Theory of Laser-Controlled Competing Superconducting and Charge Orders

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Nonequilibrium superconductivity

Why?

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

How?

- laser near resonance with collective modes

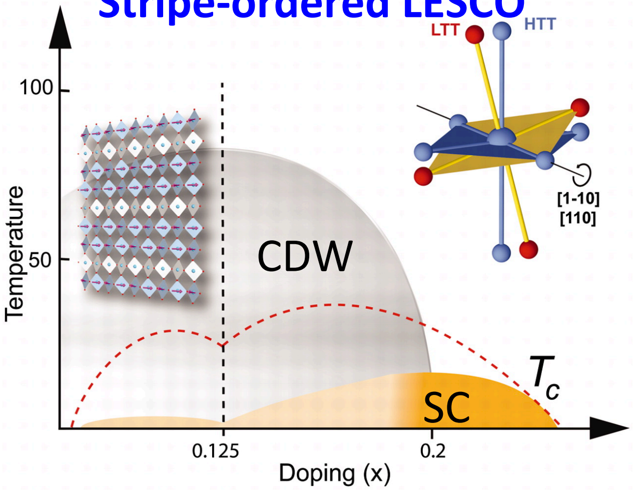
Generic mechanism to control competing orders with light?

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

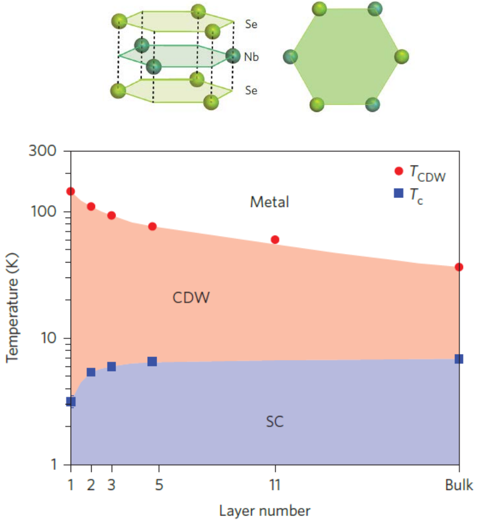
Experimental motivation: competing orders

Stripe-ordered LESCO



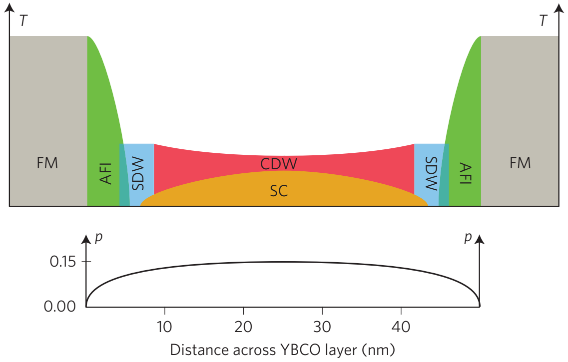
D. Fausti et al.,
Science, 331, 189 (2011)

NbSe2



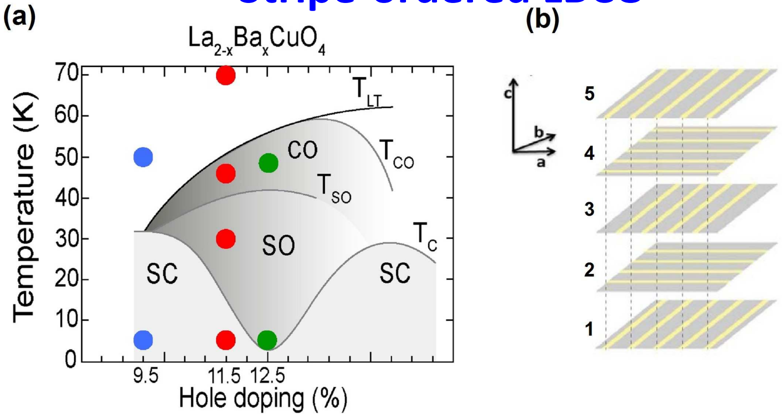
X. Xi et al., Nat. Nanotechnol. 10, 765 (2015)

