Mottness and Holography

Thanks to:
NSF, EFRC (DOE)

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and
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T.-P. Choy

R. G. Leigh

What is Mottness?

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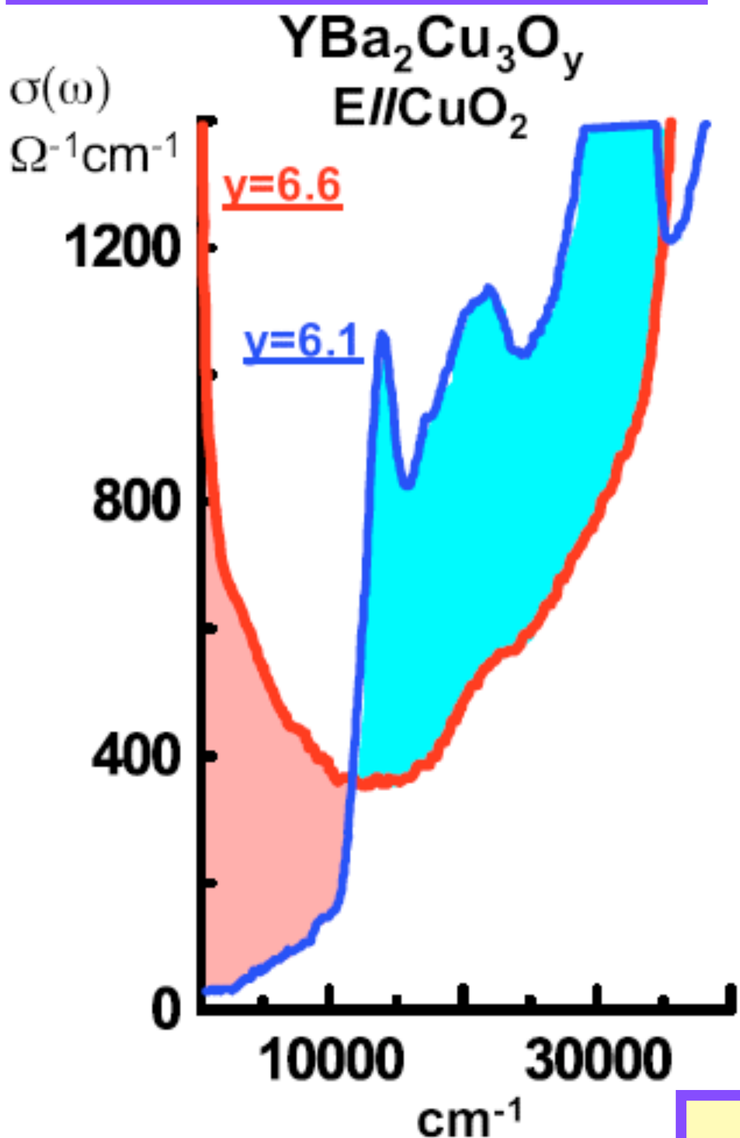
physics of a non-rigid band:
UV-IR mixing

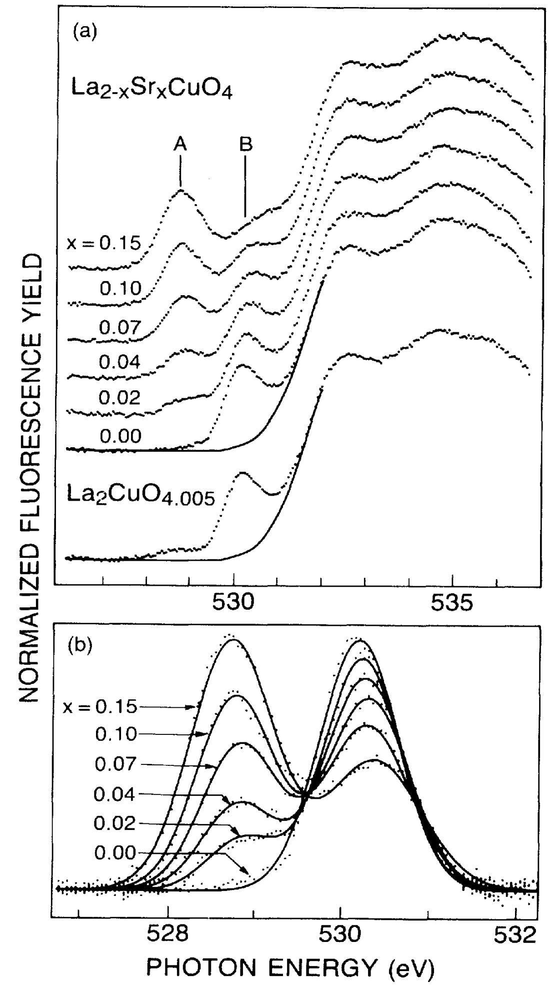
What is Mottness?

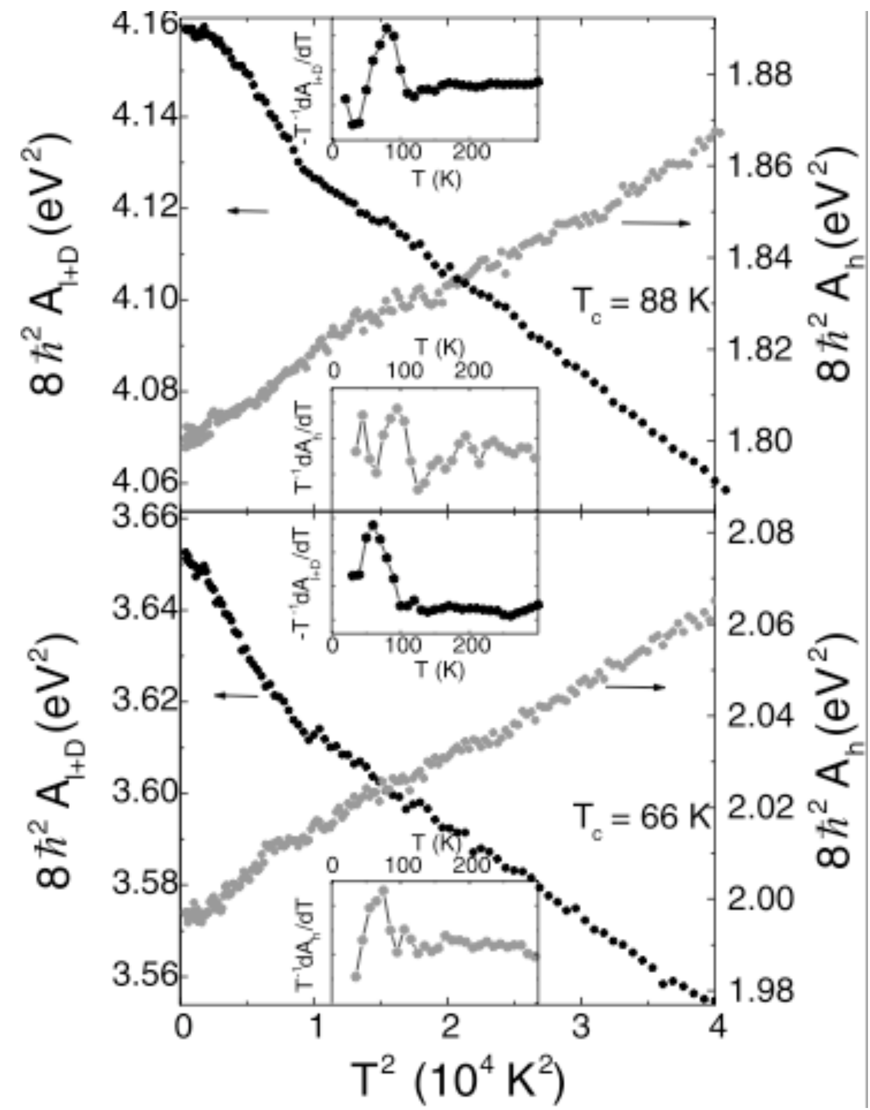
SC state

2-particle probe



1-particle





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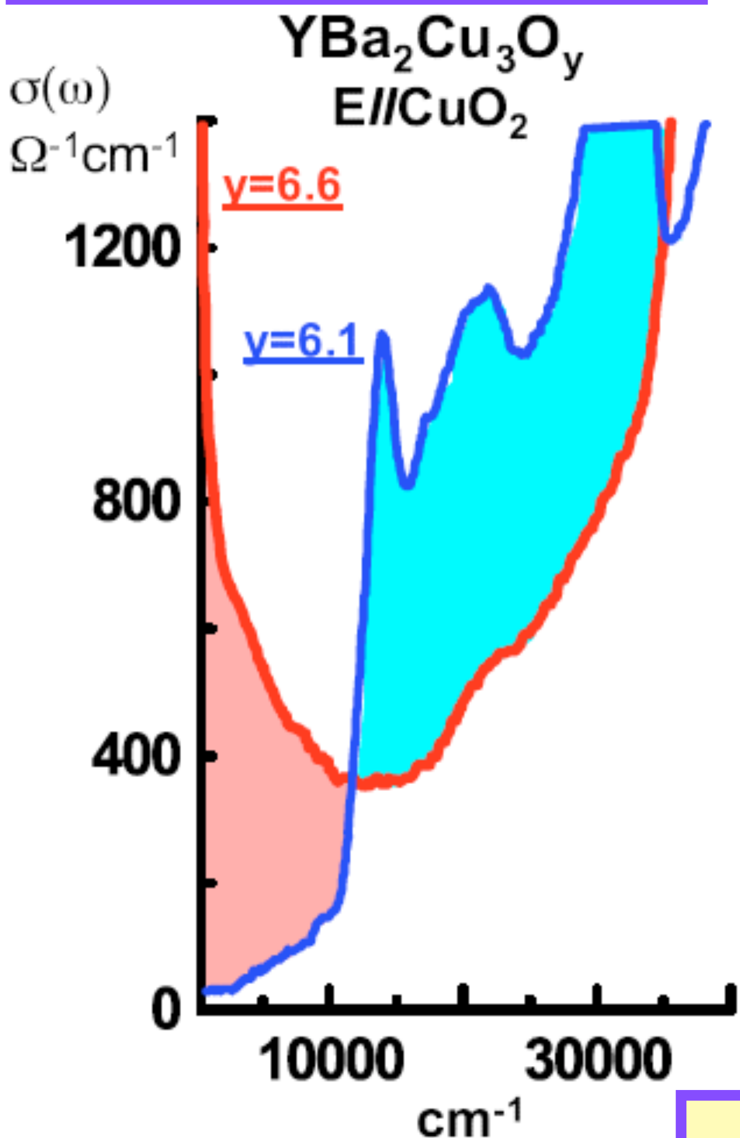

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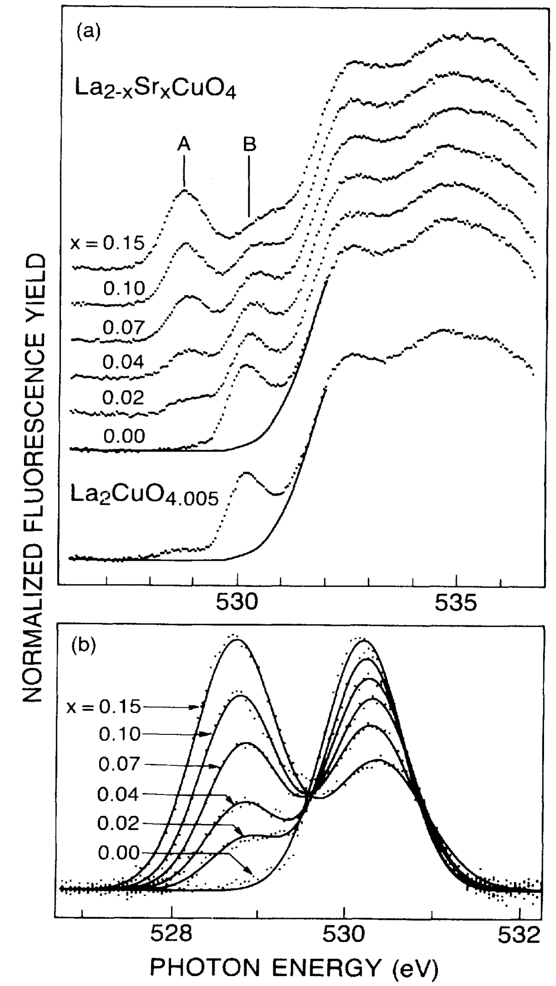

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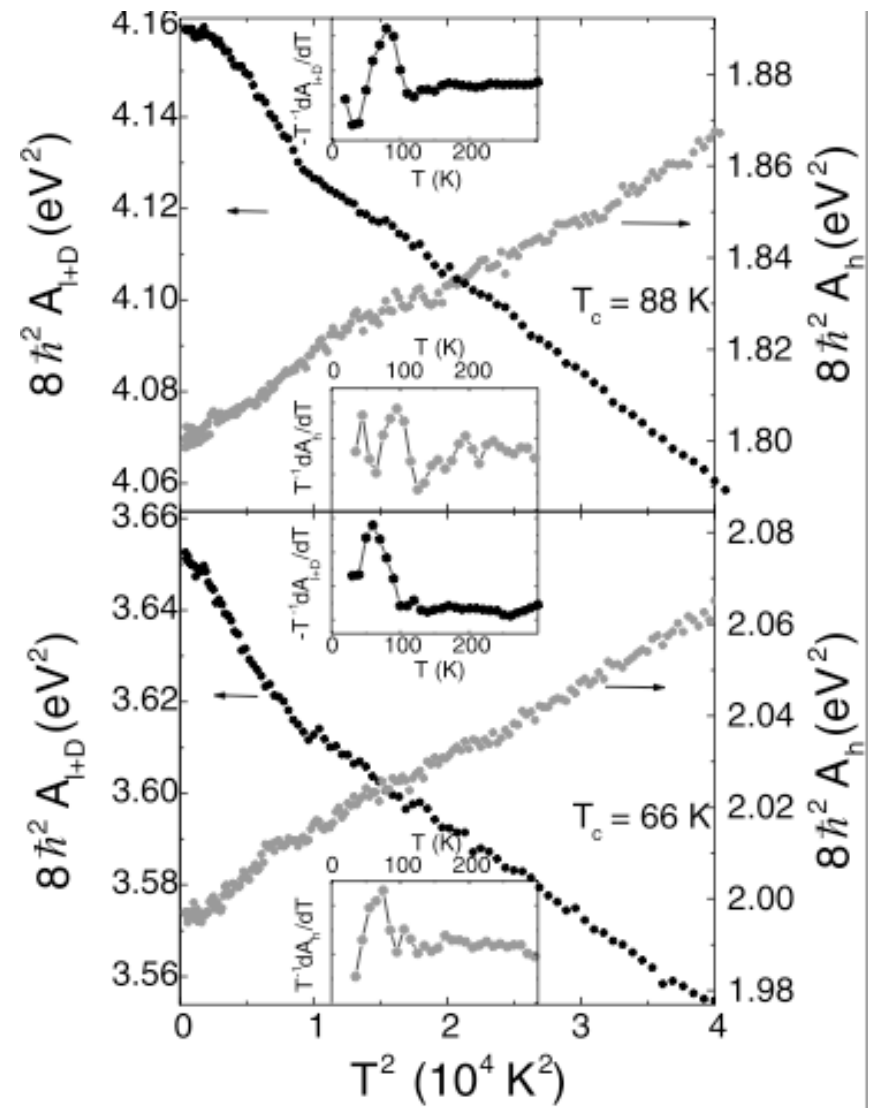

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physics of a non-rigid band: UV-IR mixing

current= what particle

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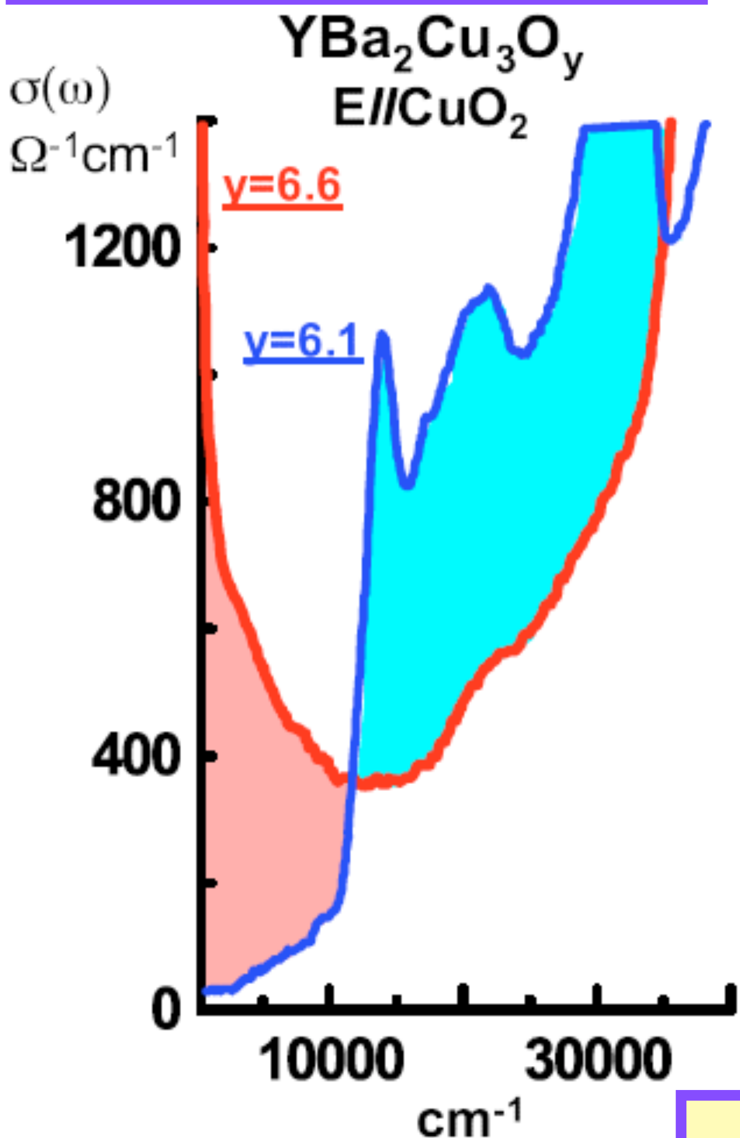
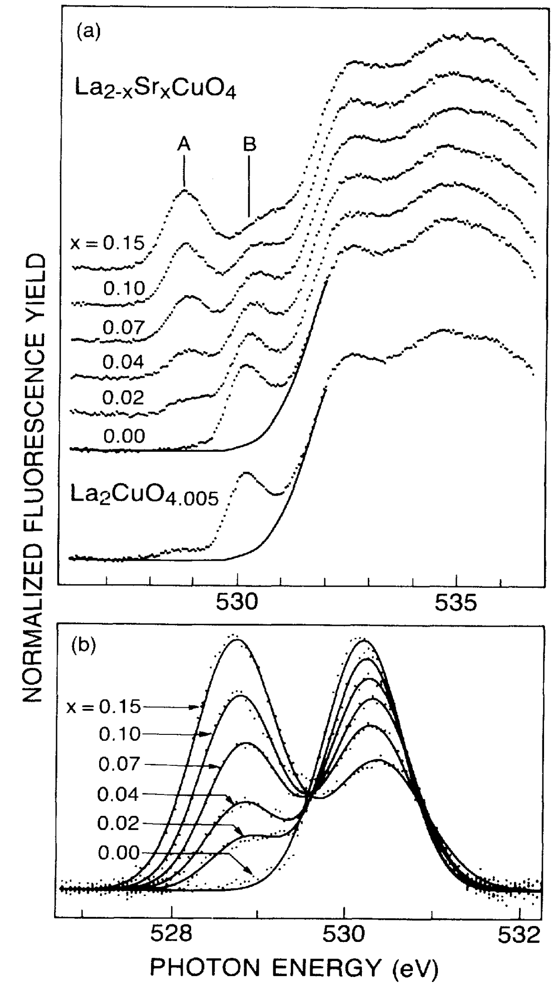


