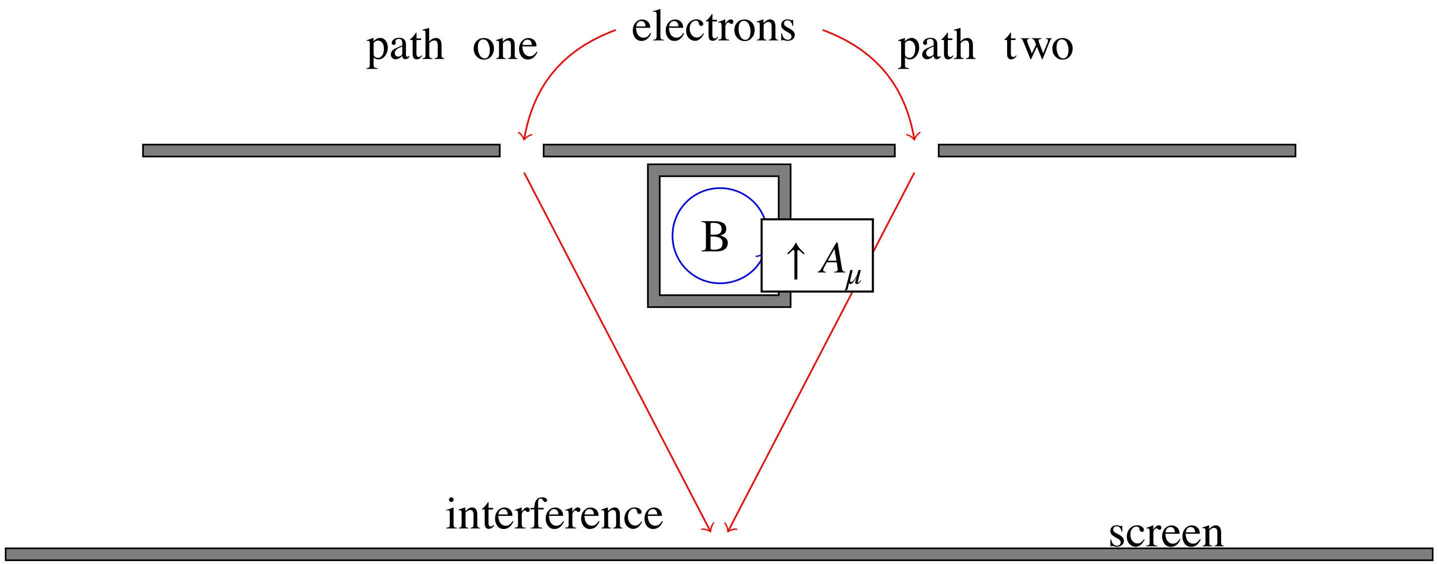
Thoughts about the Gravitational Ahoronov-Bohm Effect

MAGIS meeting, Dec. 7th 2022

John Ellis

KING'S College LONDON

Aharonov-Bohm Effect



- Electron wave function picks up phase, even though $\mathbf{B}, \mathbf{E} = 0$, from the potential $\mathbf{A}$ generated by the $\mathbf{B}$ flux through loop

$$\varphi = \frac{q}{\hbar} \int_P \mathbf{A} \cdot d\mathbf{x} \qquad \Delta\varphi = \frac{q\Phi_B}{\hbar}$$

- Interpretation: Forces are an incomplete way to formulate physics, and potential energies must be used instead.
- The potential energy directly changes the phase of the electron wave function, which is measurable.

PHYSICS

Observation of a gravitational Aharonov-Bohm effect

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Gravity curves space and time. This can lead to proper time differences between freely falling, nonlocal trajectories. A spatial superposition of a massive particle is predicted to be sensitive to this effect. We measure the gravitational phase shift induced in a matter-wave interferometer by a kilogram-scale source mass close to one of the wave packets. Deflections of each interferometer arm due to the source mass are independently measured. The phase shift deviates from the deflection-induced phase contribution, as predicted by quantum mechanics. In addition, the observed scaling of the phase shift is consistent with Heisenberg's error-disturbance relation. These results show that gravity creates Aharonov-Bohm phase shifts analogous to those produced by electromagnetic interactions.

