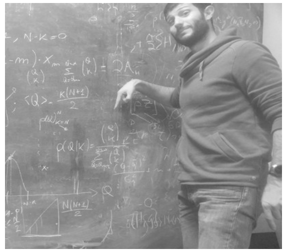
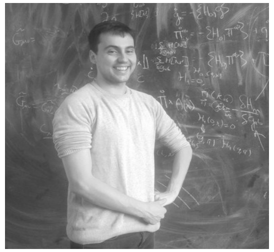
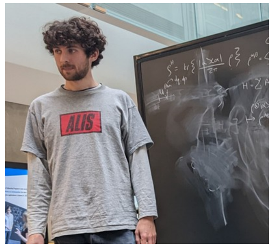
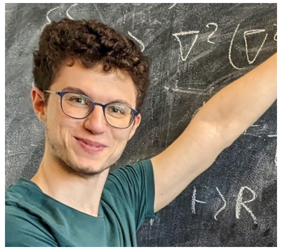
A postquantum theory of classical gravity?



WITH
Andrzej Grudka, Muhammad Sajjad, Andrea Russo, Zach Weller-Davies

Phys. Rev. X 13, 041040 (2023)
Nature Comms 14, 7910 (2023)
arXiv:2302.07283
arXiv:2402.19459
arXiv:2402.17844

Jonathan Oppenheim
@postquantum
Edinburgh
April 19, 2024

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

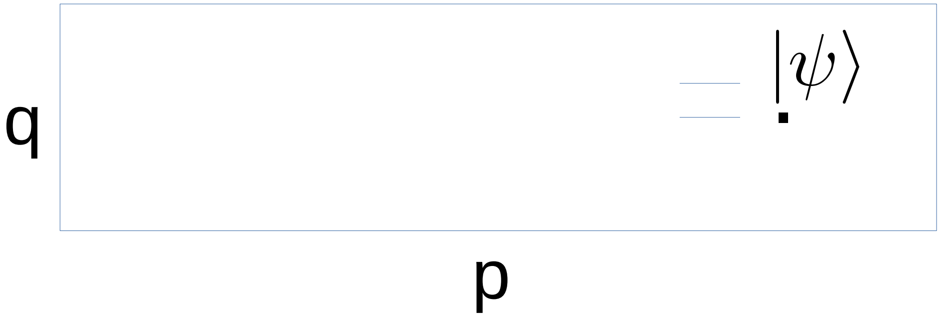
UKRI Engineering and Physical Sciences Research Council

UCL

Frameworks

Quantum Mechanics

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



Classical Mechanics

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

Frameworks

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Classical Mechanics

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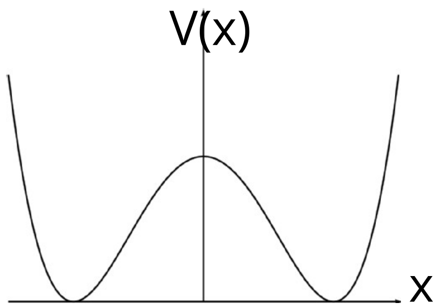
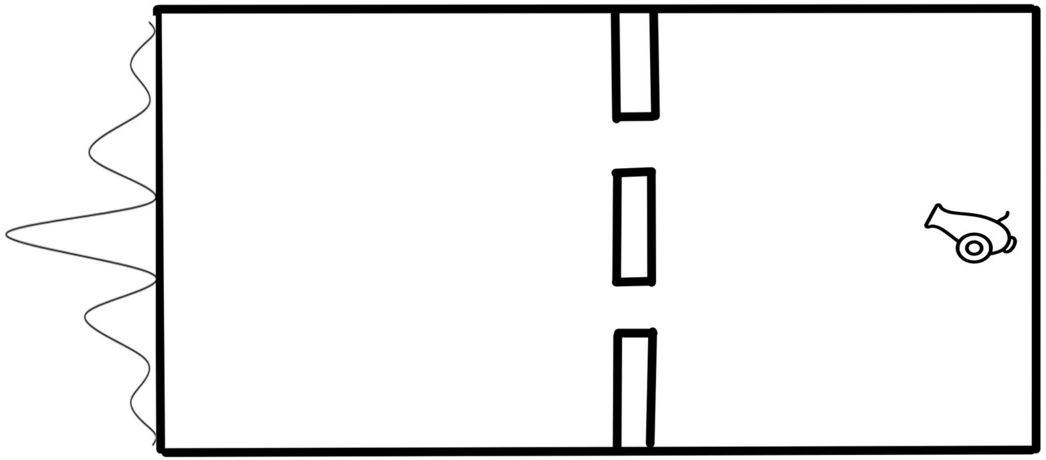


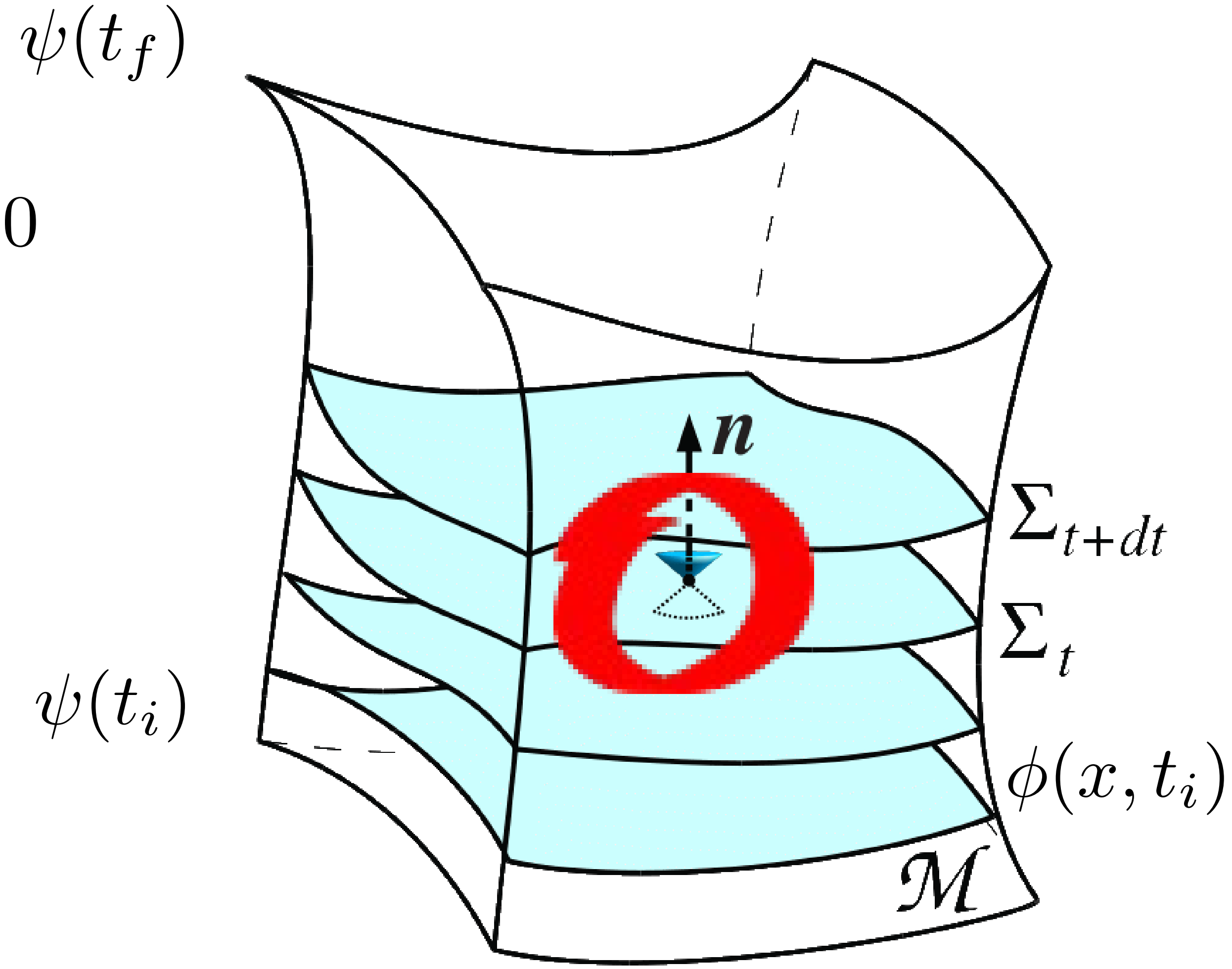


Back-reaction

Motivation (fundamental or effective)

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

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



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)

Quantum chemistry (negative probabilities)

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

Simple examples

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

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

Experiments!

Kafri & Taylor (2013);
Bose et. al. (2017);
Marletto et. al. (2017)
Lami, Pedarnals, Plenio (2022)
Carney (2108.06320)

Classical-quantum dynamics

Results

Most general form

Renormalisable without Ghosts

Small Λ
dark matter?

EXPERIMENT

Born rule & No need for Measurement postulate

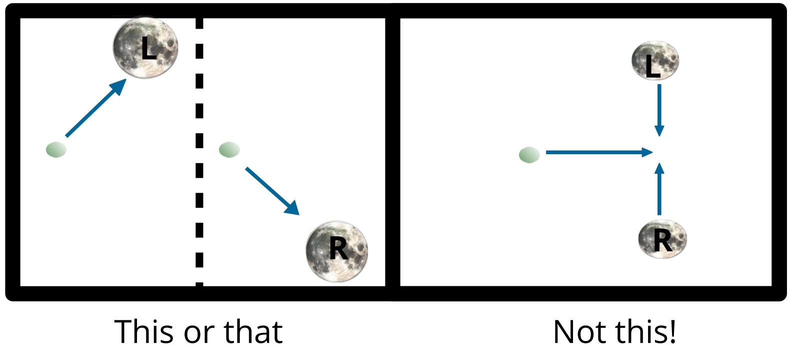
Decoherence vs Diffusion trade-off

EXPERIMENT

Semi-classical equations are pathological

$$G_{\mu\nu} = \frac{8\pi G}{c^4} \langle \hat{T}_{\mu\nu} \rangle$$

$$\rho^{(gm)} = \frac{1}{2}\rho_L^{(g)}\rho_L^{(m)} + \frac{1}{2}\rho_R^{(g)}\rho_R^{(m)}$$



Consistent Dynamics: linear and preserve state-space (completely positive and norm preserving)

Requires decoherence and diffusion

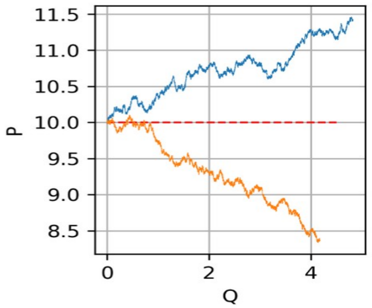
CQ Dynamics

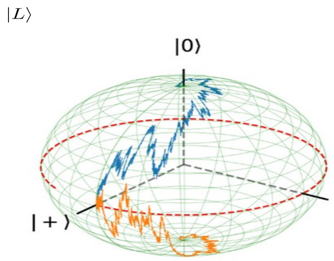
Path Integral

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

JO, Zach Weller-Davies

Trajectories





JO, I. Layton, Z. Weller-Davies

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

A post-quantum theory of classical gravity?

Renormalisable

without Ghosts!

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

What is the most general form of CQ dynamics?

Decoherence vs Diffusion: testing quantum gravity

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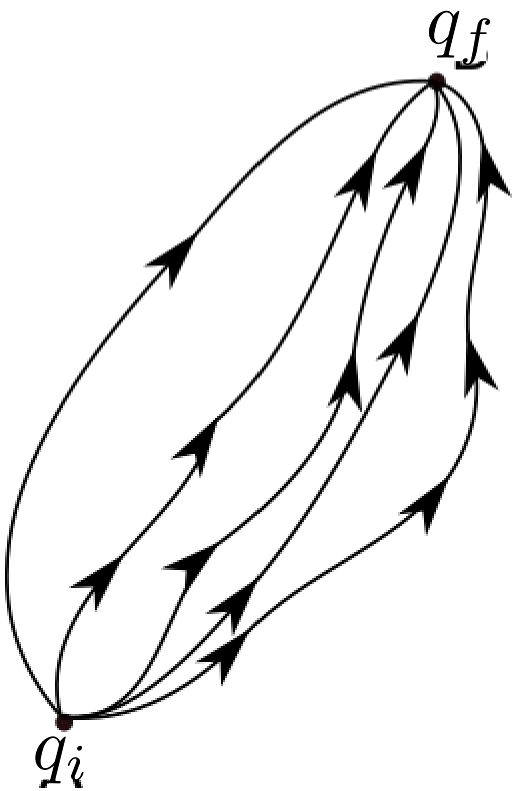
Path Integrals

Quantum Mechanics

$$\langle q_f, t_f | q_i, t_i \rangle = \int_{q_i}^{q_f} \mathcal{D}q \; e^{i \int dt \left(\frac{1}{2} m \dot{q}^2 - V(q) \right)}$$



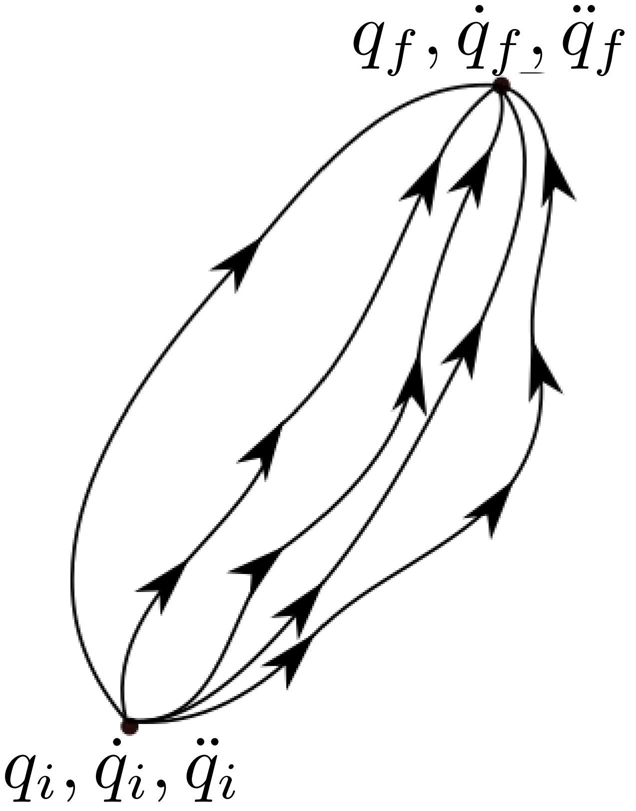
Brownian motion

Classical Mechanics (stochastic)

$$\ddot{q} = \frac{F}{m} + j(t)$$

$$\langle j(t) \rangle = 0, \quad \langle j(t) j(s) \rangle = D_2 \delta(s,t)$$

Langevin Eqn (or Fokker-Planck, or Ito)



