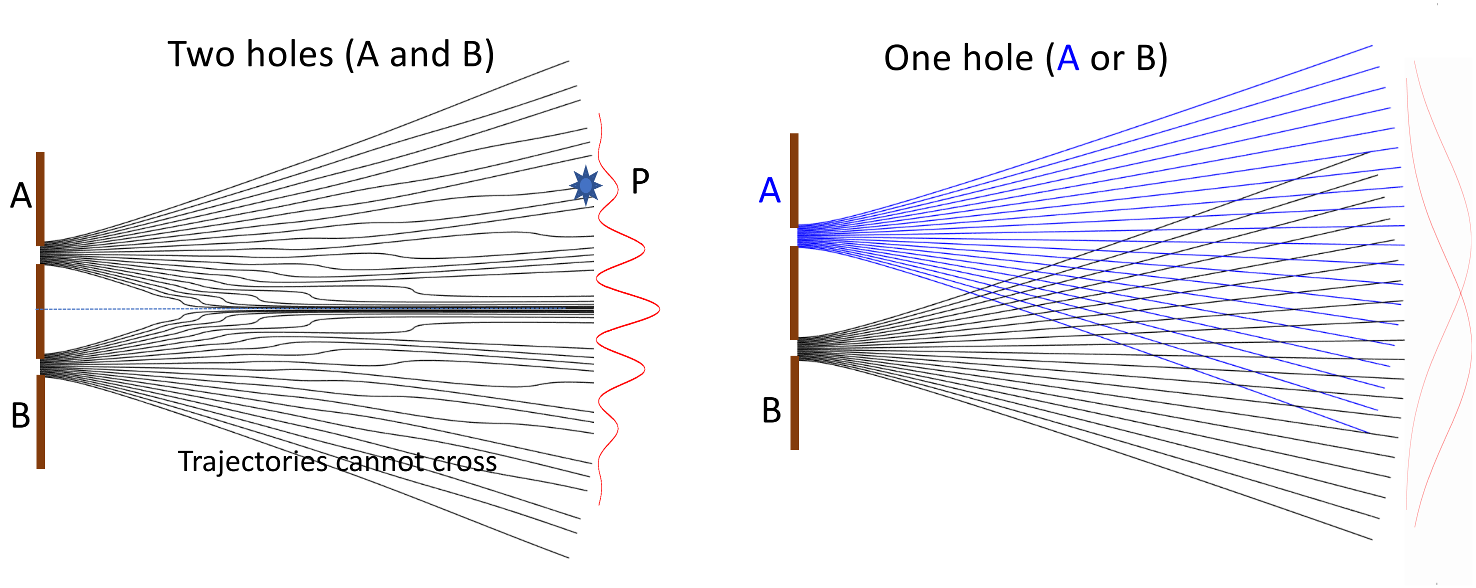
$$m\frac{d}{dt}\vec{v}_\psi(x(t),t) = -\vec{\nabla} V(x(t),t) - \vec{\nabla} Q_\psi(x(t),t)$$

Born's law (quantum equilibrium):

$$\rho_\psi(x,t) = |\psi(x,t)|^2$$



Explaining wave-particle duality with the dBB theory



- Deterministic and contextual and reproduces QM statistical predictions

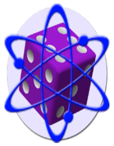
- **Measurements** must be interpreted afterwards (not with classical prejudices)

  If we detect the particle at P we know it came from A

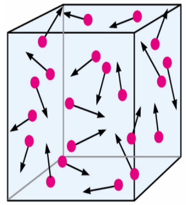
  → We have both Interference and path information

Important issues answered in the dBB framework

A) Can we complete quantum mechanics?

