“It from Qubit” Postdocs and studentships

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Jonathan Oppenheim (University College London)

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Daniel Harlow (MIT)

Alex Maloney (McGill)

Juan Maldacena (IAS)

Rob Myers (Perimeter)

Scott Aaronson (UT Austin)

Dorit Aharonov (Jerusalem)

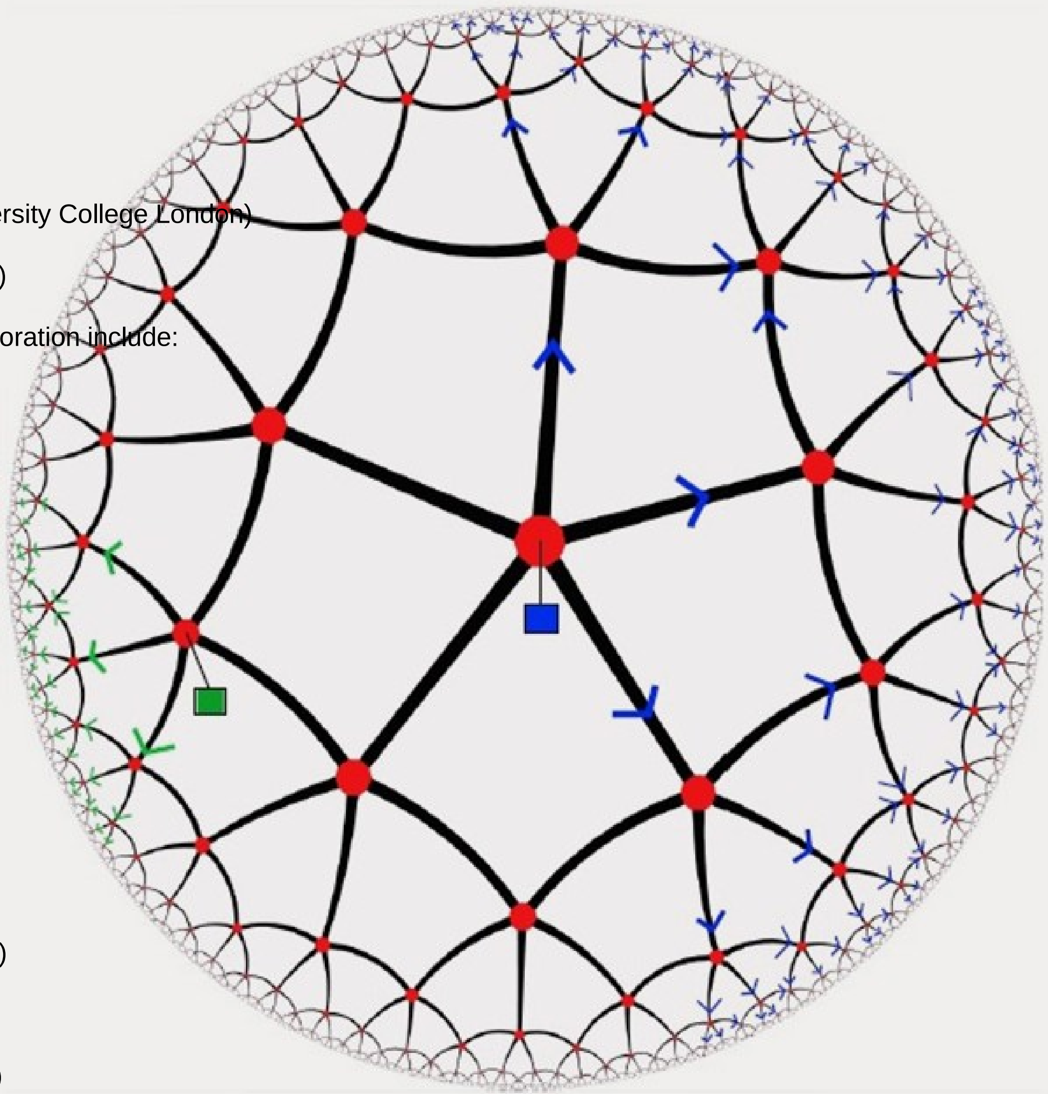
Brian Swingle (Maryland)

Tadashi Takayanagi (Kyoto)

Matthew Headrick (Brandeis)

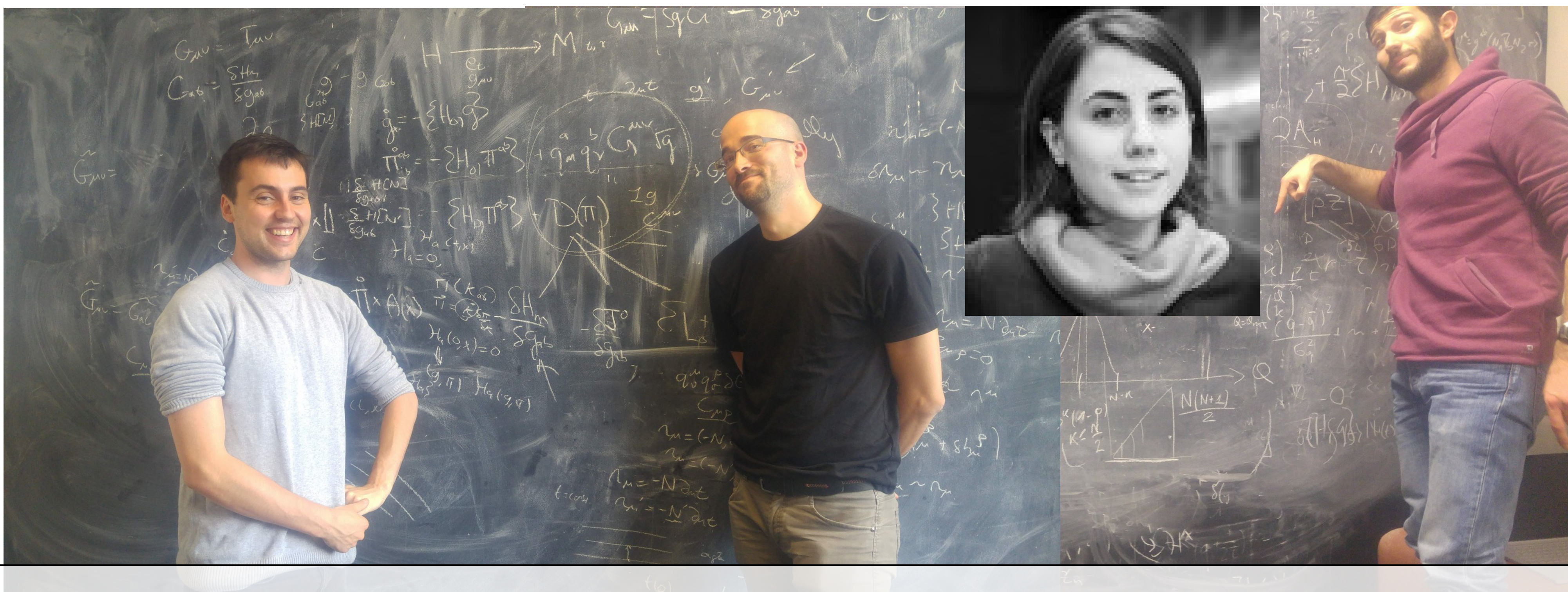
John Preskill (Caltech)

Leonard Susskind (Stanford)



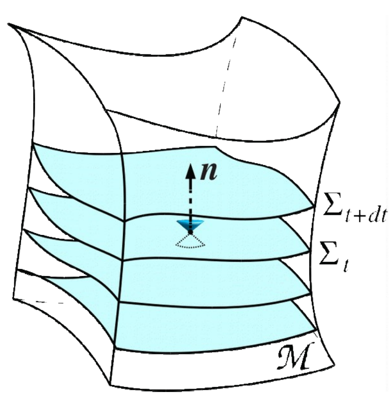
A post-quantum theory of classical gravity?