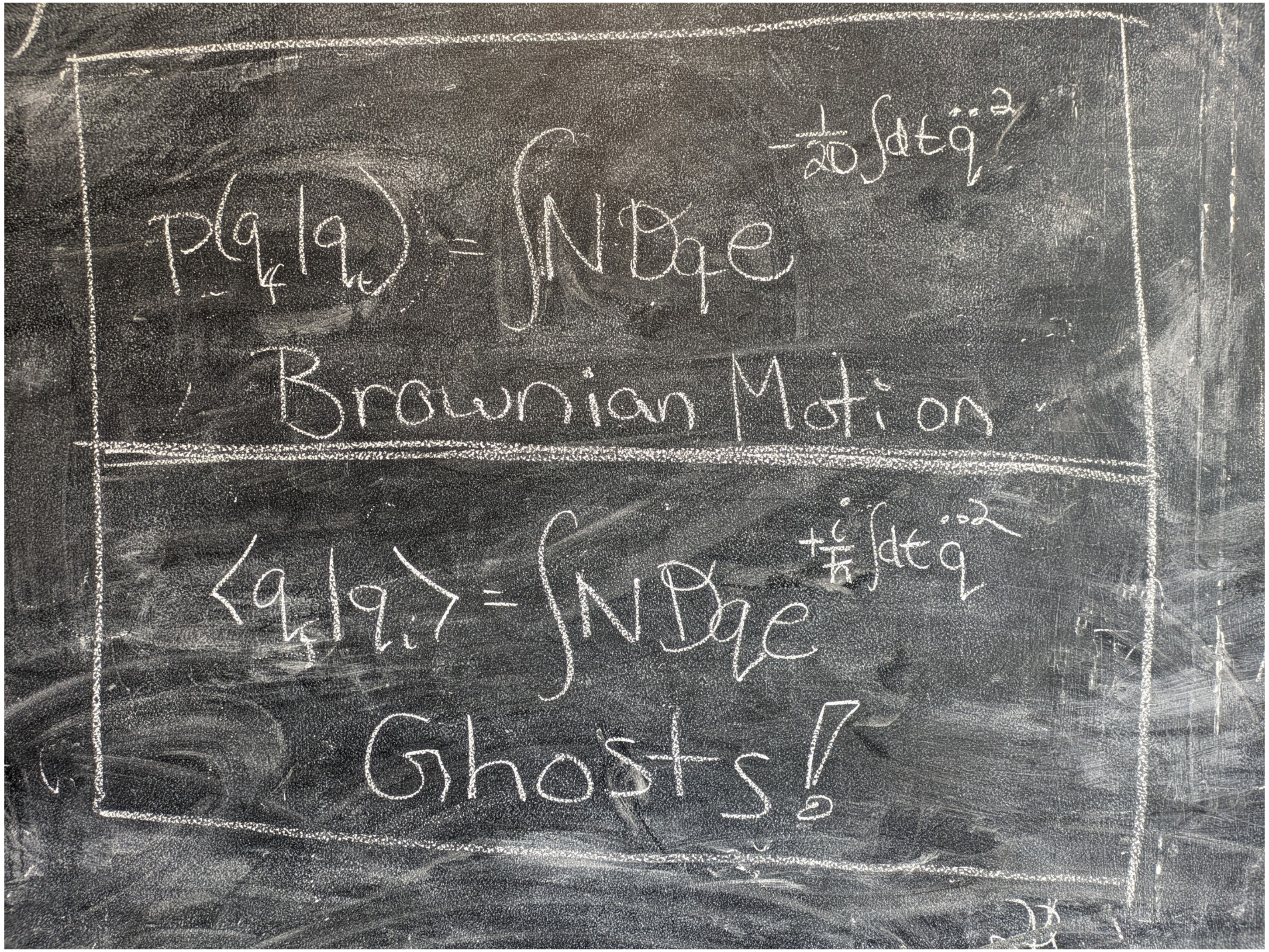
Path Integral for Brownian motion

Classical Mechanics (stochastic)

$$\rho(q_f, t_f | q_i, \dot{q}_i, \ddot{q}_i, t_i) = \mathcal{N} \int_{q_i, \dot{q}_i, \ddot{q}_i}^{q_f} \mathcal{D}q e^{-\frac{1}{2D_2}\int dt (m\ddot{q} - F)^2}$$

Onsager-Machlup

Main Message!



No Ostrogradsky Instability

$$\mathcal{I}_{OM} = -\frac{1}{2D_2}\int dt\,(m\ddot{q} - F)^2 \qquad \mathcal{I}_{QM} = \frac{i}{\hbar}\int dt\,(m\ddot{q} - F)^2$$

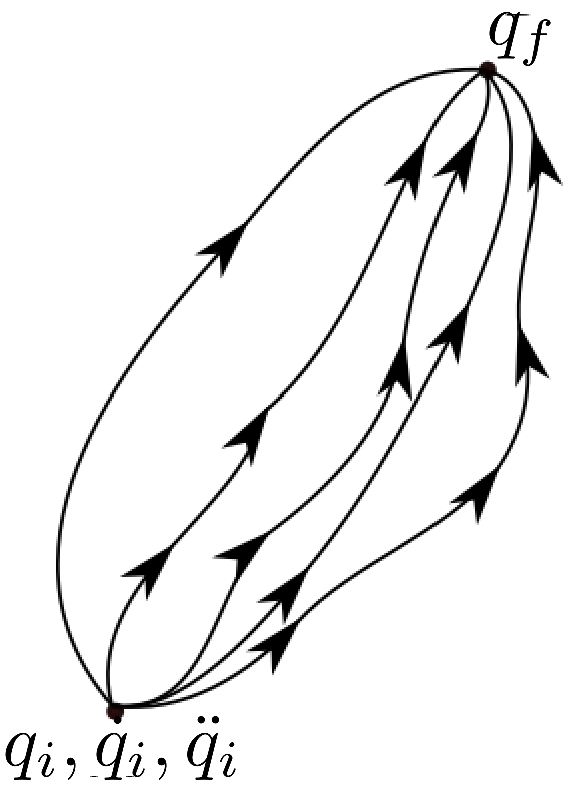
$$H = \frac{p^2}{2m} + V(q) + j(t) \qquad H = \frac{D_2 P_1^2}{2m^2} + P_1 X_2 + \frac{F P_2}{m}$$

Path Integral for Stochastic Dynamics

"Equation of Motion Squared"

$$\mathcal{I} = -\frac{1}{2D_2}\int dt\,(m\ddot{q} - F)^2$$

$$\mathcal{I} = -\frac{1}{2D_2}\int dt\left(\frac{d}{dt}\frac{\partial\mathcal{L}}{\partial\dot{q}} - \frac{\partial\mathcal{L}}{\partial q}\right)^2$$



Onsager-Machlup

Path Integral for Stochastic GR

"Equation of Motion Squared"

$$\mathcal{I} = -\frac{1}{2D_2}\int dt \left(\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{q}} - \frac{\partial \mathcal{L}}{\partial q}\right)^2$$

$$\mathcal{I} = -\frac{1}{2D_2}\int dt \left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right)\left(R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R\right)$$

JO, Weller-Davies 2302.07283

Path Integral for Stochastic GR

Stochastic GR vs Quadratic Gravity

$$\mathcal{I} = -\frac{1}{2D_2}\int dt \left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right)\left(R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R\right)$$

$$\mathcal{I} = -\frac{1}{2D_2}\int dt \left(R_{\mu\nu}R^{\mu\nu} + |\beta|R^2\right)$$

Grudka, JO, Sajjad, Russo, 2402.17844

Path Integral for Stochastic GR

Stochastic GR vs Quadratic Gravity

$$\mathcal{I}^{(gr)} = -\int d^4x \left(\frac{1}{2D_2} R^2 + \frac{1}{2D_w} C^2 + \frac{1}{\alpha} \mathcal{G} \right)$$

$$\mathcal{I}^{(m)} = -\frac{G_N}{16\pi D_2} \int dx \sqrt{-g} \left[-2\bar{T}^{\mu\nu} R_{\mu\nu} + (1-2\beta)\,\bar{T} R \; -8\pi G_N \beta \bar{T}^2 + 8\pi G_N \bar{T}^{\mu\nu} \bar{T}_{\mu\nu} \right]$$

Grudka, JO, Sajjad, Russo, 2402.17844

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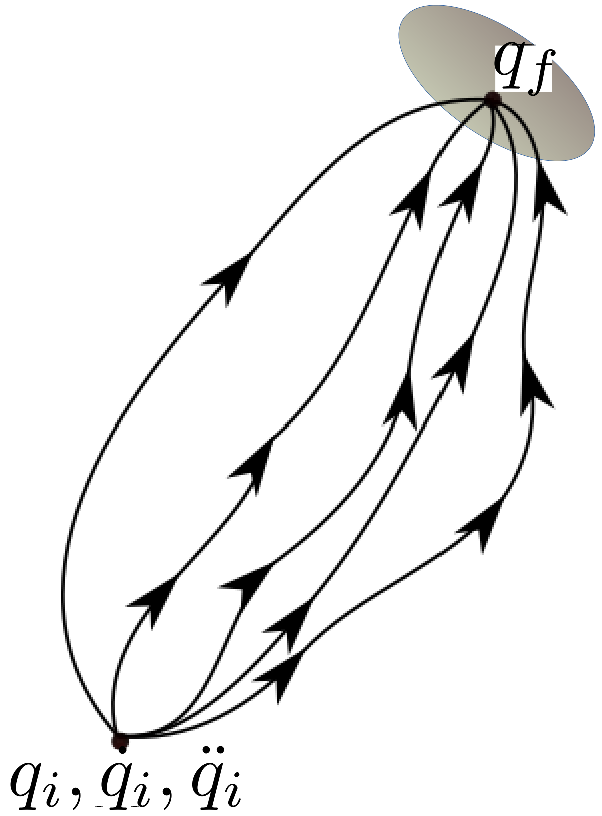
Anomalous contribution (Brownian motion)

The most probably path (MPP)

$$\mathcal{I} = -\frac{1}{2D_2}\int dt\,(m\ddot{q})^2$$

$$\frac{d^4q}{dt^4} = 0$$

$$q_{\mathrm{MPP}} = \kappa_0 + \kappa_1 t + \frac{1}{2}\kappa_2 t^2 + \frac{1}{6}\kappa_3 t^3$$



Onsager-Machlup

Anomalous contribution (Brownian motion)

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$$\mathcal{I} = -\frac{1}{2D_2}\int dt\,(m\ddot{q})^2$$

$$\frac{d^4q}{dt^4} = 0$$

$$Z = \int \mathcal{D}q e^{-\frac{1}{2D_2}\int dt (m\ddot{q})^2}$$

$$q_{\text{MPP}} = \kappa_0 + \kappa_1 t + \frac{1}{2}\kappa_2 t^2 + \frac{1}{6}\kappa_3 t^3$$

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$$Z_{MPP} = \int \mathcal{D}\kappa e^{-\frac{1}{2D_2}\int dt(\kappa_2 + t\kappa_3)^2}$$

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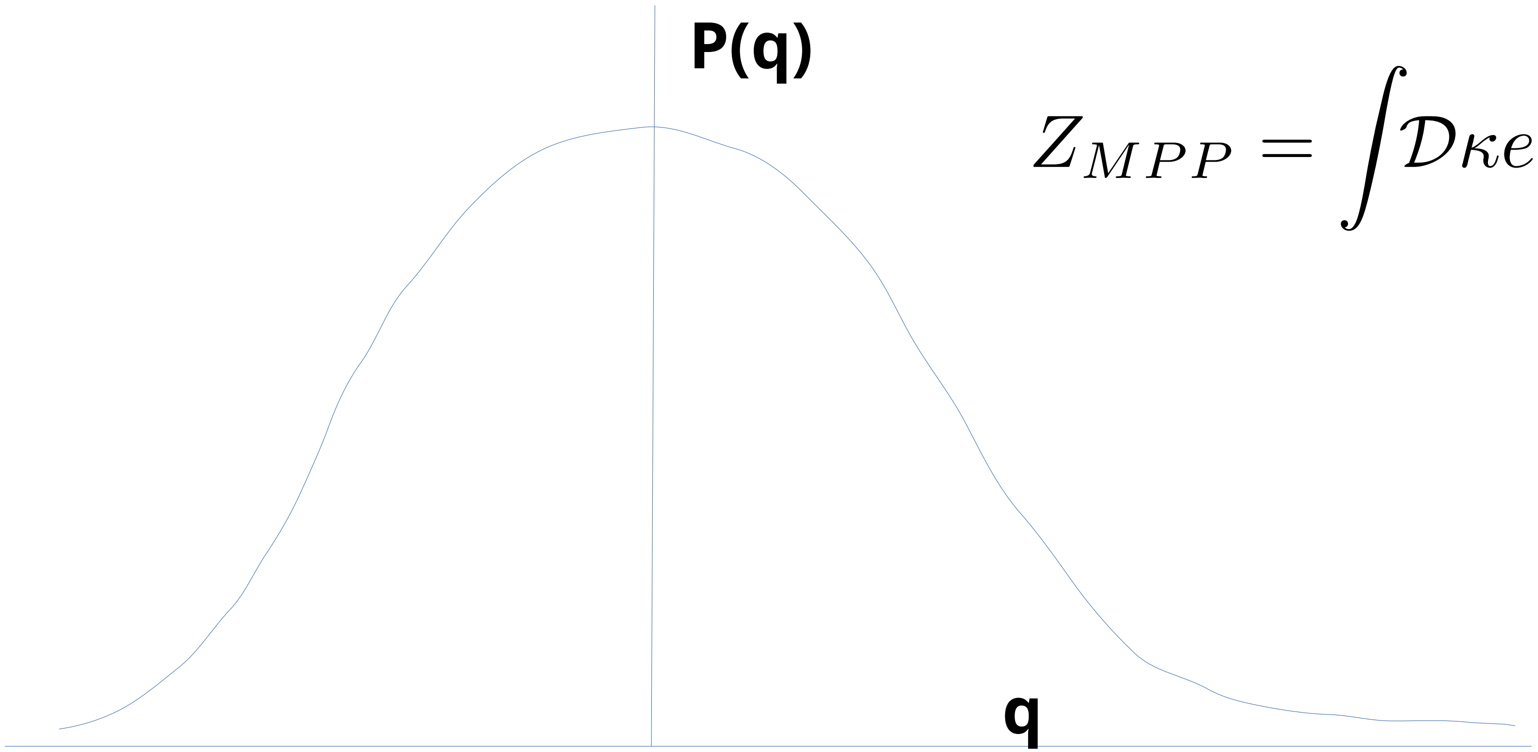
Anomalous contribution (Brownian motion)



$$Z_{MPP} = \int \mathcal{D}\kappa e^{-\frac{1}{2D_2}\int dt(\kappa_2 + t\kappa_3)^2}$$

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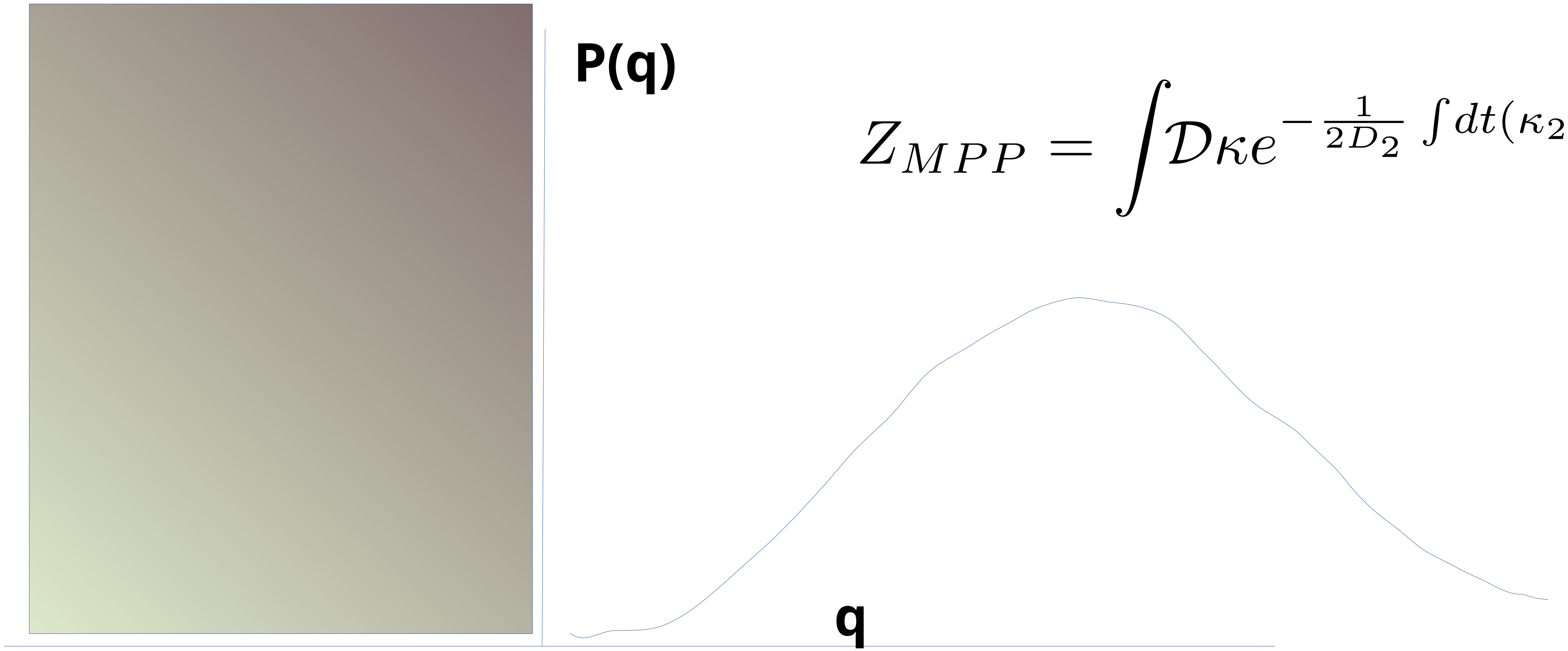

