Toward Testing Quantum Mechanics and Gravity in the Lab

Quantum Information: *Quo Vadis?*

Vancouver, Nov 2019

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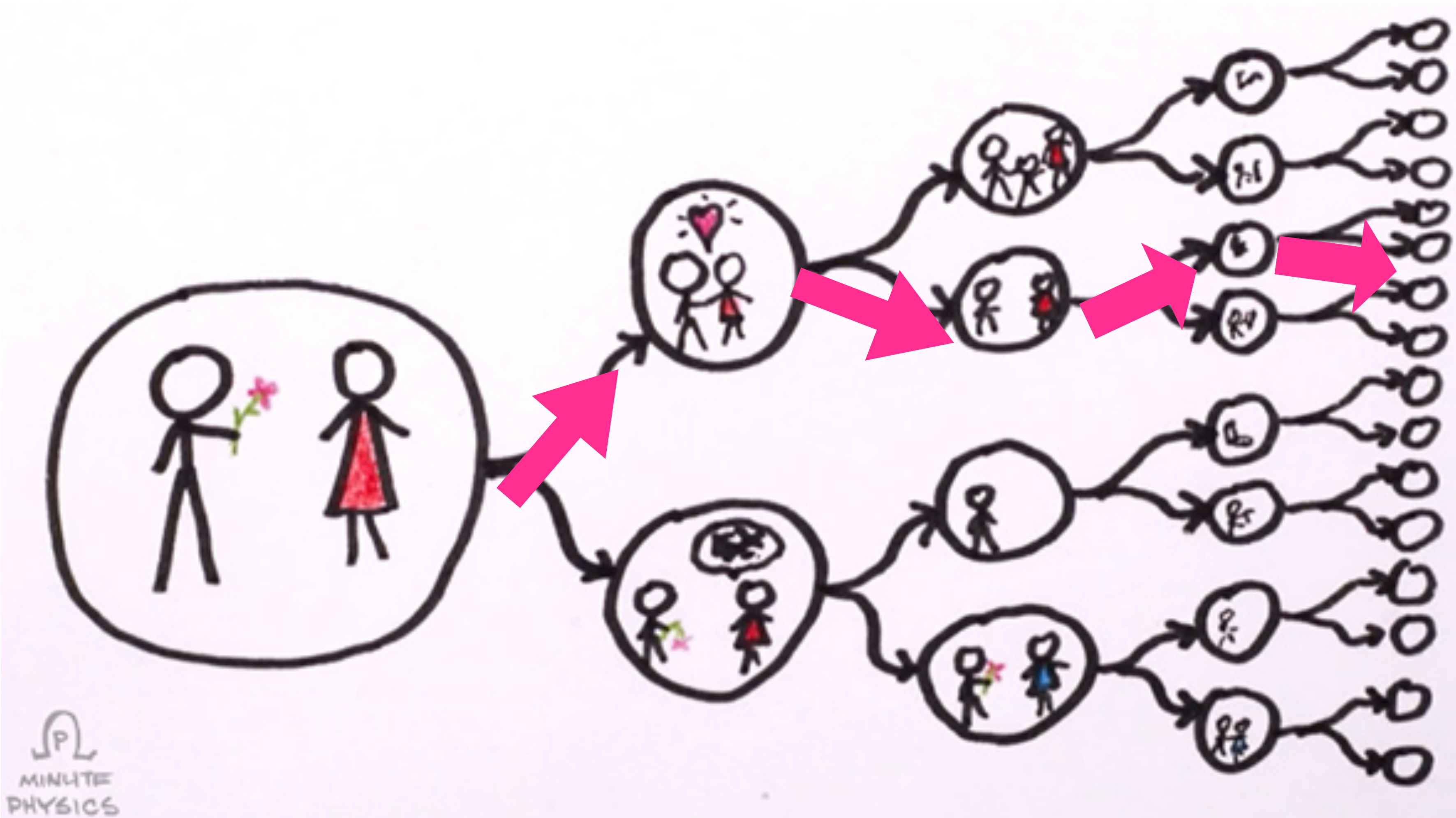
Motivations

- Quantum Mechanics provides consistent predictions on the **probability distribution** of measurement results … but not any particular path of outcomes.



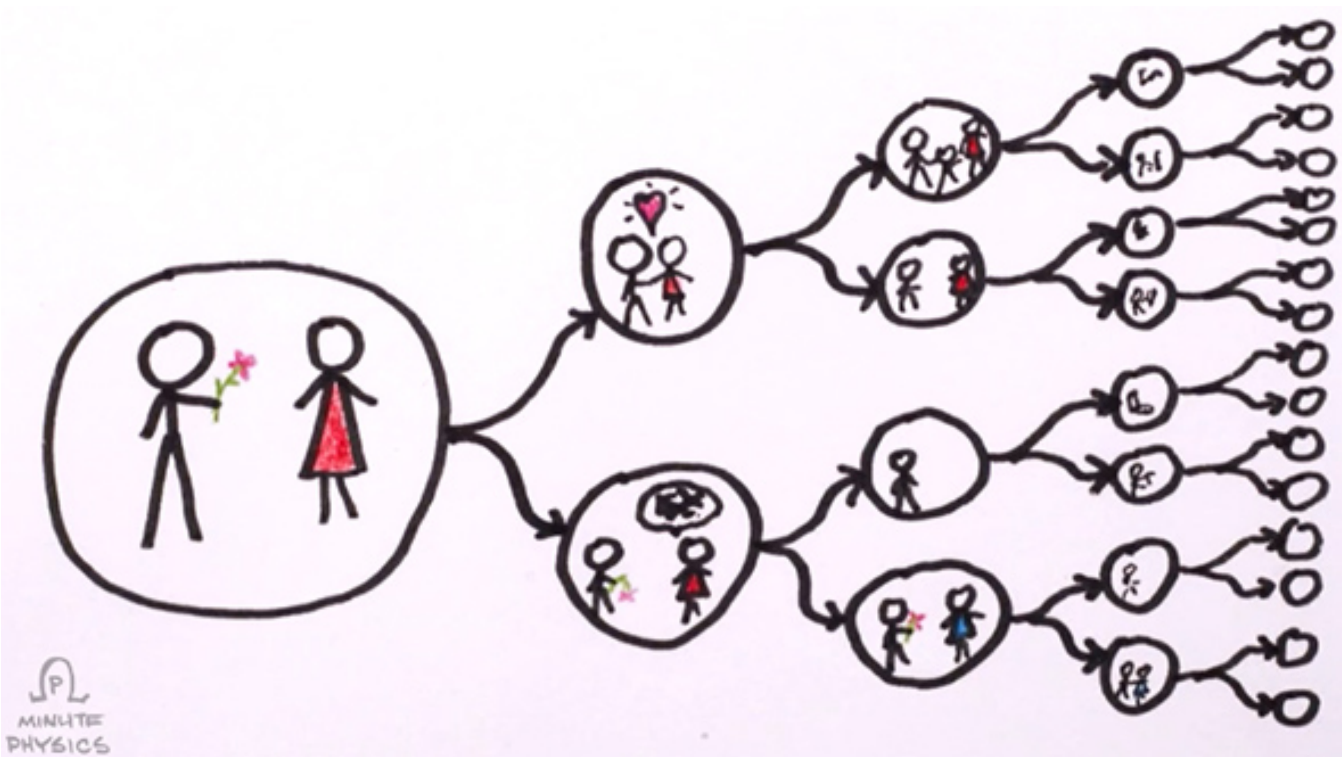
- Classical General Relativity generically leads to singularities inside black holes and at the beginning of the universe: Penrose-Hawking Singularity Theorems.

Testing QM and Gravity in the Lab …

- Collapse Models, which "objectively" collapse the quantum state of the universe, including "Gravity Decoherence".
- Testing quantum nature of gravity. Can we formulate gravitational interaction classically?
- Alternative formulations of quantum gravity, e.g., the Correlated World Line (CWL) theory. [Partly motivated by gravity decoherence]

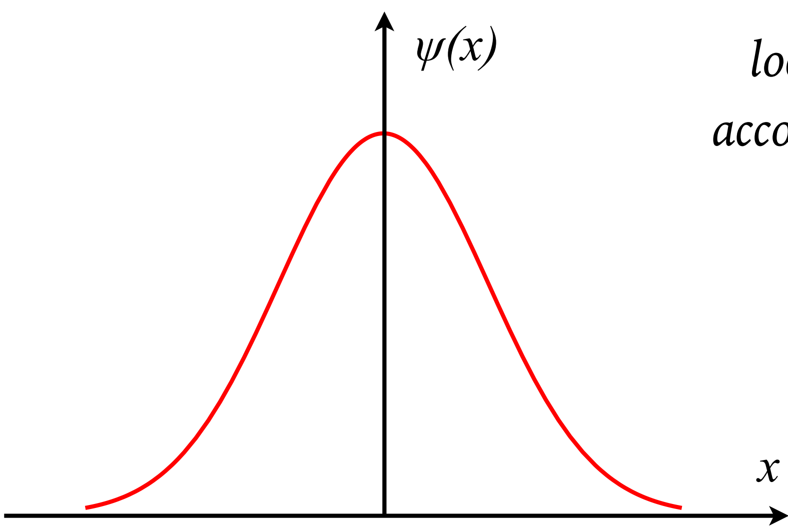
- Collaborators
  - Bassam Helou (Caltech)
  - Sabina Scully, Bram Slagmolen and David McClelland (ANU)
  - Philip Stamp and Jordan Wilson-Gerow (UBC)