YBCO-LCMO heterostructure



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

Stripe-ordered LBCO



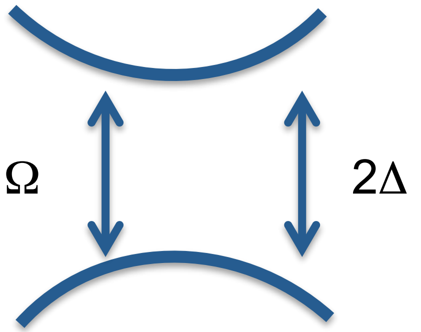
D. Nicoletti et al.,
PRB 90, 100503 (2014)

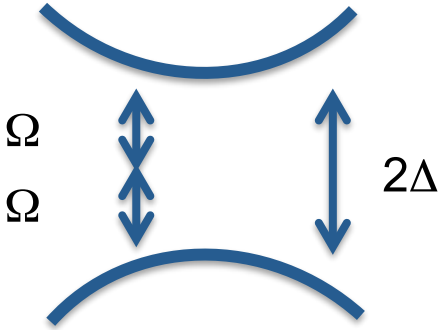
Driven SC/CDW

CDW ~ A
1-photon resonance

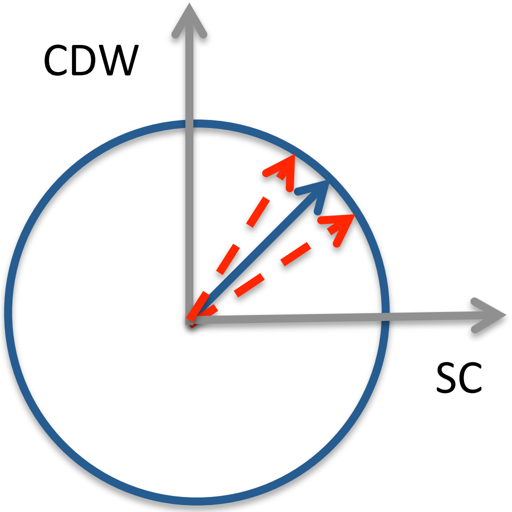
SC ~ A^2
2-photon resonance

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



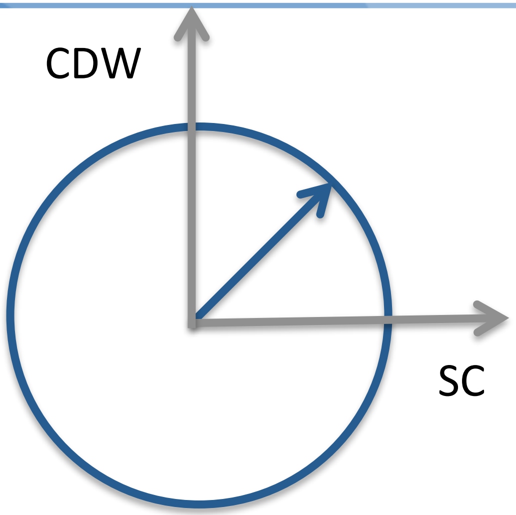


... laser lifts SC/CDW degeneracy
... Goldstone-like collective mode?



Competing orders

- attractive -U Hubbard model
- degeneracy of SC and CDW at perfect nesting
- SO(4) symmetry (SC, CDW, eta pairing)

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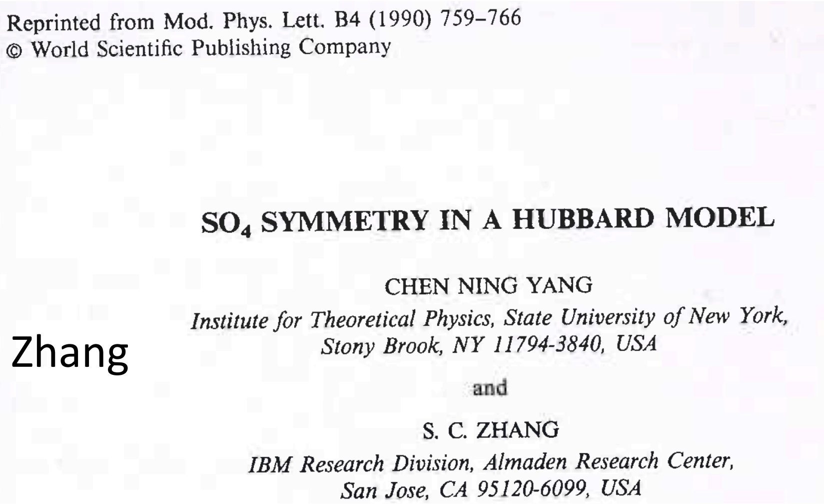
η Pairing and Off-Diagonal Long-Range Order in a Hubbard Model

