Mottness and Holography: Strange Metal from UV-IR Mixing

Thanks to:

M. Edalati

R. G. Leigh

T.-P. Choy

Seungmin Hong
and
S. Chakraborty

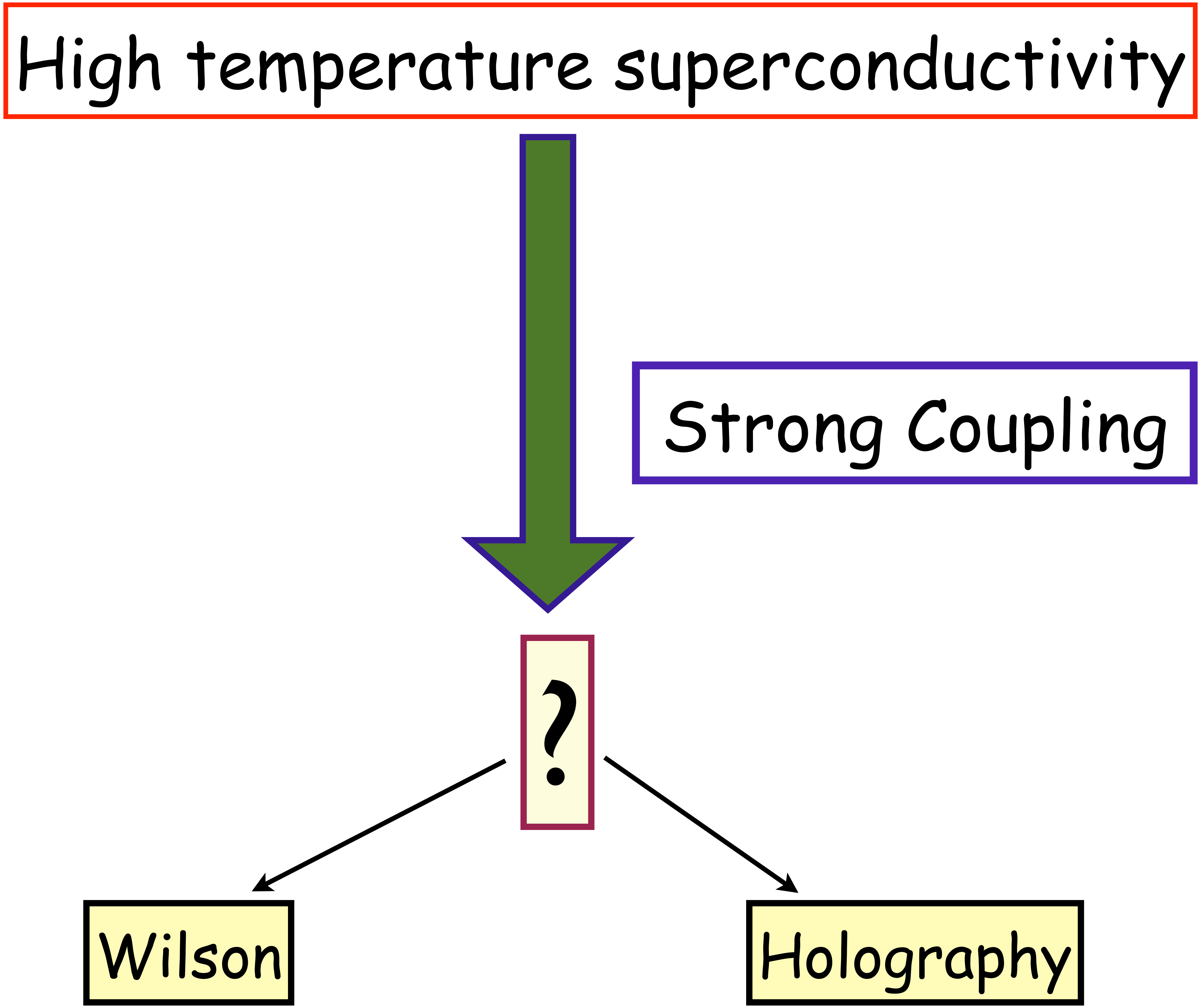
High temperature superconductivity

?

High temperature superconductivity

Strong Coupling

?


High temperature superconductivity
Strong Coupling
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Wilson
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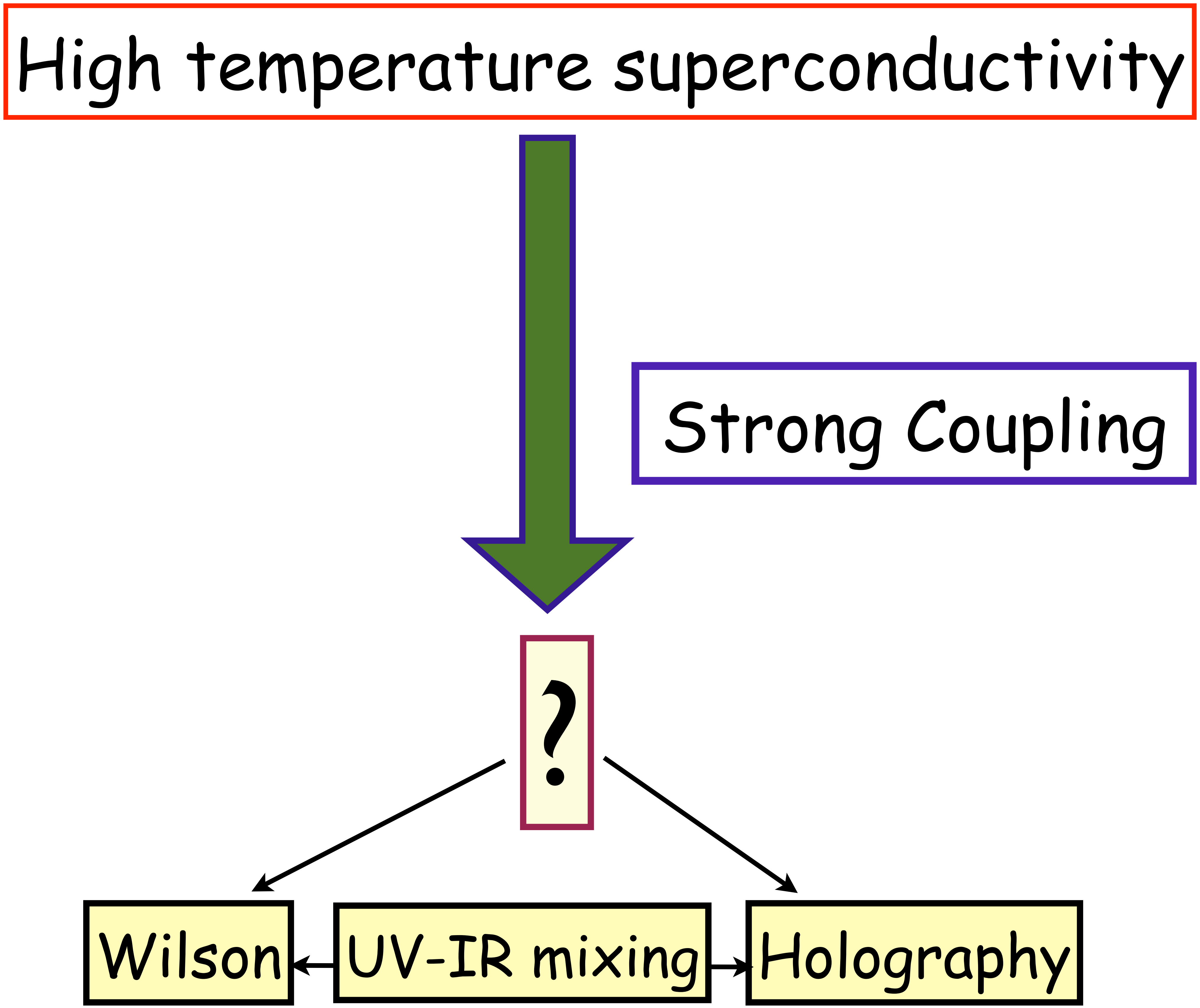

High temperature superconductivity
Strong Coupling
?
Wilson
UV-IR mixing
Holography

High temperature superconductor?

High temperature superconductor?

Unusually
Good Metal

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

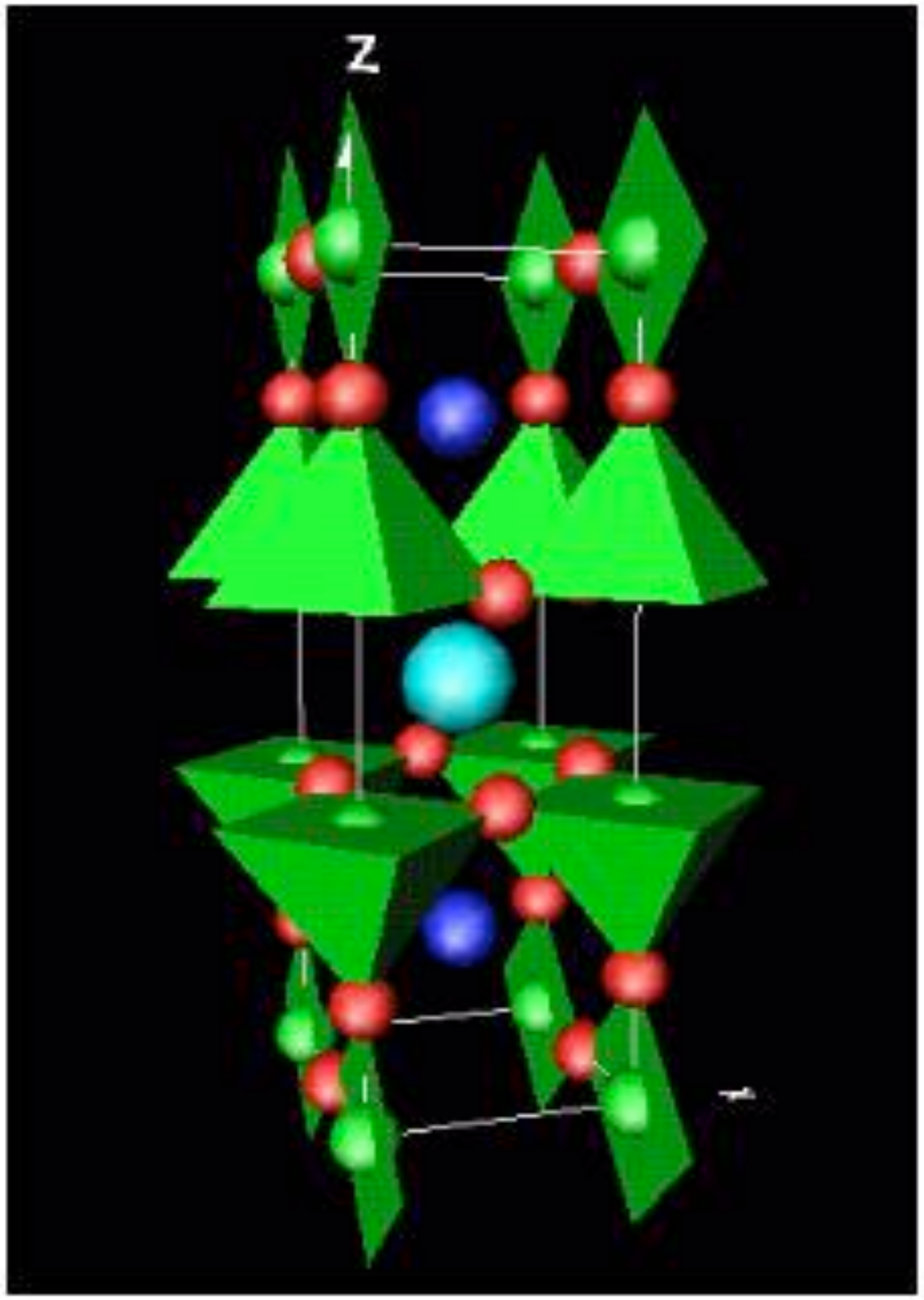
3.) avoid magnetism

4.) avoid insulators

5.) don't talk to theorists!!

Matthias, Bernd T.

orthorhombic
not cubic



$Y\,Ba_2Cu_3O_7$
Cuprate Superconductors

ceramics

What is left of Matthias' Rules?

1.) cubic structures

2.) avoid oxygen

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4.) avoid insulators

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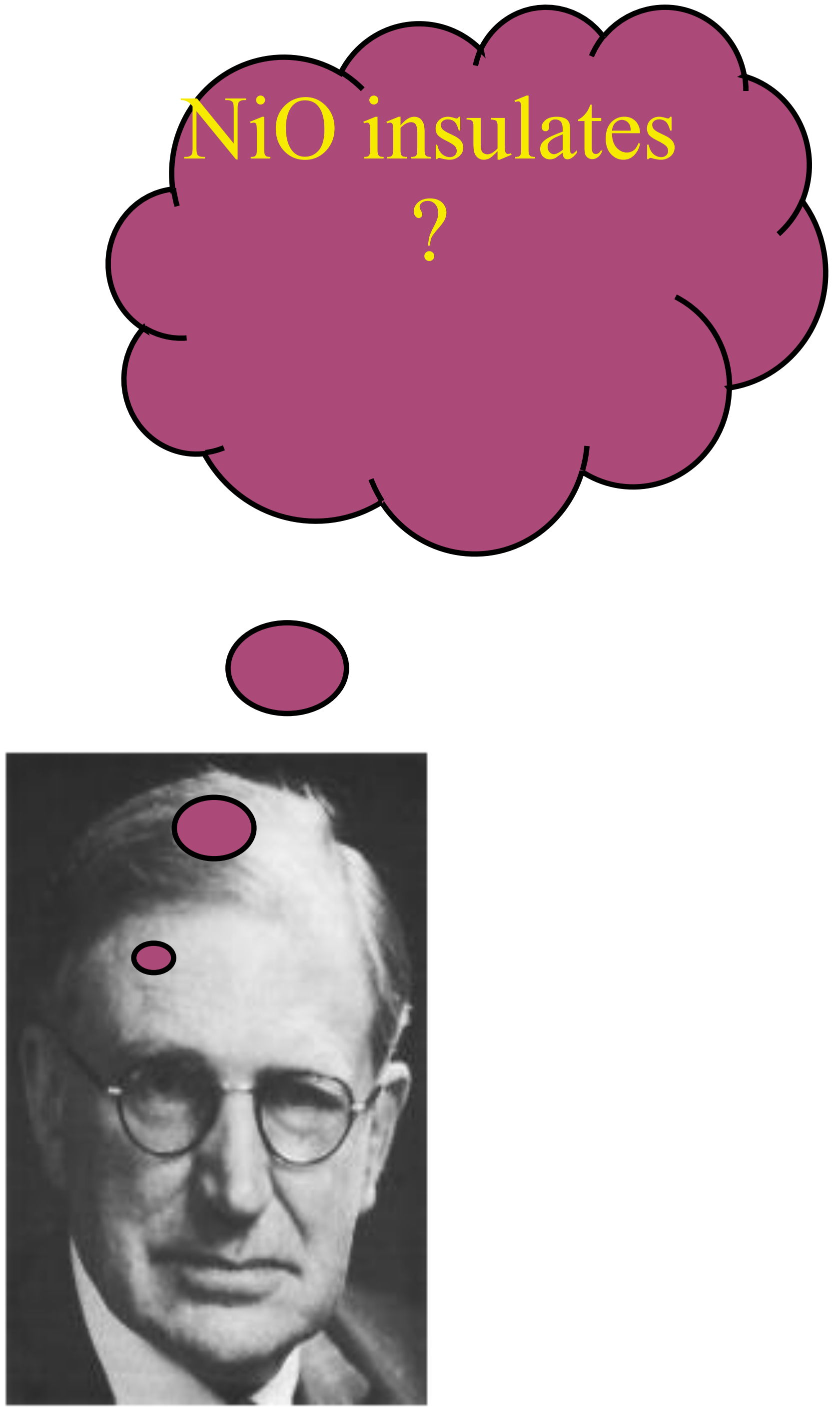
What is left of Matthias' Rules?

New Problem: Mottness

Sir Neville Mott
Nobel Prize, 1977

Mott
Insulators

What is a Mott Insulator?



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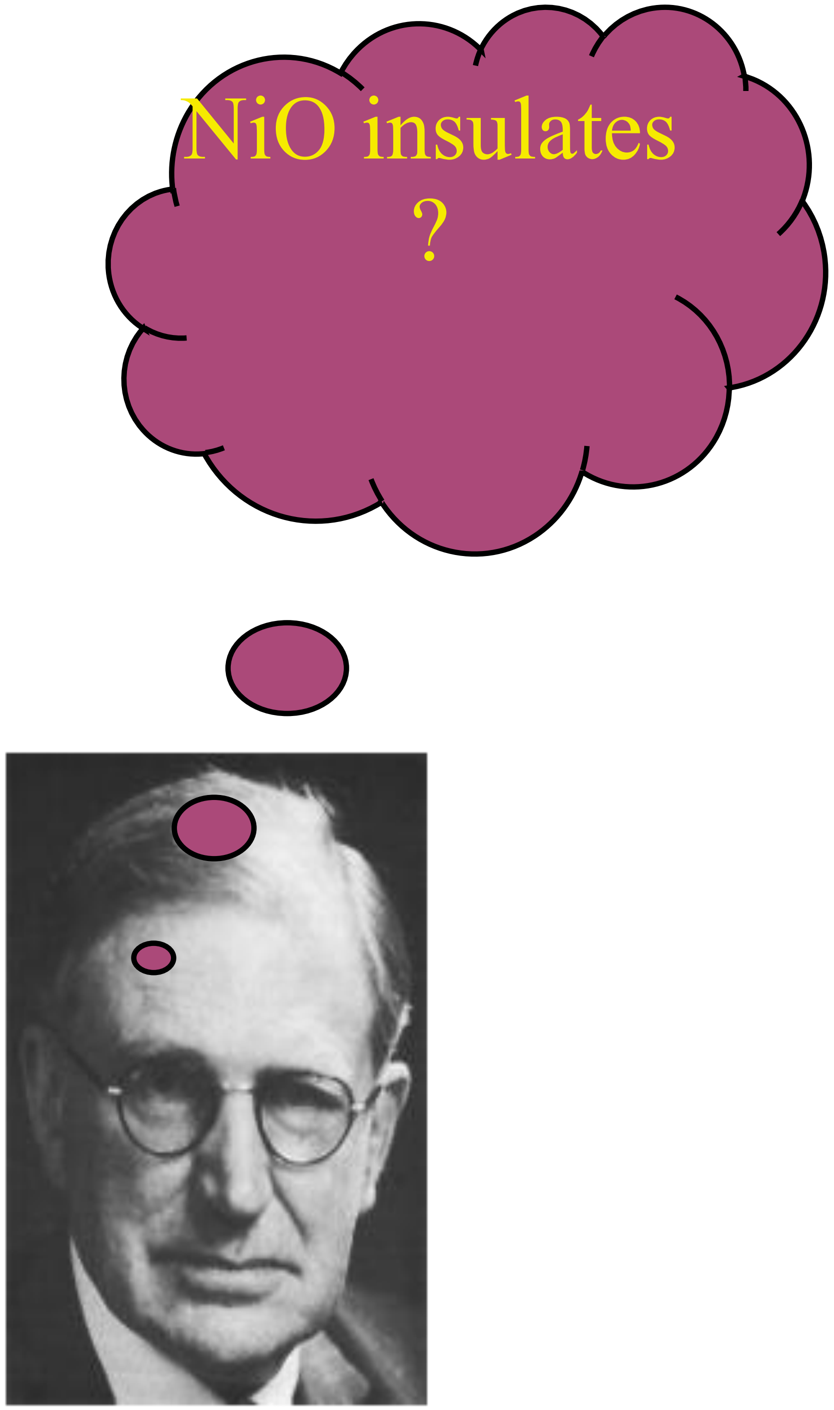
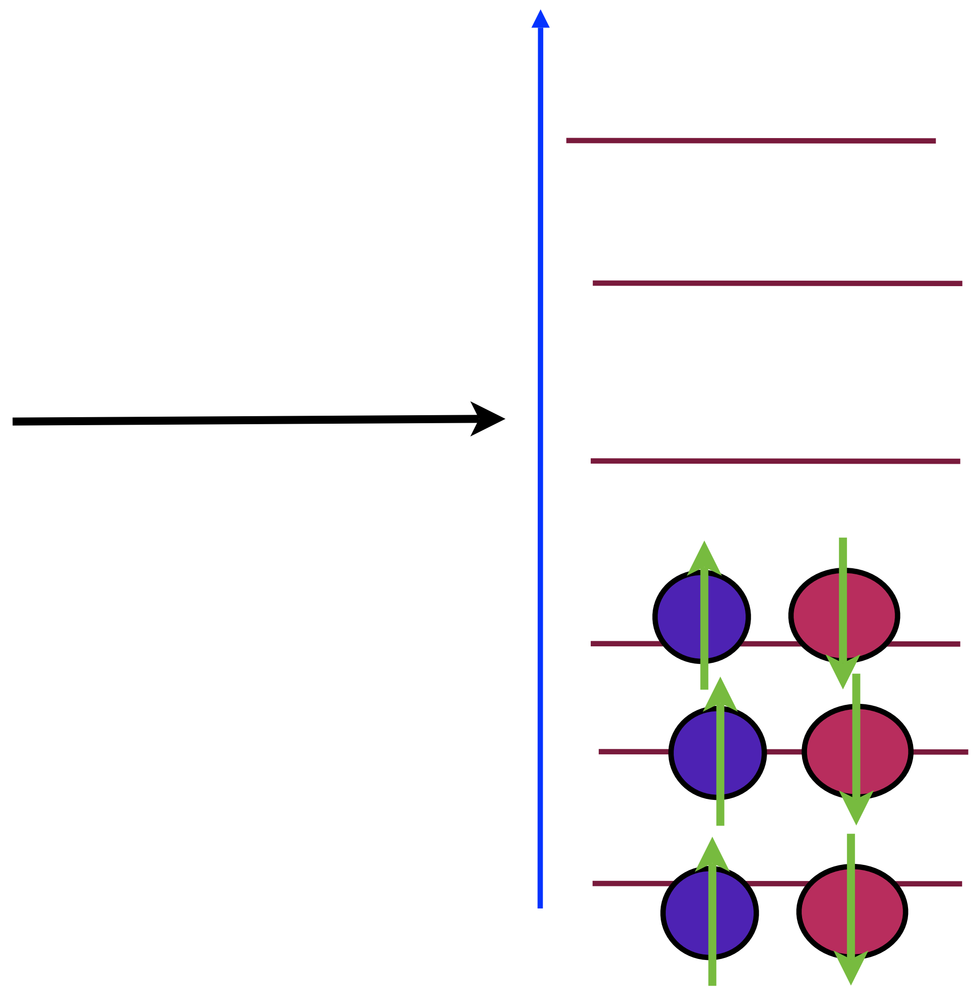
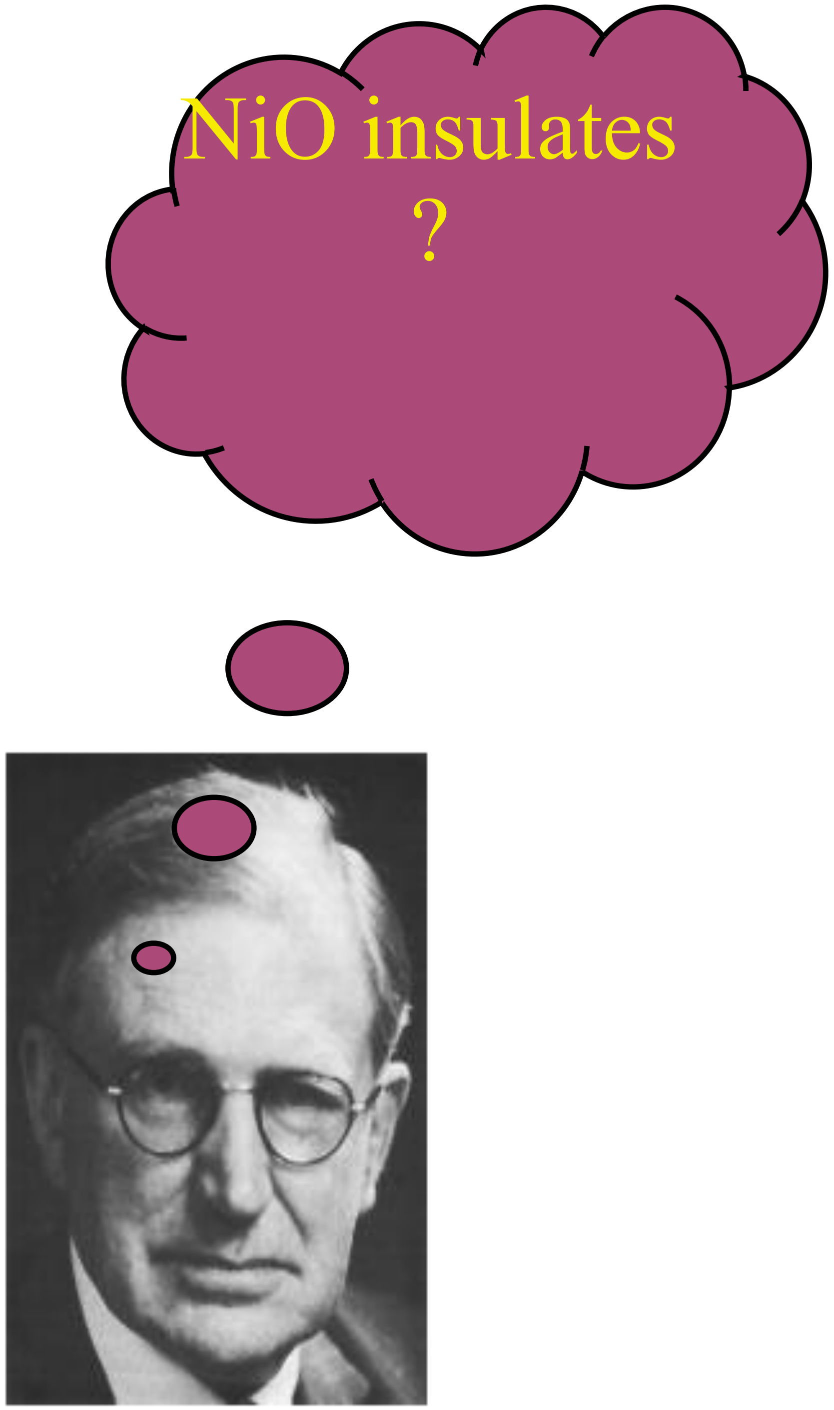
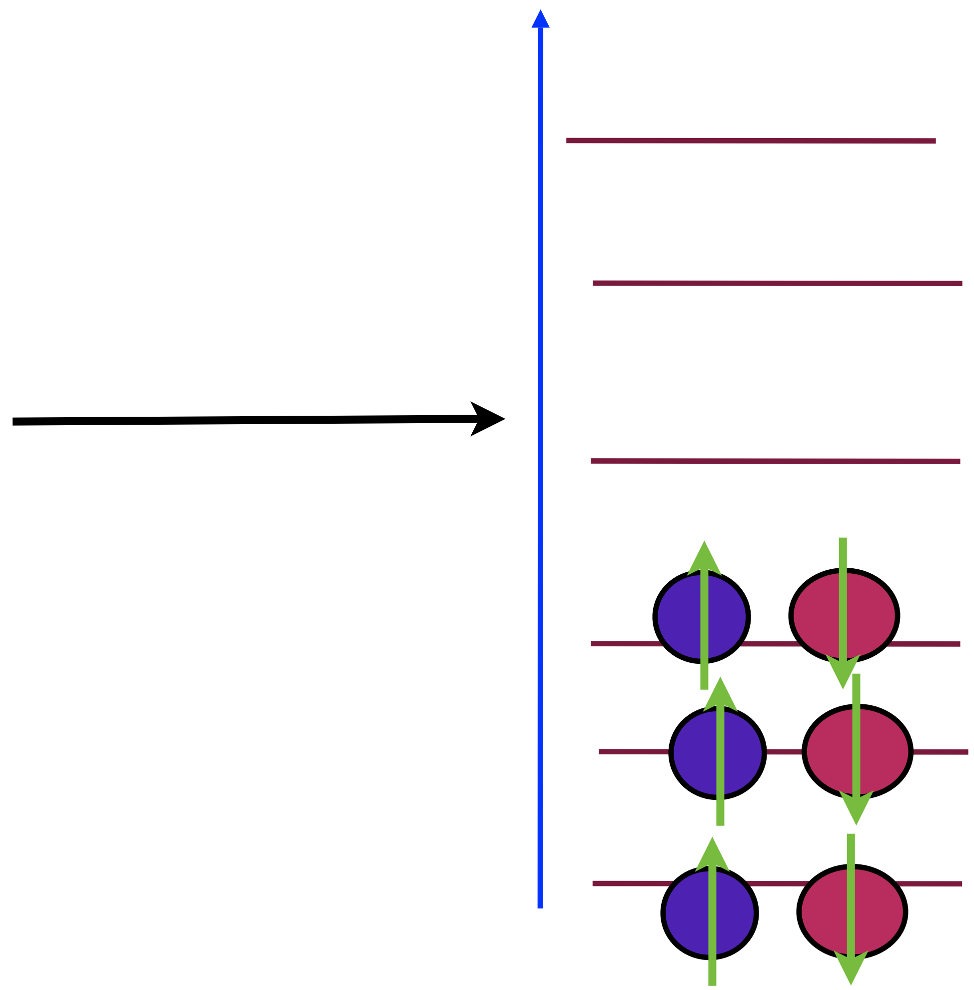




EMPTY STATES=
METAL

What is a Mott Insulator?

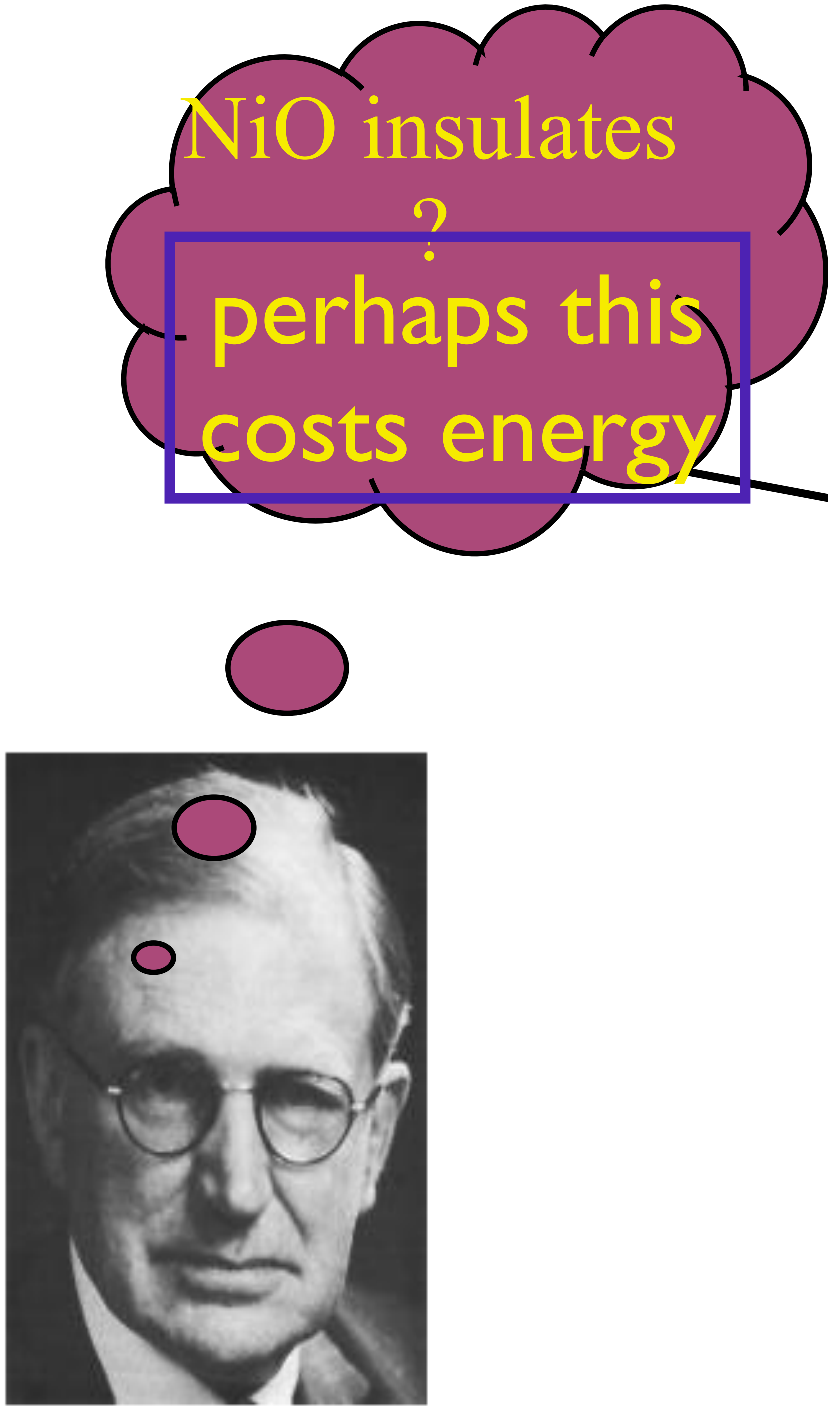


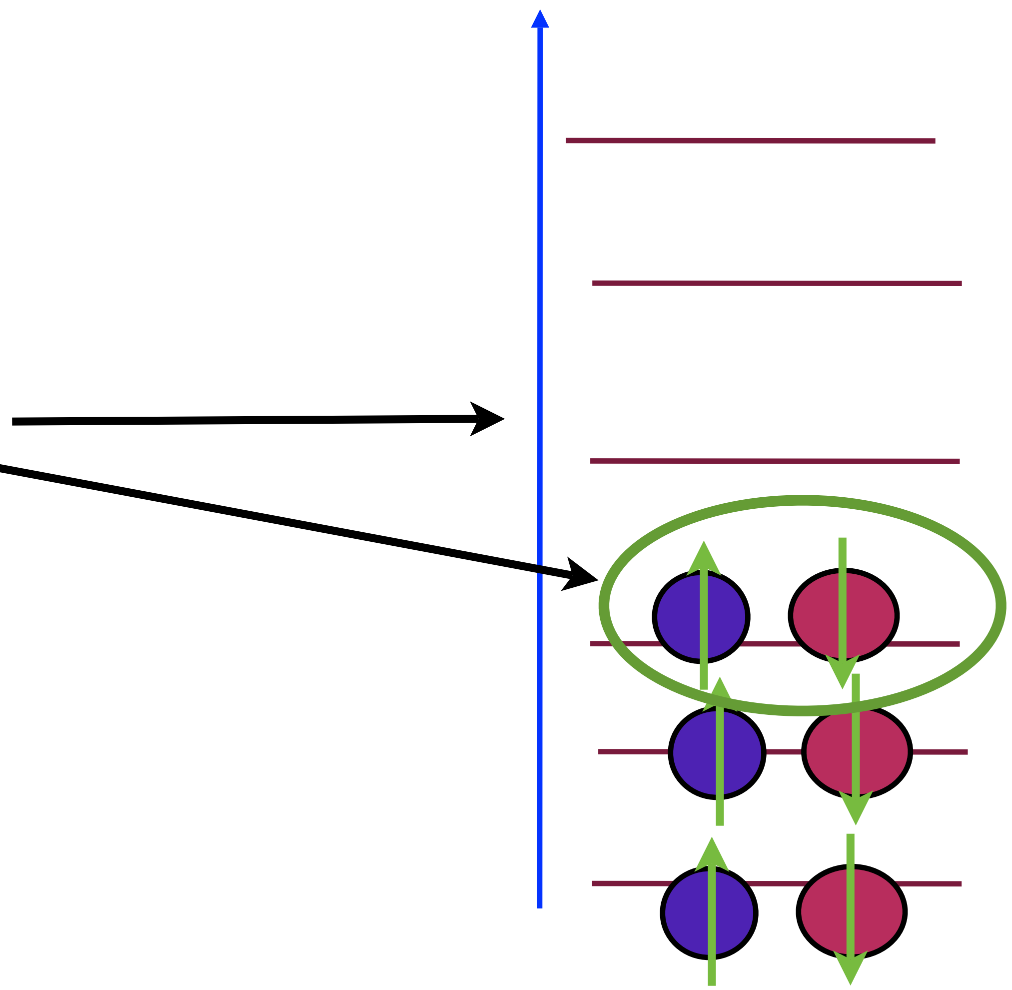


EMPTY STATES=
METAL

band theory fails!

What is a Mott Insulator?



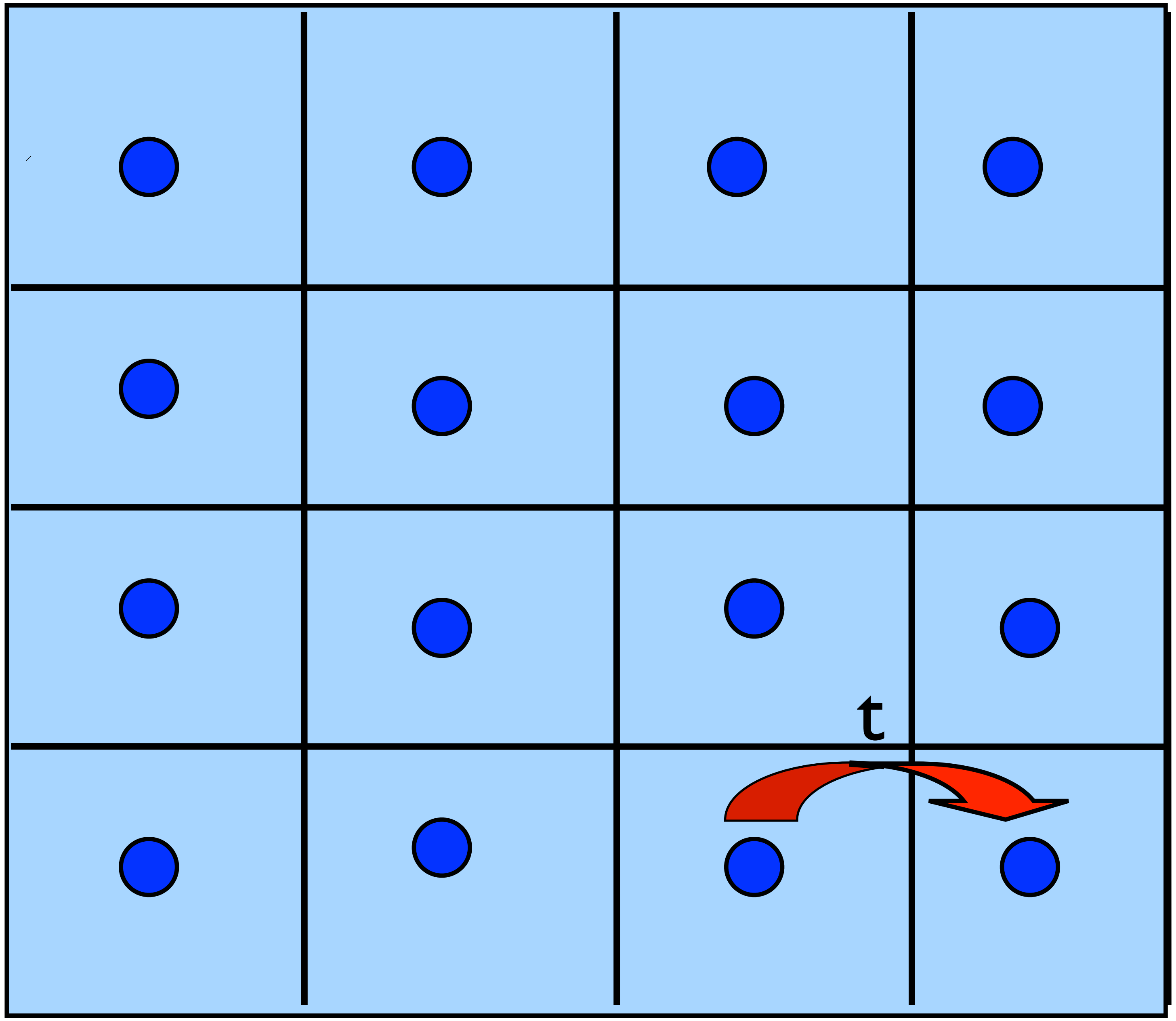


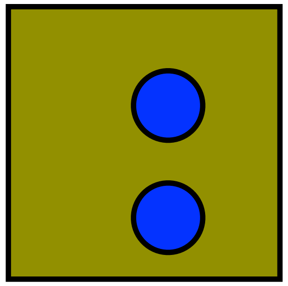
EMPTY STATES=
METAL

band theory fails!

