Ultrafast Control of Orders and Couplings in Solids

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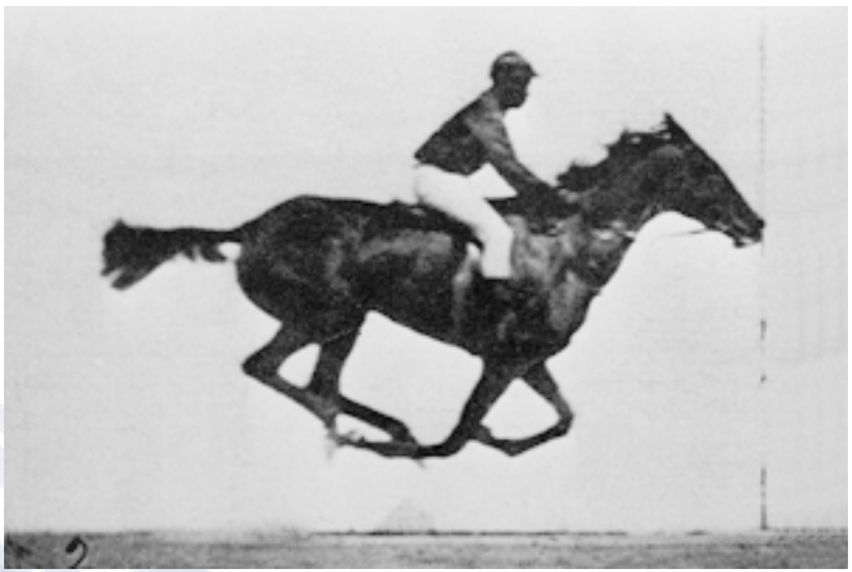
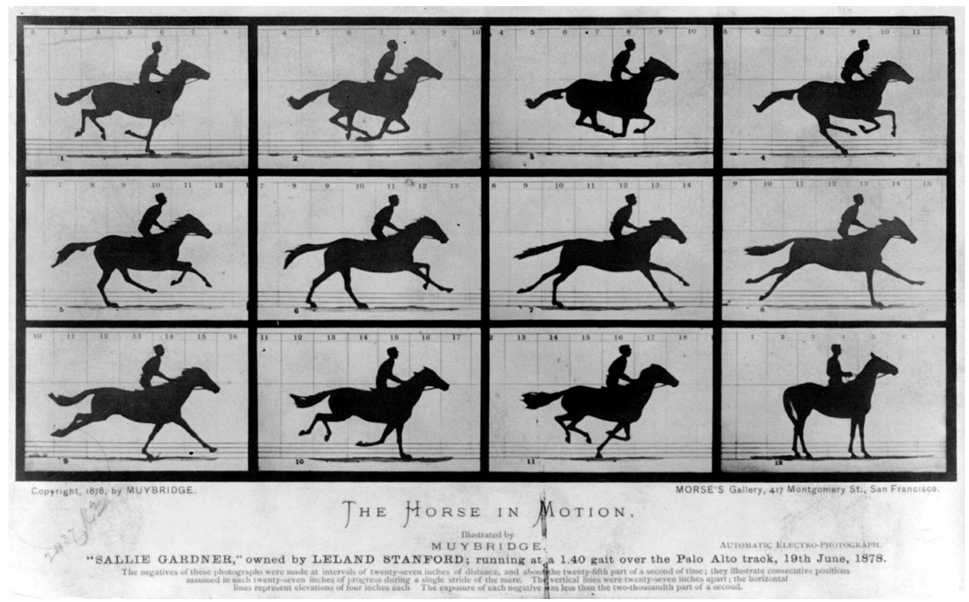
Pump-probe spectroscopy (1887)

- stroboscopic investigations of dynamic phenomena

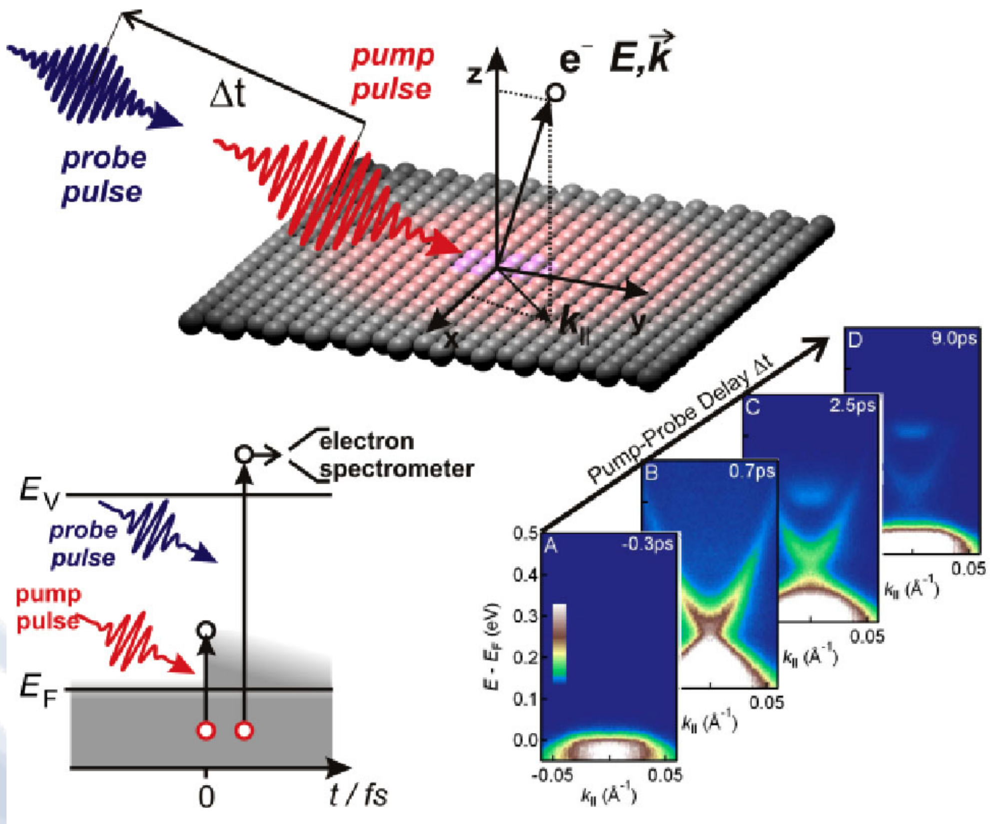




Muybridge 1887

Pump-probe spectroscopy (today)

- stroboscopic investigations of dynamic phenomena



TbTe3 CDW metal

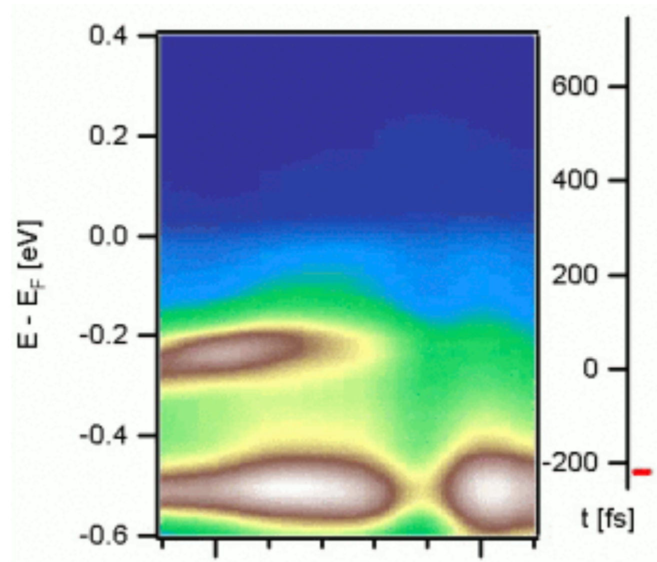


Image courtesy:
J. Sobota / F. Schmitt

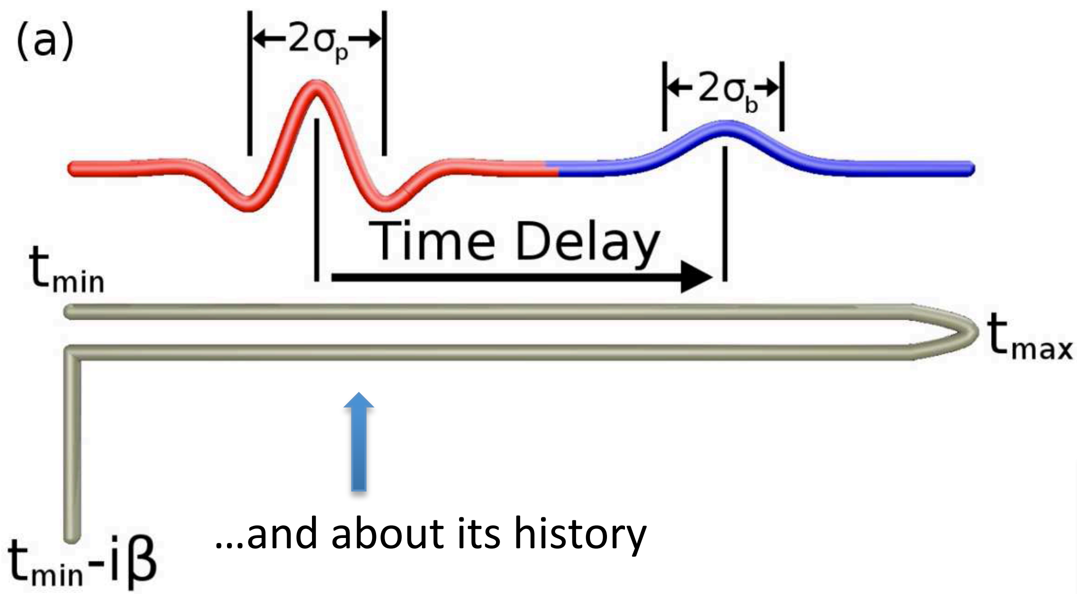
Non-Equilibrium Keldysh Formalism

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

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

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

same problem as in equilibrium (but worse):
use your favorite self-energy approximation, e.g. perturbation theory, nonequilibrium DMFT, ...



