⟨Quantum|Gravity⟩Society

Towards Observational Signatures of Quantum Gravity

Yanbei Chen

Towards Observational Signatures of Quantum Gravity

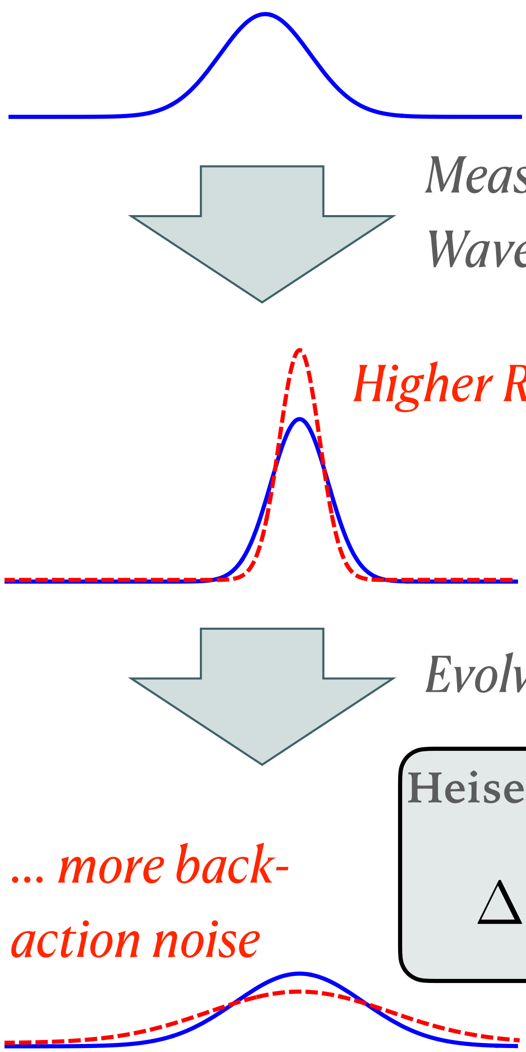
Yanbei Chen
California Institute of Technology

Quantum Gravity Conference, Vancouver, 2002

Probing Position of Test Mass

- Continuous measurement of position

[Braginsky, 1960s; Caves, Thorne, 1970s]



Measurement: Wavepacket Collapse

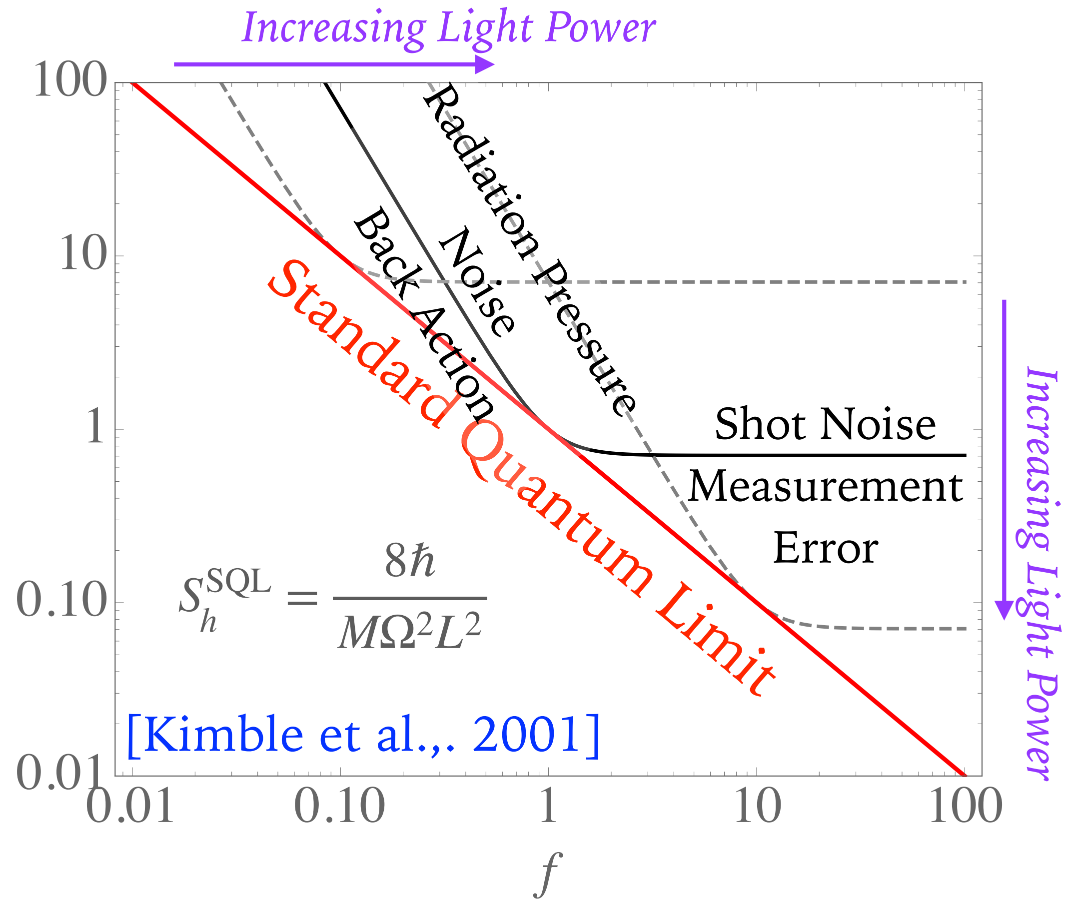
Higher Resolution

Evolve into ...

