Understanding and reducing electromagnetic heat transfer

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META'15 session 'Thermoplasmonics and near-field ...' (NYC August 2015)

merci à :
G. Barton (Sussex, UK), V. E. Mkrtchian (Ashtarak, ARM), DFG (€ 'IANV hybrids')

details in:
'Friction forces on atoms after acceleration'
F. Intravaia & al, *J Phys Cond Matt* **27** (2015) 214020

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Abstract key words

small particles as second thermal contact
– settings: atom chips, ion traps
– goal: reduce thermal contact (already weak ...)

lower magnetic noise
– metal strips (biomagnetism expts)
– work on alloys (Ron) and semiconductors (Harald)
– outline numerical method

quantum friction: "**elementary processes**"
– also: e-ifm and path decoherence (Scheel & Buhmann, *Phys Rev A* 2012)
– low-v behaviour
– local thermal equilibrium: is it valid? what does it mean?

Understanding and reducing . . .

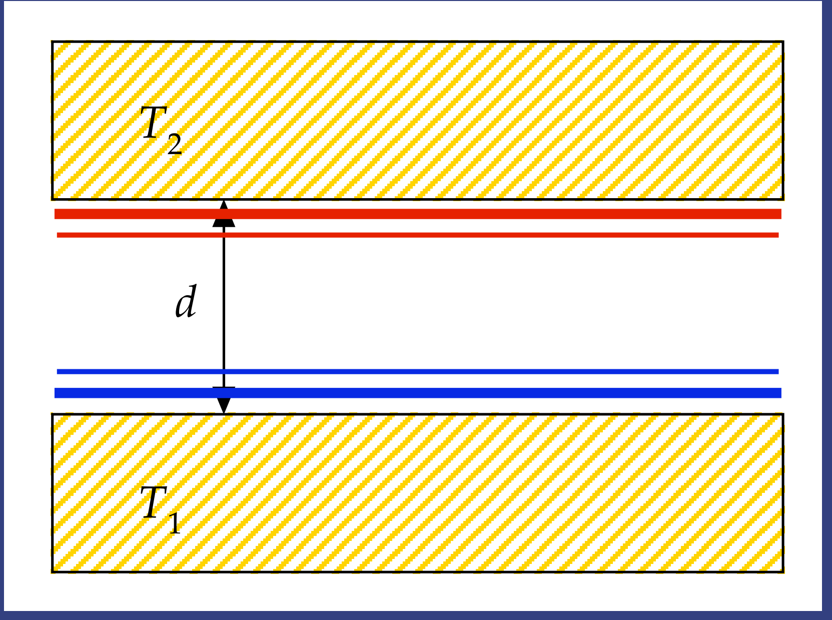
weburbanist.com (2013)

"Curved skyscraper melts cars, starts fires with heat of Sun"

Understanding and reducing ...

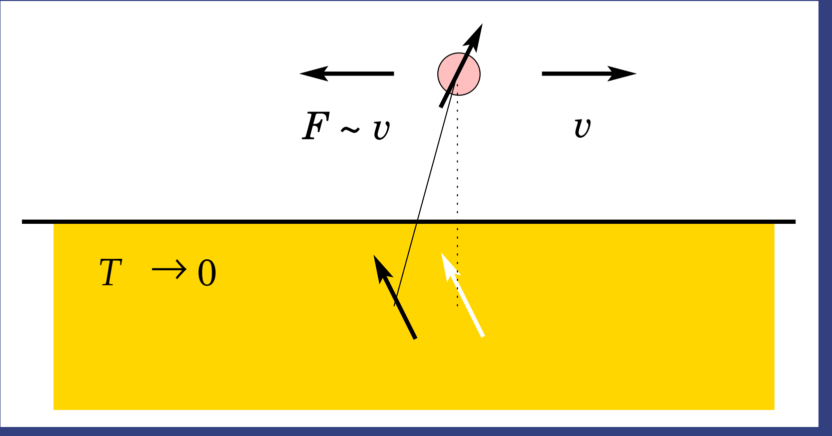
- Basic mechanisms:
  emission T_1 & absorption T_2
  frequency spectra

dilute one medium



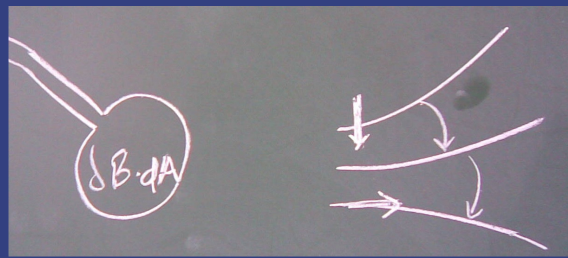
driven by temperature difference

$\rightarrow$ elementary emitter / absorber



by relative motion: friction

Understanding heat transfer with small probes



magnetic noise spectrum

Varpula & Poutanen (*J Appl Phys* 1984)