Chen Ning Yang

C. N. Yang

S.-C. Zhang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SO$_4$ SYMMETRY IN A HUBBARD MODEL

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Minimal 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

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

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

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

Mean-field equations

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

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

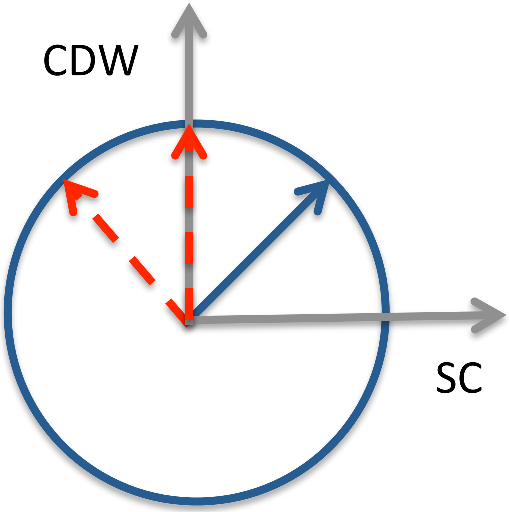
$$\Delta_{CDW} = U \sum_k g_k,$$

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

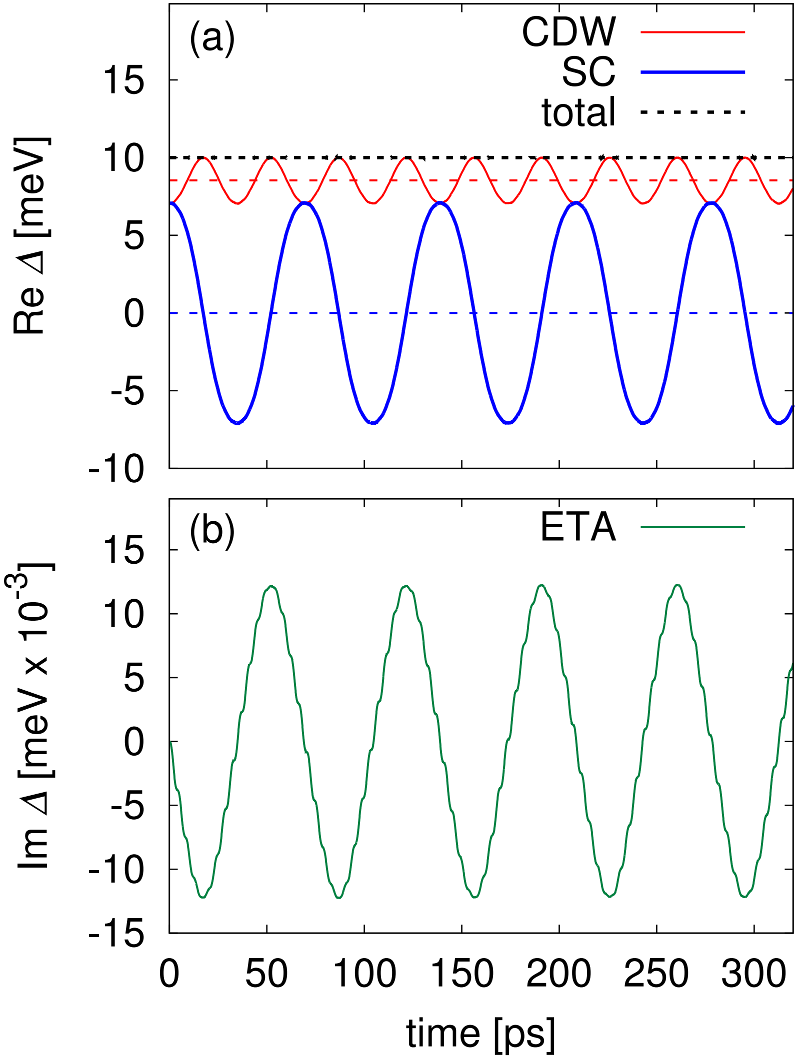
Nonequilibrium:
Periodic driving field: $A(t) = A_{max} \sin(\omega t)\,(e_x + e_y)$
$A_{max} = 5 \times 10^{-5}$, $E_{max} \sim 10\text{-}100$ V/cm – weak fields!

