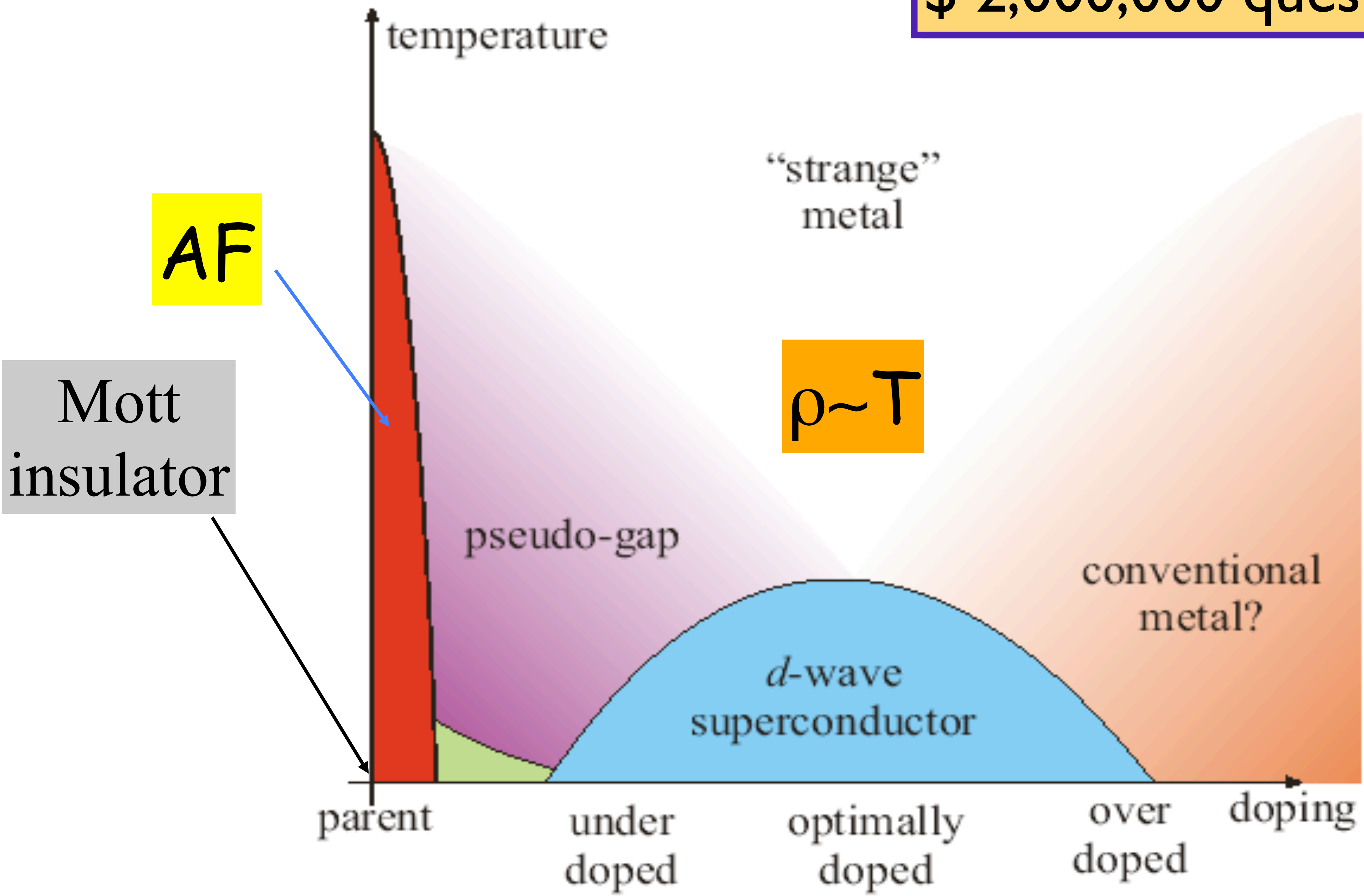
Does the thermopower solve the riddle of high temperature superconductivity?

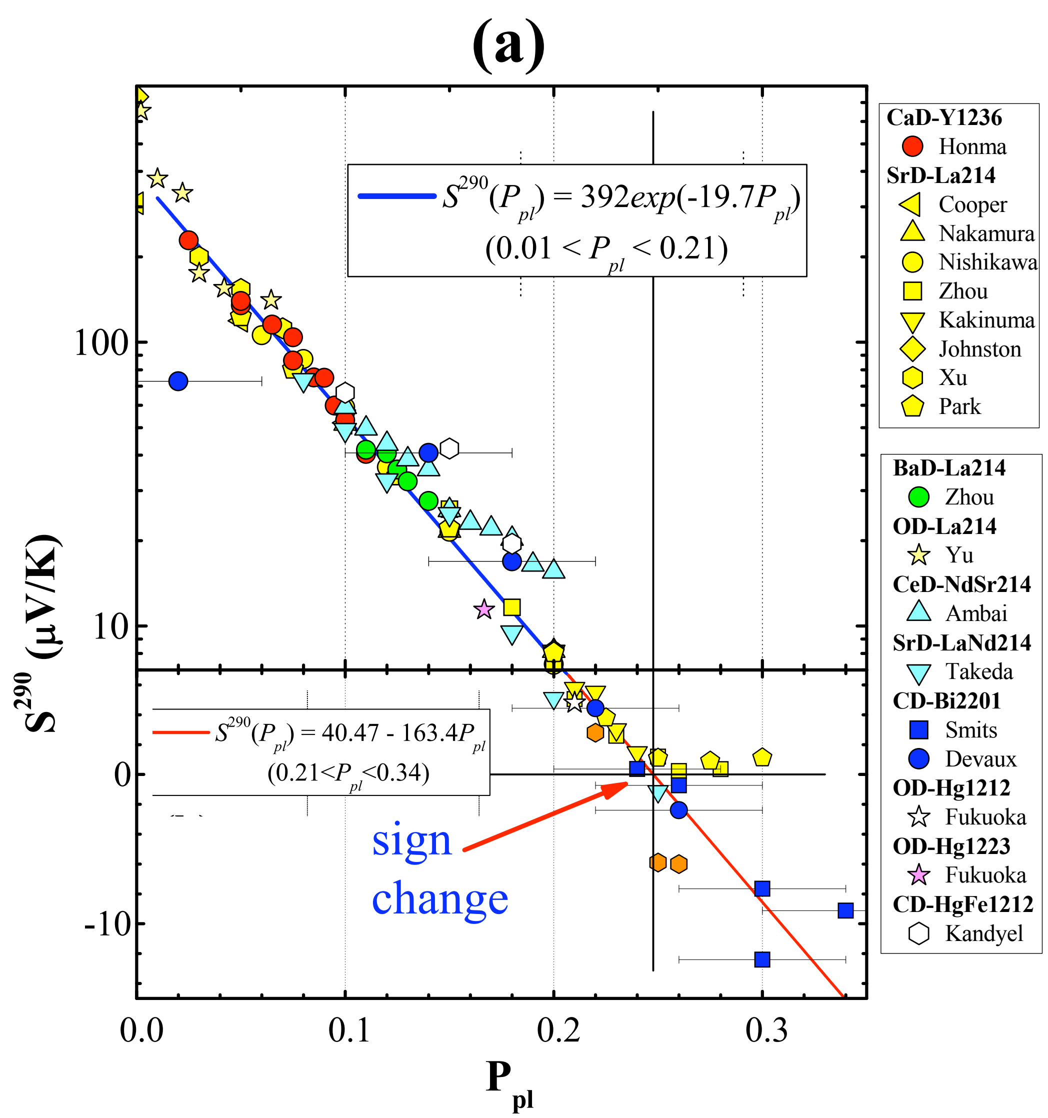
Thanks to: T.-P. Choy, R. G. Leigh, S. Chakraborty, S. Hong
(PRL, 99, 46404 (2007);
PRB, 77, 14512 (2008); ibid, 77, 104524 (2008))

Why is the T_c region dome-shaped?

$ 2,000,000 question?



Universal sign change of thermopower



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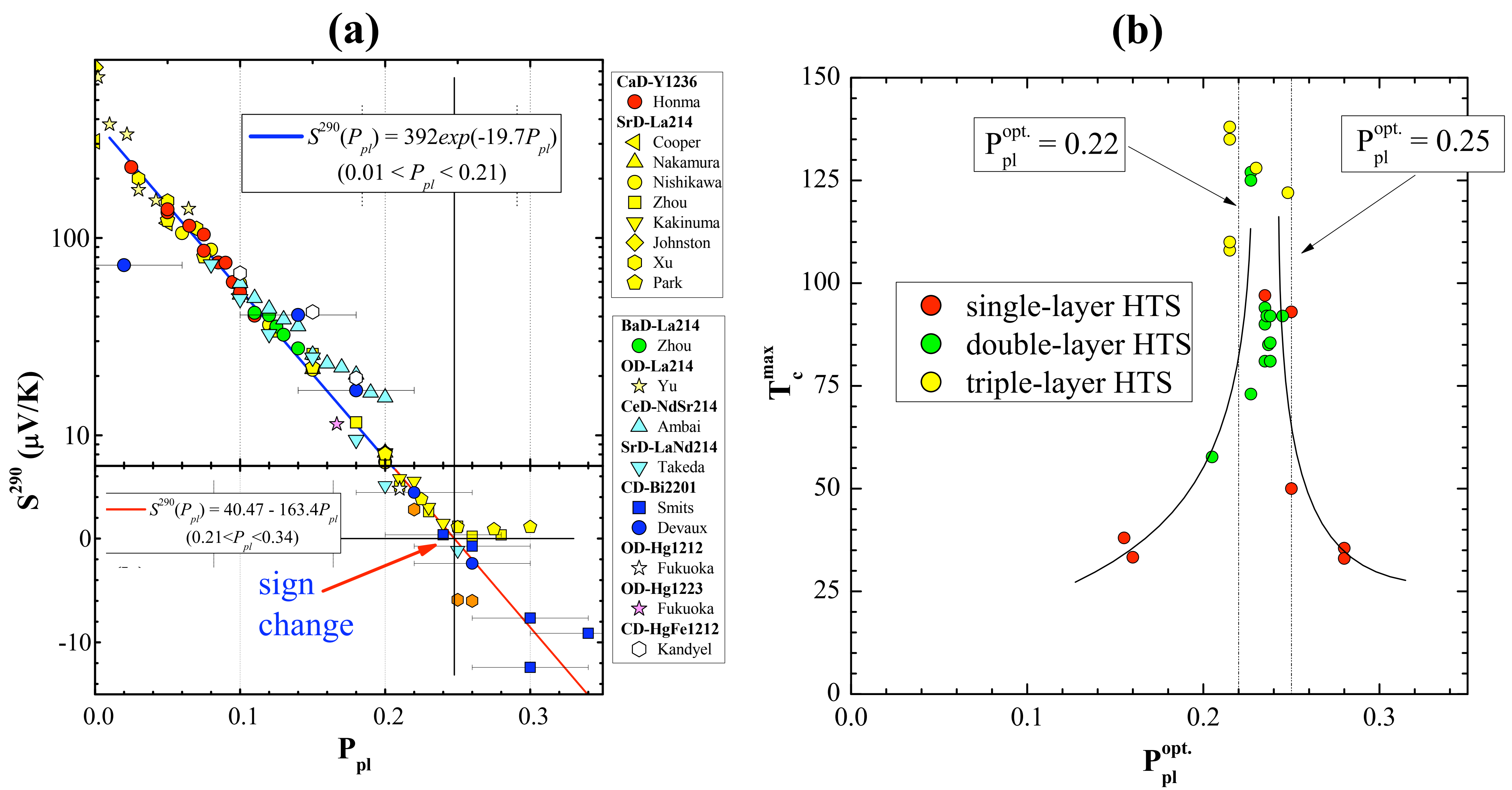

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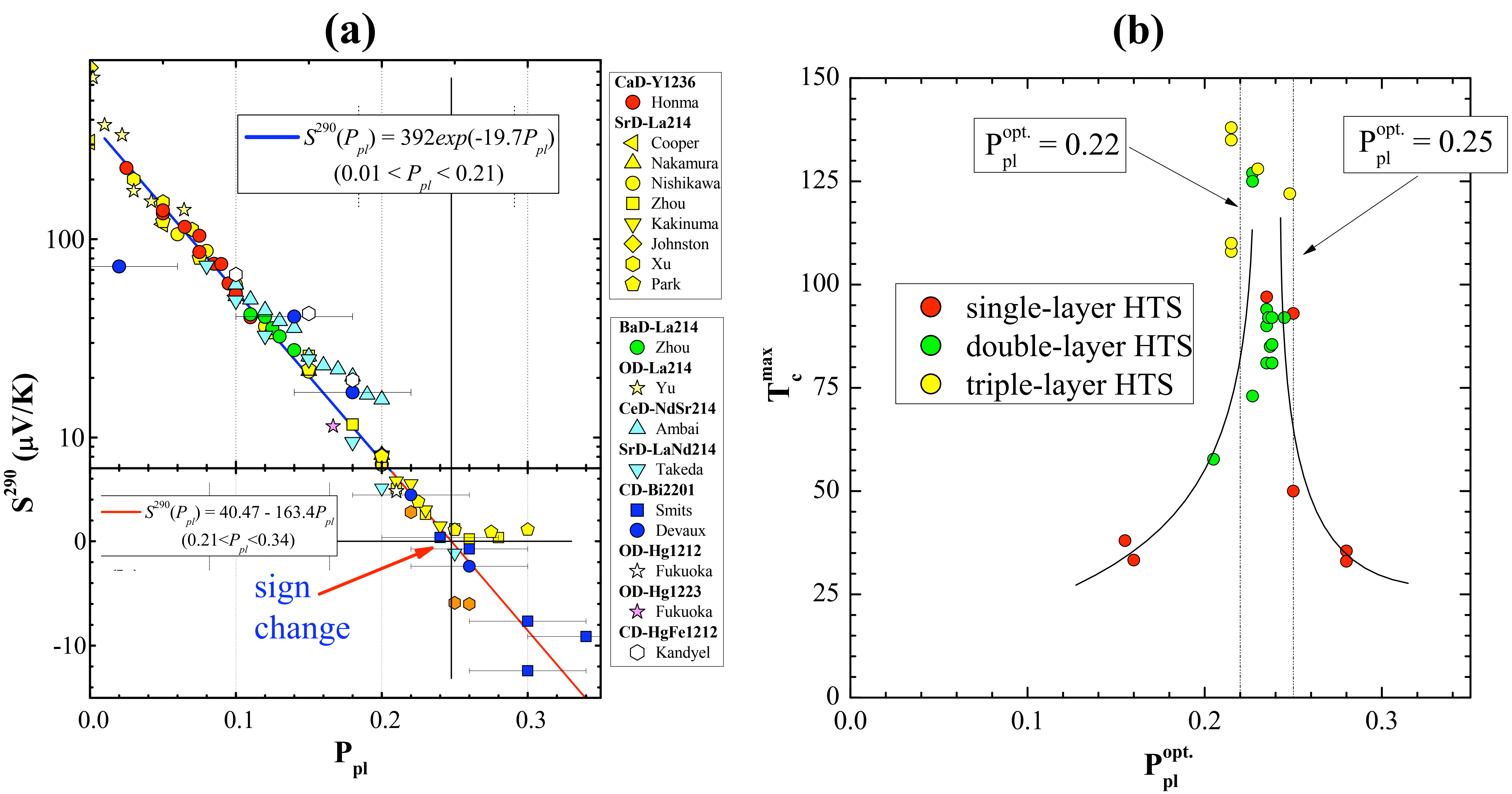
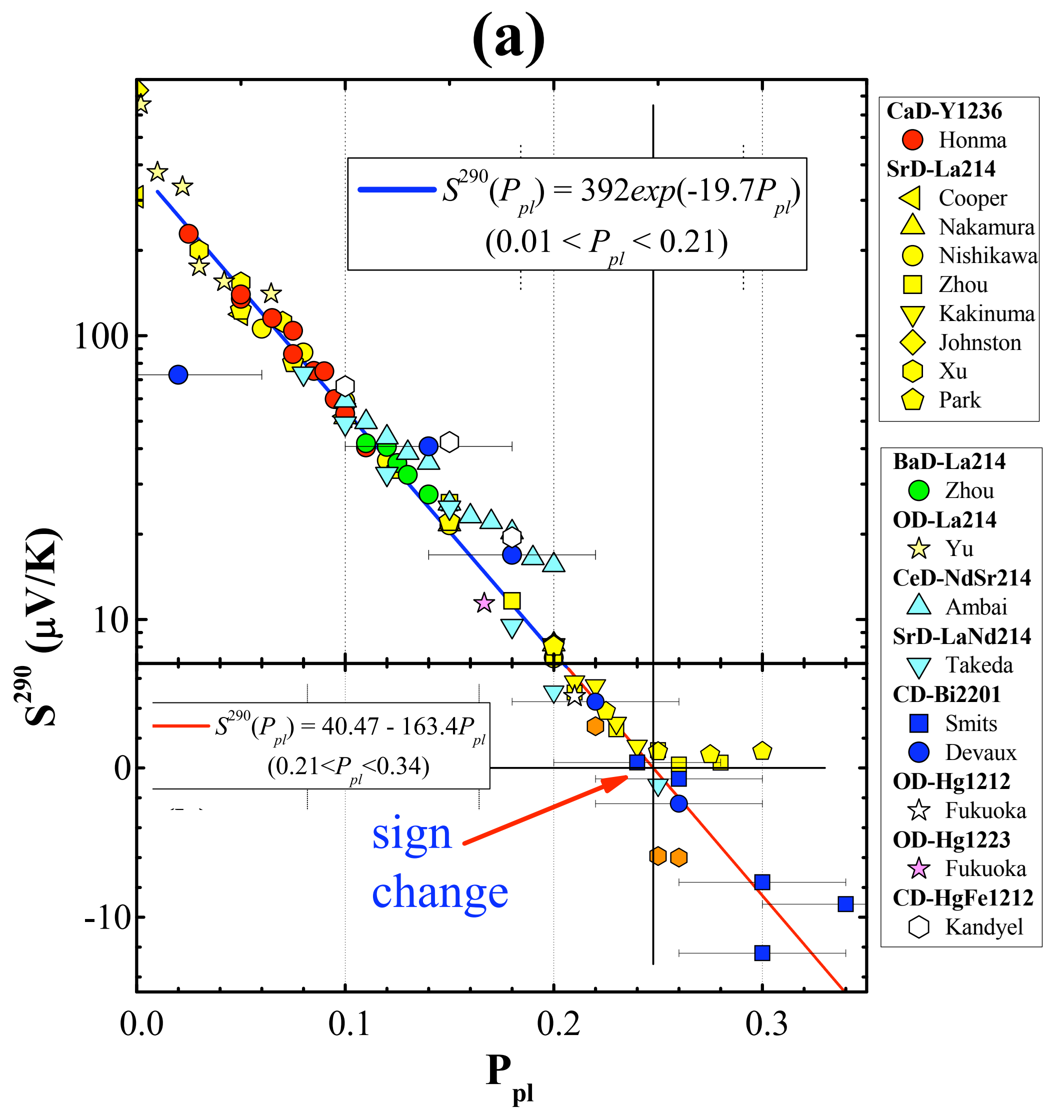
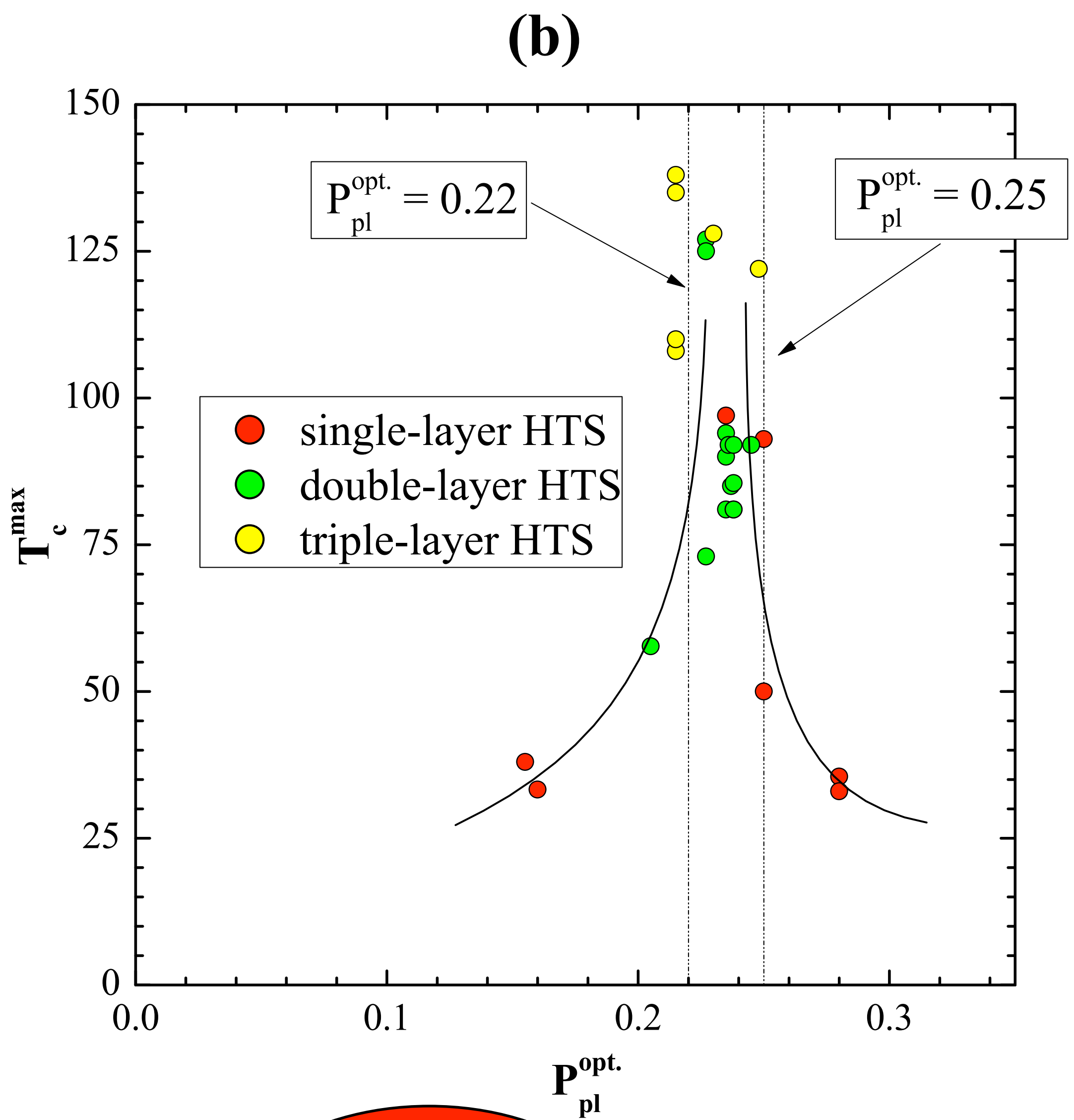
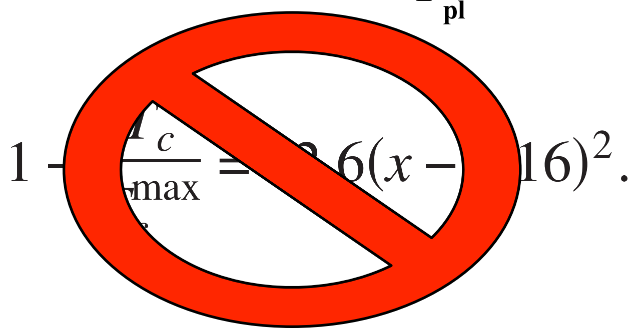


