

# A theory of the underdoped cuprates



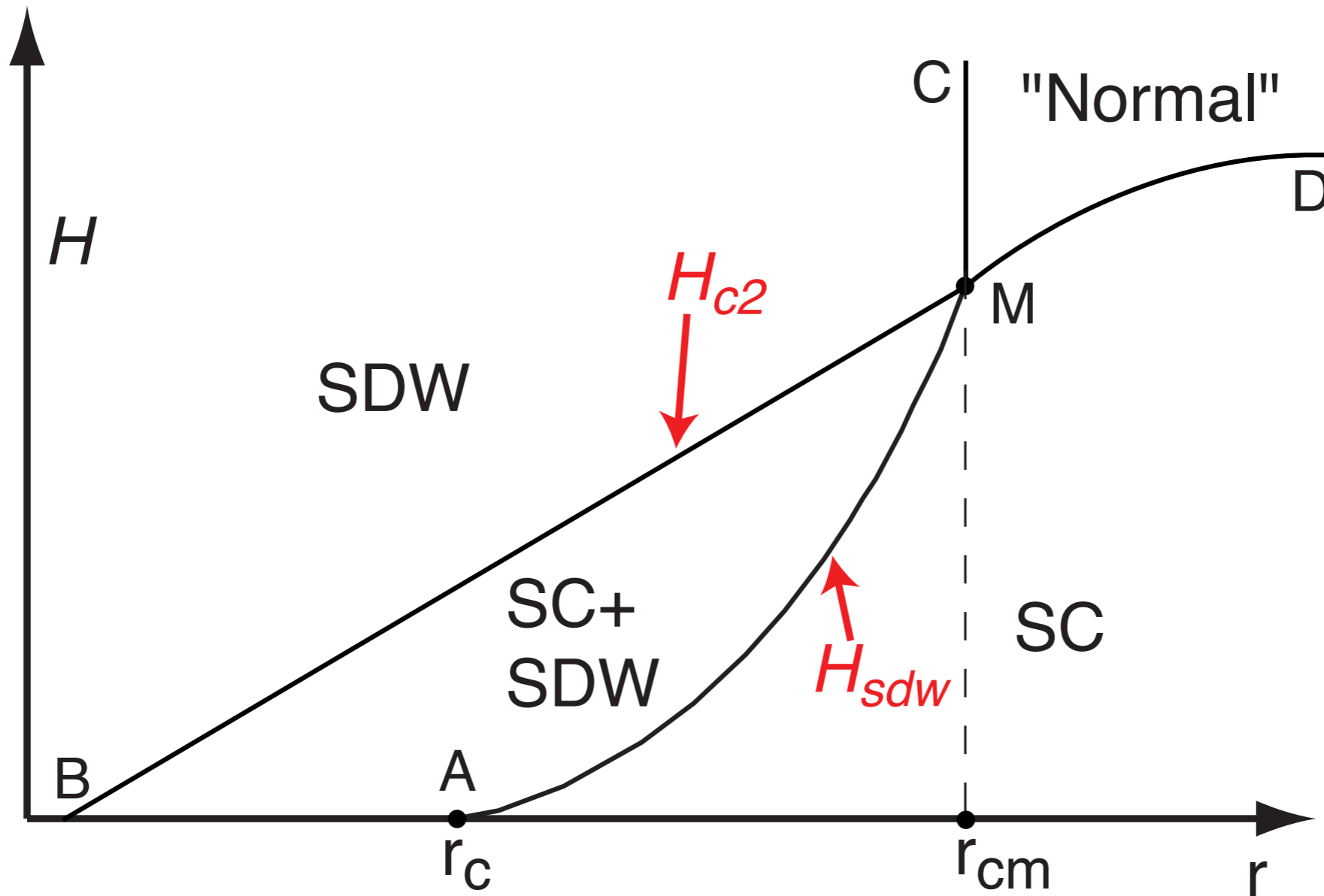
Destruction of Neel order in the cuprates by electron doping, R. K. Kaul, M. Metlitski, S. Sachdev, and C. Xu, *Physical Review B* **78**, 045110 (2008).

Paired electron pockets in the underdoped cuprates, V. Galitski and S. Sachdev, *Physical Review B* **79**, 134512 (2009).

Competing orders in the underdoped cuprates, Eun Gook Moon and S. Sachdev, *to appear*

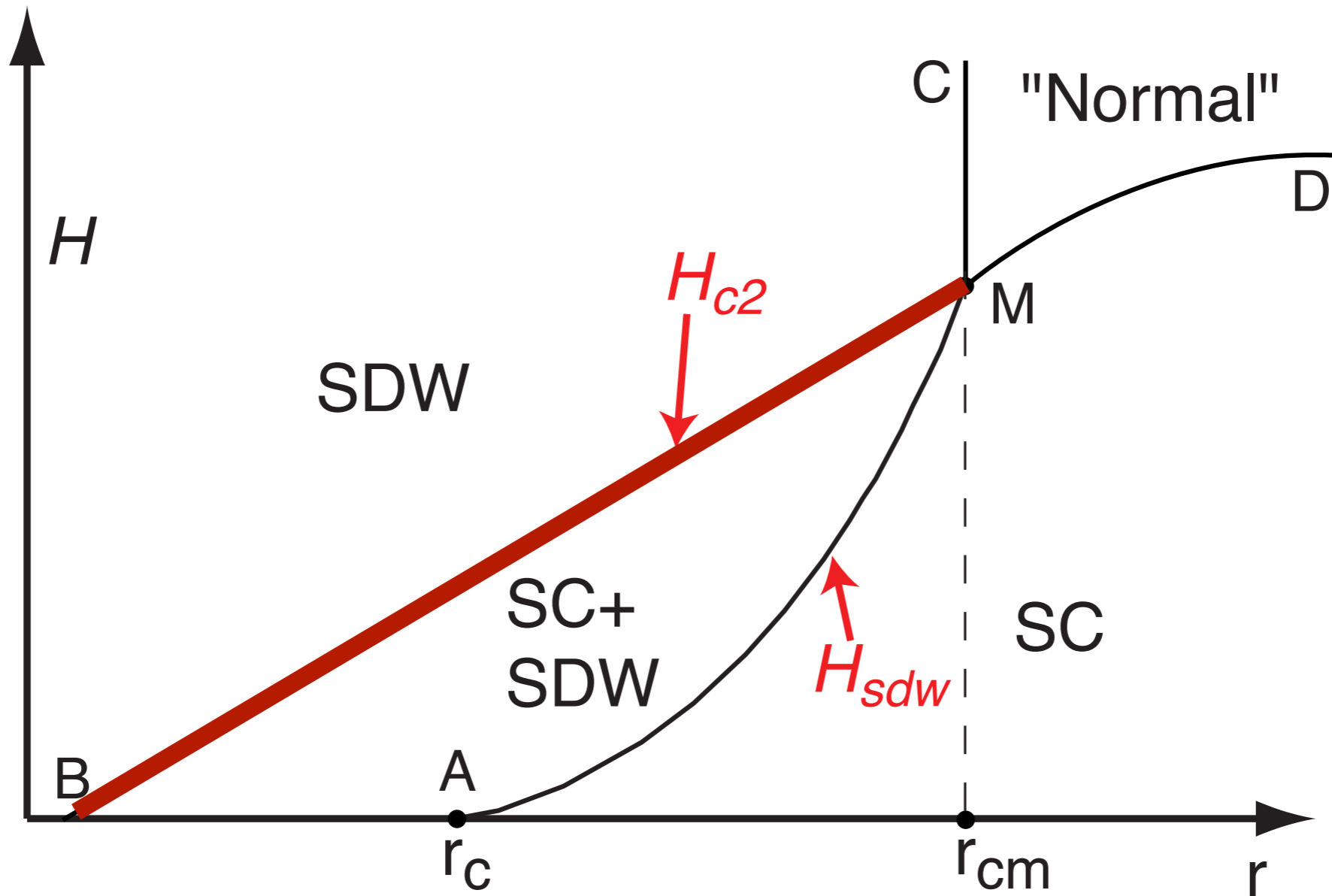
# Phenomenological quantum theory of competing orders