In classical physics, the state of a particle is given by its position and momentum. Because the trajectory of a classical particle is determined by its interactions with local fields, the deflection of a particle can be used to observe a field. However, a classical particle cannot measure the action along its trajectory.

The situation is different in quantum mechanics. As Aharonov and Bohm argued in 1959, a particle in a spatial superposition is sensitive to the potential energy difference between its wave packets even if the field vanishes along their trajectories (*1*). A matter-wave interferometer can therefore measure a phase shift due to the potential even if the interferometer arms are not deflected. This phase shift ϕ_{AB} is given by the action difference ΔS between arms according to the expression $\phi_{AB} = \Delta S/\hbar$ (*1*). The Aharonov-Bohm effect can be described in terms of a quantum particle interacting with a classical electromagnetic potential (*1*) or in terms of a quantum particle interacting locally with a quantized electromagnetic field and source (*2*).

The Aharonov-Bohm effect induced by a magnetic field was first observed in 1960 (*3*). Since then, experiments have identified related effects in a variety of systems (*4*, *5*). The successful observation of Aharonov-Bohm phase shifts in the electromagnetic domain raises a question: Can analogous phase shifts be caused by gravity as well? Quantum mechanics predicts that gravity can create an action difference between interferometer arms, giving rise to a "gravitational Aharonov-Bohm effect" (*6*). In general relativity, this phenomenon is described by the gravitationally induced proper time difference between the geodesics corresponding to the interferometer arm trajectories. This effect has not previously been observed. Its experimental detection in an atom interferometer was proposed in (*7*).

Prior experiments (*8*) were not sensitive to the gravitational Aharonov-Bohm effect because $\Delta S \approx 0$ when the wave packet separation is small compared to the length scale of the gravitational potential (*9*, *10*). The interferometer phase in this regime is proportional to the deflection of the atomic wave packet with respect to its beam splitters (*11*, *12*) and is independent of the particle mass m. However, when the wave packet separation is large, ΔS becomes nonzero. Qualitatively, an interferometer enters this nonlocal regime when the wave packet separation becomes larger than the distance between the source mass and an interferometer arm.

We use a light-pulse ^{87}Rb atom interferometer (*12*) with large–momentum-transfer beam splitters ($52\hbar k$, where k is the laser wave number) and large wave packet separation (25 cm) to measure the phase shift induced by a tungsten source mass. At its closest approach, one interferometer arm passes within 7.5 cm of the source mass, which alters its proper time (Fig. 1A). The source mass also deflects the interferometer arms. To quantify the influence of deflections on the phase shift, we measure the deflections with a pair of $4\hbar k$ interferometers (2-cm wave packet separation). The phase shift of the $52\hbar k$ interferometer deviates strongly from the deflection-induced phase contribution. We show that $\phi_{AB} \neq 0$, demonstrating the gravitational Aharonov-Bohm effect in this system.

In the experiment (*13*, *14*), a cloud of ^{87}Rb is evaporatively cooled to ~1 μK in a magnetic trap, magnetically lensed to a velocity width of 2 mm/s, and launched into a 10-m vacuum chamber at 13 m/s by an optical lattice. The lattice depth is decreased for a short interval during the launch to release half of the atoms at a lower velocity [see materials and methods for details (*15*)]. After the launch, the two clouds are decelerated to a relative momentum of $2\hbar k$ by sequential Bragg transitions and are used as the inputs of a single-source gradiometer (*16*) with baseline 24 cm (Fig. 1B). The matter-wave beam splitters and mirrors consist of laser pulses that transfer momentum to the atoms via Bragg transitions. The midpoint trajectory of each $4\hbar k$ interferometer is matched to the trajectory of one arm of the $52\hbar k$ interferometer. The $52\hbar k$, upper $4\hbar k$, and lower $4\hbar k$ gradiometers are implemented in separate shots. The upper interferometer in each gradiometer is sensitive to the source mass, whereas the lower interferometer mainly acts as a phase reference. This reference is necessary to remove contributions to the phase shift arising from fluctuations in the phase of the optical field. The time between the initial beam splitter pulse and the mirror pulse (interferometer time T) is

