# Gravitational Decoherence and the Possibility of Its Interferometric Detection

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We present a general master equation describing the quantum dynamics of a scalar bosonic field interacting with an external weak and stochastic gravitational field. The dynamics predicts decoherence both in position and in energy momentum. We show how the master equation reproduces, thus generalizing, the previous results in the literature by taking appropriate limits. We estimate the effect of gravitational decoherence in atom interferometers, providing also a straightforward way to assess the magnitude of the effect.

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*Introduction.*—The direct detection of gravitational waves by the LIGO collaboration [1,2], which marked a new era in astrophysics, is pushing the scientific community towards the design and construction of more and more sophisticated ground and space based detectors [3–7] to observe waves in a variety of ranges. The ultimate goal is to observe the cosmic background of gravitational radiation, which would open a window on the universe at its very primordial stage, at about $10^{-22}$ s after the big bang [8], where we also expect our classical description of gravity to fail because of quantum effects [9,10].

In this scenario, the extreme sensitivity of matter waves [11–14] to gravity gradients [15–21] raises the question whether matter-wave interferometers can compete with, or even outperform, "classical" devices in exploring gravitational waves [8,22,23] and, at the same time, in possibly answering some fundamental questions regarding the nature of gravity [24–28], and its coupling to quantum matter. Here we focus on stochastic gravitational backgrounds.

Besides the technological challenge of building sensitive (therefore large) enough matter-wave interferometers, which realistically would have to operate in outer space, even from the theoretical point of view it is not clear how they would respond to a gravitational background produced by random (or quantum) sources.

In general terms, its effect on quantum superpositions is a path dependent phase shift which ultimately leads to decoherence [29,30]. The first isolated works on the topic trace back to the late 1980s and early 1990s [31,32], the subject then gaining the interest of a growing part of the scientific community since the turn of the century [33–44]. These works however differ quite significantly in the description of the effect: some models predict decoherence in momentum and/or energy [33,35], others predict decoherence in position [32,36,37]. These differences amount to very different predictions, also of several orders of magnitude, about the sensitivity of the matter-wave interferometers to a gravitational background. The differences ultimately rest in the different premises underlying the analyses, yet a comprehensive picture of the effect is lacking; as such, it is not clear what the magnitude of the expected decoherence effect should be.

The goal of this Letter is twofold. In the first part, we present the (nonrelativistic) master equation describing gravitational decoherence from classical fluctuations of the metric [45]. Our result is very general, and is based on the least number of approximations, later discussed. It includes both decoherence in position and in momentum/energy; as such, it reproduces the different results in the literature, which can be understood as a limiting case of our overarching model under well-defined additional approximations.

In the second part, we estimate the sensitivity of atom interferometers to stochastic gravitational backgrounds, since they currently represent the most advanced quantum platform for gravity exploration [18,46–48]. We will estimate their capability to detect the different degrees of freedom of the metric perturbations, some of which couple to the position of the atom, some to the momentum. Because of this different coupling, as we will see, atom interferometers are much more sensitive to scalar perturbations of the metric (in particular, of the Newtonian potential) than to the tensorial perturbations (gravitational waves). Still, in both cases major technological advances need to be achieved before atom interferometers become sensitive to the expected gravitational perturbations.

*The theoretical model.*—We consider a scalar field $\phi(x)$ minimally coupled to the metric $g_{\mu\nu}$; eventually, we will quantize the matter field, while gravity will remain classical. The mathematical details are contained in Ref. [45]: here we present the logic of the derivation and the final result, which is what is relevant for the subsequent analysis.

 

The first step is to consider the weak-field limit for the gravitational field, i.e., $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $|h_{\mu\nu}| \ll 1$. The equations of motion for the scalar field then follow in a straightforward manner from the action: they are rather long, but in a nutshell they describe the evolution of a relativistic scalar matter field on flat spacetime, and the effect of the metric perturbation $h_{\mu\nu}$ amounts an external force described by its coupling with the (flat) matter stress-energy tensor.

The nonrelativistic limit for the matter field is the delicate part of the analysis, as it always is when dealing with a relativistic interacting quantum theory, where the distinction between positive and negative energy solutions is not clear [49]. Once this limit is performed, quantization follows in the canonical way.

