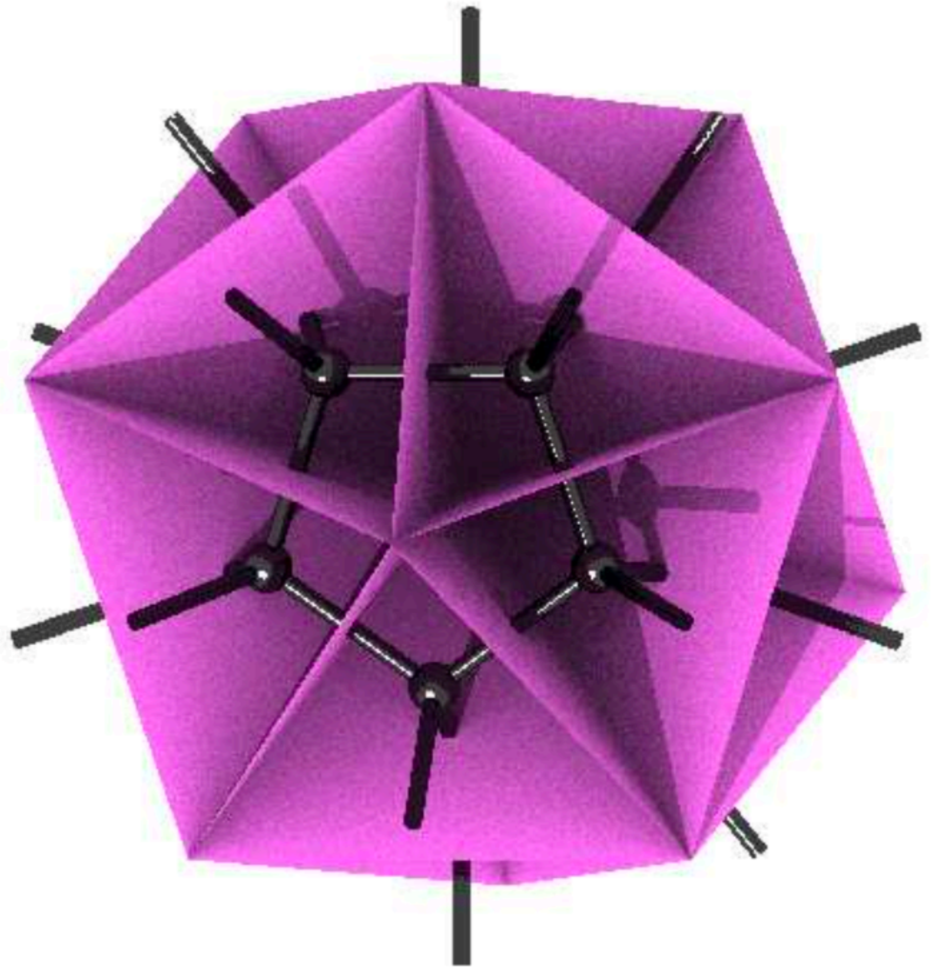
Low Energy QG Experiments

Quantum Information brings Quantum Gravity to the lab

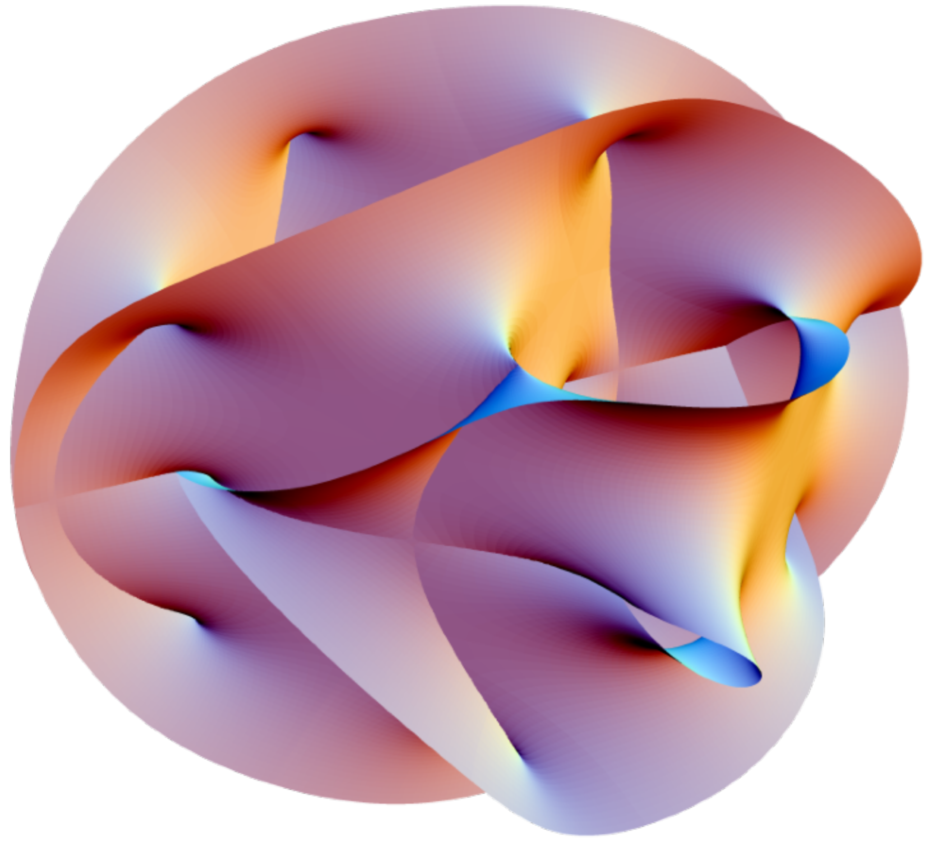
Andrea Di Biagio,
LQG Summer school 2021

Competing QG Theories

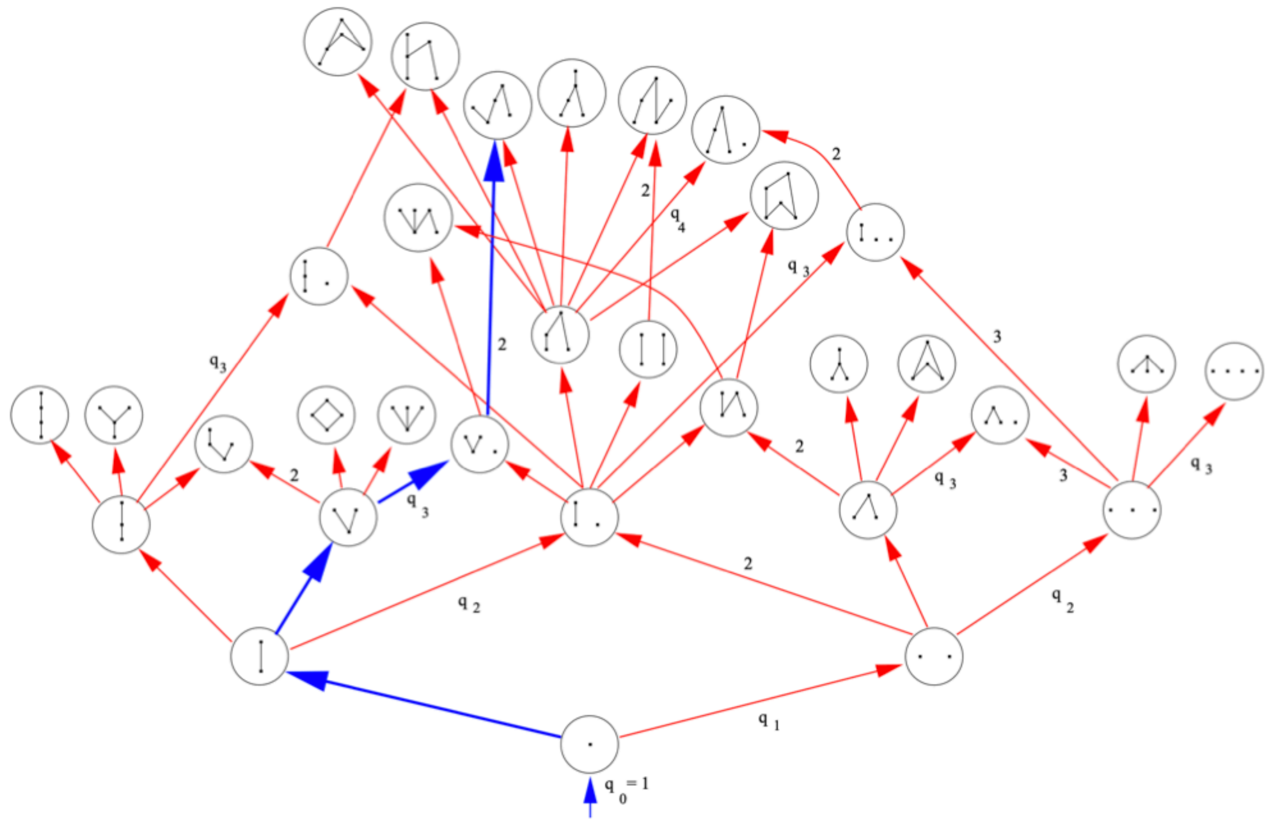
LQG



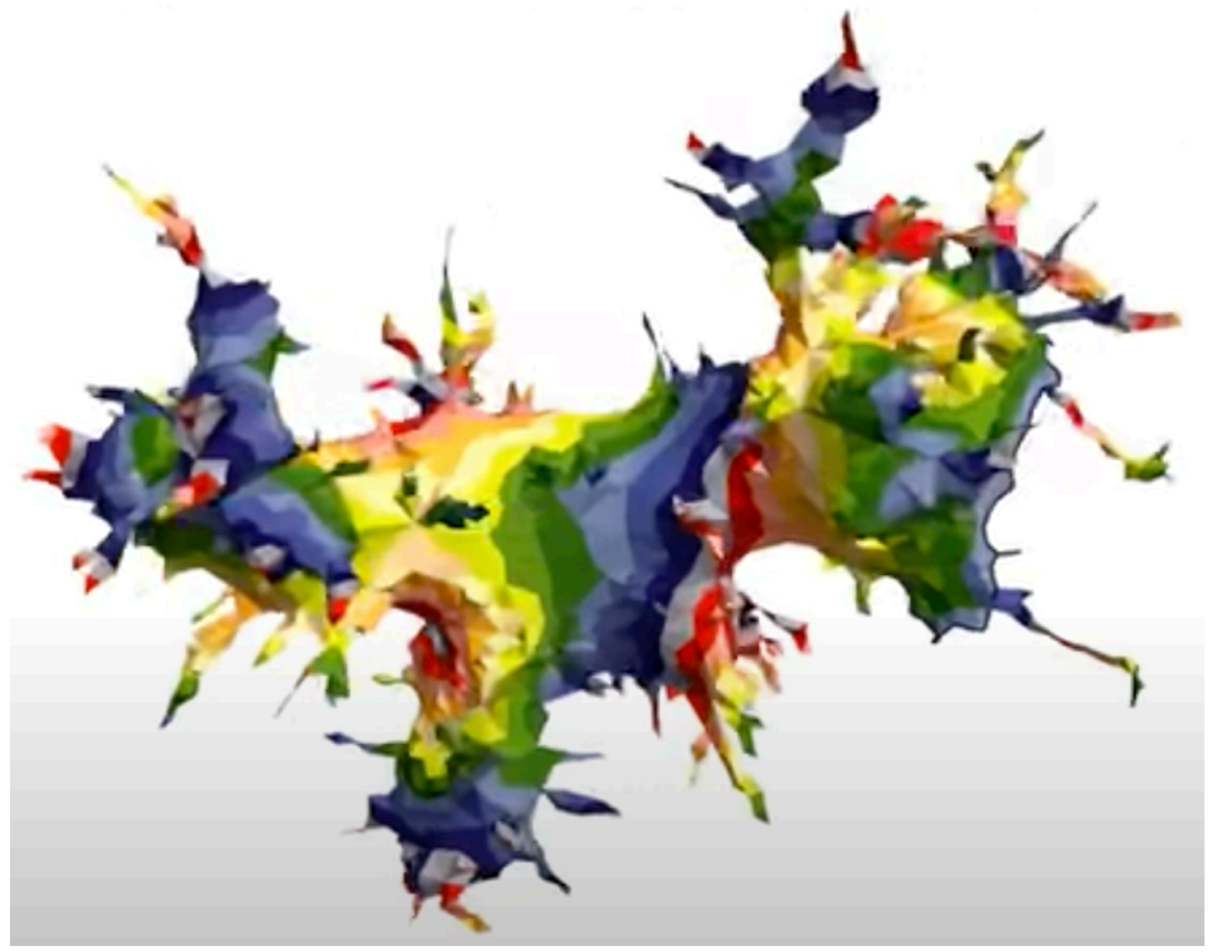
String Theory



Causal Set Theory

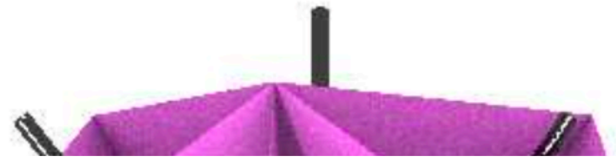


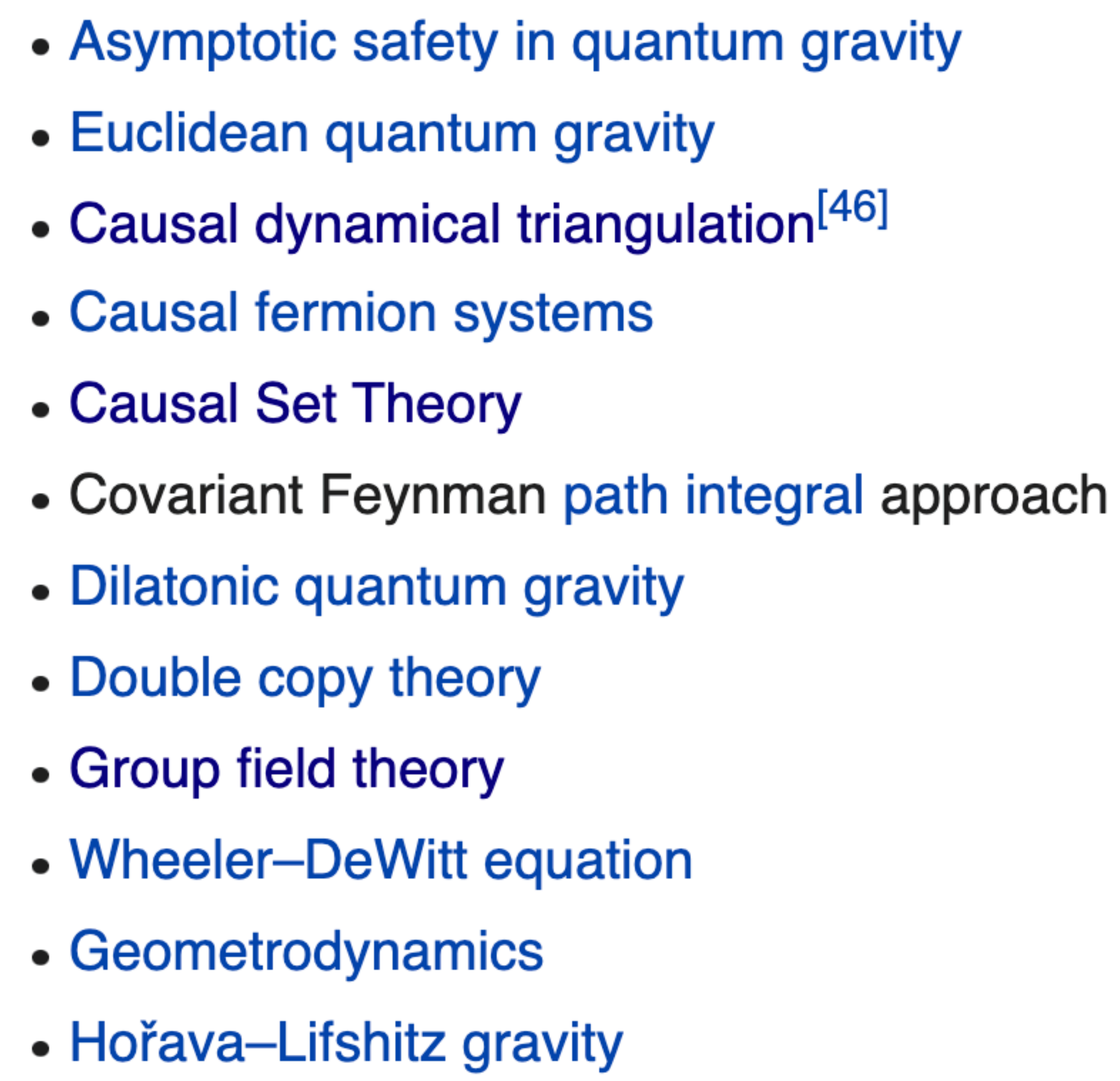
Causal Dynamical Triangulations



Competing QG Theories

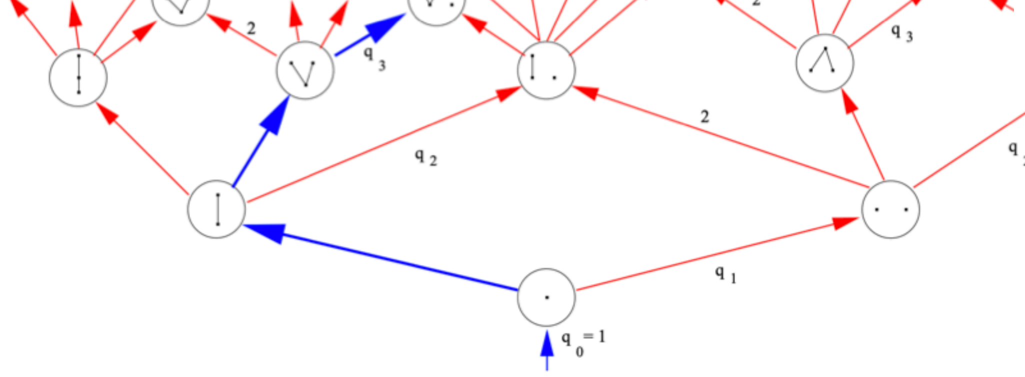
LC



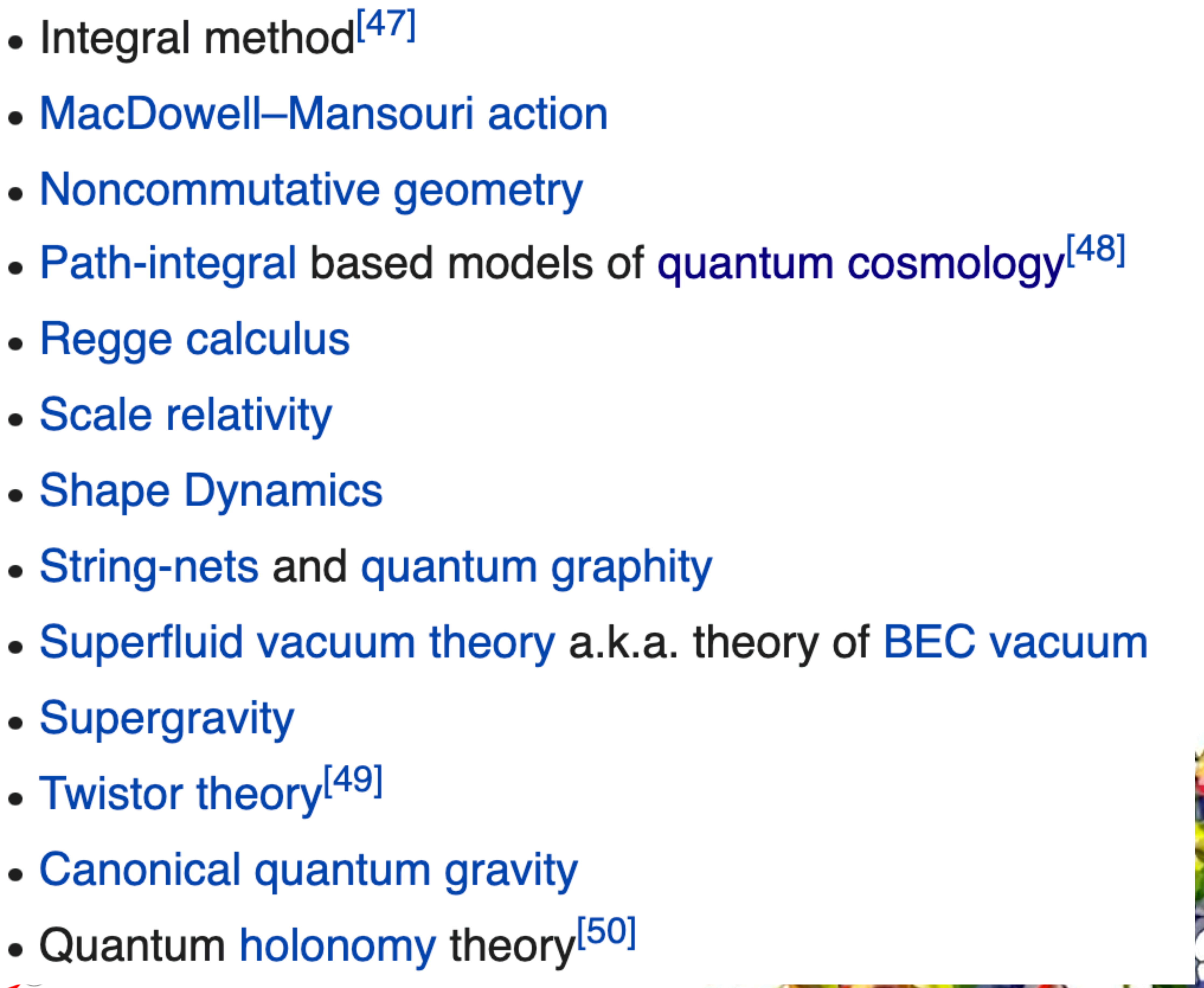


- Asymptotic safety in quantum gravity
- Euclidean quantum gravity
- Causal dynamical triangulation[46]
- Causal fermion systems
- Causal Set Theory
- Covariant Feynman path integral approach
- Dilatonic quantum gravity
- Double copy theory
- Group field theory
- Wheeler–DeWitt equation
- Geometrodynamics
- Hořava–Lifshitz gravity

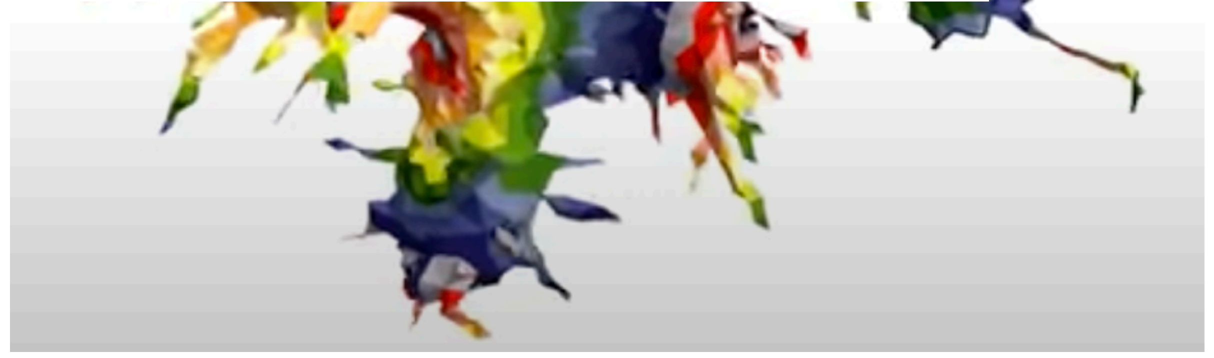
Cau



String Theory



- Integral method[47]
- MacDowell–Mansouri action
- Noncommutative geometry
- Path-integral based models of quantum cosmology[48]
- Regge calculus
- Scale relativity
- Shape Dynamics
- String-nets and quantum graphity
- Superfluid vacuum theory a.k.a. theory of BEC vacuum
- Supergravity
- Twistor theory[49]
- Canonical quantum gravity
- Quantum holonomy theory[50]

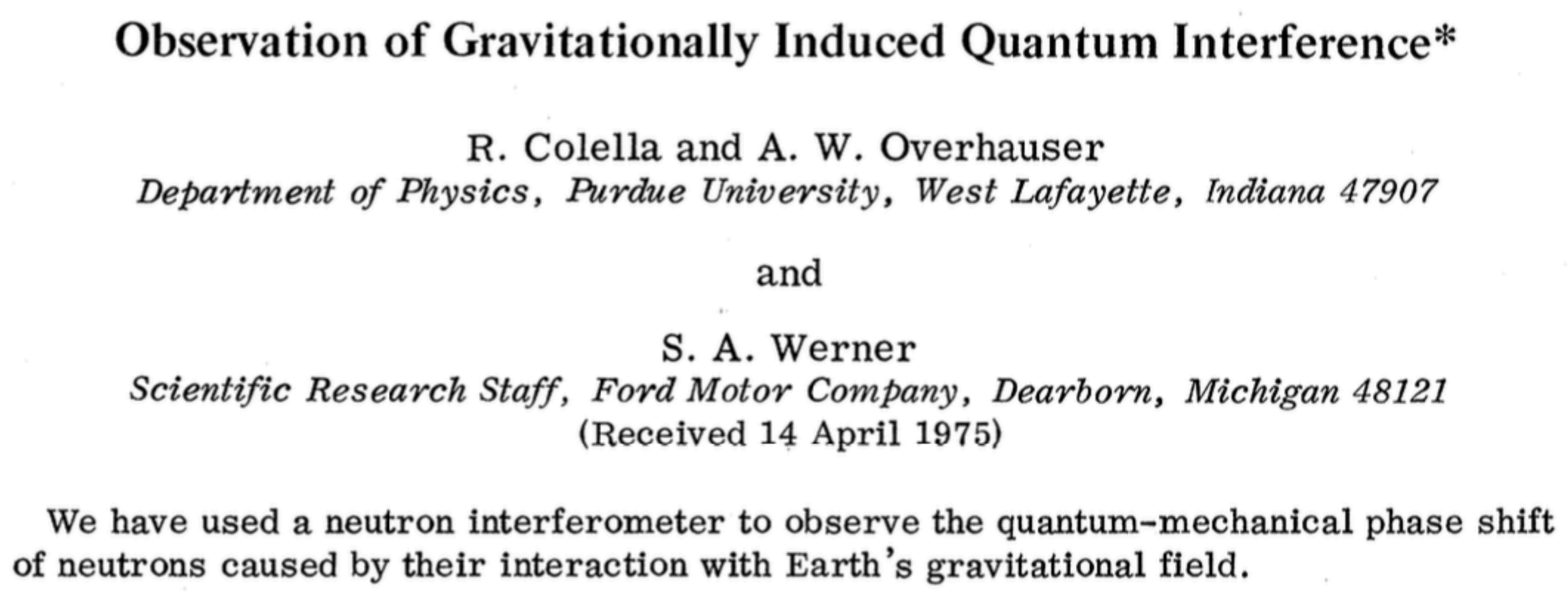


Competing QG Theories

How do we choose between different (versions of) theories?

Make contact with experiments!