1-particle



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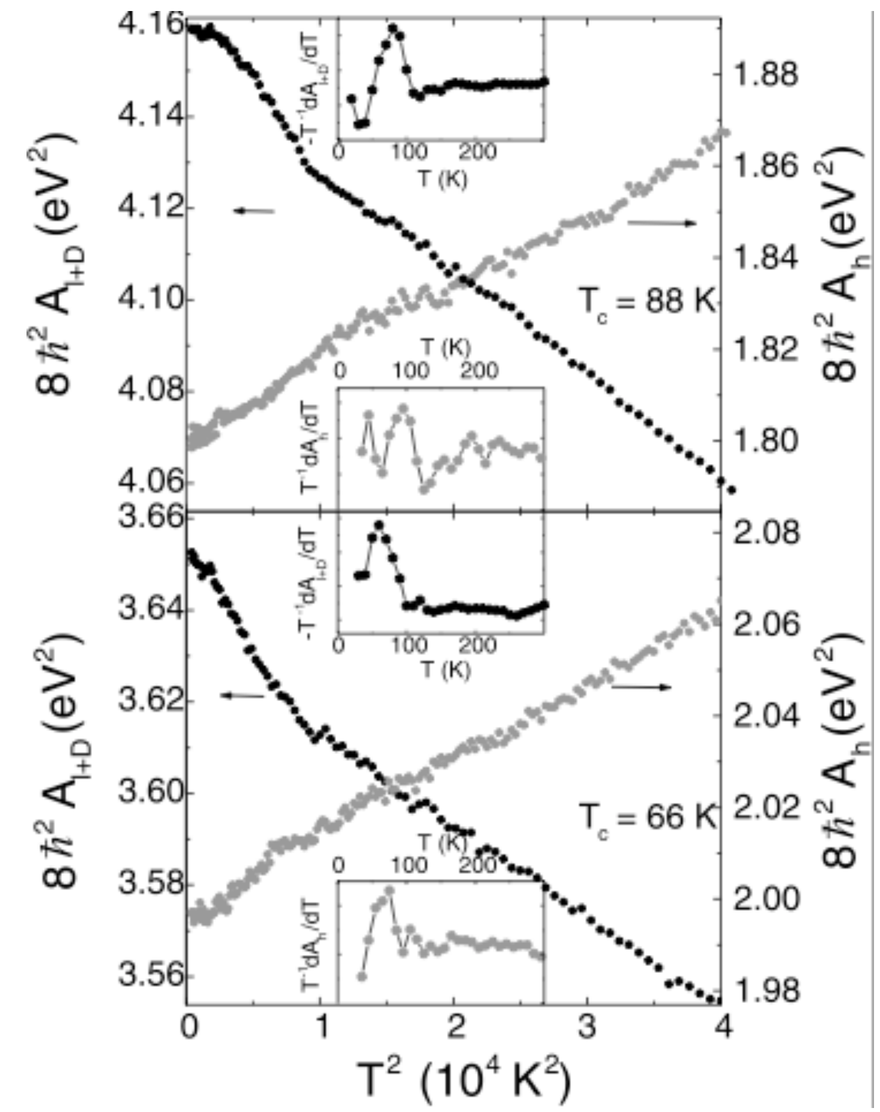

non-BCS

physics of a non-rigid band:
UV-IR mixing

Wilsonian program

current=
what particle

holography

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

Wilsonian program

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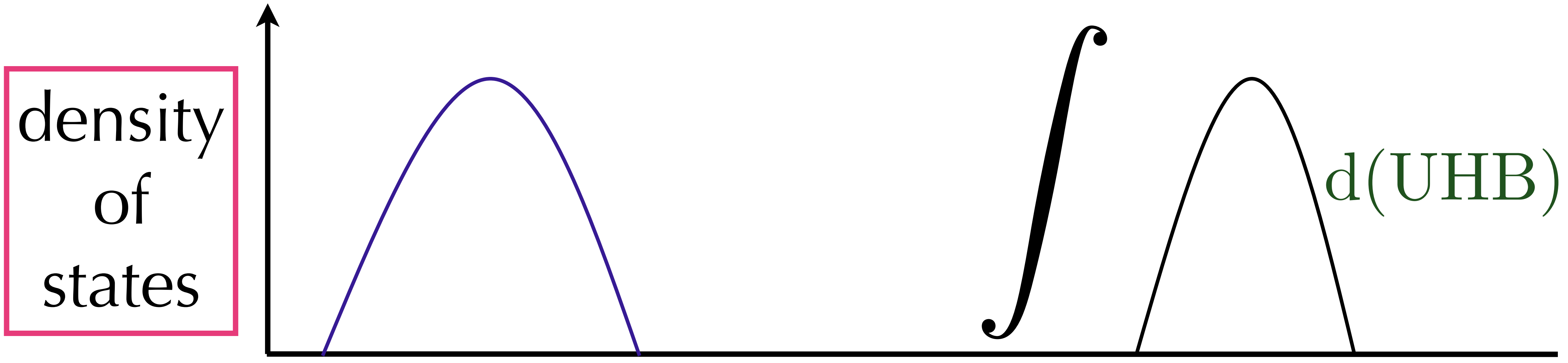

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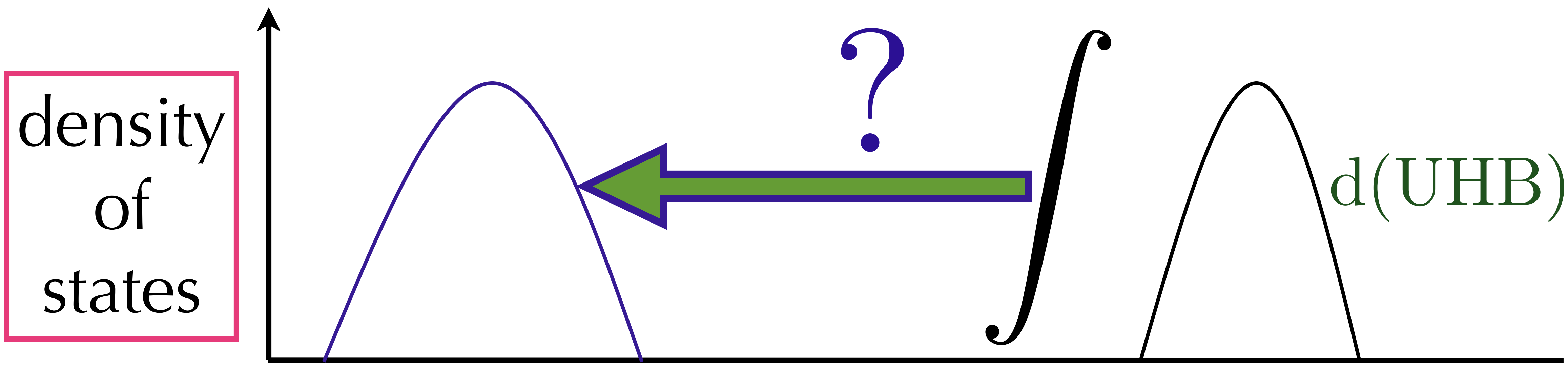
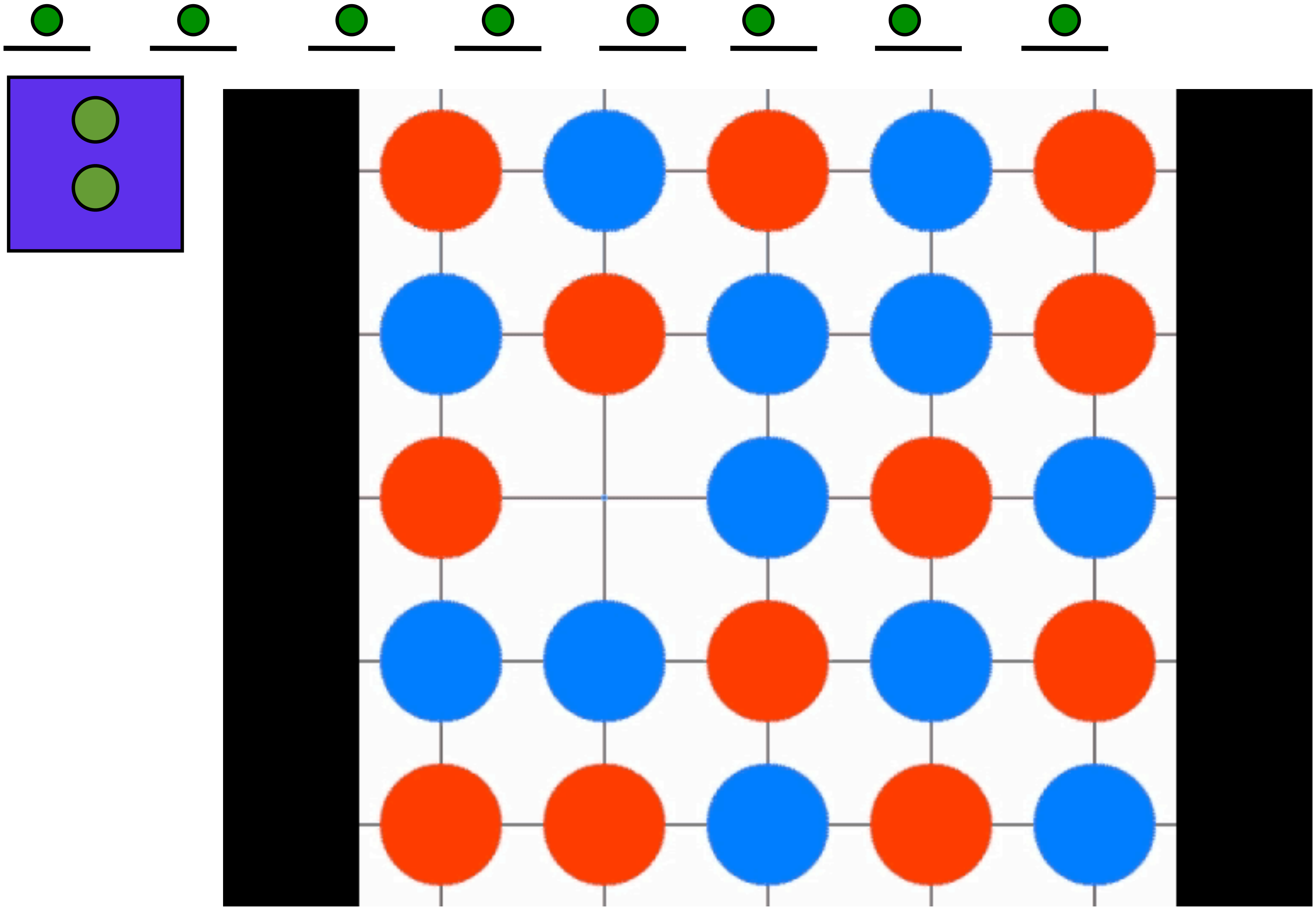


What is transferred down?

classical limit



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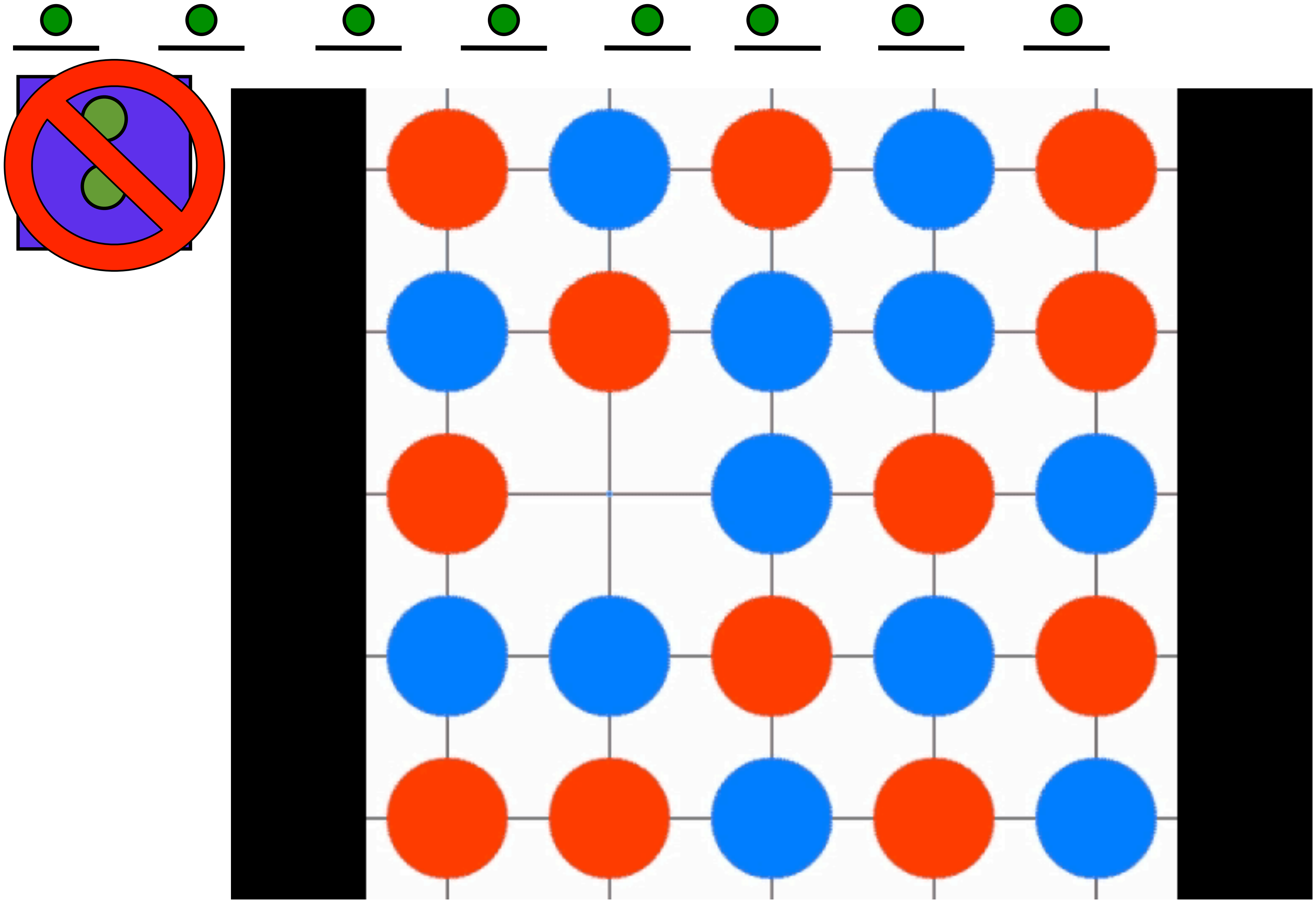
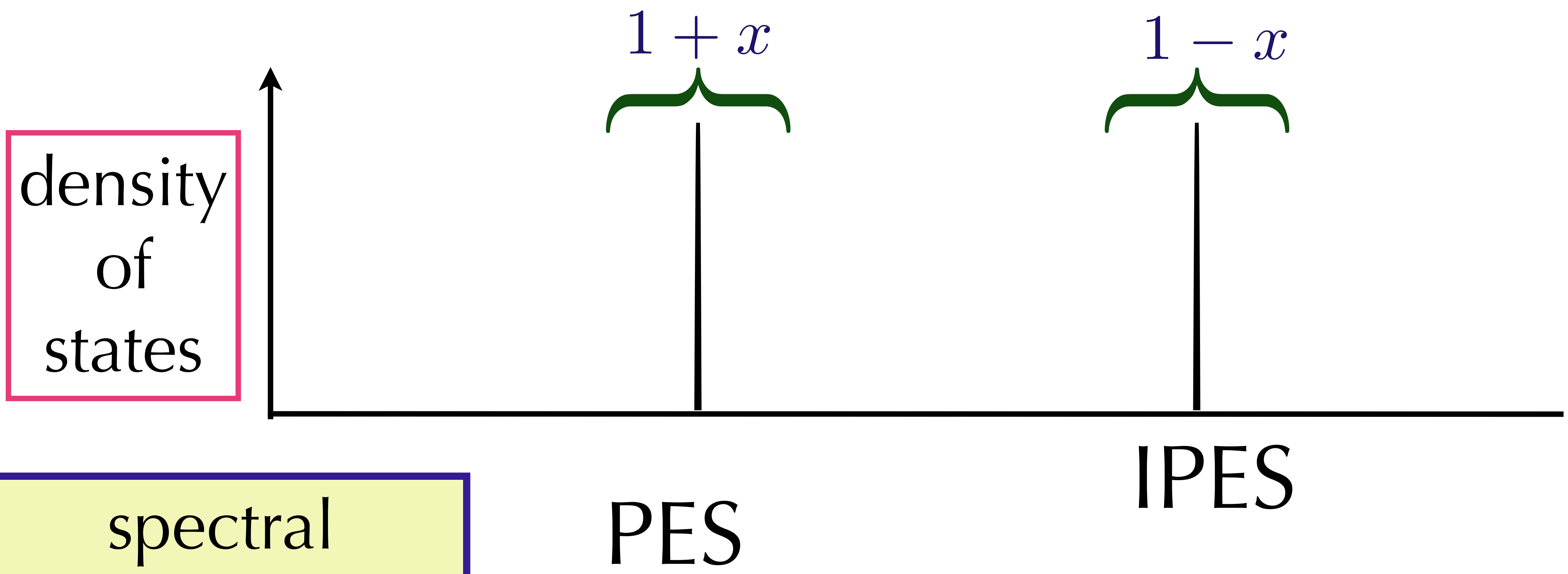


atomic limit: x holes



spectral weight: x-dependent

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

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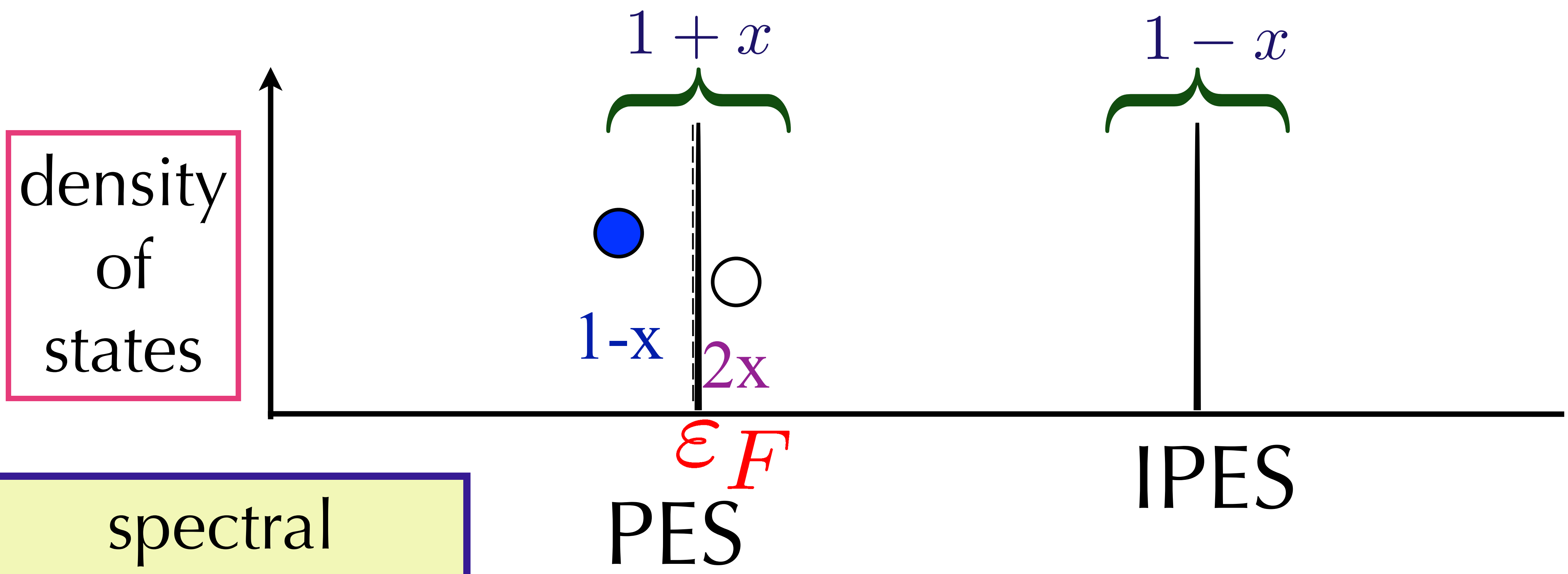

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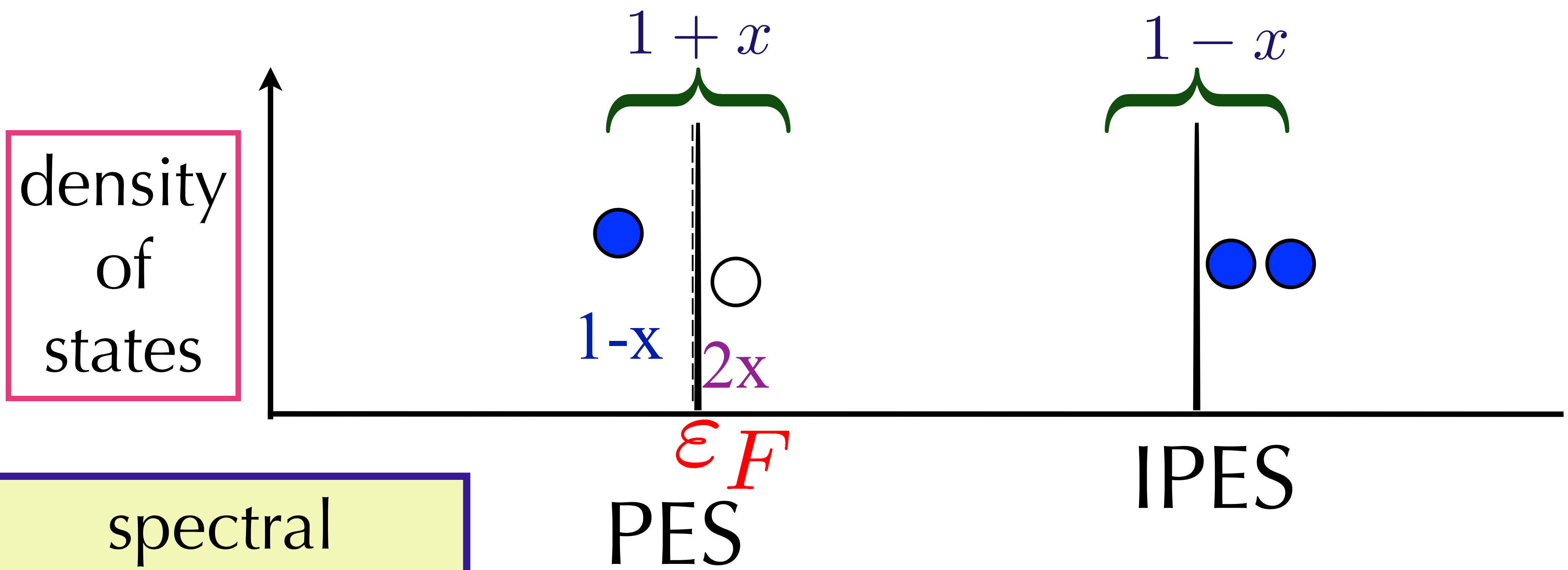

