Theory of laser-driven nonequilibrium superconductivity

PRB 92, 224517 (2015)
PRB 93, 144506 (2016)

Collaborators:
A. F. Kemper, B. Moritz, J. K. Freericks, T. P. Devereaux,
A. Georges, C. Kollath, A. Tokuno

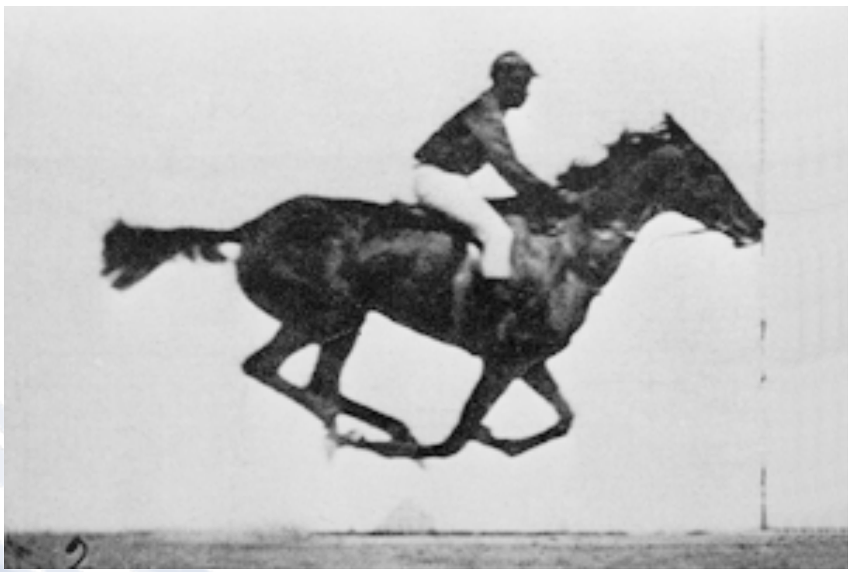
Michael Sentef

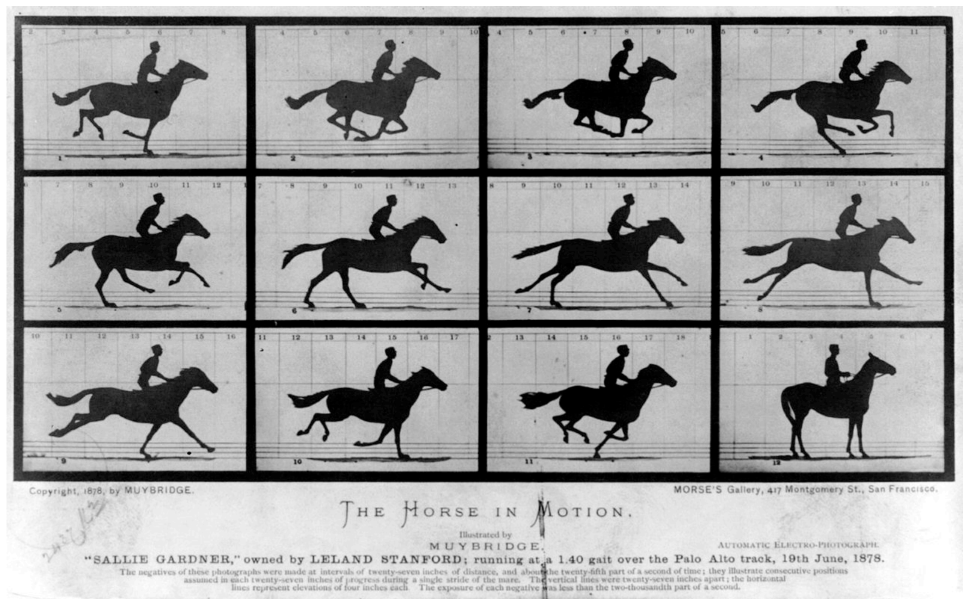
SIMES Seminar, February 12, 2016

Max Planck Institute for the Structure and Dynamics of Matter

Pump-probe spectroscopy (1887)

- stroboscopic investigations of dynamic phenomena

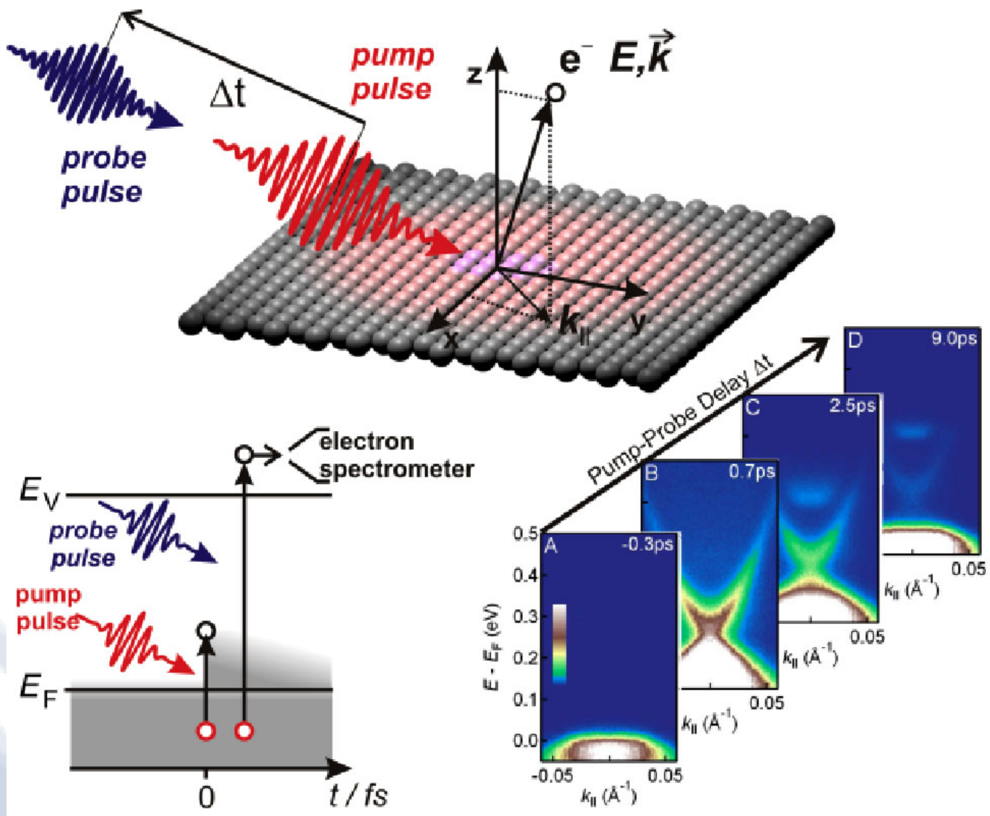




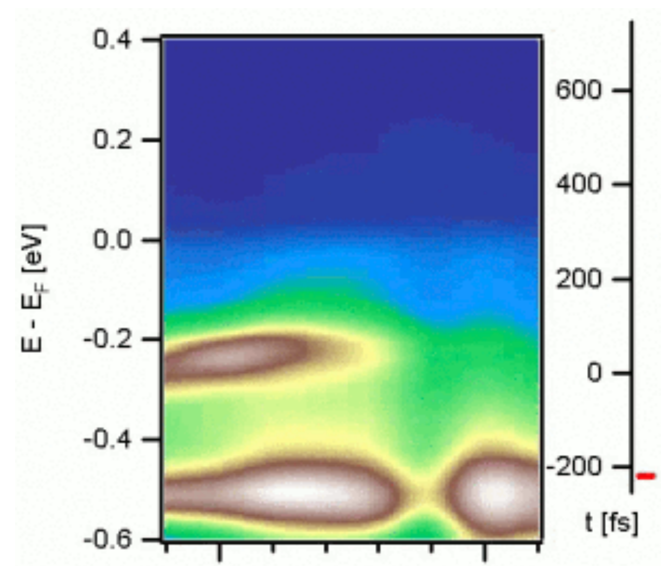
Muybridge 1887

Pump-probe spectroscopy (today)

- stroboscopic investigations of dynamic phenomena



TbTe3 CDW metal



J. Sobota et al., PRL 108, 117403 (2012)
F. Schmitt et al., Science 321, 1649 (2008)
Image courtesy: J. Sobota / F. Schmitt

Ultrafast Materials Science

Understanding the nature of quasi-particles

- Relaxation channels and dynamics

Understanding ordered phases

- Collective oscillations
- Light-enhanced order
- Competing order parameters

Creating new states of matter

- Photo-induced phase transitions
- Non-thermal phases

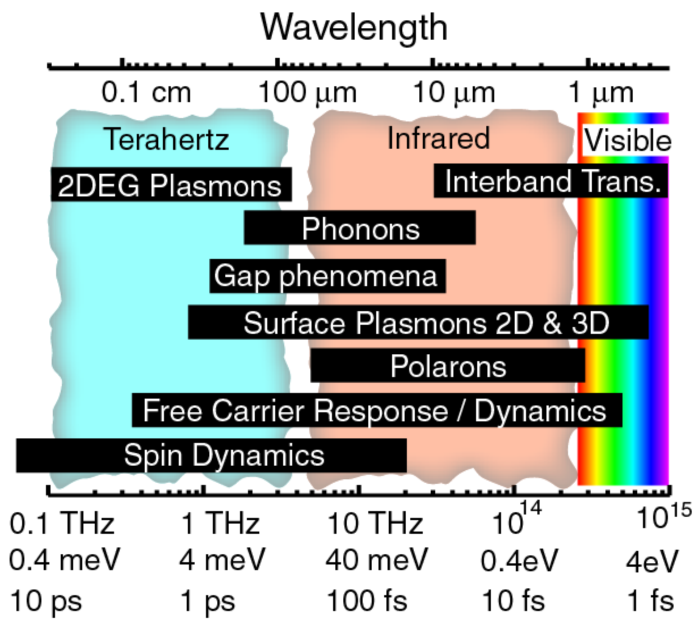


Image courtesy: D. Basov

Outline

- Light-superconductor coupling
- Keldysh Green functions
- Ordered states: Driven superconductors
  - Higgs amplitude mode oscillations for optical pumping (1.5 eV laser)
    PRB 92, 224517 (2015)
  - light-enhanced superconductivity via coherent hopping control
    arXiv:1505.07575
- competing orders (preliminary results)

Higgs amplitude mode (BCS)

Dynamics of superconductors

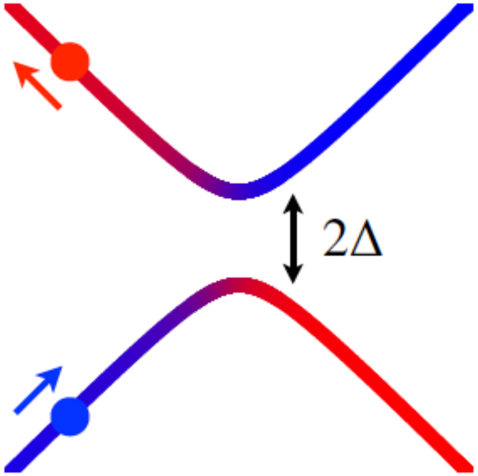
- Bogoliubov-de Gennes equation coupled to an electric field

electron

$$i\partial_t \Psi_k = \begin{pmatrix} \epsilon_{k-eA(t)} & -\Delta^* \\ -\Delta & -\epsilon_{k+eA(t)} \end{pmatrix} \Psi_k$$

hole

$$\Psi_k = \begin{pmatrix} c_{k\uparrow} \\ c^\dagger_{-k\downarrow} \end{pmatrix}$$: Nambu spinor



Higgs amplitude mode (BCS)

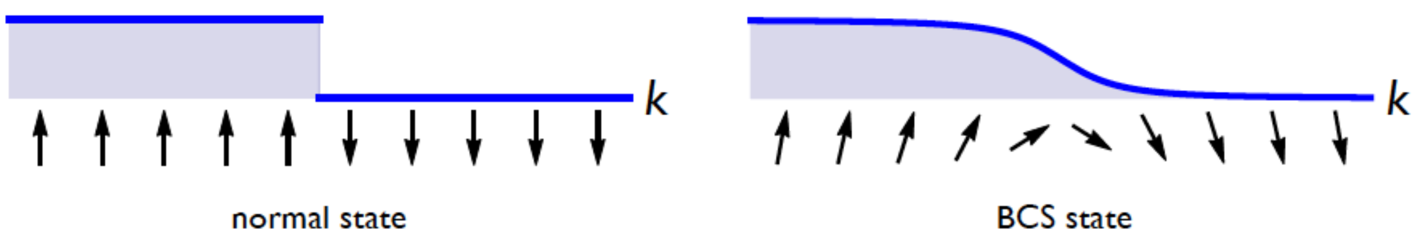
Anderson pseudospin

$$\sigma_k = \frac{1}{2}\Psi_k^\dagger \cdot \boldsymbol{\tau} \cdot \Psi_k$$

Anderson, Phys. Rev. 112, 1900 (1958)

$$\partial_t \sigma_k = 2 b_k \times \sigma_k \qquad b_k = \left(-\Delta', -\Delta'', \frac{\epsilon_{k-eA(t)} + \epsilon_{k+eA(t)}}{2}\right)$$

Tsuji, Aoki, arXiv:1404.2711



- Particle-hole symmetric by construction.
- Linear response vanishes.

