Quantum friction – field theory analysis

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merci à:
G. Barton
G. Pieplow

F. Intravaia & al,
J Phys Cond Matt 2015
[*arXiv*:1502.01117]

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Motivation

key concepts

lag between dipole and field (friction force in laser cooling)

energy conservation: excitations that escape (constant velocity drive)

outline

force on dipole (averaging)

literature results (material and particle modelling)

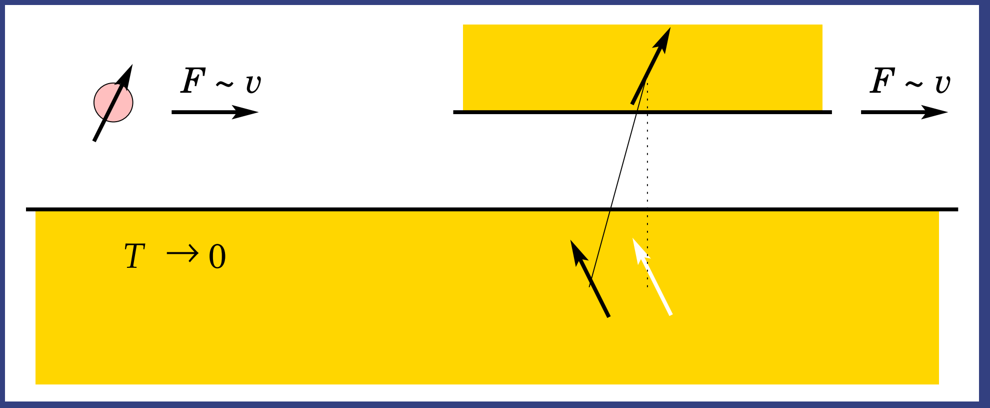
typical numbers, 'experimental' settings, 'clean AMO physics' (Stefan's: for Rb87 at 3nm: $< 10^3\,\mathrm{s}$ damping time) (Francesco: at $10^3\,\mathrm{m/s}$, time scale $> 10^9\,\mathrm{s}$)

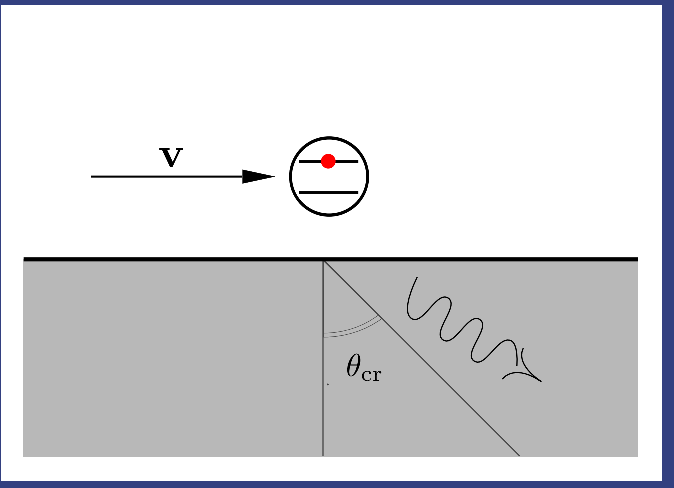
ordering of time scales, beyond perturbation theory

main point: 'transient' – excitation at launch

other point: low-frequency fluctuations

Two Pictures for Friction





delay between particle
and image dipole (surface charge)
• lateral force

zero friction above perfect conductor

excitations (photons . . .) leave the system
& energy conservation
– internal energy (“heat”)
– open boundaries

friction force vs power: $\mathbf{F}(\mathbf{v}) \cdot \mathbf{v} + P(v) = 0$

Discussion in the Literature

Ferrell & Ritchie 1980
Schaich & Harris 1981
Persson (& Volokitin) 1982...
Levitov 1989
Liebsch 1997
Despoja, Echenique, & Šunjić 2011

matter excitations
(electron-hole pairs ...)
carrier scattering

Teodorovich 1978
Polevoi 1990
Barton 1996...
Pendry 1998
Dedkov & Kyasov 1999...
Dorofeyev 1999...
Philbin & Leonhardt 2009...
Silveirinha 2013...

e.m. excitations
(plasmon-polaritons)
macroscopic QED

Fulling & Davies 1976
Unruh 1976
Barton 1991...
Braginsky & Khalili 1991...
Høye & Brevik 1992...
Jaekel & Reynaud 1992...
Maia Neto & Reynaud 1993...
Dodonov 2001 ...
Bei-Lok Hu & al 2003...
Passante & al 2007...