Gravity +Quantum



Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

and

S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121

(Received 14 April 1975)

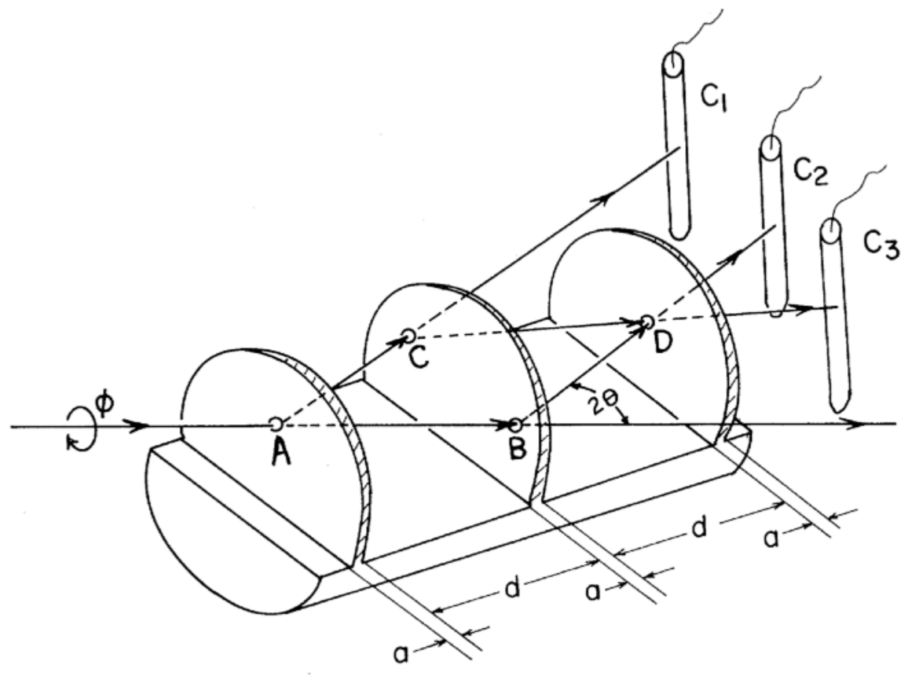
We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

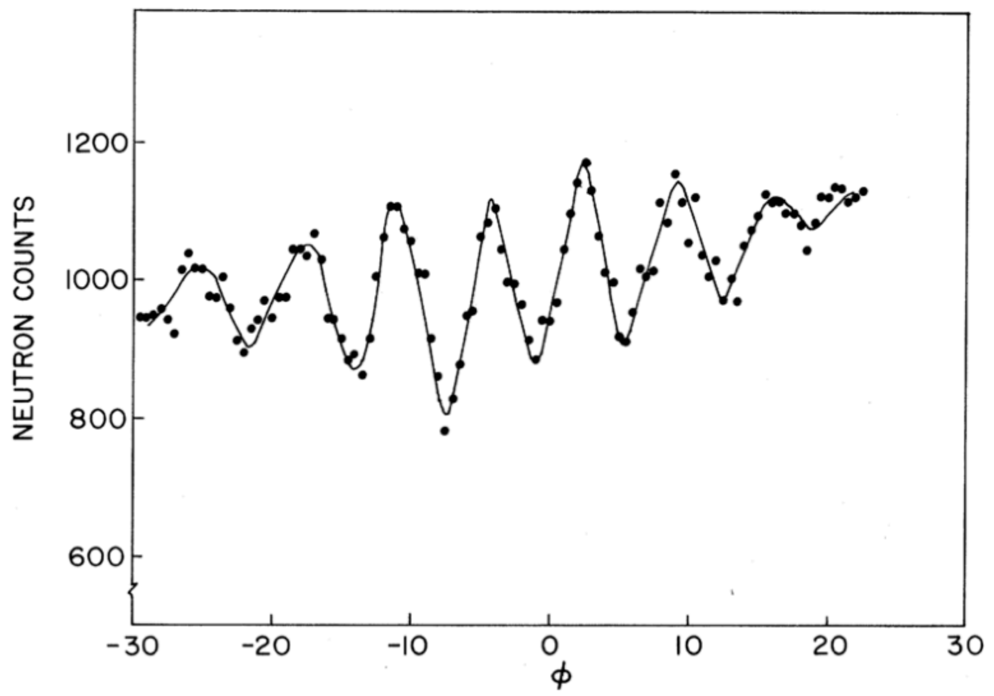
REPORT

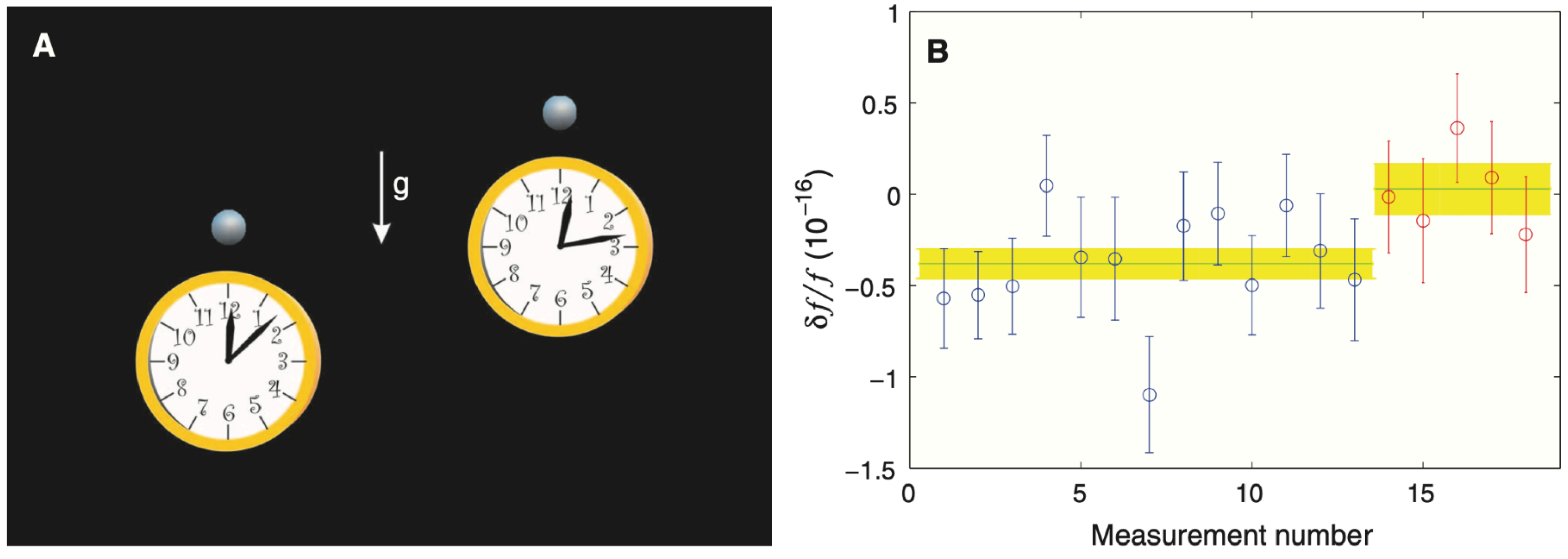
Optical Clocks and Relativity

C. W. Chou*, D. B. Hume, T. Rosenband, D. J. Wineland
+ See all authors and affiliations

Science 24 Sep 2010:
Vol. 329, Issue 5999, pp. 1630-1633
DOI: 10.1126/science.1192720

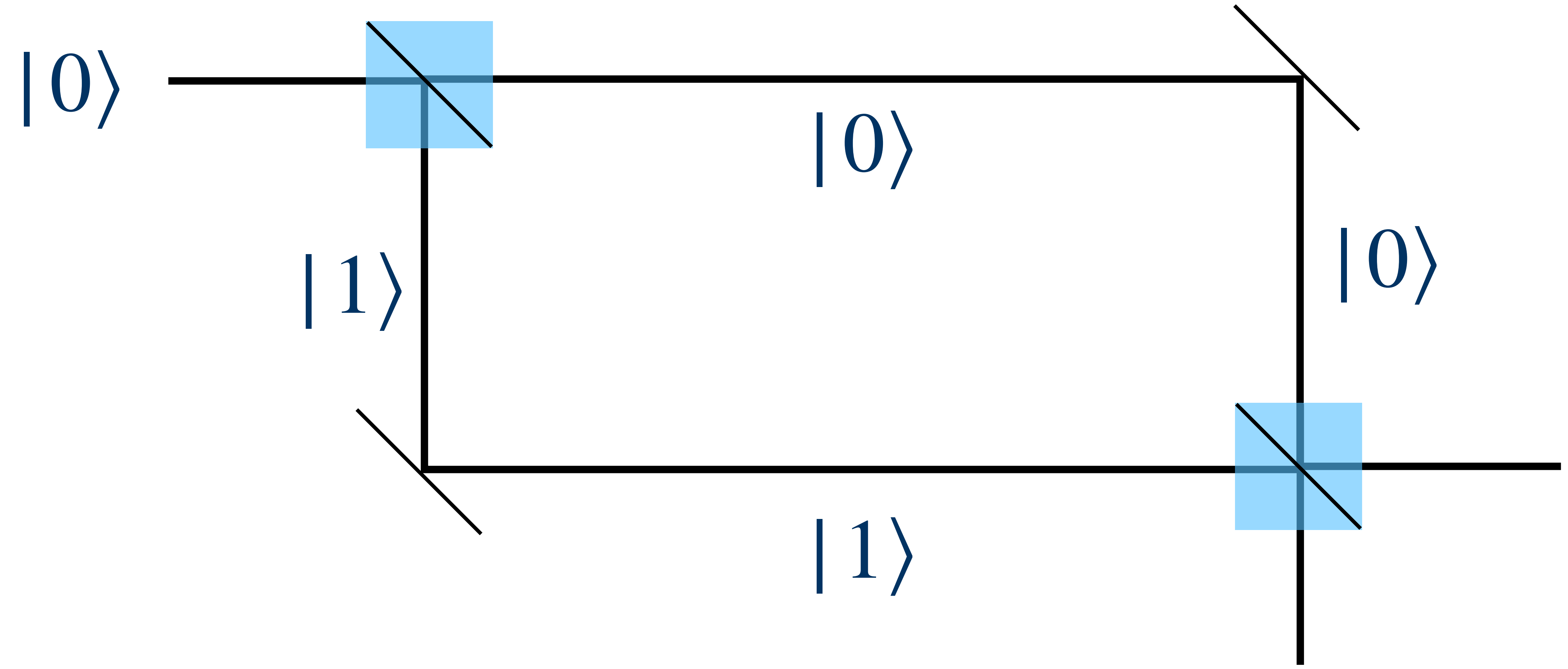




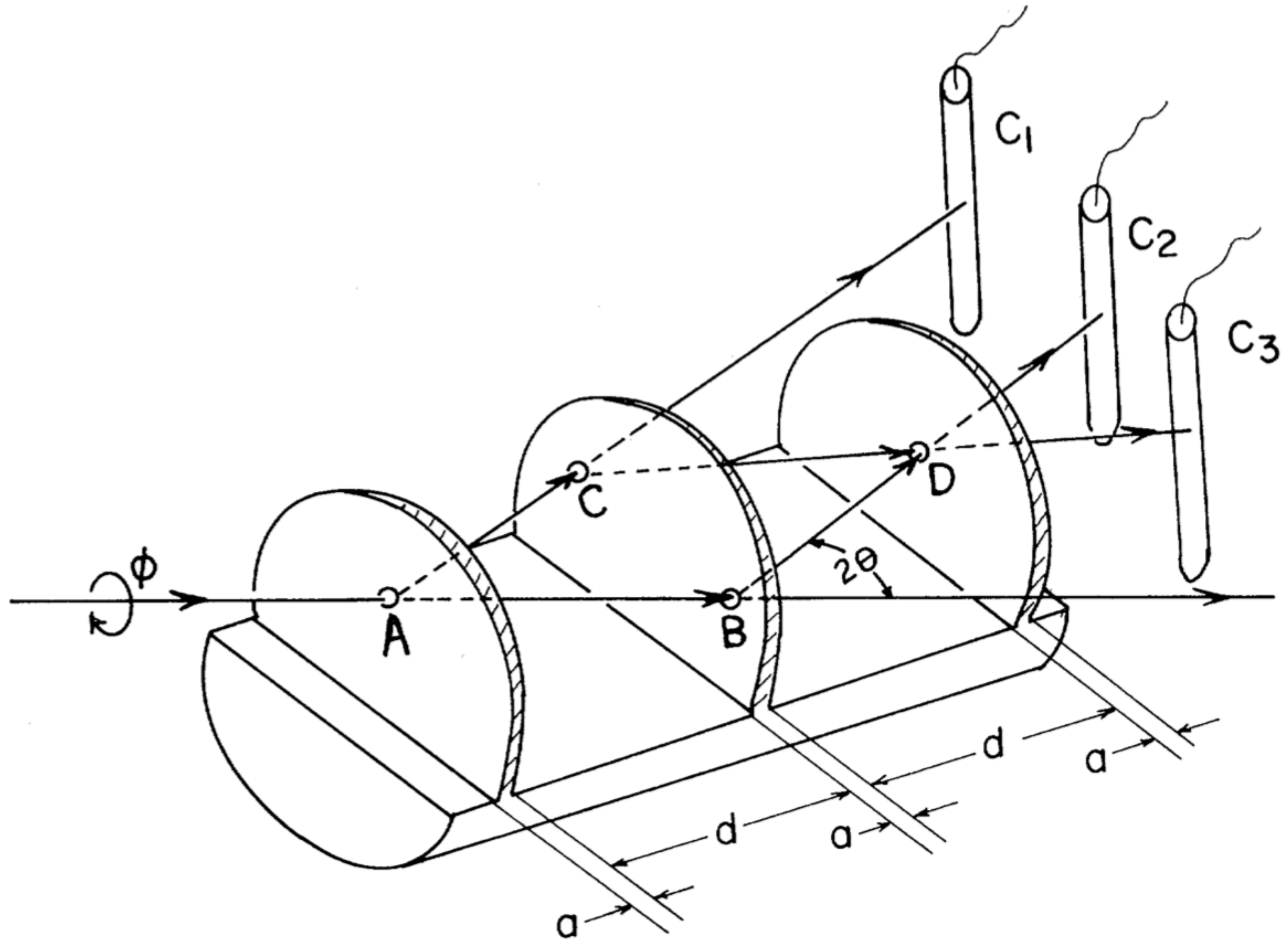


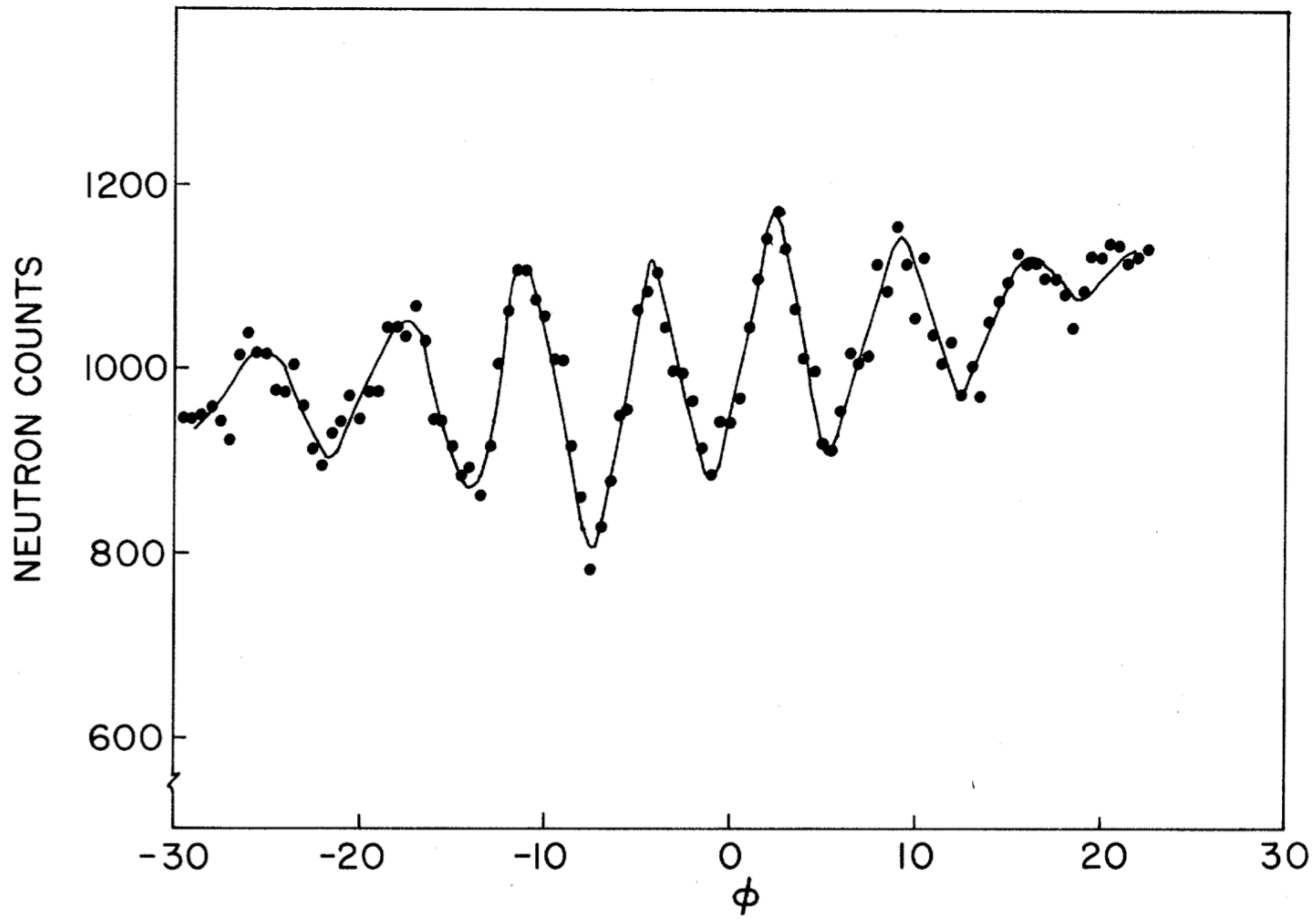
Neat! But gravity is classical....

COW



$$\delta\phi = -\frac{\delta E t}{\hbar} = -mg\delta h\frac{t}{\hbar}$$

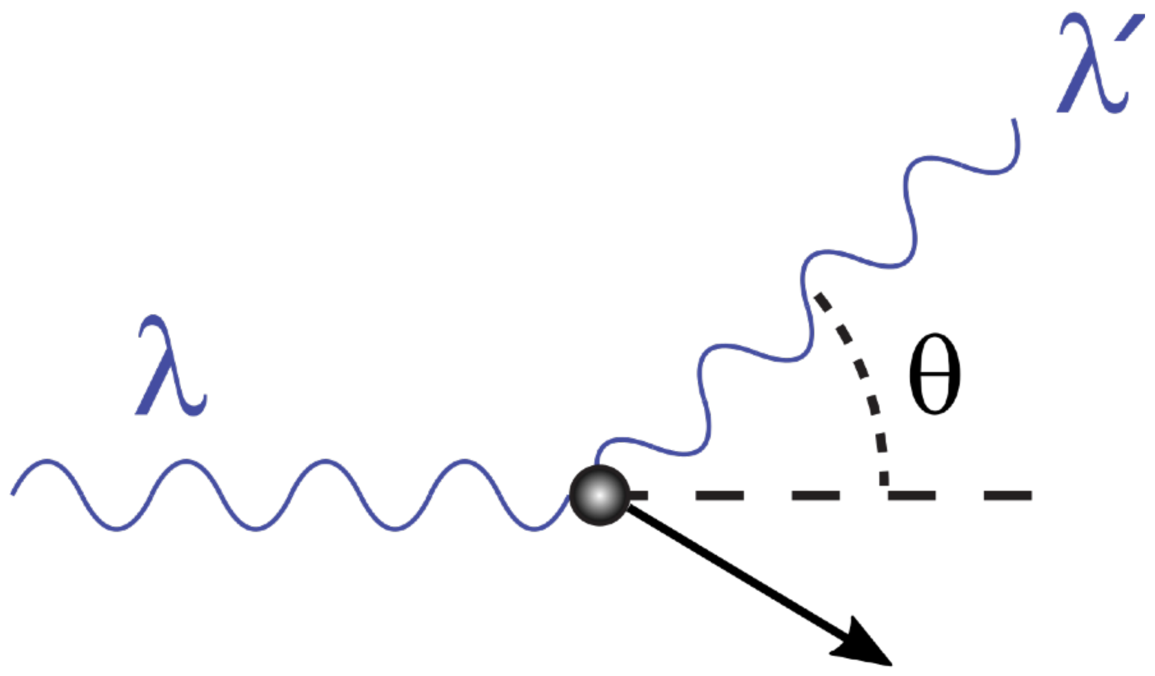




Gravitons might never be detected

Establishing that a field is quantum:

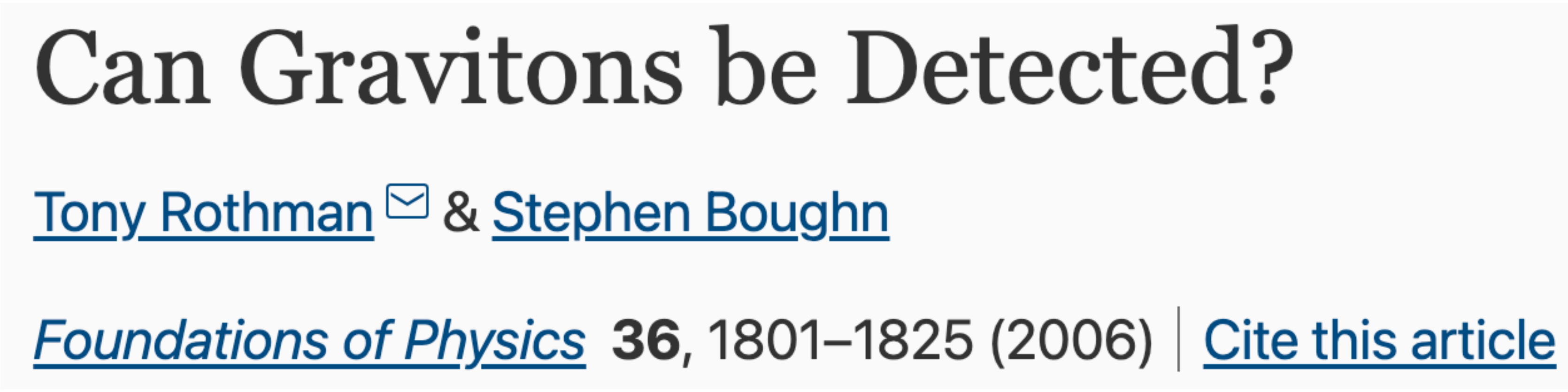
The existence of a particle of the field.



In EM, the existence of the photon has been determined by the photoelectric effect and Compton scattering.

These methods do not work for gravity in our universe.

To detect Compton scattering from a graviton one would need a detector the size of Jupiter, who might collapse under its own weight.



Can Gravitons be Detected?

Tony Rothman & Stephen Boughn

Foundations of Physics **36**, 1801–1825 (2006) | Cite this article

Do we even need QG?

Probing the QG regime of particle physics is impractical.

$m_P \approx 10^{16}$ TeV/c^2

Planck-Mass

14 TeV/c^2

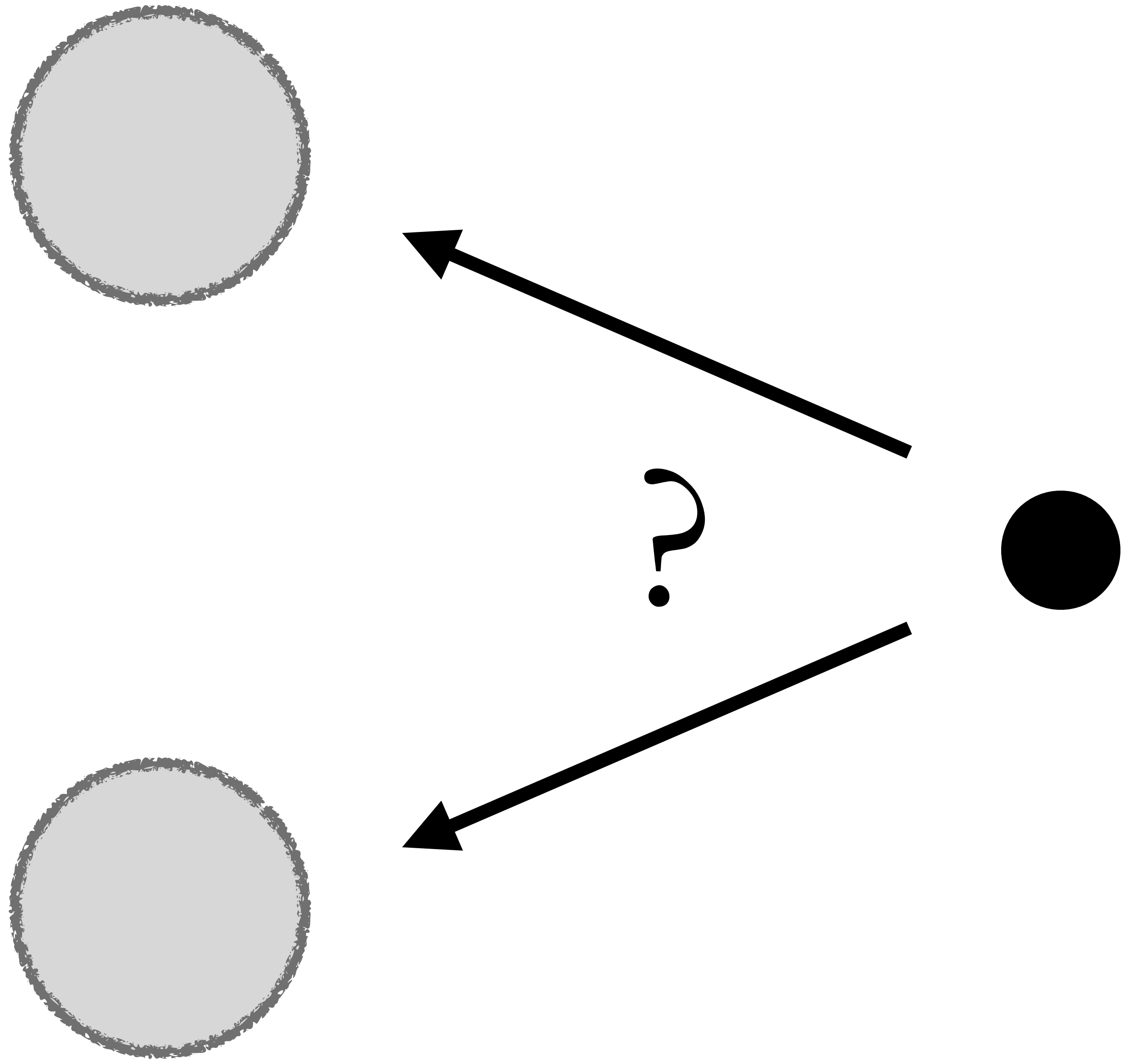
CM energy at the LHC

Fundamental limits on testing predictions of quantum cosmology.

If QG has no experimental consequences (short of jumping into a black hole), does it exist?

Field sourced by a superposition

What is the field generated by a mass in superposition?



If the field is classical...

It might (wait for the) collapse of the superposition.

Penrose Diósi or Ghirardi-Rimini-Weber models

Field sourced by a superposition

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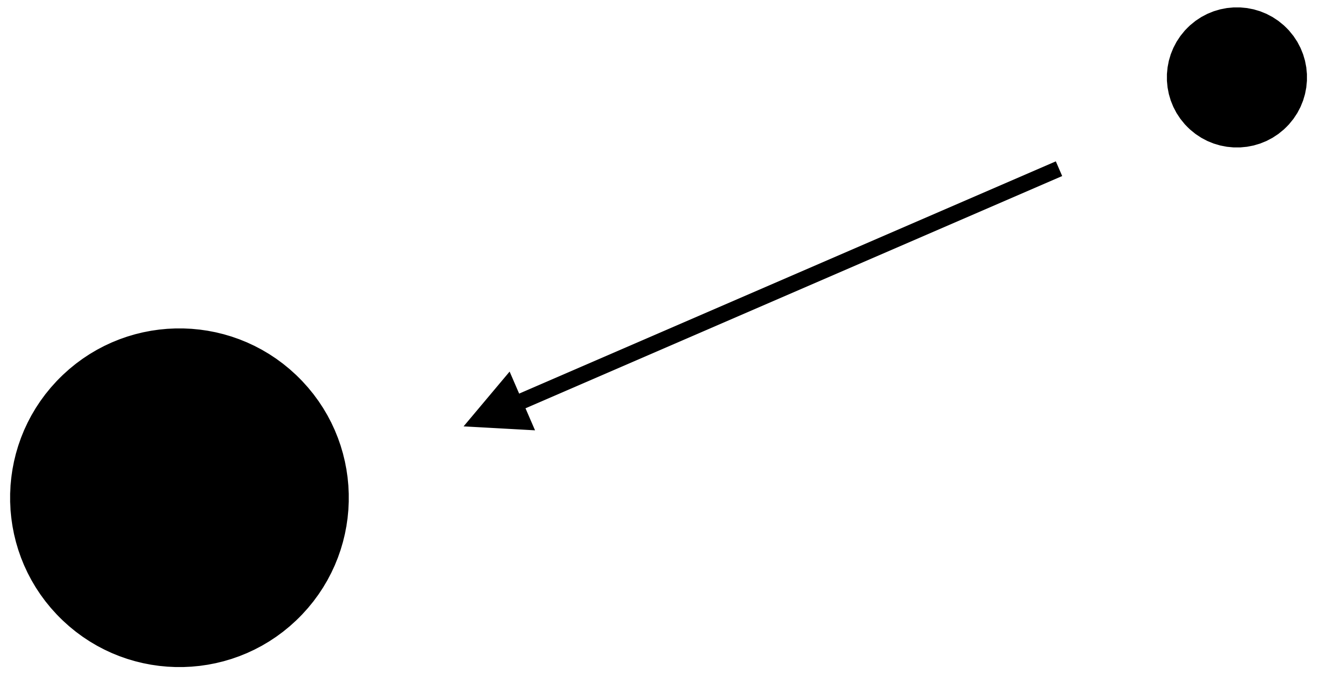
If the field is classical...



