Quantum information for fundamental physics

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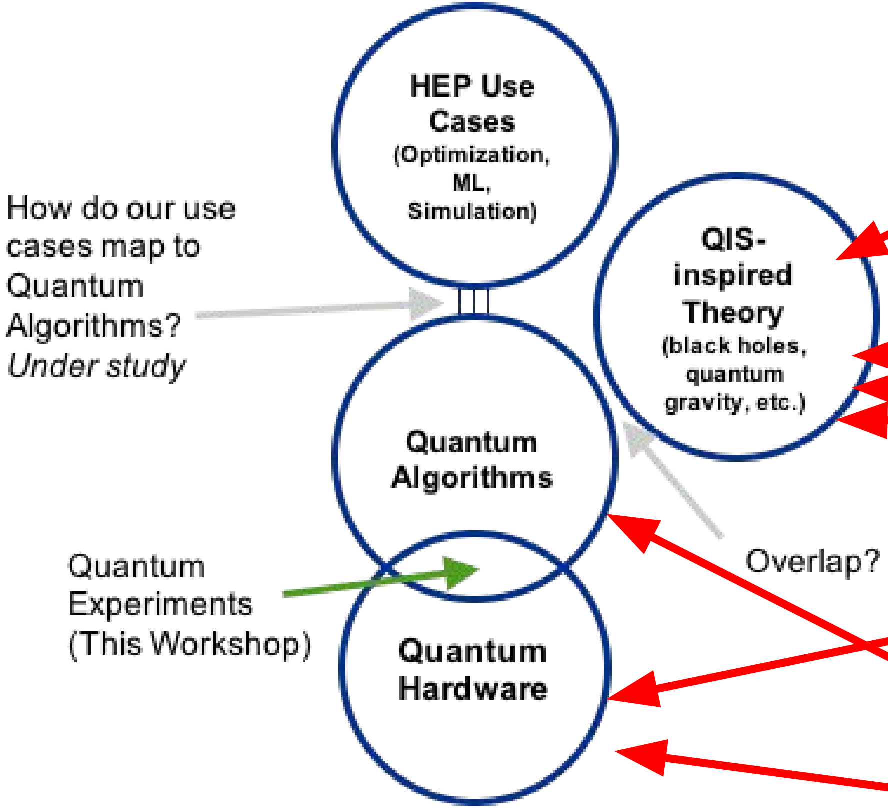
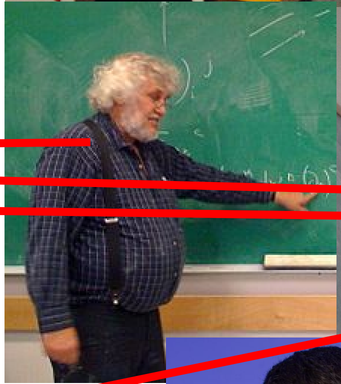
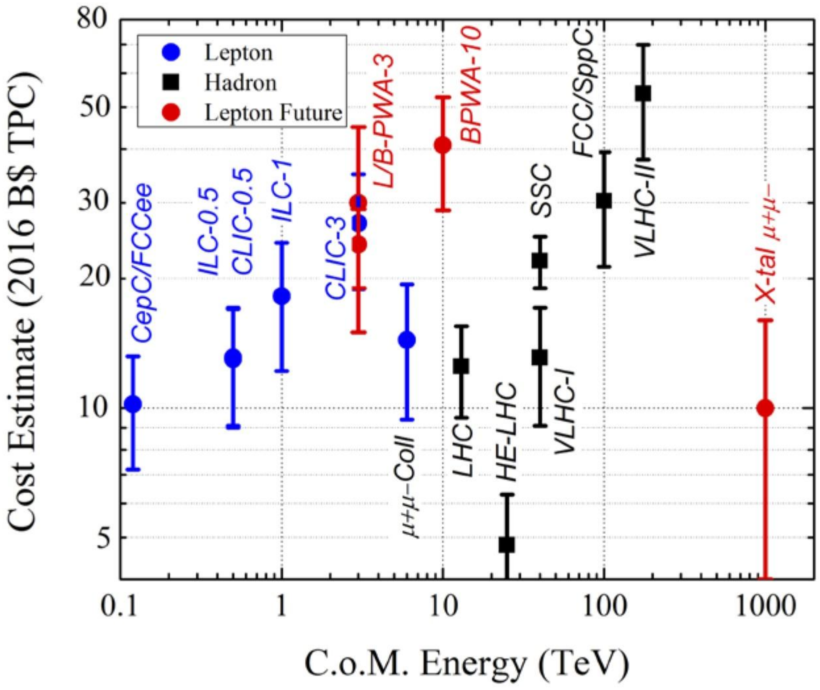




(Venn diagram from James Amundson’s talk)

How can we leverage quantum information theory and technologies to learn about fundamental physics?

The energy frontier is *really* expensive



From V. Shiltsev, FNAL report 2016

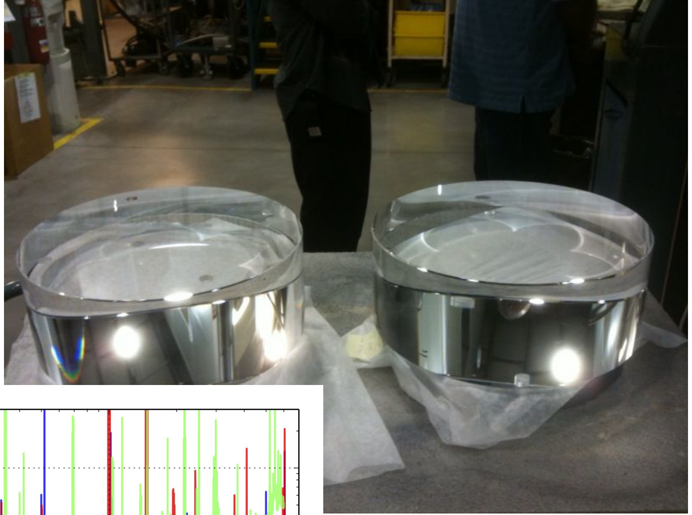
Challenges and opportunities

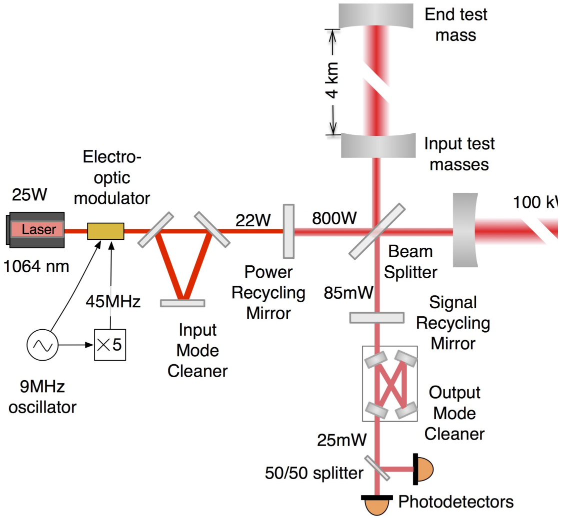
Traditional approach: build collider/fixed target, throw things together, compare probabilities of various outgoing states to predictions from a Lagrangian. Progress relies heavily on increasing energy/luminosity.