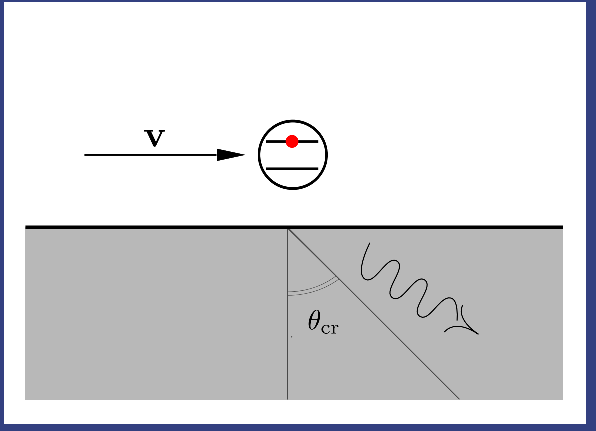
macroscopic objects
moving boundaries
scalar fields

Volokitin & Persson (*RMP* 2007)

Kardar & Golestanian (*RMP* 1999)

Buhmann (*Springer* 2012/13)

“Matters of Taste” – our Setting



neutral particle (atom, molecule, nano-object)

“macroscopic” distance $z \gg 1\,\text{Å}$

electron decoherence (Scheel & Buhmann 2012)

relativistic particle (Pieplow & Henkel 2013)

body with smooth surface: index n, $\varepsilon(\omega)$, $\mu(\omega)$

Discussion goes on ... friction $\mathbf{F}(\mathbf{v})$ as $T \to 0$

linear $\mathbf{F} \propto \mathbf{v}$

Schaich & Harris 1981

Scheel & Buhmann 2009...

Barton 2010...

Milonni 2013

cubic $\mathbf{F} \propto \mathbf{v}^3$

Polevoi 1990

Pendry 1998...

Dedkov & Kyasov 1999...

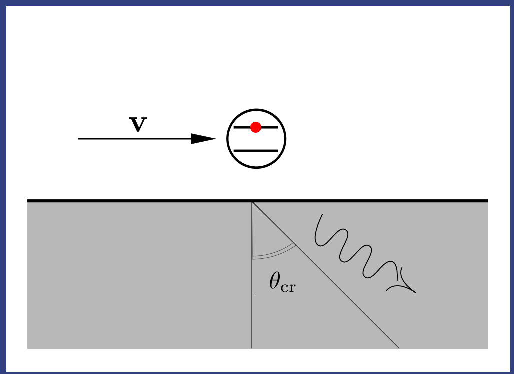
Høye & Brevik 2014...

zero quantum friction

Philbin & Leonhardt 2009...

this paper

"Matters of Taste" – our Setting



neutral particle

"macroscopic" distance $z \gg 1\,\text{Å}$

body with smooth surface

Discussion goes on ... a theorists' playground

linear $\mathbf{F} \propto \mathbf{v}$

Schaich & Harris 1981

Deceleration time

$\sim 10^3$ s for Rb87 @ 3nm

Milonni 2013

cubic $\mathbf{F} \propto \mathbf{v}^3$

Polevoi 1990

Time scale

$> 10^9$ s for Rb87 @ 10^3 m/s

Høye & Brevik 2014...

zero quantum friction

Philbin & Leonhardt 2009...

this paper

Quantum Field Theory – Barton's minimal model

Atomic levels $|g\rangle, \underbrace{|x\rangle, |y\rangle, |z\rangle}_{|\vec{\eta}\rangle \text{ or } |e\rangle}, \quad E_A = 0,\, \hbar\Omega$

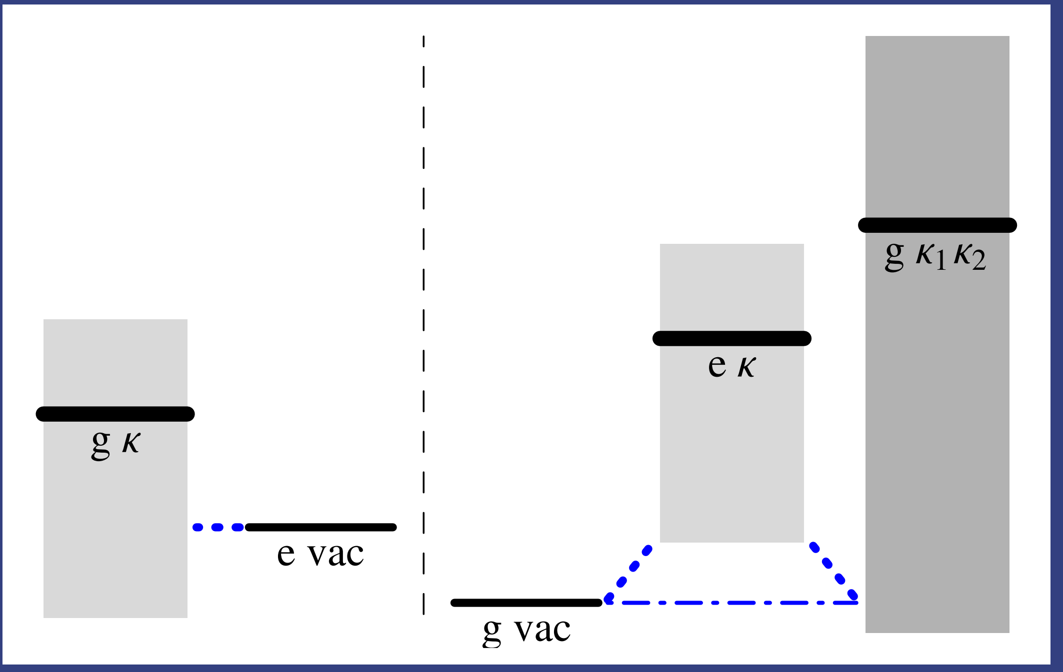
one-'photon' states $|\kappa\rangle = |\mathbf{k}, \omega\rangle$