Higgs amplitude mode (BCS)

mpsd

Light-pseudospin coupling

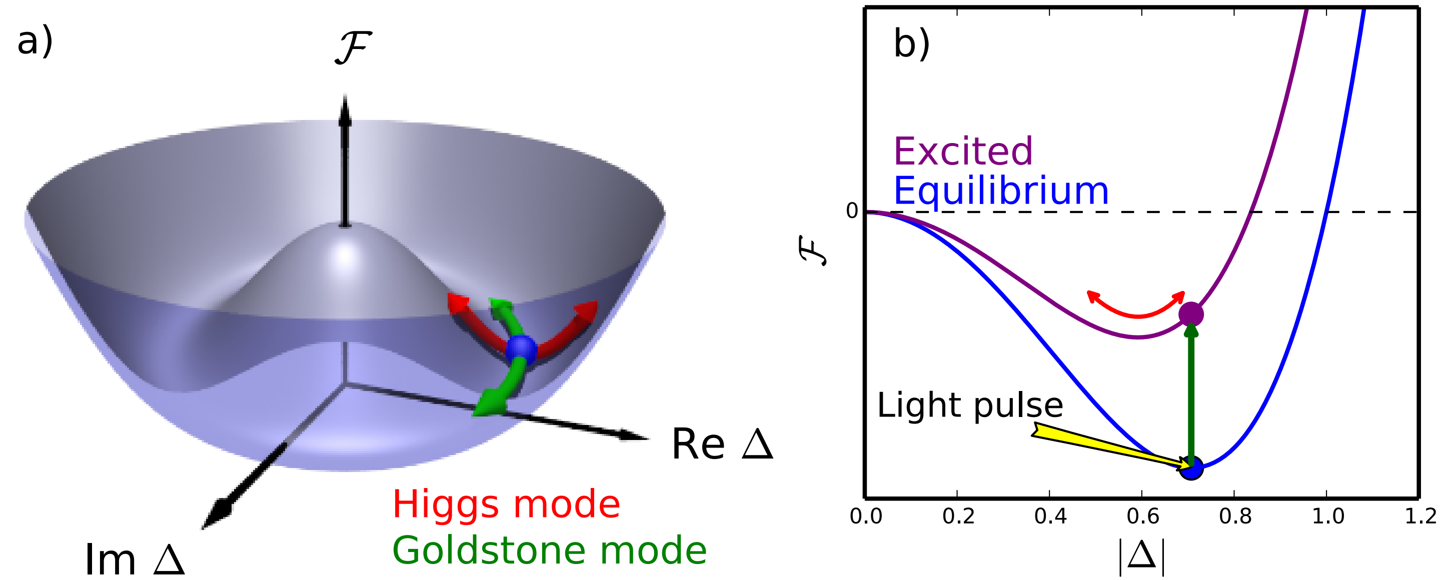
$$\partial_t \boldsymbol{\sigma}_k = 2\boldsymbol{b}_k \times \boldsymbol{\sigma}_k \qquad \boldsymbol{b}_k = \left(-\Delta', -\Delta'', \frac{\epsilon_{k-eA(t)} + \epsilon_{k+eA(t)}}{2}\right)$$

$$\epsilon(k-A) + \epsilon(k+A) = 2\epsilon(k) + \mathcal{O}(A^2),$$

A^2 coupling: „Anderson pseudospin (Higgs) resonance" at 2 ω = 2 Δ

Tsuji & Aoki, PRB 92, 064508 (2015)
R. Matsunaga et al., Science 345, 1145 (2014)

Higgs amplitude mode



Include the effects of driving field through Peierls substitution

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

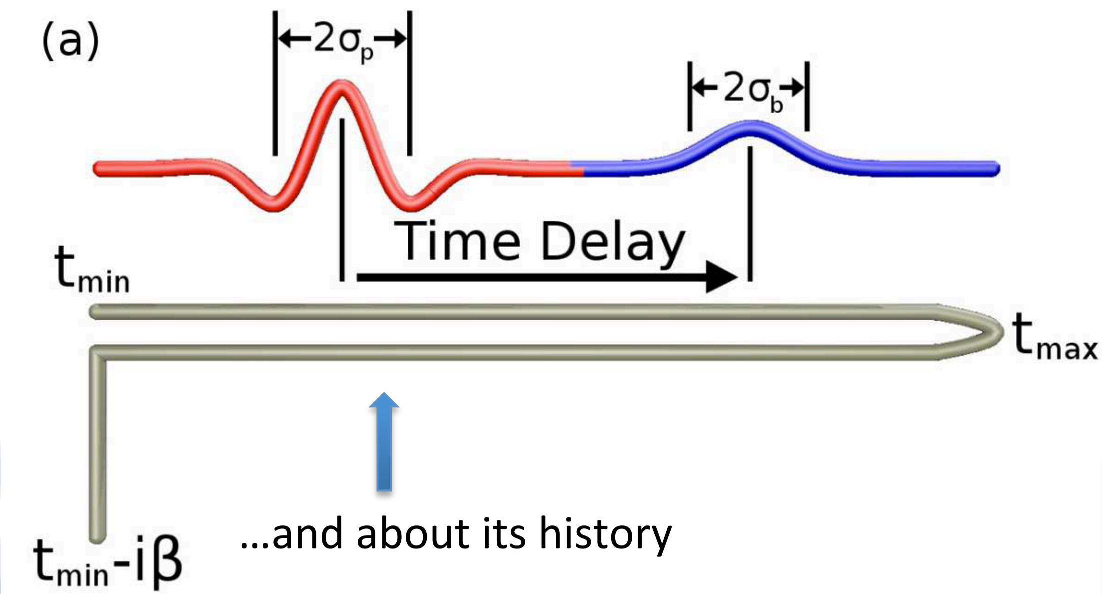
Non-Equilibrium Keldysh Formalism

Beyond BCS

$$G_k(t,t') = G^0_k(t,t') + \oint dt_1\, dt_2\, G^0_k(t,t_1)\,\Sigma(t_1,t_2)\,G_k(t_2,t')$$

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

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



...and about its history

System knows about its thermal initial state...

Include the effects of driving field through time-dependent electronic dispersion

$$\varepsilon(k) \rightarrow \varepsilon(k,t)$$

Model and Method

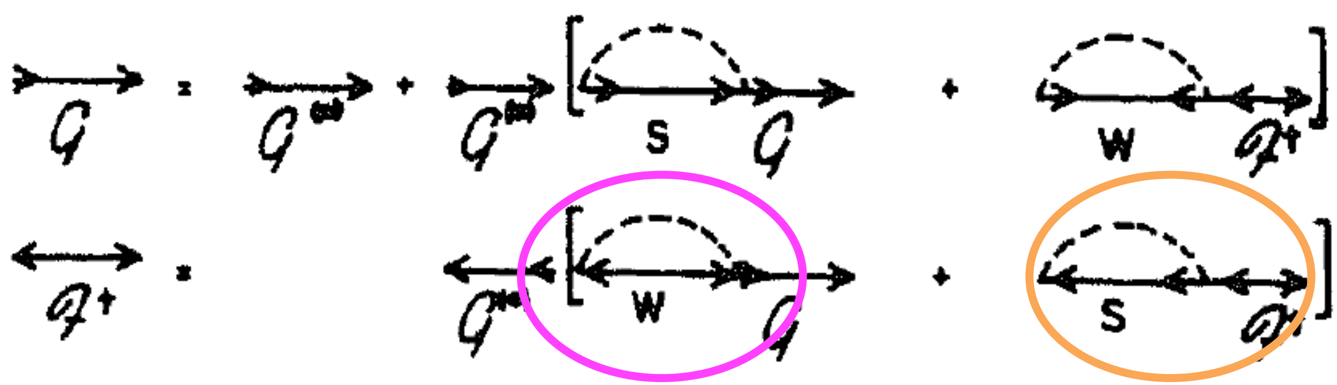
$$\mathcal{H} = \sum_{\boldsymbol{k}\sigma} \epsilon(\boldsymbol{k},t) c^\dagger_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} + \sum_{\boldsymbol{q},\gamma} \Omega_\gamma b^\dagger_{\boldsymbol{q},\gamma} b_{\boldsymbol{q},\gamma} - \sum_{\boldsymbol{q},\gamma,\sigma} g_\gamma c^\dagger_{\boldsymbol{k}+\boldsymbol{q}\sigma} c_{\boldsymbol{k}\sigma} \left(b_{\boldsymbol{q},\gamma} + b^\dagger_{-\boldsymbol{q},\gamma} \right)$$

- electrons (2D square latt.) + spectrum of phonons + el-ph coupling (Holstein)
- Migdal-Eliashberg (1st Born) + phonon heat bath approximation

superconductor:

normal

anomalous

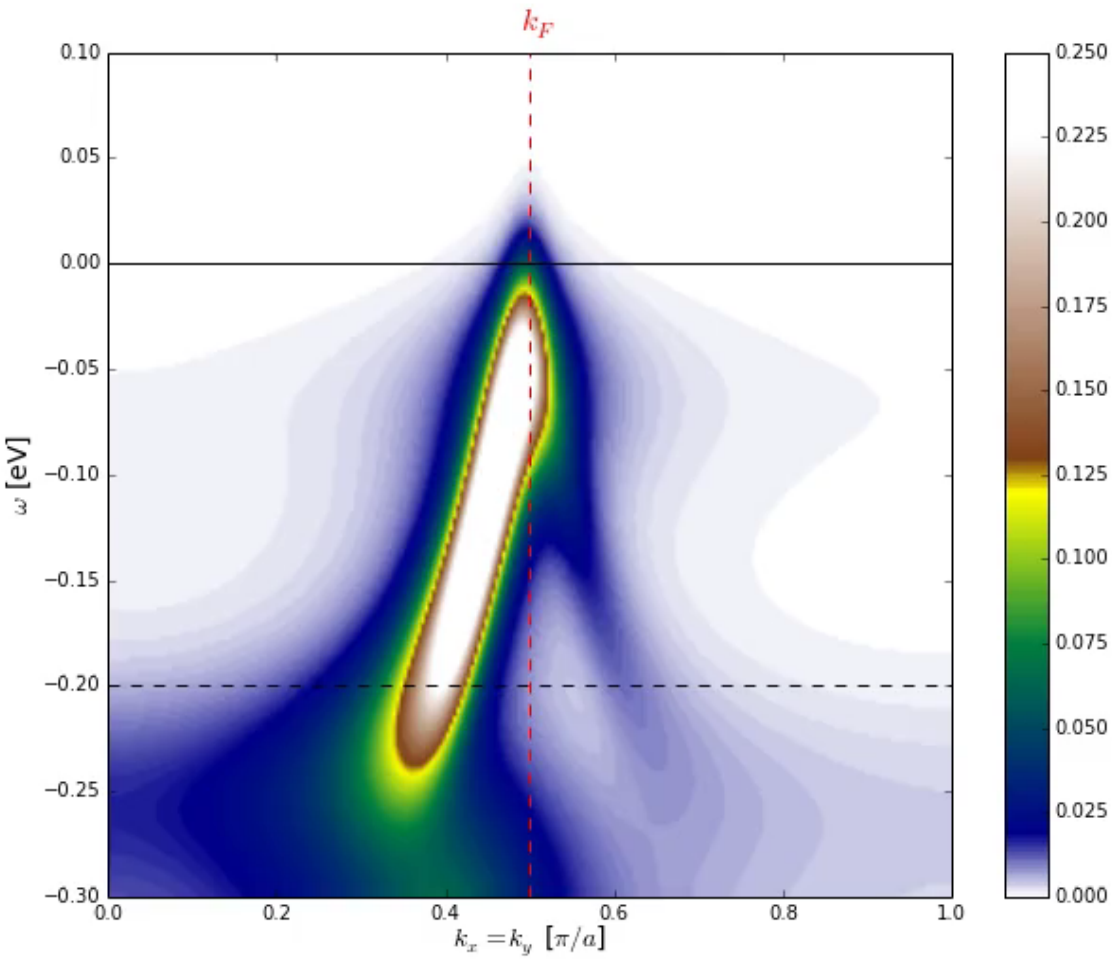


order parameter Δ, condensate dynamics

el-ph single-particle scattering

cf. textbooks (Mahan, AGD, ...) for Migdal-Eliashberg approx.

