Title: The back-reaction problem in quantum foundations and gravity

Speakers: Jonathan Oppenheim

Series: Quantum Foundations

Date: December 01, 2022 - 11:00 AM

URL: https://pirsa.org/22120047

Abstract: We consider two interacting systems when one is treated classically while the other remains quantum. Despite several famous no-go arguments, consistent dynamics of this coupling exist, and its most general form can be derived. We discuss the application of these dynamics to the foundations of quantum theory, and to the problem of understanding gravity when space-time is treated classically while matter has a quantum nature.

The talk will be informal and I'll review and follow on from joint work with Isaac Layton, Andrea Russo, Carlo Sparaciari, Barbara ?oda & Zachary Weller-Davies

https://arxiv.org/abs/2208.11722
https://arxiv.org/abs/2203.01982
https://arxiv.org/abs/1811.03116

Zoom link: https://pitp.zoom.us/j/92520708199?pwd=WUowdnd4Z0k3dlU2YjVmVlAva3Q0UT09

Saturating the decoherence vs diffusion trade off



WITH

Isaac Layton, Carlo Sparaciari, Barbara Šoda, Zach Weller-Davies

arXiv

1811.03116 • 2203.01982 • 2203.01332

Jonathan Oppenheim
@postquantum
PI
Dec 1, 2022

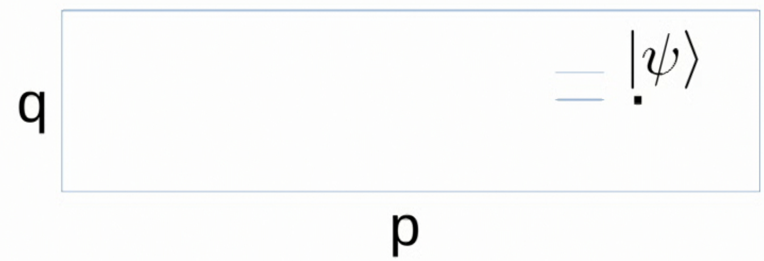
It from Qubit
Simons Collaboration on Quantum Fields, Gravity and Information

Engineering and Physical Sciences Research Council

Frameworks

Quantum Mechanics

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



Classical Mechanics

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

Frameworks

Quantum Mechanics

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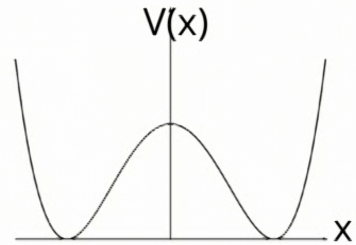

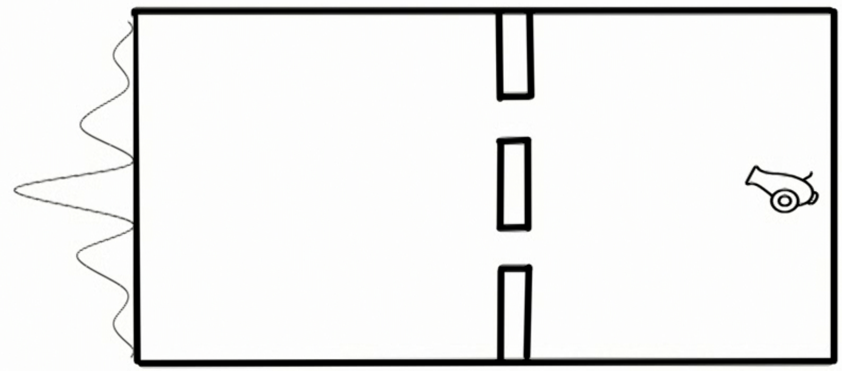

Back-reaction

Classical-quantum dynamics

Debate

No

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

Maybe

Sherry & Sudarshan (1978)
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);
Poulin (2017);
Diosi (1995)

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

Entanglement experiments

Kafri & Taylor (2013);
Bose et. al. (2017);
Marletto et. al. (2017)

Classical-quantum dynamics

Motivation

Information destruction in black holes

A sandbox/foil for quantum gravity

An effective theory

- Semi-classical limit

A fundamental theory of QFT + classical GR

- Near term experiments

Saturating the trade-off

Decoherence vs Diffusion: testing quantum gravity

Path integrals for CQ dynamics.