Competition between superconductivity (SC) and spin-density wave (SDW) order



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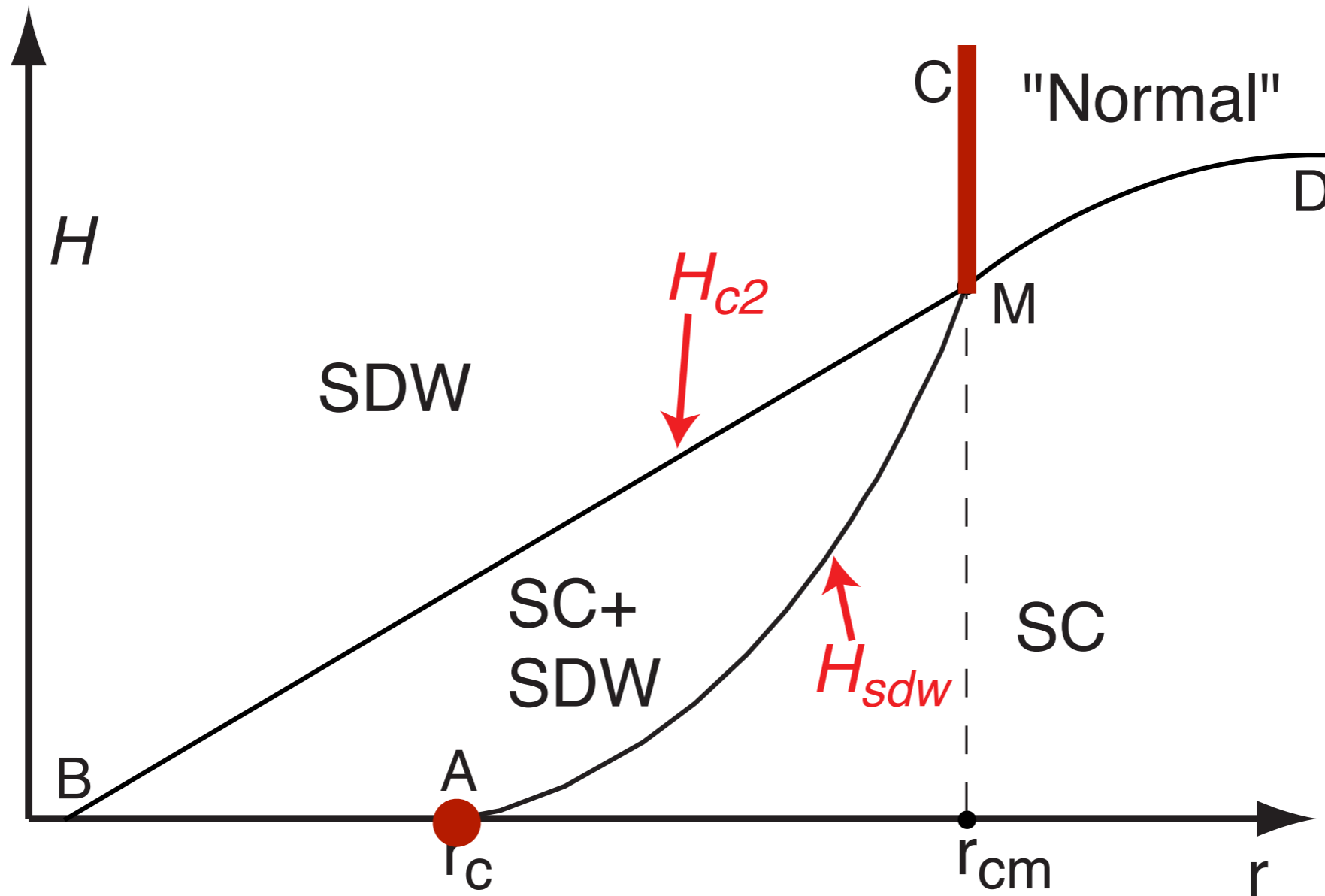
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- Upper-critical field,  $H_{c2}$ , decreases as SDW is enhanced with decreasing doping ( $r$ )