Collapse Models

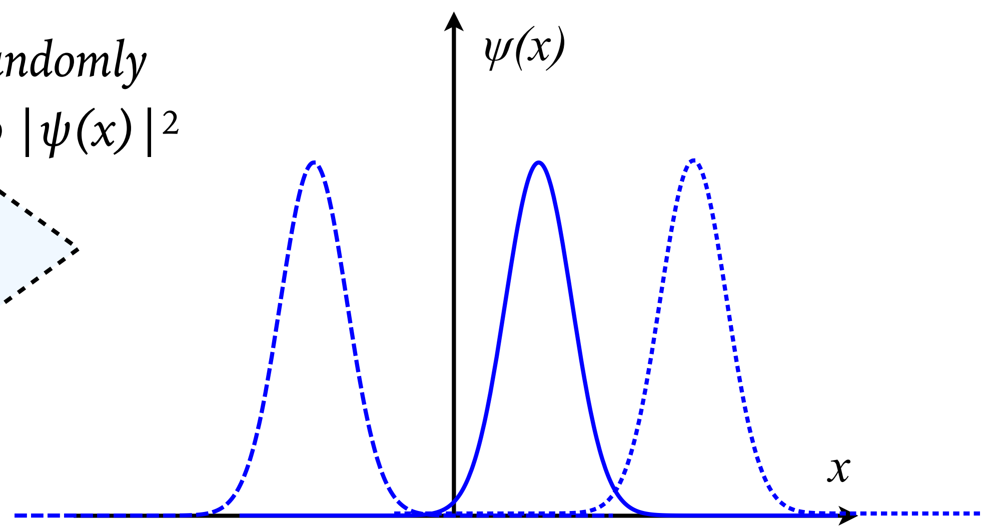


One particular path is *somehow* chosen; wave function of the universe collapsed by an *external agent*

Proposed by Ghirardi, Rimini and Weber, studied extensively by Adler, Bassi, Diosi, et al.



localize randomly according to $|\psi(x)|^2$



Mathematical Description

- Lindblad Master Equation: modeling the collapse process.

$$\dot{\rho} = \frac{i}{\hbar}[H, \rho] - \sum_{j,k} \frac{\lambda_{jk}}{2} \left[L_j, [L_k, \rho]\right]$$

- Can be understood in two steps

$$H_{\text{tot}} = H - \sum_j f_j(t) L_j$$

$$\langle f_j(t) f_k(t') \rangle = \lambda_{jk} \delta(t - t')$$

a set of random white forces acting on a set of variables

will cause diffusion in linear systems

- Can be constrained in weak force measurement experiments
  - micro-cantilevers, gravitational-wave detectors, torsional pendulum experiments.

Continuous Stochastic Localization

$$\mathcal{L}\hat{\rho} = -\frac{C^{AB}}{2\hbar^2}\int d^3\mathbf{s}\left[\hat{\Phi}_A(\mathbf{s}),\left[\hat{\Phi}_B(\mathbf{s}),\hat{\rho}\right]\right]$$

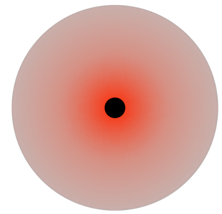
values of a field continuously monitored

$$\hat{\Phi}(\mathbf{s}) = \int \hat{\mu}(\mathbf{z})e^{-(\mathbf{s}-\mathbf{z})^2/(2r_{\mathrm{CSL}}^2)}d^3\mathbf{z}$$

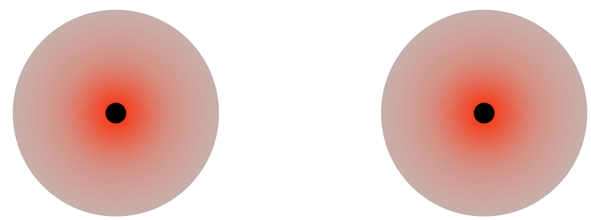
field generated by matter distribution

$$C_{\mathrm{CSL}} = \frac{\lambda_{\mathrm{CSL}}}{\pi^{3/2}r_{\mathrm{CSL}}^3\,\mathrm{amu}^2}$$

matter distribution in our space-time being measured by external observers that enter via an extra dimension



Each particle sources Gaussian packet (scale r_{CSL}) the **total field** $\mathrm{m}(\mathbf{s})$ *gets measured independently at different locations, causing decoherence strength characterized by λ_{CSL}*



superpositions separated by less than r_{CSL} does **not** undergo decoherence
those separated by larger distance **will** undergo decoherence.

Continuous Stochastic Localization

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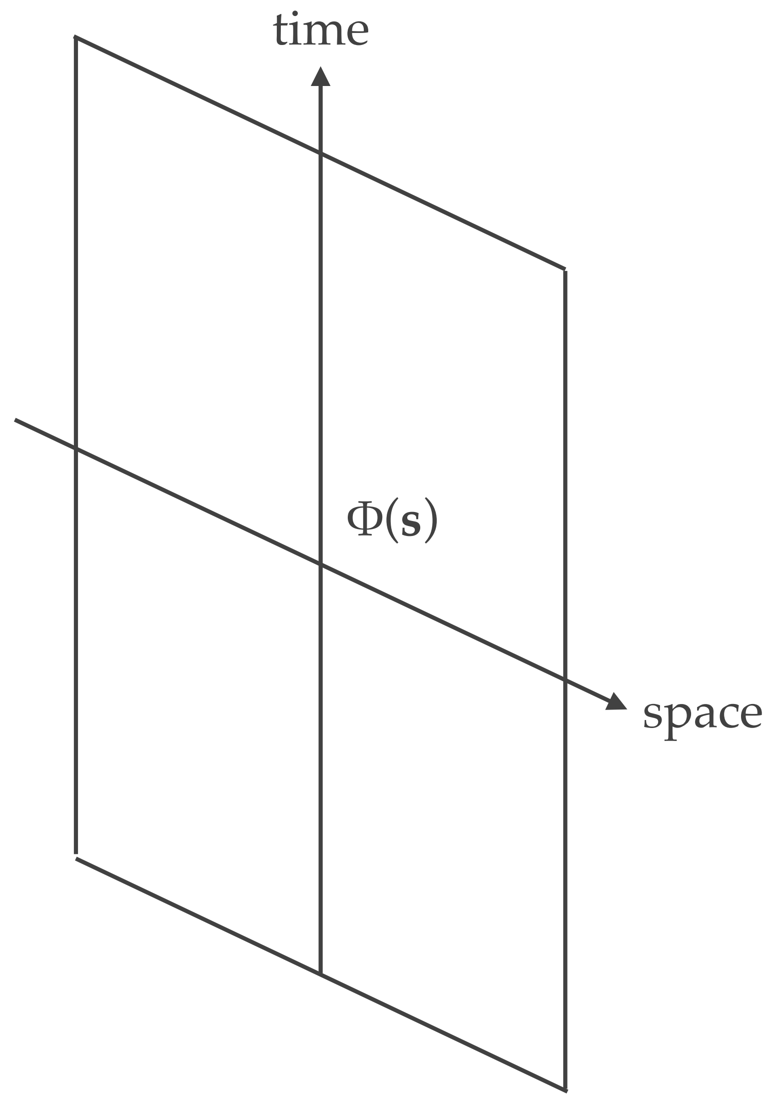


Diosi-Penrose

the DP Lindblad term measures **gravity acceleration**!

$$\mathcal{L}_{\mathrm{DP}}\rho = -\frac{1}{32\pi^2\hbar G}\sum_{jk}\delta_{jk}\int d^3\mathbf{s}\,[g_j(\mathbf{s}),[g_k(\mathbf{s}),\rho]]$$

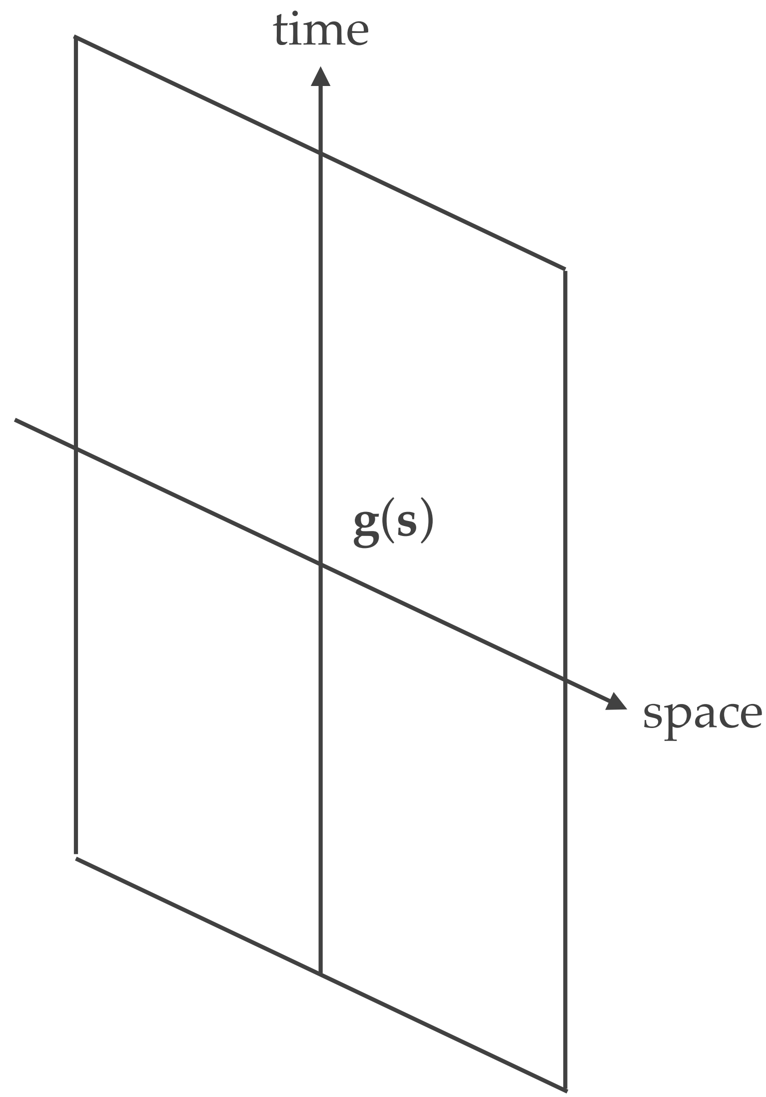
g_j diverges near a point particle!