Mott Problem: NiO (Band theory failure)

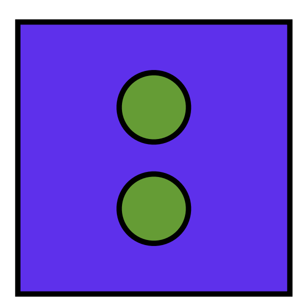
(N rooms N occupants)





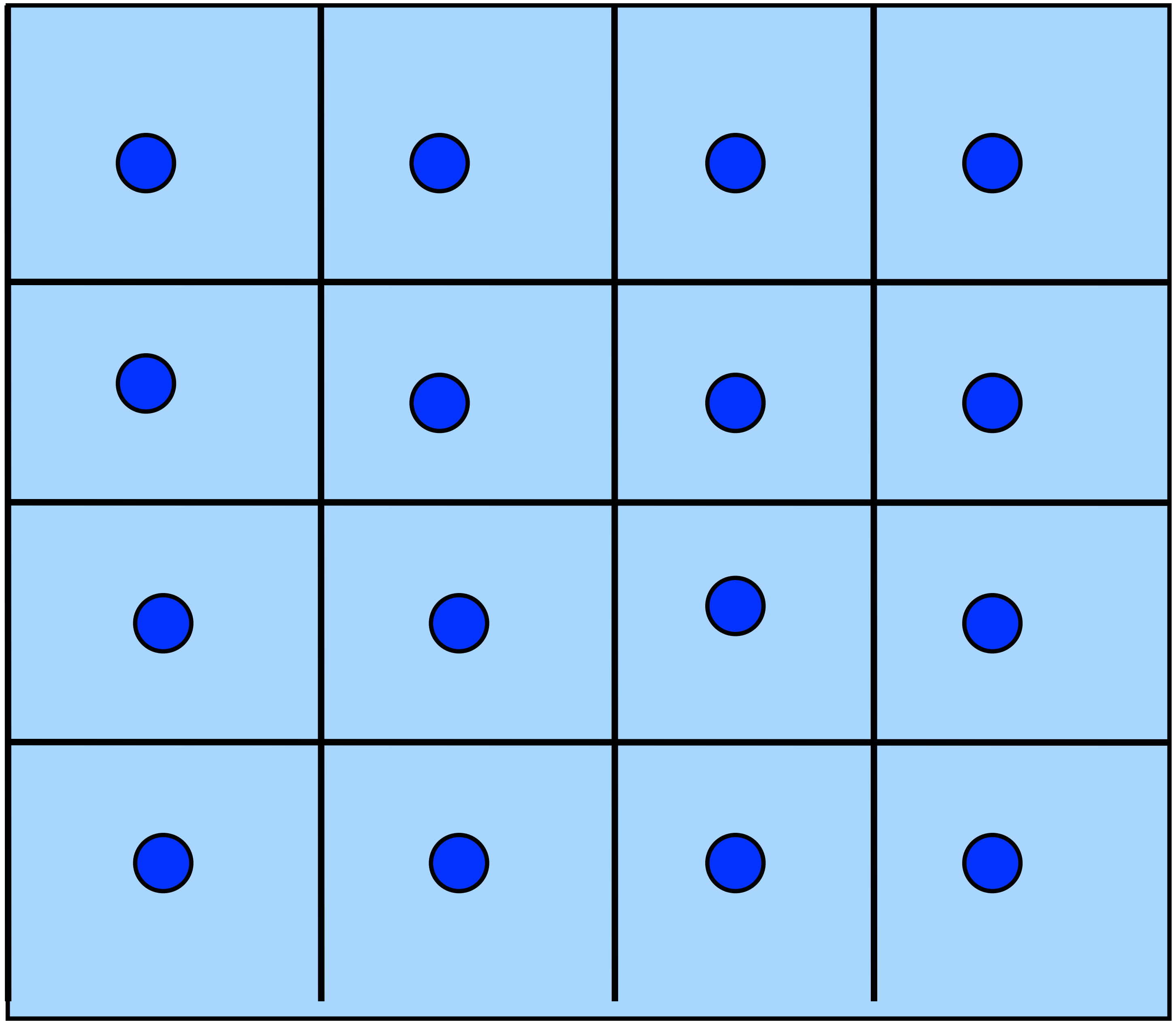
$U \gg t$

classical picture

 is forbidden

Doping a Mott insulator

x= fraction of empty rooms (holes)



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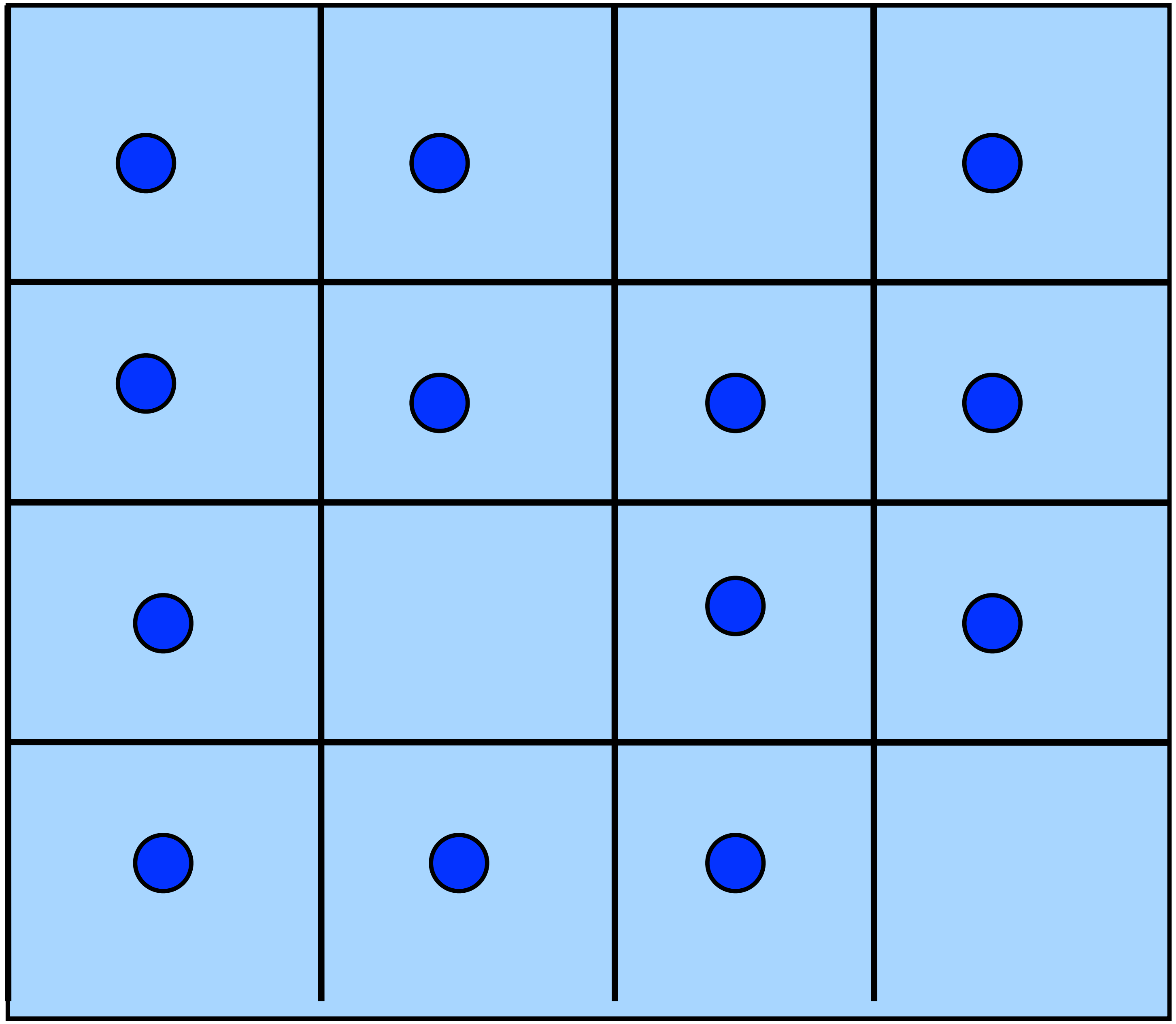

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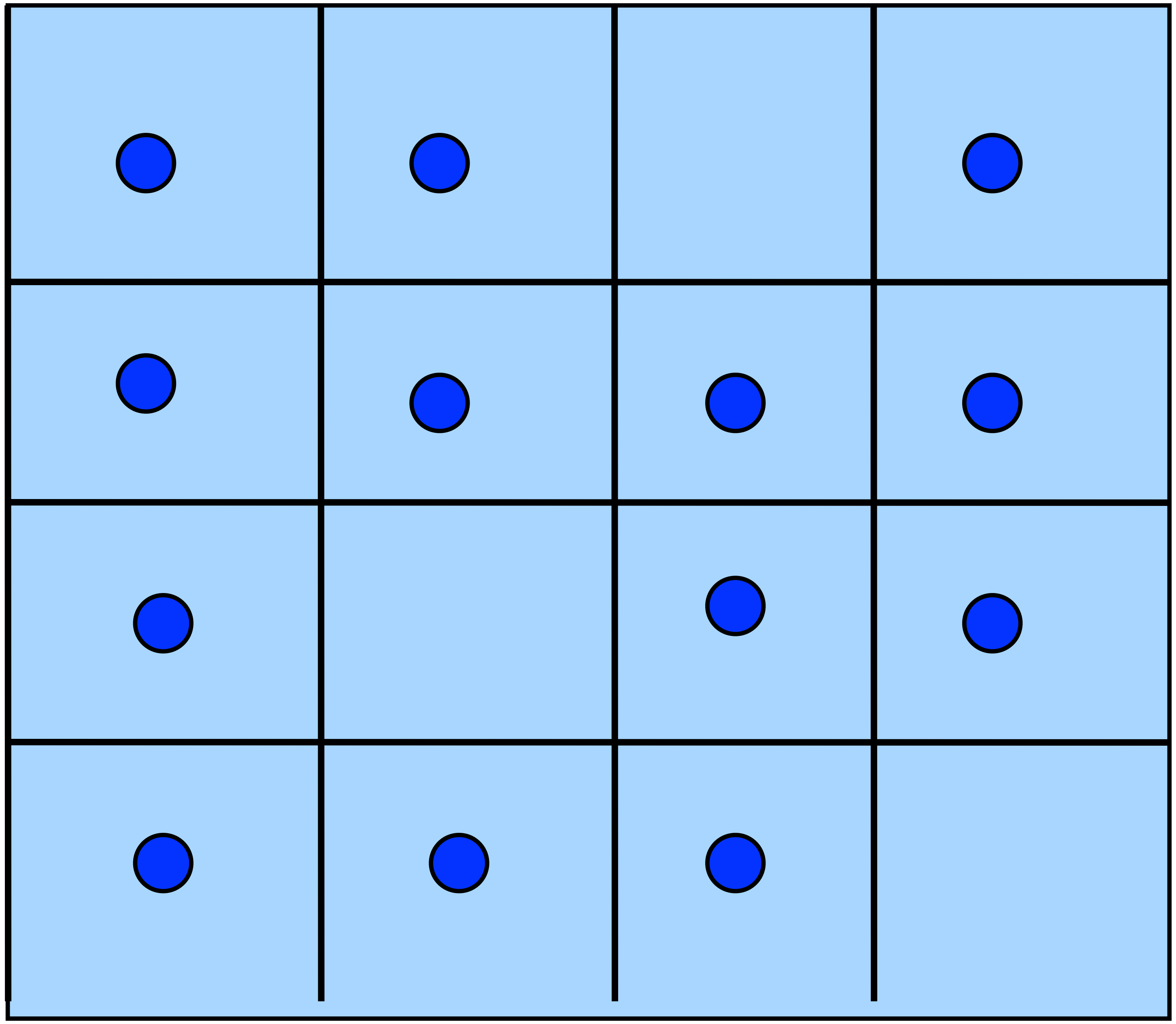
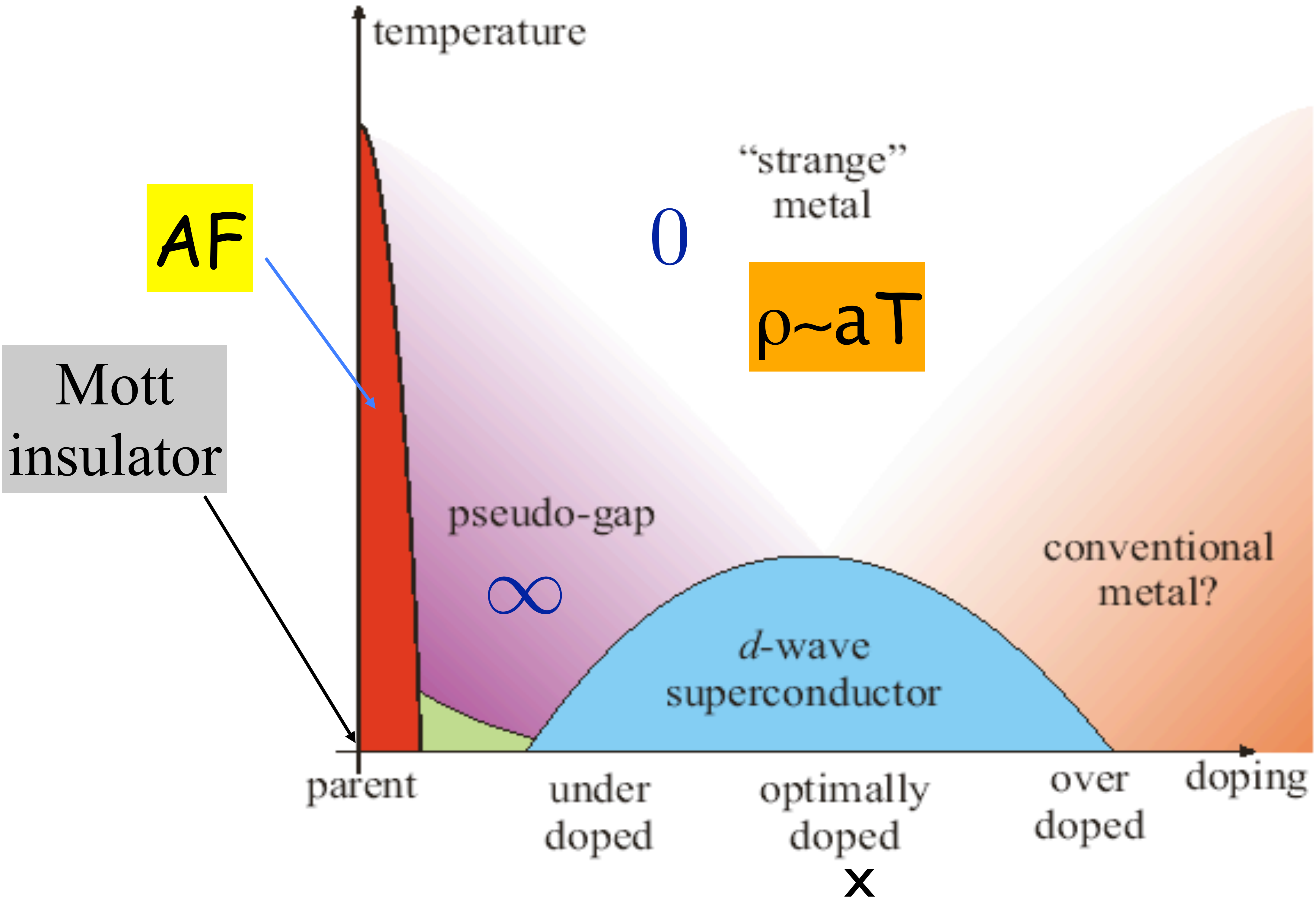
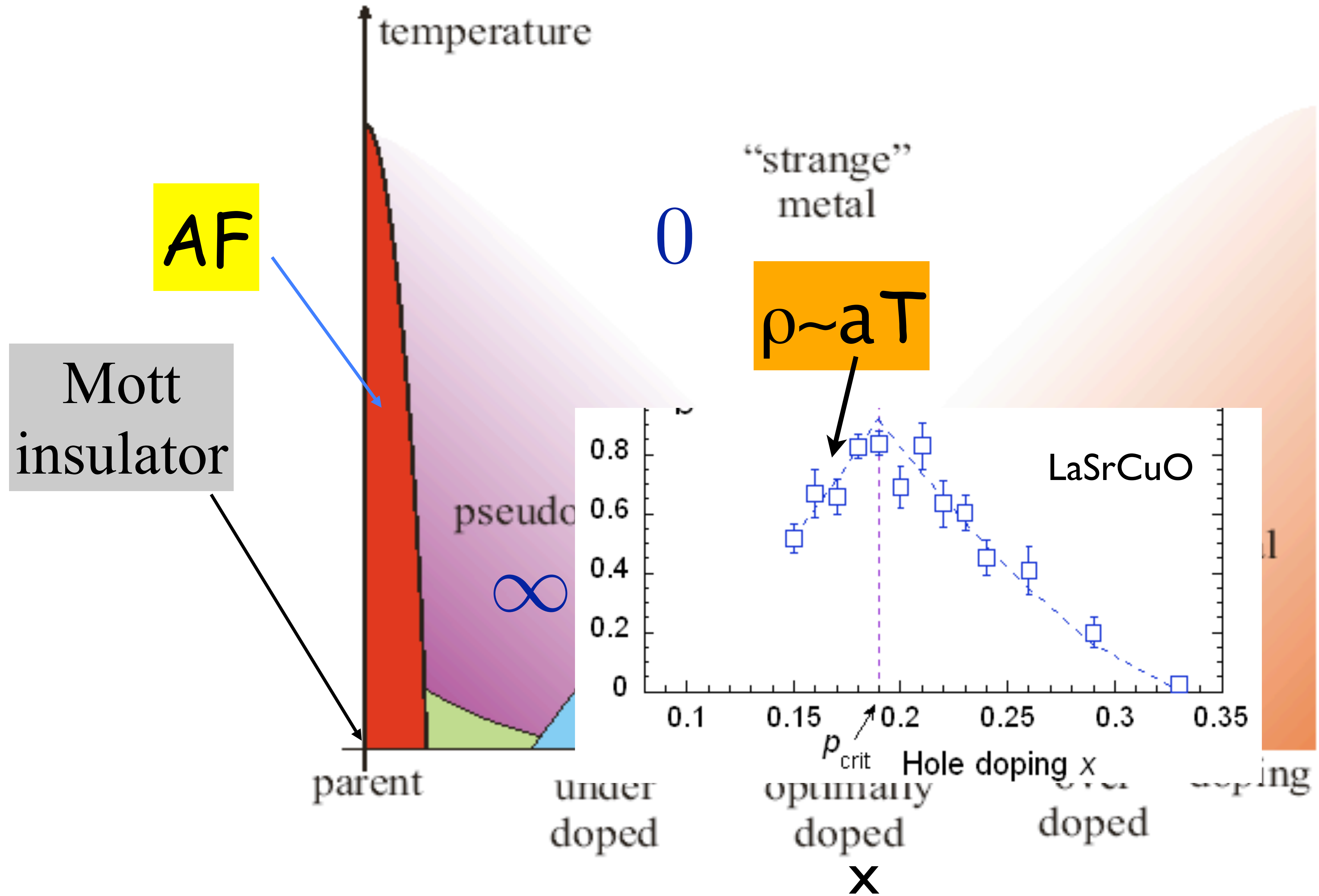
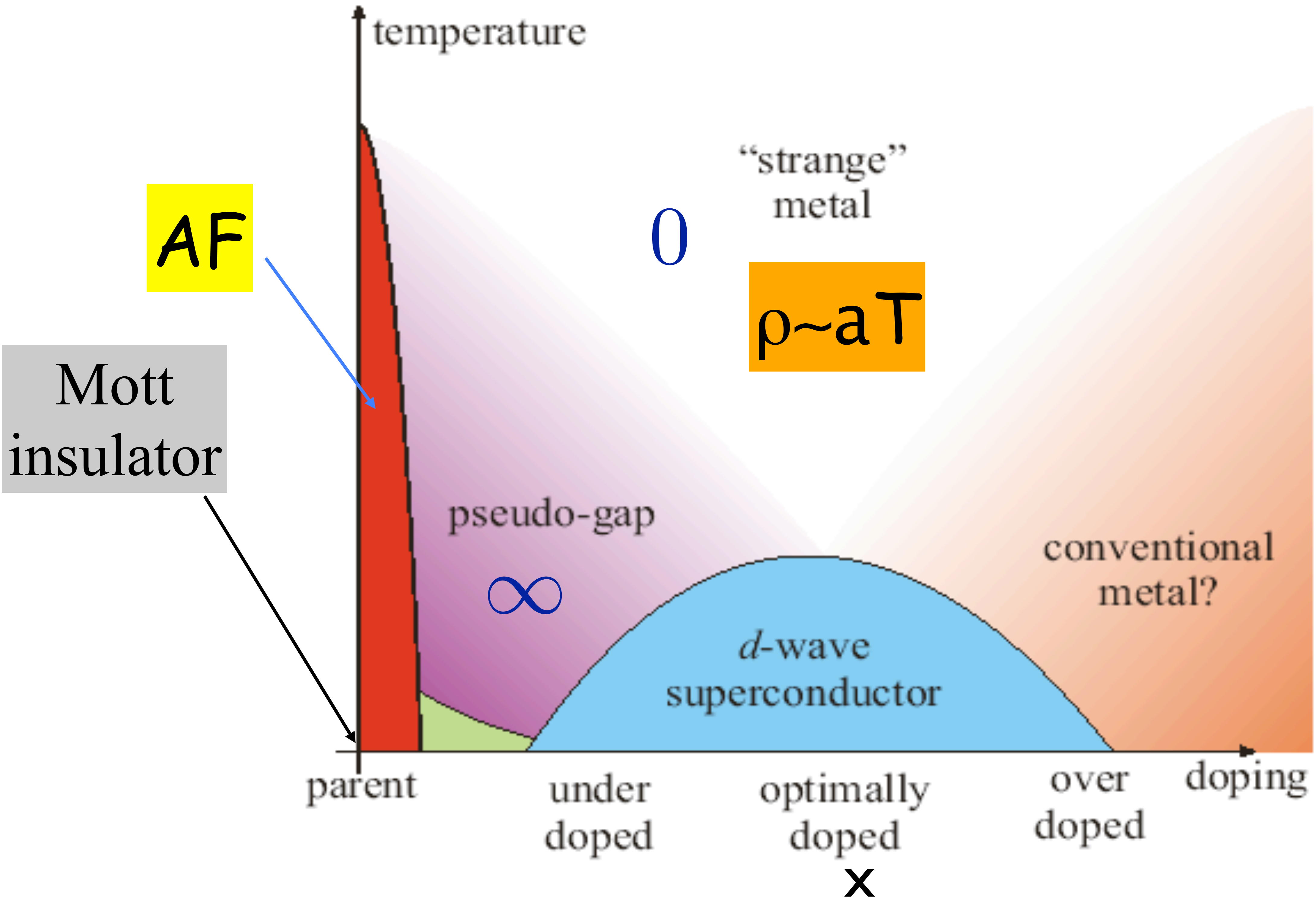


X=3/16


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



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



temperature
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metal
ρ~aT
pseudo-gap
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d-wave
superconductor
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under
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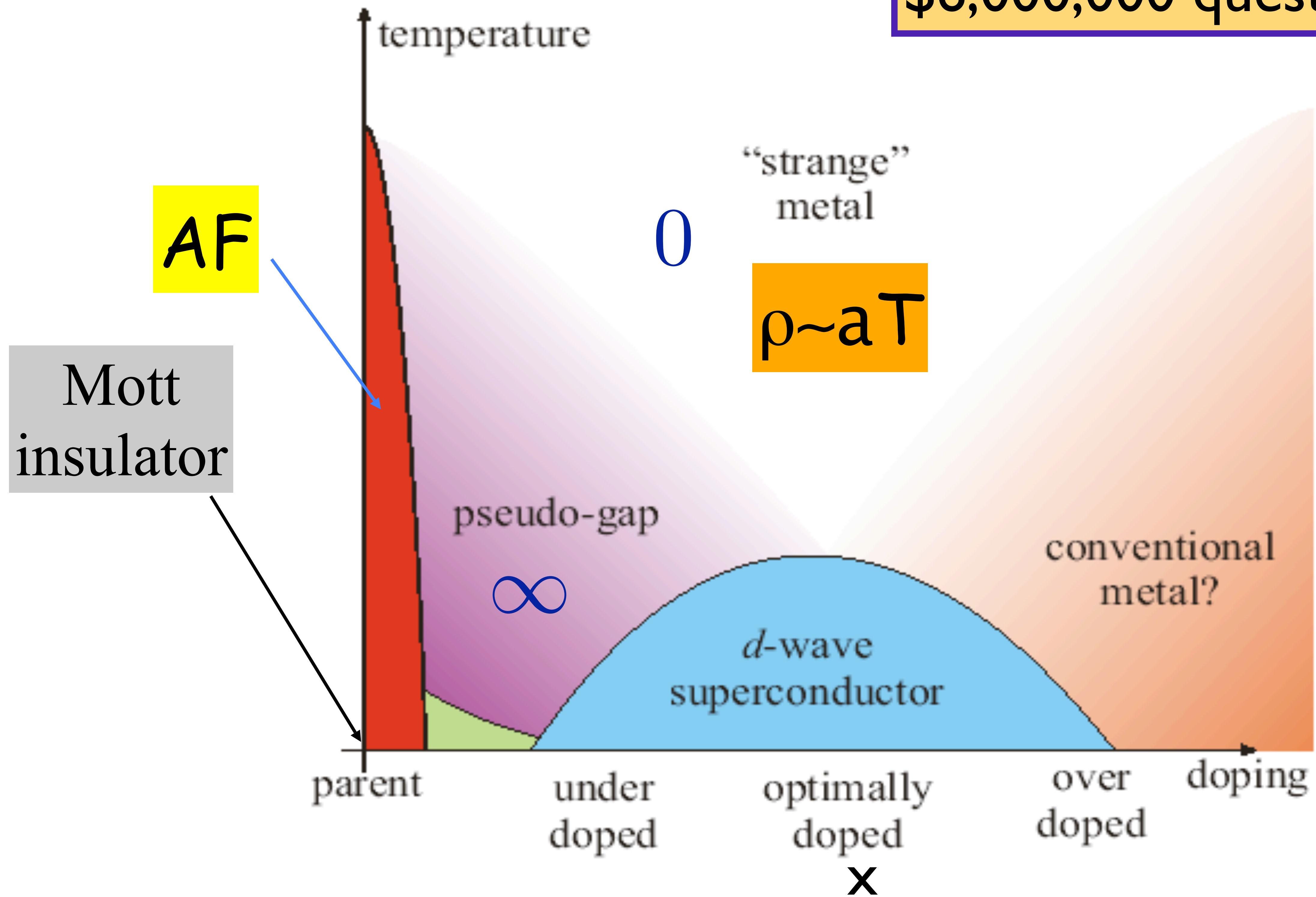
optimally
doped
over
doped
doping
x

How does Fermi Liquid Theory Breakdown?

$6,000,000 question?



T-linear Resistivity?

Metals: $\rho \approx T^2$

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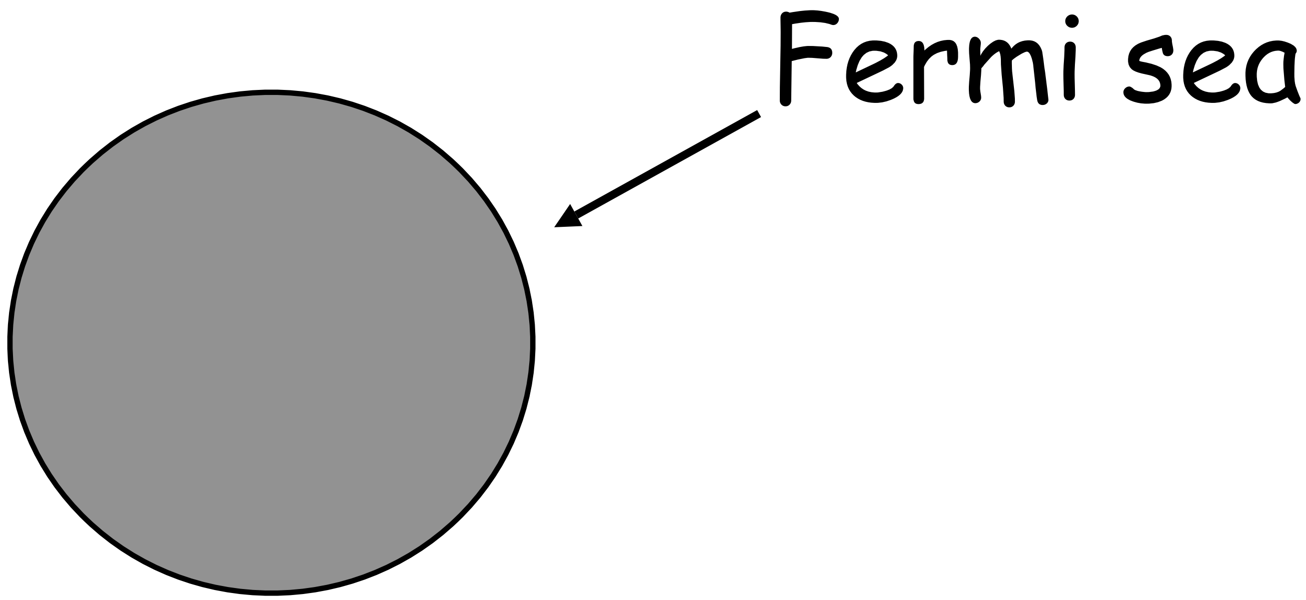

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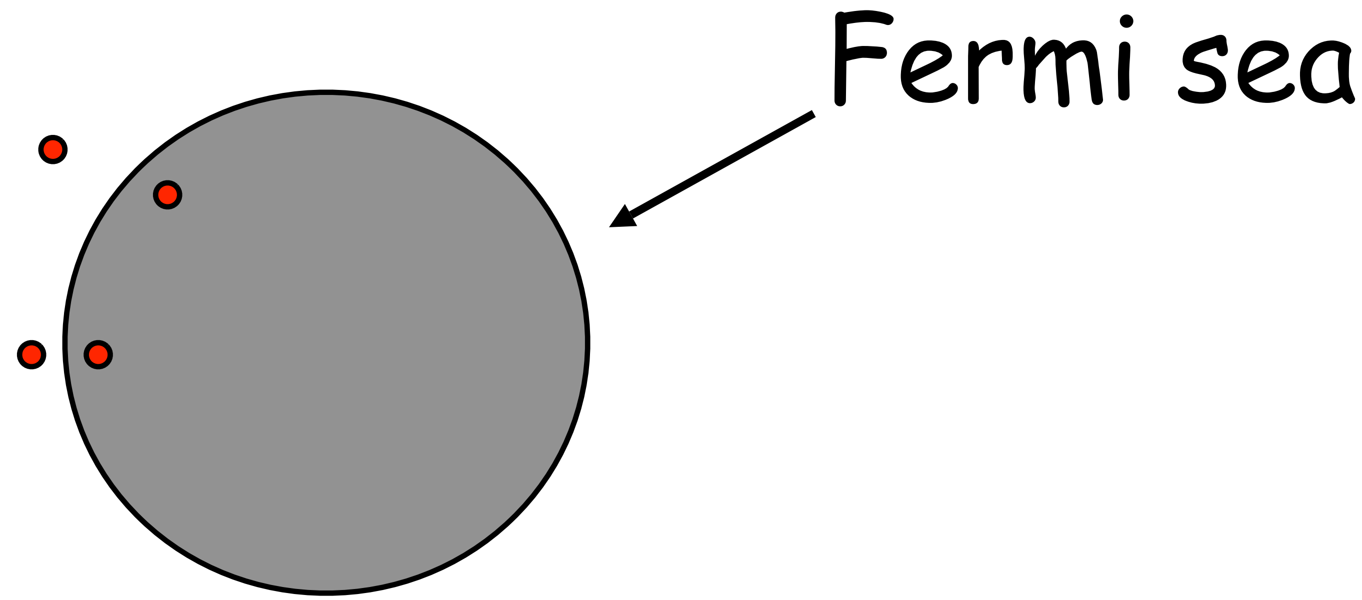

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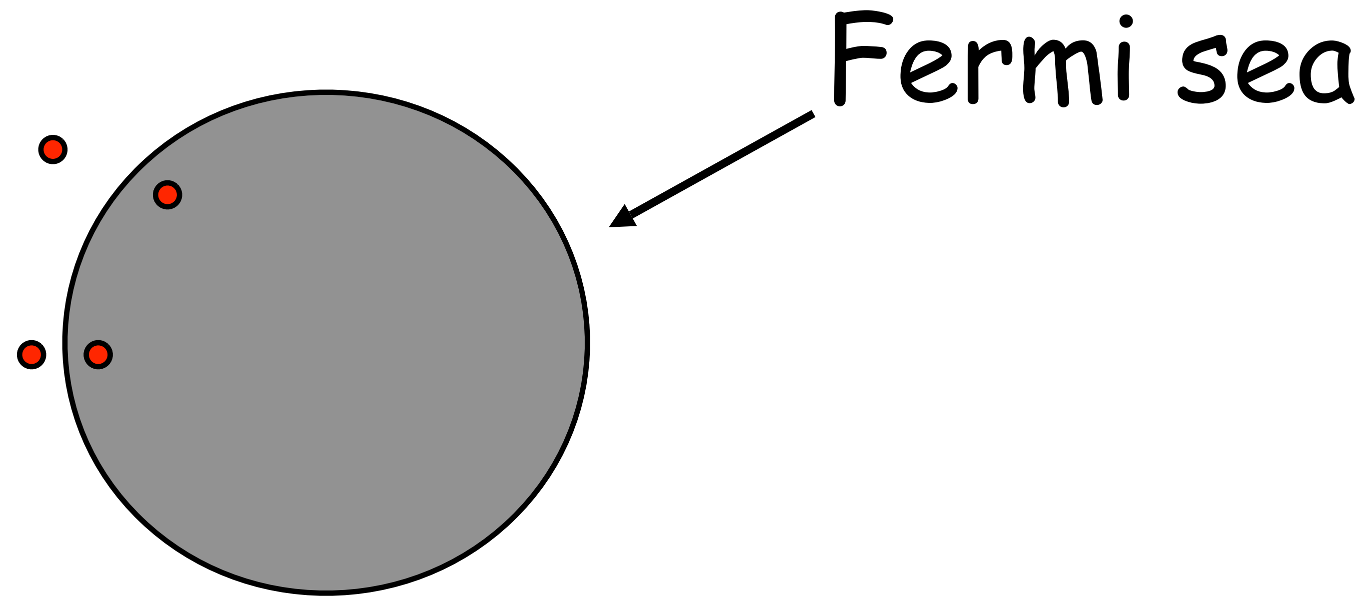
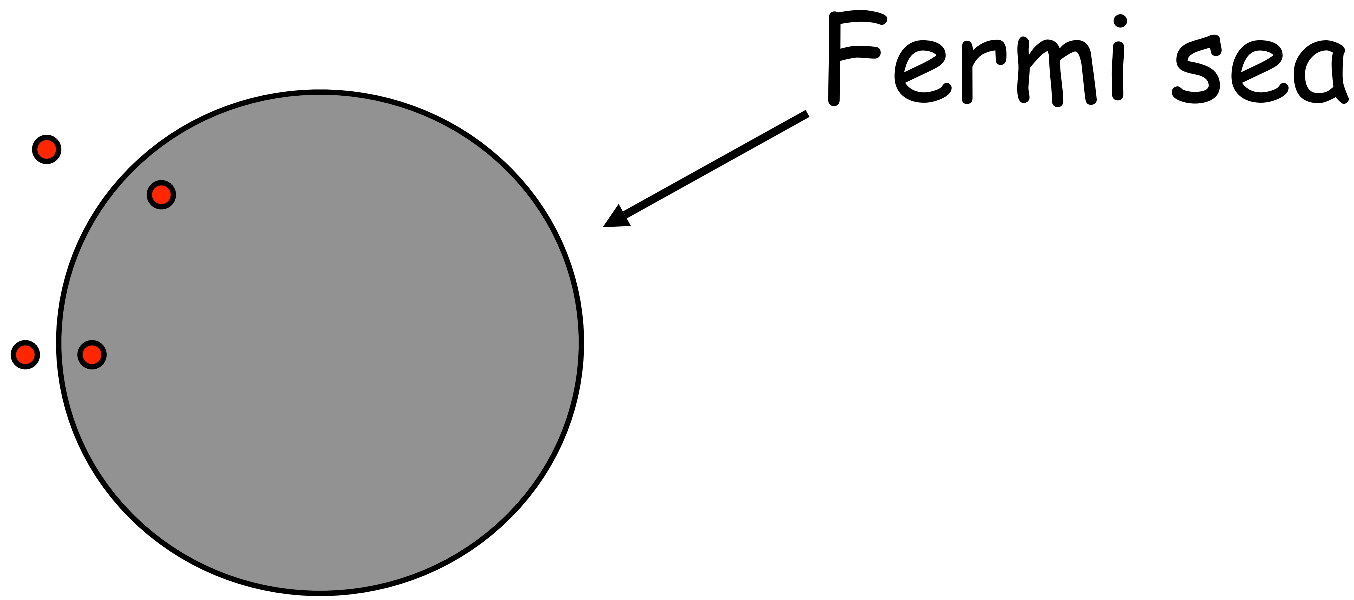


Two degrees of freedom

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

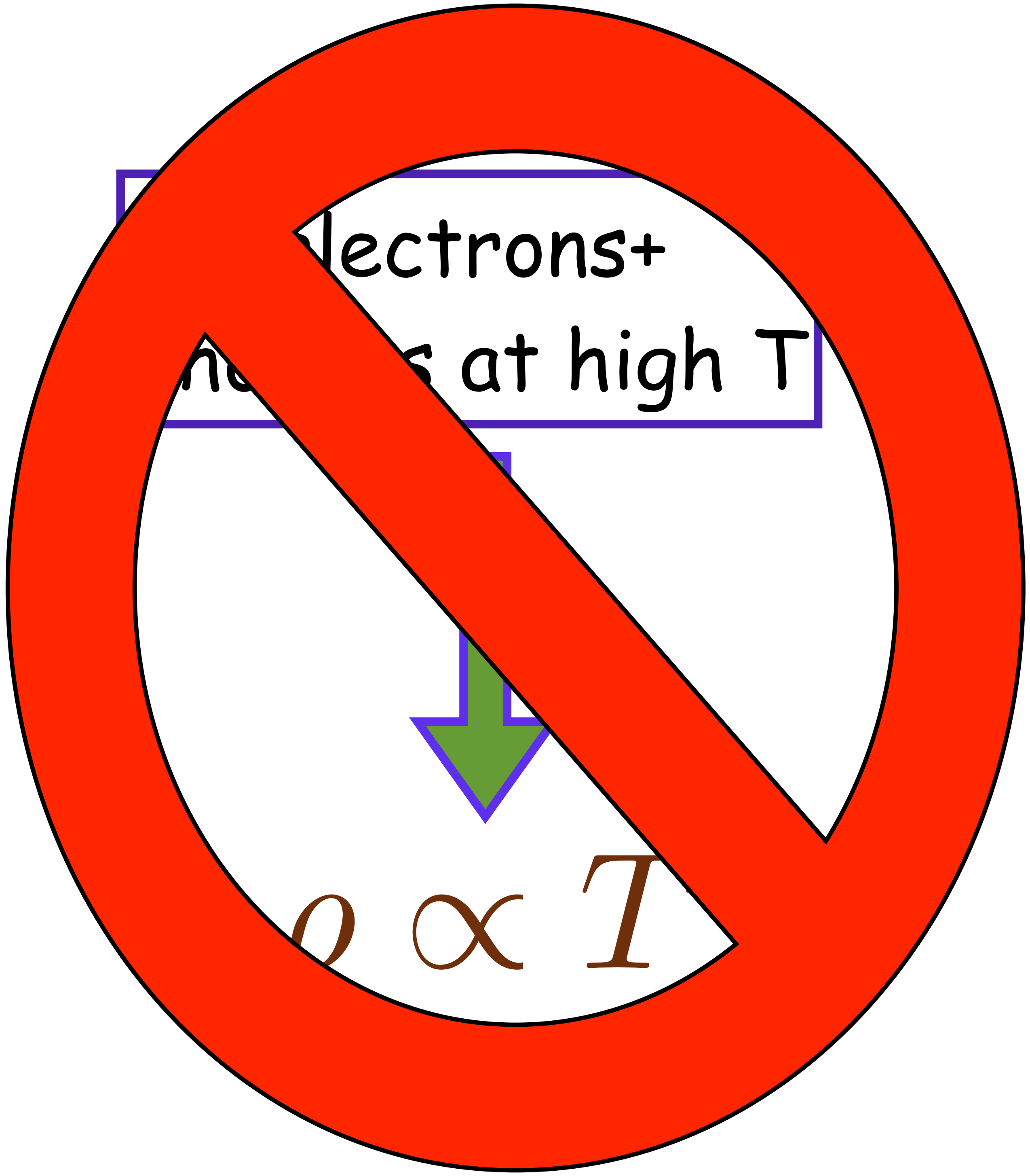
$$\frac{\hbar}{\tau} \equiv \# k_B T$$

Planckian limit of dissipation

breakdown of standard
Fermi liquid
picture

electrons+
phonons at high T

$$\rho \propto T$$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at high T
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Cuprates: The Perfect Storm

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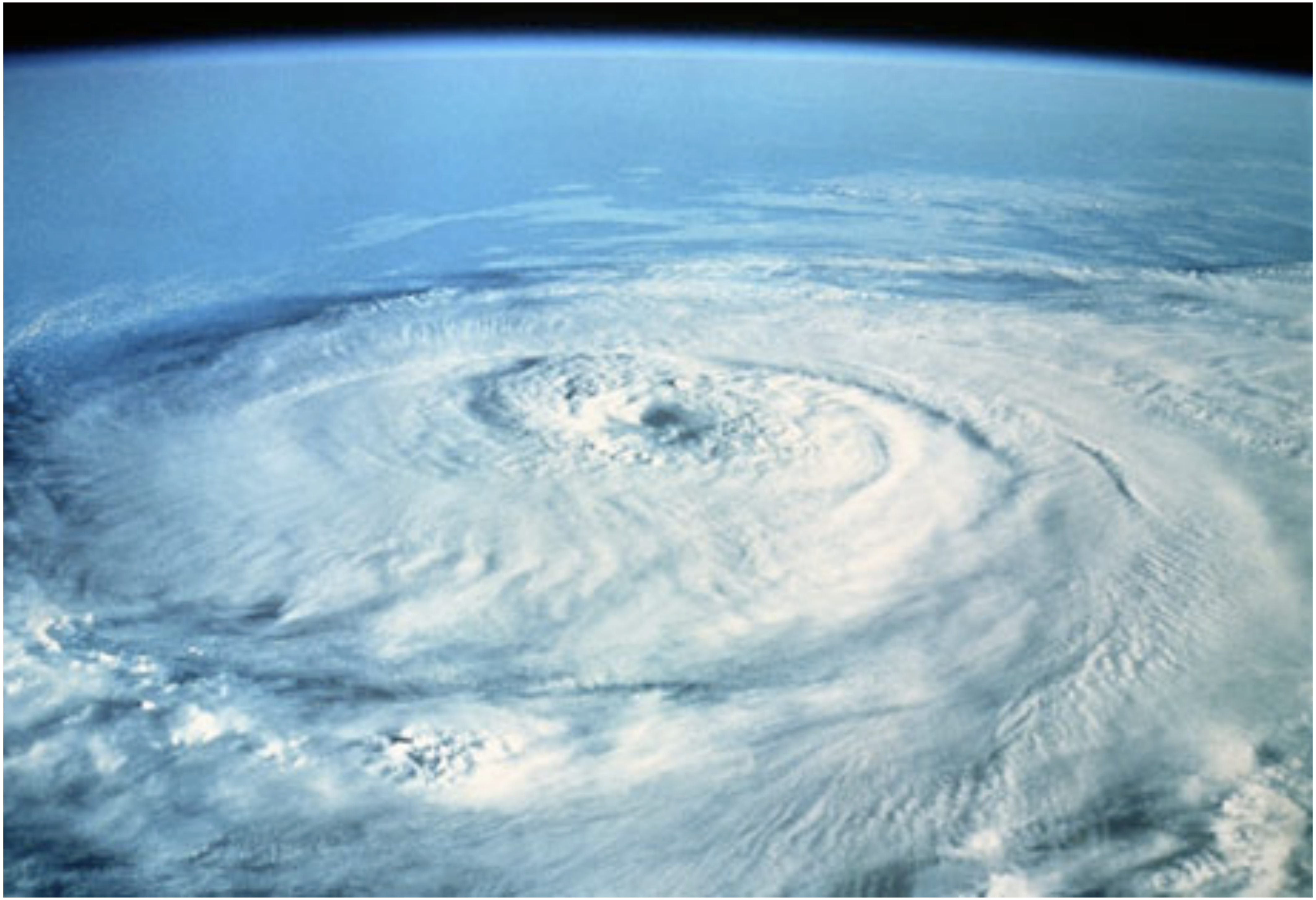


collective failure

collective failure

New Concept

collective failure

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

New Concept

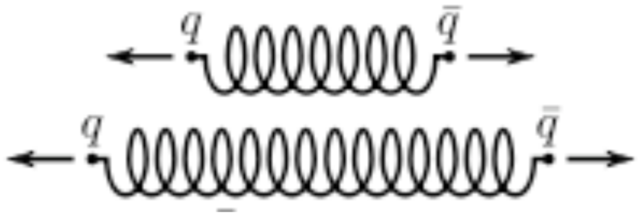
Strong Coupling

composite or bound states not in UV theory

Strong Coupling

composite or bound states not in UV theory

QCD



Strong Coupling

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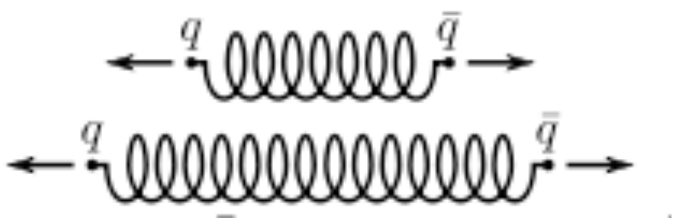
QCD

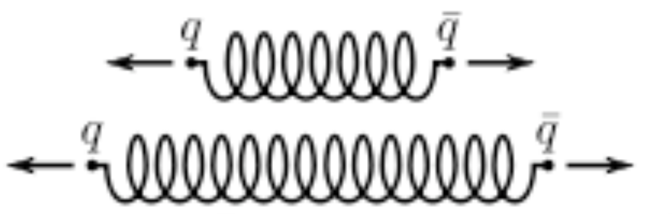


vulcanization

Strong Coupling

composite or bound states not in UV theory

QCD



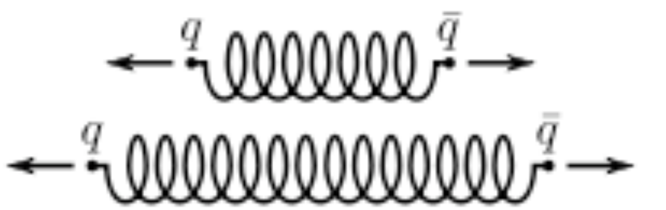
vulcanization

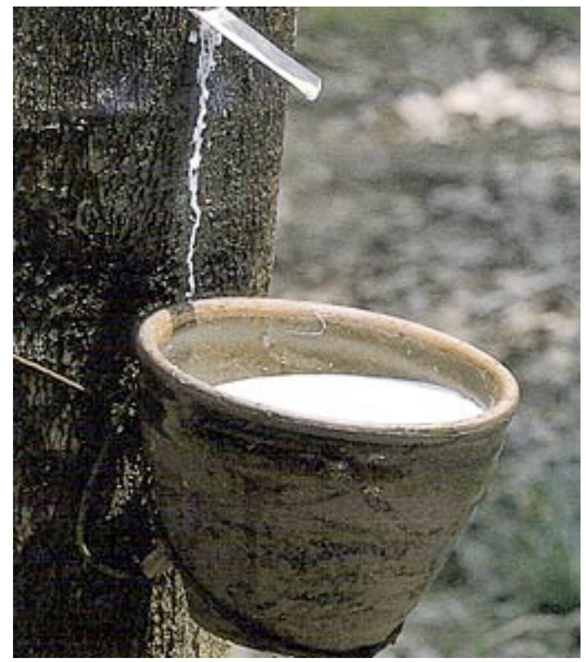
emergent
low-energy physics

Strong Coupling

composite or bound states not in UV theory

QCD



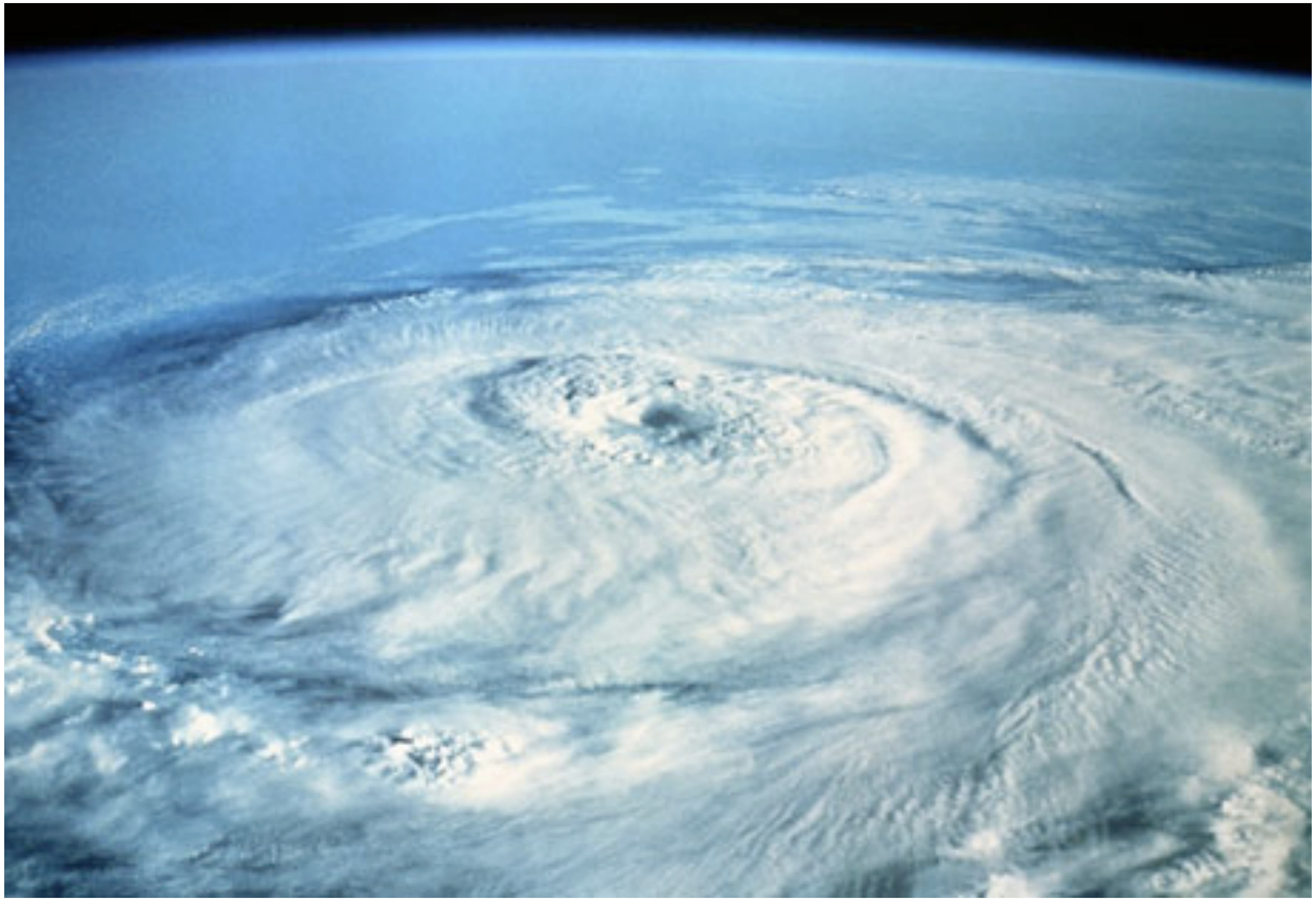


vulcanization

Laminar and turbulent flow of cigarette smoke.

turbulence?

emergent
low-energy physics



weakly interacting

goal:

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

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

Landau Correspondence

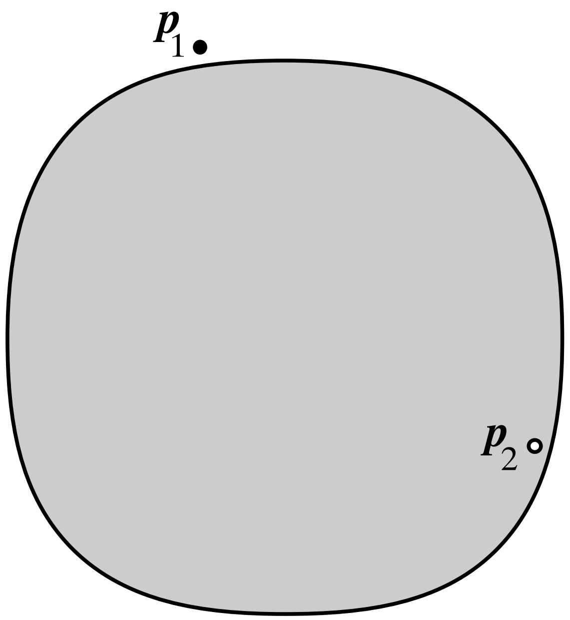
Free system

low-energy:
one-to-one
correspondence

Interacting
system

How does this break down?

