I. INTRODUCTION

There is renewed and growing interest in producing hard experimental evidence that gravity requires a quantum description. The origins of this quest can be traced back to at least the Chapel Hill Conference in 1957 on “The role of gravitation in physics”. At this conference, to make the point “that we’re in trouble if we believe in quantum mechanics but don’t quantize gravitational theory” [1], Feynman proposed a gedankenexperiment with macroscopic superpositions of massive objects that are coupled via gravity. Since the interaction involves superpositions of the gravitational field, a correct description of the experiment would also have to involve a quantum description of gravity. More than 50 years later, Claus Kiefer and I were part of a working group on “Historical Roots of Quantum Gravity Research” at the Max Planck Institute for the History of Sciences, where the newly published transcript of the Chapel Hill conference was heavily discussed during several sessions in Berlin [2]. Claus brought the transcript to the attention of Dieter Zeh, who responded with a fantastic comment on Feynman’s contributions [3]. I am following up on this debate by addressing a question that was asked by another Chapel Hill participant, Louis Witten: “What prevents this from becoming a practical experiment?”. Feynman’s initial response to Witten’s question was clearly in the spirit of Zeh’s decoherence: “You might argue this way: Somewhere in your apparatus this idea of [probability] amplitude has been lost. You don’t need it any more, so you drop it. The wave packet would be reduced (or something). Even though you don’t know where it’s reduced, it’s reduced. And then you can’t do an experiment which distinguishes interfering alternatives from just plain odds (like with dice).” In other words: the attempt to amplify quantum coherence to the level of macroscopic superpositions will likely result in loss of information to the environment. It is fair to say that at that time there was no prospect for actual experiments that involve gravitational source masses in the quantum regime. Amazingly, this has changed. Looking at today’s landscape of quantum experiments involving objects of increasing mass and complexity in spatial superpositions [4, 5] and the fast progress in quantum controlling the motion of solid state objects [6] such experiments seem to be possible in principle - provided that we manage to prevent decoherence from happening too fast.

II. FEYNMAN’S GEDANKENEXPERIMENT

The original idea put forward by Feynman is simple: “One should think about designing an experiment which uses a gravitational link and at the same time shows quantum interference” [1]. Concretely, a Stern-Gerlach magnet produces a spatial superposition of a gravitational source mass carrying a net spin of 1/2. The source mass state is then described by $|\Psi_0\rangle_s = |x_L\rangle_s + |x_R\rangle_s$, with $x_{L,R}$ being two positions (say left, right) of the center of mass along the x-axis that are macroscopically distinct ($\langle x_L|x_R \rangle_s \ll 1$). In a next step, the delocalized mass couples via gravity to a distant test mass $|\Psi_0\rangle_t = |x_0\rangle_t$ at location $x_0$. If quantum mechanics holds, the test mass experiences two possible accelerations $a_{L,R} = Gm_s/(|x_{L,R} - x_0|^2)$ (G: Newton’s constant; $m_s$: source mass) that result in entanglement between the masses once the separation in test mass displacement is sufficiently large, i.e. $|\Psi_0\rangle_s \otimes |\Phi_0\rangle_t \rightarrow |x_L\rangle_s|x_L\rangle_t + |x_R\rangle_s|x_R\rangle_t$ for $\langle x_L|x_R \rangle_s \ll 1$.

From a non-relativistic quantum physics point of view the generation of entanglement is a trivial consequence of gravitational coupling between the two masses, where each branch of the superposition is treated separately. From a field point of view, the generation of entanglement requires the gravitational field of the source mass configuration to be in a quantum superposition. This, however, poses a problem for general relativity. Such a superposed field configuration is not a valid solution of Einstein’s field equations of gravity[7]. Simply said: a classical field theory cannot produce a quantum superposition of fields because it cannot deal with sources that are placed in superpositions to start with. This is the case discussed by Feynman. This incompatibility also emerges on the level...
of an effective Hamiltonian description: for instantaneous interactions, entanglement is generated by the classical Newtonian potential. If one takes into account that the interaction is mediated locally via the gravitational field, entanglement between the masses can only be created when the mediator itself is genuinely non-classical (see e.g. [8–11], and [12] for a more general no-go theorem). It is also instructive to analyze the situation from the geometric viewpoint of general relativity, in which gravitational interaction is understood as geodesic motion in a non-Minkowski space-time metric. In the low-energy limit of solar system dynamics or table-top experiments this is effectively described by $g_{00}$ being sourced by the mass density configuration $\rho(x)$. The Newtonian potential $\phi$ is then simply given by the flat-space perturbation $\delta \rho = 1 - g_{00}$ as $\phi = -\frac{1}{2} \delta \rho = -G \frac{\rho}{r}$. A test mass freely falling in a fixed metric will not be able to become entangled in either position or momentum. Entanglement can only occur if the space-time metric itself is in a quantum superposition position [13].