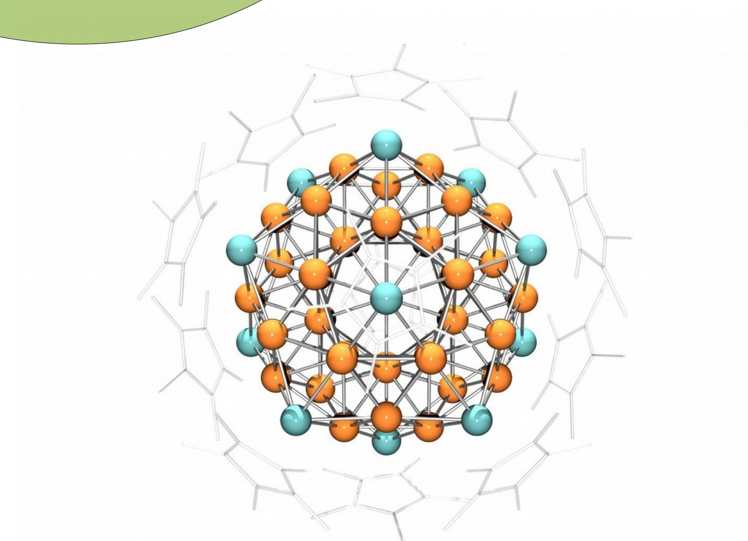
- arXiv:1811.03116, ...
- w/ Camps, Soda, Sparaciari, Weller-Davies



General Relativity & Quantum theory

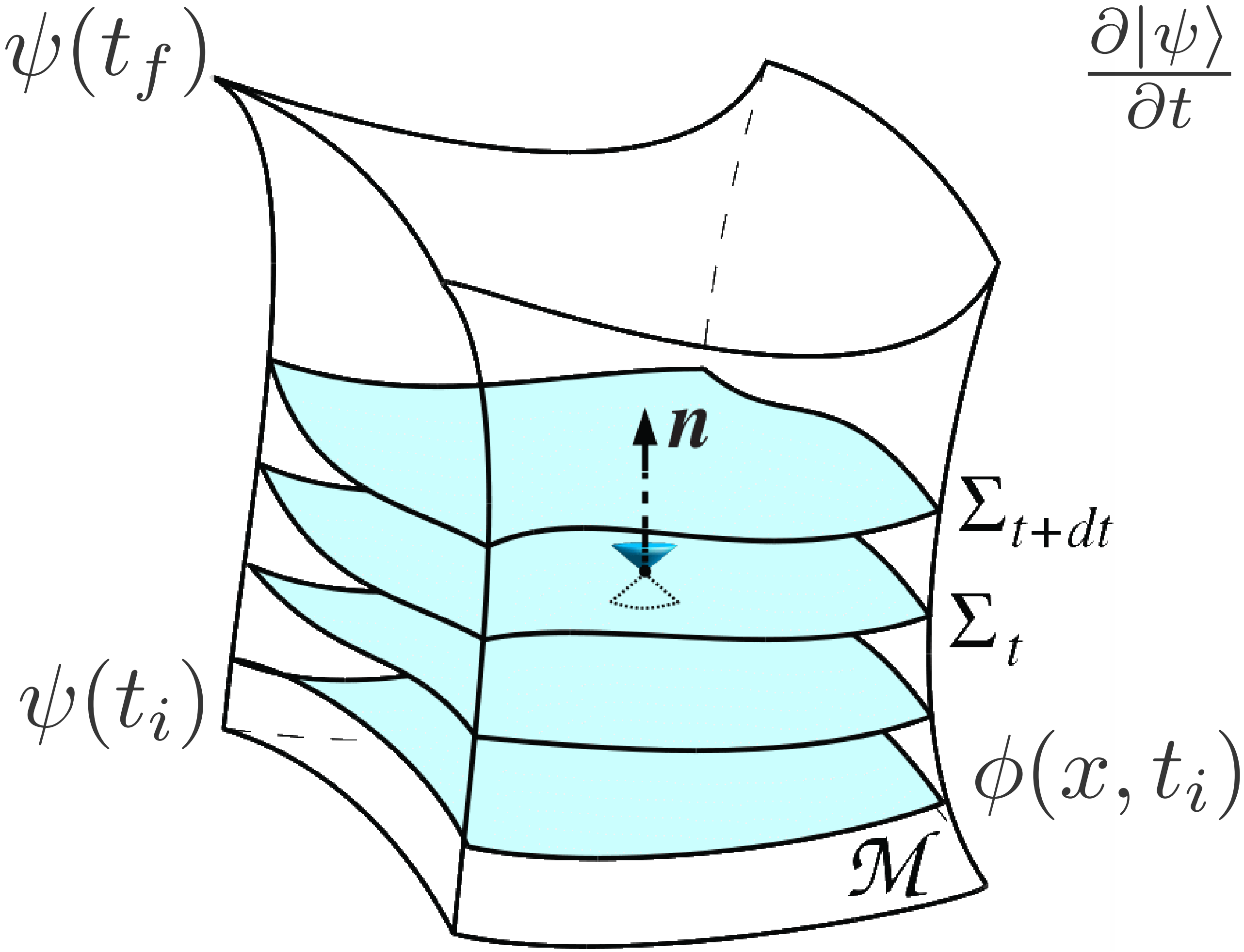
$$G_{\mu\nu} = \frac{8\pi G}{c^4}\mathbf{T}_{\mu\nu}$$





