Role of Interlayer Coupling on the Competition Between Charge Order and Superconductivity

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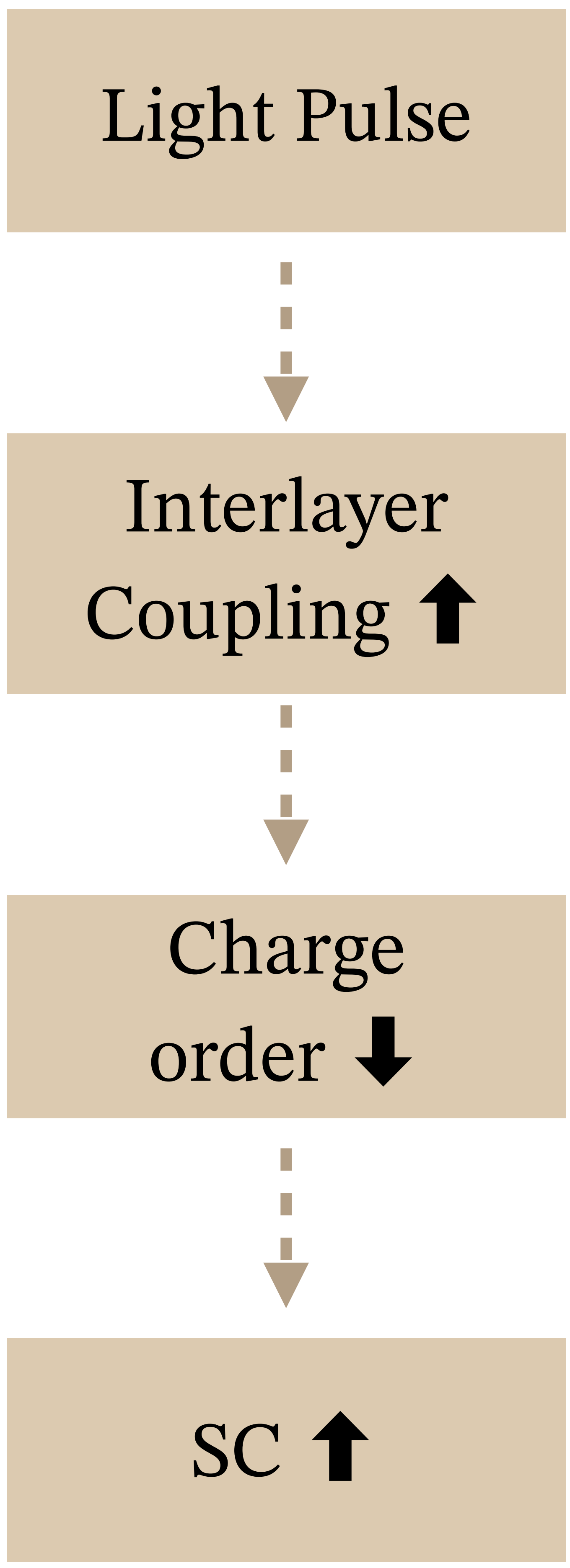
Outline

- Light induced enhancement of pairing correlations - *Context*
- Competing charge order and superconductivity in cuprates - *A quick survey*
- Competition of orders in a bilayer - *Model and phase diagram*
- Effects of phase pinning - *The role of charge order domains*



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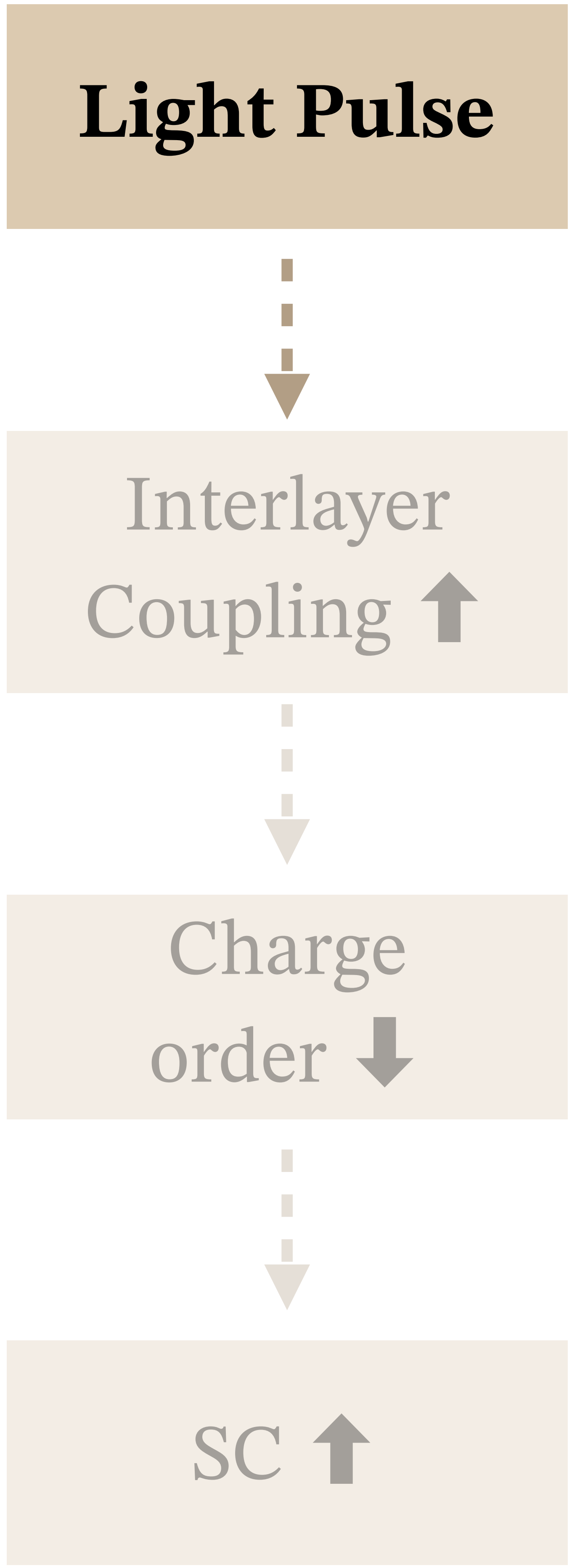

LETTER

doi:10.1038/nature13875

Nonlinear lattice dynamics as a basis for enhanced superconductivity in $YBa_2Cu_3O_{6.5}$

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Light-Induced Supercond
Stripe-Ordered Cuprate

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T. Takayama,[3] H. Takagi,[3,4] A. Cavalleri[1,2]*

One of the most intriguing features of some high-temperatur
interplay between one-dimensional "striped" spin order and
We used mid-infrared femtosecond pulses to transform one s
nonsuperconducting $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$, into a transient
The emergence of coherent interlayer transport was evidence
Josephson plasma resonance in the *c*-axis optical properties.
needed to form the superconducting phase is estimated to be 1 to 2 picoseconds, which is significantly faster than expected. This places stringent new constraints on our understanding of stripe order and its relation to superconductivity.

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ABSTRACT
Recent advances in laser technology have made it possible to generate of precisely shaped strong-field pulses at terahertz frequencies. These pulses are especially useful to selectively drive collective modes of solids, for example, to drive materials in a fashion similar to what done in the synthetic environment of optical lattices. One of the most interesting applications involves the creation of non-equilibrium phases with new emergent properties. Here, I discuss coherent control of the lattice to favour superconductivity at 'ultra-high' temperatures, sometimes far above the thermodynamic critical temperature T_c.

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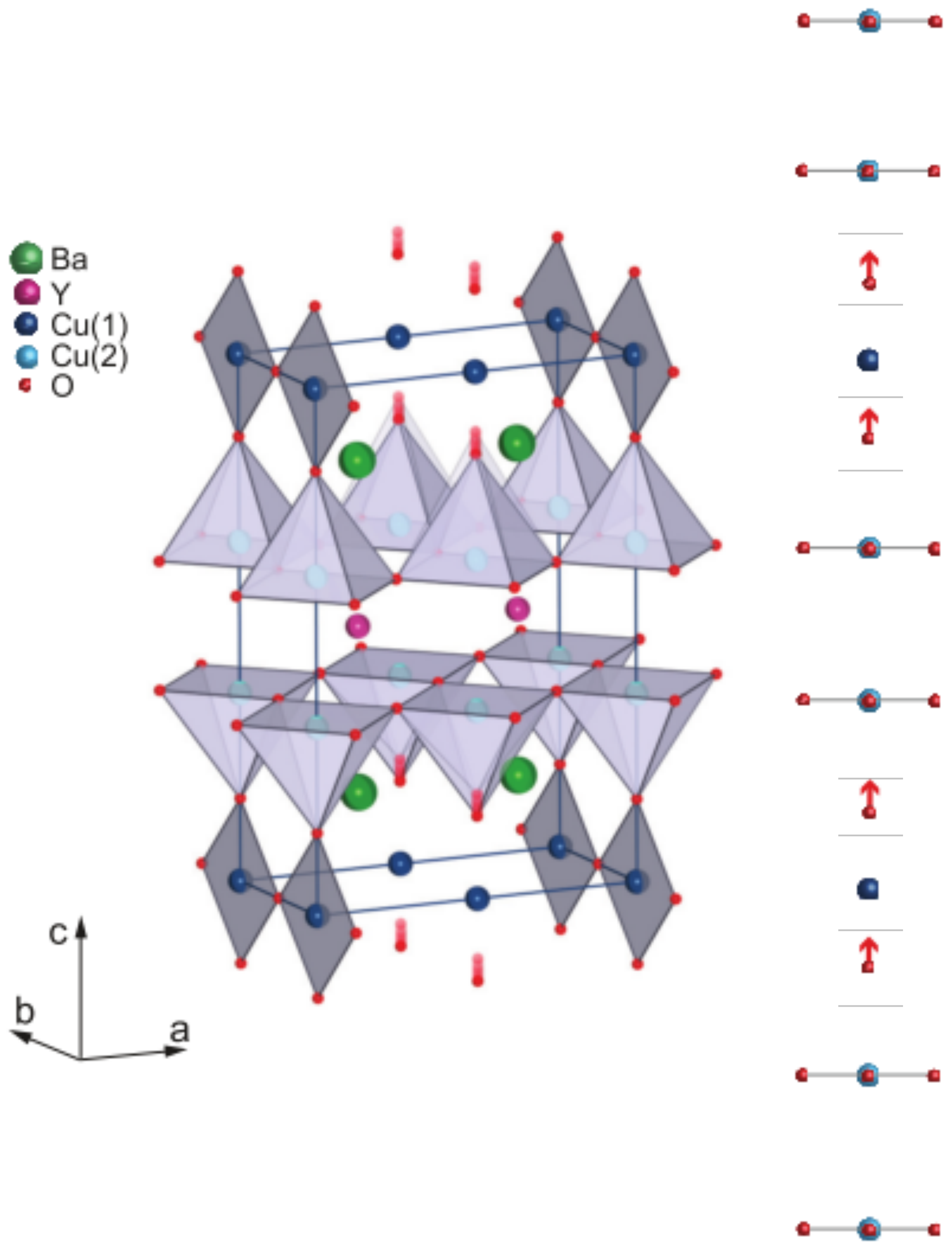
y enhanced coherent transport in
$_3O_{6.5}$ by ultrafast redistribution of
interlayer coupling

W. Hu[1†], S. Kaiser[1†], D. Nicoletti[1†], C. R. Hunt[1,2†], I. Gierz[1], M. C. Hoffmann[1], M. Le Tacon[3], T. Loew[3], B. Keimer[3] and A. Cavalleri[1,4]*

