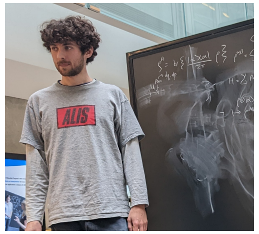
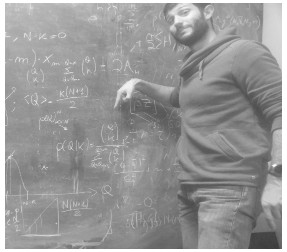
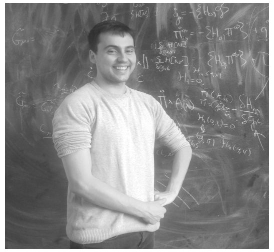
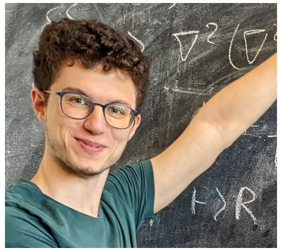
Decoherence vs Diffusion: Testing the Quantum Nature of Spacetime









WITH
A. Grudka, T. Morris, Muhammad Sajjad, Andrea Russo, Zach Weller-Davies, Barbara Soda, Carlo Sparaciari, Emanuele Panella, A. Pontzen

Phys. Rev. X 13, 041040 (2023)
Nature Comms 14, 7910 (2023)
arXiv:2302.07283
arXiv:2402.17844

Jonathan Oppenheim
@postquantum
ISQIQC Kokata
31 March 2025

It from Qubit
Simons Collaboration on Quantum Fields, Gravity and Information

Engineering and Physical Sciences Research Council

UCL

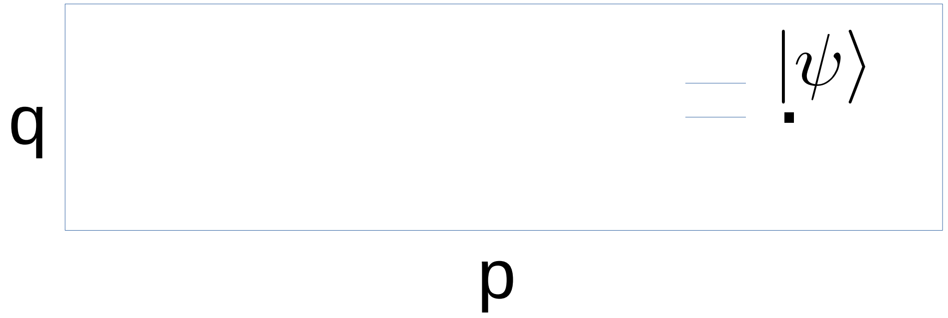
Frameworks

Quantum Mechanics

$$\frac{\partial \hat{\sigma}}{\partial t} = -i[\hat{H}, \hat{\sigma}]$$

Classical Mechanics

$$\frac{\partial \rho(q,p)}{\partial t} = \{H(q,p), \rho(q,p)\}$$



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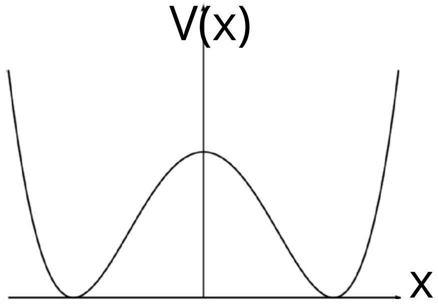
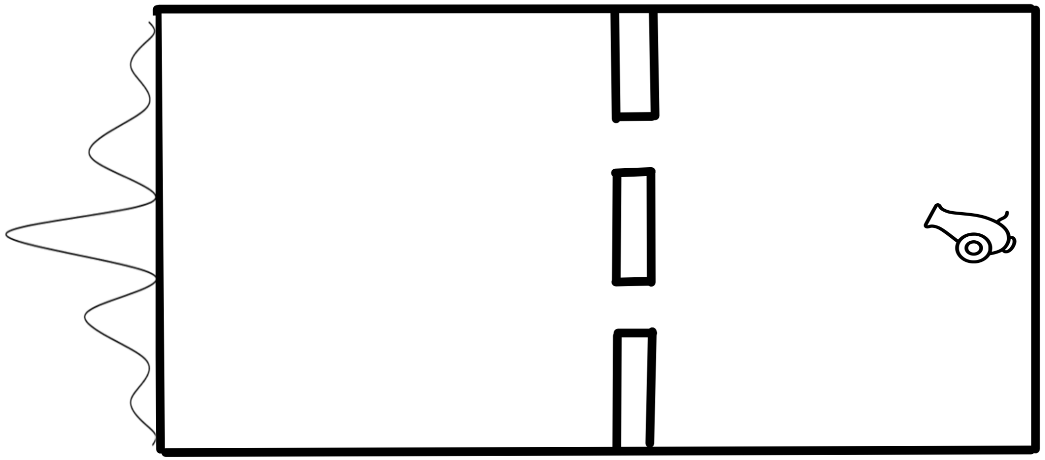
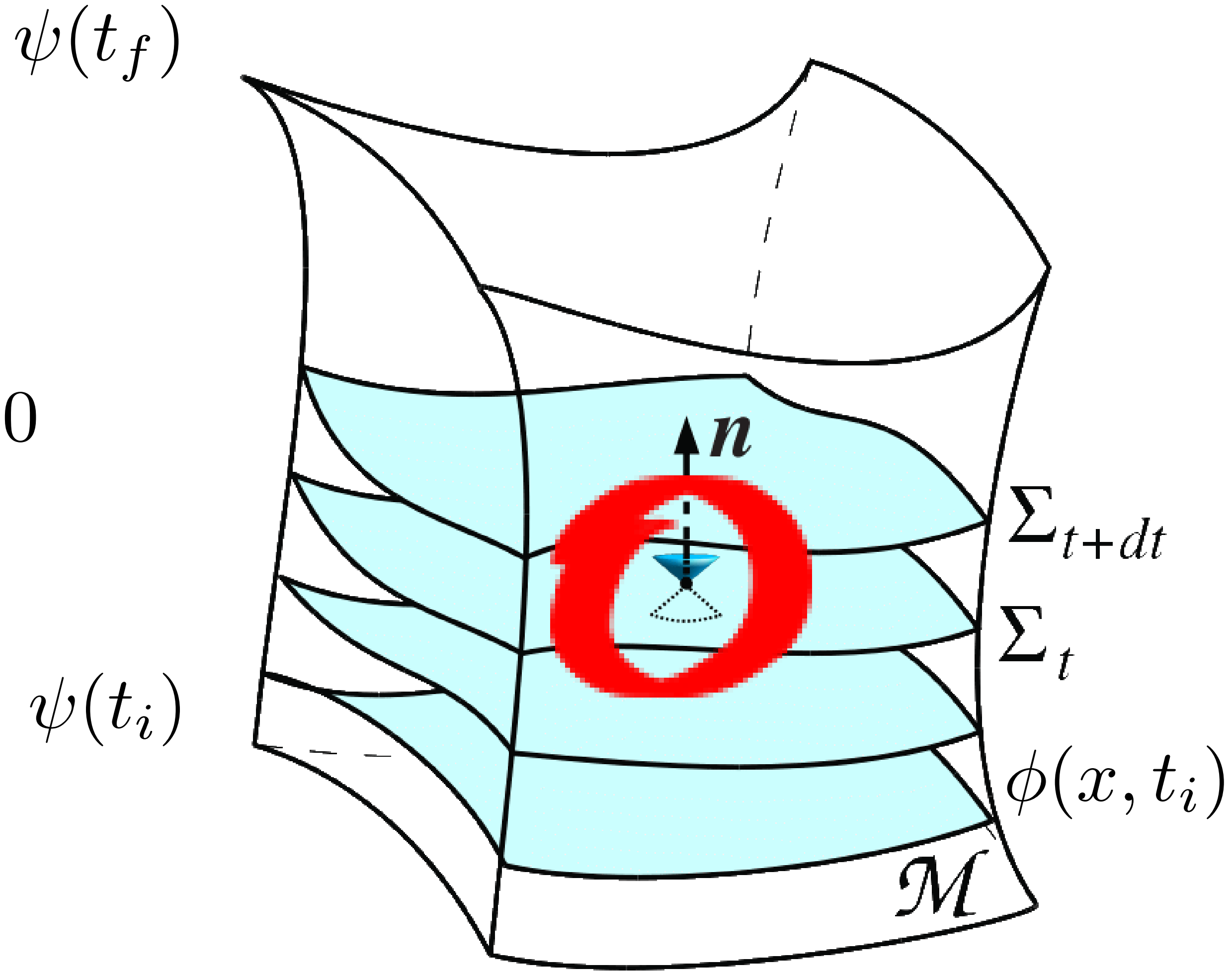




