Mottness and Holography: Spectral weight transfer and T-linear Resistivity

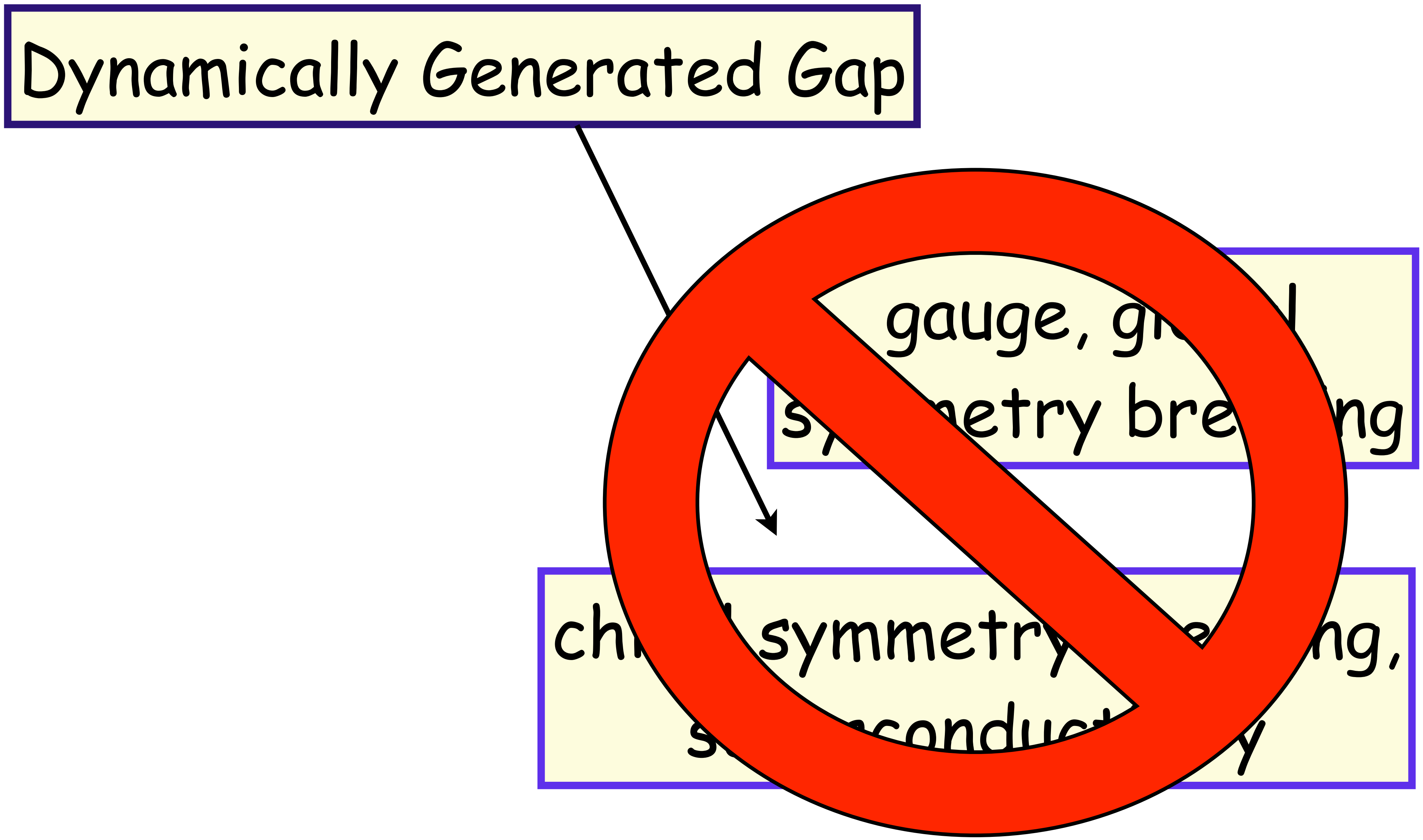
Thanks to: T.-P. Choy, R. G. Leigh, S. Chakraborty, M. Edalati, S. Hong
PRL, 99, 46404 (2007);
PRB, 77, 14512 (2008); ibid, 77, 104524 (2008));
ibid, 79,245120 (2009); RMP, 82, 1719 (2010)..., DMR/NSF

GGI Talk: Nov. 4, 2010

Dynamically Generated Gap

gauge, global symmetry breaking

chiral symmetry breaking, superconductivity


Dynamically Generated Gap
gauge, gl
s
metry bre
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ng,
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conduc
y

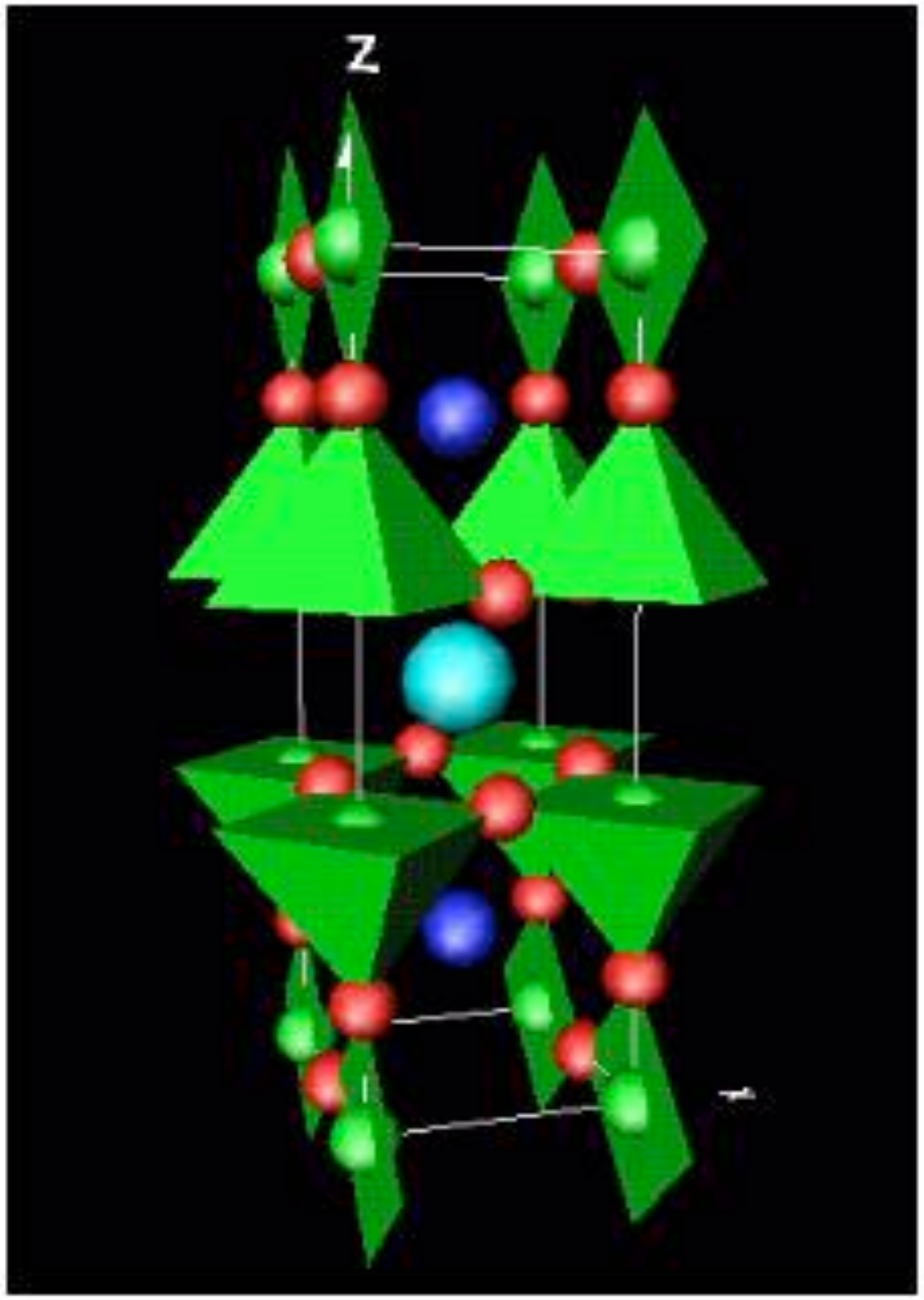
Dynamically Generated Gap

No symmetry breaking

emergent bound states not in UV: QCD(pions), vulcanized rubber, Mott insulators

gauge, gl... l sy...etry bre...ing

chi... symmetry ...e...ng, s...conduc... y

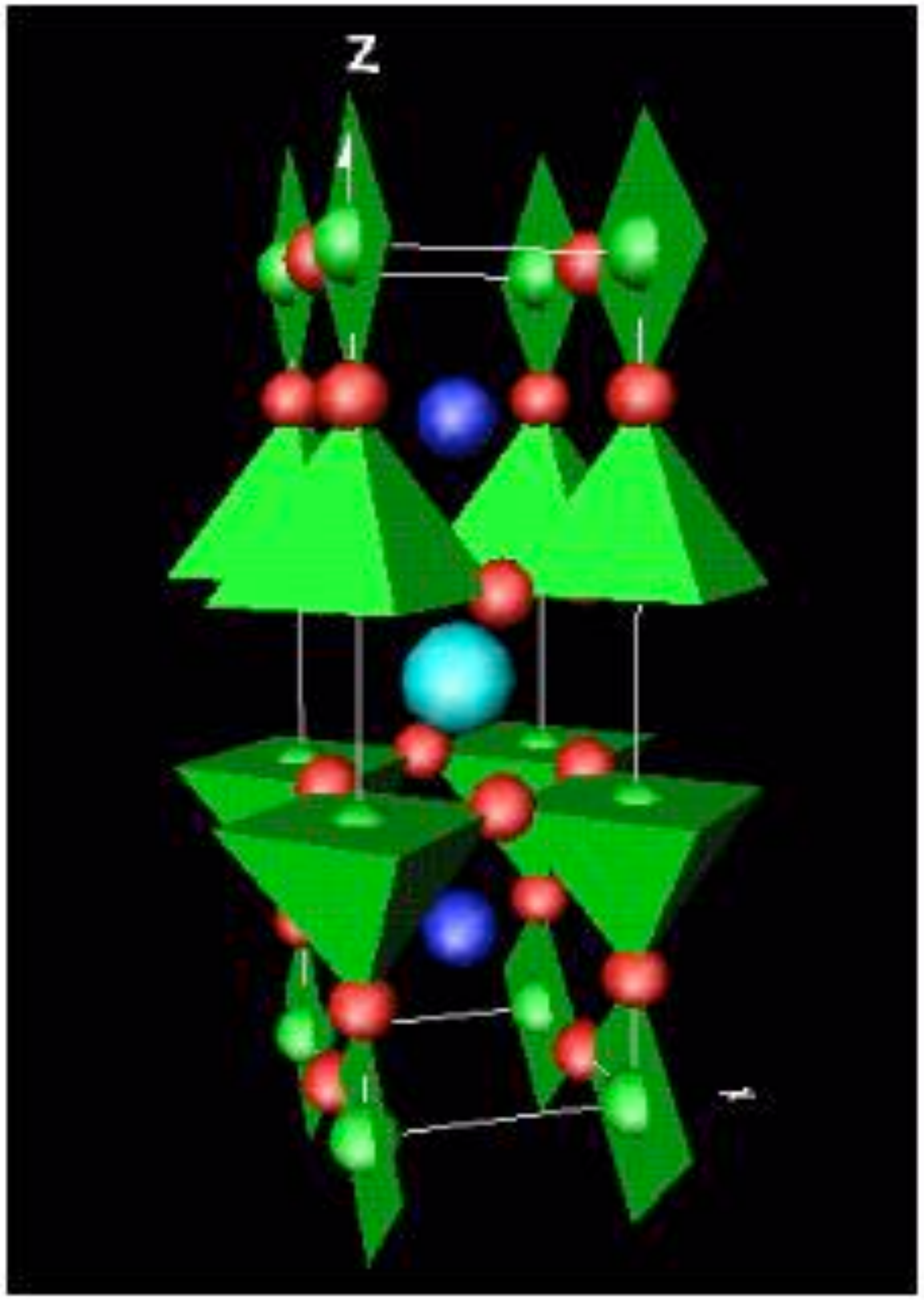


$Y\,Ba_2Cu_3O_7$

Cuprate Superconductors

$$U/t = 10 \gg 1$$

interactions dominate:
Strong Coupling Physics



$Y Ba_2Cu_3O_7$
Cuprate Superconductors

2D Hubbard Model

$$U/t = 10 \gg 1$$

interactions dominate:
Strong Coupling Physics

$$H = -t \sum_{i,j} c^{\dagger}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{\downarrow}$$

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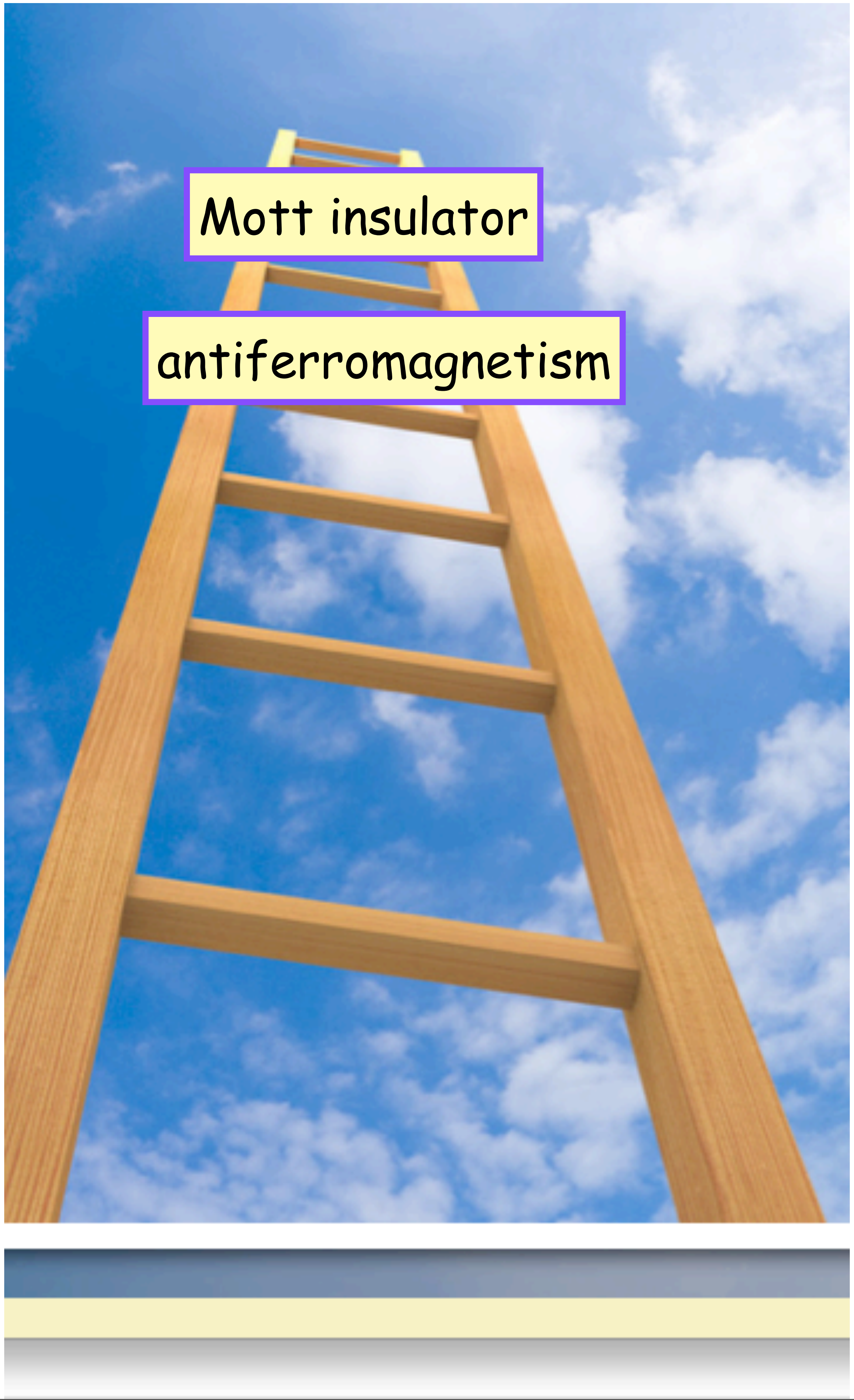

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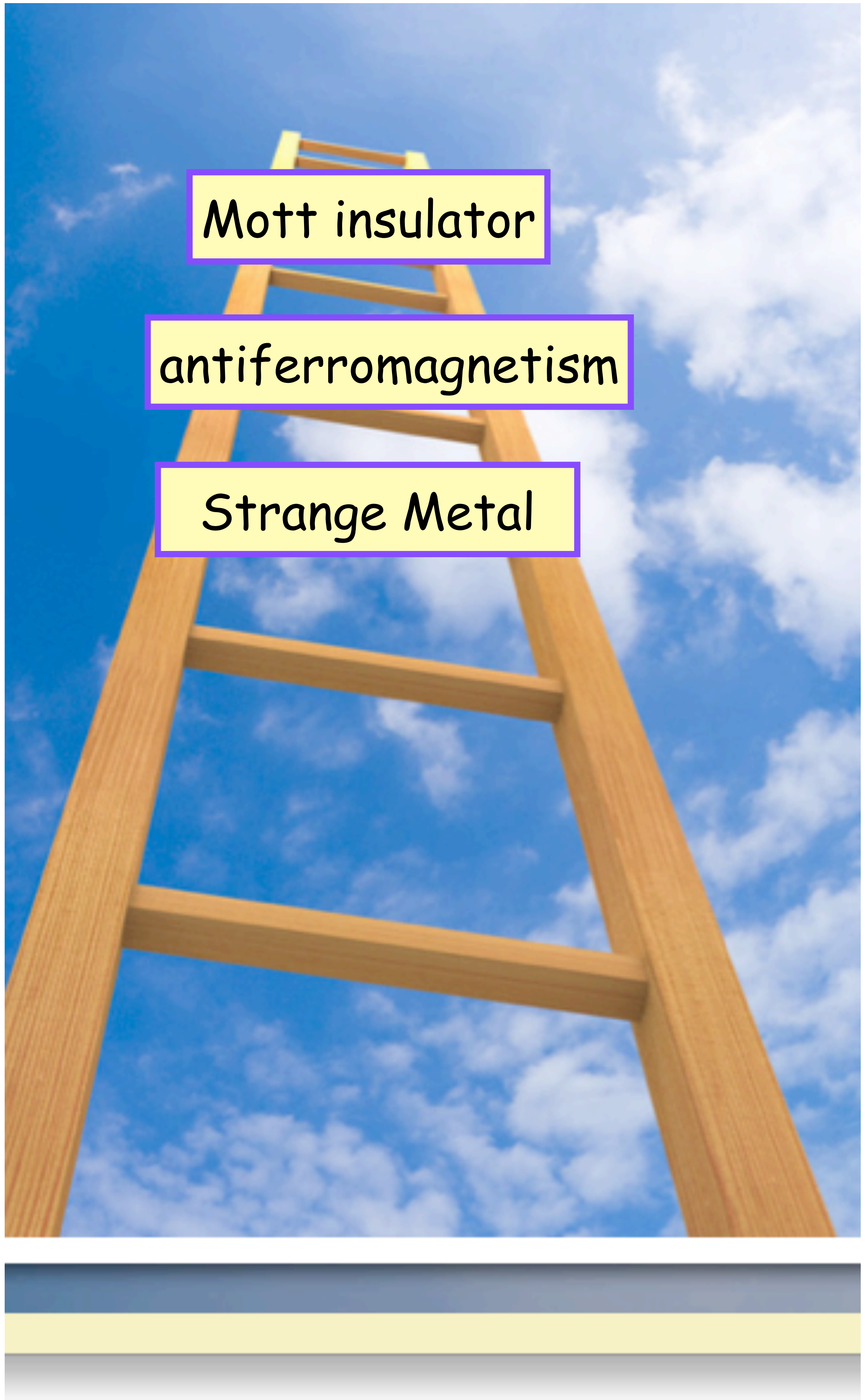

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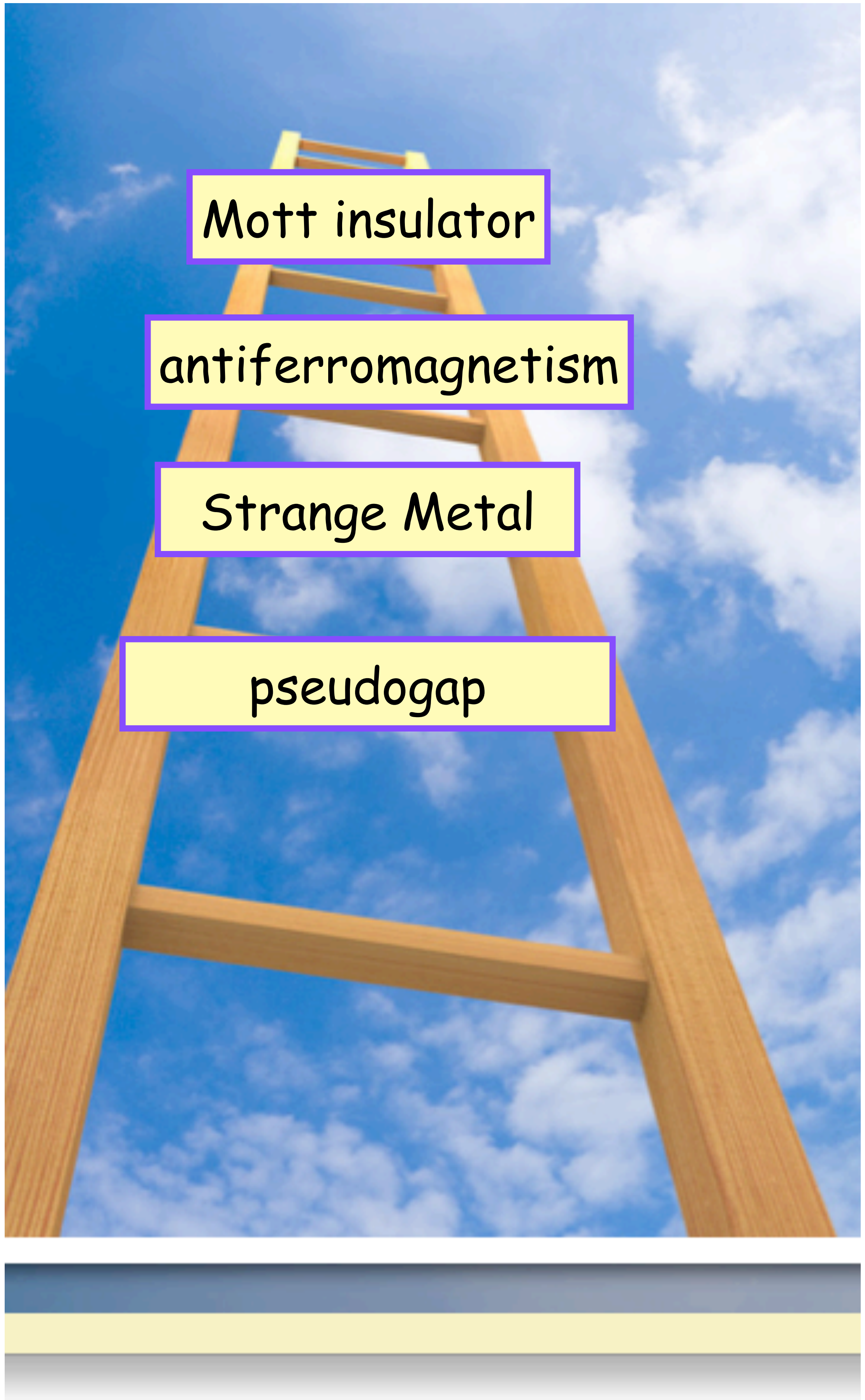

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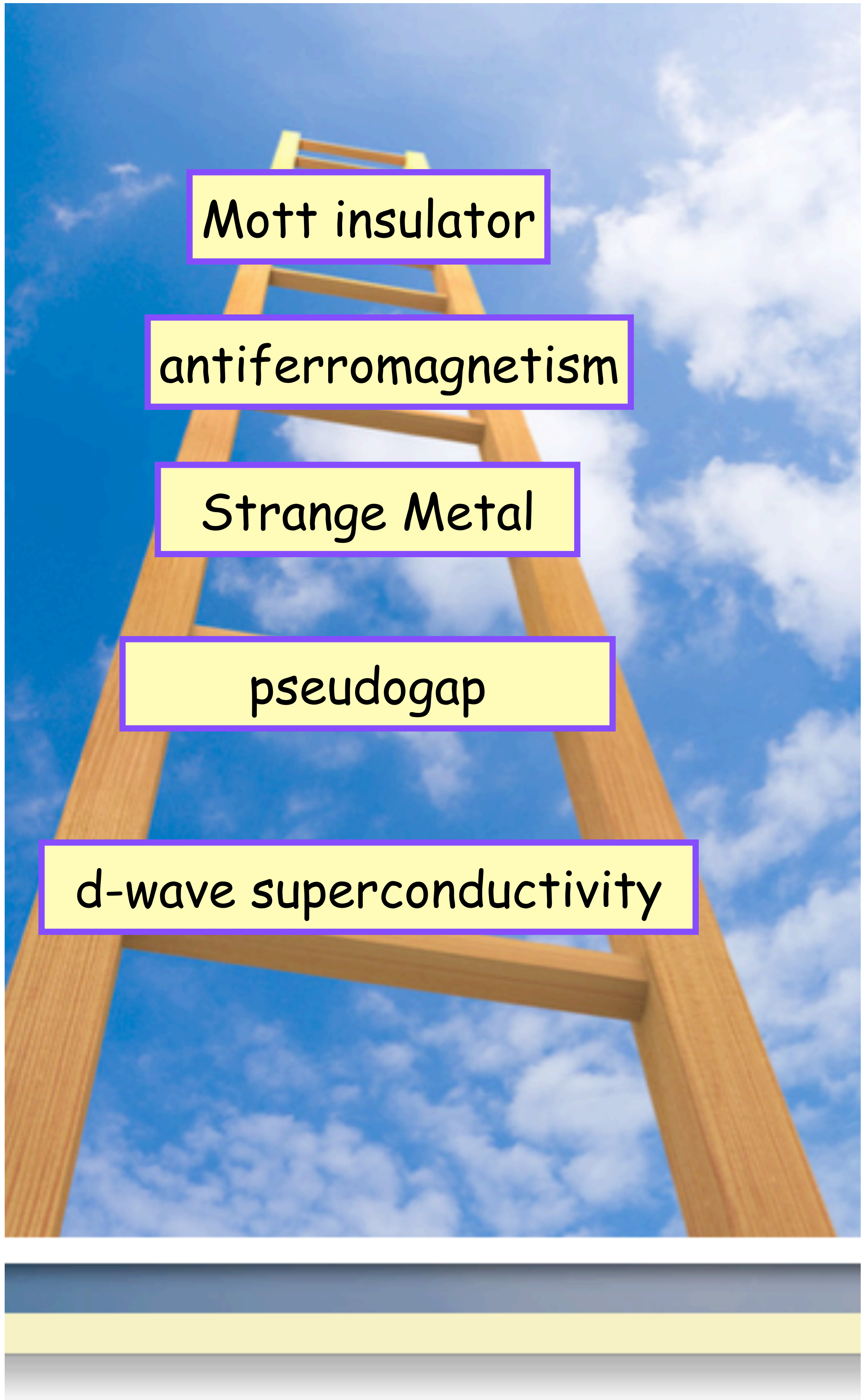

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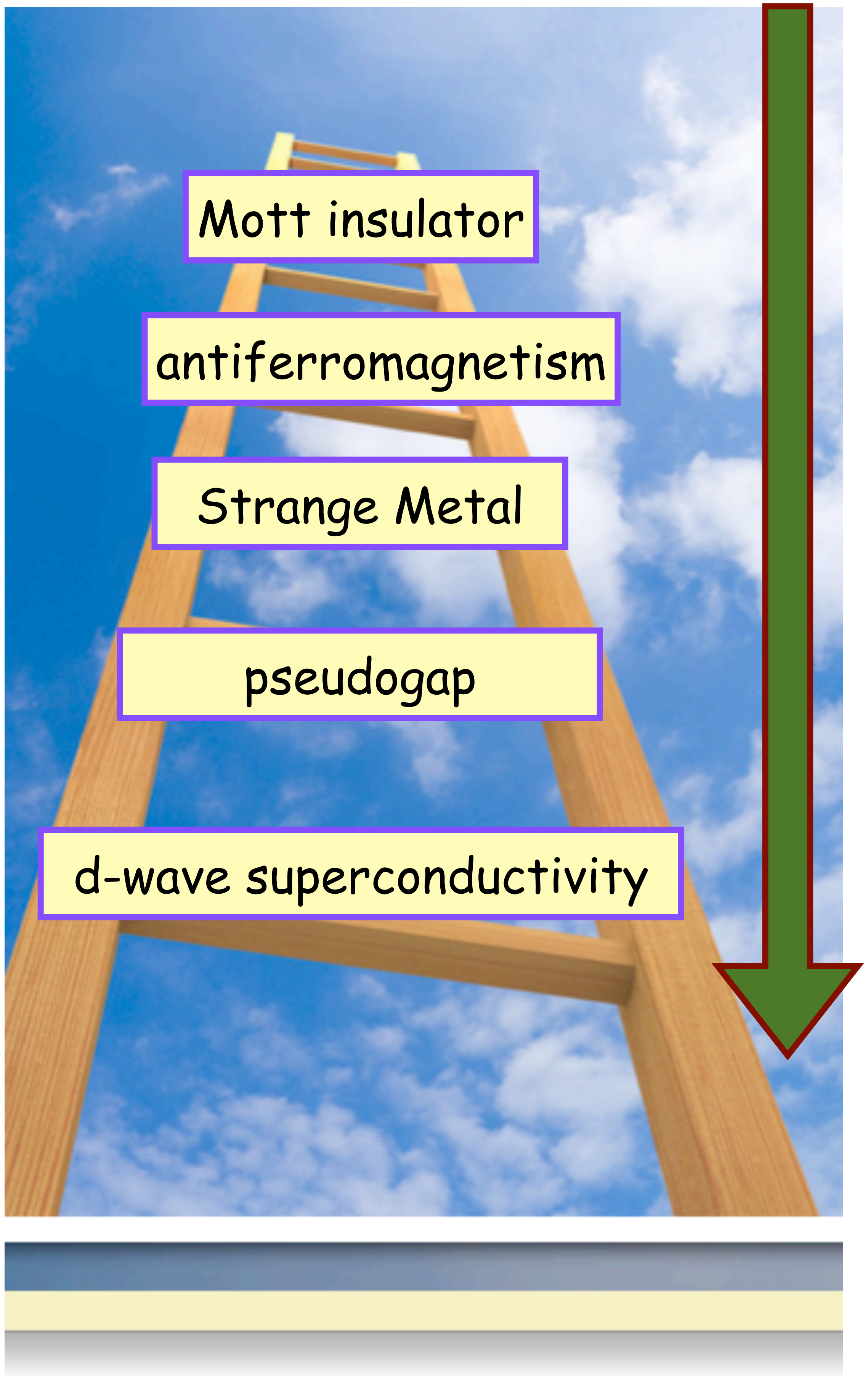

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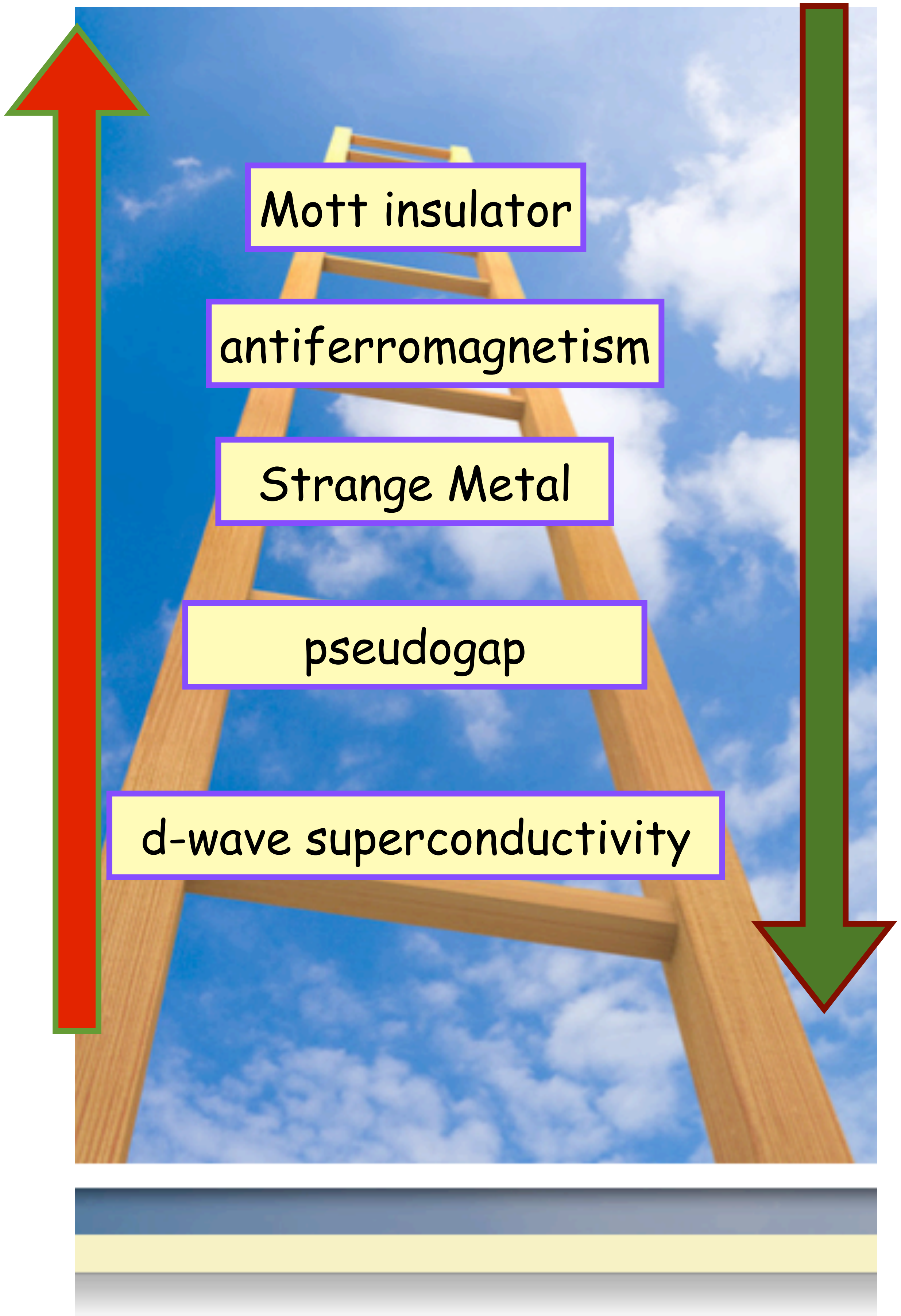

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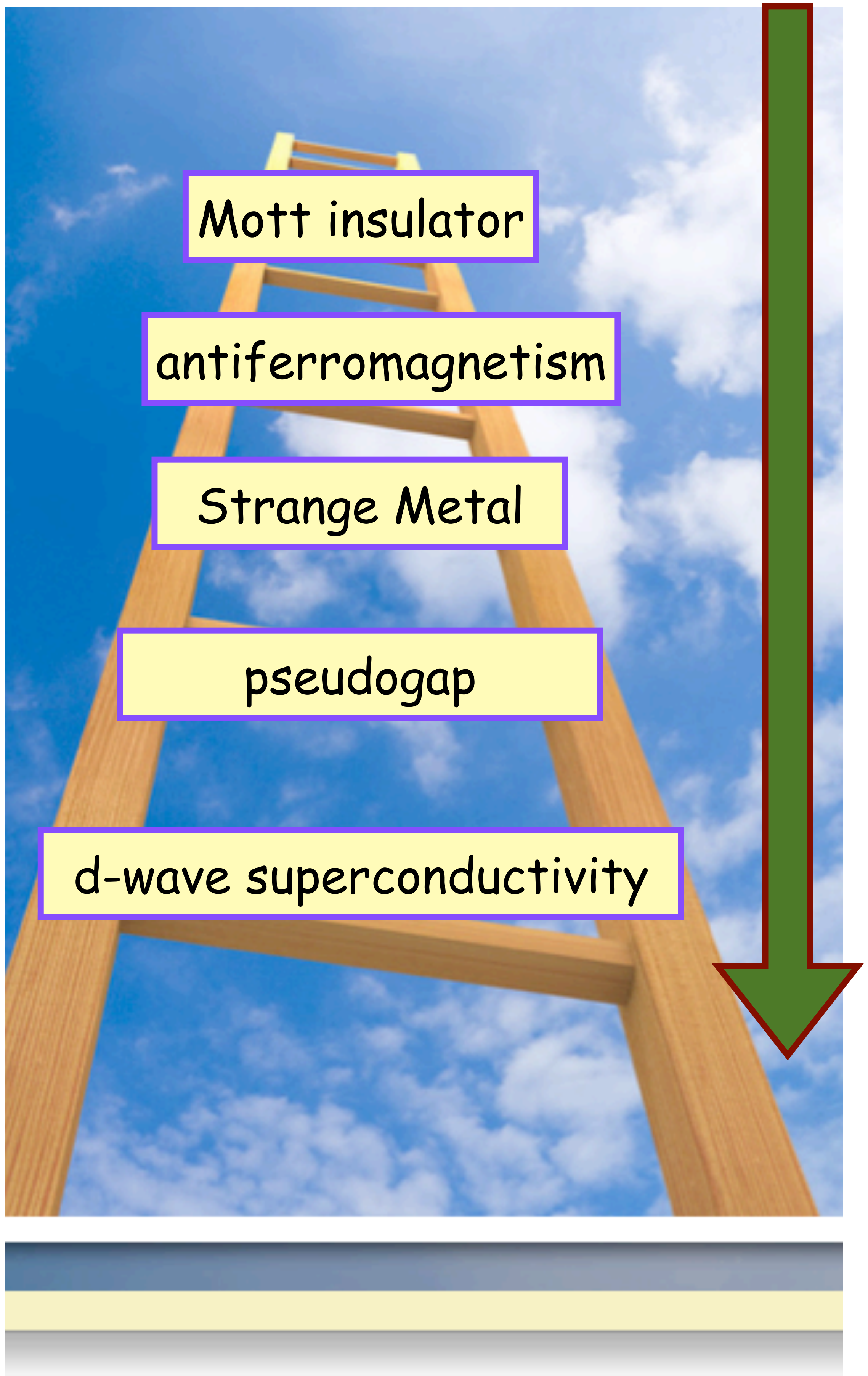
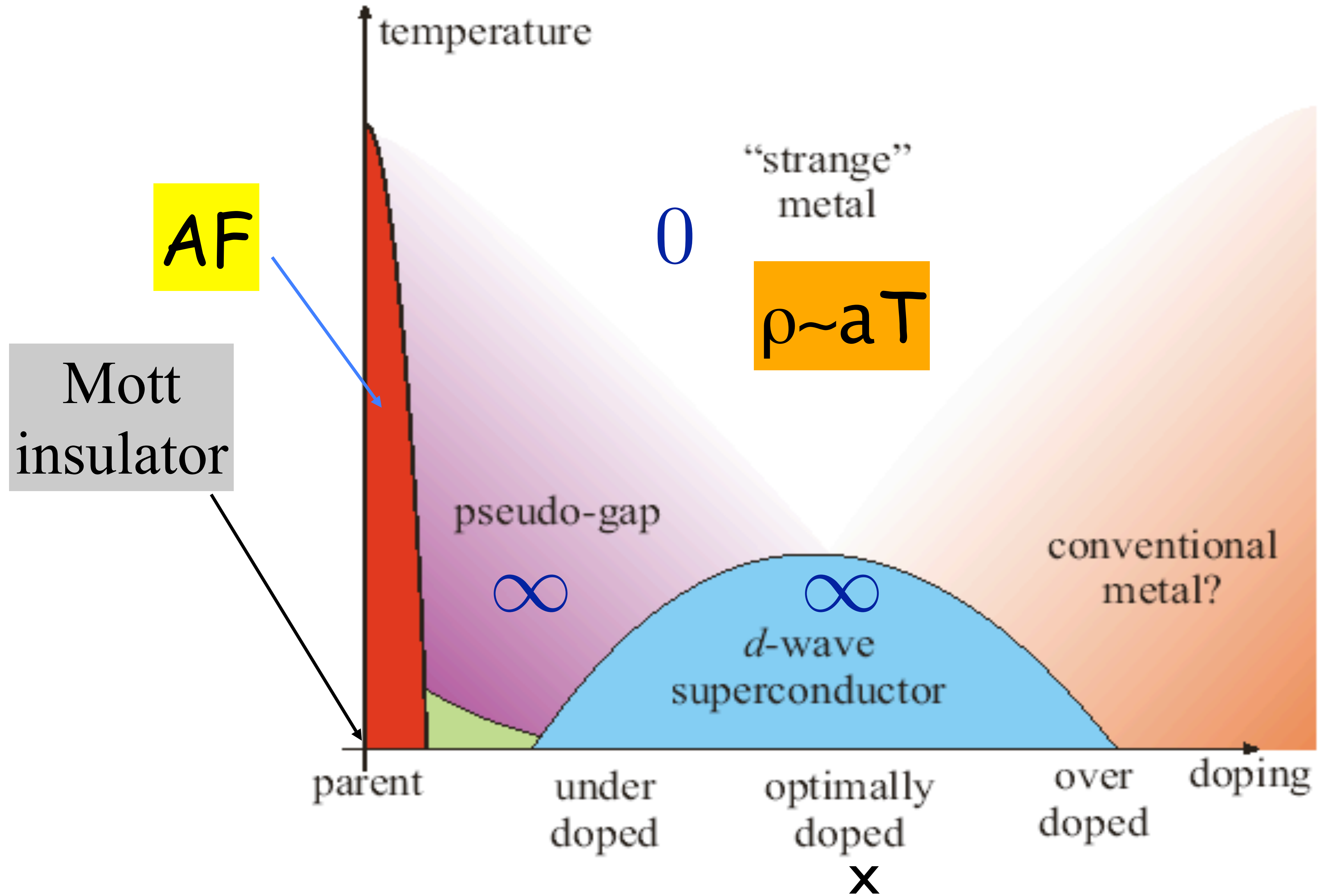
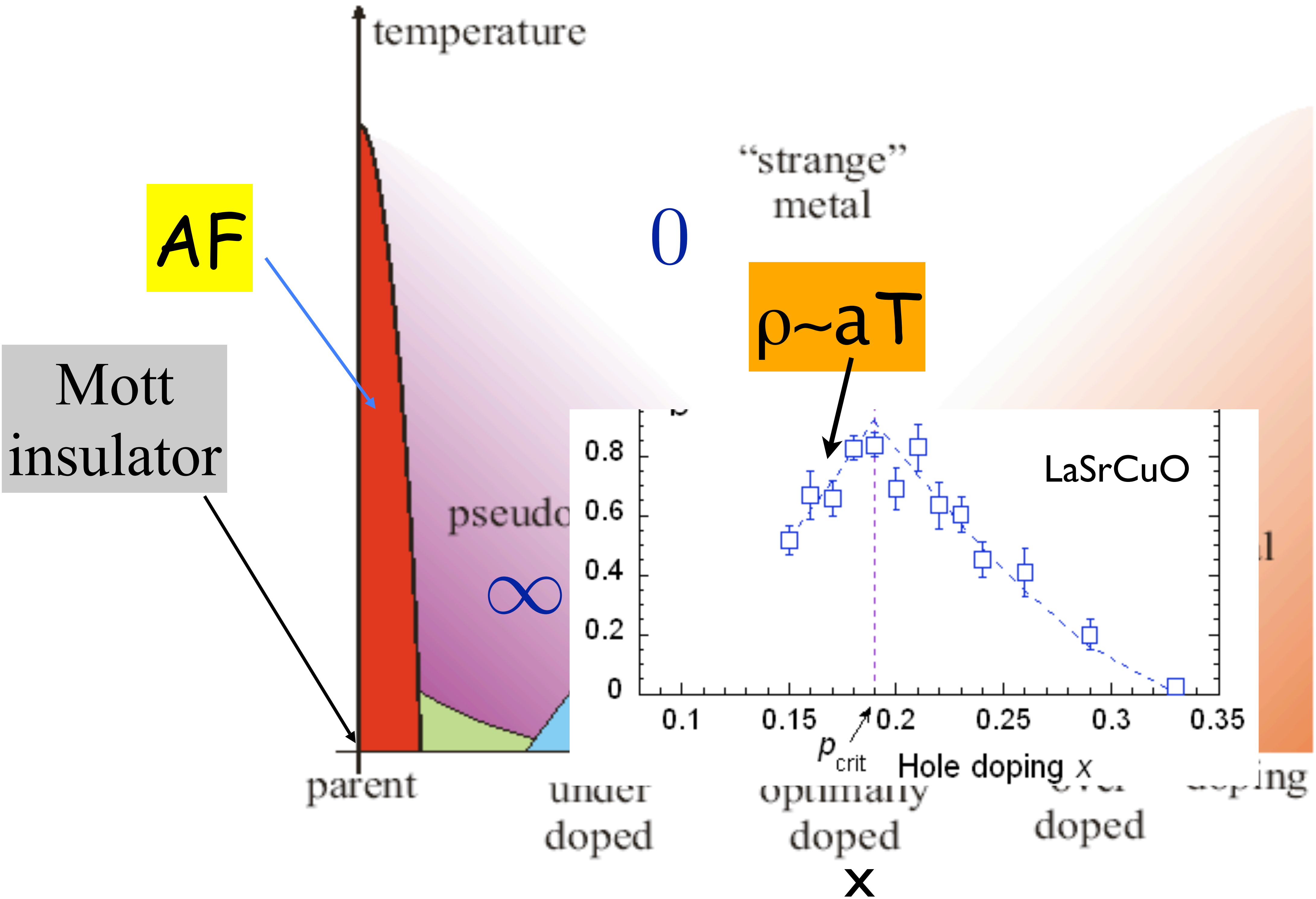
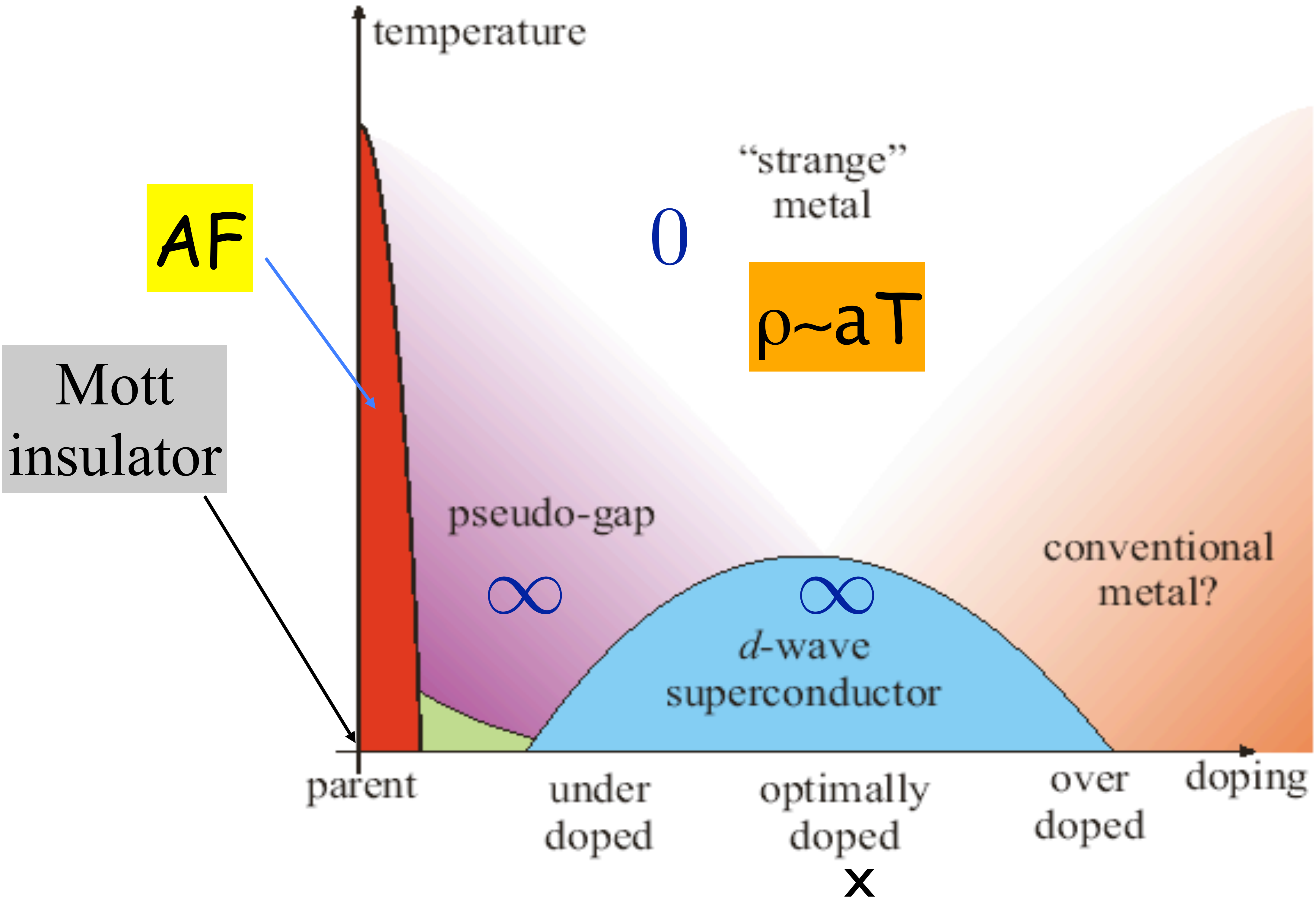



temperature
AF
Mott
insulator
0
"strange"
metal
ρ~aT
pseudo-gap
∞
∞
d-wave
superconductor
conventional
metal?
parent
under
doped
optimally
doped
over
doped
doping
x


temperature
"strange"
metal
AF
0
ρ~aT
Mott
insulator
pseudo
∞
0.8
0.6
0.4
0.2
0
0.1
0.15
0.2
0.25
0.3
0.35
LaSrCuO
p_{crit}
Hole doping x
parent
under
doped
optimally
doped
over
doped
doping
x


