Demystifying the Strange Metal in High-temperature Superconductors: Composite Excitations

Thanks to: T.-P. Choy, R. G. Leigh, S. Chakraborty, S. Hong
PRL, 99, 46404 (2007);
PRB, 77, 14512 (2008); ibid, 77, 104524 (2008));
ibid, 79,245120 (2009); ibid, 80, 132505 (2009)..., DMR/
NSF-ACIF

High temperature superconductor?

High temperature superconductor?

Unusually
Good Metal

Matthias Rules for Superconductivity

Matthias Rules for Superconductivity

Matthias, Bernd T.

Matthias Rules for Superconductivity

1.) cubic structures

2.) avoid oxygen

3.) avoid magnetism

4.) avoid insulators

Matthias, Bernd T.

Matthias Rules for Superconductivity

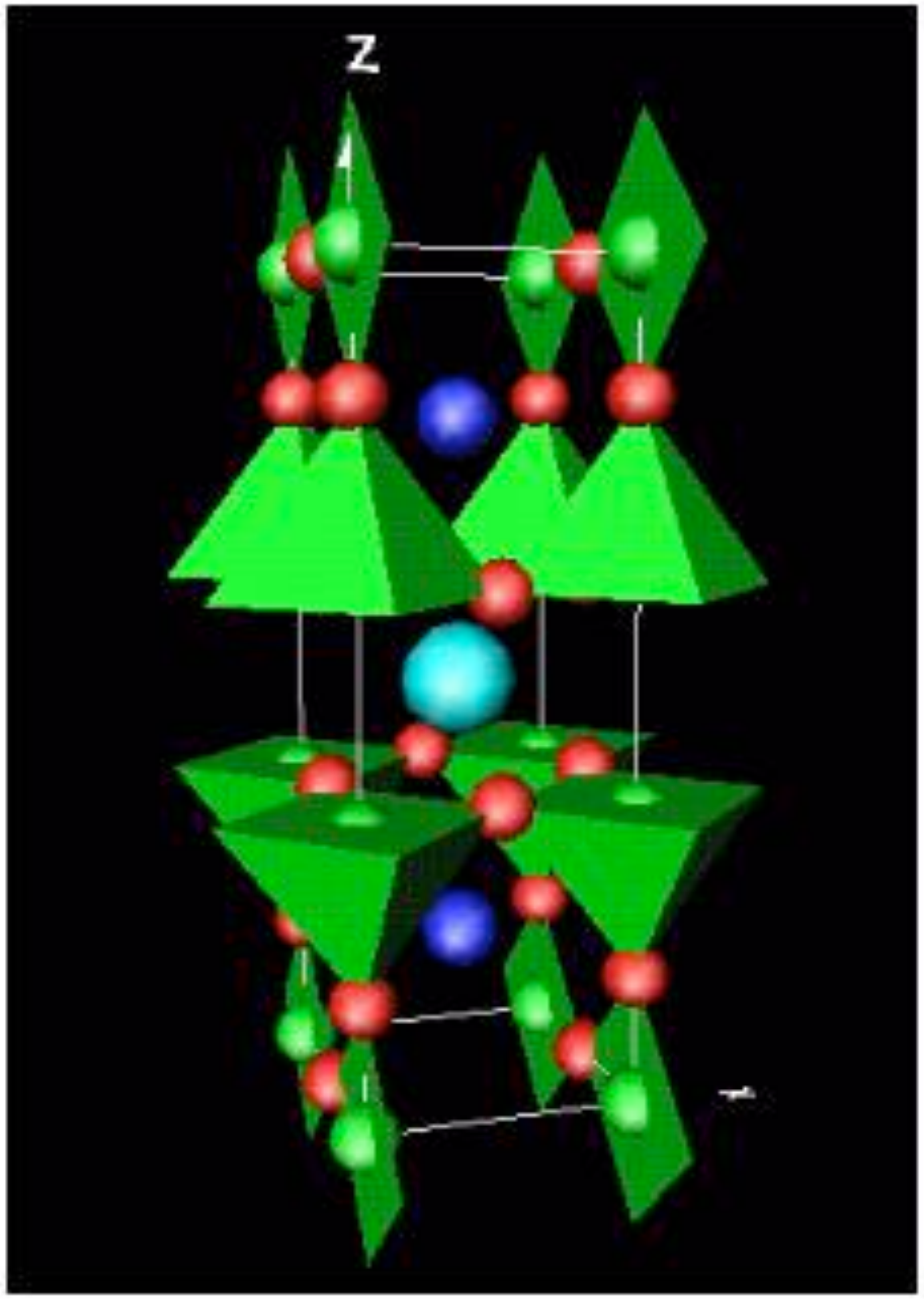
1.) cubic structures

2.) avoid oxygen

3.) avoid magnetism

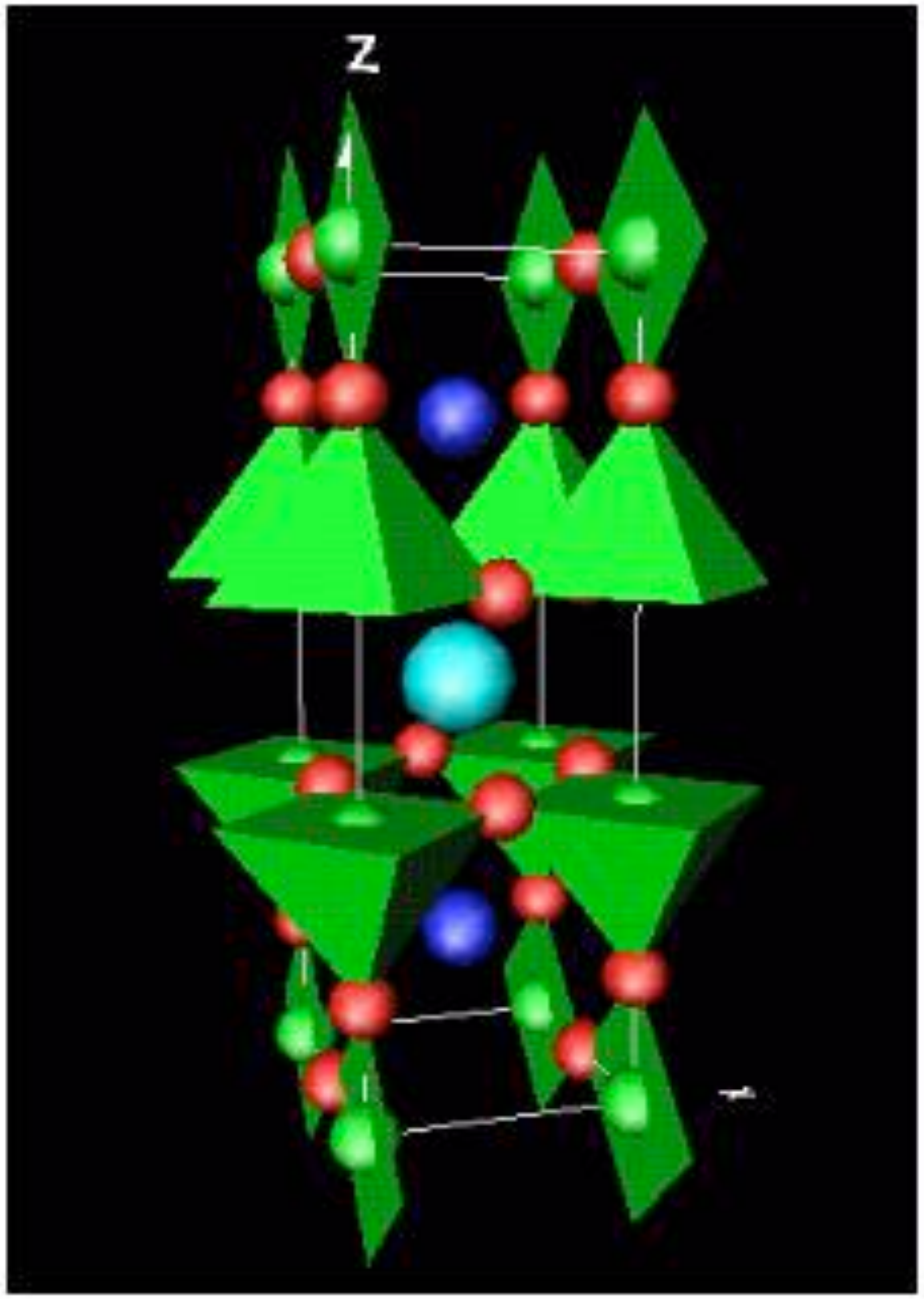
4.) avoid insulators

5.) don't talk to theorists!!



$Y Ba_2Cu_3O_7$

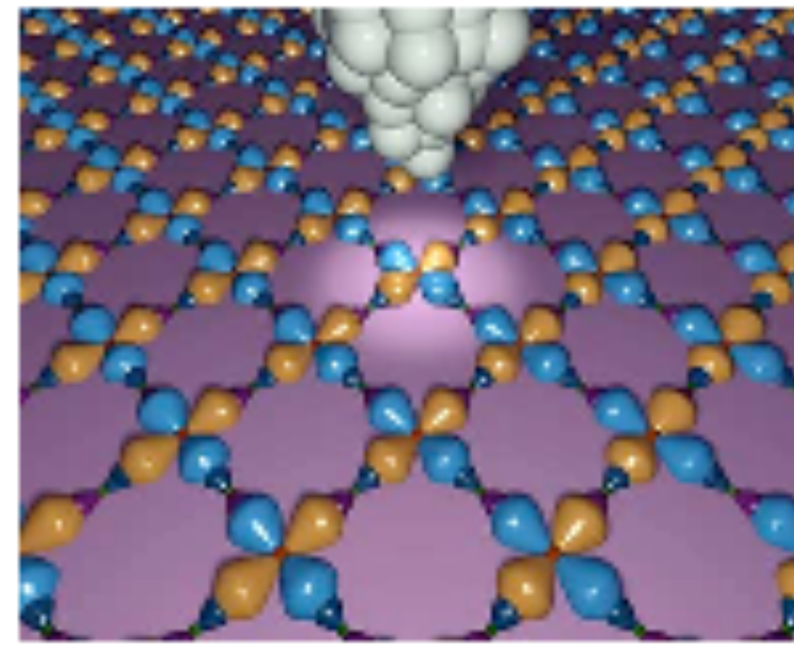
Cuprate Superconductors

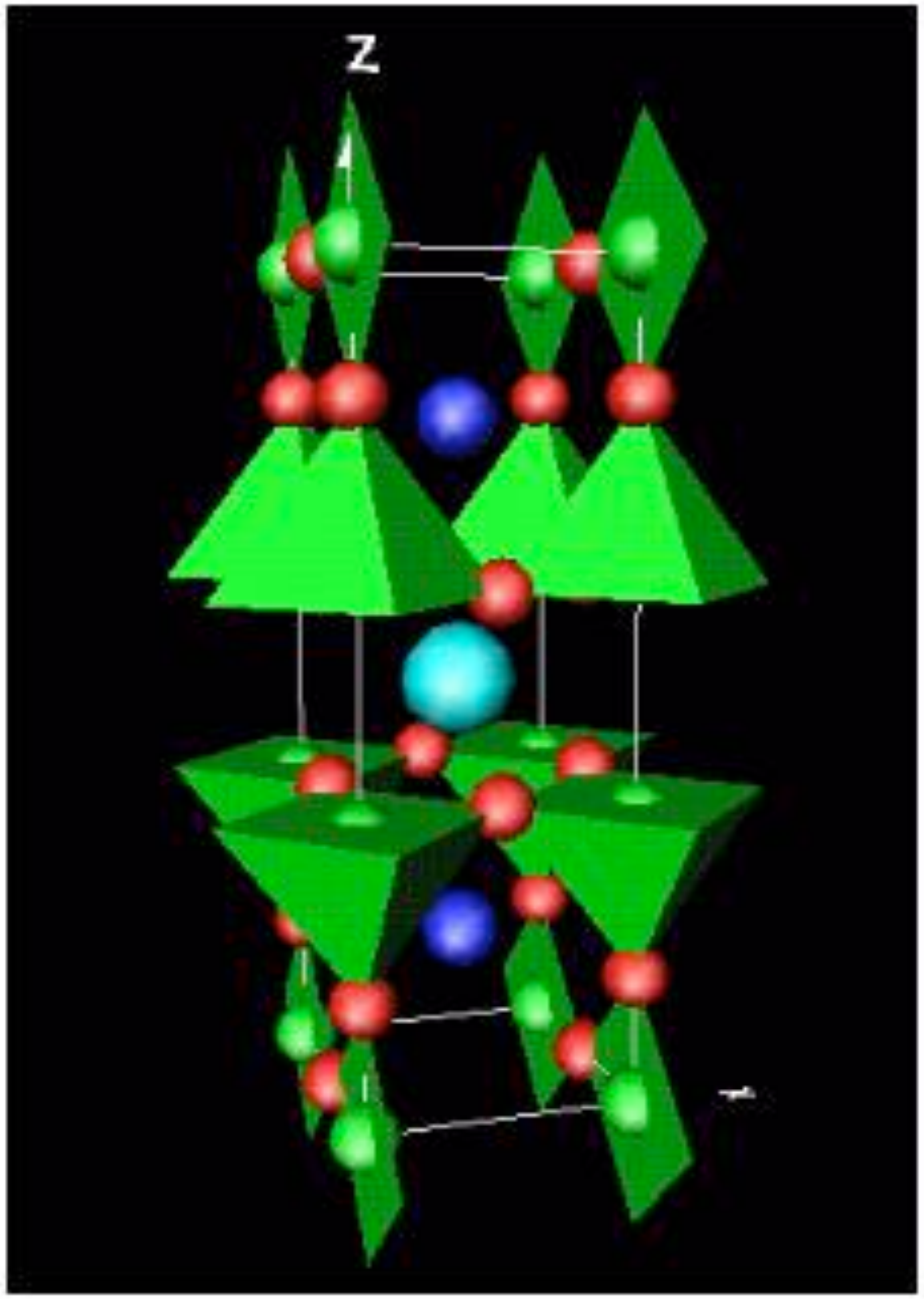


$YBa_2Cu_3O_7$

Cuprate Superconductors

Cu-O plane





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Cuprate Superconductors

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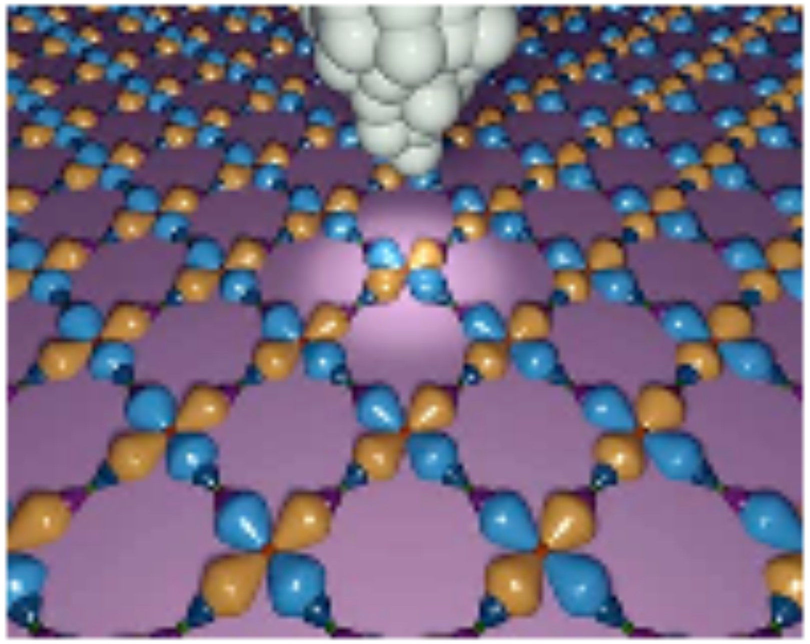
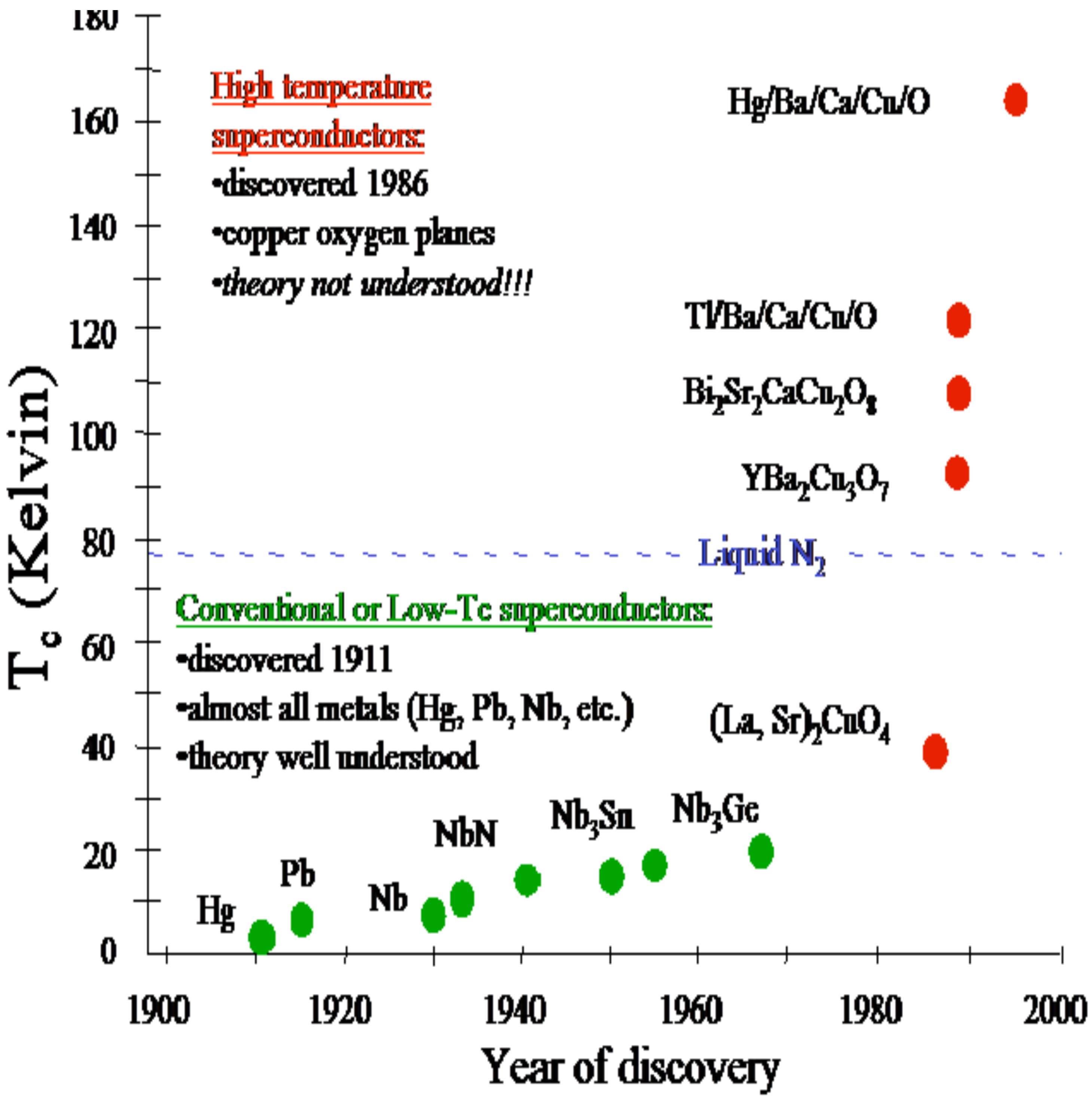


Orthorhombic: asymmetric in xy (a-b) plane



180
160
140
120
100
80
60
40
20
0
Tc (Kelvin)
High temperature superconductors:
•discovered 1986
•copper oxygen planes
•theory not understood!!!
Hg/Ba/Ca/Cu/O
Tl/Ba/Ca/Cu/O
$Bi_2Sr_2CaCu_2O_8$
$YBa_2Cu_3O_7$
Liquid N_2
Conventional or Low-Tc superconductors:
•discovered 1911
•almost all metals (Hg, Pb, Nb, etc.)
•theory well understood
$(La, Sr)_2CuO_4$
Hg
Pb
Nb
NbN
Nb_3Sn
Nb_3Ge
1900
1920
1940
1960
1980
2000
Year of discovery

What is left of Matthias' Rules?

1.) cubic structures

2.) avoid oxygen

3.) avoid magnetism

4.) avoid insulators

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What is left of Matthias' Rules?

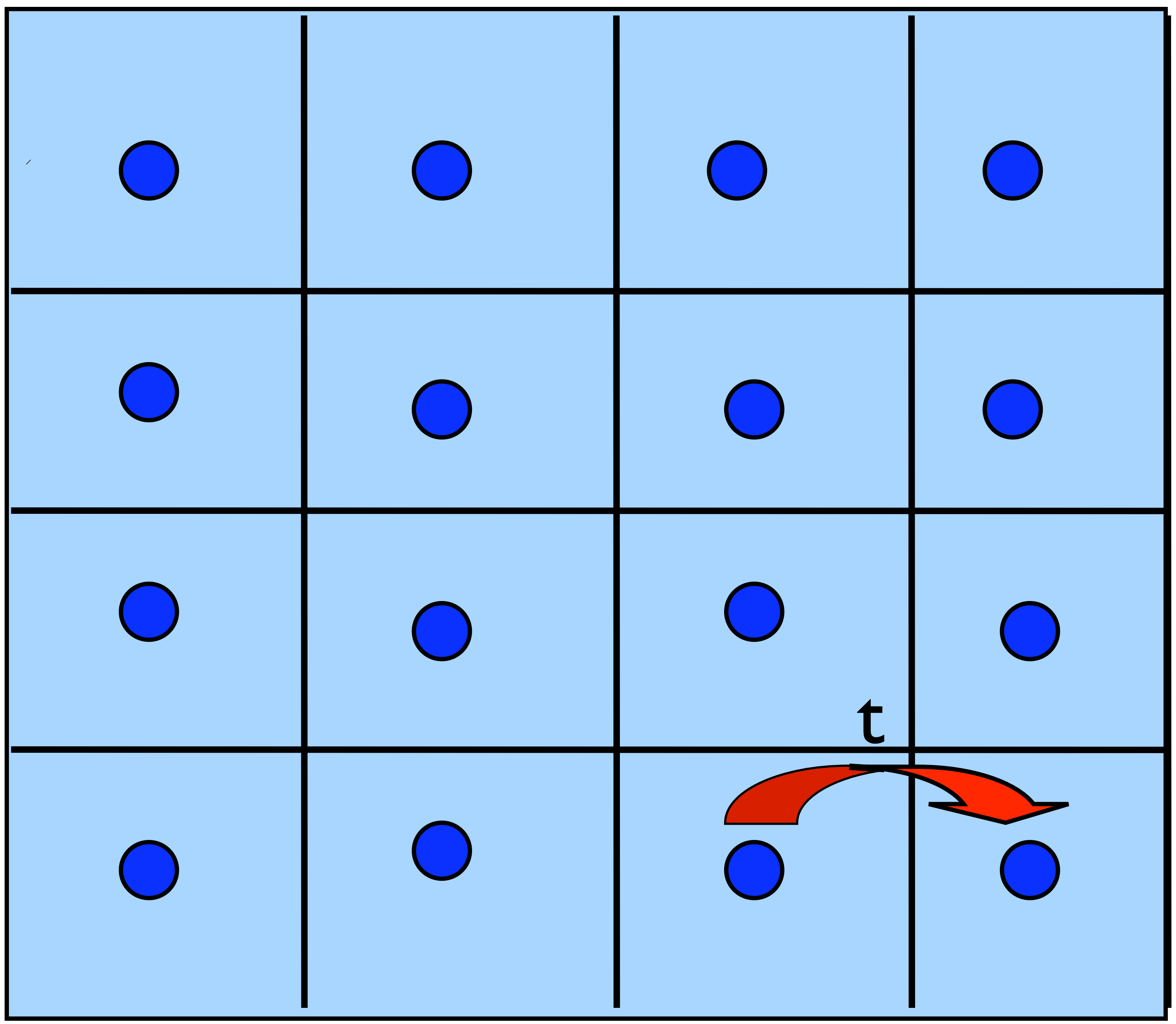
New Problem: Mottness

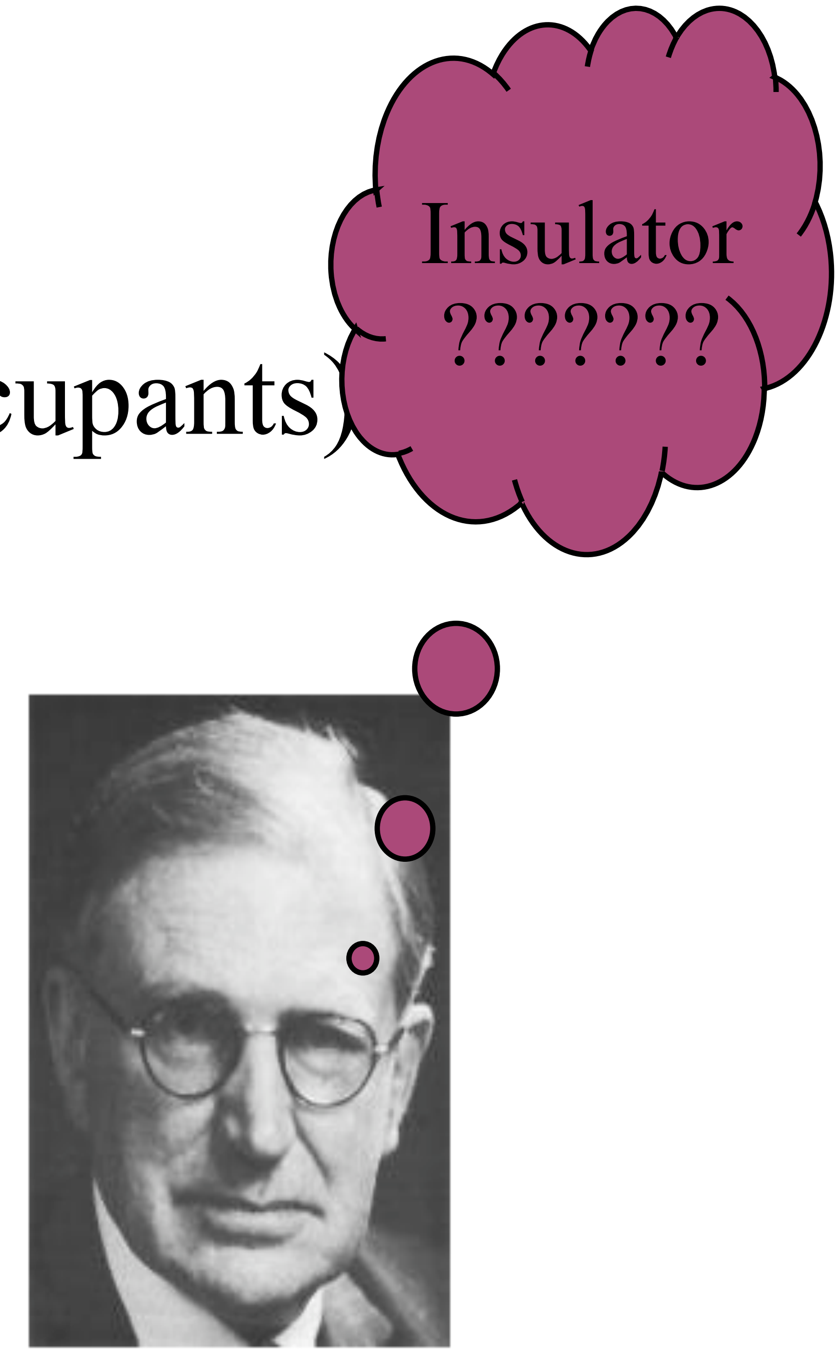
Sir Neville Mott
Nobel Prize, 1977

Mott
Insulators

Mott Problem: NiO (Band theory failure)

Loomis floor plan (N rooms N occupants)





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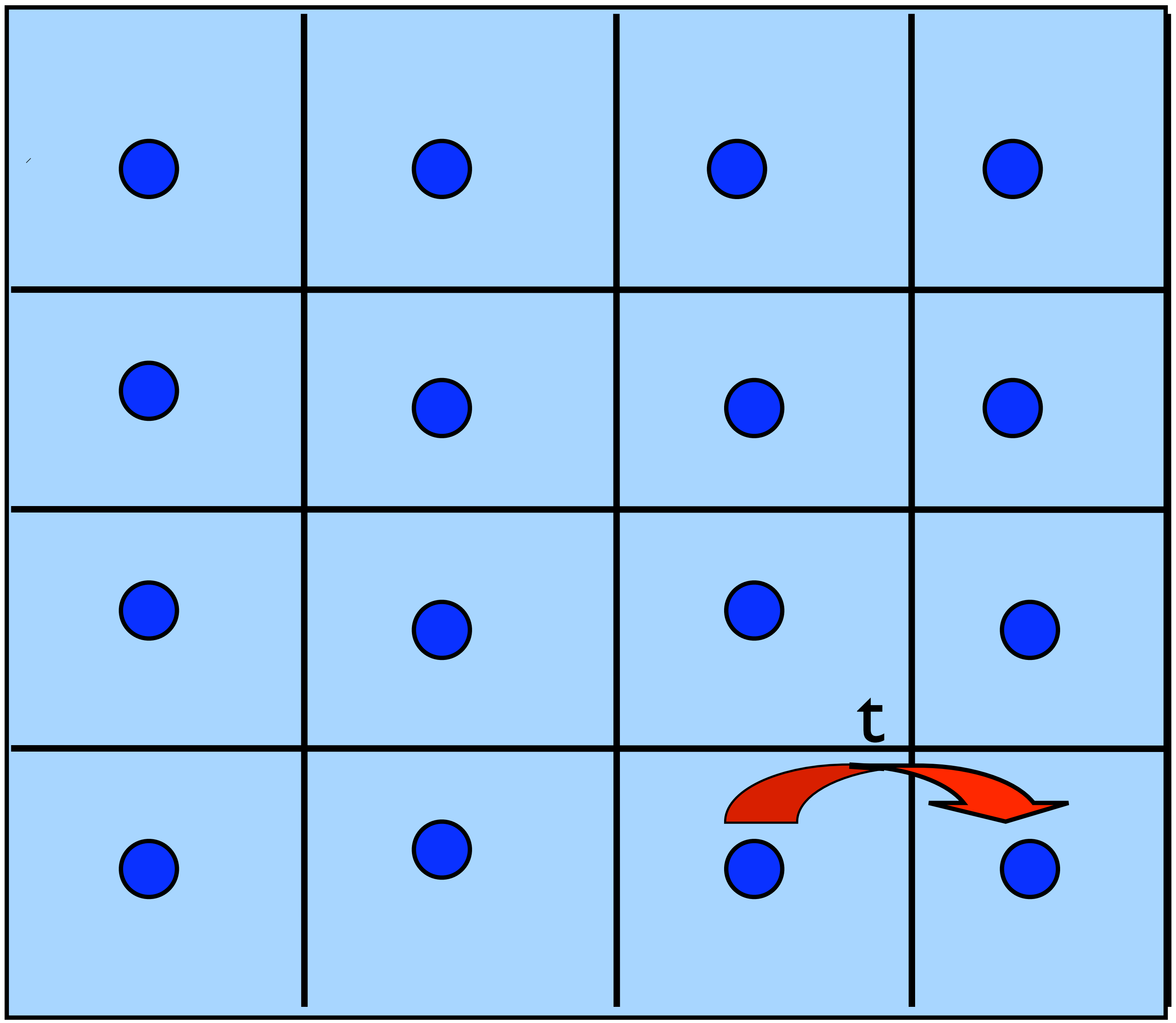
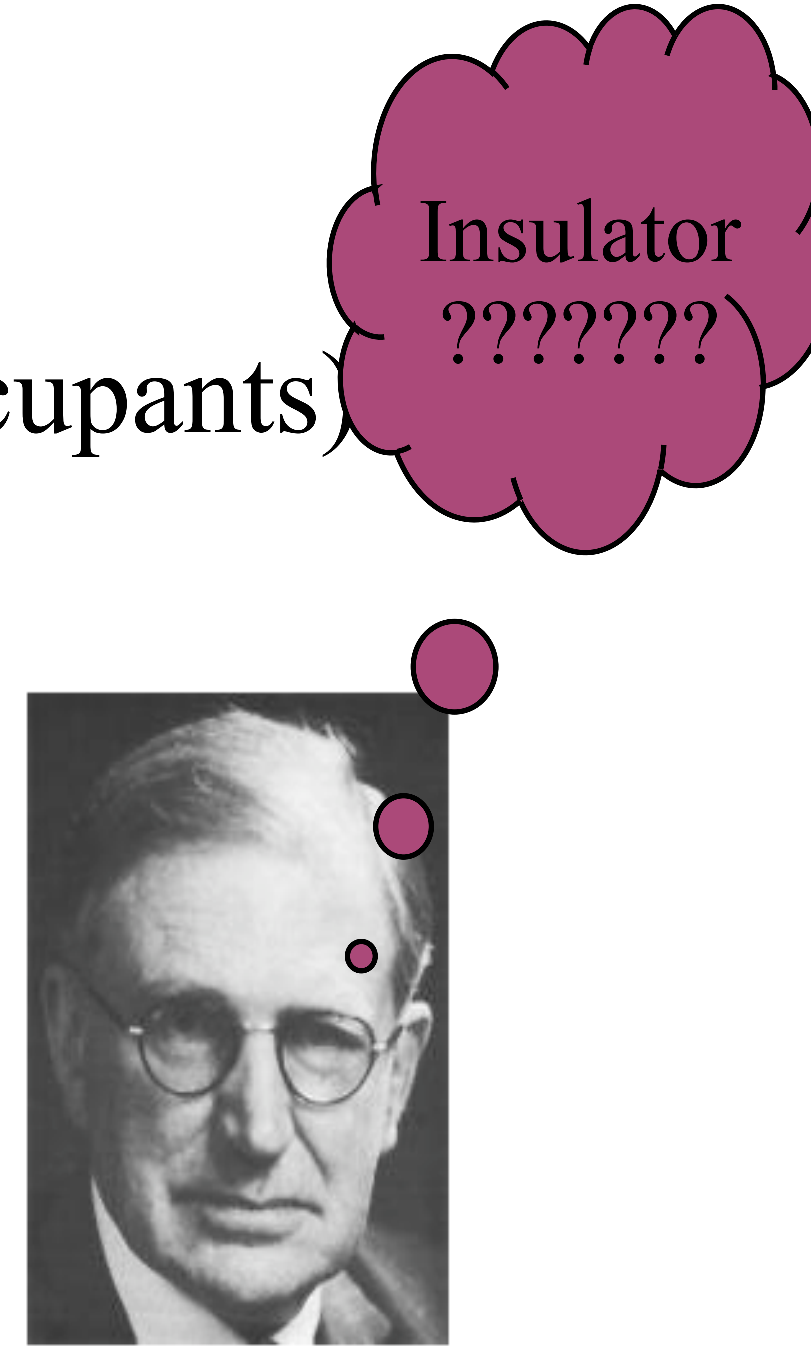
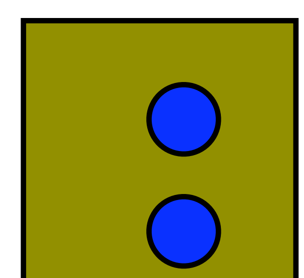






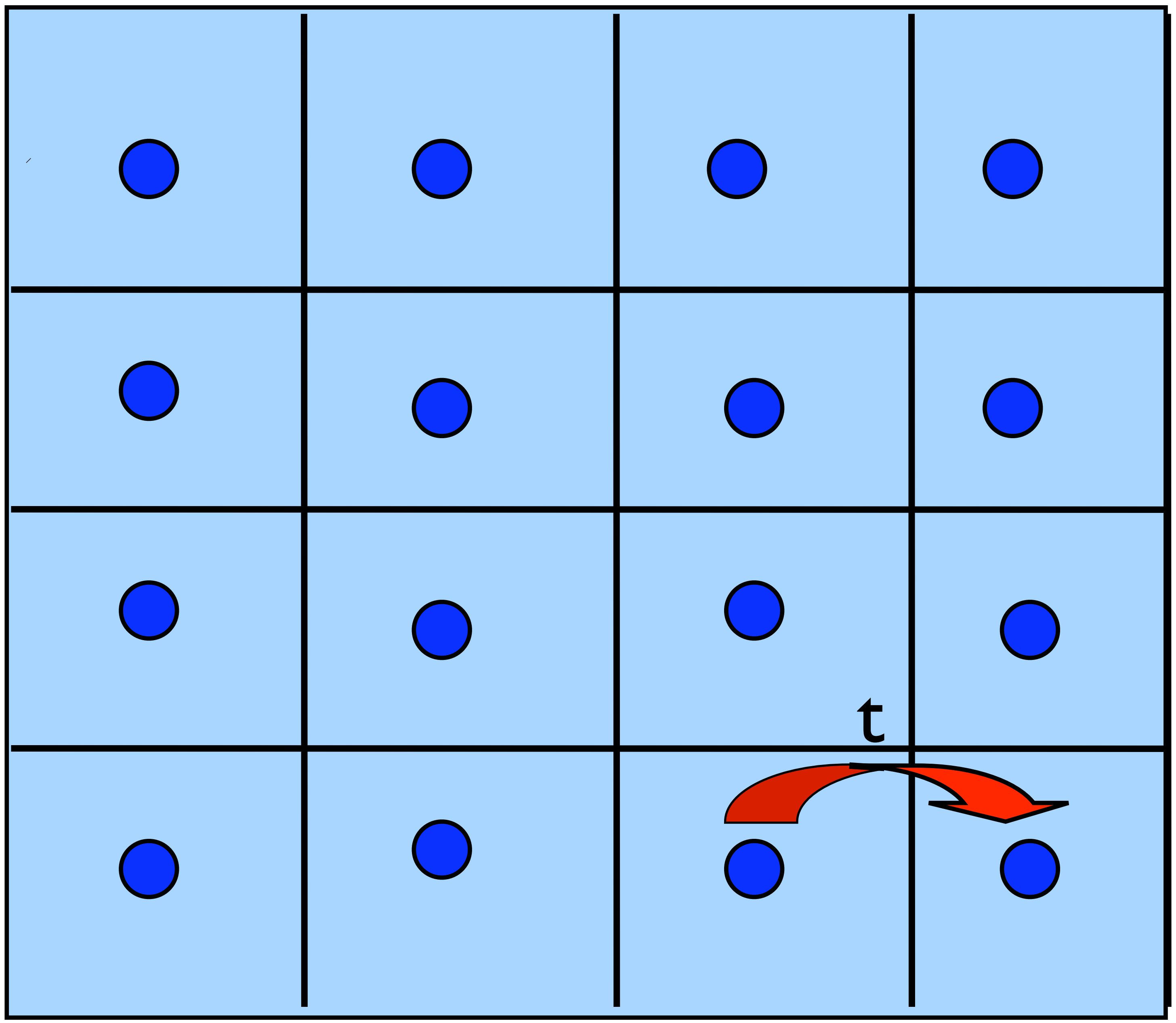
$\Delta E = U \gg K.E.$

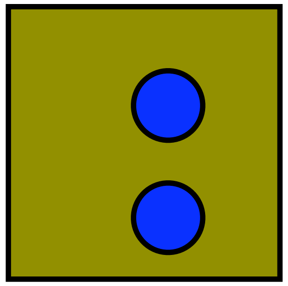
Mott Problem: NiO (Band theory failure)

Cuprates:
$U=4eV$
$t=.5eV$

Insulator ???????

