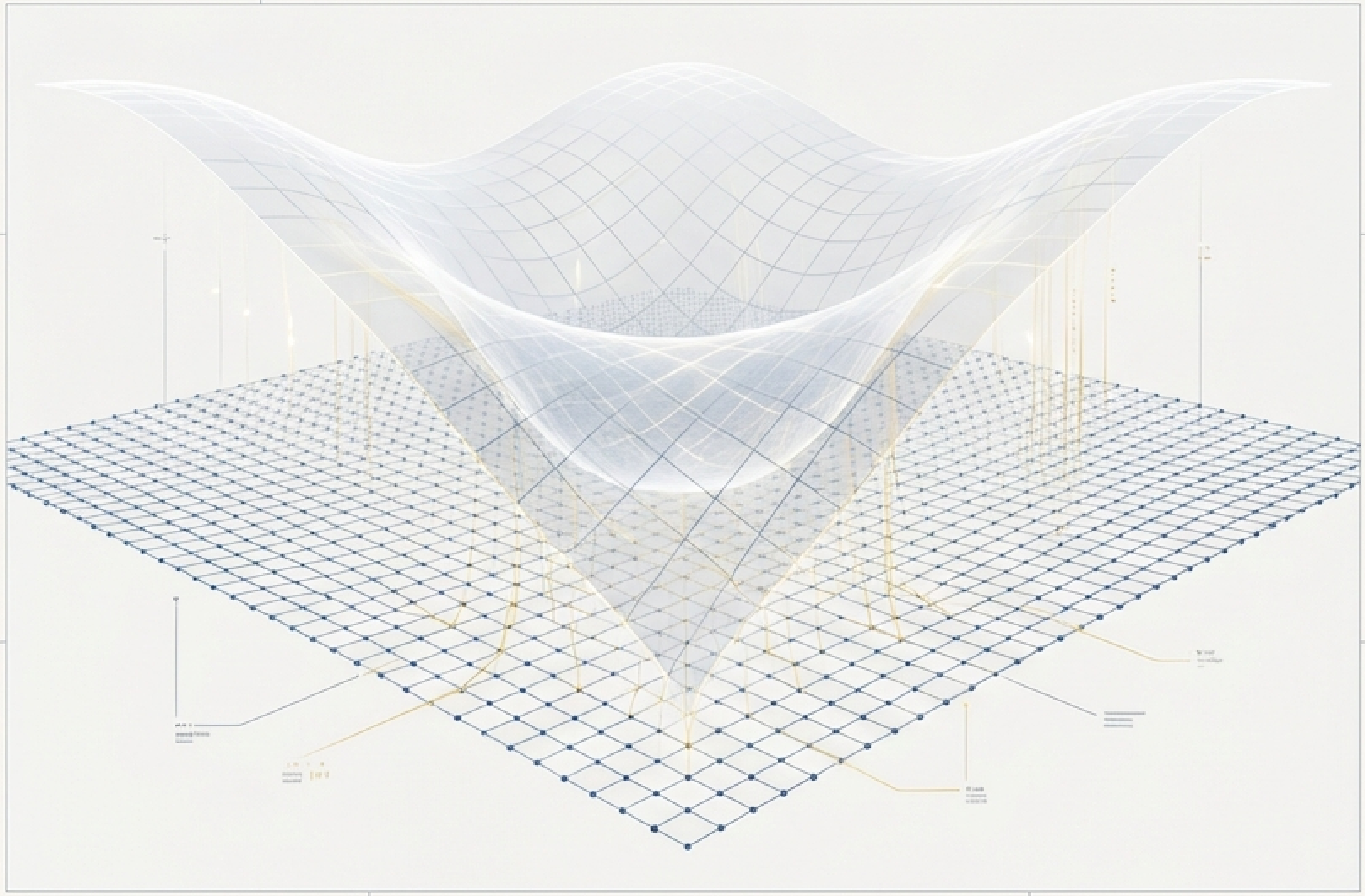
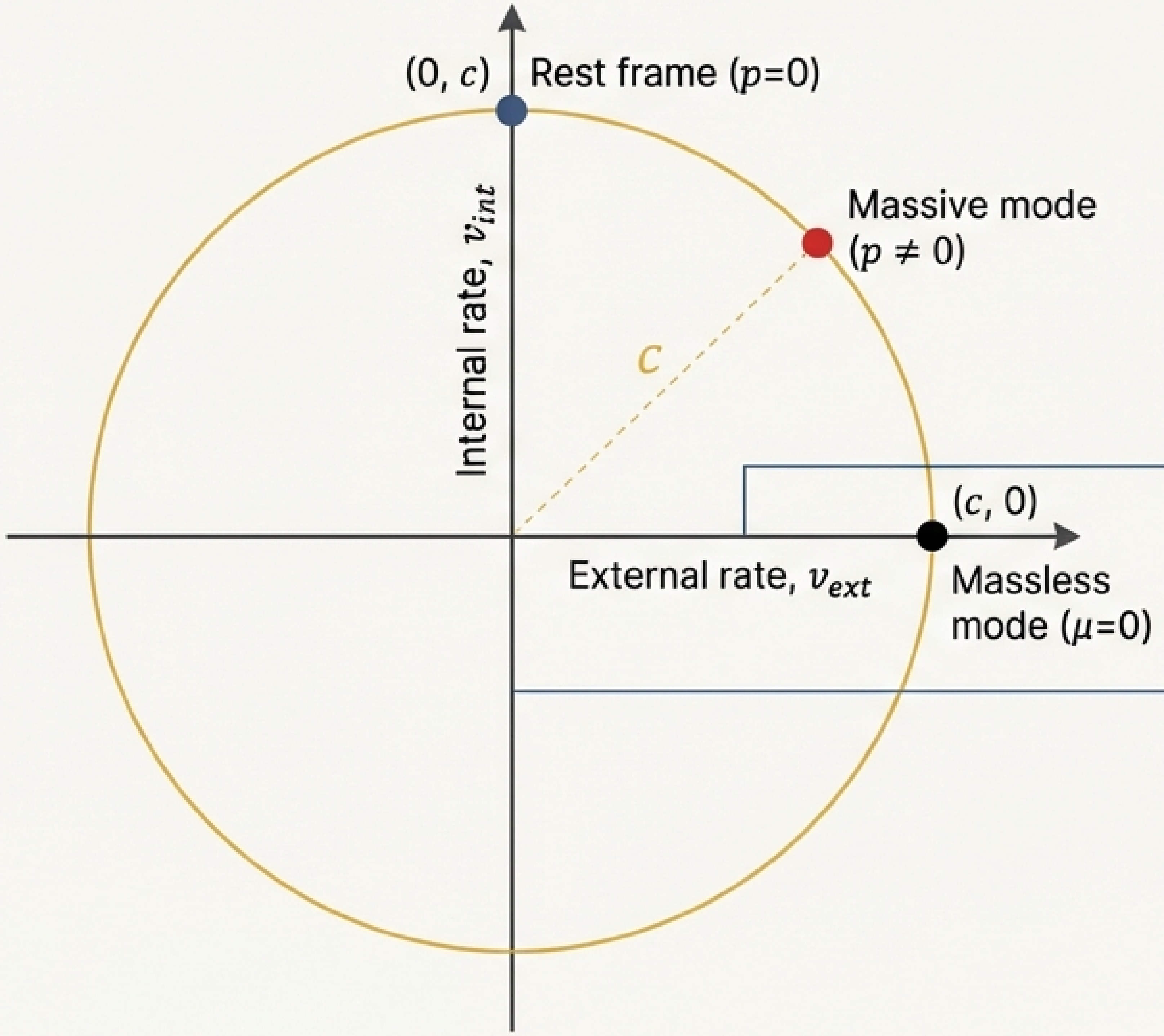
What if Spacetime is the Output, Not the Stage?



- Our deepest theories, from relativity to quantum fields, treat spacetime as a continuous, fundamental background.
- But what if reality is built on something more elemental? A discrete grid of quantum systems, evolving in local, unitary steps—a **Quantum Cellular Automaton.**
- In this view, spacetime geometry isn't a given. It is an *emergent* property of a vast quantum computation.
- This presentation reveals a fundamental law of this computational universe—a geometric principle that organizes relativistic physics from the code up.