Polchinski (and others)



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

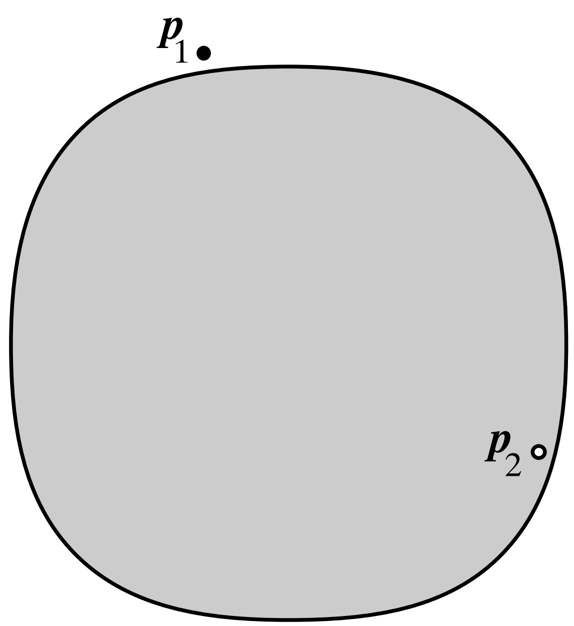
1.) e- charge carriers

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

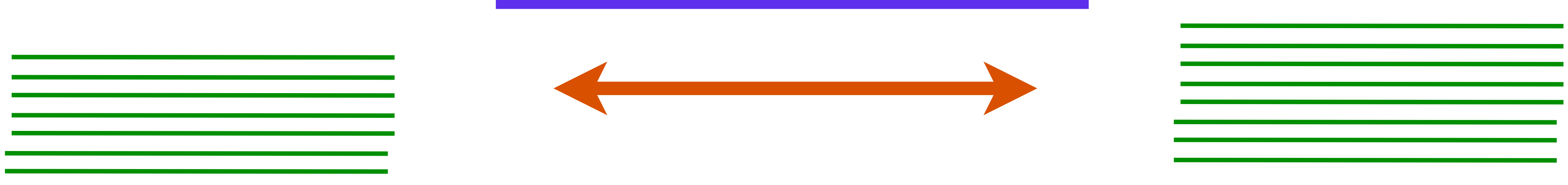
So what does one add to break this correspondence?

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

Interacting system

Free system

low-energy: one-to-one correspondence



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Interacting system

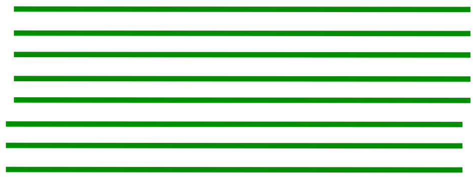
Free system

new degrees of freedom!

So what does one add to break this correspondence?

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

Free system



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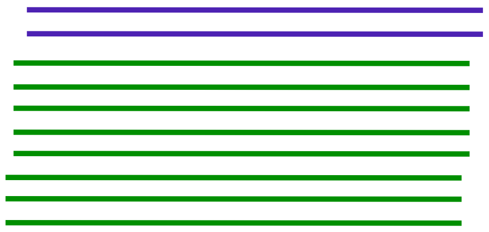

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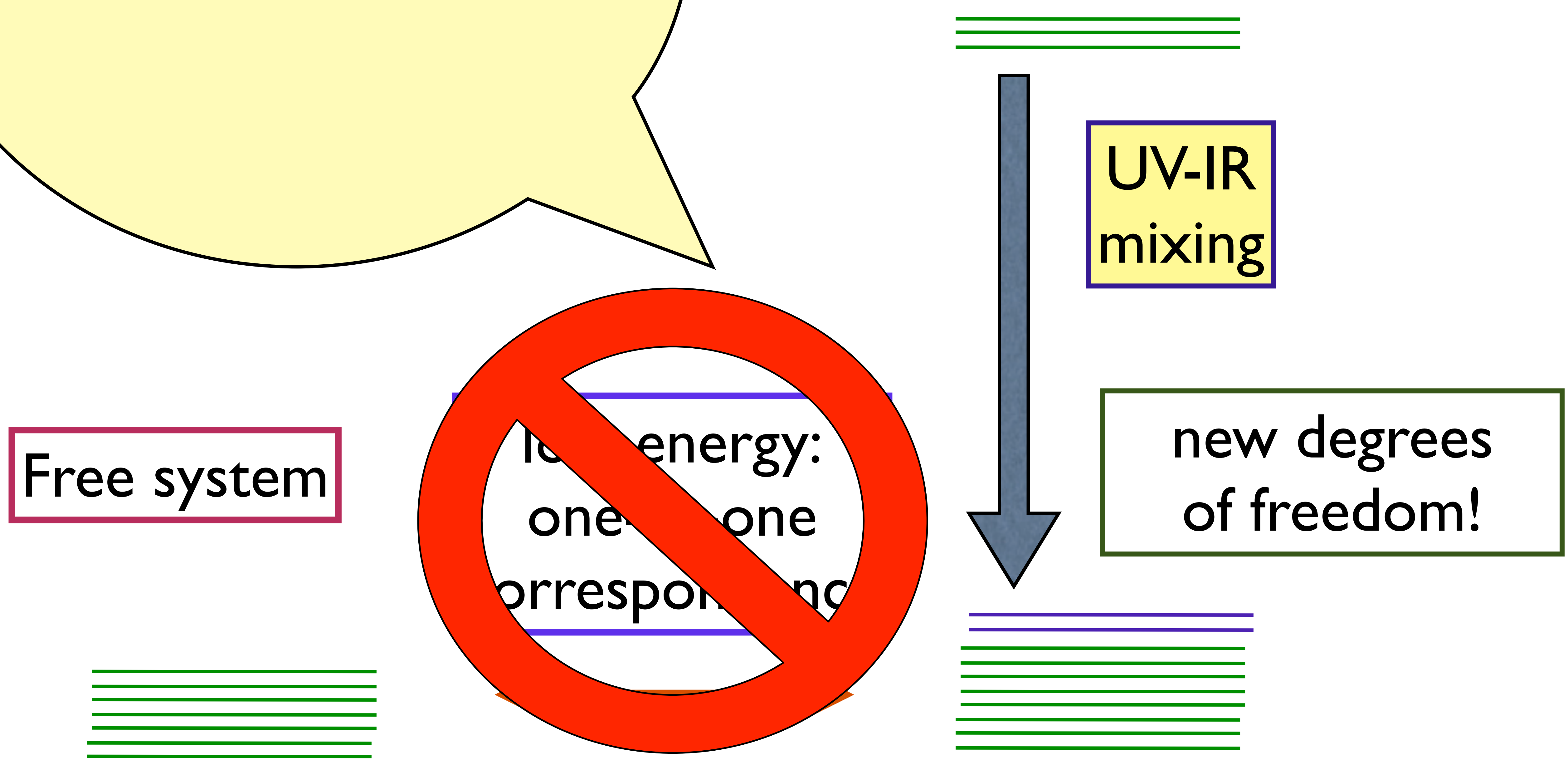

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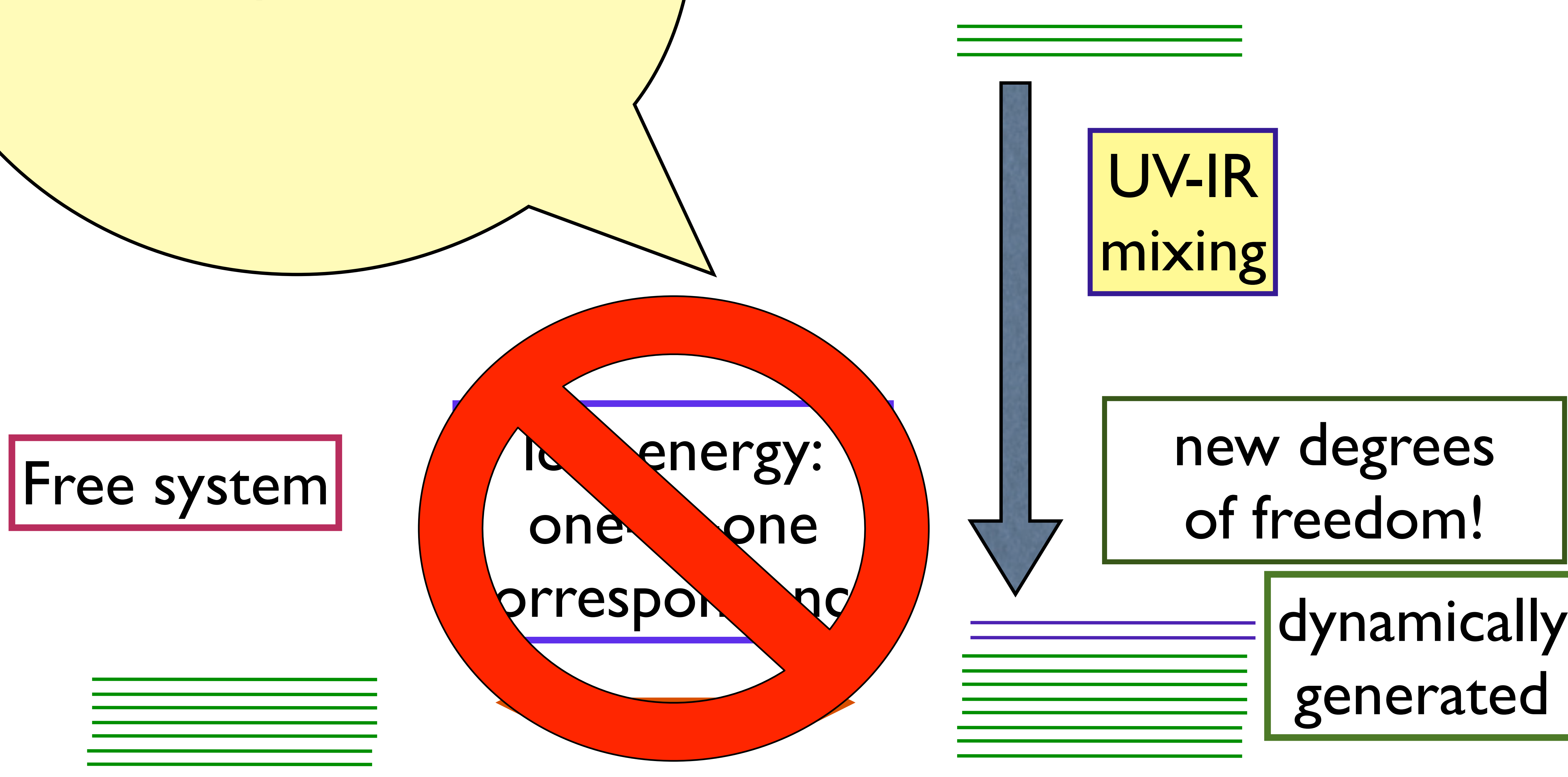
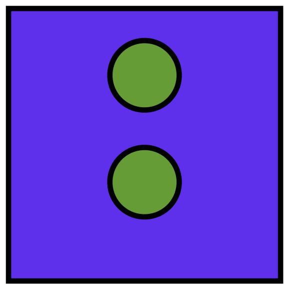


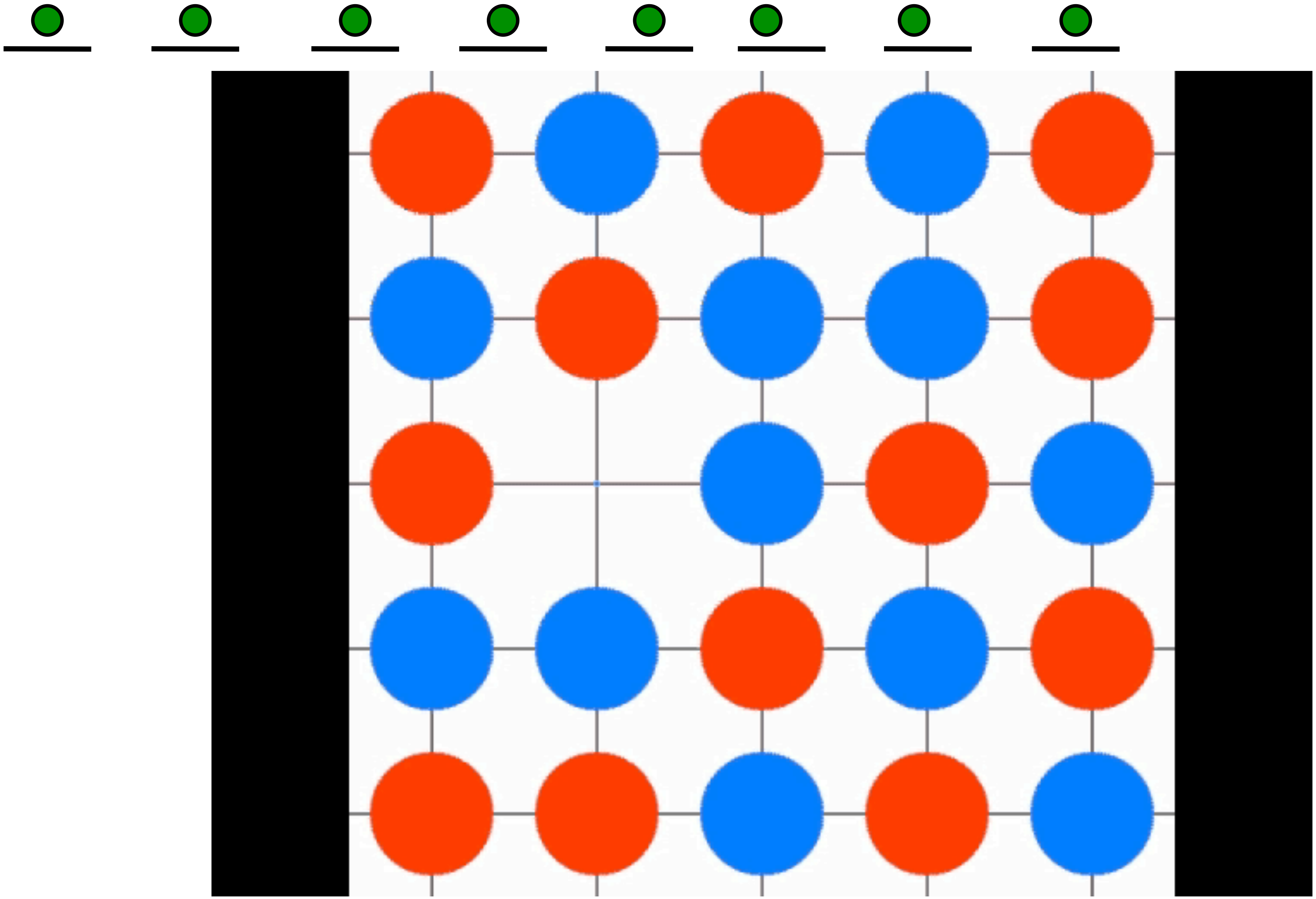
classical Mottness



is forbidden

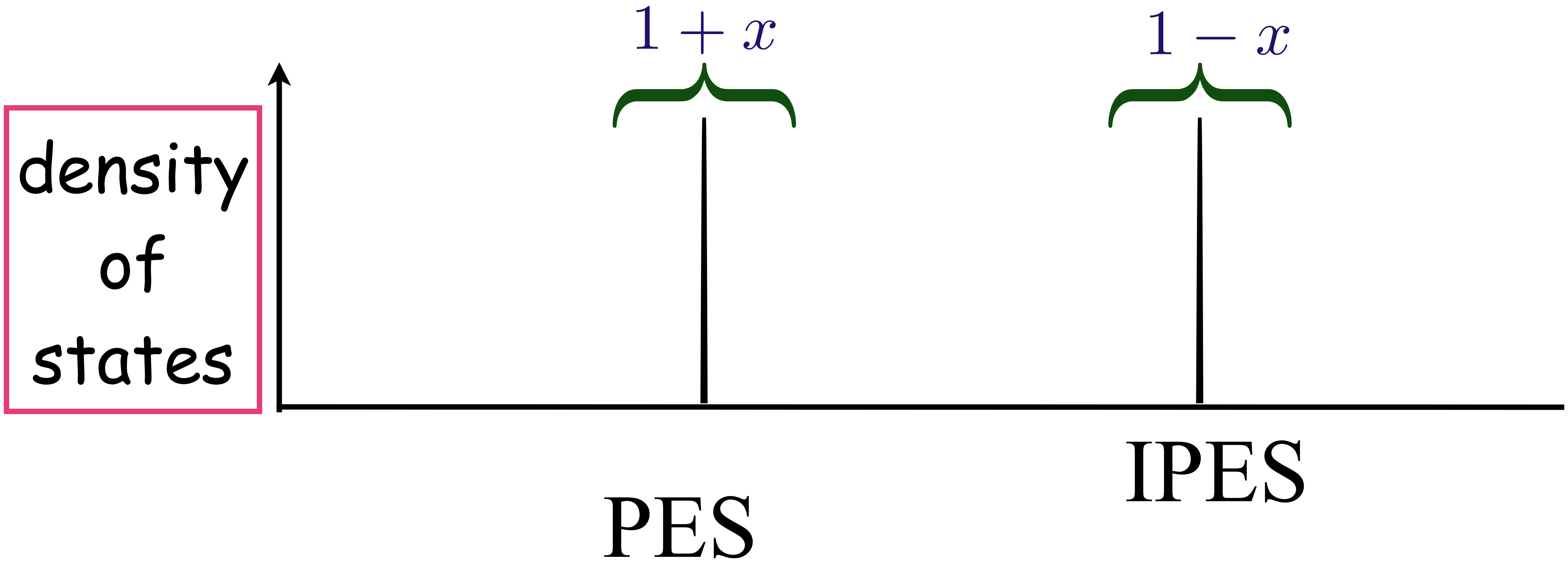
classical Mottness

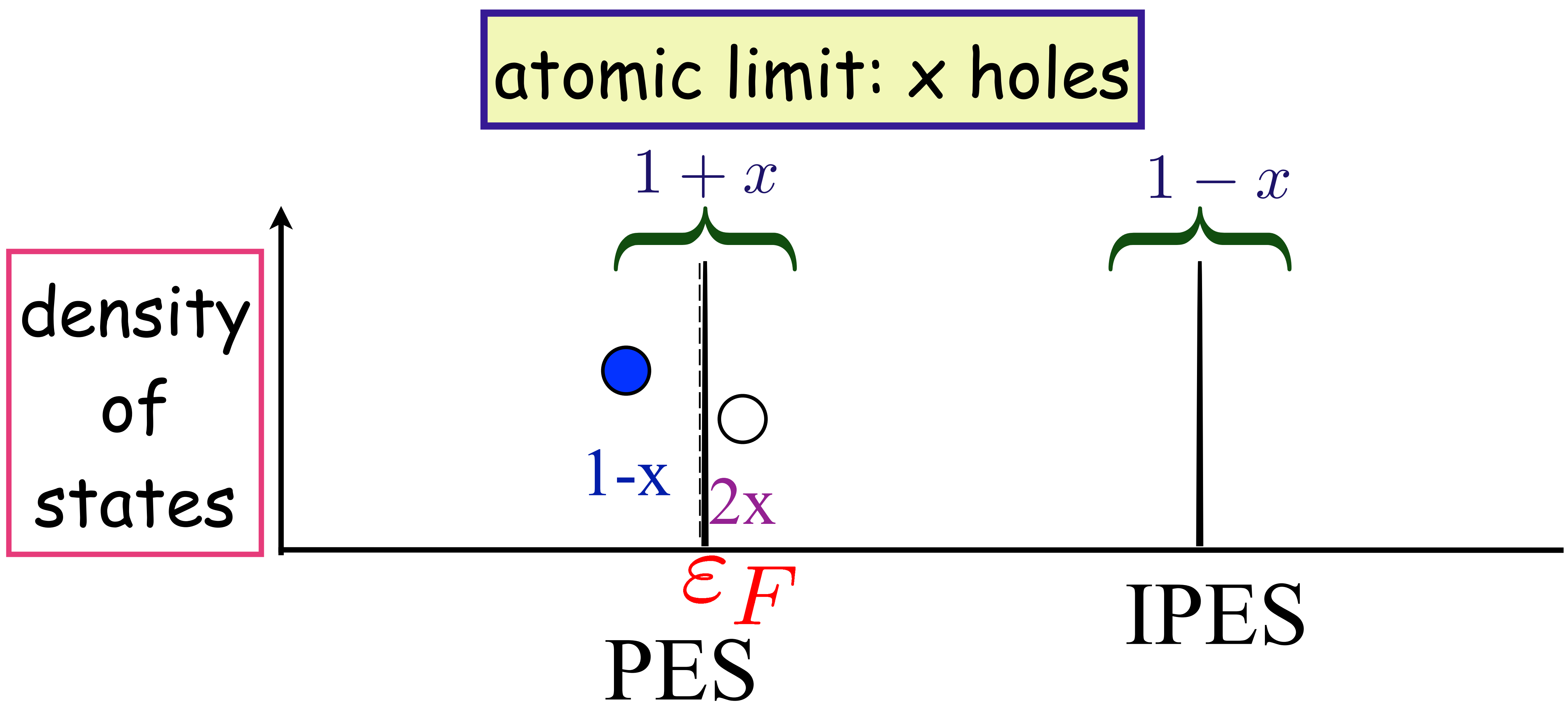
classical Mottness



atomic limit: x holes

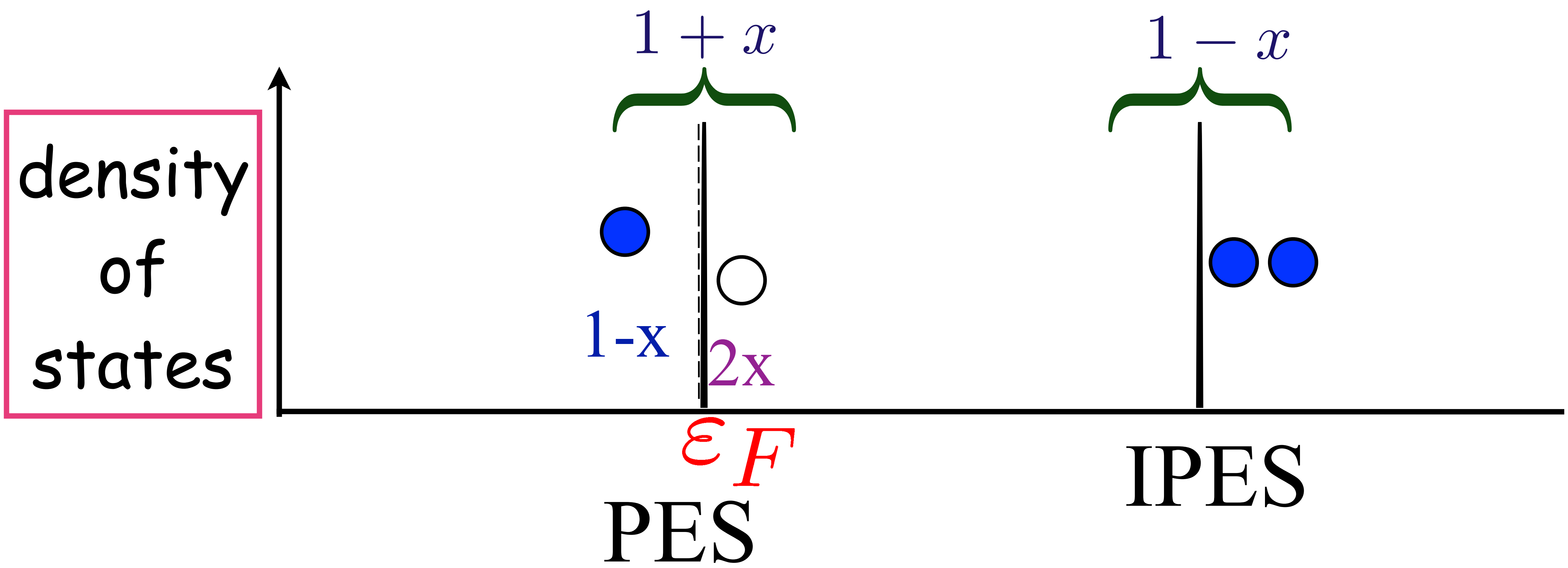
atomic limit: x holes





atomic limit: x holes
$1+x$
$1-x$
density
of
states
1-x
2x
ε_F
PES
IPES

atomic limit: x holes



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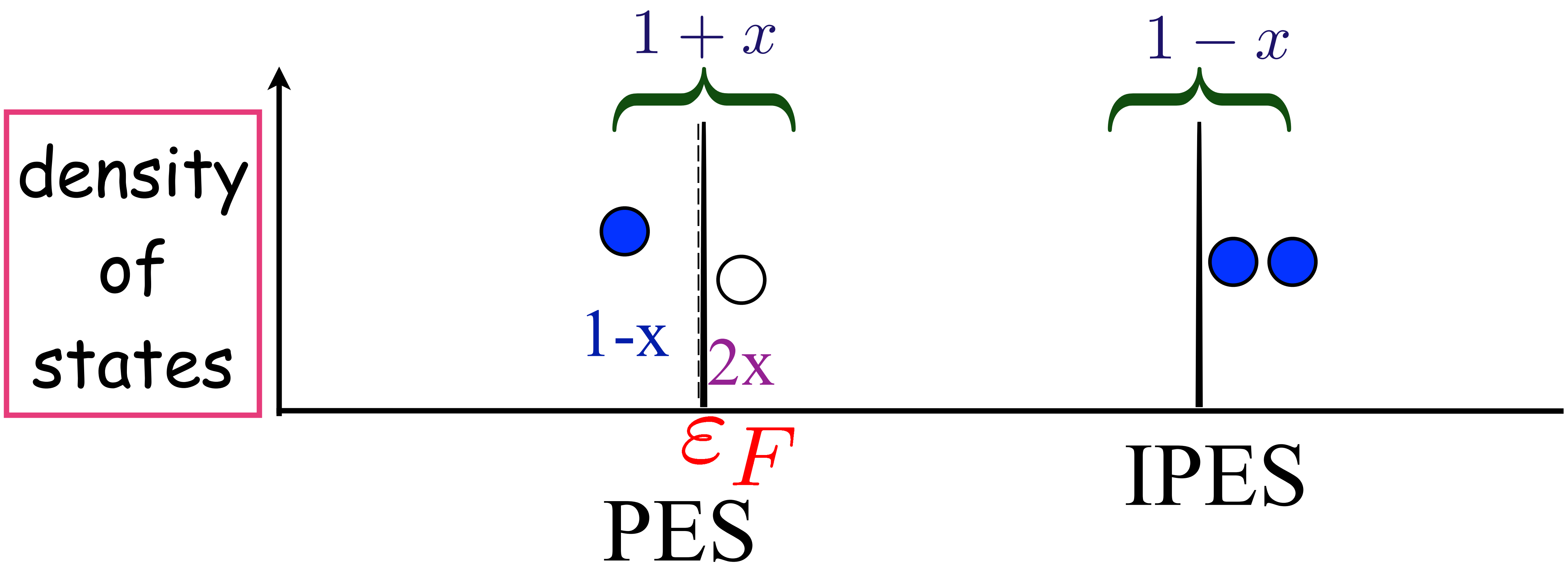
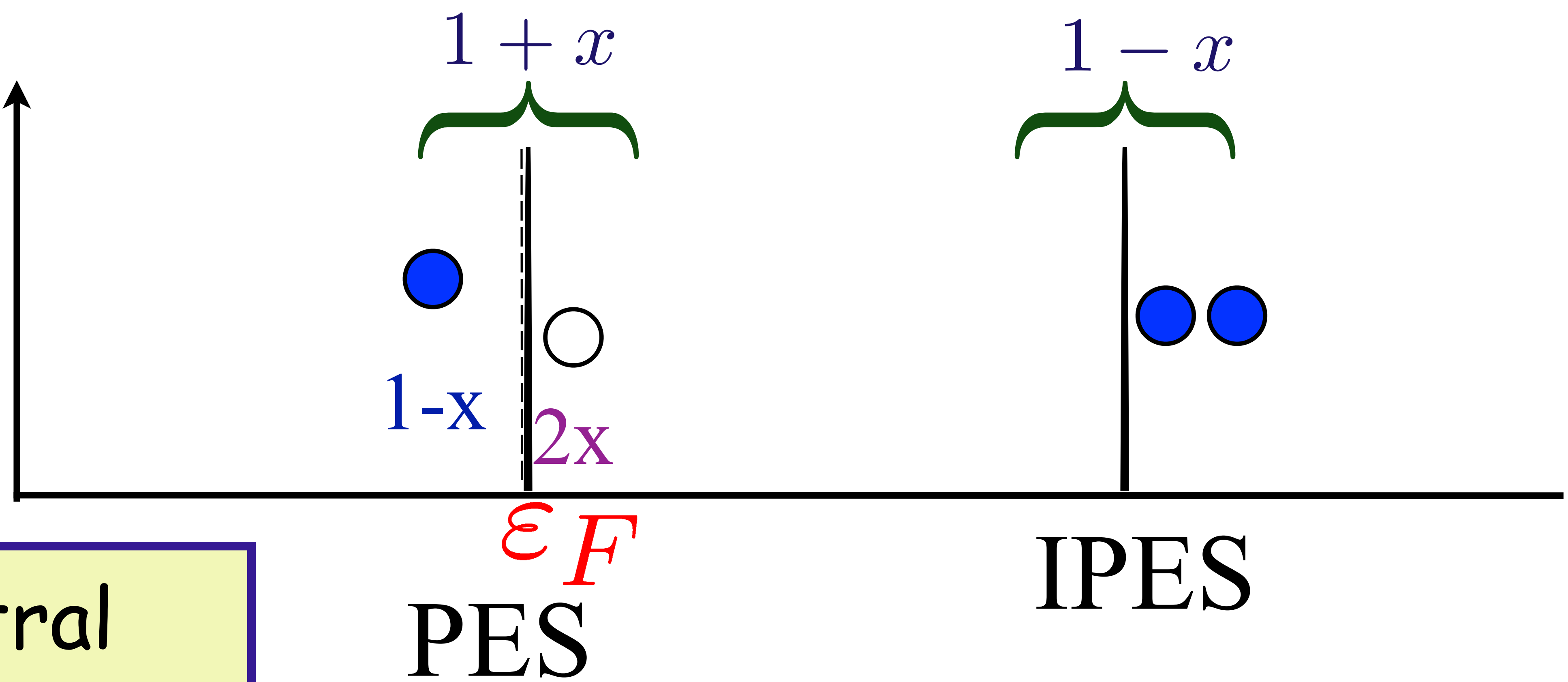


$$G(\omega,k)=\frac{1+x}{\omega-\mu+U/2}+\frac{1-x}{\omega-\mu-U/2}$$

atomic limit: x holes

density of states



spectral weight: x-dependent

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

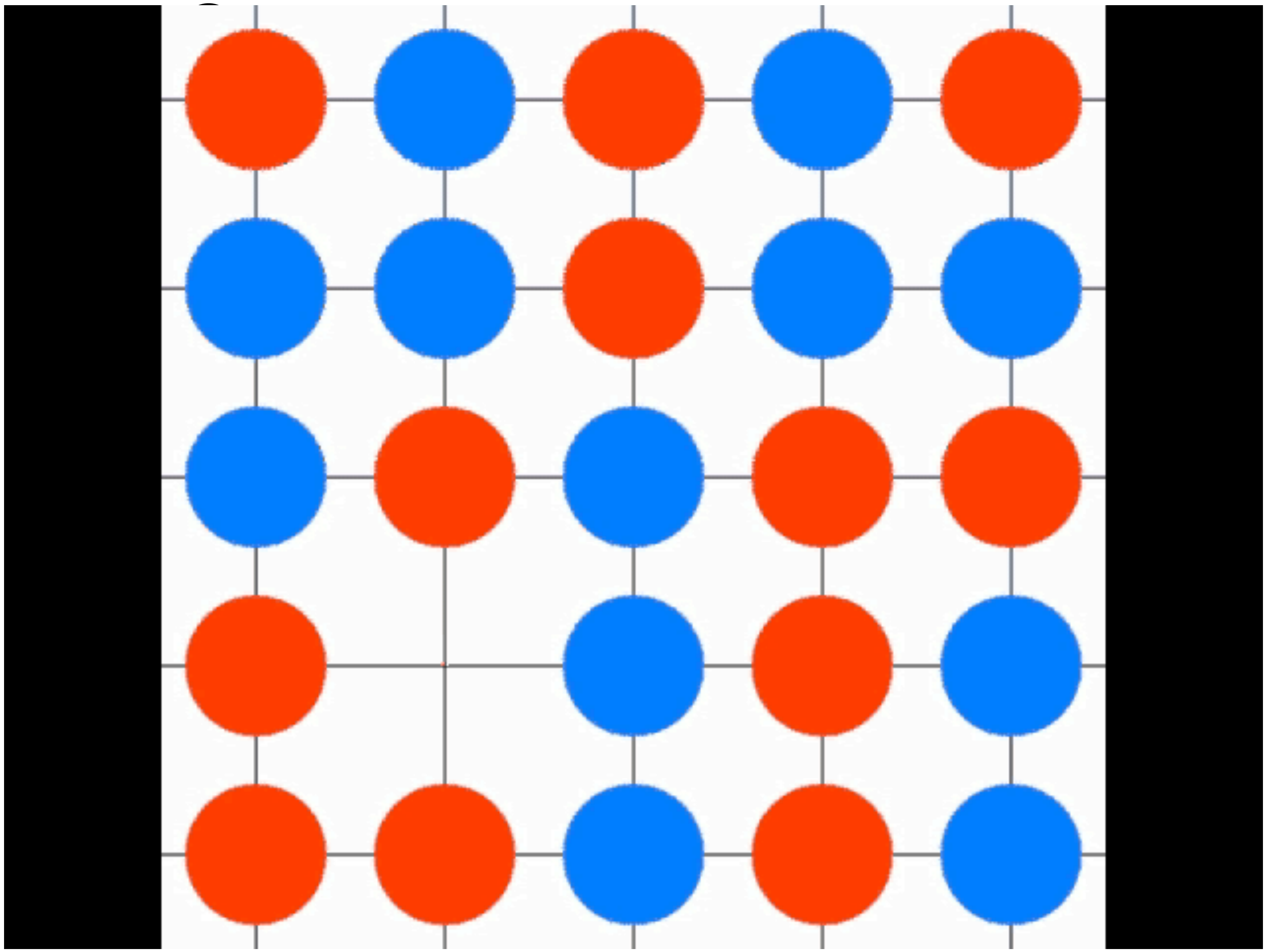
atomic limit

total weight=1+x= # of electron states 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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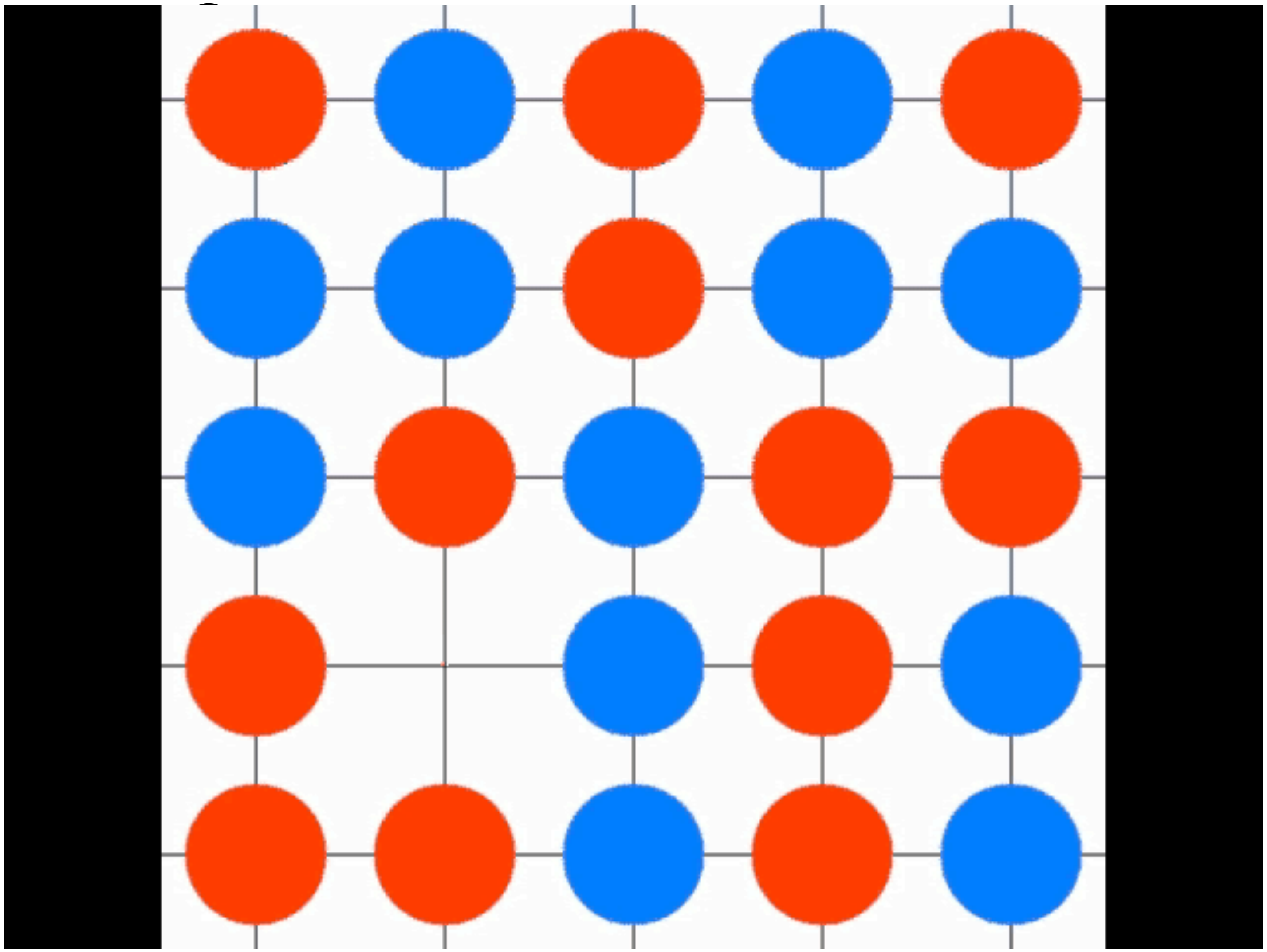
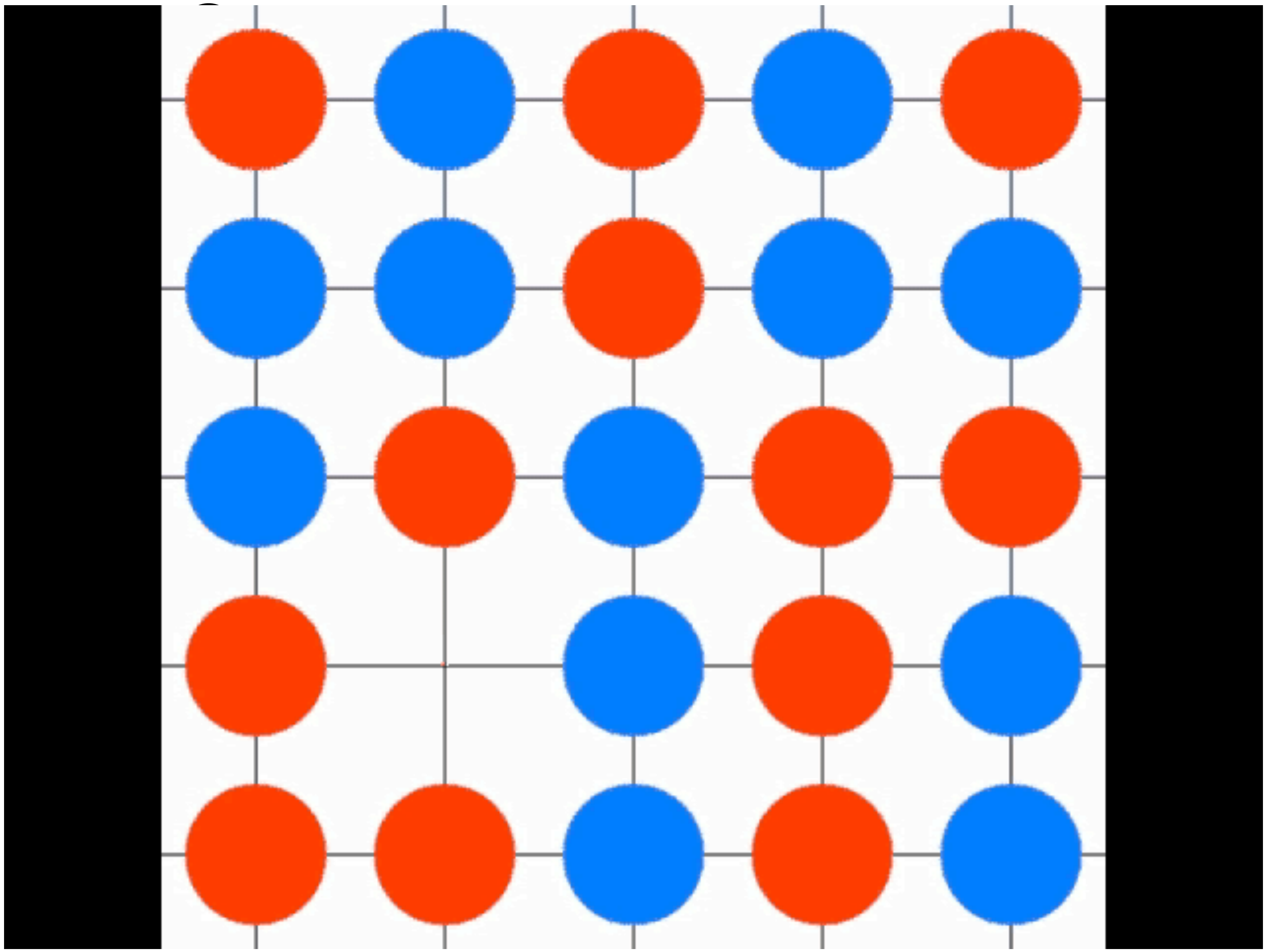


double occupancy in ground state!!

quantum Mottness: U finite

$U \gg t$



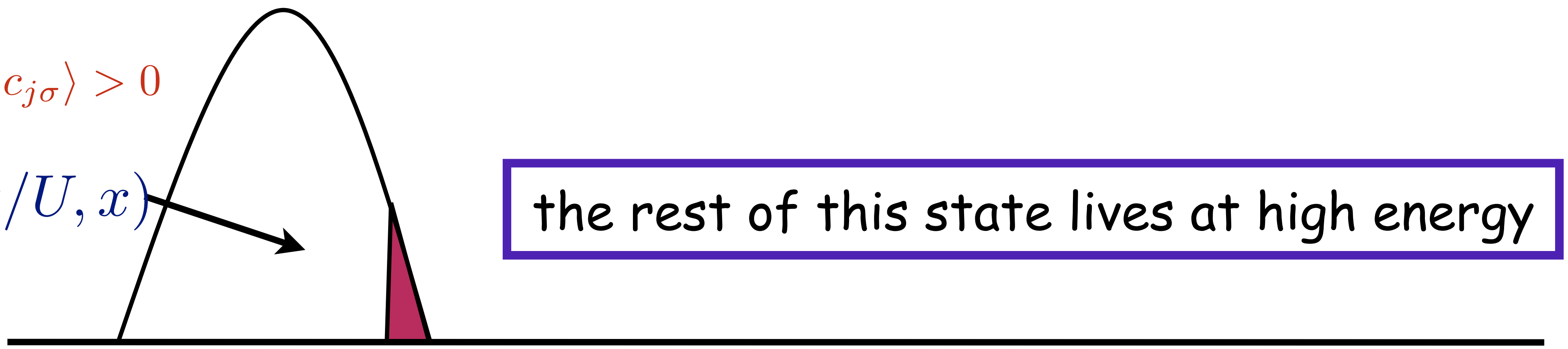
double occupancy in ground state!!