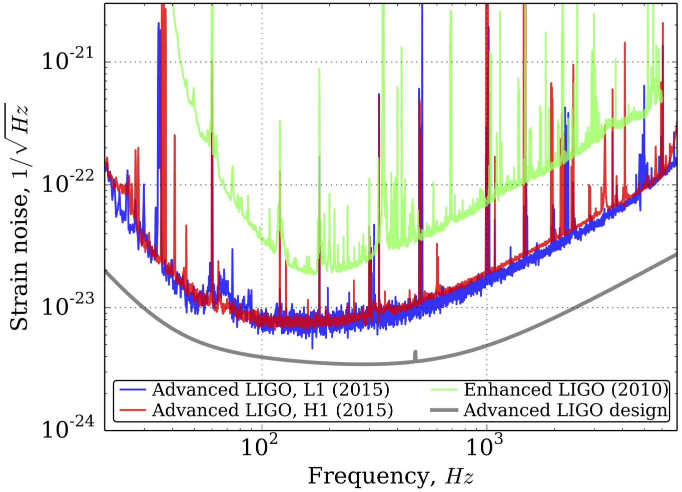
Quantum info opportunities:

- Simulation of QFTs, see other talks today
- New ways to think about fundamental physics (Ryu-Takayanagi etc. in AdS/CFT, quantum info in low energy EFT, …)
- Increased precision and new observables at fixed energy (wave-packet engineering, metrology, ...)
- Radically new systems: macroscopic superpositions

LIGO as the new norm



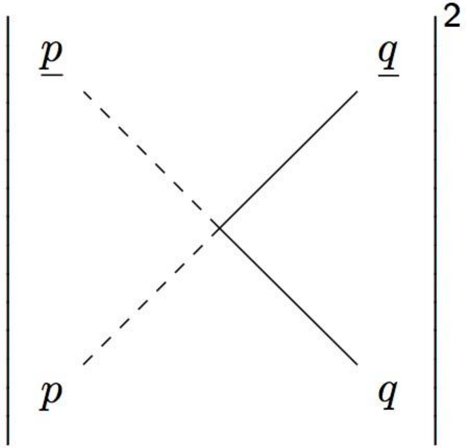




Particle physics interferometry

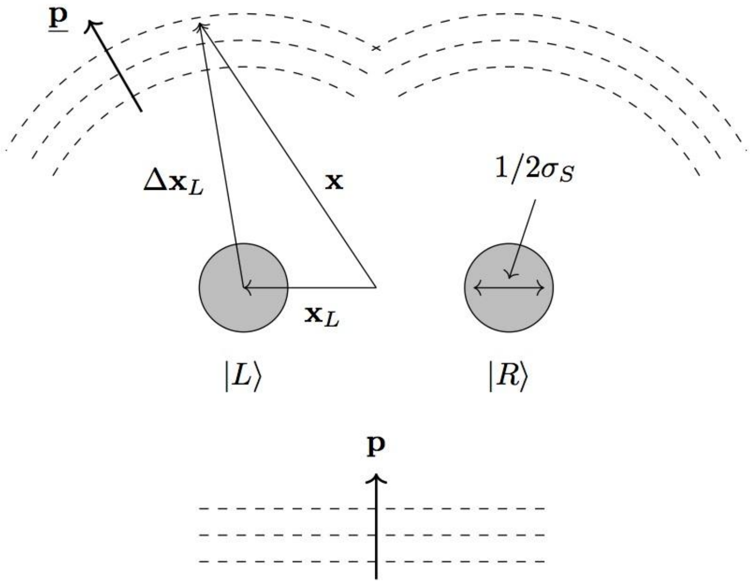
Consider two scalar fields coupled via $\lambda\varphi^2\chi^2$, try to measure λ.

$$\mathrm{Prob}(\mathbf{p}', \mathbf{q}') \sim |M^2| =$$



$$\sim \lambda^2$$

Exploiting wavepacket engineering



$$\rho_{initial} = |\mathbf{p}\rangle\langle\mathbf{p}|_{\psi} \otimes \begin{pmatrix} \frac{1}{2} & \alpha \\ \alpha & \frac{1}{2} \end{pmatrix}_{\phi}$$

$$P(\underline{\mathbf{p}}) \sim \delta_{\mathbf{p}',\mathbf{p}} - |M|^2(1+\alpha) \sim \delta_{\mathbf{p}',\mathbf{p}} - \lambda^2(1+\alpha)$$

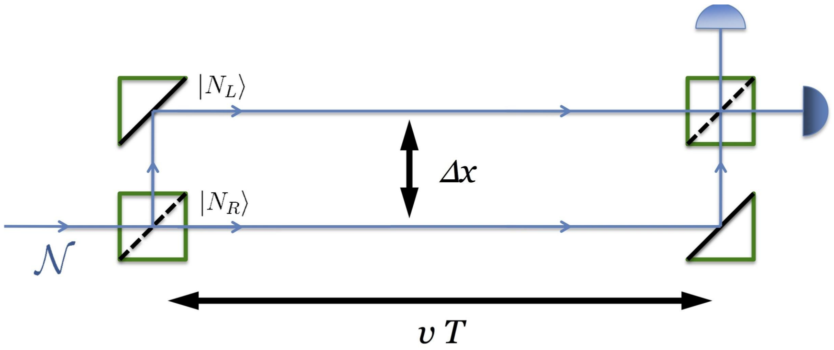
$$P(\mathbf{x}, t) = A(\mathbf{x}, t)\sin\left(\phi_{LR}(\mathbf{x}, t)\right)$$

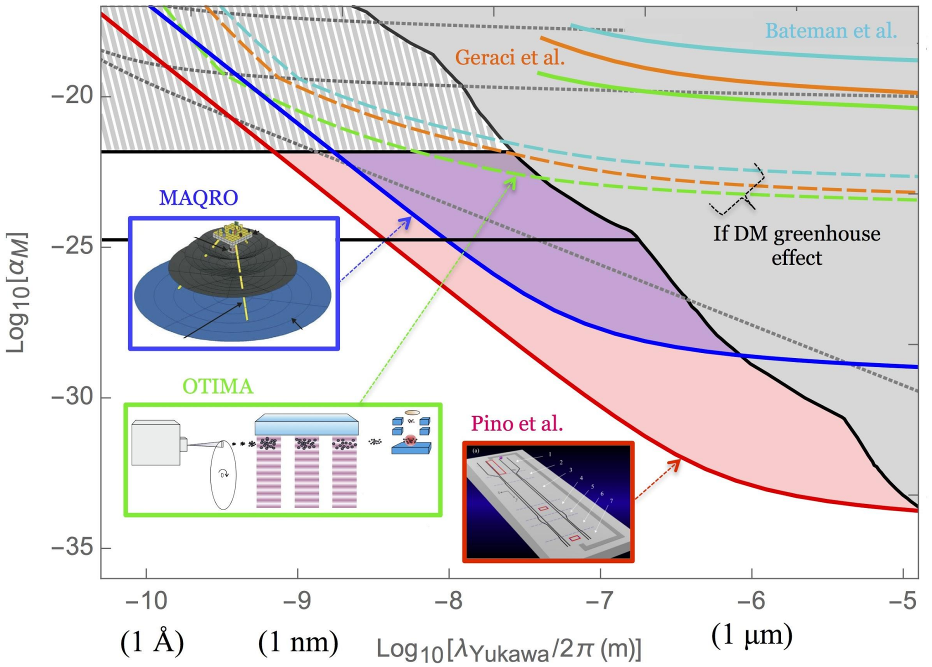
$$A \sim \alpha M \sim \alpha\lambda$$

DC, Chaurette, Semenoff 1606.03103

Dark matter detection via decoherence

Instead of looking for direct DM collisions, can try to infer existence of DM by its action as a decoherence channel.





Riedel PRD 2013 and PRA 2015

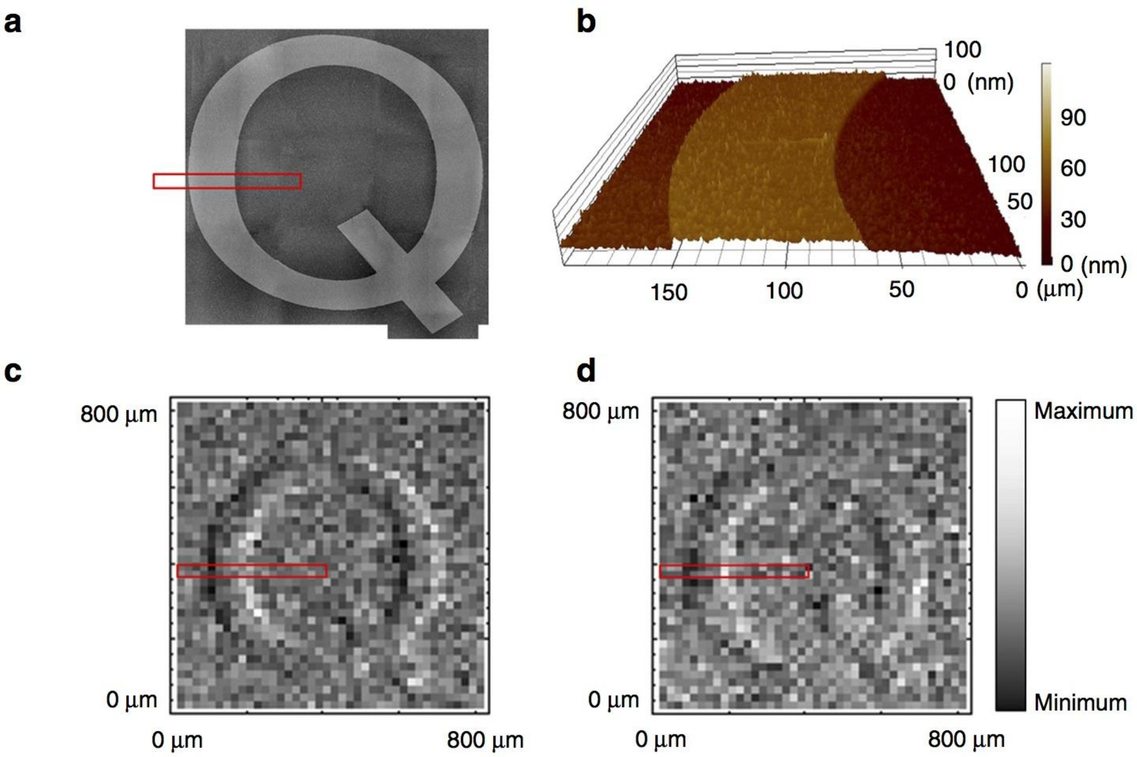
Yavin and Riedel PRD 2017

Quantum metrology

Classical measurements, with n uncorrelated sources: error ~1/sqrt(n)