Oscillations in photocurrent



Amplitude mode oscillations

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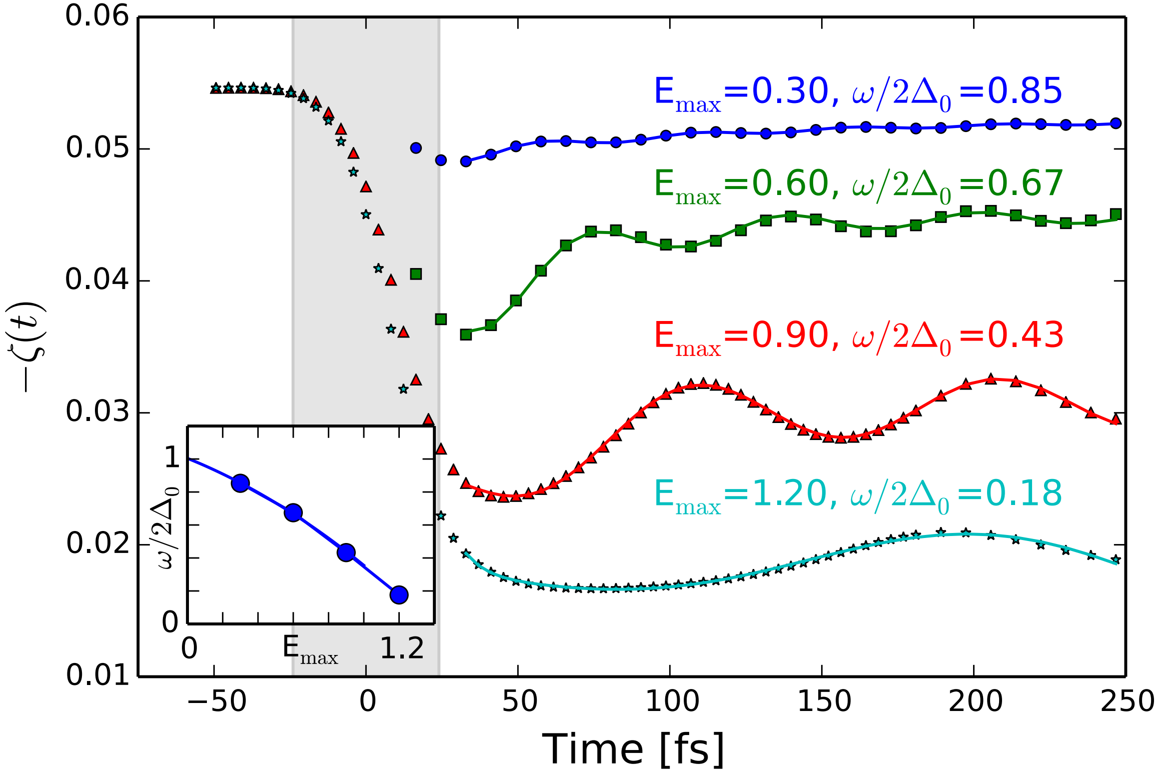


PRB 92, 224517 (2015)

Amplitude ("Higgs") mode oscillations predicted in time-resolved ARPES
Reduced order parameter sets oscillation frequency
Dissipation: Exciting Higgs even far away from gap resonance

Optics: Matsunaga et al., Phys. Rev. Lett. 111, 057002 (2013), Science 2014 [10.1126/science.1254697]
Theory: Volkov & Kogan 1974, Barankov PRL 2004, Yuzbashyan PRL 2006, Tsuji PRL 2013

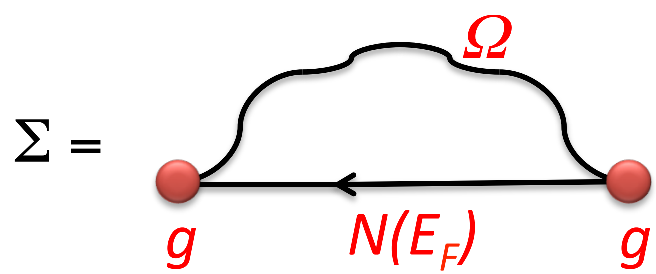
How to enhance boson-mediated SC?

mpsd

- BCS theory – plain vanilla SC (weak coupling)

$$\Delta \approx 2\hbar\Omega_c \exp(-1/V_0 N(E_F))$$

- effective attraction $V_0 \sim g^2/(\hbar\,\Omega)$
- e-boson coupling g
- boson frequency Ω
- electronic DOS $N(E_F)$



Migdal-Eliashberg theory
boson-mediated pairing

How to enhance boson-mediated SC?

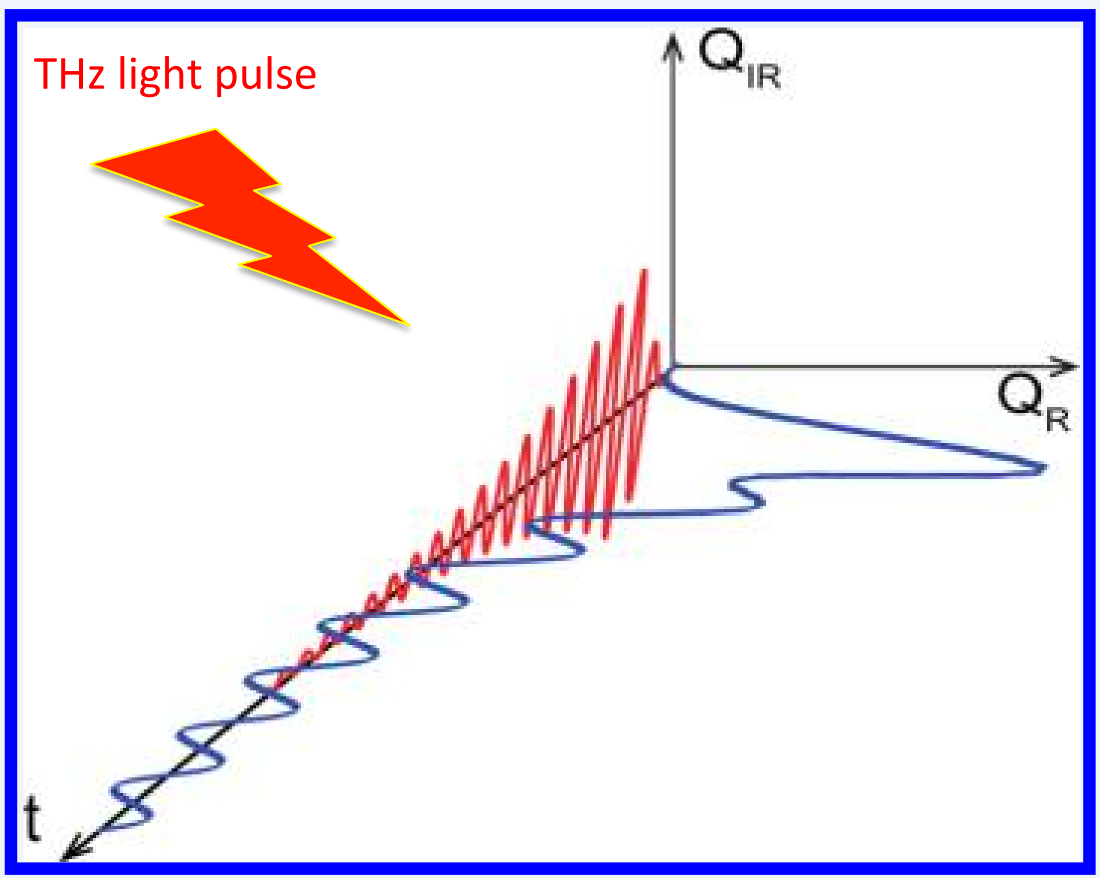
mpsd

- nonlinear phononics Q^2Q: resonant excitation of vibrational modes – effects?

1. tune model parameters
   - e-boson coupling g
   - boson frequency Ω
     } α^2F – Eliashberg function
   - electronic DOS $N(E_F)$ — **Gedankenexperiment (what if?)**
2. dynamical effect
   - effective Hamiltonian (e.g., Floquet)

also see: Knap et al., arXiv:1511.07874

Classical lattice dynamics



$$\ddot{Q}_{IR} + \Omega_{IR}^2 Q_{IR} = \frac{e^* E_0}{\sqrt{M_{IR}}} \sin(\Omega_{IR} t) F(t)$$

$$\ddot{Q}_{RS} + \Omega_{RS}^2 Q_{RS} = A Q_{IR}^2$$

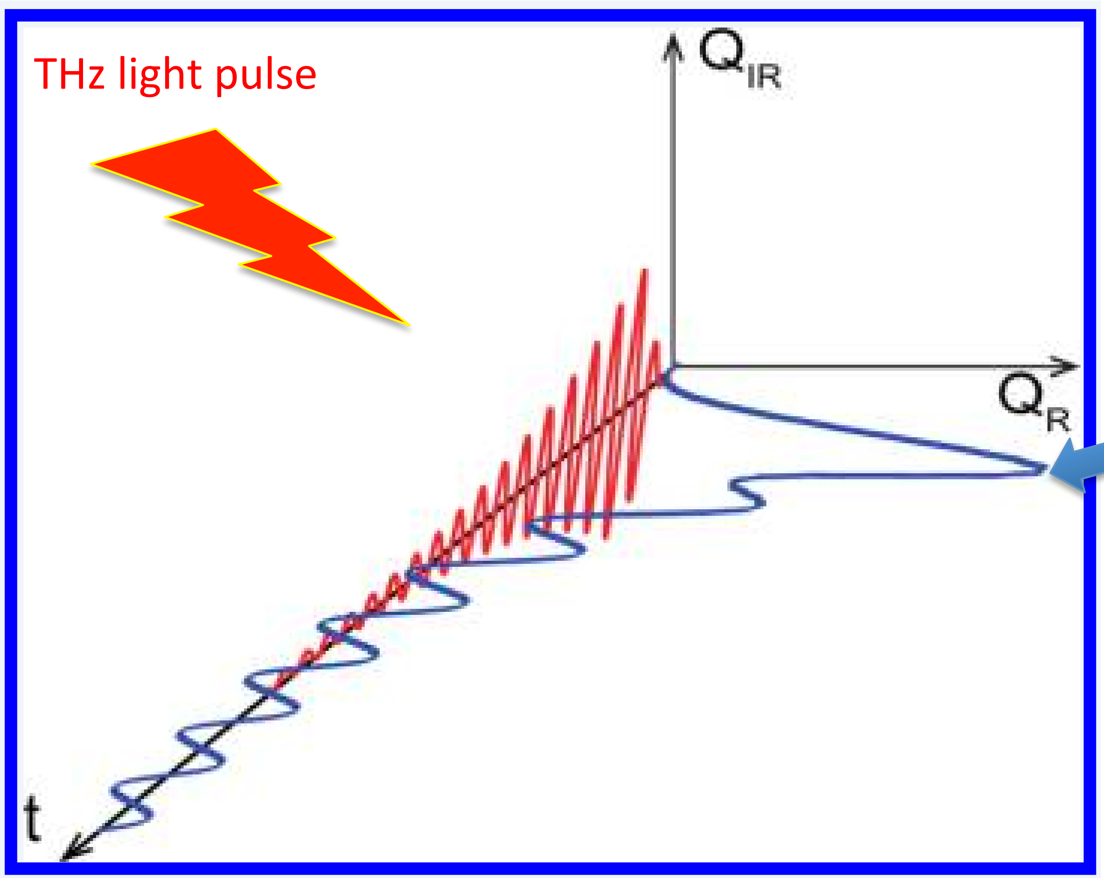
Rectification of a second (Raman) phonon via coherent driving of a first (IR) phonon

„Nonlinear phononics“

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

A. Subedi, A. Cavalleri, A. Georges, PRB 89, 220301R (2014)

Classical lattice dynamics



Displaced Raman mode assumed to lead to temporal change of electronic hopping

Gedankenexperiment (what if?)