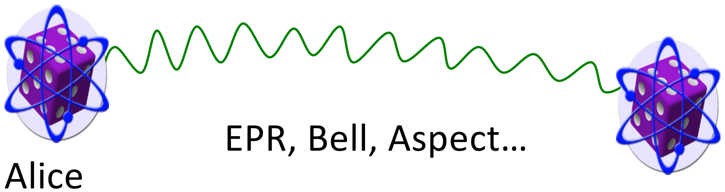


Genuine randomness
(MQ complete)



Hidden variables
(MQ incomplete)

A) Can we conciliate quantum mechanics and relativity ?



Alice

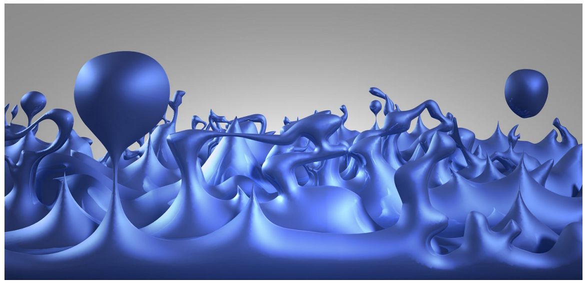
EPR, Bell, Aspect…

Nonlocality-Contextuality

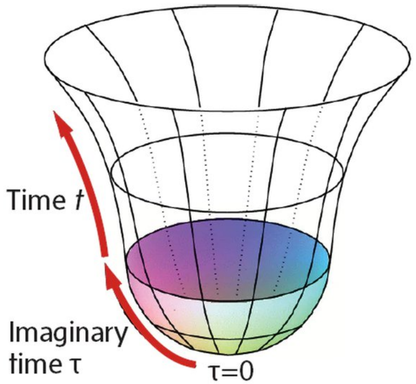
Bob

Quantum Gravity/Cosmology and the Universal wave-function

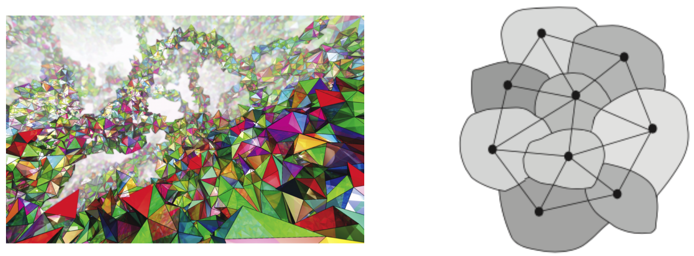
$$i\hbar\frac{d}{dt}\Psi[h_{ij},\phi,...] = \mathcal{H}\Psi[h_{ij},\phi,...] = 0$$



Quantum foam (Wheeler-DeWitt)



No boundary condition
(Hawking-Hartle)