...and about its history

System knows about its thermal initial state...

Include the effects of driving field on real time axis

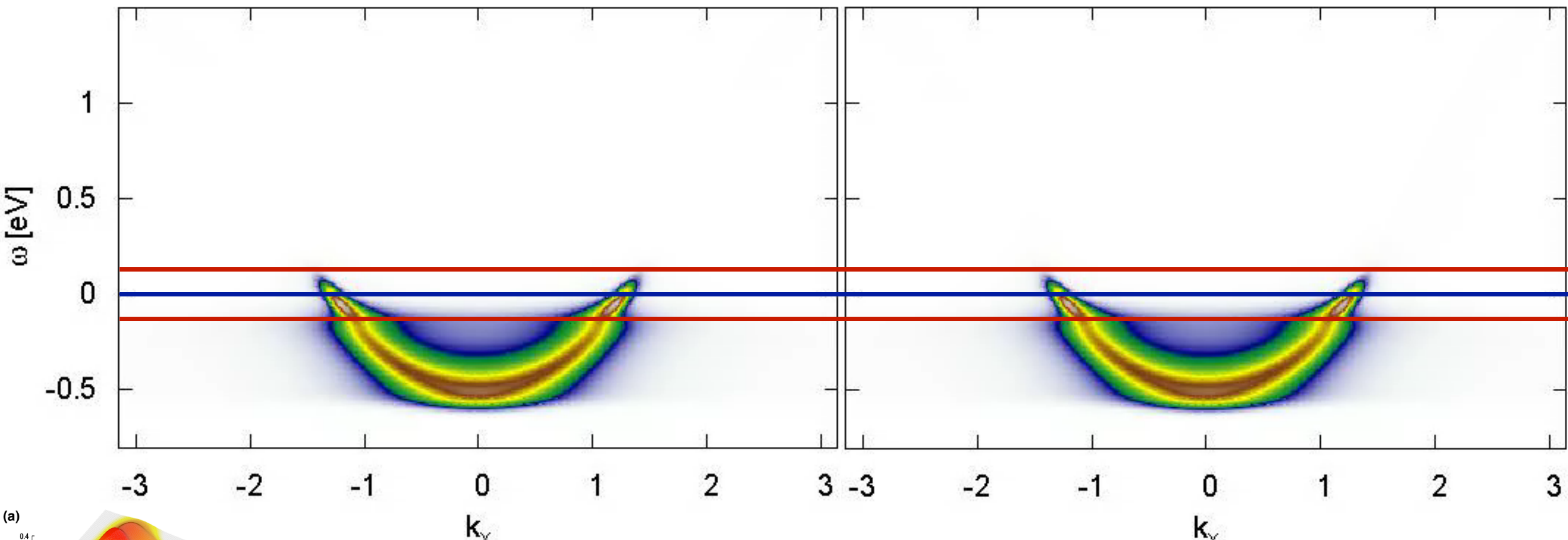
Electron-boson coupling

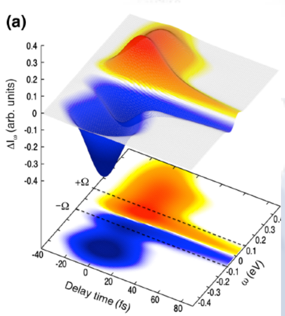
PRX 3, 041033 (2013)

Weak pump

Strong pump

time unit = 0.66 fs





boson window effect for fast versus slow relaxation

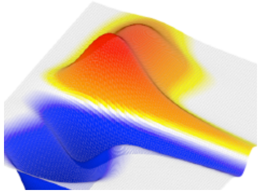
nonlinear response for strong pump

Ultrafast Materials Science today

Understanding the nature of quasiparticles

- Relaxation dynamics
- Control of couplings

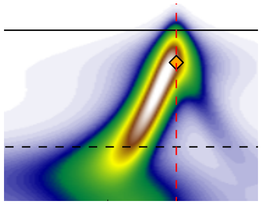
PRL 111, 077401 (2013)
PRX 3, 041033 (2013)
PRB 87, 235139 (2013)
PRB 90, 075126 (2014)
Nature Commun. 7, 13761 (2016)
PRB 95, 024304 (2017)
PRB 95, 205111 (2017)



Understanding ordered phases

- Collective oscillations
- Competing orders

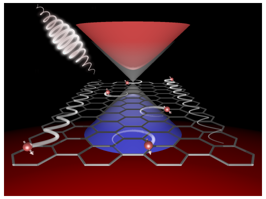
PRB 92, 224517 (2015)
PRB 93, 144506 (2016)
PRL 118, 087002 (2017)



Creating new states of matter

- Floquet topological states

Nature Commun. 6, 7047 (2015)
Nature Commun. 8, 13940 (2017)



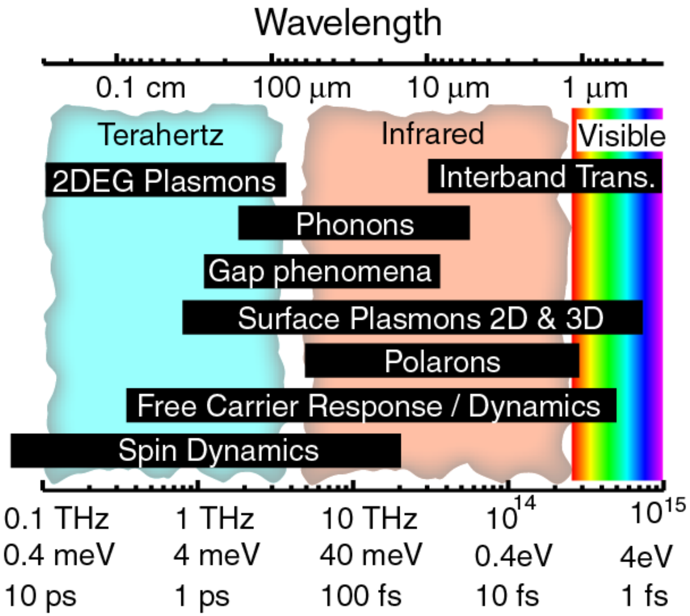


Image courtesy: D. Basov

Outline

mpsd

- ~~Part I: Floquet engineering of topological solids~~
  - ~~Floquet Chern insulator in graphene~~

    ~~*Nature Commun. 6, 7047 (2015)*~~
  - ~~Floquet-Weyl semimetal in Na_3Bi~~

    ~~*Nature Commun. 8, 13940 (2017)*~~

- Part II: Light-enhanced electron-phonon coupling

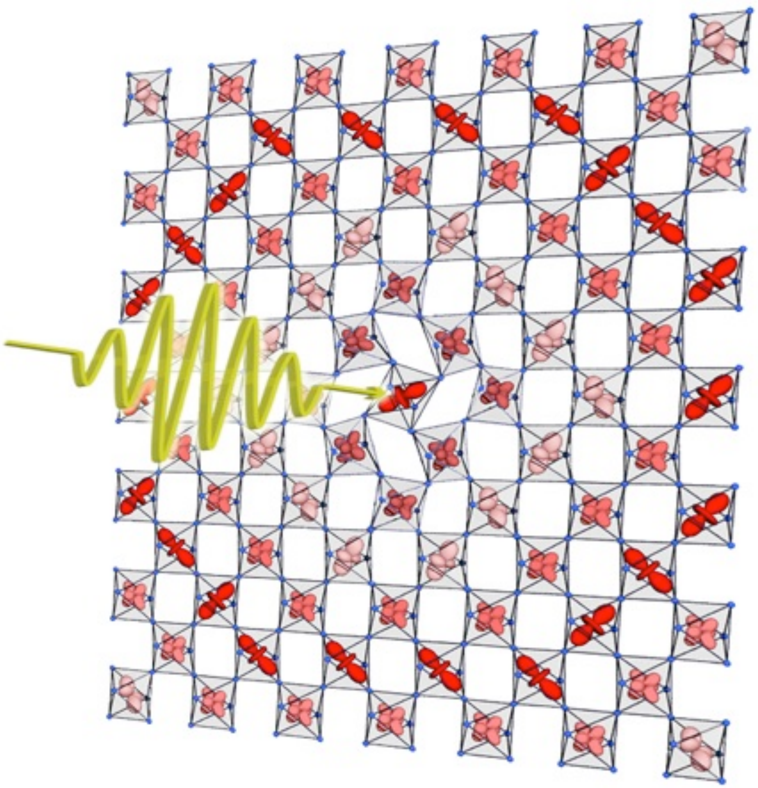
  PRB 95, 024304 (2017) - experiment
  PRB 95, 205111 (2017) - theory

- Part III: Laser-controlled competing orders

  PRL 118, 087002 (2017)

