TDCDFT and plasmon damping: breakdown of the local approximation in quasi-2D systems

Carsten A. Ullrich
University of Missouri

Toulouse
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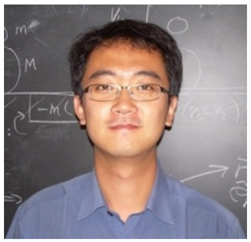
Acknowledgments

Current group members:

Yonghui Li



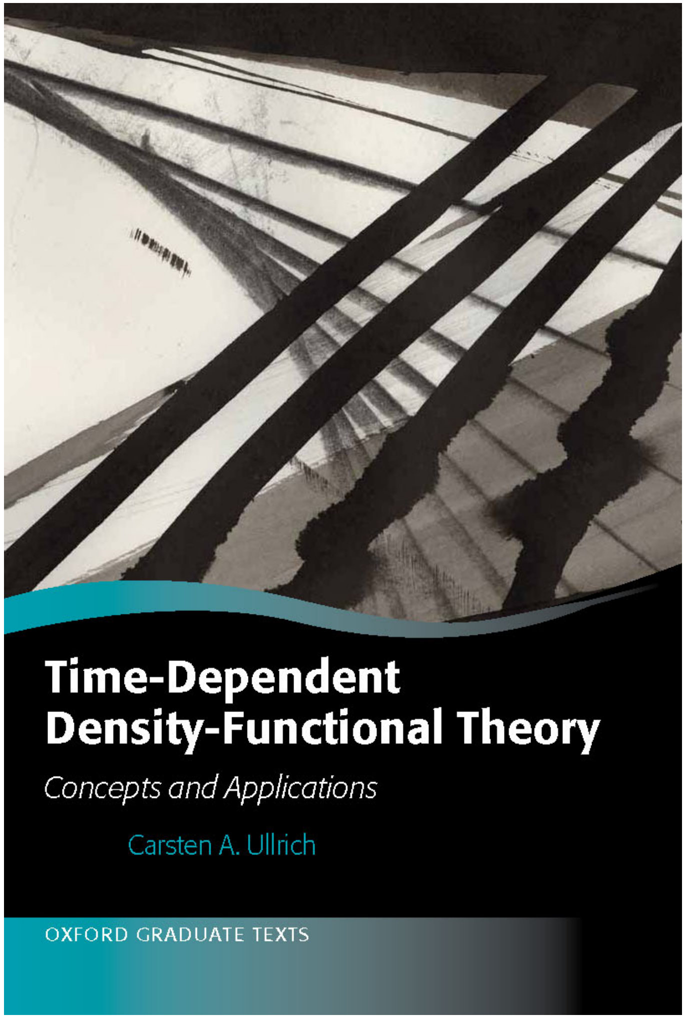
Zeng-hui Yang

Mehul Dixit

Shahrzad Karimi

In collaboration with
Irene D'Amico (York)

Outline



TDCDFT: basic formalism and ultranonlocality

Damping of charge and spin plasmons

Spin Coulomb drag: local approximation vs microscopic formulation

Why TDCDFT?

TDCDFT overcomes several formal limitations of TDDFT:

allows treatment of **electromagnetic waves**, vector potentials, uniform applied electric fields.

works for all **extended systems**. One does not need the condition that the current density vanishes at infinity.

Vignale, PRB **70**, 201102 (2004), Maitra, Souza & Burke, PRB **68**, 045109 (2003)

But TDCDFT is also practically useful in situations that could, in principle, be fully described with TDDFT:

Upgrading to the current density can be a more “natural” way to describe dynamical systems.

Helps to deal with the **ultranonlocality** problem of TDDFT

Provides ways to construct **nonadiabatic** approximations

The adiabatic approximation

$$V_{xc}^{A}[n](\mathbf{r},t) = V_{xc}^{static}[n(\mathbf{r},t)](\mathbf{r}) \qquad V_{xc}^{ALDA}(\mathbf{r},t) = \left.\frac{de_{xc}^{unif}(\bar{n})}{d\bar{n}}\right|_{\bar{n}=n(\mathbf{r},t)}$$

In general, the adiabatic approximation works well for excitations which have an analogue in the KS system (single excitations)

formally justified only for infinitely slow electron dynamics. But why is it that the frequency dependence seems less important?

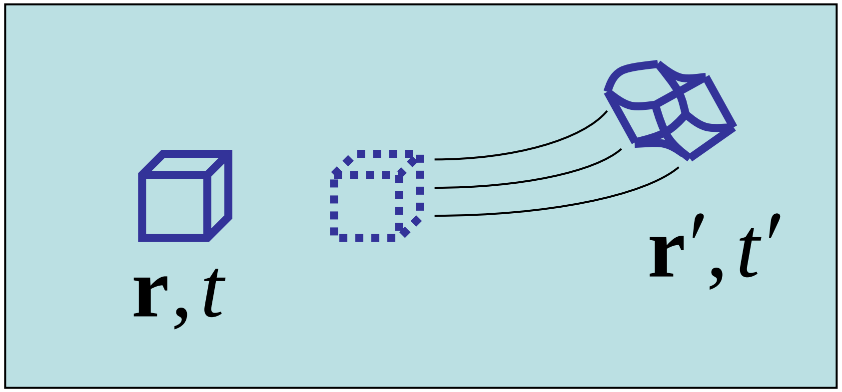
The frequency scale of f_{xc} is set by correlated multiple excitations, which are absent in the KS spectrum.

Adiabatic approximation fails for more complicated excitations (multiple, charge-transfer).

misses dissipation of long-wavelength plasmon excitations

Nonlocality in space and time

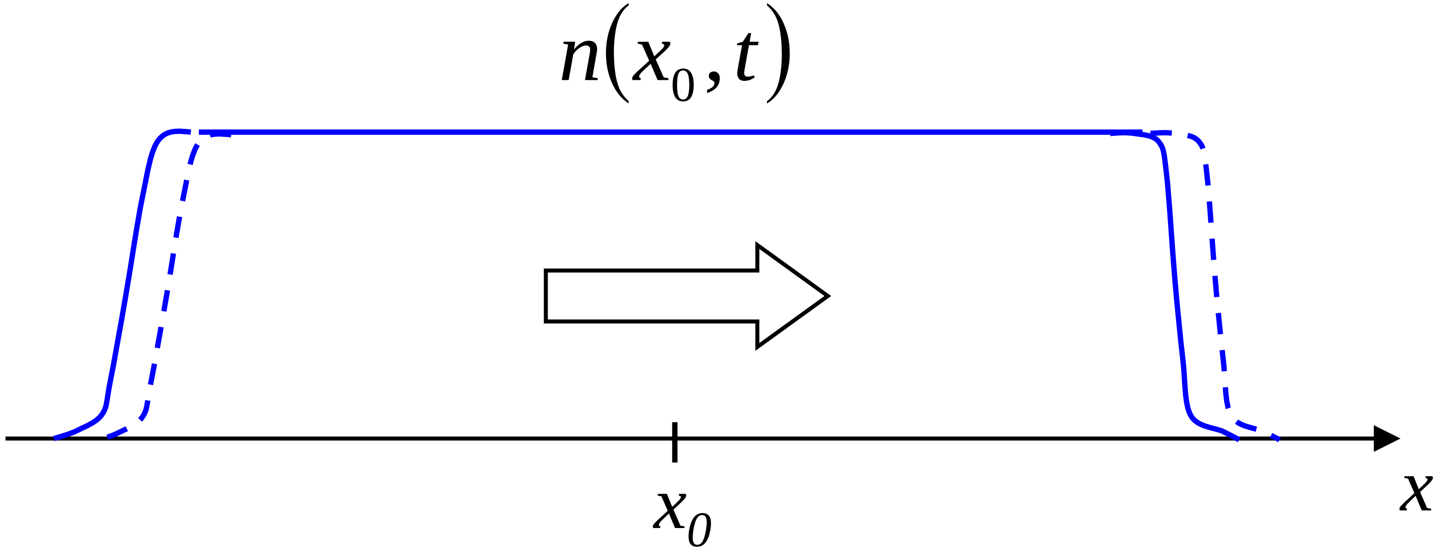
Visualize electron dynamics as the motion (and deformation) of infinitesimal fluid elements:



Nonlocality in time (memory) implies nonlocality in space!