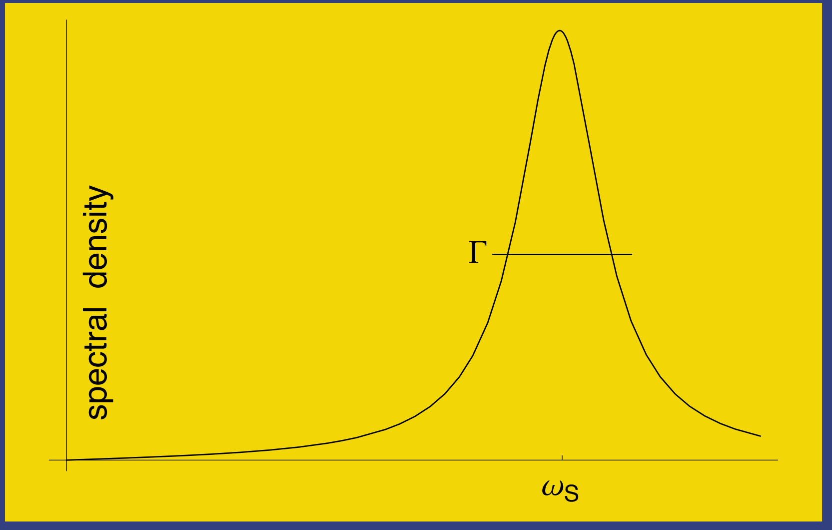
electric potential

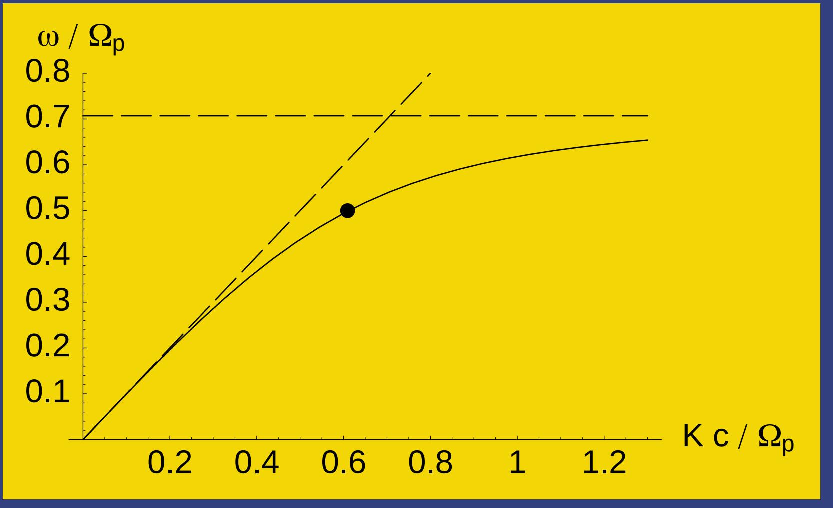
$$\phi(\vec{r}(t)) = \int \mathrm{d}\kappa\, \phi_\kappa\, \mathrm{e}^{\mathrm{i}\mathbf{k}\cdot\mathbf{r}(t)} \mathrm{e}^{-kz} a_\kappa \mathrm{e}^{-\mathrm{i}\omega t} + \mathrm{h.c.}$$

spectral density of surface plasmon polaritons

Barton (1970s … *New J Phys* 2010)

