TRACES OF QUANTUM FRICTION IN THE ACCUMULATED GEOMETRIC PHASE

FERNANDO C. LOMBARDO

UC SANTA BARBARA
Kavli Institute for
Theoretical Physics

Departamento de Física
.UBAexactas

OUTLINE

VACUUM
FLUCTUATIONS
AND INDUCED EFFECTS

NON-CONTACT
QUANTUM FRICTION

EXPERIMENTAL
PROPOSAL

OUTLINE

VACUUM FLUCTUATIONS
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NON-CONTACT QUANTUM FRICTION

EXPERIMENTAL PROPOSAL

VACUUM FLUCTUATIONS
AND INDUCED EFFECTS

One of the most exciting features of QFT is based on the nontrivial structure of the vacuum state and the observable macroscopic effects associated to quantum vacuum fluctuations

- **CASIMIR EFFECT**

The most renewed example is the Casimir force between two neutral bodies

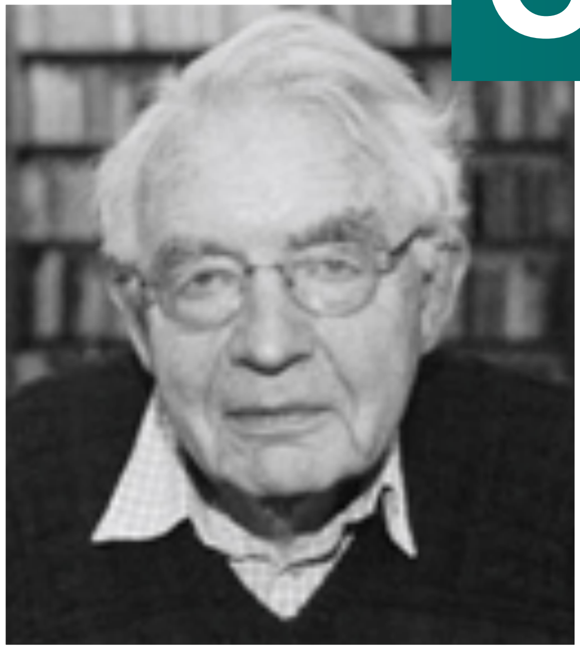
- **DYNAMICAL CASIMIR EFFECT**

Another fascinating effect arises when a mirror moves in space at relativistic velocities: the dynamical Casimir effect

- **QUANTUM FRICTION**

Two bodies moving without contact relative to each other at constant velocity experience a force that opposes to motion

CASIMIR EFFECT



Hendrick Casimir (1948)

Zero-point energy
in vacuum

$$E_0 = \sum_{\lambda} \frac{1}{2}\hbar\omega_{\lambda} = \infty$$

Zero-point energy
with boundaries

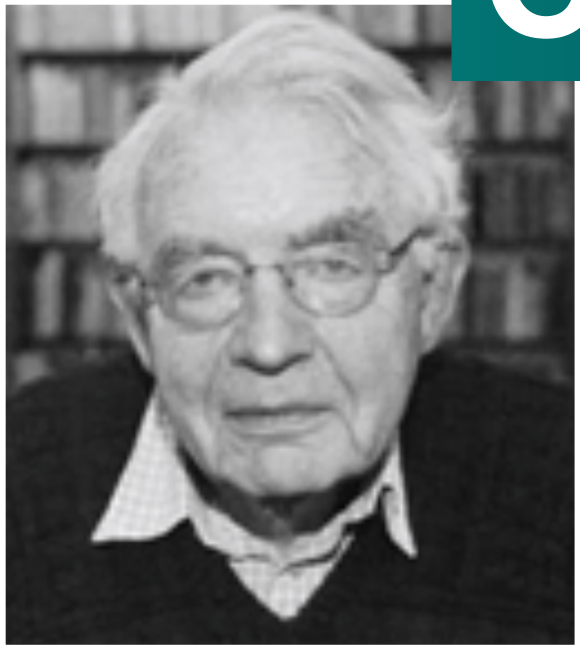
$$E_0(d) = \sum_{\lambda'} \frac{1}{2}\hbar\omega_{\lambda'} = \infty$$

But $E_0 - E_0(d) \neq \infty$!

CASIMIR FORCE BETWEEN TWO
PERFECTLY CONDUCTING PLATES

$$\frac{F}{A} = -\frac{\pi^2}{240}\frac{\hbar c}{d^4}$$

CASIMIR EFFECT



Hendrick Casimir (1948)

CASIMIR FORCE BETWEEN TWO PERFECTLY CONDUCTING PLATES

$$\frac{F}{A} = -\frac{\pi^2}{240}\frac{\hbar c}{d^4}$$

HAS BEEN MEASURED

Lamoreaux, S. K. Phys. Rev. Lett. 78, 5 (1997).

Mohideen, U. & Roy, A. Phys. Rev. Lett. 81, 4549 (1998).

Ederth, T. Phys. Rev. A 62, 062104 (2000).

Chan, H. V., Aksyuk, V. A., Kleiman, R. N., Bishop, D. J. & Capasso, F. Science 291, 1941 (2001).

Bressi, G., Carugno, G., Onofrio, R. & Ruoso, G. Phys. Rev. Lett. 88, 041804 (2002).

Decca, R. S., López, D., Fischbach, E. & Krause, D. E. Phys. Rev. Lett. 91, 050402 (2003).

DYNAMICAL CASIMIR EFFECT

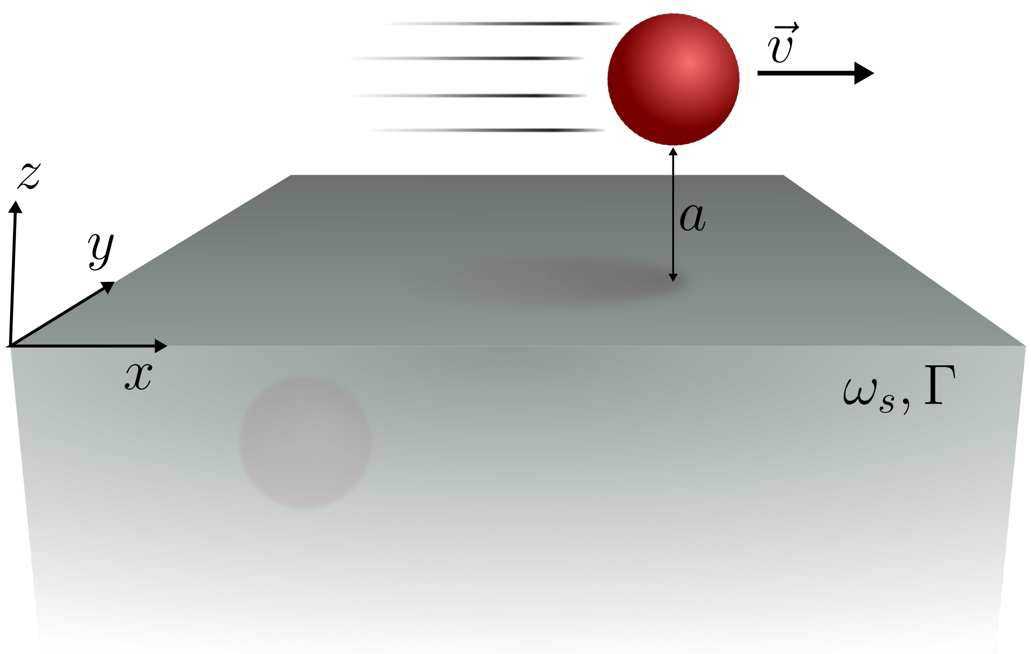
WHEN A MIRROR MOVES THROUGH SPACE AT RELATIVISTIC SPEEDS: SOME PHOTONS BECOME SEPARATED FROM THEIR PARTNERS AND THE MIRROR BEGINS TO PRODUCE LIGHT

Experimental observation of DCE was based on electromagnetic analogs of a moving mirror using a tunable reflecting element in a superconducting device

Wilson, C. M. et al. Observation of the dynamical Casimir effect in a superconducting circuit. Nature 479, 376 (2011).

Lähteenmäki, P., Paraoanu, G. S., Hassel, J. & Hakonen, P. J. Dynamical Casimir effect in a Josephson metamaterial. Proc. Natl Acad. Sci USA 110, 4234 (2013).

QUANTUM FRICTION



Two bodies which are not in contact and are in relative motion to each other at constant velocity experience a **dissipative force that opposes the motion due to the exchange of Doppler shifted virtual photons**.

Quantum friction is **very small in magnitude and short ranged**, its experimental detection has become an absolute challenge so far, even though there have been a variety of configurations and theoretical efforts devoted to finding favorable conditions for its observation

We propose to track traces of quantum friction through the measurement of the geometric phase accumulated by an atom moving at constant velocity in front a dielectric material in vacuum. The geometric phase shift is manifested as a relative phase between components of a superposition of atomic states.

QUANTUM VACUUM EFFECTS

How about direct observation of vacuum fluctuations?

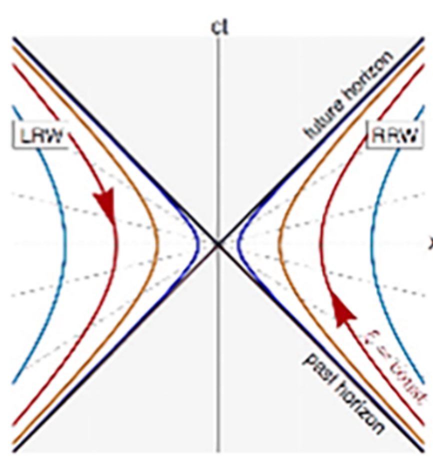
→Amplification of vacuum fluctuations

Vacuum fluctuations at the event horizon results in the breaking up of pairs of virtual particles. One is trapped in the BH and the other escapes to infinity

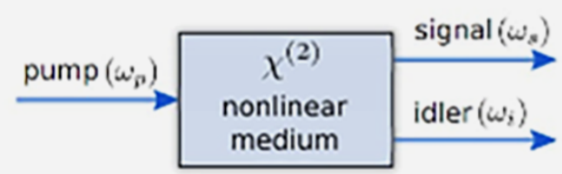
Hawking Radiation

An accelerated observer in vacuum sees a field in a thermal state. Vacuum fluctuations "promoted" to thermal fluctuations

Unruh effect

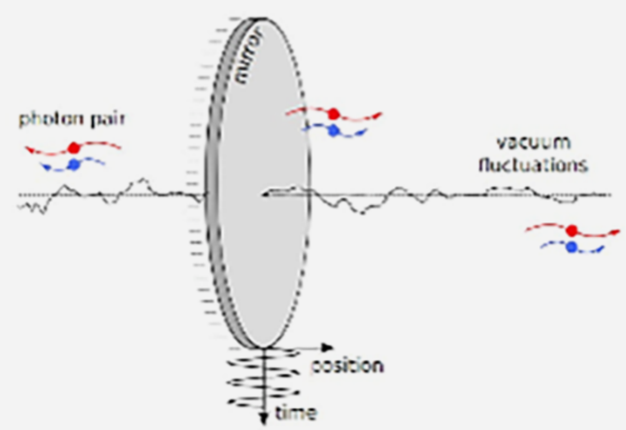


Parametric amplifier



Note: HR and UE only involved an observer, which only detects the state of the field and does not affect the modes of the field as in DCE

Dynamical Casimir effect



A mirror undergoing nonuniform relativistic motion can modify the mode structure of vacuum non-adiabatically. Can result in the conversion of virtual photons (vacuum fluctuations) to real detectable photons.