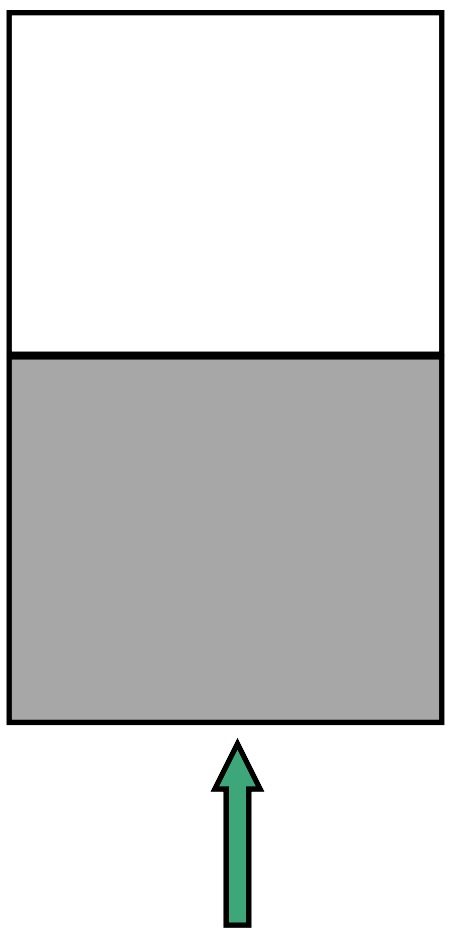
Loomis floor plan (N rooms N occupants)





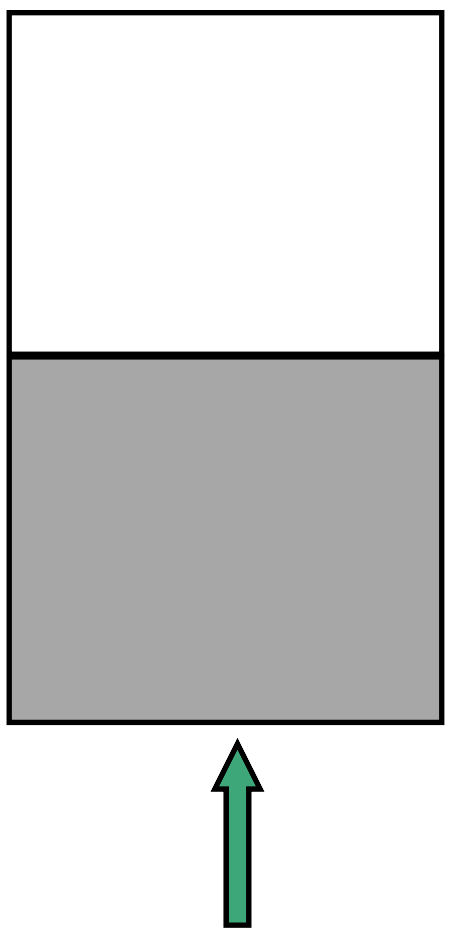
$\Delta E = U \gg K.E.$

Half-filled band



Free electrons

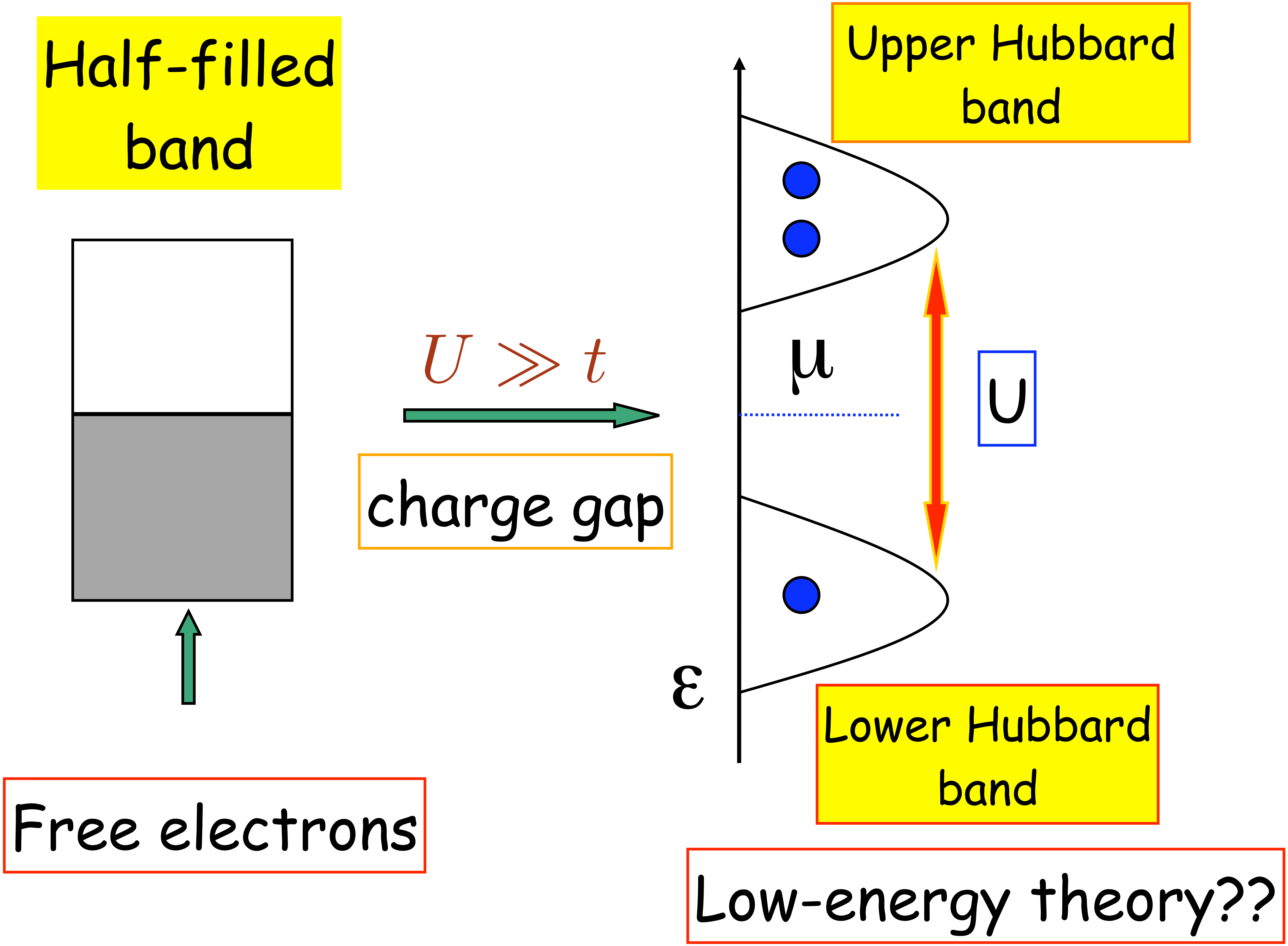
Half-filled band



$U \gg t$

charge gap

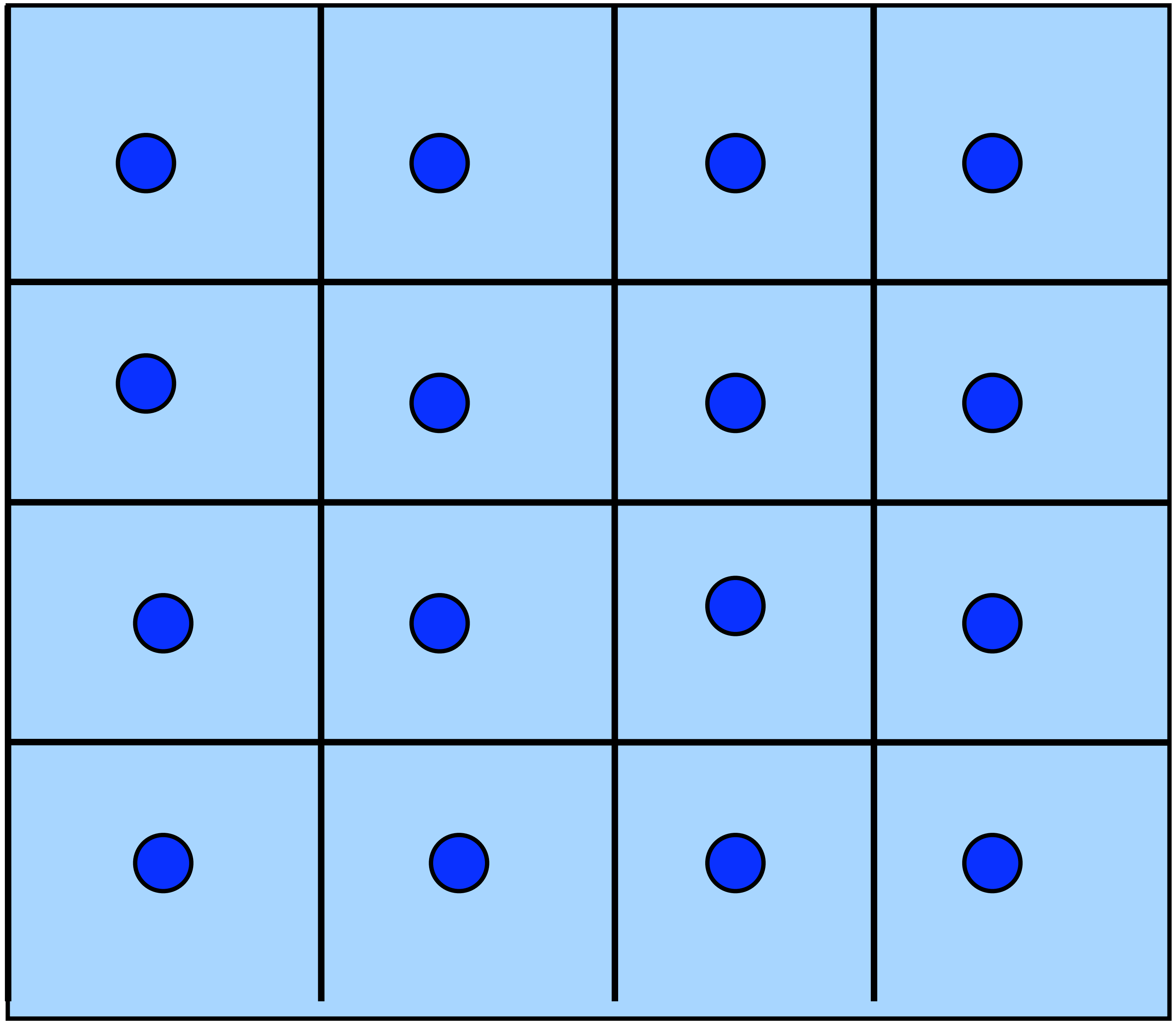
Free electrons



Half-filled band
$U \gg t$
charge gap
Upper Hubbard band
μ
U
ε
Lower Hubbard band
Free electrons
Low-energy theory??

Doping a Mott insulator

x= fraction of empty rooms (holes)



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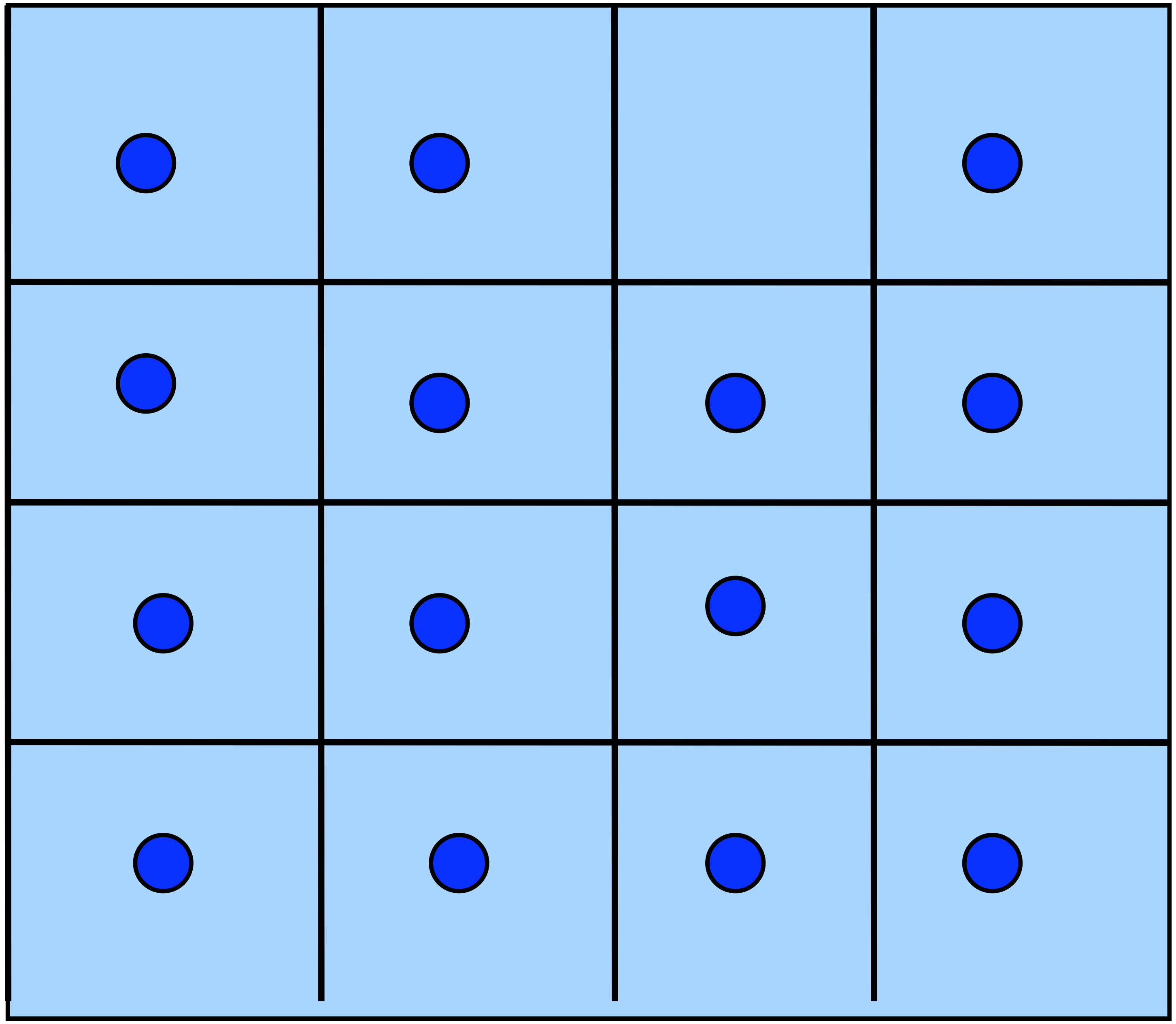
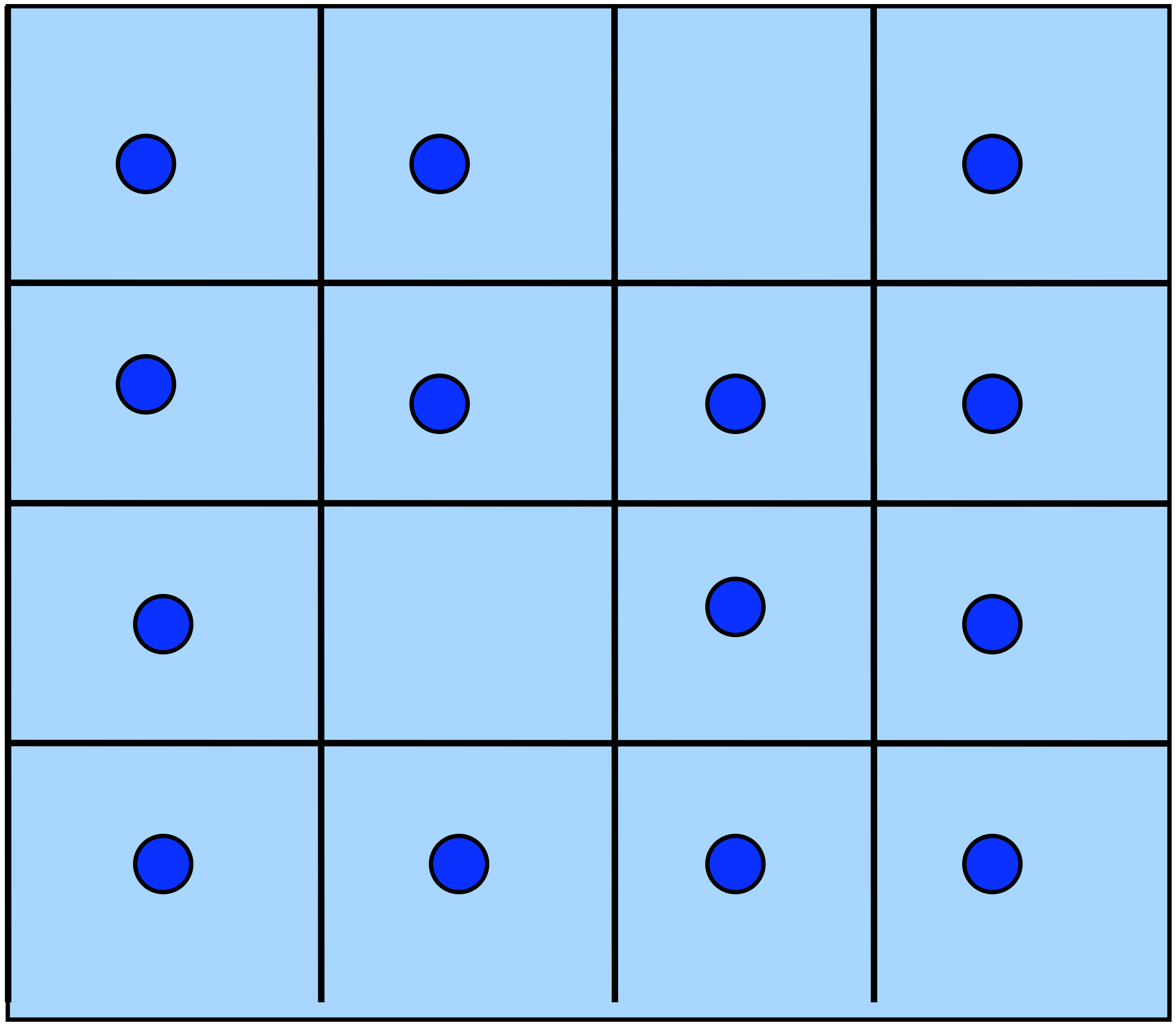


Doping a Mott insulator

x= fraction of empty rooms (holes)



Doping a Mott insulator

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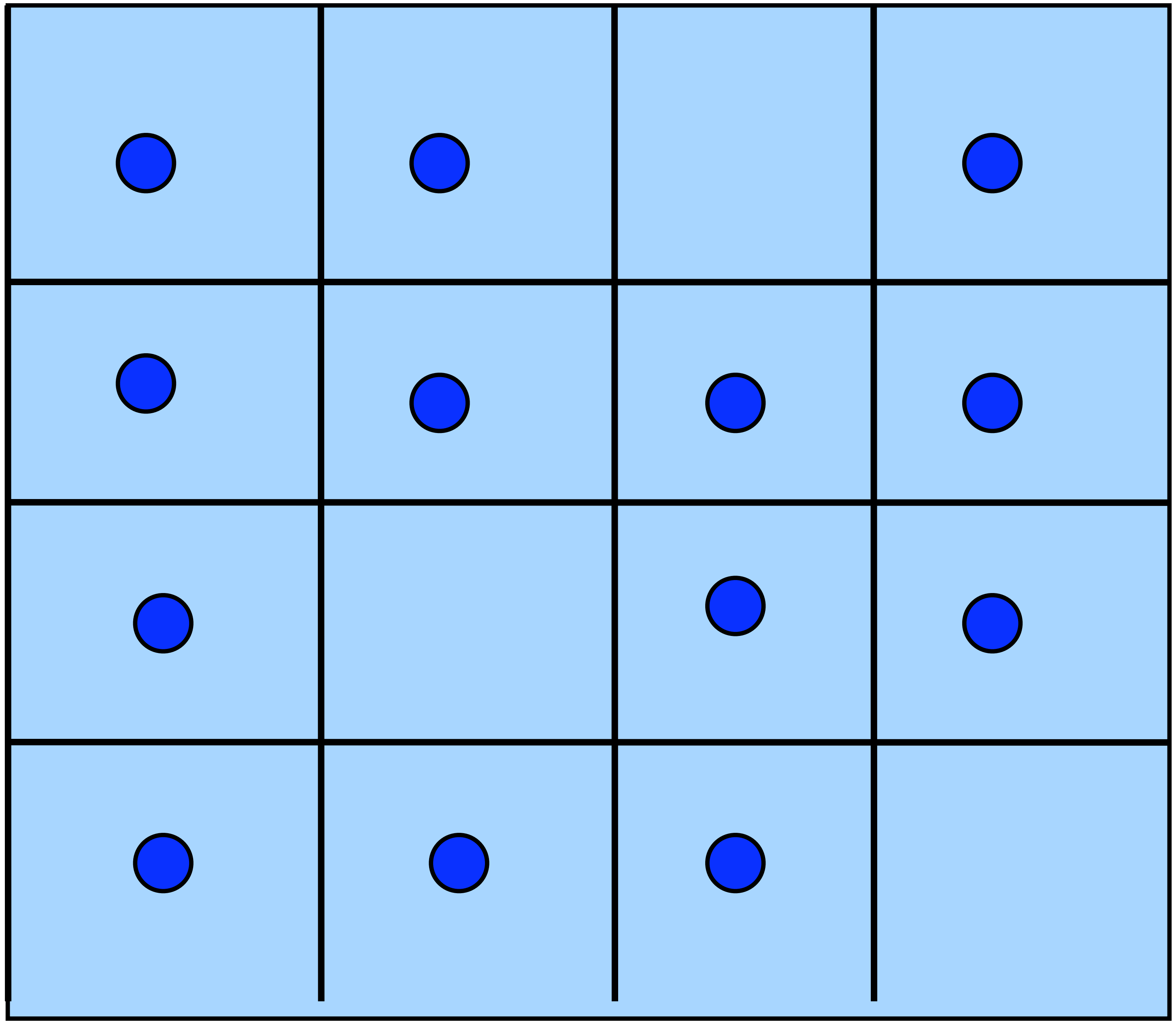
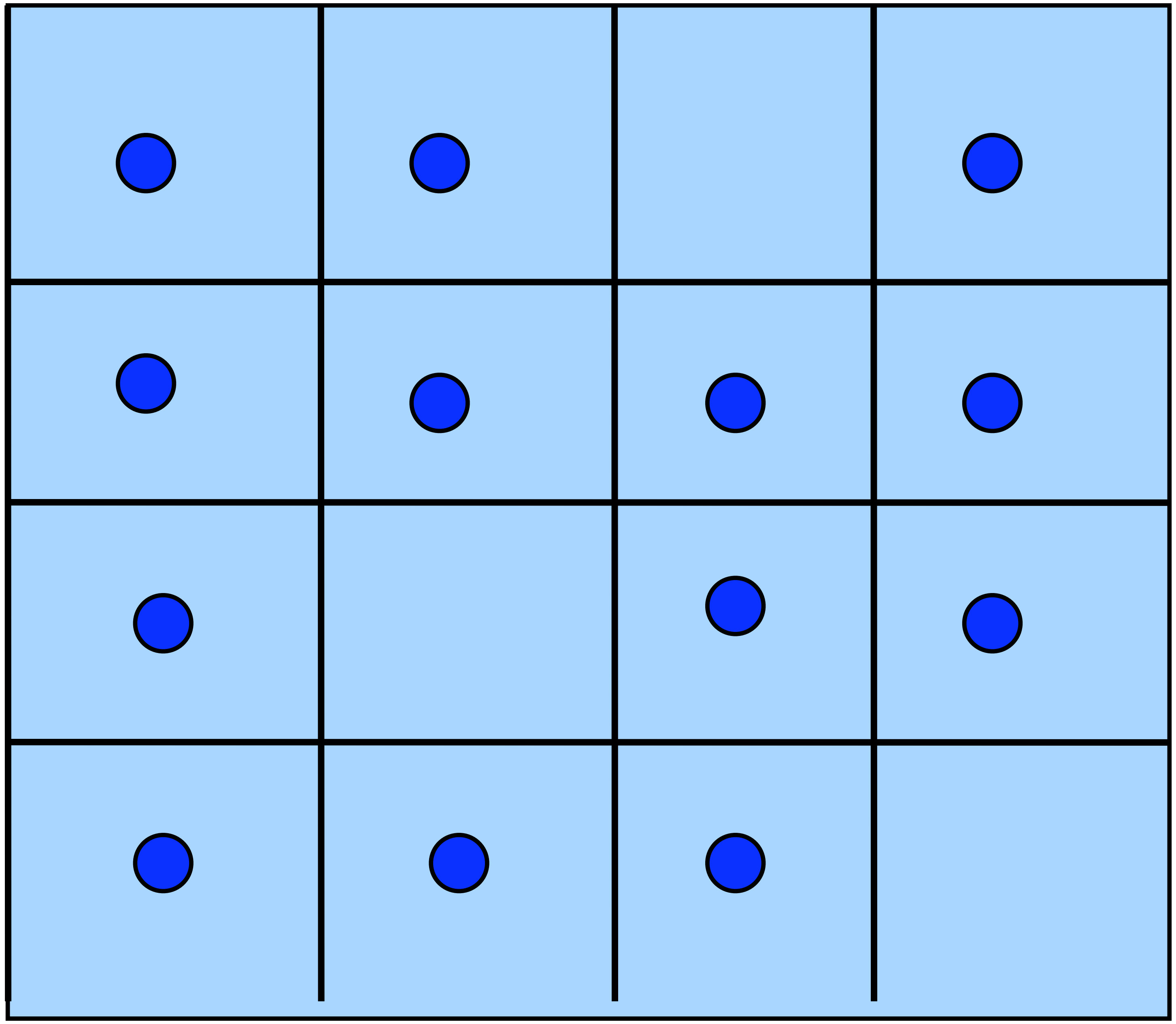
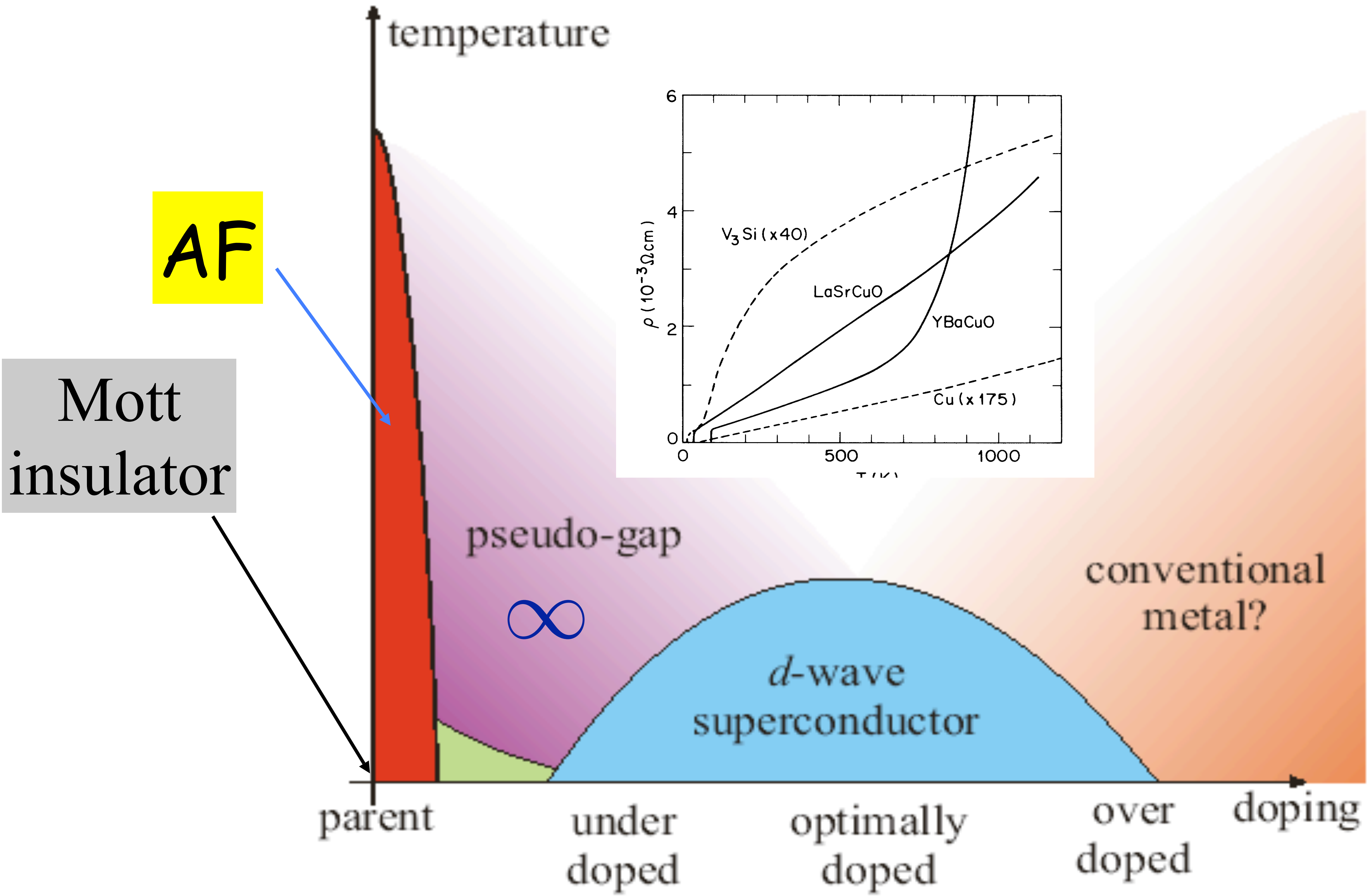


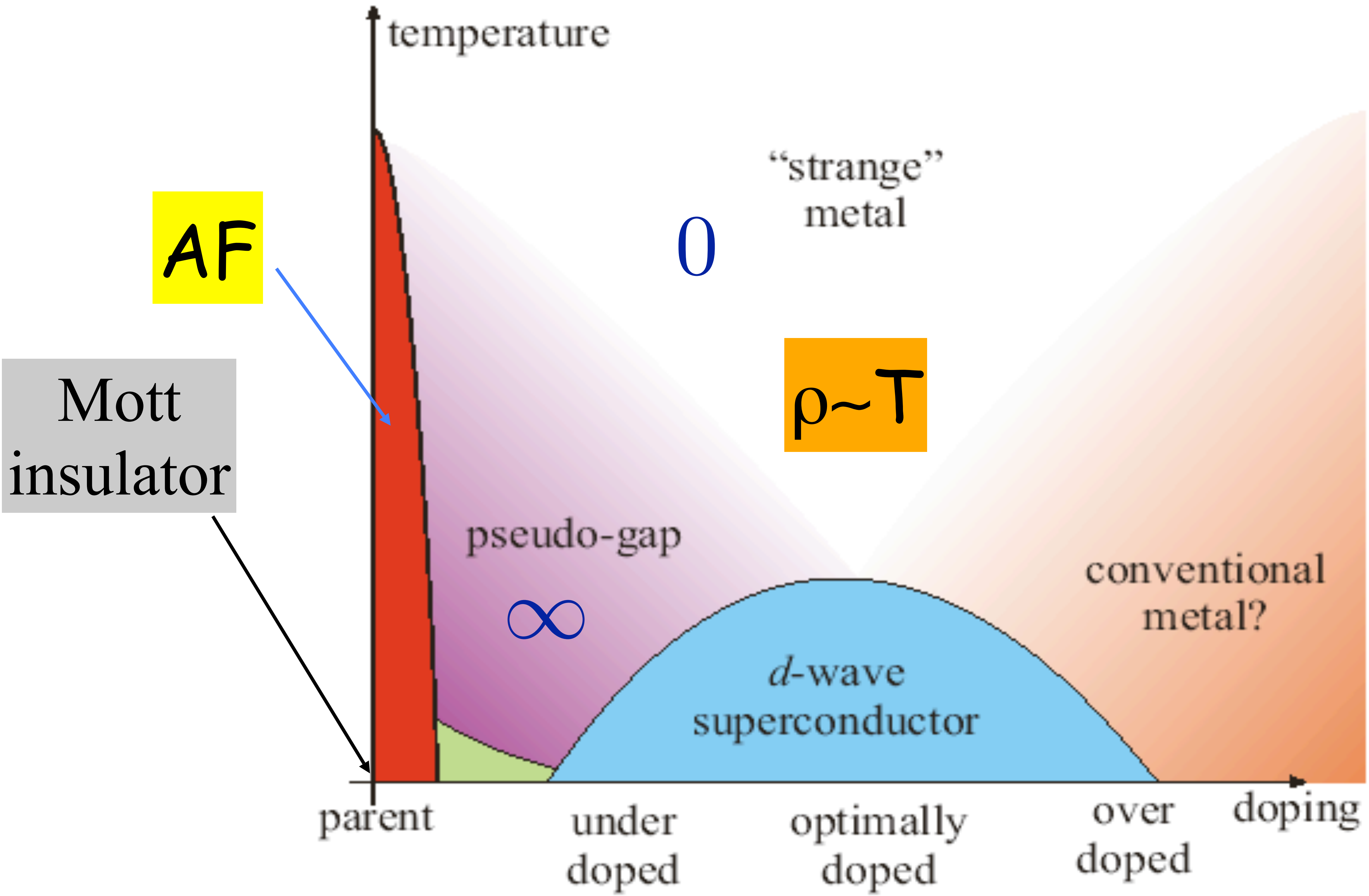
Doping a Mott insulator

x= fraction of empty rooms (holes)

X=3/16



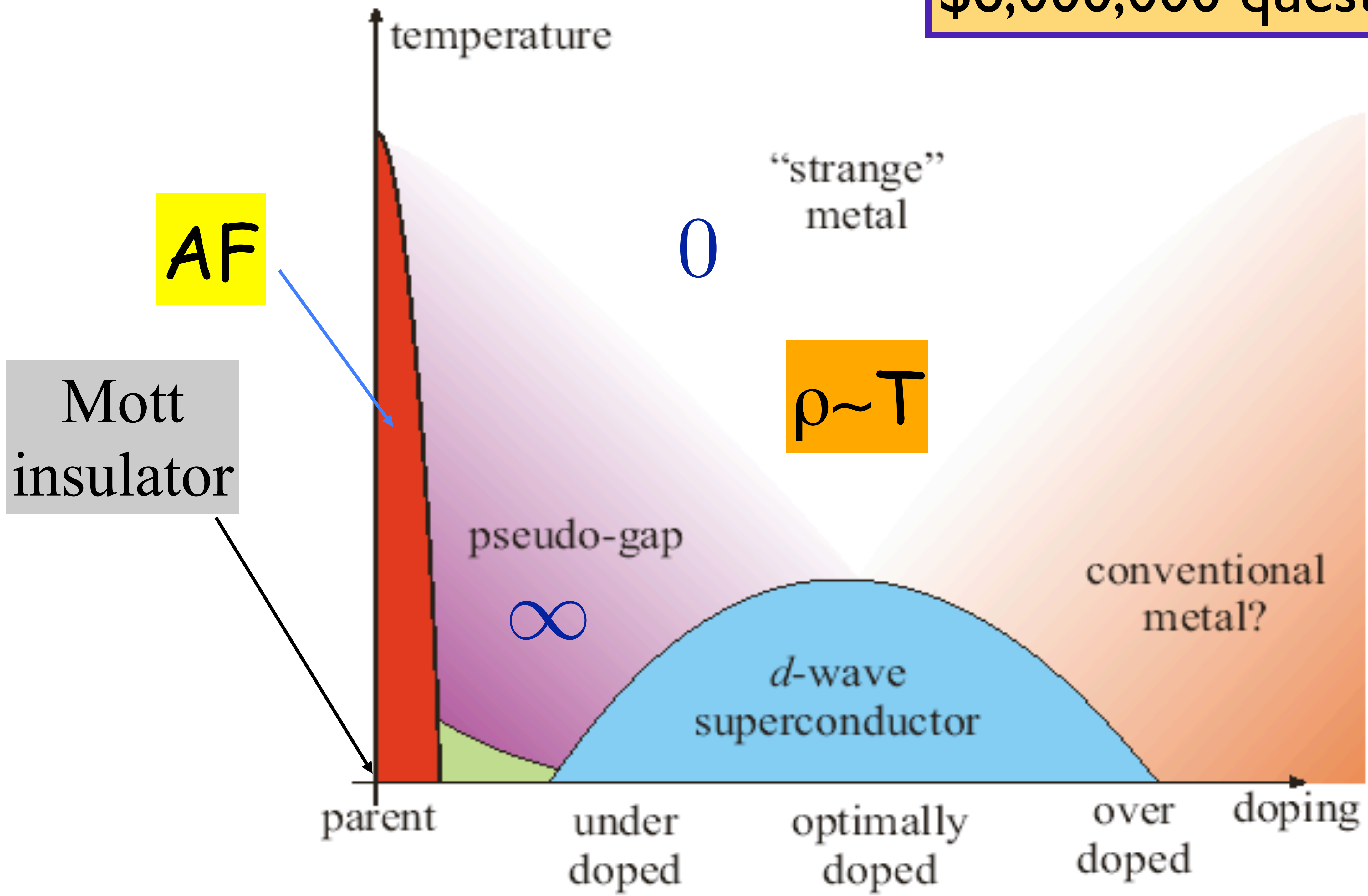

temperature
AF
Mott insulator
pseudo-gap
∞
d-wave superconductor
conventional metal?
parent
under doped
optimally doped
over doped
doping
6
4
2
0
ρ (10⁻³Ωcm)
V3 Si (x40)
LaSrCuO
YBaCuO
Cu (x175)
0
500
1000



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

How does Fermi Liquid Theory Breakdown?

$6,000,000 question?



T-linear Resistivity?