$$1 - \frac{T_c}{T_c^{\max}} = 82.6(x - 0.16)^2.$$

Universal sign change of thermopower







How valid is the thermopower doping scale?

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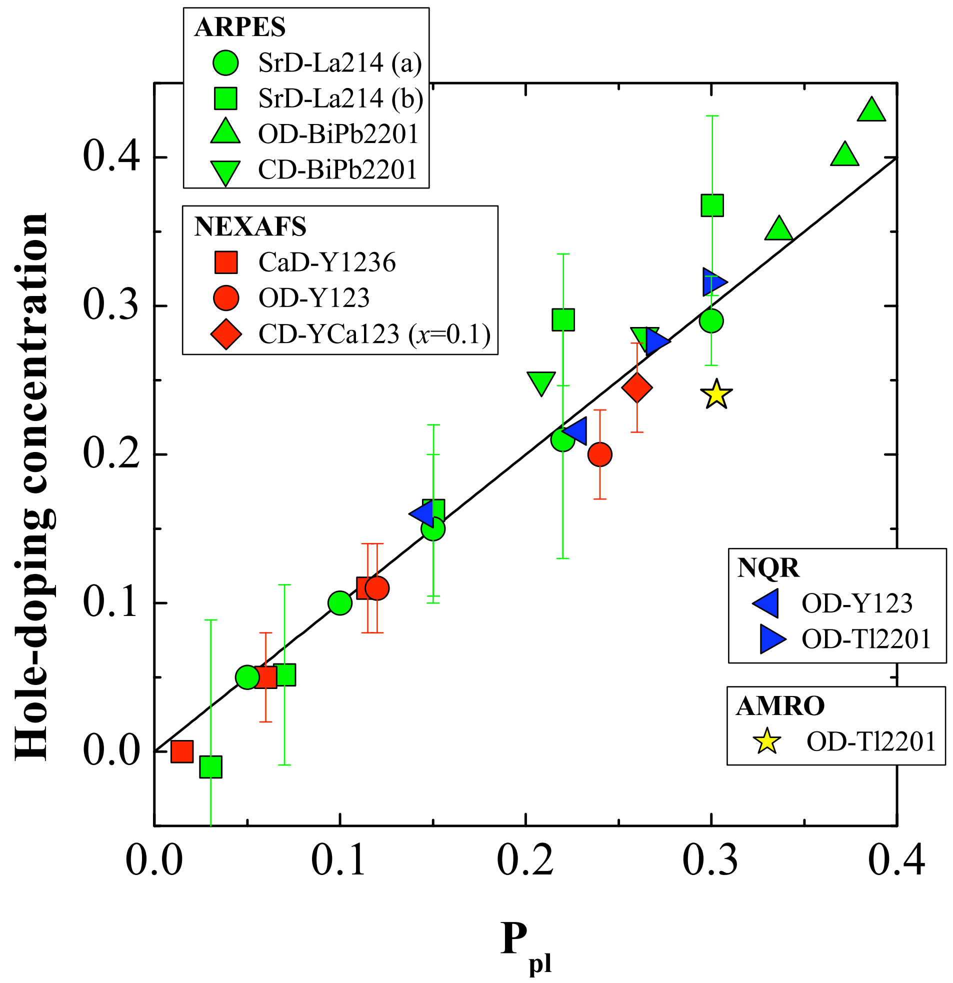
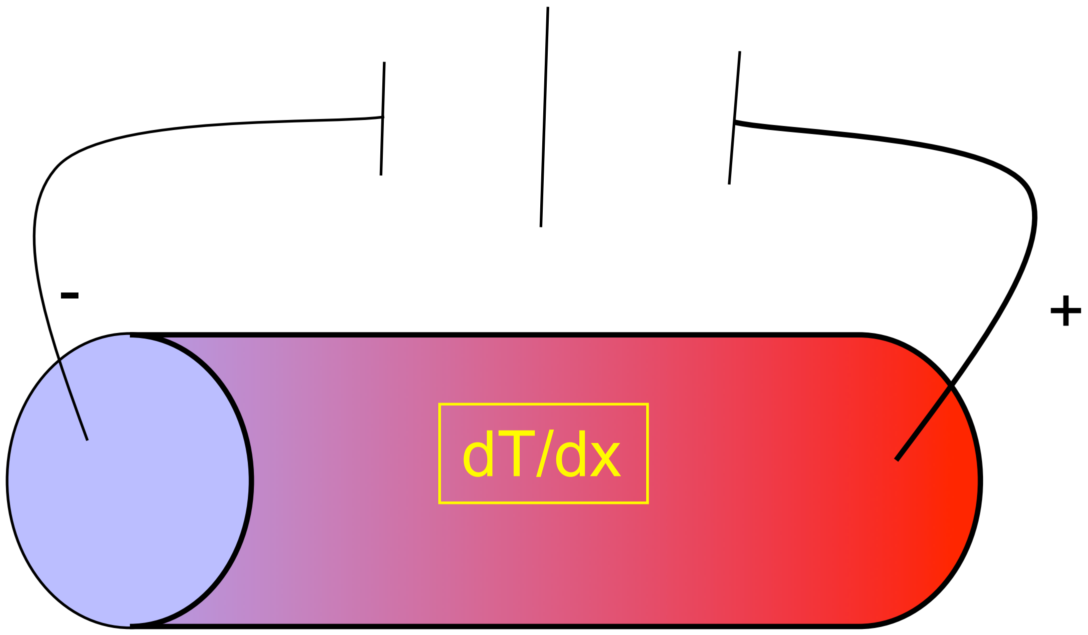


Why?

Mottness



$S=V/\Delta T$

entropy per carrier

particle-number conservation

Thermopower Primer

$$S = -\frac{k_B}{e}\beta\frac{L_{12}}{L_{11}}$$

$$L_{ij} = \int_{-\infty}^{\infty} d\omega(-\frac{\partial f(\omega)}{\partial \omega})\tau^i(\omega)\omega^{j-1}$$

$$\tau(\omega) = \frac{1}{N}\sum_{\mathbf{k},\sigma}(\frac{\partial \epsilon_{\mathbf{k}}}{\partial k_x})^2 A^2(\mathbf{k},\omega)$$

spectral function

1.) τ must be symmetric about the chemical potential for S=0

2.) but if A is momentum-independent, S=0 by particle-hole symmetry

G. Beni, Phys. Rev. B vol. 10, 2186 (1973).

Exact calculation of S for atomic (t=0) limit of Hubbard model

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vanishes at half-filling

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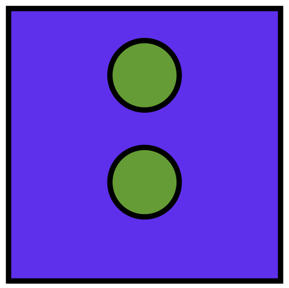
S=0 when x=1/3; WHY?

What is so special about 2x and 1-x?

Why is the atomic limit of the Hubbard model p-h symmetric at $x=1/3$?

classical Mottness



is forbidden

classical Mottness

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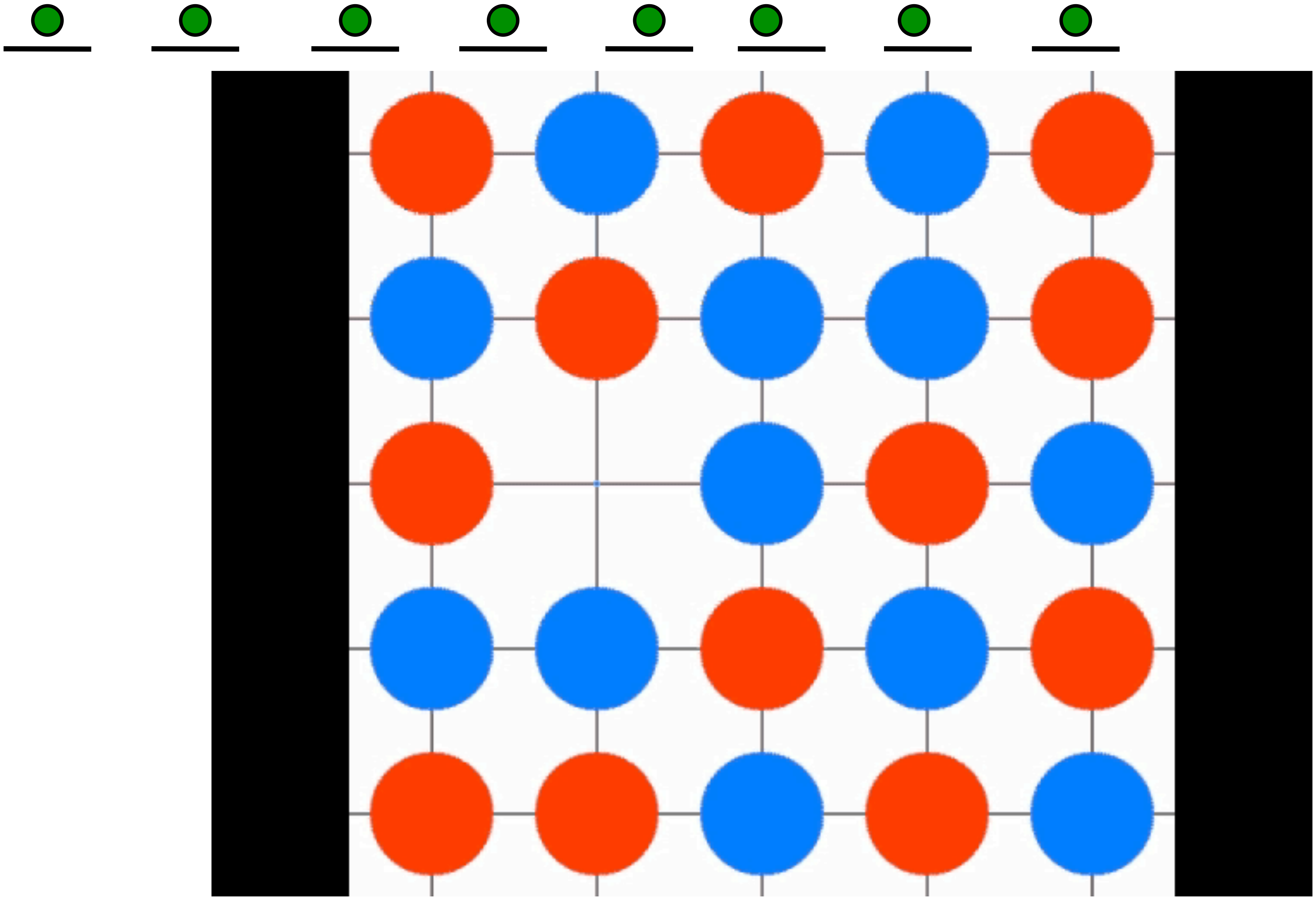
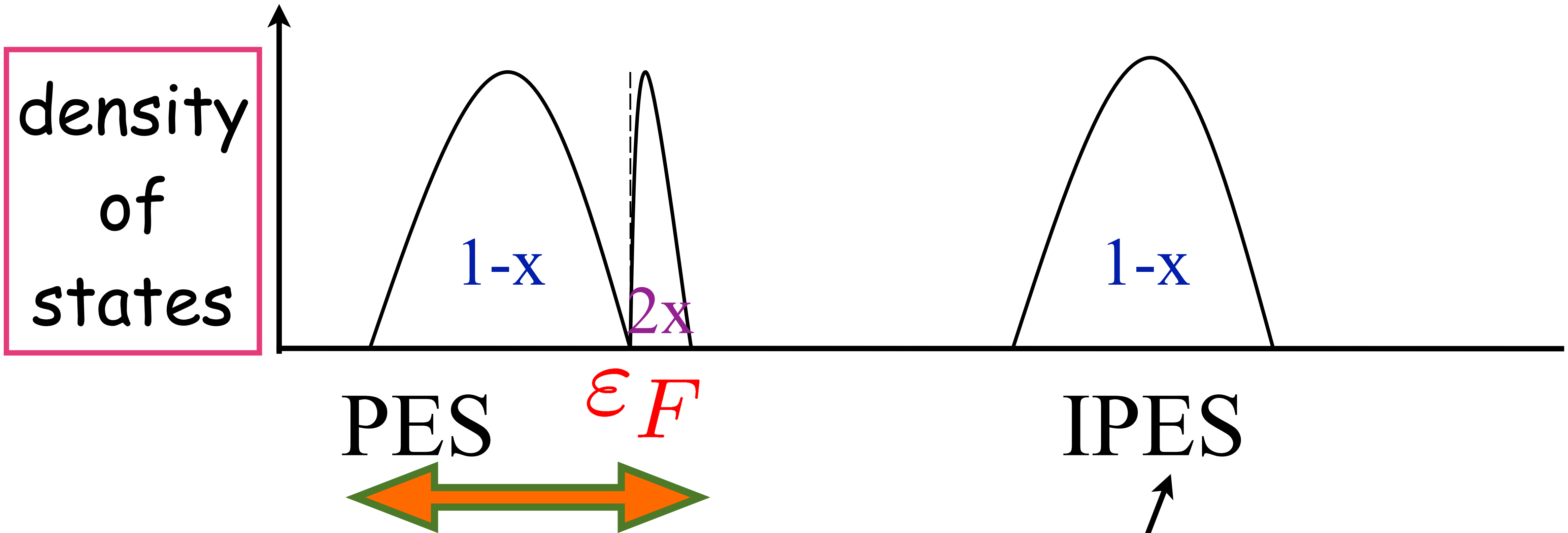
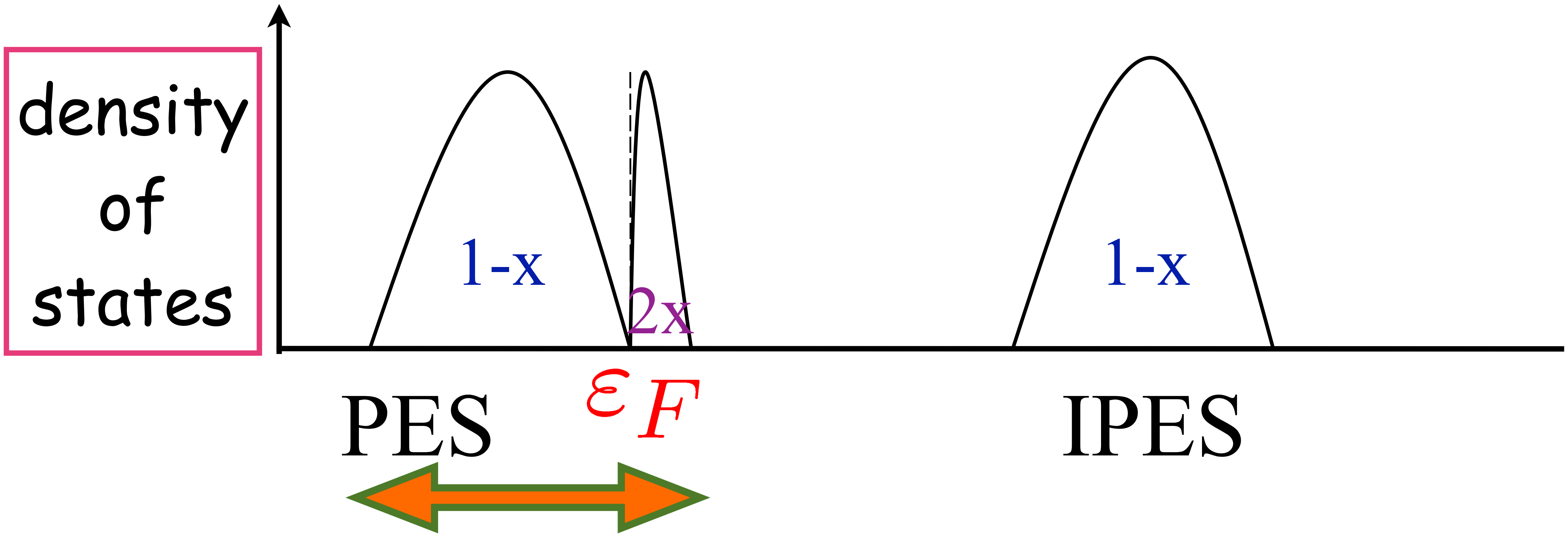