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$$q_{\text{MPP}} = \kappa_0 + \kappa_1 t + \tfrac{1}{2}\kappa_2 t^2 + \tfrac{1}{6}\kappa_3 t^3$$

Anomalous contribution (Newtonian gravity)

The most probably path (MPP)

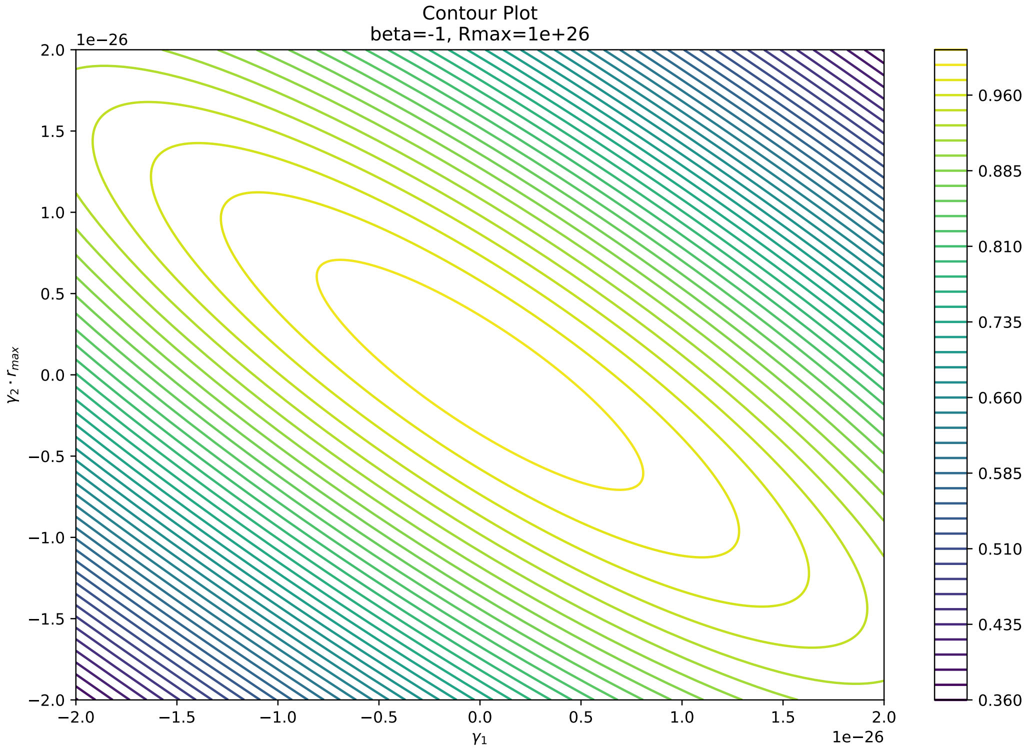
$$\mathcal{I} = -\frac{1}{2D_2}\int d^3x\left(\nabla^2\Phi - 4\pi G m\right)^2$$

$$\nabla^4\Phi = 0$$

$$\Phi_{\text{MPP}} = -\frac{\kappa_m}{r} + \kappa_1 8\pi r + \kappa_2 r^2$$

JO, Russo, 2402.19495

Anomalous contribution (Schwarschild-deSitter)



$$\mathcal{I}_\gamma = -\frac{6\pi VT}{D_2}\left(\frac{5-18\beta}{r_{\max}^2}\gamma_1^2 + 6(1-4\beta)\gamma_2^2 + \frac{9(1-4\beta)}{r_{max}}\gamma_1\gamma_2\right)$$

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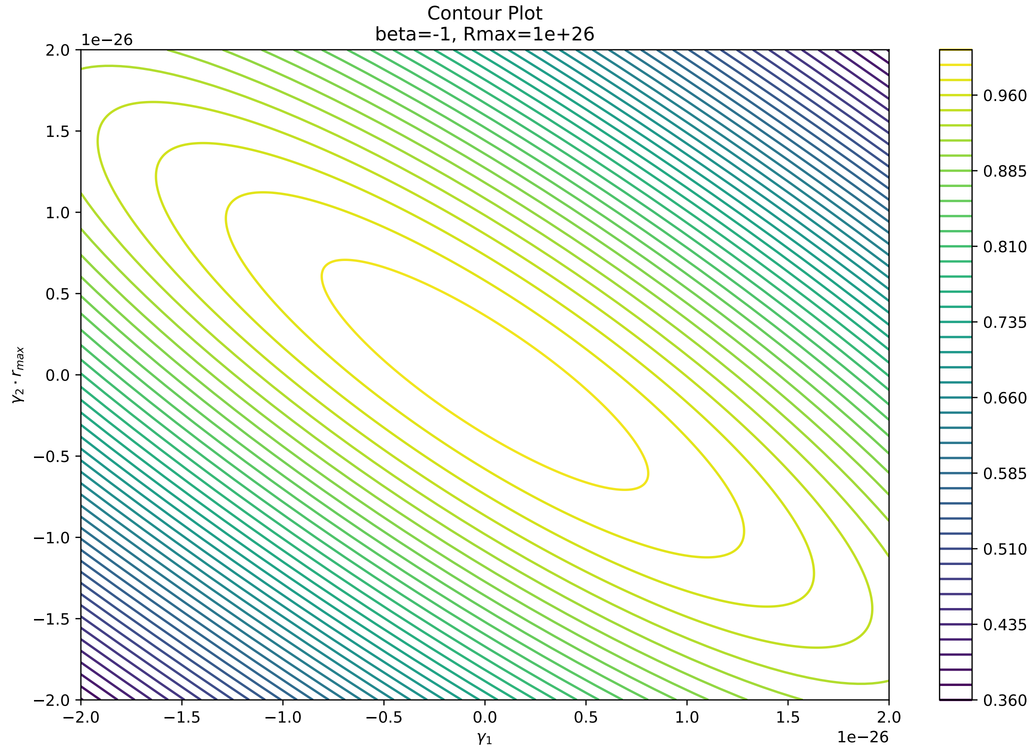
$$ds^2 = -\left(1 - \frac{2MG_N}{r} - \gamma_1 r - \gamma_2 r^2\right)dt^2 + \left(1 - \frac{2MG_N}{r} - \gamma_1 r - \gamma_2 r^2\right)^{-1} dr^2 + r^2 d\Omega^2$$

Riegert (1984)
Mannheim, Kazanas (1989)

Anomalous contribution (Schwarschild-deSitter)



$$a_0 \approx \frac{1}{2\pi}\sqrt{\frac{\Lambda}{3}}$$

Milgrom (1983)

JO, Russo, 2402.19495

$$ds^2 = -\left(1 - \frac{2MG_N}{r} - \gamma_1 r - \gamma_2 r^2\right) dt^2 + \left(1 - \frac{2MG_N}{r} - \gamma_1 r - \gamma_2 r^2\right)^{-1} dr^2 + r^2 d\Omega^2$$

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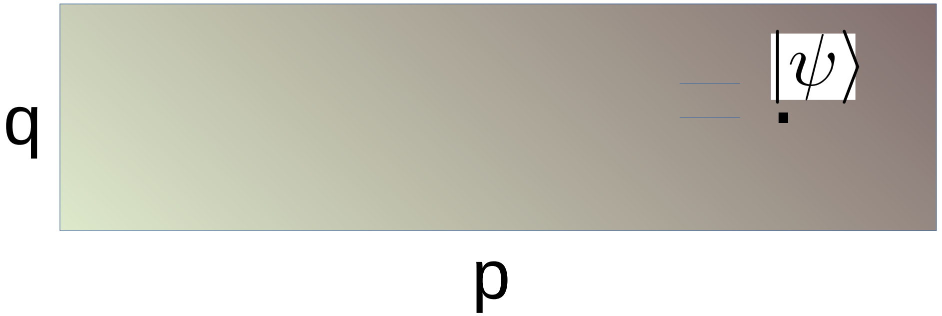

Classical Mechanics

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

Frameworks

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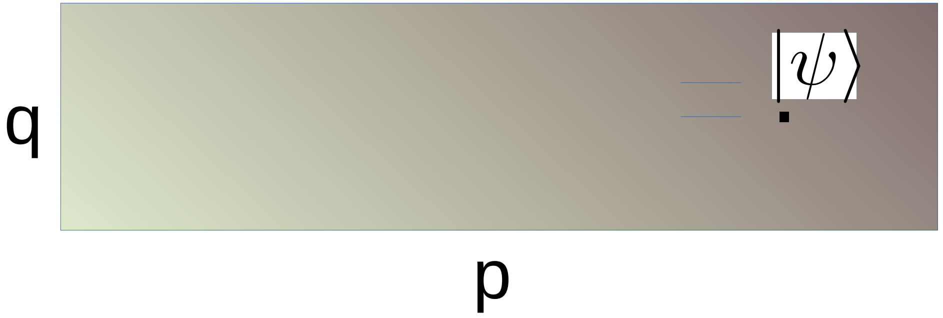
$$\frac{\partial \hat{\sigma}}{\partial t} = -i[\hat{H}, \hat{\sigma}]$$



Classical Mechanics

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

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

Classical, quantum, & CQ States

Q

HILBERT SPACE

$\hat{\sigma}$

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

POSITIVE MATRIX

C

PHASE SPACE

$\rho(q,p)$

$$\int dqdp\rho(q,p) = 1$$

POSITIVE DISTRIBUTION

CQ

$$\hat{\rho}(z;t) = \rho(z;t)\hat{\sigma}(z;t)$$

$$z := (q,p)$$

$\hat{\rho}(z)$

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

POSITIVE MATRIX AT EACH Z

Classical, quantum, & CQ States

Q

HILBERT SPACE

$$\hat{\sigma}$$

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

POSITIVE MATRIX

C

PHASE SPACE

$$\rho(q, p)$$

$$\int dqdp\rho(q,p) = 1$$

POSITIVE DISTRIBUTION

CQ

$$\hat{\rho}(z;t) = \rho(z;t)\sigma(z;t)$$

$$\hat{\rho}(z)$$

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

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

POSITIVE MATRIX AT EACH Z

Classical, quantum, & CQ States

Q

HILBERT SPACE

$$\hat{\sigma}$$

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

POSITIVE MATRIX

C

PHASE SPACE

$$\rho(q,p)$$

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

POSITIVE DISTRIBUTION

CQ

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

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

$$\hat{\rho}(z)$$

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

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 z

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

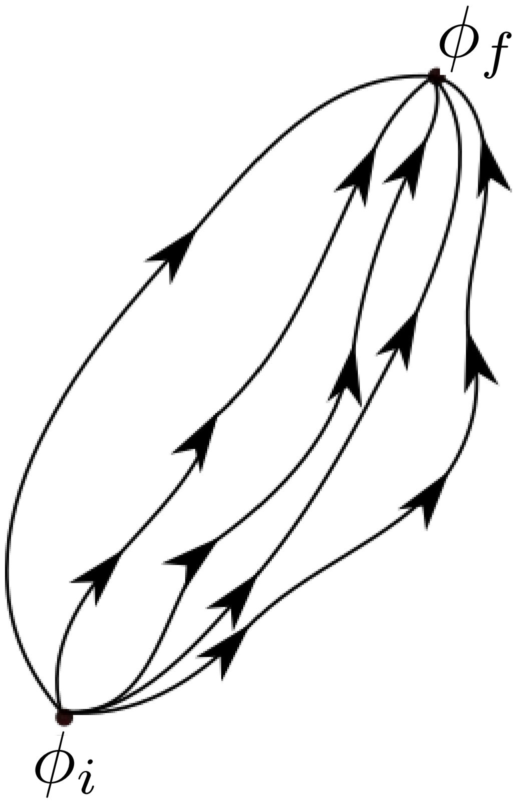
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle|\psi_L\rangle - |1\rangle|\psi_R\rangle\right) \qquad \sigma^{(m)} = \frac{1}{2}|\psi_L\rangle\langle\psi_L| + \frac{1}{2}|\psi_R\rangle\langle\psi_R|$$

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

Path Integrals

Quantum Mechanics

$$\langle \phi_f, t_f | \phi_i, t_i \rangle = \int_{\phi(t_i)=\phi_i}^{\phi(t_f)=\phi_f} \mathcal{D}\phi \; e^{iS[\phi]}$$



Path Integrals

Quantum Mechanics

$$\langle \phi^-, t_f | \phi_i, t_i \rangle \langle \phi_i, t_i | \phi^+, t_f \rangle = \int_{\phi^+=\phi^-=\phi_i}^{\phi_f^+, \phi_f^-} \mathcal{D}\phi^+ \mathcal{D}\phi^- \; e^{iS[\phi^+] - iS[\phi^-]}$$

Path Integrals

Quantum Mechanics

$$\hat{\sigma}(\phi_f^+, \phi_f^-, t_f) = \int_{\phi^+=\phi^-=\phi_i}^{\phi_f^+, \phi_f^-} \mathcal{D}\phi^+ \mathcal{D}\phi^- \; e^{iS[\phi^+]-iS[\phi^-]}$$

Path Integrals

Quantum Mechanics (open systems)

$$\hat{\sigma}(\phi_f^+, \phi_f^-, t_f) = \int \mathcal{D}\phi^+ \mathcal{D}\phi^- \; e^{iS[\phi^+] - iS[\phi^-] + iS_{FV}[\phi^+, \phi^-]}$$

$$iS_{FV} = D_0 \int_{t_i}^{t_f} d^4x \left(\phi^+\phi^- - \frac{1}{2}(\phi^-\phi^- + \phi^+\phi^+)\right)$$

Feynman-Vernon

Path Integrals

Quantum Mechanics (open systems)