Motivation: Light Induced Superconductivity in cuprates

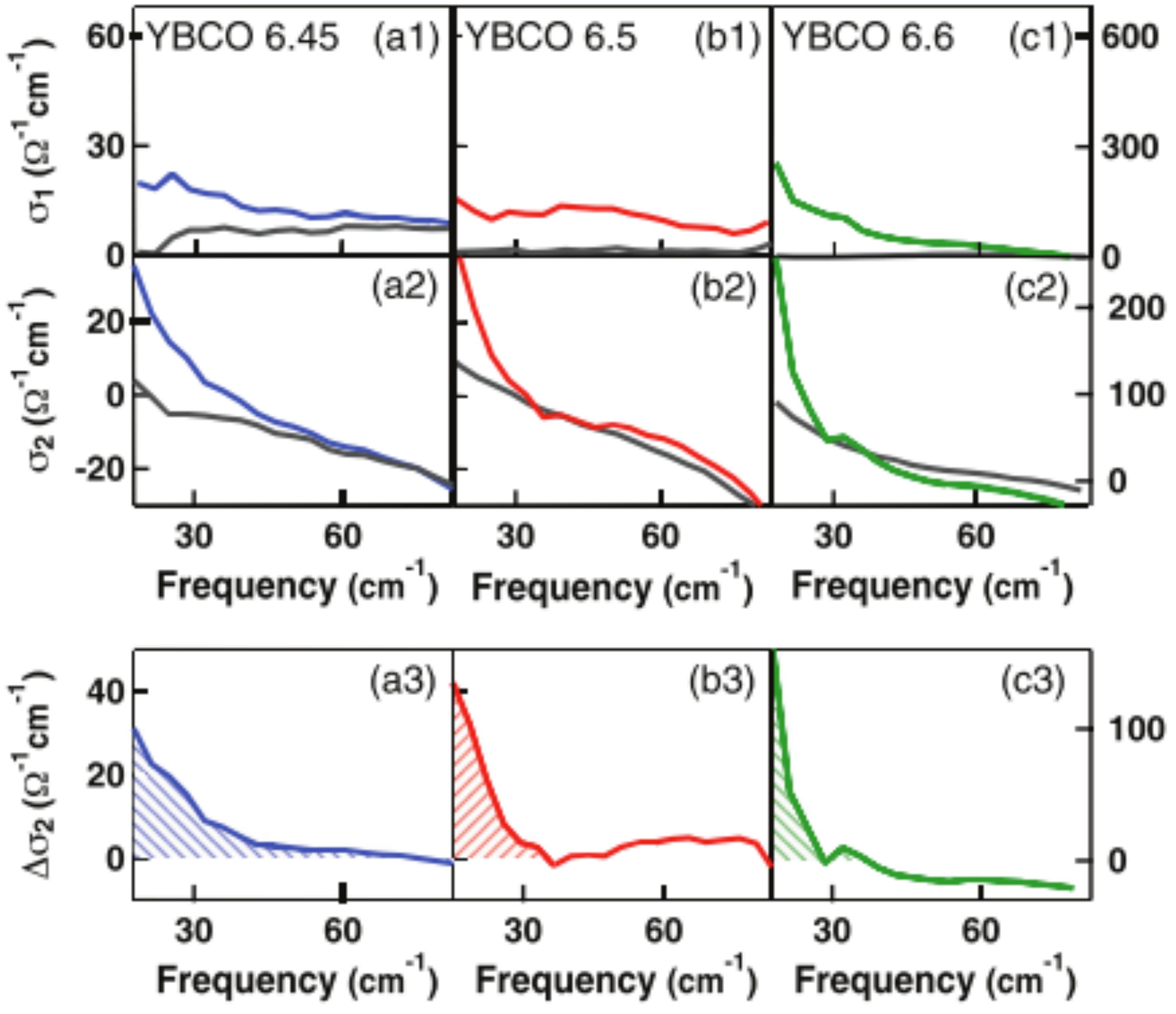


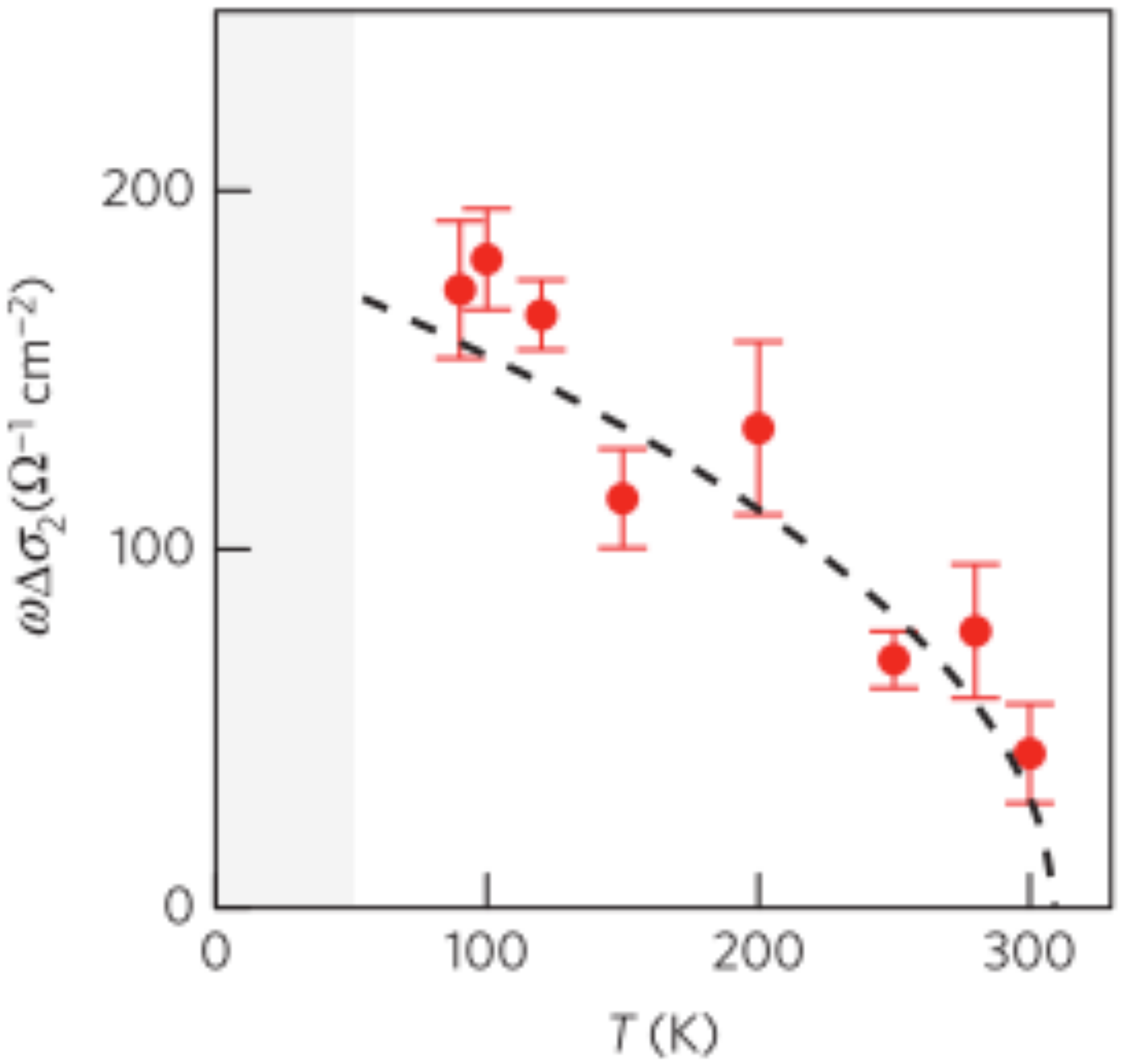
- Mid-infrared optical excitation resonant with c-axis phonons.
- This leads to displacement of the apical oxygens.

S. Kaiser et al., Phys. Rev. B 89, 184516 (2014)

Features in the optical conductivity

$$\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$$





S. Kaiser et al., Phys. Rev. B 89, 184516 (2014)

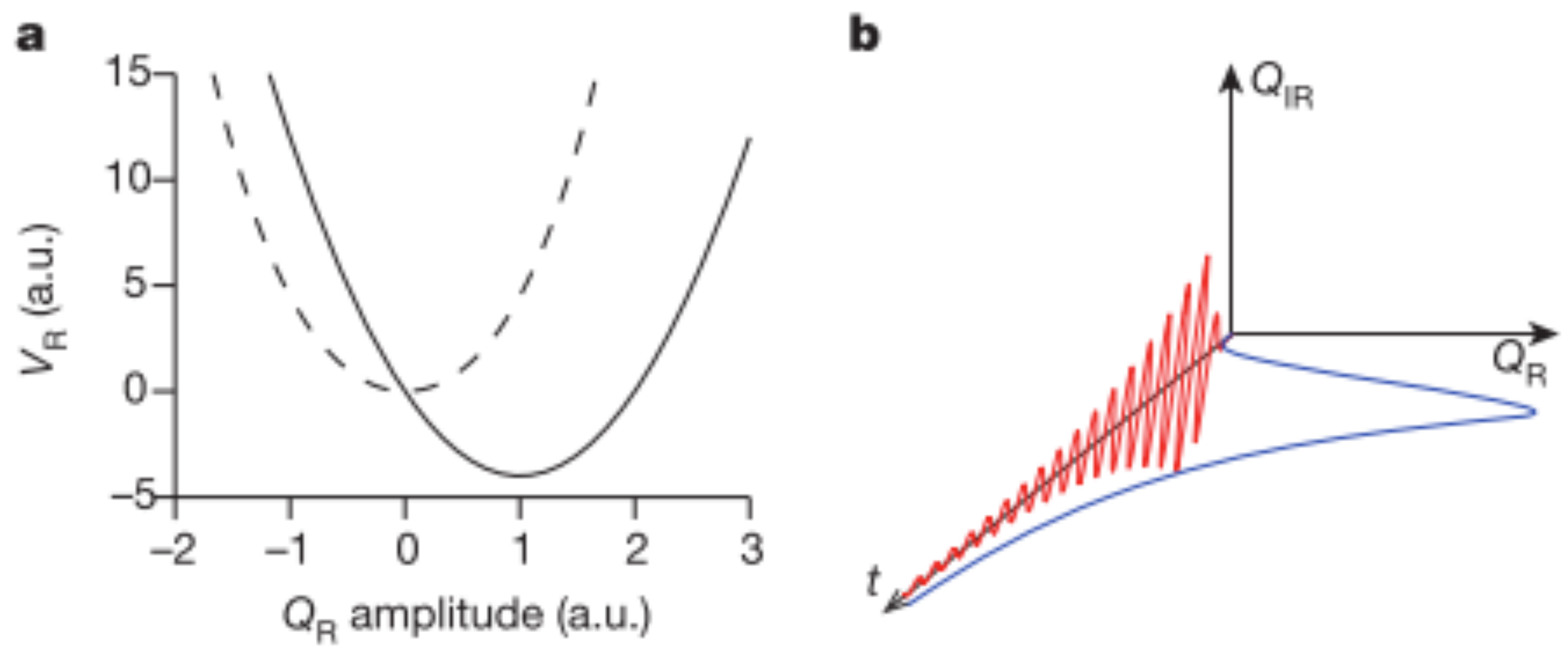
W. Hu et al., Nat. Mater. 13, 705 (2014)

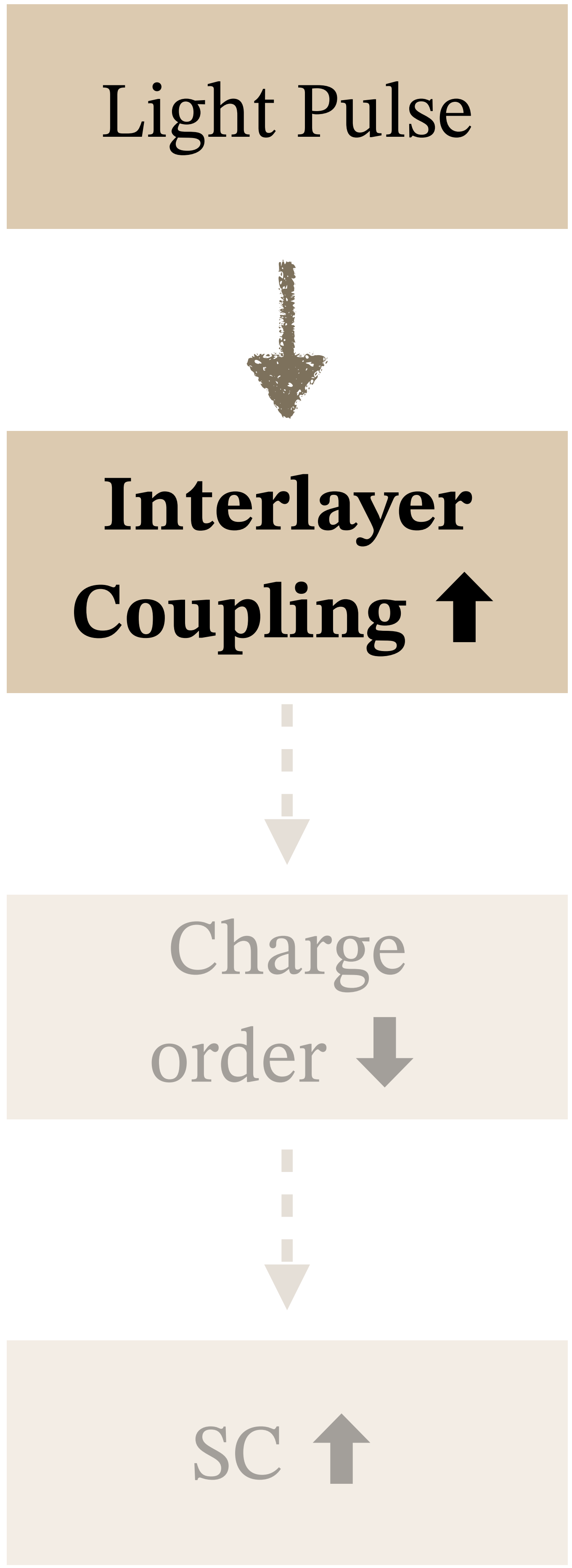
Effects of periodic modulation

Driving the system alters the structure of the system leading to

- Quasi-static shift of plane separation
  - *R. Mankowsky et al., Nature 516, 71 (2014).*

- Oscillation induced enhancement of t_z





Generically function to enhance the interlayer coupling

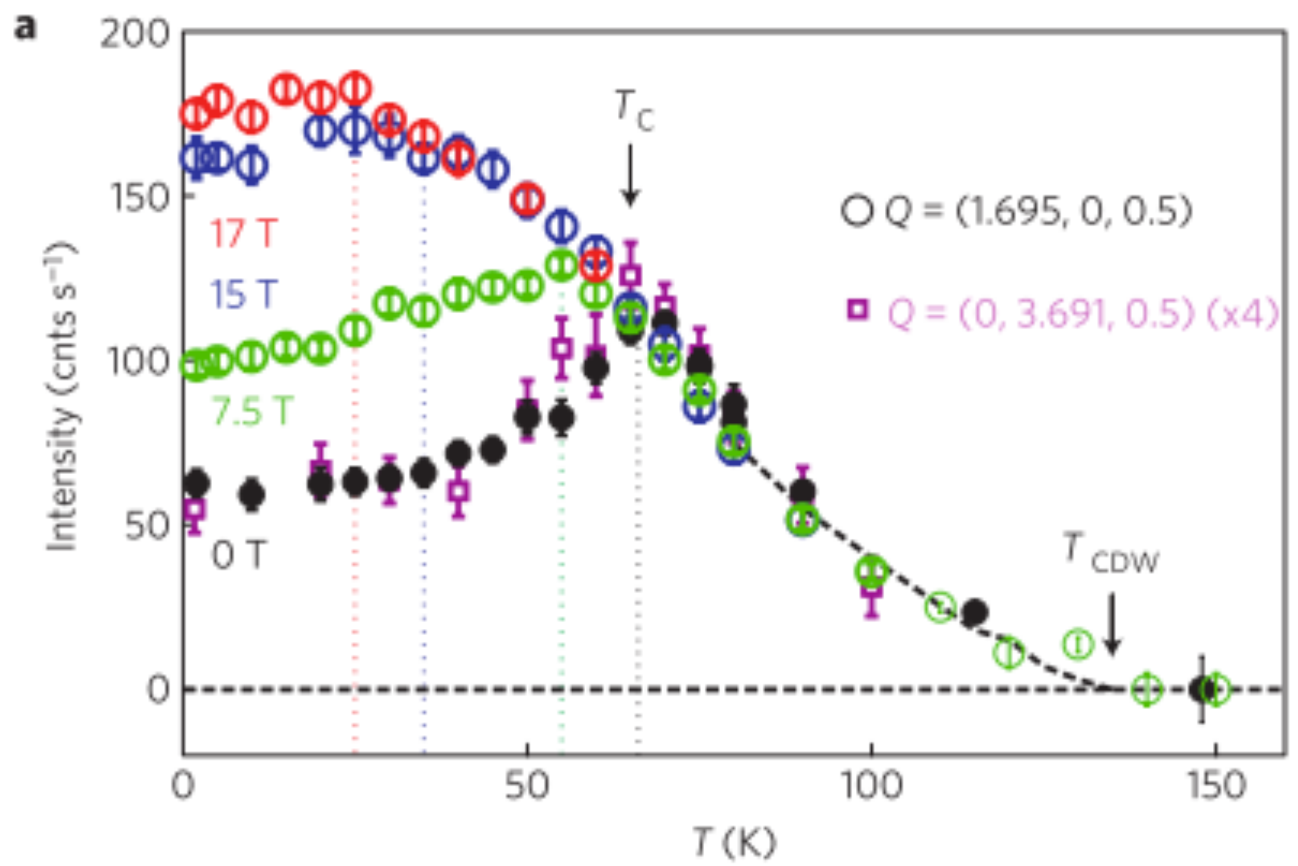
How can this enhance superconductivity?

Competition of superconductivity and charge order

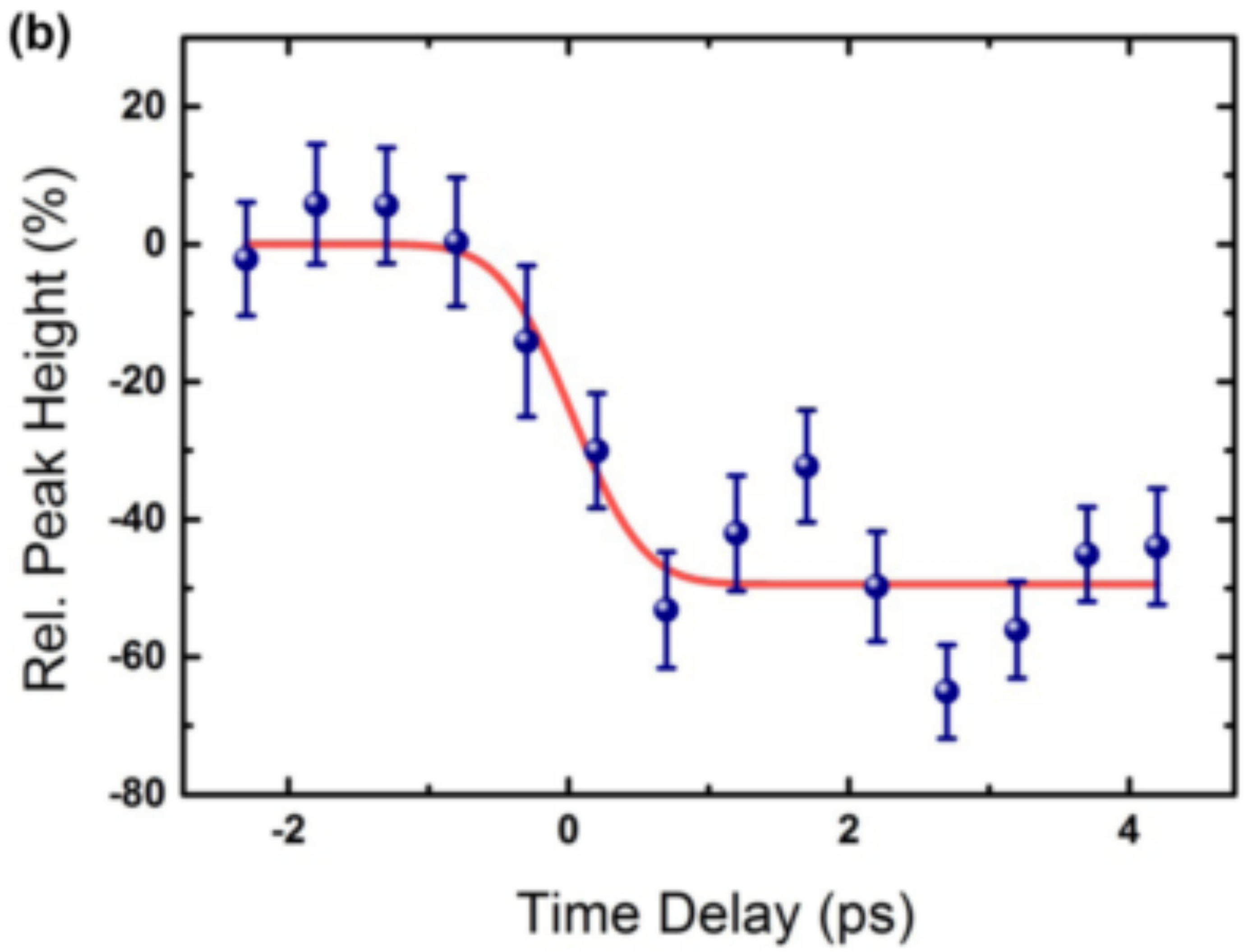
- Charge order is experimentally seen to compete with superconductivity in these systems

