Beyond the Rindler Horizon

An Interpretive Quantum Puzzle for Students of Relativity

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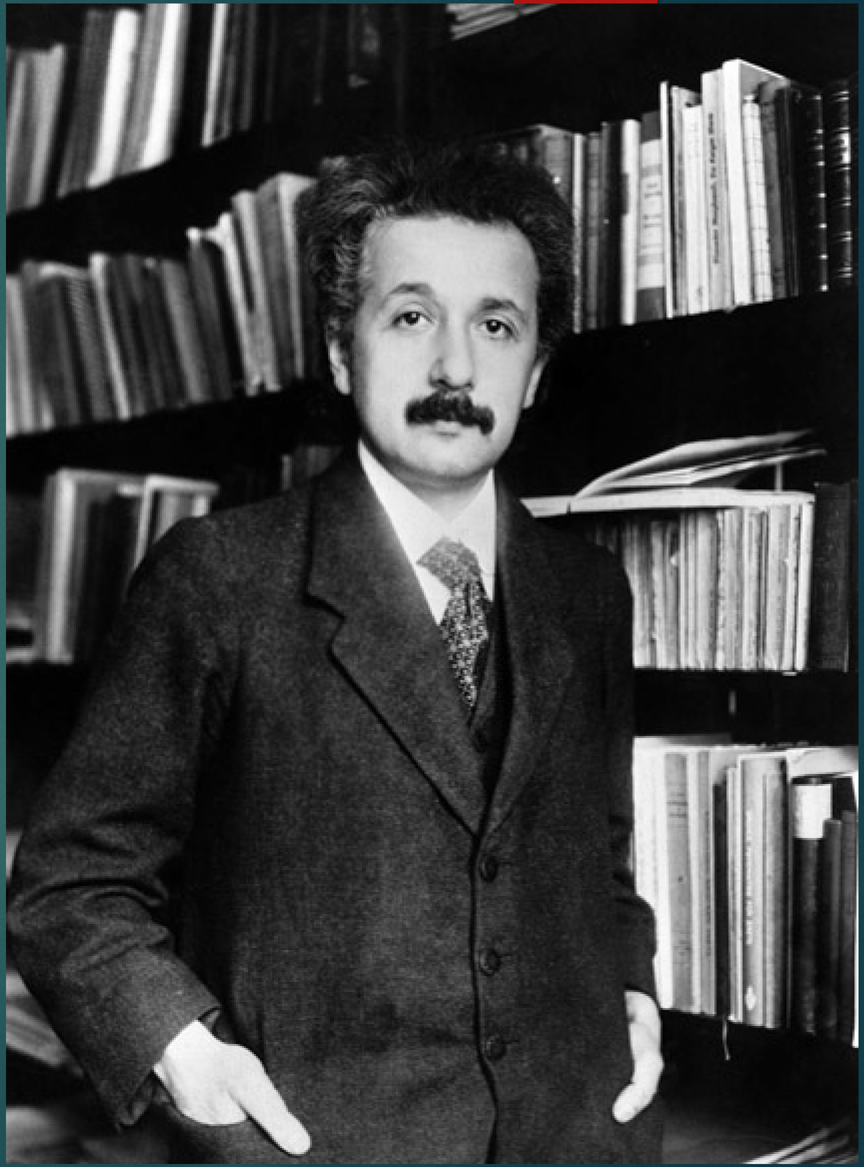
Motivation

- Students learn quantum mechanics and relativity as separate, self-consistent frameworks—but they rarely see where they come into tension.
- This talk aims to:
  - Illustrate a classroom-ready scenario where the tension between relativity and quantum mechanics becomes unavoidable
  - Motivate classroom discussion beyond standard EPR paradox and Bell's Theorem
  - Keep the mathematics and physics within the scope of upper-level undergraduates
  - Offer a pathway toward exploring different interpretive theories of quantum mechanics
- What this talk is:
  - An opportunity to motivate students toward a deeper understanding of both quantum theory and relativity.
- What this talk isn't:
  - A challenge to the operational success of quantum mechanics

