An organizing principle for 2D strongly correlated superconductivity

L. Fratino et al., Scientific Reports 6, 22715 (2016)
L. Fratino et al., Phys. Rev. B 93, 245147 (2016)

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NGSCES, 2016

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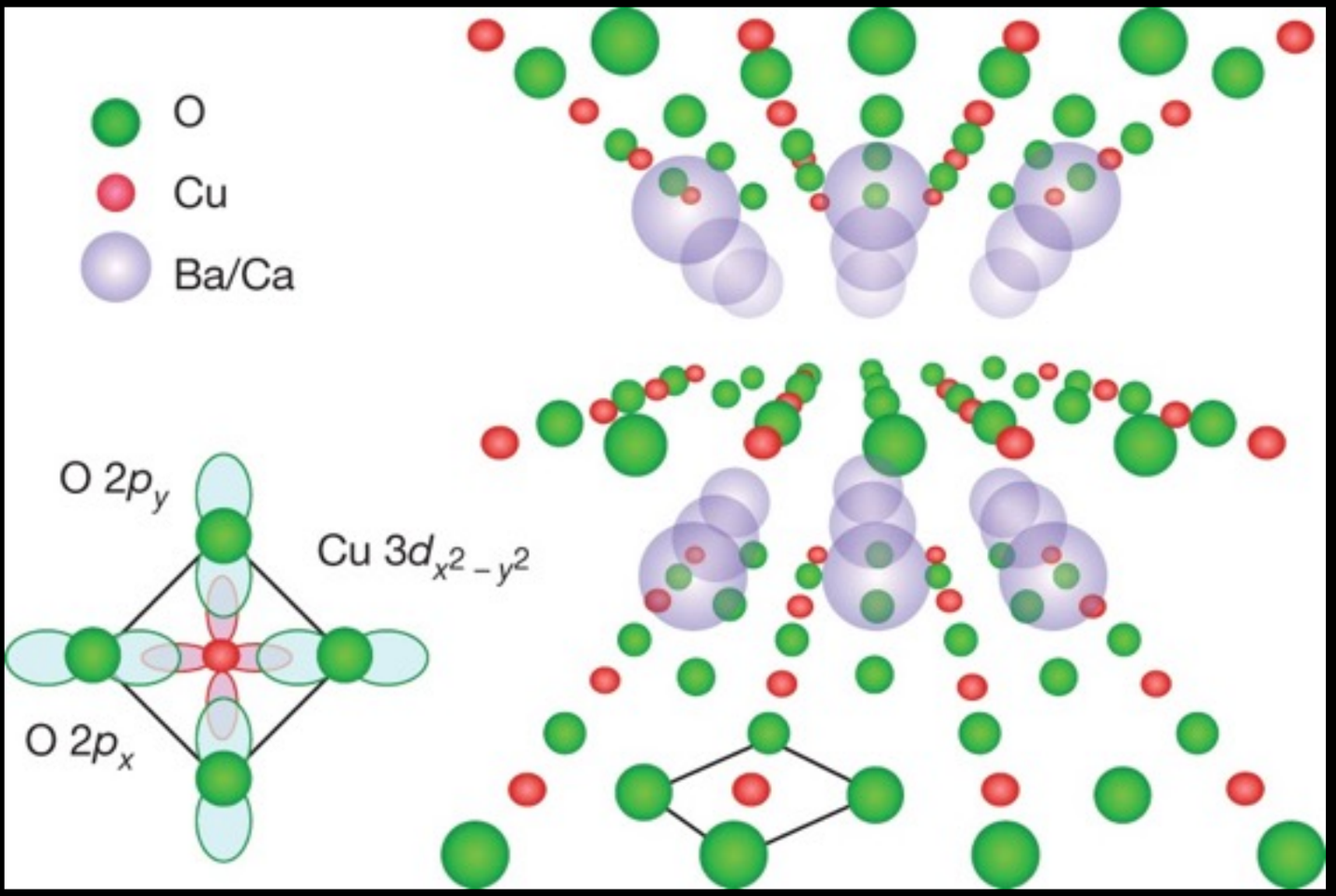
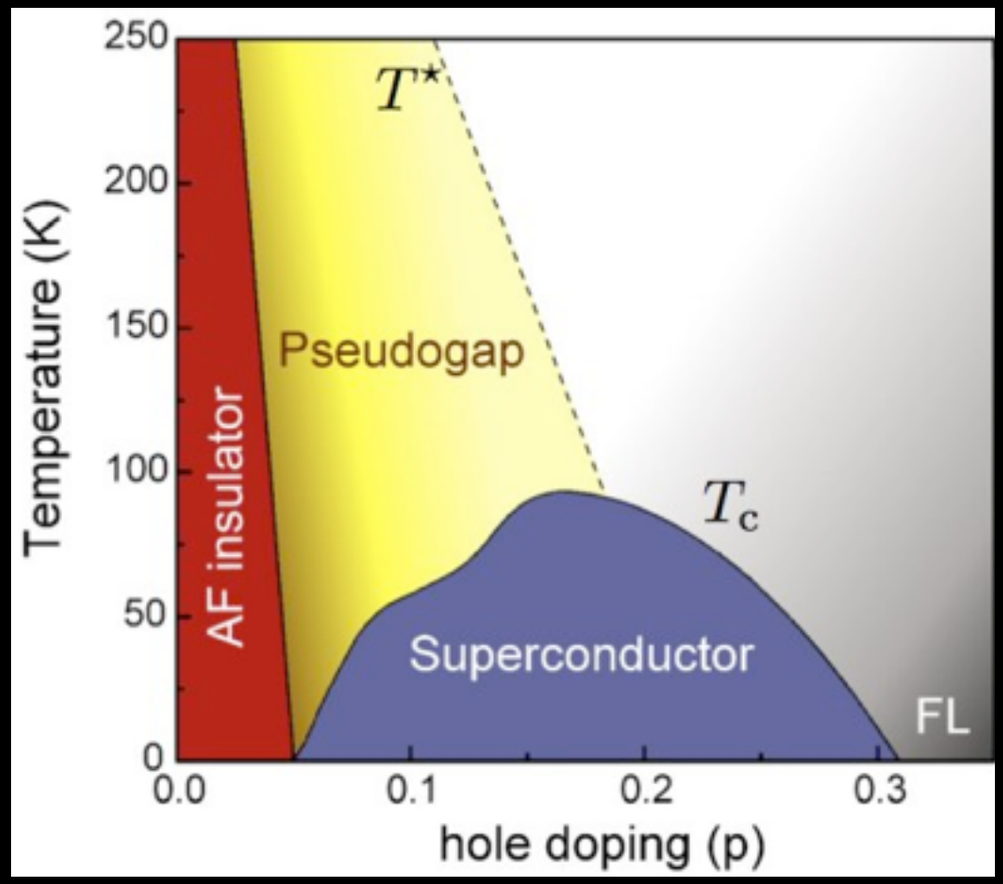
Cuprates



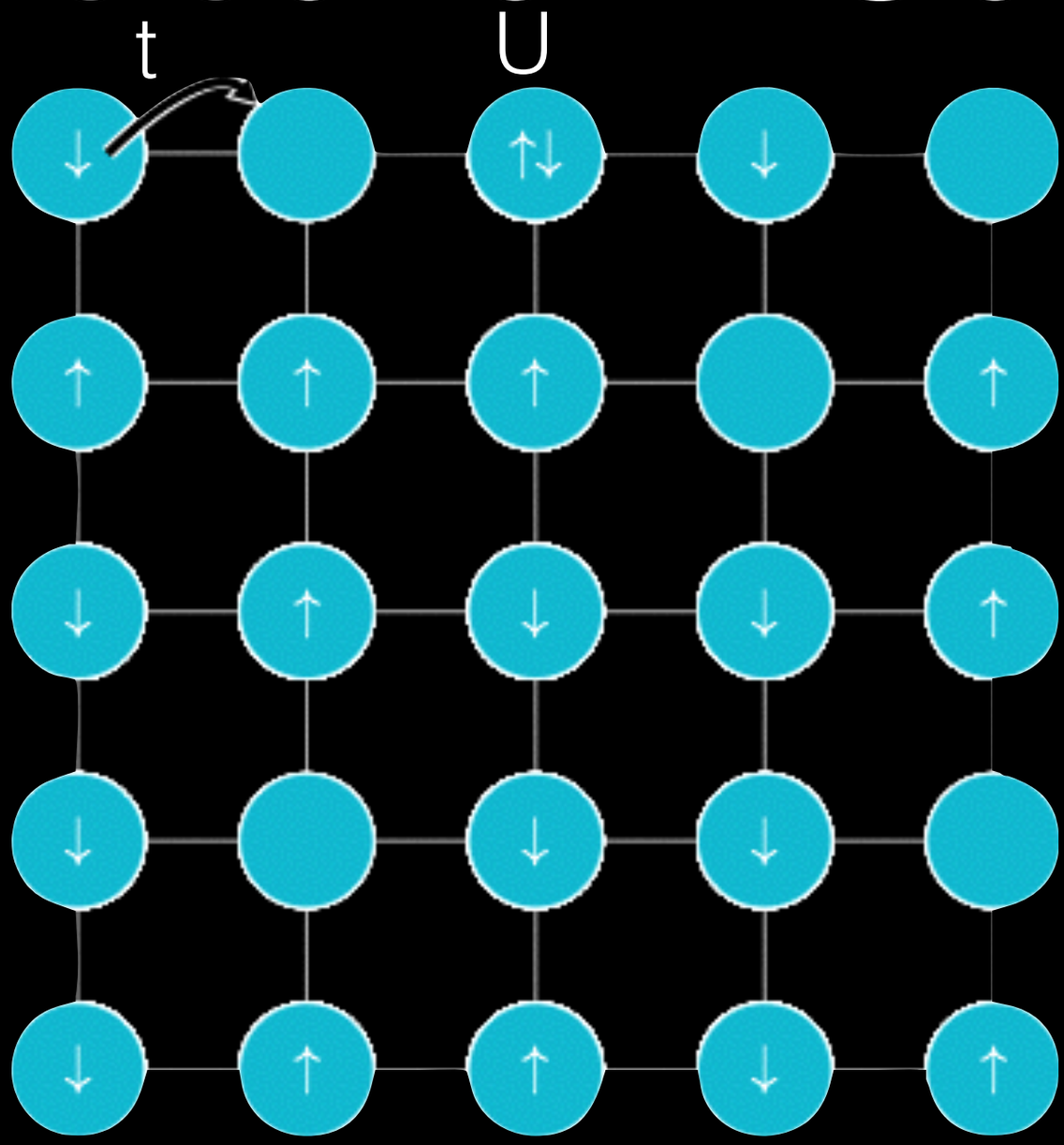
2D copper oxide layers

Keimer B., Nat. Phys. (2015)



Doped Mott insulators

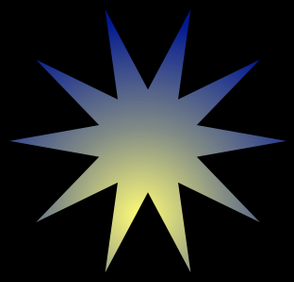
Hubbard Model



The simplest model that can capture the essential physics of such systems is the single-band Hubbard model:

$$\hat{H}_{HM} = -\sum_{\langle i,j\rangle,\sigma} t_{ij}\hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma} + U\sum_{i}\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} - \mu\sum_{\sigma,i}\hat{n}_{i\sigma}$$

doping-driven Mott transition: 2D Hubbard model scenario



our contribution:

an **organizing principle** for both normal and superconducting phase:
first-order transition at finite doping

Mott insulating phase

pseudogap phase

correlated metallic phase

sharp crossovers in
- dynamic
- thermodynamic and
- transport properties

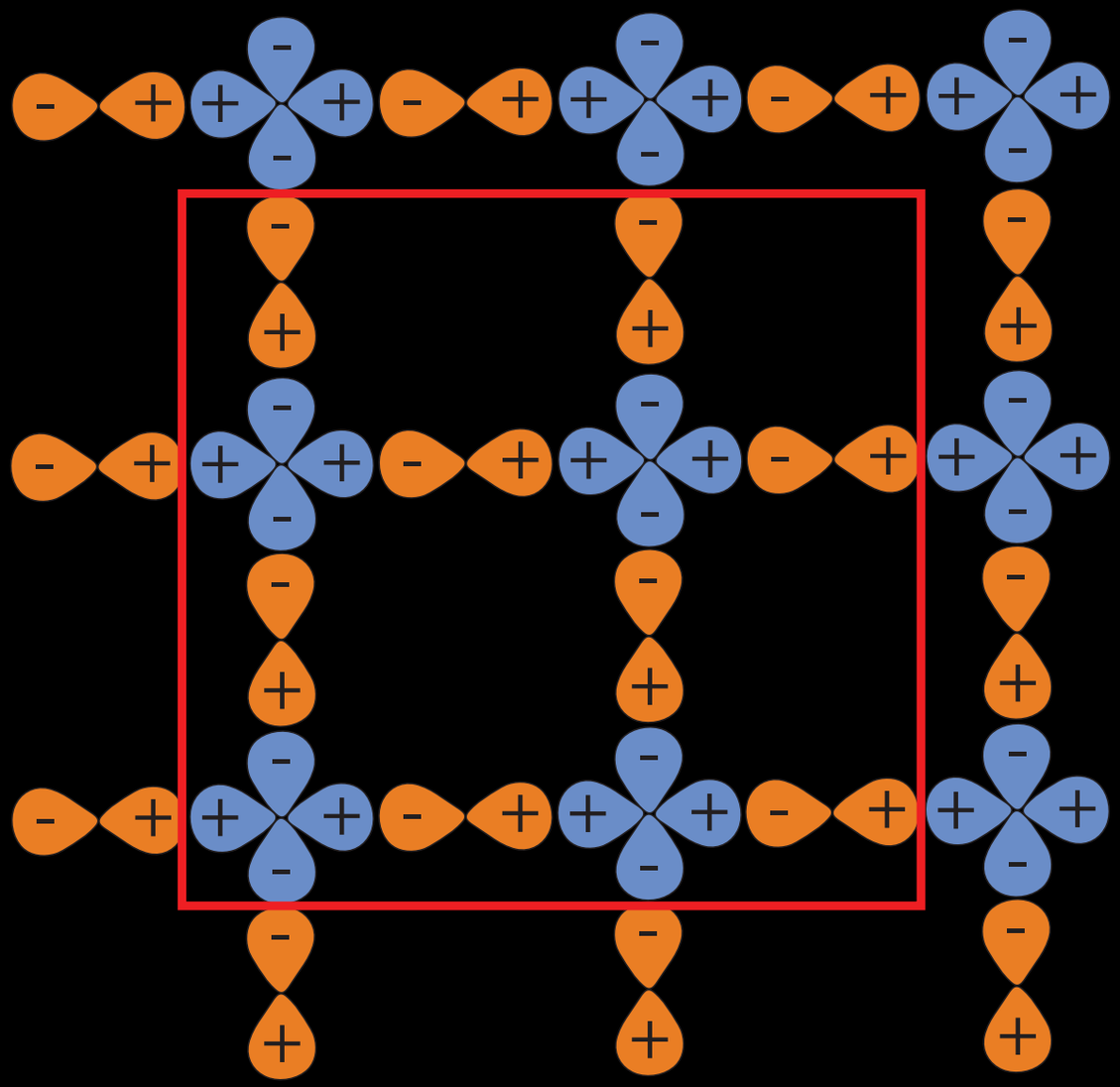
momentum differentiation

d-wave superconducting dome

energetics of SC

interplay Mott physics/ pseudogap/ superconductivity

three-band model



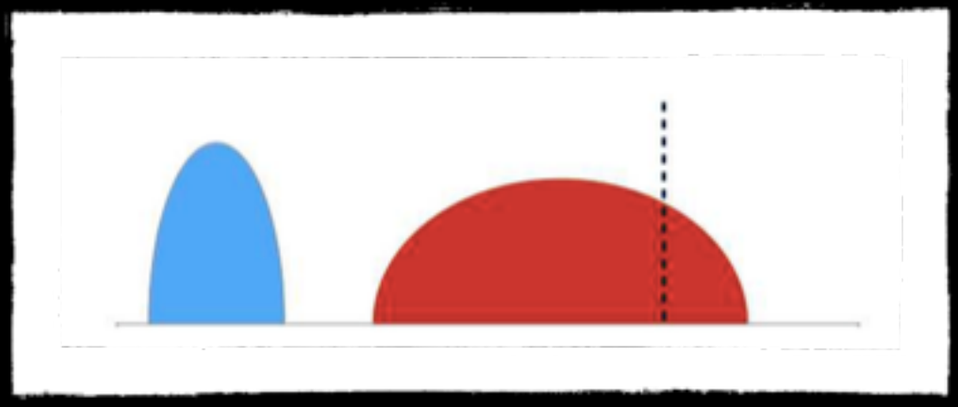
$$\mathbf{h}_0(\mathbf{k}) = \begin{pmatrix} \epsilon_d & t_{pd}(1-e^{-ik_x}) & t_{pd}(1-e^{-ik_y}) \\ t_{pd}(1-e^{ik_x}) & \epsilon_p + 2t_{pp}(\cos k_x - 1) & t_{pp}(1-e^{ik_x})(1-e^{-ik_y}) \\ t_{pd}(1-e^{ik_y}) & t_{pp}(1-e^{-ik_x})(1-e^{ik_y}) & \epsilon_p + 2t_{pp}(\cos k_y - 1) \end{pmatrix}$$