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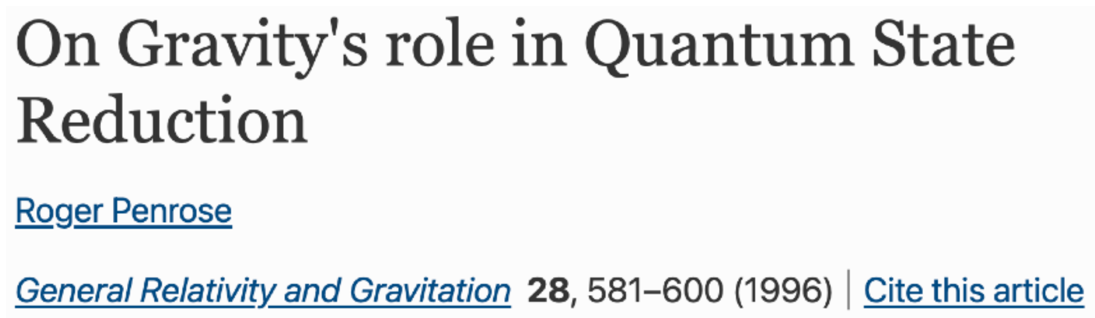

On Gravity's role in Quantum State Reduction

Roger Penrose

General Relativity and Gravitation **28**, 581–600 (1996) | Cite this article

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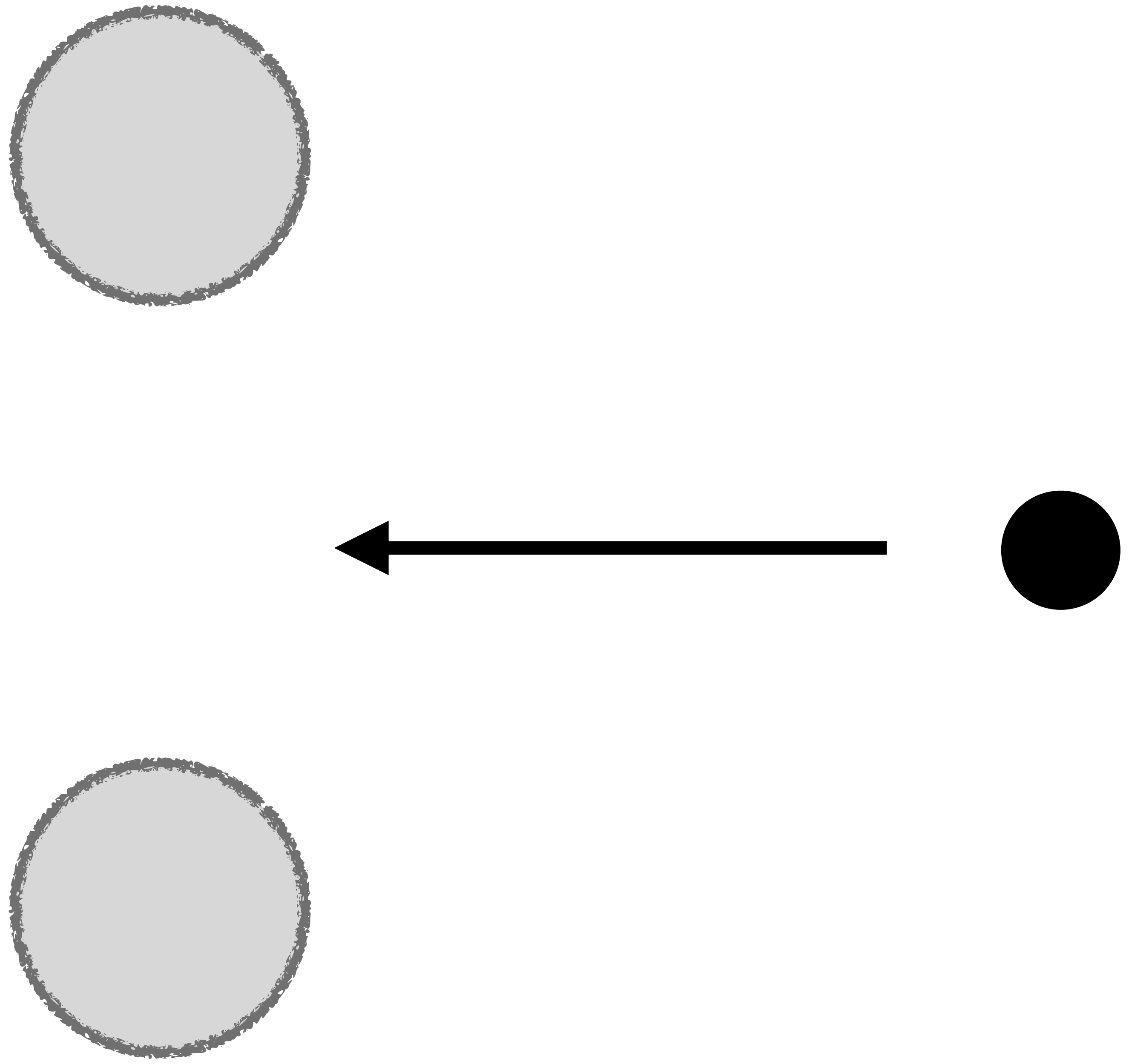


If the field is classical...

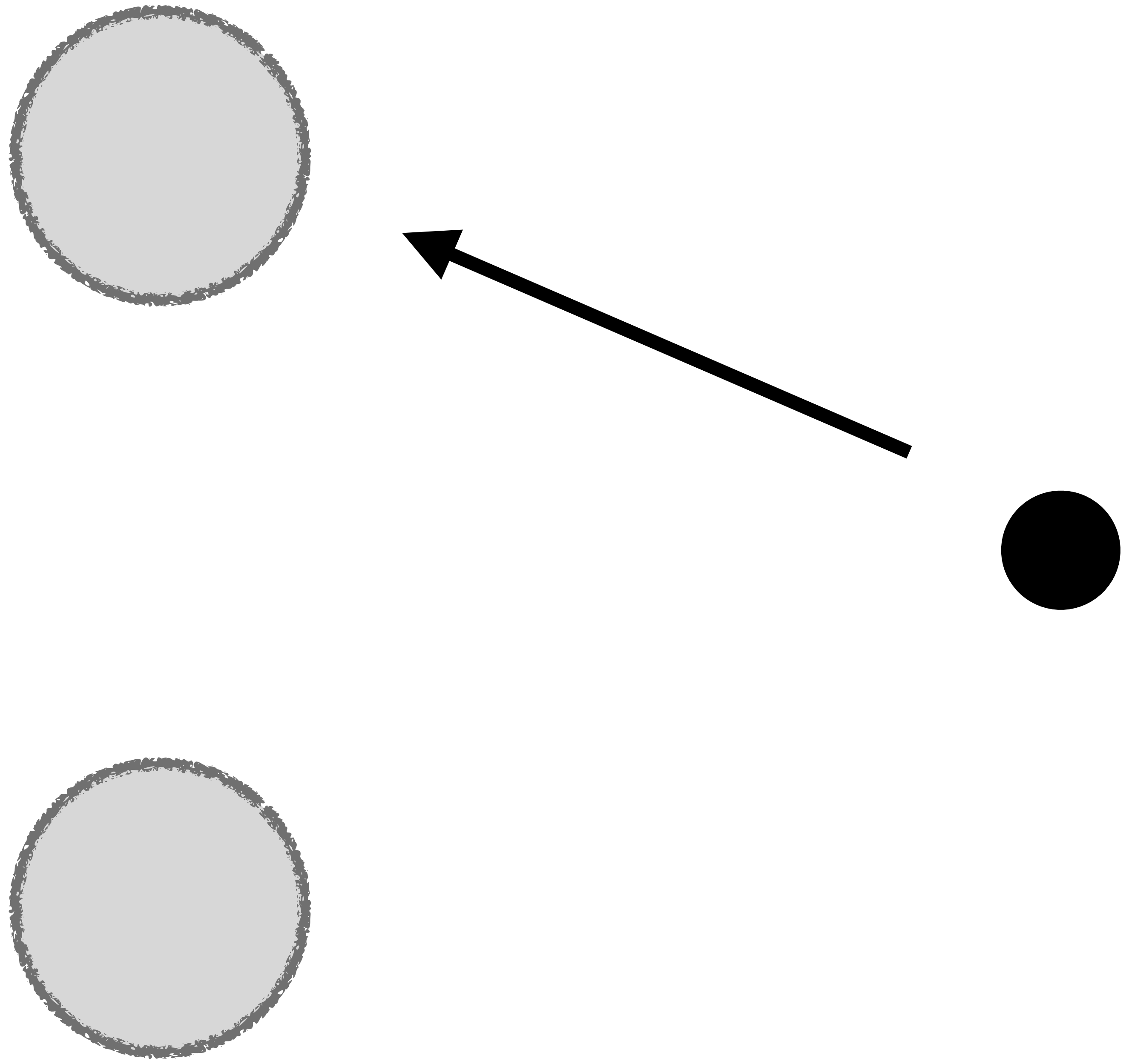
It might get sourced by the expectation value of the stress energy tensor.

Schrödinger-Newton, Semi-Classical gravity

$$G_{\mu\nu} \propto \langle \hat{T}_{\mu\nu} \rangle$$

Field sourced by a superposition

What is the field generated by a mass in superposition?



If the field is classical...

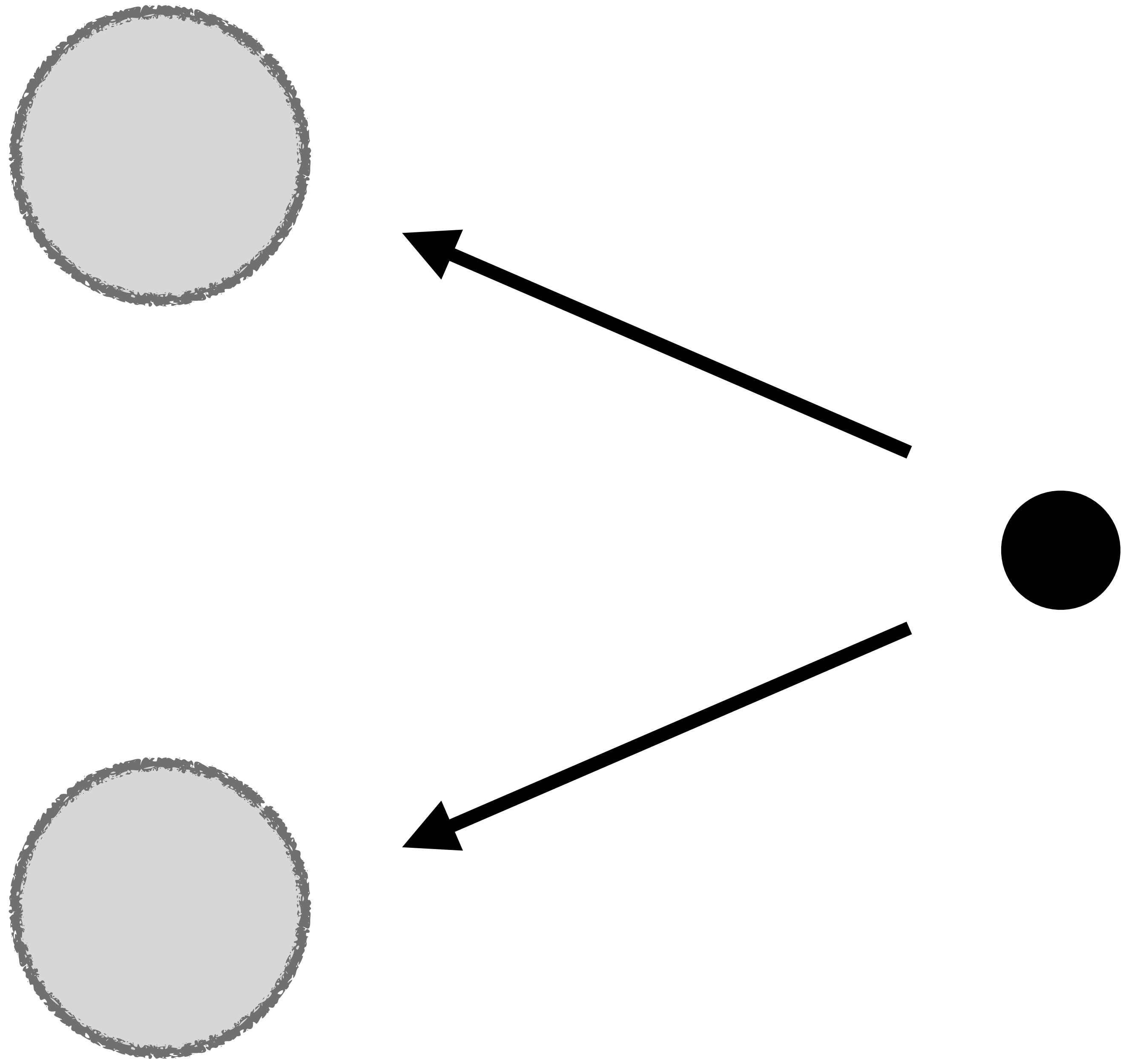
Or sourced at random from one of the terms.

Post-Quantum theories

J. Oppenheim
arxiv.org/abs/1811.03116

Field sourced by a superposition

What is the field generated by a mass in superposition?

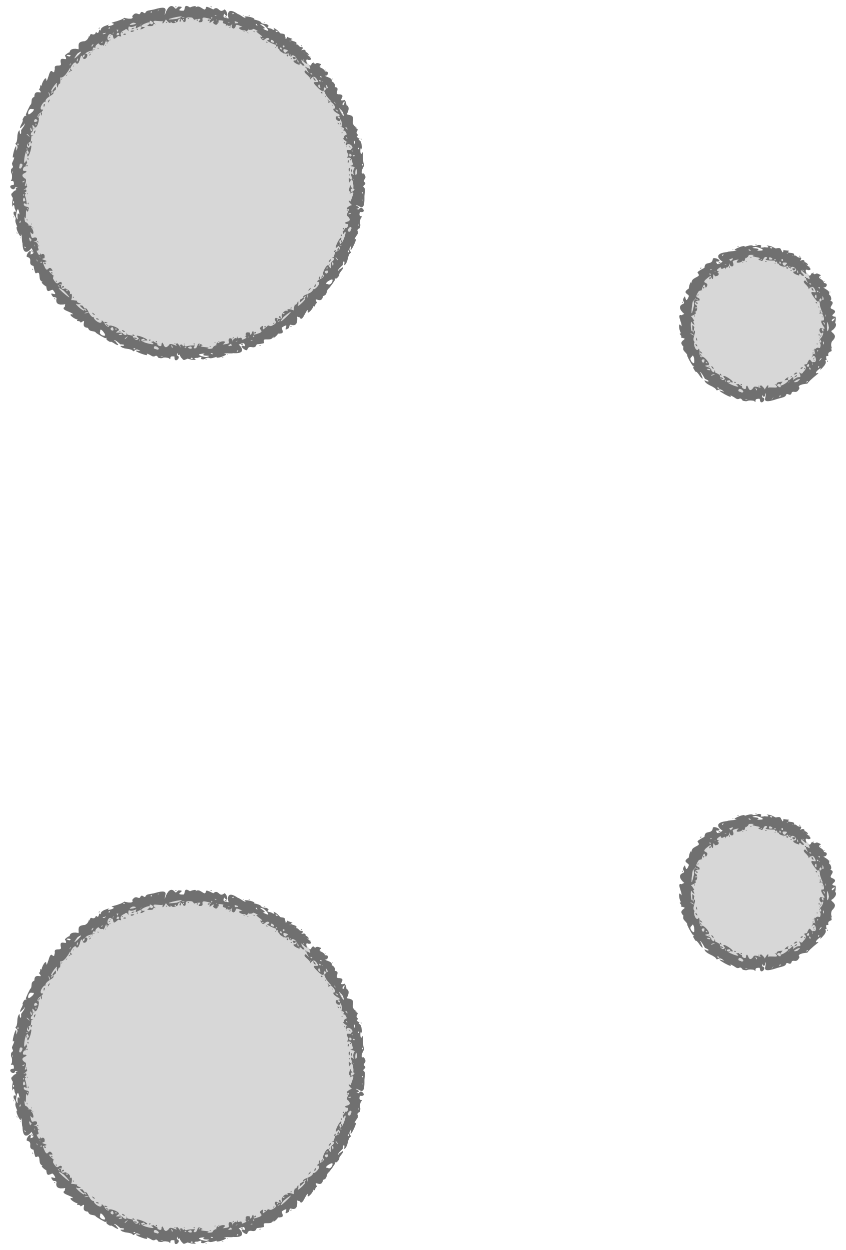


If the field is quantum...

It will be in a superposition

Field sourced by a superposition

What is the field generated by a mass in superposition?



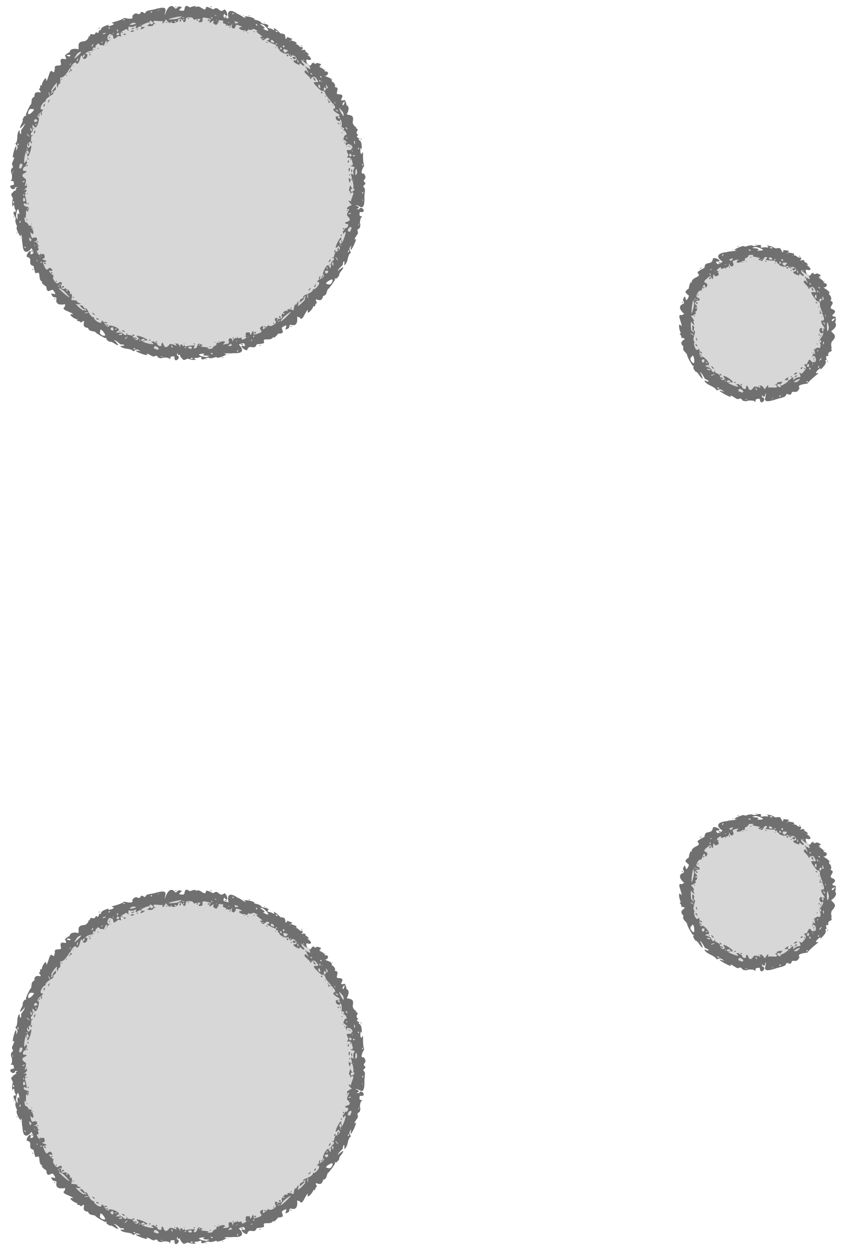
If the field is quantum...

It will be in a superposition

It will cause a superposition
in the test mass.

Field sourced by a superposition

If the gravitational field is quantum, then it can create superpositions of masses.



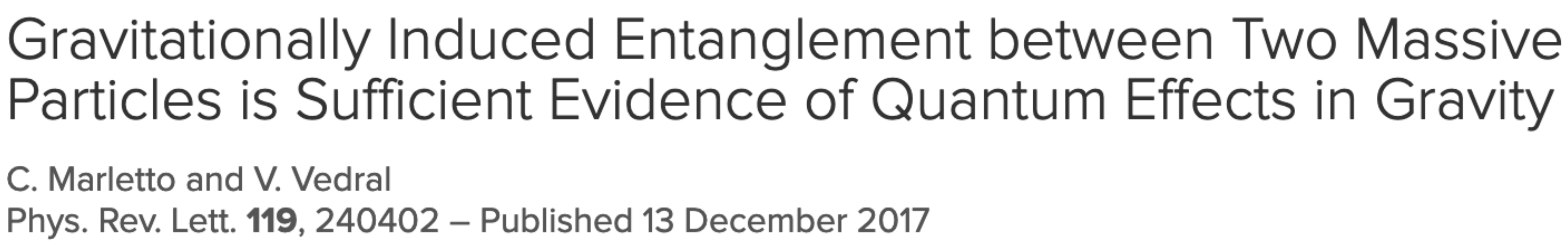
How do you detect such a superposition?

In reality, the forces are too small to displace a mass in this way.

But not only are the masses in a superposition, they are **entangled**!

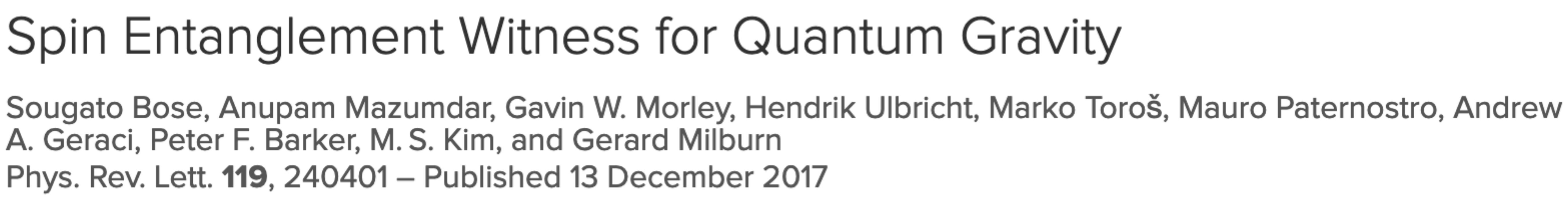
Proposals

A Test!



Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

C. Marletto and V. Vedral
Phys. Rev. Lett. **119**, 240402 – Published 13 December 2017



Spin Entanglement Witness for Quantum Gravity

Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro, Andrew A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn
Phys. Rev. Lett. **119**, 240401 – Published 13 December 2017

A classical field cannot entangle two masses.*

If gravity can entangle two masses, then gravity cannot be mediated by a classical* system.

GME

Spin Entanglement Witness for Quantum Gravity

Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro, Andrew A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn
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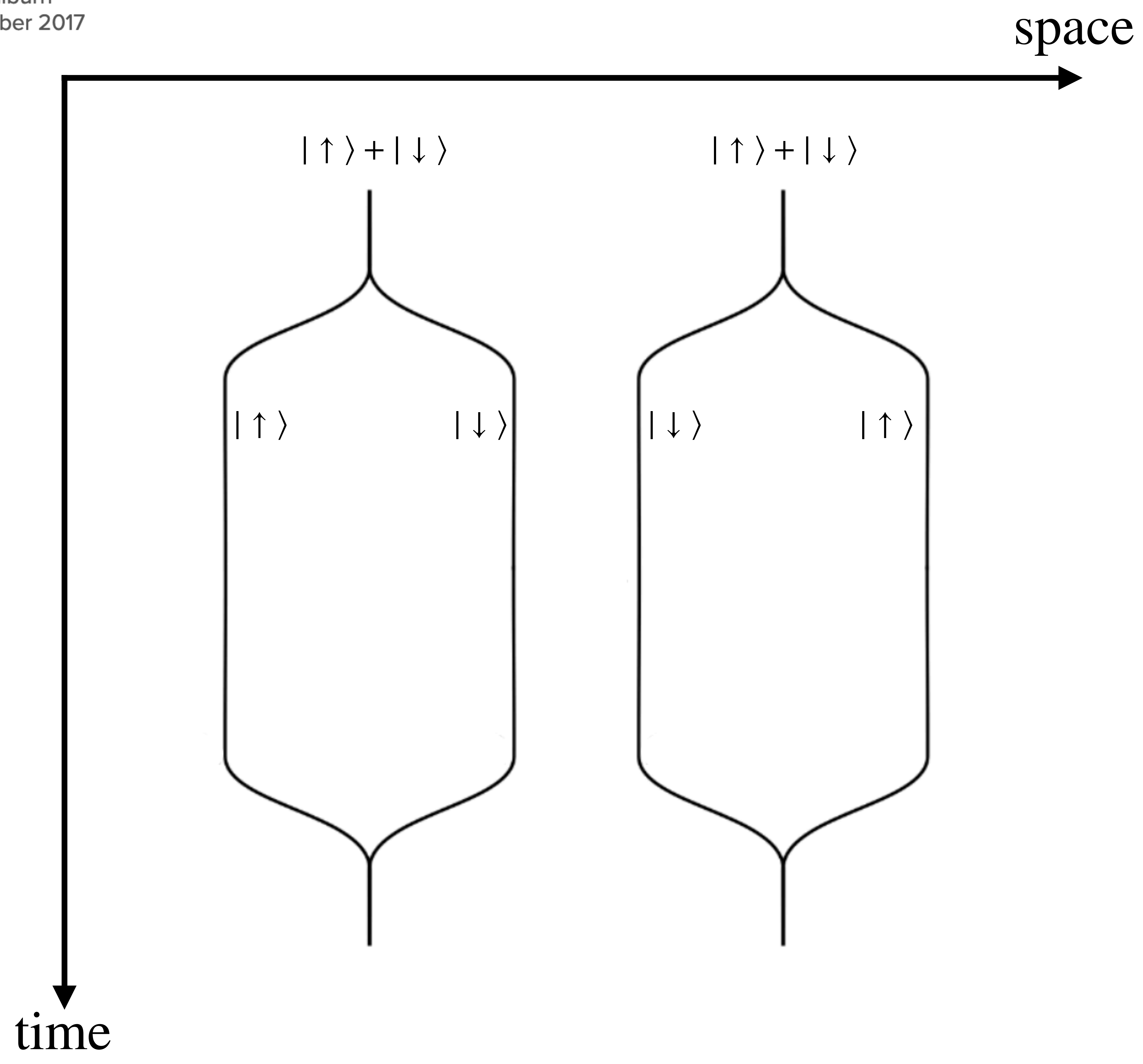


Preparation

Superposition

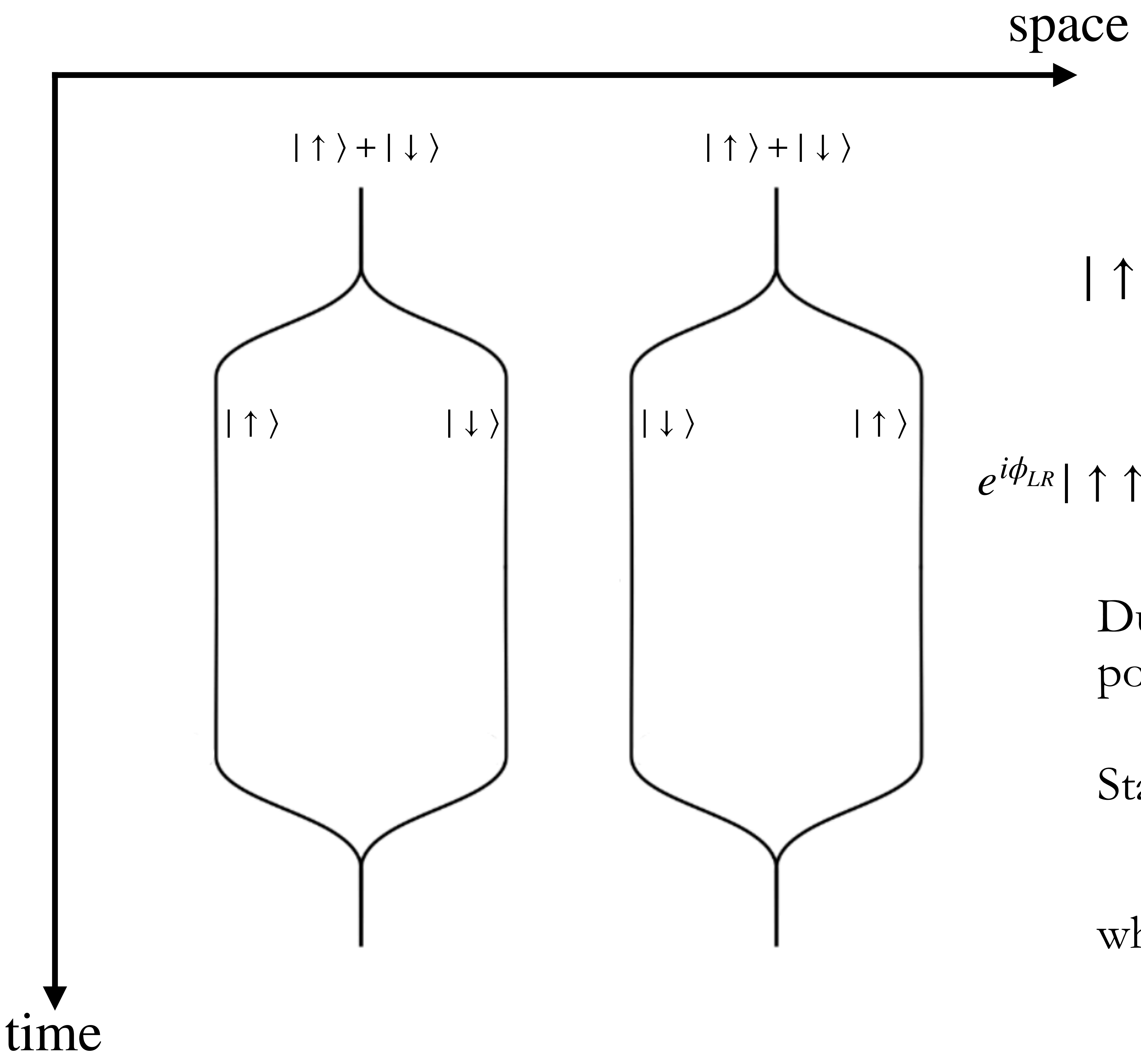
Free Fall

Recombination

Measurements

GME

$$\mathcal{H}_{\text{spin}_\text{A}} \otimes \mathcal{H}_{\text{spin}_\text{B}} \otimes \mathcal{H}_{\text{CM}_\text{A}} \otimes \mathcal{H}_{\text{CM}_\text{B}} \otimes \mathcal{H}_{\text{geometry}}$$



Preparation

$$(|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle)|CC\rangle|g_{CC}\rangle$$

Superposition

$$|\uparrow\uparrow\rangle|LR\rangle|g_{LR}\rangle + |\uparrow\downarrow\rangle|LL\rangle|g_{LL}\rangle + |\downarrow\uparrow\rangle|RR\rangle|g_{RR}\rangle + |\downarrow\downarrow\rangle|RL\rangle|g_{RL}\rangle$$

Free Fall

$$e^{i\phi_{LR}}|\uparrow\uparrow\rangle|LR\rangle|g_{LR}\rangle + e^{i\phi_{LL}}|\uparrow\downarrow\rangle|LL\rangle|g_{LL}\rangle + e^{i\phi_{RR}}|\downarrow\uparrow\rangle|RR\rangle|g_{RR}\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle|RL\rangle|g_{RL}\rangle$$