The CQ interpretation of quantum (classical) mechanics

General Relativity + QFT

Classical-quantum dynamics

Results

Most general form

Two classes:
continuous & jumping

General Relativity + QFT

Born rule & Measurement postulate for free

Coherence limit

Decoherence vs Diffusion trade-off

EXPERIMENT

Saturating the trade-off

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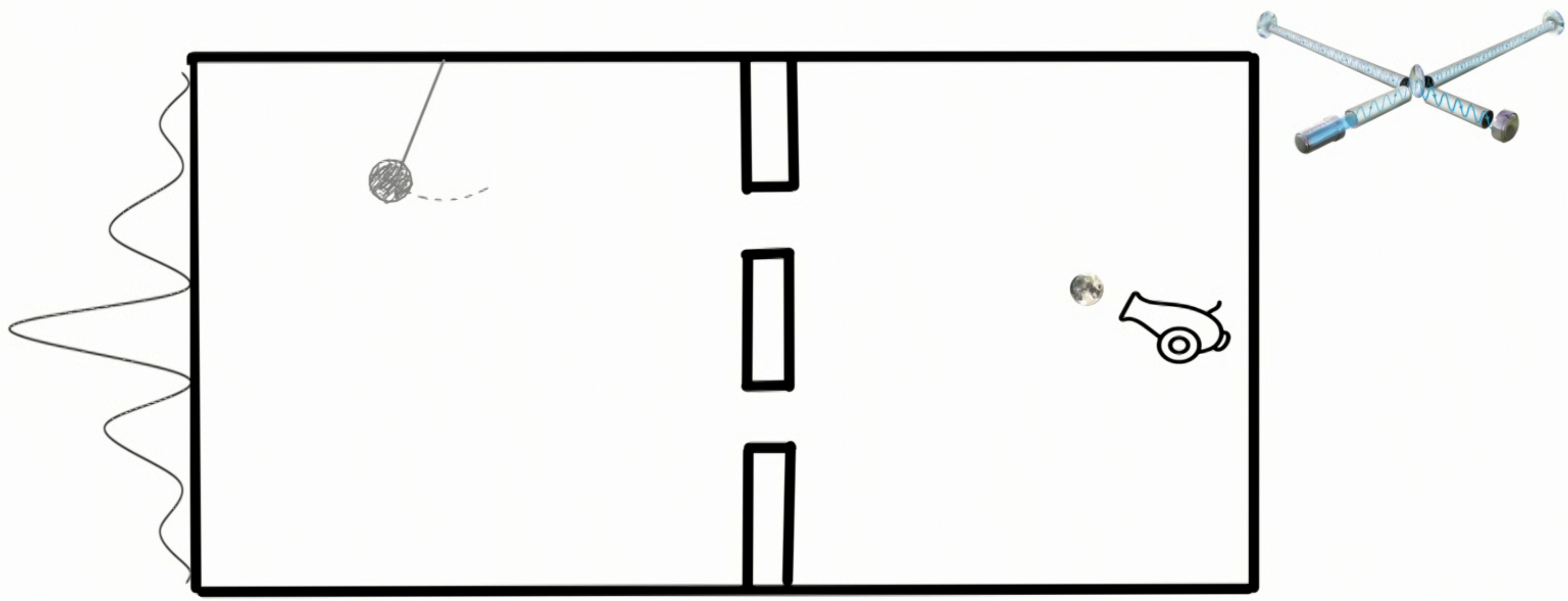
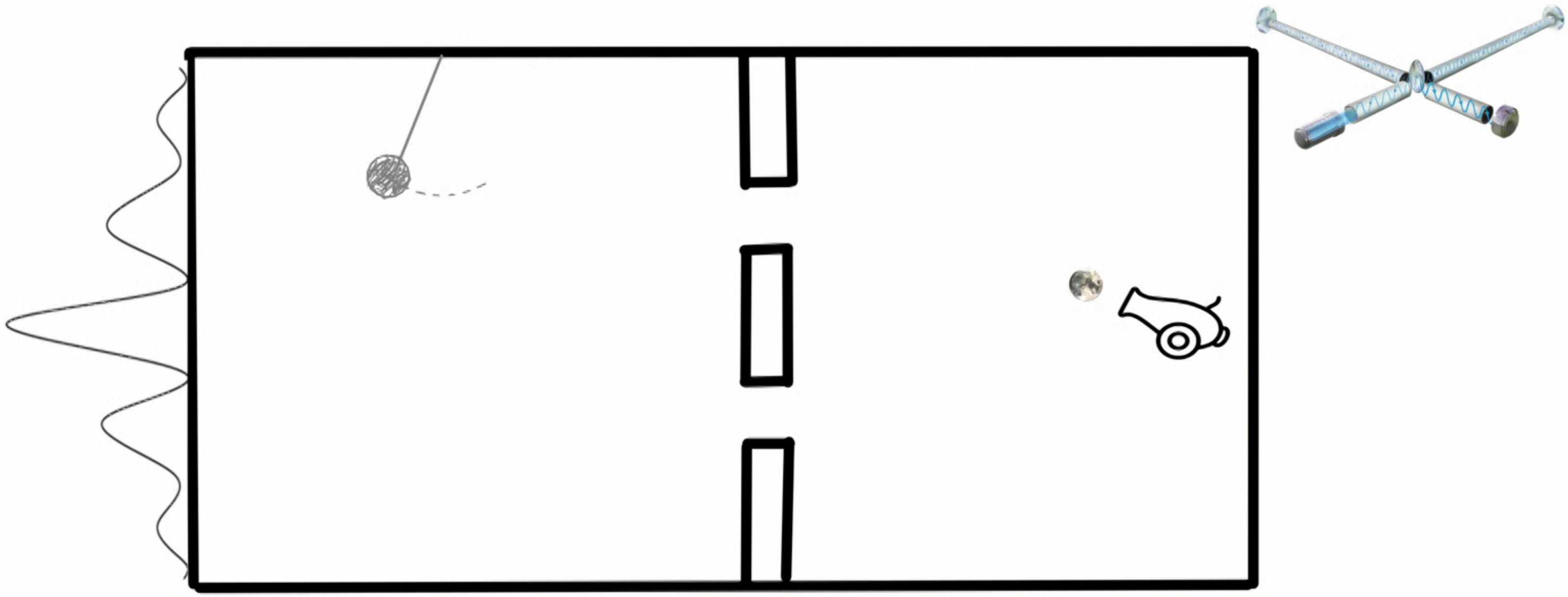
Decoherence vs diffusion



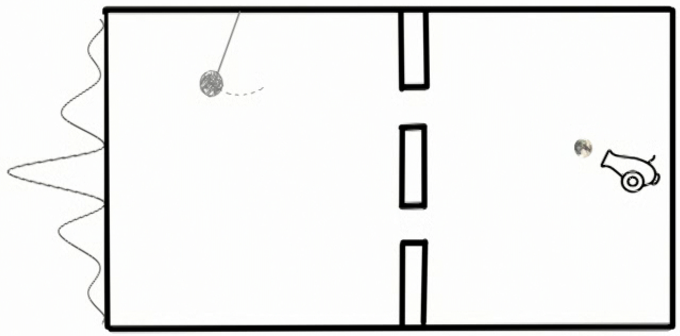
Feynman, Chapel Hill Conference (1957); Aharonov (~1986);
Eppley & Hannah (1977); Marletto & Vedral (2017)

