# Hybridization of Higgs modes in a bond-density-wave state in cuprates

**Zachary Raines**
Valentin Stanev
Victor Galitski

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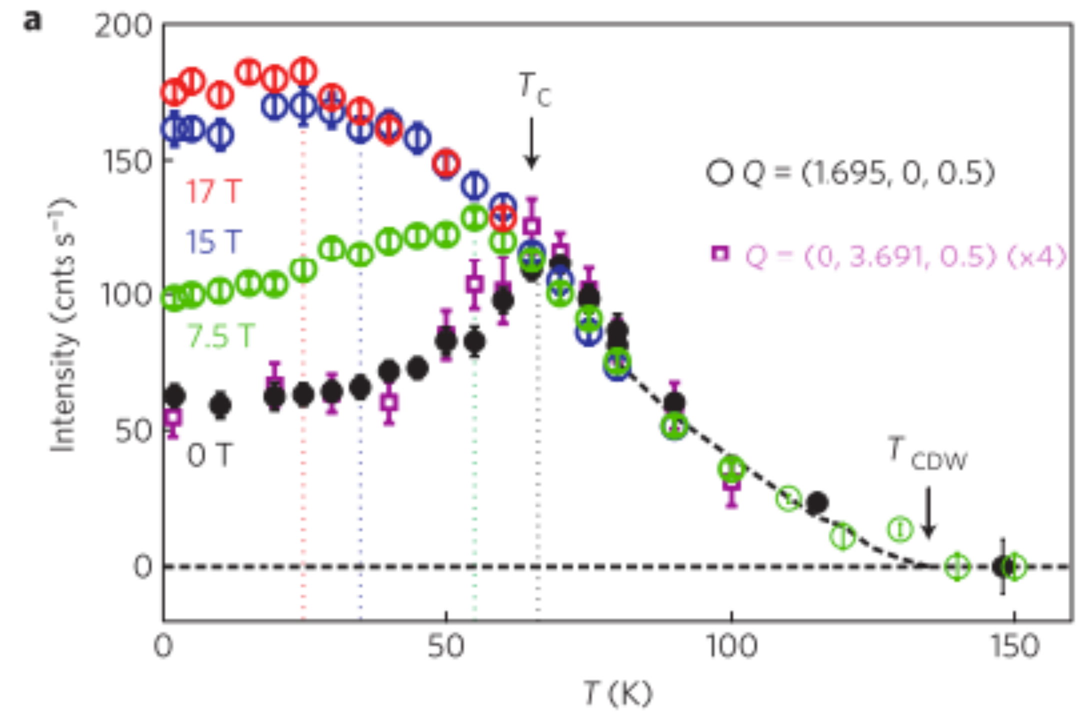
# Outline

- Competing charge order and superconductivity in cuprates - *A quick survey*
- Observation of collective modes via time-resolved reflectivity - *Background and motivation*
- Hybridization of Higgs modes - *Model and Results*
- Summary

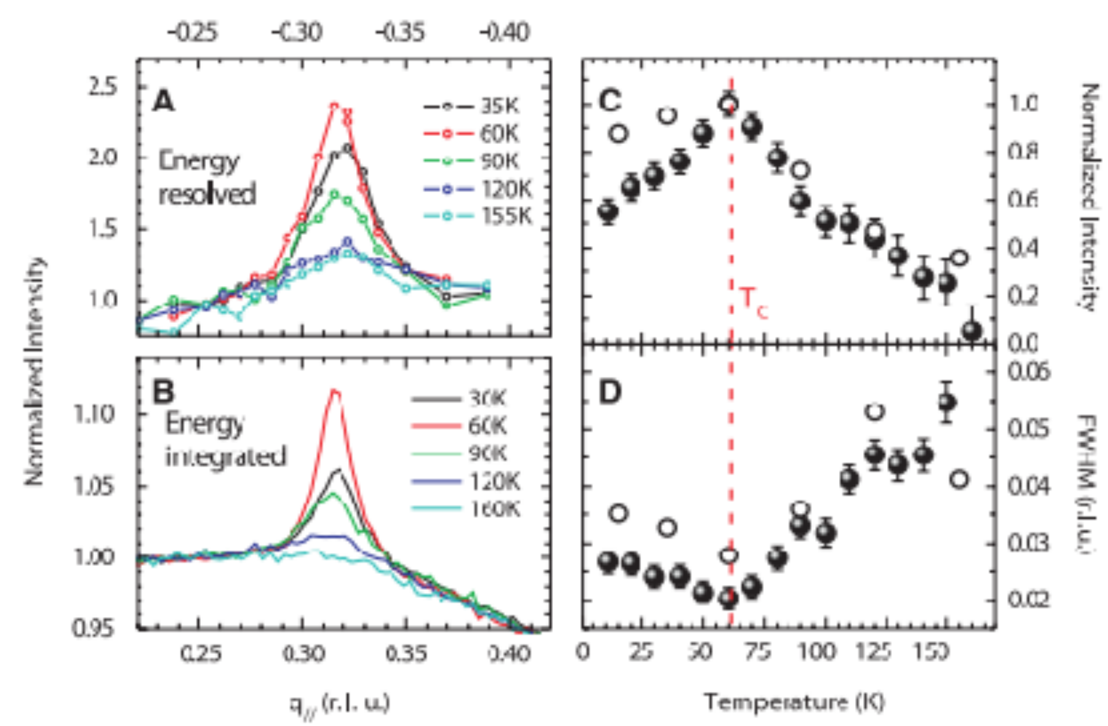
# Competition of superconductivity and charge order

Charge order is experimentally seen to compete with superconductivity in several cuprate families:

- Charge order suppressed below $T_C$
- Charge order restored when SC is destroyed by magnetic field



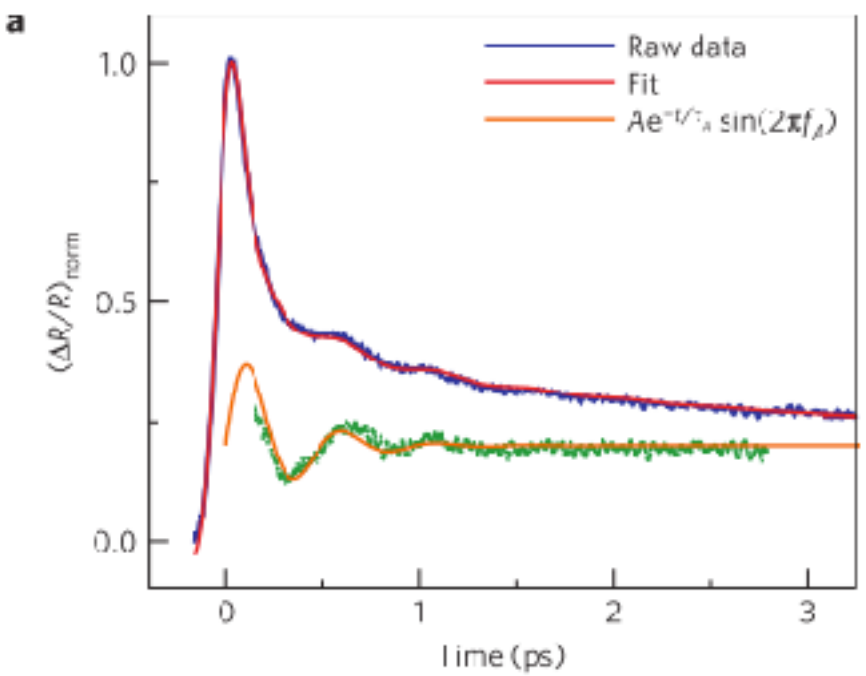

*J. Chang et al., Nat. Phys. 8, 871 (2012).*



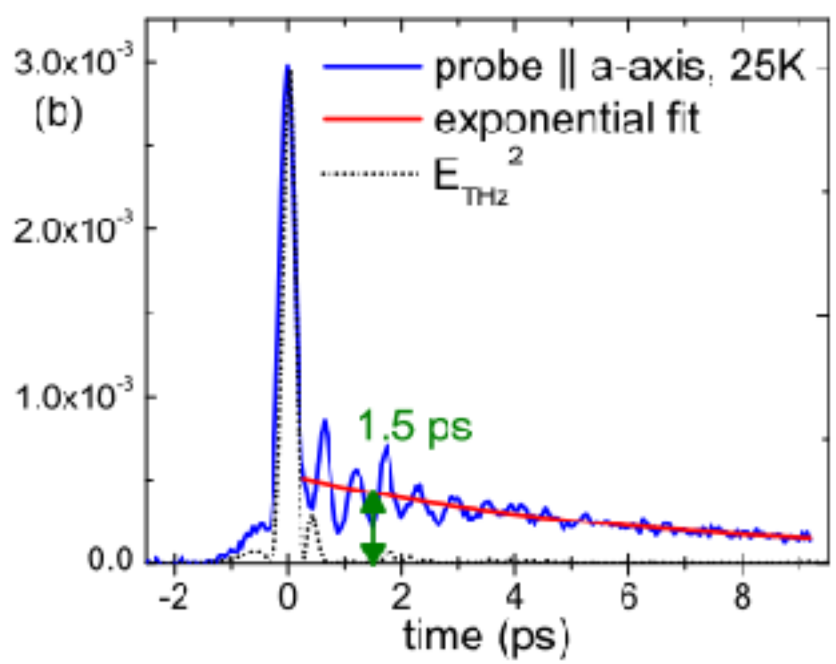

*G. Ghiringhelli,et al., Science 337, 821 (2012).*

# Observation of collective modes via time-resolved reflectivity

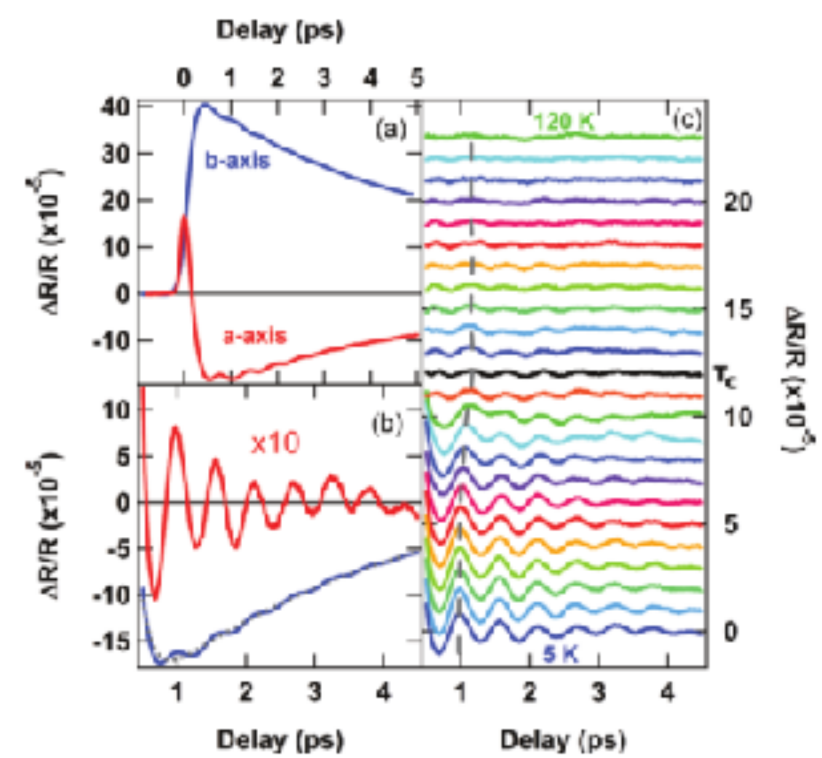
- Time domain reflectivity has been employed to study the collective modes of cuprates
- Multiple groups have observed signals associated with the collective modes of the charge order present in cuprates