Dobson, Bünner, and Gross, PRL **79**, 1905 (1997)
I.V. Tokatly, PRB **71**, 165104 and 165105 (2005), PRB **75**, 125105 (2007)
C.A. Ullrich and I.V. Tokatly, PRB **73**, 235102 (2006)

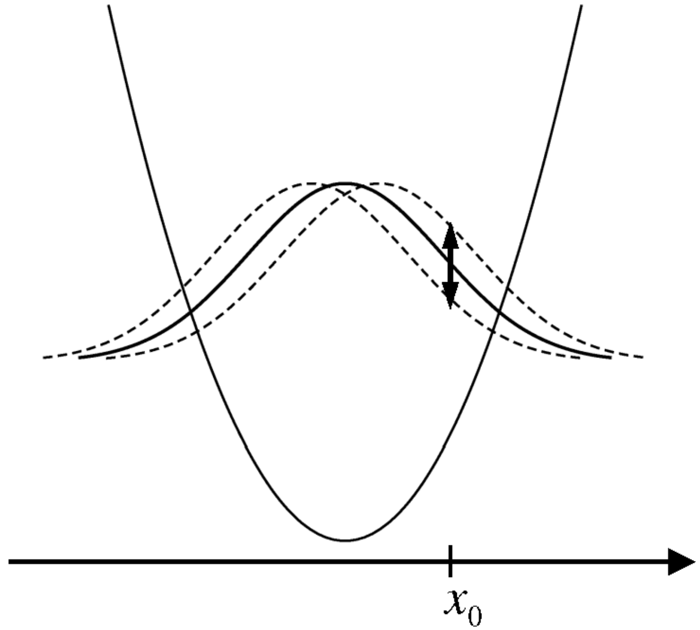
Ultranonlocality and the density

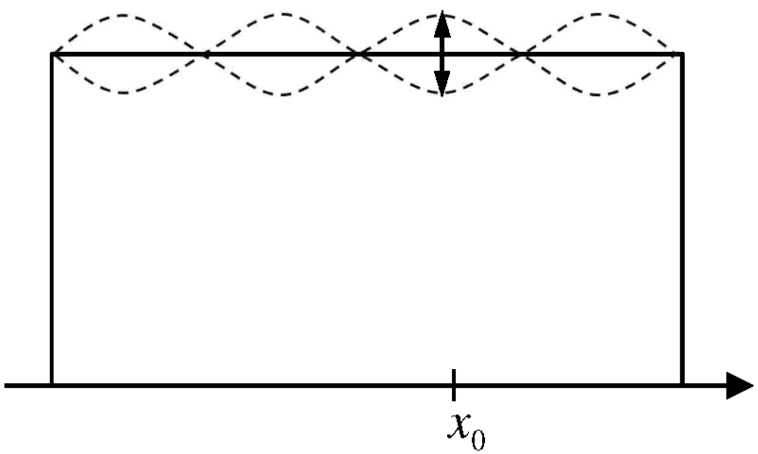


An xc functional that depends only on the local density (or its gradients) cannot see the motion of the entire slab.

A density functional needs to have a long range to see the motion through the changes at the edges.

Failure of nonadiabatic local density functionals





► undamped density oscillations
► xc potential rides along with density
► constant velocity field

► bulk plasmon: periodic compression and rarefaction of the density
► intrinsic damping due to decay of collective mode into single-particle excitations
► oscillating velocity field

xc functionals based on local **density** can't distinguish the two cases!
But one can capture the correct physics with **current** functionals.

“Upgrading” TDDFT: Current-TDDFT

$$n(\mathbf{r},t) \xleftrightarrow{\text{nonlocal}} V_{xc}(\mathbf{r},t)$$

nonlocal

$$\nabla \cdot \mathbf{j} = -\frac{\partial n}{\partial t}$$

nonlocal

$$\nabla V_{xc} = \frac{\partial \mathbf{A}_{xc}}{\partial t}$$

$$\mathbf{j}(\mathbf{r},t) \xleftrightarrow[\text{local}]{} \mathbf{A}_{xc}(\mathbf{r},t)$$

$$\mathbf{j}(\mathbf{r},t) = \mathbf{j}_L(\mathbf{r},t) + \mathbf{j}_T(\mathbf{r},t), \qquad \mathbf{j}_L(\vec{r},t) = \frac{\nabla}{4\pi}\int \frac{\dot{n}(\mathbf{r}',t)}{|\mathbf{r}-\mathbf{r}'|}$$

Continuity equation only gives the longitudinal current

TDCDFT gives also the transverse current

We can find a short-range current-dependent xc vector potential

TDKS equation in TDCDFT

generalization of RG/vL theorems: Ghosh and Dhara, PRA **38**, 1149 (1988)
G. Vignale, PRB **70**, 201102 (2004)

$$i\frac{\partial}{\partial t}\varphi_j(\mathbf{r},t)=\left(\frac{1}{2}\left[\frac{\nabla}{i}+\mathbf{A}_s(\mathbf{r},t)\right]^2+V_s(\mathbf{r},t)\right)\varphi_j(\mathbf{r},t)$$

Gauge-invariant physical current density:

$$\mathbf{j}(\mathbf{r},t)=n(\mathbf{r},t)\mathbf{A}_s(\mathbf{r},t)+\frac{1}{2i}\sum_{j=1}^{N}\left[\varphi_j^*(\mathbf{r},t)\nabla\varphi_j(\mathbf{r},t)-\varphi_j(\mathbf{r},t)\nabla\varphi_j^*(\mathbf{r},t)\right]$$

$$=\mathbf{j}_{\mathbf{dia}}(\mathbf{r},t)+\mathbf{j}_{\mathbf{para}}(\mathbf{r},t)$$

Scalar and vector potentials:

$$V_s[\mathbf{j}](\mathbf{r},t)=V(\mathbf{r},t)+V_H(\mathbf{r},t)+V_{xc}(\mathbf{r},t)$$

$$\mathbf{A}_s[\mathbf{j}](\mathbf{r},t)=\mathbf{A}(\mathbf{r},t)+\mathbf{A}_{xc}(\mathbf{r},t)$$

(ignore Hartree vector potential from induced currents)

TDCDFT in the linear response regime

$$\mathbf{j}_1(\mathbf{r},\omega) = \int d^3r' \, \overleftrightarrow{\chi}_s(\mathbf{r},\mathbf{r}',\omega)\left\{\mathbf{A}_{ext,1}(\mathbf{r},\omega) + \mathbf{A}_{H,1}(\mathbf{r},\omega) + \mathbf{A}_{xc,1}(\mathbf{r},\omega)\right\}$$

KS current-current response tensor: diamagnetic + paramagnetic part

$$\chi_{s,\mu\nu}(\mathbf{r},\mathbf{r}',\omega) = n_0(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}')\delta_{\mu\nu} + \frac{1}{2}\sum_{j,k}^{\infty} \frac{f_k - f_j}{\varepsilon_k - \varepsilon_j + \omega + i\eta} P_\mu^{kj}(\mathbf{r}) P_\nu^{jk}(\mathbf{r}')$$

where $$P_\mu^{kj} = \varphi_k^*(\mathbf{r})\nabla_\mu \varphi_j(\mathbf{r}) - \varphi_j(\mathbf{r})\nabla_\mu \varphi_k^*(\mathbf{r})$$

Note:

$$\chi_s(\mathbf{r},\mathbf{r}',\omega) = \frac{1}{\omega^2}\sum_{\mu\nu} \nabla_\mu \nabla'_\nu \chi_{s,\mu\nu}(\mathbf{r},\mathbf{r}',\omega)$$

TDCDFT: effective vector potential

$\mathbf{A}_{ext,1}(\mathbf{r},\omega)$: external perturbation. Can be a true vector potential, or a gauge transformed scalar perturbation: $\mathbf{A}_{ext,1} = \frac{1}{i\omega}\nabla V_{ext,1}$

$$\mathbf{A}_{H,1}(\mathbf{r},\omega) = \frac{\nabla}{(i\omega)^2}\int d^3r' \frac{\nabla'\cdot\mathbf{j}_1(\mathbf{r}',\omega)}{|\mathbf{r}-\mathbf{r}'|}$$

gauge transformed Hartree potential

$$\mathbf{A}_{xc,1}(\mathbf{r},\omega) = \int d^3r' \ \overleftrightarrow{f}_{xc}(\mathbf{r},\mathbf{r}',\omega)\mathbf{j}_1(\mathbf{r}',\omega)$$

the xc kernel is now a tensor!