Back-reaction

Motivation: fundamental or effective?

$$[\phi(x), \phi(y)] = 0$$



Motivation: gravity is not a gauge theory

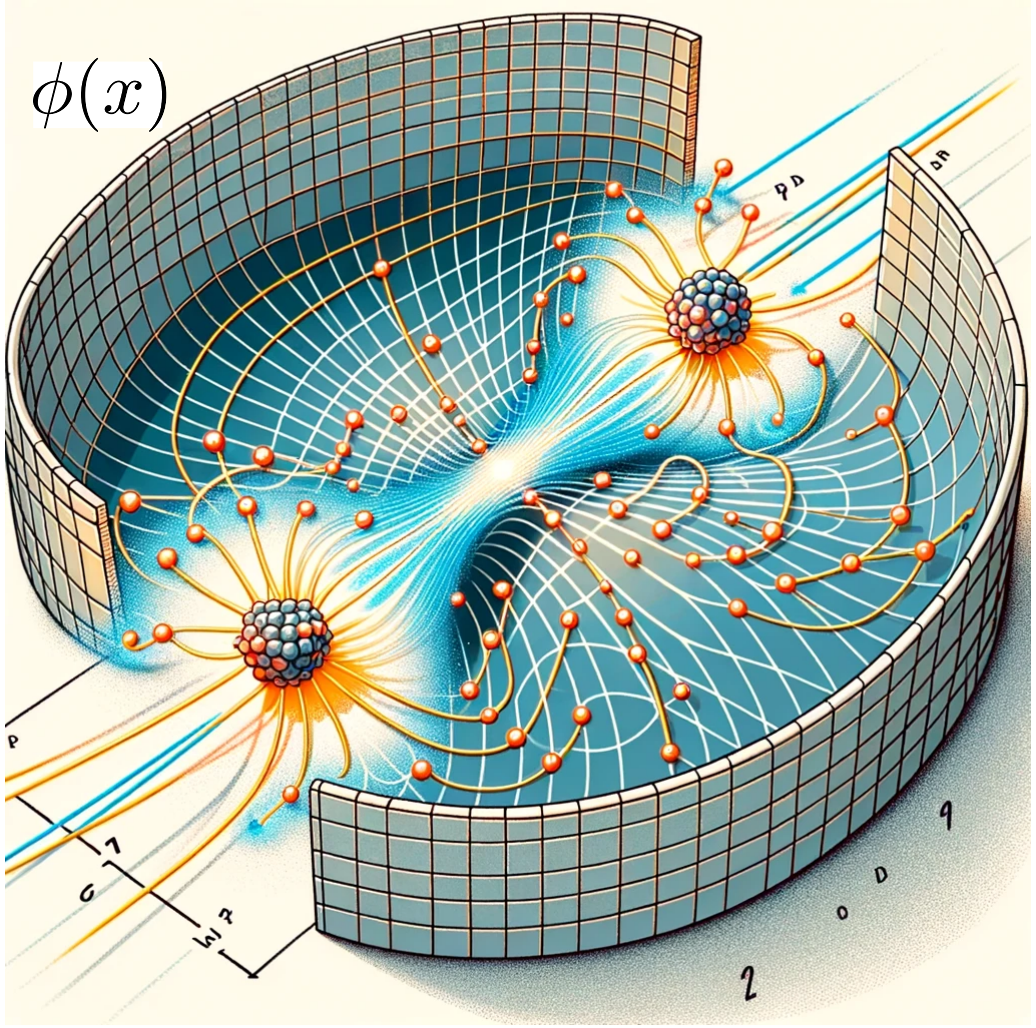
Gauge transformations act on Ψ(x), Diffs move x

Universal geometry on which fields live

Wheeler-deWitt Eqn

$$\mathcal{H}(x)|\psi\rangle = 0$$

Non-renormalisable (quantum theory)



Classical-quantum gravity

If true

Formally
renormalisable

Black hole information
problem?

Small Λ?
dark matter?

EXPERIMENT

Born rule & No need for
Measurement postulate

Decoherence vs
Diffusion trade-off

EXPERIMENT

Classical-quantum dynamics

Debate

No

Feynman (1957)
DeWitt (1962)
Unruh (1984)
Aharanov (~1986)
Eppley & Hannah (1977
Unruh (1984)
Caro & Salcedo (1999)
Terno (2004)
Carlip (2008)
Marletto Vedral (2017)
Galley, Giacomini, Selby (2022)

Maybe

Sherry & Sudarshan (1978)
Boucher & Traschen (1988)
Kapral (1999)
Peres & Terno (2001)
Hall & Reginatto (2005)
Mattingly (2006)
Albers, Kiefer & Reginatto (2008)
Kent (2018)

Classical-quantum dynamics

History

Semi-classical Einstein (pathological when fluctuations are large)

Page & Geilker (1981);
Gisin (1989)

Simple examples

Blanchard & Jadczyk (1994);
Diosi (1995);
Poulin (2017);

Kafri, Taylor, Milburn (2014);
Diosi, Tilloy (2016)

Quantum chemistry (negative probabilities)

Kapral review (2006);
Koopman-von Neumann (1931-32)

Experiments!

Bose et. al. (2017);
Marletto et. al. (2017)
Lami, Pedarnals, Plenio (2022)
Carney (2108.06320)

A post-quantum theory of classical gravity?

What is the most general form of CQ dynamics?

Decoherence vs Diffusion: testing quantum gravity

Renormalisable without Ghosts!

Anomalous contribution to the metric (dark matter, dark energy?)

