Assessing the effects of material-modified electromagnetic fluctuations

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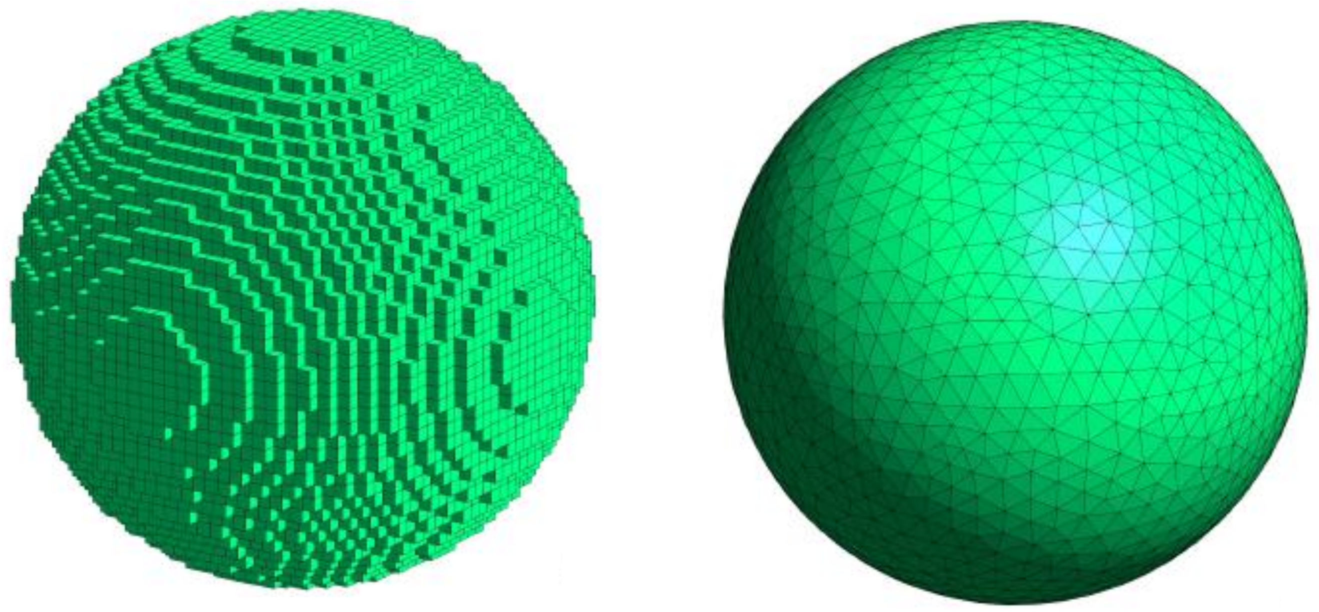
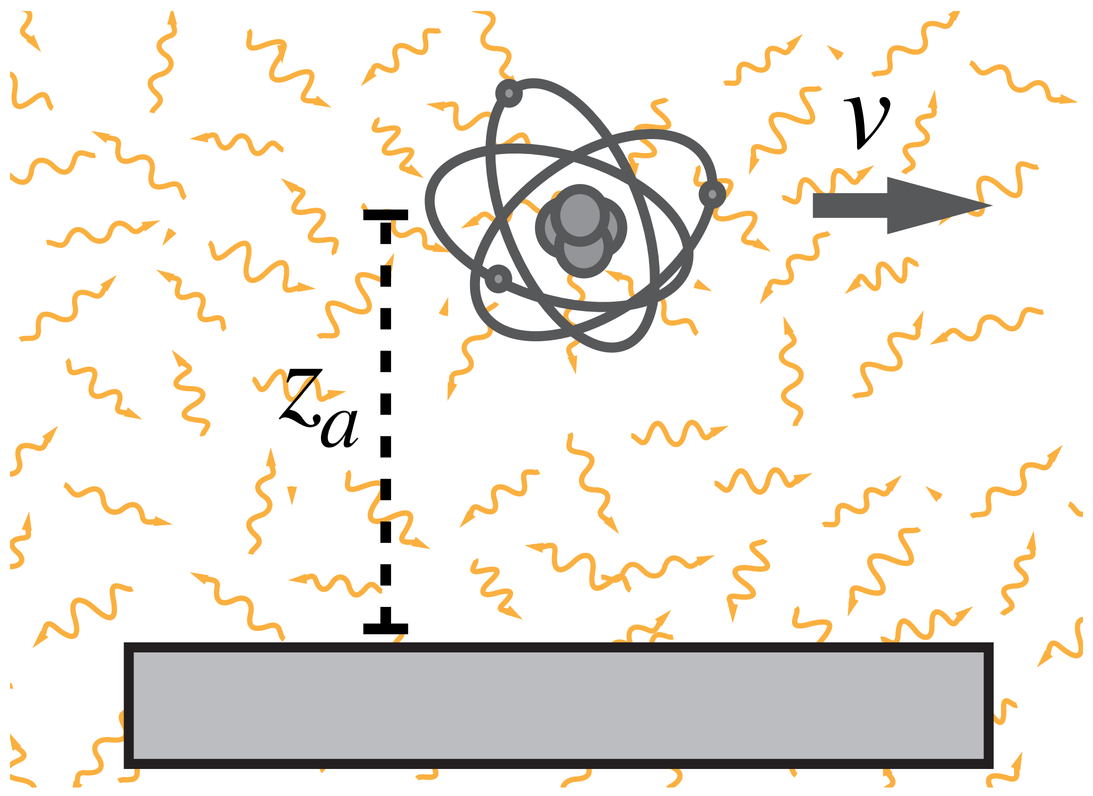
Many thanks to all the collaborators
and the organizers!

Outline

1. Equilibrium Casimir Physics

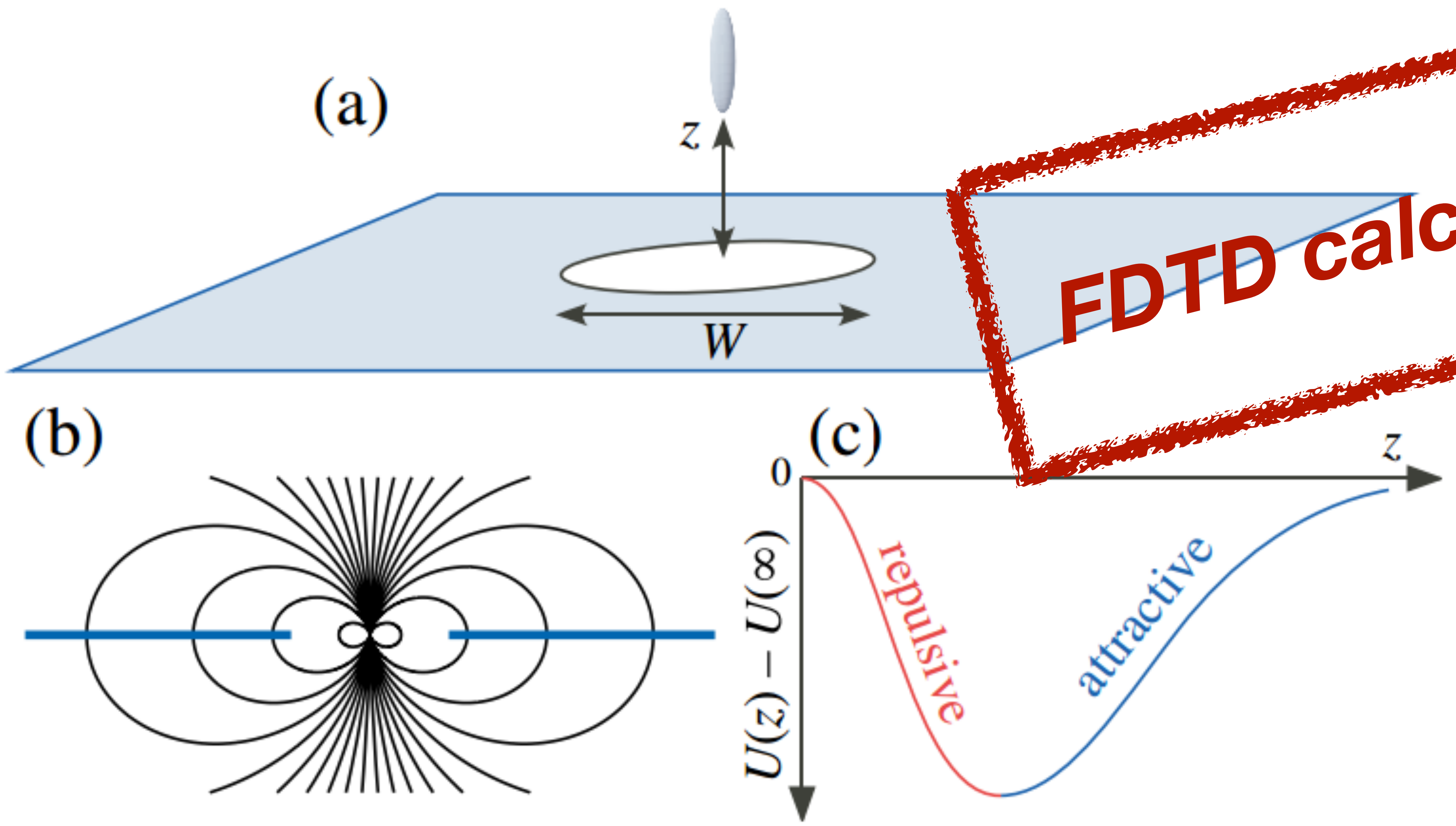


2. Nonequilibrium Casimir Physics



Controlling the Casimir interaction

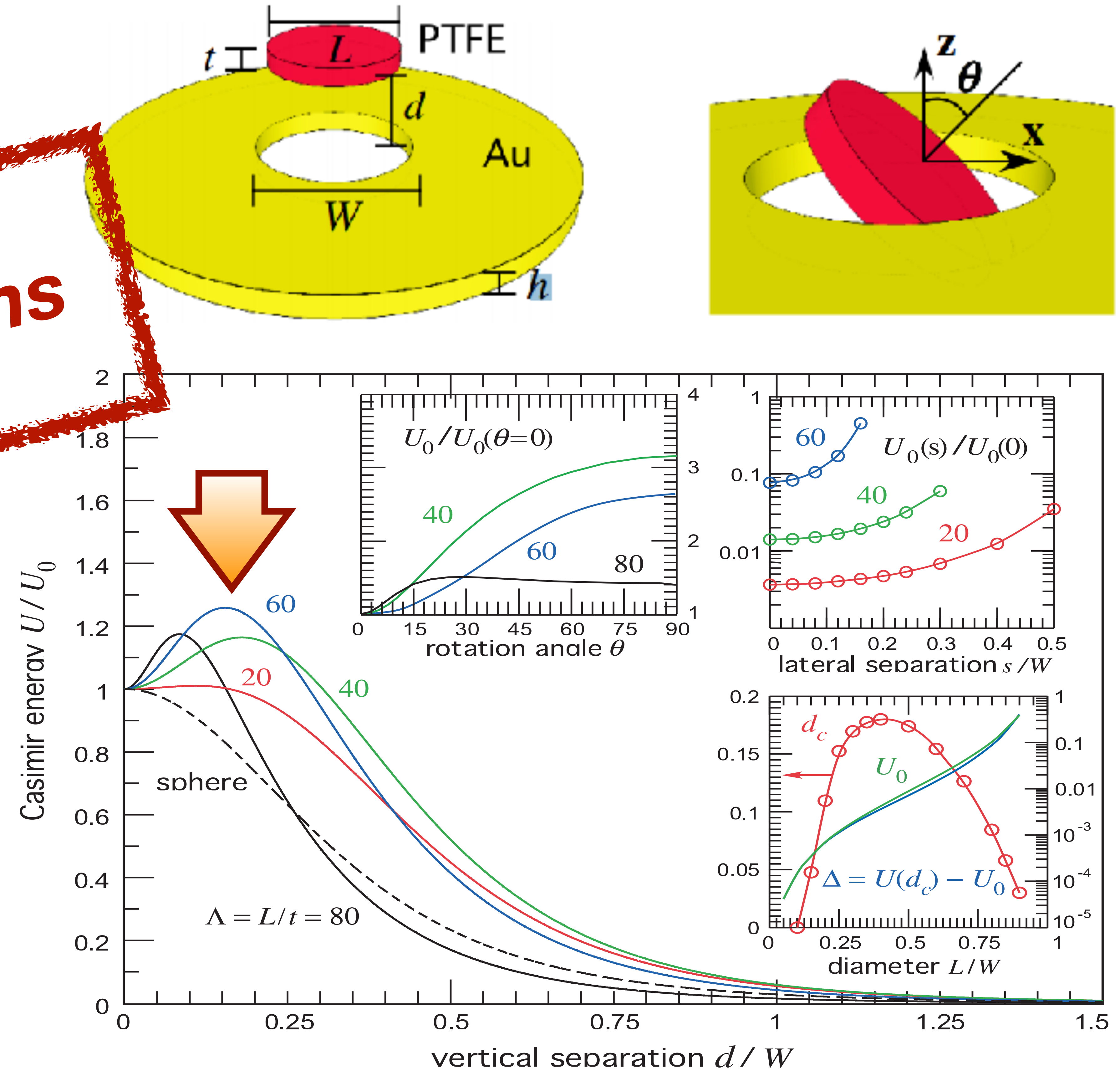
Anisotropy is key!