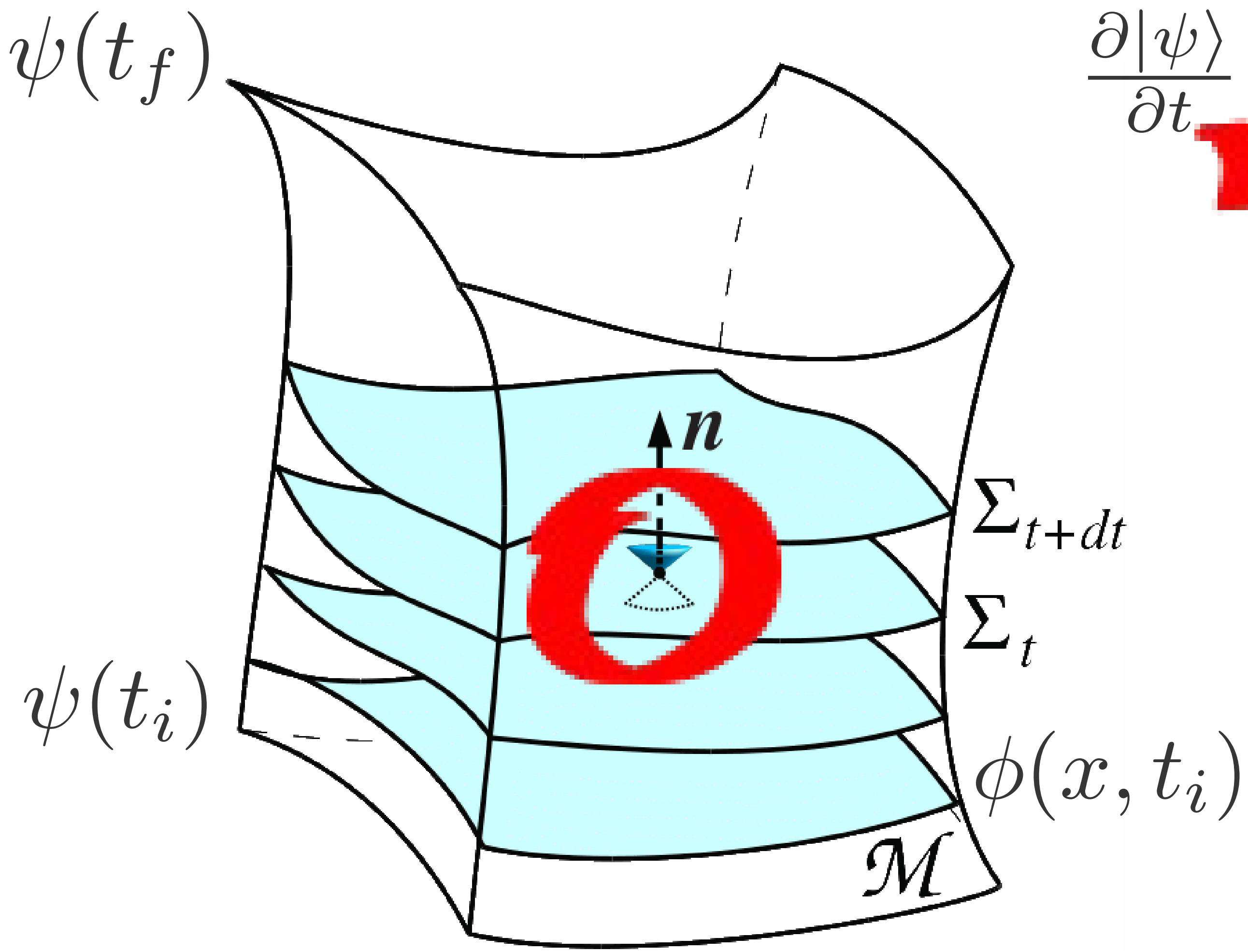
Quantum theory has a future

$$\frac{\partial|\psi\rangle}{\partial t} = -i\mathbf{H}|\psi\rangle$$

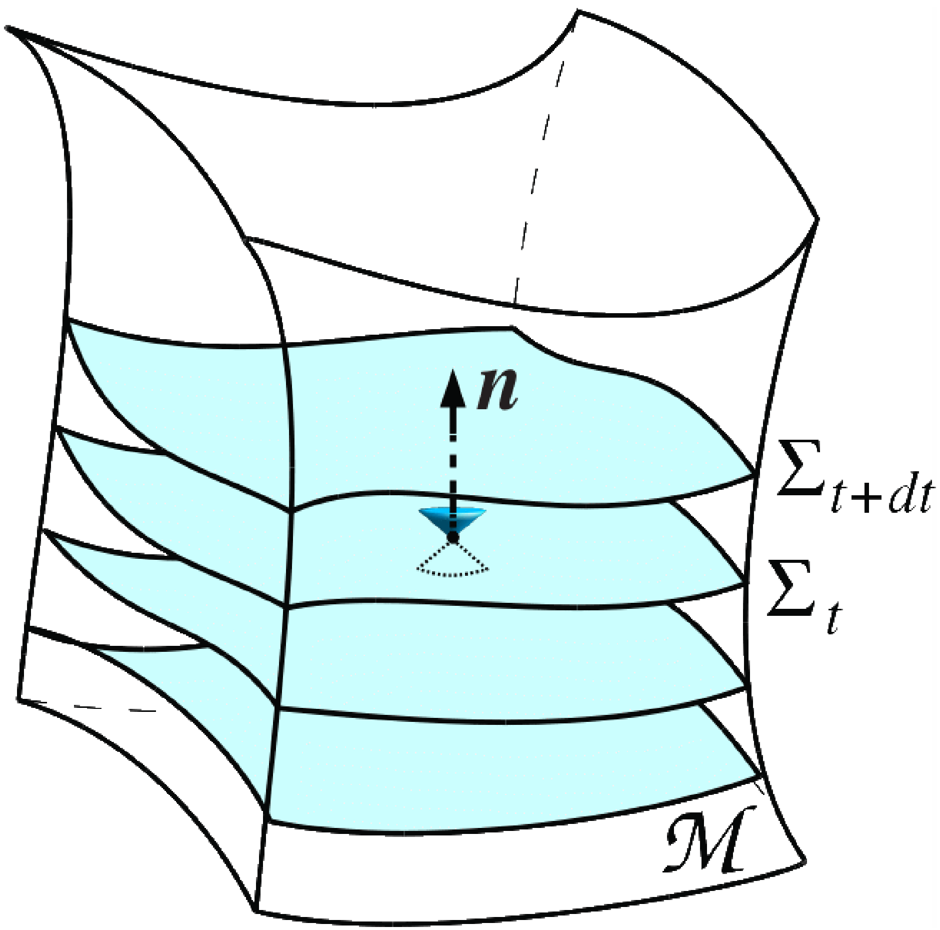


Quantum gravity, not so much...

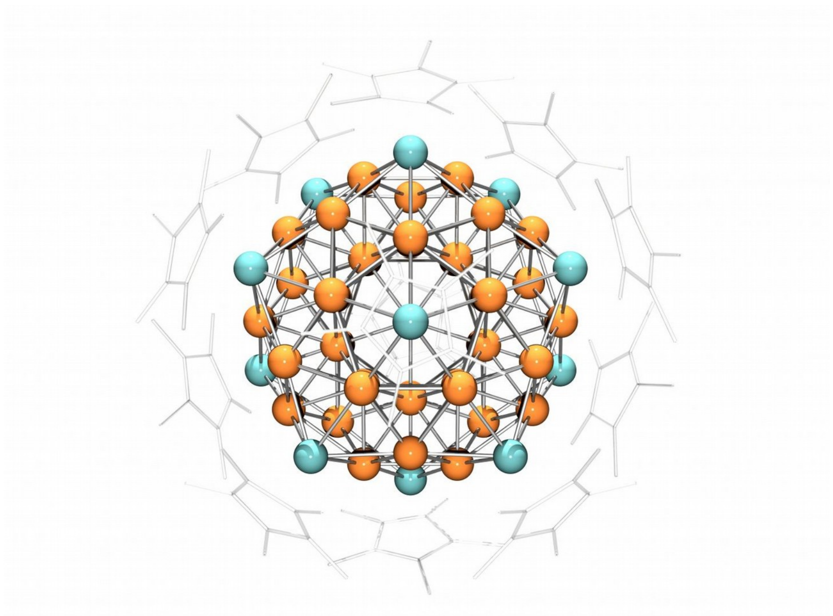
$$\frac{\partial|\psi\rangle}{\partial t} = -i\mathbf{H}|\psi\rangle$$



Should we quantise space-time?