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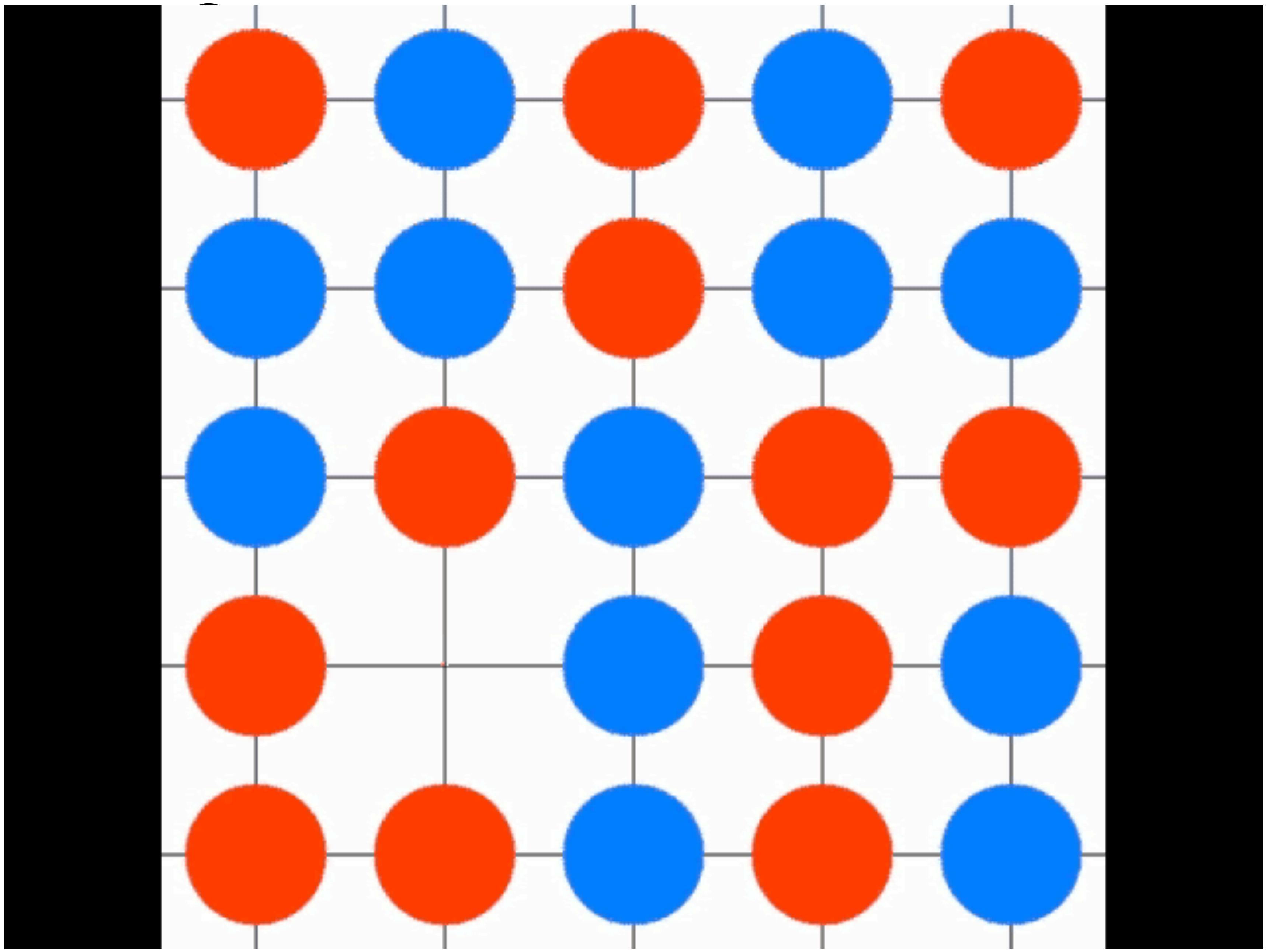
quantum Mottness: U finite $U \gg t$



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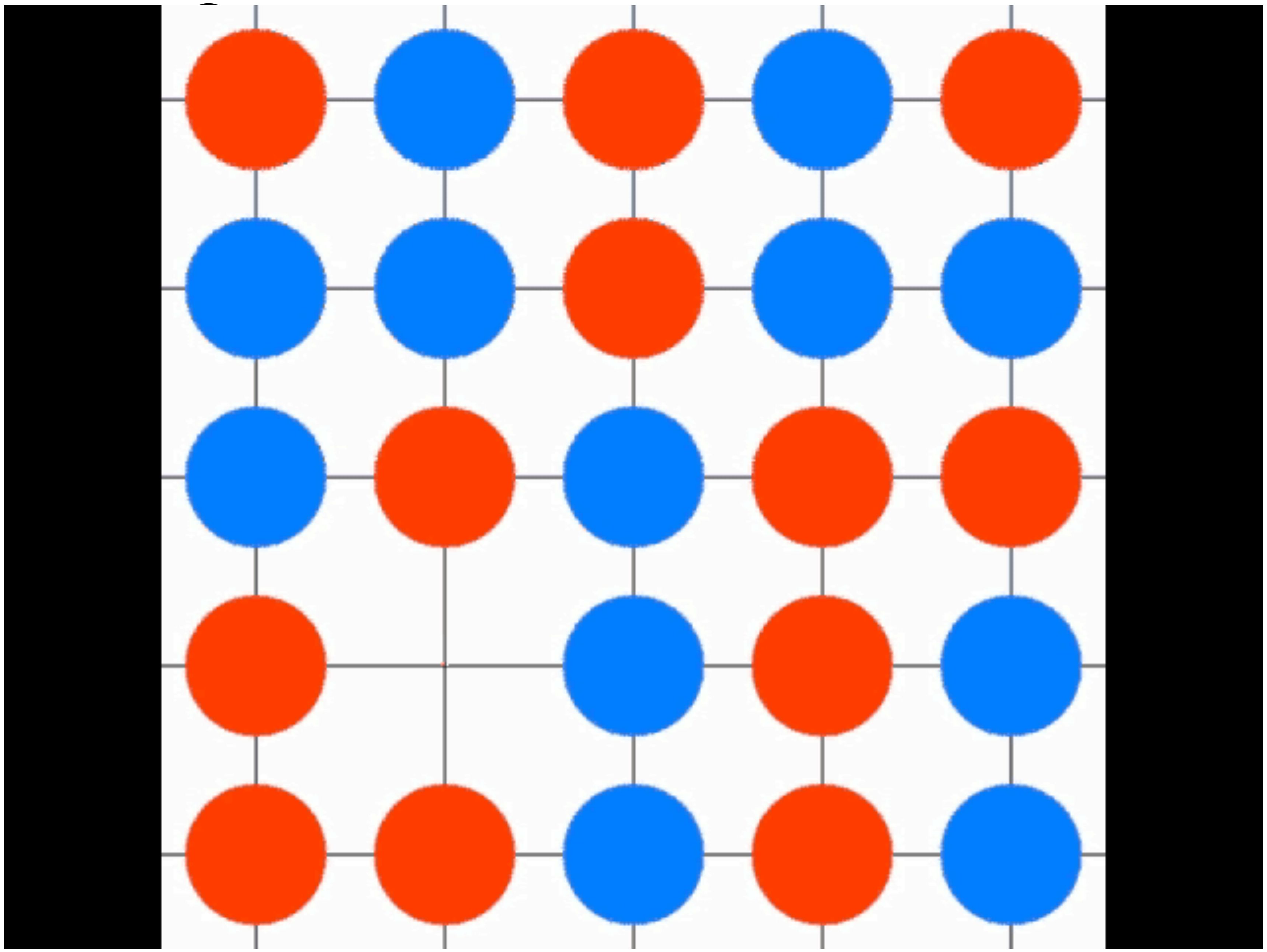

double occupancy in ground state!!

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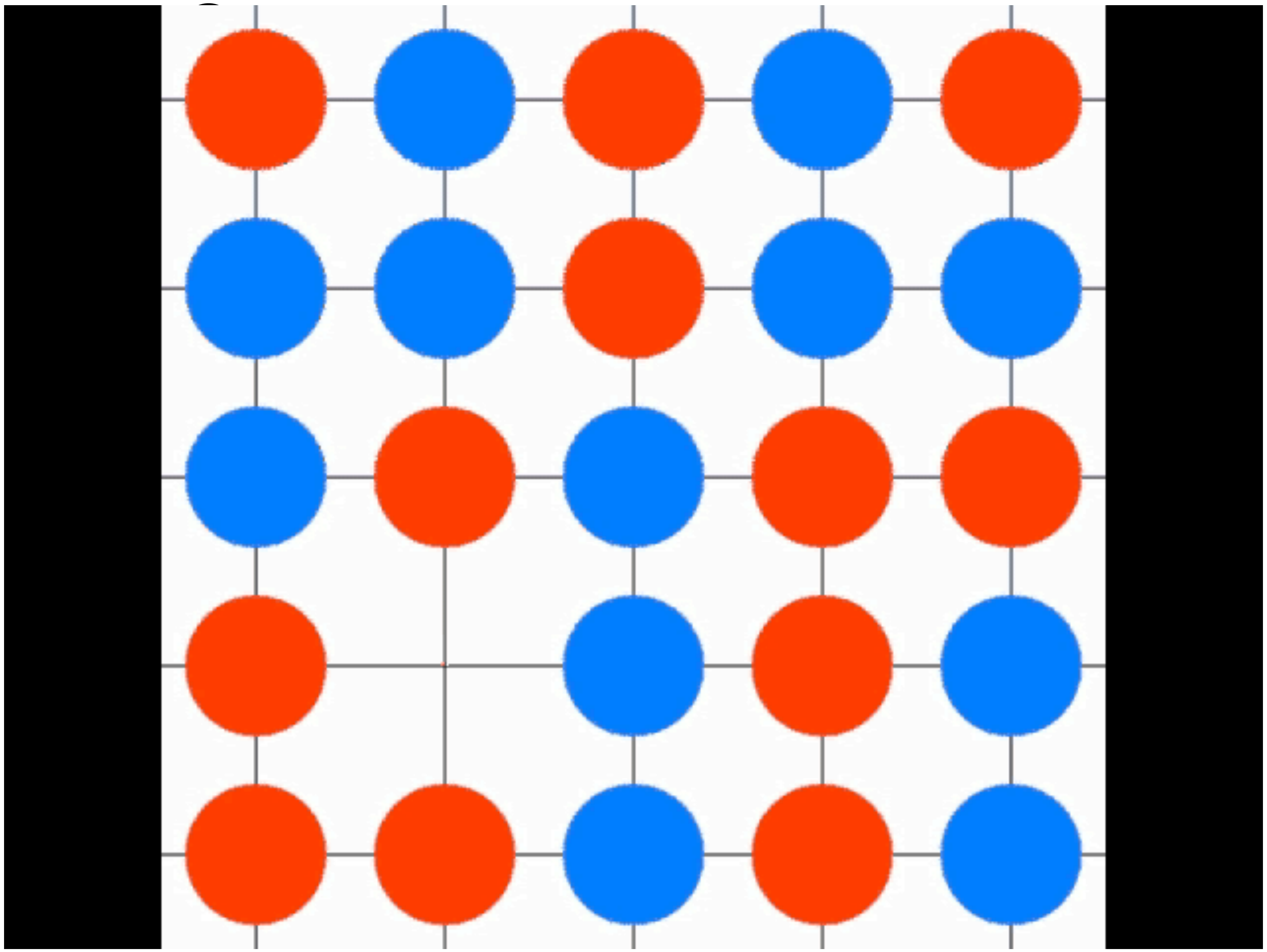
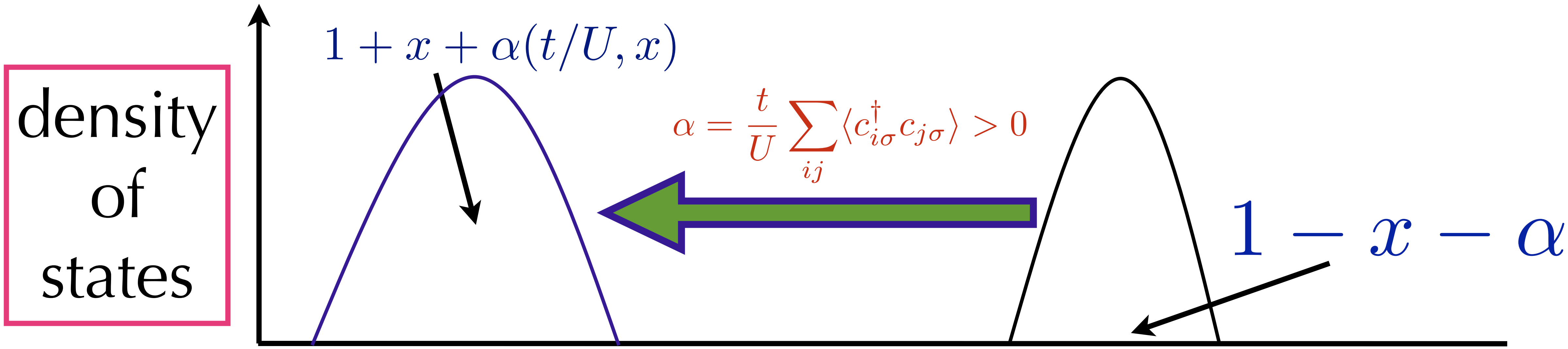


double occupancy in ground state!!

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

beyond the atomic limit: any real system



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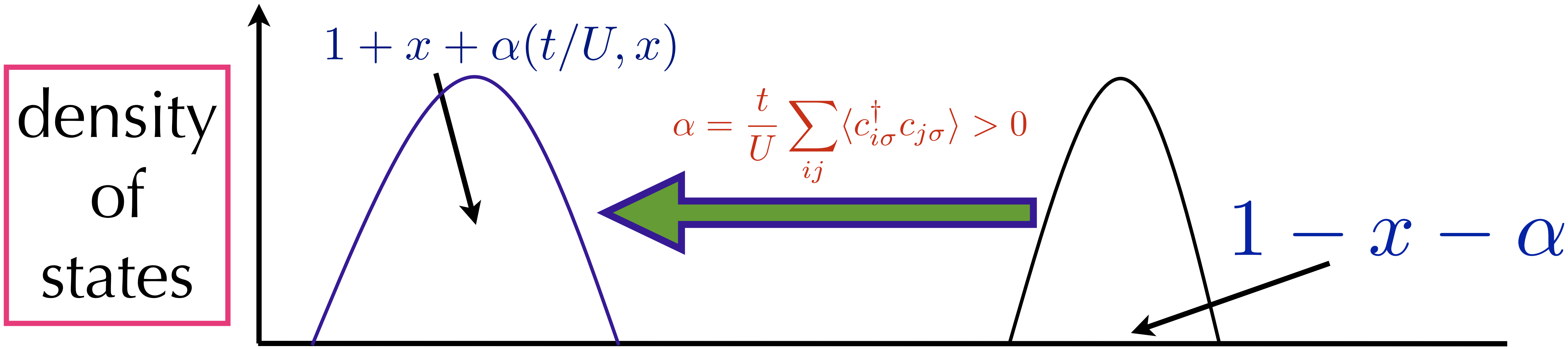
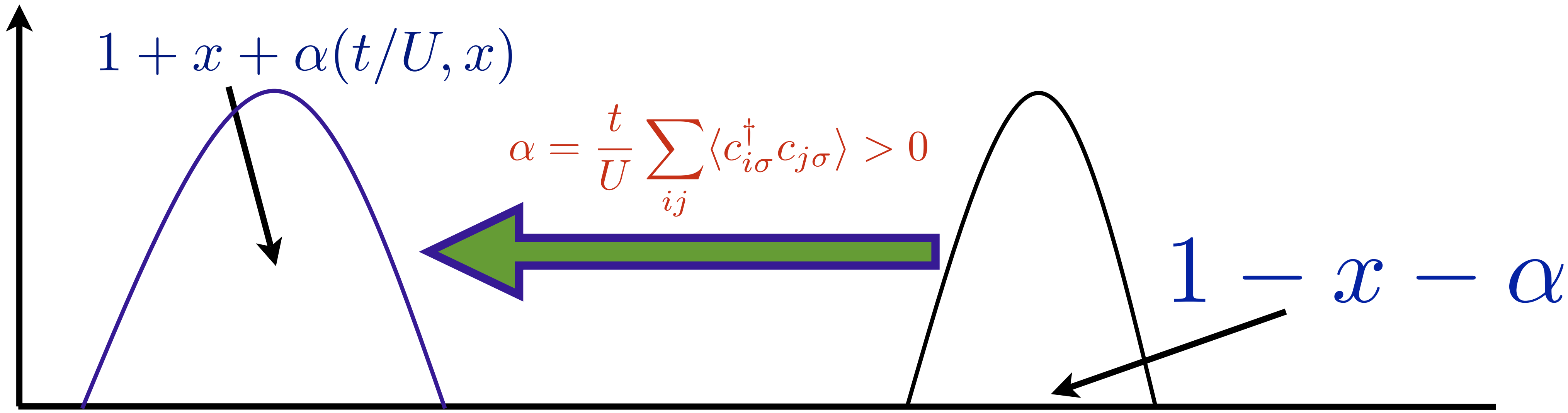


Harris & Lange, 1967

dynamical spectral weight transfer

beyond the atomic limit: any real system

density of states



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Intensity>1+x

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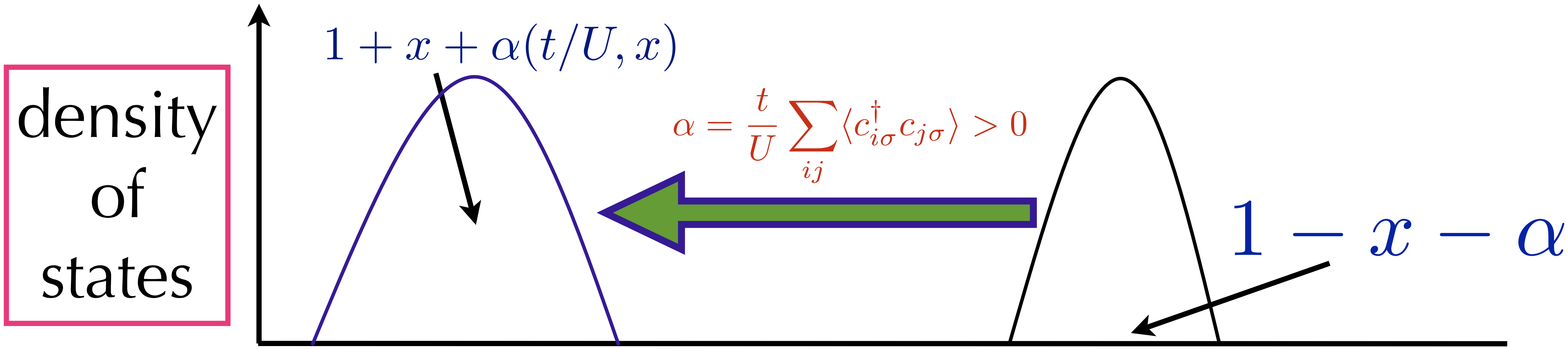

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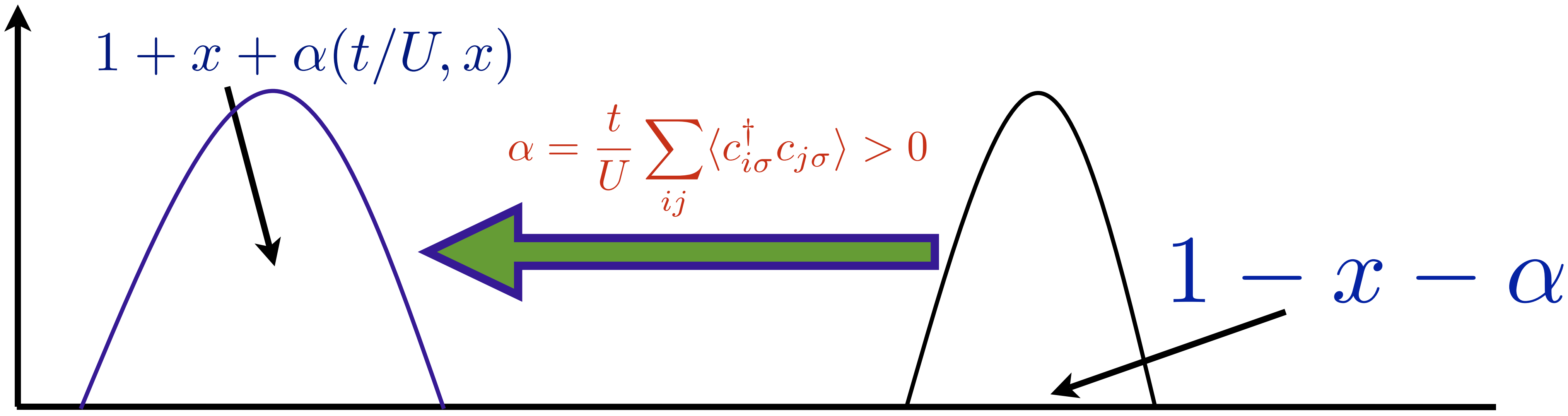