So by saying that the generation of entanglement in Feynman’s gedankenexperiment requires a quantum description of the gravitational field, what one actually means is that the observation of entanglement is inconsistent with the assumption of a purely classical source mass configuration – and hence with a well-defined space-time metric. At the same time, the outcome will likely be fully consistent with the quantum theoretical predictions based on an effective quantum field theory in the linearized regime [14–16]. This is reminiscent of quantum optics experiments in the early 1970s that were designed to exclude semiclassical theories of radiation [17, 18], and that culminated in the seminal Bell experiments [19–21] to rule out the broad class of local-realistic models as an underlying description for quantum phenomena [22]. Violating a Cauchy-Schwartz inequality in a photon correlation experiment does not imply quantization of the electromagnetic field; it rather excludes the possibility of being describable by a genuinely classical theory, while at the same time being consistent with the quantum field theoretic predictions of electrodynamics [18]. Similarly, gravity experiments whose outcome cannot be explained by a purely classical source mass configuration would rule out the possibility of genuinely classical theories of gravity [7, 23]. One specific example is semiclassical gravity, in which the quantum mechanical energy-momentum operator $\hat{T}_{\mu\nu}$ is replaced by its expectation value $\langle \hat{T}_{\mu\nu} \rangle$ as a source for the gravitational field [24, 25]. As a consequence, the space-time metric is always well defined – since even a mass in a superposition would contribute an actual energy density at each of its possible locations in the superposition – and can hence never reproduce phenomena due to quantum interference\(^2\). Formally, the resulting dynamics is captured by the non-linear Schrödinger-Newton equation [31], whose predictions for massive quantum objects provide an independent testbed for semiclassical gravity [32–34].

In the following we will focus on the actual challenge when trying to implement such experiments: to maintain full control over quantum coherence at the level of the gravitational source (and test) masses. This can only be achieved by sufficiently isolating the experiment from environmental influences such that all decoherence rates are small compared to the time scales of the wanted gravitational coupling. Otherwise, environmental decoherence [35] will result in a mass distribution that cannot, even in principle, be distinguished from an incoherent mixture and therefore will always be consistent with semiclassical gravity (as is for example the case in the first experimental attempt of Page and Geilker [23]).

### III. WITTEN’S CHALLENGE: BECOMING A PRACTICAL EXPERIMENT

We restrict the discussion to the generation of quantum entanglement via gravitational interaction, as it is at the heart of most previous debates [1, 7, 23]. Two concrete possibilities have been recently proposed in the literature: (i) Entanglement via gravitational phase evolution of superposition states [8, 9], which is an elegant adaptation of Feynman’s thought experiment, and (ii) entanglement via gravitational interaction of two quantum harmonic oscillators [36–38]. Since both cases deal with table-top experimental settings, it is sufficient to use the linearized, low-energy regime of general relativity, i.e. Newtonian dynamics. For both approaches we consider two masses $m$ that are kept at a fixed distance $d$ along the z-axis and that are free to move along one orthogonal direction (x-axis). The particles are prepared in independent initial states $|\Psi_0\rangle_1, |\Phi_0\rangle_2$ and are assumed to interact via gravity only.