*D.H. Torchinsky et al., Nat. Mater. 12, 387 (2013).*




*G.L. Dakovski, et al., Phys. Rev. B 91, 220506 (2015).*



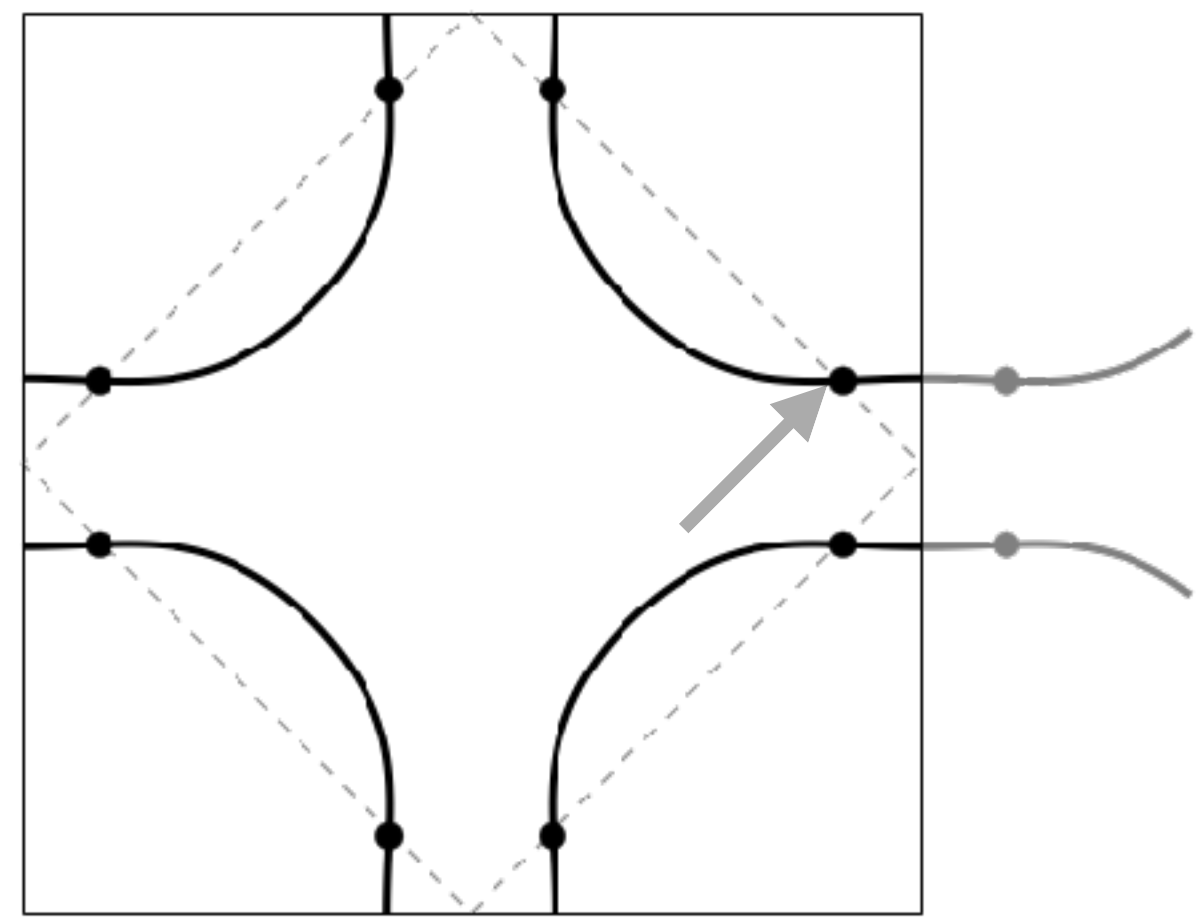

*J.P. Hinton, et al., Phys. Rev. B 88, 60508 (2013).*

# A model of competing orders

*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)*

- We consider a **hotspot model** with interactions in the superconducting and bond-density-wave channels

- This can be obtained from a lattice model (e.g. t-J-V model)

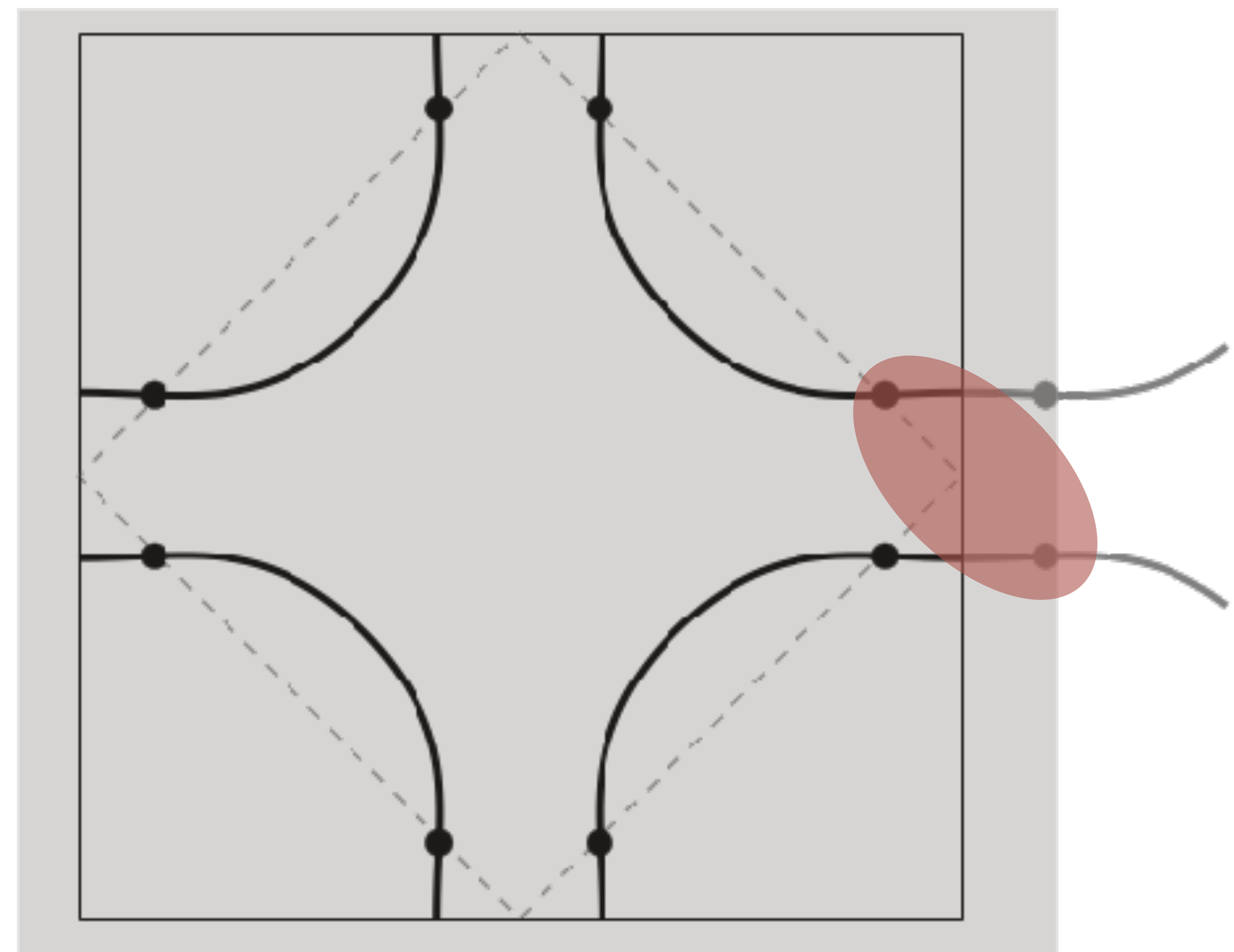


# Mean field phases

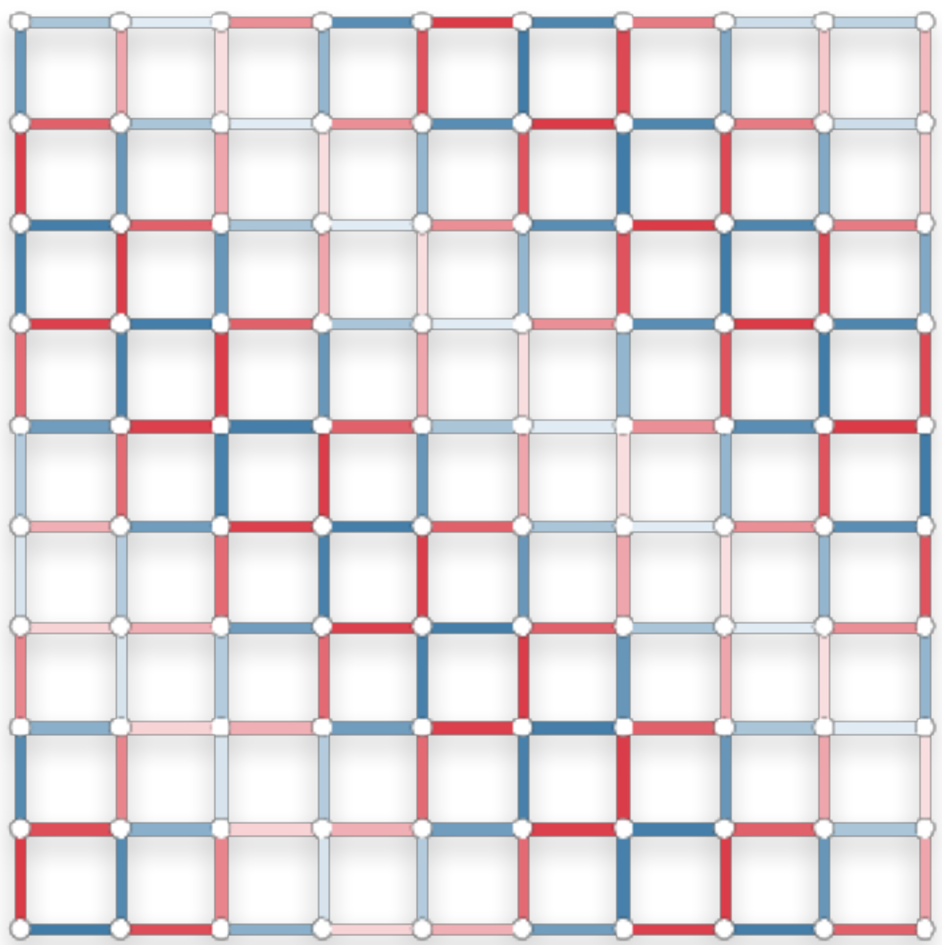
- The mean field theory contains **d-wave superconductivity** (SC) $\Delta$ and **d-form-factor density wave** (dFF-DW) $\phi$

