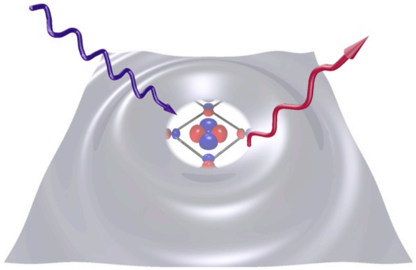


Electron-boson coupling: Beyond the equilibrium interpretation

Alexander. F. Kemper
North Carolina State University

PRX 3, 041033 (2013)
PRB 87, 235139 (2013)
PRB 90, 075126 (2014)
arXiv:1505.07055 (updated tomorrow)

APS March Meeting, March 7, 2016

M.A. Sentef (MSPD)

J.K. Freericks (Georgetown)

B. Moritz, T.P. Devereaux (Stanford/SLAC)

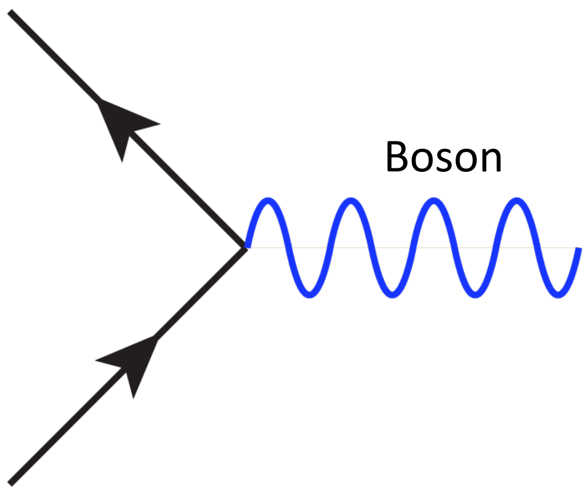
J.D. Rameau, P.D. Johnson (BNL)

S. Freutel, M. Ligges, I. Avigo, U. Bovensiepen (Duisburg-Essen)

Electron-boson coupling: Beyond the equilibrium interpretation

- Electron-boson coupling in cuprates
- Boson interactions and population decay rates
- Violation of Matthiessen's rule in the time domain

Electron-boson coupling



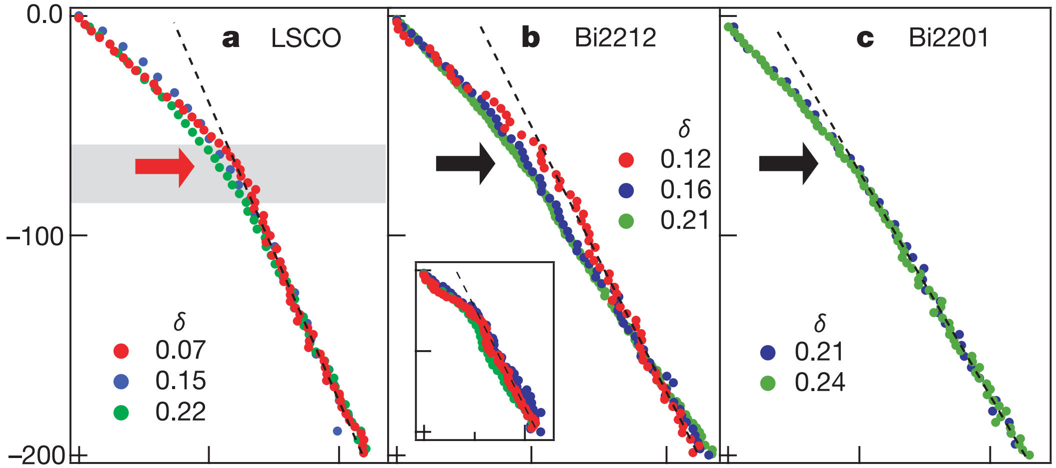
Phonons
Magnons
Spin fluctuations
Plasmons
Orbitons
...

$$H = \sum_{\mathbf{k}} \epsilon(\mathbf{k}) c^{\dagger}_{\mathbf{k}} c_{\mathbf{k}} + \sum_{q} \Omega_{\mathbf{q}} b^{\dagger}_{\mathbf{q}} b_{\mathbf{q}} + \sum_{\mathbf{kq}} g^{2}_{\mathbf{k},\mathbf{q}} c^{\dagger}_{\mathbf{k}+\mathbf{q}} c_{\mathbf{k}} (b_{\mathbf{q}} + b^{\dagger}_{-\mathbf{q}})$$

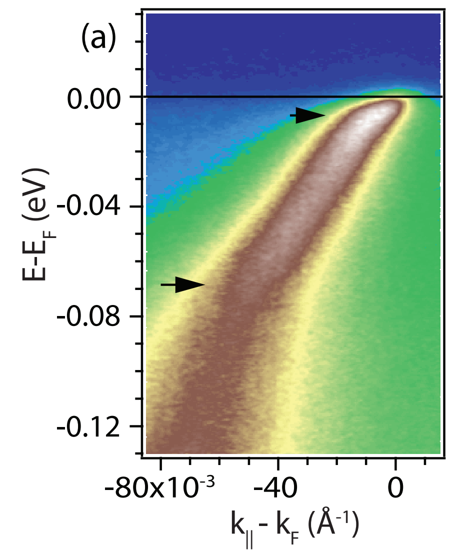
Electrons | Bosons | Electron-boson coupling

Kinks in the quasiparticle dispersion

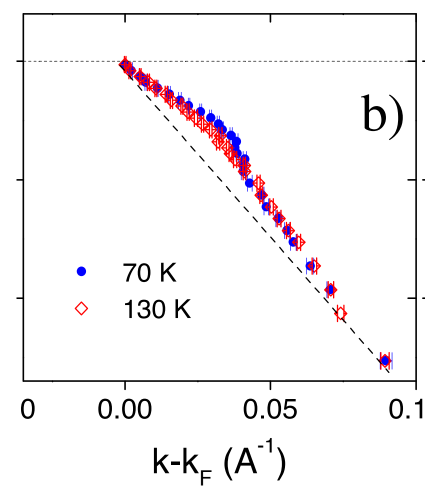
Lanzara, Nature (2001)



Johnston, PRL (2012)

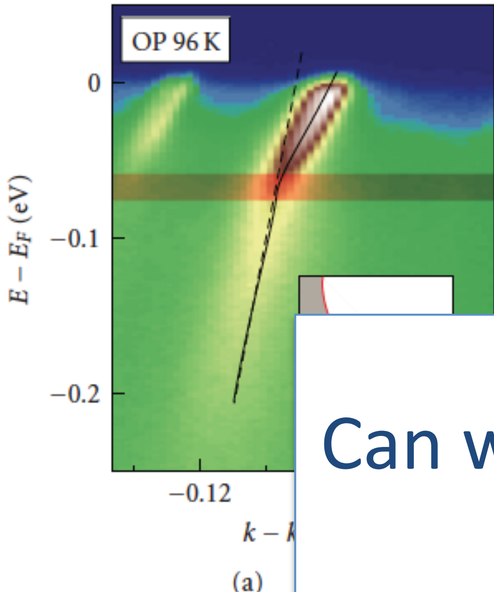


Johnson, PRL (2001)



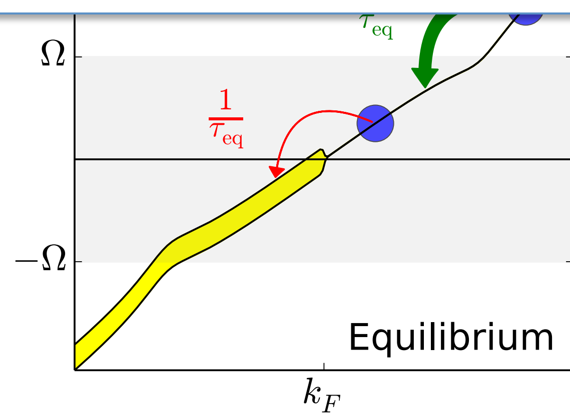
- Indications of coupling to bosons
  - Origin?
  - Effects on quasiparticles

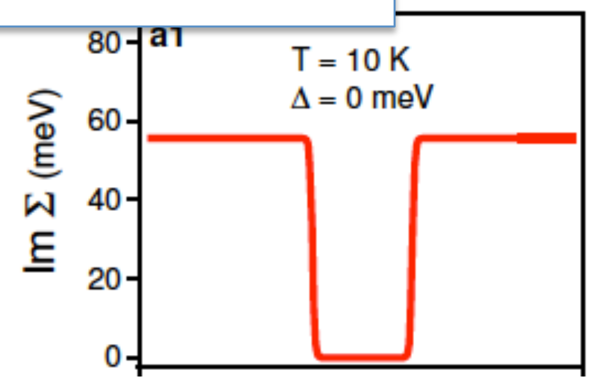
Manifestations of electron-boson interactions in spectra



Kinks in dispersion
→ coupling to bosonic modes
(phonons, spin fluctuations, …)

Can we measure lifetimes τ directly in the time domain?

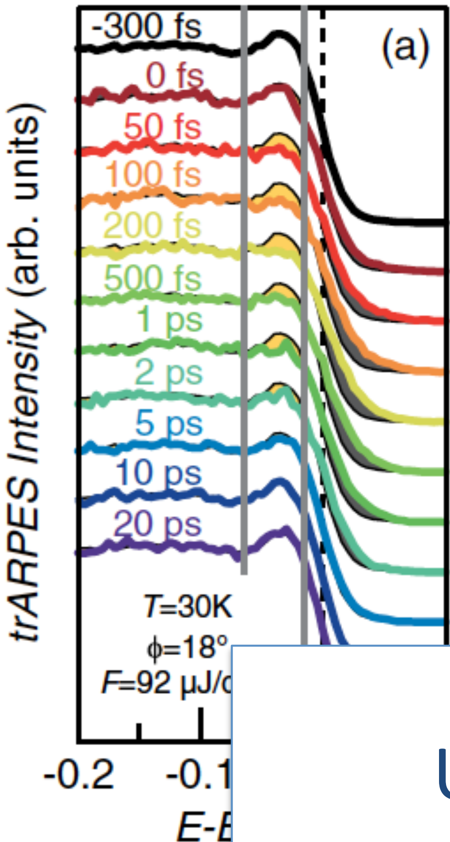


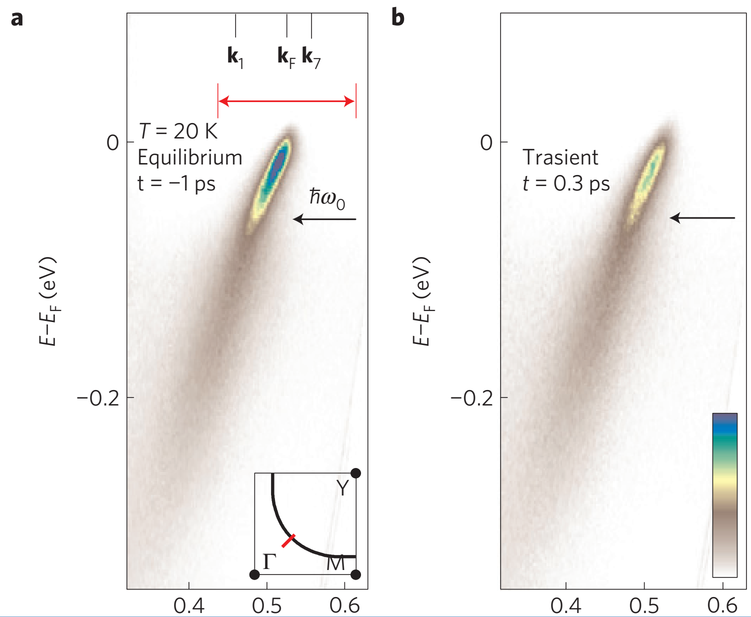


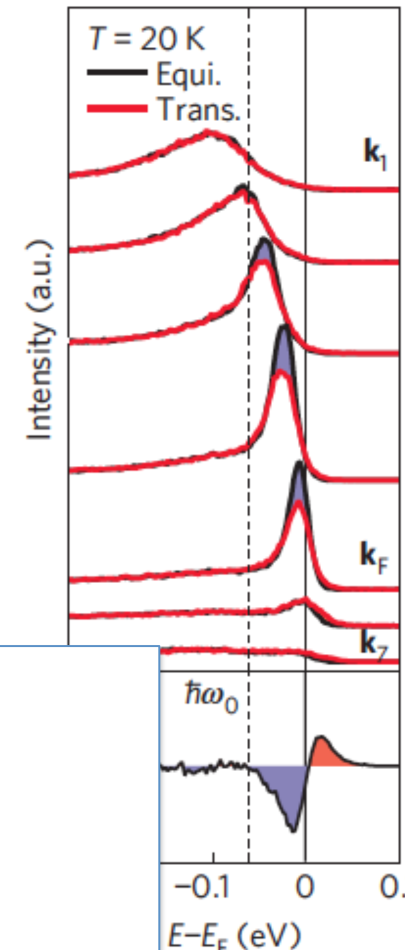
S. Johnston et al., Adv. CMP (2010)

Cuk et al, Physica Scripta (2006)

Manifestations of electron-boson interactions in time-resolved spectra







Use theory to simulate and understand time dynamics

R. Cortes et al., PRL (2011)

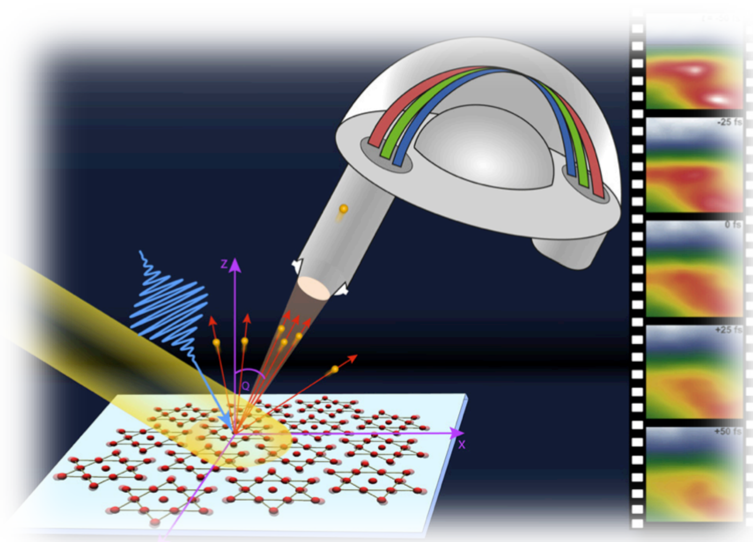
J. Graf et al., Nat. Phys. (2011)

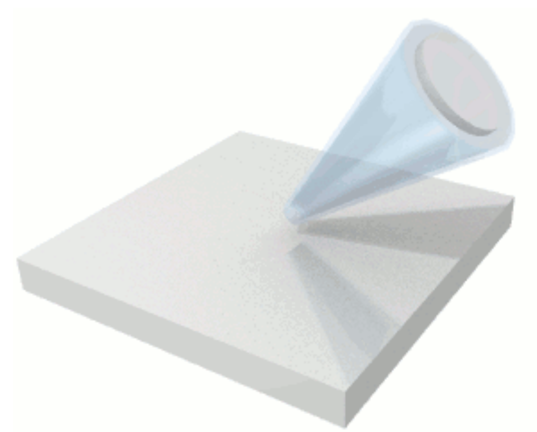
Electron-boson coupling: Beyond the equilibrium interpretation

- Electron-boson coupling in cuprates
- Boson interactions and population decay rates
- Violation of Matthiessen's rule in the time domain