Include the effects of driving field through time-dependent electronic dispersion

$$\varepsilon(k) \rightarrow \varepsilon(k,t)$$

„Nonlinear phononics“

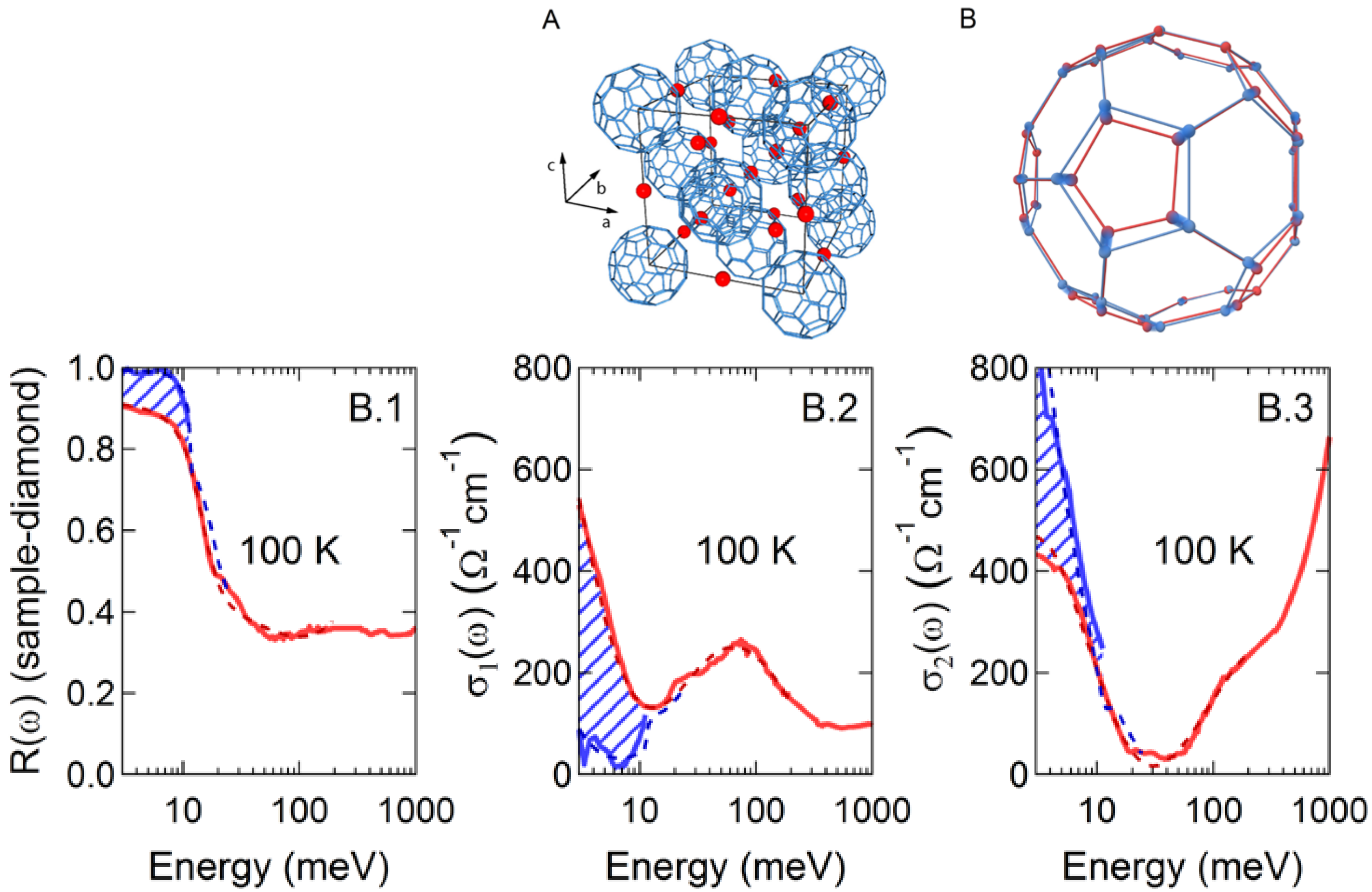
M. Först et al., Nature Physics 7, 854 (2011)

A. Subedi, A. Cavalleri, A. Georges, PRB 89, 220301R (2014)

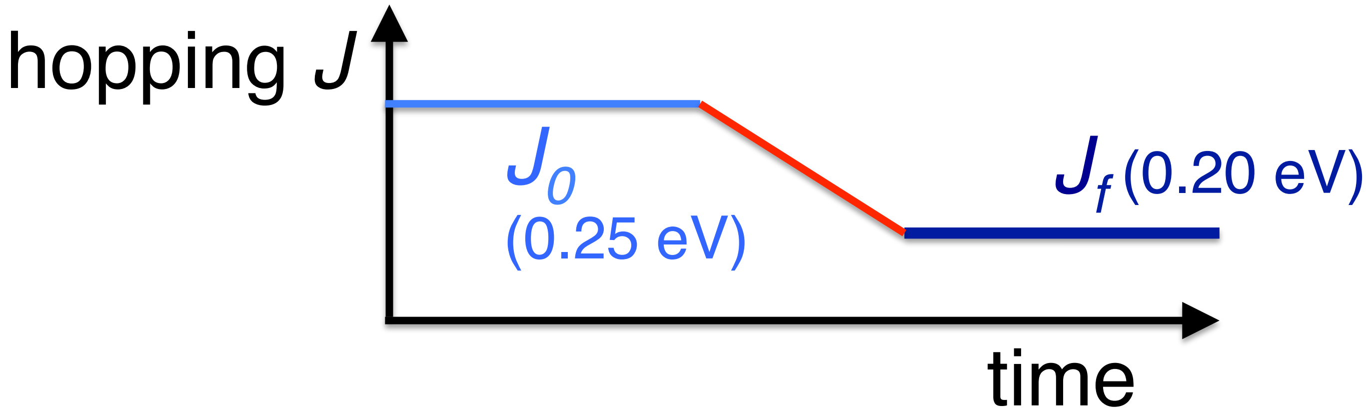
Experimental motivation

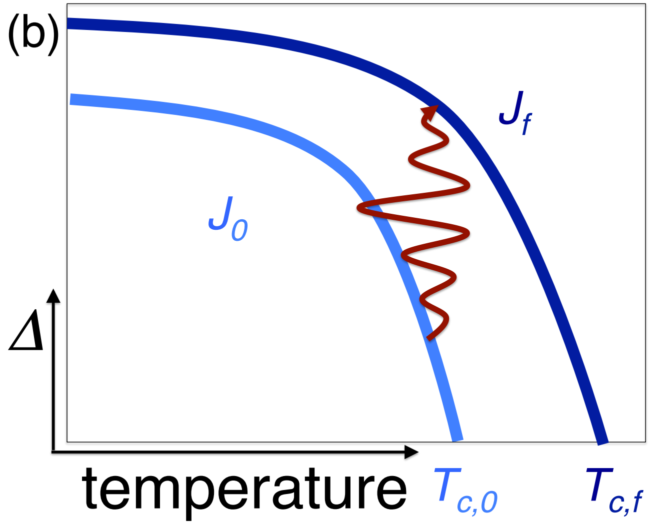
„An optically stimulated superconducting-like phase in K3C60 far above equilibrium Tc“

M. Mitrano et al., arXiv: 1505.04529 to appear in Nature



Simplest model: hopping ramp



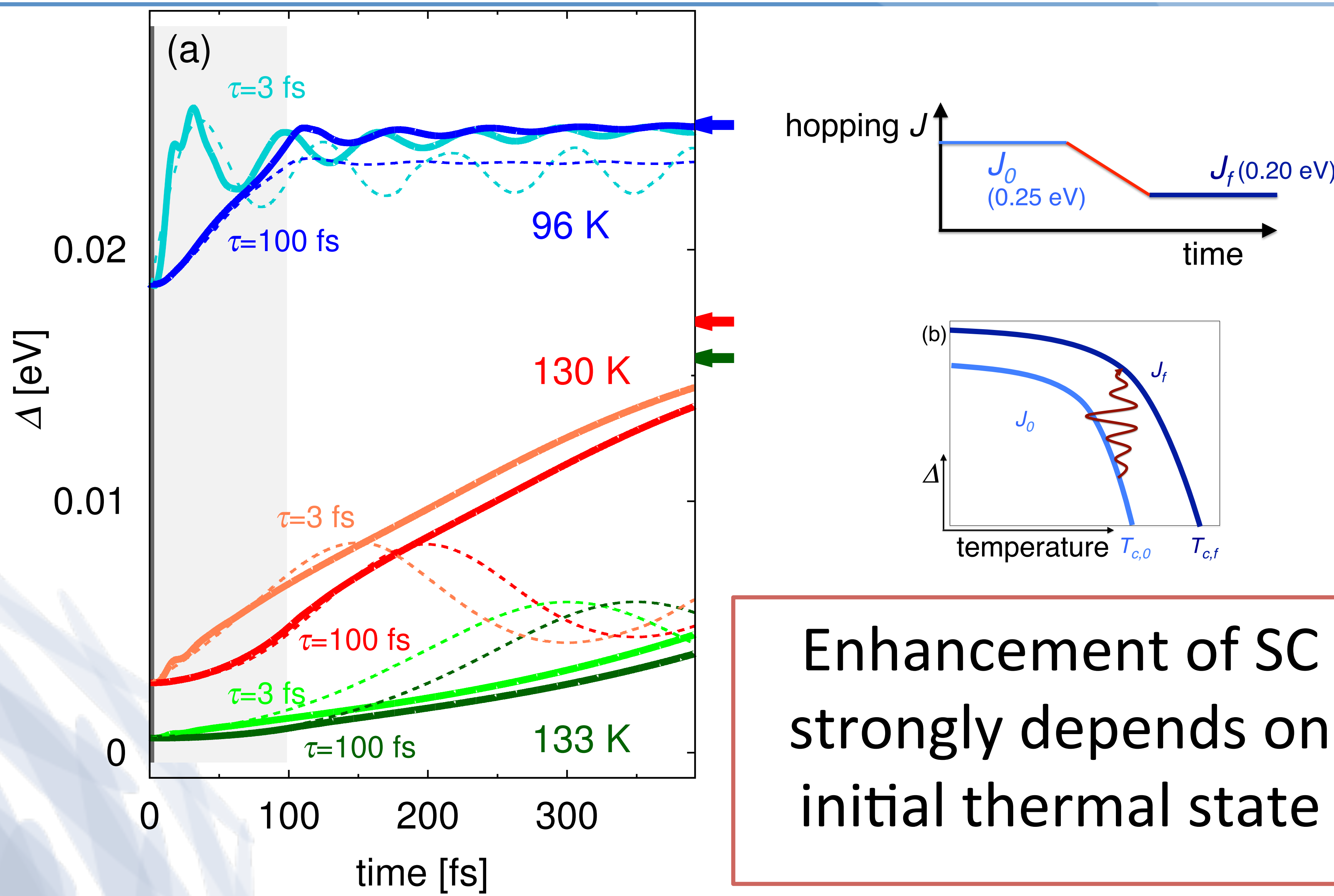


Equilibrium picture:

Enhancement of SC via enhanced DOS at Fermi energy

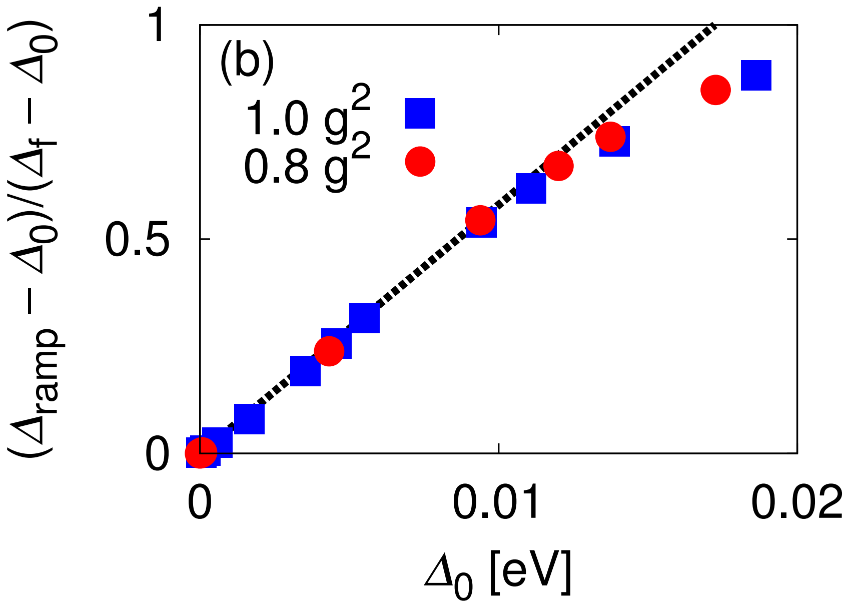
Superconductor evolution

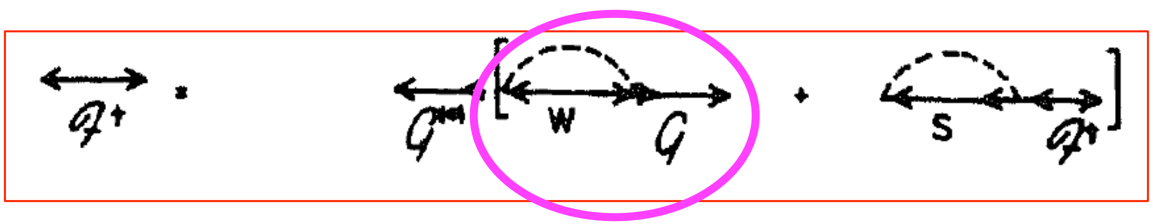
mpsd



Enhancement of SC strongly depends on initial thermal state

Enhancement during ramp

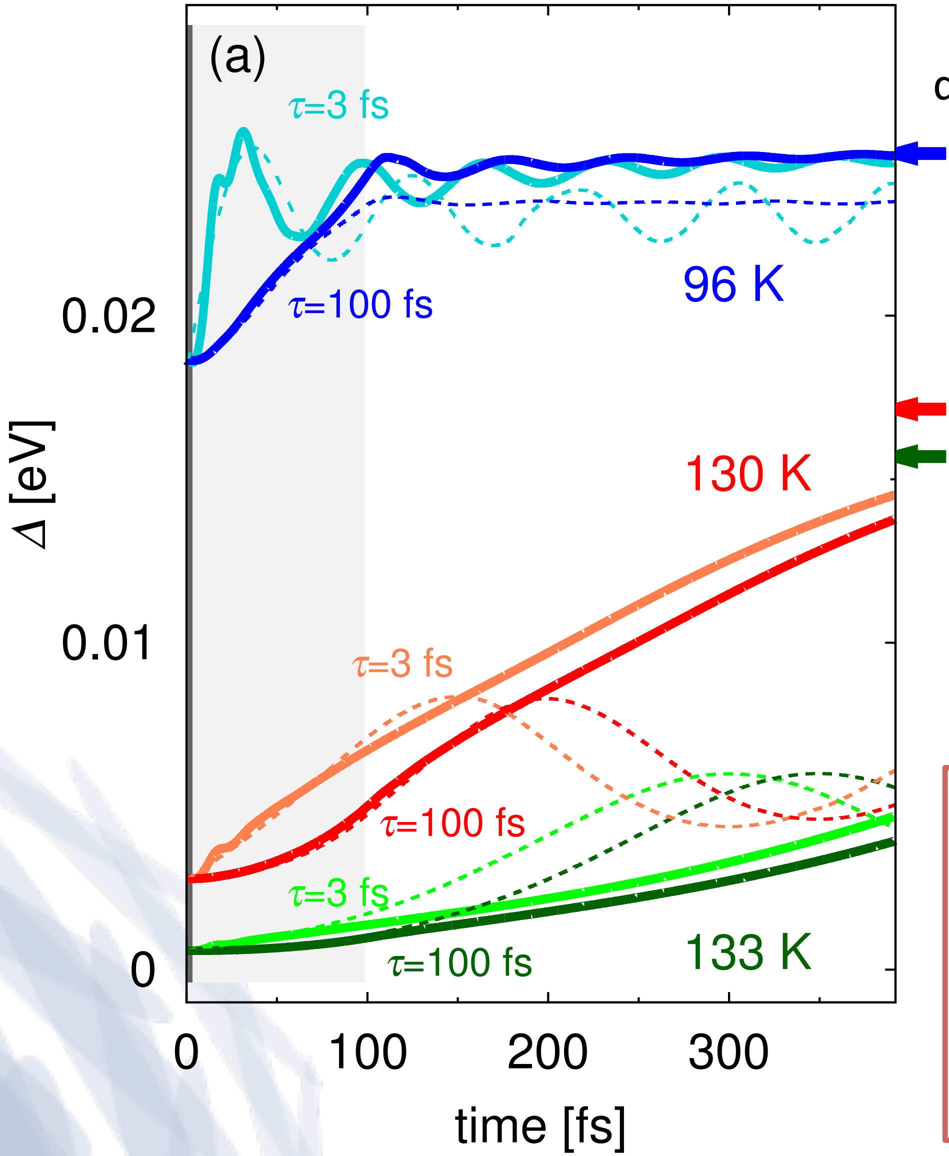




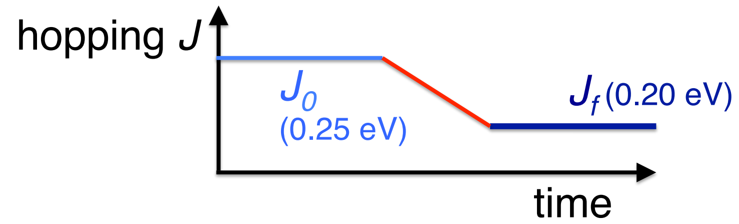
Order parameter enhancement $\sim \Delta_0$

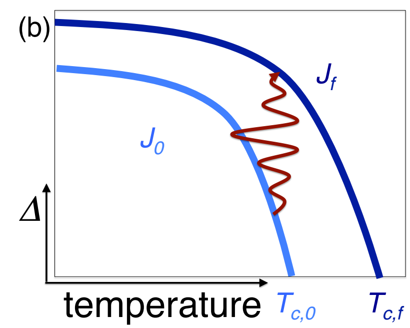
limit to time scale on which SC can be induced by quasistatic modification of effective pairing strength!

Superconductor evolution



dashed: no dissipation (BCS only)





Dissipation helps enhancement for fast ramps

Summary part 1

- Amplitude mode oscillations in pumped SC

  PRB 92, 224517 (2015)

- Light-enhanced SC via nonlinear phononics

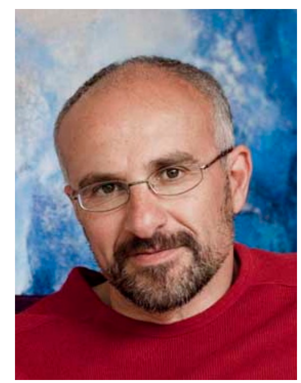
  arXiv:1505.07575


A. F. Kemper


T. P. Devereaux


B. Moritz

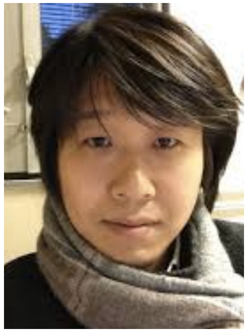

J. K. Freericks


A. Georges


C. Kollath

BERKELEY LAB
SLAC NATIONAL ACCELERATOR LABORATORY
GEORGETOWN UNIVERSITY
ÉCOLE POLYTECHNIQUE
COLLÈGE DE FRANCE 1530
universitätbonn

Theory of laser-controlled competing orders



Akiyuki Tokuno, Antoine Georges, Corinna Kollath
(Paris/Bonn)

Ultrafast order

Why?

- understand ordering mechanisms
- control ordered states
- induce new states of matter

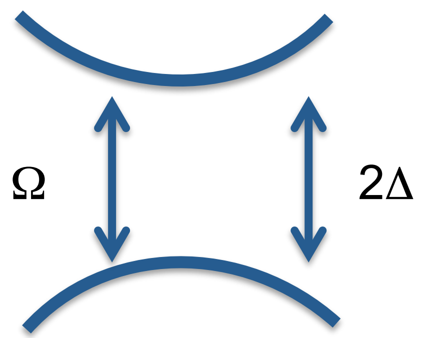
How?

- resonance with something

Is there a generic mechanism to control ordered states?

Driven SC/CDW

CDW ~ A
1-photon resonance



Driven SC/CDW

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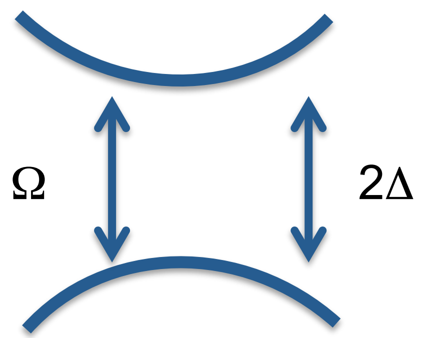
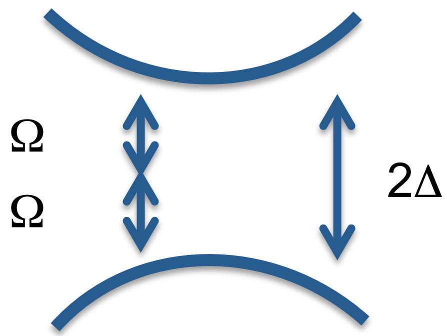
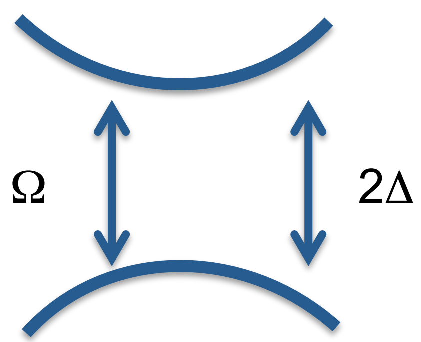