Metals: $\rho \approx T^2$

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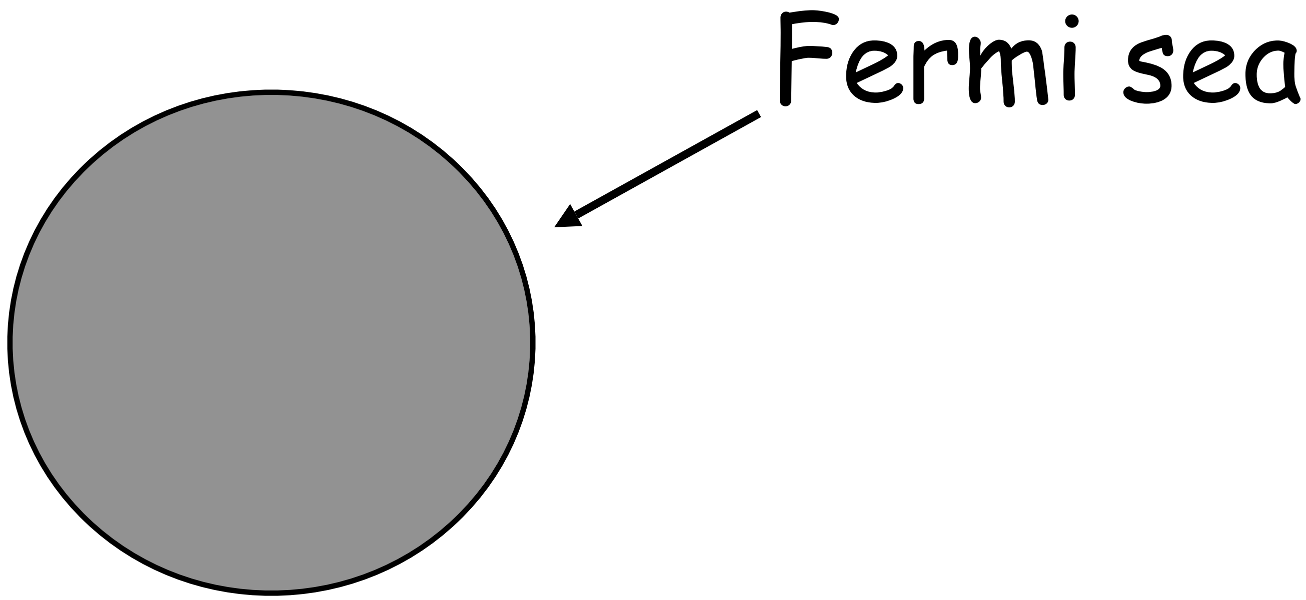

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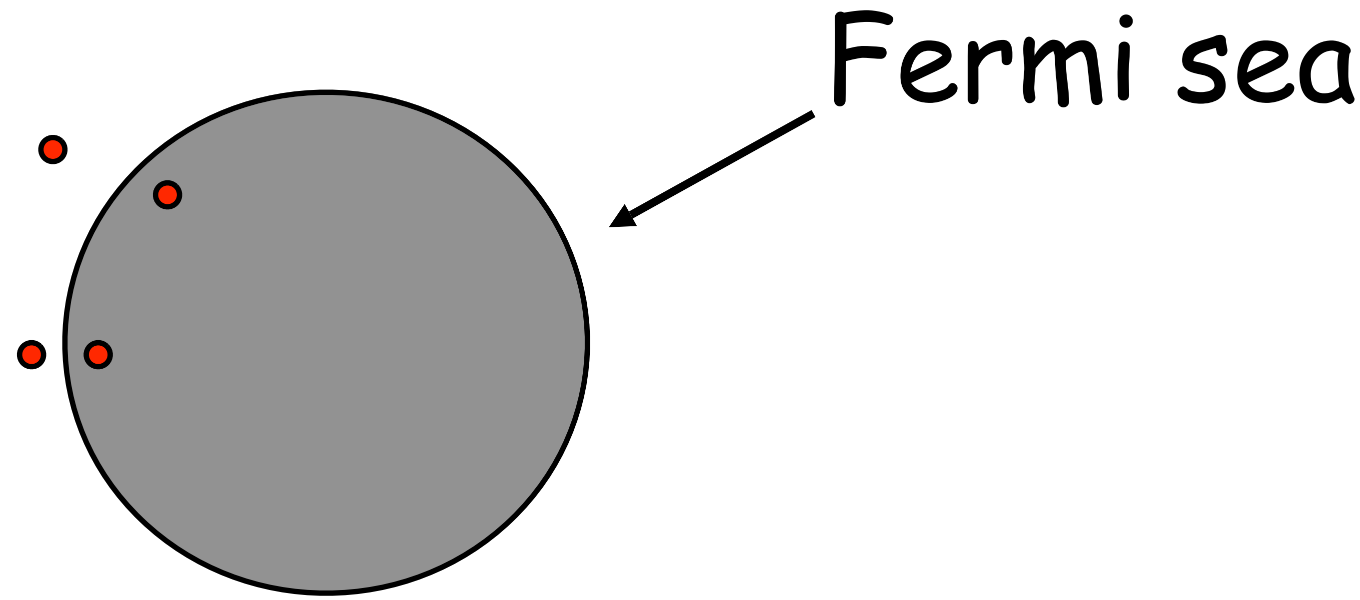

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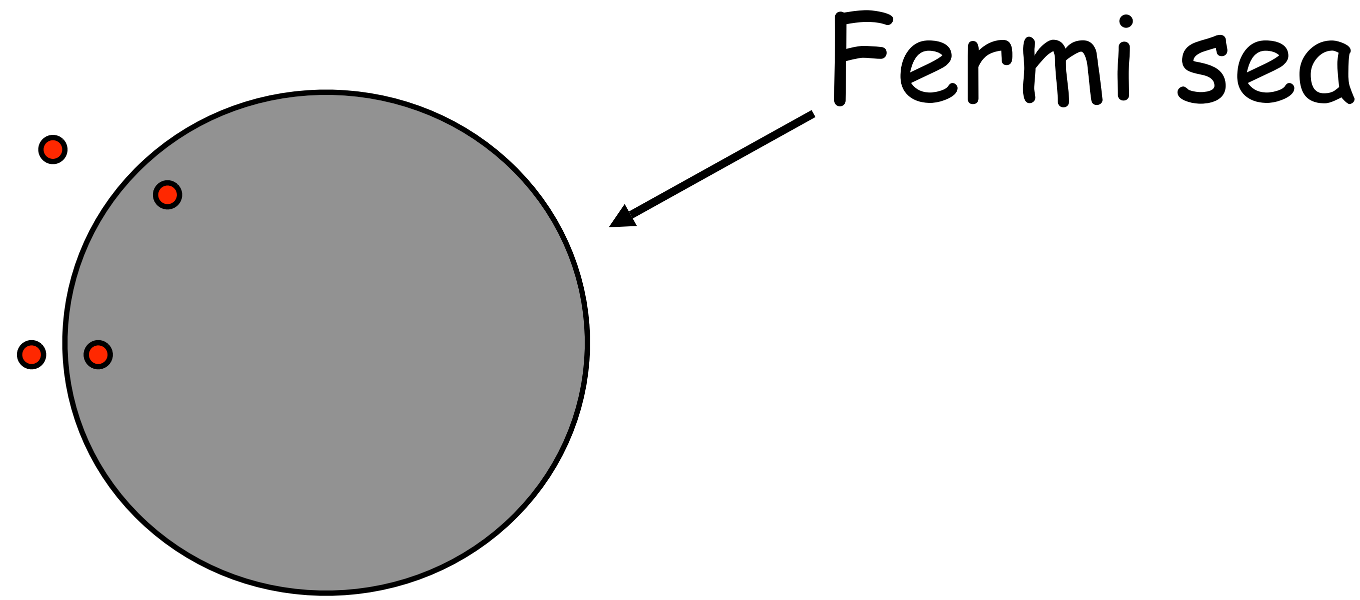
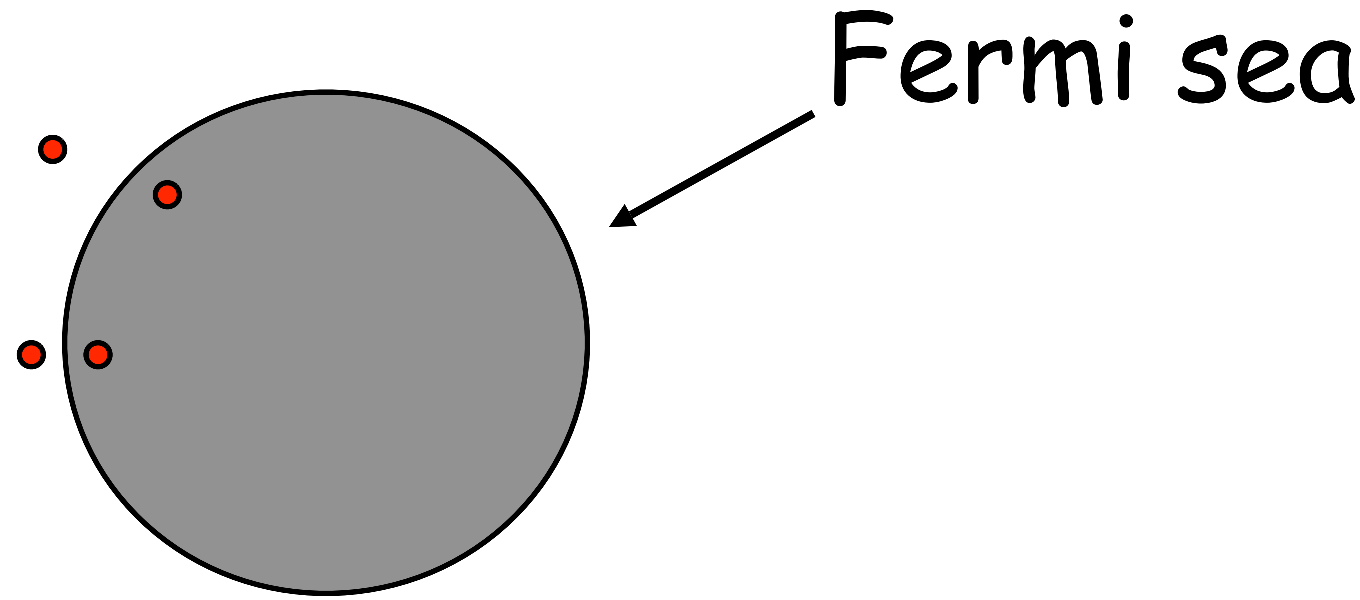


Two degrees of freedom

Metals: $\rho \approx T^2$



Two degrees of freedom

$$\frac{\hbar}{\tau} \approx \frac{\epsilon^2}{\epsilon_F} \propto \frac{T^2}{\epsilon_F}$$

T-linear Resistivity

$$\frac{\hbar}{\tau} \equiv \# k_B T$$

Planckian limit of dissipation

T-linear Resistivity

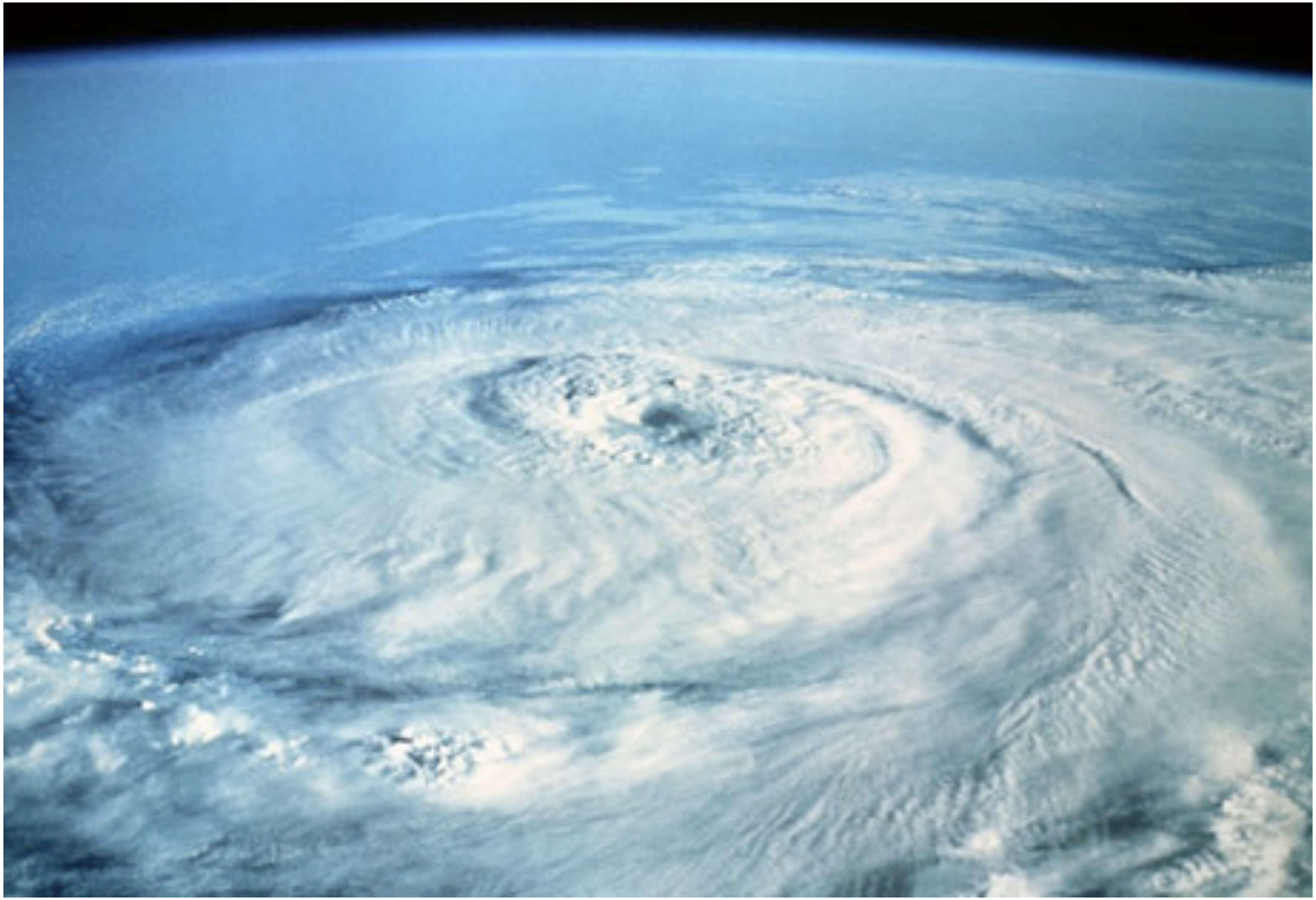
$$\frac{\hbar}{\tau} \equiv \# k_B T$$

Planckian limit of dissipation

breakdown of standard
Fermi liquid
picture

Cuprates: The Perfect Storm

Cuprates: The Perfect Storm



collective failure

collective failure

"I'm not into this detail stuff. I'm more concepty."

collective failure

"I'm not into this detail stuff. I'm more concepty."

New Concept

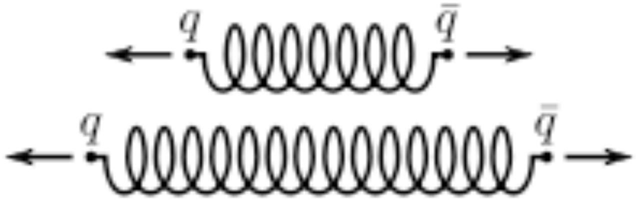
composite or bound states not in UV theory

Strong Coupling

composite or bound states not in UV theory

Strong Coupling

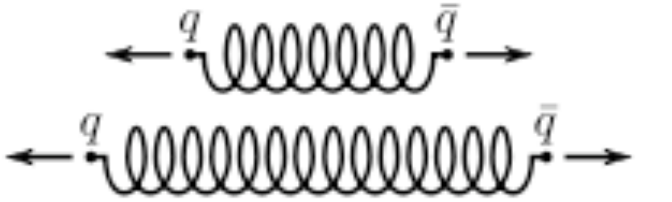
QCD

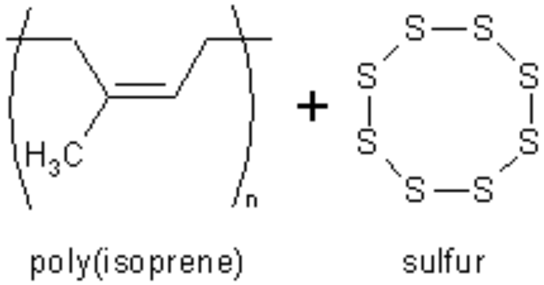


composite or bound states not in UV theory

Strong Coupling

QCD



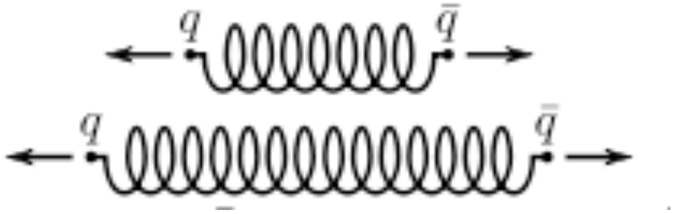


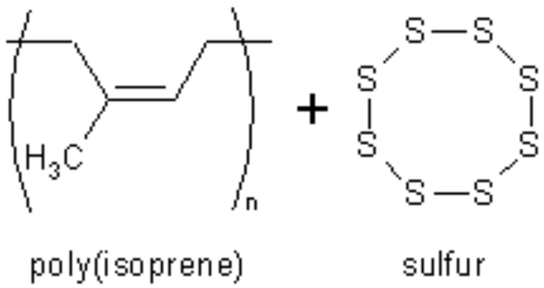
vulcanization

composite or bound states not in UV theory

Strong Coupling

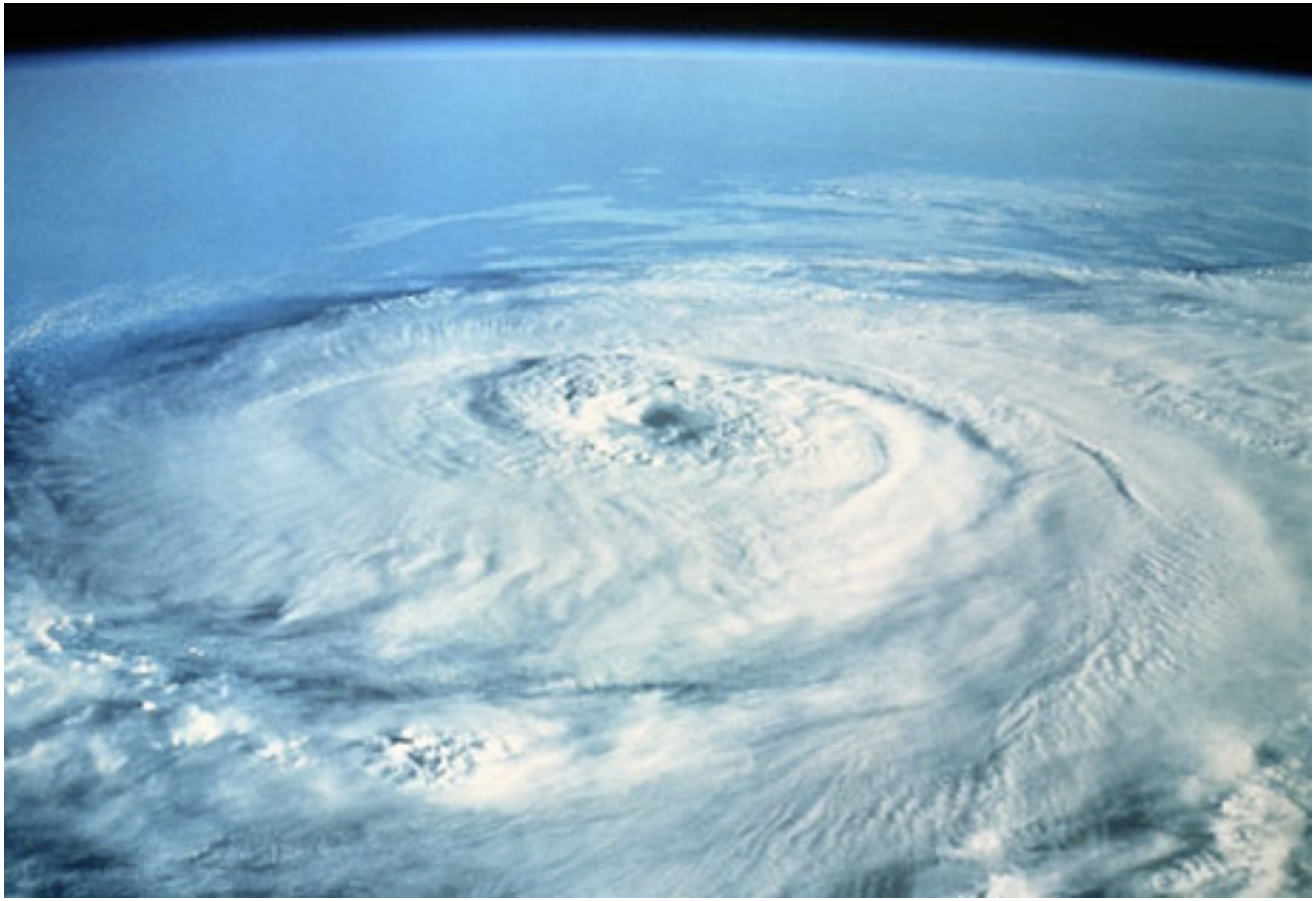
QCD





vulcanization

emergent
low-energy physics

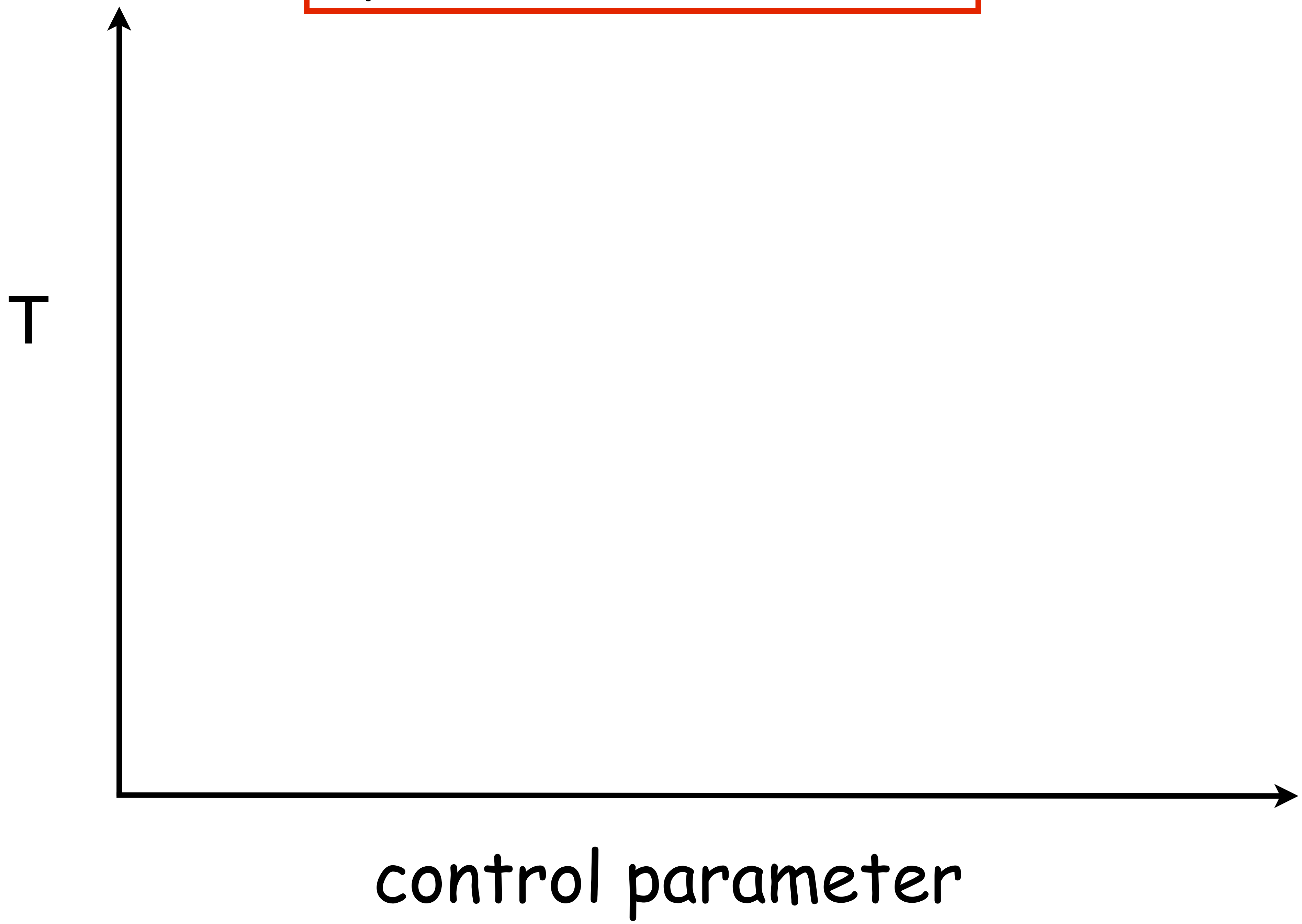


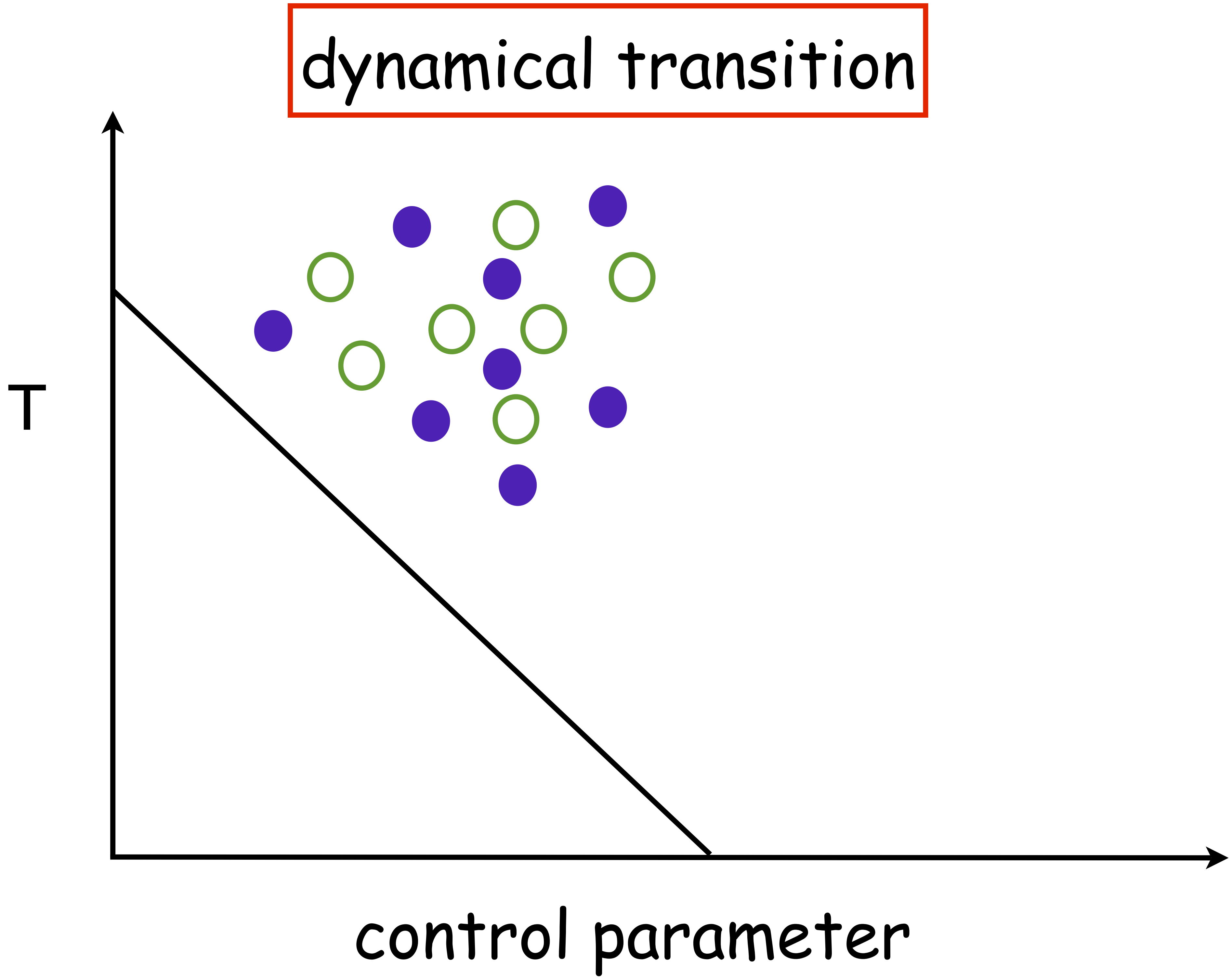
weakly interacting

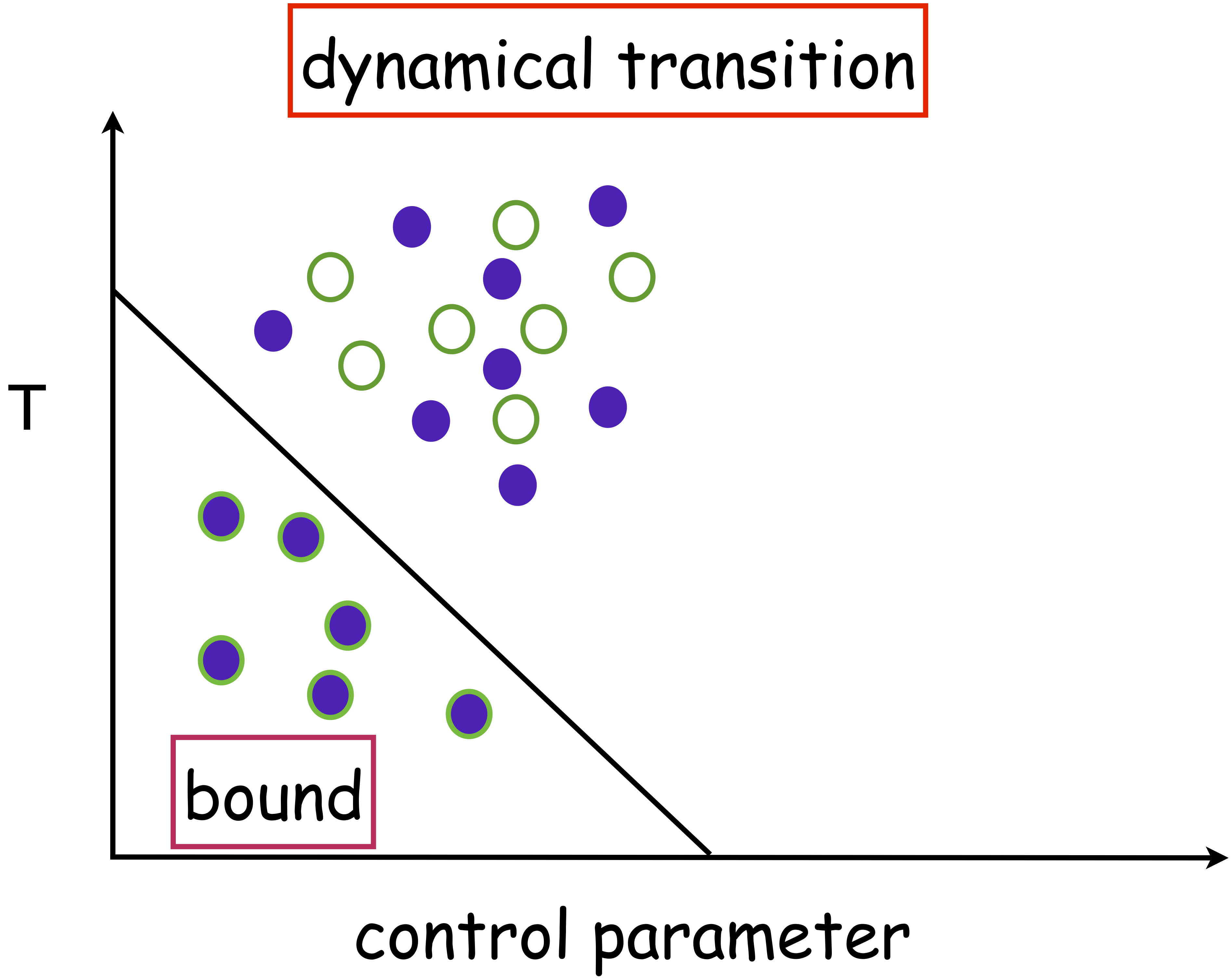
goal:

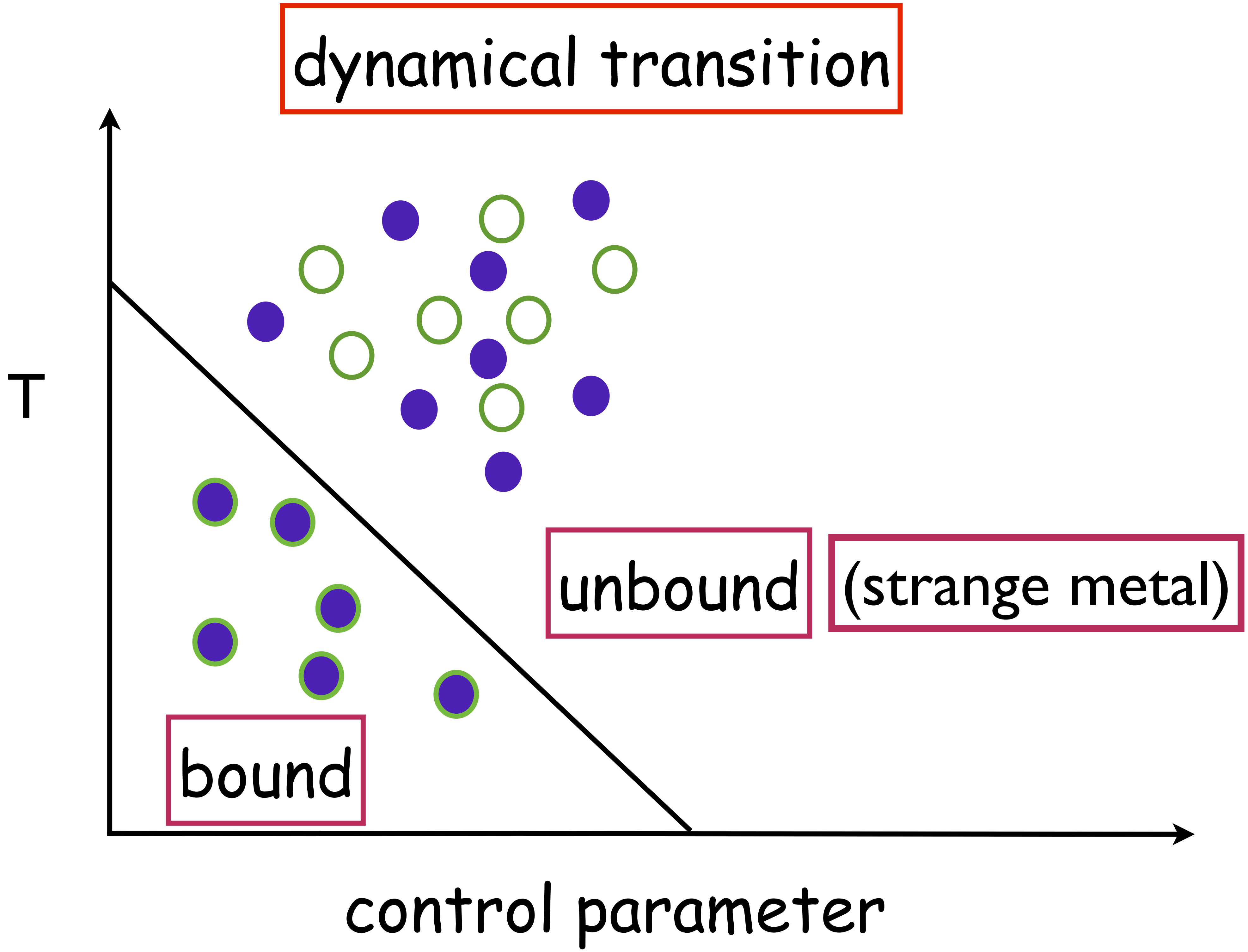
identify propagating charge degrees of freedom
in the normal state of
a high-temperature superconductor

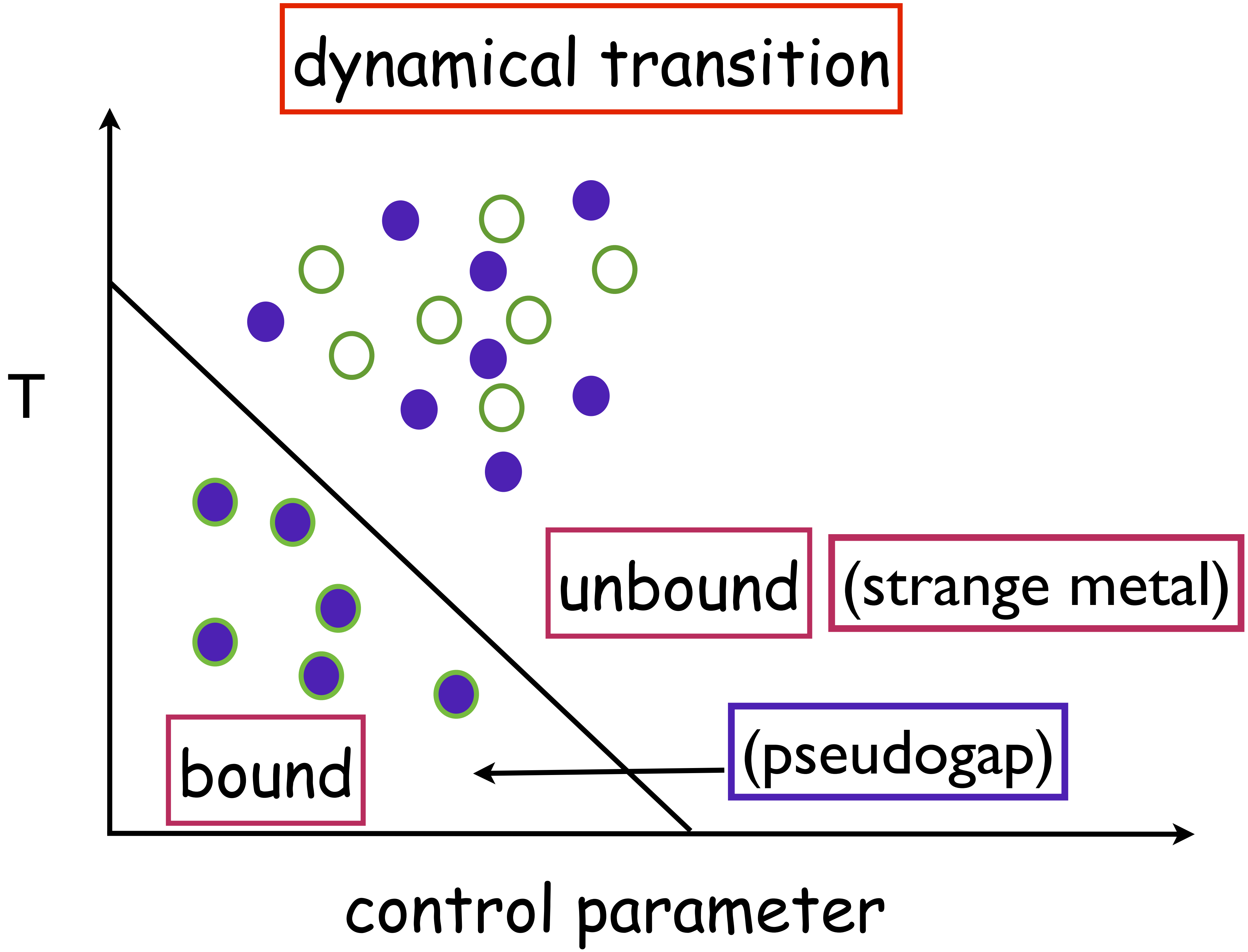
dynamical transition

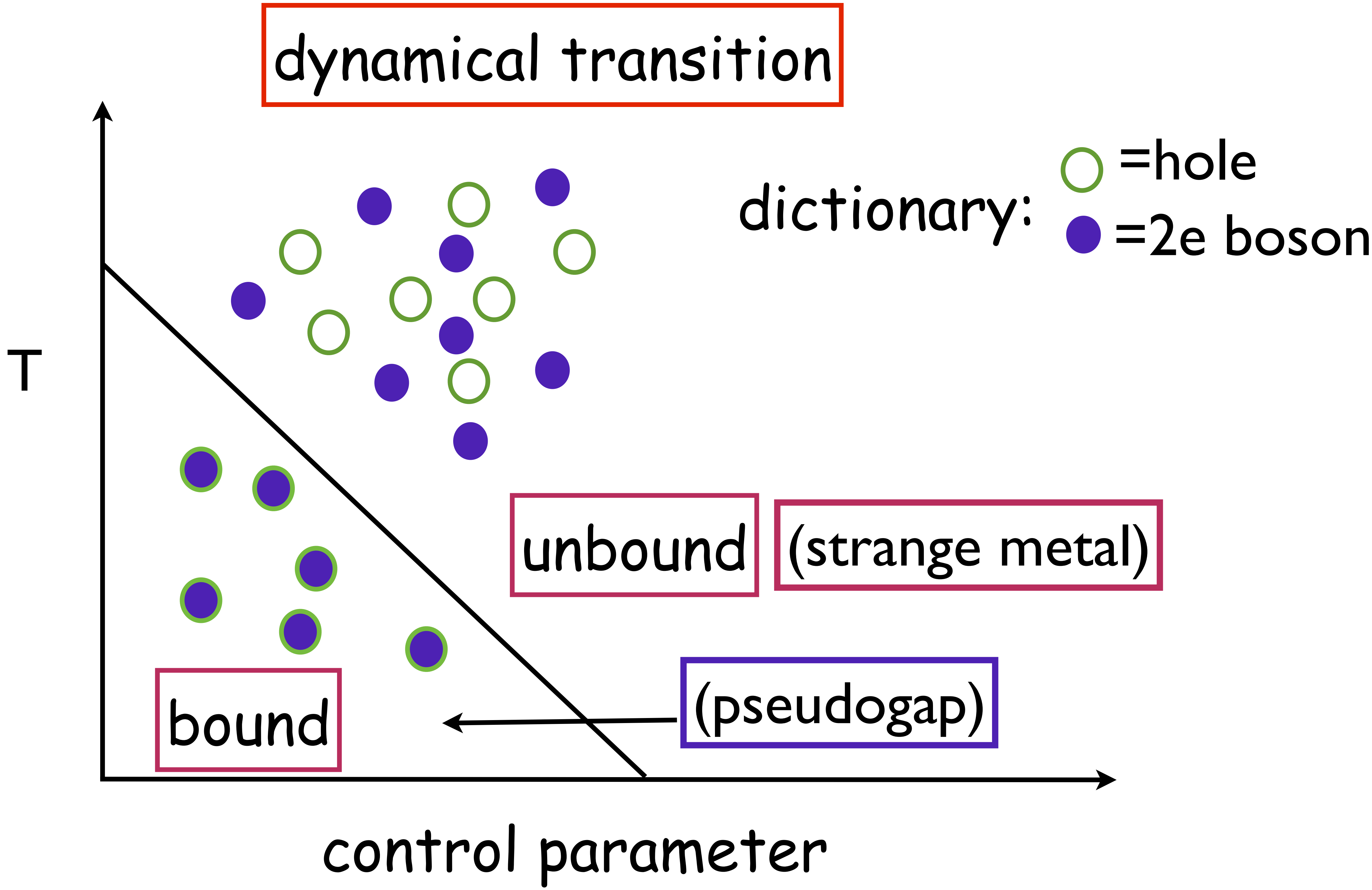



dynamical transition
T
control parameter


dynamical transition
T
bound
control parameter


dynamical transition
T
unbound
(strange metal)
bound
control parameter

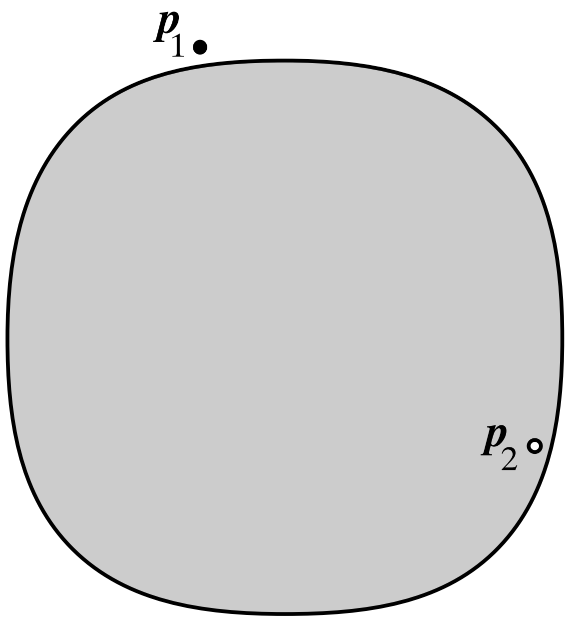

dynamical transition
T
unbound
(strange metal)
bound
(pseudogap)
control parameter



dynamical transition
dictionary:
=hole
=2e boson
T
unbound
(strange metal)
(pseudogap)
bound
control parameter

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

Polchinski (and others)



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

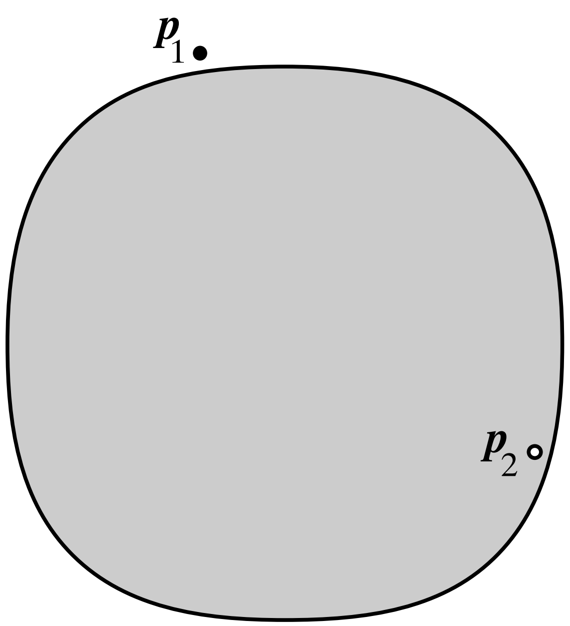
1.) e- charge carriers

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 $d \geq 2$

Polchinski (and others)



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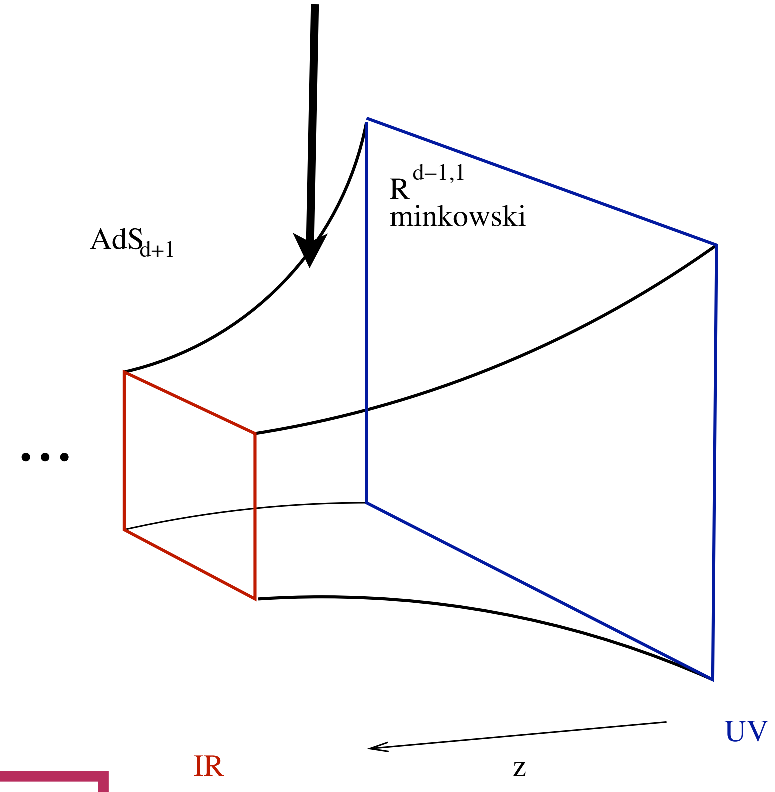
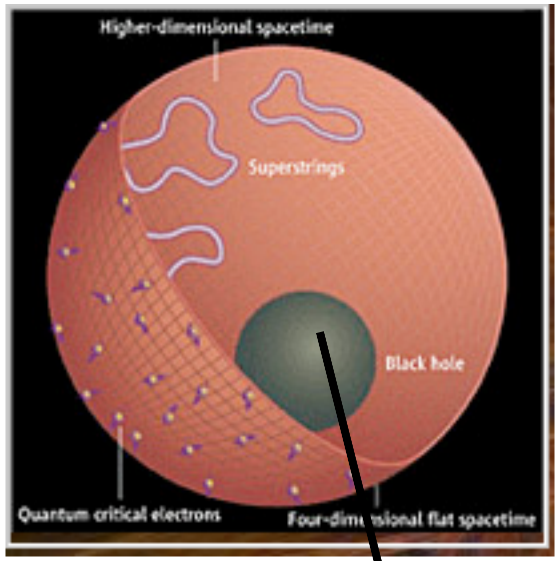
$$\psi^\dagger_\sigma(\mathbf{p}_1)\psi_\sigma(\mathbf{p}_3)\psi^\dagger_{\sigma'}(\mathbf{p}_2)\psi_{\sigma'}(\mathbf{p}_4)\delta^3(\mathbf{p}_1 + \mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4).$$

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

does gauge/gravity duality help?