- Time- and angle-resolved photoemission spectroscopy

Image courtesy of J. Harms, University of Hamburg





(1) Incoming light pulse (the pump) excites electrons and lattice

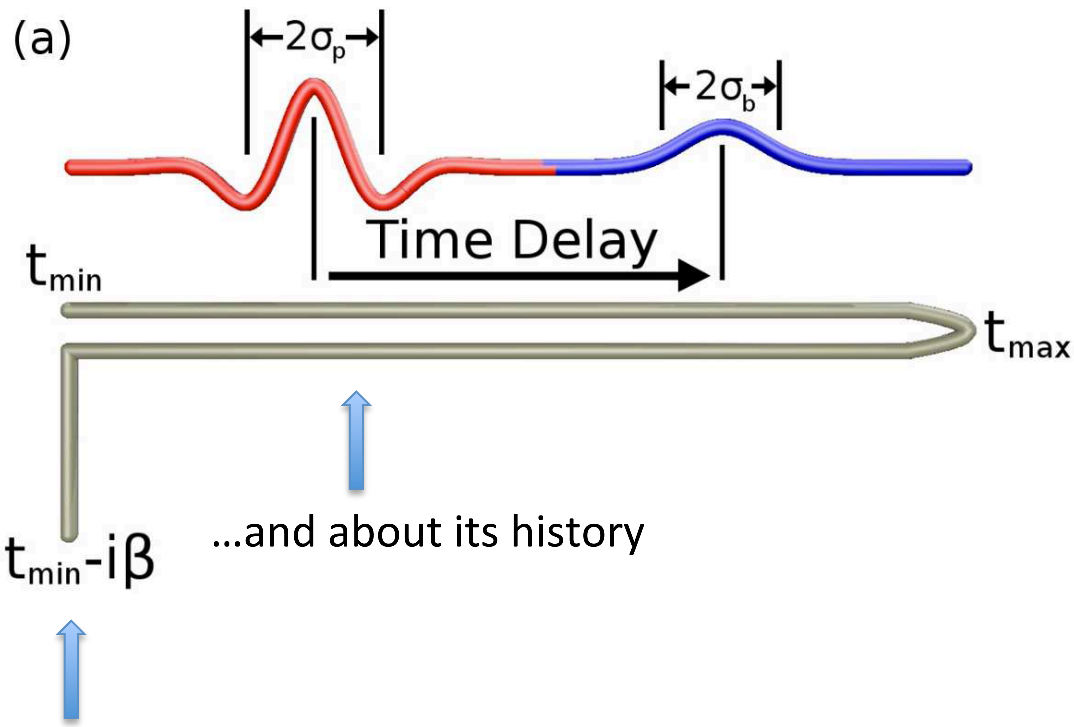
(2) Second incoming light pulse (the probe) ejects electrons (called photoemission) some time Δt later

(3) Excited electrons are measured as a function of their energy and momentum

Non-Equilibrium Keldysh Formalism

$$G_{\mathbf{k}}(t,t') = G^0_{\mathbf{k}}(t,t') + \int dt_1 dt_2 G^0_{\mathbf{k}}(t,t_1)\Sigma(t_1,t_2)G_{\mathbf{k}}(t_2,t')$$

$$G_k(\omega) = G^0_k(\omega) + G^0_k(\omega)\Sigma(\omega)G_k(\omega)$$



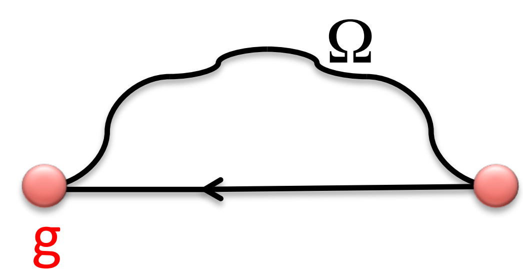
System knows about its thermal initial state...

self-energy Σ:
electron-electron scattering
electron-phonon scattering
...

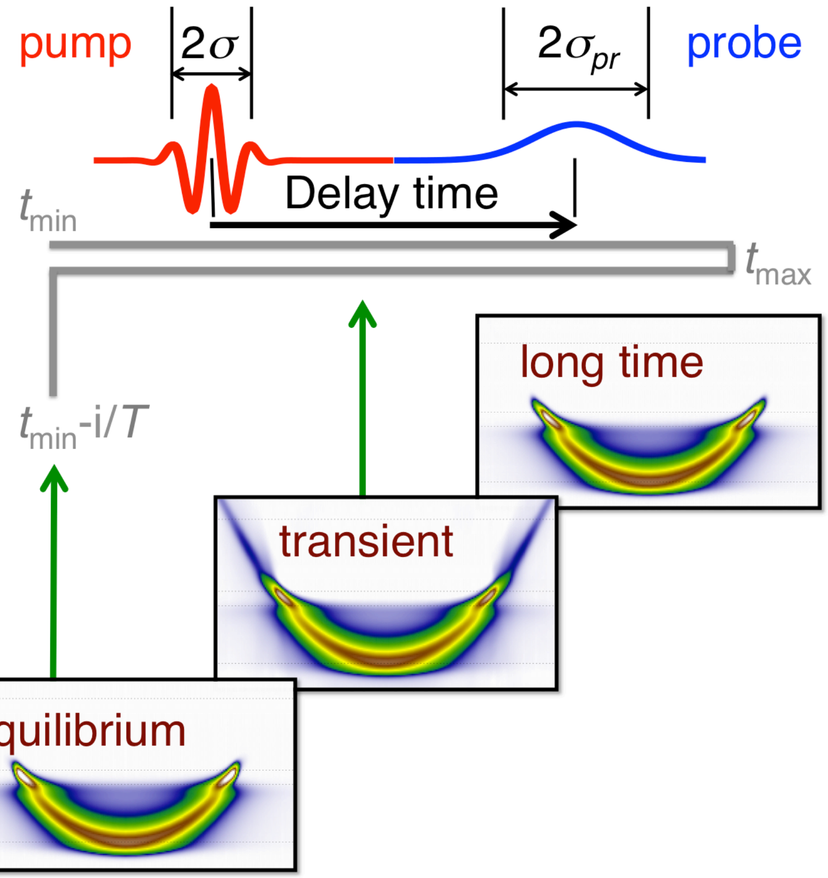
Include the effects of strong driving field through Peierls substitution

$$\boldsymbol{k} \rightarrow \boldsymbol{k} - e\mathbf{A}(t)$$

$\Sigma =$



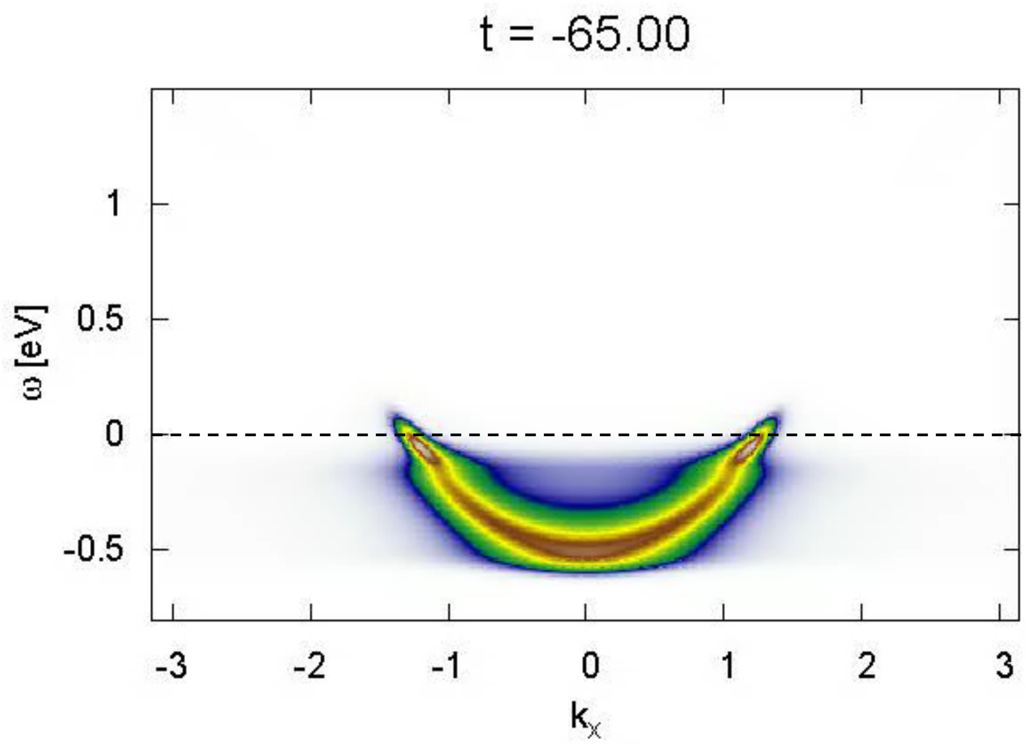
Pump-probe photoemission



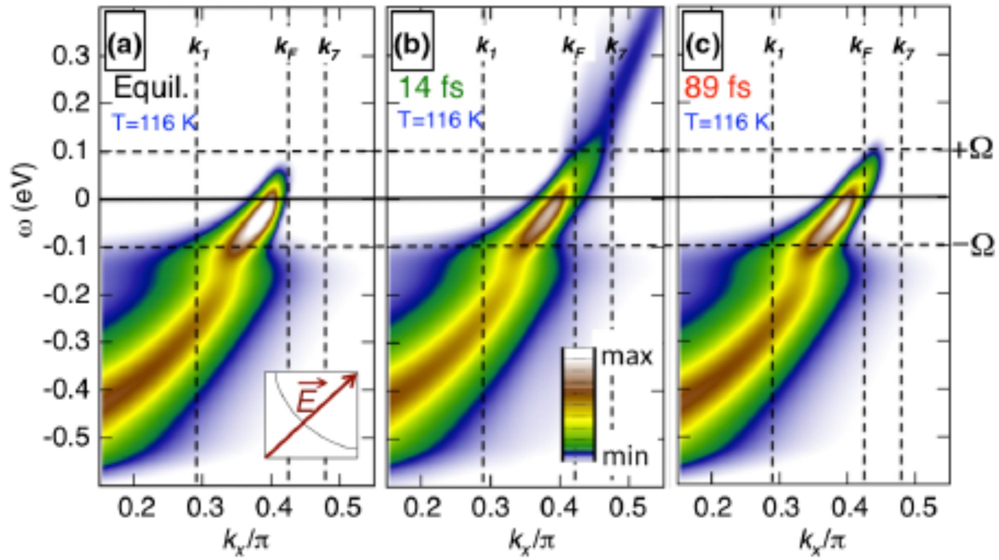
$$A_{\mathbf{k}}(\omega, t_0) = \mathrm{Im}\,\frac{1}{2\pi\sigma^2}\int dt dt' G^<_{\mathbf{k}}(t,t') e^{-(t-t_0)^2/2\sigma^2} e^{-(t'-t_0)^2/2\sigma^2} e^{i\omega(t-t')}$$