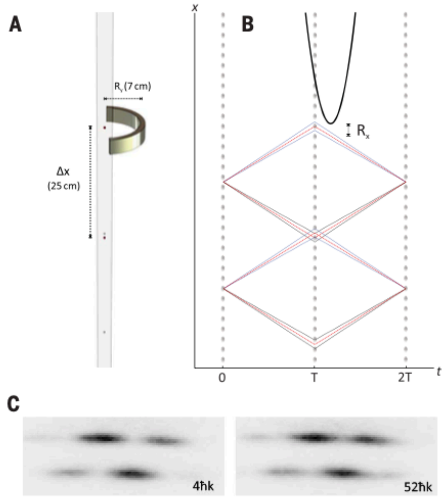

Fig. 1. Experimental setup. (**A**) Interferometer arms, tungsten source mass, and laser beam splitter. One arm of a light-pulse atom interferometer approaches the source mass, while the other arm remains far away. (**B**) Space-time diagram of gradiometer geometries in a freely falling reference frame. The red, blue, and black dotted lines represent the trajectories of the $52\hbar k$, upper $4\hbar k$, and lower $4\hbar k$ gradiometers, respectively, while the solid black line represents the trajectory of the source mass. Interferometer pulses (gray dashed lines) occur at times $t = 0$, $t = T$, and $t = 2T$. (**C**) Fluorescence images of interferometer output ports, $4\hbar k$ (left) and $52\hbar k$ (right).

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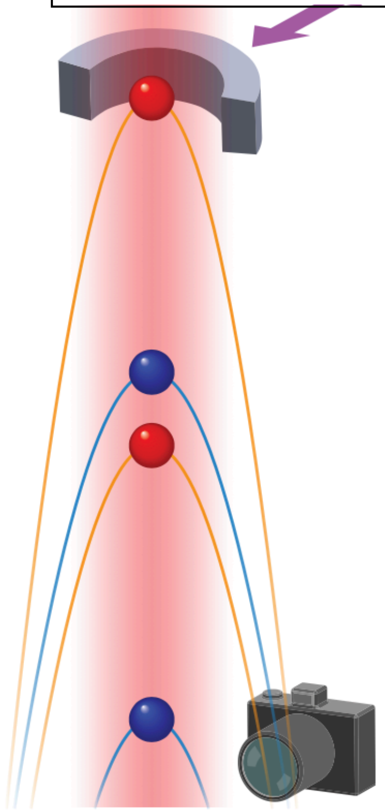
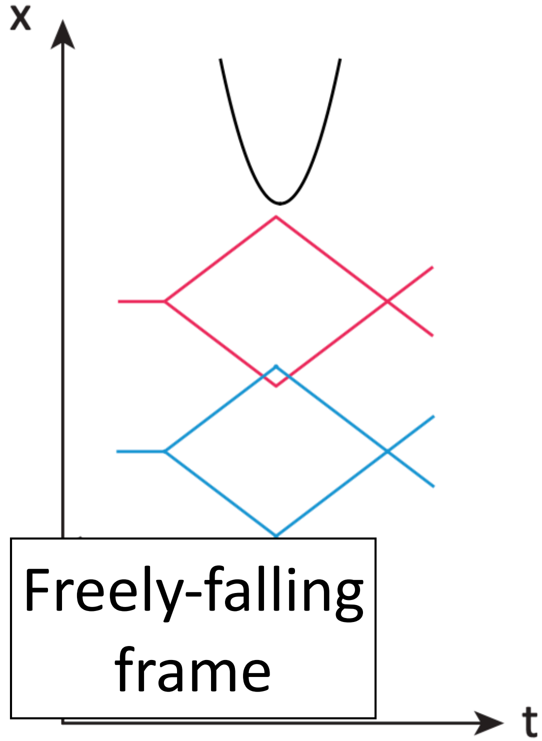
Overstreet et al, Science 375, 226 (2022)