What is the Fundamental Law of this Digital Universe?

$$v_{ext}^2(p) + v_{int}^2(p) = c^2$$



We identify an exact geometric conservation law for Dirac-type Quantum Cellular Automata: **The Information Rate Circle.**

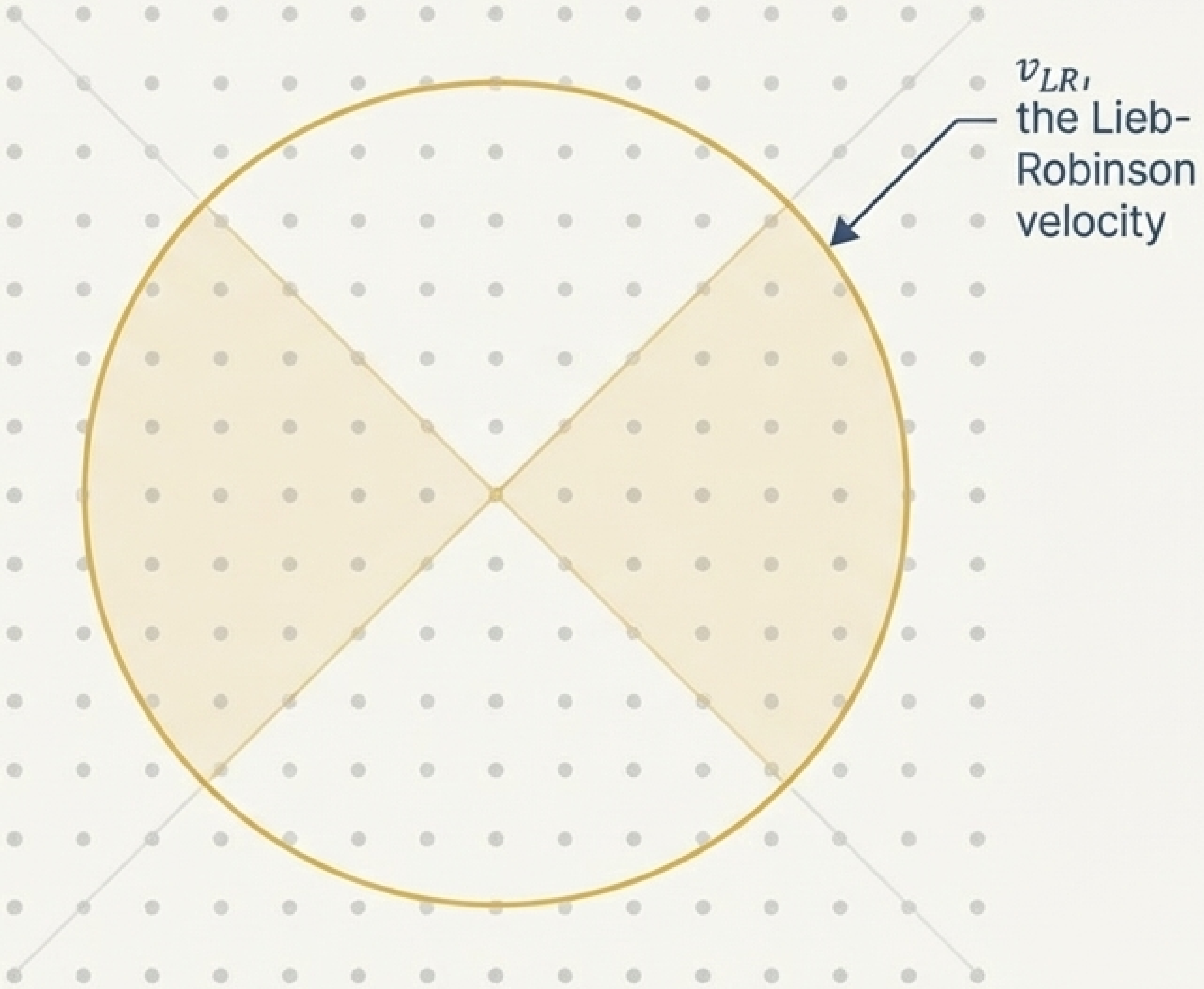
This law partitions the universe's total information capacity (c) between two channels:

- v_{ext}: **External Rate.** The speed of spatial transport; how information moves across the computational substrate.
- v_{int}: **Internal Rate.** The speed of internal quantum processing; how much computational resource is used to change a particle's internal state.

Every possible state of motion must live on this circle.
The total capacity is conserved, but dynamically allocated.

What does 'c' Truly Represent?

$$v_{ext}^2(p) + v_{int}^2(p) = c^2$$



- In this model, ‘c' is not just an empirical speed limit. It is the **Lieb-Robinson velocity (v_{LR}).**
- The Lieb-Robinson bound sets the absolute causal speed limit in any quantum lattice system. It is the universe’s ultimate **bandwidth**—the maximum rate at which information can propagate.
- Therefore, the Information Rate Circle ($v_{ext}^2 + v_{int}^2 = c^2$) is a geometric decomposition of the *total causal capacity* of the local interaction.

The universe's processing power is finite and conserved.

Where Does This Geometric Law Come From?

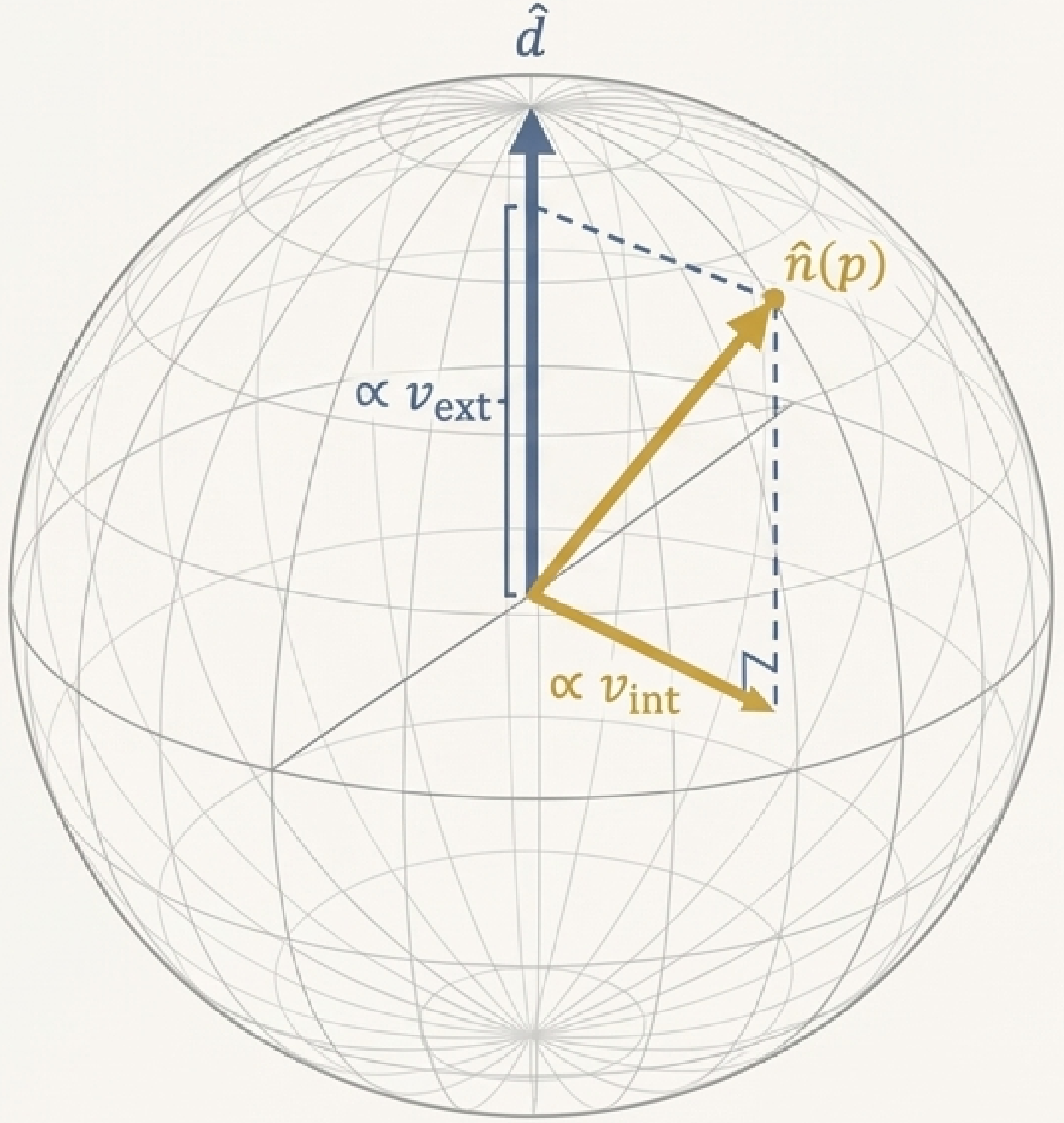
The law originates from the geometry of a single quantum bit's evolution in a **Dirac Quantum Walk**.

The state evolution for a given momentum p is a rotation on the Bloch Sphere, defined by a Bloch axis $\hat{n}(p)$.