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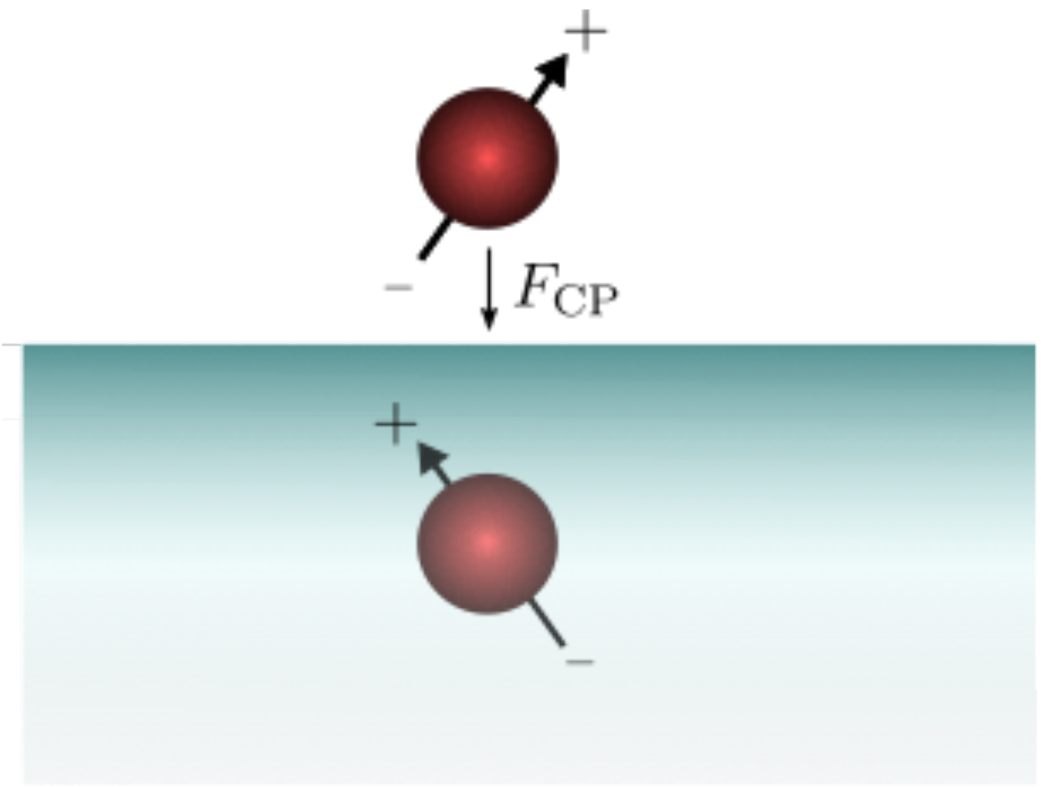
INTUITIVE PICTURE

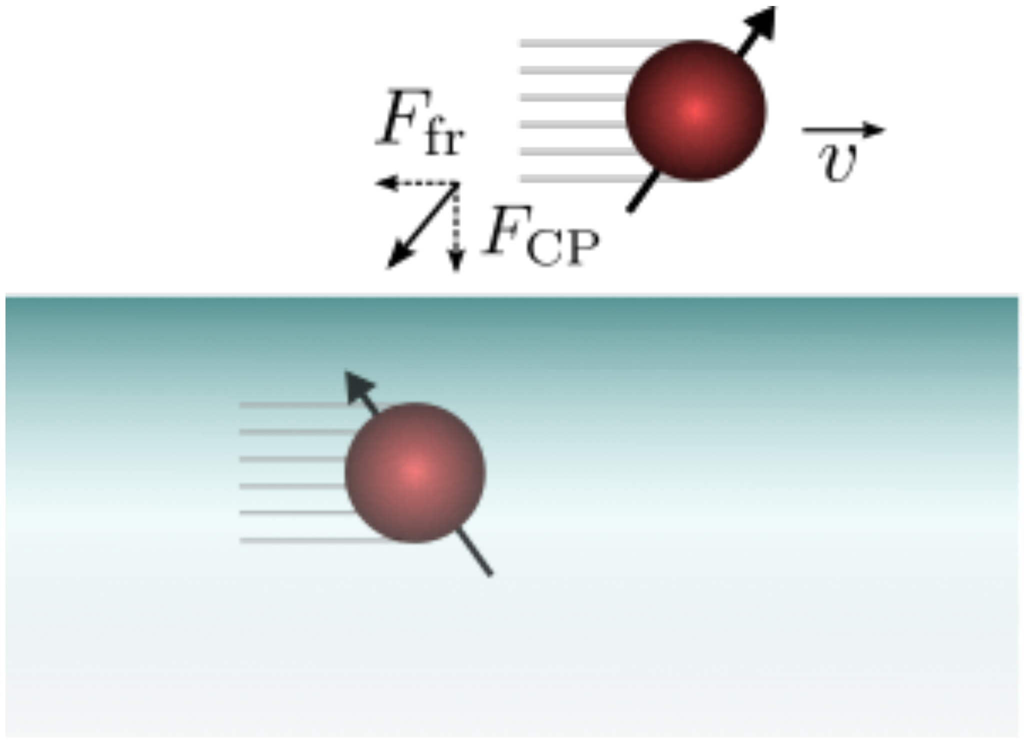


CASIMIR-POLDER

- EM fluctuations→ fluctuating dipole moment
- Image dipole inside the mirror
- Correlation between the two dipoles' oscillations
- Dipole-dipole interaction
- Attractive force
- Directed on the line that connects the two dipoles

QUANTUM FRICTION

INTUITIVE PICTURE

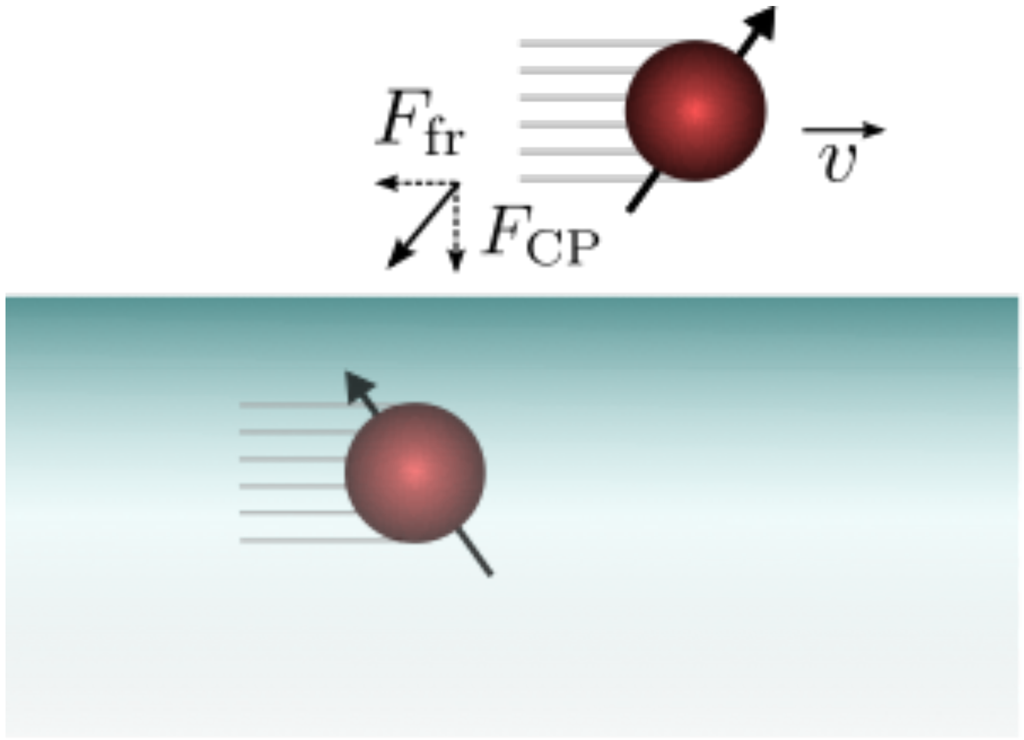


FRICTION

- Imperfect mirror → delay in the reorganization of the charges
- Image dipole left behind (Doppler shift)
- Phase lag in the correlations
- Tilted force
- Vertical component: CP
- Horizontal component: **frictional force**

QUANTUM FRICTION

INTUITIVE PICTURE



Sir John B. Pendry

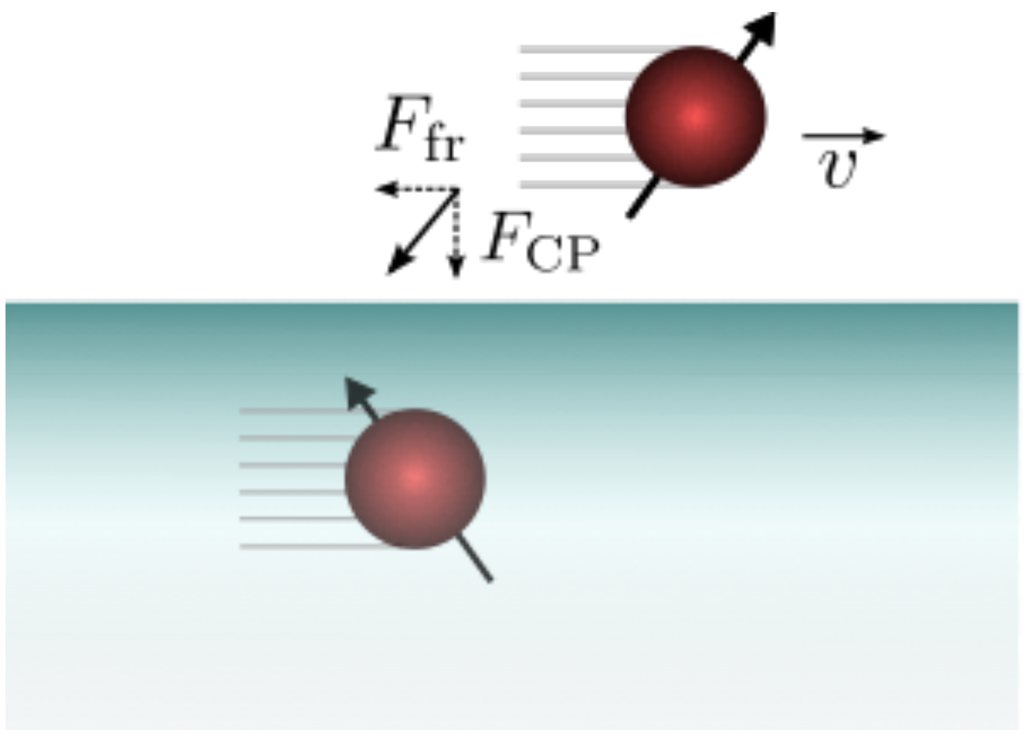
Dielectric plate (1997)

Criticized by Philbin & Leonhardt (2009)

Quantum Friction: fact or fiction? (2010)

QUANTUM FRICTION

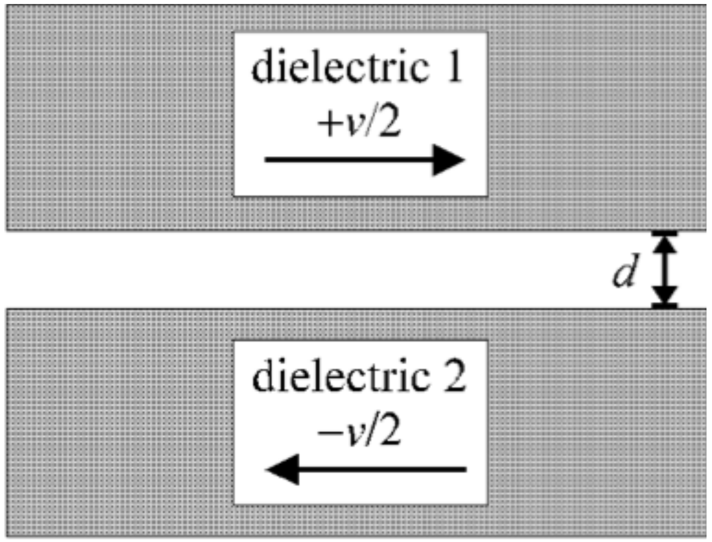
INTUITIVE PICTURE



FRICTION

- Short-ranged
- Small magnitude
- Avoids experimental detection so far
- A lot of effort being put into trying to find systems where the force is enhanced
- Or indirect ways of detecting quantum friction

OTHER DISIPATIVE EFFECTS



Friction between imperfect moving mirrors (Pendry 1997)

Simplest case:

$$F = \Im\left[\frac{\varepsilon - 1}{\varepsilon + 1}\right]^2 \frac{3\hbar\, v}{2^6 \pi^2 d^4}$$

Dissipative forces due to excitation of internal degrees of freedom (Fosco, Lombardo, Mazzitelli, 2010 y 2011)

Existence of friction force when plane mirrors which are not in contact undergo constant-speed relative parallel motion

QUANTUM FRICTION

Quantum friction can be understood in terms of an exchange of virtual photons between the two bodies, which in turn excite their internal degrees of freedom

RELATED EFFECTS

Quantum Cerenkov ($v > c_m$)

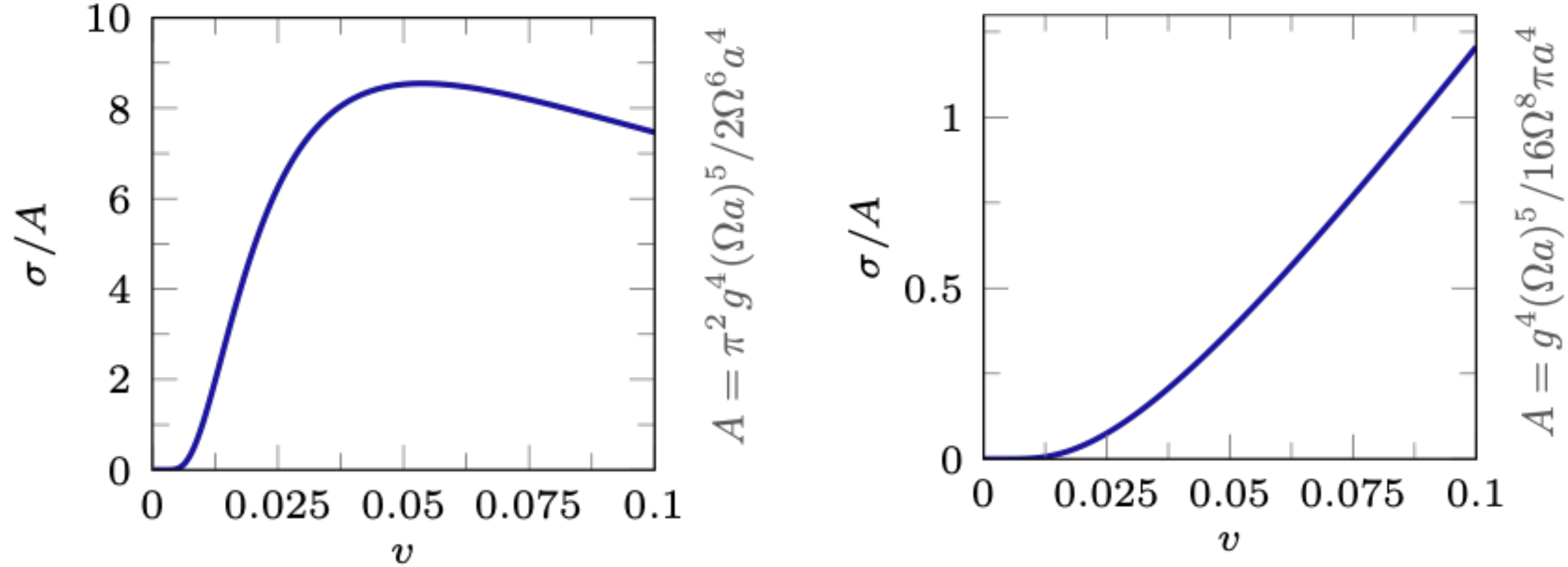
Atom - Atom

Atom - Plate (Casimir Polder)