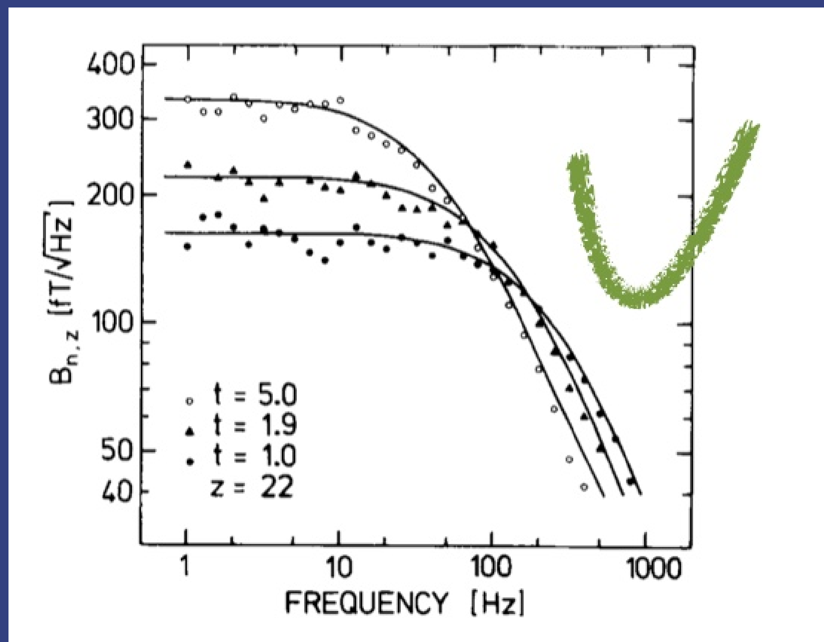
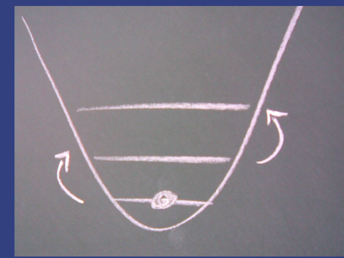


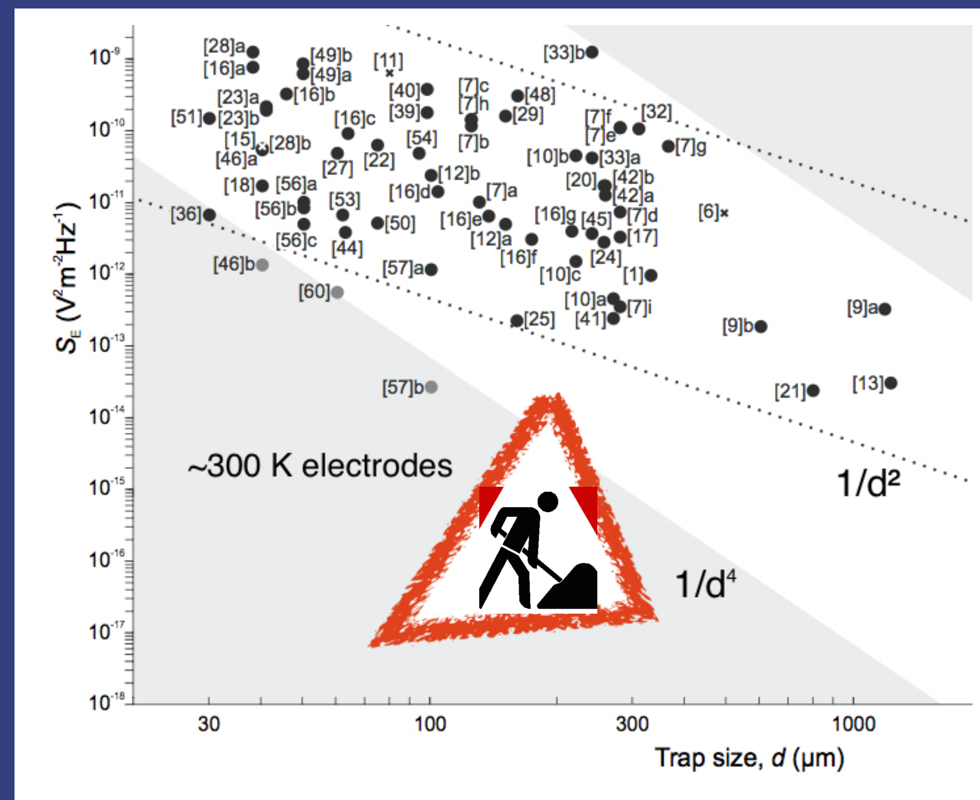
FIG. 3. Thermal magnetic noise amplitudes versus frequency measured from the copper plates at a temperature of 293 K having thicknesses of 5.0, 1.9, and 1.0 mm. The center of the gradiometer pickup coil was at a distance of 22 mm from the upper surface of the respective plate. Measured values are readings from the spectrum analyzer with magnetometer noise subtracted. The solid-line curves are calculated with Eq. (42).

——— Rytov theory



electric noise (trapped ultracold ions)

Brownnutt & Blatt group (*arXiv* 2014)



$1/d^4$ slope – ‘patch charges’, ‘adsorbates’?

Noise reduction strategies

What for?

- biomagnetic imaging (improve S/N)
- long-lived microtraps ('atom chips', 'ion chips') $\leftarrow$ IANV 'Hybrid systems' project
- ion-based quantum computing (Blatt/Innsbruck, Wineland/NIST)

Noise reduction strategies

Example: magnetic noise

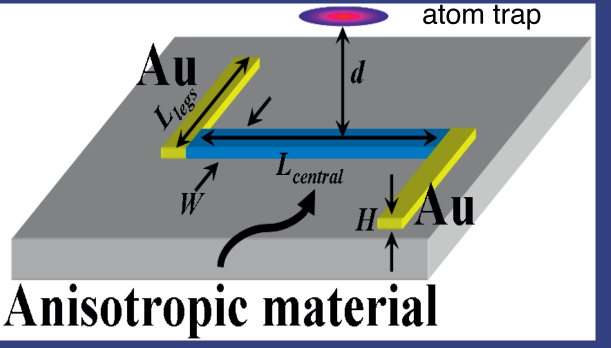
TABLE II. Thermal noise measured from a 32×25 cm^2 aluminum foil ($t=12$ μm) sliced into electrically isolated strips of the width Δ (cm). Measured noise levels $B^m_{n,z}$ are given in fT/$\sqrt{\mathrm{Hz}}$, and $B^{\mathrm{ref}}_{n,z}$ is the measured value of the unsliced foil. Gradiometer location was either at the center of the strip (|o|) or above a cut ($\not{o}$).