AF
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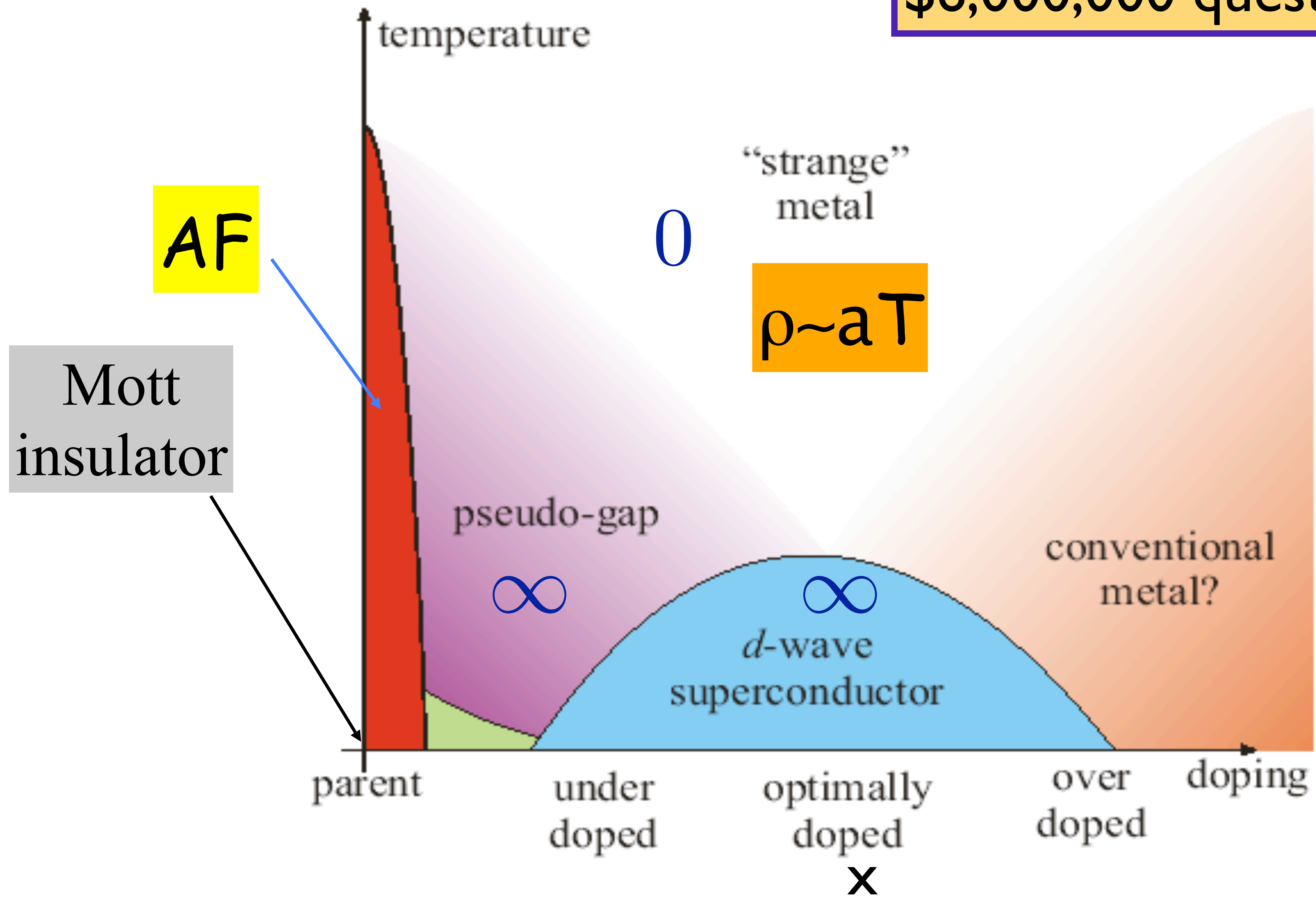
doping
x

How does Fermi Liquid Theory Breakdown?

$6,000,000 question?



T-linear resistivity

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quantum criticality

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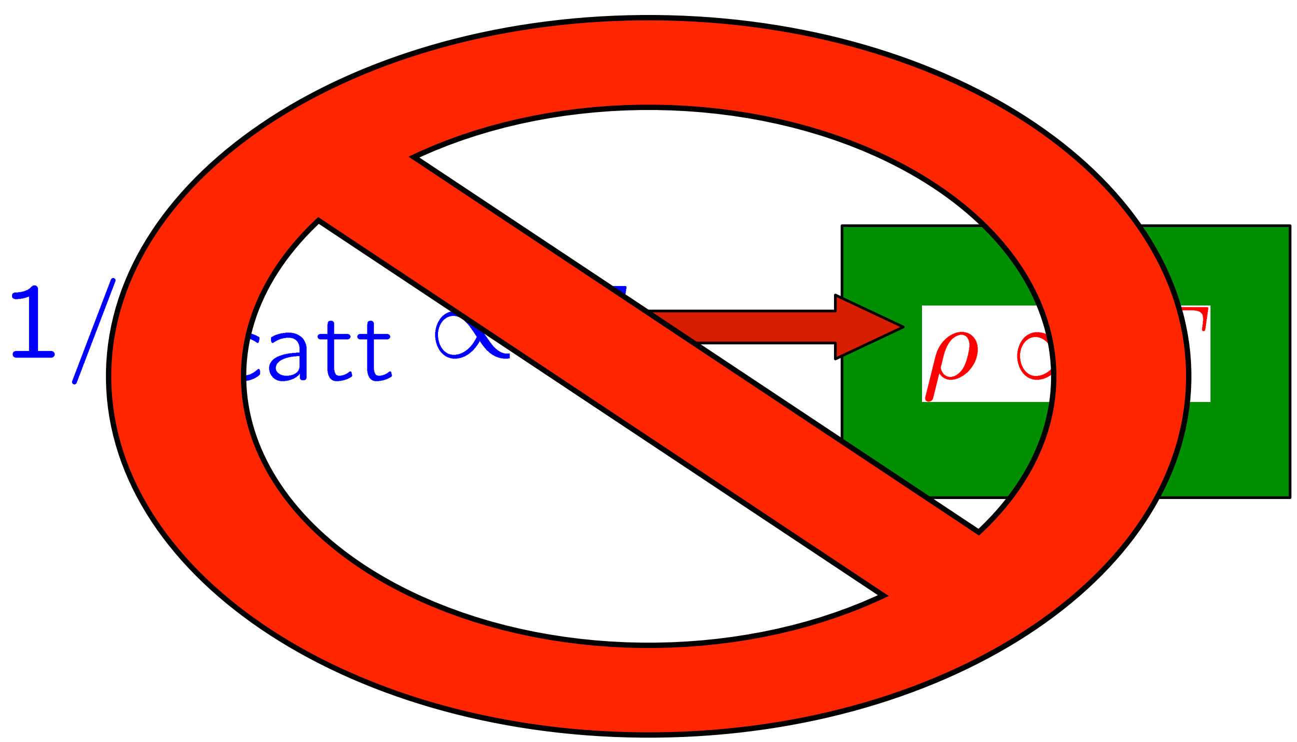
$$1/\tau_{\mathsf{scatt}} \propto T \quad \rightarrow \quad \rho \propto T$$

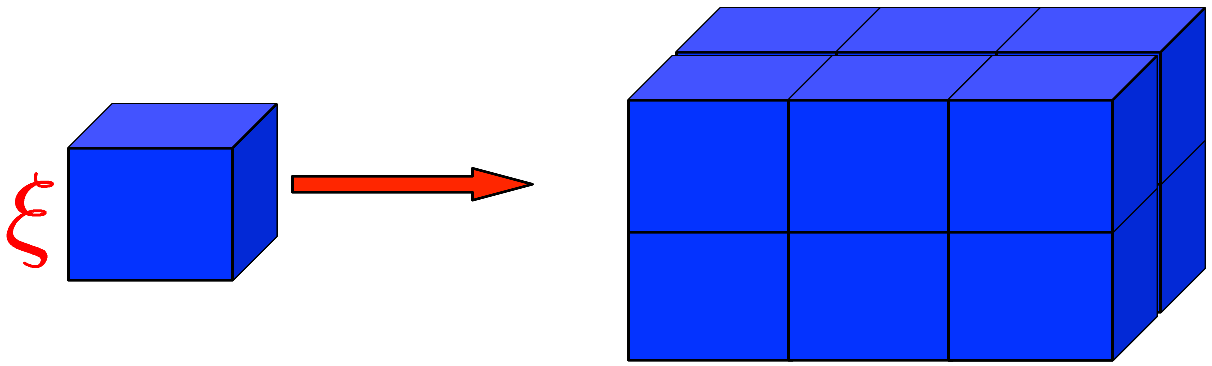
T-linear resistivity

quantum criticality



General Result

1.) one critical length scale



2.) charge carriers are critical

3.) charge conservation

$$S \rightarrow S_{\mathsf{whatever}} + \int d\tau d^d x A^{\mu} j_{\mu}$$

Vector potential

current

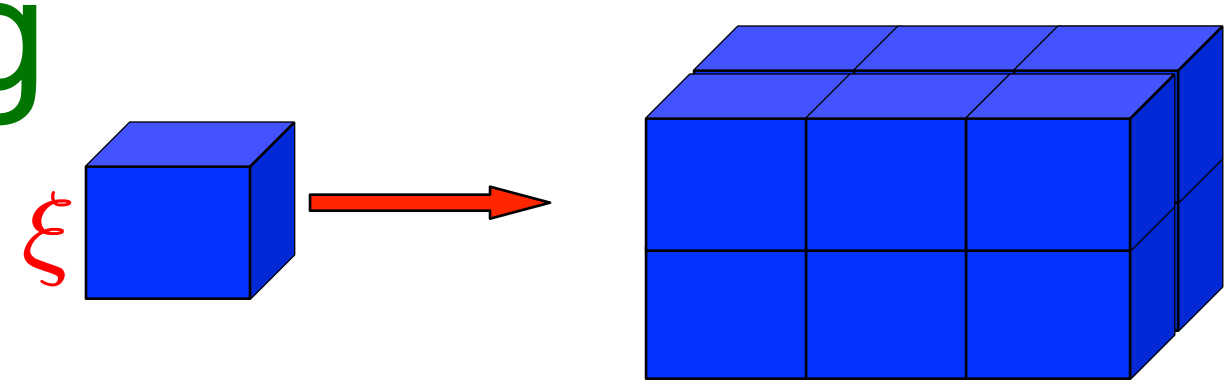
$$S \rightarrow S_{\textsf{whatever}} + \int d\tau d^d x A^\mu j_\mu$$

Vector potential

current

Charge conservation: $d_A = 1$

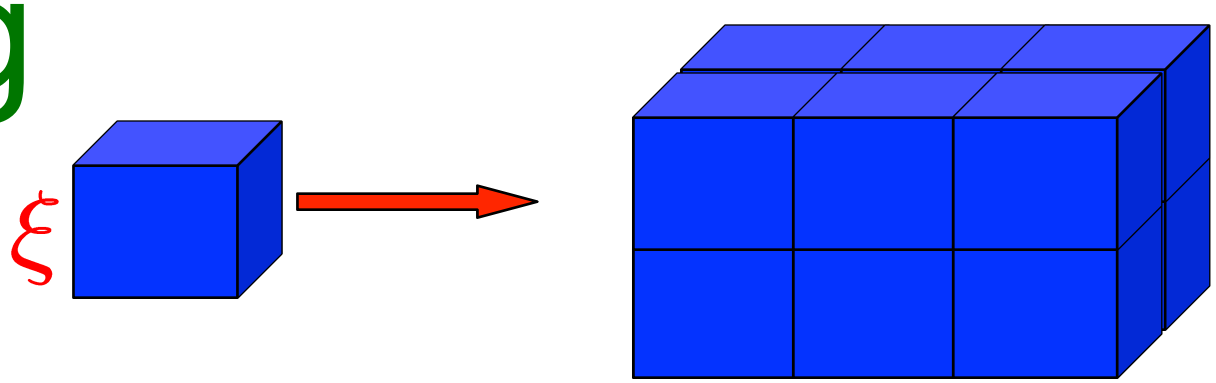
scaling



$$\ln Z = \frac{L^d \beta}{\xi^d \xi_t} F(\delta \xi^{d_\delta}, \{A^i_\lambda \xi^{d_A}\})$$

$$A^i_\lambda = A^i(\omega = \lambda \xi_t^{-1})$$

scaling



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$$A^i_\lambda = A^i(\omega = \lambda \xi_t^{-1})$$

$$\sigma_{ij} = \frac{1}{L^d \beta} \frac{1}{\omega} \frac{\delta^2 \ln Z}{\delta A^i(-\omega) \delta A^j(\omega)}$$

PP, CC, PRL, vol. 95, 107002 (2005)

$$\sigma(T) \propto T^{(d-2)/z}$$

$$E \propto p^z$$

dynamical exponent

PP, CC, PRL, vol. 95, 107002 (2005)

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d=3 ⇒

$$\rho \propto T$$

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dynamical exponent

only if z<0

PP, CC, PRL, vol. 95, 107002 (2005)

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d=3 →

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$$E \propto p^{z}$$

dynamical exponent

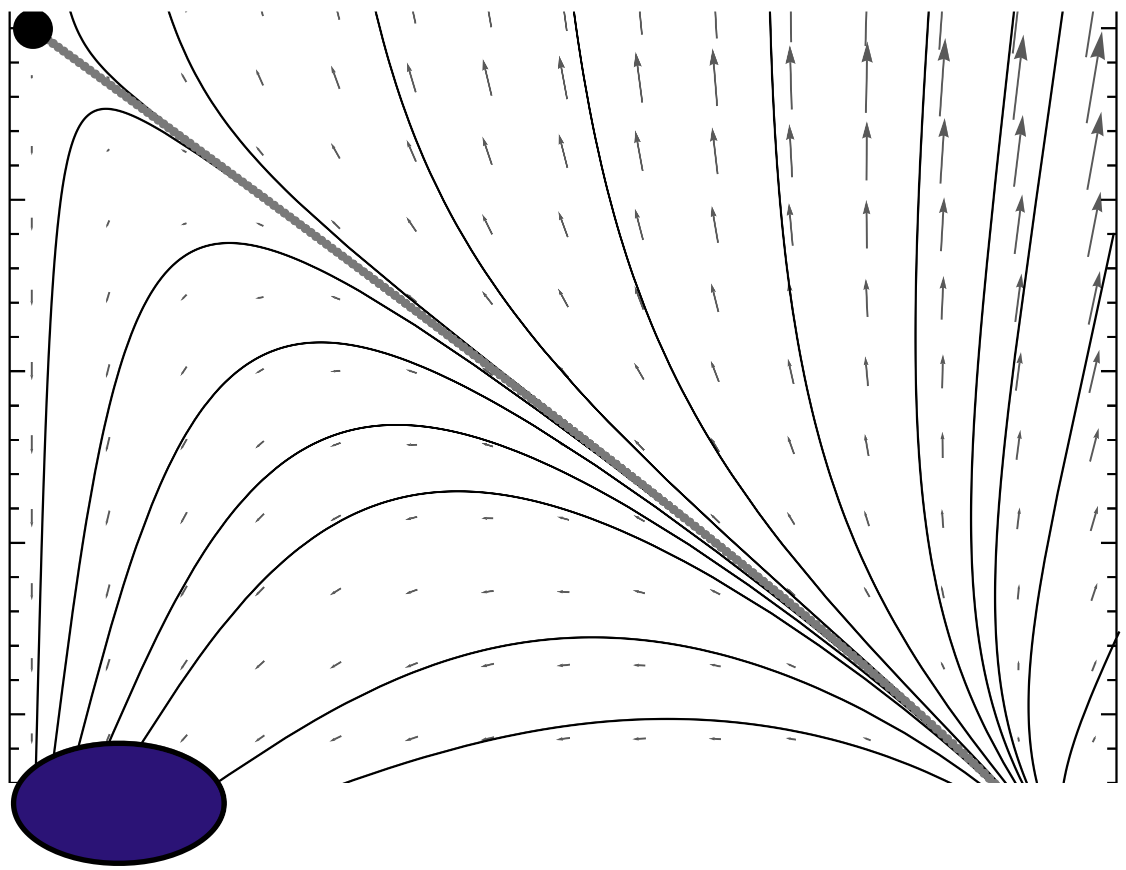
only if z<0

One-parameter Scaling breaks down

$\rho \propto T$ → new length scale

new degree of freedom

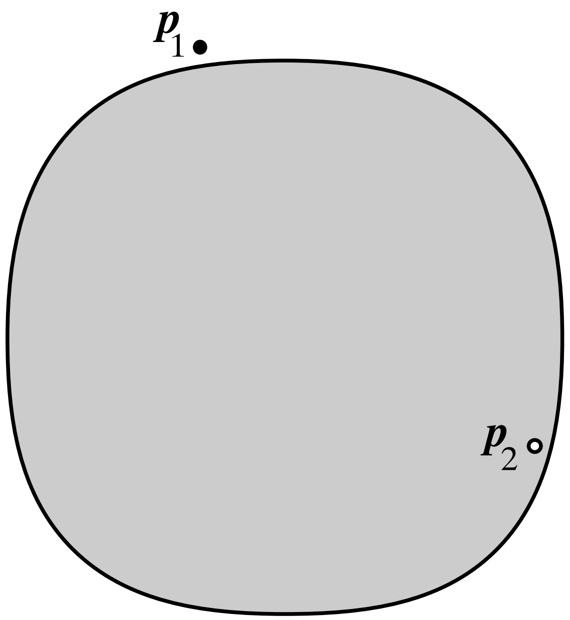
NFL?



FL

How to break Fermi liquid theory in d=2+1?

Polchinski, Shankar, others



$$\mathbf{p} = \mathbf{k} + \mathbf{l},$$

1.) e- charge carriers

2.) Fermi surface

$$\int dt\, d^2\mathbf{k}_1\, d\mathbf{l}_1\, d^2\mathbf{k}_2\, d\mathbf{l}_2\, d^2\mathbf{k}_3\, d\mathbf{l}_3\, d^2\mathbf{k}_4\, d\mathbf{l}_4\, V(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$$
$$\psi^\dagger_\sigma(\mathbf{p}_1)\psi_\sigma(\mathbf{p}_3)\psi^\dagger_{\sigma'}(\mathbf{p}_2)\psi_{\sigma'}(\mathbf{p}_4)\delta^3(\mathbf{p}_1 + \mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4).$$

No relevant short-range 4-Fermi terms in $d \geq 2$

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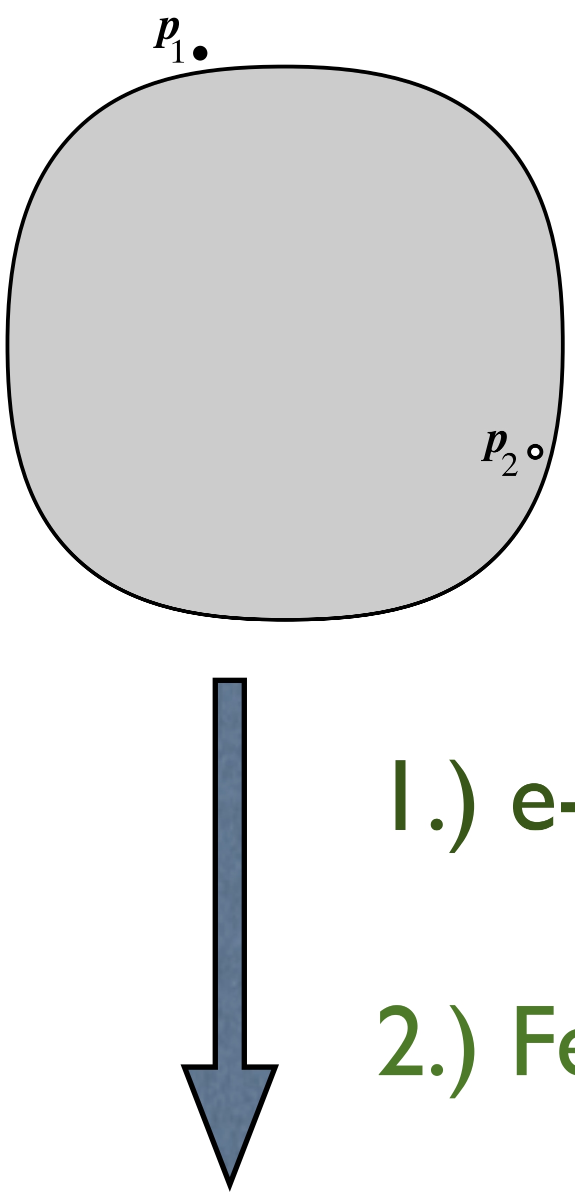

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No relevant short-range 4-Fermi terms in $d \geq 2$

Exception: Pairing

Landau Correspondence

Free system

low-energy:
one-to-one
correspondence

Interacting
system

How does this break down?

Atomic Limit of Hubbard Model

$$H_{\mathrm{Hubb}} \to U \sum_i n_{i\uparrow} n_{i\downarrow}$$

x=# of holes

Atomic Limit of Hubbard Model

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

Atomic Limit of Hubbard Model

spectral weight: x-dependent

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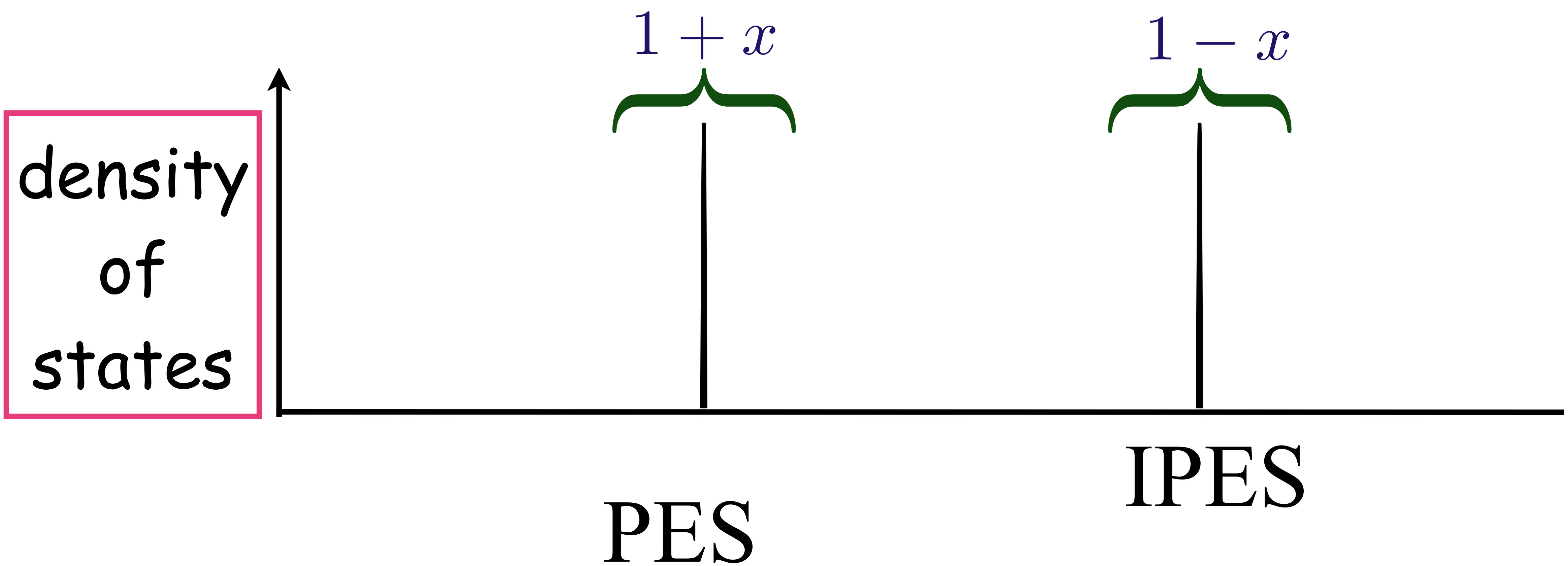

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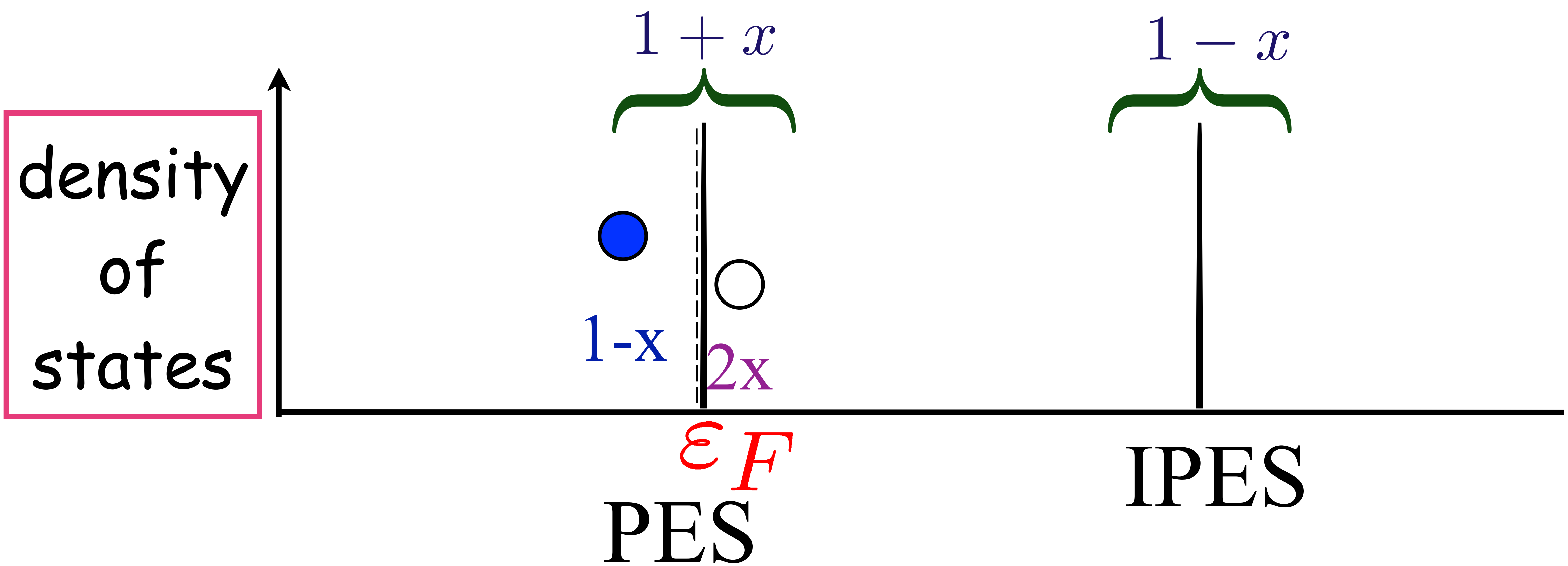

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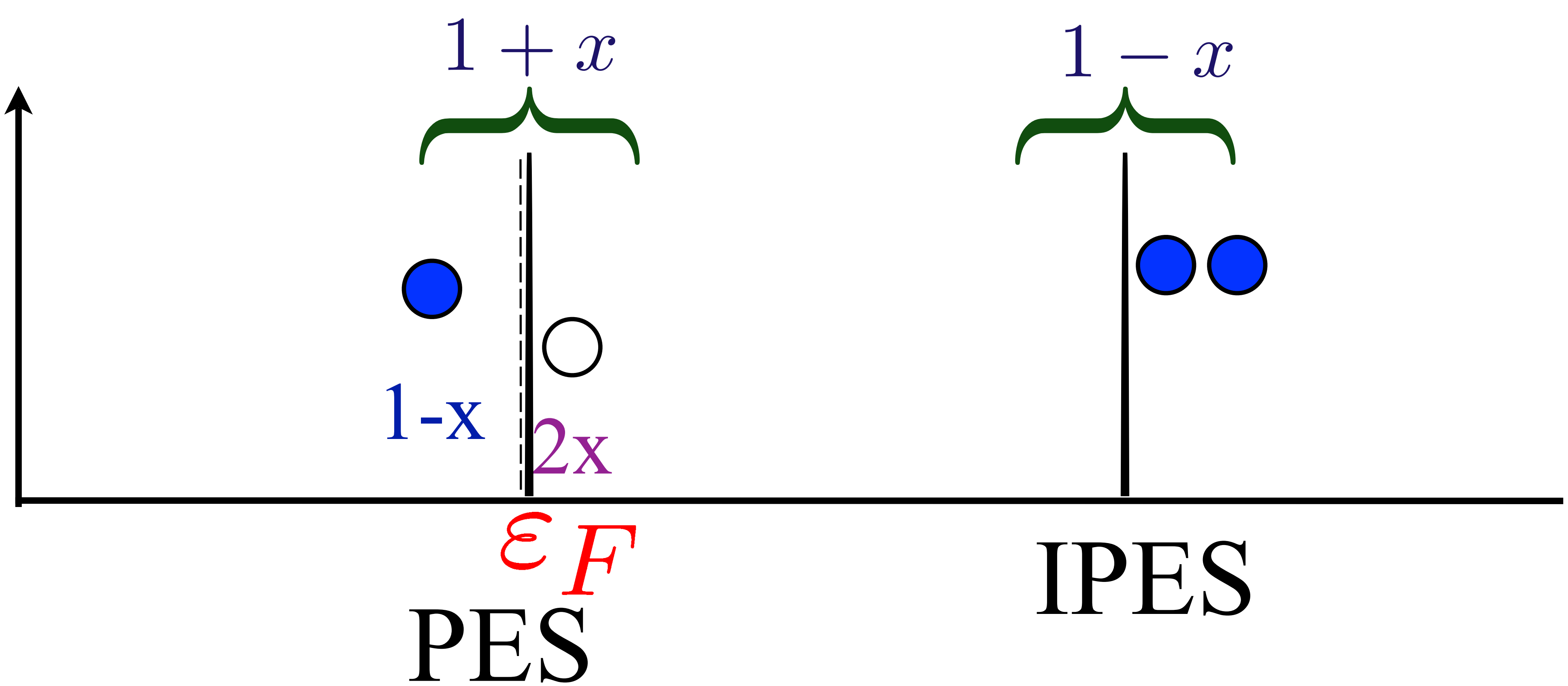
density of states



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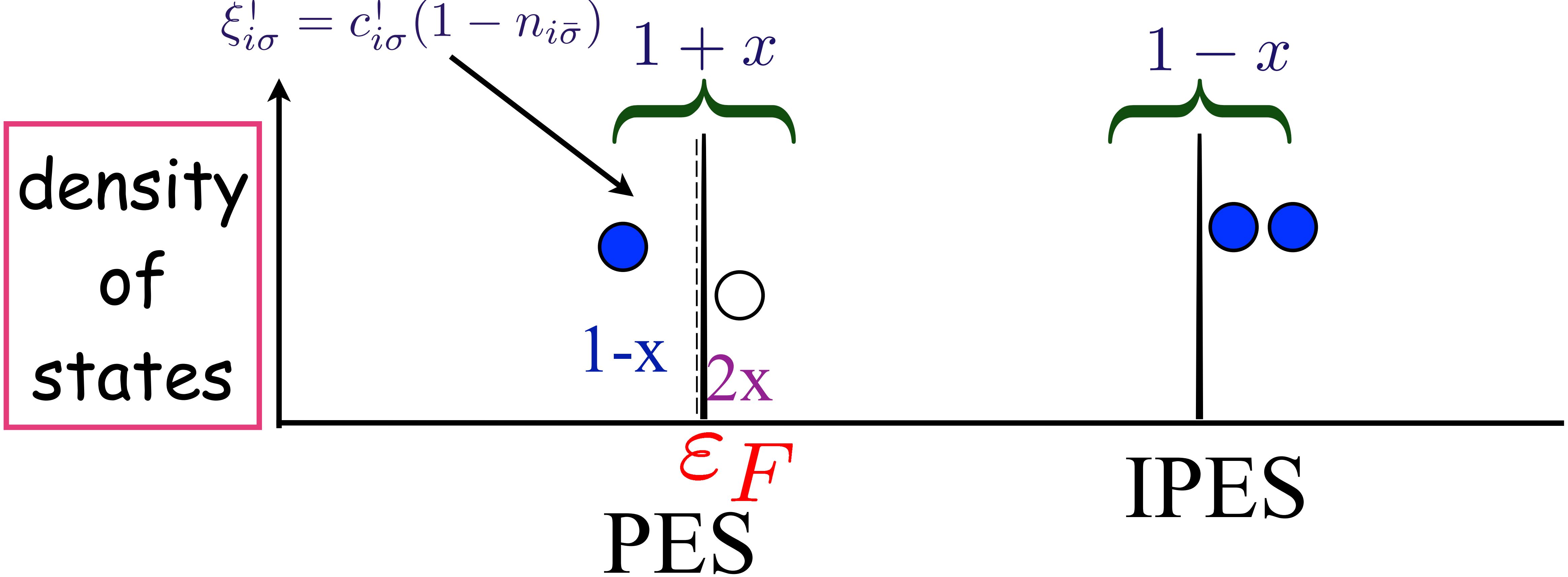
$$\xi^\dagger_{i\sigma} = c^\dagger_{i\sigma}(1-n_{i\bar{\sigma}})$$



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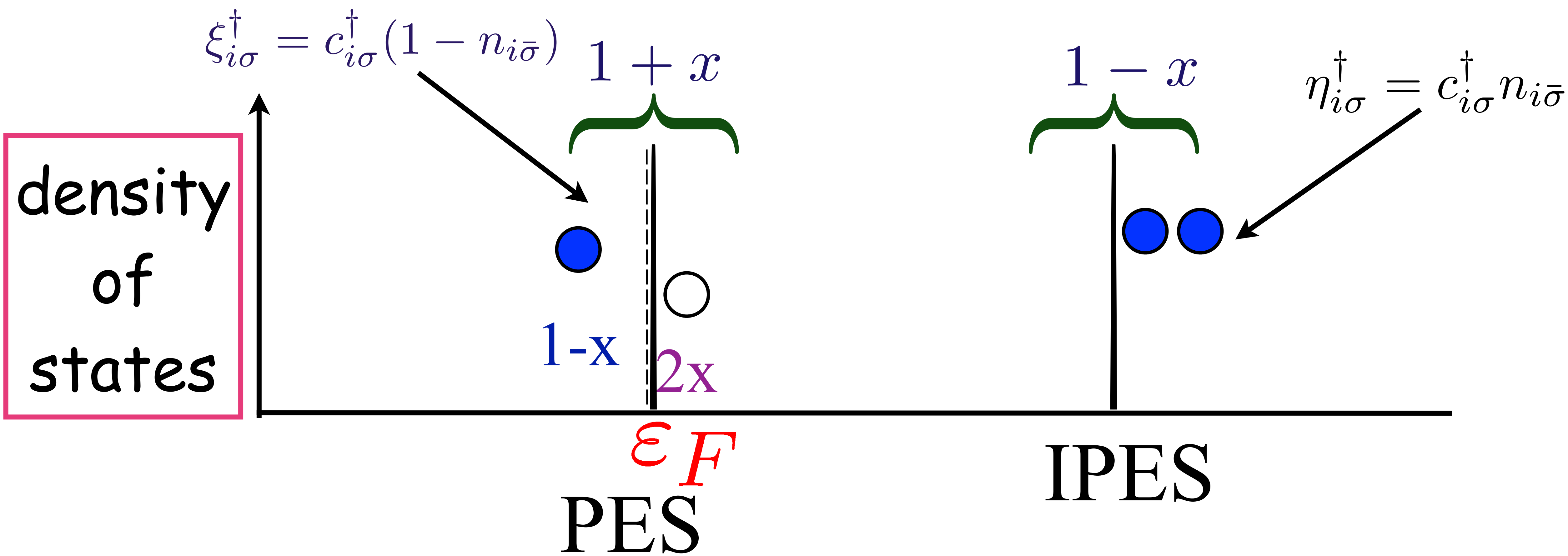


atomic limit

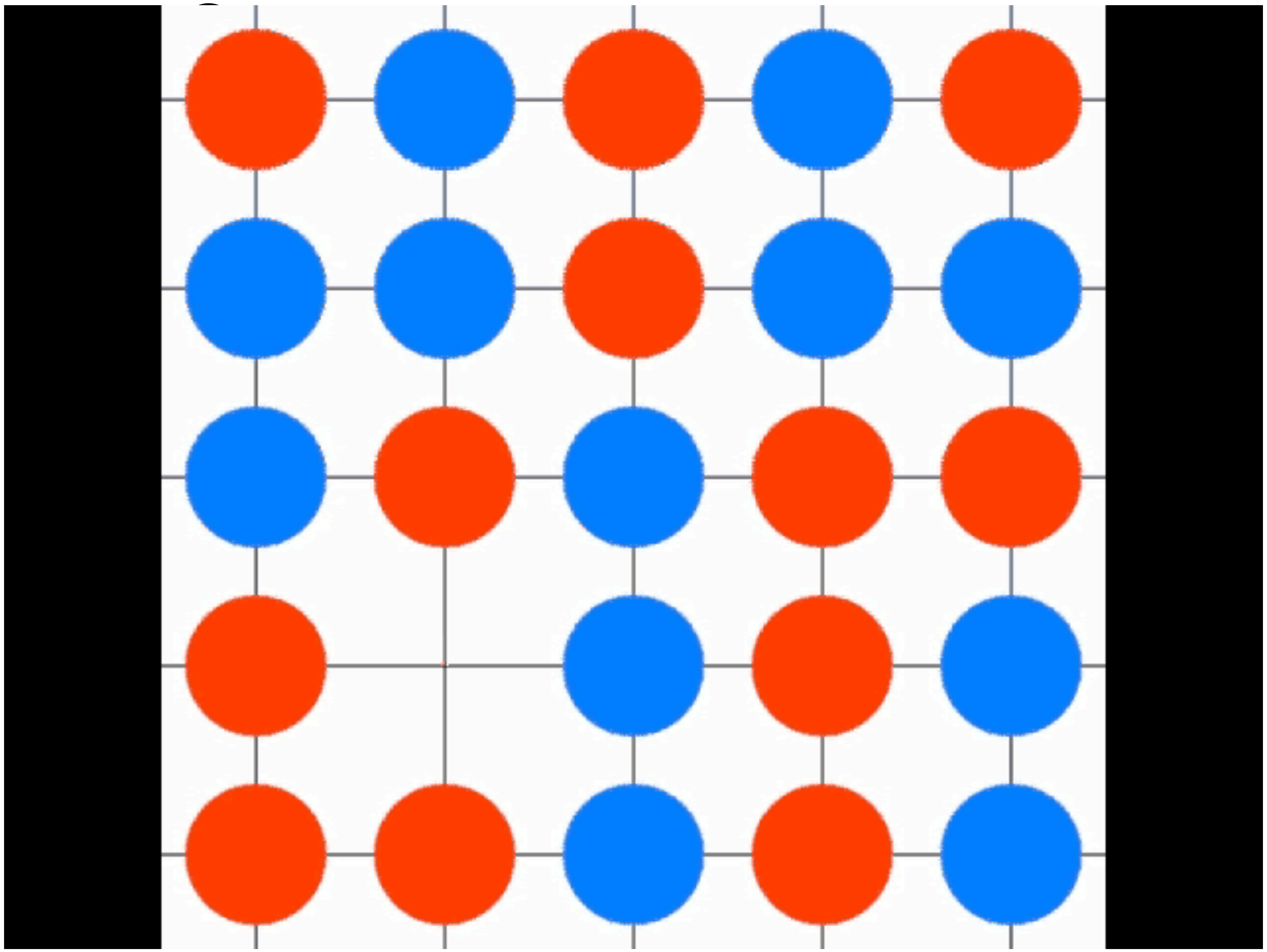
total weight=1+x= # of ways electrons can be added in lower band

intensity of lower band=# of electrons the band can hold

no problems yet!

quantum Mottness: U finite

$U \gg t$



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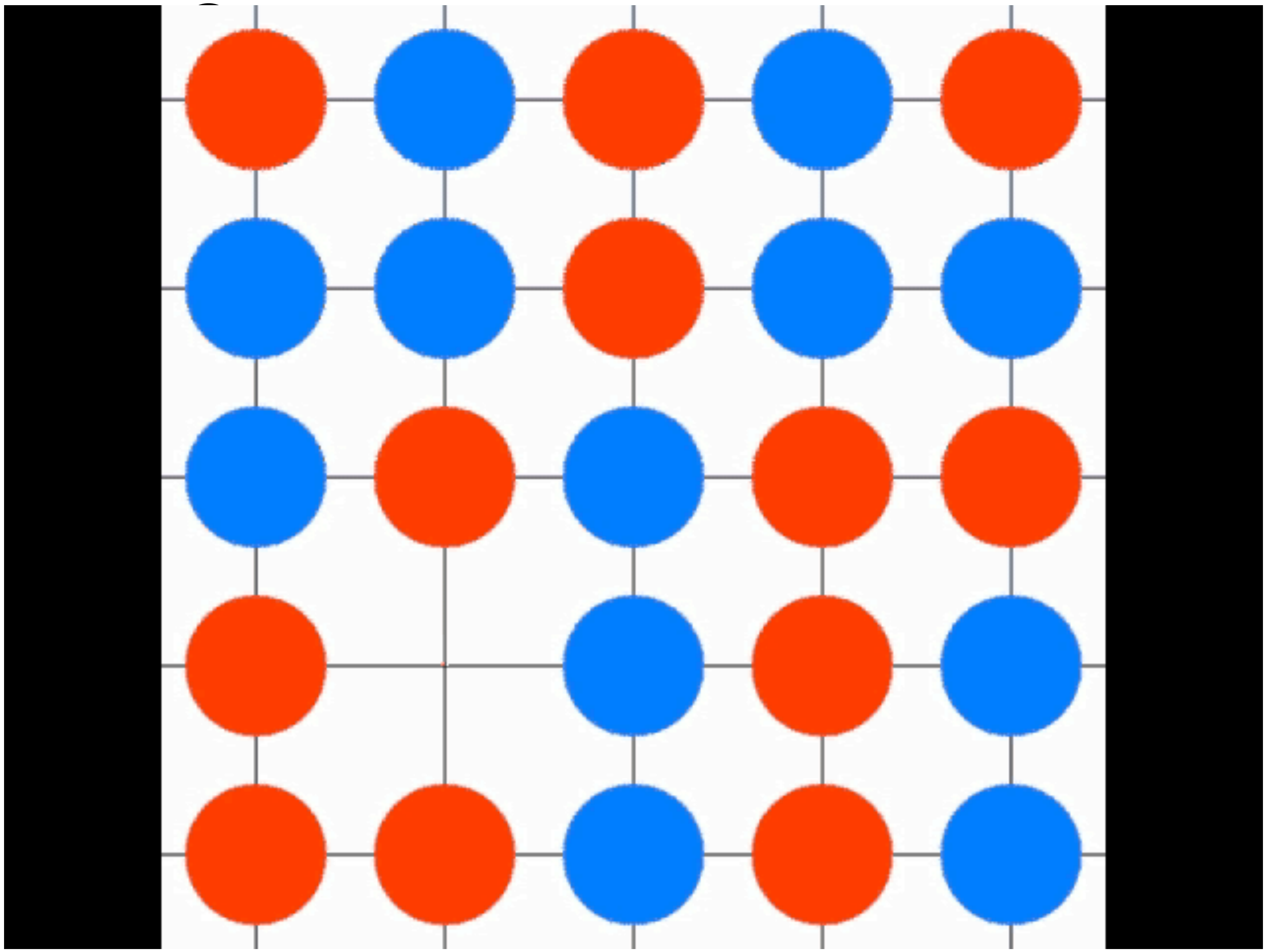

double occupancy in ground (all) state!!