Gap resonance – coexisting initial state

Below resonance:
SC down, CDW up

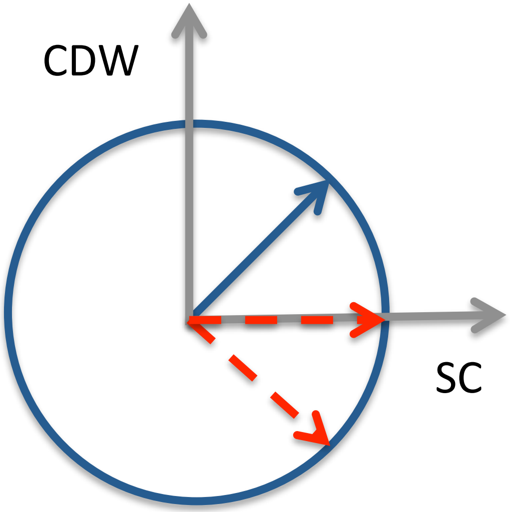


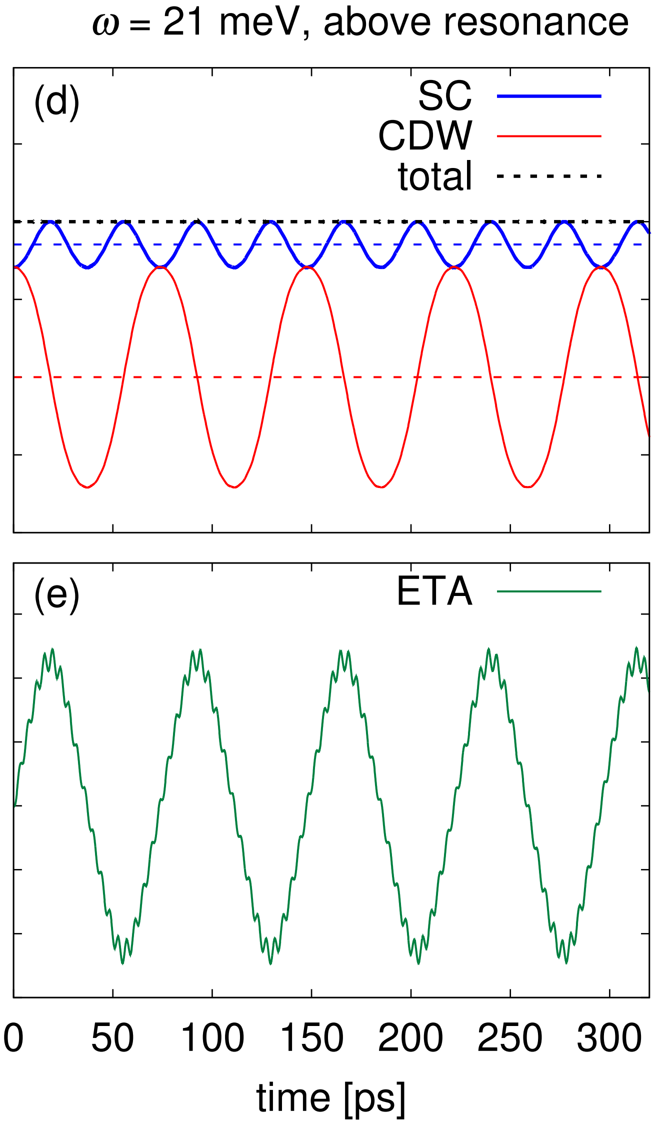
ω = 19 meV, below resonance



Gap resonance – coexisting initial state