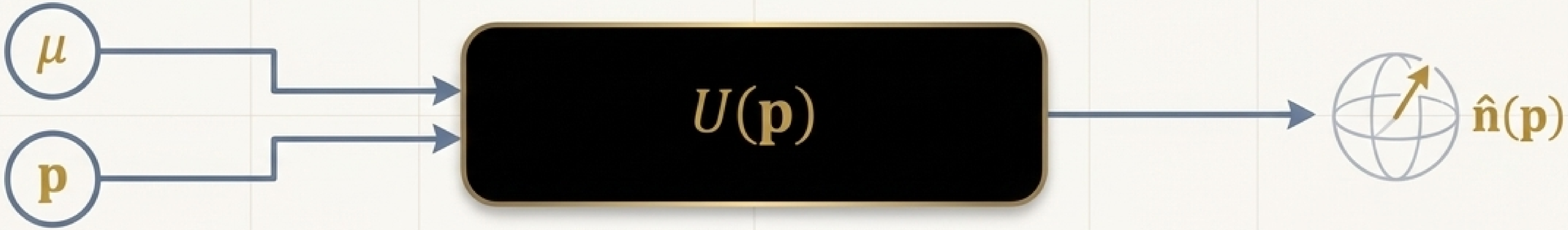
We define our rates based on the decomposition of this axis relative to a fixed propagation direction $\hat{d}$:

- **External Rate:** $\frac{v_{\text{ext}}}{c} = \hat{n}(p) \cdot \hat{d}$
  (The component parallel to propagation)
- **Internal Rate:** $\frac{v_{\text{int}}}{c} = |\hat{n}(p) \times \hat{d}|$
  (The component perpendicular to propagation)

Because $\hat{n}(p)$ is a unit vector, the geometric identity $(\hat{n} \cdot \hat{d})^2 + |\hat{n} \times \hat{d}|^2 = 1$ is always true. Multiplying by c^2 yields the Information Rate Circle. It is a direct consequence of the SU(2) structure.



How is the Information Flow Programmed?



$$U(\mathbf{p}) = e^{-i\Omega(\mathbf{p})\hat{\mathbf{n}}(\mathbf{p})\cdot\vec{\sigma}}$$

$$\cos(\Omega(\mathbf{p})) = \cos(\mu\Delta t)\cos(pa)$$

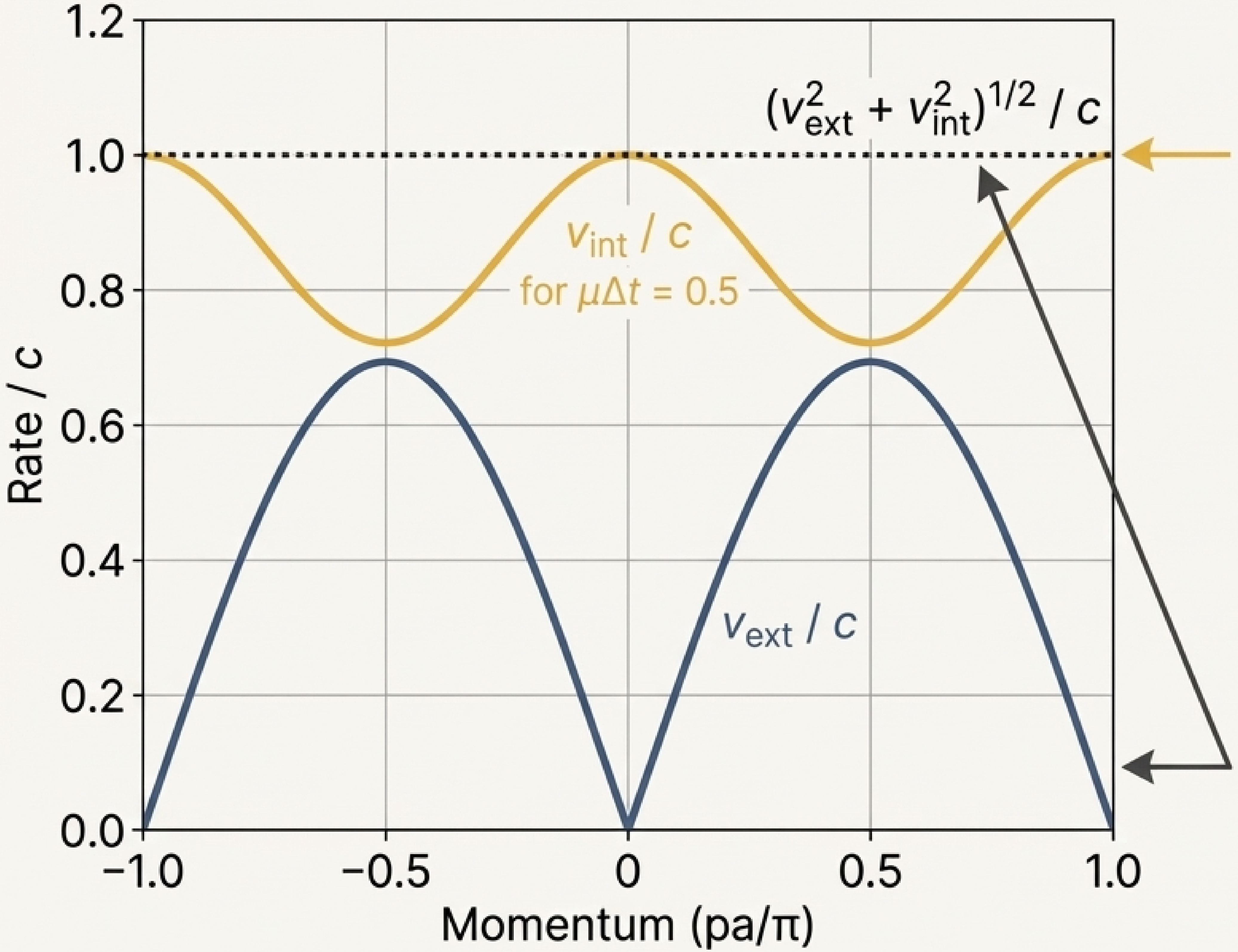
$$\hat{\mathbf{n}}(\mathbf{p})\sin\Omega(\mathbf{p}) = \hat{m}\sin(\mu\Delta t)\cos(pa) + \hat{d}\sin(pa)\cos(\mu\Delta t) - (\hat{\mathbf{m}}\times\hat{\mathbf{d}})\sin(\mu\Delta t)\sin(pa)$$

The orientation of the Bloch axis $\hat{\mathbf{n}}(\mathbf{p})$—and thus the split between v_{ext} and v_{int}—is determined by two parameters:

- $\mathbf{p}$: The lattice momentum.
- μ: A microscopic frequency parameter, which we will see corresponds to **mass**.

This machinery provides an explicit, computable link from the automaton's rules to the emergent kinematics.

How is the Universe's Bandwidth Allocated?



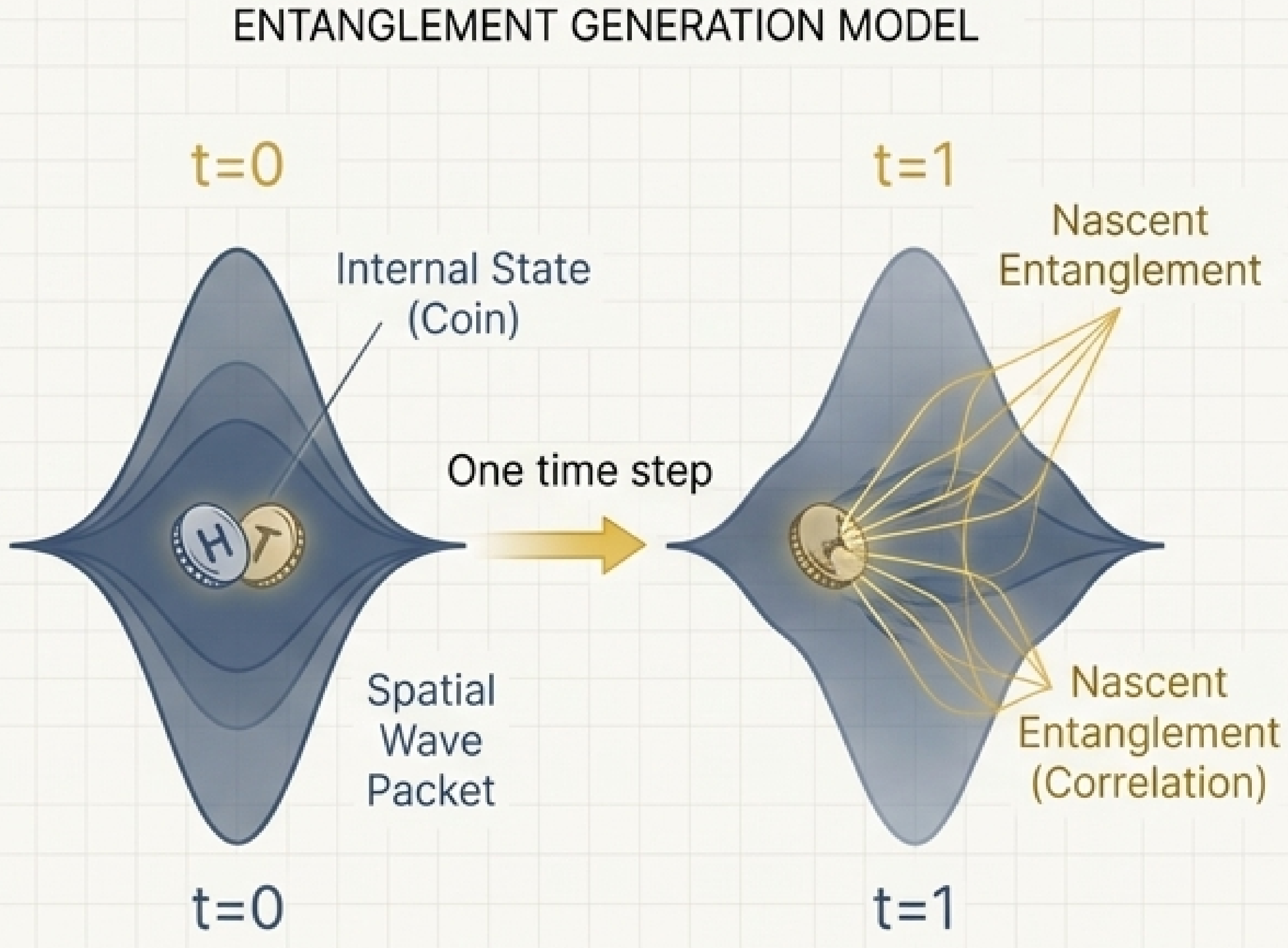
At rest ($p = 0$), all causal capacity is devoted to internal processing ($v_{int} = c$, $v_{ext} = 0$). This corresponds to the particle's rest mass.