Exploiting entanglement in sources: error ~1/n

Nice review: Giovannetti, Lloyd, Maccone, Nature Photonics 2011

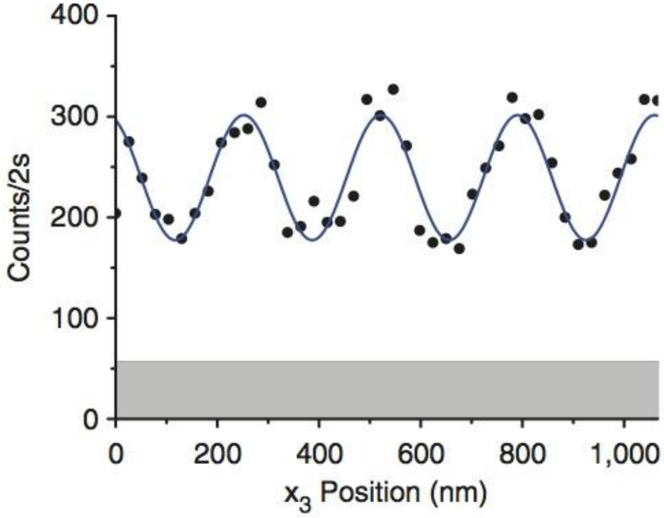


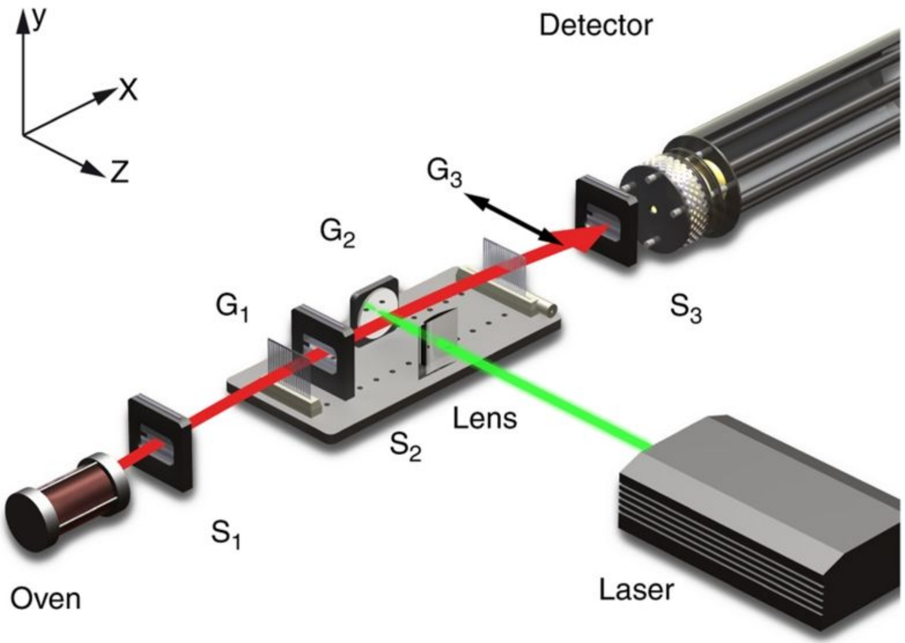
Ono, Okamoto, Takeuchi Nature Comm. 2013
“Entanglement-enhanced microscope”

Meso-to-macroscopic superpositions

Example: cold molecular beam interferometry

$R \sim 60$ Å, $M \sim 5000$ amu, $\Delta X \sim 10^{-6}$ m

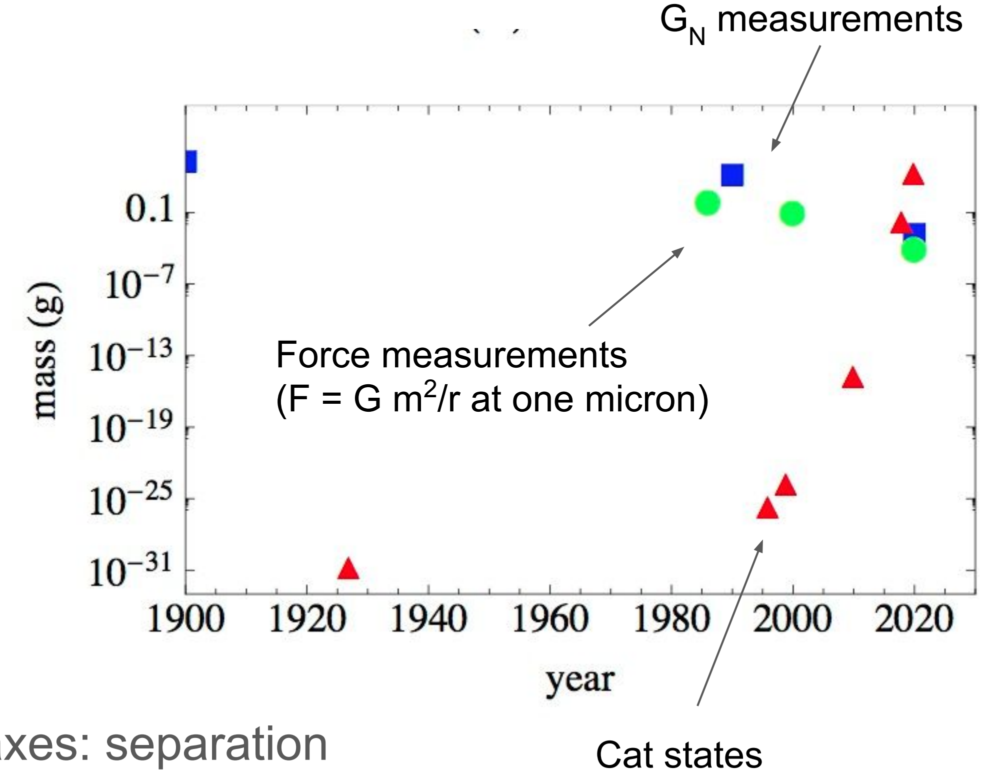




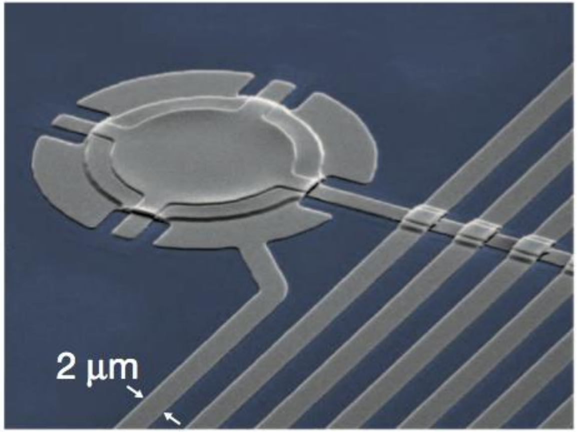
Gerlich, Arndt et. al Nature Comm. 2011

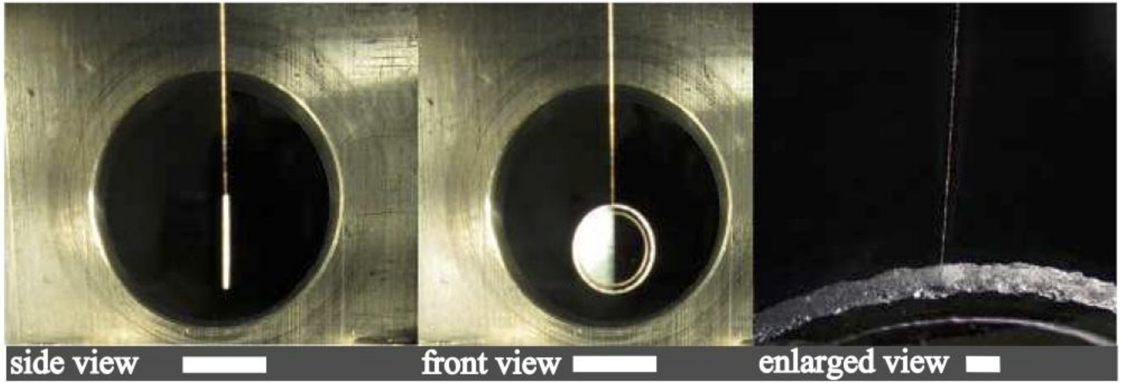
Macroscopic superpositions?