Setting the Stage

- The Teaching Gap:
  - Upper-level undergraduates in physics typically take quantum mechanics their junior or senior year
  - Dedicated upper-level course in special & general relativity is typically offered as a separate elective
  - Undergraduates are often not given the chance to delve deeply into the tensions that can arise between the two subjects
- Where this talk comes in:
  - Students in relativity courses typically have already taken quantum mechanics
  - This would be appropriate to introduce to students in their relativity course after introducing them to acceleration & the equivalence principle
  - Opens the doors to thoughtful discussions on different interpretive theories of quantum mechanics and how they interact with relativity



Outline of Talk

- Quantum Mechanics (Brief Overview)
  - Measurement & Wavefunction
  - Spin & Entanglement
- Relativity
  - Accelerated Observers
  - Rindler Coordinates
- The Core Paradox
  - Spin singlet in reflected Rindler frames
- Interpretational Implications

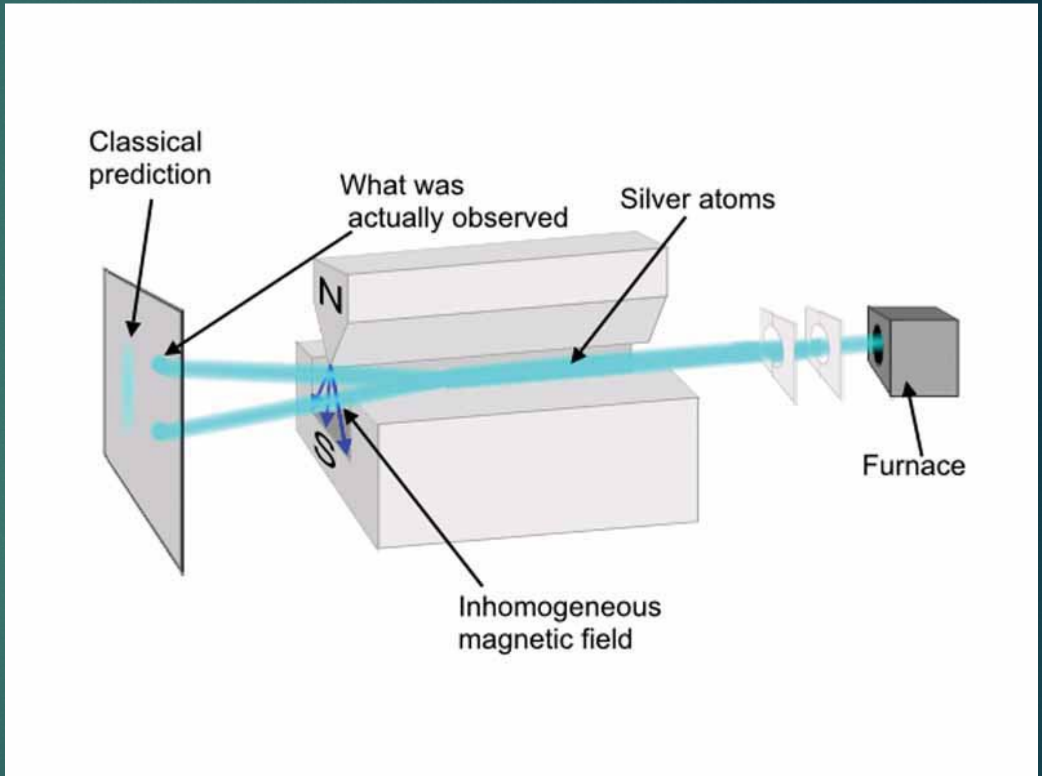
Measurement & Wavefunction Collapse: The Double-Slit Experiment

- The wavefunction encodes probabilistic predictions for measurement outcomes.
- Individual detections are localized, while repeated trials reveal a statistical distribution.
- Different observers may describe the system differently, but they must agree on the observed outcomes and their statistical correlations.

$$P(R) = \int_R |\psi(x, y)|^2 \, dx \, dy$$

Spin & Sequential Measurements

- Elementary particles carry an intrinsic quantized angular momentum known as spin
  - Electrons are spin ½ particles, and take on values of +½ or -½ along a measured direction
- Spin can be only measured along one spatial dimension
  - Subsequent measurements of spin along different axes destroys information about the previous measurement
  - Key takeaway: ordering matters!