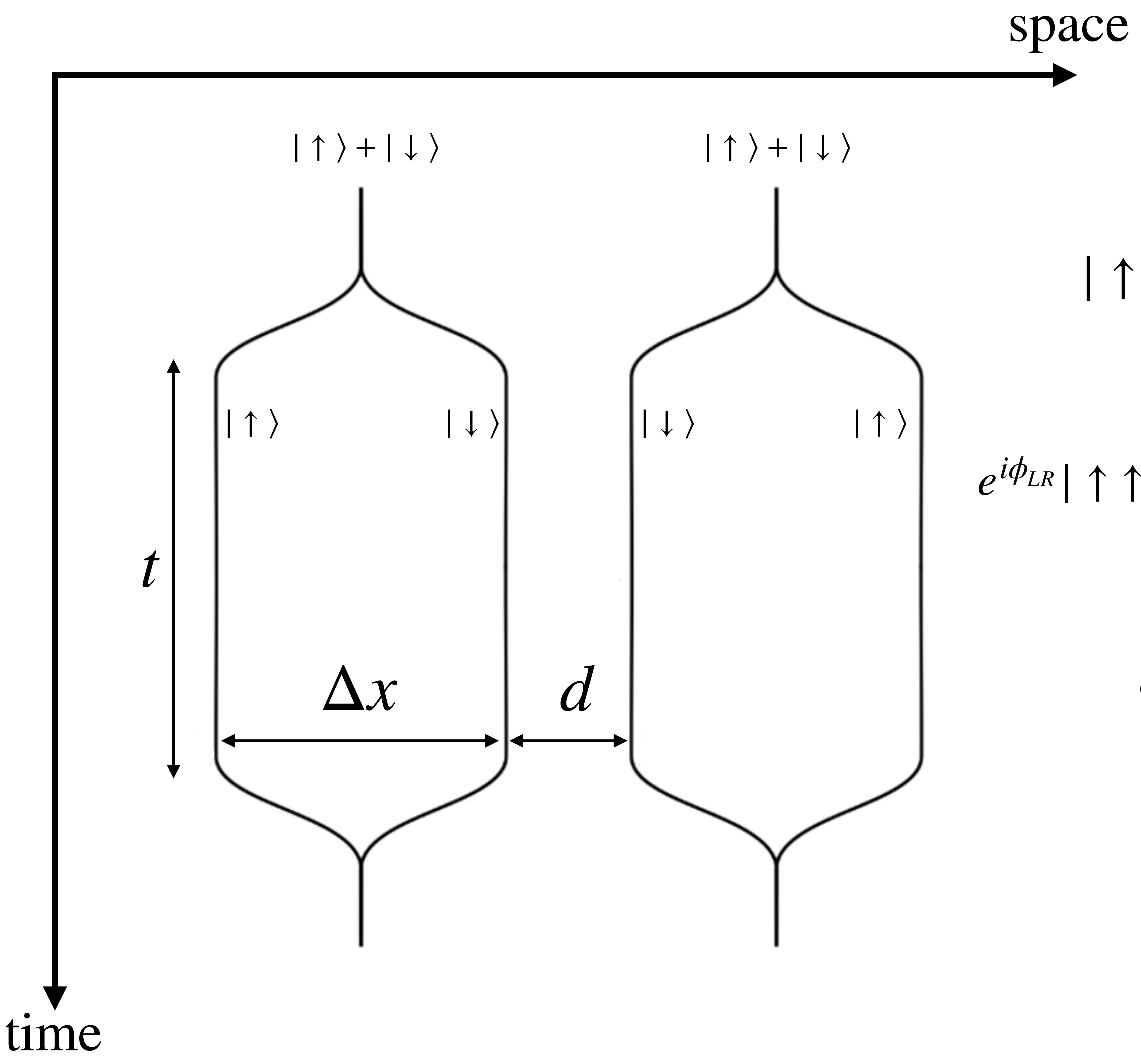
During free fall, gravity is not strong enough to appreciably change the position of the particles (Position Eigenstate Approximation)

State evolves by acquiring a phase according to $\phi = -\dfrac{Et}{\hbar}$

where E is calculated using the Newtonian potential: $E = -\dfrac{Gm^2}{r}$

GME

$$\mathscr{H}_{\mathrm{spin_A}} \otimes \mathscr{H}_{\mathrm{spin_B}} \otimes \mathscr{H}_{\mathrm{CM_A}} \otimes \mathscr{H}_{\mathrm{CM_B}} \otimes \mathscr{H}_{\mathrm{geometry}}$$



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Free Fall

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$$\phi_{RL} = \frac{Gm^2}{d}\frac{t}{\hbar} \qquad \phi_{LR} = \frac{Gm^2}{d + 2\Delta x}\frac{t}{\hbar} \qquad \phi_{RR} = \frac{Gm^2}{d + \Delta x}\frac{t}{\hbar} = \phi_{LL}$$

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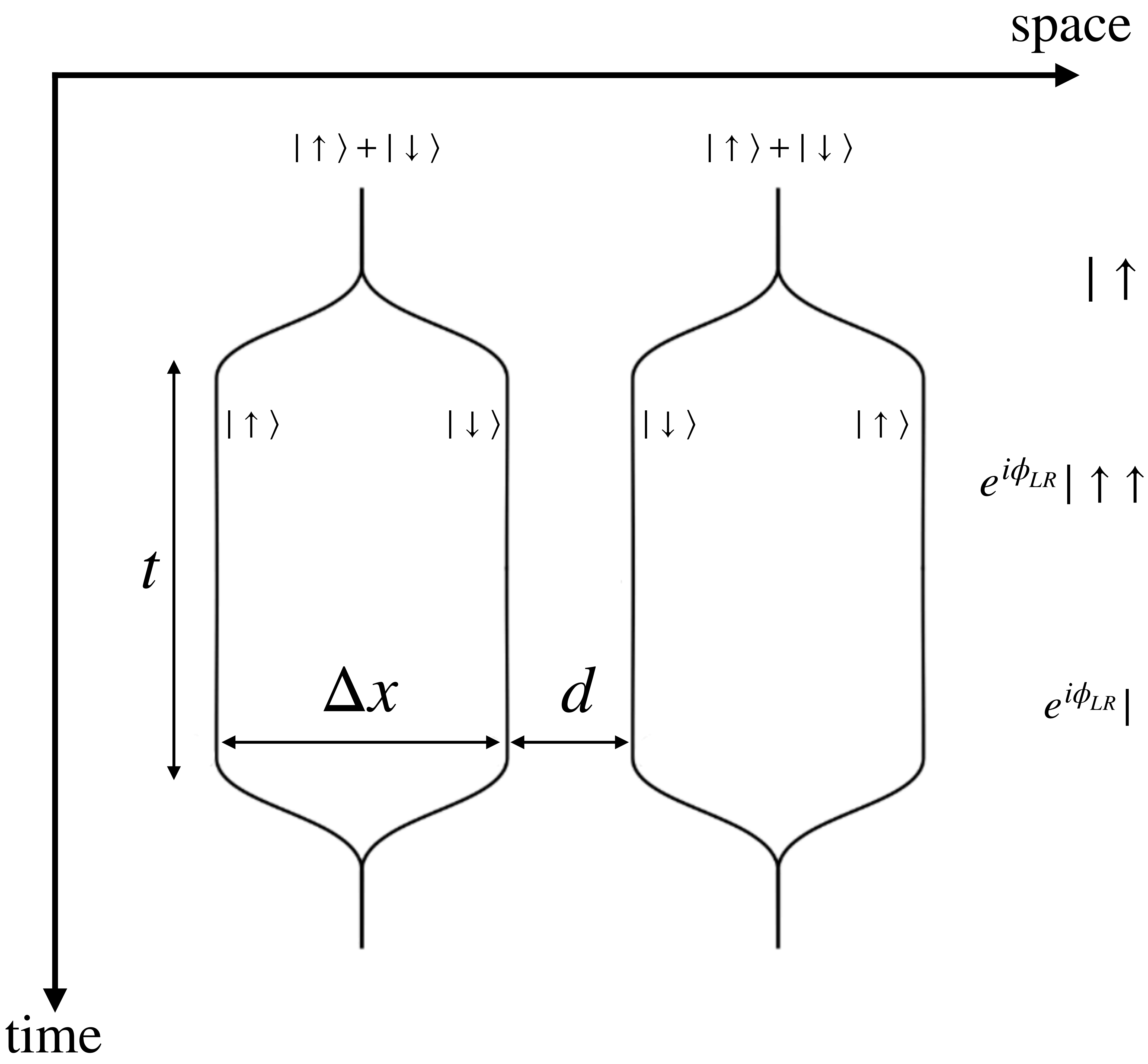
$$\mathscr{H}_{\text{spin}_\text{A}} \otimes \mathscr{H}_{\text{spin}_\text{B}} \otimes \mathscr{H}_{\text{CM}_\text{A}} \otimes \mathscr{H}_{\text{CM}_\text{B}} \otimes \mathscr{H}_{\text{geometry}}$$



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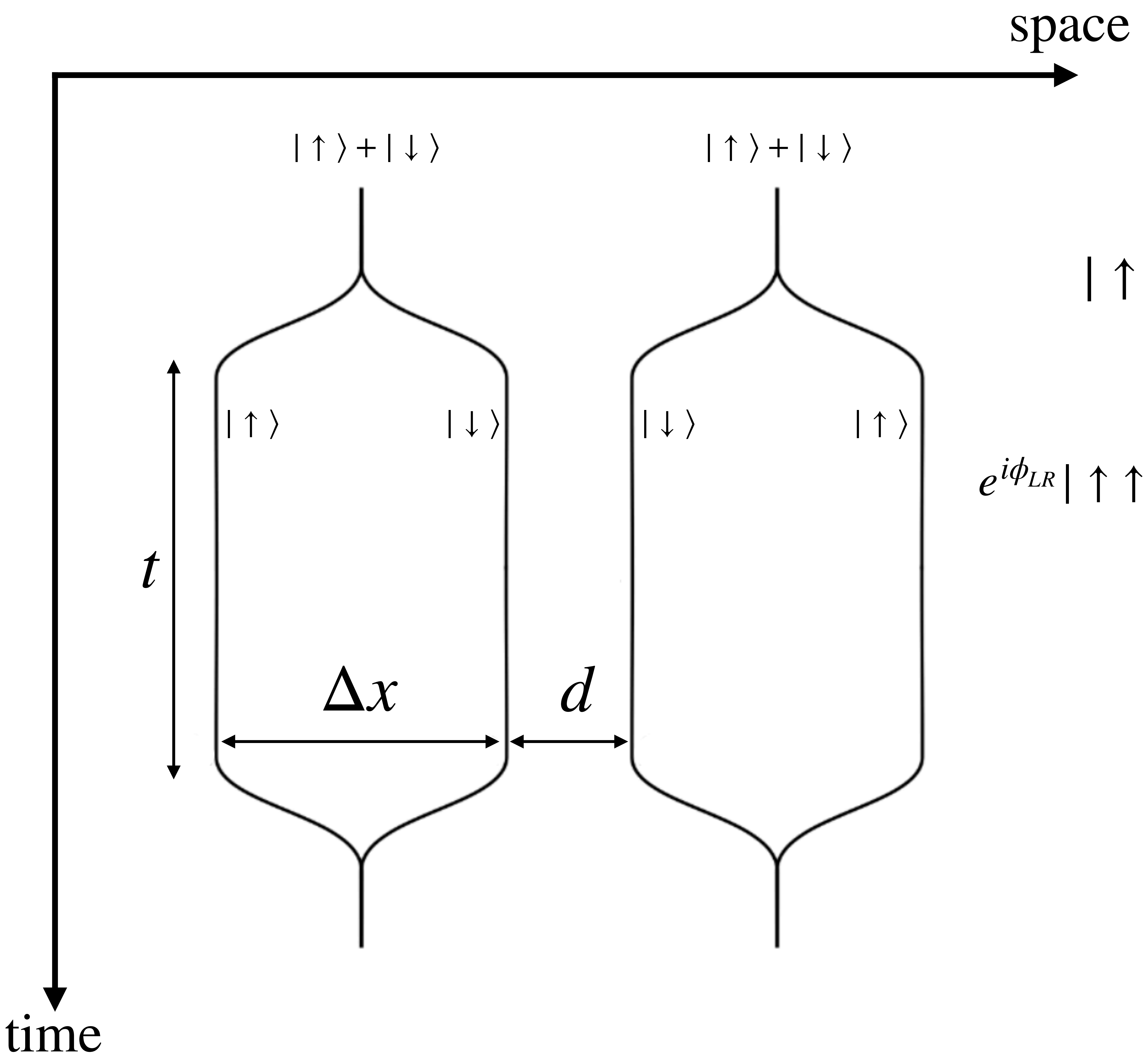
Recombination

$$e^{i\phi_{LR}}|\uparrow\uparrow\rangle|CC\rangle|g_{CC}\rangle + e^{i\phi_{LL}}|\uparrow\downarrow\rangle|CC\rangle|g_{CC}\rangle + e^{i\phi_{RR}}|\downarrow\uparrow\rangle|CC\rangle|g_{CC}\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle|CC\rangle|g_{CC}\rangle$$

GME

$$\mathscr{H}_{\mathrm{spin_A}} \otimes \mathscr{H}_{\mathrm{spin_B}} \otimes \mathscr{H}_{\mathrm{CM_A}} \otimes \mathscr{H}_{\mathrm{CM_B}} \otimes \mathscr{H}_{\mathrm{geometry}}$$



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Free Fall

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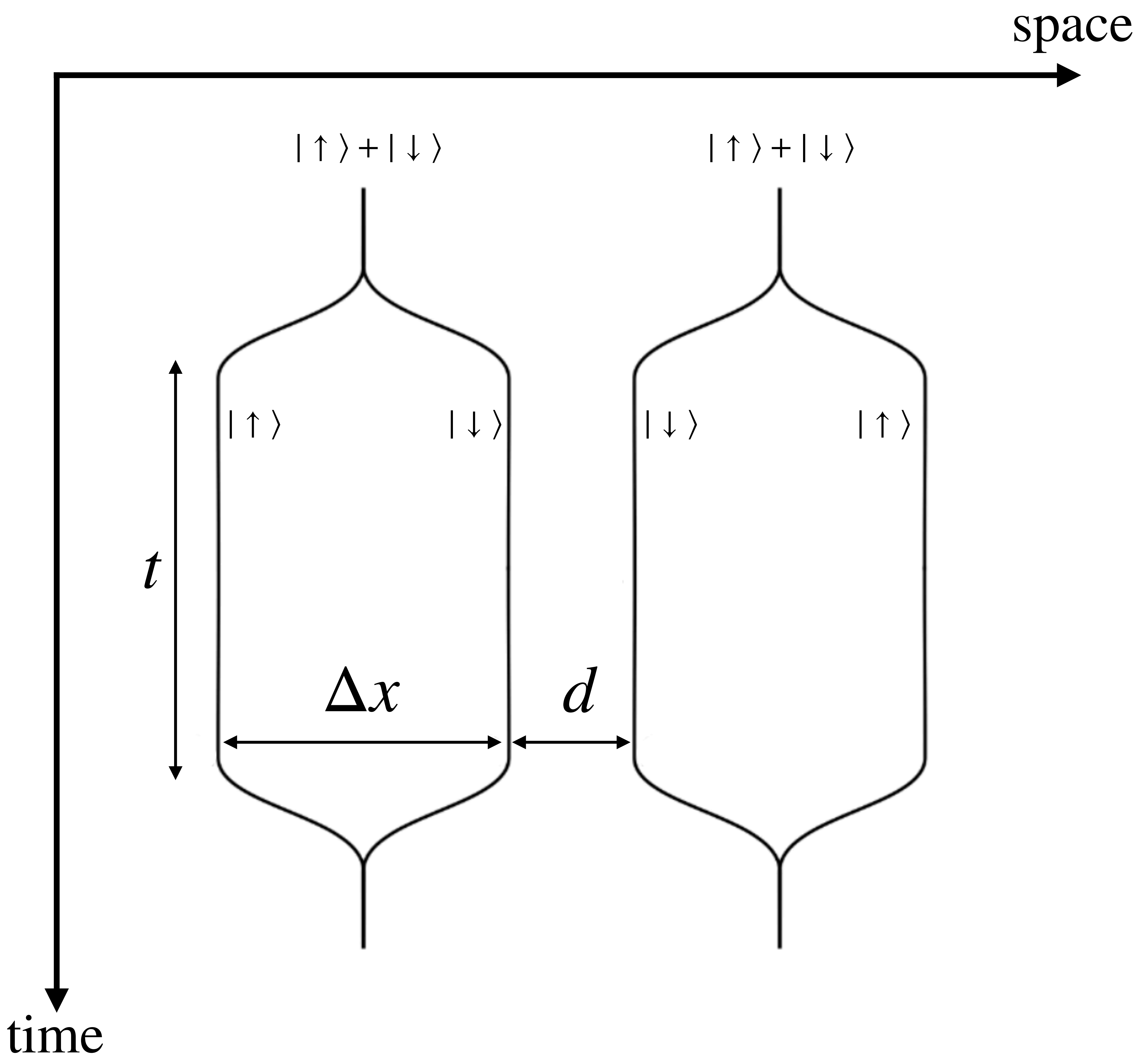
Recombination

$$\big(e^{i\phi_{LR}}|\uparrow\uparrow\rangle+e^{i\phi_{LL}}|\uparrow\downarrow\rangle+e^{i\phi_{RR}}|\downarrow\uparrow\rangle+e^{i\phi_{RL}}|\downarrow\downarrow\rangle\big)|CC\rangle|g_{CC}\rangle$$

Measurements

$$e^{i\phi_{LR}}|\uparrow\uparrow\rangle+e^{i\phi_{LL}}|\uparrow\downarrow\rangle+e^{i\phi_{RR}}|\downarrow\uparrow\rangle+e^{i\phi_{RL}}|\downarrow\downarrow\rangle$$

GME



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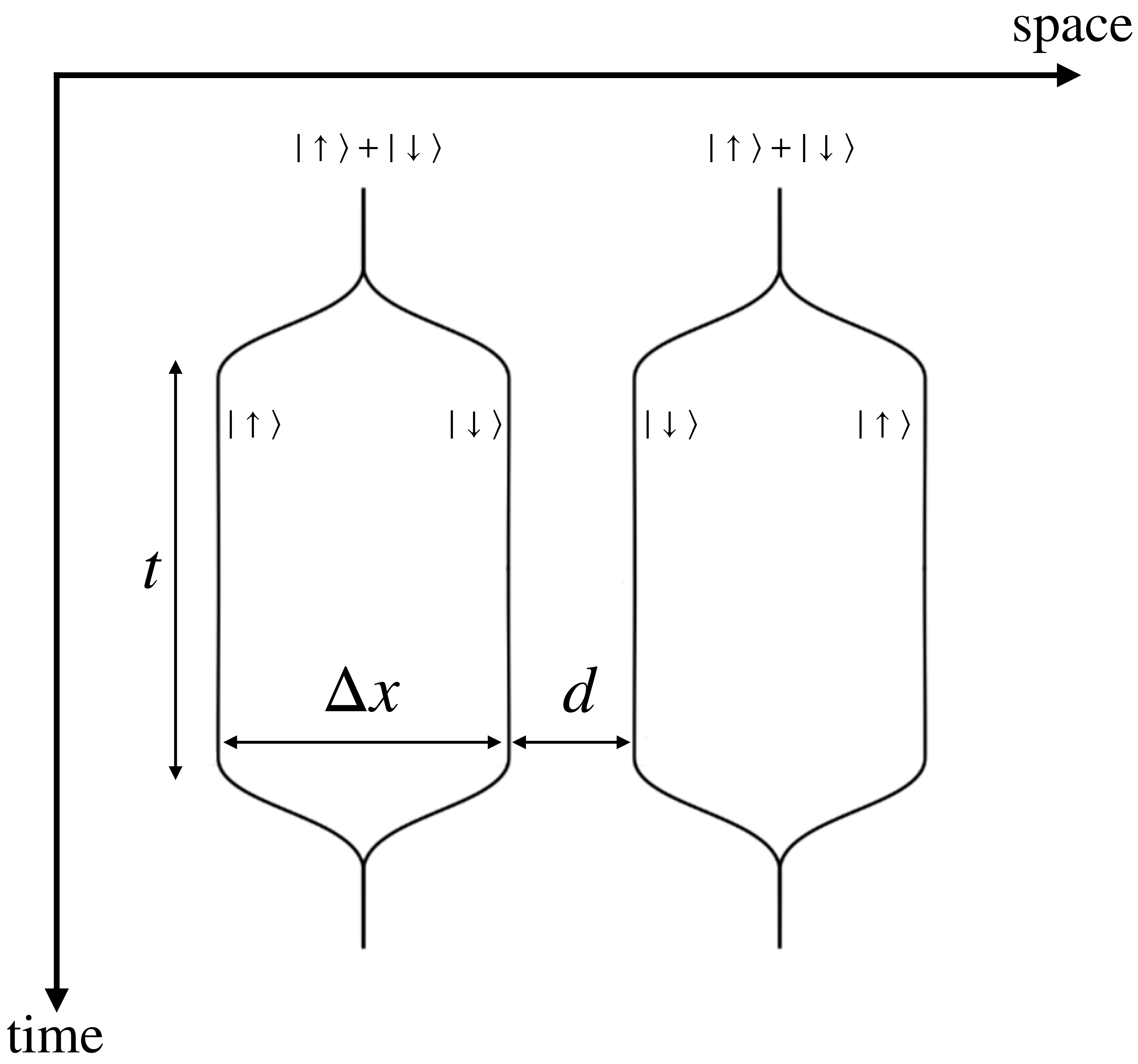
$$\Delta x \gg d \implies \phi_{RL} \gg \phi_{LL}, \phi_{LR}, \phi_{RR}$$

$$|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle$$

Entangled $\phi_{RL} \sim 1$

GME



$$|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle$$

Entangled $\phi_{RL} = \frac{Gm^2}{d}\frac{t}{\hbar} \approx 1$

Decoherence: $t \approx 1\text{s}$

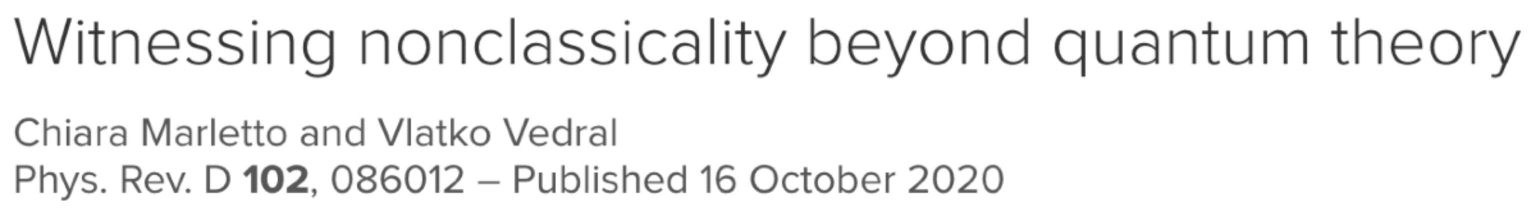
EM Isolation: $d \approx 200\mu\text{m}$

$$\implies m \approx 10^{-14}\text{kg} \approx 10^{12}\text{amu}$$

$$\approx 10^{-6} m_P$$

So what?

If two systems A and B are interacting via a third system G, and they become entangled as a result, then G cannot be a classical system.



Witnessing nonclassicality beyond quantum theory

Chiara Marletto and Vlatko Vedral
Phys. Rev. D **102**, 086012 – Published 16 October 2020

[Submitted on 2 Dec 2020]

A no-go theorem on the nature of the gravitational field beyond quantum theory

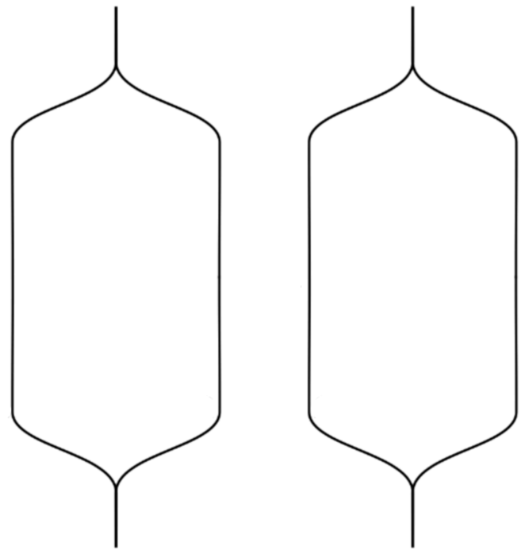
Thomas D. Galley, Flaminia Giacomini, John H. Selby

Classical defined as "no interference effects" or "no non-commuting variables".

If GEM is detected then:

- gravitational field is not classical (but not necessarily quantum!)
- gravitational field is a non-causal classical field,
- gravity is not mediated by a field: direct interparticle interaction,

So what?

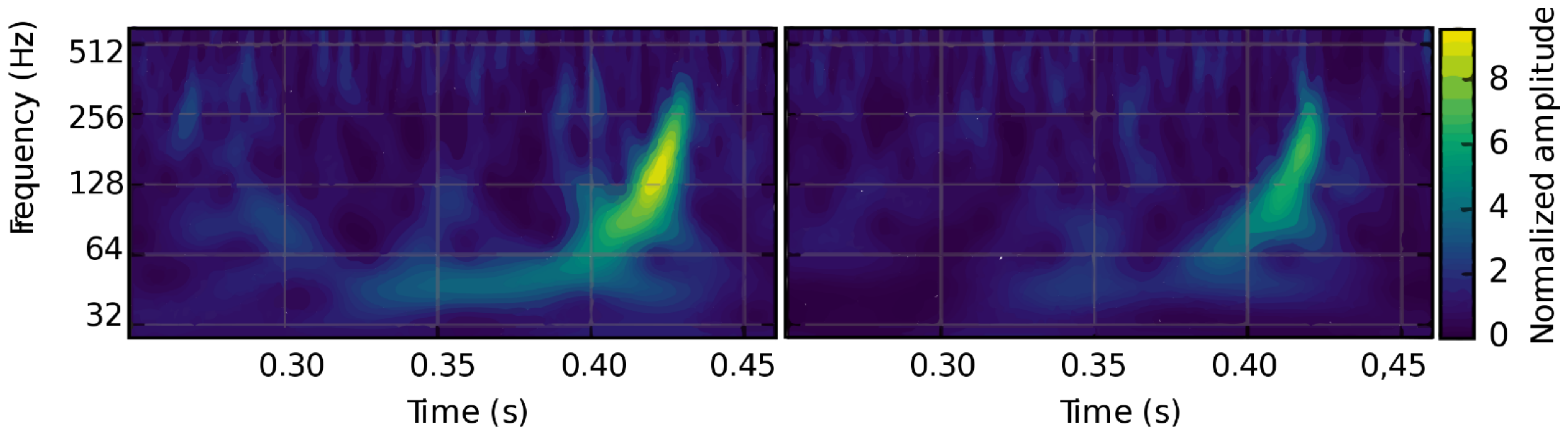


We used the Newtonian term $H_G = -\dfrac{GMm}{|x_1 - x_2|}$ to compute the phases.

GR tells us that gravity is mediated locally by a field, the metric tensor.

This is a valid approximation in this situation: small velocities and $|x_1 - x_2| \ll ct$.

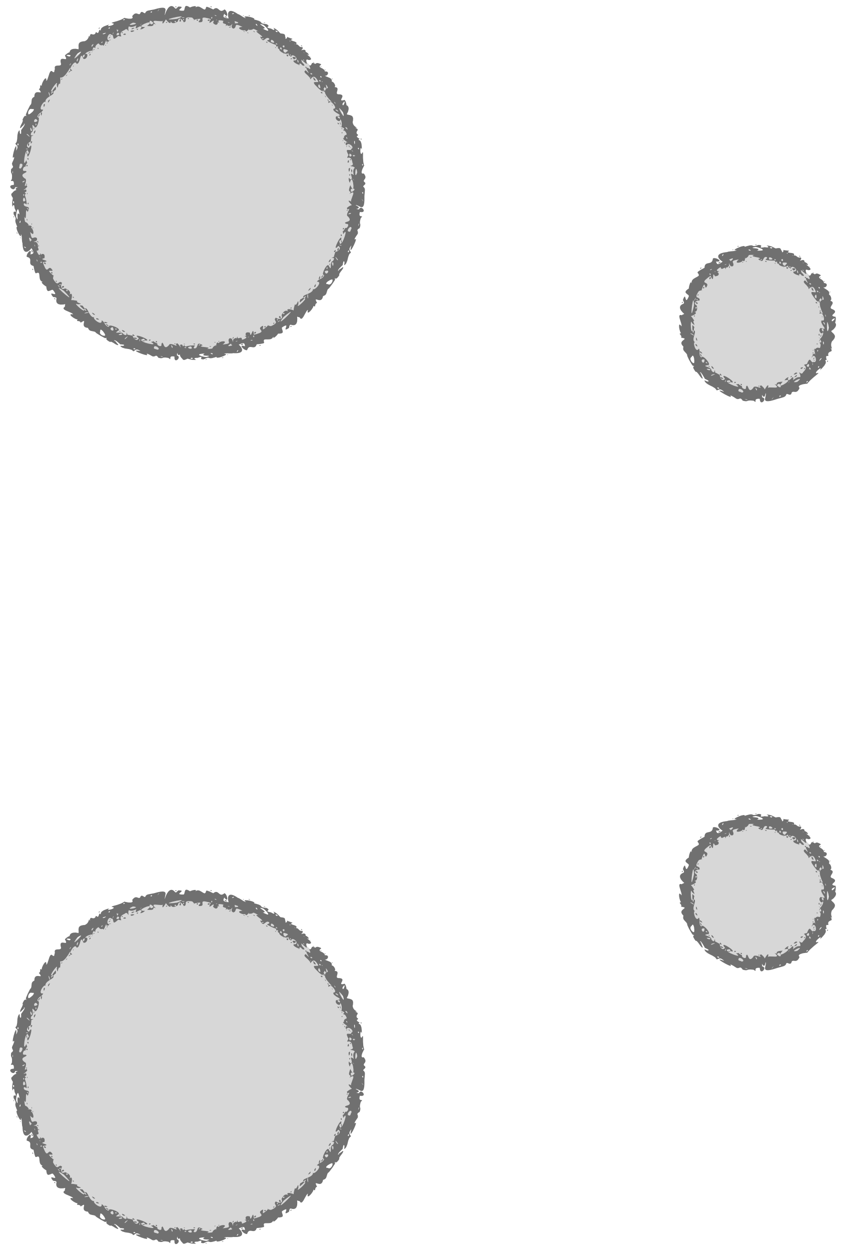
This has physical degrees of freedom: gravitational waves.