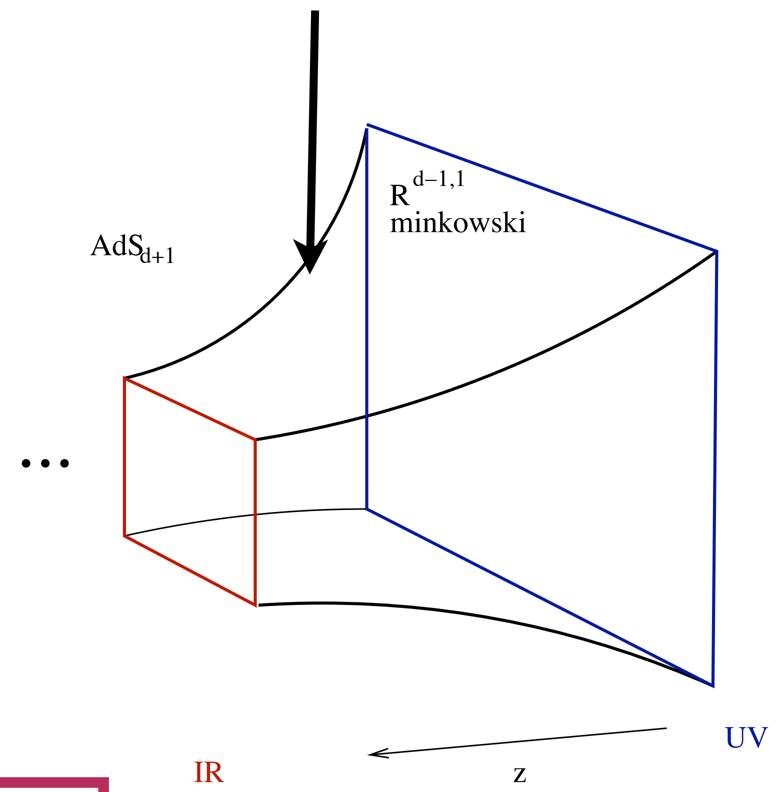


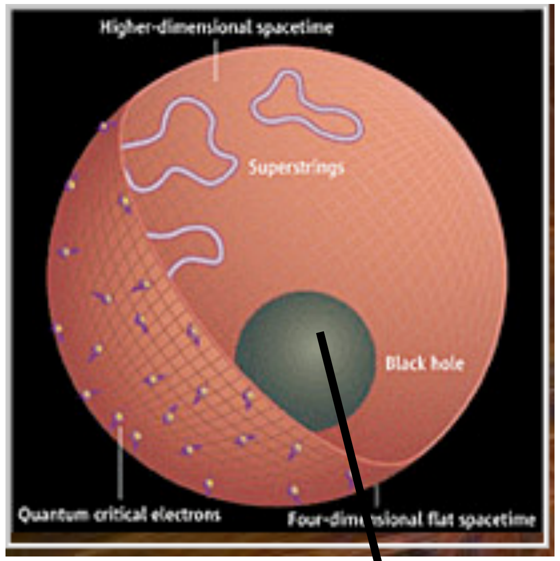
McGreevy, Liu

$\rho \propto T$

$AdS_4 \longrightarrow AdS_2 \times R^2$

does gauge/gravity duality help?





McGreevy, Liu

$\rho \propto T$

$AdS_4 \longrightarrow AdS_2 \times R^2$

Mechanism??

No

So what does one add to break this correspondence?

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

Interacting system

Free system

low-energy: one-to-one correspondence

So what does one add to break this correspondence?

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

Interacting system

new degrees of freedom!

Free system

~~lo energy: one- one orrespo nc~~

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Free system

~~lo energy: one- one orrespo nc~~

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UV-IR mixing

new degrees of freedom!

Free system

So what does one add to break this correspondence?

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

UV-IR mixing

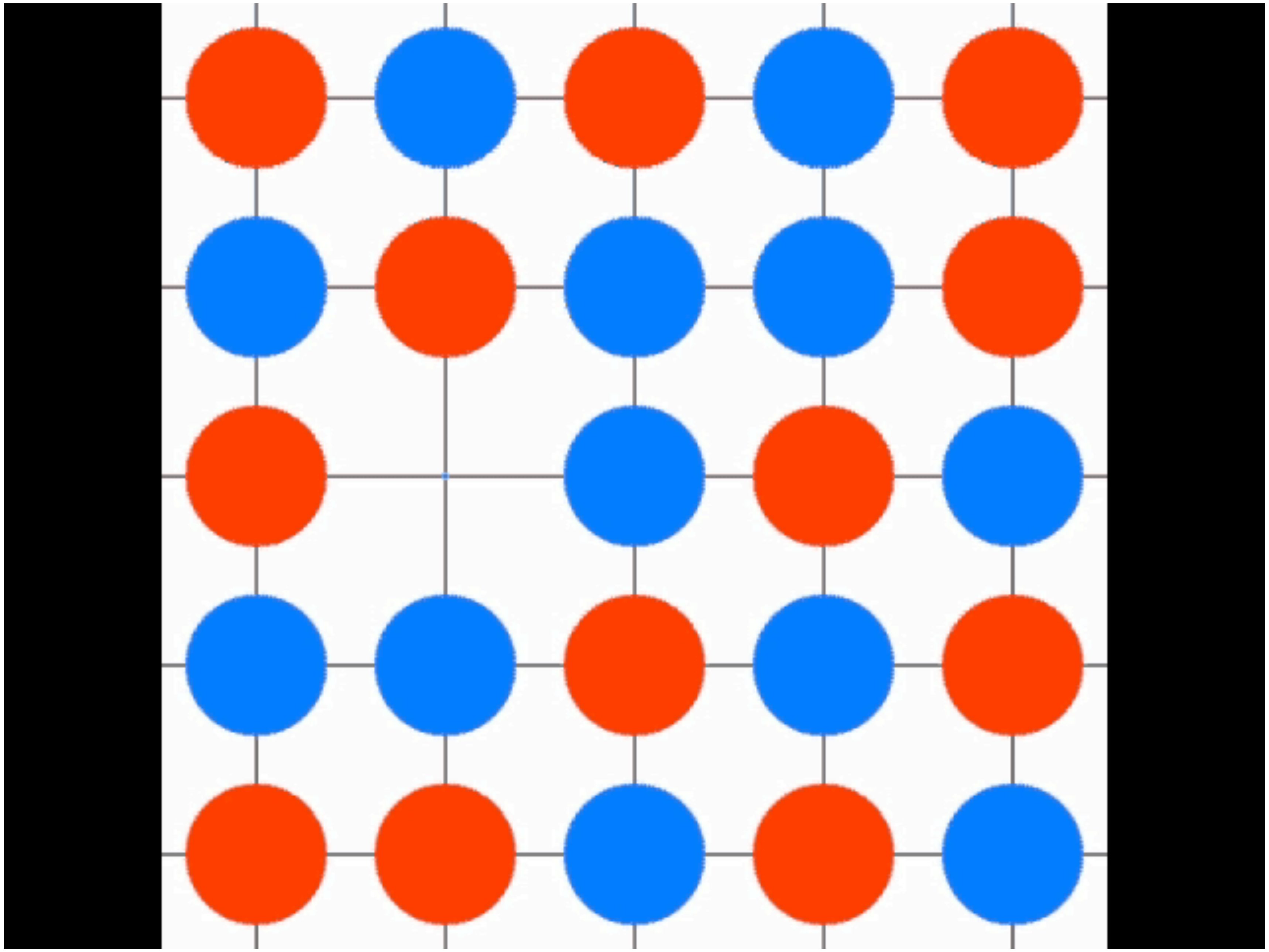
Free system

lo energy:
one- one
orrespo nc

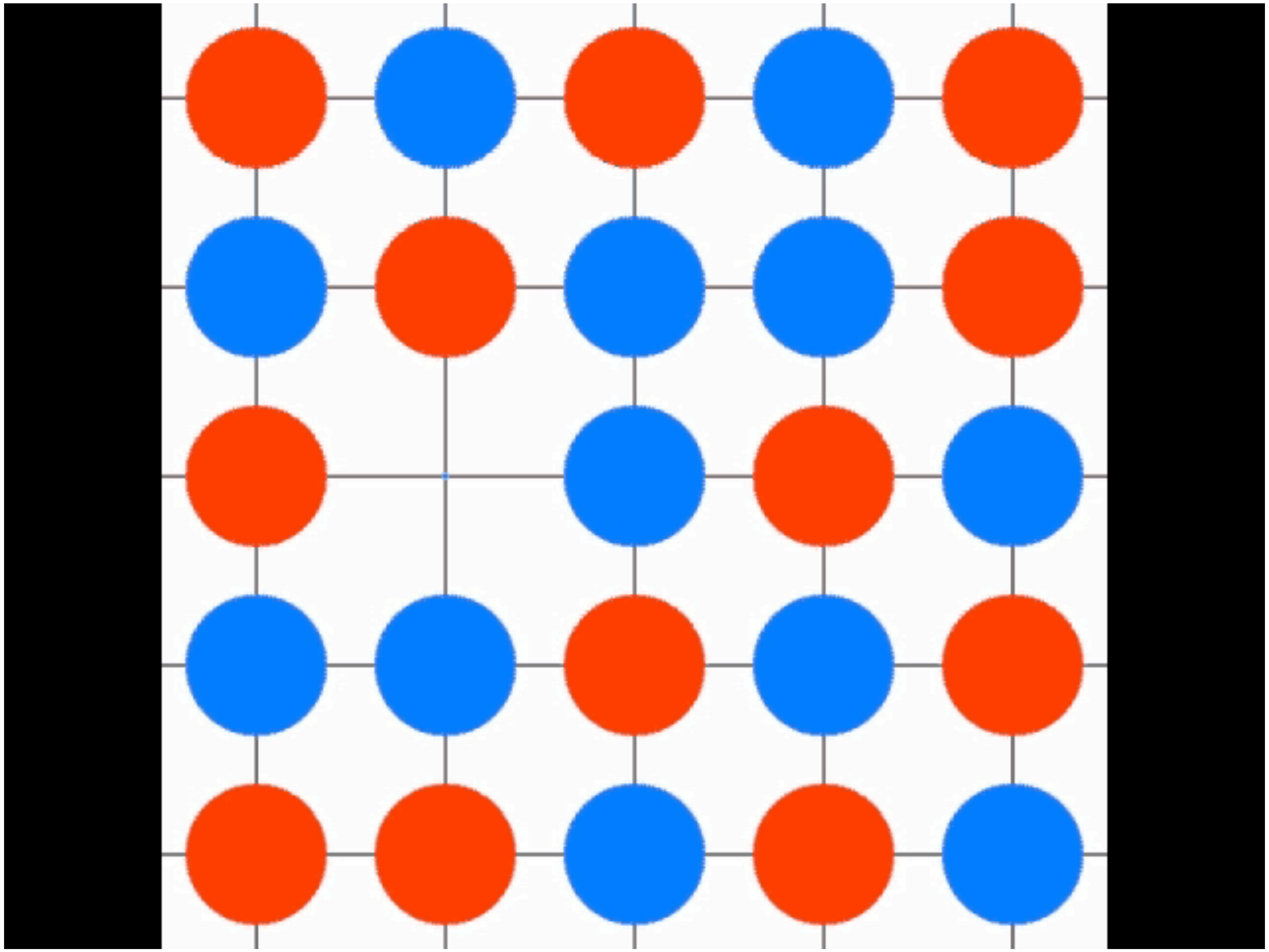
new degrees of freedom!

dynamically generated

$U = \infty$

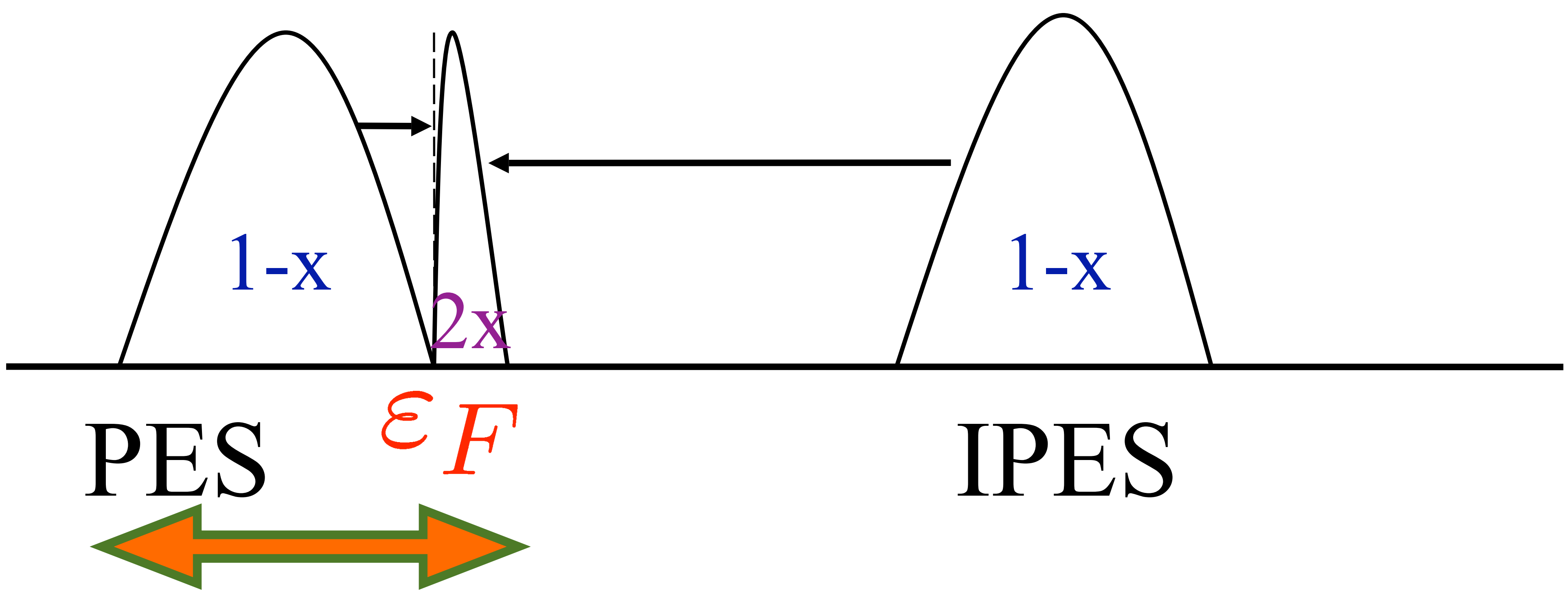


$U = \infty$



No dynamics with doubly-occupied sector:
each electron blocks 2 states

atomic limit: x holes



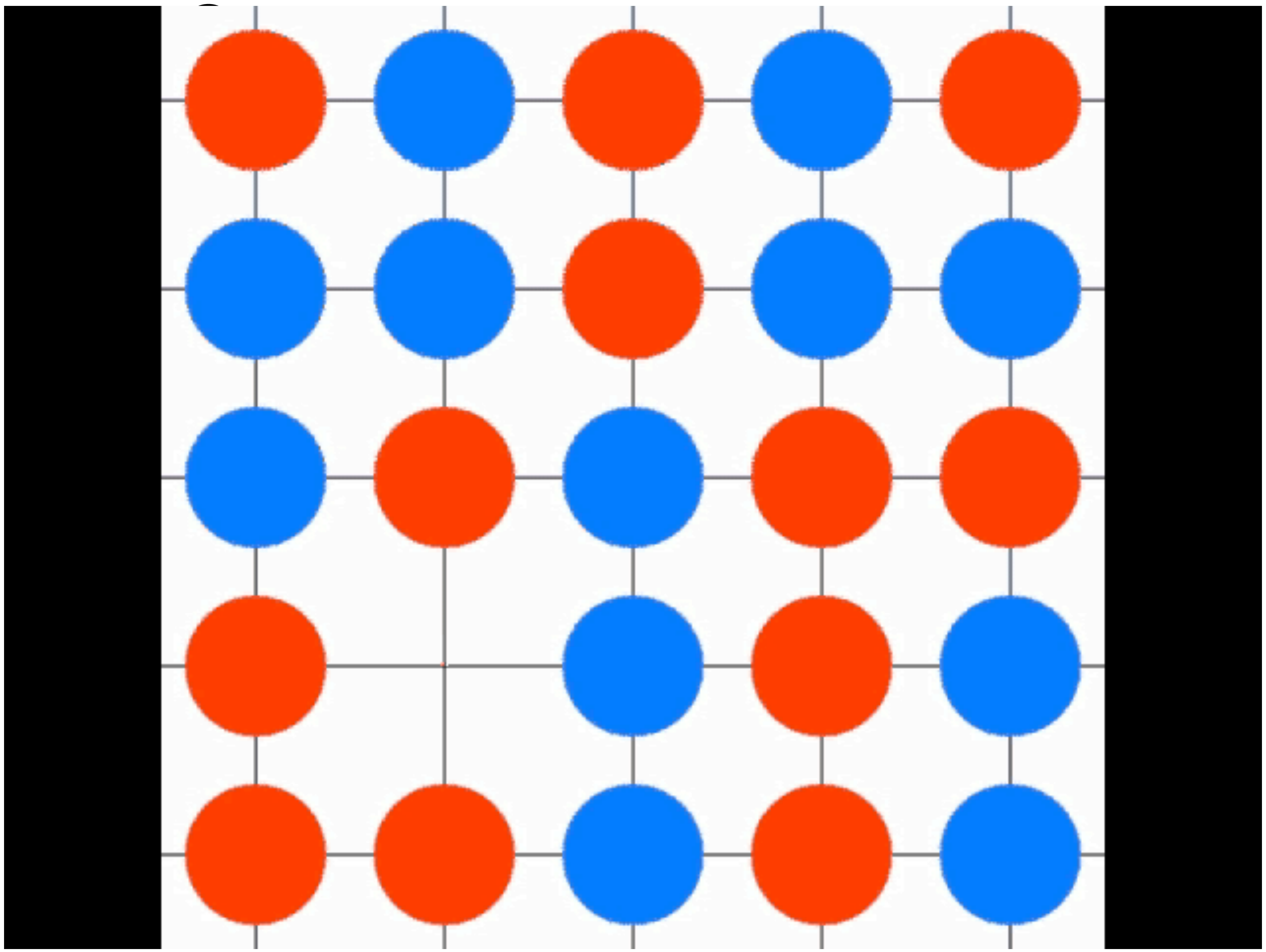
total weight=1+x= # of ways electrons can be added in lower band

No problems yet!

atomic limit

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

U finite $U \gg t$



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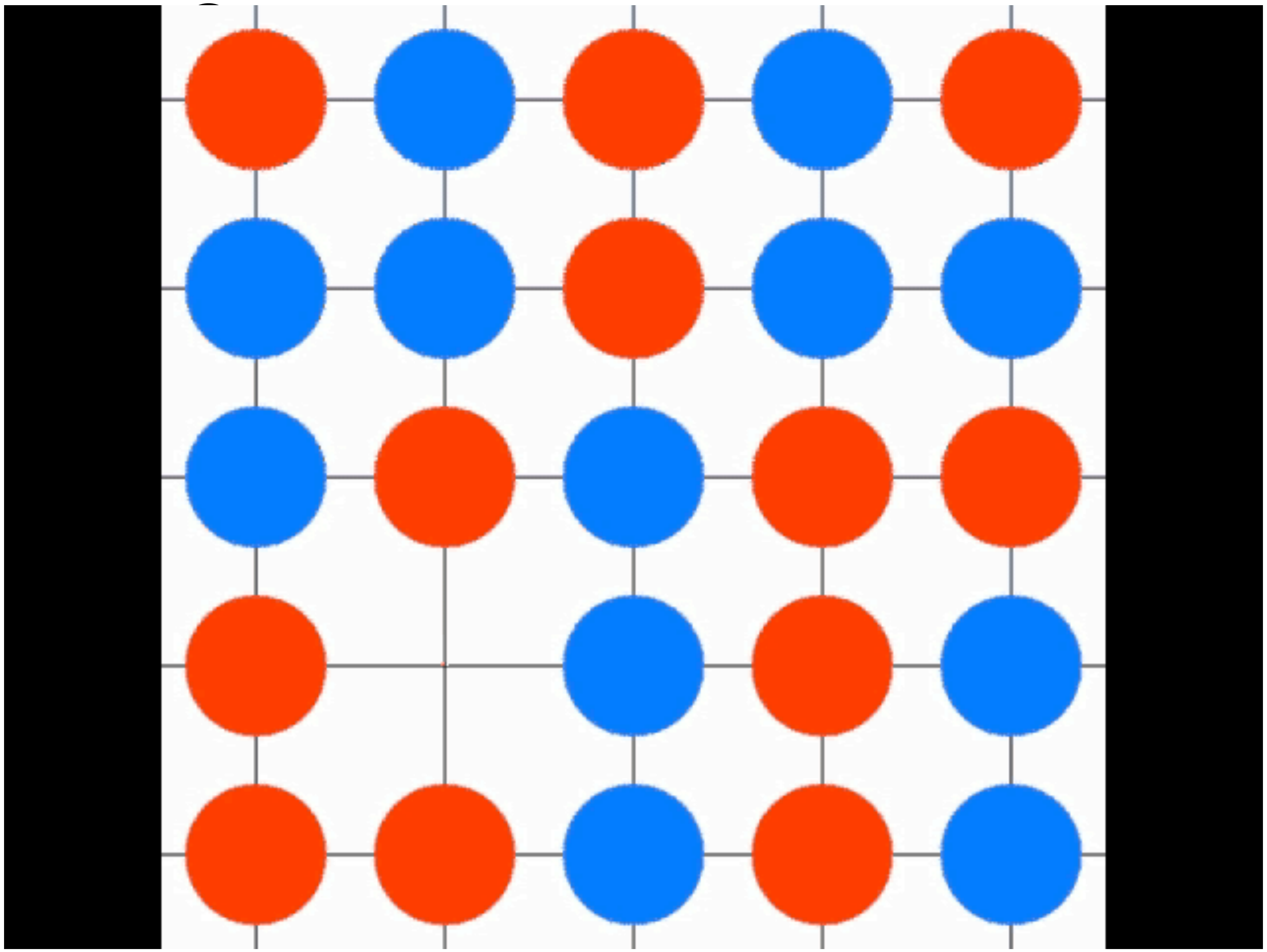

double occupancy in ground state!!

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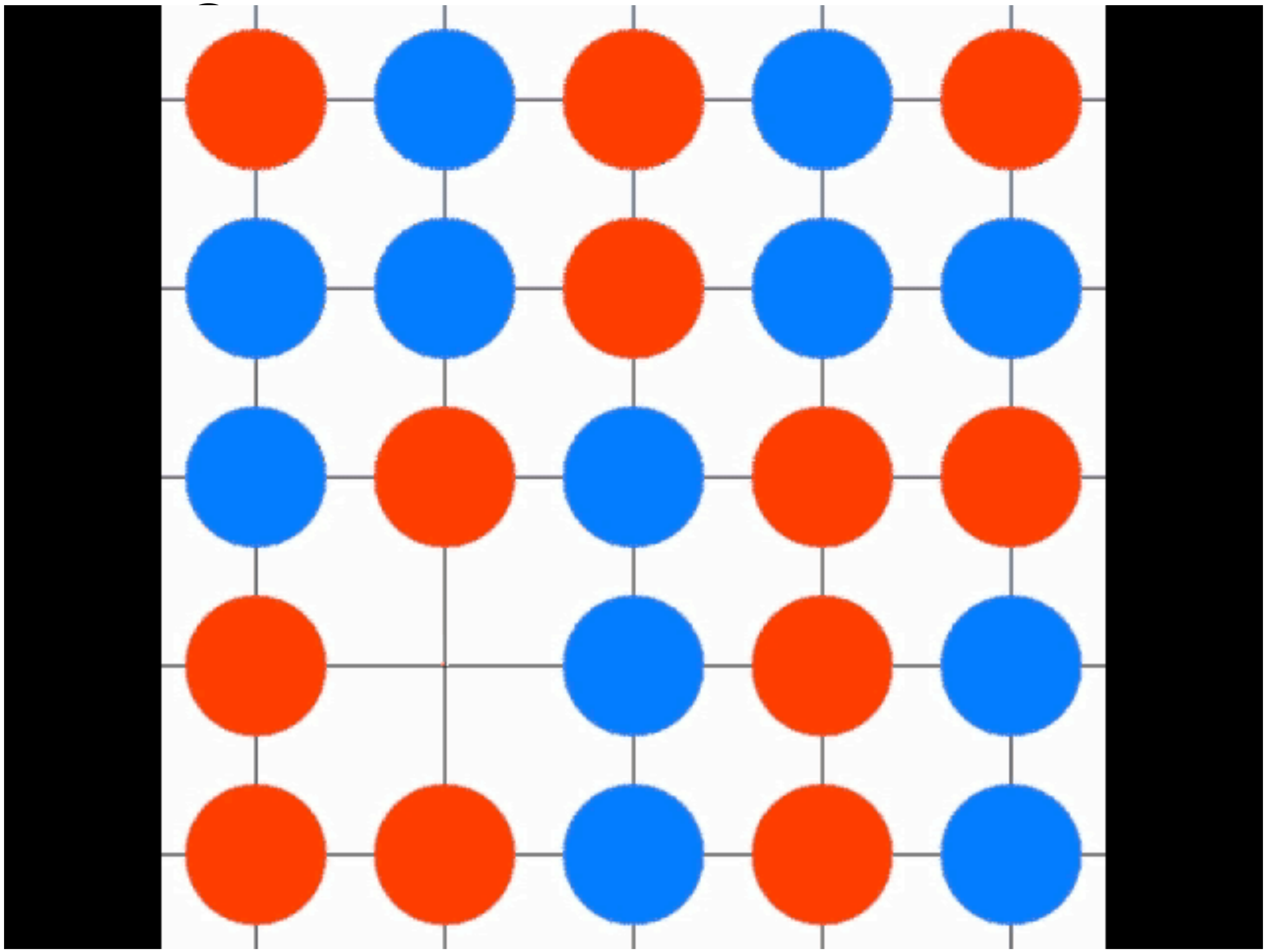
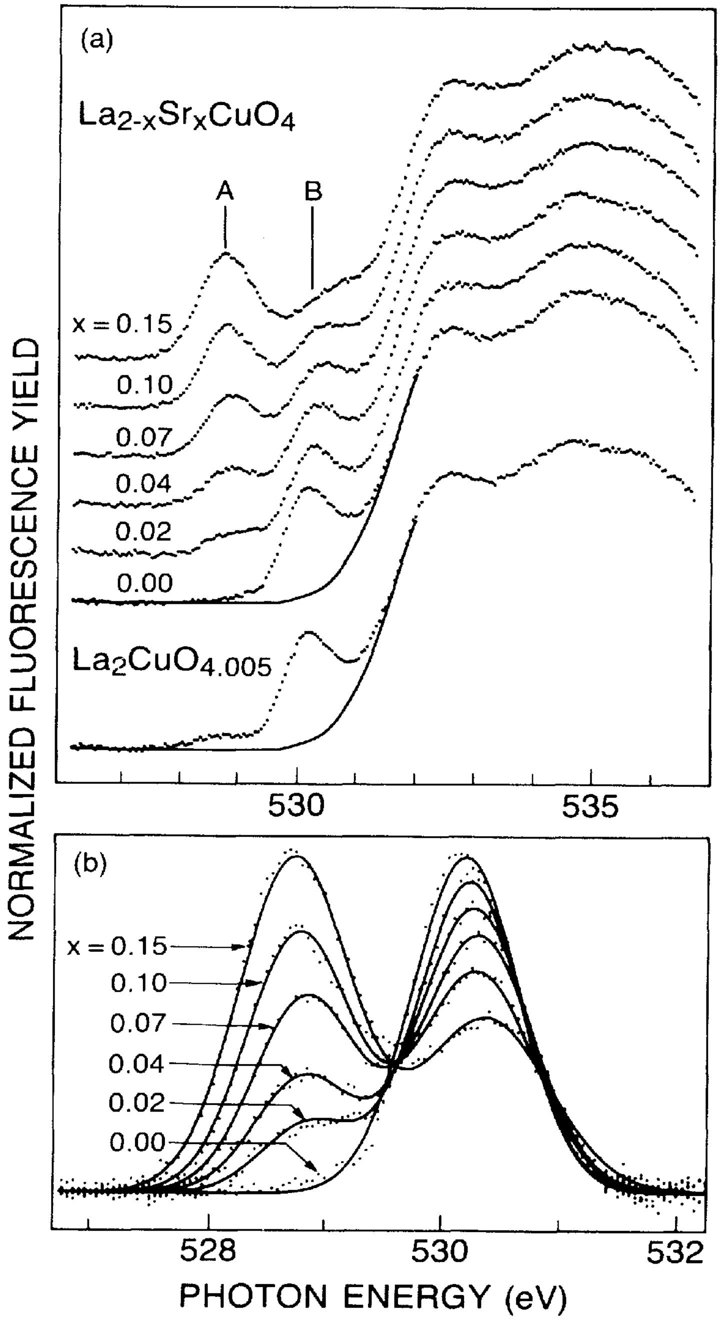


double occupancy in ground state!! $W_{\rm PES} > 1 + x$

C. T. Chen, Batlogg, et al. 1990



What does

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

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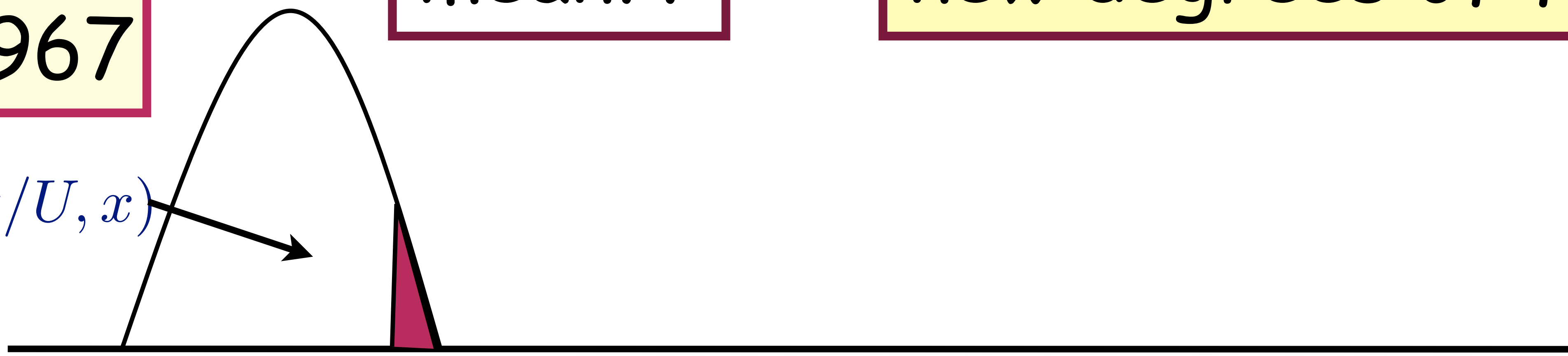
H&L, 1967



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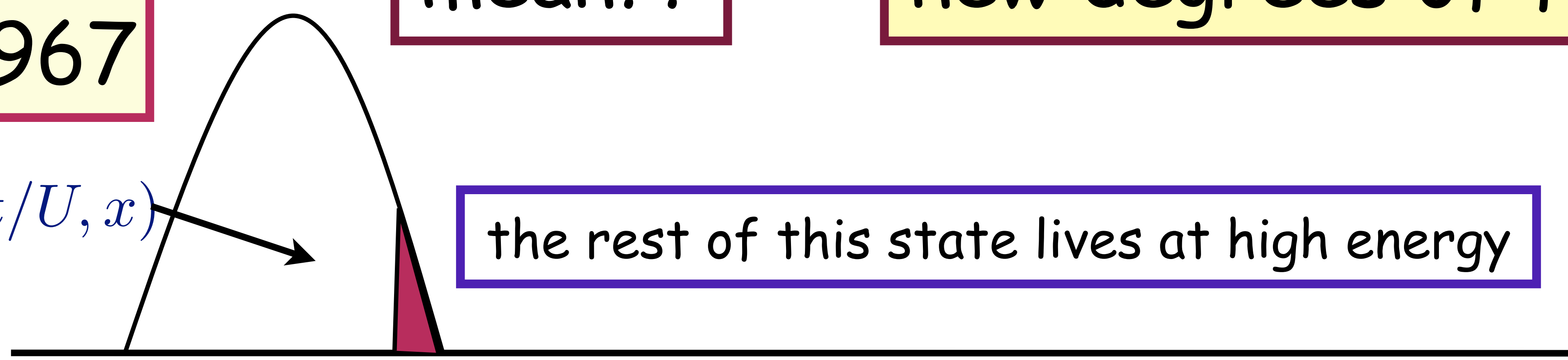
new degrees of freedom

H&L, 1967

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



the rest of this state lives at high energy

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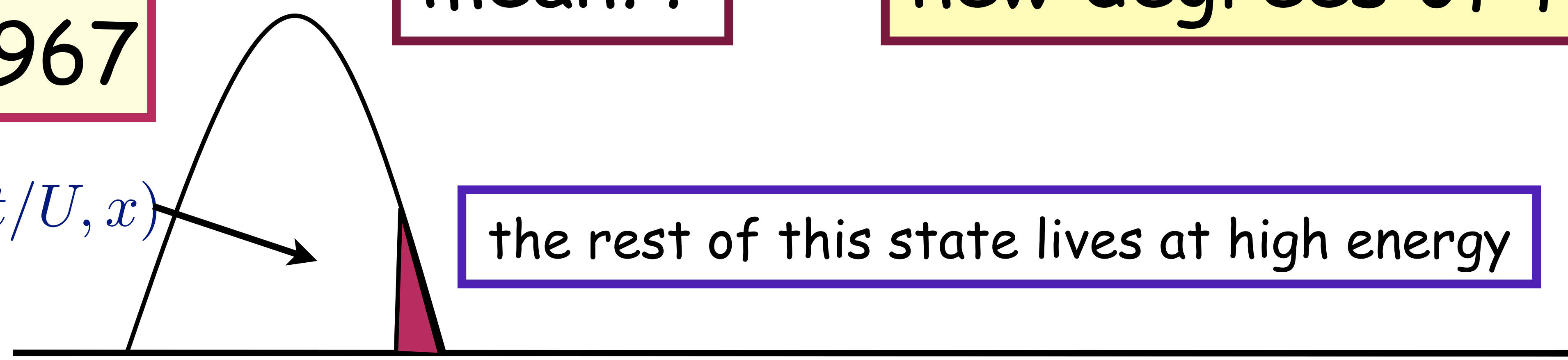

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# of ways of adding electrons remains 1+x