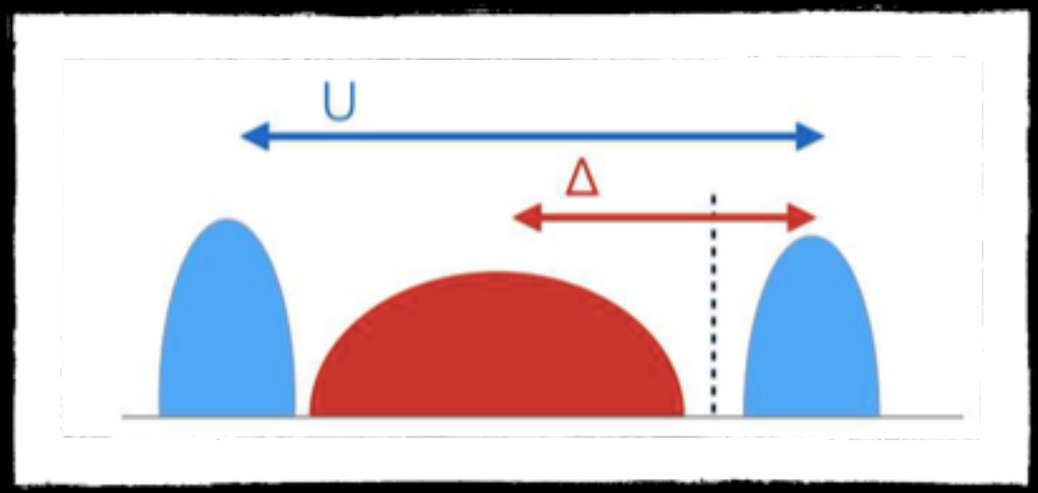
Zaanen-Sawatzky-Allen scheme

Charge transfer insulators

Cu O

DOS

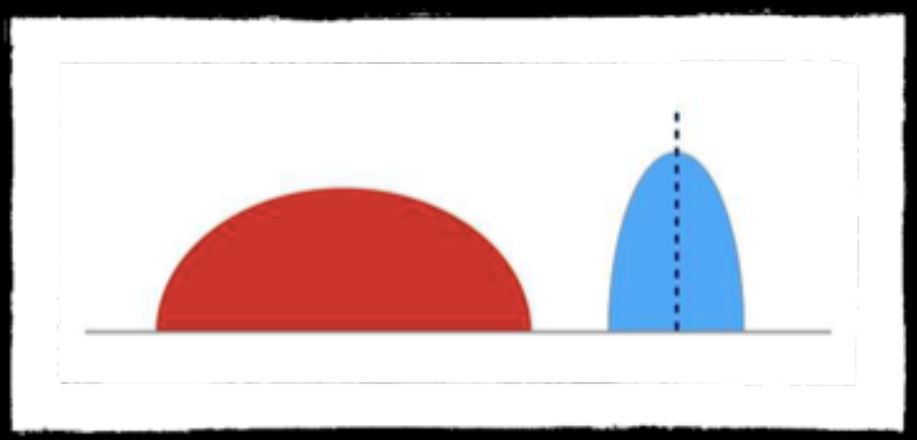


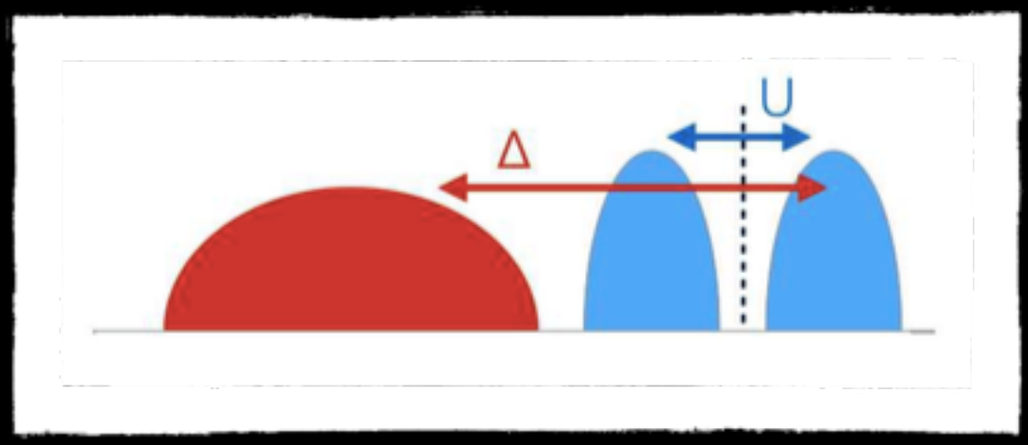


charge-transfer gap expected at $n_{tot}=n_d+2n_p=5$

Mott-Hubbard insulators

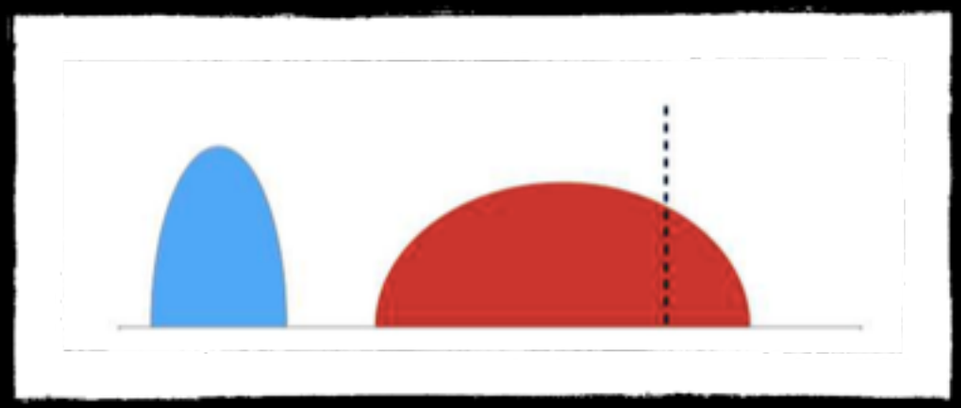
DOS

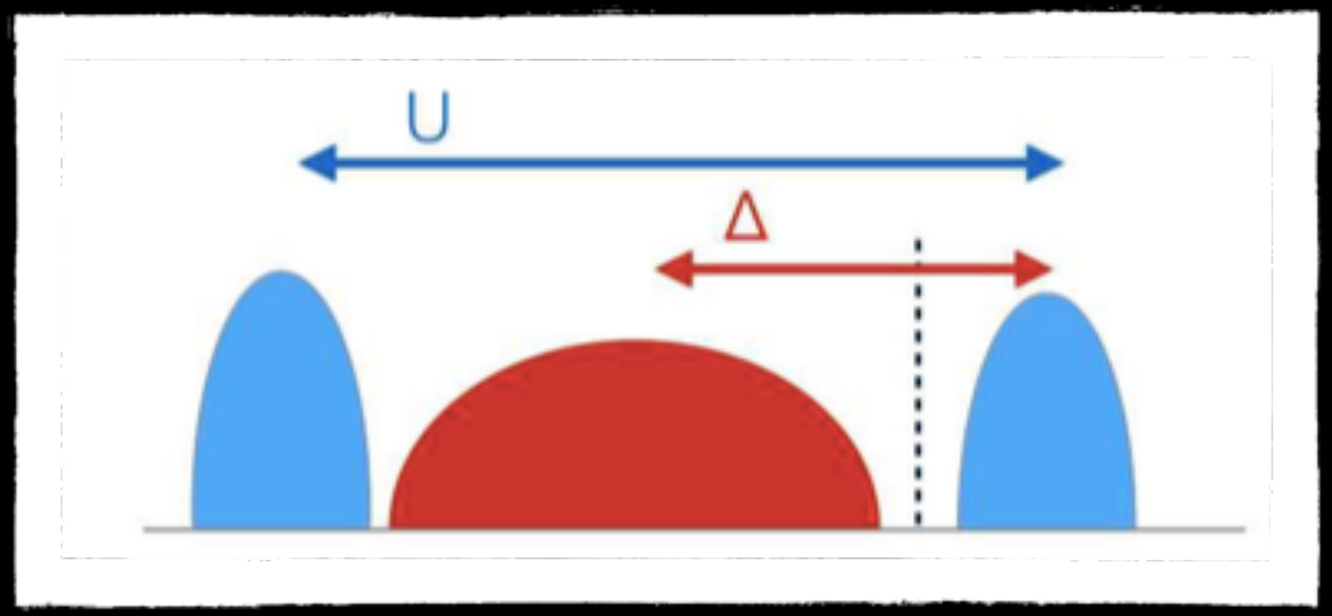




Mott-Hubbard gap expected at $n_{tot}=n_d+2n_p=5$

Charge transfer insulators





charge-transfer gap
expected at $n_{tot}=n_d+2n_p=5$

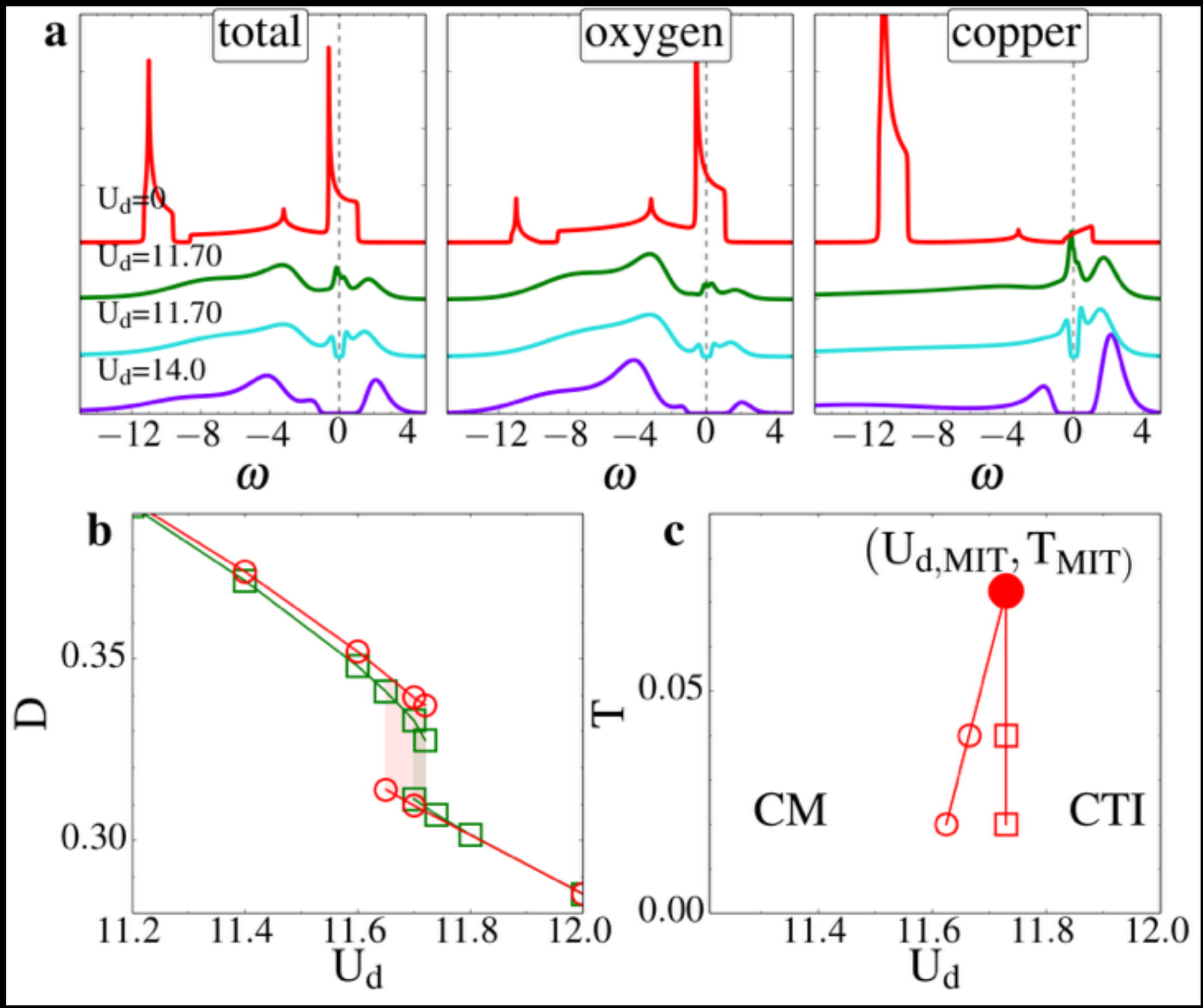
within cellular DMFT, we explore **two routes**:

- **U_d driven** metal to charge-transfer insulator transition
- **doping driven** metal to charge-transfer insulator transition