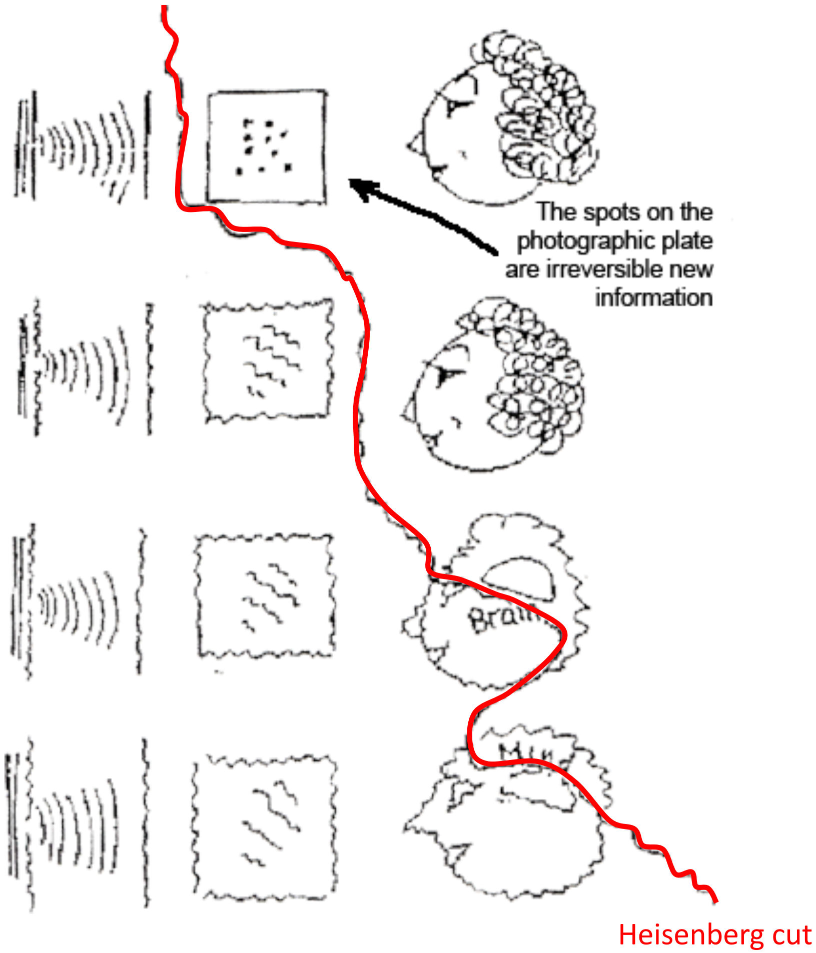


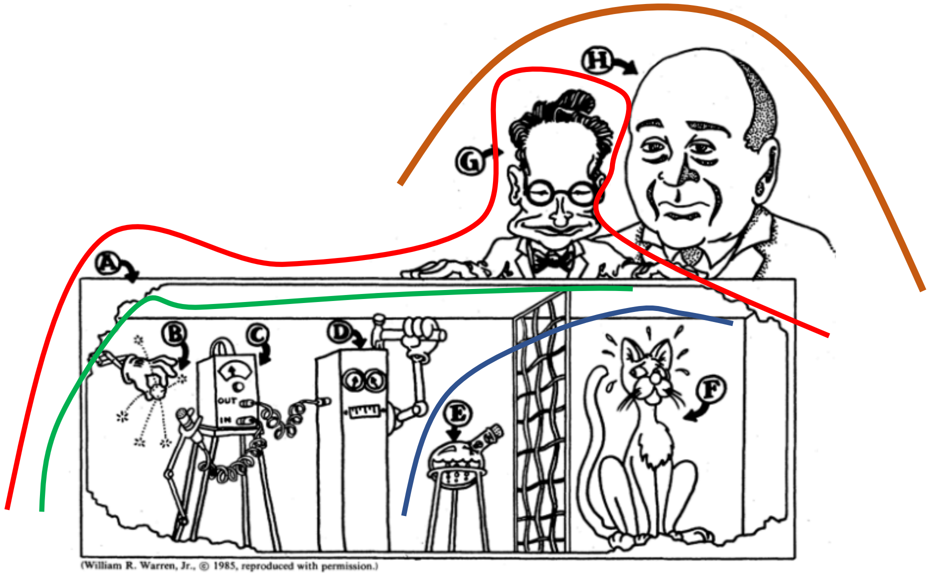
Loop Quantum Gravity
(Ashtekar-Rovelli-Smolin)

Quantum Gravity/Cosmology and the problem of the observer

- **Many-worlds - Relative state** [Everett, DeWitt]
- **Consistent (Decoherent) histories** [Gell-Mann, Hartle]
- **Relational quantum mechanics** [Rovelli]
- **Bohmian mechanics** [Vink, Valentini, Struyve]

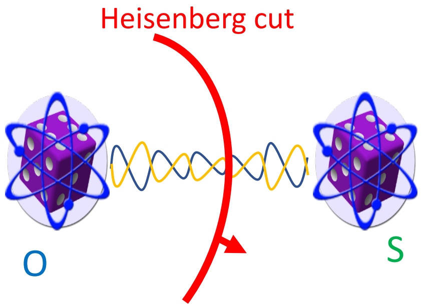
Von Neumann infinite regression and The Wigner friend problem