The Stern-Gerlach experiment was the first to demonstrate that atomic spin is quantized

The Spin Singlet State

- Quantum entanglement: a system of particles (or photons) described by a shared quantum state
  - Individual particles in the system cannot be described independently from each other
  - Measurement of the quantum state of one particle determines the quantum state of the other, thus altering the state of the system as a whole
- Consider a pair of electrons A and B in a spin singlet state
  - Measurements along the same axis are anti-correlated
  - Changing measurement order destroys correlation
  - Thus, predicted correlations depend on the order of measurement
    - E.g. If $x \prec y$ for A, and $y \prec x$ for B, there will be no correlation

Dirac notation of a spin singlet state:

$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Measurement of one particle's spin direction along an axis will collapse the system into one of the following states:

$$|\uparrow\rangle_A\,|\downarrow\rangle_B \quad \text{or} \quad |\downarrow\rangle_A\,|\uparrow\rangle_B$$

where A and B subscripts denote the individual states of particles A and B

Acceleration & Rindler Coordinates

- The Rindler coordinates for a worldline maintaining constant local acceleration are given by hyperbolic curves:

$$t = r\sinh(a\omega), \;\; x = r\cosh(a\omega)$$

with metric:

$$ds^2 = -(ar)^2 d\omega^2 + dr^2 + dy^2 + dz^2$$

- Here x and t are the Minkowsk space and time coordinates as measured by the stationary observer.
- The hyperbolic radius r and angle $a\omega$ trace out the spacelike and timelike coordinates (r, ω) of the Rindler observer undergoing acceleration a
- The region of positive r and ω for the accelerating observer is fully contained in the flat spacetime region shown on the right

