Dispersion interactions with long-time tails or beyond local equilibrium

Carsten Henkel

PIERS session 'Casimir effect and heat transfer' (Praha July 2015)

merci à :

G. Barton (Sussex, UK), B. Budaev (Berkeley, CA)

details in:

'Friction forces on atoms after acceleration'

F. Intravaia & al, *J Phys Cond Matt* **27** (2015) 214020

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Motivation

Dispersion Interactions

Casimir energy

quantum fluctuations

van der Waals force

radiative heat transfer

Planck spectrum

non-equilibrium steady state

nano-scale heating

...

'field theory' vs 'radiation engineering'

Motivation

	fields	matter
	Maxwell	Schrödinger
	$\varepsilon_0 \partial_t \mathbf{E} = \nabla \times \mathbf{H} - \mathbf{j}$	
	. . . .	. . . .
approximations		Newton $\partial_t \mathbf{j} \approx \frac{\rho_0}{m} \mathbf{f}$
	Coulomb	relaxation time approximation
	$\varepsilon_0 \nabla^2 \phi = -\rho$	$\partial_t f(x,t) = \ldots - \frac{f(x,t) - f_{\text{eq}}(x)}{\tau}$
		Ohm $\mathbf{j}(\mathbf{r};\omega) = \sigma(\omega)\mathbf{E}(\mathbf{r};\omega)$

why?

response of matter system is nonlinear

need approximations: popular is 'Born-Markov'

central assumption: separation of time scales

fast	thermalization
slow	radiative heating

→ local thermal equilibrium $T(\mathbf{r}, t)$

Motivation

Example

Born-Markov master equation for two-level medium (continuous)

$$\begin{aligned}
\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} &= -(\mathrm{i}\omega_A + \Gamma)\mathbf{P} + \mathrm{i}\chi(N_g - N_e)\mathbf{E} \\
\frac{\mathrm{d}N_e}{\mathrm{d}t} &= -\gamma N_e + \frac{1}{\hbar}\,\mathrm{Im}(\mathbf{P}^* \cdot \mathbf{E}) \\
\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} &= \nabla \times \mathbf{H} - \frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t}
\end{aligned}$$

separation of time scales:

'ultra-fast'	response of field, correlation time	
	Markovian decay	flat (white) spectrum
'fast'	response of matter, radiative (spontaneous) decay,	
'slow'	re-distribution of populations	narrow (peaked) spectrum

Outline

Matter response to radiation:

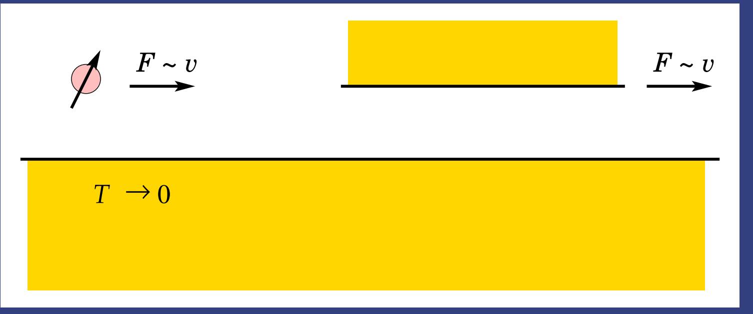
Born-Markov approximation

separation of time scales

This talk:

spectra of (vacuum) field fluctuations

'ultra-slow', 'non-Markovian' correlations



• case study: metallic half-space, two-level system at short distance $z \ll \lambda$

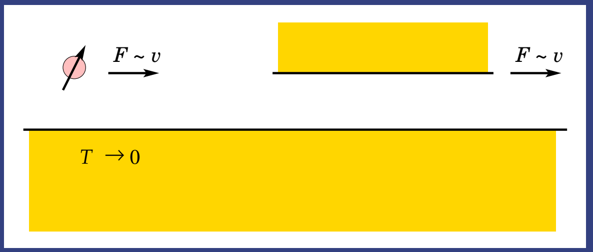
relevant to 'quantum friction':