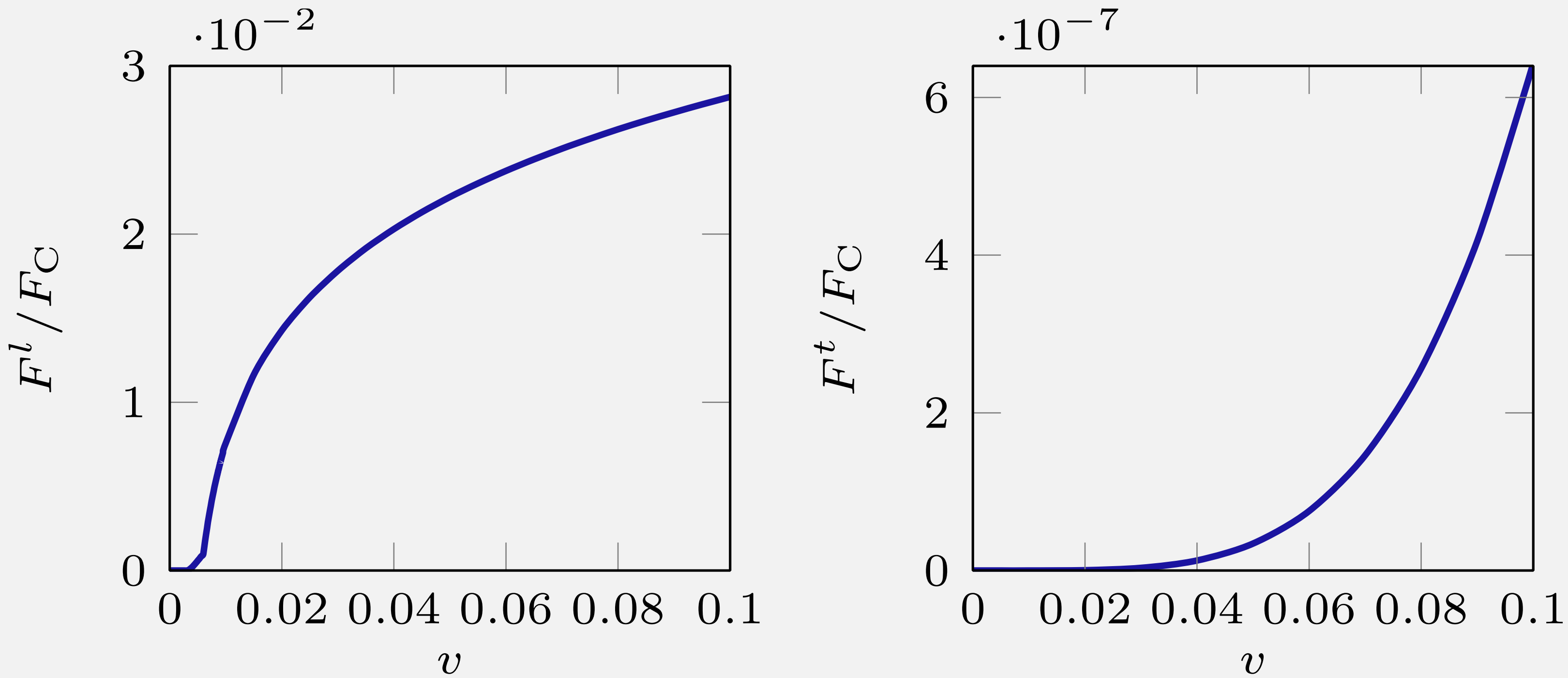
Tip of an Atomic Force Microscope - surface

Dynamical Casimir (real photons/accelerated objects)

$$\sigma = -\frac{\pi^2}{2a^4}\frac{g^4}{\Omega^6}\,\frac{1}{v}(\Omega\, a)^5 \int dx\, \frac{e^{-\frac{2}{v}\sqrt{(\Omega a)^2(4-v^2)+x^2}}}{(\Omega a)^2(4-v^2)+x^2}$$



M.B. Farías, C.D. Fosco, F.C.L, F.D Mazzitelli, & A.E. R. López, *Phys. Rev. D* ***91*** (2015) 105020

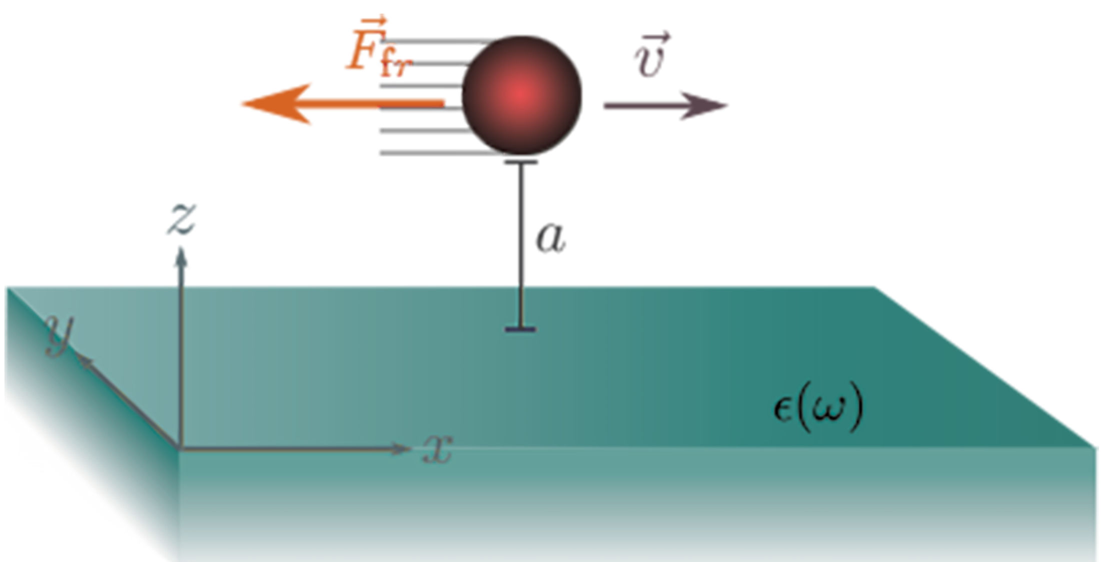


$$F_C \approx \frac{3\alpha_N^2}{128\pi}\frac{1}{a^4}\frac{1}{v_F}$$

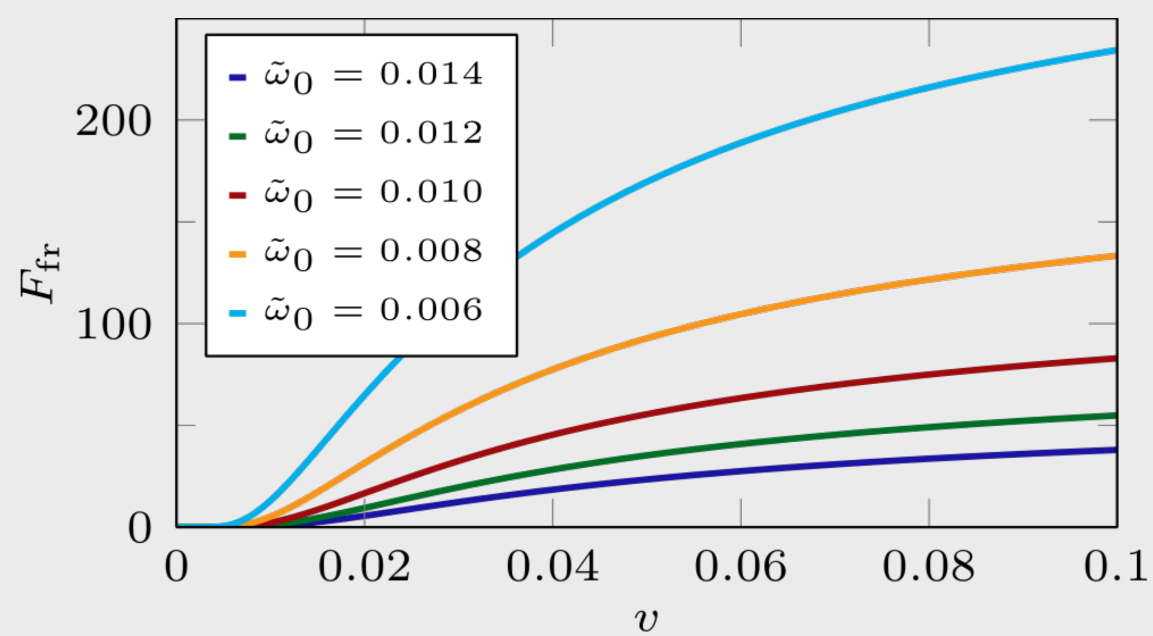
For speeds of 1% of the speed of light (very high) the force results in two orders of magnitude less than that of static Casimir (which is even less than the force between perfect conductors)

M.B. Farias, C.D. Fosco, F.C.L. & F.D. Mazzitelli. "Quantum friction between graphene sheets." *Phys. Rev. D* **95**, (2017) 065012

FRICTION FORCE: ATOM - MIRROR

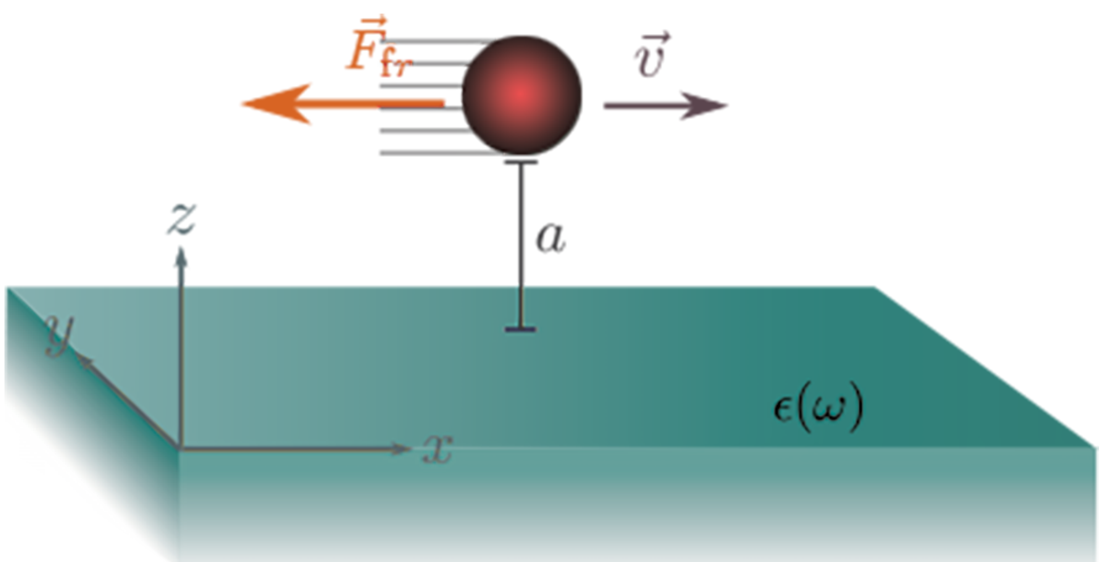


$$F_{fr} = \frac{\pi^2}{2a^2}\lambda^2 g^2 \frac{\tilde{\Omega}^3}{\Omega^3}\frac{\tilde{\omega}_0}{\omega_0}\frac{e^{-\frac{2}{v}\sqrt{(\tilde{\omega}_0+\tilde{\Omega})^2 - v^2\tilde{\Omega}^2}}}{(\tilde{\omega}_0+\tilde{\Omega})^2 - v^2\tilde{\Omega}^2}$$