ALDA: $\mathbf{A}^{ALDA}_{xc,1}(\mathbf{r},\omega) = \frac{\nabla}{(i\omega)^2}\int d^3r' \ f^{ALDA}_{xc}(\mathbf{r},\mathbf{r}')\nabla\cdot\mathbf{j}_1(\mathbf{r}',\omega)$

TDCDFT beyond the ALDA: the VK functional

G. Vignale and W. Kohn, Phys. Rev. Lett. **77**, 2037 (1996)
G. Vignale, C. A. Ullrich, and S. Conti, Phys. Rev. Lett. **79**, 4878 (1997)

$$\mathbf{A}_{xc,1}^{VK}(\mathbf{r},\omega) = \mathbf{A}_{xc,1}^{ALDA}(\mathbf{r},\omega) - \frac{1}{i\omega n_0(\mathbf{r})} \nabla \cdot \overleftrightarrow{\sigma}_{xc}(\mathbf{r},\omega)$$

xc viscoelastic stress tensor:

$$\sigma_{xc,\mu\nu}(\omega) = \eta_{xc}\left(\nabla_\nu u_{1,\mu} + \nabla_\mu u_{1,\nu} - \frac{2}{3}\nabla \cdot \mathbf{u}_1 \delta_{\mu\nu}\right) + \zeta_{xc} \nabla \cdot \mathbf{u}_1 \delta_{\mu\nu}$$

$$\mathbf{u}(\mathbf{r},\omega) = \mathbf{j}(\mathbf{r},\omega) / n_0(\mathbf{r})$$ velocity field

automatically satisfies zero-force theorem/Newton’s 3rd law
automatically satisfies the Harmonic Potential theorem
is local in the current, but nonlocal in the density
introduces dissipation/retardation effects

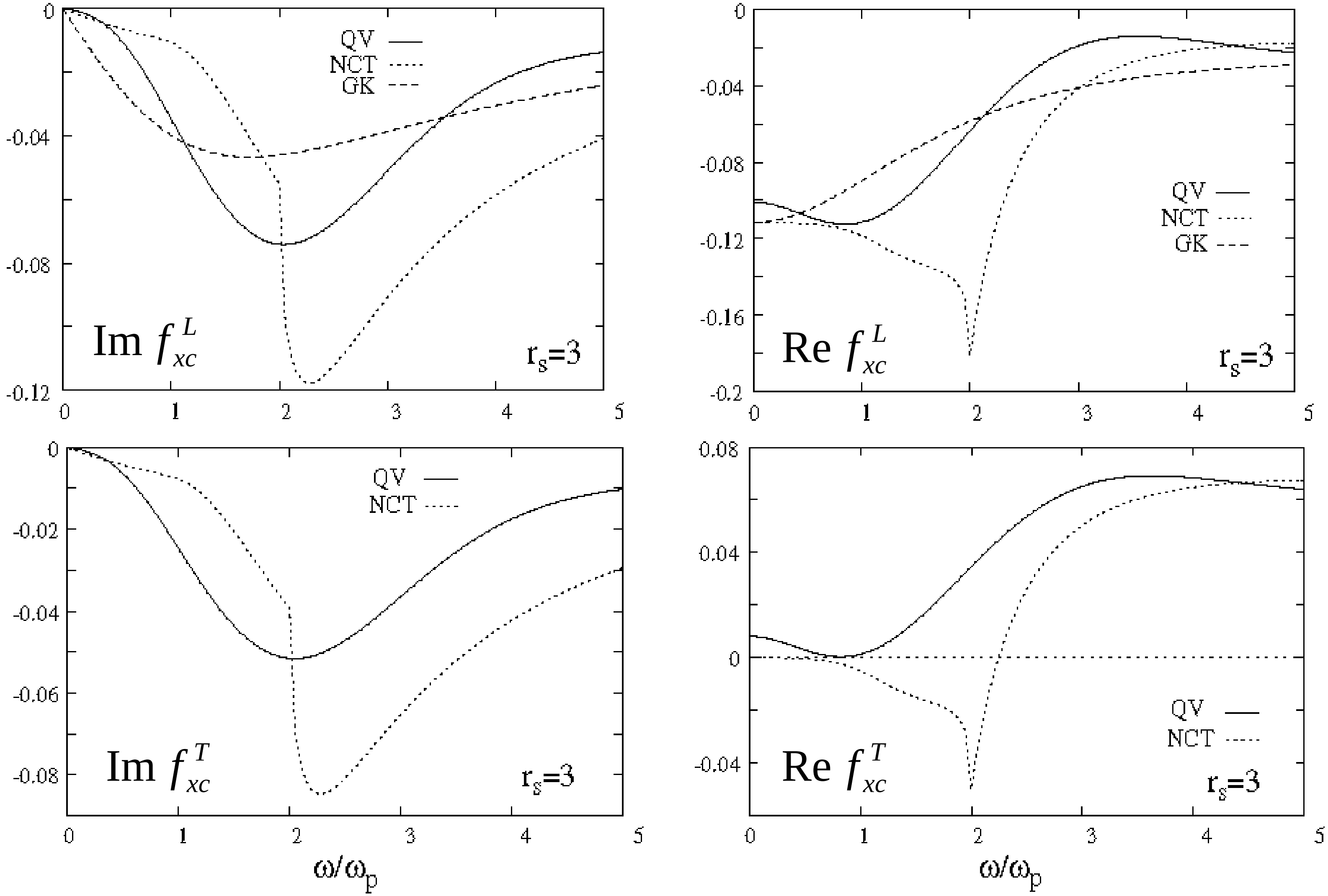
xc viscosity coefficients

$$\eta_{xc}(n,\omega) = -\frac{n^2}{i\omega} f_{xc}^{T}(n,\omega)$$

$$\zeta_{xc}(n,\omega) = -\frac{n^2}{i\omega}\left(f_{xc}^{L}(n,\omega) - \frac{4}{3} f_{xc}^{T}(n,\omega) - \frac{d^2 e_{xc}^{unif}}{dn^2} \right)$$

The xc viscosities have both real and imaginary parts, describing **dissipative** and **elastic** behavior.

xc kernels of the homogeneous electron gas



GK: E.K.U. Gross and W. Kohn, PRL **55**, 2850 (1985)
NCT: R. Nifosi, S. Conti, and M.P. Tosi, PRB **58**, 12758 (1998)
QV: X. Qian and G. Vignale, PRB **65**, 235121 (2002)

Applications of the VK functional

(A) In the (quasi)-static $\omega \to 0$ limit:

Polarizabilities of π-conjugated polymers (van Faassen et al.)
Nanoscale transport (Vignale, Di Ventra et al.)
Stopping power of slow ions in metals (Nazarov et al.)

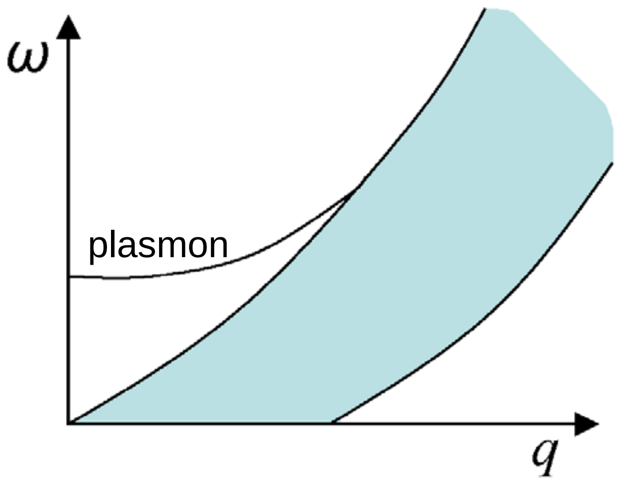
These applications profit from the fact that VK does not reduce to the ALDA in the static limit.

(B) To describe excitations at finite frequencies:

atomic and molecular excitation energies
plasmon excitations in doped semiconductor structures
optical properties of bulk metals and insulators
(De Boeij, Berger, Romaniello, van Leeuwen)

Here the picture is less clear. Some situations are well described, others fail.

Metallic systems vs. insulators

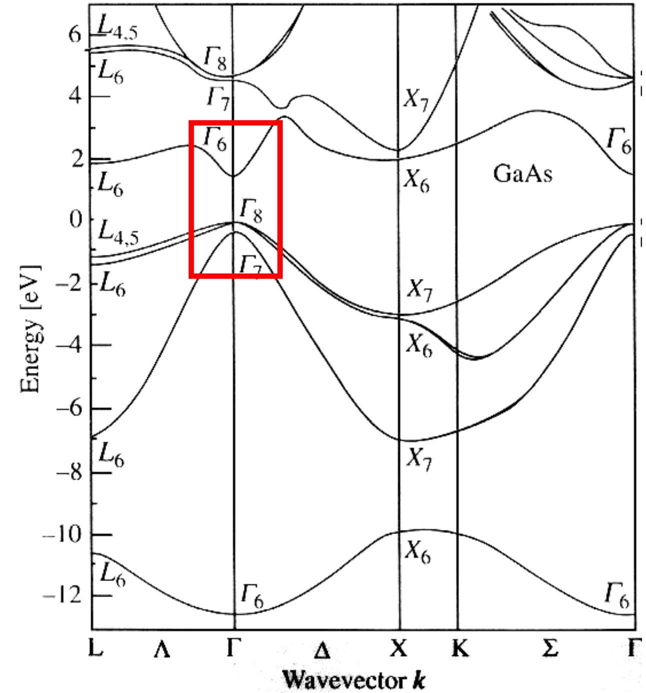


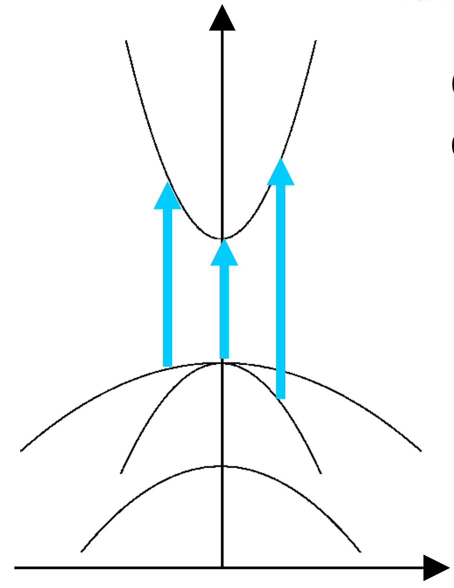
Excitation spectrum of simple metals:

single particle-hole continuum
(incoherent)

collective plasmon mode

RPA/ALDA misses plasmon
damping (multiple e-h excitations)