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# of electron states in lower band

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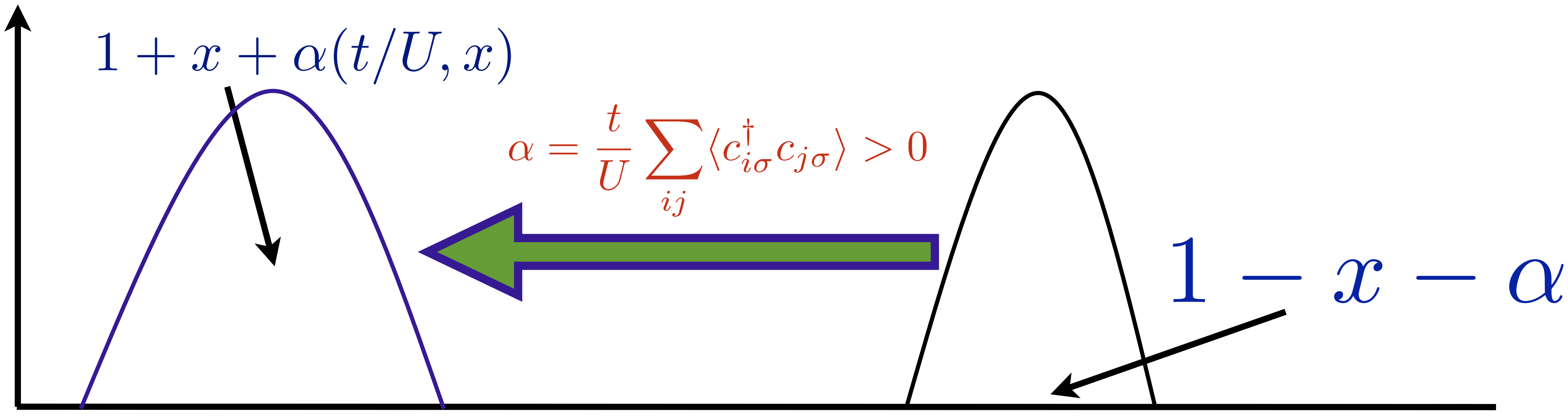

Harris & Lange, 1967

dynamical spectral weight transfer

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

$$1 = 2 - 1$$

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$$e = 2e - e$$

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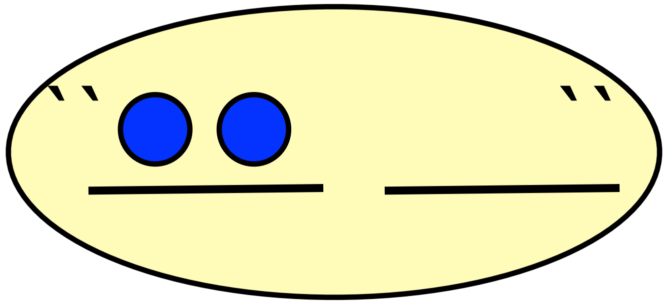
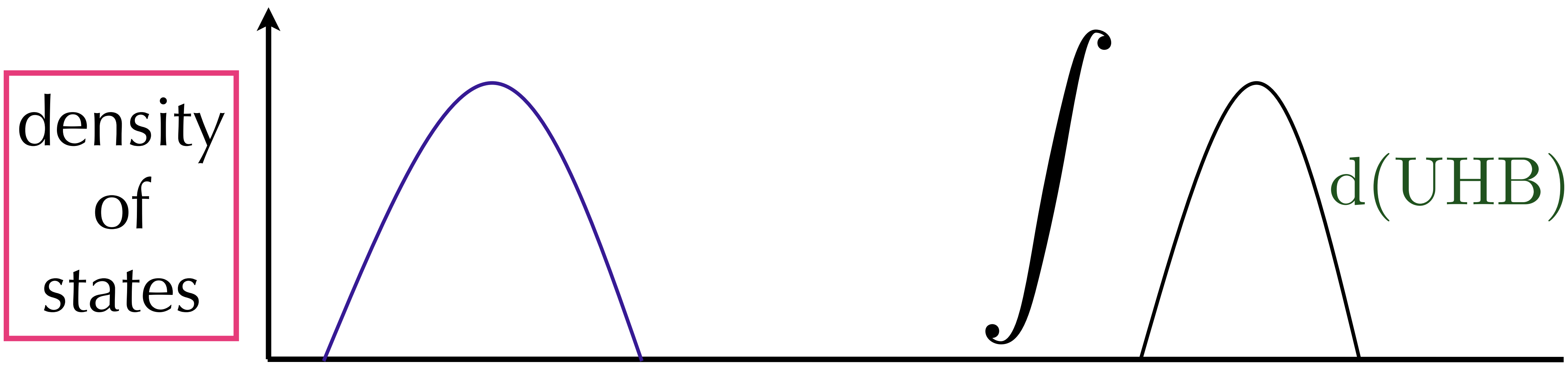
composite (bound) excitation

2e(boson)
+
hole



Hubbard bands are not rigid: Mottness

We now know what ? is



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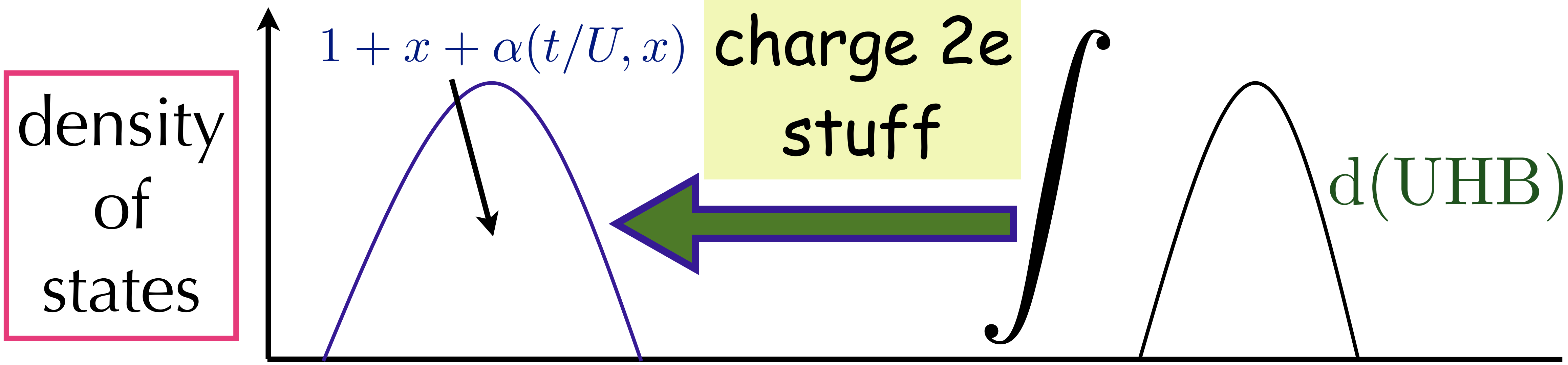

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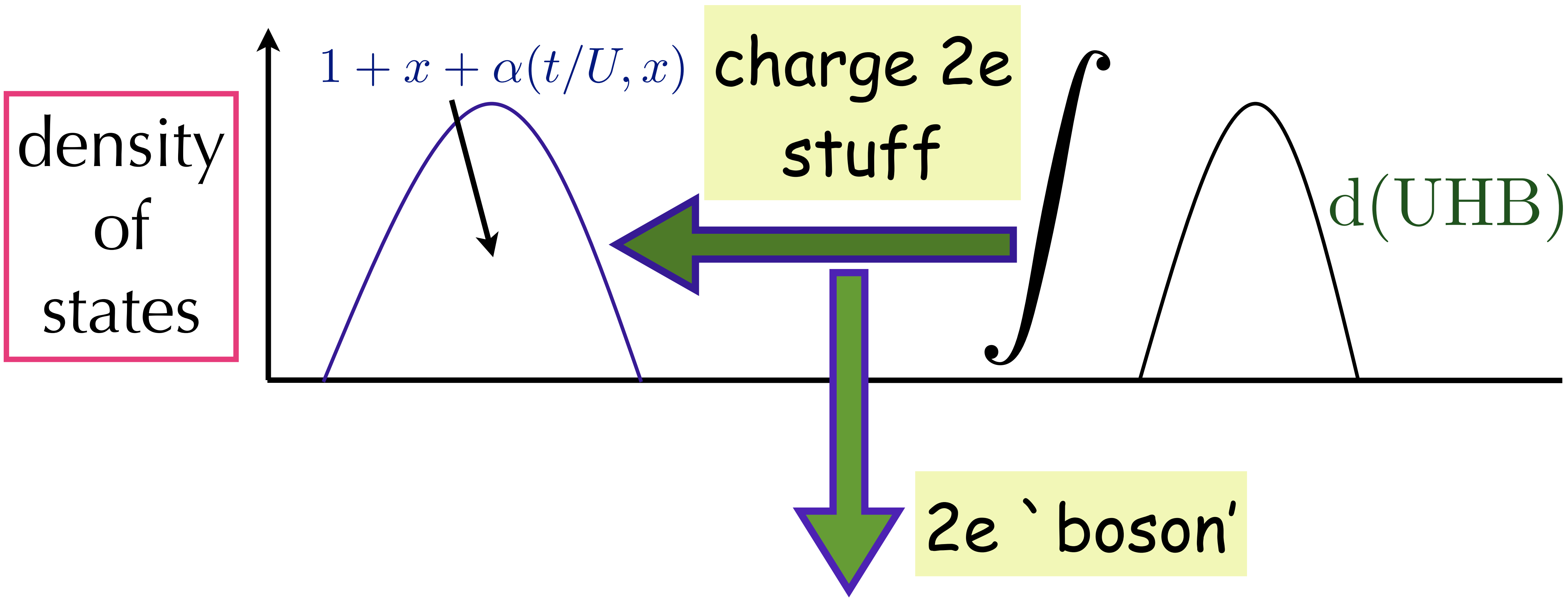
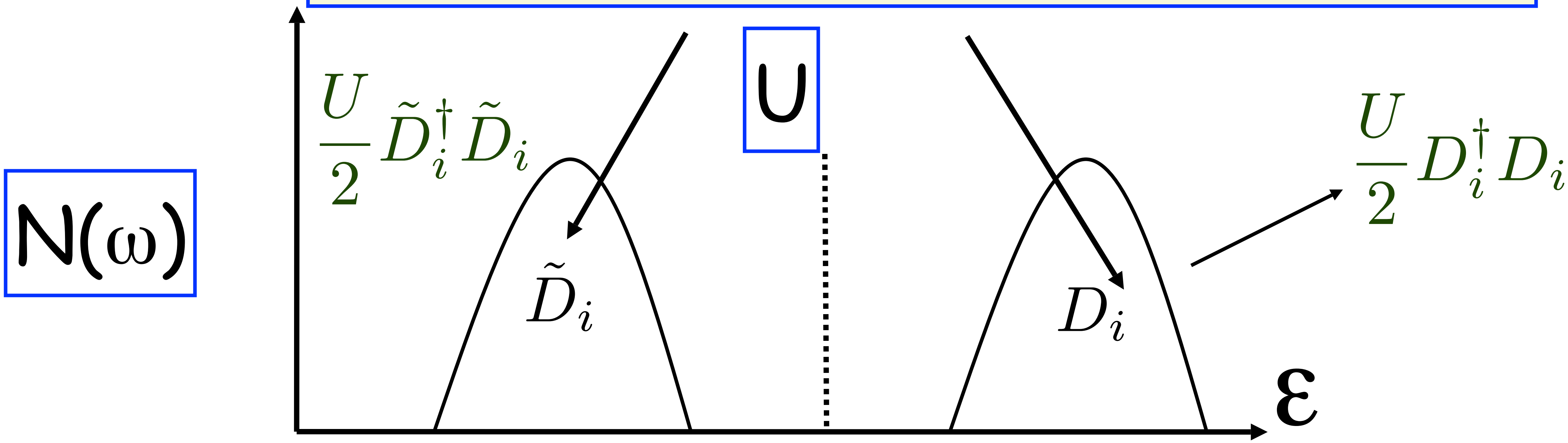
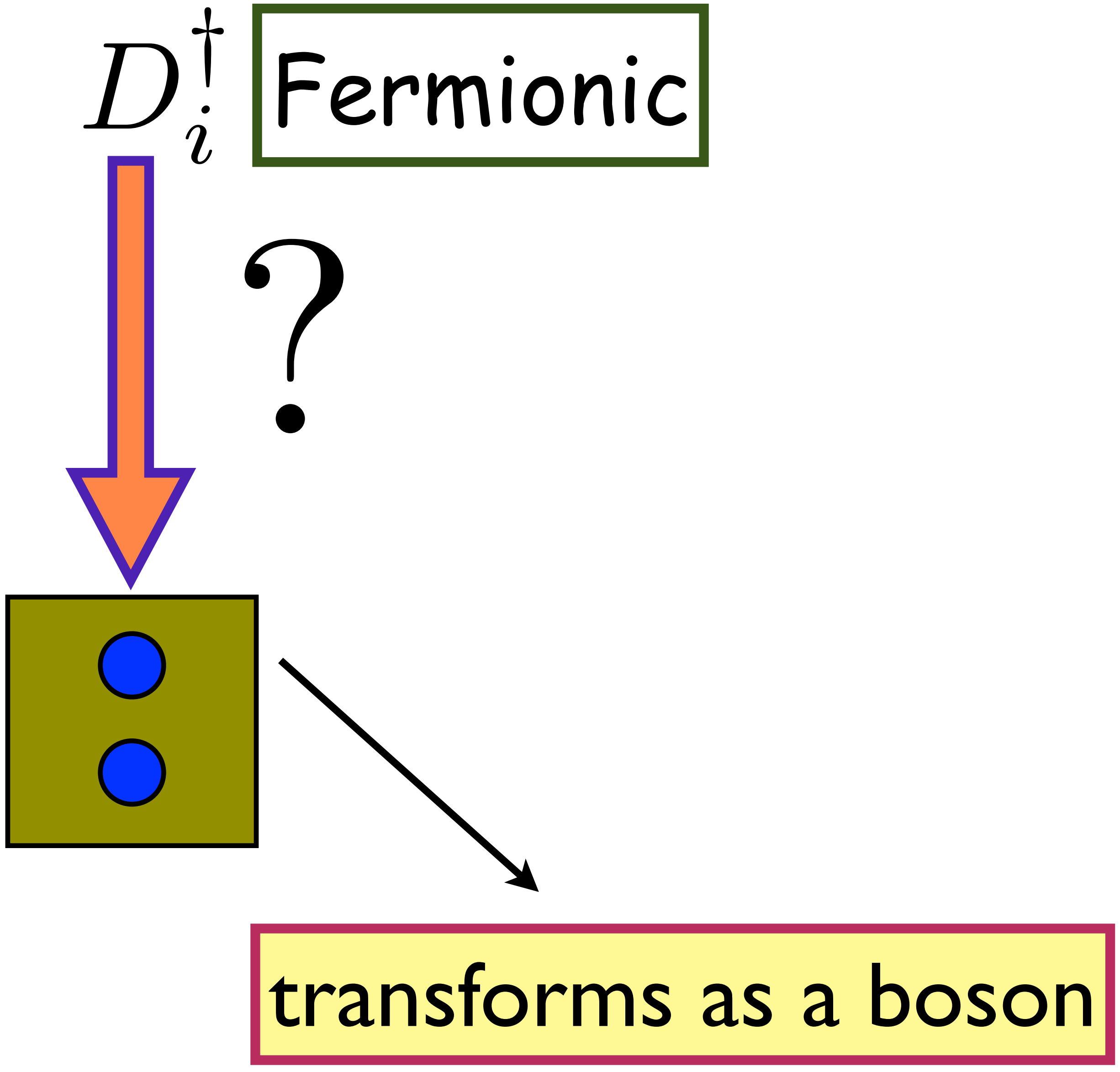