Relational quantum mechanics (RQM)- the perspectival approach

1° Everything must be quantum
2° In RQM we consider description of subsystem S from the perspective of subsystem O



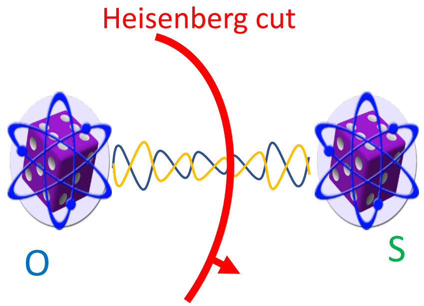
$$|\Psi_{SO}\rangle = \iint dx_S dx_O \psi(x_S, x_O, t)|x_S\rangle \otimes |x_O\rangle$$

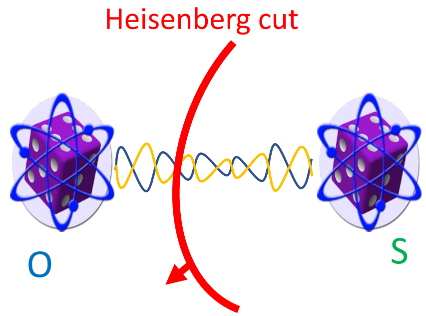
Observer (pointer) variables are classical (actualized)

$$|\Psi_{SO}\rangle = \iint dx_S dp_O \psi'(x_S, p_O, t)|x_S\rangle \otimes |p_O\rangle$$

What are the good pointer variables ? (**basis problem**)

Relational quantum mechanics (RQM)- the perspectival approach





$$\hat{\rho}_{S|O}^{(red.)} = \mathrm{Tr}_O[\hat{\rho}_{SO}] = \mathrm{Tr}_O[|\Psi_{SO}\rangle\langle\Psi_{SO}|]$$
$$= \iiint dx_S dx'_S dx_0 \psi^*(x_S, x_O, t)\psi(x'_S, x_O, t)|x'_S\rangle\langle x_S|$$
$$= \iiint dx_S dx'_S dp_0 \psi'^*(x_S, p_O, t)\psi'(x'_S, p_O, t)|x'_S\rangle\langle x_S|$$

$$\hat{\rho}_{O|S}^{(red.)} = \mathrm{Tr}_S[\hat{\rho}_{SO}]].$$

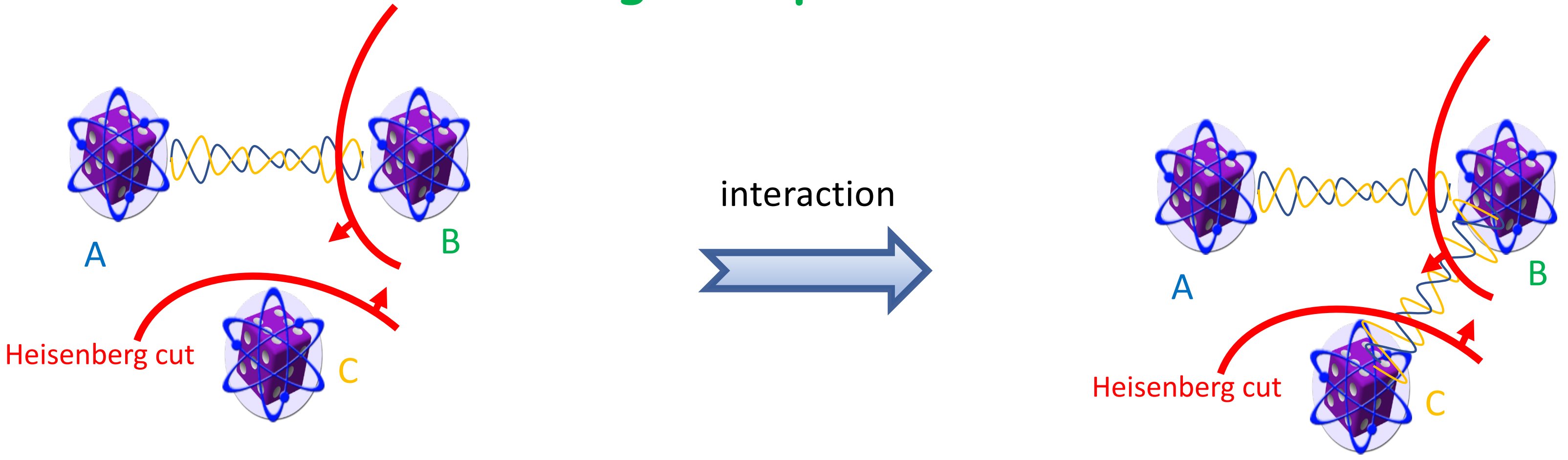
...