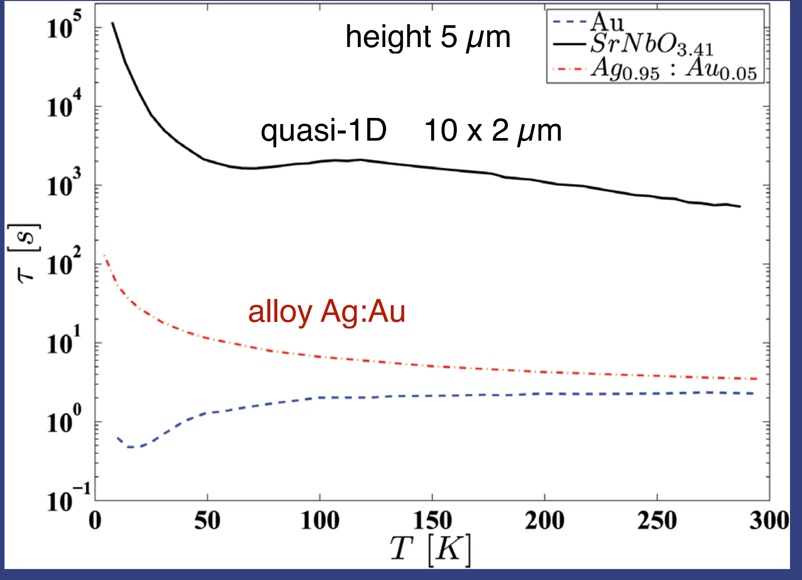
Δ	Location	$B^m_{n,z}$	$B^m_{n,z}/B^{\mathrm{ref}}_{n,z}$
32	|o|	13.7	1.00
16	$\not{o}$	6.8	0.49
8	|o|	12.3	0.90
8	$\not{o}$	6.4	0.47
4	|o|	8.9	0.64
4	$\not{o}$	6.3	0.46
2	|o|, $\not{o}$	4.7	0.34
1	|o|, $\not{o}$	2.7	0.20

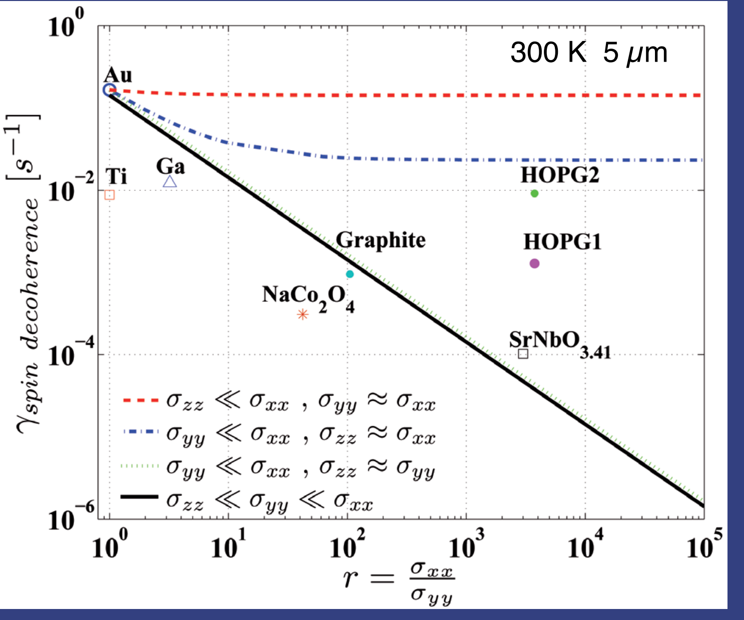
Nenonen, Montonen & Katila, ‘Thermal noise in biomagnetic measurements’ (*Rev Sci Instr* 1996)

Noise reduction strategies

Proposal for atom traps
– cooling
– alloys
– anisotropic conductors

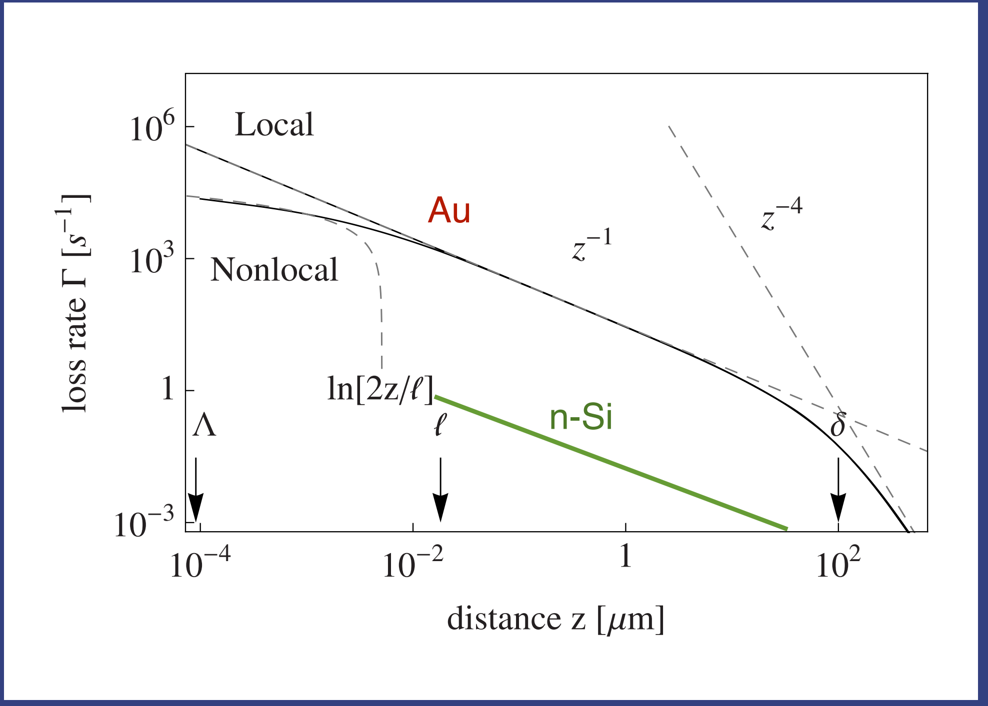






David & Folman group, 'Magnetic interactions of cold atoms with anisotropic conductors' (*Eur Phys J D* 2008)