„as time permits“

Resonant excitation of crystal lattice

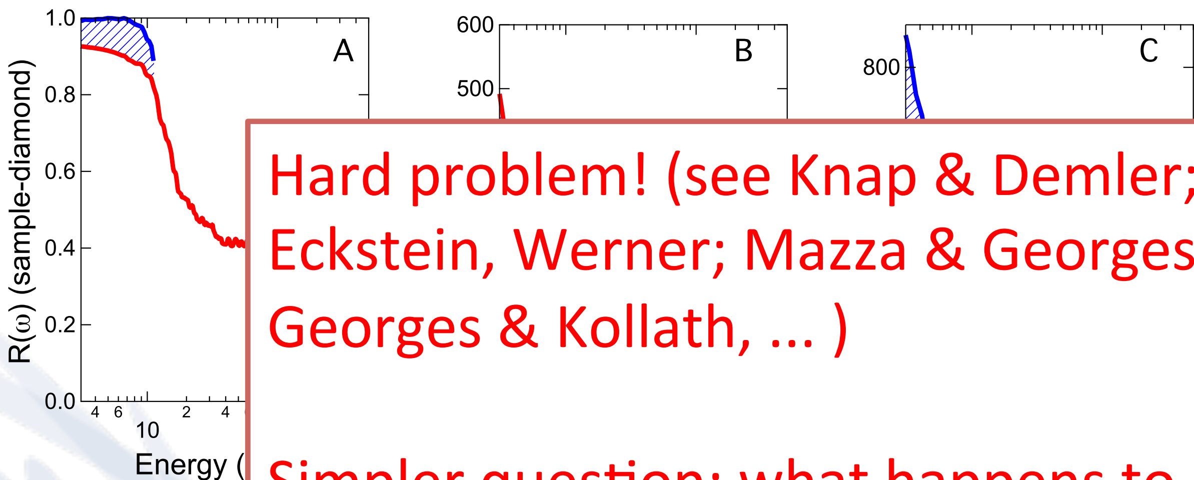


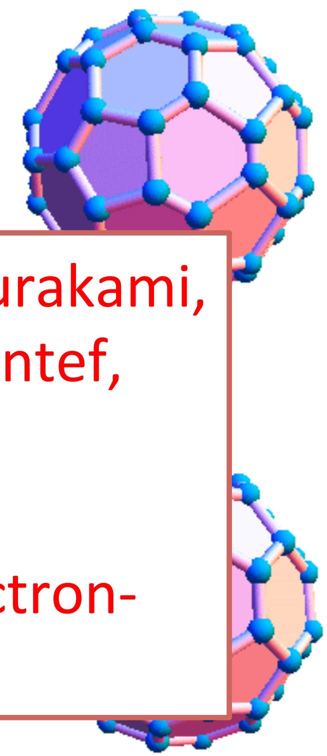
M. Först et al., Nature Physics 7, 854 (2011)

Light-induced superconductivity?

M. Mitrano et al.,
Nature 530, 461 (2016)

Lattice control of reflectivity in K_3C_{60}





Hard problem! (see Knap & Demler; Murakami, Eckstein, Werner; Mazza & Georges; Sentef, Georges & Kollath, ...)

Simpler question: what happens to electron-phonon coupling under driving?

Electron-boson coupling (bilinear)

Holstein model (minimal version):

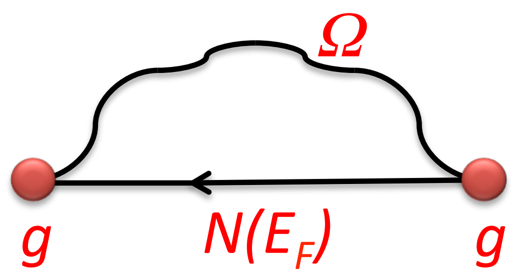
$$H = \sum_{\boldsymbol{k}} \epsilon(\boldsymbol{k}) c_{\boldsymbol{k}}^{\dagger} c_{\boldsymbol{k}} + \Omega \sum_i b_i^{\dagger} b_i - g \sum_i c_i^{\dagger} c_i (b_i + b_i^{\dagger})$$

Electrons
(Fermi gas/liquid)

Bosons
(e.g., Einstein phonon)

Electron-boson
coupling

$\Sigma =$



Migdal-Eliashberg theory
boson-mediated pairing

Electron-phonon coupling: signatures in relaxation dynamics

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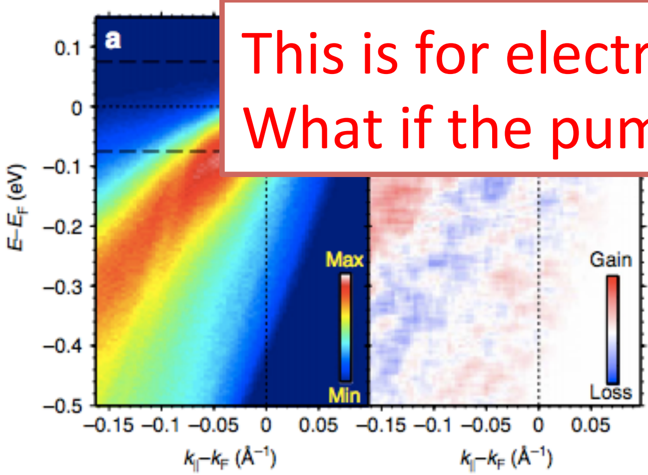
ARTICLE

Received 28 Mar 2016 | Accepted 31 Oct 2016 | Published 20 Dec 2016 DOI: 10.1038/ncomms13761 OPEN

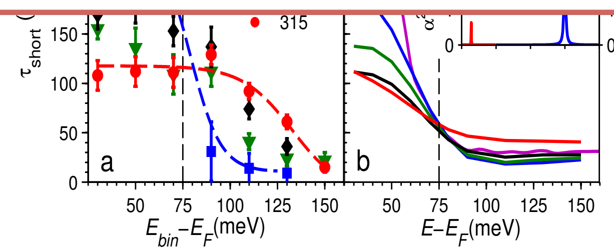
Energy dissipation from a correlated system driven out of equilibrium

J.D. Rameau[1], S. Freutel[2], A.F. Kemper[3,4], M.A. Sentef[5,6], J.K. Freericks[7], I. Avigo[2], M. Ligges[2], L. Rettig[2,†], Y. Yoshida[8], H. Eisaki[8], J. Schneeloch[1], R.D. Zhong[1], Z.J. Xu[1], G.D. Gu[1], P.D. Johnson[1] & U. Bovensiepen[2]

Time-resolved angle-resolved photoemission spectroscopy (tr-ARPES)



This is for electronic excitation (1.5 eV photon energy)
What if the pump laser is resonant with phonons?



experiment theory

...mmun. ...(2016)

comparison with experiment

Signature of dominantly coupled bosonic mode in fermionic relaxation dynamics above E_F
Increasing pump fluence: redistribution of nonequibrium scattering rates (self-energy)

II Dynamically enhanced coupling

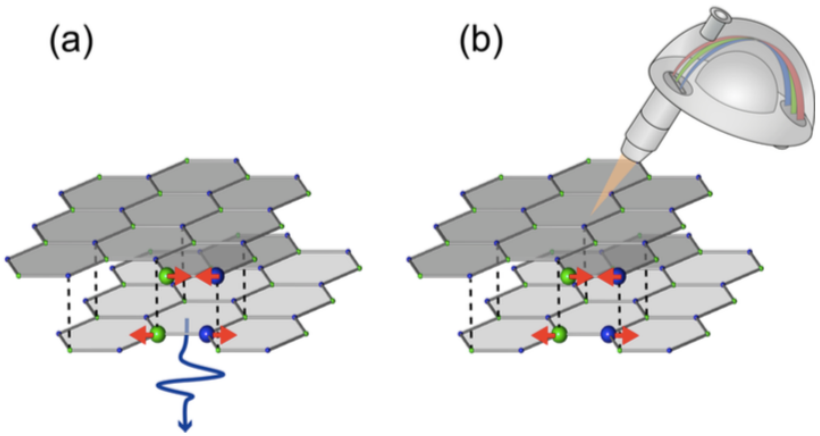
Enhanced electron-phonon coupling in graphene with periodically distorted lattice

E. Pomarico, M. Mitrano, H. Bromberger, M. A. Sentef, A. Al-Temimy, C. Coletti, A. Stöhr, S. Link, U. Starke, C. Cacho, R. Chapman, E. Springate, A. Cavalleri, and I. Gierz

Phys. Rev. B **95**, 024304 – Published 13 January 2017

PRB 95, 024304 (2017)

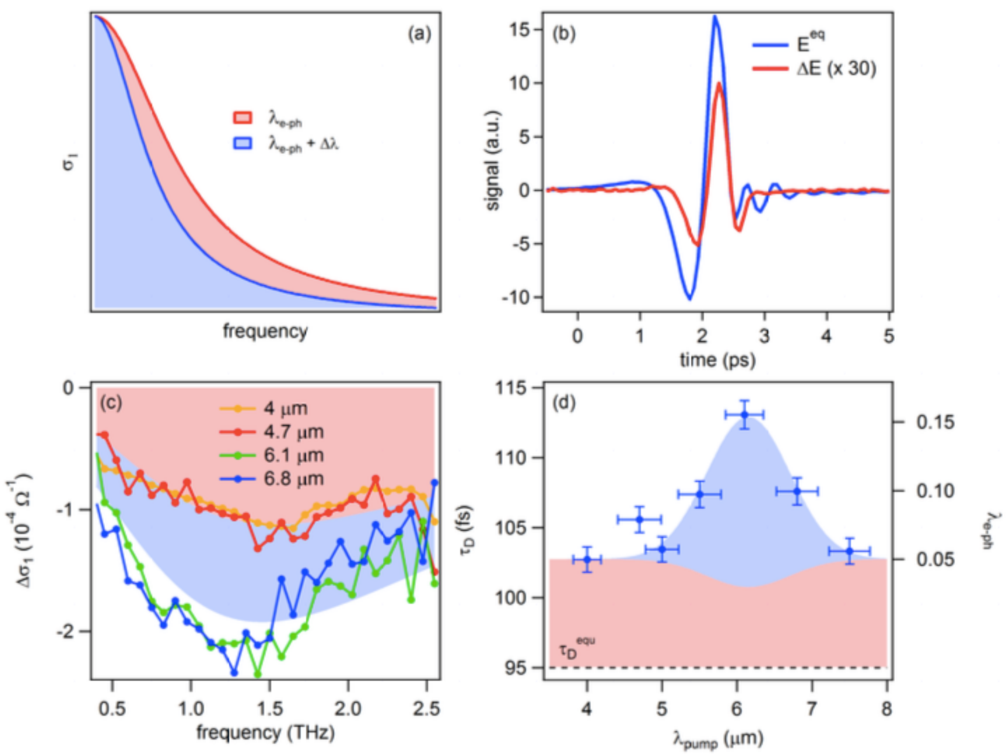
enhanced electron-phonon for pump on resonance with IR phonon