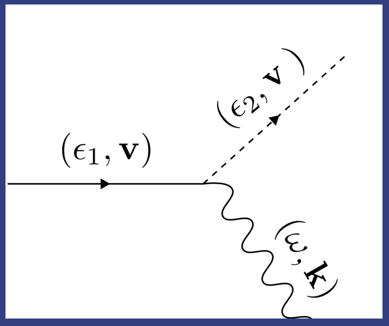




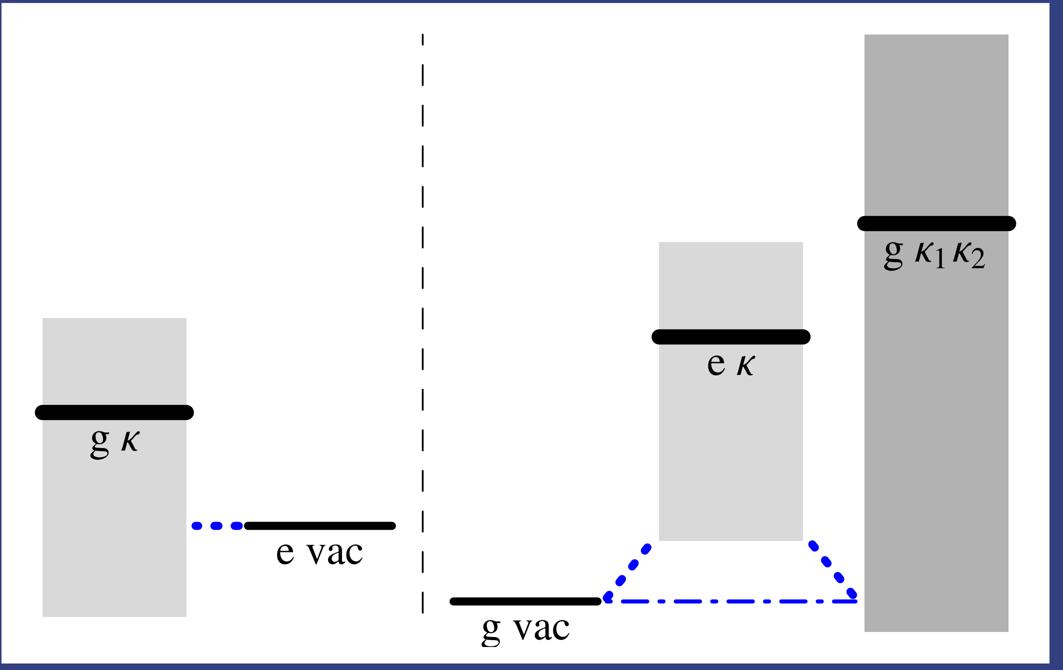


Time-dependent atom+field state

Atom+field coupling



$$V(t) = \vec{d} \cdot \vec{\nabla}\phi(\vec{r}(t))$$
$$\propto (|e\rangle\langle g| + |g\rangle\langle e|)\, (a_\kappa + a^\dagger_\kappa)$$



Standard perturbation theory

$$|\Psi(t)\rangle = \left(1 + c_0^{(2)}(t) + \ldots\right) |g\,\text{vac}\rangle$$
$$+ \int \mathrm{d}\kappa \left(c_1^{(1)}(t) + c_1^{(3)}(t)\right) |e\,\kappa\rangle \qquad \text{one-photon process}$$
$$+ \int \mathrm{d}\kappa_1\, \mathrm{d}\kappa_2\, c_2^{(2)}(t) |g\,\kappa_1 \kappa_2\rangle \qquad \text{photon pair creation}$$

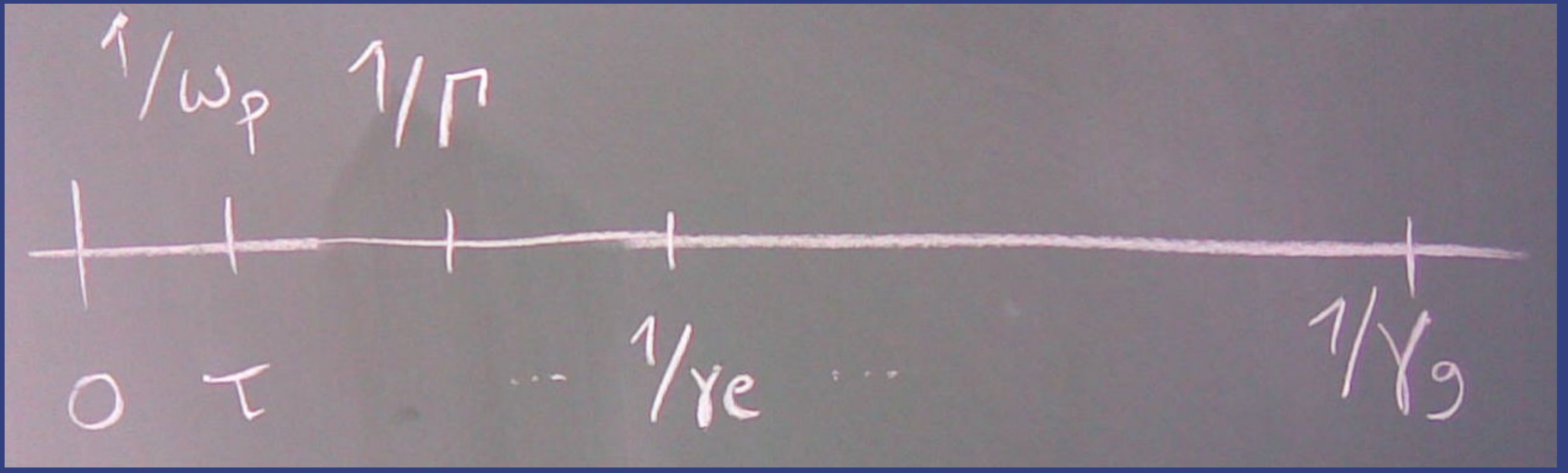
- tedious calculation
  for generic path $\mathbf{r}(t)$ at const. height z

Barton (*New J Phys* 2010)

Intravaia & al (*J Phys Cond Matt* 2015)

challenge: capture long-time state, constant velocity

Relevant time scales



acceleration time τ = "launch"

Barton: $\tau = 0$ 'instantaneous'

surface response $1/\omega_S, 1/\Gamma$ = "image delay"

...

atomic lifetime $1/\gamma_e$ = "resonant decay"

