Round Table: Quantum Friction

Carsten Henkel*, Francesco Intravaia**, Fernando Lombardi***

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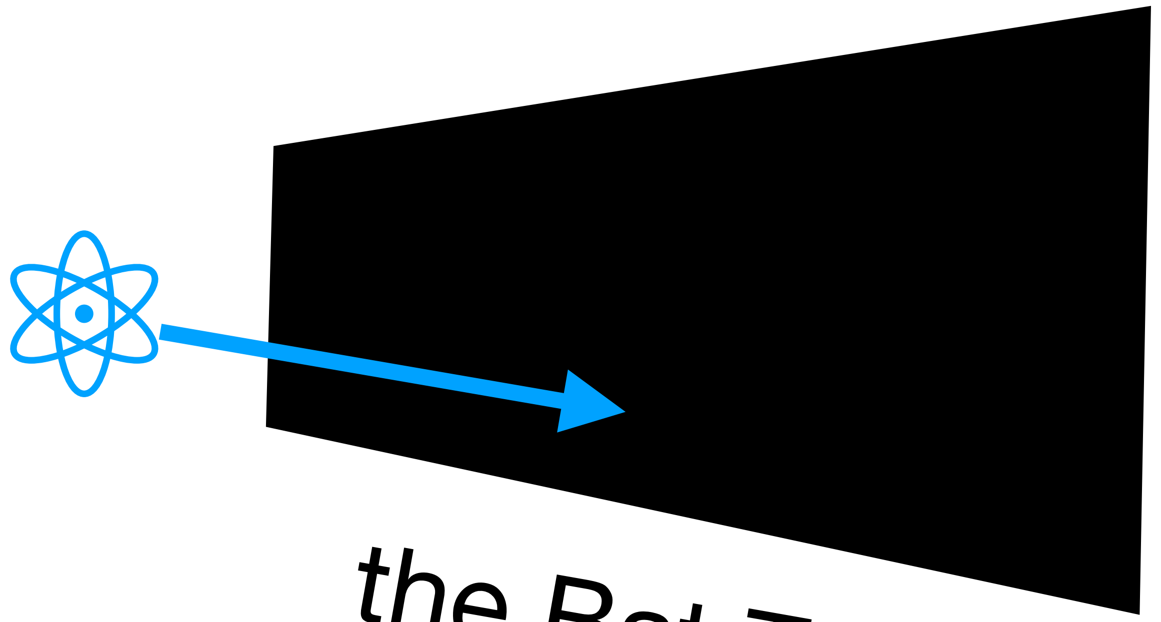
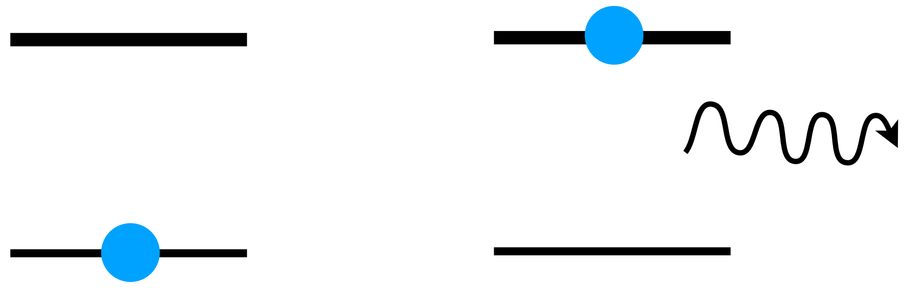


the Bat Train



anomalous Doppler effect

Flectro’22 Workshop – KITP St. Barbara 20 June–05 Aug 2022

Outline

Concept & History (Carsten Henkel)
— "viscosity of the vacuum"
— "anomalous Doppler effect"

Einstein (1916/17)
Mkrtchian, *Phys. Lett. A* **207** (1995) 299
Milton, Høye & Brevik, *Symmetry* **8** (2016) 29
> 130 references

Equation of motion approach, details (Francesco Intravaia)
— scaling with velocity v, in particular for $T = 0$
— beyond LTE

Buhmann, *Dispersion Forces II* (Springer 2013)
Intravaia & al, *J. Phys. Condens. Matt.* **27** (2015) 214020
Volokitin & Persson, *Electromagnetic Fluctuations at the Nanoscale* (Springer 2017)

From friction force to (internal) decoherence (Fernando Lombardi)
— master equations with friction and momentum diffusion
— Wigner function: disappearance of (oscillating) interference terms

Shresta & Hu, *Phys. Rev. A* **68** (2003) 012110
Belén Farías & al, *npj Quantum Inf.* **6** (2020) 25

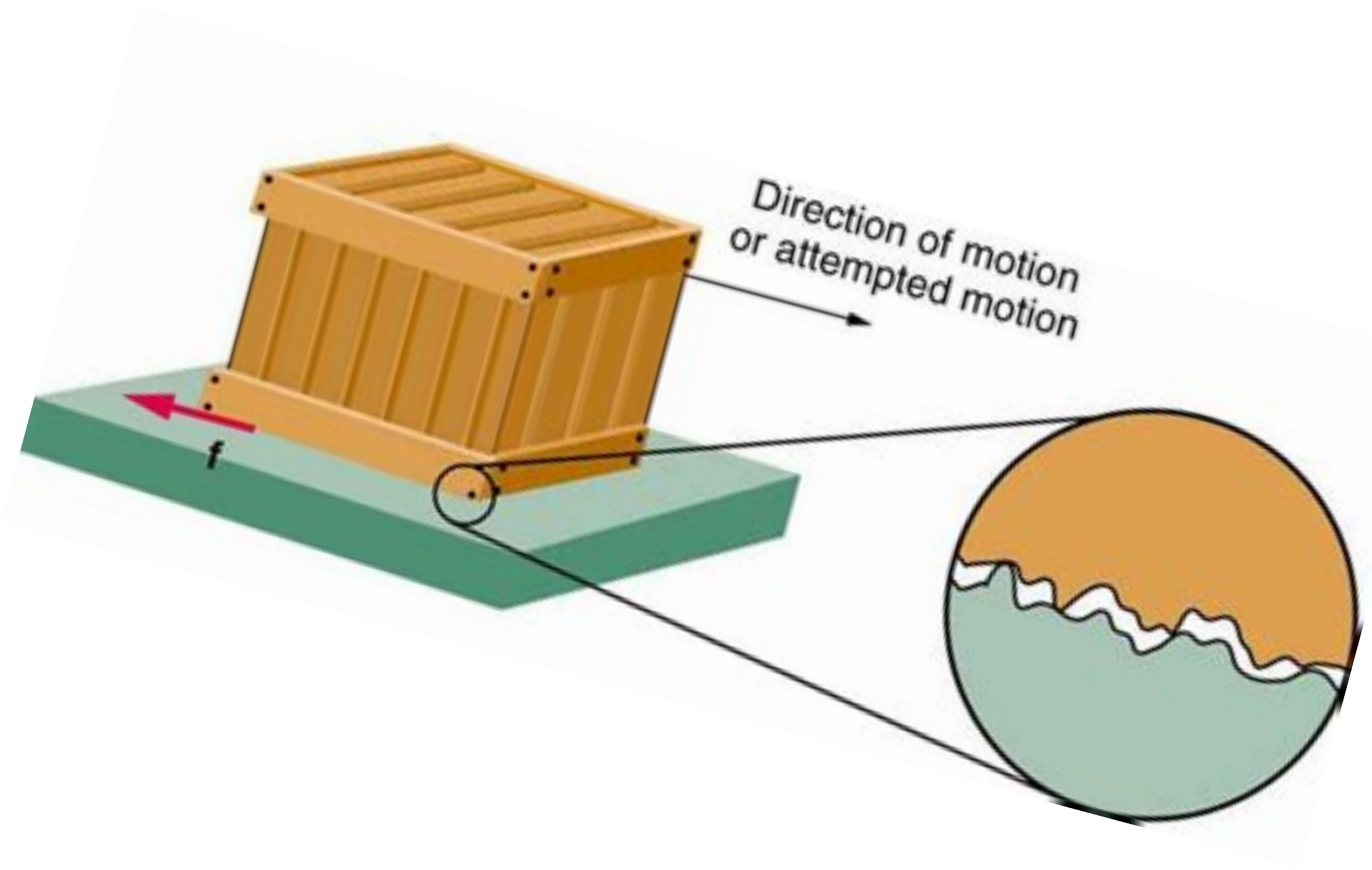
Concept: Friction

across the scales

– driving through air $F \propto v$ (Stokes), $\propto v^2$ (turbulent)

– breaking a car, slip sliding away

– tidal friction



brilliant.org

microscopic picture

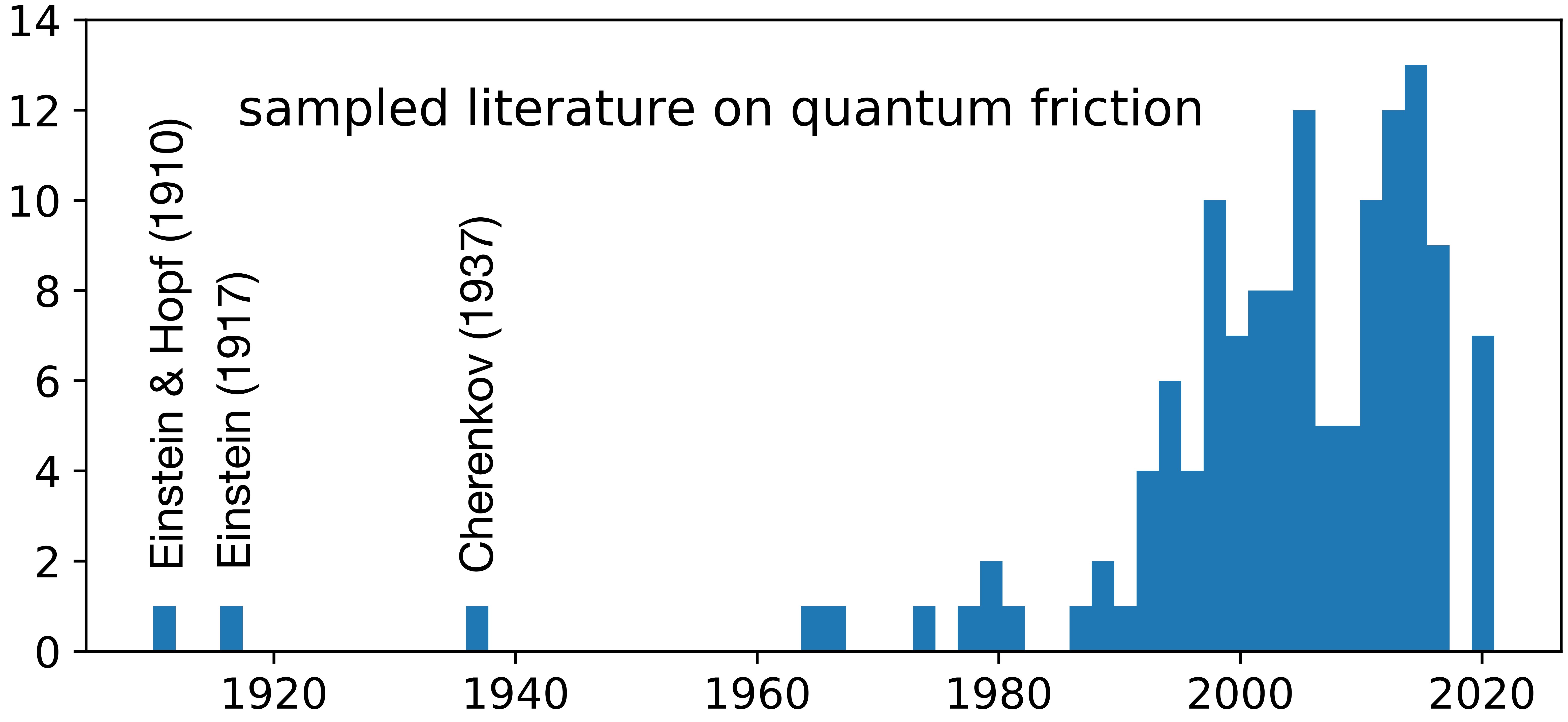
– non-smooth surfaces, abrasion

– multi-phase layers (viscosity / lubrification)

– ...

fusion.com.au

Concept: Friction



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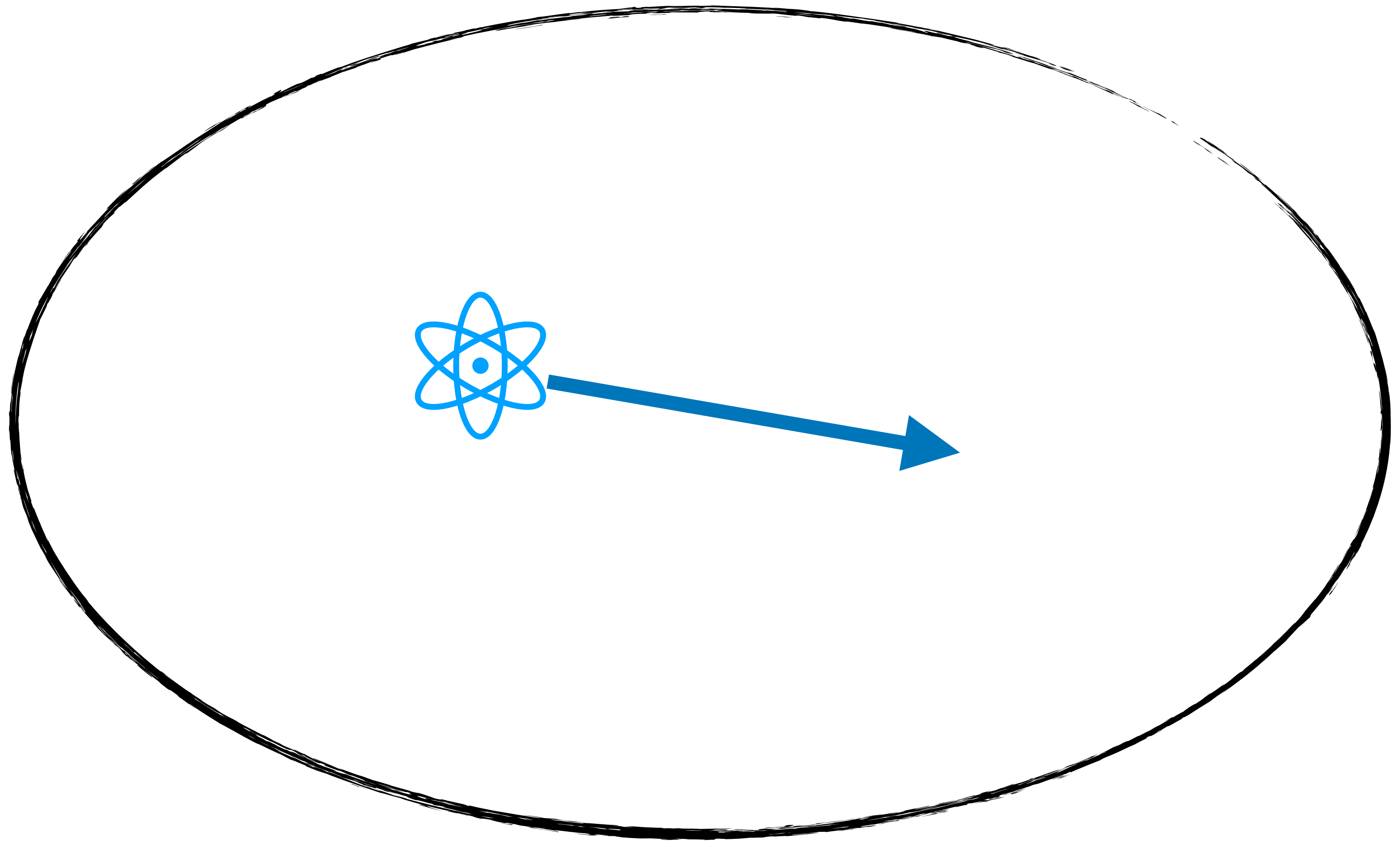
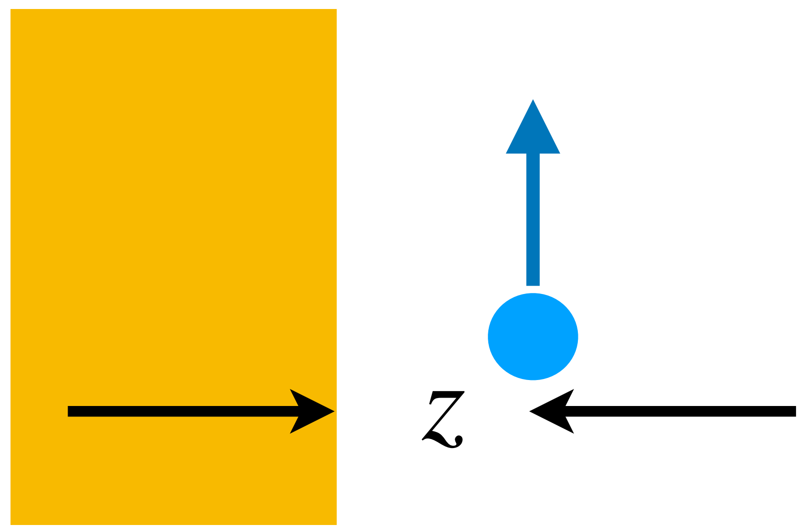
list of papers

Concept: Friction

particle & radiation



particle & plate



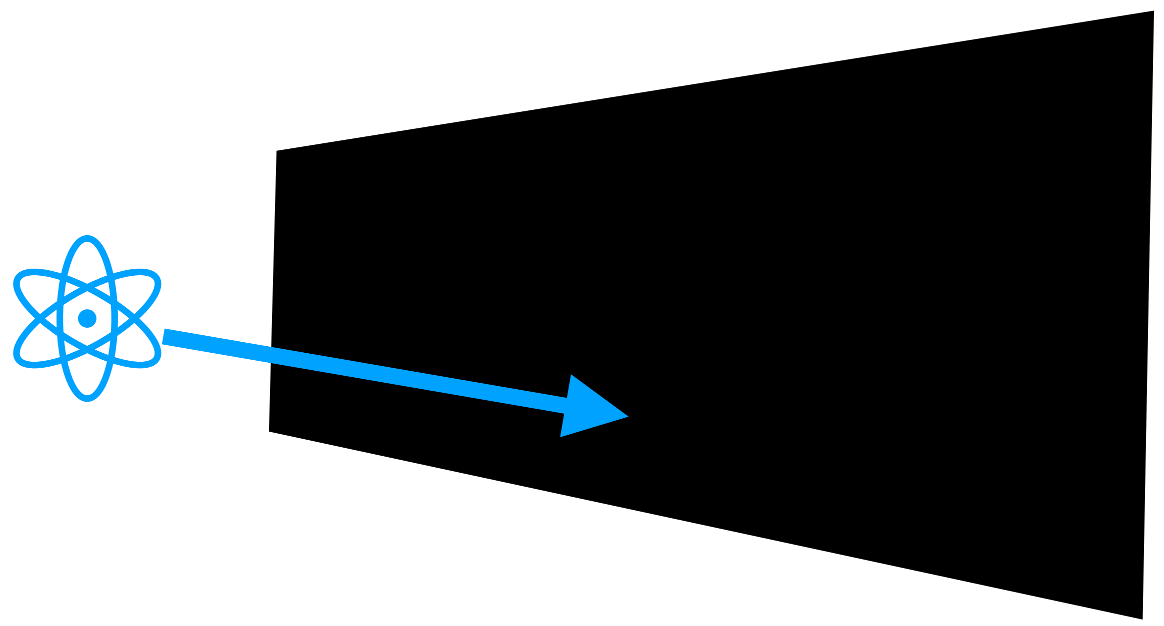
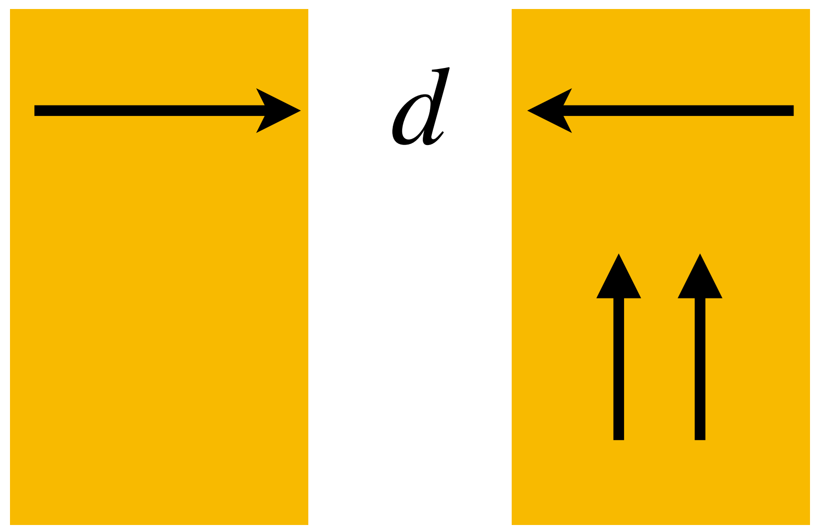