By B. P. Abbott et al. PhysRevLett.116.061102 .

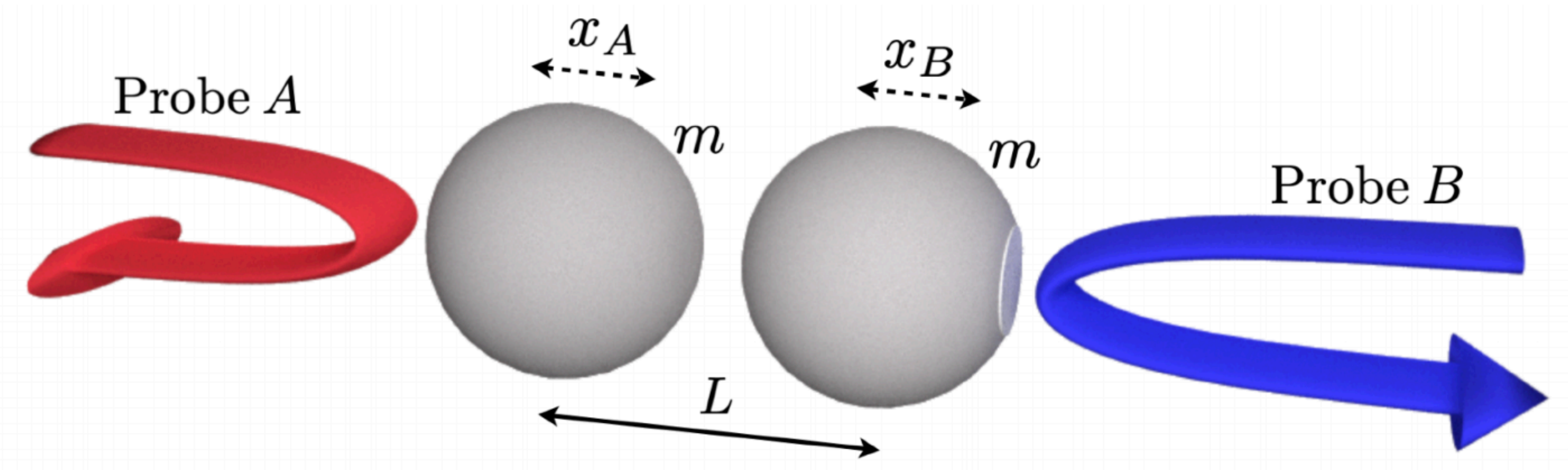
Superpositions of geometries

GR tells us that gravity is mediated locally by a field, the metric tensor.



If GME is detected then we have superpositions of spacetimes in the lab.

GME



Observable quantum entanglement due to gravity

Tanjung Krisnanda, Guo Yao Tham, Mauro Paternostro & Tomasz Paterek

npj Quantum Information **6**, Article number: 12 (2020) | Cite this article

Two masses in optical traps a distance L from each other

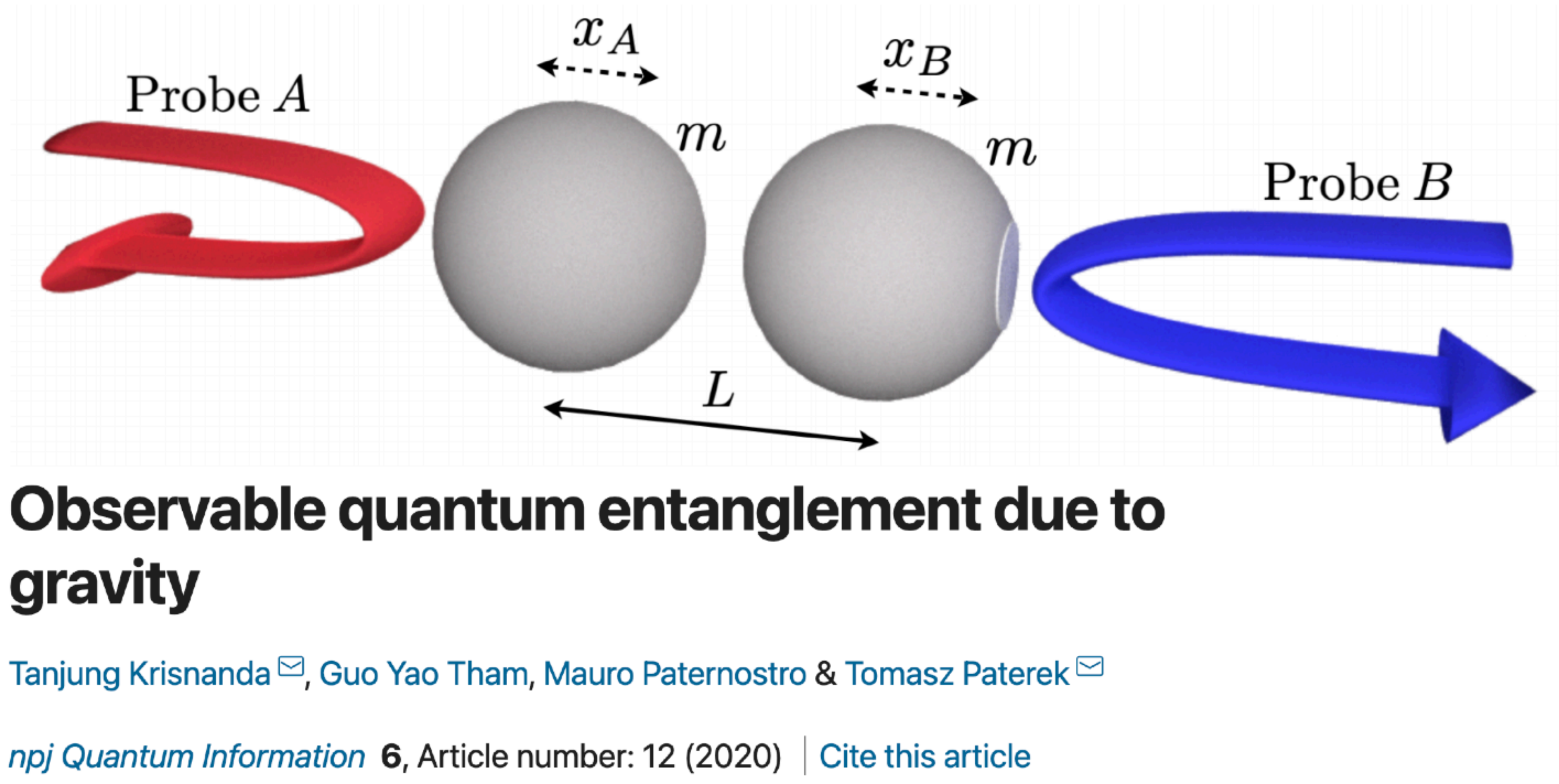
$$H = H_0 + H_g$$

$$H_0 = \frac{p_A^2}{2m} + \frac{1}{2}\omega^2 x_A^2 + \frac{p_B^2}{2m} + \frac{1}{2}\omega^2 x_B^2$$

$$H_g = -\frac{Gm^2}{L + x_B - x_A}$$

$$H_g \approx -\frac{Gm^2}{L}\left(1 + \frac{x_A - x_B}{L} + \frac{(x_A - x_B)^2}{L^2}\right) \quad \text{if} \quad |x_A - x_B| \ll L$$

GME



Observable quantum entanglement due to gravity

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Hope for entanglement if $$\frac{Gm^2(x_A - x_B)^2}{L^2} \sim \hbar\omega$$

Near the ground state of the oscillators: $$\langle (x_A - x_B)^2 \rangle \sim \langle x_A^2 \rangle + \langle x_B^2 \rangle \sim \frac{2\hbar}{m\omega}$$

$$\eta := \frac{2Gm}{\omega^2 L^3} \sim 1$$

Non-Gaussianity

Non-Gaussianity as a Signature of a Quantum Theory of Gravity

Richard Howl, Vlatko Vedral, Devang Naik, Marios Christodoulou, Carlo Rovelli, and Aditya Iyer
PRX Quantum **2**, 010325 – Published 17 February 2021

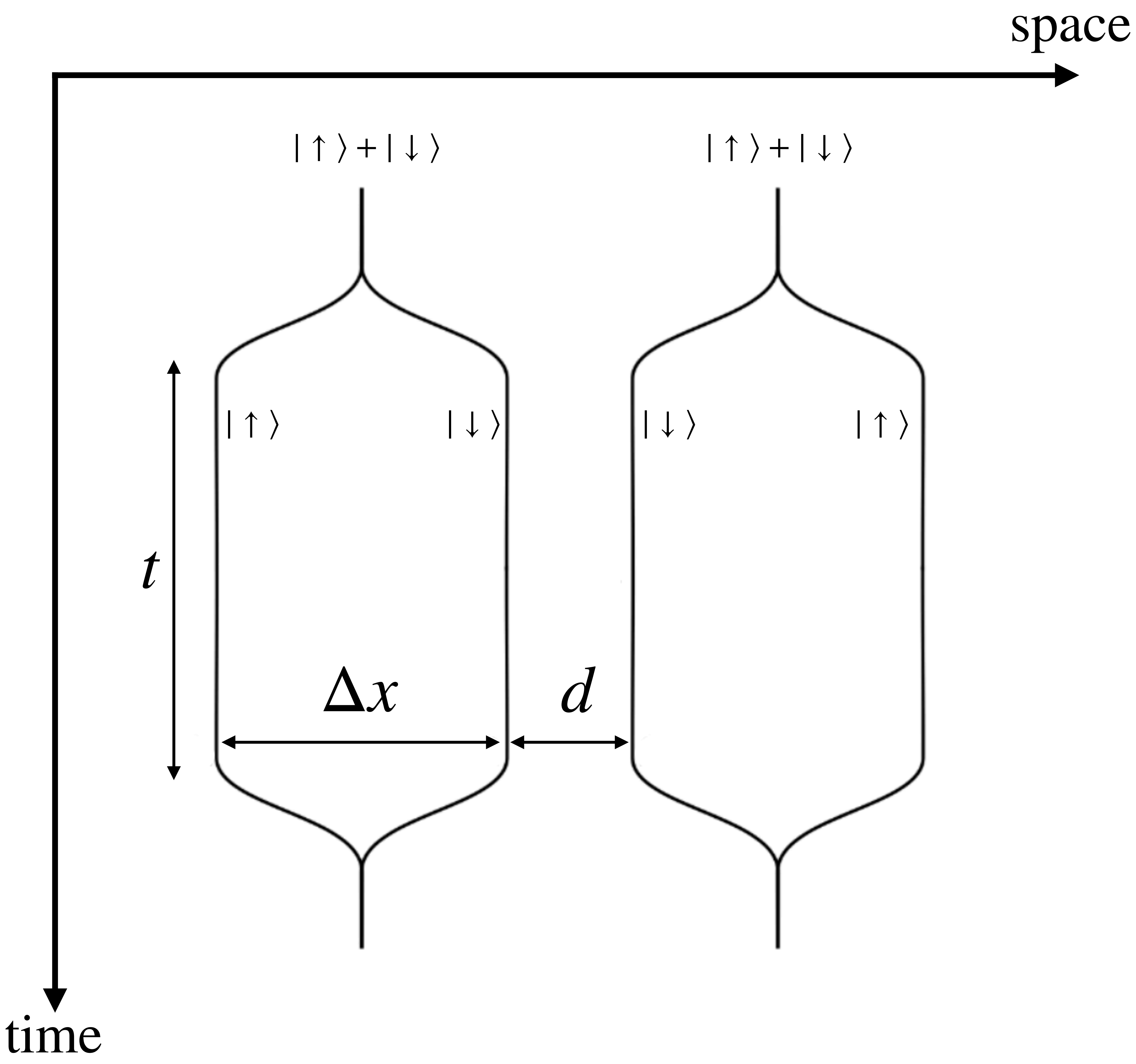
Like entanglement, Non-Gaussianity is a quantum information resource.

Non-Gaussianity cannot be created by an interaction with a classical field.

Linearised Quantum Gravity predicts that a Bose-Einstein condensate will develop non-gaussianity as a result of self-gravitation.

Practicalities

GME



$$e^{i\phi_{LR}}|\uparrow\uparrow\rangle + e^{i\phi_{LL}}|\uparrow\downarrow\rangle + e^{i\phi_{RR}}|\downarrow\uparrow\rangle + e^{i\phi_{RL}}|\downarrow\downarrow\rangle$$

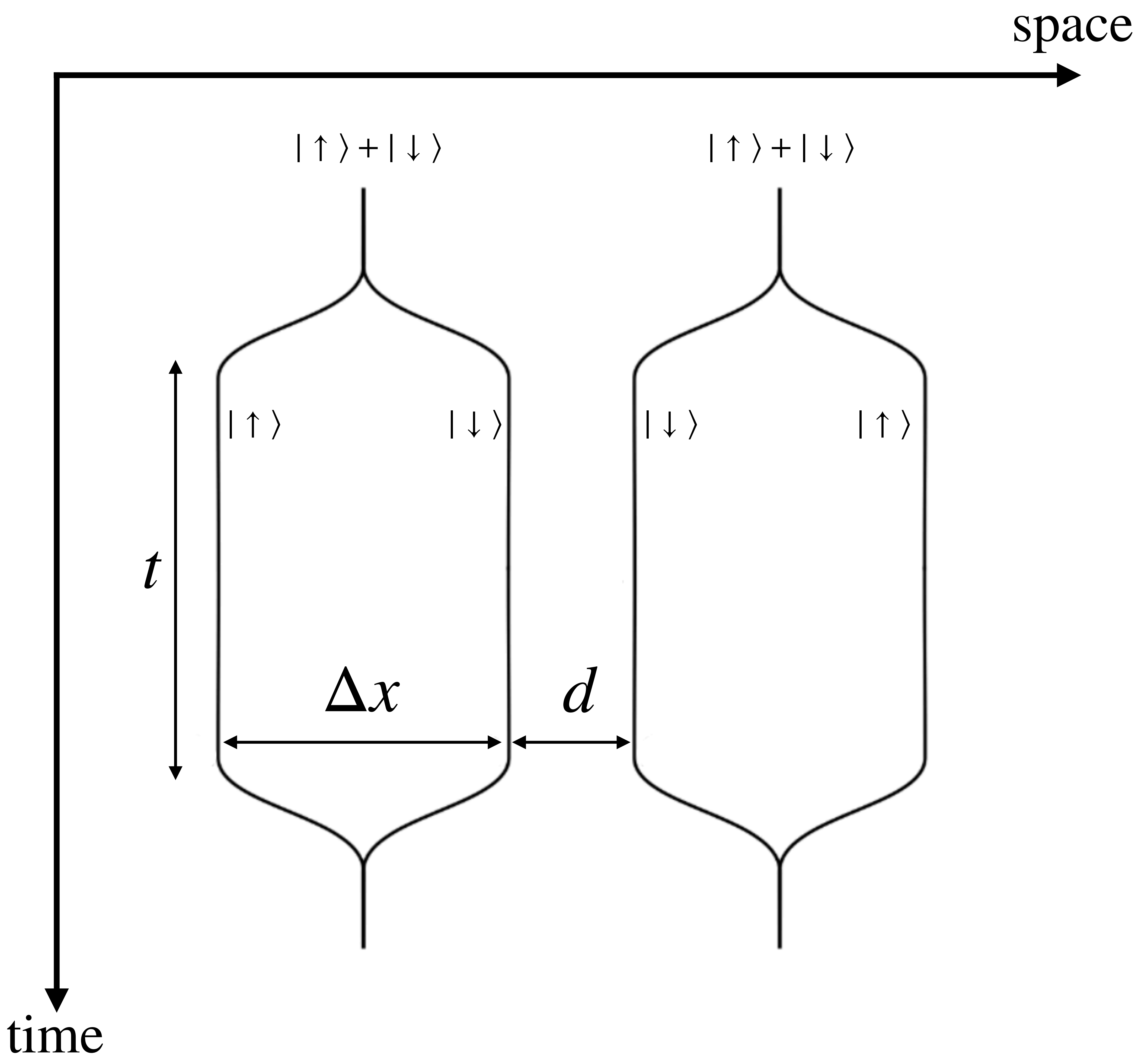
$$\phi_{RL} = \frac{Gm^2}{d}\frac{t}{\hbar} \qquad \phi_{LR} = \frac{Gm^2}{d+2\Delta x}\frac{t}{\hbar} \qquad \phi_{RR} = \frac{Gm^2}{d+\Delta x}\frac{t}{\hbar} = \phi_{LL}$$

$$e^{i\Delta\phi_{LR}}|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + e^{i\Delta\phi_{RL}}|\downarrow\downarrow\rangle$$

$$|\uparrow\rangle\left(e^{i\Delta\phi_{LR}}|\uparrow\rangle + |\downarrow\rangle\right) + |\downarrow\rangle\left(|\uparrow\rangle + e^{i\Delta\phi_{RL}}|\downarrow\rangle\right)$$

$$\Delta\phi_{RL} = \phi_{RL} - \phi_{RR}, \quad \Delta\phi_{LR} = \phi_{LR} - \phi_{RR}$$

GME



$$|\uparrow\rangle\left(e^{i\Delta\phi_{LR}}|\uparrow\rangle + |\downarrow\rangle\right) + |\downarrow\rangle\left(|\uparrow\rangle + e^{i\Delta\phi_{RL}}|\downarrow\rangle\right)$$

as entangled as

$$|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + e^{i\phi_{\text{eff}}}|\downarrow\downarrow\rangle$$

with

$$\phi_{\text{eff}} = \Delta\phi_{RL} + \Delta\phi_{LR}$$

$$= \frac{Gm^2 t}{\hbar}\left[\frac{1}{d} + \frac{1}{d+2\Delta x} - \frac{2}{d+\Delta x}\right]$$

Entanglement

In QM, two systems are entangled if their state cannot be written as a product state:

$$|\Psi\rangle_{\text{ent}} \neq |\psi\rangle|\phi\rangle$$

How do you detect entanglement?

Entanglement witness: an observable W such that

$\mathrm{tr}(W\rho) \geq 0 \quad \forall$ separable ρ, and $\mathrm{tr}(W\rho) < 0$ for at least one entangled ρ

$$\therefore \quad \mathrm{tr}(W\rho) < 0 \implies \rho \text{ is entangled}$$

This only works if you assume you know the physics of the system described by ρ

Decoherence

If the two masses interact with the environment, they will get entangled with it, and this will make it impossible to see the interference effects.

$$|\Psi_{t_0}\rangle = \frac{1}{\sqrt{2}}\big(|0\rangle + |1\rangle\big)|\psi\rangle_{\text{env}} \quad \longrightarrow |\Psi_{t_1}\rangle = \frac{1}{\sqrt{2}}\big(|0\rangle|\psi_0\rangle + |1\rangle|\psi_1\rangle\big)$$

$$|\Psi_{t_1}\rangle\langle\Psi_{t_1}| = \frac{1}{2}\big(|0\,\psi_0\rangle\langle 0\,\psi_0| + |0\,\psi_0\rangle\langle 1\,\psi_1| + |1\,\psi_1\rangle\langle 0\,\psi_0| + |1\,\psi_1\rangle\langle 1\,\psi_1|\big)$$

$$\text{tr}_E\,|\Psi_{t_1}\rangle\langle\Psi_{t_1}| = \frac{1}{2}\big(|0\rangle\langle 0| + \alpha|0\rangle\langle 1| + \bar{\alpha}|1\rangle\langle 0| + |1\rangle\langle 1|\big)$$

$$\alpha = \langle\psi_1|\psi_0\rangle$$

Decoherence

Decoherence on the position basis is well understood theoretically and experimentally.

Modelled by a master equation:

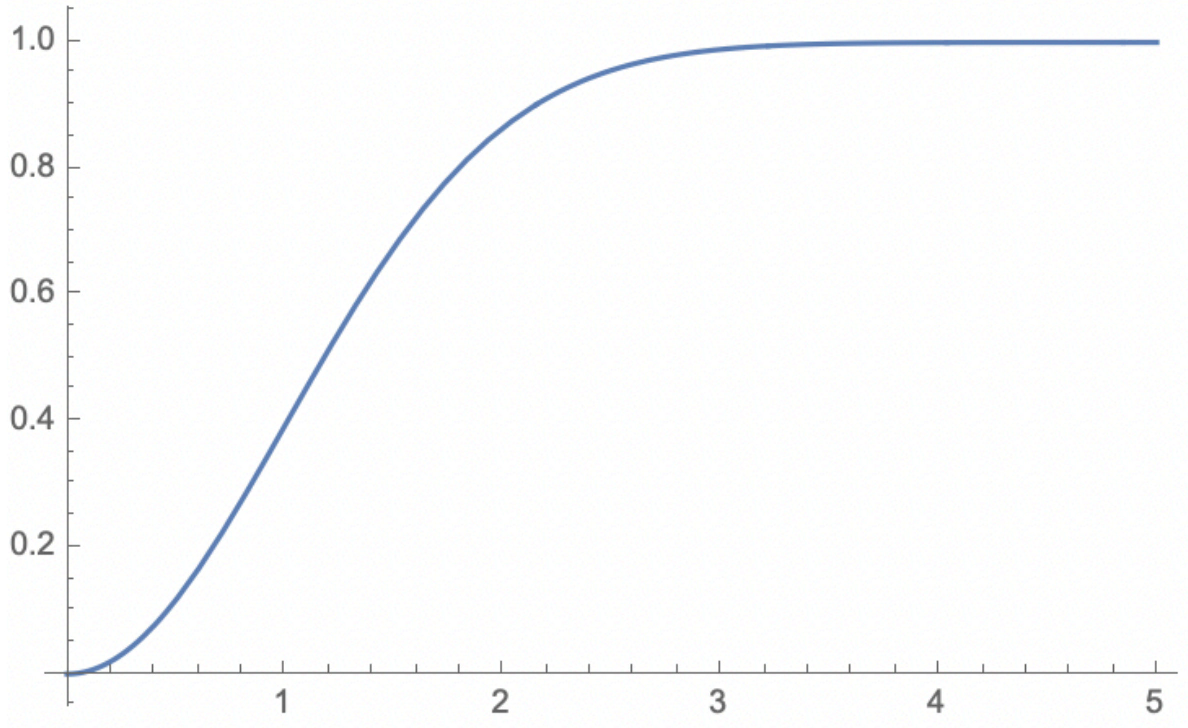
$$\langle x|\dot{\rho}|x'\rangle = \frac{i}{\hbar}\langle x|[\rho, H]|x'\rangle - \Gamma(x-x')\langle x|\rho|x'\rangle$$

Γ controls the decay of off-diagonal terms in the position basis.

$$\langle x|[\rho, H]|x'\rangle \approx 0 \implies \quad \langle x|\rho(t)|x'\rangle = e^{-\Gamma(x-x')t}\langle x|\rho(0)|x'\rangle$$

Decoherence

$$\langle x | \rho(t) | x' \rangle = e^{-\Gamma(x-x')t} \langle x | \rho(0) | x' \rangle$$



$$\Gamma(\Delta x) = \gamma \left(1 - \exp\left[-\frac{\Delta x^2}{\lambda} \right] \right)$$

Two limiting regimes, depending on the wavelength λ of the probing system:

Long Wavelength (LW): $\lambda \gg |x - x'| \implies \Gamma(x - x') \sim \Lambda |x - x'|^2$

Larger superpositions decay faster.

Short Wavelength (SW): $\lambda \ll |x - x'| \implies \Gamma(x - x') \sim \gamma$

Decay-rate saturates: one collision is enough to tell where the system is.

Decoherence

Thermal photons: $\lambda^{\mathrm{bb}} \propto \dfrac{1}{k_B T}$ and for $T = 5\mathrm{K}$ we have $\lambda^{bb} \sim 1\mathrm{mm} \Longrightarrow$ LW regime.

Air molecules: $\lambda^{\mathrm{air}} \propto \dfrac{1}{\sqrt{k_B T}}$ and for $T = 5\mathrm{K}$ we have $\lambda^{air} \sim 0.1\mathrm{nm} \Longrightarrow$ SW regime.

$$\Gamma^{\mathrm{bb}}_{\mathrm{sc}} \approx 10^{36}\mathrm{s}^{-1}\, R^6 T^9 \Delta x^2 \qquad \Gamma^{\mathrm{air}} \approx 10^{26}\ \mathrm{s}^{-1}\ P R^2 T^{-1/2}$$

$$T \approx 4\,\mathrm{K} \qquad P \approx 10^{-17}\mathrm{mbar}$$

Hard, but not unprecedented

Casimir-Polder

Need to make sure that the only force present is gravity.

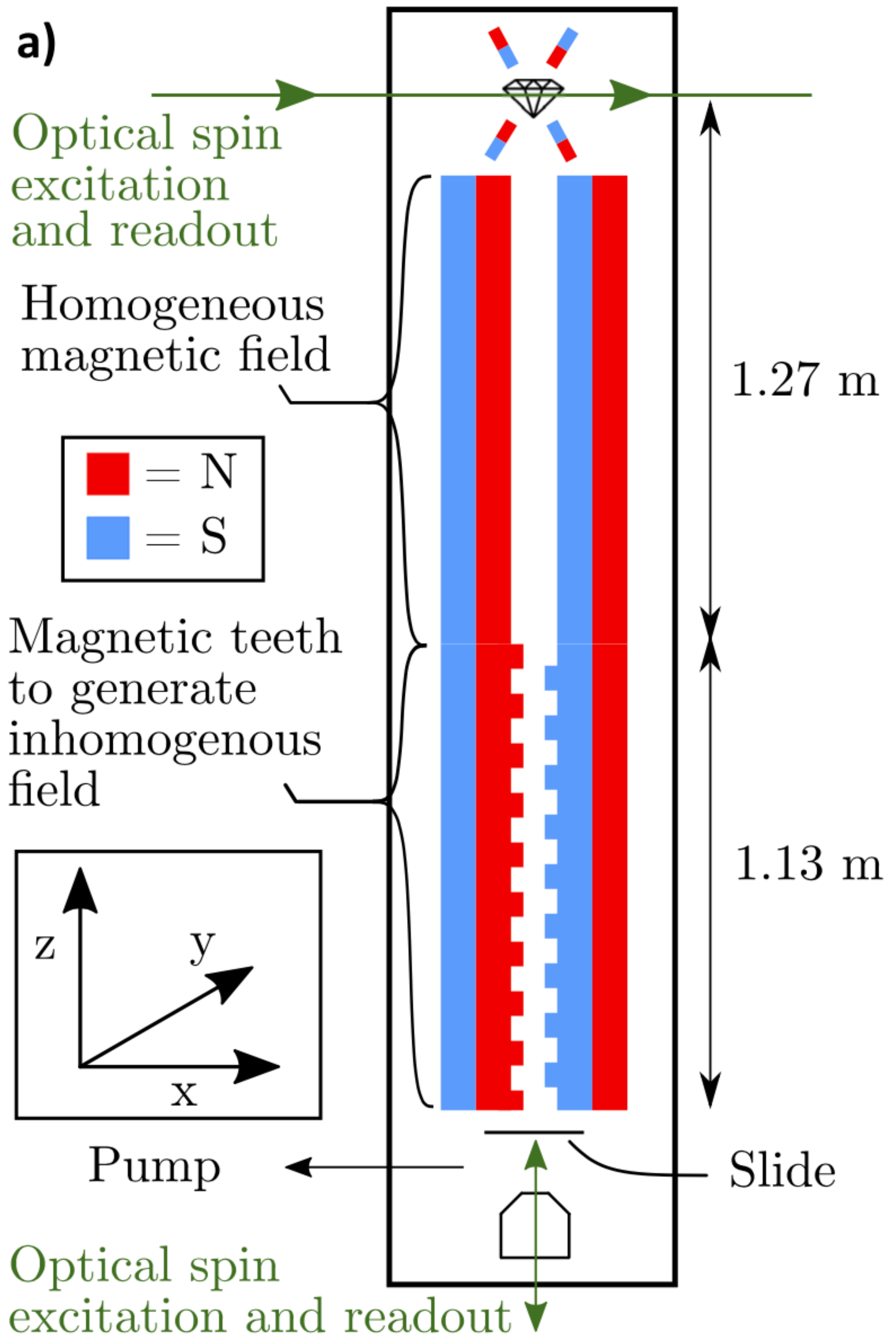
Dielectric masses will feel a force due to changes in the zero-point energy of the vacuum.

$$V_{CP} \propto \hbar c \frac{R}{r^7}$$

This will dominate over the gravitational attraction at short distances.

Imposes a limit on the distance of closest approach on the masses.