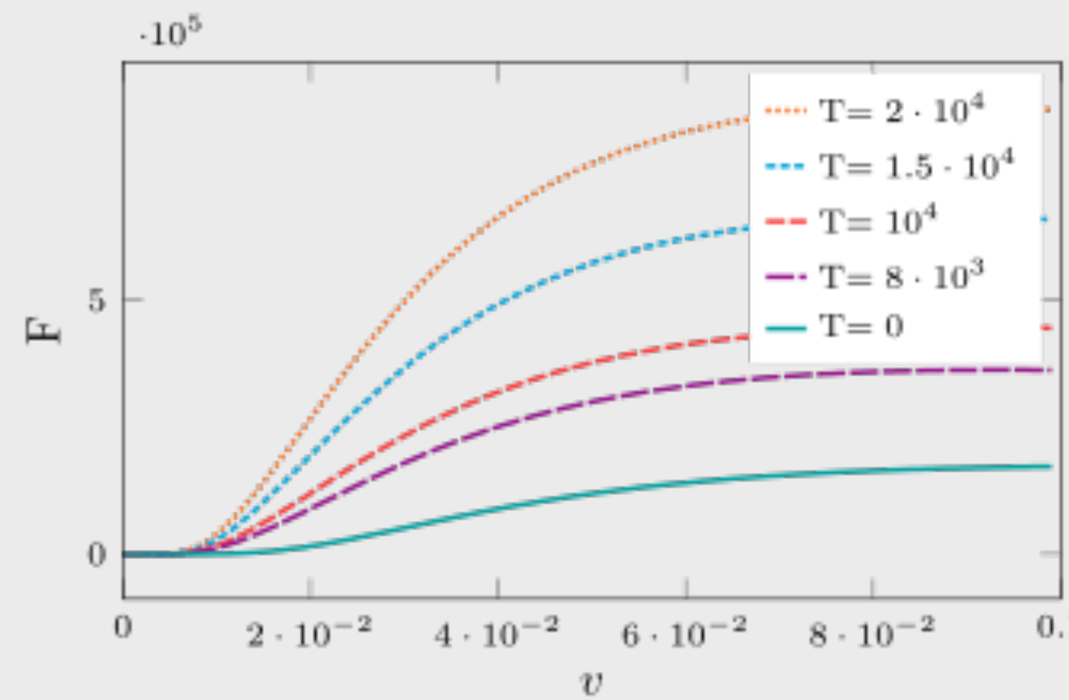


M.B. Farías & F.C. L, *Phys. Rev. D* ***93*** (2016) 065035

FRICTION FORCE: ATOM - MIRROR



$$F_{fr} = \frac{\pi^2}{2a^2}\lambda^2 g^2 \frac{\tilde{\Omega}^3}{\Omega^3}\frac{\tilde{\omega}_0}{\omega_0}\frac{e^{-\frac{2}{v}\sqrt{(\tilde{\omega}_0+\tilde{\Omega})^2 - v^2\tilde{\Omega}^2}}}{(\tilde{\omega}_0+\tilde{\Omega})^2 - v^2\tilde{\Omega}^2}$$

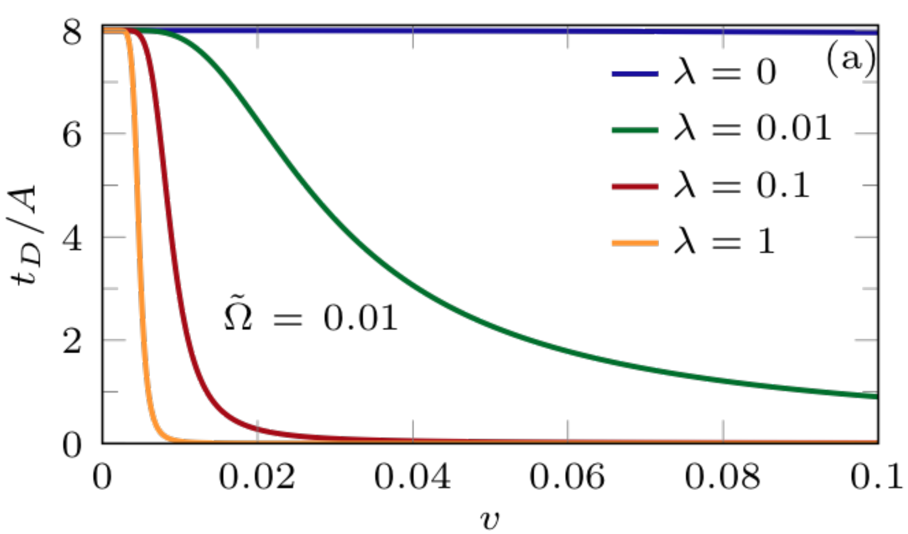


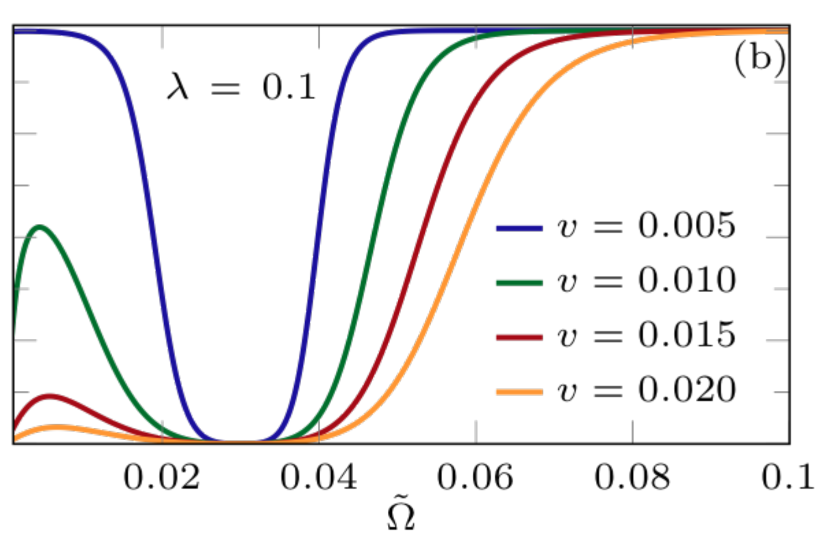
L. Viotti, M.B. Farías, F.C. L, & P.I. Villar, "Thermal corrections to quantum friction", *Phys. Rev. D* ***99*** (2019) 105095

DECOHERENCE OVER THE ATOM

Enhancement of the decoherence due to friction

The presence of the plate reduces the decoherence time, but only for non-vanishing relative velocity. For very small velocities, decoherence time is not reduced, even for greater values of the coupling constant between the plate and the vacuum field. t_D is shown as a function of the plate's characteristic dimensionless frequency, for different values of its macroscopic velocity v. A clear minimum appears for every value of v, and it is located in $\Omega = \omega_0$. Decoherence is maximal in the resonant case, hence making the decoherence time vanish. Far from the resonance, for $\Omega >> \omega_0$, decoherence time tends to the limiting value that corresponds to the case $\lambda = 0$ (the case with no plate)





Model: Quantum harmonic oscillator as particle immersed in bath represented by Klein Gordon field in front of a quantum harmonic oscillators plate

M.B. Farias & F.C.L. *Phys. Rev. D* 93, 065035 (2016)

QUANTUM FRICTION INPRINTS ON THE GEOMETRIC PHASE ACQUIRED BY MOVING ATOM

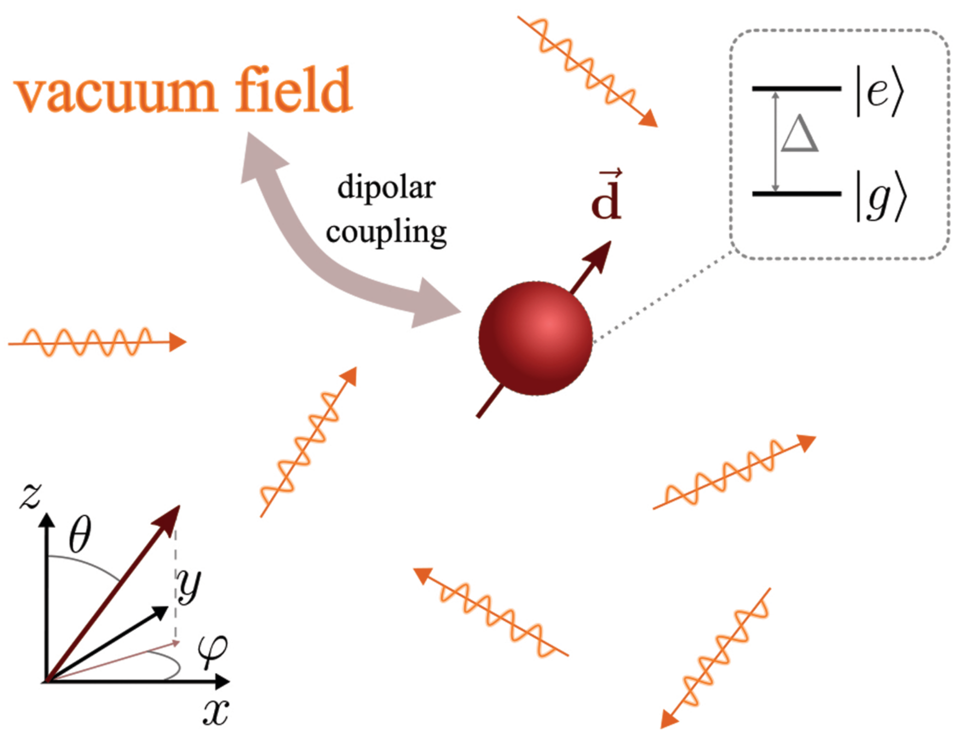
- As a consequence of quantum friction, we compute the non-unitary geometric phase for the moving particle under the presence of the vacuum field and the dielectric mirror

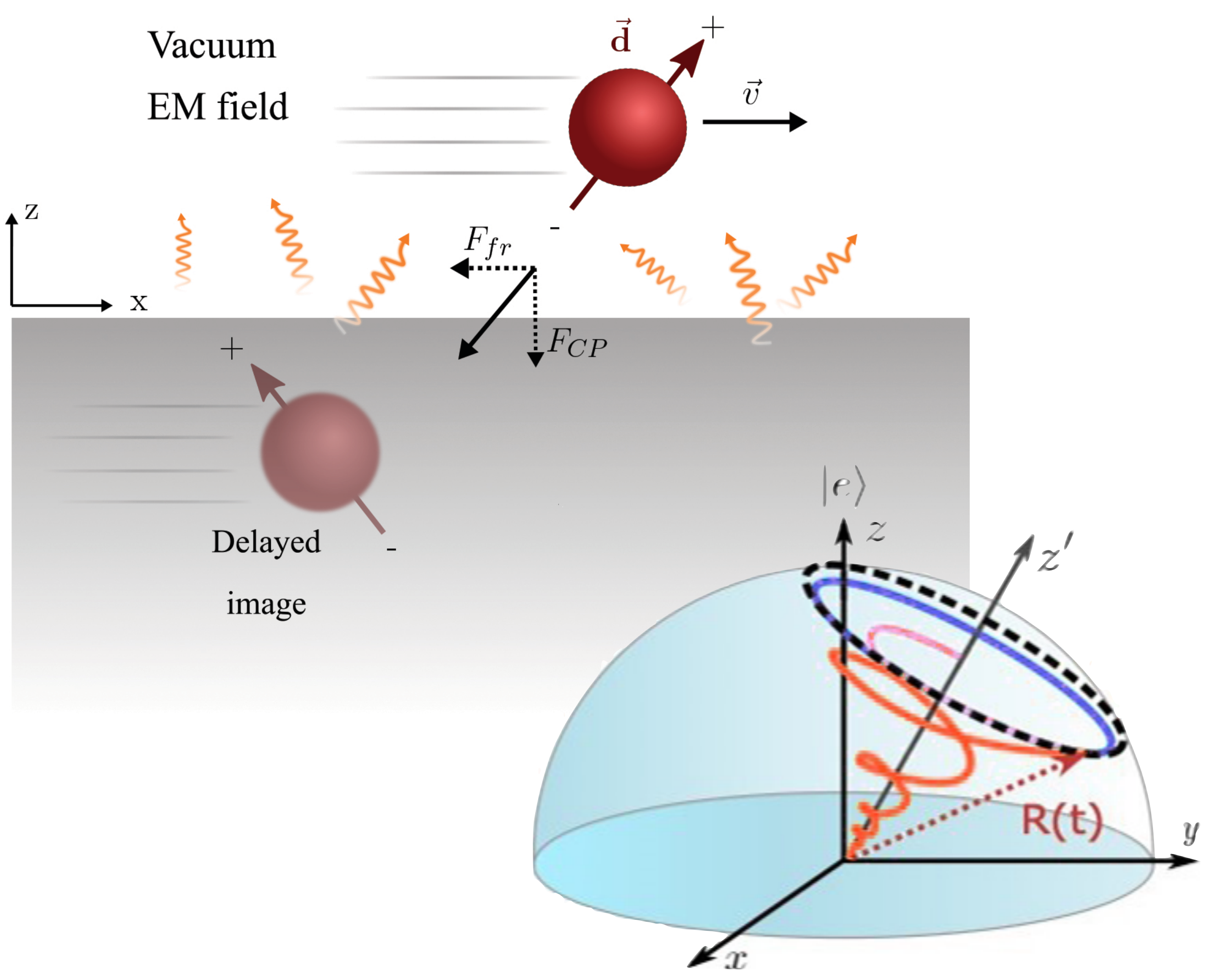
- We show in which cases decoherence effects could, in principle, be controlled in order to perform a measurement of the geometric phase using standard procedures as Ramsey interferometry, spin-echo, and/or quantum tomography