plate & plate



vacuum viscosity

$$\eta \sim \frac{\hbar}{d^3}$$

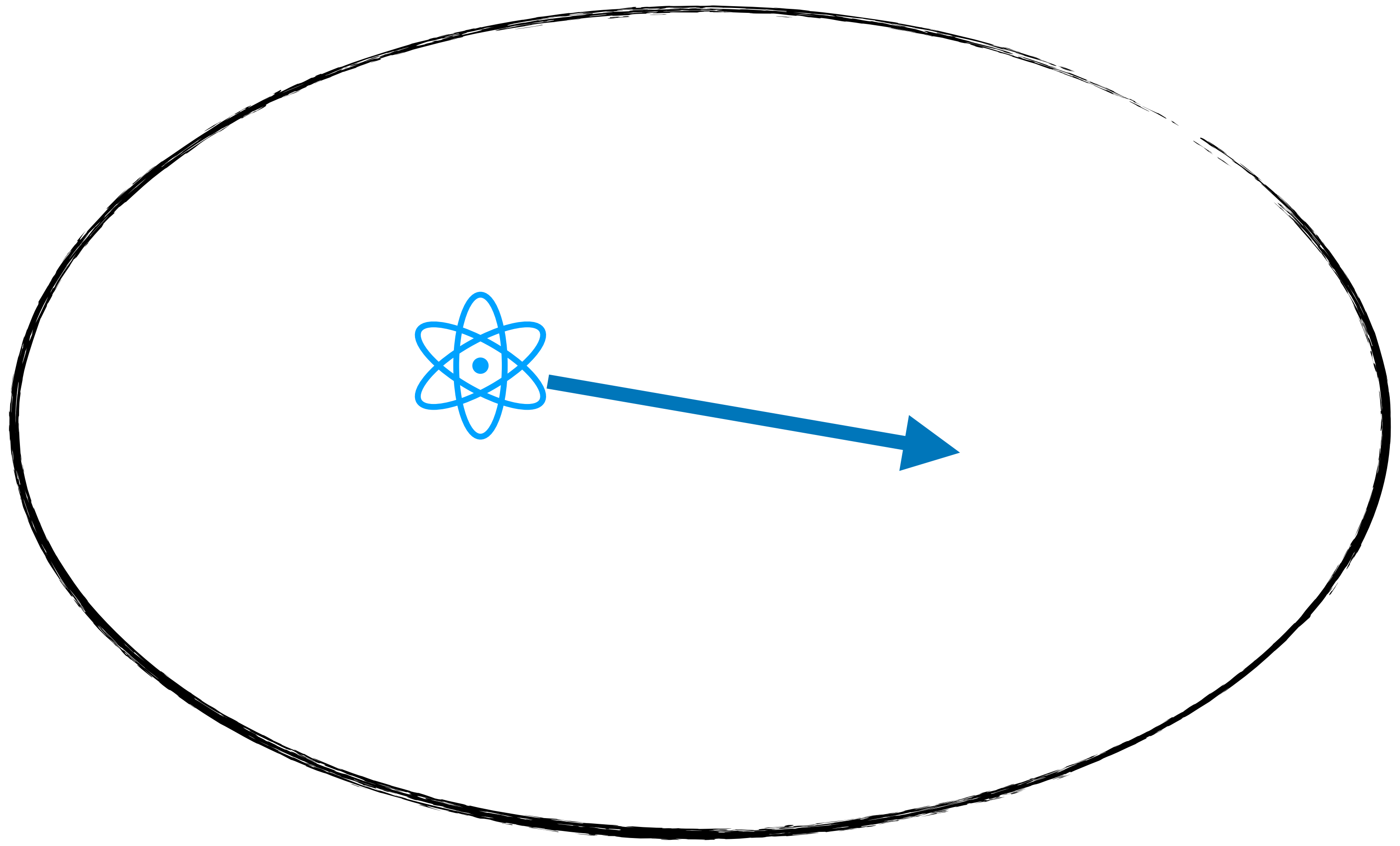
0.1μm: $10^{-13}\,\mathrm{Pa\,s}$

air: $\sim 10^{-5}\,\mathrm{Pa\,s}$

electromagnetic basics

Concept: Friction

particle & radiation



particle & plate

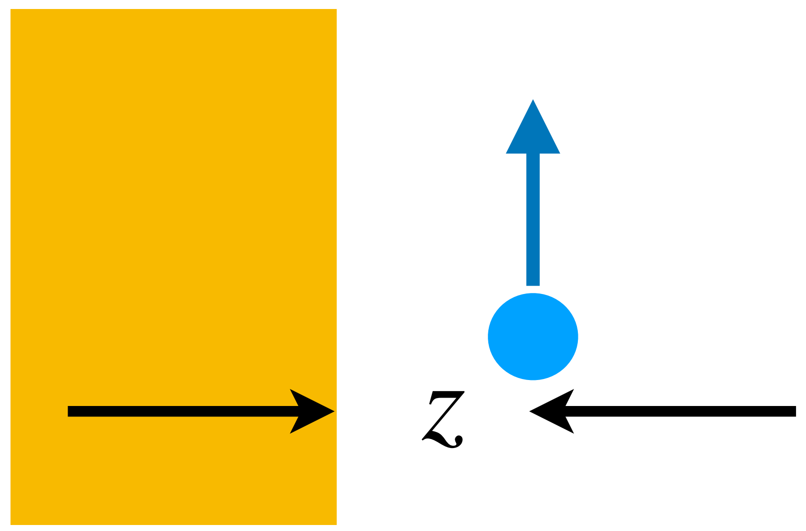
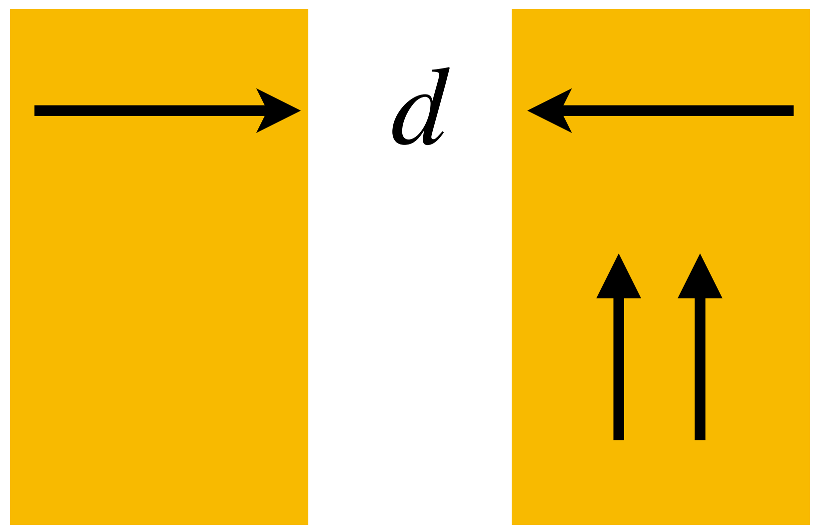
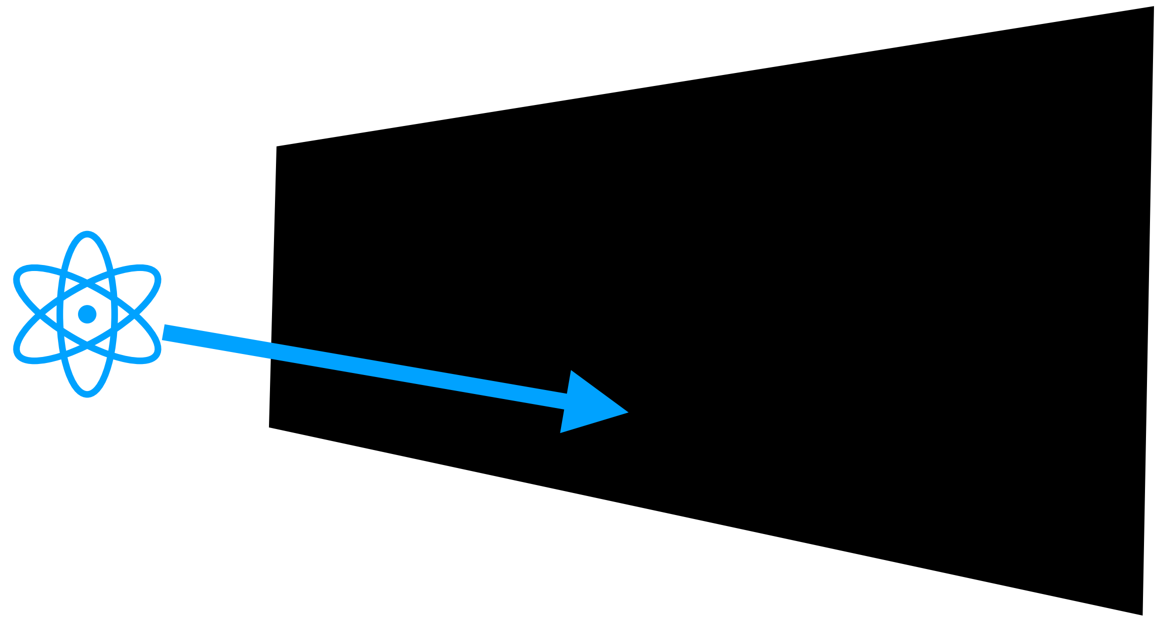
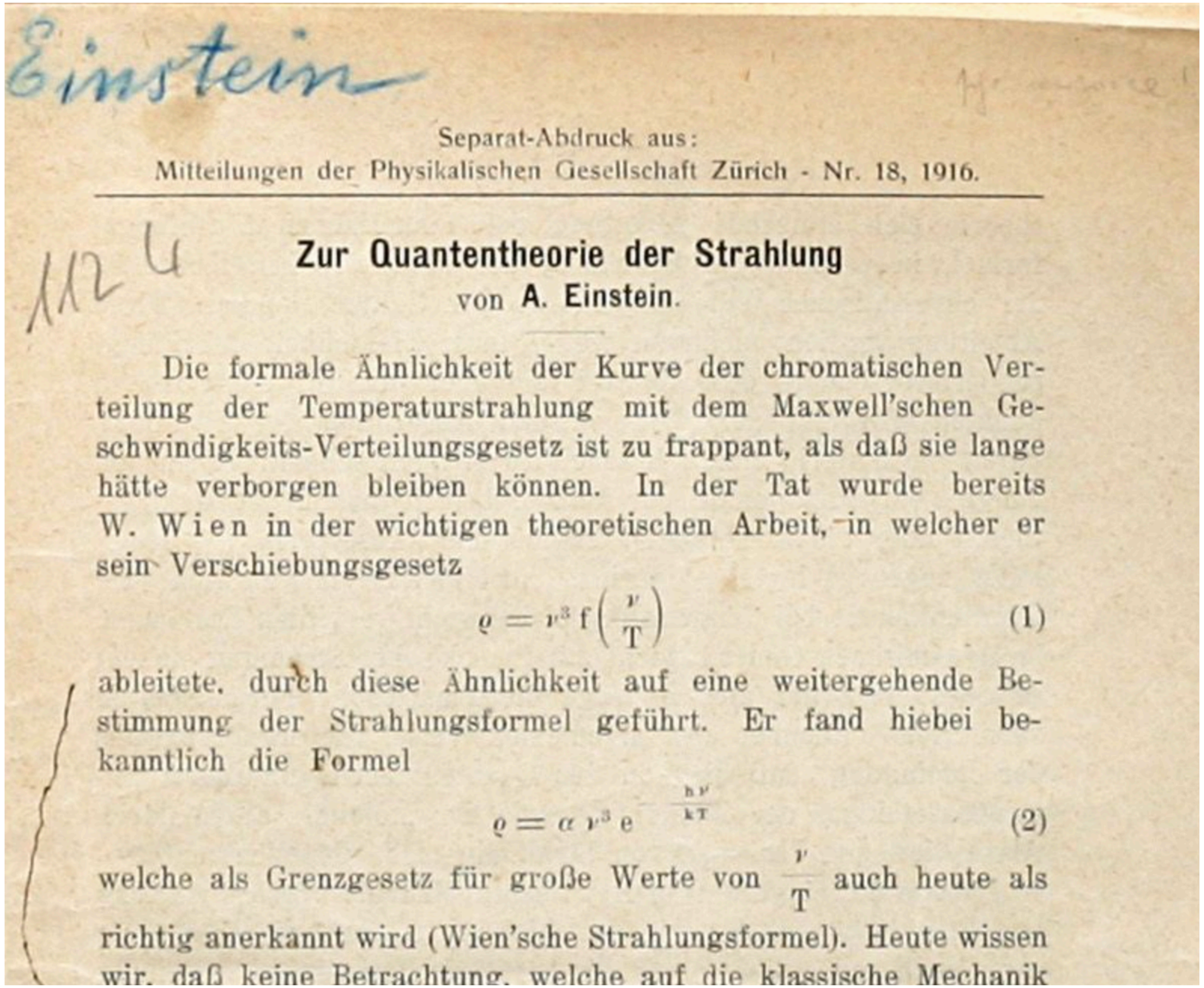


plate & plate





History


Einstein

Separat-Abdruck aus:
Mitteilungen der Physikalischen Gesellschaft Zürich - Nr. 18, 1916.

Zur Quantentheorie der Strahlung
von **A. Einstein**.

Die formale Ähnlichkeit der Kurve der chromatischen Verteilung der Temperaturstrahlung mit dem Maxwell'schen Geschwindigkeits-Verteilungsgesetz ist zu frappant, als daß sie lange hätte verborgen bleiben können. In der Tat wurde bereits W. Wien in der wichtigen theoretischen Arbeit, in welcher er sein Verschiebungsgesetz

$$\varrho = \nu^3 f\left(\frac{\nu}{T}\right) \qquad (1)$$

ableitete, durch diese Ähnlichkeit auf eine weitergehende Bestimmung der Strahlungsformel geführt. Er fand hiebei bekanntlich die Formel

$$\varrho = \alpha \nu^3 e^{-\frac{h\nu}{kT}} \qquad (2)$$

welche als Grenzgesetz für große Werte von $\frac{\nu}{T}$ auch heute als richtig anerkannt wird (Wien'sche Strahlungsformel). Heute wissen wir, daß keine Betrachtung, welche auf die klassische Mechanik

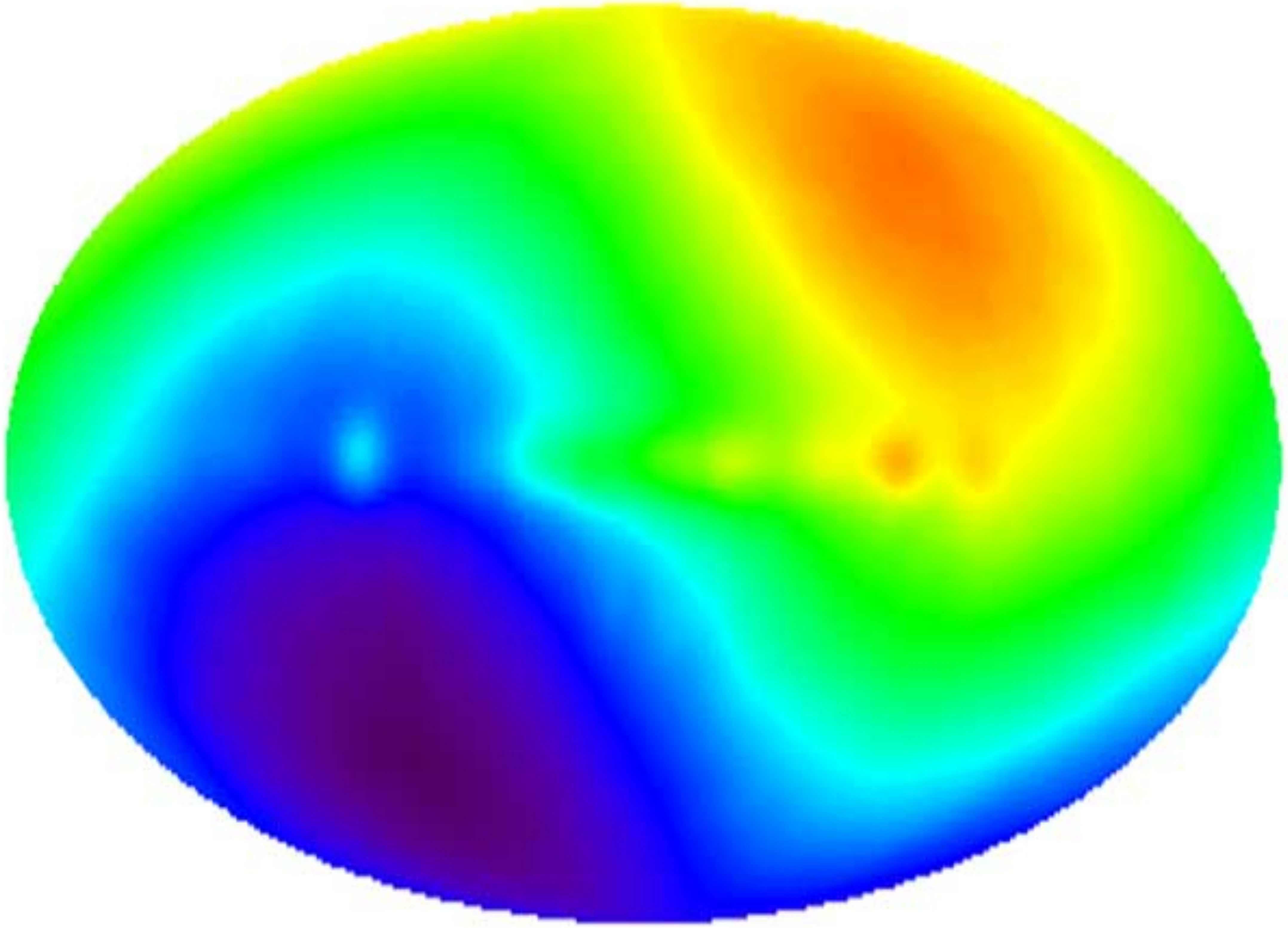
Albert Einstein
Zur Quantentheorie der Strahlung
Mitt. Phys. Ges. Zürich **18** (1916)
Phys. Z. **18** (1917) 121–28

K. von Mosengeil,
Theorie der stationären Strahlung in einem gleichförmig bewegten Hohlraum
Ann. Phys. (*Leipzig*) **22** (1907) 867–906

D. Kleppner
Rereading Einstein on Radiation
Physics Today (February 2005) 30

History

APOD (Astronomy Picture of the Day) 2003 Feb 09



Earth – Sun – centre of the Galaxy – Local Group — Virgo Cluster

But these speeds are less than the speed that all of these objects together move relative to the cosmic microwave background (CMB).

In the above all-sky map (COBE data), radiation in the Earth's direction of motion appears blueshifted and hence hotter, while radiation on the opposite side of the sky is redshifted and colder.

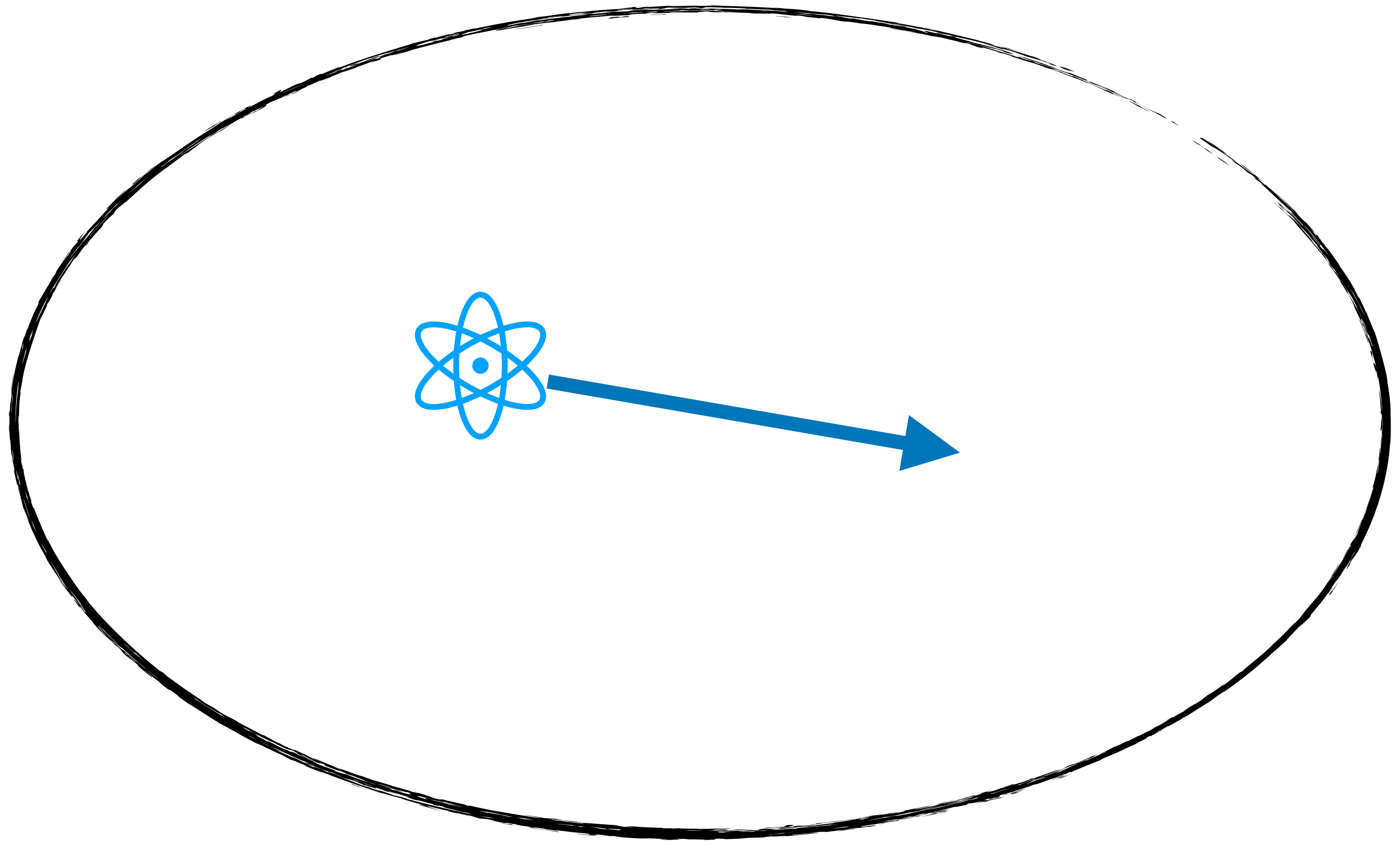
Local Group ~ 600 km/s = $0.002\, c$ relative to the primordial radiation.

... unexpected high speed, still unexplained (2003). Why are we moving so fast? What is out there?

electromagnetic basics

Concept: Friction

particle & radiation



particle & plate

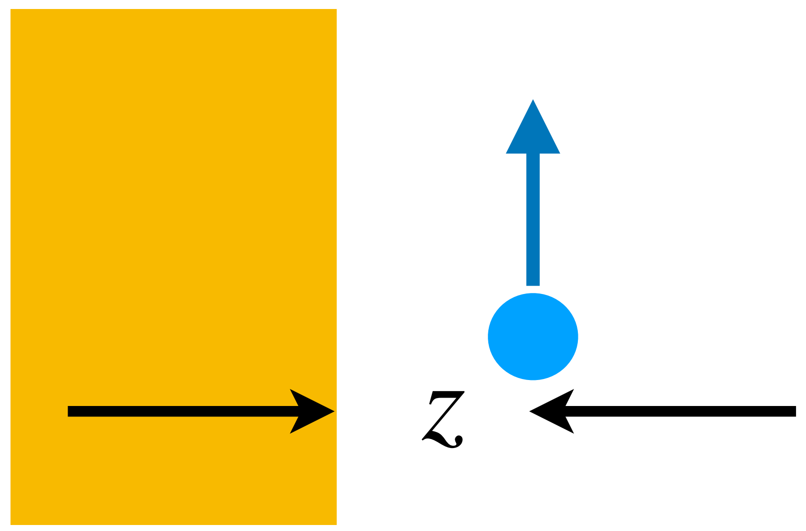
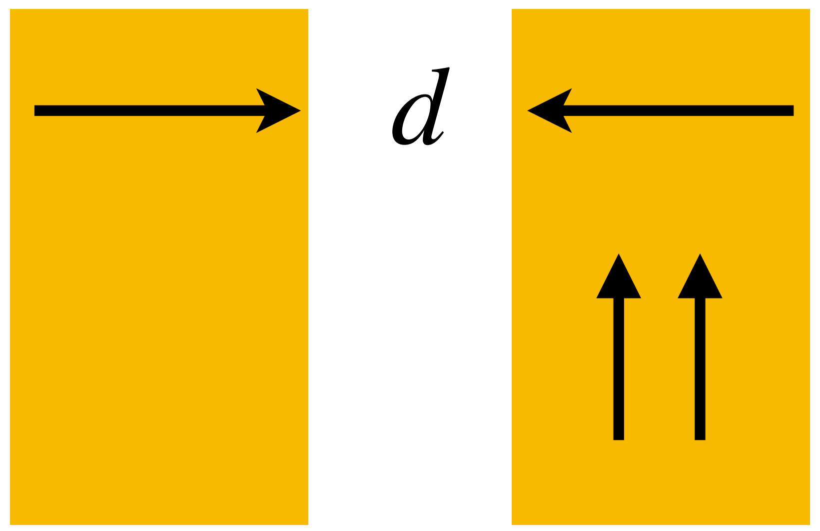


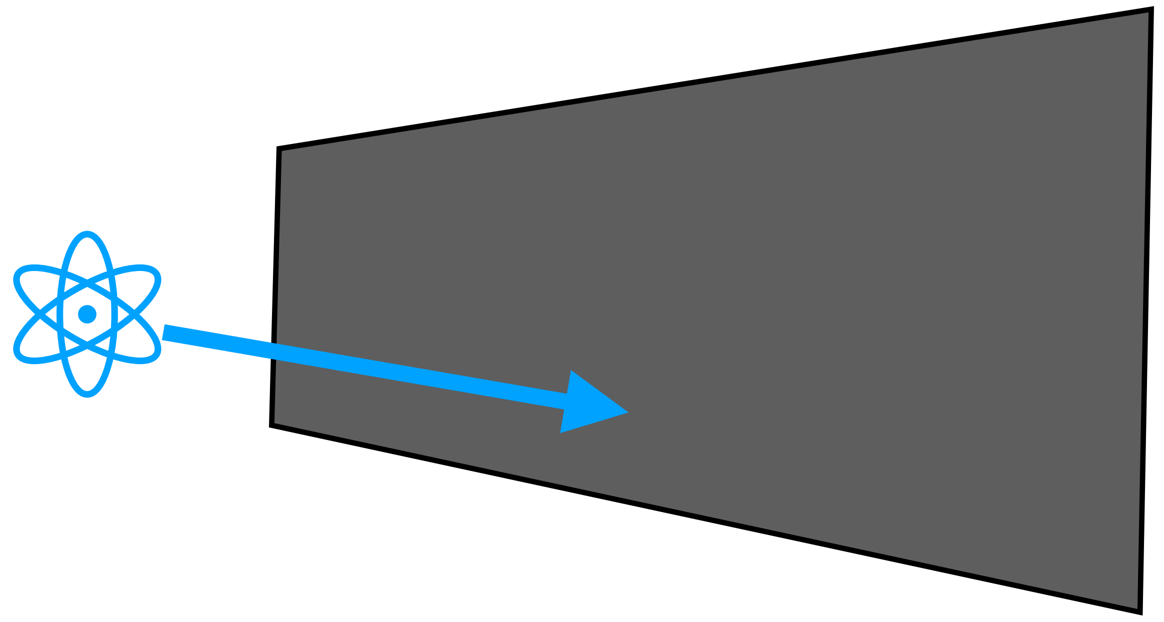
plate & plate



$$F_x = -\gamma\, v_x + \dots$$

Einstein, Kubo & Kirkwood

$$\gamma = \frac{1}{k_B T} \int_0^\infty \mathrm{d}t\, \langle \delta F_x(t)\, \delta F_x(0) \rangle^{\mathrm{eq}}$$



... talking about Spectra

$F_x = -\gamma v_x + \dots$

Einstein, Kubo & Kirkwood

$$\hat{\gamma}_{ij} = \frac{1}{k_B T}\int_0^\infty dt \langle \delta F_i(t)\delta F_j(0)\rangle^{\mathrm{eq}} = \frac{2\hbar^2}{\pi k_B T}\int_0^\infty d\omega \times \frac{e^{\hbar\omega/k_B T}}{(e^{\hbar\omega/k_B T}-1)^2}\mathrm{Im}\mathrm{Tr}\{\partial_i(1+\mathbb{G}_0\mathbb{T})\partial_j \mathrm{Im}[\mathbb{G}_0]\mathbb{T}^*\}. \quad (15)$$

scattering matrix of particle e.m. Green tensor (free space)