Noise reduction: semiconductors



scaling law of magnetic field spectrum at low frequencies

$$\langle B_i(\mathbf{r}, t') B_j(\mathbf{r}, t) \rangle_\omega \approx \frac{\mu_0^2 k_B T \sigma}{32\pi} \frac{\delta_{ij} + \hat{z}_i \hat{z}_j}{z}, \qquad \ell \ll z \ll \delta = \sqrt{\frac{2}{\mu_0 \omega \sigma}}$$

Haakh & CH, 'Magnetic near fields as a probe of charge transport in spatially dispersive conductors' (*Eur Phys J B* 2012)

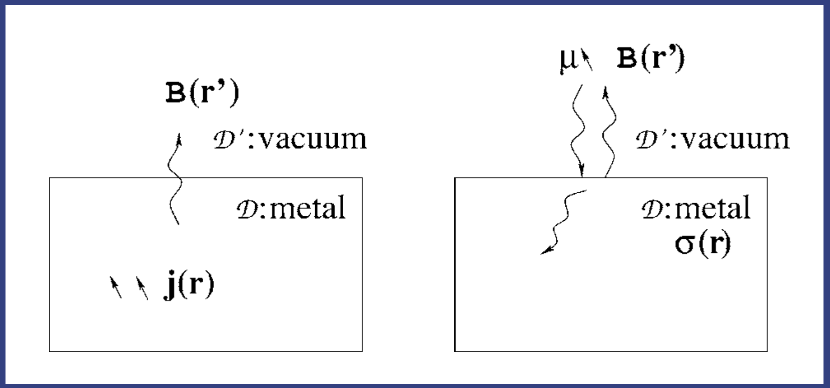
‘Full’ numerics

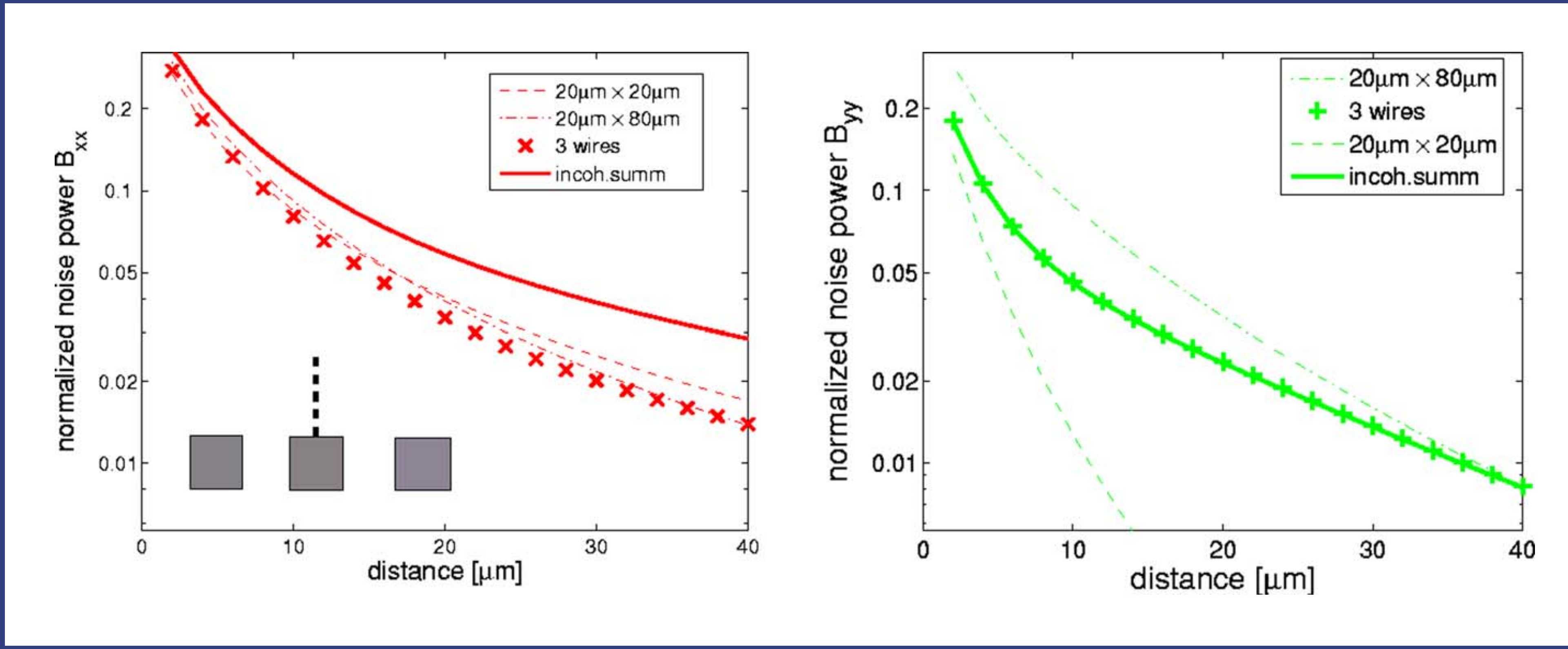
Equilibrium near field correlations

$$\langle B_i(\mathbf{r}', t') B_j(\mathbf{r}, t) \rangle_\omega \approx \frac{2 k_B T}{\omega} \, \mathrm{Im} \, G_{ij}(\mathbf{r}', \mathbf{r}; \omega)$$