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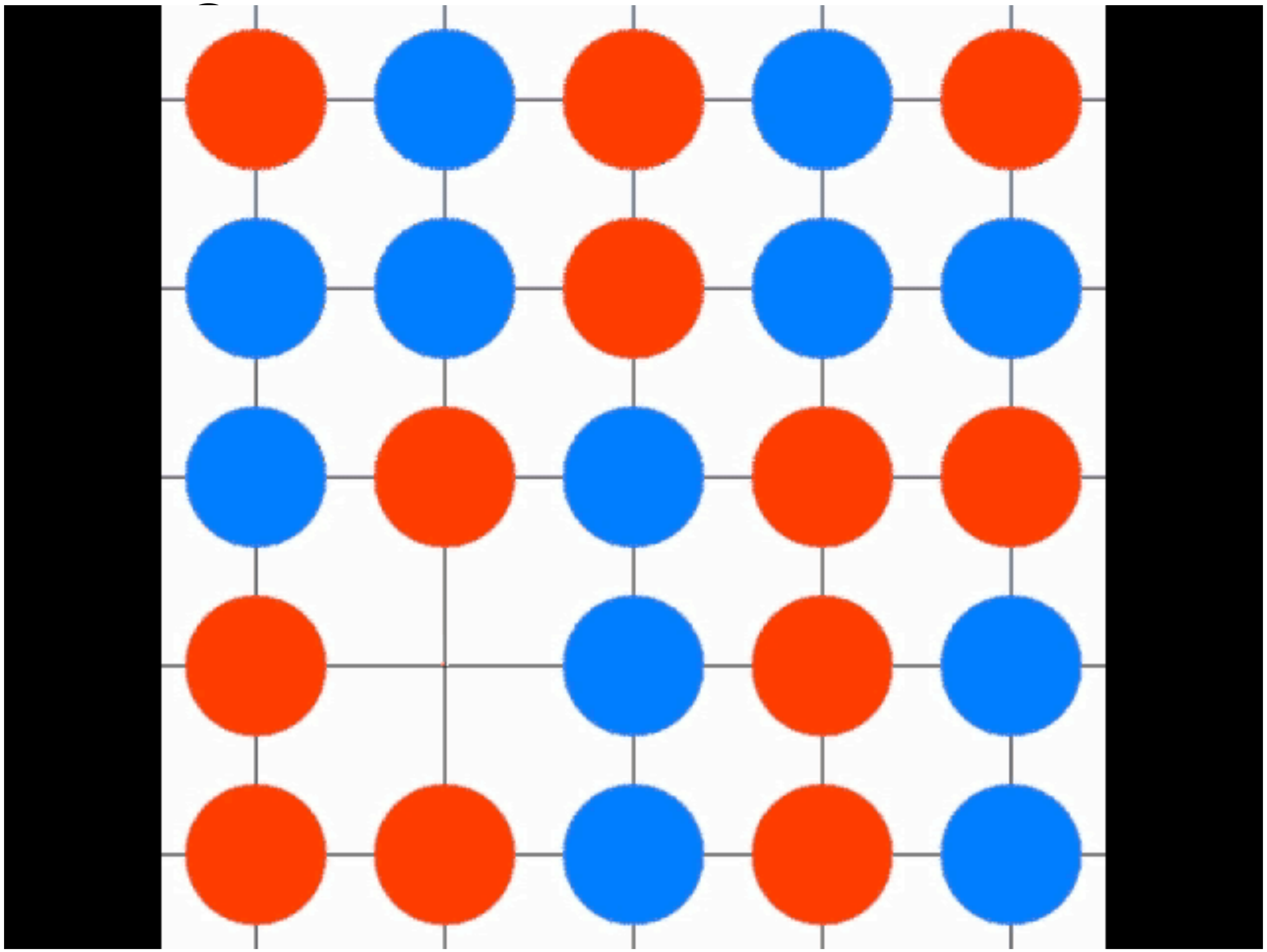


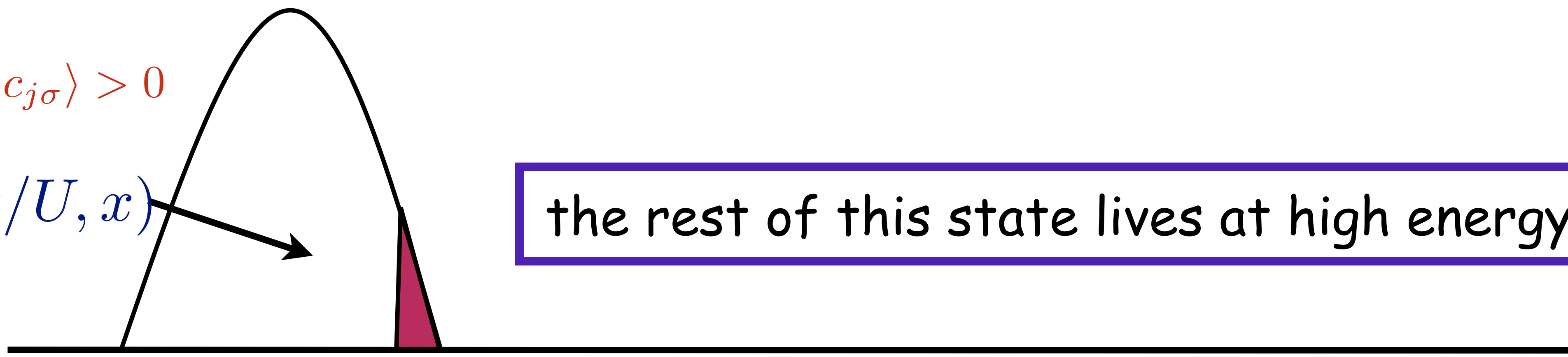
double occupancy in ground (all) state!!

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

Harris & Lange, 1967

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

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



the rest of this state lives at high energy

Harris & Lange, 1967

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

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

Harris & Lange, 1967

dynamical spectral weight transfer

Harris & Lange, 1967

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dynamical spectral weight transfer

Intensity>1+x

New non-electron degrees of freedom

Harris & Lange, 1967

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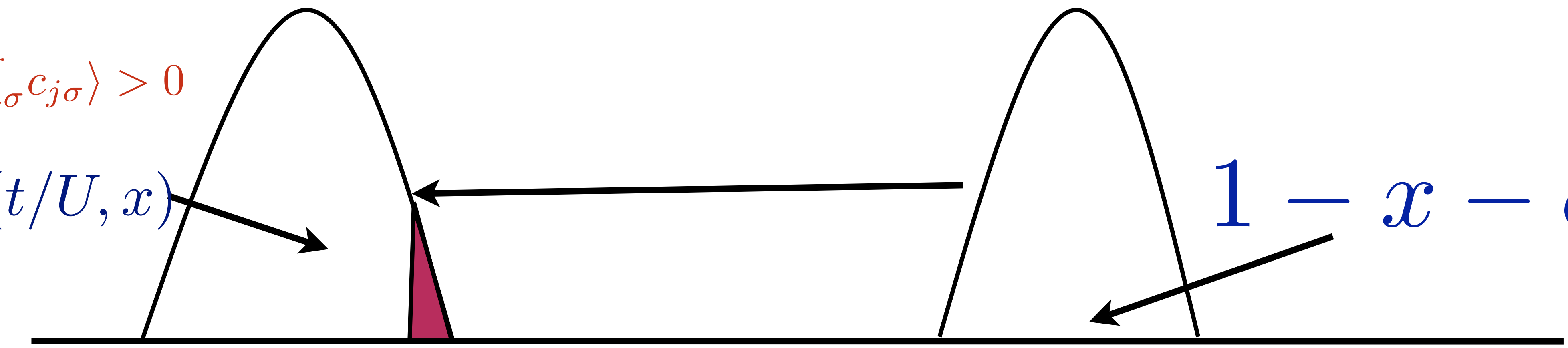


$1 - x - \alpha$

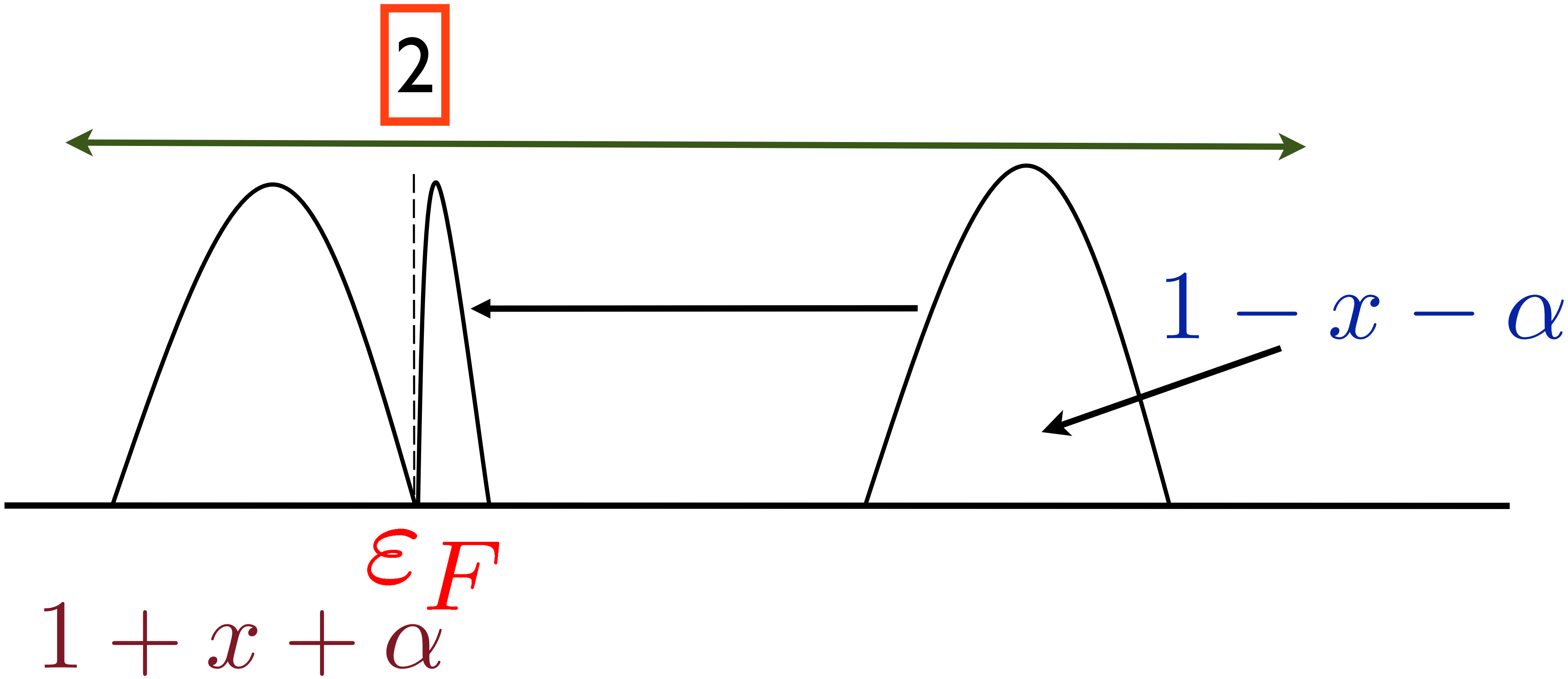
Intensity>1+x

New non-electron degrees of freedom

Can this system be a Fermi liquid?

No

what are the low-energy fermionic excitations?



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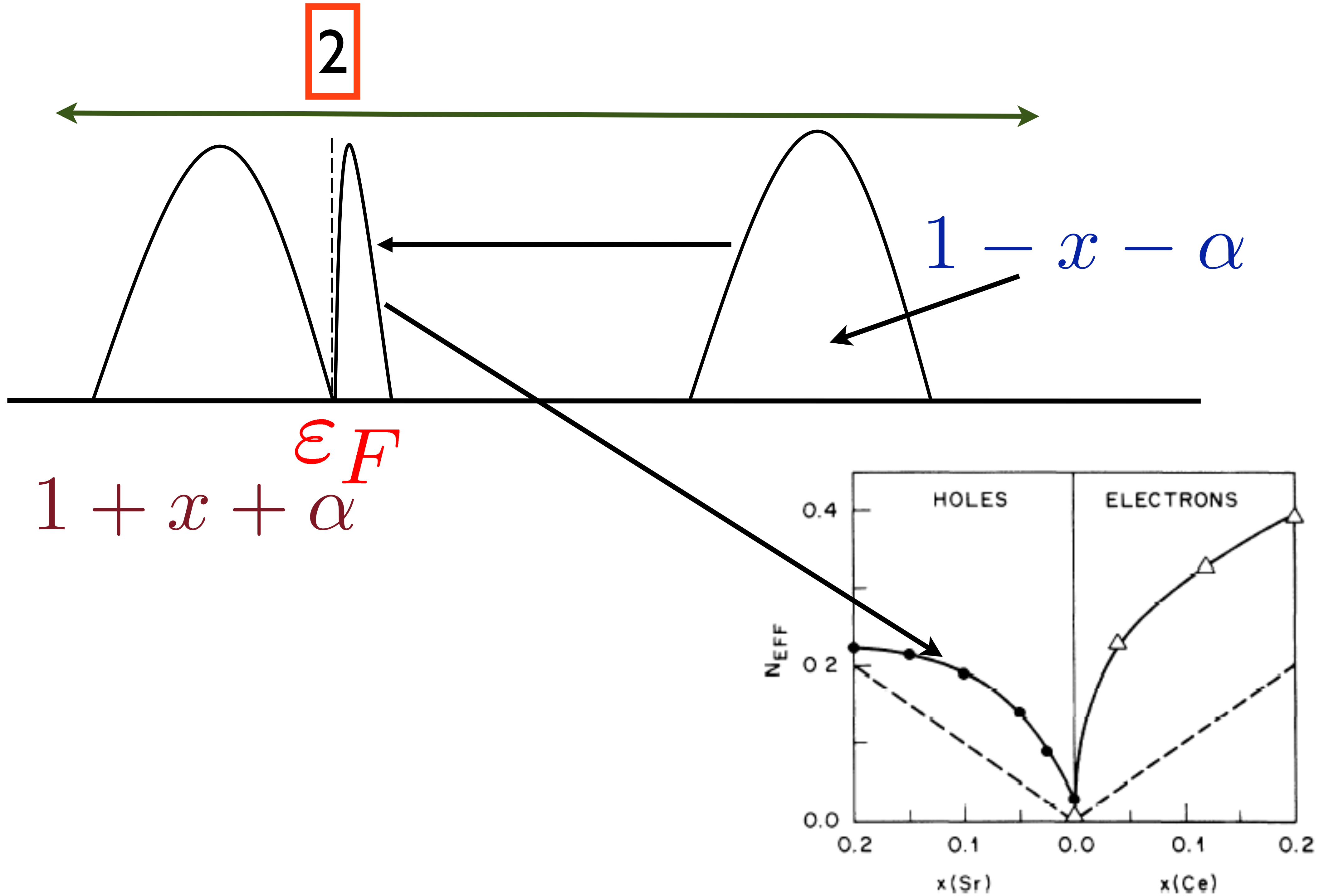
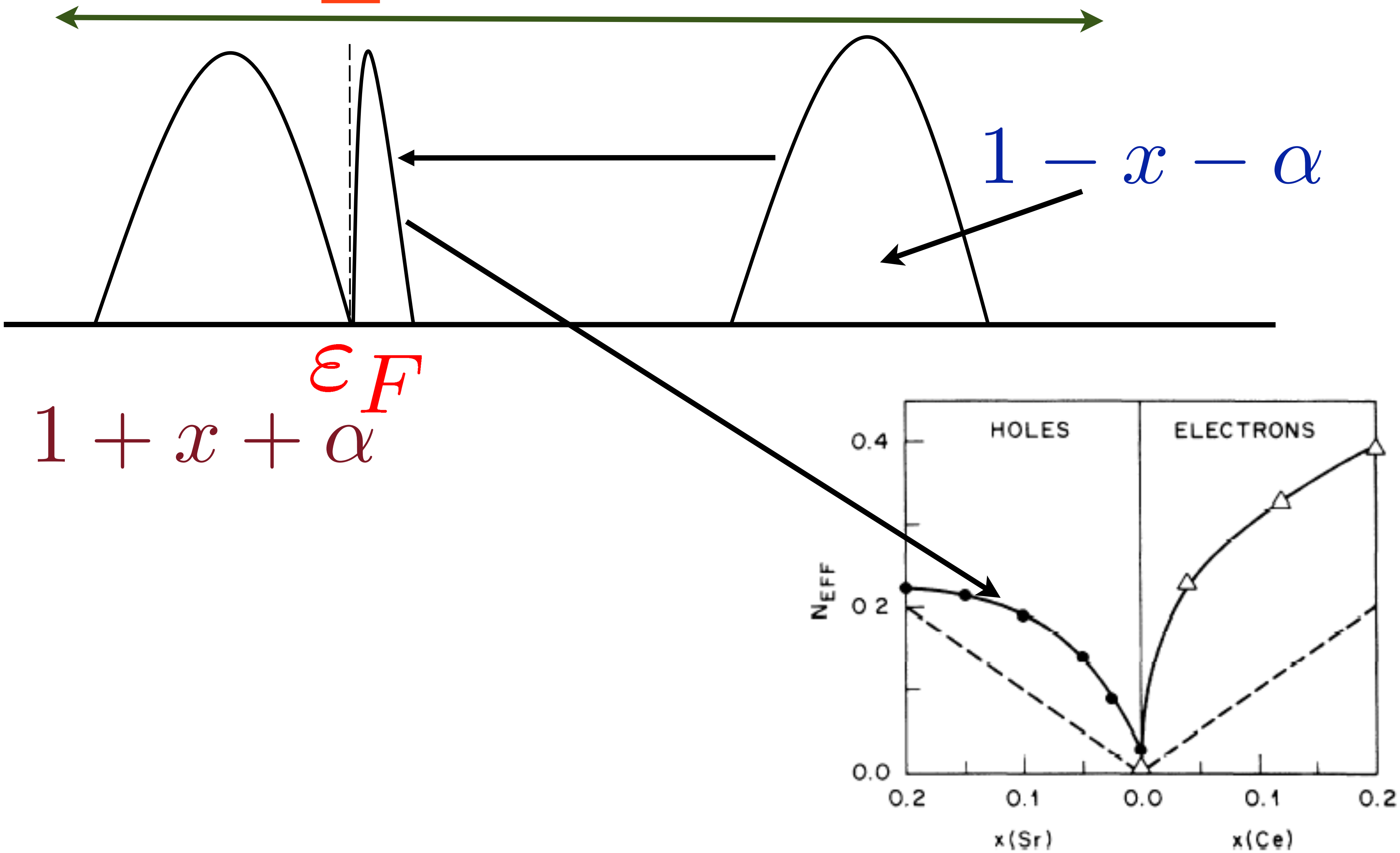


what are the low-energy fermionic excitations?

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



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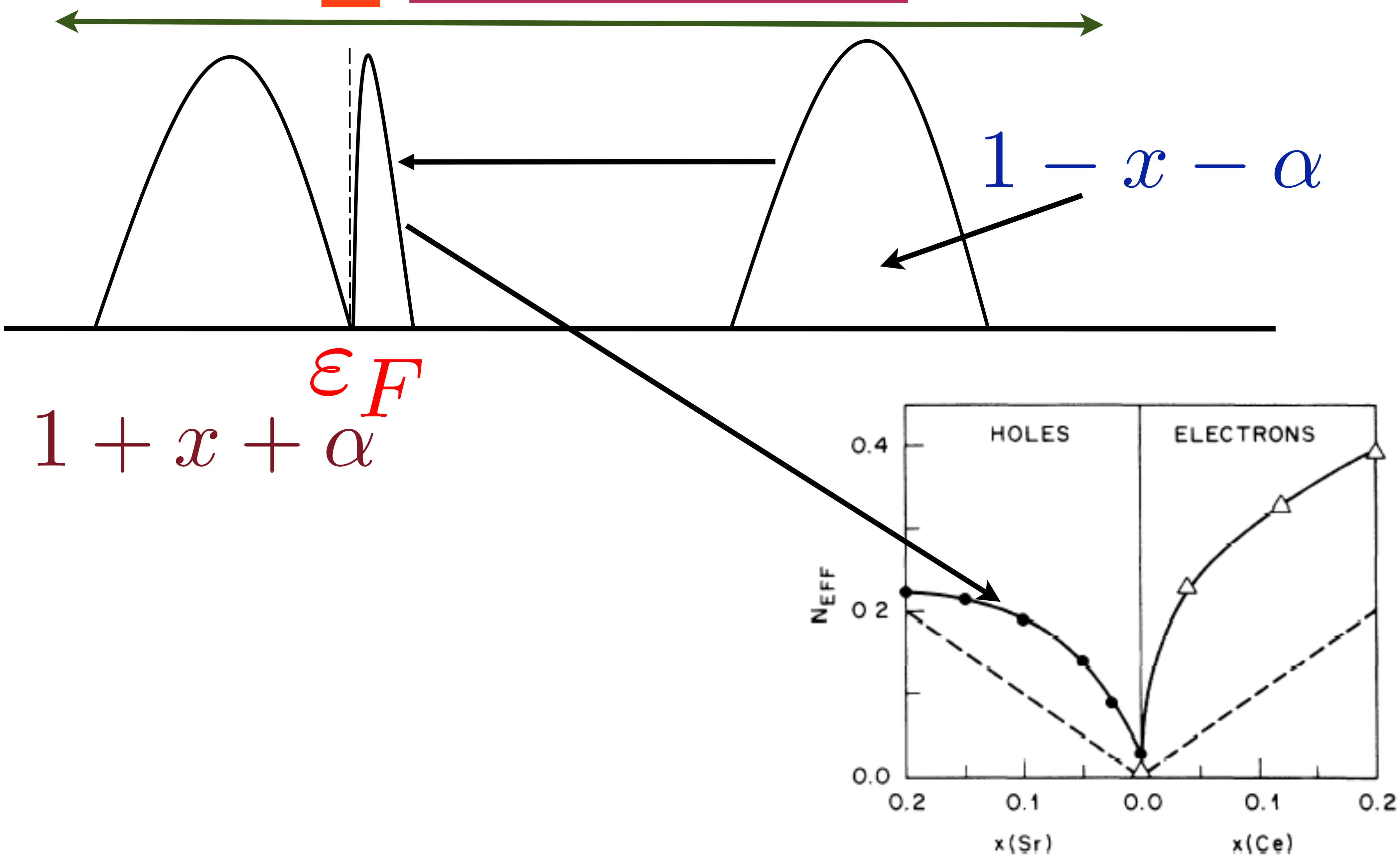

get rid of dynamical mixing

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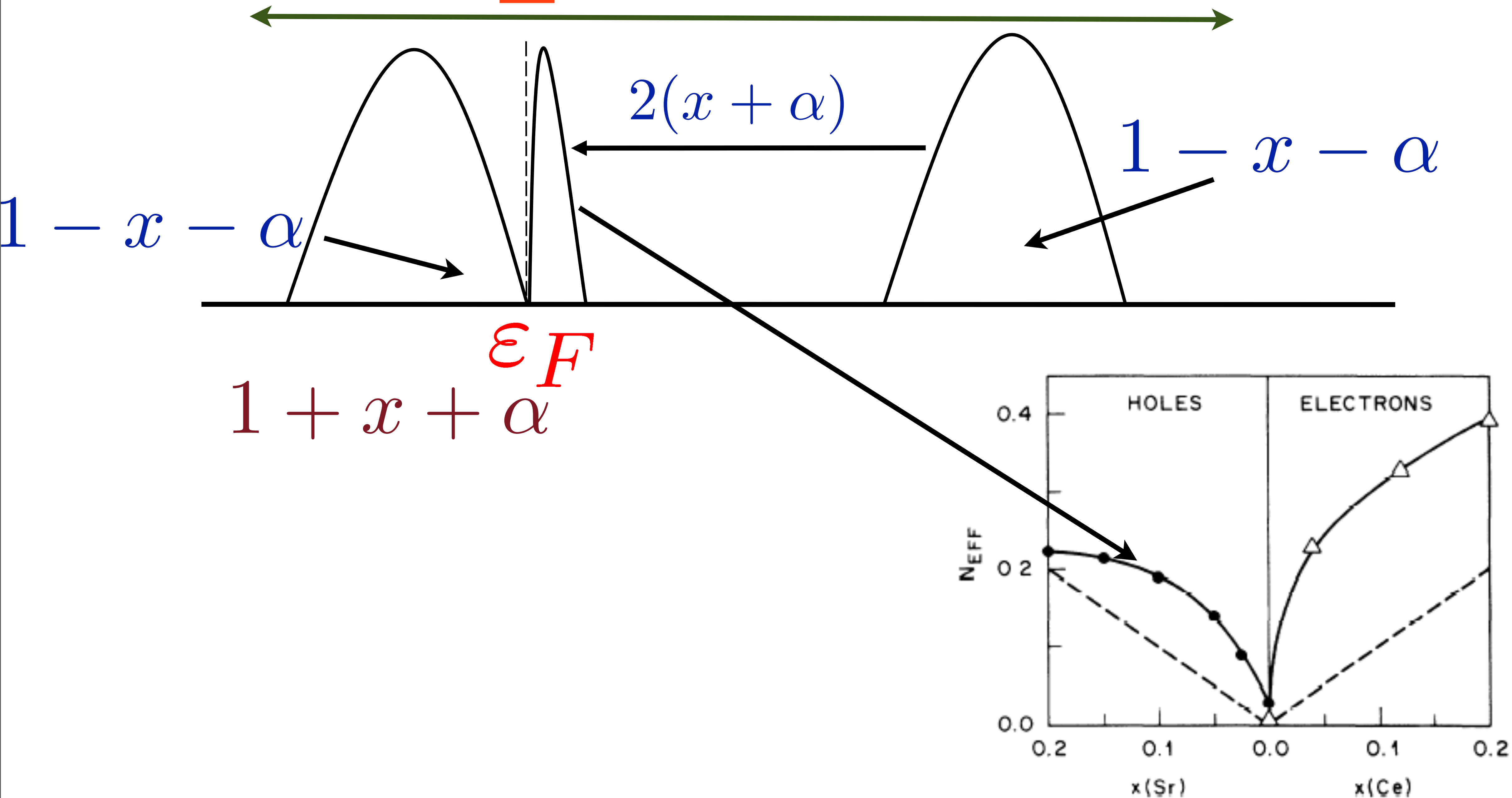

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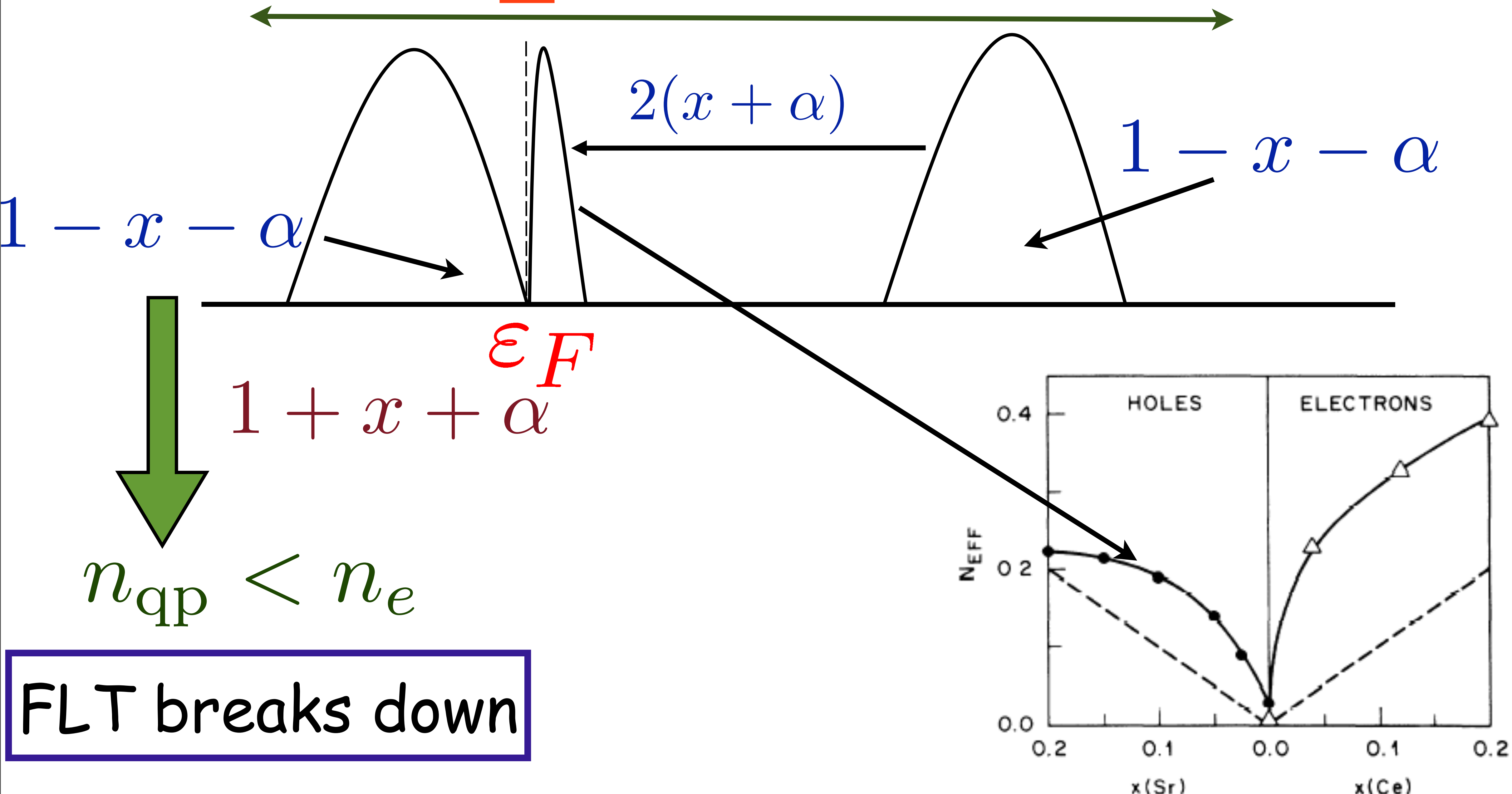
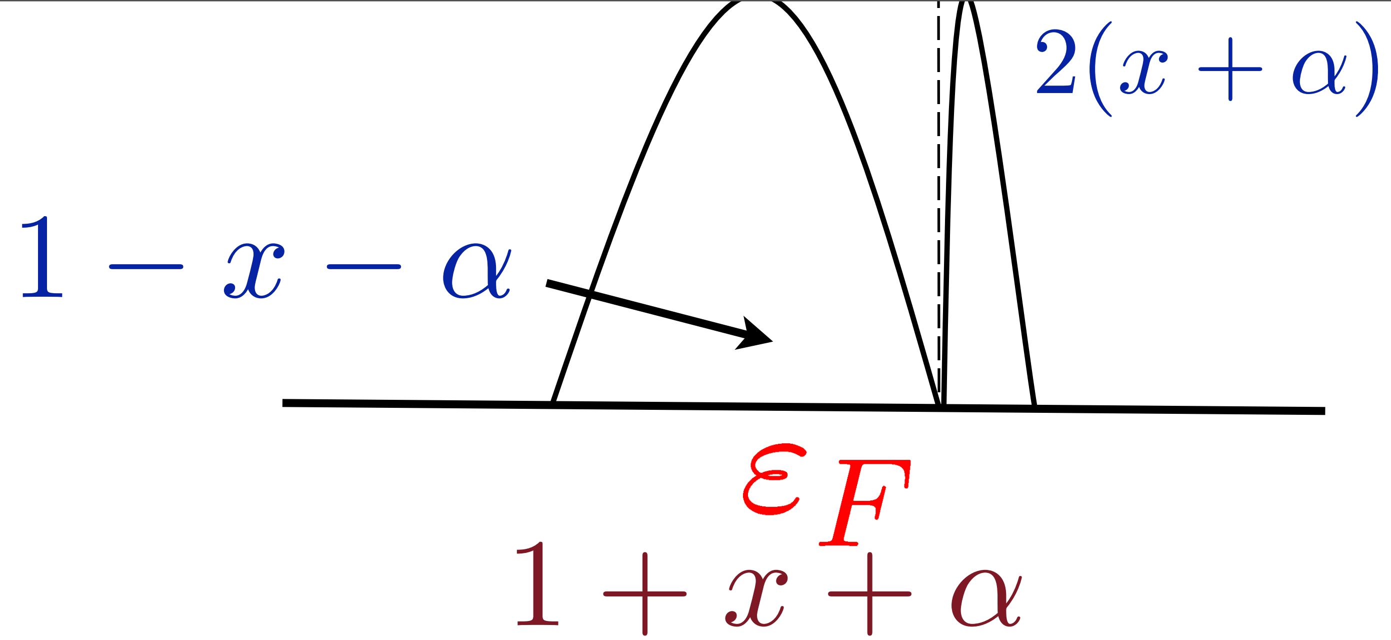
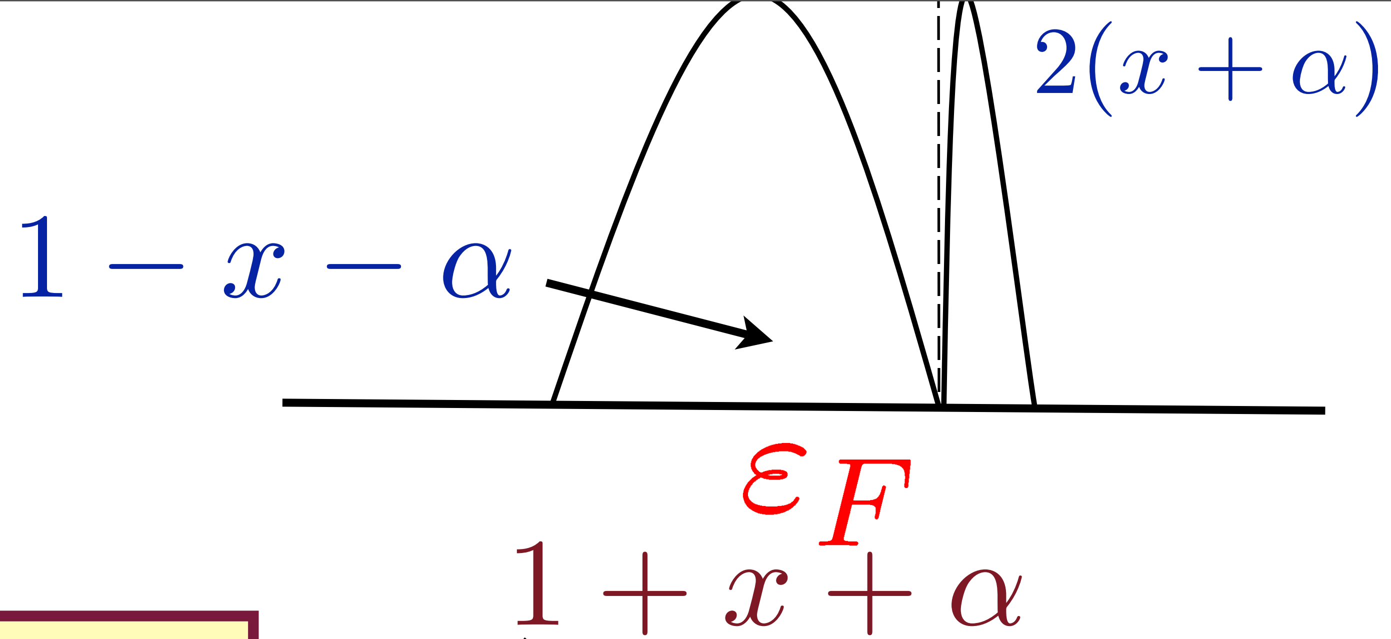


FLT breaks down

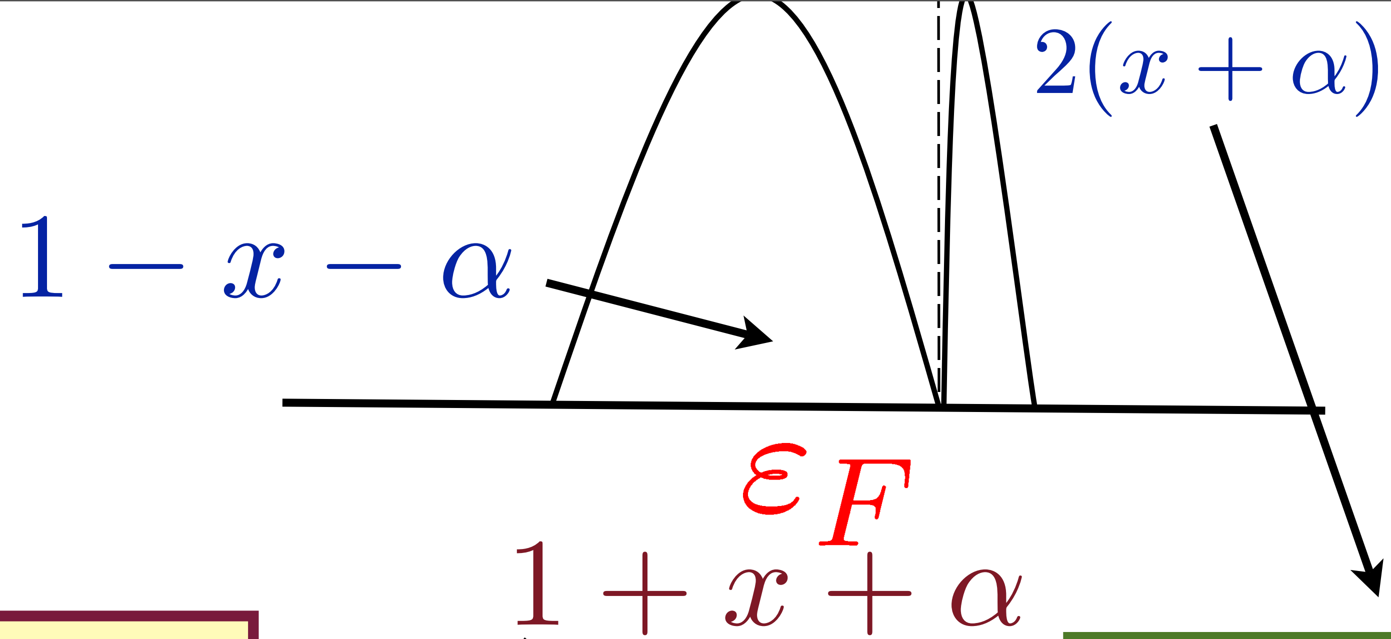
get rid of dynamical mixing


$2(x+\alpha)$
$1-x-\alpha$
ε_F
$1+x+\alpha$



new degrees of freedom

number of fermionic qp < number of bare electrons=> FL theory breaks down



new degrees of freedom

# of addition states per e per spin>1

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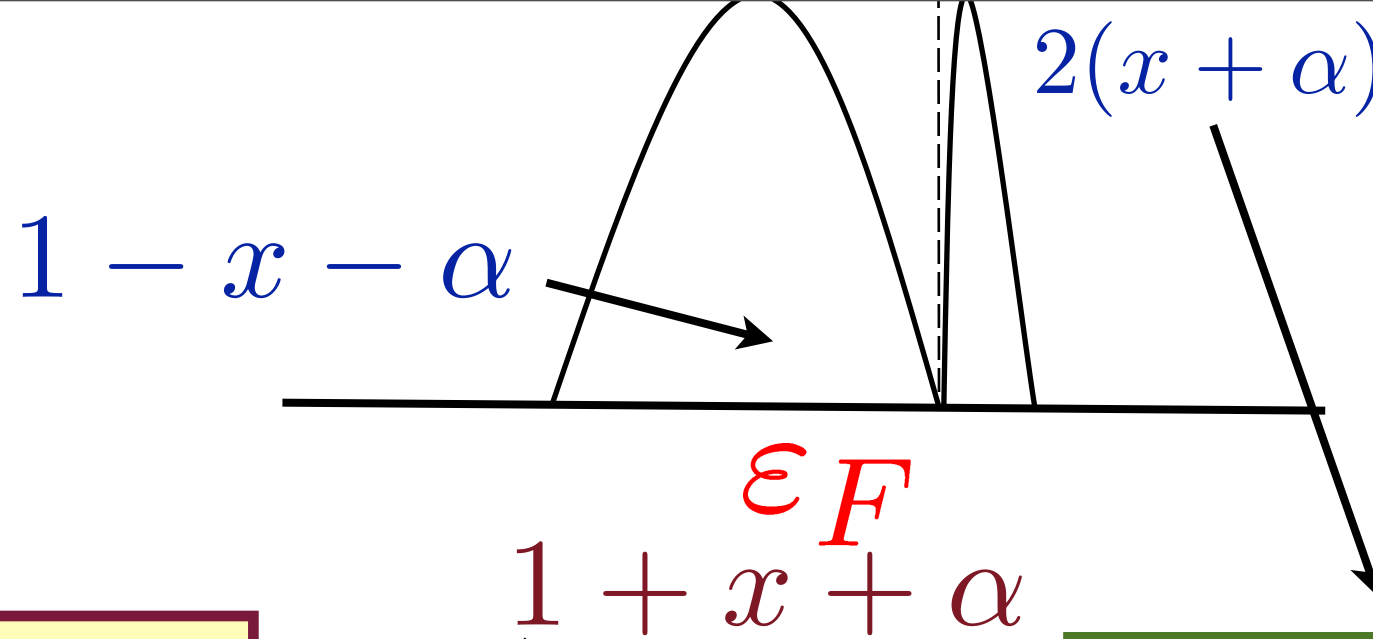