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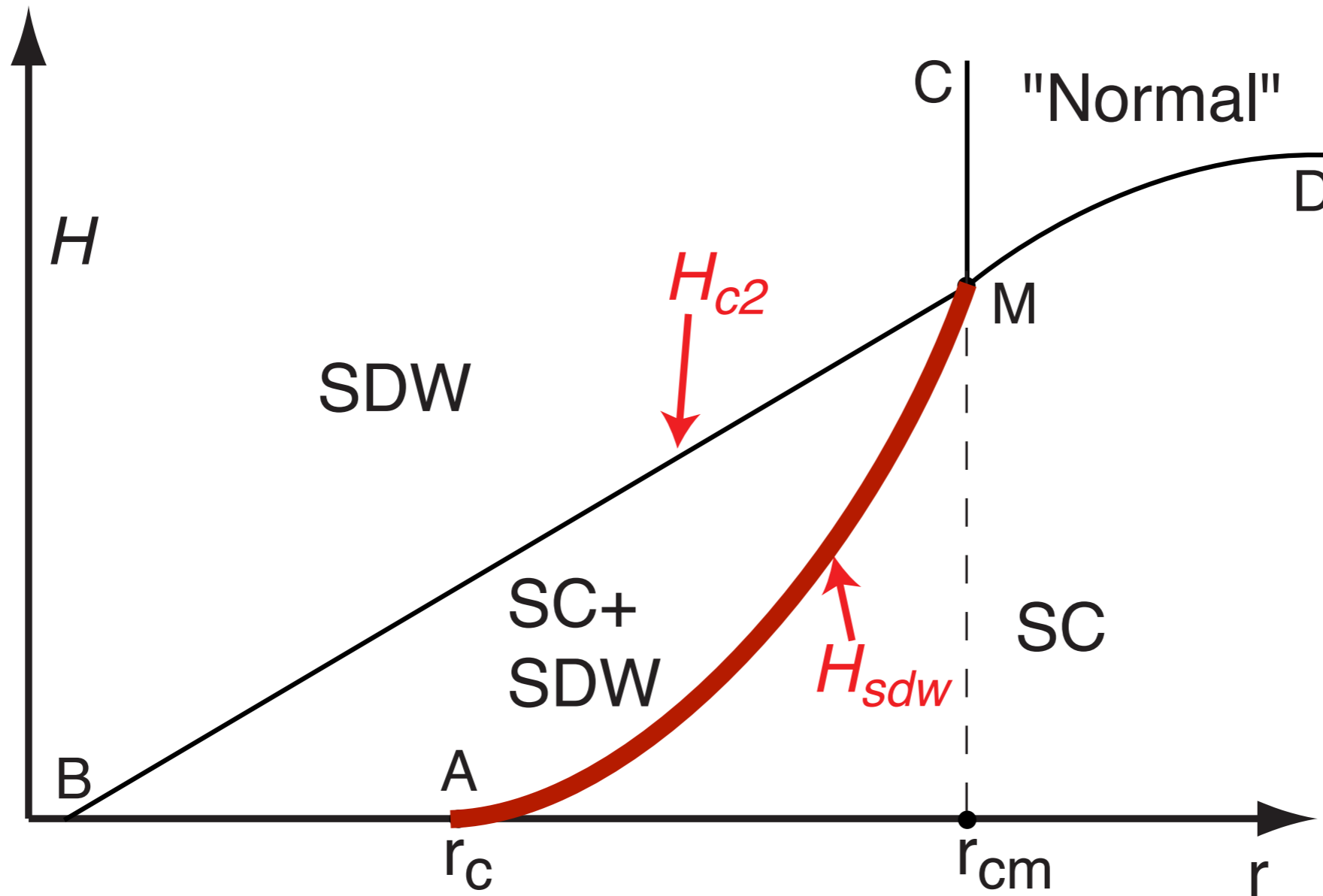
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- SDW order is more stable in the metal than in the superconductor:  $r_{cm} > r_c$ .

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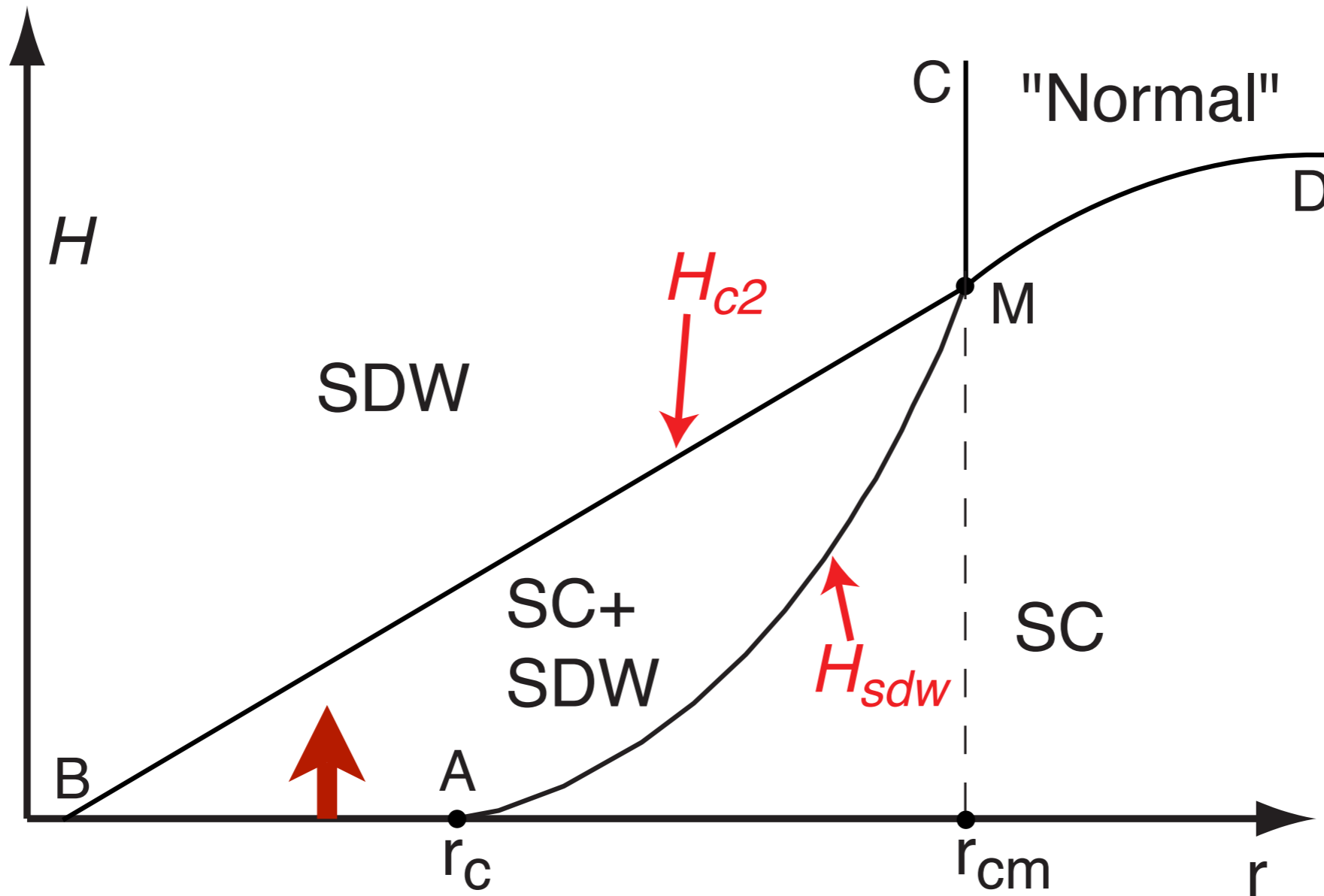
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- For doping with  $r_c < r < r_{cm}$ , SDW order appears at a quantum phase transition at  $H = H_{sdw} > 0$ .