SC ~ A^2
2-photon resonance

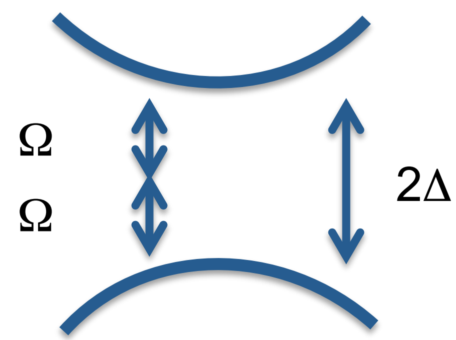


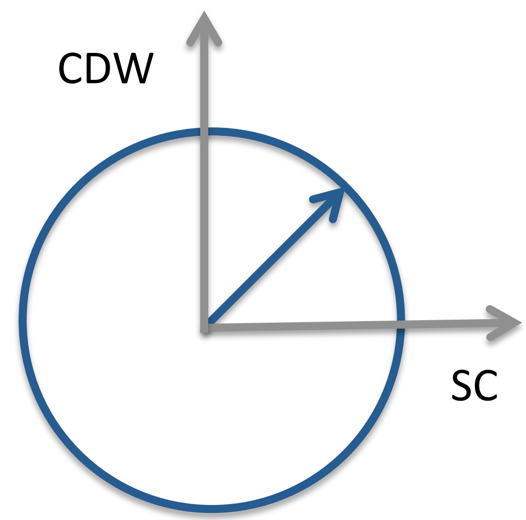
Driven SC/CDW

CDW ~ A
1-photon resonance



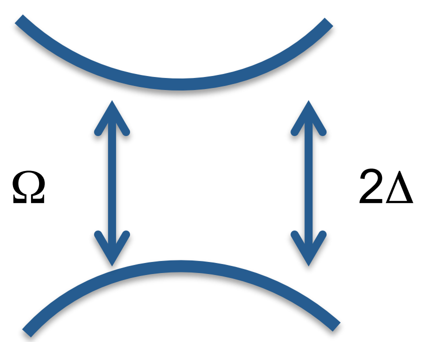
SC ~ A^2
2-photon resonance



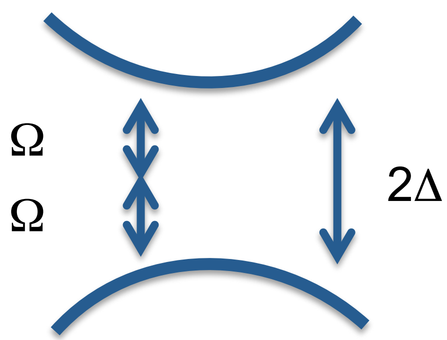


Driven SC/CDW

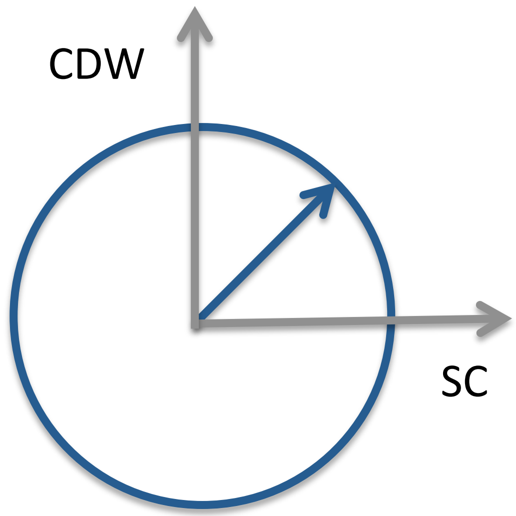
CDW ~ A
1-photon resonance



SC ~ A^2
2-photon resonance

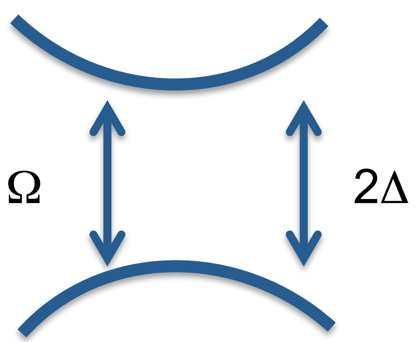


... laser lifts SC/CDW degeneracy

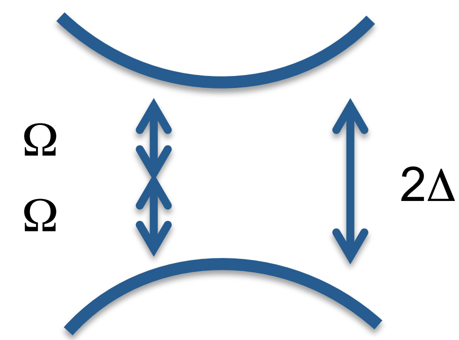


Driven SC/CDW

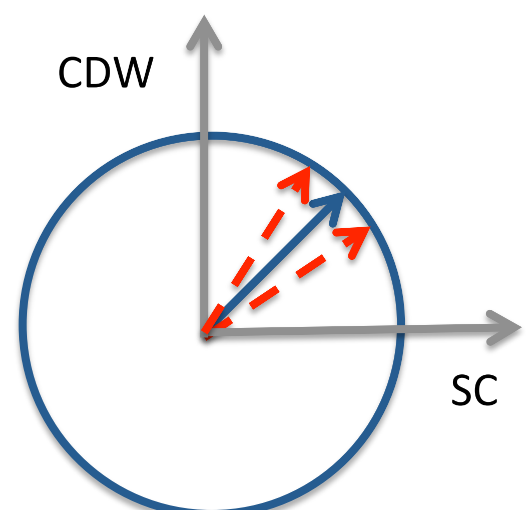
CDW ~ A
1-photon resonance



SC ~ A^2
2-photon resonance

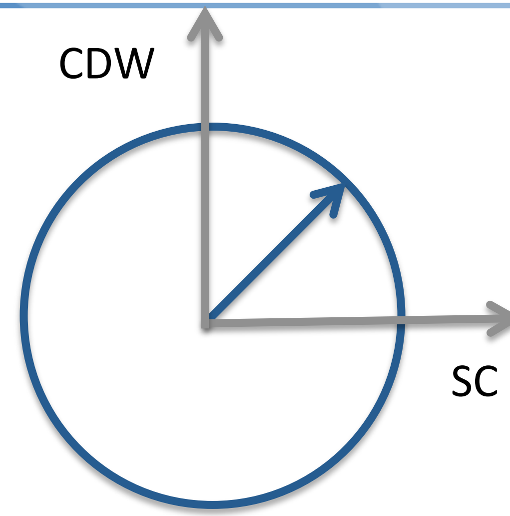


... laser lifts SC/CDW degeneracy
... Goldstone-like collective mode?



Competing orders

- attractive -U Hubbard model
- degeneracy of SC and CDW at perfect nesting
- 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
(1957 Nobel for parity violation in weak interaction)

S.-C. Zhang
(Topological Insulators)

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

Simplistic Model

$$H = \sum_{k\sigma} \epsilon(k) n_{k\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} = H_J + H_U,$$

$$\epsilon(k) = -2J(\cos(k_x) + \cos(k_y)),$$

attractive U + mean-field decoupling

$$\Delta_{SC} = U \sum_k f_k, \qquad f_k \equiv \langle c_{-k\downarrow} c_{k\uparrow} \rangle \qquad \text{(SC)},$$

$$\Delta_{CDW} = U \sum_k g_k, \qquad g_k \equiv \frac{1}{2} \sum_\sigma \langle c^\dagger_{k\sigma} c_{k+Q\sigma} \rangle \qquad \text{(CDW)},$$

$$\Delta_\eta = U \sum_k \eta_k. \qquad \eta_k \equiv \langle c_{-(k+Q)\downarrow} c_{k\uparrow} \rangle \qquad (\eta \text{ pairing}).$$

Mean-field Hamiltonian

$$H_{MF} = \sum_k \begin{pmatrix} c^\dagger_{k\uparrow} \\ c^\dagger_{k+Q\uparrow} \\ c_{-k\downarrow} \\ c_{-(k+Q)\downarrow} \end{pmatrix}^T \begin{pmatrix} \epsilon(k-A) & \Delta^*_{CDW} & \Delta_{SC} & \Delta_\eta \\ \Delta_{CDW} & \epsilon(k+Q-A) & \Delta_\eta & \Delta_{SC} \\ \Delta^*_{SC} & \Delta^*_\eta & -\epsilon(k+A) & -\Delta_{CDW} \\ \Delta^*_\eta & \Delta^*_{SC} & -\Delta^*_{CDW} & -\epsilon(k+Q+A) \end{pmatrix} \begin{pmatrix} c_{k\uparrow} \\ c_{k+Q\uparrow} \\ c^\dagger_{-k\downarrow} \\ c^\dagger_{-(k+Q)\downarrow} \end{pmatrix}$$

4x4 matrix: SO(4) algebra

$$\Delta_{SC} = U\sum_k f_k, \qquad f_k \equiv \langle c_{-k\downarrow} c_{k\uparrow}\rangle \quad \text{(SC)},$$

$$\Delta_{CDW} = U\sum_k g_k, \qquad g_k \equiv \frac{1}{2}\sum_\sigma \langle c^\dagger_{k\sigma} c_{k+Q\sigma}\rangle \quad \text{(CDW)},$$

$$\Delta_\eta = U\sum_k \eta_k. \qquad \eta_k \equiv \langle c_{-(k+Q)\downarrow} c_{k\uparrow}\rangle \quad (\eta \text{ pairing}).$$

Mean-field equations

$$[G^{<}_{k}(t,t')]_{\alpha\beta} = +i\langle[\Psi^{\dagger}_{k}(t')]_{\beta}[\Psi_{k}(t)]_{\alpha}\rangle.$$

$$i\partial_t G^{<}_{k}(t,t) = [H_{MF}(k,t), G^{<}_{k}(t,t)].$$

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:

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

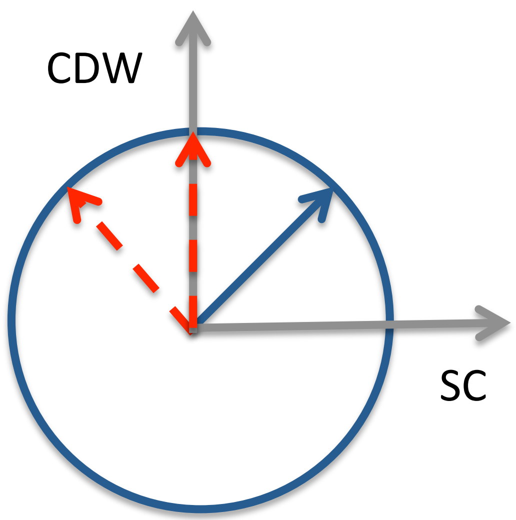
$$\Delta_{CDW} = U\sum_k g_k,$$

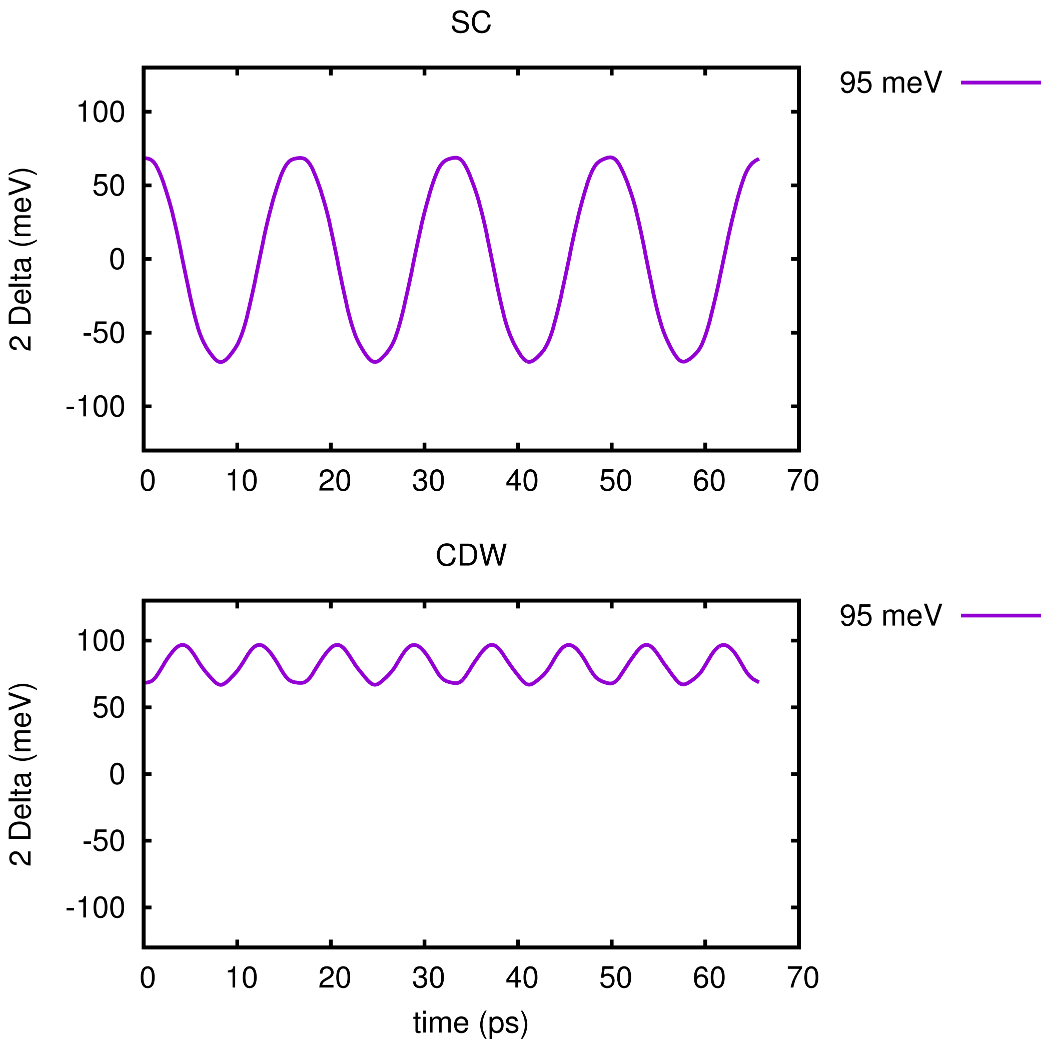
$$\Delta_\eta = U\sum_k \eta_k.$$

Laser hits degenerate orders

Gap resonance – cw driving

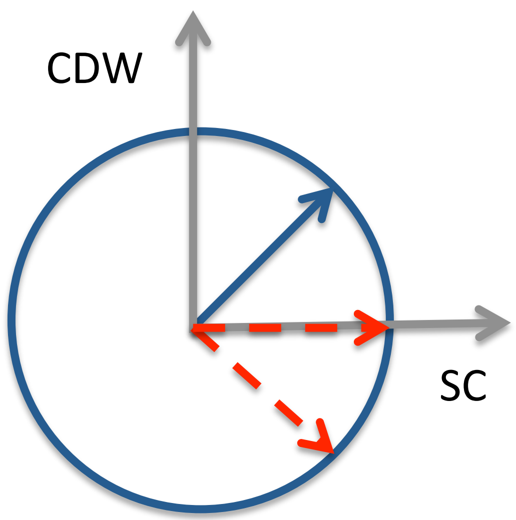
Below resonance:
SC down, CDW up

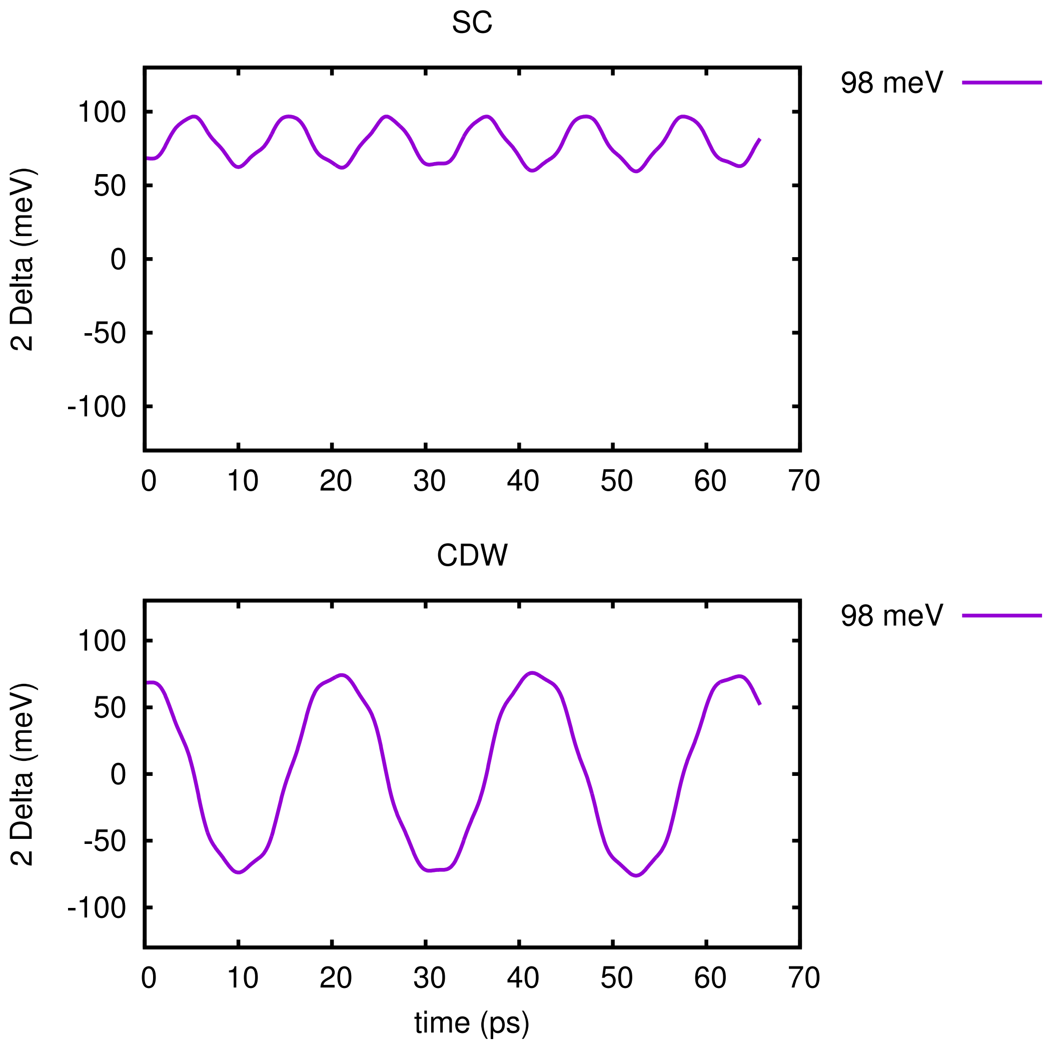




Gap resonance – cw driving

Above resonance:
SC up, CDW down





Gap resonance – cw driving

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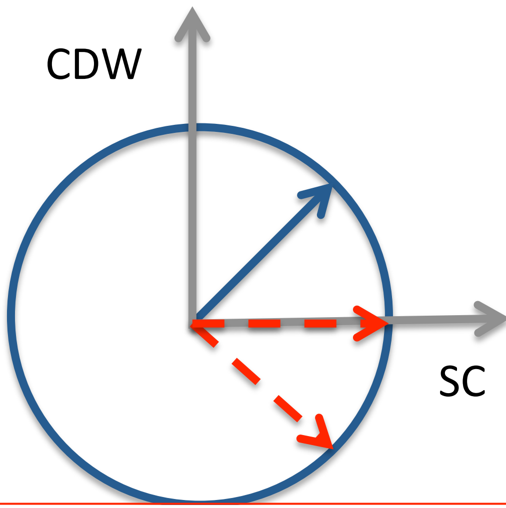
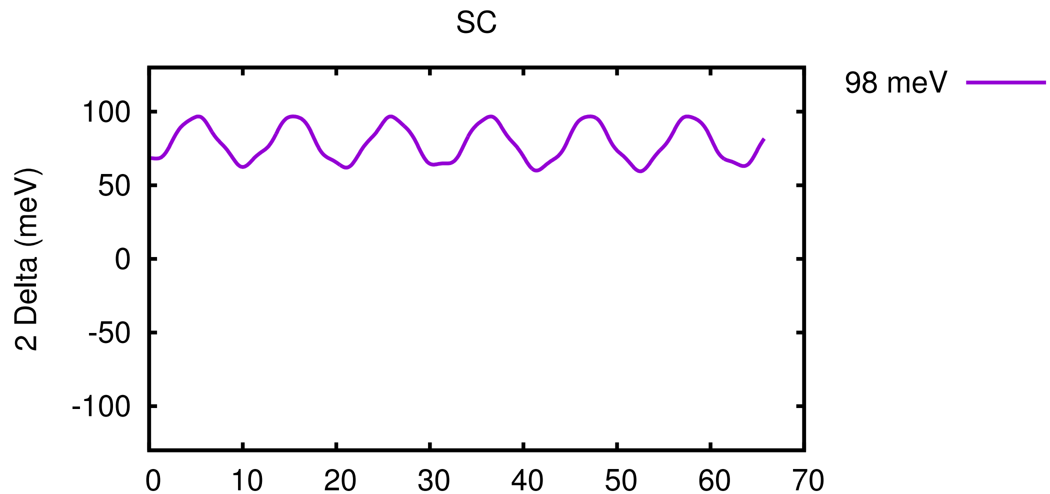
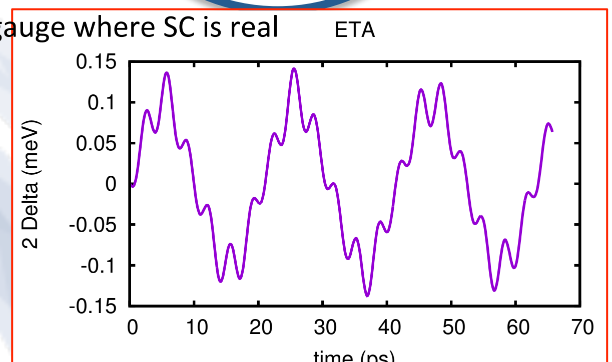
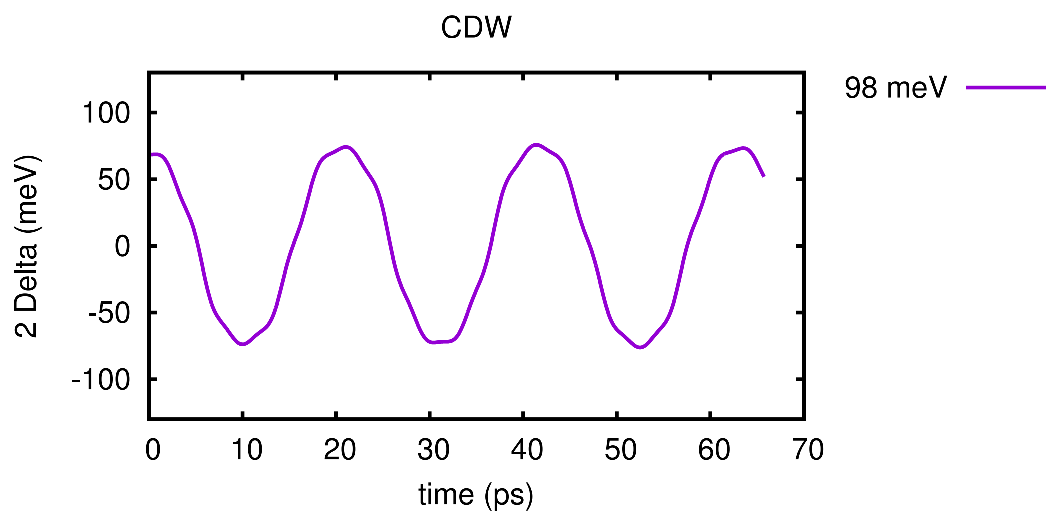
SC up, CDW down