M. Eckstein and M. Kollar, PRB (2008), J. K. Freericks et al., PRL (2009), J. K. Freericks et al.

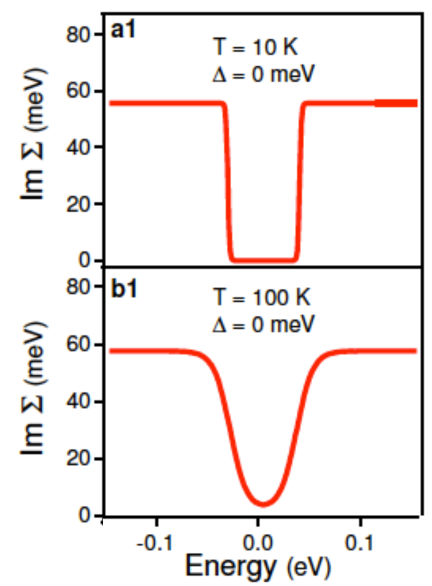
Electron-lattice coupling

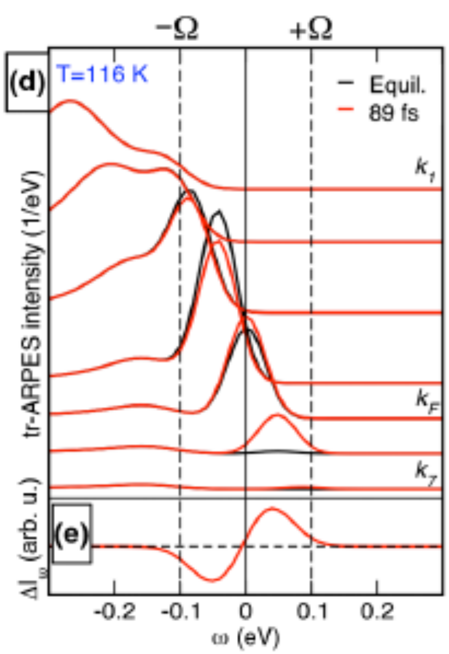


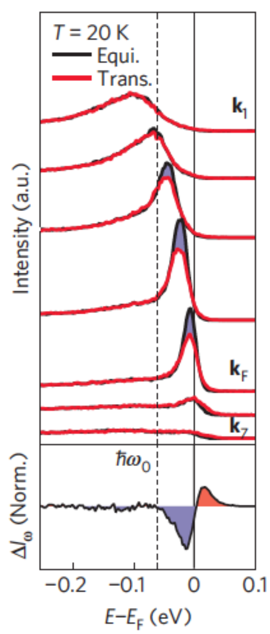
Phys. Rev. X 3, 041033



Return to equilibrium significantly slowed within a window around E_F

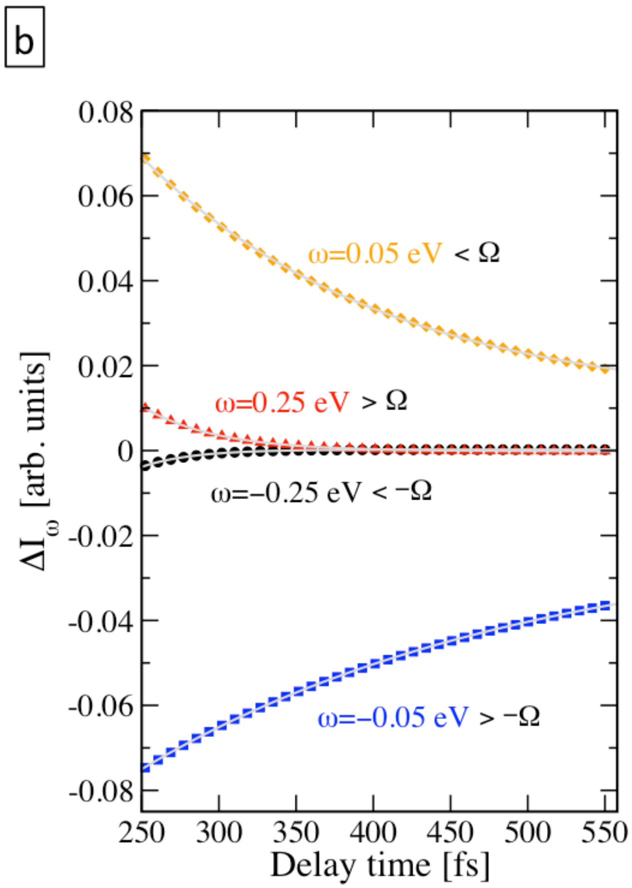


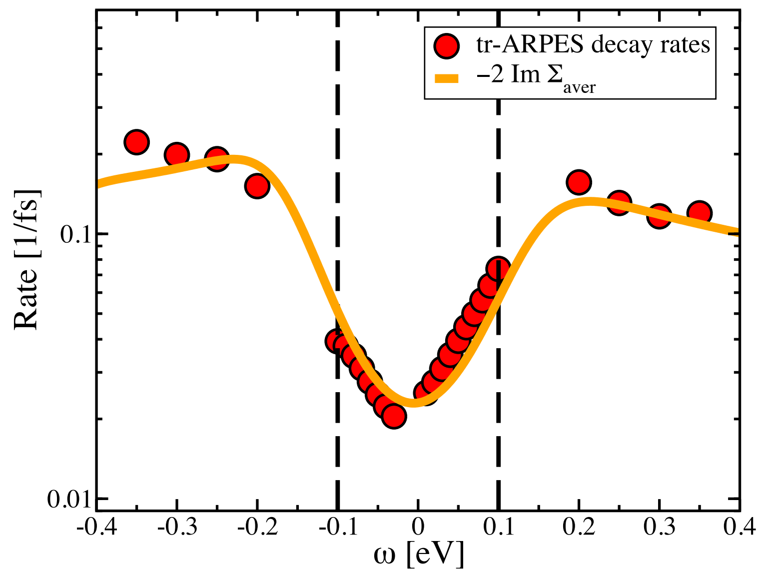


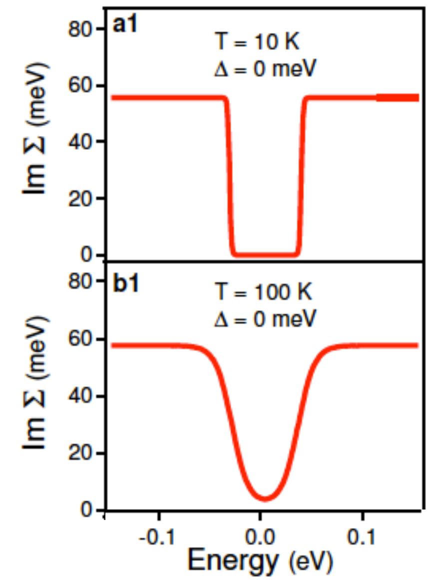


J. Graf et al., Nat. Phys. (2011)

Electron-lattice coupling



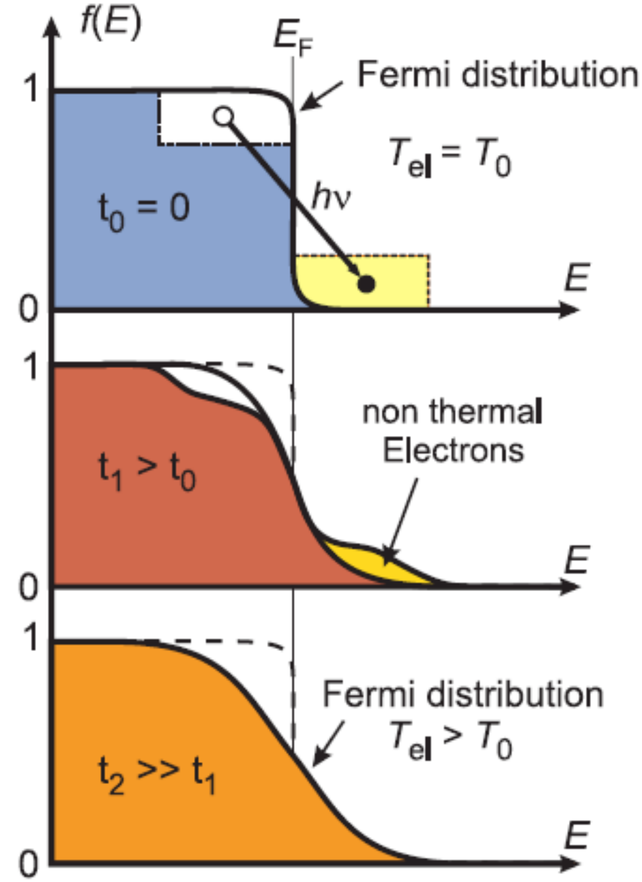




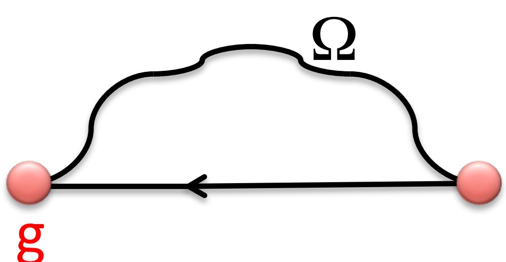
$$1/\tau(\omega)$$

M. Sentef, Phys. Rev. X 3, 041033

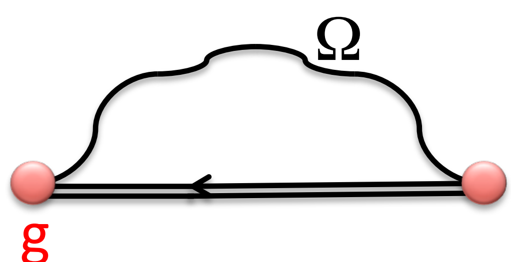
How does the pump fluence affect these results?



We should account for the changes in the distribution self-consistently.

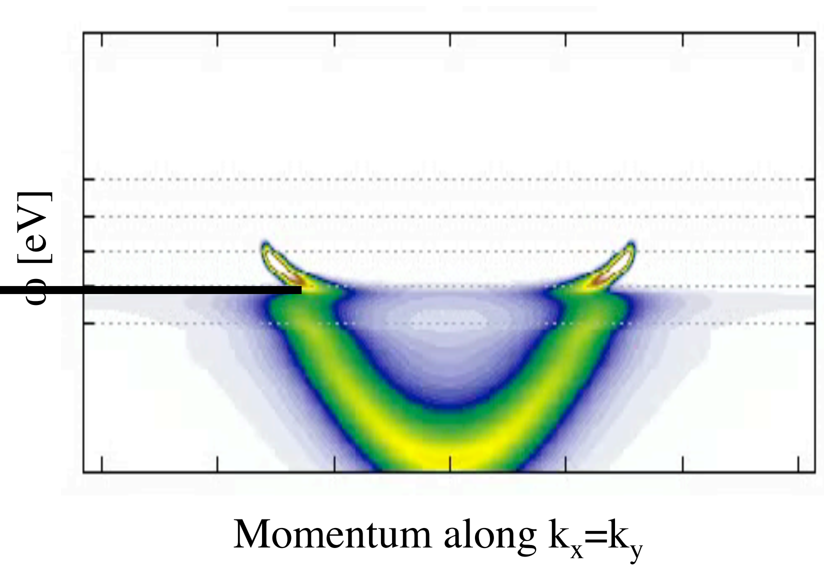
$\Sigma =$ 

$\Sigma[G^0]$

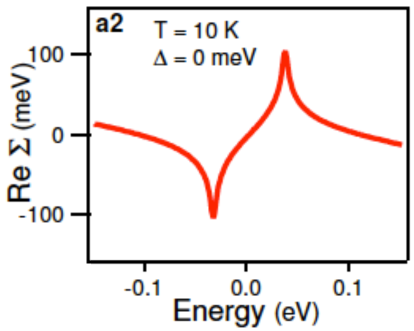
$\Sigma =$ 

$\Sigma[G]$

Driving beyond the weak limit



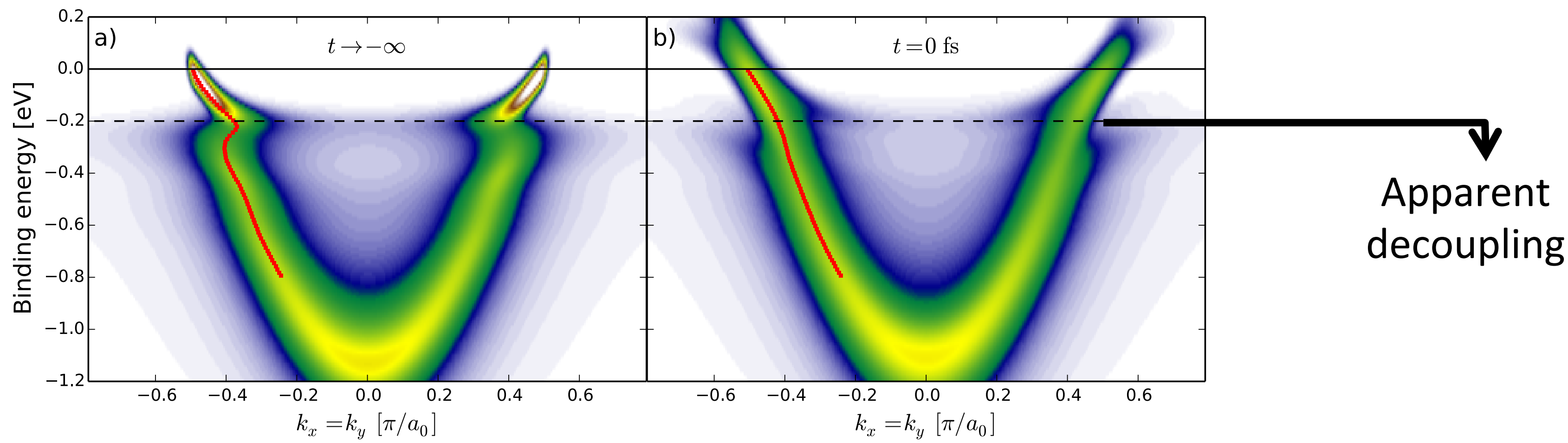
Sharp kink is a signature of large electron-boson coupling