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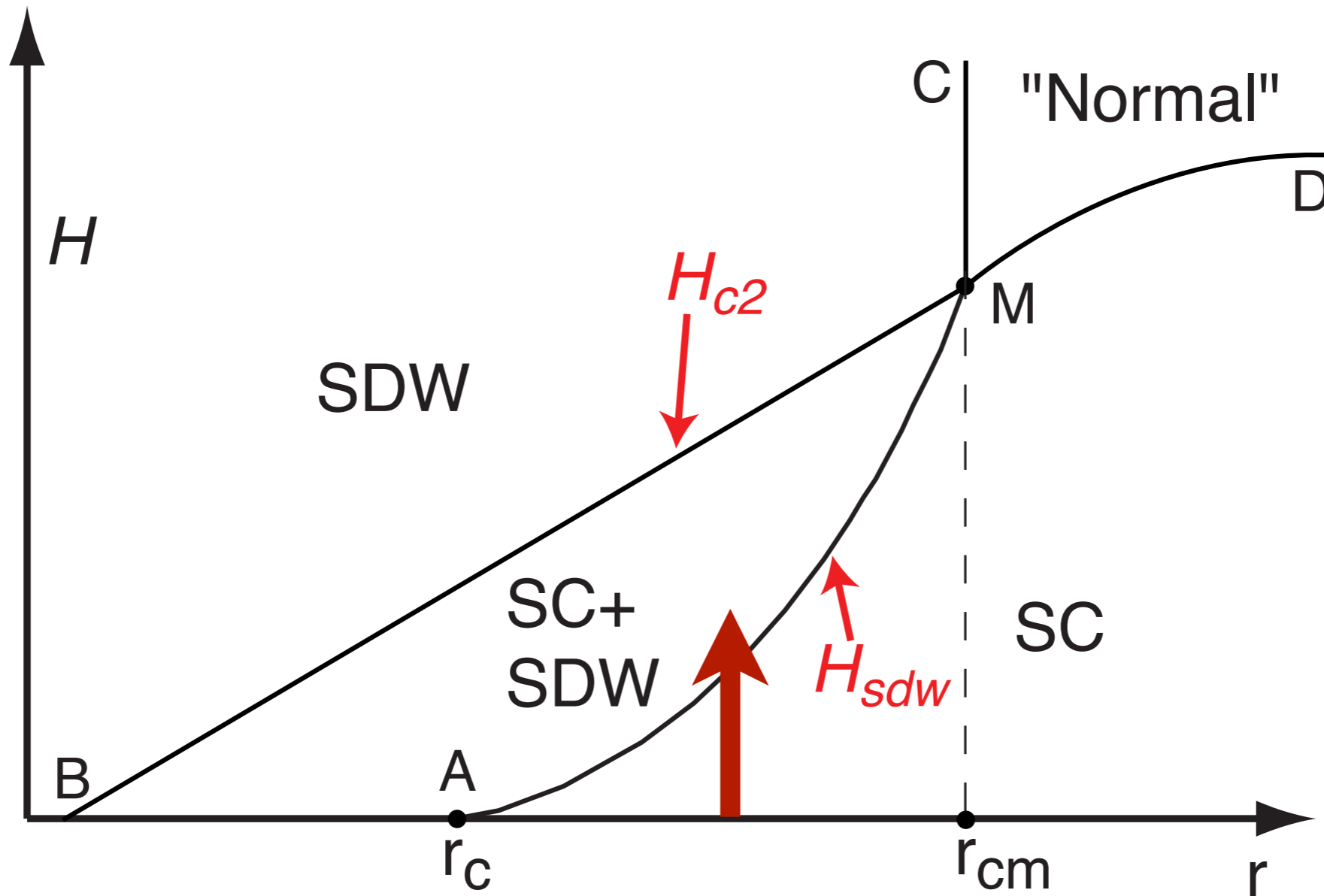


Neutron scattering on  $\text{La}_{1.9}\text{Sr}_{0.1}\text{CuO}_4$   
B. Lake *et al.*, *Nature* **415**, 299 (2002)

E. Demler, S. Sachdev and Y. Zhang, *Phys. Rev. Lett.* **87**, 067202 (2001).

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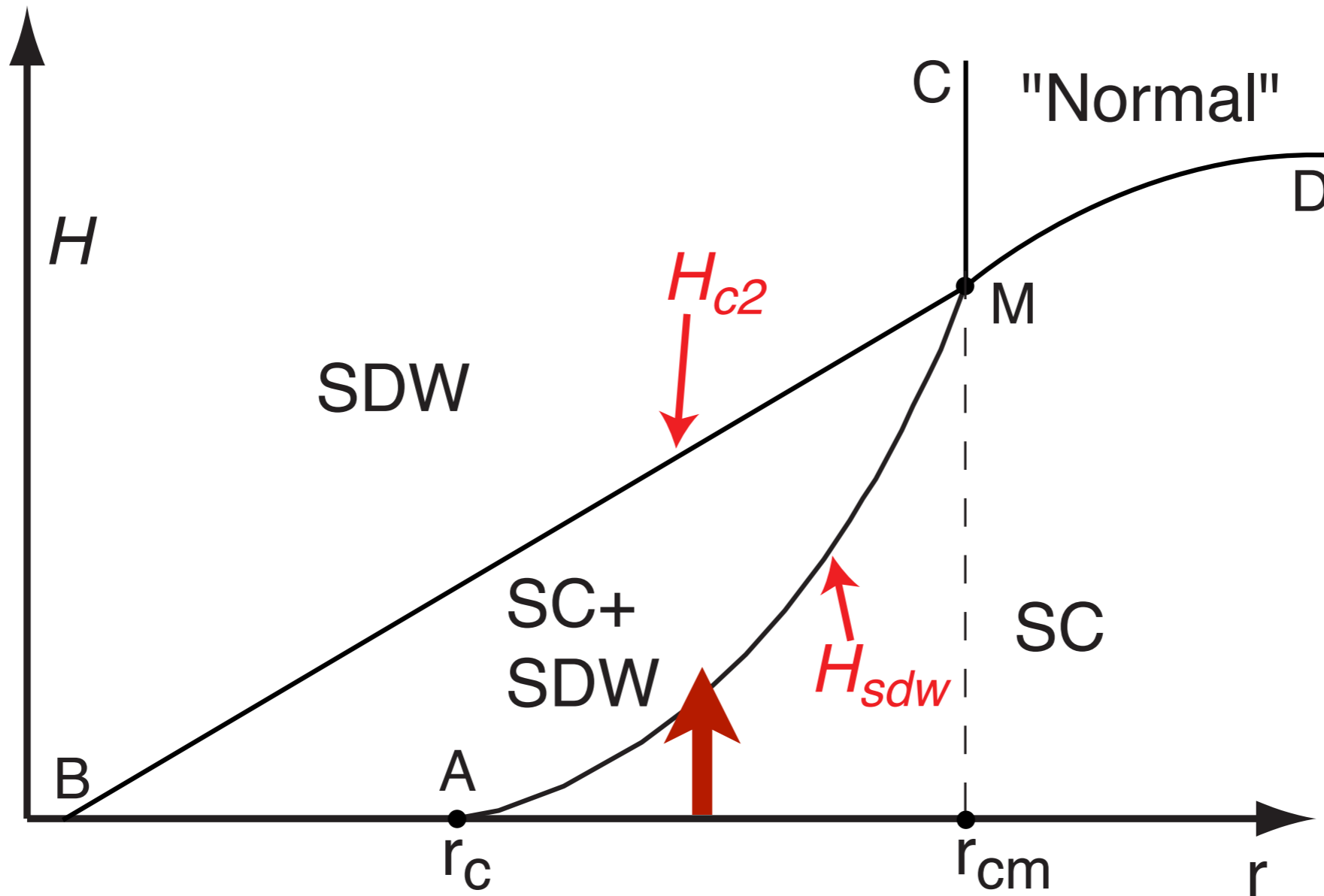
Competition between superconductivity (SC) and spin-density wave (SDW) order