M. Levin, A. P. McCauley, A. W. Rodriguez, M. T. H. Reid, and S. G. Johnson, Phys. Rev. Lett. **105**, 090403 (2010).

FDTD calculations

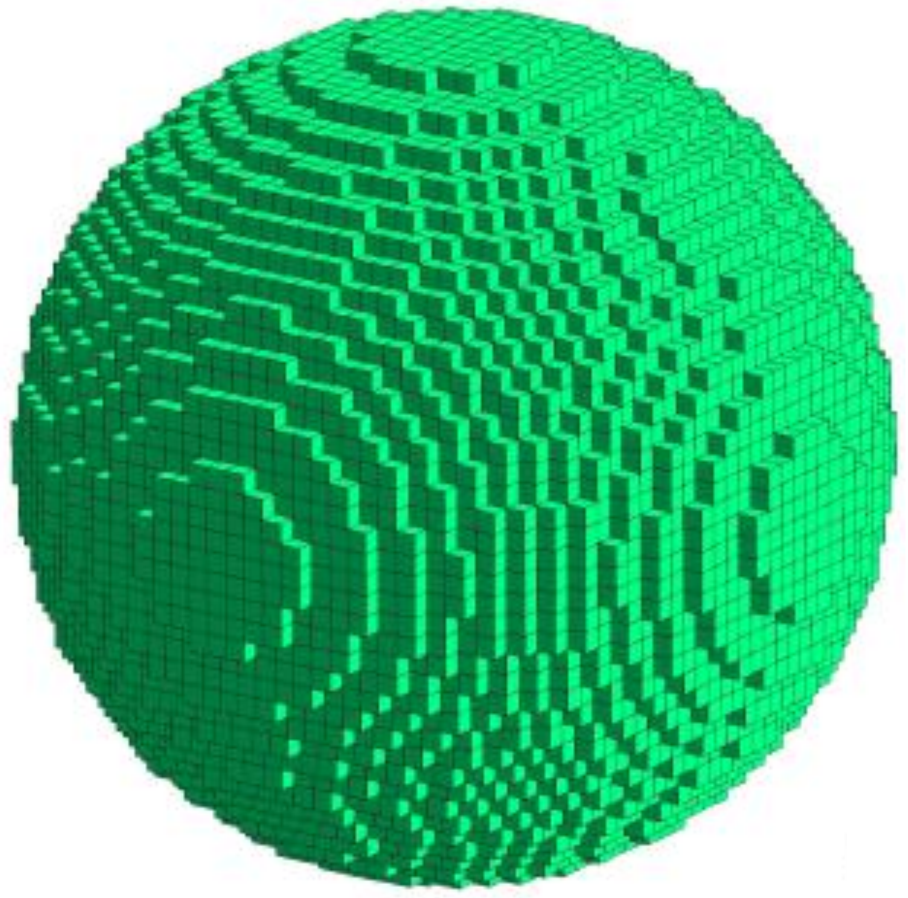
Anisotropy and Interaction within a fluid



A. W. Rodriguez, M. T. H. Reid, F. Intravaia, A. Woolf, D. A. R. Dalvit, F. Capasso, and S. G. Johnson, Phys. Rev. Lett. **111**, 180402 (2013).

FDTD vs FEM meshing

FDTD



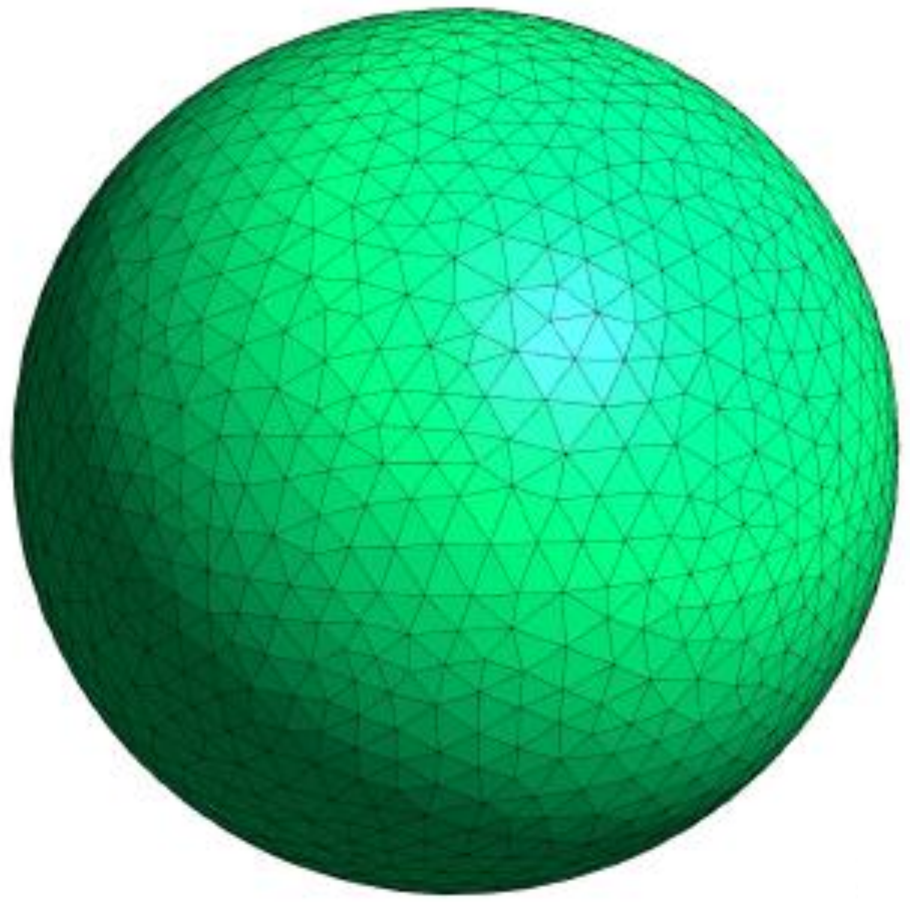
Structured mesh (Yee grid)

Aliasing

Staircase effects

Spatial accuracy

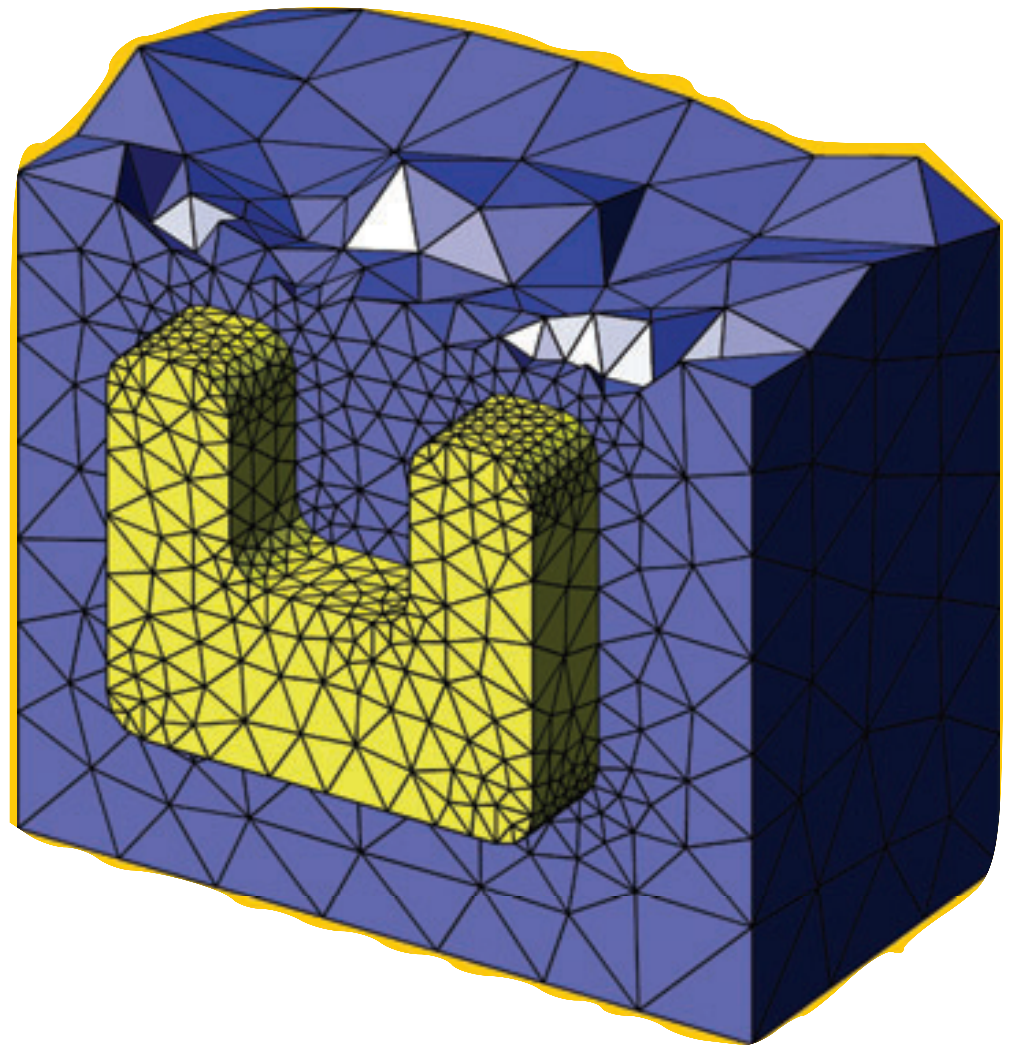
FEM



Unstructured mesh

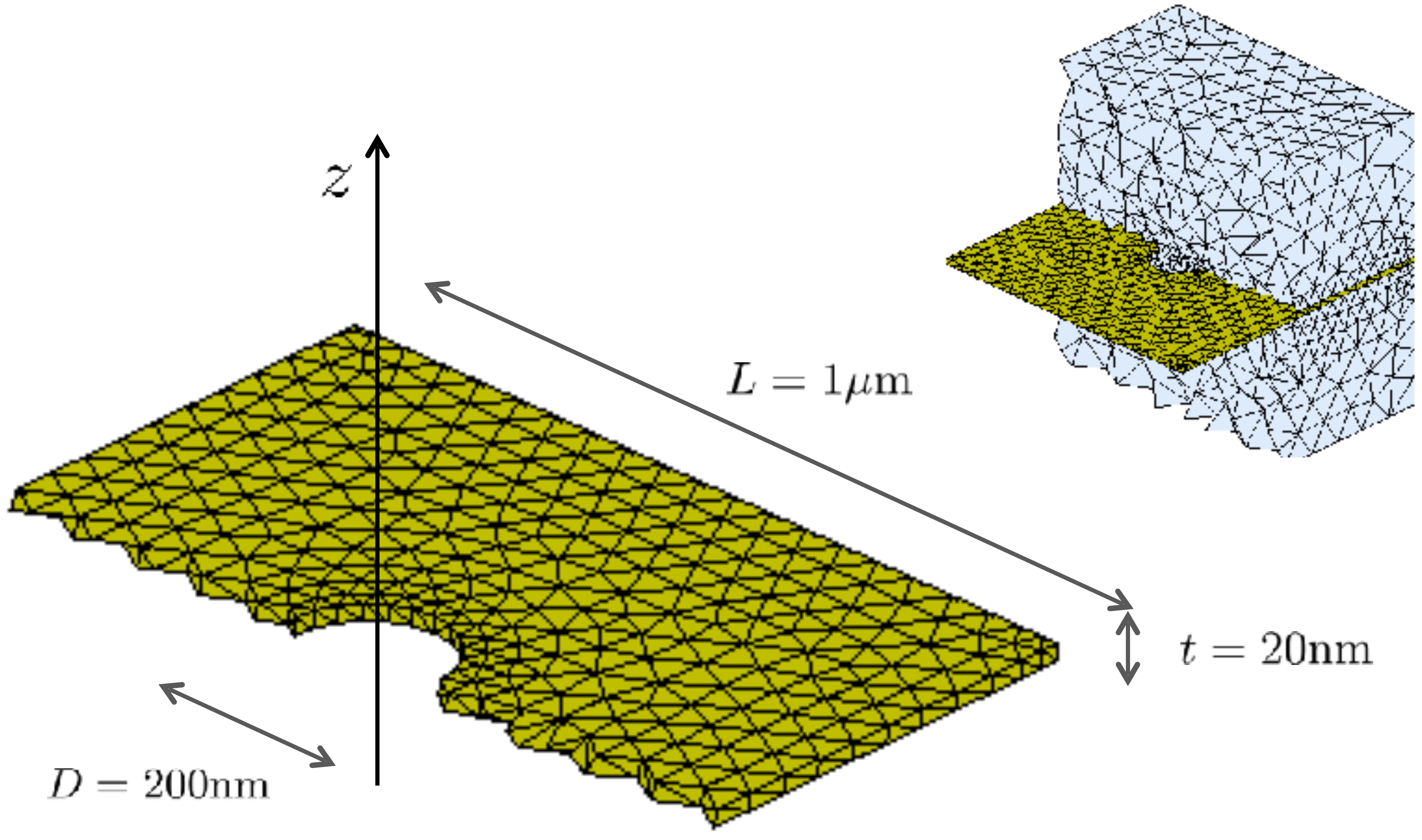
M. K. Berens, I. D. Flintoft, J. F. Dawson. IEEE **58**, 45-55 (2016)