– radiation of magnetic dipole $\boldsymbol{\mu}$

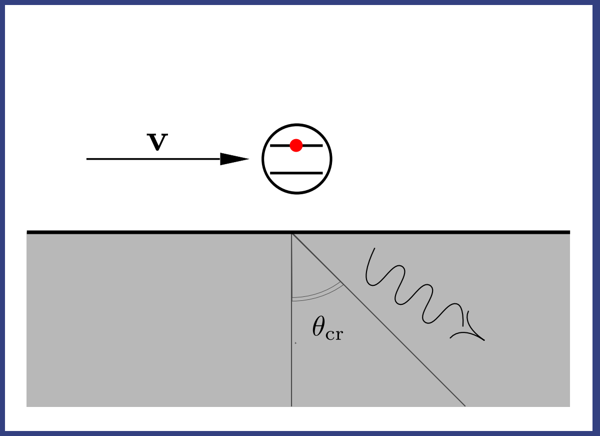
– object surface: boundary conditions





Zhang & CH, ‘Magnetic noise around metallic microstructures’ (*J Appl Phys* 2007)

Understanding fundamentals: friction forces

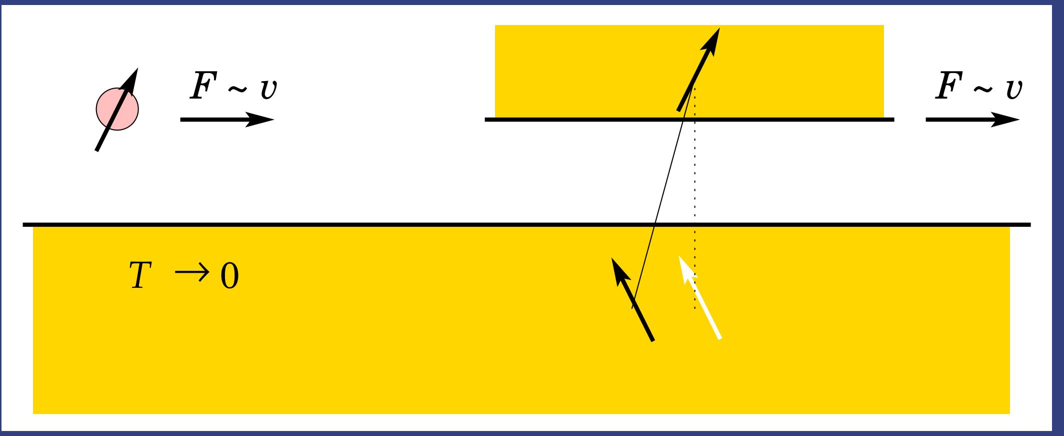


excitations (photons ...) leave the system

& energy conservation

– internal energy ("heat")

– open boundaries



delay between particle
and image dipole (surface charge)

- lateral force

zero friction above perfect conductor

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)

Barton's minimal quantum field theory

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 $|\kappa\rangle = |\mathbf{k}, \omega\rangle$