AION

Gravitational Aharonov-Bohm

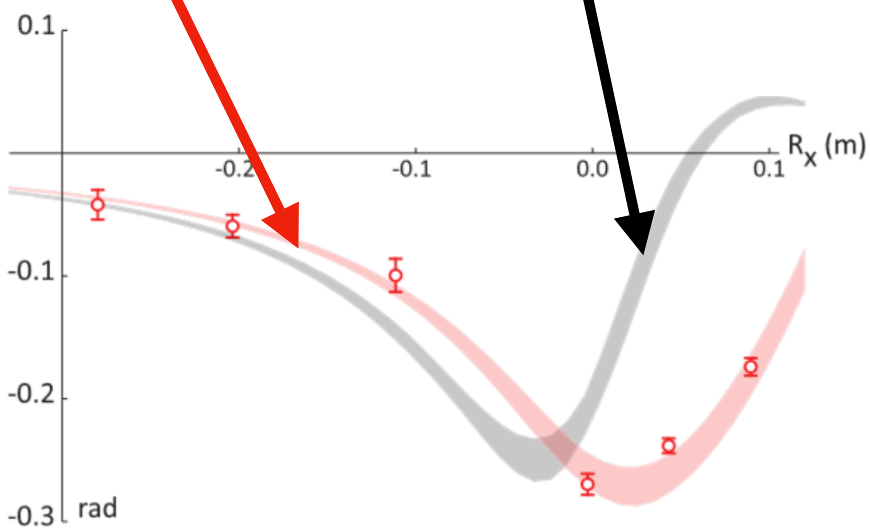
Tungsten collar around vertical shaft





Laboratory frame

- Upper cloud feels extra gravitational field
- Induces phase shift: not due to gravitational deflection alone



Phase shift due to energy stored in superposed gravitational fields:

Evidence for Quantum Gravity?

Overstreet et al, arXiv:2209.02214

Overstreet et al, Science 375, 226 (2022)

AION

Gravitational Aharonov-Bohm

- Analysis in classical reference frame
- Gravitational field energy in weak Newtonian limit

$$E_G = -\frac{1}{8\pi G}\int |\mathbf{g}|^2 d^4x : \ \mathbf{g} = \mathbf{g}_{\text{Atom}} + \mathbf{g}_{\text{Tungsten}}$$

- Phase shift $\Delta\phi = \int (E_1 - E_2)dt$ where $E_{1,2}$ are gravitational energies for two arms

$$\Delta\phi = -\frac{GmM}{\hbar}\int_{t=0}^{2T}\left[\frac{1}{|x_1 - x_s|} - \frac{1}{|x_2 - x_s|}\right]dt$$

- Phase shift is due to energy stored in superposed gravitational fields

nature COMMUNICATIONS

ARTICLE

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Quantum mechanics and the covariance of physical laws in quantum reference frames

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In physics, every observation is made with respect to a frame of reference. Although reference frames are usually not considered as degrees of freedom, in all practical situations it is a physical system which constitutes a reference frame. Can a quantum system be considered as a reference frame and, if so, which description would it give of the world? Here, we introduce a general method to quantise reference frame transformations, which generalises the usual reference frame transformation to a "superposition of coordinate transformations". We describe states, measurement, and dynamical evolution in different quantum reference frames, without appealing to an external, absolute reference frame, and find that entanglement and superposition are frame-dependent features. The transformation also leads to a generalisation of the notion of covariance of dynamical physical laws, to an extension of the weak equivalence principle, and to the possibility of defining the rest frame of a quantum system.