Discontinuous **G**alerking **T**ime **D**omain **(DGTD)** method

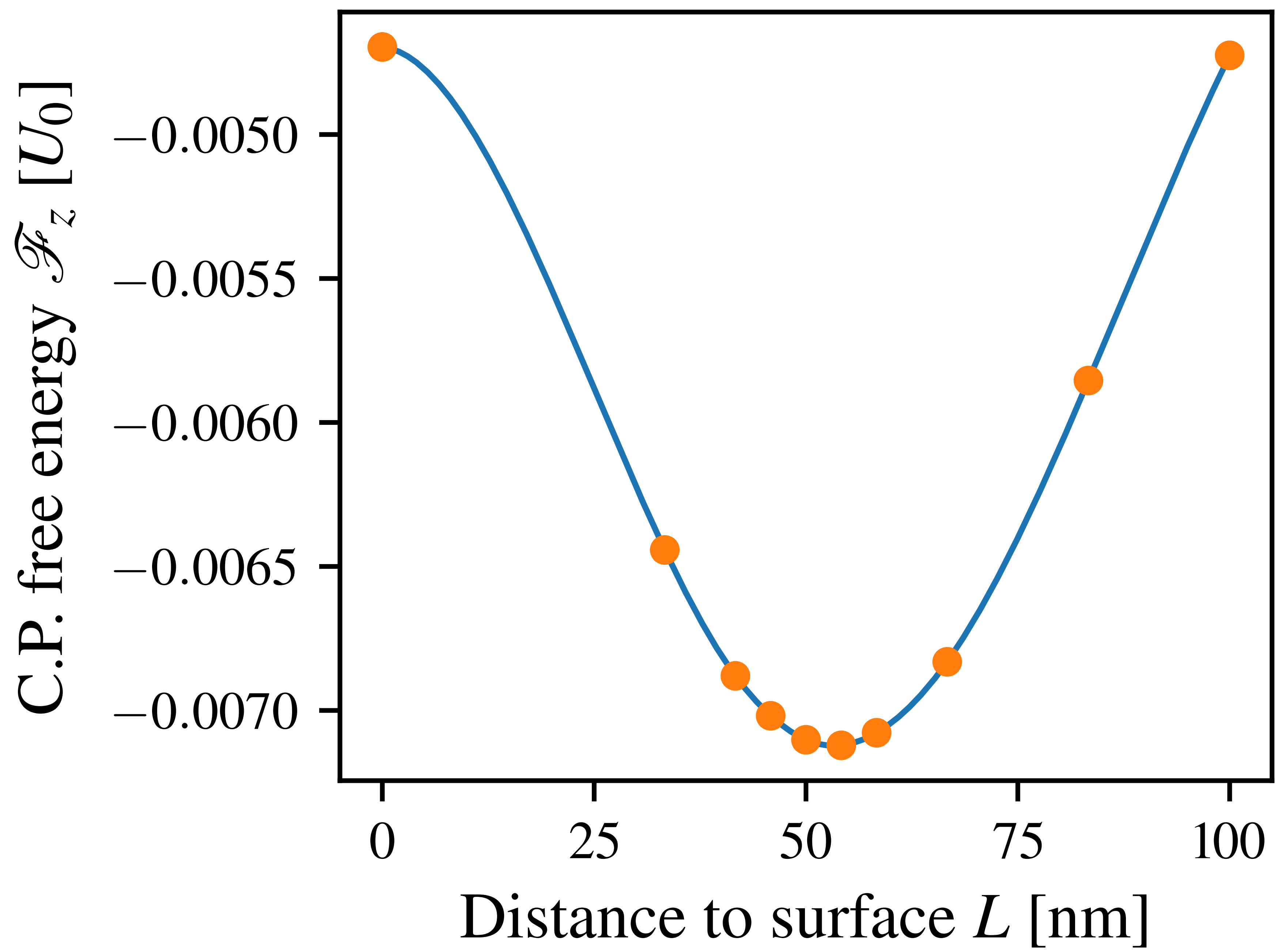


K. Busch, M. König, and J. Niegemann, Laser and Photonics Rev. **5**, 773 (2011).

Implementation with the DGTD



Courtesy of P. Kristensen



Using dispersive Drude model for gold:

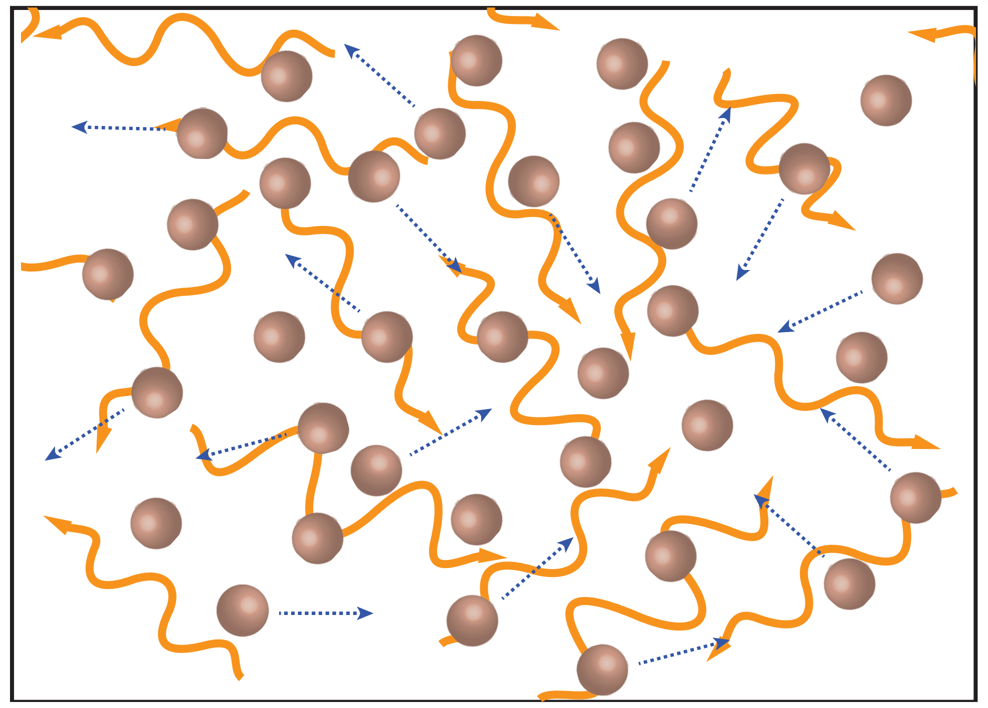
$$\epsilon_{\mathrm{Au}}(\omega) = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2 + \mathrm{i}\omega\gamma}$$

- Flexible
- Highly parallelizable

- **Efficient (Scattered field formulation)**
- **Highly accurate (Exponential convergence)**

P. Kristensen, B. Beverungen, F. Intravaia, K. Busch, to be submitted (2022)

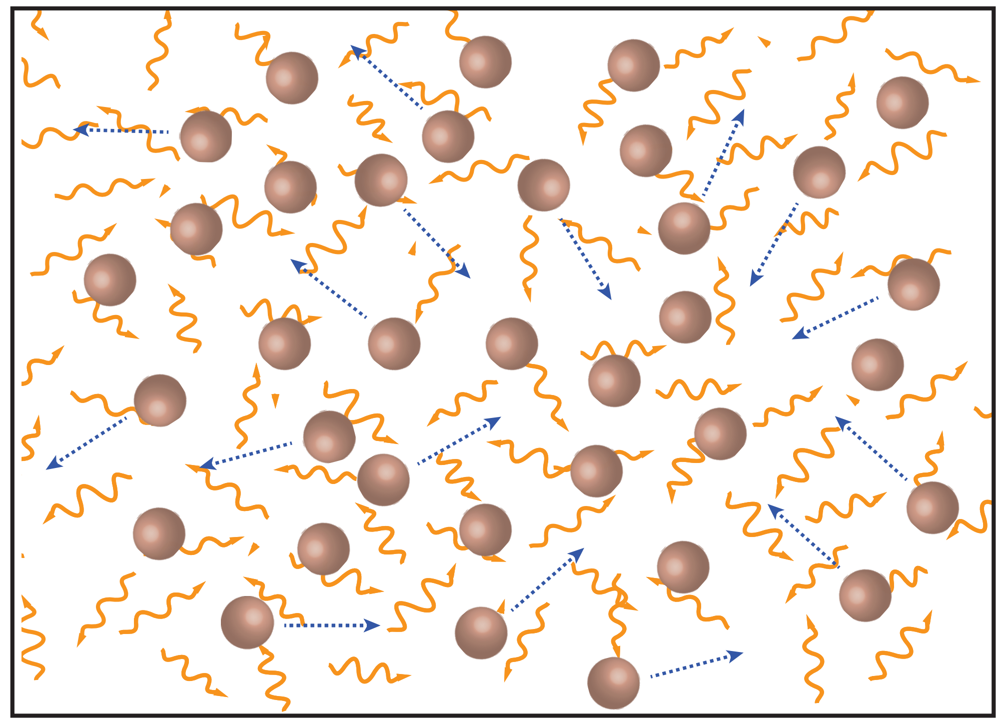
Including nonlocality



Local description

The radiation's wavelength is larger than electron's mean free path.

⇨ $\epsilon(\omega)$



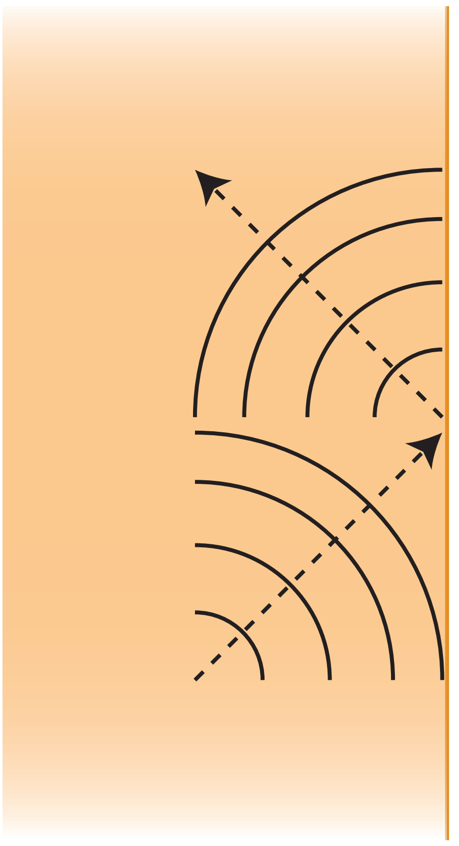
Nonlocality

The electromagnetic radiation can resolve the motion of the electrons.