F.C.L & P.I. Villar, Europhys. Letts. 118, 50003 (2017)

ATOM MOVING IN EM FIELD

$$H = \frac{\hbar}{2}\Delta\hat{\sigma}_z + H_{SE} + H_E \quad H_{SE} = \hat{\mathbf{d}} \cdot \nabla\Phi(\mathbf{r}_s) \quad d_i = \langle g | \hat{d}_i | e \rangle = \langle e | \hat{d}_i | g \rangle$$





EM POTENTIAL
DRESSED PHOTONS

$$\hat{H} = \frac{\hbar}{2}\Delta\sigma_z + \hat{H}_{em} + \hat{H}_{int}$$

$$\hat{H}_{int} = -\,\hat{\mathbf{d}} \otimes \hat{\mathbf{E}}(\mathbf{r}_s) = \hat{\mathbf{d}} \otimes \nabla\hat{\Phi}(\mathbf{r}_s)$$

$$\hat{\Phi}(\mathbf{r},t) = \int d^2k \int_0^\infty d\omega\ \left(\phi(\mathbf{r},t)\hat{a}_{\mathbf{k},\omega}\, e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} + h.c.\right)$$

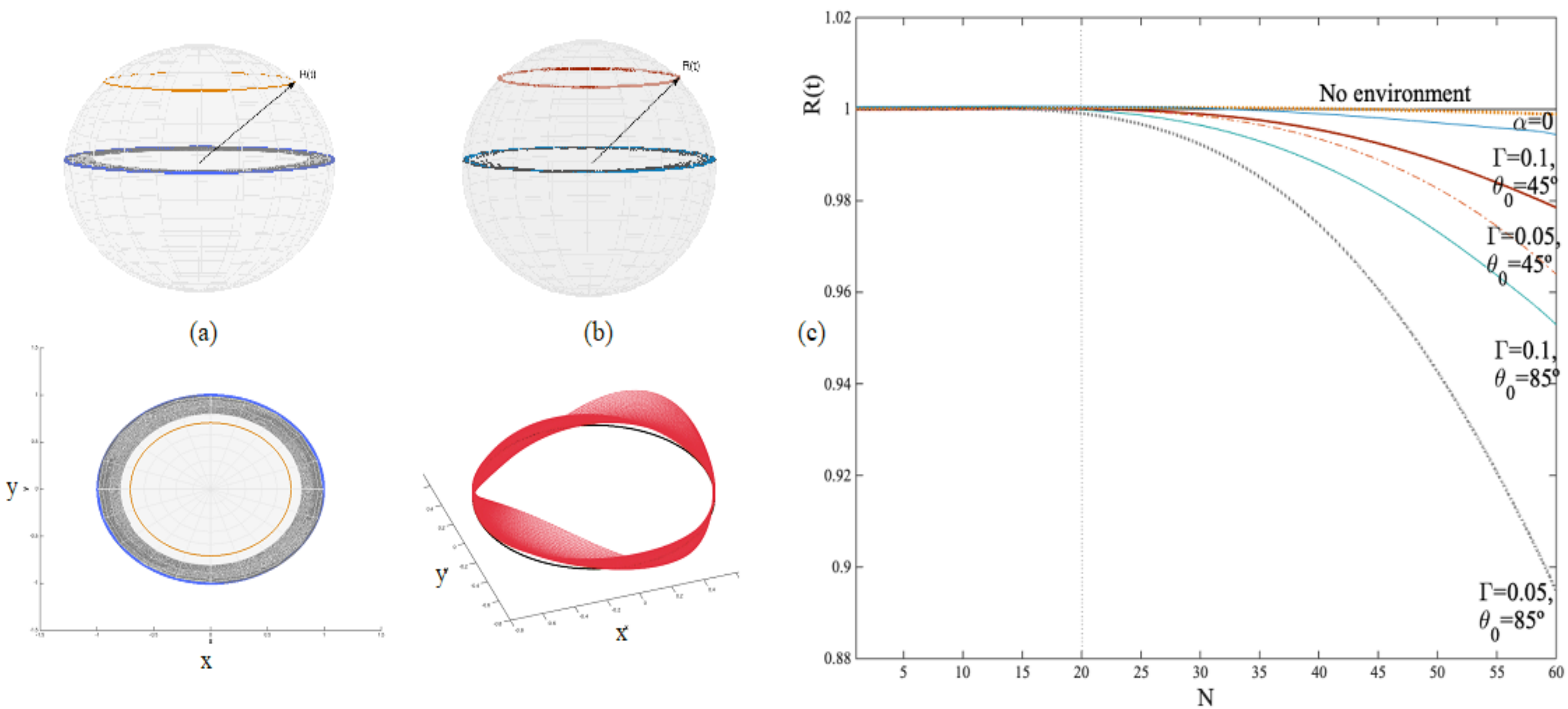
creating and destroying "photons" in a wider meaning, since they are creation and destruction operators of composite states (field plus material)

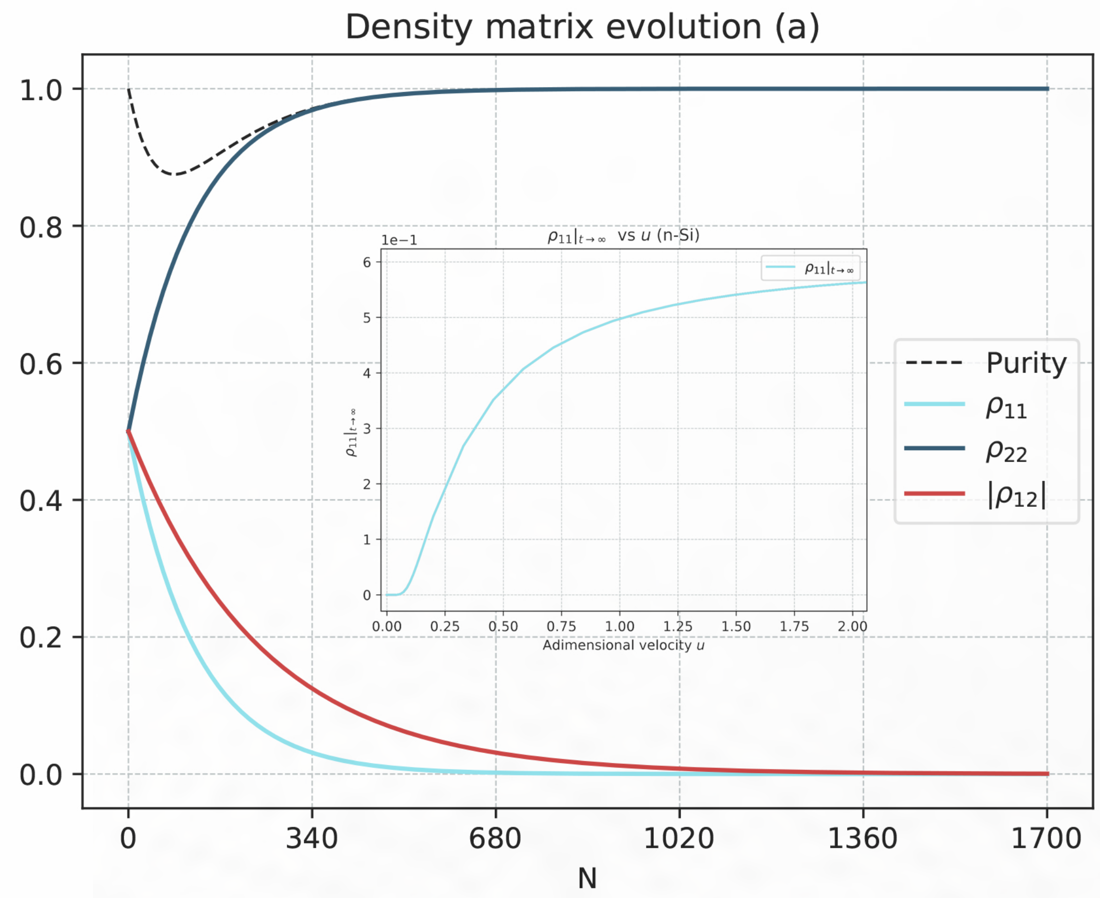
$$\phi(\mathbf{k},\omega) = \sqrt{\frac{\omega\Gamma}{\omega_s}}\sqrt{\frac{\hbar}{2\pi^2 k}}e^{-kz}\frac{\omega_p}{\omega^2-\omega_s^2-i\omega\Gamma}$$

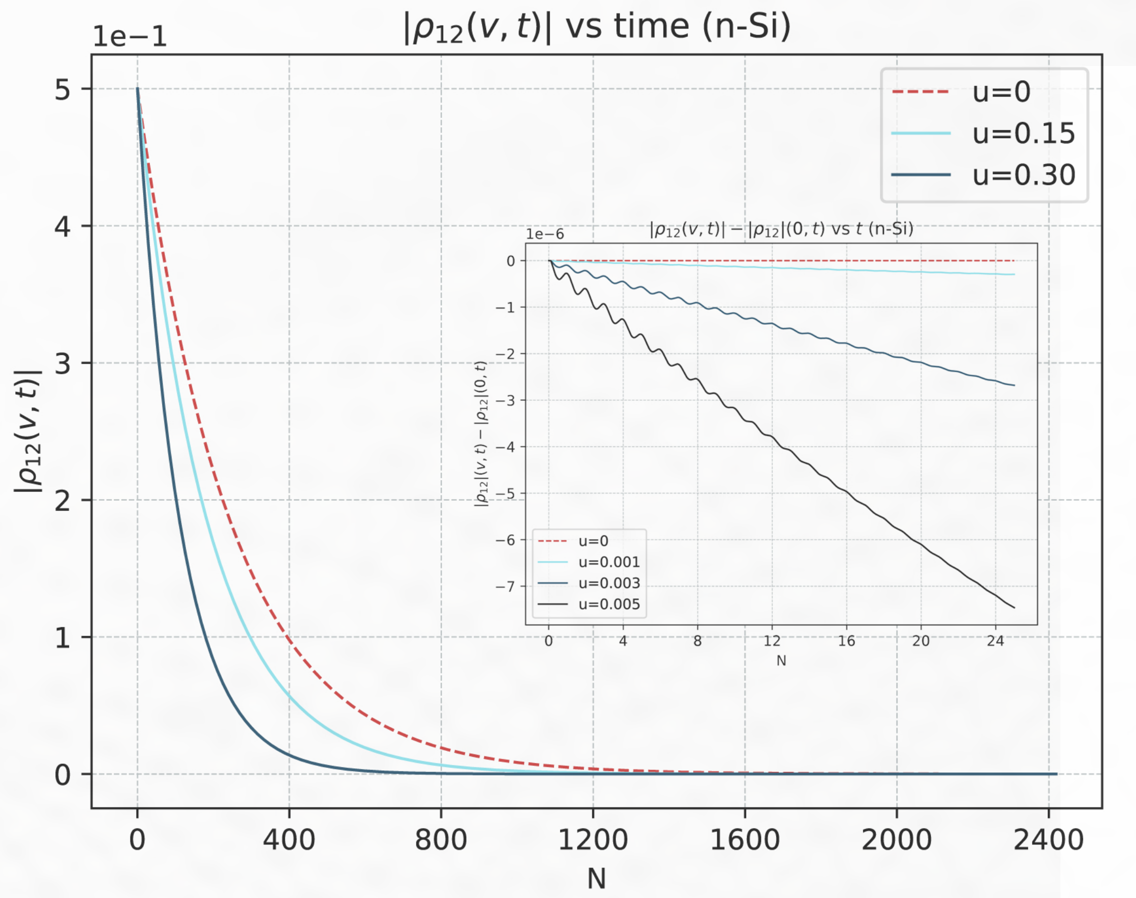
Drude-Lorentz model

Intravaia, Behunin, Henkel, Bush & Dalvit, Phys. Rev. A94 (2016)

$$\hbar\dot{\rho} = -i\left[H_a, \rho\right] - D(\mathbf{r}, t)[\sigma_x, [\sigma_x, \rho]] - f(\mathbf{r}, t)[\sigma_x, [\sigma_y, \rho]] + i\zeta(\mathbf{r}, t)[\sigma_x, \{\sigma_y, \rho\}]$$