Toward macroscopic superpositions



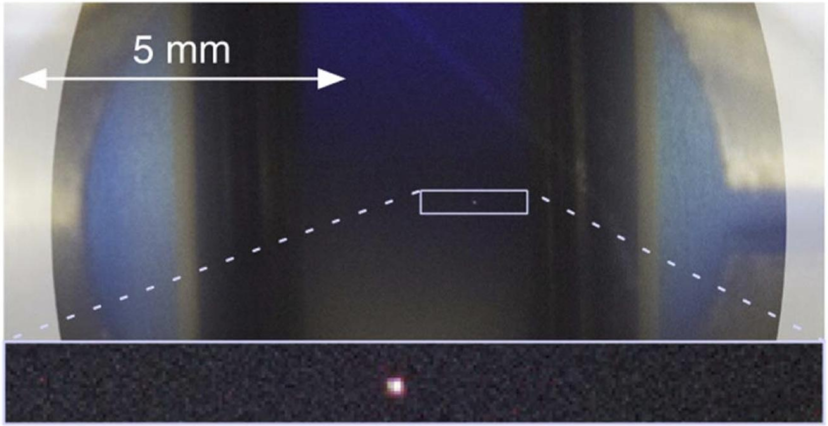
Suppressed axes: separation scale ΔX, coherence scale Δt, ...

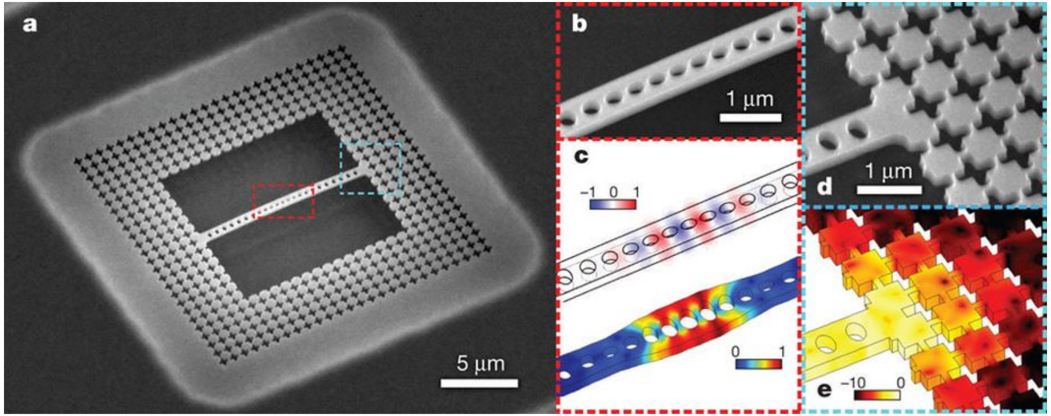




Teufel et al, Nature 2011

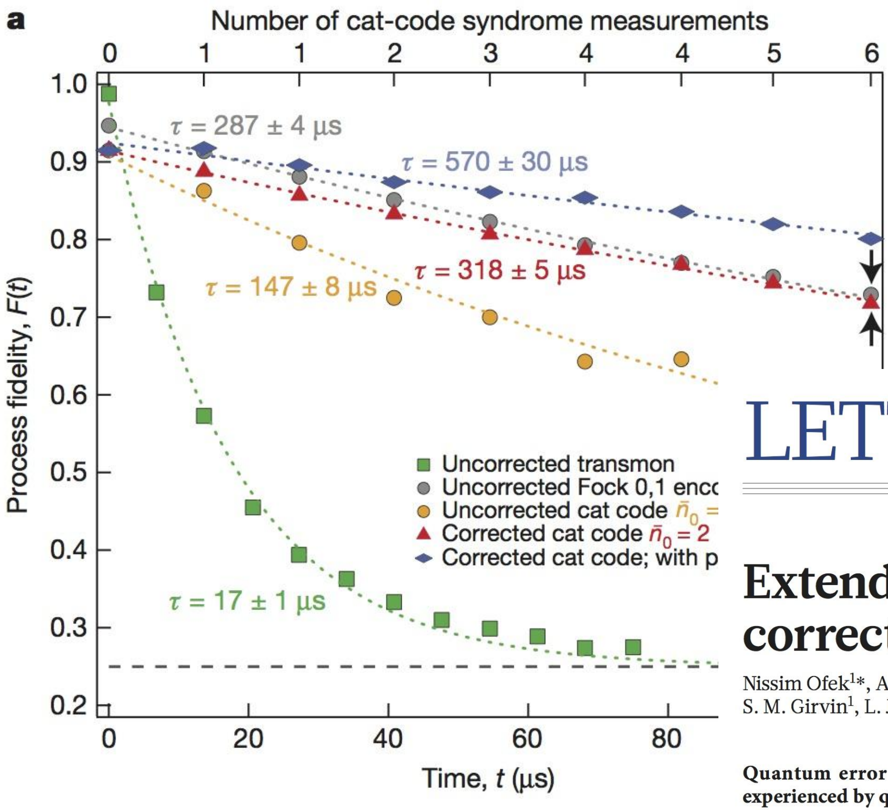
Matsumoto et al, PRA 2015





Aspelmeyer ICTP slides 2013

Painter et al, Nature 2011



Nature 2016

LETTER

doi:10.1038/nature18949

Extending the lifetime of a quantum bit with error correction in superconducting circuits

Nissim Ofek[1]*, Andrei Petrenko[1]*, Reinier Heeres[1], Philip Reinhold[1], Zaki Leghtas[1]†, Brian Vlastakis[1], Yehan Liu[1], Luigi Frunzio[1], S. M. Girvin[1], L. Jiang[1], Mazyar Mirrahimi[1,2], M. H. Devoret[1] & R. J. Schoelkopf[1]

Quantum error correction (QEC) can overcome the errors experienced by qubits[1] and is therefore an essential component of a future quantum computer. To implement QEC, a qubit is redundantly encoded in a higher-dimensional space using quantum states with carefully tailored symmetry properties. Projective

to operate within a continuous-variable framework[23], the cat code exploits the fact that a coherent state $|\alpha\rangle$ is an eigenstate of the resonator lowering operator $\hat{a}$: $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$. Using a logical basis comprised of superpositions of cat states, which are eigenstates of photon-number parity, the cat code requires just a single ancilla to monitor the dominant

Quantum gravity

Perturbative quantum general relativity at low energies is an excellent effective field theory. Corrections to tree diagrams are suppressed by E/M_{pl}.

But is it really an effective field theory? How would we know?

Can we test this basic idea with macroscopic QM systems?