Above resonance:
SC up, CDW down





Gap resonance – coexisting initial state

nature

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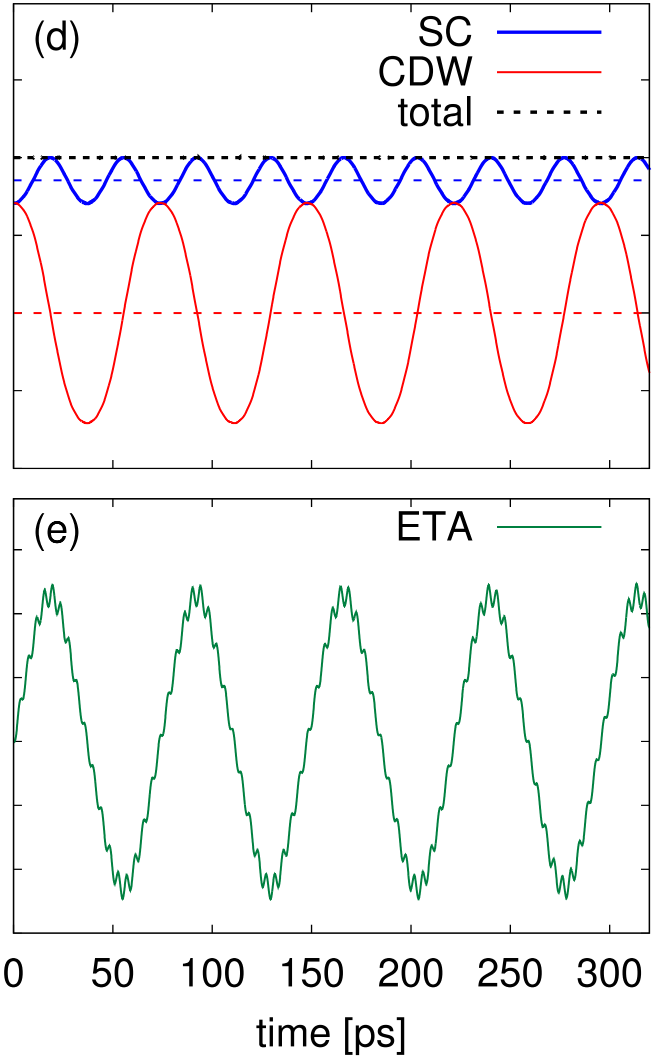
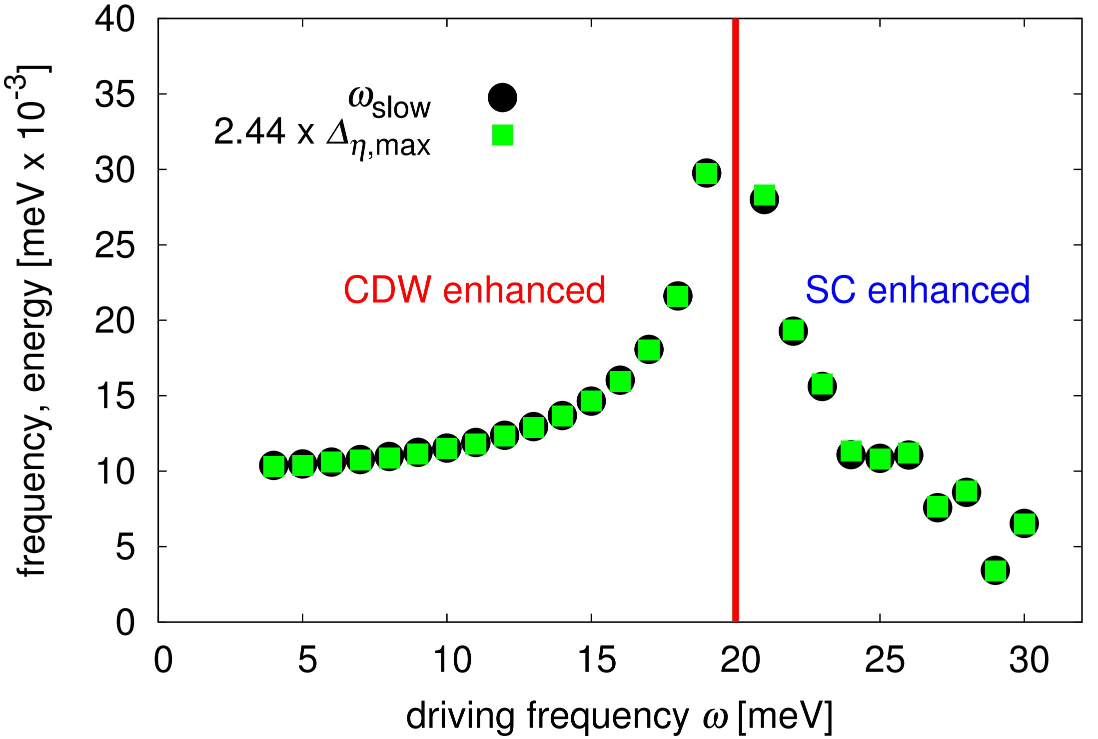
„Floquet time crystal“??