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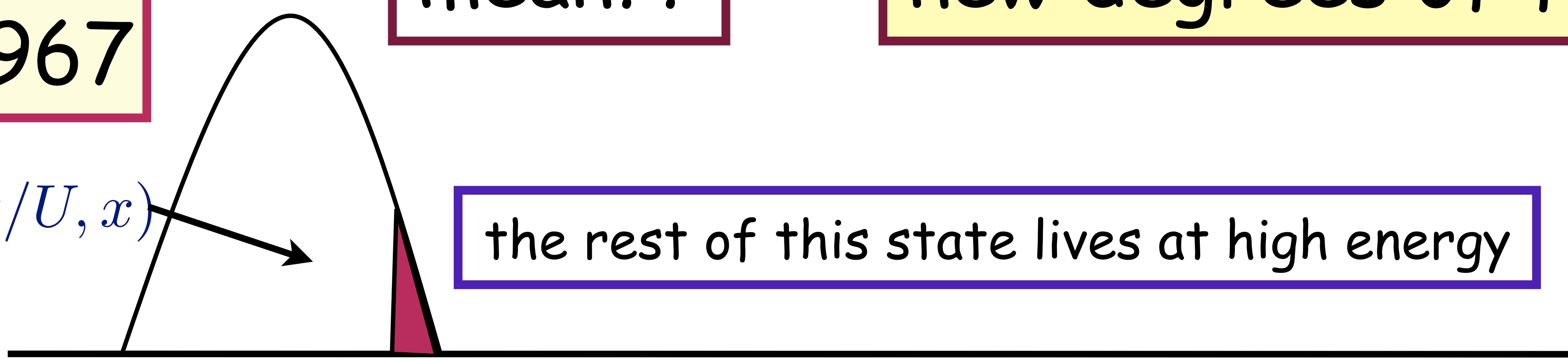

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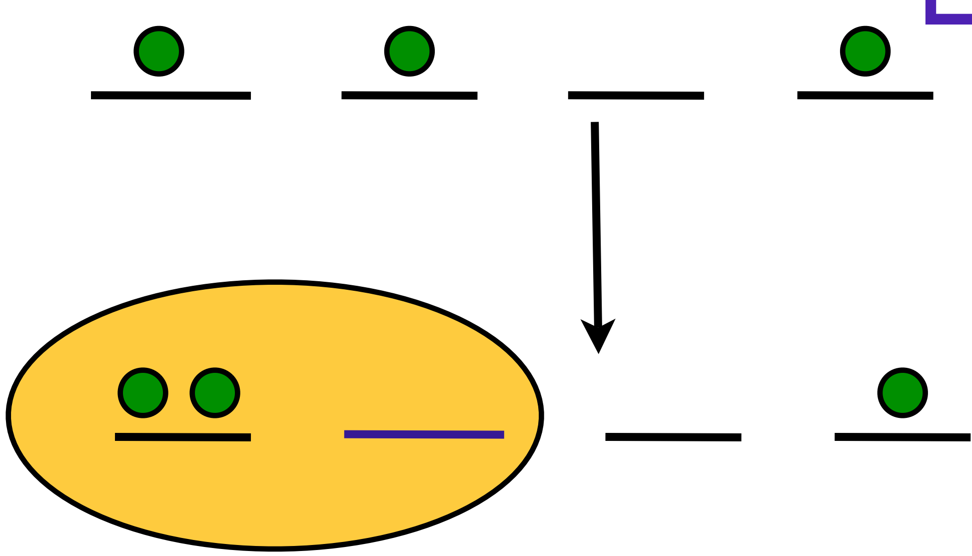

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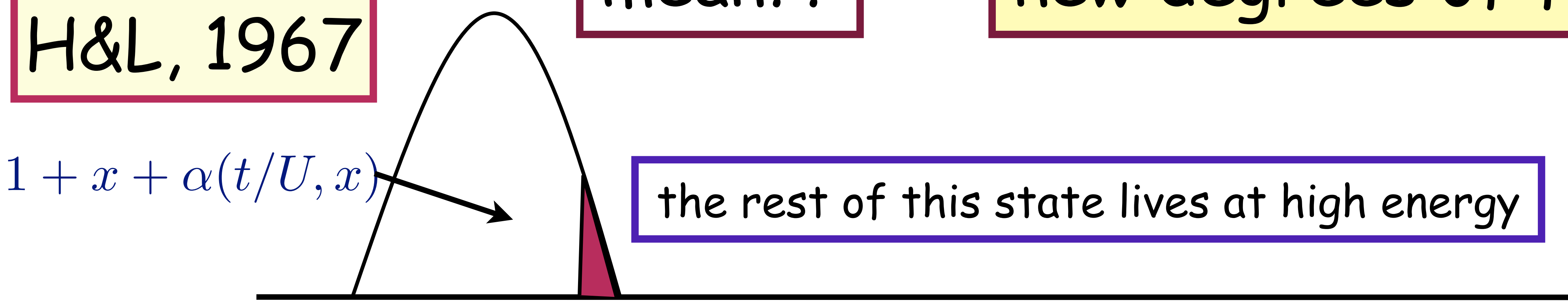

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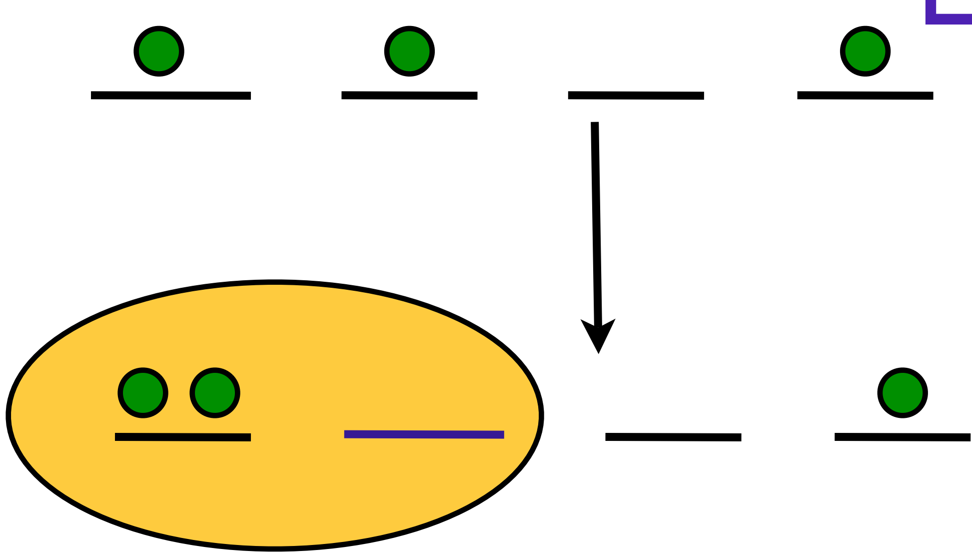
$$\alpha \neq 0 \implies dn_e/d\mu = 0$$



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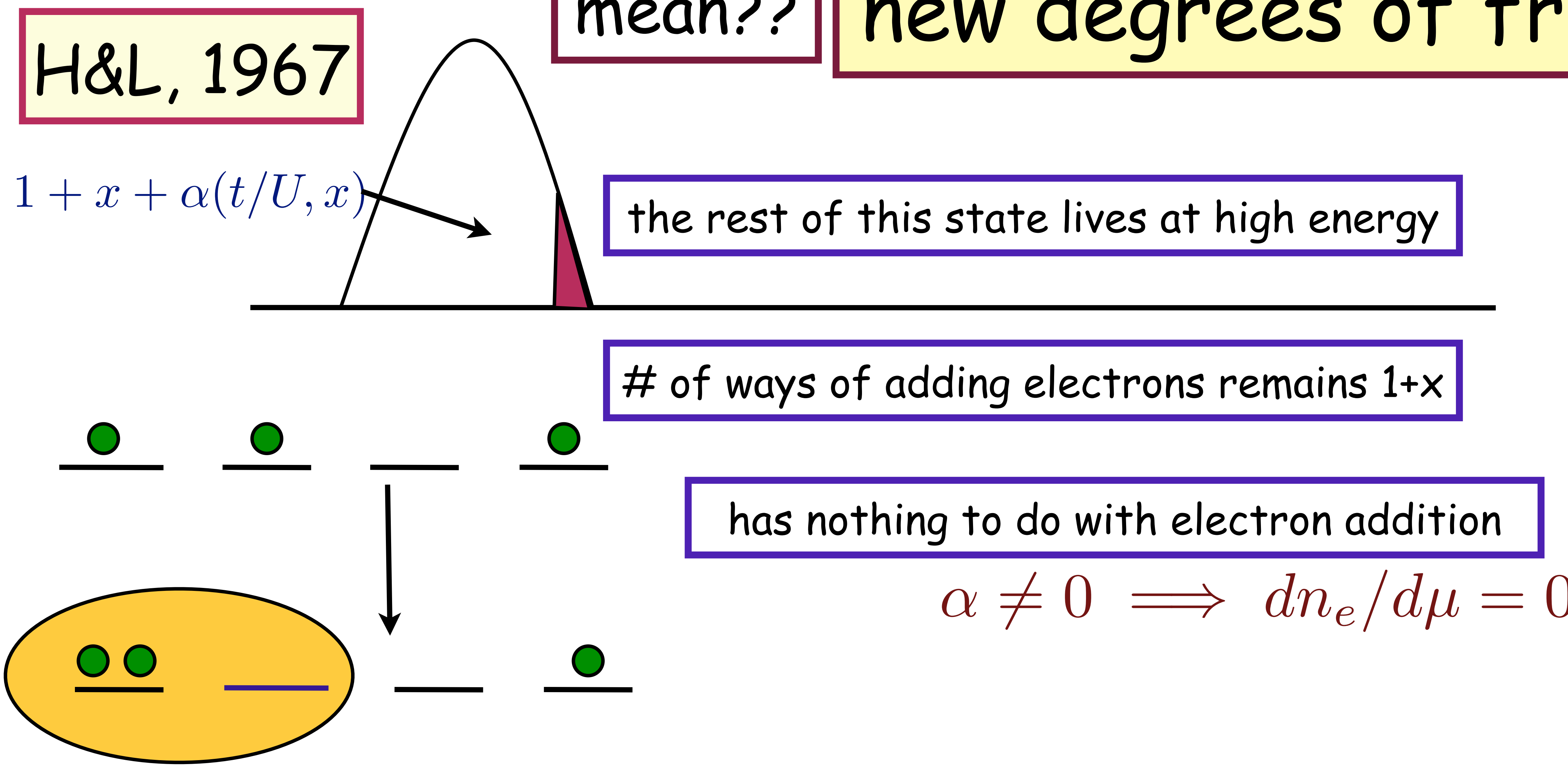
new degrees of freedo



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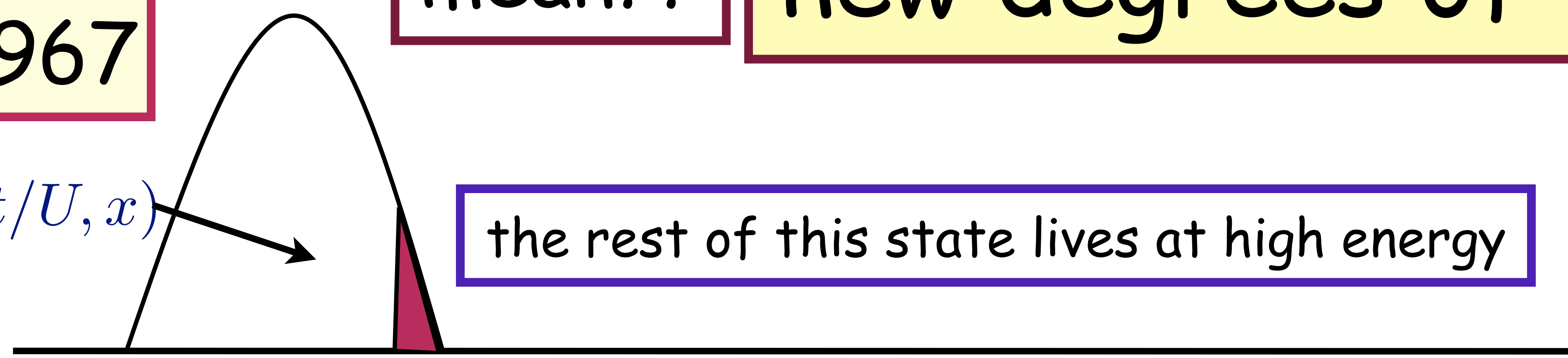

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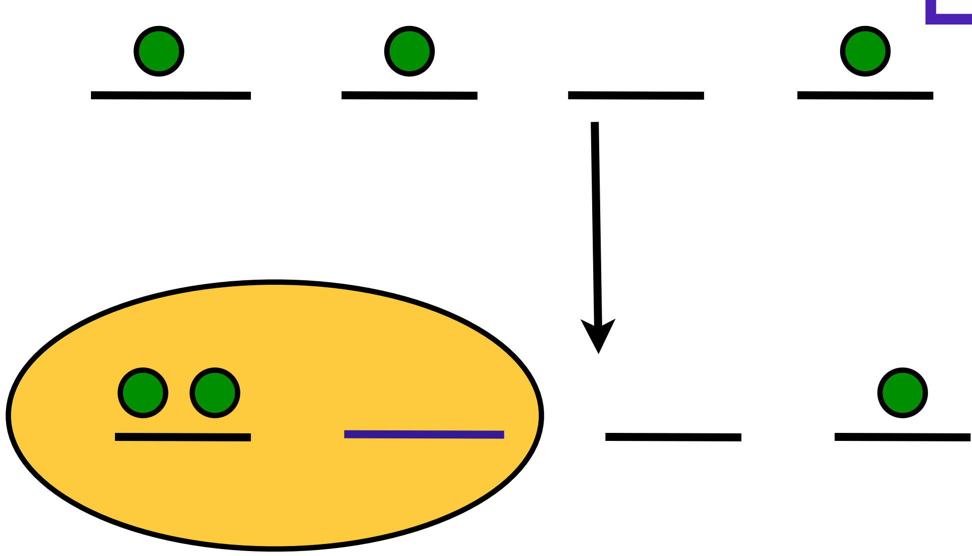

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$$n_e = n_{\mathrm{qp}} + n_{\mathrm{newstuff}} > n_{\mathrm{qp}}$$

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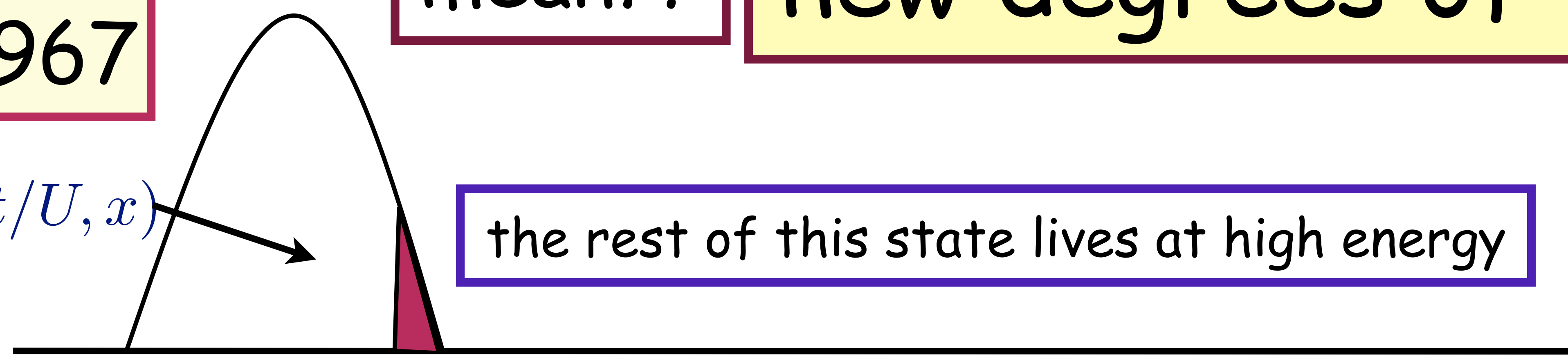

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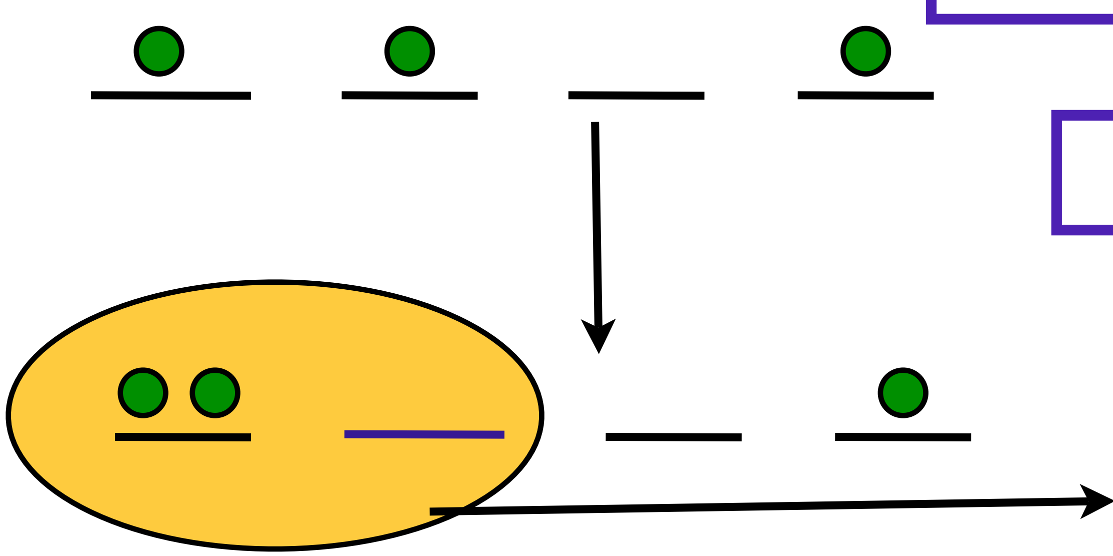

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hole screened with double occupancy:local

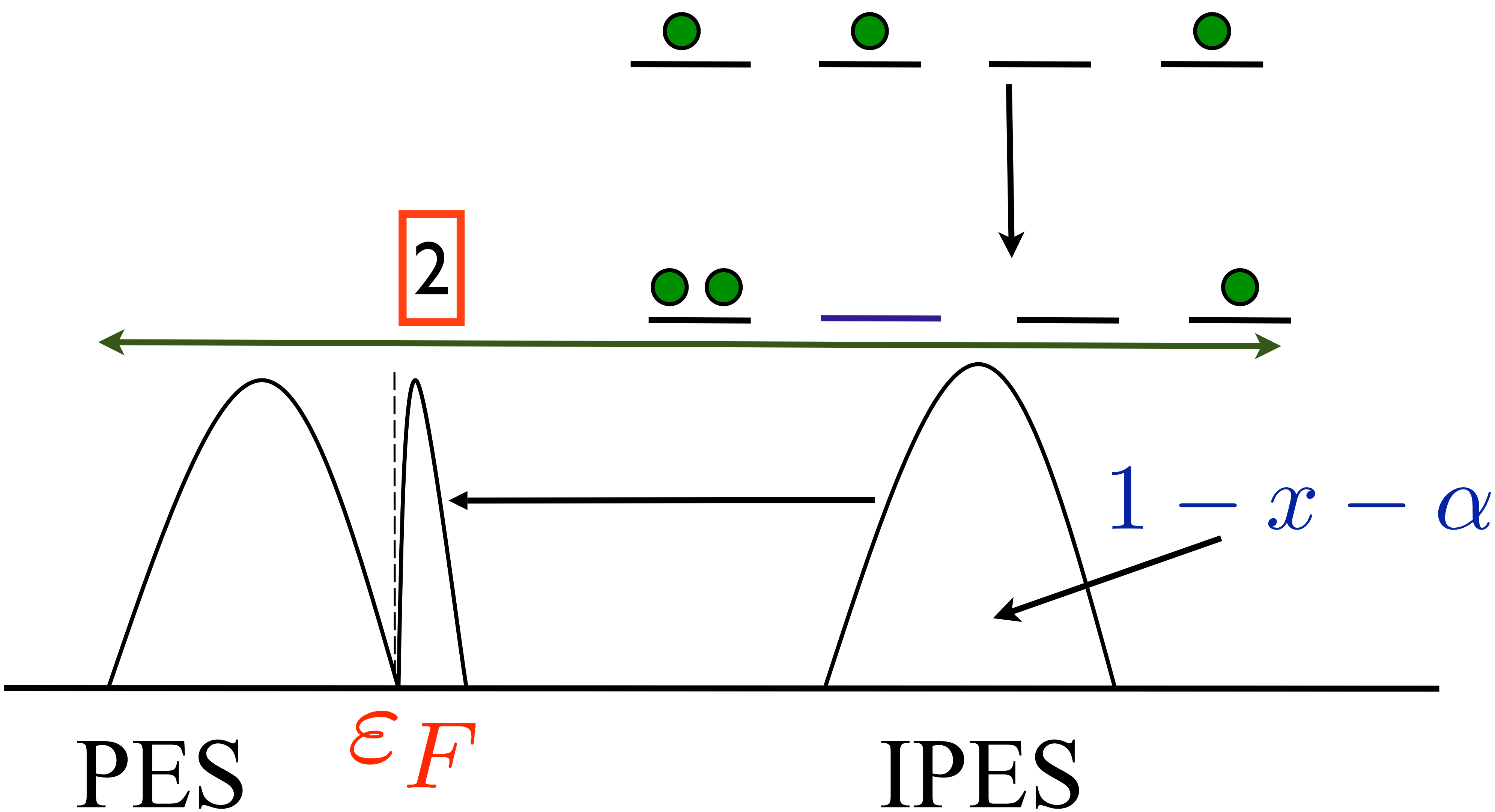
conserved charge

$$n_e = n_{\mathrm{qp}} + n_{\mathrm{newstuff}} > n_{\mathrm{qp}}$$

What are the low-energy quasi-particles?

spectral weights are equal

low-energy qp picture

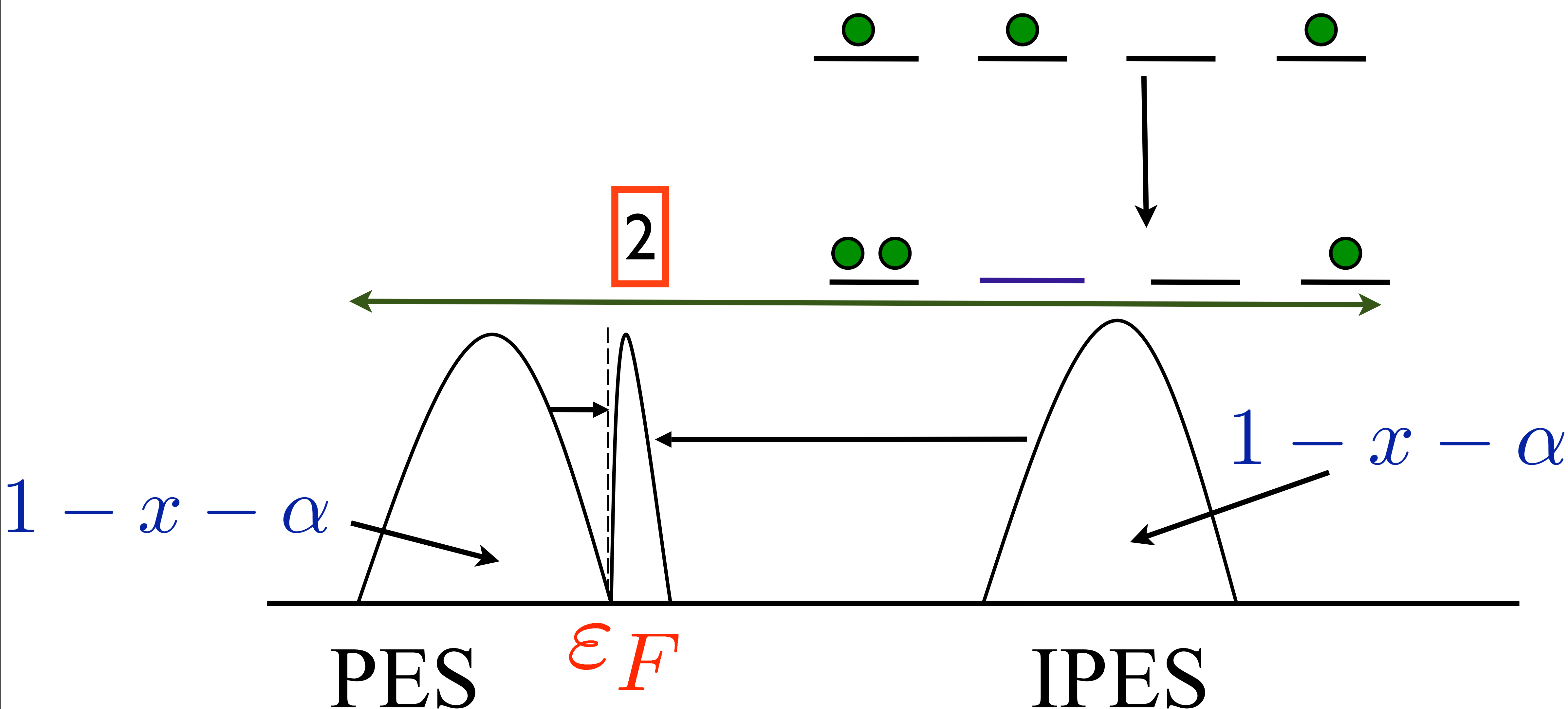


weight>1+x, conserved

charge =1-x=>

$n_{\mathrm{qp}} < 1 - x$

low-energy qp picture



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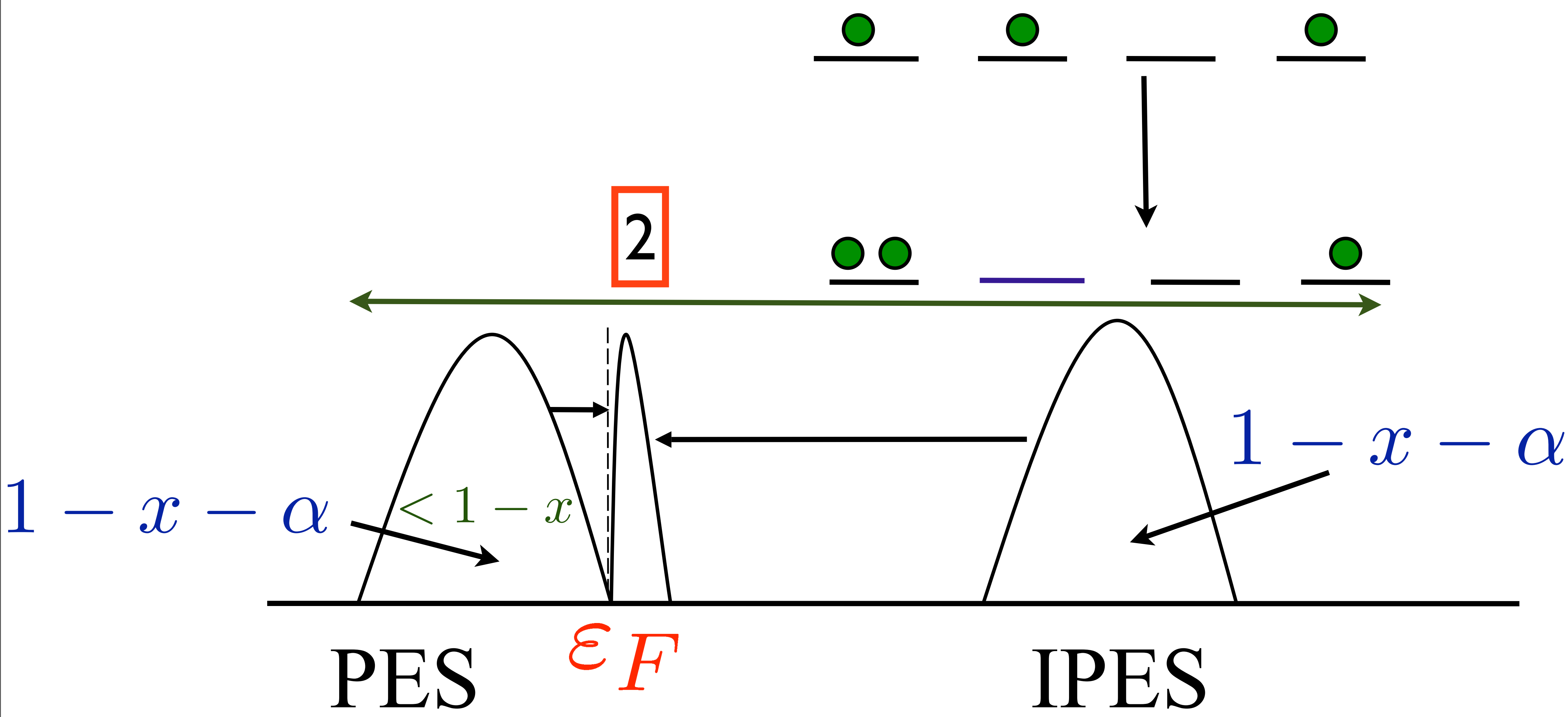

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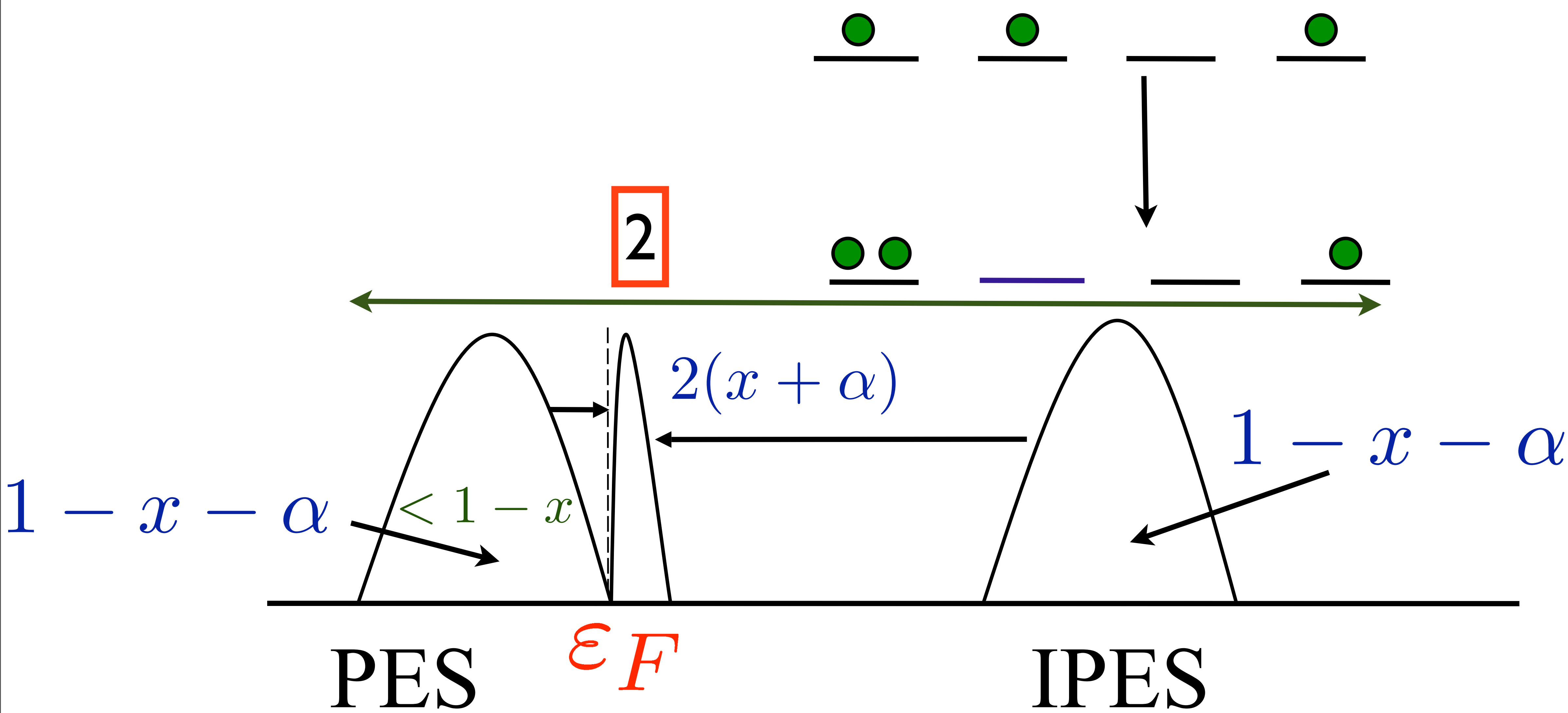

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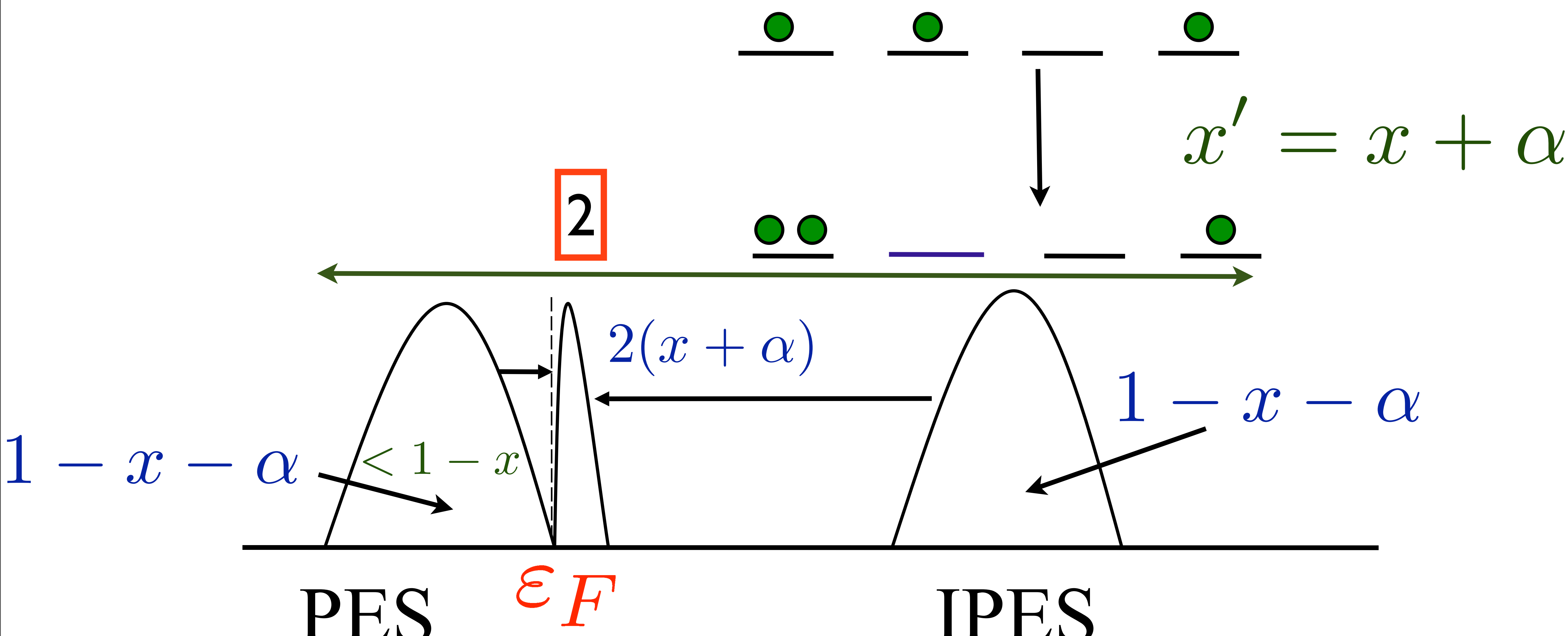

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dynamical spectral weight transfer: beyond $U = \infty$

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ways to add a particle but not an electron (gapped spectrum) dynamical spectral weight transfer: beyond $U=\infty$

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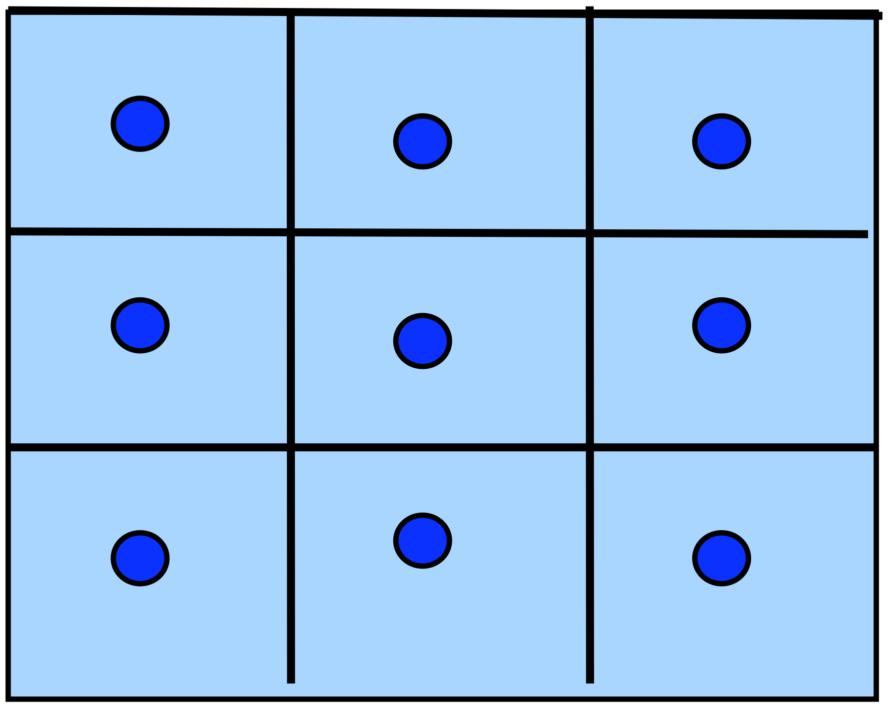
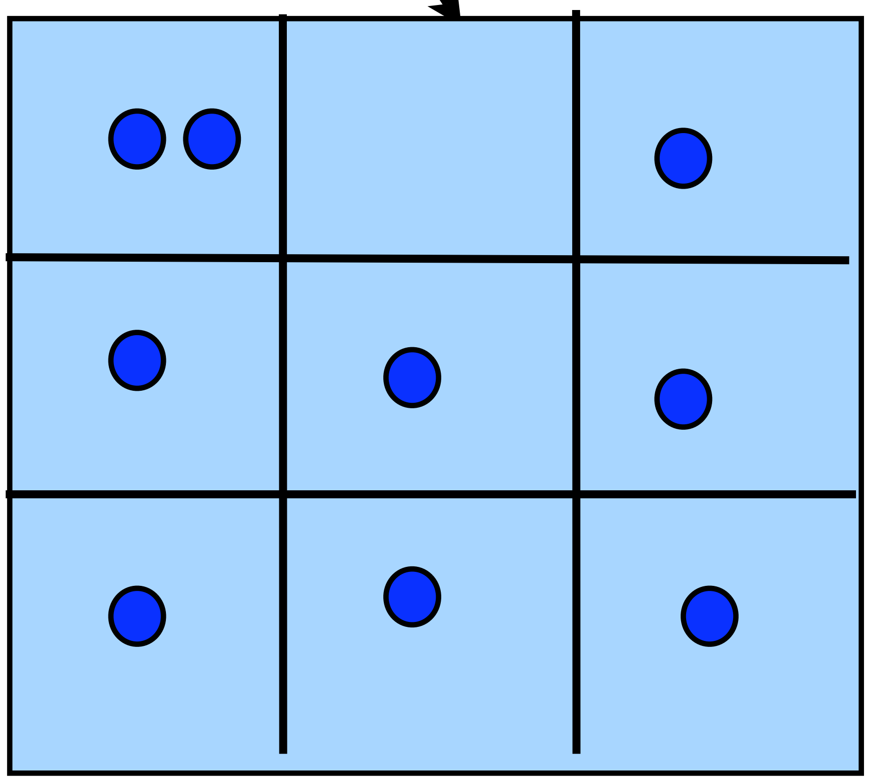
number of electron qp < number of bare electrons=> FL theory breaks down

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

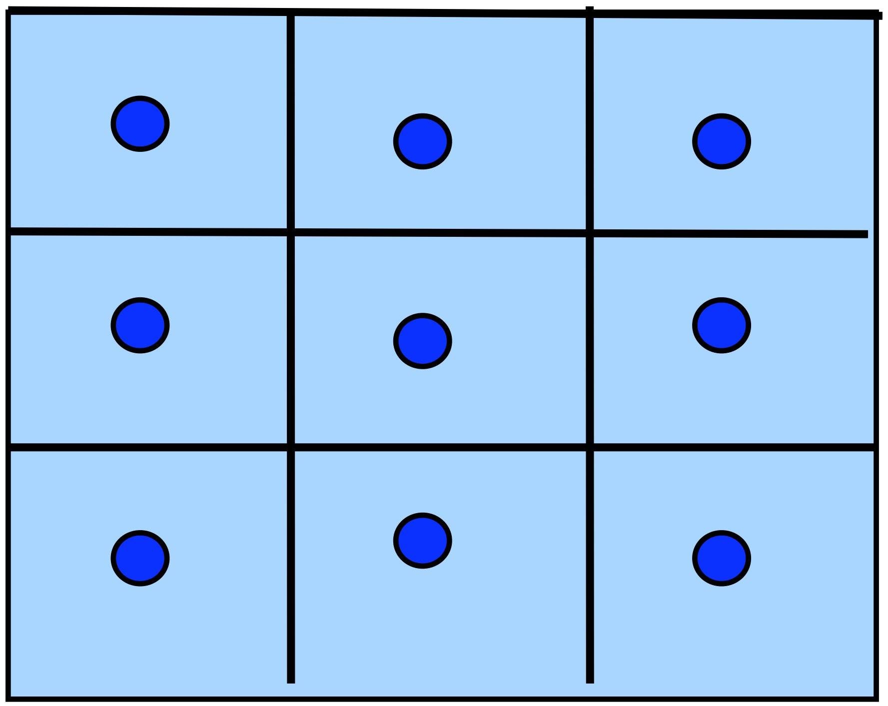
breakdown of electron quasi-particle picture: Mottness is the empty site mobile??