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

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

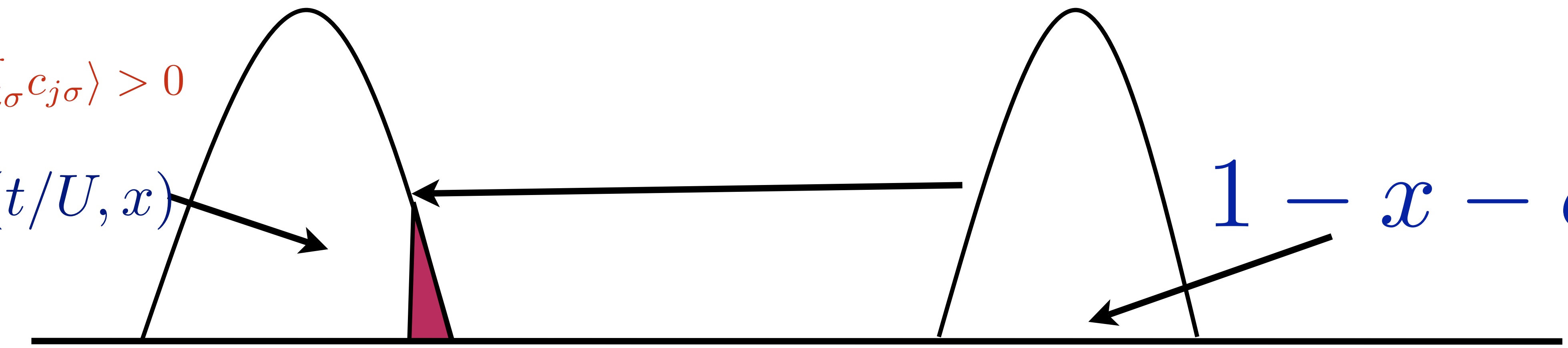
$$\alpha = \frac{t}{U}\sum_{ij}\langle c^{\dagger}_{i\sigma}c_{j\sigma}\rangle > 0$$

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

Harris & Lange, 1967

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

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



$$1 - x - \alpha$$

Harris & Lange, 1967

dynamical spectral weight transfer

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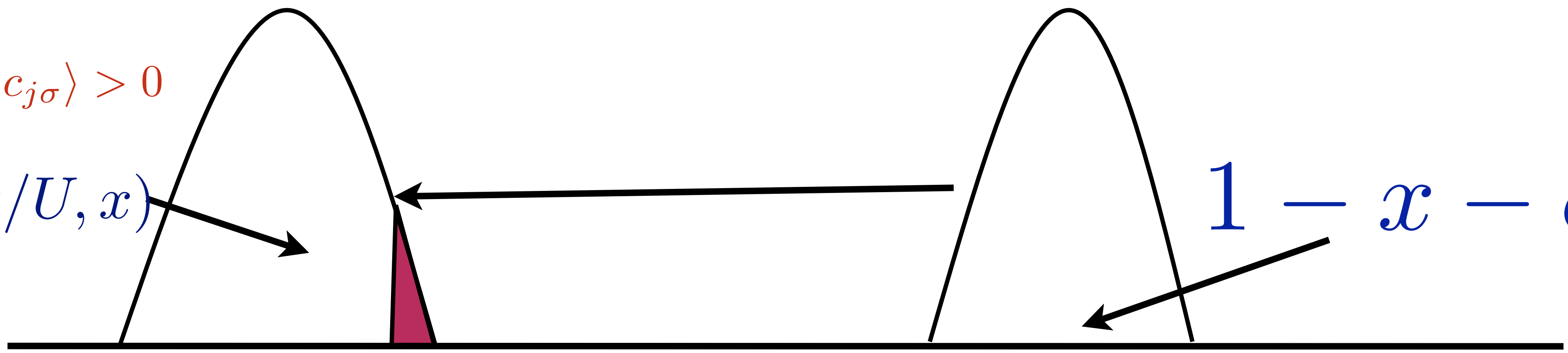

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Intensity>1+x

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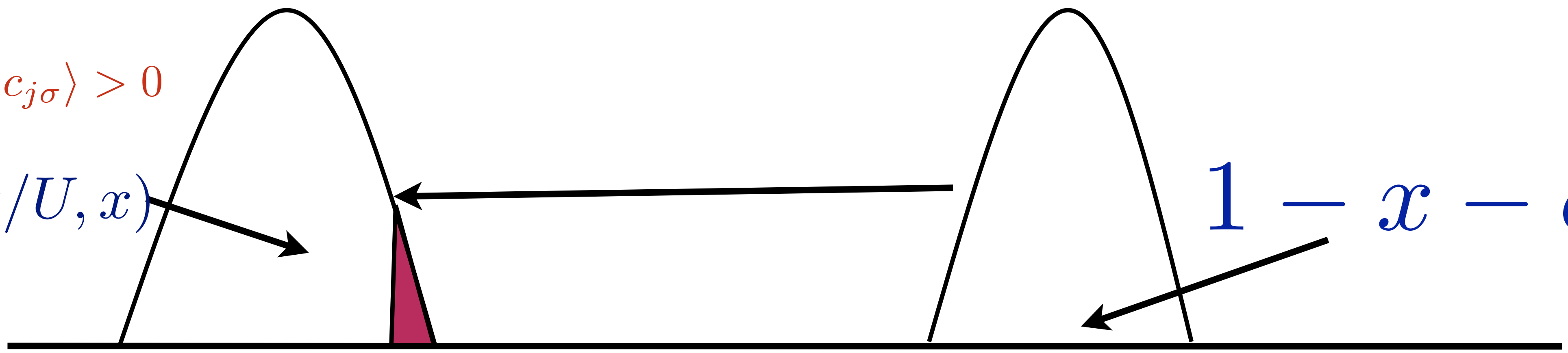

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Intensity>1+x

# of electron states
in lower band

Harris & Lange, 1967

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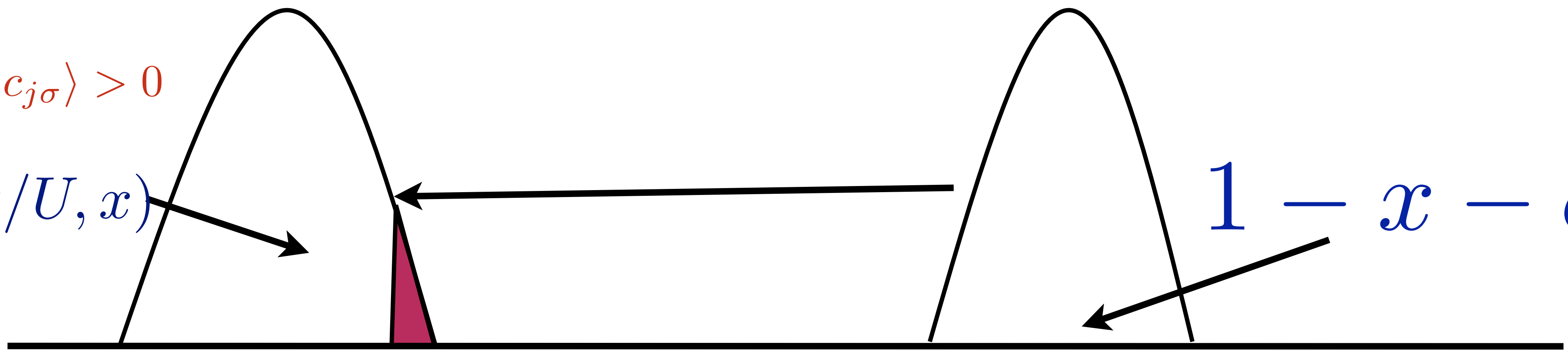

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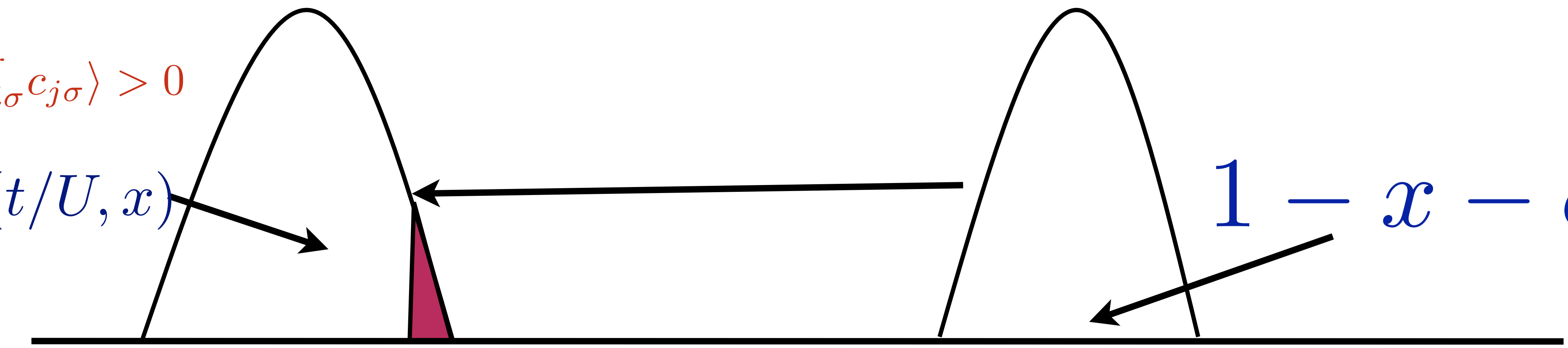

$$1 - x - \alpha$$

Intensity>1+x

# of charge e states

# of electron states in lower band

not exhausted by counting electrons alone?

What are the extra states (degrees of freedom)?

Key Equation

$$1 = 2 - 1$$

Key Equation

$$1 = 2 - 1$$

$$e = 2e - e$$

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composite (bound) excitation

2e(boson)
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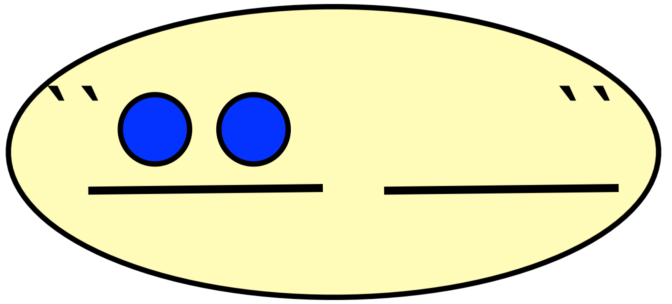
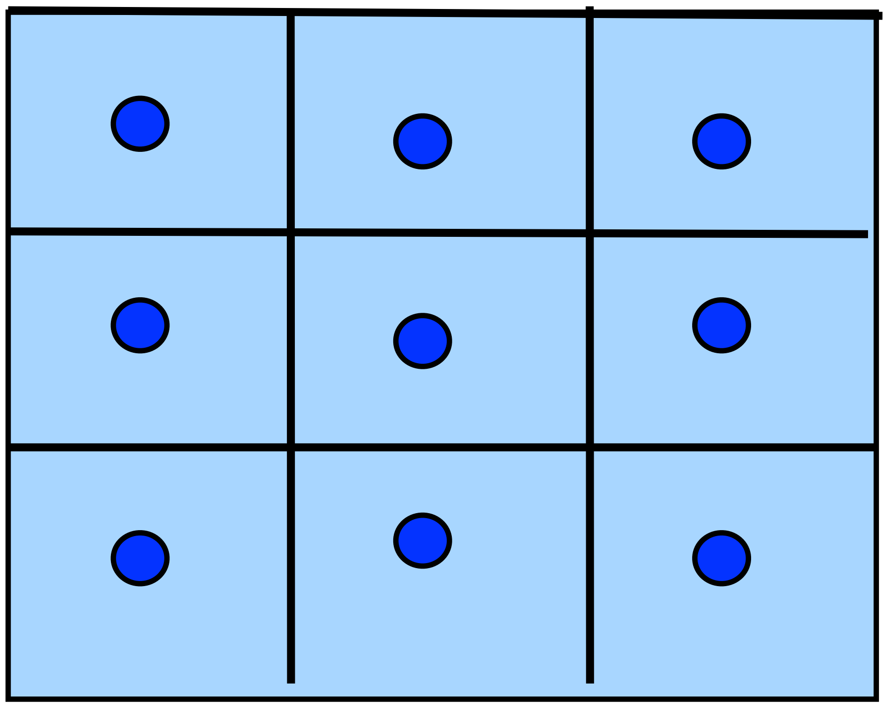
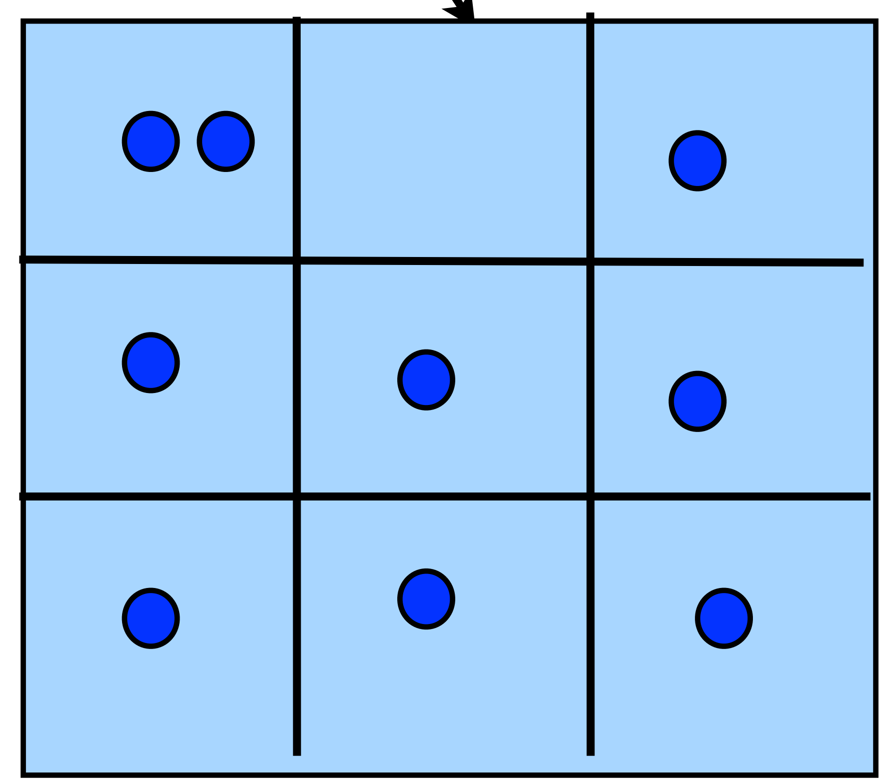


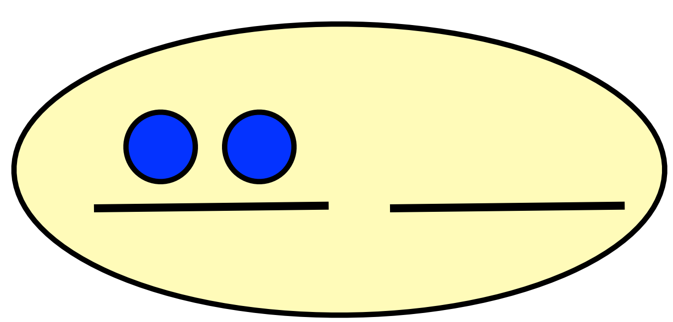
Same Physics at half-filling

is the empty site mobile??



+ t/U

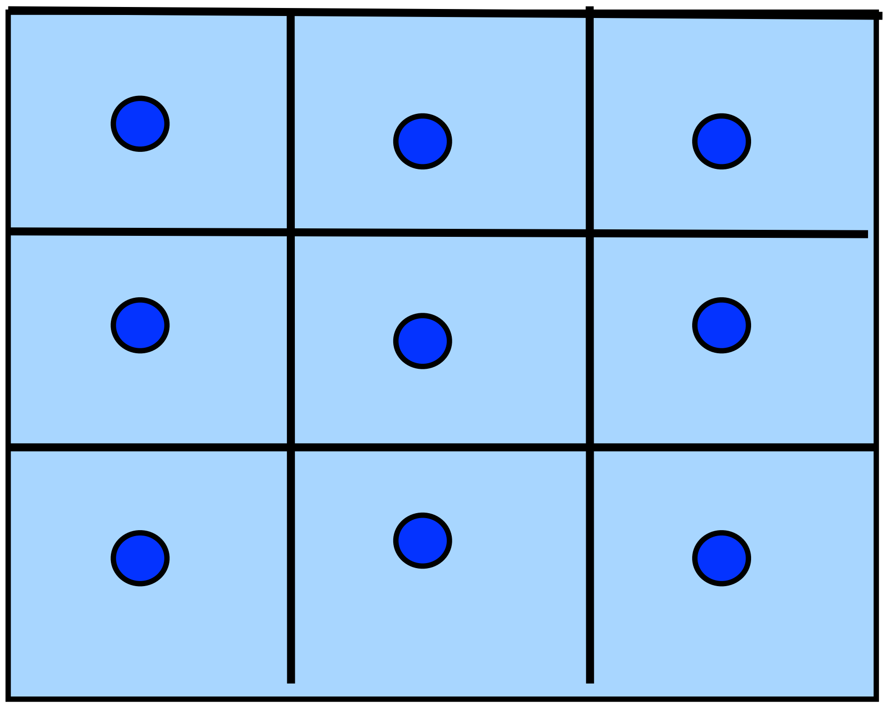




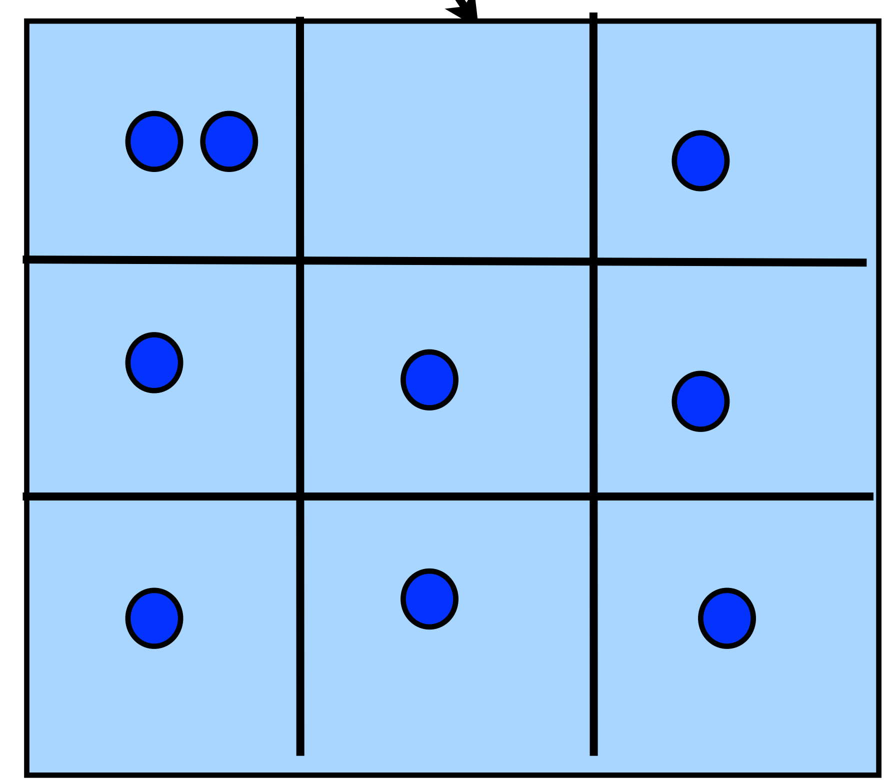
No proof exists?
Mottness is ill-defined

Same Physics at half-filling

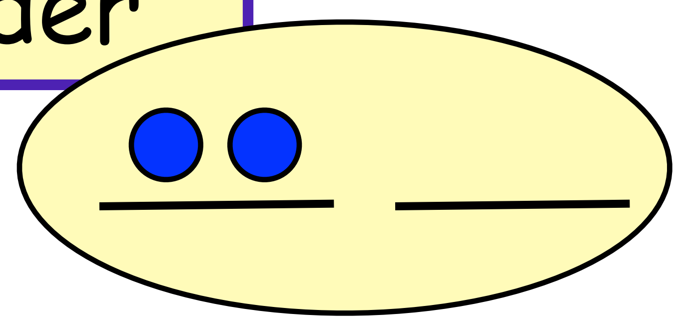
is the empty site mobile??



+ t/U



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



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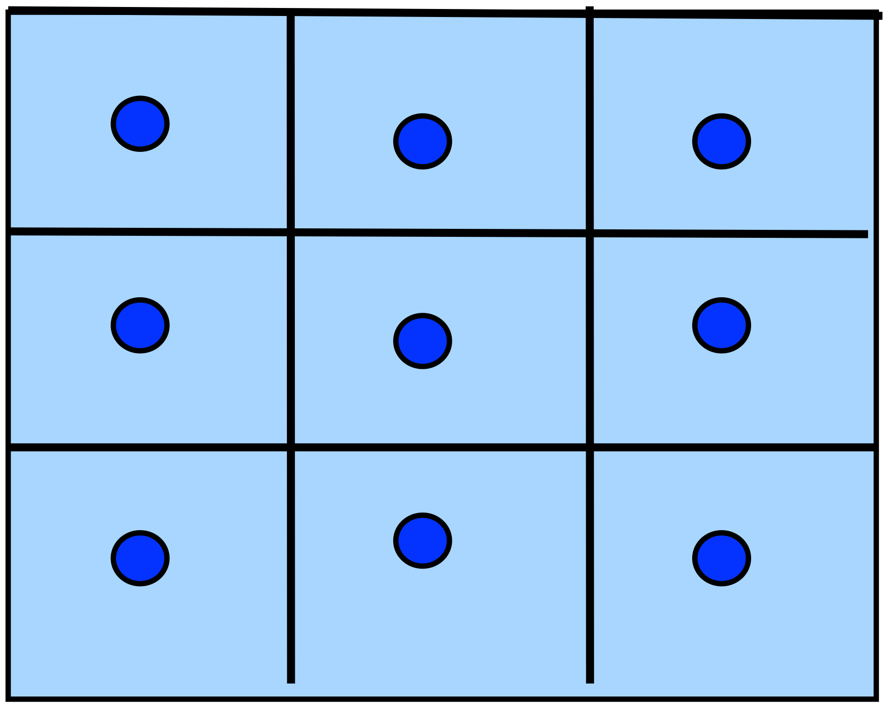
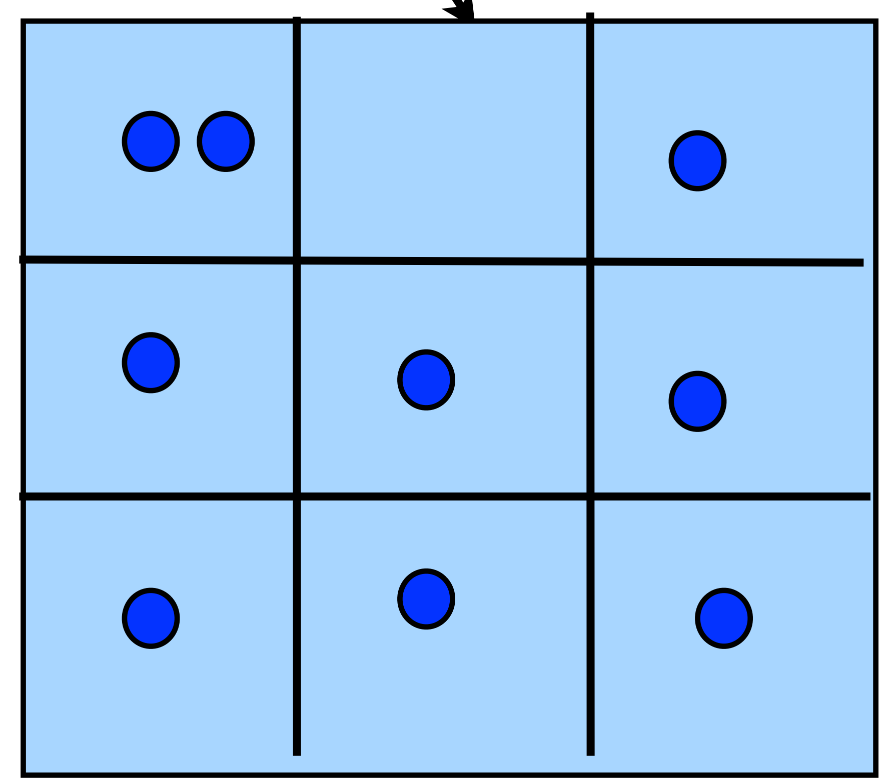


+ t/U



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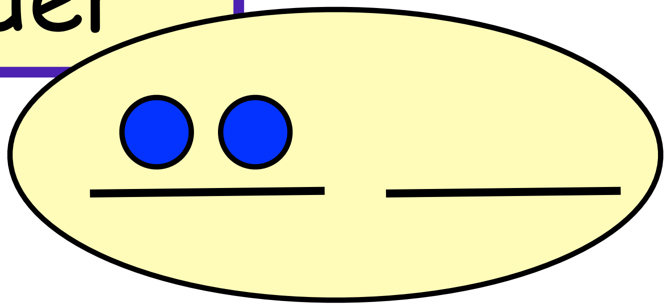

No proof exists?
Mottness is ill-defined

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
of weak
coupling

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

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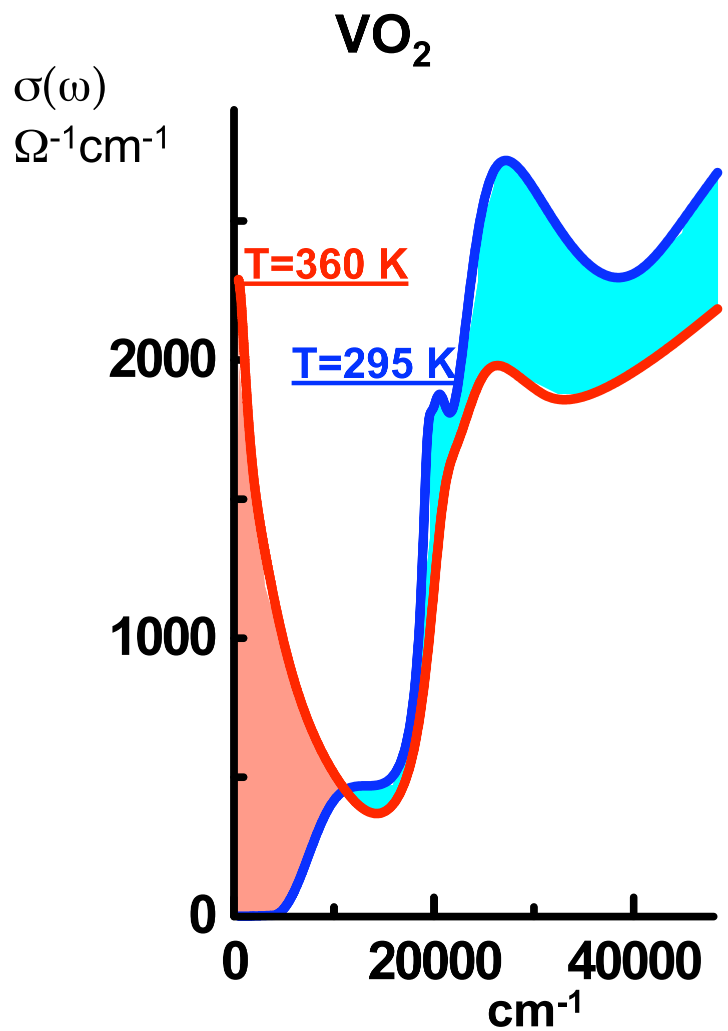
$$\Delta = 0.6eV > \Delta_{\text{dimerization}}$$ (Mott, 1976) $\boxed{\dfrac{\Delta}{T_{\text{crit}}} \approx 20}$



transfer of spectral weight to high energies beyond any ordering scale

Recall, $eV = 10^4 K$

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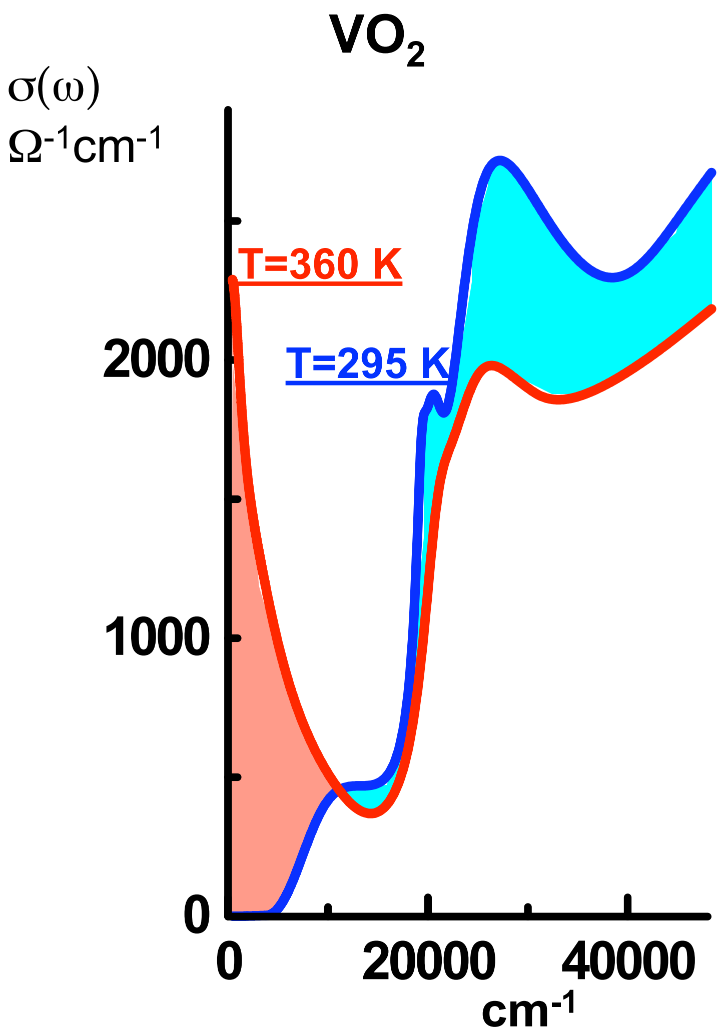

M. M. Qazilbash, K. S. Burch, D. Whisler, D. Shrekenhamer, B. G. Chae, H. T. Kim, and D. N. Basov PRB 74, 205118 (2006)

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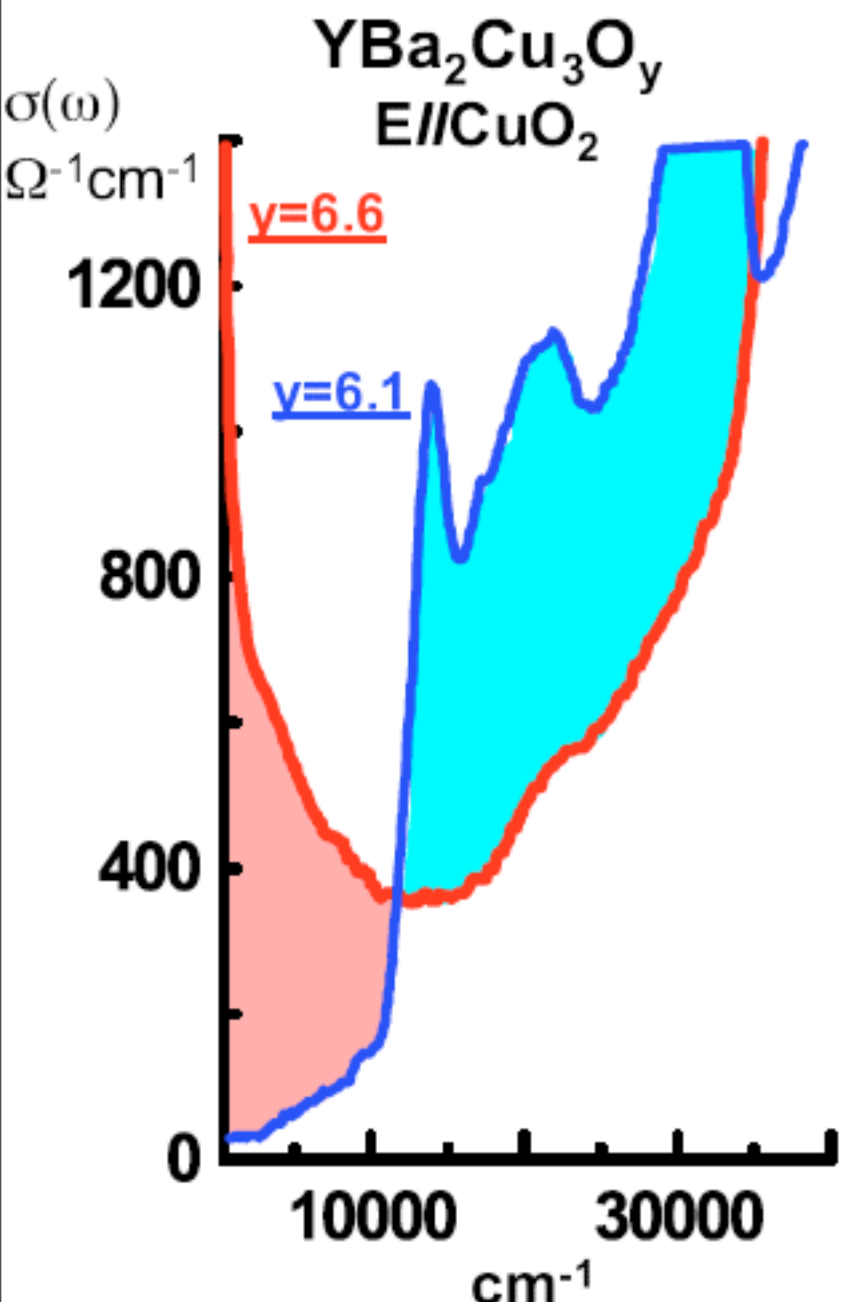

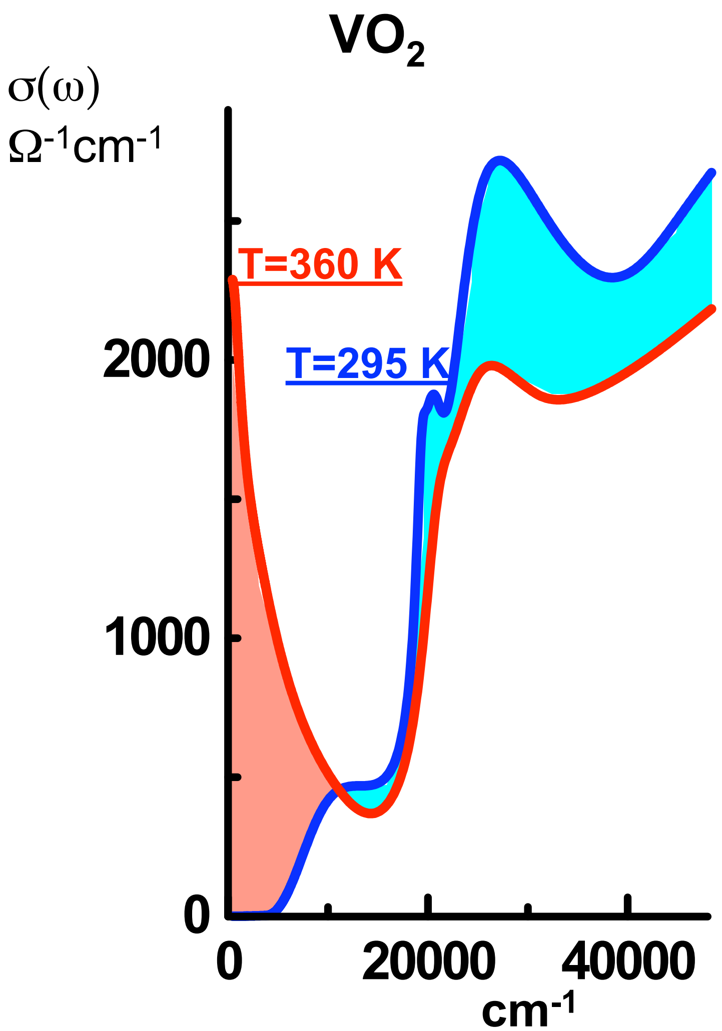

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transfer of spectral weight to high energies beyond any ordering scale

Recall, $eV = 10^4 K$

composite excitation: bound state

half-filling:
Mott gap

doping:
SWT, pseudogap?

charge 2e boson

How?