... more back-action noise

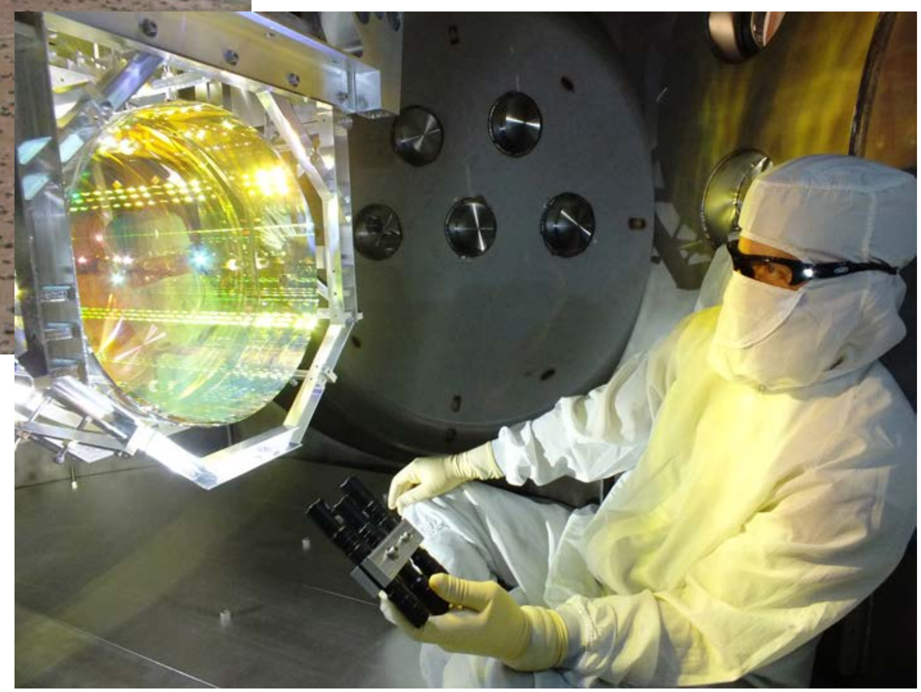
Heisenberg Uncertainty

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

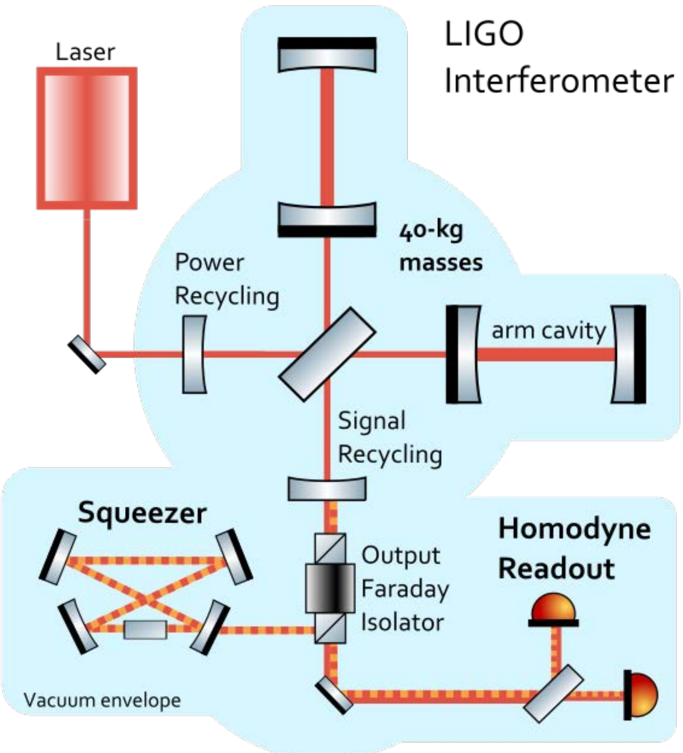


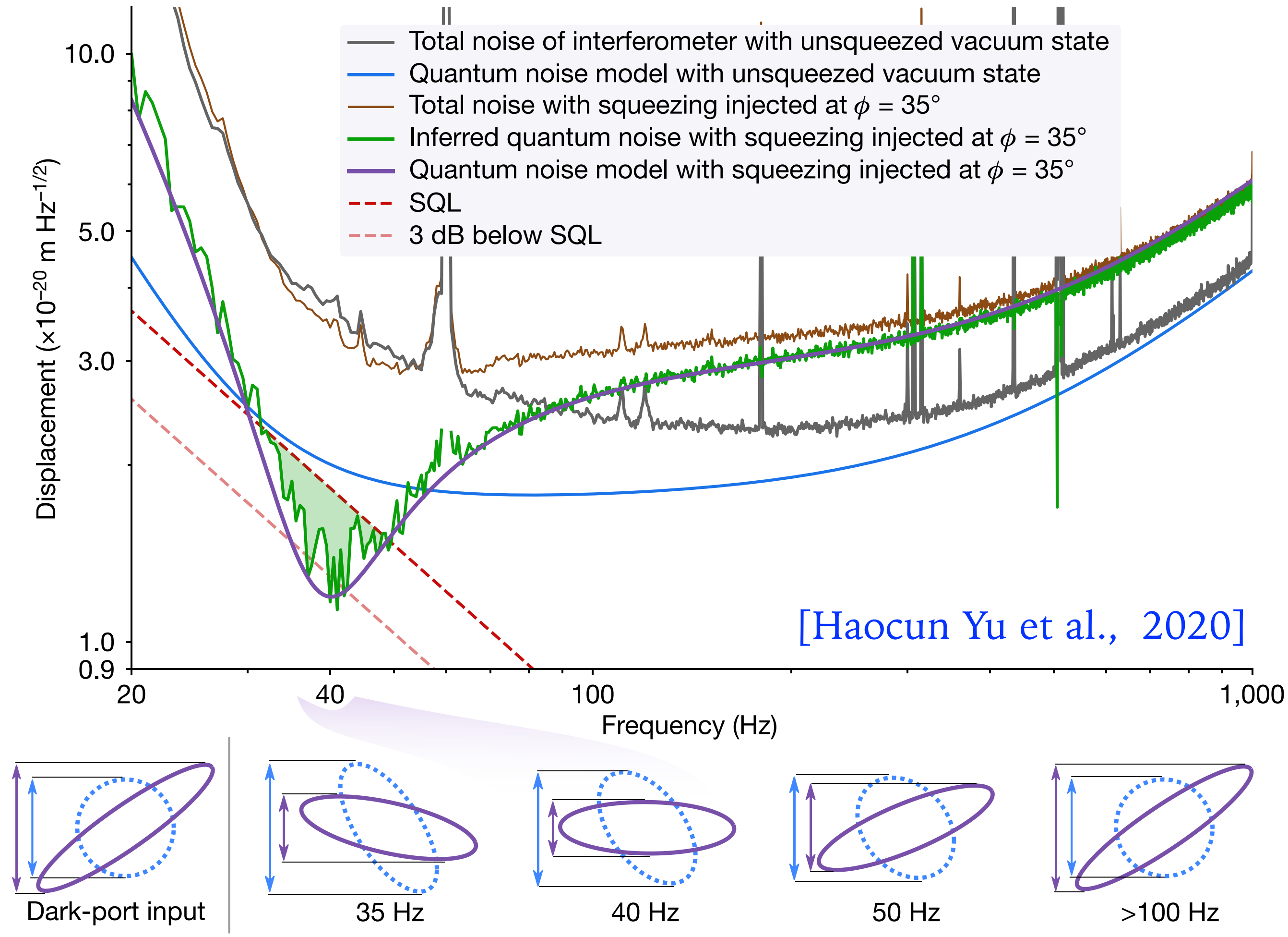
- Heisenberg Uncertainty Principle causes Limit
- Can be surpassed by building quantum correlations, e.g., using squeezed vacuum.

Laser Interferometer Gravitational-Wave Observatory



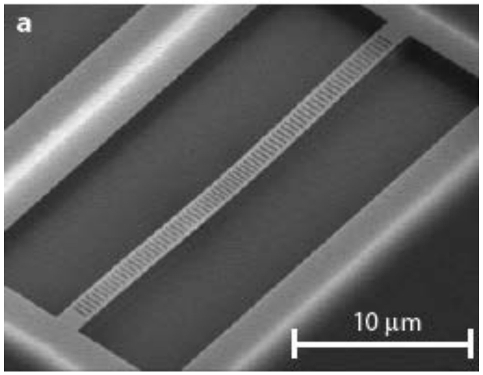
"Beyond Heisenberg Uncertainty"

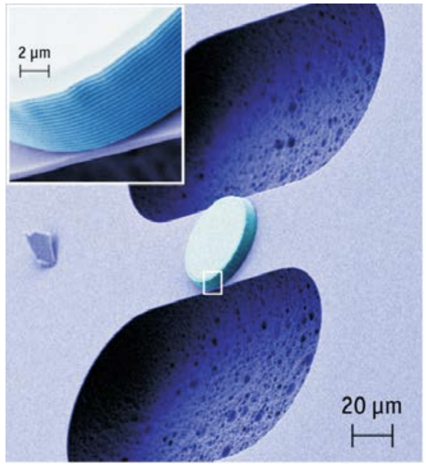


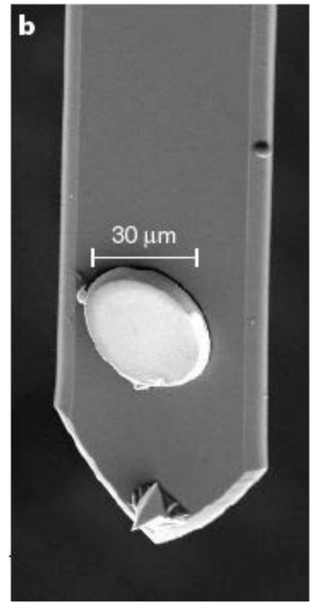


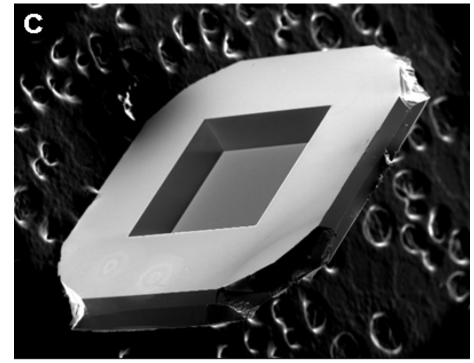
Quantum Correlation between light and mass,
manipulated by injected **squeezed vacuum**,
allows quantum noise below Standard Quantum Limit
[Unruh, 1980s]