Decoherence vs diffusion



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

Decoherence vs diffusion

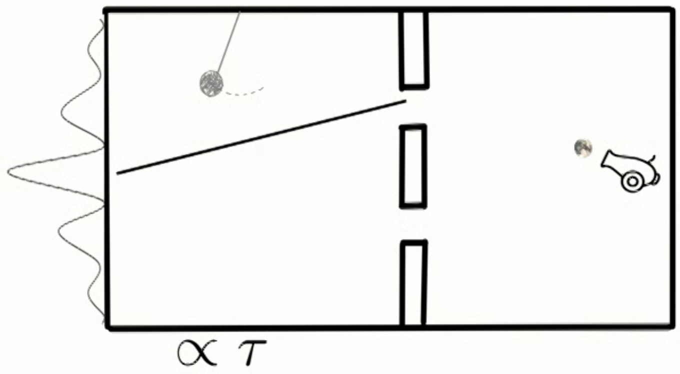


$$\hat{\sigma}(t) = \begin{pmatrix} \frac{1}{2} & \alpha^*(t) \\ \alpha(t) & \frac{1}{2} \end{pmatrix}$$

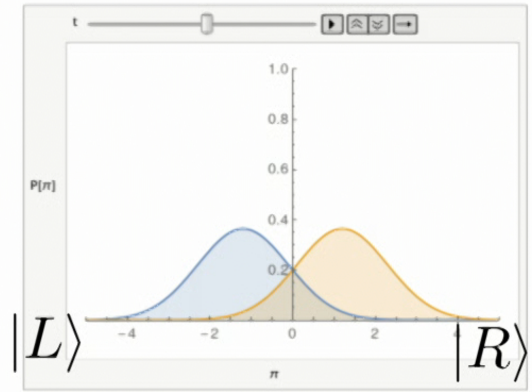
$$\alpha(t) = \langle E_L(t) | E_R(t) \rangle$$

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

Decoherence vs diffusion



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



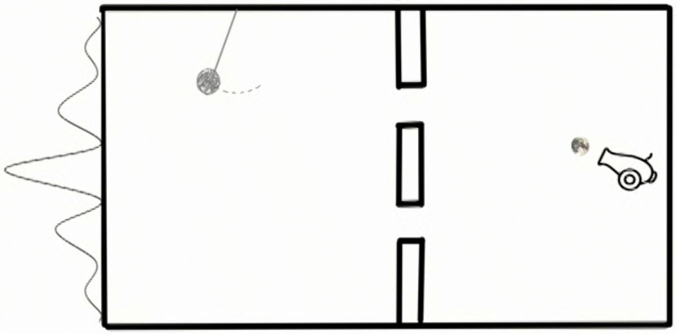
$$D_2(z) - D_1^\dagger(z) D_0^{-1}(z) D_1(z) \succeq 0$$

Holds for all classical-quantum dynamics

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

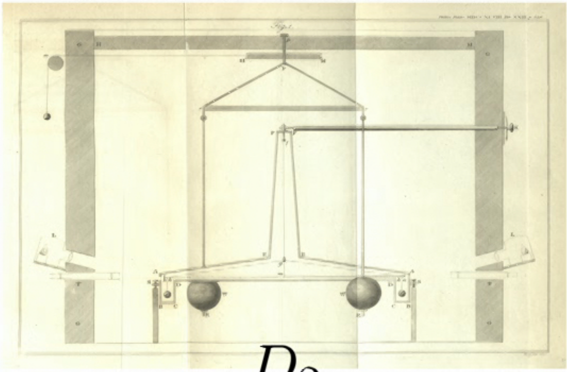
Decoherence vs diffusion

Double Slit Experiment



τ

Cavendish Experiment



D_2

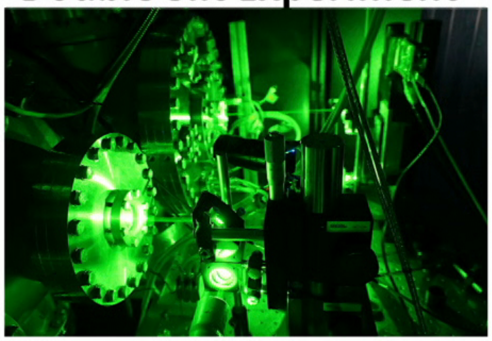
$$\langle F(x)\rangle = \langle \hat{m}(x)\rangle$$