Effective Theories:

$S(\phi)$ at half-filling

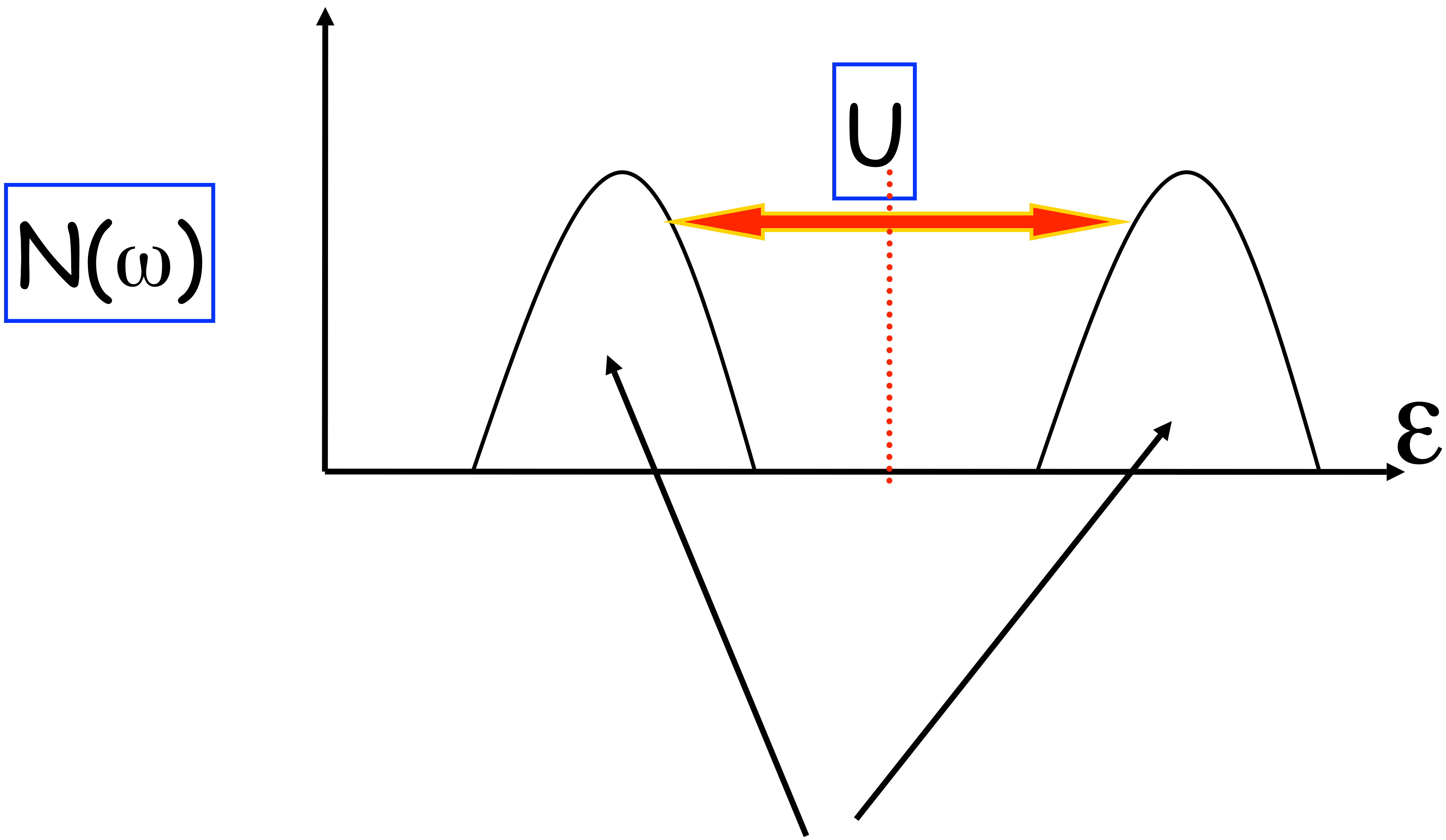
Integrate Out high Energy fields

$\phi=\phi_L+\phi_H$

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

Low-energy theory of M I

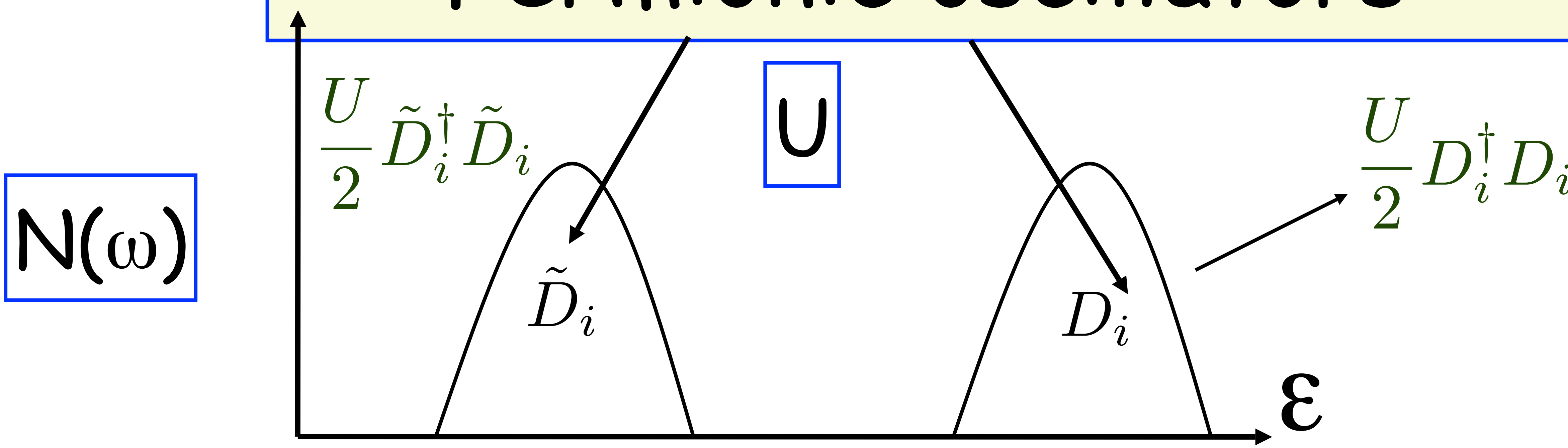
Half-filling

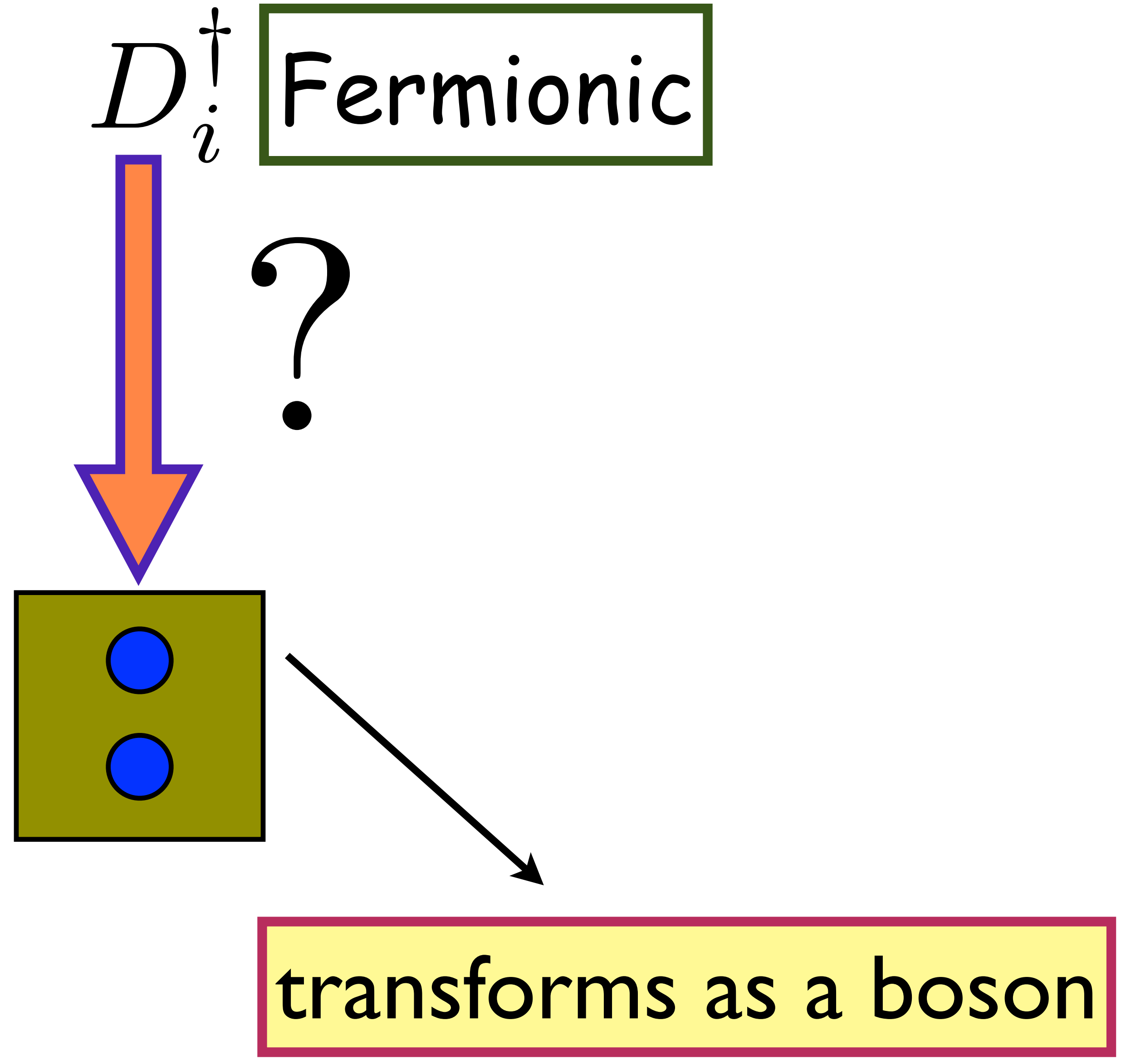


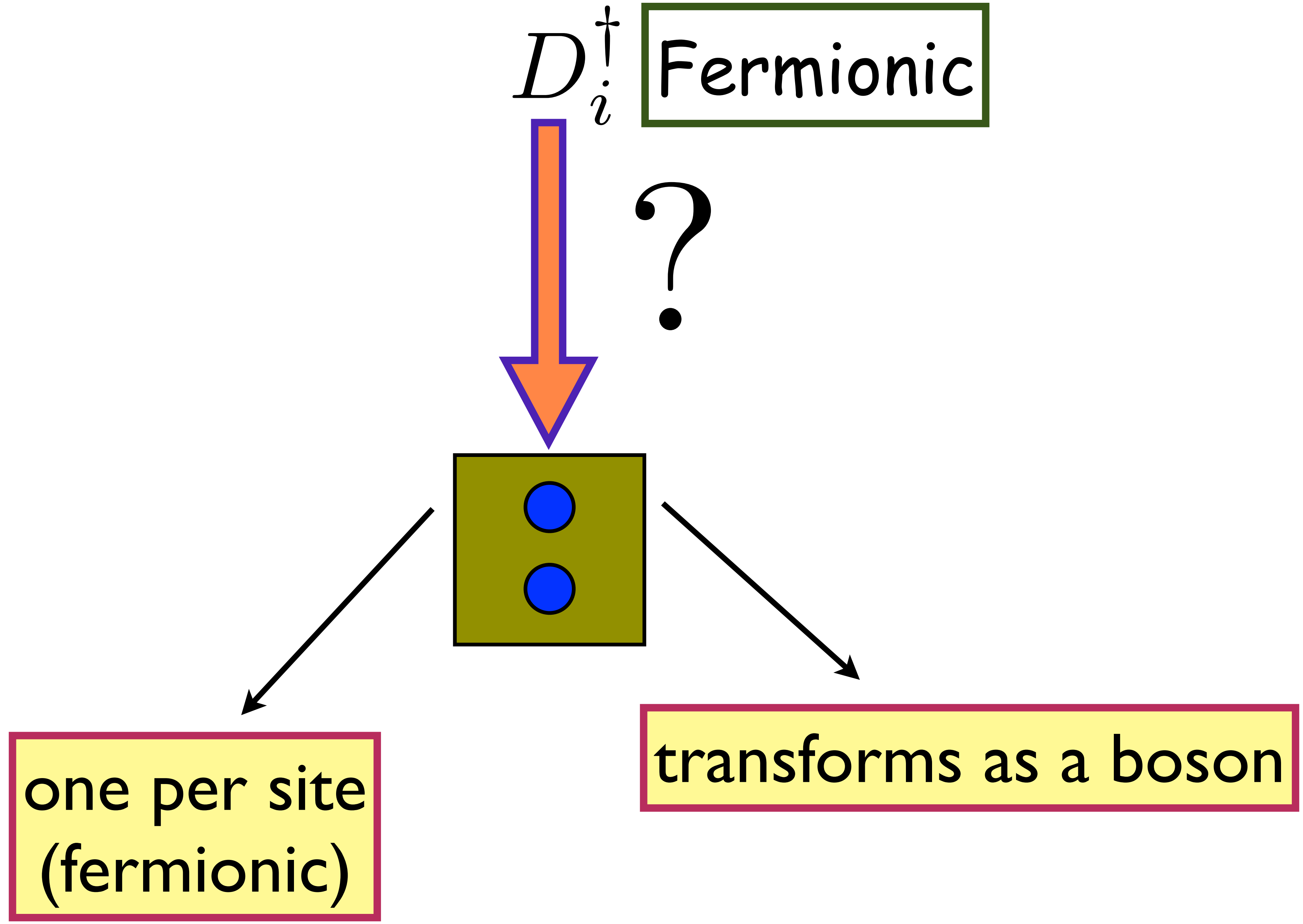
Integrate out both

Key idea: similar to Bohm/Pines

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




$D_i^\dagger$
Fermionic
?
transforms as a boson


$D_i^\dagger$
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one per site (fermionic)
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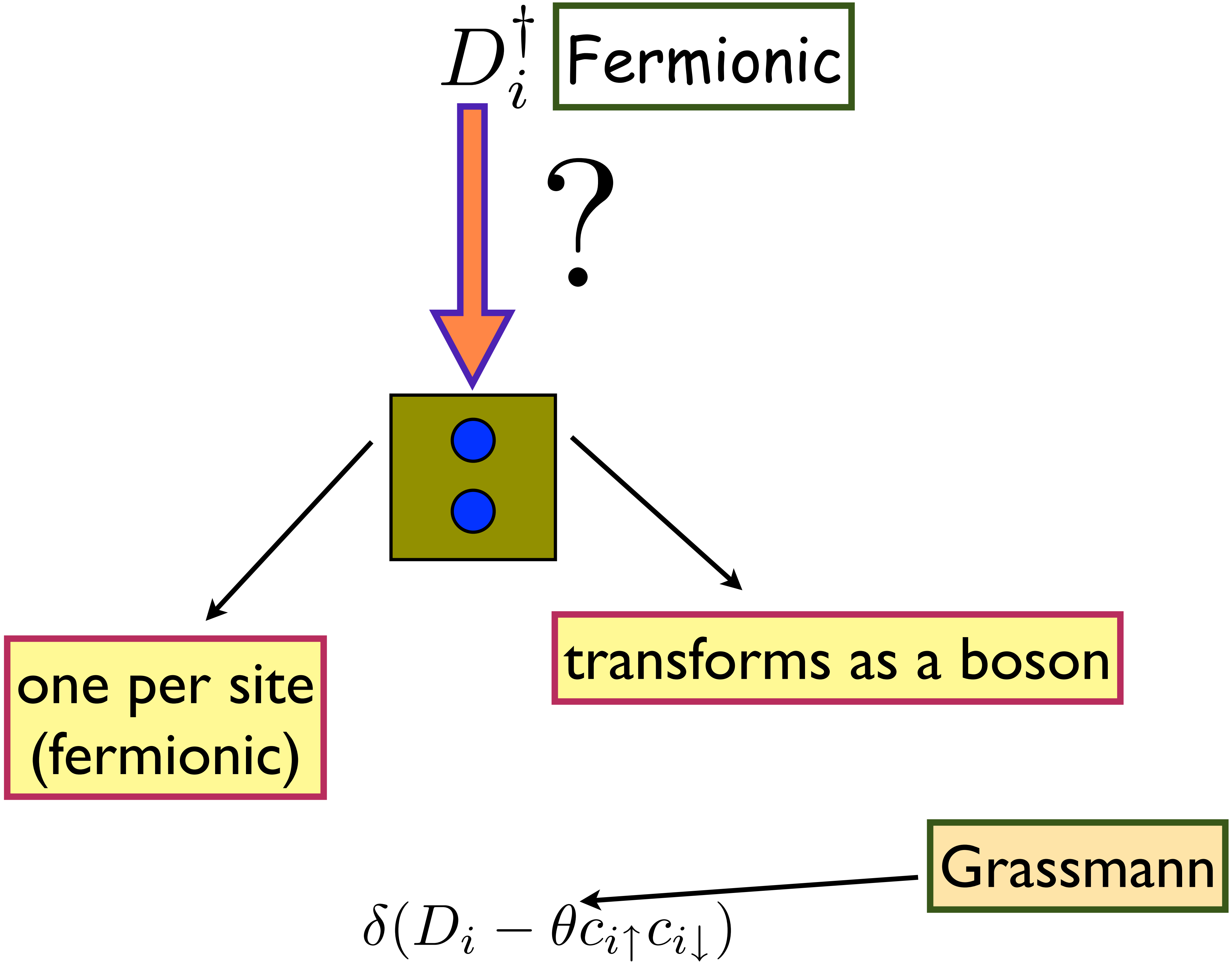
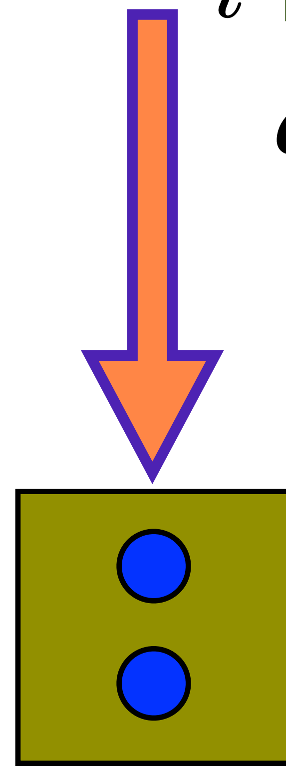

$D_i^\dagger$
Fermionic
?
one per site
(fermionic)
transforms as a boson
Grassmann
$\delta(D_i - \theta c_{i\uparrow} c_{i\downarrow})$

$D_i^\dagger$ Fermionic

?



one per site (fermionic)

transforms as a boson

Grassmann

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

$\theta \varphi_i^\dagger \longrightarrow$ charge 2e boson

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)

Exact low-energy Lagrangian

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

$$+f(\omega)L_{\rm int}(c,\varphi) \quad +\tilde{f}(\omega)L_{\rm int}(c,\tilde{\varphi})$$

$$\Psi^\dagger\Psi \qquad\qquad \tilde{\Psi}^\dagger\tilde{\Psi}$$

quadratic form: composite or bound excitations of

$\varphi^\dagger c_{i\sigma}$

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

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

$$+ \underbrace{f(\omega)}_{f(\omega)=0} \underbrace{L_{\text{int}}}_{\Psi^\dagger\Psi}(c,\varphi) \; + \tilde{f}(\omega) \underbrace{L_{\text{int}}}_{\tilde{\Psi}^\dagger\tilde{\Psi}}(c,\tilde{\varphi})$$

$f(\omega) = 0$

dispersion of propagating light modes

$\Psi^\dagger\Psi$ $\quad$ $\tilde{\Psi}^\dagger\tilde{\Psi}$

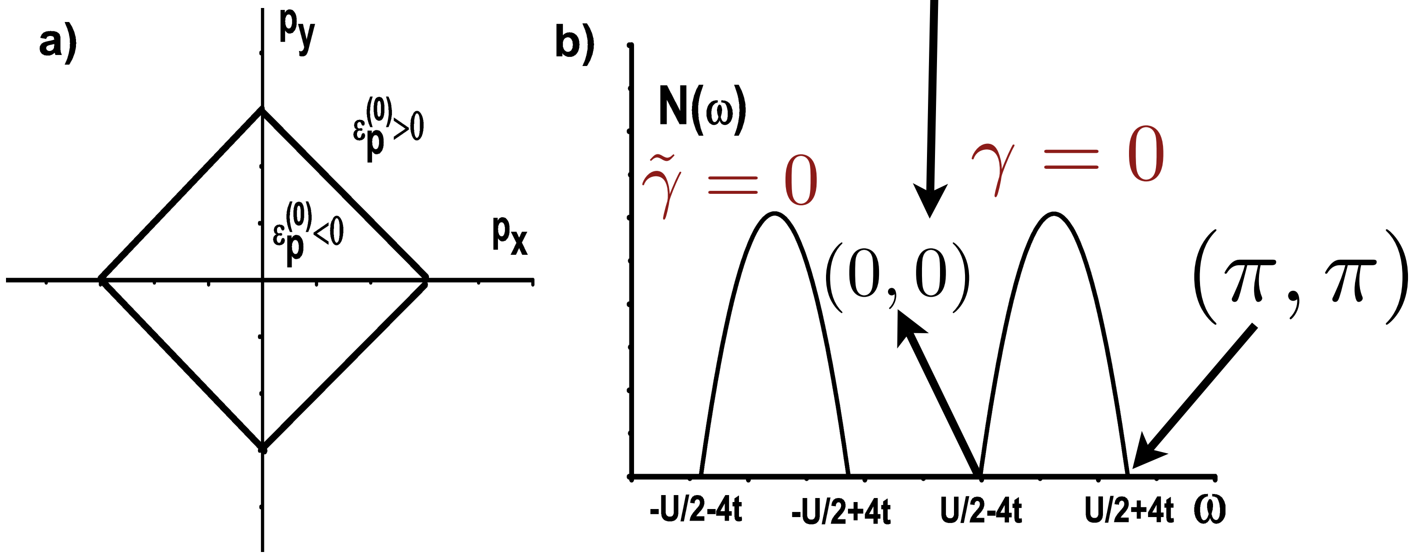
quadratic form: composite or bound excitations of $\varphi^\dagger c_{i\sigma}$

composite excitations determine spectral density

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

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

$\Delta = U - 4dt$



each momentum has SD at two distinct energies

A Critique of Two Metals

R. B. Laughlin

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$\varphi^\dagger c_{i\sigma}$ determines turn-on of spectral density

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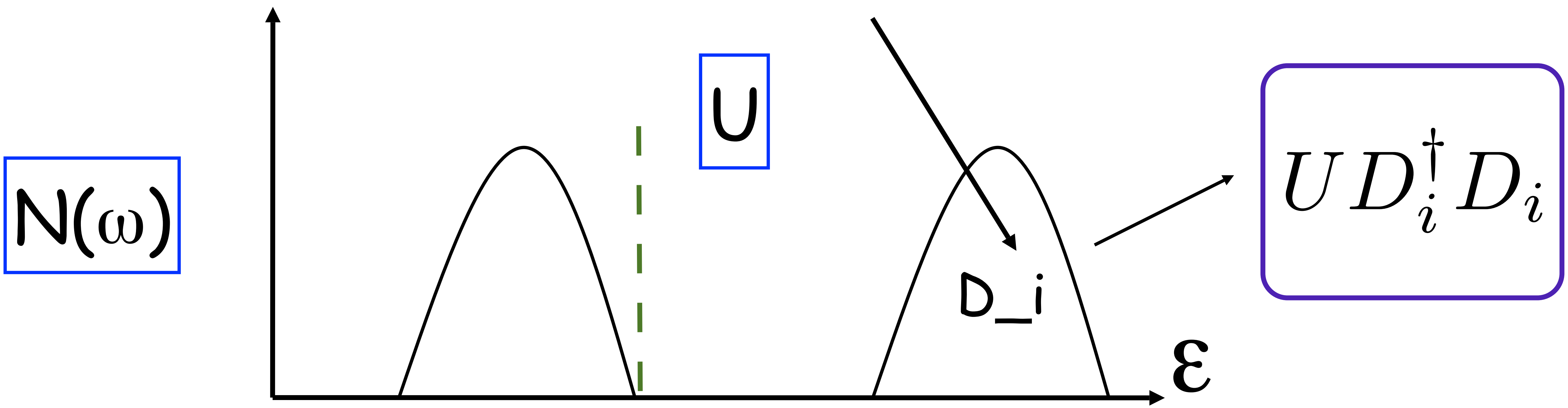
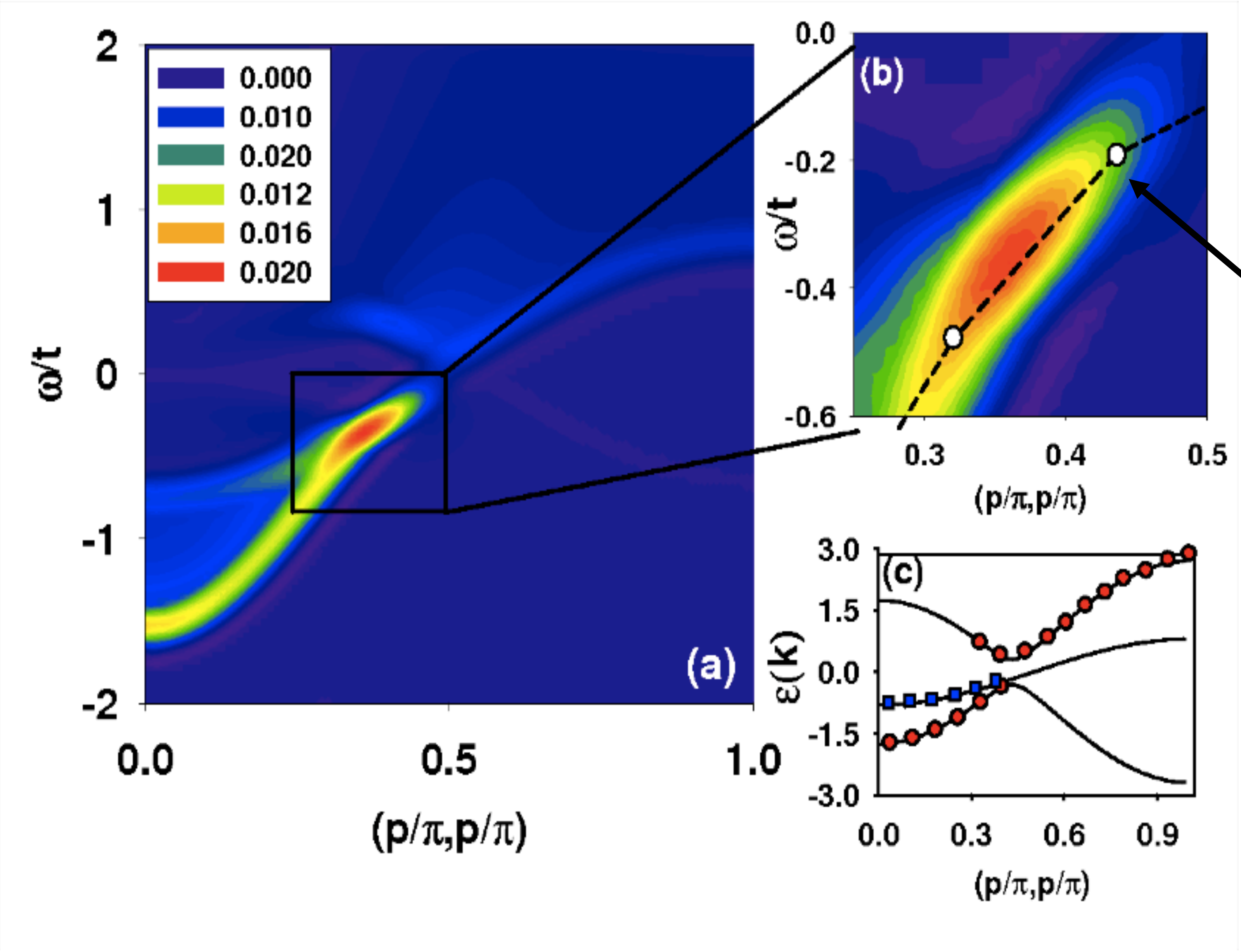
hole-doping?

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

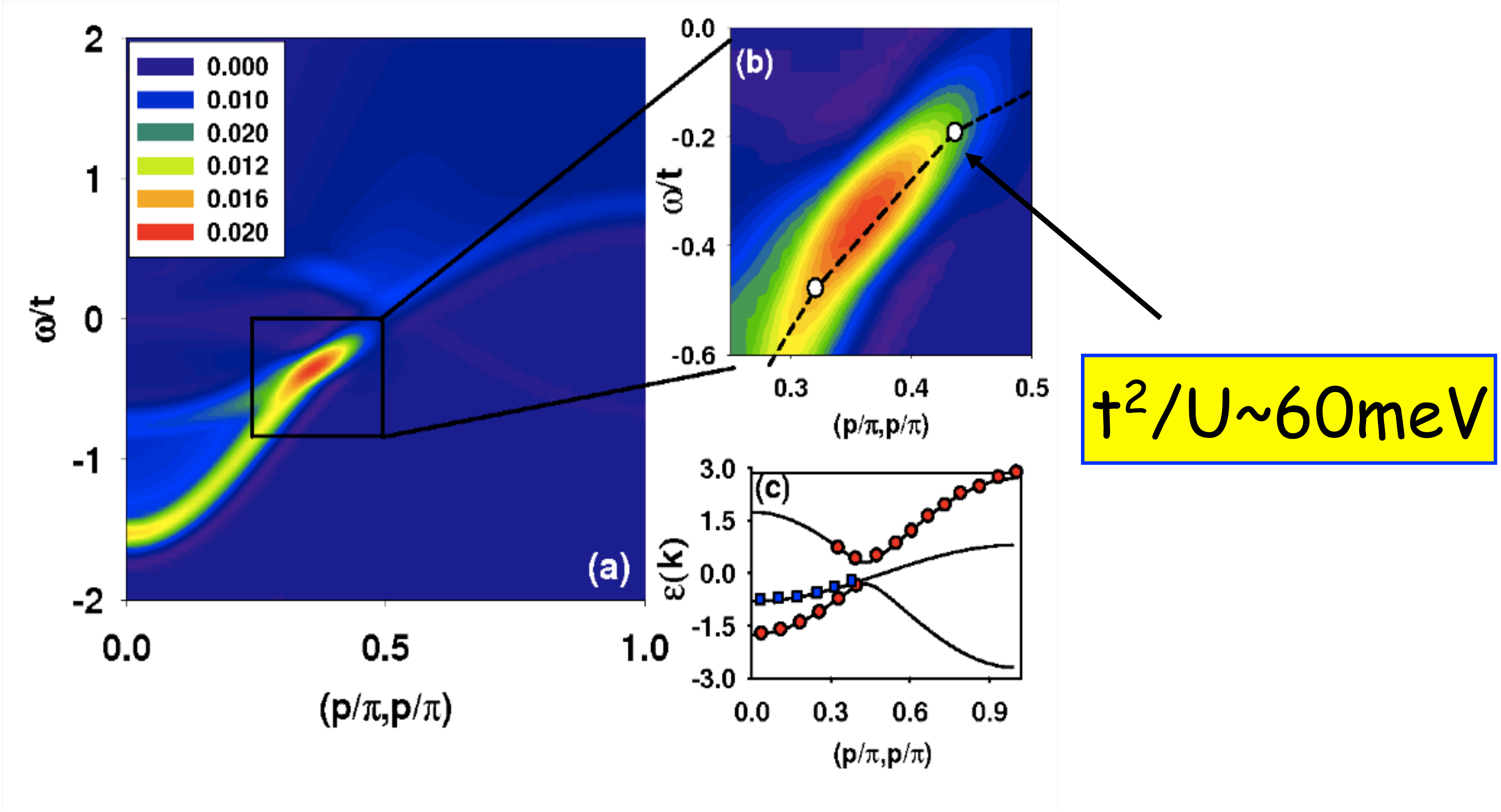


Electron spectral function



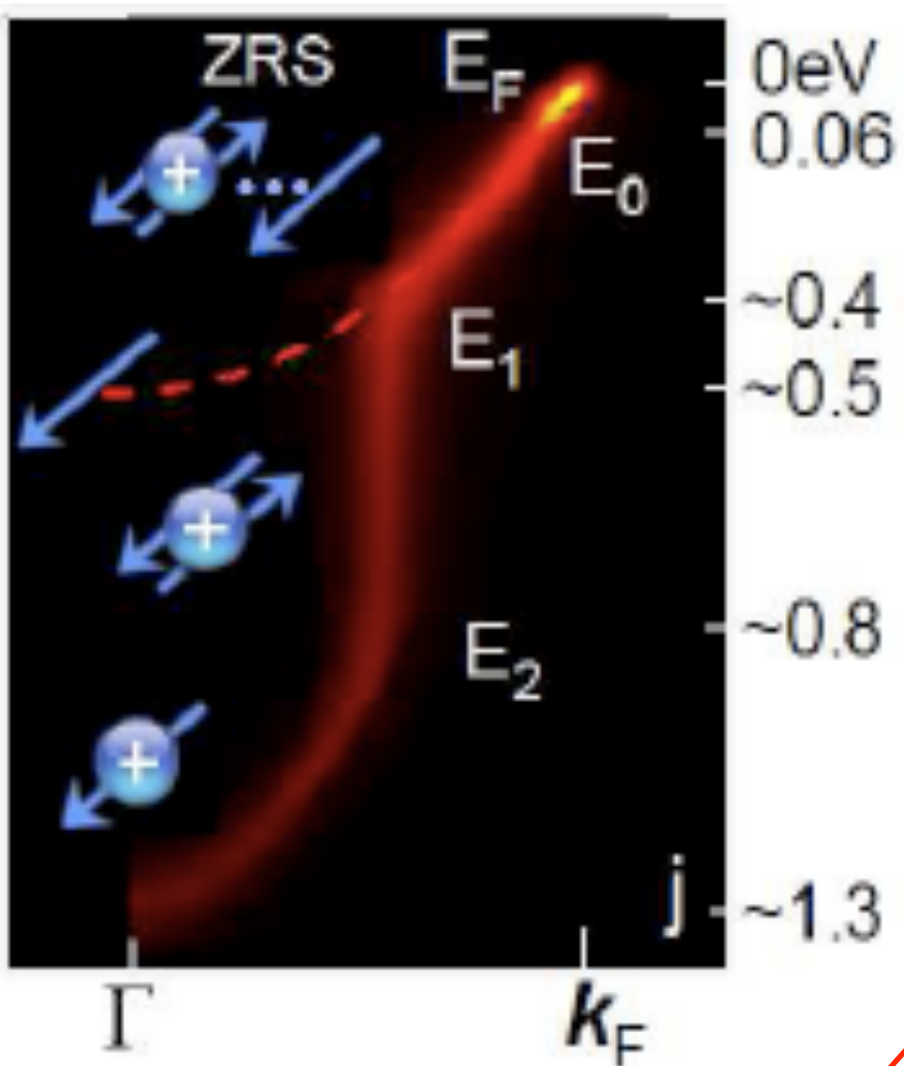
t^2/U~60meV

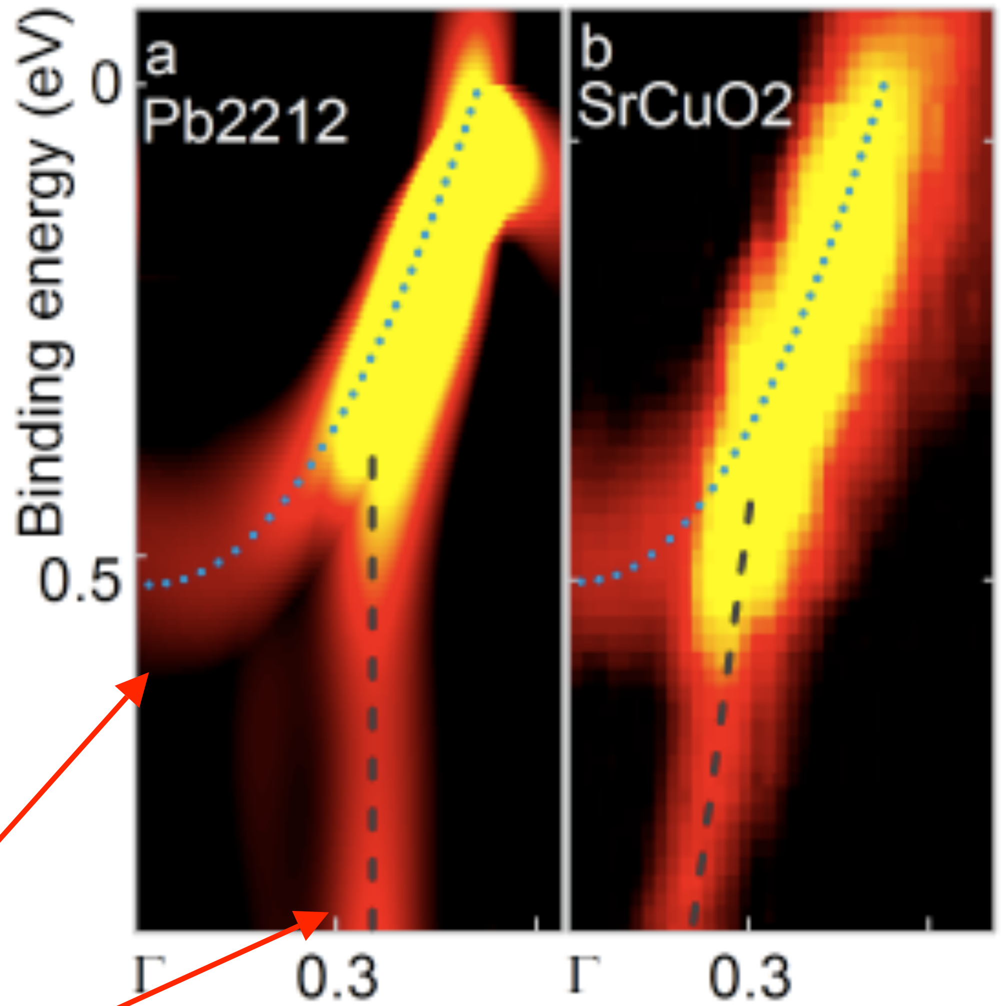
Electron spectral function



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

Origin of two bands

Two charge e excitations

$c_{i\sigma}$

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

New bound state

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

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

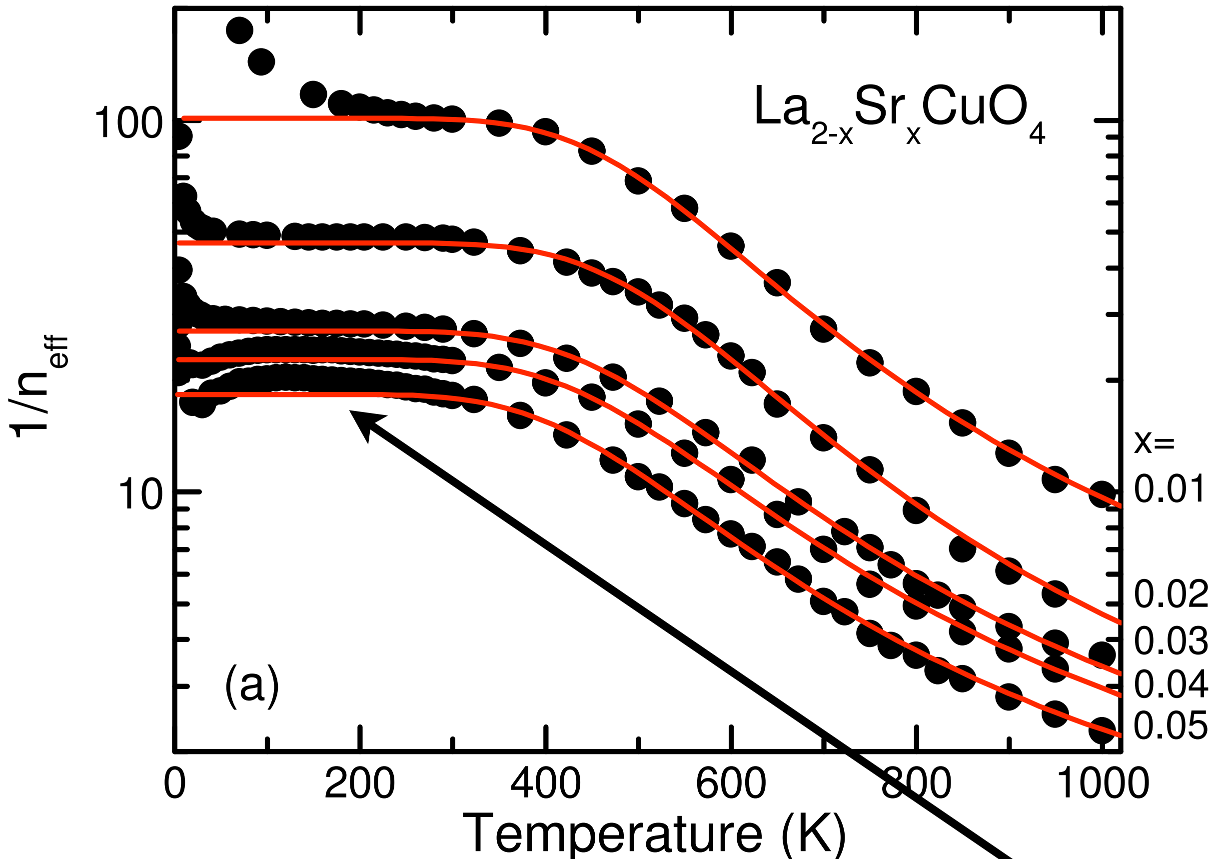
direct evidence

$\boxed{\text{direct evidence}}$

$\boxed{\text{charge carrier density:}}$

direct evidence

charge carrier density:



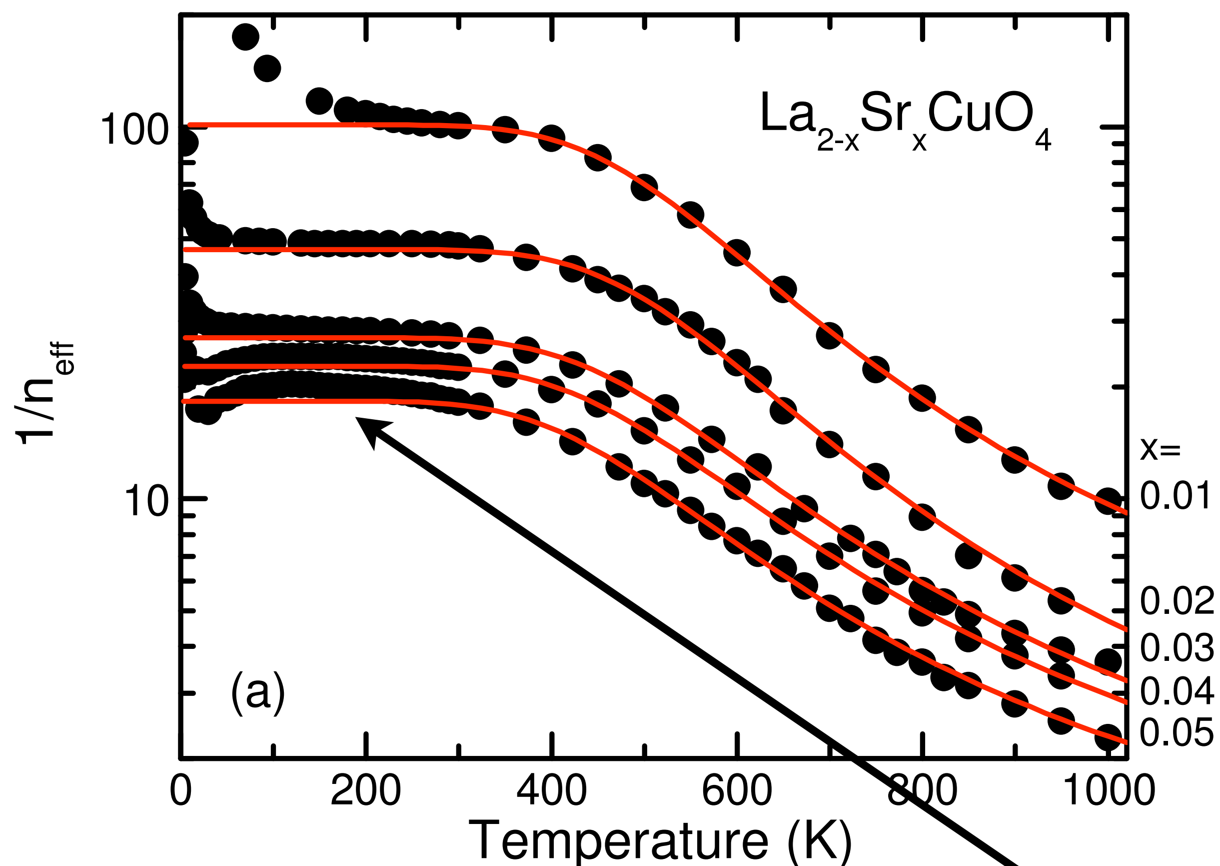
Ono, et al., Phys. Rev. B 75, 024515 (2007)

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

PRL, vol. 97, 247003 (2006).

direct evidence

charge carrier density:

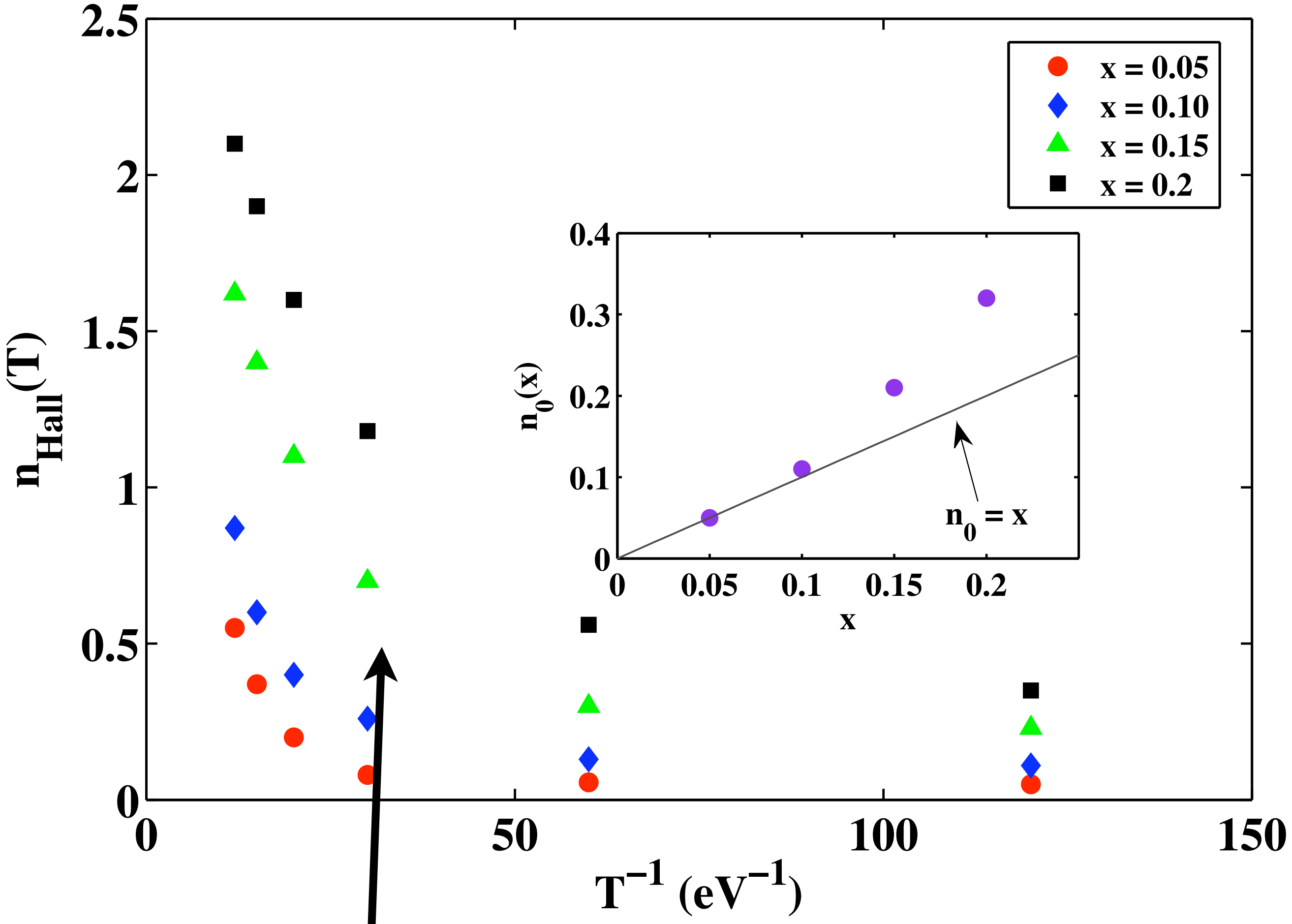


Ono, et al., Phys. Rev. B 75, 024515 (2007)