collective excitation from double occupancy:
incoherence at low energies

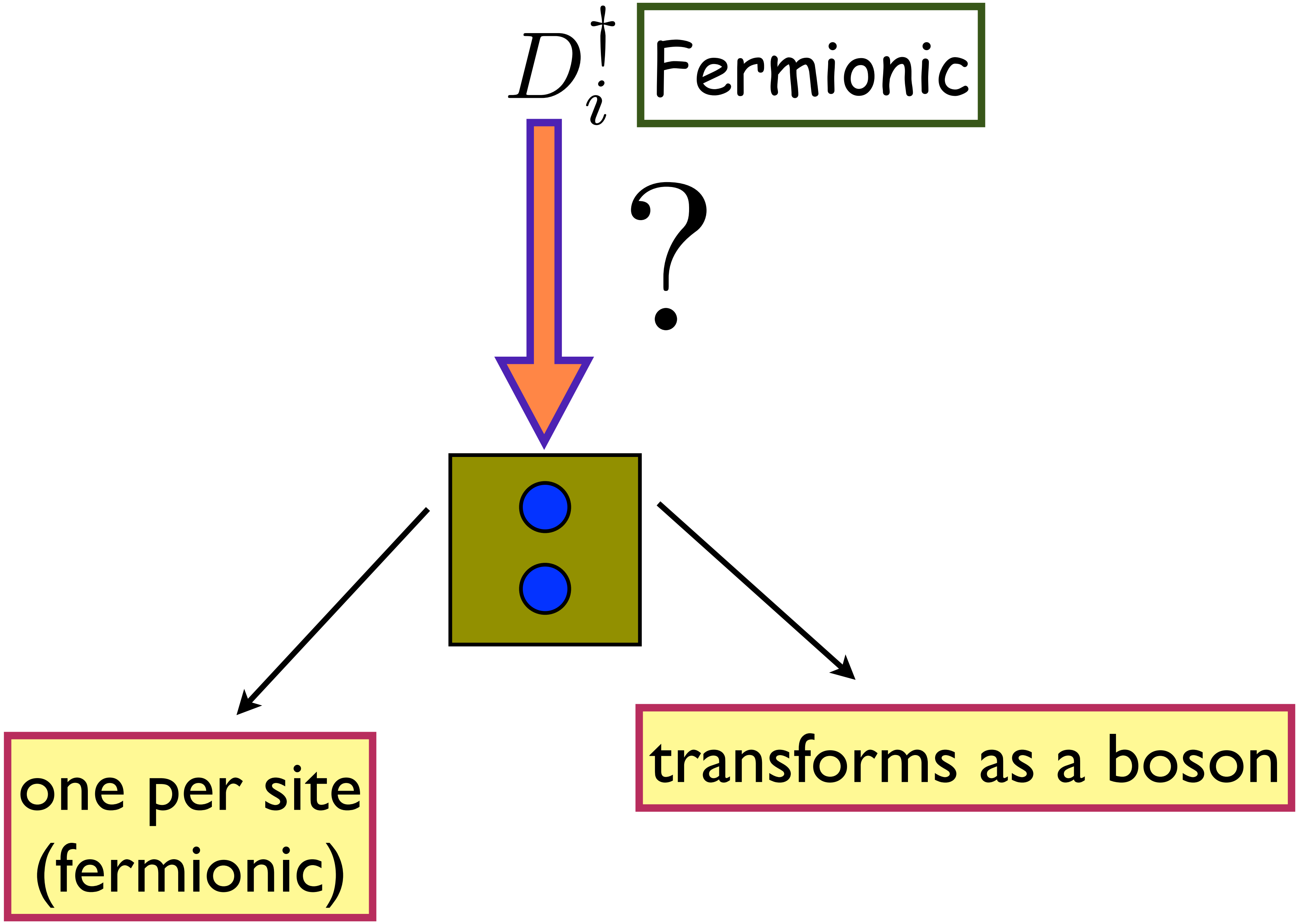
Key idea: similar to Bohm/Pines

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





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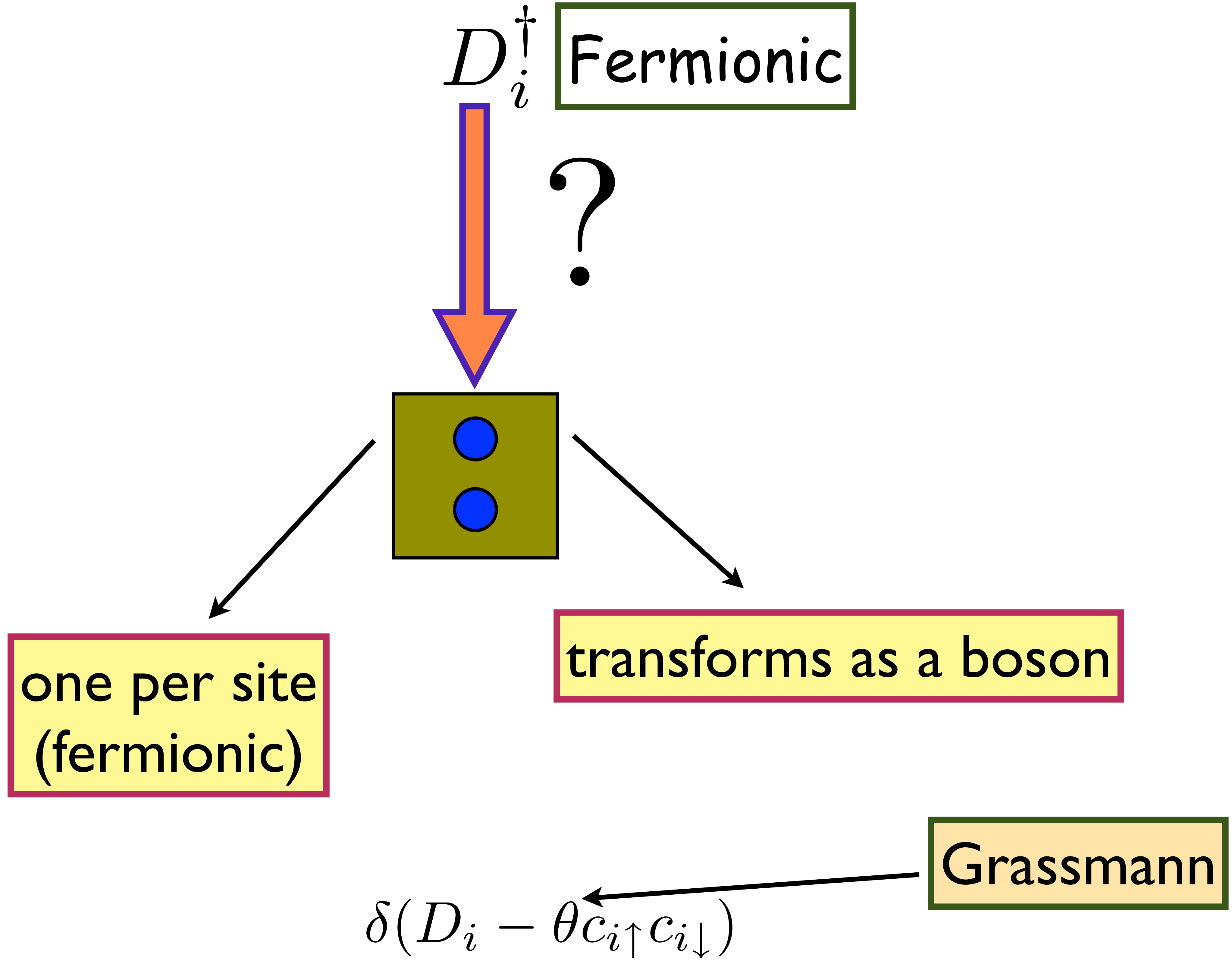
$D_i^\dagger$
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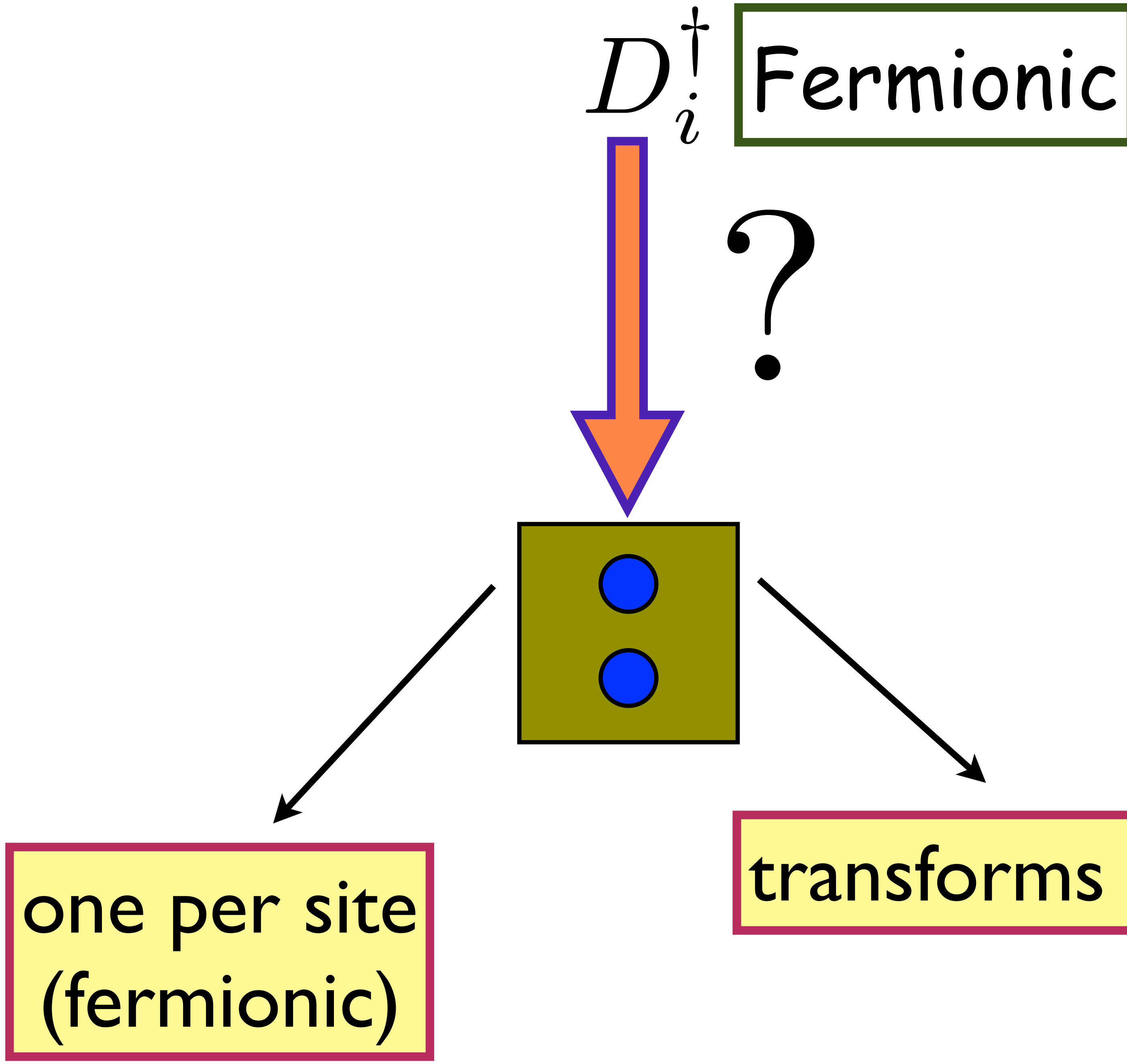
Grassmann
$\delta(D_i - \theta c_{i\uparrow} c_{i\downarrow})$



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

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

Exact low-energy Lagrangian

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

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

$$\downarrow \qquad\qquad \downarrow$$

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

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

Exact low-energy Lagrangian

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

$f(\omega)=0$ → dispersion of propagating light modes

$L_{\rm int}(c,\varphi)$ → $\Psi^\dagger\Psi$

$L_{\rm int}(c,\tilde{\varphi})$ → $\tilde{\Psi}^\dagger\tilde{\Psi}$

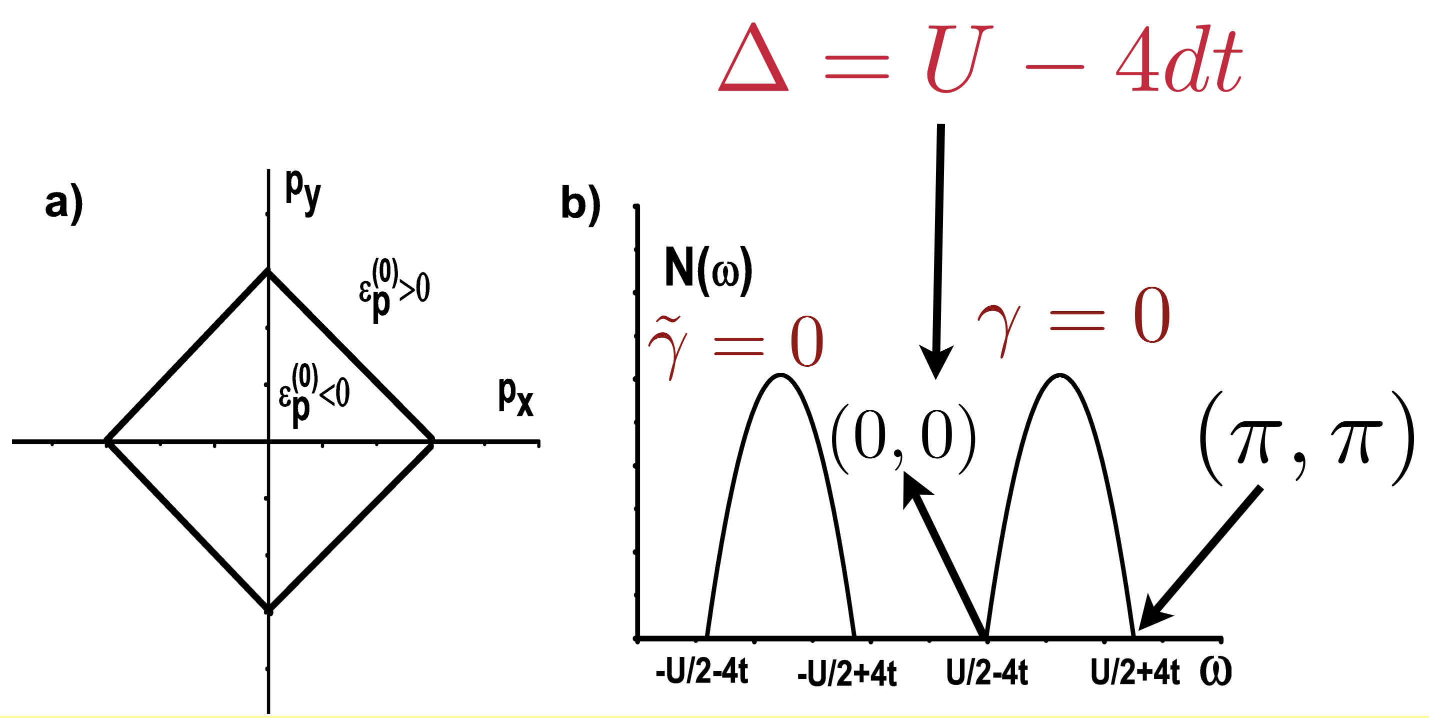
quadratic form: composite or bound excitations of

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

composite excitations determine spectral density: Mott gap

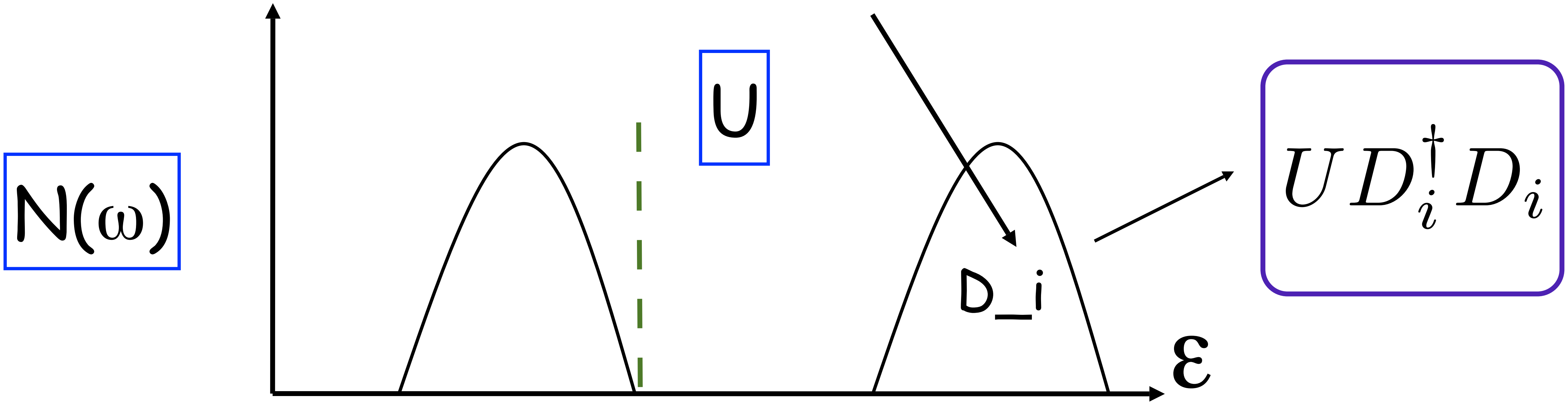
$$\gamma_{\vec{p}}^{(\vec{k})}(\omega) = \frac{U - t\varepsilon_{\vec{p}}^{(\vec{k})} - 2\omega}{U}\sqrt{1 + 2\omega/U}$$

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



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

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

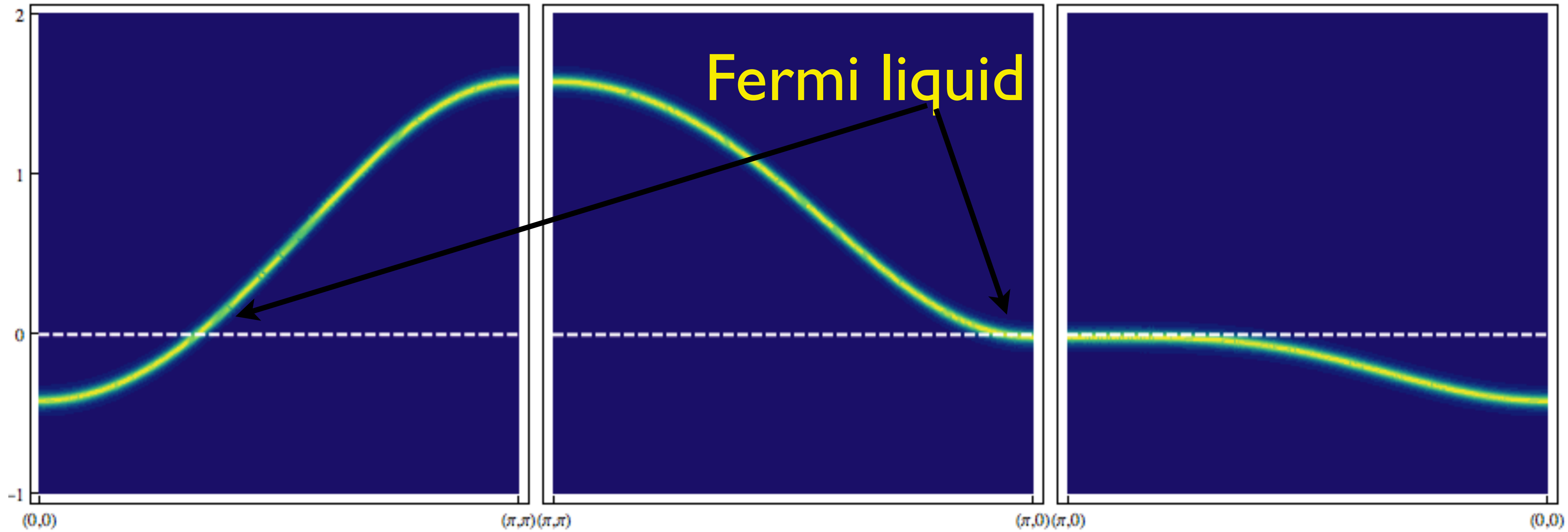


$$\mathcal{L}_{\mathrm{IR}} = L_{\mathrm{spinstuff}}(c_i, c_i^\dagger) + \boxed{L_{\mathrm{charge}}(c_i, c_i^\dagger, \varphi_i)}$$

↓ quadratic

spectral function

Electron Dispersion



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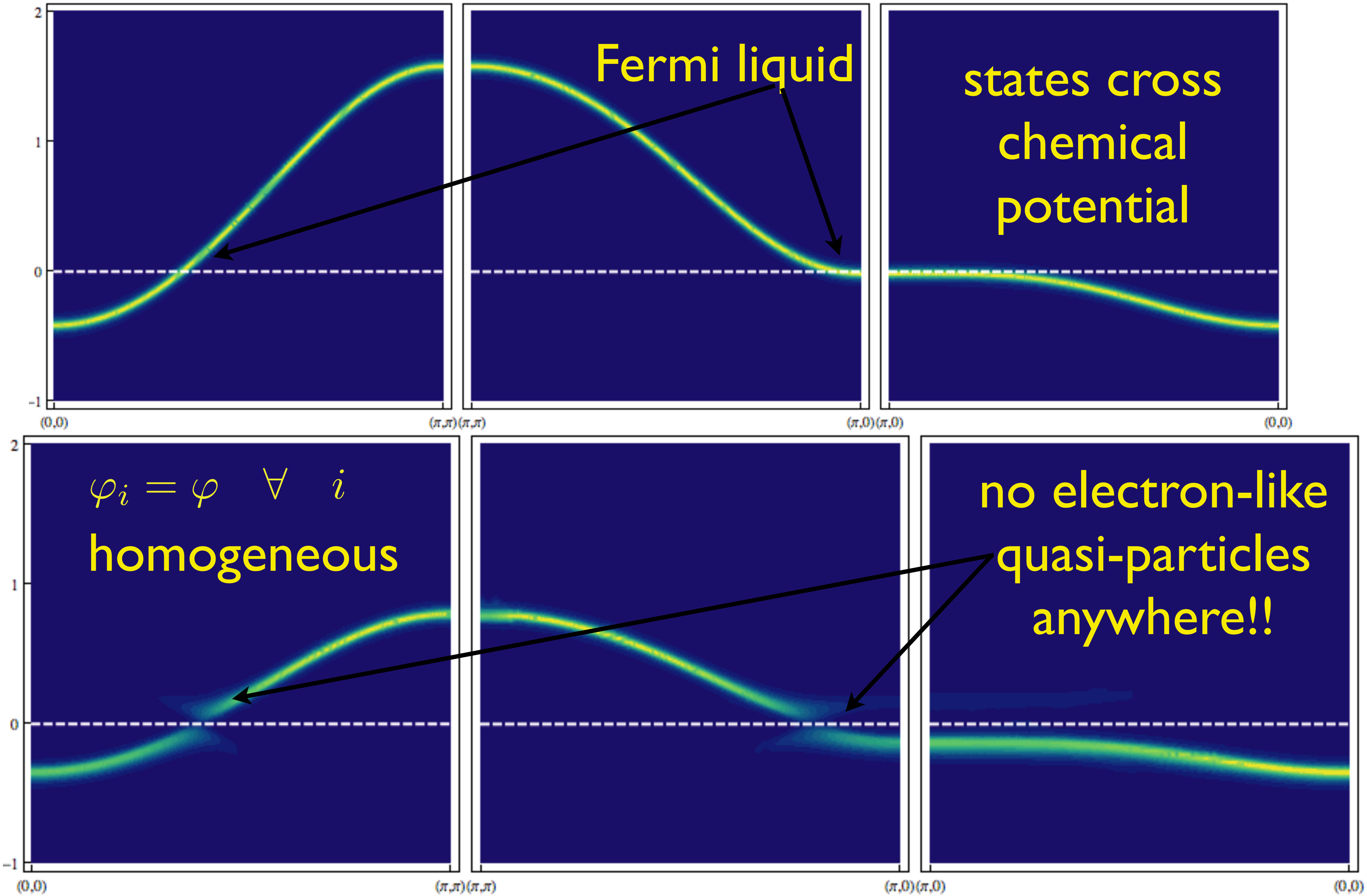

What is seen experimentally?
Are there 0-energy excitations?