Independent of the basis

$$\langle\hat{A}_S\rangle = \mathrm{Tr}_{SO}[\hat{A}_S\hat{\rho}_{SO}] = \mathrm{Tr}_S[\hat{A}_S\hat{\rho}_{S|O}^{(red.)}]$$

- **Any** subsystem can be an observer (**symmetry**)
- '**Facts**' are relative to subsystems
- No **self measurement**

Wigner's paradox debunked



$$|\Psi_{AB}\rangle|\emptyset_C\rangle = \frac{|\uparrow_A 0_B\rangle + |\downarrow_A 1_B\rangle}{\sqrt{2}}|\emptyset_C\rangle$$

$$|\Psi_{ABC}\rangle = \frac{|\uparrow_A 0_B \spadesuit_C\rangle + |\downarrow_A 1_B \heartsuit_C\rangle}{\sqrt{2}}$$

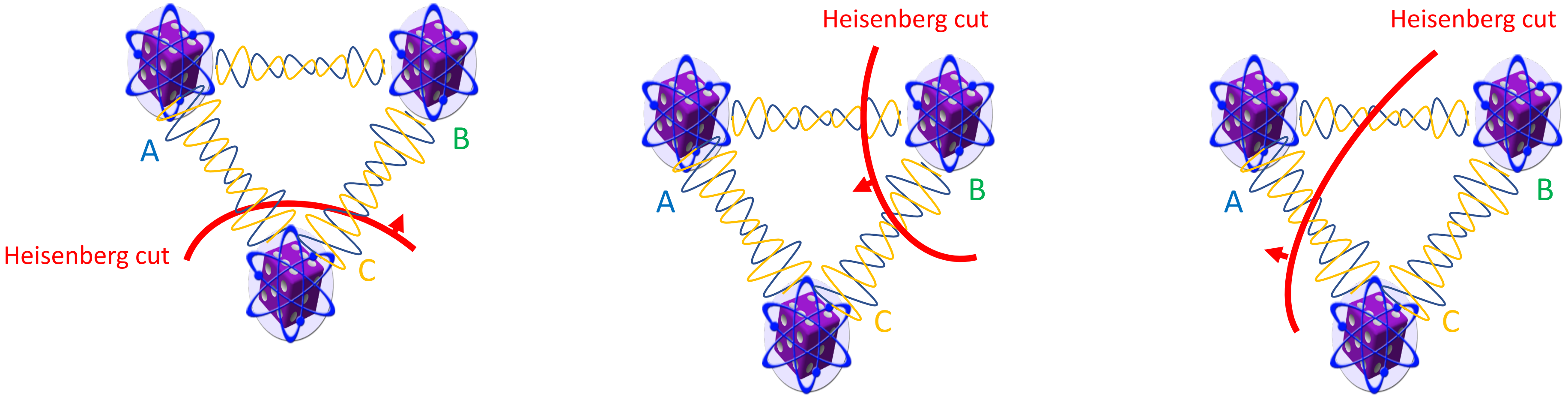
$$\hat{\rho}^{(red.)}_{AC|B} = \frac{1}{2}(|\uparrow_A\rangle\langle\uparrow_A| + |\downarrow_A\rangle\langle\downarrow_A|) \otimes |\emptyset_C\rangle\langle\emptyset_C|$$