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

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

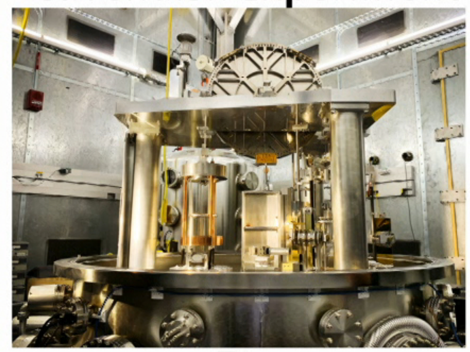
Decoherence vs diffusion

Double Slit Experiment



τ

Cavendish Experiment

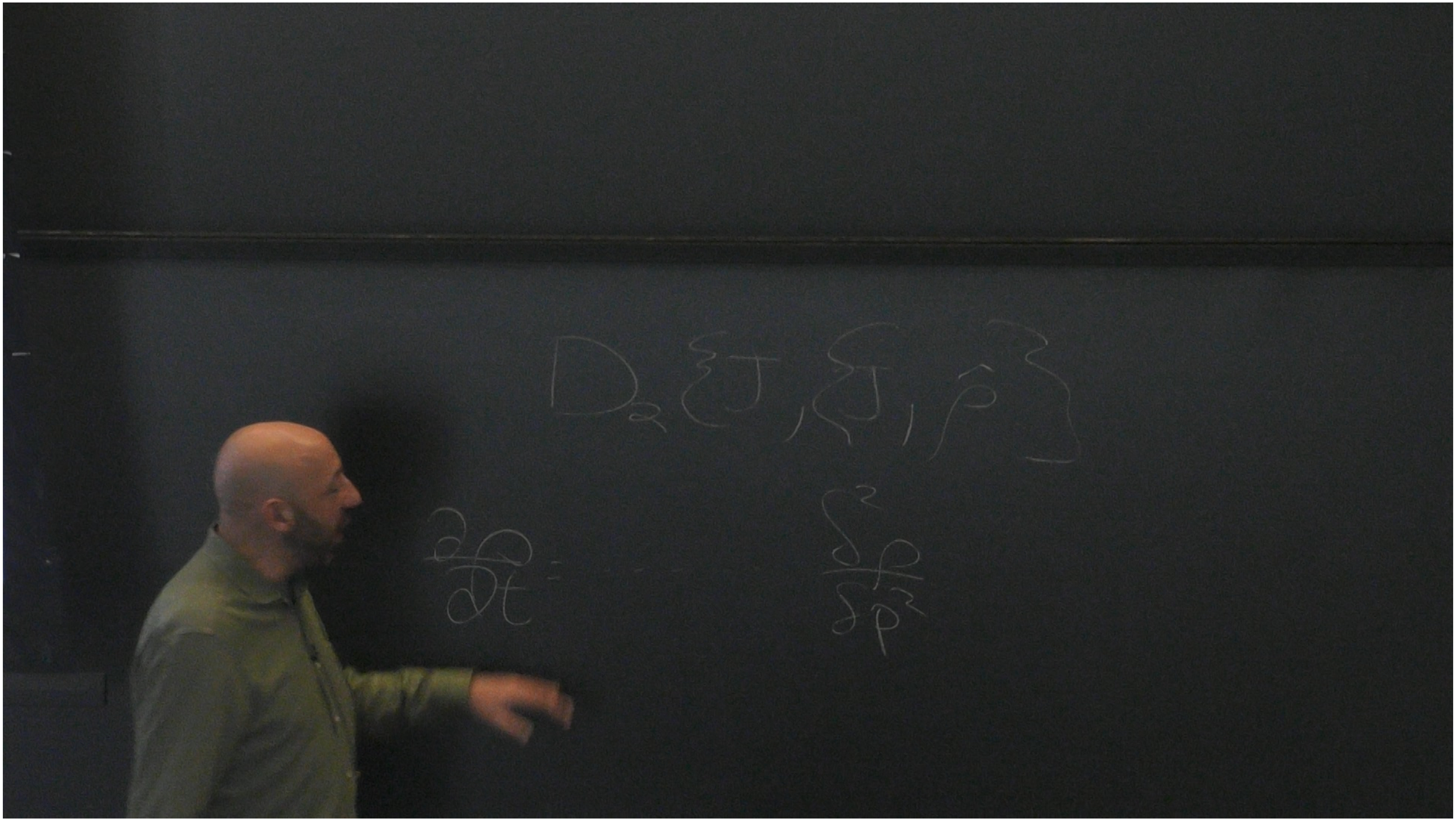


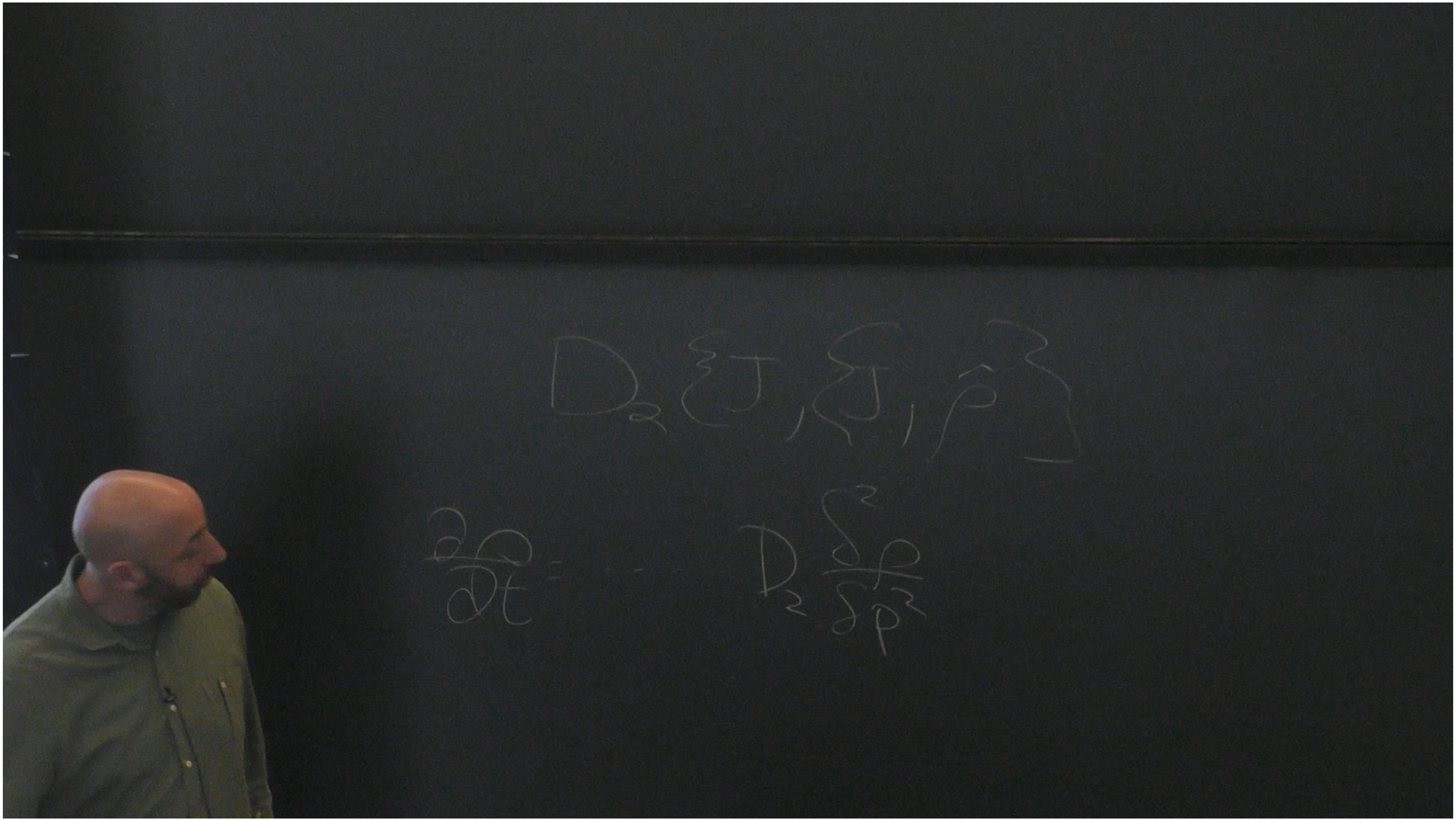
D_2

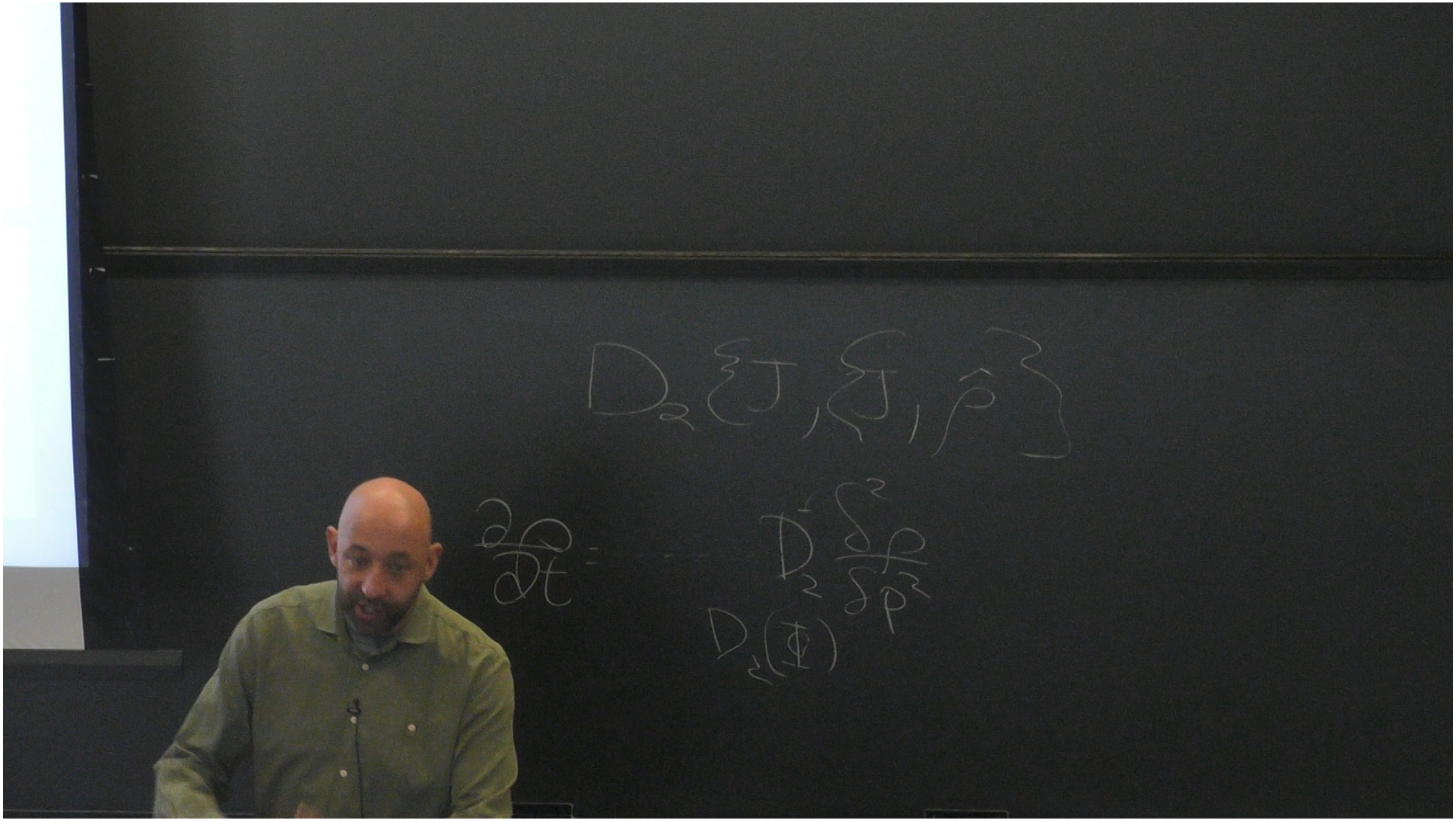
$$\langle F(x) \rangle = \langle \hat{m}(x) \rangle$$

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

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




$D_2\{J,\{J,\rho\}\}$
$\frac{\partial\rho}{\partial t} = \dots D_2 \frac{\delta^2\rho}{\delta p^2}$



Saturating the trade-off

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Path integrals for CQ dynamics.