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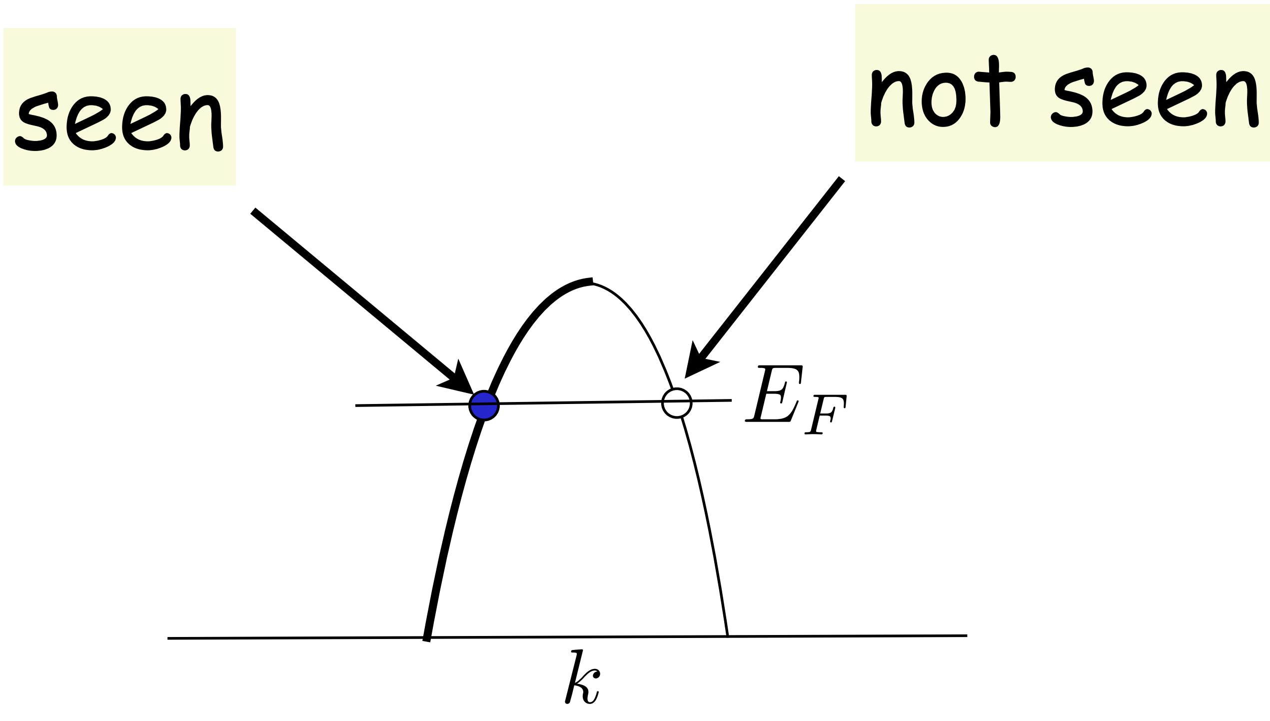

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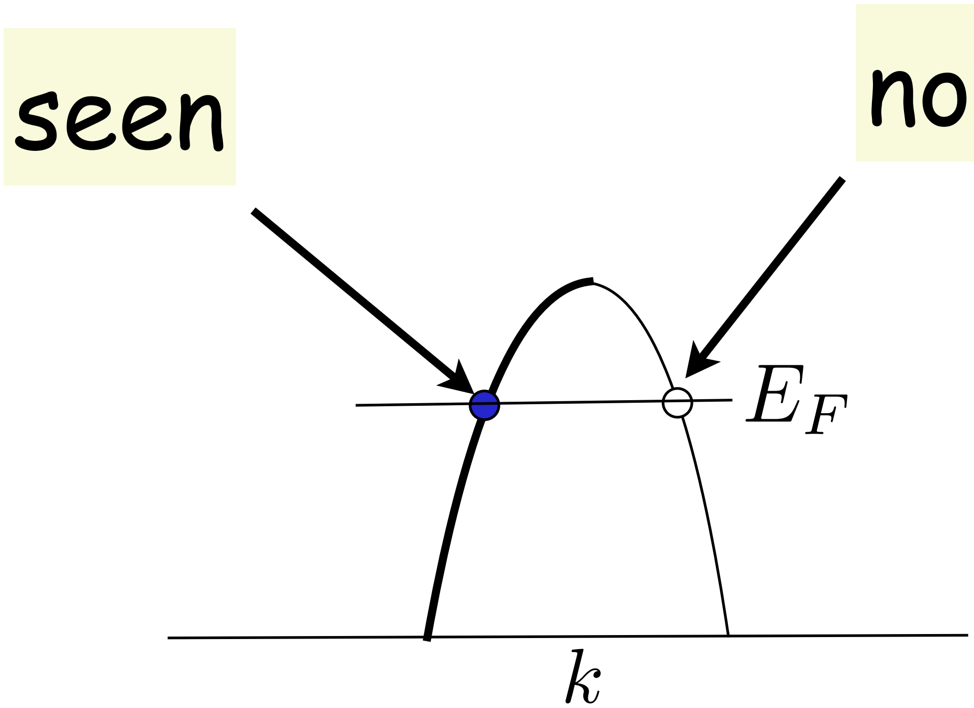

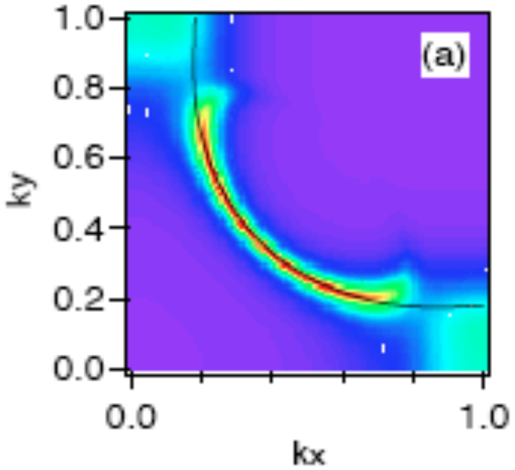

Fermi arcs: no double crossings (PDJ,JCC,ZXS)

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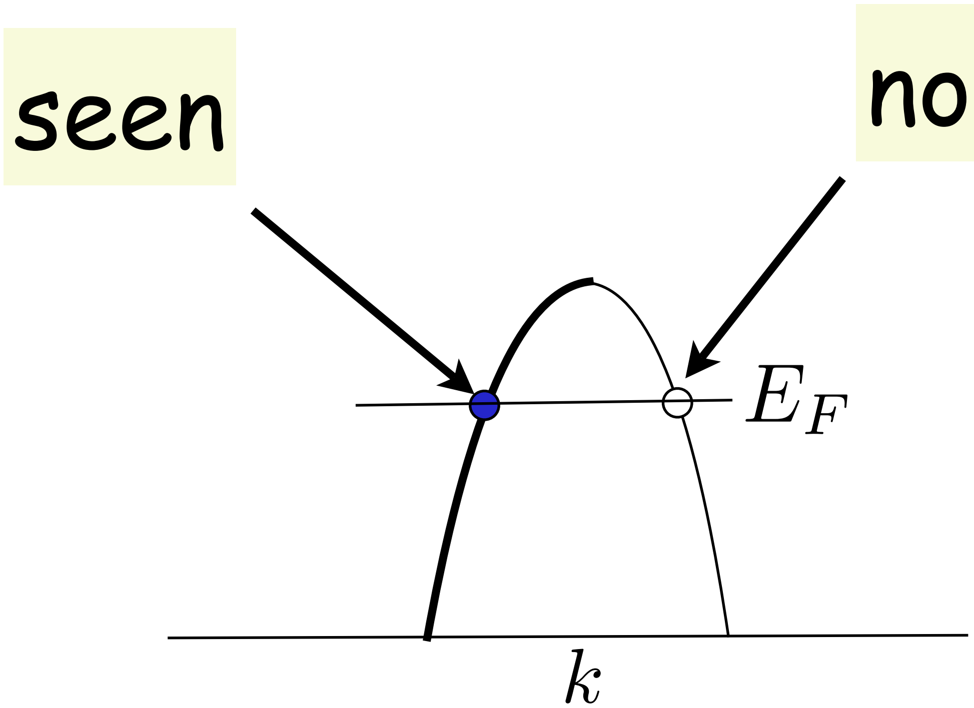

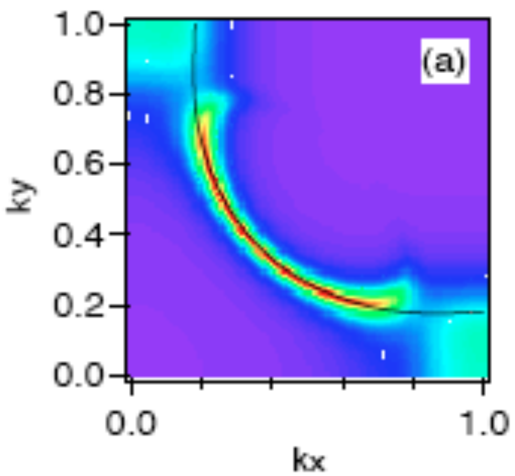

meaning?

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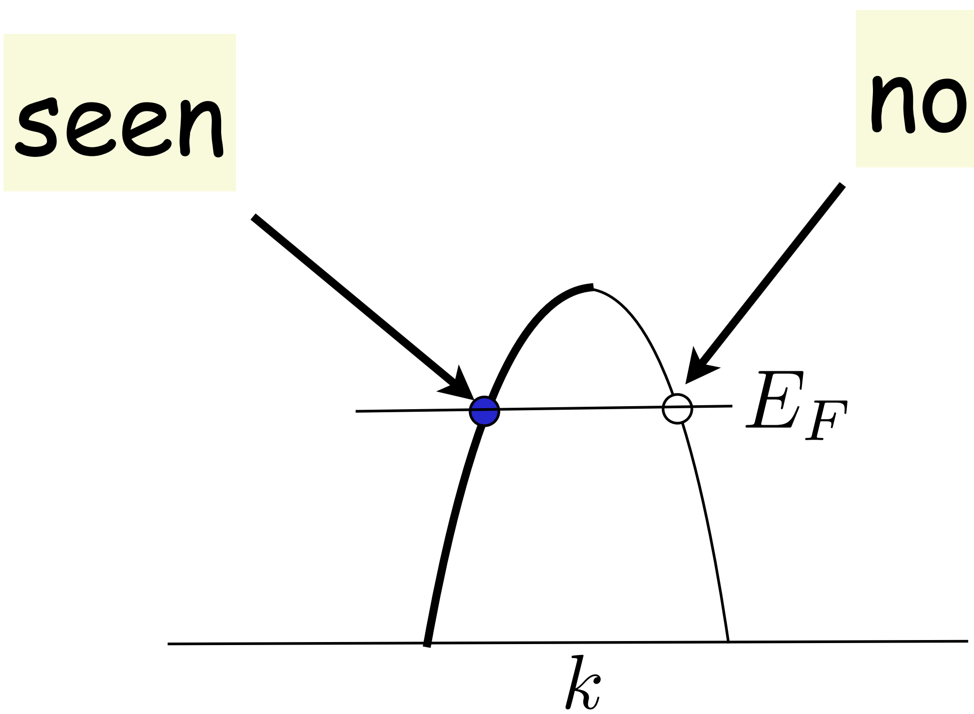

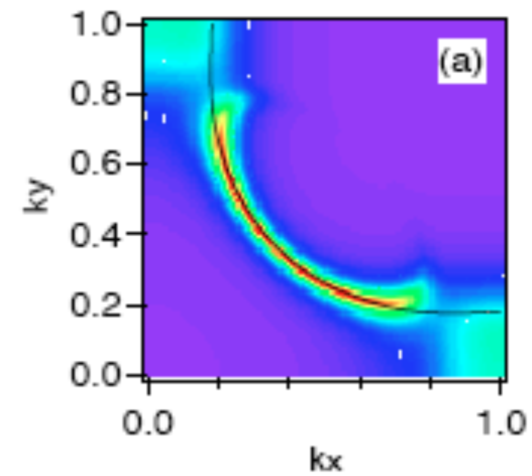

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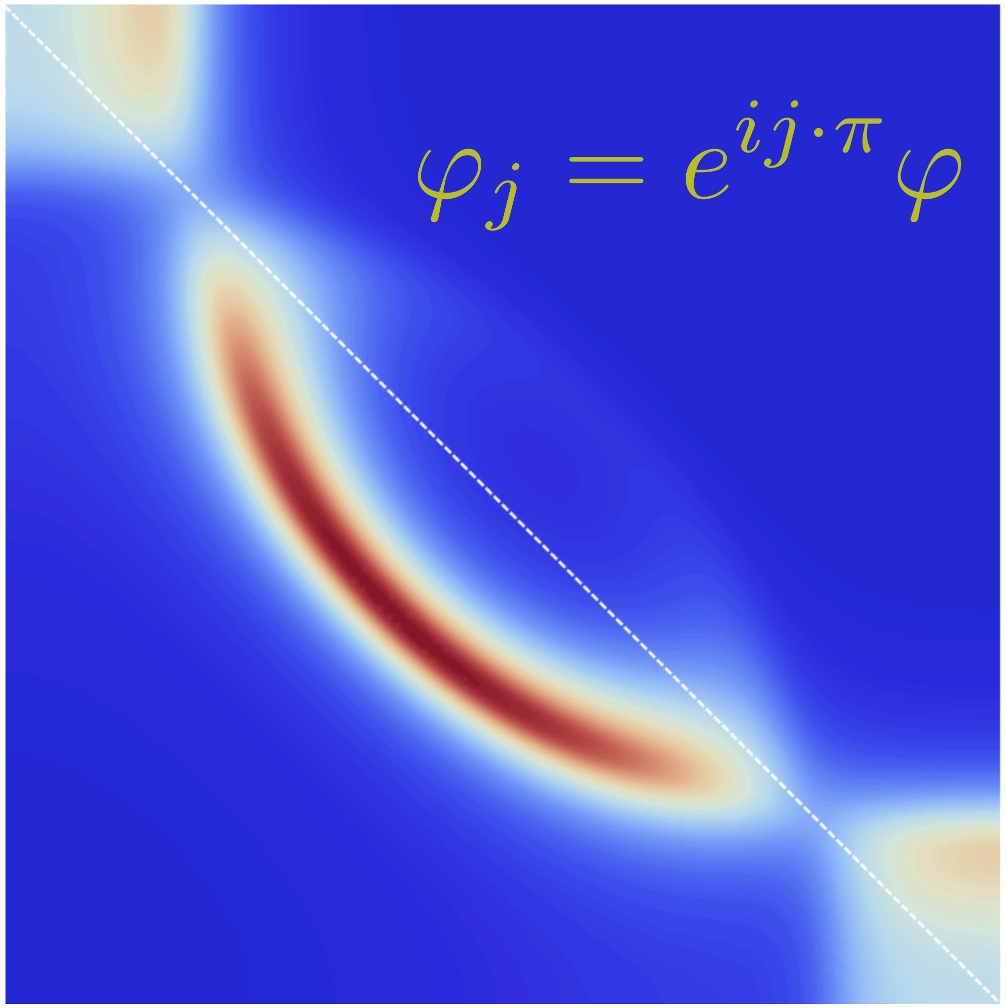
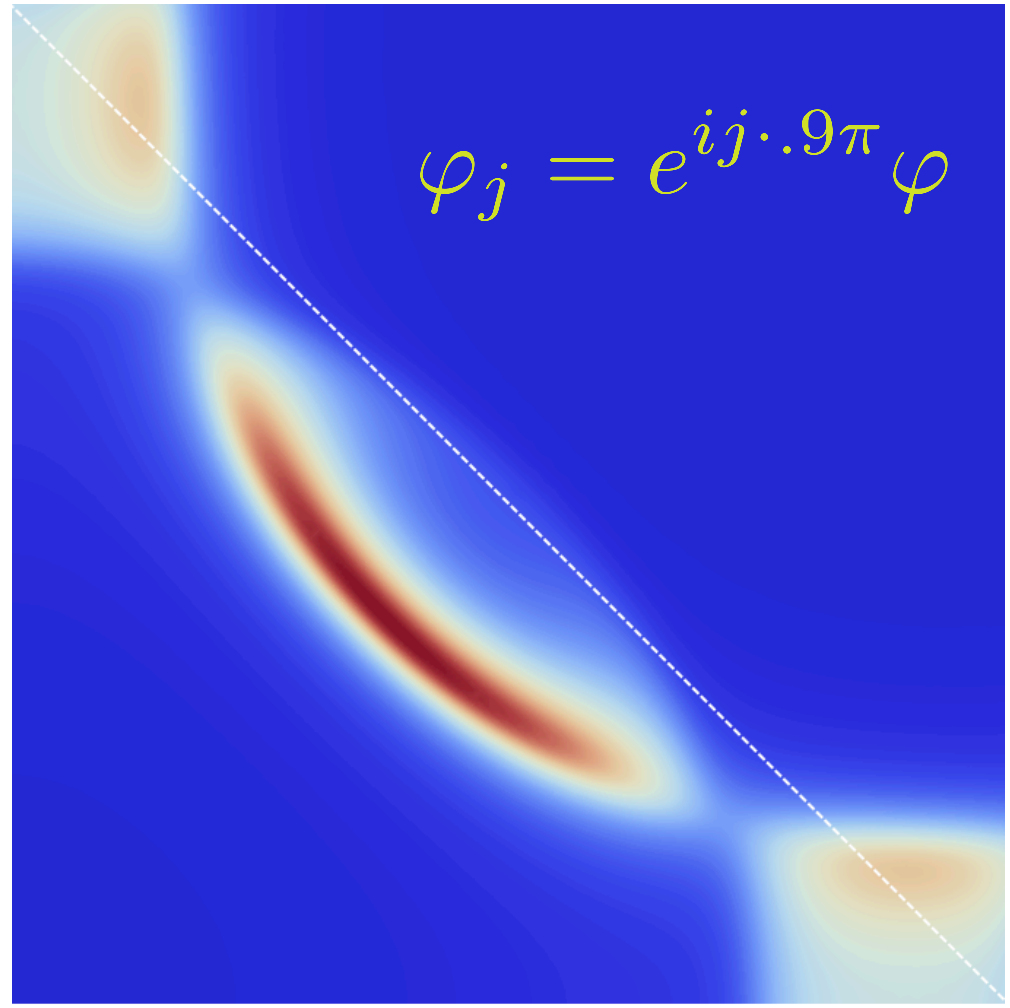
meaning?

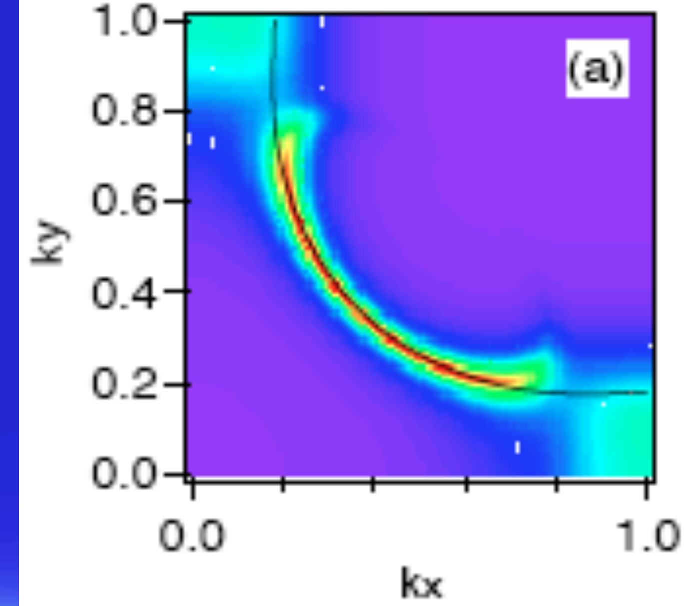
can we explain this?

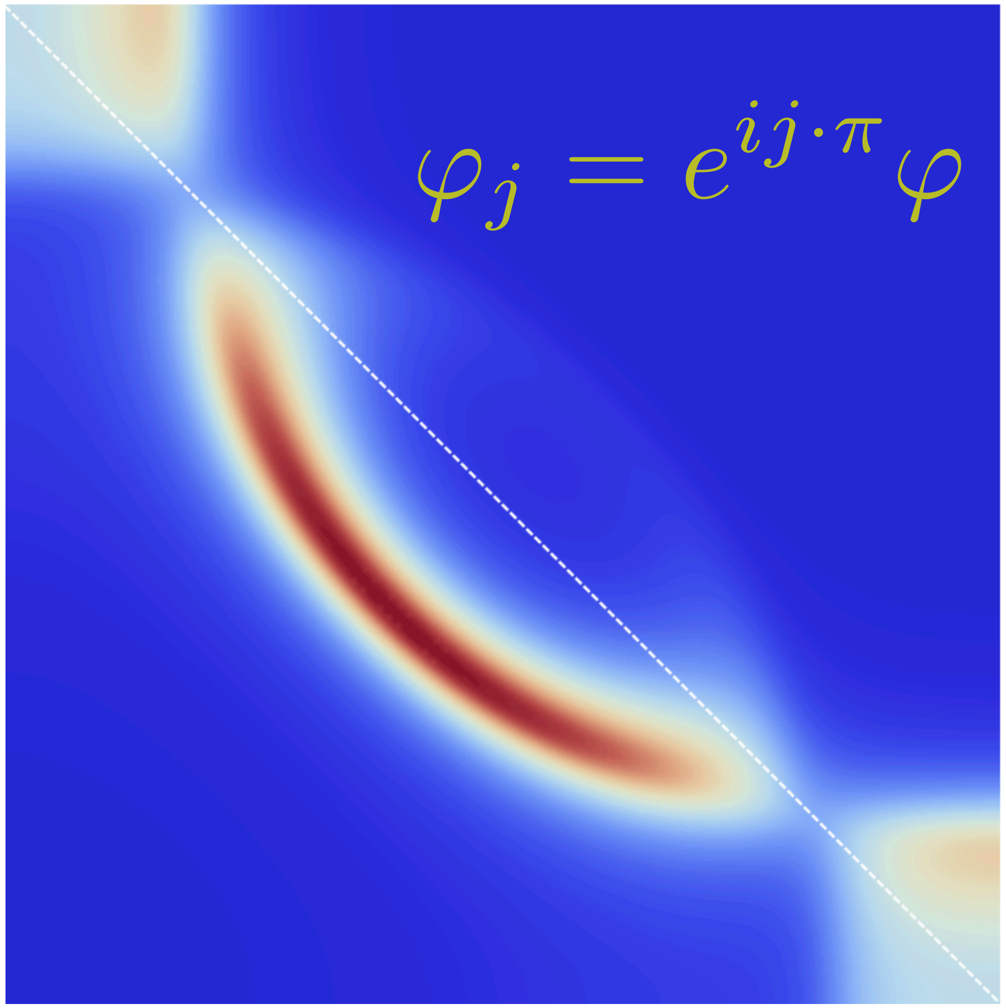
yes

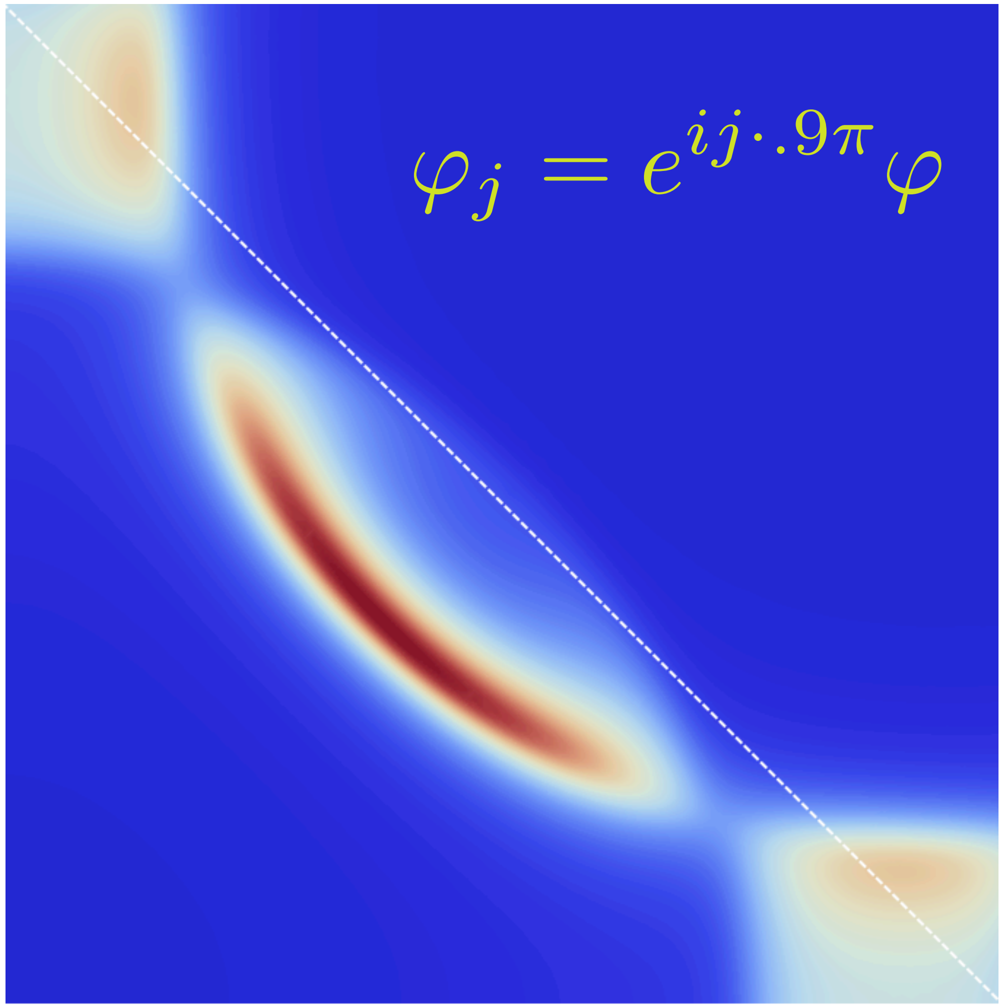

$\varphi_j = e^{ij\cdot\pi}\varphi$


$\varphi_j = e^{ij\cdot .9\pi}\varphi$

Expt.