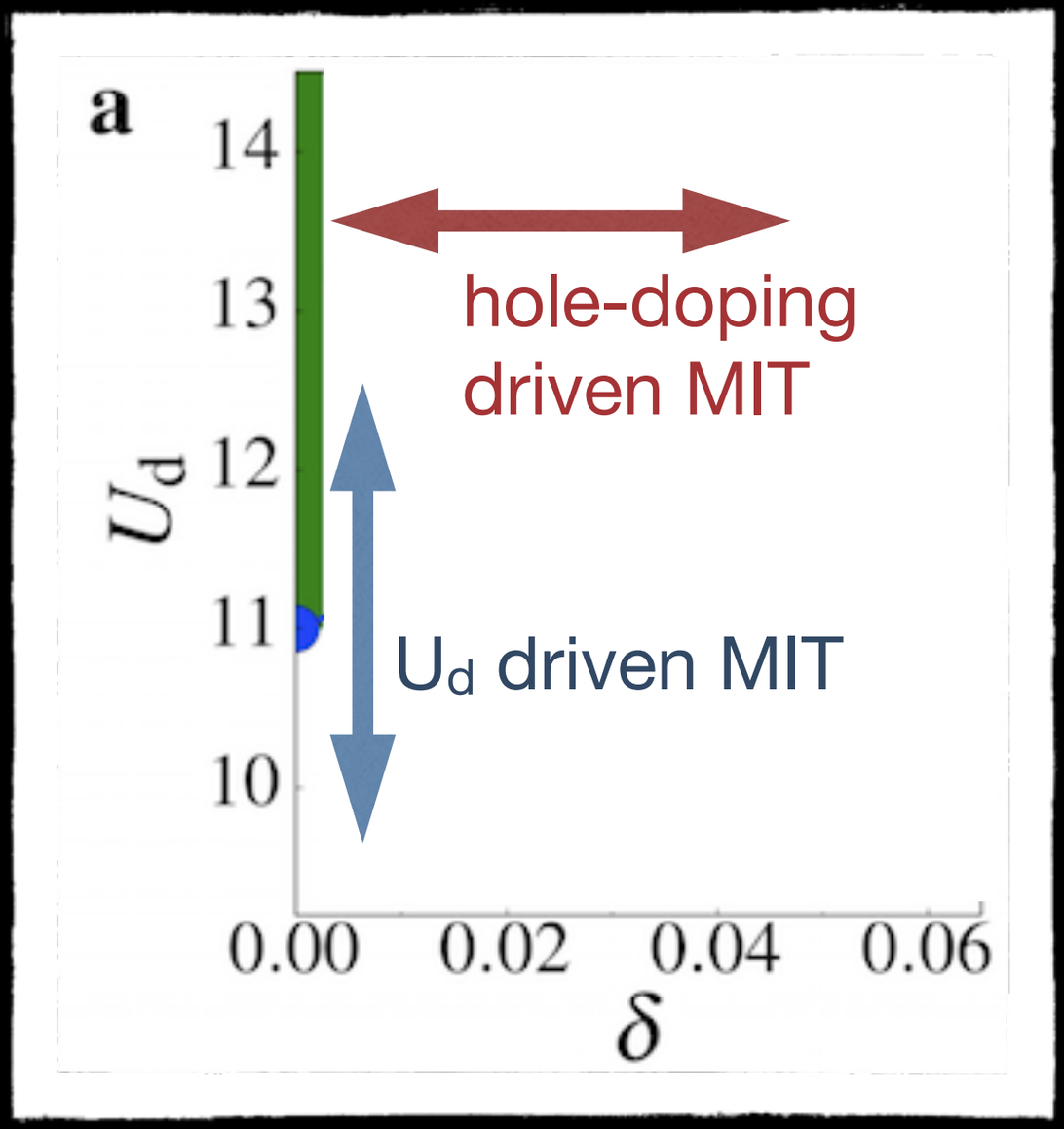
Normal state

Superconducting phase

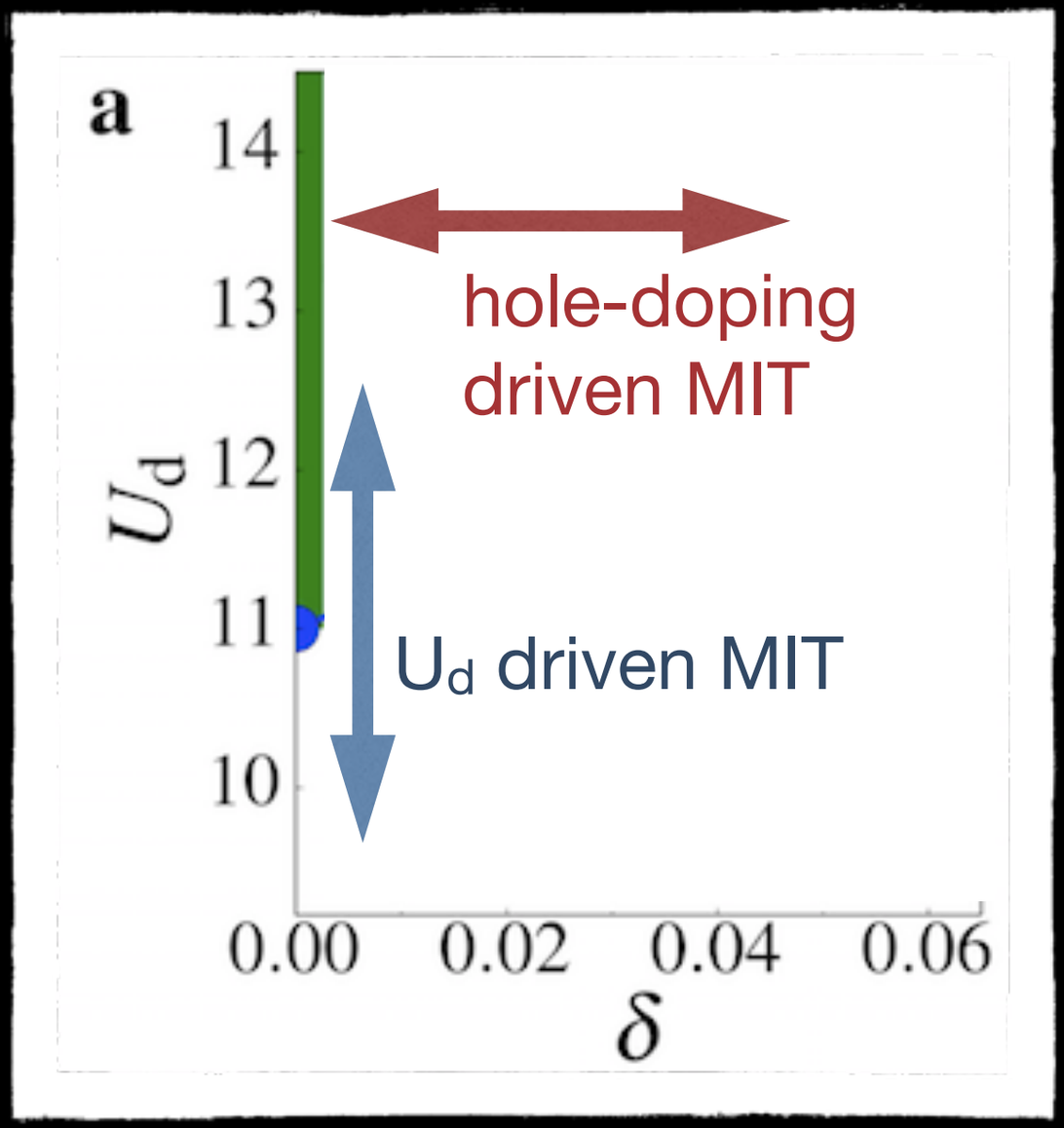
U_d driven metal-insulator transition at n_{tot}=5

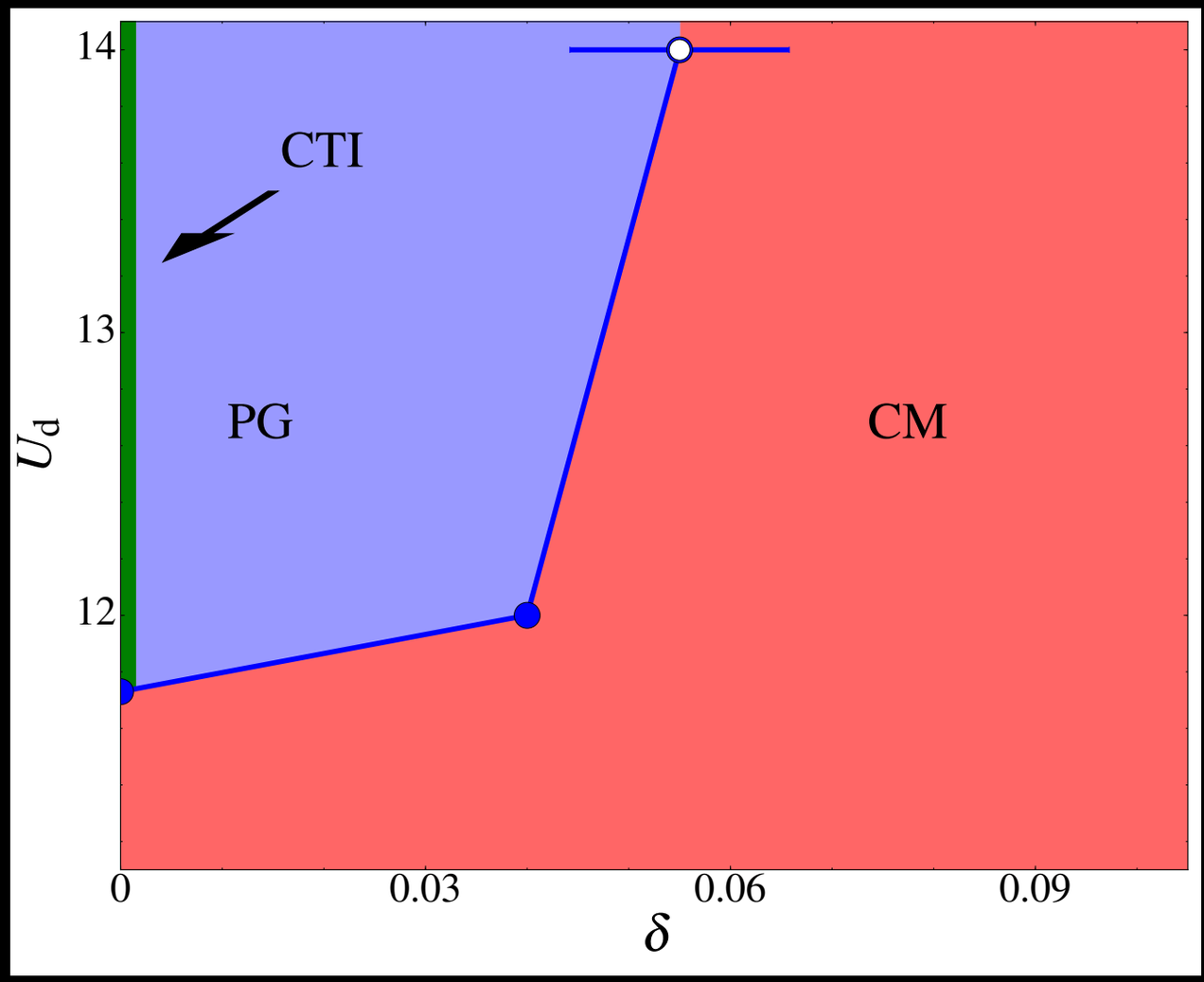


hole-doping driven metal-insulator transition

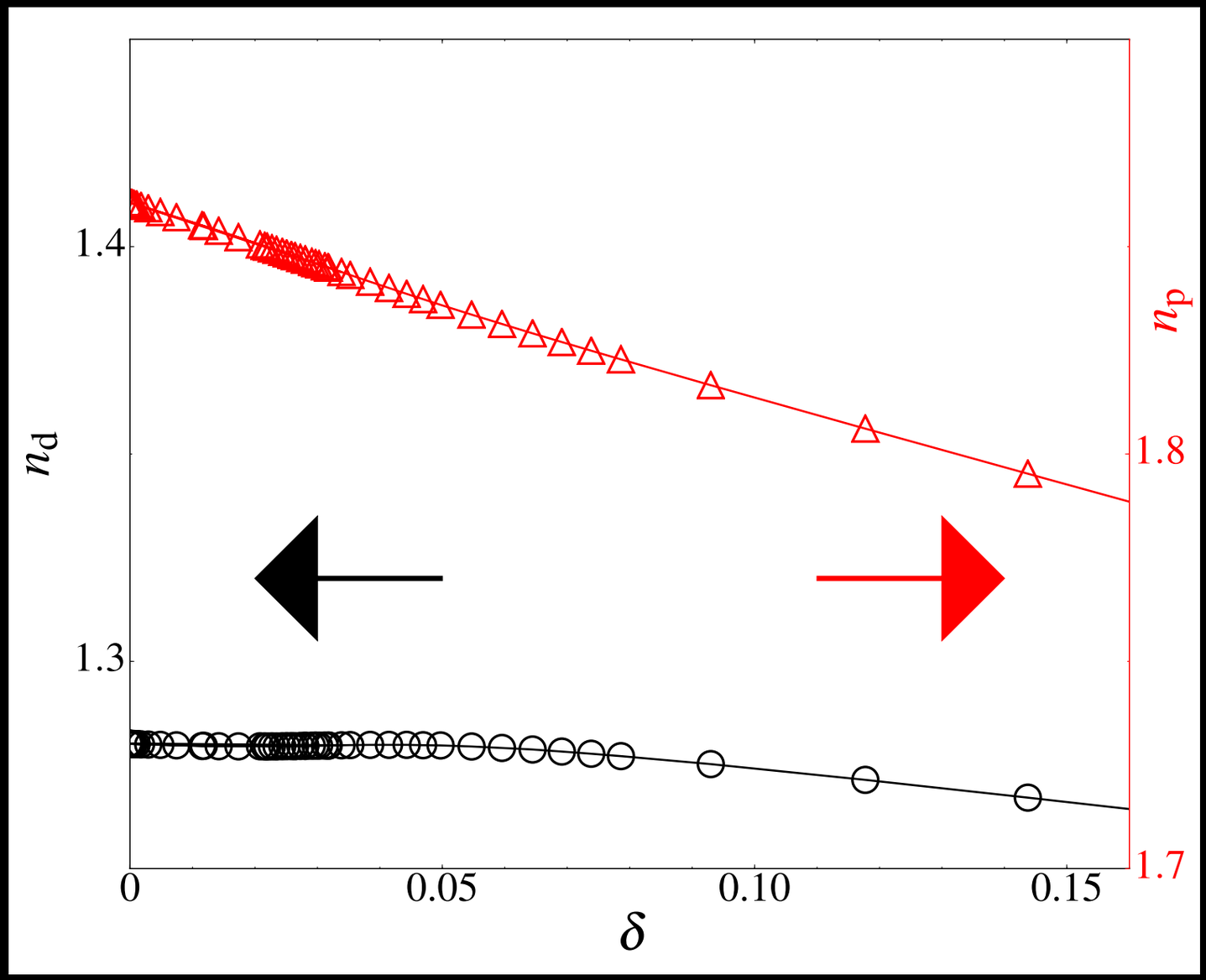


hole-doping driven metal-insulator transition





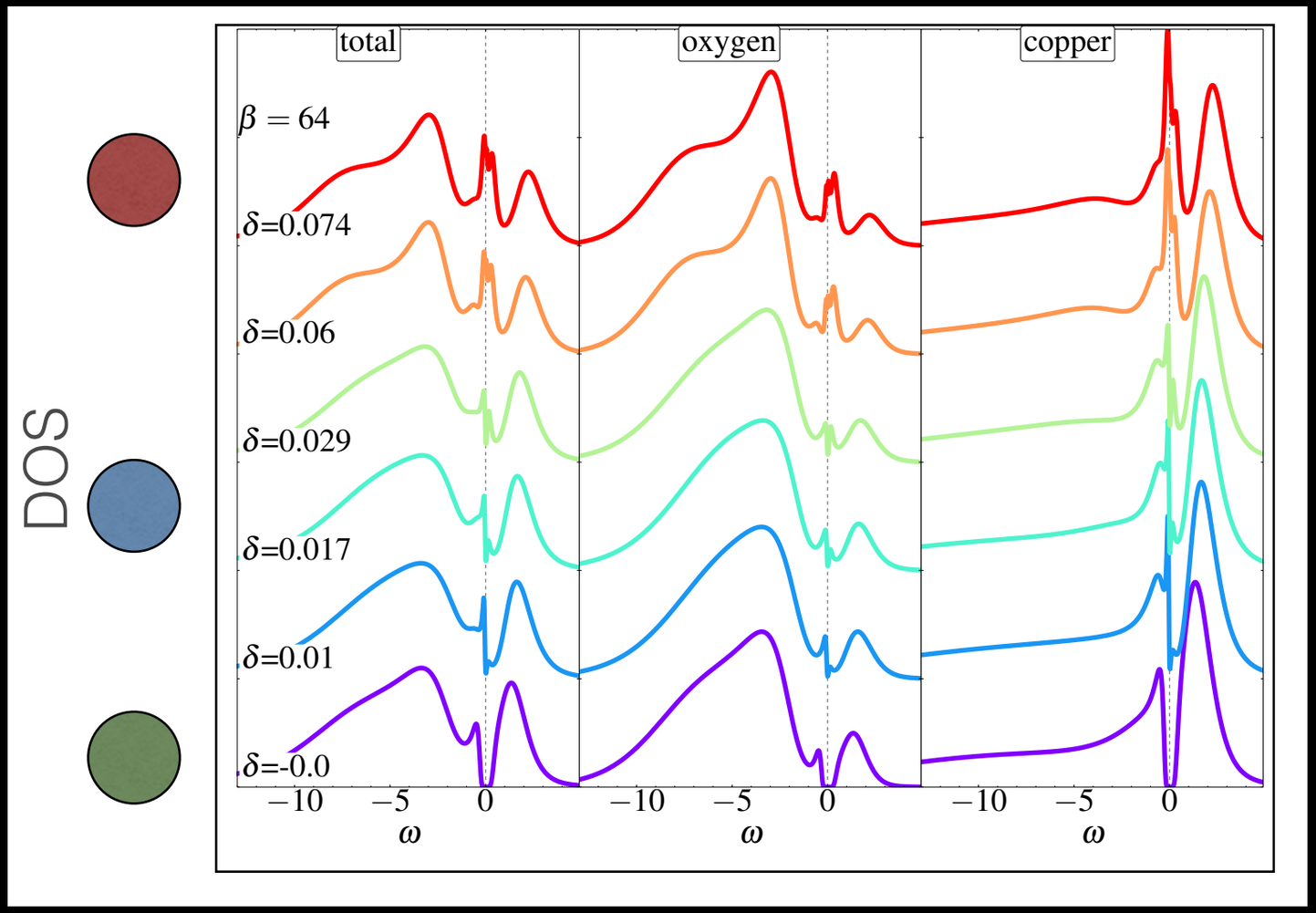
hole-doping driven metal-insulator transition