$g_{ab}(x,t)$



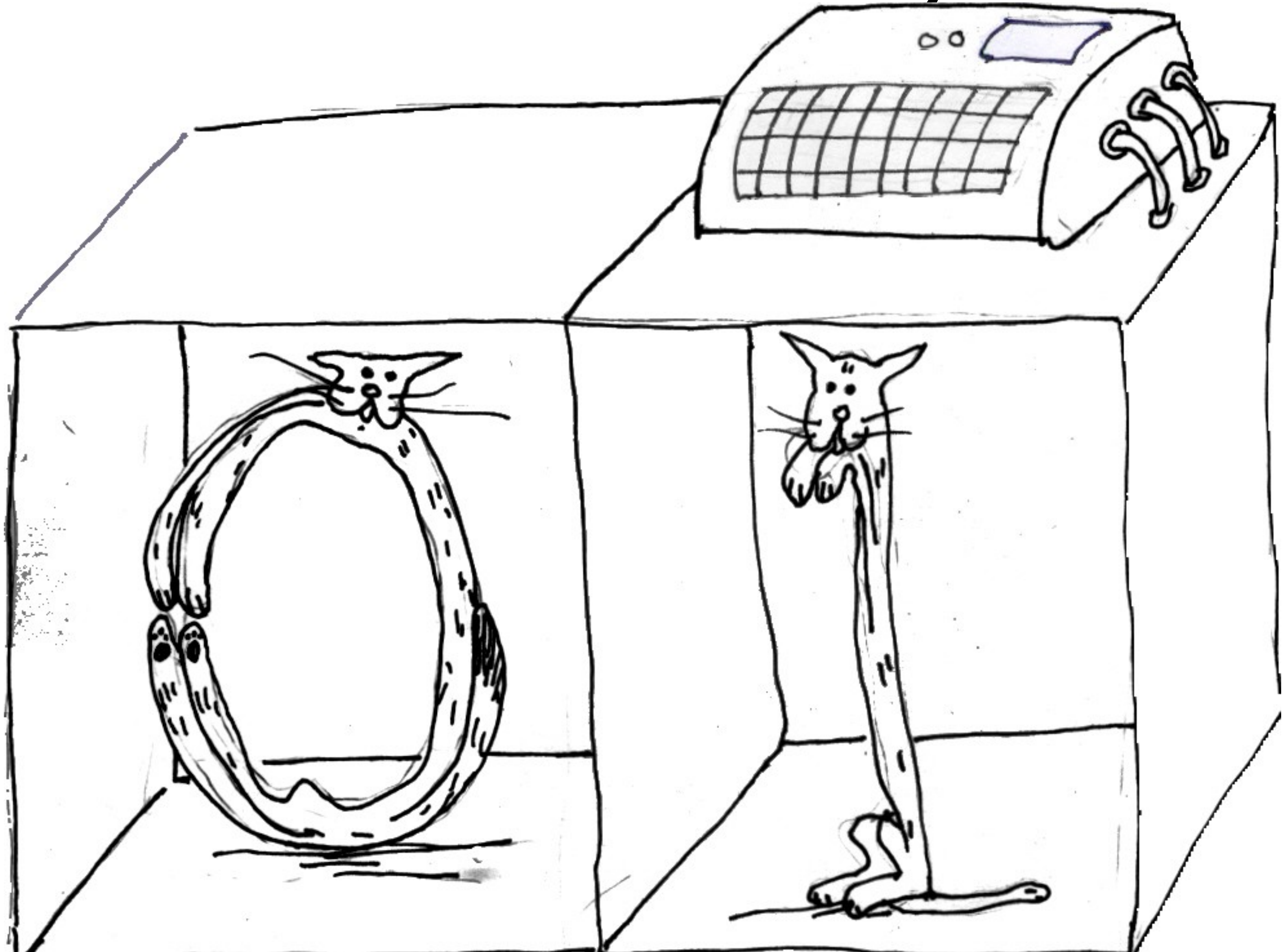
$\phi(x,t)$

Is space-time classical?

I have no idea. But….

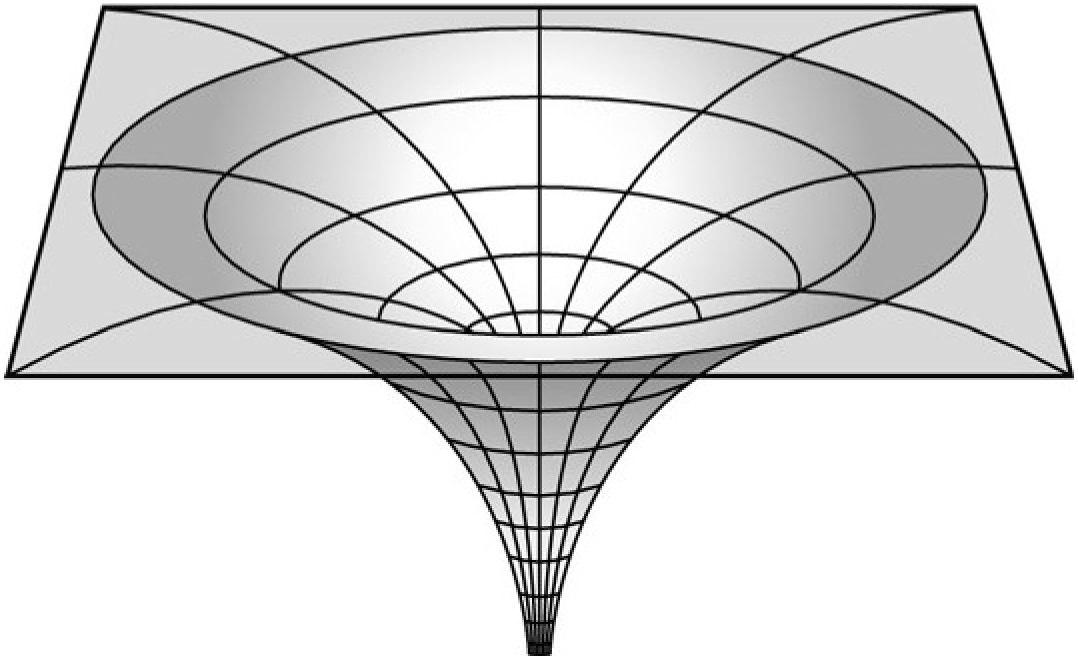
- It can be
- It would necessarily cause “collapse of the wave-function”
- It would necessarily lead to information destruction
- Effective theory?

Does it make any sense to speak of the emergence of classicality without classical systems?



$$|\psi\rangle = \frac{1}{\sqrt{2}}\Big(|0000000...\rangle + |1111111...\rangle\Big)$$

Black hole information problem 2.0



AMPS: If information is preserved we must break the equivalence principle (a firewall).

BPS: If information is destroyed we must sacrifice locality or energy conservation.

Hawking (1976)
Almheiri, Marolf, Polchinski, Sully (2012)
Banks, Peskin, Susskind (1984)

Outline

- Can we couple quantum and classical systems?
- What is the general form of this dynamics?
- Application to General Relativity/QFT ▽

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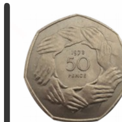
Can we?