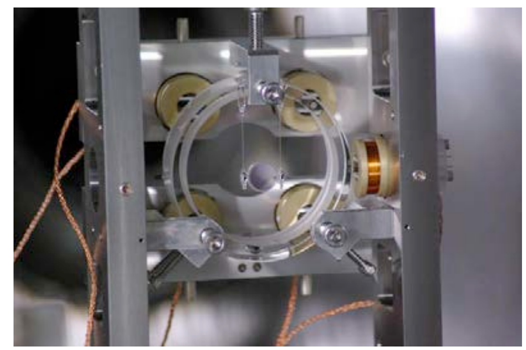
Optomechanical Systems

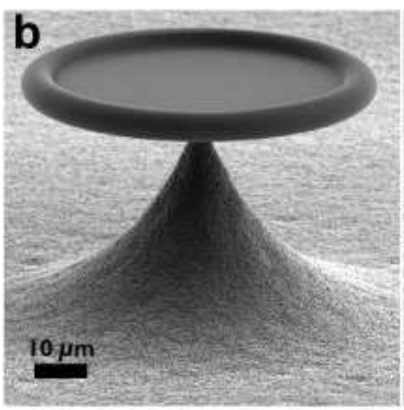


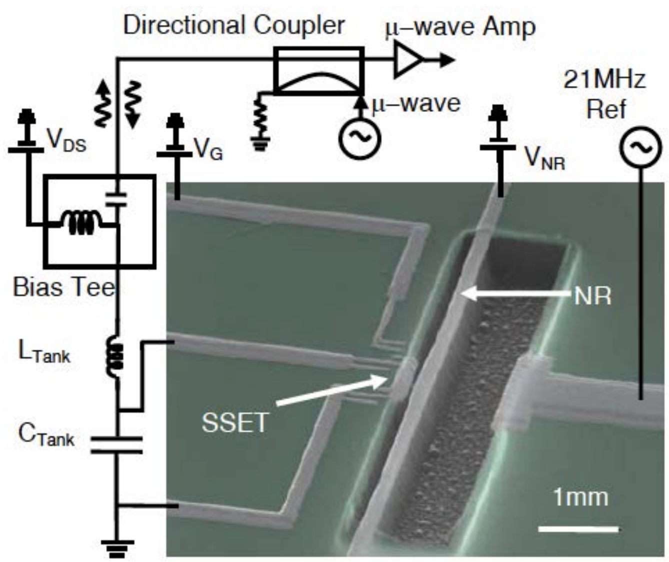


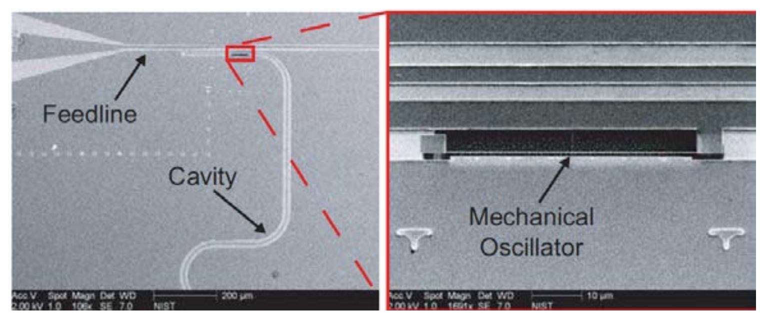




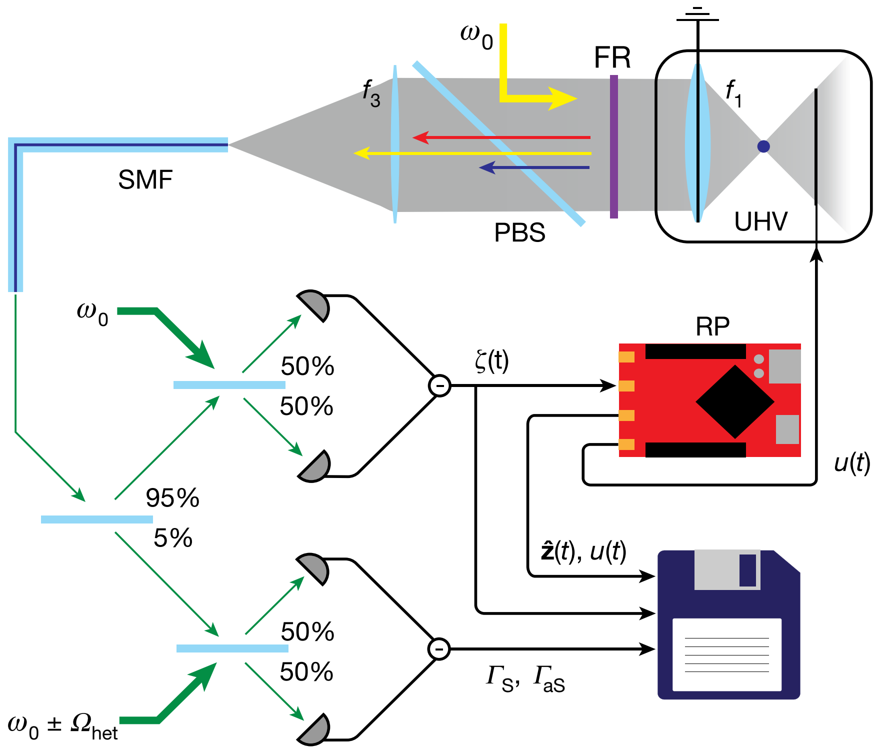




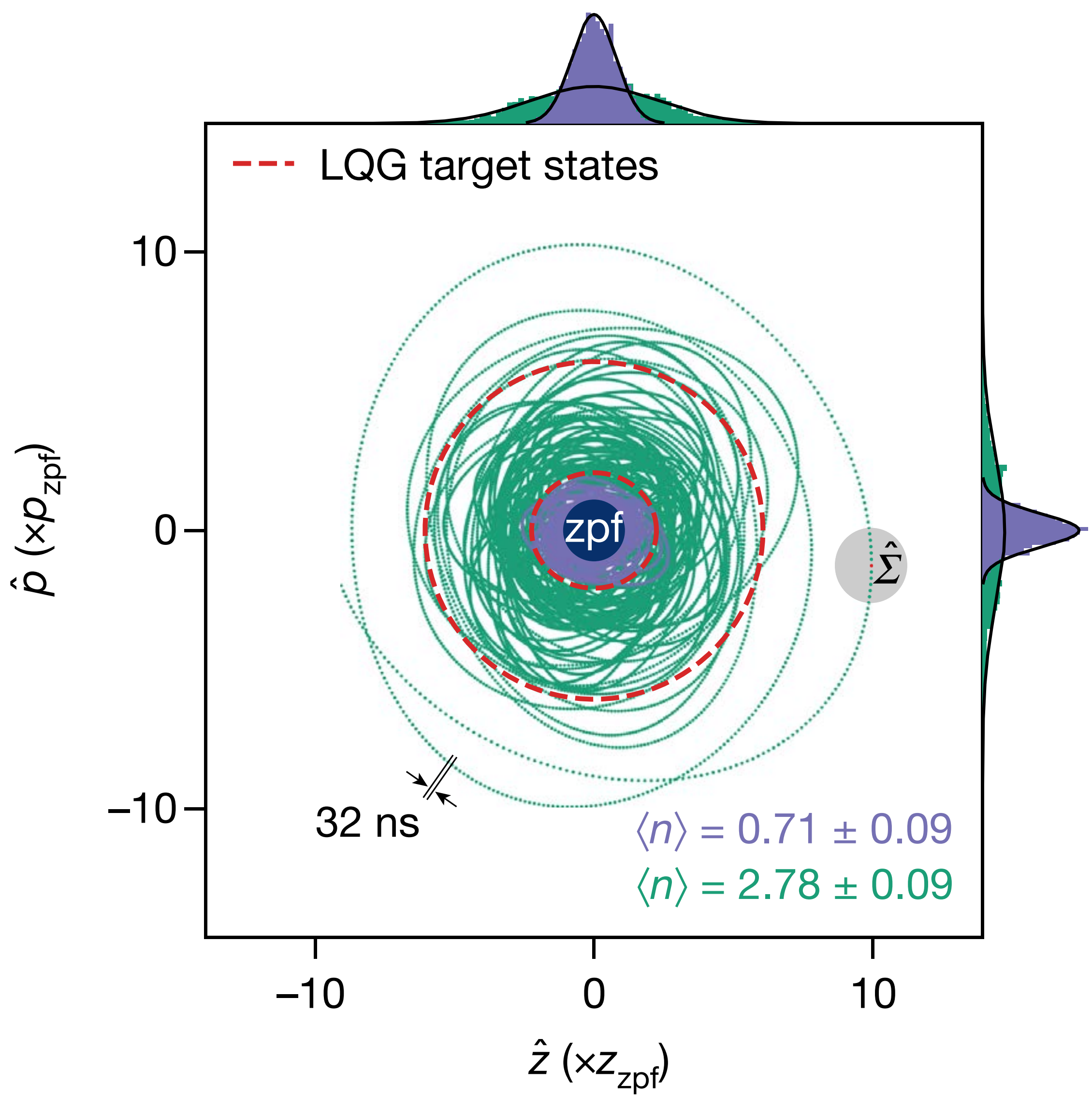




Levitated Quantum Objects



Magrini et al., 2021

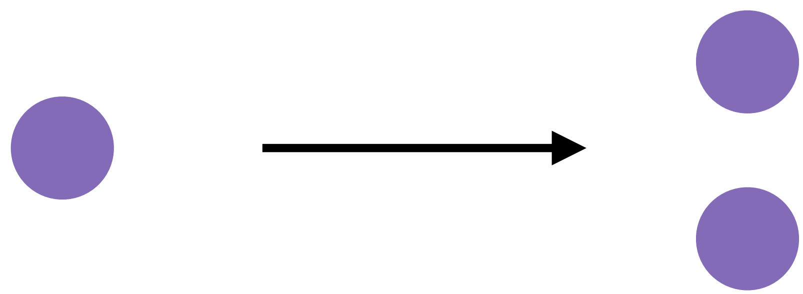


Towards Quantum Gravity

We are already observing **space-time geometry around black holes** and **macroscopic objects in the quantum regime**

- "**Stern-Gerlach Experiment**" with large masses: is there limit on how massive a "quantum object" can be? **Gravity?**

massive object(s)

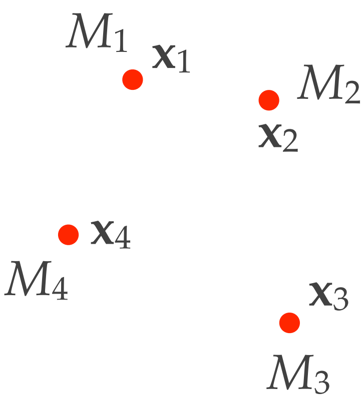


Can quantum superpositions form and evolve following the same laws?

- **Weak-force detection** limited by Heisenberg Uncertainty: is there "fundamental quantum limit to sensitivity"? **Space-time Fluctuations?**

distance fluctuations due to quantum gravity?

Quantum Nature of Gravity?



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

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

This potential term appears in the Schrödinger Equation

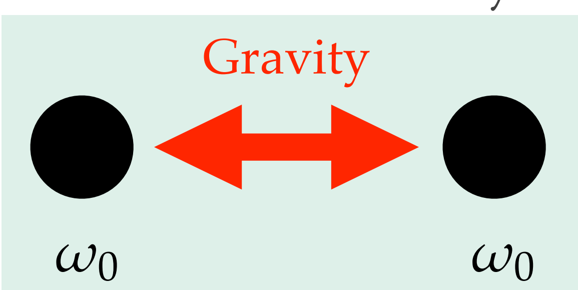
"If quantum information can pass from A to B through $\hat{\phi}$, then gravity must be quantum."

[Wald and Carney Talk]

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

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

Effect is very weak; time scale is very long! *[Kafri & Taylor, 2014]*



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

$63\,\mu\text{Hz}$

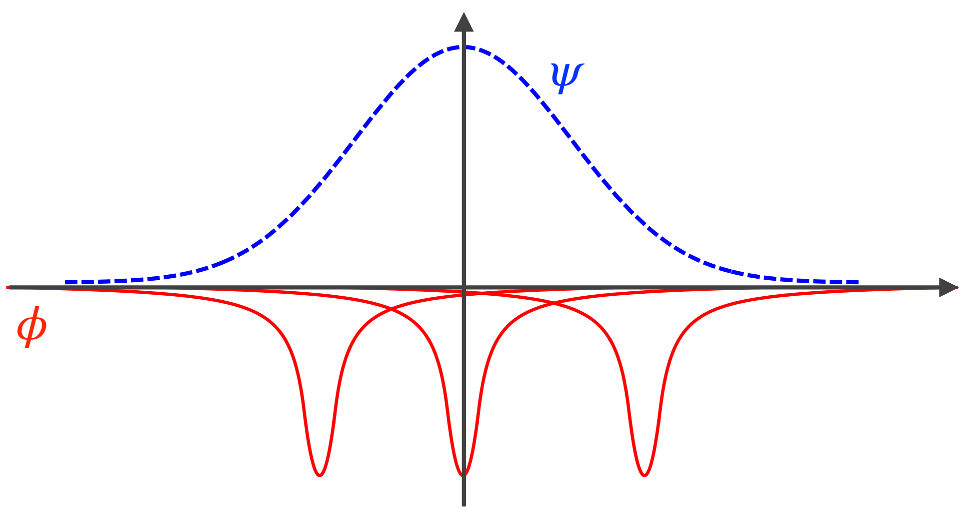
Schrödinger-Newton Equation

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

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

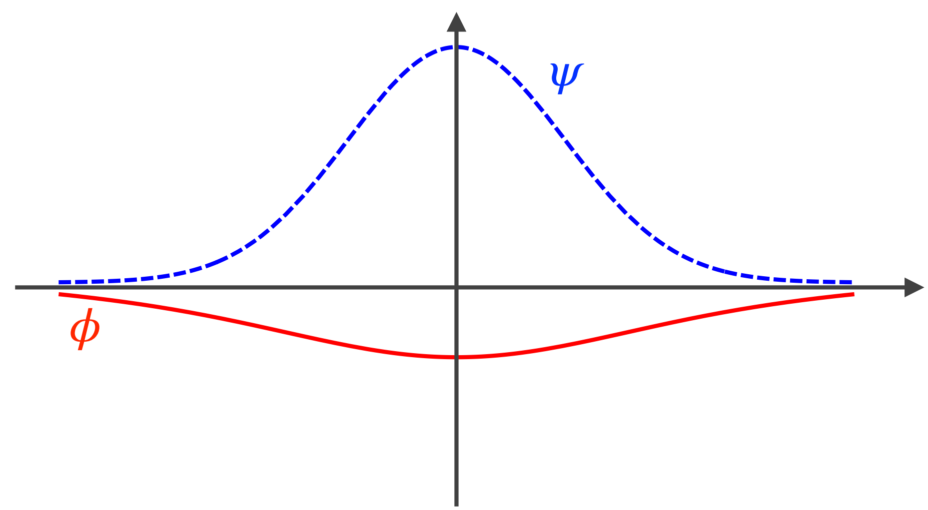
[Møller 1962, Rosenfeld 1963; Kibble 1976; … ; Guilini 2012; H. Yang et al., 2013]

Quantum "Self Gravity"



particle carries own gravity field

Classical "Self Gravity"