(a)
ky
kx
0.0
0.2
0.4
0.6
0.8
1.0
0.0
1.0





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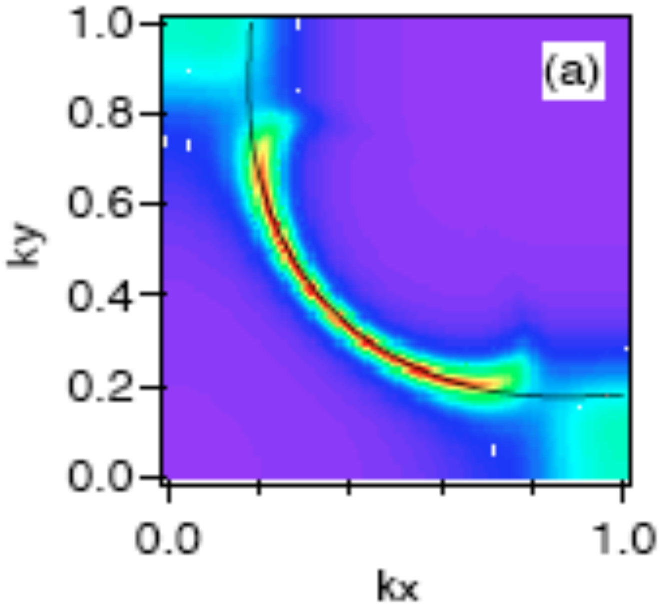
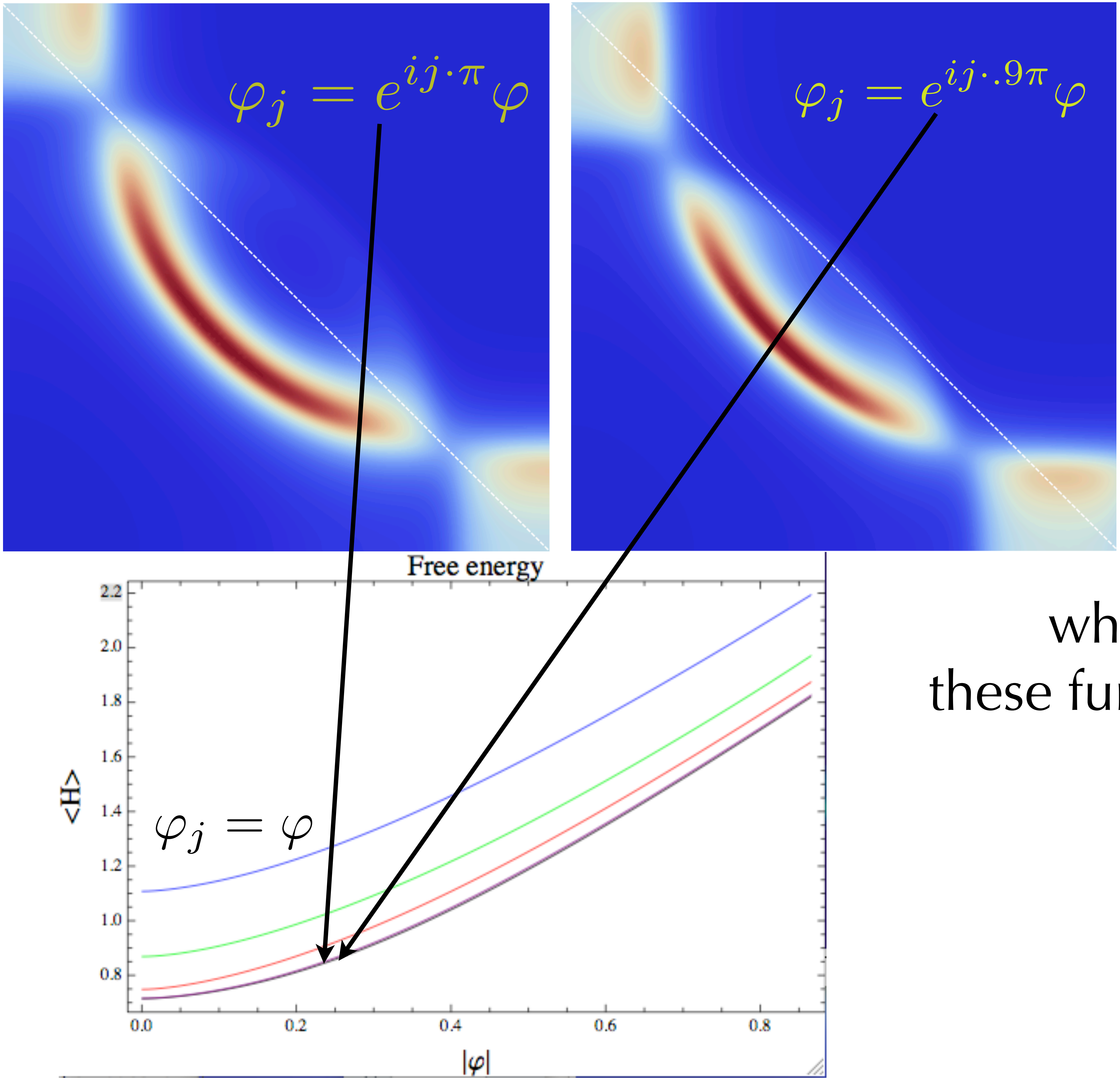


why choose
these funky solutions?



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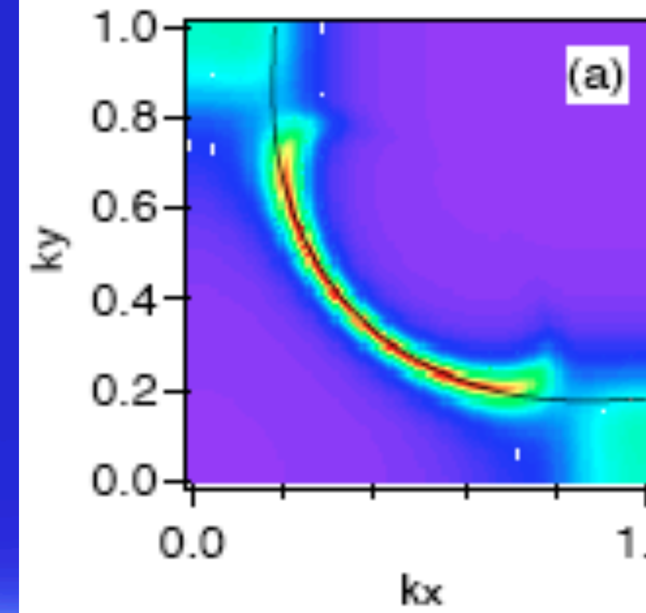

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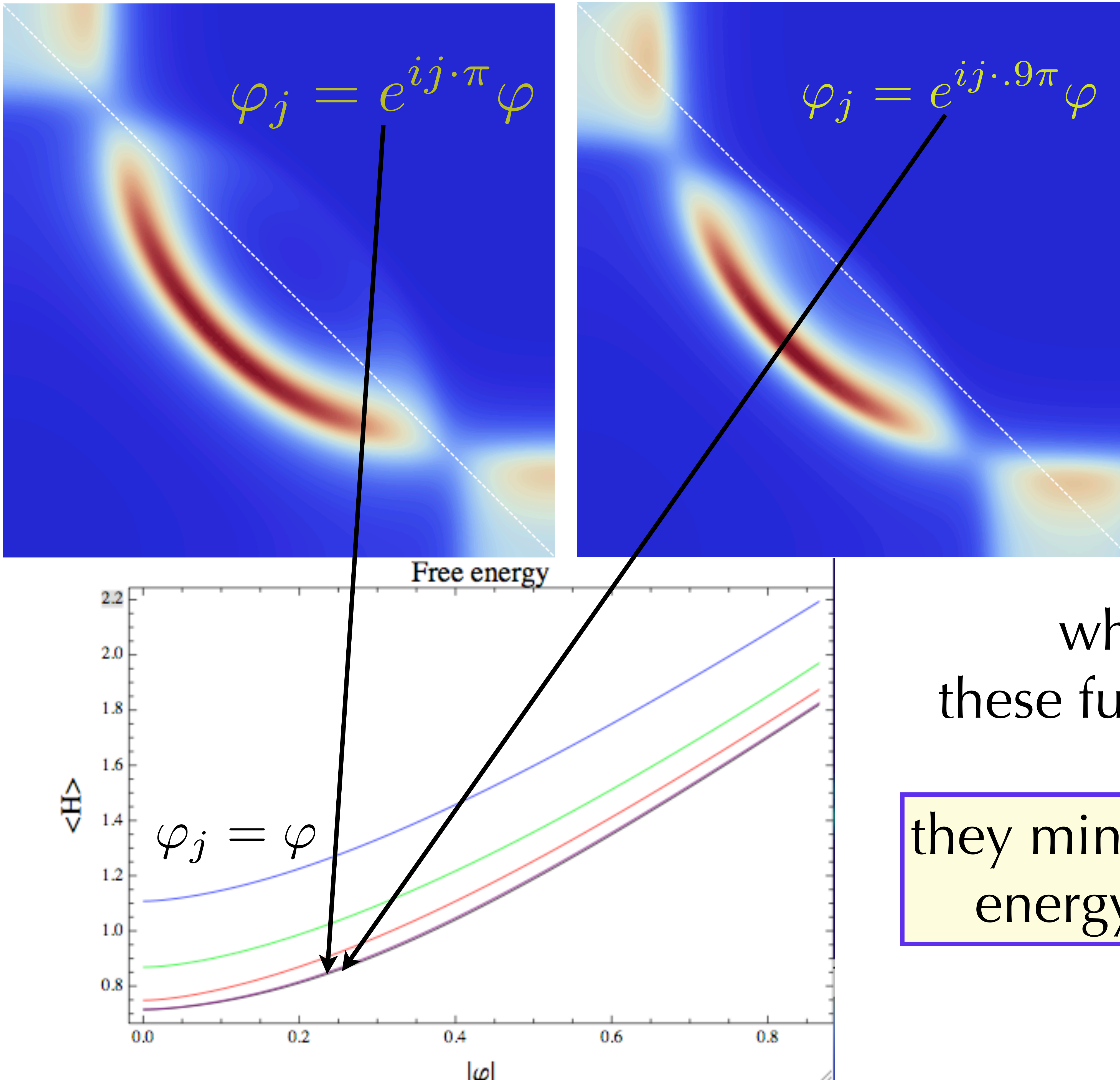

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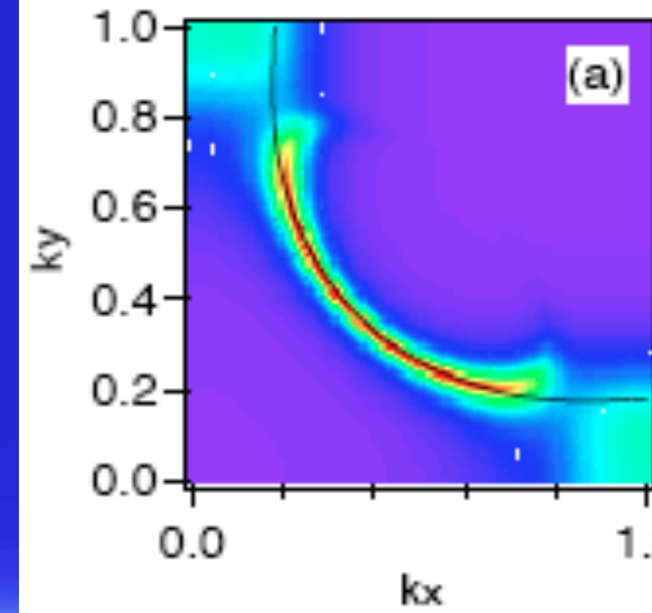

why choose
these funky solutions?

they minimize the free energy (no order)

what causes the ghost states?

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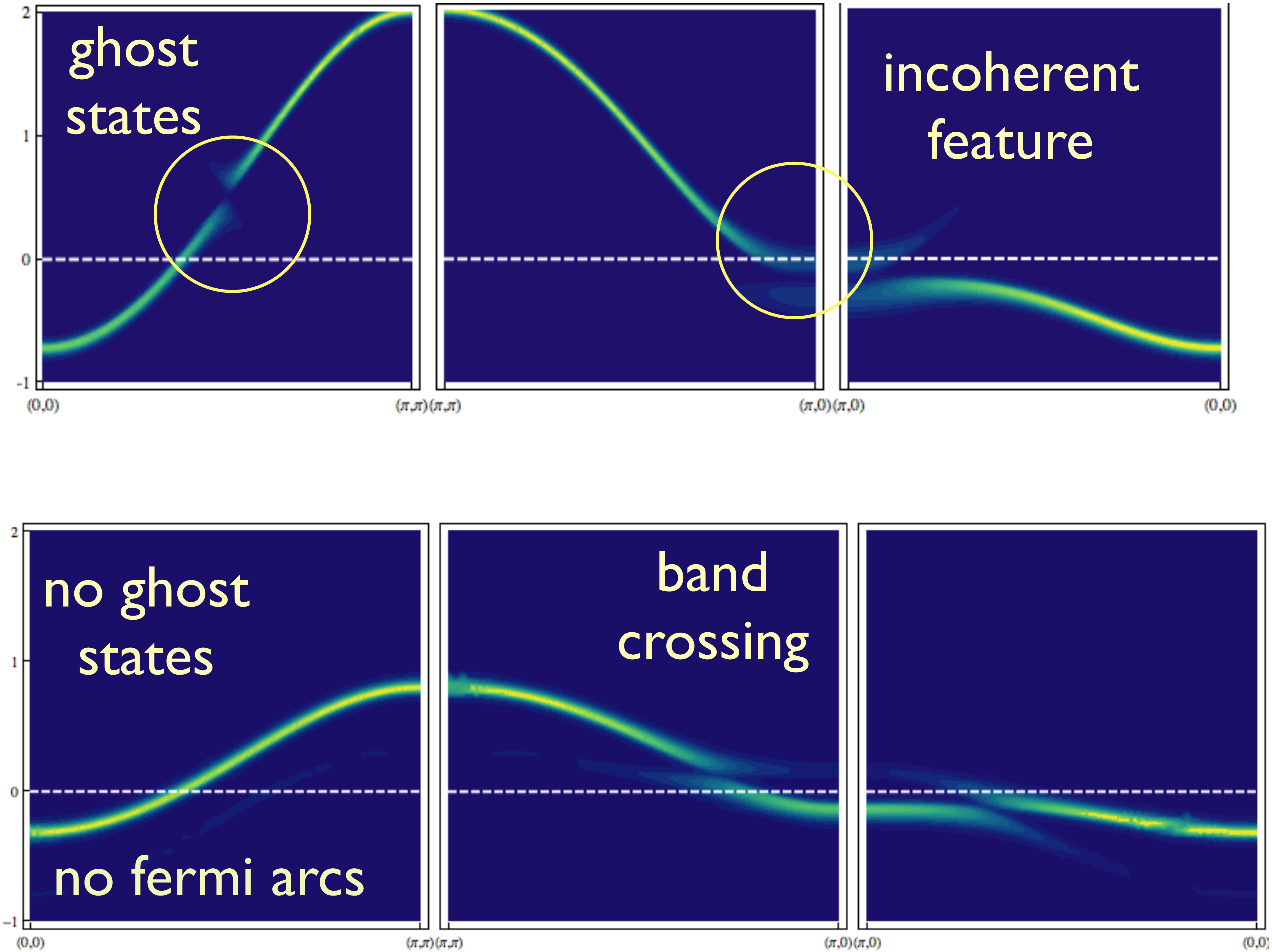