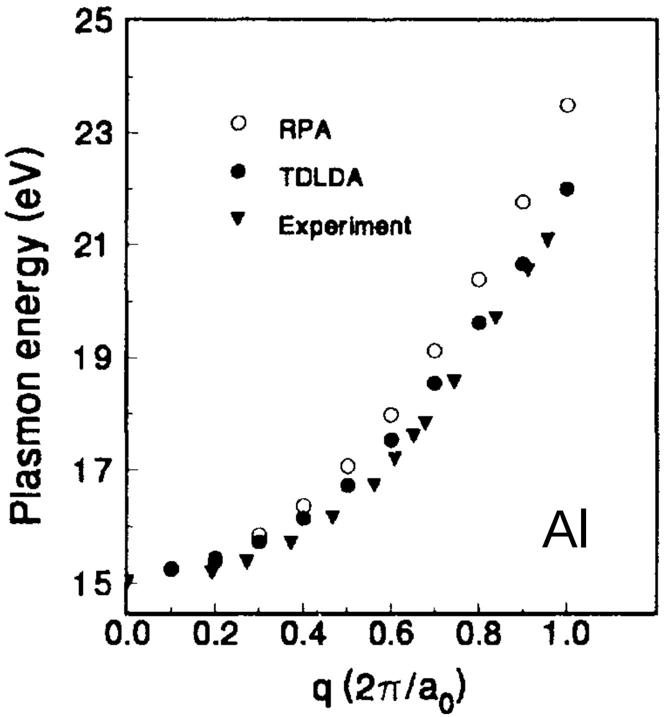




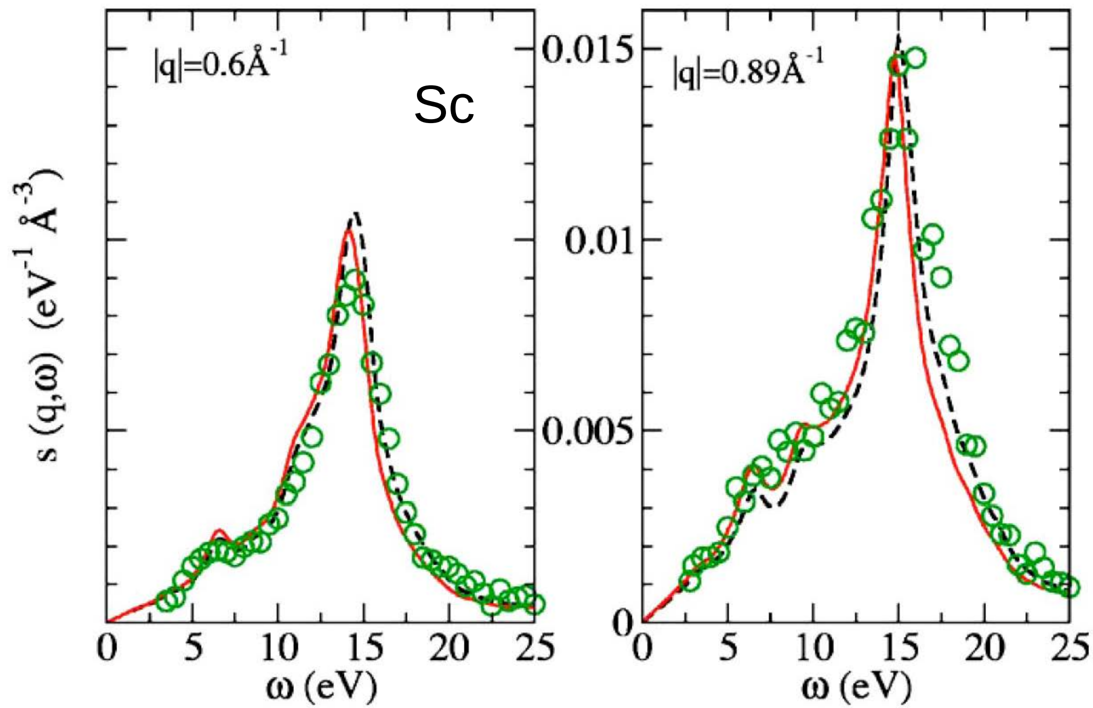
Optical excitations
of insulators:

interband transitions
excitons (bound
electron-hole pairs)

Plasmon excitations in bulk metals



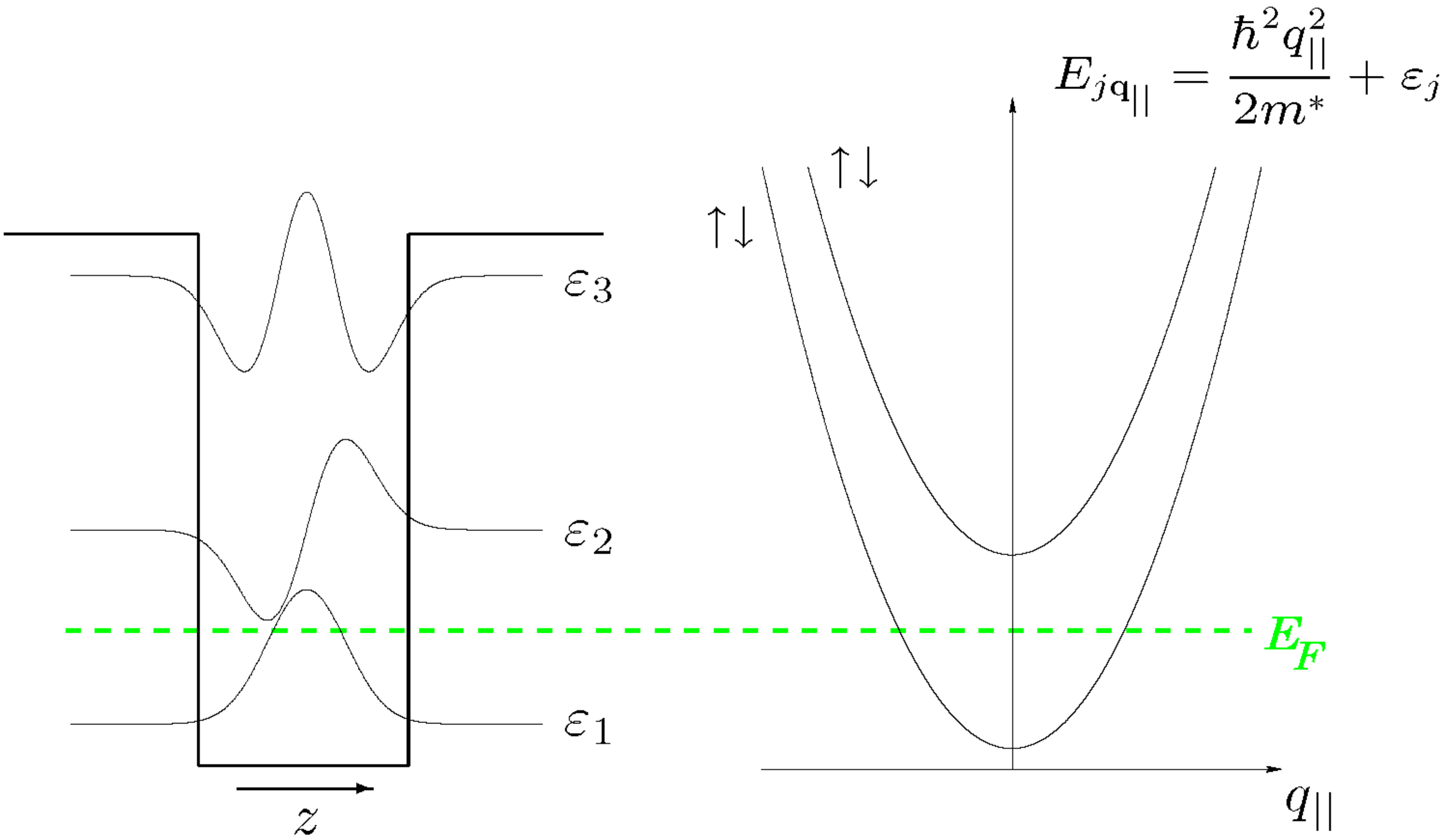
Quong and Eguiluz,
PRL **70**, 3955 (1993)