⇨ $\epsilon(\omega, \mathbf{k})$

V. B. Svetovoy and R. Esquivel, The Casimir free energy in high- and low-temperature limits, J. Phys. A Math. Gen. 39, 6777 (2006).

Additional **B**oundary **C**onditions



Specular reflection at the interface (symmetry properties)

➡ Hydrodynamic model

T. V. Teperik et al., Phys. Rev. Lett. **110**, 263901 (2013).
S. Raza et al., Phys. Rev. B **84**, 121412 (2011).
P. J. Feibelman, Prog. Surf Sci. **12**, 287 (1982).

⇨ See Bettina Beverungen's Poster

P. Kristensen, B. Beverungen, F. Intravaia, K. Busch, to be submitted (2022)

(Talks by C. Henkel, G. Klimchitskaya, U. Mohideen, P. Maia Neto, J. Wang)

Frictional interactions

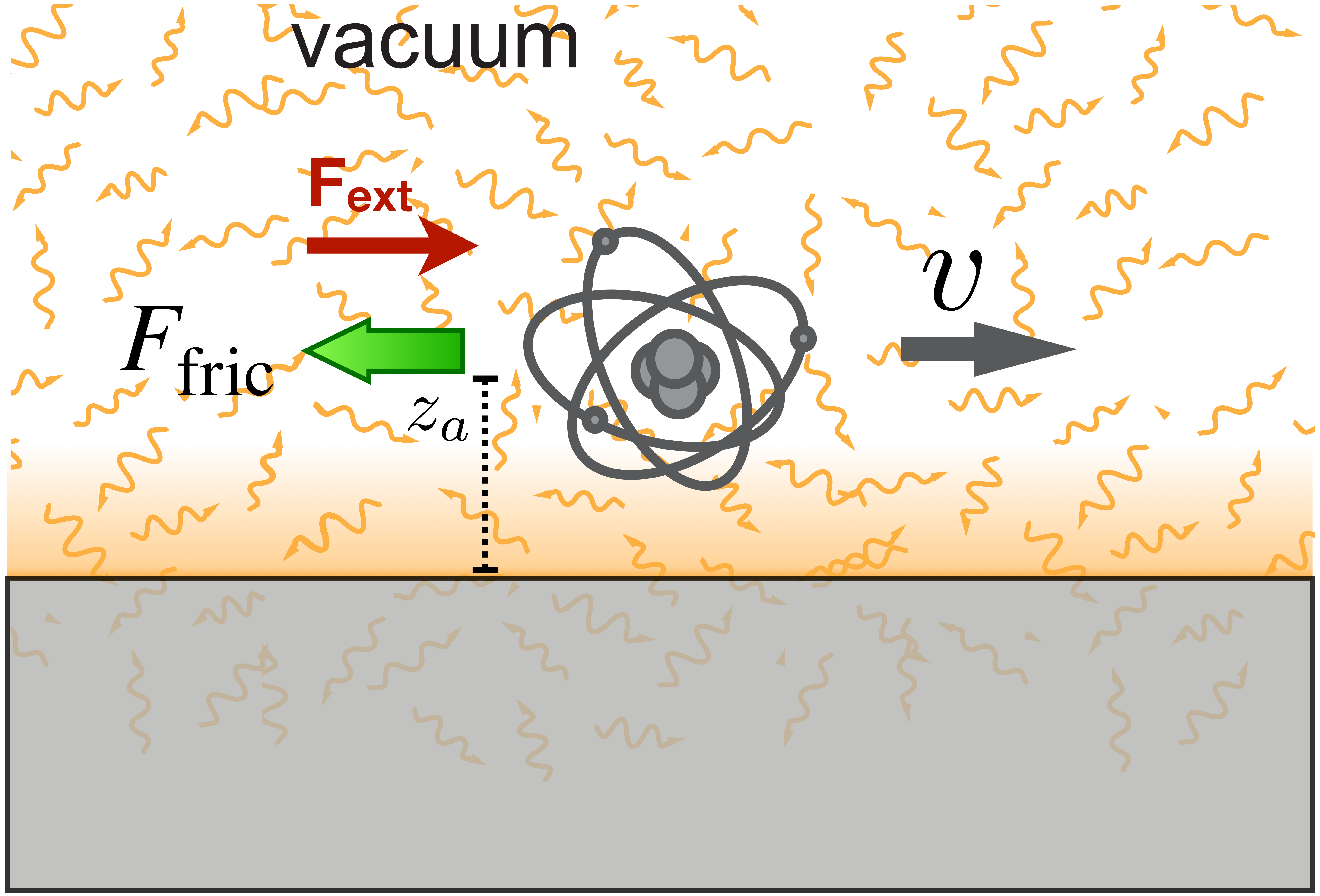
M. Oelschläger, D. Reiche, C. H. Egerland, K. Busch and F. Intravaia, arXiv:2110.13635 (2021)

(Talks by
K. Milton,
F. Lombardo,
R. Decca)

$T = 0$

Blackbody Friction

Quantum Friction



Near field

Dispersion
Dissipation

Some previous work on quantum friction

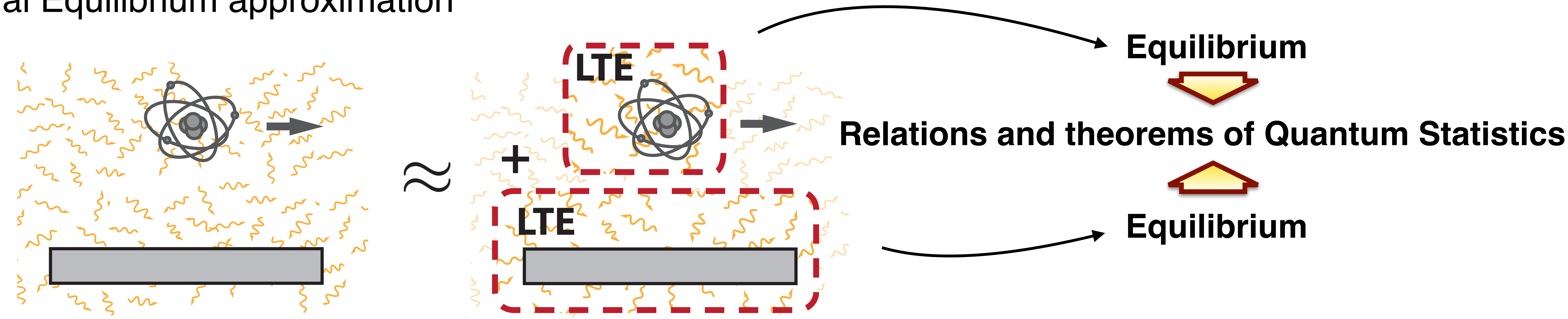
Authors	**Low velocity dependency**	**Distance dependency**	**Comments**
Mahanty 1980	**v**	z_a^{-5}	Approach similar to the calculations of vdW forces but with mistakes
Schaich and Harris 1981	**v**	z_a^{-10}	**Two-state atom** with a transition dipole moment normal to a metal surface
Scheel and Buhmann 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
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.

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)

Local Thermal Equilibrium approximation



Equilibrium

Relations and theorems of Quantum Statistics

Equilibrium

Our approach

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

Corrections to the LTE approximation

F. Intravaia, R. O. Behunin, C. Henkel, K. Busch, and D. A. R. Dalvit, Phys. Rev. Lett. **117**, 100402 (2016).

Low-velocity limit (T=0)

$$F_{\mathrm{fric}} \propto -\hbar \underline{\alpha}_0^2 \underline{\rho}^2 \frac{\boxed{v^3}}{\boxed{(2z_a)^{10}}}$$

(Ohmic materials)

(Local homogenesous materials)

$$F_{\mathrm{fric}} = F^{\mathrm{LTE}} + F^J$$

Local thermal equilibrium term ↗

↖ Nonequilibrium correction

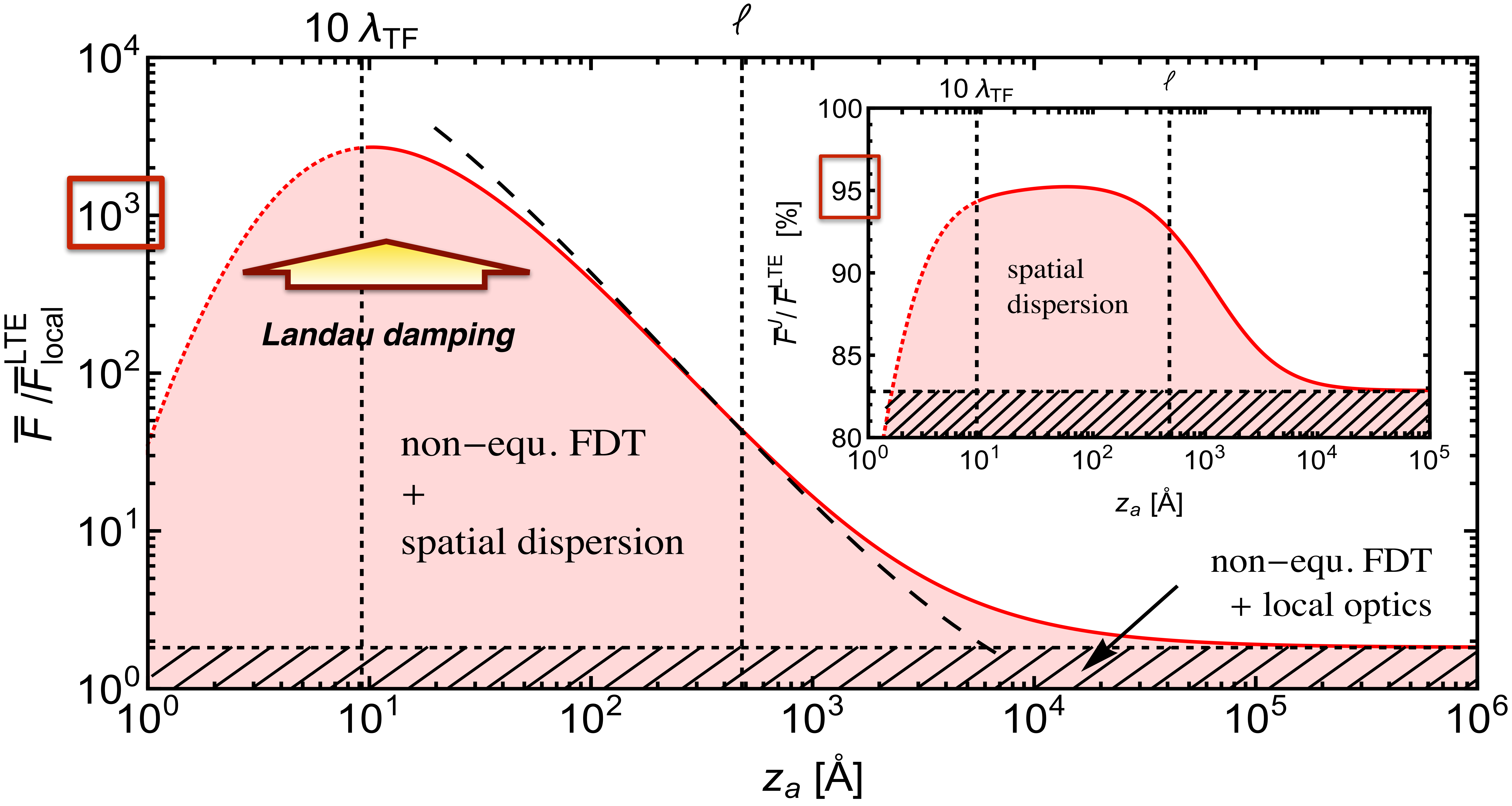
$$\frac{F^J}{F^{\mathrm{LTE}}} \approx 0.8$$

45% contribution to the force due to nonequilibrium

The frictional acceleration is weak

Nonlocality in quantum friction

D. Reiche, D. A. R. Dalvit, K. Busch and F. Intravaia, Phys. Rev. B **95**, 155448 (2017)
D. Reiche, M. Oelschla¨ger, K. Busch, and F. Intravaia, J. Opt. Soc. Am. B **36**, C52 (2019).
A. I. Volokitin and B. N. J. Persson, Rev. Mod. Phys. **79**, 1291 (2007).