G. Barton, *Proc Roy Soc (London) A* **453** (1997); *J Phys Cond Matt* **23** (2011)

F. Intravaia & al, *J Phys Cond Matt* **27** (2015)

Field response

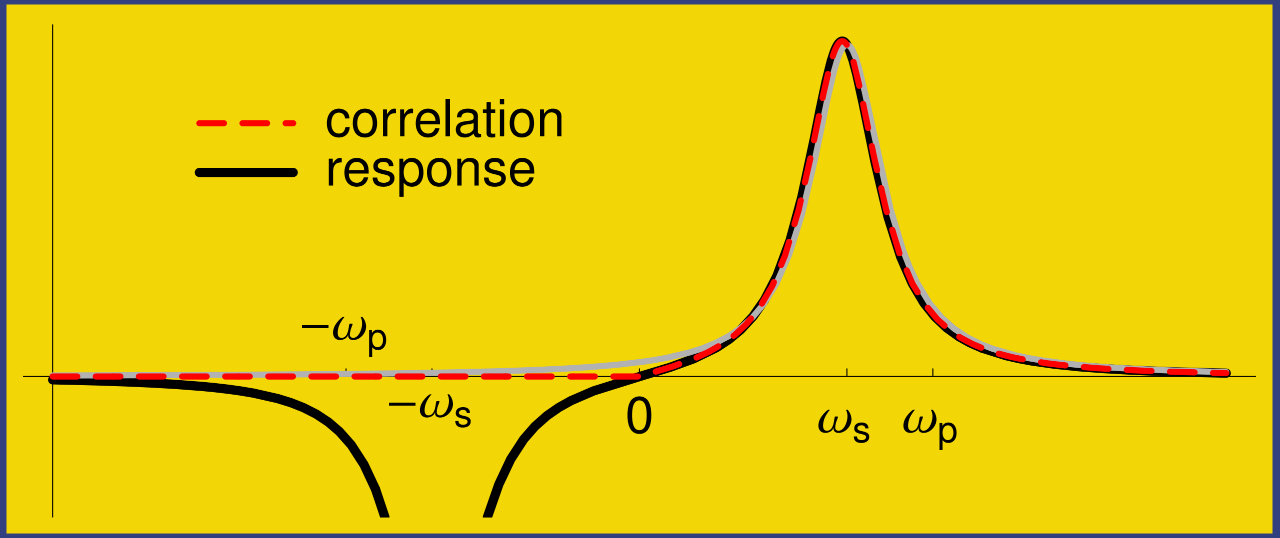
Barton's model: recap potential



$$\phi(\mathbf{r}, z, t) = \int \mathrm{d}^2 k \int \mathrm{d}\omega \, \phi_{\mathbf{k}\omega} \, \exp(\mathrm{i}\mathbf{k}\cdot\mathbf{r} - kz) \, a_{\mathbf{k}\omega}(t) + \text{h.c.}$$

linear response to charge density $\delta\langle\phi(x)\rangle = \int \mathrm{d}x' \, \chi(x, x')\rho(x')$ $\qquad x = (\mathbf{r}, z, t)$

Kubo formula $\qquad \chi(x, x') = -\frac{\mathrm{i}}{\hbar}\langle[\phi(x), \, \phi(x')]\rangle\Theta(t - t')$



Drude metal

surface plasmon $\omega_s = \omega_p/\sqrt{2}$, damping $\Gamma = 0.3\,\omega_p$

non-retarded response

$$\chi(z, z'; \mathbf{k}, \omega) = -\frac{\mathrm{e}^{-k(z+z')}}{2\varepsilon_0 k} R(\omega)$$

$$R(\omega) = \frac{\varepsilon(\omega) - 1}{\varepsilon(\omega) + 1}$$

Field response

$$\phi(\mathbf{r}, z, t) = \int \mathrm{d}^2 k \int \mathrm{d}\omega \, \phi_{\mathbf{k}\omega} \, \exp(\mathrm{i}\mathbf{k}\cdot\mathbf{r} - kz) \, a_{\mathbf{k}\omega}(t) + \text{h.c.}$$