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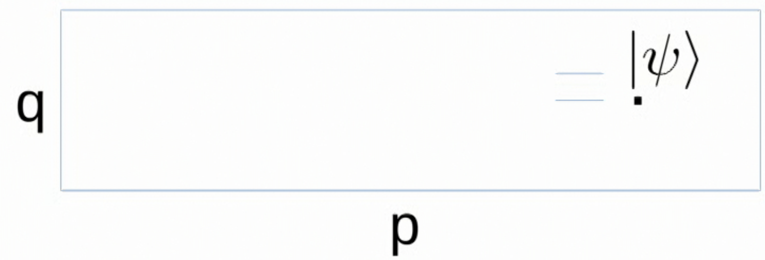


Classical Mechanics

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

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

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

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

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

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

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

POSITIVE MATRIX AT EACH Z

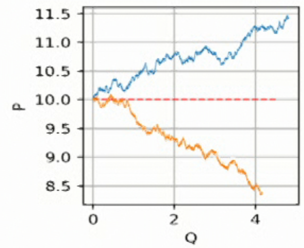
CQ Dynamics

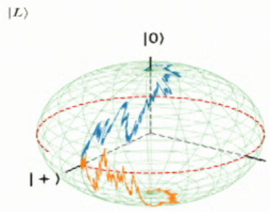
Path Integral

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

JO, Zach Weller-Davies

Trajectories





JO, I. Layton, Z. Weller-Davies

Master Eqn

CPTP MAP

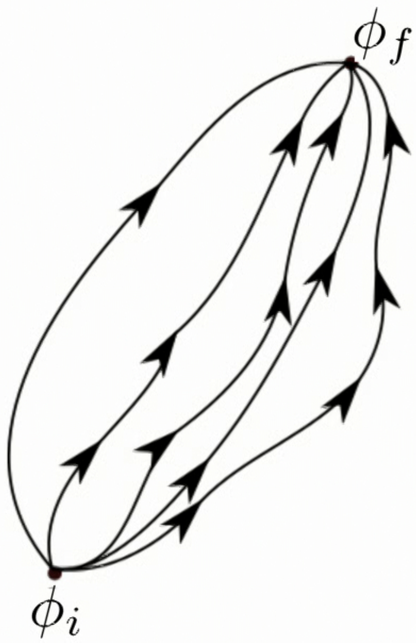
$$\frac{\partial\hat{\rho}}{\partial t} \approx \{H^{(grav)},\hat{\rho}\} - i[\hat{H}^{(m)},\hat{\rho}] + \frac{1}{2}\{\hat{H}^{(m)},\hat{\rho}\} - \frac{1}{2}\{\hat{\rho},\hat{H}^{(m)}\}$$
$$+\int dx dx' \frac{\delta^2}{\delta\pi_\Phi(x)\delta\pi_\Phi(x')}(D_2(x,x')\hat{\rho}) + \frac{1}{2}\int dx dx'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

JO, Sparaciari, Soda, Weller-Davies

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

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

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)

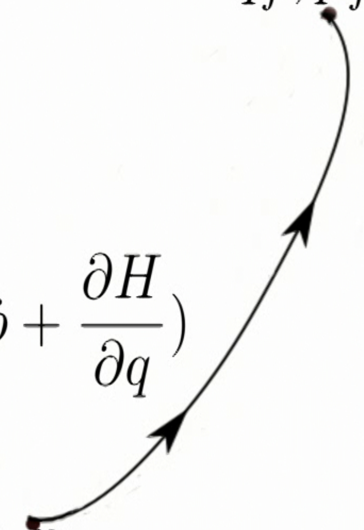
$$\hat{\sigma}(\phi_f^+, \phi_f^-, t_f) = \int \mathcal{D}\phi^+ \mathcal{D}\phi^- \; e^{iS[\phi^+] - iS[\phi^-] + iS_{FV}[\phi^+, \phi^-]}$$

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

Path Integrals

Classical Mechanics

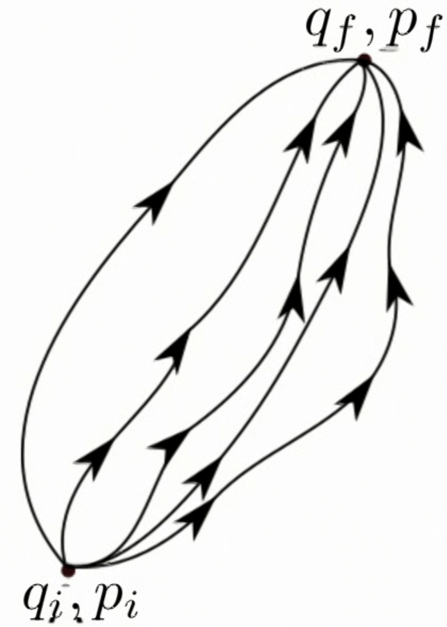
$$\rho(q_f, p_f, t_f | q_i, p_i t_i) = \int_{q_i, p_i}^{q_f, p_f} \mathcal{D}q \mathcal{D}p \delta(\dot{q} - \frac{\partial H}{\partial p}) \delta(\dot{p} + \frac{\partial H}{\partial q})$$



Path Integrals

Classical Mechanics (stochastic)

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



Onsager-Machlup

Q, C & CQ Path integral

Q

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

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

C

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

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

CQ

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

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

$$4D_2 \succeq D_0$$

Q, C & CQ Path integral

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

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

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Saturating the trade-off

Decoherence vs Diffusion: testing quantum gravity

Path integrals for CQ dynamics.

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Saturating the trade-off

Classical-Quantum

$$\rho(\phi^+,\phi^-,q_f,p_f,t_f|\phi_i,q_i,p_it_i) = \mathcal{N}\int \mathcal{D}q\mathcal{D}p\mathcal{D}\phi^+\mathcal{D}\phi^-\delta(\dot{q}-\frac{\partial H}{\partial p})e^{iS[\phi^+,\phi^-,q,p]}$$

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

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

$$4D_2 \succeq D_0$$

JO, Zach Weller-Davies

Saturating the trade-off

Saturating the trade-off

$$iS[\phi^+,\phi^-,q,p] = iS[\phi^+] - \frac{D_0}{4}\left(\left(\frac{\partial H^+}{\partial q}\right)^2 + 2\dot{p}\frac{\partial H^+}{\partial q}\right) - iS[\phi^-] - \frac{D_0}{4}\left(\left(\frac{\partial H^-}{\partial q}\right)^2 + 2\dot{p}\frac{\partial H^-}{\partial q}\right) - \frac{D_0}{2}\dot{p}^2$$

A miracle occurs!