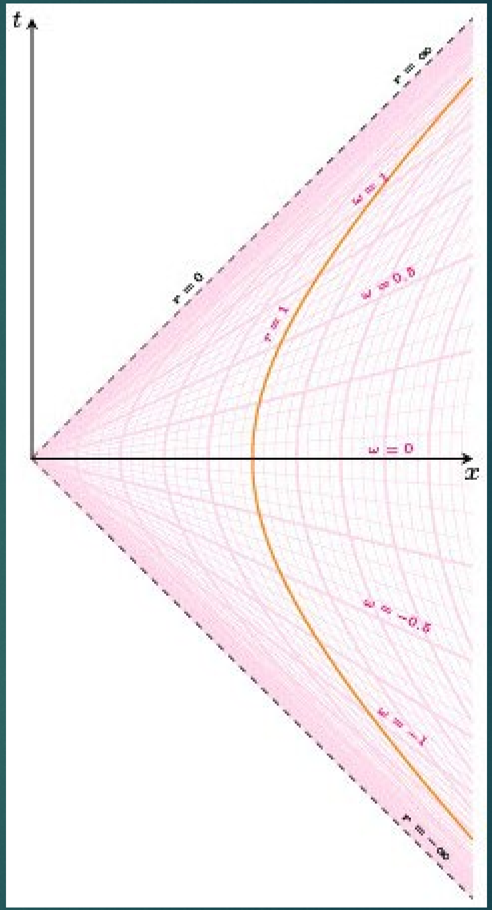


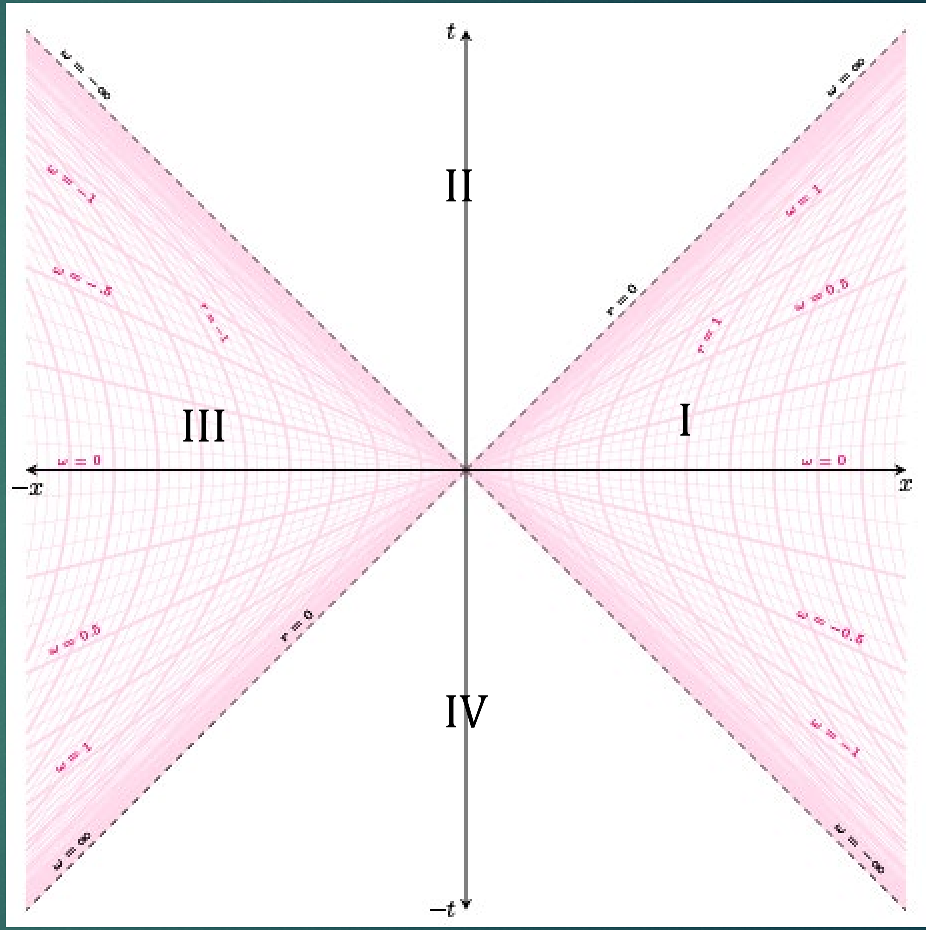
Diagram of the Rindler coordinates for an accelerating observer with local acceleration $a = 1$. The dashed line represents the Rindler Horizon

Extending the Rindler Coordinates

- The hyperbolic radius r in Rindler coordinates represents the spatial coordinate x' for a boosted observer at a particular moment in time
- We can thus naturally extend the r coordinate to include negative values, just as we would be able to do with a Lorentz-boosted observer
- Differentiation of the Minkowski time coordinate t with respect to the accelerating observer's time coordinate ω along each hyperbolic curve yields the following:

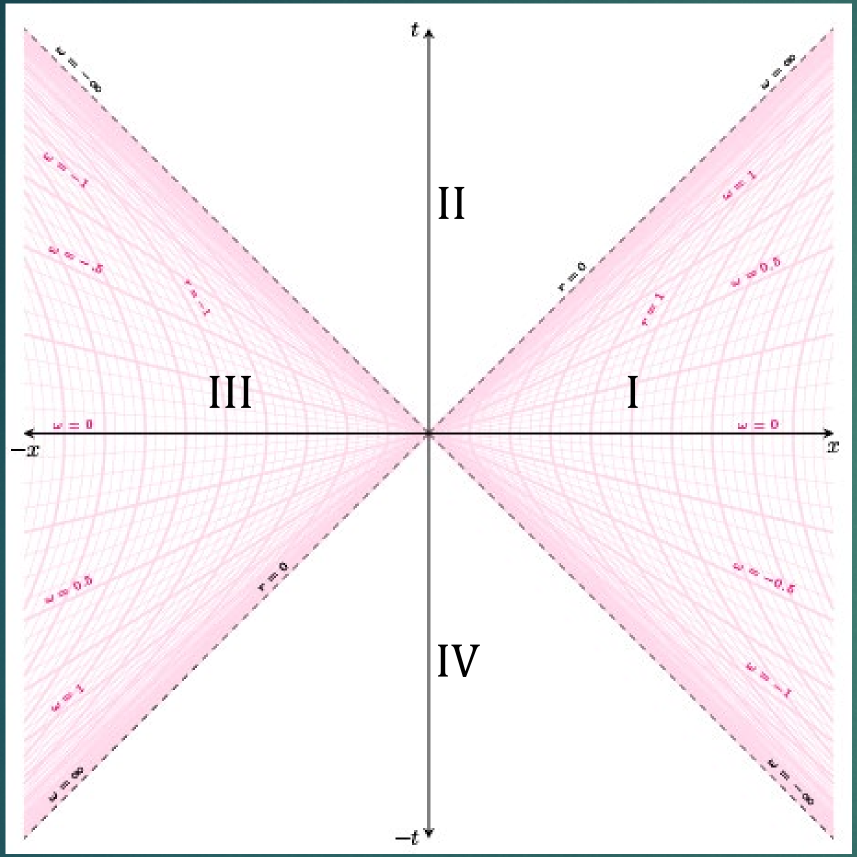
$$\frac{dt}{d\omega} = r\cosh(a\omega)$$