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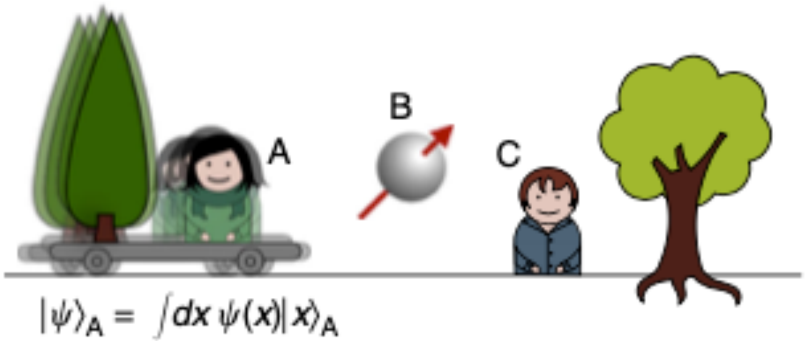
Giacomini, Castro-Ruiz & Brukner, Nature Comms 10, 494 (2019)

Quantum Reference Frame

- Quantum relativity principle: The laws of physics take the same form in every reference frame, including reference frames associated with quantum particles (quantum reference frames)

- Does a reference frame need to be classical? Can one use a quantum superposition of reference frames?



- Reference frame A is in a superposition of positions as observed from the laboratory C (the superposition is illustrated by the fuzziness of laboratory A).

- A and B are in quantum states according to observer in reference frame C

- What are the states of B and C as defined with respect to the reference frame of A?

Inference of gravitational field superposition from quantum measurements

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Experiments are beginning to probe the interaction of quantum particles with gravitational fields beyond the uniform-field regime. In standard quantum mechanics, the gravitational field in such experiments is written as a superposition state. We empirically demonstrate that alternative theories of gravity can avoid gravitational superposition states only by decoupling the gravitational field energy from the quantum particle's time evolution. Furthermore, such theories must specify a preferred quantum reference frame in which the equations of motion are valid. To the extent that these properties are theoretically implausible, recent experiments provide indirect evidence that gravity has quantum features. Proposed experiments with superposed gravitational sources would provide even stronger evidence that gravity is nonclassical.

I. INTRODUCTION

Understanding the fundamental nature of gravity is a significant open problem in theoretical physics. Unlike the other interactions, gravity lacks a satisfactory description as a quantum field, leaving open the possibility that gravity is fundamentally classical [1] or entropic [2] rather than quantum. On the other hand, several arguments [3–11] suggest that gravity ought to have quantum features.

For many years, it was believed that experiments could not contribute meaningfully to this discussion. Owing to the weakness of the gravitational interaction, it is not feasible to detect a single graviton in a gravitational-wave observatory or a particle detector [12]. Experimental evidence of the quantum nature of gravity is expected to appear at the energy scale corresponding to the Planck mass (10^{19} GeV), which is far beyond the reach of collider experiments.

Although the quantization of gravity cannot be probed directly, it may be possible to obtain experimental evidence of gravity's fundamental nature through indirect means. Two proposals [7, 8] ("BMV experiments") suggest searching for entanglement generation in a pair of matter-wave interferometers that interact gravitationally. Such low-energy tests might open the first observational window on the quantum description of the gravitational field, but the precise theoretical implication of these experiments is still an open question [9–11, 13–27]. However, it is widely believed that if gravity mediates entanglement between two quantum systems, then the gravitational field cannot be classical [28]. The experiments described in these proposals are challenging to implement because they require quantum control of large test masses ($\sim 10^{12}$ amu). Nevertheless, the idea of indirectly observing quantum-gravitational properties motivates an assessment of what we can infer from previous gravitational measurements in quantum systems.