regularize?

$$\phi(\mathbf{s}) \to -\frac{GM}{|\mathbf{s}-\mathbf{r}|+\sigma_{\mathrm{DP}}}$$

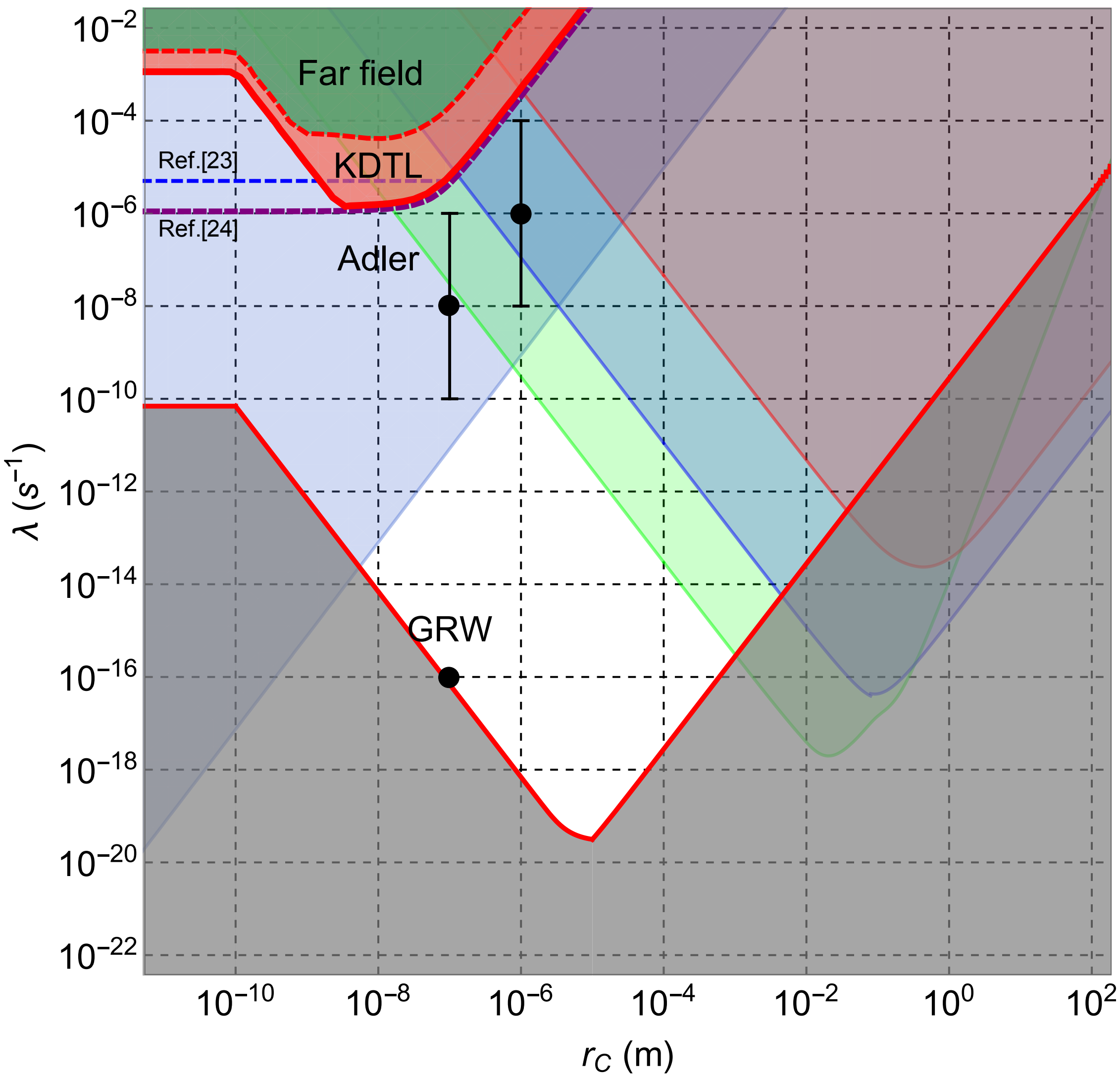
L. Diosi proposed that

$$\sigma_{\mathrm{DP}} = 10^{-14}\,\mathrm{m}$$



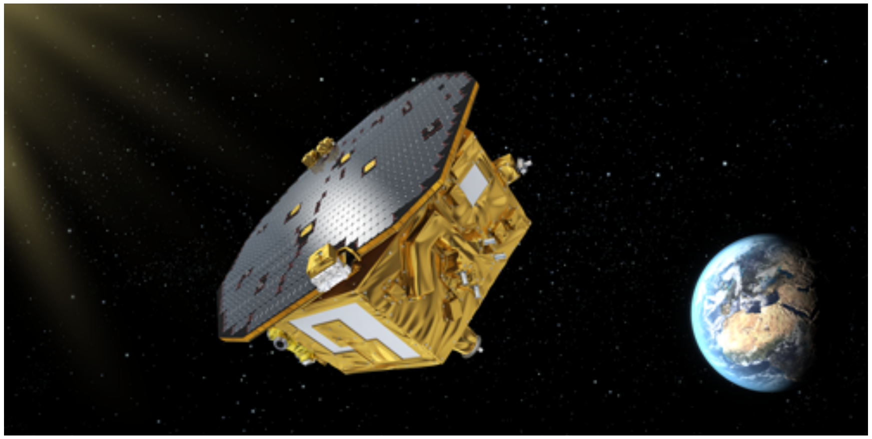
the larger the σ, the weaker the effect

Bounds on CSL and DP



[Bassi et al., 2016]

[Helou, Slagmolen, McClelland and YC, 2016]

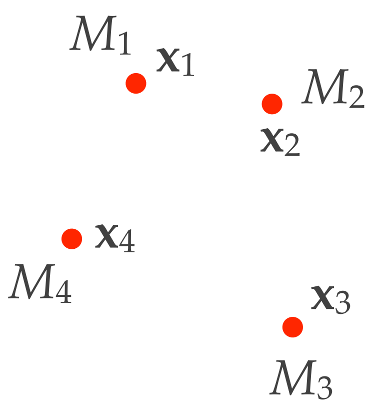


$\sigma_{DP} < 4 \times 10^{-14}$m

similar bounds from *LISA pathfinder* and *Advanced LIGO*

Collapse models can be further bounded, but we still need the microphysics underlying these collapses.

Is Gravity Quantum?



$$\hat{\phi}(\mathbf{x}) = -\sum G \frac{M_j}{|\mathbf{x} - \hat{\mathbf{x}}_j|}$$

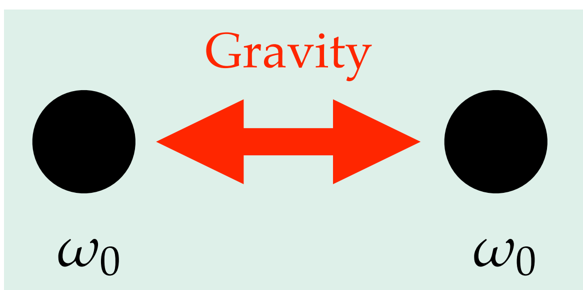
$$\hat{V} = \sum_i -\frac{1}{2} M_j \hat{\phi}(\hat{\mathbf{x}}_j) = -\sum_{i<k} \frac{G M_j M_k}{|\hat{\mathbf{x}}_j - \hat{\mathbf{x}}_k|} + (\text{Self Energy})$$

This potential term appears in the Schrödinger Equation

If quantum information can pass from A to B through $\hat{\phi}$, then gravity must be quantum.

However, directly confirming quantum information transfer via gravity is very hard.

[Kafri & Taylor, 2014]



$$\Delta \approx \frac{\omega_g^2}{2\omega_0} \qquad \omega_g^{\text{Si}} \lesssim \sqrt{G\rho} \sim 4 \times 10^{-4}\,\text{s}^{-1}$$

Alternative point of view:

If Gravity is classical, self-gravitating objects will not be completely quantum.