In the first scenario [8, 9] we start out with each of the masses being prepared in a spatial superposition state of size $\Delta x = |x_L - x_R|$, i.e. $|\Psi_0\rangle_1 = |x_L\rangle_1 + |x_R\rangle_1$ and $|\Phi_0\rangle_2 = |x_L\rangle_2 + |x_R\rangle_2$. Again, $x_{L,R}$ are two macroscopically distinct positions of the center of mass of each particle along the x-axis, i.e. $\langle x_L | x_R \rangle \ll 1$. In the pres-

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\(^2\) Note that this is also one underlying assumption in gravitational collapse hypotheses as formulated by Penrose [26] and others [27, 28]. Therefore any observation of gravitationally induced entanglement would rule out the validity of these models by principle. Some quantum theories of gravity also expect a breakdown of the superposition principle[29, 30], but they have not yet been analyzed in the context of the discussed experiments.
ence of a gravitational potential φ each particle wave-
function picks up a dynamical phase φ = \frac{1}{2} \int m\phi dt.
This was used in the seminal “COW” experiment by
Colella, Overhauser and Werner to generate quantum in-
terference of neutrons induced by Earth’s gravitational
field [39, 40]. Here, in contrast, the source for the
gravitational field is one of the particles. The pos-
tential experienced by the other particle can take the val-
ues φ_{0,1} = Gm/|r_{0,1}| (r: center-of-mass distance) with
|r_0| = d and |r_1| = \sqrt{d^2 + \Delta x^2}. Since the source
mass is in a superposition state, the resulting condi-
tional “COW” phase shifts φ_{0,1}(t) = \frac{1}{2} m\phi_{0,1}t can gen-
erate entanglement between the previously independent par-
cles. Specifically, the evolution of the 2-particle state is
given by |\Psi_0⟩_1 ⊗ |Φ_0⟩_2 \rightarrow |x_L⟩_1 |\tilde{x}_L⟩_2 + |x_R⟩_1 |\tilde{x}_R⟩_2, with
|\tilde{x}_L⟩_2 = |x_L⟩_2 + e^{i\Delta \varphi} |x_R⟩_2, |\tilde{x}_R⟩_2 = e^{i\Delta \varphi} |x_L⟩_2 + |x_R⟩_2 and ⟨\tilde{x}_L |\tilde{x}_R⟩_2 \propto [1 + \cos(2\Delta \varphi)], where Δ \varphi = \psi_1 - \psi_0. As a
result, entanglement is generated for Δ \varphi > 0 and at a
rate Γ_{ent} = \frac{d}{dt} \Delta \varphi \approx (G/h)(m^2 \Delta x^2/d^3), consistent with
[8, 9].
In the second scenario, two harmonically bound masses are prepared in pure quantum states with wavepacket extensions Δ x = \eta \sigma_0 (\eta: expansion parameter; \sigma_0 = \sqrt{\hbar/(m\omega_0)}: quantum ground state position uncertainty; 
\omega_0: trap frequency). In most cases, this will likely be realized by squeezed states of motion quantified by
\eta = e^s, where s is the corresponding squeezing parameter.
Newtonian gravity facilitates a 1/r coupling be-
tween the masses via the Hamiltonian \hat{H}_G = -Gm^2/|\tilde{r}|, with
the center of mass distance |\tilde{r}| = \sqrt{d^2 + |x_1 - x_2|^2}.
Taylor expansion yields the first relevant entangling in-
teraction term \hat{H}_{ent} \approx (Gm^2/d^3)\hat{x}_1 \hat{x}_2 = \hat{H}_{ent} \hat{x}_1 \hat{x}_2/\Delta x^2, with
Γ_{ent} \approx (G/h)(m^2 \Delta x^2/d^3) being the rate at which
Gaussian entanglement is created⁴ and consistent with
[36–38].
Somewhat surprisingly, even though both scenarios are experimentally very different they generate entanglement at the same rate Γ_{ent} (in the ideal case of pure states).
The relevant parameters are the mass m, the center-of-
mass distance d and the size of the delocalization Δ x
of each of the masses. For scenario 1, Δ x is the sepa-
ration between two center-of-mass states of a spatial
superposition, for scenario 2 it is the spatial extent of a
Gaussian wavepacket. To provide an example: if we as-
sume that we can keep two masses at a distance d = 1\mu m
and can prepare a delocalization Δ x \approx 100 nm, it would require at least N \approx 10^{11} silicon atoms to achieve
entanglement rates on the order of seconds. Given that
the confinement of these atoms needs to be on a scale
much smaller than d³ this will require solid-state den-
sities for each mass. In the following we will therefore
restrict the discussion to quantum states of motion of
solids (rather than atomic gases or molecules) and to
the idealized case of spherical masses. In order to avoid
unphysical constraints (center-of-mass distance smaller
than object sizes) we parametrize the center-of-mass dis-
tance via d = 2Rα, with particle radius R and α > 1 (e.g. α = 2 corresponds to a surface-to-surface distance
between the masses of 2R). Using m \approx 4R³ \rho (\rho: material density) this results in Γ_{ent} \approx (G/h)(2\rho^2/\alpha^3)R^3 \Delta x^2.
Coming back to Witten’s question: it is obvious that
environmental decoherence will be able to prevent this
from becoming a practical experiment. So what are the
sources of decoherence and how can we overcome them?