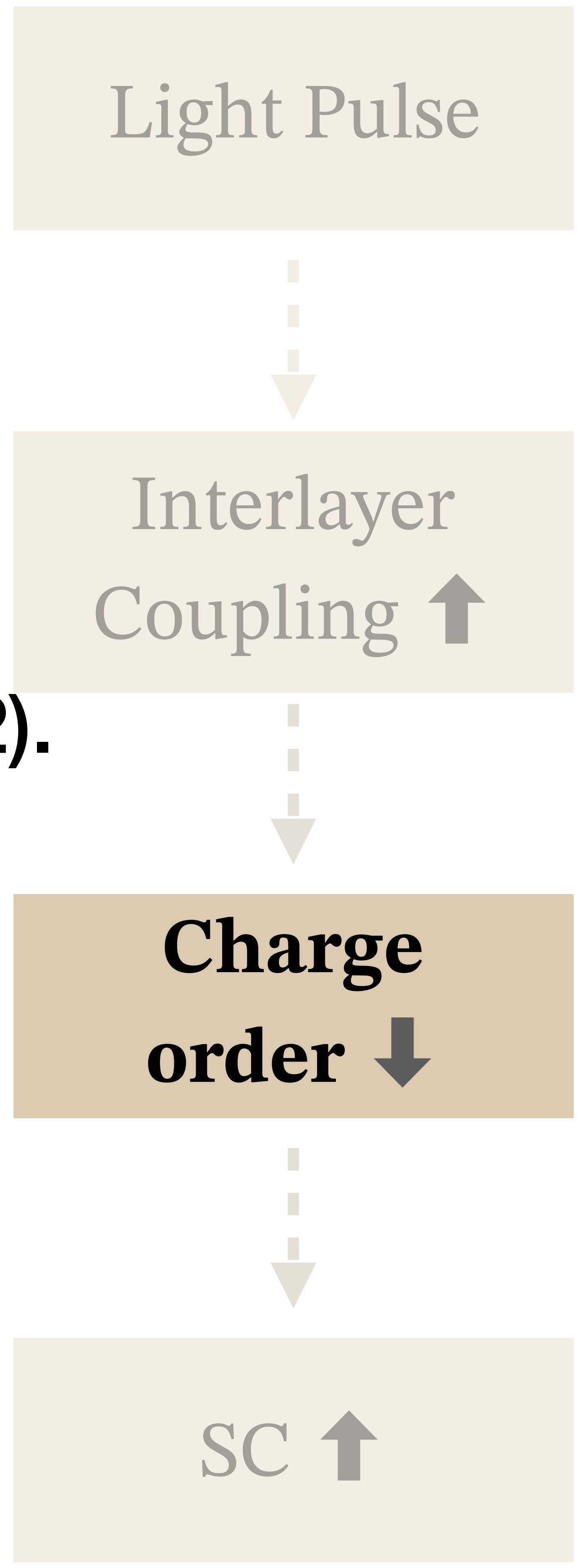
- A melting of charge order is observed coinciding with emergence of the transient pairing signal.

M. Först et al., Phys. Rev. B 90, 184514 (2014).



J. Chang et al., Nat. Phys. 8, 871 (2012).





A model of Copper Oxide planes

The Hamiltonian consists of hopping on square lattice, nearest neighbor exchange, and nearest neighbor Coulomb repulsion.

$$H = \sum_{i,j} t_{ij} c^{\dagger}_{\sigma,i} c_{\sigma,j} + \frac{1}{2} \sum_{\langle i,j \rangle} J \hat{\vec{S}}_i \cdot \hat{\vec{S}}_j + \frac{1}{2} \sum_{\langle i,j \rangle} V \hat{n}_i \hat{n}_j$$

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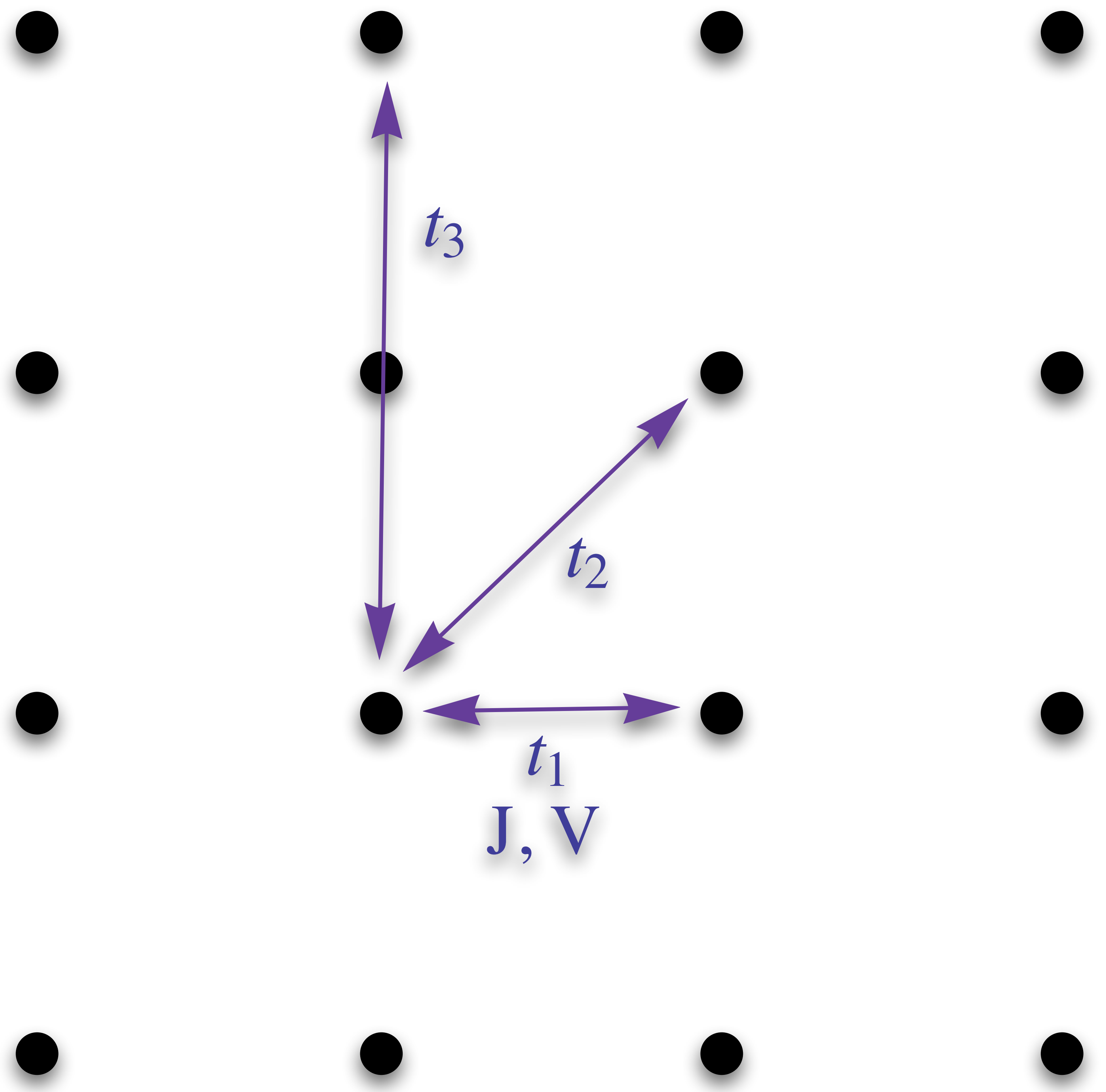
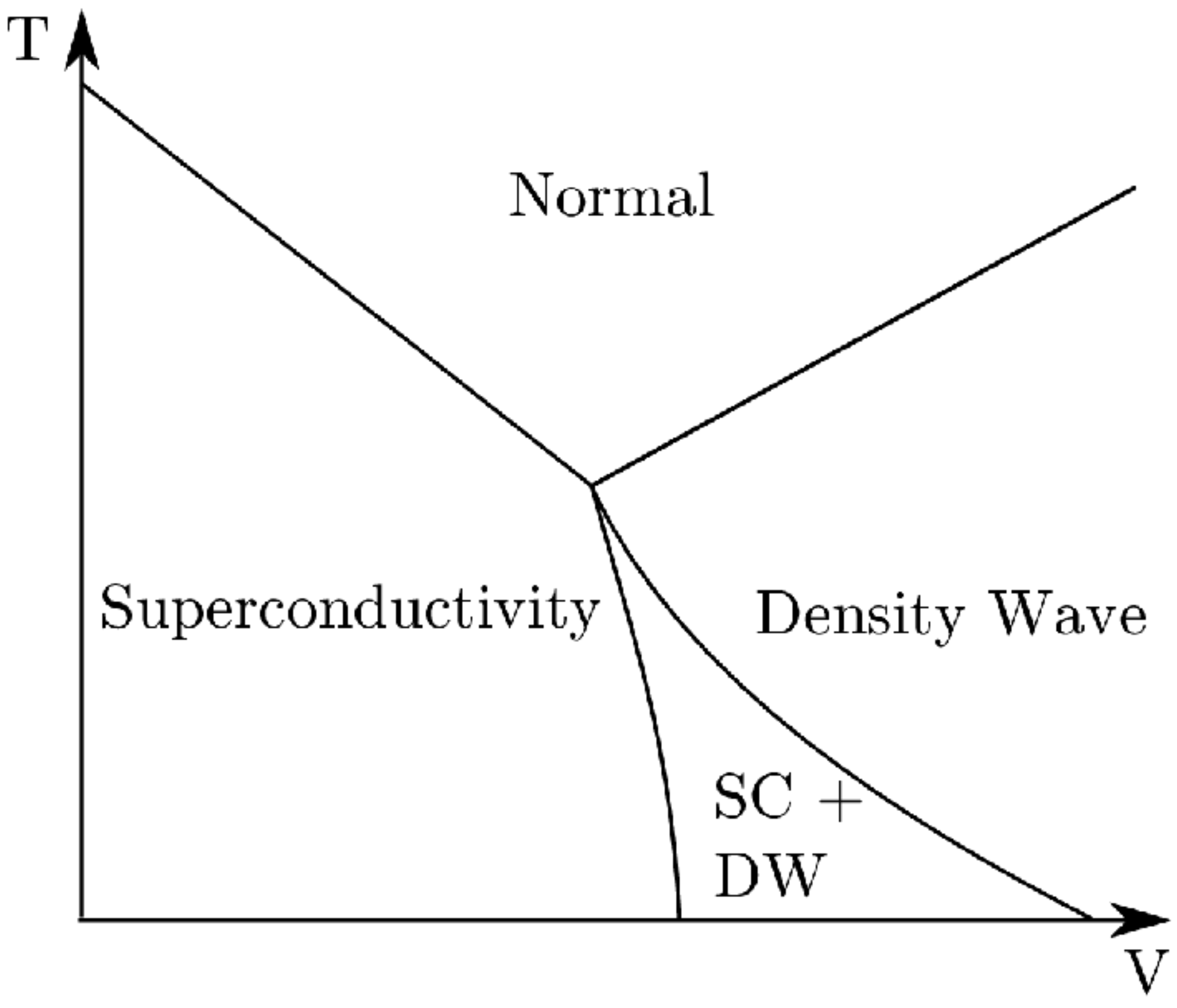


e.g.
M.A. Metlitski and S. Sachdev, Phys. Rev. B 82, 075128 (2010)
J. D. Sau and S. Sachdev, Phys. Rev. B 89, 075129 (2014)
Y. Wang and A. V Chubukov, Phys. Rev. B 90, 035149 (2014)

Mean-field theory of competing orders

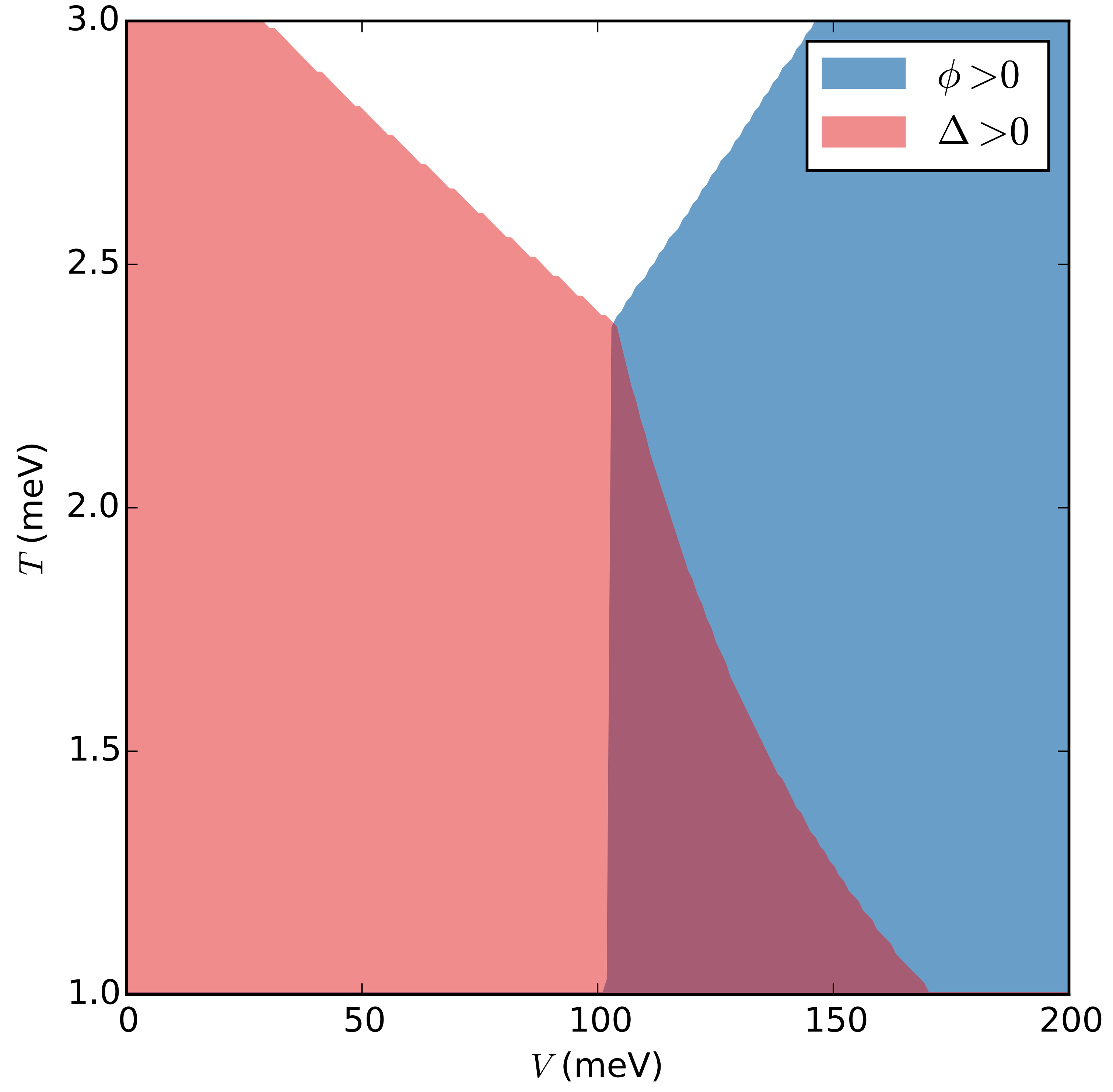
$$\phi(\mathbf{Q}) = \frac{g_\phi}{2} \sum_{\mathbf{k},\sigma} f(\mathbf{k}) \langle c^\dagger_{\mathbf{k}-\mathbf{Q}/2,\sigma} c_{\mathbf{k}+\mathbf{Q}/\mathbf{2},\sigma} \rangle$$

$$\Delta = \frac{g_\Delta}{4} \sum_{\mathbf{k},\sigma,\sigma'} f(\mathbf{k}) \langle c_{-\mathbf{k},\sigma} (-i\sigma^2_{\sigma\sigma'}) c_{\mathbf{k},\sigma'} \rangle$$