$\frac{1}{\sqrt{2}}\Big|$  $\Big\rangle\Big|$ 

$\Big\rangle + \frac{1}{\sqrt{2}}\Big|$  $\Big\rangle\Big|$ 

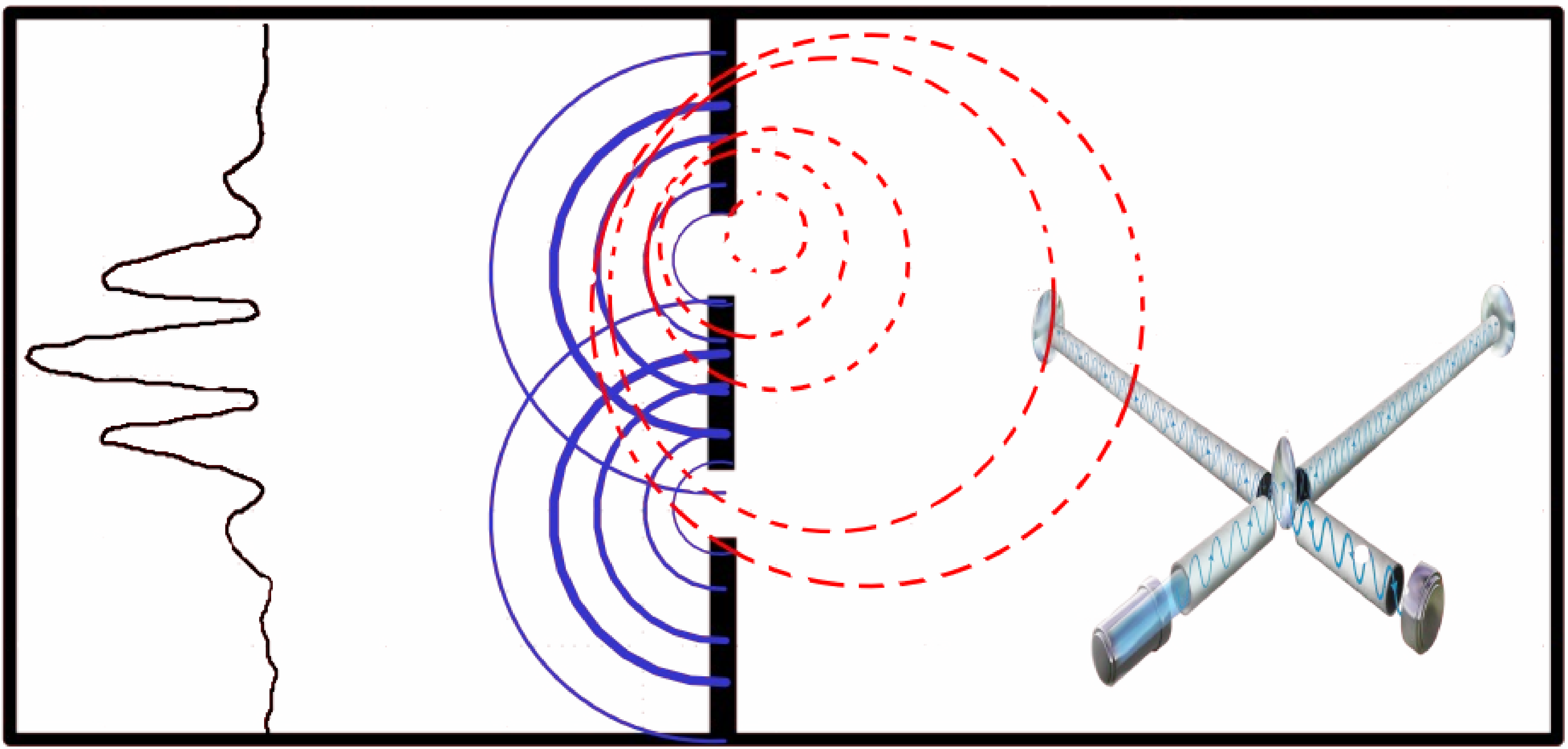
$\Big\rangle$

$$\sigma_c = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$$

$$\sigma_p = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$$

Feynman, Chapel Hill Conference (1957)
Eppley and Hannah (1977)
Marletto and Vedral (2017)

Can we?



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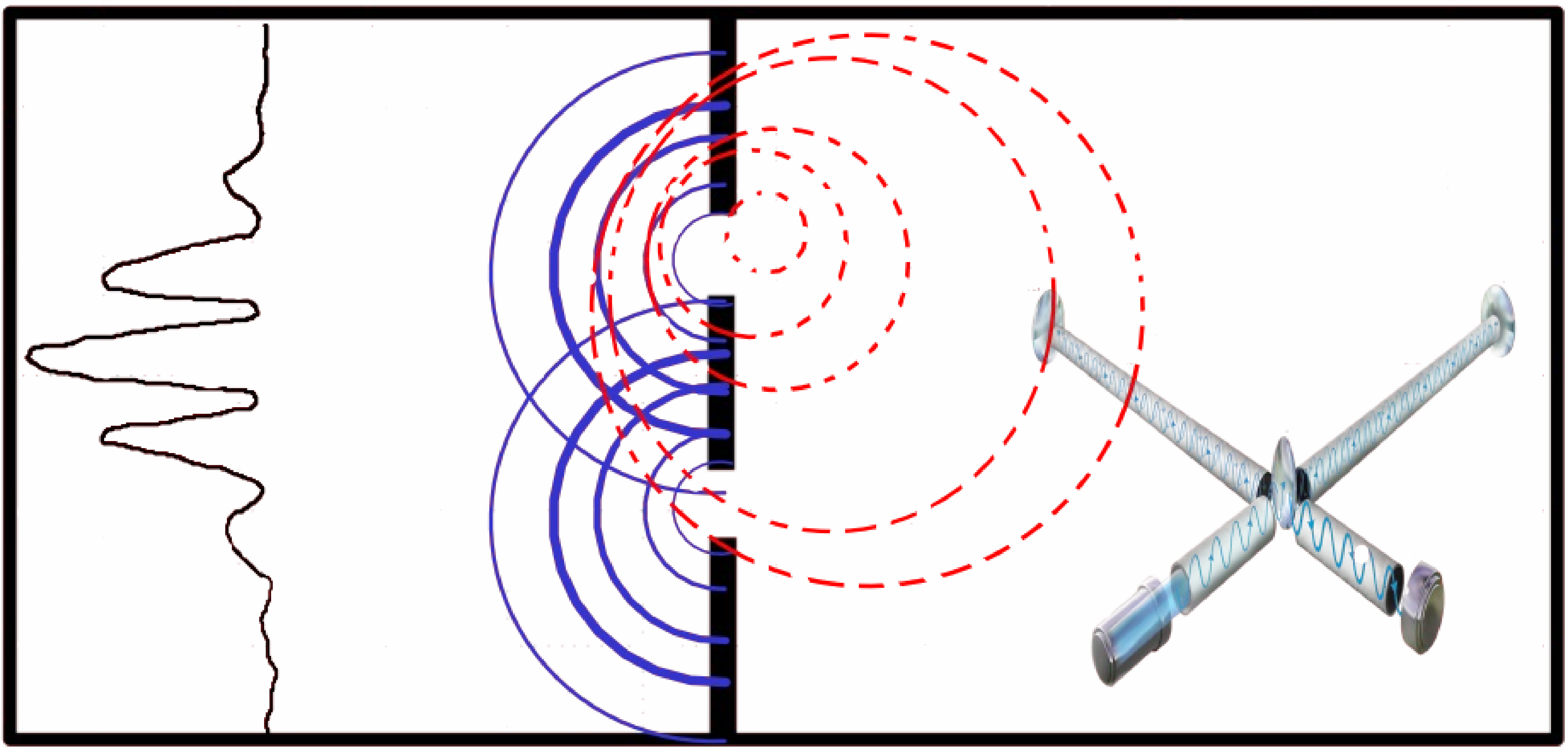

$$\frac{1}{\sqrt{2}}\left|E_L\right\rangle\left|\text{L}\right\rangle + \frac{1}{\sqrt{2}}\left|E_R\right\rangle\left|\text{R}\right\rangle$$

Can we?

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

$$\alpha = \langle E_L|E_R\rangle \qquad \sigma_p = \begin{pmatrix} \frac{1}{2} & \alpha^* \\ \alpha & \frac{1}{2} \end{pmatrix}$$