- The symmetry of the orders allows us to restrict our attention to the vicinity of two hotspots

d-wave form factor +
time reversal symmetry



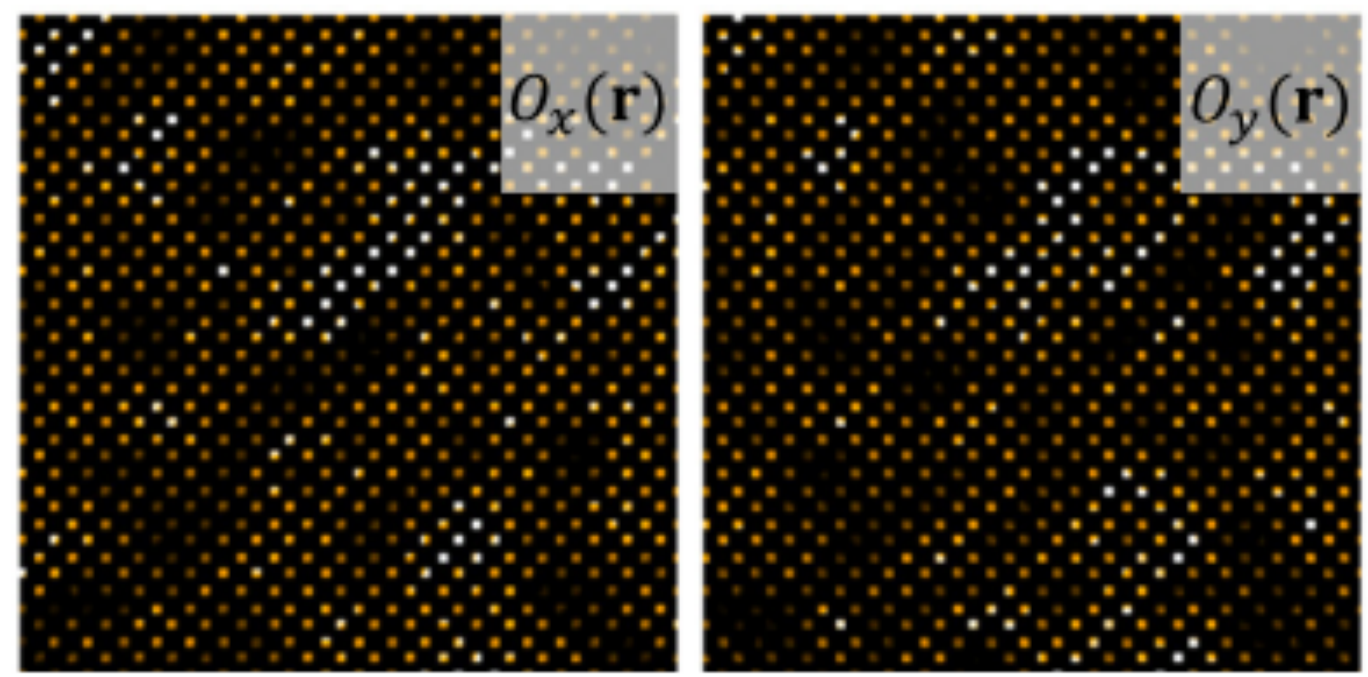
# d-form-factor density wave



Bond-density-wave

$$H_{\phi,\mathrm{MF}} = \sum_{ij} \phi_{ij} c^{\dagger}_{i\sigma} c_{j\sigma}$$

$$\phi_{ij} \sim \cos\left(\vec{Q}\cdot\frac{\vec{r}_i+\vec{r}_j}{2}\right)(\mathrm{NNx}_{ij} - \mathrm{NNy}_{ij})$$




*K. Fujita et al., Proc. Natl. Acad. Sci. 111, E3026 (2014).*

*J. D. Sau and S. Sachdev, Phys. Rev. B 89, 075129 (2014).*

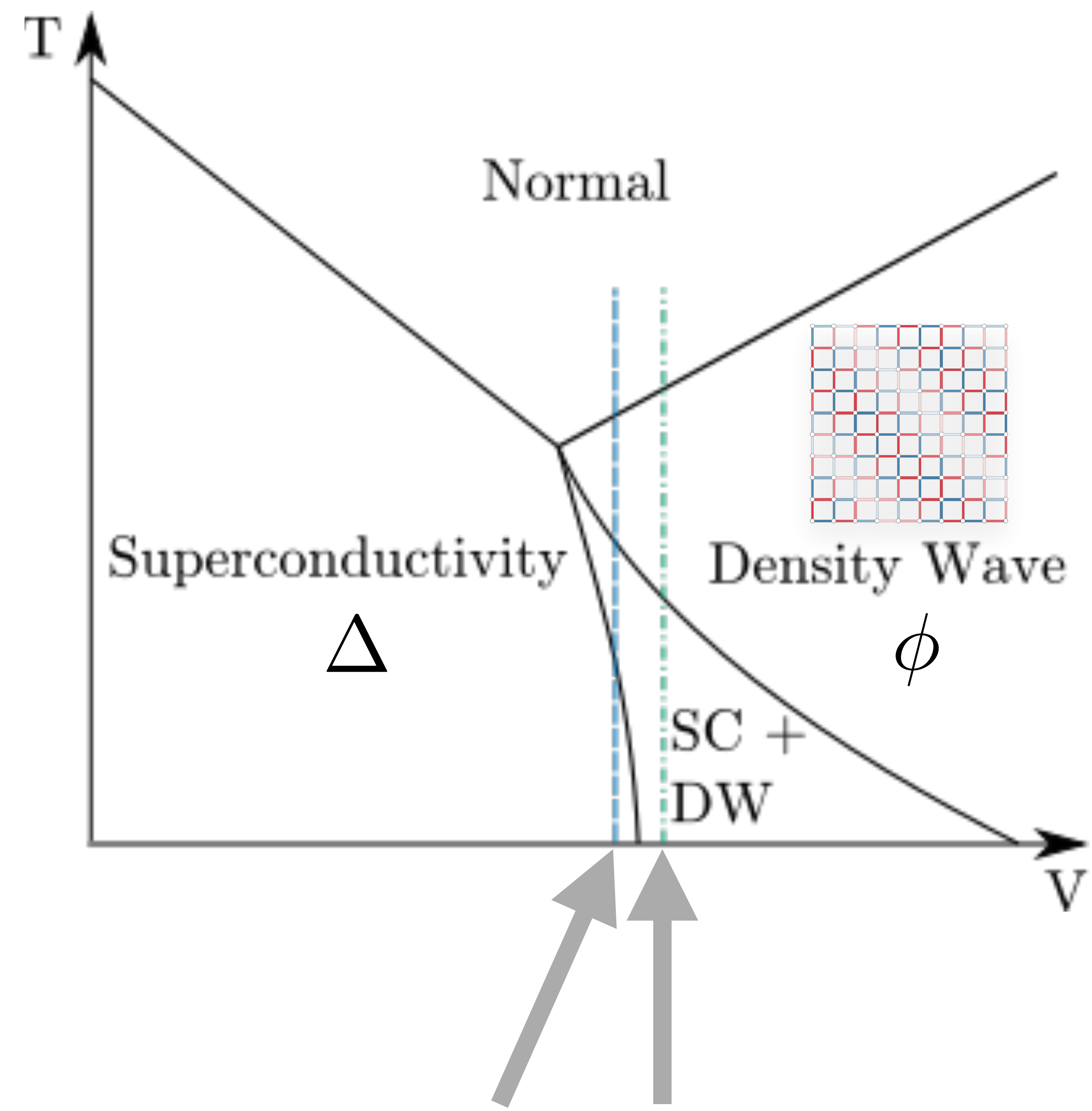
*K.B. Efetov et al., Nat. Phys. 9, 442 (2013).*

*Y. Wang and A. V Chubukov, Phys. Rev. B 90, 035149 (2014).*

# The problem considered

- We consider four phases: *normal*, *density wave*, *superconductivity*, and **coexistent**

- We wish to study the evolution of collective modes with temperature as we enter the coexistent phase

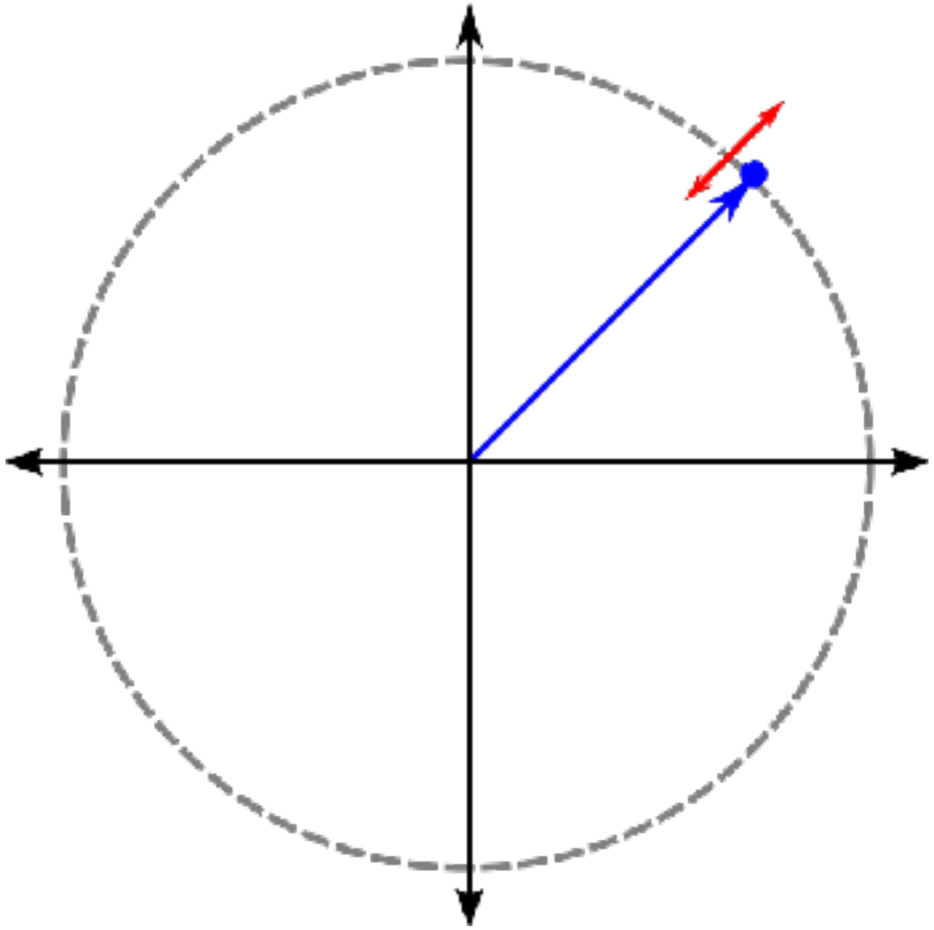


# Collective modes: Higgs Modes

- Fluctuations of the order parameters can occur on top of the mean field state
- Here we consider the amplitude modes of the superconducting and density wave order parameters