IV. ZEH’S DECOHERENCE: AVOIDING THE
APPEARANCE OF A CLASSICAL WORLD

Let us start again with scenario 1, the “CSIGN” ap-
proach to gravitational entanglement. As of today it is
unclear how well one can realize the initial state |\Psi_0⟩ = |x_L⟩ + |x_R⟩ that is required for this protocol, namely
a superposition of macroscopically distinct states of the
center of mass position of a massive object. The trend in
existing experiments indicates a clear trade-off between
separation Δ x and mass m. For example, while experi-
ments with individual neutrons or atoms achieve separa-
tions over tens of centimeters [39, 42], experiments with
macromolecules comprising up to 2,000 atoms achieve
separations over hundreds of nanometers [43], and
experiments with solid-state resonators made of more than
10^{12} atoms separations only on the level of femtometers
[44]⁵. There are proposals in the literature to overthrow
this trend, both for dielectric [45, 46] and superconduc-
ting [47, 48] solids, however thus far no experiment has
entered these extreme regimes of macroscopic quantum
superpositions. For now we assume that the prepara-
tion of such states is possible and ask for the minimum
requirements on the initial state to implement the en-
tanglement protocol. A first strict bound is provided by
the achievable vacuum level in the experiment. Cryo-
genic XUV experiments operating at environment tem-
peratures T_e \approx 1K can achieve gas densities that cor-
spond to pressure levels below 10^{-17}mbar [49]. Typi-
cal de-Broglie wavelengths of hydrogen molecules, the
dominating rest gas species in this regime, are on the
order of \lambda_{th} = 2\pi\hbar/(\sqrt{2\pi m T_e K_B}) \approx 1nm, which is
likely much smaller than the superposition size Δ x. This
means that scattering of a single molecule is sufficient to
localize the superposition state. As a consequence, deco-
herence from rest gas scattering occurs at a rate [35, 50]
Γ_q = (\lambda_{th}/\hbar)(16\pi/3)pR² \approx 2 \times 10^{26}pR² (p: gas pres-
sure, R: particle radius). To generate entanglement in

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³ For Δφ = π this is known in quantum information as an en-
tangling CSIGN gate. [41]
⁴ Higher-order terms of the expansion likely yield non-Gaussian
correlations to the entanglement formation.
⁵ To state a fun fact: in all of the existing macroscopic quantum
experiments the trade-off between mass and superposition size is
of the same order of magnitude with Δ x · m \approx 10^{-28} kg m.
the presence of rest gas requires $\Gamma_{\text{ent}} > \Gamma_g$, which reduces to the condition $R \Delta x^2 > 10^{26}(\hbar/G)(\alpha^3/\rho^2) \approx 10^{-12}(1/\rho^2)$ for $p = 10^{-17}\text{mbar}=10^{-15}\text{Pa}$ and $\alpha = 2$. Ideally, one chooses large particles at large delocalization, since the mass coupling ($\propto R^3$) grows faster than the decoherence due to scattering ($\propto R^2$). Practically, as is mentioned above, there will be a trade-off between those two numbers. Looking at current experiments, silica nanoparticles ($\rho \approx 2 \times 10^3 \text{kg m}^{-3}$) with $R \approx 75\text{nm}$ have now been prepared in their quantum ground state of motion[51–53]. They could provide a promising starting point for this experiment, albeit at a required superposition size of $\Delta x > 2 \mu \text{m}$, which seems challenging. At the other end of the spectrum, a Planck-mass lead particle ($R \approx 70\mu \text{m}$, $\rho \approx 10^5 \text{kg m}^{-3}$) would require $\Delta x > 12\text{nm}$, but it is unclear as of yet if quantum control can be extended to this mass regime.