Some painful truths

Graviton loops: suppressed by $E_{collider}/M_{pl} << 10^{-15}$

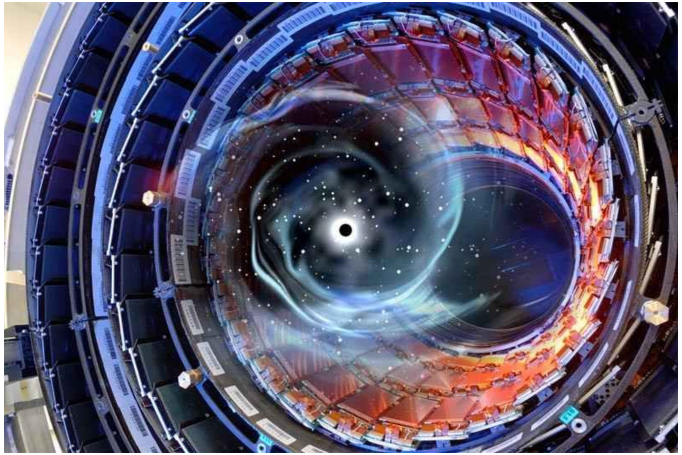
Hawking radiation $T_{Hawking}/T_{CMB} << 10^{-9}$

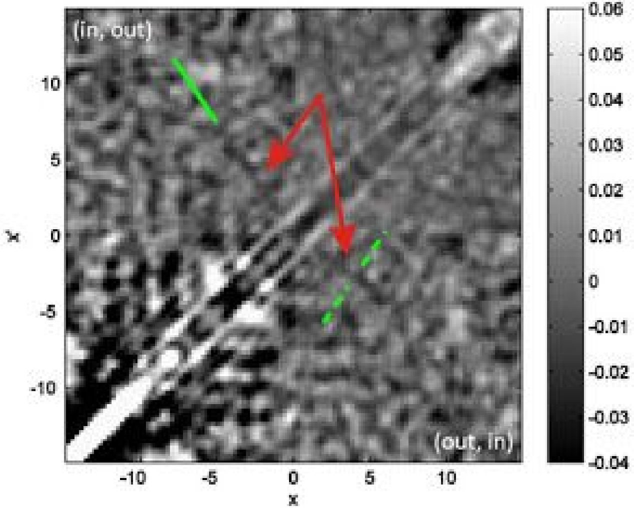
(although cf. Steinhauer et al analogue systems)

Mini black holes, Randall-Sundrum-style effects, similar QG exotica not seen so far at LHC

AdS/CFT predictions for eg. RIHC, high-Tc not looking good, and would provide circumstantial evidence at best

→ Re-evaluate basic assumptions for loopholes!





Steinhauer, Nature Phys. 2016

Is gravity quantum at all?

Feynman: early development of graviton, but also interesting “what if something goes wrong” passage in *Lectures on Gravitation*

In spite of these arguments, we would like to keep an open mind. It is still possible that quantum theory does not absolutely guarantee that gravity *has* to be quantized. I don't want to be misunderstood here—by

… lots of text about how not to misunderstand him...

If this failure of quantum mechanics is connected with gravity, we might speculatively expect this to happen for masses such that $GM^2/\hbar c = 1$, of M near 10^{-5} grams, which corresponds to some 10^{18} particles. Now quantum mechanics gives

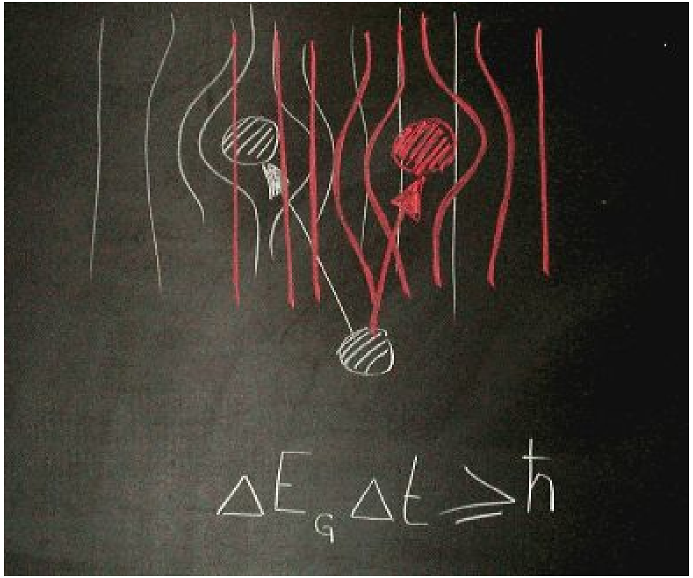
Non-canonical gravitational decoherence

Penrose: posit “fundamental” collapse time; order-of-magnitude effect, Newtonian limit. (GRG 1996), cf. Diosi’s work

Detailed, covariant path integral versions: Stamp 1506.05065; DC, Stamp, Barvinsky

$$Q[J] = \sum_{n=1}^{\infty} Q_n[J]$$

$$Q_n[J] = \int DgD\psi_1 \cdots D\psi_n \Delta[g]$$
$$\times \exp\left\{ -i \left(S_{EH}[g] + \frac{1}{n} \sum_{i=1}^{n} S_{mat}[g, \psi_i] + \int d^d x \, \sqrt{-g} J(x) \psi_i \right) \right\}.$$



(Bouwmeester PITP slides, 2011)

Interferometric tests

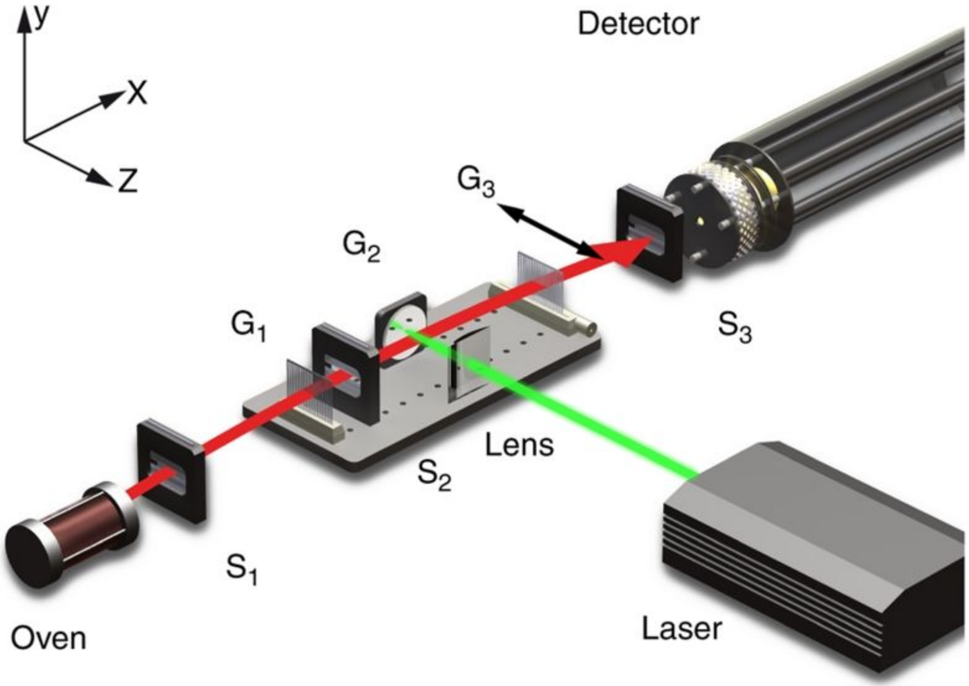
Diosi: (eg. J. Phys. A 2007)

$$\Delta t \sim \frac{\hbar R^3}{G_N M^2 \Delta x^2}$$

Cold molecular beam interferometry:

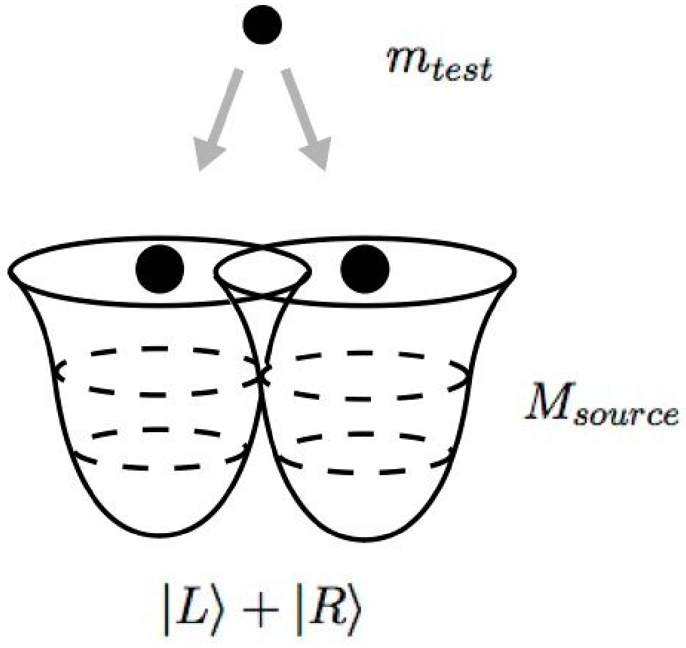
R ~ 60 Å, M ~ 5000 amu, $\Delta X \sim 10^{-6}$ m

---> $\Delta t \sim 10^{-2-3}$ sec!



Gerlich, Arndt et. al Nature Comm. 2011

Can gravity entangle objects?



Standard GR as EFT scenario: yes.