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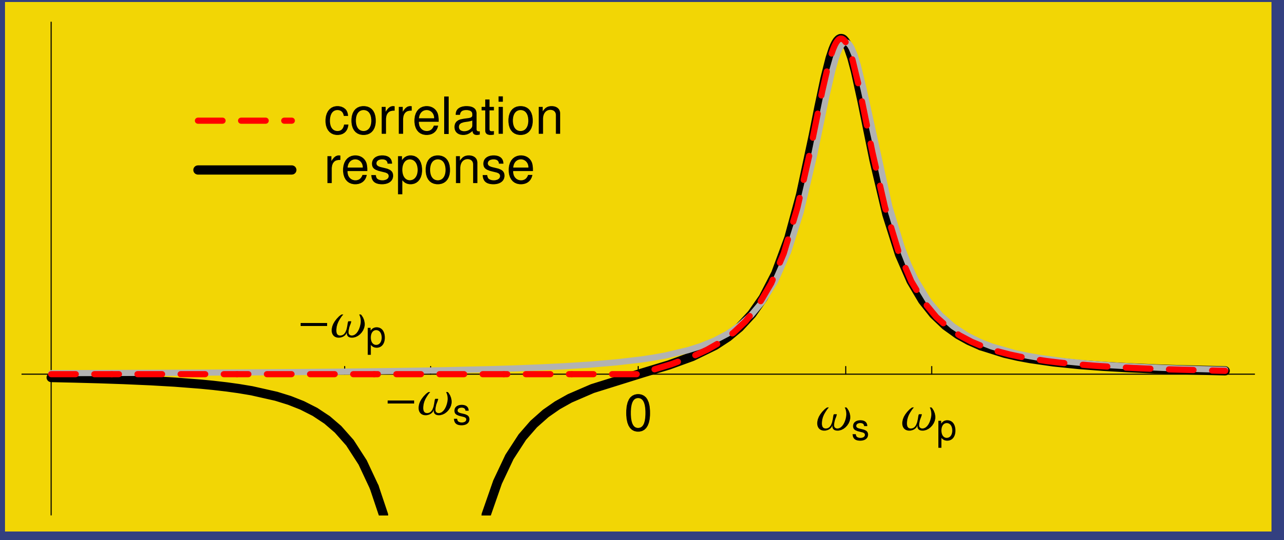

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back in time domain (damped oscillator)

$$\chi(\vec{r}, \vec{r}\,', \tau) = -\frac{\omega_s \sin(\omega_s \tau)\, \mathrm{e}^{-\Gamma\tau/2}}{4\pi\varepsilon_0 |\vec{r} - \vec{r}\,'_{\mathrm{im}}|}\,\Theta(\tau)$$

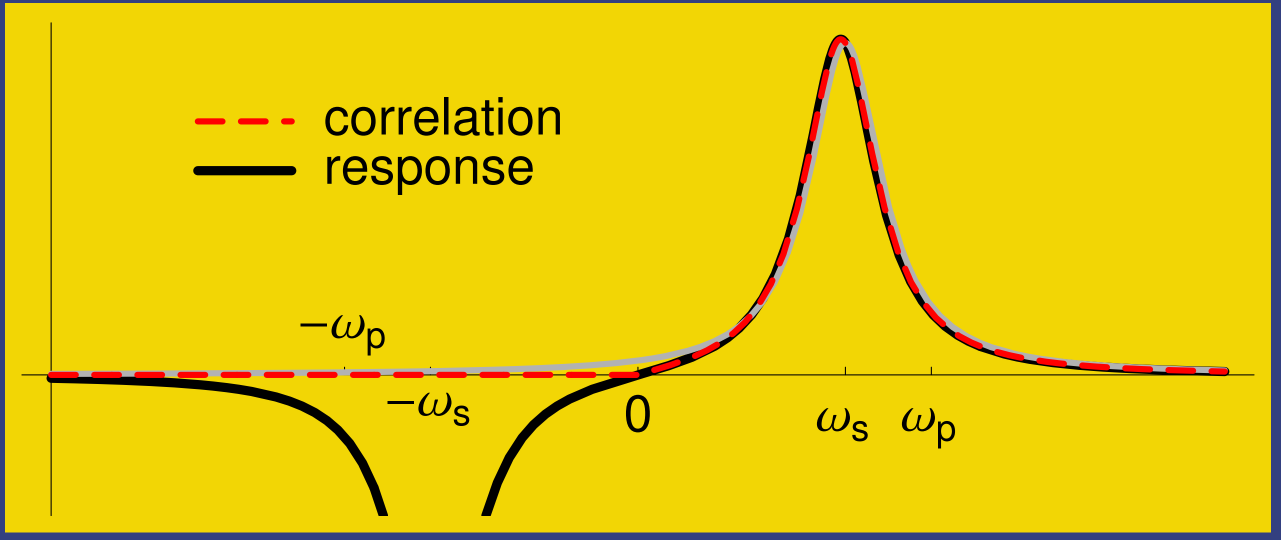
image charge at $\vec{r}\,'_{\mathrm{im}}$

Field response & correlations

positive frequency part $\phi(x) = \phi^{(+)}(x) + \phi^{(-)}(x) = \ldots a_\kappa(t) + \ldots a_\kappa^\dagger(t)$

field vacuum state $\phi^{(+)}(x)|\mathrm{vac}\rangle = 0$

Kubo formula $\chi^{(+)}(x, x') = -\frac{\mathrm{i}}{\hbar}\langle[\phi^{(+)}(x),\, \phi(x')]\rangle\Theta(t - t')$