+ t/U



is the empty site
mobile??



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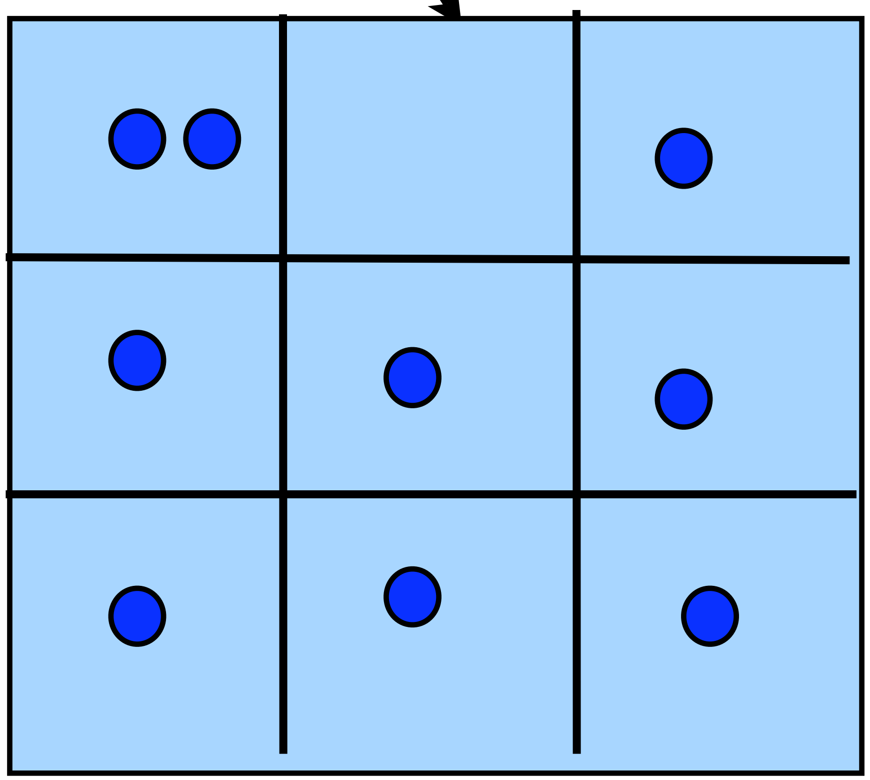
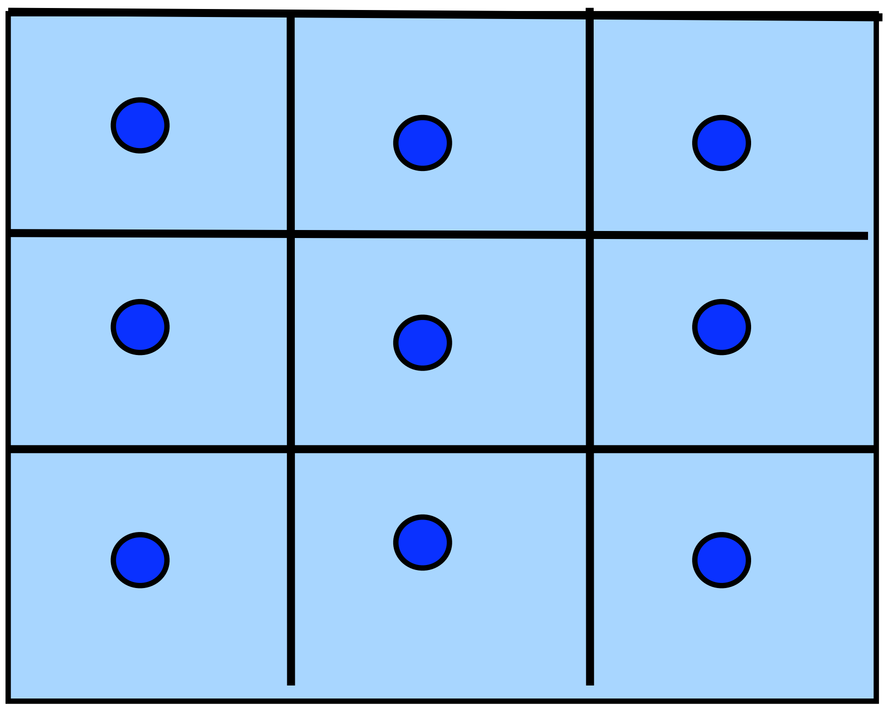


if yes, then 1.)
Mott insulator is a metal,
2.) no magnetic order

is the empty site mobile??



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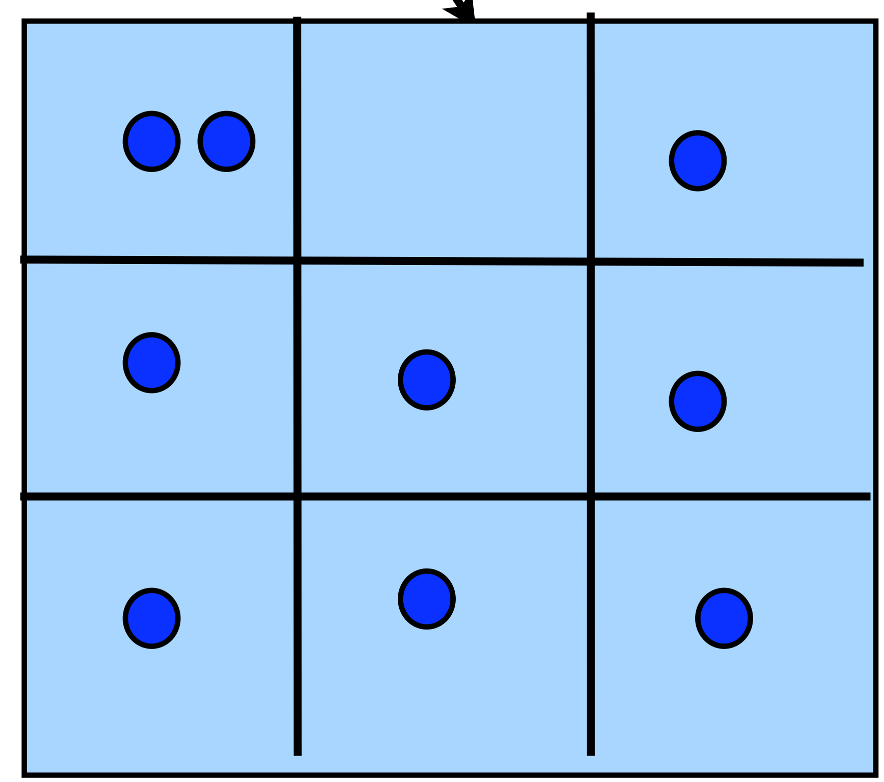

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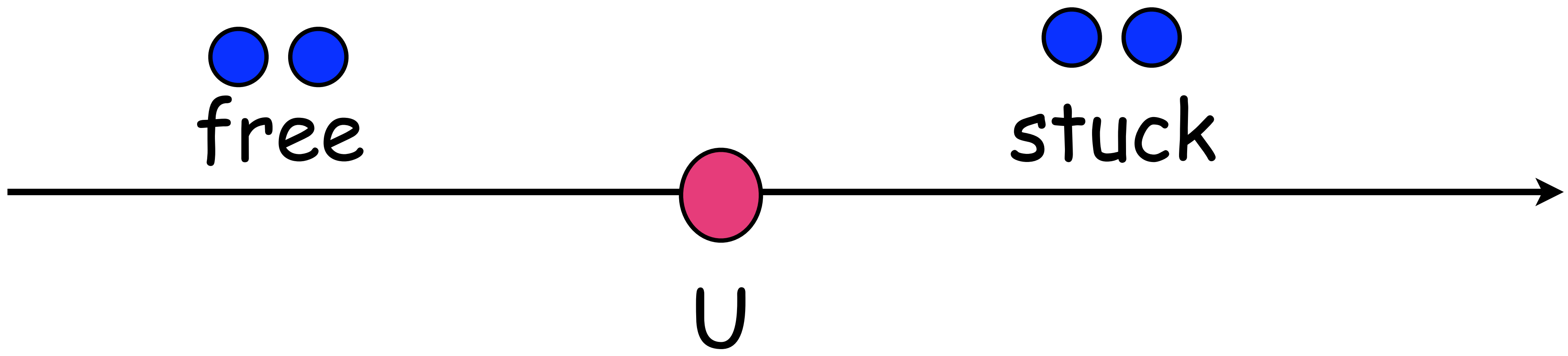
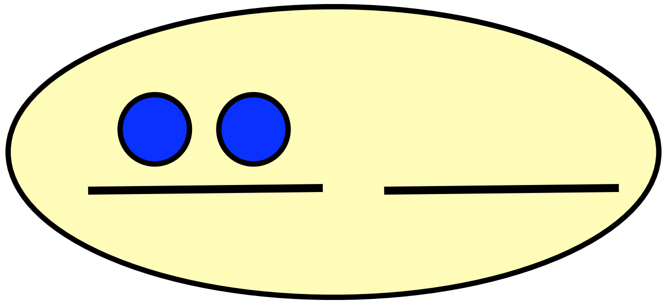
localisation criterion



Mott Problem: what is the dynamical degree of freedom that makes this happen?

new bound states

Kohn, Mott, Castellani, others



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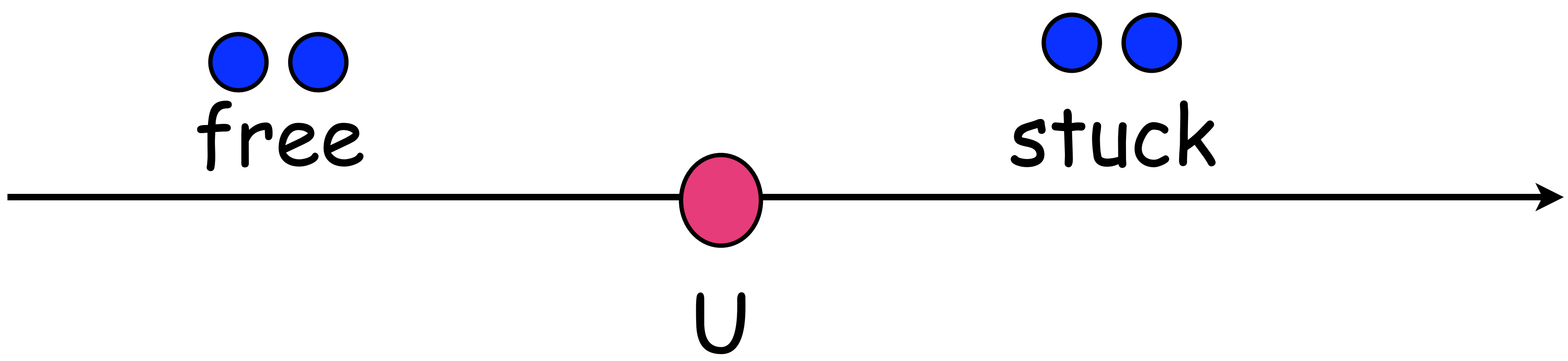

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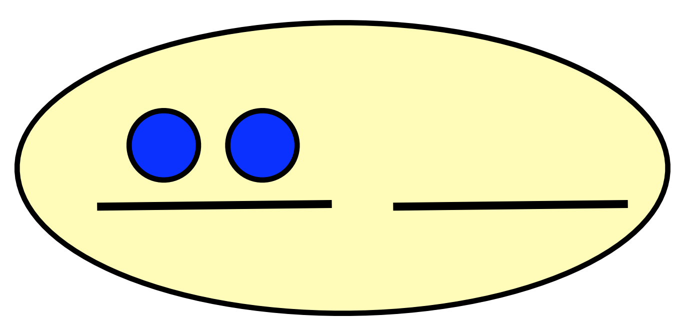

No proof exists? Mottness is ill-defined

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.

Church
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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

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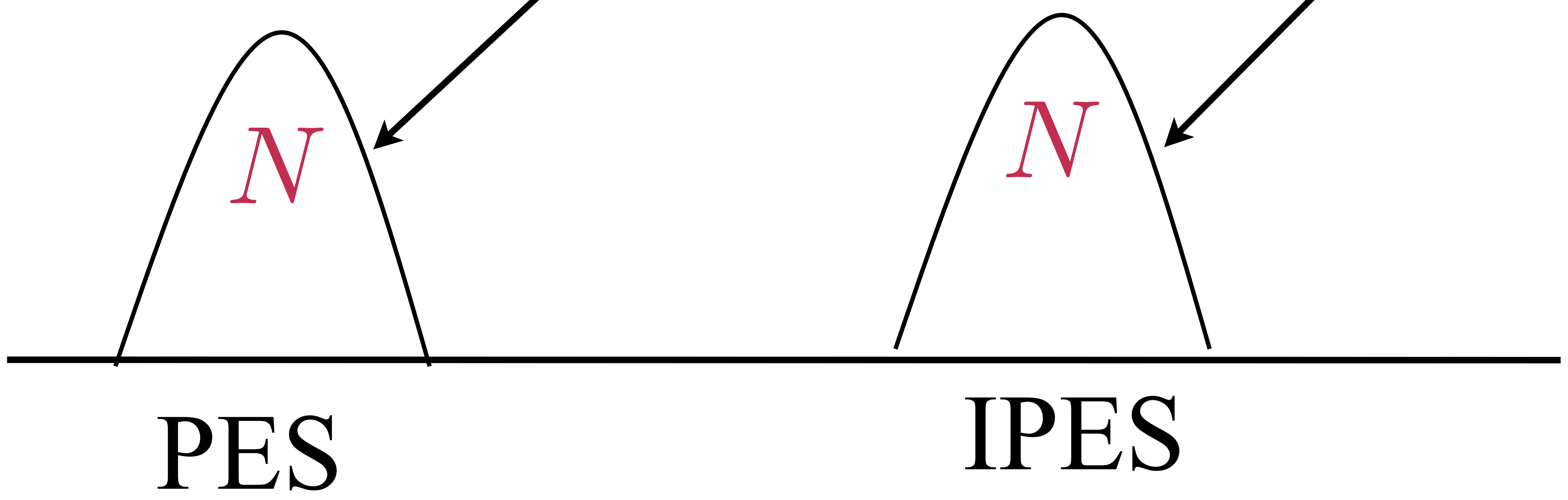
Fermi-liquid analogy

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

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

How?

Effective Theories:

$S(\phi)$ at half-filling

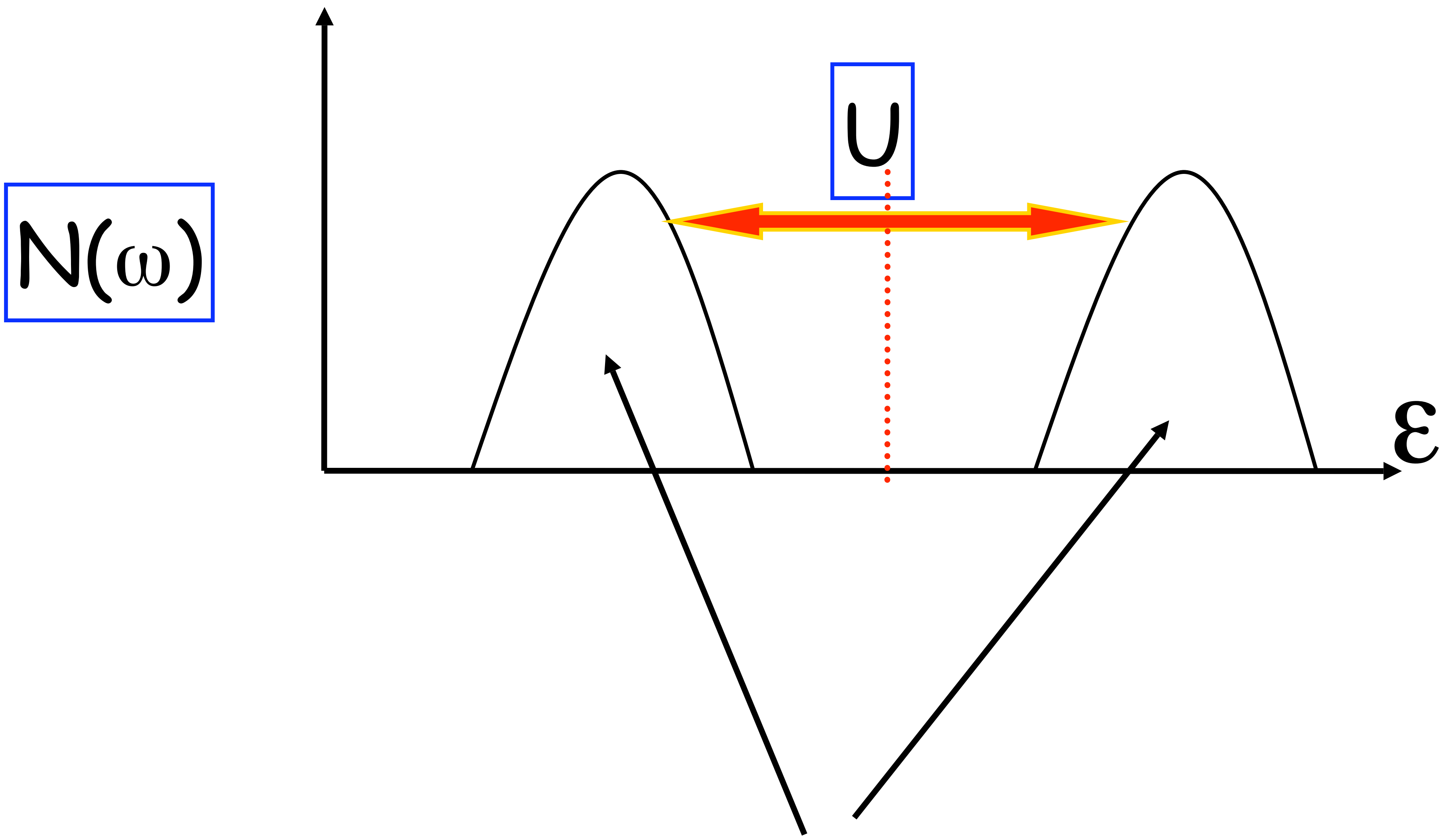
Integrate Out high Energy fields

$\phi = \phi_L + \phi_H$

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

Low-energy theory of M I

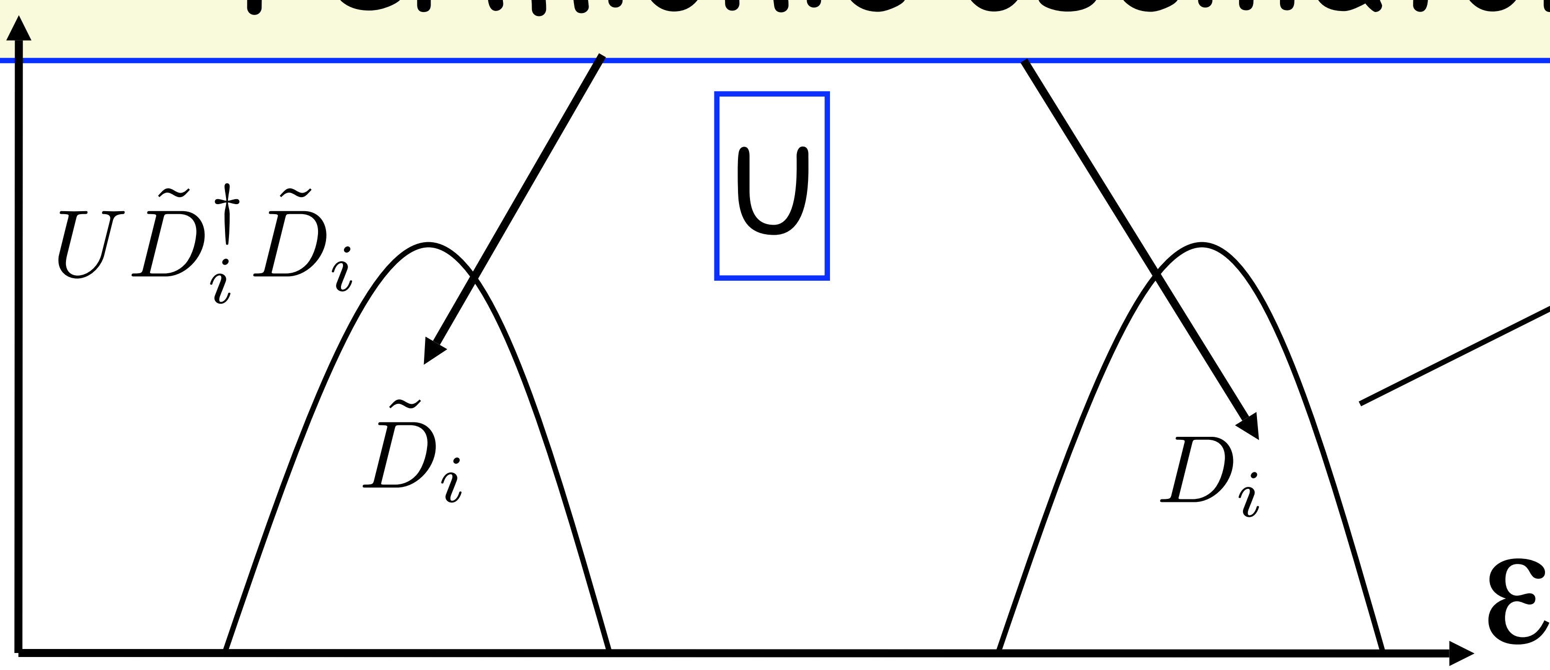
Half-filling



Integrate out both

Key idea: similar to Bohm/Pines

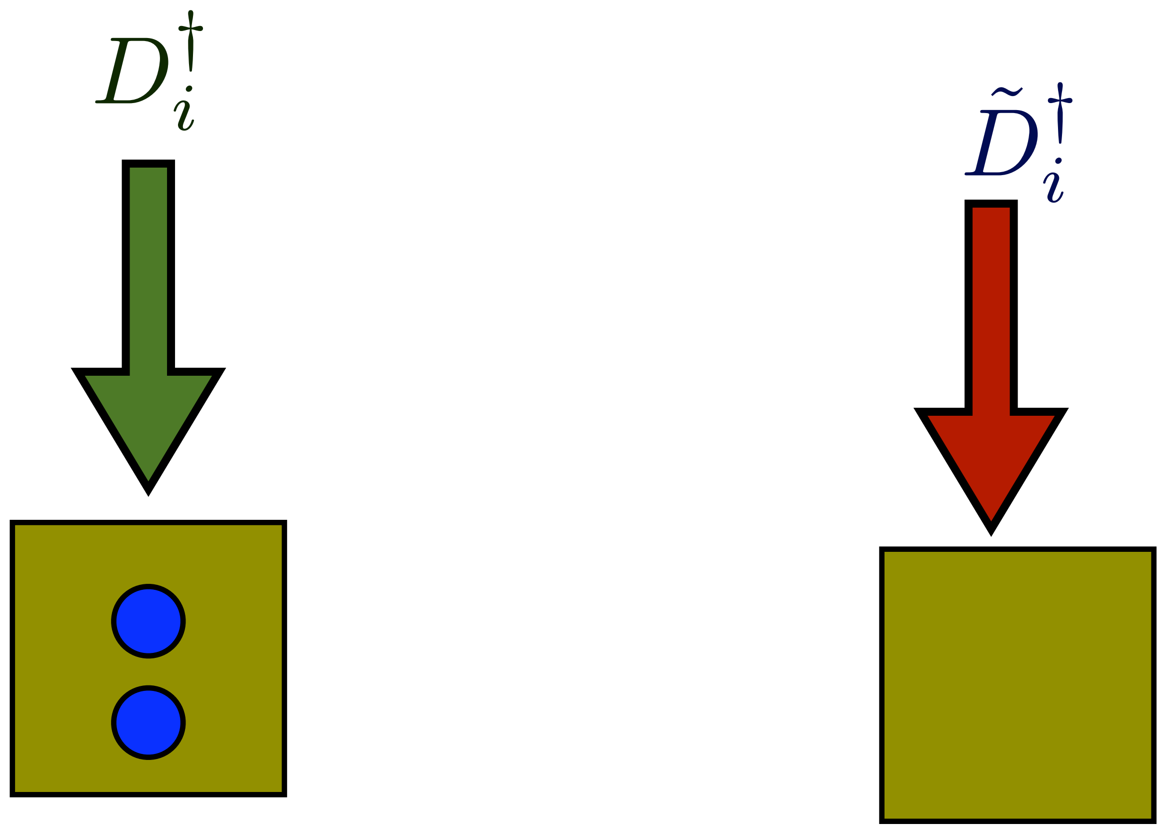
Extend the Hilbert space: Associate with U-scale new Fermionic oscillators



N(ω)

$$U D_i^\dagger D_i$$

Impose Constraint:

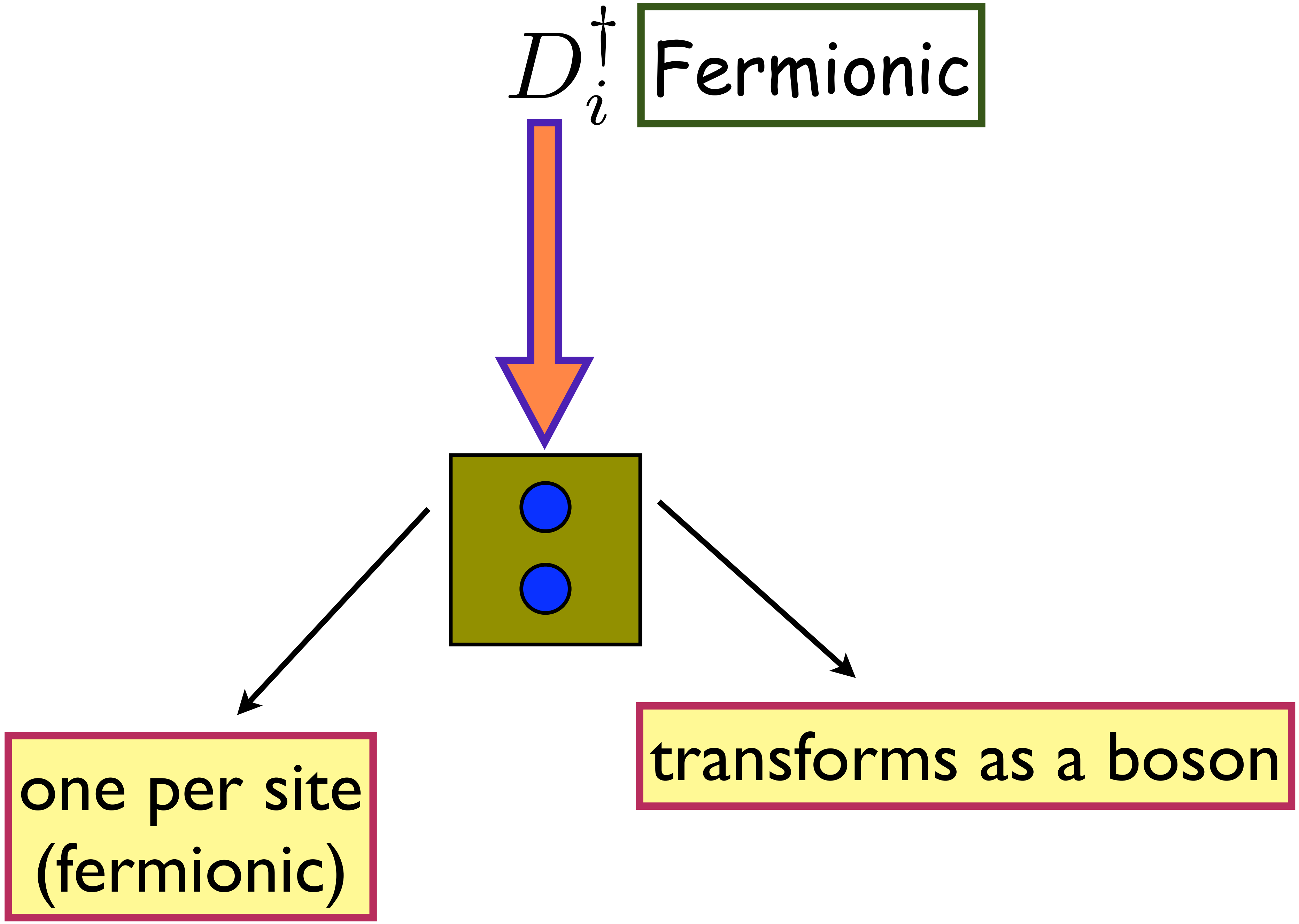


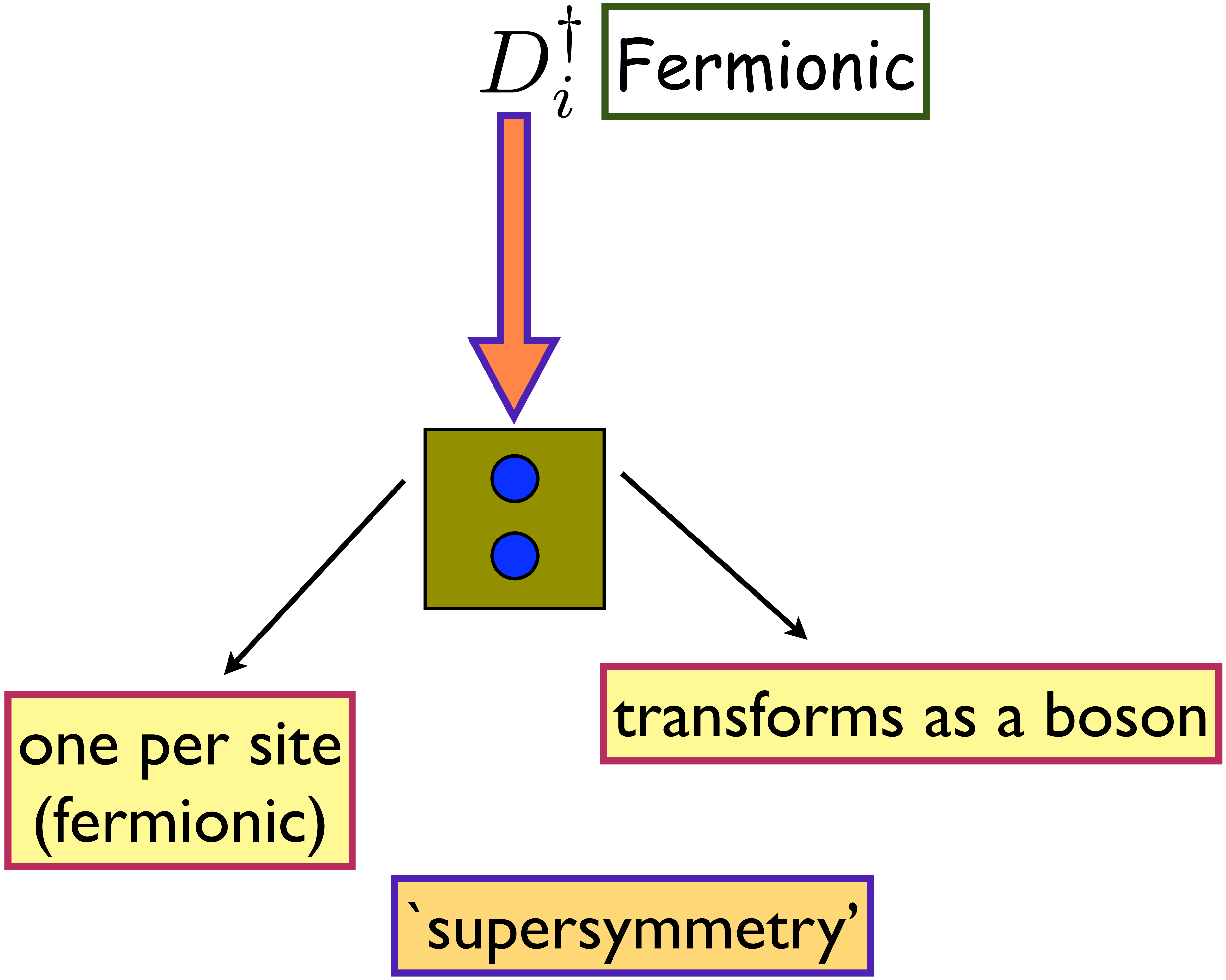
How is this possible with Fermions?

$D_i^\dagger$ Fermionic

one per site (fermionic)

transforms as a boson


$D_i^\dagger$
Fermionic
one per site
(fermionic)
transforms as a boson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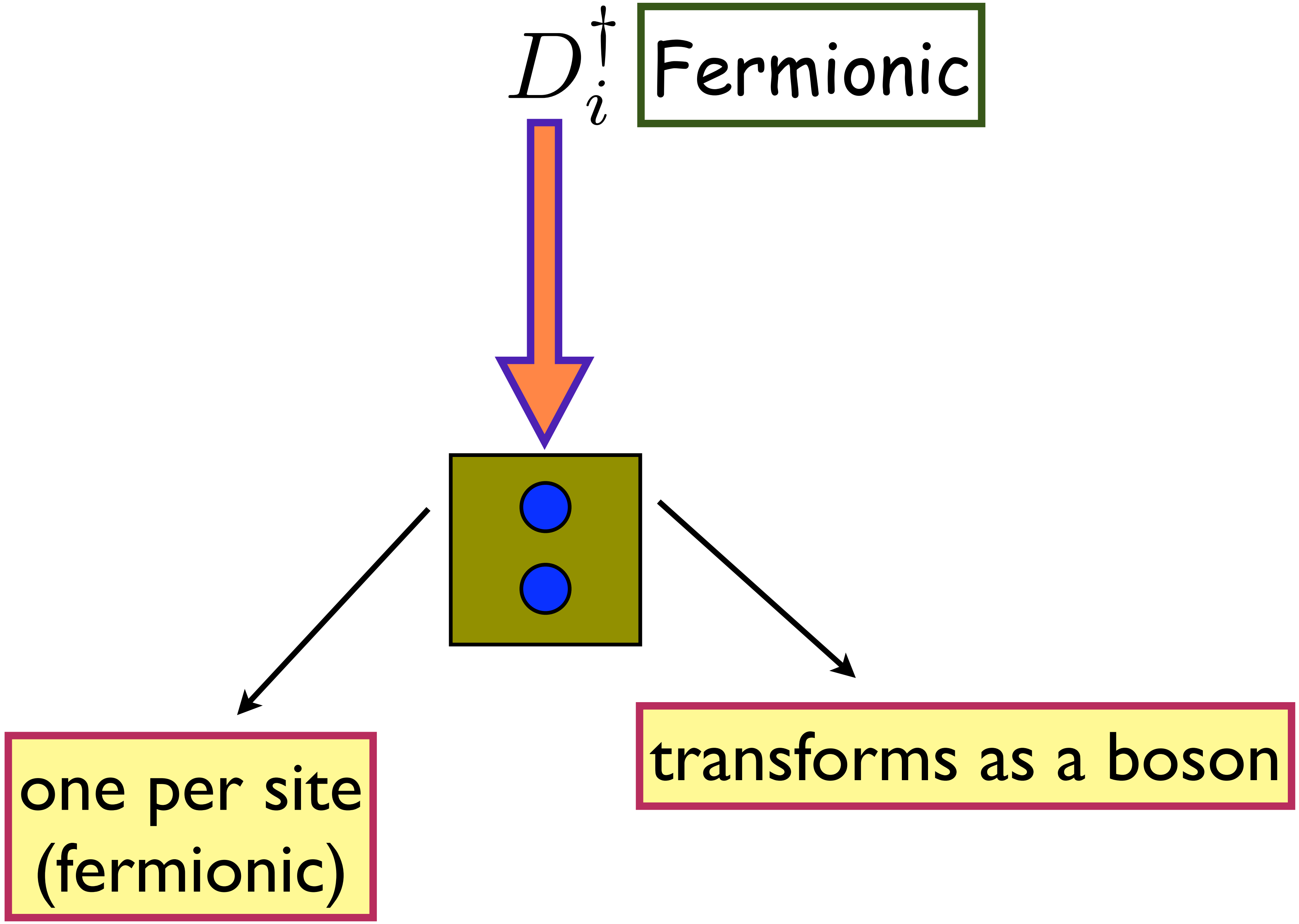
`supersymmetry'

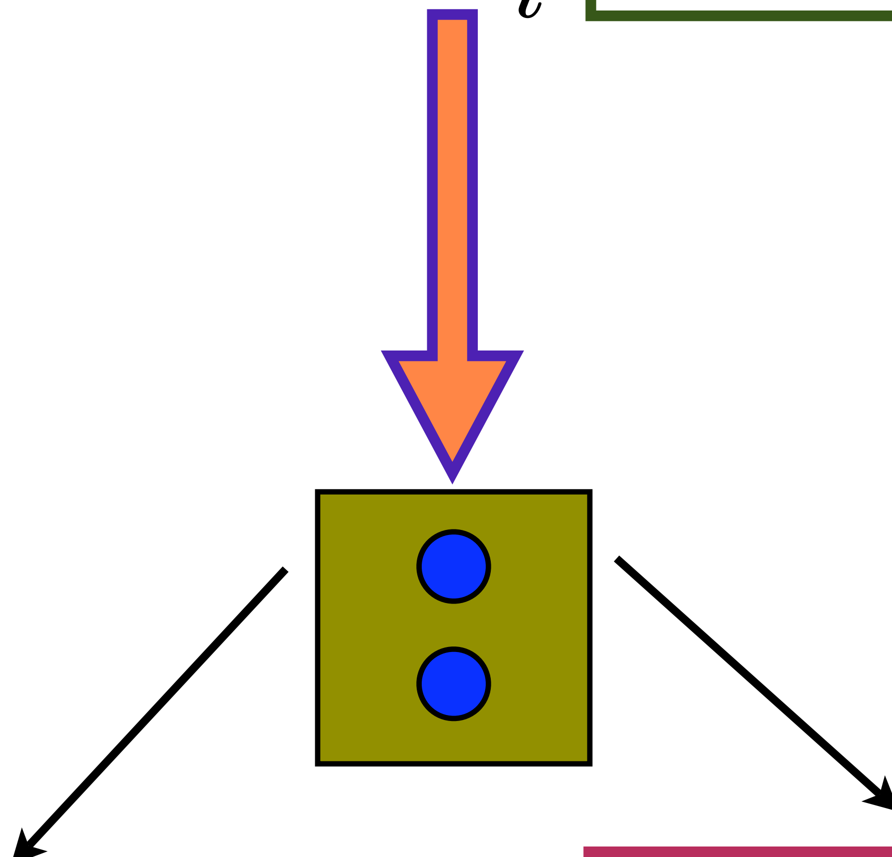


`supersymmetry'

Grassmann

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

$D_i^\dagger$ Fermionic



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\`supersymmetry'

Grassmann

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

String theory: $X^\mu(\sigma, \theta) = X^\mu(\sigma) + \theta \gamma^\mu(\sigma)$

Dual Theory

solve constraint

integrate over heavy fields

UV limit

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

Exact low-energy theory (IR limit)

$\boxed{\text{Exact low-energy Lagrangian}}$

$$L \quad = \quad \#L_{\text{bare}}(\text{electrons}) + \#\text{L}_{\text{bare}}(\text{bosons})$$

$$+f(\omega)L_{\text{int}}(c,\varphi) \;+\tilde{f}(\omega)L_{\text{int}}(c,\tilde{\varphi})$$

$$f(\omega) = 0$$

dispersion
of propagating
modes

composite excitations

$\boxed{\text{New interactions beyond spin physics}}$

$$L \quad = \quad \# L_{\text{bare}}(\text{electrons}) + \#\mathrm{L}_{\text{bare}}(\text{bosons})$$