Gurtubay et al., PRB **72**, 125114 (2005)

- In general, excitations in (simple) metals very well described by ALDA.
- Time-dependent Hartree already gives the dominant contribution
- f_{xc} typically gives some (minor) corrections (damping!)
- This is also the case for 2DEGs in doped semiconductor heterostructures

Quantum well subbands

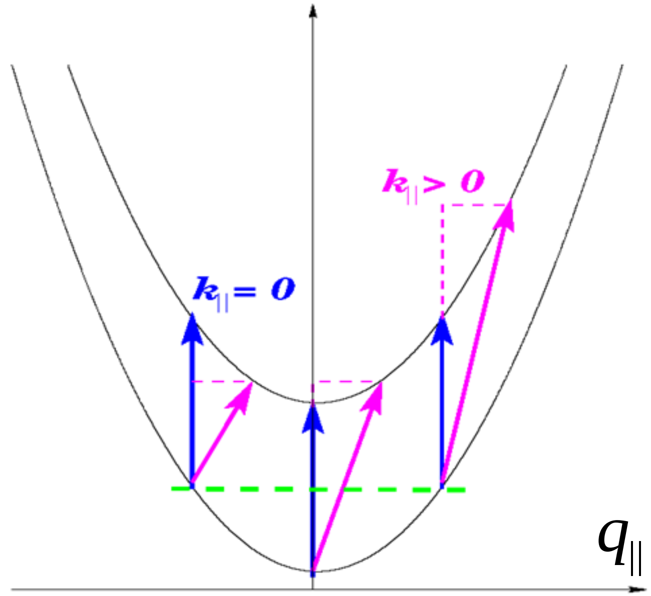


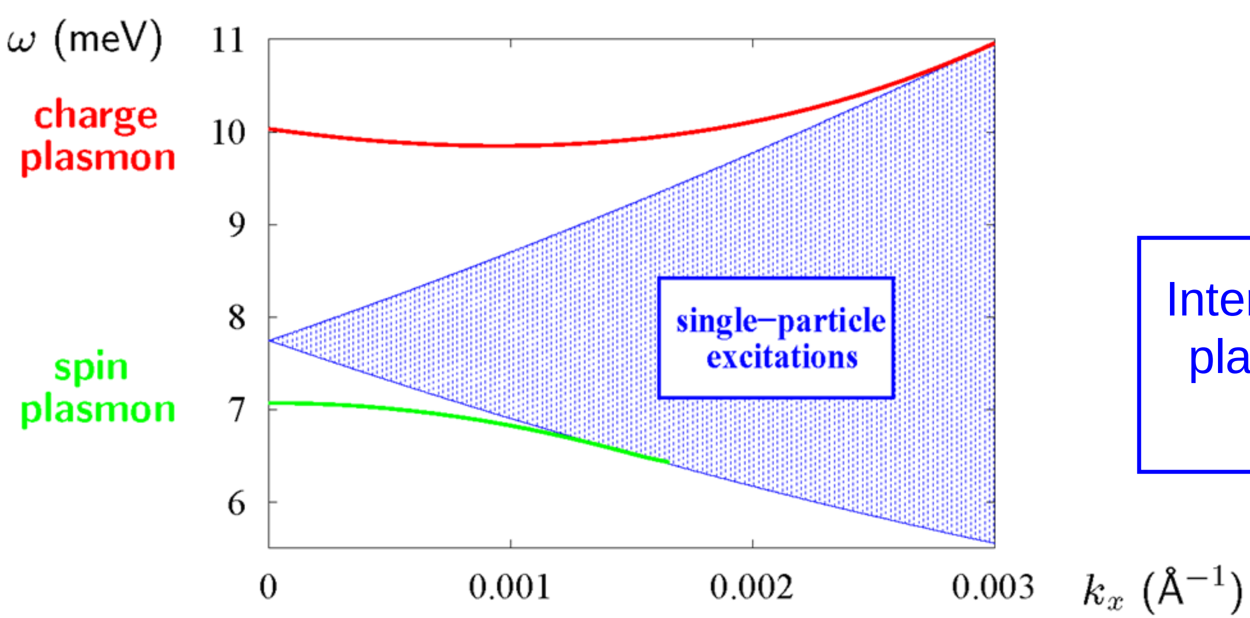
Electrons in a quantum well:

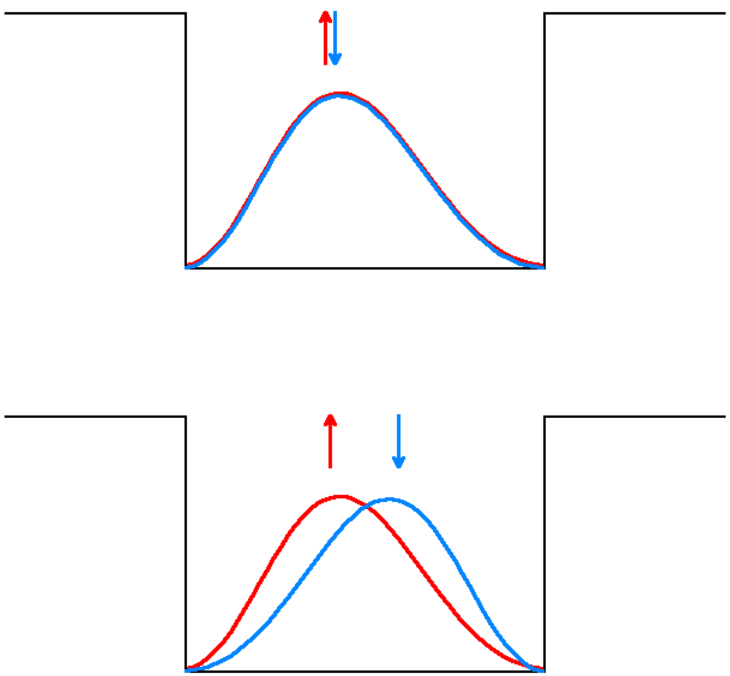
quantized in z-direction (discrete subbands)

►free in the x-y plane (each subband is parabolic)