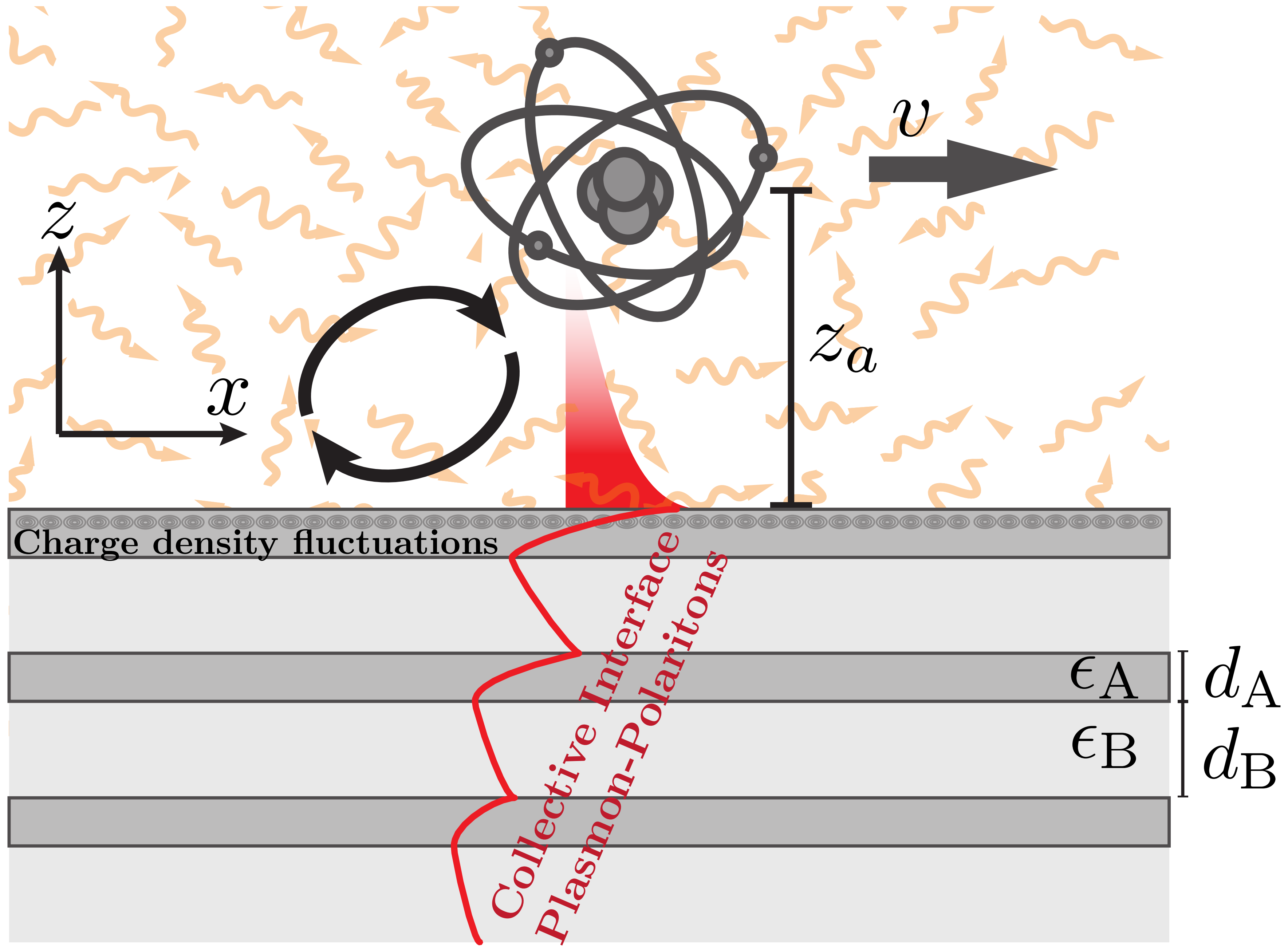


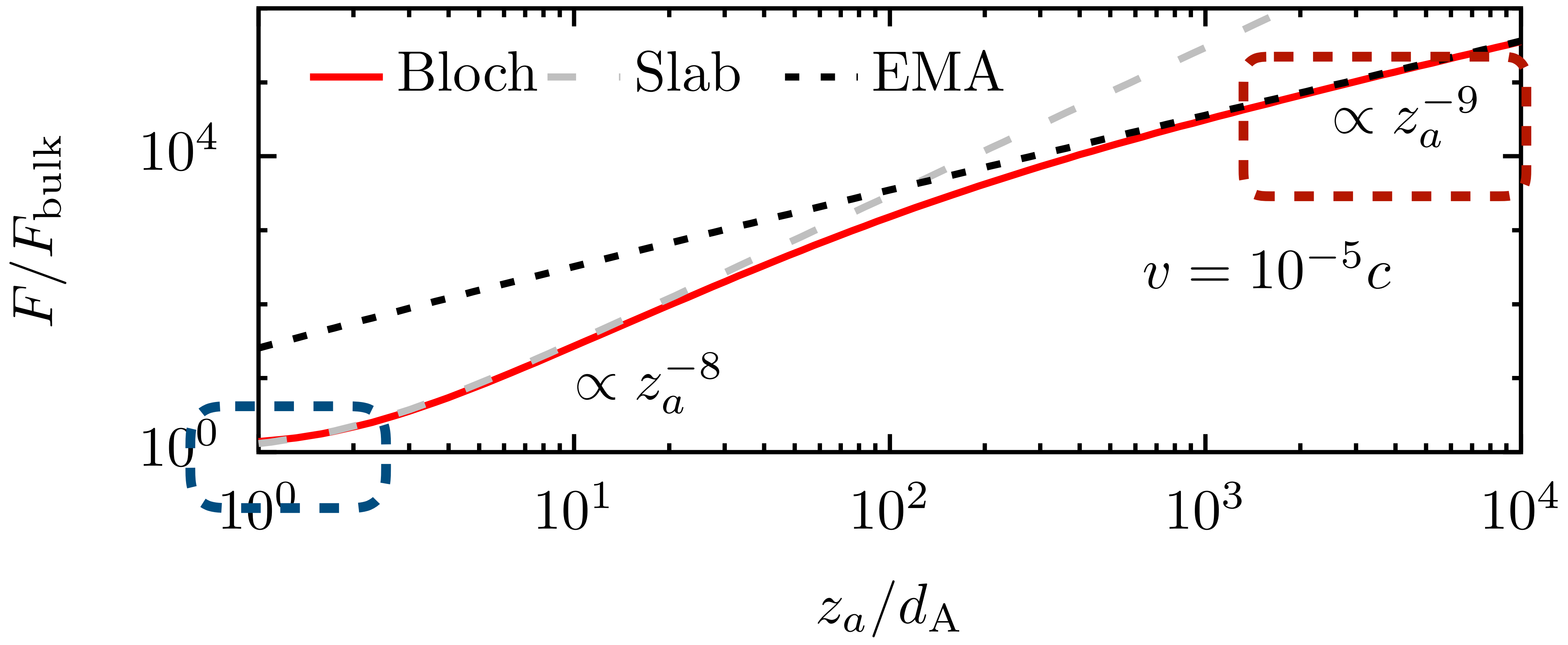
$$\frac{F^J}{F^{\mathrm{LTE}}} \approx 0.95$$

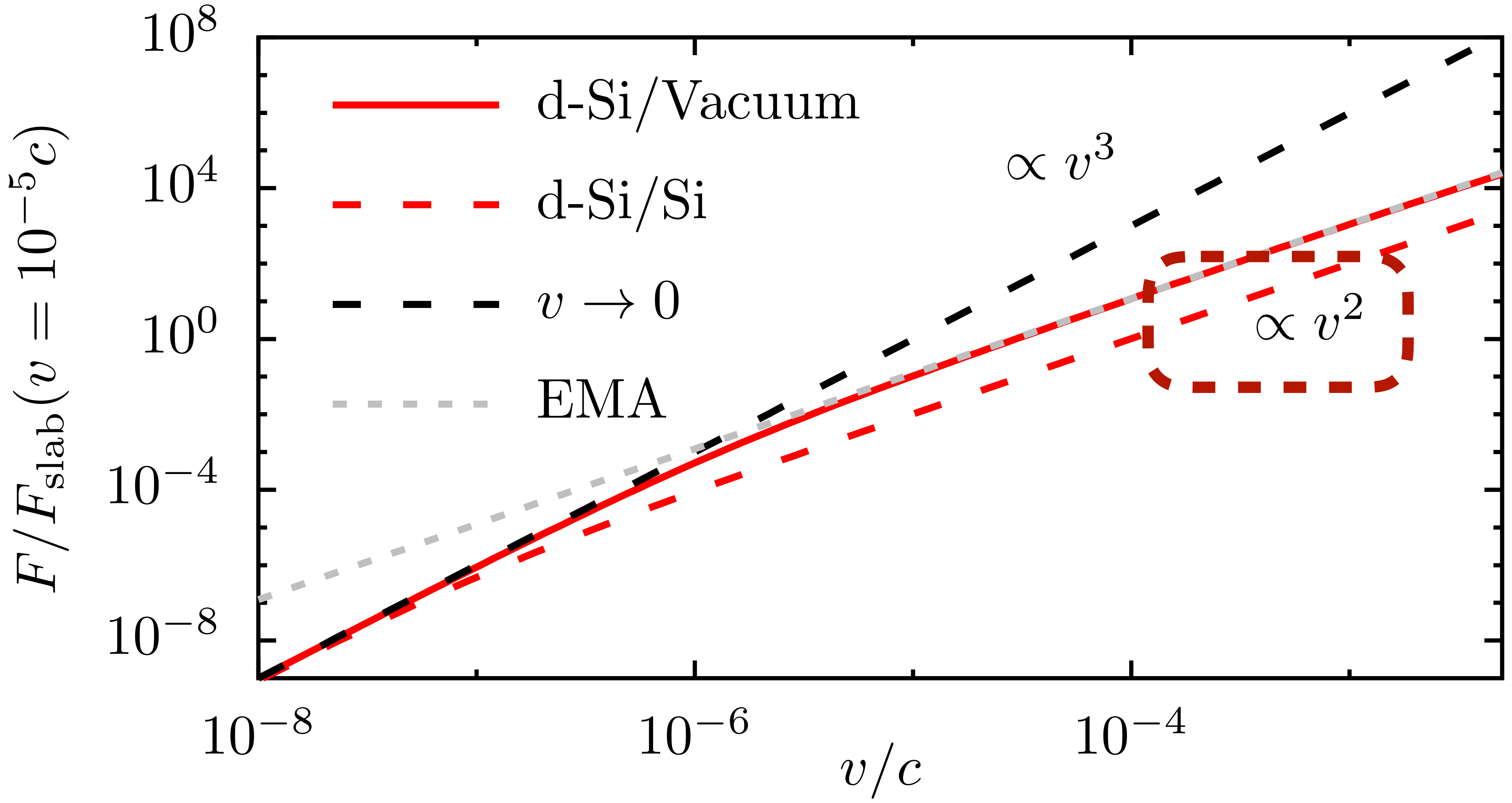
ℓ	Electron's mean free path
λ_{TF}	Thomas-Fermi screening length

Tuning the interaction

M. Oelschläger, K. Busch, and F. Intravaia, Phys. Rev. A **97**, 062507 (2018).





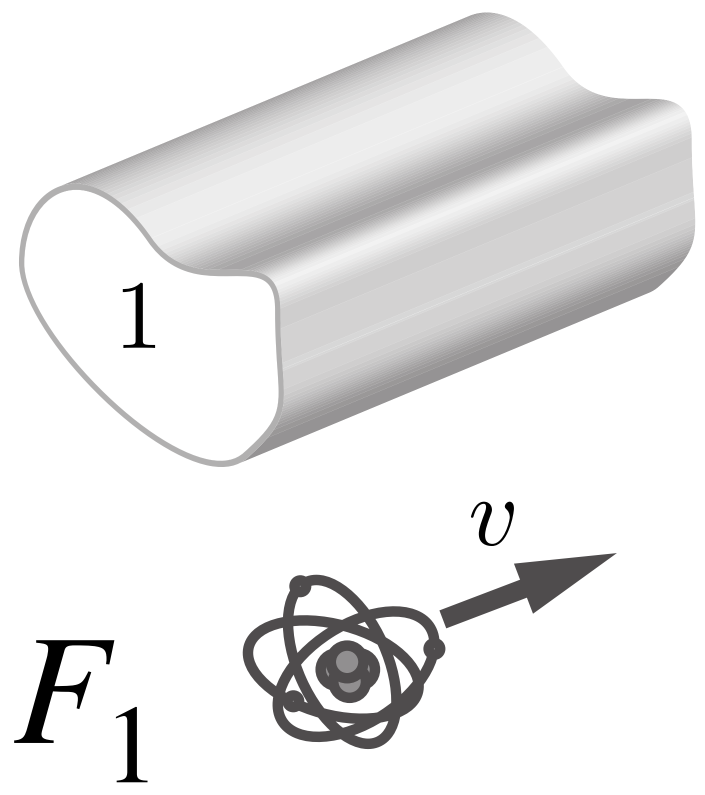


The properties of the medium can be controlled by changing the material and the geometry