As momentum increases, the system reallocates its causal budget from internal processing to external propagation.

For a massless particle ($\mu = 0$), v_{int} is always zero. The entire budget is dedicated to external motion: $|v_{ext}| = c$.

The total rate (dotted line) is always c, perfectly conserved across all momentum modes.

Is ‘Internal Rate’ Just Math, or a Physical Resource?



Proposition 1:

The internal rate v_{int} has a direct, operational meaning: **it sets a rigorous upper bound on the generation of coin-position entanglement.**

For a narrow wave packet, the entanglement S_{lin} generated in one step is bounded by:

$$S_{\mathrm{lin}}(1) \le 2\sigma_p^2 \Delta t^2 \left[v_{\mathrm{ext}}^2(p_0) + \kappa v_{\mathrm{int}}^2(p_0) \right]$$

Interpretation:

- v_{int} is not a mathematical fiction. It is the physical scale governing the rate at which quantum correlations are generated.
- This elevates the Information Rate Circle from a kinematic curiosity to a fundamental constraint on quantum information resources.

How Does Internal Processing Create Quantum Correlations?

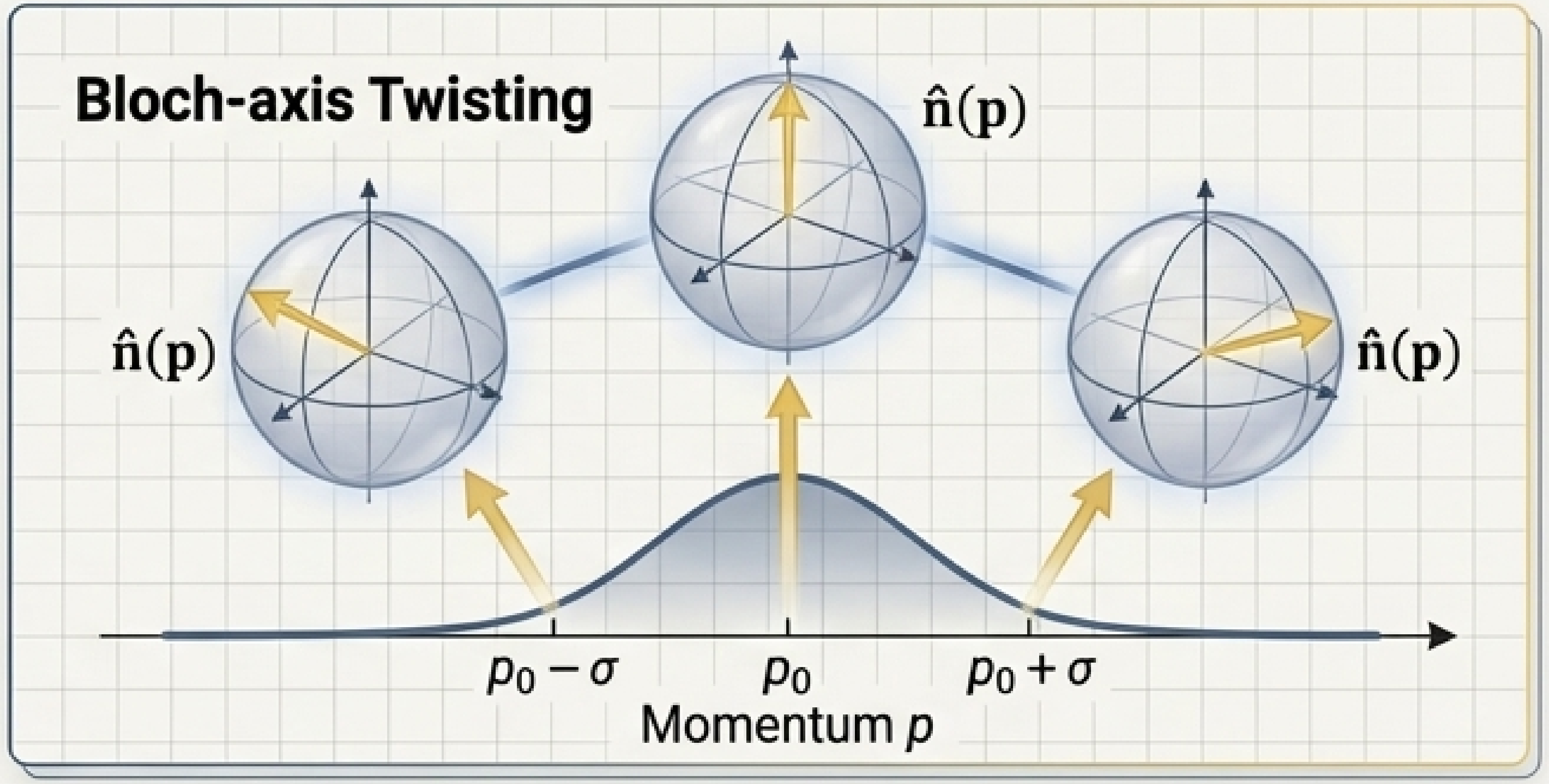
Entanglement arises from two mechanisms:

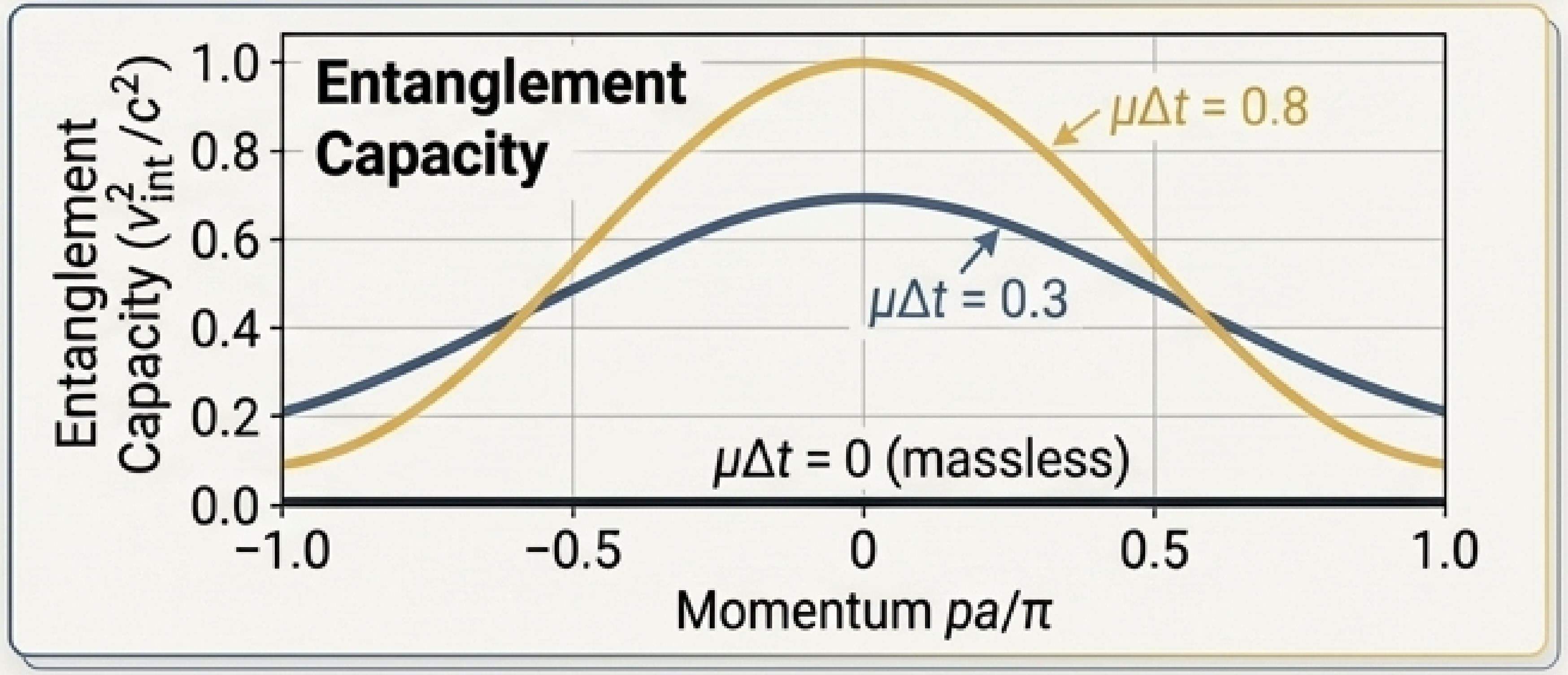
1. **Dispersion ($\propto v_{\text{ext}}^2$):** Different momentum components travel at different speeds, causing phase shifts.
2. **Bloch-axis Twisting ($\propto v_{\text{int}}^2$):** The quantum rotation axis $\hat{\mathbf{n}}(\mathbf{p})$ itself changes across the wave packet. Different momentum components undergo *different types of rotation*.