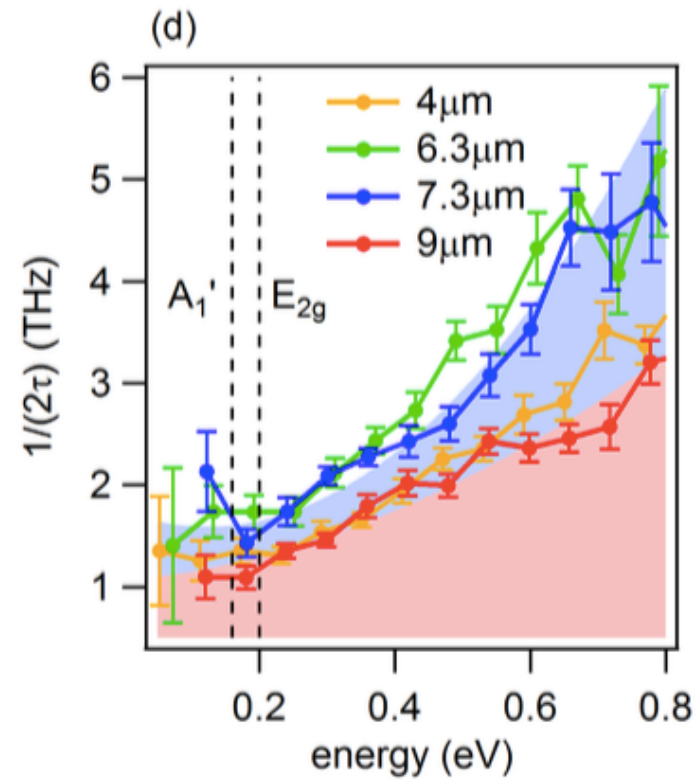
Dynamically enhanced coupling?

Enhanced electron-phonon coupling in graphene with periodically distorted lattice *PRB 95, 024304 (2017)*

transient reduction of Drude weight



enhanced tr-ARPES relaxation



3-fold enhancement of effective $\lambda_{el\text{-}ph}$! Why?

2-site model with nonlinear coupling

PRB 95, 205111 (2017)

$$\hat{H}(t) = -J\sum_{\sigma}(c^{\dagger}_{1,\sigma}c_{2,\sigma} + c^{\dagger}_{2,\sigma}c_{1,\sigma}) + g_2 \sum_{\sigma,l=1,2} \hat{n}_{l,\sigma}(b_l + b_l^{\dagger})^2 + \Omega \sum_{l=1,2} b_l^{\dagger}b_l + F(t)\sum_{l=1,2}(b_l + b_l^{\dagger}),$$

also cf.
Kennes et al.,
Nature Physics 13, 479 (2017),
1609.03802

Idea: Drive nonlinearly coupled phonon and look at electronic response

Drive: $$F(t) = F\sin(\omega t),$$

Response: time-resolved spectral function

$$I(\omega, t_0) = \mathrm{Re}\int dt_1\, dt_2\, e^{i\omega(t_1-t_2)} s_{t_1,t_2,\tau}(t_0) \times \Big[\langle\psi(t_2)|c^{\dagger}_{1,\uparrow}\mathcal{T}e^{-i\int_{t_1}^{t_2} H(t)dt} c_{1,\uparrow}|\psi(t_1)\rangle + + \langle\psi(t_1)|c_{1,\uparrow}\mathcal{T}e^{-i\int_{t_2}^{t_1} H(t)dt} c^{\dagger}_{1,\uparrow}|\psi(t_2)\rangle\Big],$$

Time-resolved el spectrum *PRB 95, 205111 (2017)*

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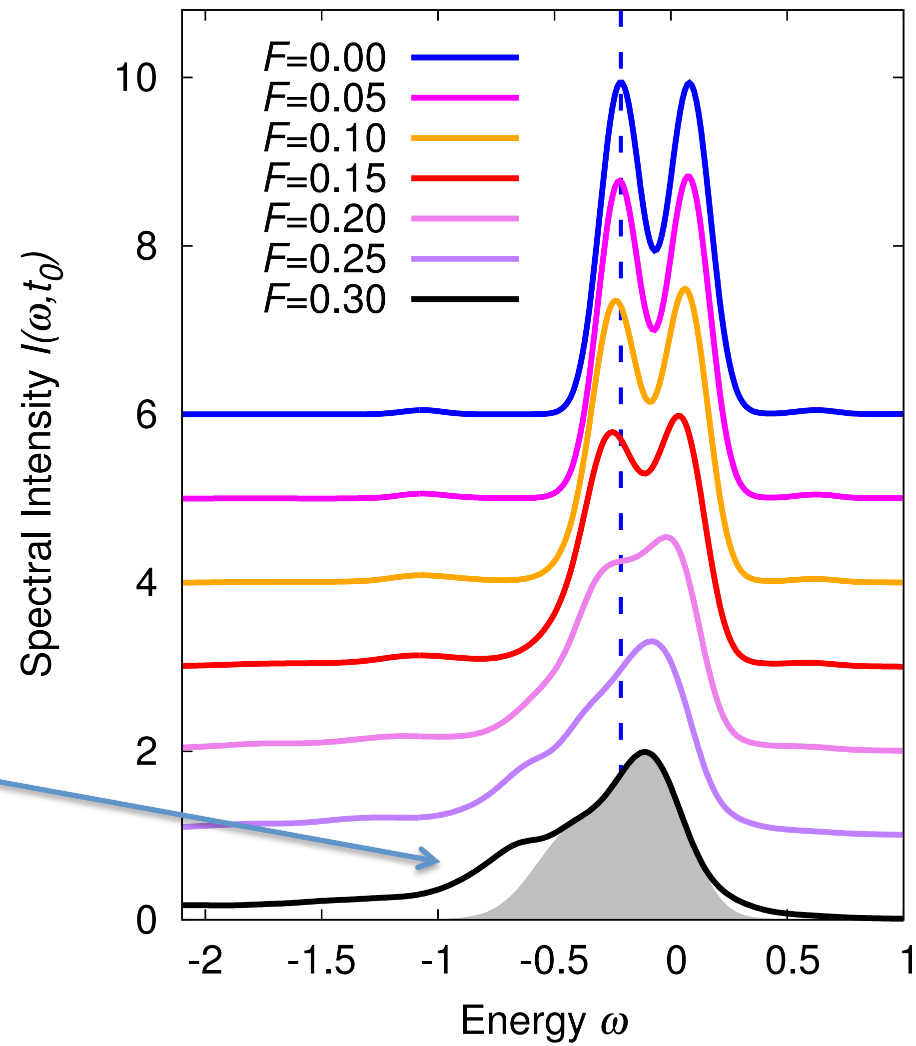
Reduced coherence peaks with stronger driving

Looks like enhanced el-ph coupling

light-induced polaron formation



Field scaling

PRB 95, 205111 (2017)

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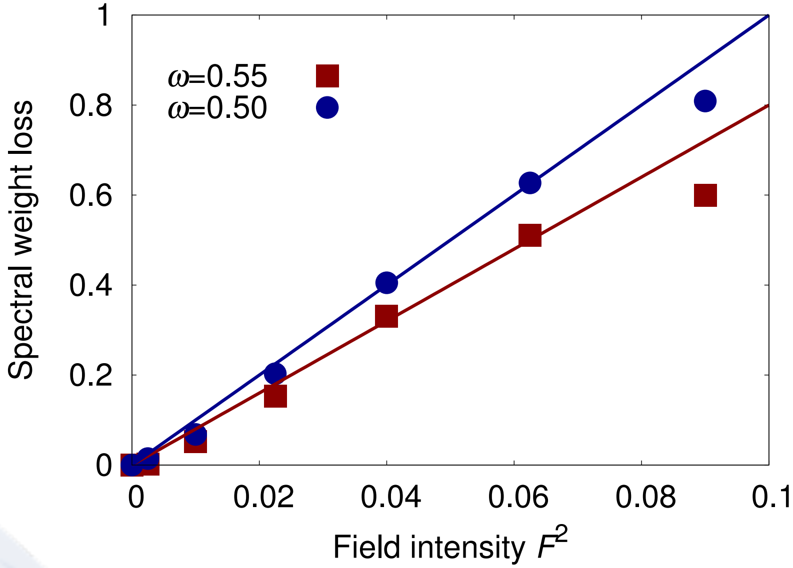
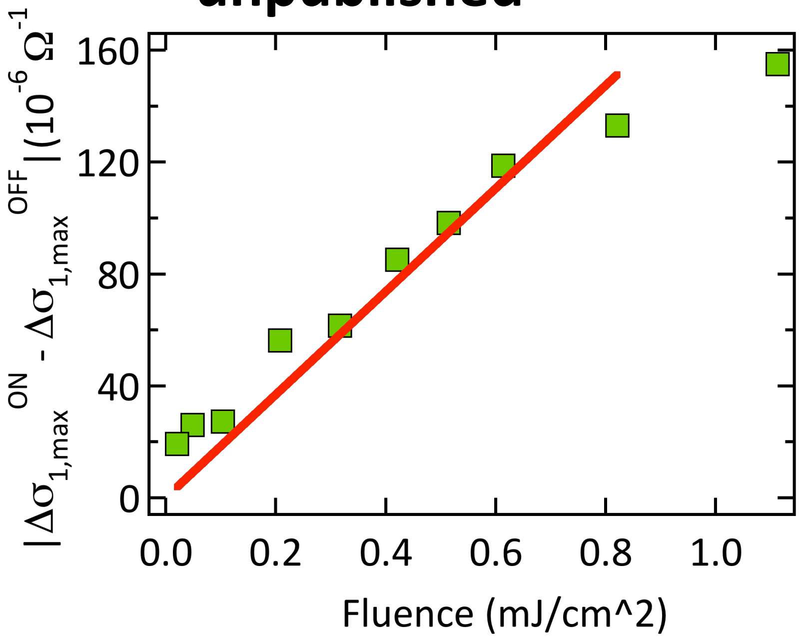
Theory