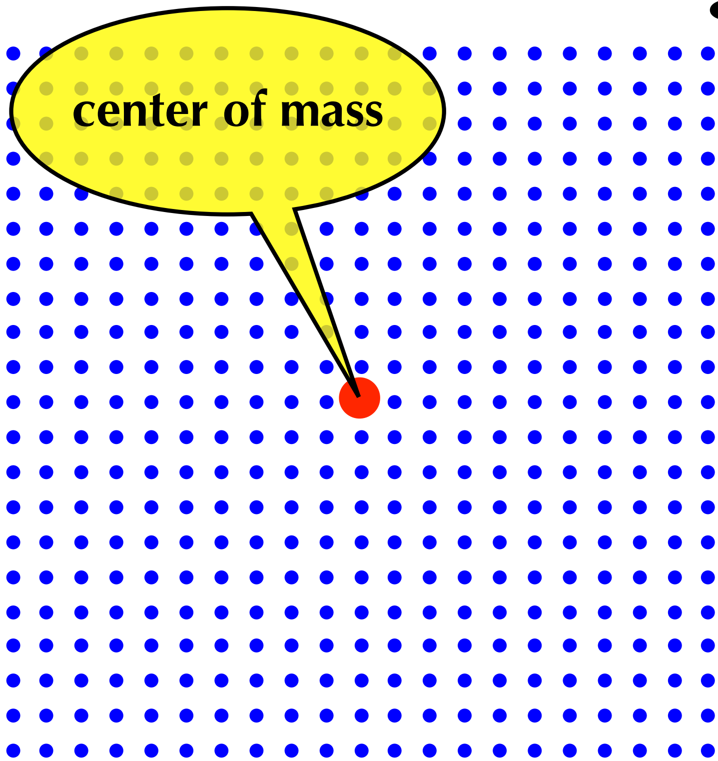


unique classical field

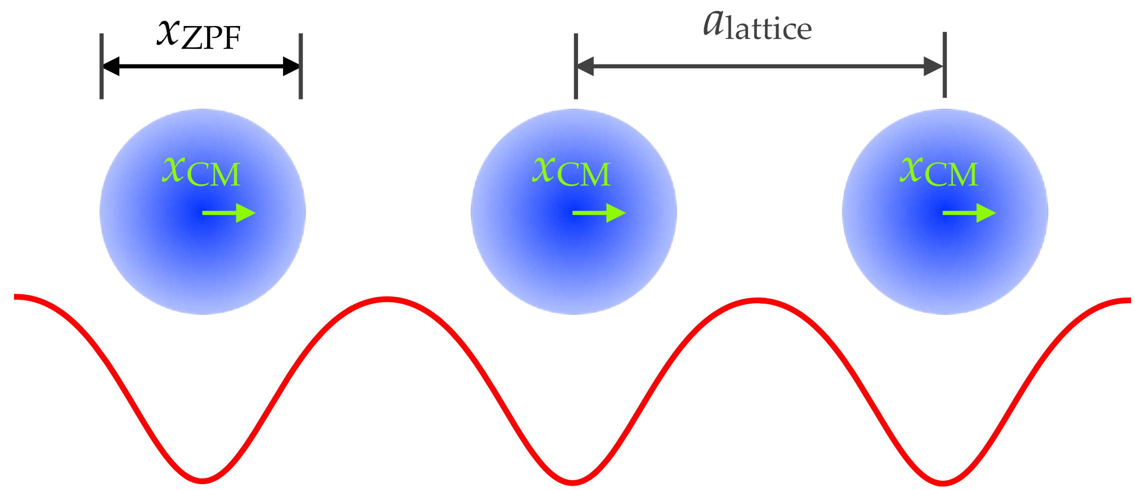
wave packet attracted by its own potential

Since wavefunction ψ now gravitates, it becomes "physical reality"

Schrödinger-Newton Equation



a **macroscopic crystal** made up from atoms



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

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

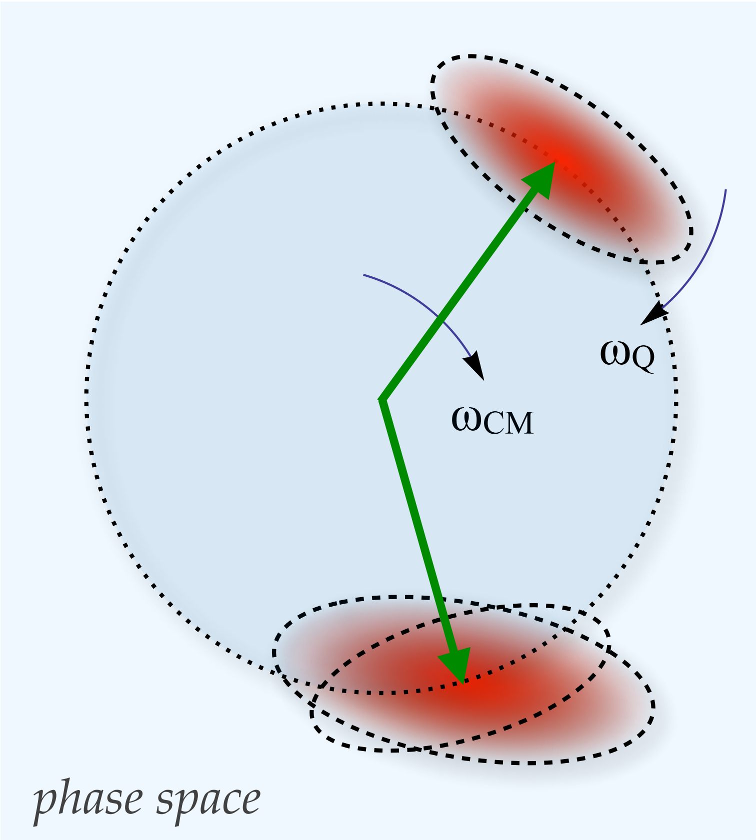
$$i\hbar\frac{\partial \Psi_{\mathrm{CM}}}{\partial t} = \left[-\frac{\hbar^2\nabla^2}{2M} + \frac{1}{2}M\omega_{\mathrm{CM}}^2 x^2 + \frac{1}{2}M\omega_{\mathrm{SN}}^2 (x - \langle x \rangle)^2\right]\Psi_{\mathrm{CM}}$$

$$\omega_{\mathrm{SN}}^2 = \frac{Gm}{12\sqrt{\pi}\,x_{\mathrm{ZPF}}^3} \gg \omega_g^2 \qquad \omega_{\mathrm{SN}}^{\mathrm{Si}} = 4\times 10^{-2}\,\mathrm{s}^{-1} \approx 100\,\omega_g^{\mathrm{Si}}$$

Birgitta Whaley & Jordan Wilson-Gerow talks

7 mHz, 57 mHz for Tungsten

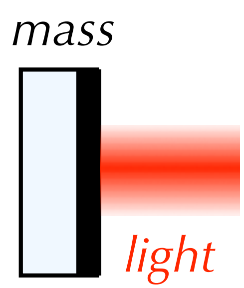
Naive Schrödinger-Newton Phenomenology

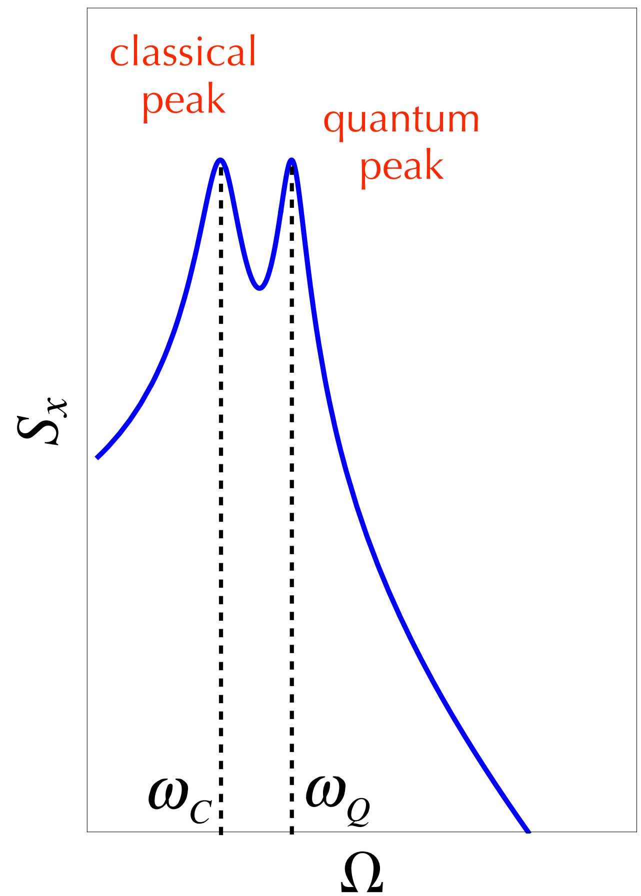


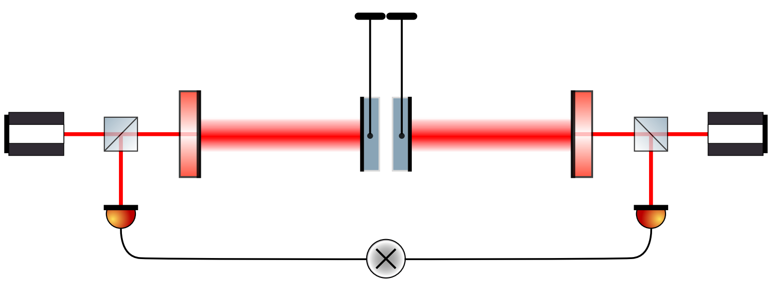
$$\dot{\hat{x}} = \hat{p}/M$$
$$\dot{\hat{p}} = -M\omega_{\mathrm{CM}}^2\hat{x} - M\omega_{\mathrm{SN}}^2(\hat{x} - \langle\hat{x}\rangle)$$