Achieving Superposition



$$\Delta x \approx 50\text{nm}$$

$$t \approx 10\mu\text{s} \qquad m \approx 10^{-21}\text{kg}$$

[Submitted on 5 May 2021]

Matter and spin superposition in vacuum experiment (MASSIVE)

B. D. Wood, G. A. Stimpson, J. E. March, Y. N. D. Lekhai, C. J. Stephen, B. L. Green, A. C. Frangeskou, L. Ginés, S. Mandal, O. A. Williams, S. Bose, G. W. Morley

Realization of a complete Stern-Gerlach interferometer: Toward a test of quantum gravity

Yair Margalit[1,*,†], Or Dobkowski[1], Zhifan Zhou[1], Omer Amit[1], Yonathan Japha[1], Samuel Moukouri[1], Daniel Rohrlich[1], A...

+ See all authors and affiliations

Science Advances 28 May 2021:
Vol. 7, no. 22, eabg2879
DOI: 10.1126/sciadv.abg2879

Summary

First direct evidence of the non-classical nature of gravity.

Low energy experiment possible thanks to advances in quantum technology.

Claims based on quantum information-theoretics arguments.

If we trust our best theories (GR+QM) then this will be the first direct evidence of the quantum nature of spacetime.

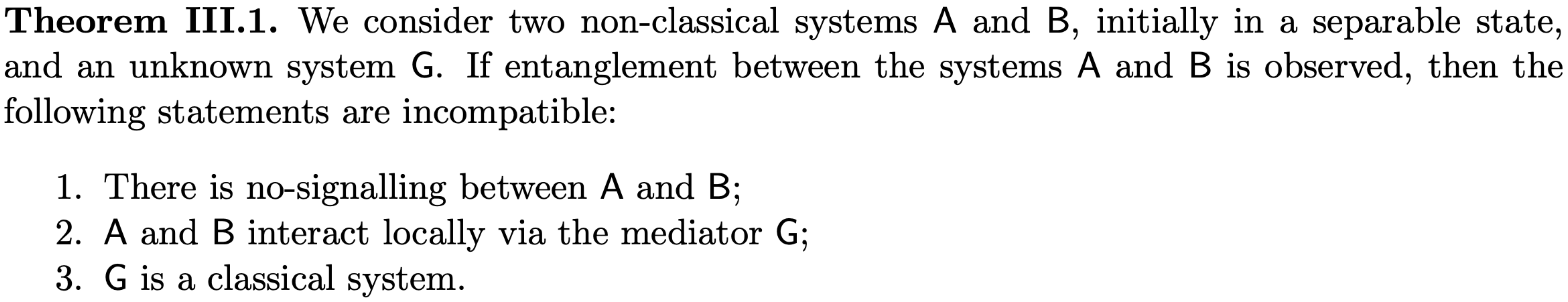
Theory

No-Go Theorem

[Submitted on 2 Dec 2020]

A no-go theorem on the nature of the gravitational field beyond quantum theory

Thomas D. Galley, Flaminia Giacomini, John H. Selby



Theorem III.1. We consider two non-classical systems A and B, initially in a separable state, and an unknown system G. If entanglement between the systems A and B is observed, then the following statements are incompatible:

1. There is no-signalling between A and B;
2. A and B interact locally via the mediator G;
3. G is a classical system.

No-Go Theorems

Examples

Bell's 1st theorem: a local hidden-variable theory cannot reproduce the statistics of entanglement.

Kochen-Specker theorem: there is no joint probability distribution for the results of incompatible measurements.

Local Friendliness: If QT is universally valid, then either A. consequences of free choices propagate superluminally, or B. facts are relative.

Theory Lesson Plan

- Introduction to process theories
- Causal process theories
- Generalised probabilistic theories
- Diagrammatic characterisation of classicality + entanglement
- Proof of the no-go theorem

Theory Lesson Plan

- **Introduction to process theories**
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Process Theories

Process Theories are a new framework for understanding and building theories that highlights transformations and compositionality.

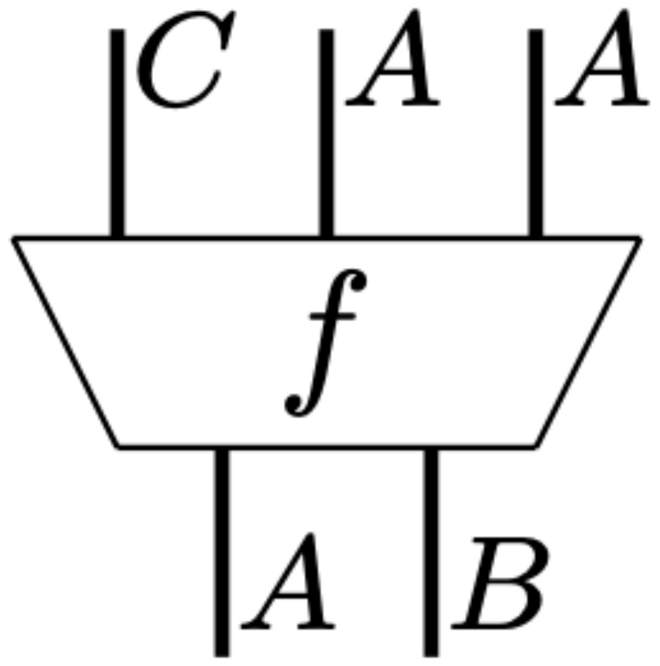
They have their roots in Category Theory, but they are used in computing, natural language processing, and quantum foundations + quantum information theory.

They come with an expressive graphical calculus.

There are two main components of a process theory:

Systems

Processes



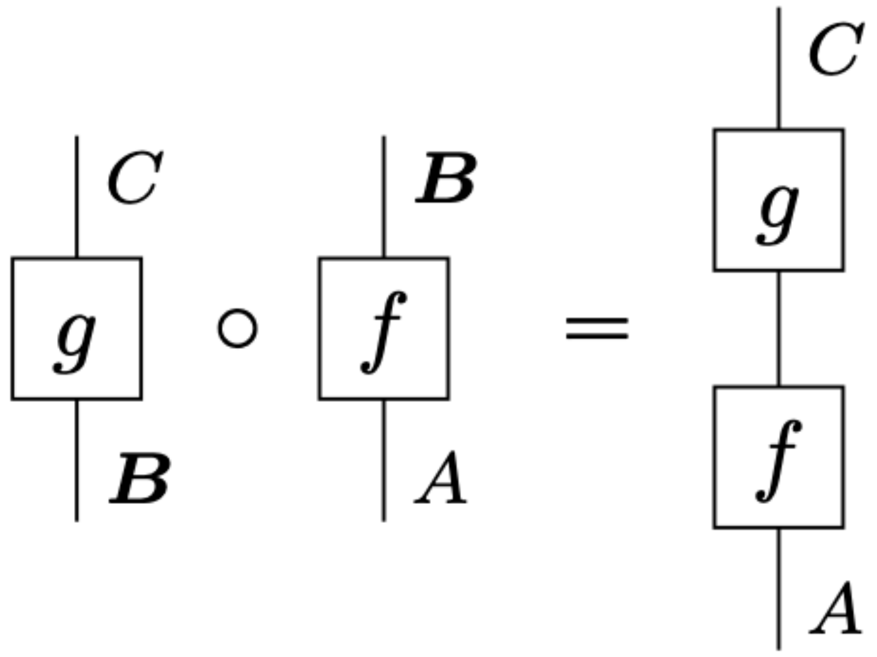
Process Theories

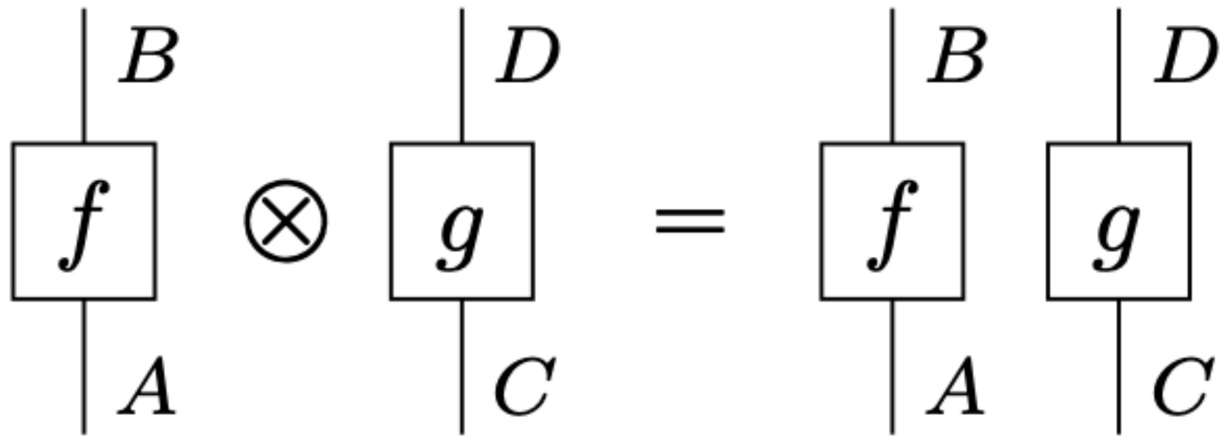
Examples of process theories:

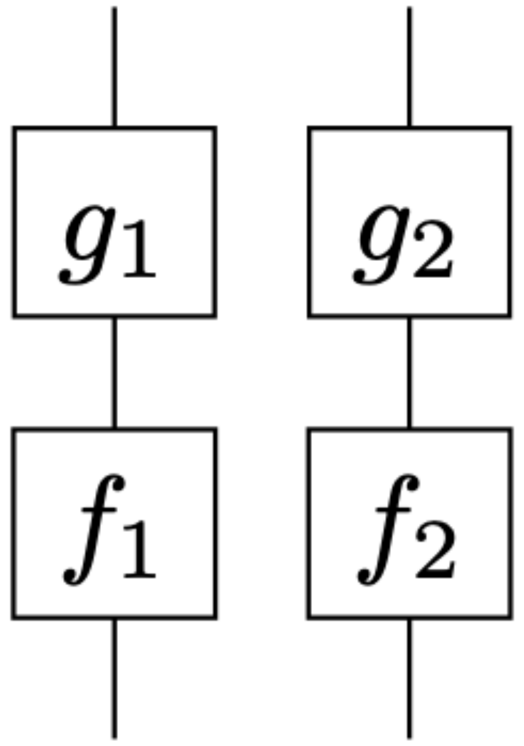
Theory	System labels	Processes
Set Theory	Sets	Functions
Topology	Topological spaces	Continuous Maps
Linear Algebra	Vector spaces	Linear transformations
Pure QM	Hilbert spaces	Unitary transformations, pure states preparations, pure state projectors.
Operational QM	Hilbert spaces	Trace-non-increasing transformations

Process Theories

Processes are wired together via systems to give new processes:



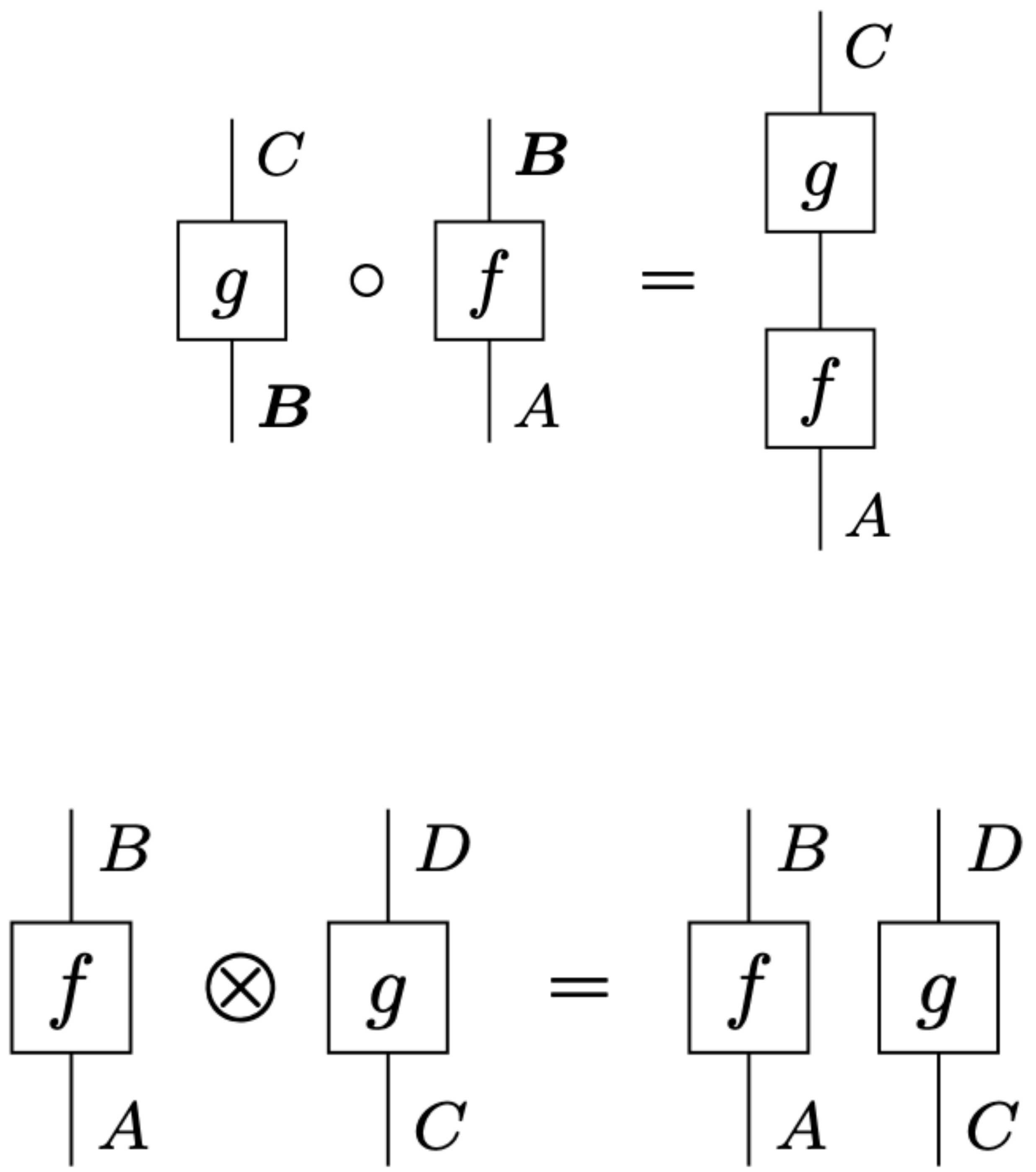


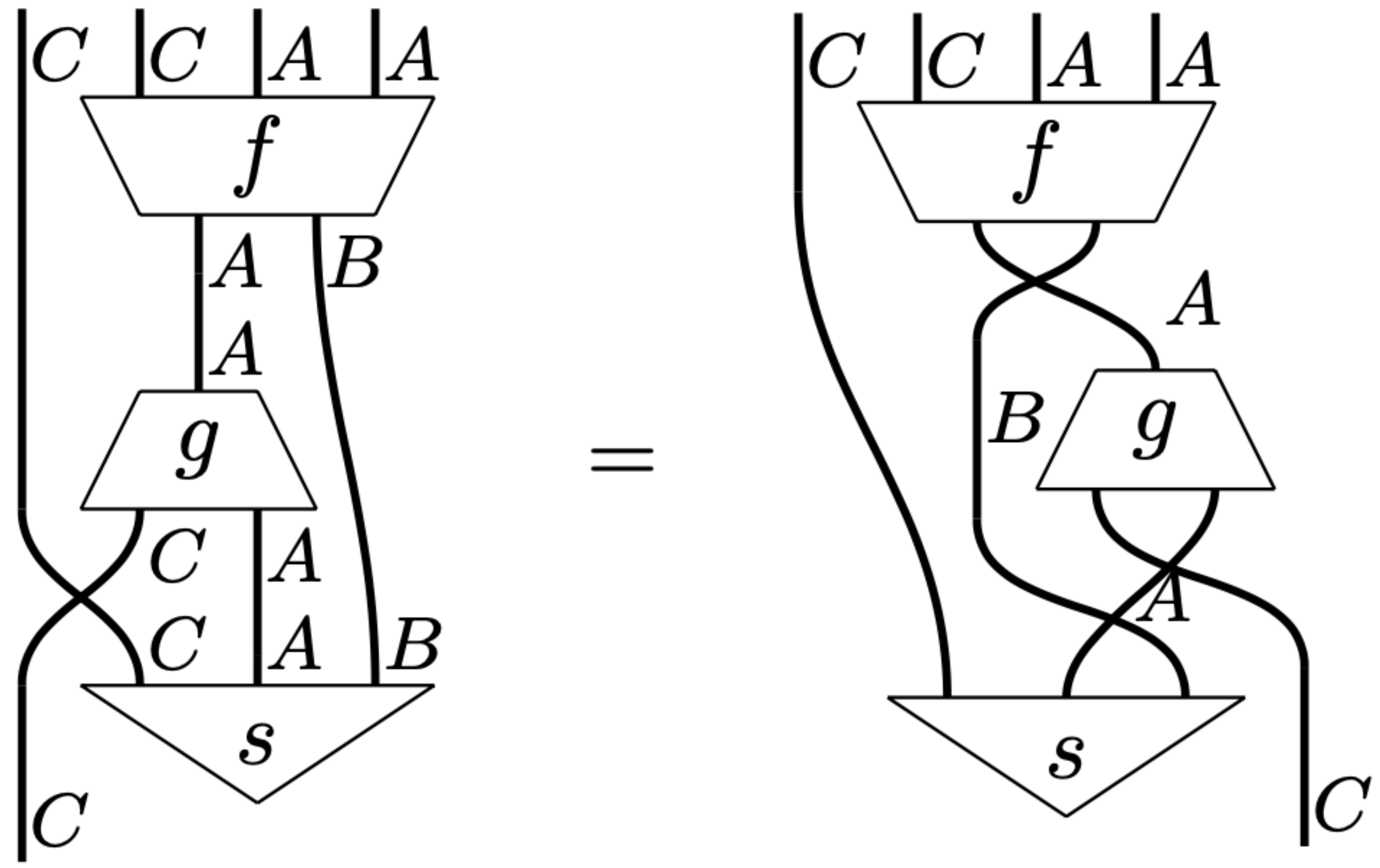


↔ $(g_1 \otimes g_2) \circ (f_1 \otimes f_2) = (g_1 \circ f_1) \otimes (g_2 \circ f_2)$

Process Theories

Processes are wired together via systems to give new processes:

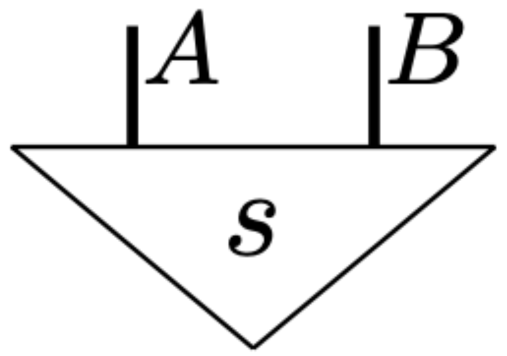




The wires in the diagrams can be deformed, what matters is the connectivity.

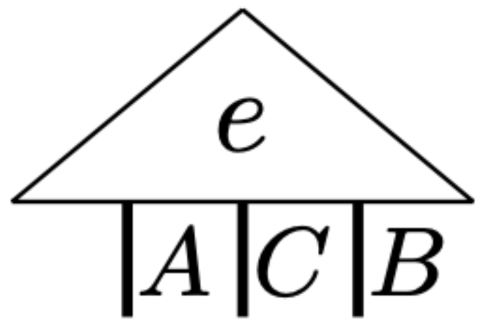
Process Theories

There are three kinds of distinguished processes:



States

Scalars

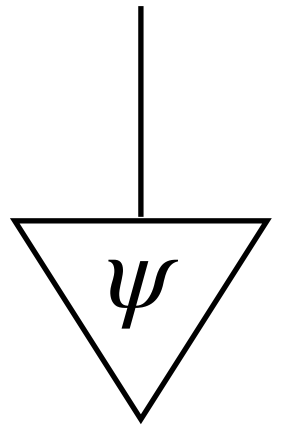


Effects

QM as a process theory

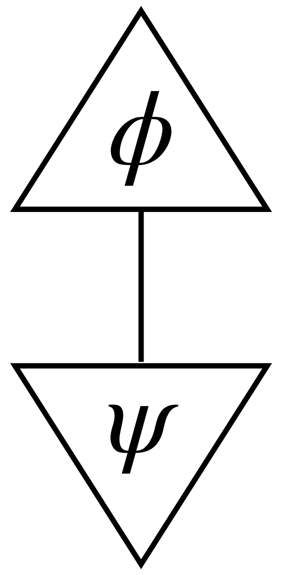
Close-similarity with bra-ket notation:

State ↔ ket



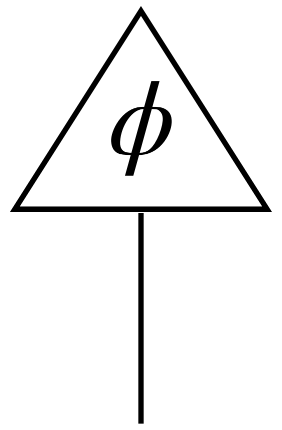
$\leftrightarrow |\psi\rangle$

Scalars ↔ amplitudes



$\leftrightarrow \langle\phi|\psi\rangle$

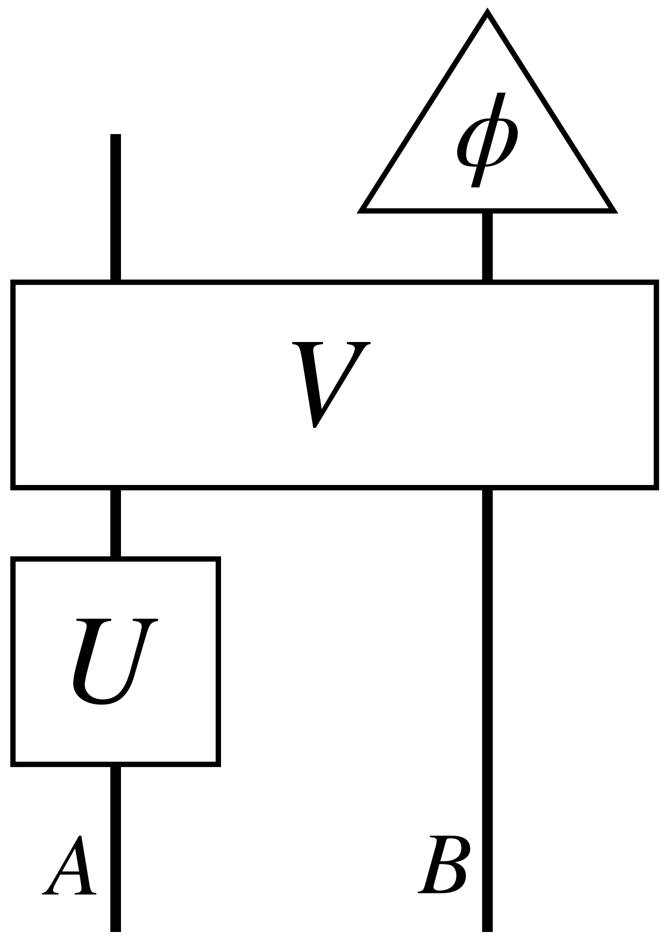
Effect ↔ bra



$\leftrightarrow \langle\phi|$

QM as a process theory

But easier to read:



$$\leftrightarrow \left(\mathbb{1}_A \otimes \langle \phi |\right) V \left(U \otimes \mathbb{1}_B\right)$$

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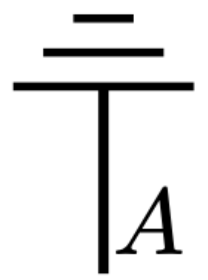
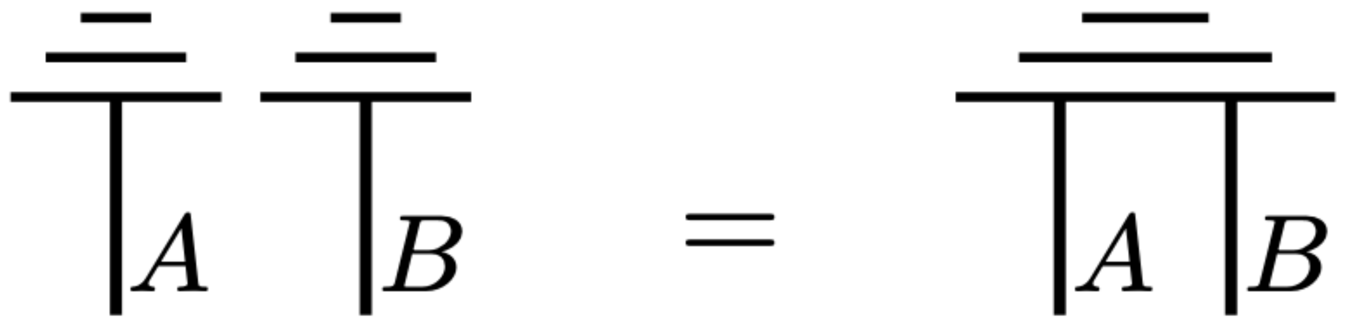
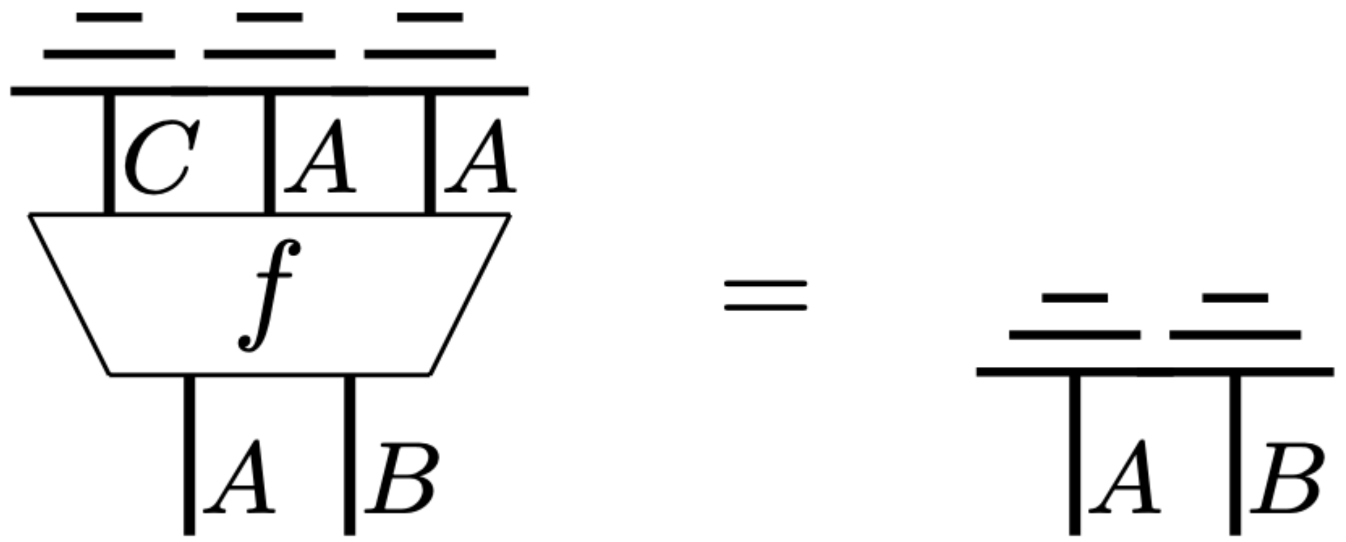
Causal Process Theory

A PT is **causal** if there exists a **unique effect** for each system type.







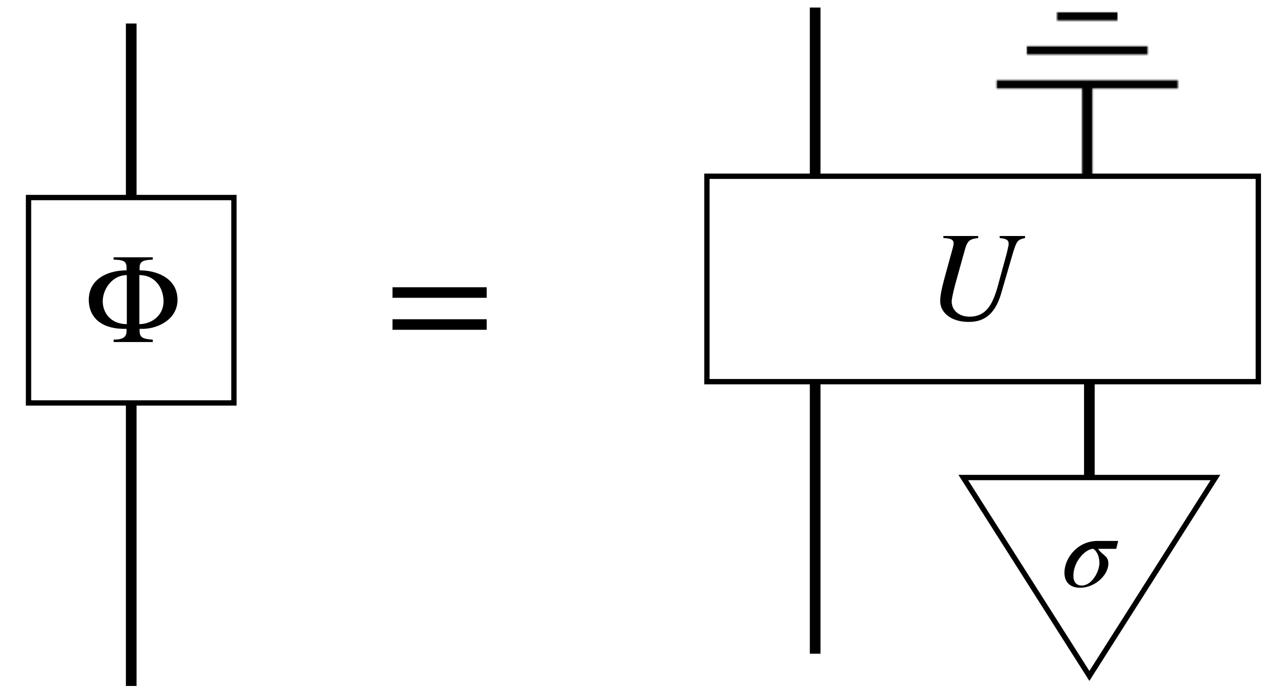
$\Longrightarrow$there is also a unique scalar.