Single-particle and collective excitations

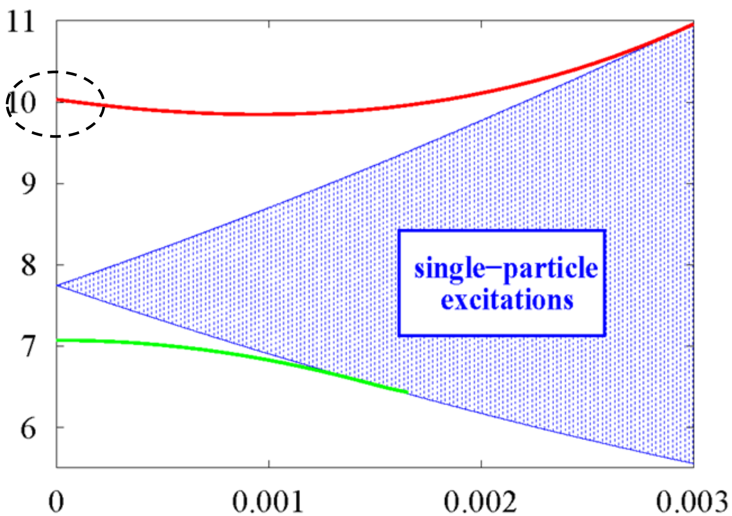


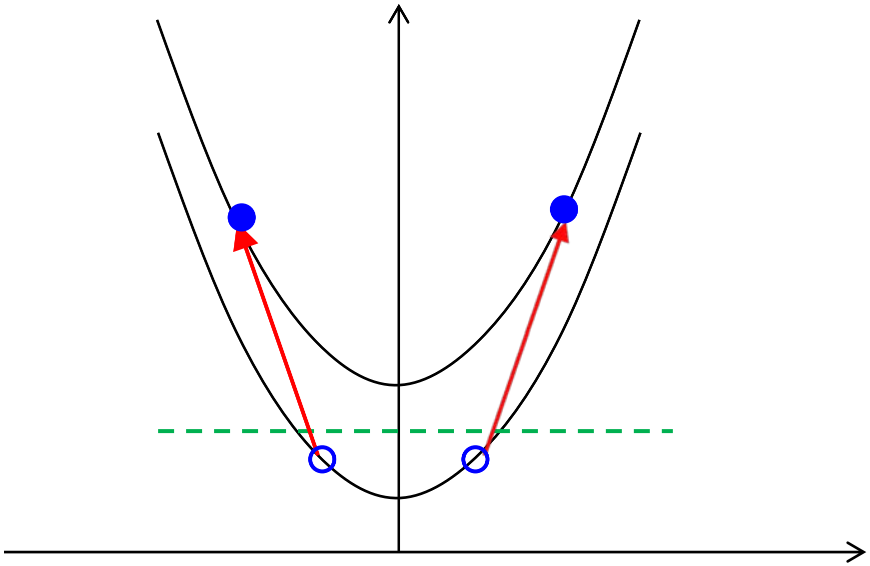


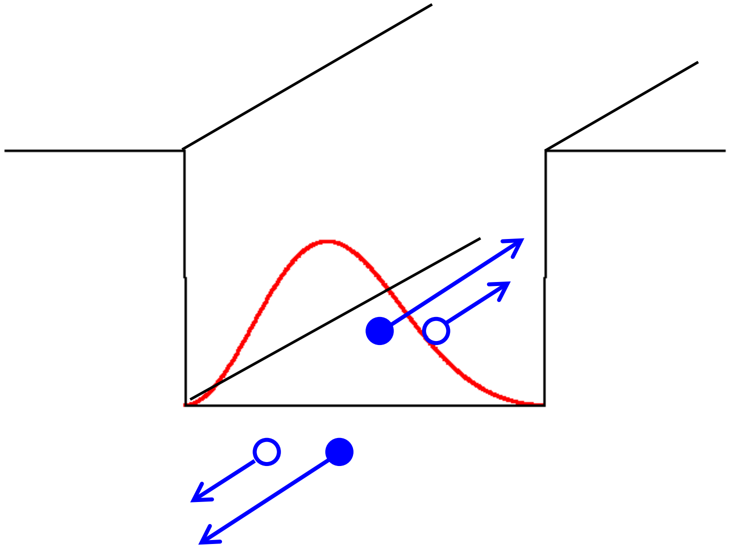


Intersubband charge and spin plasmons: ↑ and ↓ densities in and out of phase

Intrinsic plasmon damping mechanism







► Plasmon has energy and momentum different from any single p-h pair
→ **plasmon is robust**

► But, can find two p-h pairs at right energy, and combined right total momentum
→ **(weak) decay channel, requires Coulomb correlation beyond ALDA**

ISB plasmon frequency Ω and linewidth Γ

	Experiment	ALDA	GK_{GK}	GK_{NCT}	VK_{GK}	VK_{NCT}
Ω (single)	10.7	10.25	10.63	10.23	10.31	10.24
Γ (single)	0.53	—	0.683	0.655	0.128	0.104
Ω (double)	14.6	13.85	14.24	13.88	20.64	12.55
Γ (double)	1.17	—	1.00	0.403	8.55	4.15

Single well: VK gives good results for electronic linewidth
Double well: VK overestimates linewidth. The tunneling barrier makes the electronic flow very "non-hydrodynamic".

C.A. Ullrich and G. Vignale, Phys. Rev. B **58**, 15756 (1998)

Ultranonlocality in DFT: "upgrades"

Band insulators:

$$f_{xc}(\mathbf{k},\mathbf{k},0) \xrightarrow[k\to 0]{} \frac{\alpha}{k^2} \quad \Rightarrow \quad \textbf{Polarization DFT}$$

Gonze, Ghosez, and Godby, PRL **74**, 4035 (1995)

TDDFT:

$$f_{xc}(\mathbf{k},\mathbf{k},\omega) \xrightarrow[k\to 0]{} \frac{\alpha(\omega)}{k^2} \quad \Rightarrow \quad \textbf{TDCDFT}$$

Vignale and Kohn, PRL **77**, 2037 (1996),
Nazarov, Vignale & Chang, PRL **102**, 113001 (2009)

Spin-TDDFT:

$$f_{xc,\sigma\sigma'}^{unif}(\mathbf{k},\omega) \xrightarrow[k\to 0]{} \frac{A(\omega)}{k^2}\frac{\sigma\sigma' n^2}{4n_\sigma n_{\sigma'}} + B_{\sigma\sigma'}(\omega) \quad \Rightarrow \quad \textbf{TDSCDFT}$$

Situation even worse: ultranonlocality appears in the homogeneous case!

Qian, Constantinescu, Vignale, PRL **90**, 066402 (2003)

Spin-dependent generalization of VK functional

Qian, Constantinescu, Vignale,
PRL **90**, 066402 (2003)

spin-dependent generalization of the xc viscoelastic stress tensor depends on velocity gradients

$$\mathbf{A}_{xc,1\sigma}(\mathbf{r},\omega) = \mathbf{A}^{ALDA}_{xc,1\sigma}(\mathbf{r},\omega) - \frac{1}{i\omega n_\sigma(\mathbf{r})}\sum_{\sigma'} \nabla\cdot\overleftrightarrow{\sigma}_{xc,\sigma\sigma'}(\mathbf{r},\omega)$$
$$+\frac{n_\uparrow(\mathbf{r})n_\downarrow(\mathbf{r})\rho_{\uparrow\downarrow}(\mathbf{r},\omega)}{i\omega}\sum_{\sigma'}\frac{\sigma\sigma'}{n_\sigma(\mathbf{r})n_{\sigma'}(\mathbf{r})}\mathbf{j}_{\sigma'}(\mathbf{r},\omega)$$

$\rho_{\uparrow\downarrow}(\omega)$

spin-transresistivity

new term, depends on the velocities themselves
disappears in the static limit ($\rho_{\uparrow\downarrow}\sim\omega$)
real part: spin mass
imaginary part: spin Coulomb drag

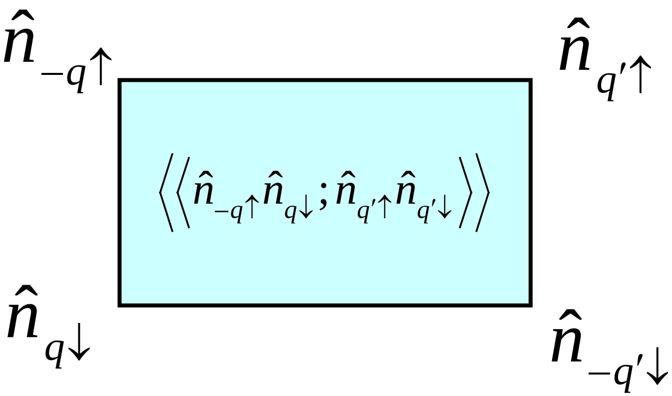
Microscopic theory of SCD (hom. systems)

Kubo formula: $$\sigma_{\alpha\beta}(\omega) = -\frac{1}{i\omega}\frac{e^2}{m}\left(n_\alpha \delta_{\alpha\beta} + \frac{1}{m}\langle\langle \mathbf{P}_\alpha ; \mathbf{P}_\beta \rangle\rangle_\omega\right)$$

$$\Rightarrow \quad \rho_{\uparrow\downarrow}(\omega) = \frac{i\omega}{e^2 n_\uparrow n_\downarrow}\langle\langle \mathbf{P}_\uparrow ; \mathbf{P}_\downarrow \rangle\rangle_\omega$$

can re-write this in terms of a force-force correlation function:

$$\mathrm{Re}\,\rho_{\uparrow\downarrow}(\omega) = -\frac{1}{e^2 n_\uparrow n_\downarrow \omega}\mathrm{Im}\langle\langle \mathbf{F}_\uparrow ; \mathbf{F}_\downarrow \rangle\rangle_\omega$$



$$\approx \left\{ \begin{matrix} \chi_{\uparrow\uparrow}(q,\omega') \\ \chi_{\downarrow\downarrow}(q,\omega') \end{matrix} \right\} + \left\{ \begin{matrix} \chi_{\downarrow\uparrow}(q,\omega-\omega') \\ \chi_{\uparrow\downarrow}(q,\omega-\omega') \end{matrix} \right\}$$

mode coupling approx.