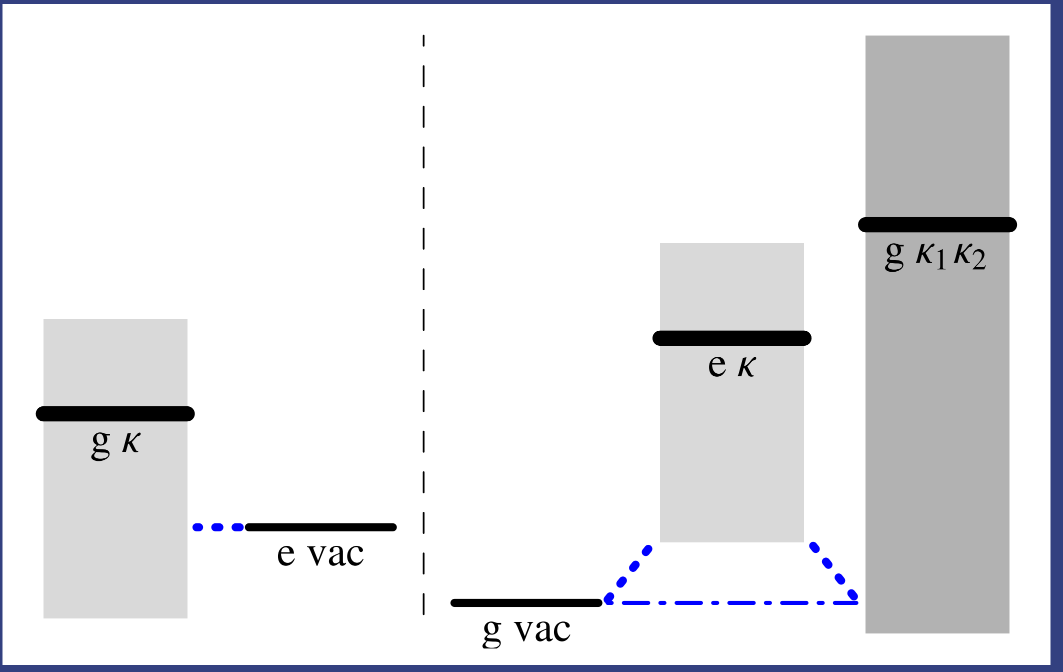
electric potential

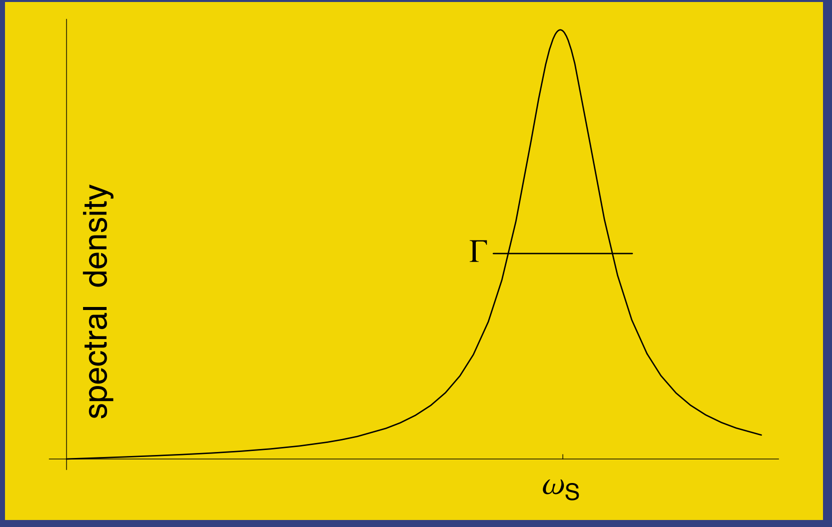
$$\phi(\vec{r}(t)) = \int \mathrm{d}\kappa\, \phi_\kappa\, \mathrm{e}^{\mathrm{i}\mathbf{k}\cdot\mathbf{r}(t)} \mathrm{e}^{-kz} a_\kappa \mathrm{e}^{-\mathrm{i}\omega t} + \mathrm{h.c.}$$

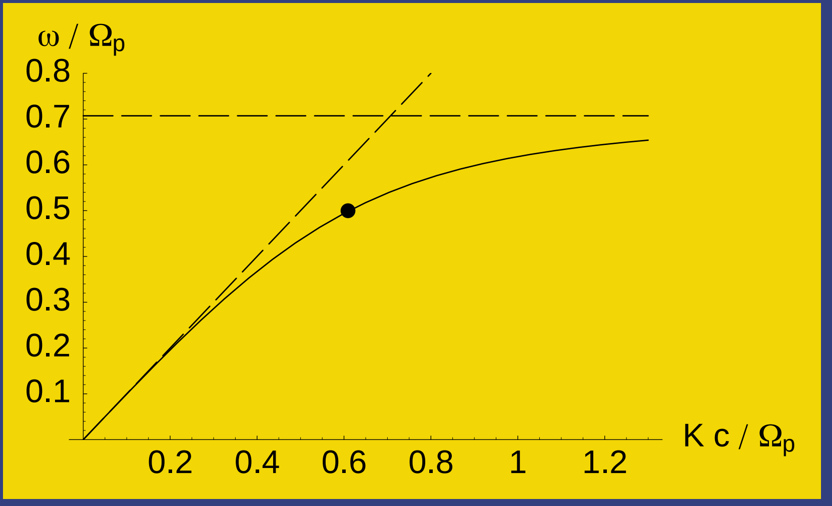
spectral density of surface plasmon polaritons

Barton (1970s ... *New J Phys* 2010)

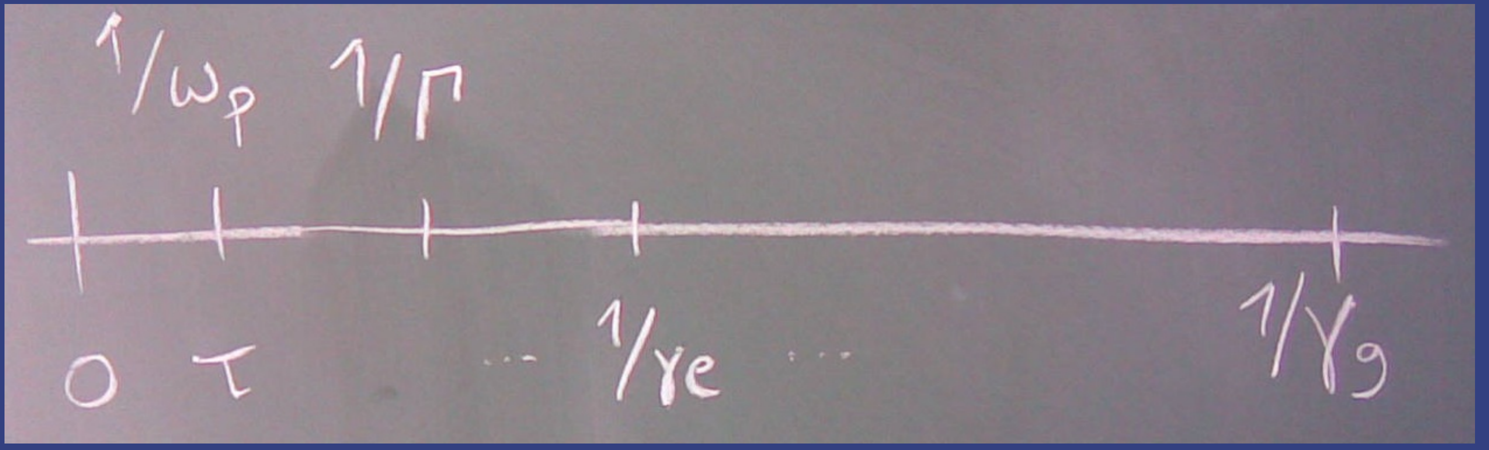
Barton (*New J Phys* **12** (2010) 113045)