Quantum noise ellipse rotate at a different frequency:

$$\omega_{\mathrm{Q}}^2 = \omega_{\mathrm{CM}}^2 + \omega_{\mathrm{SN}}^2$$

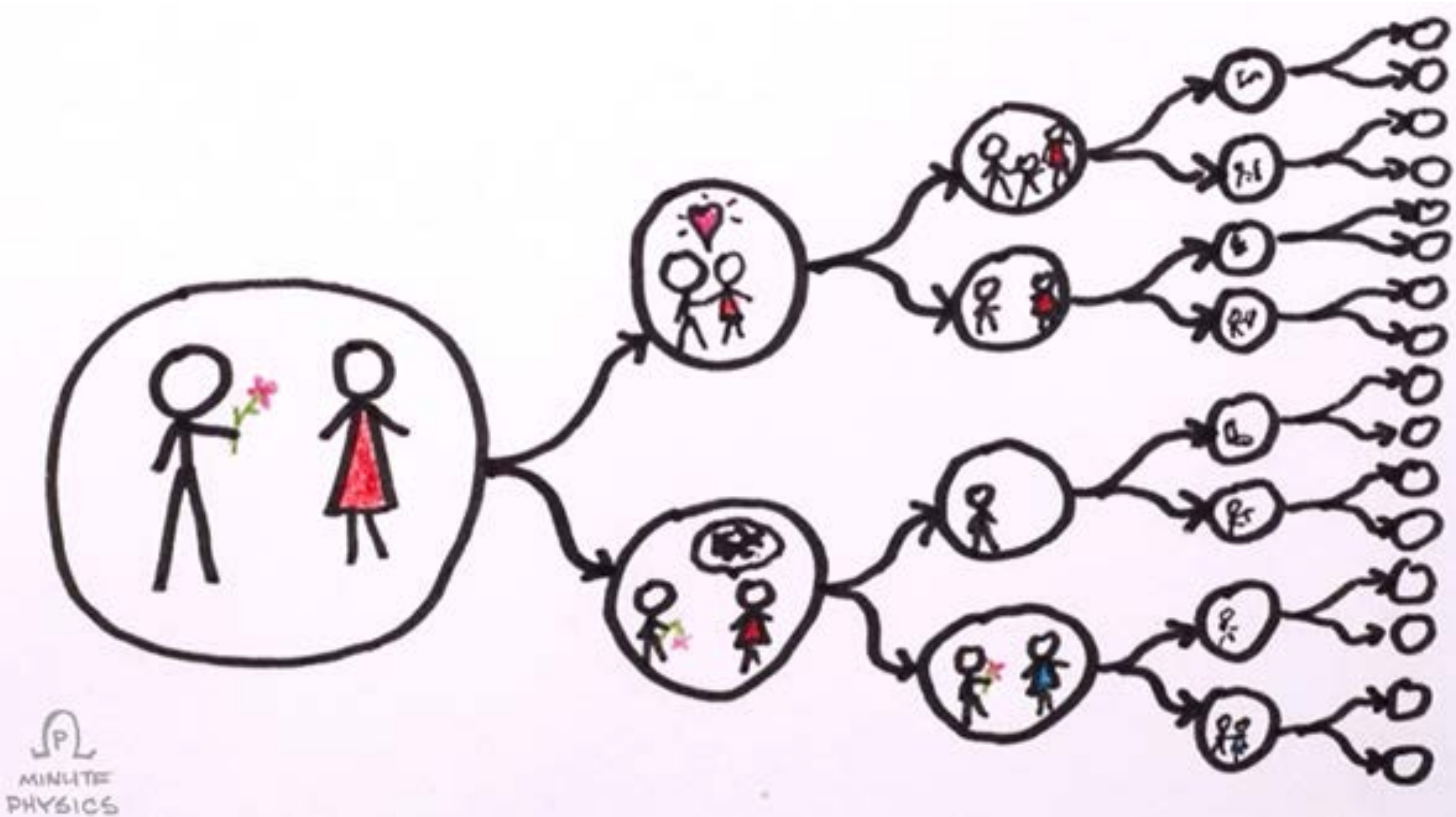




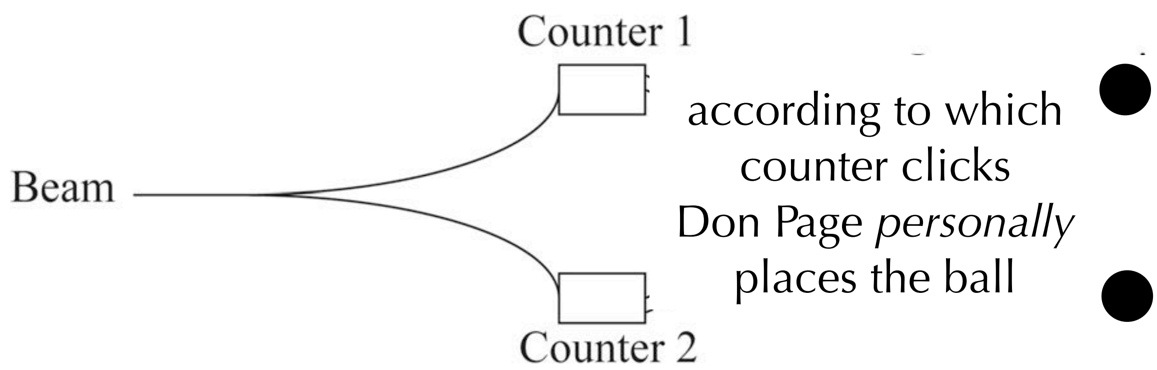


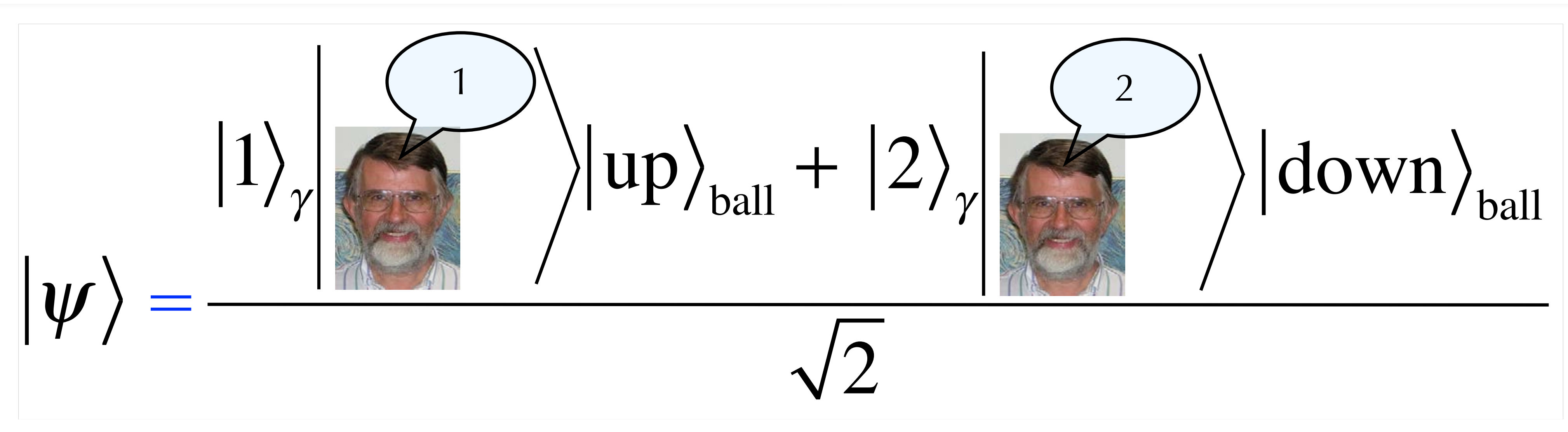
Will lead to experimental signatures!

Do we collapse the quantum state?



Don Page's Thought Experiment





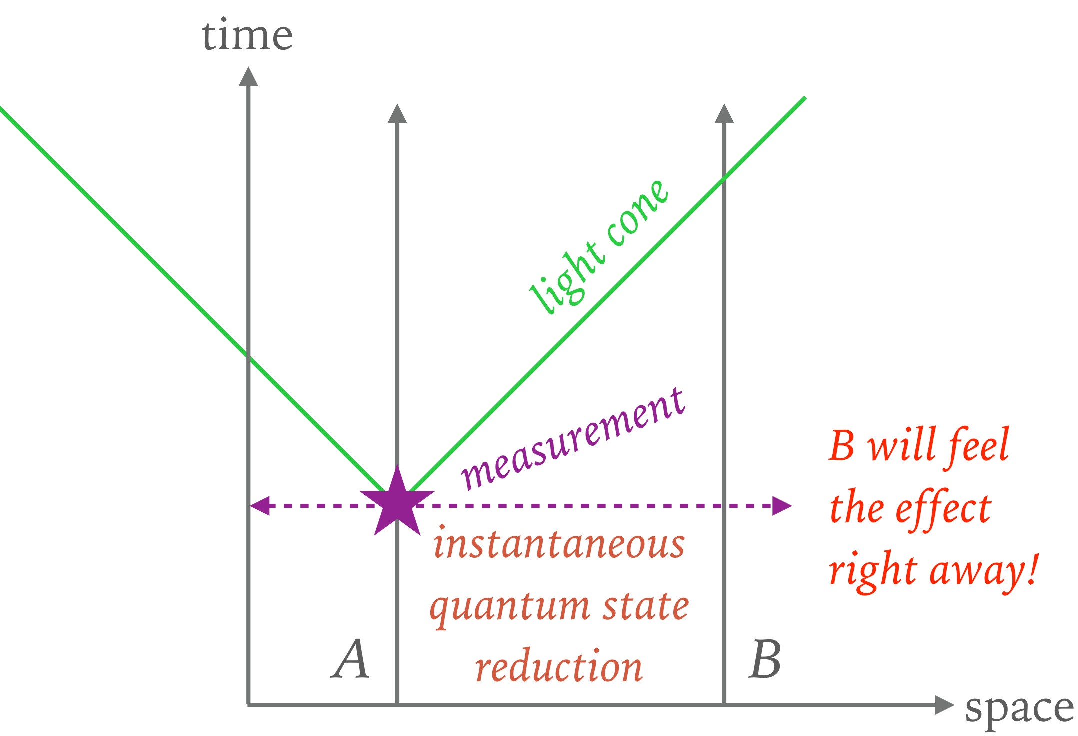
Expected Gravity of the Balls Average Out!