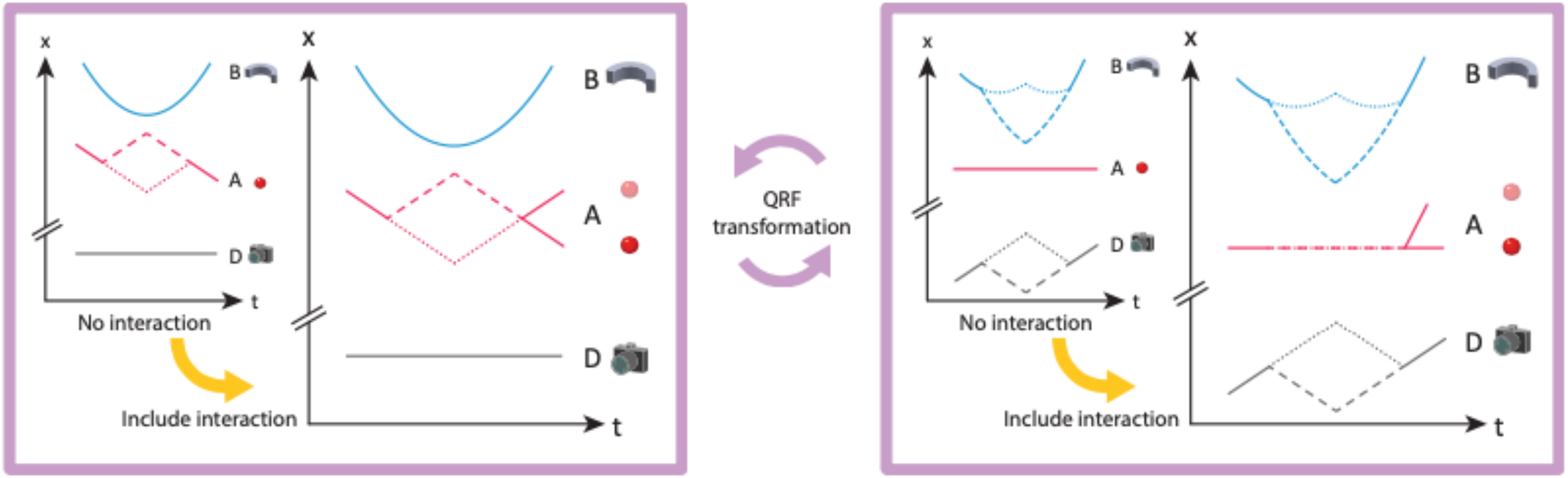
Beginning with the COW experiment in 1975 [29], many matter-wave interferometers have demonstrated sensitivity to inertial forces. Until recently, these experiments operated in a regime where the gravitational field is approximately uniform at the length scale of the measuring device. According to the equivalence principle [30], all observable effects in such experiments arise from the relative acceleration between the matter waves and the phase reference, which is induced by the nongravitational forces that keep the laboratory in place on the surface of the Earth. Hence, in these experiments, the observed phase shift is caused by non-gravitational forces [31]. Matter-wave interferometers in the uniform-field regime test the equivalence principle [32, 33] but do not provide quantum tests of any other gravitational properties [31]. Throughout this work, we will assume that the equivalence principle is valid to the accuracy of the experimental results we describe.

Genuine gravitational effects in quantum systems appear when the gravitational field is measurably nonuniform across the quantum state. Recent experiments have begun to investigate this scenario. Observations of phase shifts associated with gravitational tidal forces [34] and a gravitational Aharonov-Bohm effect [35] indicate that the trajectory [34] and action [35] of a matter wave in a nontrivial gravitational field are correctly predicted by standard quantum mechanics.

Taken by themselves, these results might appear to provide little information about gravity's fundamental nature. However, their implications are much stronger if one makes additional assumptions about the fundamental principles underlying the description of the experiment. In particular, we identify the following three principles:

1. *Existence of gravitational fields*: Any massive particle that is well-localized at a position $\mathbf{x_0}$ sources a gravitational field $\mathbf{g}$ with functional form $\mathbf{g}(\mathbf{x}-\mathbf{x_0})$ [36].

Gravitational AB Experiment in AION Quantum Reference Frame



- Phase shift $\Delta\phi$ is given by difference of potential energies of two quantum-mechanical paths

$$\Delta\phi = \frac{1}{\hbar}\int_{t=0}^{2T} \left[U(|y_{B,1}|) - U(|y_{B,2}|)\right] dt$$
$$= -\frac{GmM}{\hbar}\int_{t=0}^{2T} \left[\frac{1}{|x_1 - x_s|} - \frac{1}{|x_2 - x_s|}\right] dt$$