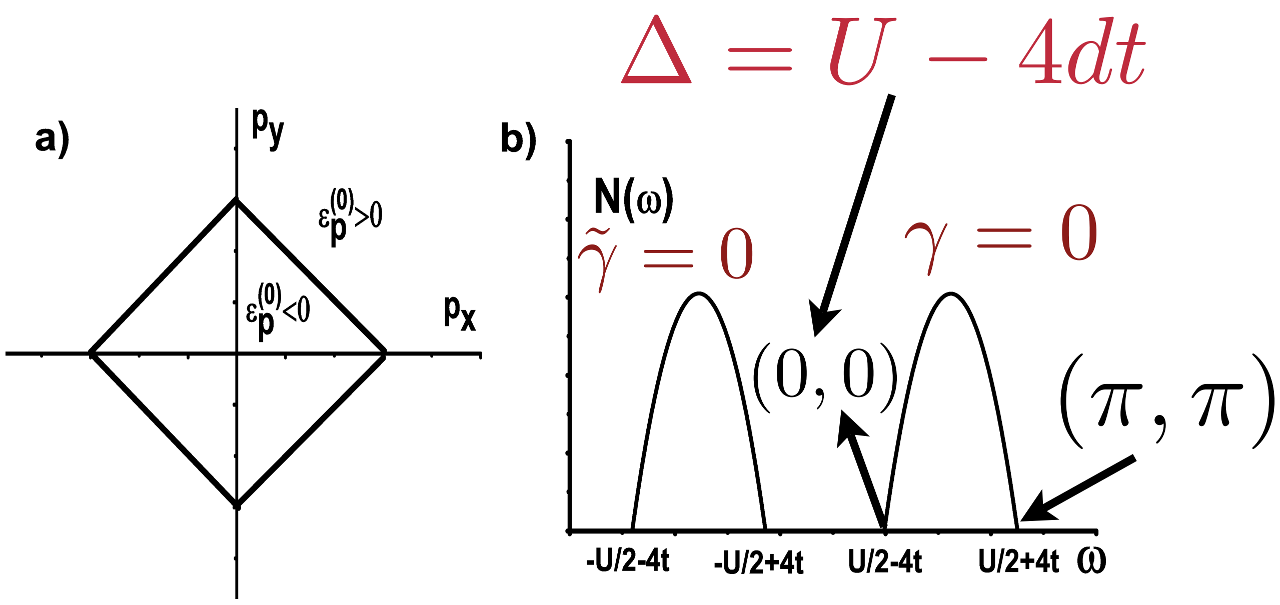
$$+f(\omega) \underbrace{L_{\text{int}}}_{\Psi^\dagger \Psi}(c,\varphi) \; + \tilde{f}(\omega) \underbrace{L_{\text{int}}}_{\tilde{\Psi}^\dagger \tilde{\Psi}}(c,\tilde{\varphi})$$

quadratic form:
composite or bound
excitations of
$\varphi^\dagger c_{i\sigma}$

composite excitations determine spectral density

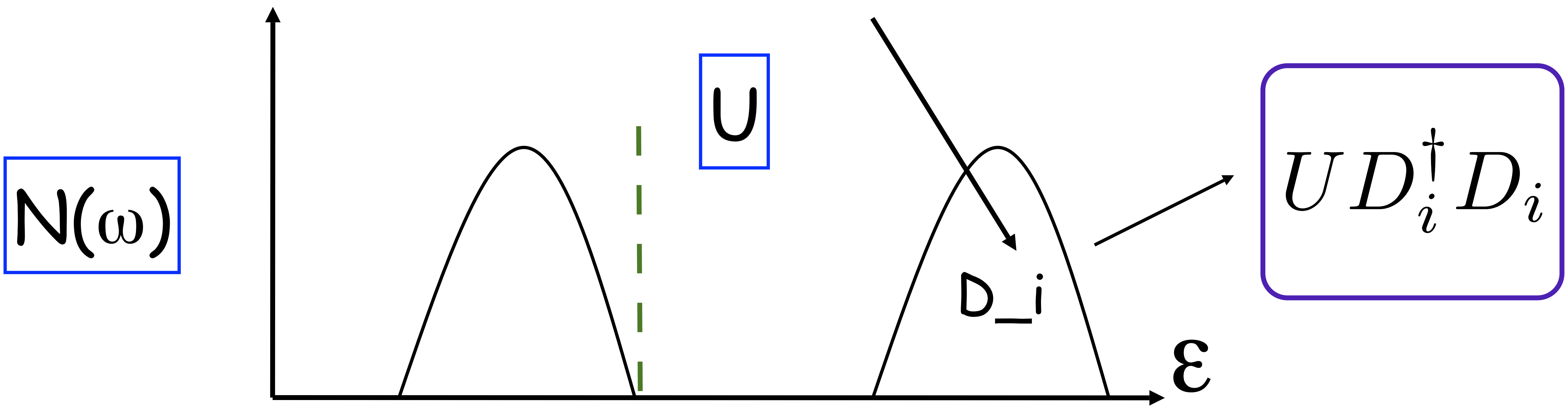
$$\gamma_{\vec{p}}^{(\vec{k})}(\omega) = \frac{U - t\varepsilon_{\vec{p}}^{(\vec{k})} - 2\omega}{U}\sqrt{1 + 2\omega/U}$$

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



each momentum has SD at two distinct energies hole-doping

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



charge 2e boson field (non-propagating)

$$H_h^{IR} = H_{t-J} \quad \boxed{-\frac{t^2}{U}\sum_i \varphi_i^\dagger \varphi_i - t\sum_j \varphi_j^\dagger c_{j,\uparrow} c_{j,\downarrow} + \frac{t^2}{U}\sum_{i,j} \varphi_i^\dagger b_i + h.c.} \quad ,$$

Non-projective

$$b_i = \sum_j g_{ij}(c_{i\downarrow}c_{j\uparrow} - c_{i\uparrow}c_{j\downarrow})$$

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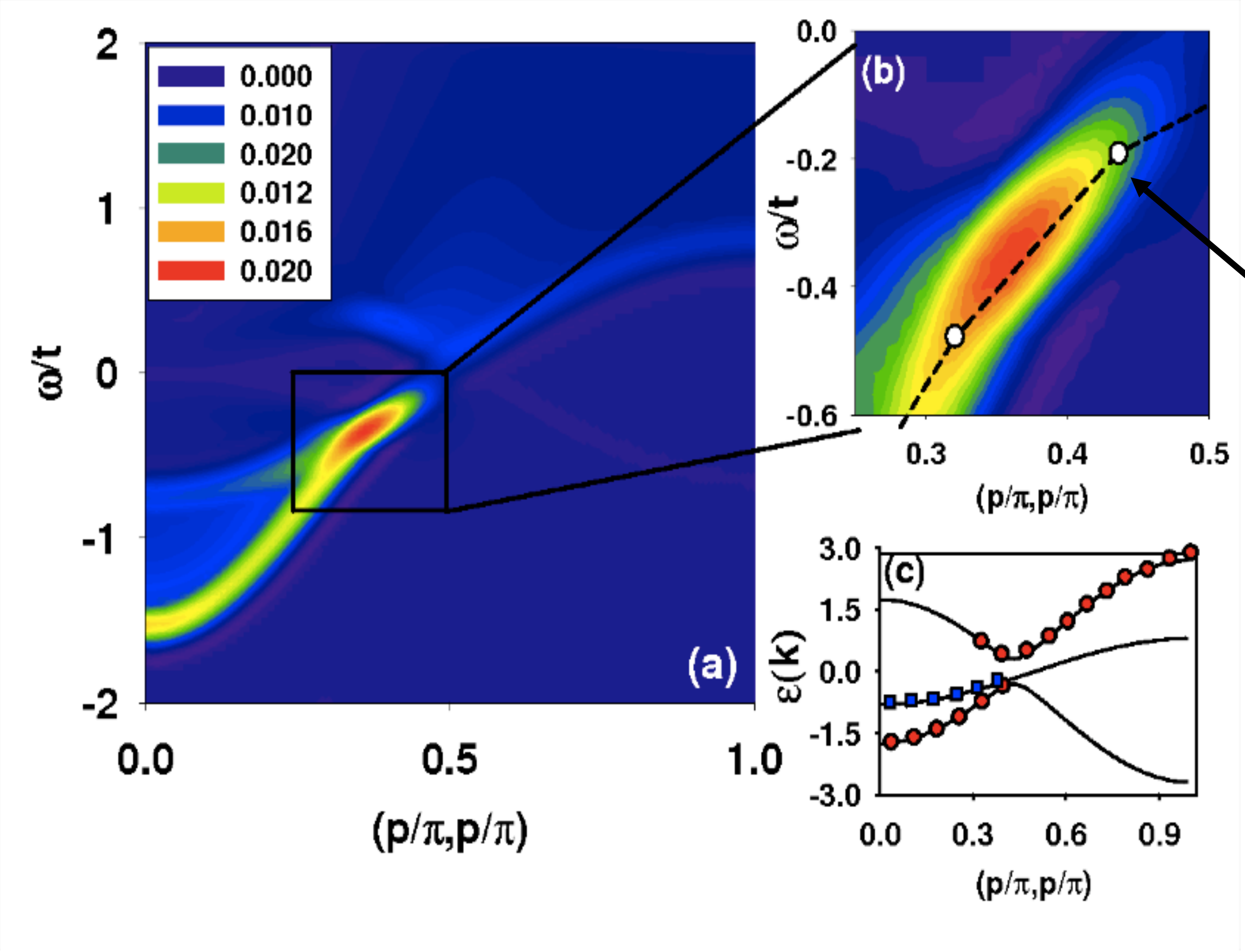
Non-projective

$$b_i = \sum_j g_{ij}(c_{i\downarrow}c_{j\uparrow} - c_{i\uparrow}c_{j\downarrow})$$

φ_i is an emergent degree of freedom

Not made out of the elemental fields

Electron spectral function

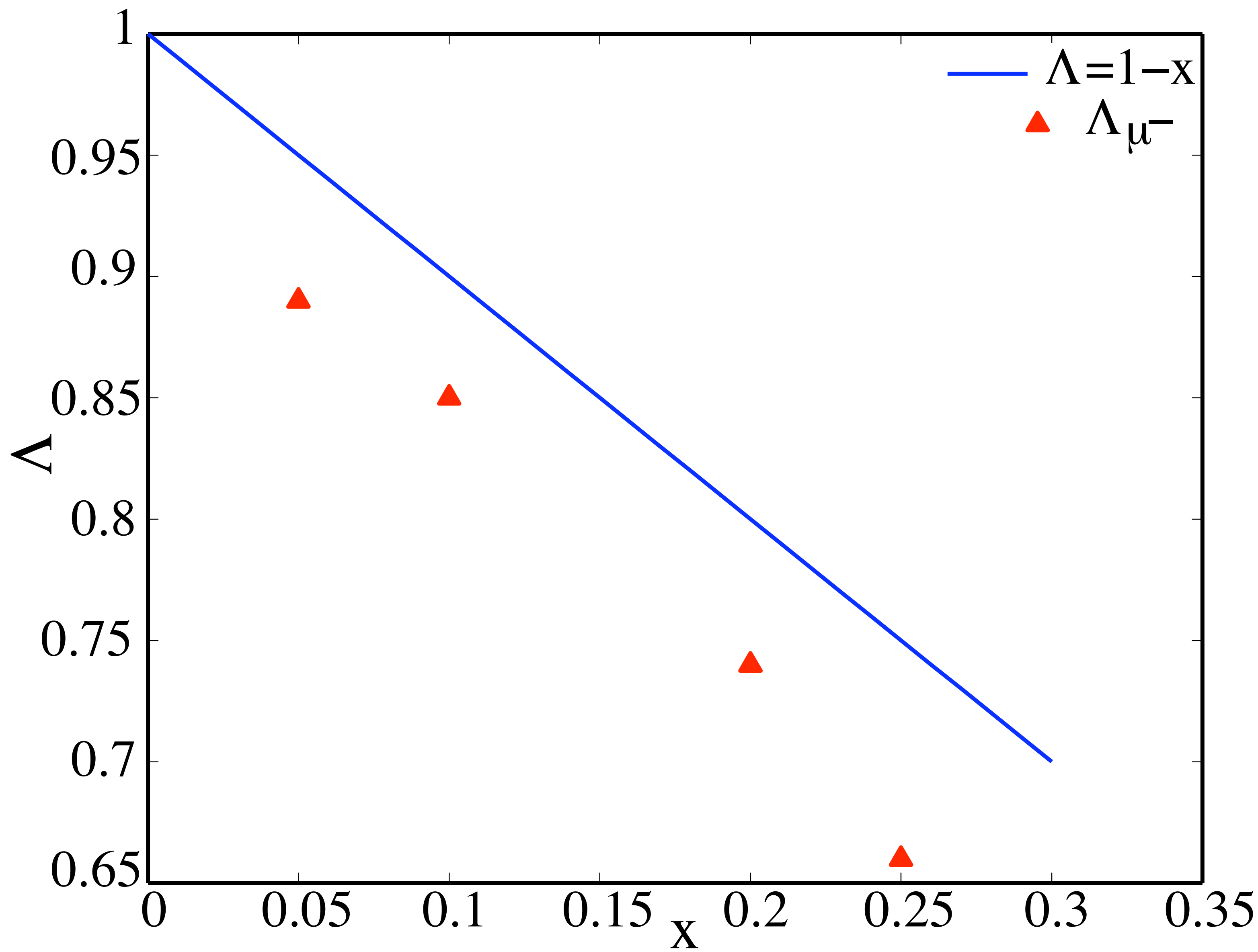


$t^2/U \sim 60$meV

Electron spectral function

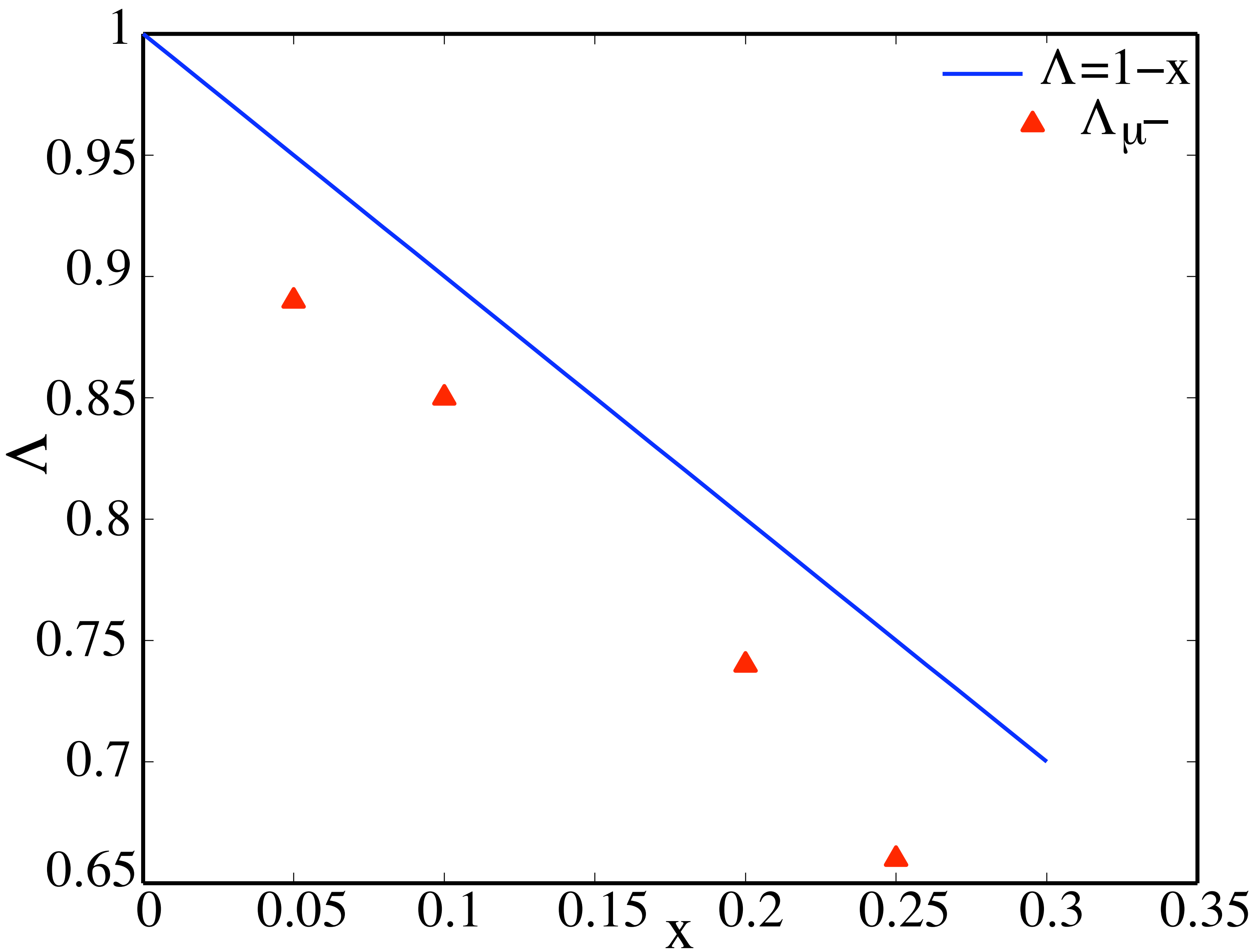
$t^2/U \sim 60\text{meV}$

Electron spectral function



²/U~60meV

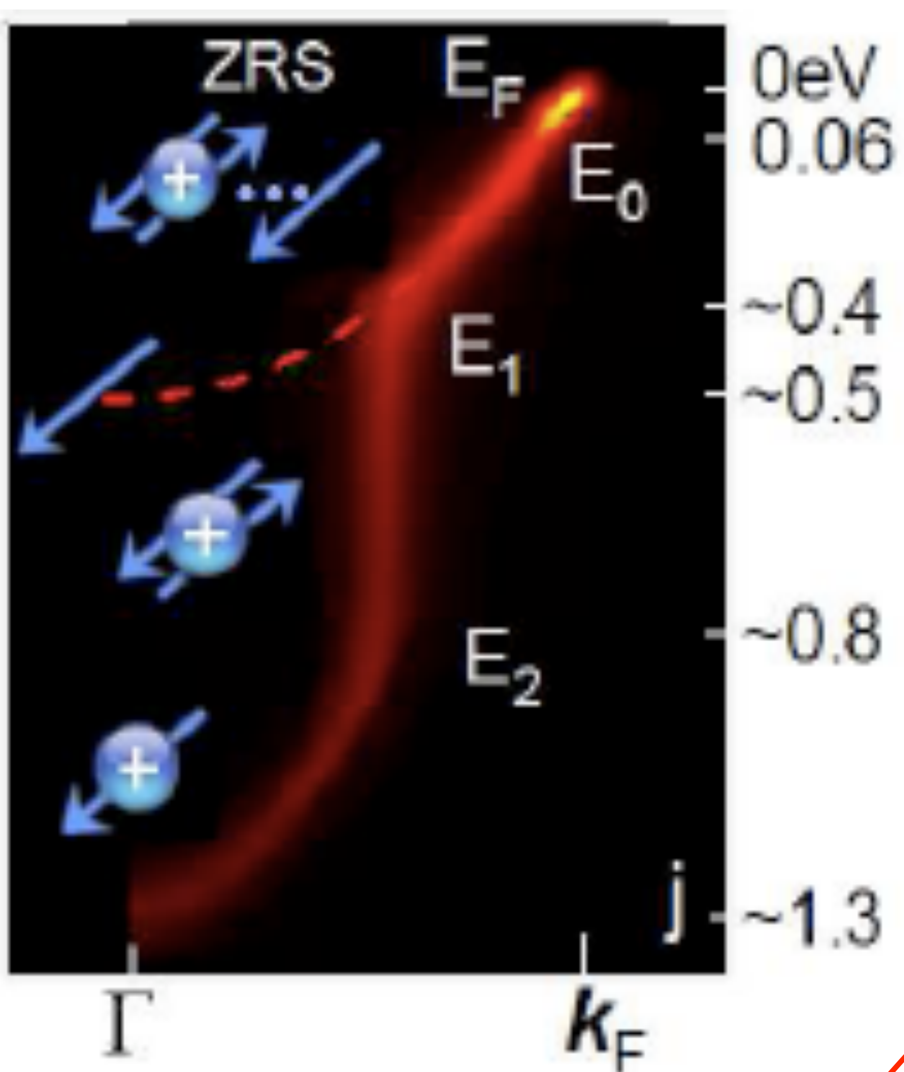
Electron spectral function

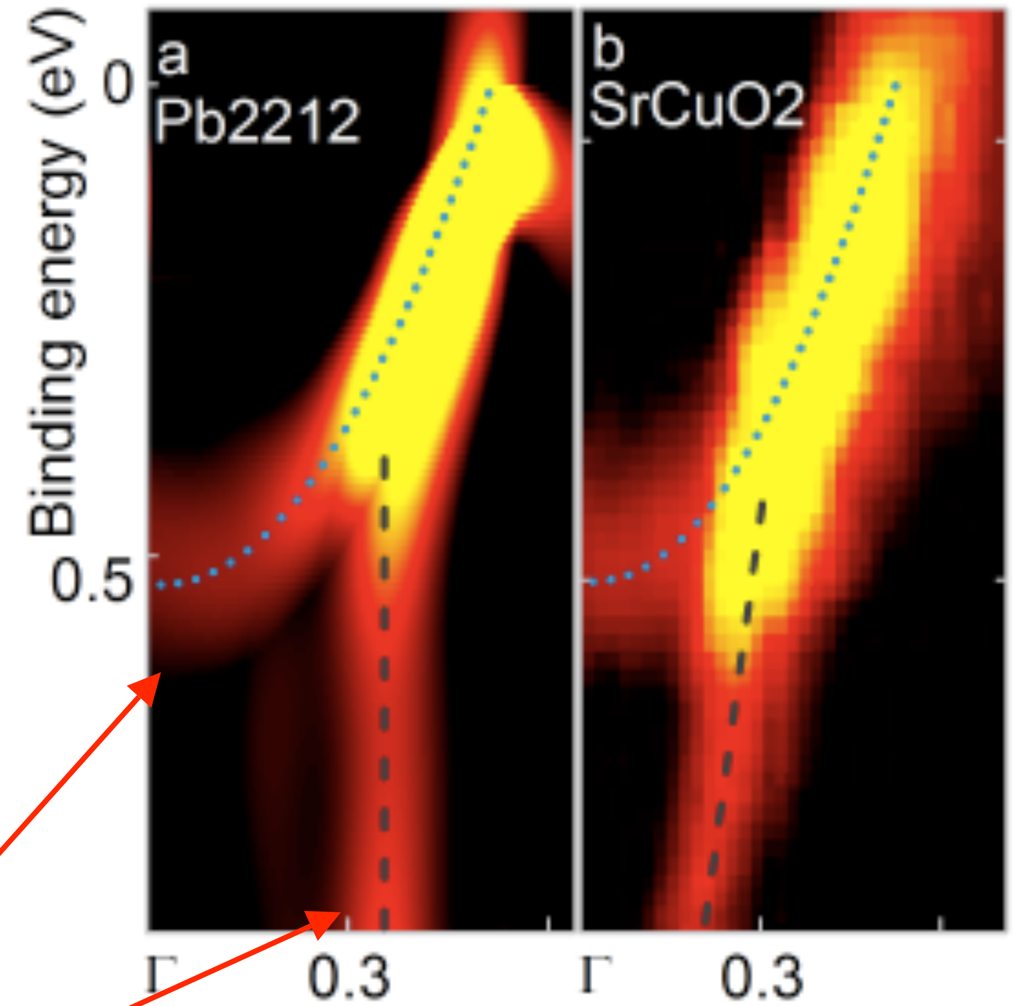


²/U~60meV

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?

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

Origin of two bands

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

Origin of two bands

Two charge e excitations

$c_{i\sigma}$

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

New bound state

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

Origin of two bands

Two charge e excitations

$c_{i\sigma}$

φ_i is confined (no kinetic energy)

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

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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

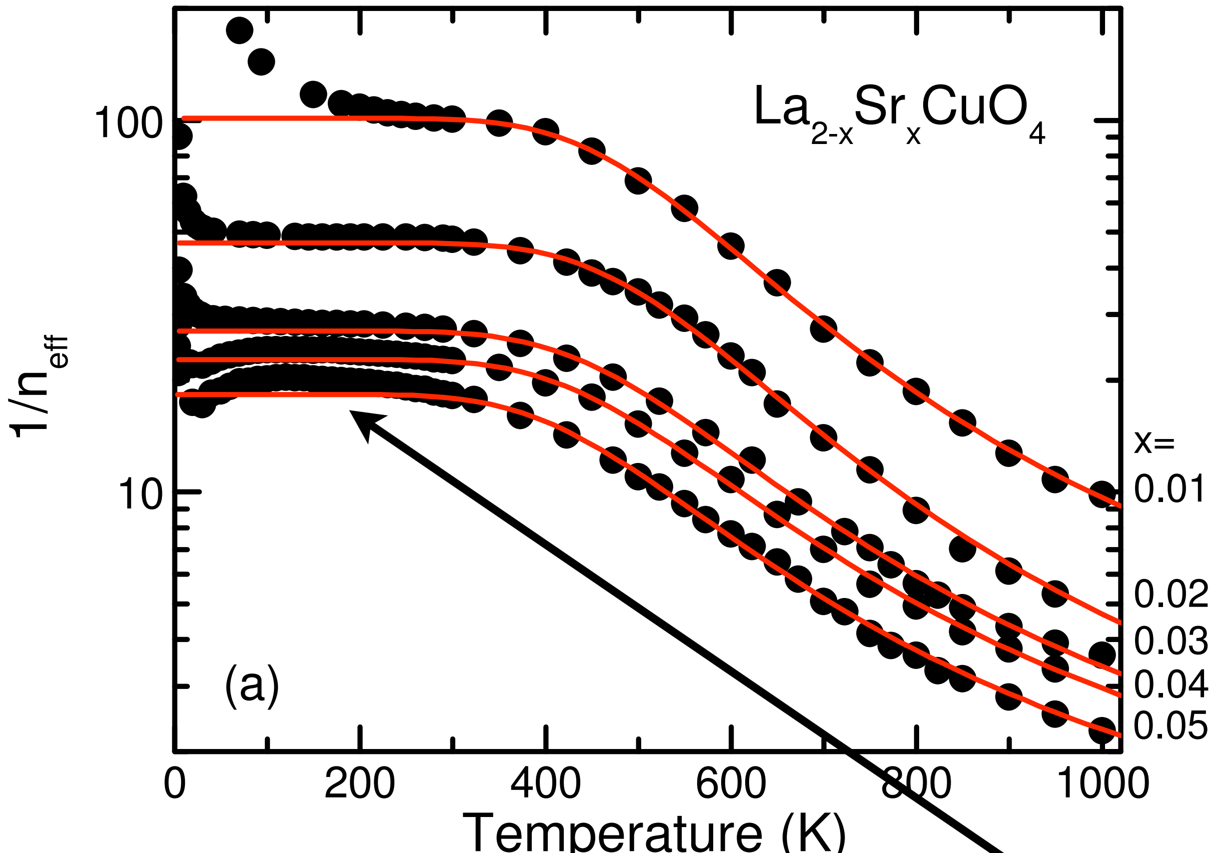
direct evidence

direct evidence

charge carrier density:

direct evidence

charge carrier density:

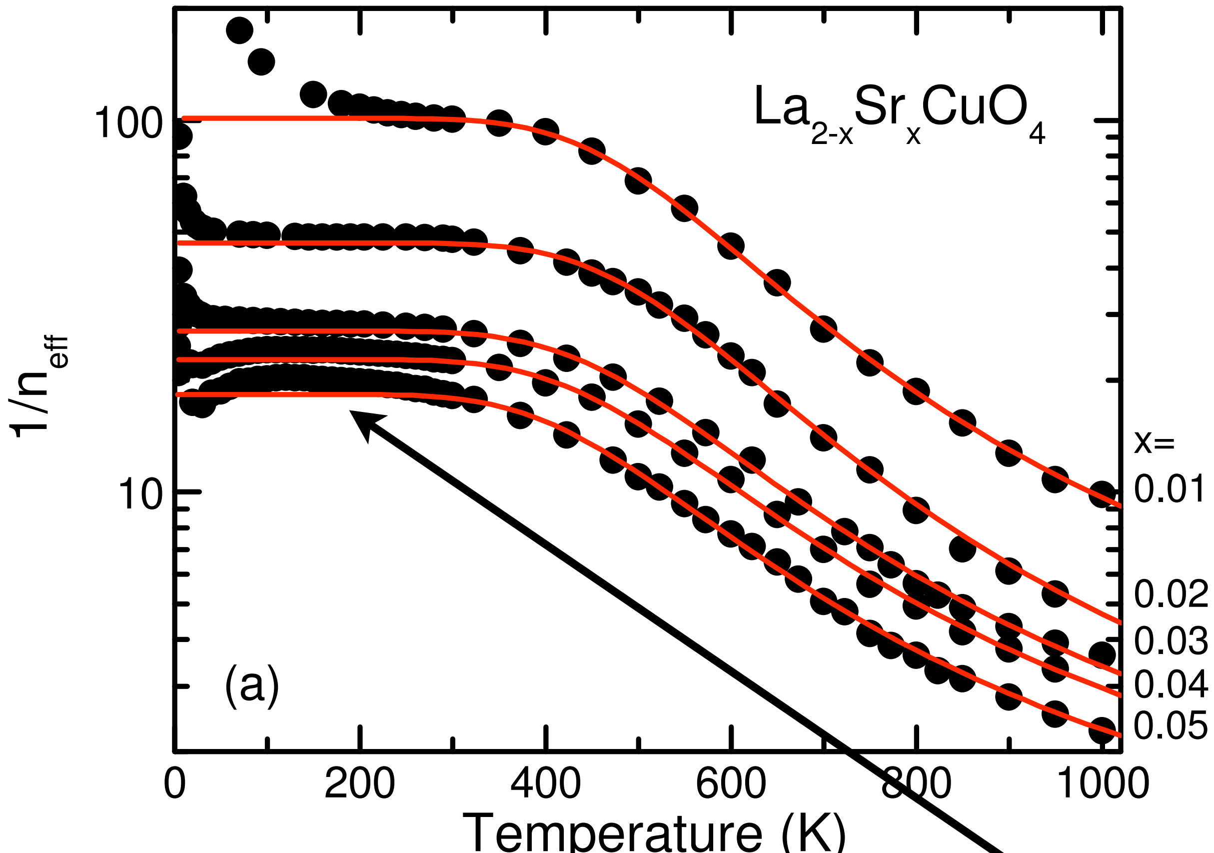


Ono, et al., Phys. Rev. B 75, 024515 (2007)

$$n_{\rm Hall}(x,T) = n_0(x) + n_1(x)\exp(-\Delta(x)/T),$$ PRL, vol. 97, 247003 (2006).

direct evidence

charge carrier density:

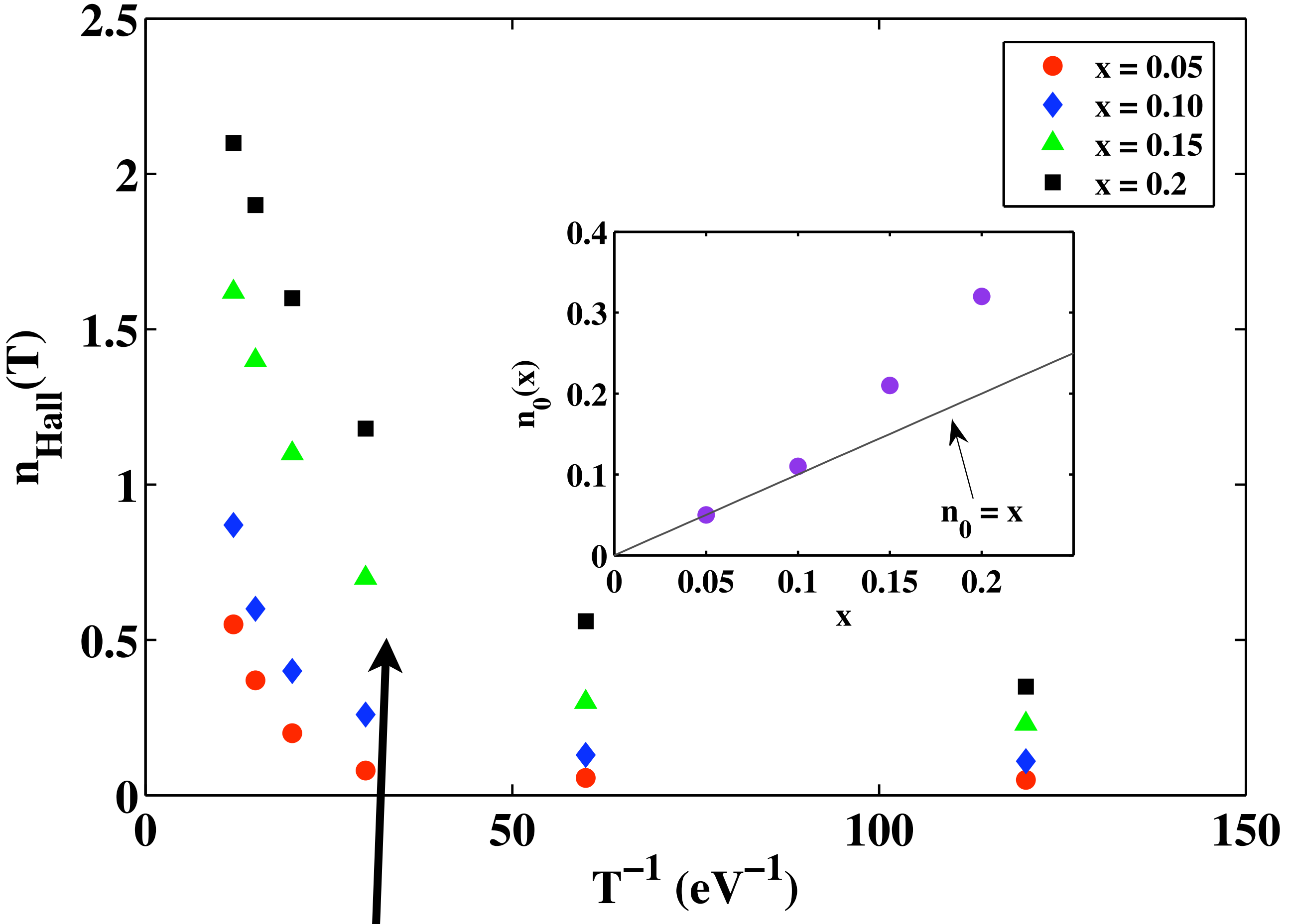


Ono, et al., Phys. Rev. B 75, 024515 (2007)

$$n_{\mathrm{Hall}}(x,T) = n_0(x) + n_1(x)\exp(-\Delta(x)/T),$$ PRL, vol. 97, 247003 (2006).