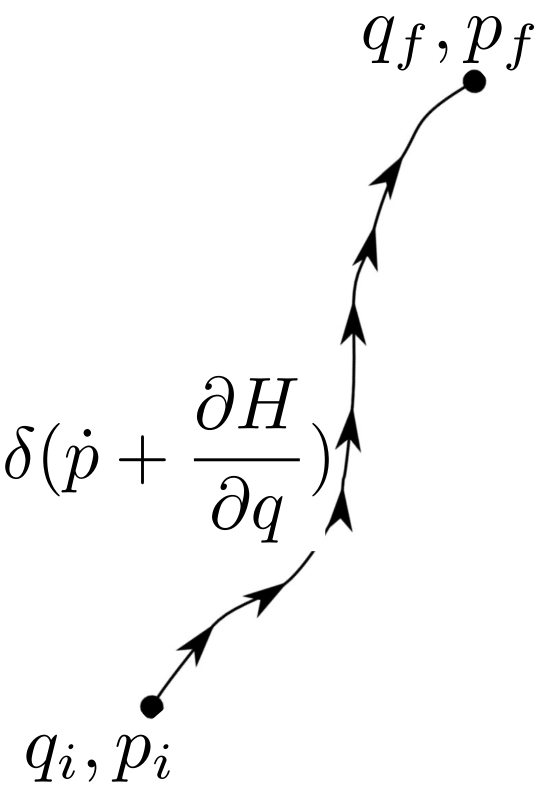
$$\hat{\sigma}(\phi_f^+, \phi_f^-, t_f) = \int \mathcal{D}\phi^+ \mathcal{D}\phi^- \; e^{iS[\phi^+] - iS[\phi^-] + iS_{FV}[\phi^+, \phi^-]}$$

$$iS_{FV} = -\frac{1}{2} D_0 \int_{t_i}^{t_f} d^4x \left(\phi^+ - \phi^-\right)^2$$

Path Integrals

Classical Mechanics

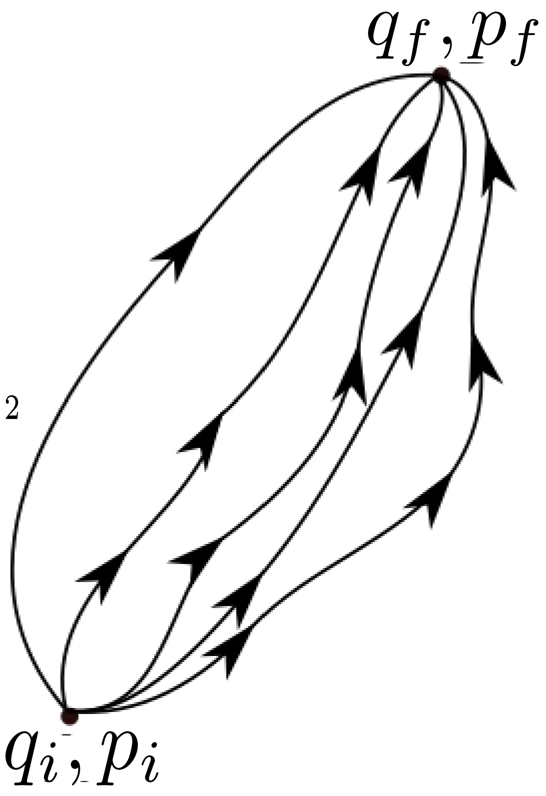
$$\rho(q_f, p_f, t_f | q_i, p_i t_i) = \int_{q_i, p_i}^{q_f, p_f} \mathcal{D}q\mathcal{D}p\Pi_t \delta(\dot{q} - \frac{\partial H}{\partial p})\delta(\dot{p} + \frac{\partial H}{\partial q})$$



Path Integrals

Classical Mechanics (stochastic)

$$\rho(q_f, p_f, t_f | q_i, p_i t_i) = \mathcal{N} \int_{q_i, p_i}^{q_f, p_f} \mathcal{D}q\mathcal{D}p\delta(\dot{q} - \frac{\partial H}{\partial p})e^{-\frac{1}{2D_2}\int dt\left(\dot{p}+\frac{\partial H}{\partial q}\right)^2}$$

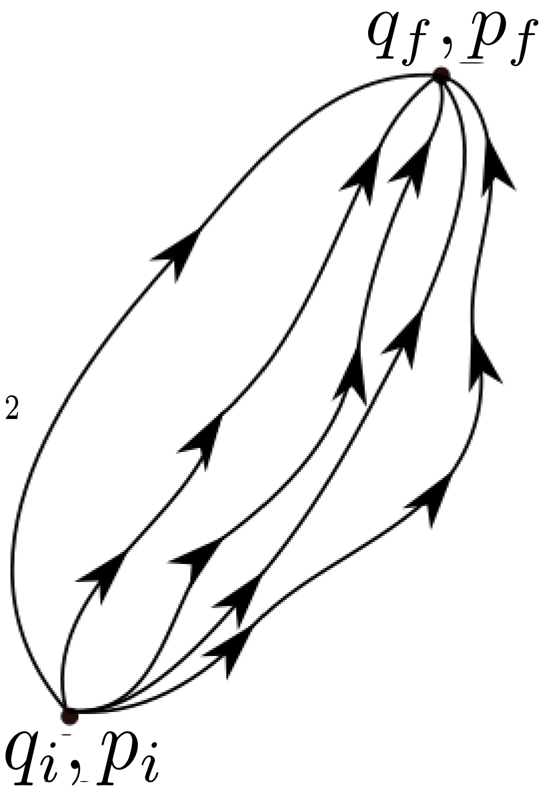


Onsager-Machlup

Path Integrals

Classical Mechanics (stochastic)

$$\rho(q_f, p_f, t_f | q_i, p_i t_i) = \mathcal{N} \int_{q_i, p_i}^{q_f, p_f} \mathcal{D}q \mathcal{D}p \, \delta(\dot{q} - \frac{\partial H}{\partial p}) e^{-\frac{1}{2D_2} \int dt \left(\dot{p} + \frac{\partial H}{\partial q}\right)^2}$$



Onsager-Machlup

Q, C & CQ Path integral

Q

$$iS_Q[\phi^+,\Phi^-] := iS[\phi^+] - iS[\phi^-] + iS_{FV}[\phi^+,\phi^-]$$

$$iS_{FV} = -\frac{1}{2}D_0\int_{t_i}^{t_f} d^4x\left(\phi^+ - \phi^-\right)^2$$

C

$$iS_C[q,p] = -\frac{1}{2D_2}\int dt(\dot{p} + \frac{\partial H}{\partial q})^2$$

Onsager. Machlup (1953);
Freidlin, Wentzell (1998)

CQ

$$iS[\phi^+,\phi^-,q,p] = S_Q[\phi^+,\phi^-] - \frac{1}{2D_2}\int dt(\dot{p} + \frac{1}{2}\frac{\partial \hat{H}^+}{\partial q} + \frac{1}{2}\frac{\partial \hat{H}^-}{\partial q})^2$$

$$iS_{FV} = -\frac{1}{2}\int dt D_0\left(\frac{\partial \hat{H}^+}{\partial q} - \frac{\partial \hat{H}^-}{\partial q}\right)^2$$

$$4D_2 \succeq D_0^{-1}$$

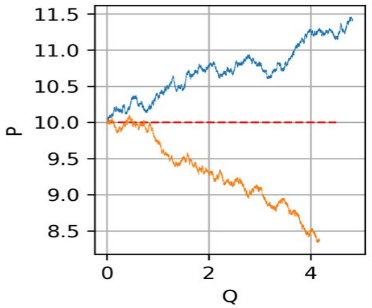
CQ Dynamics

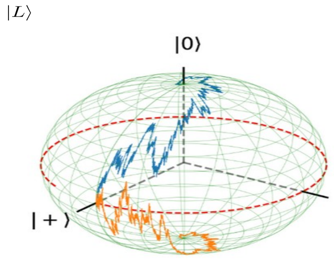
Path Integral

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

JO, Zach Weller-Davies

Trajectories





JO, I. Layton, Z. Weller-Davies

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

Q, C & CQ Dynamics (jumps)

Q

$$\frac{\partial \hat{\sigma}}{\partial t} = -i[\hat{H}, \hat{\sigma}] + \sum_{\alpha\beta} W^{\alpha\beta} \hat{L}_\alpha \hat{\sigma} \hat{L}_\beta^\dagger - \frac{1}{2} W^{\alpha\beta} \{\hat{L}_\beta^\dagger \hat{L}_\alpha, \hat{\sigma}\}_+$$

$$W^{\alpha\beta} \succeq 0$$

C

$$\frac{\rho(z)}{\partial t} = \{H(z), \rho(z)\} + \int dz' \left(W(z|z')\rho(z') - W(z)\rho(z)\right)$$

$$W(z|z') \geq 0 \;\; \forall z, z'$$

CQ

$$\frac{\partial \hat{\rho}(z;t)}{\partial t} = -i[\hat{H}(z), \hat{\rho}(z;t)] + \sum_{\alpha\beta} \int dz' W^{\alpha\beta}(z|z') \hat{L}_\alpha \hat{\rho}(z';t) \hat{L}_\beta^\dagger - \frac{1}{2} W^{\alpha\beta}(z) \{\hat{L}_\beta^\dagger \hat{L}_\alpha, \hat{\rho}(z;t)\}$$

$$W^{\alpha\beta} \succeq 0 \; \forall z, z'$$

Blanchard, Jadzyk (1994);
Poulin (2017);
JO (2018)

Q, C & CQ Dynamics (continuous)

Q

$$\frac{\partial \hat{\sigma}}{\partial t} = -i[\hat{H}, \hat{\sigma}] + \sum_{\alpha\beta} W^{\alpha\beta} \hat{L}_\alpha \hat{\sigma} \hat{L}_\beta^\dagger - \frac{1}{2} W^{\alpha\beta} \{\hat{L}_\beta^\dagger \hat{L}_\alpha, \hat{\sigma}\}_+$$

$$W^{\alpha\beta} \succeq 0$$

C

$$\frac{\partial \rho(z)}{\partial t} = -\sum_i \frac{\partial}{\partial z_i} (D_{1,i}\rho(z)) + \sum_{ij} \frac{\partial^2}{\partial z_i \partial z_j} (D_{2,ij}\rho(z))$$

$$D_2(z) \succeq 0$$

Fokker-Planck Equation

CQ

$$\frac{\partial \hat{\rho}(z)}{\partial t} = -i[H(z), \hat{\rho}(z)] + \mathcal{L}_{FP}\hat{\rho}(z) + \frac{\partial}{\partial z_i} \left(D_{1,i}^{0\alpha} \hat{\rho}(z) L_\alpha^\dagger\right) + \frac{\partial}{\partial z_i} \left(D_{1,i}^{\alpha 0} L_\alpha \hat{\rho}(z)\right)$$
$$+ D_0^{\alpha\beta}(z) L_\alpha \hat{\rho}(z) L_\beta^\dagger - \frac{1}{2} D_0^{\alpha\beta} \{L_\beta^\dagger L_\alpha, \hat{\rho}(z)\}_+$$

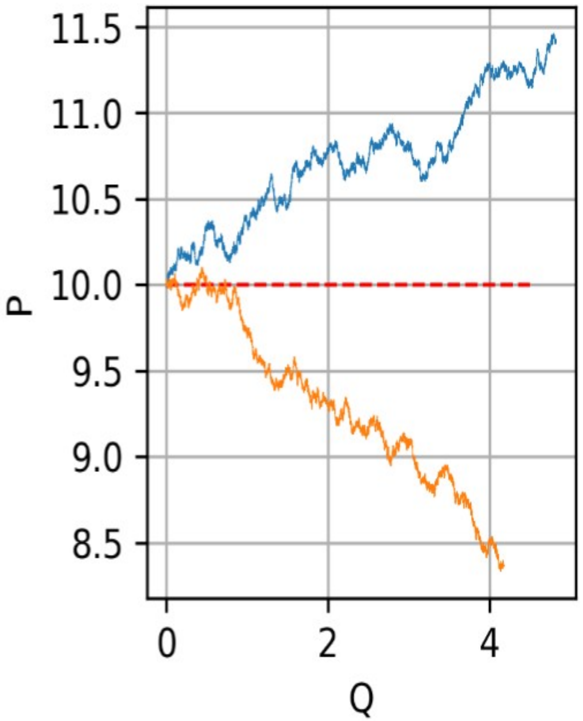
$$\mathrm{D}_2(z) - D_1^\dagger(z) D_0^{-1}(z) D_1(z) \succeq 0$$

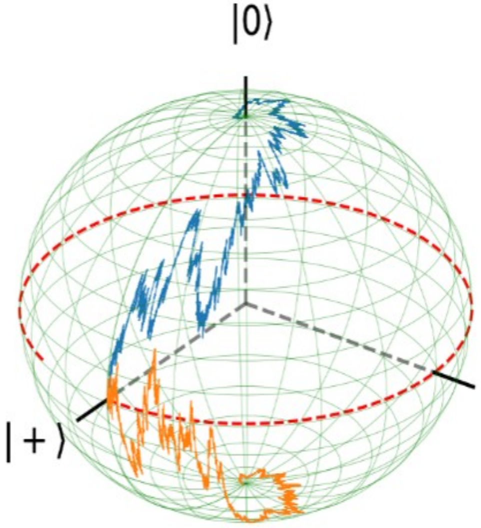
JO (2018);
JO, Soda, Sparaciari, Weller-Davies (2022)

Example of continuous master-equation

Stern-Gerlach

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





$$D_2 D_0 \succeq D_1^2$$

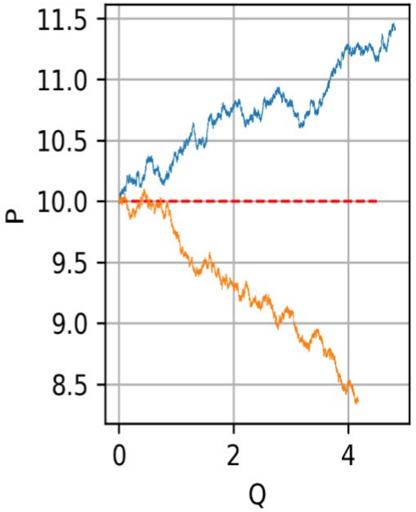
JO, Isaac Layton, Zach Weller-Davies

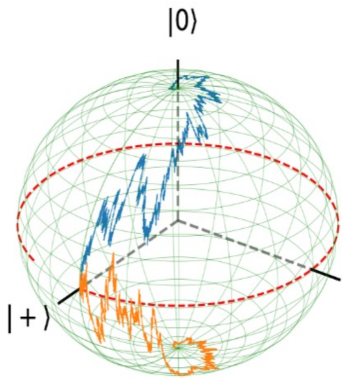
Example of continuous master-equation

Stern-Gerlach

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

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





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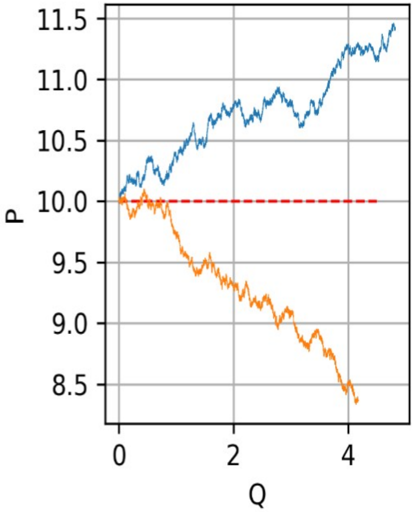
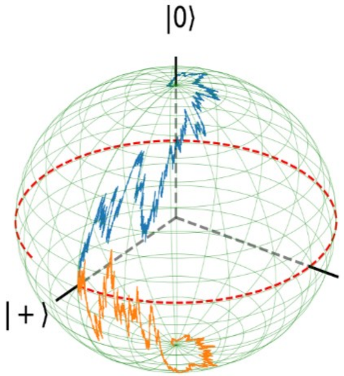
Diosi (1995)
Isaac Layton, JO, Zach Weller-Davies (2022)

Example of continuous master-equation

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

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





$$D_2 D_0 = D_1^2$$

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

A post-quantum theory of classical gravity?