Next, one has to characterize the gravitational background. We take it to be random, with the average equal to zero: $\mathbb{E}[h_{\mu\nu}(\mathbf{x}, t)] = 0$, homogeneous, isotropic, and white in time; to simplify the analysis, we also assume that different components of the metric perturbations are statistically independent. (In Ref. [45], a more general situation is considered). The variance then reads $\mathbb{E}[h_{\mu\nu}(\mathbf{x}, t)h_{\mu\nu}(\mathbf{y}, s)] = \alpha^2 u_{\mu\nu}(\mathbf{x}-\mathbf{y})\lambda\delta(t-s)$, where $u_{\mu\nu}(\mathbf{x}-\mathbf{y})$ is a real function of order 1, $\alpha$ measures the strength of the fluctuations, and $\lambda$ is a characteristic time of the fluctuating dynamics.

A quantum system evolving under the influence of a stochastic background decoheres. Given the assumptions previously outlined, the general master equation reads [45]

$$\begin{aligned}\partial_t\hat{\rho}_t = &-\frac{i}{\hbar}\left[\frac{\hat{\mathbf{P}}^2}{2M},\hat{\rho}_t\right] - \frac{\alpha^2\lambda c^4}{4(2\pi)^{3/2}\hbar^5}\int d^3q\tilde{u}^{00}(\mathbf{q})\frac{m^2(\mathbf{q})}{M^2}\left[\left\{e^{i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},\left(\frac{\hat{\mathbf{P}}^2}{4M}+\frac{Mc^2}{2}\right)\right\},\ \left[\left\{e^{-i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},\left(\frac{\hat{\mathbf{P}}^2}{4M}+\frac{Mc^2}{2}\right)\right\},\hat{\rho}_t\right]\right]+\\ &-\frac{\alpha^2\lambda c^2}{4(2\pi)^{3/2}\hbar^5}\int d^3q\tilde{u}^{0i}(\mathbf{q})\frac{m^2(\mathbf{q})}{M^2}[\{e^{i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},\hat{P}_i\},[\{e^{-i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},\hat{P}_i\},\hat{\rho}_t]]+\\ &-\frac{\alpha^2\lambda}{4(2\pi)^{3/2}\hbar^5}\int d^3q\tilde{u}^{ij}(\mathbf{q})\frac{m^2(\mathbf{q})}{M^2}\left[\left\{e^{i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},\frac{\hat{P}_i\hat{P}_j}{2M}\right\},\left[\left\{e^{-i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},\frac{\hat{P}_i\hat{P}_j}{2M}\right\},\hat{\rho}_t\right]\right] \qquad (1)\end{aligned}$$

where $\hat{\rho}_t$ is the density matrix of the system, $\hat{\mathbf{X}}$ and $\hat{\mathbf{P}}$ are the center-of-mass position and momentum operators, $\tilde{u}^{\mu\nu}(\mathbf{q})$ and $m(\mathbf{q})$ are, respectively, the Fourier transform of the noise correlation function and of the mass density of the system, and $M$ is the total mass. Furthermore, $\lambda = \min(t, \tau_c)$ [50]; we also assume the correlation time $\tau_c$ to be $\tau_c = L/c$, where $L$ is the correlation length of the gravitational perturbation and $c$ is the speed of light.

The decoherence mechanism described by our model involves all relevant degrees of freedom: position, momentum, and energy, which are coupled to the different components of the correlation function. We study them separately, and show how the existing literature [32,33, 35–37] is accounted for by Eq. (1) as limiting cases.

*Recovering position decoherence.*—Pure decoherence in position is recovered when the scalar component $h^{00}$ of the metric fluctuations is at least of the same order of magnitude of the other components, i.e., $h^{00} \gtrsim h^{0i}$, $h^{ij}$. Taking into account that in the nonrelativistic limit $c|P|$, $P^2/2M \ll Mc^2$, it follows that $ch^{0i}P_i$, $h^{ij}(P_iP_j/2M)$, $h^{00}(P^2/2M) \ll h^{00}Mc^2$, and we are allowed to neglect the terms containing $h^{0i}$, $h^{ij}$. Thus Eq. (1) simplifies to