Drude metal

surface plasmon $\omega_s = \omega_p/\sqrt{2}$, damping $\Gamma = 0.3\,\omega_p$

pos freq response

$$\chi^{(+)}(z, z'; \mathbf{k}, \omega) = -\mathrm{i}\frac{\mathrm{e}^{-k(z+z')}}{\varepsilon_0 k}\,\mathrm{Im}\,R(\omega)\Theta(\omega) * \frac{1}{\mathrm{i}\omega}$$

- algebraic 'fat tail': $\tau \gg 1/\Gamma$

$$\chi^{(+)}(\vec{r}, \vec{r}\,', \tau) \approx \frac{\mathrm{i}\,\mathrm{Im}\,R'(0)}{4\pi\varepsilon_0|\vec{r} - \vec{r}\,'_{\mathrm{im}}|}\,\frac{\Theta(\tau)}{\pi\tau^2}$$

same tail in correlations $\langle\phi(x)\phi(x')\rangle_{\mathrm{vac}}$
(fluctuation–dissipation / Shiba relation)

Davidson & Kozak, *J Math Phys* **12** (1971);
Wodkiewicz & Eberly, *Ann Phys (NY)* **101** (1976)

Non-Markovian challenges

Comment on fluctuation-dissipation relation (kink near zero frequency)

Shiba relation, Sassetti & Weiss 1990

(Tauber rule) power law tails

...are a problem for Markov approximation ('eternal slip'?) Haake & Reibold 1985

Challenge: self-consistent field+atom spectral function near zero frequency, beyond factorising initial conditions Slutskin & al 2011

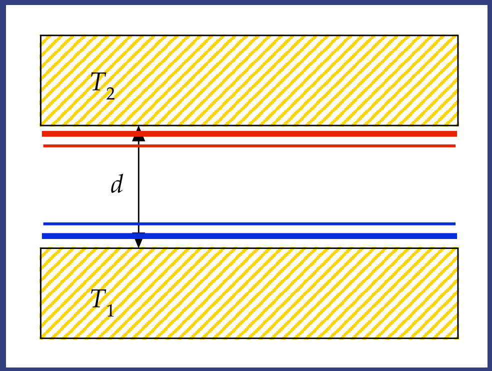
Q friction

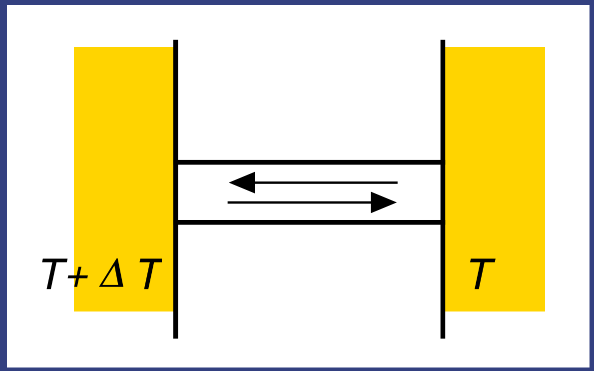
power law in velocity v depends on shape of spectrum near $\omega = 0$

Intravaia & al 2014/15

Discussing with Bair Budaev

Budaev & Bogy, *Ann Phys (Berlin)* **523** (2011);
Appl Phys Lett **99** (2011)





Thermal radiation with heat current $\dot{Q}$:
$S(\omega; T, \dot{Q})$ beyond Planck *Ann Phys (Berlin)* 2011

- radiation thermalizes poorly — signals from astronomy
- matter huge thermal reservoir — the Sun: our black body
- preferred frame: energy current vs crystal lattice — CMB spectroscopy vs condensed matter

Exit evanescent waves:
reproduce radiative heat transfer without (cit'n?)