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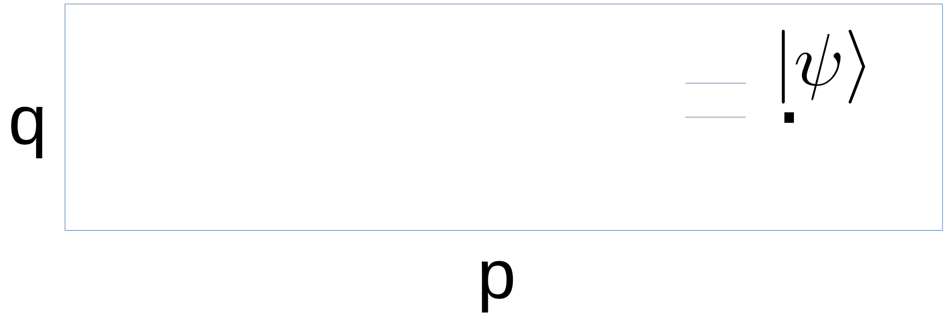


Classical Mechanics

$$\frac{\partial \rho(q,p)}{\partial t} = \{H(q,p), \rho(q,p)\}$$

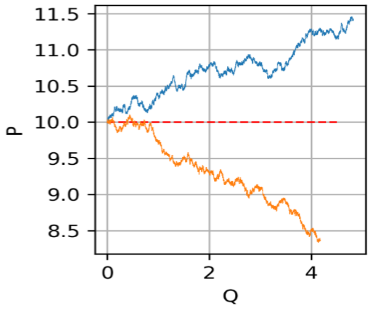
CQ Dynamics

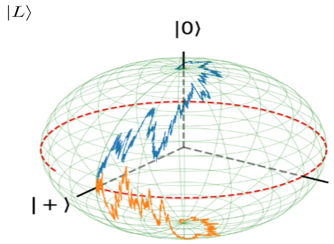
Path Integral

$$\rho(q,p,\phi^{\pm},t_f) = \int \mathcal{D}q\mathcal{D}p\mathcal{D}\phi^{\pm}\, e^{iS_C[q,p]+iS[\phi^+]-iS[\phi^-]+iS_{FV}[\phi^{\pm}]+iS_{CQ}[q,p,\phi^{\pm}]}\delta(\dot{q}-\frac{p}{m})\rho(q,p,\phi^{\pm},t_i)$$

JO, Zach Weller-Davies (2023)

Trajectories





JO, I. Layton, Z. Weller-Davies (2022)
Tilloy (2024)

Master Eqn

CPTP MAP

$$\frac{\partial \hat{\rho}}{\partial t} \approx \{H^{(grav)},\hat{\rho}\} - i[\hat{H}^{(m)},\hat{\rho}] + \frac{1}{2}\{\hat{H}^{(m)},\hat{\rho}\} - \frac{1}{2}\{\hat{\rho},\hat{H}^{(m)}\}$$
$$+\int dx dx' \frac{\delta^2}{\delta\pi_\Phi(x)\delta\pi_\Phi(x')}(D_2(x,x')\hat{\rho}) + \frac{1}{2}\int dx dx' D_0(x,x')\left([\hat{m}(x),[\hat{\rho},\hat{m}(x')]]\right)$$

JO, Sparaciari, Soda, Weller-Davies

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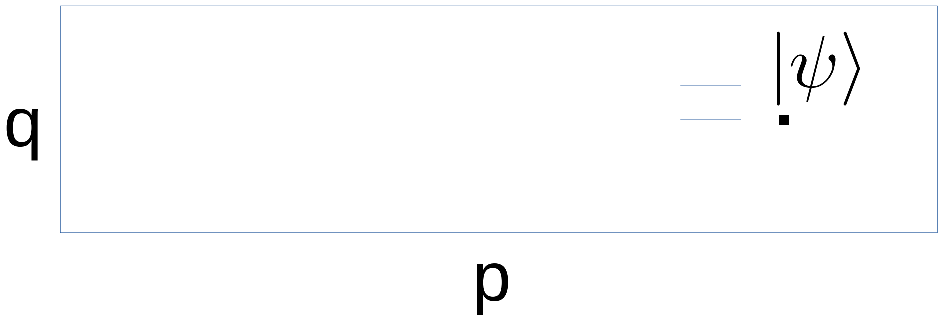


Classical Mechanics

$$\frac{\partial\rho(q,p)}{\partial t} = \{H(q,p), \rho(q,p)\}$$

$$\hat{\rho}(\mathrm{q,p}) = \rho(q,p)\begin{pmatrix} p(0|q,p) & \alpha(q,p) \\ \alpha^*(q,p) & p(1|q,p) \end{pmatrix}$$

Classical, quantum, & CQ States

Q

HILBERT SPACE

$\hat{\sigma}$

$$\text{tr}\,\hat{\sigma} = 1$$

POSITIVE MATRIX

C

PHASE SPACE

$\rho(q,p)$

$$\int dq dp \rho(q,p) = 1$$

POSITIVE DISTRIBUTION

CQ

$$\hat{\rho}(q,p) = \rho(q,p)\hat{\sigma}(q,p)$$

$\hat{\rho}(q,p)$

$$\int dq dp tr \hat{\rho}(q,p) = 1$$

POSITIVE MATRIX AT EACH POINT

Classical, quantum, & CQ States

Q

HILBERT SPACE

$$\mathrm{tr}\,\hat{\sigma} = 1 \qquad \hat{\sigma} = \begin{pmatrix} p(0) & \alpha \\ \alpha^* & p(1) \end{pmatrix}$$

POSITIVE MATRIX

C

PHASE SPACE

$$\int dq dp \rho(q,p) = 1$$

POSITIVE DISTRIBUTION

CQ

$$\hat{\sigma}_{cq} = \int dz \rho(z;t) |z\rangle\langle z| \otimes \sigma(z;t)$$

$$\hat{\rho}(z) = \rho(z) \begin{pmatrix} p(0|z) & \alpha(z) \\ \alpha^*(z) & p(1|z) \end{pmatrix}$$

$$\int dz tr \hat{\rho}(z) = 1$$

POSITIVE MATRIX AT EACH Z

Dynamics must be linear and preserve state-space

$$\mathbb{1} \otimes \mathcal{L}$$

Must be positive

Norm preserving

positive matrix at each q,p

$$\int dqdptr\,\hat{\rho}(q,p) = 1$$

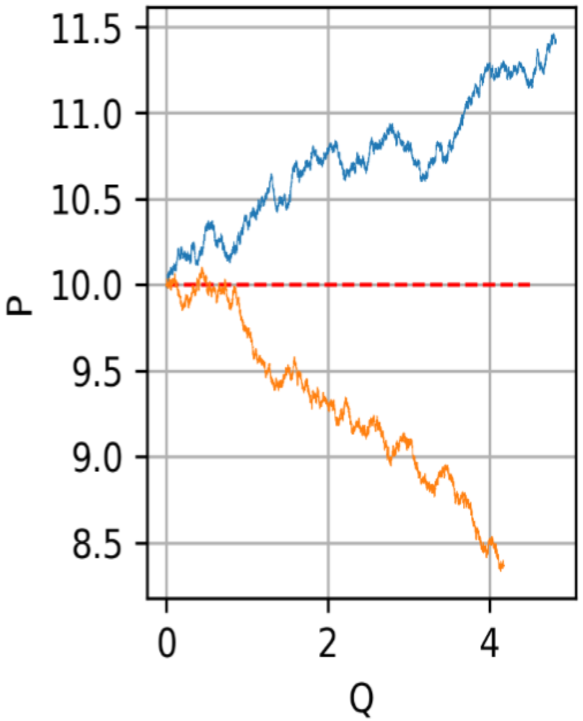
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle|\psi_L\rangle - |1\rangle|\psi_R\rangle\right) \qquad \sigma^{(m)} = \frac{1}{2}|\psi_L\rangle\langle\psi_L| + \frac{1}{2}|\psi_R\rangle\langle\psi_R|$$