$$\begin{aligned}\partial_t\hat{\rho}_t = &-\frac{i}{\hbar}\left[\frac{\hat{\mathbf{P}}^2}{2M},\hat{\rho}_t\right]\\ &-\frac{\alpha^2 Lc^3}{(2\pi)^{3/2}\hbar^5}\int d^3q\tilde{u}^{00}(\mathbf{q})m^2(\mathbf{q})[e^{i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},[e^{-i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar},\hat{\rho}_t]] \qquad (2)\end{aligned}$$

where we have replaced $\lambda = \tau_c = L/c$. This is formally equivalent to the Gallis-Fleming master equation [51], which describes the decoherence induced on a particle by collisions with a surrounding thermal gas, therefore allowing for a collisional interpretation of the result.

For a pointlike particle [$m(\mathbf{r}) = M\delta^3(\mathbf{r}-\mathbf{r}_0)$ with $\mathbf{r}_0$ the particle position, i.e., $m(\mathbf{q}) = (2\pi\hbar)^{-3/2}e^{-i\mathbf{q}\cdot\mathbf{r}_0/\hbar}$], Eq. (2) reduces to

$$\partial_t\hat{\rho}(\mathbf{x},\mathbf{y},t) = -\frac{i}{\hbar}\left[\frac{\hat{\mathbf{P}}^2}{2M},\hat{\rho}_t\right] - \gamma(\mathbf{x},\mathbf{y})\hat{\rho}(\mathbf{x},\mathbf{y},t), \qquad (3)$$

with the decoherence function given by

$$\gamma(\mathbf{x},\mathbf{y}) = \frac{2\alpha^2M^2Lc^3}{\hbar^2}[u^{00}(\mathbf{x}-\mathbf{y})-1]. \qquad (4)$$

A typical Ansatz for the correlation function is $\tilde{u}^{00}(\mathbf{x}) = e^{-(x^2/2L^2)}$, corresponding to $\tilde{u}^{00}(\mathbf{q}) = L^3\hbar^3e^{-\mathbf{q}^2L^2/(2\hbar^2)}$, in which case $\gamma(\mathbf{x},\mathbf{y})$ becomes

$$\gamma(\mathbf{x},\mathbf{y}) = -\frac{2\alpha^2M^2Lc^3}{\hbar^2}(1-e^{-[(\mathbf{x}-\mathbf{y})^2/2L^2]}). \qquad (5)$$

With these assumptions, we recover the gravitational decoherence model presented in Ref. [32] and the same functional behavior discussed in Ref. [36], which also predict gravitational decoherence in position. Choosing instead $u^{00}(\mathbf{x}-\mathbf{x}') = L^3\delta^3(\mathbf{x}-\mathbf{x}')$ one recovers the model in Ref. [37] with a minor mismatch in the rate functions. Such a mismatch can be accounted to a different treatment of the gravitational perturbation in the two models; in Ref. [37] the perturbations are described by a quantum noise, thus allowing for complex correlation functions, while in our case the gravitational noise is classical.

*Recovering momentum and energy decoherence.*—The master equation Eq. (1) describes decoherence in momentum when the correlation length of the noise is much larger than the particle's spatial coherence. This is the typical situation in astrophysics and cosmology, since classical fluctuations occur over distances much longer than the typical size of matter-wave interferometers ($\lesssim 1$ m). In this regime there is a low-momentum transfer from the noise to the quantum system, and we are allowed to make the following approximation $e^{i\mathbf{q}\cdot\hat{\mathbf{X}}/\hbar} \sim \hat{\mathbb{1}}$ to simplify Eq. (1) as follows:

$$\partial_t\hat{\rho}_t = -\frac{i}{\hbar}\left[\frac{\hat{\mathbf{P}}^2}{2M},\hat{\rho}_t\right] - \frac{\alpha^2\lambda c^2}{(2\pi)^{3/2}\hbar^5}D^{0i}[\hat{P}_i,[\hat{P}_i,\hat{\rho}_t)] - \frac{\alpha^2\lambda}{(2\pi)^{3/2}\hbar^5}D^{00}\left[\frac{\hat{\mathbf{P}}^2}{2M},\left[\frac{\hat{\mathbf{P}}^2}{2M},\hat{\rho}_t\right]\right] - \frac{\alpha^2\lambda}{(2\pi)^{3/2}\hbar^5}D^{ij}\left[\frac{\hat{P}_i\hat{P}_j}{2M},\left[\frac{\hat{P}_i\hat{P}_j}{2M},\hat{\rho}_t\right]\right] \tag{6}$$

with

$$D^{\mu\nu} = \int d^3q\,\tilde{u}^{\mu\nu}(\mathbf{q})\frac{m^2(\mathbf{q})}{M^2}. \tag{7}$$