Golyk, Krüger & Kardar, *Phys. Rev. B* **88** (2013) 155117

$$\langle \vec{F}\rangle = V\vec{v}\left(\frac{\beta\hbar^2}{3\pi c^5}\right)\int_0^\infty d\omega \frac{\omega^5 \chi_e''(\omega)}{\sinh^2(\frac{1}{2}\beta\hbar\omega)}. \quad (12)$$

dipole approximation

Mkrtchian & al, *Phys. Rev. Lett.* **91** (2003) 220801

... talking about Spectra

$F_x = -\gamma v_x + \dots$

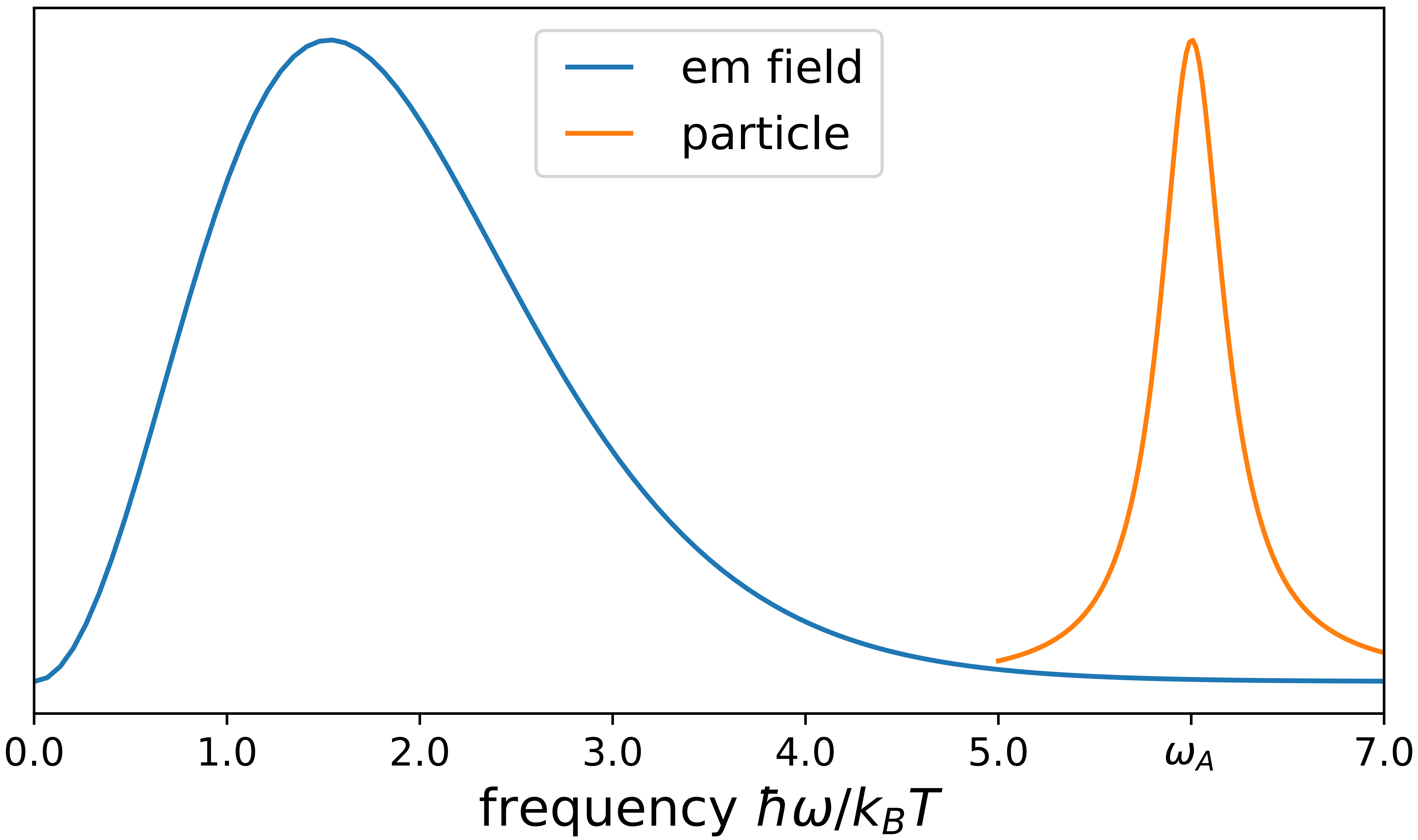
Einstein, Kubo & Kirkwood

$$\hat{\gamma}_{ij} = \frac{1}{k_B T} \int_0^\infty dt \langle \delta F_i(t) \delta F_j(0) \rangle^{\text{eq}} = \frac{2\hbar}{\pi k_}$$

$$\times \frac{e^{\hbar\omega/k_B T}}{(e^{\hbar\omega/k_B T} - 1)^2} \text{ImTr}\{\partial_i (1 + \mathbb{G}_0 \mathbb{T})$$

scattering matrix of particle

Golyk, Krüger & Kardar, *Phys. Rev. B* **88** (2013) 155117



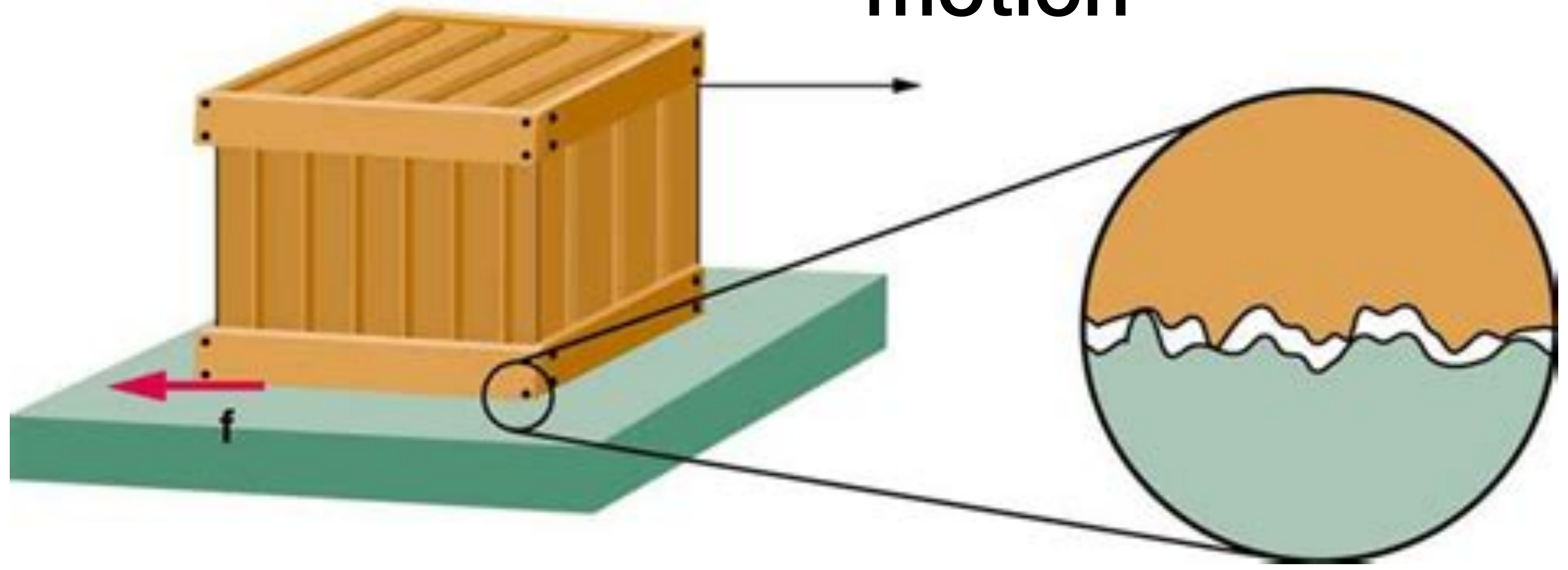
$$\langle \vec{F} \rangle = V\vec{v} \left(\frac{\beta \hbar^2}{3\pi c^5} \right) \int_0^\infty d\omega \, \frac{\omega^5 \chi_e''(\omega)}{\sinh^2(\frac{1}{2}\beta\hbar\omega)}. \qquad (12)$$

dipole approximation

Mkrtchian & al, *Phys. Rev. Lett.* **91** (2003) 220801

Steady State Scenario

in general (finite *v*): driven, non-equilibrium state



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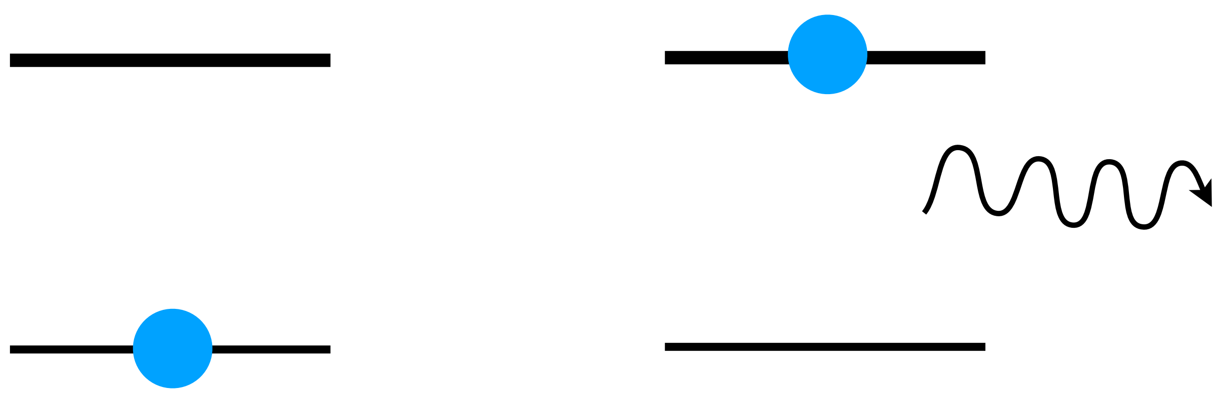
energy dissipation / entropy production ... (infinite environment reservoir)

in field/plate rest frame: $-\mathbf{F} \cdot \mathbf{v} = P_\mathrm{A} + P_\mathrm{F/env}$ (atom + field/environment)

in co-moving particle frame $\dfrac{\mathrm{d}U_A}{\mathrm{d}\tau} = u^\mu F_\mu = \gamma(P_A + \mathbf{F} \cdot \mathbf{v})$ (internal energy)

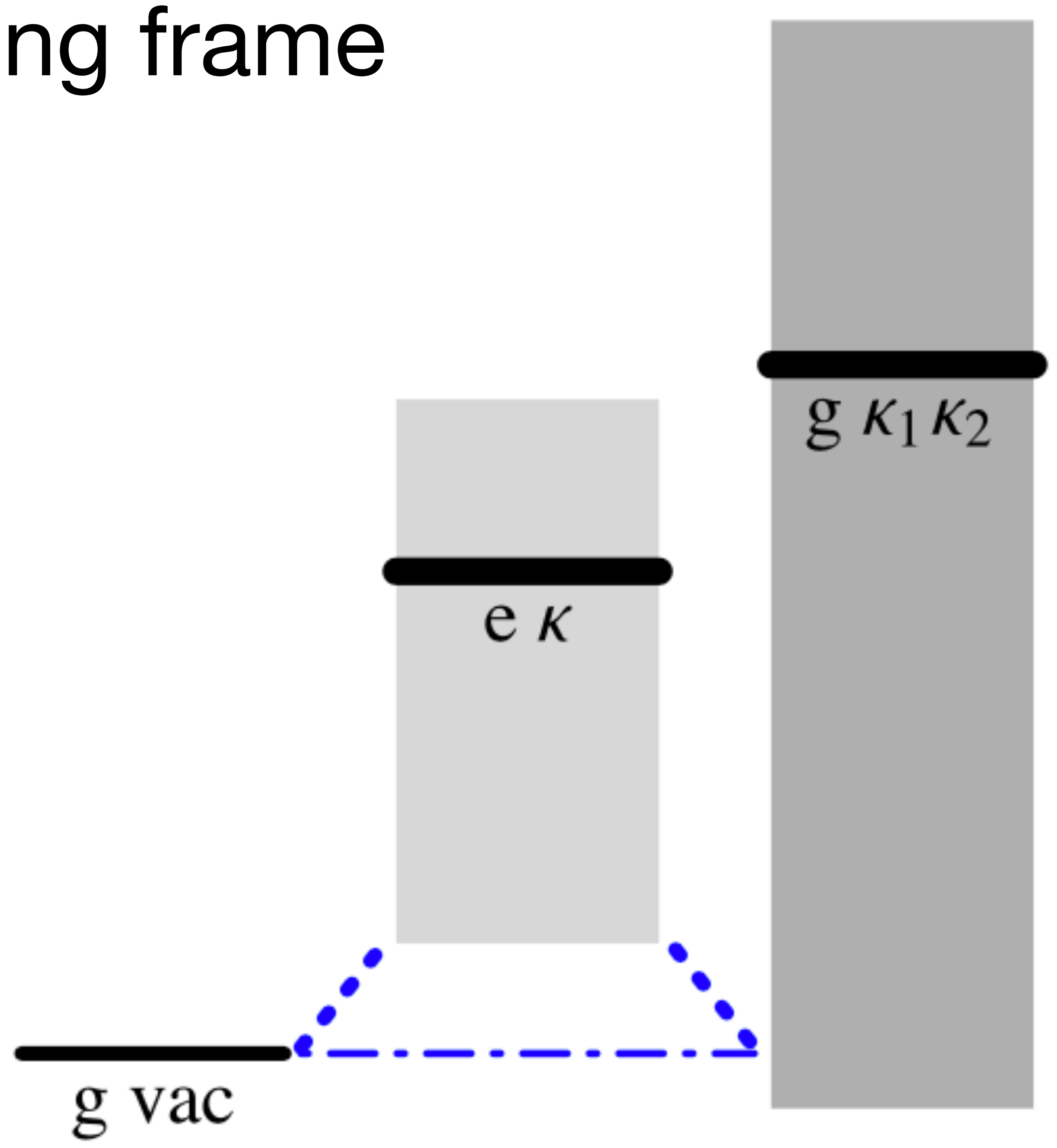
anomalous Doppler Shift

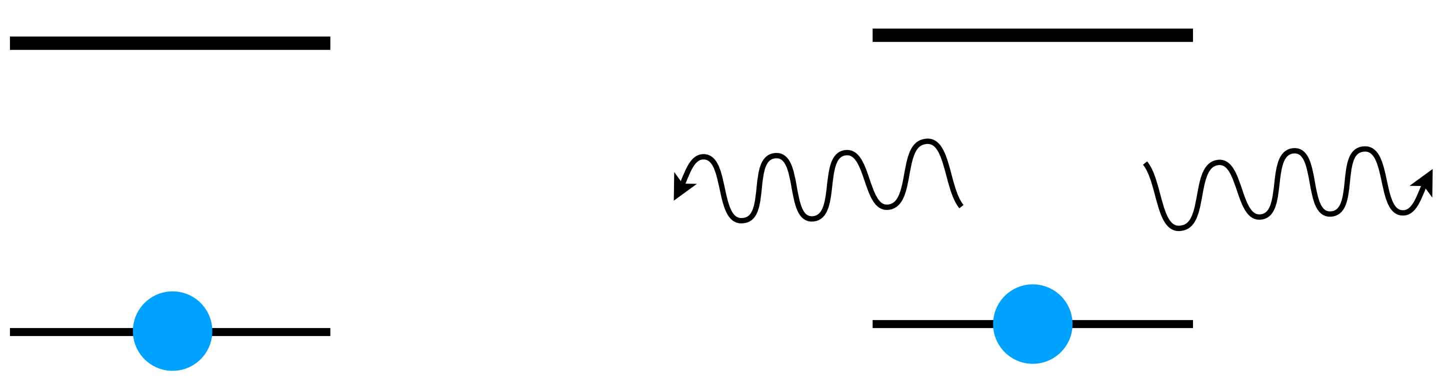


energy balance in co-moving frame

$$E_g = E_e + \hbar\gamma\underbrace{(\omega - \mathbf{k}\cdot\mathbf{v})}_{<0}$$

$$\mathbf{k}\cdot\mathbf{v} \geq \omega_{eg}$$





photon-polariton pair

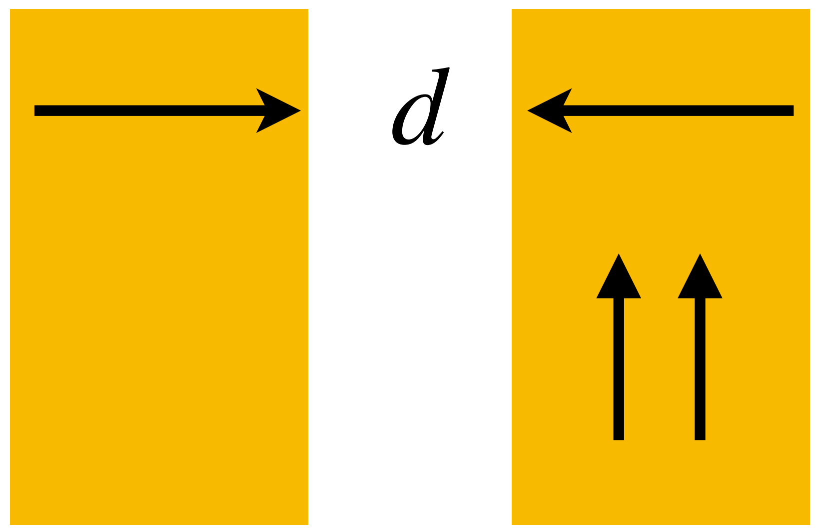
$$0 = \gamma(\omega_1 - \mathbf{k}_1\cdot\mathbf{v}) + \gamma(\omega_2 - \mathbf{k}_2\cdot\mathbf{v})$$

Pieplow & Henkel, *J. Phys.: Cond. Matt.* **27** (2015) 214001
Intravaia & al, *J. Phys. Condens. Matt.* **27** (2015) 214020

Q Friction: Pro & Con

Philbin & Leonhardt, New J. Phys. **11** (2009) 033035:
"No quantum friction between uniformly moving plates"

plate & plate



hypothesis: moving medium (Lorentz transform into rest frame)
= "gyrotropic medium", $T = 0$: stable vacuum state

$$r_{E2} = \frac{\mu_2(\mathrm{i}c\kappa')w - w_2}{\mu_2(\mathrm{i}c\kappa')w + w_2}, \qquad r_{B2} = -\frac{\varepsilon_2(\mathrm{i}c\kappa')w - w_2}{\varepsilon_2(\mathrm{i}c\kappa')w + w_2},$$

$$w_2 = \sqrt{u'^2 + v^2 + \varepsilon_2(\mathrm{i}c\kappa')\mu_2(\mathrm{i}c\kappa')\kappa'^2},$$

reflection amplitudes

... probably wrong!
• missing: anomalous Doppler shift
Bogoliubov transformation $\omega' < 0 : \quad a'_{\mathbf{k}'} = \mu\, a_{\mathbf{k}} + \upsilon\, a^{\dagger}_{\mathbf{k}}$

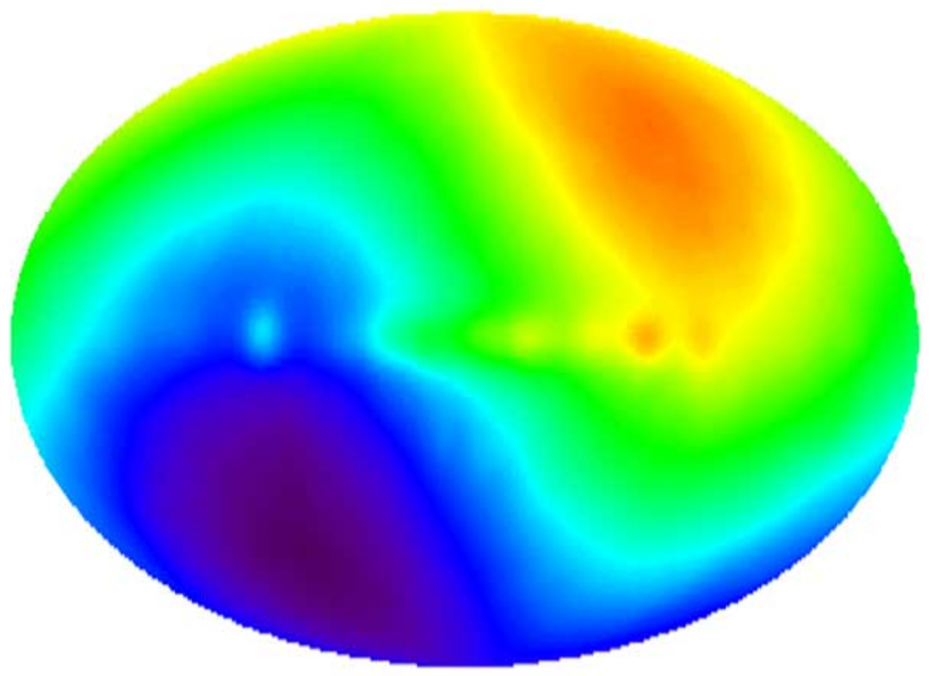
$$\coth\frac{\hbar\omega}{2k_B T_F} - \coth\frac{\hbar(u^\mu k_\mu)}{2k_B T_A}$$

(LTE approx'n)

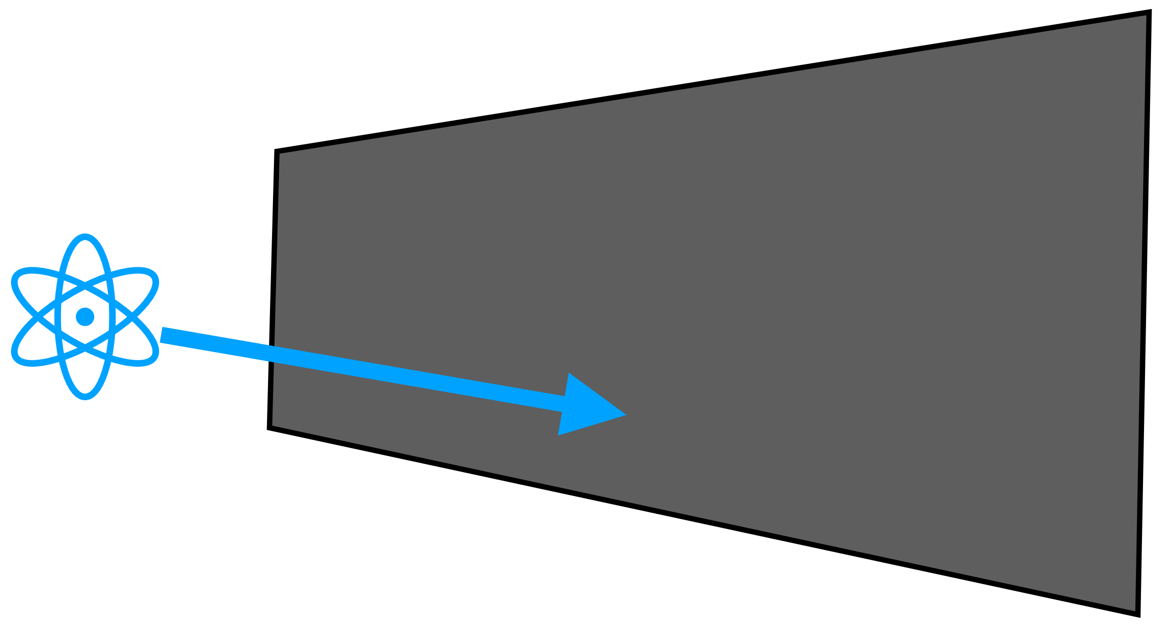
Piwnicki & Leonhardt, Optics of moving media (*Appl. Phys. B* 2000)
Polevoi, Tangential molecular forces caused between moving bodies by a fluctuating electromagnetic field (*Sov. Phys. JETP* 1990)
discussion: Volokitin & Persson (2009), Pendry (2010)

Quantum Friction: main ideas to keep

- highly idealised/simplified electromagnetic interactions ("no contact")
- preferred frames: CMB, macroscopic body



- spectra: typically, generation of low-frequency excitations
- anomalous Doppler shift $\omega - \mathbf{k} \cdot \mathbf{v} < 0$ for polaritons ($k > \omega/c$)
- useful trick: local equilibrium (in co-moving / rest frame)



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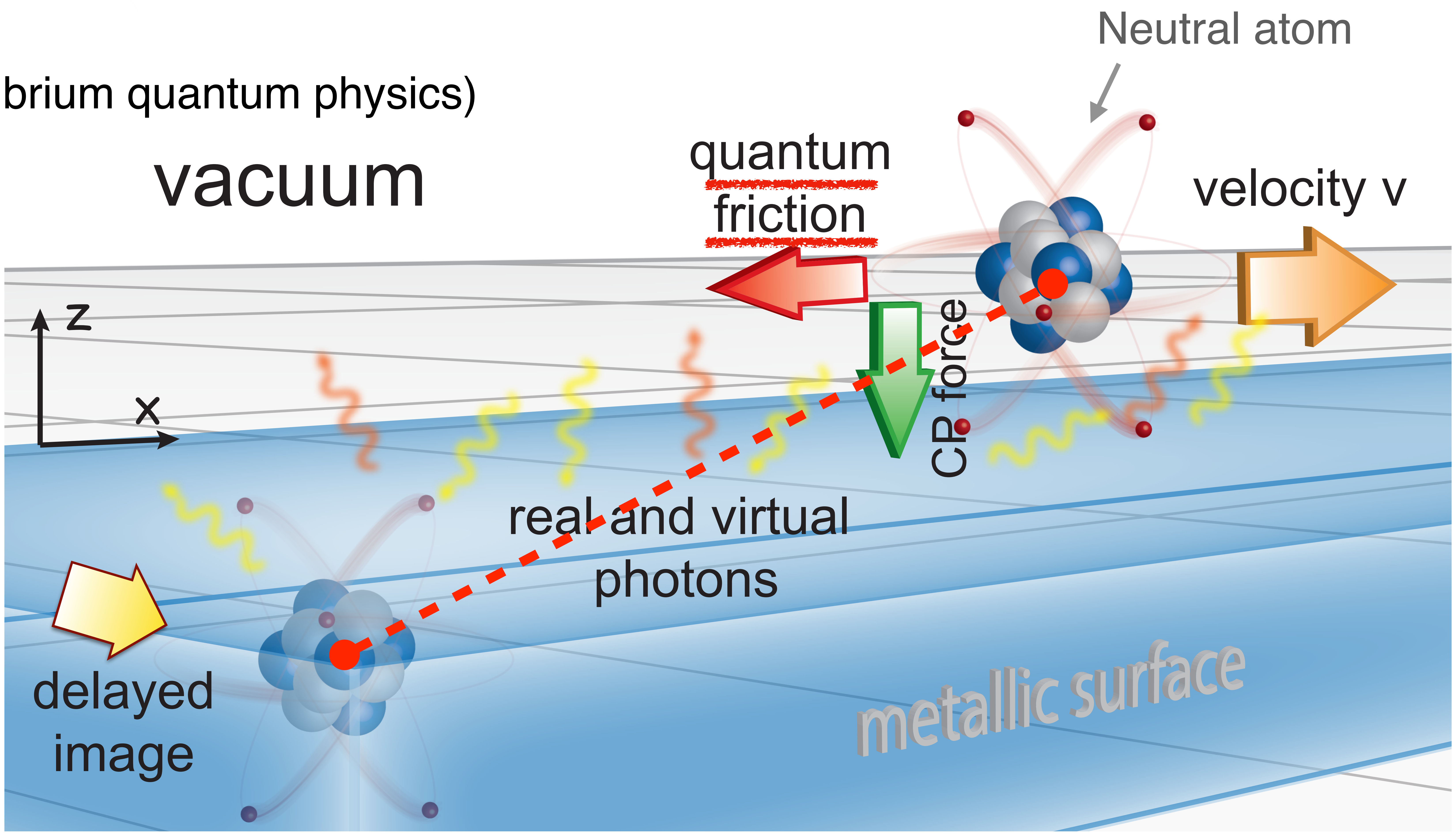
list of papers

Quantum friction: The Methodology

Quantum Frictional Interaction

T=0 (nonequilibrium quantum physics)

Dispersion
Dissipation



Some previous work on quantum friction

Authors	Low velocity dependency	Distance dependency	Comments
Mahanty 1980	**v**	**z_a^{-5}**	Approach similar to the calculations of vdW forces but with mistakes
Schaich and Harris 1981	**v**	**z_a^{-10}**	**Two-state atom** with a transition dipole moment normal to a metal surface
Scheel and Buhmann 2009	**v**	**z_a^{-8}**	Master-equation approach for **multilevel atoms** and quantum regression theorem **(QRT)**.
Barton 2010	**v**	**z_a^{-8}**	Perturbation theory using Fermi's golden rule. **Harmonic oscillator**.
Philbin and Leonhardt 2009	**-**	**-**	Relativistic calculations and analytical/numerical evaluation of the Green's tensor. The tensor is found to be diagonal.
Dedkov and Kyasov 2012	**v^3**	**z_a^{-5}**	Fluctuation-dissipation theorem **(FDT)** applied to the dipole atom as well as to the electric field

Zero Temperature The prefactors are often different. Many other authors and papers.