Another omnipresent source of decoherence is scattering, absorption and emission of blackbody radiation, which provides a temperature limit to both the environment temperature $T_e$ (for scattering and absorption) and the internal particle temperature $T_i$ (for emission). The thermal wavelength of the photons $\lambda_{th} = \pi^2/3hc/(k_B T_{e,i}) \approx 5\text{mm}$ for $T_{e,i} \approx 1\text{K}$ is significantly larger than $\Delta x$ and hence decoherence occurs at a rate $\Gamma_{bb} = \Lambda_{bb} \Delta x^2$. Scattering of blackbody photons is described by equations [35, 50]

$$\Lambda_{bb}^{\text{eff}} = (1/\lambda_{th})^3 (818\xi(9)\pi^3 c^3 R^6/9) \text{Re}((\epsilon - 1)/(\epsilon + 2)) \approx 5 \times 10^{36} R^6 T_e^4 (\epsilon; \text{ Riemann Zeta function, } \epsilon; \text{ dielectric constant}),$$

and emission and absorption by

$$\Lambda_{bb}^{\text{em}} = (1/\lambda_{th})^6 (16\pi^9 c^3 R^3/189) \text{Im}((\epsilon - 1)/(\epsilon + 2)) \approx 5 \times 10^{25} R^6 T_e^4.$$  

Here we have assumed the worst case scenario of large dispersion and absorption, for which $(\epsilon - 1)/(\epsilon + 2) \approx 1$. Using again the examples from above, for a 75nm silica particle $\Gamma_{\text{ent}} > \Gamma_{bb}$ results in bounds $T_{e,i} < [(G/\hbar)(2\rho^2/\alpha^3)(1.4 \times 10^{-26})]^{1/6} \approx 5\text{K}$ from blackbody emission and absorption, and $T_e < [(G/\hbar)(2\rho^2/\alpha^3)(1/\alpha^3)(3 \times 10^{-37})]^{1/9} \approx 40\text{K}$ from blackbody scattering. For a Planck mass lead particle, one obtains $T_{e,i} < 8\text{K}$ from emission and absorption, and $T_e < 6\text{K}$ from scattering. The limits on internal temperature are independent of the object size and ultimately set by the material absorption properties. In the case of levitated superconductors or magnets, small internal temperatures should be easily achievable as state preparation will likely occur at cryogenic temperatures in a magnetic trap [48, 54, 55], while optically levitated particles need to implement either active cooling methods or switch to “dark” traps such as electrostatic traps [56–58]. On the other hand, the available environment temperature will set an ultimate bound on the object size. For the extreme case of a 10cm glass object, such as the mirrors used in gravitational wave detectors, environment temperatures below 300mK would be required to avoid localization via blackbody scattering on the time scale relevant for entanglement generation.