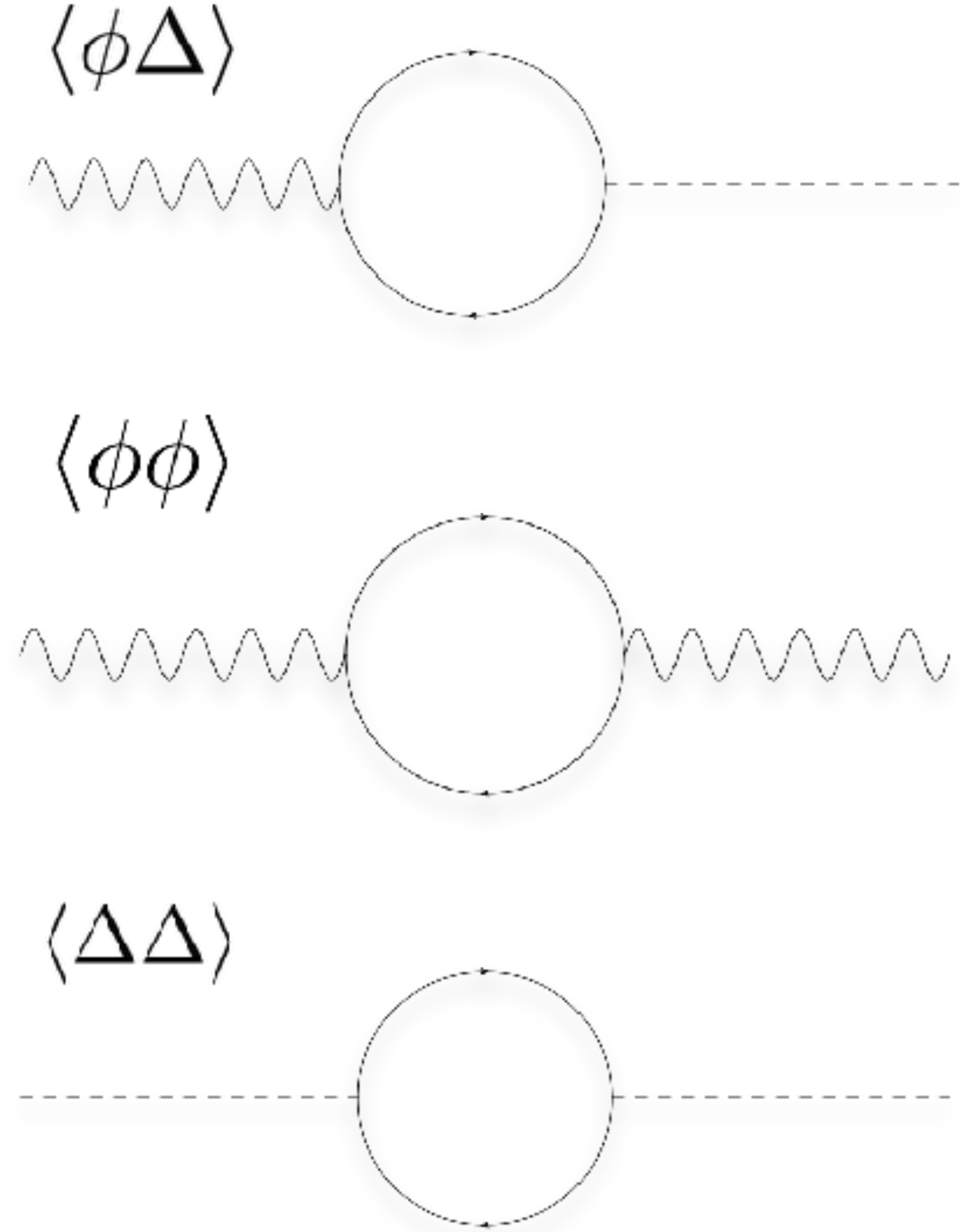
$$\Delta_0 + \Delta(\omega, \mathbf{q})$$

$$\phi_0 + \phi(\omega, \mathbf{q})$$



# Hybridization of Higgs (amplitude) modes

- Collective modes are related to response functions of order parameters
- Disturbing one order parameter can cause fluctuations in another



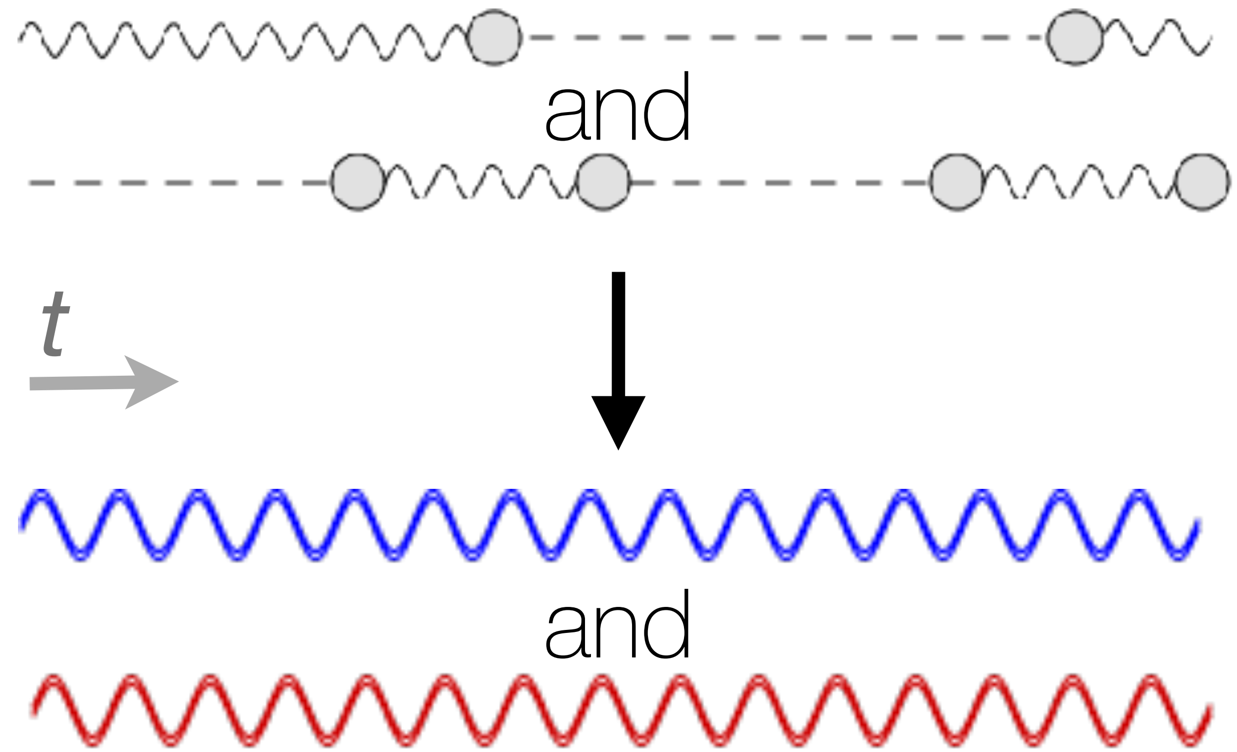

*ZMR, V. Stanev, V. Galitski, doi:10.1103/PhysRevB.92.184511*

# Hybrid Higgs modes

- Because of the coupling between the two modes, we look at the **eigenmodes** of the amplitude response

- These eigenmodes have a sharp frequency response corresponding to the dispersion of the collective modes

    - As a bonus, these modes are *more visible experimentally* due to their mixed nature




$$\langle O_i(q) O_j(-q) \rangle = D_q^{(i)} \delta_{ij}$$ Eigenmodes

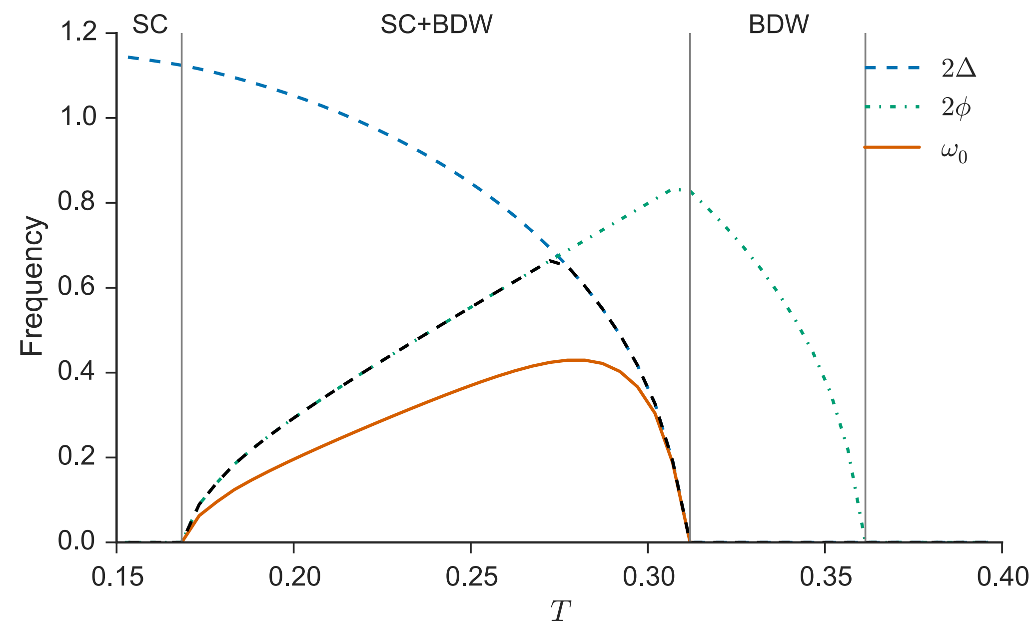
$$\left( D_i^R(\omega_i(\mathbf{q}), \mathbf{q}) \right)^{-1} = 0$$ Mode dispersion