If the tensorial fluctuations associated with gravitational waves dominate ($h^{ij} \gg h^{0i}$, $h^{00}$), and assuming spatial isotropy [$\tilde{u}^{ij}(\mathbf{q}) = \delta^{ij}\tilde{u}(\mathbf{q})$], Eq. (6) reduces to

$$\partial_t\hat{\rho}_t = -\frac{i}{\hbar}\left[\frac{\hat{\mathbf{P}}^2}{2M},\hat{\rho}_t\right] - \Lambda\left[\frac{\hat{\mathbf{P}}^2}{2M},\left[\frac{\hat{\mathbf{P}}^2}{2M},\hat{\rho}_t\right]\right] \tag{8}$$

with $\Lambda = [\alpha^2\lambda/(2\pi)^{3/2}\hbar^5]D$ and $D$ is defined as in Eq. (7) with $\tilde{u}^{\mu\nu}(\mathbf{q})$ replaced by $\tilde{u}(\mathbf{q})$. For a pointlike particle and a Gaussian correlation function $\tilde{u}(\mathbf{q}) = L^3\hbar^3 e^{-\mathbf{q}^2L^2/(2\hbar^2)}$, then $\Lambda = \alpha^2\lambda/\hbar^2$. With this choice, we reproduce the model presented [35]. We also recover the result of Ref. [33] with a minor difference in the rate function, that can again be accounted to the quantum treatment of the gravitational noise.

Our result shows that the effect of spacetime fluctuations on nonrelativistic quantum systems can result both in position and/or momentum decoherence depending on the properties of the noise relative to the state of the particle. It also sets the regimes of validity of the models in the existing literature, thus combining the different descriptions in one general framework.

*Application: Atom interferometry.*—We now estimate the decoherence effect of a stochastic gravitational background in matter-wave experiments, specifically in atom interferometers. We consider only perturbations with large correlation length $L$ with respect to the size of the experimental setup, because quantum interferometers are small in size, and also because this limiting case embeds both decoherence in position and in energy, described respectively by Eq. (3) and Eq. (8). As discussed before, these situations are of particular interest as they correspond to when the scalar or the tensorial components of the gravitational perturbation, respectively, are dominant [52].

We can derive a first estimate of the decoherence effect by a crude use of Eqs. (3) and (8). When scalar perturbations are dominant and position decoherence occurs, Eq. (5) tells that $\gamma(\mathbf{x},\mathbf{y}) \sim -(\alpha^2M^2c^3/L\hbar^2)(\mathbf{x}-\mathbf{y})^2$ for $\Delta x \ll L$, which is a realistic approximation. the off-diagonal elements of the density matrix decay exponentially in time, according to the formula

$$\text{position decoherence} \sim \exp\left(-\frac{p_k^2\alpha^2Lc^3t^3}{4L^2\hbar^2}\right) \tag{9}$$

where $t$ is the time of flight and we used the relation $p_k = 2M\Delta x/t$, where $p_k$ is the transverse momentum of the atom and $\Delta x$ is the distance between the two branches of the interferometer. Note that the decoherence effect scales with the cube power of time, while in usual applications of atom interferometers to gravimetry, the sensitivity scales linearly or quadratically. The scaling with the cube power of time is an effect of the symmetric Mach-Zehnder geometry and has recently been realized in a Stern-Gerlach–type atom interferometer [53].

In the case of energy decoherence, following Eq. (8) an estimate of the decoherence rate can be given by $\Lambda(p_k^2/2M)^2$, which again produces an exponential decay of the off-diagonal elements. Considering a pointlike particle and a Gaussian correlation function of the noise, it reads

$$\text{momentum decoherence} \sim \exp\left(-\frac{p_k^4\alpha^2\beta_t}{4\hbar^2M^2}\right) \tag{10}$$

where $\beta_t = t\tau_c$ when $t < \tau_c$, and $\beta_t = t^2/2$ when $t > \tau_c$.