Understanding the differences

"[…] in view of the manifold current controversies about quantum-governed frictional forces generally, it seems well worth exploring whether such differences reflect substantive disagreement or only a confusion of terms."

— G. Barton

New Journal of Physics **12**, 113044 (2010).

Time-dependent perturbation theory

G. Barton, New J. Phys. **12**, 113045 (2010).
F. Intravaia, V. E. Mkrtchian, S. Y. Buhmann, S. Scheel, D. A. R. Dalvit, and C. Henkel, J. Phys. Condens. Matter **27**, 214020 (2015).

Solution of the joint atom+field/matter dynamics in time-dependent perturbation theory

$$P = -vF$$

Fourth order calculation in the dipole moment

$$V(t) = -\hat{\mathbf{d}}(t) \cdot \hat{\mathbf{E}}(t, \mathbf{r})$$

Advantages of the calculation

- no correlation times
- no linear response
- no local thermodynamic equilibrium

Time-dependent perturbation theory

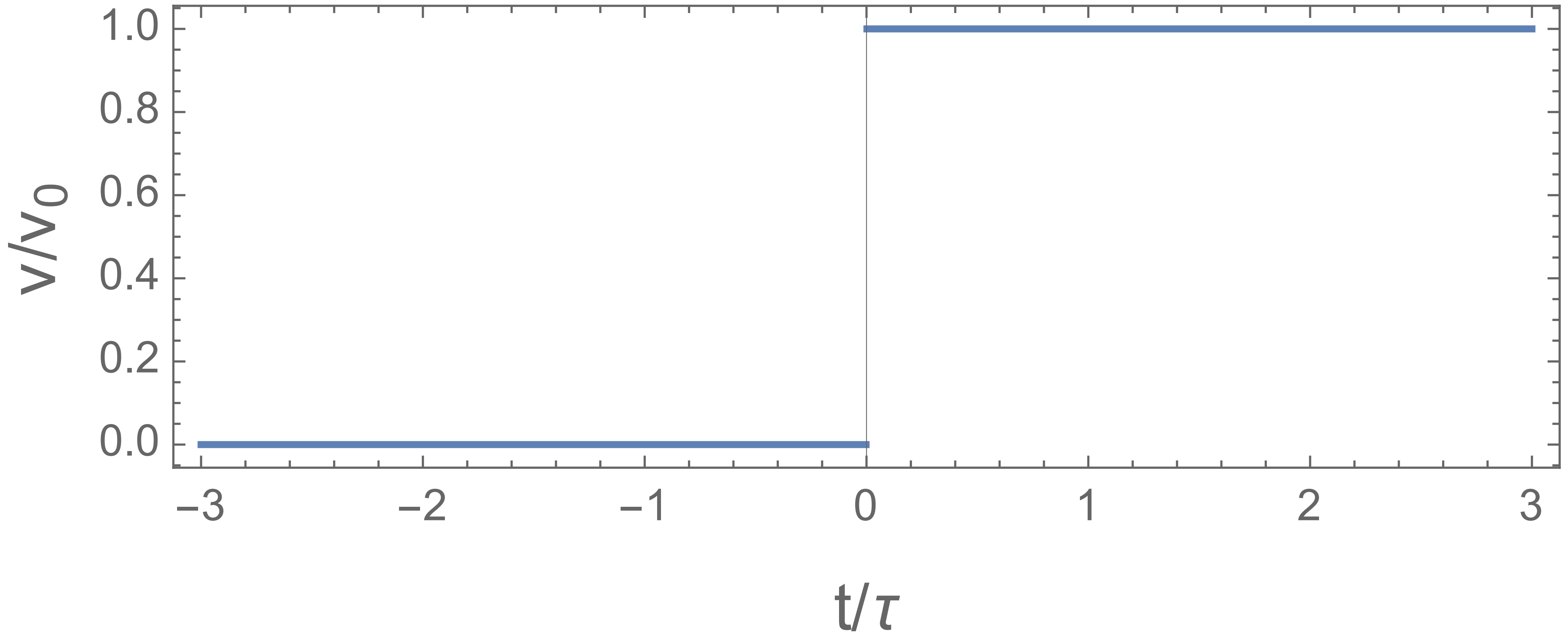
G. Barton, New J. Phys. **12**, 113045 (2010).
F. Intravaia, V. E. Mkrtchian, S. Y. Buhmann, S. Scheel, D. A. R. Dalvit, and C. Henkel, J. Phys. Condens. Matter **27**, 214020 (2015).

Initial state: the atom and the field/matter subsystems are both in their ('bare') ground states

$$P = -vF = P_{\mathrm{A}} + P_{\mathrm{B}}$$

$(T = 0)$

$P_{\mathrm{A}} \propto v^2$ $\quad$ $P_{\mathrm{B}} \propto v^4$



Dominant contribution → Quantum friction scales as $\propto v$

Up to a factor 16/3 equal to S. Scheel and S. Y. Buhmann, Phys. Rev. A **80,** 042902 (2009).

Time-dependent perturbation theory

G. Barton, New J. Phys. **12**, 113045 (2010).
F. Intravaia, V. E. Mkrtchian, S. Y. Buhmann, S. Scheel, D. A. R. Dalvit, and C. Henkel, J. Phys. Condens. Matter **27**, 214020 (2015).

$$P = -vF \quad (T=0) \quad = P_A + P_B - P_A$$

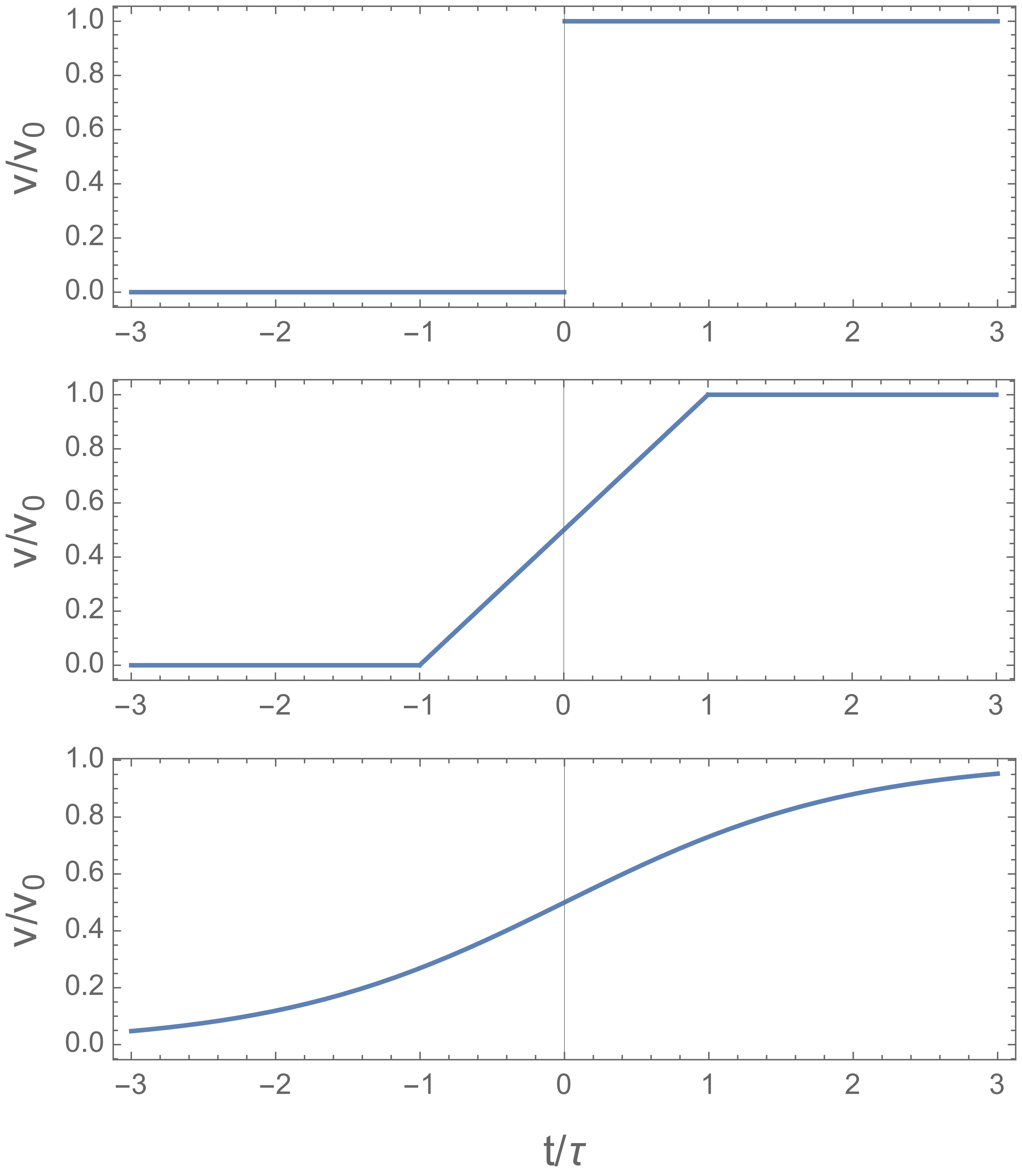
$\propto v^2$ $\propto v^4$ Excitation of the atom

Smaller prefactor with "smoother" accelerations

$$= P_B$$

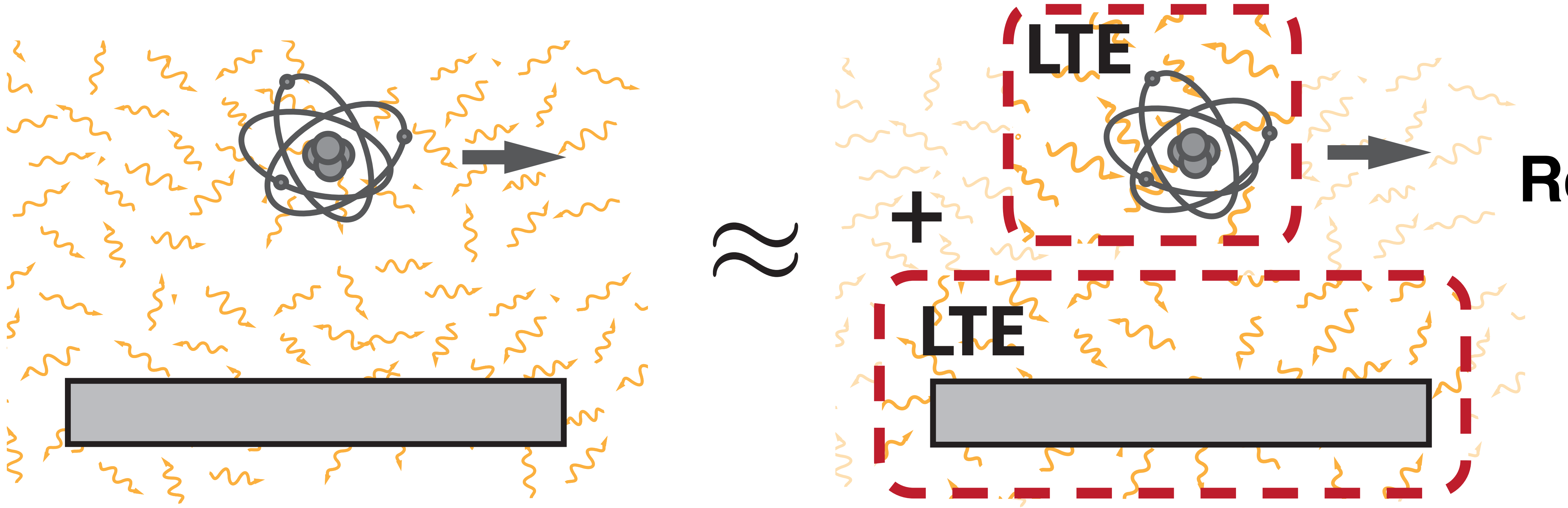
Quantum friction scales as $\propto v^3$

Up to a factor 5 equal to
F. Intravaia, R. O. Behunin, and D. A. R. Dalvit, Phys. Rev. A **89**, 050101(R) (2014).



Local Thermal Equilibrium

G. Dedkov and A. Kyasov, Phys. Solid State **44**, 1809 (2002).



Equilibrium

Relations and theorems of Quantum Statistics

Equilibrium

From the Lorentz force

$$\hat{\mathbf{d}} = \hat{\mathbf{d}}^{\mathrm{sp}} + \hat{\mathbf{d}}^{\mathrm{ind}} \qquad \hat{\mathbf{E}} = \hat{\mathbf{E}}^{\mathrm{sp}} + \hat{\mathbf{E}}^{\mathrm{ind}}$$

$$F_{x_i} = \langle \hat{\mathbf{d}}(t) \cdot \partial_{x_i} \hat{\mathbf{E}}(\mathbf{r}_a(t), t) \rangle = \langle \hat{\mathbf{d}}^{\mathrm{sp}}(t) \cdot \partial_{x_i} \hat{\mathbf{E}}^{\mathrm{ind}}(\mathbf{r}_a(t), t) \rangle + \langle \hat{\mathbf{d}}^{\mathrm{ind}}(t) \cdot \partial_{x_i} \hat{\mathbf{E}}^{\mathrm{sp}}(\mathbf{r}_a(t), t) \rangle$$

Fluctuations-dissipation Theorem

Local Thermal Equilibrium

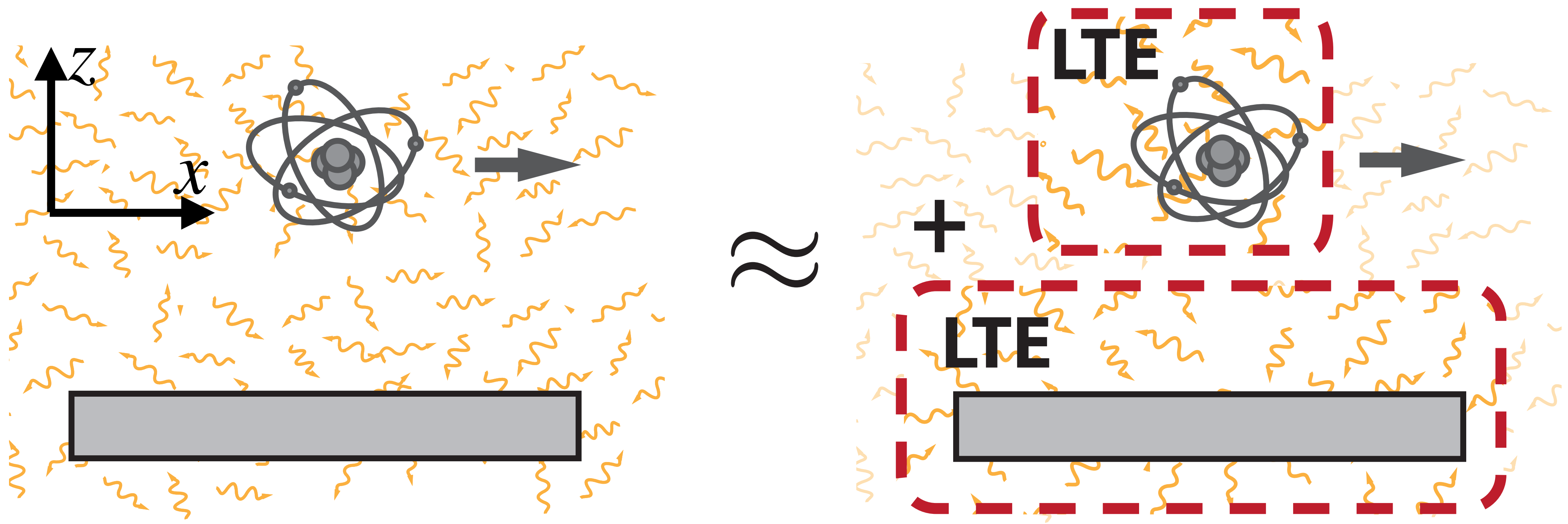
J. B. Pendry, J. Phys. Condens. Matter **9**, 10301 (1997).
A. I. Volokitin and B. N. J. Persson, Rev. Mod. Phys. **79**, 1291 (2007).
G. Dedkov and A. Kyasov, Phys. Solid State **44**, 1809 (2002).
R. Zhao, A. Manjavacas, F. J. García de Abajo, and J. B. Pendry, Phys. Rev. Lett. **109**, 123604 (2012).
G. Pieplow and C. Henkel, New J. Phys. **15**, 023027 (2013).

$$F_{\text{fric}} = -\frac{2\hbar}{\pi}\int_{-\infty}^{\infty}\frac{dk_y}{2\pi}\int_0^{\infty}\frac{dk_x}{2\pi}k_x\int_0^{k_x v_x} d\omega \operatorname{Tr}\left[\underline{\alpha_I}(\overbrace{k_x v_x-\omega}^{-(\omega-\mathbf{k}\cdot\mathbf{v})=-\omega'};0)\cdot \underline{G_I}(\mathbf{k},z_a,\omega)\right]$$

$\omega' < 0$ ➡ $0 \le \omega < \mathbf{k}\cdot\mathbf{v} < c\,|\mathbf{k}|$

Dominated by the evanescent field

(Anomalous Doppler effect)



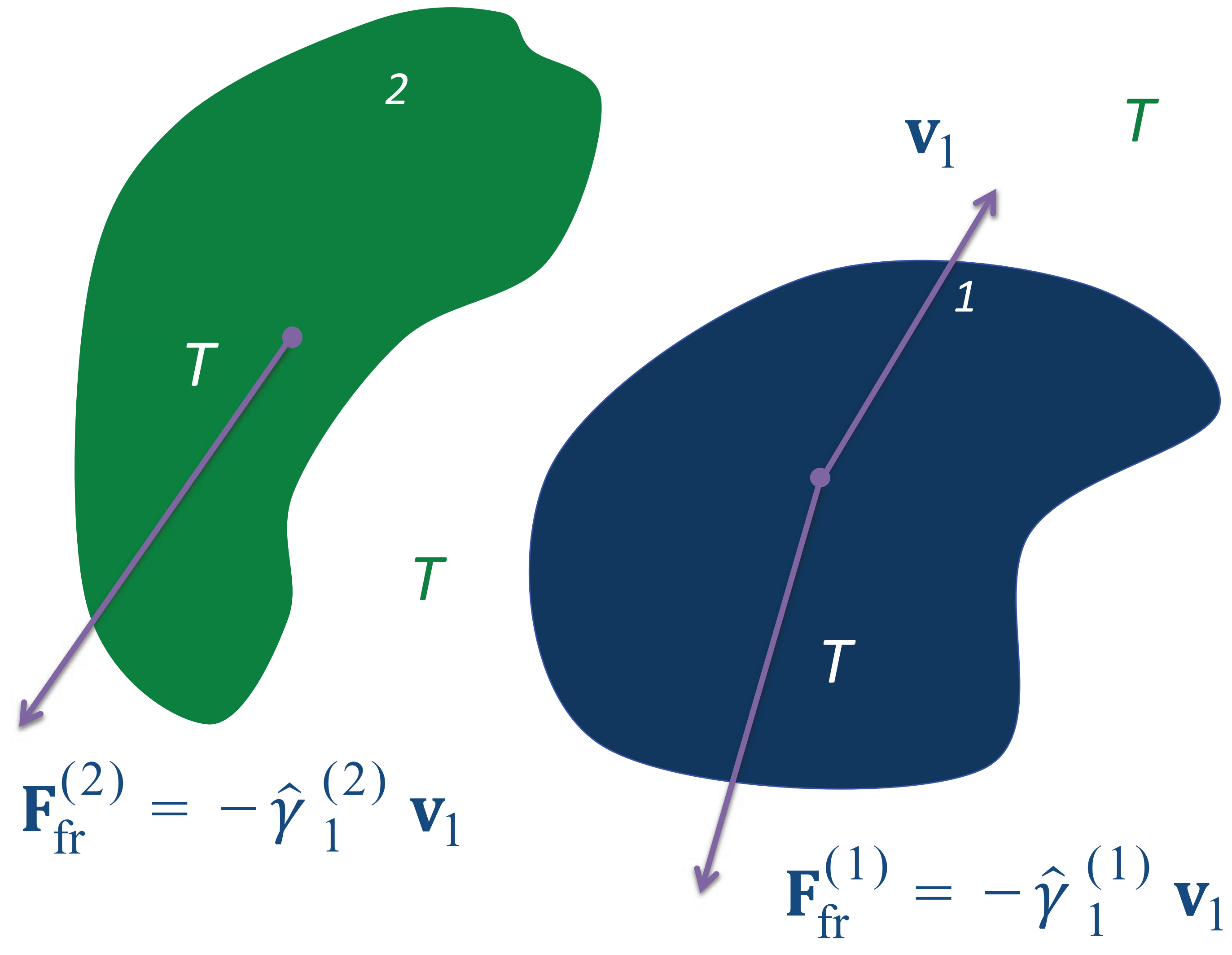
Good for a strong intrinsic dissipation (nanoparticle)

$$F_{\text{fric}} \propto -\hbar\,\alpha_0\epsilon_0\,\rho_{\text{np}}\rho\,\frac{v^3}{(2z_a)^7}$$

Kubo/Kirkwood formalism

A.I. Volokitin and B. N. J. Persson, Rev. Mod. Phys. **79**, 1291 (2007).
J. S. Høye and I. Brevik, Europhys. Lett. **91**, 60003 (2010).
M. Krüger, T. Emig, and M. Kardar, Phys. Rev. Lett. **106**, 210404 (2011).

A consequence of the Fluctuation-Dissipation theorem



$$\left(\hat{\gamma}^{(\beta)}_{\alpha}\right)_{ij} = \frac{1}{k_B T}\int_0^\infty dt\, \langle \delta F_i^{(\beta)}(t)\delta F_j^{(\alpha)}(0)\rangle^{\rm eq}$$

Fluctuating part of the force acting on the particle

$$\mathbf{F}^{\beta}_{\rm fric} = -\underline{\gamma}^{(\beta)}_{\alpha}(T)\mathbf{v}_{\alpha}$$

$$\underline{\gamma}^{(\beta)}_{\alpha}(T) \xrightarrow{T\to 0} 0$$

No contribution linear in $\mathbf{v}$ at $T = 0$

A different approach

F. Intravaia, R. O. Behunin, C. Henkel, K. Busch, and D. A. R. Dalvit, Phys. Rev. A **94** (2016).

Without having recourse to the local thermal equilibrium approximation

dipole's correlation tensor (model independent)

Electromagnetic Green tensor

$(T = 0)$

$$\mathbf{F}_{\text{fric}} = -\operatorname{Re}\left\{\frac{2}{\pi}\int_0^\infty d\omega \int \frac{d^2\mathbf{k}}{(2\pi)^2}\mathbf{k}\int_0^\infty d\tau\, e^{-\mathrm{i}(\omega-\mathbf{k}\cdot\mathbf{v})\tau}\,\mathrm{Tr}\left[\underline{C}(\tau, v)\cdot\underline{G}^{\mathsf{T}}_{\mathfrak{I}}(\mathbf{k}, z_a, \omega)\right]\right\}$$

$$= -2\int_0^\infty d\omega \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2}\mathbf{k}\,\mathrm{Im}\,\mathrm{Tr}\left[\underline{S}^{\mathsf{T}}(\mathbf{k}\cdot\mathbf{v}-\omega, \mathbf{v})\cdot\underline{G}(\mathbf{k}, z_a, \omega)\right]$$

dipole's power spectrum tensor (model independent)

Contains other formulations:

G. Dedkov and A. Kyasov, Phys. Solid State **44**, 1809 (2002).
A. I. Volokitin and B. N. J. Persson, Rev. Mod. Phys. **79**, 1291 (2007).
G. Pieplow and C. Henkel, New J. Phys. 15, 023027 (2013).
J. S. Høye, I. Brevik, and K. A. Milton, J. Phys. A Math. Theor. 48, 365004 (2015).