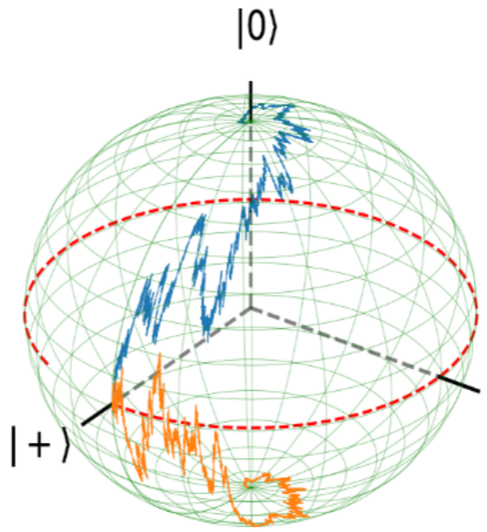
$$\frac{1}{2}\mathcal{L}(|\psi_L\rangle\langle\psi_L|) + \frac{1}{2}\mathcal{L}(|\psi_R\rangle\langle\psi_R|) = \mathcal{L}\left(\frac{1}{2}|\psi_L\rangle\langle\psi_L| + \frac{1}{2}|\psi_R\rangle\langle\psi_R|\right)$$

Example of continuous master-equation

Stern-Gerlach

$$\hat{H} = \frac{p^2}{2m} + D_1 q \hat{\sigma}$$





$$D_2 D_0 \succeq D_1^2$$

JO, Isaac Layton, Zach Weller-Davies

Example of continuous master-equation

Stern-Gerlach

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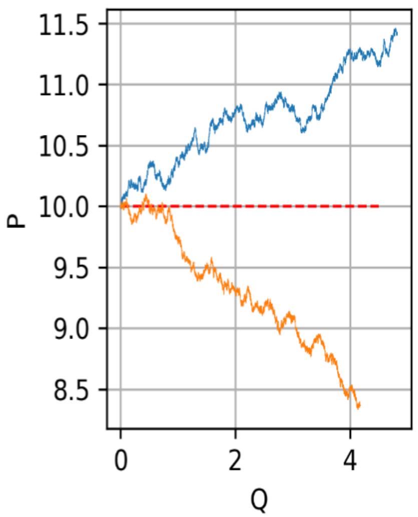
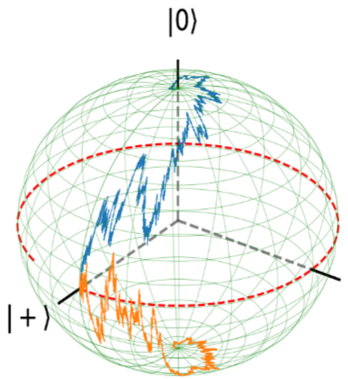
$$\frac{\partial \hat{\rho}}{\partial t} = -i[\hat{H}, \hat{\rho}] + \frac{1}{2}\{\hat{H}, \hat{\rho}\} - \frac{1}{2}\{\hat{\rho}, \hat{H}\} + \frac{D_2}{2}\{q, \{q, \hat{\rho}\}\} + \frac{D_0}{2}[\hat{\sigma}, [\hat{\rho}, \hat{\sigma}]]$$





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Diosi (1995)
Isaac Layton, JO, Zach Weller-Davies (2022)

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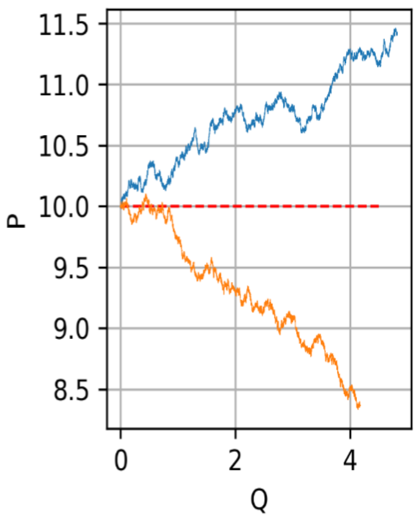
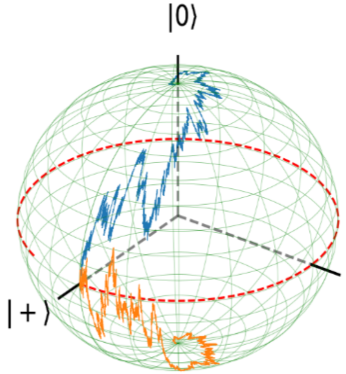
$$\frac{\partial\hat{\rho}}{\partial t} = -i[\hat{H},\hat{\rho}] + \frac{D_1}{2}\left(\hat{\sigma}\frac{\partial\hat{\rho}}{\partial p} + \frac{\partial\hat{\rho}}{\partial p}\hat{\sigma}\right) + \frac{D_2}{2}\frac{\partial^2\hat{\rho}}{\partial p^2} + \frac{D_0}{2}[\hat{\sigma},[\hat{\rho},\hat{\sigma}]]$$