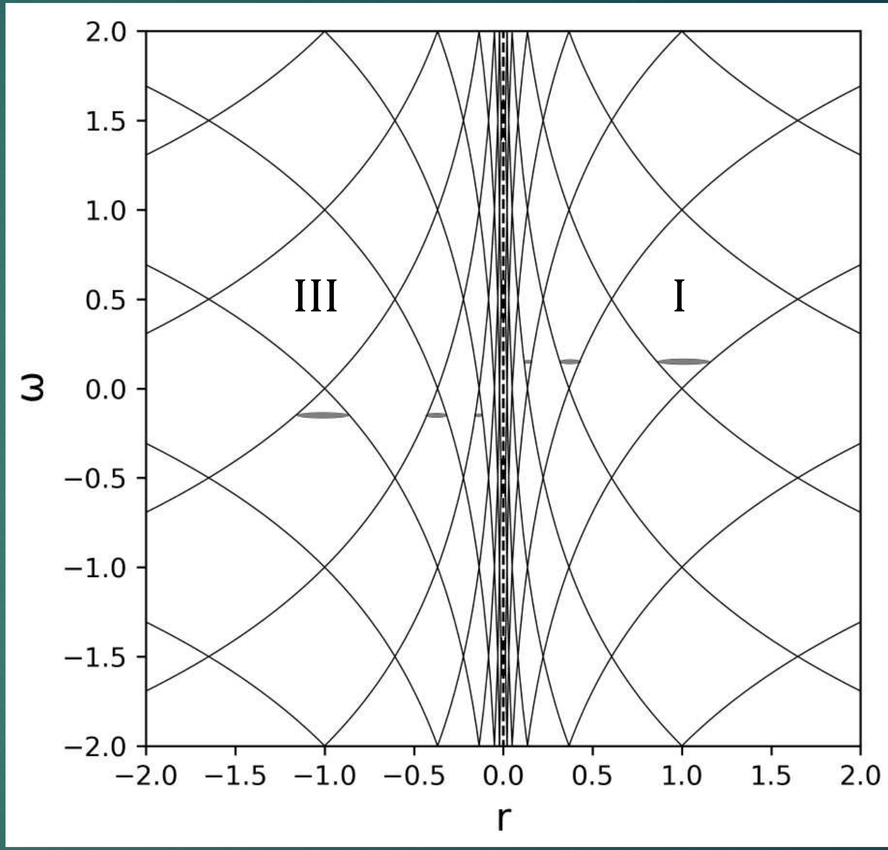
- Note that for negative values of r, the resulting differential goes negative
  - **Accelerating observers assign different global time orderings across the Rindler Horizon**



Extended Minkowski diagram of the Rindler coordinates. The left wedge (region III) represents the spacelike extension of the accelerating observer in region I