- d-wave superconductivity Δ
- d-form-factor density wave (dFF-DW) ϕ

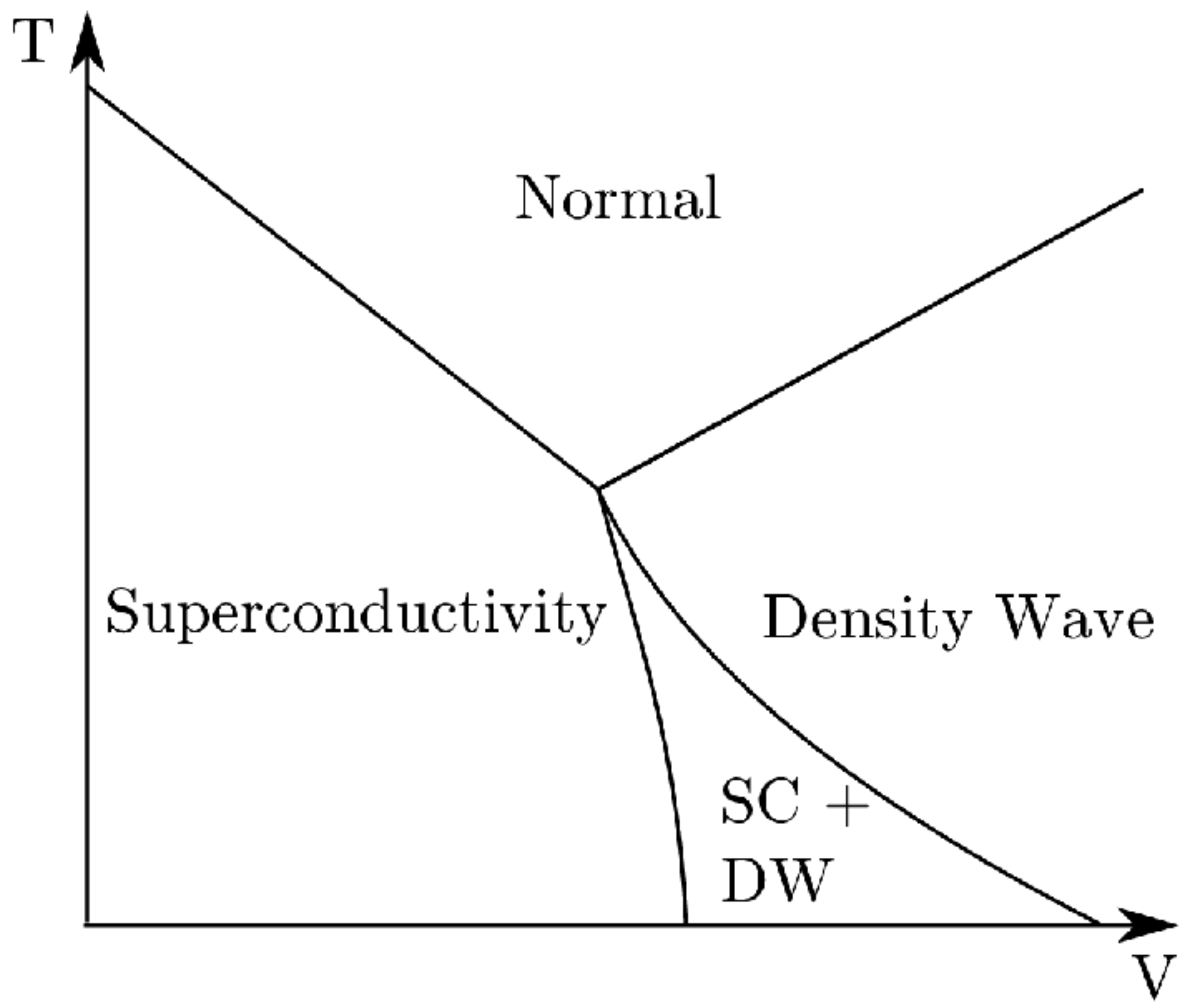
Landau theory of competing orders

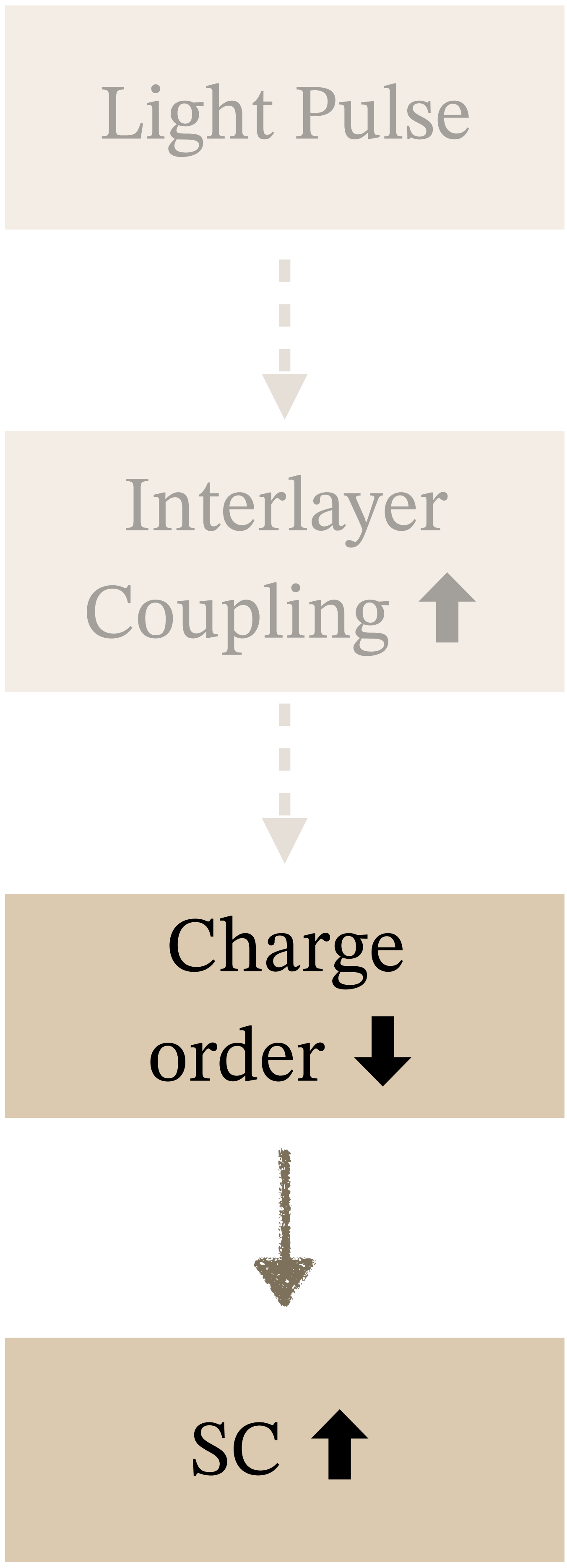


ZMR, V. Stanev, and V. M. Galitski, PRB, (2015).

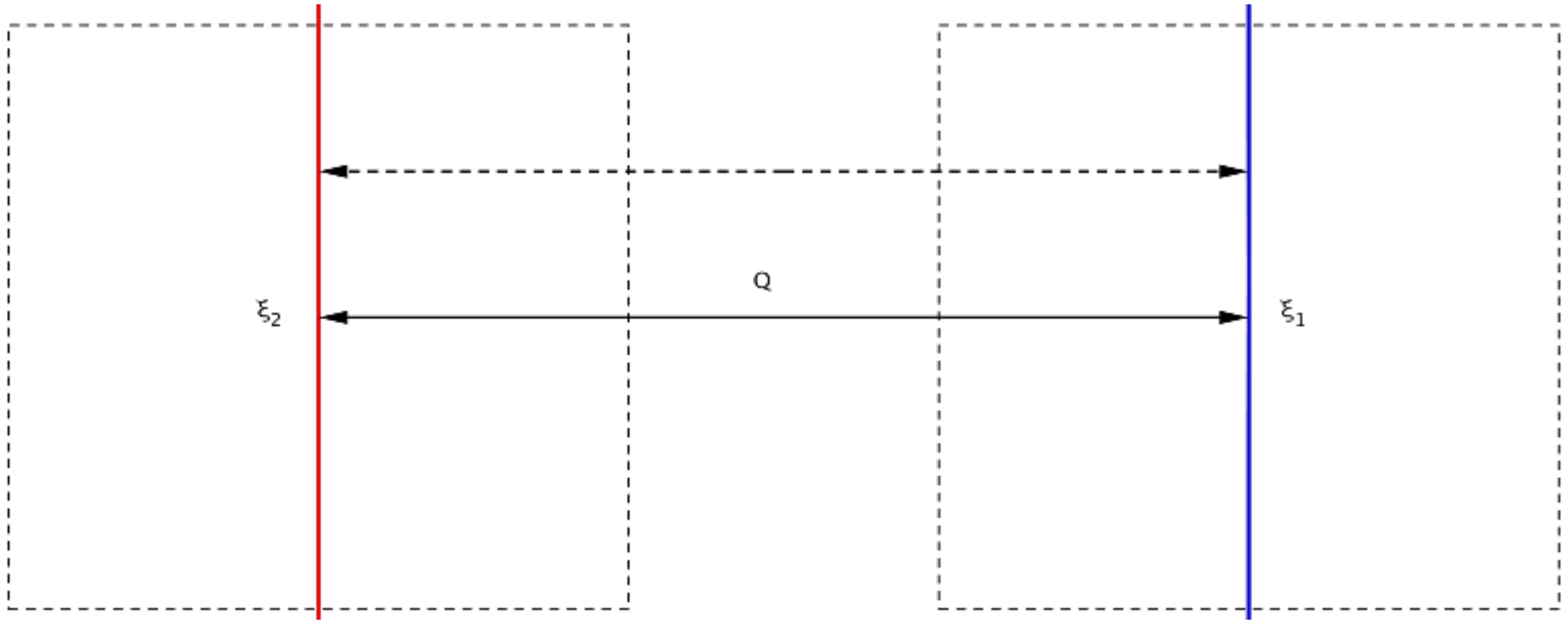
$$\mathcal{F} = \alpha_\Delta \Delta^2 + \beta_\Delta \Delta^4 + \alpha_\phi \phi^2 + \beta_\phi \phi^4 + \gamma \phi^2 \Delta^2$$

$$(\phi, \Delta) \in (0,0), (\phi_0, 0), (0, \Delta_0), (\phi_{co}, \Delta_{co})$$