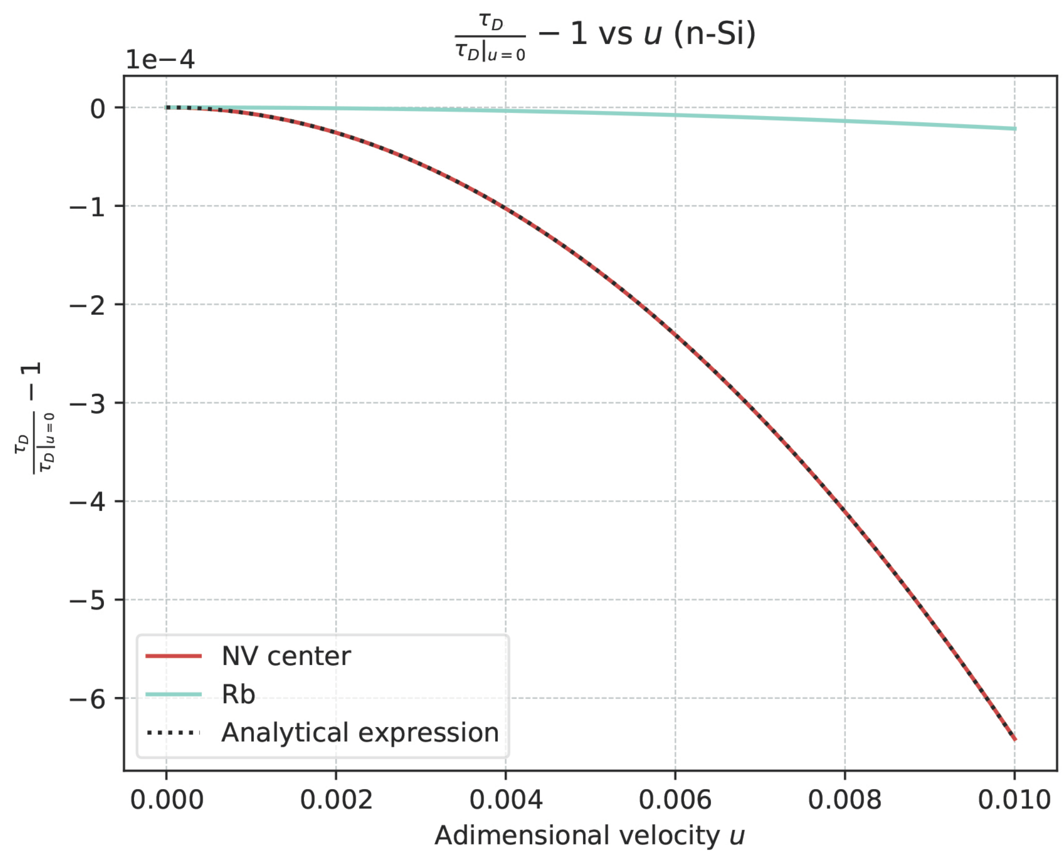


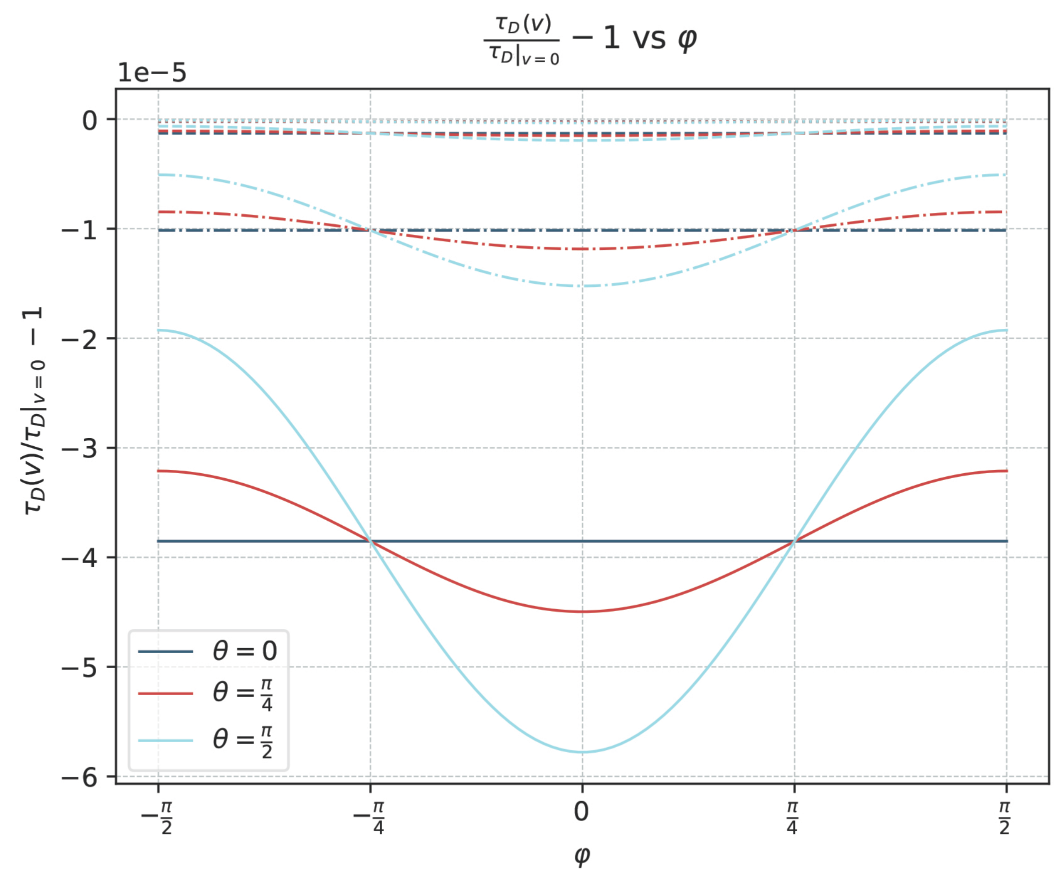


Model: Two level system as particle immersed in EM field in front of Drude-Lorentz dielectric plate

L. Viotti, F.C.Lombardo &. P.I. Villar *Phys. Rev. A 103*, 032809 (2021)

Model: Two level system as particle immersed in EM field in front of Drude-Lorentz dielectric plate





Decoherence time is at its smallest value when the polarization is perpendicular to the dielectric surface. **If tilted, the coherences fall sooner when the polarization is in the direction of the velocity**. We showed that for the same dipole orientation the force increases and τ_D decreases, implying that decoherence effects are stronger in that case. Direct link between decoherence and quantum friction since they exhibit a qualitative inverse proportionality: **the larger the decoherence effect (shorter decoherence time), the bigger the frictional force**. The results obtained reinforce the idea that the velocity-dependent effects induced on the atom depend on the material and particle. $\tau_D/\tau_{D_{u=0}}$ can be enhanced up to a factor 10^2 by considering an NV center moving over an n-Si coated surface, when compared to an Rb atom moving over a gold-coated surface

L. Viotti, F.C.Lombardo &. P.I. Villar *Phys. Rev. A 103*, 032809 (2021)

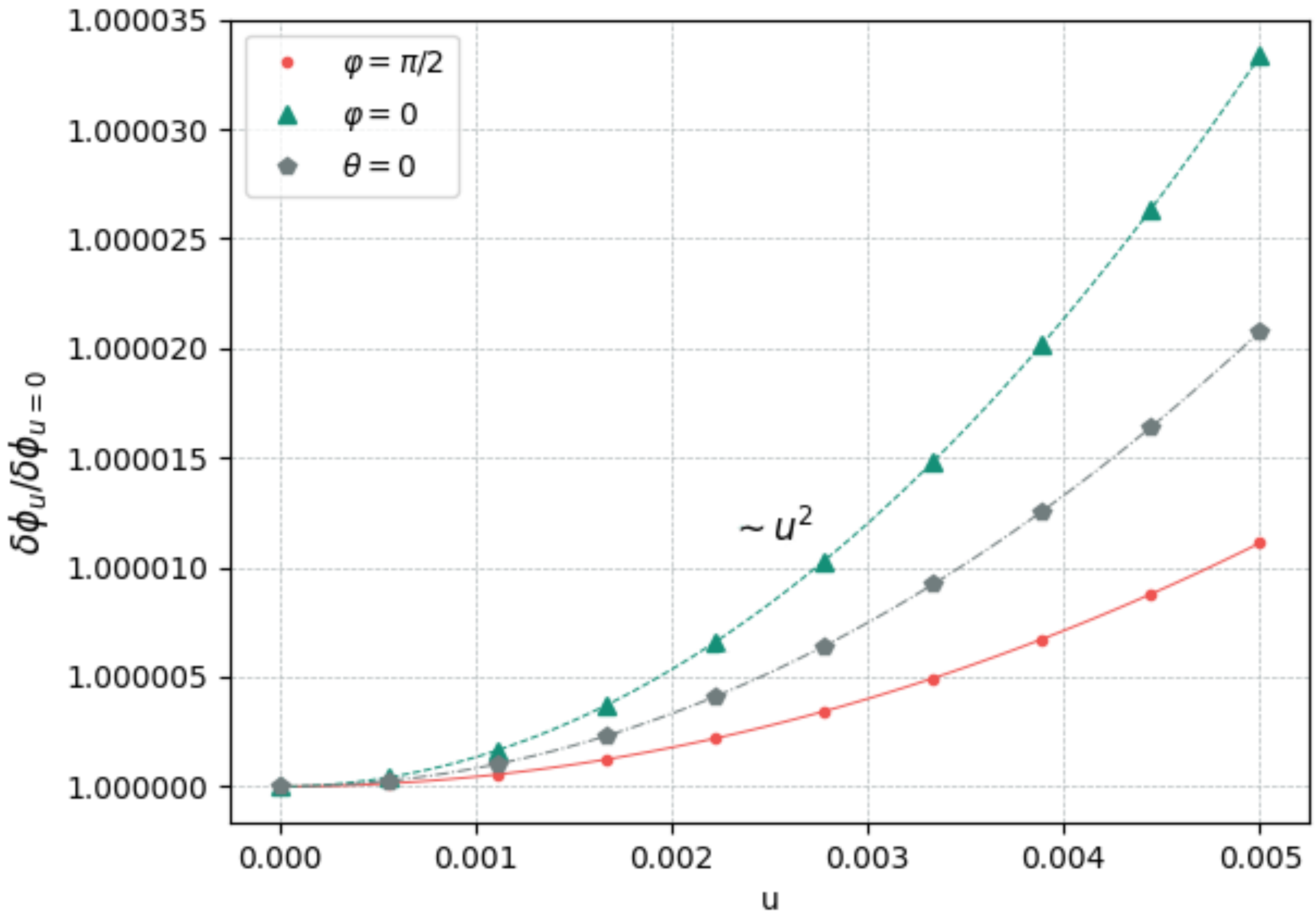
GEOMETRIC PHASE

$$\phi_g = \mathrm{Arg}\left\{ \sum_k \sqrt{\varepsilon_k(0)\varepsilon_k(t)}\, \langle \Psi_k(0) | \Psi_k(t) \rangle \times e^{-\int_0^t dt' \langle \Psi(t') | \dot{\Psi}(t') \rangle} \right\}$$

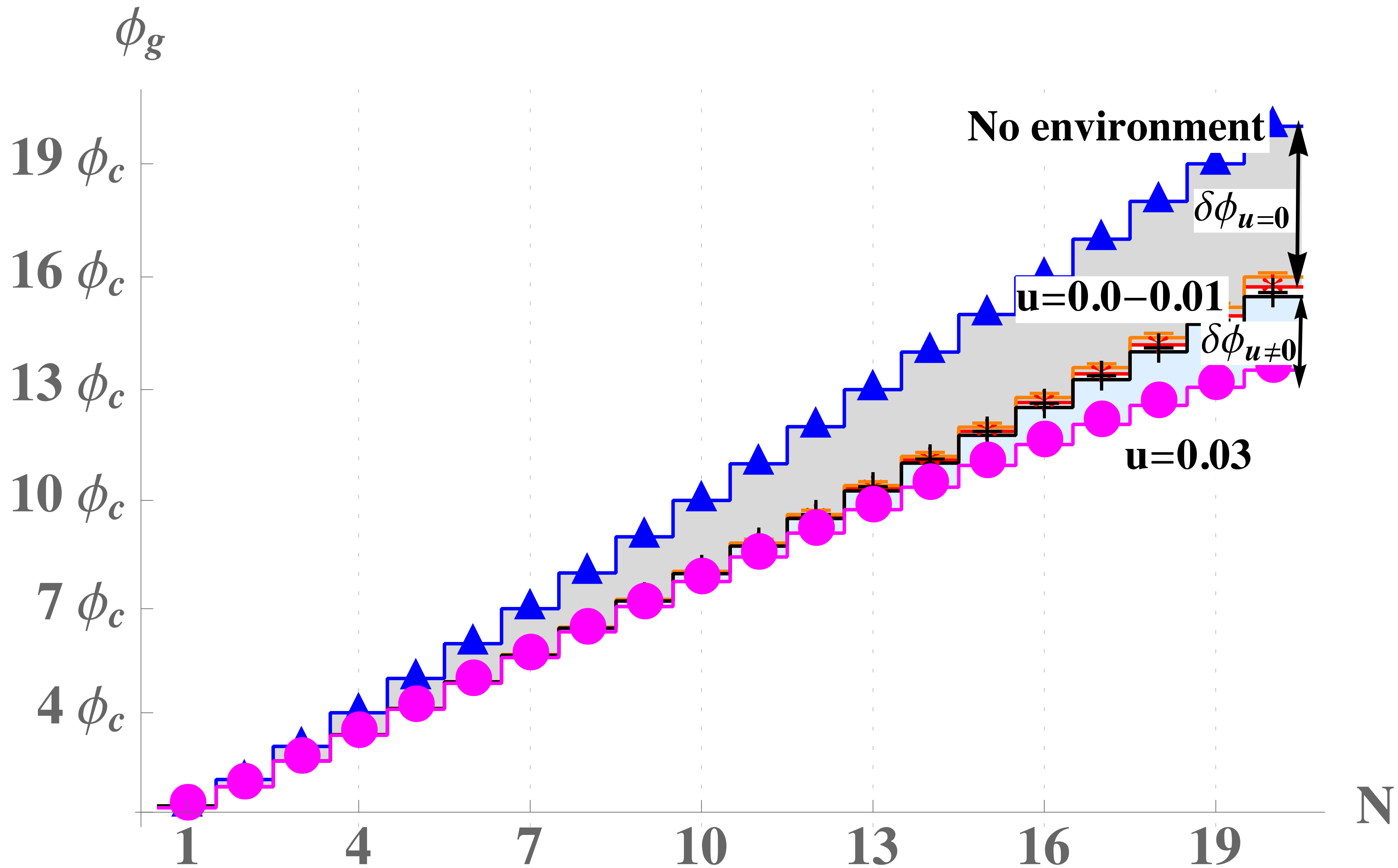
This geometric phase which generalizes Berry's and following results to nonunitarily evolution of mixed states leads to these well-known results when the evolution is unitary.
It is gauge invariant in the sense that it only depends upon the path in ray space of the considered system.