v_{int} directly controls this second, more subtle mechanism. A higher internal rate means the quantum evolution is more sensitive to momentum.

Plot Interpretation:

The capacity to generate entanglement (v_{int}^2) is highest for massive particles near rest, and zero for massless particles.





How Does This Law Reconstruct Our Familiar Reality?

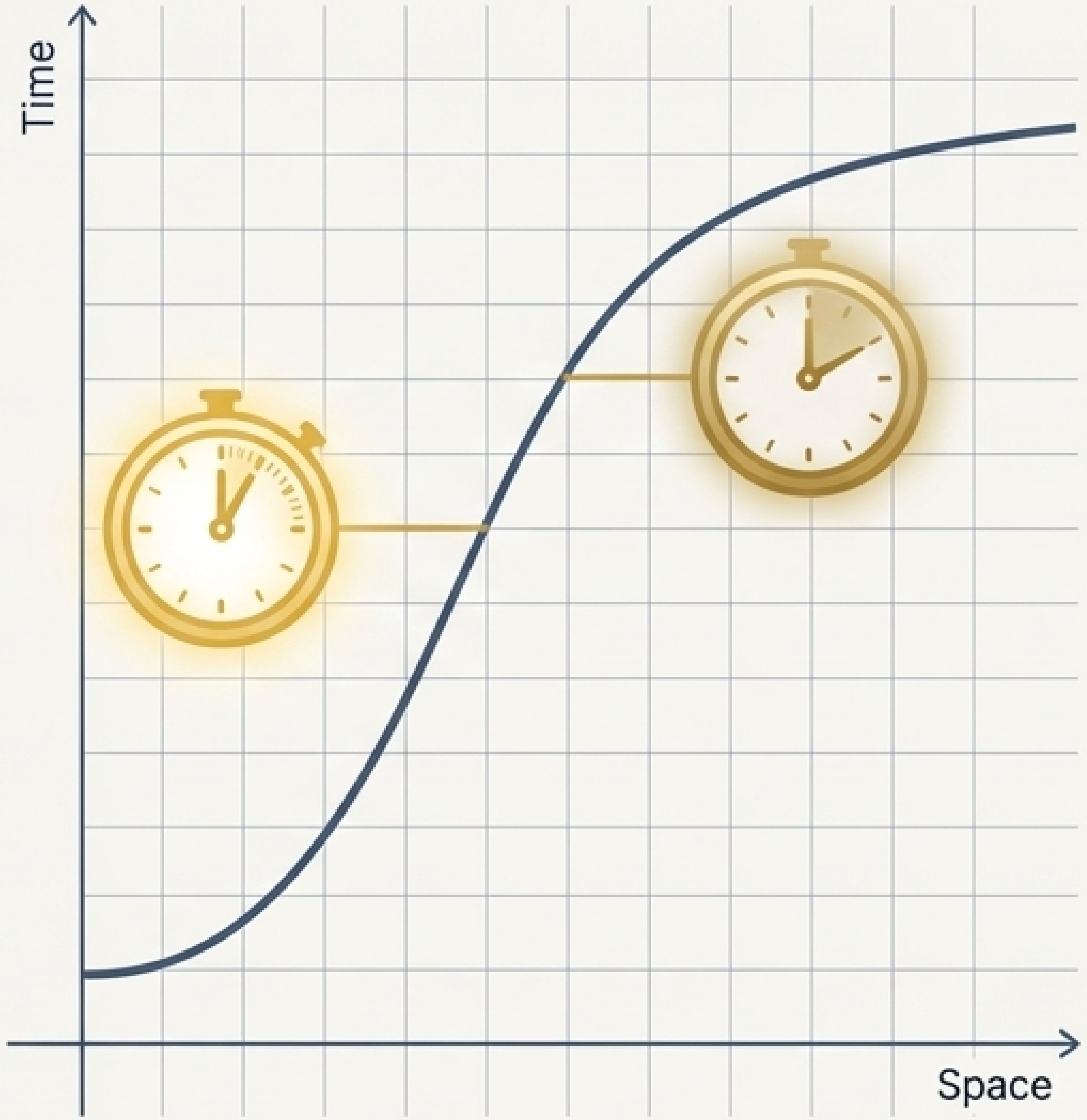
The Bridge Definition

Given the **information rate circle**, we can define a new time parameter τ, whose rate is set by the internal processing fraction:

$$d\tau := \frac{v_{\text{int}}}{c}\, dt$$

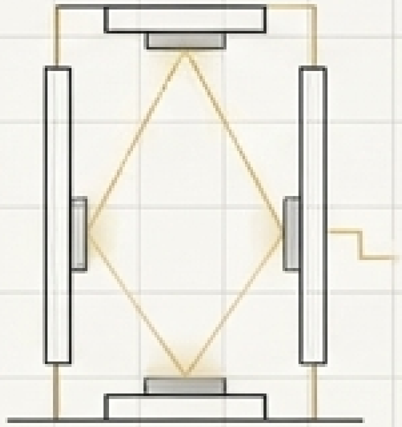
Interpretation:

- We identify τ with Minkowski proper time—the time measured by a clock moving with the particle.
- This definition is not an assumption; it is a direct consequence of interpreting the internal processing rate as the rate of the particle's own "internal clock".
- From this single geometric definition, the entire kinematic structure of special relativity emerges.



Can This Single Law Unify Relativistic Kinematics?

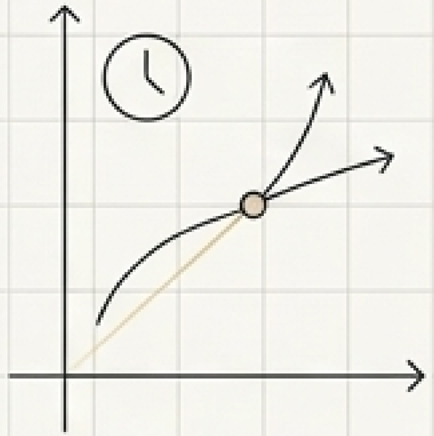
Time Dilation



Since $v_{\text{ext}}^2 + v_{\text{int}}^2 = c^2$, we have $v_{\text{int}} = \sqrt{c^2 - v_{\text{ext}}^2}$. Let $v = v_{\text{ext}}$.

$$\frac{d\tau}{dt} = \frac{v_{\text{int}}}{c} = \sqrt{1 - \frac{v^2}{c^2}}$$

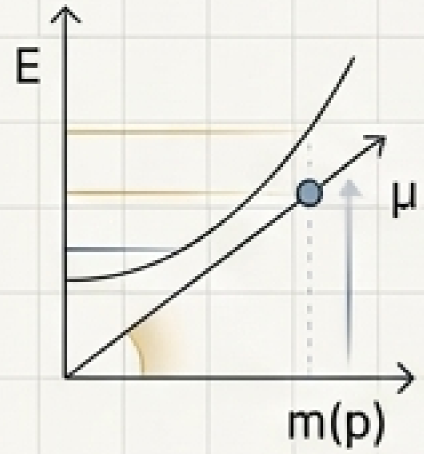
Four-Velocity Normalization



The four-velocity $u^\mu = \frac{dx^\mu}{d\tau}$ is calculated with this new proper time.