Gravity must depend on Results of Measurement

Gravity Must Depend Results of Measurement

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

Hamiltonian depends on quantum state



Nonlinear QM

$+$

Instantaneous State Reduction

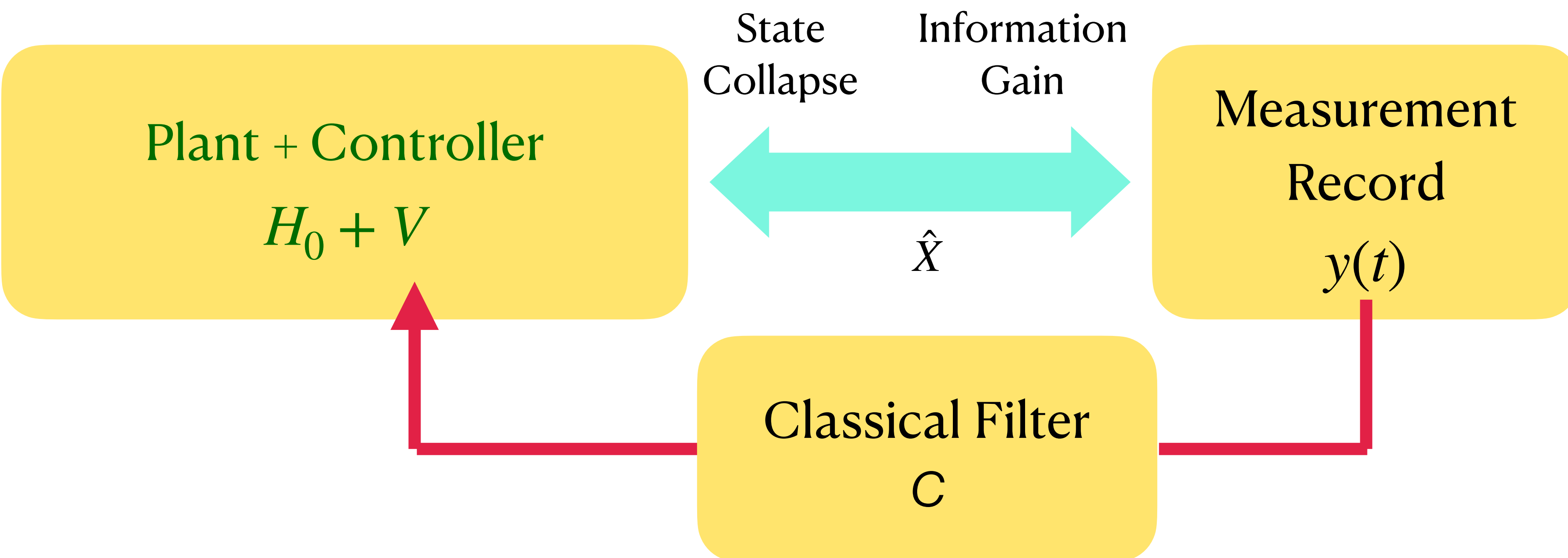
$\downarrow$

superluminal communication

Polchinski 1991

- **Loophole**
  - Hamiltonian can depend on measurement results, instead of directly on states.
  - Dependence can be causal.

Gravity as Measurement-Based Quantum Feedback

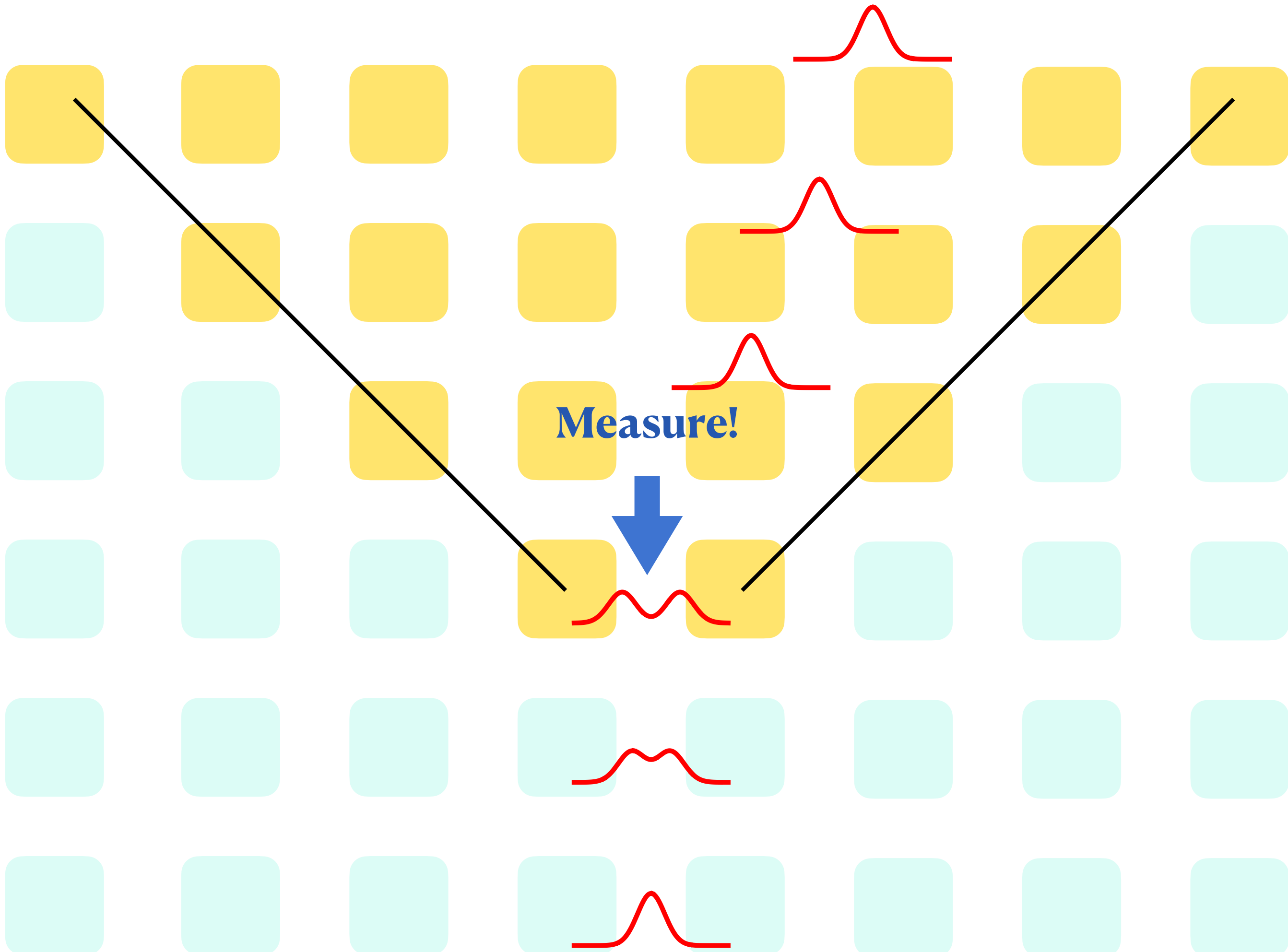


$$d\hat{\rho} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}]dt - \frac{\alpha^2}{8}[\hat{x},[\hat{x},\hat{\rho}]] + \frac{1}{2}\alpha(\hat{x}\hat{\rho} + \hat{\rho}\hat{x} - 2\langle\hat{x}\rangle\hat{\rho})dW + \boxed{\hat{V}\left[\left\{y(t') : t' < t\right\}\right]}$$

$$dy = \alpha\langle x\rangle dt + dW$$

Nonlinear, and breaks linear superposition!

Classical Gravity as Quantum Feedback

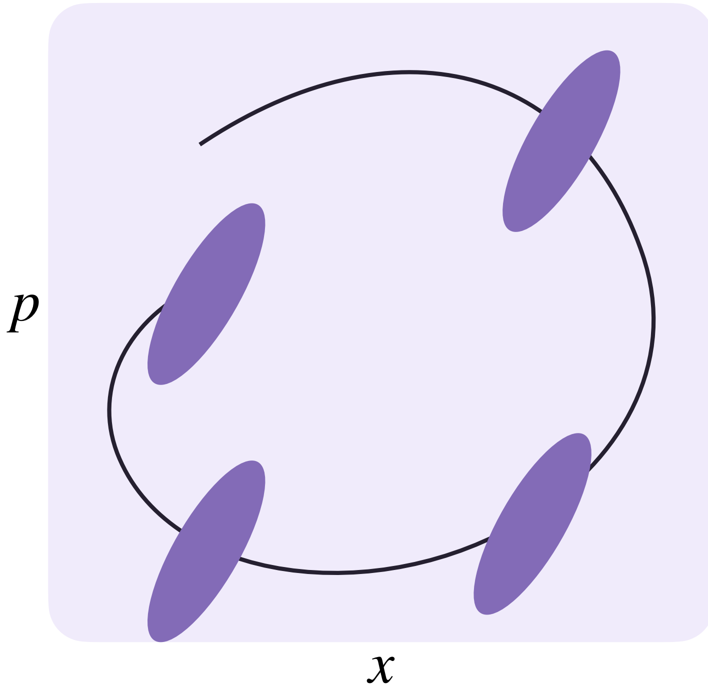


Bassam Helou
2017 & 2019

Each “actuator” generates gravity according to results inside **its** past light cone.

Fundamental Questions Remain: What is a Measurement?
Light that is “lost”, are they measured? which variables measured?

Optomechanical Signatures



Eigenfrequency for **mean values** same as before

Uncertainties modified

$$\omega_m \to \omega_q = \sqrt{\omega_m^2 + \omega_{\rm SN}^2}$$

$$d\langle \hat{x}\rangle_c = \frac{\langle \hat{p}\rangle_c}{M} dt + \sqrt{2}\alpha V_{xx}^c \sin\theta\, dW,$$

$$d\langle \hat{p}\rangle_c = -M\omega_{\rm m}^2 \langle x\rangle_c dt - \gamma_m \langle \hat{p}\rangle_c dt + \sqrt{2}\alpha V_{xp}^c \sin\theta\, dW + \frac{\hbar\alpha}{\sqrt{2}} \cos\theta\, dW,$$

stochastic evolution of **conditional expectations**

$$\dot{V}_{xx}^c = \frac{2V_{xp}^c}{M} - 2\alpha^2 \sin^2\theta V_{xx}^{c2},$$

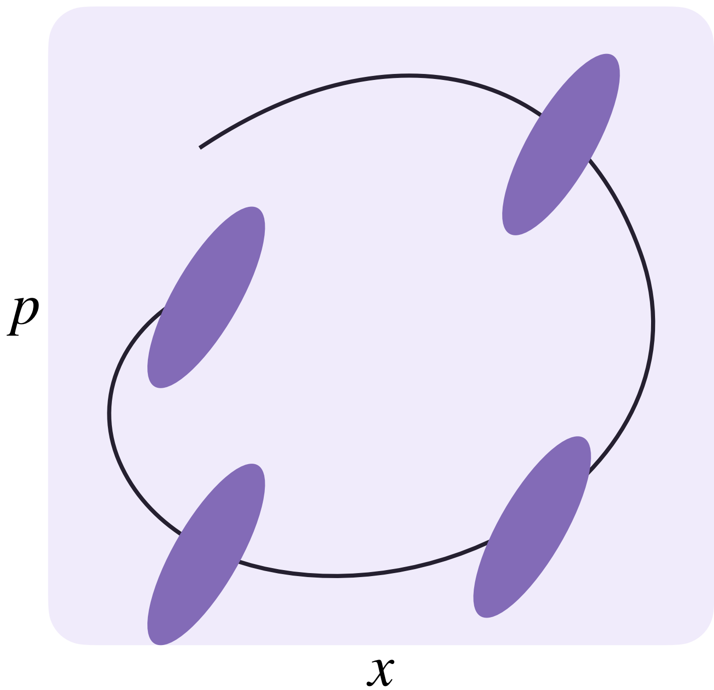
$$\dot{V}_{xp}^c = \frac{V_{pp}^c}{M} + M\omega_q^2 V_{xx}^c - 2\alpha^2 \sin^2\theta V_{xx}^c V_{xp}^c - \alpha^2 \sin\theta\cos\theta\hbar V_{xx},$$