A glimpse in the theory

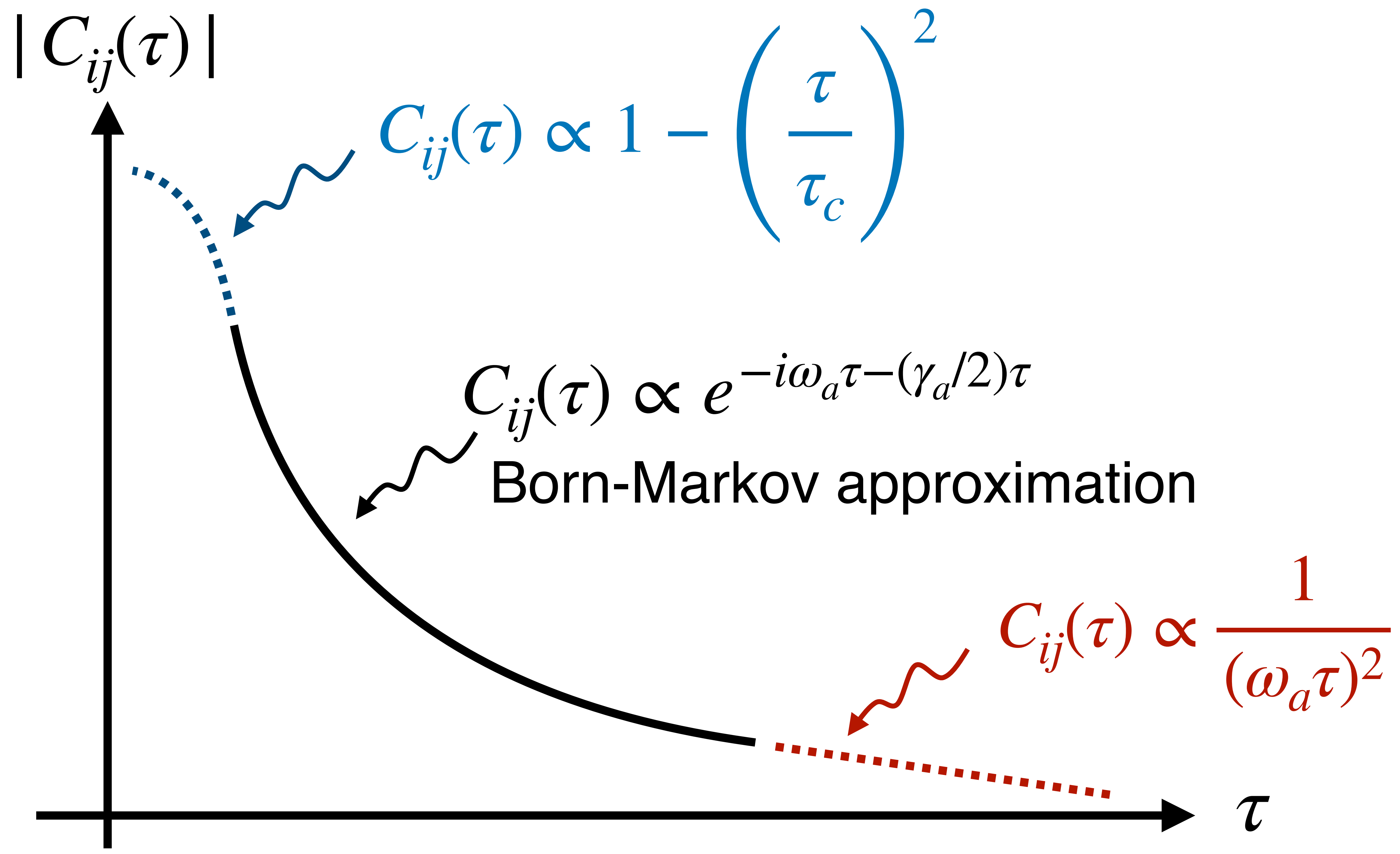
F. Intravaia, R. O. Behunin, C. Henkel, K. Busch, and D. A. R. Dalvit, Phys. Rev. A **94** (2016).

Dipole's correlation tensor

$$\langle \mathbf{d}^2(t) \rangle \Rightarrow \quad C_{ij}(\tau) = \langle \hat{d}_i(\tau)\hat{d}_j(0) \rangle$$

Better description: Master Equation

G. Boedecker and C. Henkel, Ann. Physik **524**, 805 (2012).
J. Klatt, C. M. Kropf, and S. Y. Buhmann, Phys. Rev. Lett. **126**, 210401 (2021).



R. Davidson and J. J. Kozak, J. Math. Phys. **11**, 189 (1970)
P. L. Knight and P. W. Milonni, Phys. Lett. A **56,** 275 (1976).
C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg. Atom-photon interactions.
P. R. Berman and G. W. Ford, in *Advances In Atomic, Molecular, and Optical Physics*, volume **59**, 175

A glimpse in the theory

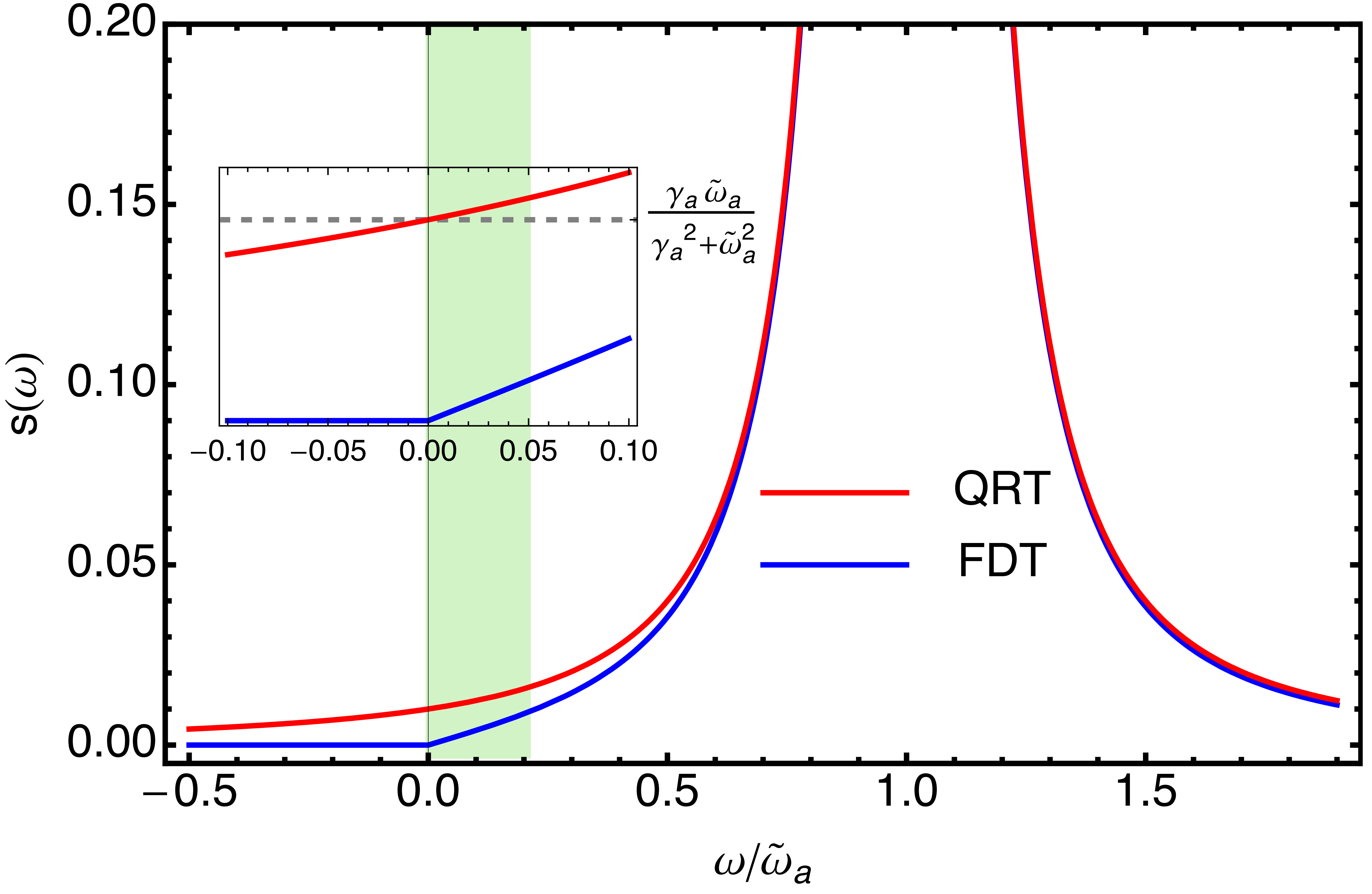
F. Intravaia, R. O. Behunin, C. Henkel, K. Busch, and D. A. R. Dalvit, Phys. Rev. A **94** (2016).

Relevant for quantum friction

$$\underbrace{}\; 0 \leq \omega < \mathbf{k}\cdot\mathbf{v} \sim |\mathbf{v}|/z_a$$

Dipole's power spectrum tensor

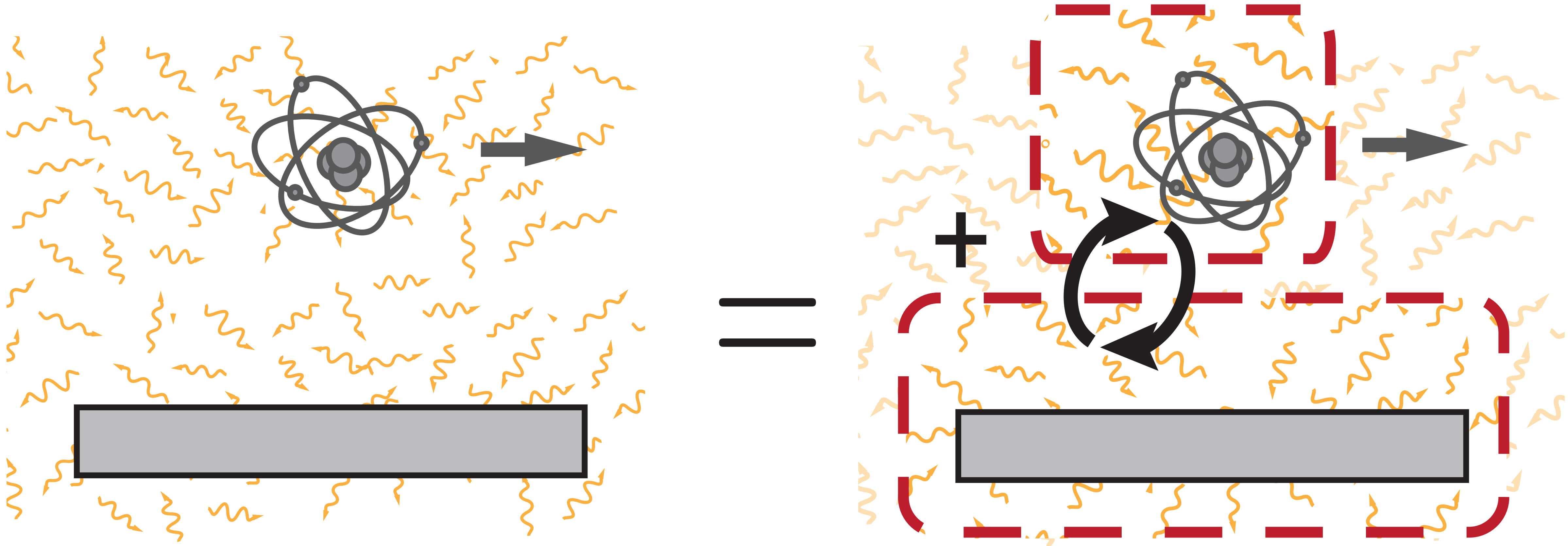
$$\underline{S}(\omega) = \int_{-\infty}^{\infty} \frac{d\tau}{2\pi} e^{i\omega\tau} \underline{C}(\tau)$$



(QRT = Born-Markov approximation)

Beyond Local Thermal Equilibrium

F. Intravaia, R. O. Behunin, C. Henkel, K. Busch, and D. A. R. Dalvit, Phys. Rev. Lett. **117**, 100402 (2016)
D. Reiche, F. Intravaia, J.-T. Hsiang, K. Busch, and B. L. Hu, Phys. Rev. A **102,** 050203(R) (2020)



Self-consistent description of the Nonequilibrium Steady State (NESS)

$$F_{\rm fric} \propto -\hbar \alpha_0^2 \rho^2 \, \frac{v^3}{(2z_a)^{10}}$$

A non-equilibrium correction to the FDT

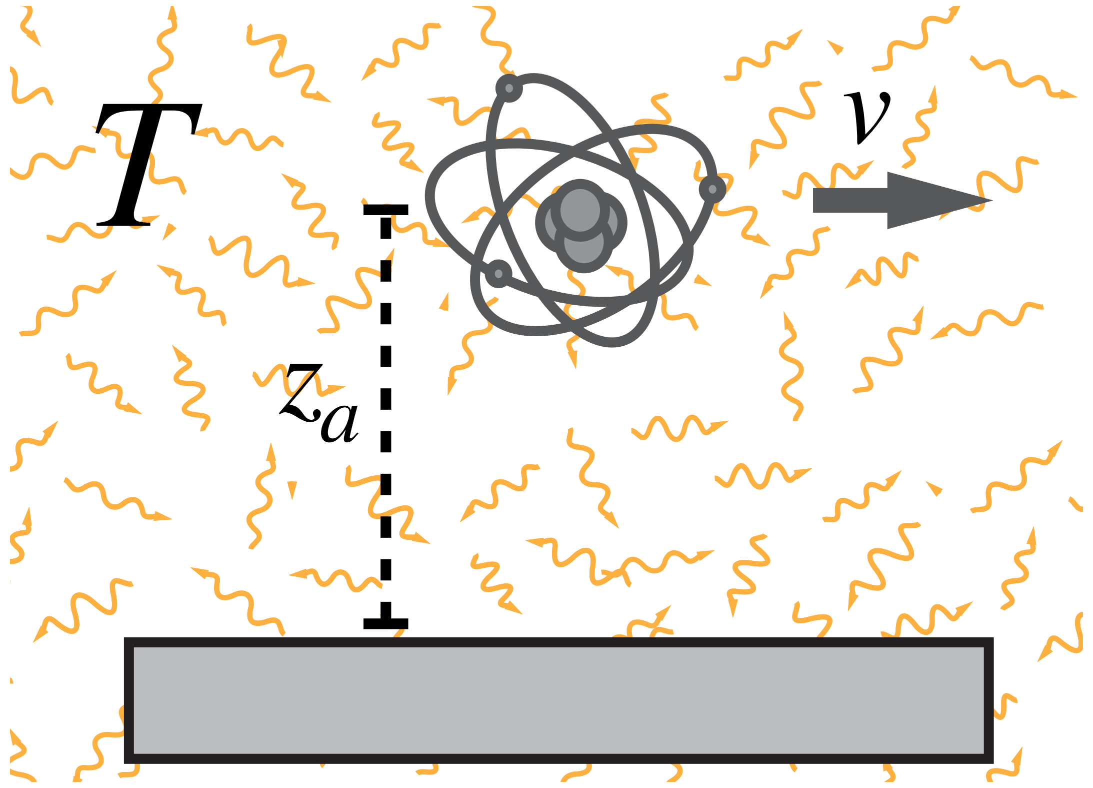
$$\underline{S}(\omega; v) = \frac{\hbar}{\pi}\theta(\omega)\underline{\alpha}_I(\omega; v) + \frac{\hbar}{\pi}\underline{J}(\omega; v)$$

$$F_{\rm fric} = F_{\rm fric}^{\rm LTE} + F_{\rm fric}^{J}$$

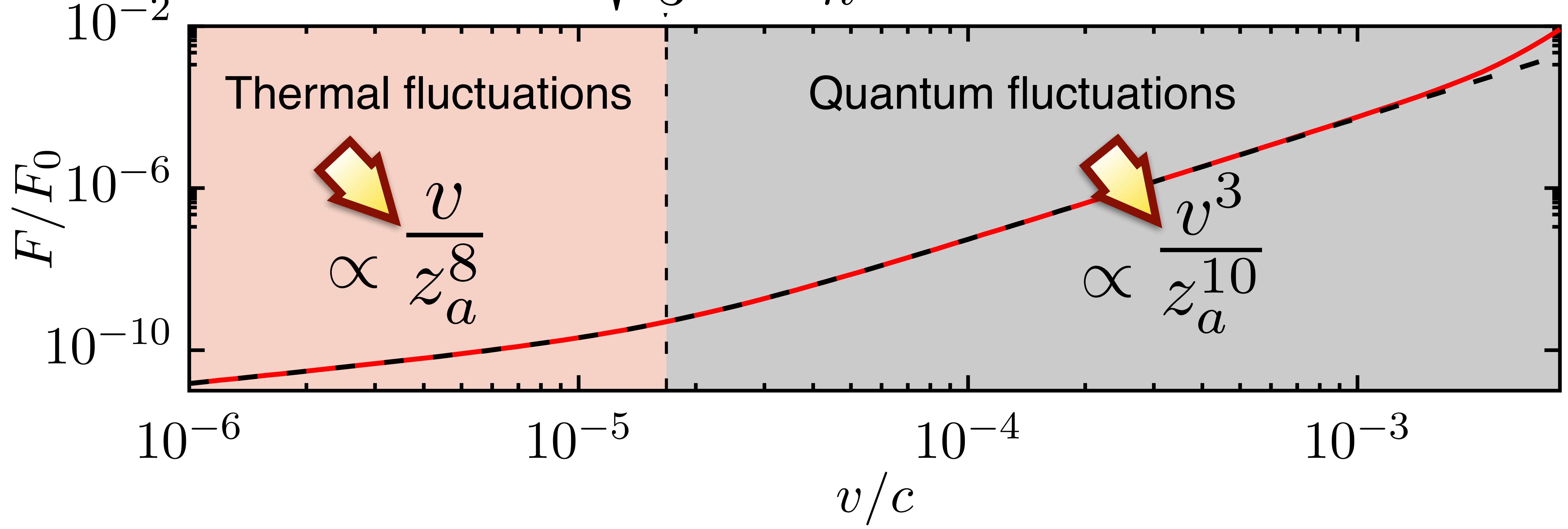
Correction needed also for thermodynamical consistence

Thermal Effects

M. Oelschläger, D. Reiche, C. H. Egerland, K. Busch and F. Intravaia, arXiv:2110.13635 (2021)

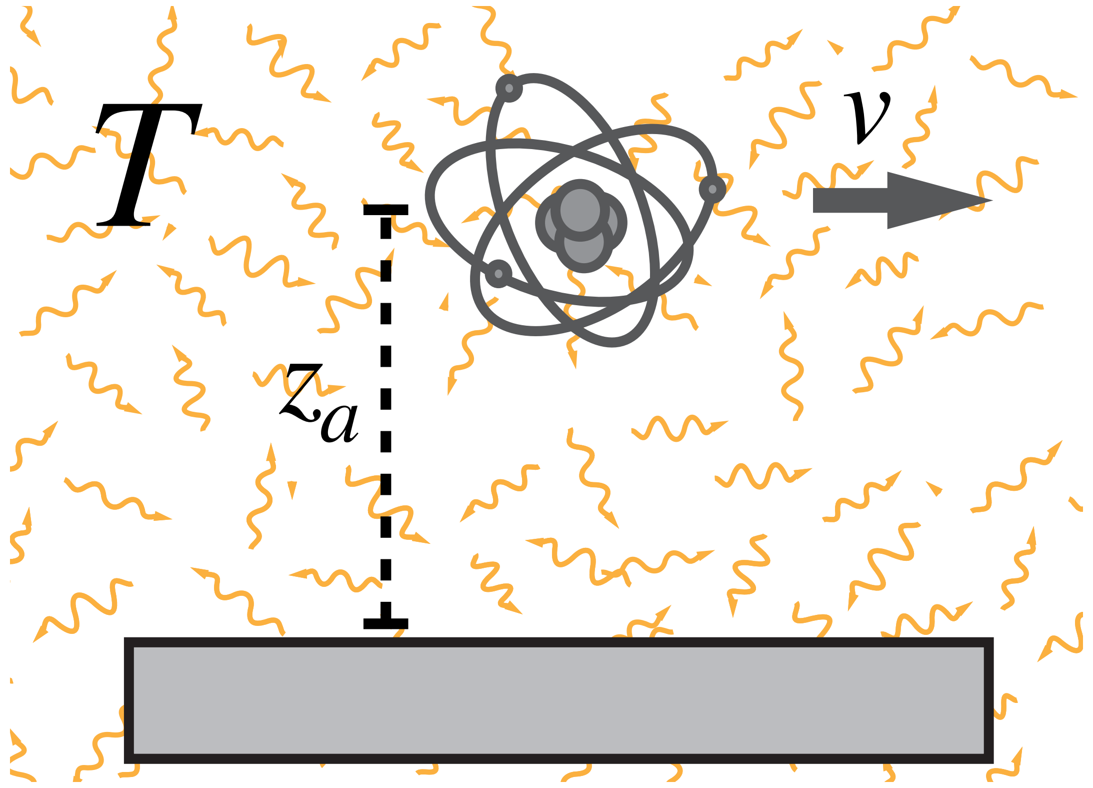


$$v_c \equiv \sqrt{\frac{2}{3}}\pi \frac{z_a\, k_{\mathrm{B}}\, T}{\hbar}$$

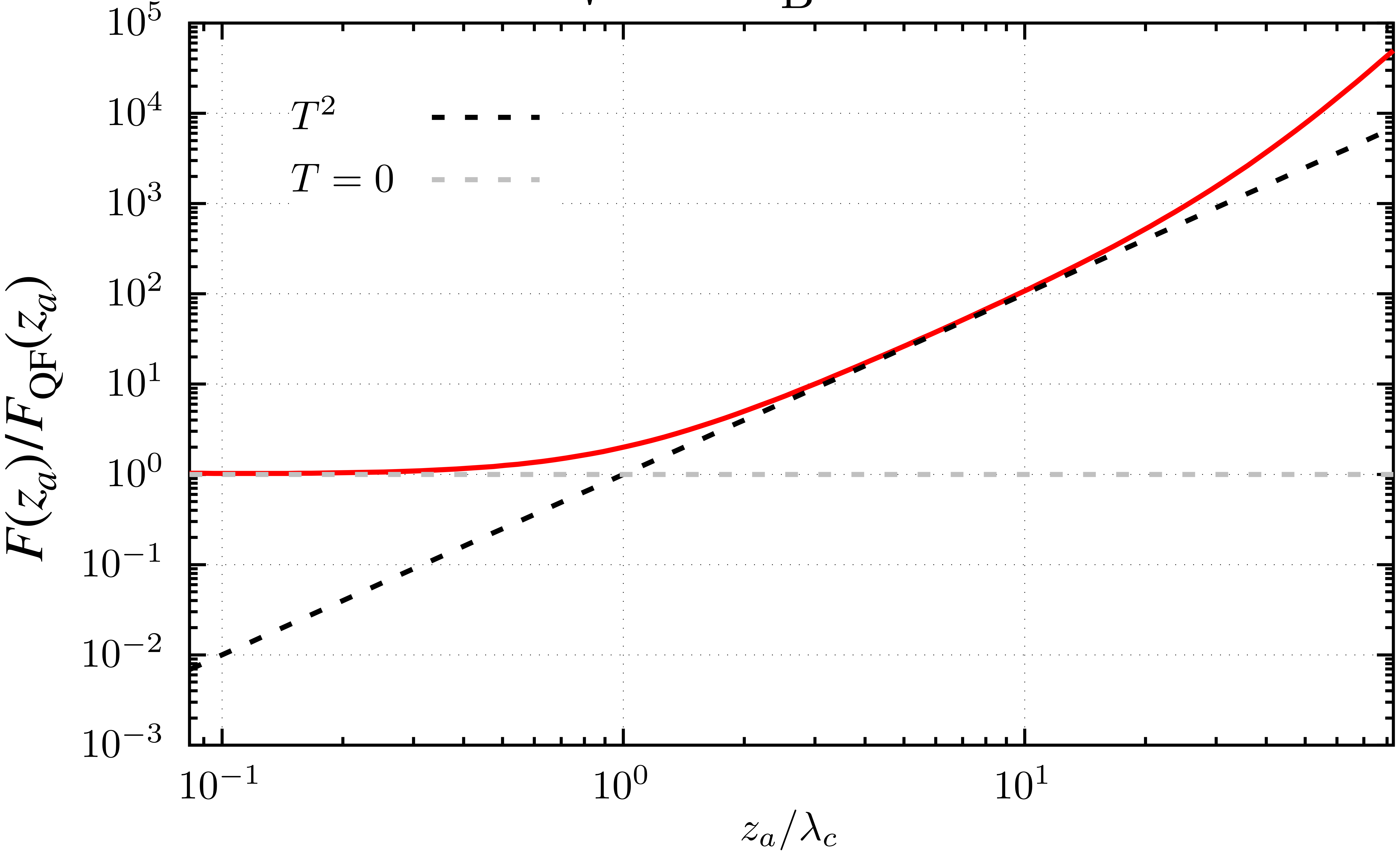


Thermal Effects

M. Oelschläger, D. Reiche, C. H. Egerland, K. Busch and F. Intravaia, arXiv:2110.13635 (2021)



$$\lambda_c \equiv \sqrt{\frac{3}{2\pi^2}\frac{\hbar v}{k_B T}}$$



$$F_{\rm fric} \sim -\frac{3}{\pi}\hbar\alpha_0^2\rho^2\frac{(k_B T/\hbar)^2}{(2z_a)^8}v$$

No contribution linear in **v** at $T = 0$

Summary

Finite temperature

		Atoms	Nanoparticle
Perturbation theory →	Second order	$F_{\text{fric}} \propto e^{-a/v}$	
	Fourth order	$F_{\text{fric}} \propto \frac{v^3}{z_a^{10}}$	
LTE (FDT) →	relevance of low frequencies; steady state	$F_{\text{fric}} \propto \frac{v^3}{z_a^{10}}$	$F_{\text{fric}} \propto \frac{v^3}{z_a^7}$
(Kubo Formula) →	Thermal state	No contribution linear in $\mathbf{v}$ at $T = 0$	
QRT (Markov) →	Problems at low frequencies; Transients	$F_{\text{fric}} \propto \frac{v}{z_a^8}$	
Noneq. FDT →	Strong contribution of the nonequilibrium physics	$F_{\text{fric}} \propto \frac{v^3}{z_a^{10}}$	$F_{\text{fric}} \propto \frac{v^3}{z_a^7}$

Thank you for you attention!