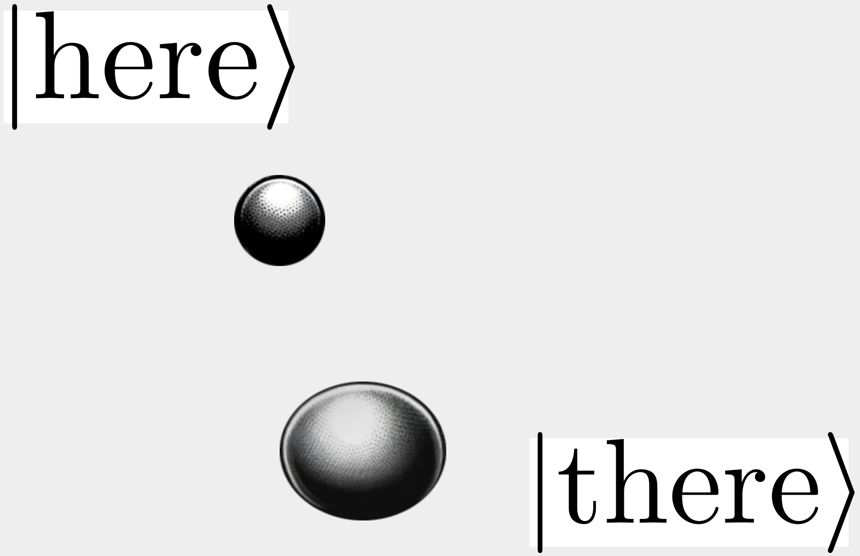
Renormalisable without Ghosts!

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

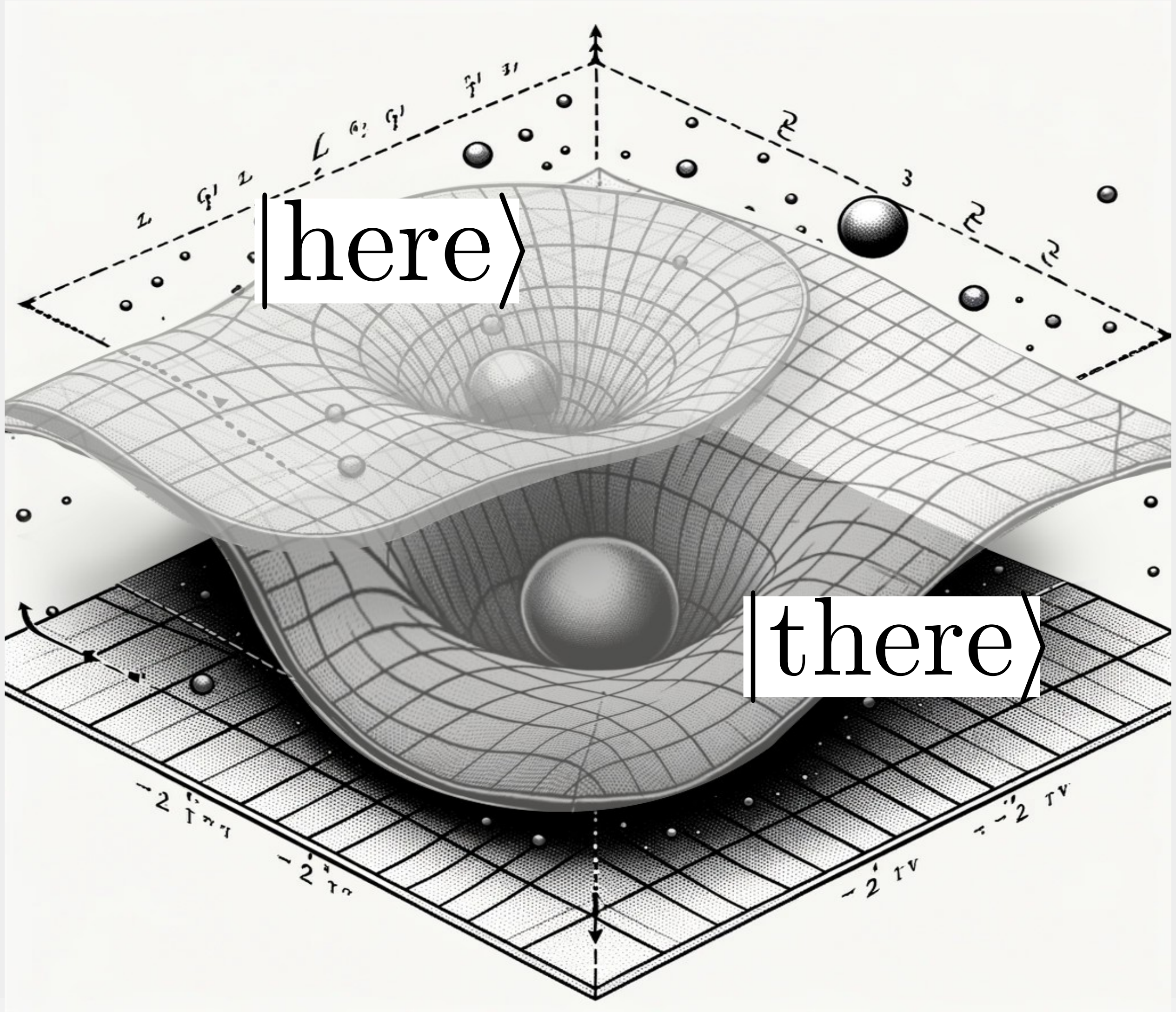
What is the most general form of CQ dynamics?

Decoherence vs Diffusion: testing quantum gravity

Decoherence vs diffusion trade-off



Decoherence vs diffusion trade-off



Decoherence vs diffusion trade-off

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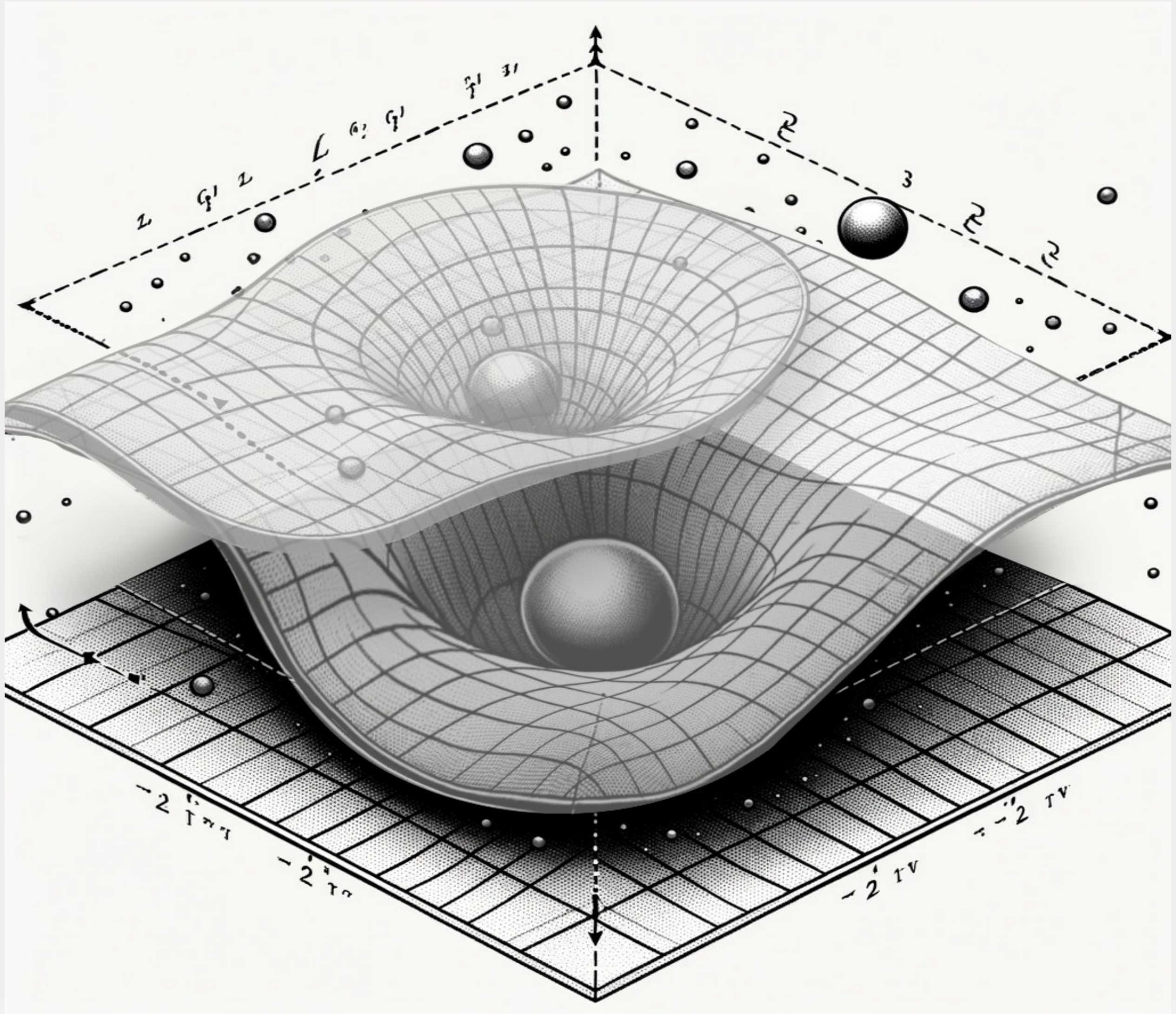

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Decoherence vs diffusion trade-off

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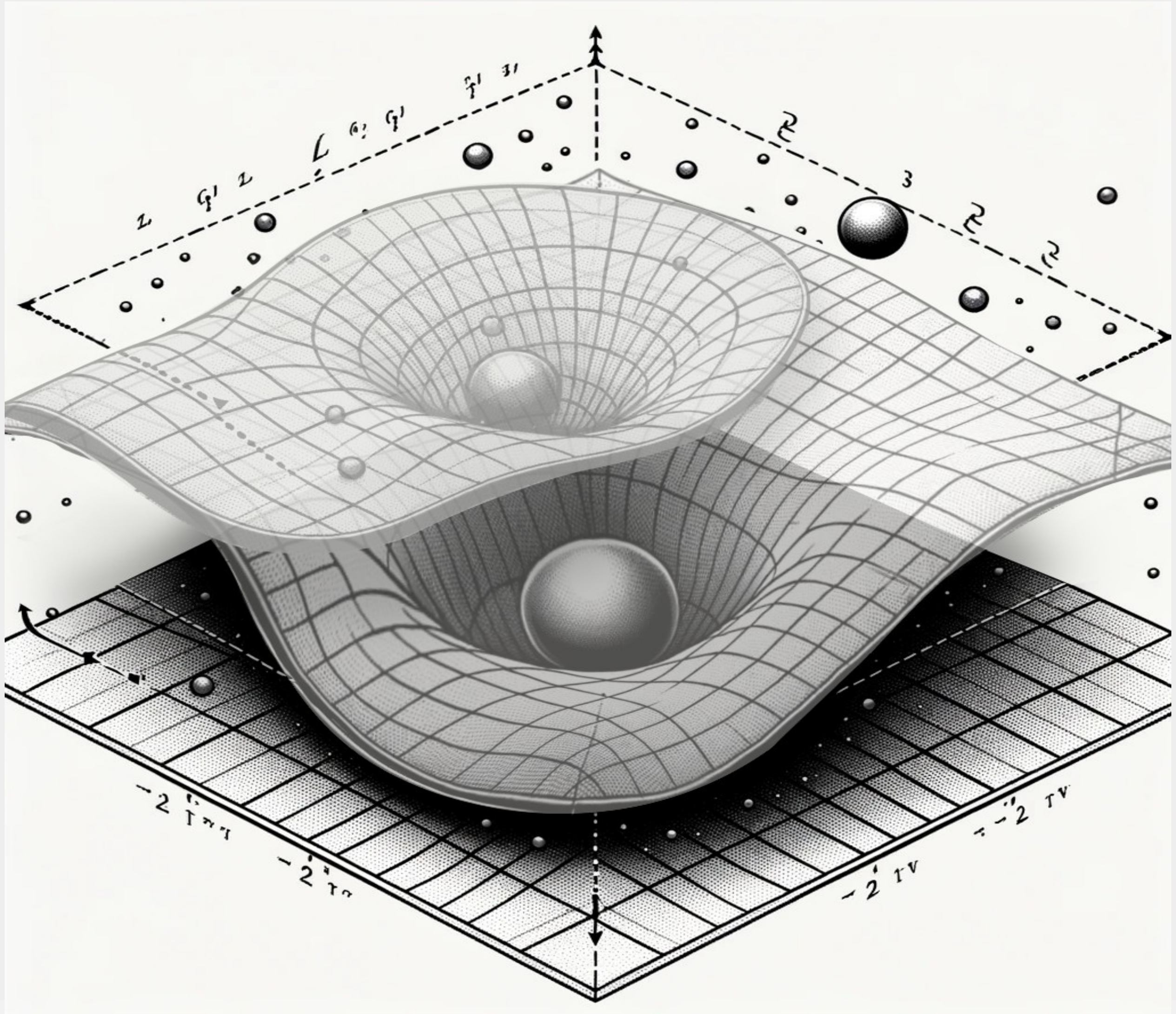

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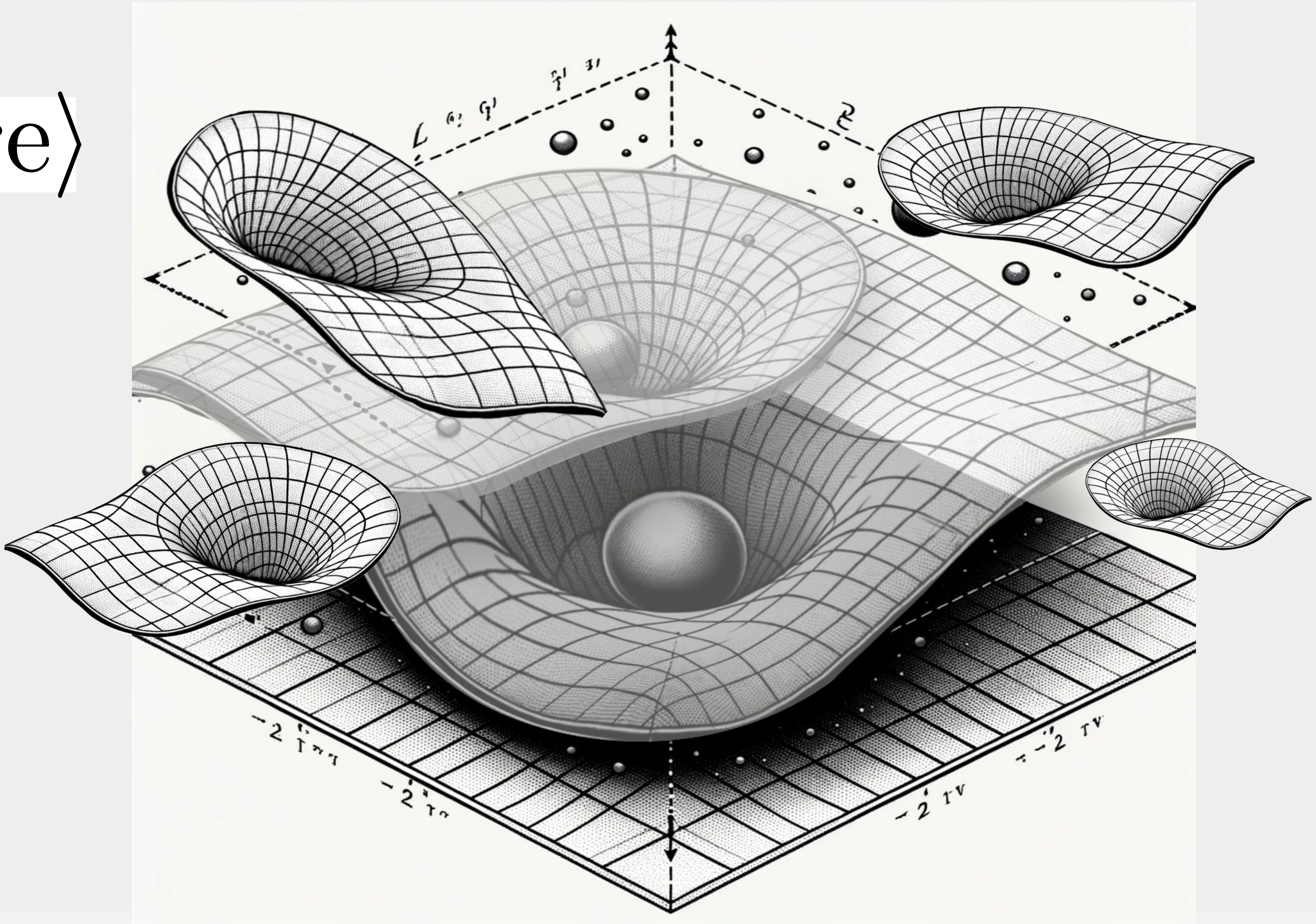