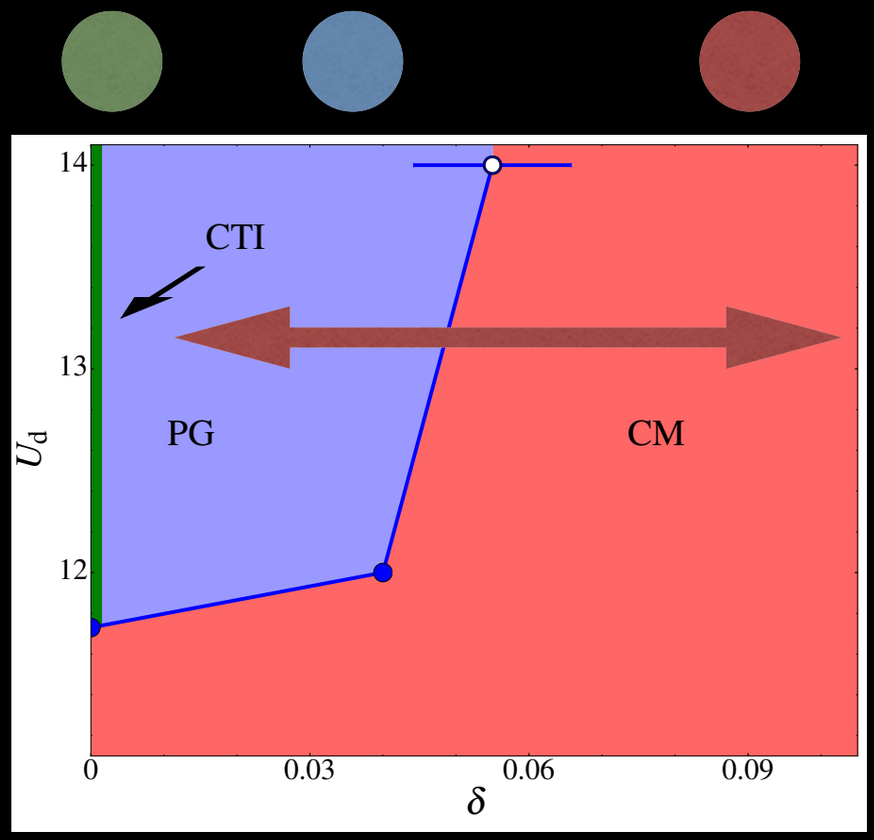


doped holes mainly resides on oxygen

N. Gauquelin, et al., Nat. Comm. (2014)

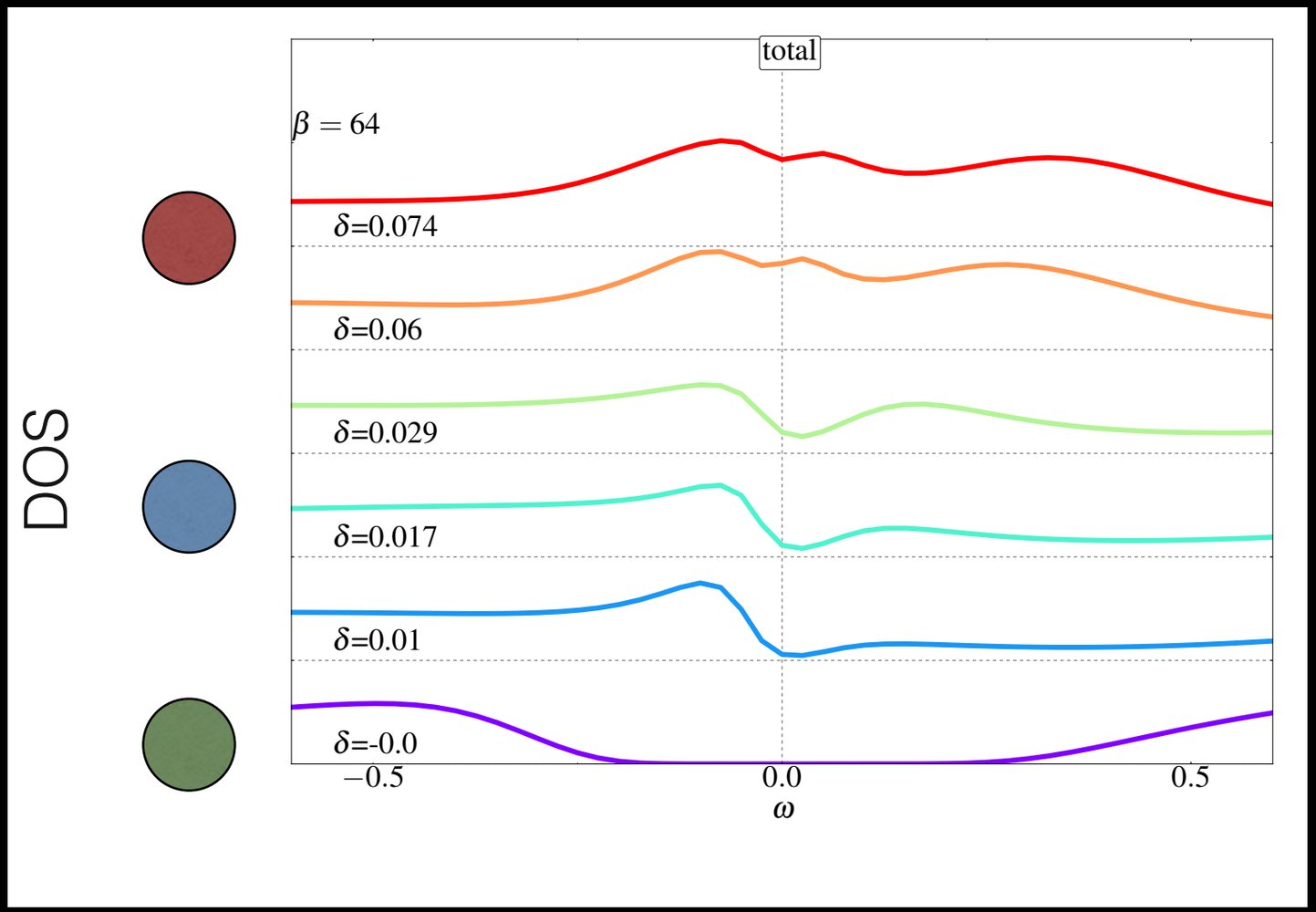
hole-doping driven metal-insulator transition