Extending the Rindler Coordinates

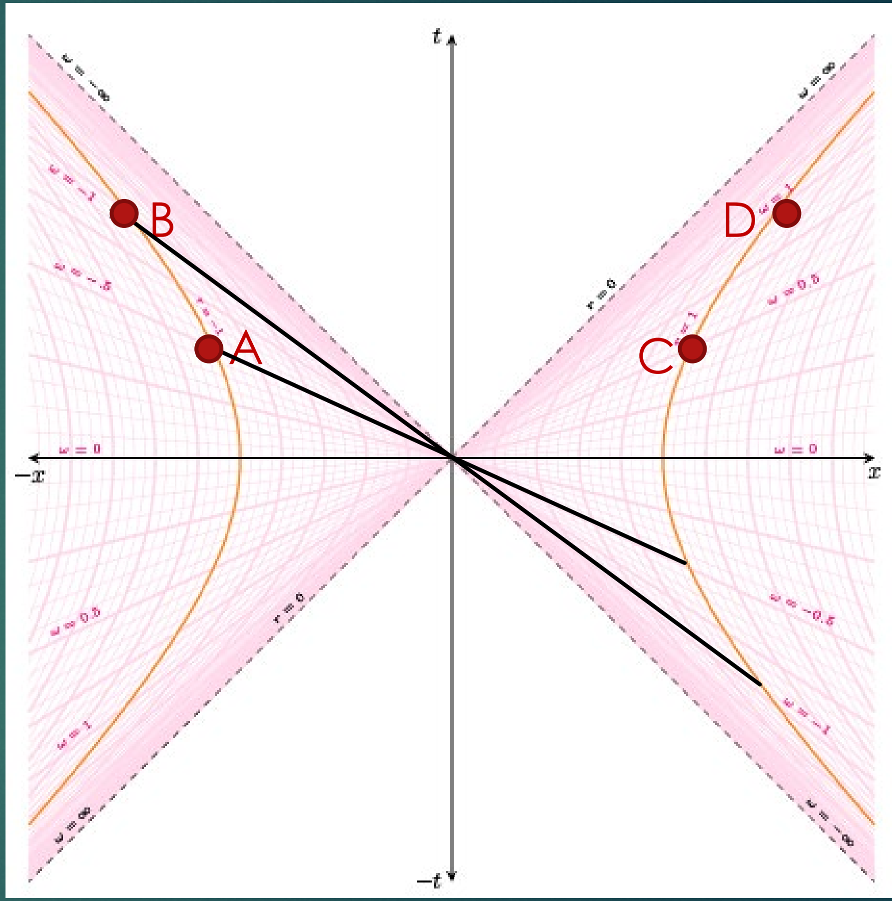




Hyperbolic curves of Rindler coordinates as seen in the stationary inertial frame (left) which define the lines of constant r in the accelerating frame (right). Note that the forward local Minkowski light cones point *backward* in region III.