QT as a Causal Process Theory

Completely Positive Trace Preserving (CPTP) Maps are a causal process theory.

They are the most general maps from density operators to density operators.

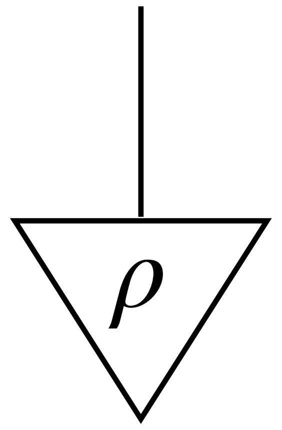
$$\Phi[\rho] = \mathrm{tr}_Y\big[U[\rho \otimes \sigma]\big]$$



QT as a Causal Process Theory

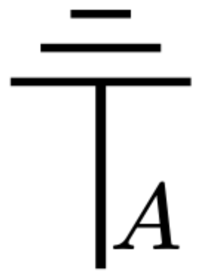
Completely Positive Trace Preserving (CPTP) Maps are a causal process theory.

States ↔ density matrices



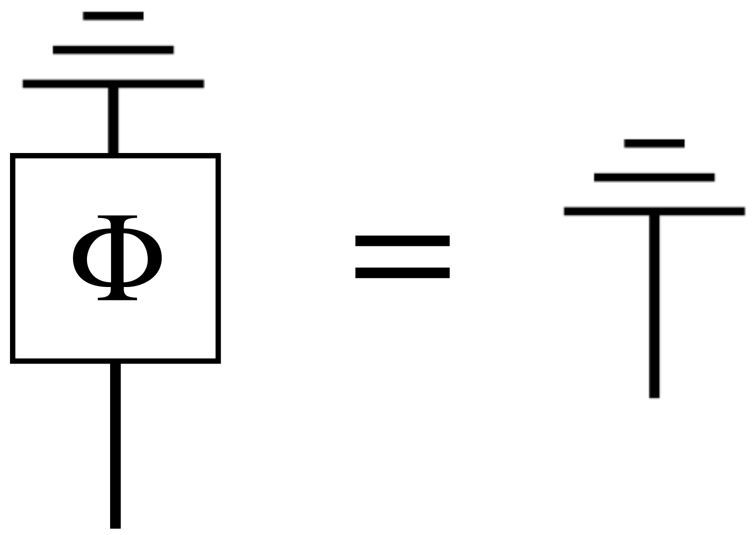
$$\leftrightarrow \quad \begin{array}{c} \rho \geq 0 \\ \operatorname{tr}\rho = 1 \end{array}$$

Discard ↔ tracing



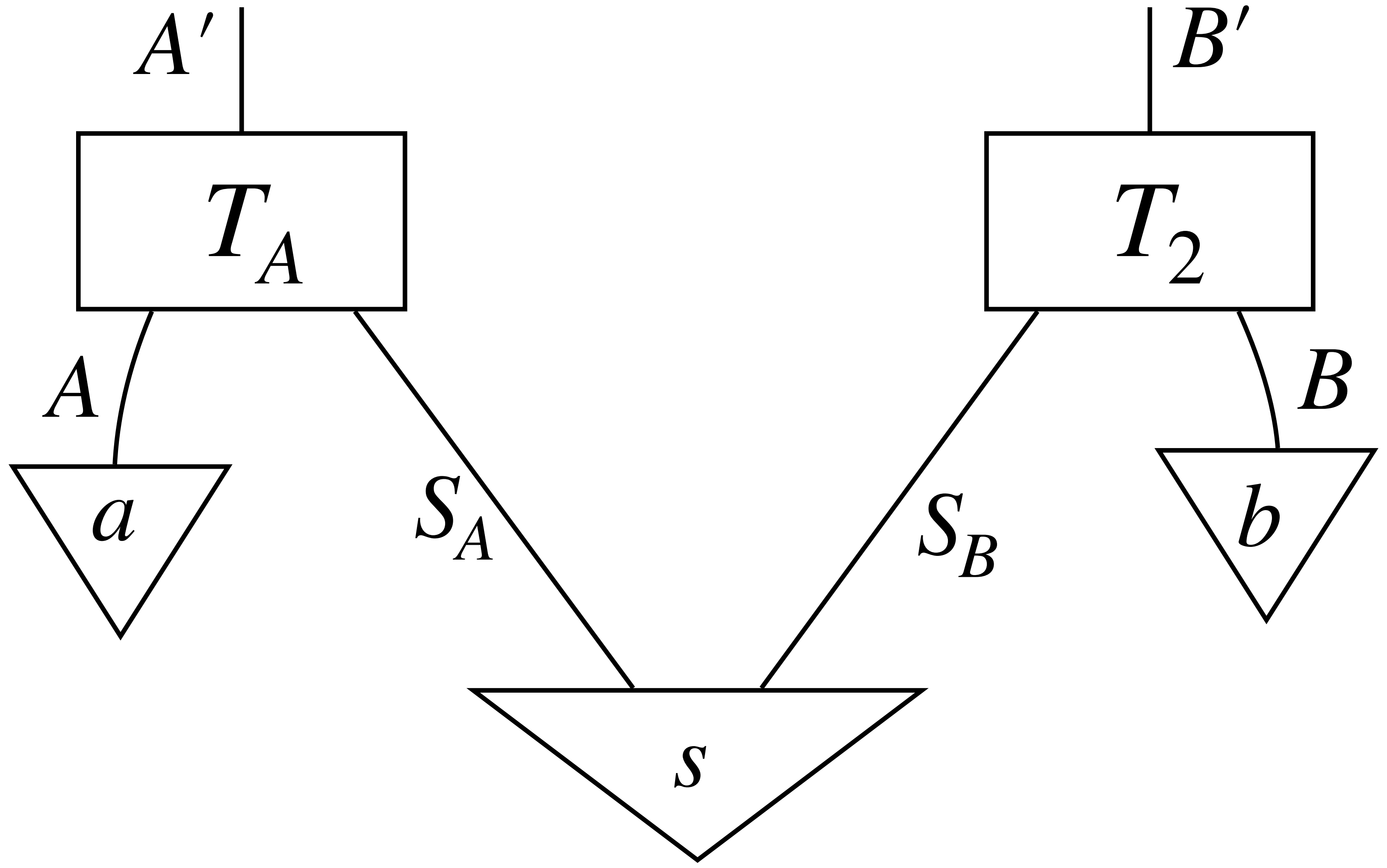
$$\leftrightarrow \operatorname{tr}_A$$

A linear map Φ is trace-preserving $\iff \forall\rho: \operatorname{tr}\Phi[\rho] = \operatorname{tr}\rho$



Causal Process Theory

Causal Process Theories are automatically non-signalling:



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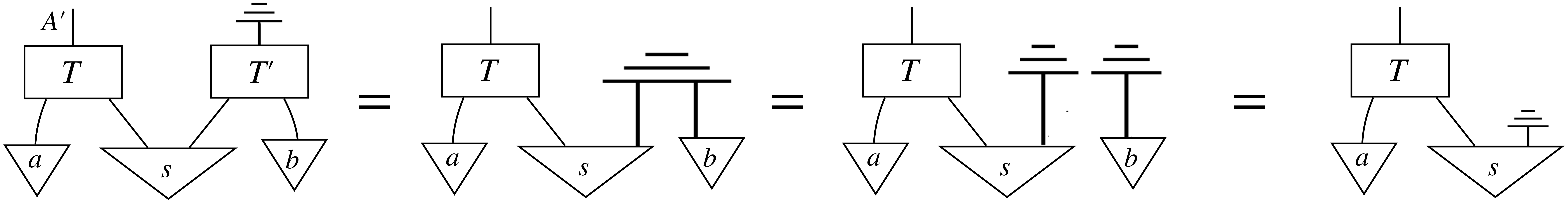

Theory Lesson Plan

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GPT

Generalised Probabilistic theories are process theories designed to deal with theories with probabilistic predictions.

Processes belong to convex spaces.

"If you can do two things, then a third thing you can do is flip a coin to chose which one to do"

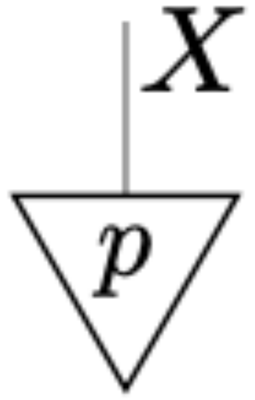
If ϕ and ψ are states, then there is a state $p\phi + (1-p)\psi$ for any $p \in [0,1]$.

Given a transformation T, then $T[p\,\phi + (1-p)\,\psi] = p\,T[\phi] + (1-p)\,T[\psi]$.

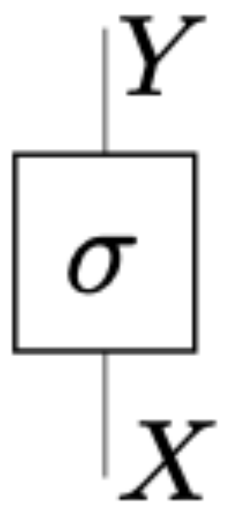
Classical Systems in GPTs

A classical system with configurations space X:

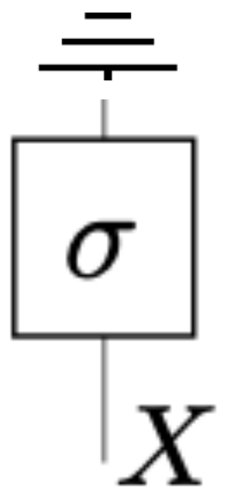
state ↔ probability distribution over X



processes ↔ stochastic maps

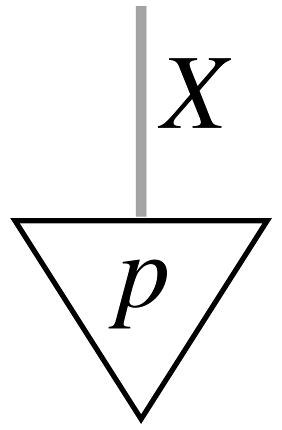


discarding ↔ marginalising over X

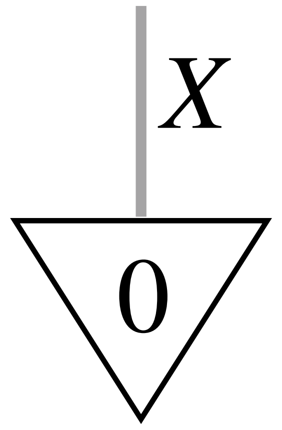


Classical Bit

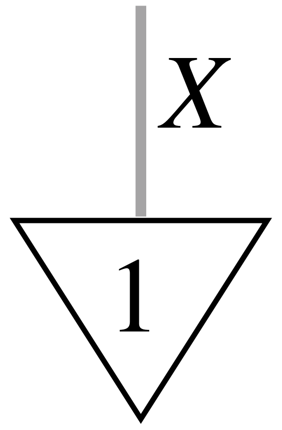
$$X = \{0,1\}$$



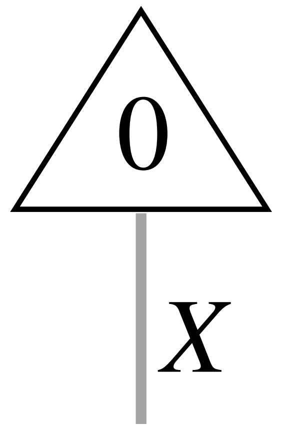
$\leftrightarrow \begin{pmatrix} p_0 \\ p_1 \end{pmatrix}$



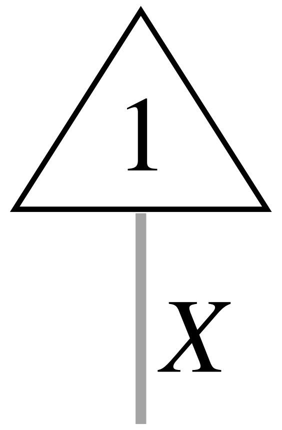
$\leftrightarrow \begin{pmatrix} 1 \\ 0 \end{pmatrix}$



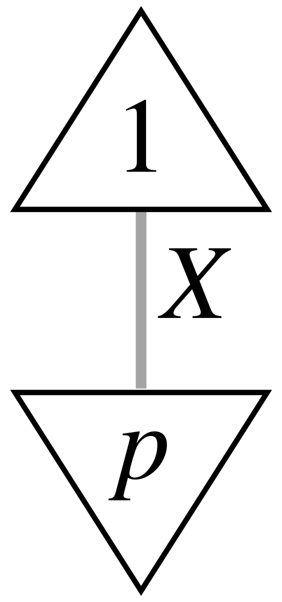
$\leftrightarrow \begin{pmatrix} 0 \\ 1 \end{pmatrix}$



$\leftrightarrow (1 \quad 0)$



$\leftrightarrow (0 \quad 1)$

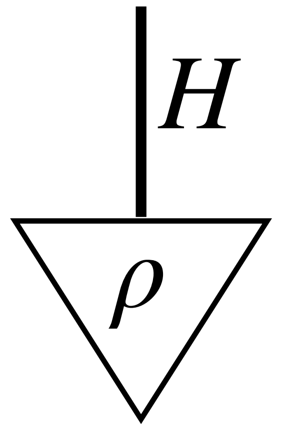


$= P(1\,|\,p) = (0 \quad 1) \cdot \begin{pmatrix} p_0 \\ p_1 \end{pmatrix} = p_1$

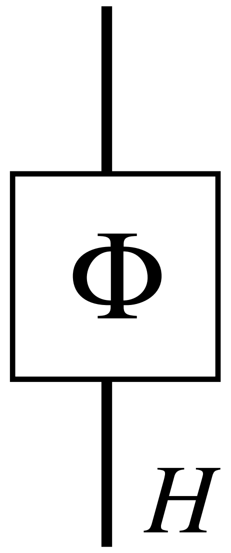
Quantum systems in GPTs

A quantum system with Hilbert space H:

state ↔ density operators on H



processes ↔ CPTP maps



discarding ↔ tracing over H.

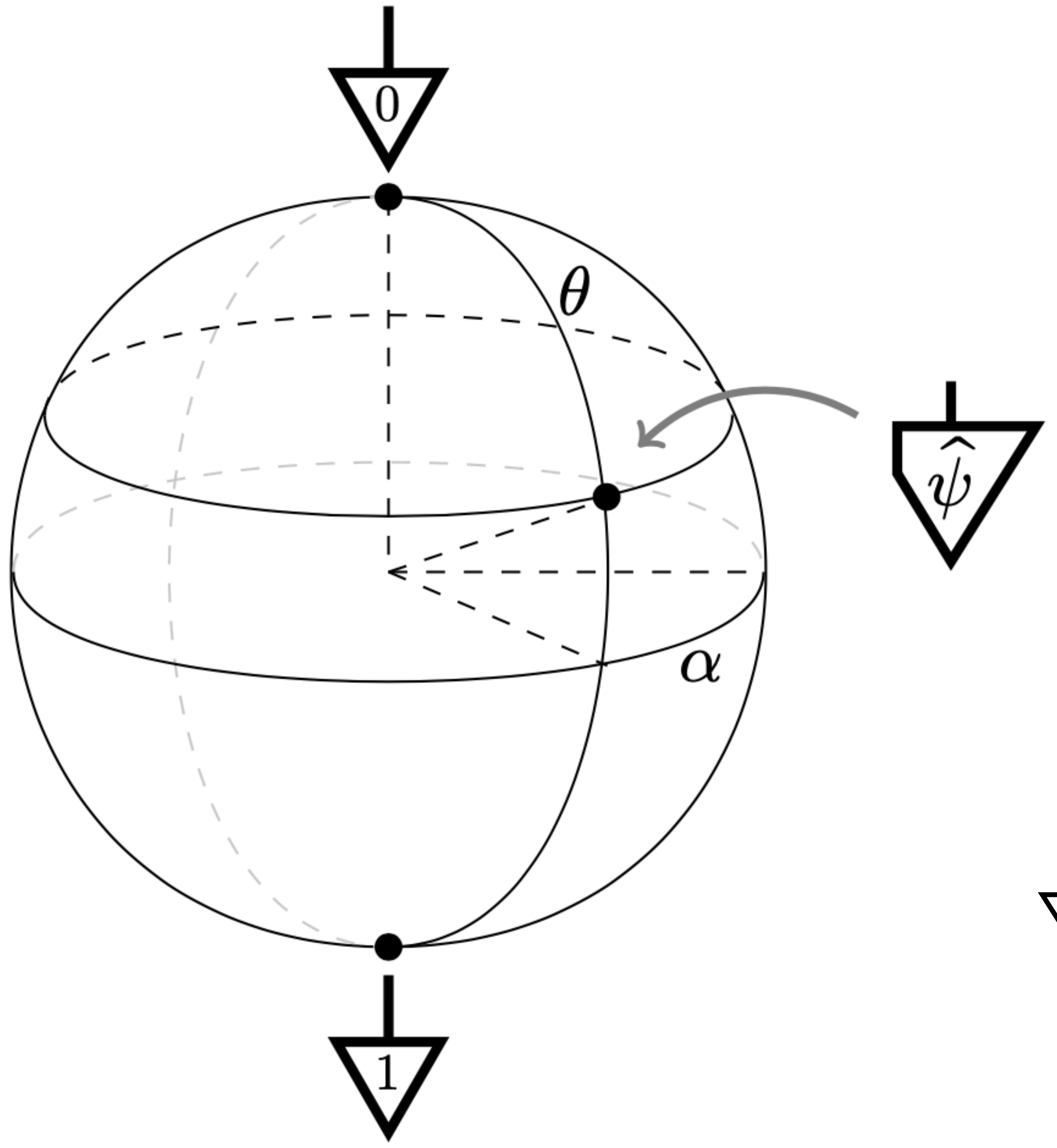
Quantum systems in GPTs

The causal GPT associated to QM is that of density matrices and CPTP maps

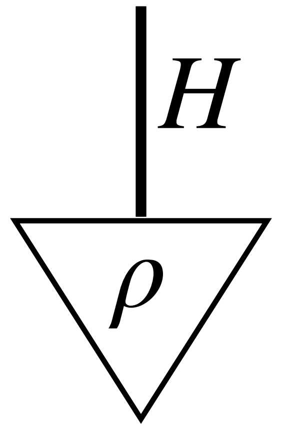
The vectors of H are not the states of a causal GPT!

If $|\psi\rangle, |\phi\rangle \in H$ are normalised states, $p|\psi\rangle + (1-p)|\phi\rangle$ is not a normalised state.

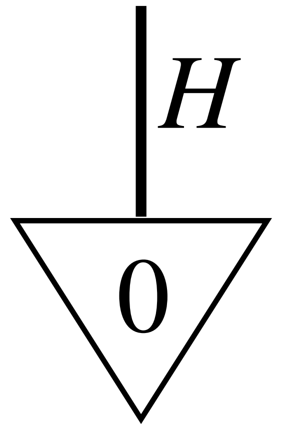
Qubit



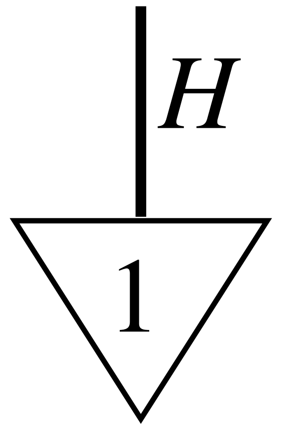
$$H = \mathbb{C}^2$$



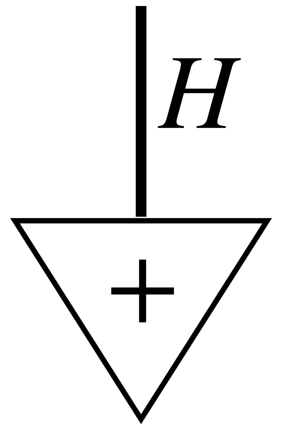
$$\leftrightarrow \frac{1}{2}\left(\mathbb{I}_{2\times 2} + \vec{r}\cdot\vec{\sigma}\right)$$



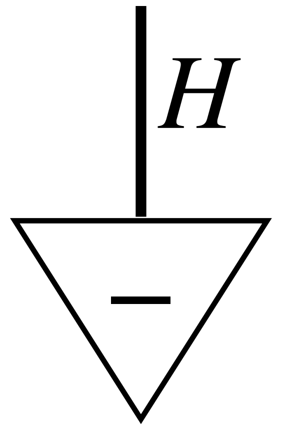
$$\leftrightarrow \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$



$$\leftrightarrow \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$



$$\leftrightarrow \begin{pmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{pmatrix} = \frac{1}{2}\left(|0\rangle + |1\rangle\right)\left(\langle 0| + \langle 1|\right)$$

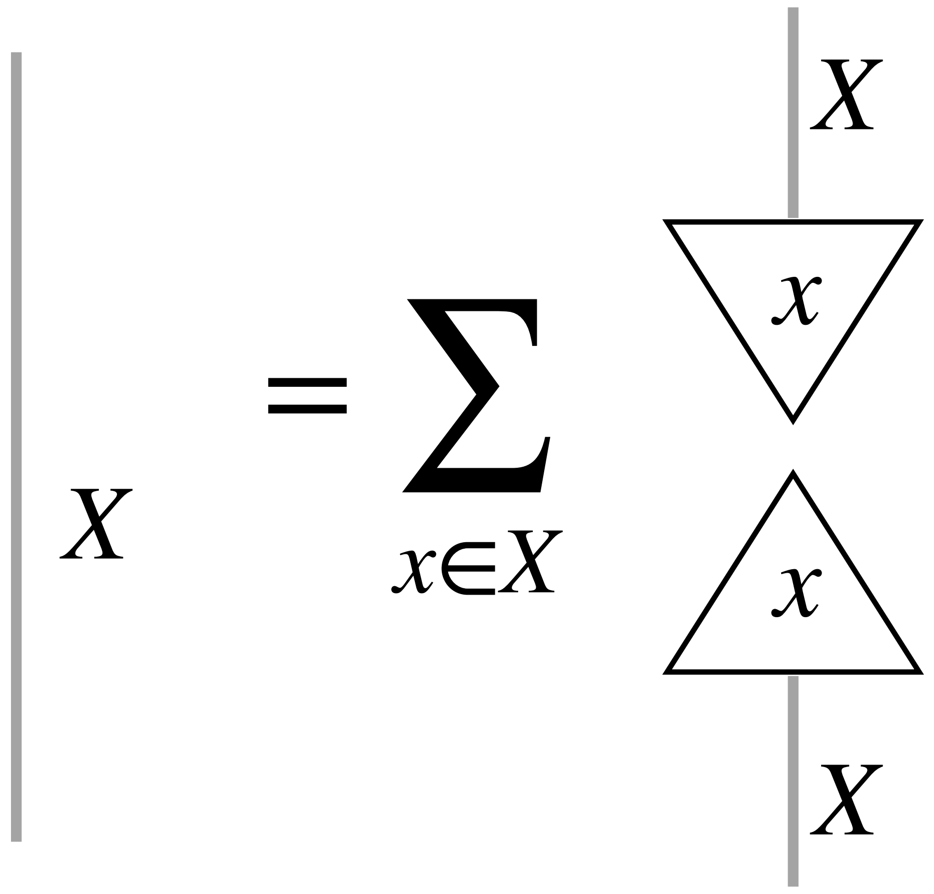


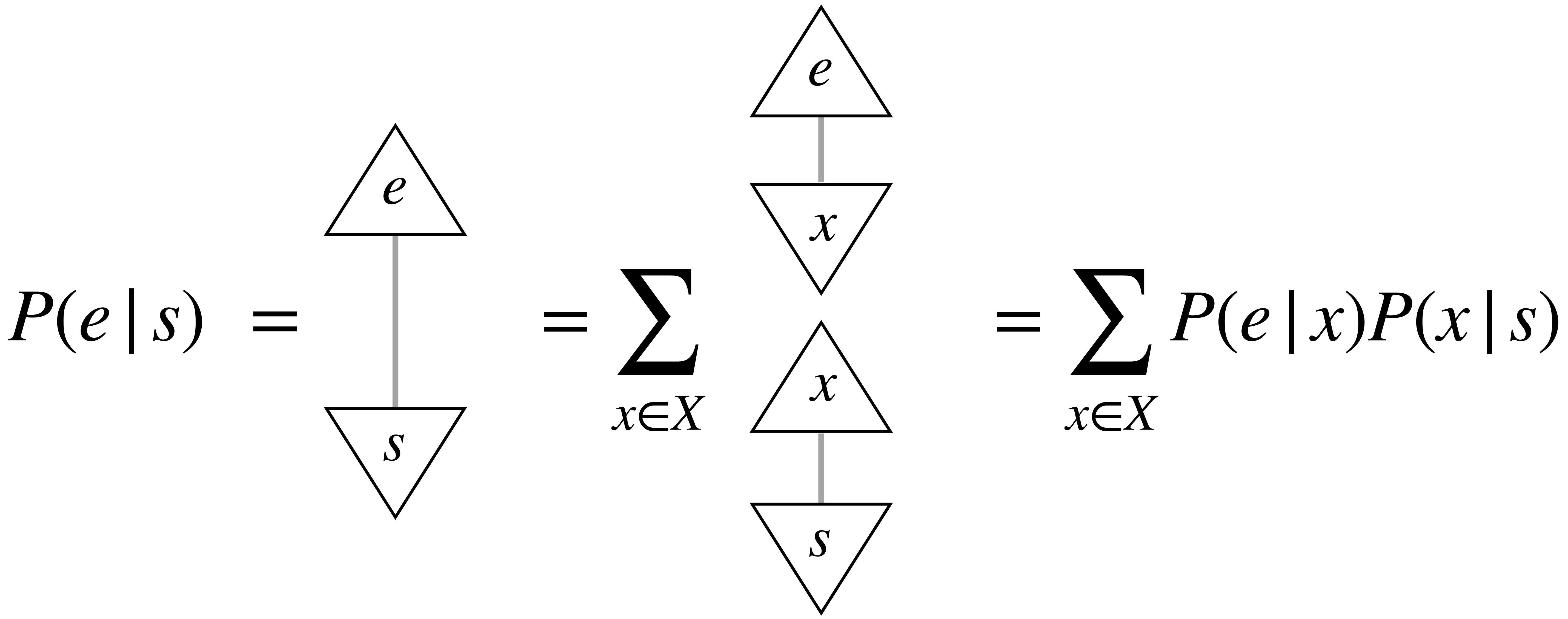
$$\leftrightarrow \begin{pmatrix} 1/2 & -1/2 \\ -1/2 & 1/2 \end{pmatrix}$$

Theory Lesson Plan

- Introduction to process theories
- Causal process theories
- Generalised probabilistic theories
- **Diagrammatic characterisation of classicality + entanglement**
- Proof of the no-go theorem

Classicality in GPTs

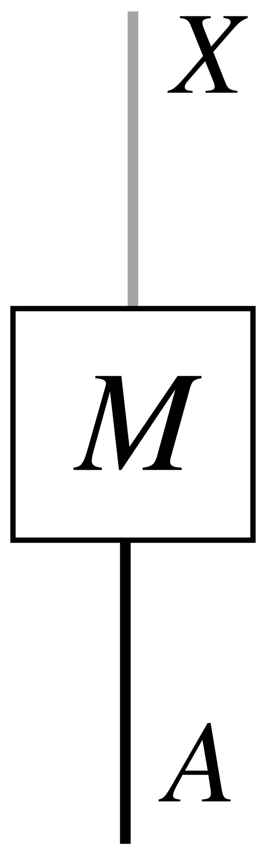




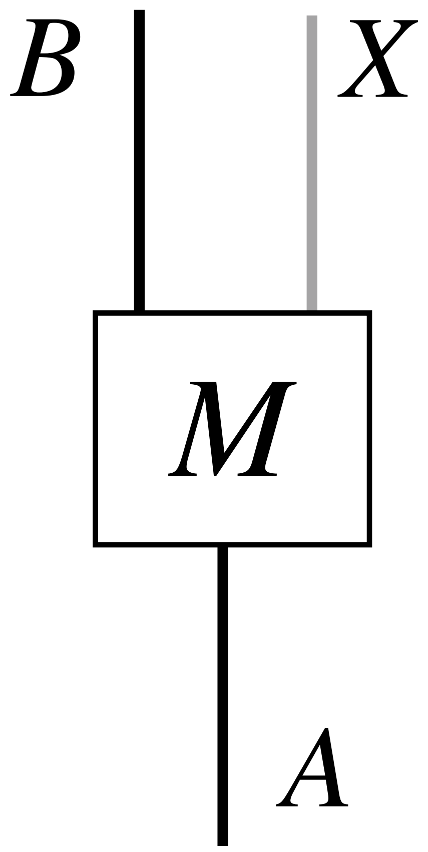
The absence of interference as the characterising feature of classicality.