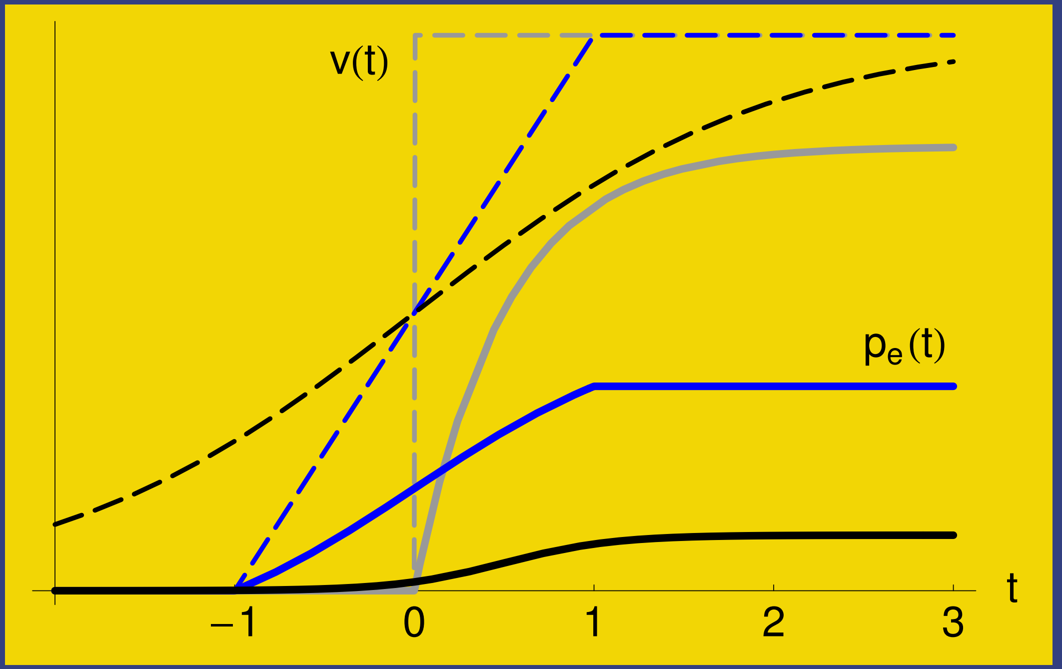
...

quasi-stationary state

...

spontaneous excitation $1/\gamma_g$ = "Cherenkov process"

Barton's transient = excitation after launch



three launches: "kick-start" vs "smooth"

excitation probability

$$p_e(t) = \int \mathrm{d}\kappa \, |\langle e\kappa|\Psi(t)\rangle|^2$$

- virtual ("dressed $|g\rangle$") + real excitation

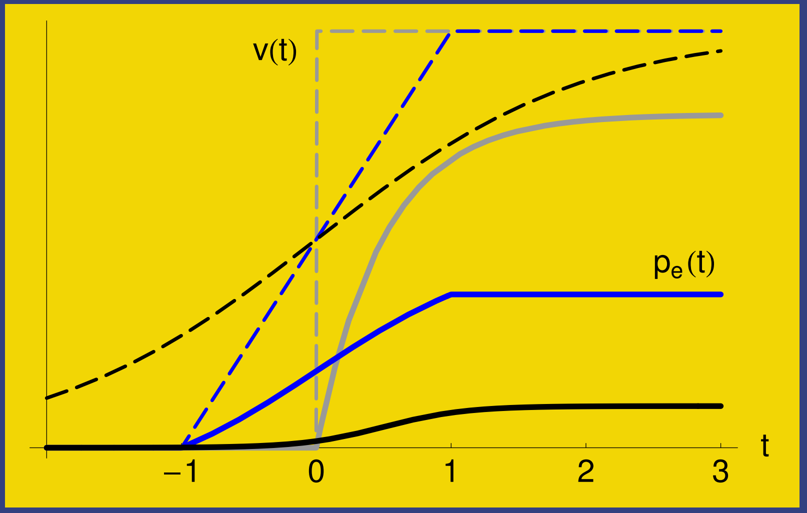
$$= \int \mathrm{d}\kappa \, |c_1^{(1)}(t) + c_1^{(3)}(t)|^2$$

excitation $\propto v^2 S_a(\tau)^2$ acceleration spectrum

Barton & Calogeracos (*J Phys A* 2008)

Passante & co-w (*Phys Lett A* 1983...)

Barton's transient = excitation after launch



excitation probability

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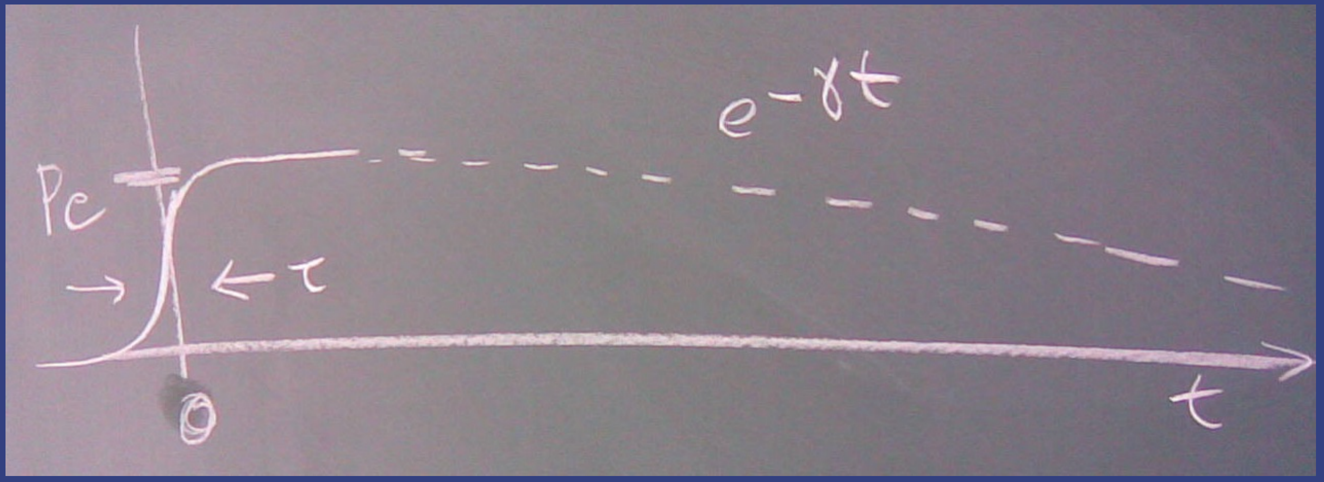


spontaneous decay relevant for power balance

$$P_{\rm sp} \sim -\hbar(\Omega + \omega_S) p_e(\text{real}) \gamma_e$$
$$\propto -v^2$$