*ZMR, V. Stanev, V. Galitski, doi:10.1103/PhysRevB.92.184511*

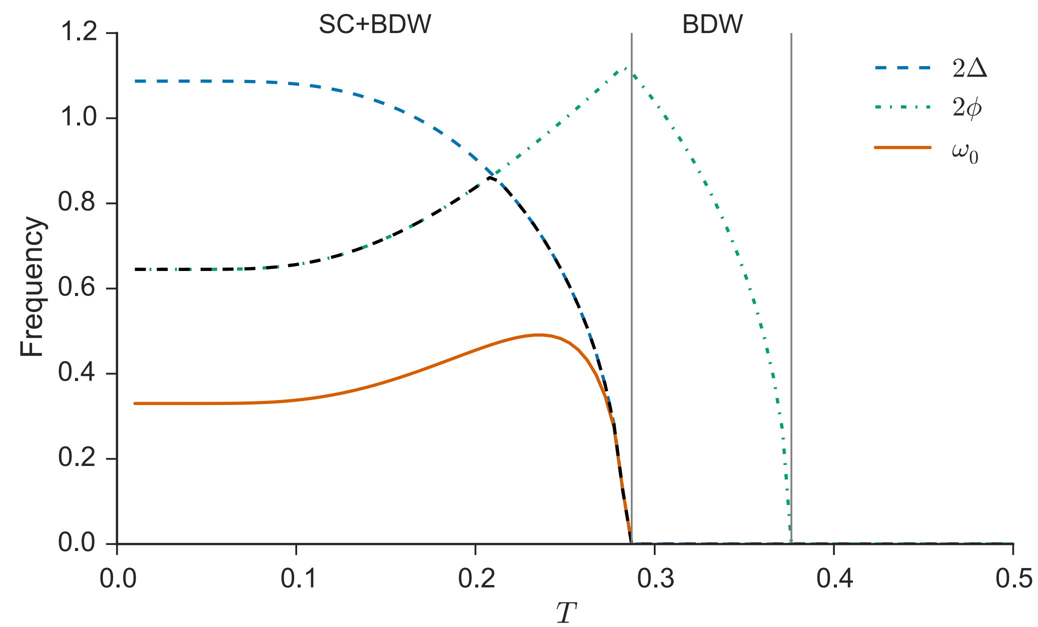
# Higgs mass

- The **mass** of the Higgs mode is the energy gap for creating a collective excitation

- We focus here on modes with frequencies at or below the pair creation energy
  - These should be protected from decaying to particle-hole pairs