Cucchietti, Zhang, F. L., Villar, Laflamme Phys. Rev. Lett. 105, 240406 (2010)

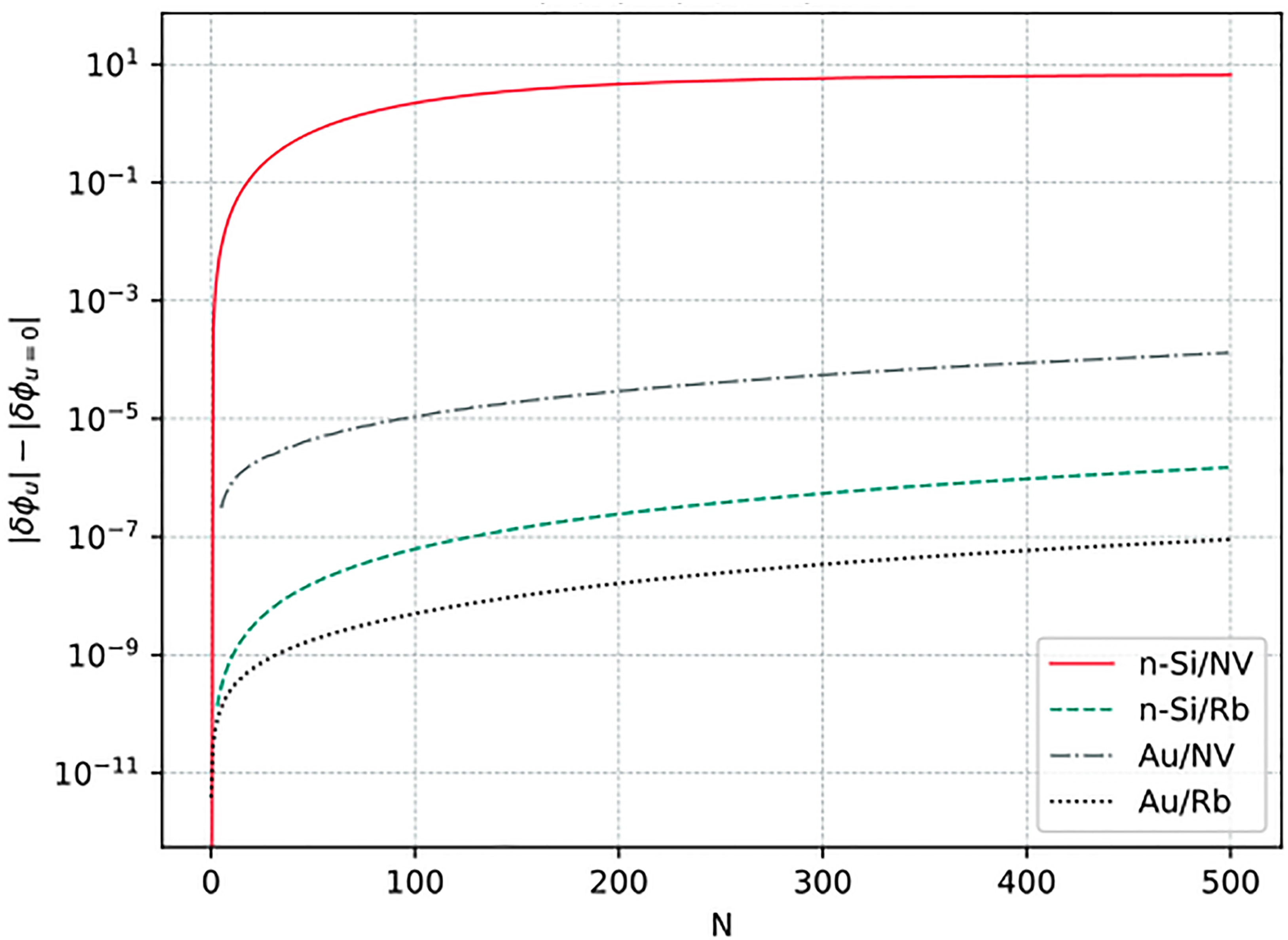
Tong, Sjoqvist, Kwek, and Oh Phys. Rev. Lett.93, 080405 (2004)



1.000035
1.000030
1.000025
1.000020
1.000015
1.000010
1.000005
1.000000
$\delta\phi_u/\delta\phi_{u=0}$
$\varphi = \pi/2$
$\varphi = 0$
$\theta = 0$
$\sim u^2$
0.000
0.001
0.002
0.003
0.004
0.005
u



It is possible to see that for N >> 5, the correction to the GP can be detected even for the smaller velocity u considered. When u = 0.03, the correction for N = 20 is about 60%.


$|\delta\phi_u| - |\delta\phi_{u=0}|$
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
0
100
200
300
400
500
N
n-Si/NV
n-Si/Rb
Au/NV
Au/Rb

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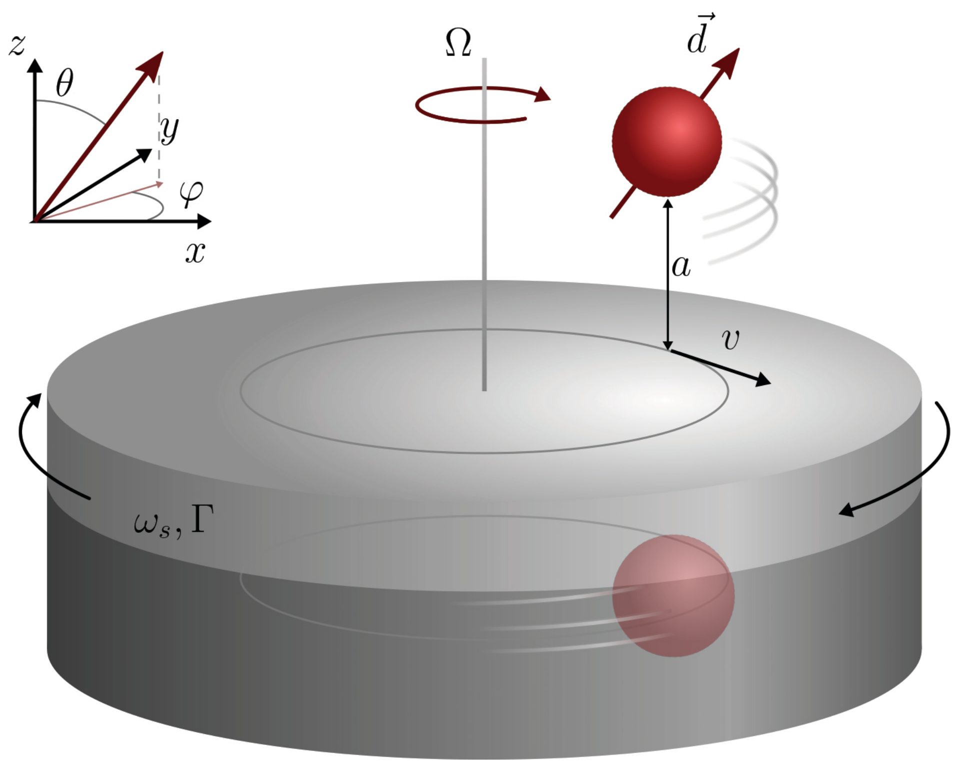


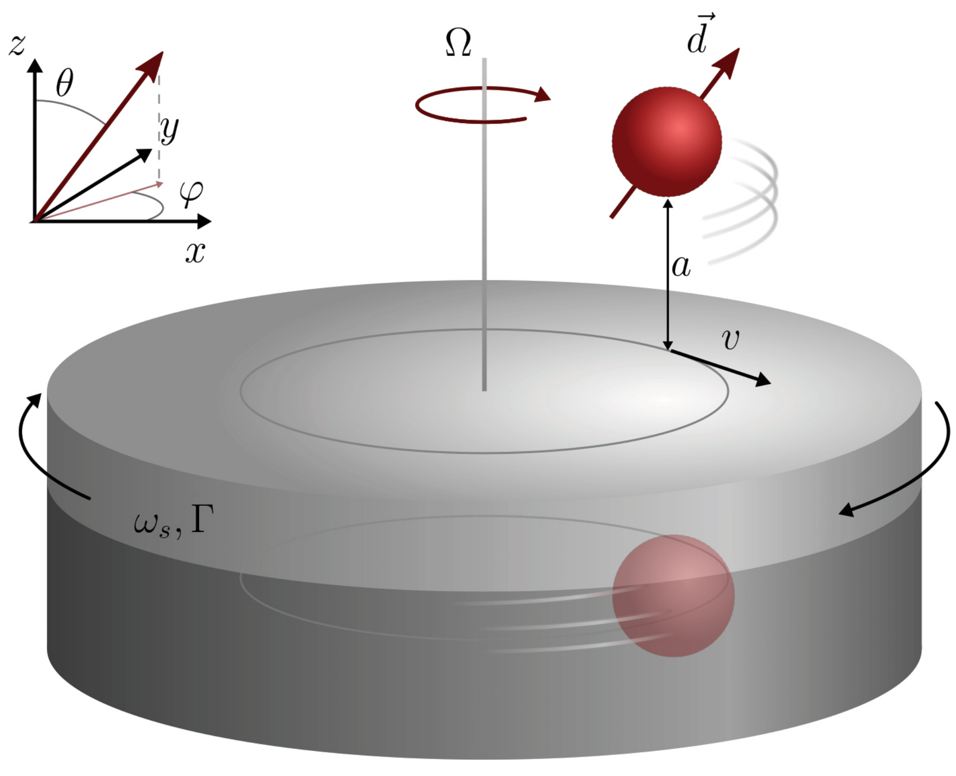
12cm diameter Au-coated Si disks rotated up to Ω = 2π7000 rad/s.

Our feasible experimental setup would be based on the use of a single NV center in diamond as an effective two-level system at the tip of a modified AFM tip.
The distance can be controlled from a few nanometers to tenths of nanometers with sub-nanometer resolution. The NV system presents itself as an excellent tool for studying geometric phases

Non-inertial effects can be completely neglected in order to model a particle moving at a constant speed on the material sheet. Since it is critical to keep the separation uniform, to prevent spurious decoherence, it is important to asses the plausibility of the proposed experimental setup.