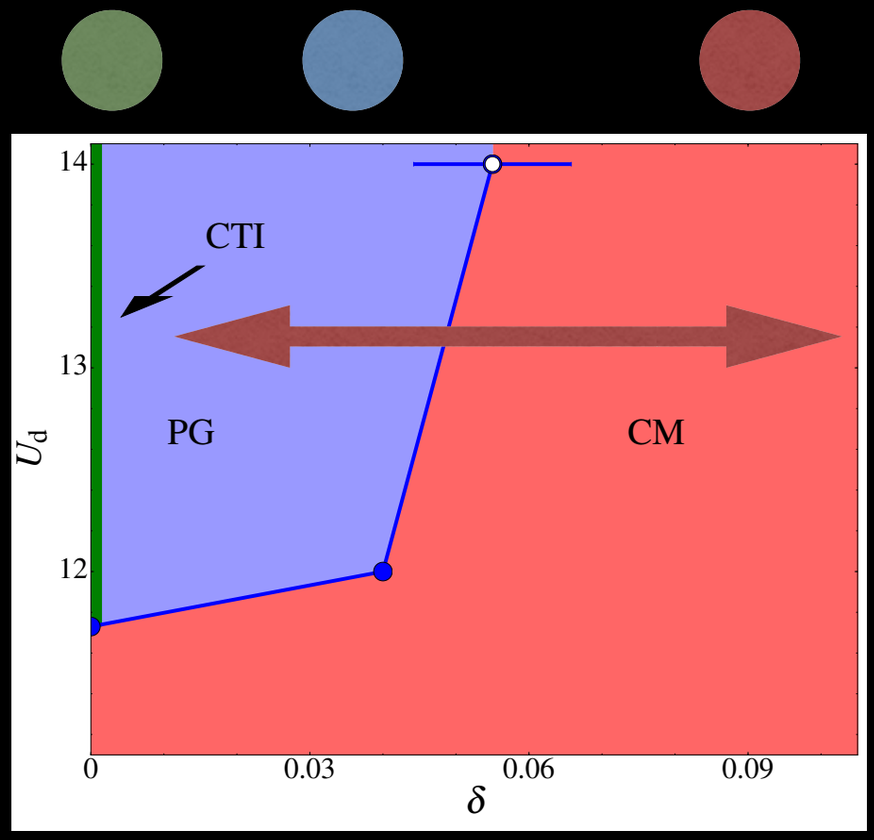




charge-transfer-insulating phase
pseudogap phase
correlated metallic phase

hole-doping driven metal-insulator transition





charge-transfer-insulating phase
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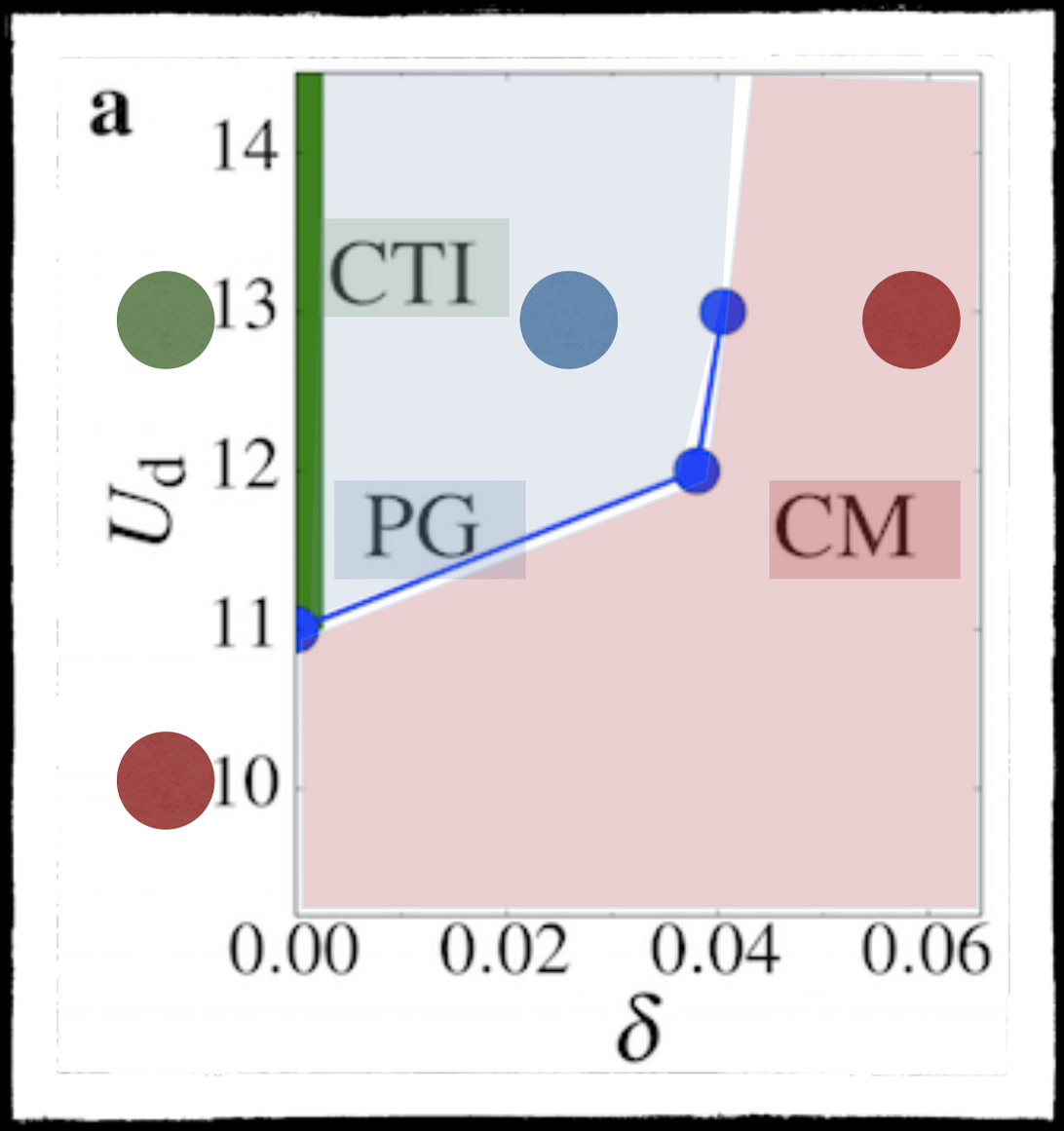
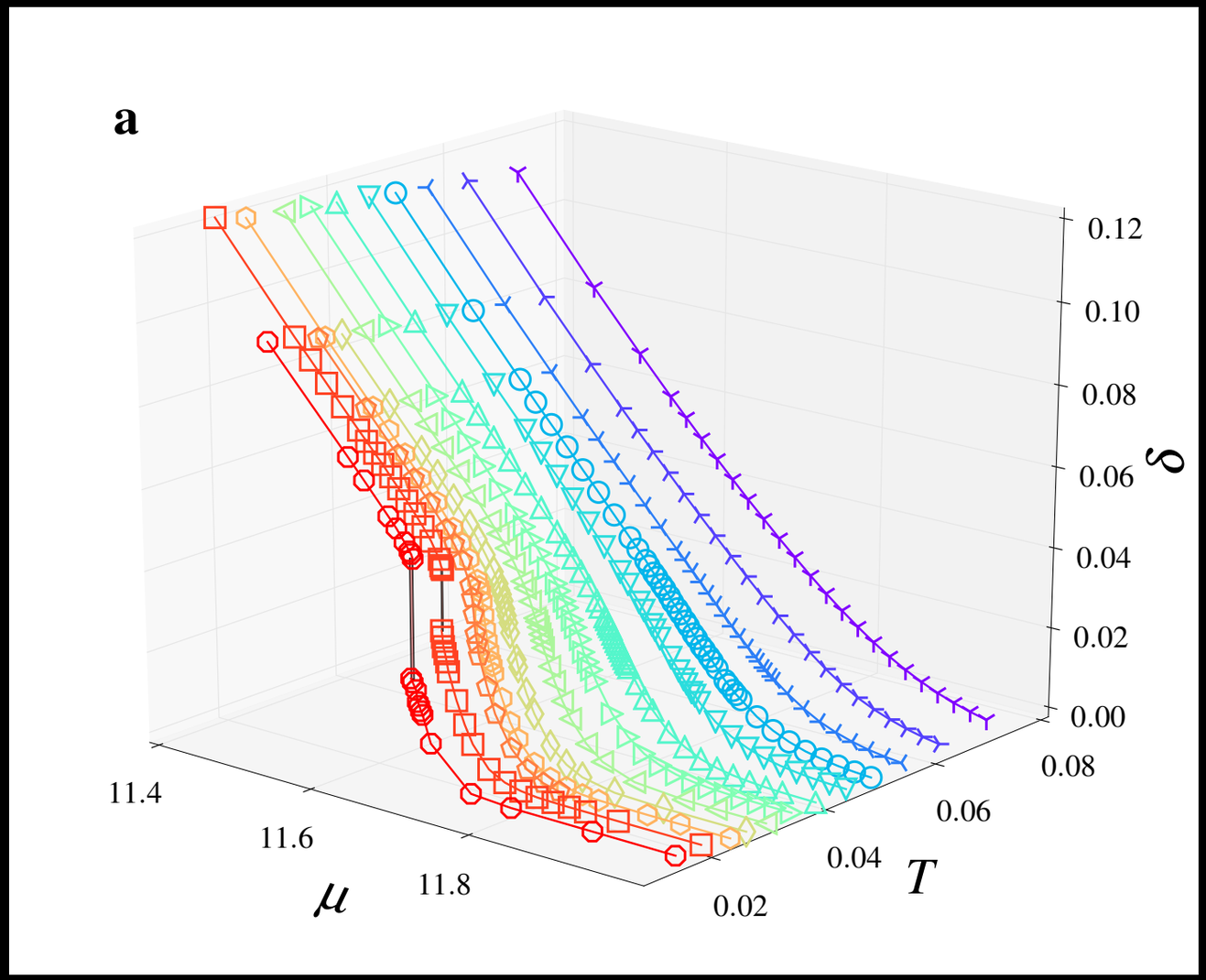
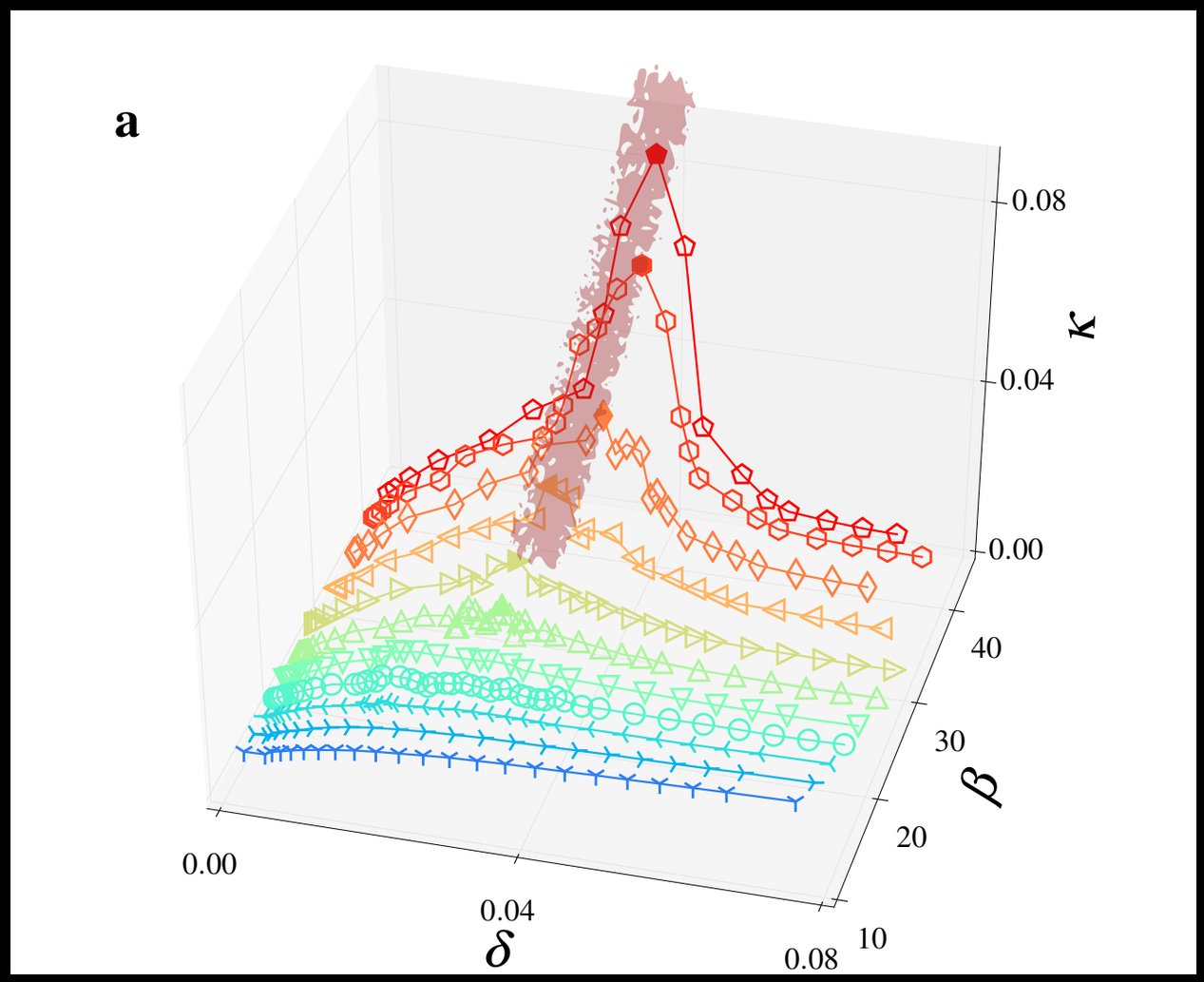
hole-doping driven metal-insulator transition

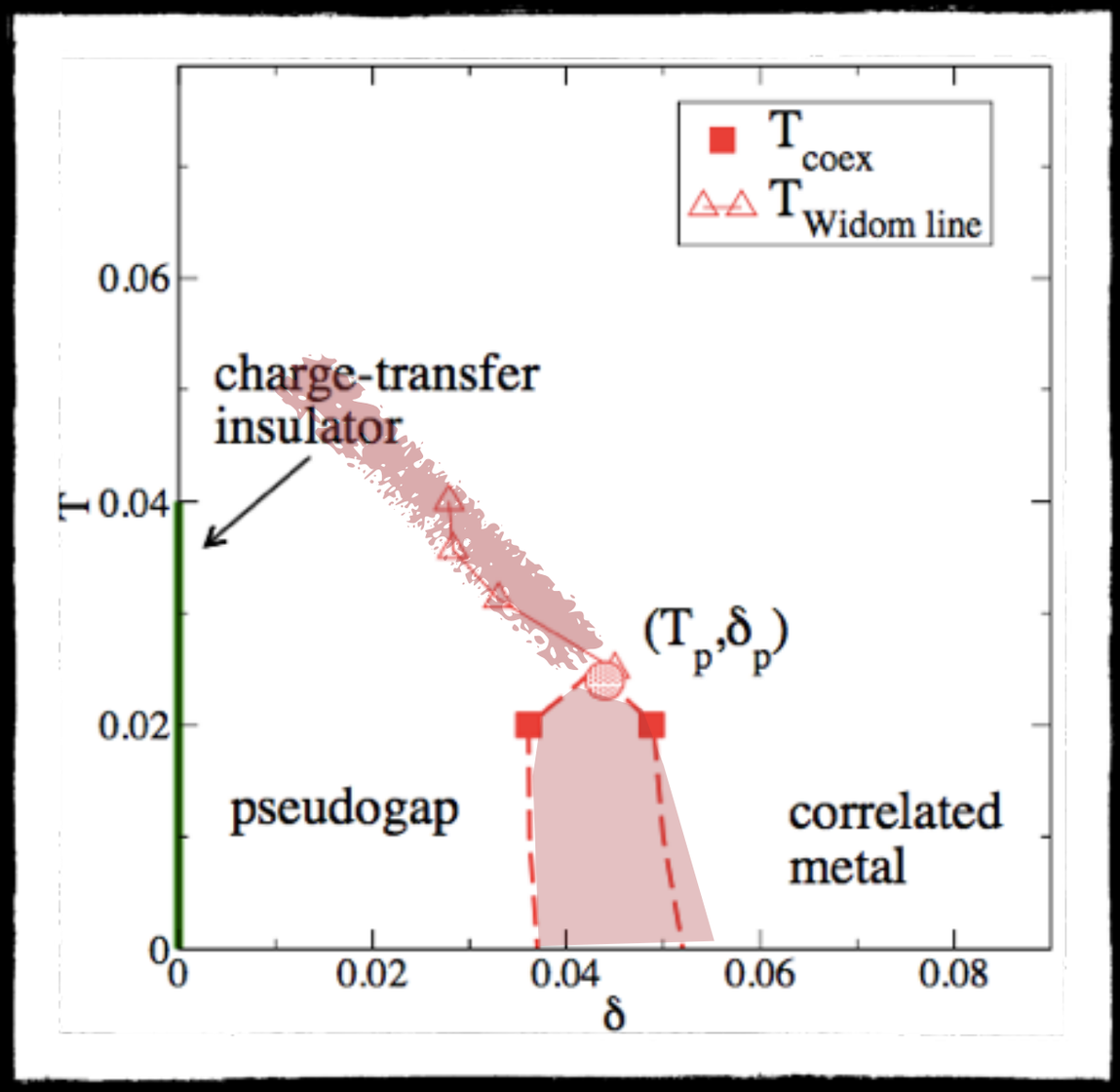




First-order transition at finite doping between two different metals linked to Mott physics

hole-doping driven metal-insulator transition

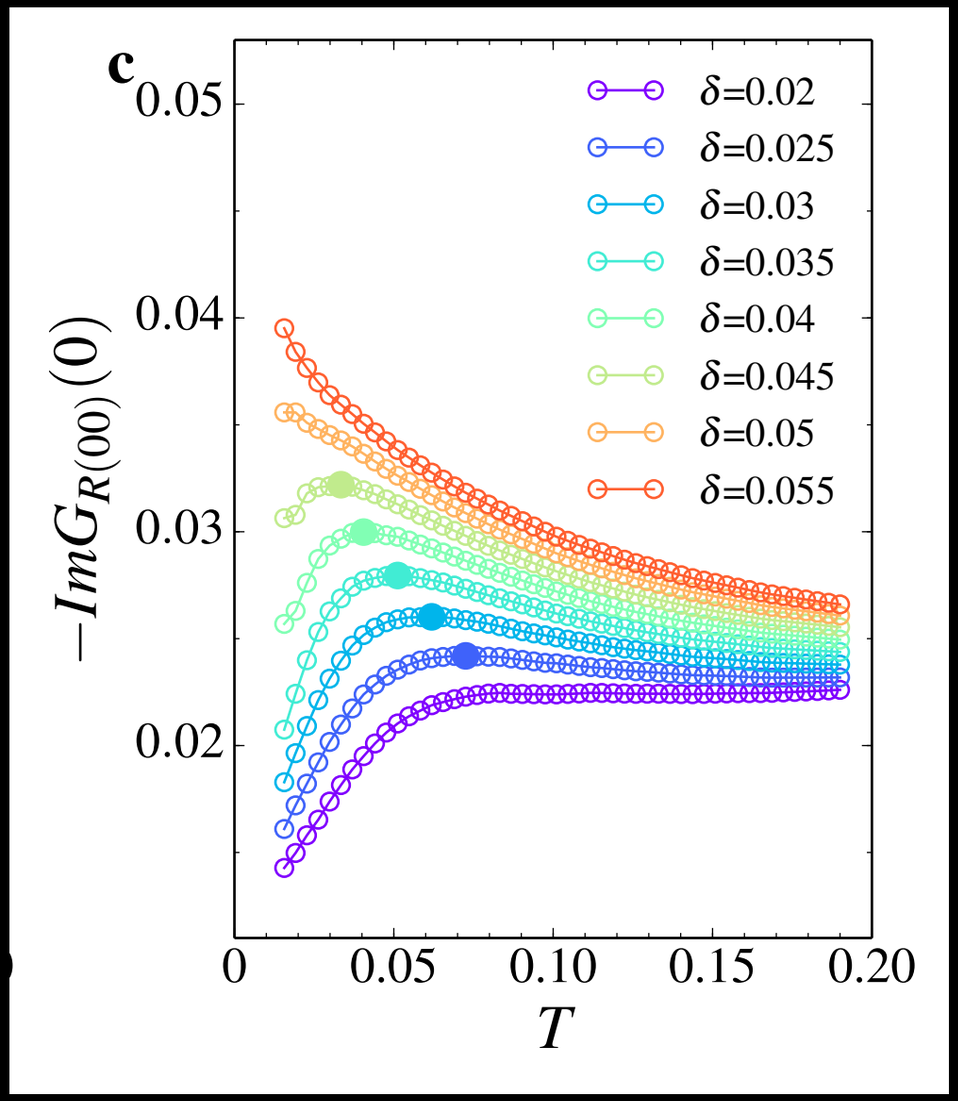


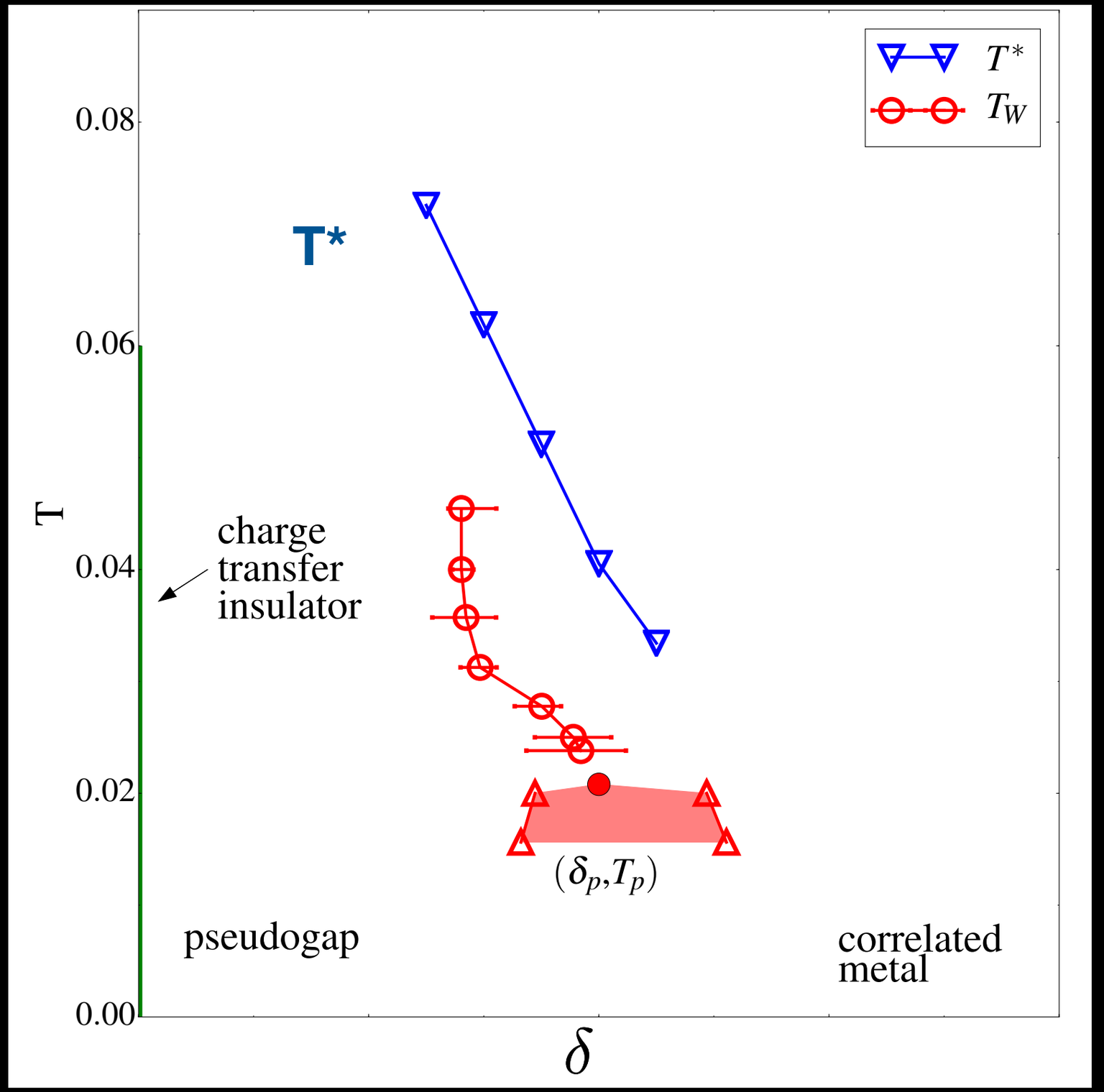


Widom line:
continuation of the coexistence line in the supercritical region
line where the maxima of different response functions touch each other asymptotically as $T \rightarrow T_p$