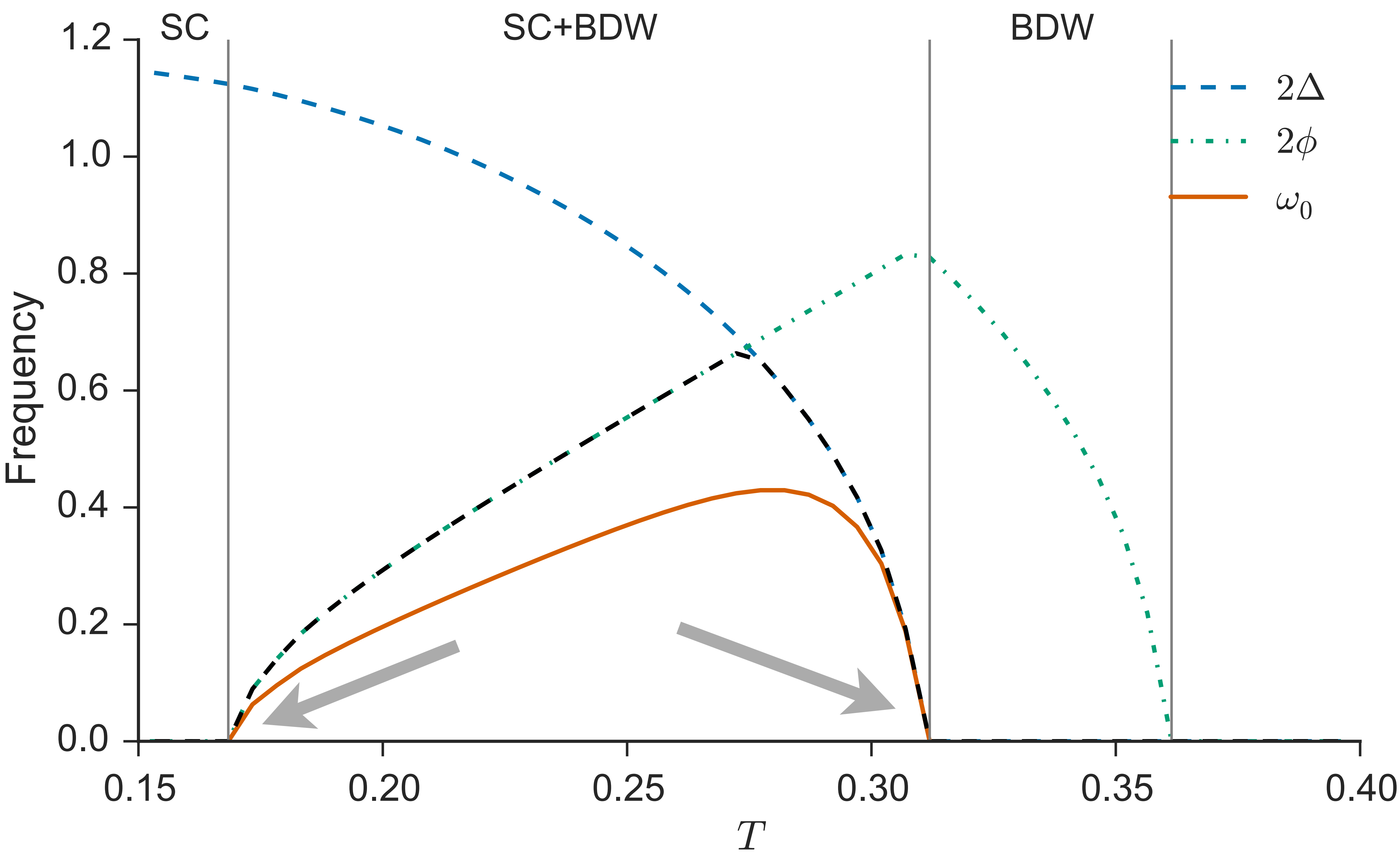



$$\omega_0 \equiv \mathrm{Re}\left[\omega(\mathbf{q} \to 0)\right]$$



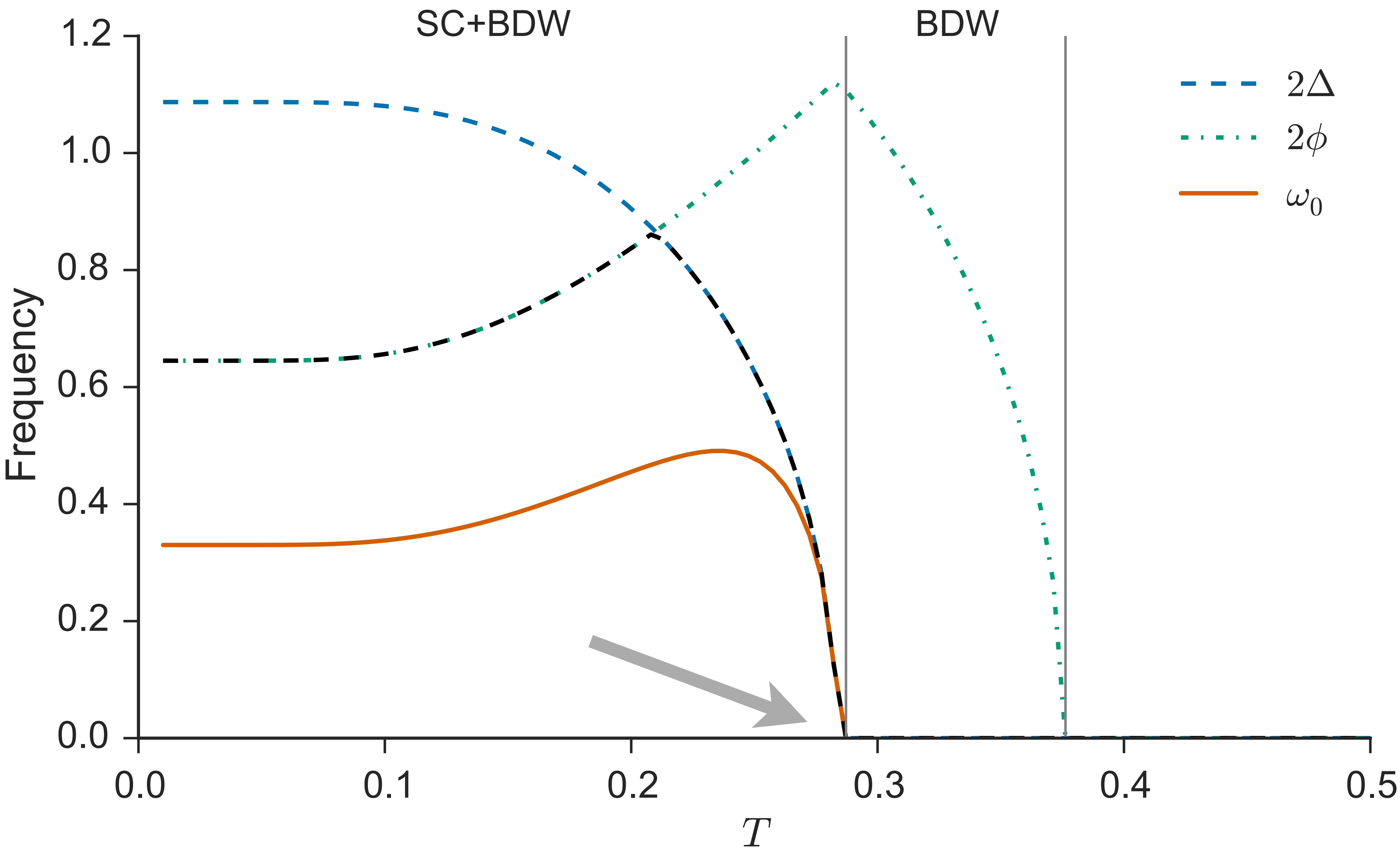

*ZMR, V. Stanev, V. Galitski, doi:10.1103/PhysRevB.92.184511*

# Higgs mass




*ZMR, V. Stanev, V. Galitski, doi:10.1103/PhysRevB.92.184511*

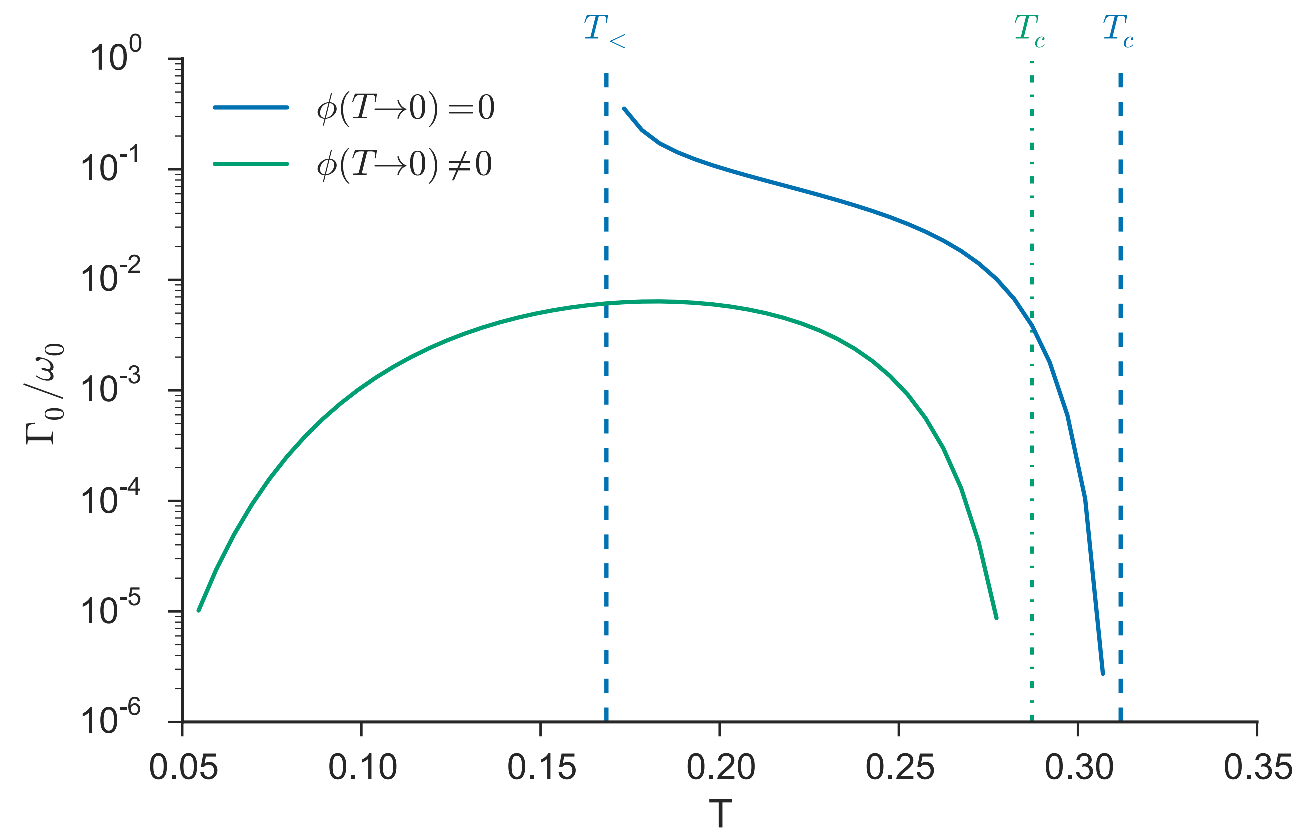
# Higgs mass



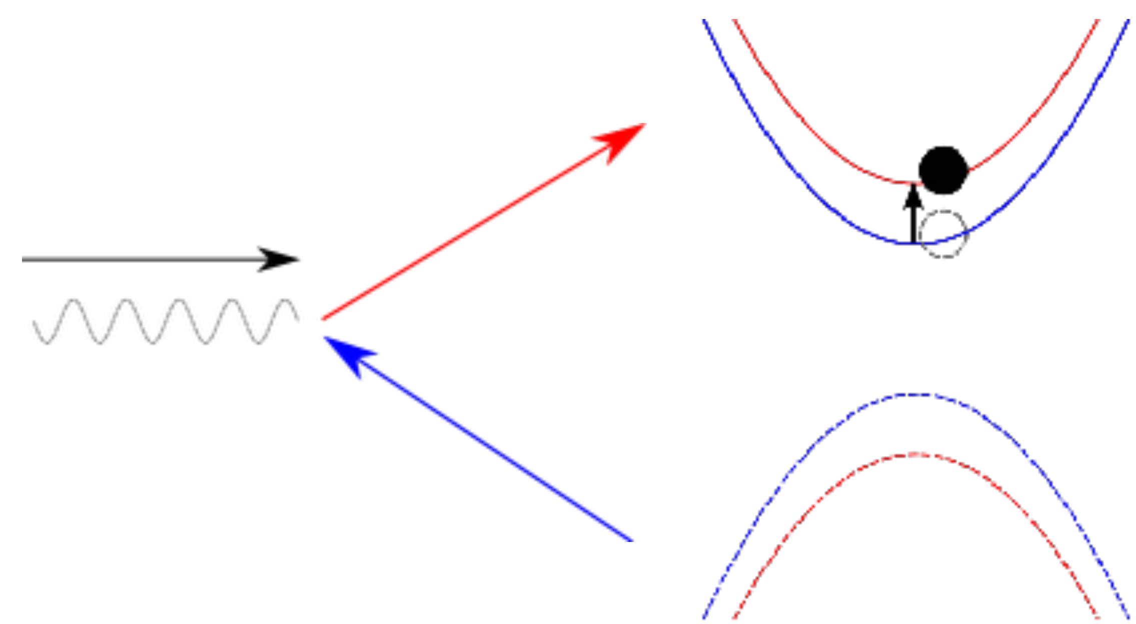

*ZMR, V. Stanev, V. Galitski, doi:10.1103/PhysRevB.92.184511*

# Damping of collective modes

- The in-gap mode is still damped.
    - Damping is due to scattering of thermally excited quasiparticles
- Notably the strength of damping initially increases inside the coexistent phase




$$\Gamma_0 \equiv -\mathrm{Im}\left[\omega(\mathbf{q} \to 0)\right]$$



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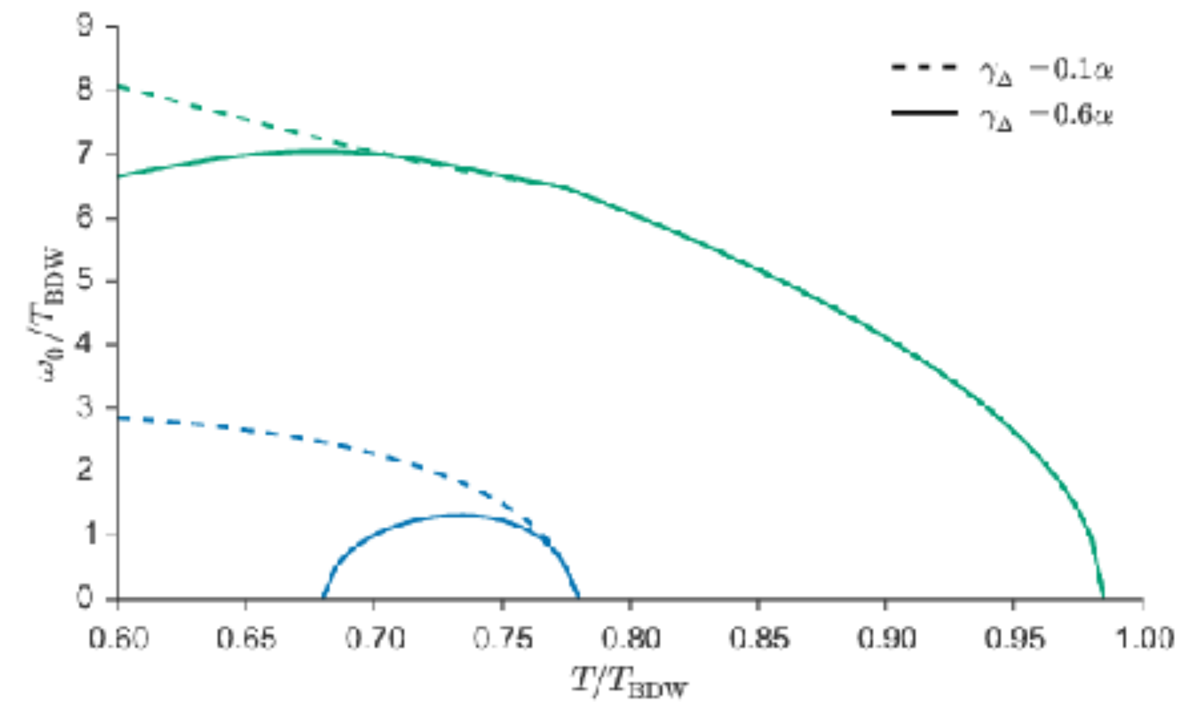
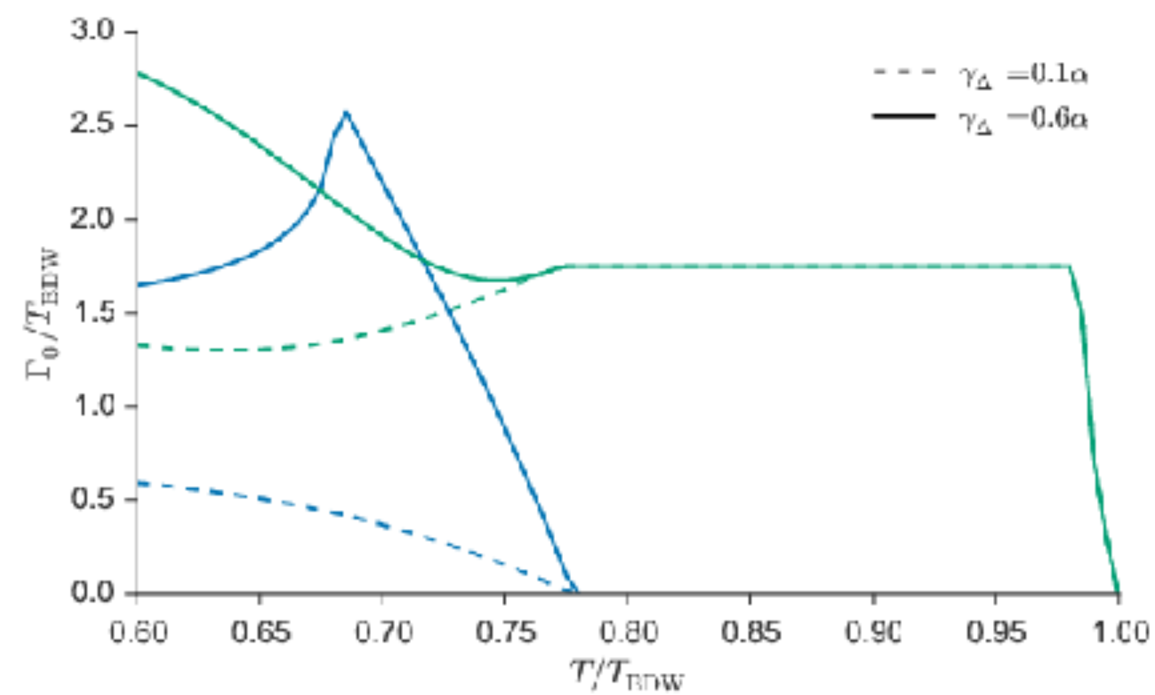
# Effect of damping from the nodal regions