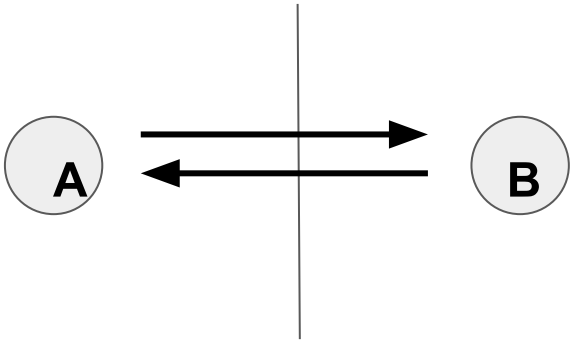
AdS/CFT: yes.

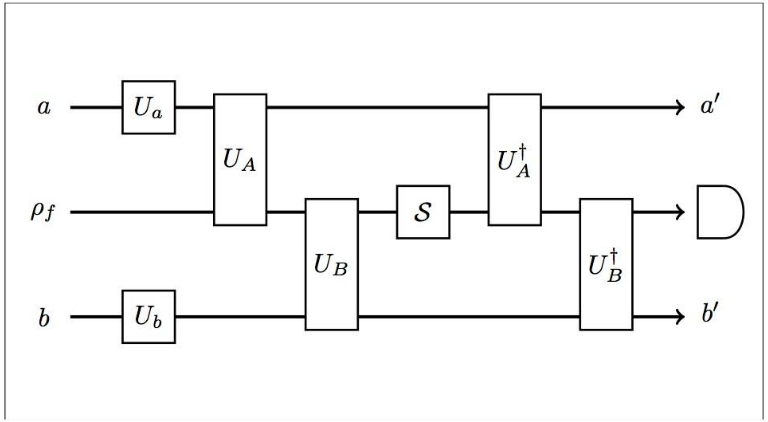
But are there other viable options?

Can we test them?

Gravity as a classical communications channel

Classical force laws without entanglement generation:





Kafri, Taylor 1311.4558

Kafri, Taylor, Milburn 1401.0946 & 1404.3214

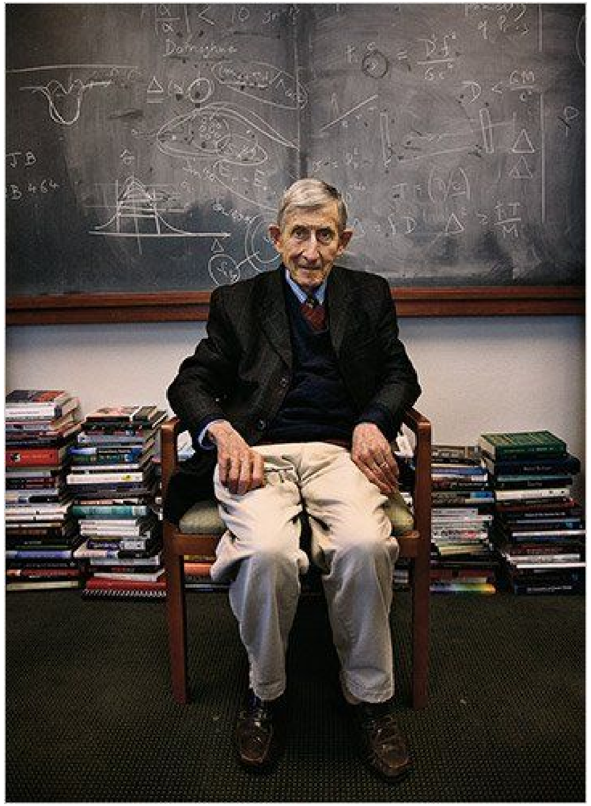
Inevitable, minimal amount of noise in the effective dynamics

For V=GMm/r, cf. long-lifetime Rb87 condensates, t ~ 5 sec means heating < 10^{-30} J/s, which puts bound a > 10^{-13} m as a discretization scale in this model.

GR as EFT. Any insights from quantum info?

Dyson 2012 (Poincare prize lecture): gravitons probably not detectable even “in principle” (based on some study of prototypical graviton detector designs)

Possible option: infer existence of graviton via decoherence?



Infrared quantum information

Naive scattering picture: incoming momentum eigenstate scatters to outgoing coherent, pure superposition of momentum eigenstates

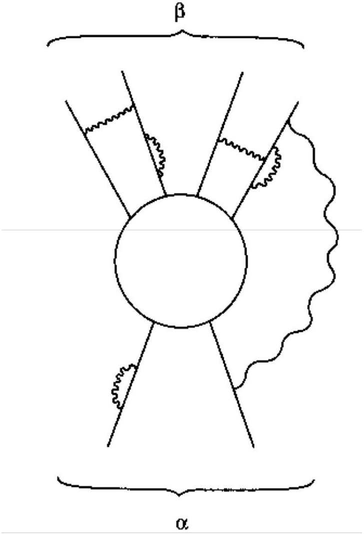
$$|\psi\rangle = |p_1 p_2 \cdots\rangle \to \int dq_1 dq_2 \cdots \; S_{q_1 q_2 \ldots; p_1 p_2 \ldots} |q_1 q_2 \cdots\rangle$$

Bloch-Nordsieck, Weinberg: in QED and perturbative GR, virtual IR divergences render S = 0 if the outgoing states have finite numbers of gauge bosons. IR catastrophe!

Infrared catastrophe and decoherence

Solution: must include arbitrary soft boson emission and average over states.

But this leads to somewhat radical info-theoretic answer:



$$|\psi\rangle\langle\psi| \xrightarrow[\text{trace soft}]{} \rho_{hard} \sim \begin{pmatrix} \left(\frac{E}{\Lambda}\right)^A |S_{qp}|^2 & 0 & \cdots \\ 0 & \ddots & \\ \vdots & & \end{pmatrix}$$

DC, Chaurette, Neuenfeld, Semenoff 1706.03782 (PRL 2017) & 1710.02531

Strominger 1706.07143: application to black hole information loss?

Measuring graviton-induced decoherence

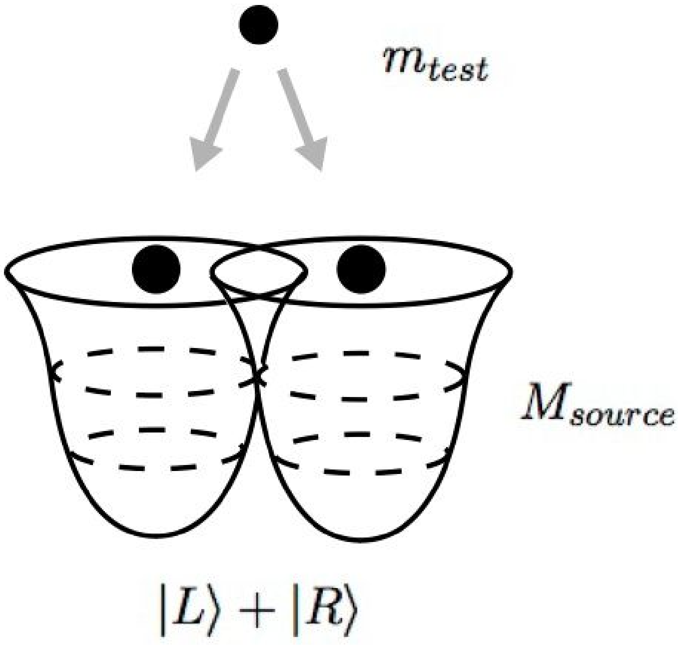
Simple model: background graviton bath at temperature T coupled to system in superposition of two energy states. Causes decoherence.

Dimensional analysis (eg. Blencowe PRL 2013, although grain of salt here):

$$\Gamma_{\mathrm{decohere}} \sim \frac{k_B T}{\hbar}\left(\frac{E - \tilde{E}}{E_P}\right)^2,$$

~ 100 Hz given N_A x 1 eV energy split, T ~ 1 K

Macroscopic superpositions can test these ideas



Theory space includes:

- Standard GR as EFT
- Penrose, Diosi, et al style collapse models
- Emergent gravity (eg. Jacobson, Padmanabhan thermodynamic gravity)
- Classical channel models
- Pheno models (non-commutative geometry, holographic noise, …)

These are ALL potentially testable/falsifiable!