Data by E. Pomarico, unpublished



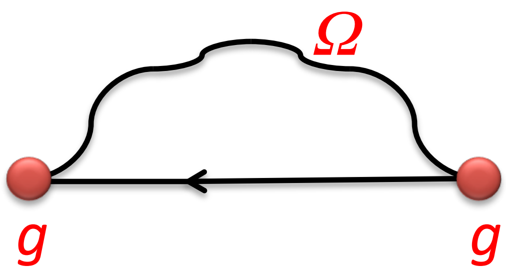
Scaling of coherent spectral weight loss: proportional to field intensity consistent with experiments

Mechanism behind enhanced coupling

Forced coherent oscillation $\langle \hat{x}_l(t) \rangle \propto F \sin(\omega t)$

Coupling term in „mean-field“: $g_2 \hat{n}_l (b_l \langle b_l(t) \rangle + b_l^\dagger \langle b_l^\dagger(t) \rangle)$

~F ~F

$\Sigma =$ 

Migdal-Eliashberg theory

$$\Sigma(t,t') = i g(t) g^*(t') G(t,t') D(t,t')$$

with time-dependent linear coupling and g^2 ~ F^2
=> light-induced coupling, effective lambda scales ~ F^2

Enhanced double occupancy: attraction?

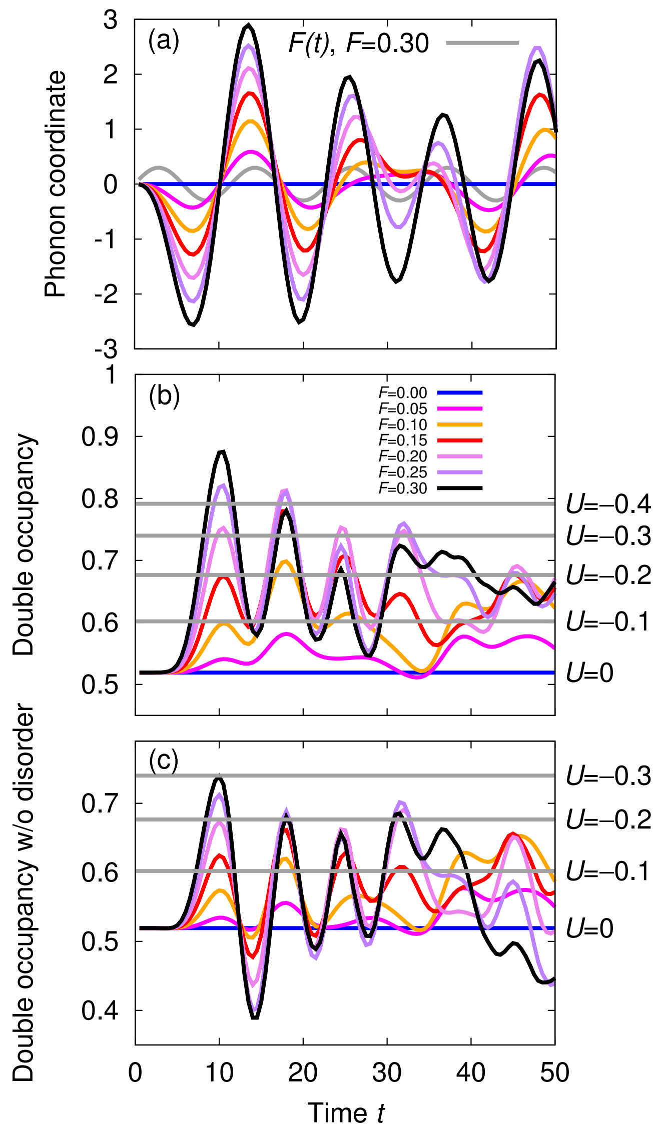
Coherent phonon oscillation

Enhanced double occupancy (above „random“ value)

Contribution from „disorder“ term (localization)

$$g_2 \hat{n}_l 2 b_l^\dagger b_l$$

subtracting disorder contribution: effective attraction when drive is not too strong

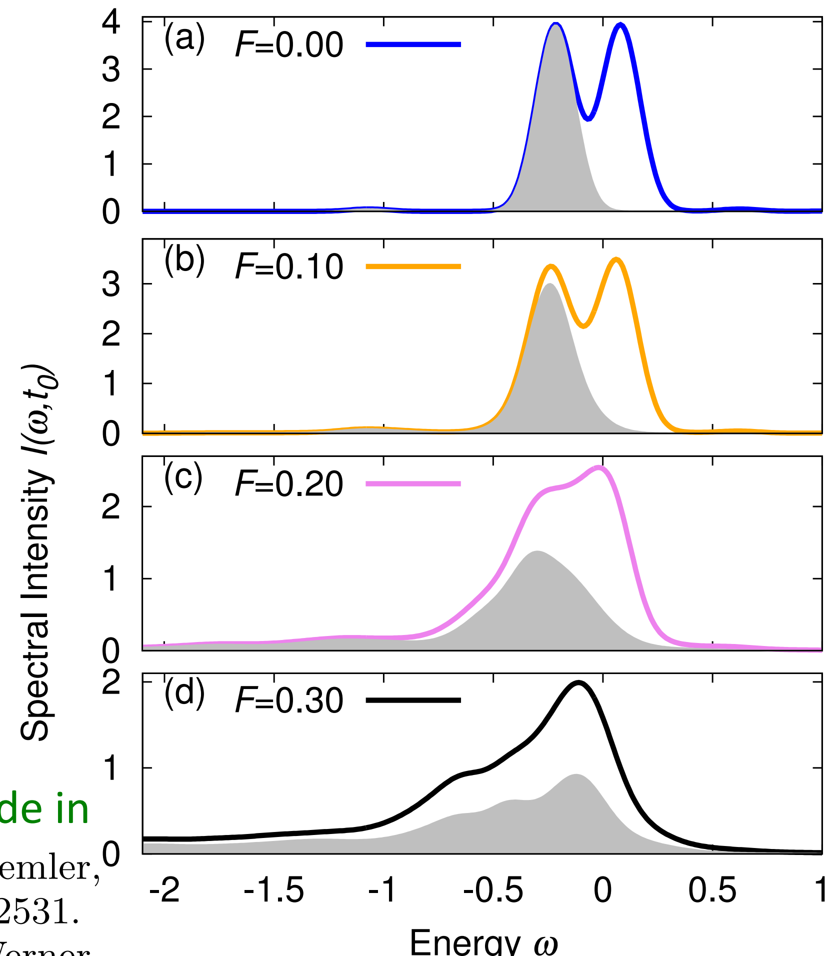


Electronic heating?

Electronic excitations: Occupied spectrum

Heating effects (conduction band occupation) scale with higher power than linear in fluence

Sweet spot for light-enhanced superconductivity?



See discussions for linearly coupled driven mode in

M. Babadi, M. Knap, I. Martin, G. Refael, and E. Demler, arXiv:1702.02531 [cond-mat] (2017), arXiv: 1702.02531.
Y. Murakami, N. Tsuji, M. Eckstein, and P. Werner, arXiv:1702.02942 [cond-mat] (2017), arXiv: 1702.02942.

Summary II

- enhanced electron-phonon coupling in phononically driven bilayer graphene

PRB 95, 024304 (2017)

E. Pomarico

I. Gierz

A. Cavalleri

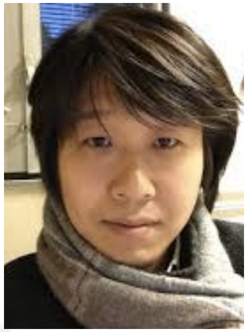
Exact solution of electron-phonon model system:

- theoretical proposal: nonlinear el-ph coupling as mechanism behind this enhancement

arXiv:1702.00952; PRB 95, 205111 (2017)

III Theory of laser-controlled competing orders

Phys. Rev. Lett. 118, 087002 (2017)

Akiyuki Tokuno Antoine Georges Corinna Kollath
Palaiseau/Paris/Geneva University of Bonn

Nonequilibrium superconductivity

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Why?

- understand ordering mechanisms
- control ordered states: ultrafast switching
- induce new states of matter

How?