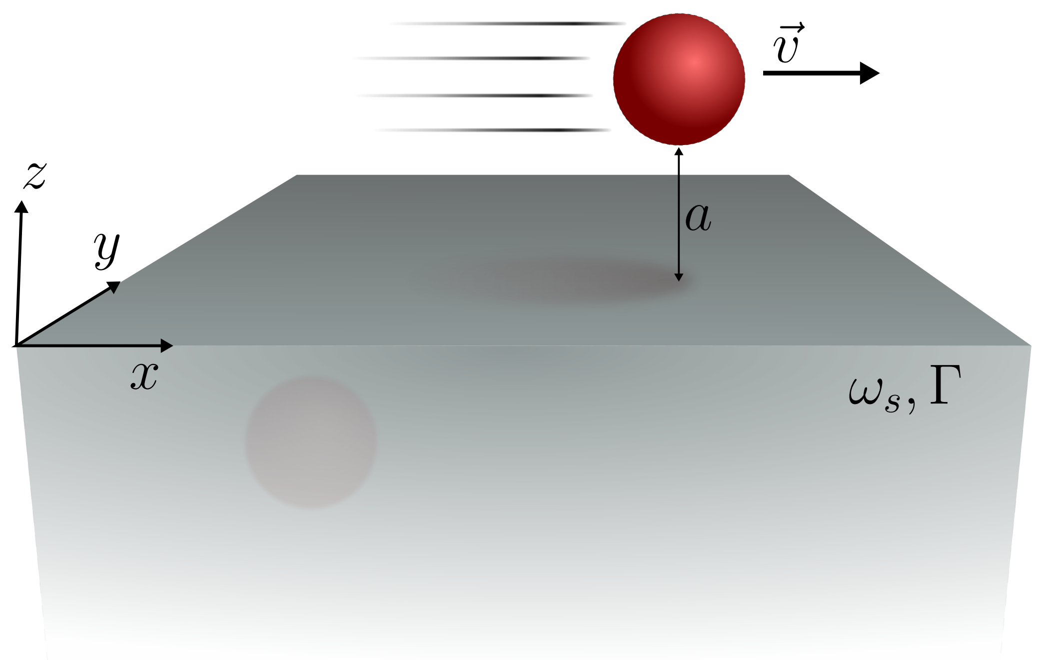
Enhanced decoherence for a neutral particle sliding on a metallic surface in vacuum

FERNANDO C. LOMBARDO

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

Departamento de Física
.UBAexactas

QUANTUM FRICTION



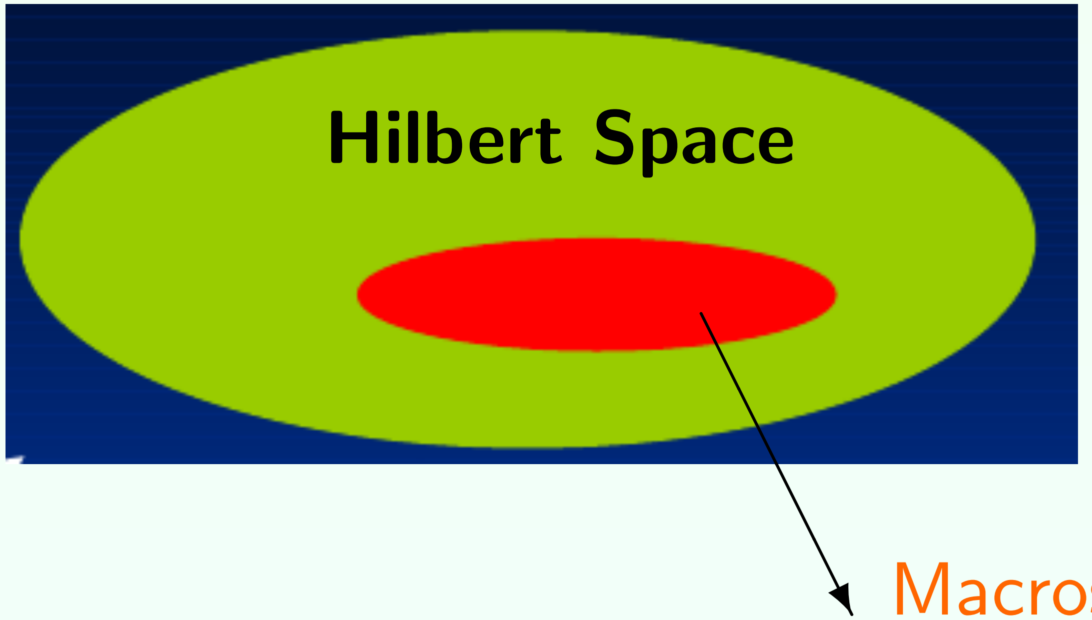
Two bodies which are not in contact and are in relative motion to each other at constant velocity experience a **dissipative force that opposes the motion due to the exchange of Doppler shifted virtual photons**.

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

Non-contact friction enhances the decoherence of the moving atom. Further, its effect can be enlarged by a thorough selection of the two-level particle and the Drude-Lorentz parameters of the material. Measuring decoherence times through velocity dependence of coherences could indirectly demonstrate the existence of quantum friction

Quantum Open System approach to quantum friction: decoherence

Decoherence and the Quantum-Classical Transition



Macroscopically quantum states are never isolated

Hilbert Space is Huge

Every state is allowed. The superposition principle reigns. If $\Psi = \Psi_1 + \Psi_2$, then

$$P = |\Psi_1|^2 + |\Psi_2|^2 + 2\mathrm{Re}(\psi_1 * \psi_2)$$

Classical states

They are a small subgroup, where interferences are forbidden. If $\Psi = \Psi_1 + \Psi_2$, then

$$P = |\Psi_1|^2 + |\Psi_2|^2$$

New Paradigm: classicality is an emergent property

If we toss a coin, it is in either one state or the other

We perceive only one outcome!

$\xcancel{2\mathrm{Re}(\psi_1 * \psi_2)}$

Decoherence is at the root of the QC Transition

It is the dynamic supression of the quantum interferences induced in subsystems due to the interacction of the environment

Quantum-Classical Transition

For a system to be considered classical it should fulfill both conditions

The wave function should predict a strong correlation between the canonical variables

$\Downarrow$

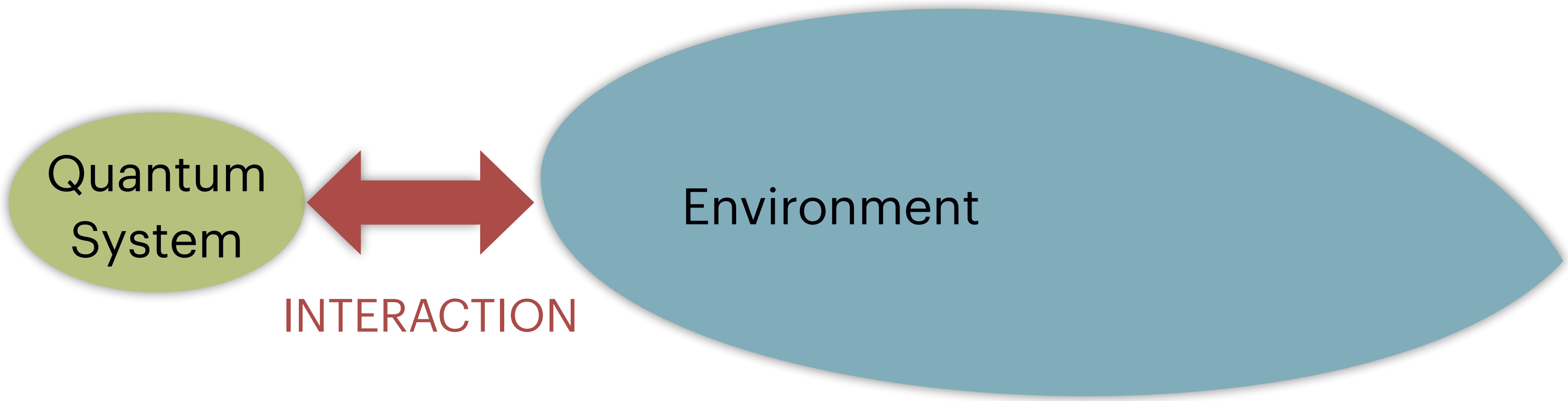
For example, the Wigner Function should have a peak at the classical trajectories

The interference between the different classical configurations should be insignificant

$\Downarrow$

The reduced density matrix becomes diagonal due to the supression of the coherences (DECOHERENCE)

Open quantum systems are characterized by non-unitary evolutions



The description of the dynamics is based on a master equation that considers non-unit effects such as decoherence and dissipation

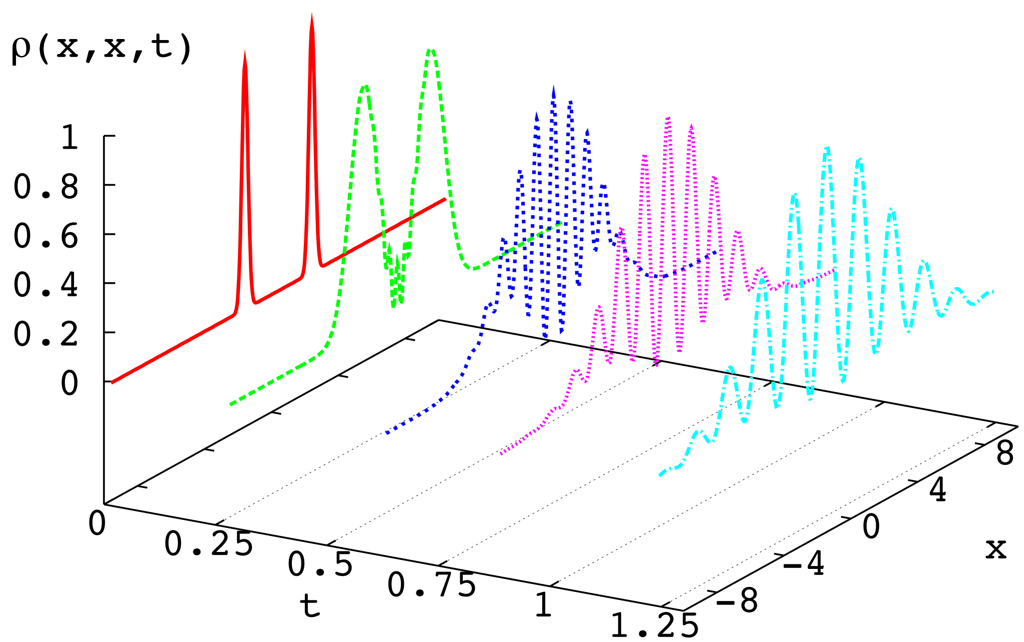
$$\dot{\rho}(t) = -i\left[H_s, \rho\right] - D(t)\left[\sigma_x, \left[\sigma_x, \rho\right]\right] - f(t)\left[\sigma_x, \left[\sigma_y, \rho\right]\right] + i\zeta(t)\left[\sigma_x, \left\{\sigma_y, \rho\right\}\right]$$

Unitary evolution

Diffusion and dissipation

Two slit experiment

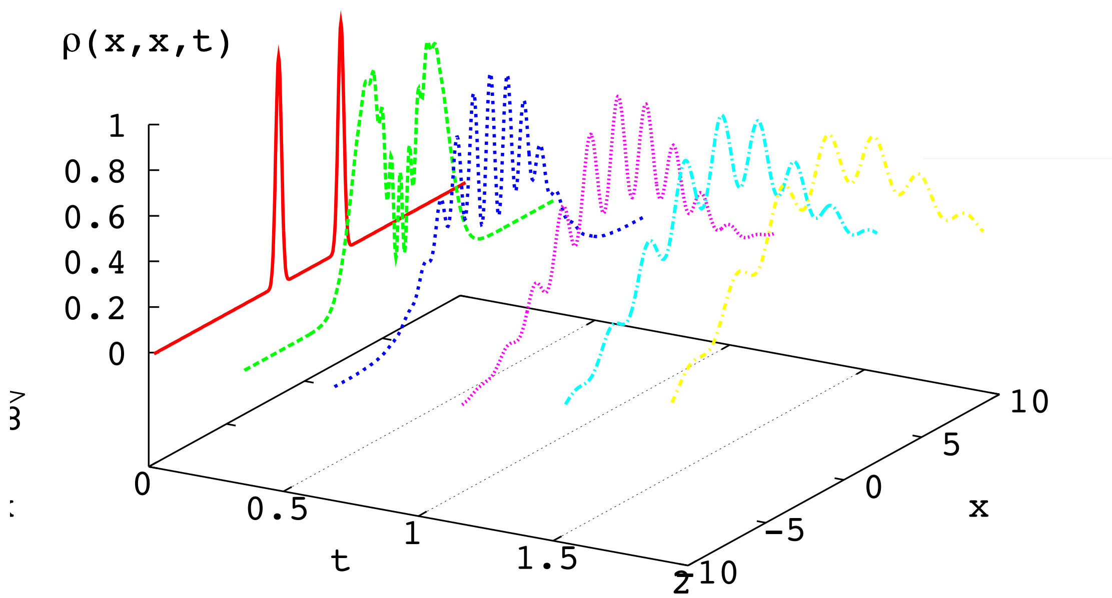
Closed quantum system



$$\rho(t) = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix}$$

With decoherence

Open quantum system



$$\rho_r(t) = \begin{pmatrix} \rho_{11} & \mathscr{D}(t)\rho_{12} \\ \mathscr{D}(t)\rho_{21} & \rho_{22} \end{pmatrix}$$

$\mathscr{D}(t)$ is the factor by which coherences are destroy

In order to study the role of the vacuum fluctuations as a source of decoherence we will start by the paradigmatic example of Quantum Brownian Motion

Not only does it renormalize the system's parameters: $\Longrightarrow$ source of NOISE and DISSIPATION

We shall couple our system of mass M and frequency Ω to an environment at zero temperature (QUANTUM ENVIRONMENT): infinite set of harmonic oscillators of mass m_n and frequency ω_n.

The paradigmatic QBM model

Total action of the system+environment ($\hbar = 1$)

$$S[x, q_n] = \int_0^t ds \left[\frac{1}{2} M(\dot{x}^2 - \Omega^2 x^2)\right] - \sum_n \lambda_n x q_n$$
$$+ \int_0^t ds \left[\sum_n \frac{1}{2} m_n (\dot{q}_n^2 - \omega_n^2 q_n^2)\right]$$

Relevant objects to analyze

$$\rho_{\mathrm{r}}(x, x', t) = \int d\bar{q}\ \rho(x, \bar{q}, x', \bar{q}, t)$$

$$W_{\mathrm{r}}(x, p, t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} dy\ e^{ipy}\ \rho_{\mathrm{r}}(x + \frac{y}{2}, x - \frac{y}{2}, t).$$

The reduced density matrix satisfies

$$
\begin{aligned}
i\frac{\partial}{\partial t}\rho_{\mathrm{r}}(x,x',t) &= \left[-\frac{1}{2M^2}\left(\partial_x^2-\partial_{x'}^2\right)\right]\rho_{\mathrm{r}}+\frac{1}{2}M\Omega^2(x^2-x'^2)\rho_{\mathrm{r}} \\
&+ \frac{1}{2}M\delta\Omega^2(t)(x^2-x'^2)\rho_{\mathrm{r}} - i\gamma(t)(x-x')\left(\partial_x-\partial_{x'}\right)\rho_{\mathrm{r}} \\
&- iM\mathcal{D}(t)(x-x')^2\rho_{\mathrm{r}} - f(t)(x-x')\left(\partial_x+\partial_{x'}\right)\rho_{\mathrm{r}}
\end{aligned}
$$

At High Temperature $\rightarrow \delta\Omega^2(t)\sim 0$, $f(t)\sim 0$, $\gamma(t)\sim\gamma_0$, and $\mathcal{D}(t)\sim 2m\gamma_0 K_B T$. CONSTANTS!

At $T=0\rightarrow \delta\Omega^2(t)$, $\gamma(t)$, $\mathcal{D}(t)$ and $f(t)$ are time dependent functions!

B.L. Hu, J.P. Paz, and Y. Zhang, Phys. Rev. D45, 2843 (1993)

Decoherence Process

Aim

Study the dynamics of the particle in interaction with the environment

Procedure

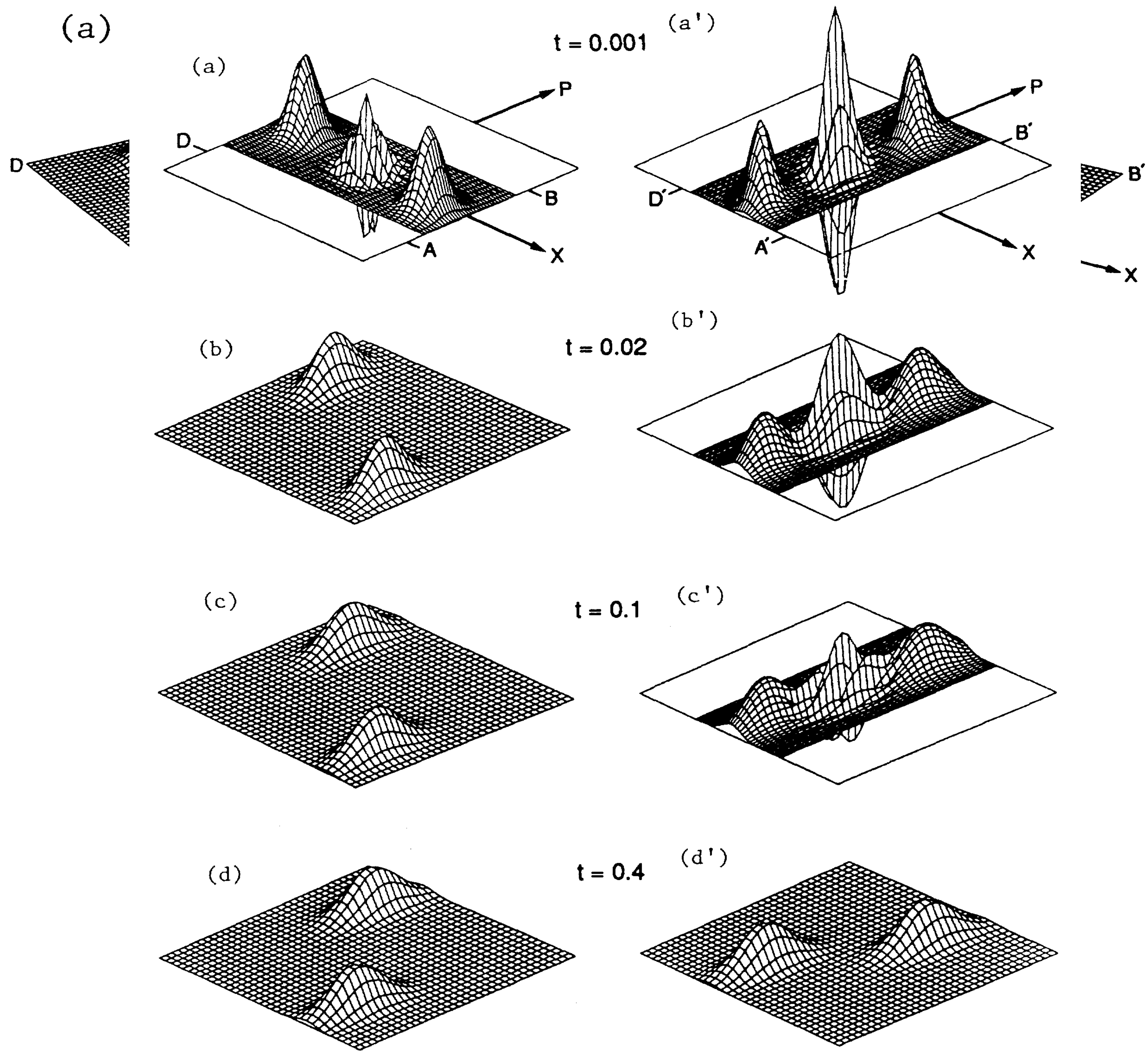
We solve the master equation for the initial density matrix and obtain $\rho_r(t)$ for all times. Initially: $\Psi(x, t=0) = \Psi_1(x) + \Psi_2(x)$, a superposition of two gaussian packets simmetrically localized

For $t > 0$, $W(x,p,t) = W_1(x,p,t) + W_2(x,p,t) + W_{\mathrm{int}}(x,p,t)$

DECOHERENCE FACTOR

$$\Gamma(t) = \exp(-A_{\mathrm{int}}) = \frac{1}{2}\frac{W_{\mathrm{int}}(x,p)|_{\mathrm{peak}}}{[W_1(x,p)|_{\mathrm{peak}} W_2(x,p)|_{\mathrm{peak}}]^{\frac{1}{2}}}.$$

J.P.Paz, S. Habib, and W. H. Zurek, Phys.Rev.**D 47**, 488 (1993)


(a)
t = 0.001
(a)
(a')
P
D
B
A
X
B′
D′
A′
t = 0.02
(b)
(b')
t = 0.1
(c)
(c')
t = 0.4
(d)
(d')

Spin Boson Model...

An exactly solvable model

$$H_{\mathrm{SB}} = \frac{1}{2}\hbar\Omega\sigma_z + \frac{1}{2}\sigma_z \sum_k \lambda_k (g_k a_k^\dagger + g_k^* a_k) + \sum_k \hbar\omega_k a_k^\dagger a_k,$$

As $[\sigma_z, H_{\mathrm{int}}] = 0$, the populations remain constant, the master equation for the reduced density matrix is

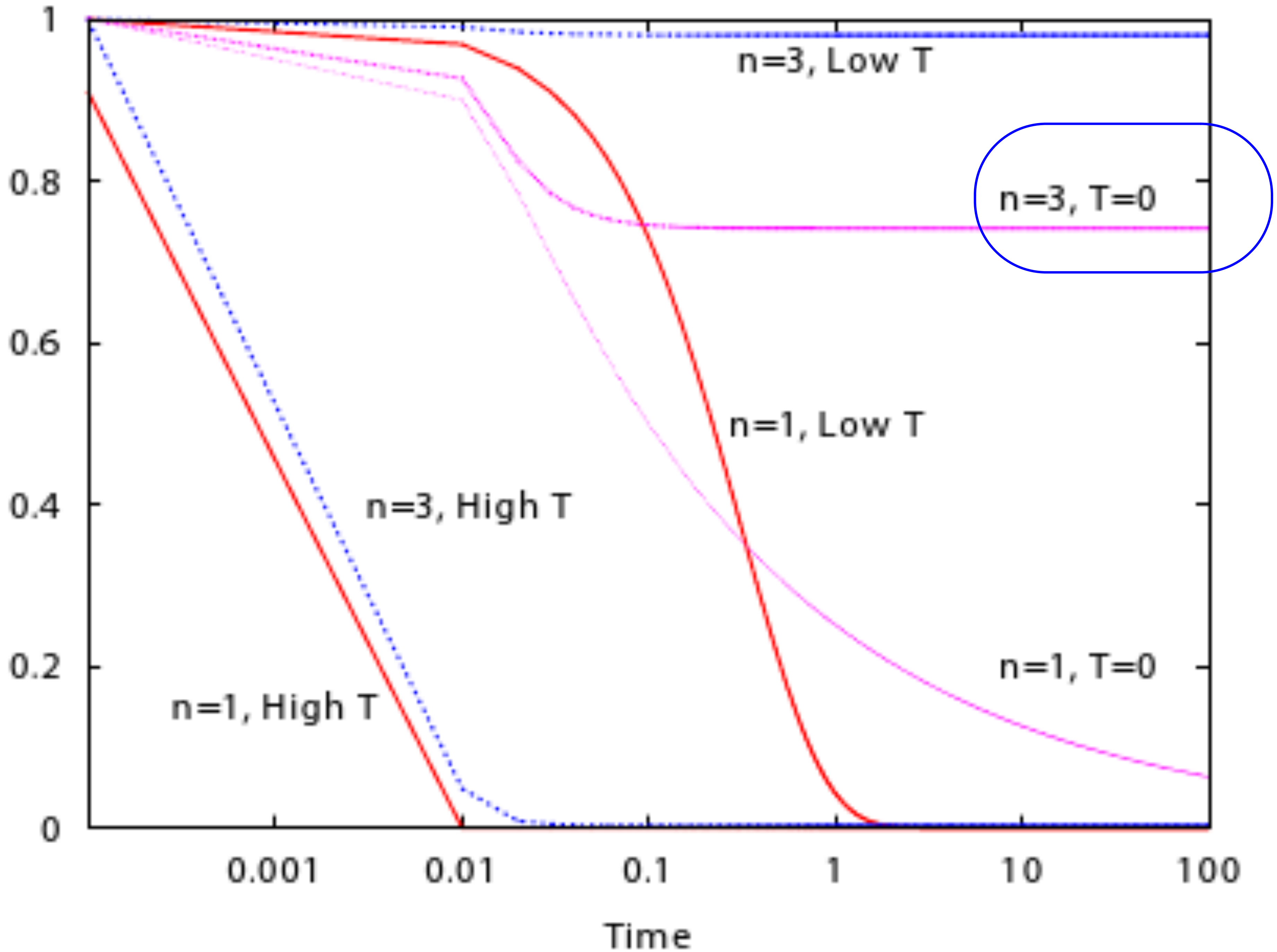
$$\dot{\rho}_{\mathrm{r}} = -i\Omega[\sigma_z, \rho_{\mathrm{r}}] - \mathcal{D}(t)[\sigma_z, [\sigma_z, \rho_{\mathrm{r}}]],$$

with $\mathcal{D}(s) = \int_0^s ds' \int_0^\infty d\omega I(\omega) \coth\left(\frac{\omega}{2k_B T}\right) \cos(\omega(s - s'))$

So, the solution to this master equation is:

$$\rho_{\mathrm{r}_{01}}(t) = e^{-i\Omega t - \mathcal{A}(t)} \rho_{\mathrm{r}_{01}}(0)$$

and $\mathcal{A}(t) = \int_0^t ds \mathcal{D}(t)$ and $\Gamma(t) = e^{-\mathcal{A}(t)}$ the decoherence factor



No decoherence

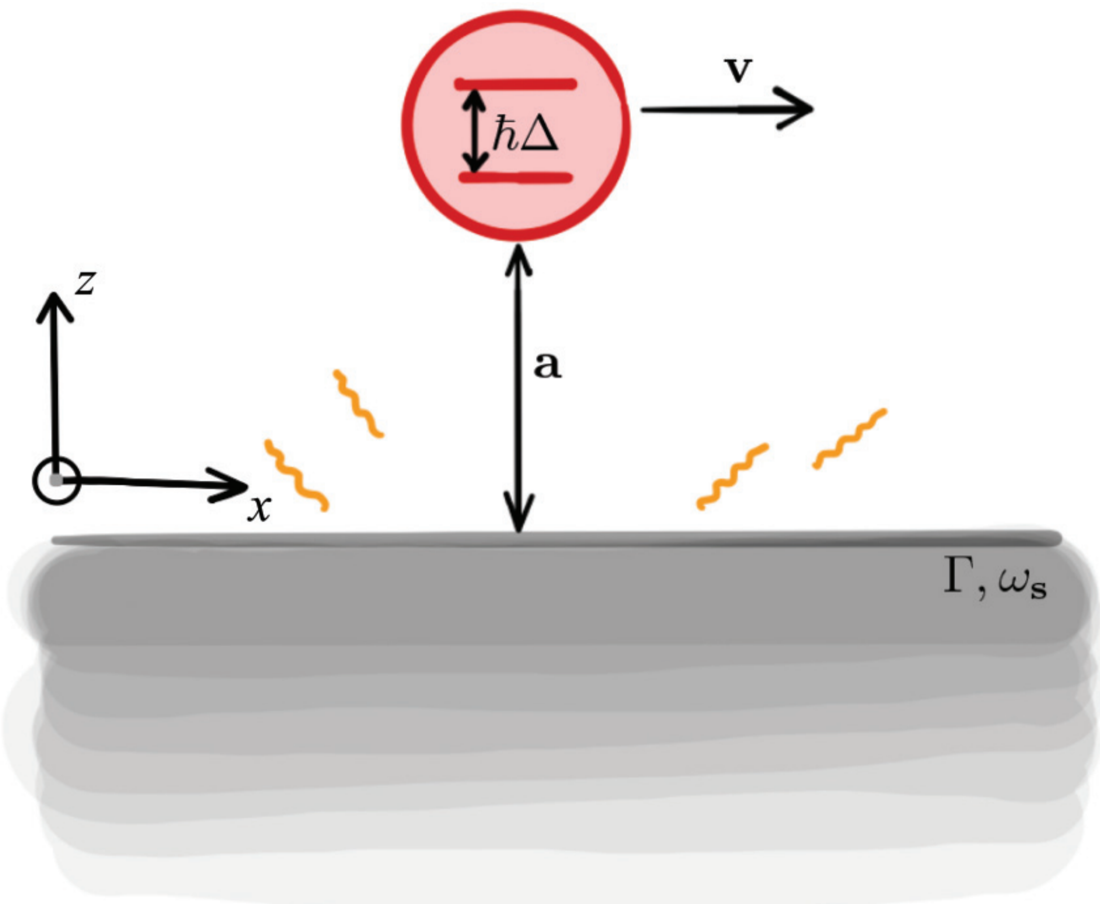
F.C.Lombardo & P.I.V, Phys. Rev **A 74**, 042311 (2006)

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.