$$4D_2 = D_0$$

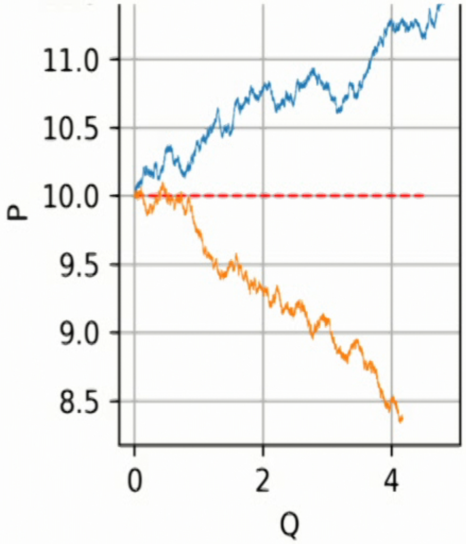
JO, Zach Weller-Davies

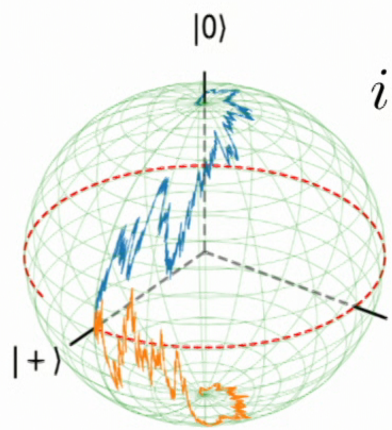
Saturating the trade-off

$$iS[\sigma^+,\sigma^-,q,p] = -iq\hat{\sigma}_z^+ - \frac{D_0}{4}\left(\mathbb{1}+2\dot{p}\hat{\sigma}^+\right) + iq\hat{\sigma}_z^- - \frac{D_0}{4}\left(\mathbb{1}+2\dot{p}\hat{\sigma}^-\right) - \frac{D_0}{2}\dot{p}^2$$

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

$$iS[\phi^+,\phi^-,q,p] = iq\hat{\sigma}^+ - iq\hat{\sigma}^- + iS_{FV} - \frac{1}{2D_2}(\dot{p} + \frac{1}{2}\hat{\sigma}^+ + \frac{1}{2}\hat{\sigma}^-)^2$$





$$iS_{FV} = -\frac{1}{2}D_0\left(\hat{\sigma}^+ - \hat{\sigma}^-\right)^2$$

$$4D_2 = D_0$$

JO, Isaac Layton, Zach Weller-Davies

Standard axioms for Quantum Theory

- States are represented by a vector in Hilbert space $|\psi\rangle$
- Dynamics are given by unitary transformations $U|\psi\rangle$
- Observables are represented by self-adjoint operators $\hat{A}$
- Expectation values of observables are given by $\langle\psi|\hat{A}|\psi\rangle$
- The collapse postulate