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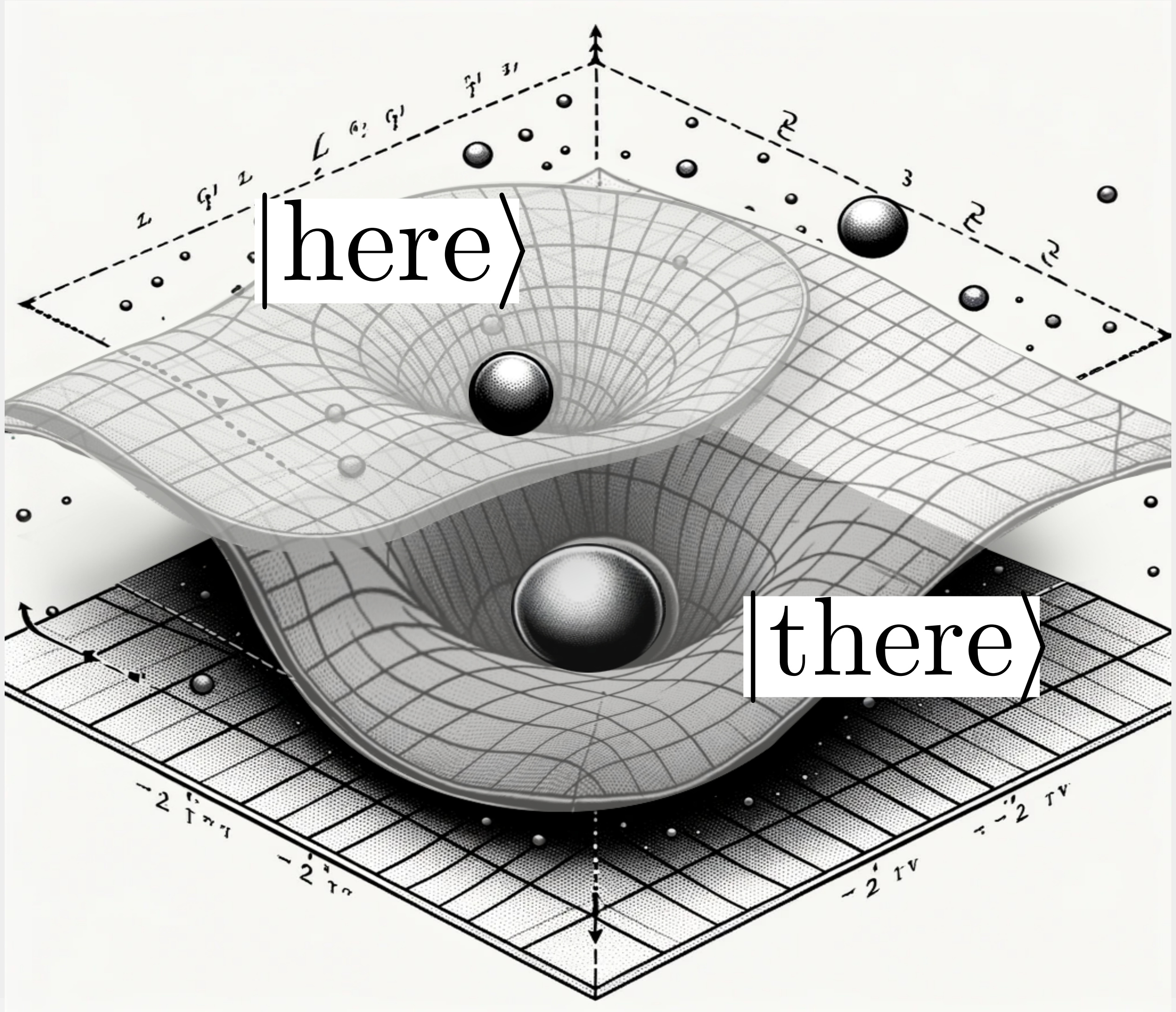
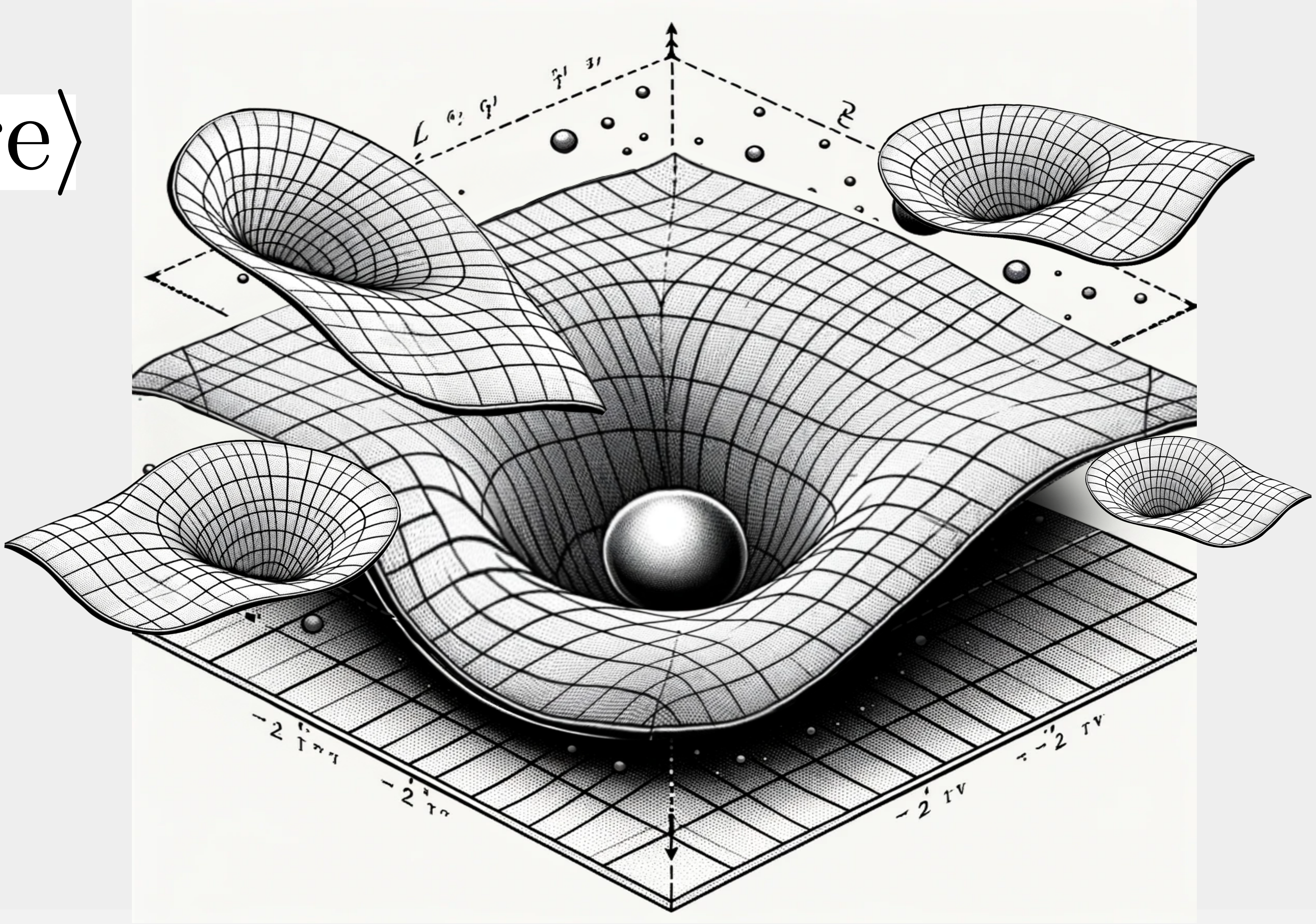


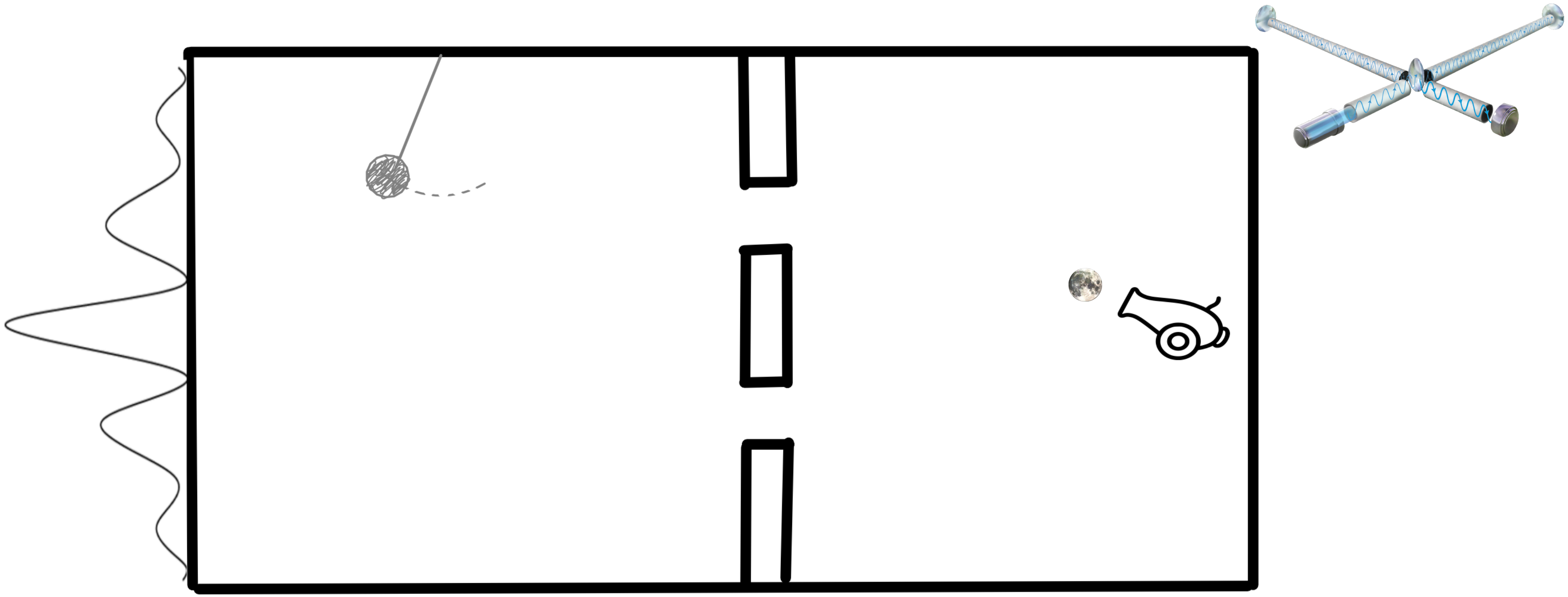
Decoherence vs diffusion trade-off

$|\text{here}\rangle$



$|\text{there}\rangle$

Decoherence vs diffusion



Feynman, Chapel Hill Conference (1957); Aharonov (~1986); Eppley & Hannah (1977); Marletto & Vedral (2017)