$$\hat{\rho}^{(red.)}_{AB|C} = \frac{1}{2}|\uparrow_A 0_B\rangle\langle\uparrow_A 0_B| + \frac{1}{2}|\downarrow_A 1_B\rangle\langle\downarrow_A 1_B|$$

$$\hat{\rho}^{(red.)}_{AB|C} = |\Psi_{AB}\rangle\langle\Psi_{AB}|$$

No (Wigner) paradox!: Answers queries by Brukner and Zukowski [Bohrians], Pienaar [QBism]…

RQM is mathematically unambiguous and self-consistent



$$\hat{\rho}^{(red.)}_{AB|C} = \mathrm{Tr}_C[\hat{\rho}_{ABC}]$$

$$\hat{\rho}^{(red.)}_{AC|B} = \mathrm{Tr}_B[\hat{\rho}_{ABC}]$$

$$\hat{\rho}^{(red.)}_{A|BC} = \mathrm{Tr}_{BC}[\hat{\rho}_{ABC}]$$

...

*RQM is nothing else than a **minimal extension** of the textbook Copenhagen interpretation, based on the realisation that **any physical system** can play the role of the ''**observer**'' and **any interaction** can play the role of a ''**measurement**''.*

Rovelli

But what is an interaction ?

There are no properties outside of interactions

Rovelli

$$|\Psi_{AB}\rangle|\emptyset_C\rangle = \frac{|\uparrow_A 0_B\rangle + |\downarrow_A 1_B\rangle}{\sqrt{2}}|\emptyset_C\rangle$$

$$\hat{\rho}^{(red.)}_{AB|C} = |\Psi_{AB}\rangle\langle\Psi_{AB}|$$

interaction

$$\mathcal{U}_{int}(t) = e^{-i\mathcal{H}_{int}t}$$

$$|\Psi_{ABC}\rangle = \frac{|\uparrow_A 0_B \spadesuit_C\rangle + |\downarrow_A 1_B \heartsuit_C\rangle}{\sqrt{2}}$$

$$\hat{\rho}^{(red.)}_{AB|C} = \frac{1}{2}|\uparrow_A 0_B\rangle\langle\uparrow_A 0_B| + \frac{1}{2}|\downarrow_A 1_B\rangle\langle\downarrow_A 1_B|$$

Be aware: Vagueness and magical forces are sneaking !

Remember :

Information? Whose information? Information about what?

Bell

It cries for an explanation (ontology) !
→ Hidden variables (dBB)

$$\Psi_{ABC}(x_A, y_B, z_C, t) \Longrightarrow \Psi_{AB|C}(x_A, y_B, t) =_{def} \Psi_{ABC}(x_A, y_B, \boxed{Z_C(t)}, t)$$

Wave-function

Conditional Wave-function

(Dürr, Goldstein, Zanghì)

dBB

There are no relations without relata…

Which interpretation for the XXIst century?

→ **de Broglie-Bohm (relata)**
→ **RQM (relations)**

- No black quantum magic
- No vagueness
- No measurement paradox
- Ontological clarity (determinism)
  = **natural completion** of QM
- Contextual and non-local
- Recovers RQM at the **epistemic level**

Thank you for listening !

So much to do !

Soliton theory of dBB particles

Bohmian QFT!

Quantum cosmology !

Relativistic dBB theory!

Contact me!

Physics!

Philosophy!

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