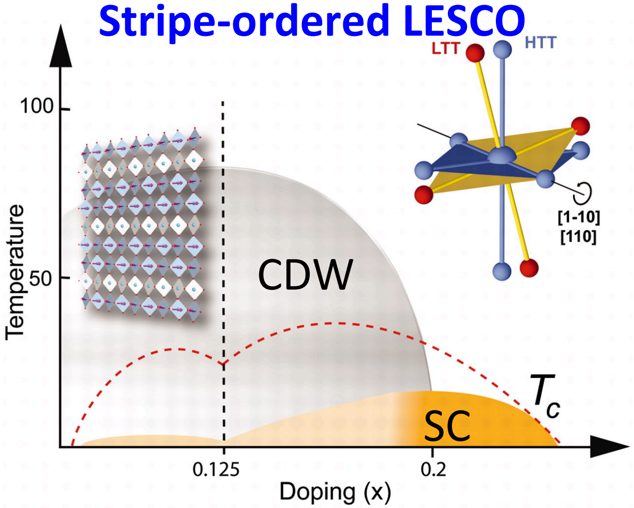
- laser near resonance with collective modes

Generic mechanism to control competing orders with light?

Recent theories on laser-controlled couplings and competing orders:
Akbari et al., EPL 101, 17003 (2013); Moor et al., PRB 90, 024511 (2014); Fu et al., PRB 90, 024506 (2014); Dzero et al., PRB 91, 214505 (2015); Tsuji&Aoki, PRB 92, 064508 (2015); Cea et al., PRB 93, 180507 (2016); Kemper et al., PRB 92, 224517 (2015); Sentef et al., PRB 93, 144506 (2016); Krull et al., Nat. Commun. 7, 11921 (2016); Patel&Eberlein, PRB 93, 195139 (2016); Knap et al., PRB 94, 214504 (2016); Komnik&Thorwart EPJB 89, 244 (2016); Coulthard et al., 1608.03964; Kennes et al., Nat. Physics (2017), doi:10.1038/nphys4024; Sentef, 1702.00952; Babadi et al. 1702.02531; Murakami et al.,1702.02942; Mazza&Georges, 1702.04675; Dehghani&Mitra, 1703.01621 ...

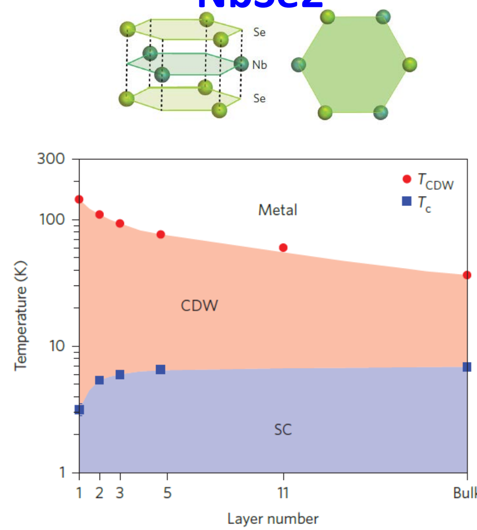
Experimental motivation: competing orders

Stripe-ordered LESCO



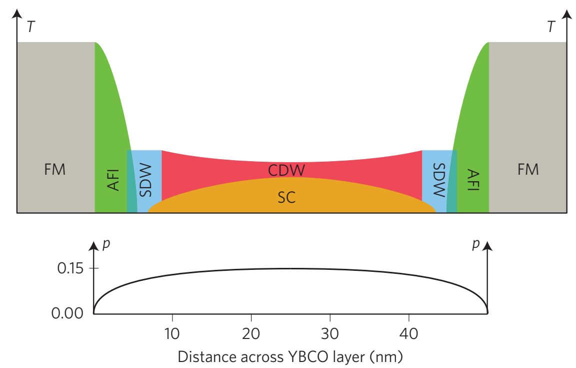
D. Fausti et al.,
Science, 331, 189 (2011)

NbSe2



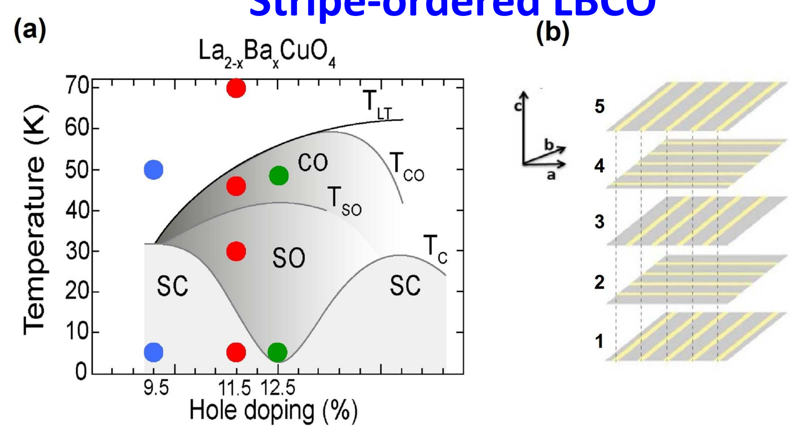
X. Xi et al., Nat. Nanotechnol. 10, 765 (2015)

YBCO-LCMO heterostructure



A. Frano et al.,
Nat. Mater. 15, 831 (2016)

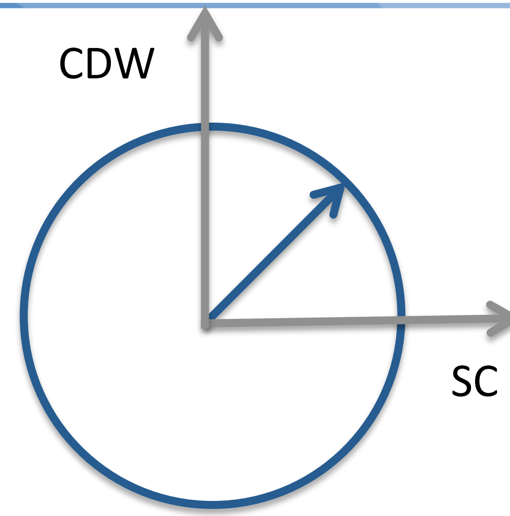
Stripe-ordered LBCO



D. Nicoletti et al.,
PRB 90, 100503 (2014)

Competing orders

- attractive -U Hubbard model
- degeneracy of SC and CDW at particle-hole symmetry (SU(2))
- SO(4) symmetry (SC, CDW, eta pairing)



VOLUME 63, NUMBER 19 PHYSICAL REVIEW LETTERS 6 NOVEMBER 1989

η Pairing and Off-Diagonal Long-Range Order in a Hubbard Model

Chen Ning Yang

C. N. Yang

S.-C. Zhang

Reprinted from Mod. Phys. Lett. B4 (1990) 759–766

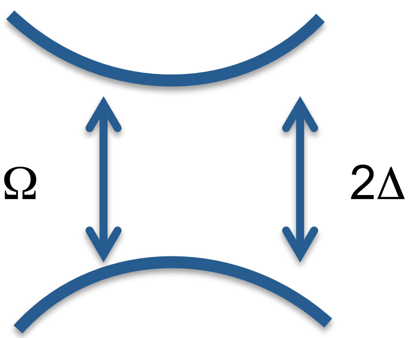
SO_4 SYMMETRY IN A HUBBARD MODEL

CHEN NING YANG
Institute for Theoretical Physics, State University of New York, Stony Brook, NY 11794-3840, USA
and
S. C. ZHANG
IBM Research Division, Almaden Research Center, San Jose, CA 95120-6099, USA

also see: Demler, Hanke, Zhang, SO(5) theory of antiferromagnetism and dSC, RMP 76, 909 (2004)

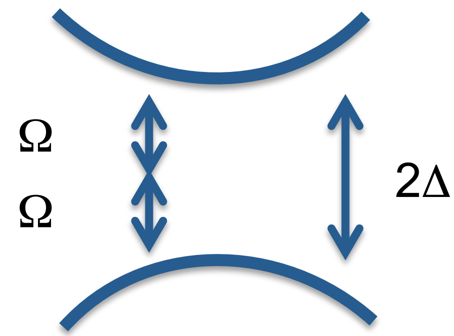
Driven SC/CDW: Gauge field coupling

CDW ~ A
1-photon resonance

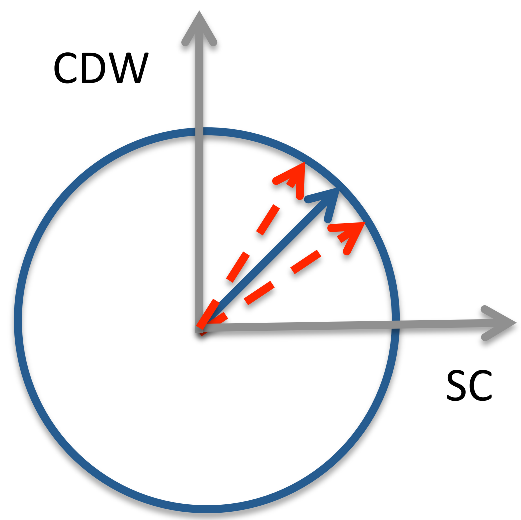


SC ~ A^2
2-photon resonance

Tsuji&Aoki, PRB 92, 064508 (2015)
Cea et al., PRB 93, 180507 (2016)



... laser lifts SC/CDW degeneracy
... Goldstone-like collective mode?