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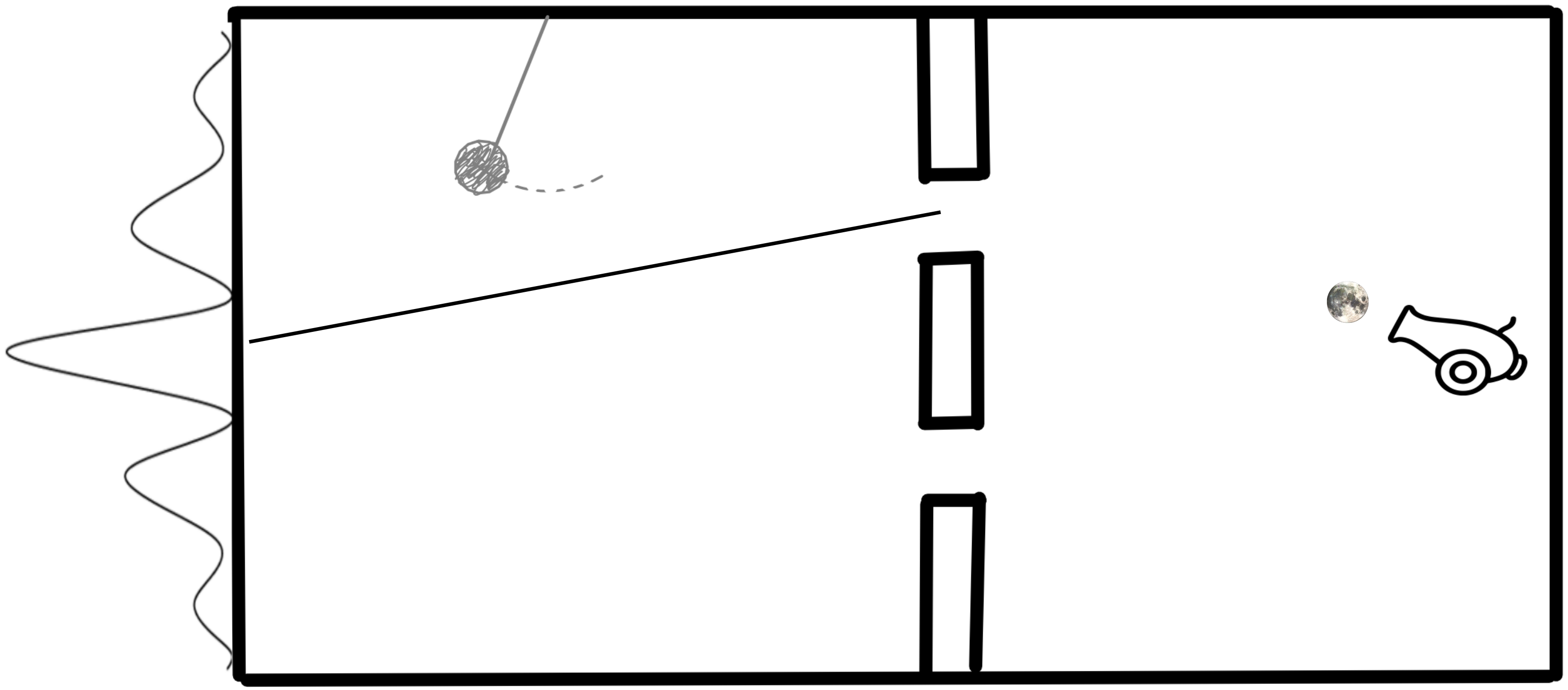

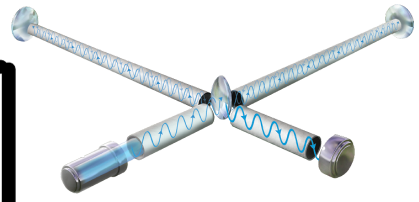

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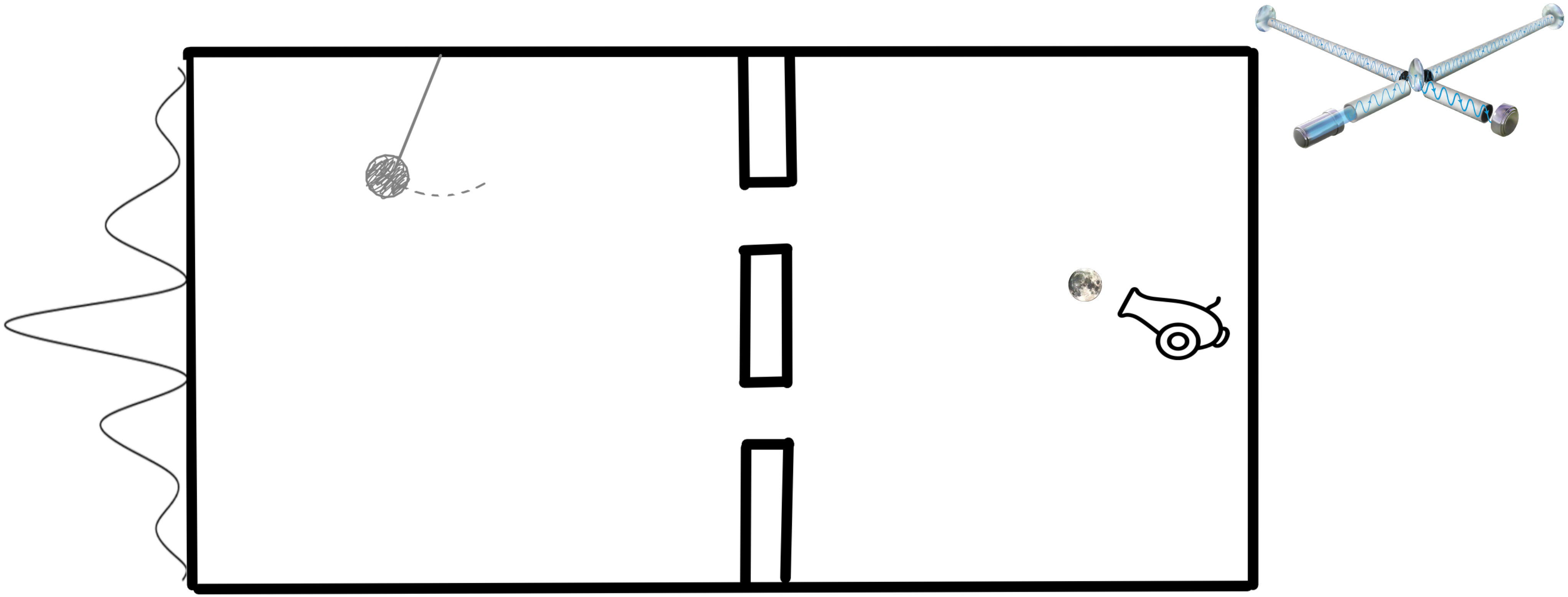
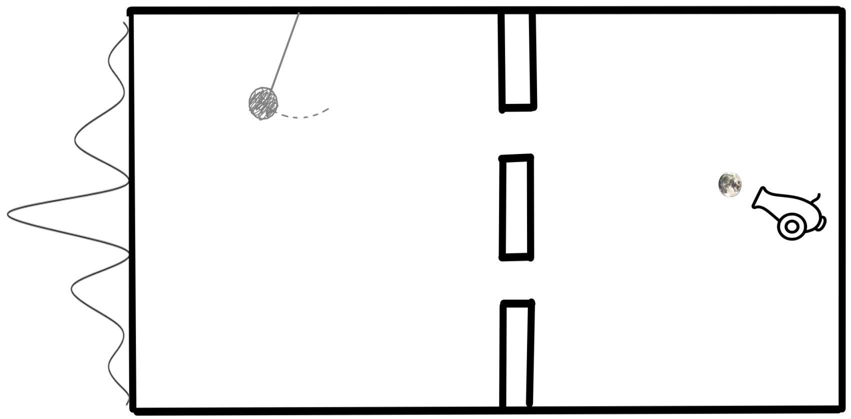