Microscopic theory of the SCD

$$\mathrm{Re}\,\rho_{\uparrow\downarrow}(\omega,T)=\frac{\hbar^2}{n_\uparrow n_\downarrow V e^2}\sum_q \frac{q^2 v_q^2}{d}\frac{\left(e^{-\hbar\omega/k_BT}-1\right)}{\omega}$$

$$\times\int\frac{d\omega'}{\pi}\frac{\left[\chi''_{\uparrow\uparrow}(q,\omega')\chi''_{\downarrow\downarrow}(q,\omega-\omega')-\chi''_{\uparrow\downarrow}(q,\omega')\chi''_{\downarrow\uparrow}(q,\omega-\omega')\right]}{\left(e^{-\hbar\omega'/k_BT}-1\right)\left(e^{-\hbar(\omega-\omega')/k_BT}-1\right)}$$

In the DC limit, one obtains

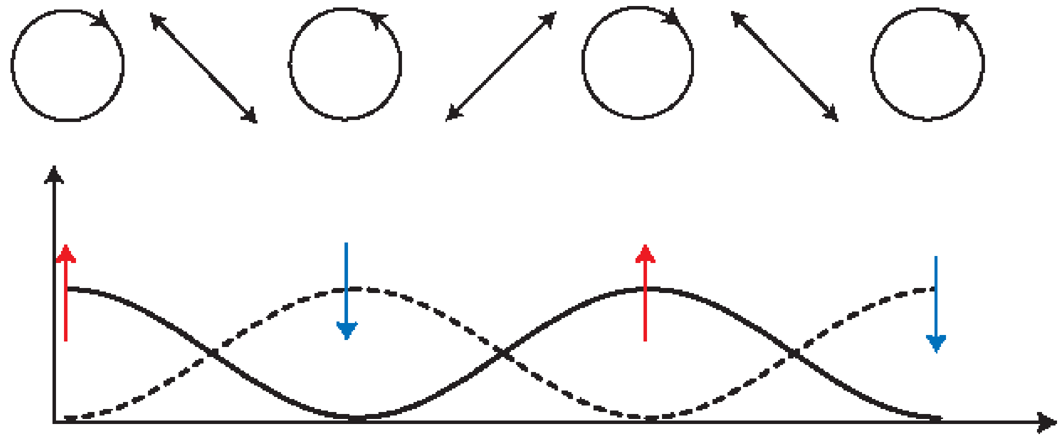
$$\rho_{\uparrow\downarrow}(T)=\frac{\hbar^2}{4n_\uparrow n_\downarrow k_B T V e^2}\sum_q \frac{q^2 v_q^2}{d}\int_0^\infty\frac{d\omega'}{\pi}\frac{\mathrm{Im}\,\chi_{0\uparrow}(q,\omega')\,\mathrm{Im}\,\chi_{0\downarrow}(q,\omega')}{\left|\varepsilon(q,\omega')\right|^2\sinh^2\left(\hbar\omega'/2k_BT\right)}$$

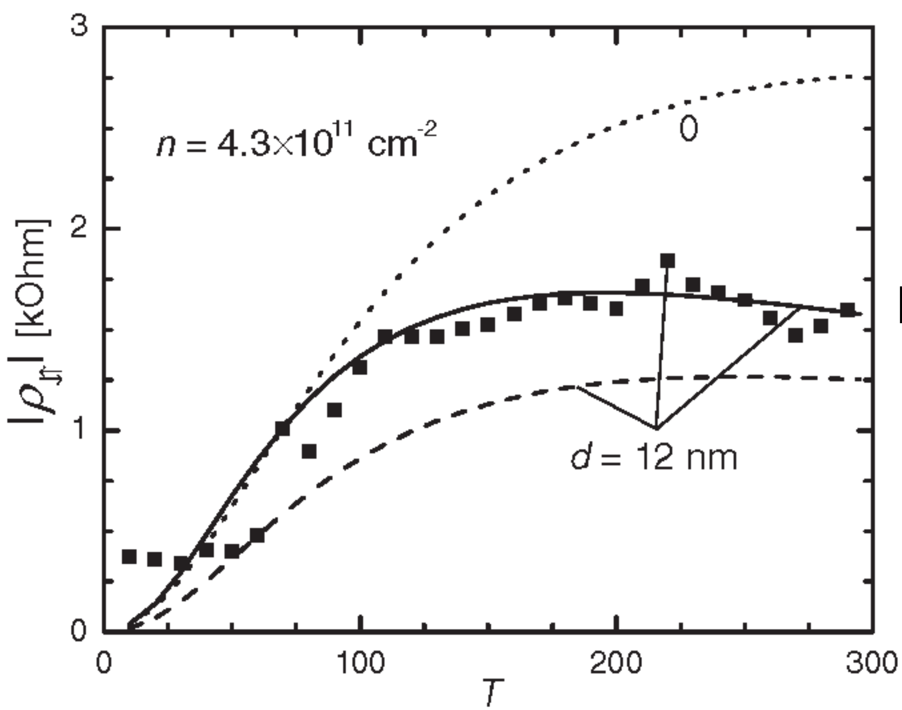
RPA: D'Amico and Vignale, PRB **62**, 4853 (2000)
Beyond RPA: Badalyan, Kim, and Vignale, PRL **100**, 016603 (2008)

Experimental evidence of SCD

Weber, Gedik, Moore, Orenstein, Stephens, and Awschalom, Nature **437**, 1330 (2005)

Transient spin grating plus time-resolved Kerr effect spectroscopy to measure spin diffusion constant





RPA, 2D

RPA+XC, finite width

RPA, finite width

Badalyan, Kim, and Vignale, PRL **100**, 016603 (2008)

Spin-resolved excitation spectrum in TDDFT

(complex) excitation frequency

$$\Omega_{\pm\sigma}^2 \approx \omega_{pq\sigma}^2 + 2\omega_{pq\sigma} S_{\pm\sigma}$$

linewidth

$$\Gamma_{\pm} \approx \mathrm{Im}\, S_{\pm\sigma}$$

$\omega_{pq\sigma}$ = bare single-particle excitation frequency between levels p and q

$$S_{\pm\sigma} = \left(S_{\sigma\bar{\sigma}}^{H+ALDA} \pm S_{\sigma\bar{\sigma}}^{H+ALDA}\right) + \left(S_{\sigma\bar{\sigma}}^{VE} \pm S_{\sigma\bar{\sigma}}^{VE}\right) + \left(S_{\sigma\bar{\sigma}}^{SCD} \pm S_{\sigma\bar{\sigma}}^{SCD}\right)$$

Hartree + ALDA: real
(no dissipation)

Viscoelastic + SCD: complex
(dissipative)

Total linewidth: $\Gamma_{\pm} = \Gamma_{\pm}^{disorder} + \Gamma_{\pm}^{VE} + \Gamma_{\pm}^{SCD}$

I. D'Amico and C.A. Ullrich, Phys. Rev. B **74**, 121303(R) (2006)

SC-TDDFT energy shift for excitation energies

$$S_{\sigma\sigma'}^{H+ALDA} = \int d^3r \int d^3r' \left[\frac{1}{|\vec{r}-\vec{r}'|} + f_{xc,\sigma\sigma'}^{ALDA}(\vec{r},\vec{r}') \right] \varphi_{p\sigma}(\vec{r})\varphi_{q\sigma}(\vec{r})\varphi_{p\sigma'}(\vec{r}')\varphi_{q\sigma'}(\vec{r}')$$

$$S_{\sigma\sigma'}^{VE} = \frac{i\omega}{\omega_{pq\sigma}^2} \int d^3r \overleftrightarrow{\sigma}_{\sigma\sigma'}^{xc,pq}(\vec{r},\omega) \vec{\nabla} \left[\frac{\vec{j}_{pq\sigma}(\vec{r})}{n_\sigma(\vec{r})} \right]$$

$$\left(S_{\sigma\bar{\sigma}}^{SCD} \pm S_{\sigma\bar{\sigma}}^{SCD} \right) = \frac{ie^2\omega}{\omega_{pq\sigma}^2} \int d^3r \left[\frac{n_{\bar{\sigma}}}{n_\sigma} \left| \vec{j}_{pq\sigma} \right|^2 \mp \vec{j}_{pq\bar{\sigma}} \cdot \vec{j}_{pq\sigma} \right] \rho_{\uparrow\downarrow}(\omega; n_\uparrow, n_\downarrow)$$

structure of a (complex) power loss
term in an AC spintronics circuit

Comparison with experiment

VOLUME 63, NUMBER 15 PHYSICAL REVIEW LETTERS 9 OCTOBER 1989

Large Exchange Interactions in the Electron Gas of GaAs Quantum Wells

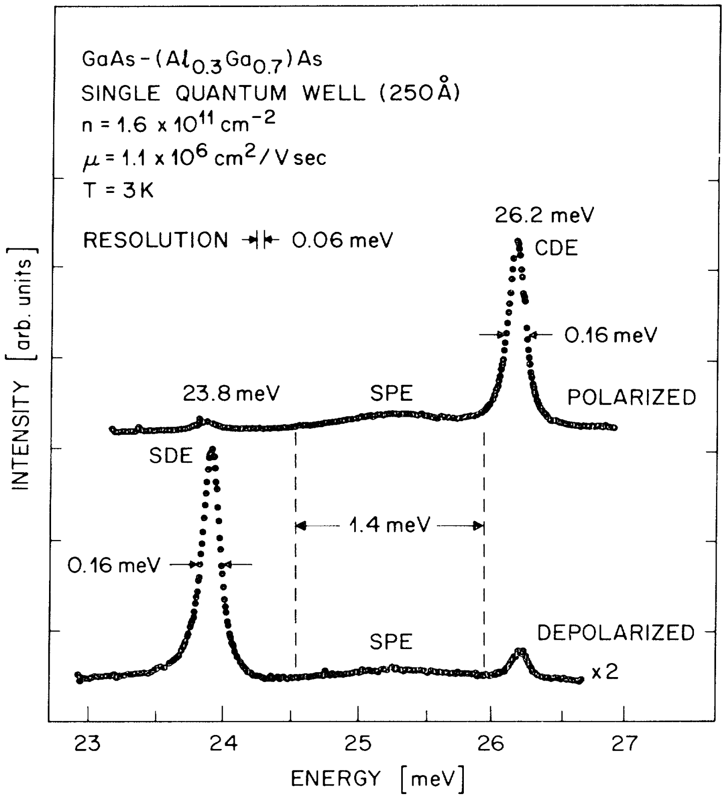
A. Pinczuk, S. Schmitt-Rink, G. Danan, J. P. Valladares, L. N. Pfeiffer, and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