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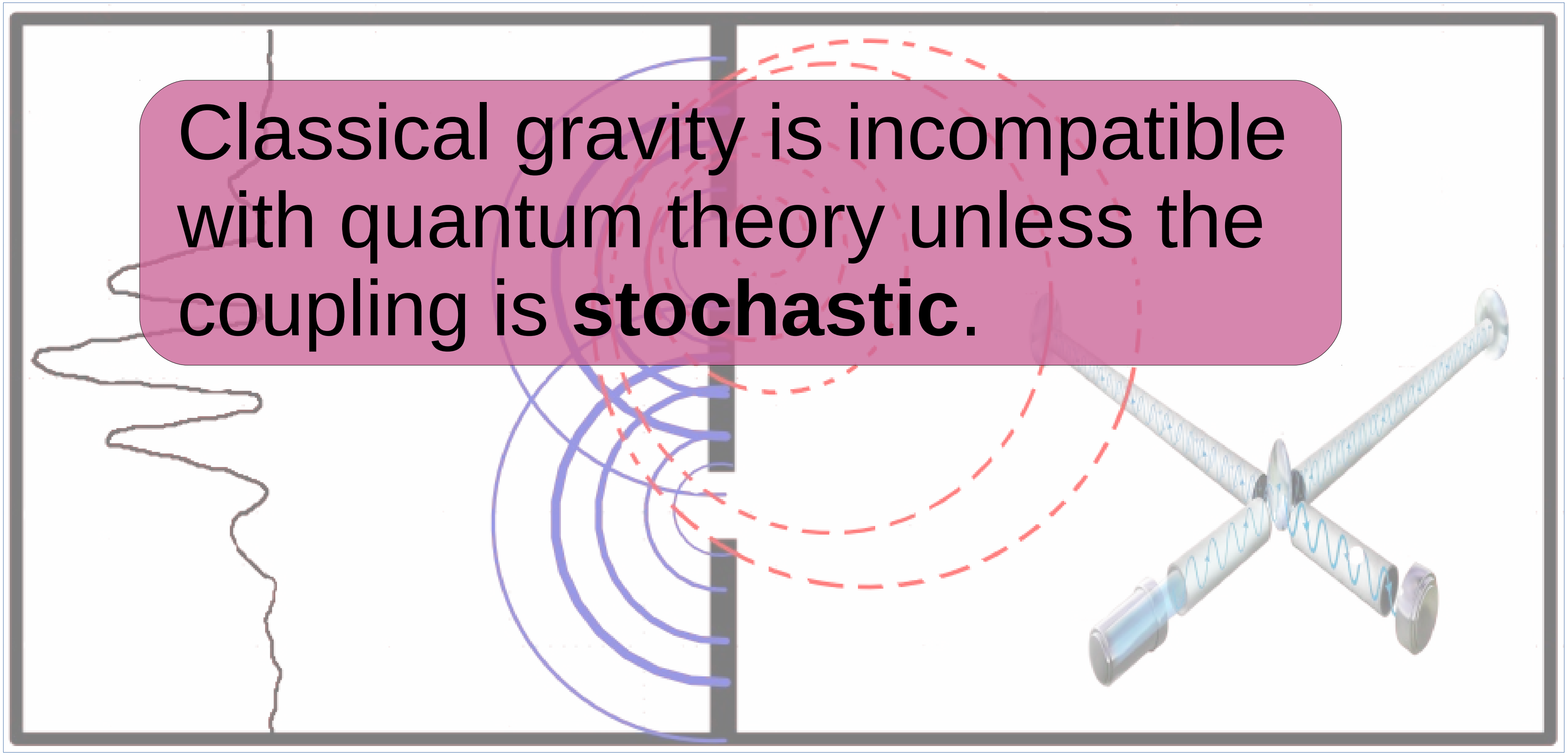
Can we?



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Can we?

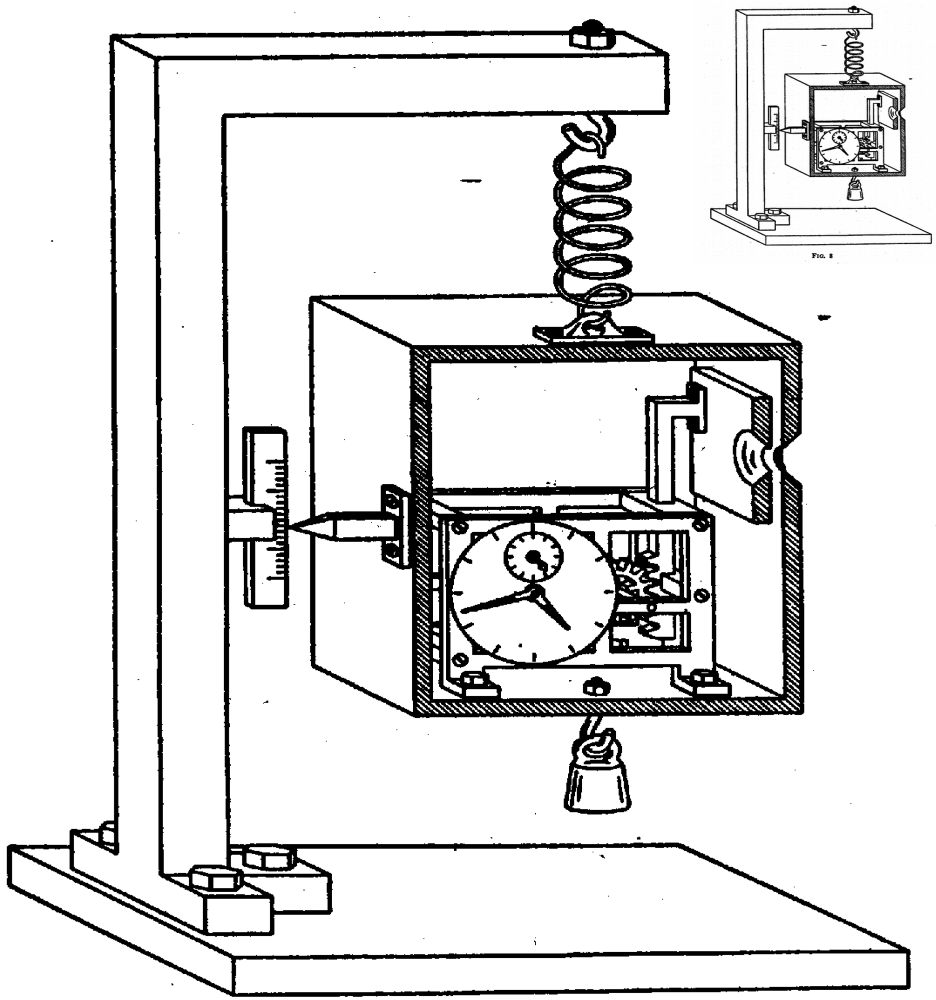
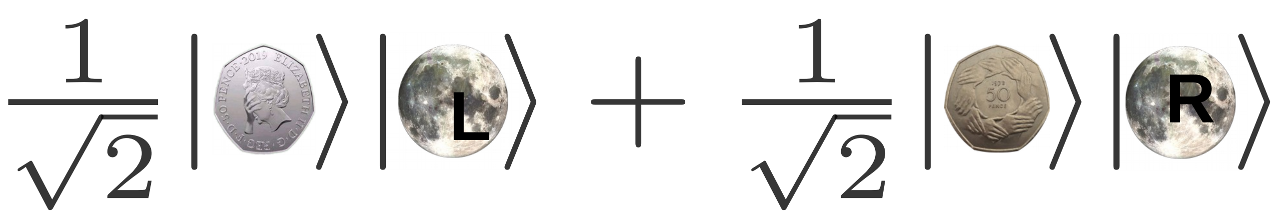


FIG. 8

Semi-classical gravity?