$$g^{\mu\nu} u^\mu u^\nu = -c^2$$

Energy-Momentum Relation



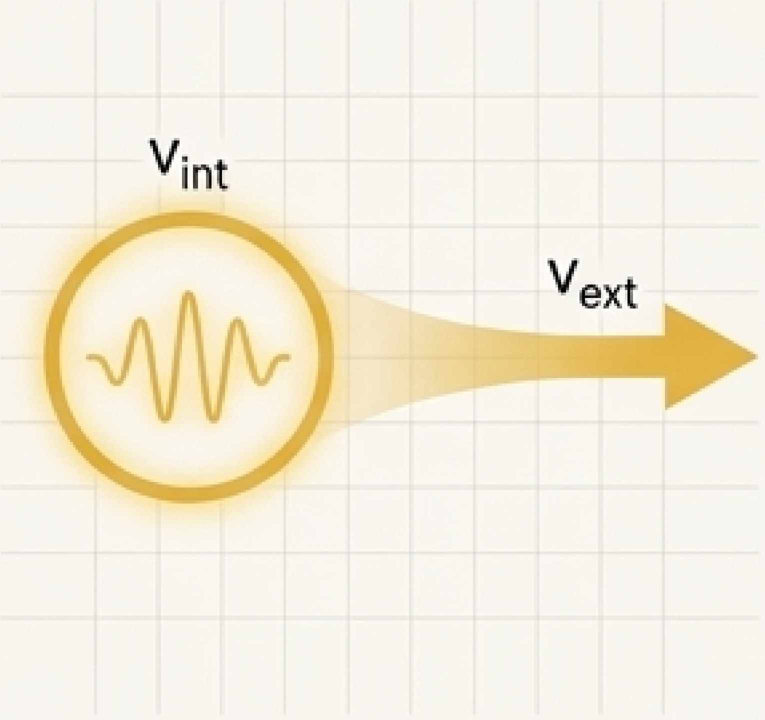
In the low-energy limit, we find $\frac{v_{\text{int}}}{c} \approx \frac{\mu}{\omega(p)}$ where ω is frequency. Identifying mass $m = \hbar\mu/c^2$ and energy $E = \hbar\omega$, this gives $\frac{d\tau}{dt} = \frac{mc^2}{E}$.

$$E^2 = p_{\text{phys}}^2 c^2 + m^2 c^4$$

NotebookLM

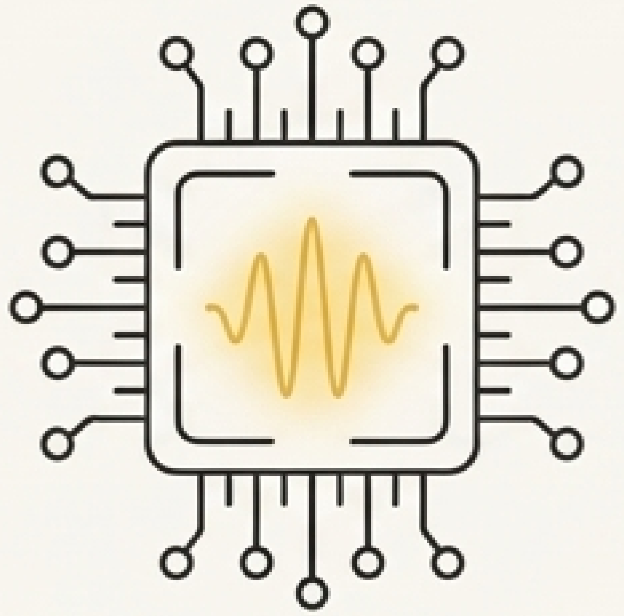
What Does Relativity Mean in a Computational Universe?

Inertia



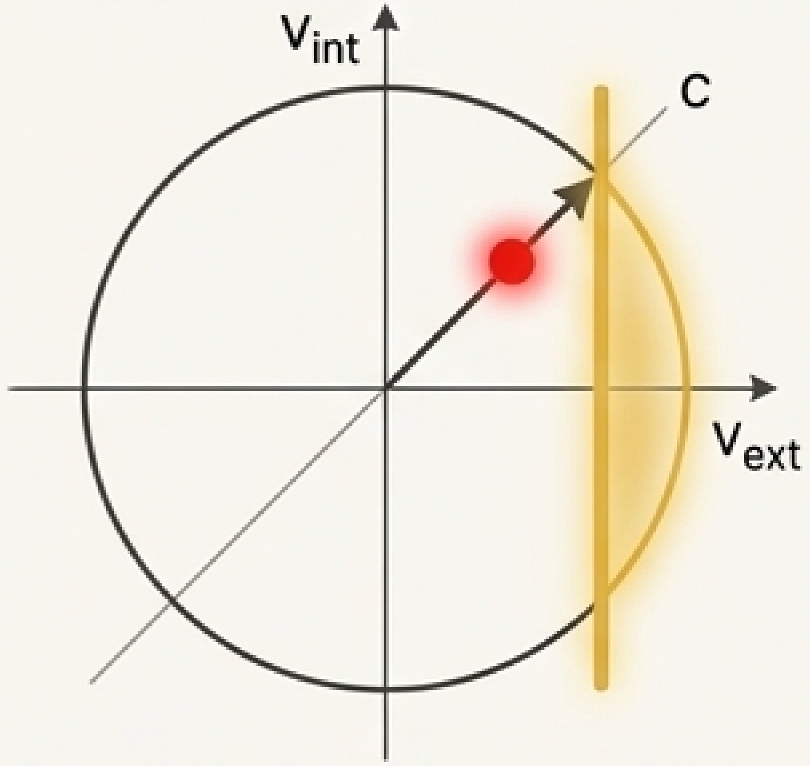
Inertia: The resistance to acceleration. In this model, it is the "computational cost" of reallocating the causal budget c from internal processing (v_{int}) to external propagation (v_{ext}).

Mass



Mass: Not an intrinsic property, but a measure of a particle's **internal processing load** ($m = \hbar\mu/c^2$). A higher mass means a higher internal clock rate that consumes more of the causal budget at rest.

The Light-Speed Limit

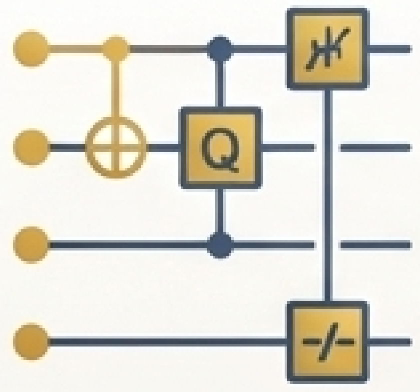


The Light-Speed Limit: A particle with mass ($\mu > 0$) *must* have a non-zero internal rate ($v_{int} > 0$). By the circle law, this forces its external rate to be strictly less than c. Only massless particles ($\mu=0$, $v_{int}=0$) can devote their entire information budget to external propagation.

E = mc²: Rest energy is the energy of the internal quantum process running at its maximum rate.

How Can We Find this Code in the Real World?

Reconstruct



Reconstruct

Use quantum process tomography to experimentally reconstruct the single-step unitary operator $\mathbf{U}(\mathbf{p})$ for a chosen momentum $\mathbf{p}$.

Extract

Extract

From the measured $\mathbf{U}(\mathbf{p})$, mathematically extract the Bloch axis $\hat{\mathbf{n}}(\mathbf{p})$.

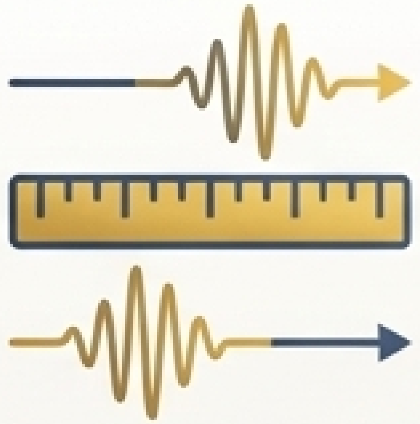
Calculate

Calculate

Compute the internal rate directly from its geometric definition:

$\mathbf{v}_{\text{int}}(\mathbf{p}) = c\,|\hat{\mathbf{n}}(\mathbf{p}) \times \hat{\mathbf{d}}|$

Measure



Measure

Independently, measure the group velocity $\mathbf{v}_{\text{ext}}(\mathbf{p})$ by tracking the motion of a prepared wave packet.