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

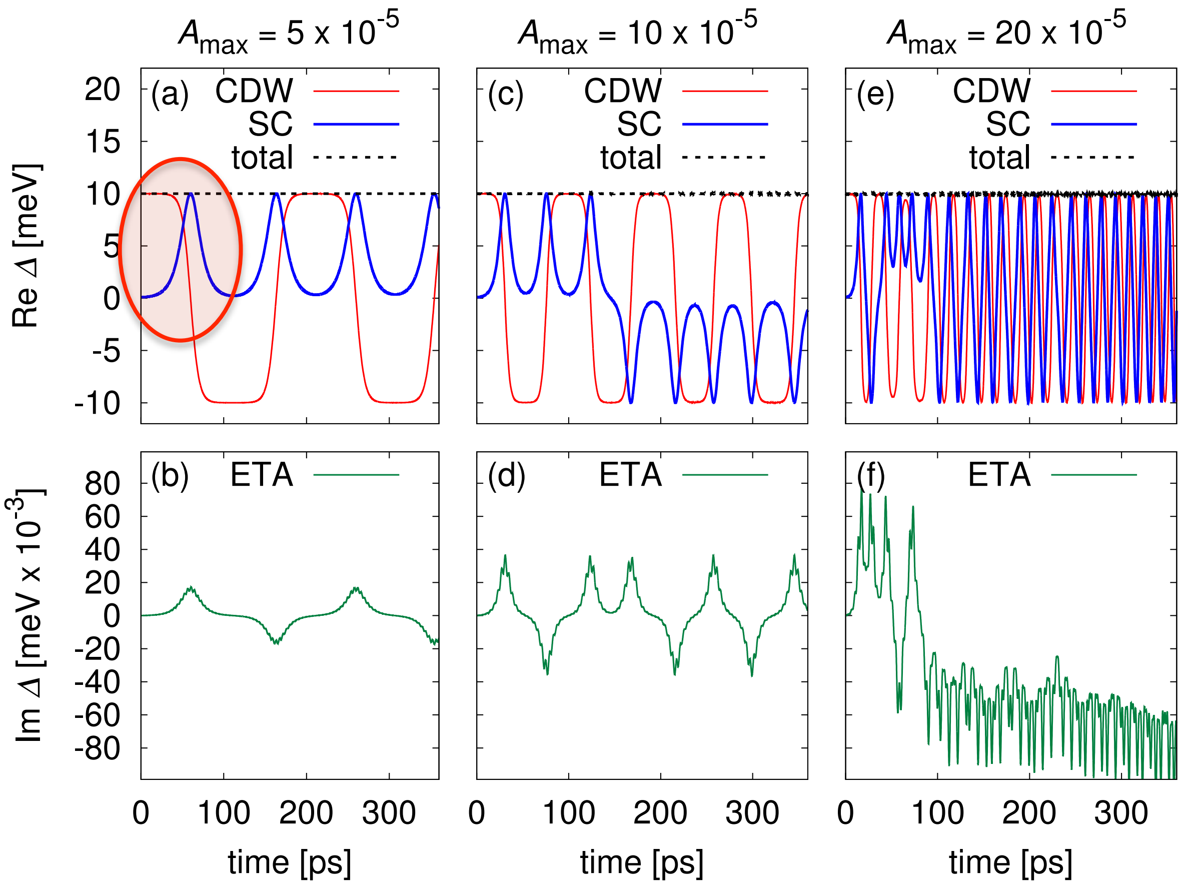
Inducing superconductivity

99% CDW initial state

Drive slightly above gap

SC comes alive!

Irregular behavior for stronger driving



Summary

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

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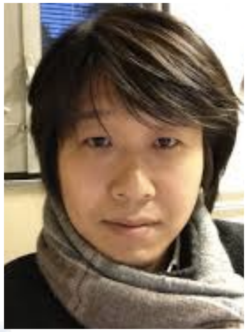
THANK YOU!



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