Model

$$H=\sum_{k\sigma}\epsilon(k)n_{k\sigma}+U\sum_{i}n_{i\uparrow}n_{i\downarrow}=H_J+H_U,$$
$$\epsilon(k)=-2J(\cos(k_x)+\cos(k_y)),$$

2D square lattice + attractive U + mean-field decoupling

$$\Delta_{SC}=U\sum_k f_k,\qquad f_k\equiv\langle c_{-k\downarrow}c_{k\uparrow}\rangle\qquad \text{(SC)},$$
$$\Delta_{CDW}=U\sum_k g_k,\qquad g_k\equiv\frac{1}{2}\sum_\sigma\langle c^\dagger_{k\sigma}c_{k+Q\sigma}\rangle\quad \text{(CDW)},$$
$$\Delta_\eta=U\sum_k \eta_k.\qquad \eta_k\equiv\langle c_{-(k+Q)\downarrow}c_{k\uparrow}\rangle\quad (\eta\ \text{pairing}).$$

Mean-field equations

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Equations of motion for electronic driving:

eta pairing provides coupling

$$i\partial_t n_k = -\Delta_{SC}(f_k - f_k^*) + \Delta_{CDW}(g_k - g_k^*) - \Delta_\eta^* \eta_k + \Delta_\eta \eta_k^*,$$

$$i\partial_t f_k = \Delta_{SC}(1 - (n_k + n_{-k})) + (\epsilon(k-A) + \epsilon(k+A)) f_k + \Delta_{CDW}(\eta_k + \eta_{k+Q}) - \Delta_\eta (g_k^* + g_{-k}^*),$$

$$i\partial_t g_k = \Delta_{CDW}(n_k - n_{k+Q}) - 2\epsilon(k-A) g_k + \Delta_{SC}(\eta_k^* - \eta_{k+Q}) + \Delta_\eta f_k^* - \Delta_\eta^* f_{k+Q},$$

$$i\partial_t \eta_k = \eta_k(\epsilon(k-A) - \epsilon(k+A)) + \Delta_{CDW}(f_k + f_{k+Q}) - \Delta_{SC}(g_{-k} + g_k^*) - \Delta_\eta (n_k + n_{-(k+Q)} - 1).$$

nonlinear equations:
self-consistency in real time

$$\Delta_{SC} = U \sum_k f_k,$$

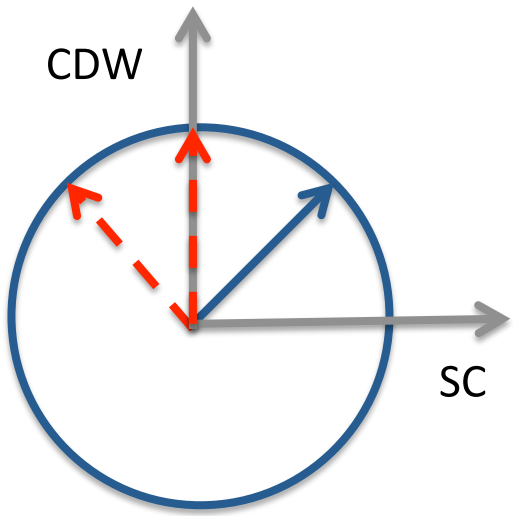
$$\Delta_{CDW} = U \sum_k g_k,$$

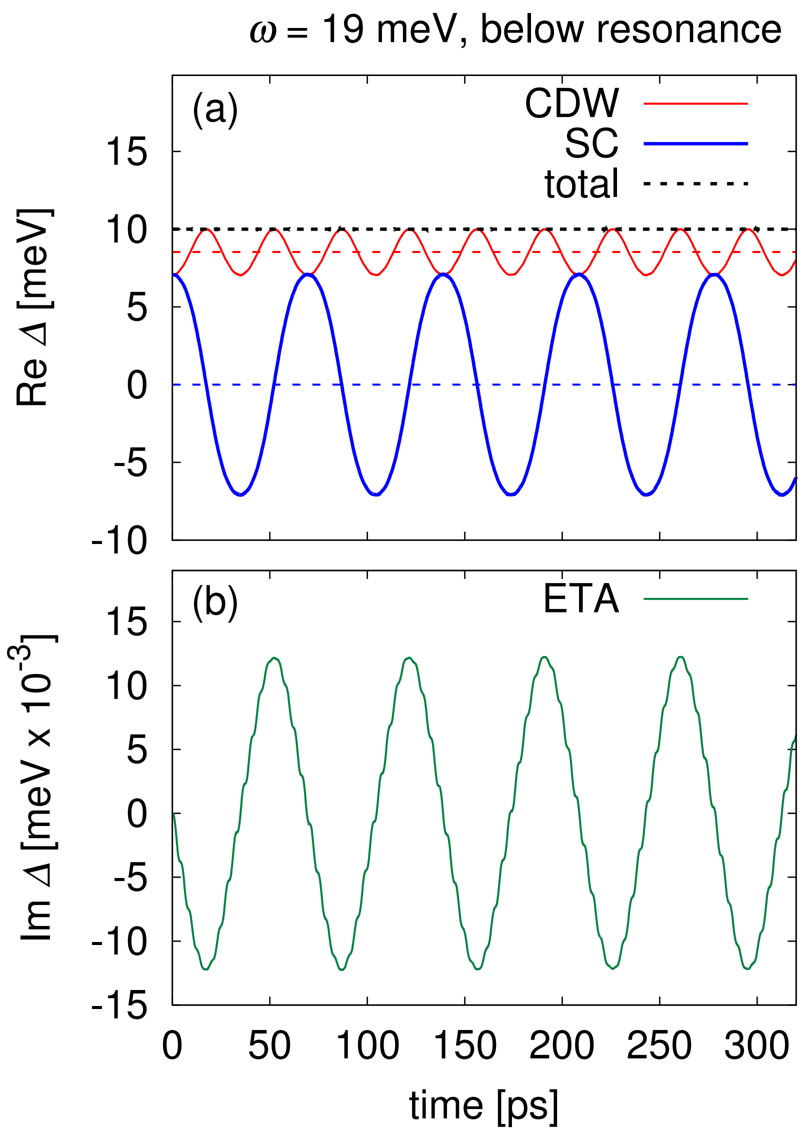
$$\Delta_\eta = U \sum_k \eta_k.$$

Nonequilibrium:
Periodic driving field: $A(t) = A_{max} \sin(\omega t)\,(e_x + e_y)$
$A_{max} = 5 \times 10^{-5}$, $E_{max} \sim 10\text{-}100$ V/cm – weak fields!