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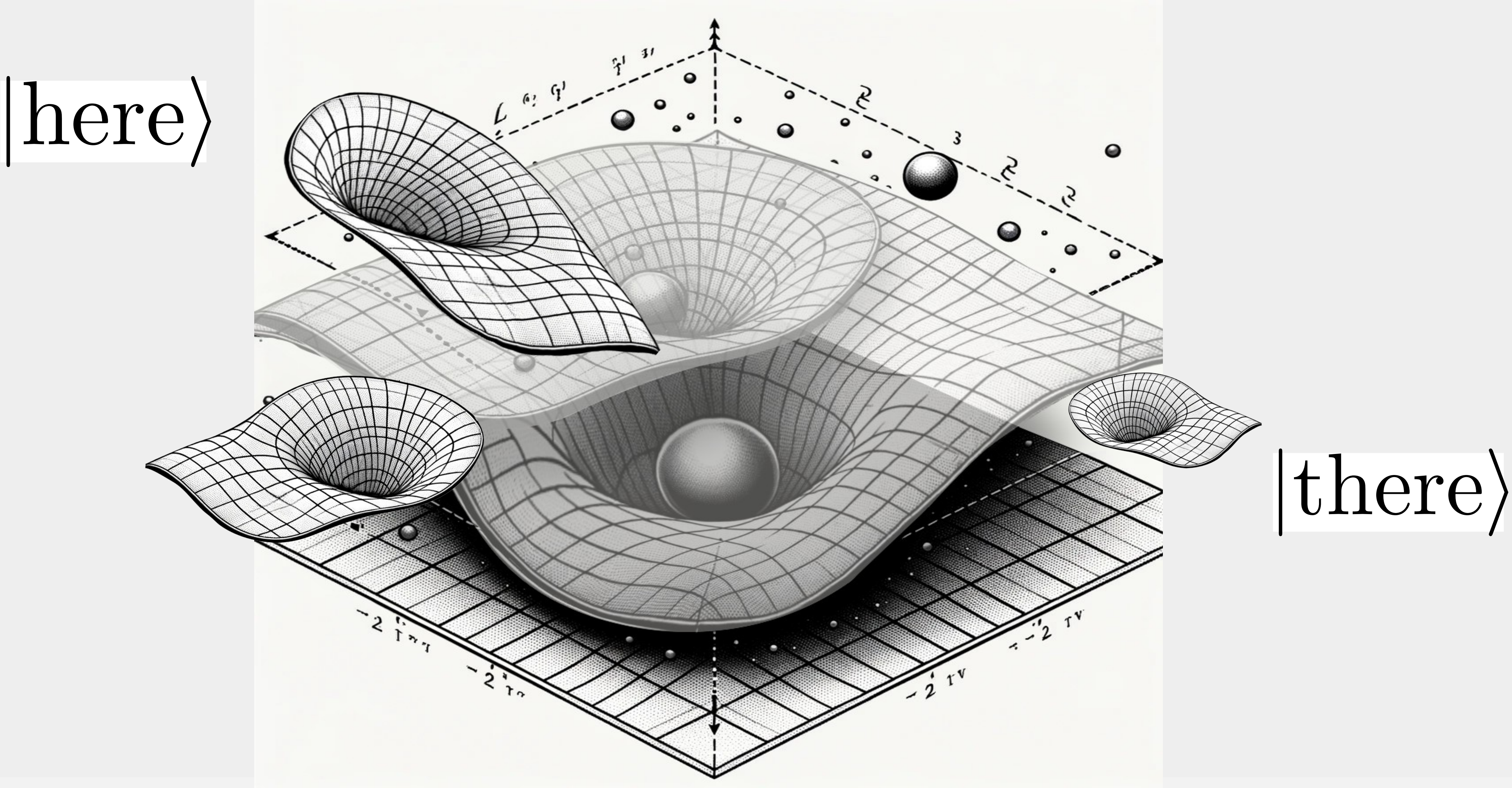

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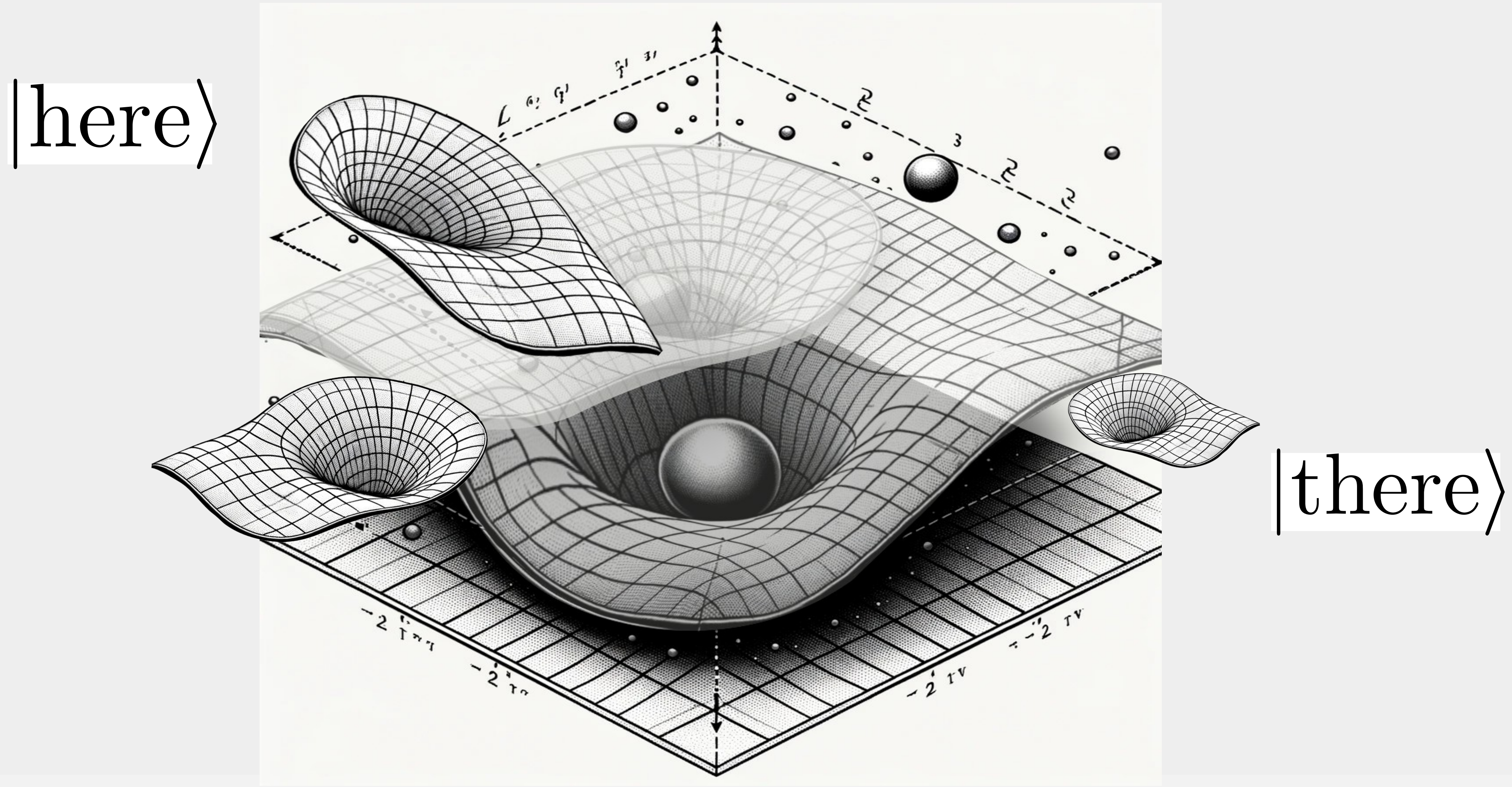

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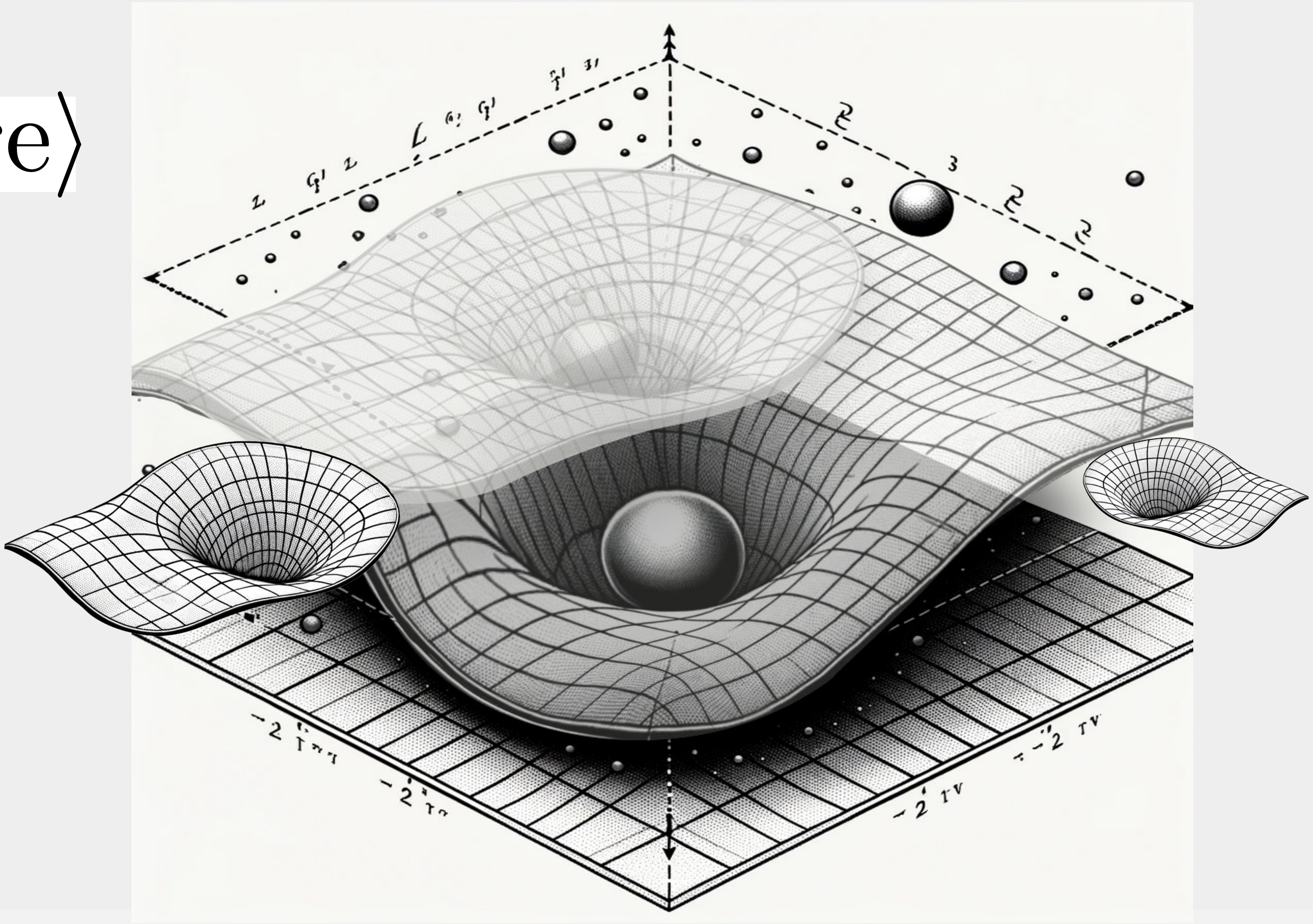

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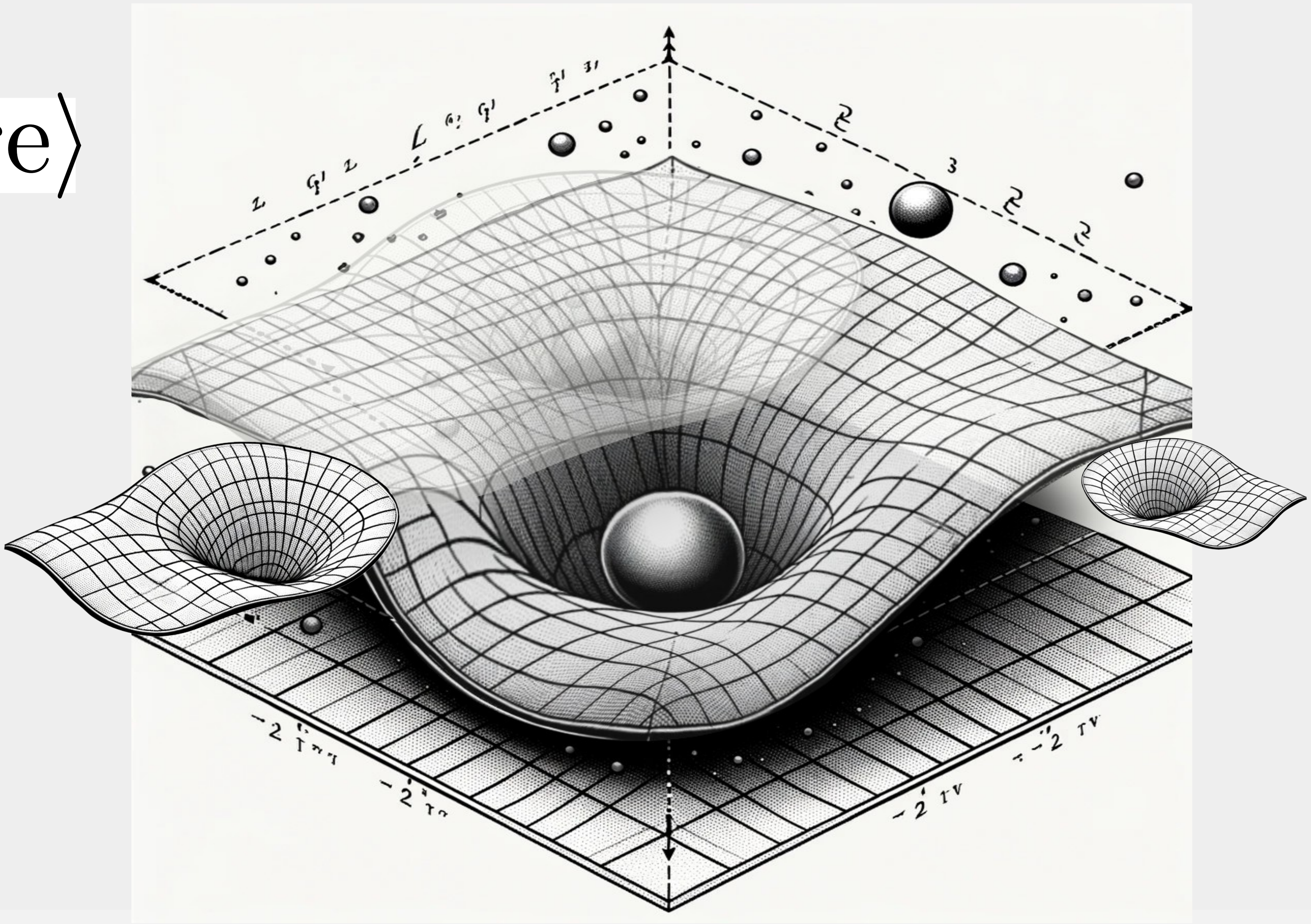