atomic limit: x holes



$$G_\sigma(\omega,k) = \frac{\frac{1}{2}(1+x)}{\omega-\mu+\frac{U}{2}} + \frac{\frac{1}{2}(1-x)}{\omega-\mu-\frac{U}{2}}$$

atomic limit: x holes



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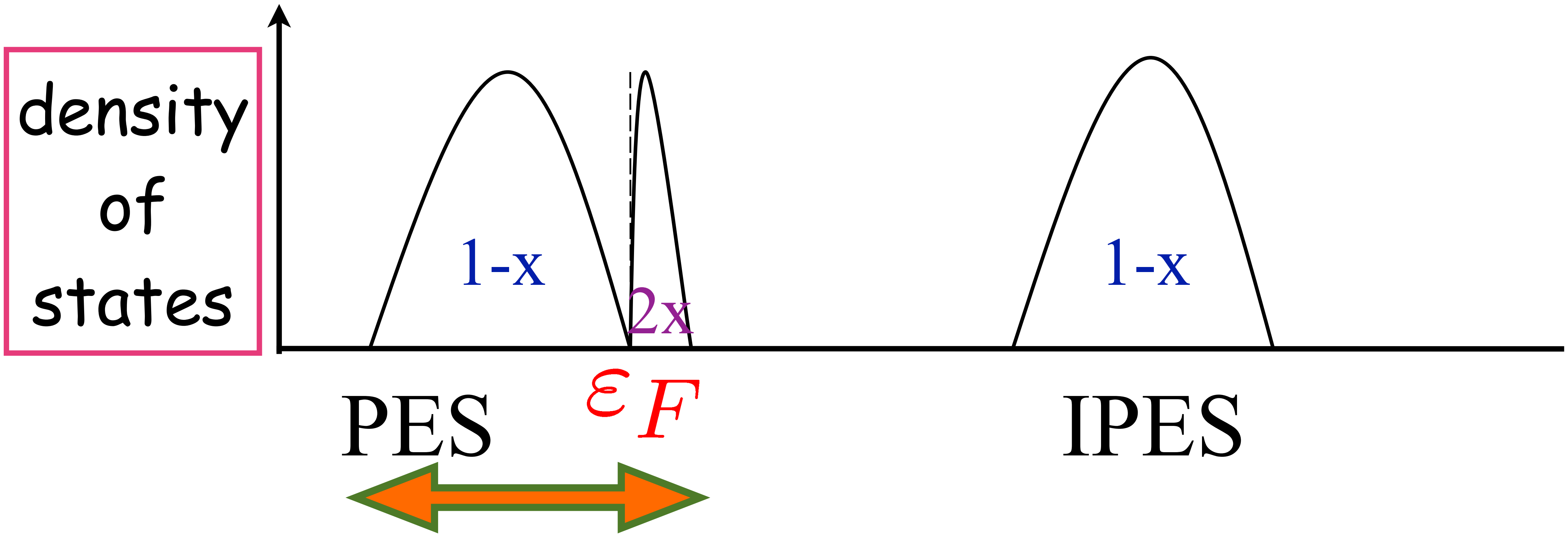


criterion for vanishing of thermopower

LESW above ε_F = LESW below ε_F

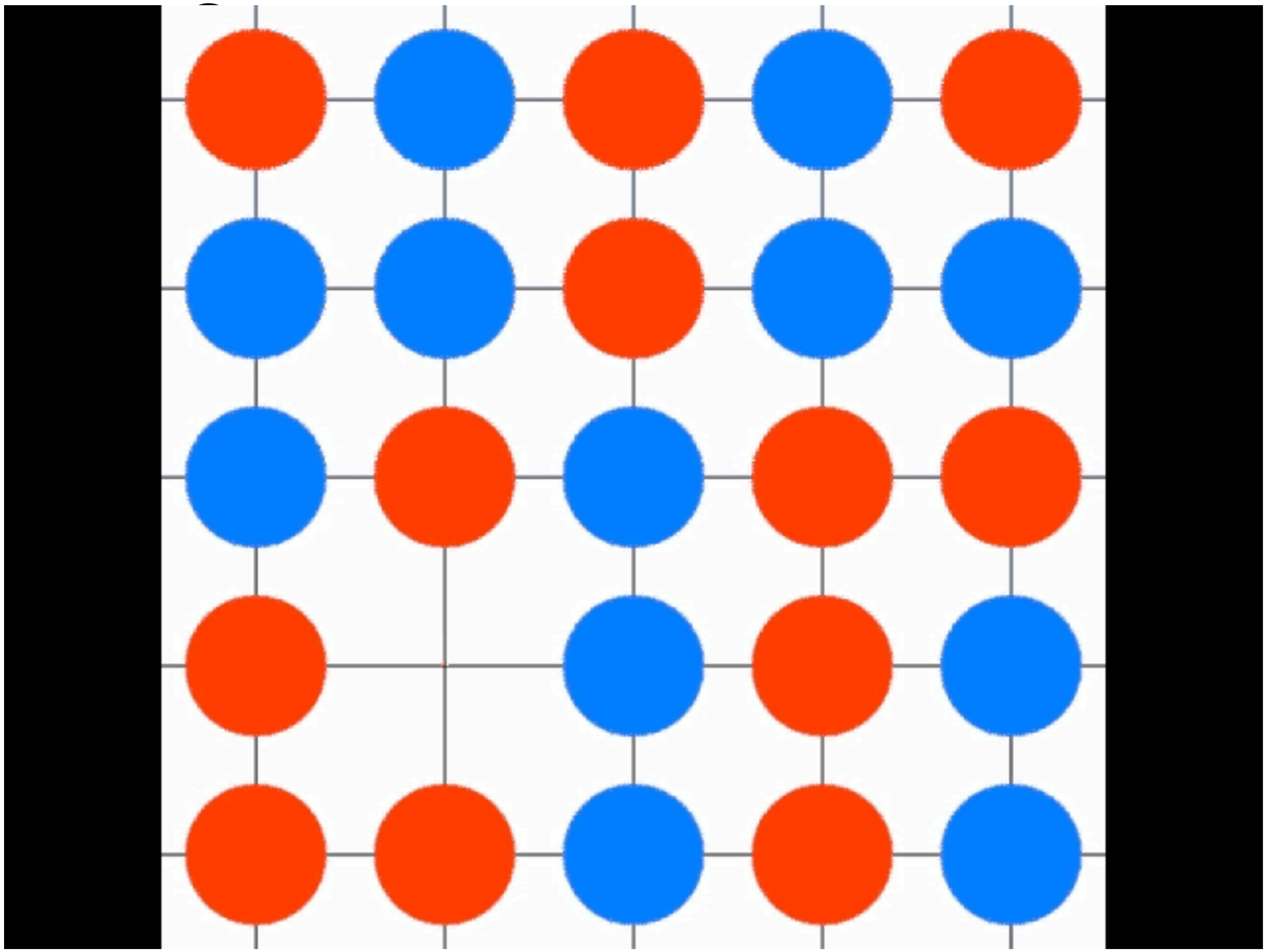
2x=1-x $\rightarrow$ $\boxed{x=1/3!}$

sign change occurs for $x<1/3$

Why?

quantum Mottness: U finite

$U \gg t$



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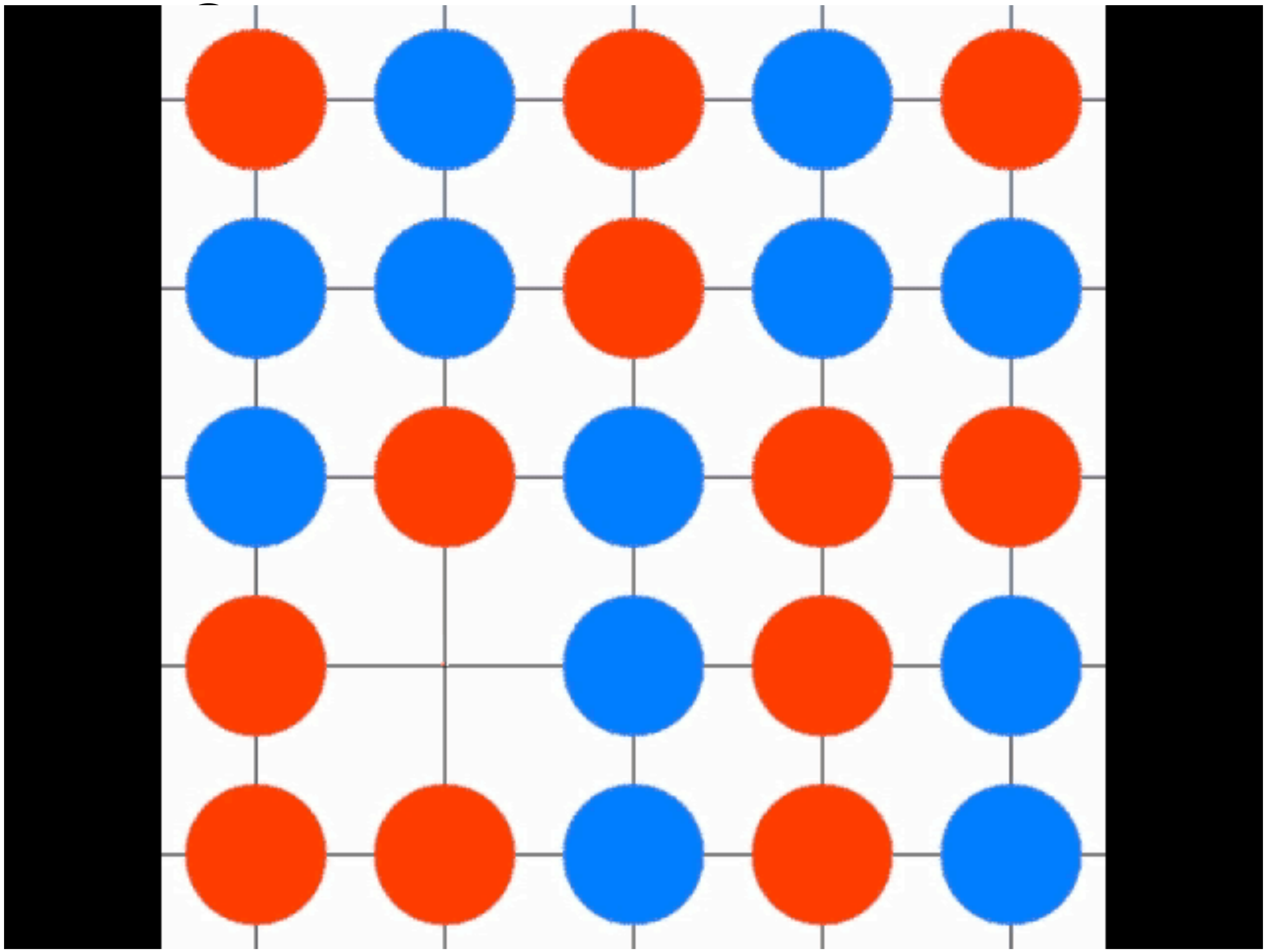

double occupancy in ground state!!

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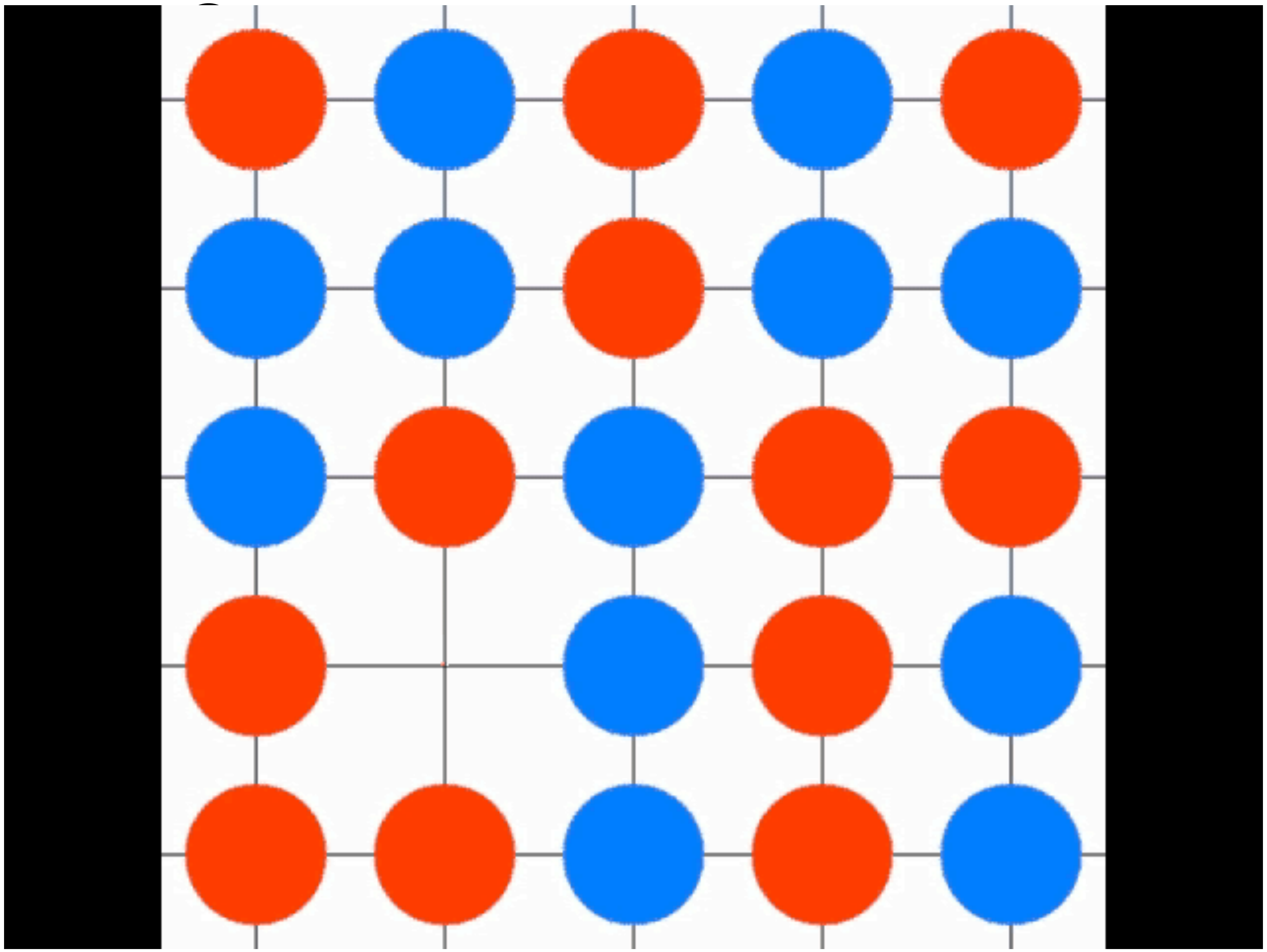


double occupancy in ground state!!