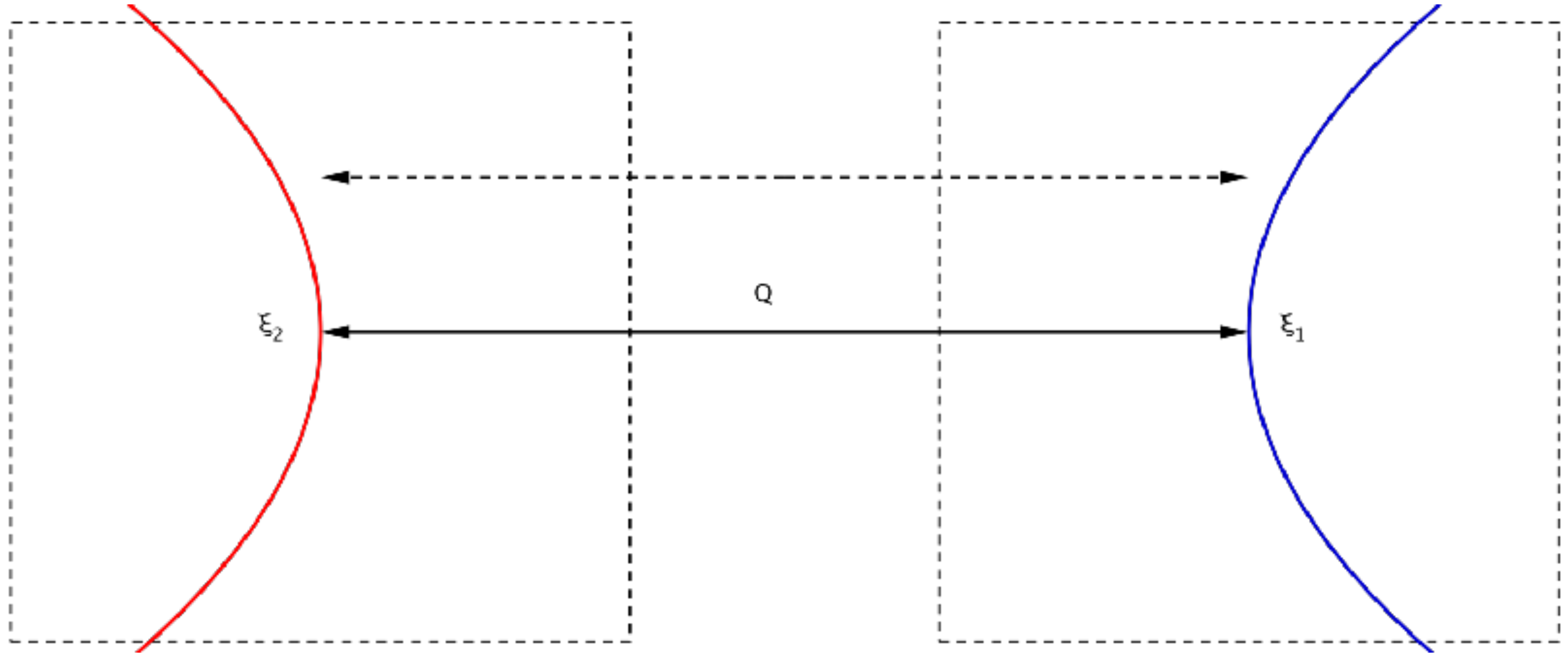




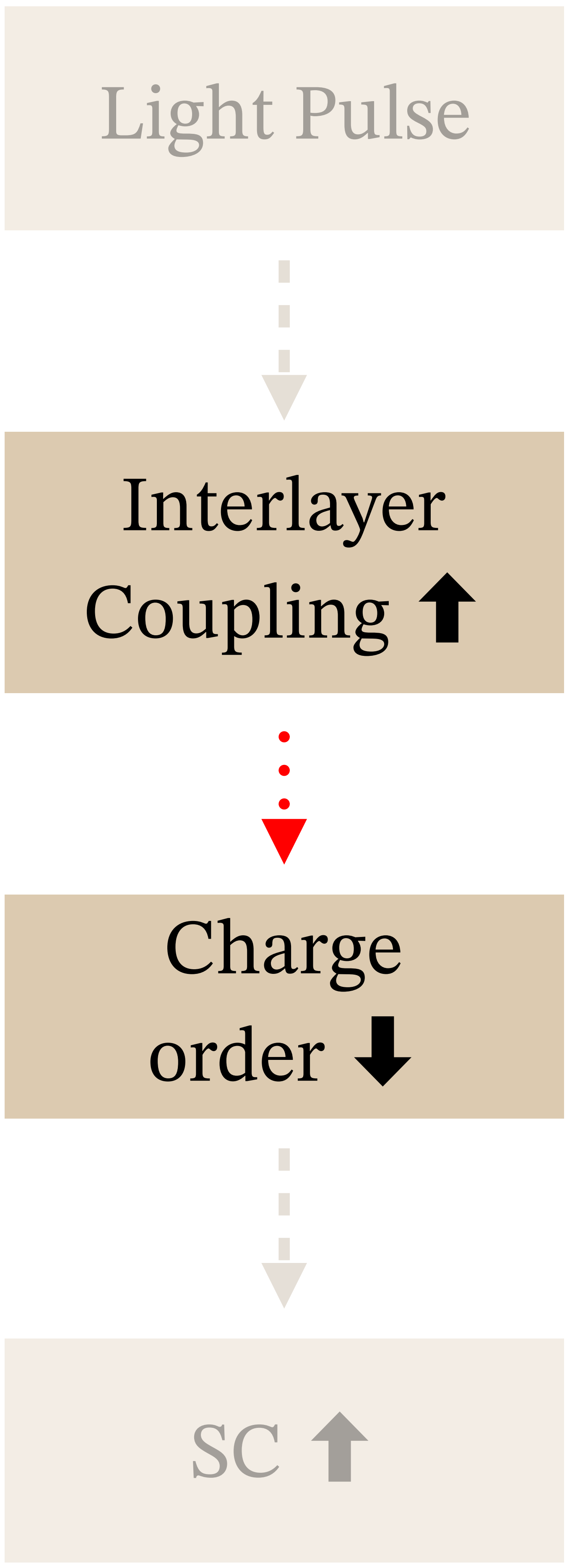
Mechanism: The role of curvature



Nested



Nesting weakened by curvature



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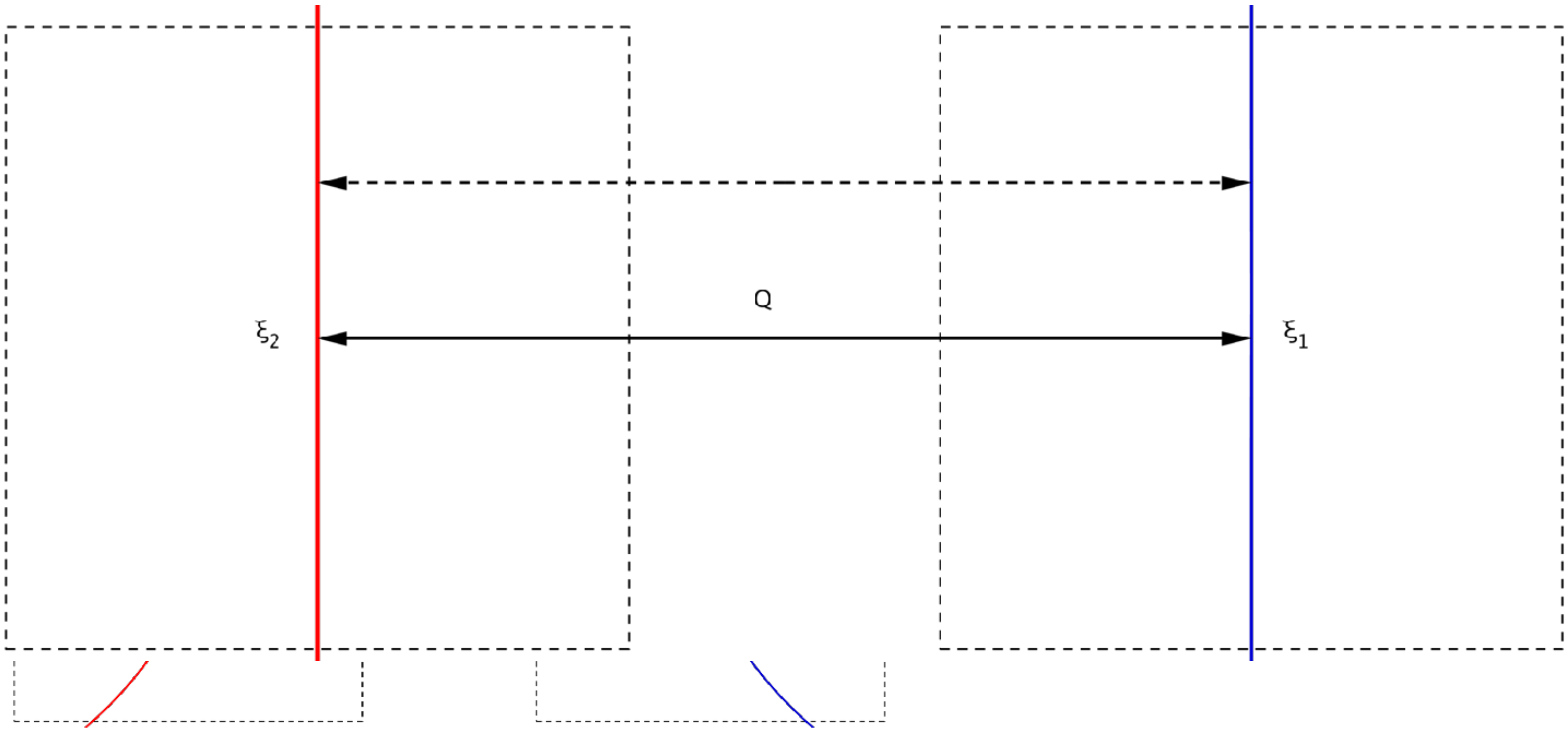

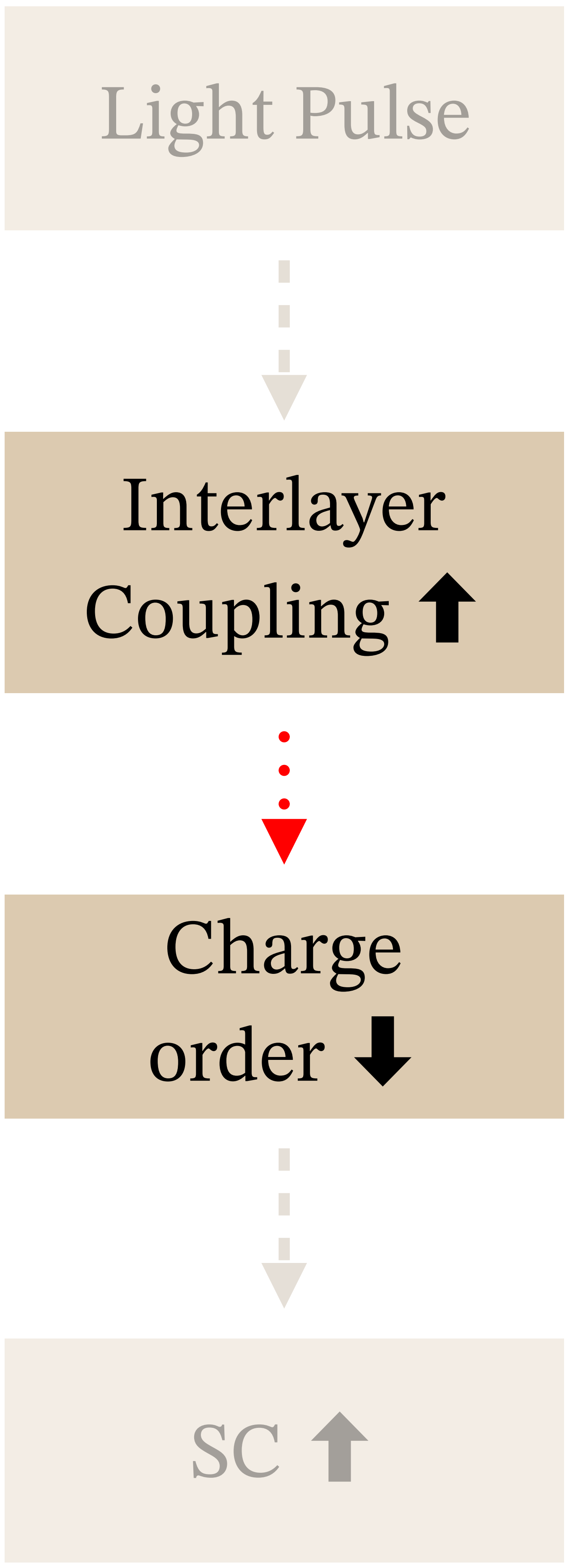

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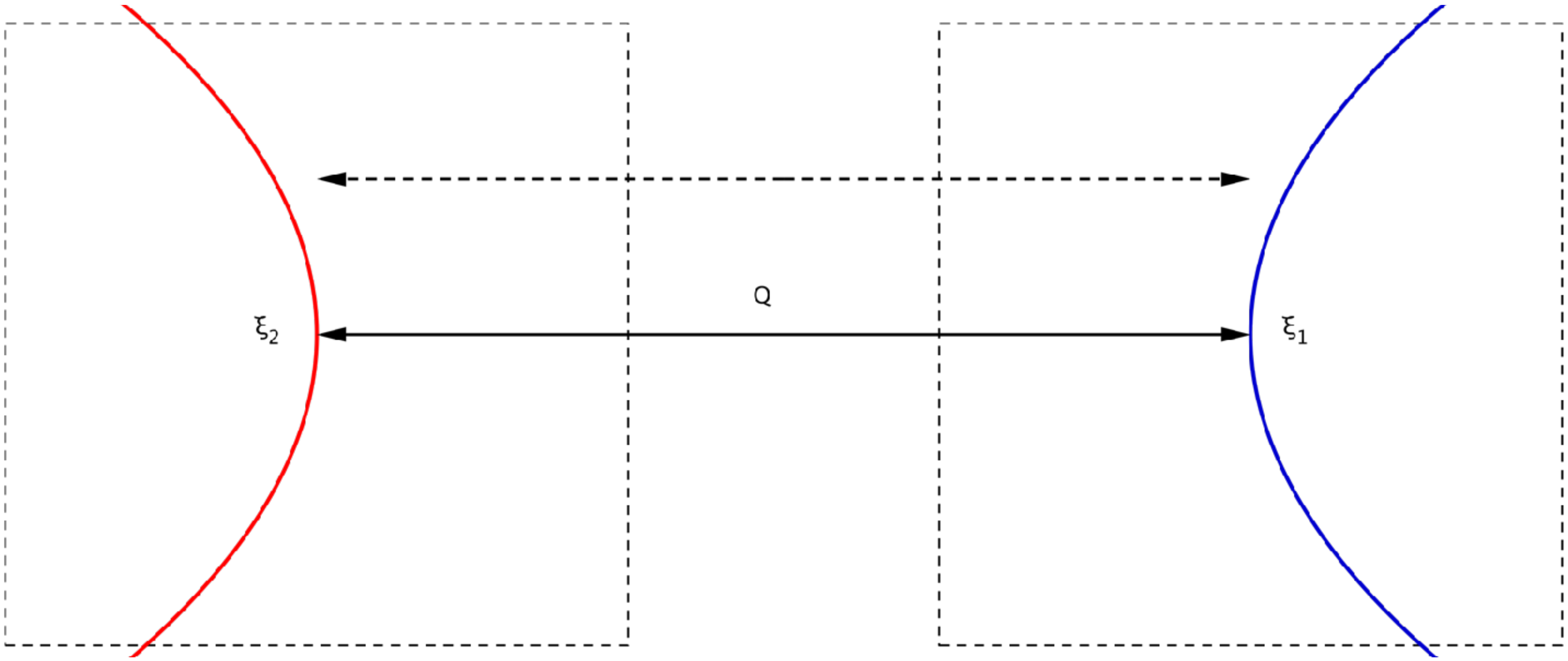
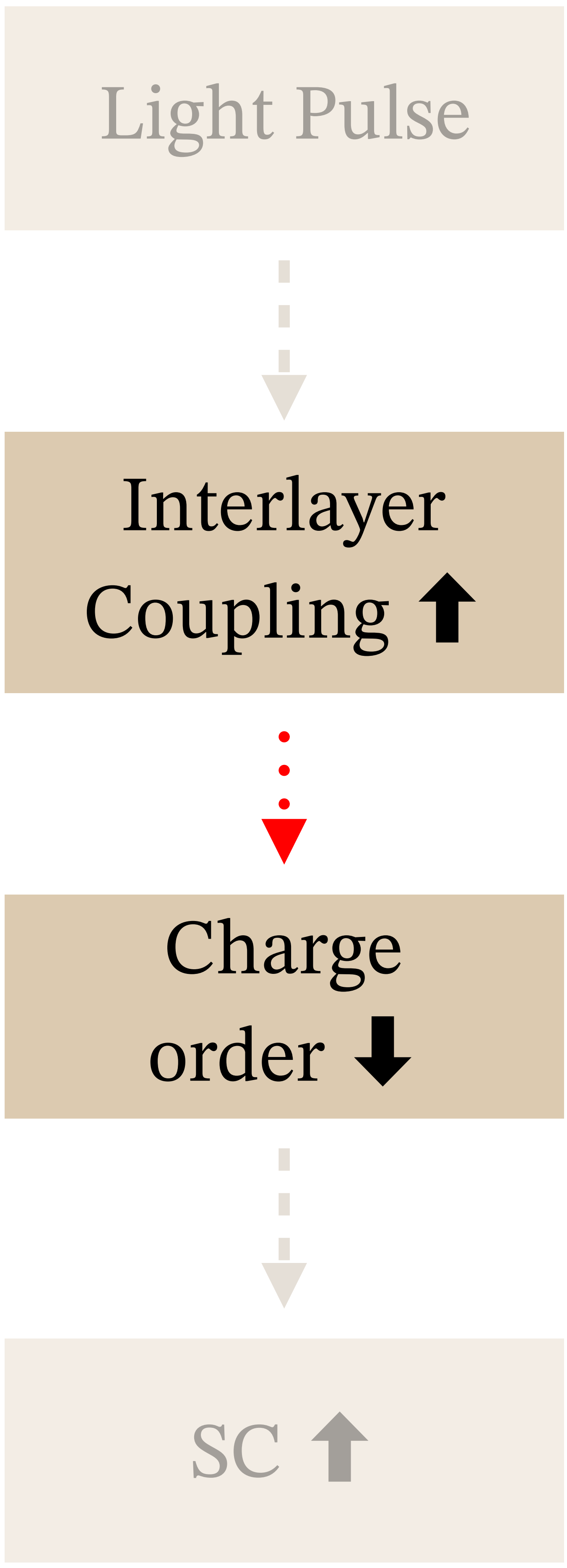




Including the effect of interlayer coupling

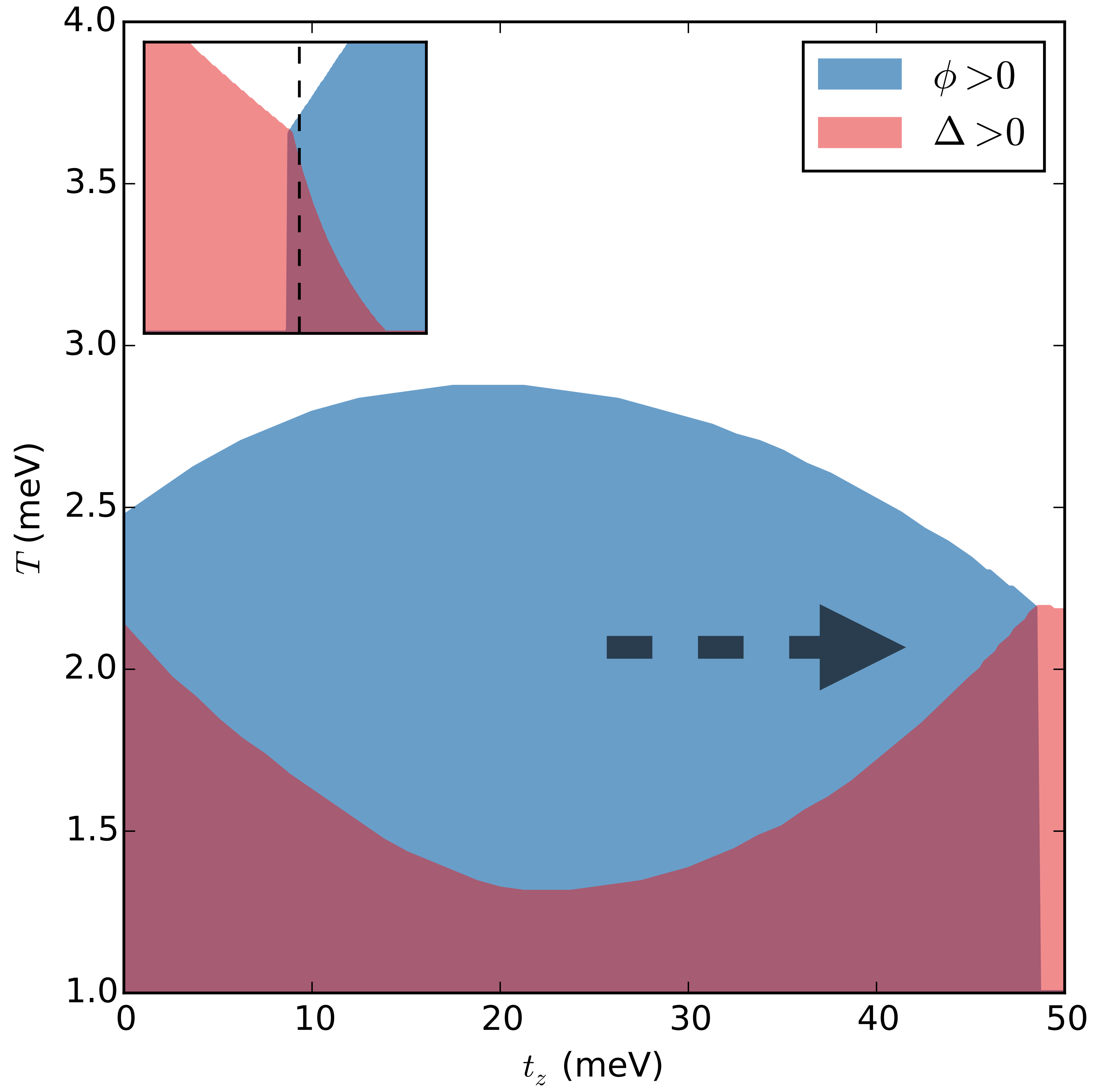
Extend to 3 dimensions and consider the effect of interlayer coupling