- To consider the effect of nodal pair-production we employed a time-dependent Ginzburg-Landau treatment

- Large enough damping can restrict the in-gap hybrid mode to a small vicinity of $T_c$

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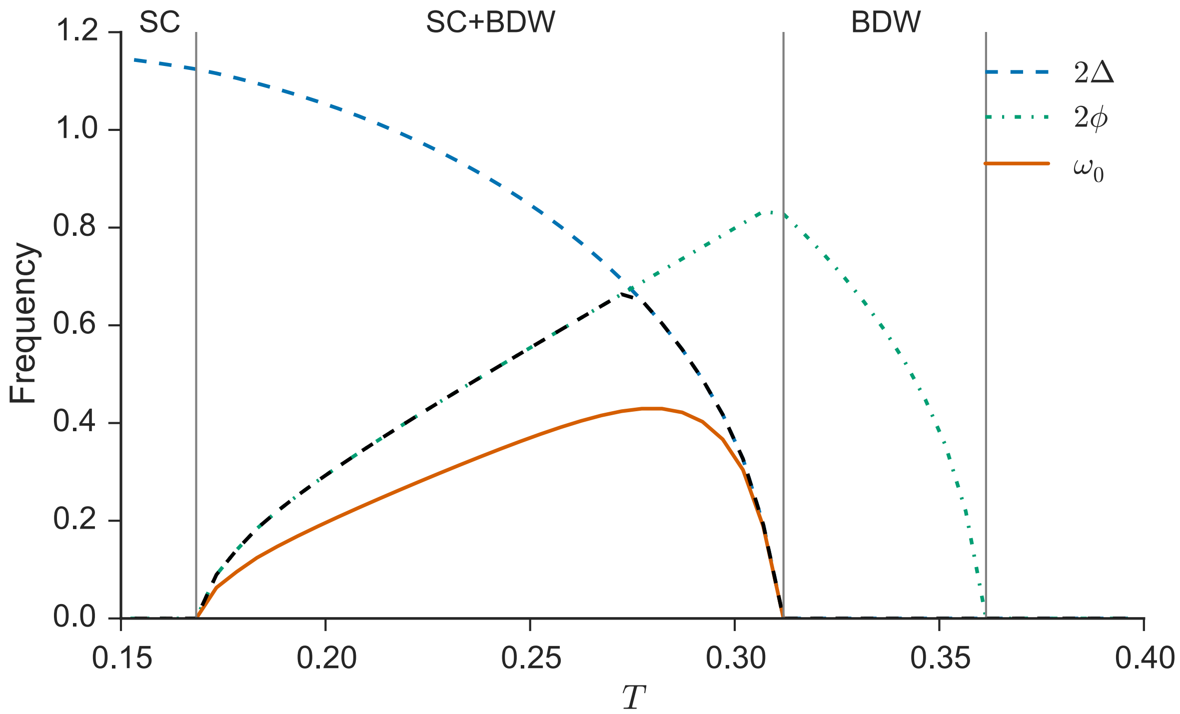
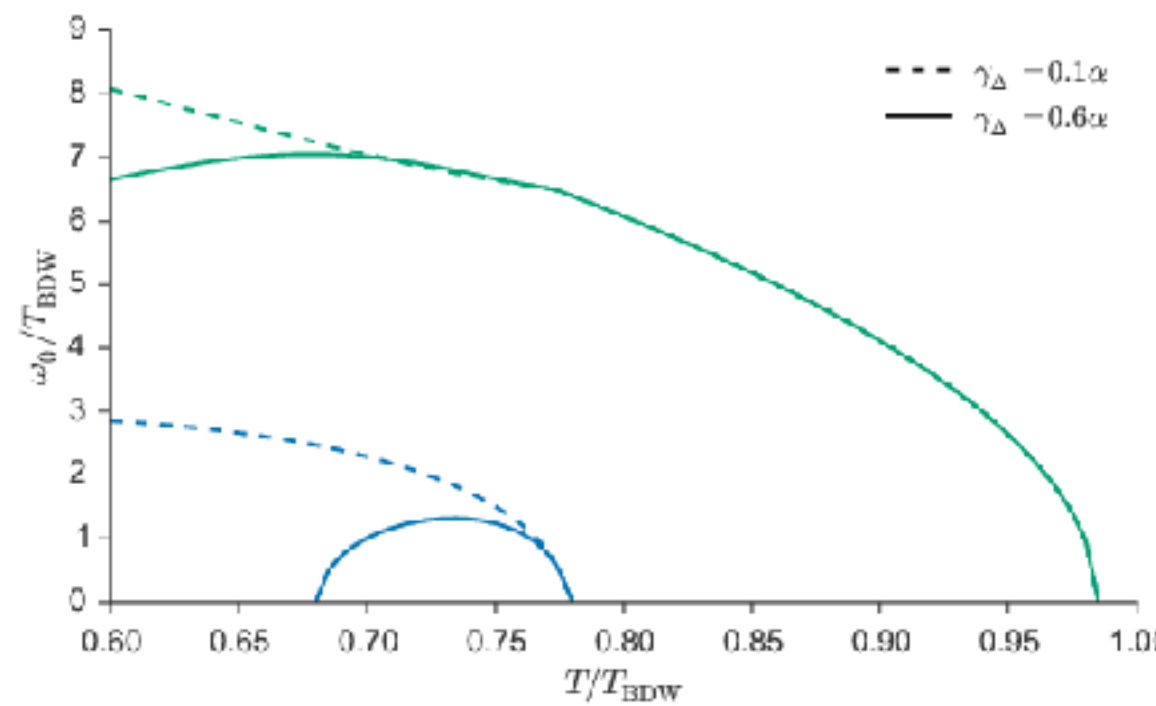
# Summary

- We studied the **mixed amplitude modes** of *SC* and *dFF-DW* in a hotspot model and found
    - A slow mode inside the gap, which is nonetheless weakly damped
    - A fast mode outside the gap
- For sufficiently strong nodal damping the slow mode is restricted to a small vicinity of Tc




**Thank you**

*ZMR, V. Stanev, V. Galitski, doi:10.1103/PhysRevB.92.184511*

# Extra Slides

# Hamiltonian and mean field theory

$$\check{H}_{\mathrm{MF}} = \check{H}_0 + \Delta \check{V}_\Delta + \phi \check{V}_\phi,$$
$$\check{H}_0 = \mathrm{diag}(\xi_1, \xi_2) \otimes \hat{\tau}_z,$$
$$\check{V}_\Delta = \hat{\rho}_0 \otimes \hat{\tau}_1, \quad \check{V}_\phi = \hat{\rho}_1 \otimes \hat{\tau}_3,$$

$$\Delta = \frac{g_s}{4} T \sum_k \mathrm{tr} \check{V}_\Delta \check{G}_k,$$
$$\phi = \frac{g_c}{4} T \sum_k \mathrm{tr} \check{V}_\phi \check{G}_k,$$

$$\mathcal{H}_{\mathrm{int}}^{\Delta} = \frac{g_s}{4} \sum_{k,p,q} \Psi_{k+q,a}^{\dagger} \check{V}_\Delta \Psi_{k,a} \Psi_{p-q,b}^{\dagger} \check{V}_\Delta \Psi_{p,b}$$

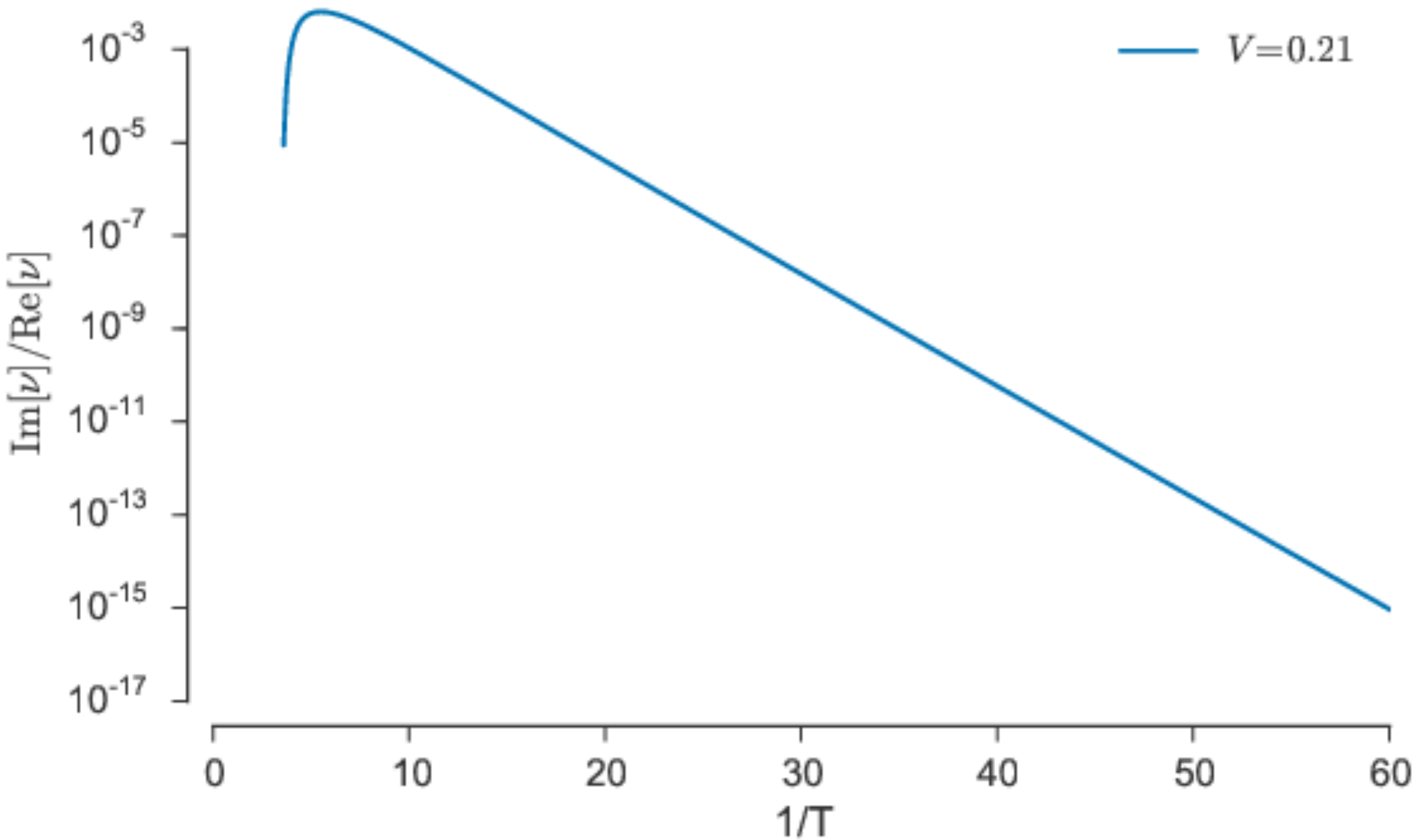
$$\mathcal{H}_{\mathrm{int}}^{\phi} = \frac{g_c}{4} \sum_{k,p,q} \Psi_{k+q,a}^{\dagger} \check{V}_\phi \Psi_{k,a} \Psi_{p-q,b}^{\dagger} \check{V}_\phi \Psi_{p,b}$$