Summary

Energy frontier is difficult to push

Quantum information suggests new theories, new observables and new experimental methods

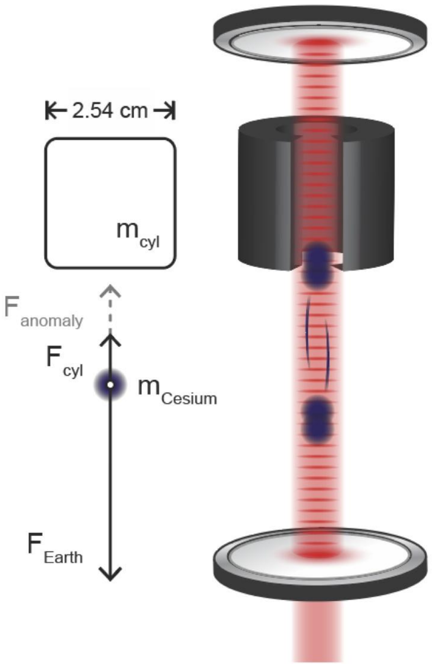
Techniques and theory are developing for many reasons (quantum computing, etc), and operate at currently-accessible energies

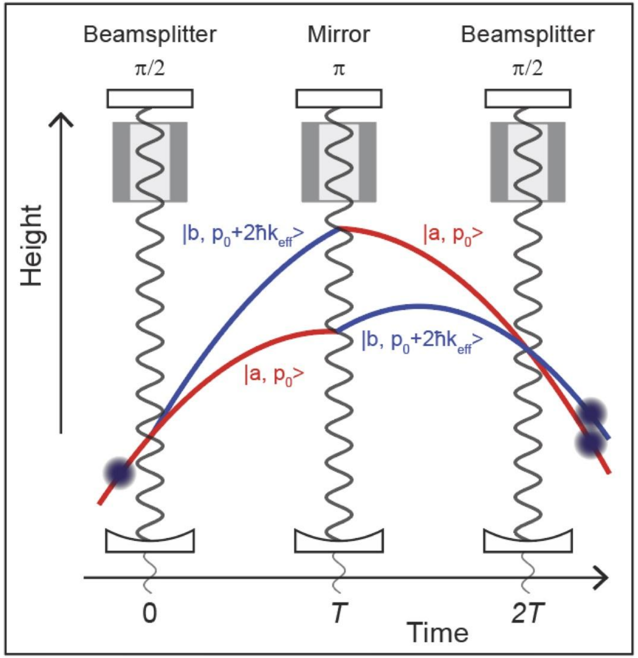
Very definite applications to probing quantum gravity. Some new variations on standard scattering experiments also possible

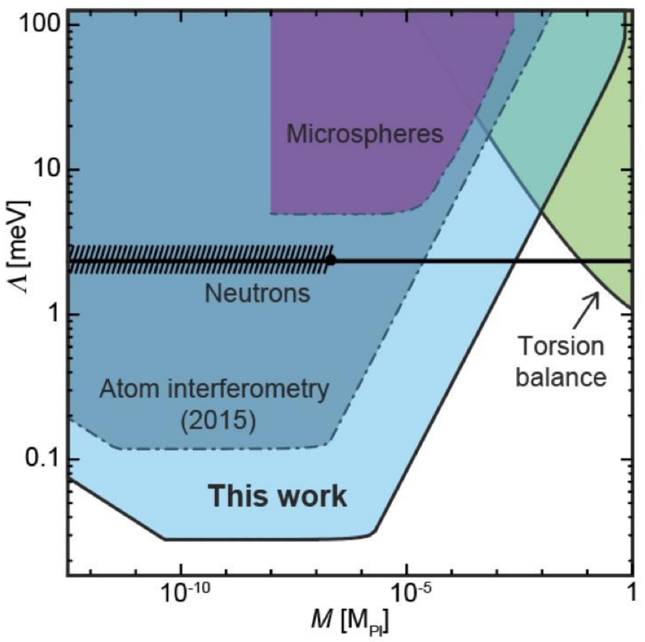
5th-force experiments

$$V(\varphi) = \Lambda^4 + \frac{\Lambda^{4+n}}{\varphi^n}$$

$$V_{\mathrm{int}} = \rho_{\mathrm{m}} \varphi / M$$

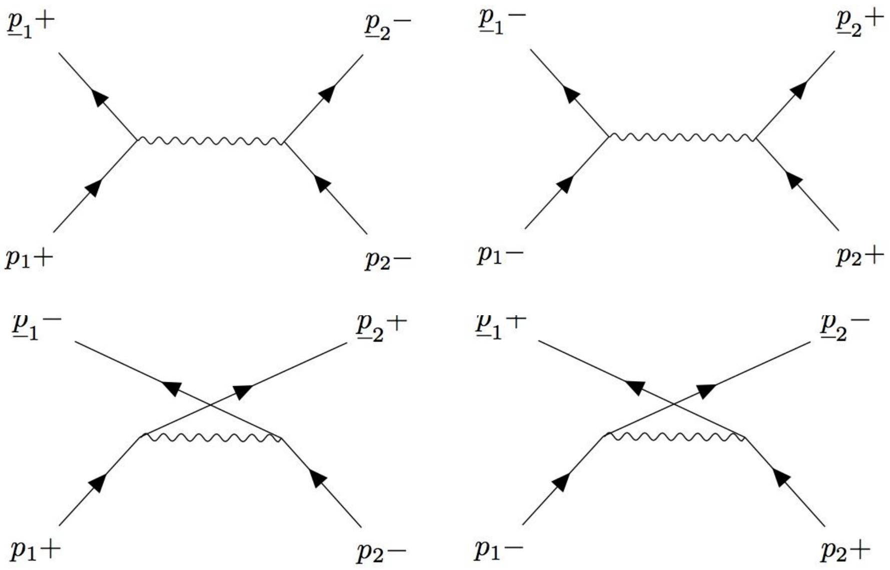






Khoury, Muller et al, Nature Phys 2017

Exploiting initial-state entanglement



Toy problem: massless QED

$$|\psi\rangle = a\,|\mathbf{p}_1+,\mathbf{p}_2-\rangle + b\,|\mathbf{p}_1-,\mathbf{p}_2+\rangle$$

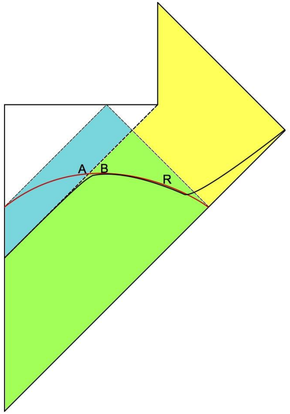
$$\begin{aligned} P(\underline{\mathbf{p}}) &= \left|aM_{+-;+-} + bM_{+-;-+}\right|^2 + \left|aM_{-+;+-} + bM_{-+;-+}\right|^2 \\ &= \frac{e^4}{(2\pi)^6 p^4}\left[\left|a\frac{1+\cos\theta}{1-2\cos\theta} - b\frac{1-\cos\theta}{1+2\cos\theta}\right|^2 \right. \\ &\quad \left. + \left|a\frac{1-\cos\theta}{1+2\cos\theta} - b\frac{1+\cos\theta}{1-2\cos\theta}\right|^2\right]. \end{aligned}$$

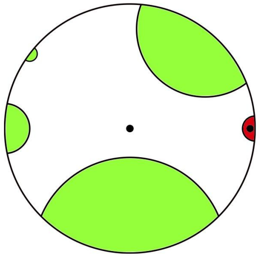
Nice pie-in-the-sky example: graviton-mediated ***γγ*** scattering (Ratzel, Wilkens, Menzel 1511.01237)

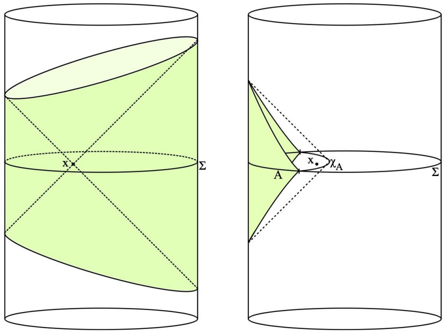
Finite-time soft corrections are tiny:

$$0 \to \lambda^A, \quad A \sim (e^2 + E/M_p^2)\Delta v^2$$

Beyond low-energy: BHs, AdS/CFT, QEC, etc.







Almheiri, Marolf, Polchinski, Sully, (Stanford) 2012: black holes in tension with strong subadditivity

Hayden, Harlow 2013: doesn't matter, can't do computation to verify the entanglement before you fall onto the singularity

Cf. other people like Oppenheim, Unruh: you can do the computation if the black hole is pre-computed, ...

Almheiri, Dong, Harlow 2014: local operators error-encoded by boundary CFT

Lifetimes

Can we exploit quantum error correction to stabilize these systems?