[e.g., Feynman, Lectures on Gravitation, 1957]

Demonstrating Quantum Nature of Gravity

PRL **119,** 240402 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

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

C. Marletto[1] and V. Vedral[1,2]

PRL **119,** 240401 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

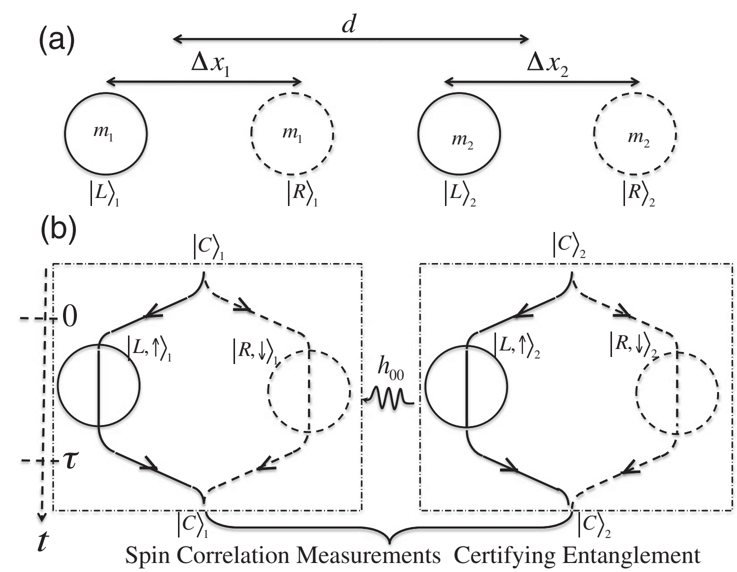
Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew A. Geraci,[6] Peter F. Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]

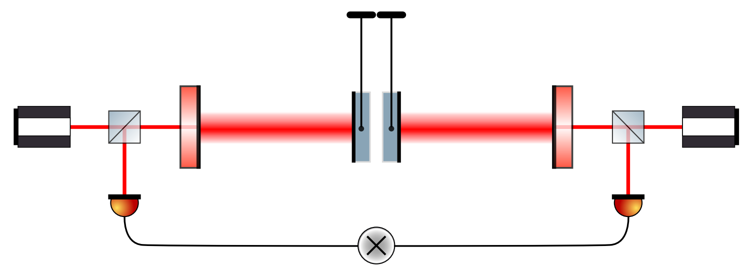
Quantum correlation of light mediated by gravity

Haixing Miao,[1,*] Denis Martynov,[1,†] and Huan Yang[2,3,‡]

[1]*School of Physics and Astronomy, and Institute for Gravitational Wave Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2L2Y5, Canada*
[3]*University of Guelph, Guelph, ON N2L3G1, Canada*

https://arxiv.org/pdf/1901.05827.pdf





Information Content of the Gravitational Field of a Quantum Superposition

Alessio Belenchia,[1,*] Robert M. Wald,[2,†] Flaminia Giacomini,[3,‡] Esteban Castro-Ruiz,[3,§] Časlav Brukner,[3,¶] and Markus Aspelmeyer[3,**]

https://arxiv.org/pdf/1905.04496.pdf

Using Newtonian Gravity Field to Transfer Quantum Information

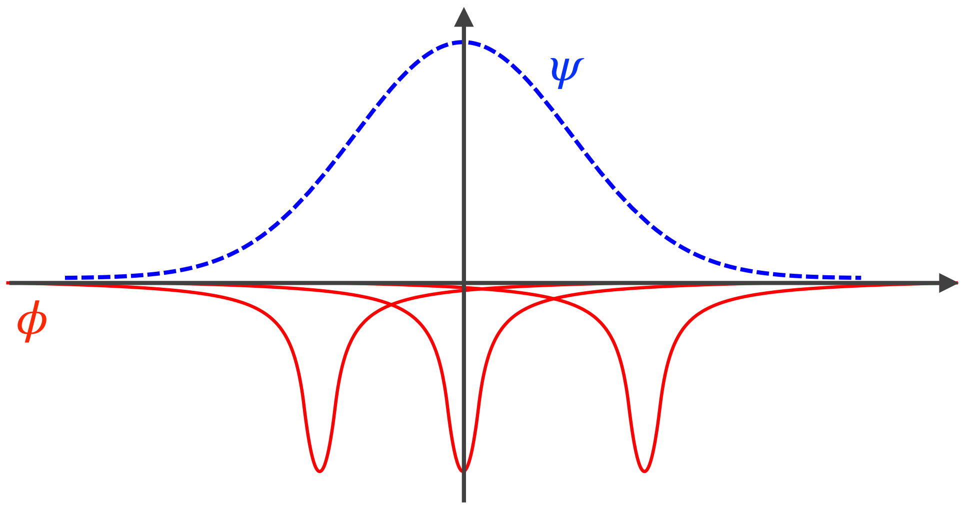
Can gravity be "classical"?

$$\nabla^2 \phi = 4\pi G \langle \hat{\rho} \rangle \Rightarrow \phi(\mathbf{x}) = -\int d^3\mathbf{y} \frac{G\langle \hat{\rho}(\mathbf{y}) \rangle}{|\mathbf{x}-\mathbf{y}|}$$

$$i\hbar\partial_t \psi(\mathbf{x}_1,\ldots,\mathbf{x}_n) = \hat{H}_0 \psi(\mathbf{x}_1,\ldots,\mathbf{x}_n) - \frac{1}{2}\sum_j M_j \phi(\mathbf{x}_j)\psi(\mathbf{x}_1,\ldots,\mathbf{x}_n)$$

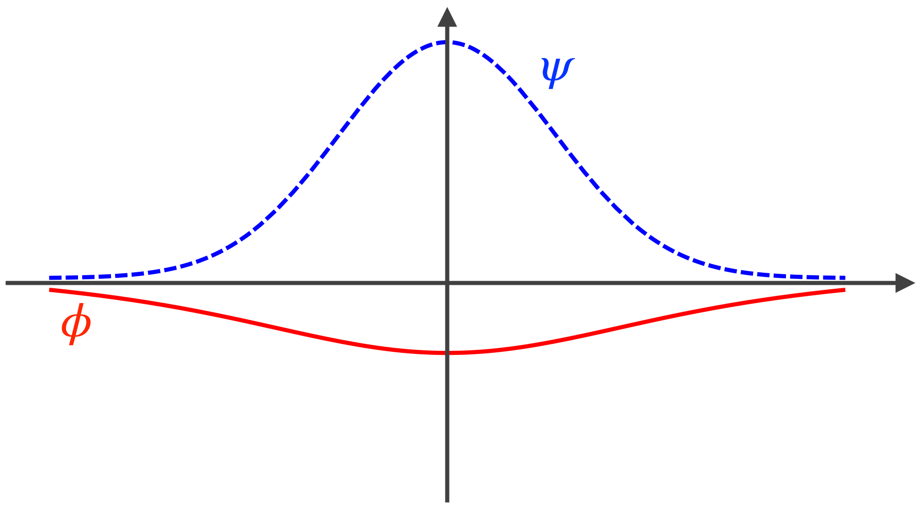
[Møller 1962, Rosenfeld 1963; Kibble 1976; … ; Guilini 2012; H. Yang et al., 2013]

Quantum "Self Gravity"



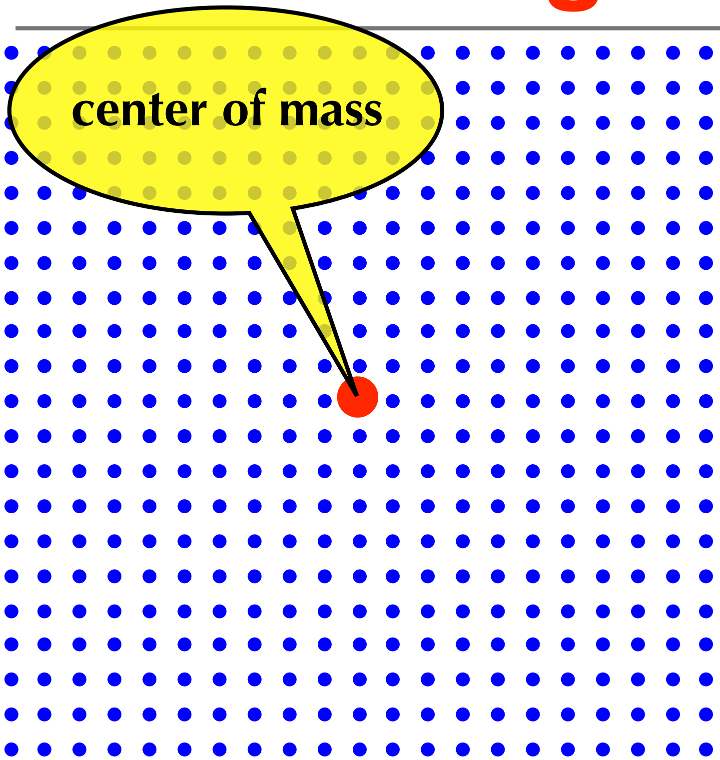
particle carries own gravity field
gravity field entangled with particle
back action negligible

Classical "Self Gravity"