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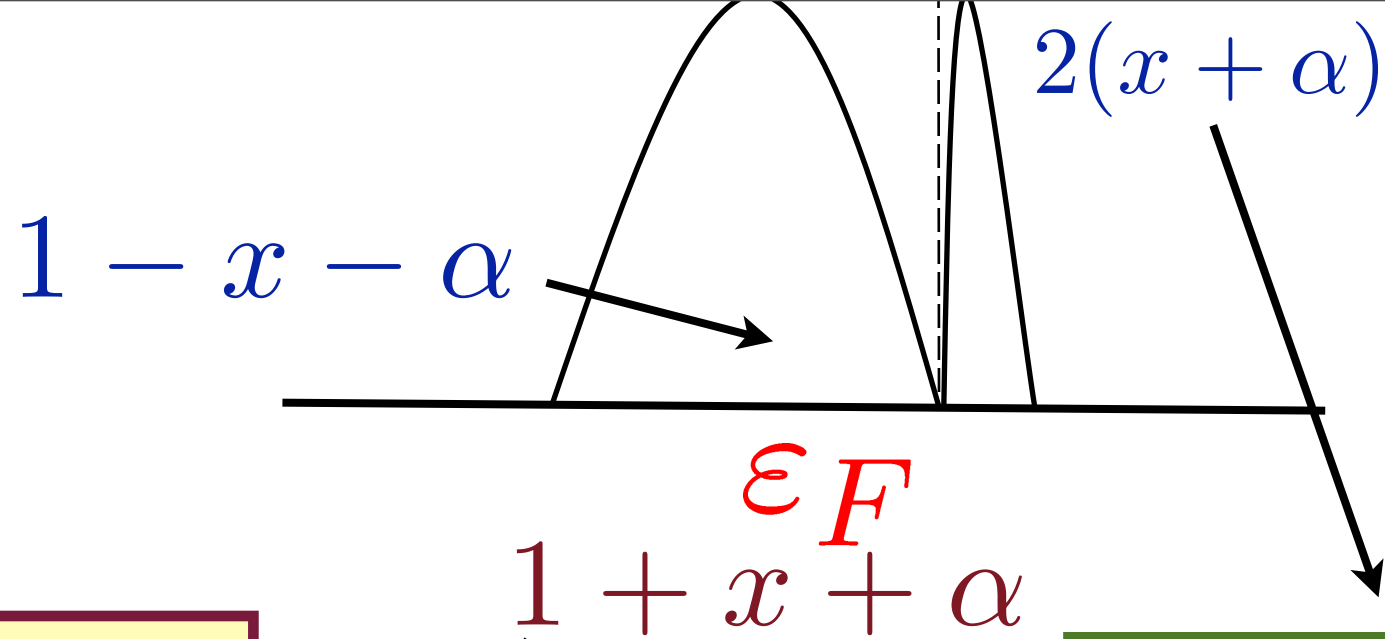
ways to add a particle but not an electron (gapped spectrum)



new degrees of freedom

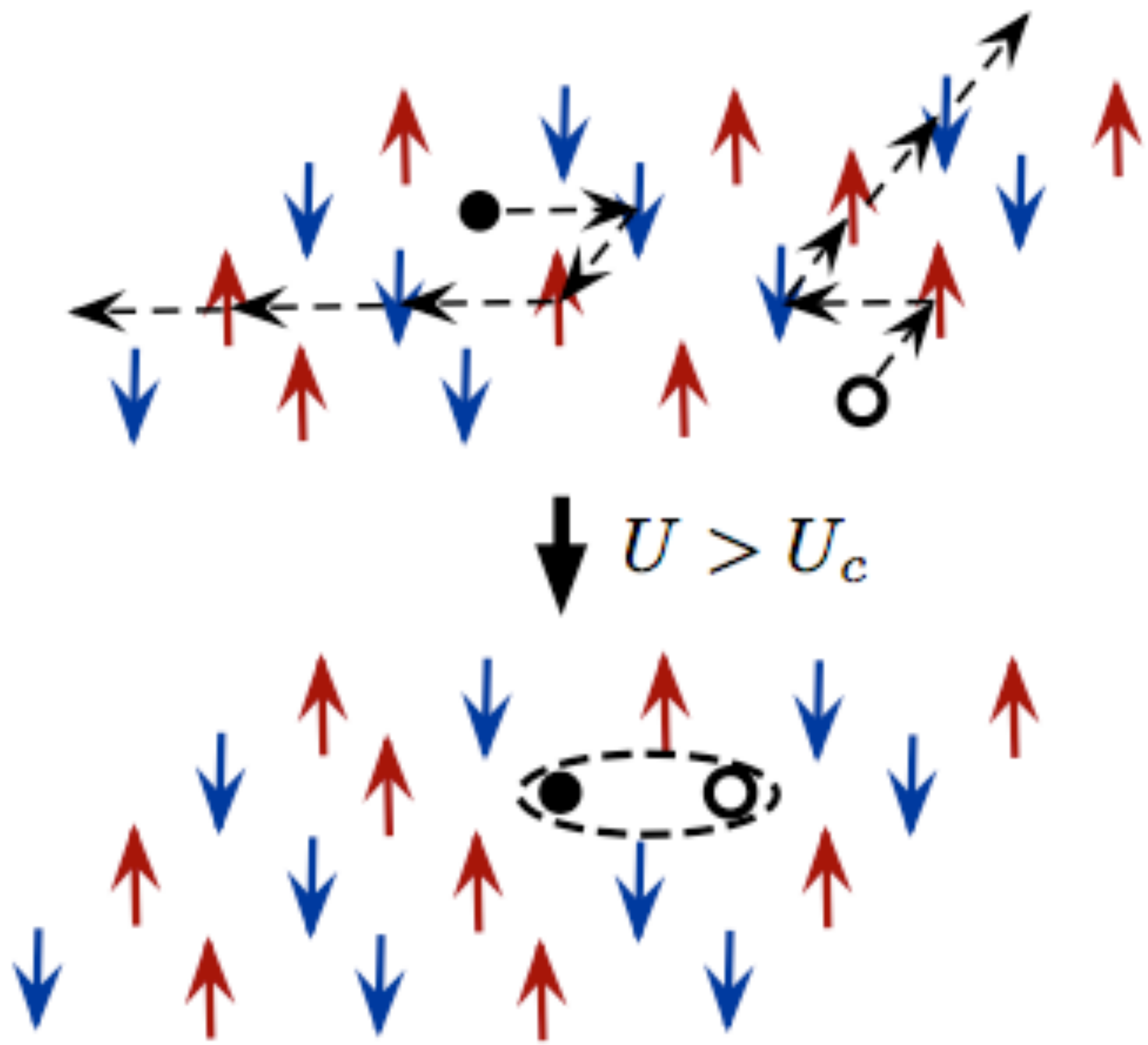
# of addition states per e per spin>1

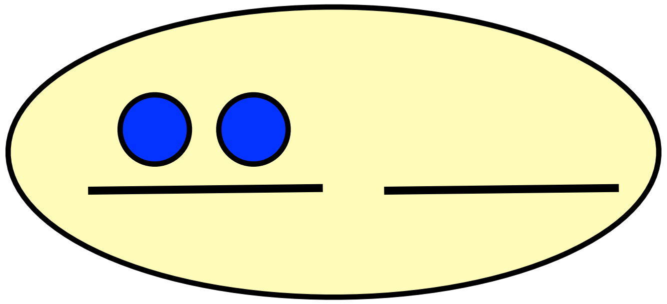
number of fermionic qp < number of bare electrons=> FL theory breaks down

ways to add a particle but not an electron (gapped spectrum)

breakdown of electron quasi-particle picture: Mottness

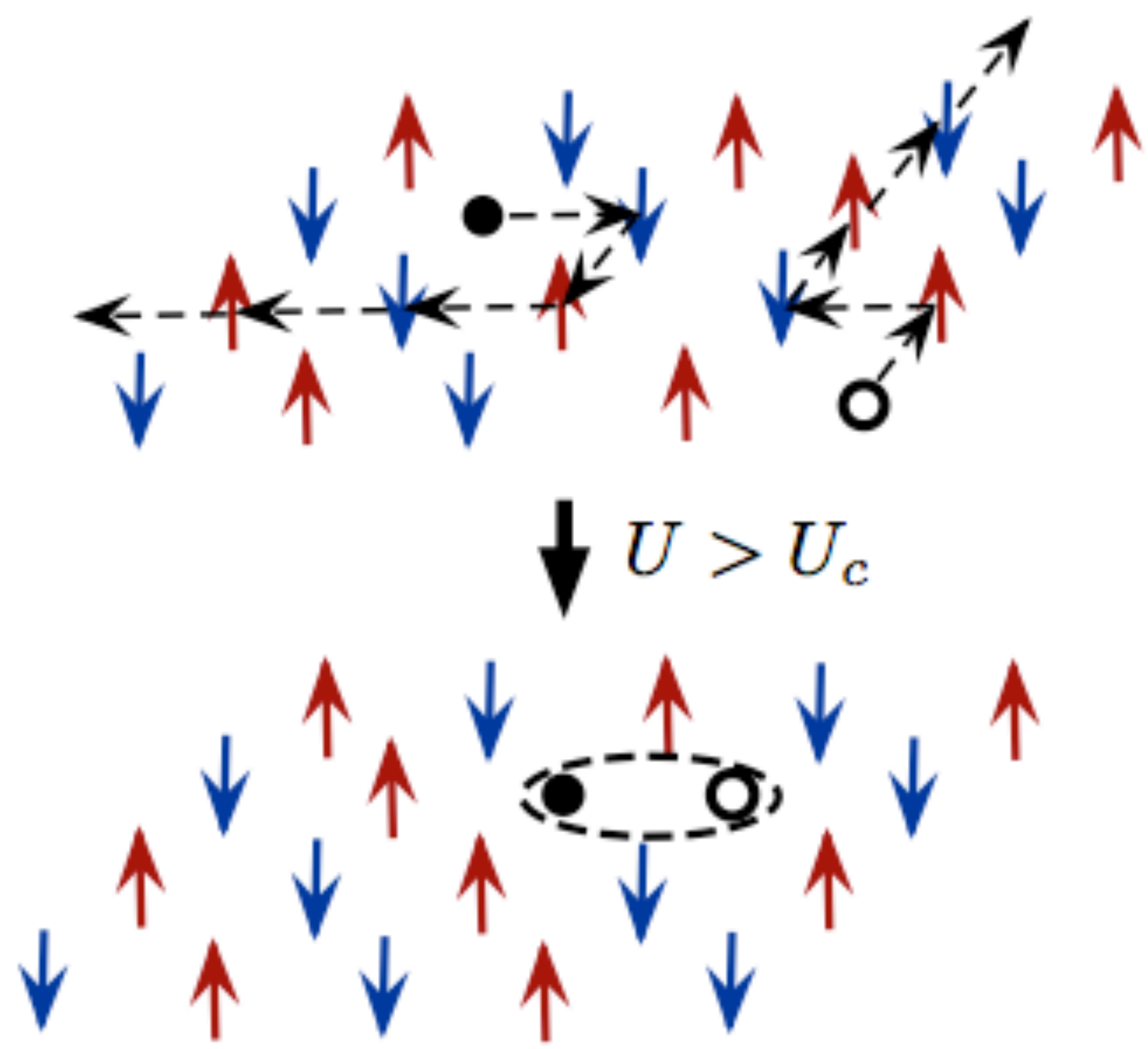
Same Physics at half-filling

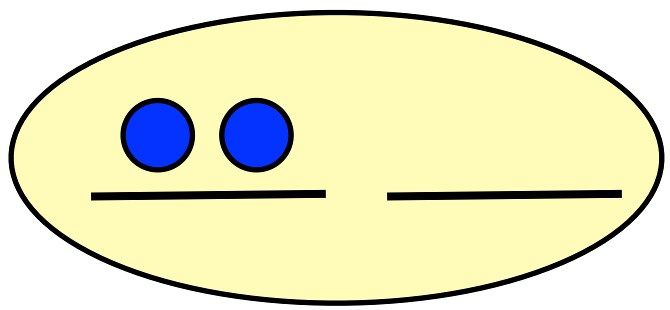




No proof exists?
Mottness is ill-defined

Same Physics at half-filling



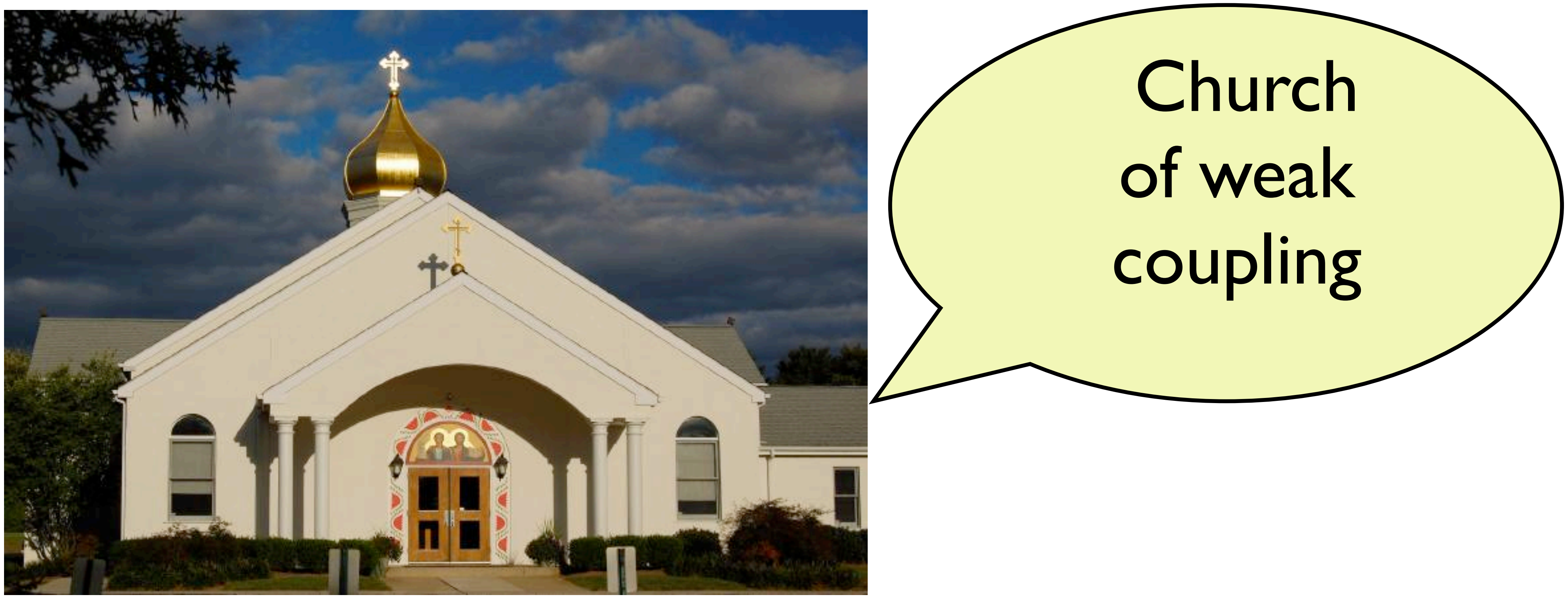


No proof exists?
Mottness is ill-defined

A Critique of Two Metals

R. B. Laughlin

idea is either missing or improperly understood. Another indicator that something is deeply wrong is the inability of anyone to describe the elementary excitation spectrum of the Mott insulator precisely even as pure phenomenology. Nowhere can one find a quantitative band structure of the elementary particle whose spectrum becomes gapped. Nowhere can one find precise information about the particle whose gapless spectrum causes the paramagnetism. Nowhere can one find information about the interactions among these particles or of their potential bound state spectroscopies. Nowhere can one find precise definitions of Mott insulator terminology. The upper and lower Hubbard bands, for example, are vague analogues of the valence and conduction bands of a semiconductor, except that they coexist and mix with soft magnetic excitations no one knows how to describe very well.



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Church of weak coupling

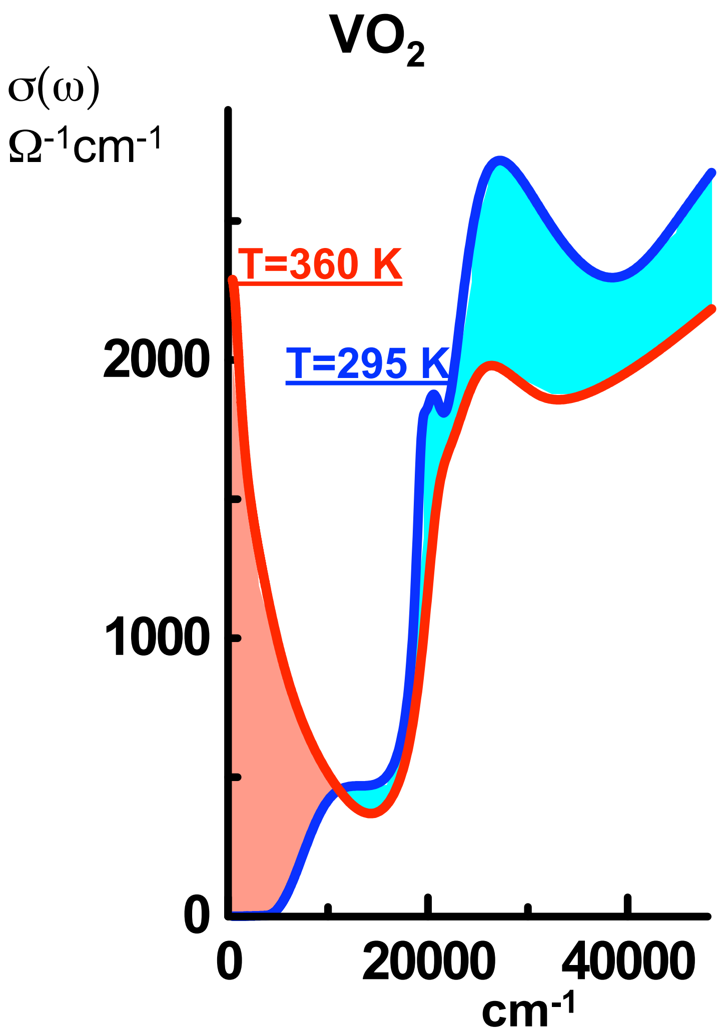
Beliefs:
Mott gap is heresy?
HF is the way!
No UHB and LHB!

A Critique of Two Metals

R. B. Laughlin

idea is either missing or improperly understood. Another indicator that something is deeply wrong is the inability of anyone to describe the elementary excitation spectrum of the Mott insulator precisely even as pure phenomenology. Nowhere can one find a quantitative band structure of the elementary particle whose spectrum becomes gapped. Nowhere can one find precise information about the particle whose gapless spectrum causes the paramagnetism. Nowhere can one find information about the interactions among these particles or of their potential bound state spectroscopies. Nowhere can one find precise definitions of Mott insulator terminology. The upper and lower Hubbard bands, for example, are vague analogues of the valence and conduction bands of a semiconductor, except that they coexist and mix with soft magnetic excitations no one knows how to describe very well.

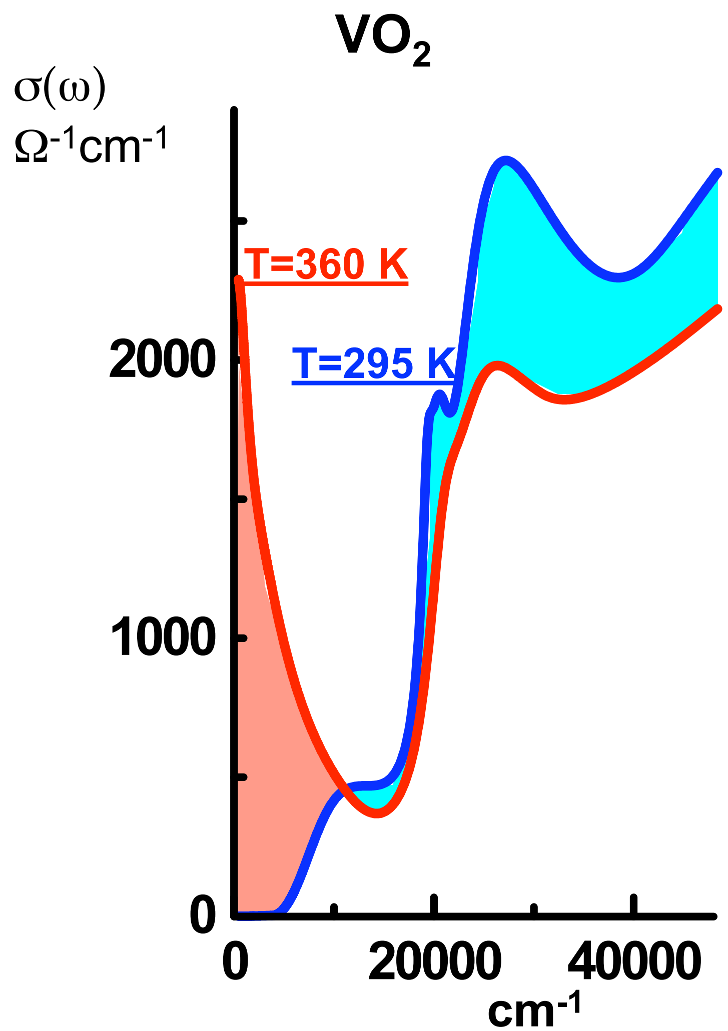
$\Delta = 0.6eV > \Delta_{\text{dimerization}}$ (Mott, 1976) $\frac{\Delta}{T_{\text{crit}}} \approx 20$



transfer
of spectral
weight to
high energies
beyond any ordering
scale

Recall, $eV = 10^4 K$

$$\Delta = 0.6eV > \Delta_{\text{dimerization}}$$ (Mott, 1976) $$\frac{\Delta}{T_{\text{crit}}} \approx 20$$



M. M. Qazilbash, K. S. Burch, D. Whisler, D. Shrekenhamer, B. G. Chae, H. T. Kim, and D. N. Basov PRB 74, 205118 (2006)

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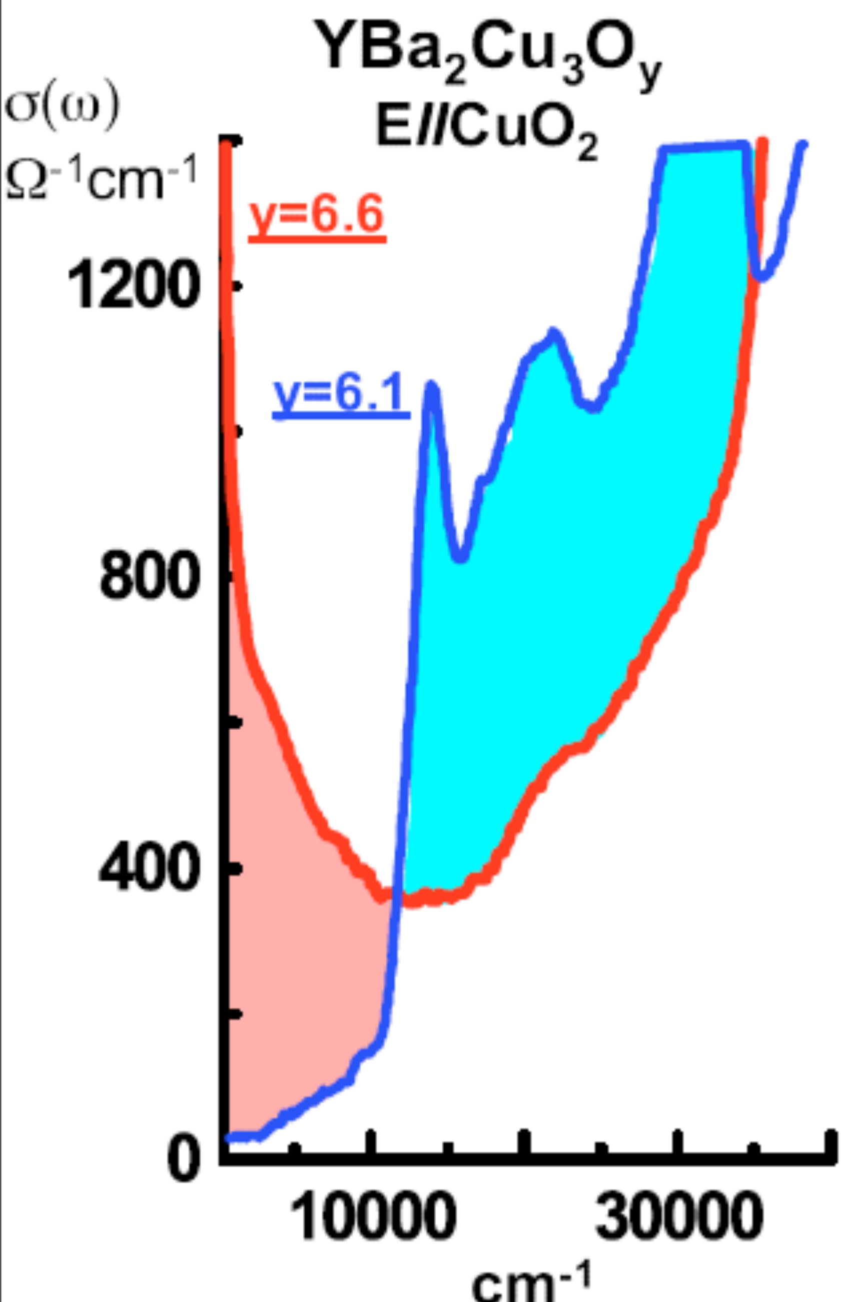

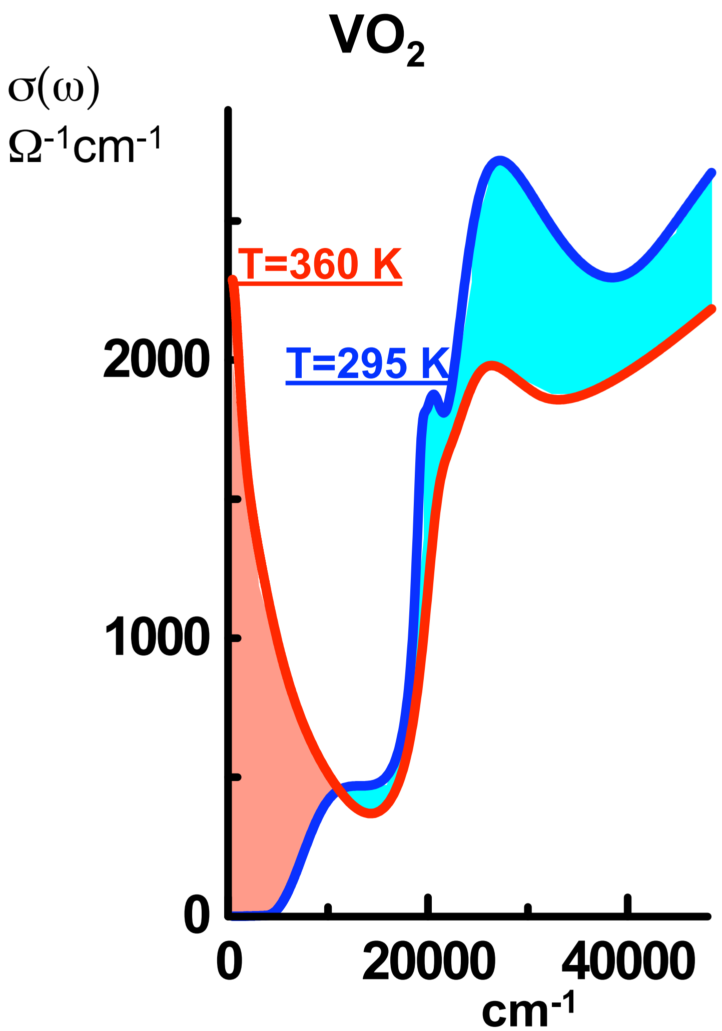

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transfer of spectral weight to high energies beyond any ordering scale

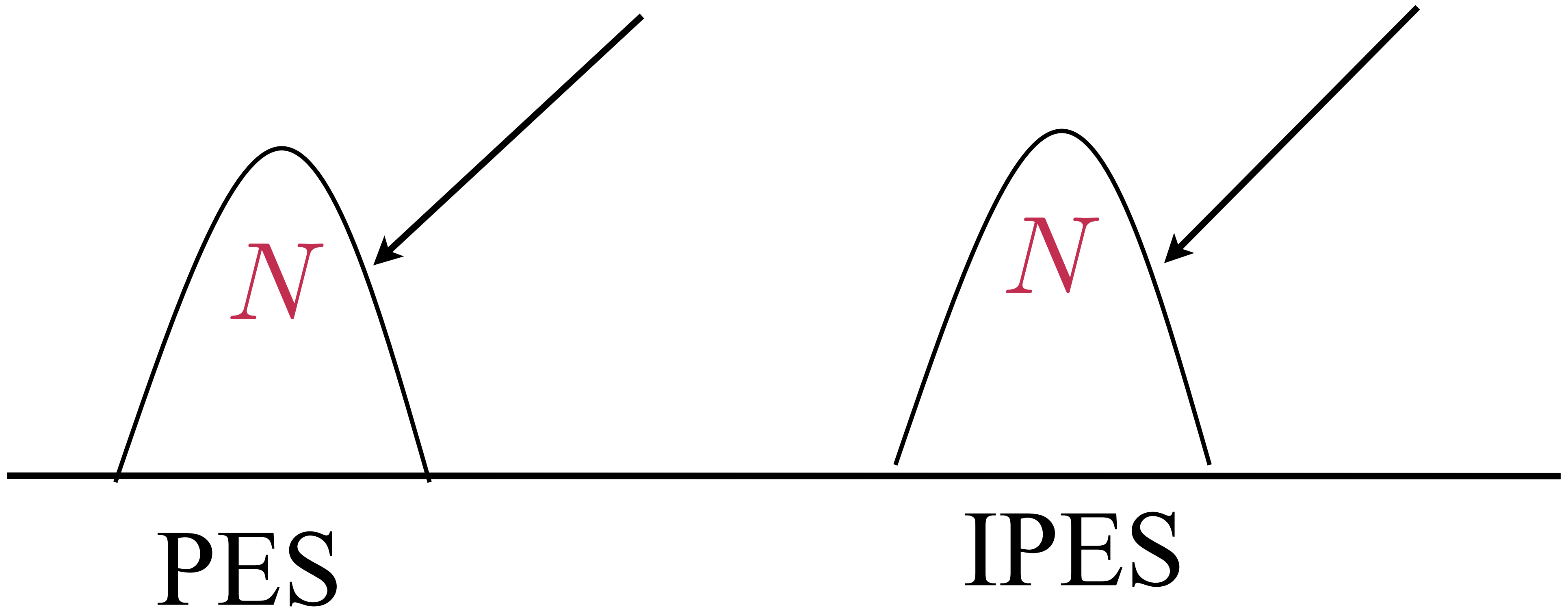
Recall, $eV = 10^4 K$

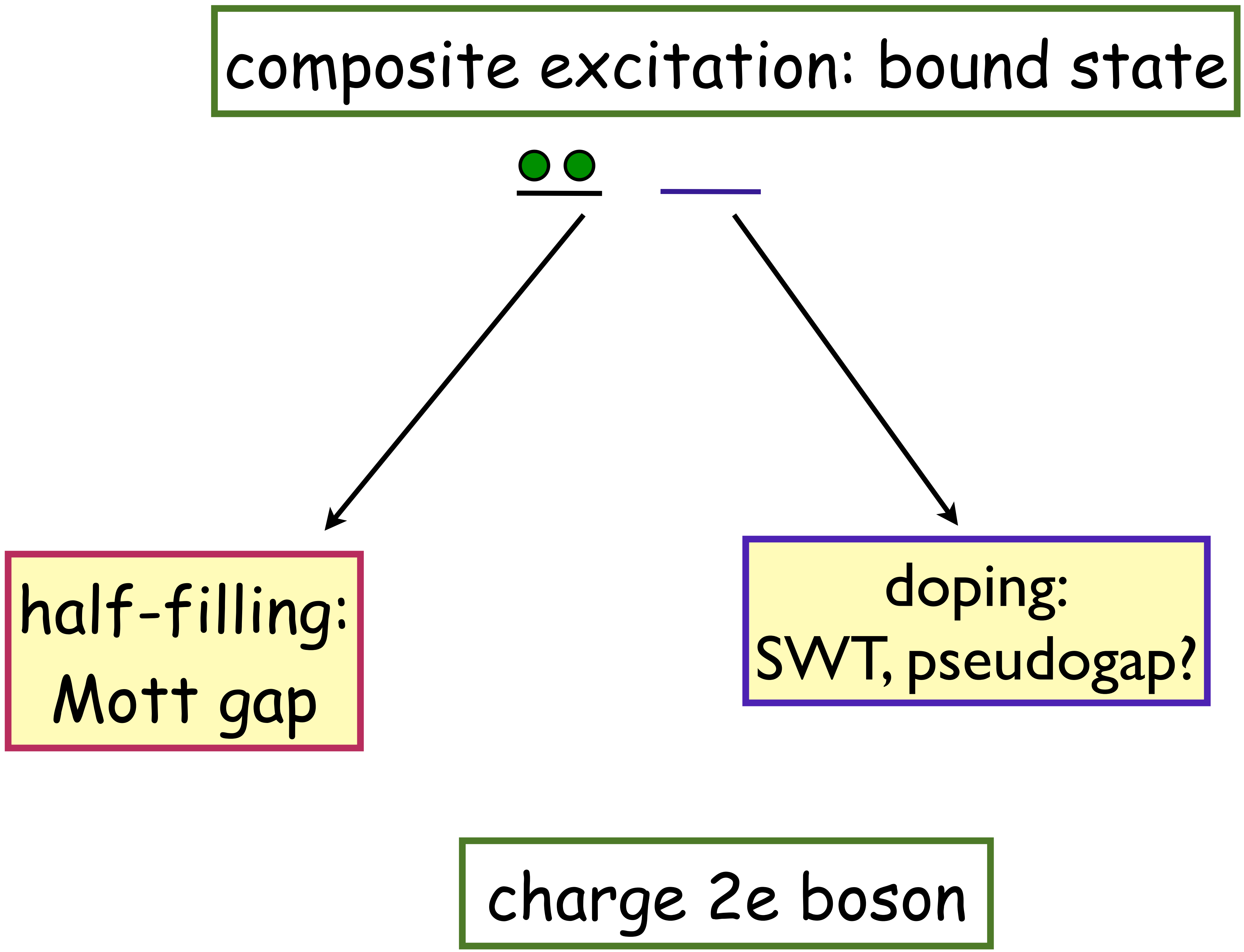
Fermi-liquid analogy

$$L_{\mathrm{FL}} \propto (\omega - \epsilon_k)|\psi_k|^2$$

Mott Problem?

$$L_{\mathrm{MI}} = (\omega - E_{\mathrm{LHB}}(k))|\eta_k|^2 + (\omega - E_{\mathrm{UHB}}(k))|\tilde{\eta}_k|^2$$




composite excitation: bound state
half-filling:
Mott gap
doping:
SWT, pseudogap?
charge 2e boson

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

How?

Effective Theories:

$S(\phi)$ at half-filling

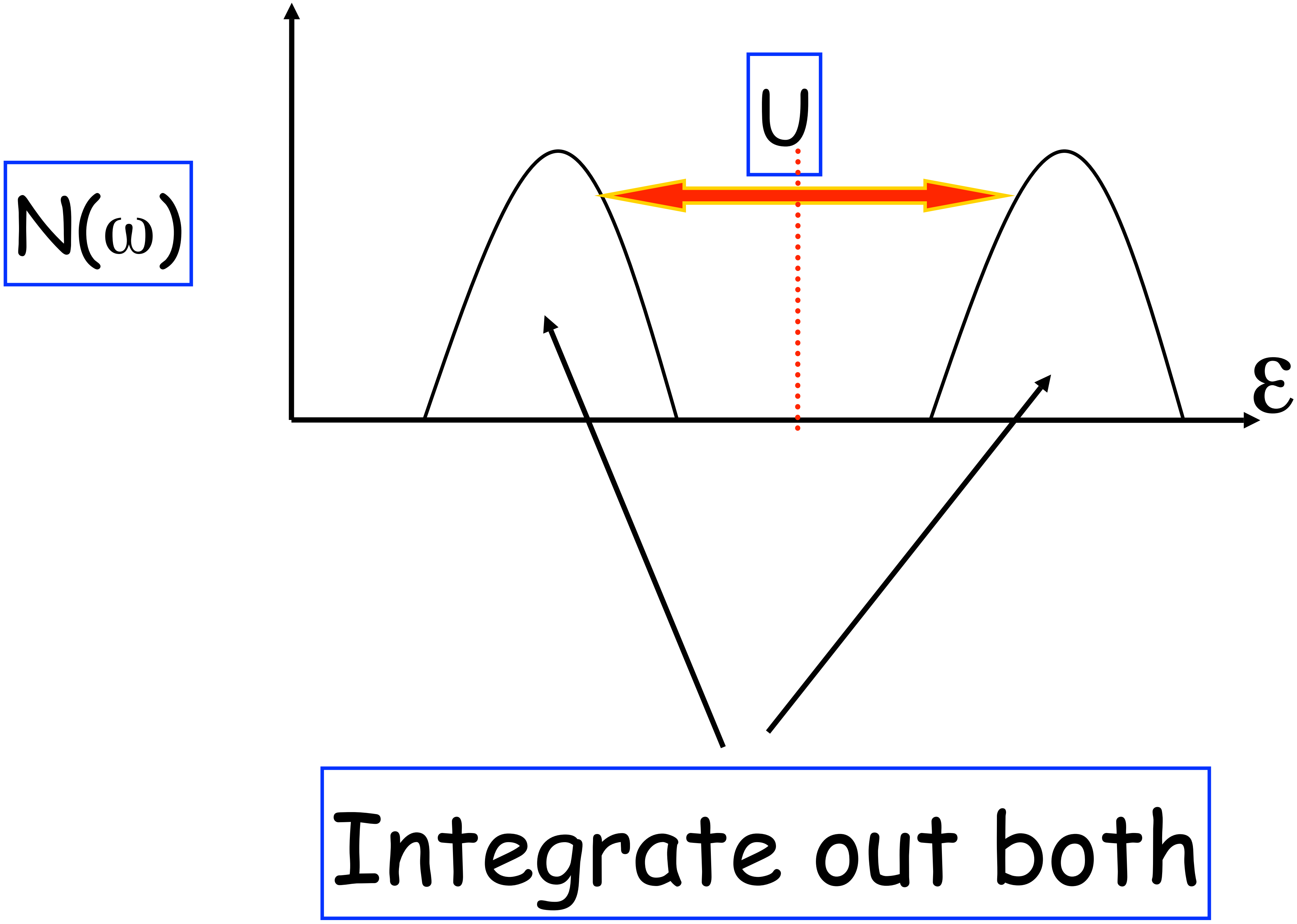
Integrate Out high Energy fields

$\phi = \phi_L + \phi_H$

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

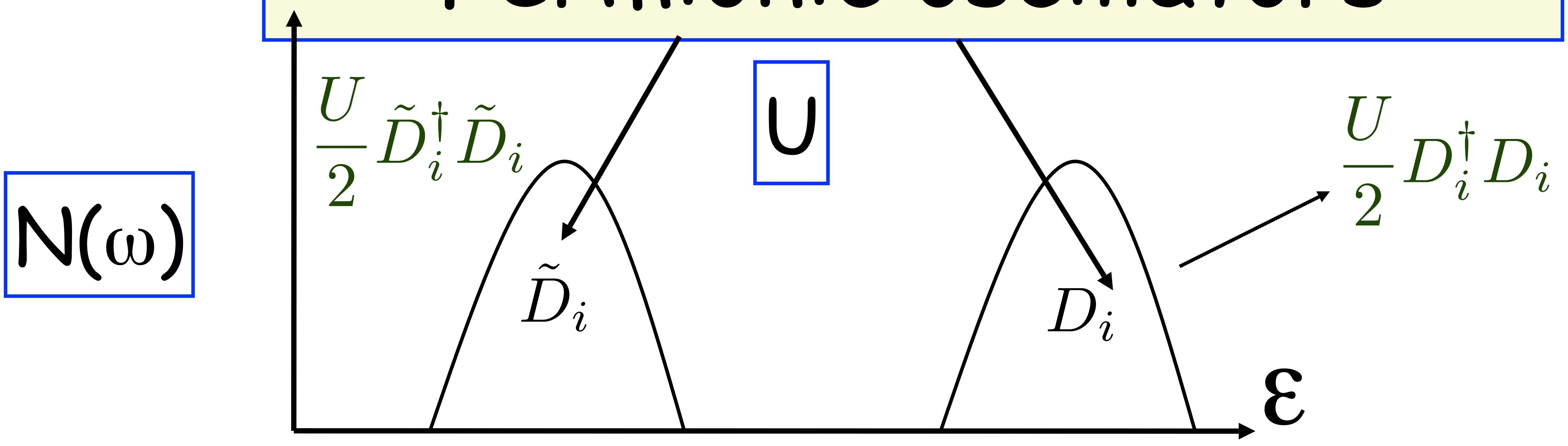
Low-energy theory of M I

Half-filling



Key idea: similar to Bohm/Pines

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

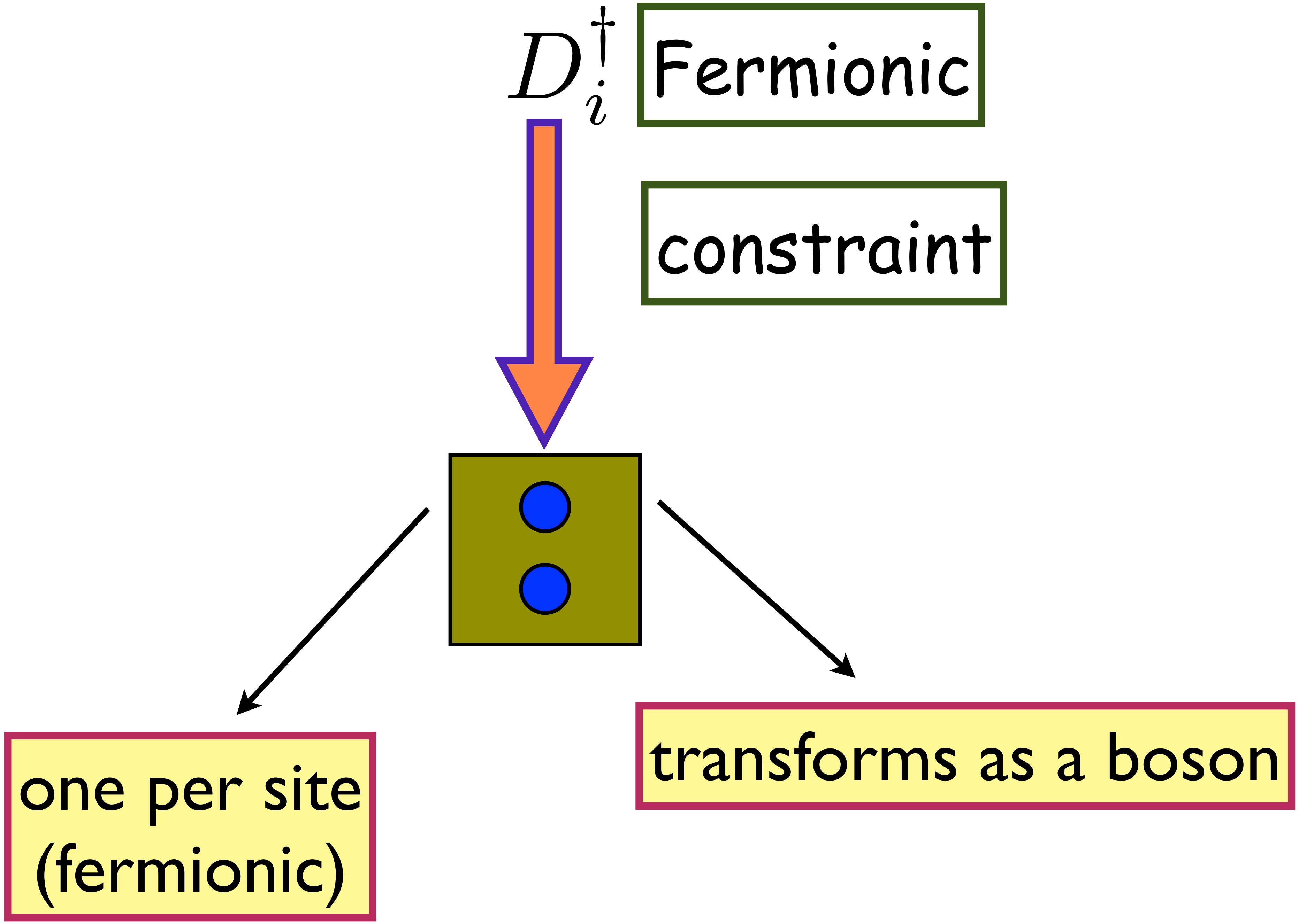


$D_i^\dagger$ Fermionic

constraint

one per site (fermionic)

transforms as a boson



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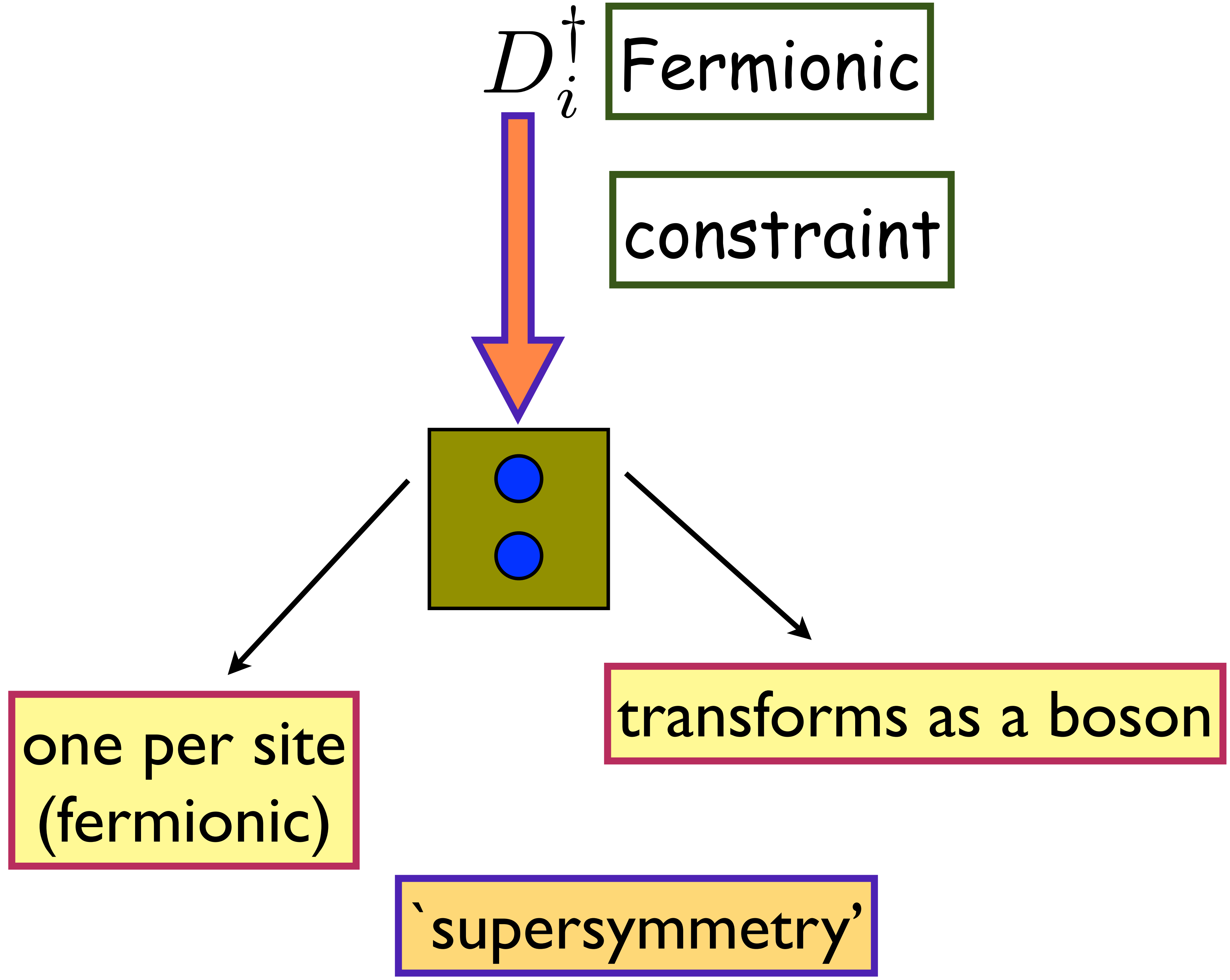