To confirm the validity of the above estimates, we simulated the decoherence effect for a symmetric Mach-Zehnder interferometer as depicted in Fig. 1. We consider a particle of mass $m$ whose initial state is a Gaussian wave packet with spread $\sigma$, which separates in two parts moving along the two branches of the interferometer with

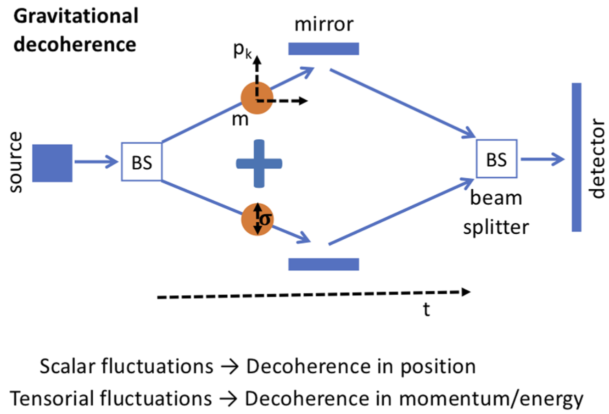


FIG. 1. A quantum system moving in a stochastic gravitational background decoheres. If the scalar component of the metric dominates, then decoherence occurs in position. If the tensorial components dominate then decoherence occurs in momentum and/or energy. Decoherence can be detected by matter-wave interferometers, for example, atom interferometers. A wave packet is split in two parts traveling along different paths, before they recombine by a detector measuring the interference. The relevant parameters are the time of flight $t$ and the transverse momentum $p_k$.

transverse momentum $p_k$. The two packets are reflected by the mirrors and recombine on the other side after a time $t$. As for the gravitational noise, we consider a Gaussian correlation function, therefore we solve Eq. (3) with $\gamma$ given by Eq. (5) for decoherence in position given by scalar fluctuations, and Eq. (8) with $\Lambda = 2\alpha^2\lambda/\hbar^2$ for decoherence in energy produced by the tensorial fluctuations; see Ref. [54] for more details.

We consider a representative class of atom interferometers [59–64], and in Table I we report the relevant parameters. For each of them we compute the interferometric visibility:

$$\nu = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}} \tag{11}$$

TABLE I. List of representative atom interferometers, and of their relevant parameters: mass $M$ and transverse momentum $p_k$ of the atom, time of flight $t_{\text{tot}}$, and spread $\sigma$ of the wave packet. The list includes HYPER [59], STE-QUEST [60,61], the proposal by Xu *et al.* [62], by Muntiga *et al.* [63] and by Kovachy *et al.* [64].

Table I: Parameters for the selected interferometers

| | M [kg] | $p_k$ [kg m/s] | $t_{\text{tot}}$ [s] | $\sigma$ [m] |
|---|---|---|---|---|
| HYPER | $2.5 \times 10^{-25}$ | $8.8 \times 10^{-28}$ | 1.5 | $6.4 \times 10^{-7}$ |
| STE-QUEST | $1.6 \times 10^{-25}$ | $3.4 \times 10^{-27}$ | 10.0 | $3.0 \times 10^{-5}$ |
| Xu *et al.* | $2.5 \times 10^{-25}$ | $1.5 \times 10^{-27}$ | 20.0 | $3.9 \times 10^{-6}$ |
| Muntiga *et al.* | $1.6 \times 10^{-25}$ | $1.9 \times 10^{-27}$ | 0.6 | $5.0 \times 10^{-5}$ |
| Kovachy *et al.* | $1.6 \times 10^{-25}$ | $8.5 \times 10^{-28}$ | 2.1 | $5.6 \times 10^{-5}$ |

where $P_{\max}$ and $P_{\min}$ are, respectively, the maximum and the minimum of the intensity of the interference pattern. The visibility is computed as a function of the strain $\alpha$ and the correlation length $L$ of the noise. The theoretical analysis is discussed in the Supplemental Material.

The results are reported by Fig. 2 for the scalar gravitational perturbations inducing decoherence in position, and Fig. 3 for the tensorial gravitational perturbations inducing decoherence in energy.