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

exponentially suppressed: confinement

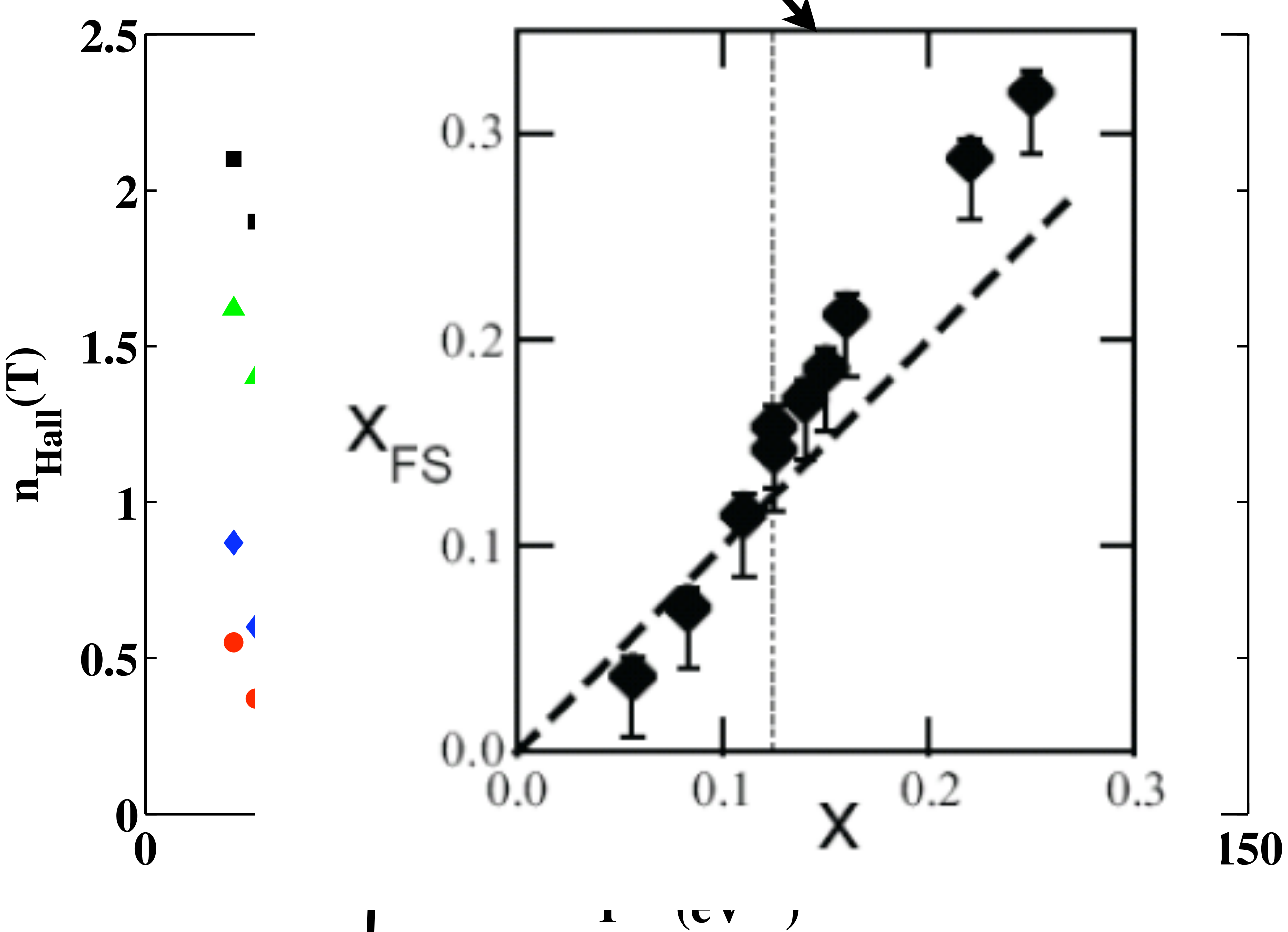
Our Theory



exponential
T-dependence

Our Theory

R. He, ZX Shen,...



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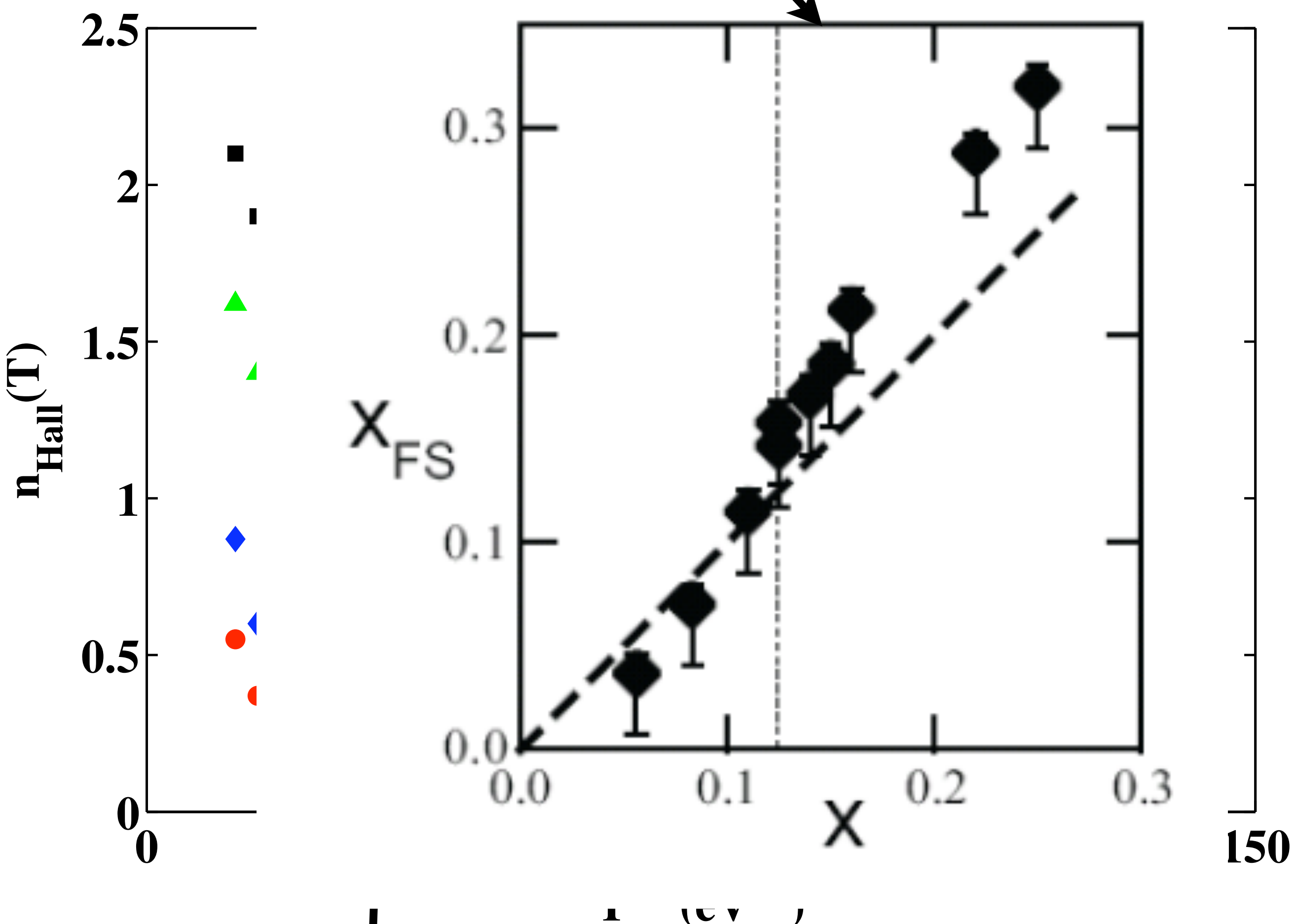
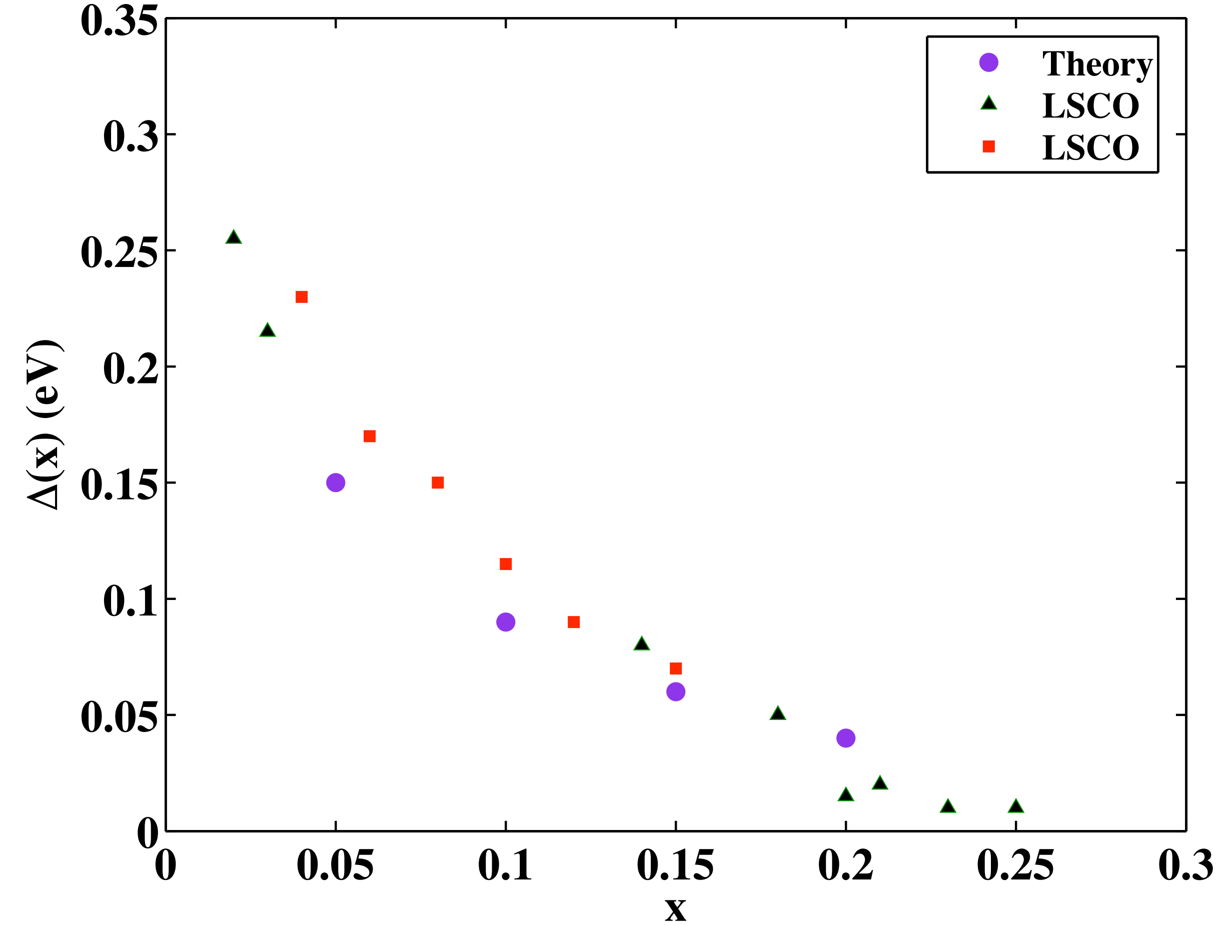


gap



exponential T-dependence

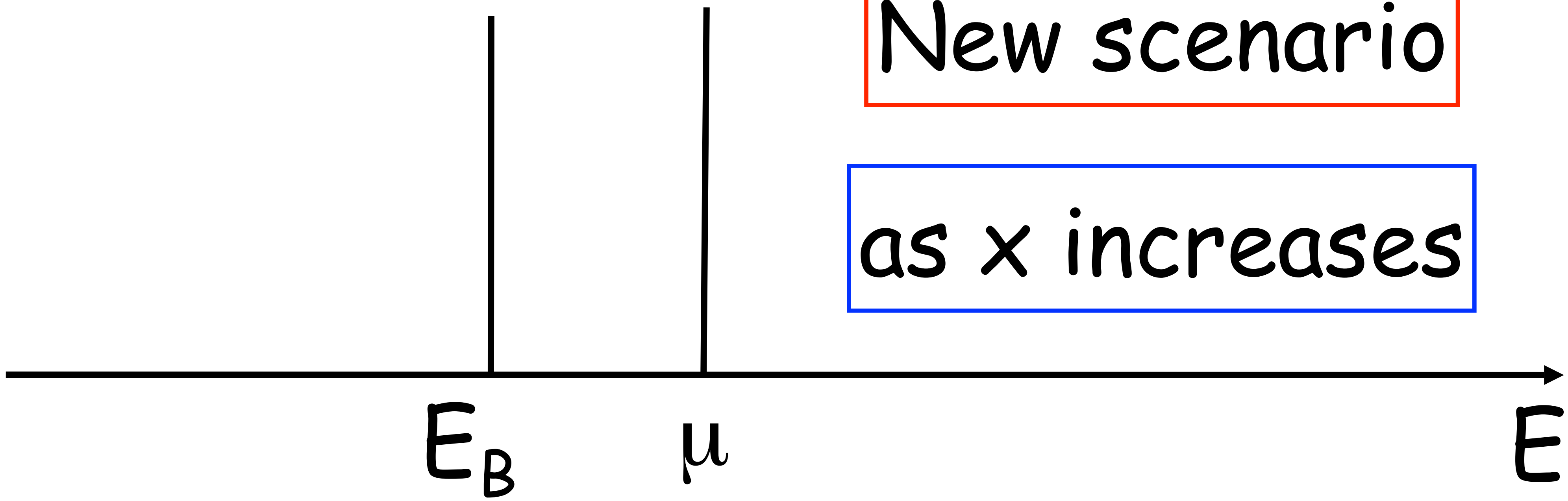
no model-dependent free parameters: just t/U

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

T-linear resistivity

New scenario

as x increases



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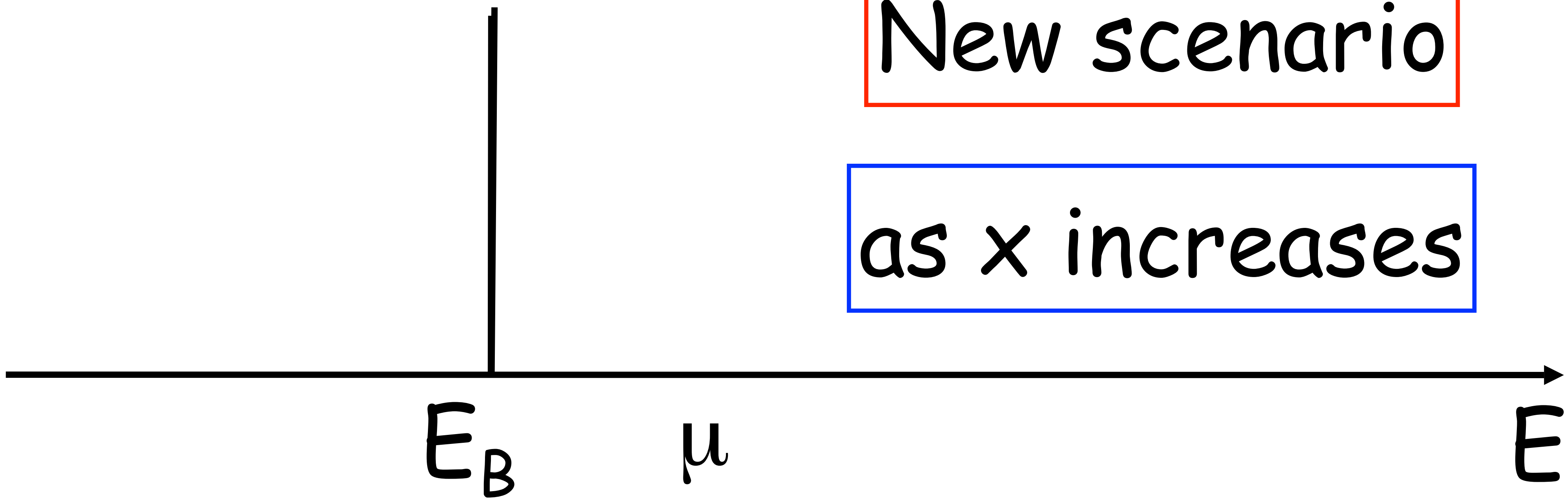

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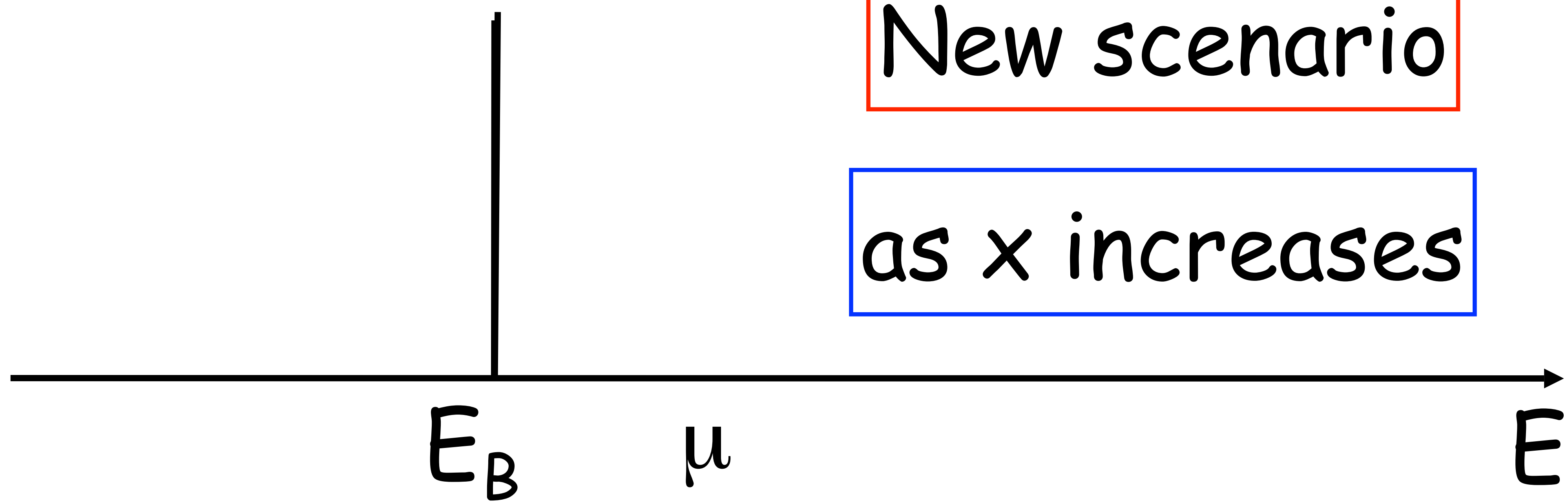
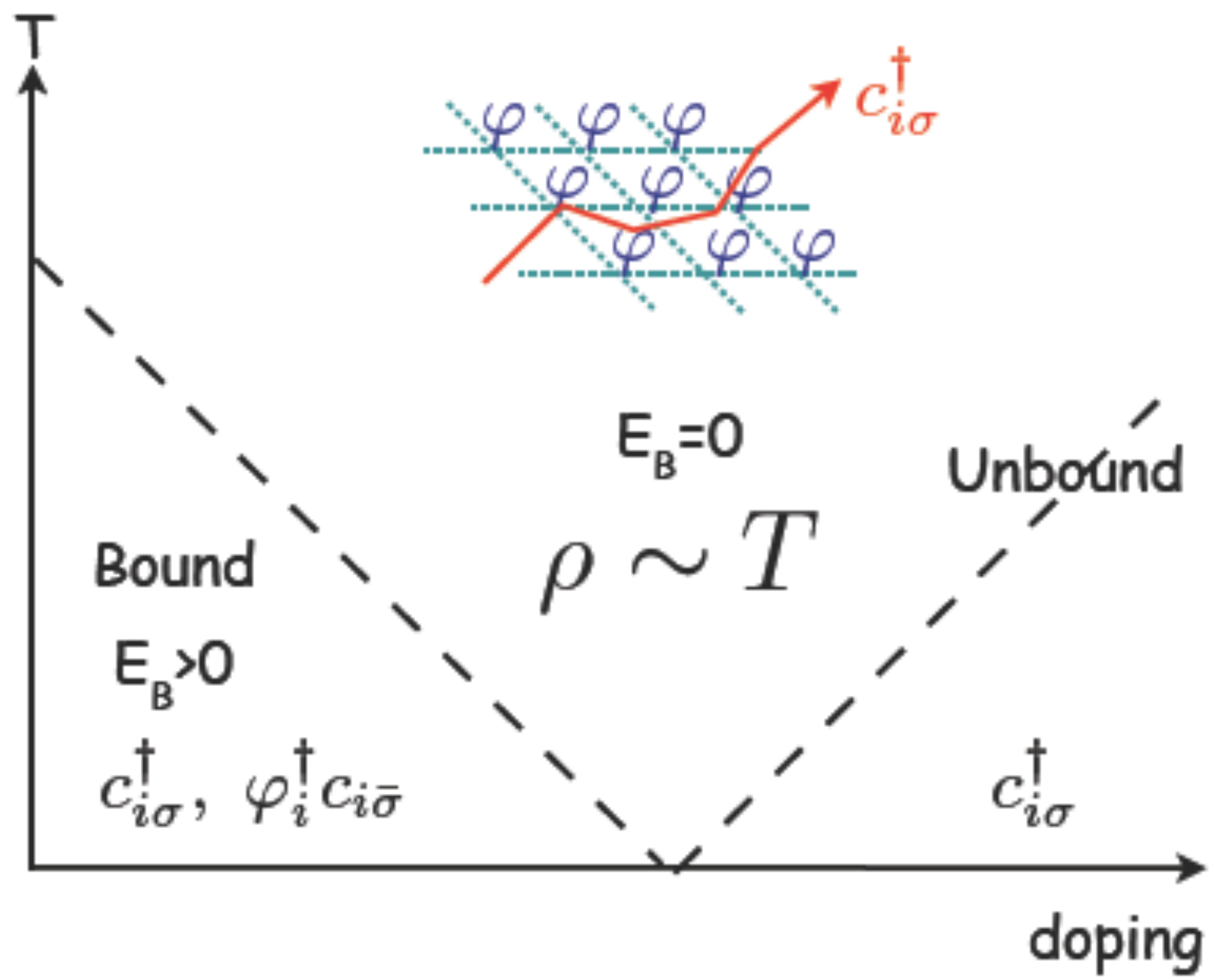
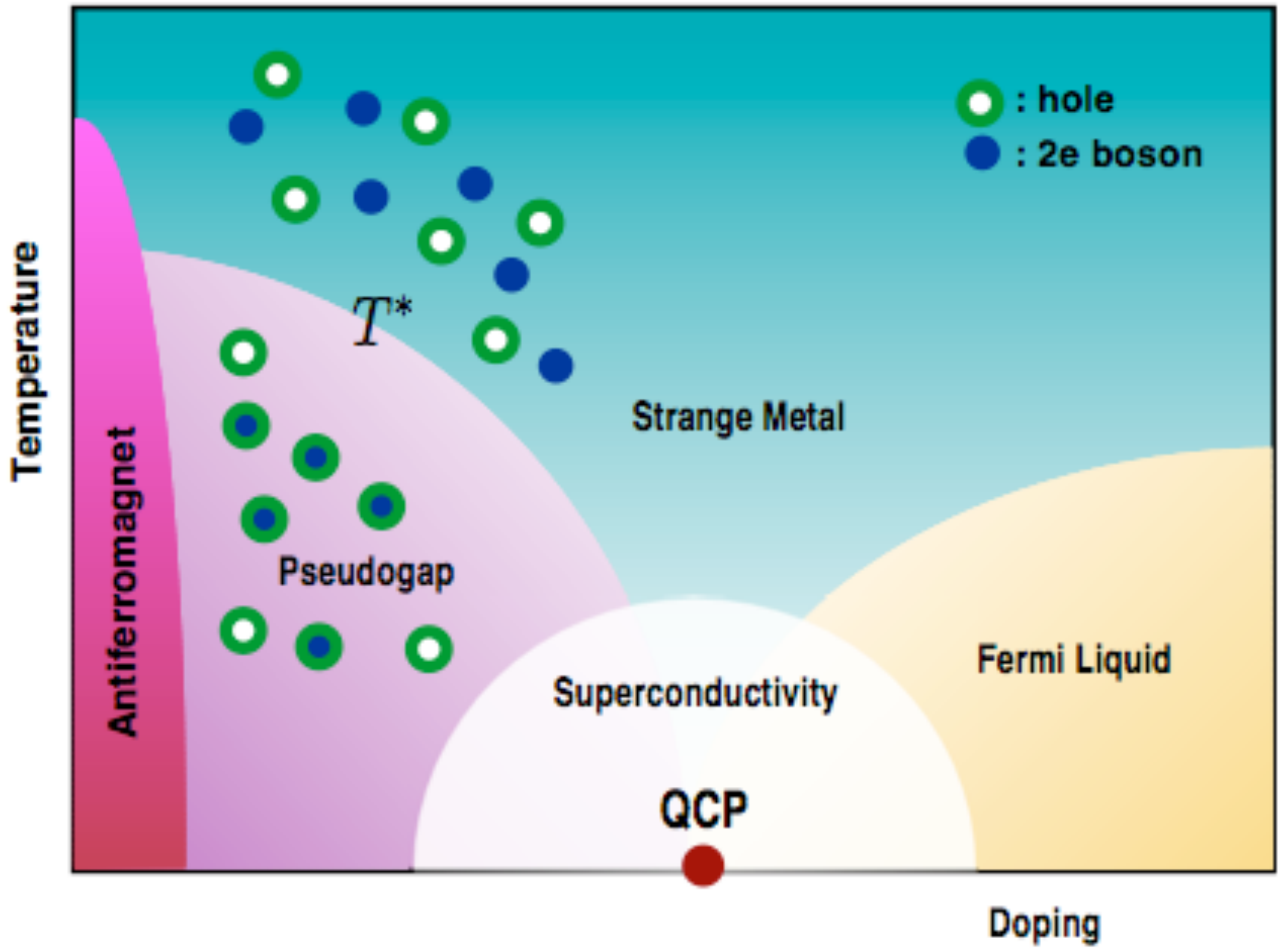


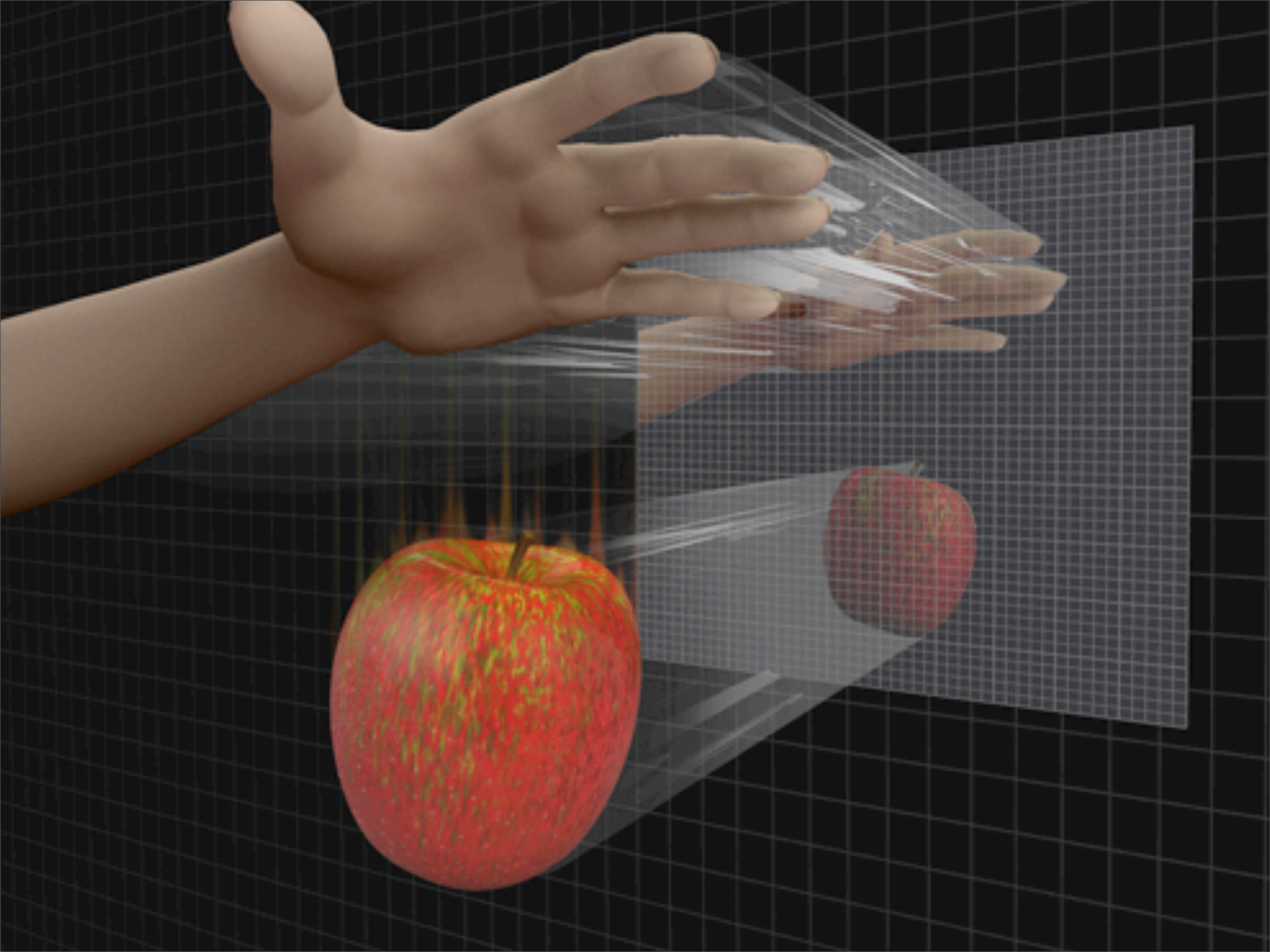


Pseudogap=`confinement'



composite or bound states not in UV theory

Is string theory the answer?



`Holography'

strongly coupled
QFT in d-dimensions

$\Updownarrow$

weakly-coupled
classical gravity
in d+1

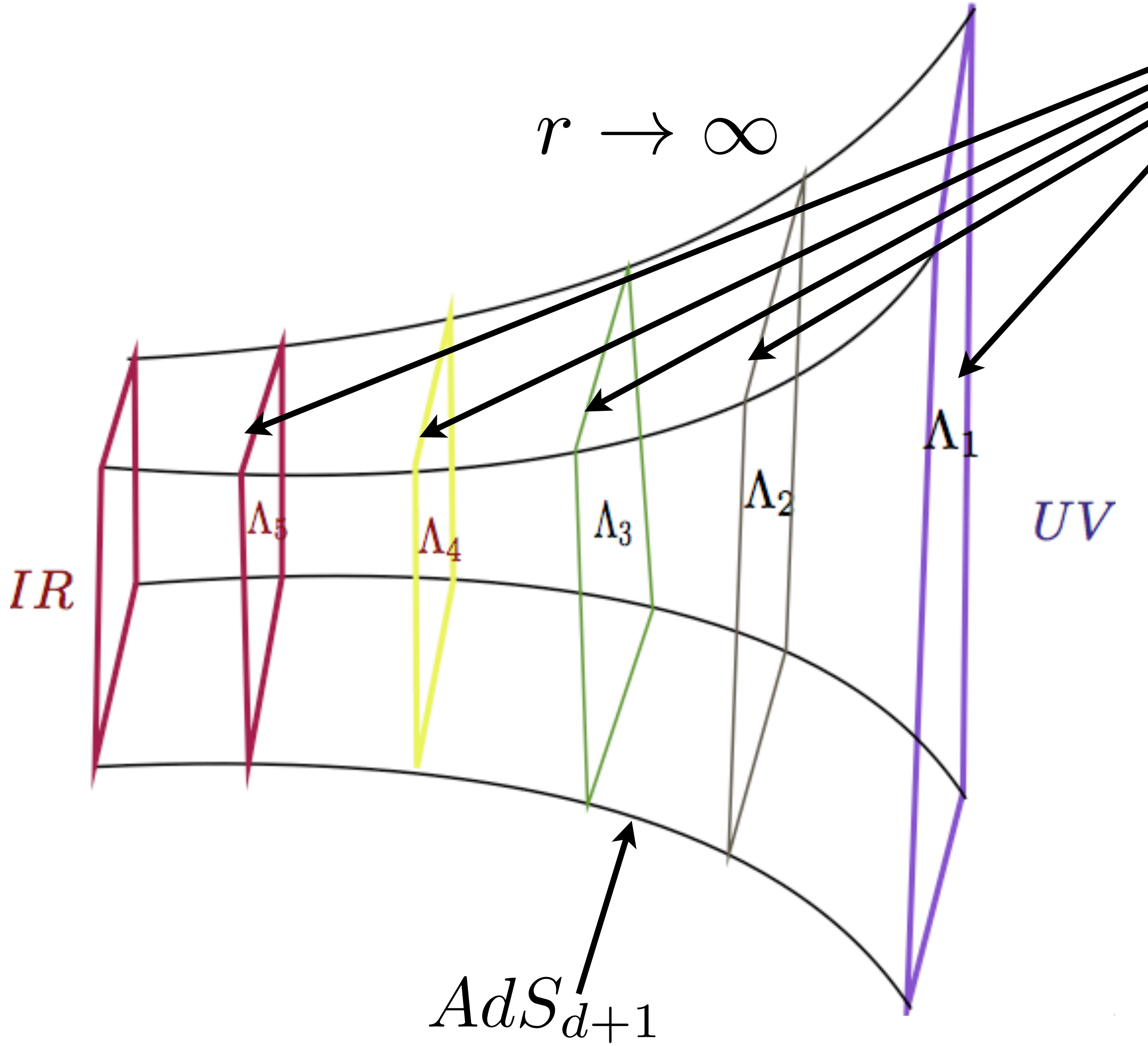
`Holography'

strongly coupled QFT in d-dimensions

weakly-coupled classical gravity in d+1

$\beta(g)$ is local
geometrize RG flow

`Holography'

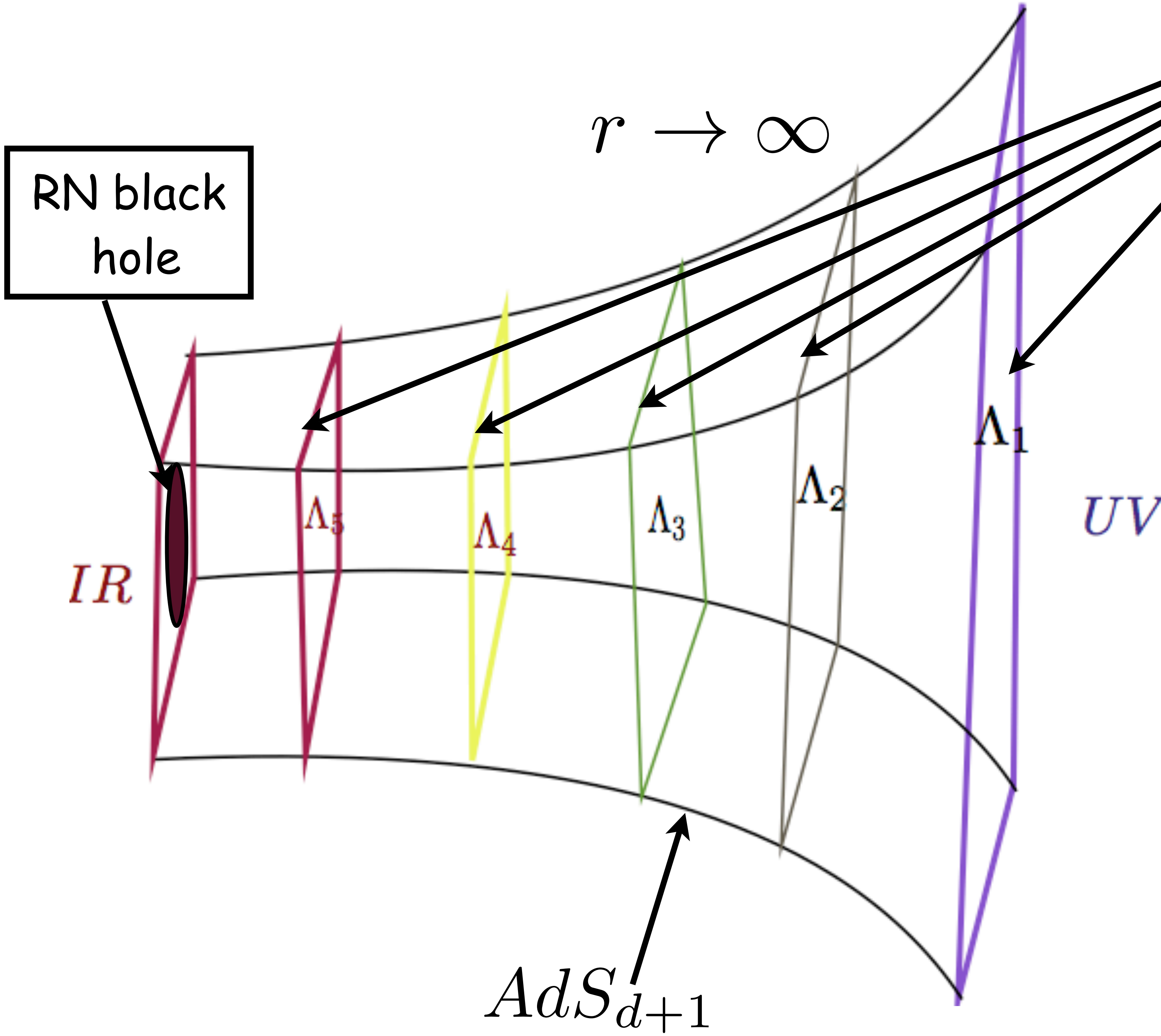


strongly coupled QFT in d-dimensions

weakly-coupled classical gravity in d+1

$\beta(g)$ is local
geometrize RG flow

`Holography'



strongly coupled QFT in d-dimensions

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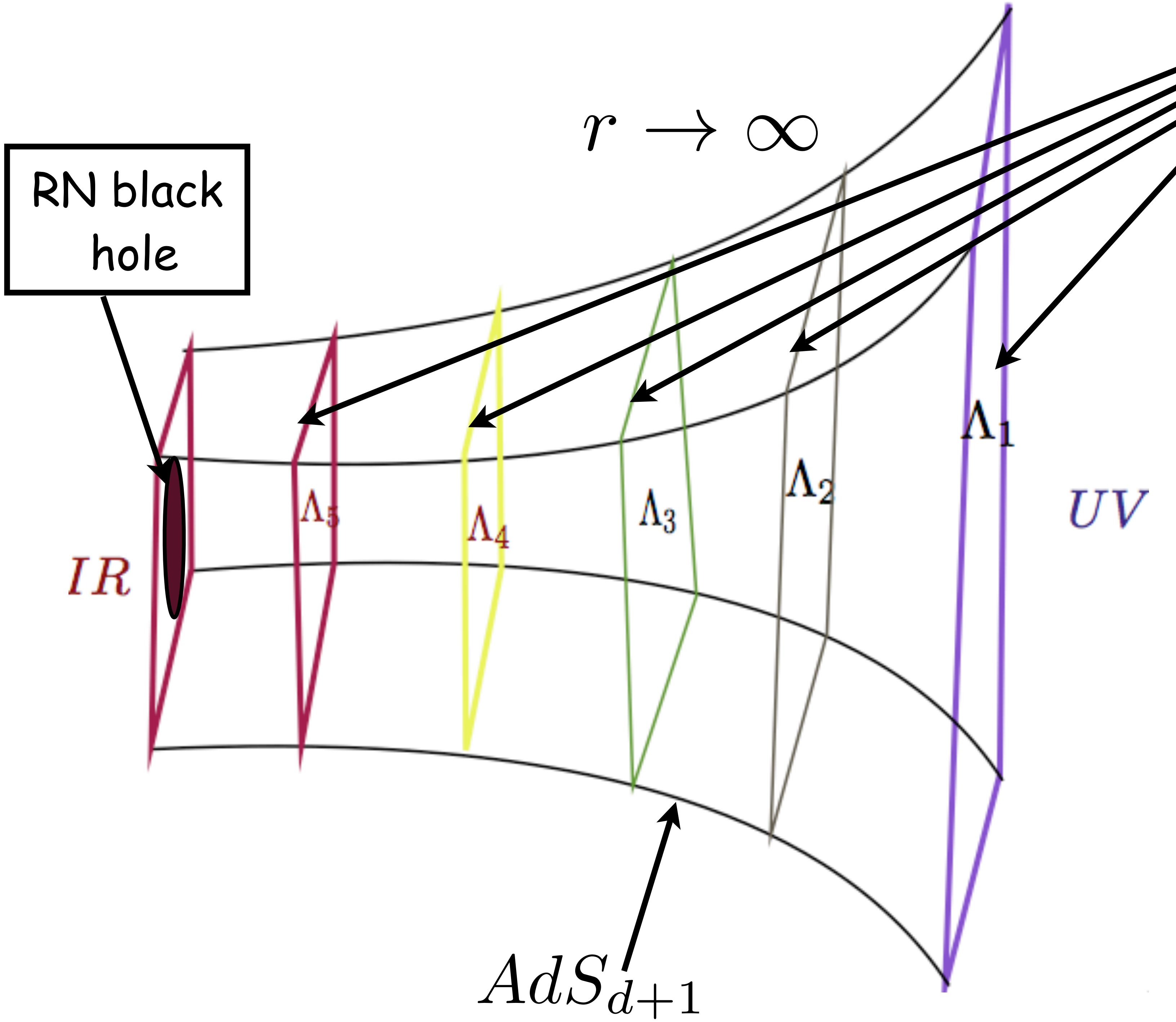
geometrize RG flow