exponentially suppressed: confinement

Our Theory

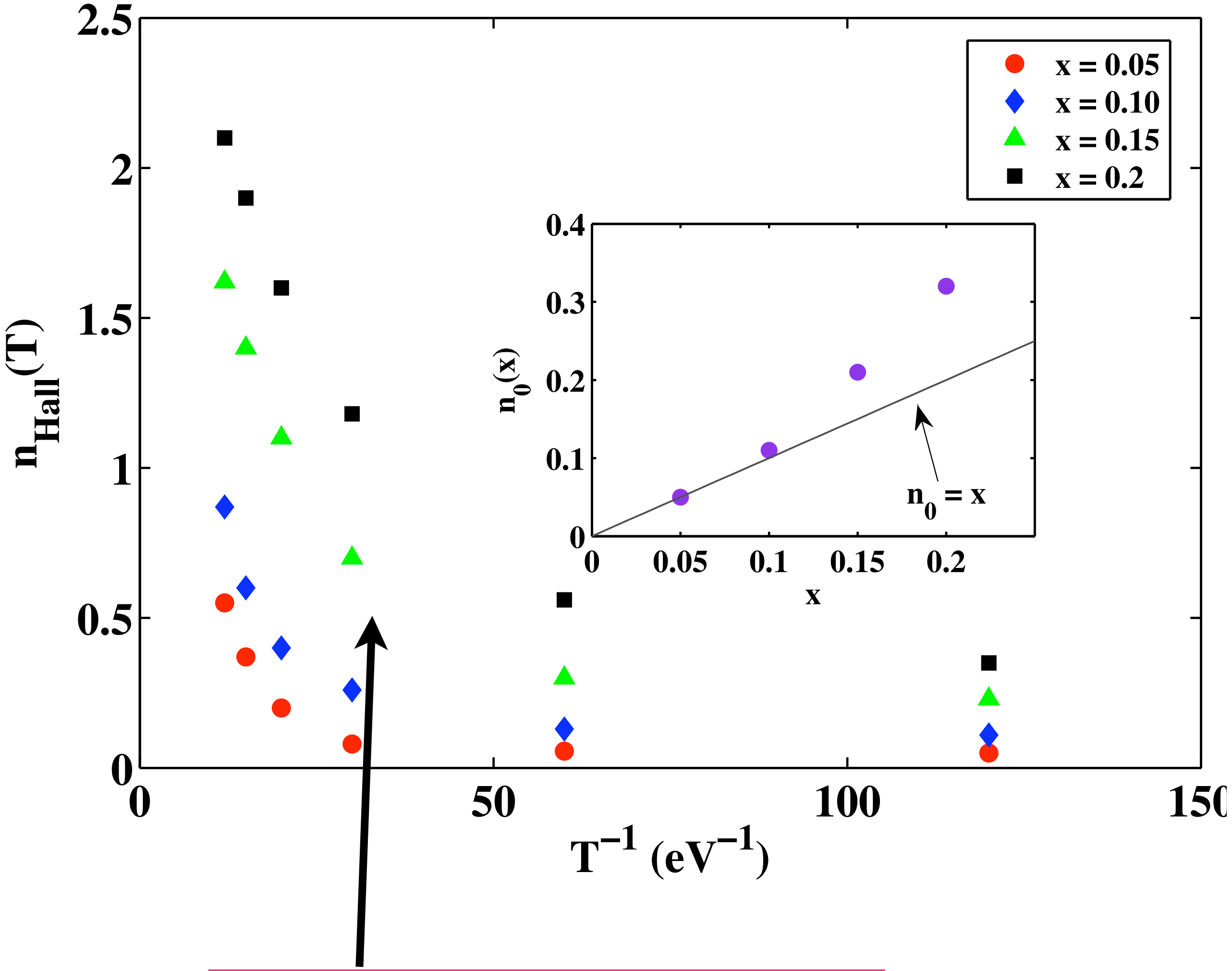


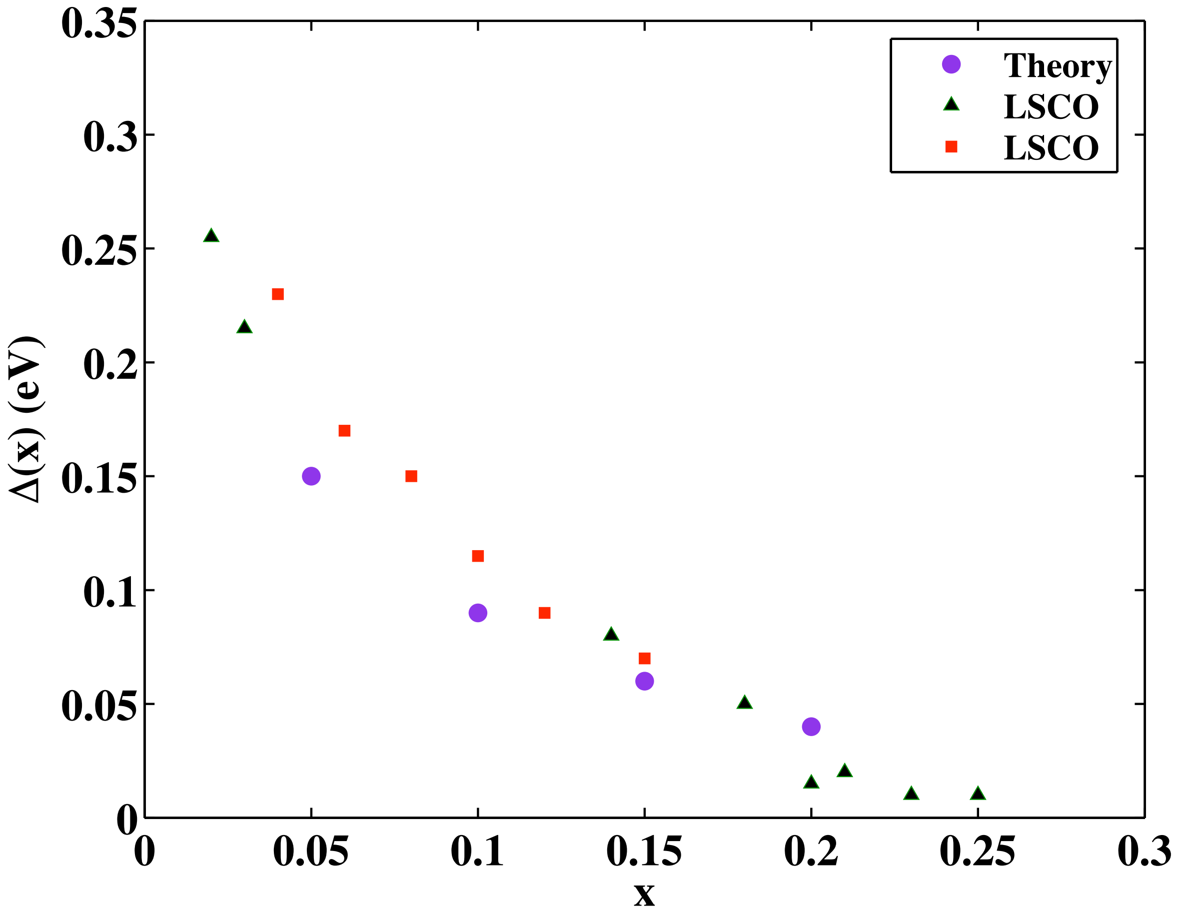
exponential T-dependence

no model-dependent free parameters: just t/U

Our Theory

gap



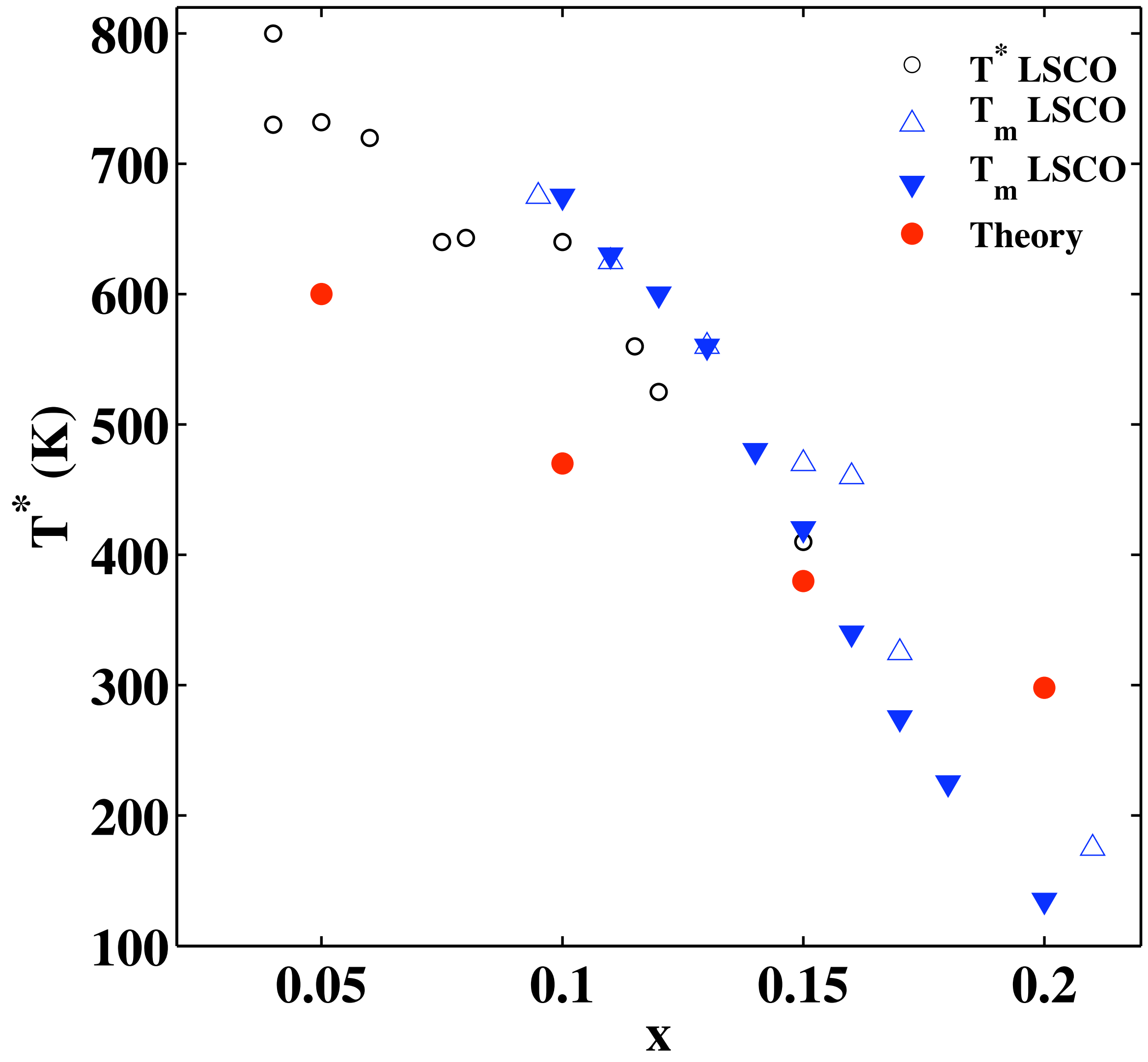


exponential T-dependence

no model-dependent free parameters: just t/U

Like Mott gap,
Pseudogap is a bound-state
problem with new IR modes

strange metal: breakup (deconfinement) of bound states



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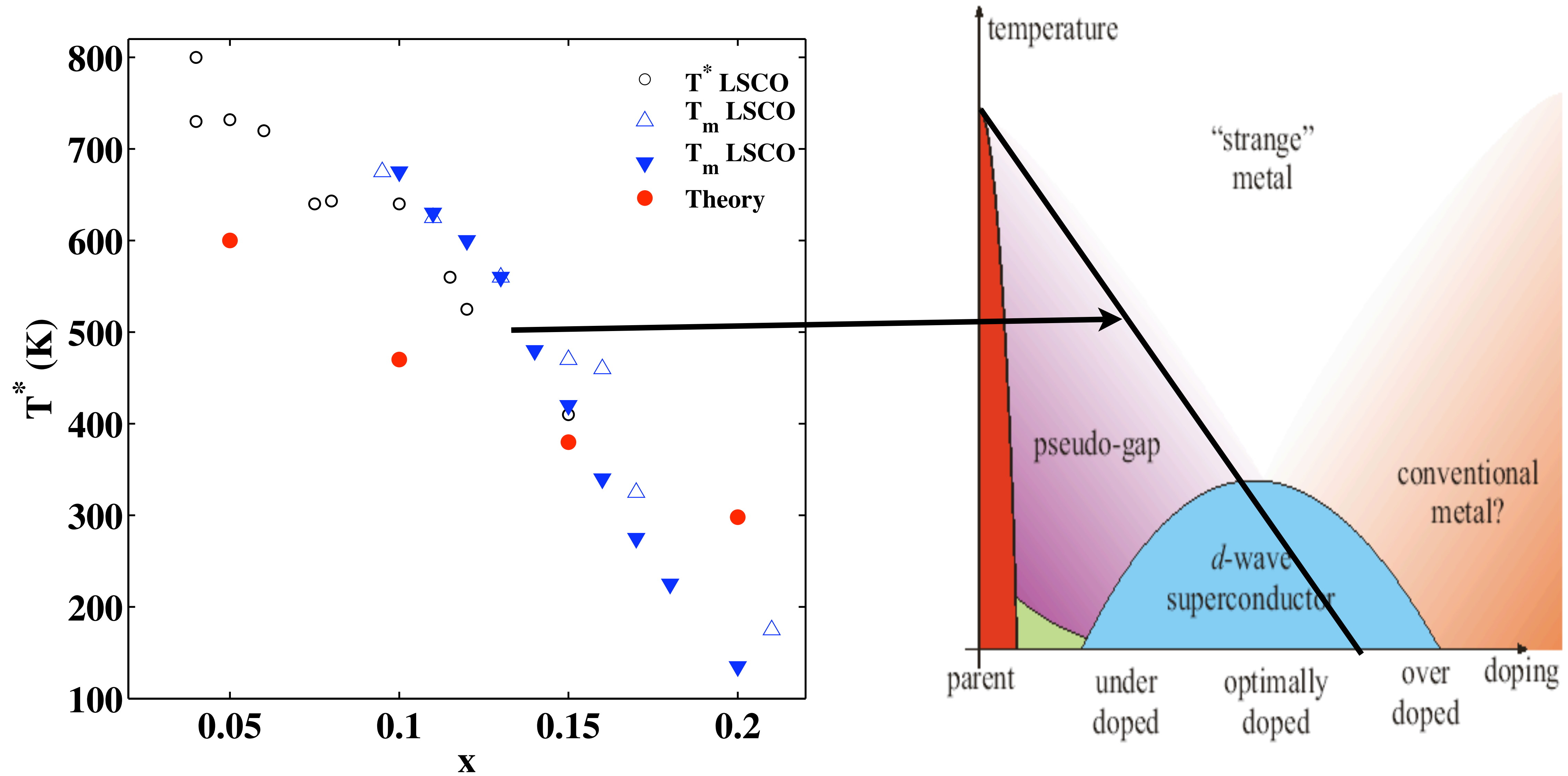

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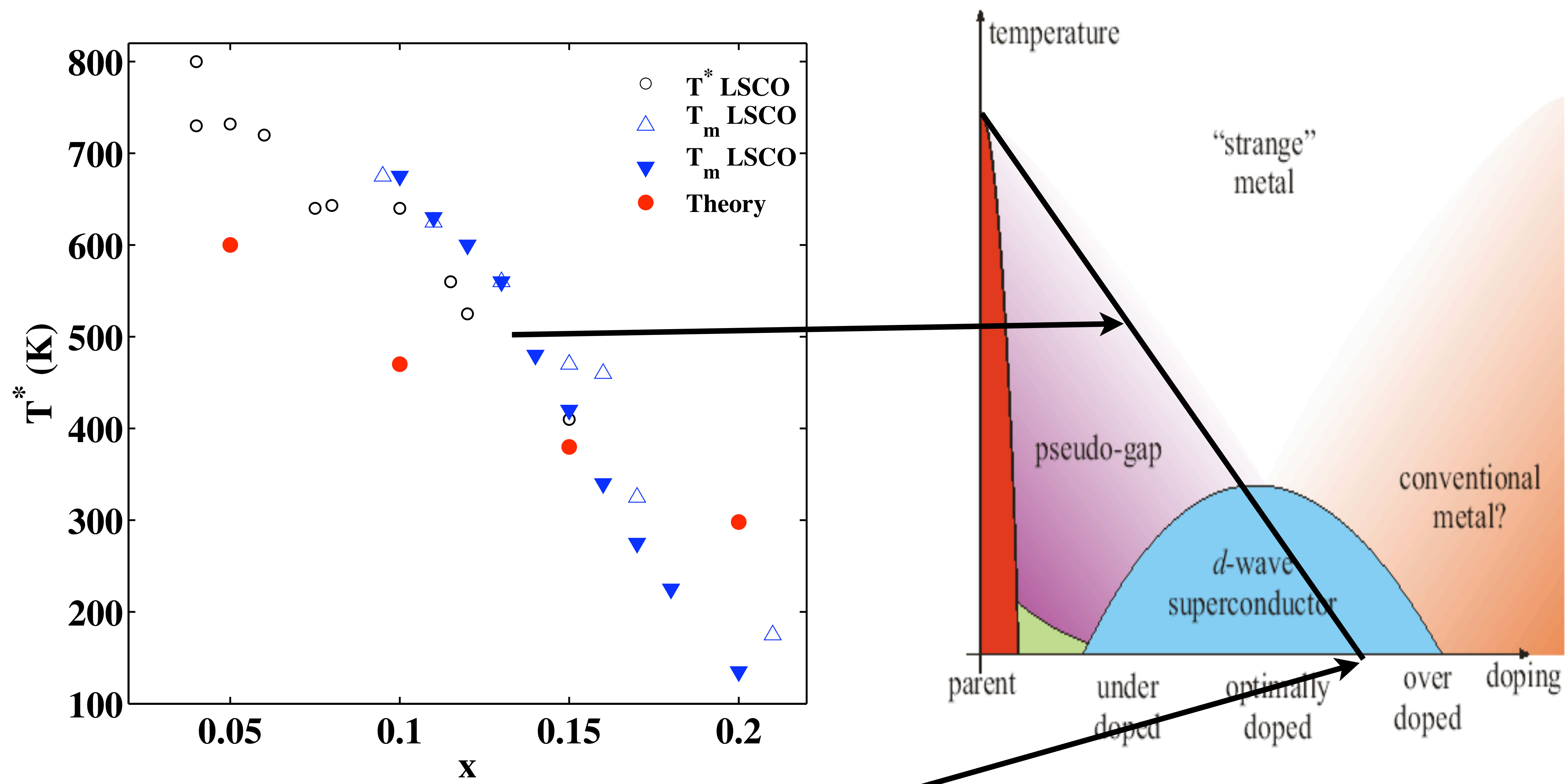
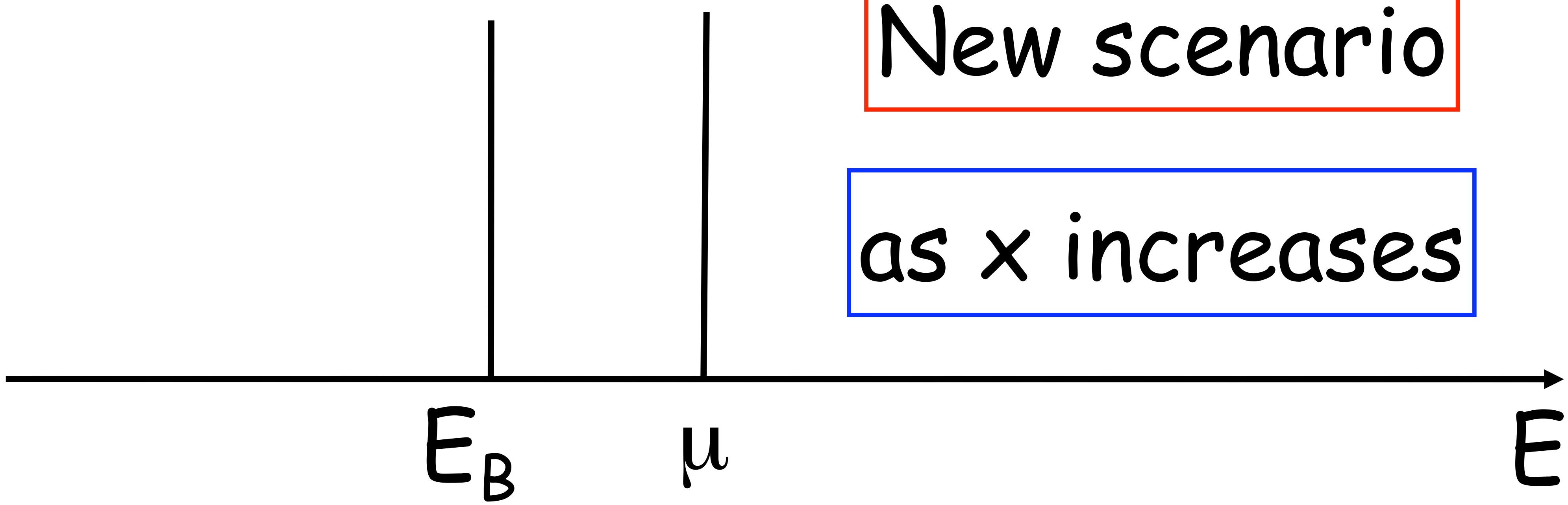


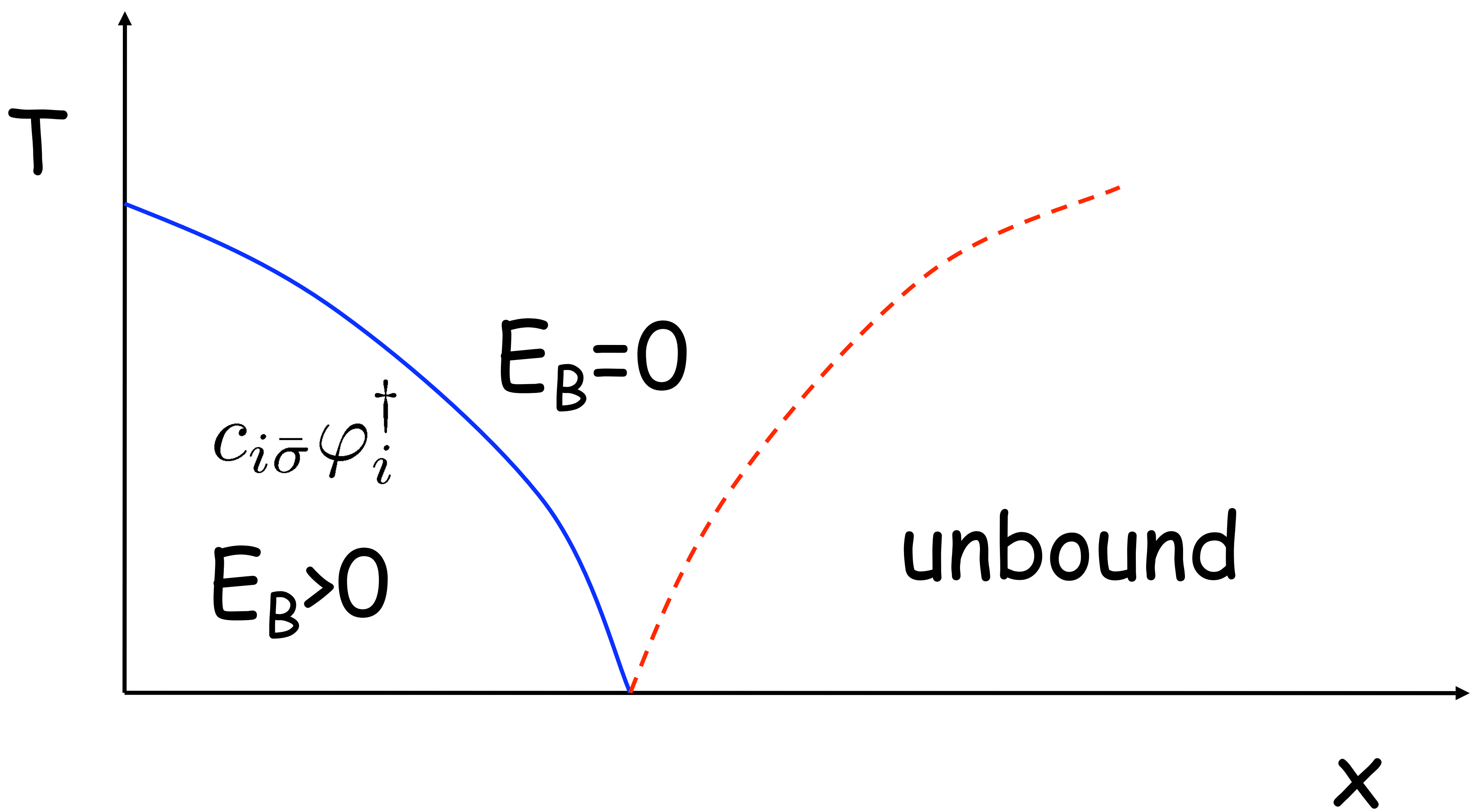
QCP:

T-linear resistivity

New scenario

as x increases





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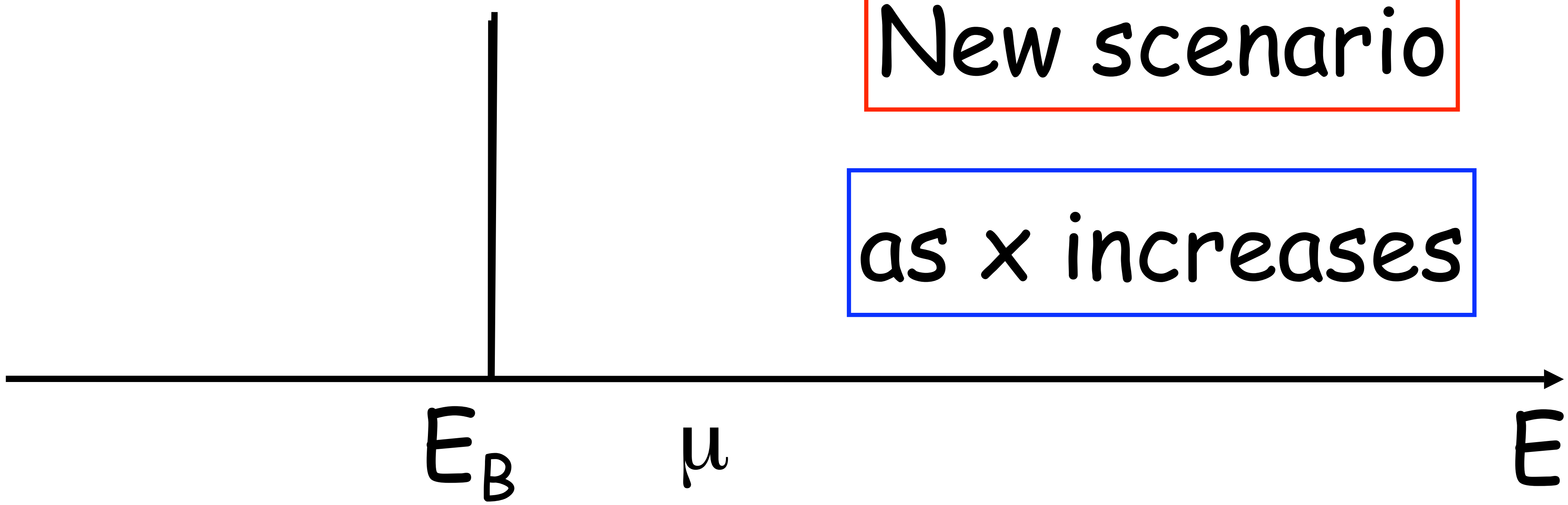
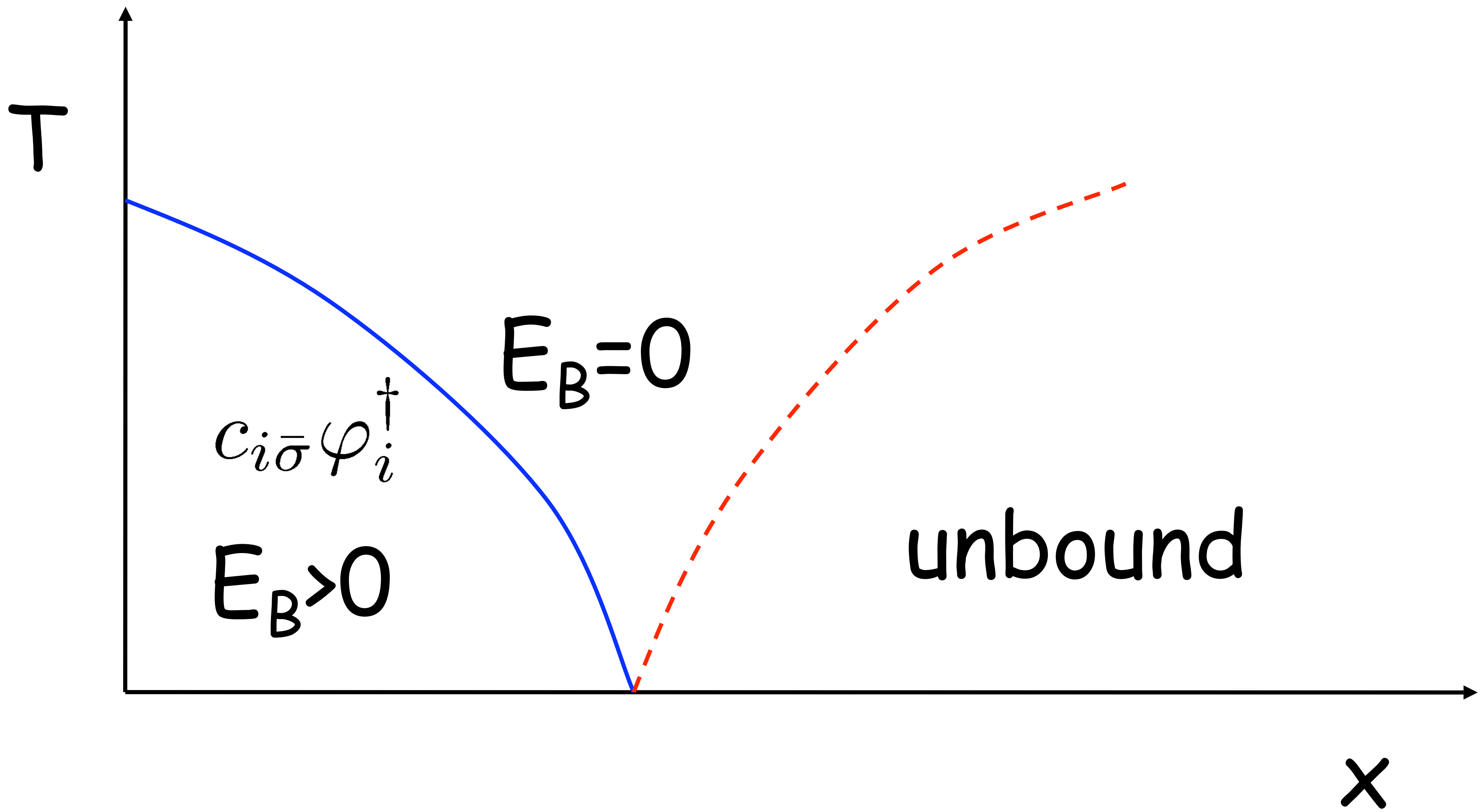
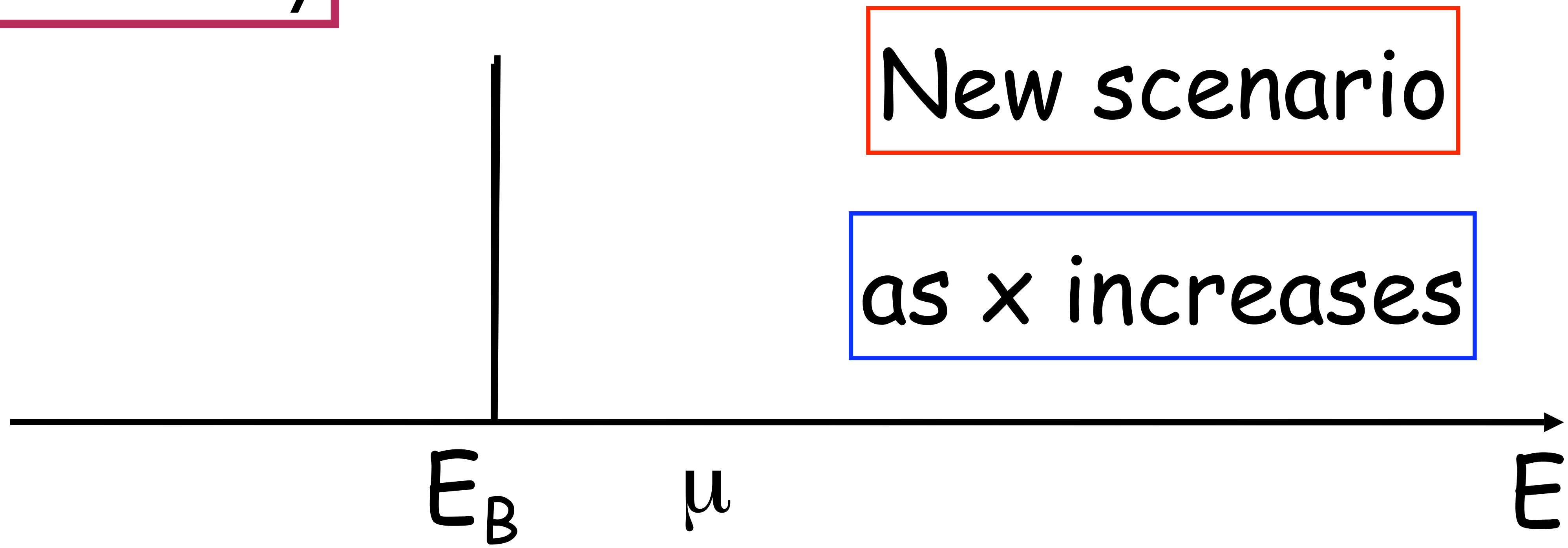
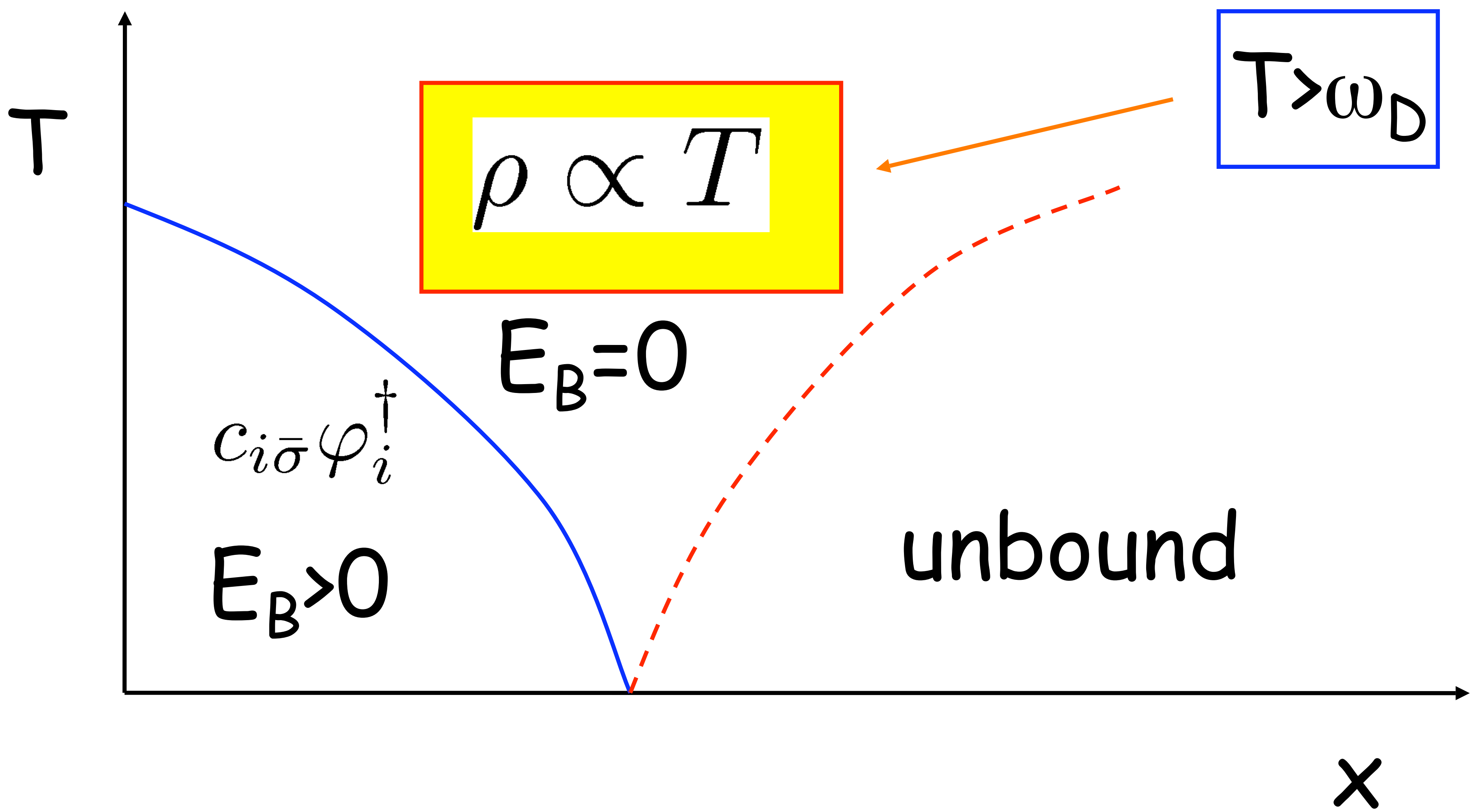
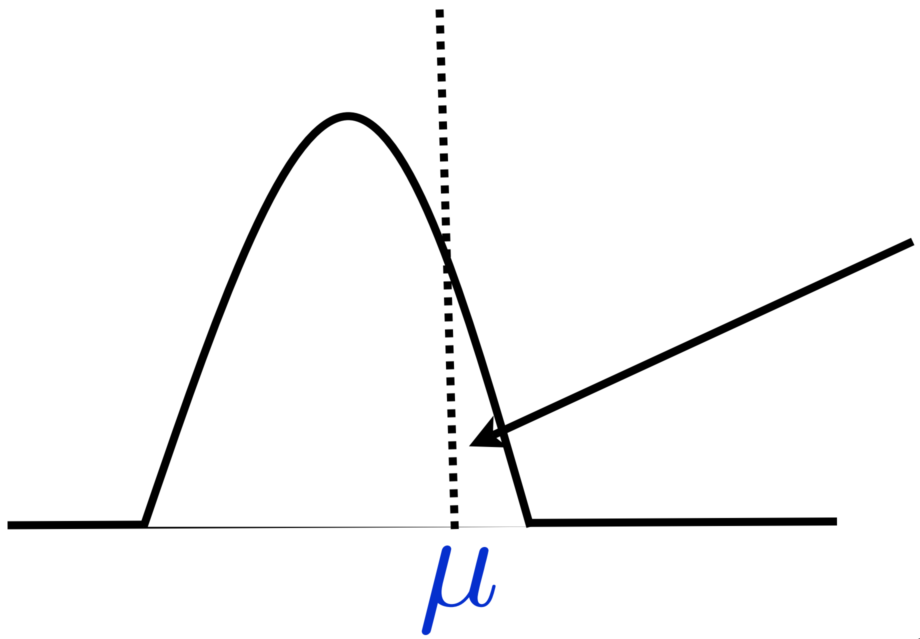




T-linear resistivity





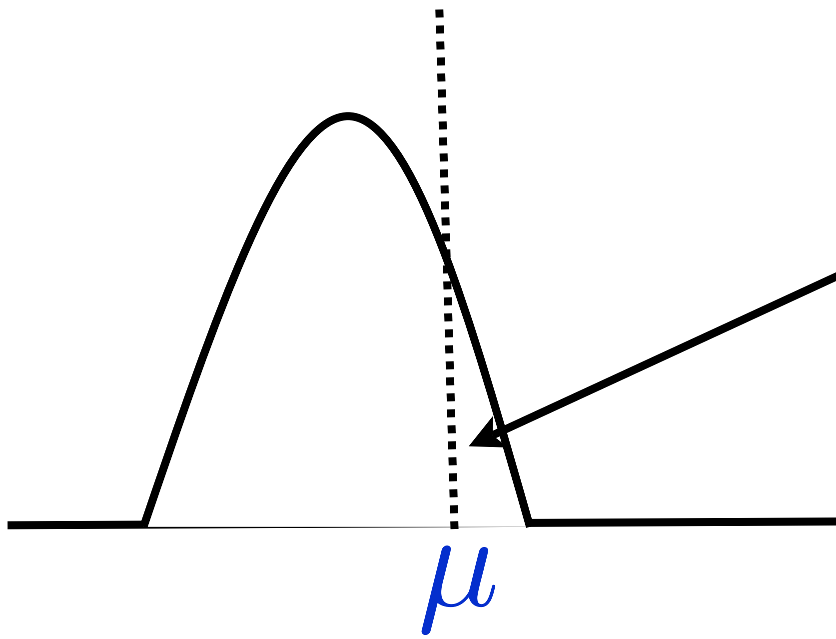


L =Area/# of sites

$$\boxed{\int_{\mu}^{\Lambda} N(\omega)\, d\omega}$$

L=# of single-particle addition states (qp)

n_h= # of ways electrons can be added= # of holes created by the dopants



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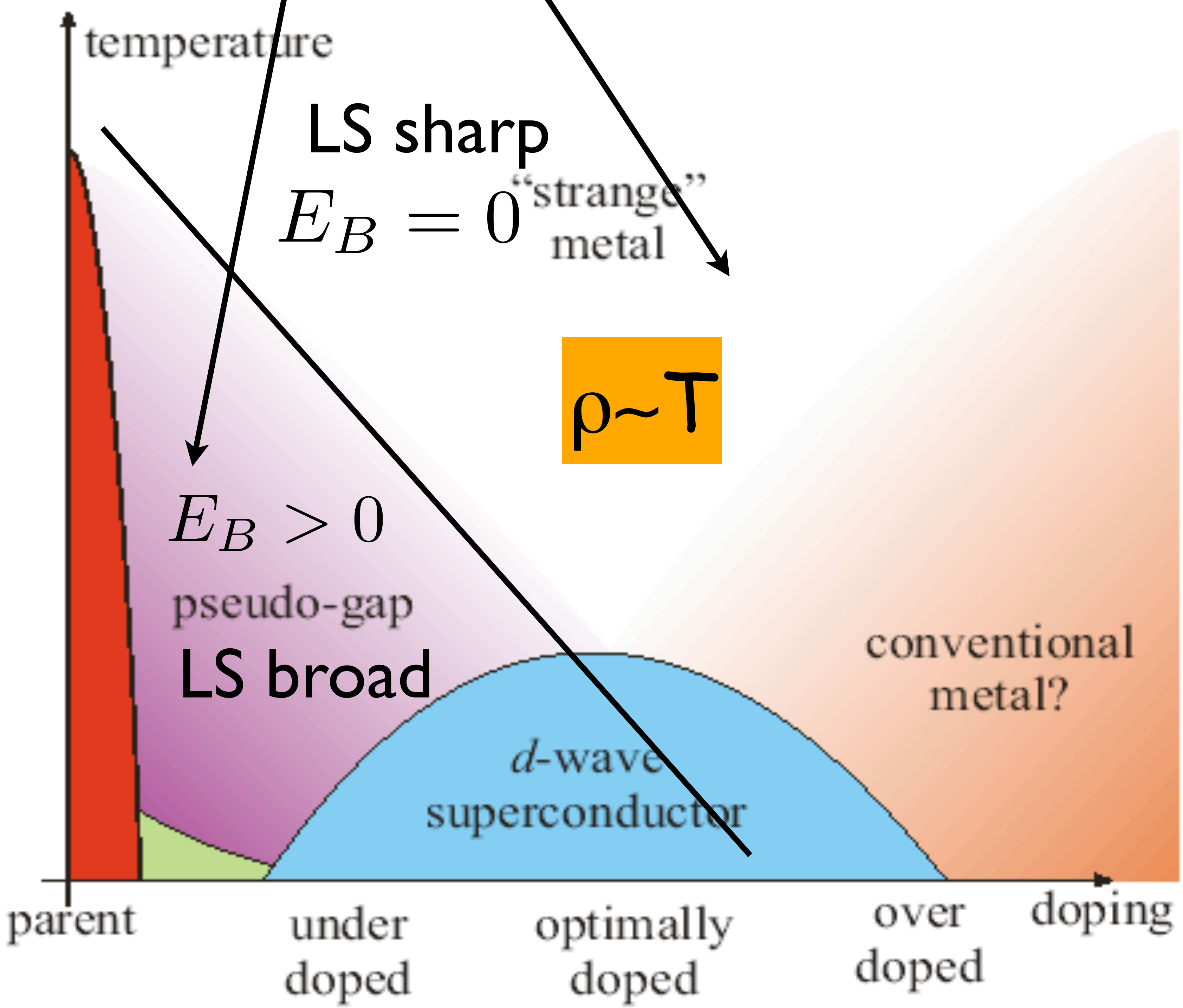
Equivalent in Fermi liquid

Experimental Prediction:

$L/n_h > 1$

$L/n_h = 1$

More states at lower temperature



Experiments

How did I start working with Rob?

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

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

quantum criticality

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

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

quantum criticality

d=3

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

only if z<0

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$$\sigma(T) \propto T^{(d-2)/z} \xrightarrow{d=3} \cancel{\rho \propto T}$$

only if z<0

$$E \propto p^z$$

dynamical exponent

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UV-IR mixing

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in on-c mutati

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UV-IR mixing

Mottness: Strong Coupling

low-energy reduction

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~~bare particles~~

Mottness: Strong Coupling

low-energy reduction

bare particles

Pseudogap=confinement

Mottness: Strong Coupling

low-energy reduction

~~bare particles~~

composite or bound states not in UV theory

Pseudogap=confinement

Predictions:

$$x \rightarrow x + \alpha$$

STM asymmetry: $2(x+\alpha)/(1-x-\alpha)$

QO oscillations: $V_{\mathrm{hp}} - V_{\mathrm{ep}} = 2(x+\alpha)$

Superfluid density: $\rho_s \propto x + \alpha$

pairing from Mott scale

optical conductivity: $n_{\mathrm{eff}} \propto (x+\alpha) > x$

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