Neutron scattering on  $\text{La}_{1.855}\text{Sr}_{0.145}\text{CuO}_4$   
J. Chang *et al.*, arXiv:0902.1191

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Competition between superconductivity (SC) and spin-density wave (SDW) order

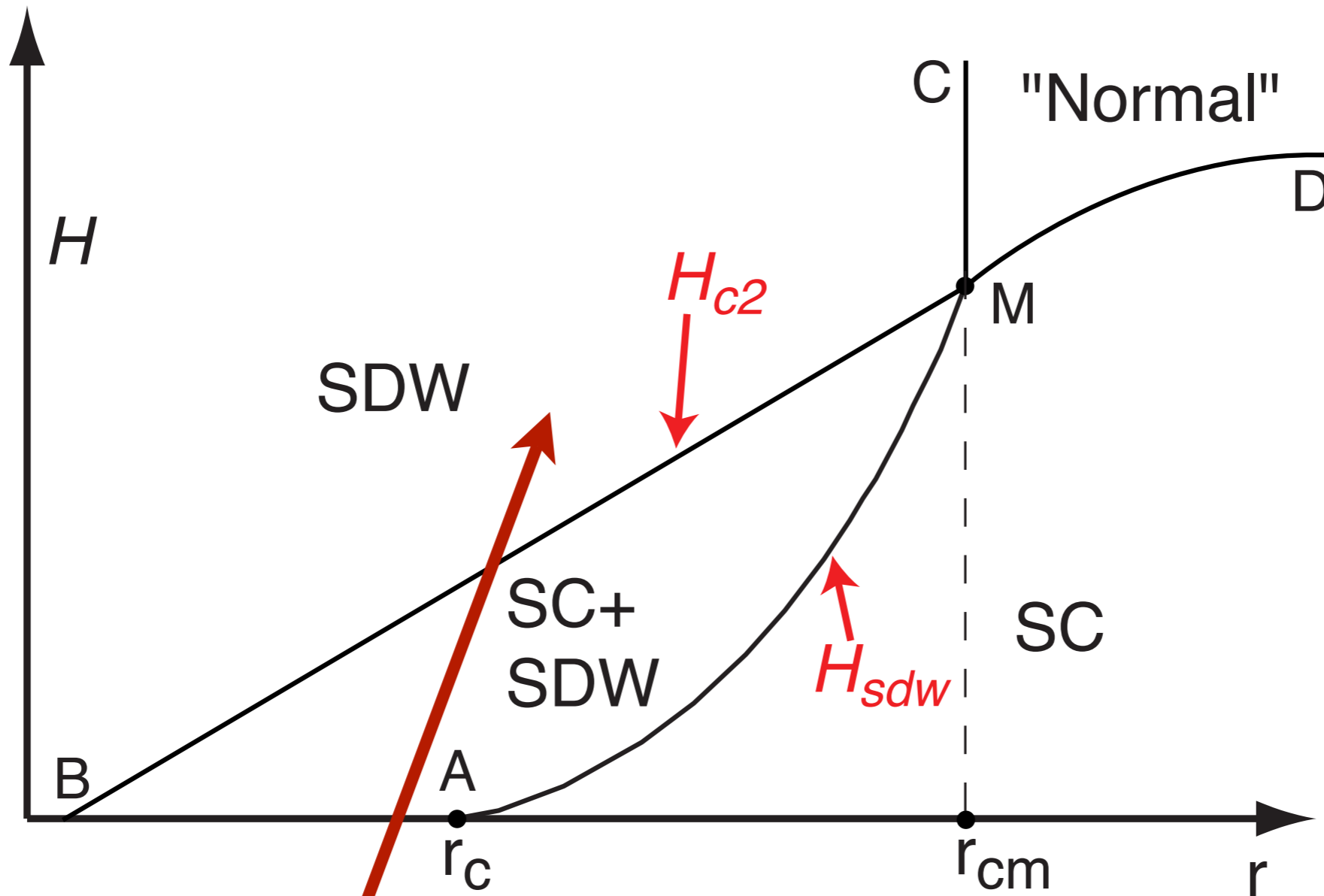


Neutron scattering on  $\text{YBa}_2\text{Cu}_3\text{O}_{6.45}$   
D. Haug *et al.*, arXiv:0902.3335