- Or by superposition of potential energies of two locations of metal collars

Overstreet et al. arXiv:2209.02214

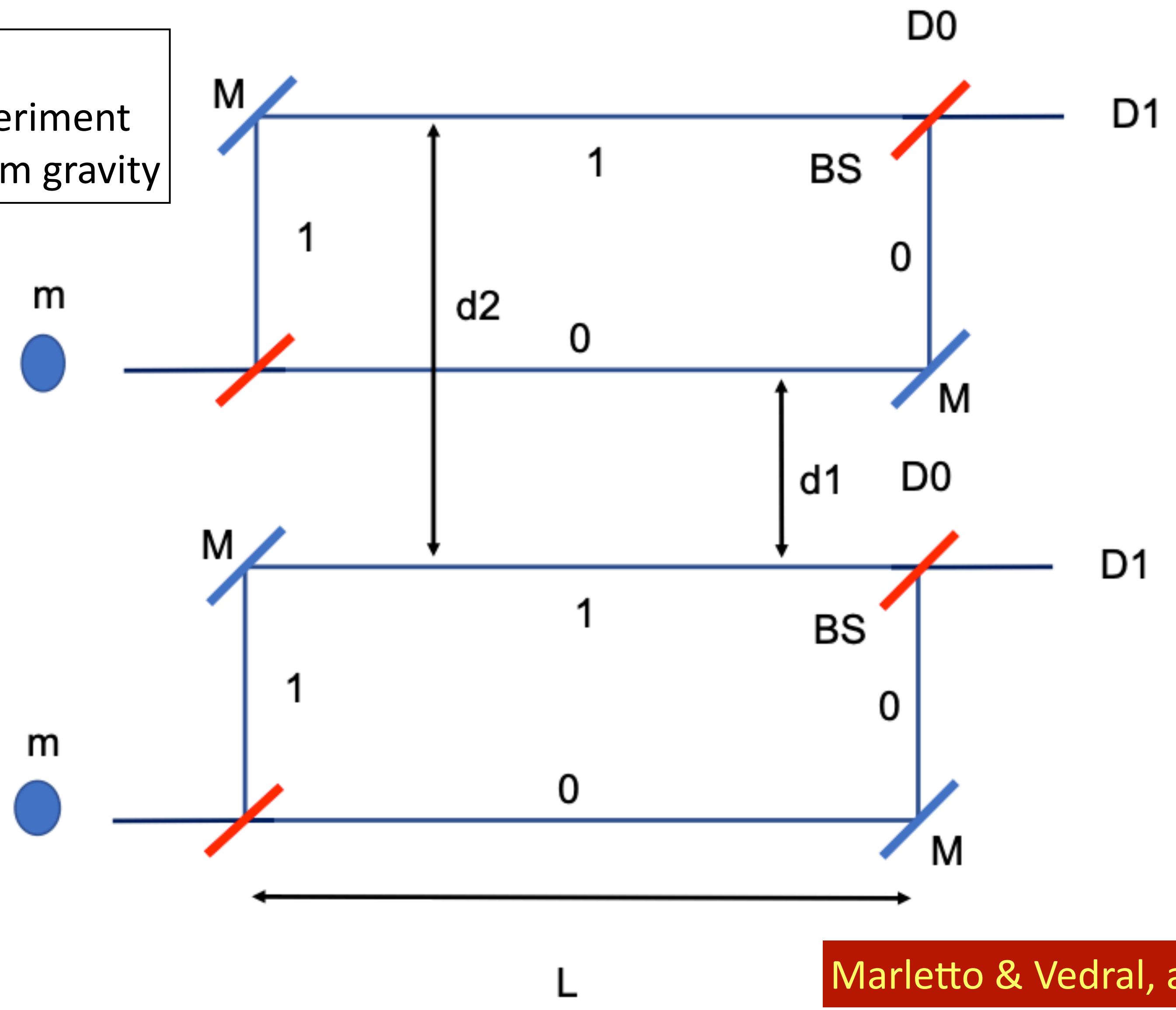
Gravitational field is in quantum superposition

So is entire Universe!

Radical, non-minimal interpretation!

Gravitational Entanglement of Two Mach-Zehnder Interferometers

(So far)
Gedanken Experiment
to probe quantum gravity



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