- compensates linear friction

Review of Barton's Results

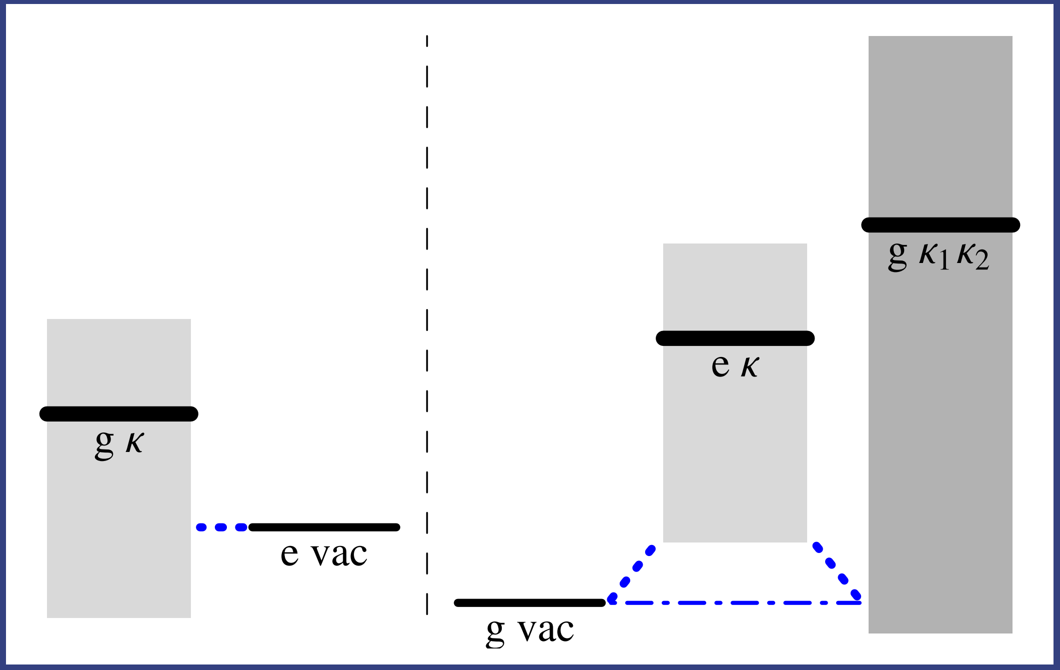
Barton (*New J Phys* **12** (2010) 113045)

Two-photon power $g \to g + h\nu_1 + h\nu_2$

$$P_2 = \int \mathrm{d}\kappa_1\, \mathrm{d}\kappa_2\, \hbar(\omega_1 + \omega_2) \frac{\mathrm{d}}{\mathrm{d}t} |c_2(t)|^2$$
$$= (P_A \propto v^4) + (P_B \propto v^2)$$

process 'A': resonance condition $0 = \omega_1 - \mathbf{k}_1 \cdot \mathbf{v} + \omega_2 - \mathbf{k}_2 \cdot \mathbf{v} = \omega_1' + \omega_2'$

process 'B': $\Omega = \omega_1 - \mathbf{k}_1 \cdot \mathbf{v}$ resonant decay



One-photon + excitation power

$g \to e + h\nu$

$$P_1 = \int \mathrm{d}\kappa\, \hbar(\Omega + \omega) \frac{\mathrm{d}}{\mathrm{d}t} |c_1(t)|^2 \quad \propto -v^2$$