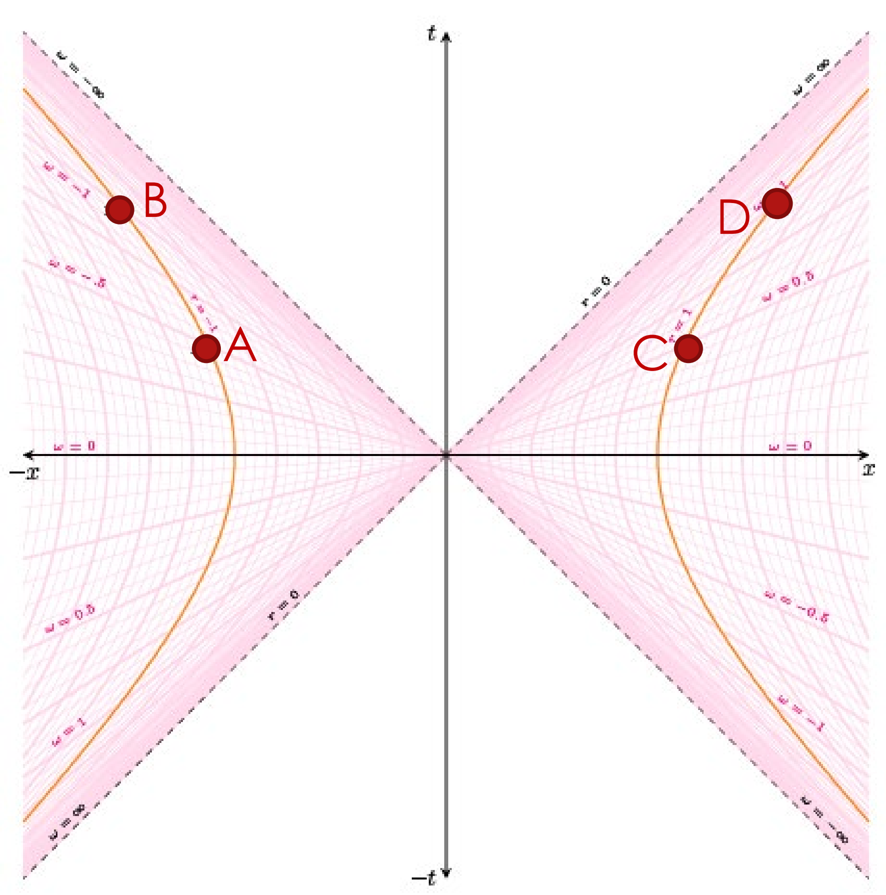
The Core Paradox

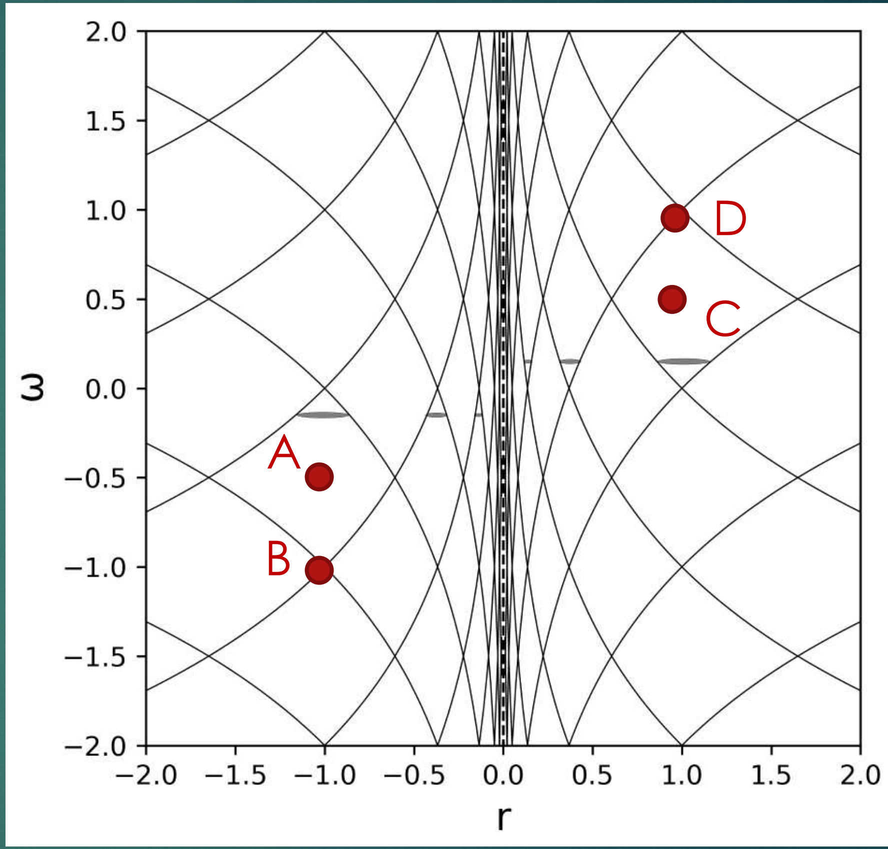
- Consider the spin singlet state
- Embed each particle along a worldline in regions I and III respectively
- Measure events A, B (particle 1) & C, D (particle 2):
  - A: x-direction
  - B: y-direction
  - C: x-direction
  - D: y-direction
- Each observer assigns a different ordering to the distant measurements
- Because measurement order affects outcomes, they predict different correlations



Projection of the Region III worldline's measurement sequence onto the Region I worldline shows event B occurring first