$W_{\rm PES} > 1 + x$

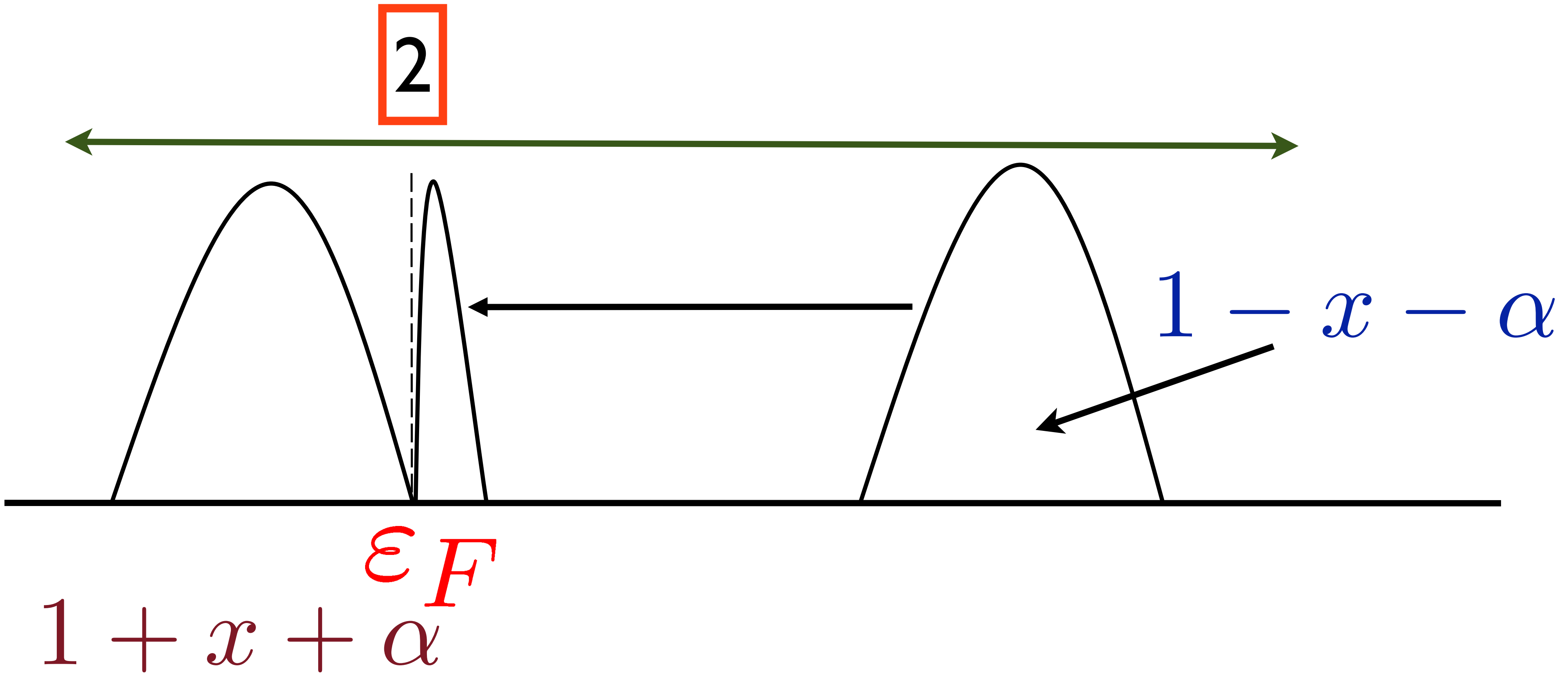
Harris & Lange, 1967

$$\alpha = \frac{t}{U}\sum_{ij}\langle c_{i\sigma}^{\dagger} c_{j\sigma}\rangle > 0$$

$$1 + x + \alpha(t/U, x)$$

What is the new symmetry condition for the LHB ?

re-establish static band picture



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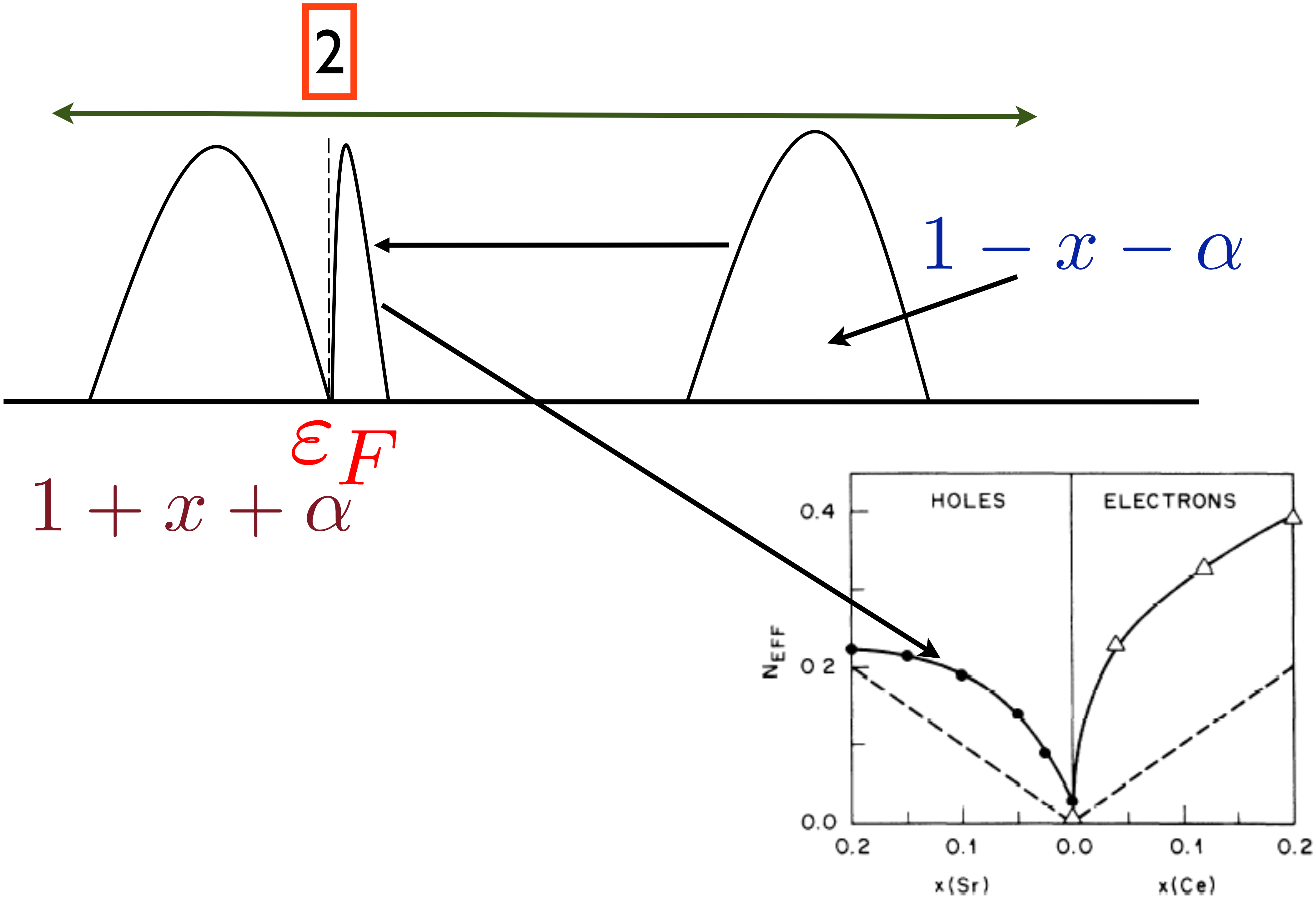
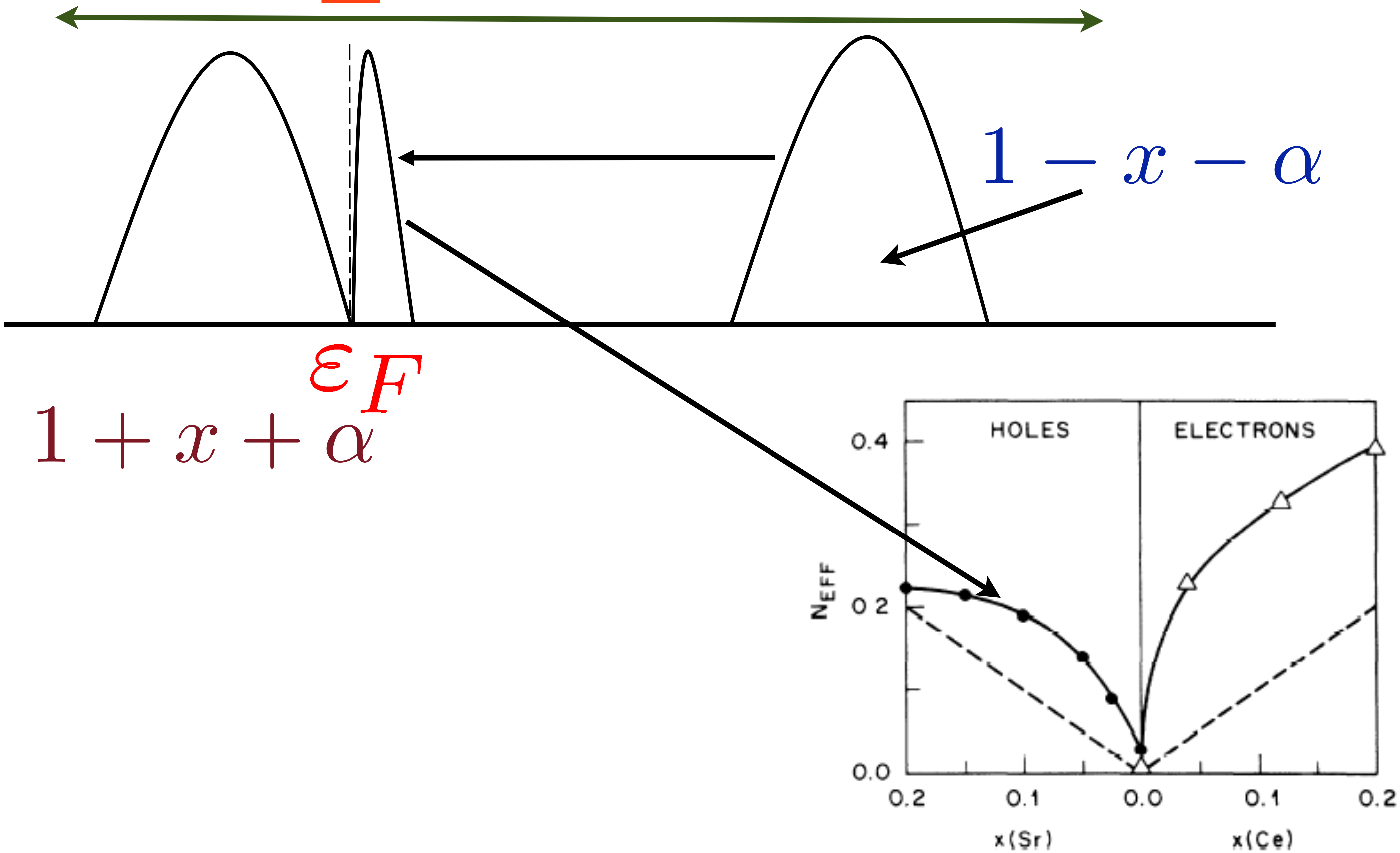


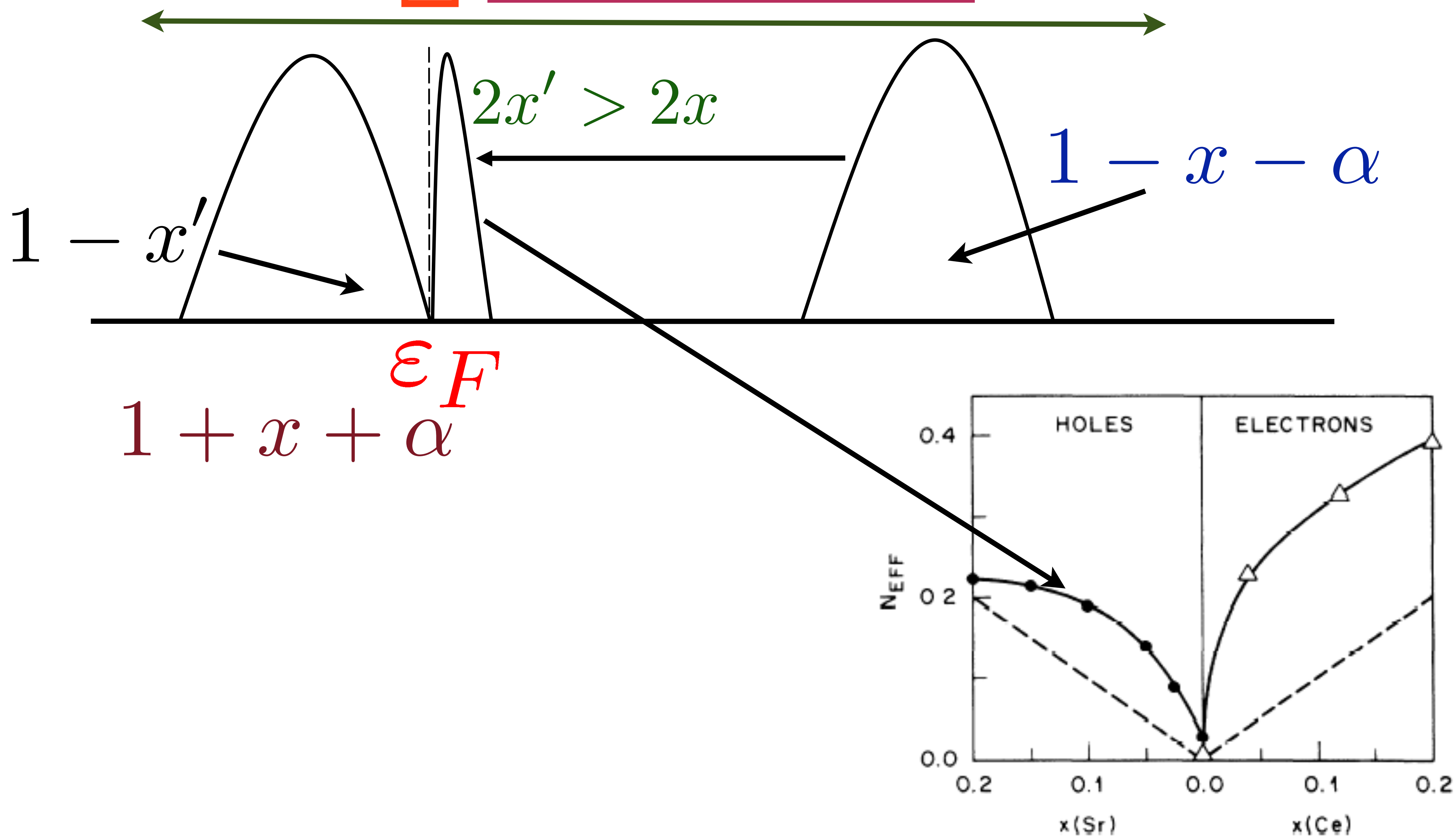
re-establish static band picture

$\boxed{2}$ re-definition: $x' = x + \alpha$



re-establish static band picture

2 re-definition: $x' = x + \alpha$



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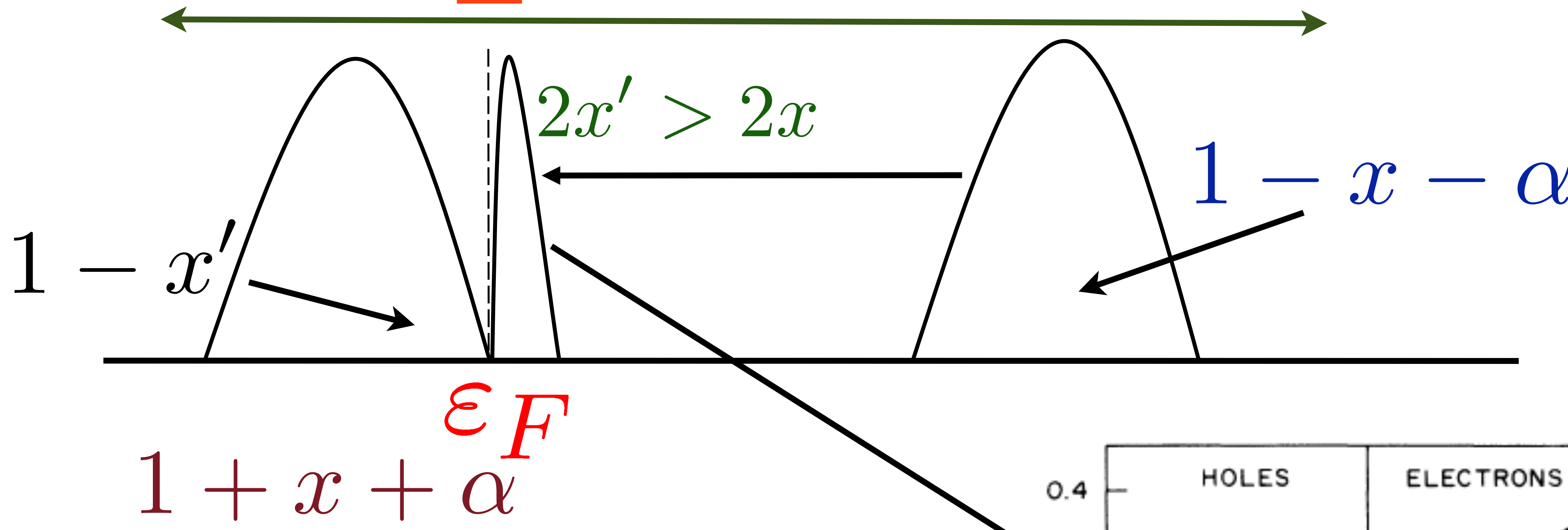