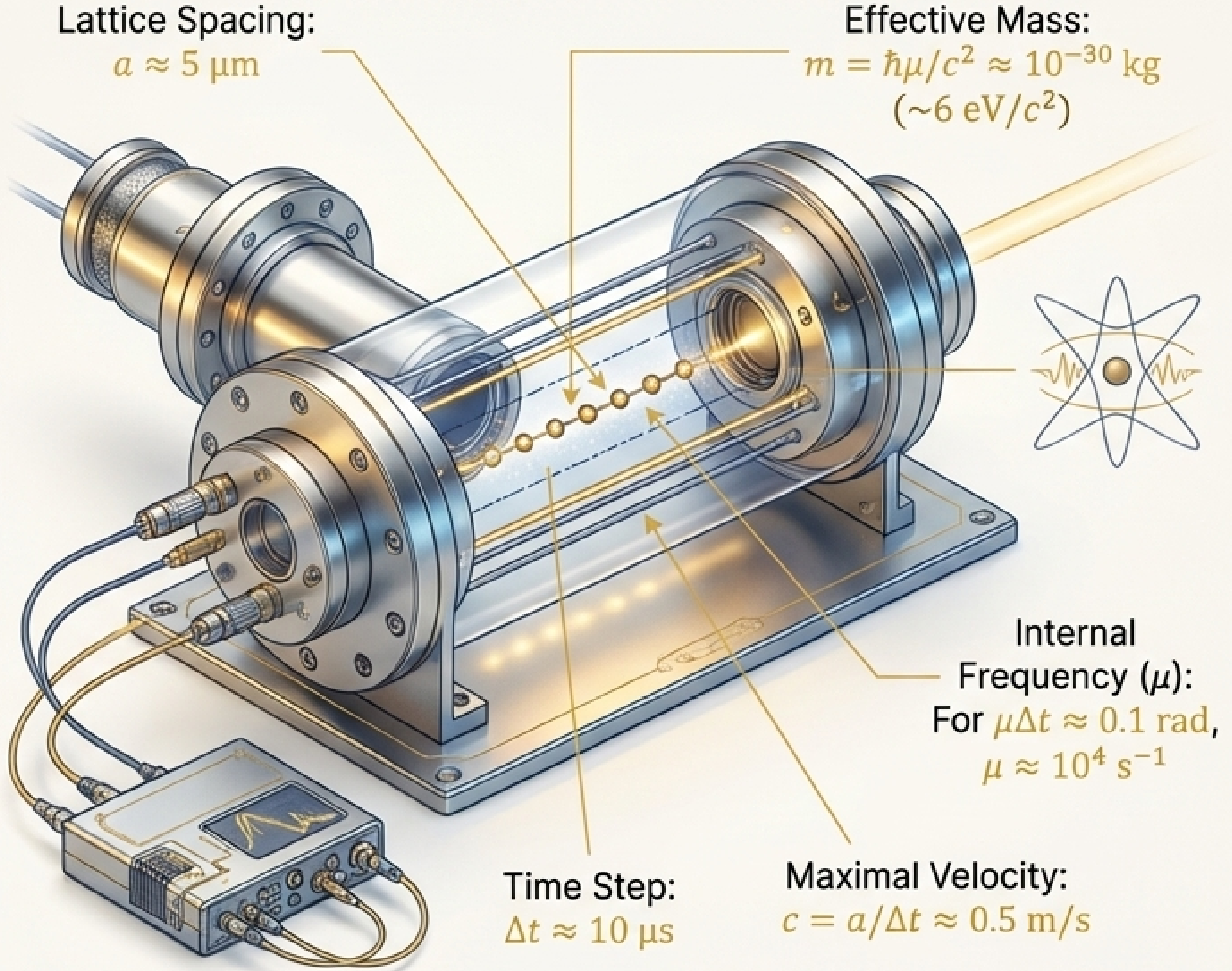
Verify

Verify

Check if the measured values satisfy $\mathbf{v}_{\text{ext}}^2(\mathbf{p}) + \mathbf{v}_{\text{int}}^2(\mathbf{p}) = c^2$ within experimental error.

The Information Rate Cirte Circle is directly testable on quanimulation simulation platforms (e.g., trapped ions, superconducting circuits).

What Would an Experiment Actually Measure?



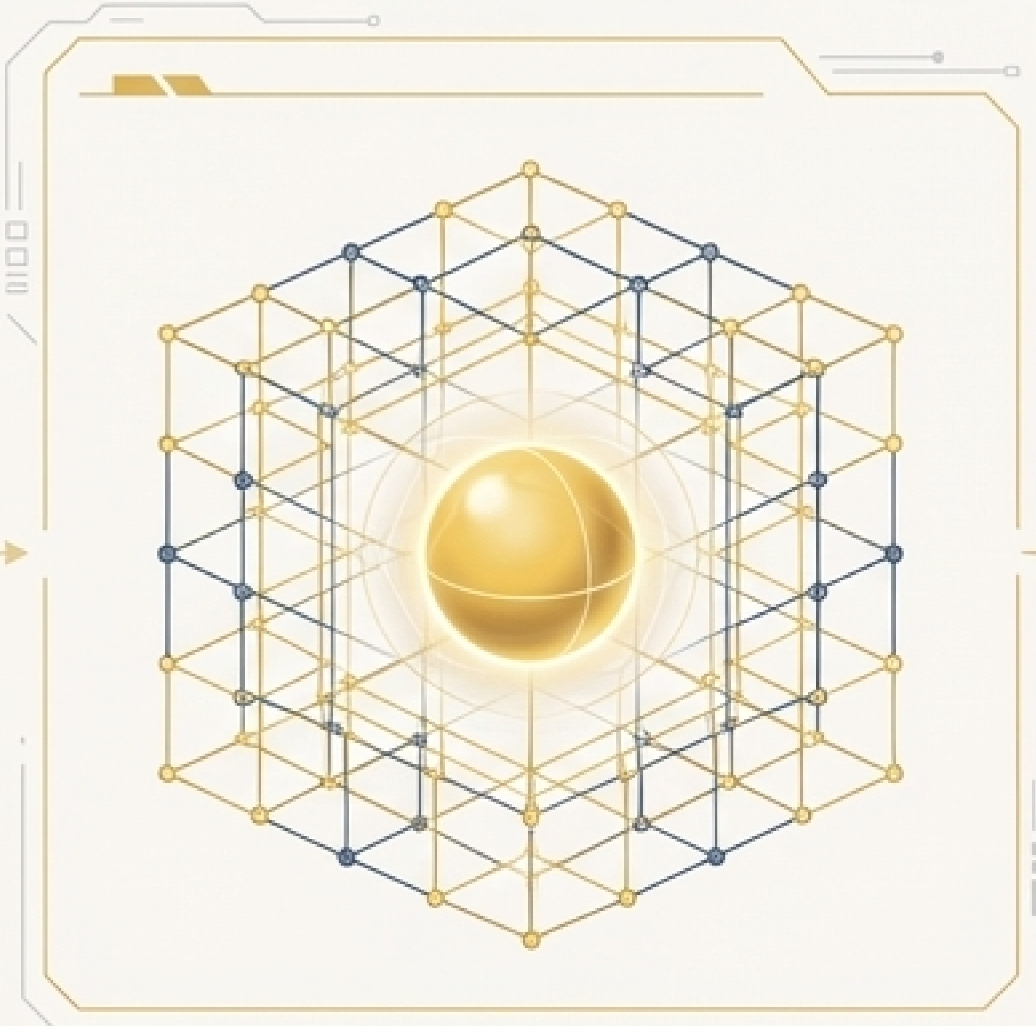
Key Takeaway

These parameters for velocity and mass are well within the resolution of current experimental setups.

Additional Test (Protocol 2)

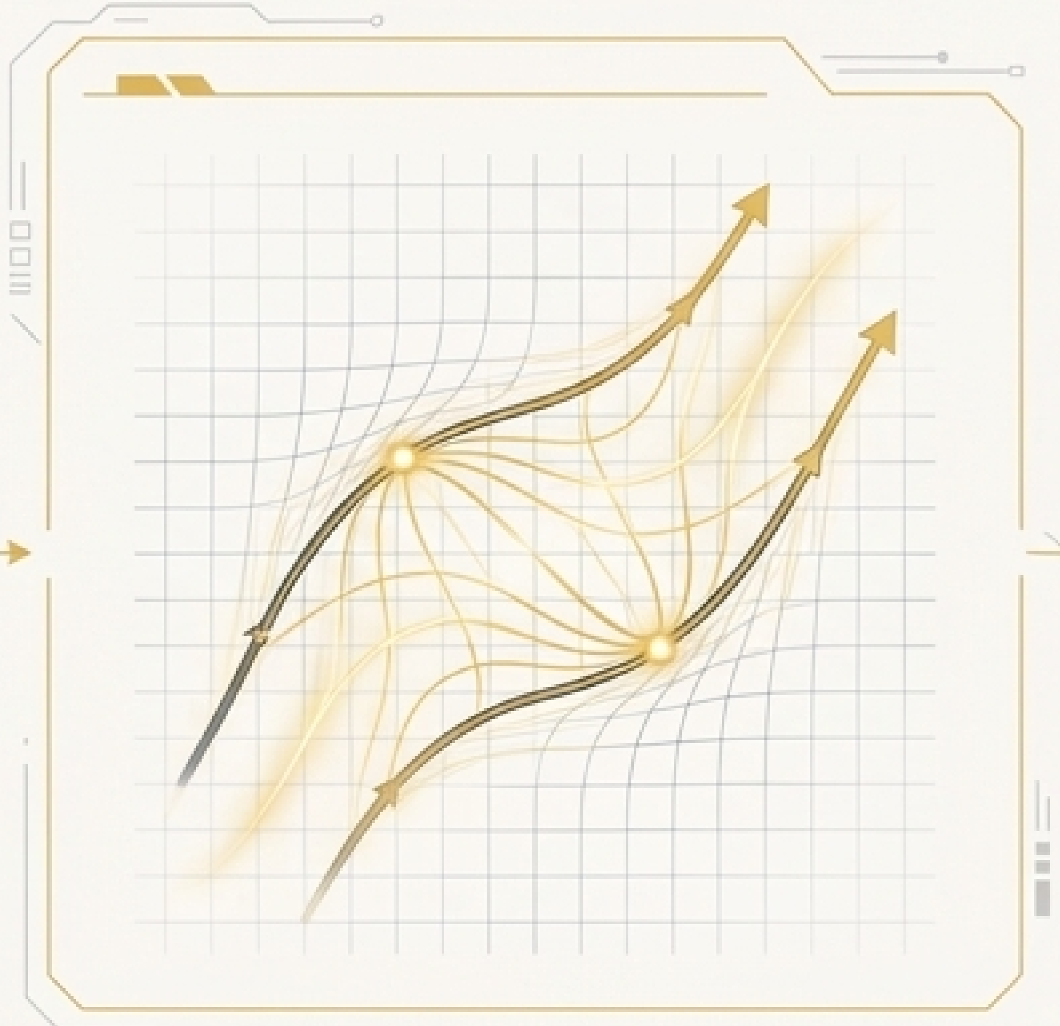
A second experiment can directly verify the link between mass and internal frequency by varying the coin rotation angle $\mu\Delta t$ and measuring the particle's rest-frame oscillation frequency $\omega(0)$, confirming that $\omega(0) \approx \mu$.