“Cat codes”: use bosonic mode in coherent state to do encoding.

$$a\,|\alpha\rangle = \alpha\,|\alpha\rangle\,, \quad \alpha \in \mathbf{C}$$

$$|\pm\alpha\rangle = |\alpha\rangle \pm |-\alpha\rangle$$

$$|0\rangle \mapsto |+\alpha\rangle$$

$$|1\rangle \mapsto |-\alpha\rangle$$

This converts amplitude damping into a bit flip error, which can be corrected by standard QEC methods!

Cochrane, Milburn, Monroe PRA 1999 & de Matos Filho and Vogel PRL 1996

Things we do know

Confirmed in detail: classical gravitational fields (eg. Earth’s) act as external potentials in the Schrodinger equation

Somewhat circumstantial: semiclassical gravity might make sense, eg. in inflation

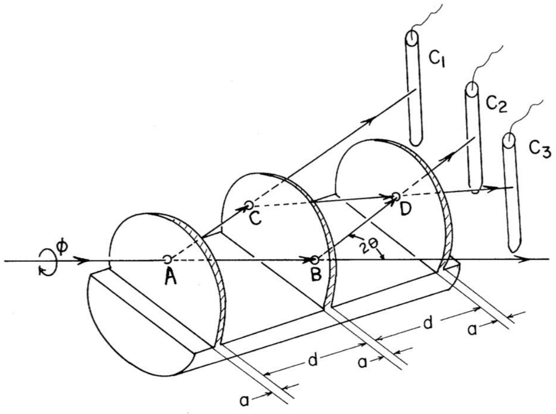
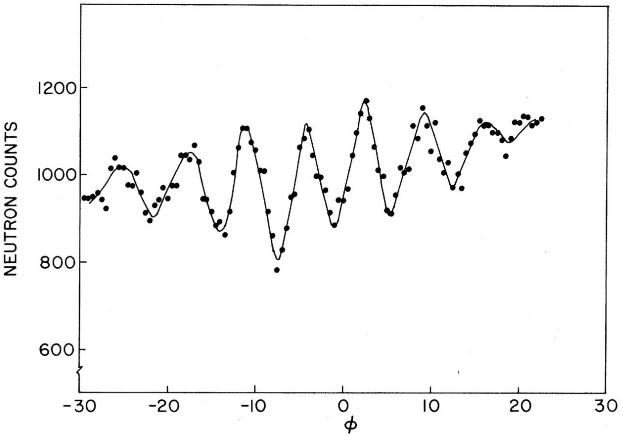
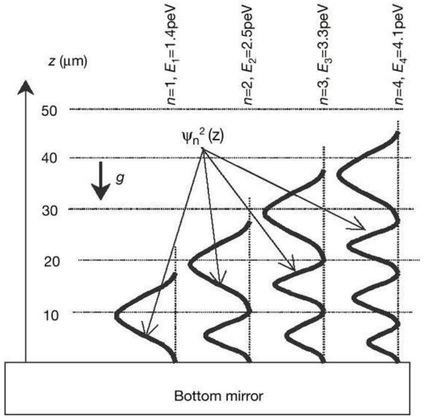
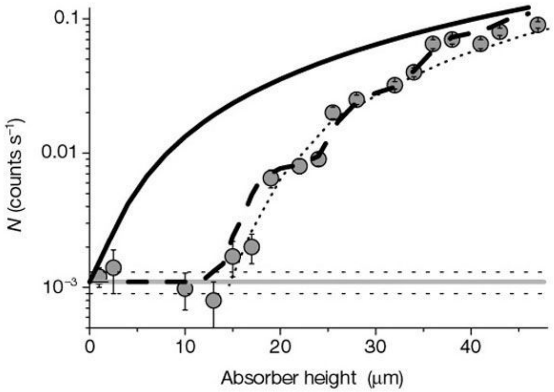


FIG. 1. Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.

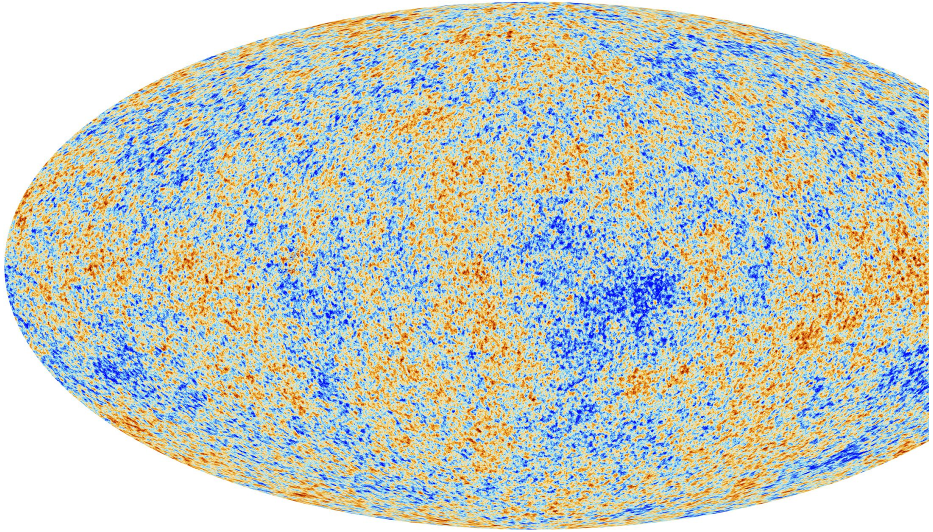


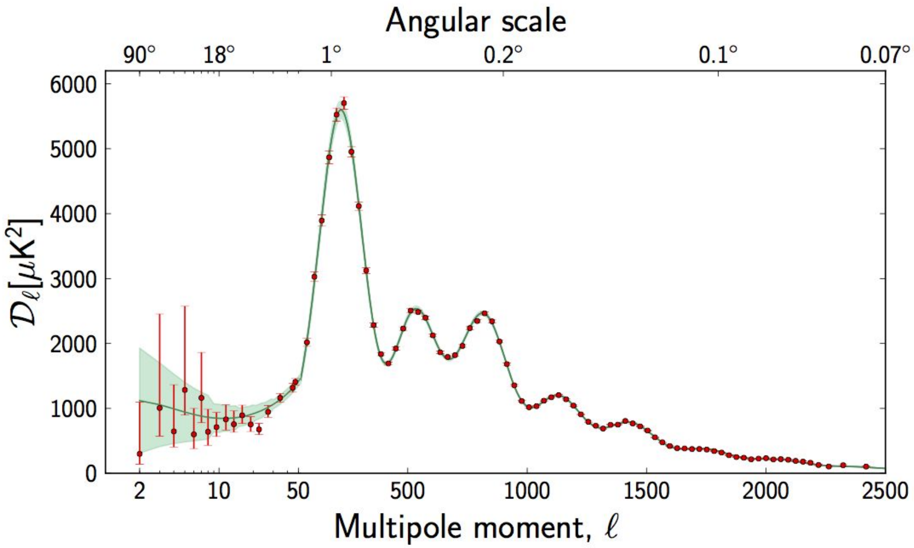




Collela, Overhauser, Werner PRL 1975

Nesvizhevsky et al. Nature 2002





$$\delta\phi = 0\,, \qquad g_{ij} = a^2[(1-2\mathcal{R})\delta_{ij} + h_{ij}]\,, \qquad \partial_i h_{ij} = h^i_i = 0\,.$$

Fine, but what about real quantum gravity?

"Semiclassical gravity"?

$$G_{\mu\nu} = M_p^{-2} \langle\psi| T_{\mu\nu} |\psi\rangle \longrightarrow \nabla^2\Phi = M_p^{-2} \langle\psi|\rho|\psi\rangle$$

$$i\partial_t |\psi\rangle = (H_{free} - \Phi_{grav}) |\psi\rangle$$

VOLUME 47, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1981

Indirect Evidence for Quantum Gravity

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and

C. D. Geilker
Department of Physics, William Jewell College, Liberty, Missouri 64068
(Received 9 June 1981)

An experiment gave results inconsistent with the simplest alternative to quantum gravity, the semiclassical Einstein equations. This evidence supports (but does not prove) the hypothesis that a consistent theory of gravity coupled to quantized matter should also have the gravitational field quantized.

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Measurable signatures of quantum mechanics in a classical spacetime

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We propose an optomechanics experiment that can search for signatures of a fundamentally classical theory of gravity and in particular of the many-body Schrödinger-Newton (SN) equation, which governs the evolution of a crystal under a self-gravitational field. The SN equation predicts that the dynamics of a