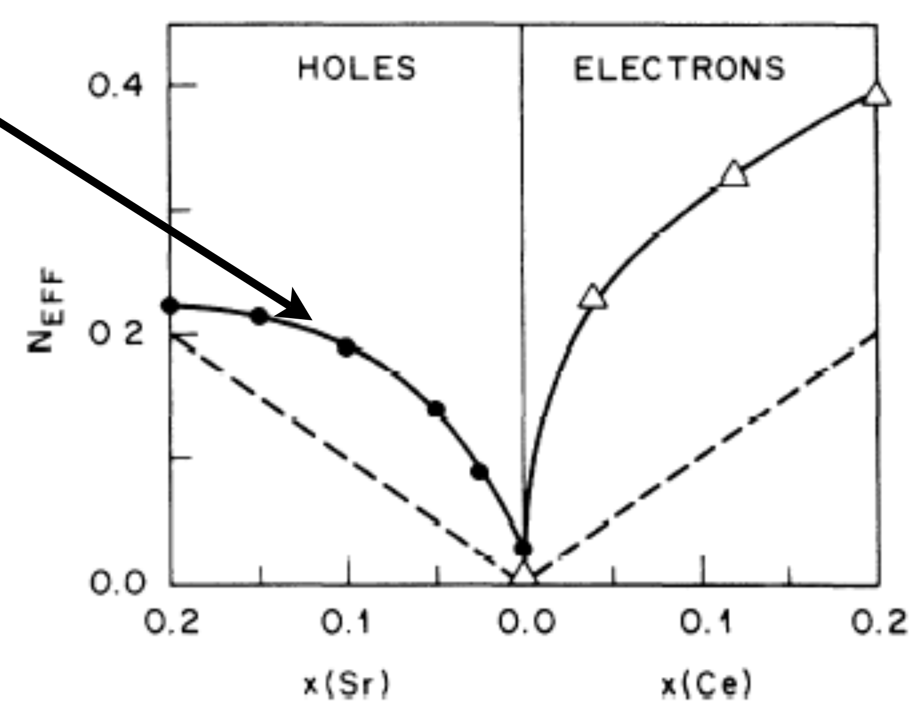

New Symmetry Condition

$2x' = 1 - x'$

re-establish static band picture

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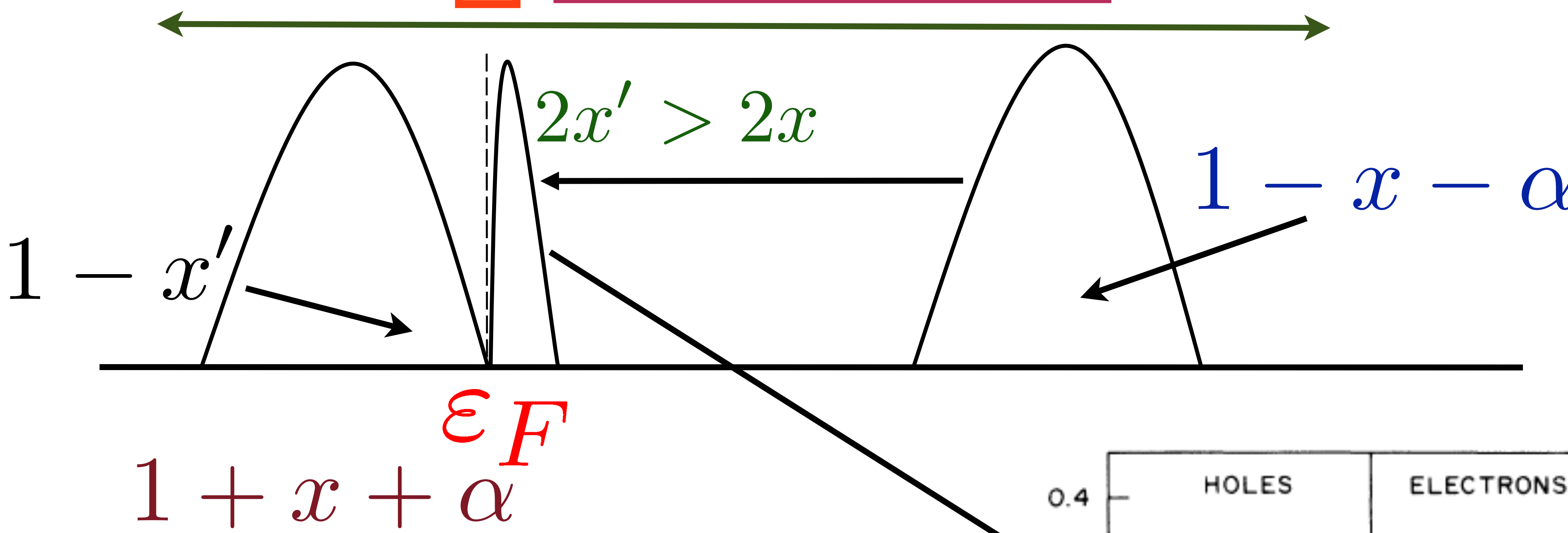
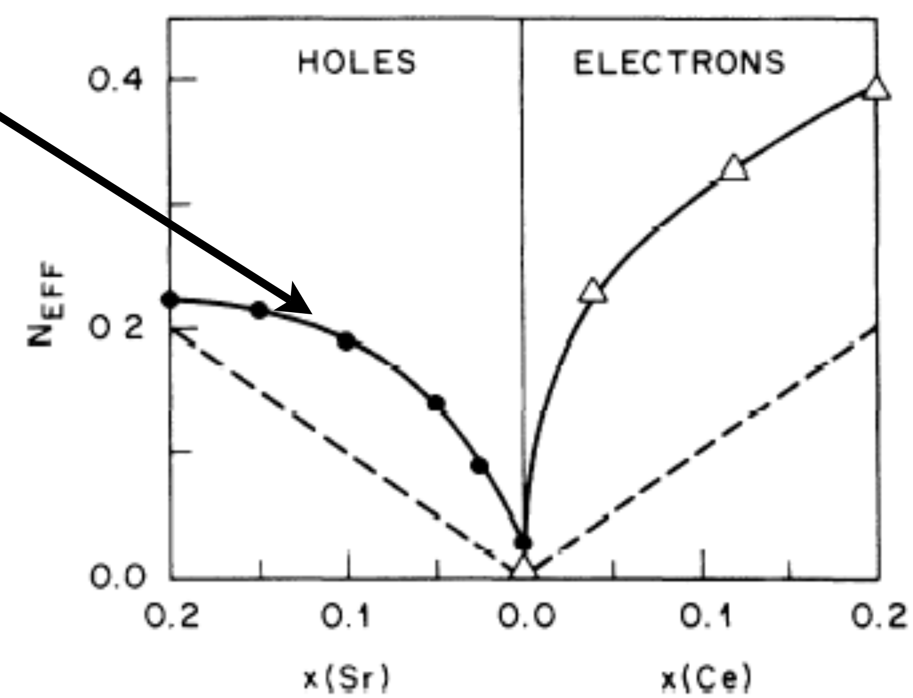


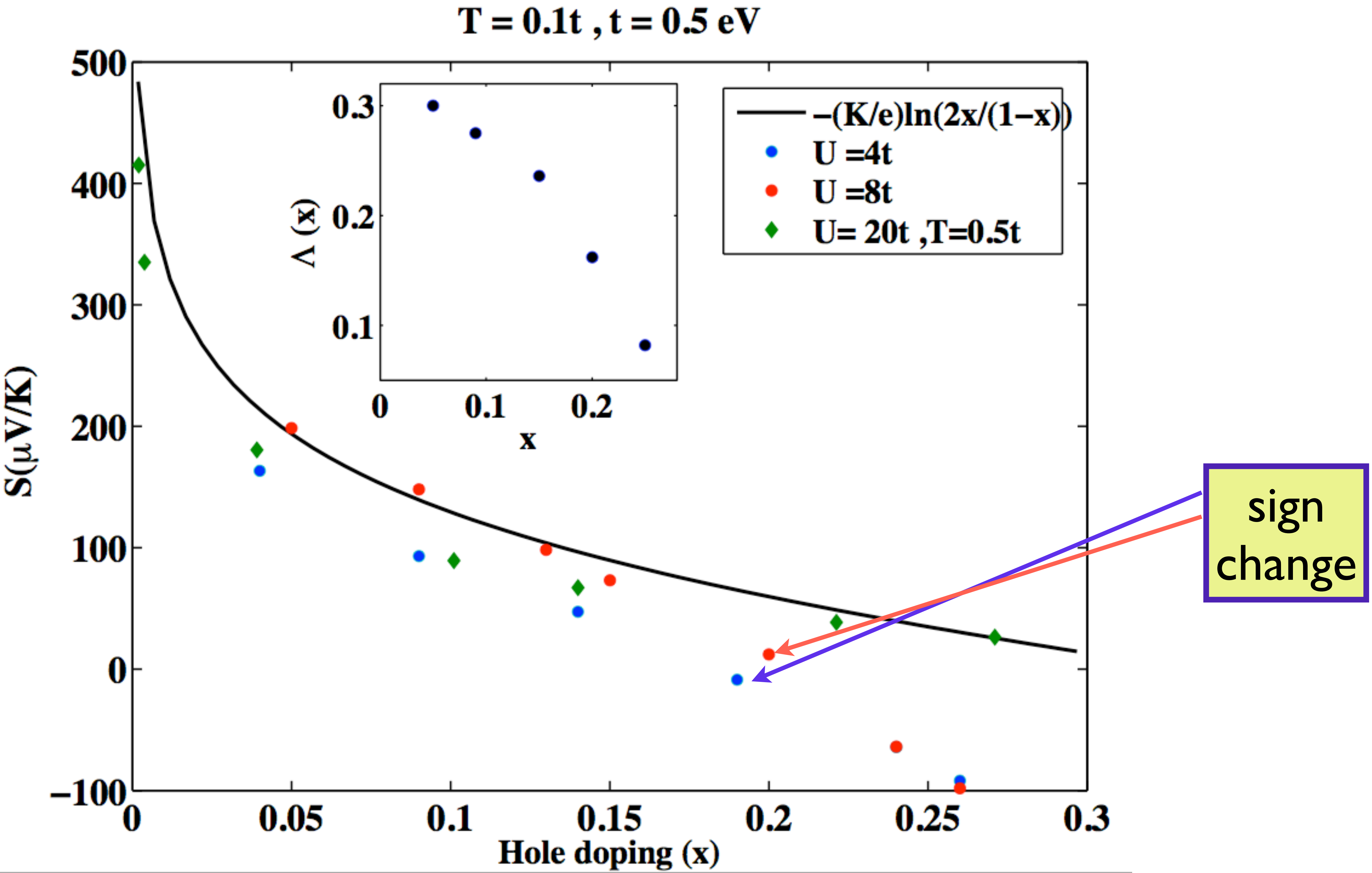


New Symmetry Condition

$$2x' = 1 - x'$$

$$x_c = \frac{1}{3} - \alpha < \frac{1}{3}$$

Hubbard Model:CDMFT



Why is T_c so high?

$$2x' = 1 - x'$$

high-low energy mixing

Is our key claim correct?

$$x' = x + \alpha$$

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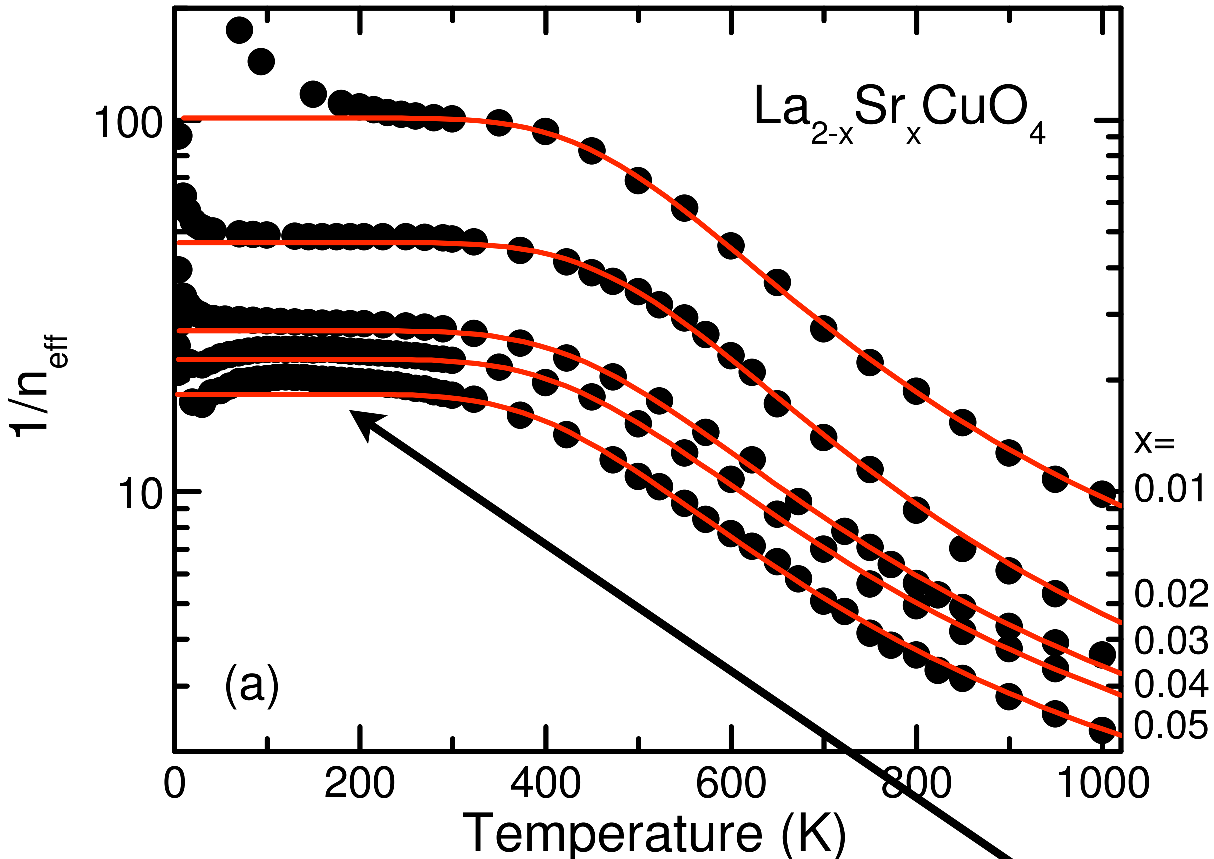
$$x' = x + \alpha$$

Does the electron filling have a dynamical component?

direct evidence



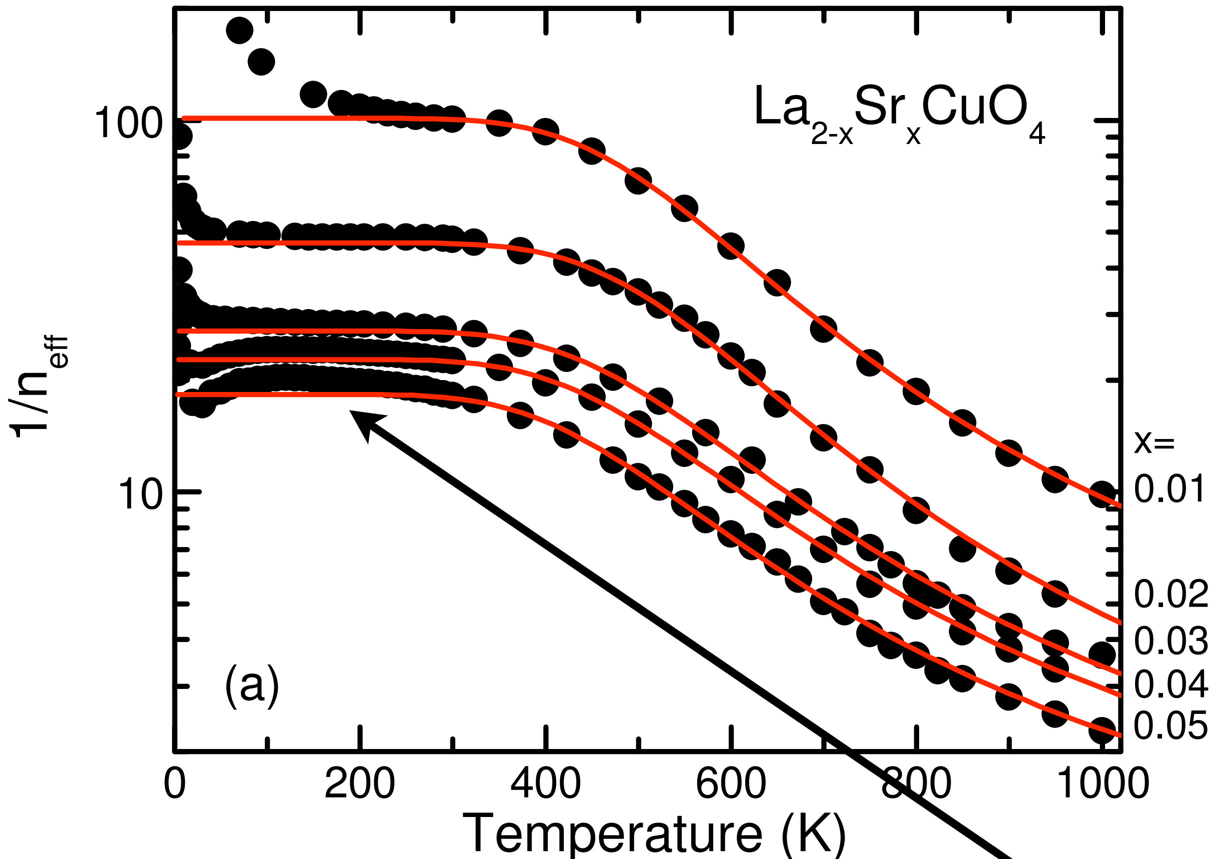
Ono, et al., Phys. Rev. B 75, 024515 (2007)

$$n_{\rm Hall}(x,T) = n_0(x) + n_1(x)\exp(-\Delta(x)/T),$$

PRL, vol. 97, 247003 (2006).