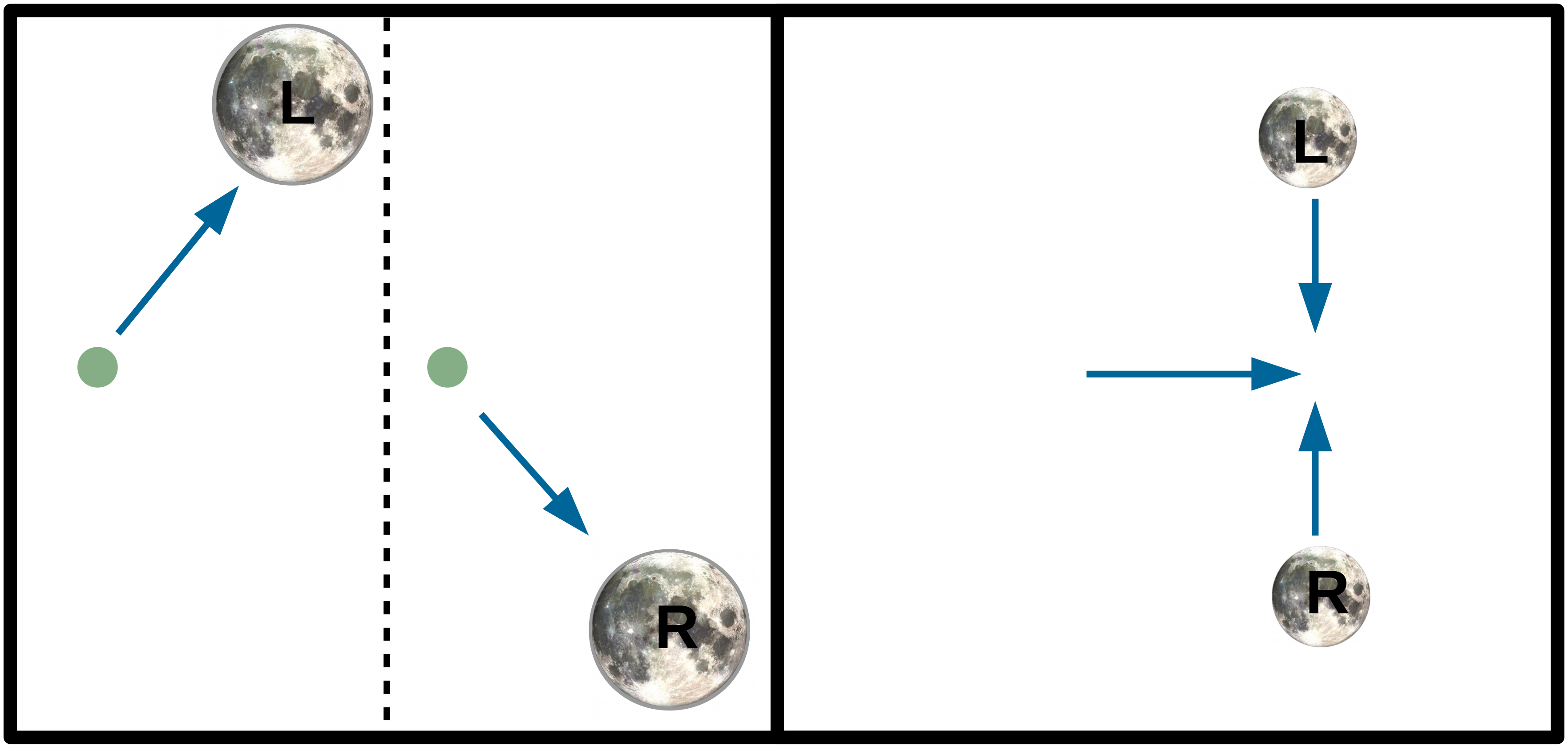
$$G_{\mu\nu} = \frac{8\pi G}{c^4}\langle \mathbf{T}_{\mu\nu} \rangle$$

$$\langle \mathbf{T}_{\mu\nu} \rangle$$



Semi-classical gravity?

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

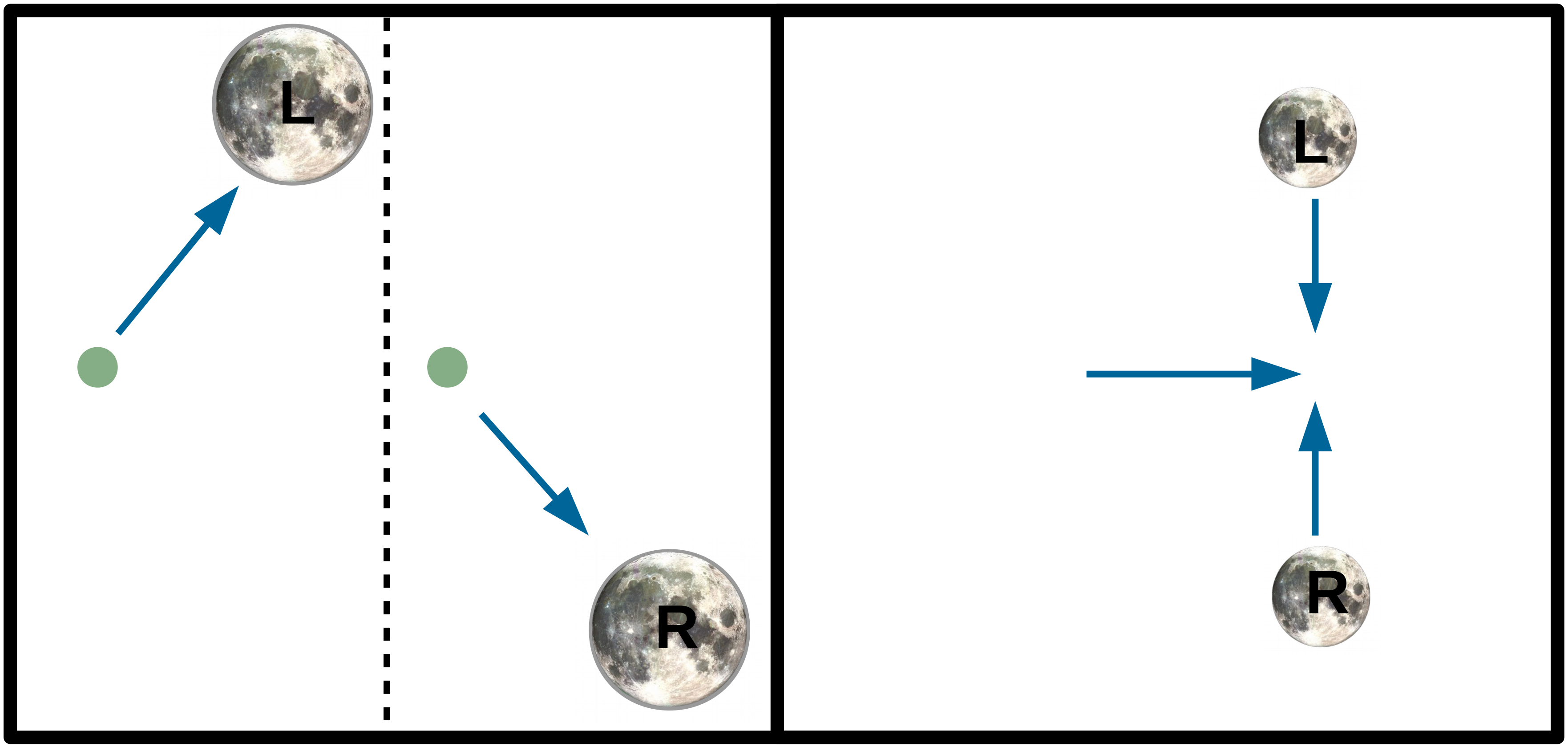


This or that

Not this!

Semi-classical gravity?

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



This or that

Not this!

Outline

- Can we couple quantum and classical systems?
- What is the general form of this dynamics?
- Application to General Relativity/QFT ▽

What kind of dynamics is allowed?

σ Quantum states are represented by a density matrix (positive, trace one) in a Hilbert space

$\rho(q,p)$ Classical states are a probability density (positive, integrate to one) over phase space

$\varrho(q,p)$ Hybrid state-space consists of a Hilbert space at each point in phase space. Hybrid states are positive, $\int dqdp\,tr\,\varrho(q,p) = 1$

What kind of dynamics is allowed?