# Time dependent Ginzburg-Landau

$$-\frac{\partial^2 \Delta}{\partial t^2} - \gamma_\Delta \frac{\partial \Delta}{\partial t} = \frac{\partial \mathcal{F}_{GL}}{\partial \Delta^*},$$
$$-\frac{\partial^2 \phi}{\partial t^2} - \gamma_\phi \frac{\partial \phi}{\partial t} = \frac{\partial \mathcal{F}_{GL}}{\partial \phi^*},$$

$$\mathcal{F}_{GL} = \alpha_\phi |\phi|^2 + \alpha_\Delta |\Delta|^2 + \beta_\phi |\phi|^4 + \beta_\Delta |\Delta|^4 + u|\phi|^2 |\Delta|^2.$$

# Exponential suppression of damping for T→0



*J. D. Sau and S. Sachdev, Phys. Rev. B 89, 075129 (2014).*

# Mean-field theory

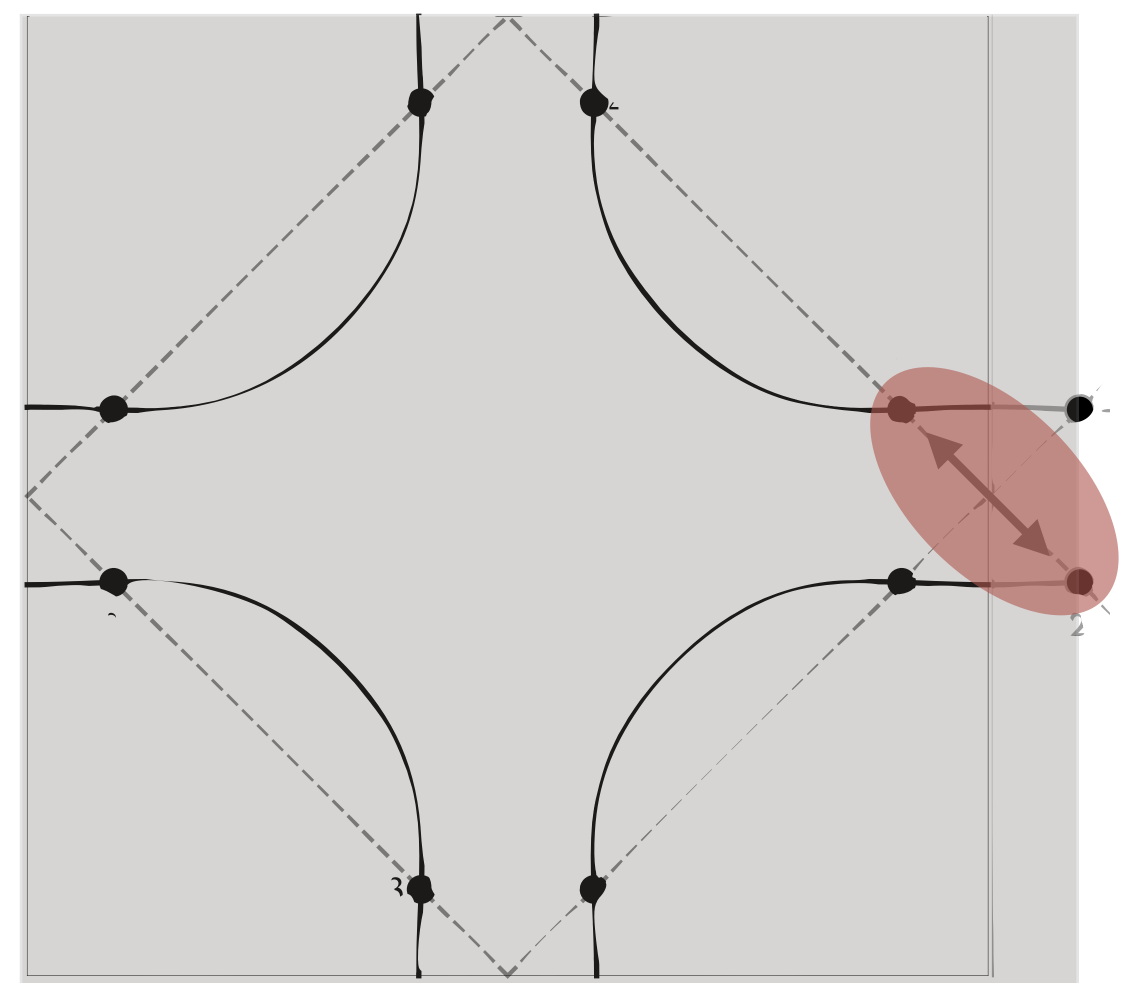
Particle — Hole

$$H_{MF} = \begin{bmatrix} \xi_1(k) & \bar{\phi} & 0 & \Delta \\ \phi & \xi_2(k) & \Delta & 0 \\ 0 & \bar{\Delta} & -\xi_1(-k) & -\bar{\phi} \\ \bar{\Delta} & 0 & -\phi & -\xi_2(-k) \end{bmatrix}$$

1

2

d-wave form factor +
time reversal symmetry

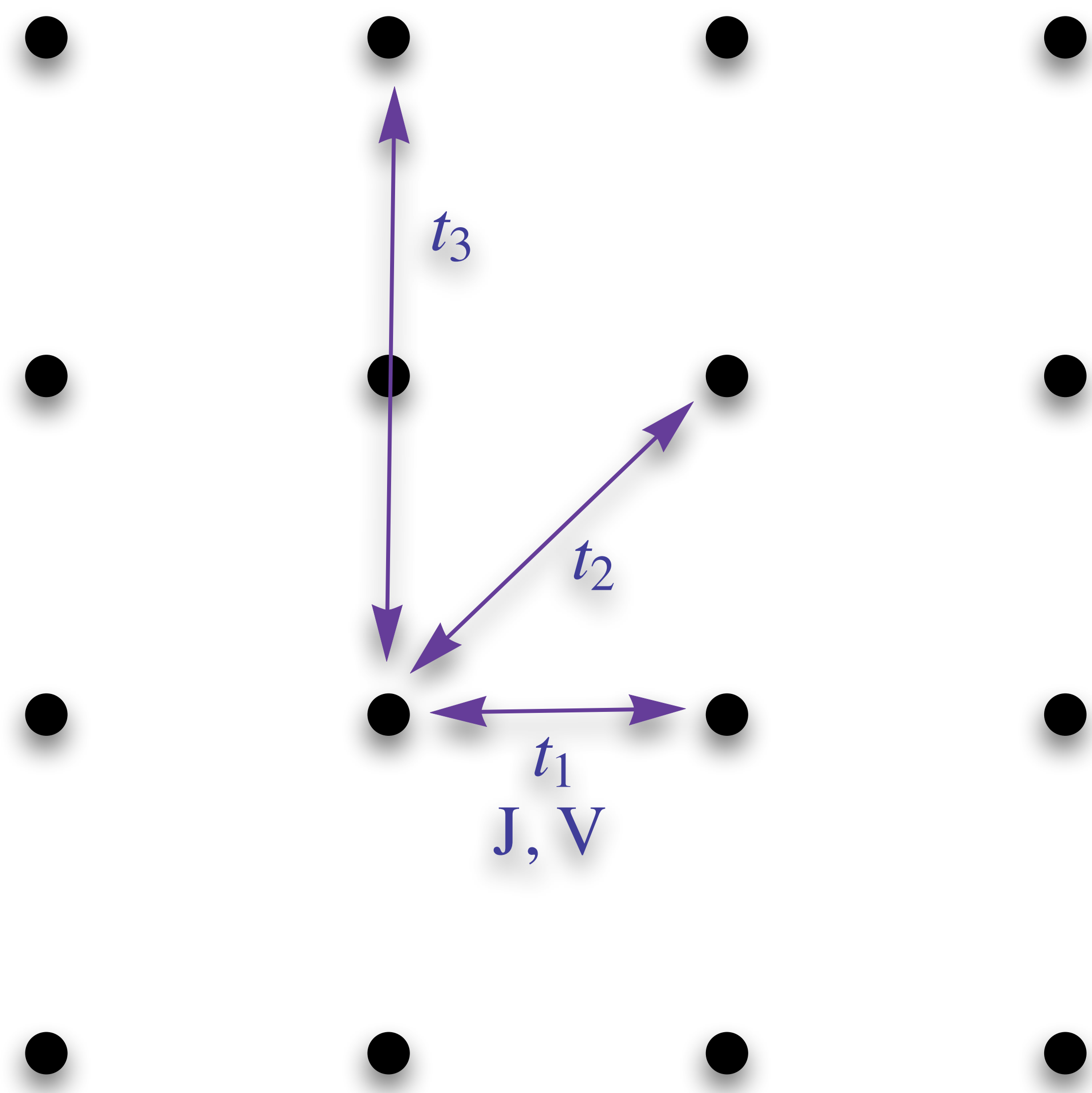


- Projecting onto channels of interest
- Restrict to vicinity of where Fermi surface intersects Magnetic Brillouin zone

# A model of CuO planes

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

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




*e.g. J. D. Sau and S. Sachdev, Phys. Rev. B 89, 075129 (2014).*