$D_i^\dagger$
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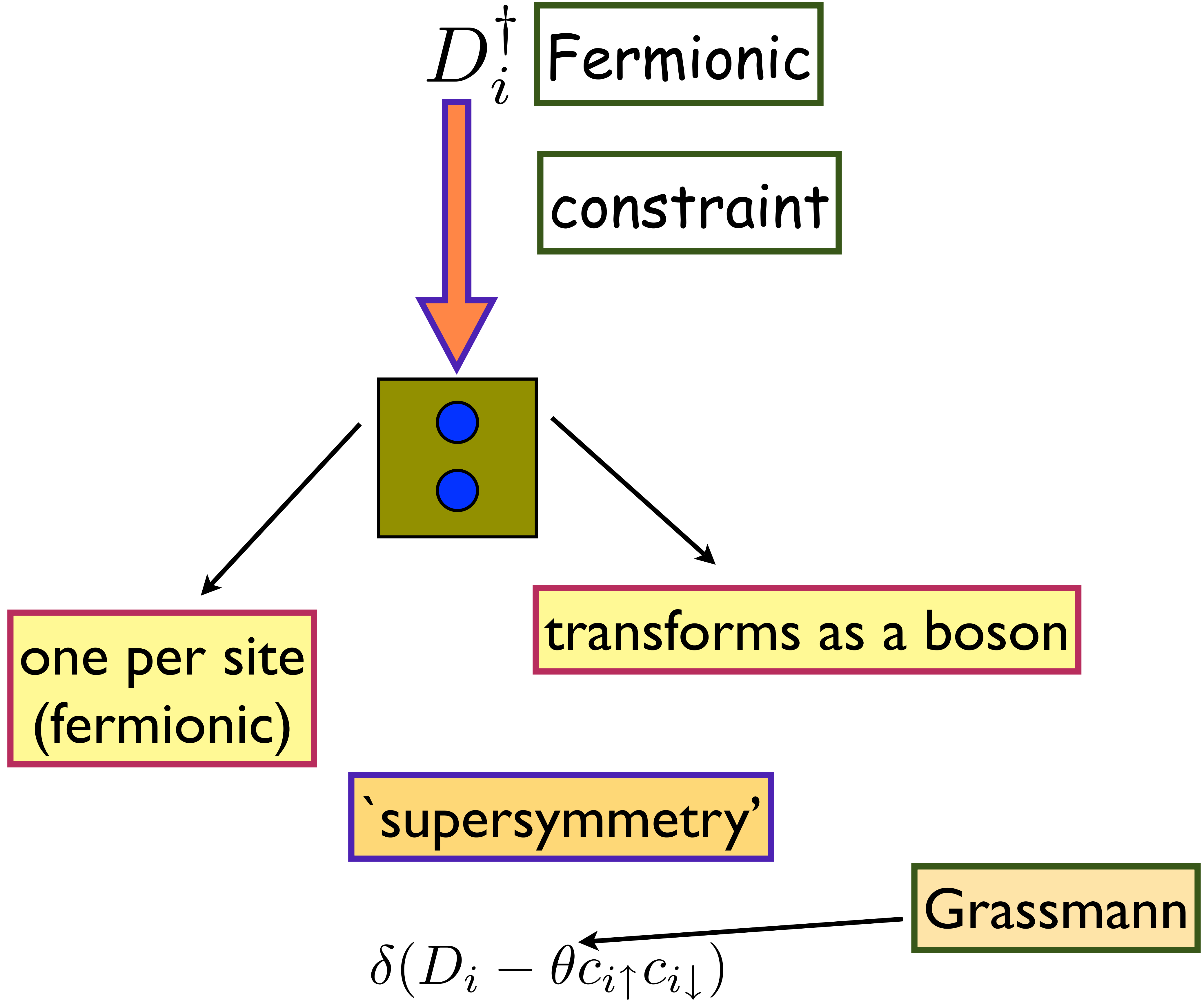
`supersymmetry'


$D_i^\dagger$
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Grassmann
$\delta(D_i - \theta c_{i\uparrow} c_{i\downarrow})$

$D_i^\dagger$ Fermionic

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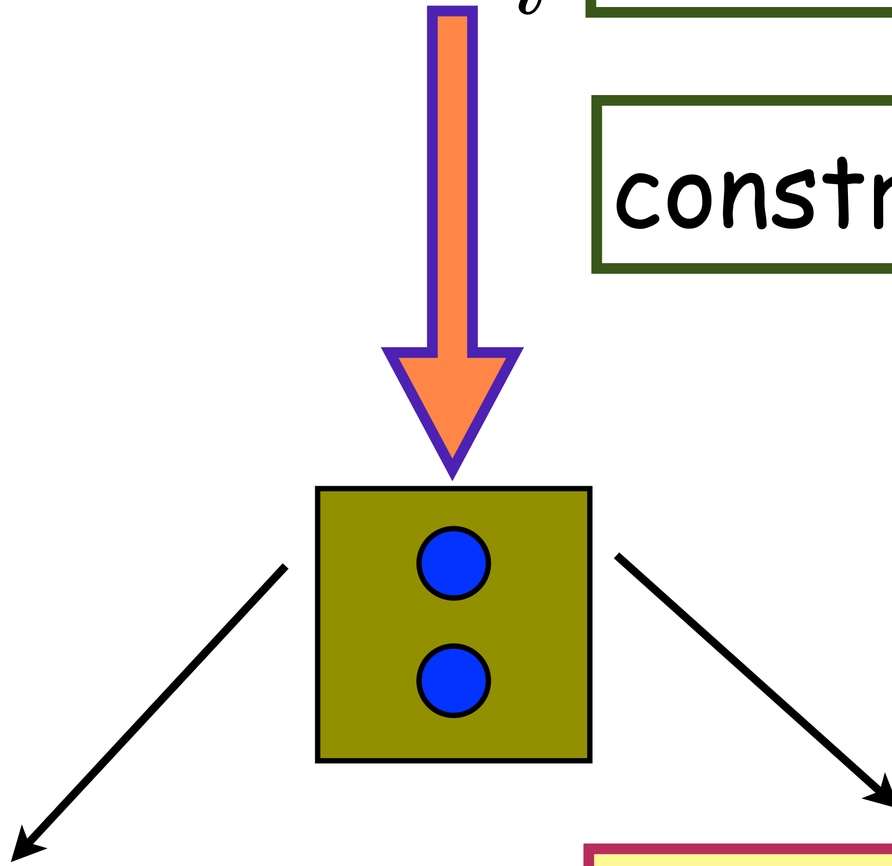


one per site (fermionic)

transforms as a boson

`supersymmetry'

Grassmann

$\delta(D_i - \theta c_{i\uparrow} c_{i\downarrow})$

$\bar{\theta}\varphi$ constraint field

Dual Theory

solve constraint

$\varphi \; (Q_\varphi = 2e)$

integrate over heavy fields

UV limit

$$\int d^2\theta \; \bar{\theta}\theta L_{\rm Hubb} = \sum_{i,\sigma} c^\dagger_{i,\sigma}\dot{c}_{i,\sigma} + H_{\rm Hubb},$$

Exact low-energy theory (IR limit)

Dual Theory

solve constraint
$\varphi \; (Q_\varphi = 2e)$

UV limit

$$\int d^2\theta \; \bar{\theta}\theta L_{\rm Hubb} = \sum_{i,\sigma} c^\dagger_{i,\sigma}\dot{c}_{i,\sigma} + H_{\rm Hubb},$$

integrate over heavy fields

Exact low-energy theory (IR limit)

$$\begin{aligned} L_{\rm UV}^{\rm hf} &= \int d^2\theta \Big[iD^\dagger\dot{D} - i\dot{\tilde{D}}^\dagger\tilde{D} - \frac{U}{2}(D^\dagger D - \tilde{D}\tilde{D}^\dagger) \\ &+ \frac{t}{2}D^\dagger\theta b + \frac{t}{2}\bar{\theta}b\tilde{D} + h.c. + s\bar{\theta}\varphi^\dagger(D - \theta c_\uparrow c_\downarrow) \\ &+ \tilde{s}\bar{\theta}\tilde{\varphi}^\dagger(\tilde{D} - \theta c^\dagger_\uparrow c^\dagger_\downarrow) + h.c.\Big] \end{aligned}$$

dynamics

of φ

Exact IR Lagrangian

bare fields have no dynamics

$$L_{\rm IR}^{\rm hf} \quad \rightarrow \quad 2\frac{|s|^2}{U}|\varphi_\omega|^2 + 2\frac{|\tilde{s}|^2}{U}|\tilde{\varphi}_{-\omega}|^2 + \frac{t^2}{U}|b_\omega|^2$$

$$\left\{ \begin{array}{l} +s\gamma_{\vec{p}}^{(\vec{k})}(\omega)\varphi^\dagger_{\omega,\vec{k}} c_{\vec{k}/2+\vec{p},\omega/2+\omega',\uparrow} c_{\vec{k}/2-\vec{p},\omega/2-\omega',\downarrow} \\ +\tilde{s}^*\tilde{\gamma}_{\vec{p}}^{(\vec{k})}(\omega)\tilde{\varphi}_{-\omega,\vec{k}} c_{\vec{k}/2+\vec{p},\omega/2+\omega',\uparrow} c_{\vec{k}/2-\vec{p},\omega/2-\omega',\downarrow} + h.c. \end{array} \right.$$

bosons
and fermions
are strongly coupled

$$\gamma_{\vec{p}}^{(\vec{k})}(\omega) = \frac{U - t\varepsilon_{\vec{p}}^{(\vec{k})} - 2\omega}{U}\sqrt{1+2\omega/U}$$

$$\tilde{\gamma}_{\vec{p}}^{(\vec{k})}(\omega) = \frac{U + t\varepsilon_{\vec{p}}^{(\vec{k})} + 2\omega}{U}\sqrt{1-2\omega/U}.$$

$$\varepsilon_{\vec{p}}^{(\vec{k})} = 4\sum_\mu \cos(k_\mu a/2)\cos(p_\mu a)$$

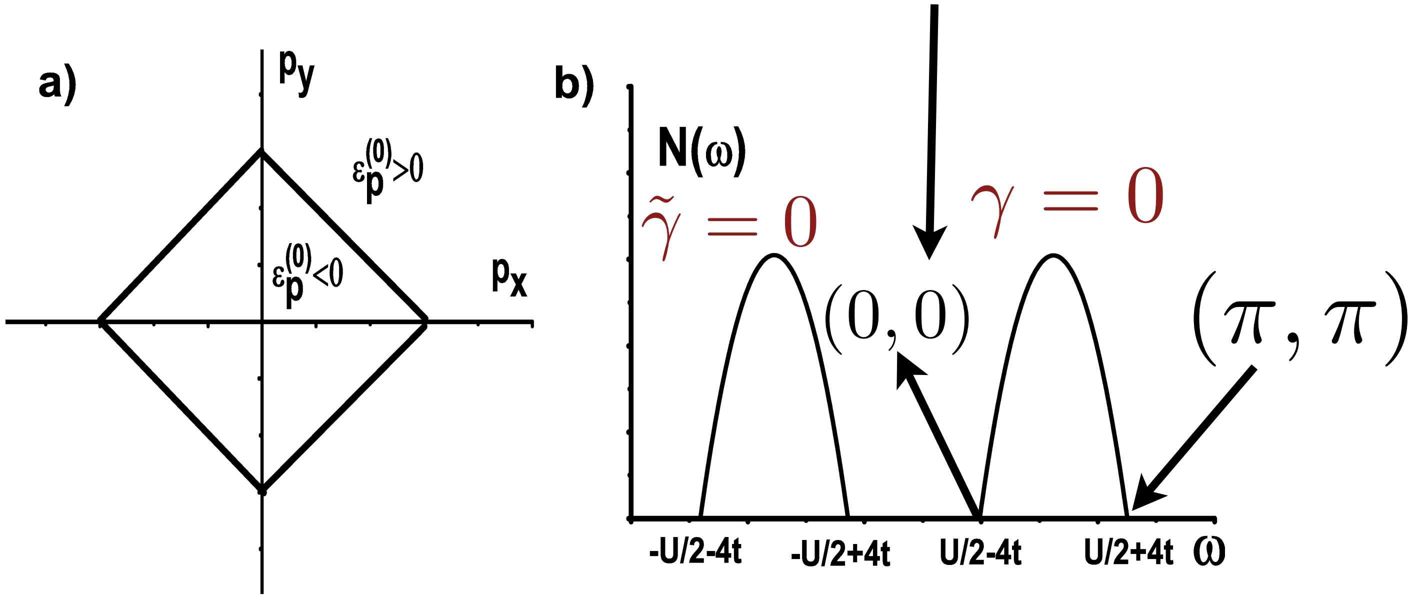
turn-on of spectral weight governed by composite excitations (CEXONS)

composite excitations determine spectral density

$$\gamma_{\vec{p}}^{(\vec{k})}(\omega) = \frac{U - t\varepsilon_{\vec{p}}^{(\vec{k})} - 2\omega}{U}\sqrt{1 + 2\omega/U}$$

$$\tilde{\gamma}_{\vec{p}}^{(\vec{k})}(\omega) = \frac{U + t\varepsilon_{\vec{p}}^{(\vec{k})} + 2\omega}{U}\sqrt{1 - 2\omega/U}.$$

$\Delta = U - 4dt$



each momentum has SD at two distinct energies hole-doping?

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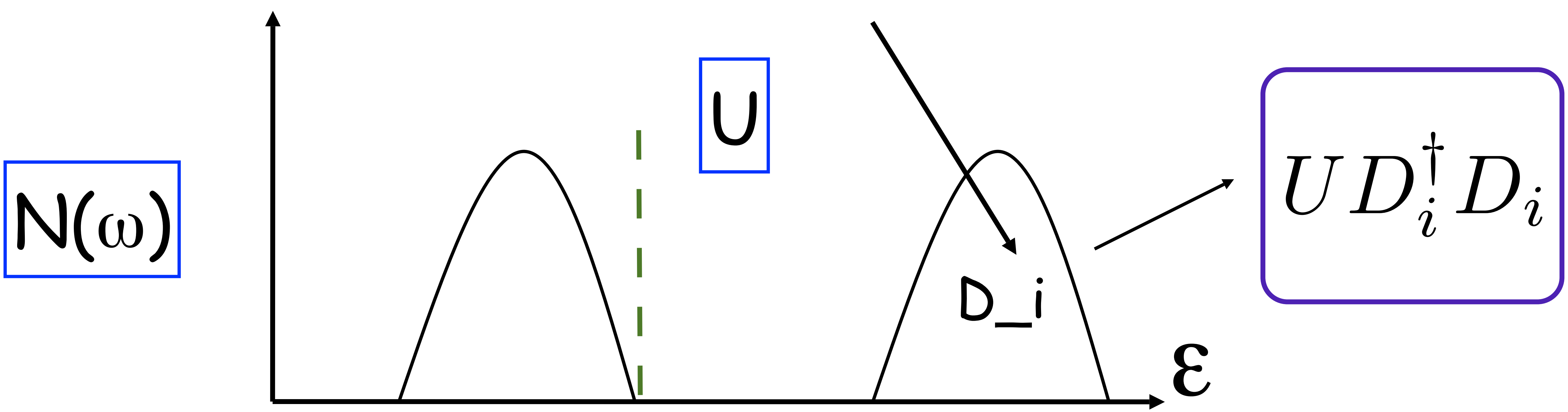
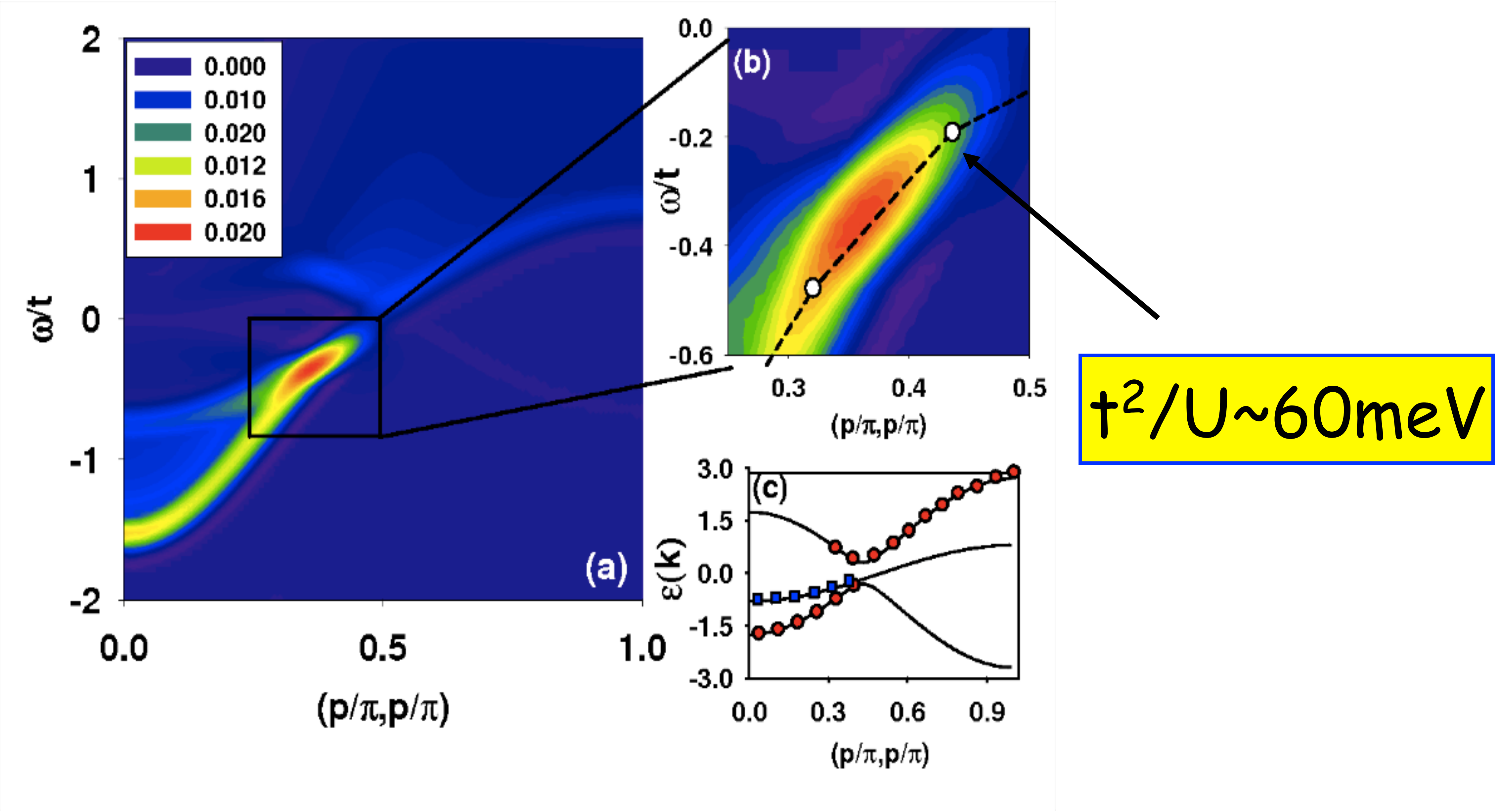


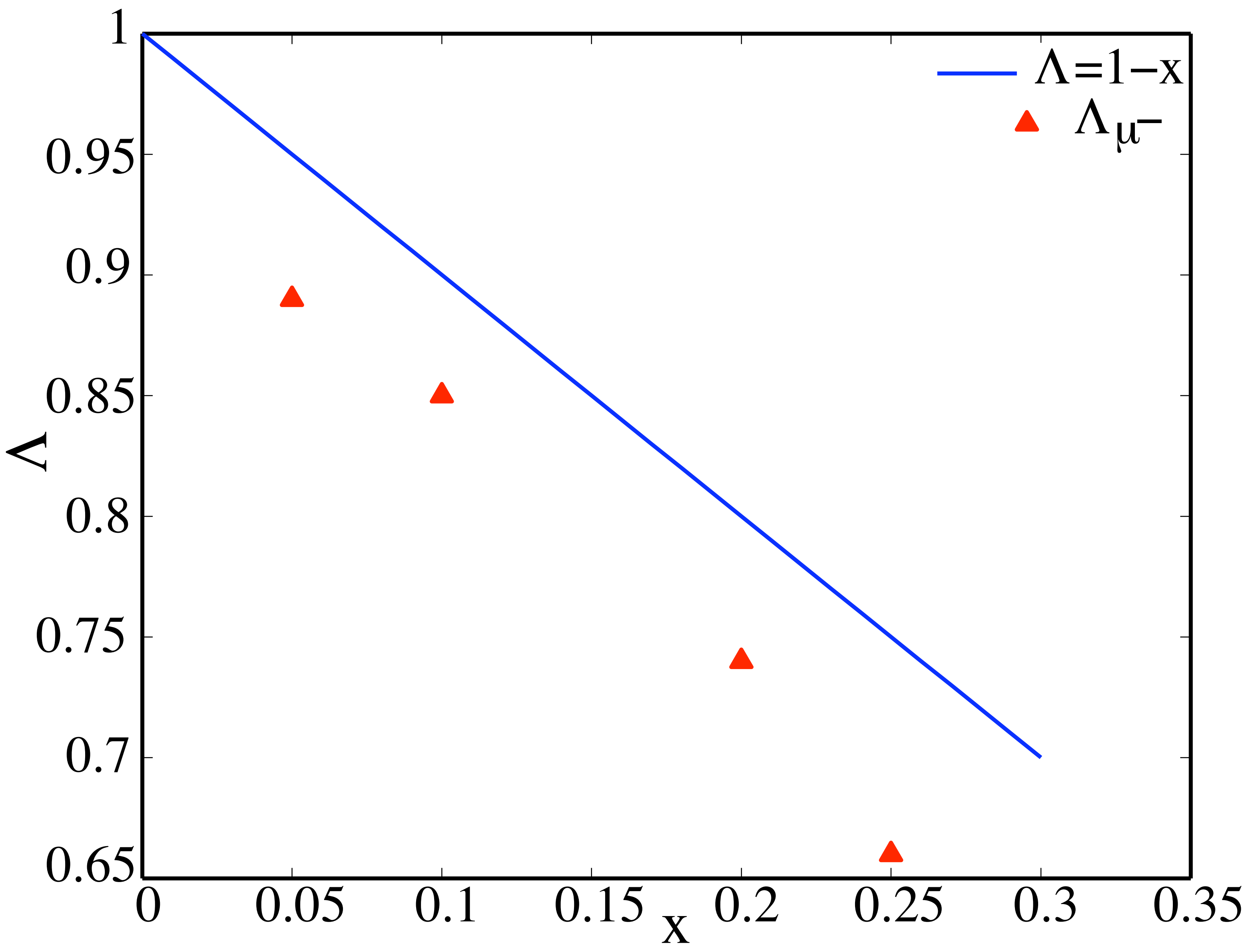
Electron spectral function



Electron spectral function

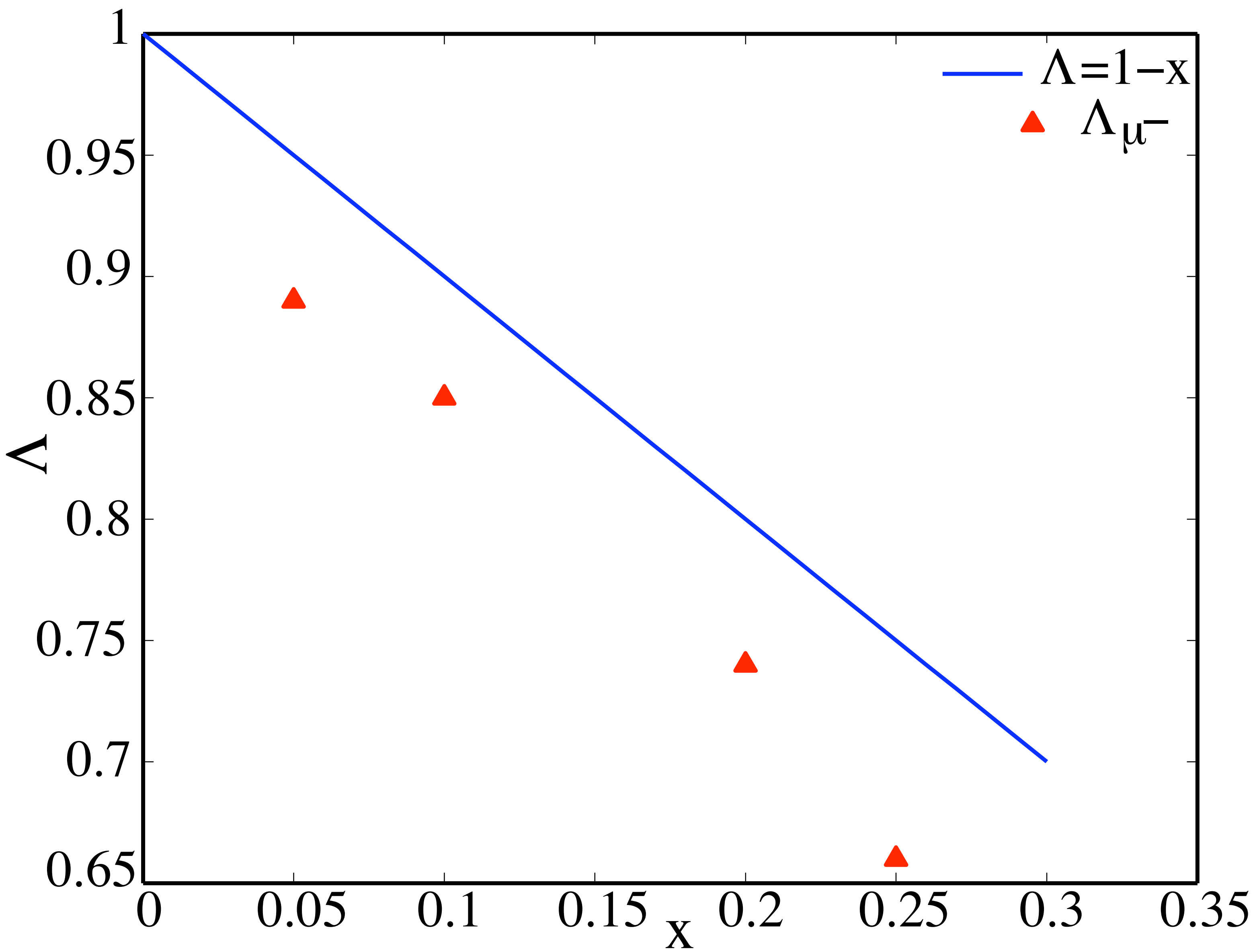
$t^2/U \sim 60$meV

Electron spectral function



^{2}/U~60meV

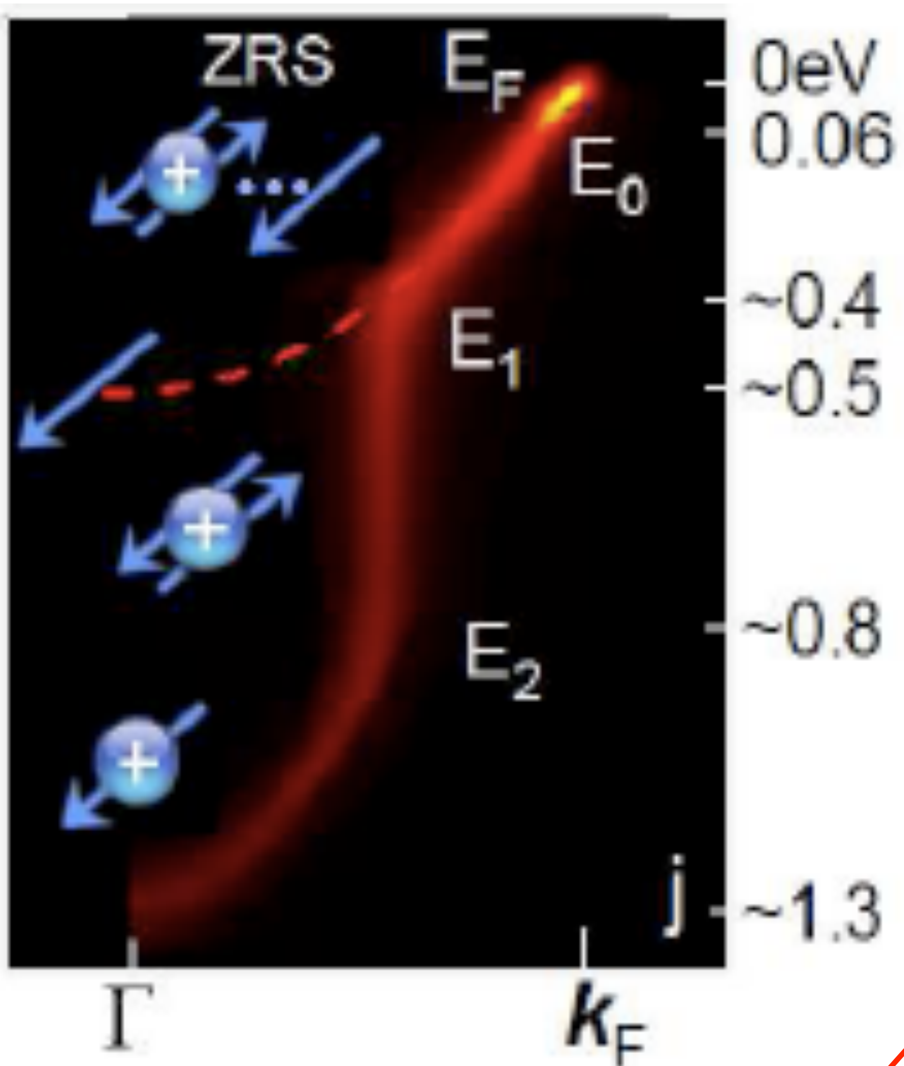
Electron spectral function

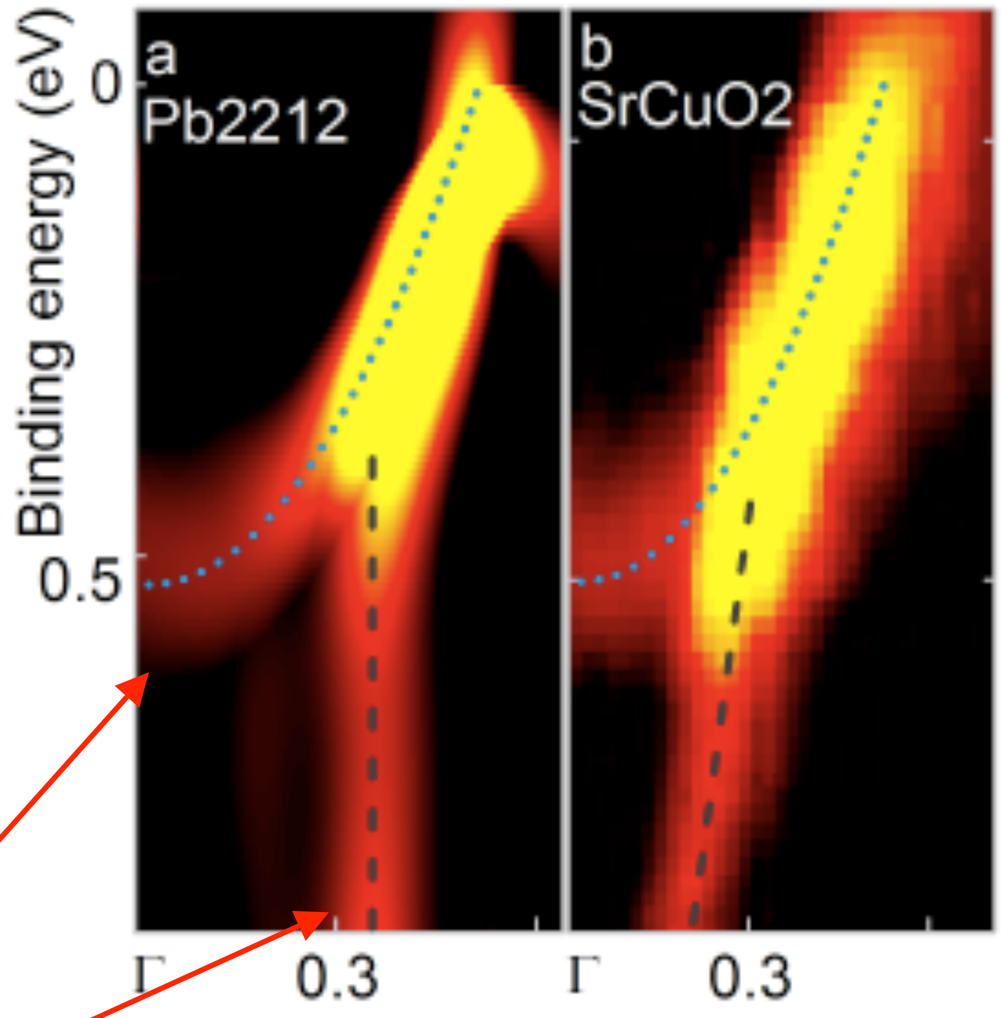


²/U~60meV

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

Graf, et al. PRL vol. 98, 67004 (2007).





Two bands!!

Spin-charge separation?

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

two types of charges

'free'

bound

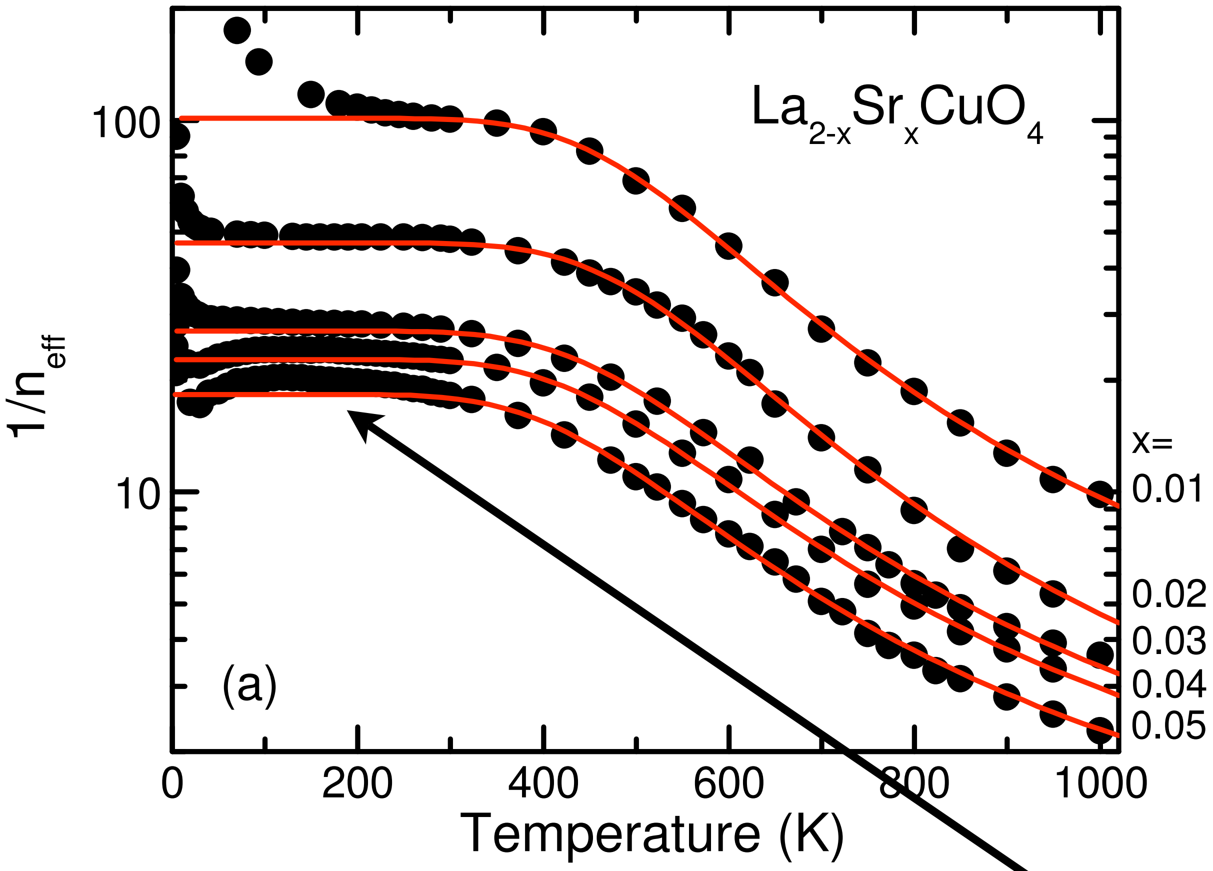
direct evidence

direct evidence

charge carrier density:

direct evidence

charge carrier density:



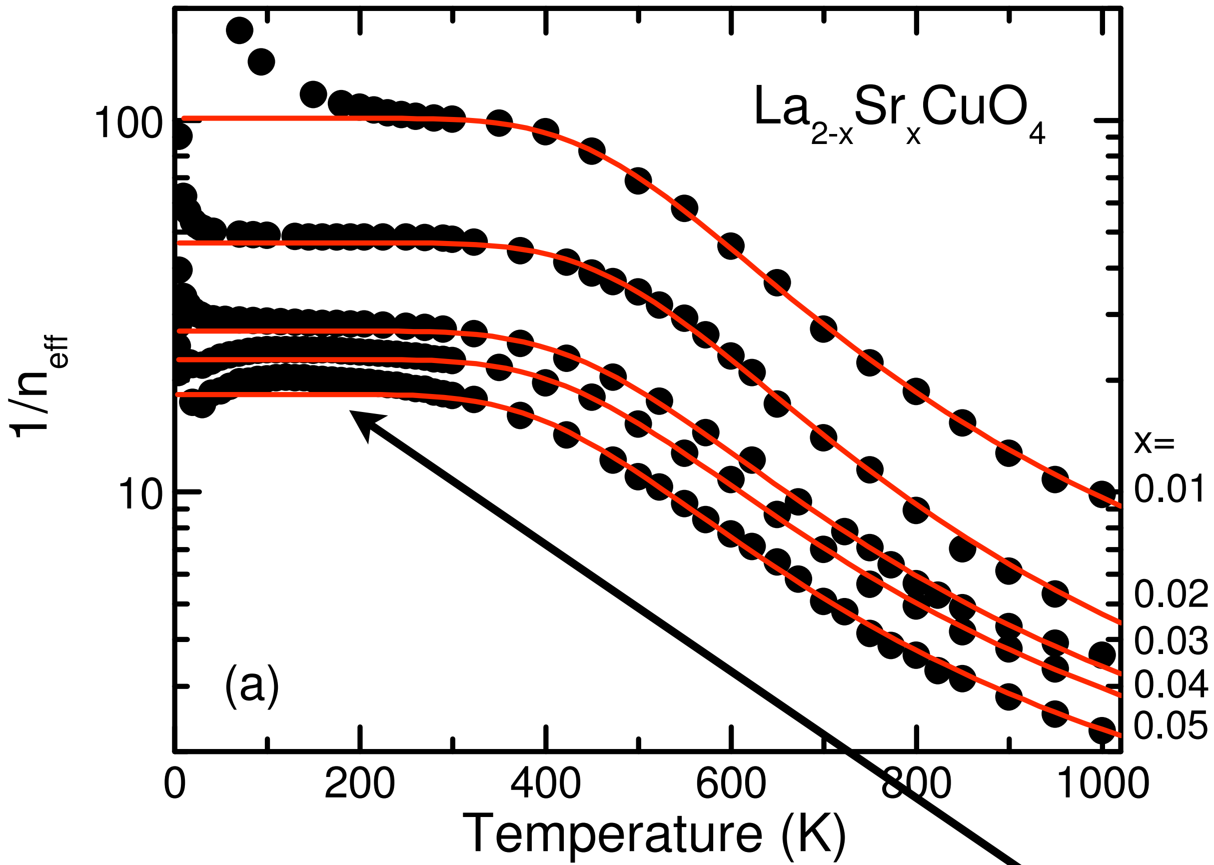
Ono, et al., Phys. Rev. B 75, 024515 (2007)

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

PRL, vol. 97, 247003 (2006).

direct evidence

charge carrier density:



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

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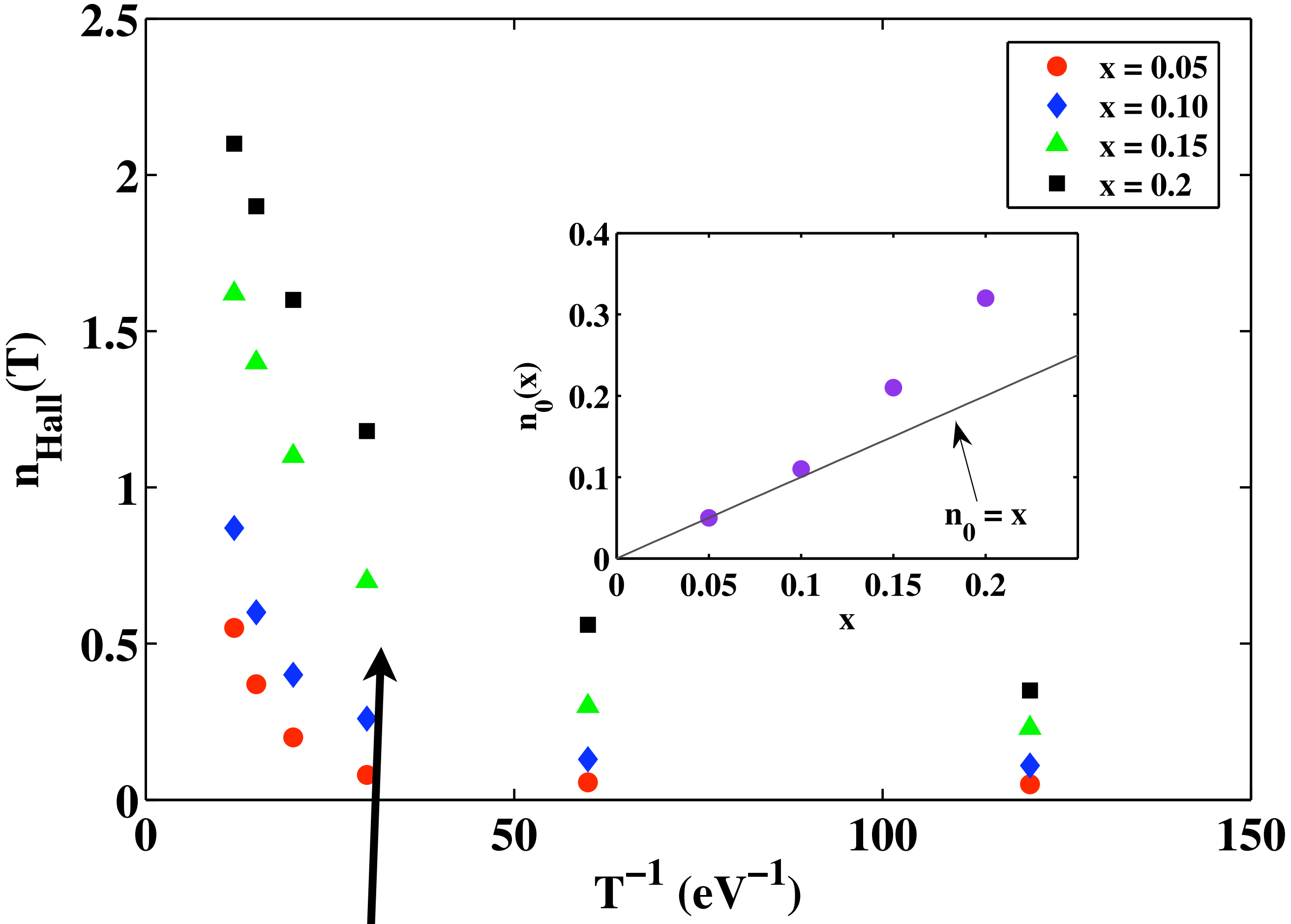
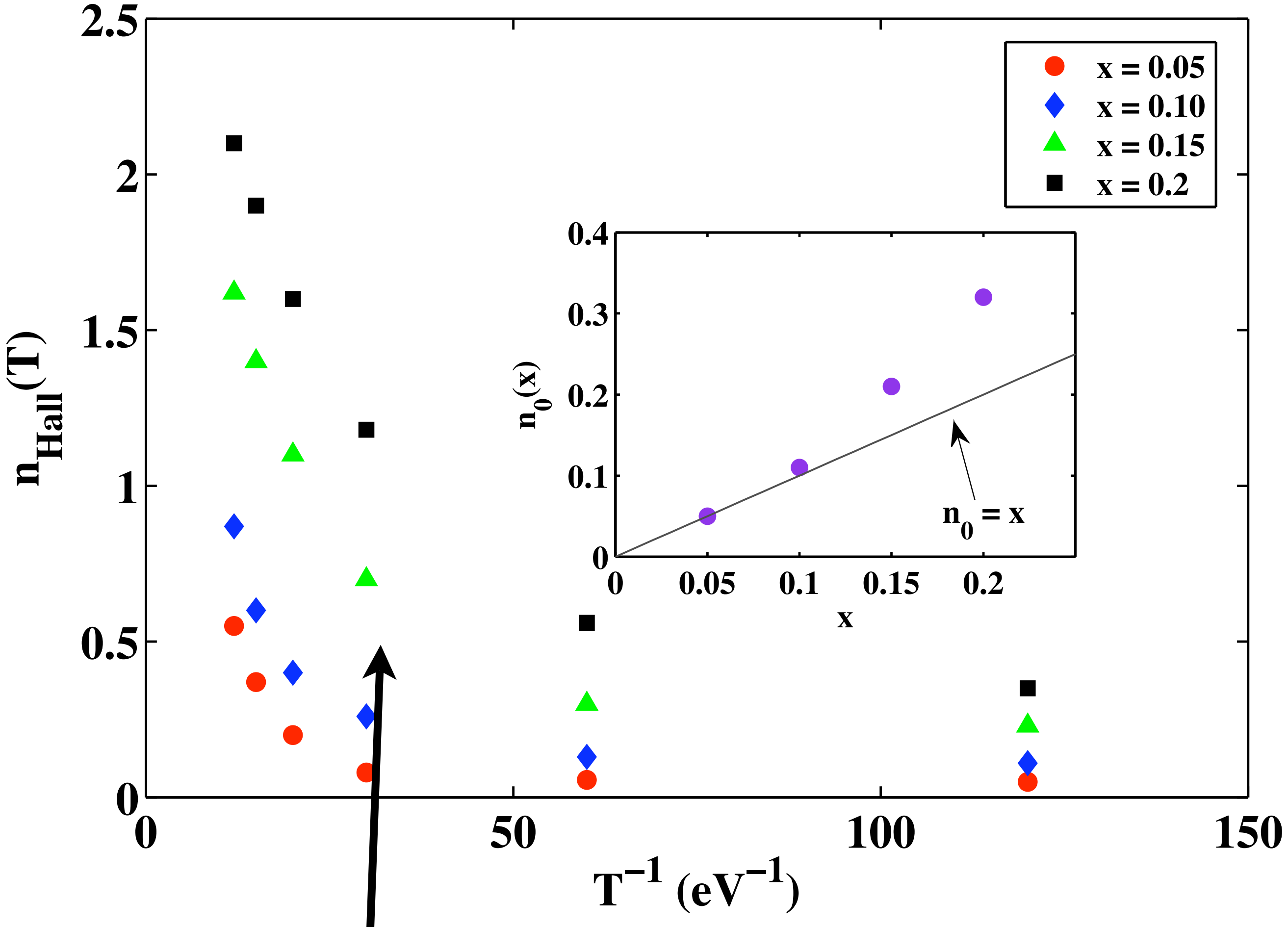
exponentially suppressed: confinement

Our Theory



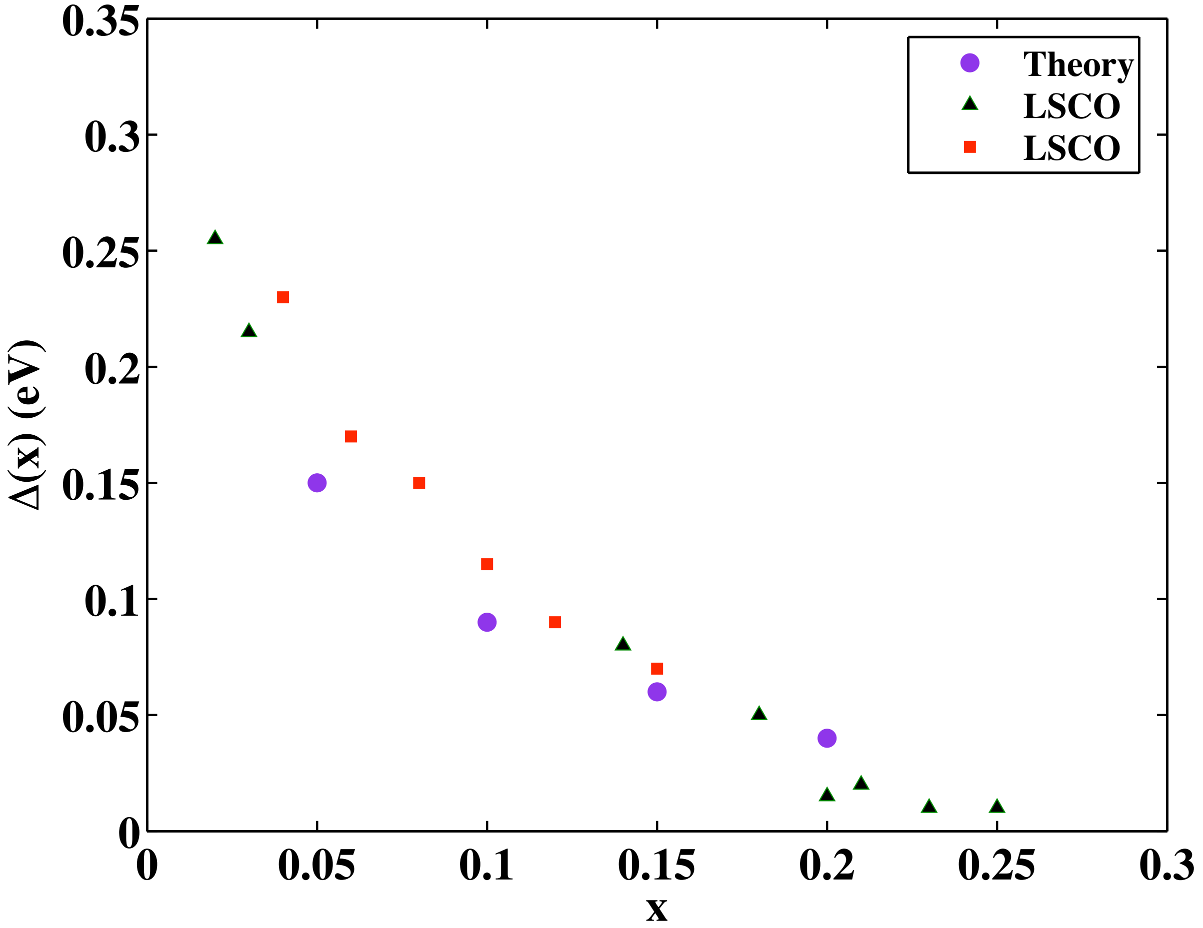
exponential
T-dependence

Our Theory



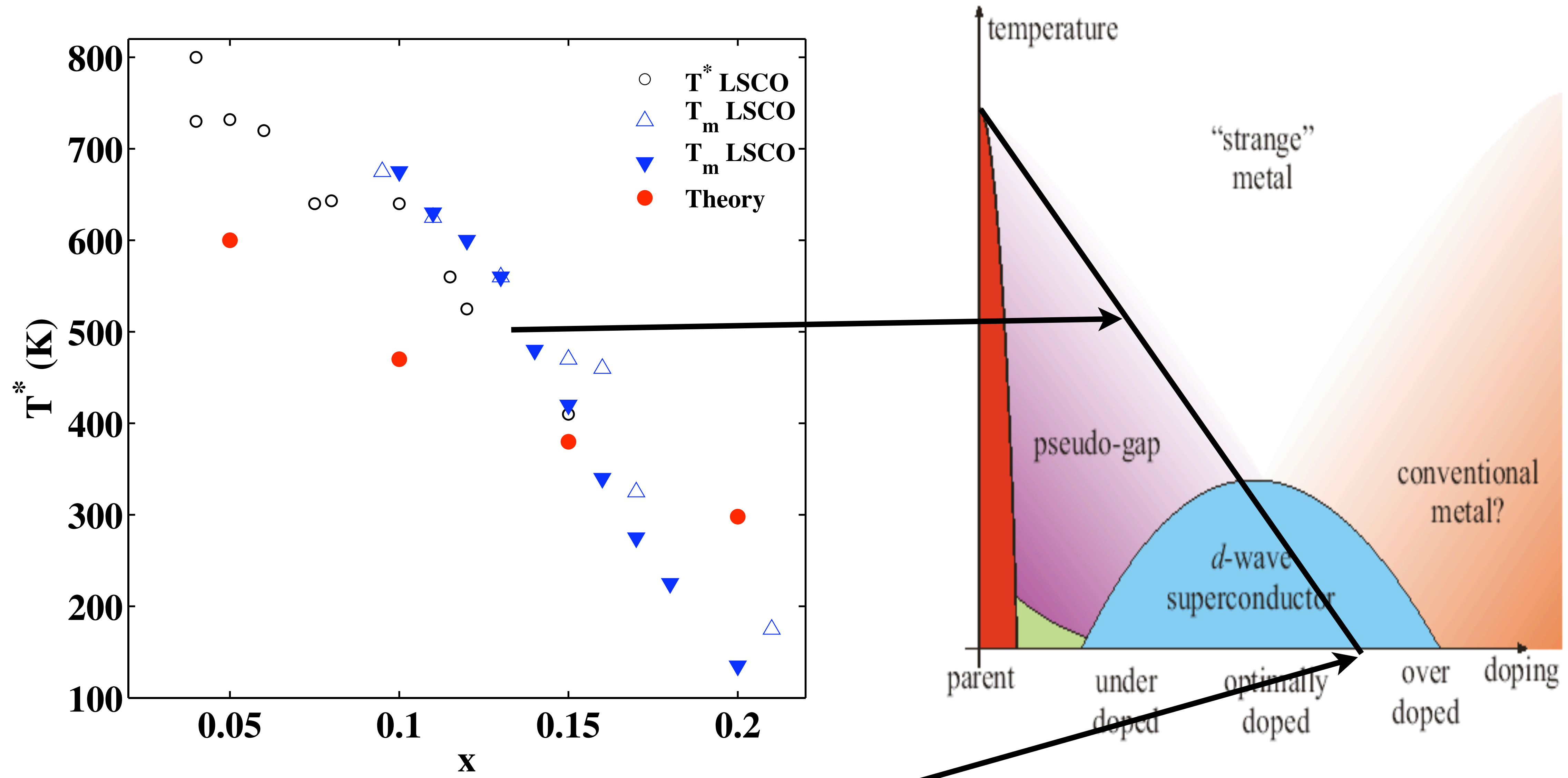
exponential T-dependence

gap



no model-dependent free parameters: just t/U

strange metal: breakup (deconfinement) of bound states

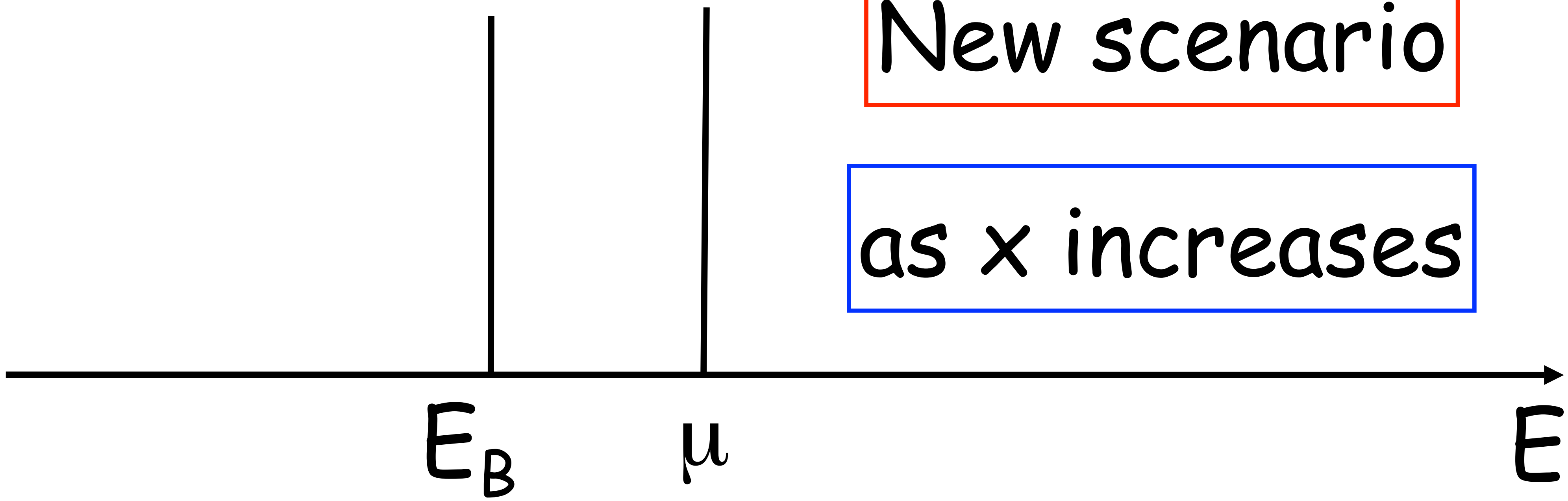


QCP:

T-linear resistivity

New scenario

as x increases



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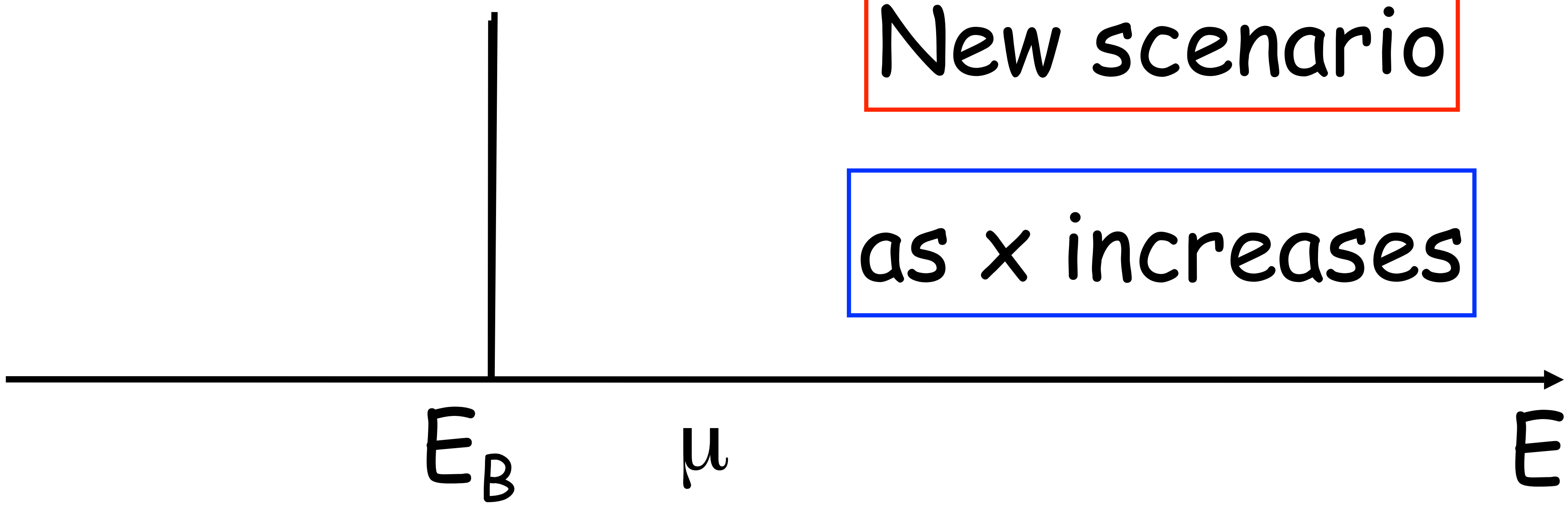

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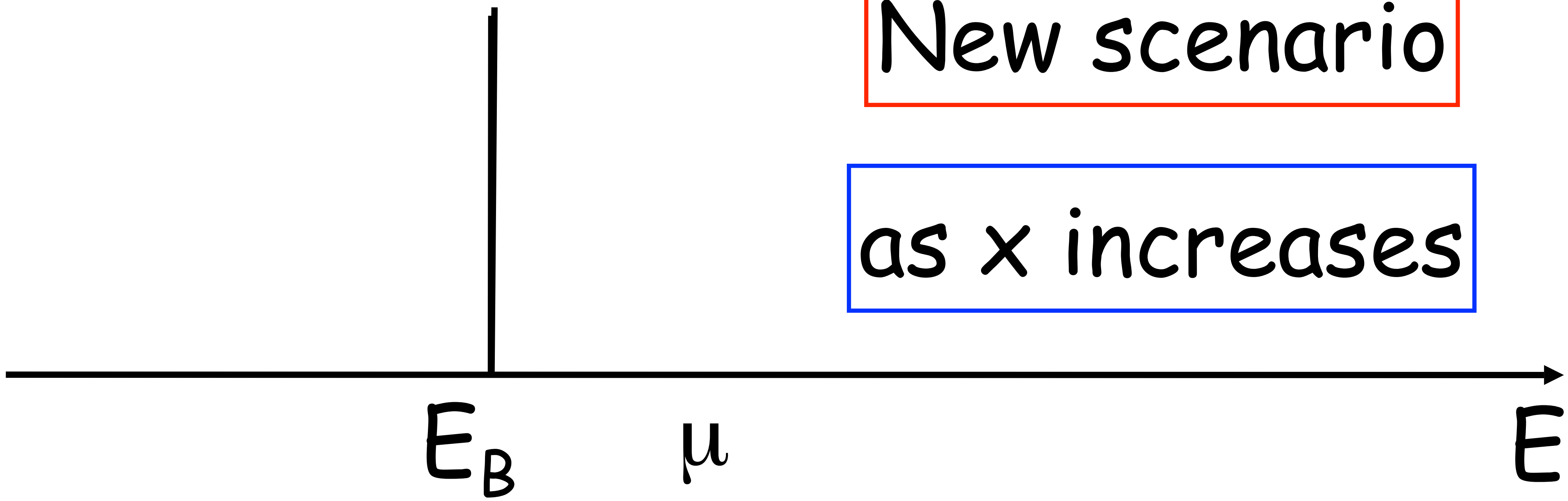
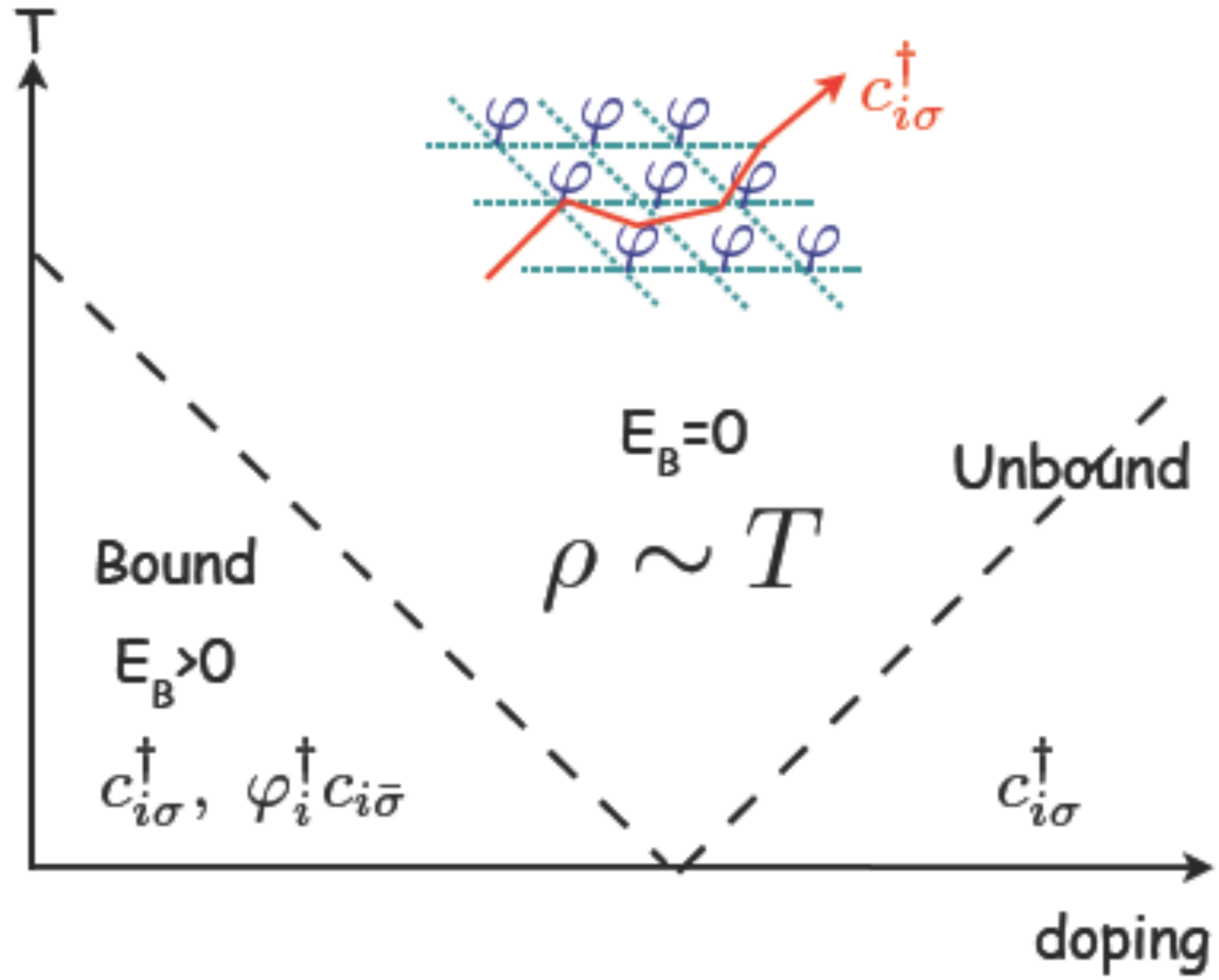
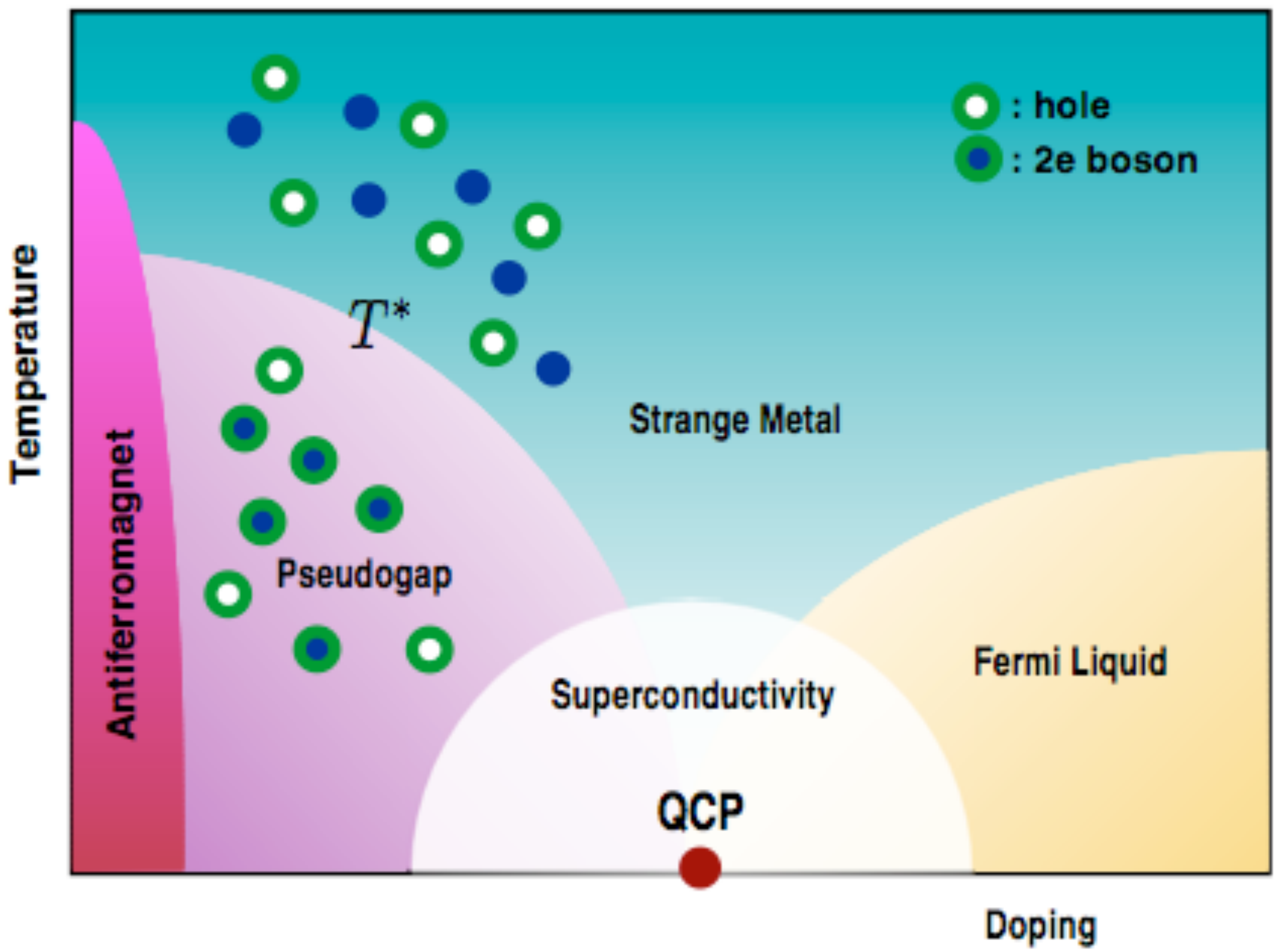
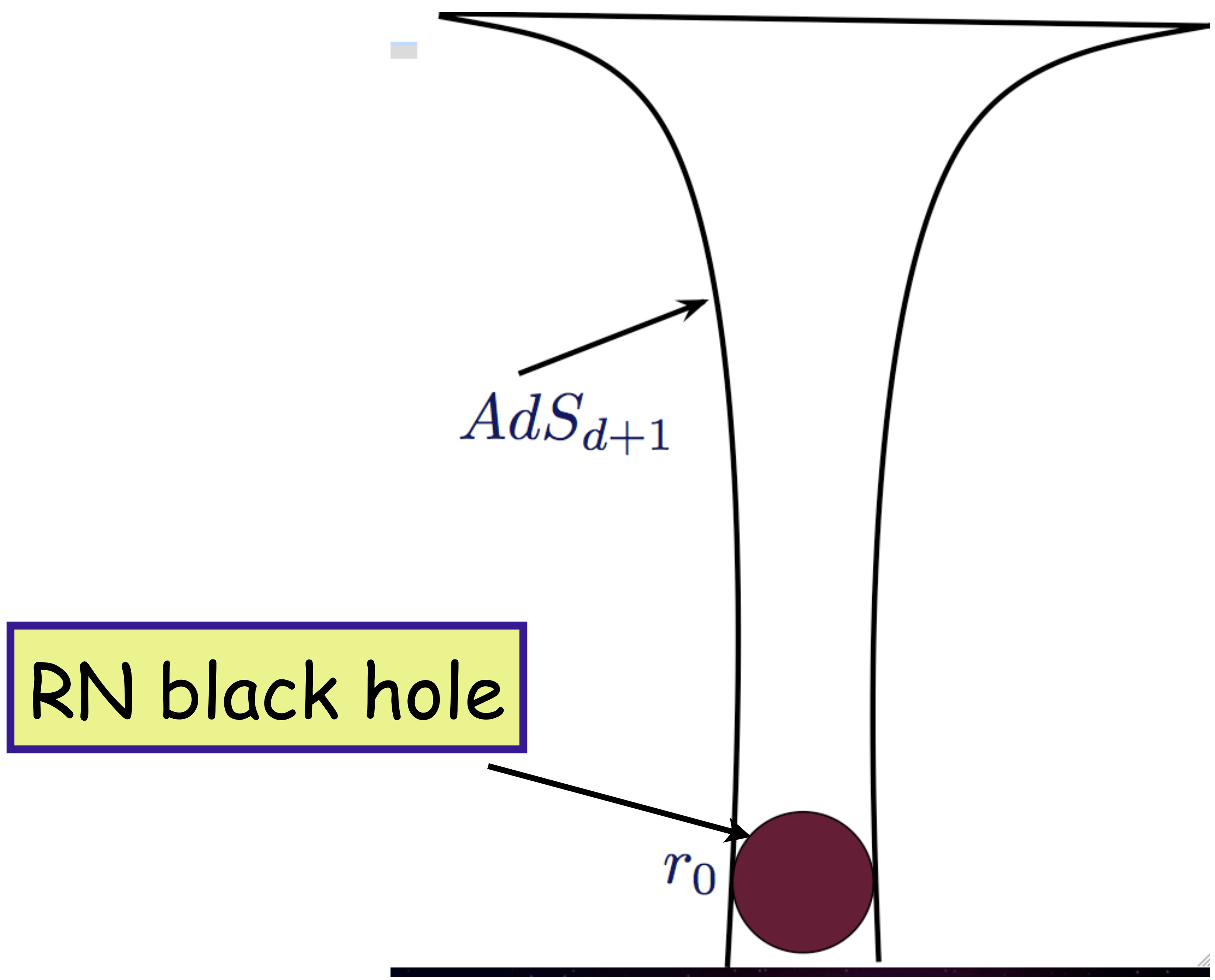





: hole
: 2e boson
T^*
Strange Metal
Pseudogap
Antiferromagnet
Temperature
Superconductivity
Fermi Liquid
QCP
Doping

Mottness from holography

$$H = -t\sum_{i,j} c^{\dagger}_{i\sigma} c_{j\sigma} + U\sum_{i} n_{i\uparrow} n_{\downarrow}$$



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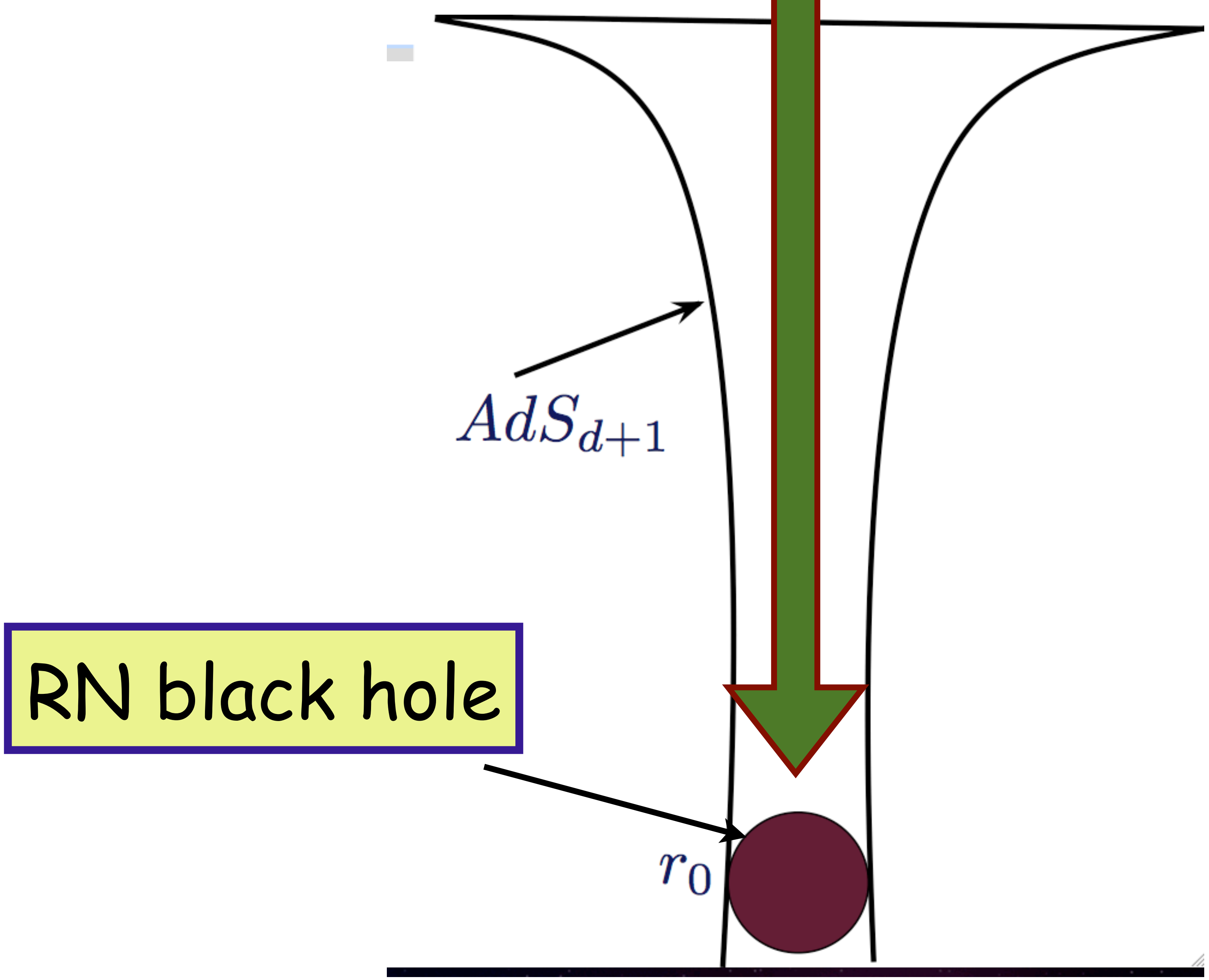

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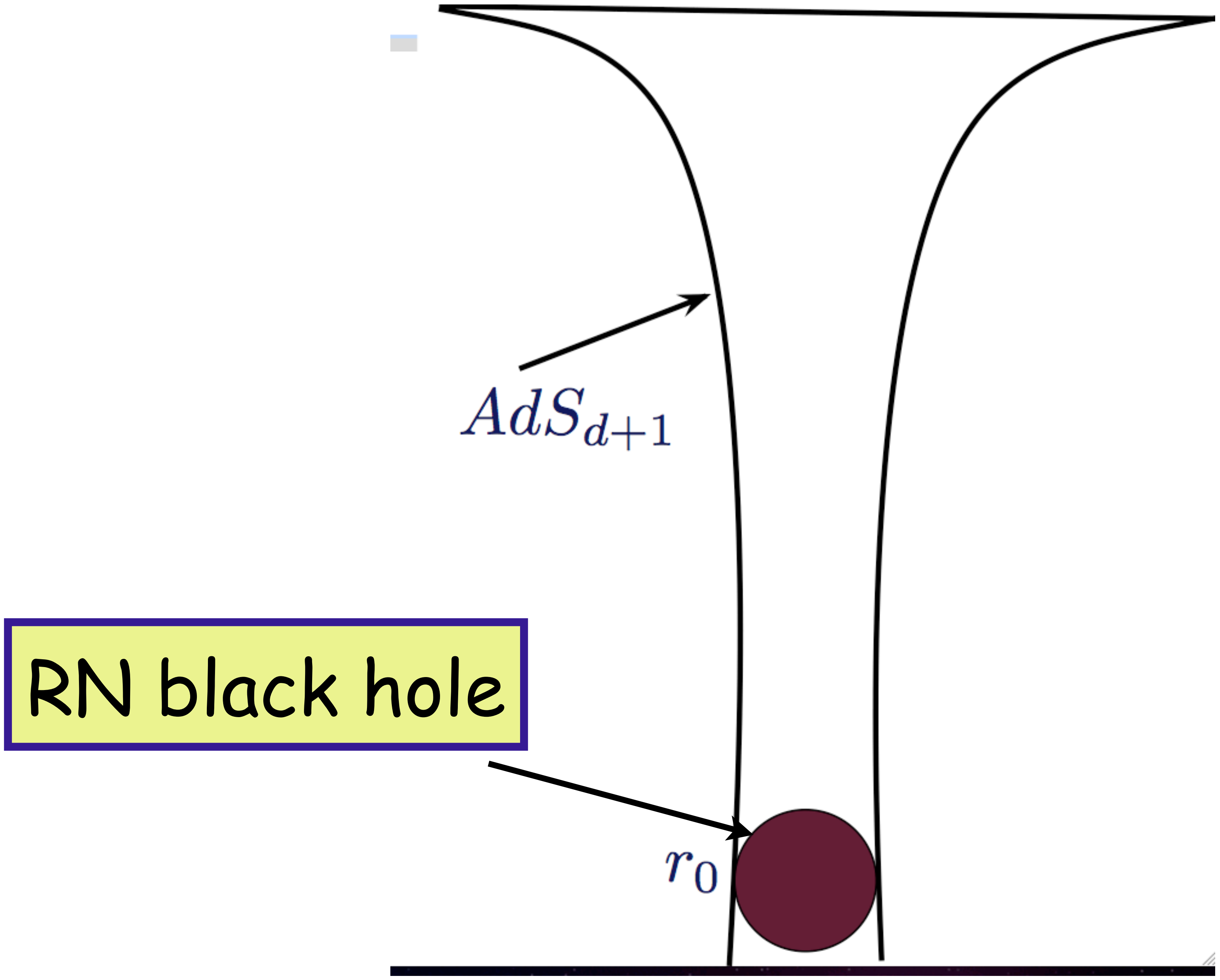

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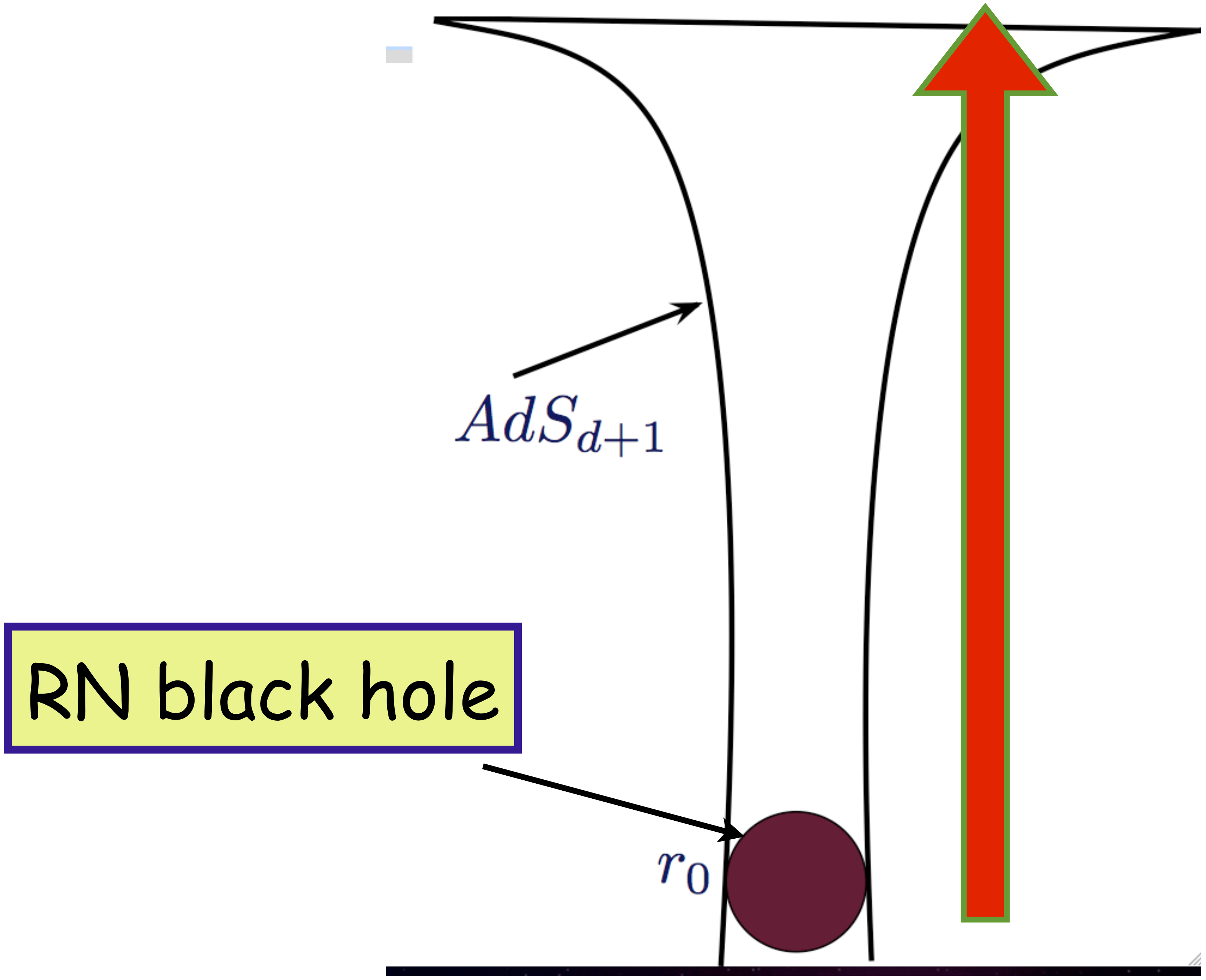


bottom-up schemes

$$\sqrt{-g}\,i\bar{\psi}(D-m)\psi$$

AdS-RN

→ `non-Fermi liquids'

bottom-up schemes

$\sqrt{-g} i \bar{\psi}(D - m)\psi$

AdS-RN → `non-Fermi liquids'

?? → Mott Insulator

bottom-up schemes

$\sqrt{-g}\, i\bar{\psi}(D - m)\psi$

AdS-RN

`non-Fermi liquids'

??