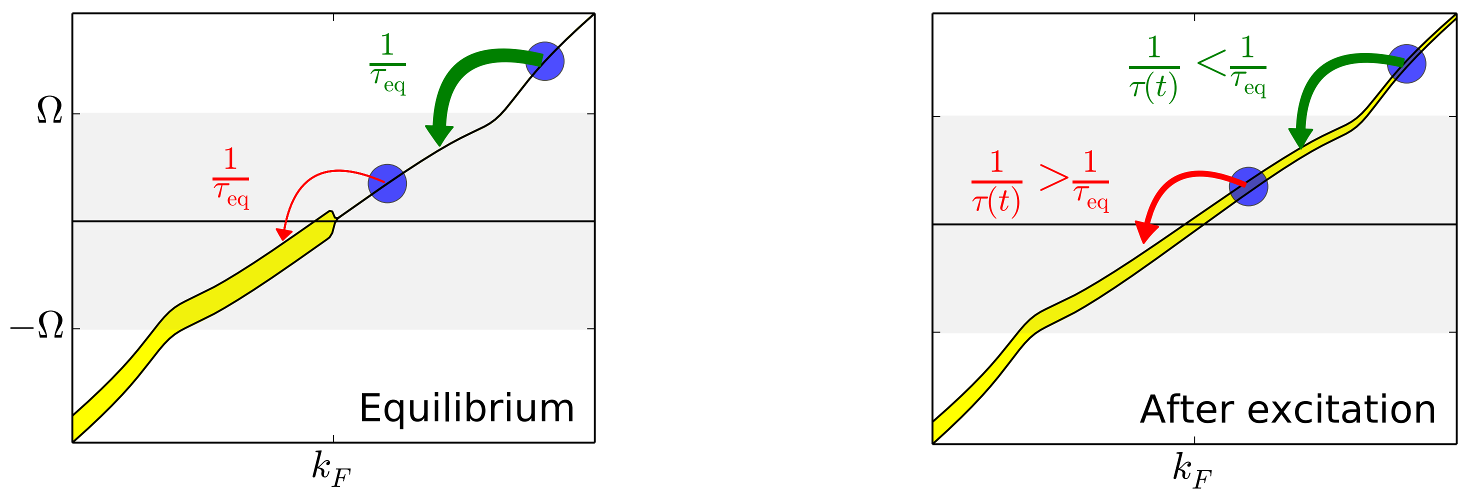


Strong excitation appears to change features of electron-phonon coupling

AFK et al PRB 2014

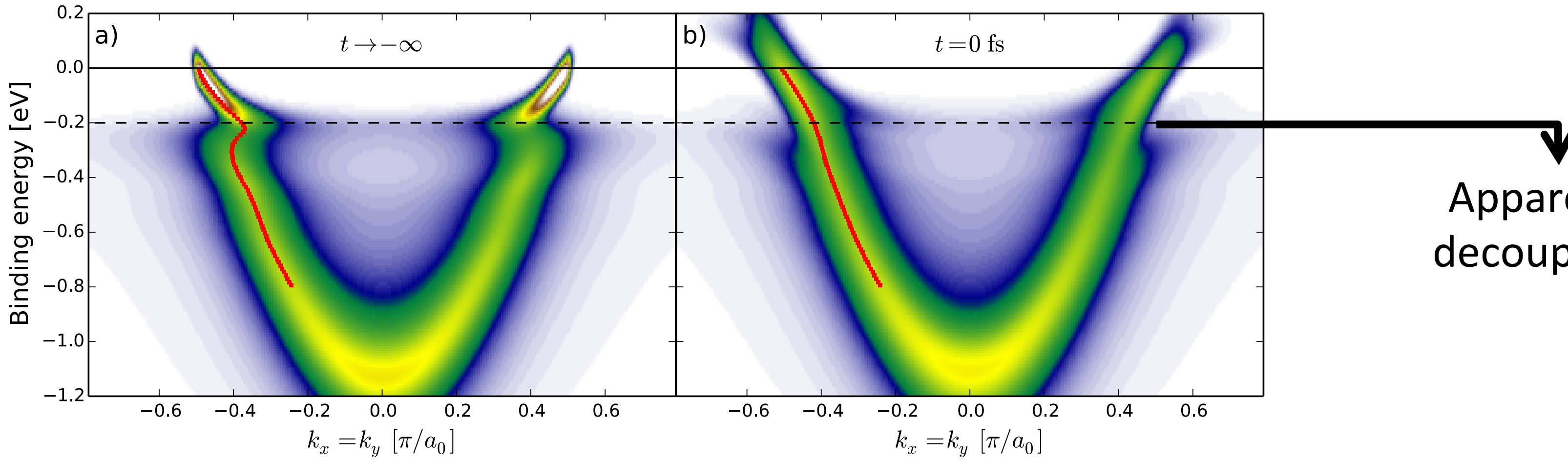
Driving beyond the weak limit



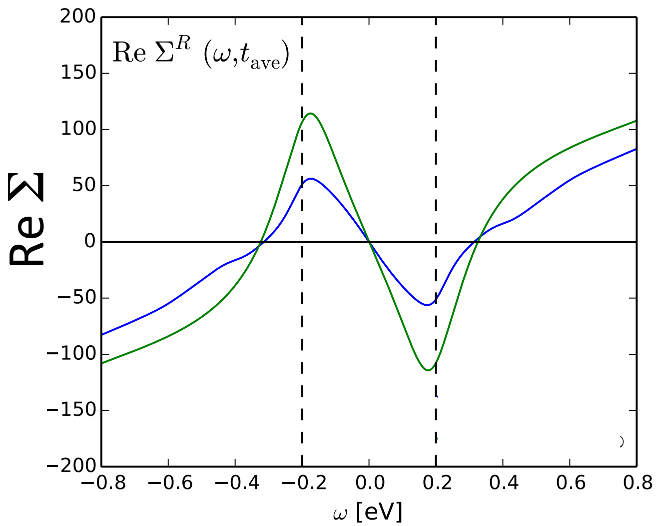


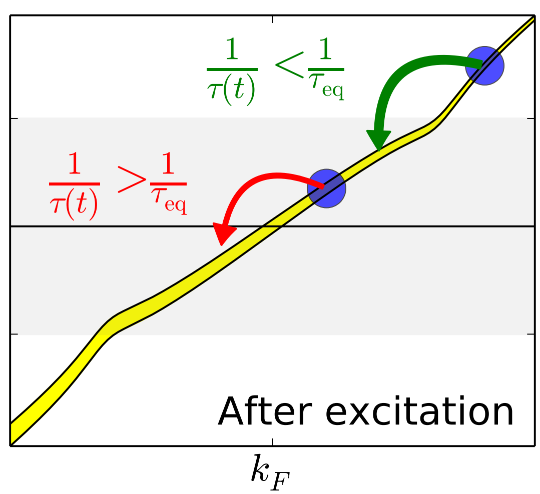
AFK et al PRB 2014

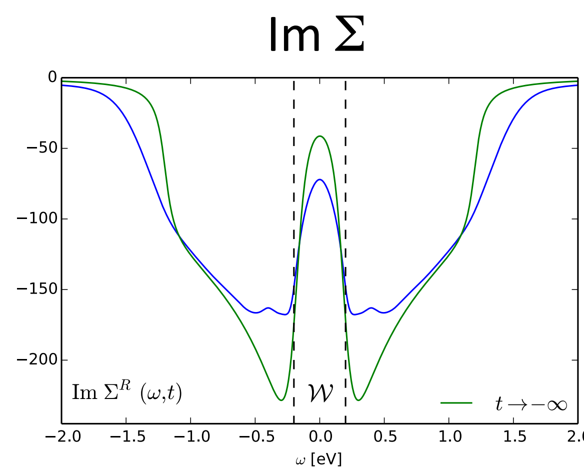
Driving beyond the weak limit



Apparent decoupling







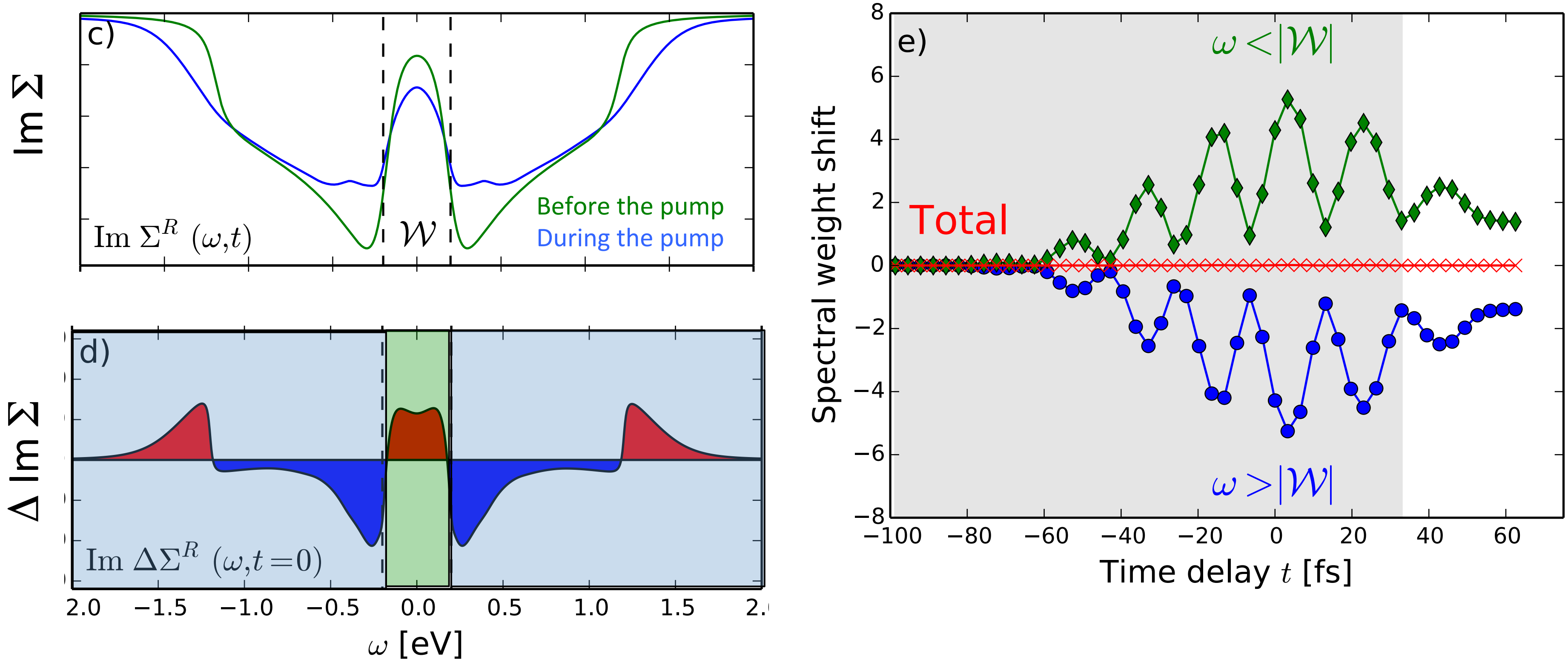
Before the pump

During the pump

AFK et al PRB 2014

Driving beyond the weak limit

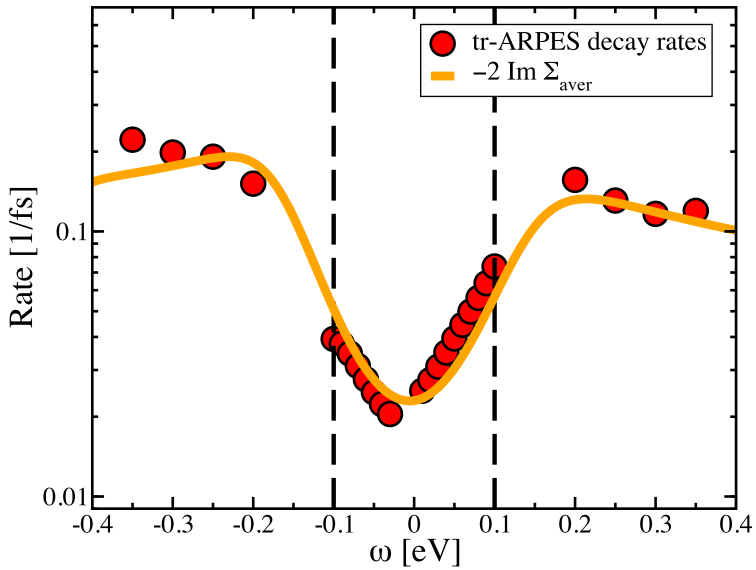
Interaction spectral weight shifts



Total interaction stays constant!

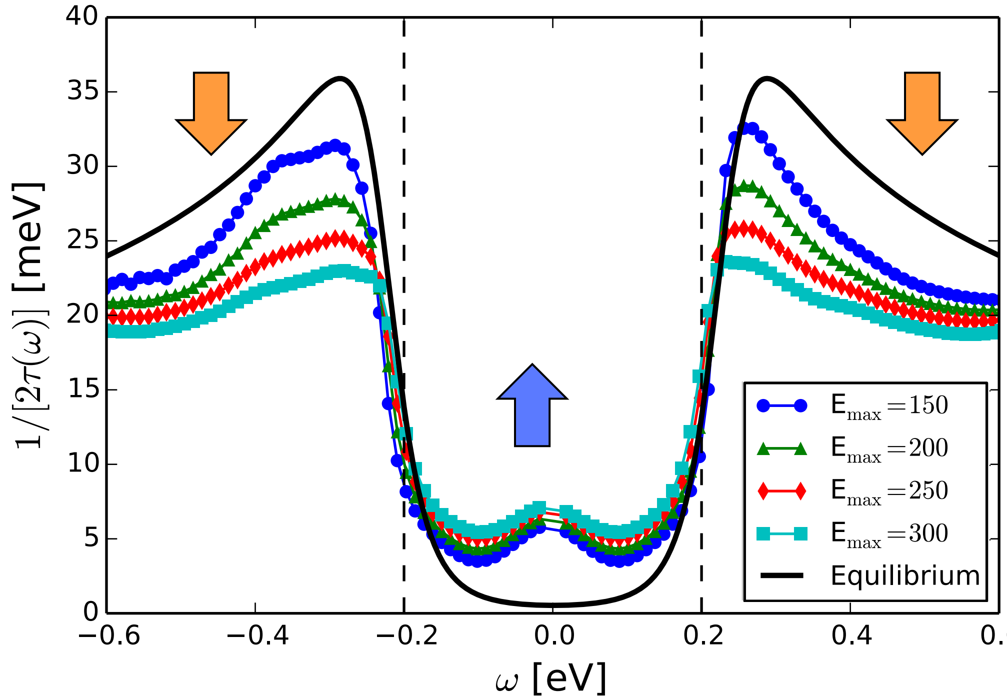
AFK et al PRB 2014

Driving beyond the weak limit



Low fluence limit
Phys. Rev. X 3, 041033

Increased excitation



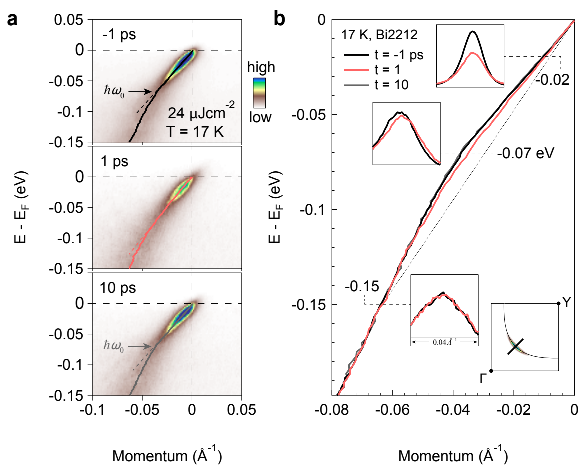
Strong pumping leads to fluence- and time-dependent interactions

$$1/\tau(\omega) \approx -2\mathrm{Im}\Sigma(\omega)$$

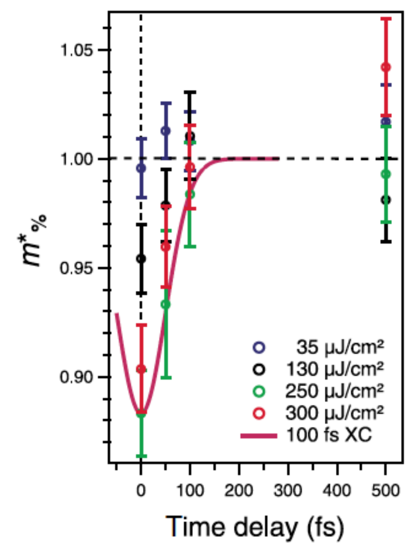
AFK et al PRB 2014

Experimental evidence for modified interactions

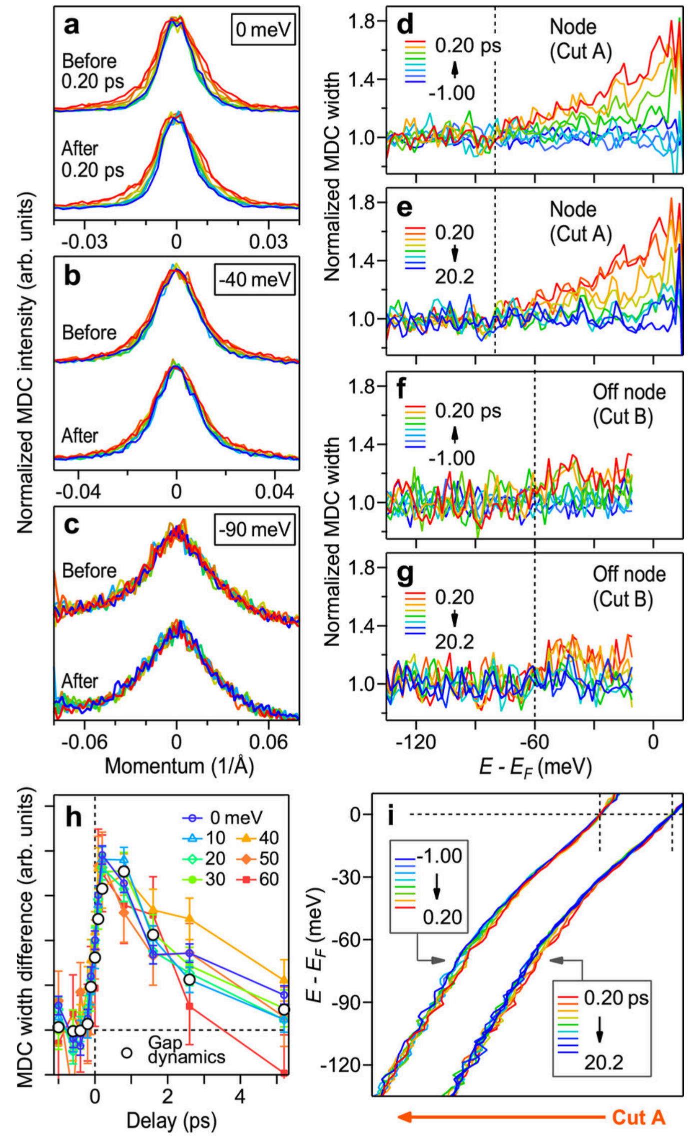
- Increase in MDC width after pumping within phonon window
- Weakening of the kink



Zhang, Nature Comm. (2014)

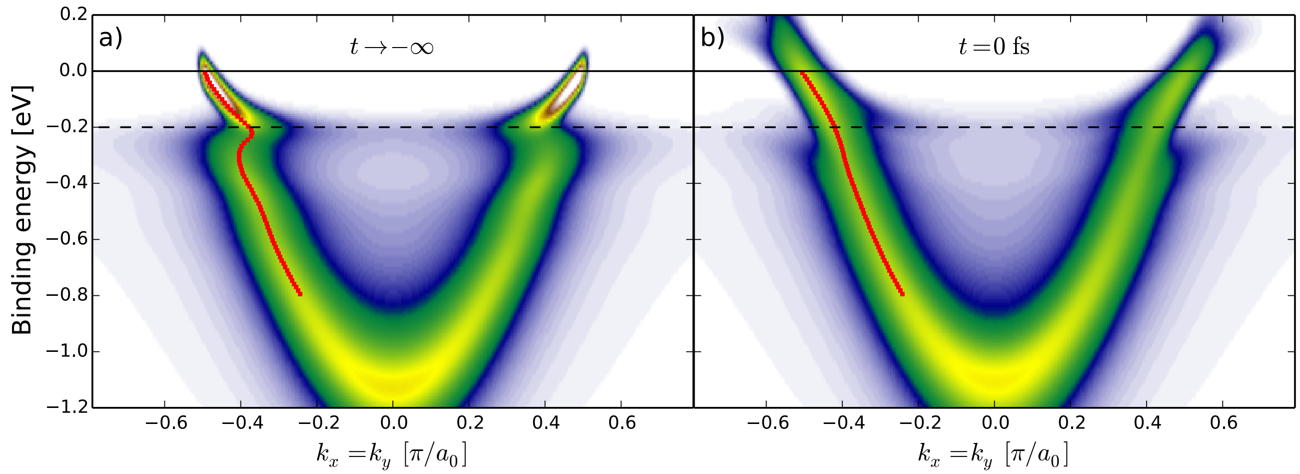


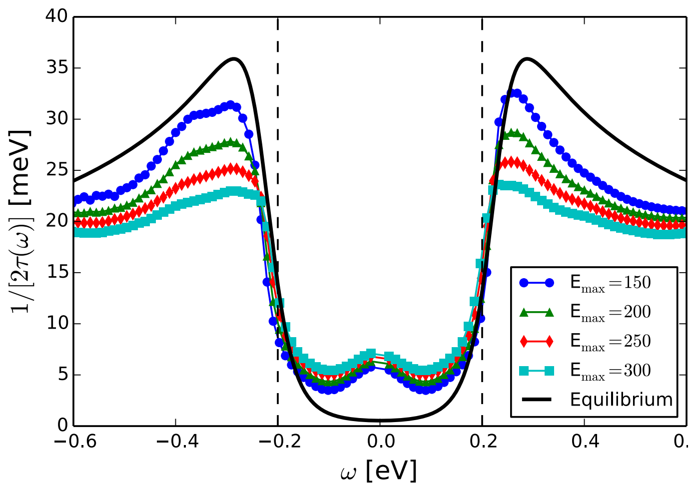
Rameau, PRB (2014)

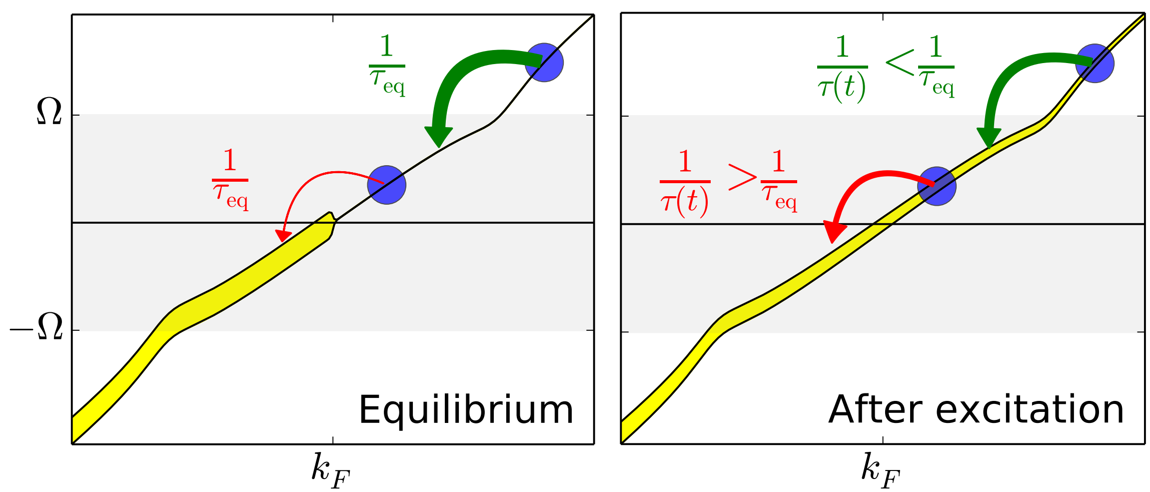


Ishida, Nat. Sci. Reports (2016)

Changes in kink, linewidth, and population decay rate after pumping can be understood simply by considering population redistribution