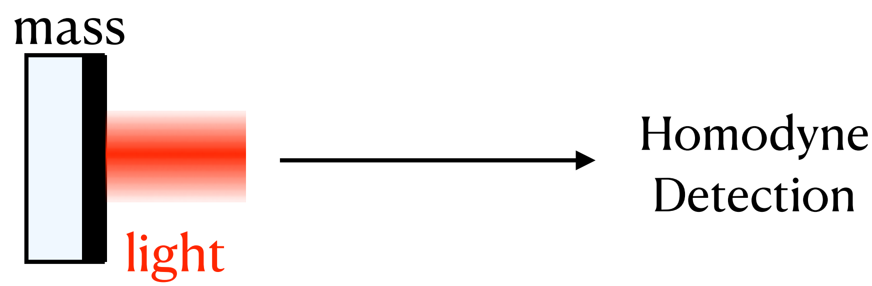
$$\dot{V}_{pp}^c = -2M\omega_q^2 V_{xp}^c - 2\alpha^2 \sin^2\theta V_{xp}^{c2} - 2\alpha^2 \sin\theta\cos\theta\hbar V_{xp} - \frac{\alpha^2\cos^2\theta\hbar^2}{2} + \frac{1}{2}\alpha^2\hbar^2,$$

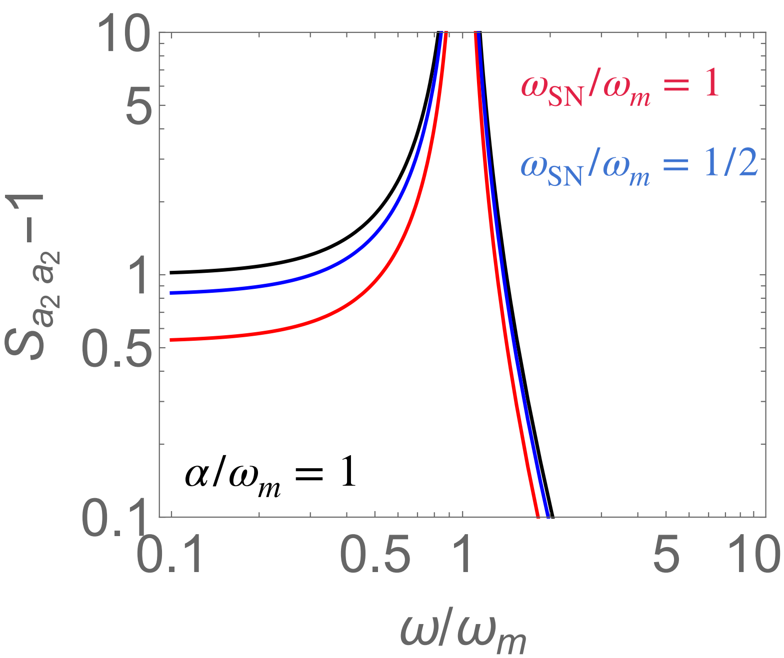
deterministic evolution of conditional variances

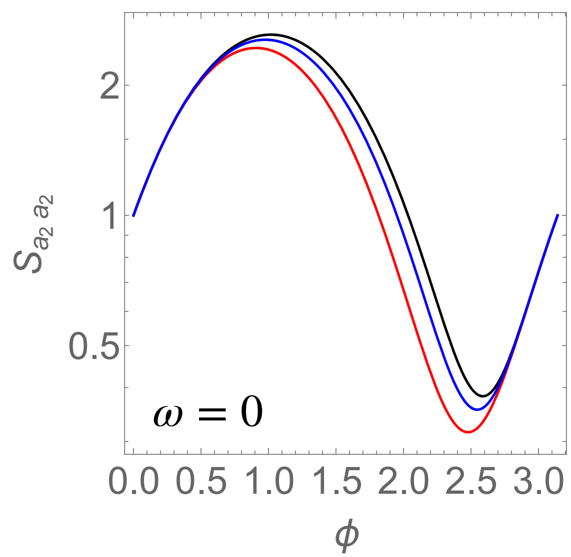
[Yubao Liu, Haixing Miao, Yanbei Chen and Yiqiu Ma, 2022]

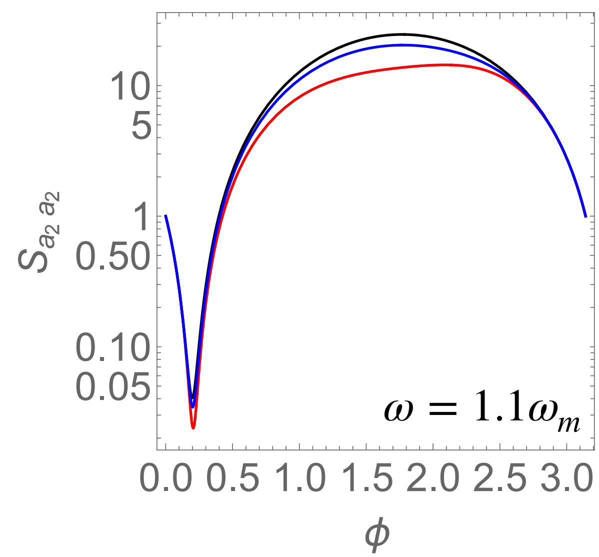
Optomechanical Signatures





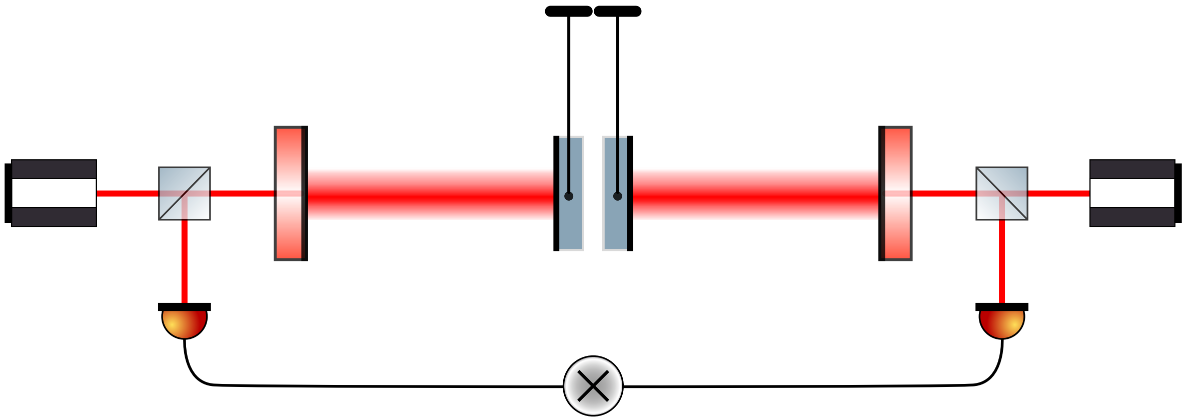






Effects visible when $\omega_{\rm SN} \sim \omega_m$

Testing Nature of Gravity?



Measure Amplitude Modulation

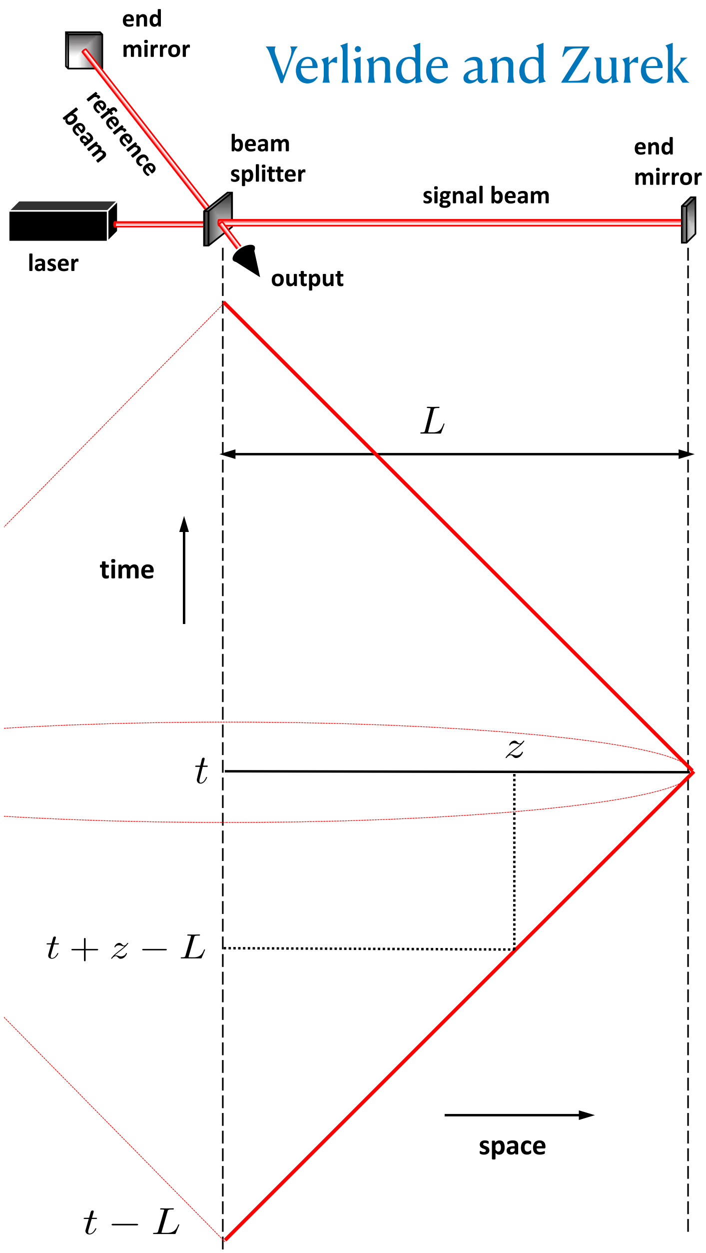
Measure Phase Modulation

still correlated!!

correlations deviate from quantum-gravity prediction only at $(\omega_{\mathrm{SN}}/\omega_m)^2$ order

[Yubao Liu, Haixing Miao, Yanbei Chen and Yiqiu Ma, 2022]