Mott Insulator

consider

$\sqrt{-g}\, i\bar{\psi}(\not{D} - m - ip\not{F})\psi$

fermions in RN Ads_{d+1} coupled to a gauge field through a dipole interaction near horizon

radial Dirac Equation

$$\psi_{I\pm}(\zeta) \quad = \psi^{(0)}_{I\pm}(\zeta) + \omega\,\psi^{(1)}_{I\pm}(\zeta) + \omega^2 \psi^{(2)}_{I\pm}(\zeta) + \cdots$$

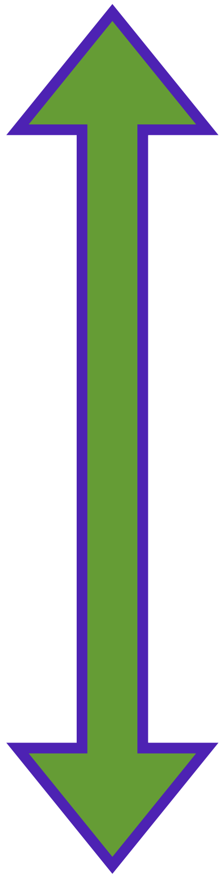
$$-\psi^{(0)\prime\prime}_{I\pm}(\zeta) = i\sigma_2 \left(1 + \frac{q e_d}{\zeta}\right) - \frac{L_2}{\zeta}\left[m\sigma_3 + \left(p e_d \pm \frac{kL}{r_0}\right)\sigma_1\right]\psi^{(0)}_{I\pm}(\zeta),$$

$$e_d = 1/\sqrt{2d(d-1)}$$

$$m_k^2 = m^2 + \left(p e_d \pm \frac{kL}{r_0}\right)^2$$

p shifts momenta up and down through mass coupling

$$\psi_{I\pm}^{(0)}(\zeta)$$



IR CFT $\quad \mathcal{O}_\pm$

scaling dimension

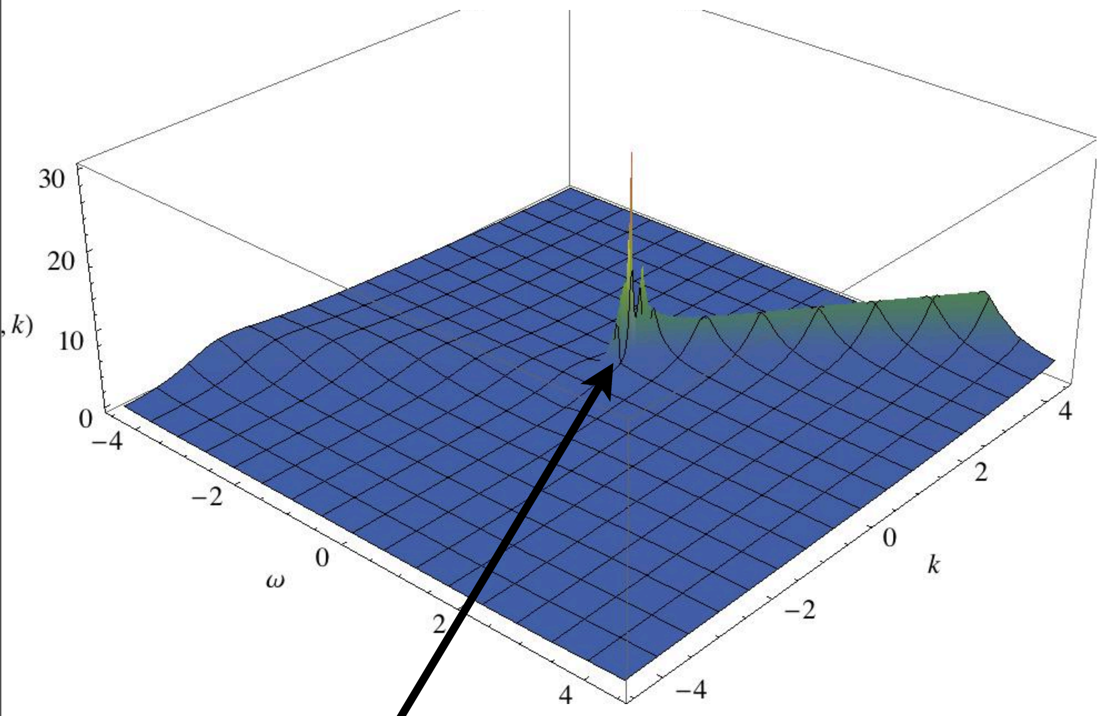
$$\delta_\pm = \nu_\pm + \frac{1}{2}$$

$$\nu_\pm = \sqrt{m_k^2 L_2^2 - q^2 e_d^2 - i\epsilon}$$

How is the spectrum modified?

How is the spectrum modified?

P=0

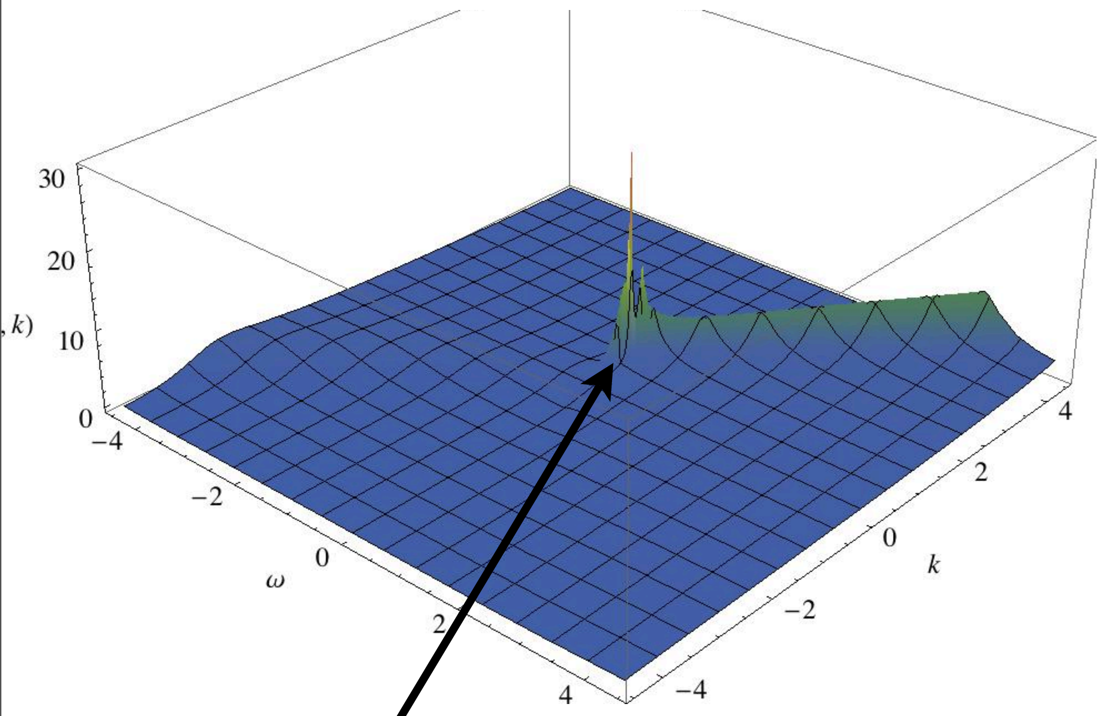


Fermi surface peak

How is the spectrum modified?

P=0

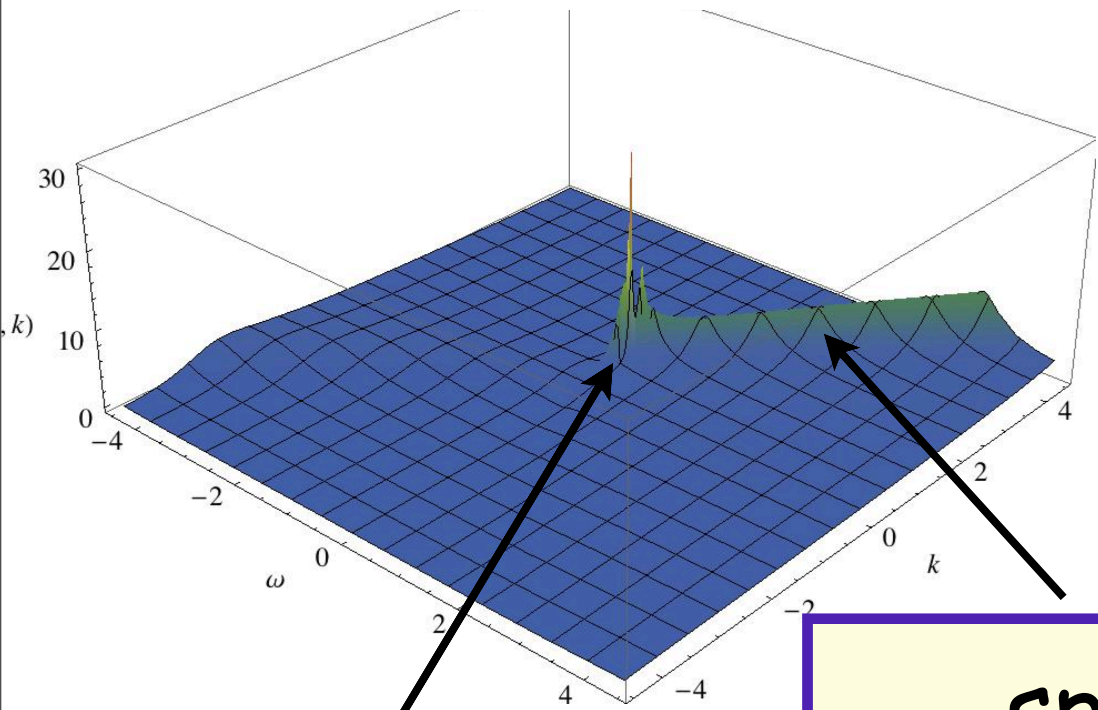
$P > 4.2$



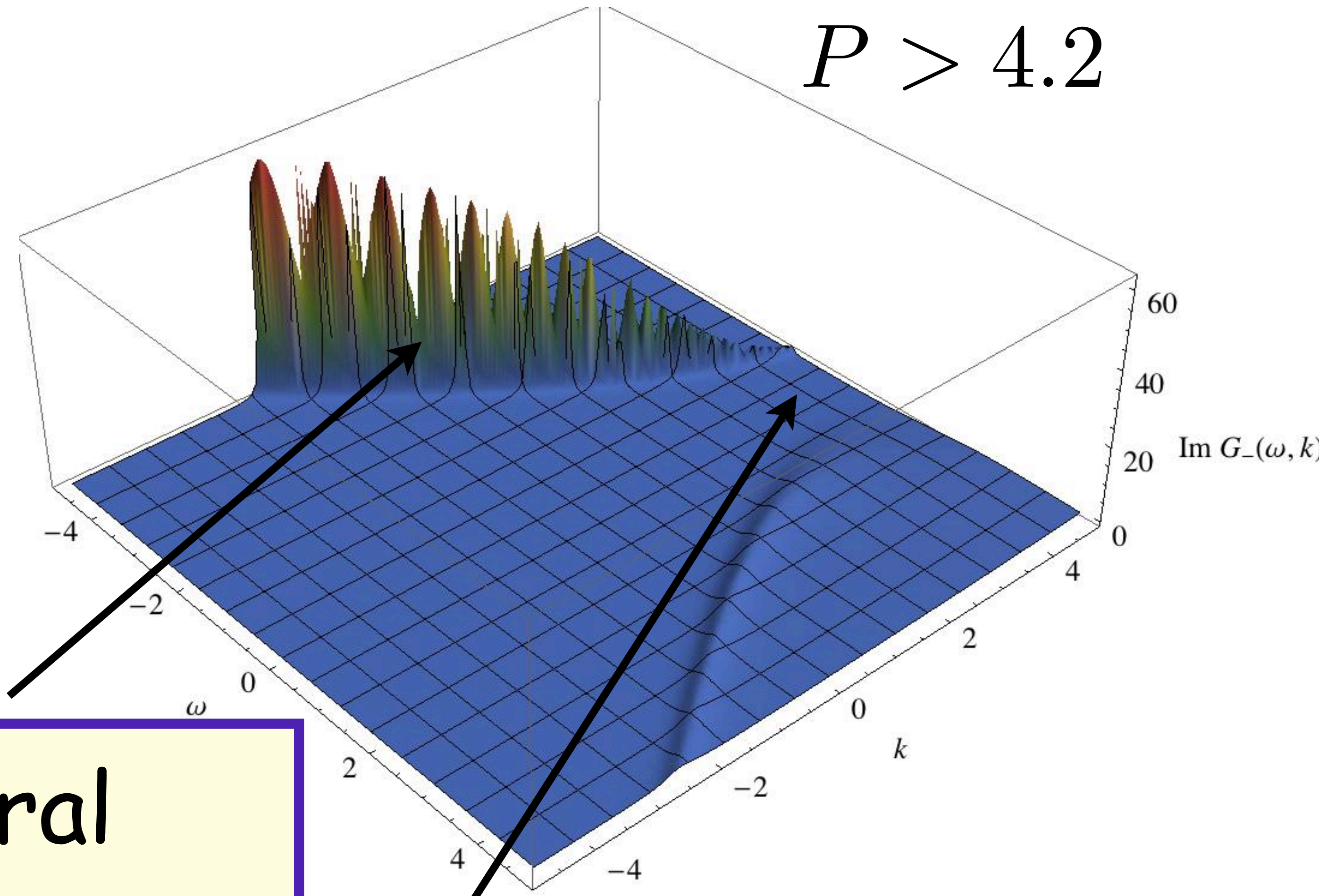
Fermi surface peak

How is the spectrum modified?

P=0



$P > 4.2$



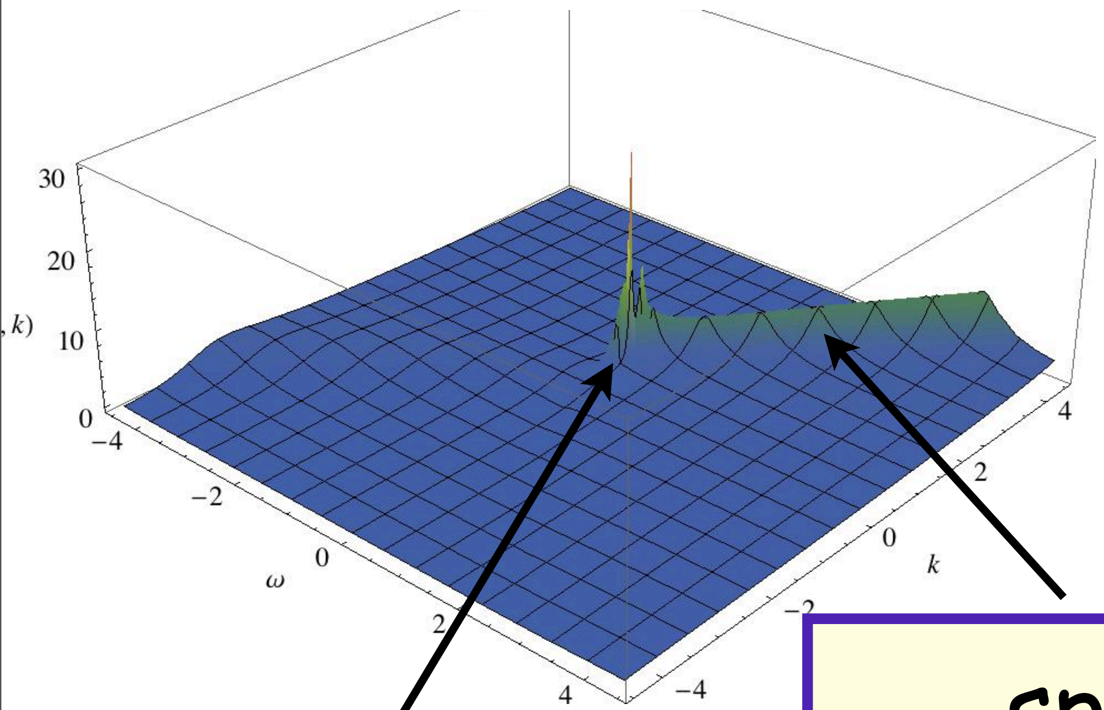
Fermi surface peak

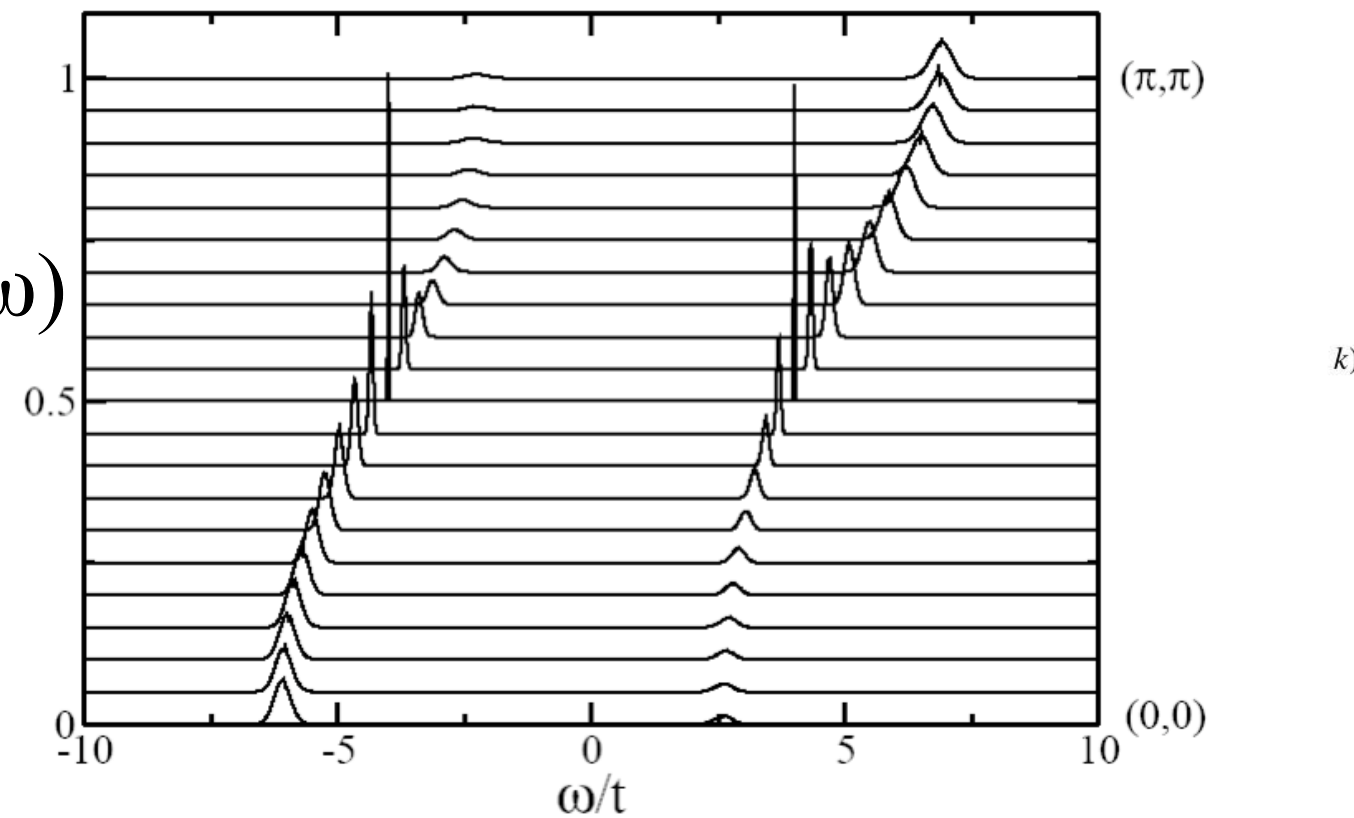
spectral weight transfer

dynamically generated gap:

How is the spectrum modified?

P=0





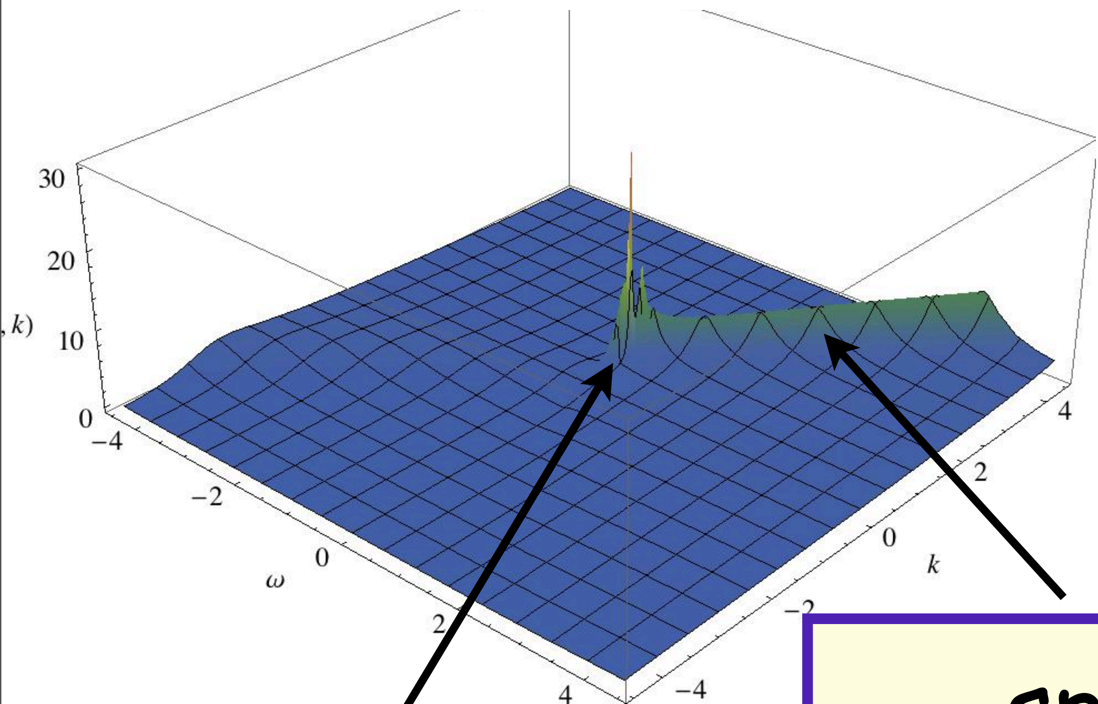
Fermi surface peak

spect
weight transfer

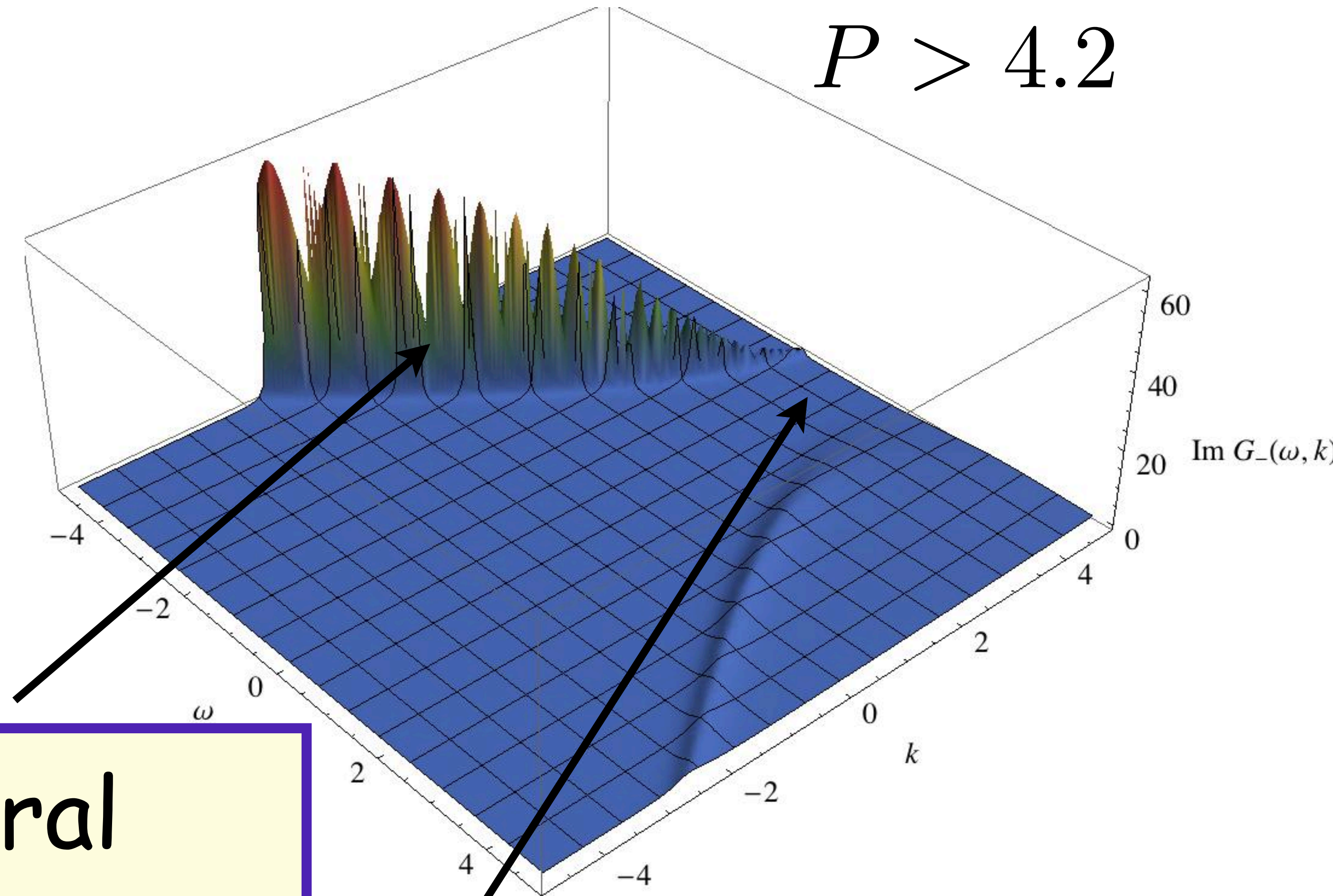
dynamically generated gap:

How is the spectrum modified?

P=0



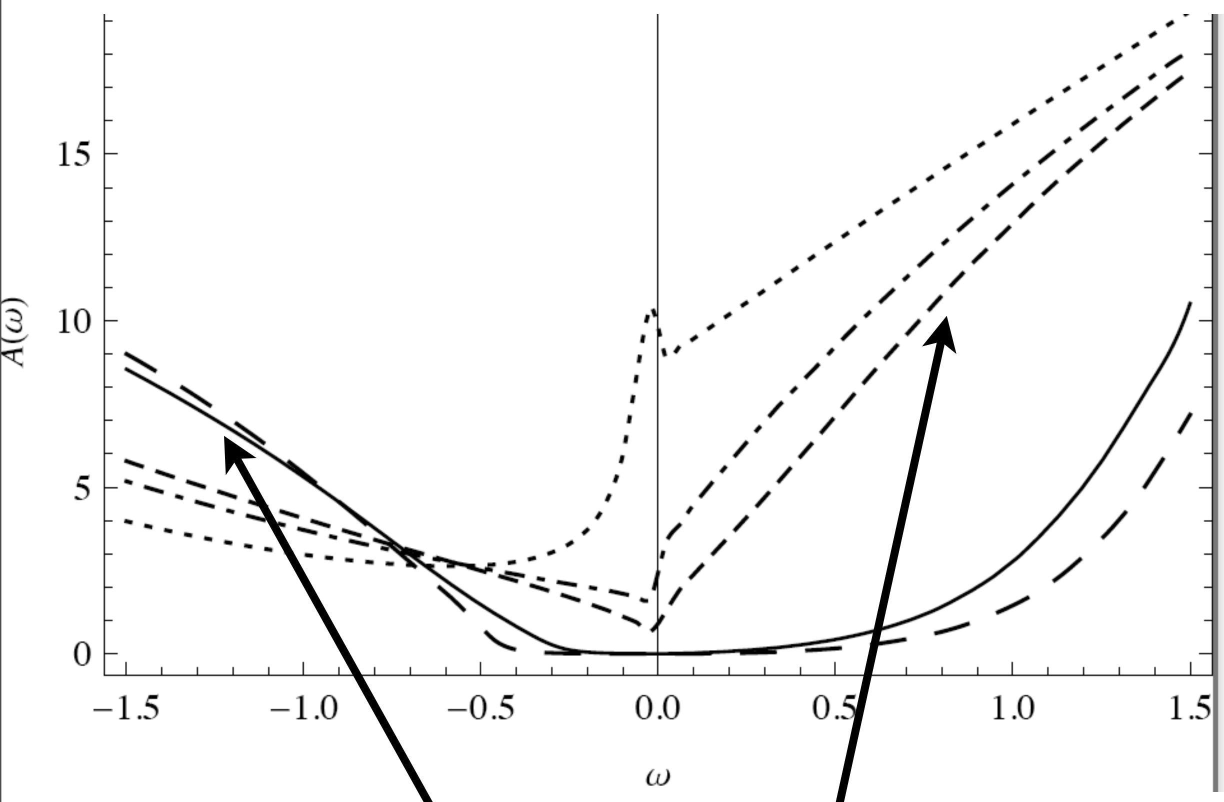
$P > 4.2$

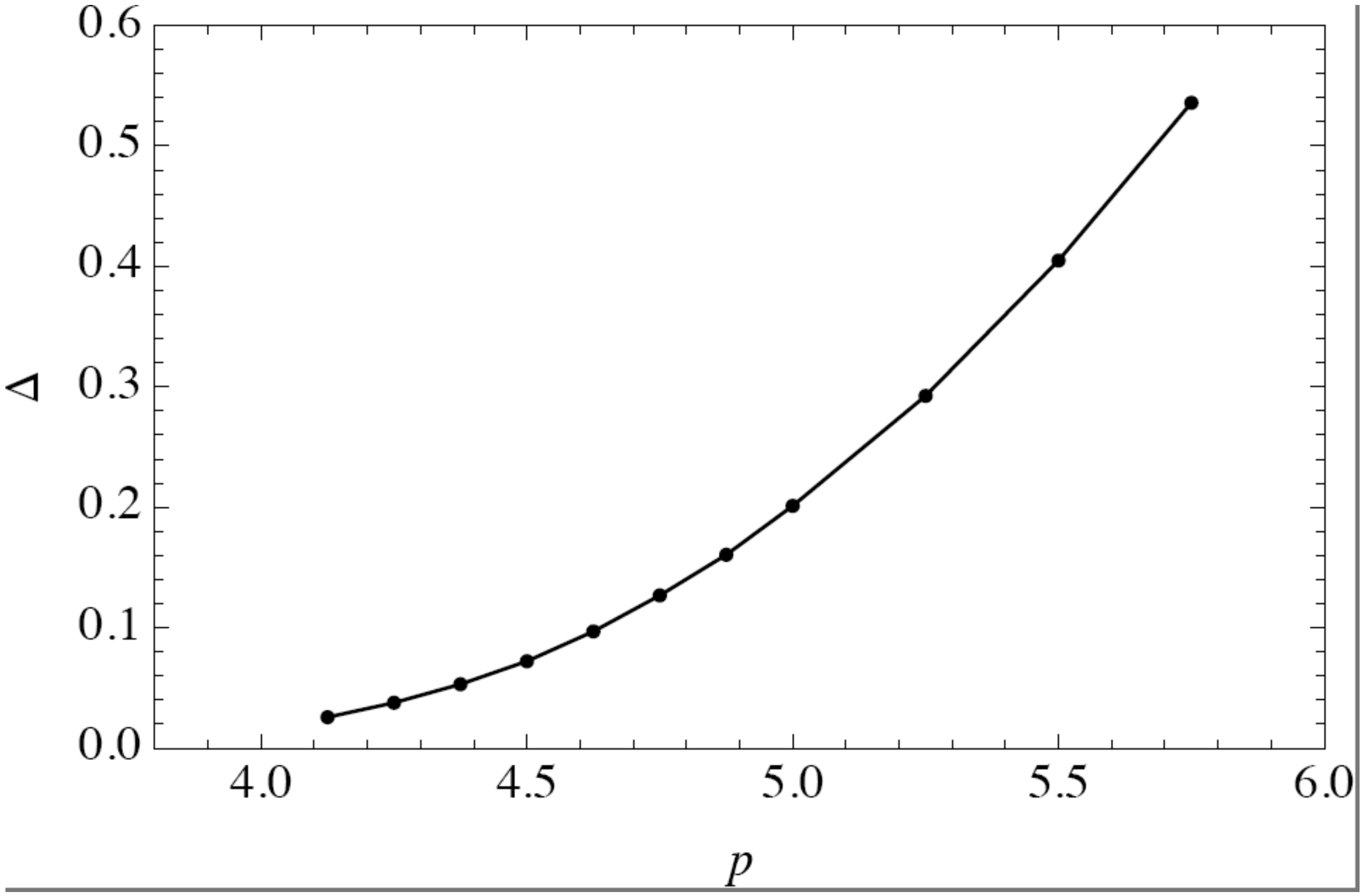


Fermi surface peak

spectral weight transfer

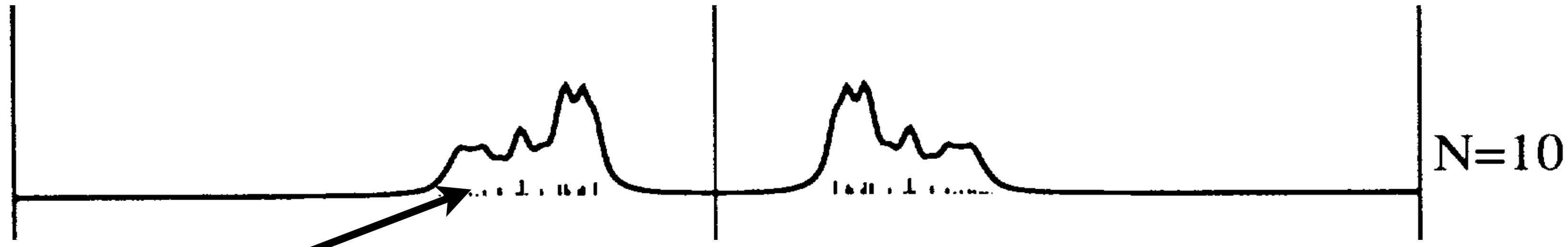
dynamically generated gap:





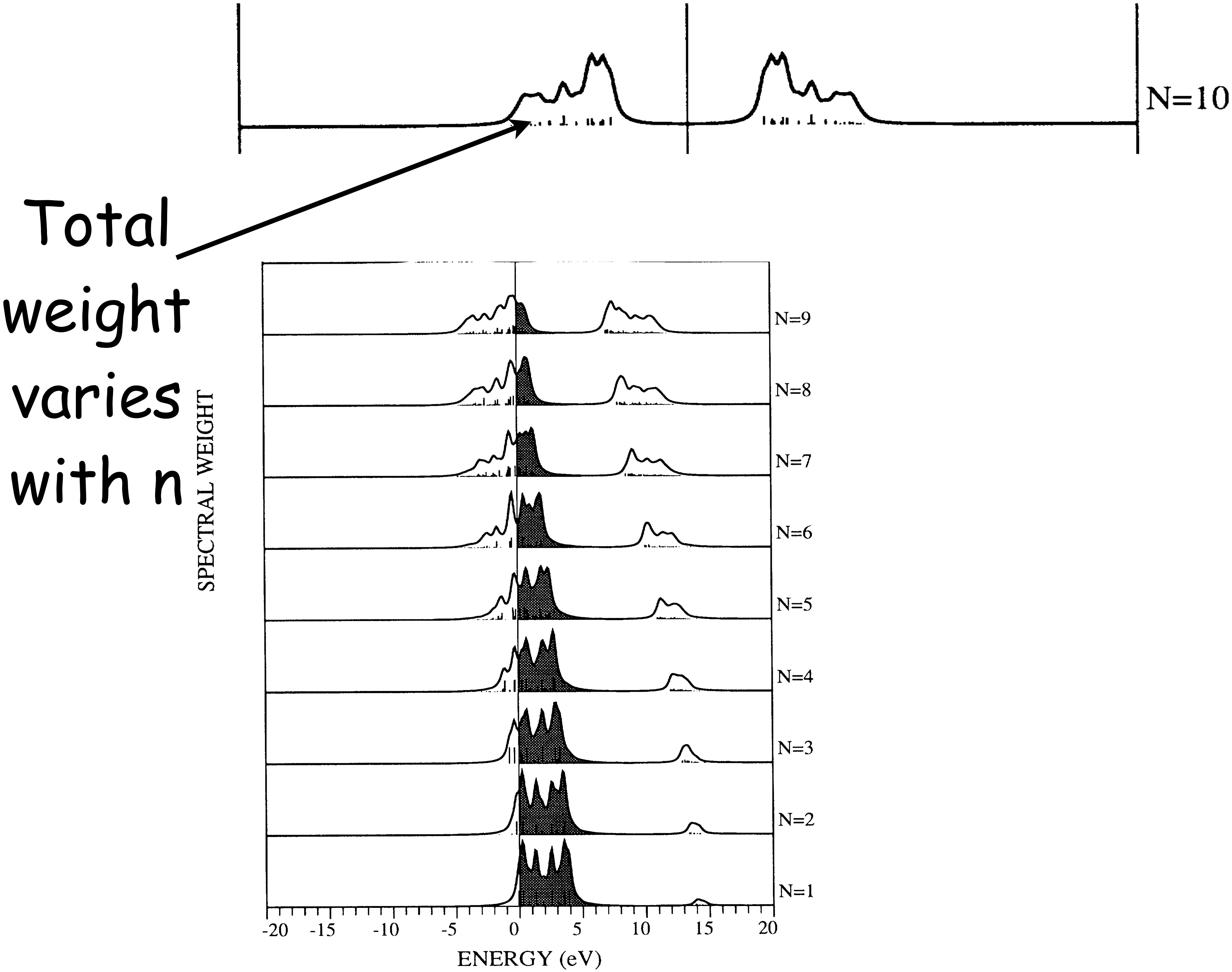
spectral weight transfer
UV-IR mixing

Mott gap

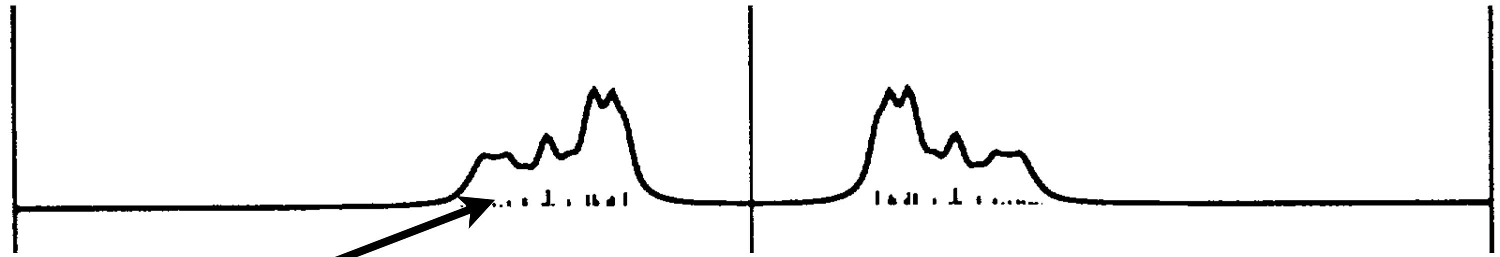


Total weight varies with n

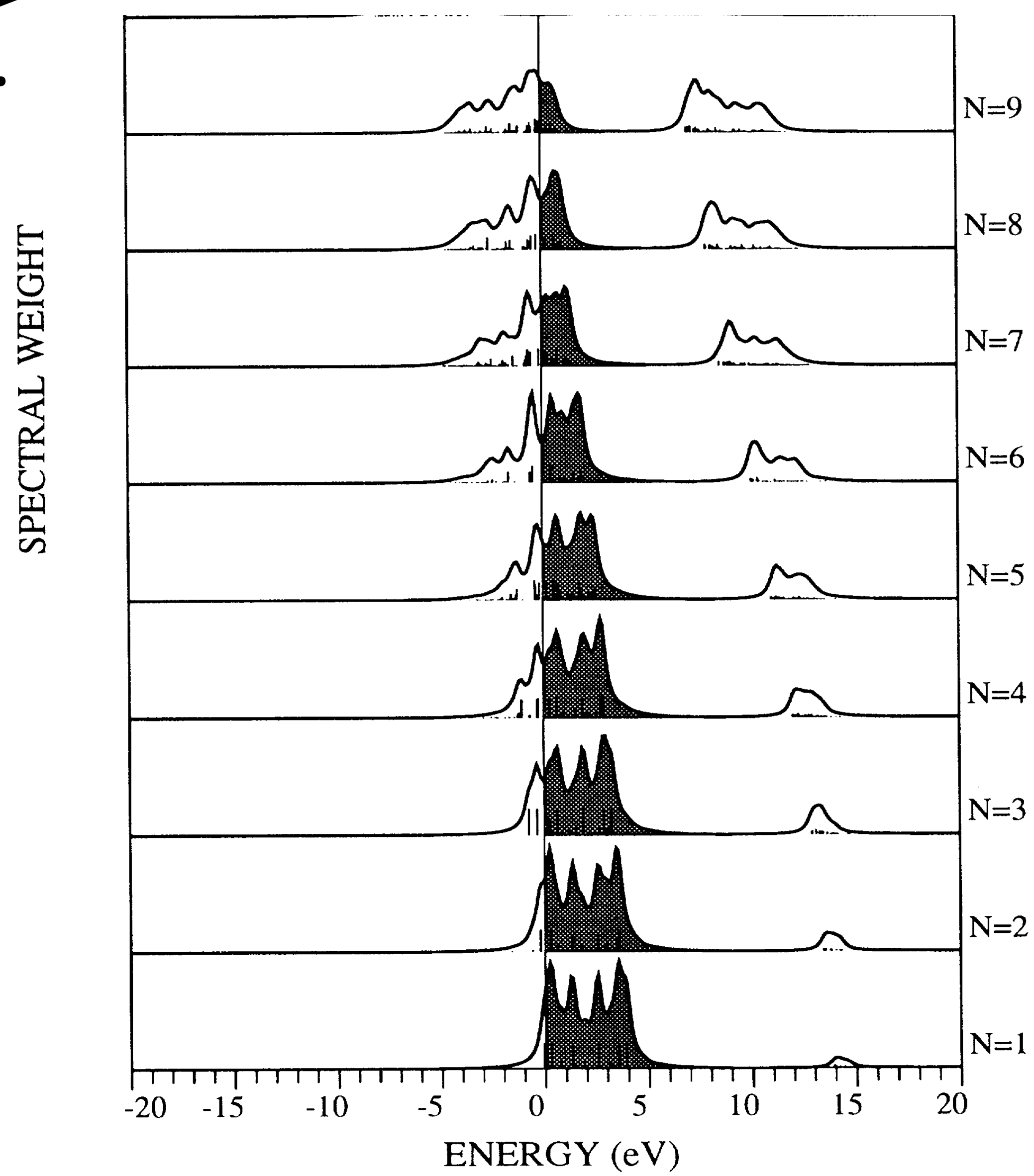
Mott gap

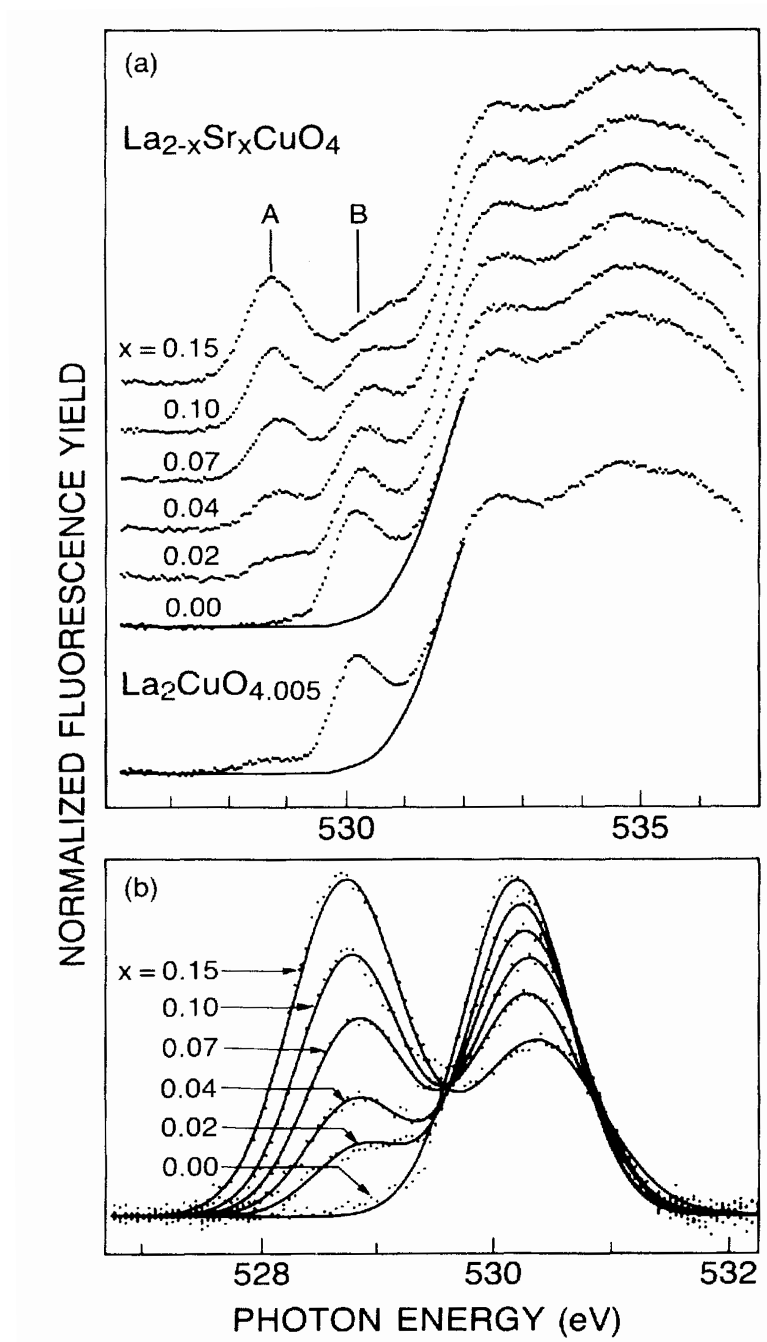

N=10
Total weight varies with n
SPECTRAL WEIGHT
N=9
N=8
N=7
N=6
N=5
N=4
N=3
N=2
N=1
-20 -15 -10 -5 0 5 10 15 20
ENERGY (eV)