Electron-boson coupling: Beyond the equilibrium interpretation

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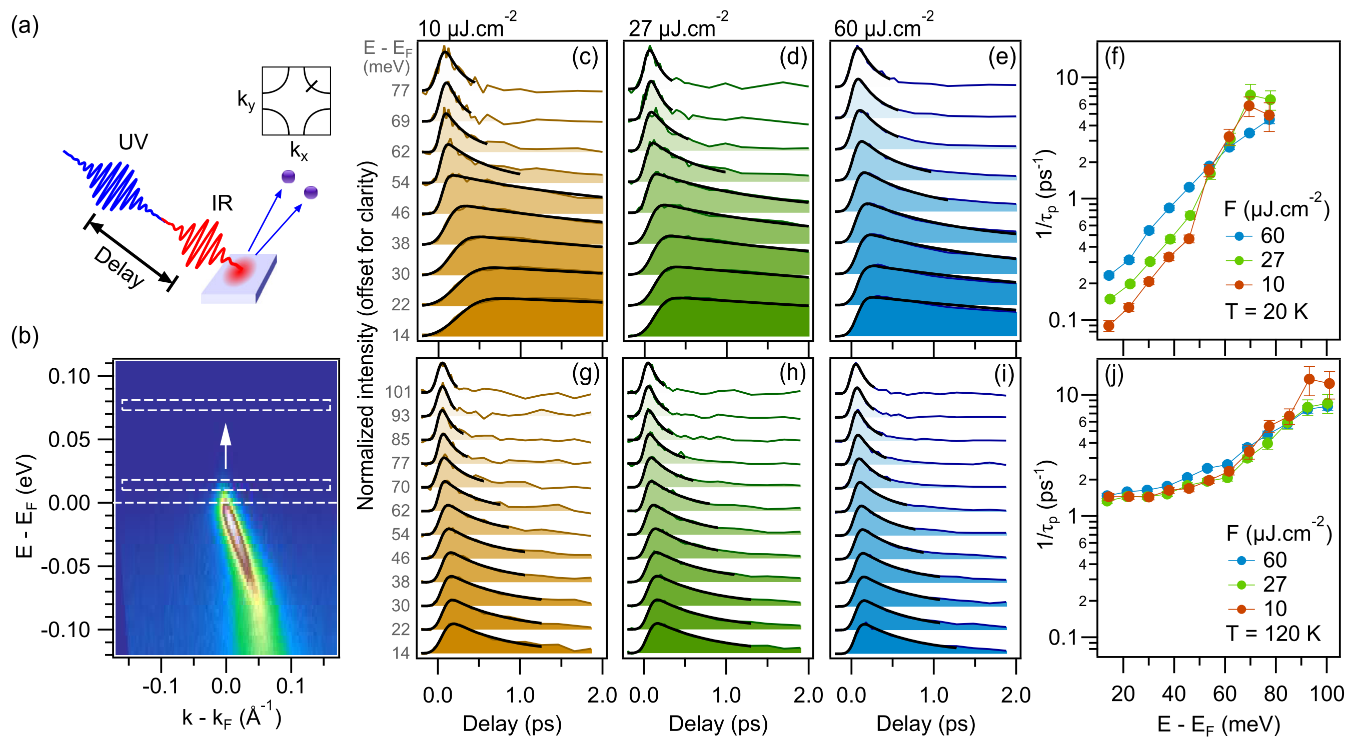
PRL **114**, 247001 (2015) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2015

Inequivalence of Single-Particle and Population Lifetimes in a Cuprate Superconductor

S.-L. Yang,[1,2] J. A. Sobota,[1,3] D. Leuenberger,[1,2] Y. He,[1,2] M. Hashimoto,[4] D. H. Lu,[4] H. Eisaki,[5]
P. S. Kirchmann,[1,*] and Z.-X. Shen[1,2,†]



Also: I. Gierz, S. Link, U. Starke, and A. Cavalleri, Faraday Discuss. 171, 311 (2014).

PRL 114, 247001 (2015) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2015

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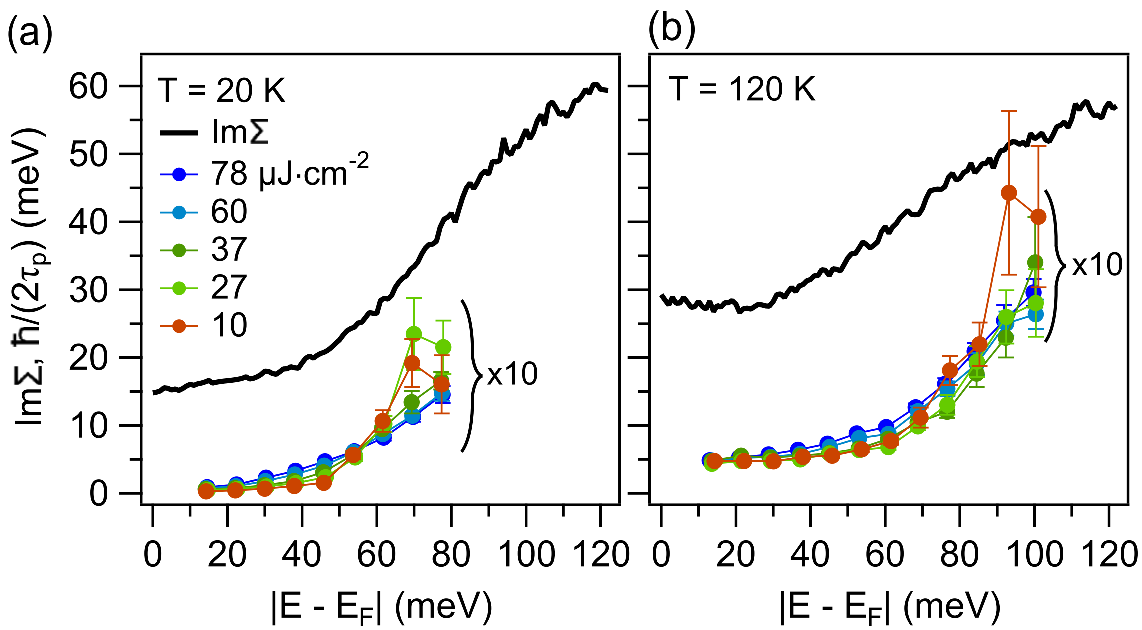


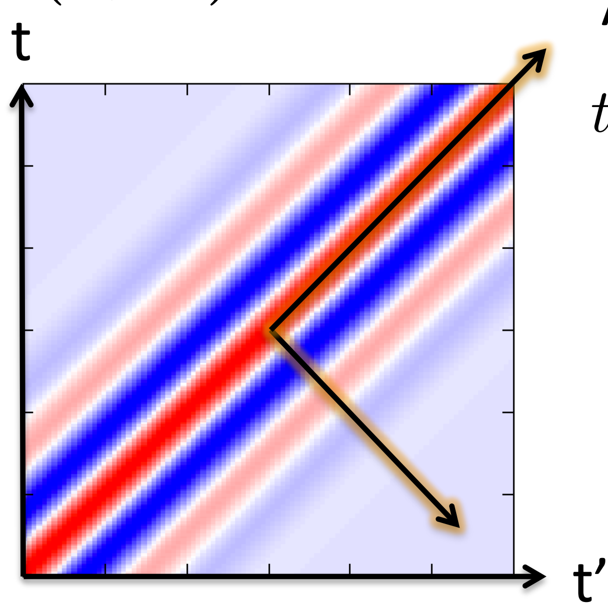
$$\frac{1}{\tau(\omega)} \stackrel{?}{=} -2\mathrm{Im}\Sigma(\omega = \epsilon_{\mathbf{k}})$$

$$\frac{1}{\tau(\omega)} \stackrel{?}{=} -2\mathrm{Im}\Sigma(\omega = \epsilon_{\mathbf{k}})$$

Population dynamics

Equilibrium self-energy

$G(t, t')$



Average time

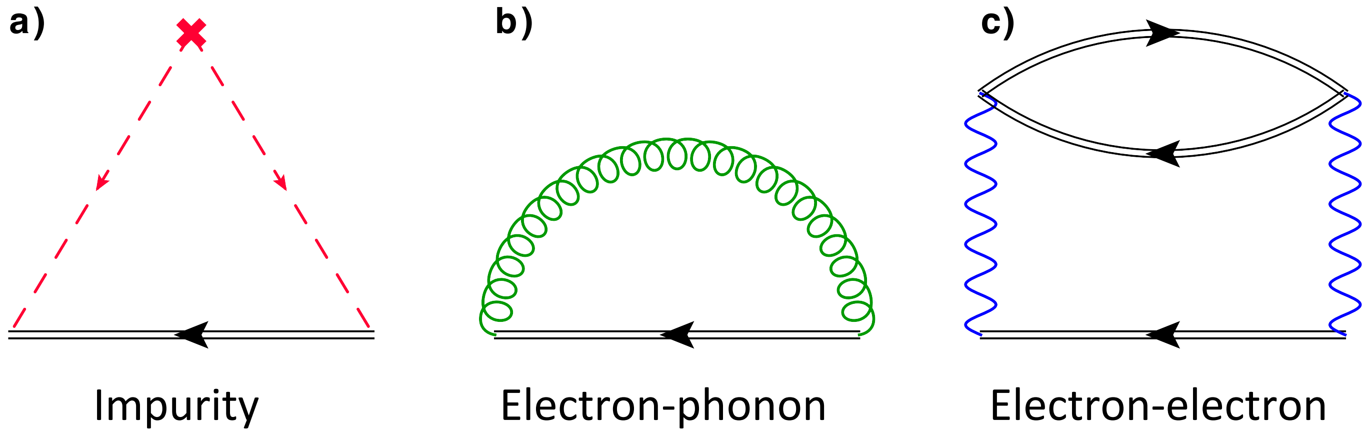
$$t_{\mathrm{ave}} = \frac{1}{2}(t + t')$$

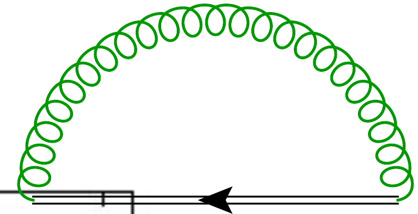
Relative time

$$t_{\mathrm{rel}} = t - t'$$

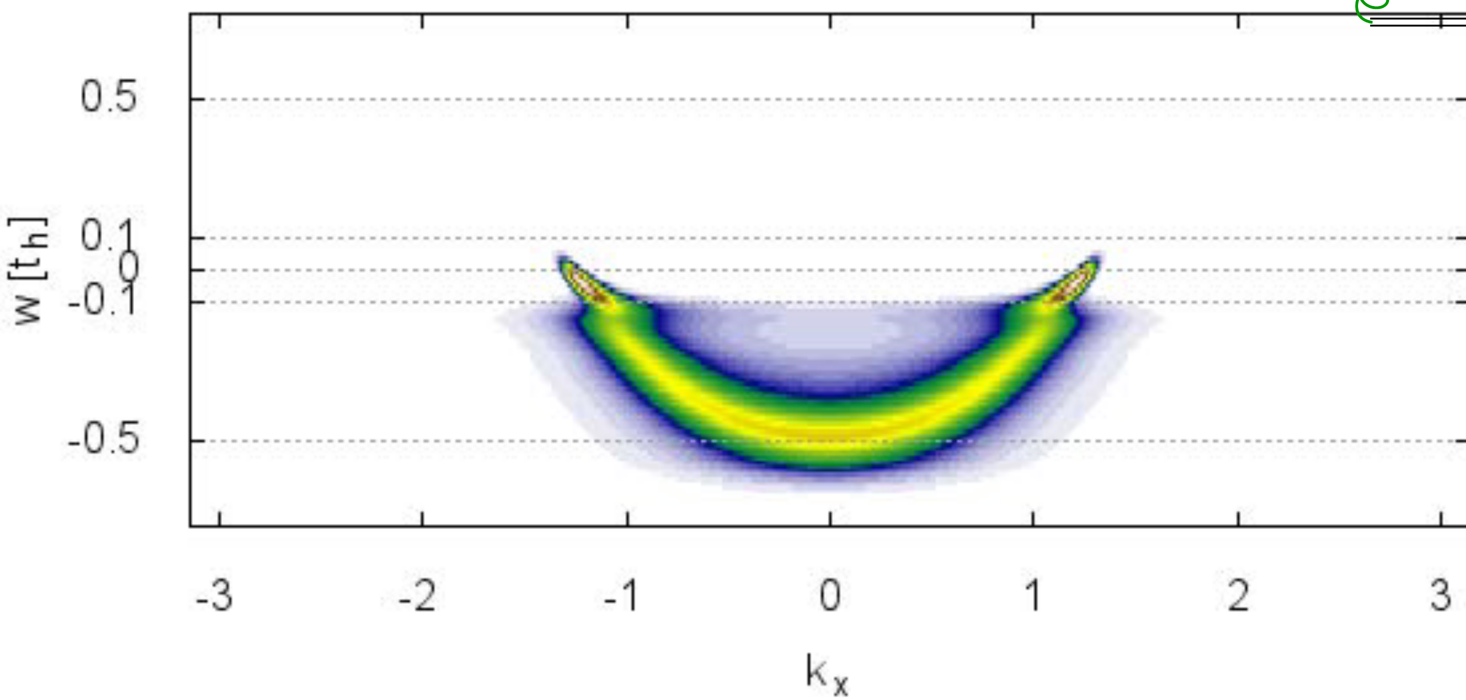
- Equilibrium frequency domain arises in t-t’ direction
- Population dynamics occurs along average time

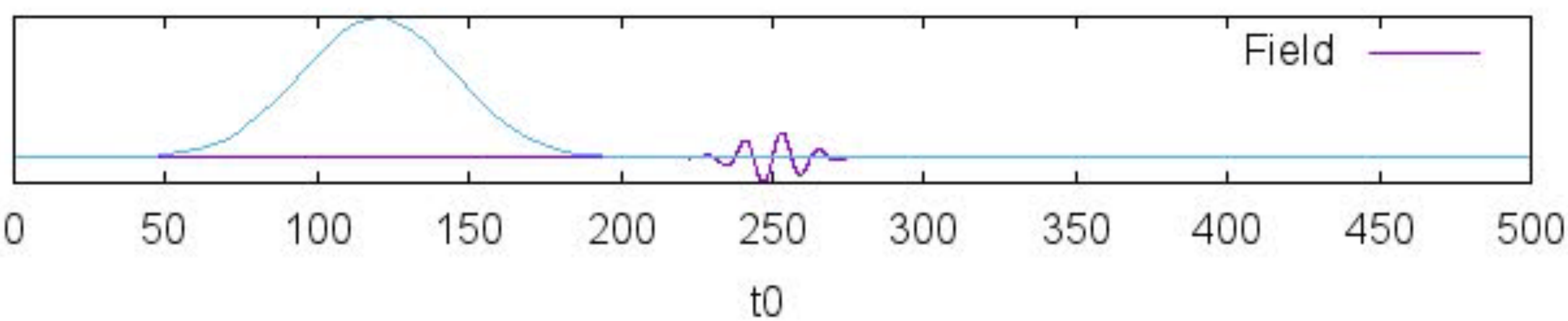
Consider interactions beyond electron-phonon coupling