Gap resonance – coexisting initial state

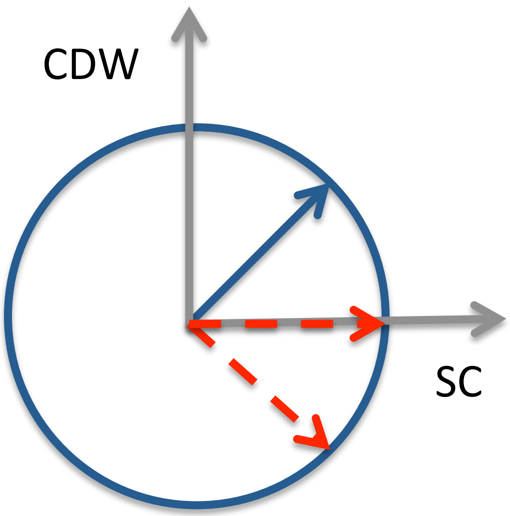
Below resonance:
SC down, CDW up

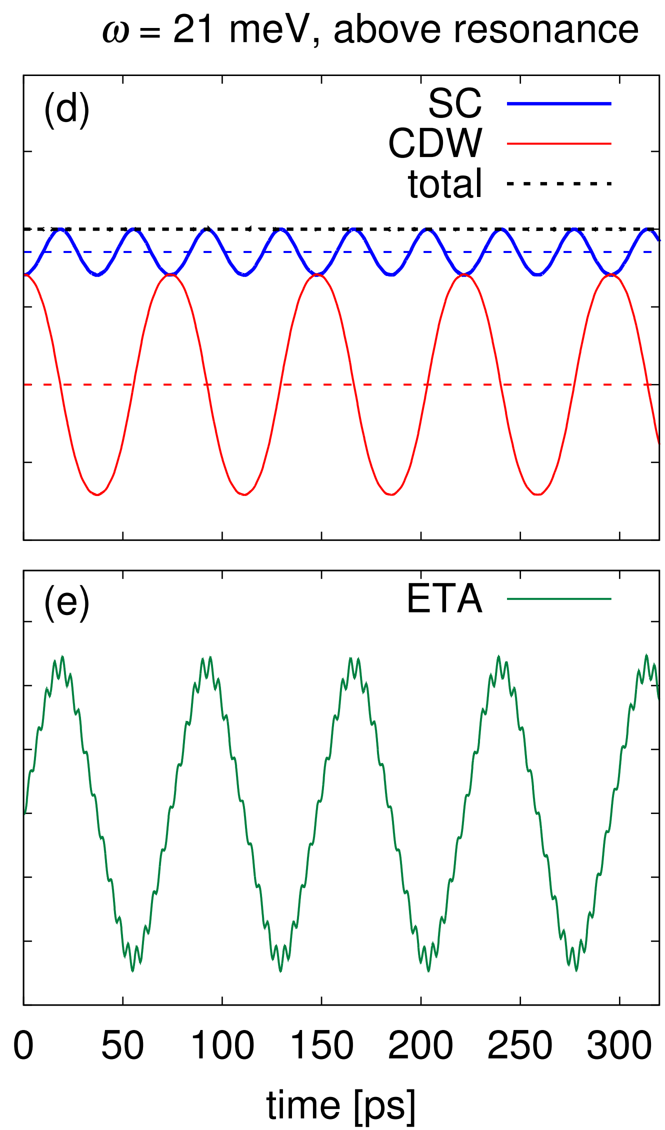




Gap resonance – coexisting initial state

Above resonance:
SC up, CDW down

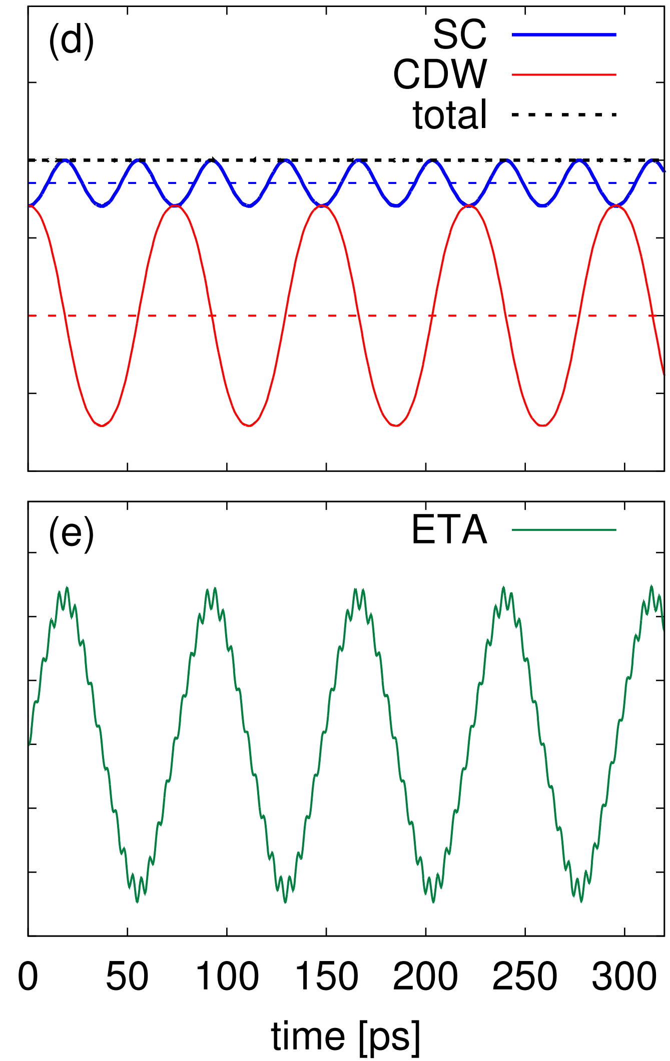




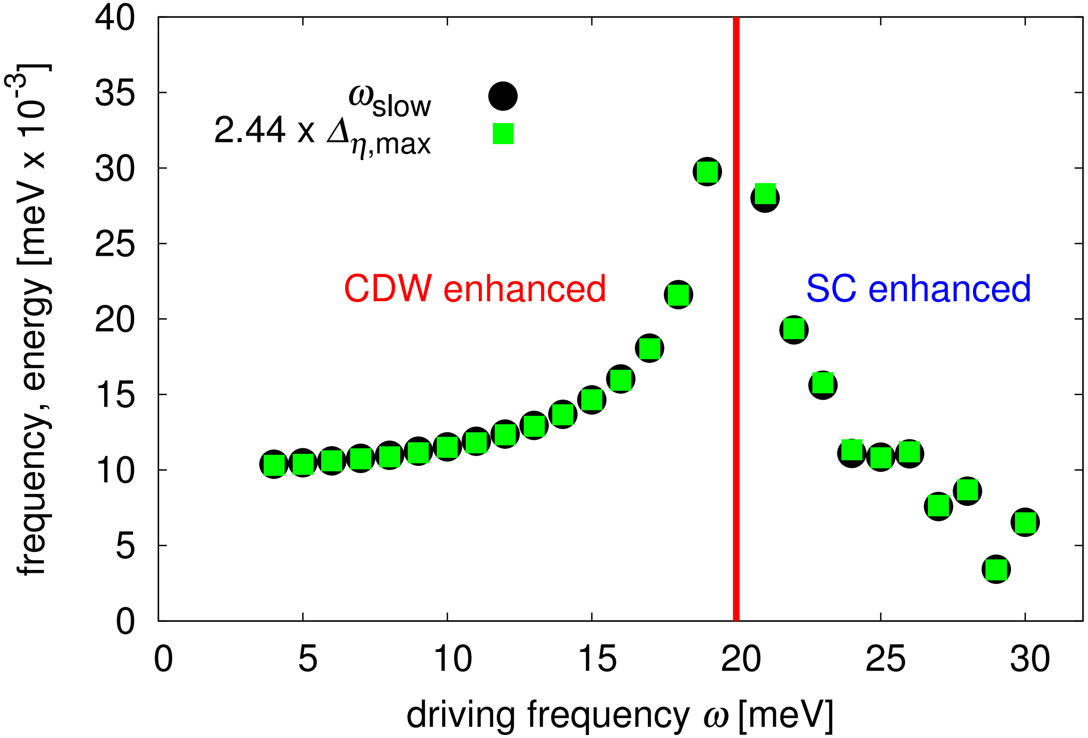
Gap resonance – coexisting initial state

„Floquet time crystal“ without many-body localization??

ω = 21 meV, above resonance



Gap resonance



oscillation frequency set by light-induced eta pairing amplitude, which gives „mass“ to collective mode

resonant behavior at $\omega=2\Delta$ = single-particle gap

Gap resonance – why?

$$\mathrm{Im}\eta_{\vec{k},2}(t) = 2A_{\vec{k},0}\int_0^t \eta_{\vec{k},1}(t')\sin(\omega t')dt'$$
$$= \frac{2A_{\vec{k},0}^2\Delta_0 g_{\vec{k},0} t}{4E_{\vec{k}}^2 - \omega^2} + \eta_{\vec{k},2,\mathrm{osc}}(t),$$

short time expansion: leading contribution resonant for light-induced eta pairing – sign change when crossing ω=2Δ

-> this triggers the dynamics between SC and CDW

generic mechanism for coexisting, non-commuting orders!

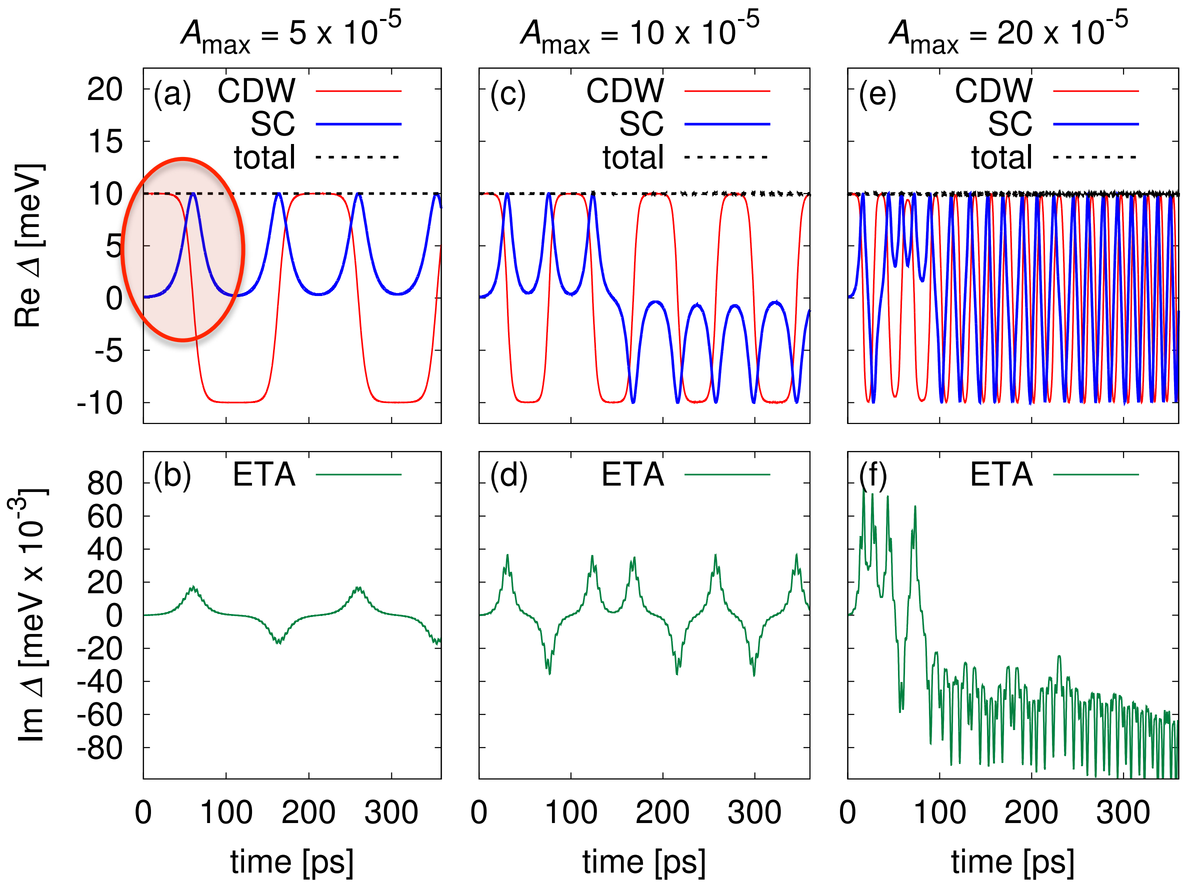
Inducing superconductivity

99% CDW initial state

Drive slightly above gap

SC comes alive!

Irregular behavior for stronger driving



Summary III

Tight-binding model + time-dependent mean-field theory:

- laser-controlled switching between SC/CDW
- path to understanding of light-induced superconductivity and light-induced CDW in systems with competing orders?

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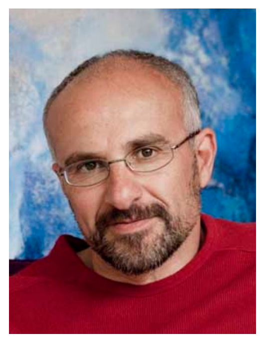

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