# Phenomenological quantum theory of competing orders

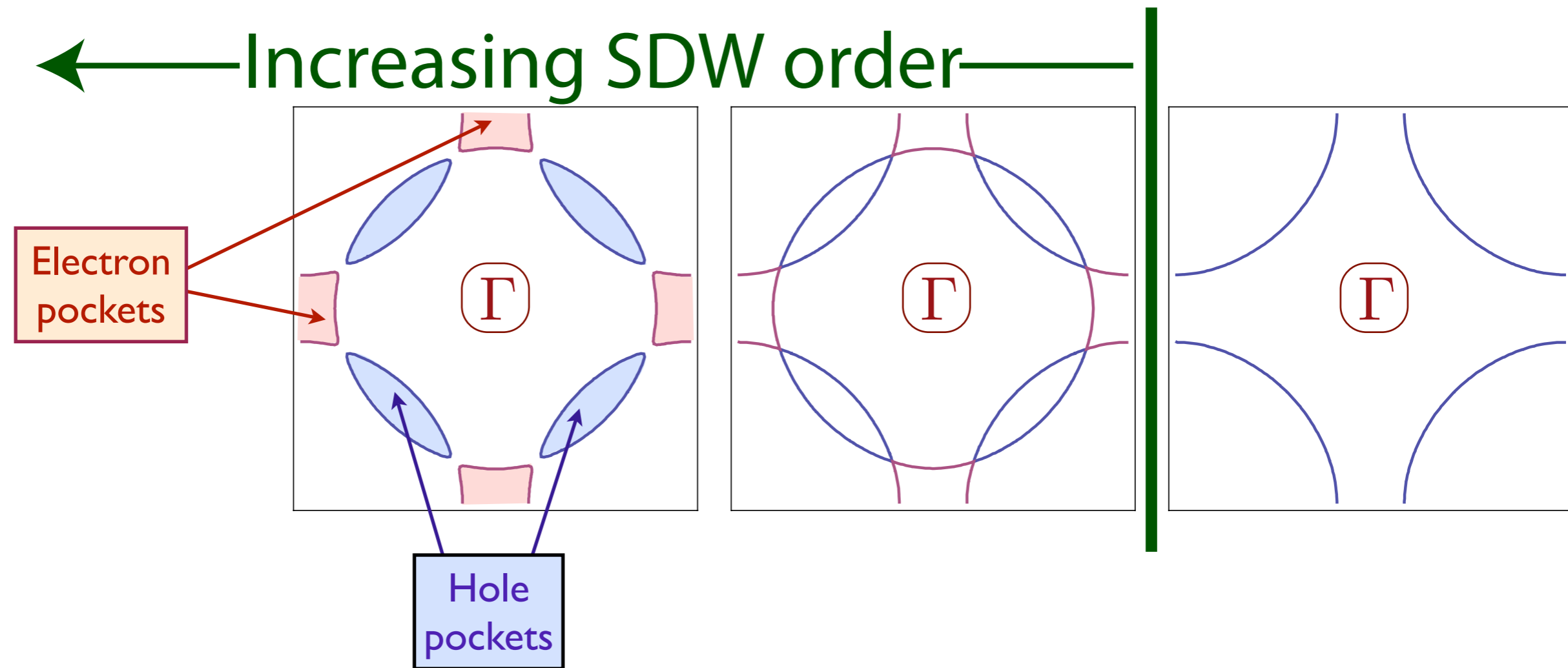
Competition between superconductivity (SC) and spin-density wave (SDW) order



Quantum oscillations without Zeeman splitting

N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J.-B. Bonnemaison, R. Liang, D. A. Bonn, W. N. Hardy, and L. Taillefer, *Nature* **447**, 565 (2007)

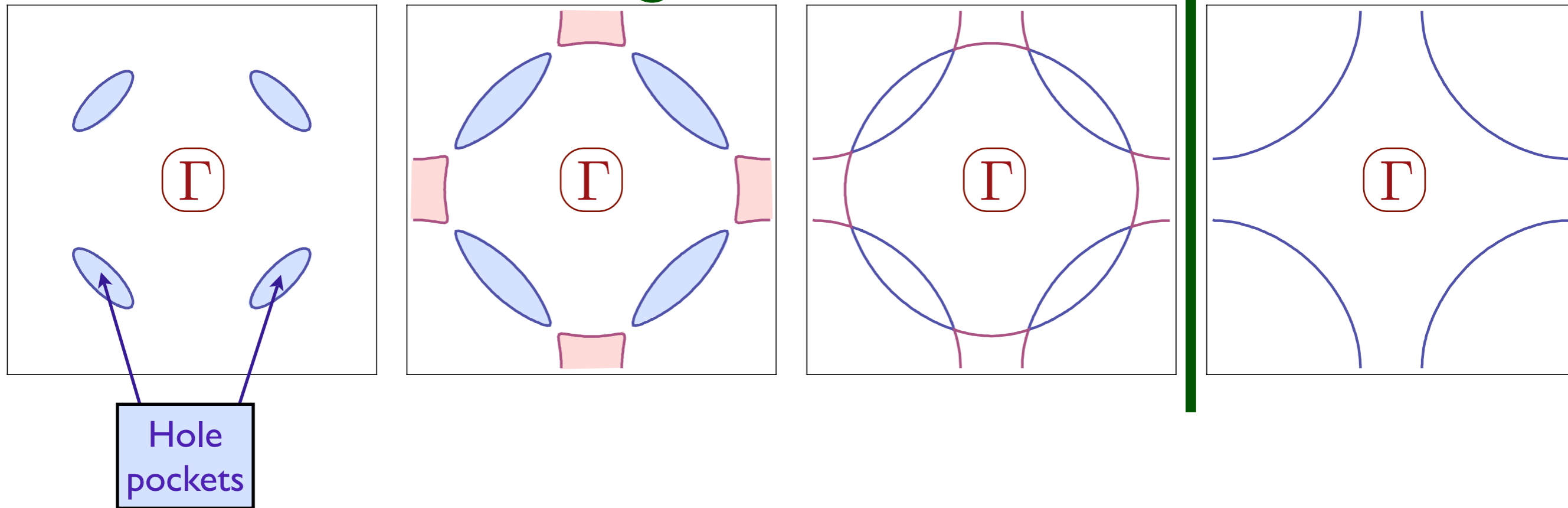
# Spin density wave theory in hole-doped cuprates



S. Sachdev, A. V. Chubukov, and A. Sokol, *Phys. Rev. B* **51**, 14874 (1995).  
A. V. Chubukov and D. K. Morr, *Physics Reports* **288**, 355 (1997).

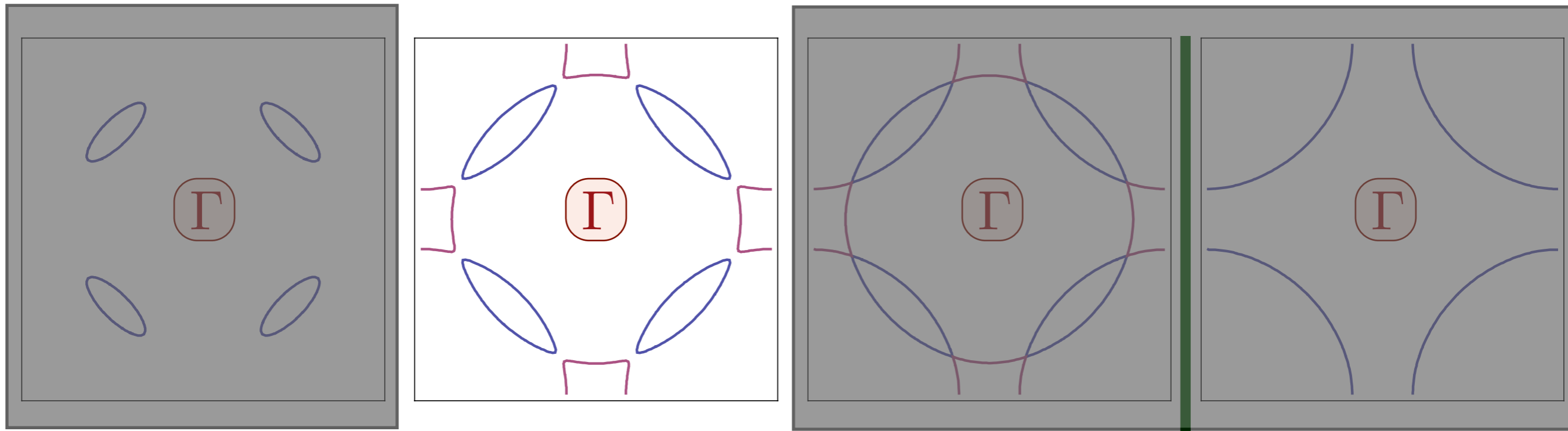
# Spin density wave theory in hole-doped cuprates