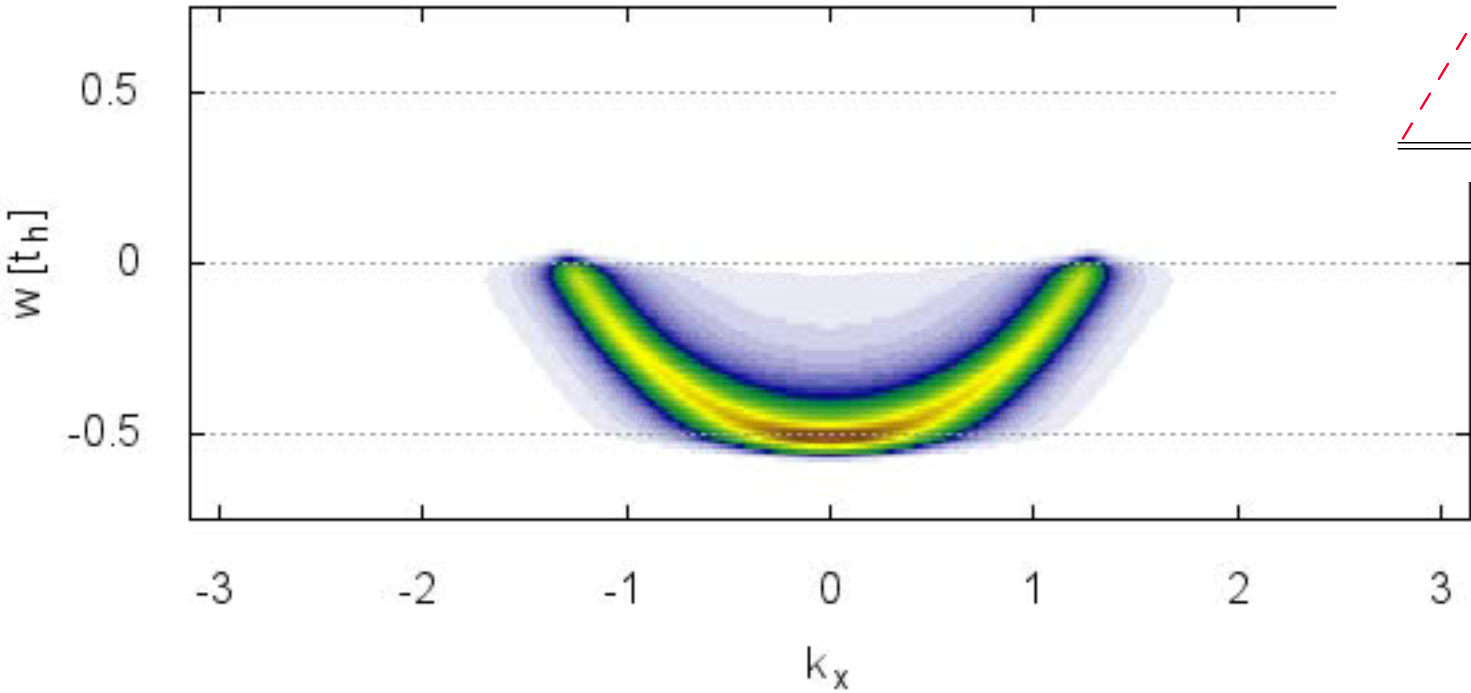


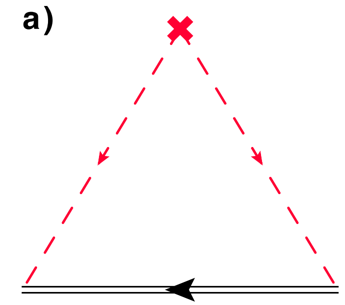
Electron-phonon

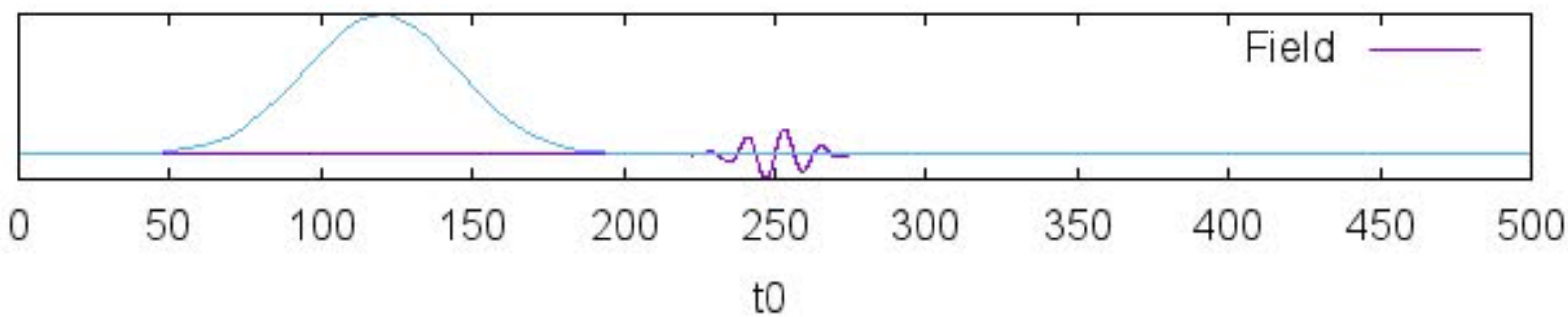




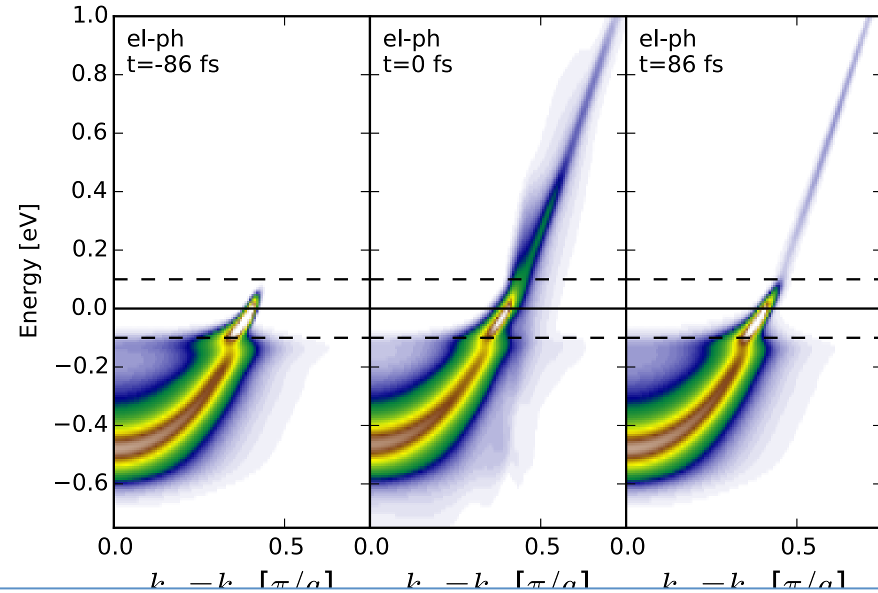
Electron-impurity





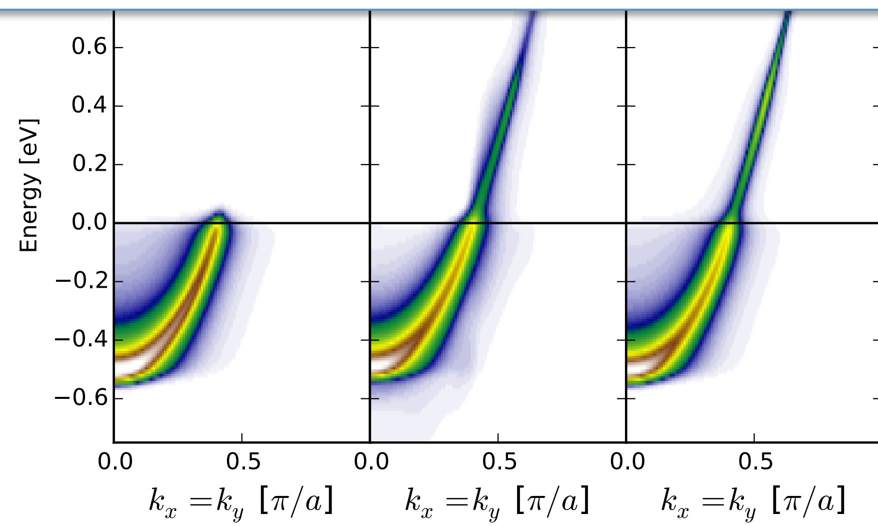


Electron-phonon



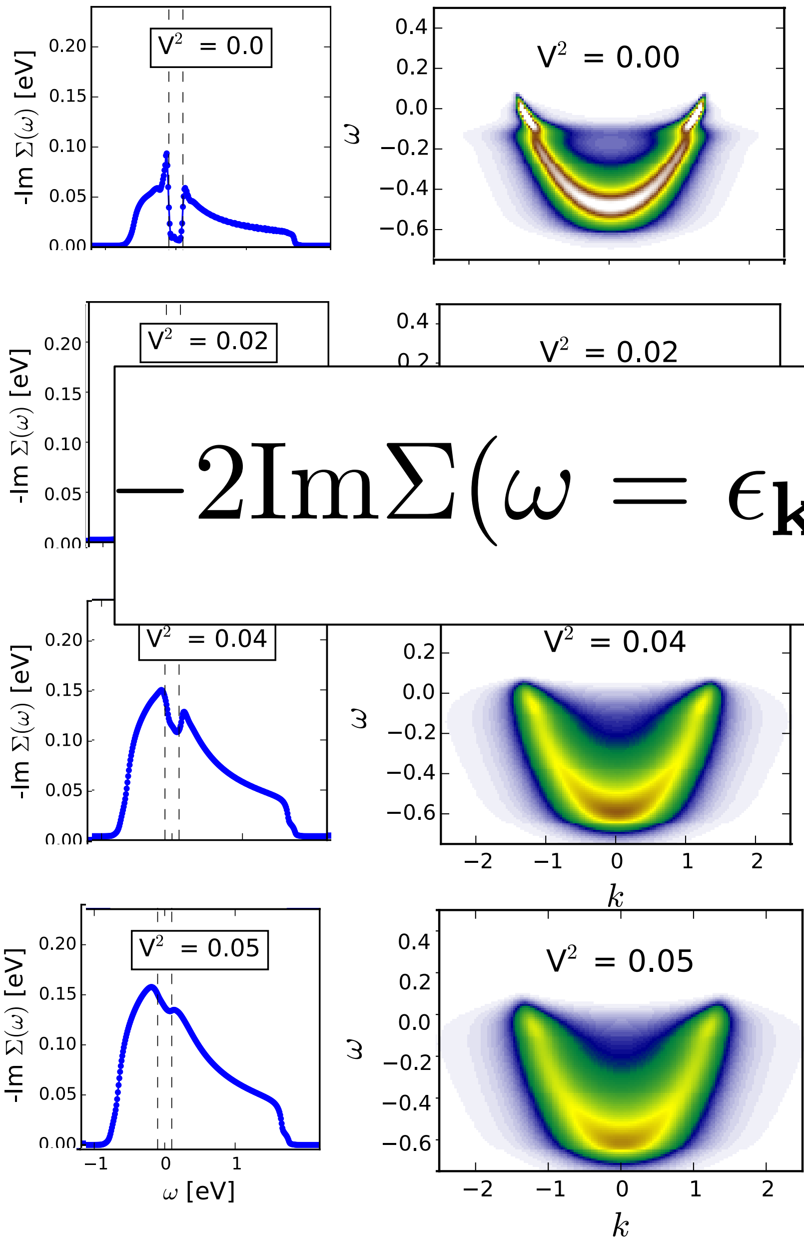
Let’s consider the combination

Electron-impurity

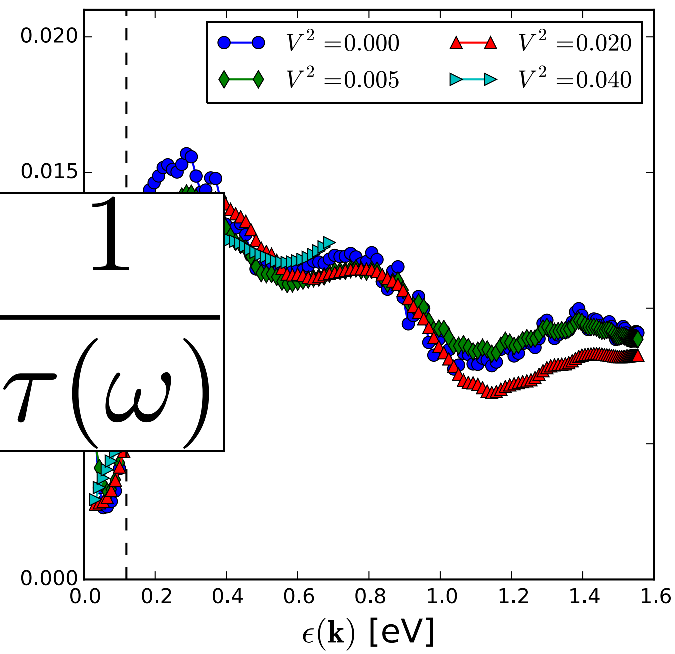


Equilibrium: quasiparticle

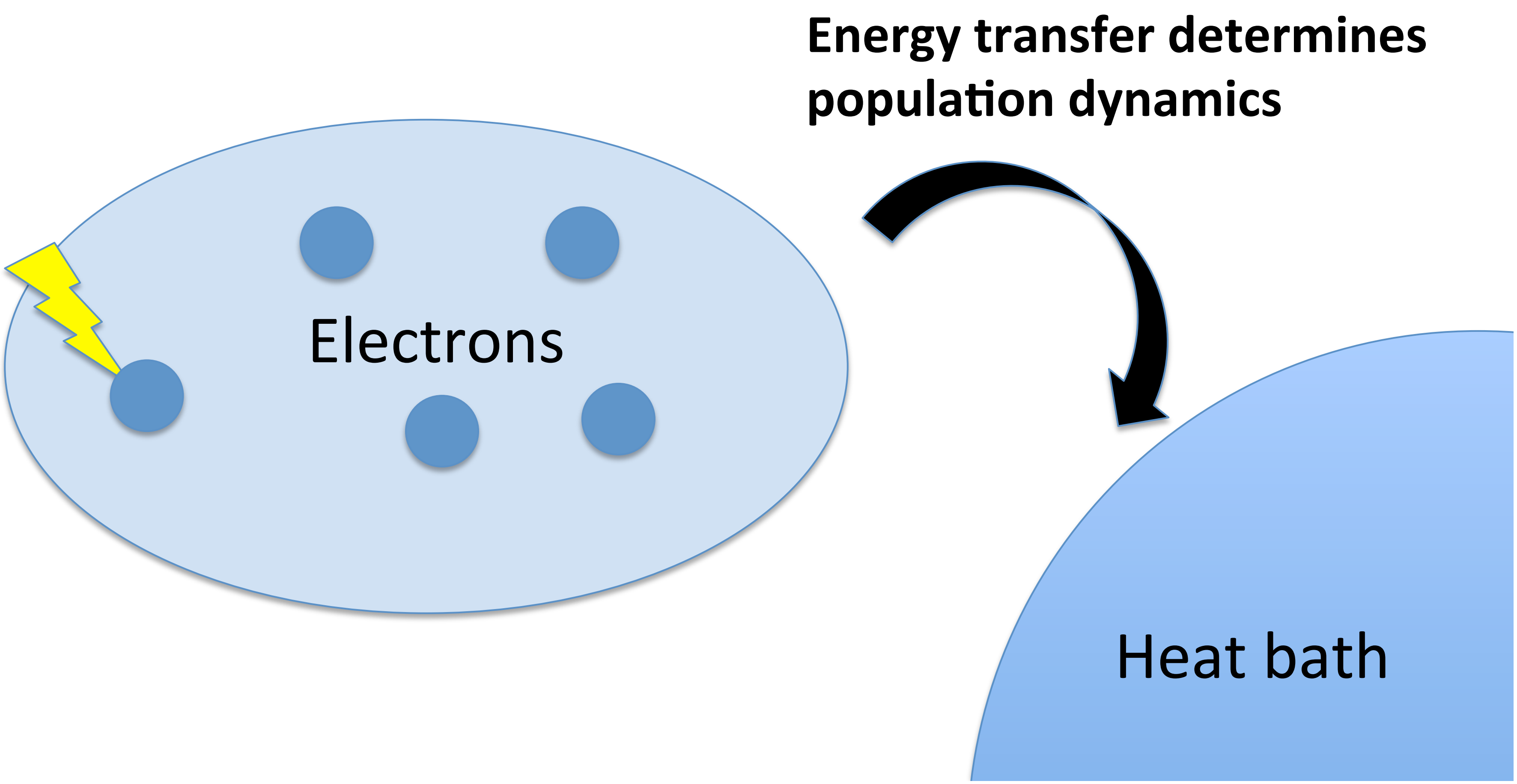
Non-equilibrium: population

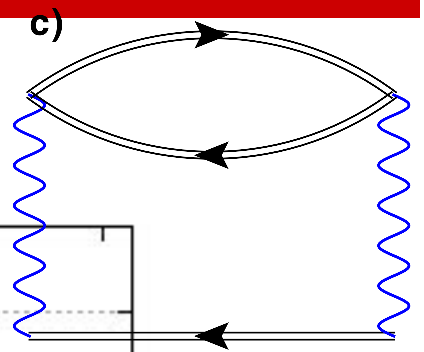


$$-2\mathrm{Im}\Sigma(\omega = \epsilon_{\mathbf{k}}) \neq \frac{1}{\tau(\omega)}$$