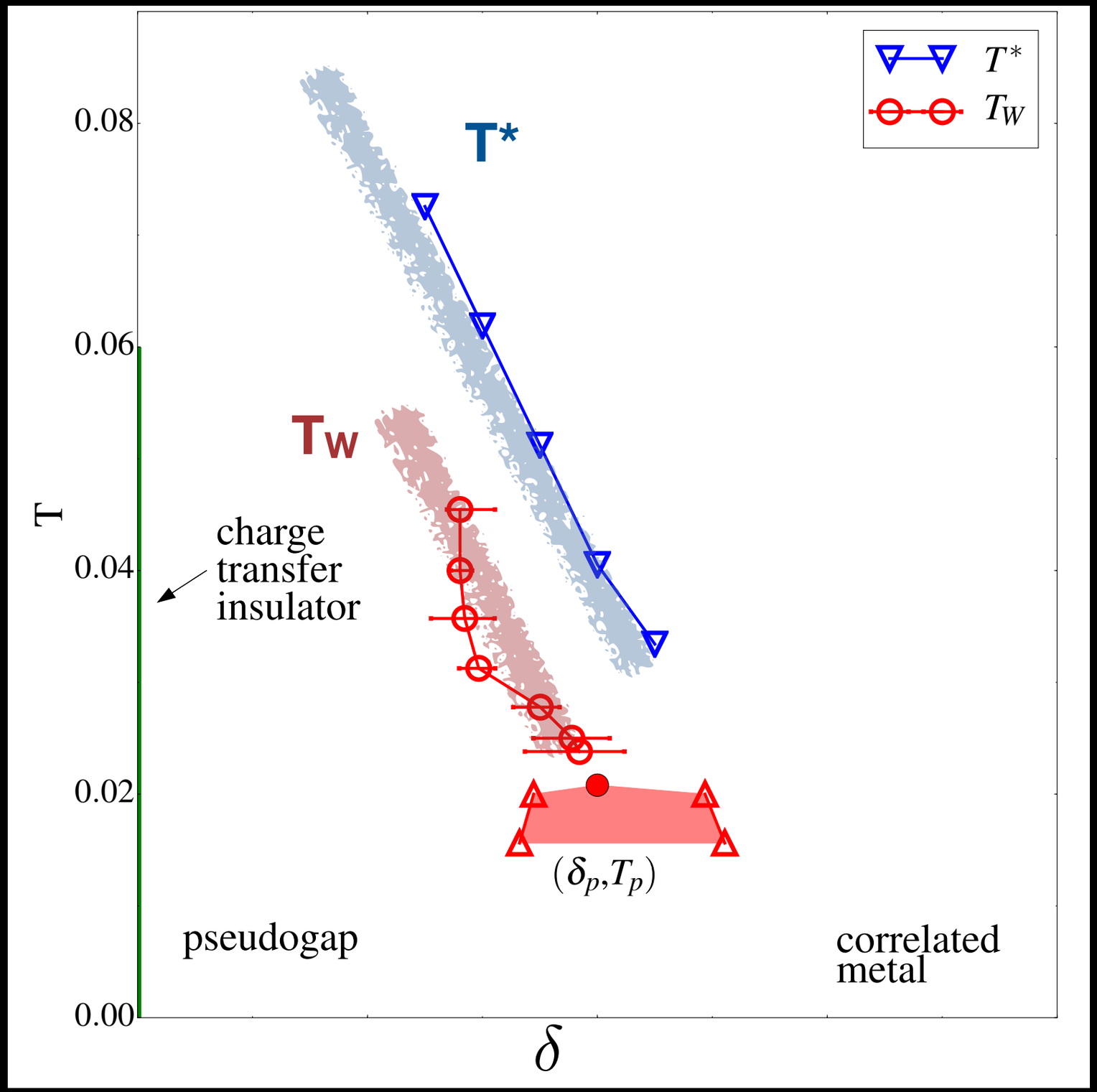
Xu et al, PNAS 2005, Simeoni et al, Nat Phys 2010

T*:onset of the pseudogap





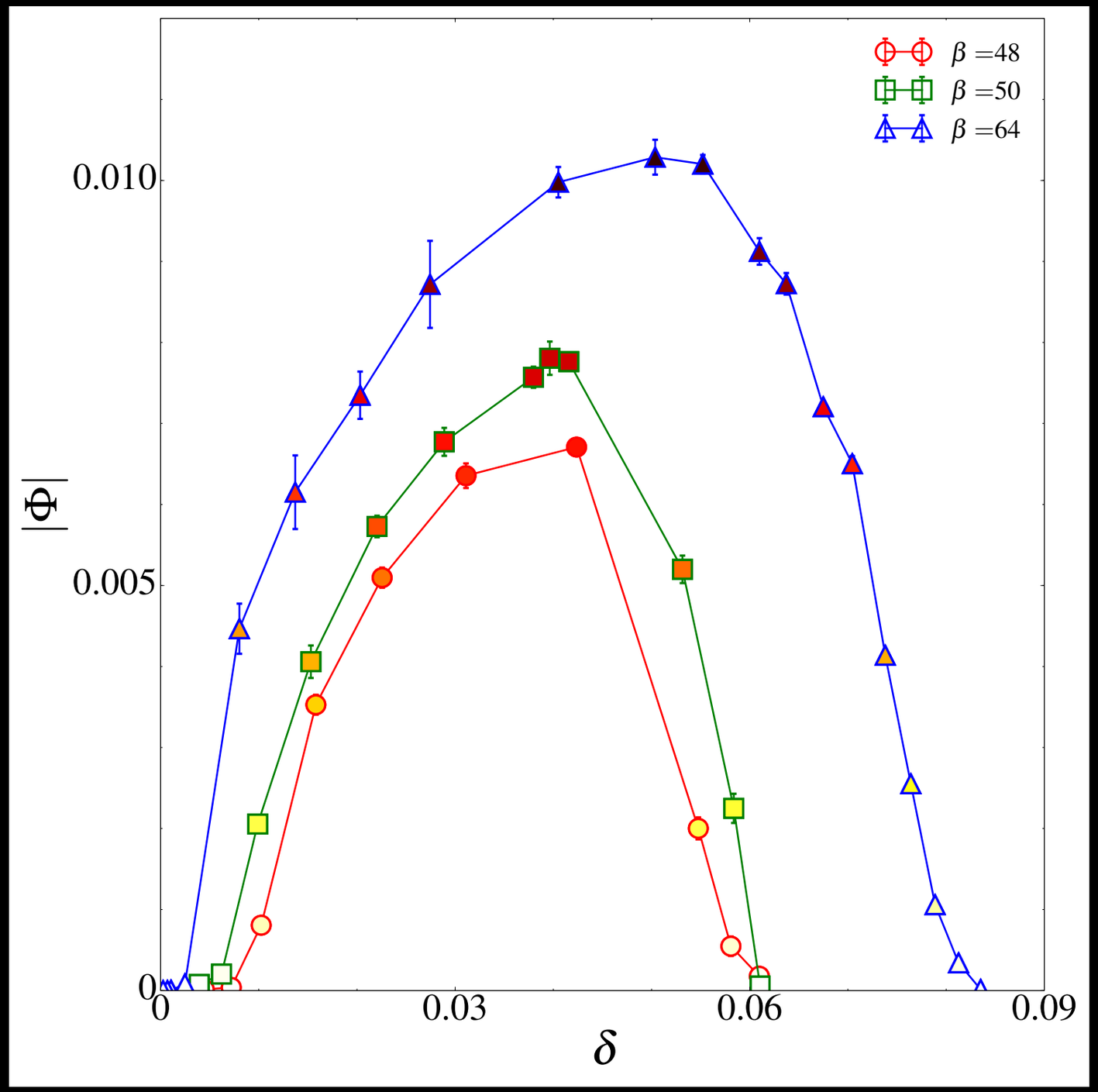
hole-doping driven metal-insulator transition



Tw : pseudogap temperature scale

T*:onset of the pseudogap (high temperature precursor of Tw)

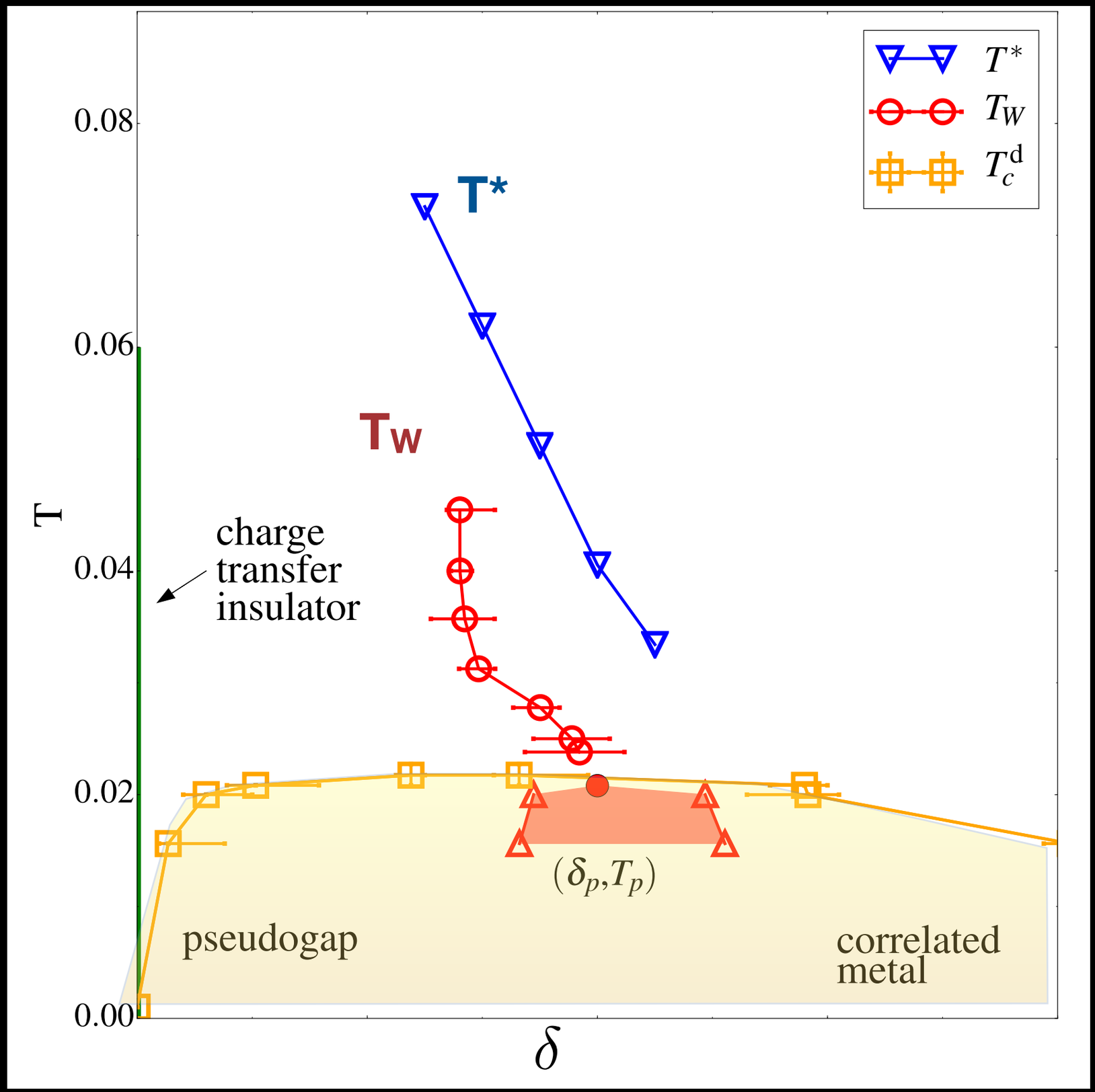
Superconducting phase



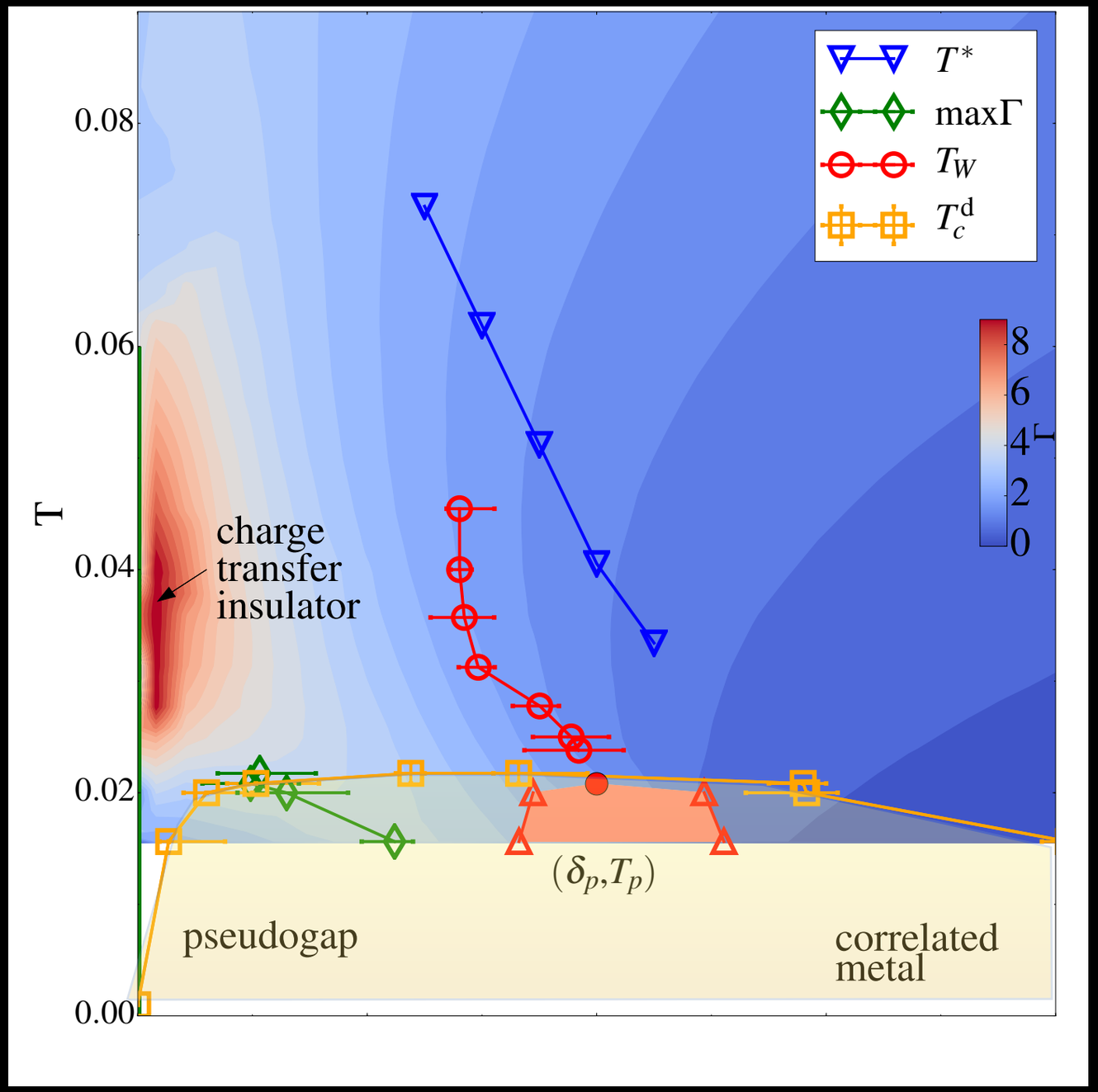
Order parameter:

$$|\Phi| \equiv |\langle d_i^\dagger d_j^\dagger \rangle|$$

d-wave superconductivity

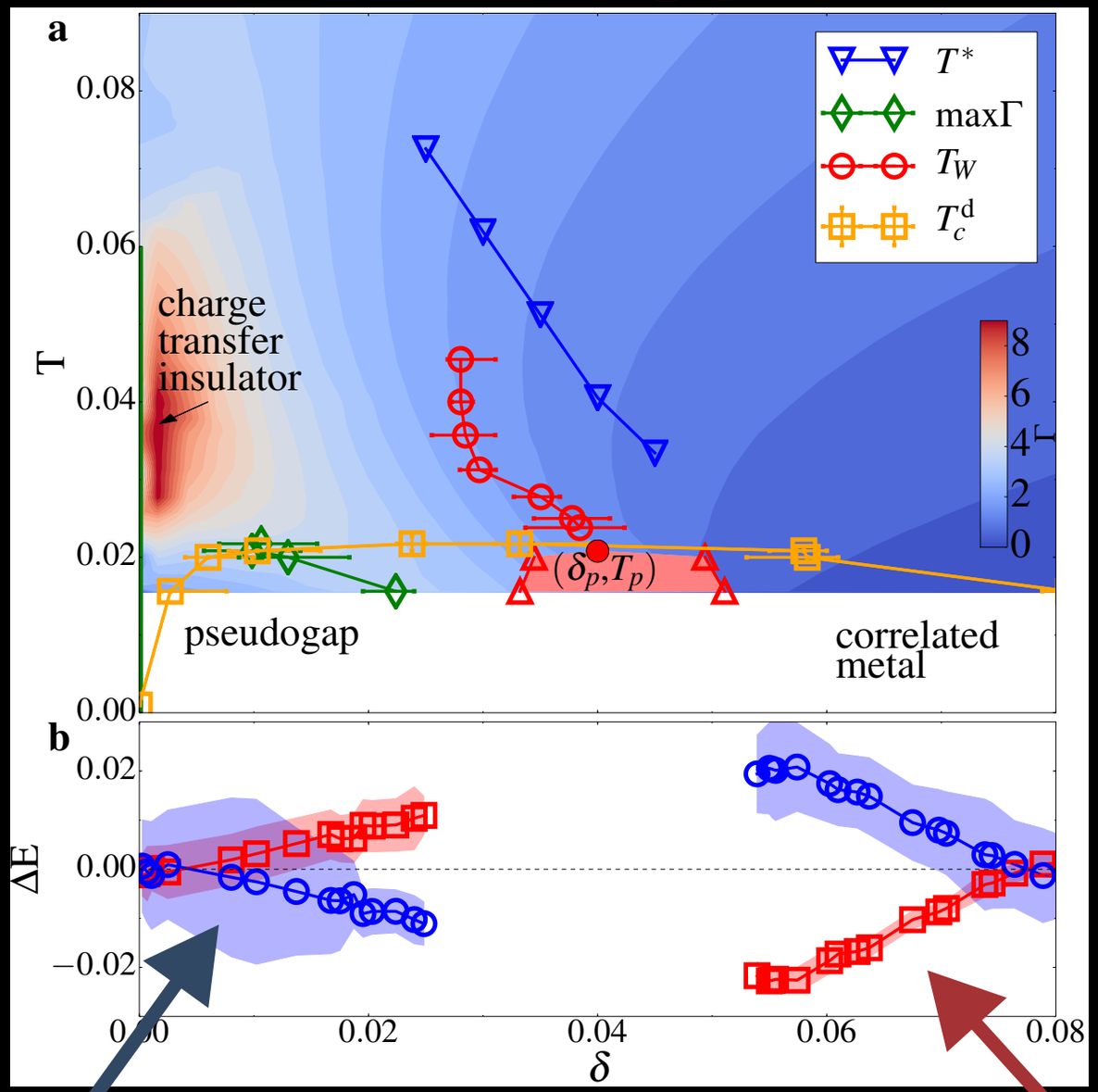


d-wave superconductivity



First order transition is the unifying feature of the self energy anisotropy

Condensation energy



kinetic energy driven SC

potential energy driven SC

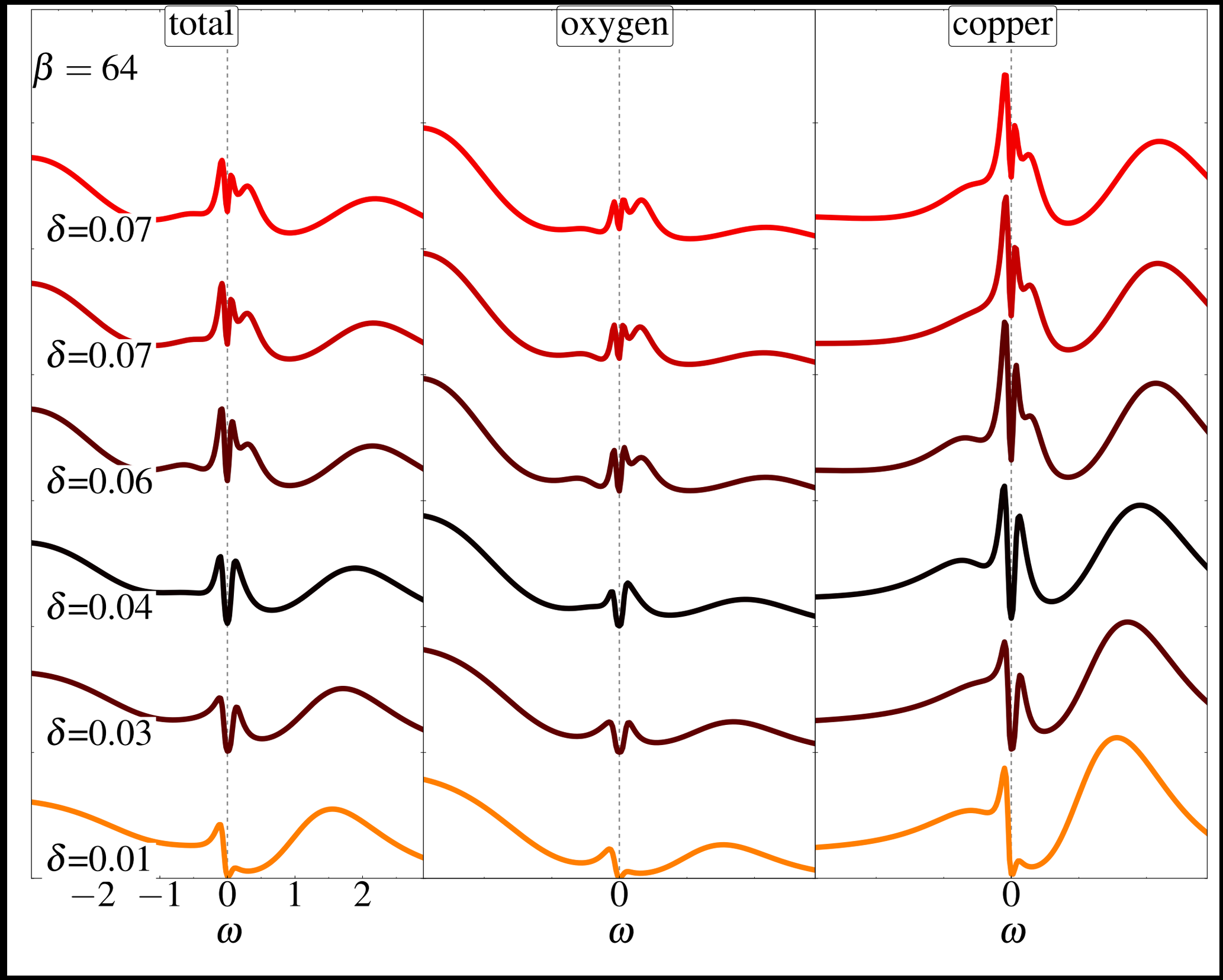
BLUE

$$\Delta E_{kin} = E_{kin}^{\mathrm{SC}} - E_{kin}^{\mathrm{NS}}$$

RED

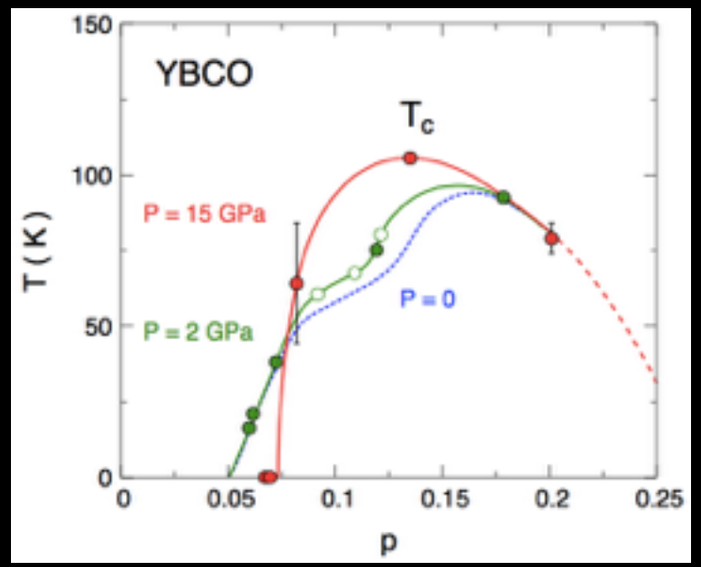
$$\Delta E_{pot} = E_{pot}^{\mathrm{SC}} - E_{pot}^{\mathrm{NS}}$$

d-wave superconductivity



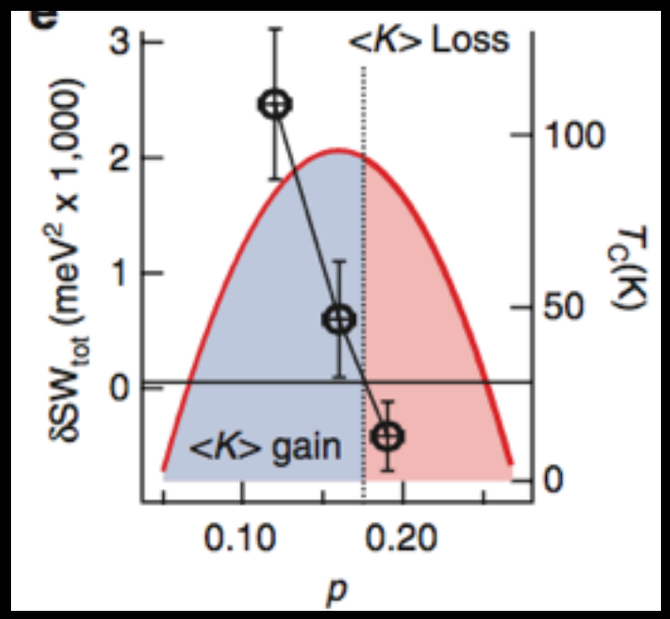
d-wave superconductivity

1. why is there a dome and why is it shaped this way?



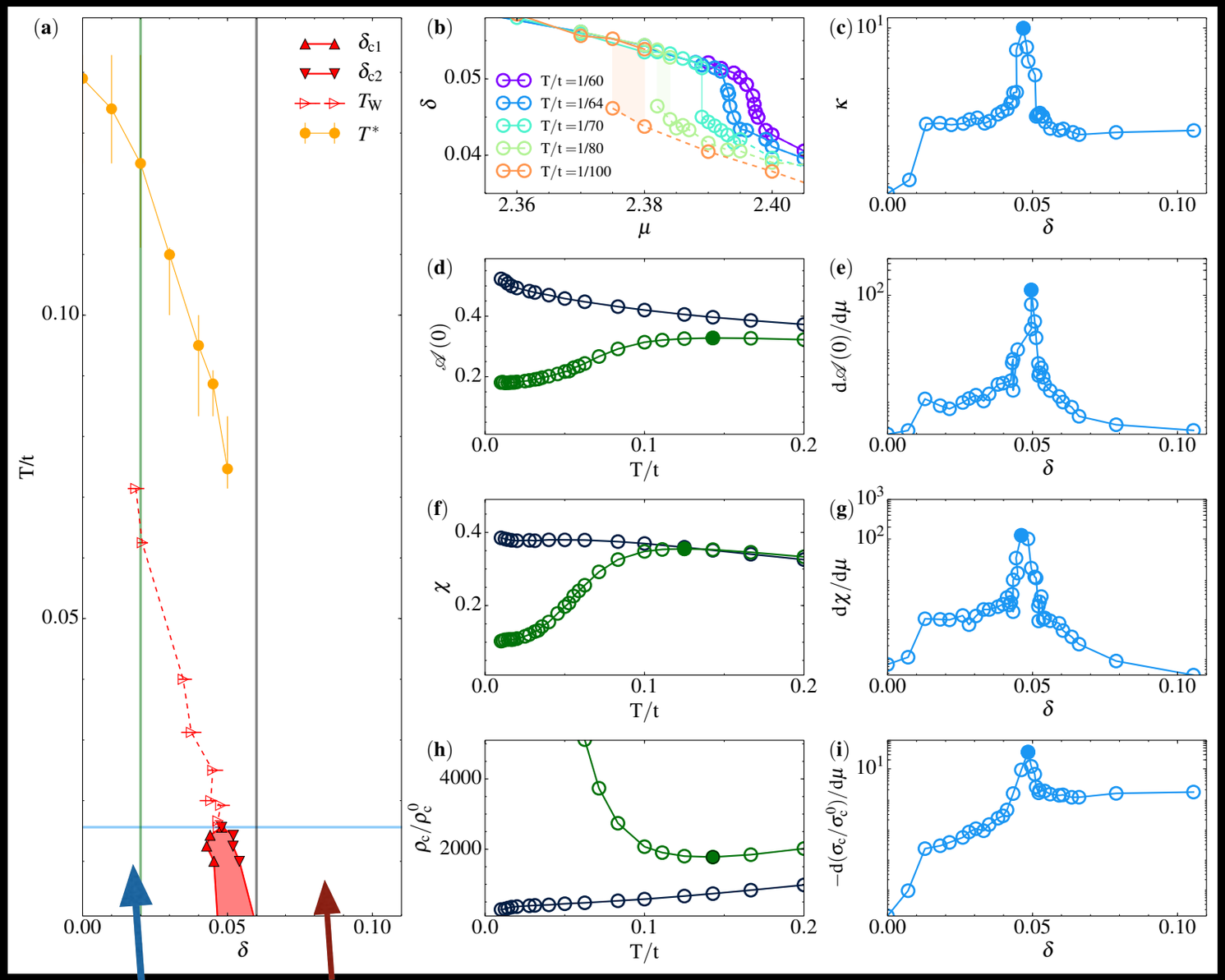
Cyr-Choiniere et al, arXiv 2015; Sadewasser et al, PRB 2000

2. what drives the change from potential energy driven to kinetic energy driven SC?