Results with local approximation:

SDE: $$\begin{cases} \Gamma^{SCD} = 0.40\,\mathrm{meV} \\ \Gamma^{VE} = 0.04\,\mathrm{meV} \end{cases}$$

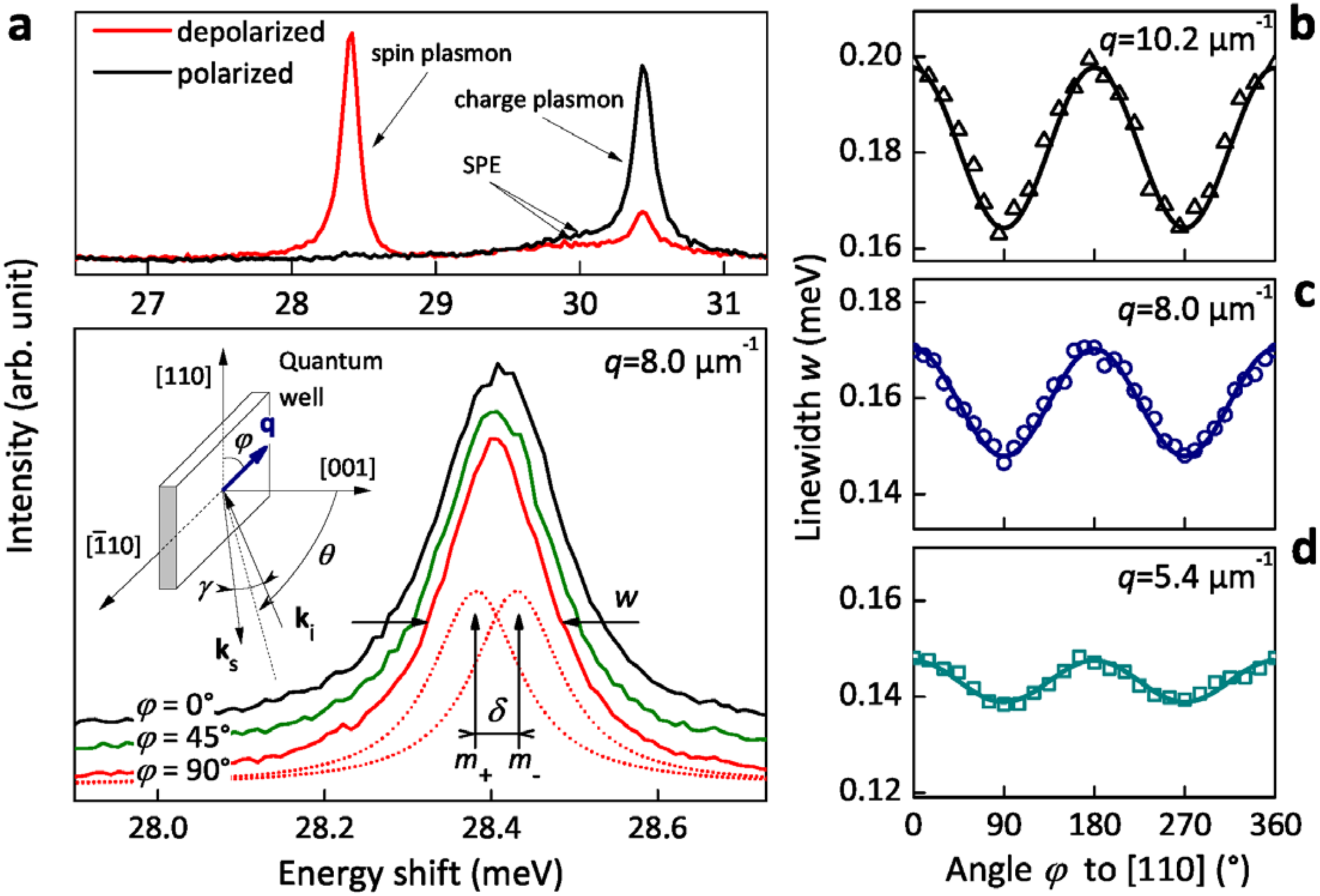
CDE: $$\Gamma^{VE} = 0.30\,\mathrm{meV}$$

overdamping!



Comparison with experiment

F. Baboux, F. Perez, C.A. Ullrich, I. D'Amico, J. Gomez, M. Bernard, PRL **109**, 166401 (2012)



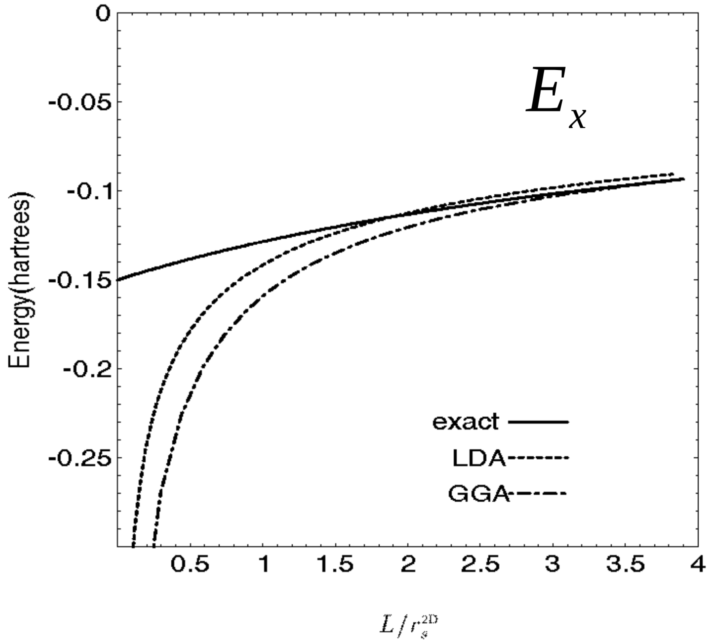
Linewidth modulated by spin-orbit coupling

Again, SCD linewidth overestimated by factor 2-3

The local approximations in quasi-2D

For structure, the 3D LDA is fine, as long as the quantum well is not too narrow: $L \geq r_s^{2D}$

L. Pollack and J.P. Perdew,
J. Phys.: Condens. Matter **12**, 1239 (2000)



Exchange and correlation energies in typical quantum wells are well reproduced.

The local approximations in quasi-2D

For dynamics, it depends:

Plasmon <u>dispersions</u> are fine with 3D ALDA (about as accurate as singlet-triplet excitation energies in atoms).

ISB plasmon is dominated by $\Delta\varepsilon = \varepsilon_2 - \varepsilon_1$ with relatively minor many-body corrections.

$$\Delta\varepsilon >> \Gamma$$

Plasmon <u>damping</u> fails with 3D local approximation: size quantization creates a bottleneck for dissipation into lateral electronic degrees of freedom.

Dissipation is purely nonclassical many-body physics:

The physics is not contained in the Kohn-Sham reference system

Need detailed information on the structure of the single-particle spectrum:

Difficult to do in terms of the local current only!

But the p-h spectrum can be accurately described in LDA (even RPA)

R. D'Agosta, M. Di Ventra, and G. Vignale, PRB **76**, 035320 (2007)

Conclusion

► TDCDFT can be used for nonadiabatic dynamics, but choosing the right reference system is crucial!

► Local approximations (based on 3D HEG) work well in the thermodynamical/bulk limit, but fail for quantum confined systems

► Plasmon damping in quantum well as an example of the crossover 3D/2D: ‘’tough’’ dynamics has no counterpart in the Kohn-Sham system

► In general, multiple/correlated excitations are better described using many-body techniques.

► A microscopic calculation of the spin plasmon linewidth was presented, which gives good agreement with experiment (the slides were removed, since they contain unpublished results).