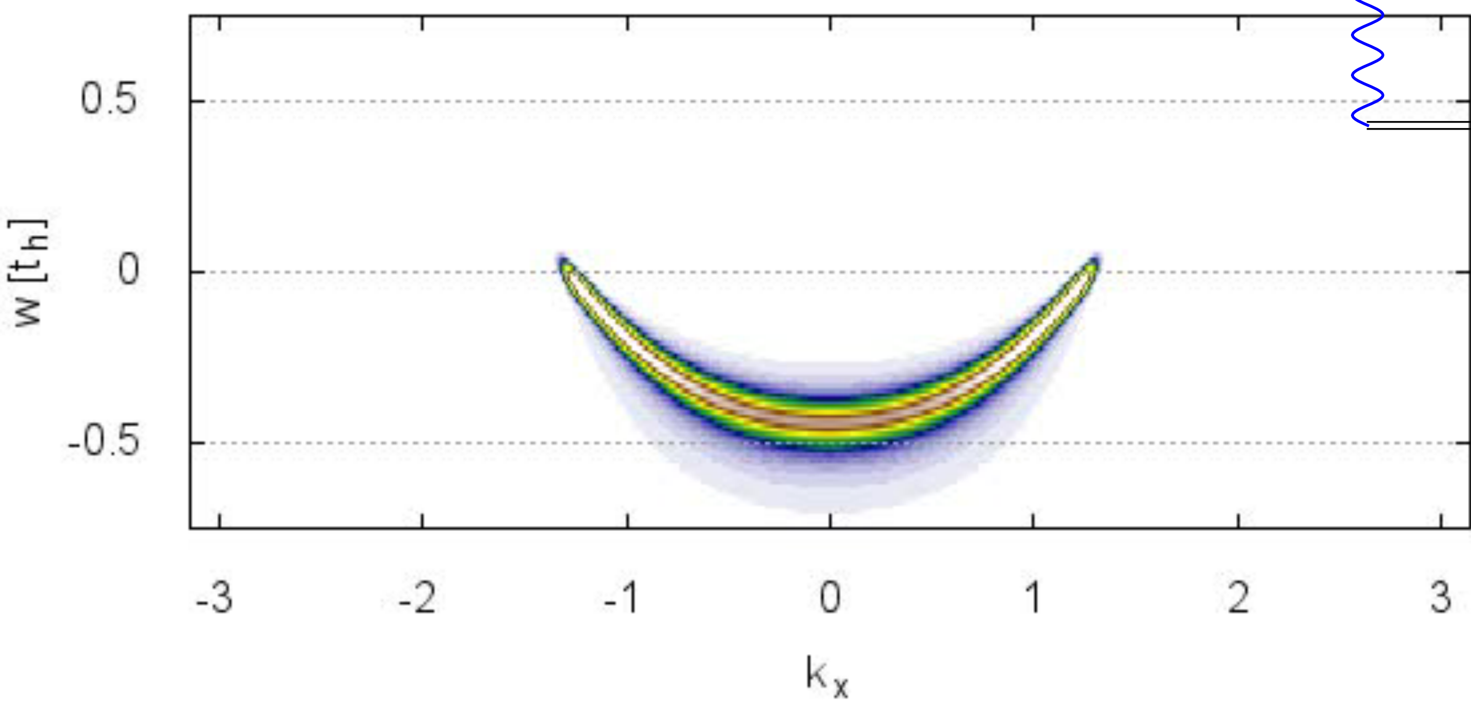


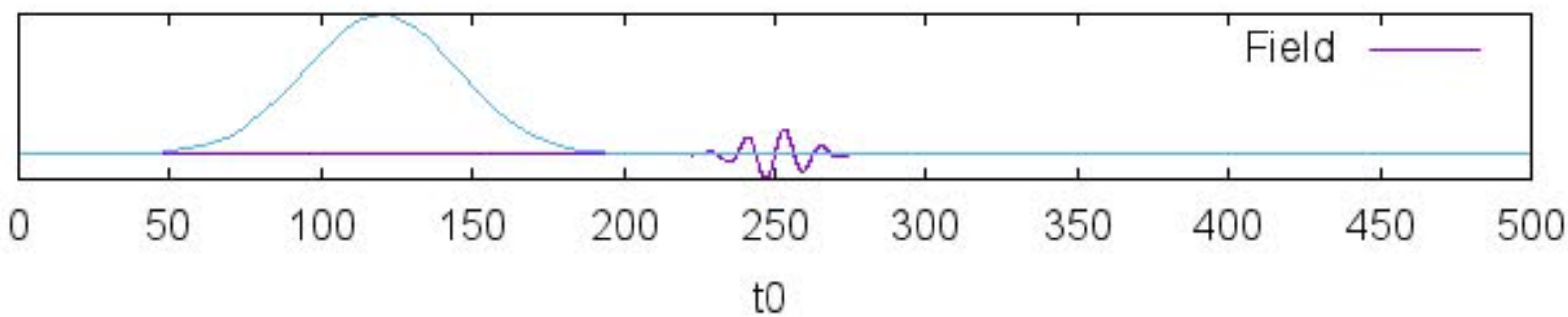
$$-2\mathrm{Im}\Sigma(\omega=\epsilon_{\mathbf{k}}) \neq \frac{1}{\tau(\omega)}$$



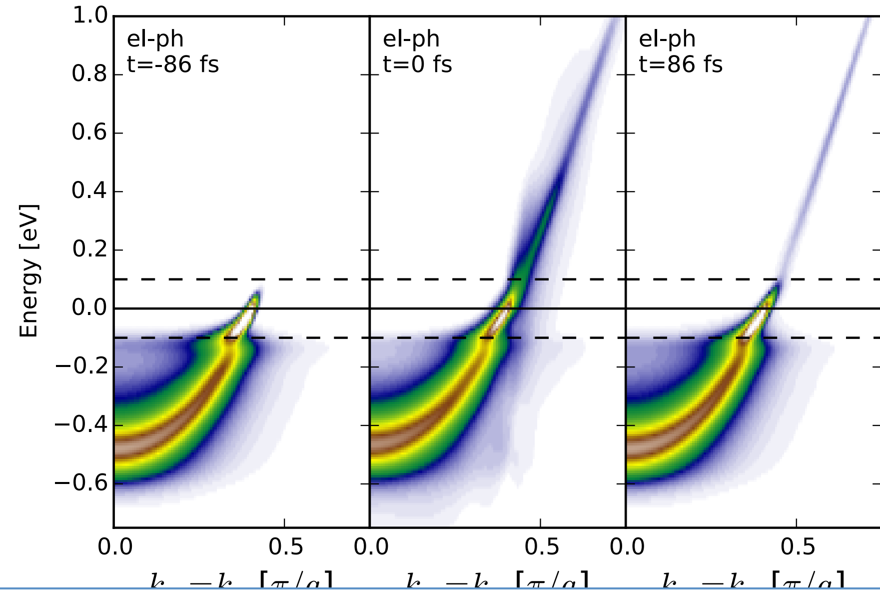


Electron-electron



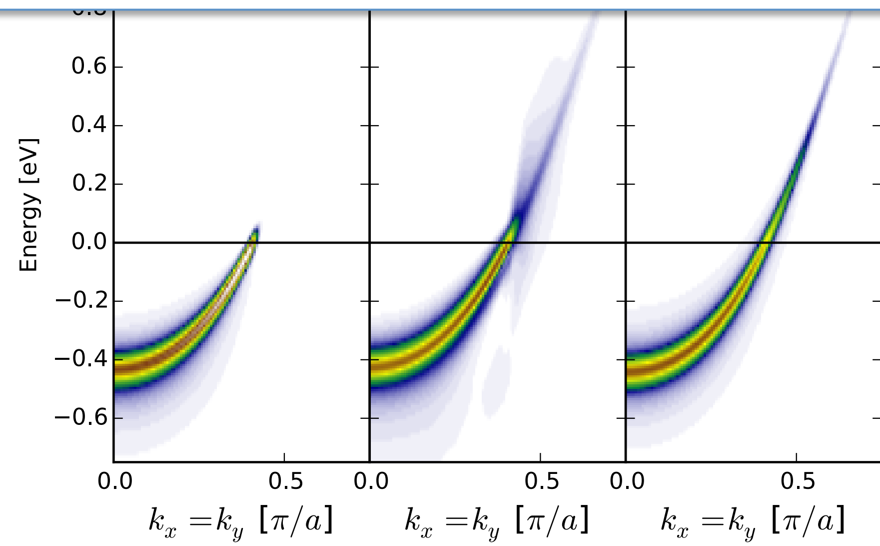


Electron-phonon



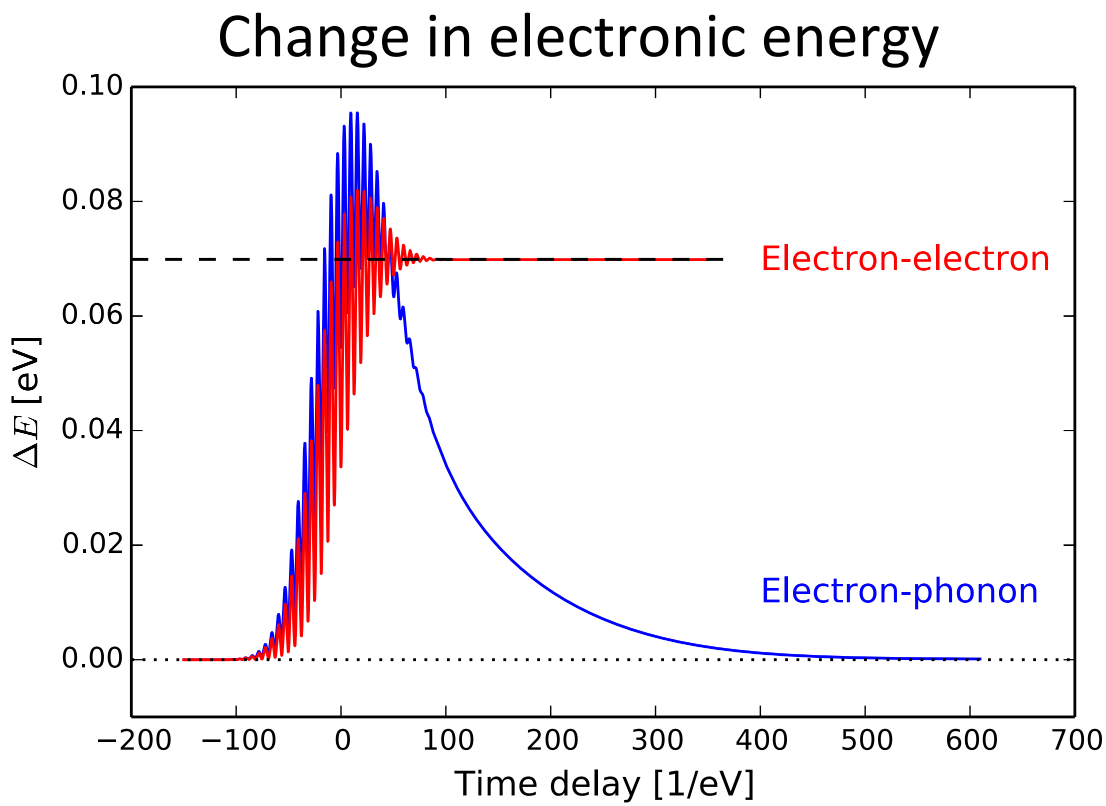
Let’s consider the combination

Electron-electron

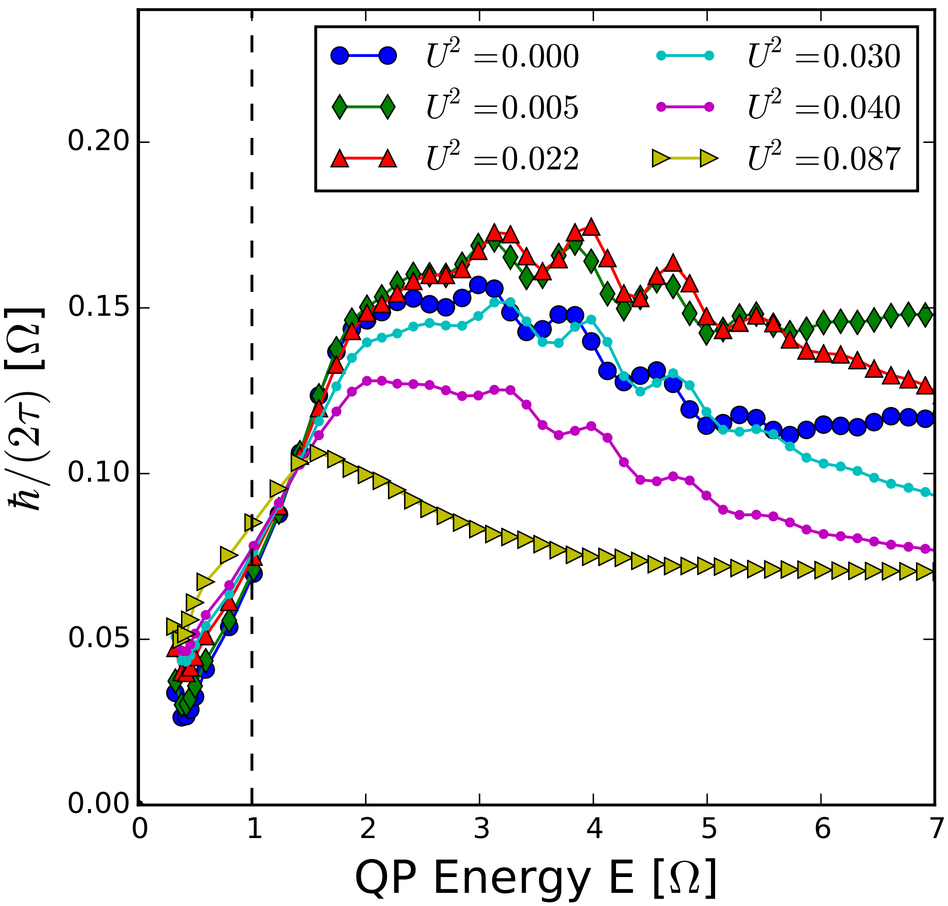


$$-2\mathrm{Im}\Sigma(\omega = \epsilon_{\mathbf{k}}) \neq \frac{1}{\tau(\omega)}$$