Classical Interface in GPTs

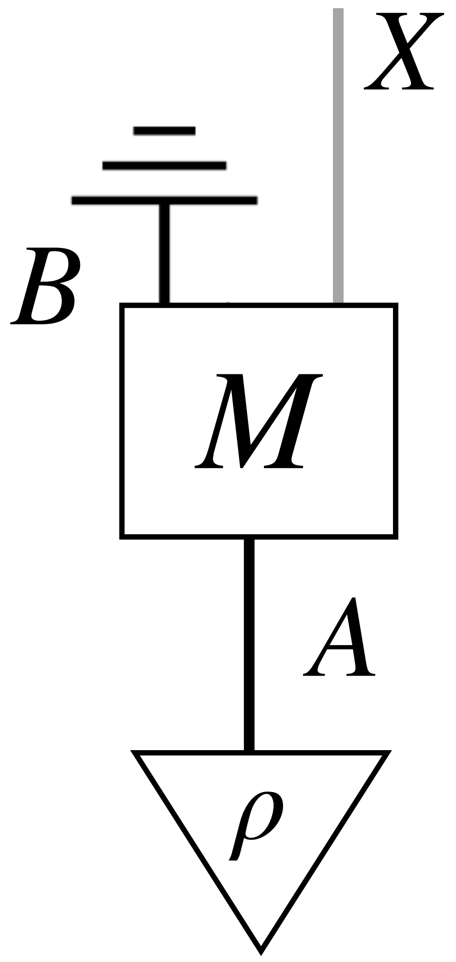
Measurements have classical outputs



Destructive
measurement



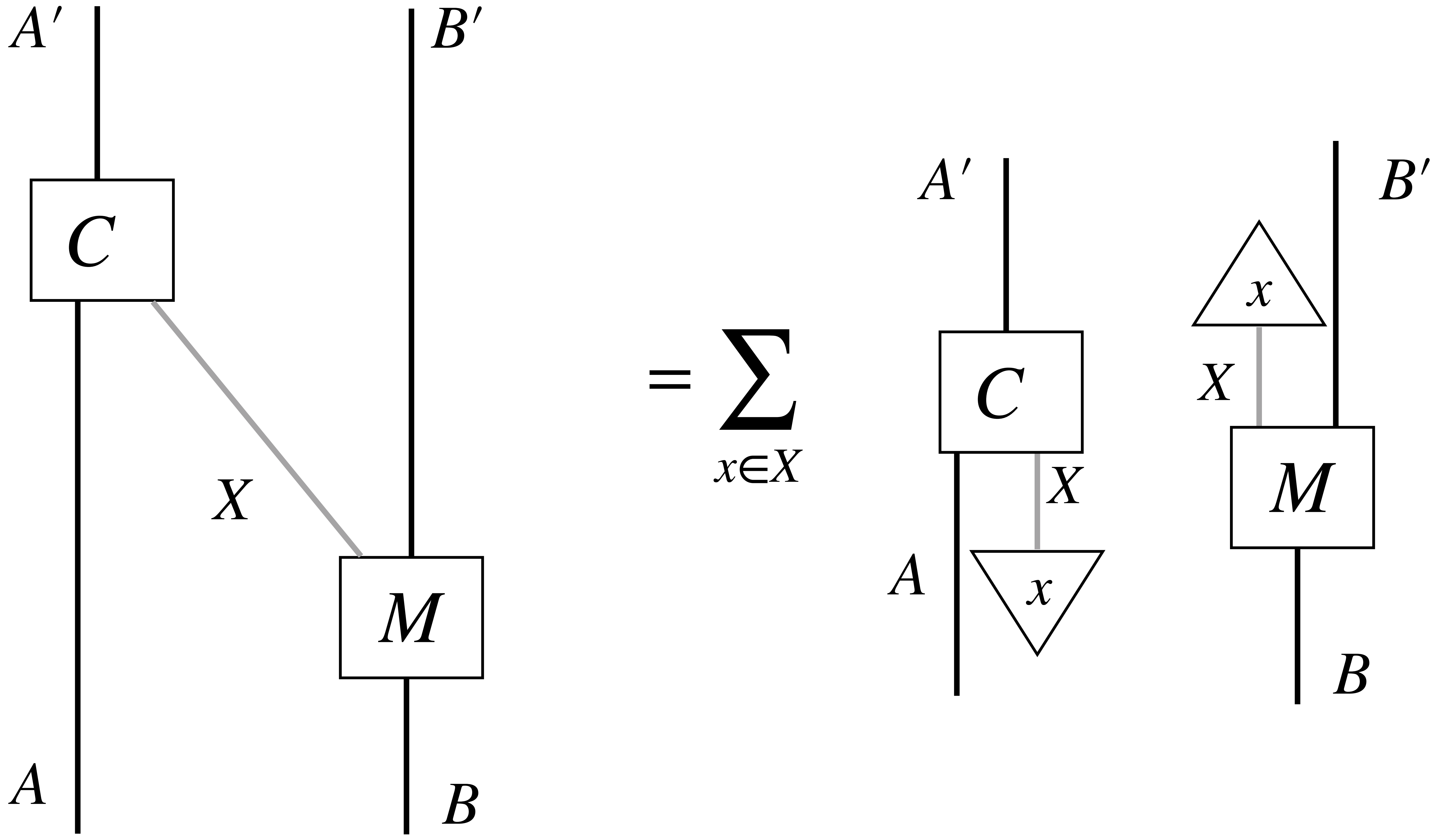
Non-destructive
measurement



Probability
distribution

Classical Interface in GPTs

Classical Communication

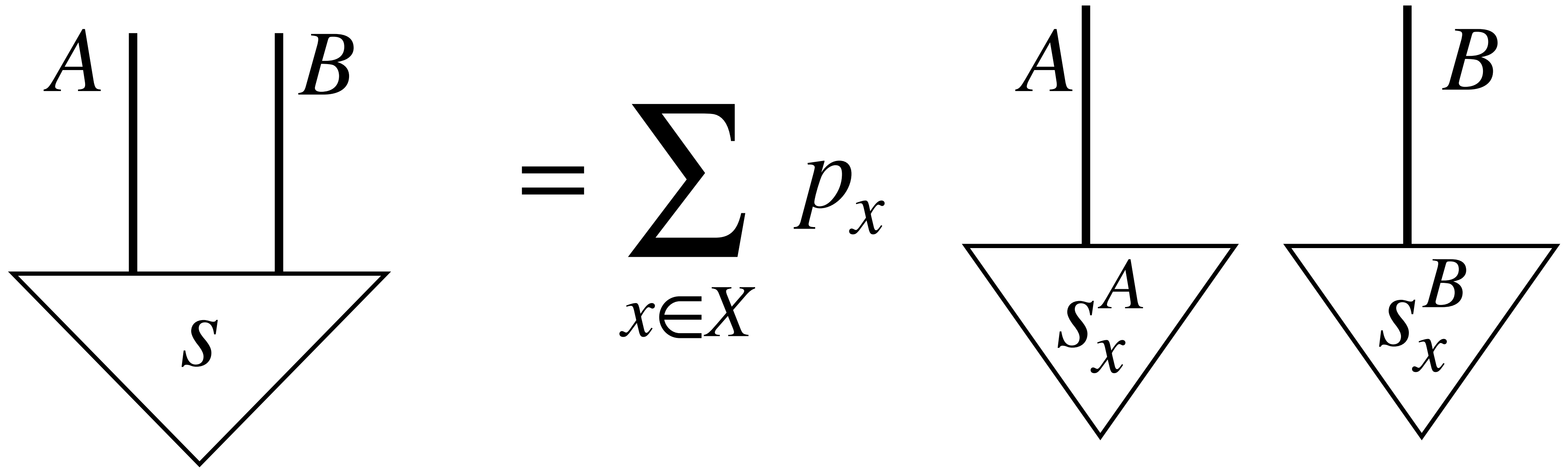


Entanglement in GPTs

A state is **entangled** if it is not separable.

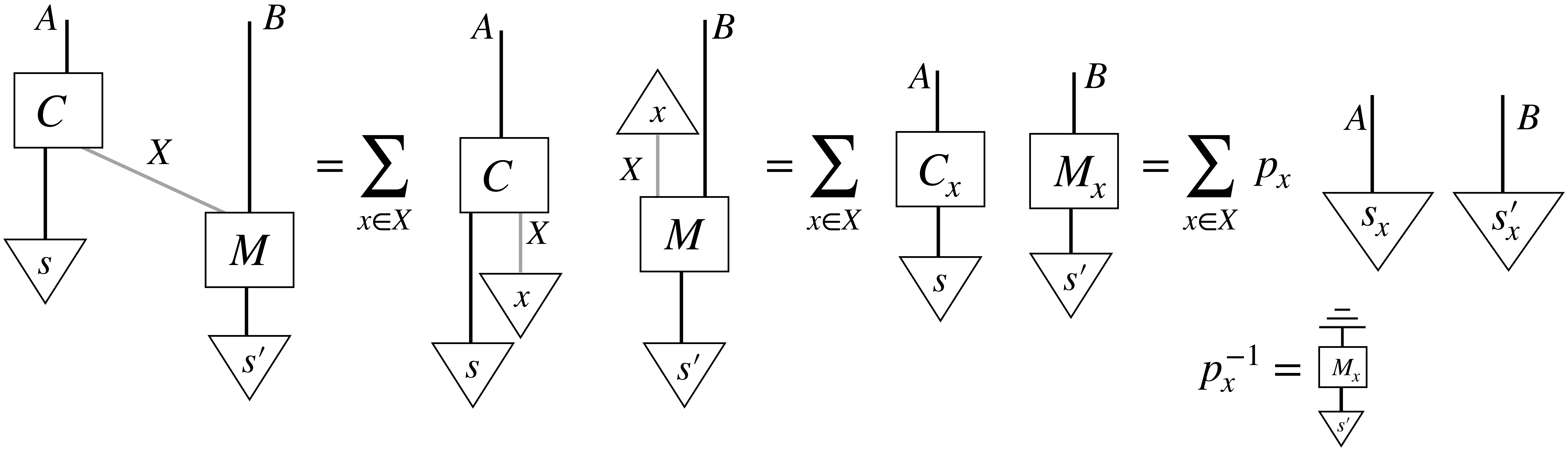
A bipartite state is **separable** if it can be written as a mixture of uncorrelated states.

Separable:



LOCC entanglement

Local operations and classical communications cannot create entanglement:



Result valid with no further assumptions about systems A and $B \Longrightarrow$ valid beyond QT.

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No-Go Theorem

[Submitted on 2 Dec 2020]

A no-go theorem on the nature of the gravitational field beyond quantum theory

Thomas D. Galley, Flaminia Giacomini, John H. Selby

Theorem III.1. We consider two non-classical systems A and B, initially in a separable state, and an unknown system G. If entanglement between the systems A and B is observed, then the following statements are incompatible:

1. There is no-signalling between A and B;
2. A and B interact locally via the mediator G;
3. G is a classical system.

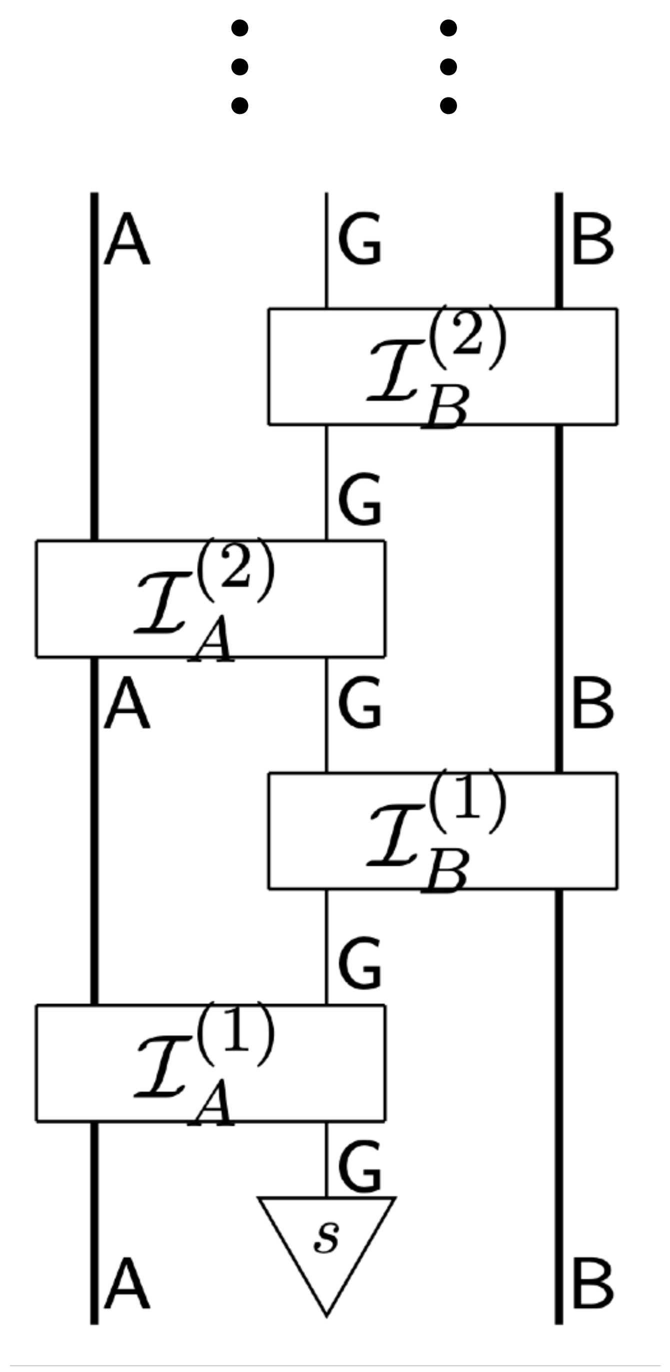
No-Go Theorem

1. No-Signalling between A and B

$\Longrightarrow$ they can be treated as different systems in a GPT.

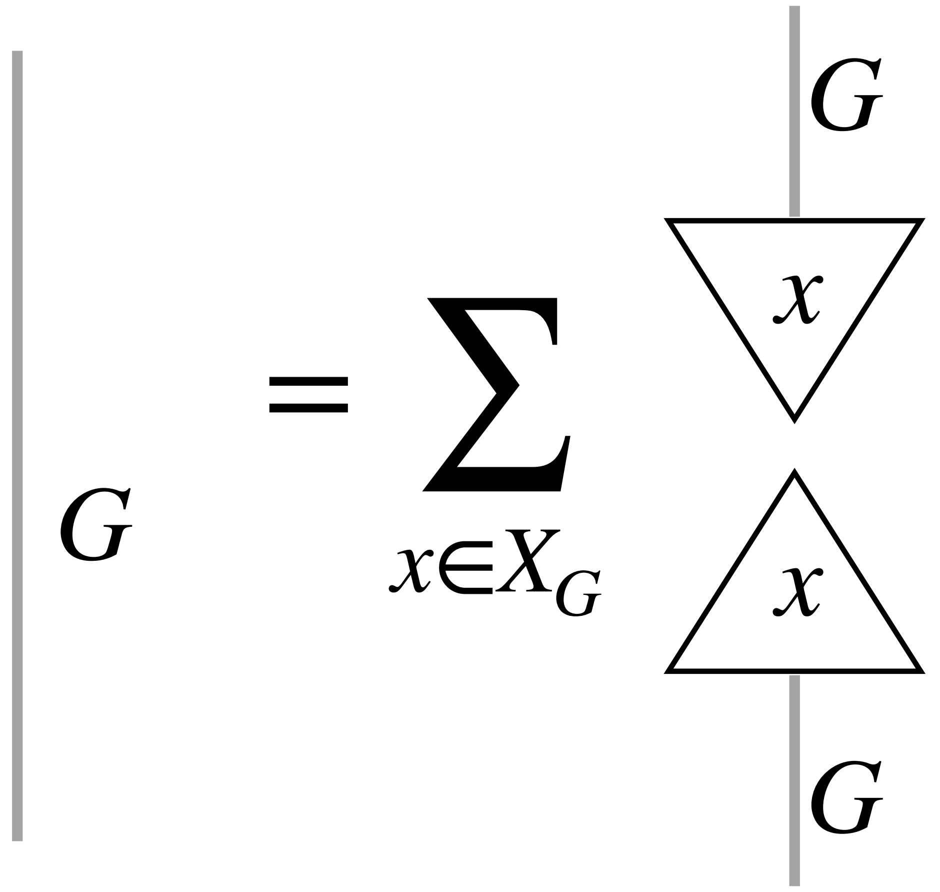
2. A and B interact indirectly via mediator G

$\Longrightarrow$ G is also a system in the GPT, and interactions are of the form:

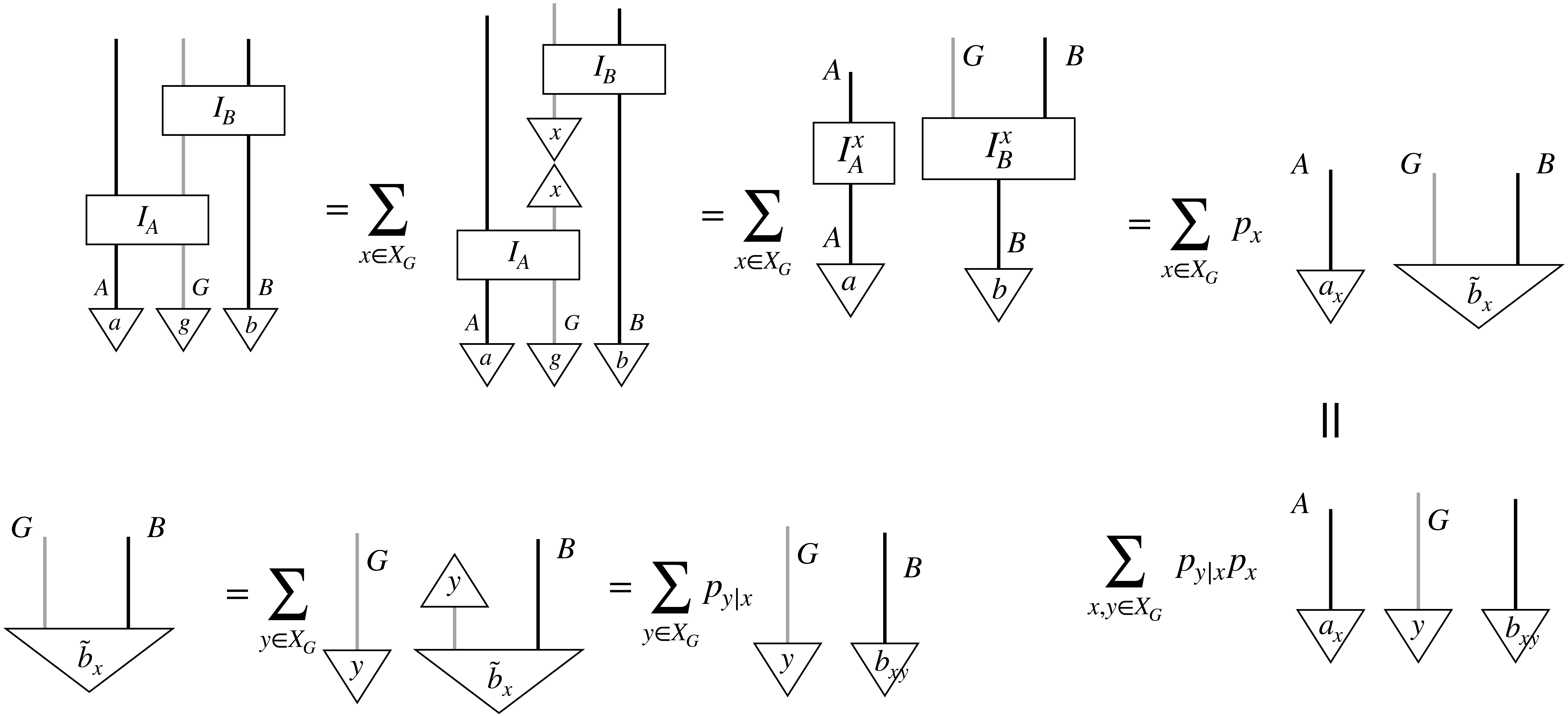


3. G is a classical system

$\Longrightarrow$the identity process for G can be decomposed



LOCC entanglement



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2. A and B interact locally via the mediator G;
3. G is a classical system.

Theories

LinQG: G is quantum

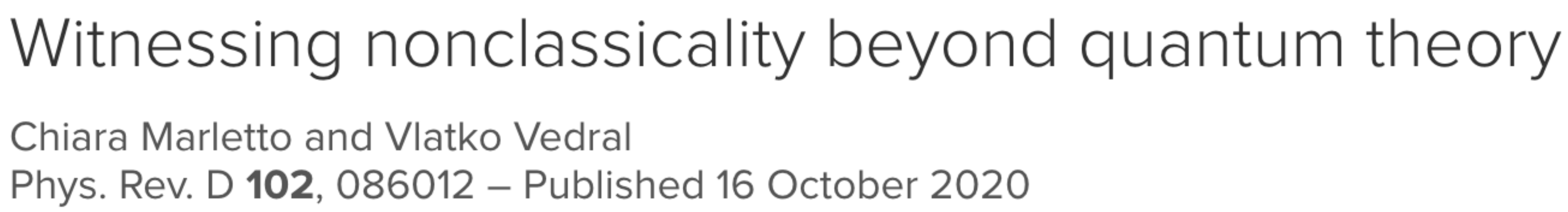
Newtonian interaction: G is not a physical system.

Schrödinger-Newton: A and B are signalling

Spontaneous collapse models: No entanglement

Post-Quantum Classical Gravity: No entanglement.

Alternative



Witnessing nonclassicality beyond quantum theory

Chiara Marletto and Vlatko Vedral
Phys. Rev. D **102**, 086012 – Published 16 October 2020

Another proof

Based on the Constructor Theory of Information

"Non-classicality" defined as the existence of non-commuting observables.

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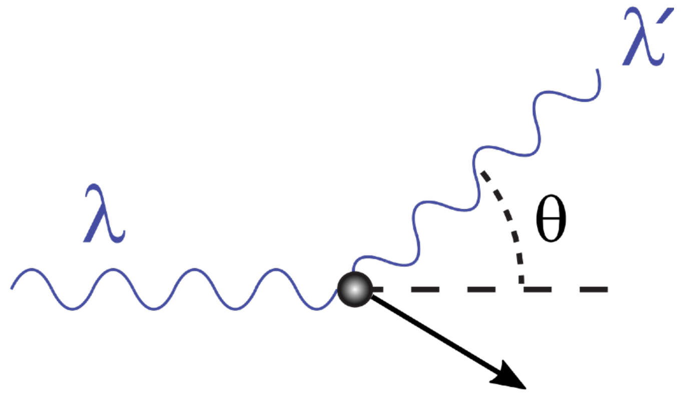

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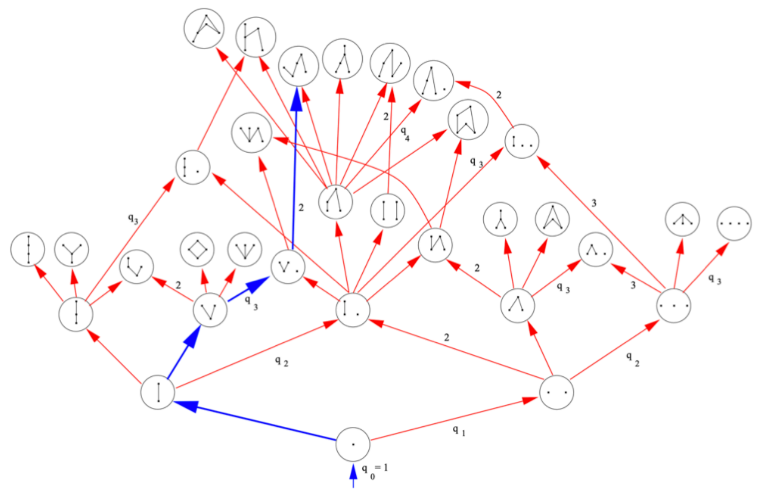

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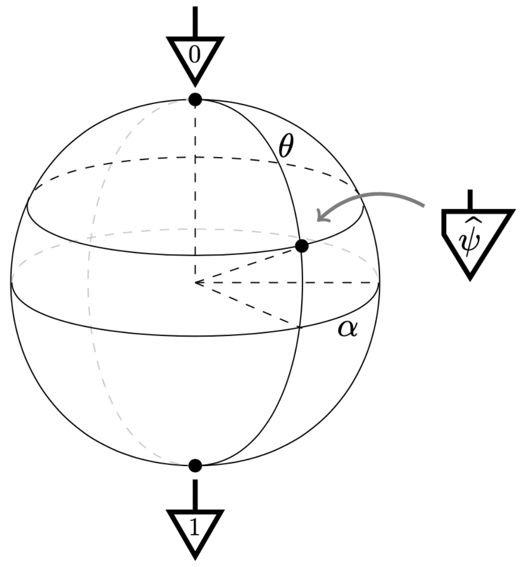

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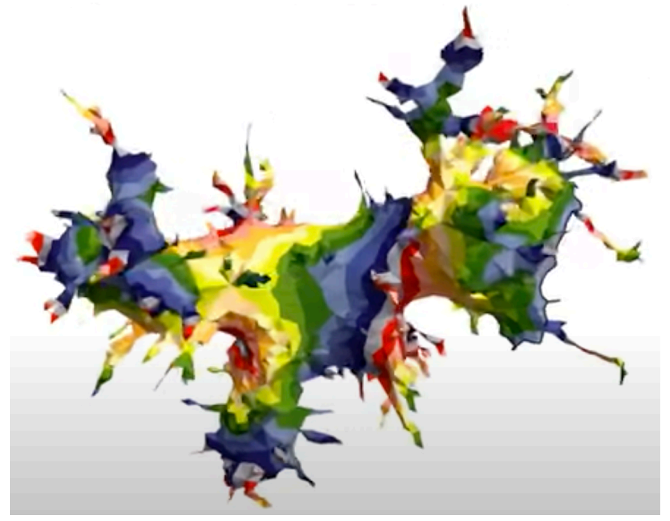
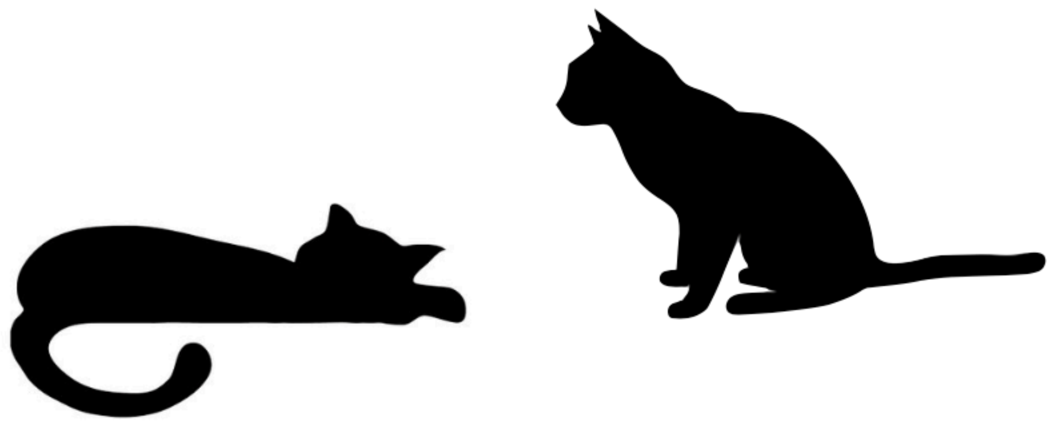


Timothy Budd
youtu.be/lzJpC78zduo



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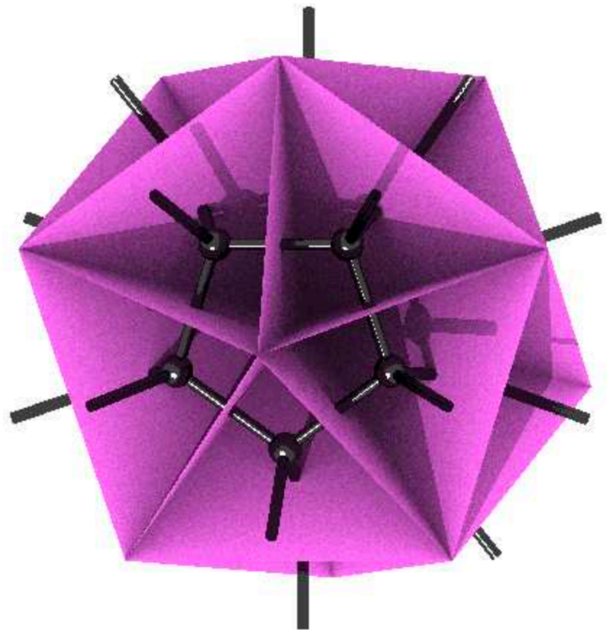

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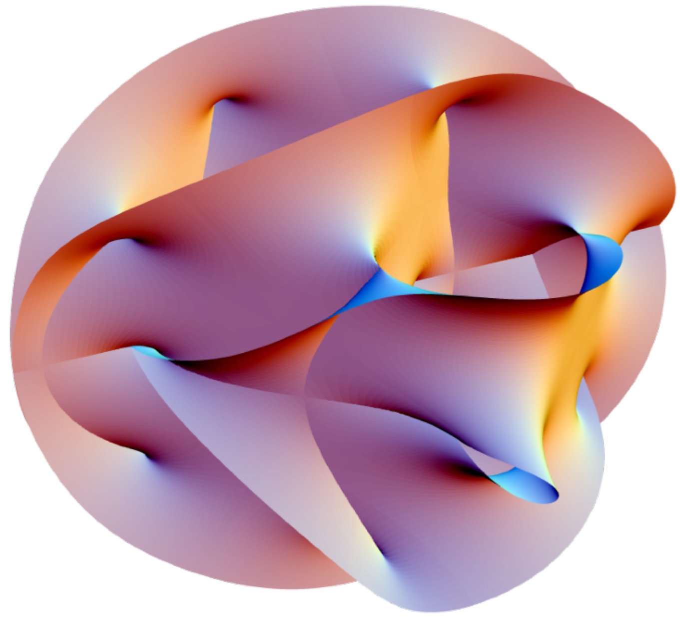

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End

Exciting times

Thanks for your attention!

Questions?