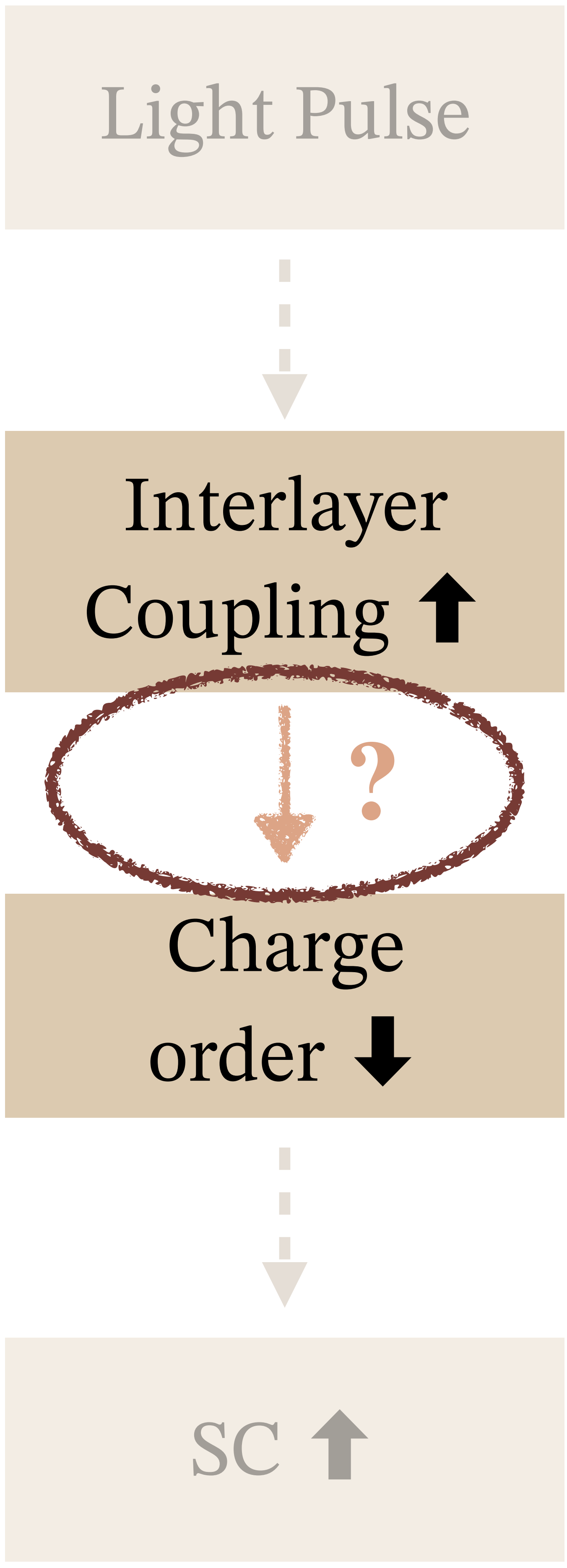
$$\mathcal{F} = \alpha_\Delta \Delta^2 + \beta_\Delta \Delta^4 + \alpha_\phi \phi^2 + \beta_\phi \phi^4 + \gamma \phi^2 \Delta^2$$

$$(\phi, \Delta) \in (0,0), (\phi_0, 0), (0, \Delta_0), (\phi_{co}, \Delta_{co})$$

When increasing t_z:

- $Q_z = 0$ DW is melted
- SC is enhanced

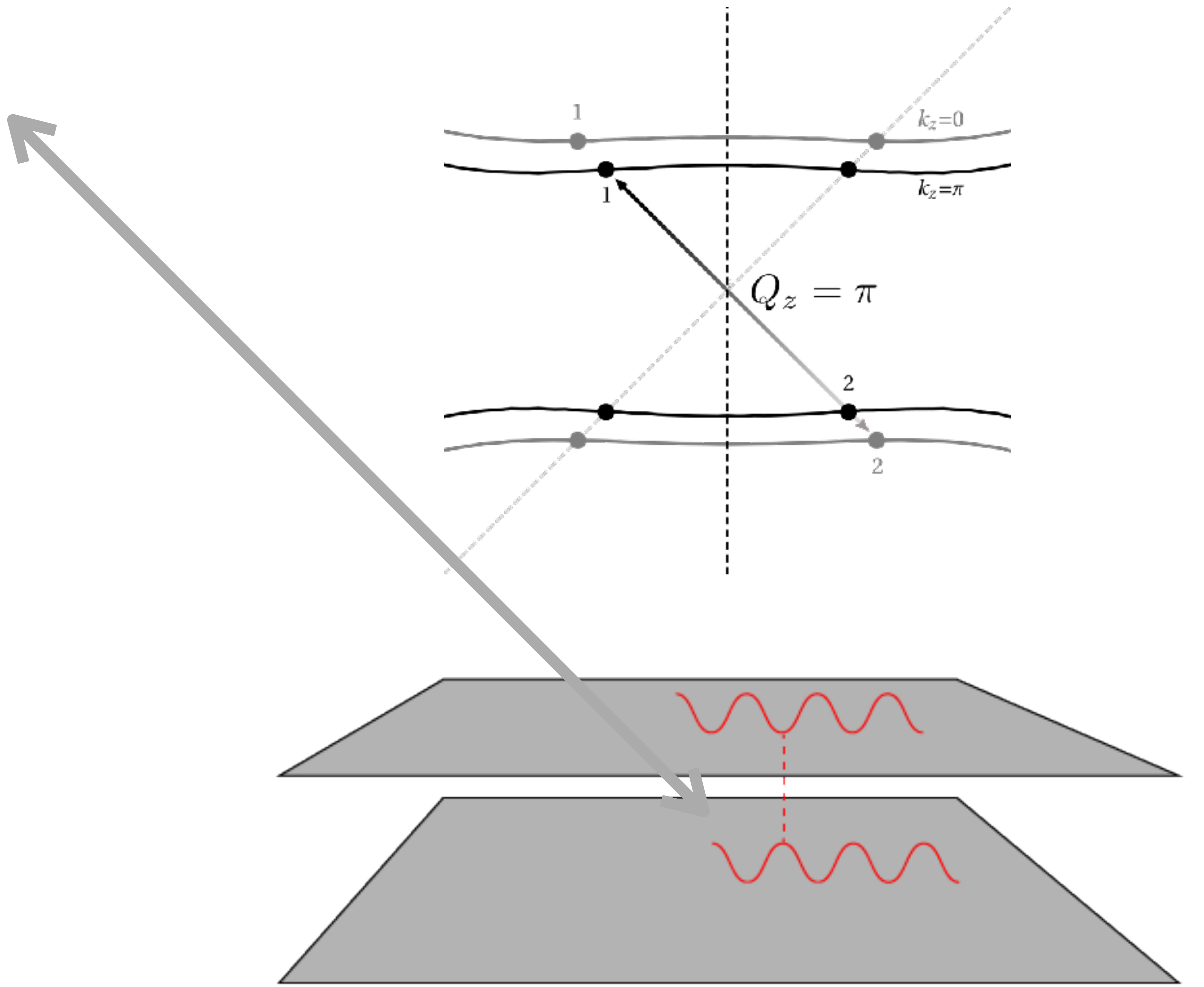




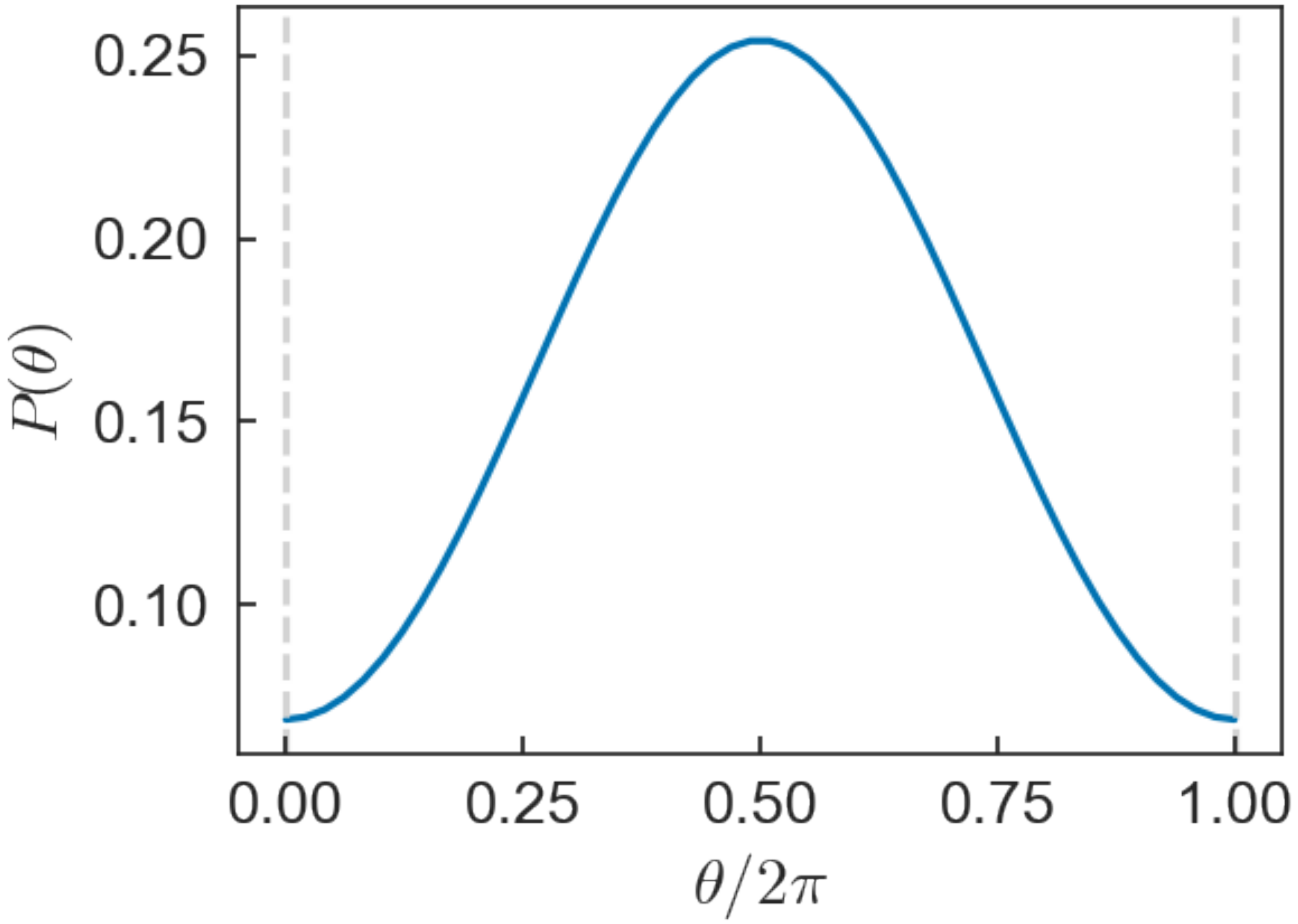
ZMR, V. Stanev, and V. M. Galitski, PRB, (2015).

Just increasing t_z is not enough

- Nesting is destroyed at $Q_z = 0$
- **But**, nesting can be preserved for ordering with $Q_z = \pi$
- This effectively decouples the layers as far as the density wave is concerned