direct evidence

charge carrier density:



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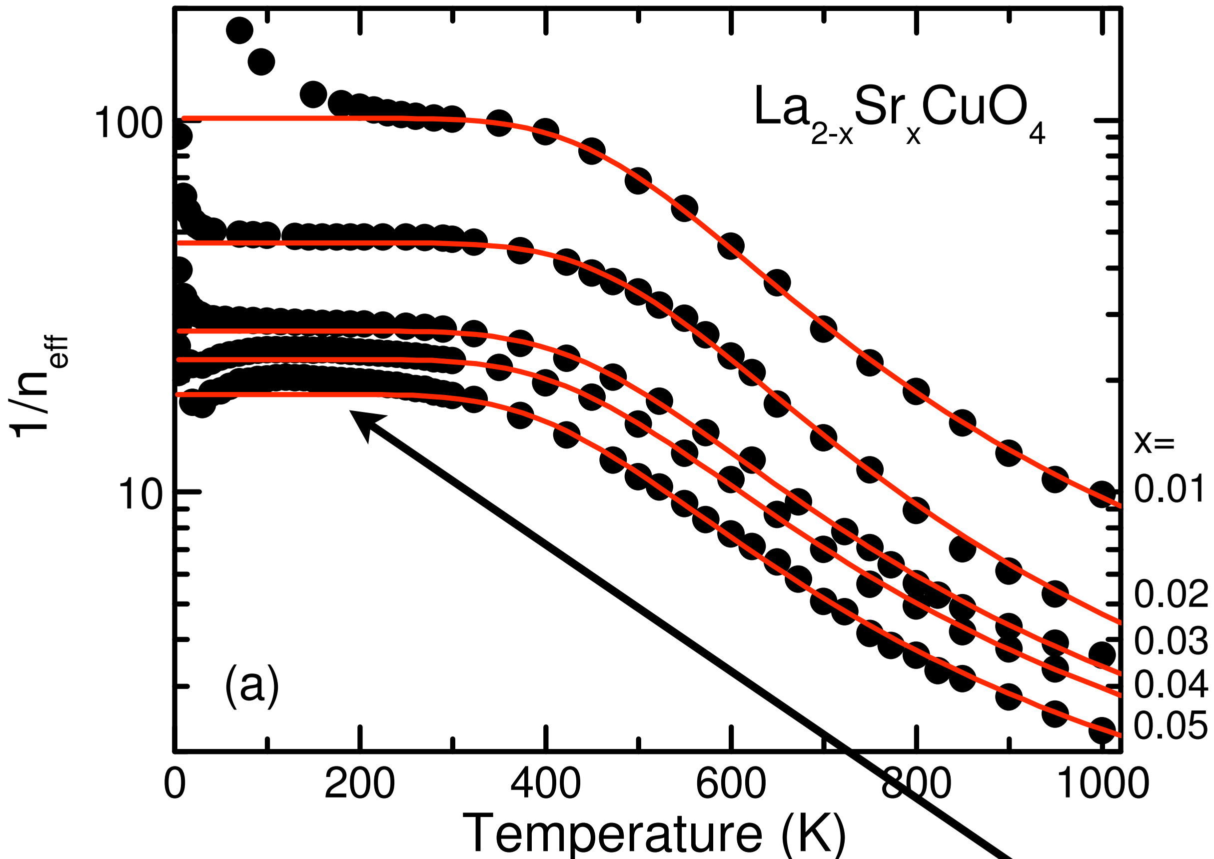

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exponentially suppressed: confinement

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gapped excitation

Two-fluid model

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Two-fluid model

$$n_{\mathrm{Hall}}(x,T) = n_0(x) + n_1(x)\exp(-\Delta(x)/T),$$

How?

$$x' = x + \alpha$$

gapped excitation

Effective Theories:

$S(\phi)$ at half-filling

Integrate Out high Energy fields

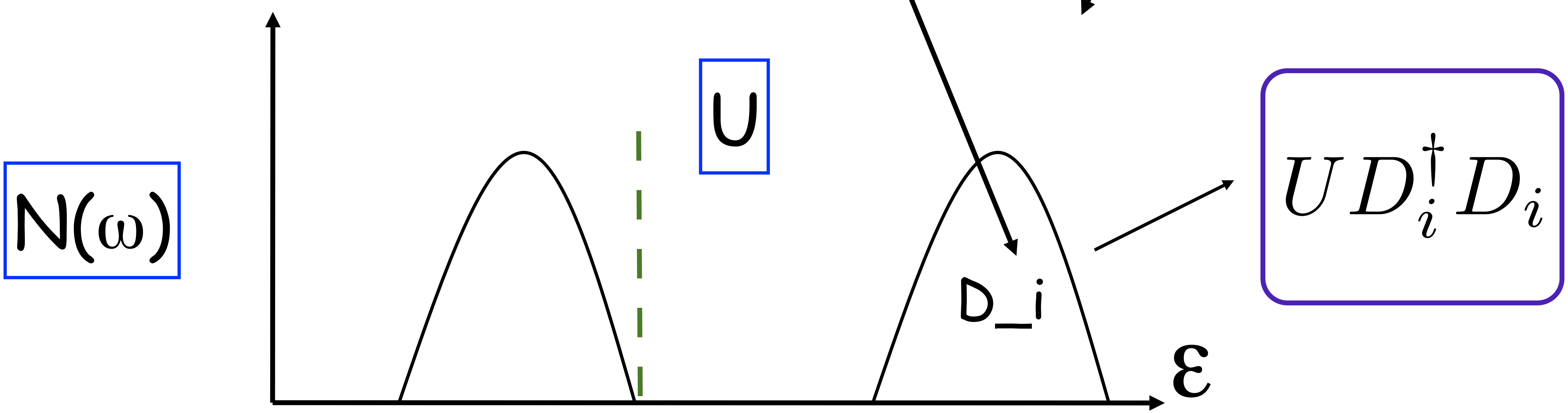
$\phi=\phi_L+\phi_H$

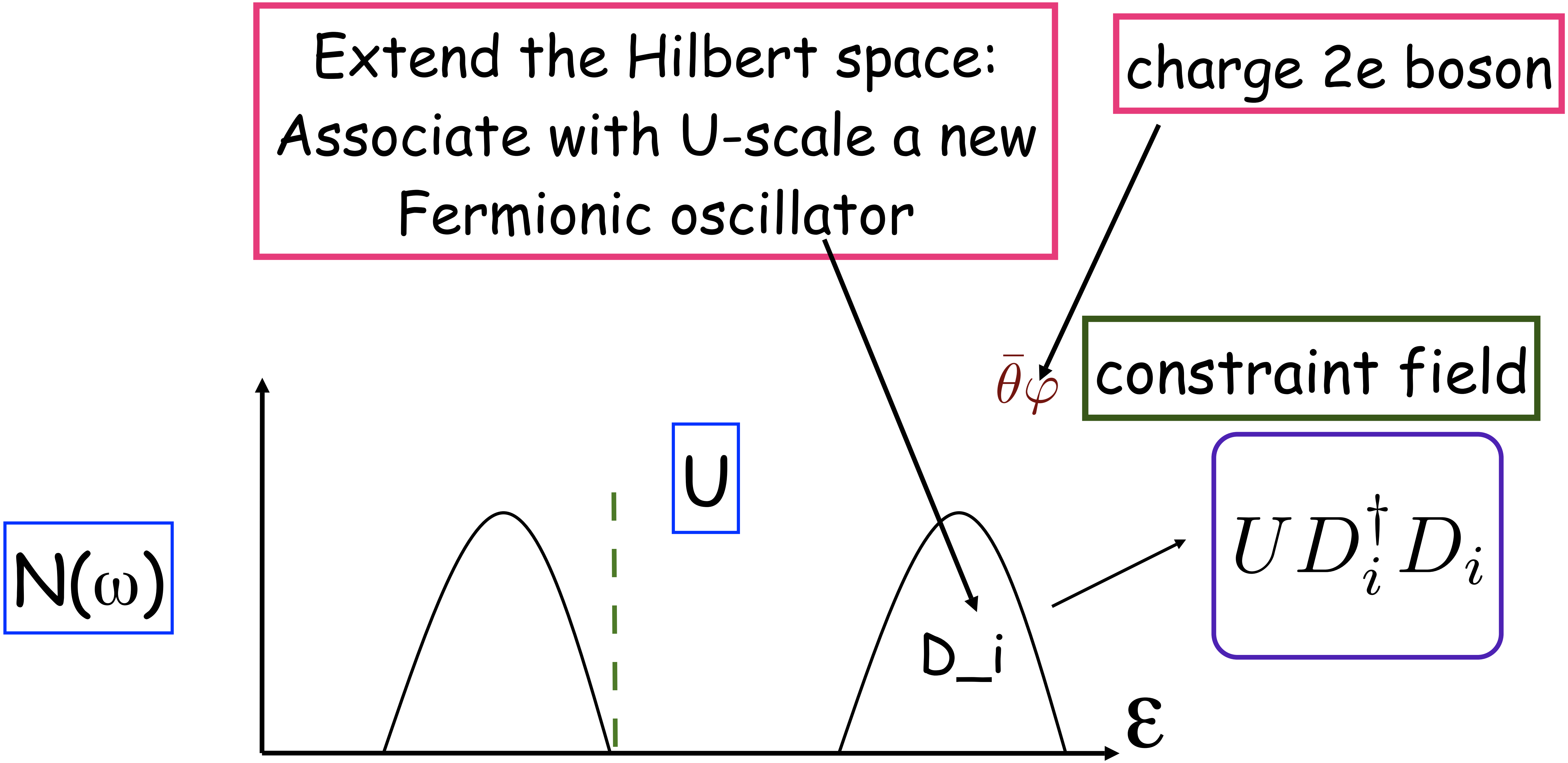
$$e^{-S_{\rm eff}[\phi_L]} = \int d\phi_H \exp -S(\phi_L,\phi_H)$$

Low-energy theory of M I

Extend the Hilbert space:
Associate with U-scale a new
Fermionic oscillator

charge 2e boson




Extend the Hilbert space:
Associate with U-scale a new
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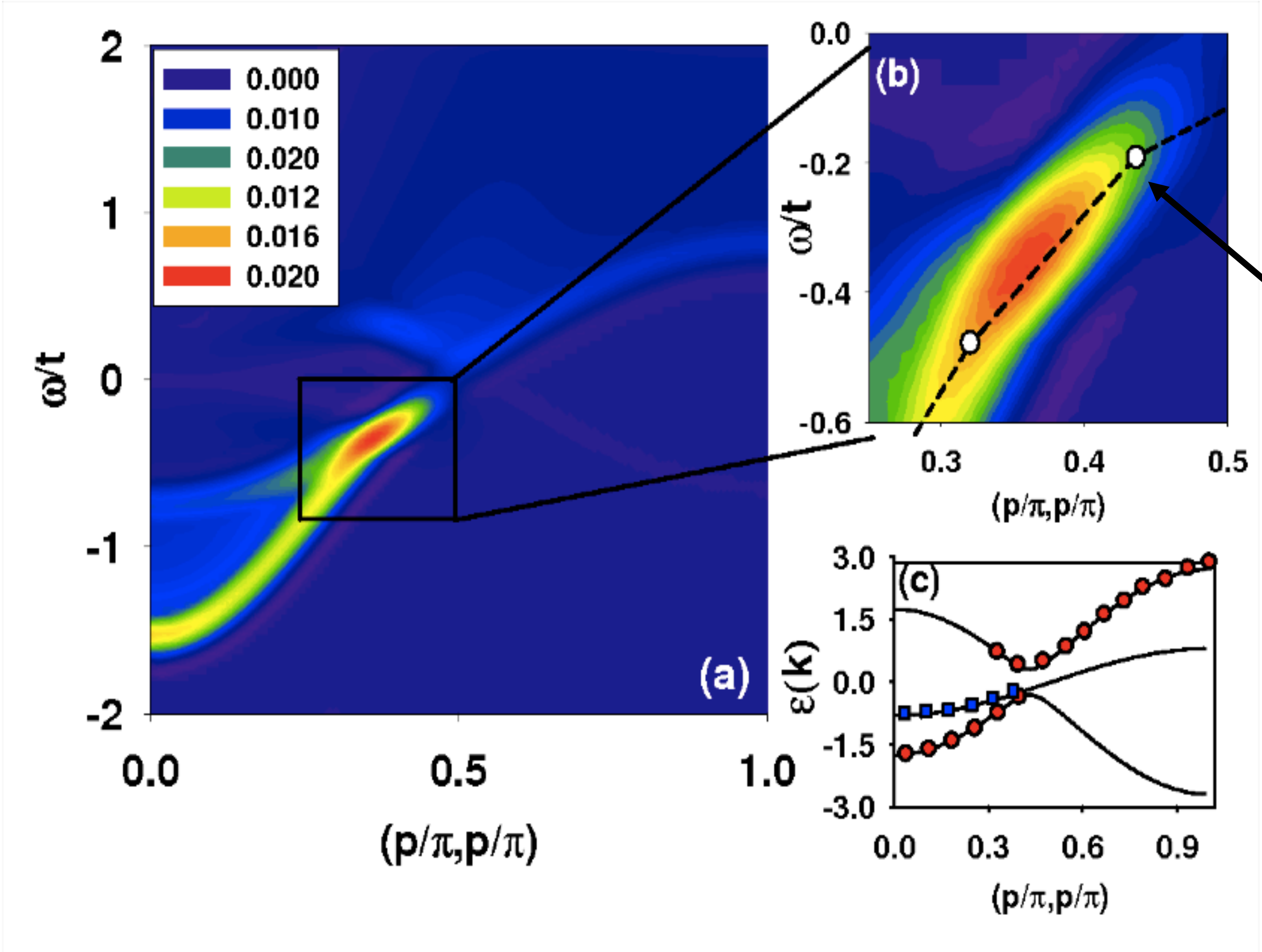
charge 2e boson
$\bar{\theta}\varphi$
constraint field
U
$U D_i^\dagger D_i$
N(ω)
D_i
ε

Electron spectral function



$t^2/U \sim 60\,meV$

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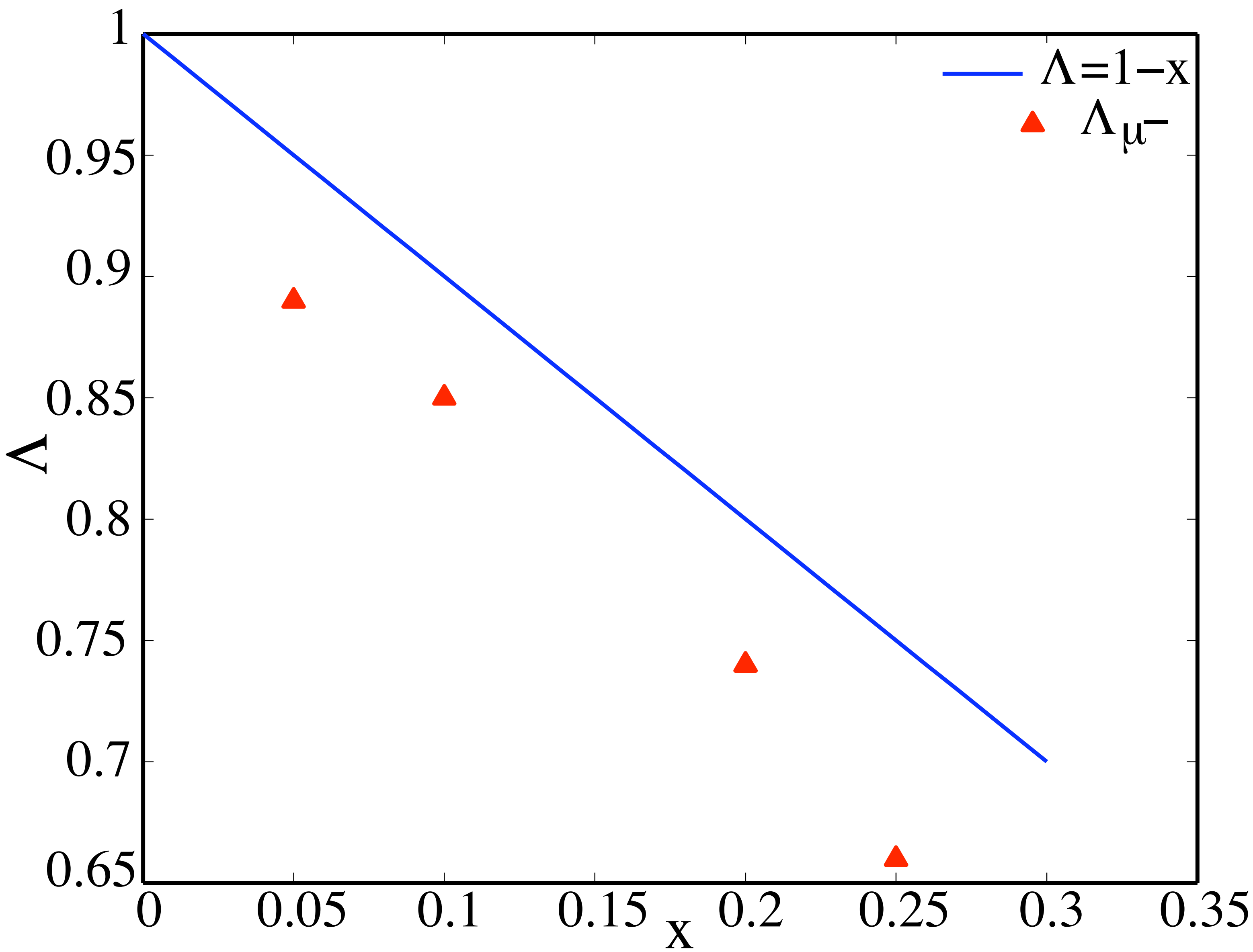