For each interferometer, Fig. 2 shows a peak in the reduction of the visibility for correlation lengths $L$ equal to the maximum superposition distance $p_k t_{\text{tot}}/(2M)$. This corresponds to $L \simeq 10^{-1}$ m (the size of the interferometer) and strain $\alpha \sim 10^{-22}$ for the best performing of them [62]. Note that a crude estimate of the reduction of the visibility given by Eq. (9) is off by less than one order of magnitude in its region of validity, namely, for $p_k t_{\text{tot}}/(2M) \ll L$ (the right part of Fig. 2). A more accurate formula that also describes the cases $p_k t_{\text{tot}}/(2M) \geq L$ can be found in the Supplemental Material.

Figure 3 shows a much lower sensitivity of atom interferometers to tensorial gravitational perturbation, as expected from a previous analysis [38]. A clear sign of decoherence can be observed only for perturbations whose strength $\alpha$ is of the order of $10^{-5}$, which is too large to be produced by any expected source of tensorial fluctuations. Also in this case a crude estimate of the effect given by Eq. (10) is off by less than an order of magnitude.

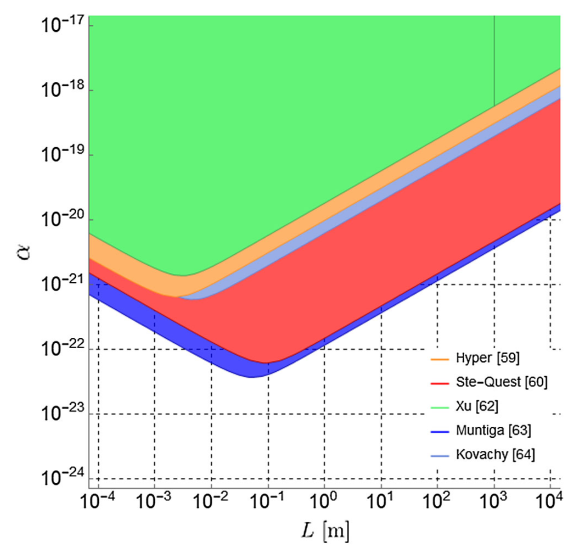


FIG. 2. Color plot showing the sensitivity of atom interferometers to stochastic *scalar* gravitational fluctuations, as a function of the correlation length $L$ and strength $\alpha$ of the fluctuations. The different shaded area represents the region of parameters where the perturbations induce a reduction of more that 10% in the visibility, for different experimental setups (see legend in the figure).

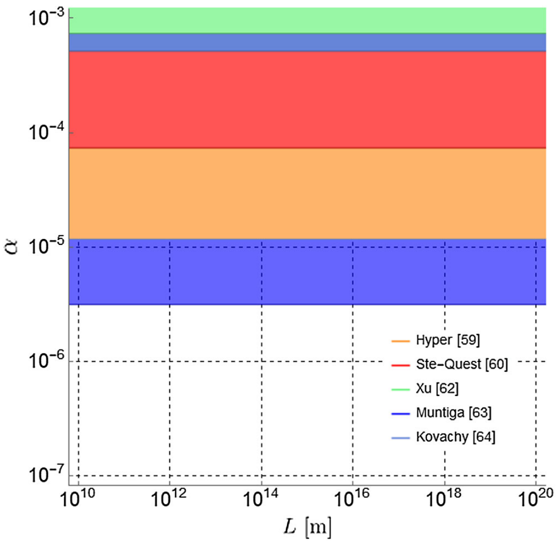


FIG. 3. Same as Fig. 2, now with reference to stochastic *tensorial* gravitational fluctuations.

*Summary and conclusions.*—We have presented a general model of gravitational decoherence. We have applied it to atom interferometry, showing to which extent it is sensitive to metric fluctuations. Additionally, we have analyzed collisional decoherence [54], showing that it can be weaker than gravitational decoherence for space based interferometers.

If such an experiment were to be performed, a crucial question will be how to disentangle the gravitational noise from other sources of decoherence. In principle this can be done by changing the parameters of the interferometer in order to explore the functional dependence of the output signal on the noise. This, together with a theoretical modeling of all known sources of noise, should allow us to extract the signal of the gravitational noise from the others. Another option is to use schemes involving two interferometers [65] to reject common mode noise.

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