Enhancing the interaction

D. Reiche, K. Busch, and F. Intravaia, Phys. Rev. Lett. **124,** 193603 (2020).

$T = 0$



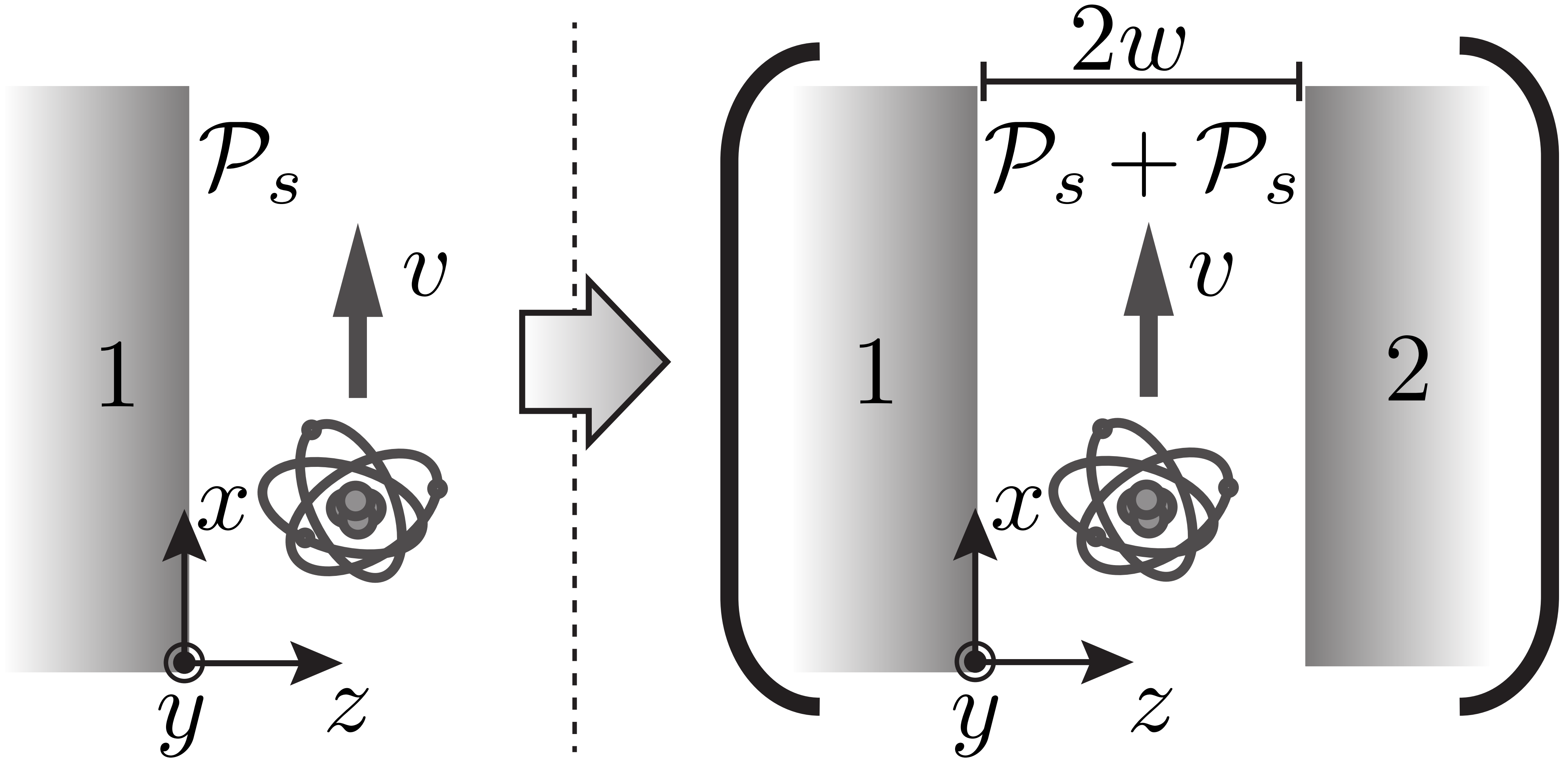
$$\xcancel{F \approx F_{\mathrm{add}} = \sum_{i=1}^{N} F_i \sim N F_1}$$ (symmetry)

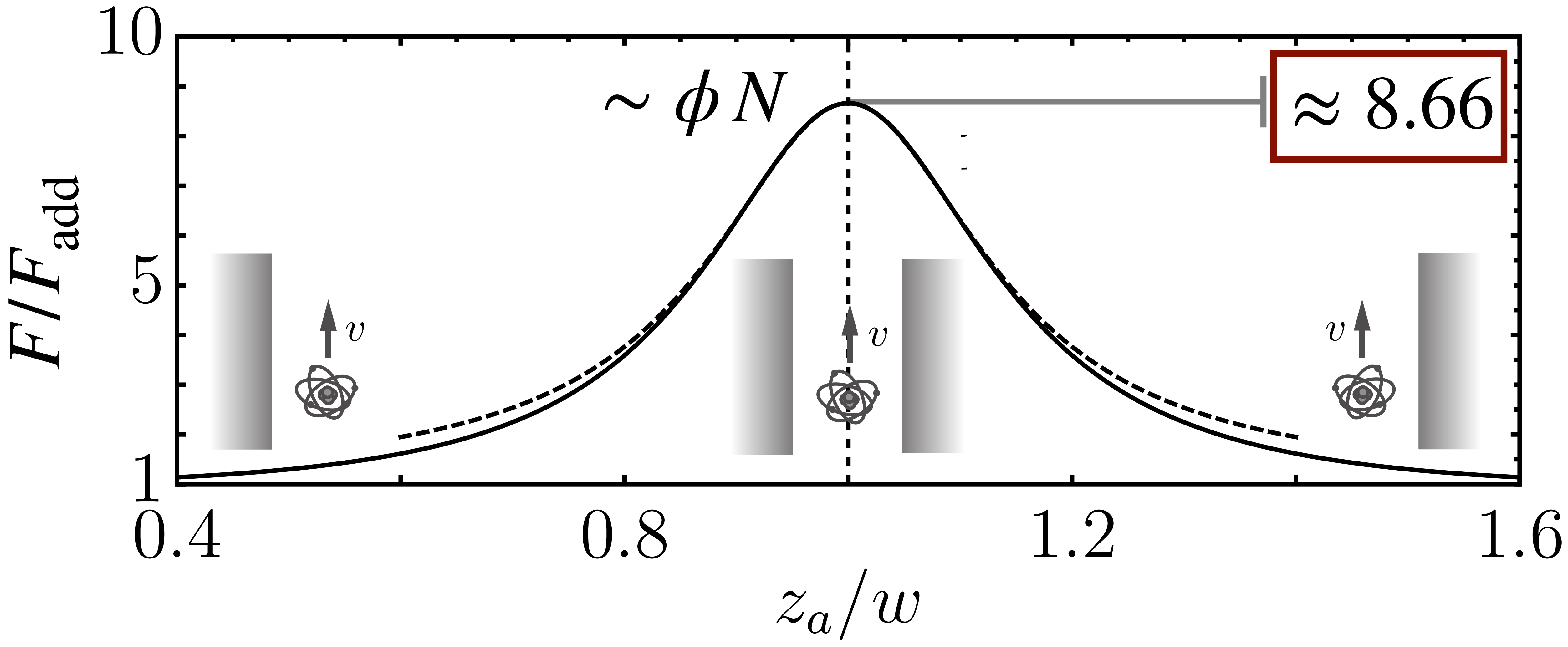
$$F \approx \phi \, N^2 \, F_1$$

An example: Atom in a cavity

D. Reiche, K. Busch, and F. Intravaia, Phys. Rev. Lett. **124,** 193603 (2020).

Planar cavity $(N = 2)$





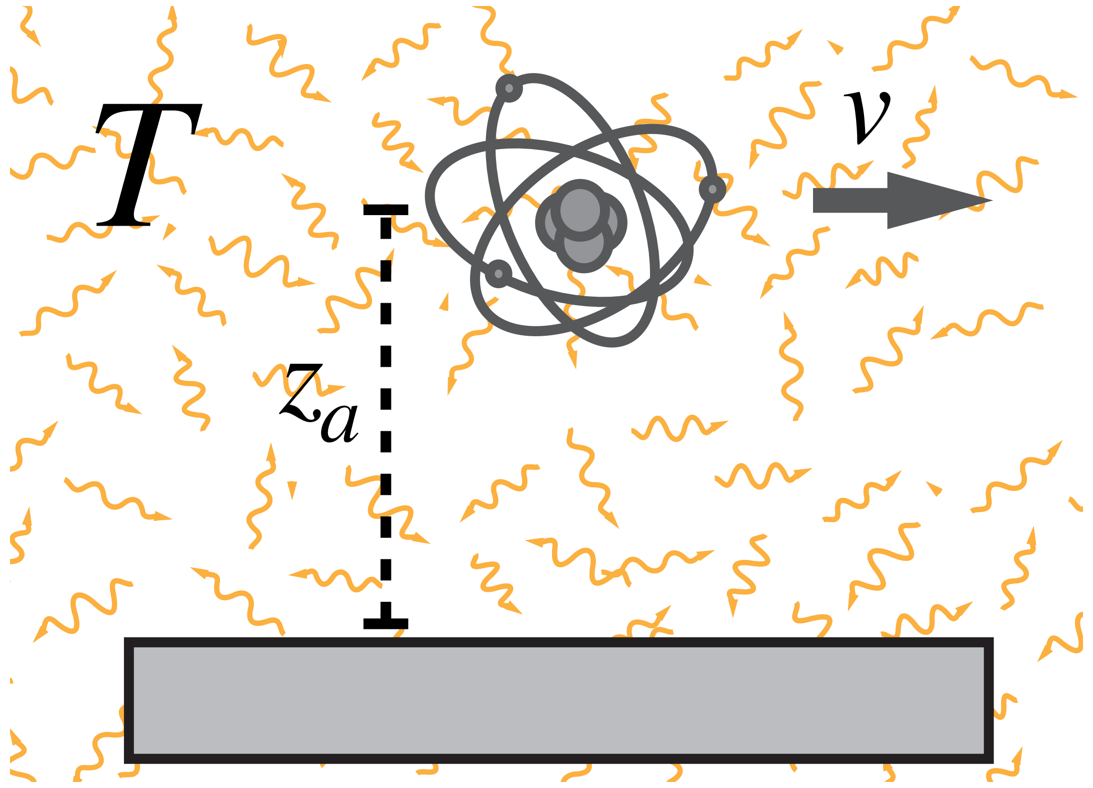
$$F_{\mathrm{add}} \sim 2 \times F_{\mathrm{surf}}$$