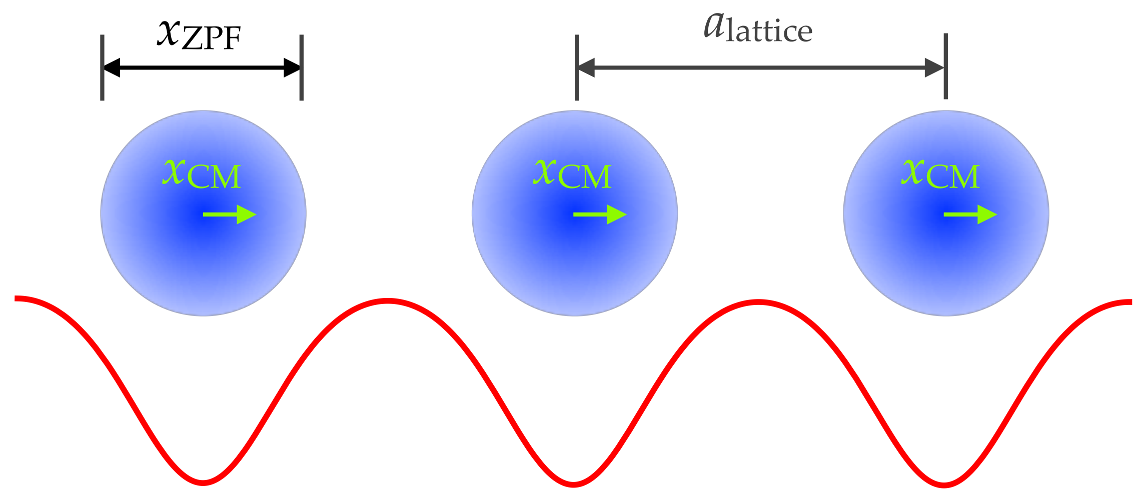


unique classical field
wave packet attracted by its own potential

Schroedinger Newton Phenomenology



a **macroscopic crystal** made up from atoms



$$x_{\rm ZPF} \sim \sqrt{\frac{\hbar}{m\omega_{\rm Debye}}} \sim 10^{-12}\,{\rm m} \ll a_{\rm lattice} \sim 10^{-10}\,{\rm m}$$

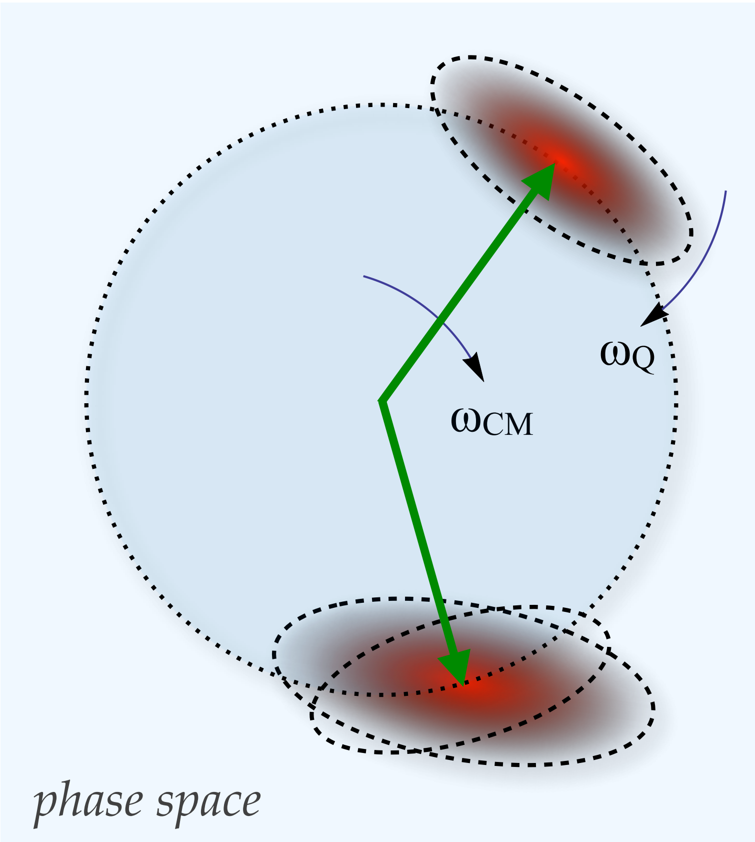
$$x_{\rm CM} \ll x_{\rm ZPF}$$

$$i\hbar\frac{\partial\Psi_{\rm CM}}{\partial t} = \left[-\frac{\hbar^2\nabla^2}{2M} + \frac{1}{2}M\omega_{\rm CM}^2 x^2 + \frac{1}{2}M\omega_{\rm SN}^2(x - \langle x\rangle)^2\right]\Psi_{\rm CM}$$

$$\omega_{\rm SN}^2 = \frac{Gm}{12\sqrt{\pi}x_{\rm ZPF}^3} \gg \omega_g^2 \qquad \omega_{\rm SN}^{\rm Si} = 4\times10^{-2}\,{\rm s}^{-1} \approx 100\,\omega_g^{\rm Si}$$

$$\omega_{\rm SN}^{\rm Os} = 0.4\,{\rm s}^{-1} \approx 2\pi\times 64\,{\rm mHz}$$

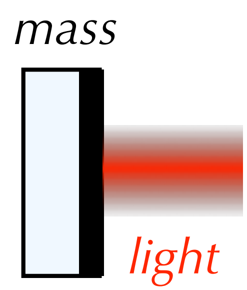
Schroedinger Newton Phenomenology

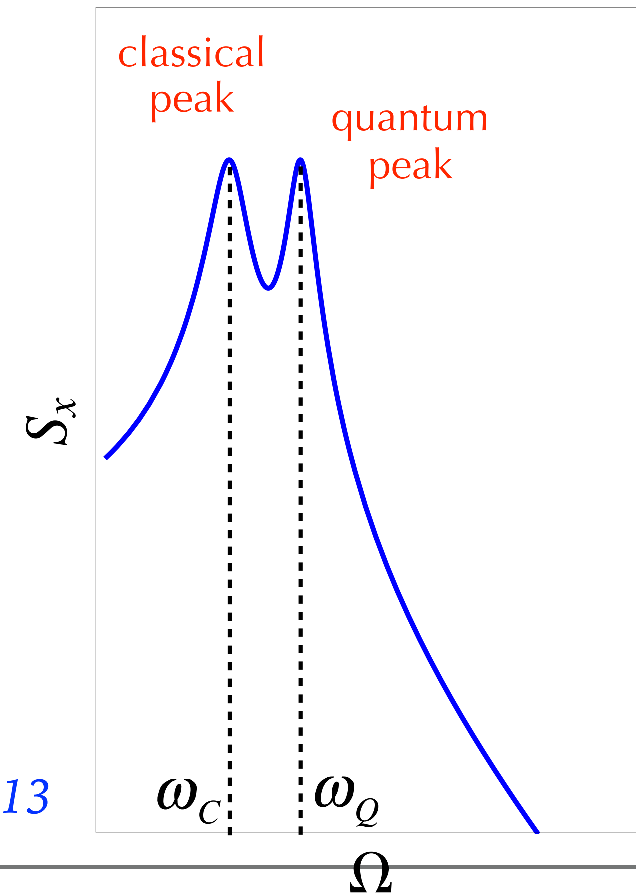


$$\dot{\hat{x}} = \hat{p}/M$$
$$\dot{\hat{p}} = -M\omega_{\rm CM}^2 \hat{x} - M\omega_{\rm SN}^2 (\hat{x} - \langle \hat{x} \rangle)$$

Quantum noise ellipse rotate at a different frequency:

$$\omega_Q^2 = \omega_{\rm CM}^2 + \omega_{\rm SN}^2$$





H. Yang et al., 2013

Nonlinear QM and Measurement

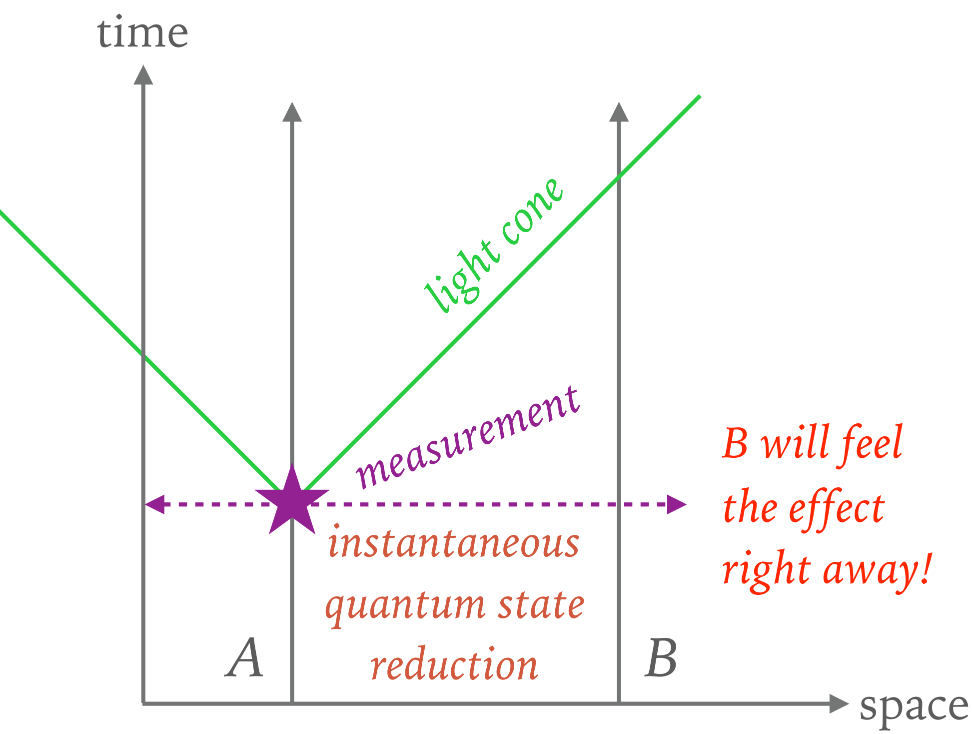
Nonlinear QM in two steps:

$$\hat{H}(t,\lambda), \quad \lambda = \lambda\big[\,|\psi\rangle\big]$$

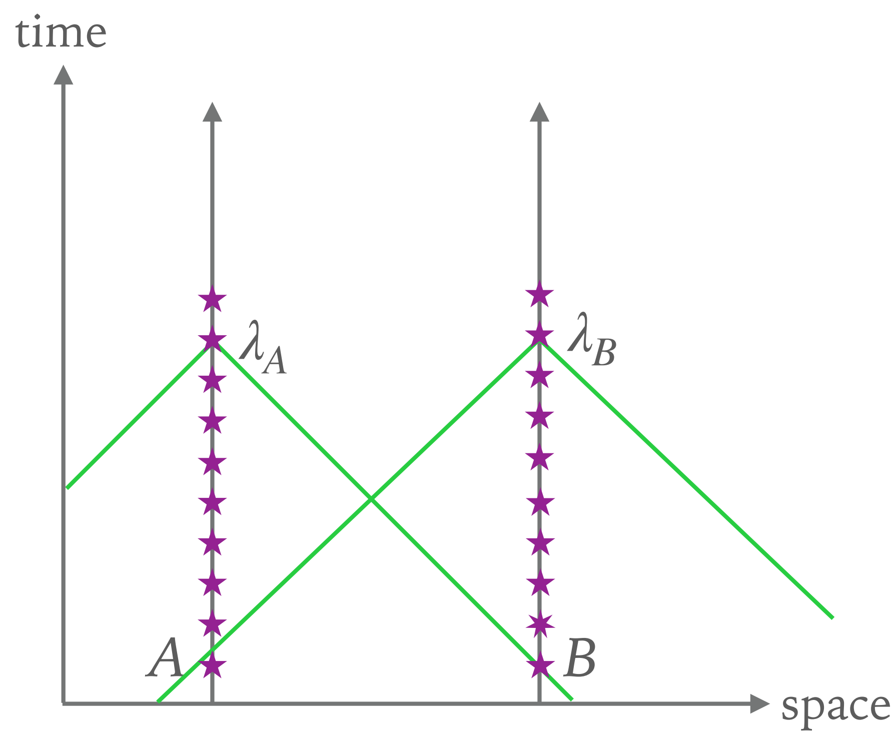
Hamiltonian depends on quantum state

$$\hat{H}(t,\lambda_A,\lambda_B)$$

$$\lambda_A = \lambda_A\big[\,|\psi_A\rangle_{\mathrm{cond}}\big],\ \lambda_B = \lambda_B\big[\,|\psi_B\rangle_{\mathrm{cond}}\big]$$



B will feel
the effect
right away!



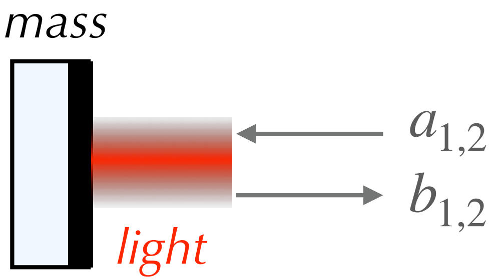
Polchinski 1991

Nonlinear QM + Instantaneous State Reduction
lead to superluminal communication

Force at each location only depends on results within past light cone [Helou, 2018; Scully, in prep]

Gravity as classical feedback!
(Kafri & Taylor)

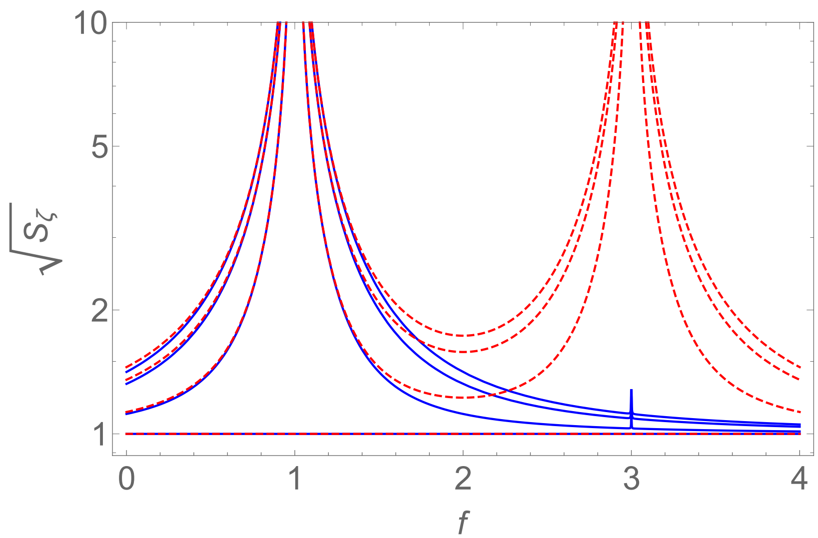
Experimental Signatures

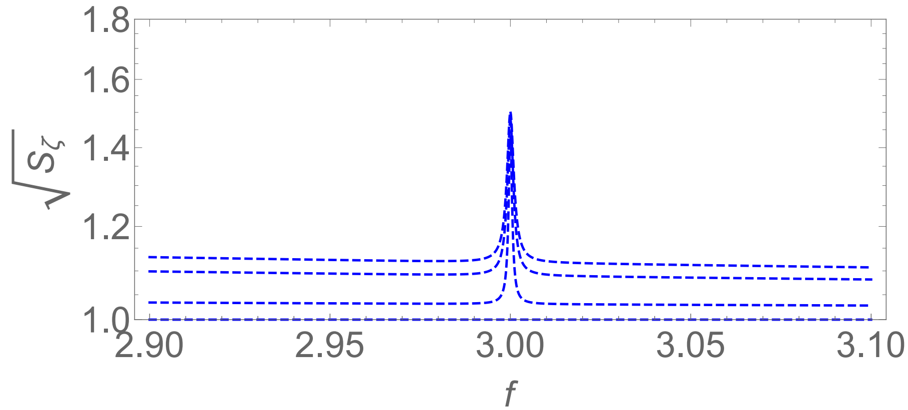


$$-M\Omega^2\hat{x} = -M\omega_c^2\hat{x} + iM\gamma_m\Omega\hat{x} - M\omega_{\rm SN}^2(\hat{x} - \langle x\rangle) + \alpha\hat{a}_1$$

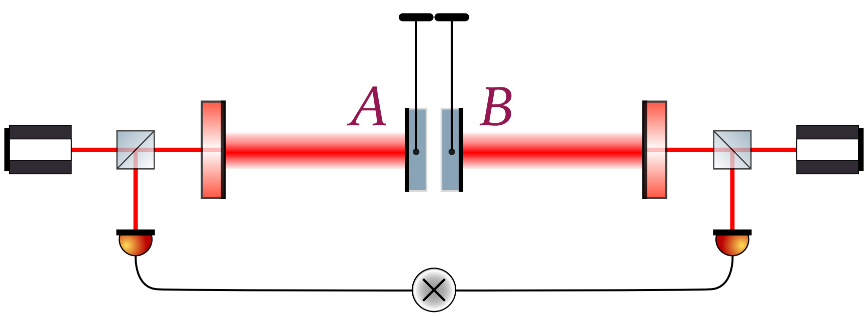
$$\hat{b}_\zeta = \hat{a}_\zeta + \frac{\alpha}{\hbar}\sin\zeta\hat{x}$$

self gravity *back action*





Out-going field spectrum has a peak near ω_Q *[S. Scully, in prep.]*



Quantum radiation-pressure-induced motion of *A* will **not** cause motion in *B* **via gravity** *[Miao, Martynov & Yang]*

Correlated World Line Theory

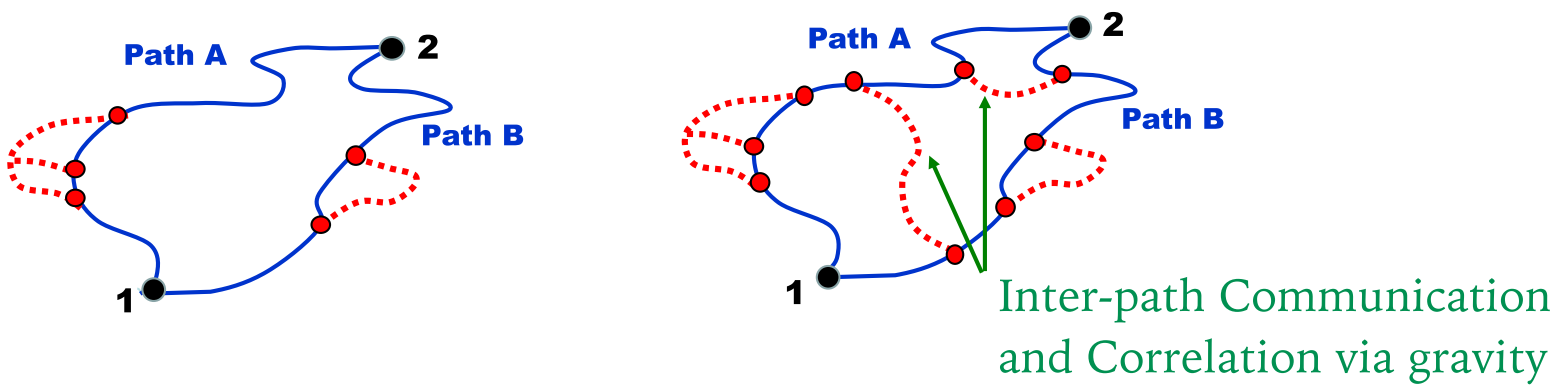
Incorporates key ideas from General Relativity and Quantum Mechanics