Decoherence effect can be enlarged by a thorough selection of the two-level particle and the Drude-Lorentz parameters of the material



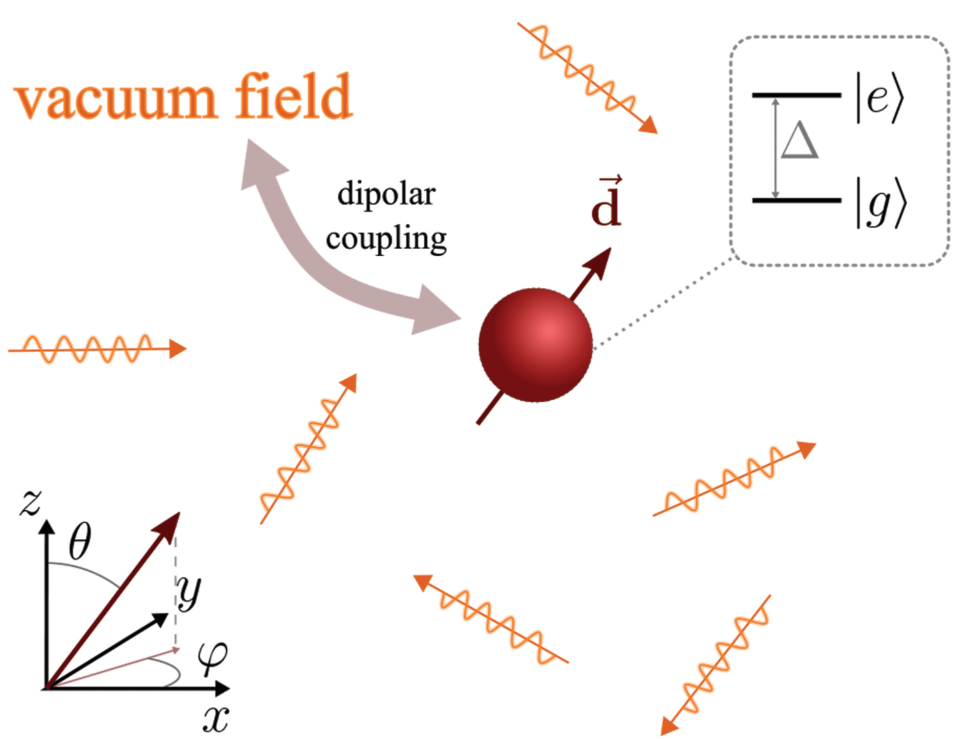
Particle-surface distante is small enough (near field regime)

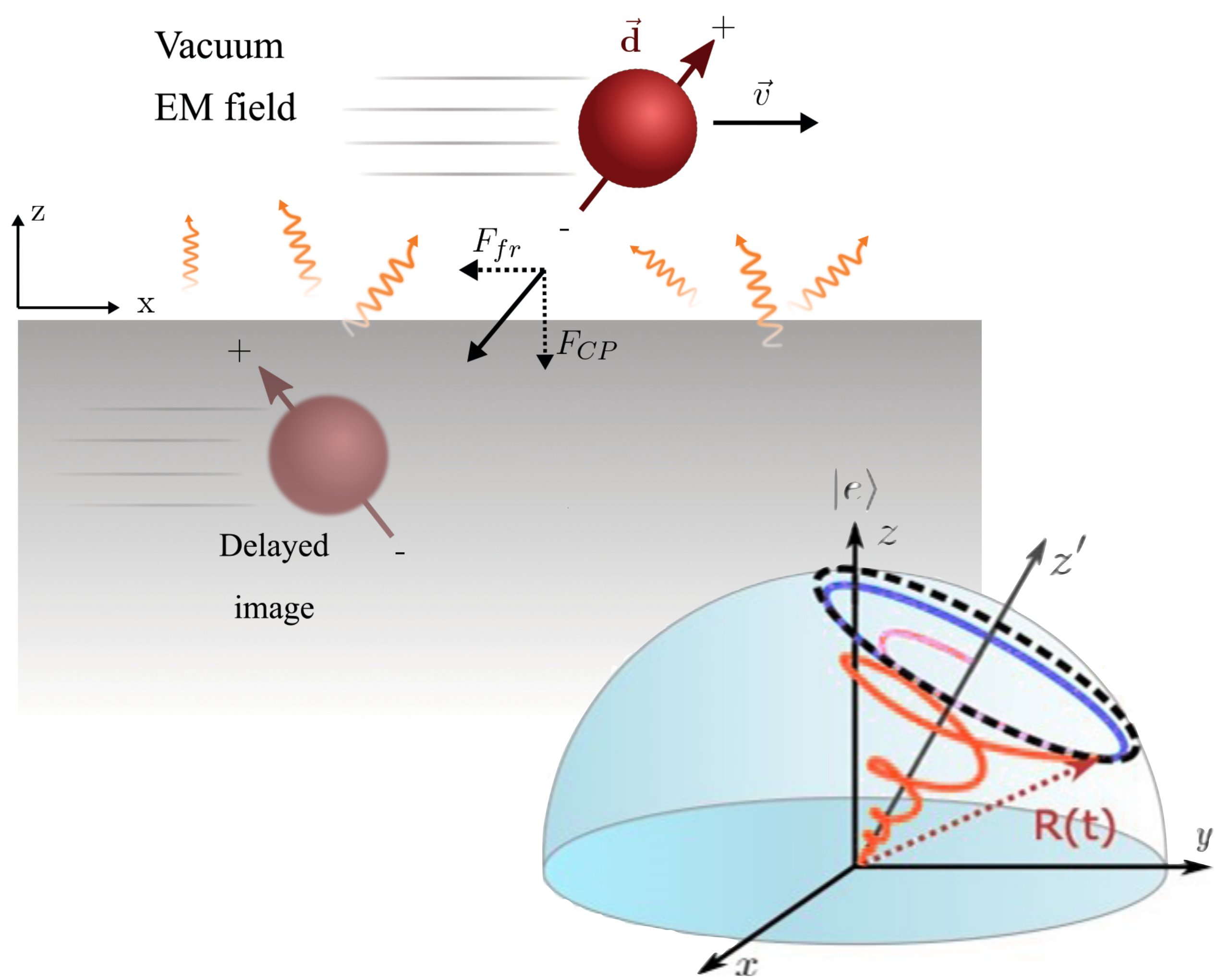
$$a\Delta/c \ll 1$$

$$\omega_p^2 = 2\omega_s^2$$

ATOM MOVING IN EM FIELD

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





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)

The master equation

$$
\begin{aligned}
\dot{\rho}_{\mathrm{s}} = &- \frac{i\Delta}{2}[\hat{\sigma}_z, \rho_{\mathrm{s}}] + i\zeta(v, t)[\sigma_x, \{\sigma_y, \rho_{\mathrm{s}}\}] \\
&- \frac{1}{2}D(v, t)([\sigma_x, [\sigma_x, \rho_{\mathrm{s}}]] + [\sigma_y, [\sigma_y, \rho_{\mathrm{s}}]]) \\
&- \frac{1}{2}f(v, t)([\sigma_x, [\sigma_y, \rho_{\mathrm{s}}]] - [\sigma_y, [\sigma_x, \rho_{\mathrm{s}}]]),
\end{aligned}
$$

The coefficients

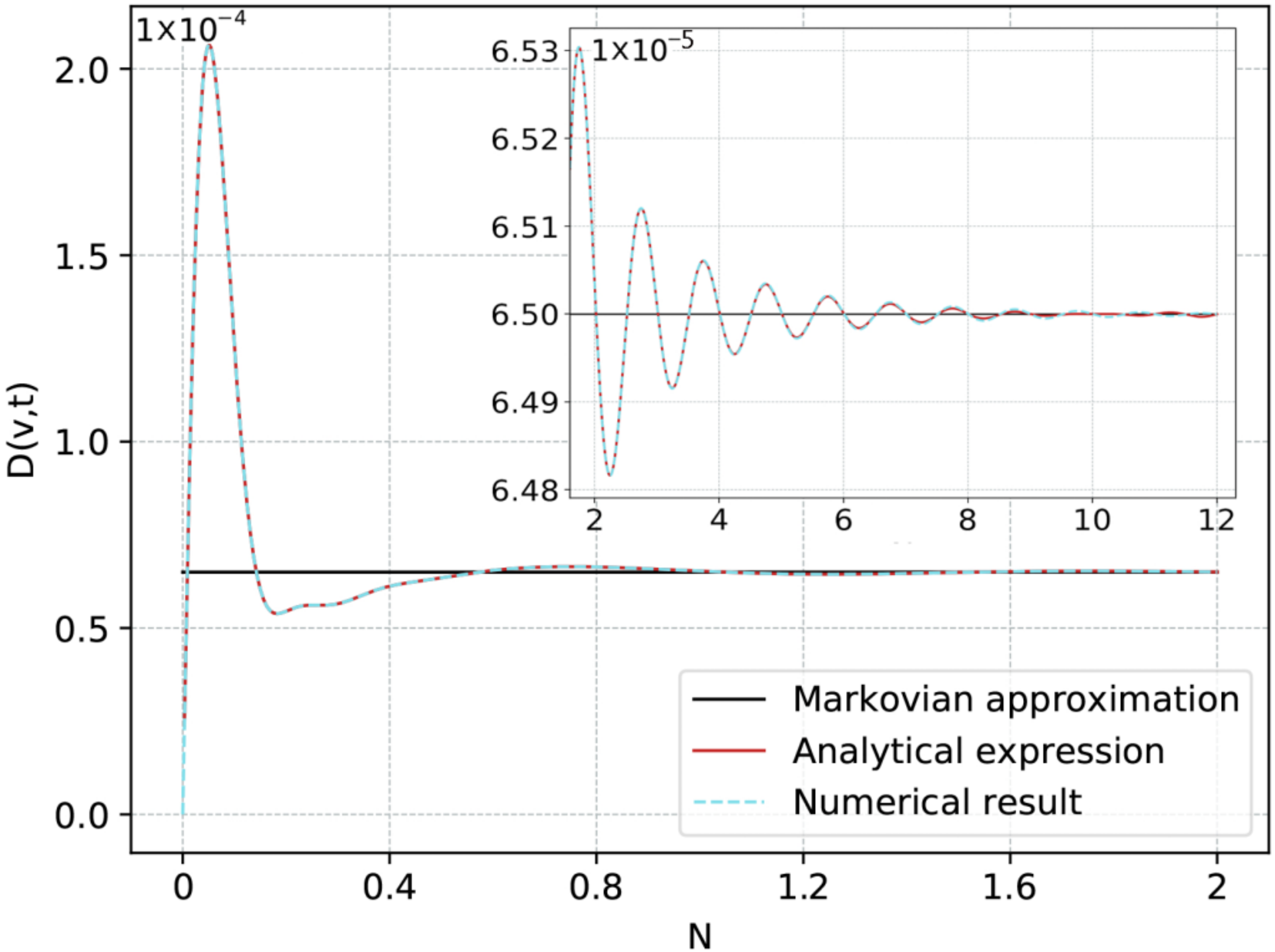
$$D(v,t) = \frac{r_0}{2\pi}\int_0^t dt' \int_0^\infty d\omega \frac{\tilde{\Gamma}\omega}{(\omega^2-1)^2+\tilde{\Gamma}^2\omega^2} \cos(\tilde{\Delta}t')\cos(\omega t')\mathbf{P}(ut'),$$
$$f(v,t) = \frac{r_0}{2\pi}\int_0^t dt' \int_0^\infty d\omega \frac{\tilde{\Gamma}\omega}{(\omega^2-1)^2+\tilde{\Gamma}^2\omega^2} \sin(\tilde{\Delta}t')\cos(\omega t')\mathbf{P}(ut'),$$
$$\zeta(v,t) = \frac{r_0}{2\pi}\int_0^t dt' \int_0^\infty d\omega \frac{\tilde{\Gamma}\omega}{(\omega^2-1)^2+\tilde{\Gamma}^2\omega^2} \sin(\tilde{\Delta}t')\sin(\omega t')\mathbf{P}(ut'),$$

$$r_0 = d^2\omega_{\rm p}^2/\hbar\omega_{\rm s}^2 a^3$$

$$\frac{\omega}{\omega_{\rm s}} \to \omega, \quad \frac{\Gamma}{\omega_{\rm s}} \to t$$

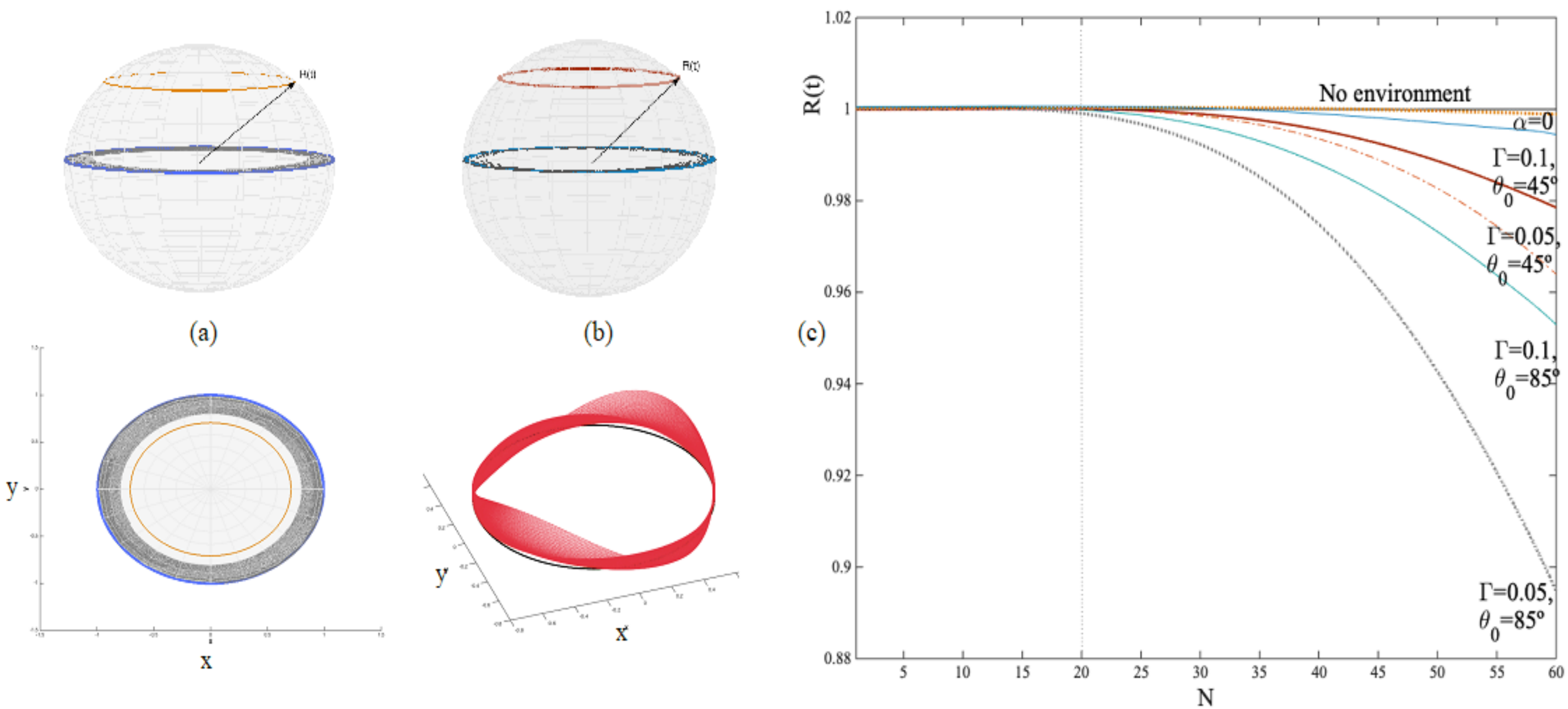
$\mathbf{P}(ut')$ is an algebraic function given by

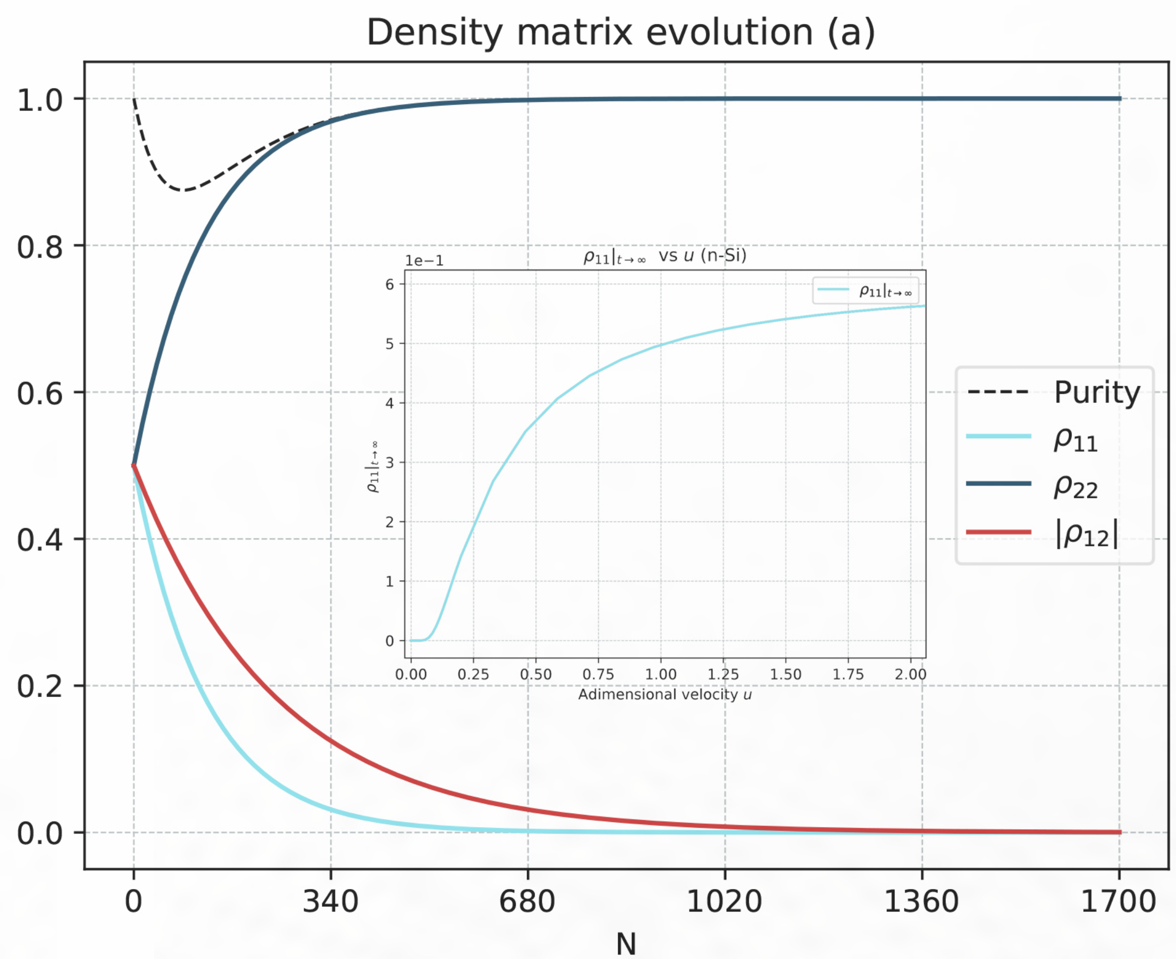
$$\mathbf{P}(ut') = 2n_x^2\frac{2-u^2t'^2}{(4+u^2t'^2)^{5/2}} + \frac{n_y^2}{(4+u^2t'^2)^{3/2}} + n_z^2\frac{(8-u^2t'^2)}{(4+u^2t'^2)^{5/2}}.$$

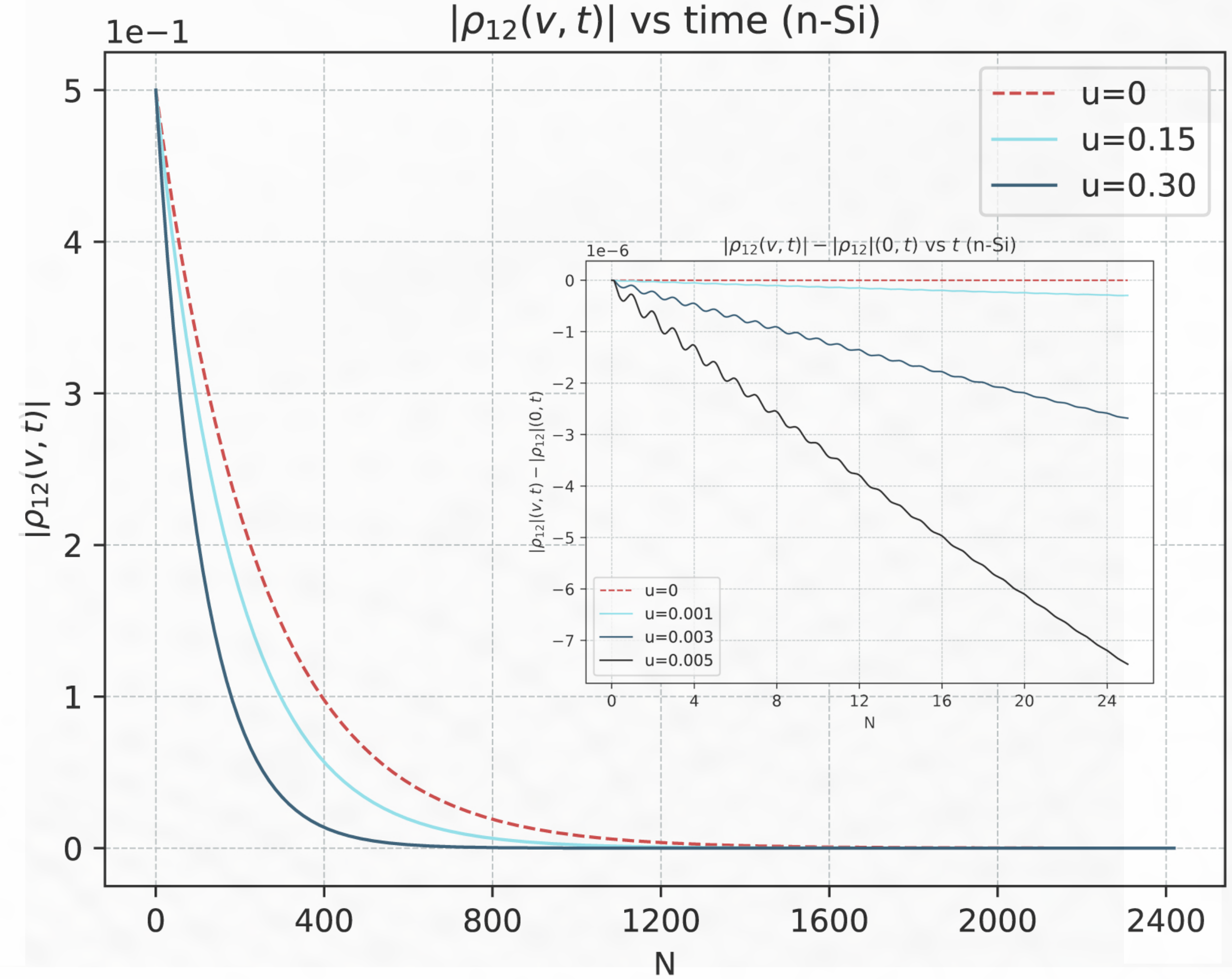


Coefficient $D(v, t)$ evolution in natural cycles $N = \frac{t}{2\pi/\tilde{\Delta}}$, comparing the analytical expression, the numerical result, and the value obtained when performing a Markov approximation. The parameter values are $a = 5$ nm, $\tilde{\Gamma} = 1$, $\tilde{\Delta} = 0.2$, $u = 0.003$, and $\mathbf{d} = d(1, 0, 0)$.

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







Coherences and ρ_{11} are indefinitely suppressed and tent to vanish for long times, leading to the system to its ground state.