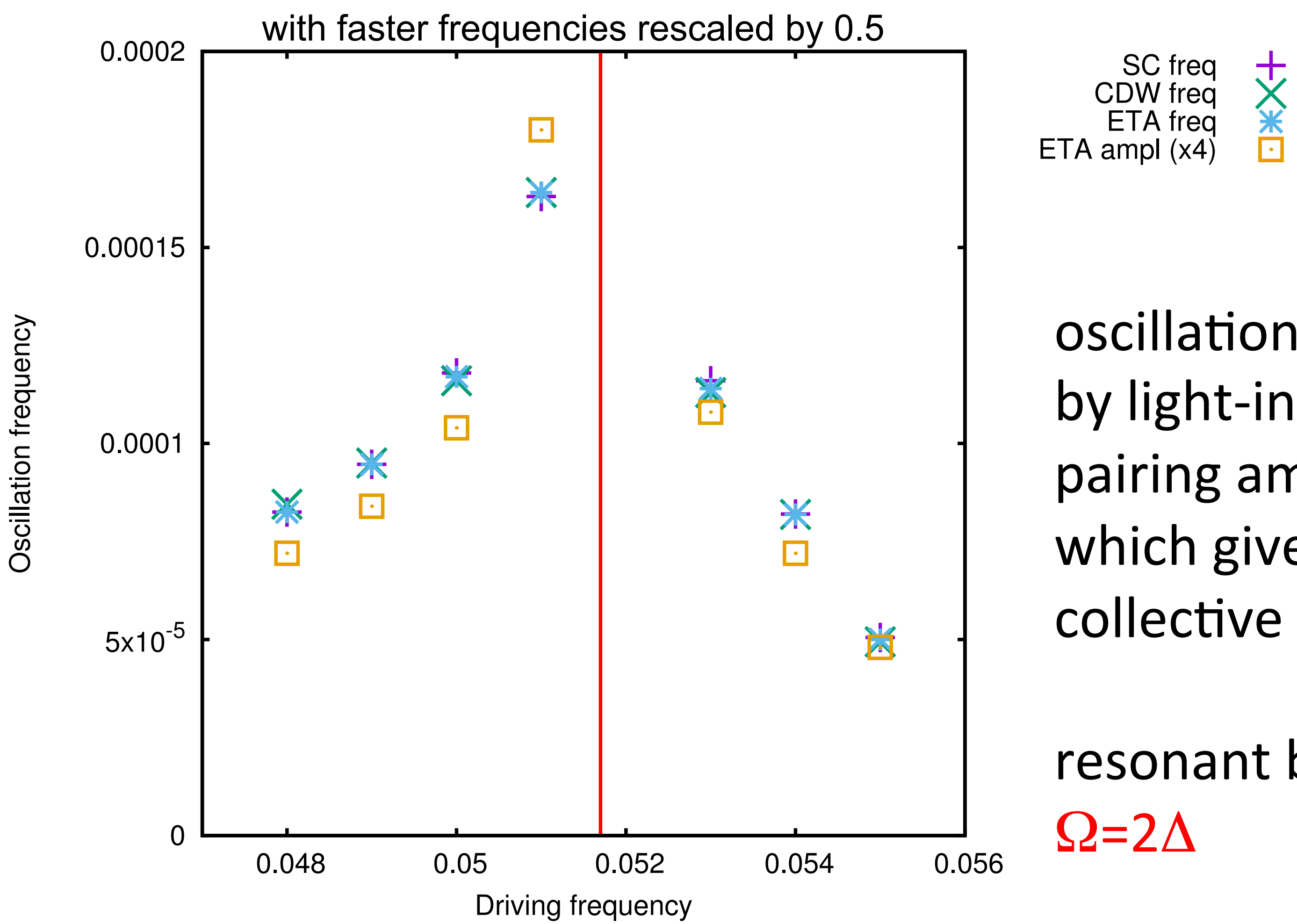


imaginary in gauge where SC is real





Gap resonance – cw driving



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

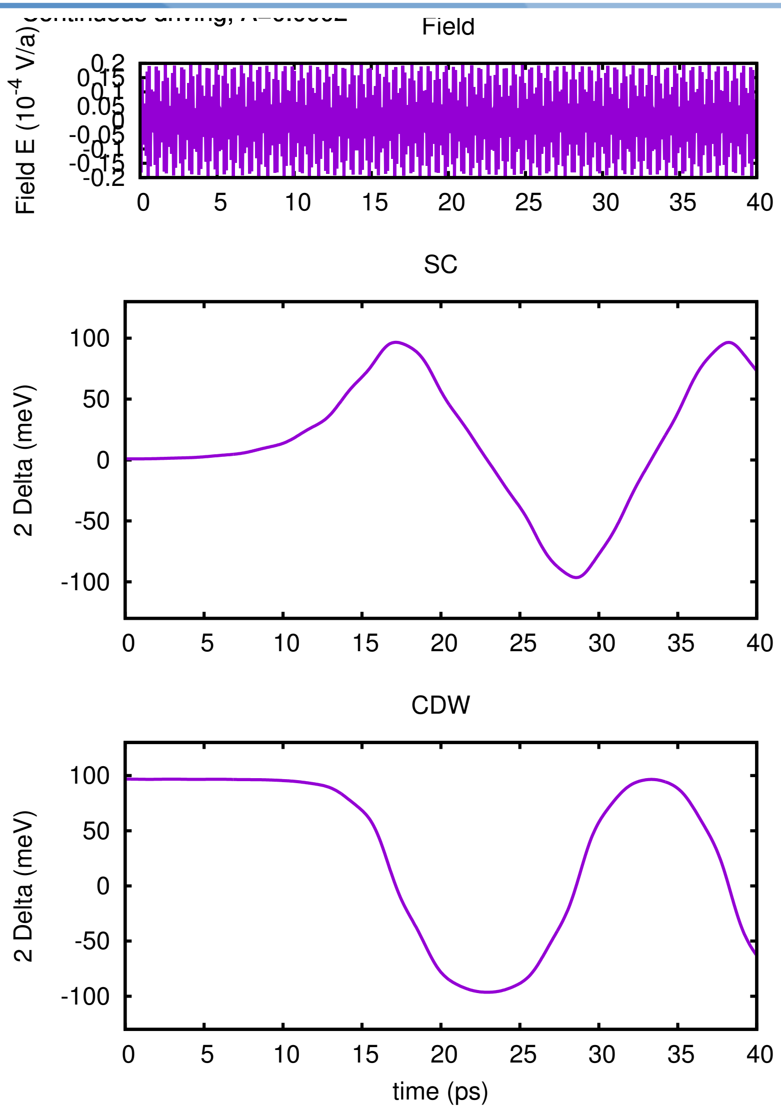
resonant behavior at $\Omega=2\Delta$

Can we bring SC alive?

Can we bring SC alive?

CDW initial state

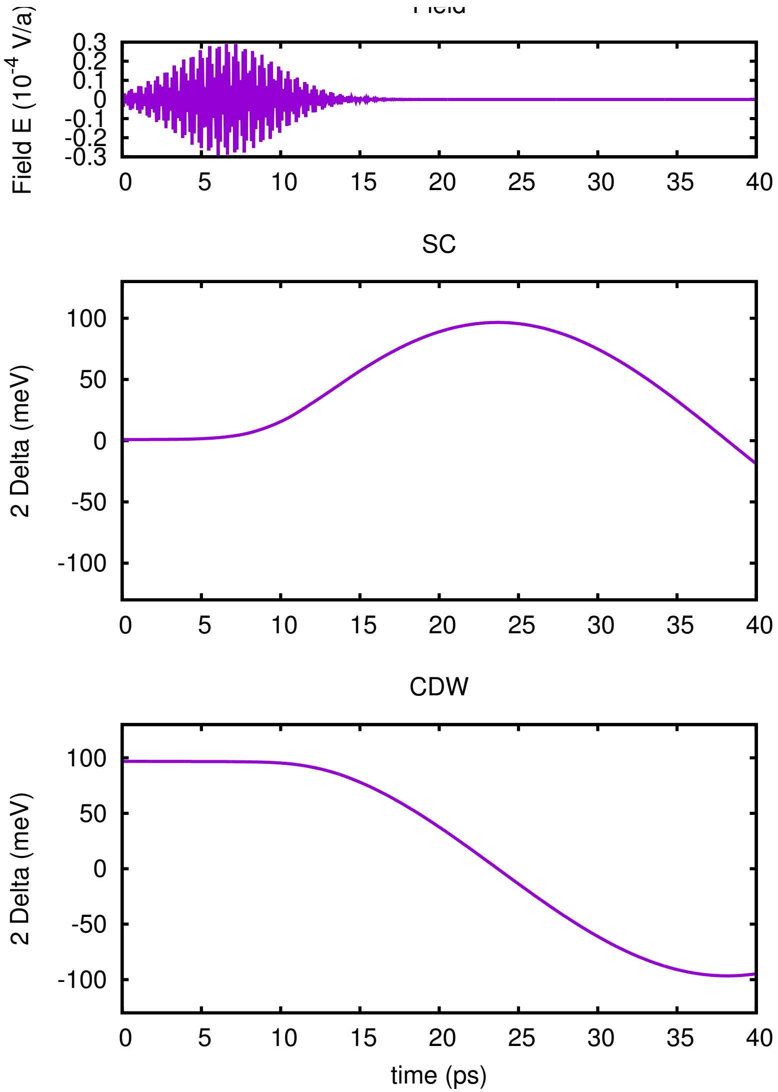
SC comes alive!



Can we bring SC alive? – pulsed field

CDW initial state

SC comes alive!

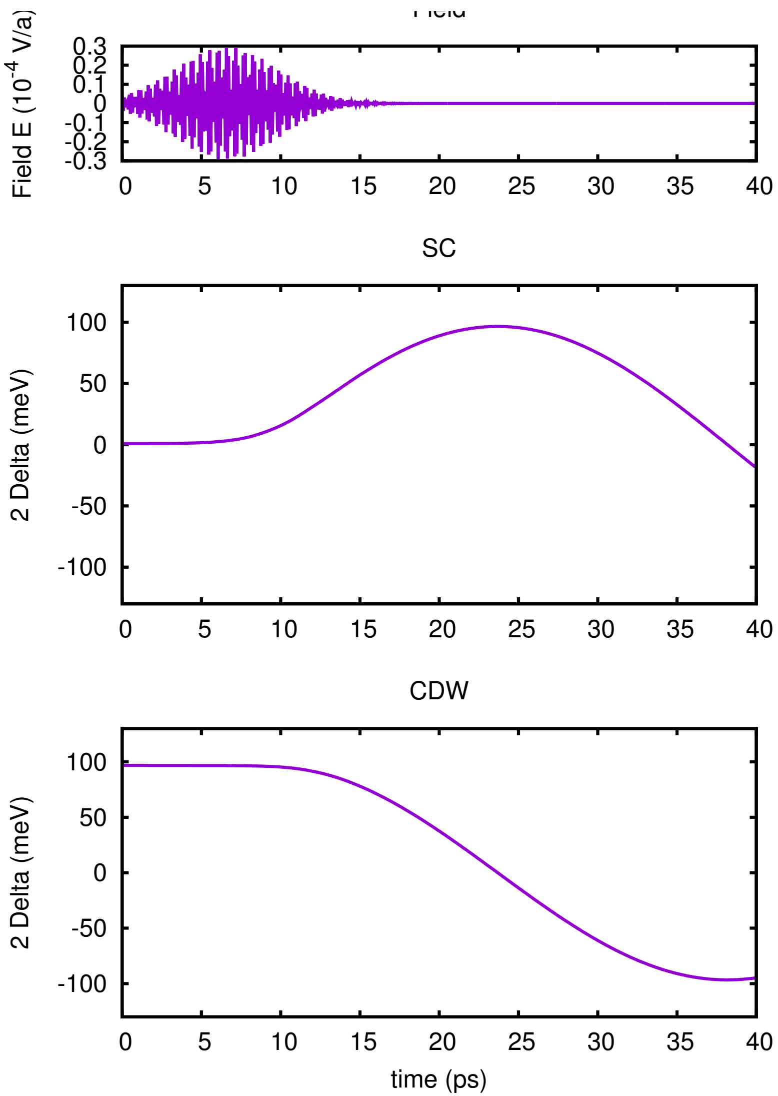


What controls the dynamics?

Short times: laser control

Long times: dissipation?

Questions:
1. Can we use dissipation to stabilize SC?
2. Nondegenerate case?



Summary part 2

- laser-controlled switching between SC/CDW
- light-induced eta pairing and a collective mode
- analytical theory?
- light-induced long-lived superconductivity possible?

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