Nonlocal Collapse Interpretation





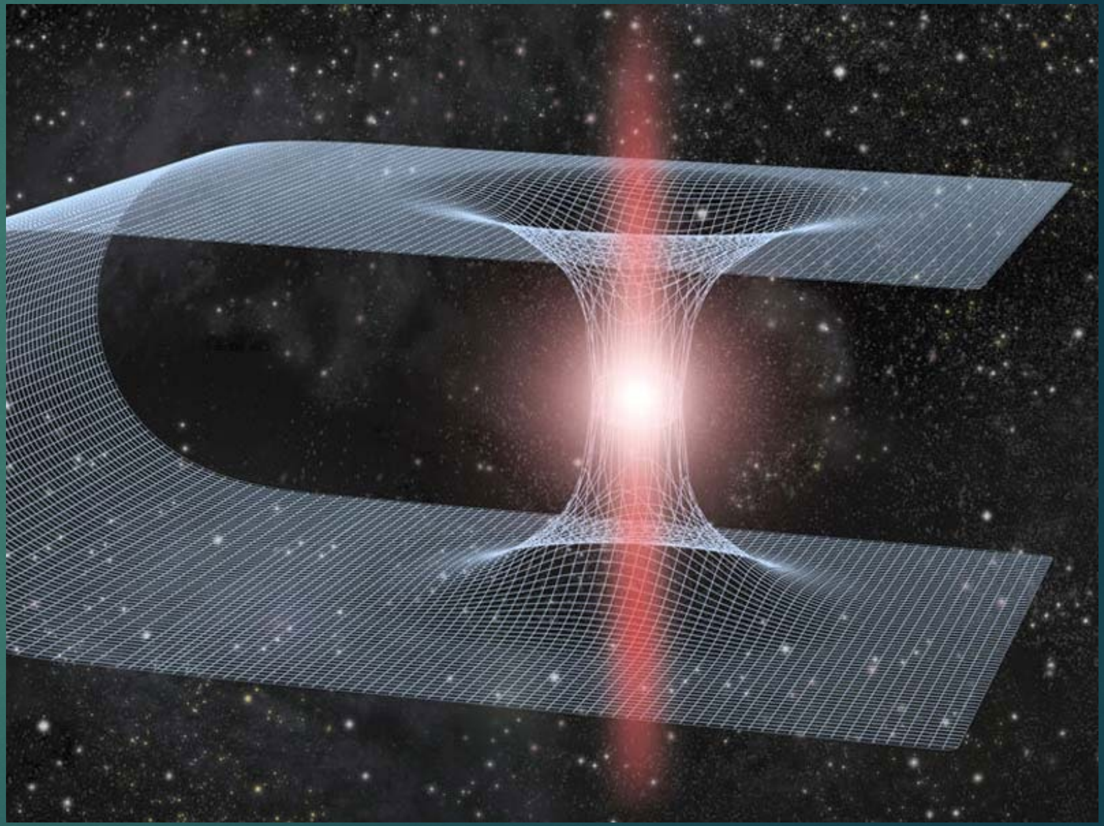
From the perspective of particle 2, event B takes place before event A. Particle 1's frame shows a similar effect, with event D taking place before event C. A nonlocal collapse interpretation cannot resolve the difference in the predicted experimental outcomes between the inertial & accelerating frames. Thus, **there is no observer-independent way to assign the collapse.**

Exploring Other Interpretations

- Relational Quantum Mechanics (Rovelli):
  - Can relational consistency be maintained for accelerating frames?
  - Does relativity constrain global consistency (and not the other way around)?
- Many Worlds (Everett):
  - How is branching defined when observers disagree on ordering?
- Two State Vector Formalism (Aharonov)
  - Does backward time evolution resolve the ambiguity?
- Indivisible Stochastic Processes (Barandes)
  - Can ordering ambiguity be resolved under “causal locality”?

Could Relativity Itself Resolve This?

- For example, ER=EPR (Maldacena & Susskind):
  - In AdS/CFT, entanglement is handled via Einstein-Rosen Bridges (a.k.a. wormholes)
  - Wormhole is connected by a string in AdS
  - Wormhole must be non-traversable (cannot violate no-signaling)
- Such a description goes well beyond a normal intro course in general relativity (but makes a great segue into GR!)
  - Requires a holographic (AdS/CFT) framework, not a standard 4D spacetime description



Final Takeaway

This paradox provides a classroom-accessible way to show that quantum measurement and relativity cannot be consistently combined without addressing interpretation.

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