Energy transfer determines population dynamics



Combining electron-electron and electron-phonon scattering



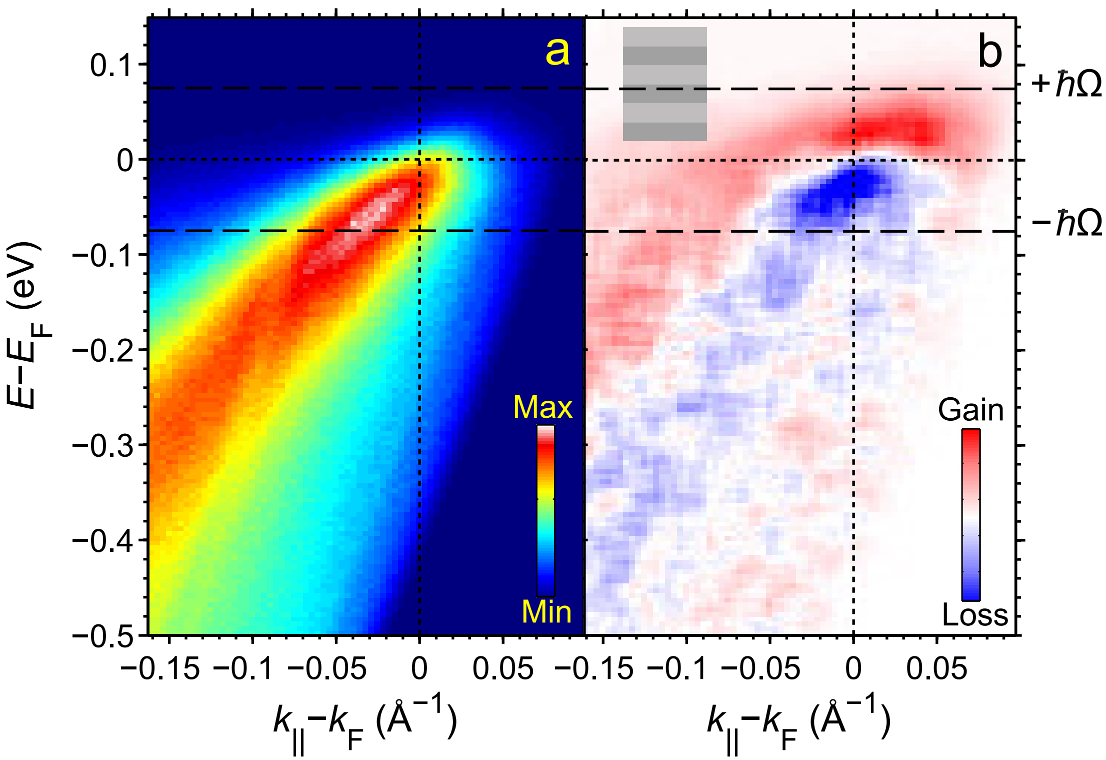
$$g^2 = 0.02$$

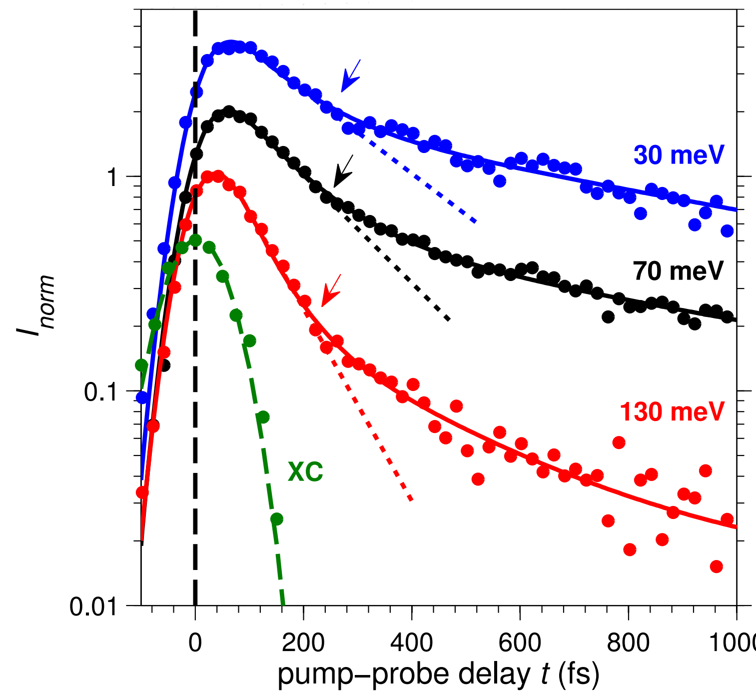
Step in lifetimes remains visible

Competition between e-p and e-e scattering

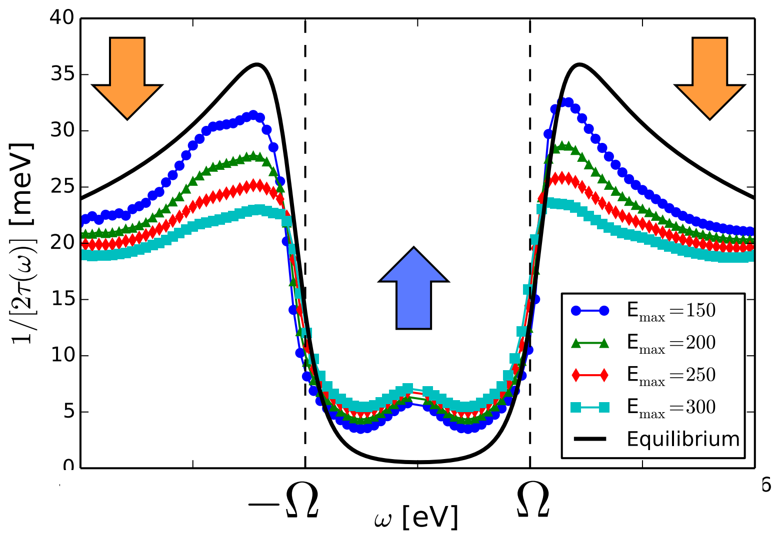
Apparent λ could be too small!

Time-resolved ARPES experiment *by J.D. Rameau, S. Freutel, I. Avigo, M. Ligges, L. Rettig, P.D. Johnson, U. Bovensiepen*



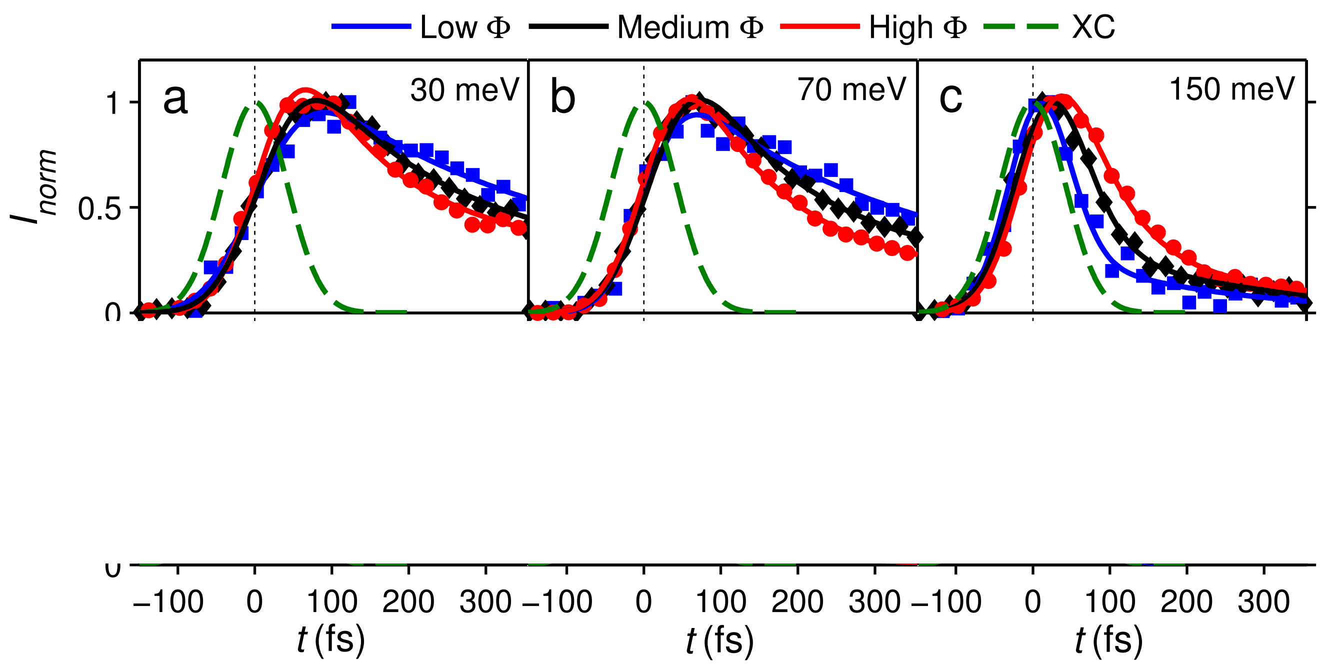


Population decay time in Bi2201 as a function of binding energy

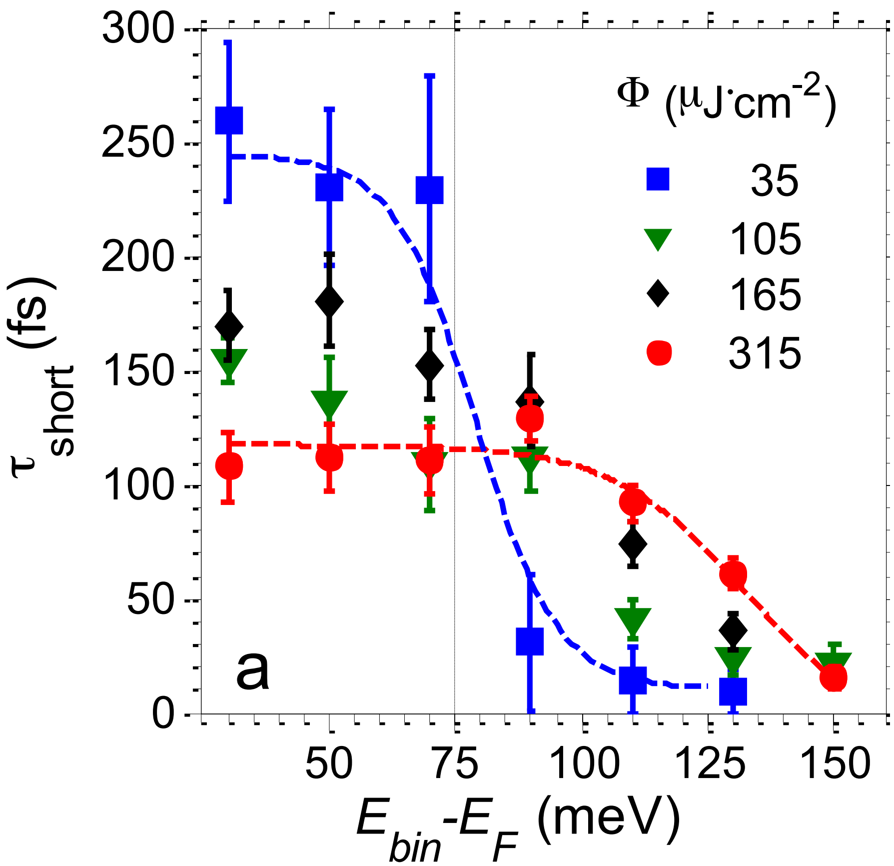


Scattering rates are fluence dependent

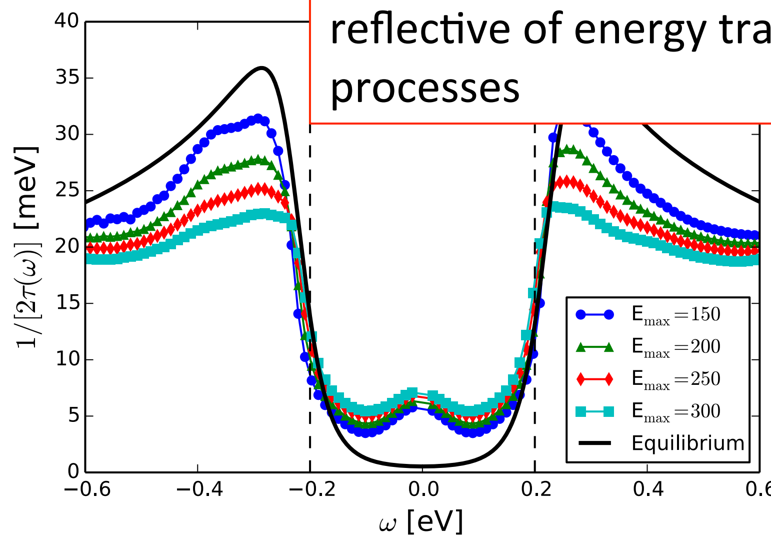
Experiment



Experiment



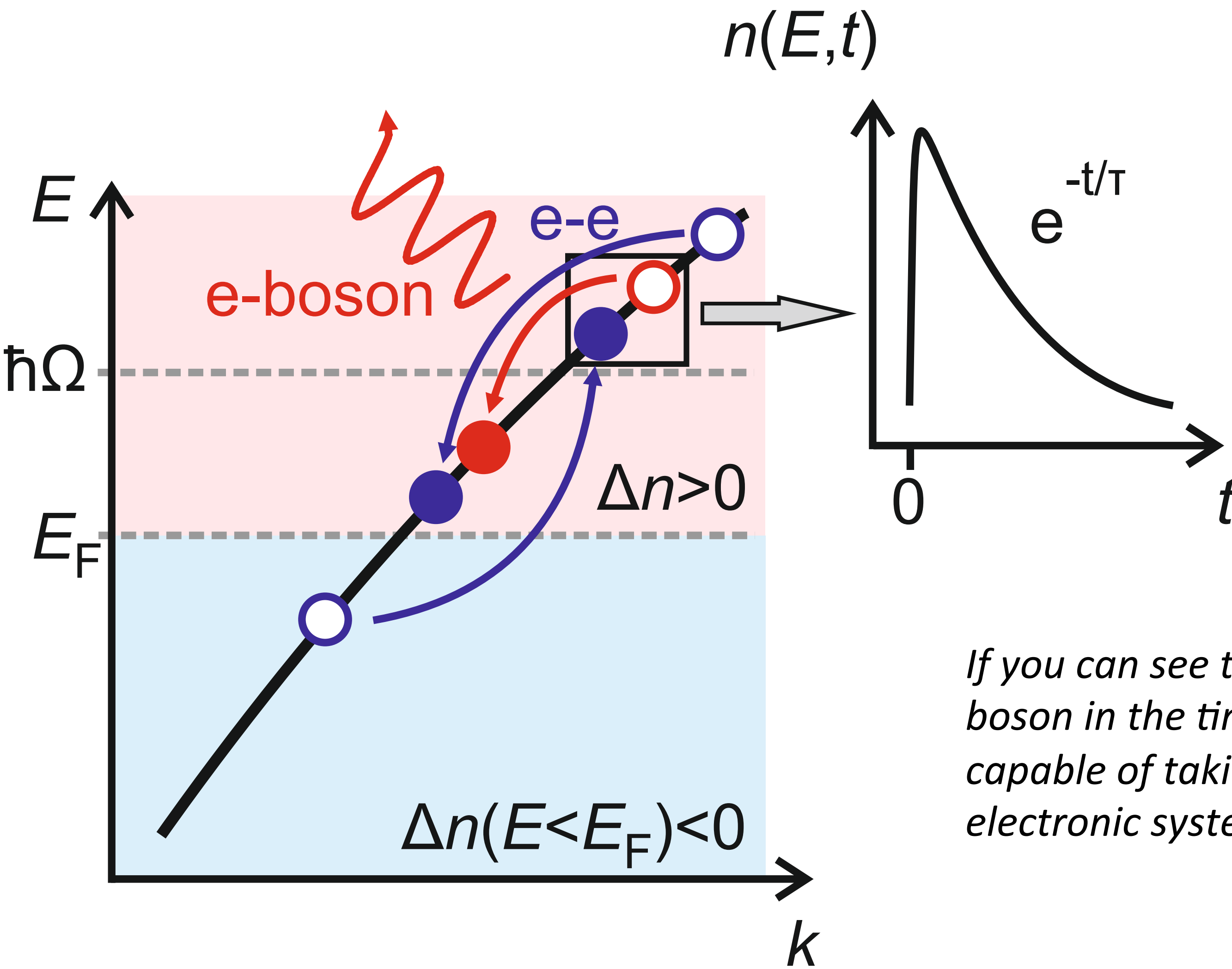
Theory



Decay rates are primarily reflective of energy transfer processes

Population dynamics can be understood with a strongly coupled boson at approximately 75 meV and $\lambda \approx 0.2$

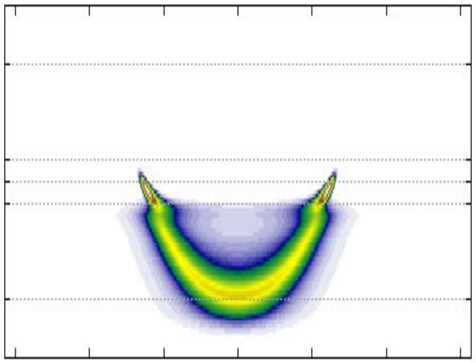
Quantitative agreement between experiment and theory

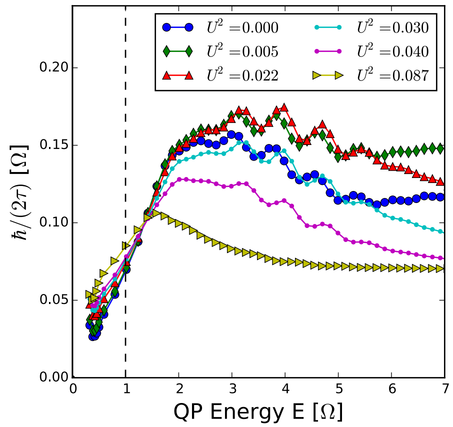


If you can see the fingerprint of a boson in the time domain, it is capable of taking energy out of the electronic system.

Summary

- Dynamics in the time domain are not always equivalent to frequency domain
- Dynamics in the time domain are principally controlled by energy transfer processes
  - We can use this to separate/suppress interactions that can obscure electron-boson interactions
  - Interpreting changes in the spectra using equilibrium language can be erroneous





PRX 3, 041033 (2013)
PRB 87, 235139 (2013)
PRB 90, 075126 (2014)
arXiv:1505.07055 (updated tomorrow)