- required by boundary conditions (charges, impurities, interfaces, nano-scale objects) — Berry, *J mod Opt* **48** (2001)
  'virtual photons' — tunnelling current
- large $k \gg \omega/c$ – 'non-radiative' transport channels attached to matter — near field

Discussing with Bair Budaev

Thermal radiation with heat current $\dot{Q}$:
$S(\omega; T, \dot{Q})$ beyond Planck *Ann Phys (Berlin)* 2011

Exit evanescent waves:
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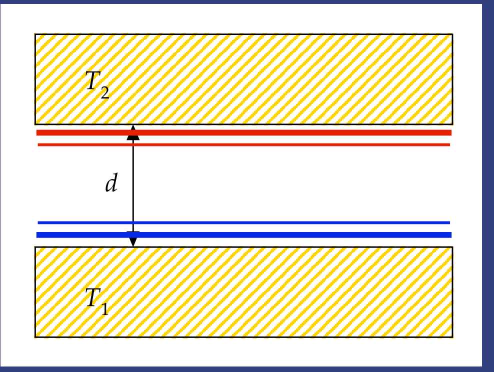
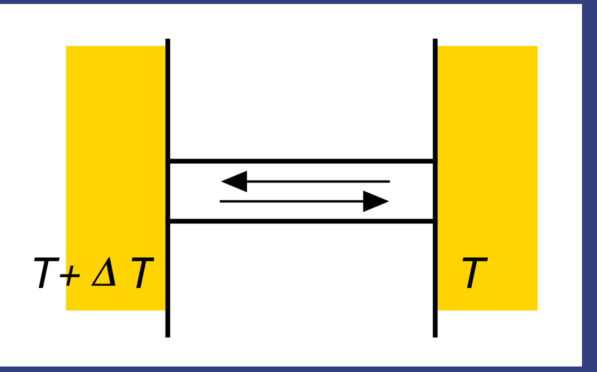
Short-distance limit of heat transfer:
recover homogeneous medium

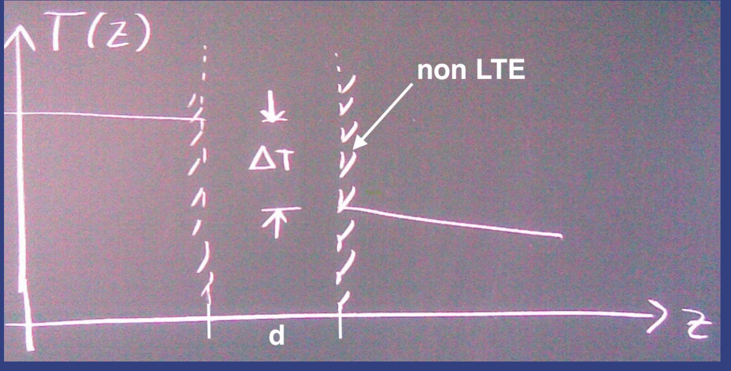


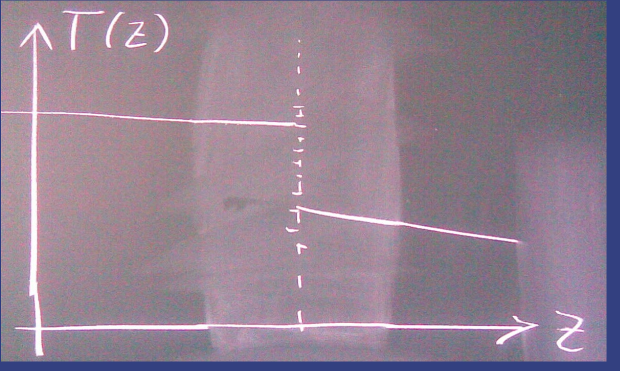


- between conductors $\dot{Q} \sim h(T)\dfrac{\Delta T}{d^2} \to \infty$ OK! (nonlocality?!)

  between dielectrics $\dot{Q} = \sigma(n)(T_1^4 - T_2^4)$ No! (Kapitza resistance?)
- radiation model does not allow for $d \to 0$ Budaev & Bogy, *Appl Phys Lett* 2011

  Ezzahri & Joulain, *Phys Rev B* 2014
- coupled oscillator model ('non-LTE') e.g. Barton, *J Phys Cond Matt* **27** (2015)





Summary & Perspectives

- Fluctuation-dissipation (Shiba) relation for vacuum field
  kink spectrum near zero frequency → 'fat correlations'
- Challenge: self-consistent field+atom spectral function near zero frequency
  Sassetti & Weiss, *Phys Rev Lett* **65** (1990);
  beyond factorising initial conditions — Slutskin & al, *Europhys Lett* **96** (2011)
- 'Easy way out': restore $T > 0$
  $1\text{–}10\,\mathrm{K} \to \hbar/k_B T \sim \mathrm{ps}$
- Locally (near) thermal equilibrium
  matter dynamics — phonons couple (Chen group, *Nat Commun* 2015)
  reasonable approximations behind near-field heat transfer