Equivalence Principle General Covariance	Indistinguishability

EXPECTATIONS/HOPES

(1) **Full non-linearity of General Relativity would make quantized theory non-linear → breakdown of superposition principle**

(2) *Anthropocentric nature* of Quantum Measurement be eliminated



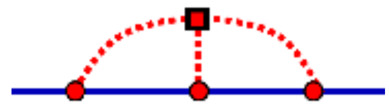
adapted from Philip Stamp's slides

CWL vs Conventional Quantum Gravity

Propagator in Conventional QG

$$K(2,1) = \mathcal{N}^{-1} \int \mathcal{D}g\, e^{iS_G[g]} \int_{\tilde{\phi}_1}^{\tilde{\phi}_2} \mathcal{D}\phi\, e^{iS_M[\phi, g]}$$

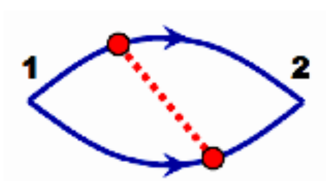
Diagrams

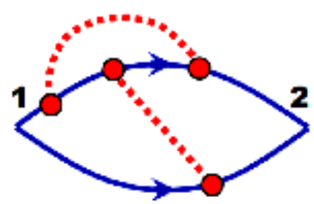


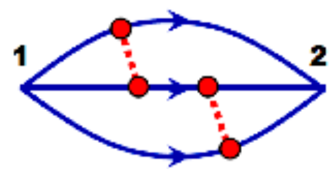
Propagator in CWL

$$\mathcal{K}(2,1) = \lim_{N\to\infty} \left[\prod_{n=1}^{N} \mathcal{N}_n^{-1} \int \mathcal{D}g_n\, e^{inS_G[g_n]} \prod_{i=1}^{n} \int_{\tilde{\phi}_1}^{\tilde{\phi}_2} \mathcal{D}\phi_i^{(n)}\, e^{iS[\phi_i^{(n)}, g_n]} \right]^{1/S_N}$$

Diagrams







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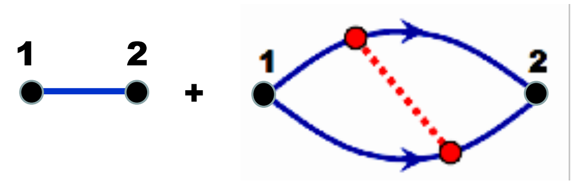
Low speed & Weak Gravity

Crude Approximation

$$\mathcal{K}(2,1) \; = $$ 

$$\mathcal{K}(2,1) \; = \; \frac{1}{K_0(2,1)} \int_1^2 \mathcal{D}X \int_1^2 \mathcal{D}X' \, e^{iS_{eff}[X,X']}$$

$$S_{eff}[X,X'] \; = \; S_0[X] + S_0[X'] + S_{CWL}[X,X']$$

$$S_{CWL}[X,X'] \; = \; -\frac{\ell_P^2}{2} \int d^4x \int d^4x' \; D^{\mu\nu\alpha\beta}(x,x') T_{\mu\nu}(x) T_{\alpha\beta}(x')$$

Can be viewed as propagator for two-particle Schroedinger Equation

$$\mathcal{H}^{(1)}_{CWL} \Psi(\mathbf{r},\mathbf{r}';t) \; = \; i\hbar\partial_t \Psi(\mathbf{r},\mathbf{r}';t)$$

$$\mathcal{H}^{(1)}_{CWL} \; = \; -\frac{\hbar^2}{2m}(\nabla^2_{\mathbf{r}} + \nabla^2_{\mathbf{r}'}) + V(\mathbf{r}) + V(\mathbf{r}') - \frac{Gm^2}{|\mathbf{r}-\mathbf{r}'|}$$

adapted from Philip Stamp's slides

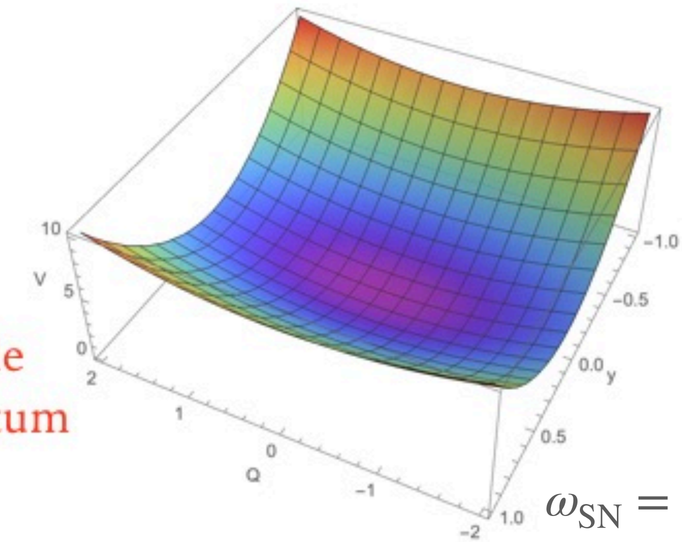
CWL Phenomenology, 1-Dimension

$$i\partial_t \Psi(Q,y,t) = \left[-\frac{\partial_Q^2}{2M} - \frac{\partial_y^2}{2\mu} + V(Q+y/2) + V(Q-y/2) + V_g(y) \right] \Psi(Q,y,t), \quad Q = \frac{q+q'}{2}, \; y = q - q'$$

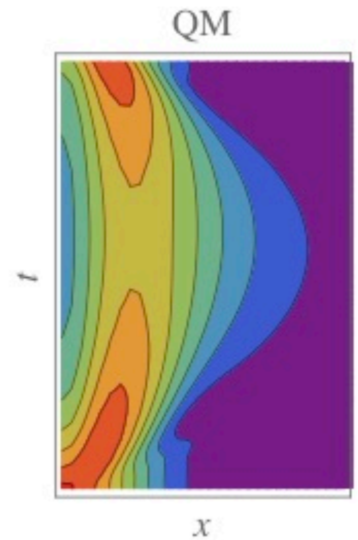
Linear Regime

$$H = -\frac{\partial_Q^2}{2M} + \frac{M\omega_c^2 Q^2}{2} - fQ$$
$$-\frac{\partial_y^2}{2\mu} + \frac{\mu\omega_c^2 y^2}{2} + V_g(y)$$

Q and y decoupled, outside world couples to Q; quantum state can be prepared



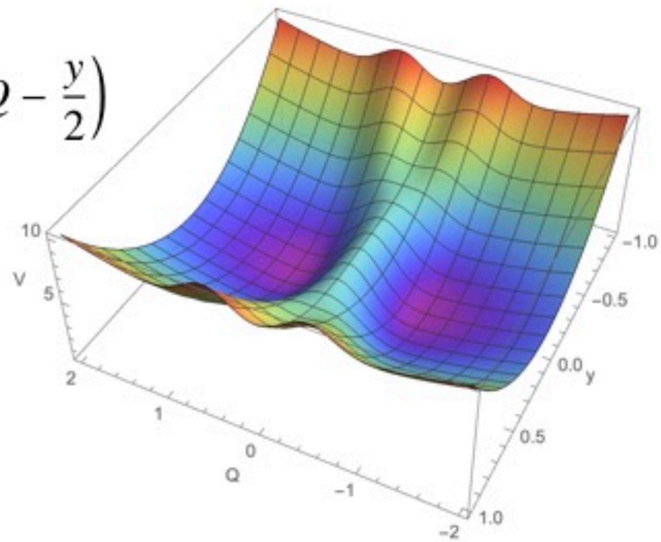
$\omega_{\mathrm{SN}} = 2\omega_c$

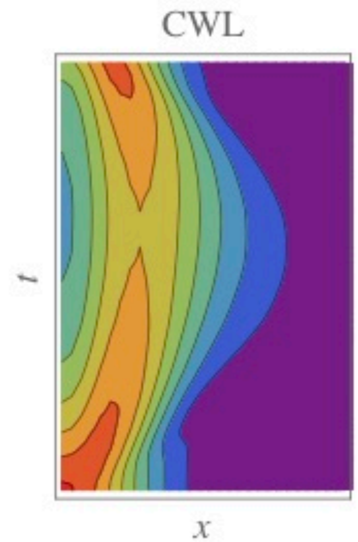


Nonlinear Regime

$$H = -\frac{\partial_Q^2}{2M} + V\left(Q + \frac{y}{2}\right) + V\left(Q - \frac{y}{2}\right)$$
$$-\frac{\partial_y^2}{2\mu} + \frac{\mu\omega_c^2 y^2}{2} + V_g(y)$$