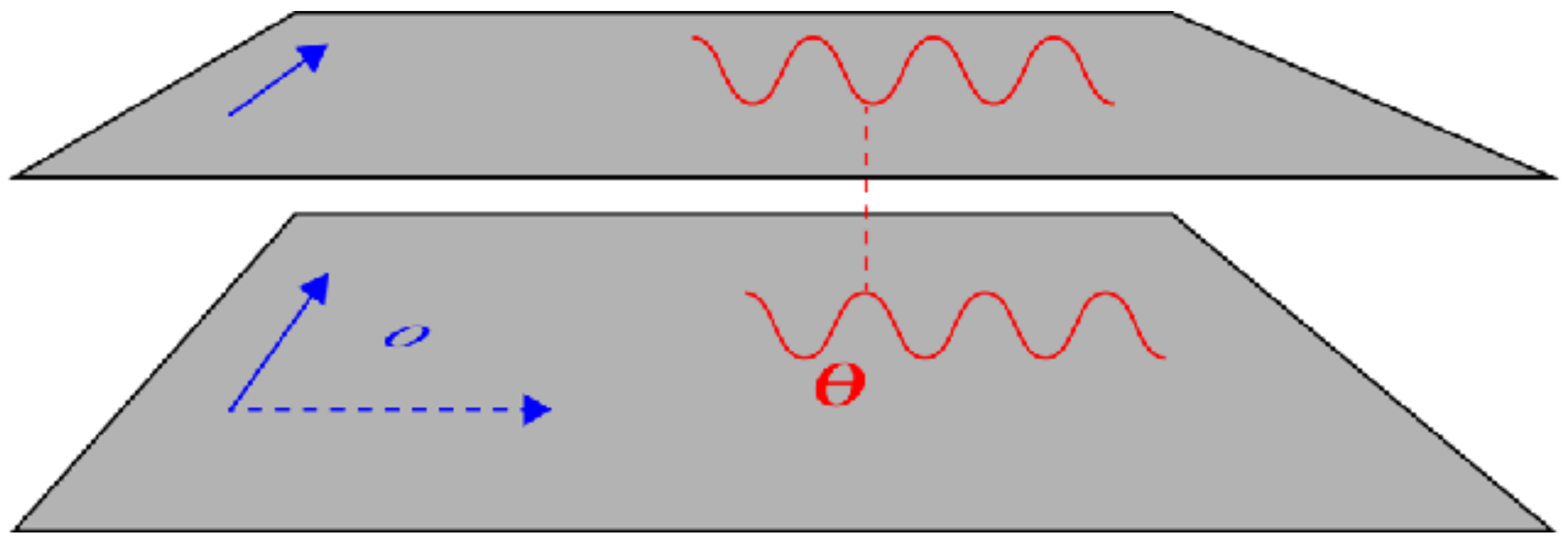


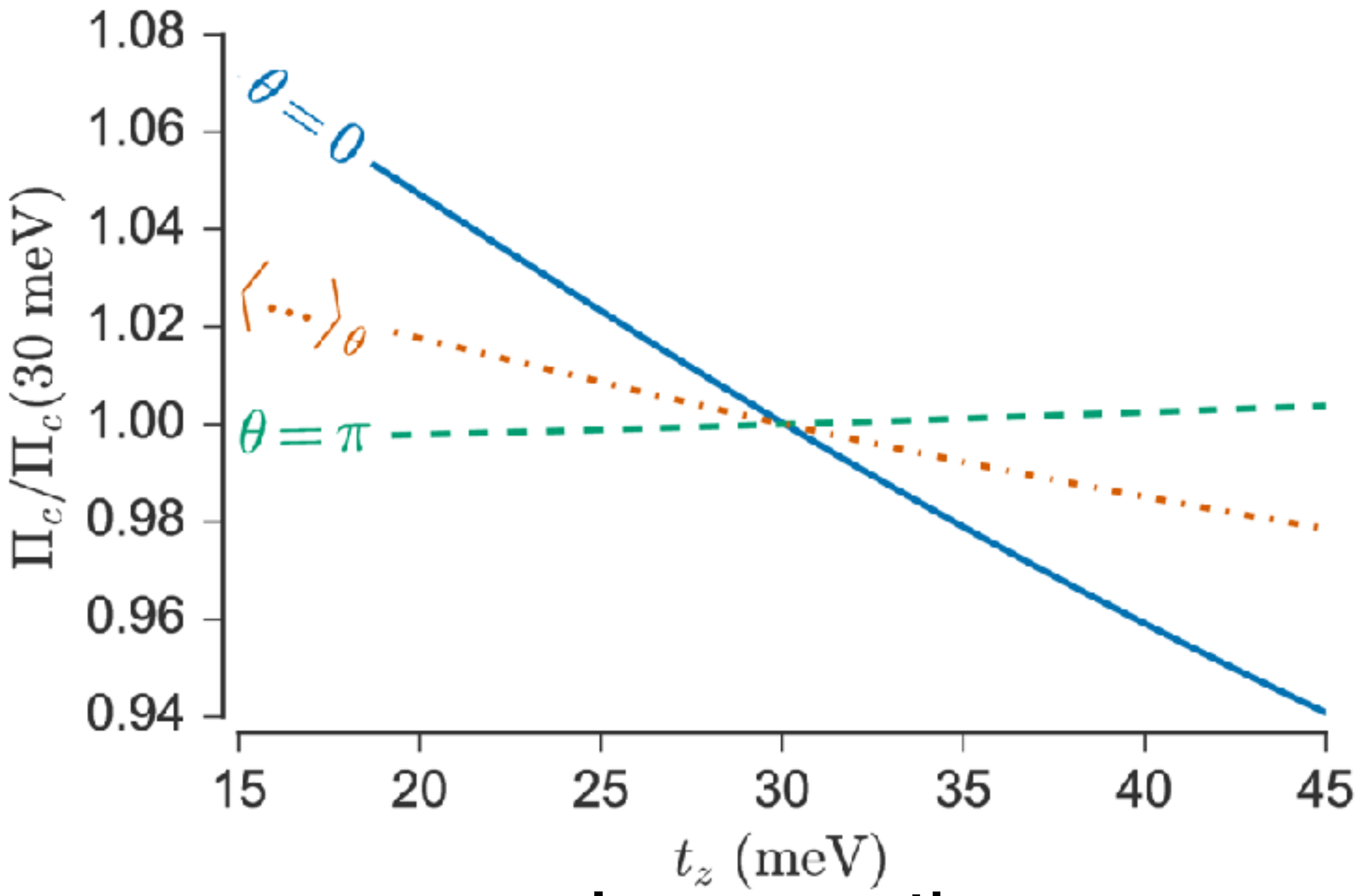
Promote phase and orientation to random variables $\phi \rightarrow \phi[O, \theta]$



- θ - the phase difference of the orders
- O - the relative orientation of the ordering vectors (∥,⊥)

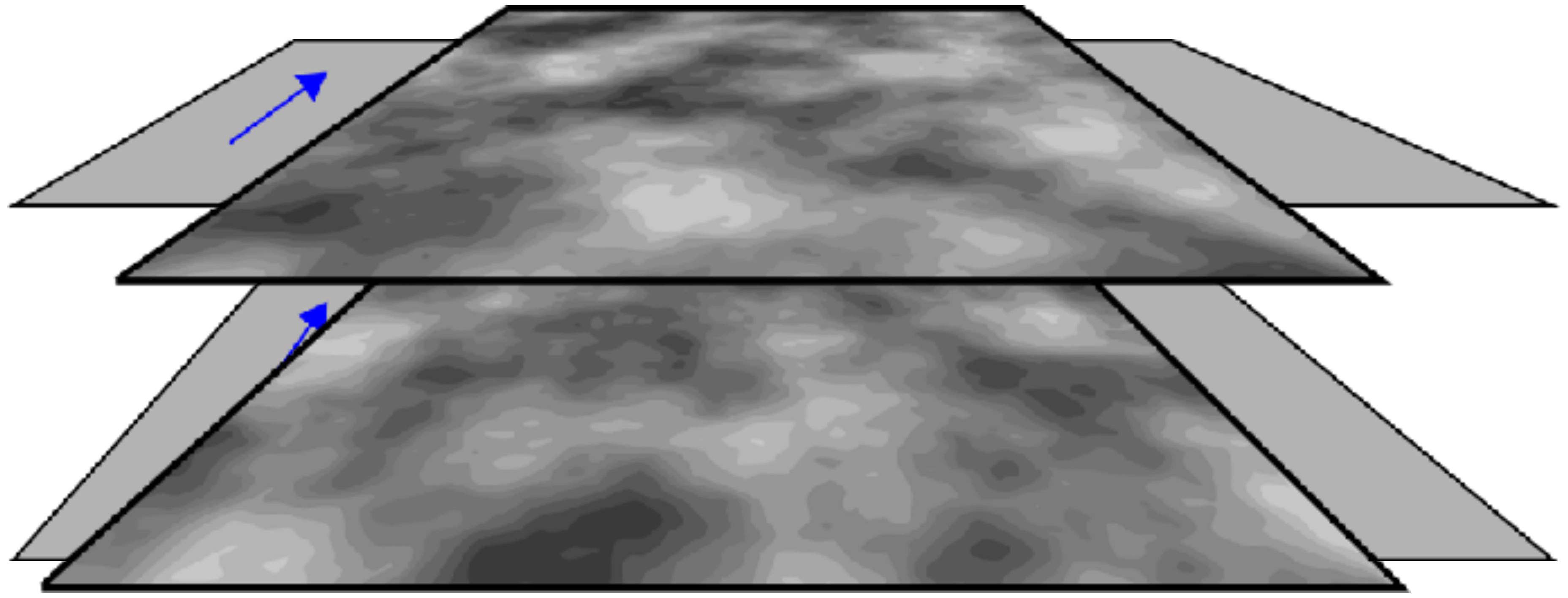
Bilayer model



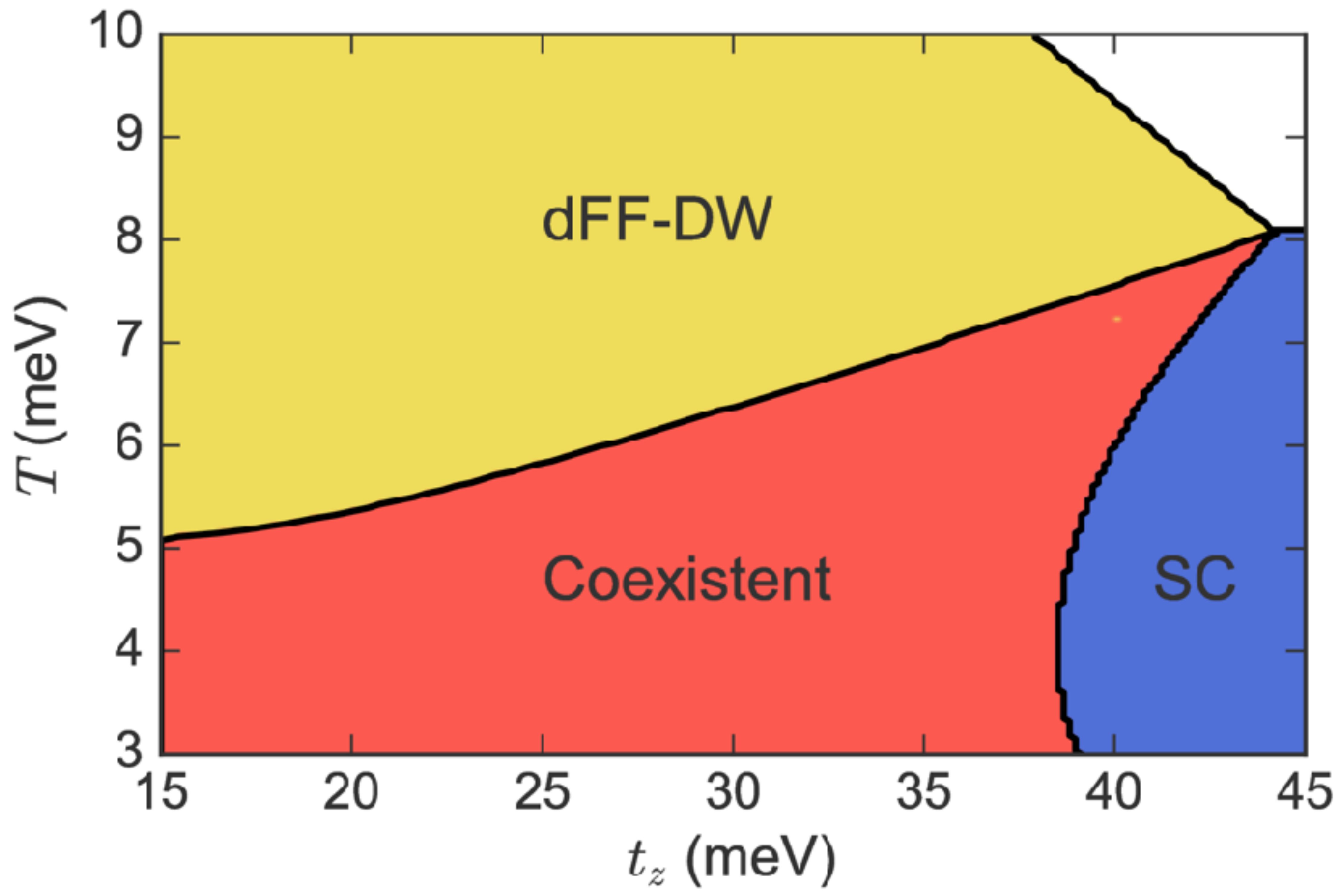


In preparation

Averaging over orientation and phase



$$\langle \mathcal{F} \rangle_{\theta,O} \rightarrow \alpha_{\triangle}\Delta^2 + \beta_{\triangle}\Delta^4 + \alpha_{\phi}\phi^2 + \beta_{\phi}\phi^4 + \gamma\phi^2\Delta^2$$