The second scenario, gravitationally coupled oscillators, is facing similar constraints. Gas scattering and blackbody radiation remain as significant sources of decoherence. The bounds on the delocalization $\Delta x$ are now bounds on the minimal extension (or amount of squeezing) of the initial oscillator wavepacket. That this will be experimentally demanding can be seen by sticking to our previous example: achieving a wavepacket size $\Delta x > 2\mu \text{m}$ for a $R = 75\text{nm}$ silica particle as used in recent experiments ($\omega/2\pi \approx 10^8\text{Hz}$) would require to extend the ground-state wavepacket $\sigma \approx 3\text{pm}$ by a factor of at least $6 \times 10^5$. Compared to the CSIGN approach, additional requirements need to be met. Trapped oscillators will dissipate energy to the environment at a rate $\gamma$ (e.g. via photon recoil, trapped magnetic flux, etc.), which results in thermal decoherence at a rate $\Gamma_{th} = \gamma/(k_B T_e/\omega_0)$. Fluctuations in trap position and frequency will add heating rates [38] $\Gamma_e = \pi\omega_0^3 S_e(\omega_0)/(4\sigma^2_\epsilon)$ and $\Gamma_\omega = \pi\omega^2 S_\omega(2\omega_0)/16$, with $S_\omega$ being the power spectral densities of position and frequency fluctuations at the relevant frequencies in the system, respectively. Current quantum experiments with massive levitated particles [51–53] are bounding these values to $\sqrt{S_e(\omega_0)} < 10^{-16}\text{ mHz}^{-0.5}$ and $\sqrt{S_\omega(2\omega_0)} < 10^{-4}\text{ Hz}^{-0.5}$ in the frequency regime around $\omega_0/2\pi = 10^6\text{Hz}$. At last the coupling needs to overcome the thermal excitations in the oscillator system. Concretely, in the absence of dissipation, the logarithmic negativity $E_N$ that detects entanglement in the system for $E_N > 0$ is given by $E_N \approx (4g_{4\pi}/\omega - 4\alpha)/\text{ln}^2 [59]$, resulting in entanglement for $\Gamma_{\text{ent}} > n\omega_0$, or $R^2 \Delta x^2 \rho^2 > (2/\pi) \times 10^{-23}m^2$. This condition can be further relaxed for example by taking into account time-dependent interactions, which can significantly alter the system dynamics [60]. Coming back to examples: optically trapped nanoparticles ($R = 75\text{nm}$, $\rho = 2 \times 10^3 \text{kg m}^{-3}$, $\omega_0/2\pi = 1 \times 10^9\text{Hz}$) in the quantum regime have been realized with a state purity $n = 0.5$ ($n$: harmonic oscillator thermal occupation) and with photon-recoil limited dissipation as low as $\gamma \approx 1 \times 10^{-3}\text{Hz}$. For these parameters, entanglement can be generated for $\Delta x > \text{4cm}$, when all other sources of decoherence can be neglected (which is the case for $p < 10^{-6}\text{Pa}$, $T_e < 40\text{K}$, $T_i < 4\text{K}$, $\sqrt{S_e(\omega_0)} < 10^{-15}\text{mHz}^{-1/2}$, $\sqrt{S_\omega(2\omega_0)} < 10^{-3}\text{Hz}^{-1/2}$).

6 In the absence of any other low-frequency noise sources, position noise $\sqrt{S_e(\omega_0)}$ is expected to scale with $1/\omega^2$. Extrapolation to 100Hz will likely require a dedicated laboratory protected against other vibrational noise sources or LIGO-scale vibration isolation.

7 Note that these numbers only define the experimental requirements once the initial conditions have been implemented. Preparing the initial states can require even more stringent environment conditions, see for example the wavepacket expansion protocol analyzed in [38]. Also note that for $\Delta x > d$ higher-order terms in the Taylor expansion of the interaction need to be taken into account.
ing these initial conditions to experimentally realistic values will likely require much better cooling in combination with non-stationary entanglement protocols [60] or effective free-fall configurations [38]. Planck-mass lead spheres would likely be suspended at lower frequencies, say $\omega_0/2\pi = 1 \times 10^{13}$ Hz. For an initial state purity of $\eta \approx 0.5$ entanglement generation then requires $\Delta x > 30$ nm (along with $\gamma < 10^{-2}$ Hz, $p < 10^{-15}$ Pa, $T_e < 6$ K, $T_i < 8$ K, $\sqrt{S_x(\omega_0)} < 10^{-2}$mHz$^{-1/2}$, $\sqrt{S_x(2\omega_0)} < 10^{-2}$Hz$^{-1/2}$). Even though this appears to be a significantly smaller displacement when compared to the nanosphere example, the relative wavepacket expansion $\eta = \Delta x/\sigma_0$ ($\sigma_0$: ground state size) is beyond current experimental reach in both cases. For example, the requirements $\eta > 10^7$ for nanoparticles and $\eta > 10^5$ for Planck-mass spheres are in stark contrast to the thus far experimentally achieved values of $\eta \approx 1.2$ [61–63].