`Holography'

strongly coupled QFT in d-dimensions



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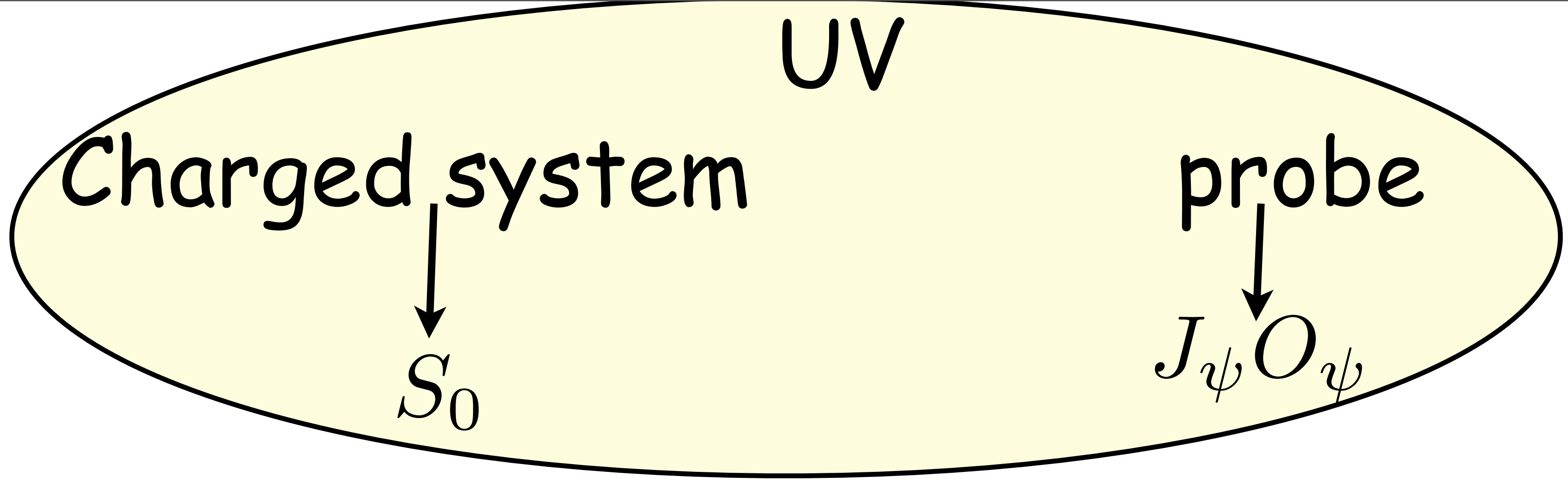
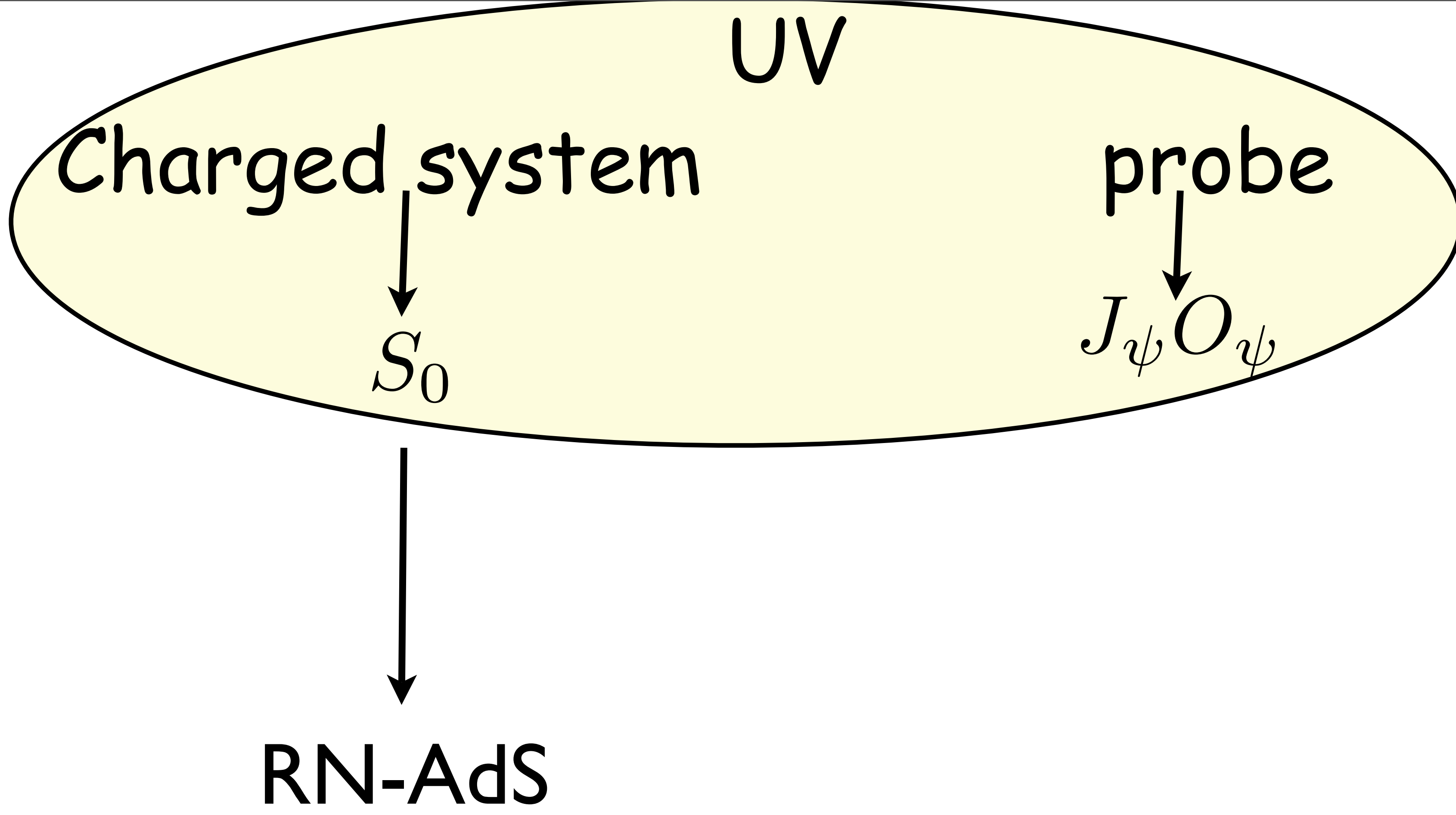
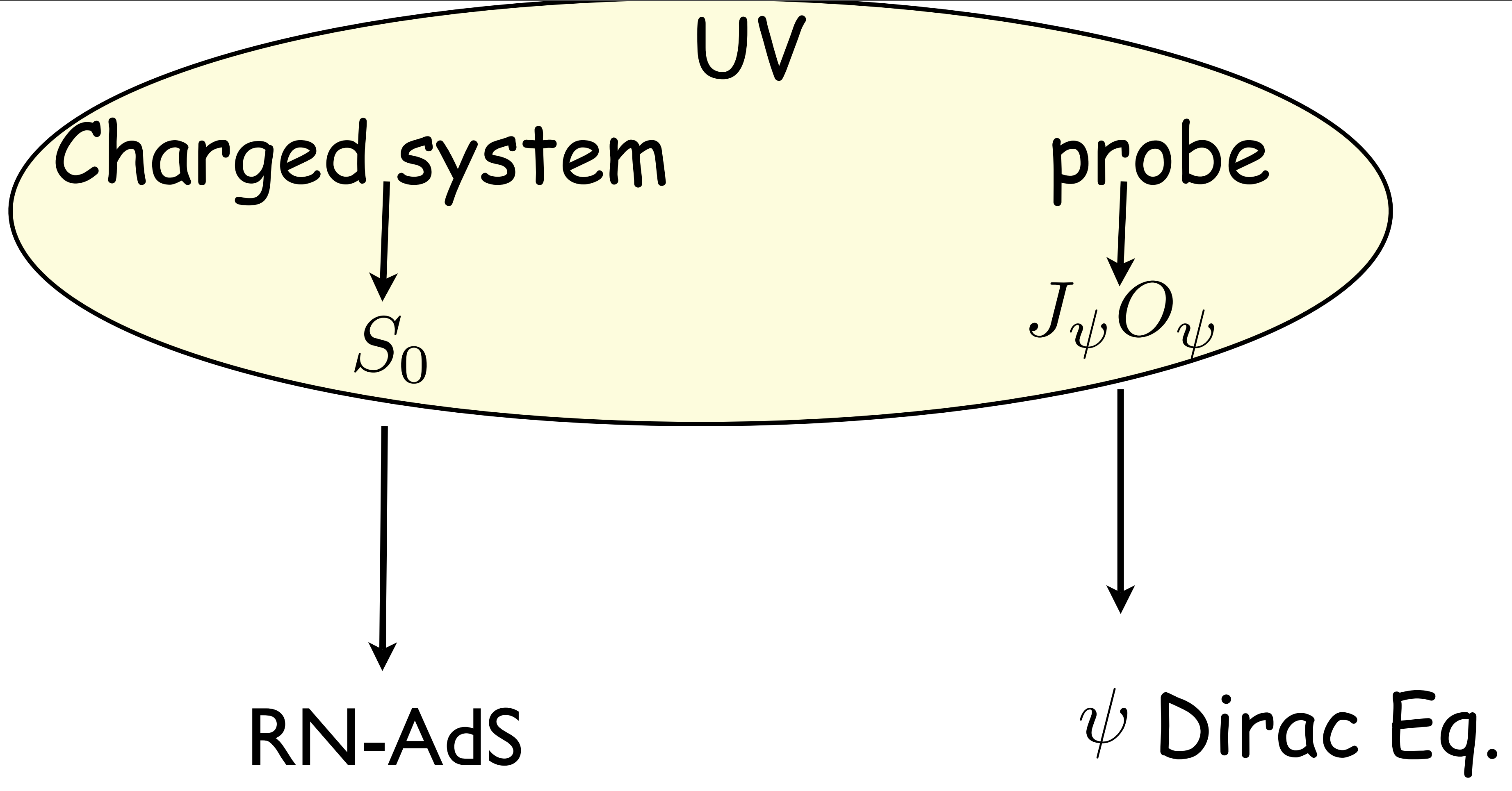

UV
Charged system
probe
S_0
$J_\psi O_\psi$


UV
Charged system
probe
S_0
$J_\psi O_\psi$
RN-AdS


UV
Charged system
probe
S_0
$J_\psi O_\psi$
RN-AdS
ψ Dirac Eq.

UV

Charged system → S_0 → RN-AdS

probe → $J_\psi O_\psi$ → ψ Dirac Eq.

in-falling boundary conditions

$$\psi(r \to \infty) \approx a r^{m} + b r^{-m}$$

Retarded Green function: $G = \dfrac{b}{a}$

UV

Charged system → S_0

probe → $J_\psi O_\psi$

RN-AdS

ψ Dirac Eq.

in-falling boundary conditions

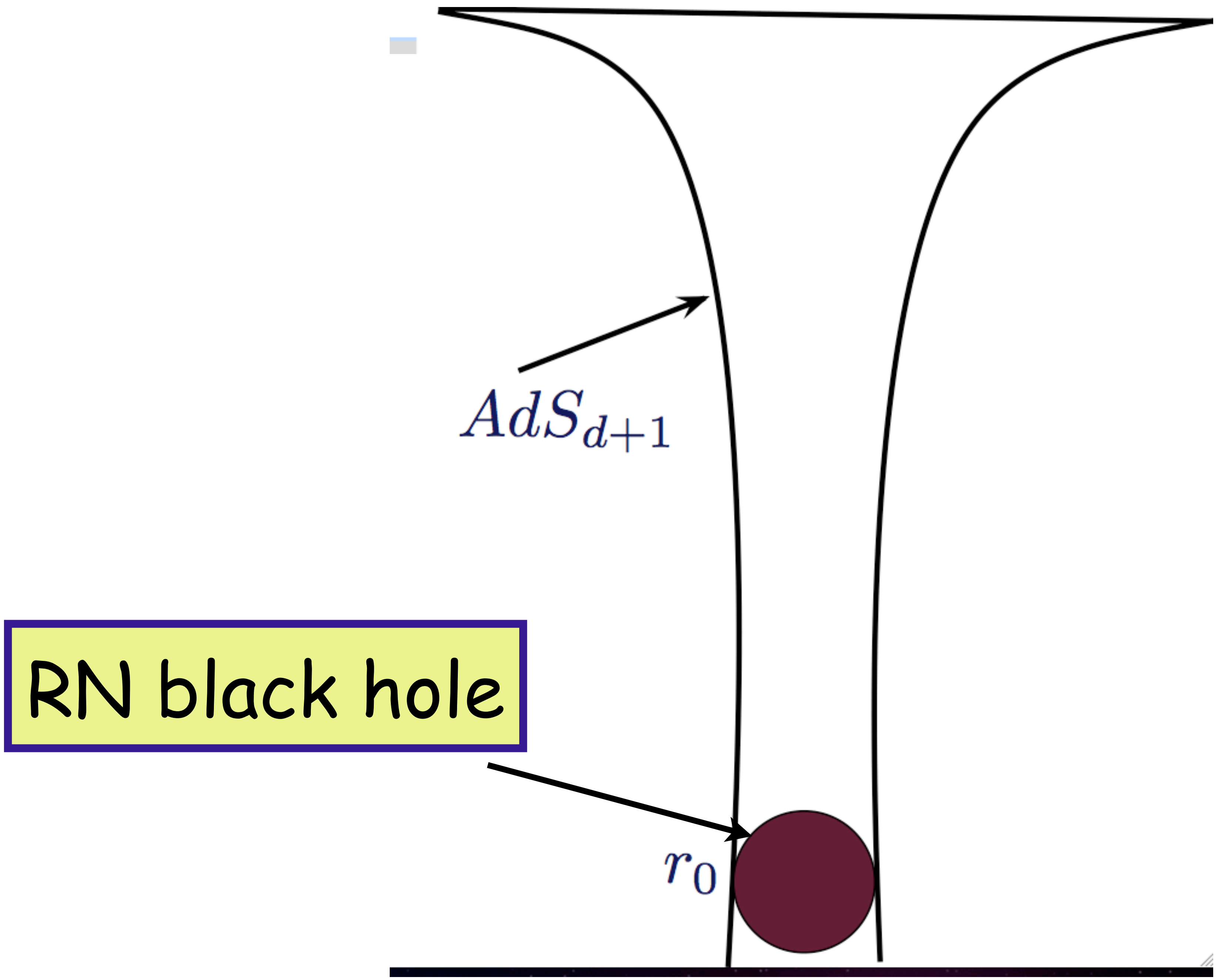
$$\psi(r \to \infty) \approx a r^{m} + b r^{-m}$$

Retarded Green function: $G = \dfrac{b}{a}$ =f(UV,IR)

Does this work for the Hubbard model?

Mottness from holography

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



Mottness from holography

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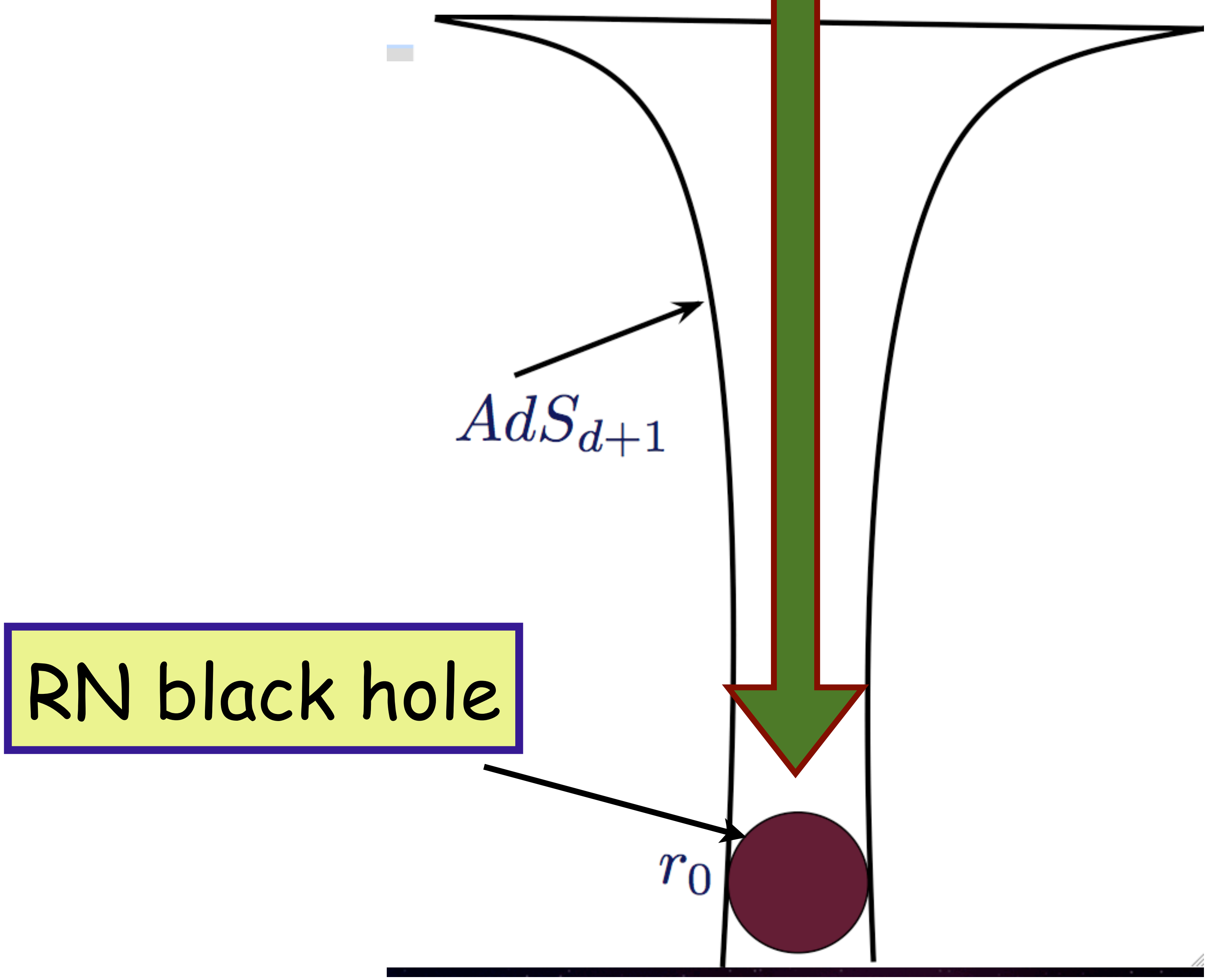

Mottness from holography

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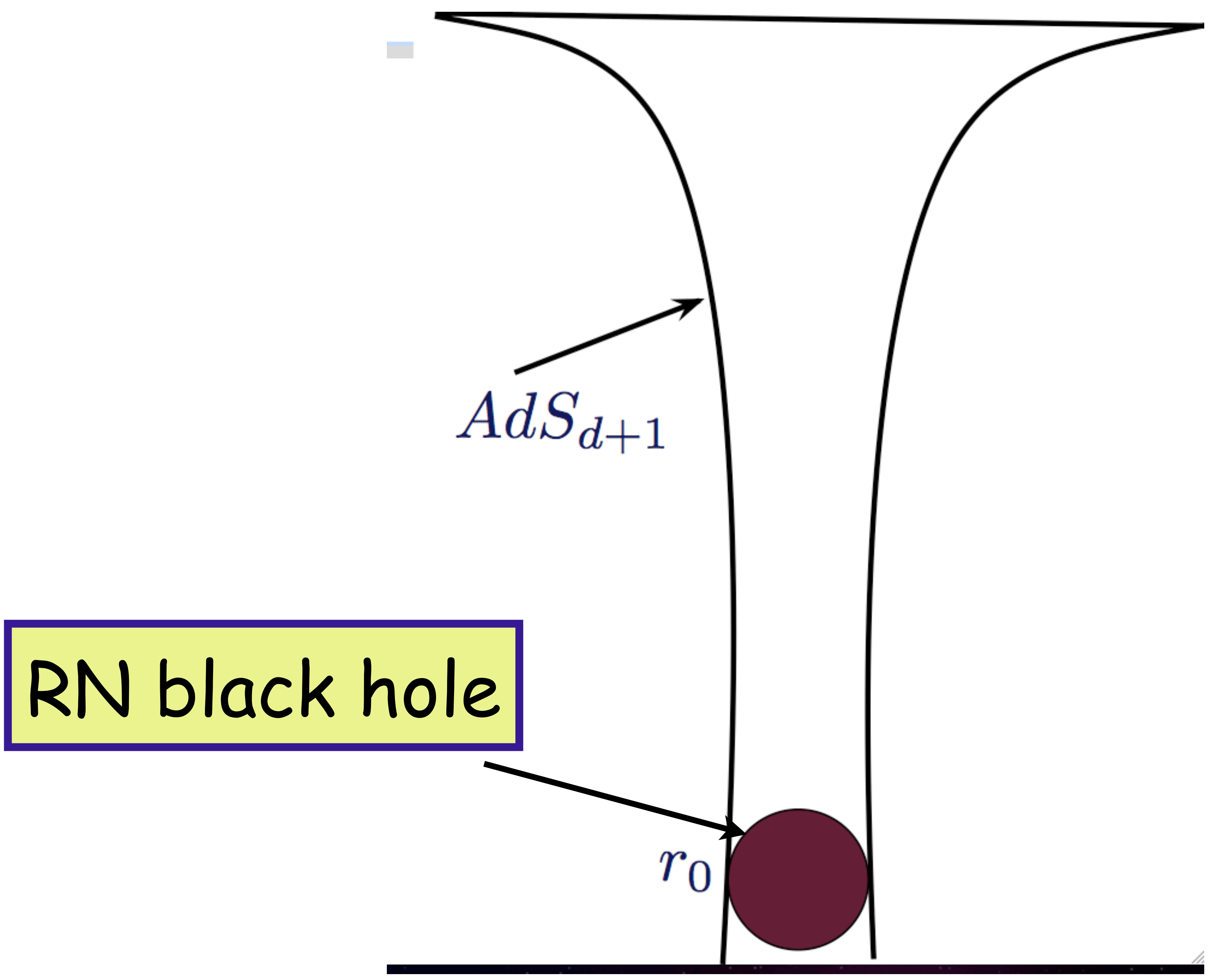

Mottness from holography

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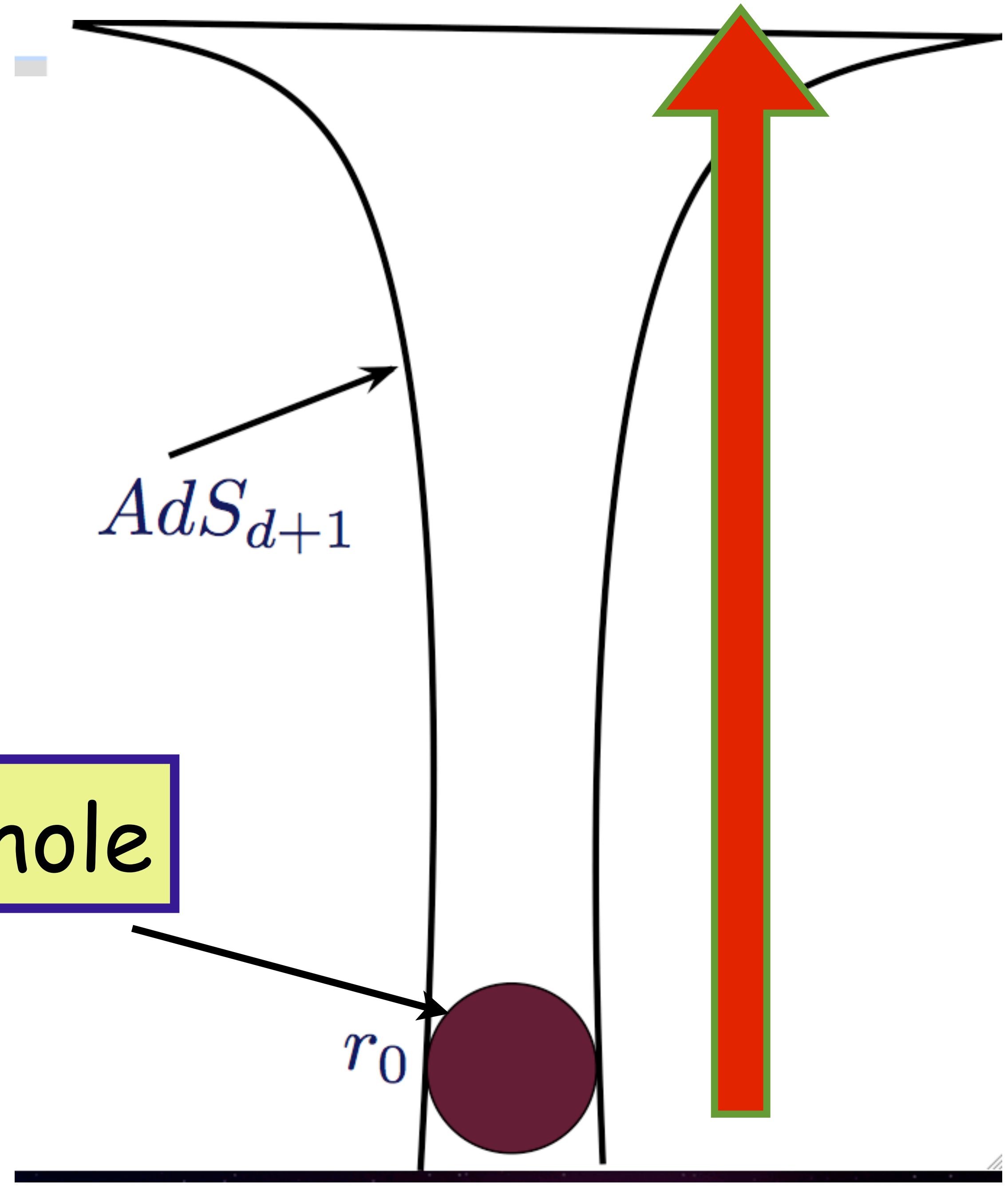


bottom-up schemes

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

AdS-RN
MIT group

`non-Fermi liquids'

bottom-up schemes

$$\sqrt{-g} i \bar{\psi}(D-m)\psi \longrightarrow \text{`non-Fermi liquids'}$$

AdS-RN
MIT group

?? $\longrightarrow$ Mott Insulator

bottom-up schemes

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

AdS-RN
MIT group

`non-Fermi liquids'

??

Mott Insulator

consider

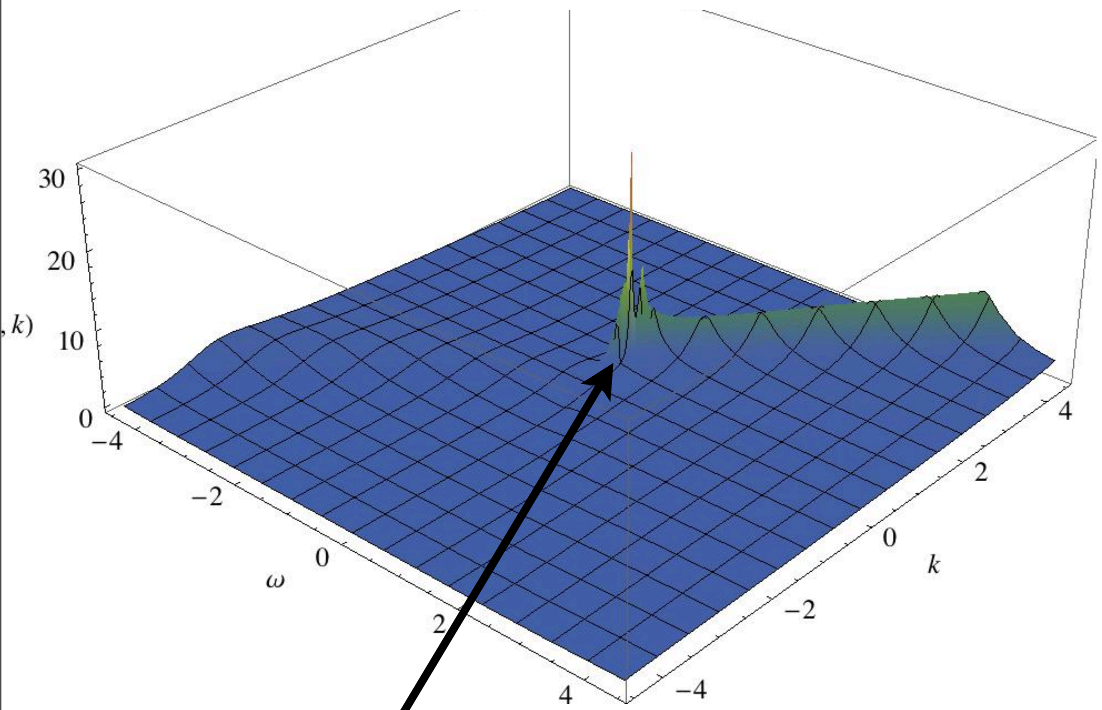
$\sqrt{-g} i\bar{\psi}(\not{D} - m - ip\not{F})\psi$

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

How is the spectrum modified?

How is the spectrum modified?

P=0

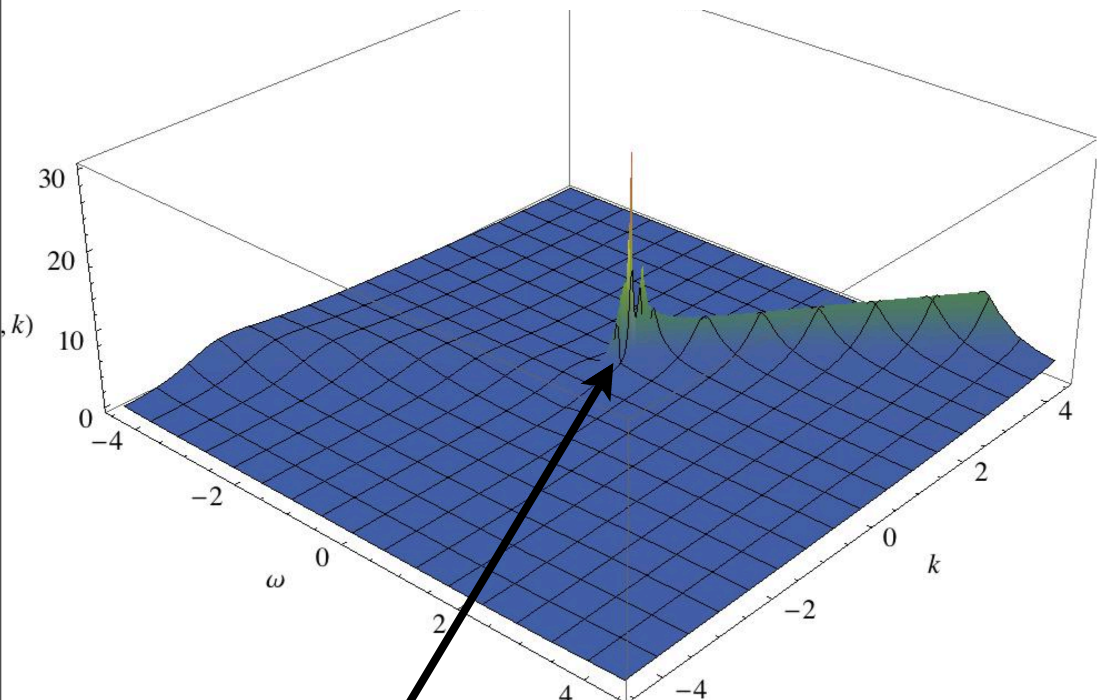


Fermi
surface
peak

How is the spectrum modified?

P=0

$P > 4.2$



Fermi surface peak

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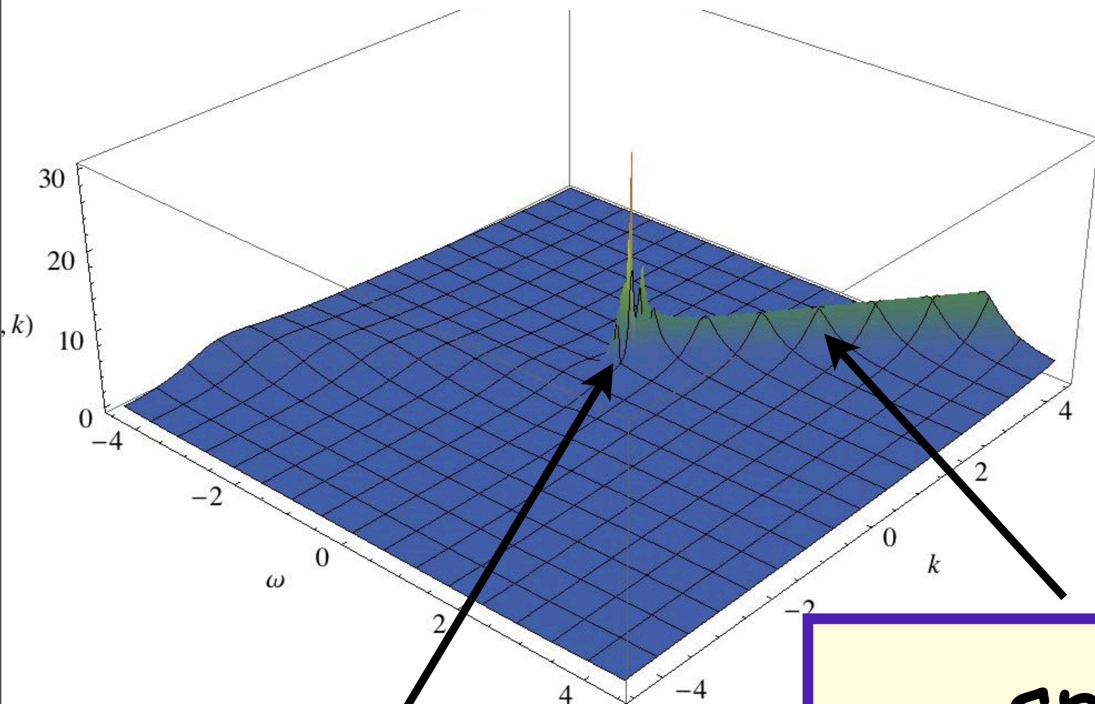
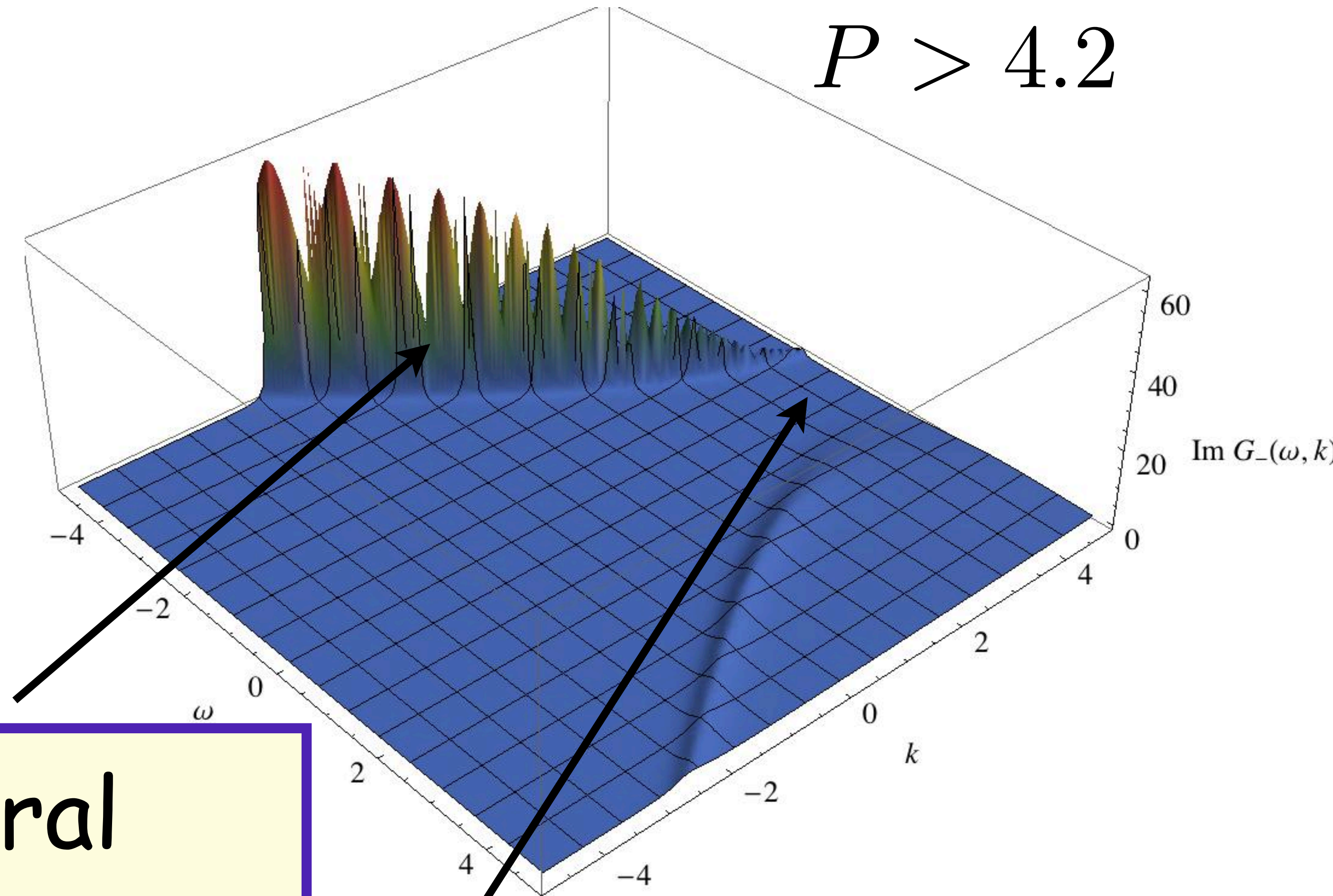


$P > 4.2$



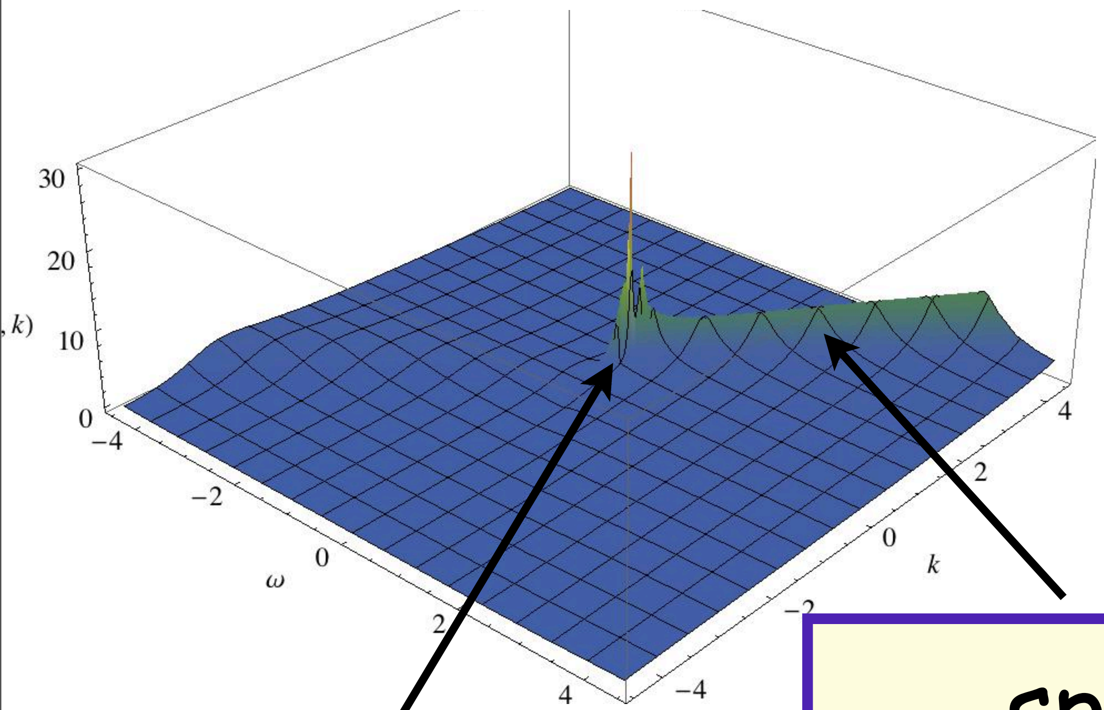
spectral weight transfer

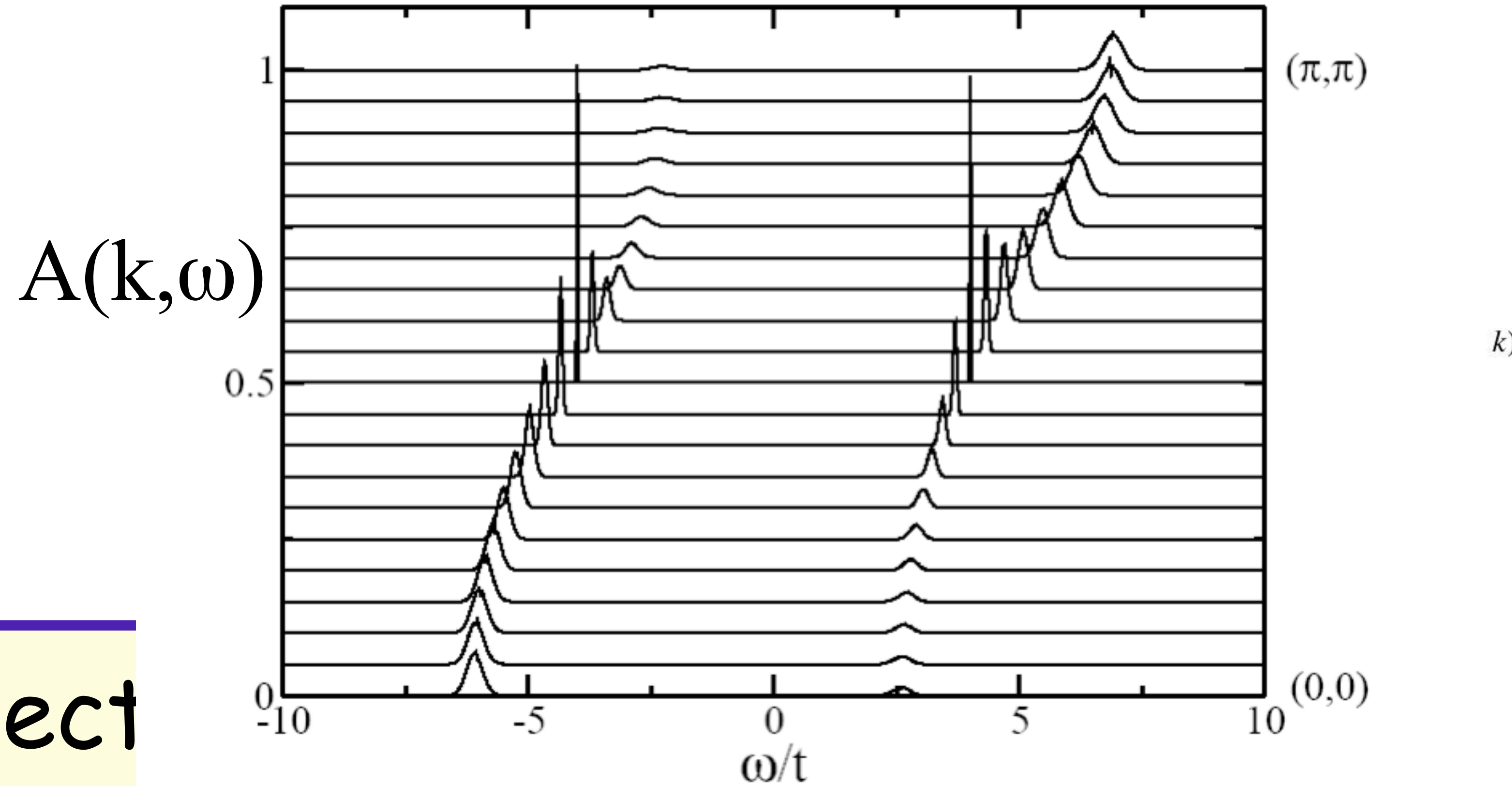
Fermi surface peak

dynamically generated gap:

How is the spectrum modified?