total power $P_1 + P_2 \propto v^4$

friction force $F \propto v^3$

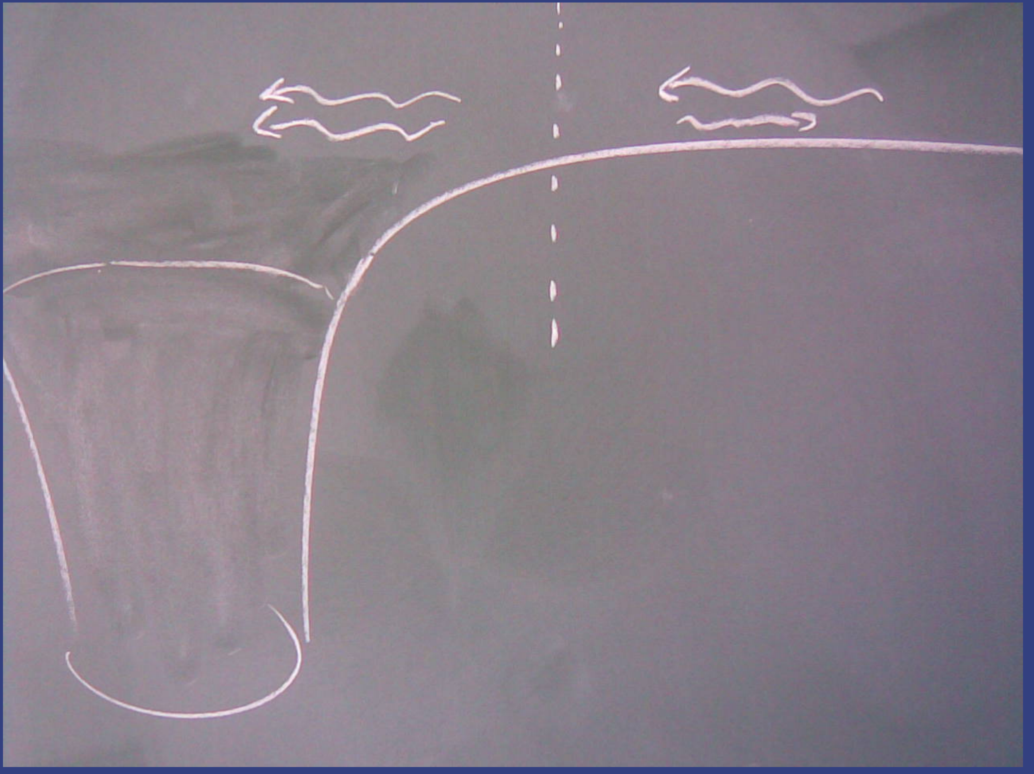
$\neq$ Barton 2010

Unstable vacuum state

Moving atom + metal: spontaneous emission of plasmon pairs

Analogy: Hawking radiation (*Nature* 1974)

particle pair creation near horizon



Power balance:

gravitational field decays = black hole evaporates

Problem solved?

... not yet:

- Evaluation of average force $\langle \mathbf{F}(t) \rangle = \langle d_i(t) \nabla E_i(\vec{r}(t), t) \rangle$

three calculations

Intravaia & al (*J Phys Cond Matt* 2015)

1 – perturbation theory in Schrödinger pic $\langle \Psi(t) | \mathbf{F} | \Psi(t) \rangle$

$$= \underbrace{\text{Cherenkov recoil}^{(2)+(4)}}_{\sim \gamma_g(v)} + \underbrace{\text{two-photon recoil}^{(4)}}_{\sim v^3} \simeq \mathcal{O}(v^3) \qquad \text{as } t \to \infty$$

2 – from dipole correlation function, Markov approximation

3 – from non-equilibrium dipole correlations, generalized FD relation

Problem solved?

... not yet:

- Evaluation of average force $\langle \mathbf{F}(t) \rangle = \langle d_i(t) \nabla E_i(\vec{r}(t), t) \rangle$

three calculations — Intravaia & al (*J Phys Cond Matt* 2015)

1 – perturbation theory in Schrödinger pic $\langle \Psi(t) | \mathbf{F} | \Psi(t) \rangle \simeq \mathcal{O}(v^3)$

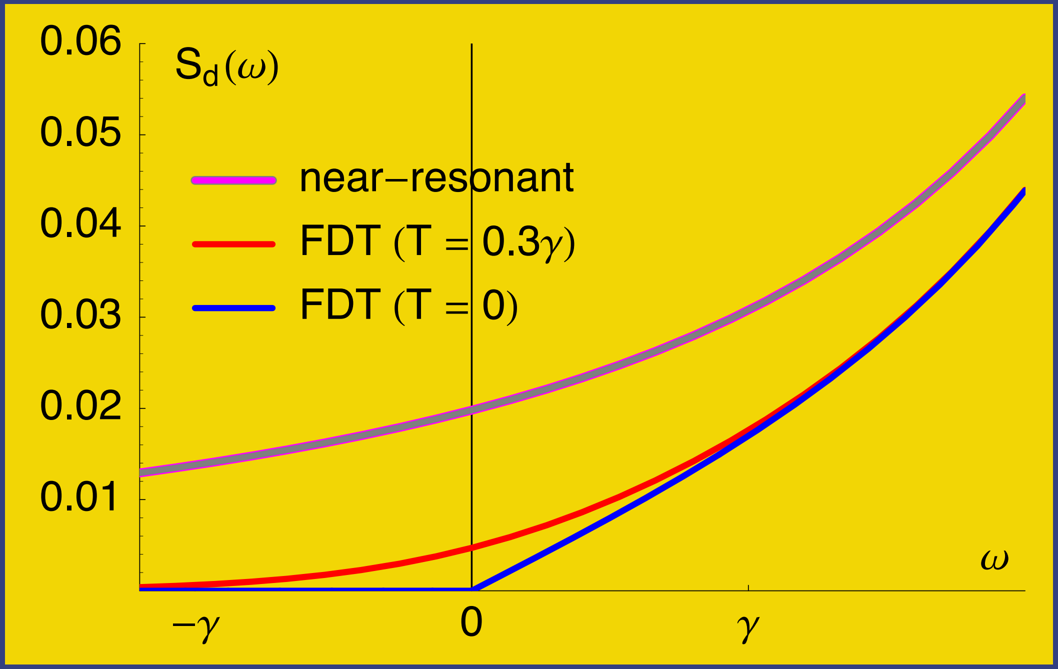
2/3 – in Heisenberg pic

$$= \int^t \mathrm{d}t' \langle d_i(t) \nabla G_{ij}(t - t') d_j(t') \rangle$$

$$= - \int_{\omega \geq 0} \mathrm{d}\kappa \underbrace{J_{ij}(\mathbf{k}, \omega)}_{\text{plasmon spec}} \underbrace{S_d^{ij}(\mathbf{k} \cdot \mathbf{v} - \omega)}_{\text{dipole spec}}$$