Relevant time scales

$-\infty \ldots$ 

couple field + atom at rest

...

acceleration time $\tau =$ "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"

One-photon Cherenkov process

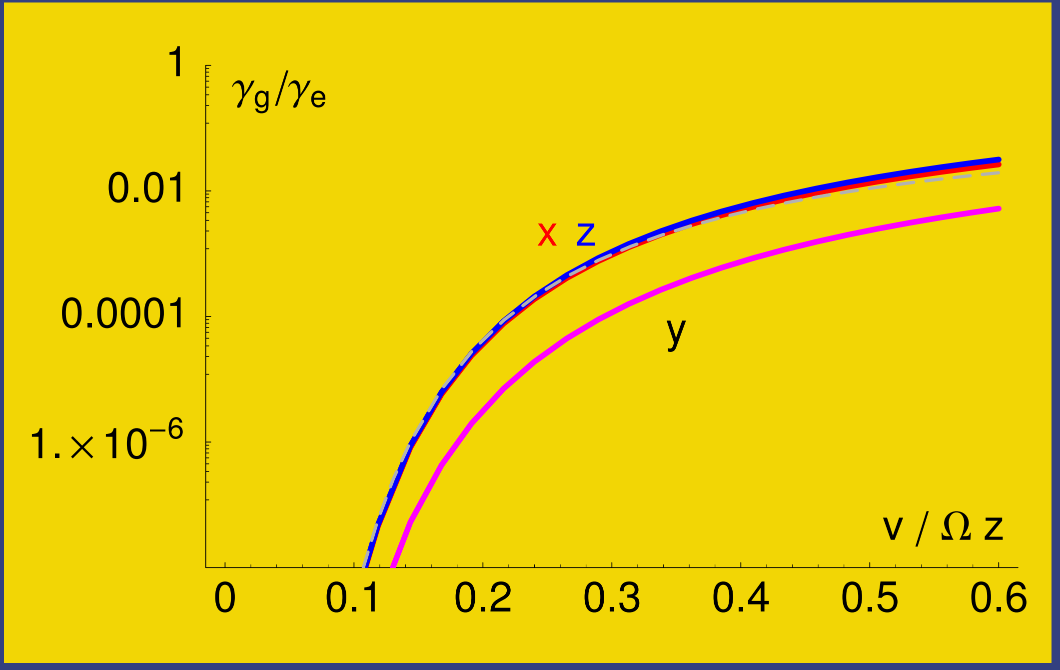
dressed ground state (incl Lamb shift)

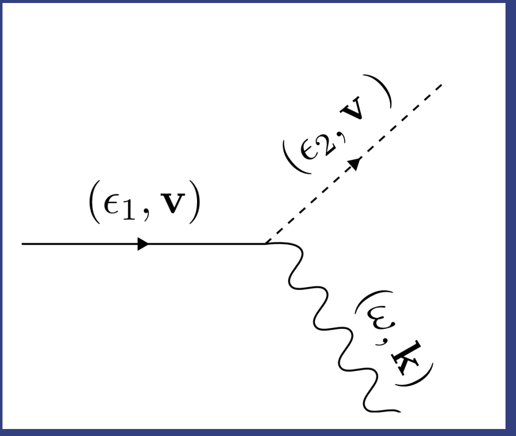
$$|G\rangle \approx \mathrm{e}^{-\mathrm{i}\delta E_g t}|g\,\mathrm{vac}\rangle + \int \mathrm{d}\kappa \frac{\langle e\kappa|V|g\,\mathrm{vac}\rangle}{\Omega + \omega - \mathbf{kv} - \mathrm{i}0}|e\kappa\rangle + \ldots$$

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

lifetime exponentially long

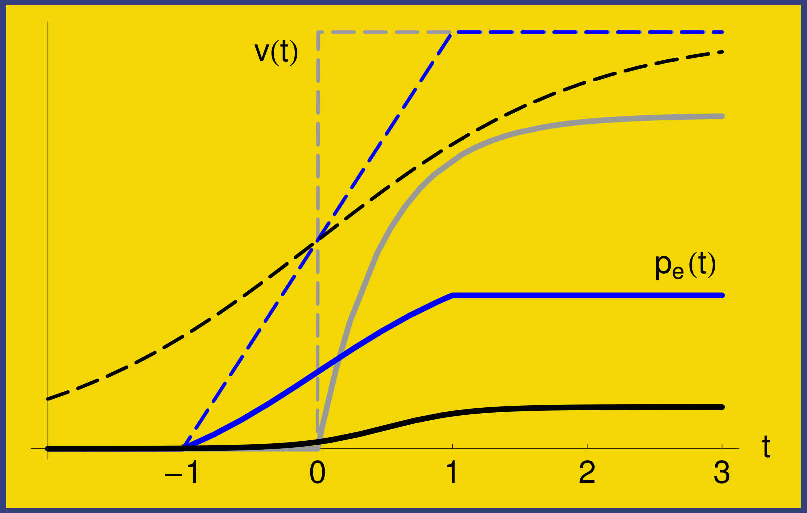
$$\gamma_g = -2\,\mathrm{Im}\,\delta E_g \propto \exp[-(\Omega + \omega_S)z/v]$$





excitation $g \to e$ with $\epsilon_2 = \epsilon_1 + \hbar\Omega$
"for free" since $\Omega + \omega' = 0$