$\varrho(q,p)$ Hybrid state-space consists of a Hilbert space at each point in phase space. Hybrid states are positive, $\int dqdp\, tr\, \varrho(q,p) = 1$

e.g. quantum qubit

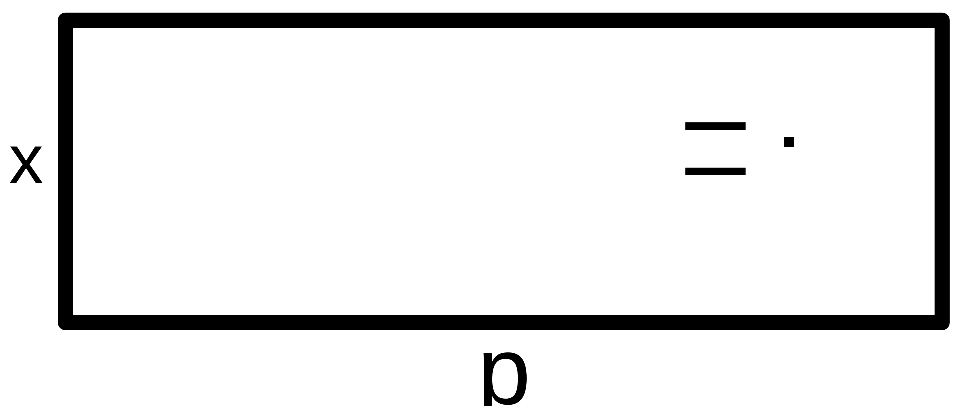
$$\sigma = \begin{pmatrix} p_0 & \alpha \\ \alpha^* & p_1 \end{pmatrix}$$

What kind of dynamics is allowed?

$\varrho(q,p)$ Hybrid state-space consists of a Hilbert space at each point in phase space. Hybrid states are positive, $\int dqdp\, tr\, \varrho(q,p) = 1$

e.g. hybrid qubit which has a classical x,p

$$\varrho(x,p) = \begin{pmatrix} p_0(x,p) & \alpha(x,p) \\ \alpha^*(x,p) & p_1(x,p) \end{pmatrix}$$



What kind of dynamics is allowed?

It must be linear in ρ, σ or $\varrho(q,p)$

$|$$\rangle\langle$$| \otimes \mathcal{L}(\rho_L)$

$|$$\rangle\langle$$| \otimes \mathcal{L}(\rho_R)$

$$\tfrac{1}{2}\mathcal{L}(\rho_L) + \tfrac{1}{2}\mathcal{L}(\rho_R)$$

$$=$$

$\frac{1}{\sqrt{2}}|$$\rangle|$

$\rangle + \frac{1}{\sqrt{2}}|$$\rangle|$

$\rangle$

$$\mathcal{L}(\tfrac{1}{2}\rho_L + \tfrac{1}{2}\rho_R)$$

What kind of dynamics is allowed?

It must preserve the state space

$$p(z),\ \ p(z) \geq 0,\ \ \sum_z p(z) = 1$$

$$p(z;t) = \sum_{z'} P(z|z')p(z';0)$$

$$P(z|z') \geq 0,\ \ \sum_z P(z|z') = 1$$

Classical Probability theory

What kind of dynamics is allowed?

It must preserve the state space

$$\sigma, \quad \sigma \geq 0, \quad tr\sigma = 1$$

$$\sigma(t) = \sum_{\mu} K_{\mu} \sigma(0) K_{\mu}^{\dagger}$$

$$K_{\mu}^{\dagger} K_{\mu} = \mathbb{1}$$

Kraus (87)

Quantum theory

What kind of dynamics is allowed?

It must preserve the state space

$$\varrho(z) \geq 0, \quad \sum_z tr\,\varrho(z) = 1$$

$$\varrho(z;t) = \sum_{z',\mu} K_\mu(z|z')\varrho(z',0)K_\mu(z|z')^\dagger$$

$$\sum_{z',\mu} K_\mu(z|z')^\dagger K_\mu(z|z') = \mathbb{1}$$

Classical-quantum theory

What kind of dynamics is allowed?

Q

$$\sigma(t) = \sum_\mu K_\mu \sigma(0) K_\mu^\dagger \qquad K_\mu^\dagger K_\mu = \mathbb{1}$$

C

$$p(z;t) = \sum_{z'} P(z|z') p(z';0) \qquad P(z|z') \geq 0, \ \sum_z P(z|z') = 1$$

CQ

$$\varrho(z;t) = \sum_{z',\mu} K_\mu(z|z') \varrho(z',0) K_\mu(z|z')^\dagger \qquad \sum_{z',\mu} K_\mu(z|z')^\dagger K_\mu(z|z') = \mathbb{1}$$

What kind of dynamics is allowed?

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

GKLS (76)

$$\frac{p(z)}{\partial t} = \{H(z), p(z)\} + \sum_{z'} \Big(W(z|z') p(z') - W(z) p(z) \Big)$$

$$\frac{\partial \varrho(z)}{\partial t} = -i[\mathbf{H}(z), \varrho] + \{H_c, \varrho\} + \sum_{z' \alpha} W^{\alpha}(z|z') \mathbf{L}_{\alpha} \varrho(z) \mathbf{L}_{\alpha}^{\dagger} - \frac{1}{2} W^{\alpha}(z) \{\mathbf{L}_{\alpha}^{\dagger} \mathbf{L}_{\alpha}, \varrho(z)\}$$

Blanchard, Jadczykczyk (93)

Assumption: memoryless (Markovian)

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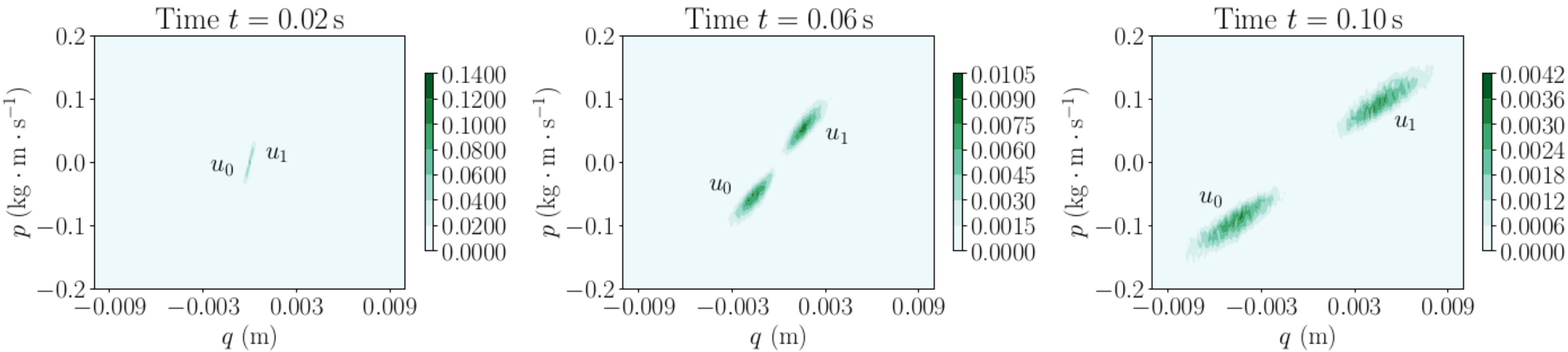
A qubit with classical q,p

$$\frac{\partial \varrho(q,p)}{\partial t} = \ldots + \frac{\omega}{\tau}|1\rangle\langle 1|\varrho(p+\tau B)|1\rangle\langle 1| + \frac{\omega}{\tau}|0\rangle\langle 0|\varrho(p-\tau B)|0\rangle\langle 0| - \frac{\omega\varrho}{\tau}$$



$$\varrho(0) = \delta(x)\delta(p)|+\rangle\langle +|$$

- Quantum state collapses to 0,1
- Discreet jump in momentum
- Trade-off: coherence rate vs dispersion

Quantum field theory in a classical space-time

1) Non-commuting Hamiltonian dynamics ∇

2) $\phi(x), \pi_\phi(x) \quad g_{ab}, \pi^{ab}, N(x), N^a$

3) Dynamical ADM master equation

4) "Gauge invariance" imposes constraints $C^\mu(\varrho(g,\pi)) \approx 0,$

5) BPS $\longrightarrow$ constraint conservation

Summary

Assume space-time is classical:

- This necessarily causes collapse of the wavefunction.
- Necessarily have stochastic and discreet classical jumps. Black holes destroy information.
- Experimentally testable
- Either fundamental, or classical limit of quantum gravity