Finally, instead of using levitated objects, entanglement could also be generated between mechanically suspended oscillators. A recent experiment has demonstrated gravitational coupling between two millimeter-sized gold spheres using a torsional pendulum operating in the mHz-regime [64]. Assuming one can extend these parameters ($R \approx 10^{-6}$m, $\rho \approx 2 \times 10^4$kg.m$^{-3}$, $\omega_0/2\pi \approx 10^{-2}$Hz) to the quantum regime ($\bar{\eta} = 0.5$) it would only require $\Delta x > 900$nm to generate entanglement. However, since the respective entanglement rates are extremely small, this comes at the cost of unrealistic pressure requirements ($P < 10^{-22}$Pa). Using $p < 10^{-15}$Pa from above results in a consistent requirement set $\Delta x > 2$nm, or a wavepacket expansion $\eta > 3 \times 10^5$, in combination with $\gamma < 3 \times 10^{-8}$Hz ($Q > 2 \times 10^6$), $p < 10^{-15}$Pa, $T_e < 2.8$ K, $T_i < 10$ K, $\sqrt{S_x(\omega_0)} < 10^{-16}$mHz$^{-1/2}$, $\sqrt{S_x(2\omega_0)} < 10^4$Hz$^{-1/2}$. Similarly, if two kilogram-scale mirrors from current gravitational wave detector experiments ($R = 10^{-1}$m, $\rho = 2 \times 10^4$kg.m$^{-3}$, $\omega_0/2\pi \approx 10^2$Hz) could be operated at conditions $\bar{\eta} < 0.5$, $p < 10^{-15}$Pa, $T_e < 0.4$ K, $T_i < 5$ K and $\gamma < 80$Hz ($Q > 10$), the generation of gravitationally induced entanglement would require a wavepacket size $\Delta x > 1.2$ nm, or an initial wavepacket expansion of $\eta > 10^{10}$.

Clearly, these considerations and related studies [37, 38, 45, 48, 65] show that we are still far away from realistic experiments and that we need better ideas (or more patience) for going the next step.

V. CONCLUSION

The topics discussed at the Chapel Hill conference included two of the most outstanding questions in gravitational physics: Do gravitational waves exist?, and Do we require a quantum description of gravity?. At that time, both questions were of theoretical nature and experimental approaches did not exist beyond the power of thought experiments. In Feynman’s words: “There exists, however, one serious difficulty, and that is the lack of experiments. Furthermore, we are not going to get any experiments, so we have to take a viewpoint of how to deal with problems where no experiments are available.” [1].

Today, more than 60 years later, we have an experimental answer to the first question. Laser interferometric gravitational wave detectors around the world unambiguously show almost on a daily basis that gravitational energy is radiated [66] and gravitational wave astronomy is now opening a completely new field in physics. In a parallel development, quantum experiments involving massive macroscopic objects have reached a level of maturity that we can confidently begin to tackle the second question. One possibility is to follow Feynman’s initial idea and entangle objects via the gravitational field. We have seen that the known mechanisms of decoherence impose strict and demanding limits on the experimental boundary conditions for this approach. And even though current experiments operate far away from these regimes, decoherence can in principle be tackled until we bump into a fundamental (or technological) showstopper. Thus far, this has not been the case. It is, however, also fair to say that optimistic claims about the technical feasibility of these experiments are -at least from today’s viewpoint- highly exaggerated. It is certainly worthwhile to also investigate other phenomena involving coherent source mass distributions that provide us with observations that are inconsistent with what we expect from a classical (fixed) space-time metric [7]. Most likely, the outcome of such experiments will be consistent with the predictions of an effective quantum field theory. Beyond the possibility that this is not the case, the actual benefit of this undertaking lies in ruling out semiclassical models of gravity and, probably more importantly, provide empirical evidence that gravity in fact requires a quantum description. An even more thrilling perspective is to gain access to the field degrees of freedom of gravity, either directly via optical clocks [68] or indirectly by observing decay of entanglement between the masses through additional entanglement with the field. This represents an even more demanding experimental challenge, but who knows what the next 60 years will bring.

VI. ACKNOWLEDGEMENTS

I am grateful to my colleagues in both the quantum and the gravity community for many insightful discussions, in

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8 I refer to this as the “level-1” excitement on the Dvali scale: the experiment shows that one cannot average space-times associated to a quantum source mass. Next levels of increasing order include the demonstration of the effect for a propagating field (level 2) [67] and the inclusion of field degrees of freedom, e.g. loss of entanglement visibility via entanglement with the field (level 3). This classification follows from discussions with Gia Dvali at the workshop “Primordial black holes, de Sitter space and quantum tests of gravity” hosted by the Hamburg Academy of Sciences in February 2019.
particularly on formulating meaningful questions at the interface of these two fields. I also thank Philip Schmidt and Klemens Winkler for double-checking my numerical estimates. This work was supported by the European Research Council (ERC), Grant 649008, by the University of Vienna, the Research Platform TURIS, and by the Austrian Academy of Sciences.

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