Space-Time Fluctuations

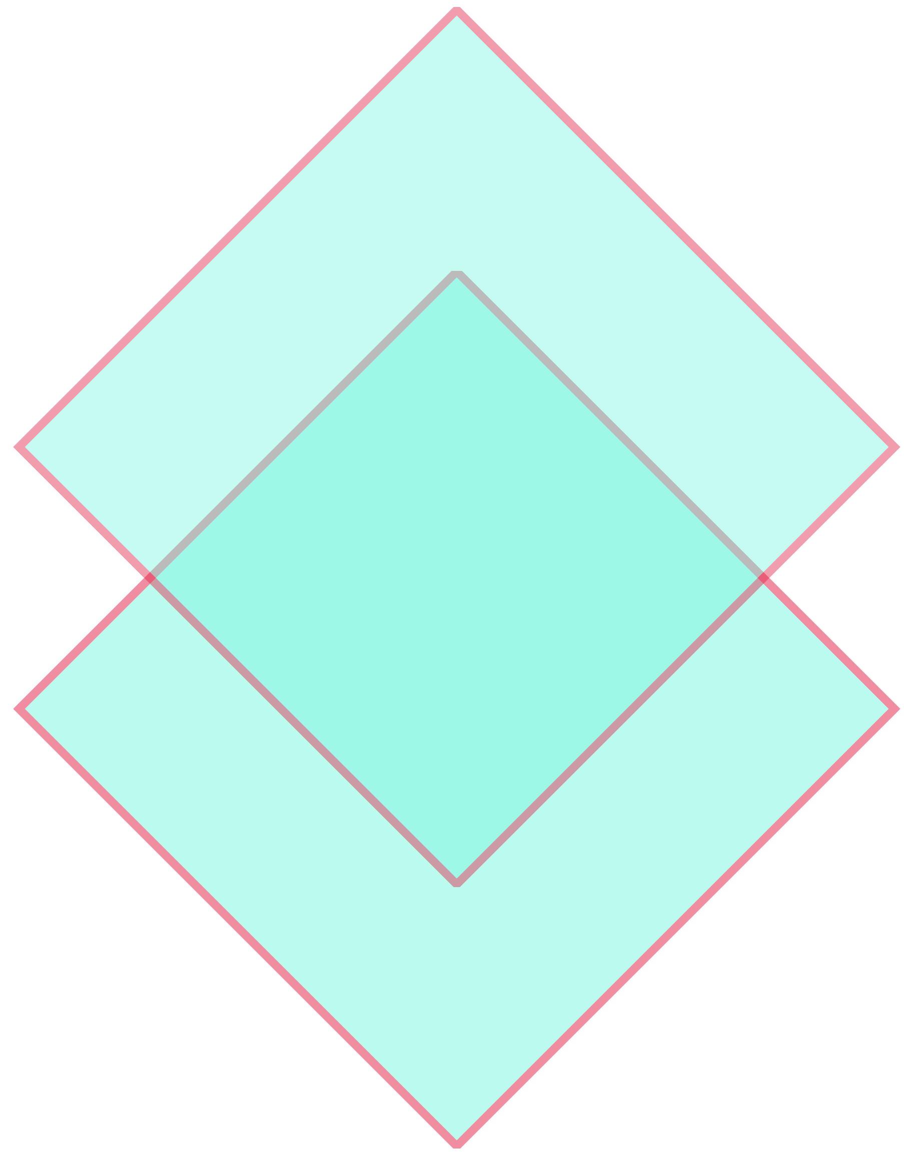


- Mechanism proposed by Verlinde and Zurek.

- GQuEST experiment at Caltech (Lee McCuller)
  - **uses photon counting instead of homodyne detection**

Space-Time Fluctuations

- Fluctuation in linear size of causal diamonds $\sim \sqrt{l_p L}$
  - Random walk along edges of the causal diamond
- Time scale of coherence $\sim L/c$
  - Two overlapping causal diamond are correlated
- Effective theory generates fluctuations measured by realistic interferometer configurations. [Zurek, 2022 and on-going work.]
- **Rana Adhikari's talk**



Collaborators

- Yubao Liu, Yiqiu Ma (Huazhong University of Science and Technology), Haixing Miao (Tsinghua University), Bassam Helou (Caltech), Sabina Scully (ANU)
- Philip Stamp, Jordan Wilson Gerow (UBC → Caltech), Birgitta Whaley and Kai-Isaak Ellers (UC Berkeley)
- Dongjun Li, Vincent S.H. Lee, Kathryn Zurek, Lee McCuller and Rana Adhikari (Caltech)

Testing Quantum Nature of Gravity

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

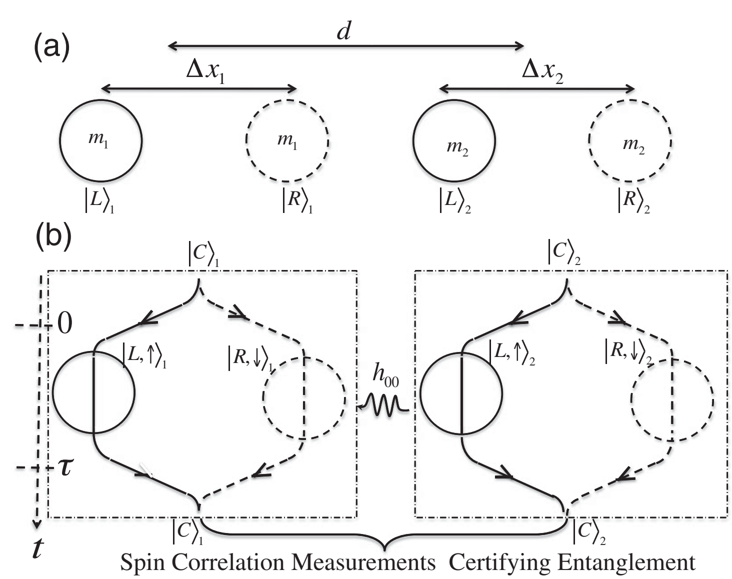
Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

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]

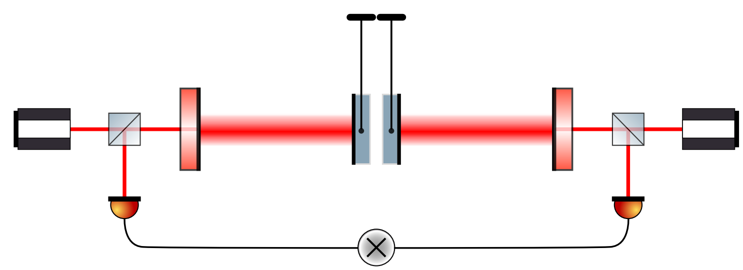


Quantum correlation of light mediated by gravity

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



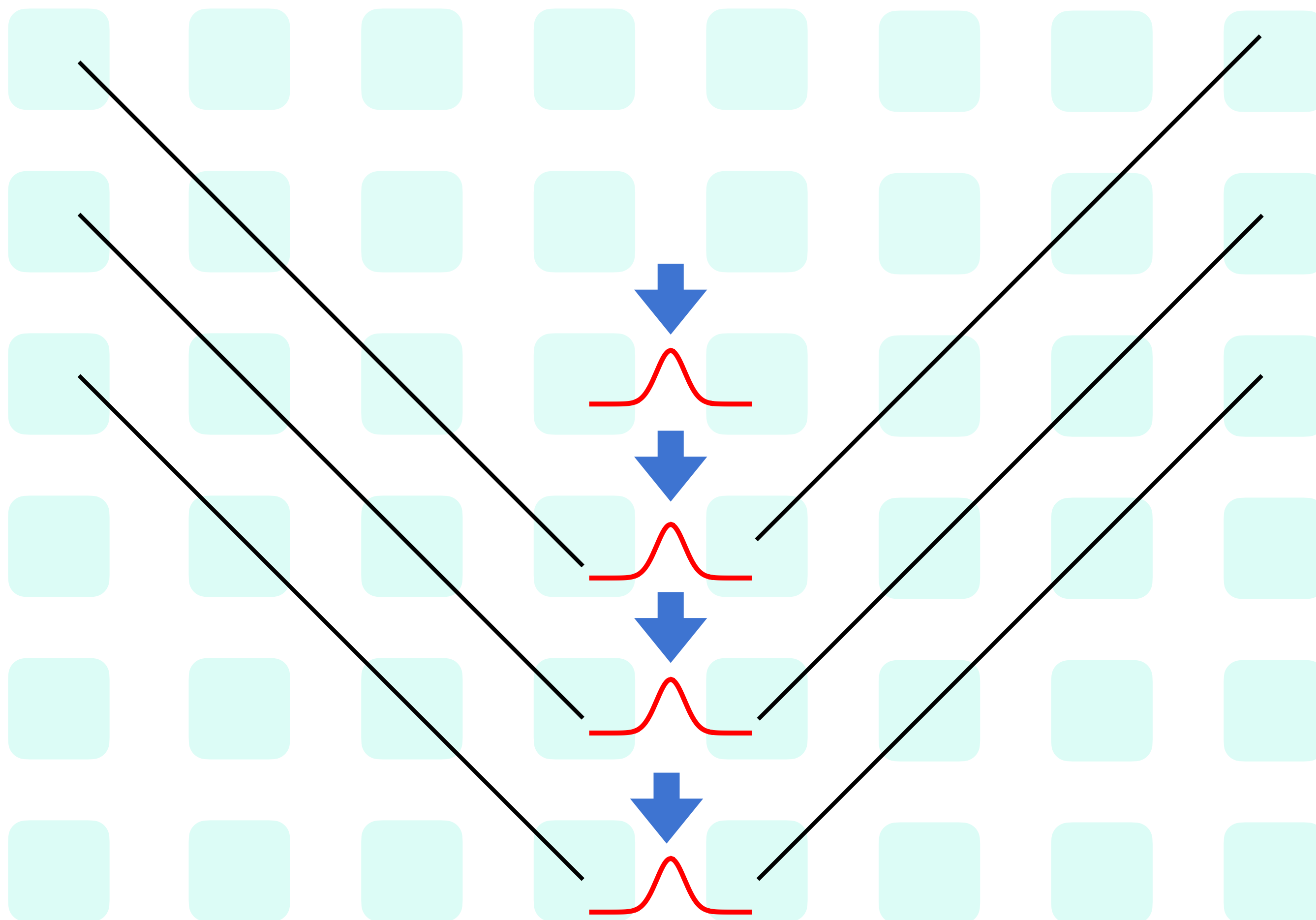
Information Content of the Gravitational Field of a Quantum Superposition

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

Kafri-Taylor-Milburn Model



All objects monitored continuously in order to generate gravity!
Universal noise at much higher level imposed on all objects!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