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|E_L\rangle|L\rangle + |E_R\rangle|R\rangle\right)$$

Decoherence vs diffusion



$$\hat{\sigma}(t) = \begin{pmatrix} \frac{1}{2} & \alpha^*(t) \\ \alpha(t) & \frac{1}{2} \end{pmatrix}$$

$$\alpha(t) = \langle E_L(t) | E_R(t) \rangle$$

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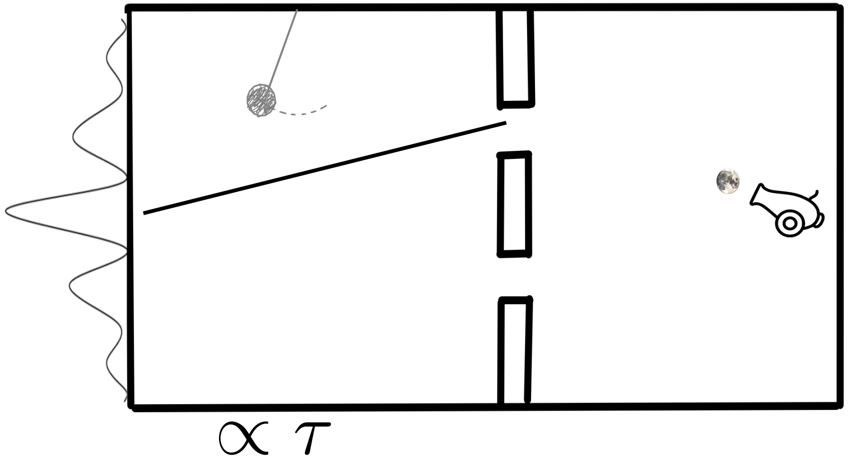
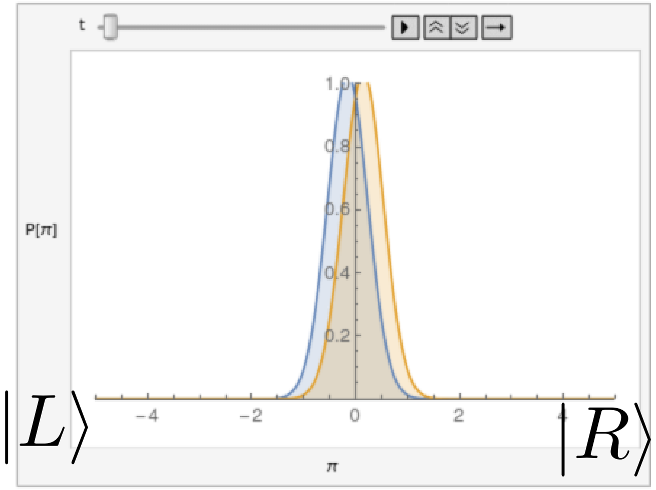
Decoherence vs diffusion



$$\tau \leq \frac{D_2}{\langle F\rangle^2}$$

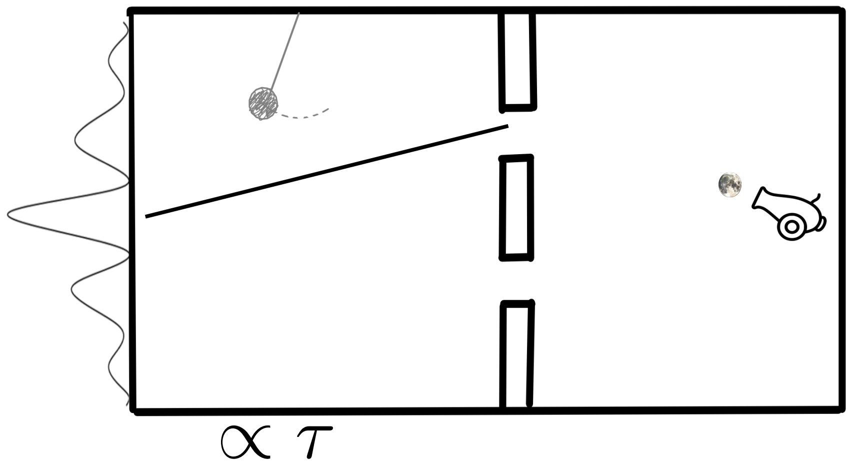


$$\mathrm{D}_2(q,p) - D_1^\dagger(q,p) D_0^{-1}(q,p) D_1(q,p) \succeq 0$$

Holds for all classical-quantum dynamics

JO, Soda, Sparaciari, Weller-Davies (2022)

Decoherence vs diffusion



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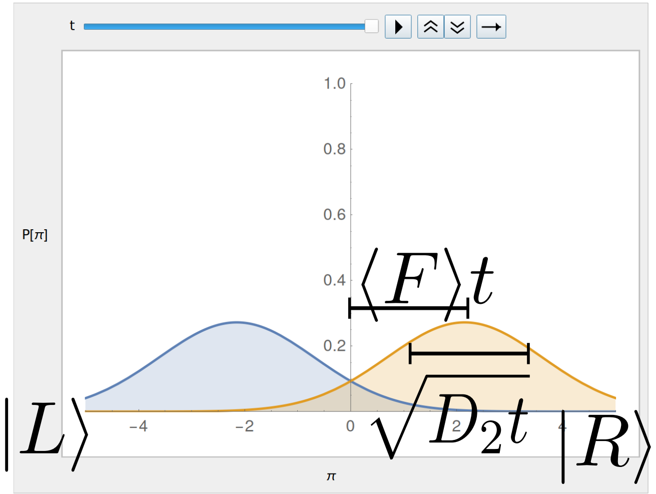