← Increasing SDW order →



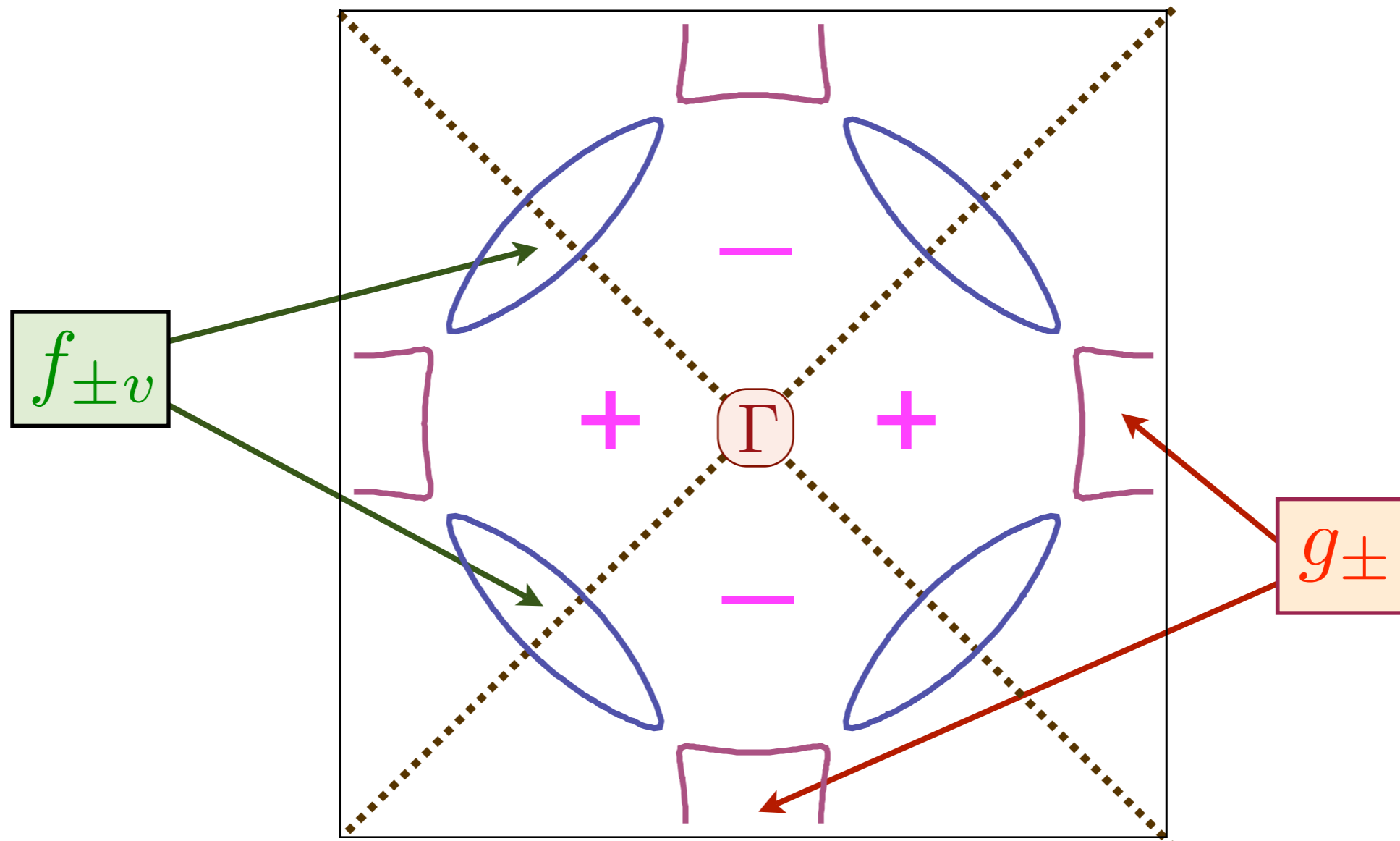
S. Sachdev, A. V. Chubukov, and A. Sokol, *Phys. Rev. B* **51**, 14874 (1995).  
A. V. Chubukov and D. K. Morr, *Physics Reports* **288**, 355 (1997).