JO, Isaac Layton, Zach Weller-Davies

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- The collapse postulate

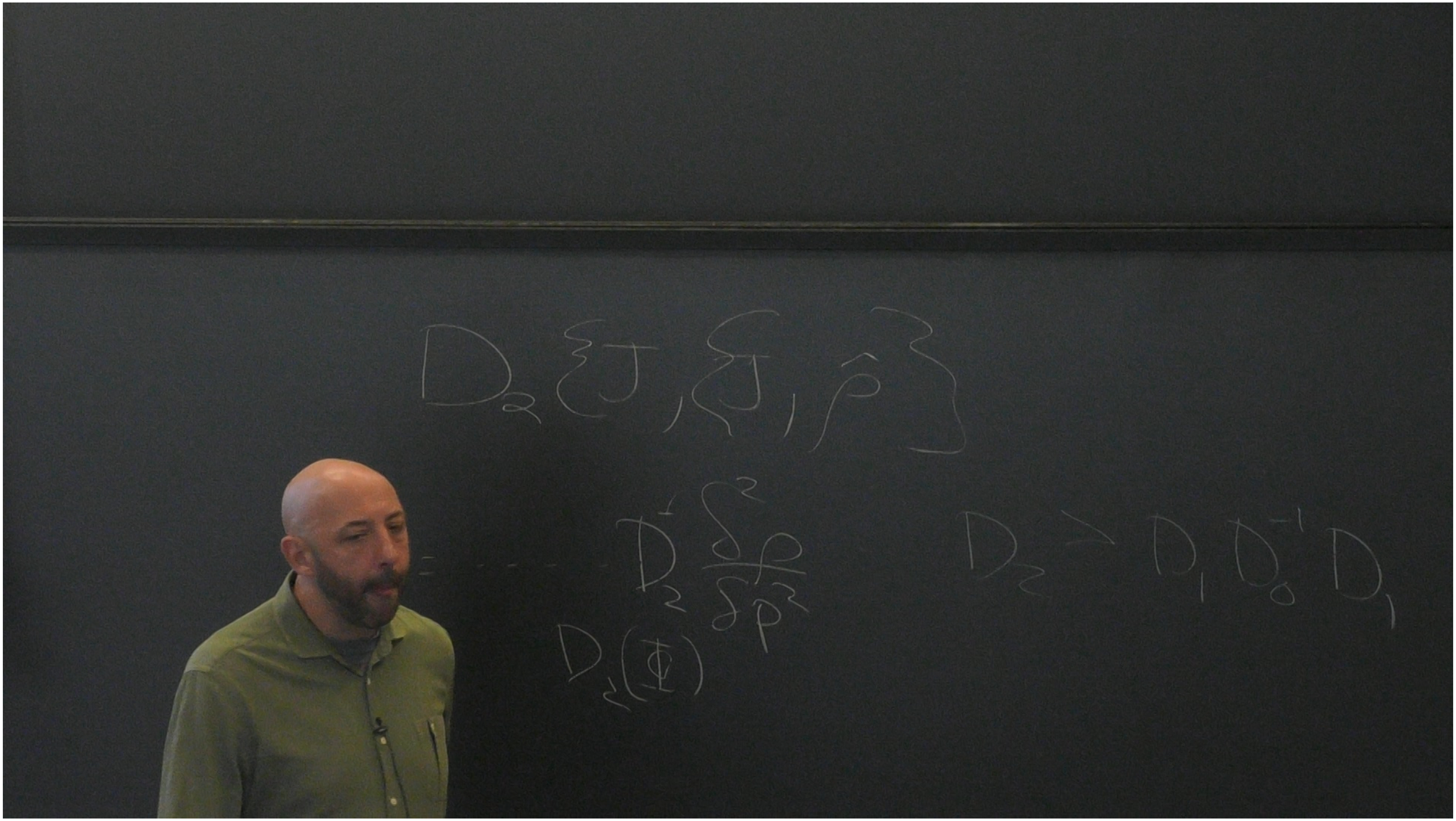
$$\langle\psi|\hat{A}|\psi\rangle$$

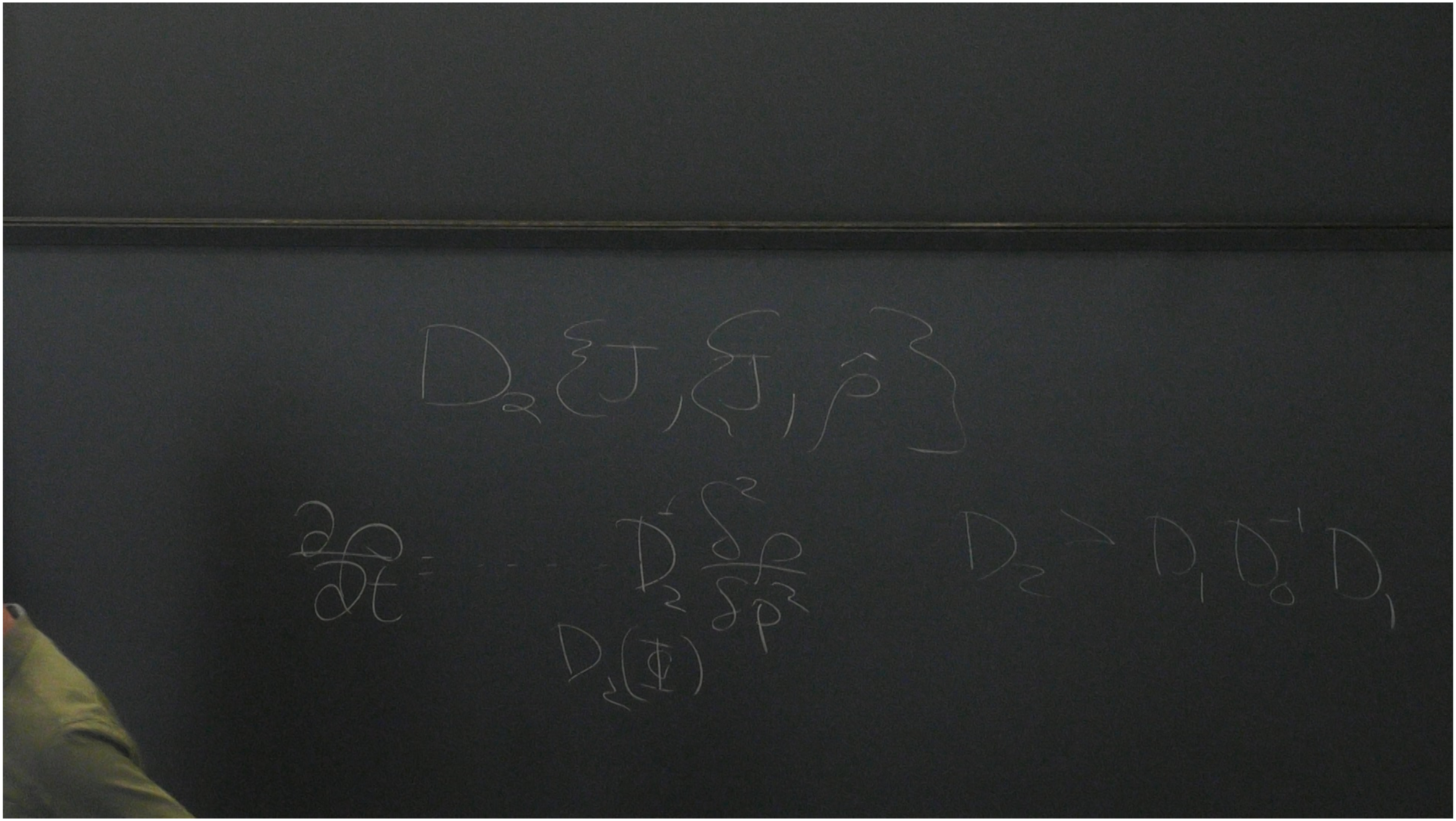
JO, Isaac Layton, Zach Weller-Davies

The CQ interpretation: $\exists$ classical systems

1. Quantum states are represented by a vector in Hilbert space $|\psi\rangle$
2. Classical states are points in phase space (q,p)
3. The phase space density $\rho(q,p)$ obeys classical probability theory
4. For fixed (q,p), the dynamics is linear on $|\psi\rangle$
5. Observables are represented by self-adjoint operators $\hat{A}$
6. Expectation values of observables are given by $\langle\psi|\hat{A}|\psi\rangle$
7. The collapse postulate

JO, Isaac Layton, Zach Weller-Davies


$D_2\{J,\{J,\hat{\rho}\}\}$
$D_2^{-1}\frac{\delta^2\rho}{\delta\hat{\rho}^2}$
$D_2(\Phi)$
$D_2 \geq D_1 D_0^{-1} D_1$


D2{J,{J,ρ}}
∂ρ/∂t = ... D2 δ²ρ/δρ²
D2(Φ)
D2 ≥ D1 D0⁻¹ D1