²/U~60meV

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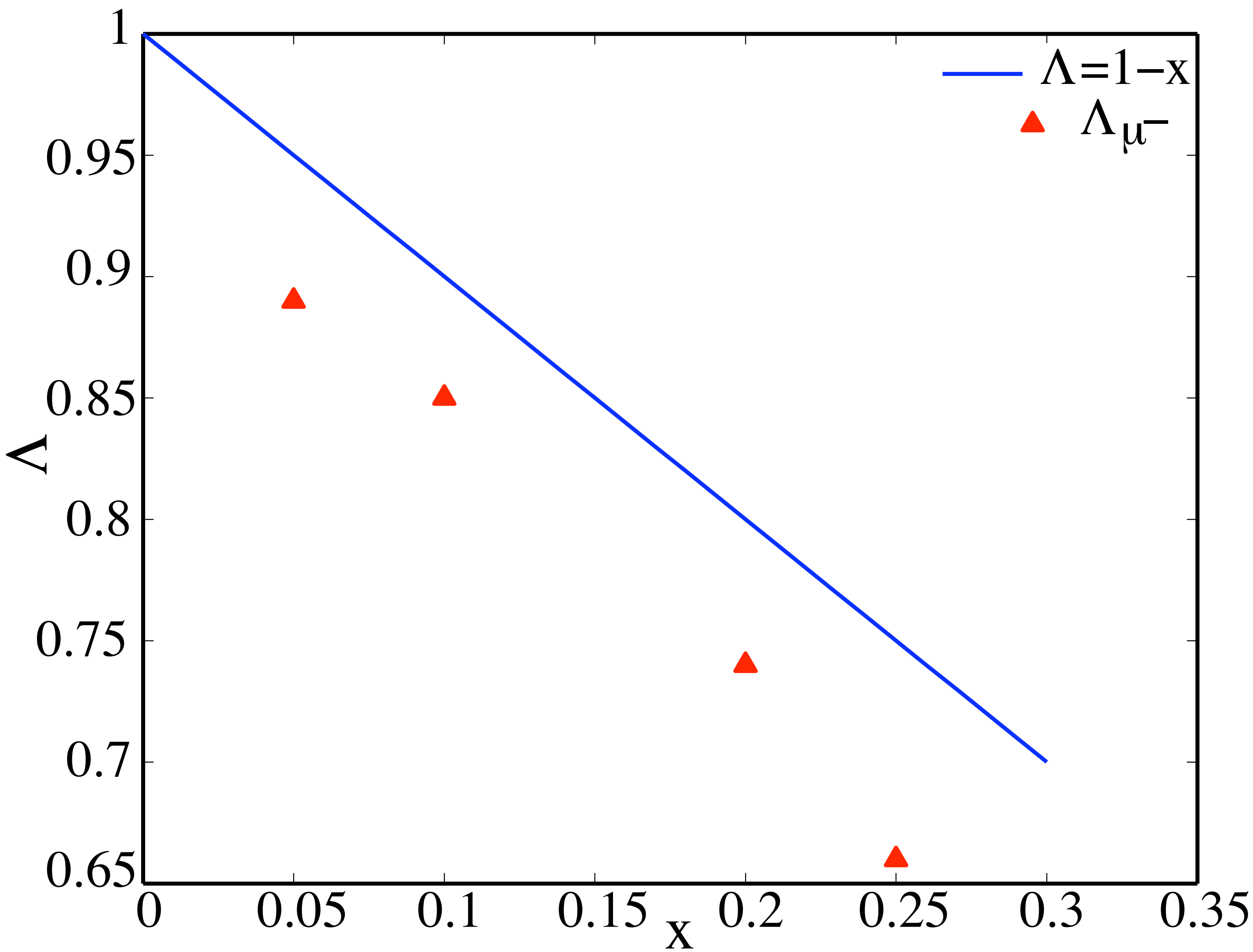


²/U~60meV

Conserved charge: $Q = \sum_i c_i^\dagger c_i + 2 \sum_i \varphi_i^\dagger \varphi_i$

Origin of two bands

Two charge e excitations

$c_{i\sigma}$

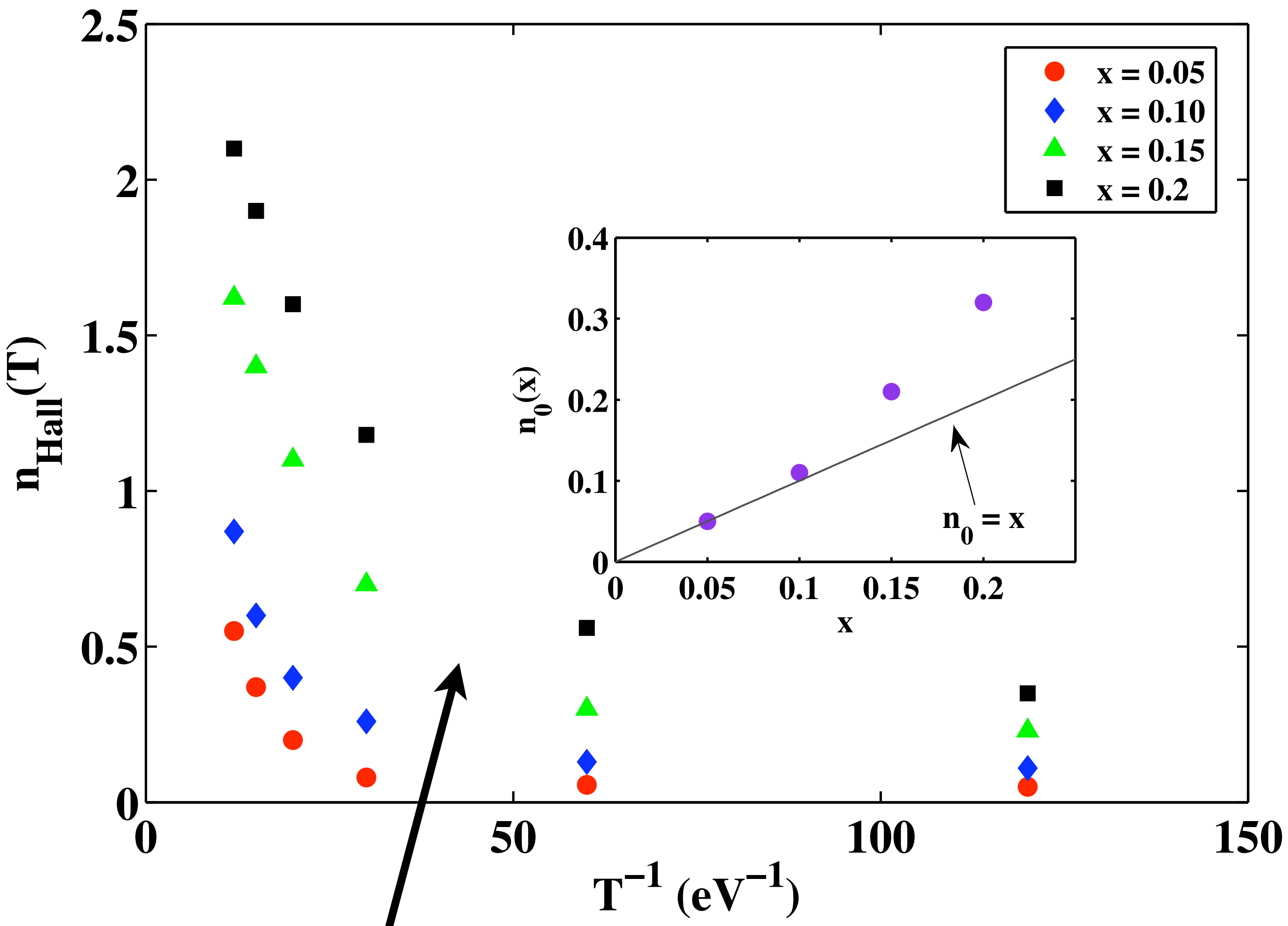
φ_i is confined (no kinetic energy)

$\varphi_i^\dagger c_{i\bar{\sigma}}$

New bound state

Pseudogap

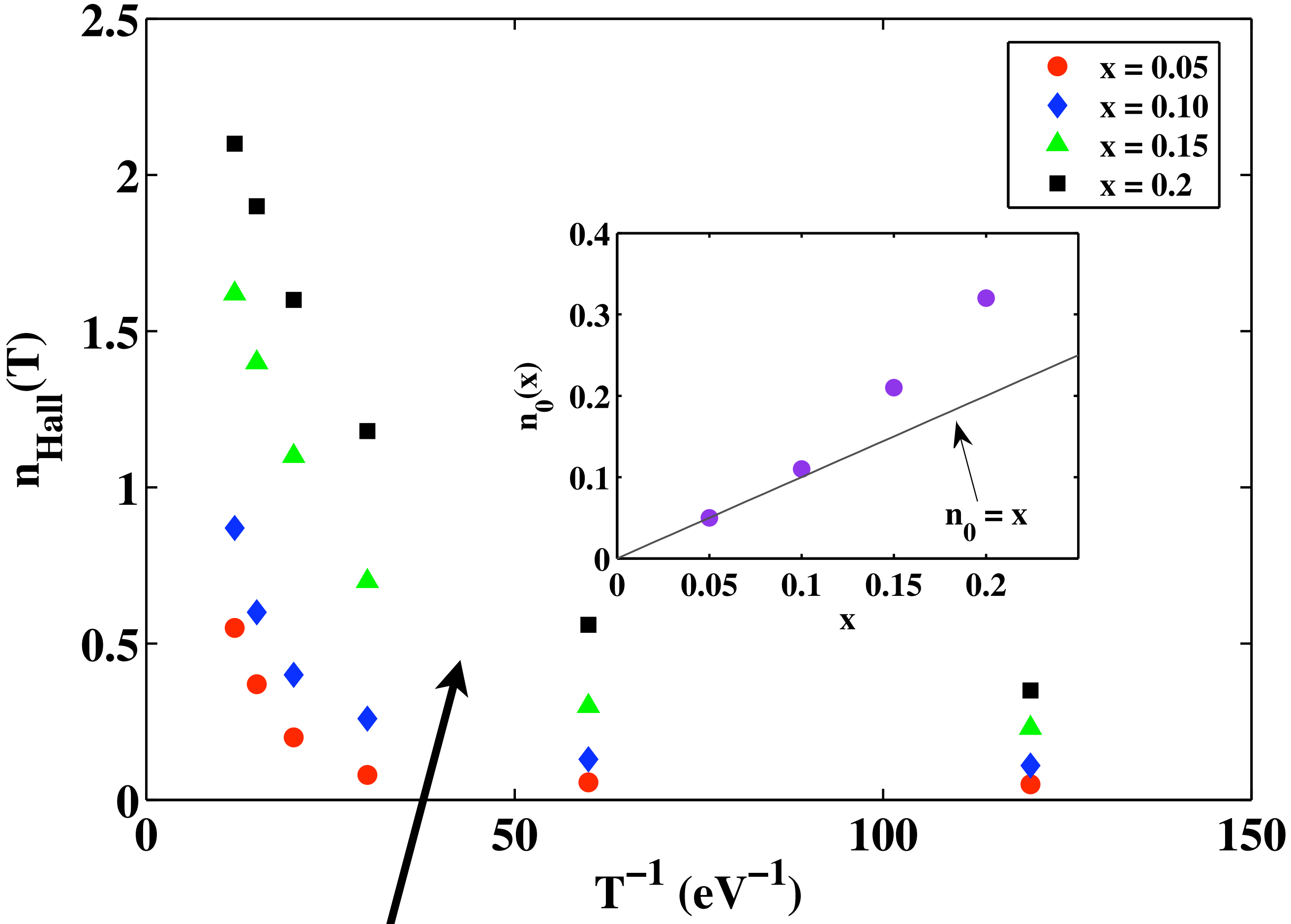
Our Theory

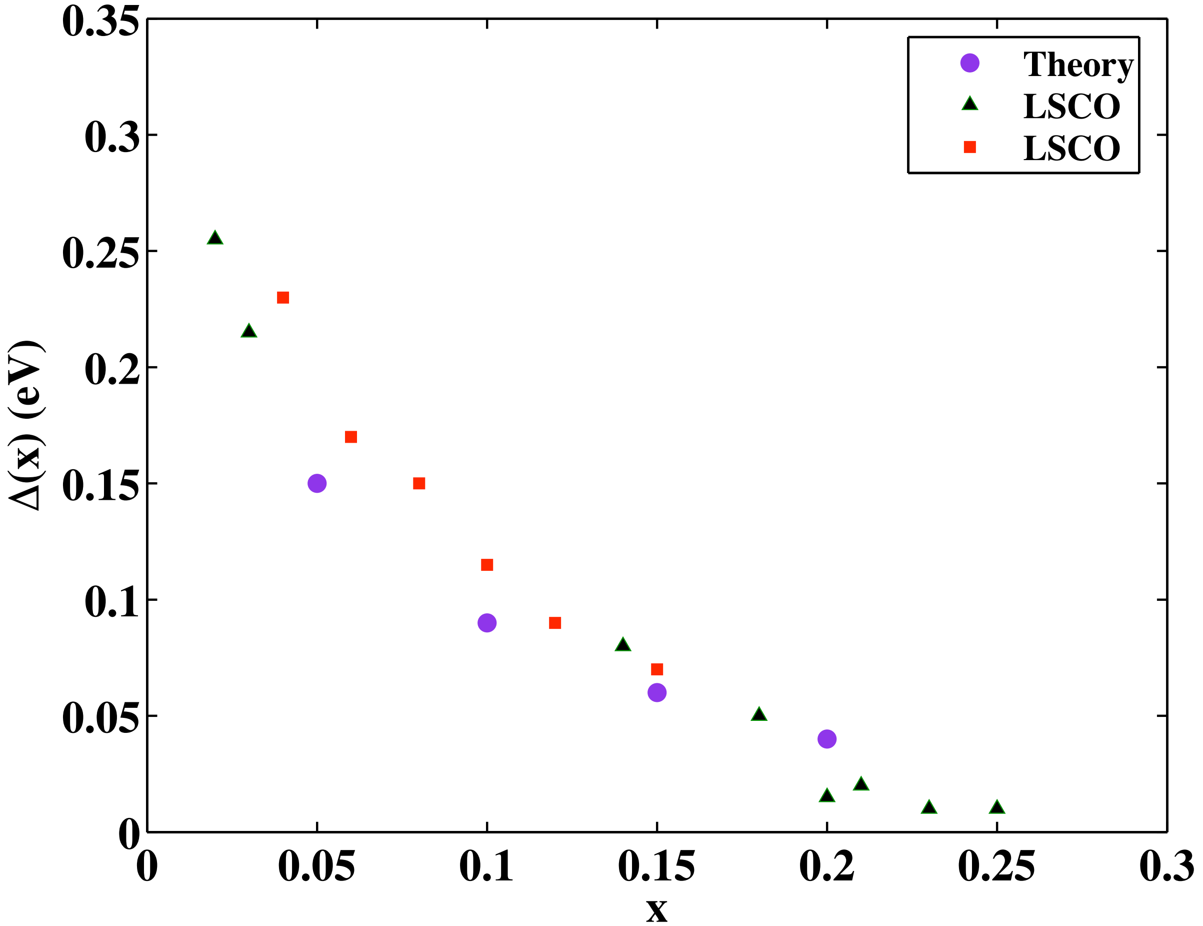


exponential T-dependence

Our Theory

gap





exponential T-dependence

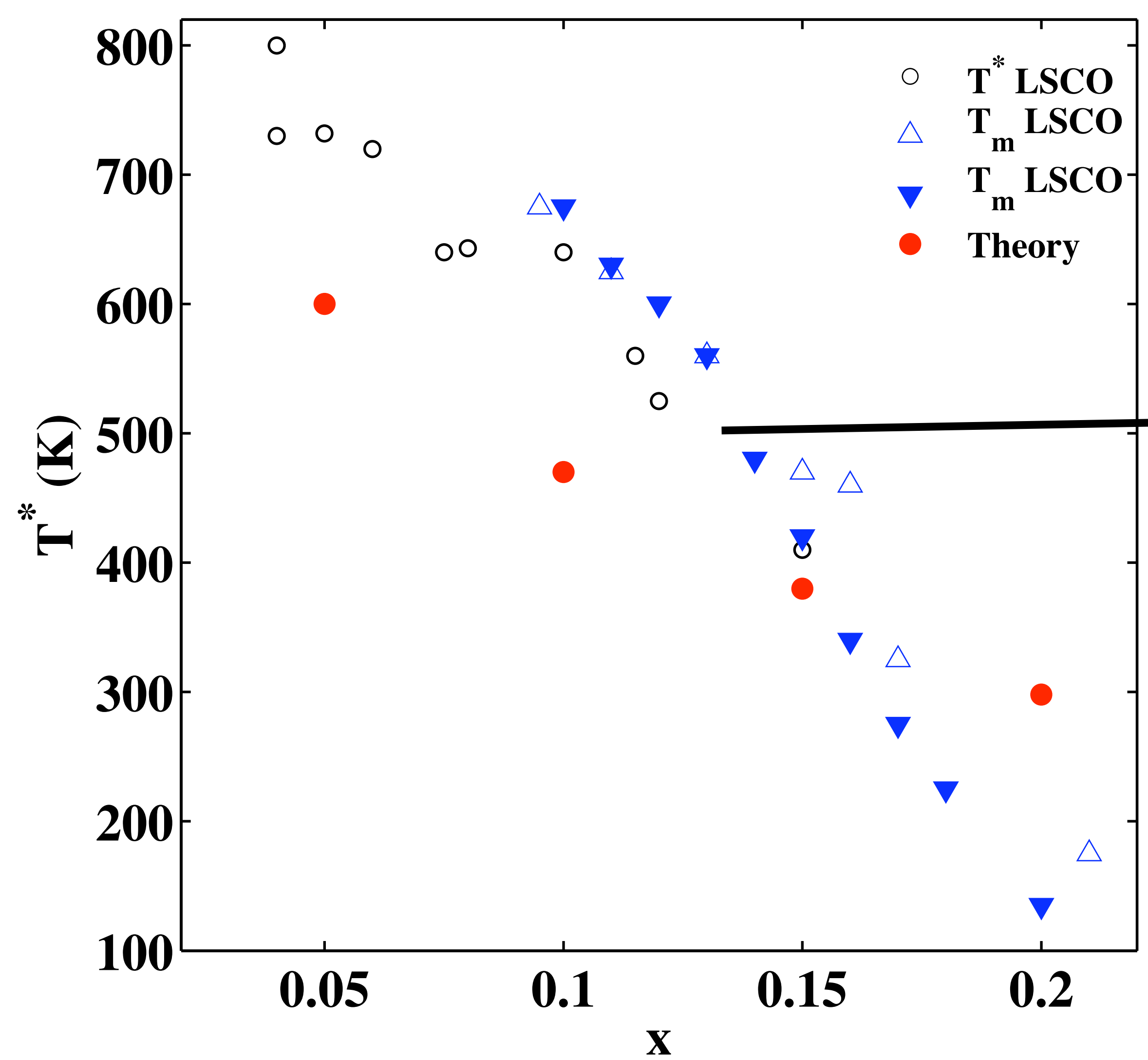
no model-dependent free parameters: just t/U