2 (mauve line) $S_d(\omega)$ from Markovian master equation

3 (blue line) $S_d(\omega)$ from generalized FD relation



integration range → | $\mathcal{O}(v/z)$

resonance →→→ Ω

→ • following talk (Q34.2) Juliane & Stefan

Summary & Perspectives

quantum friction
— a **theorists' playground** for atom-photon interactions
unstable vacuum state (two-photon emission, Unruh, Fulling–Davies, Hawking)

re-analysis of **time-dependent atom+field state**
— "exciting launch": internal excitation by acceleration
time-dependent force? long-time limit? Barton & Calogeracos (*J Phys A* 2008)

PHD position available
Quantum MHD at metallic surface

friction force and **correlation functions**
— non-equilibrium (driven) dipole spectrum
validity and generalisation of fluctuation–dissipation relations
quantum friction sensitive to low frequencies / large times Milonni & Boyd (*Phys Rev A* 2004)
— check Kubo formula: non-equilibrium force correlation

$$-\frac{\partial \mathbf{F}}{\partial \mathbf{v}} = \frac{1}{T} \,\mathrm{Re} \int \mathrm{d}t \langle \mathbf{F}(t) \cdot \mathbf{F}(0) \rangle_{\mathbf{v} \to 0}$$

One-photon Cherenkov process

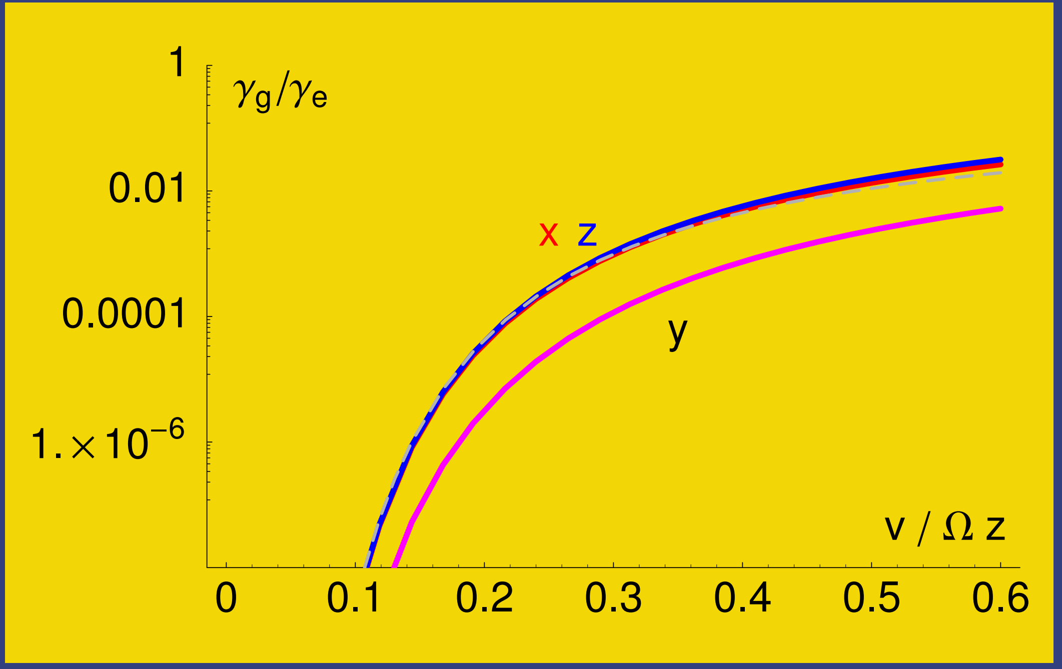
dressed ground state (incl Lamb-shift)

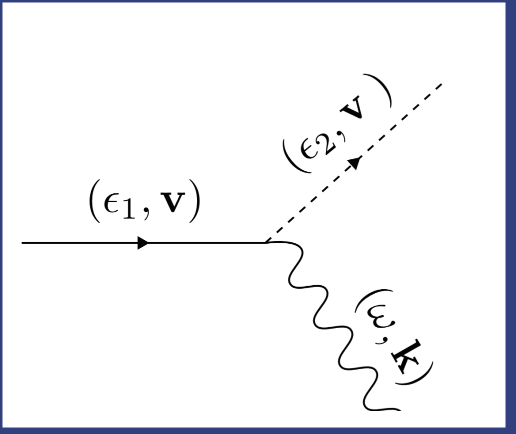
$$|G\rangle \approx \mathrm{e}^{-\mathrm{i}\delta E_g t}|g\,\mathrm{vac}\rangle + \int \mathrm{d}\kappa \frac{\langle e\kappa|V|g\,\mathrm{vac}\rangle}{\Omega + \omega - \mathbf{kv} - \mathrm{i}0}|e\kappa\rangle + \ldots$$

Doppler-shifted resonance $k \geq \dfrac{\Omega + \omega}{v}$

lifetime exponentially long

$$\gamma_g = -2\,\mathrm{Im}\,\delta E_g \propto \exp[-(\Omega + \omega_S)z/v]$$





excitation $g \to e$

with $\epsilon_2 = \epsilon_1 + \hbar\Omega$