Mott gap

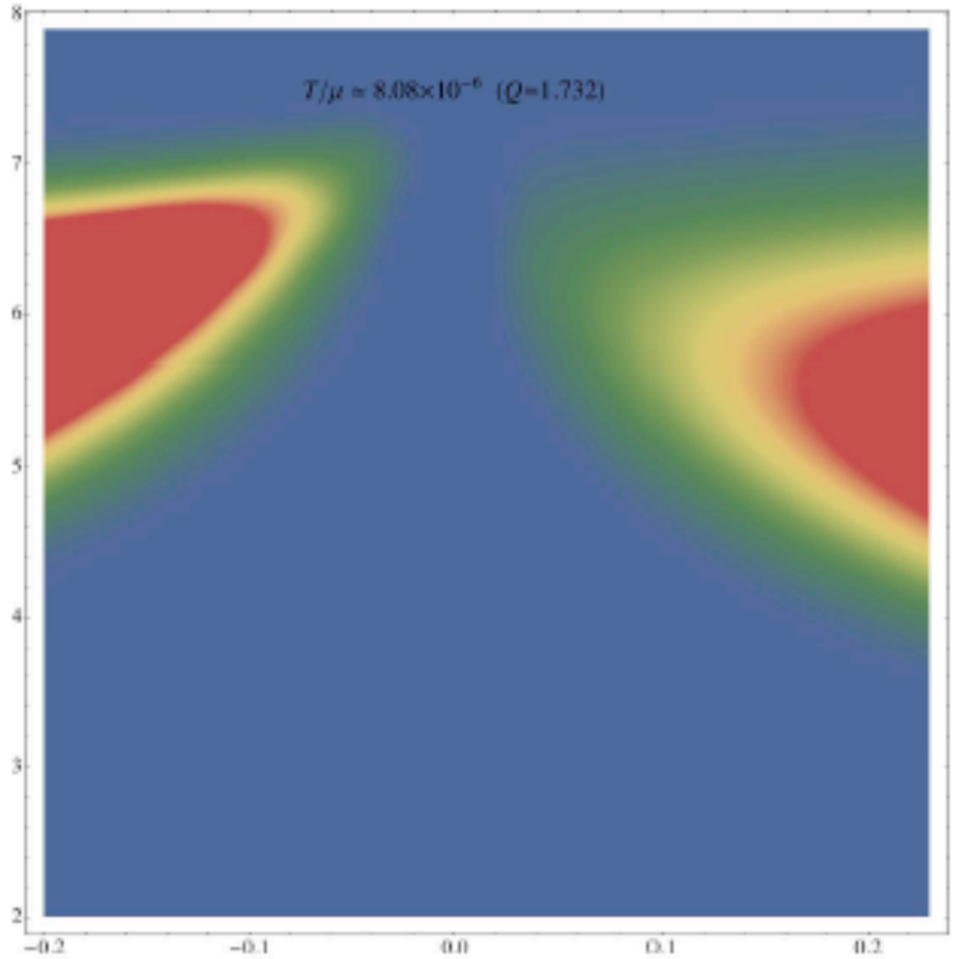


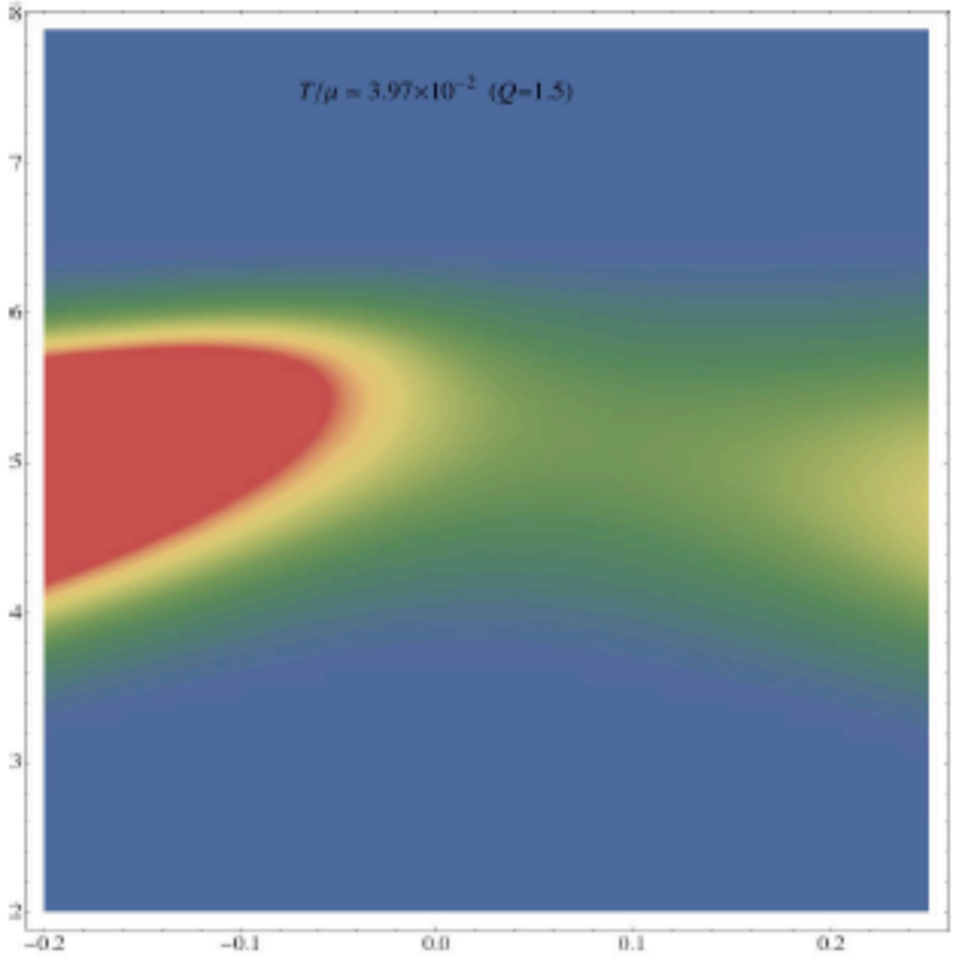
Total weight varies with n





Finite Temperature Mott transition



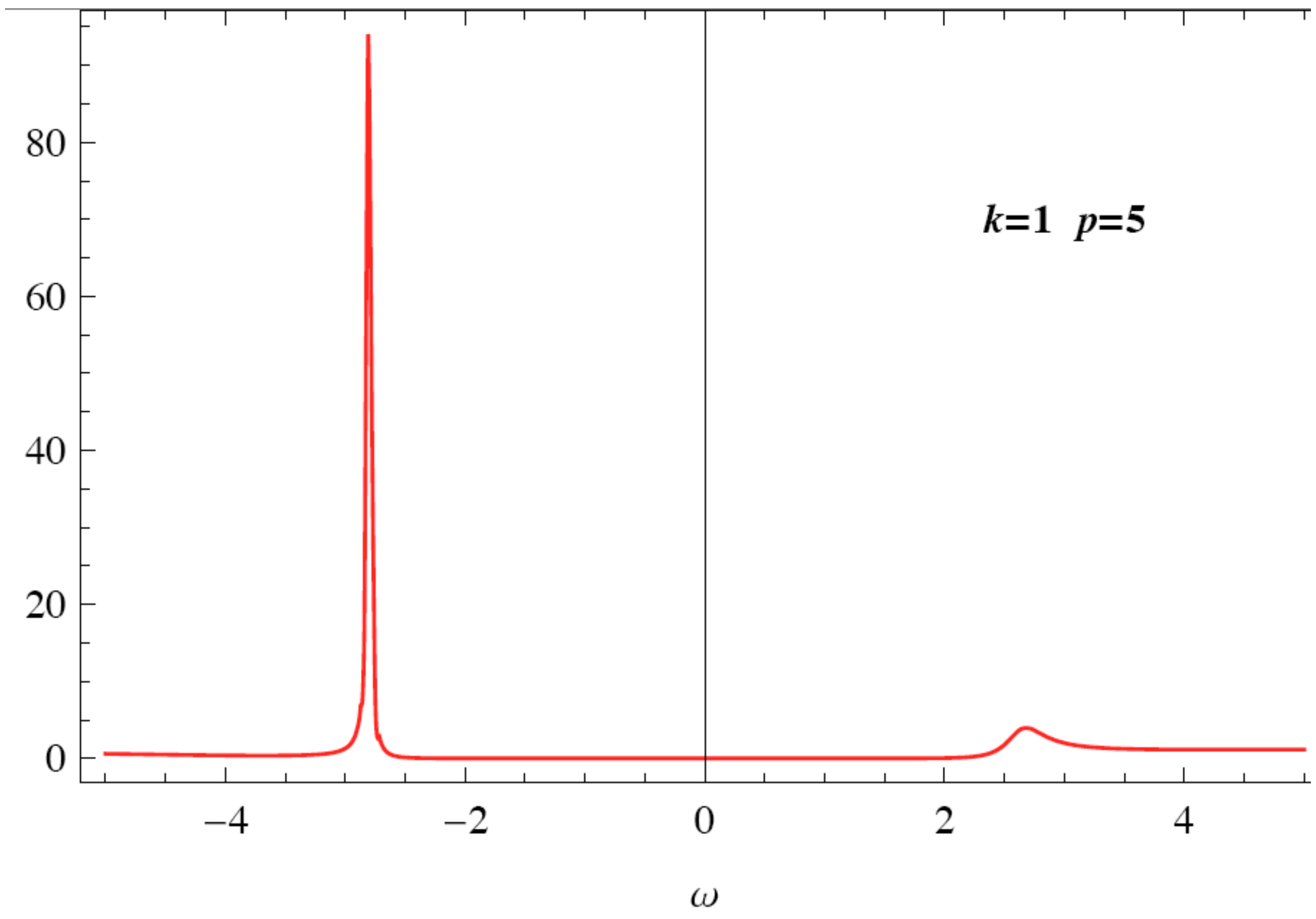


$$\frac{\Delta}{T_{\rm crit}} \approx 10^3$$

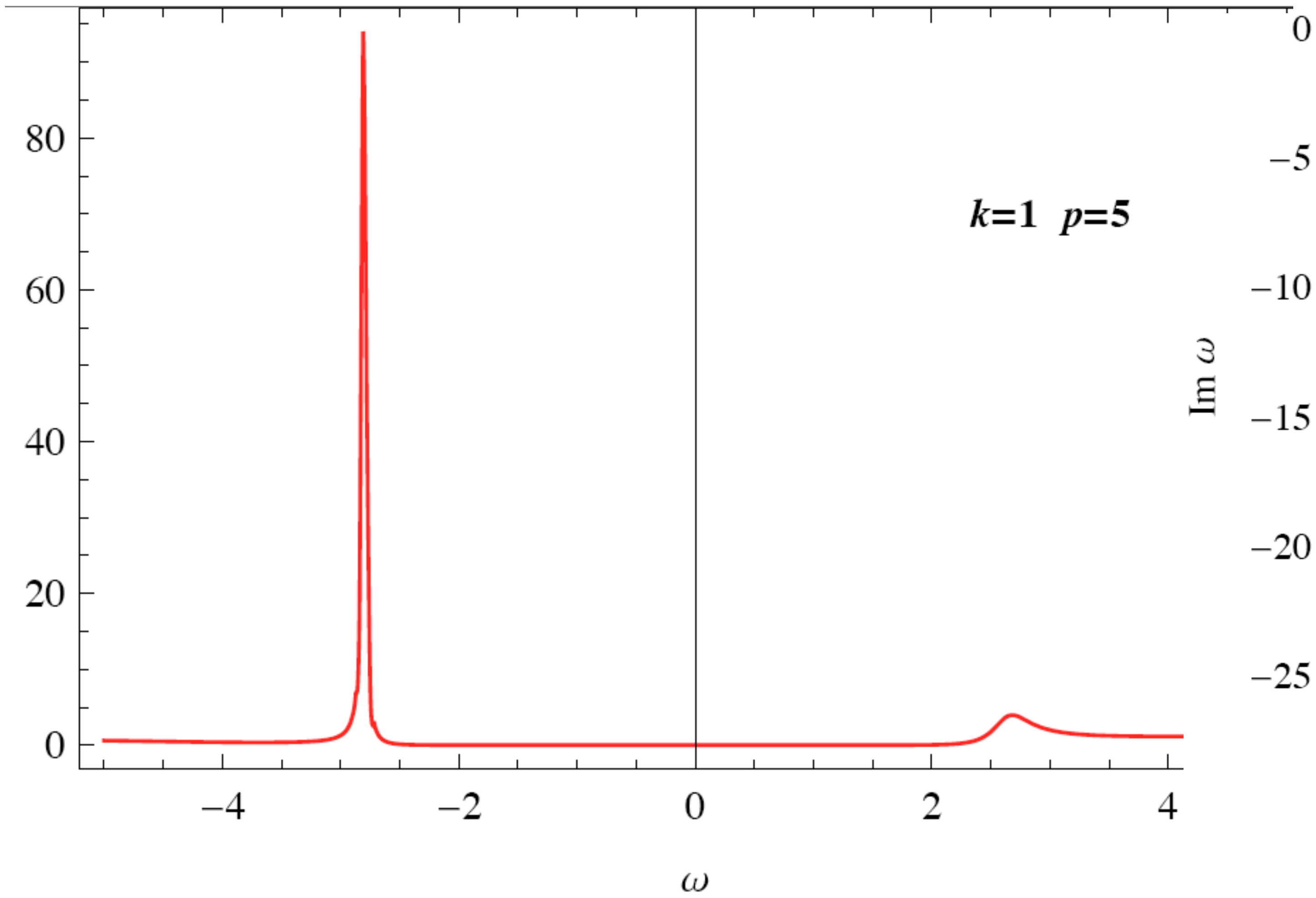
$$\frac{\Delta}{T_{\rm crit}} \approx 20$$

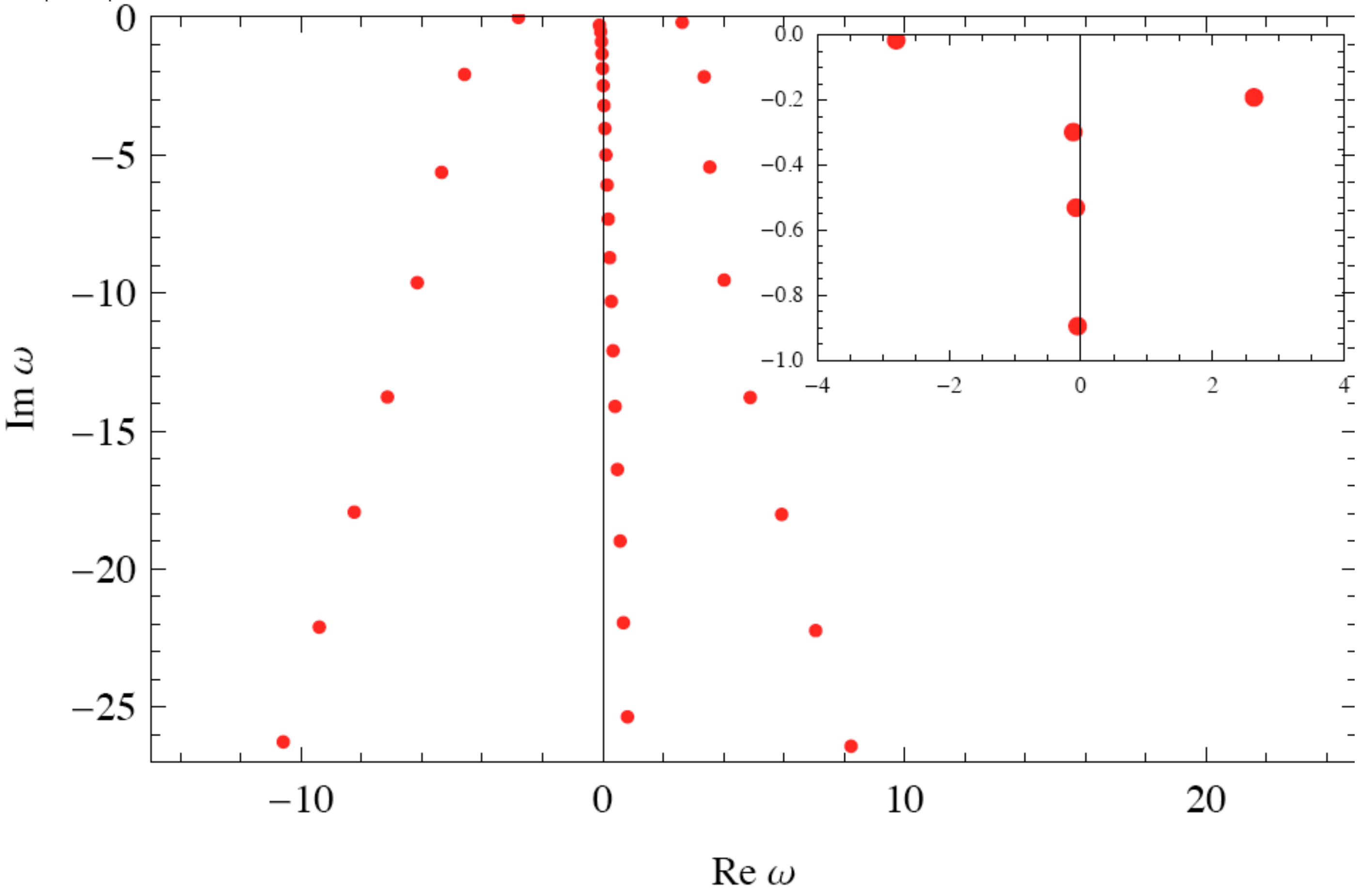
vanadium oxide

quasi-normal modes: where are the peaks?

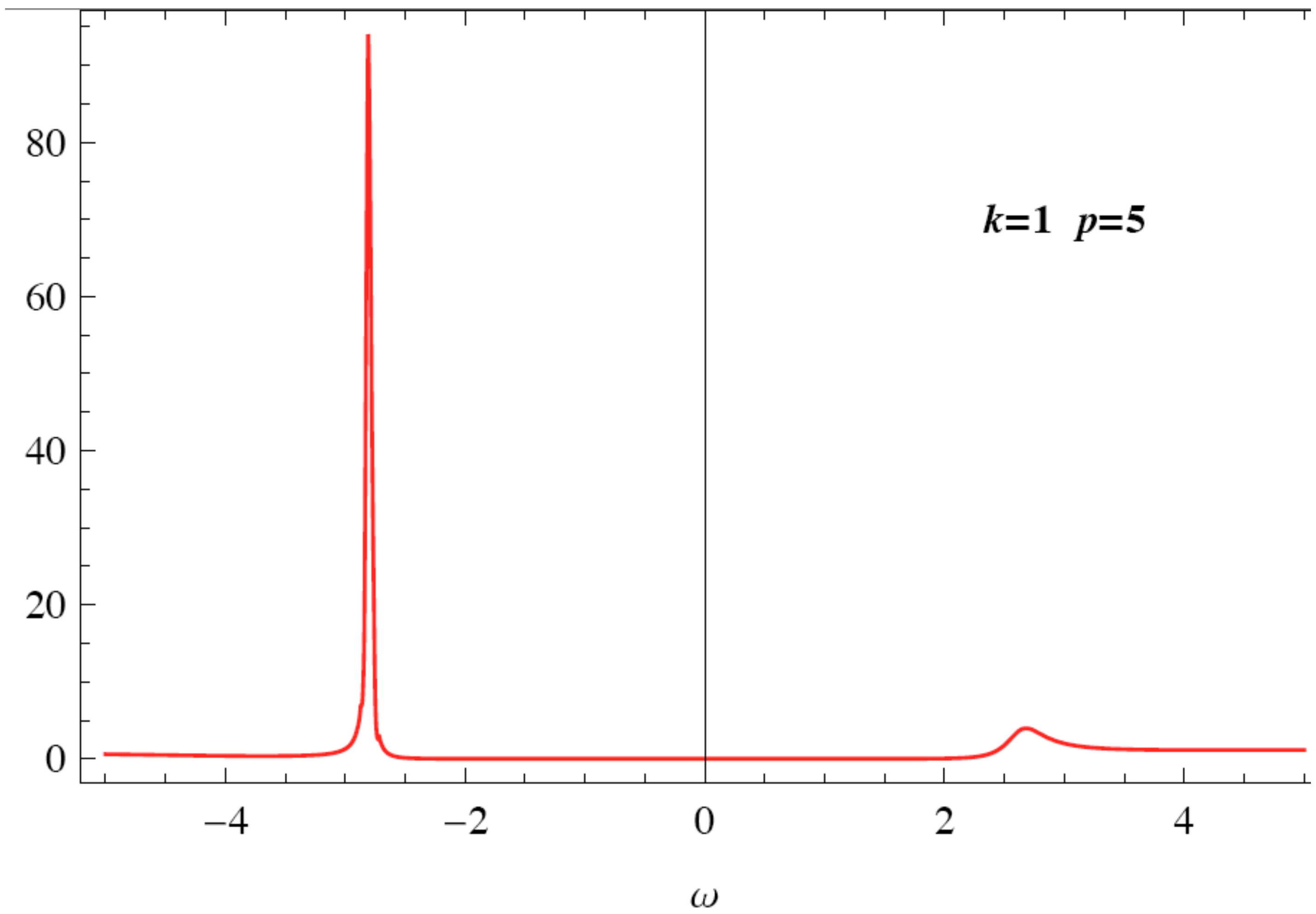


quasi-normal modes: where are the peaks?

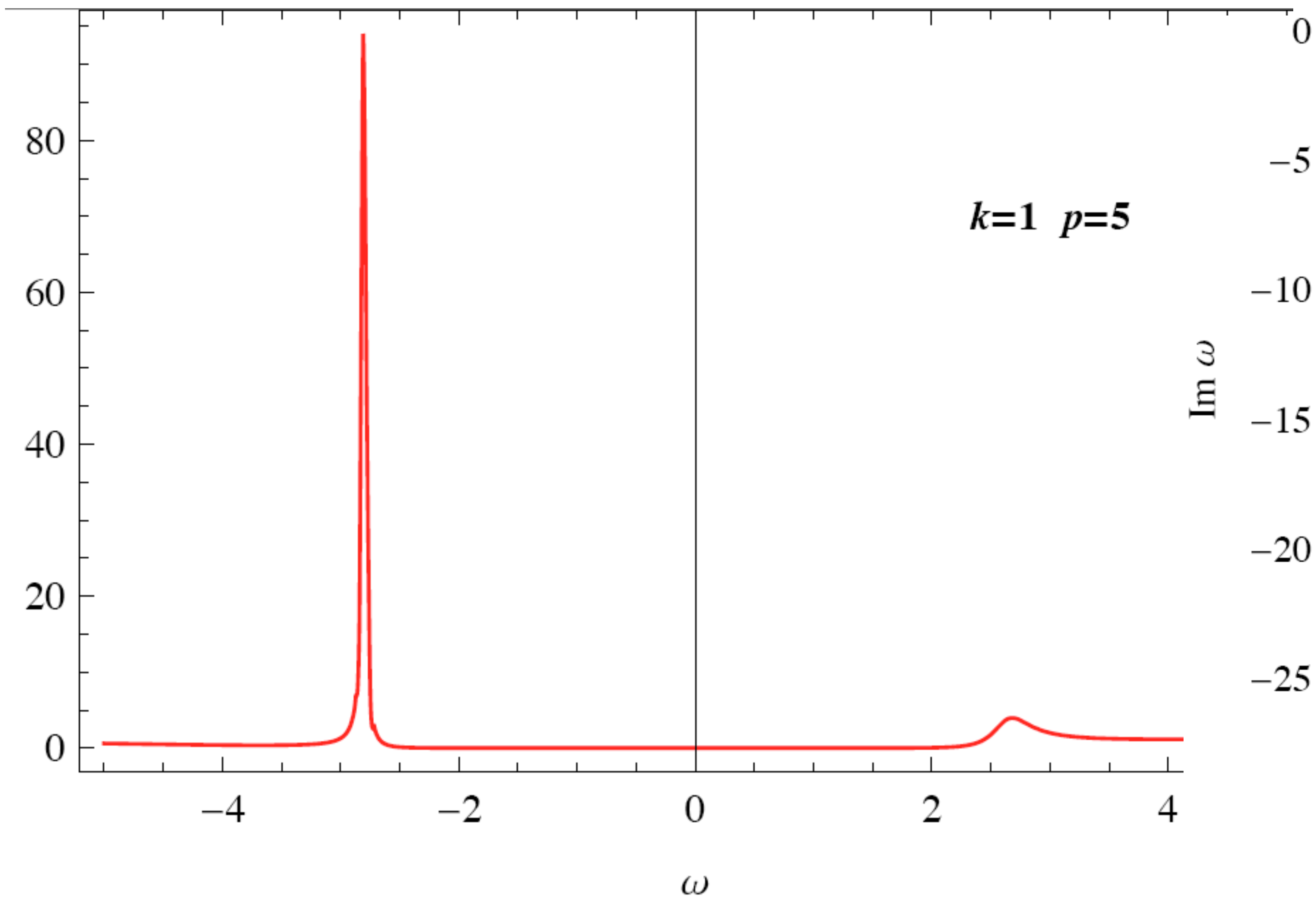


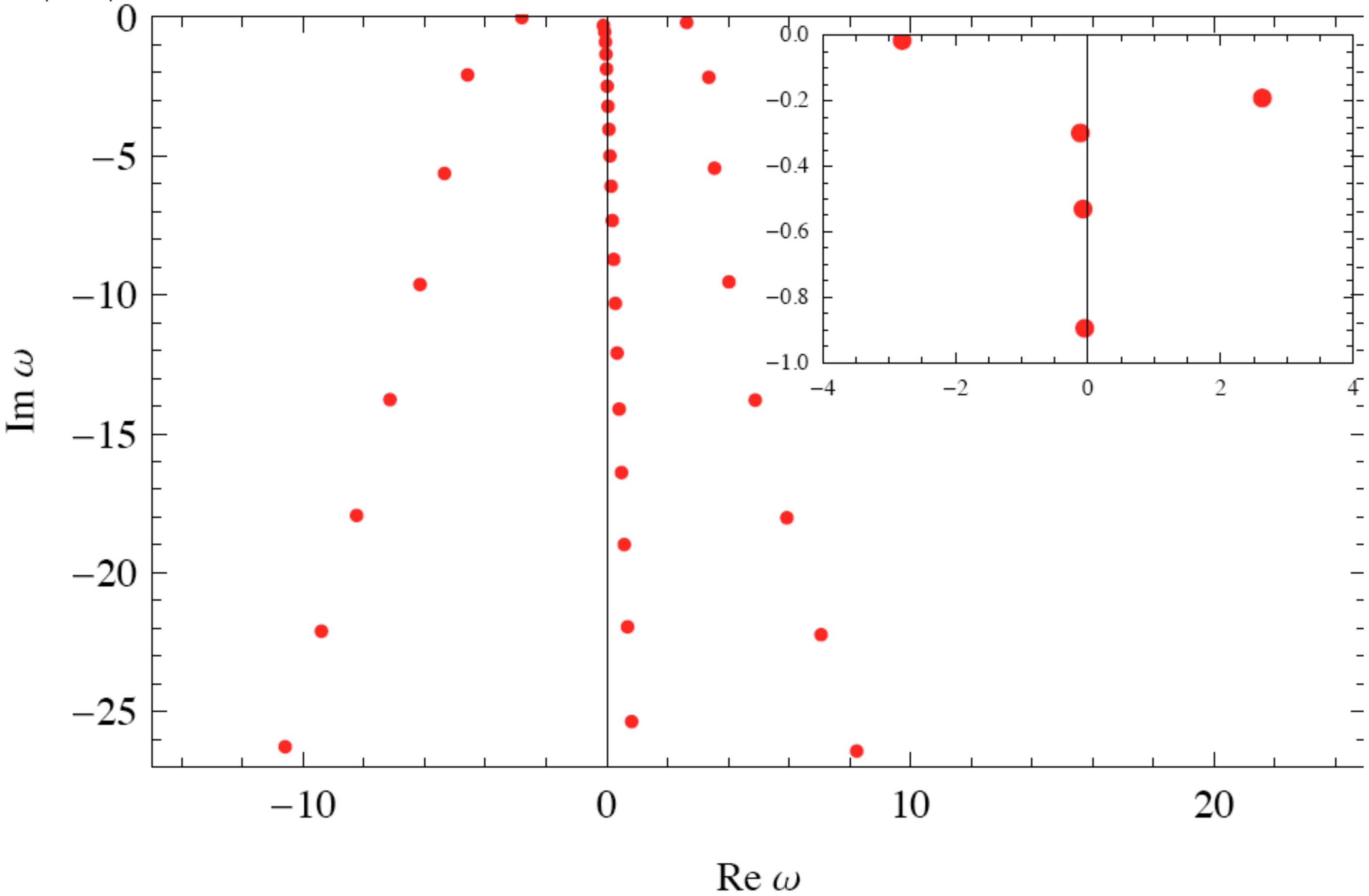


quasi-normal modes: where are the peaks?

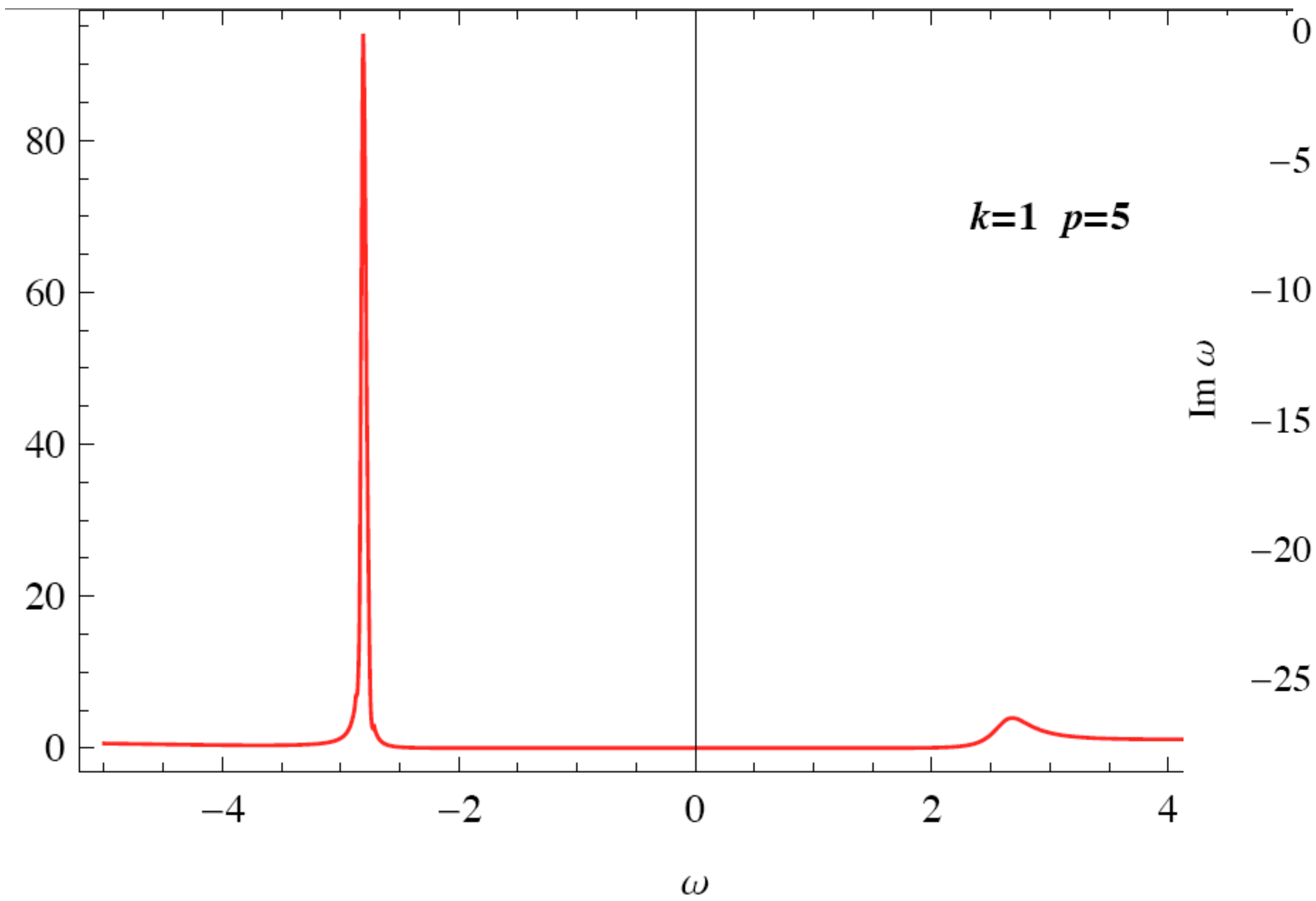


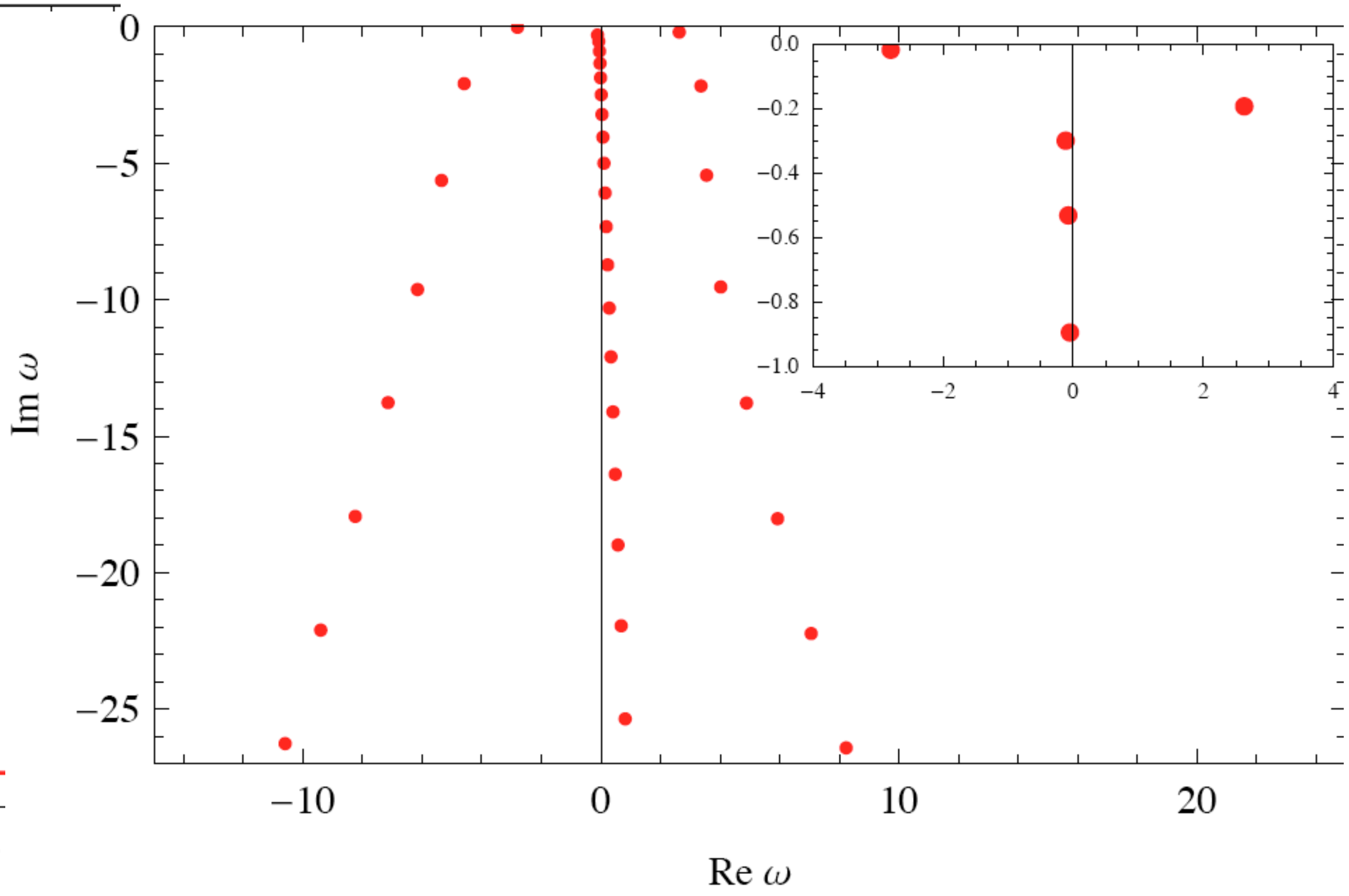
quasi-normal modes: where are the peaks?





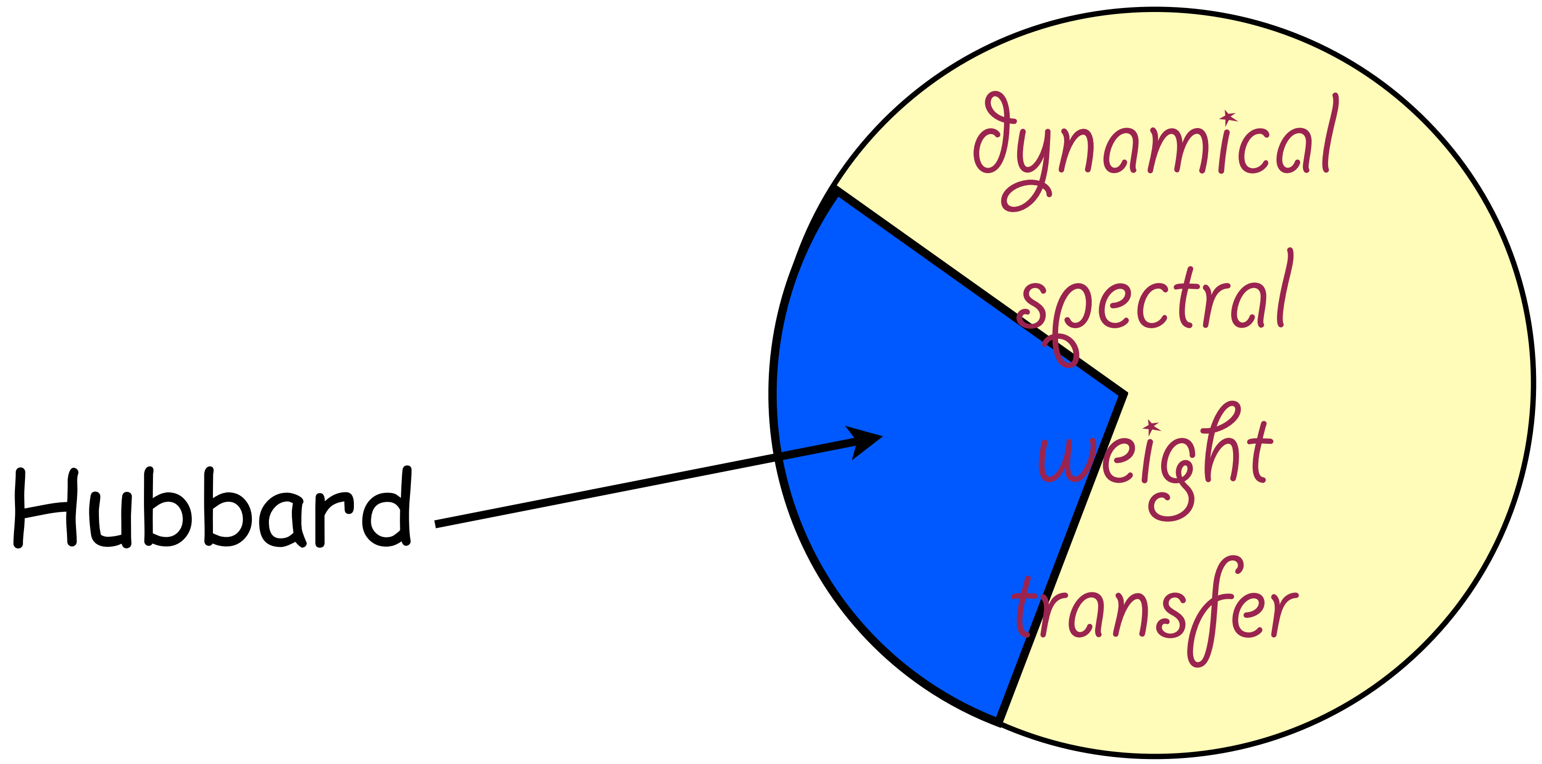
quasi-normal modes: where are the peaks?

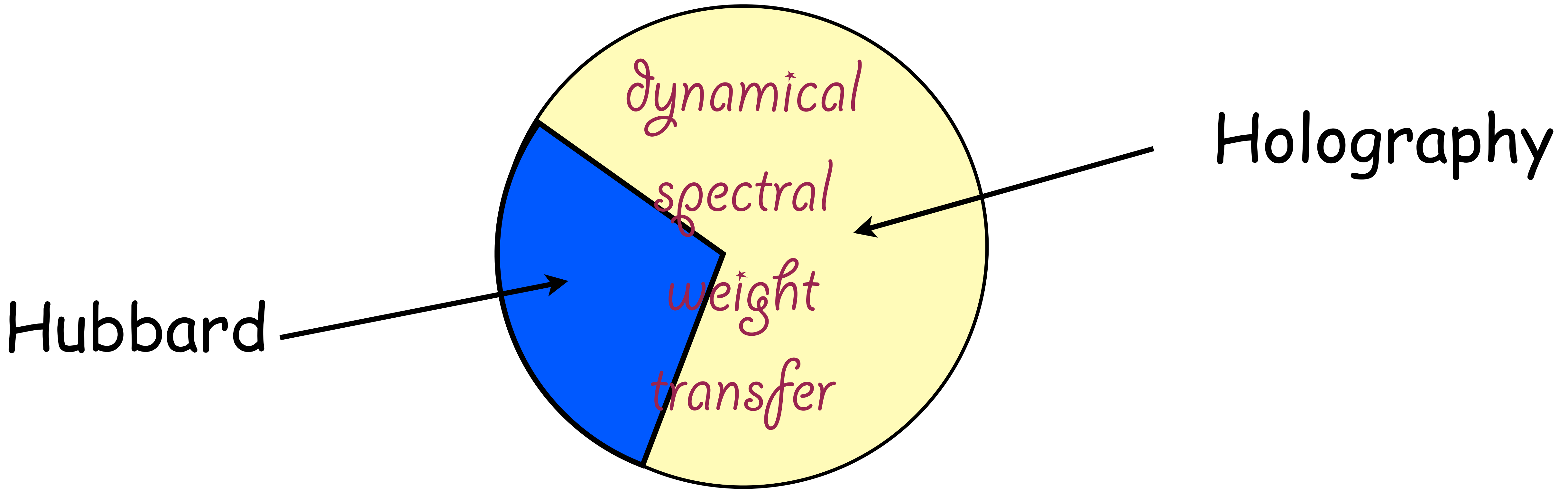




no leaking to +Im\omega: no instability

dynamical
spectral
weight
transfer


Hubbard
dynamical
spectral
weight
transfer


Holography
Hubbard
dynamical
spectral
weight
transfer

Mottness