$$T = 0 \quad \Rightarrow \quad F \approx 17.3 \times F_{\mathrm{surf}}$$

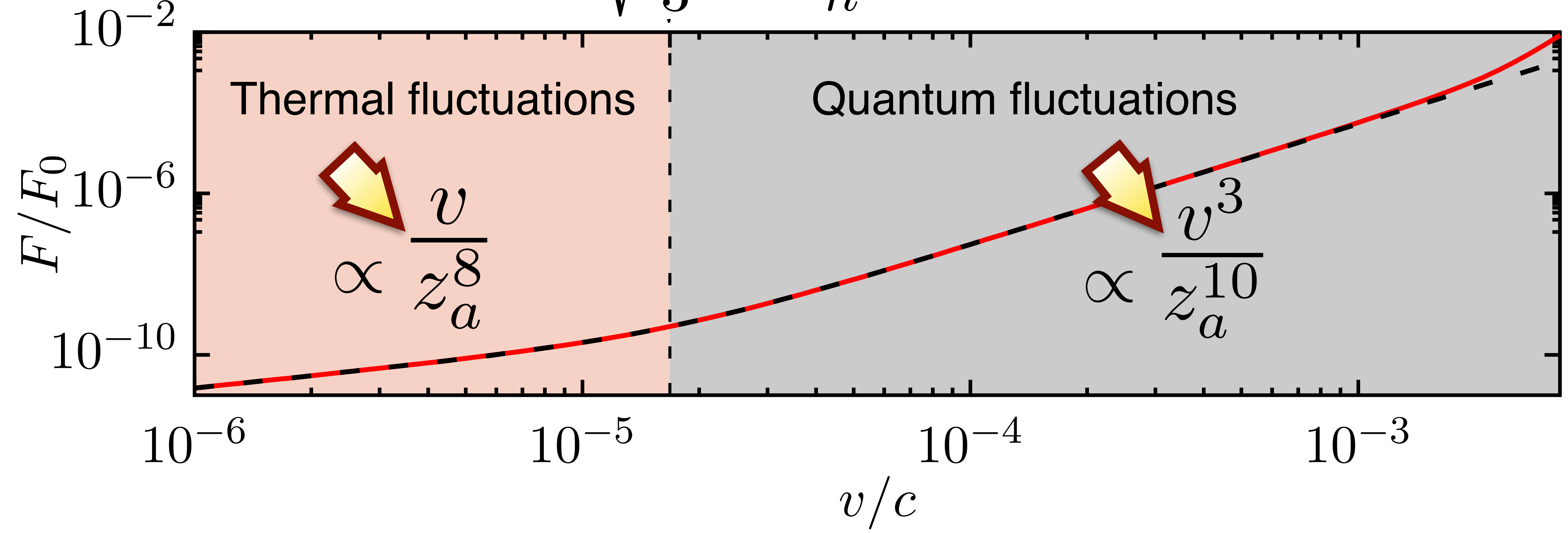
$$T \neq 0 \quad \Rightarrow \quad F \approx 11.6 \times F_{\mathrm{surf}}$$

Thermal Effects

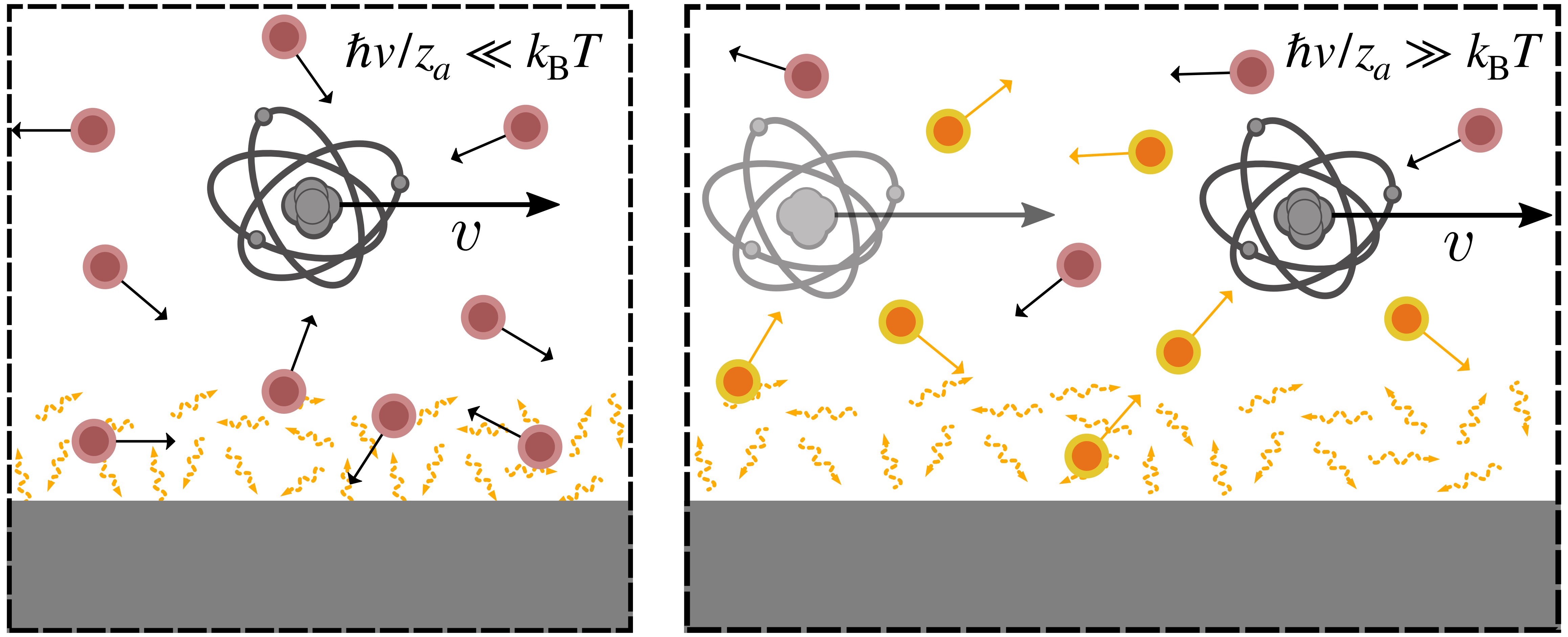
M. Oelschläger, D. Reiche, C. H. Egerland, K. Busch and F. Intravaia, arXiv:2110.13635 (2021)