# Fermi pockets in hole-doped cuprates



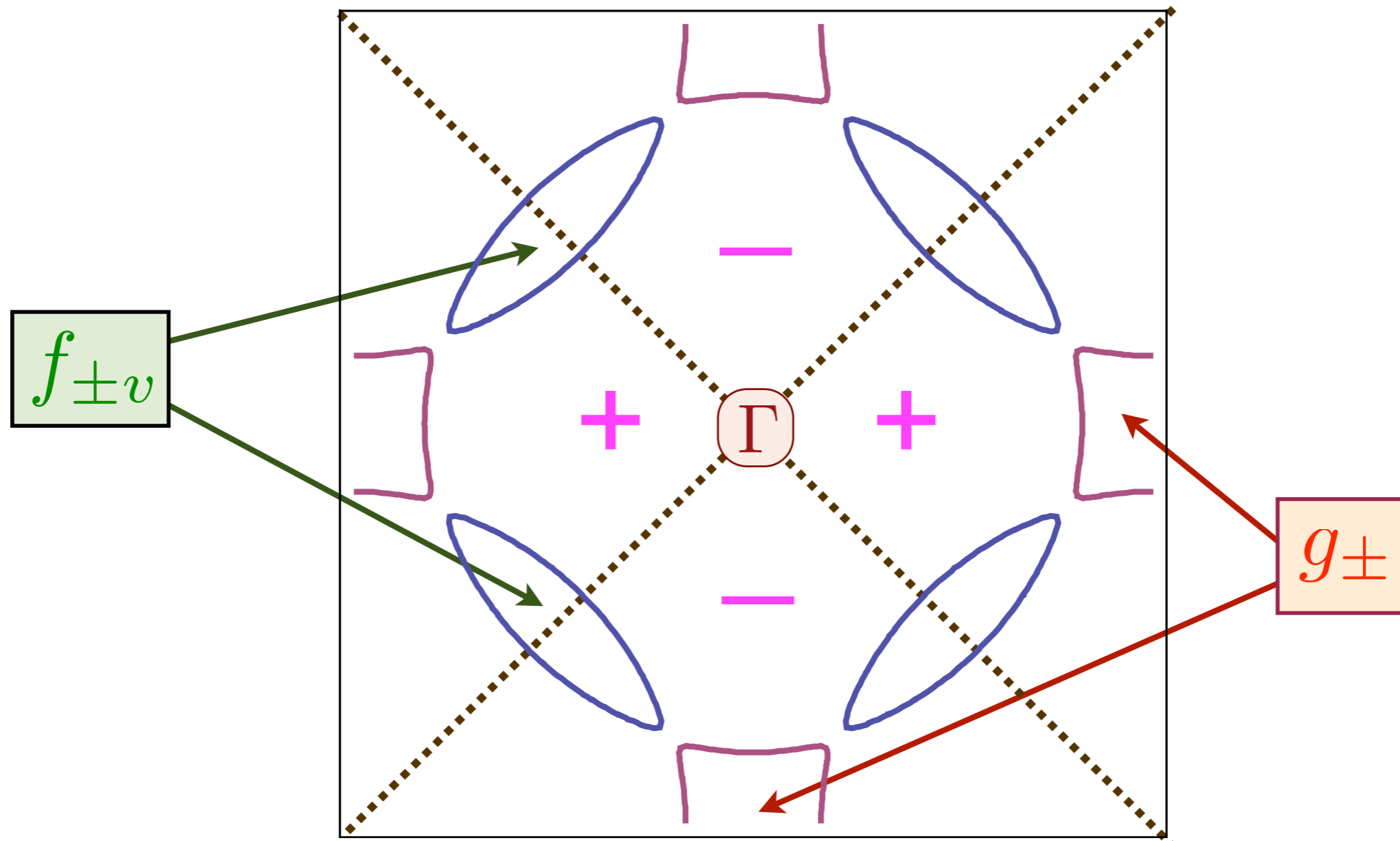
Begin with SDW ordered state, and focus on fluctuations in the *orientation* of the SDW order parameter  $\vec{\varphi}$ , by using a unit-length bosonic spinor  $z_\alpha$

$$\vec{\varphi} = z_\alpha^* \vec{\sigma}_{\alpha\beta} z_\beta$$



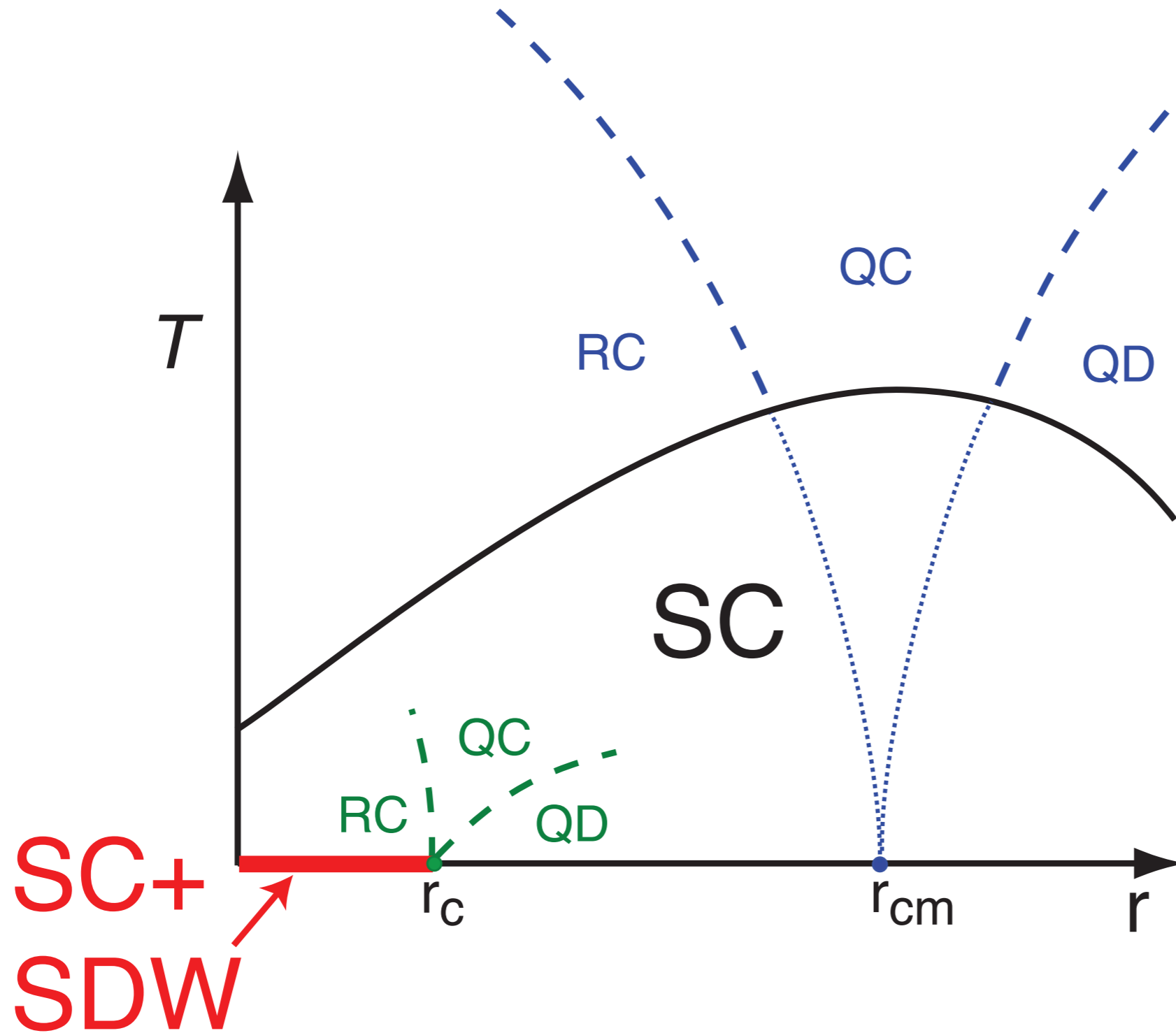
**$d$ -wave** pairing of the electrons is associated with

- **Strong  $s$ -wave** pairing of  $g_{\pm}$
- **Weak  $p$ -wave** pairing of  $f_{\pm v}$ .



Field-doping phase diagram has all the key features of the phenomenological theory of competing orders

# Finite temperature “pseudogap”



- Because  $r_{cm} > r_c$ , for  $T > T_c$  there is local SDW order which is disordered by thermal fluctuations.