Barton's transient = excitation after launch



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

excitation probability

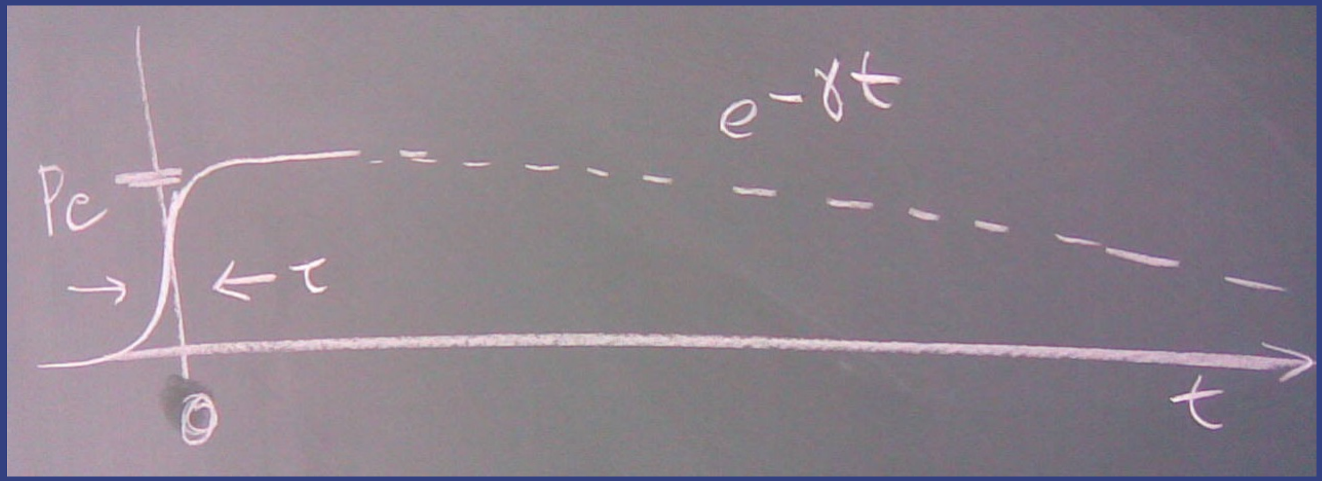
- virtual ("dressed $|g\rangle$") + real excitation ("bare $|e\rangle$")

$$p_e(t) \quad = \int \mathrm{d}\kappa\, |c_1^{(1)}(t) + c_1^{(3)}(t)|^2 \quad \to p_e(\mathrm{real}) \quad \text{for } \tau \ll t \ll 1/\gamma_e$$

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

Barton & Calogeracos (*J Phys A* 2008)

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



spontaneous decay relevant for power balance

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

- compensates linear friction $\neq$ Barton 2010

Review of Barton's Results

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

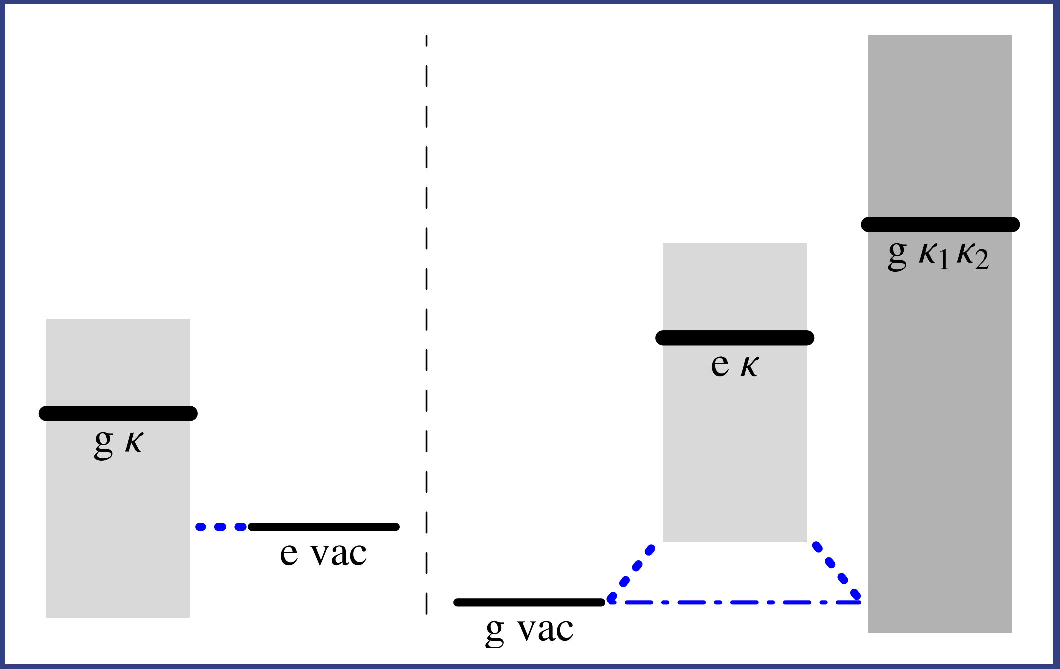
not the standard theory

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

Scheel & Buhmann (*Phys Rev A* 2009)

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
$g \to e + h\nu$

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

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

friction force $F \propto v^3$

$\neq$ Barton 2010

Summary & Perspectives

Understanding heat transfer

- (meta)material properties: $\mu, \varepsilon(\omega), \sigma(\mathbf{k}, \omega) \ldots$
- geometry: far/near field, shadows, diffraction ...
- (local) temperature: e.m. sources, field correlations, local equilibrium (or not)
- un-known sources: fluctuating adsorbates Safavi-Naini & al (*Phys Rev A* 2011)
  un-known driven (non-eq) state: ground/excited atom, relevant time scales

Reducing heat transfer

- applications: $\leftarrow$ 'IANV hybrids'
  small, ultracold, trapped particles
- reduce emission = reduce absorption
- (meta)material design: strips, conductivity, temperature

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