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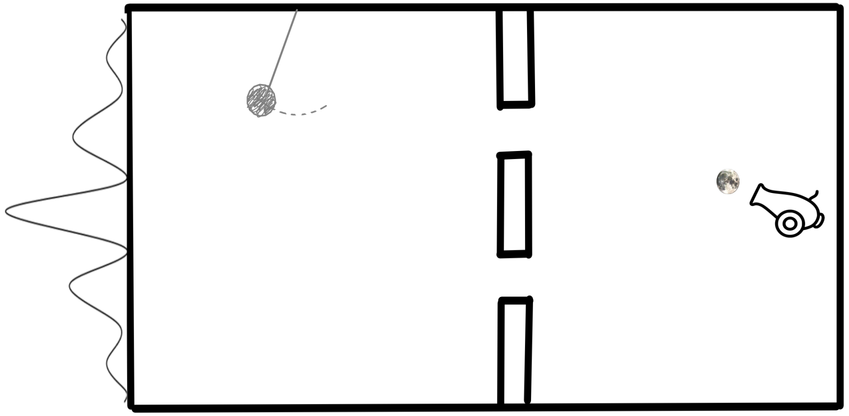
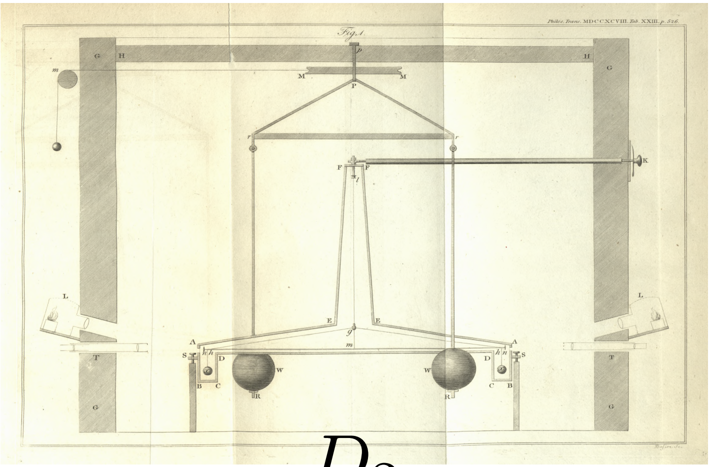
Double Slit Experiment



τ

Cavendish Experiment



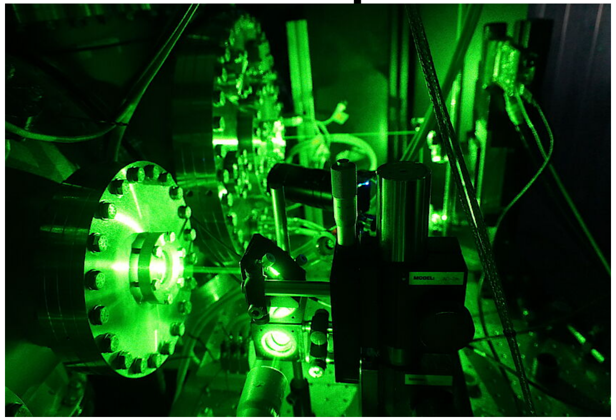
D_2

$$\langle F(x) \rangle = \langle \hat{m}(x) \rangle$$

$$\tau \leq \frac{D_2}{\langle F \rangle^2}$$

Decoherence vs diffusion

Double Slit Experiment



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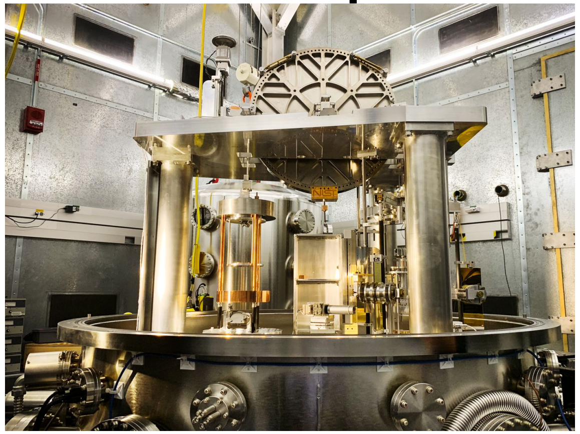

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Figures of merit

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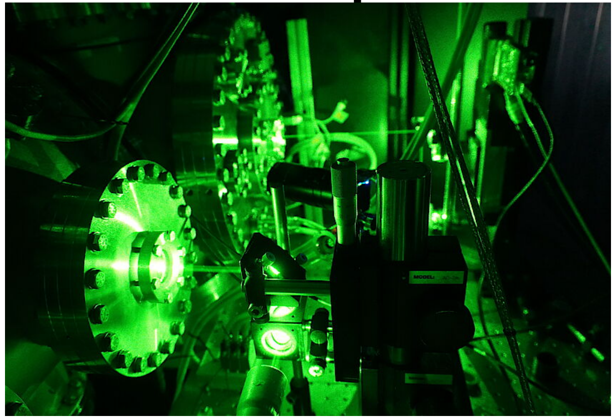

τ

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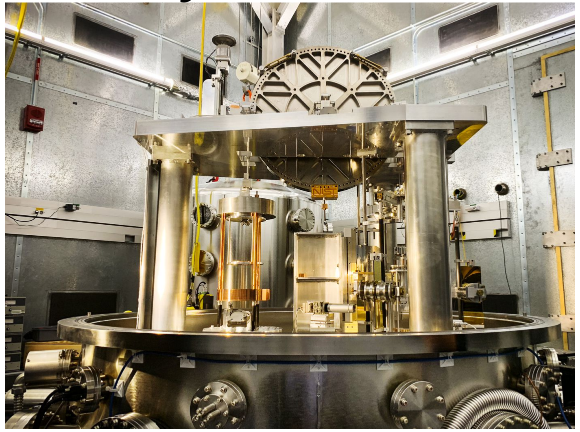
Gravity measurement



D_2

$$\tau \approx \frac{D_G c^3}{G_N^2} \frac{V}{M^2}$$

Master Equation	Diffusi…	
…inuous (ultra-local)	$D_2(\Phi; x, y) = D_2(\Phi)\delta(x, y)$ $D_2(\Phi) = \sum_n c^n \Phi^n$	$10^{-41} \geq D_2 \geq 10^{-9}\ kg^2 sm^{-3}$ (Eqn (44))
…us (Eqn (D11) or (D13))	$D_2(\Phi;$ $D_2(\Phi)$	
Discrete (ultra-local)	$D_2(\Phi;$ $D_2(\Phi) = \sum_n c^n \Phi^n$	[illegible]

$$S_{aa}(\vec{x}, \vec{x}'; \omega) := \langle a(x) a(x') \rangle - \langle a(x) \rangle \langle a(x') \rangle$$

$$S_{aa}(\vec{x}, \vec{x}'; \omega)|_{\omega_0 \to 0} = \frac{D_G c^3}{4\pi} \left(\frac{\omega^3}{\omega_0^2 c} + \frac{1}{|x - x'|} \right)$$

Challenges

Tensions?

CPTP

Covariant

Renormalisable

Vacuum stability

Renormalisable in matter sector?

GR in the classical limit

Is space-time classical?

I have no idea. But, But… THANK YOU for your attention

It could be

1:5000 ODDS

Information is lost but quantum state remains pure

DIFFUSION

Measurement postulate not needed.

COHERENCE LIMIT

Decoherence vs Diffusion trade-off

EXPERIMENT

Effective vs fundamental vs alternative hypothesis?

Dark matter?
Dark energy?

Renormalisable w/o Ghosts