Giannetti et al, Nat Comm 2014; Deutscher et al, PRB 2005; Molegraaf et al, Science 2002; Carbone et al, PRB 2006

1-band scenario: The first order transition as organising principle of the normal state



Above it a crossover line can be defined from characteristic anomalies of:

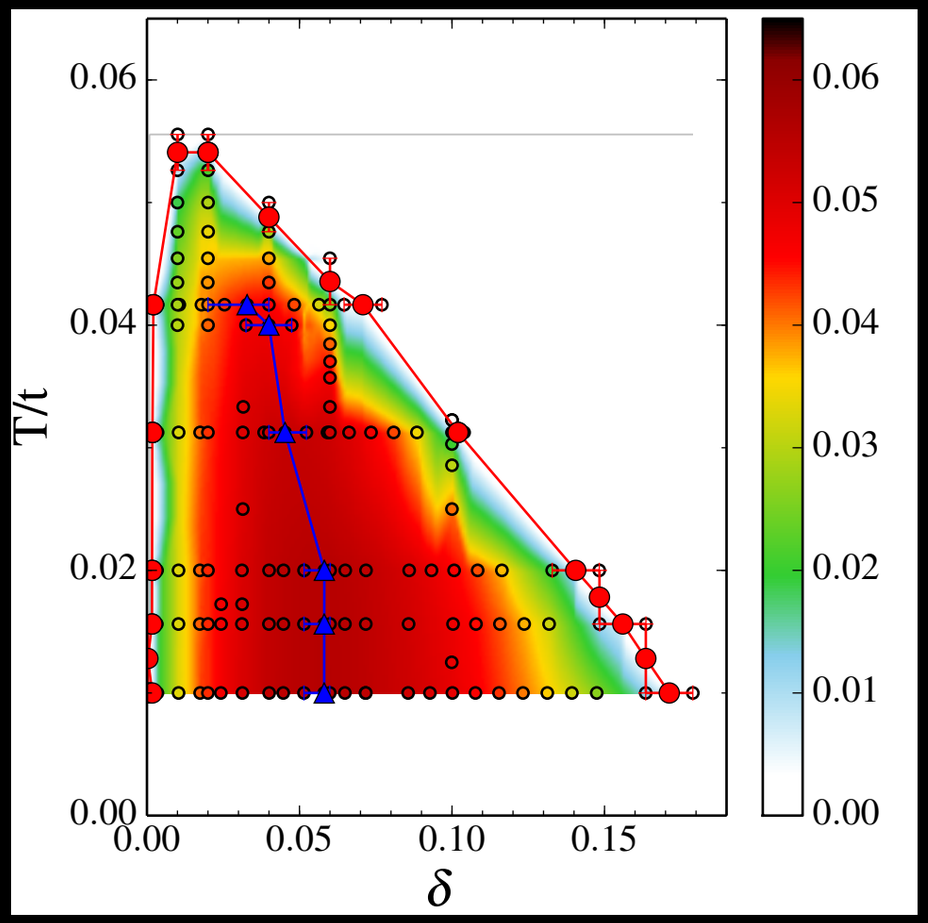
- thermodynamic
- dynamic
- transport

Correlated metal

Pseudo gap

Sordi G. et al., PRL (2010), PRB (2011), Sci. Rep. (2012)

Superconducting state



Order parameter:

$$\Phi \equiv < \hat{c}_{\mathbf{K},\uparrow} \hat{c}_{-\mathbf{K},\downarrow} >$$

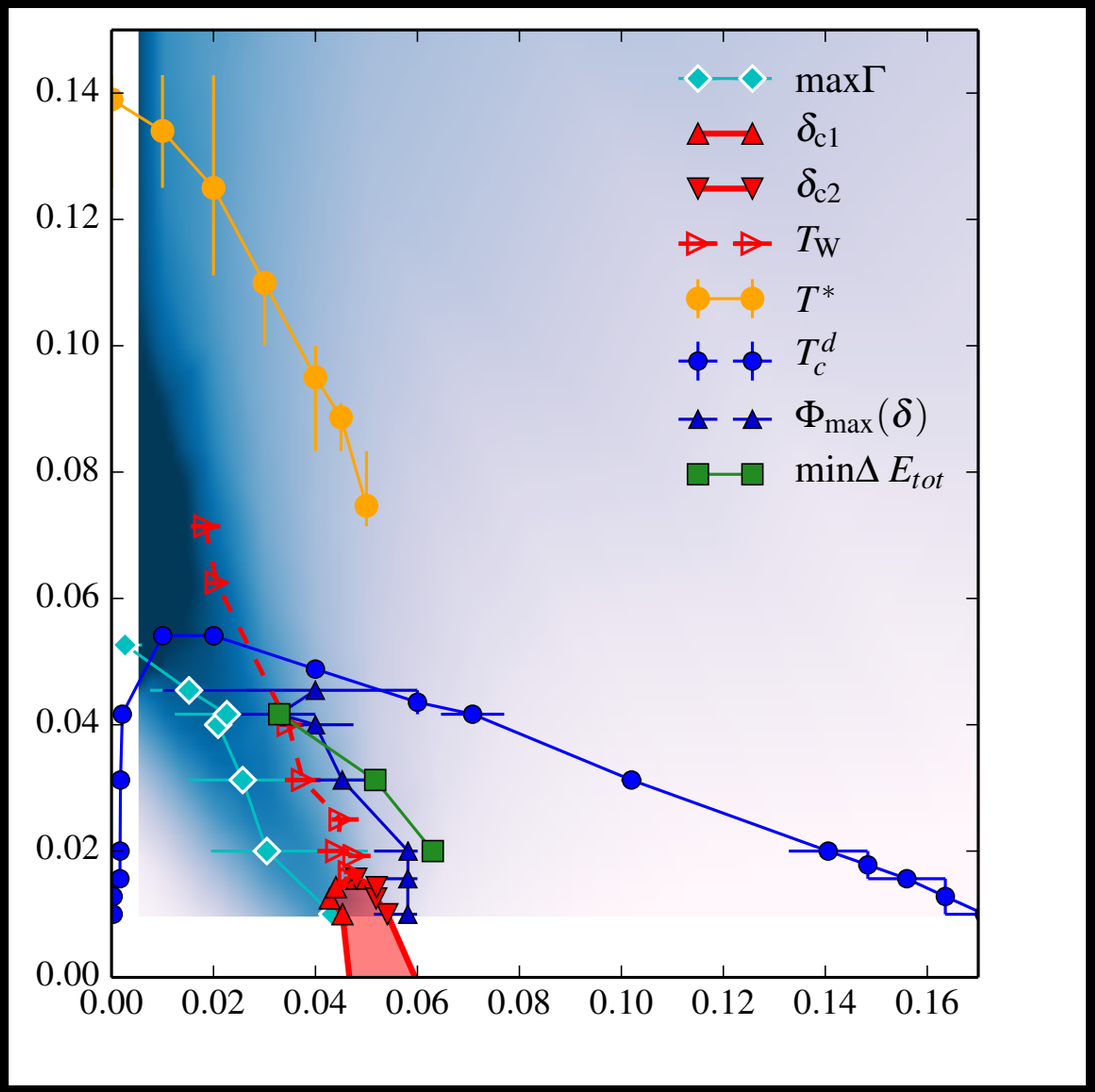
with $\mathbf{K} = (\pi, 0)$

Tc does not scale with ϕ

asymmetry of SC dome is linked to ϕ_{max}

L. Fratino et al., Scientific Reports 6, 22715 (2016)

The organising principle of SC

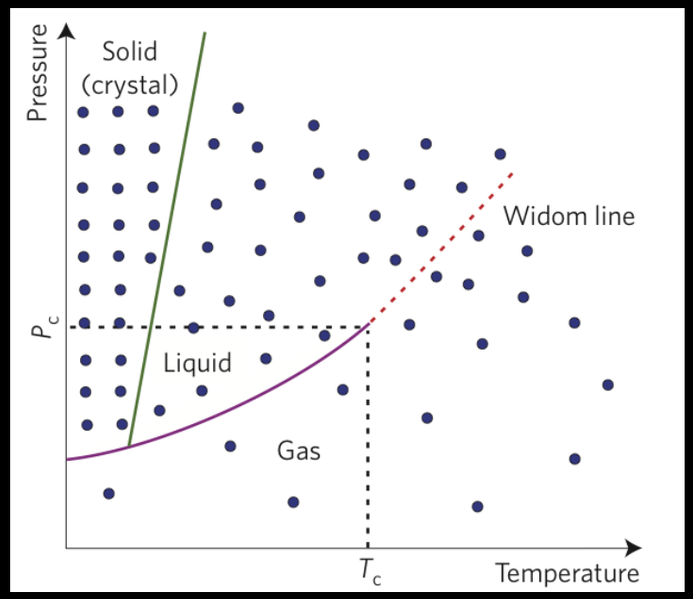


- Φ_{max} closely parallels to T_W
- Φ_{max} closely parallels to $\mathbf{\Gamma}_{max}$
- $\mathbf{\Gamma}_{max}$ crosses Tc at δ_{opt}
- SC emerges from pseudo gap or from correlated metal
- condensation energy parallels Φ_{max}

superconductivity and pseudogap are intertwined phenomena

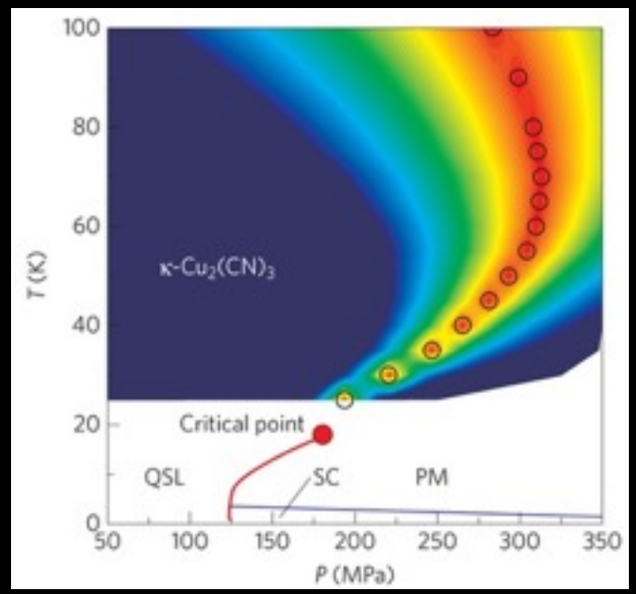
Widom line found in water

McMillan and Stanley, Nat Phys 2010

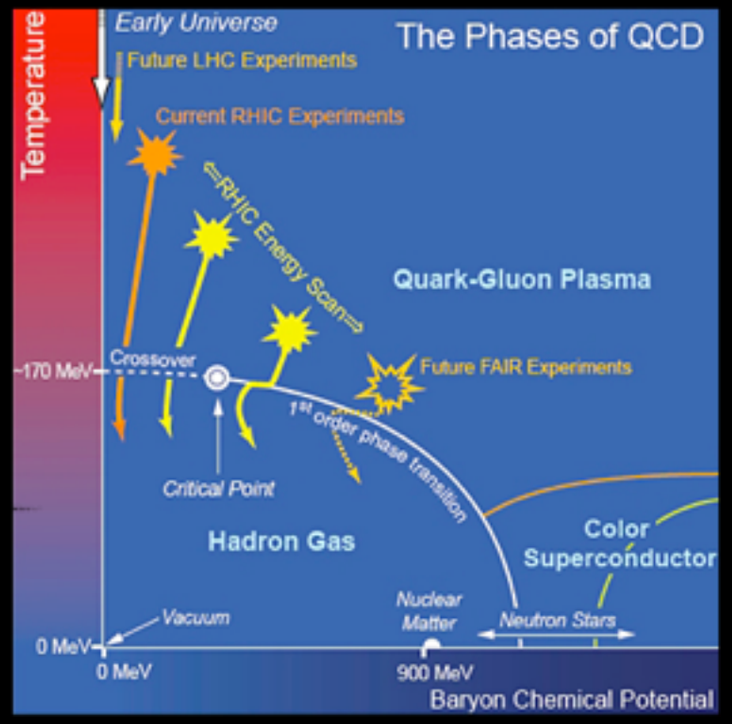


Widom line found in k-organics!

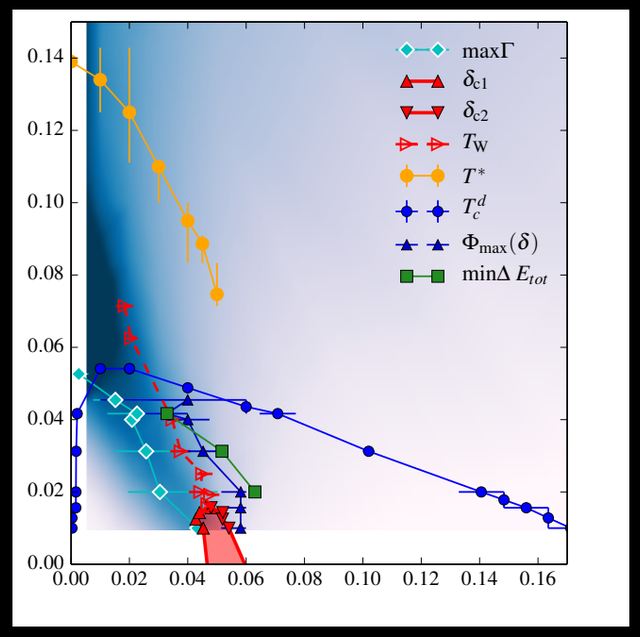
Furukawa, Nat. Phys. (2015)



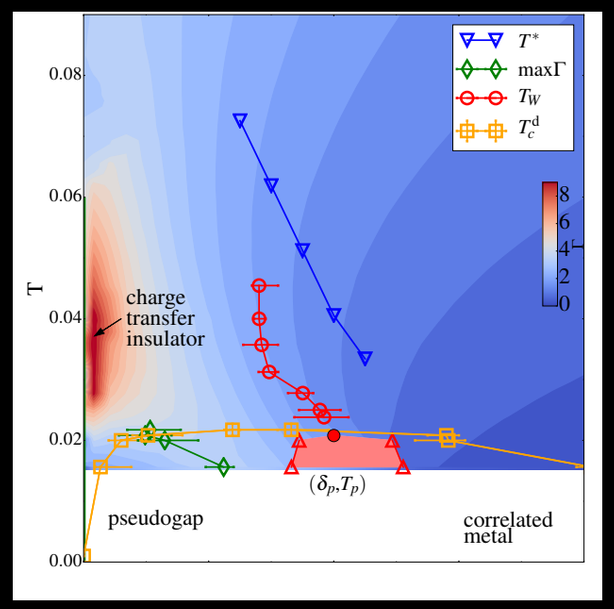
Widom line in the QCD phase diagram?



Widom line a universal organising principle in physics!



L. Fratino et al., Scientific Reports 6, 22715 (2016)



L. Fratino et al., Phys. Rev. B 93, 245147 (2016)

I am currently looking for a postdoc

Do you have funding for the next year?
Let's talk about it!

Thank you for the attention!