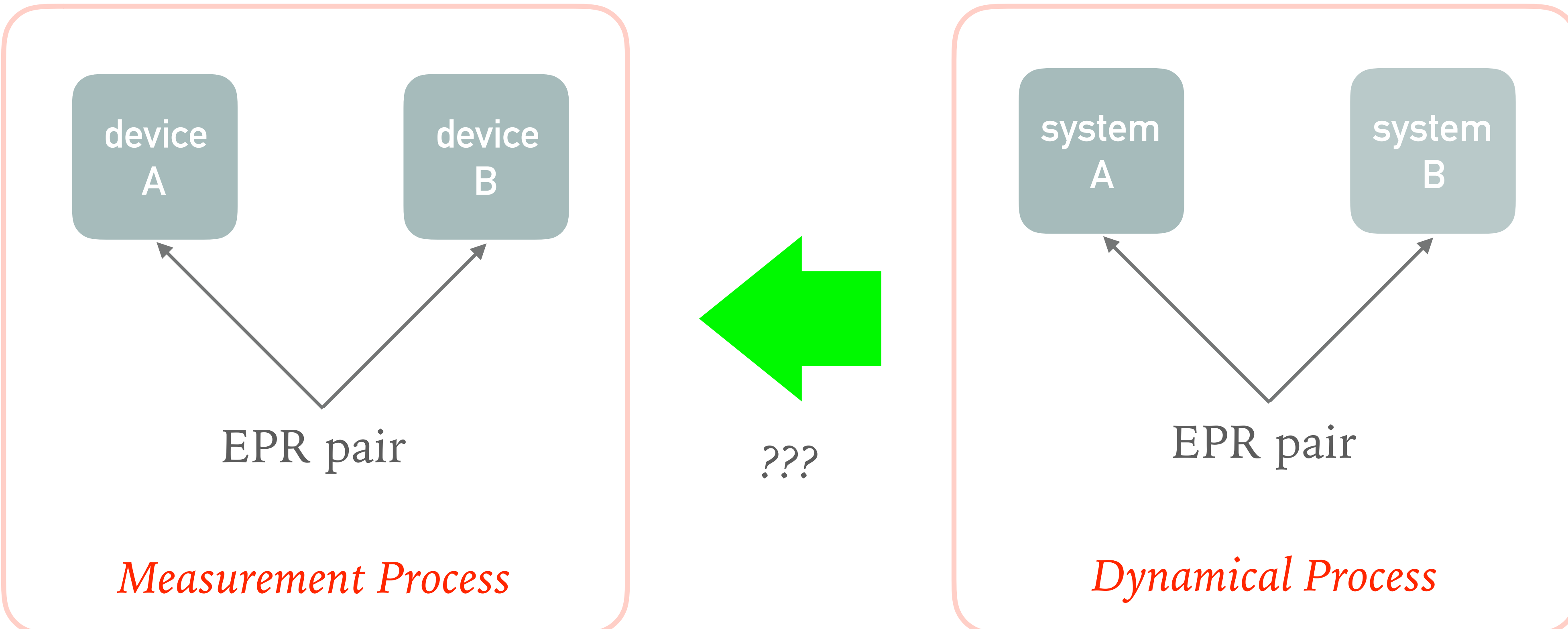
Q and y now coupled





Quo vadis?

- We discussed
  - collapse models, quantum/classical nature of gravity, and CWL
- Signatures that deviate from QM may be found.
- What about anthropogenic nature of quantum measurement?



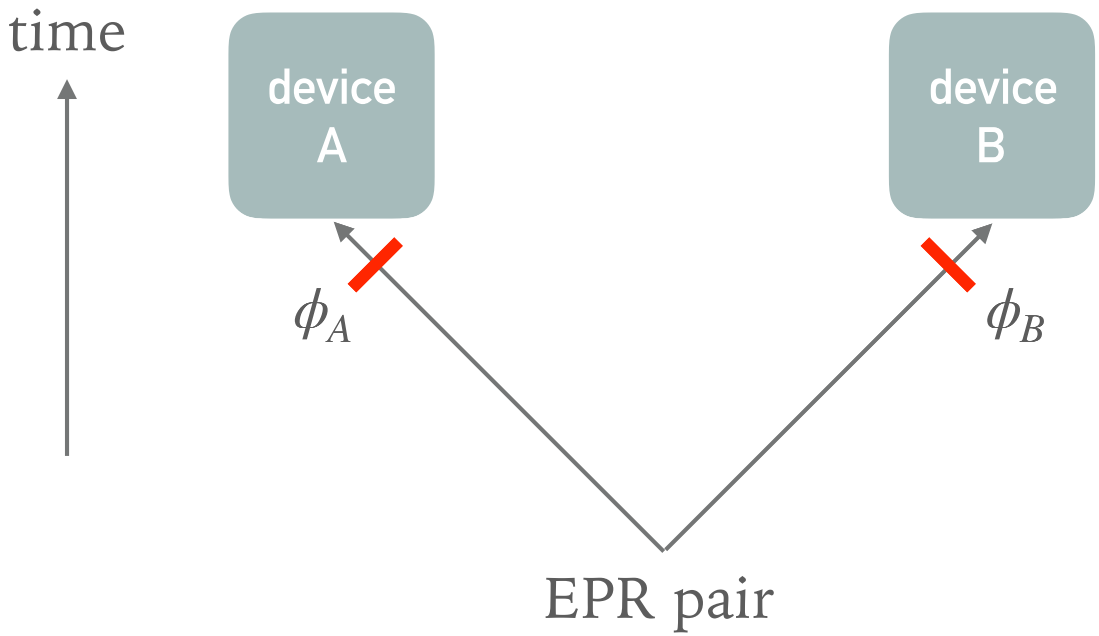
Collapse of Quantum State: Random

Unitary Evolution (Deterministic)

No-Go Theorems!!

Quo vadis?

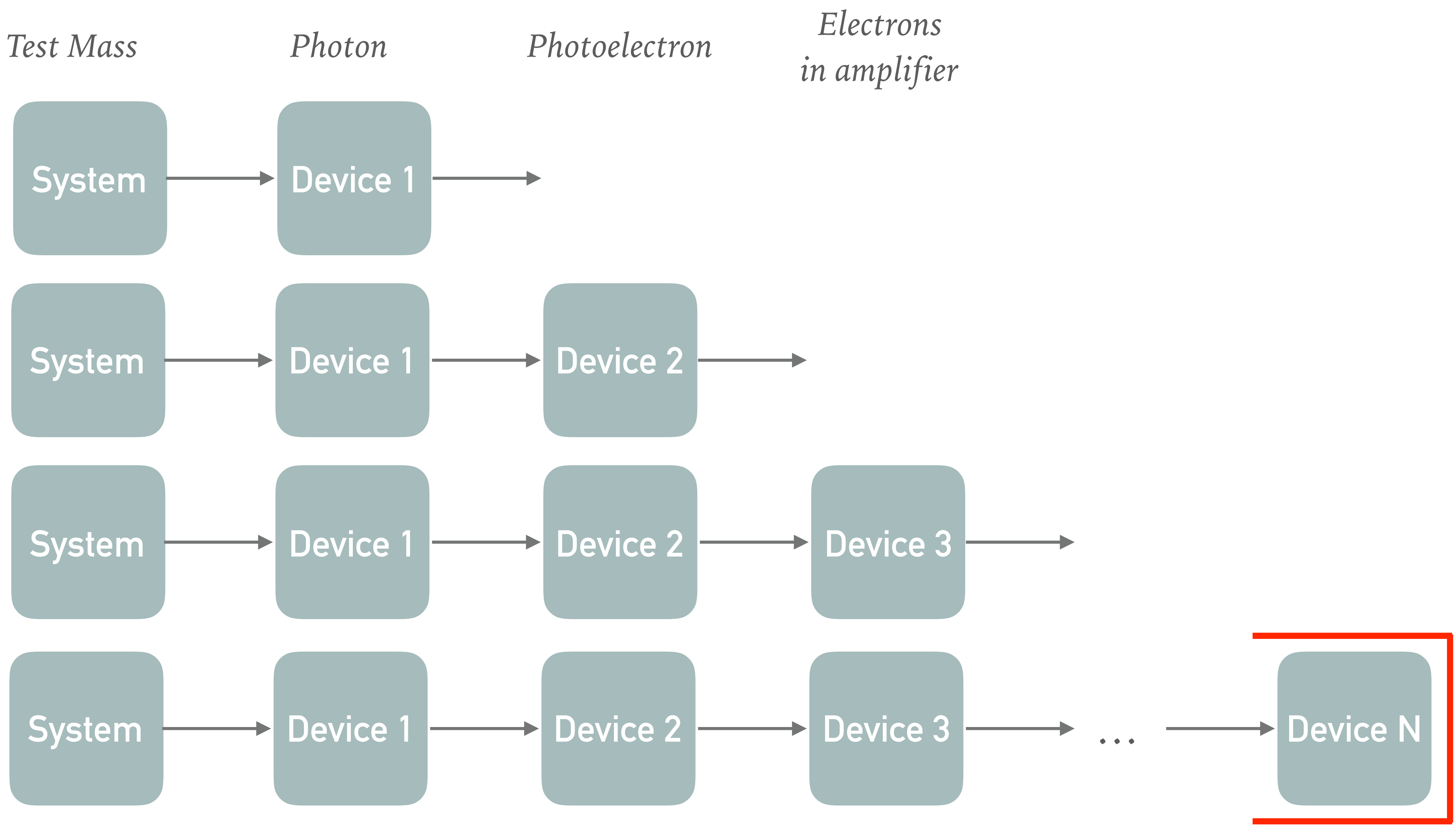
Contradiction required by proving No-Go Theorems: no superluminal communication



Results of devices [evolutions of systems] depends on the other polarizer: evolution allows B to know A's setting before $2L/c$, then build a time machine to tell A what her setting would be.

For this to happen, both systems must be ***closed***, and at pre-determined states. ***B*** cannot get out of the closed system to build his time machine.

Quo vadis?



Only closed "measuring systems" can be mapped to a unitary evolution?