$$v_c \equiv \sqrt{\frac{2}{3}}\pi \frac{z_a\, k_B\, T}{\hbar}$$

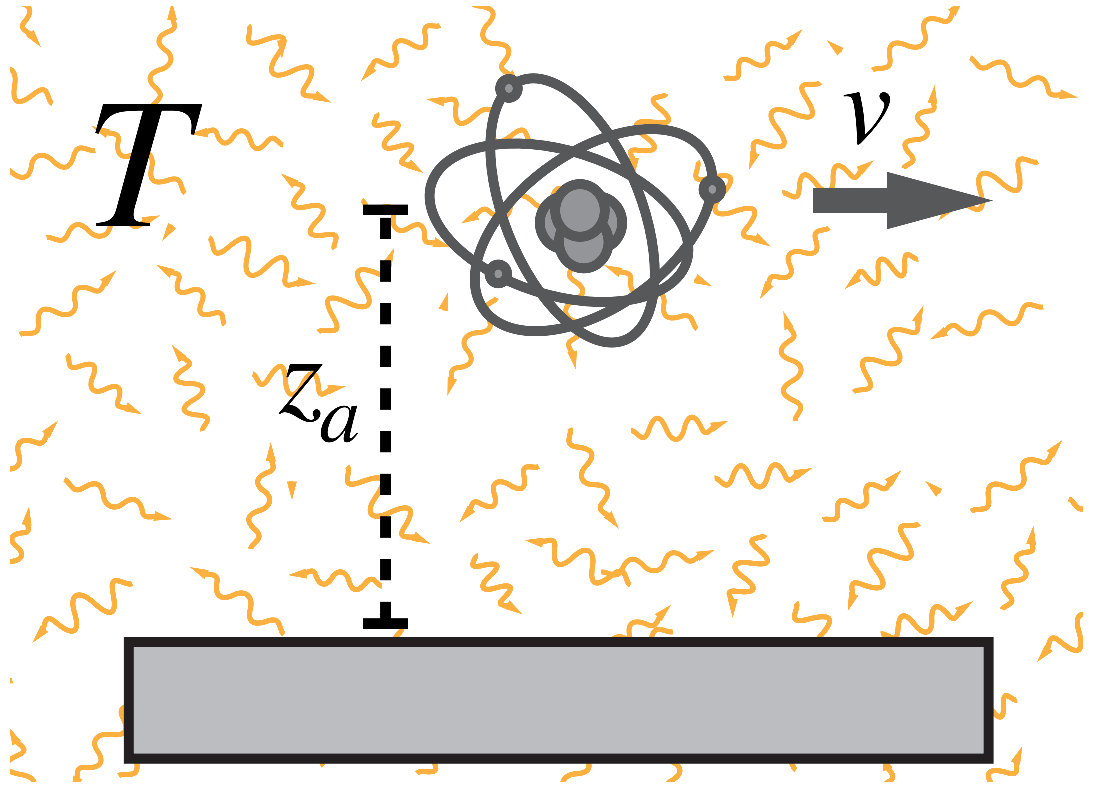


- The system becomes more "quantum" for high kinetic energy

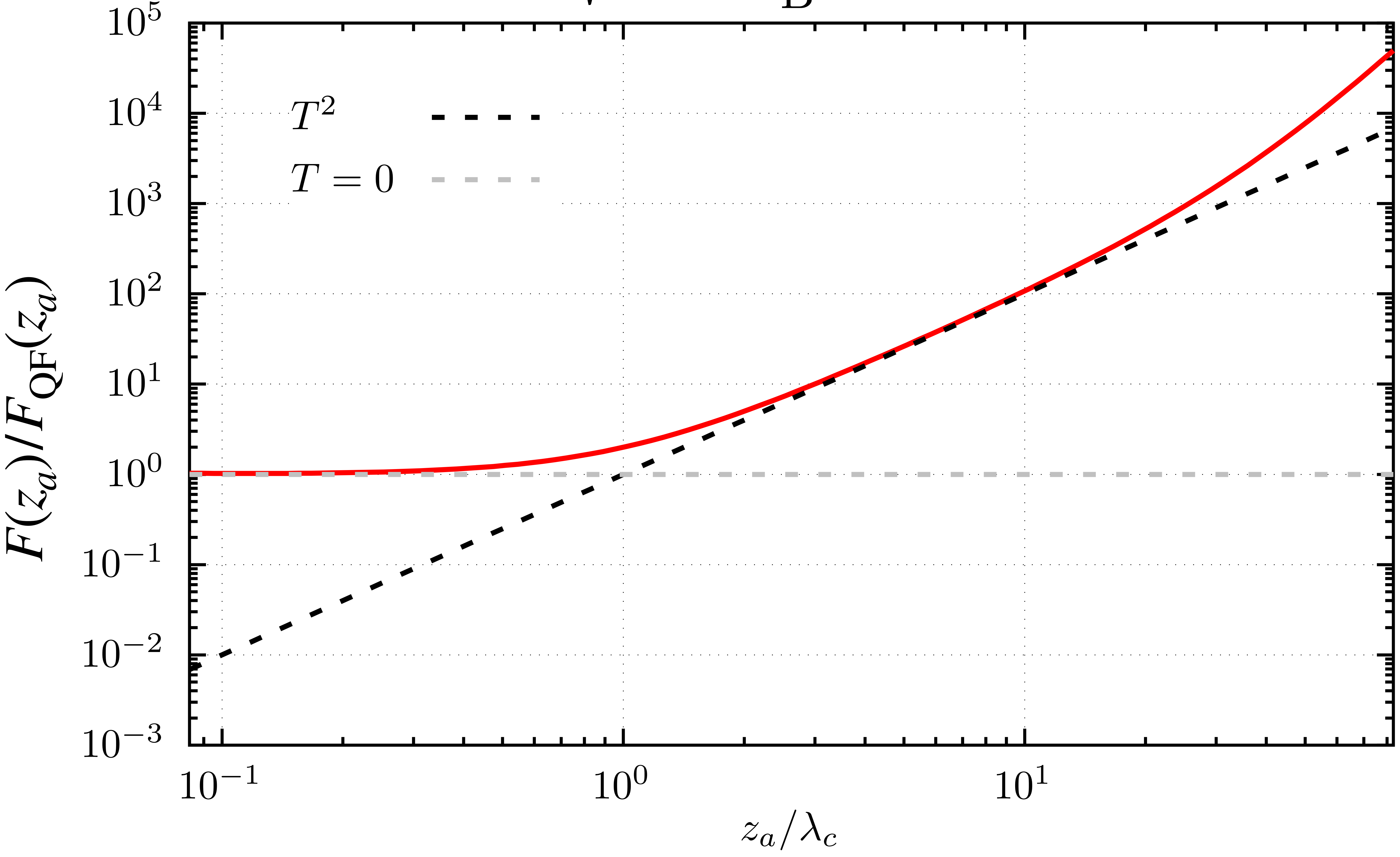


Thermal Effects

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



$$\lambda_c \equiv \sqrt{\frac{3}{2\pi^2}\frac{\hbar v}{k_\mathrm{B} T}}$$



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

Possible experimental setups

The frictional acceleration is weak

Litium: $a = 2.7\ \mu\mathrm{m/s}$

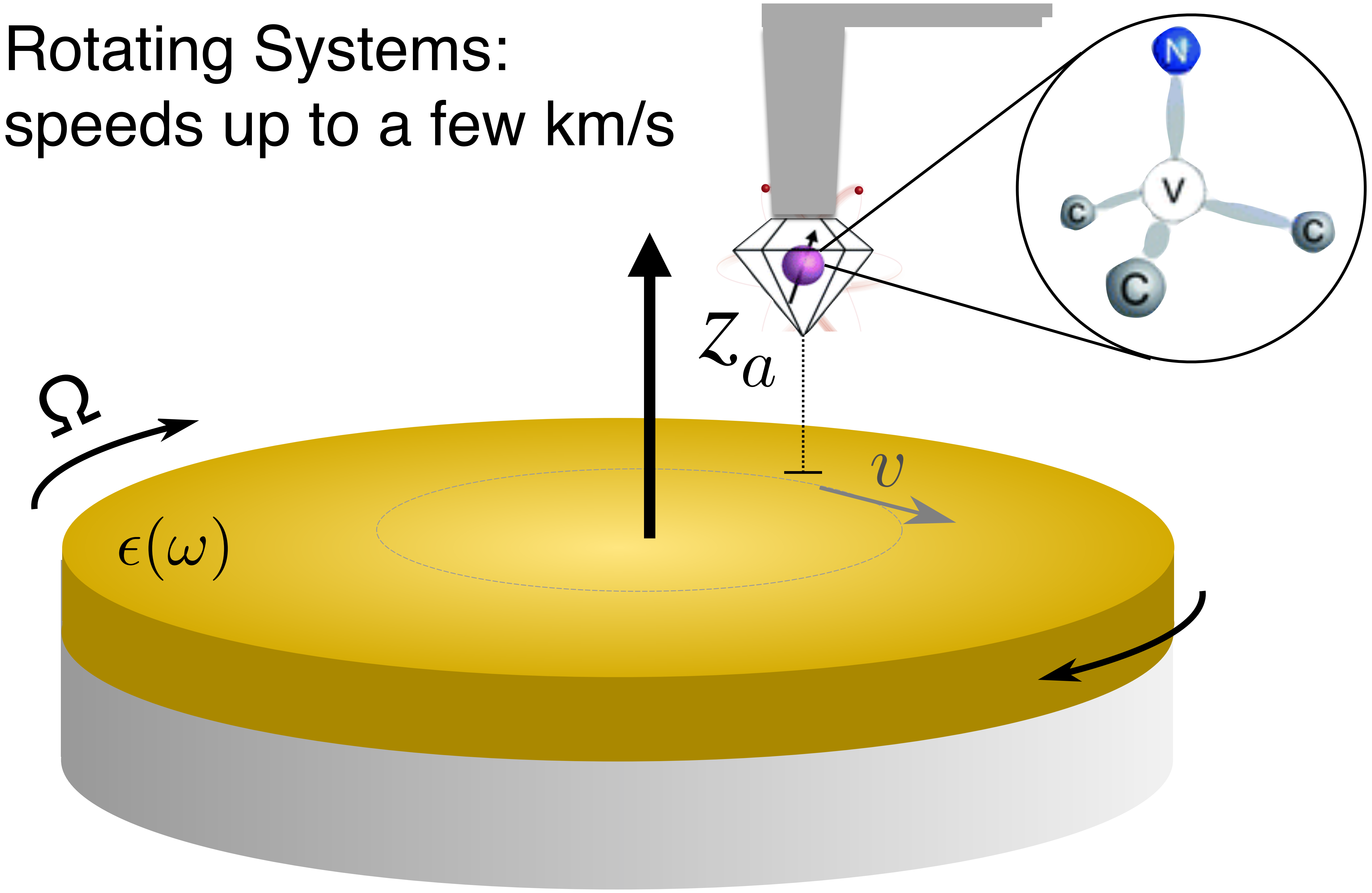
$z_a = 5$ nm

$\rho = 8 \times 10^{-7}\ \Omega\mathrm{m}$

$v \sim 10$ km/s

Atom interferometry

Rotating Systems:
speeds up to a few km/s



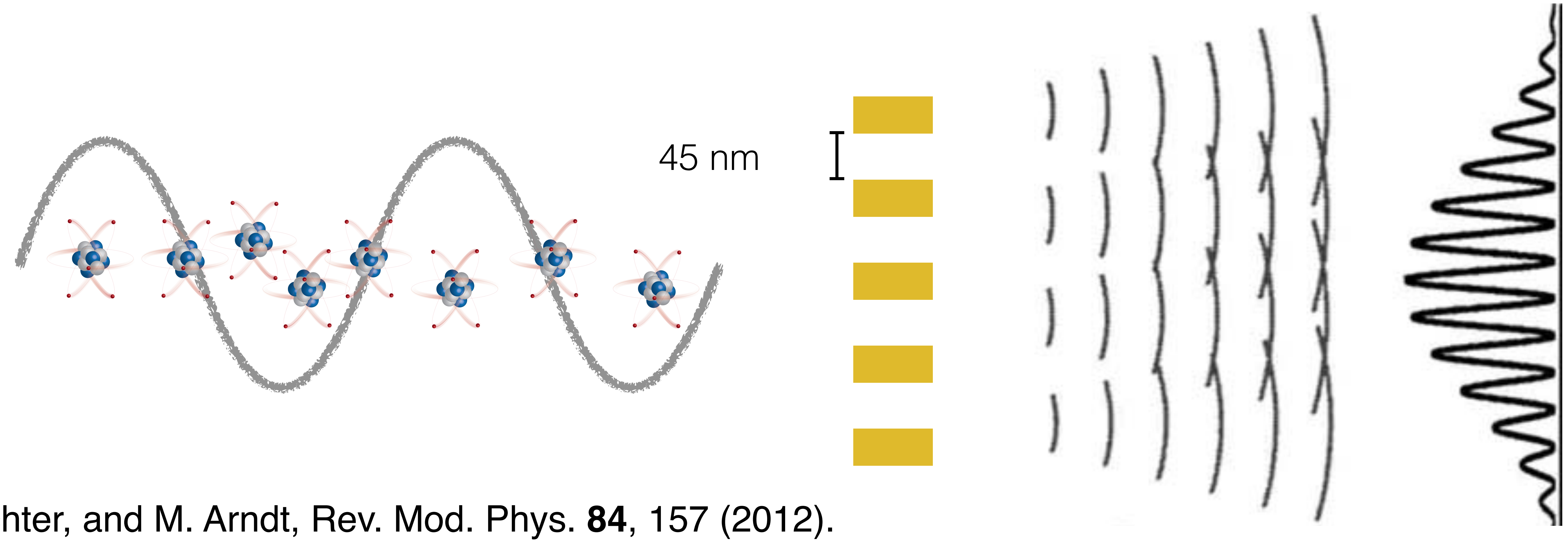
M. B. Farías, F. C. Lombardo, A. Soba, P. I. Villar, and R. S. Decca, npj Quantum Inf. **6,** 25 (2020).

Possible experimental setups

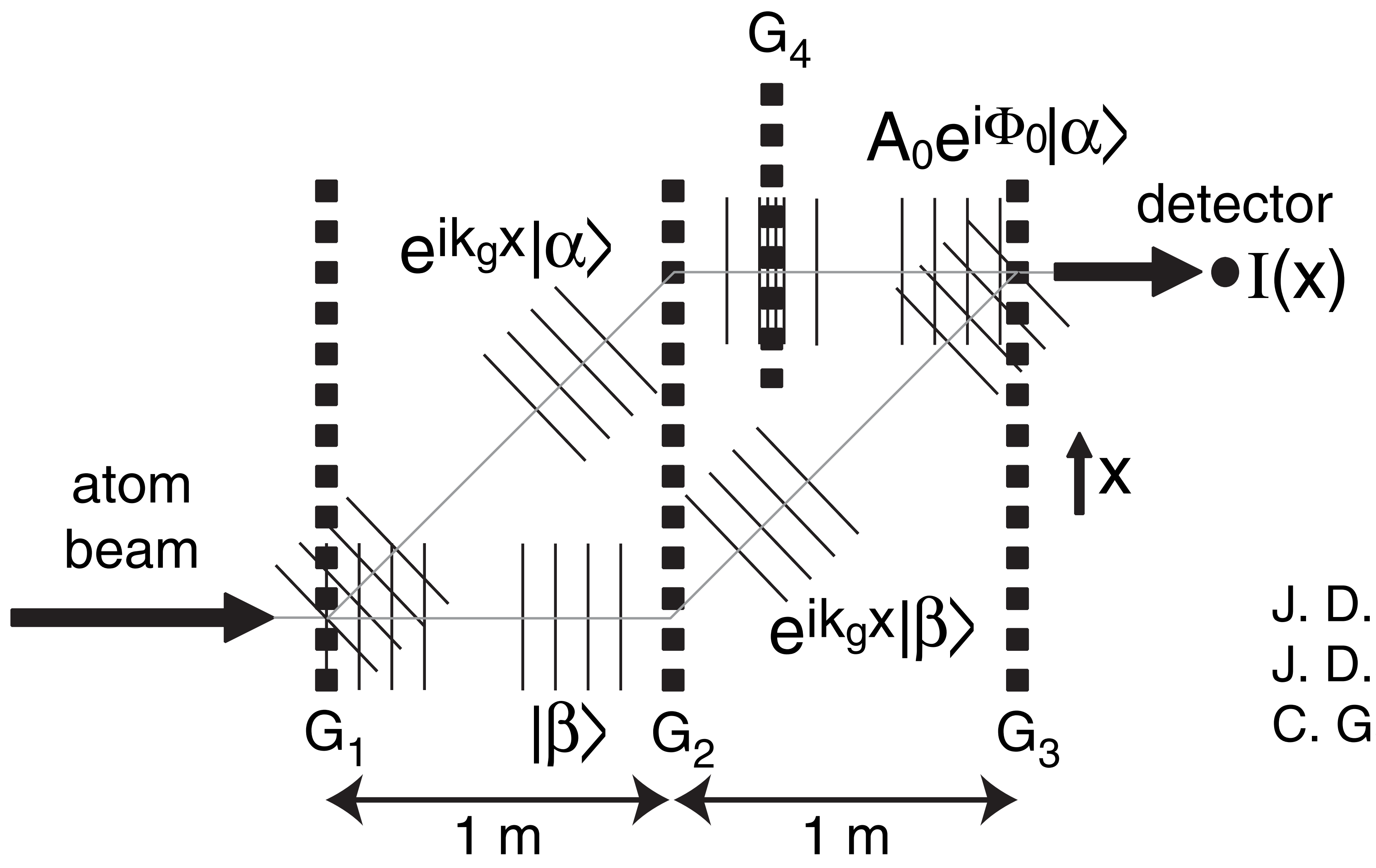
Matter-wave diffraction

v ~ 1-100 km/s

$$\lambda_{dB} = \frac{h}{mv}$$



K. Hornberger, S. Gerlich, P. Haslinger, S. Nimmrichter, and M. Arndt, Rev. Mod. Phys. **84**, 157 (2012).
C. Brand, M. Debiossac, T. Susi, F. Aguillon, J. Kotakoski, P. Roncin, and M. Arndt, New J. Phys. **21**, 033004 (2019).



Used to measure the
van der Waals / Casimir Polder force

J. D. Perreault and A. D. Cronin, Phys. Rev. Lett. **95**, 133201 (2005).
J. D. Perreault, A. D. Cronin, and T. A. Savas, Phys. Rev. A **71**, 053612 (2005).
C. Garcion, N. Fabre, H. Bricha, F. Perales, S. Scheel, M. Ducloy, and G. Dutier, Phys. Rev. Lett. **127**, 170402 (2021).

Summary

Equilibrium
Casimir Physics

- Alternative numerical approach to the calculation of the Casimir interaction
- Inclusion of interesting properties such as nonlocality.

Nonequilibrium
Casimir Physics

- The electromagnetic field can behave as a viscous medium for a particle moving with constant velocity.
- In the NESS the quantum frictional force can have a strong nonequilibrium contribution and can be tuned
- The frictional force ist strongly non-additive (good for experiments!).
- At finite temperature the interaction changes its behavior, when a critical velocity / distance is reached.