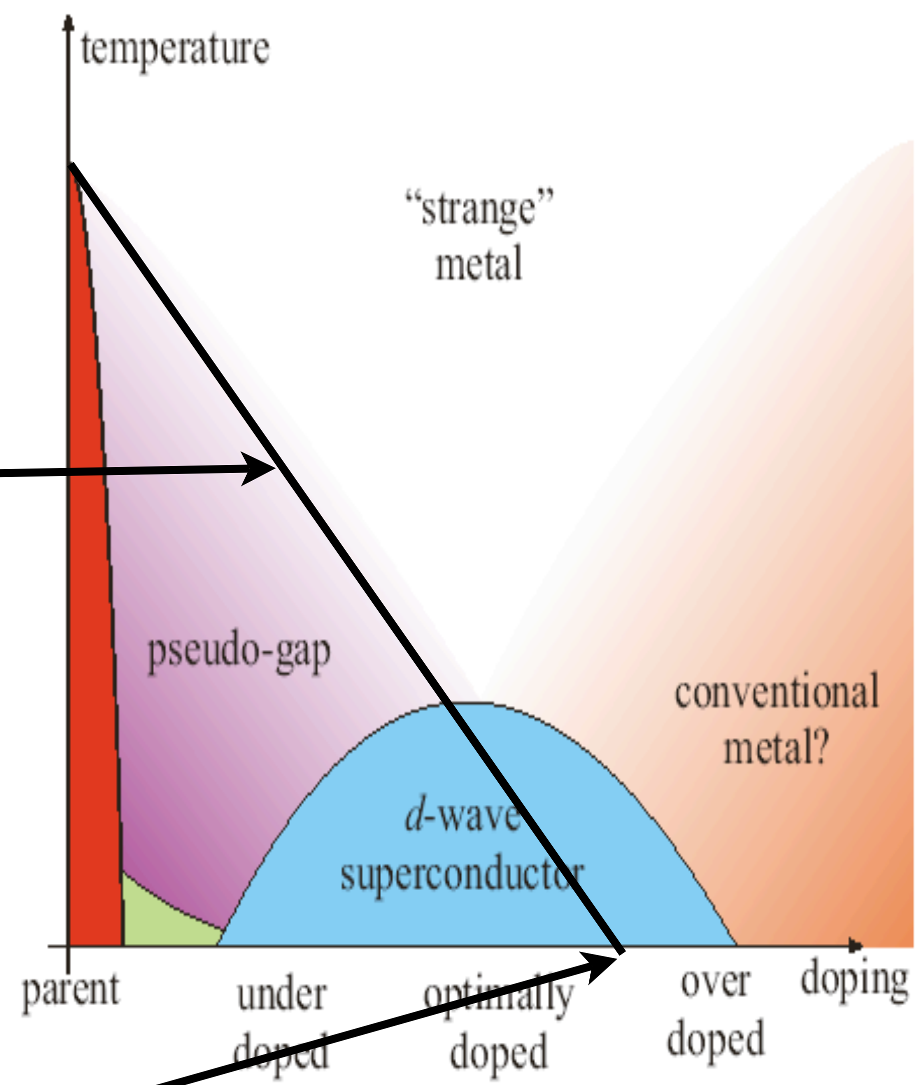
thermopower ala
Kelvin: $\partial S/\partial n$

thermopower vanishes
when the entropy is maximized:
quantum phase transition at optimal T_c

high-low energy mixing

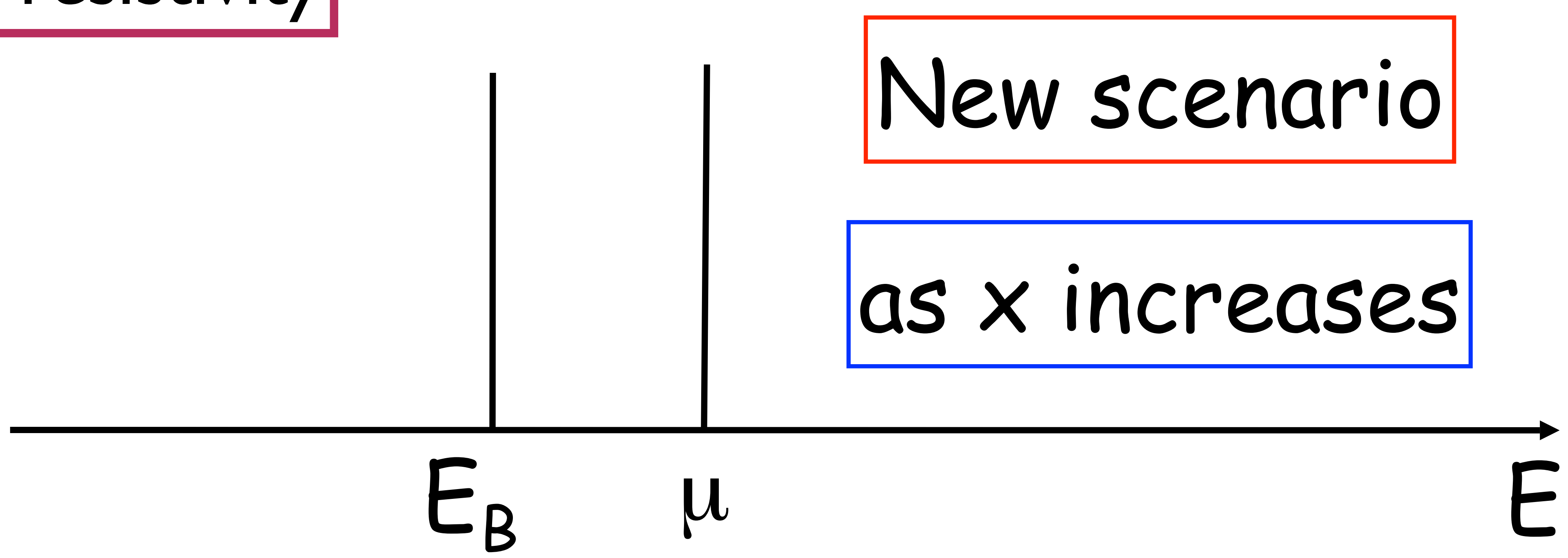
strange metal: breakup (deconfinement) of bound states





QCP:

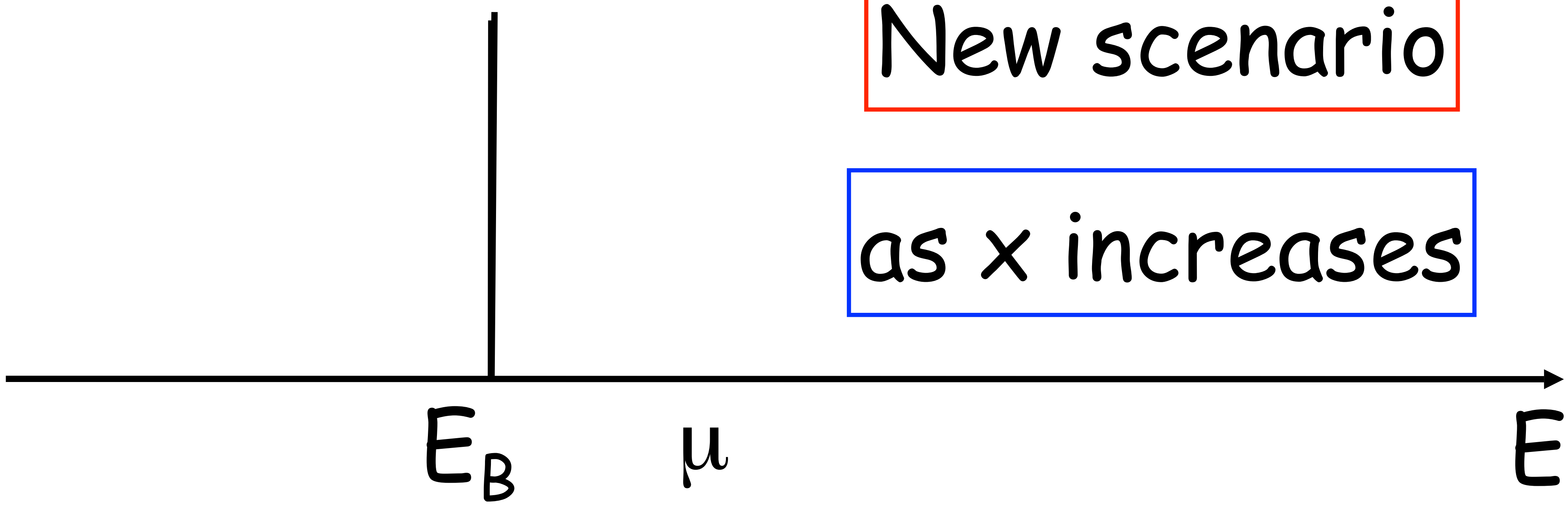
T-linear resistivity



T-linear resistivity

New scenario

as x increases



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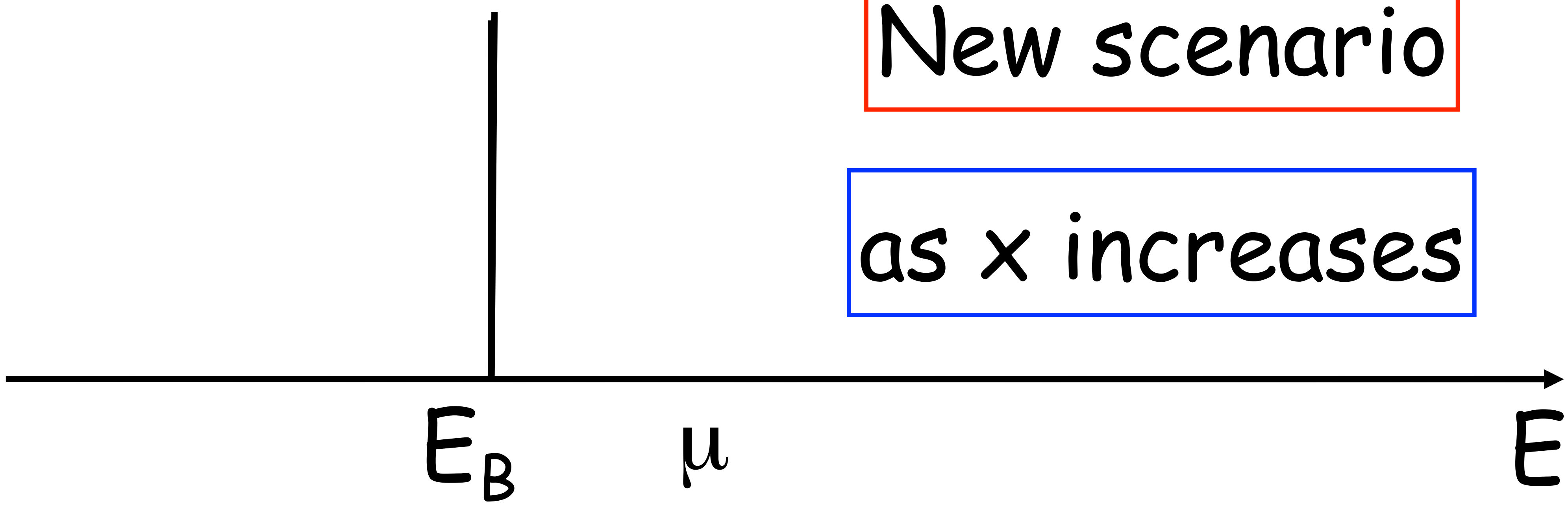

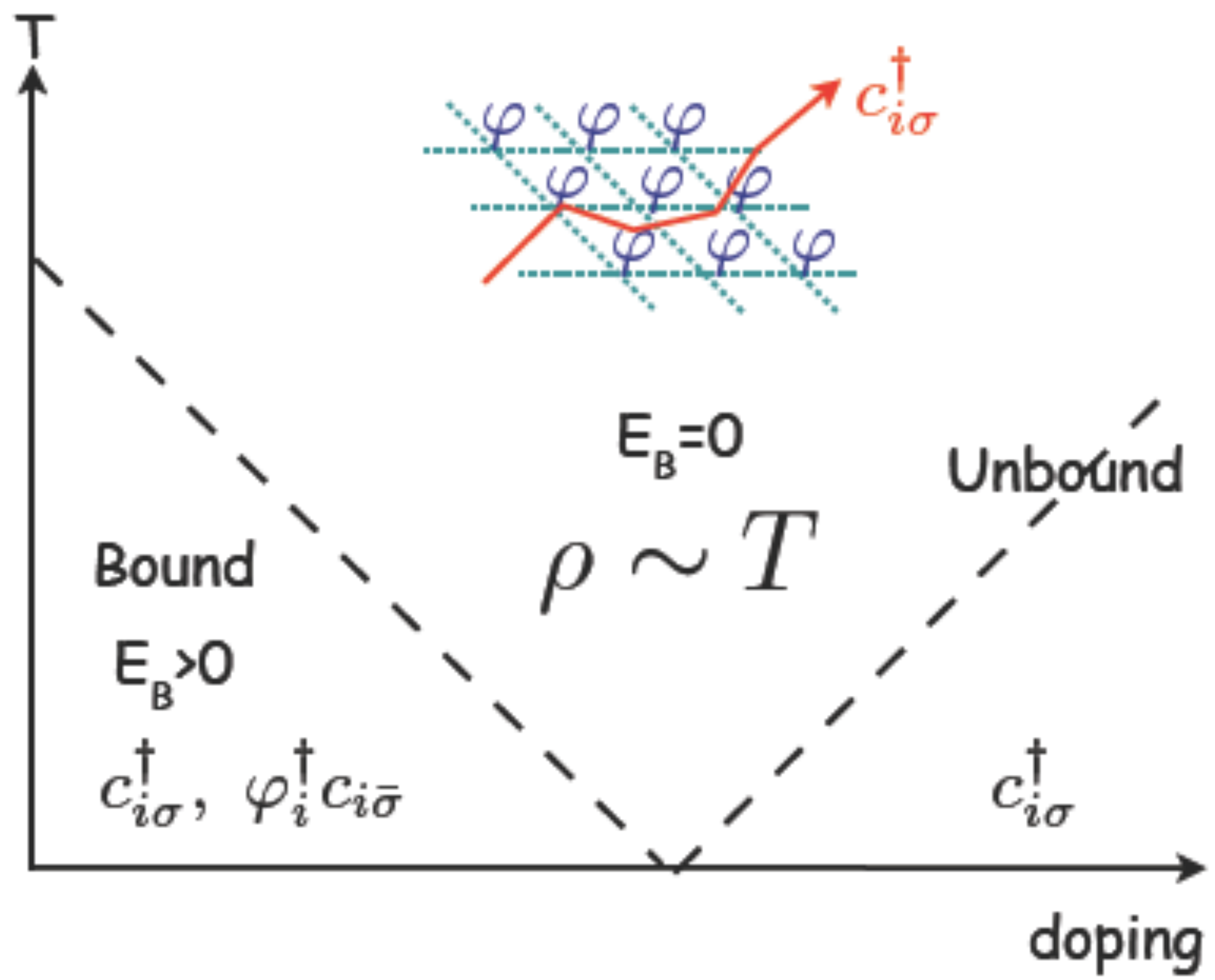

Predictions:

QO oscillations:

$$V_{\rm hp} - V_{\rm ep} = 2(x+\alpha)$$

$$x \rightarrow x + \alpha$$

Superfluid density

$$\rho_s \propto x + \alpha$$

optical conductivity:

$$n_{\rm eff} \propto (x+\alpha) > x$$

Thanks to R. G. Leigh and Ting-Pong Choy, Shiladitya Chakraborty, Seungmin Hong and DMR-NSF