What Lies Beyond This Simple Model?



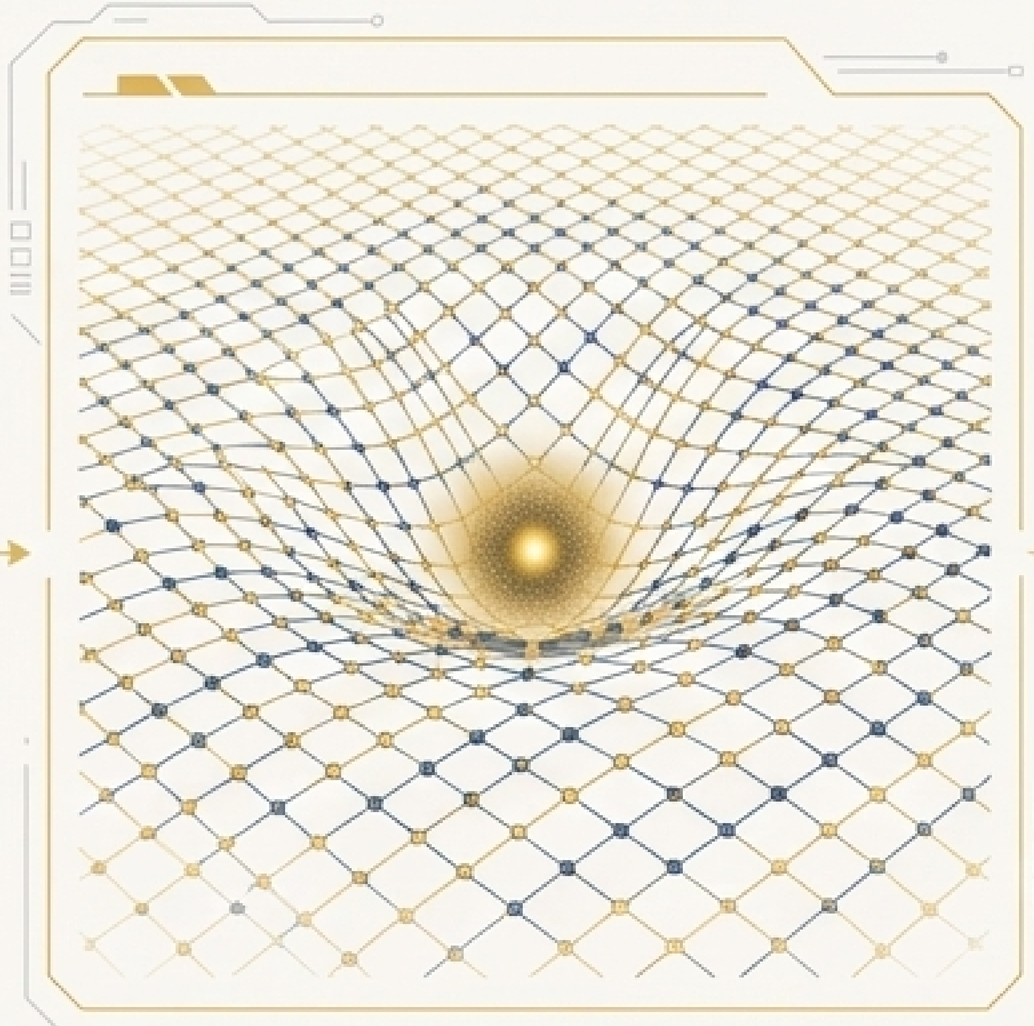
Higher Dimensions

The principle is expected to generalize to a sphere constraint in higher dimensions, where $|\vec{v}_{\mathrm{ext}}|^2 + v_{\mathrm{int}}^2 = c^2$.



Interacting Theories

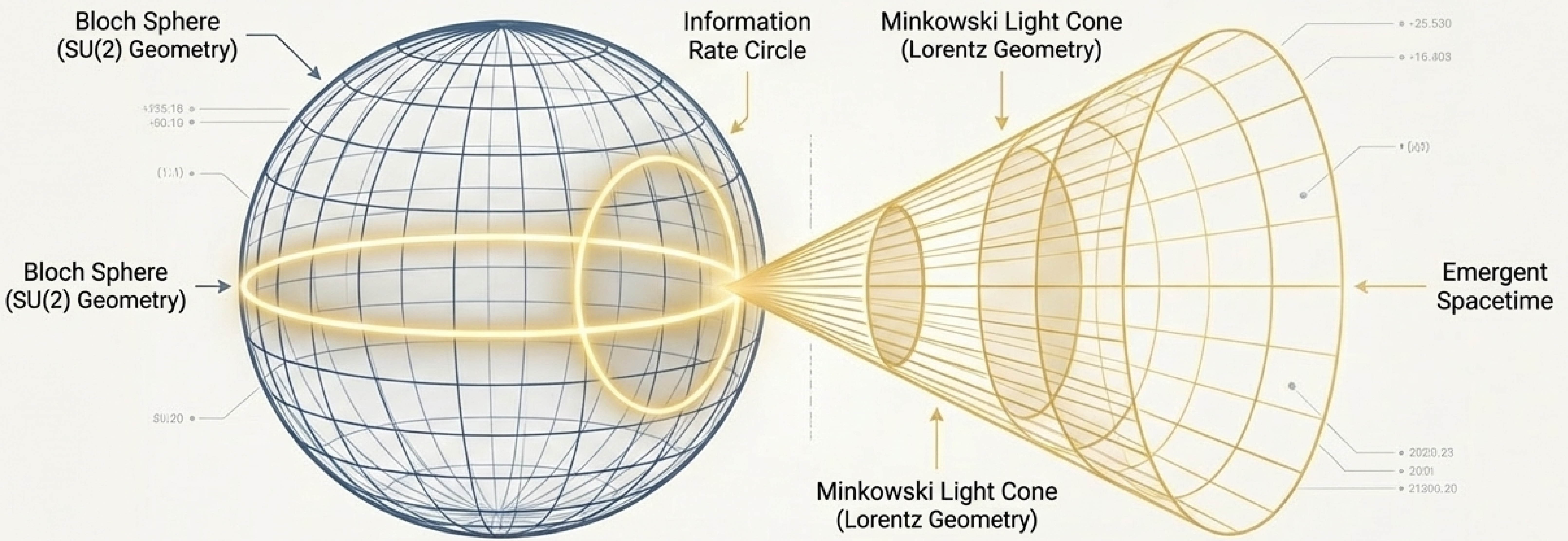
Introducing interactions and gauge fields (like electromagnetism) corresponds to deforming the local information-rate geometry. Forces emerge as variations in the computational rules.



Curved Spacetime

The ultimate goal: can we model gravity by introducing local variations in the QCA parameters (e.g., $\mu(x)$)? This offers a path to simulating quantum gravity from first principles.

Spacetime is Not the Stage, but the Story Itself.



The **Information Rate Circle** reveals that spacetime geometry is not fundamental. It is an emergent description of information flowing through a discrete quantum system with a finite causal bandwidth.

This single, exact geometric law—$v_{ext}^2 + v_{int}^2 = c^2$—connects the geometry of a quantum state (the Bloch sphere) to the kinematics of special relativity.

It suggests that the laws of physics are not just written *in* the universe; they are the processing rules that *compute* the universe.