Purity decreases until to reach a minimum value and tents to unity as the system tents to its pure ground state

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

Analytical expression of decoherence time:

$$\mathcal{D}(t) = \exp[-\tfrac{2}{\omega_s}\int_0^t dt' D(v,t')] \text{ as } \mathcal{D}(\tau_D) = e^{-2}$$

$$\tau_D = \tau_D^{\text{Markov}} + \left[\frac{-1}{\sqrt{4-\tilde{\Gamma}^2}}\frac{g(\tilde{\Delta},\tilde{\Gamma})}{h(\tilde{\Delta},\tilde{\Gamma})} + \frac{2}{\pi\tilde{\Delta}}\right] + \frac{3}{8}\frac{d^{(a)}}{d^{(i)}}u^2\left\{\left[g(\tilde{\Delta},\tilde{\Gamma})\frac{\partial^2_{\tilde{\Delta}}h(\tilde{\Delta},\tilde{\Gamma})}{h^2(\tilde{\Delta},\tilde{\Gamma})} - \frac{\partial^2_{\tilde{\Delta}}g(\tilde{\Delta},\tilde{\Gamma})}{h(\tilde{\Delta},\tilde{\Gamma})}\right] + \frac{2}{\pi h(\tilde{\Delta},\tilde{\Gamma})}\left[\partial^2_{\tilde{\Delta}}\frac{h(\tilde{\Delta},\tilde{\Gamma})}{\tilde{\Delta}} - \frac{\partial^2_{\tilde{\Delta}}h(\tilde{\Delta},\tilde{\Gamma})}{\tilde{\Delta}}\right]\right\}$$

Term corresponding to the Markovian approximation

$$\tau_D^{\text{Markov}} = \frac{\hbar\omega_s^2 a^3}{d^2\omega_p^2}\frac{32}{d^{(i)}}\left(\frac{1}{h(\tilde{\Delta},\tilde{\Gamma})} - \frac{3}{8}\frac{d^{(a)}}{d^{(i)}}u^2\frac{\partial^2_{\tilde{\Delta}}h(\tilde{\Delta},\tilde{\Gamma})}{h^2(\tilde{\Delta},\tilde{\Gamma})}\right)$$

$$h(\tilde{\Delta}, \tilde{\Gamma}) = \frac{\tilde{\Delta}\tilde{\Gamma}}{(\tilde{\Delta}^2 - 1)^2 + \tilde{\Delta}\tilde{\Gamma}},$$

$$g(\tilde{\Delta}, \tilde{\Gamma}) = \mathrm{Re}\left[\left(1 + \frac{2i}{\pi}\ln(\tilde{\omega}_\mathrm{r}/\tilde{\Delta})\right) \times \left(\frac{1}{(\tilde{\omega}_\mathrm{r} + \tilde{\Delta})^2} + \frac{1}{(\tilde{\omega}_\mathrm{r} - \tilde{\Delta})^2}\right)\right],$$

$$d^{(i)} = 1 + n_z^2$$

$$d^{(a)} = 3n_x^2 + n_y^2 + 4n_z^2$$

and

$$\tilde{\omega}_\mathrm{r} = \frac{1}{\sqrt{2}}\sqrt{2 - \tilde{\Gamma} + i\sqrt{4 - \tilde{\Gamma}}}$$

$$\tau_D \sim a - bu^2$$

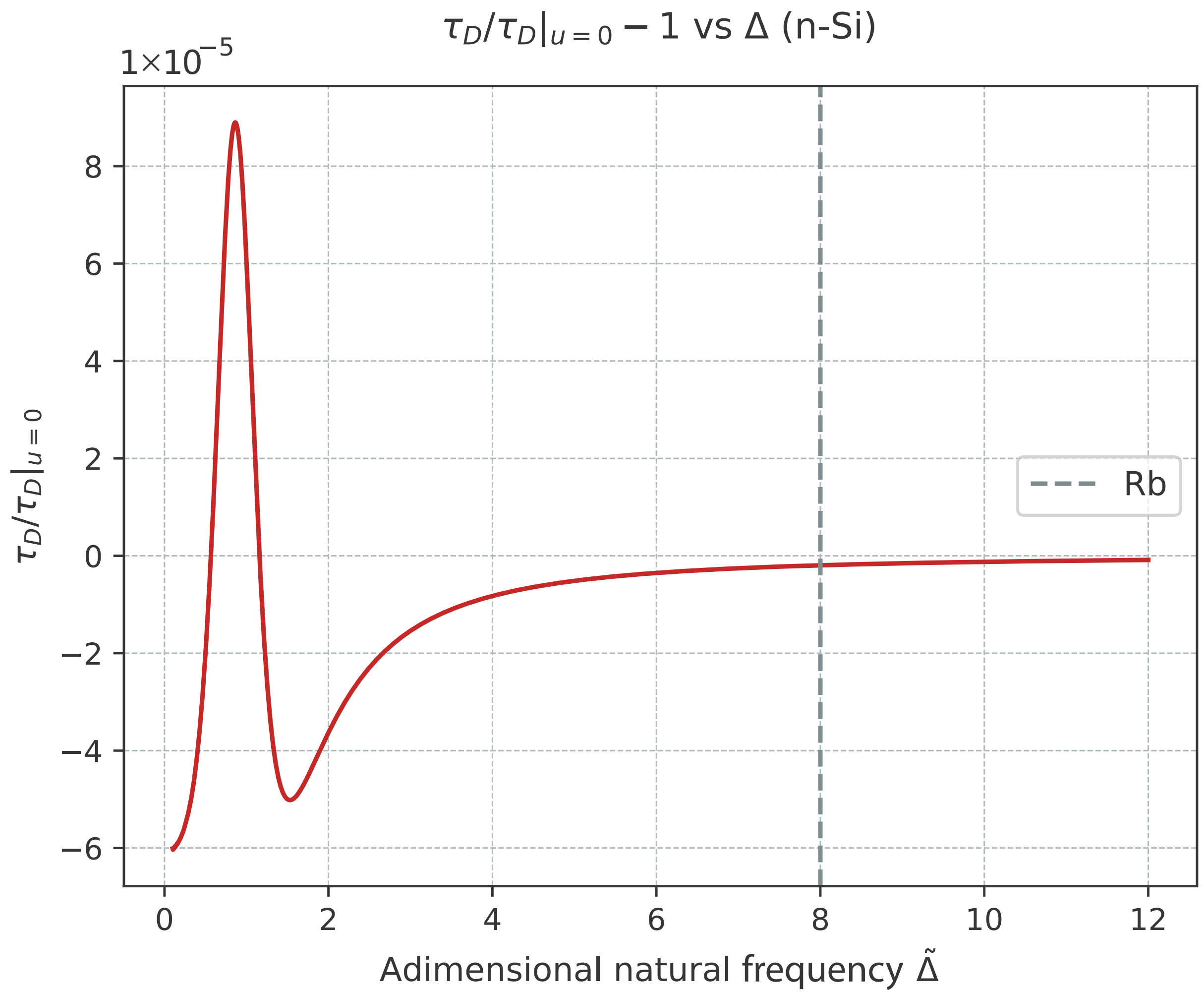
Doppler-shifted (velocity-dependent) transition frequencies: **Klatt, Bennett, Buhmann** in Phys. Rev. A (2016) "Spectroscopic signatures of quantum friction", studied the **level shift and decay rate modification** arising from the motion of the atom in the presence of a medium in the Markovian limit. **Shifts and rates are quadratic or higher in the atomic velocity**

$$b/a \sim 6.417$$

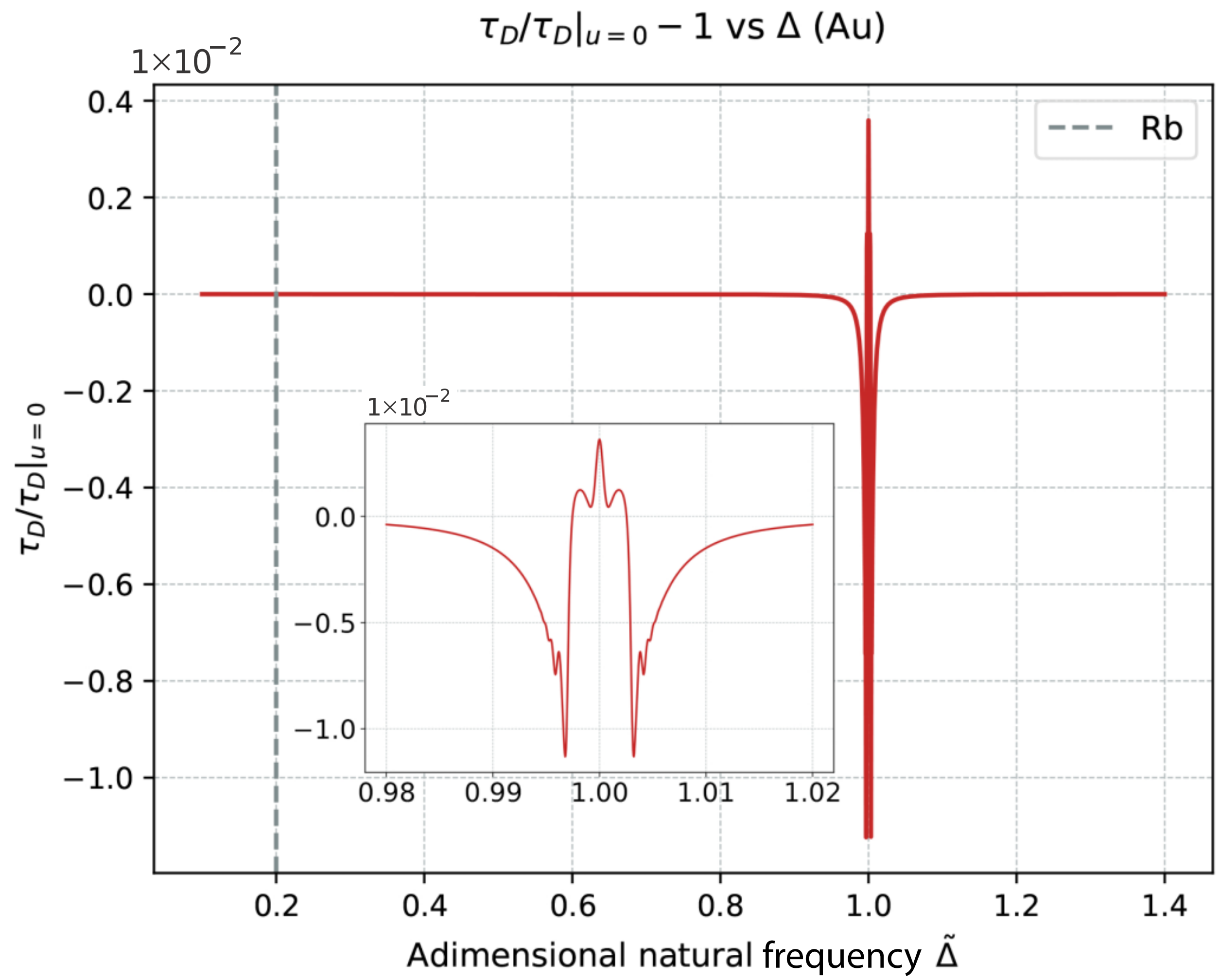
For a nitrogen-vacancy (NV) center moving over a n-doped silicon (n-Si) surface

$$b/a \sim 0.216$$

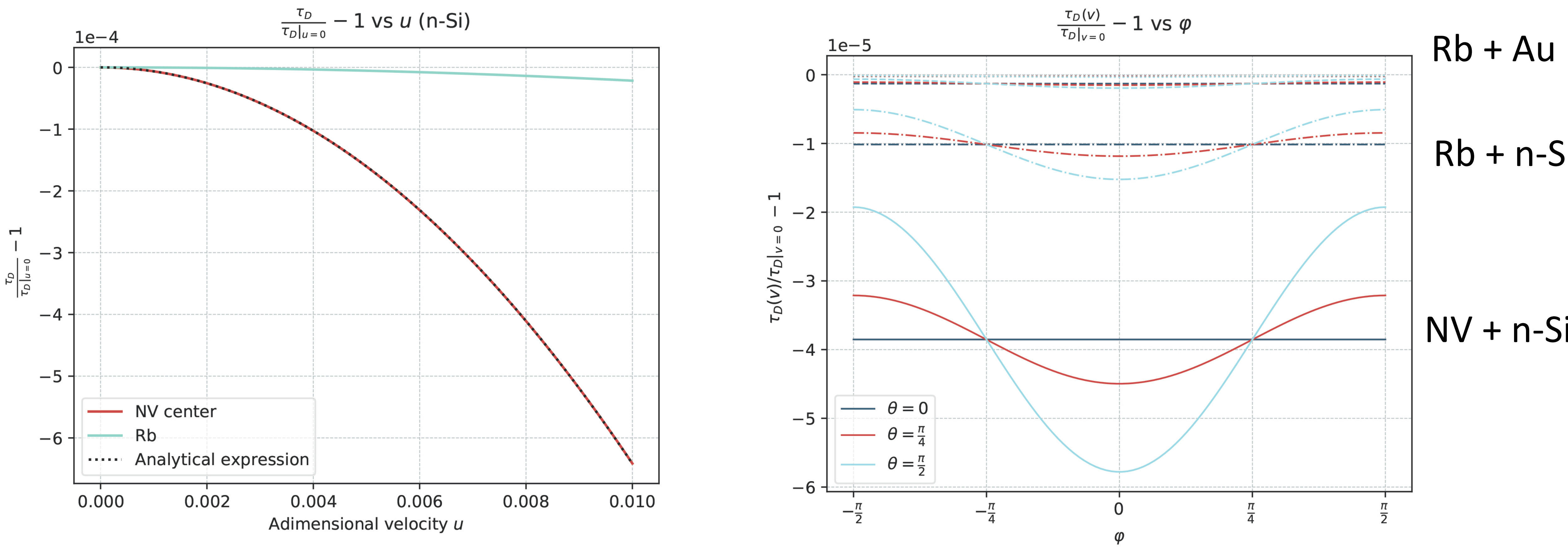
Rubidium (Rb) atom moving over n-Si surface



Decoherence time as a function of the dimensionless level spacing $\tilde{\Delta}$ of the system, normalized with the null velocity value, considering an n-Si (up) and a gold (down) dielectric. The parameter values are $\tilde{\Gamma} = 1$ and $u = 0.003$ for n-Si and $\tilde{\Gamma} = 3 \times 10^{-3}$, $u = 1.5 \times 10^{-4}$, and $\mathbf{d} = d(1, 0, 0)$ for Au.



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)

Functional methods: in-out effective action and Influence functional

PHYSICAL REVIEW D **76,** 085007 (2007)

Quantum dissipative effects in moving mirrors: A functional approach

C. D. Fosco,[1] F. C. Lombardo,[2] and F. D. Mazzitelli[2]

PHYSICAL REVIEW D **84,** 025011 (2011)

Quantum dissipative effects in moving imperfect mirrors: Sidewise and normal motions

César D. Fosco,[1,2,*] Fernando C. Lombardo,[3,†] and Francisco D. Mazzitelli[1,3,‡]

PHYSICAL REVIEW D **88,** 105004 (2013)

Quantum dissipative effects in graphenelike mirrors

César D. Fosco,[1,2] Fernando C. Lombardo,[3] Francisco D. Mazzitelli,[1,2] and María L. Remaggi[1,2]

PHYSICAL REVIEW D **91,** 105020 (2015)

Functional approach to quantum friction: Effective action and dissipative force

M. Belén Farías,[1,*] César D. Fosco,[2] Fernando C. Lombardo,[1] Francisco D. Mazzitelli,[2] and Adrián E. Rubio López[1]

PHYSICAL REVIEW D **93,** 065035 (2016)

Dissipation and decoherence effects on a moving particle in front of a dielectric plate

M. Belén Farías[*] and Fernando C. Lombardo

PHYSICAL REVIEW D **95,** 065012 (2017)

Quantum friction between graphene sheets

M. Belén Farias,[1,*] César D. Fosco,[2,†] Fernando C. Lombardo,[1,‡] and Francisco D. Mazzitelli[1]

PHYSICAL REVIEW D **100,** 036013 (2019)

Motion induced radiation and quantum friction for a moving atom

M. Belén Farías,[1,2,*] C. D. Fosco,[3,†] Fernando C. Lombardo,[1,‡] and Francisco D. Mazzitelli

PHYSICAL REVIEW D **99,** 105005 (2019)

Thermal corrections to quantum friction and decoherence: A closed-time-path approach to atom-surface interaction

Ludmila Viotti,[*] M. Belén Farías, Paula I. Villar, and Fernando C. Lombardo

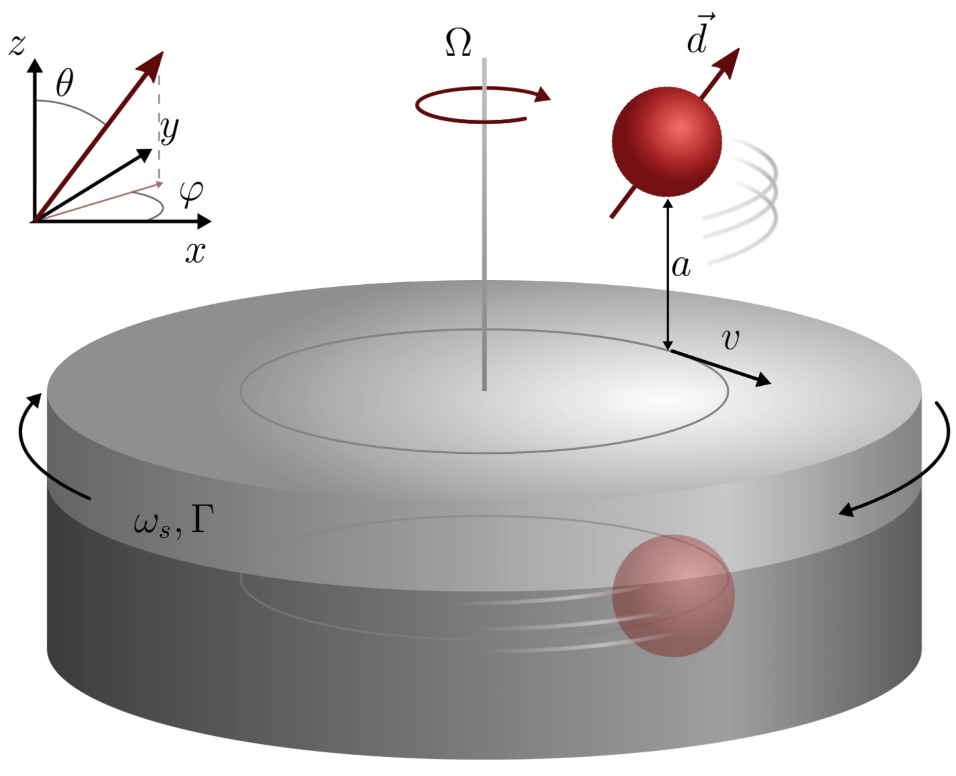
universe MDPI

Article

Motion-Induced Radiation Due to an Atom in the Presence of a Graphene Plane

César D. Fosco [1], Fernando C. Lombardo [2] and Francisco D. Mazzitelli [1,*]

EXPERIMENTAL PROPOSAL



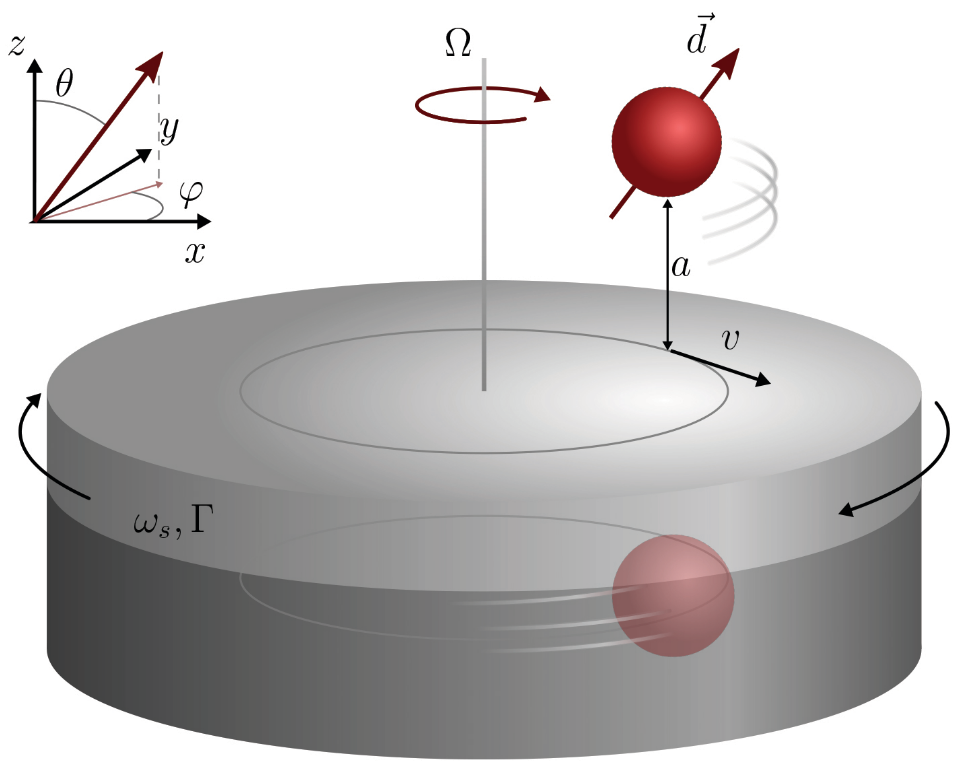
12cm diameter Au-coated Si disks rotated up to Ω = 2π7000 rad/s.

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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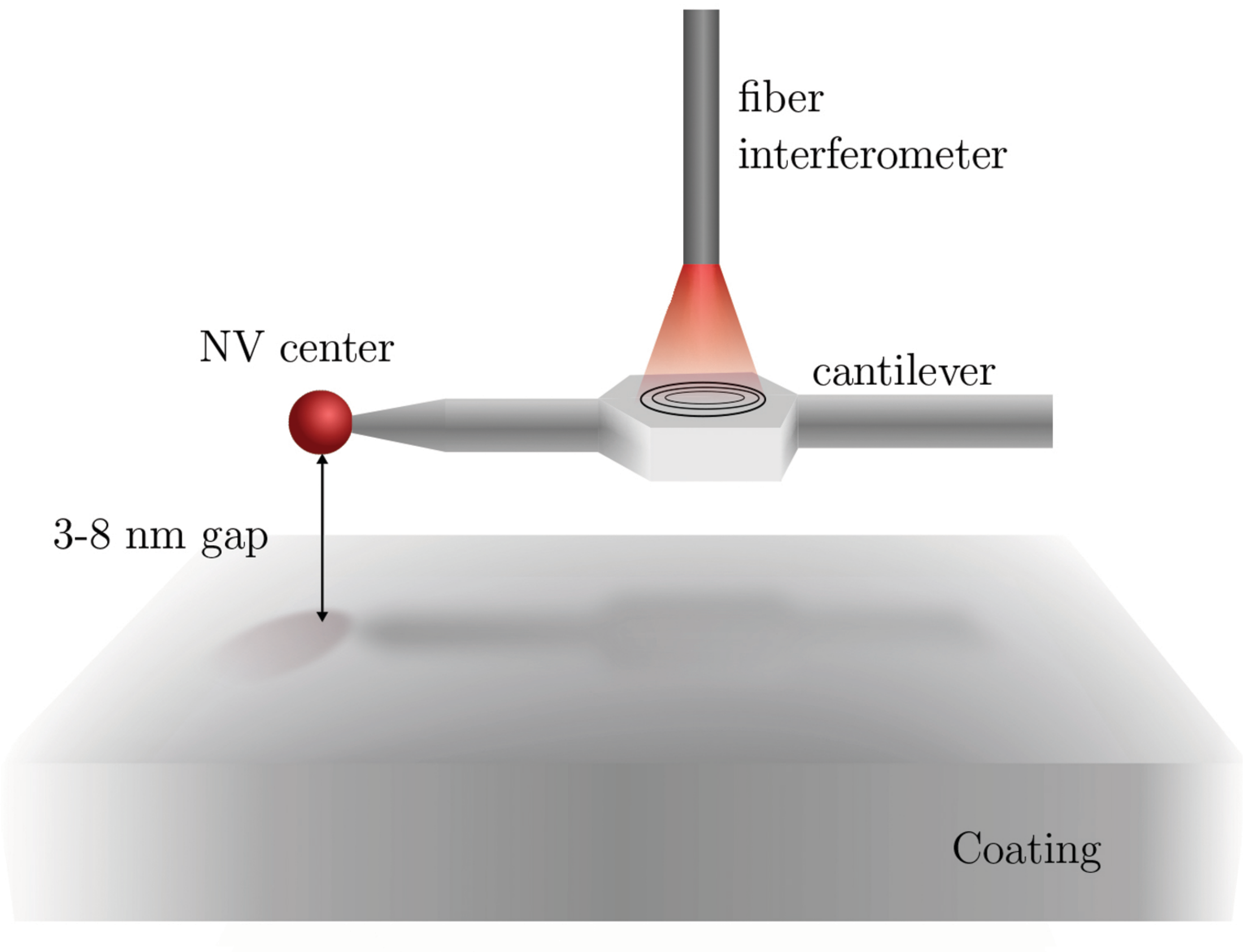
The distance can be controlled from a few nanometers to tenths of nanometers with sub-nanometer resolution

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)

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

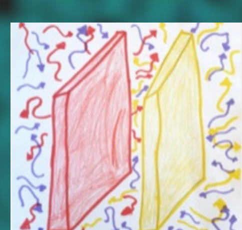
- We have further obtained an analytical y numerical expression for the decoherence time

- Both the net effect of the environment on the particle and the velocity-dependent effect are strongly dependent on the material parameters and the atom level spacing, allowing as to amplify or weaken the magnitude by a sensible choice

- A link between decoherence time and quantum friction can be established since non contact quantum friction seems to enhance the decoherence on the moving atom. Measuring decoherence time one can indirectly demonstrate the existence of quantum friction

- We have found a scenario to indirectly detect QF by measuring the the corrections on the Geometric phase induced by decoherence

THANK YOU!



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