P=0





spect
weight transfer

Fermi
surface
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dynamically generated gap:

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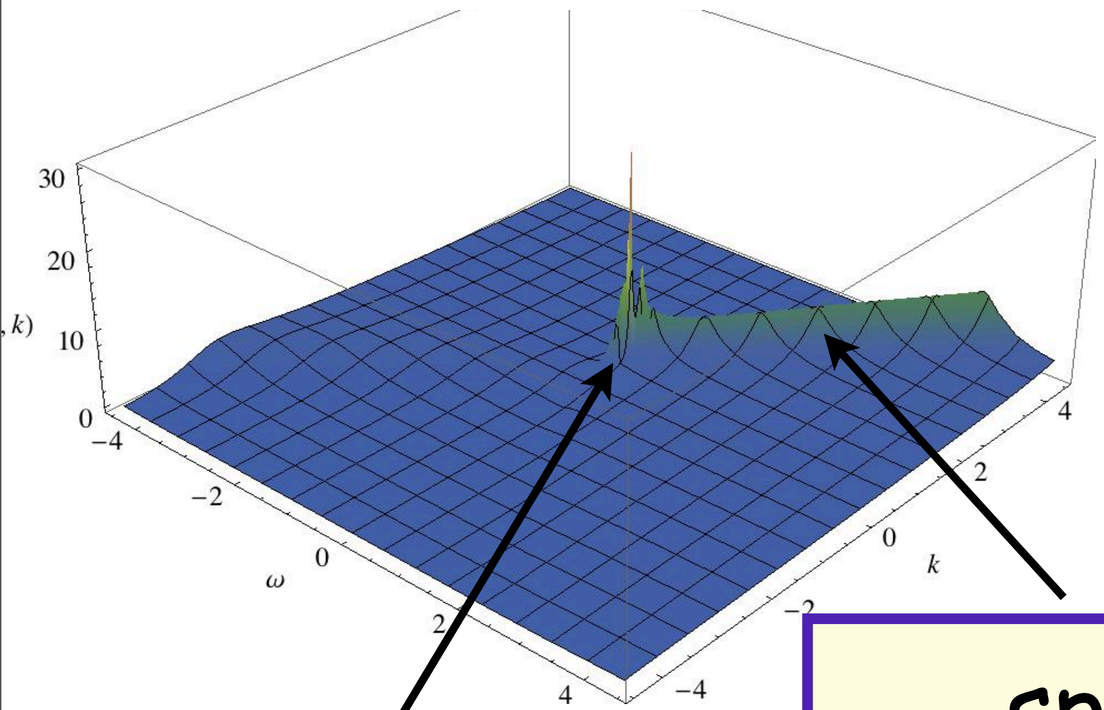

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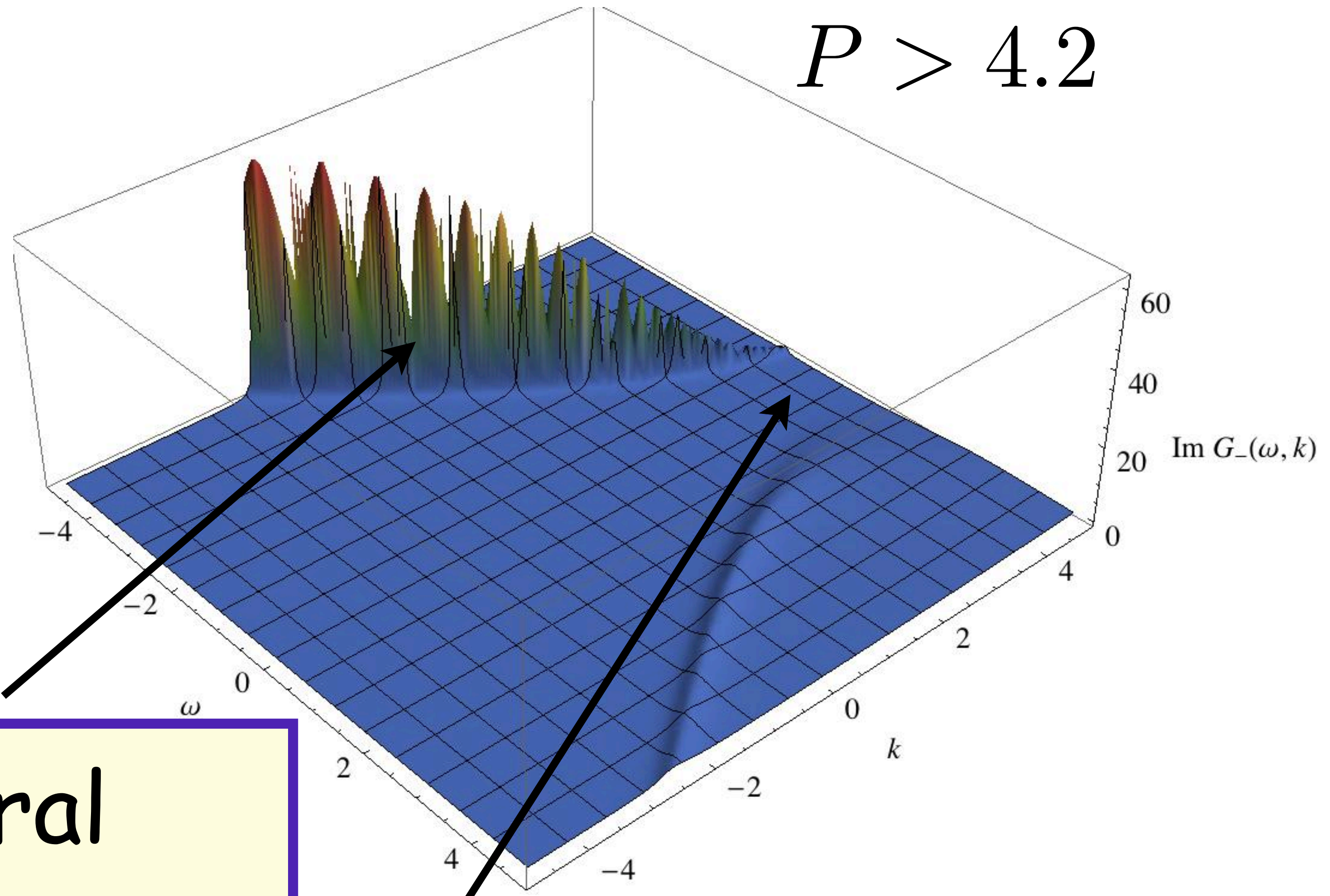
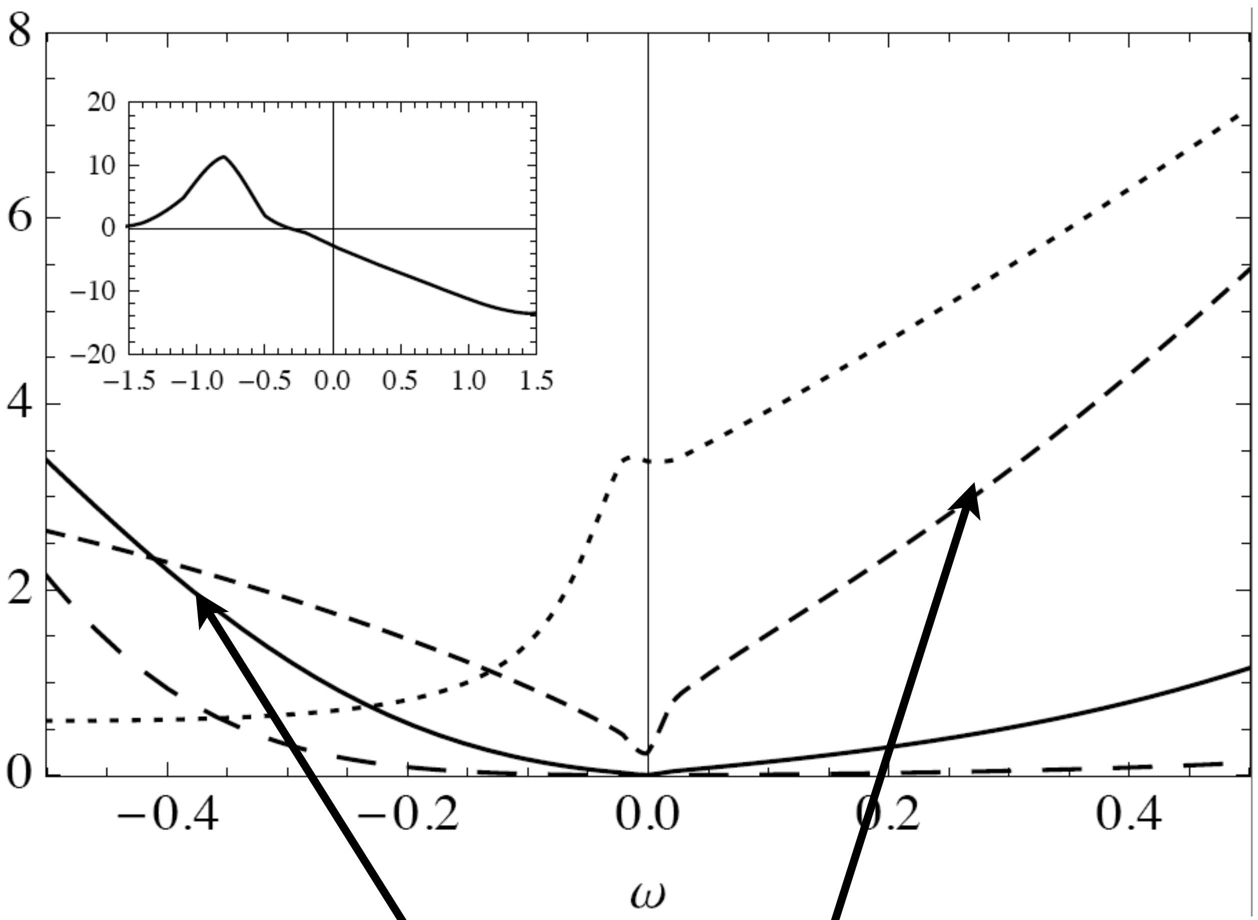
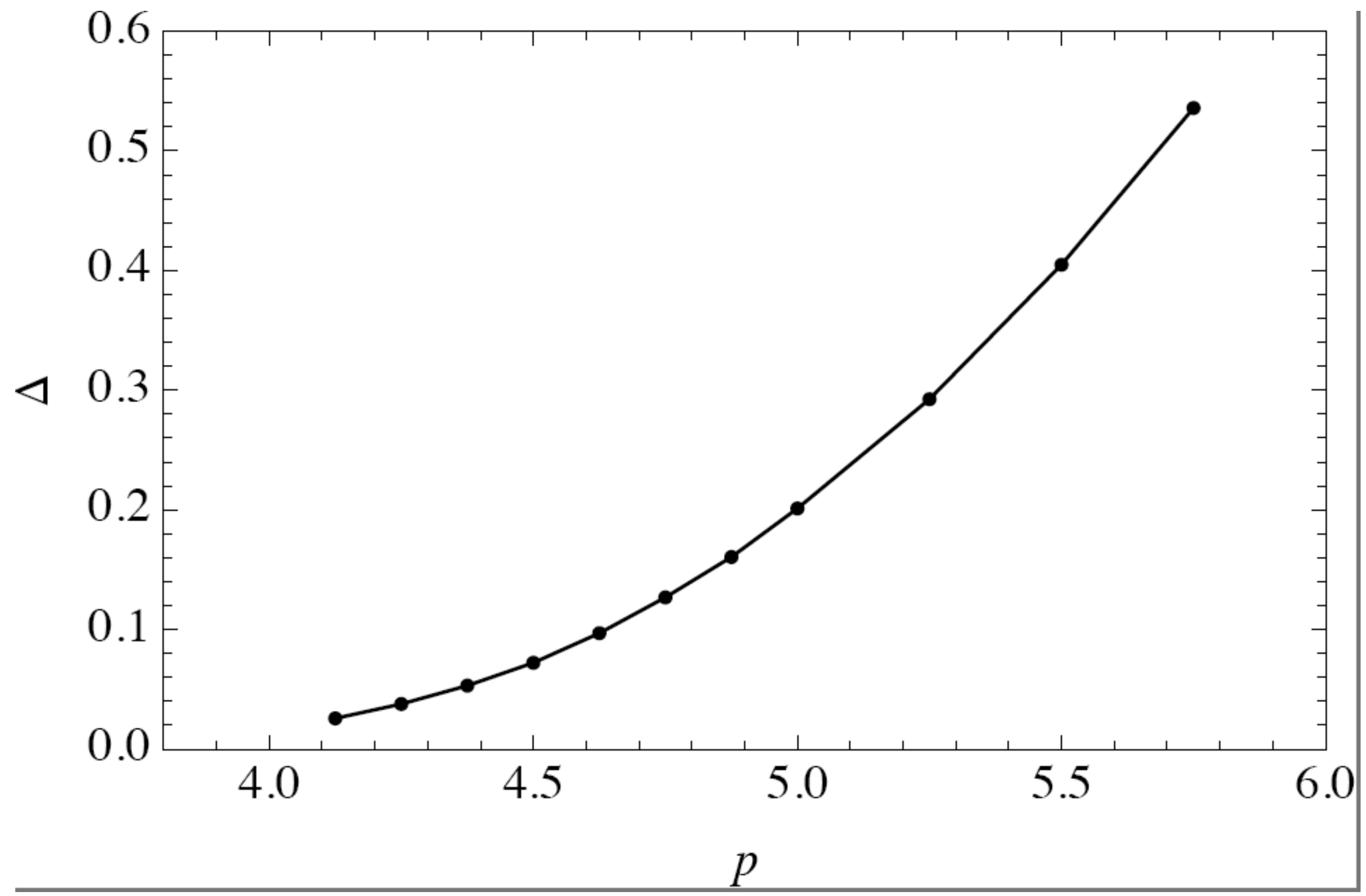


Fermi surface peak

spectral weight transfer

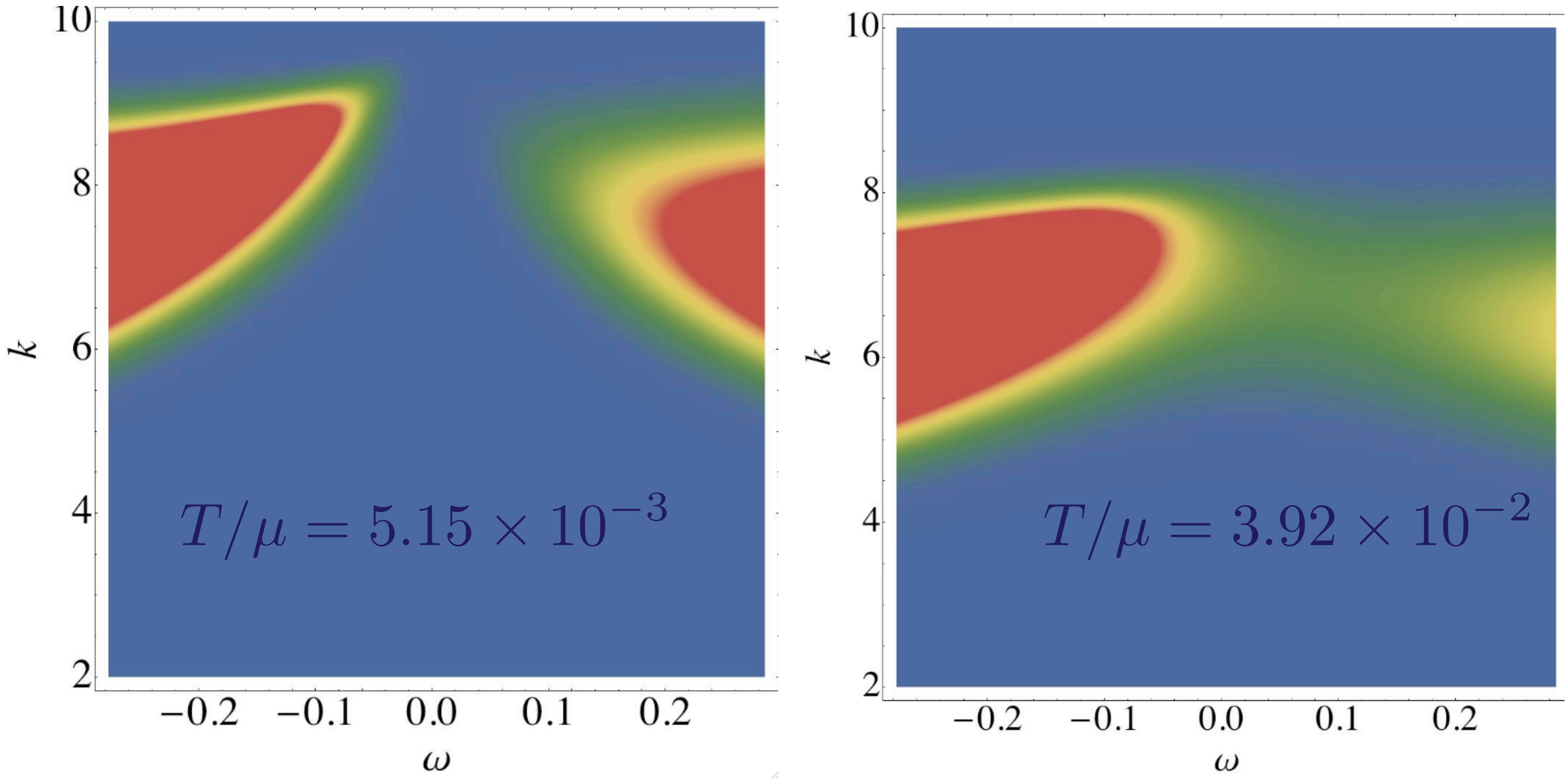
dynamically generated gap:



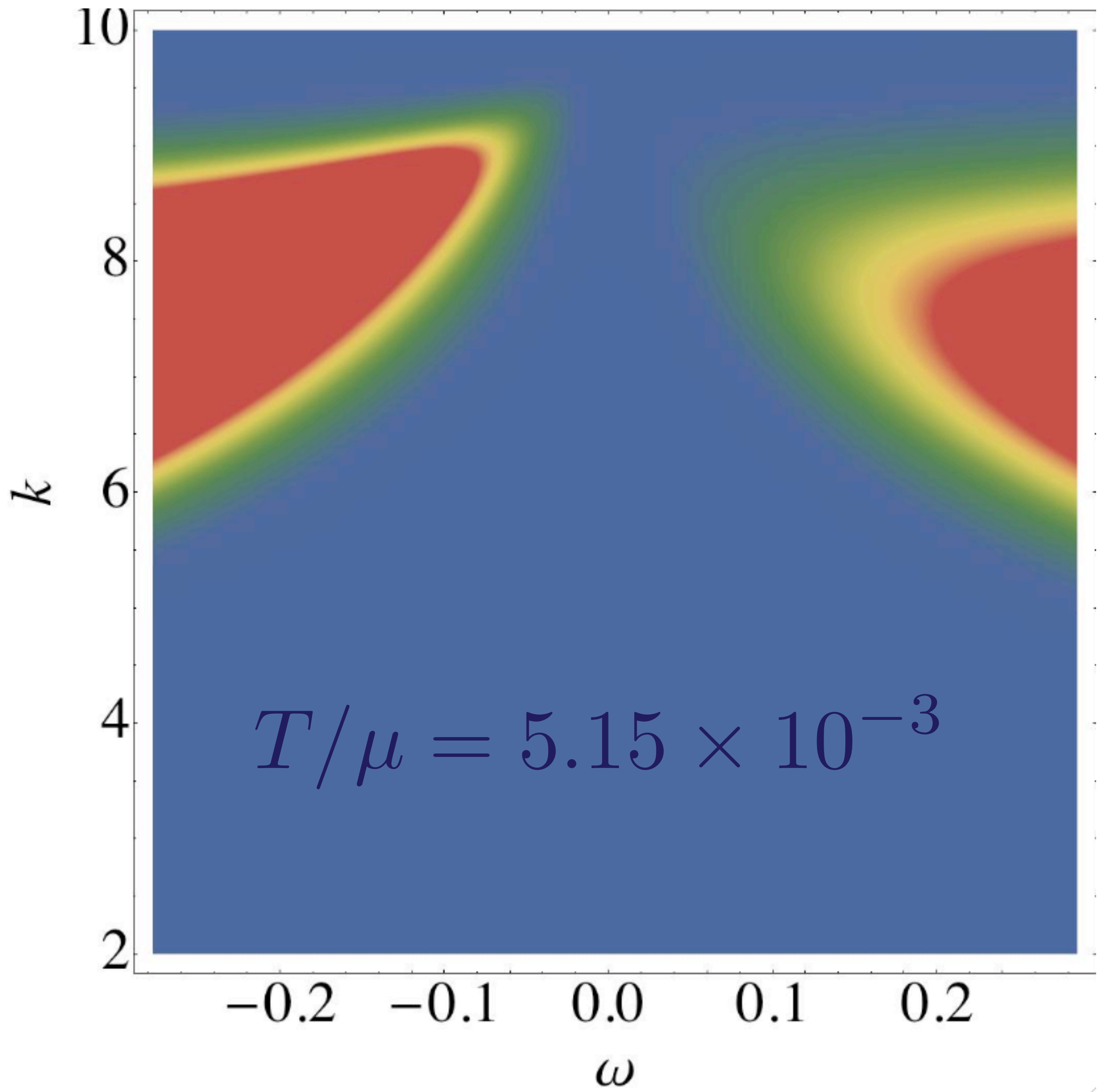


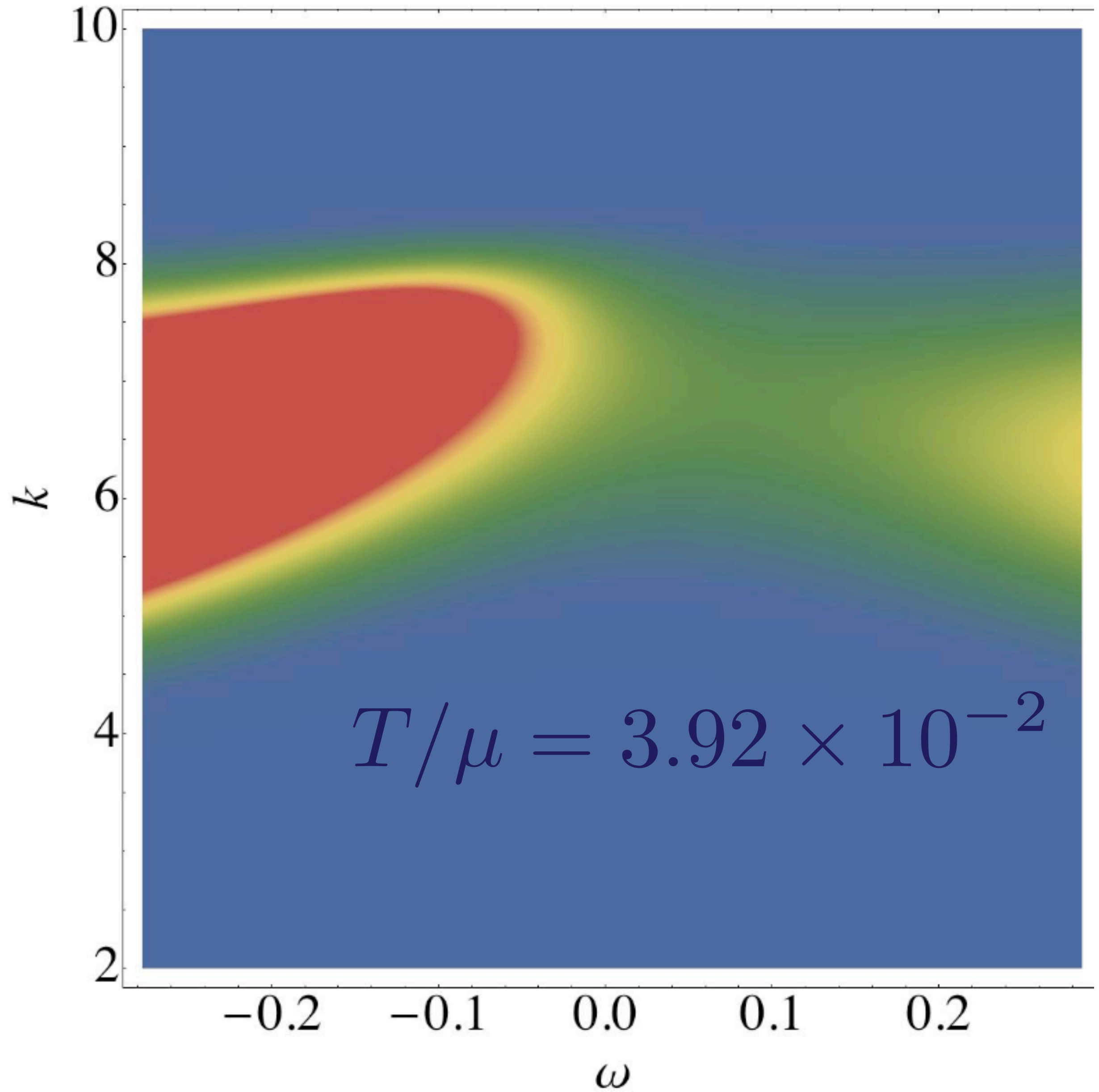
spectral weight
transfer
UV-IR mixing

Finite Temperature Mott transition



Finite Temperature Mott transition

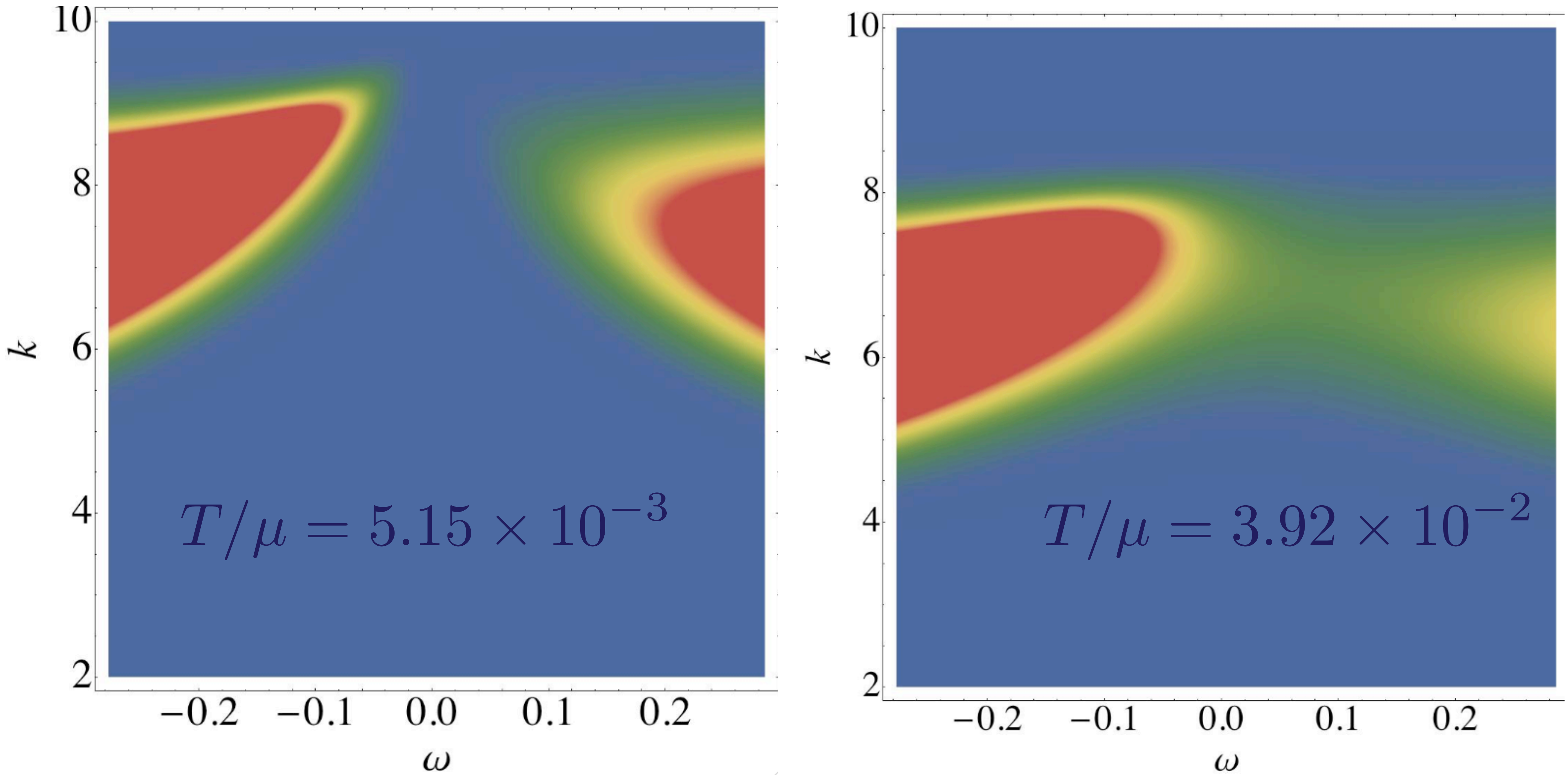




$$\frac{\Delta}{T_{\text{crit}}} \approx 20$$

vanadium oxide

Finite Temperature Mott transition

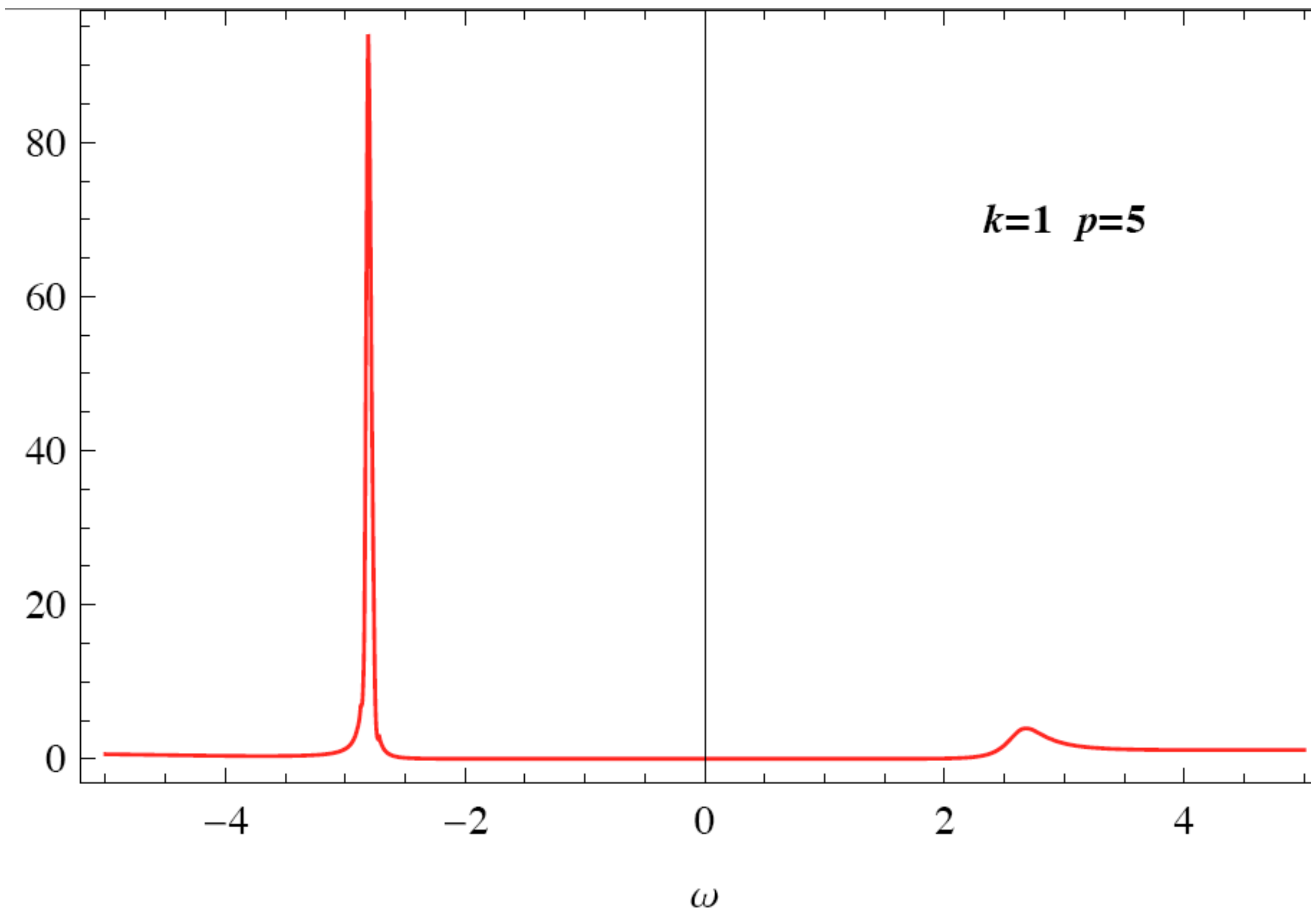


$$\frac{\Delta}{T_{\mathrm{crit}}} \approx 10$$

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

vanadium oxide

quasi-normal modes: where are the peaks?



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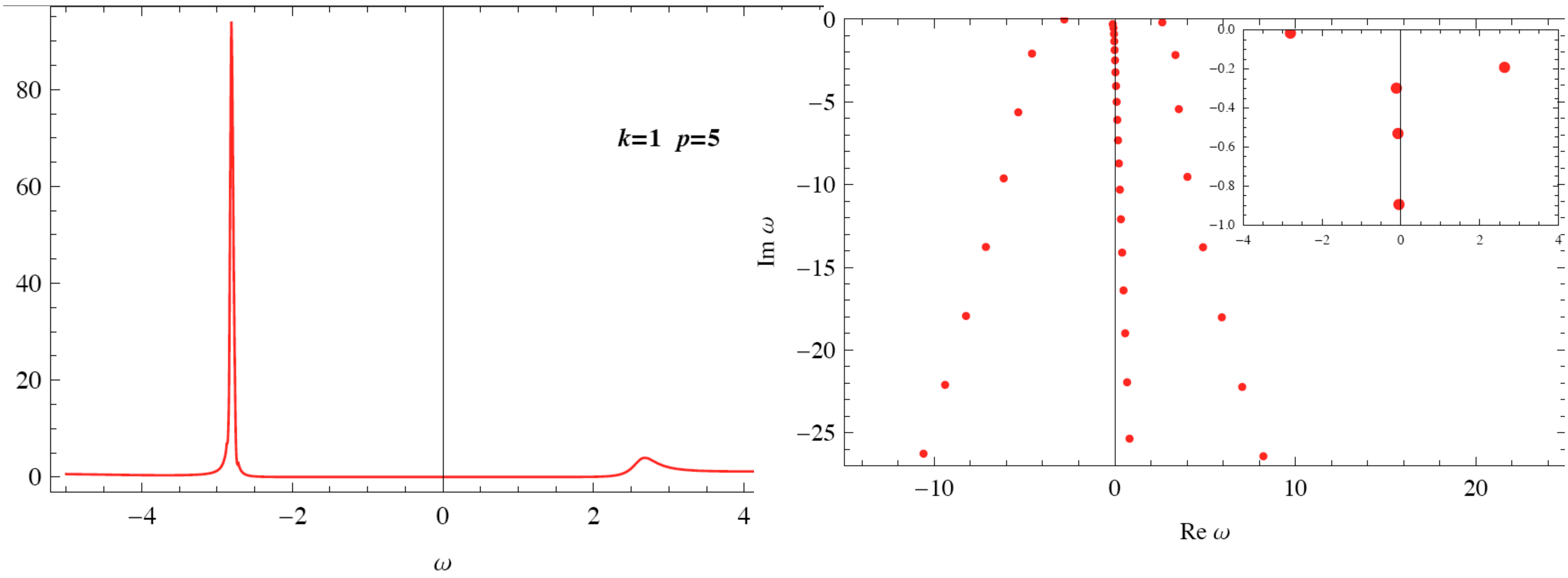

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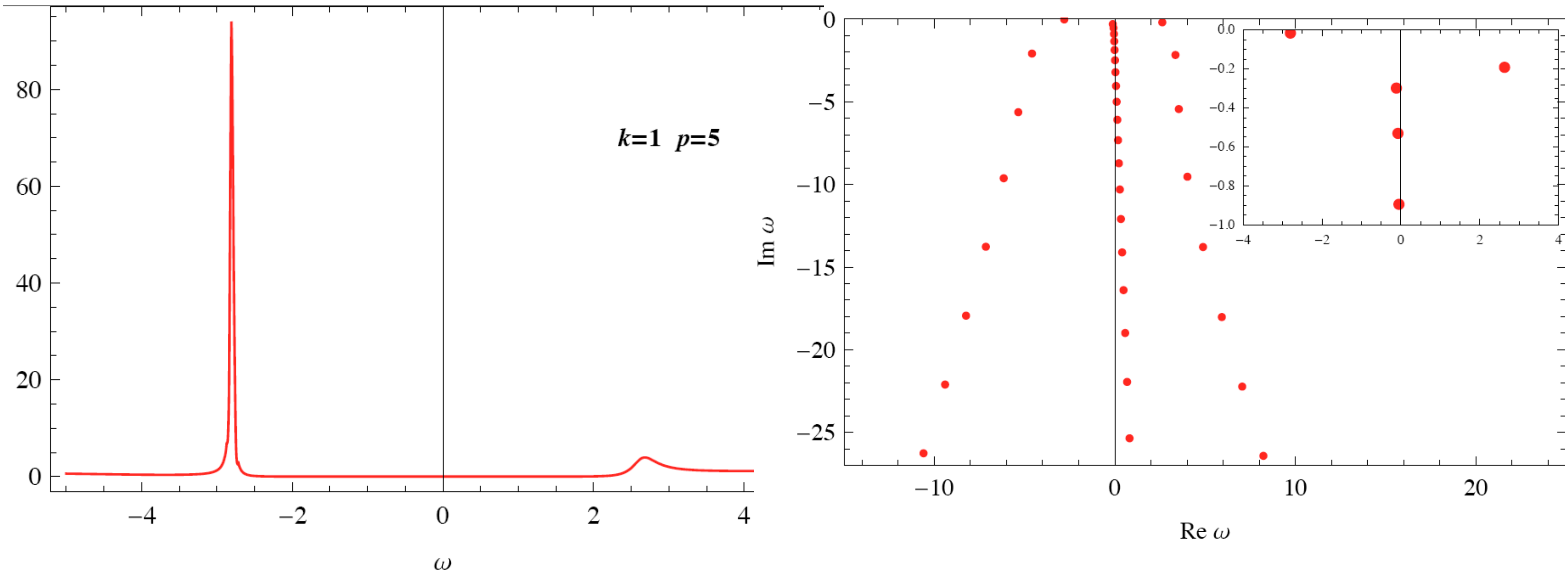
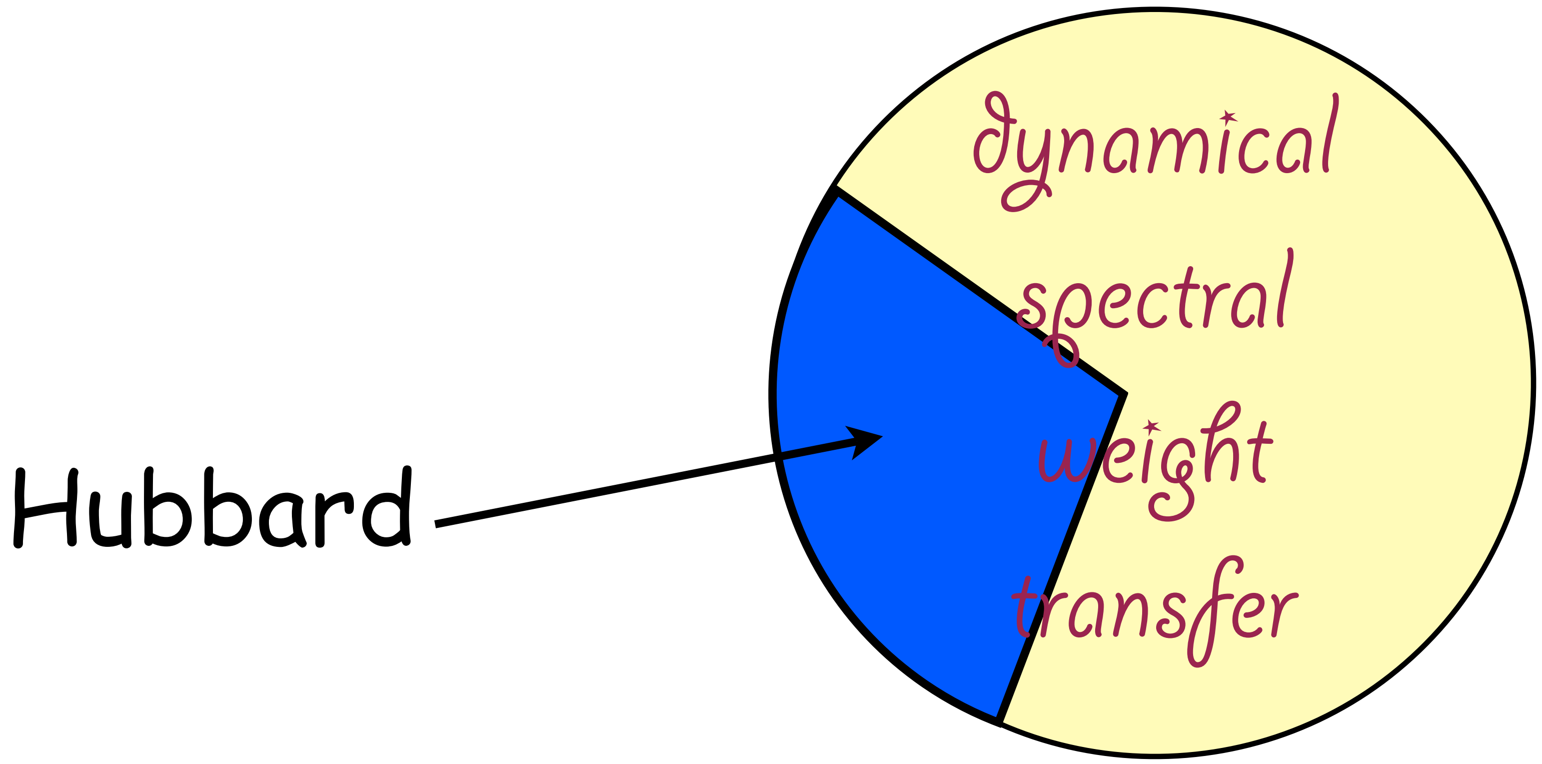
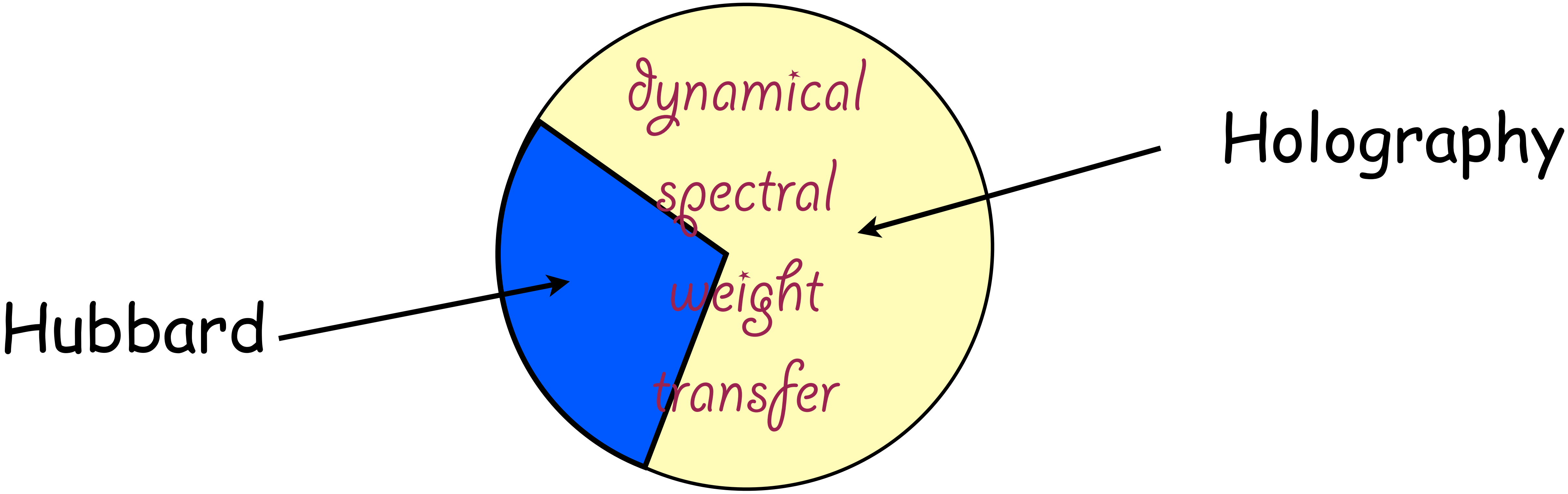


no leaking to +Im\omega: no instability

dynamical
spectral
weight
transfer


Hubbard
dynamical
spectral
weight
transfer



Hubbard
dynamical
spectral
weight
transfer
Holography

Mottness