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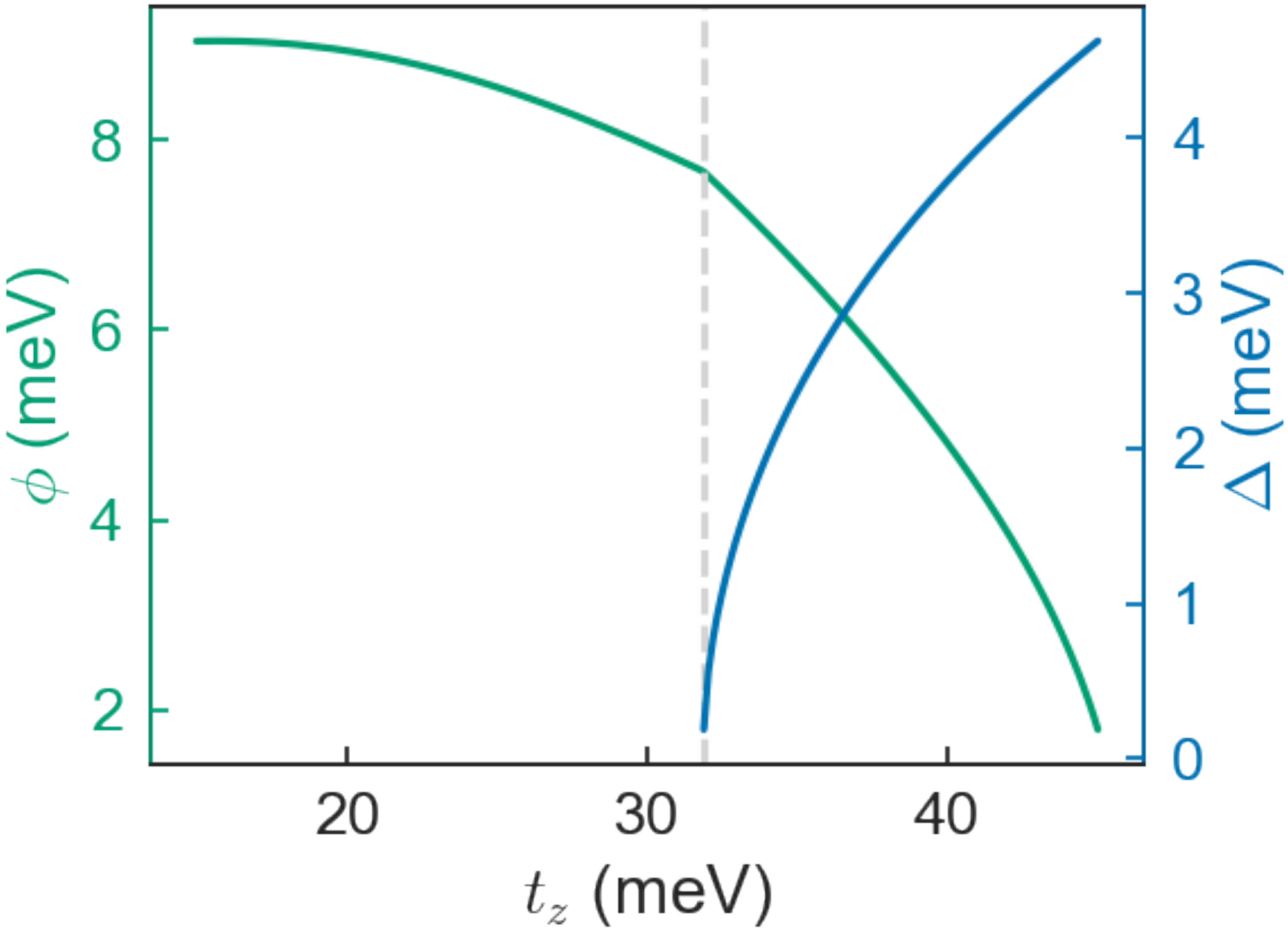
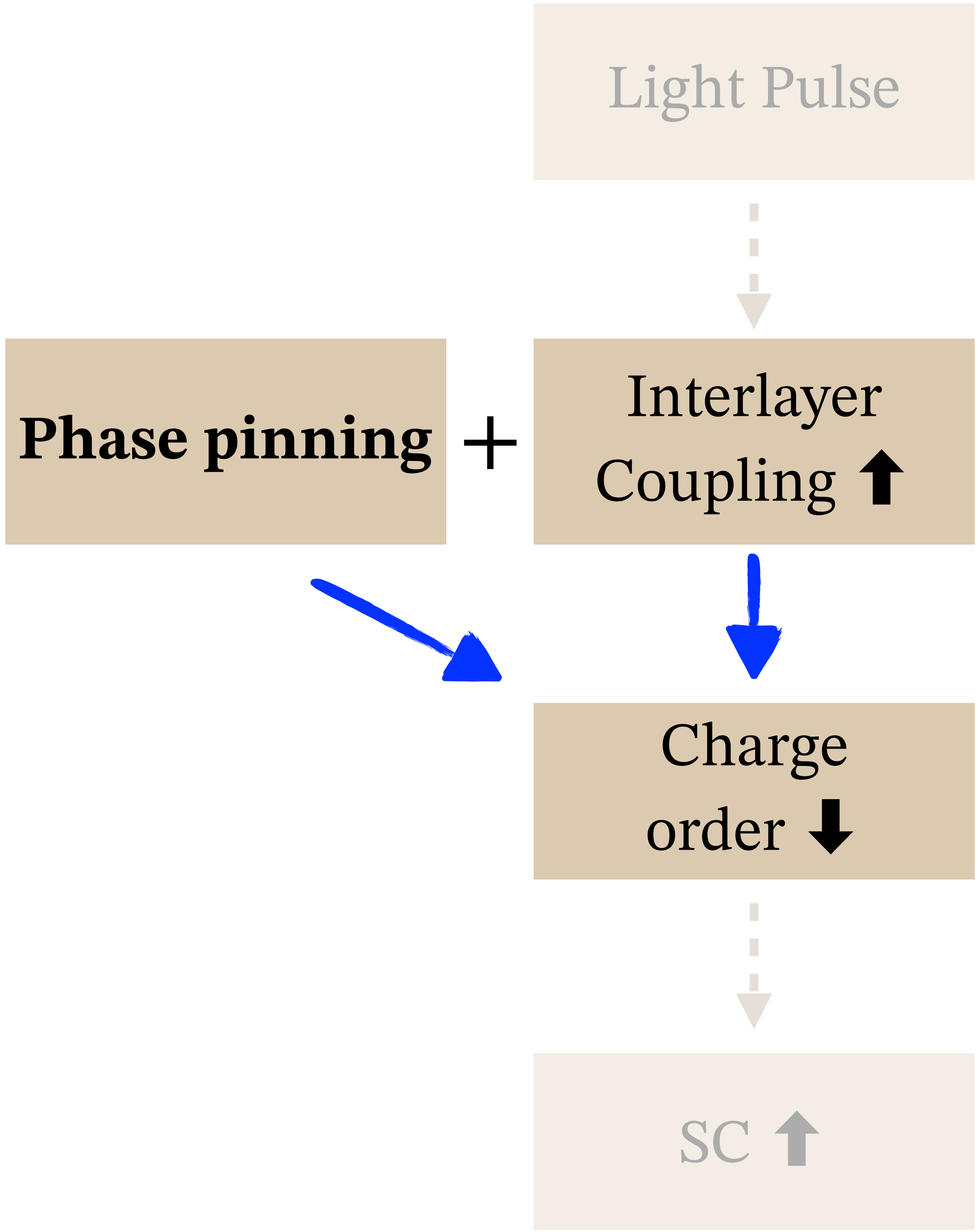
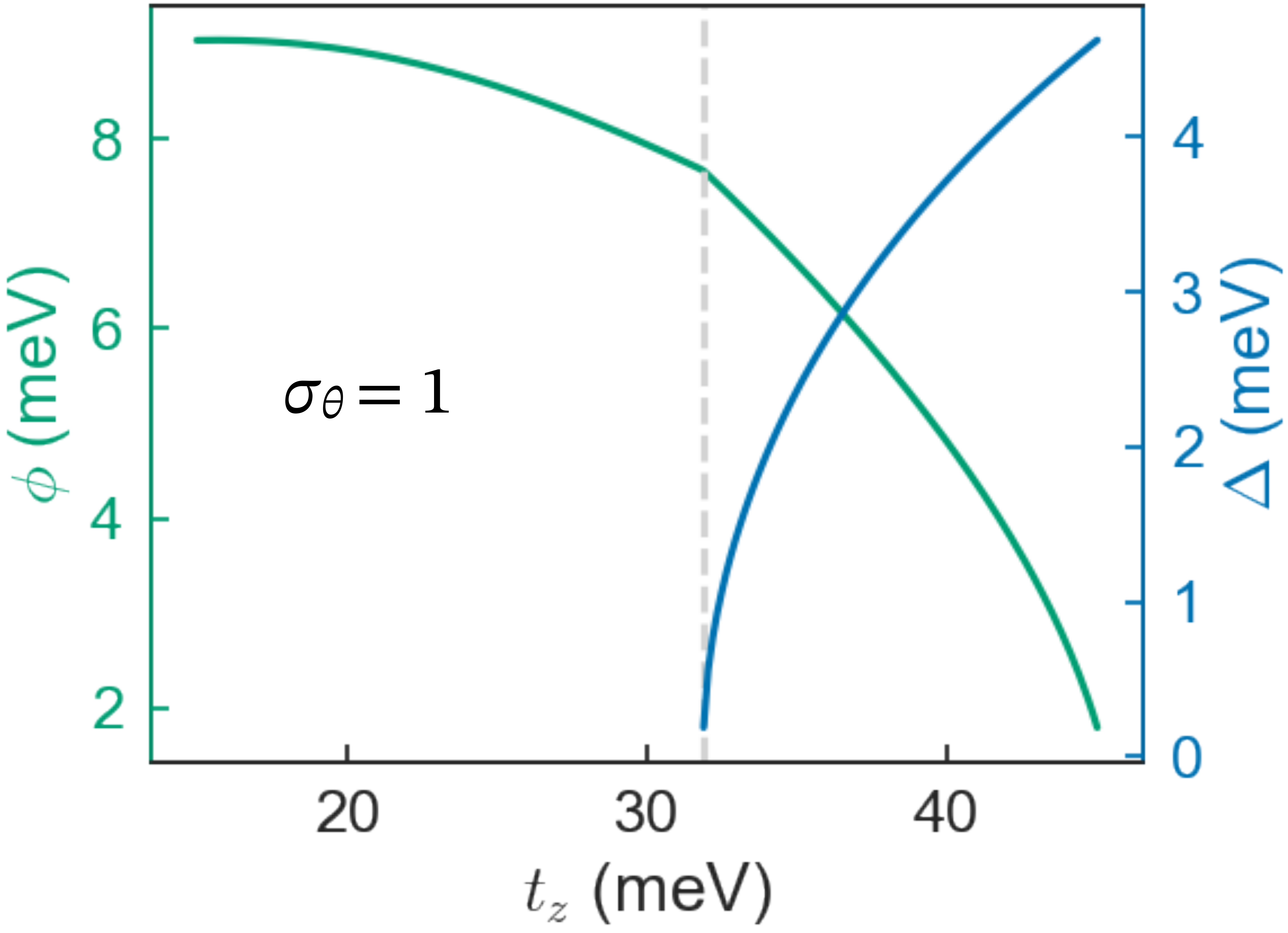
In preparation

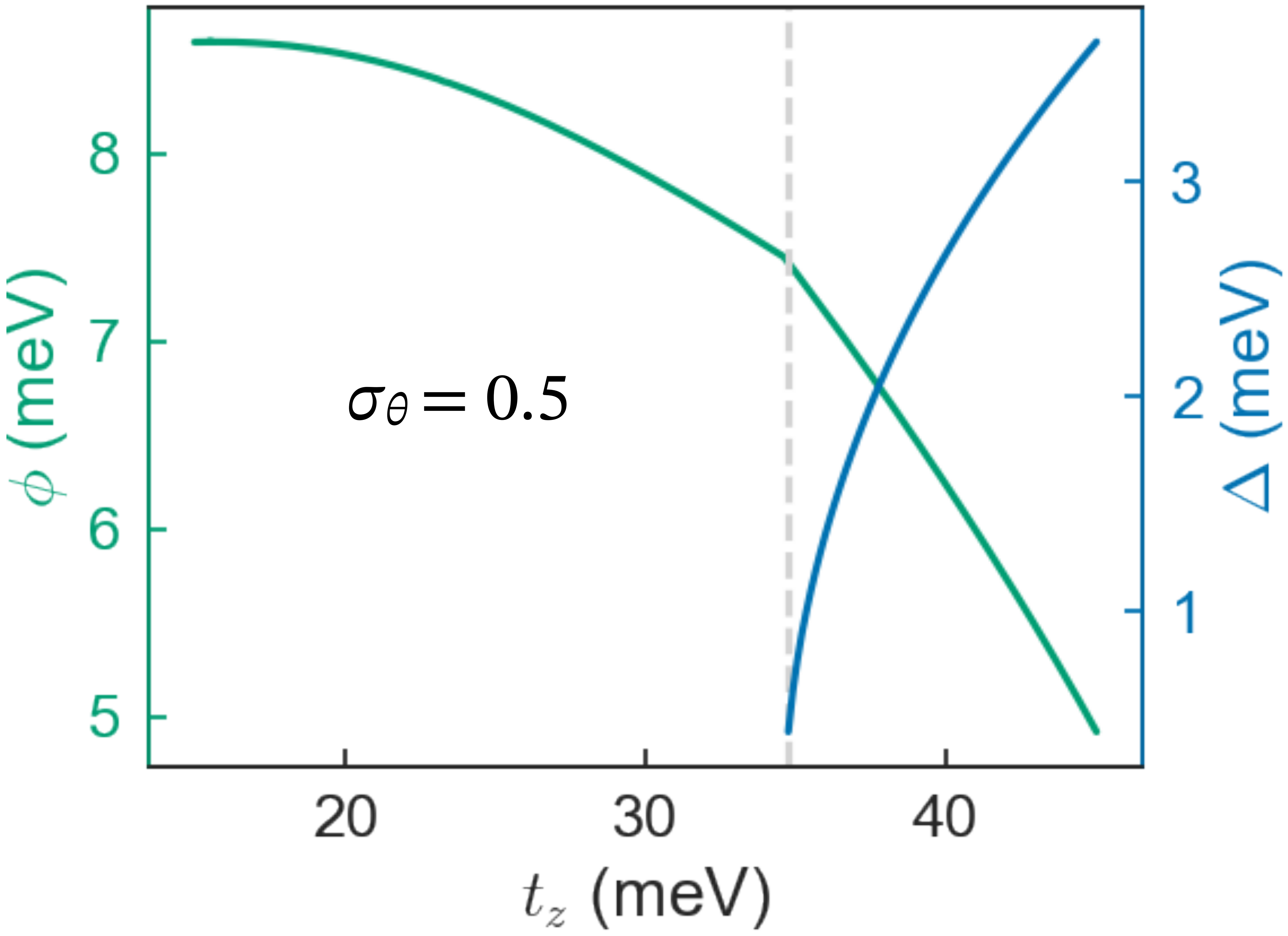
After averaging





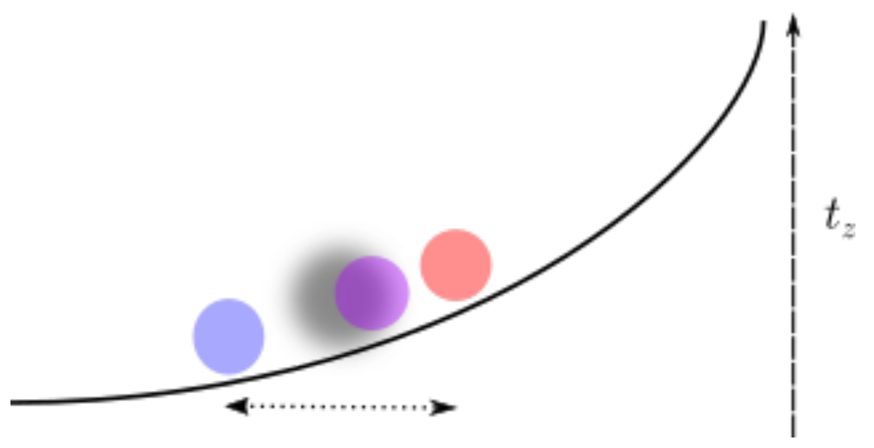
Effect is generic

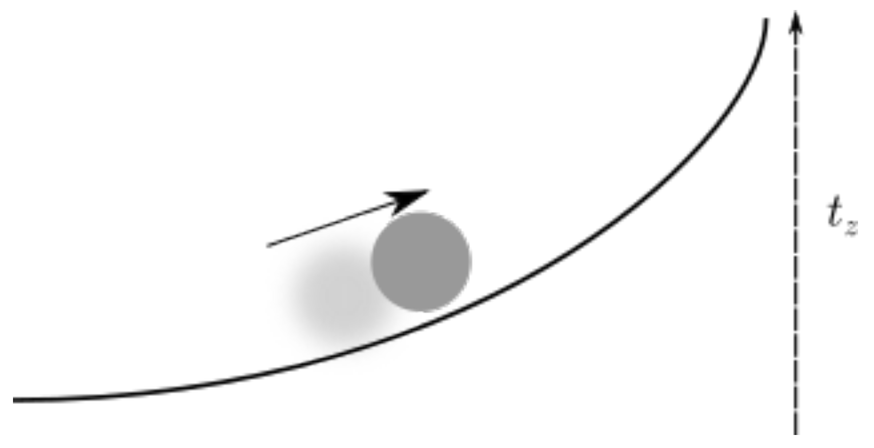


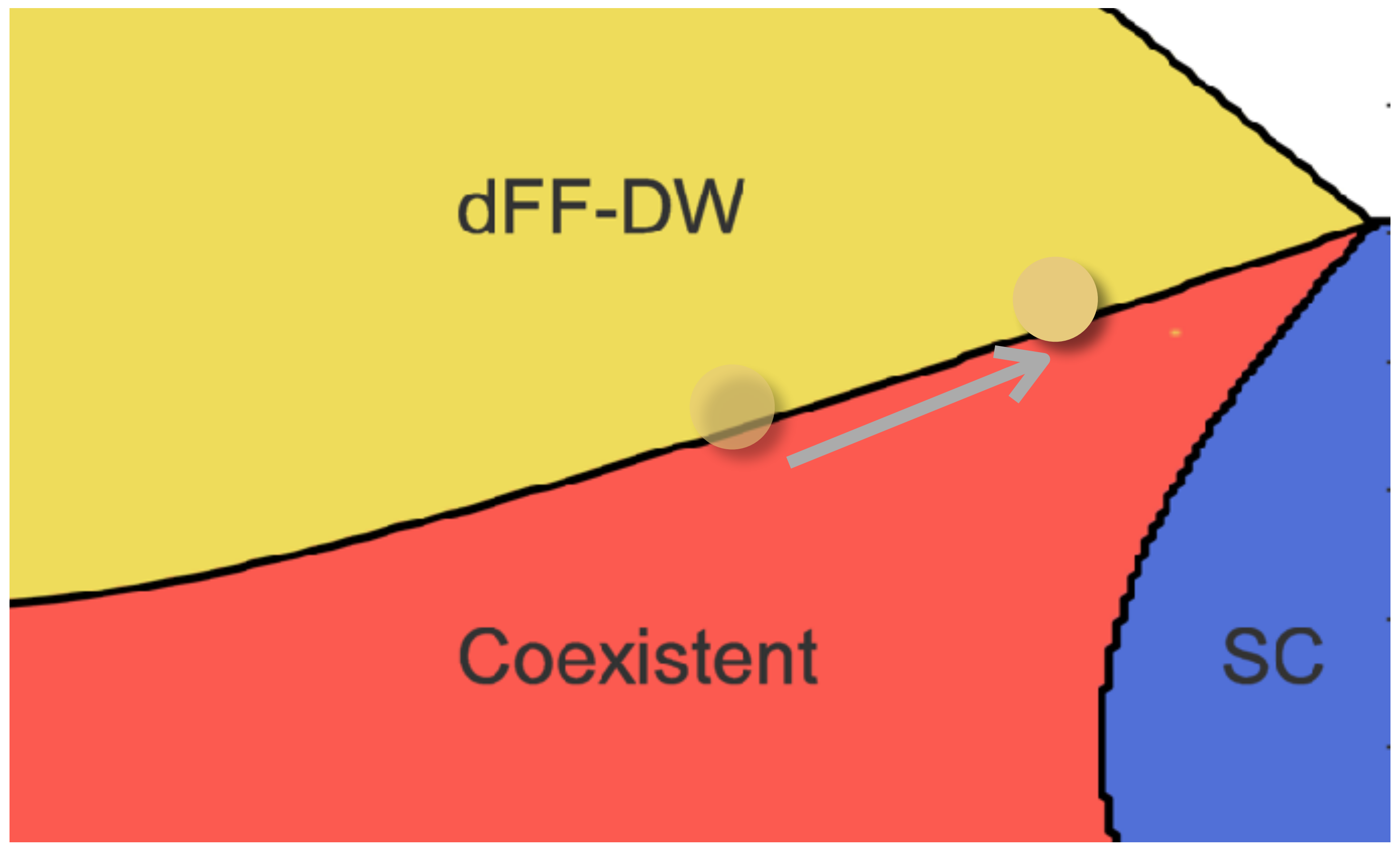


Summary

- The perturbation increases effective inter-plane coupling, t_z.
- The presence of phase pinning allows increasing t_z to melt charge order.
- Melting of charge order enhances superconductivity.







Light Pulse

Phase pinning + Interlayer Coupling ⬆

Charge order ⬇

SC ⬆

Thank You