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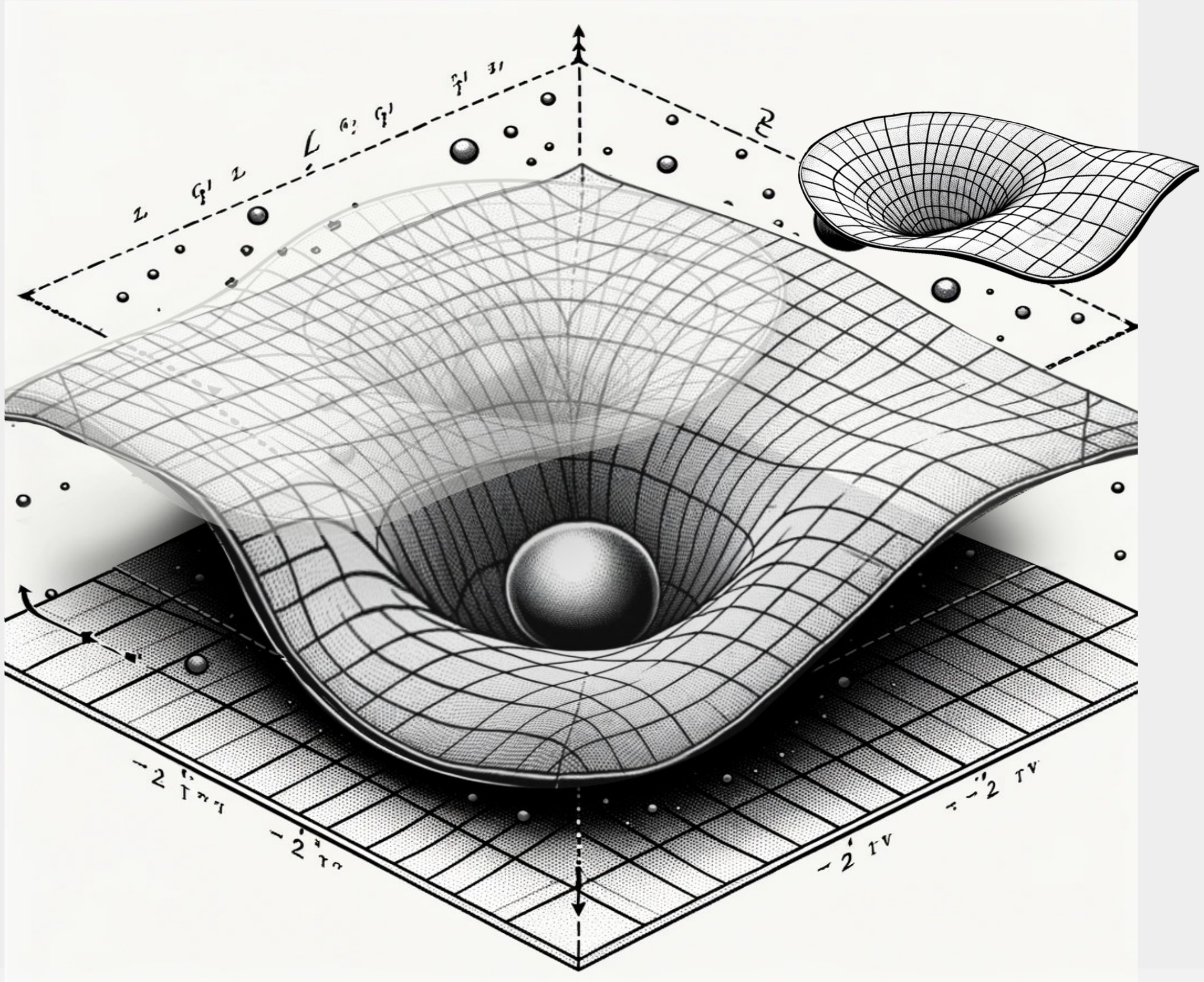

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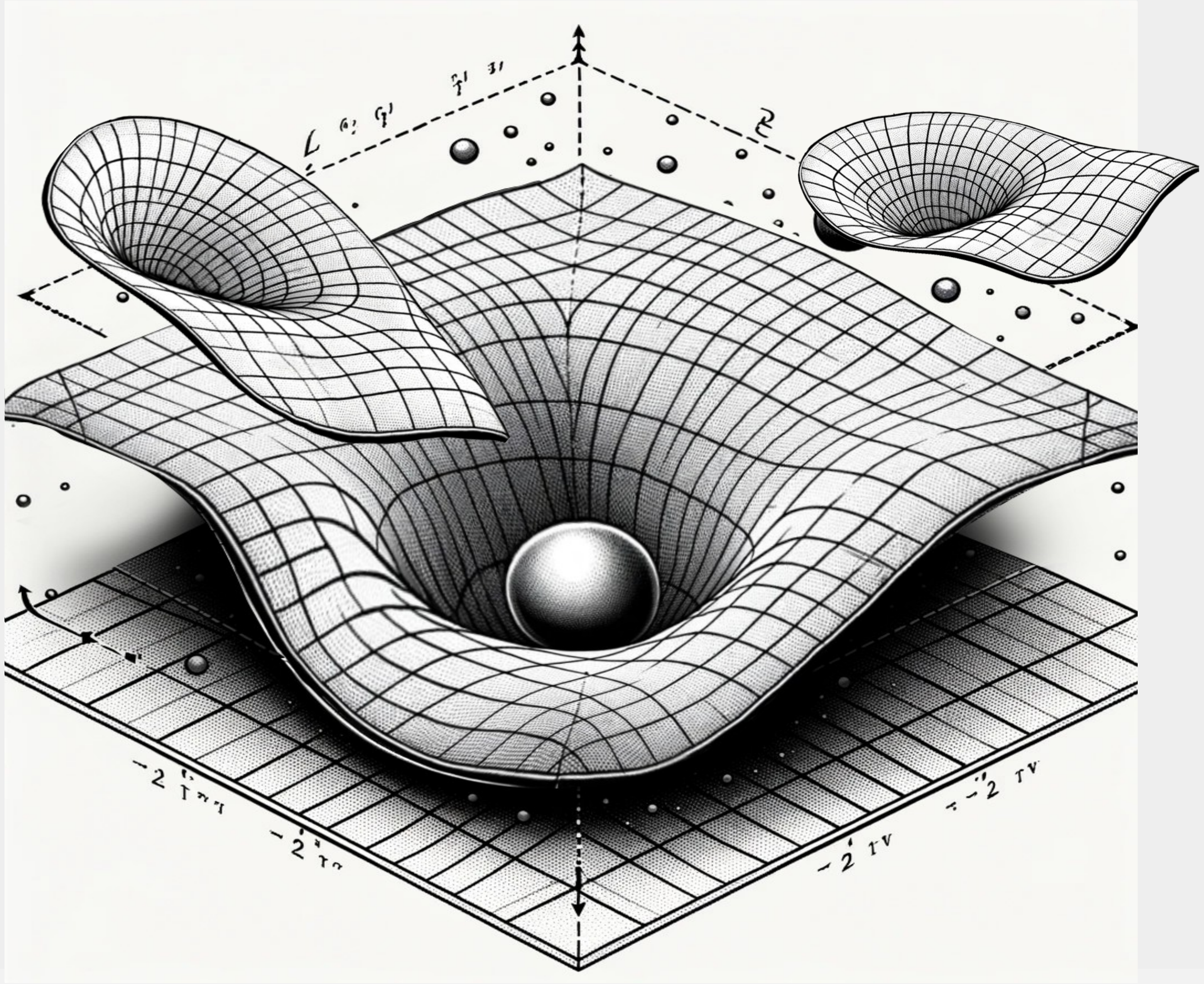

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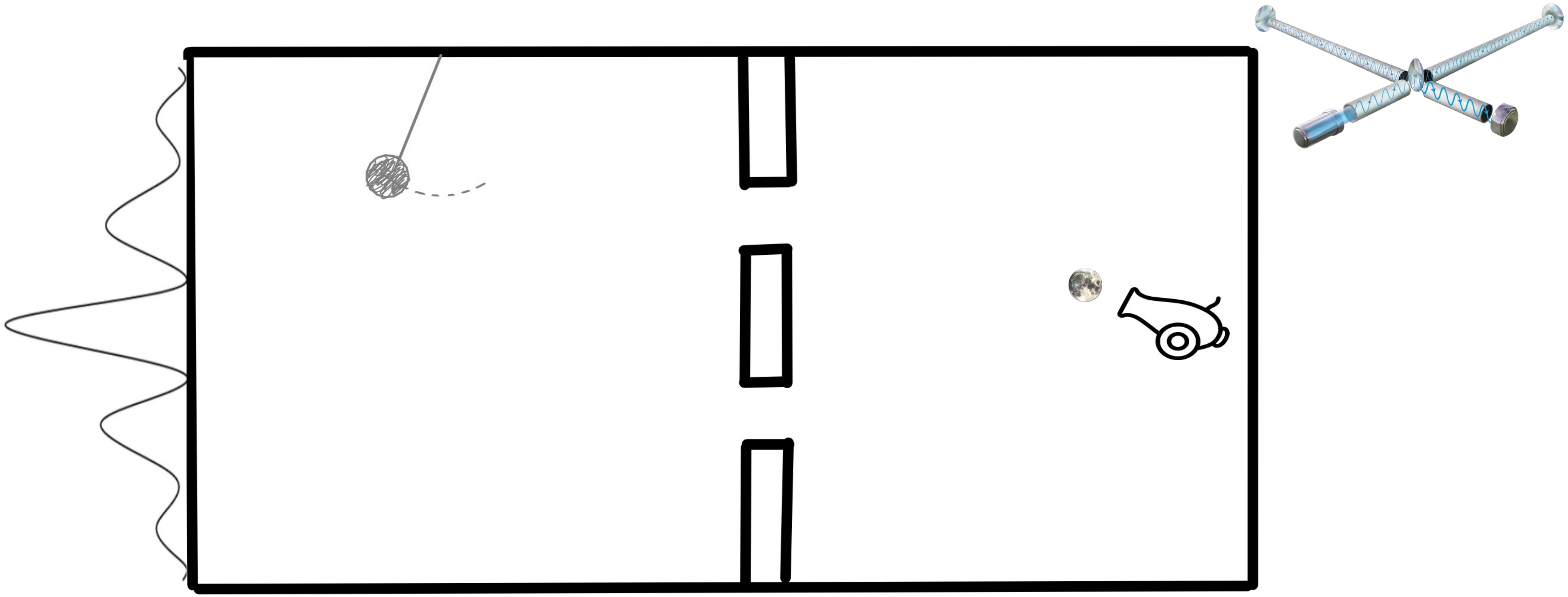
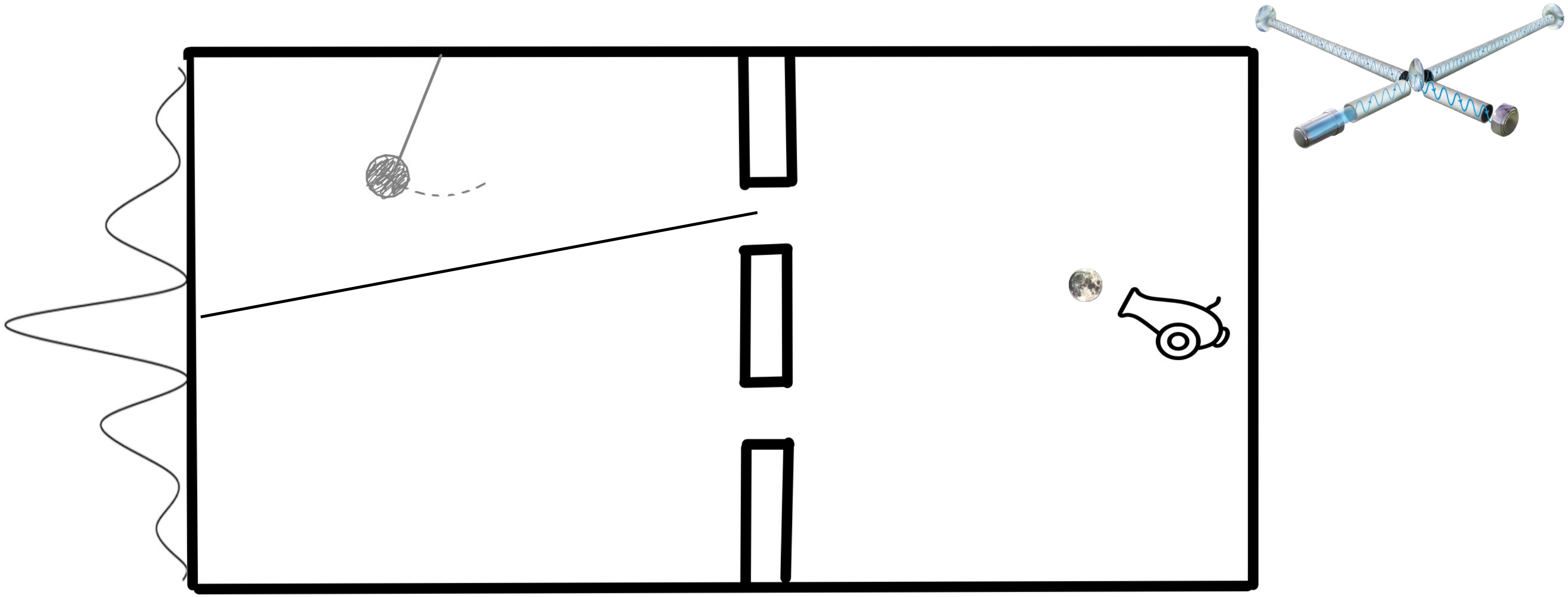
Decoherence vs diffusion