M.B. Farías, F.C.L, A.Soba, P.I. Villar & R.S. Decca; npj Quantum Information (2020) 25

EXPERIMENTAL PROPOSAL



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State-of-the-art phase-detection experiments in NV centers in diamond permit the detection of ~ 50 mrad phase change over 10^6 repetitions

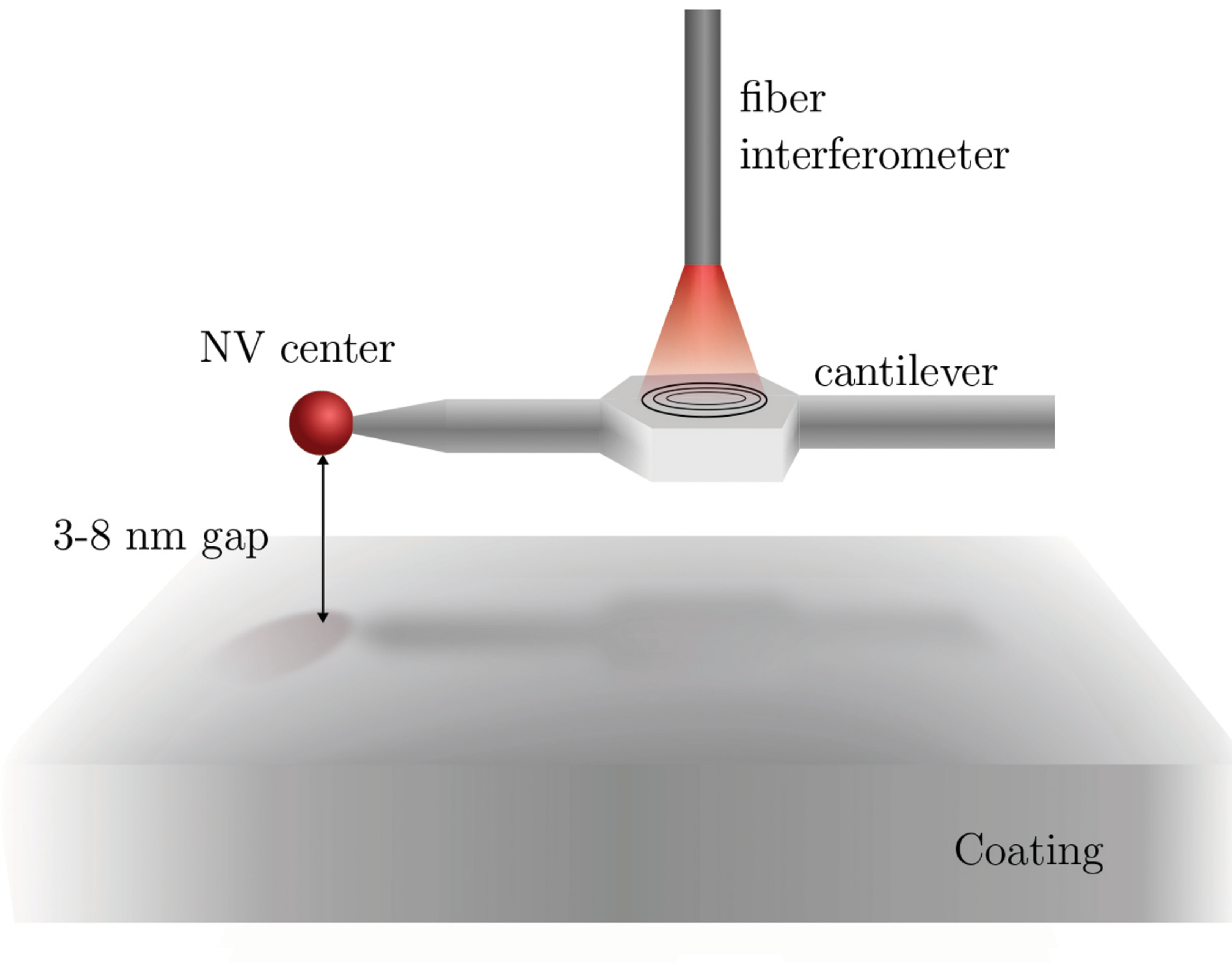
M.B. Farías, F.C.L, A.Soba, P.I. Villar & R.S. Decca; npj Quantum Information (2020)

- The NV center consists of a vacancy, or missing carbon atom, in the diamond lattice lying next to a nitrogen atom, which has substituted for one of the carbon atoms

- The NV center offers a system in which a single spin can be initialized, coherently controlled, and measured. It is also possible to mechanically move the NV center

EXPERIMENTAL PROPOSAL

In the proposed experimental setup, the sample is constituted by a Si disk laminated in metal (we propose to use Au or n-doped Si coating). The coated Si disk is mounted on a turntable.



Parameters of the Drude-Lorentz model

Au

ω_{pl} = 1.37 10^16rad/s

Γ/ω_{pl} ~ 0.05

n-Si

ω_{pl} = 3.5 10^14 rad/s

Γ/ω_{pl} ~ 1

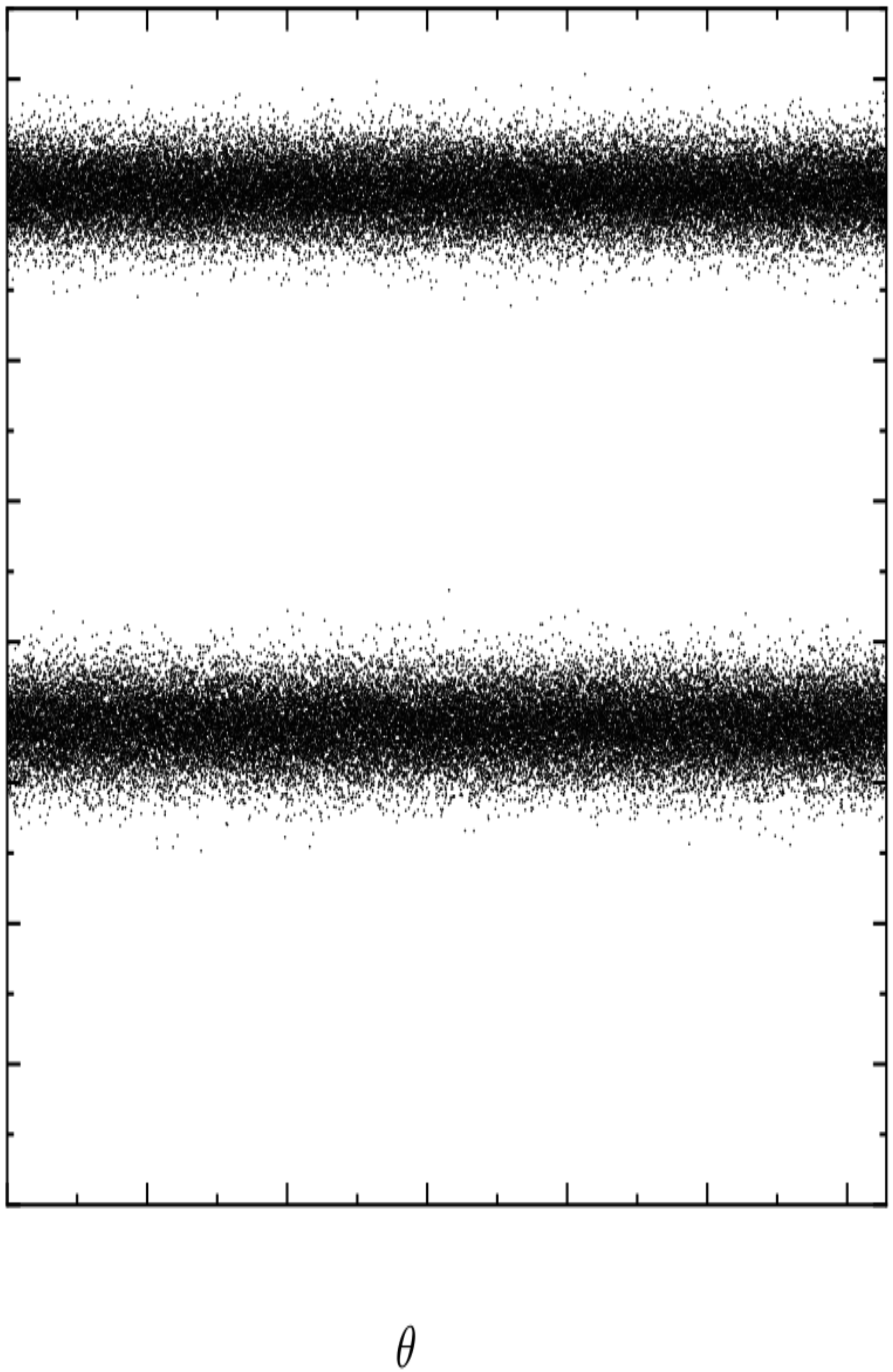
F.C.L., Ricardo S. Decca, Ludmila Viotti, and Paula I. Villar ; Adv. Quantum Technol. 2021

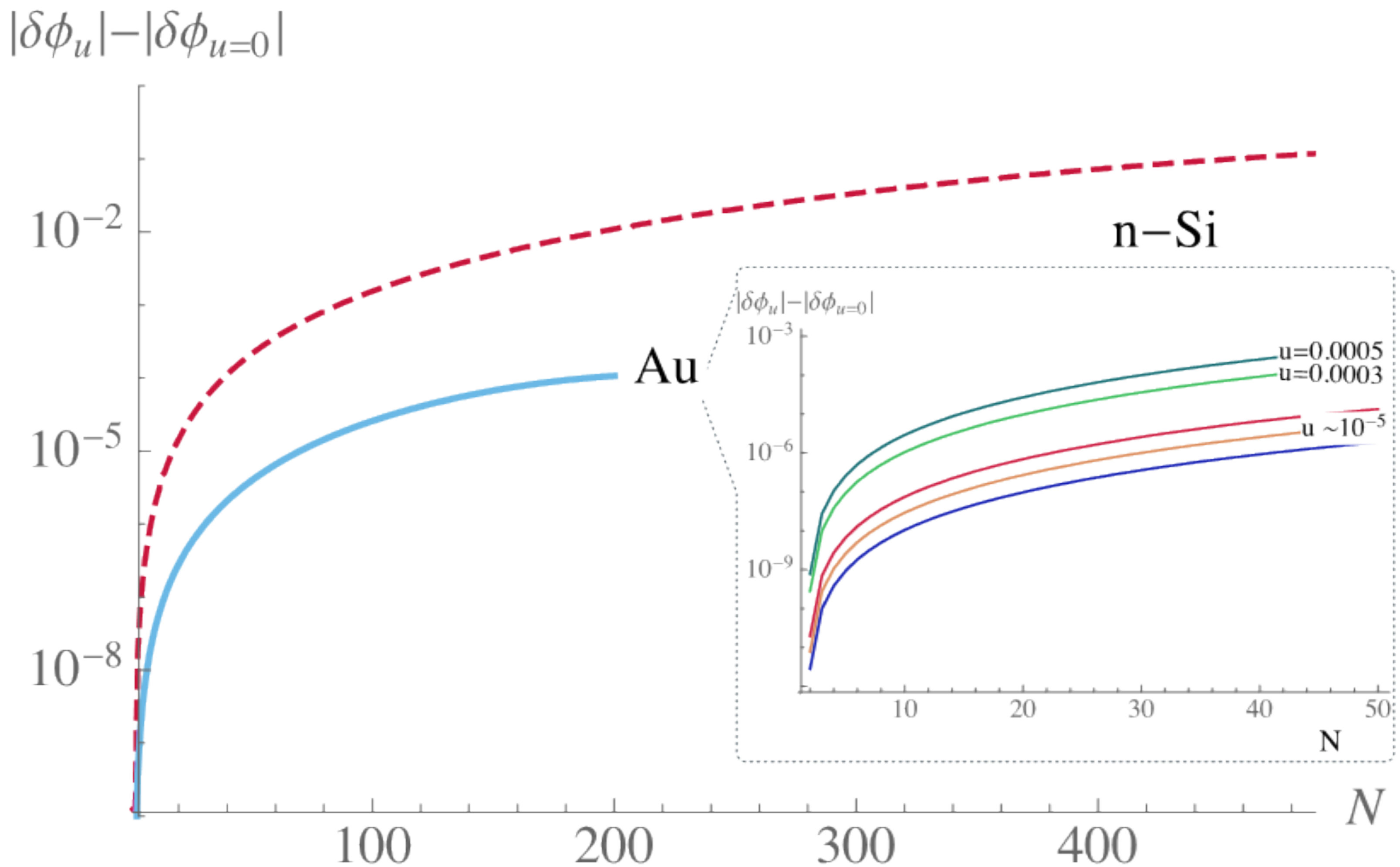
Measurement of the separation between the AFM tip

The nominal separation "a" between the tip and the sample are 7.2 and 3.4 nm.

The AFM tip moves vertically appox. 27.3 nm to keep the separation constant.

The overall change in thickness of the rotating plate could be as large as 50 nm at a given radius, the feedback control maintains the specified separation "a" to better than δa = 1 nm. The experiment is doable at a = 3 nm, with δa (possible fluctuations in distance) induced decoherence effects being negligible compared to the quantum friction ones.





Numerical simulation in experimental conditions with n-Si (u = 0.0025) and Au (u = 6.4 10^−5) coating disk.

The inset shows |δφu| − |δφu=0| for a range of velocities u derived by the assumption of values of "a" ranged between 3 and 10 nm; all of them for the case of Au coating.

$$\mathbf{u} = \frac{\mathbf{v}}{\mathbf{a}\omega_{\mathrm{pl}}}$$

In experimental conditions, we can achieve different velocities u depending the metal coating of the Si disk. When it is coated with n-doped Si, the dimensionless velocity u is bigger, u = 0.0025 making it measurable with the actual technology.

SUMMARY

- We studied the dynamics of a 2-level system in motion relative to a semi-infinite metallic material in the EM field vacuum
- We have further obtained an analytical expression for the decoherence time
- We have studied the correction to the unitary geometric phase
- The correction to the accumulated GP due to the velocity of the particle becomes relevant
- We have found a scenario to indirectly detect QF by measuring the GP accumulated by a particle moving above of a plate

THANK YOU!

UC SANTA BARBARA
Kavli Institute for
Theoretical Physics

Departamento de Física
.UBA exactas