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

Decoherence vs diffusion



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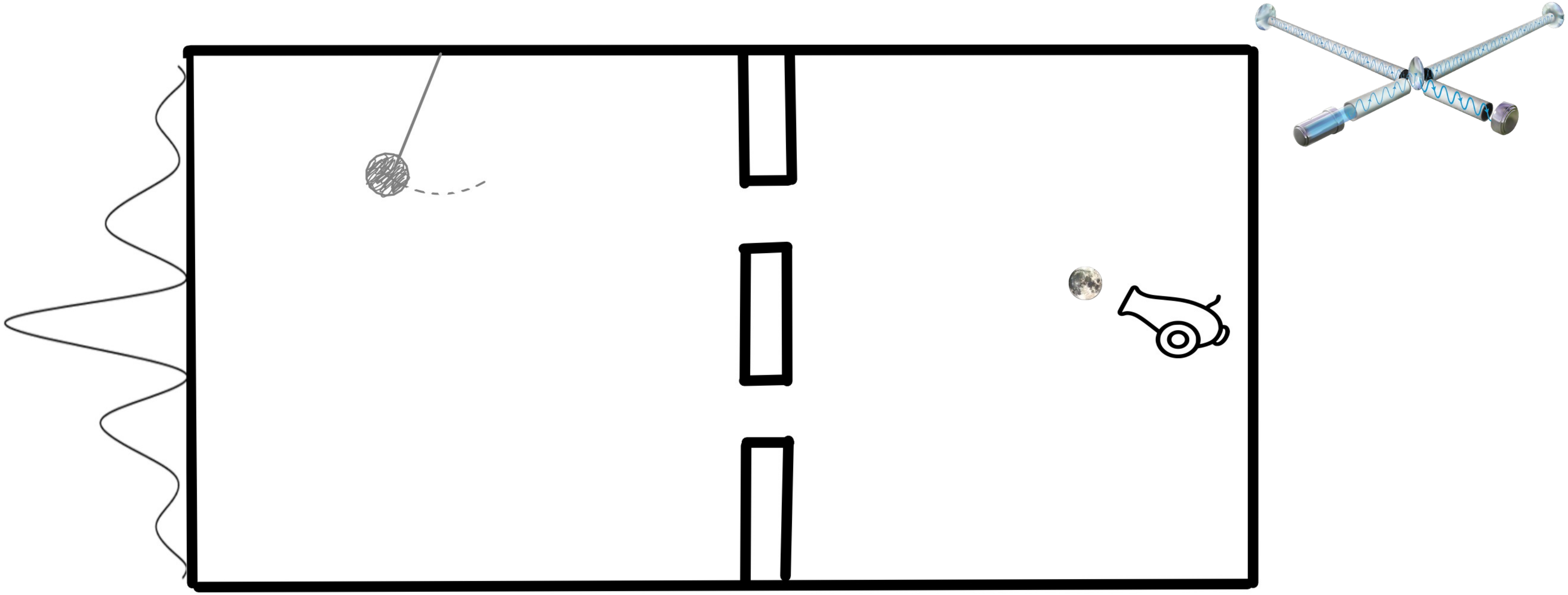
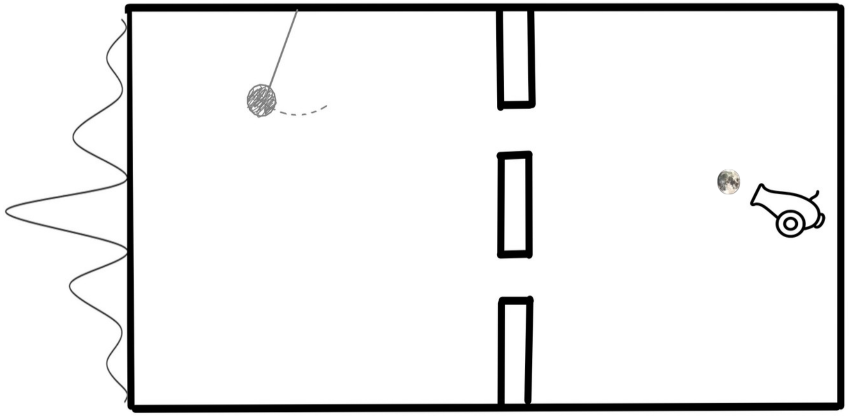


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|E_L\rangle|L\rangle + |E_R\rangle|R\rangle\right)$$

Decoherence vs diffusion

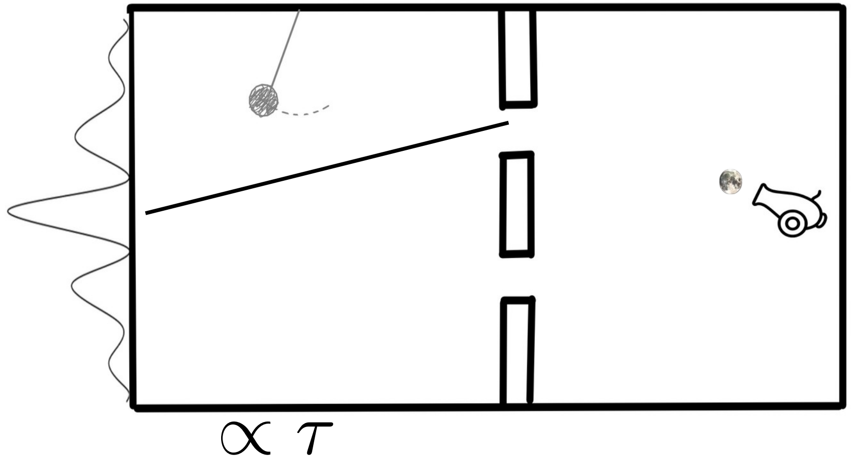


$$\hat{\sigma}(t) = \begin{pmatrix} \frac{1}{2} & \alpha^*(t) \\ \alpha(t) & \frac{1}{2} \end{pmatrix}$$

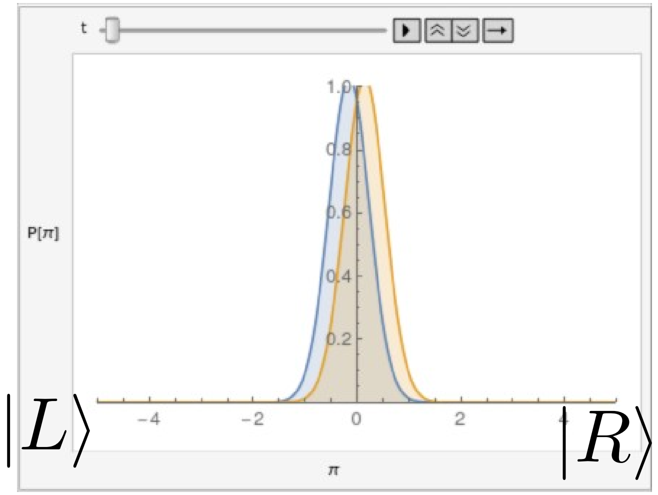
$$\alpha(t) = \langle E_L(t) | E_R(t) \rangle$$

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

Decoherence vs diffusion



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

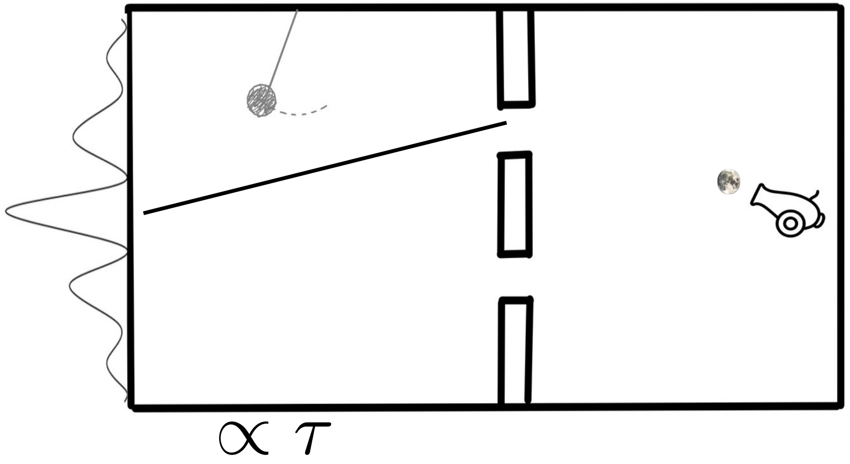


$$\mathrm{D}_2(z) - D_1^\dagger(z) D_0^{-1}(z) D_1(z) \succeq 0$$

Holds for all classical-quantum dynamics

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

Decoherence vs diffusion



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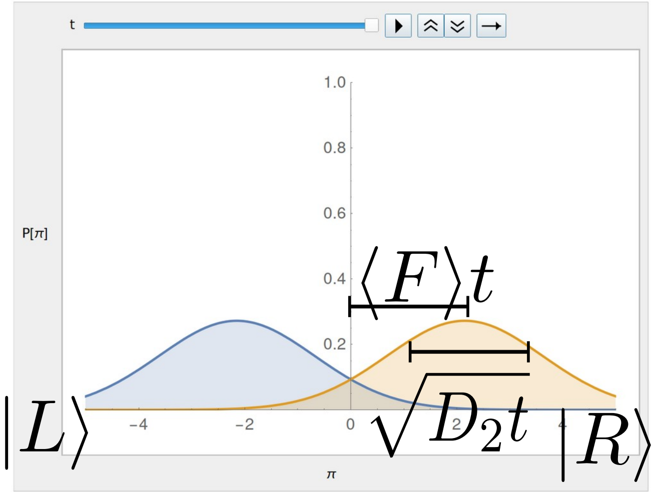

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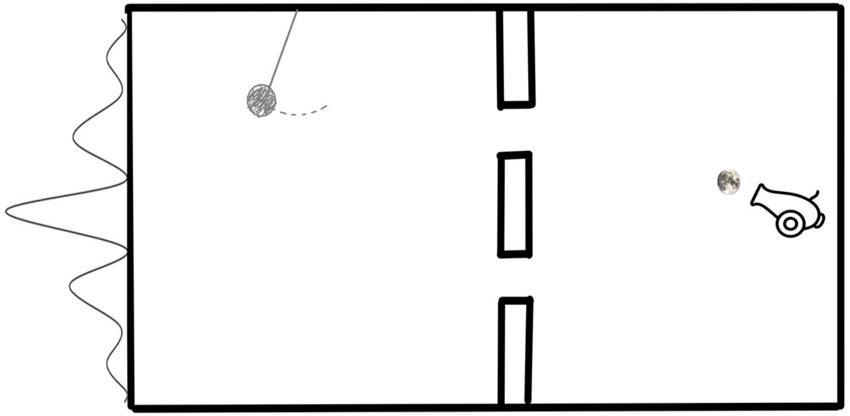
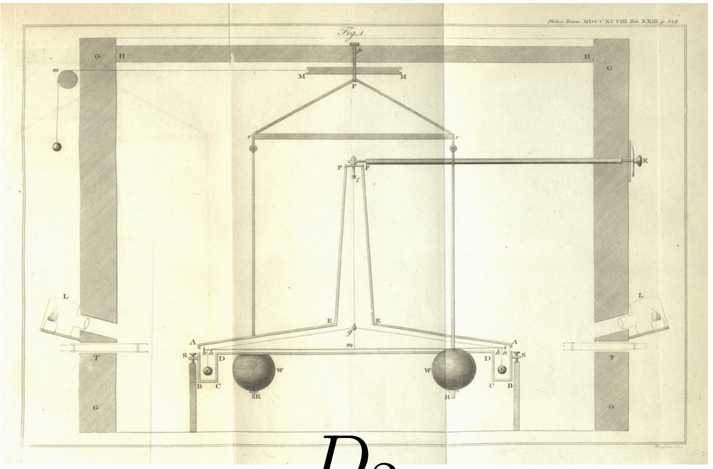
Decoherence vs diffusion

Double Slit Experiment



τ

Cavendish Experiment



D_2

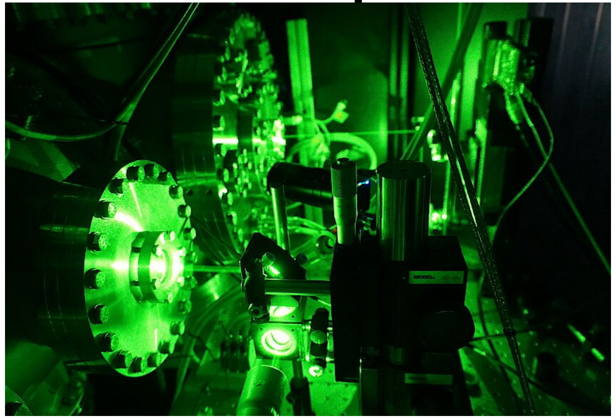
$$\langle F(x)\rangle = \langle \hat{m}(x)\rangle$$

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

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

Decoherence vs diffusion

Double Slit Experiment



τ

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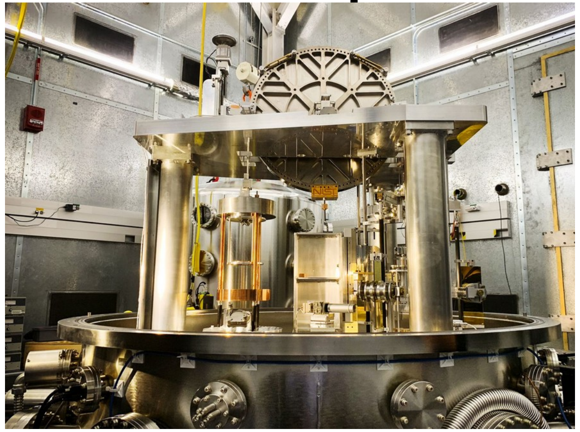

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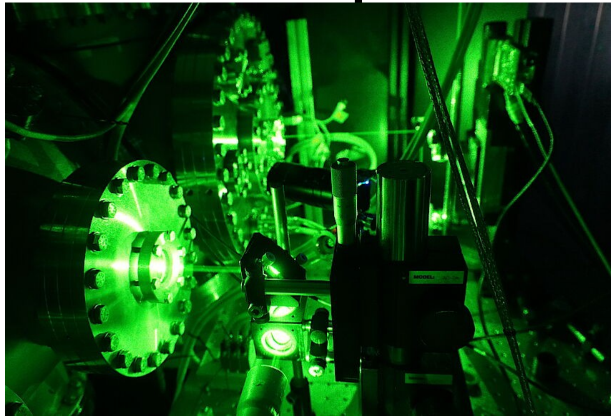
Figures of merit

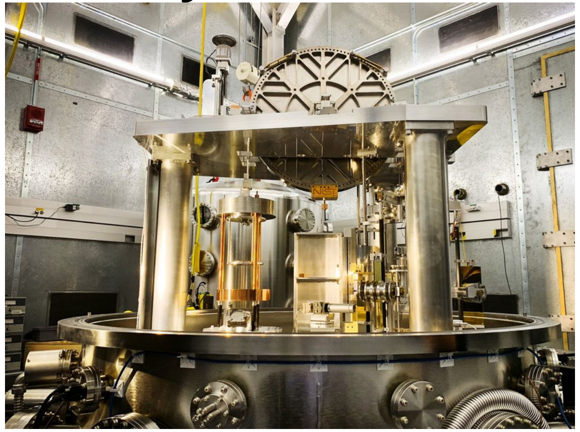
Double Slit Experiment



τ

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

Gravity measurement



D_2

$$D_2(z) - D_1^{\dagger}(z) D_0^{-1}(z) D_1(z) \succeq 0$$

Master Equation	Diffusion Kernel	Experimental squeeze
Continuous (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))
Continuous (Eqn (D11) or (D13))	$D_2(\Phi; x, y) = -l_p^2 D_2(\Phi)\nabla^2\delta(x, y)$ $D_2(\Phi) = \sum_n c^n \Phi^n$	$10^{-9} \geq l_P^2 D_2 \geq 10^{-35}\ kg^2 sm^{-1}$ (Eqn (47))
Discrete (ultra-local)	$D_2(\Phi; x, y) = \frac{l_P^2}{m_P} D_2(\Phi)\delta(x, y)$ $D_2(\Phi) = \sum_n c^n \Phi^n$	$10^{-1} \geq \frac{l_P^2 D_2}{m_P} \geq 10^{-25}\ kgs$ (Eqn (46))

Challenges

Tensions?

CPTP, normalisable

Local

Renormalisable in matter sector?

Covariant

Anomalous heating

Is space-time classical?

I have no idea.
But,

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 Foil?

Dark matter?
Dark energy?

Renormalisable w/o Ghosts

Is space-time classical?

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

It could be

1:5000 ODDS

Information is lost but quantum state remains pure

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