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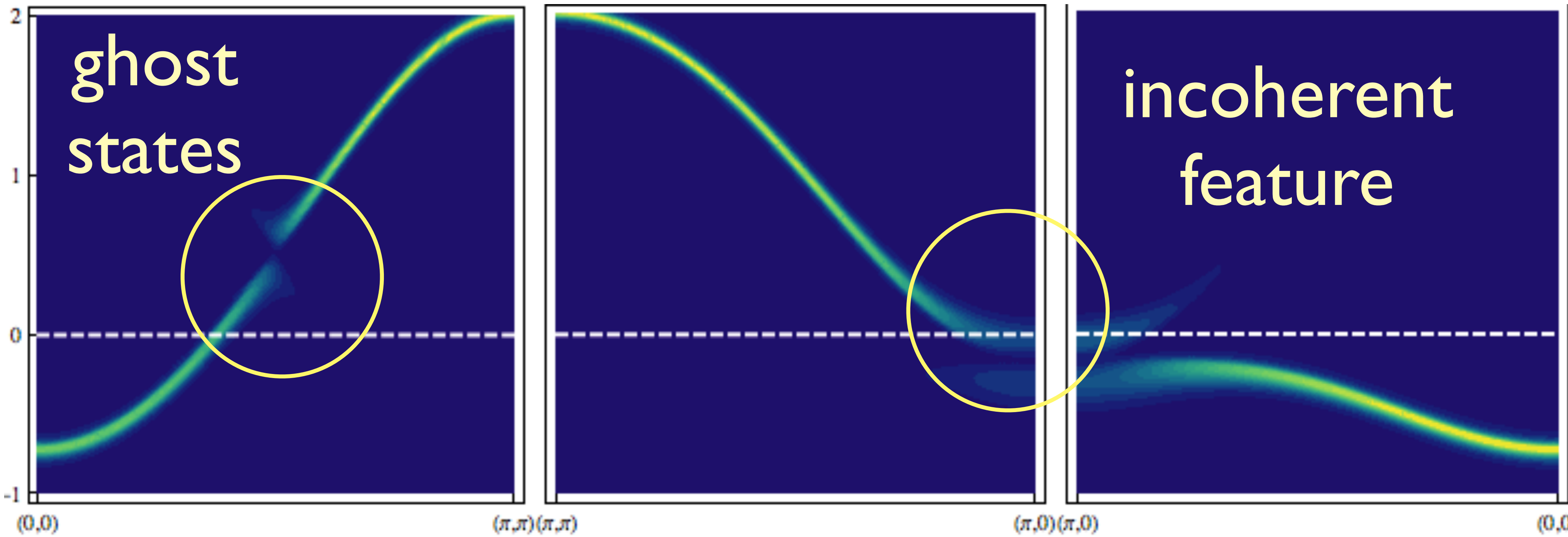
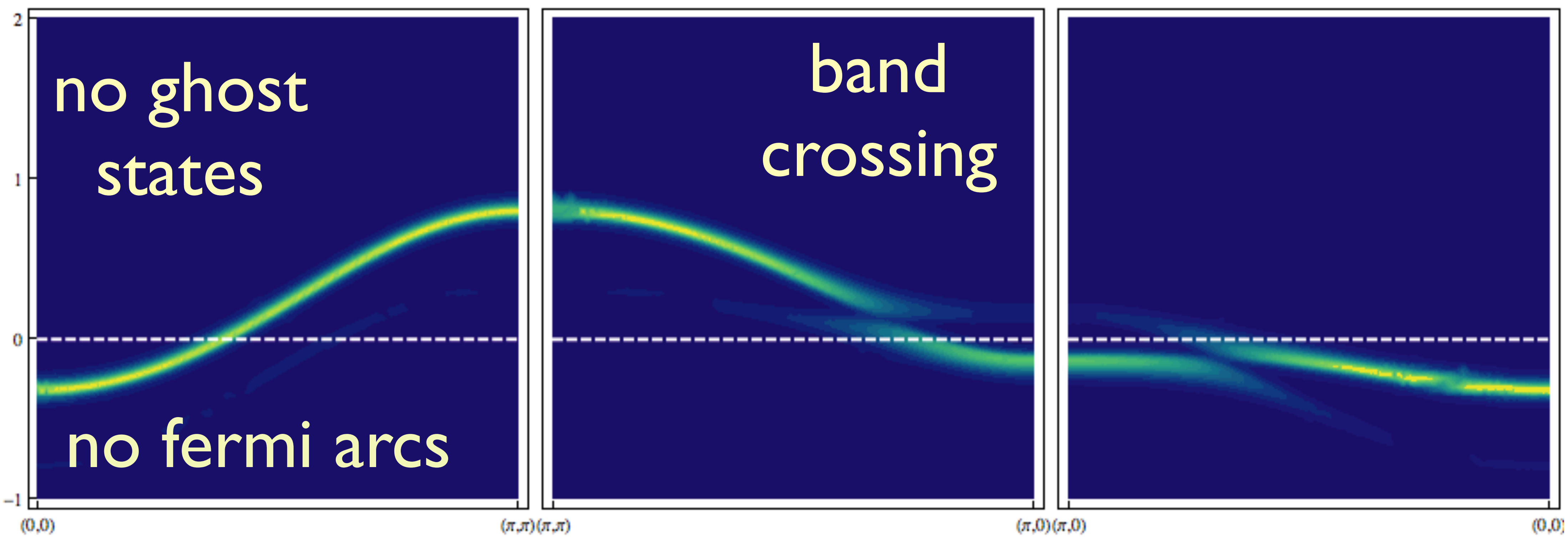
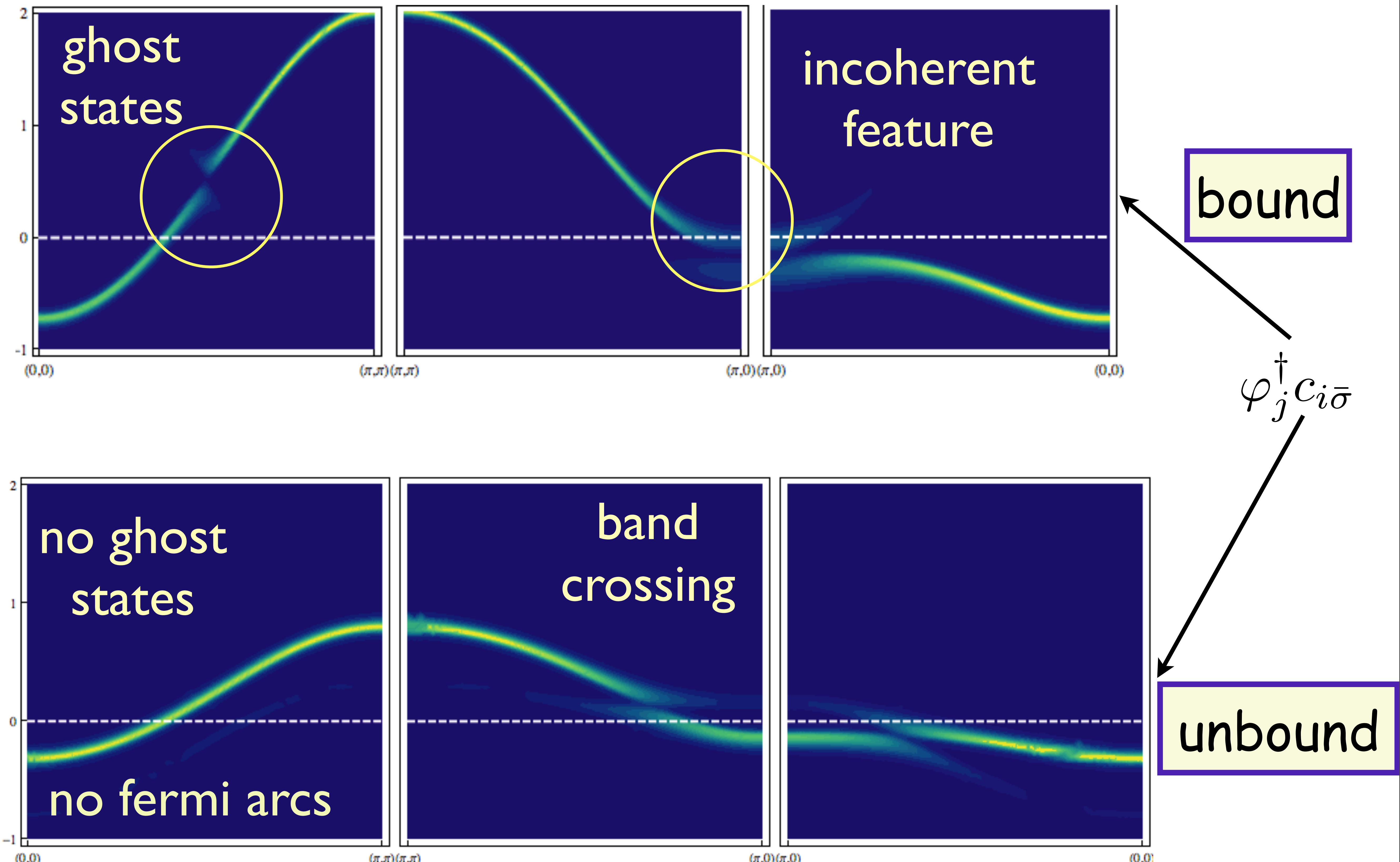


bound

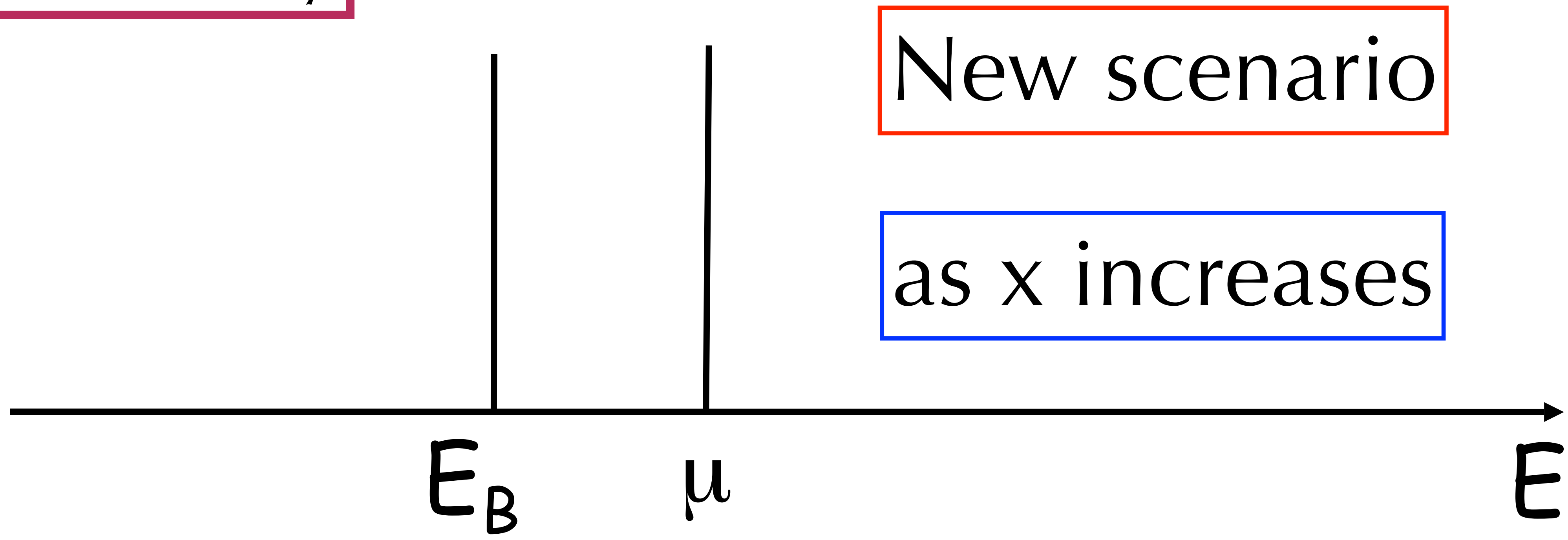
$\varphi_j^\dagger c_{i\bar{\sigma}}$



what causes the ghost states?



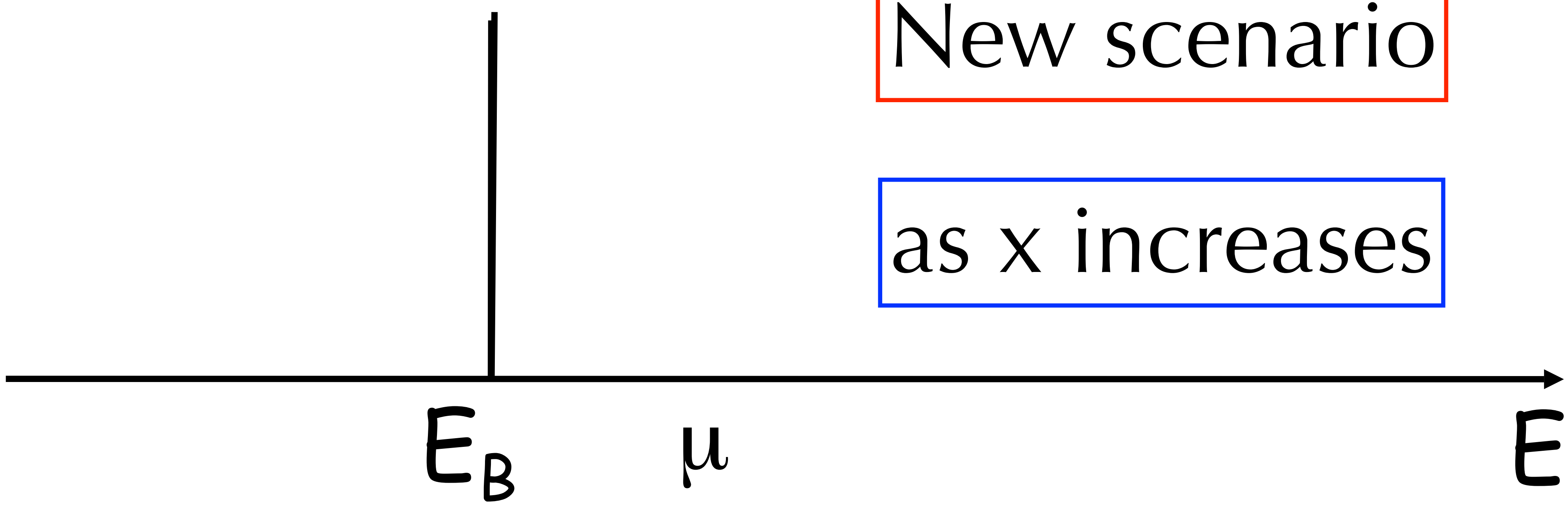
T-linear resistivity



T-linear resistivity

New scenario

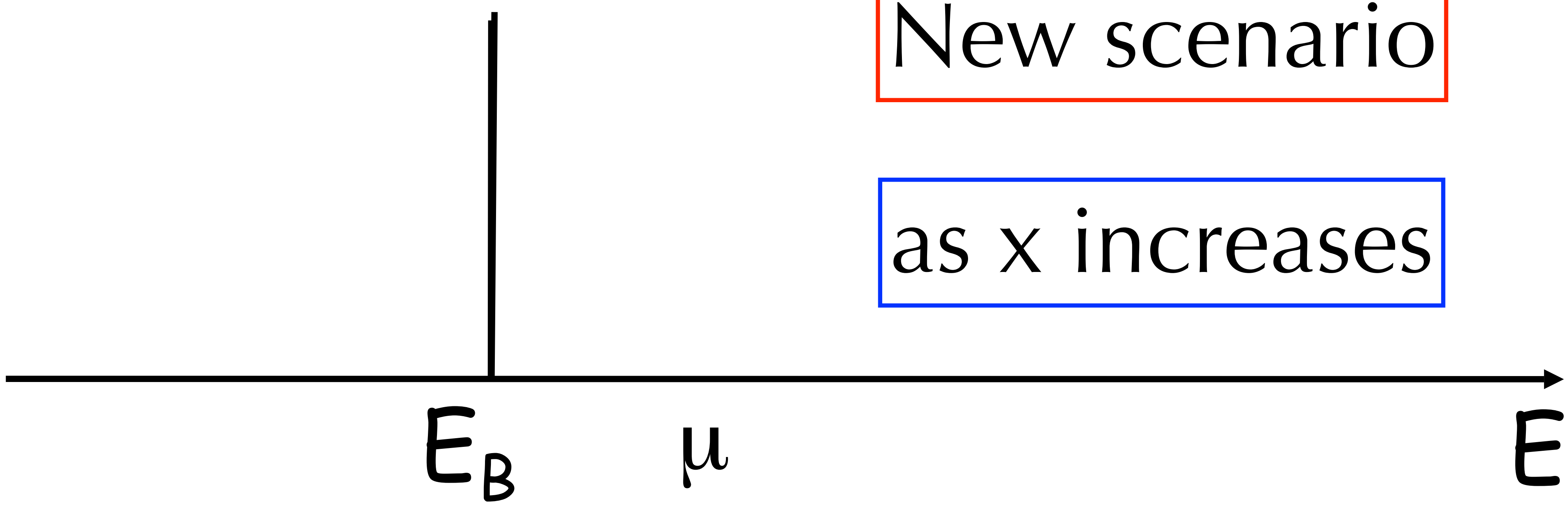
as x increases

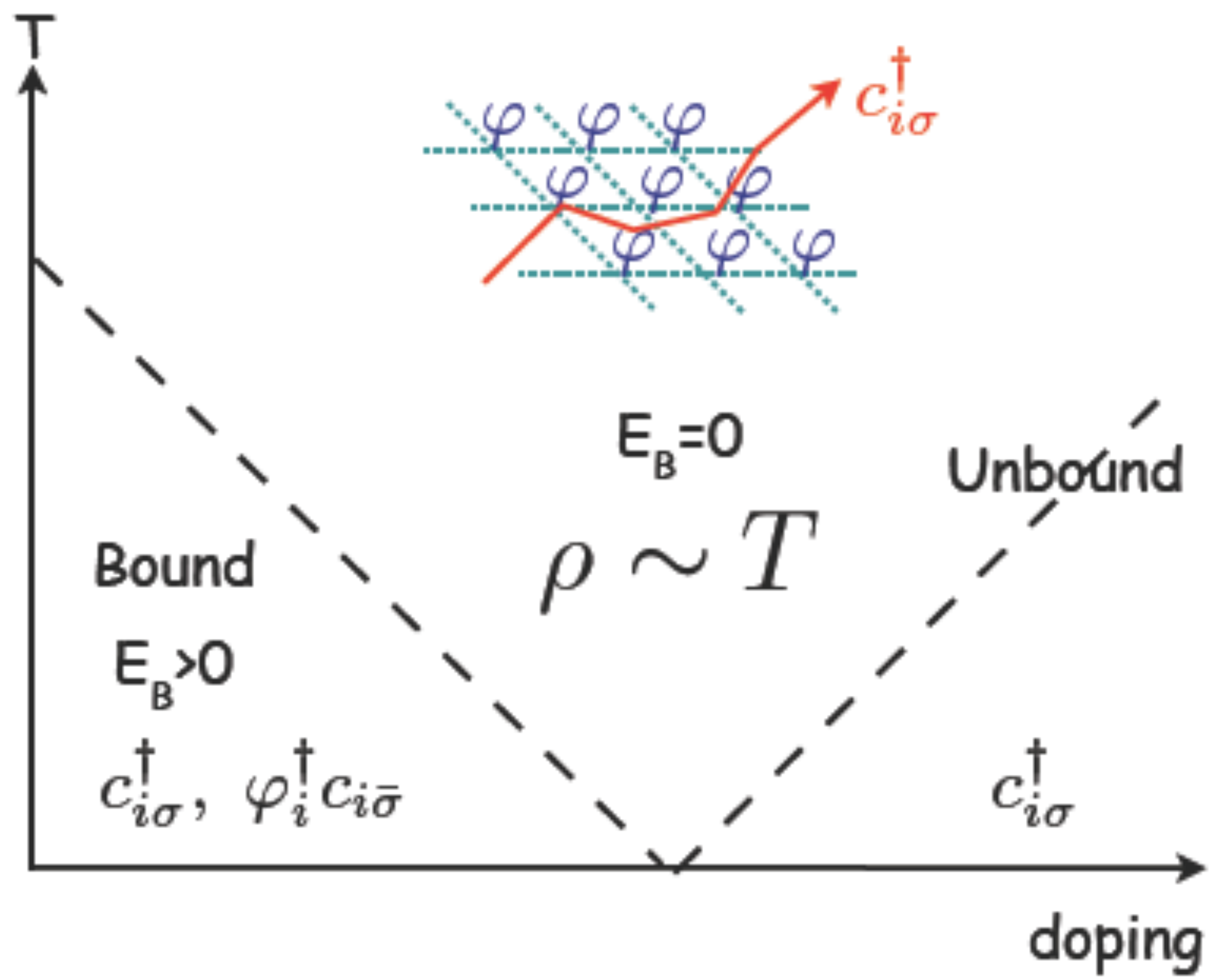


T-linear resistivity

New scenario

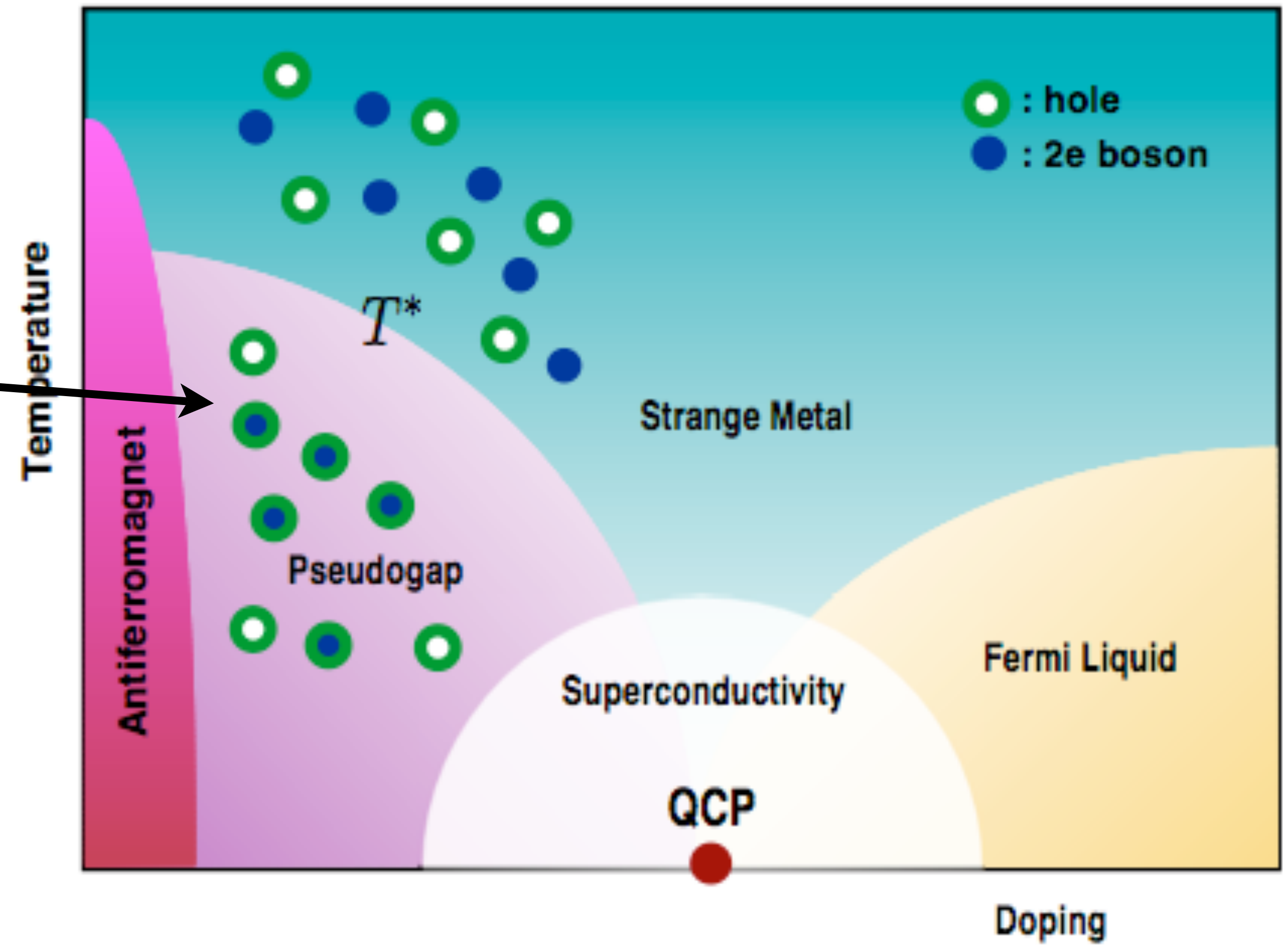
as x increases





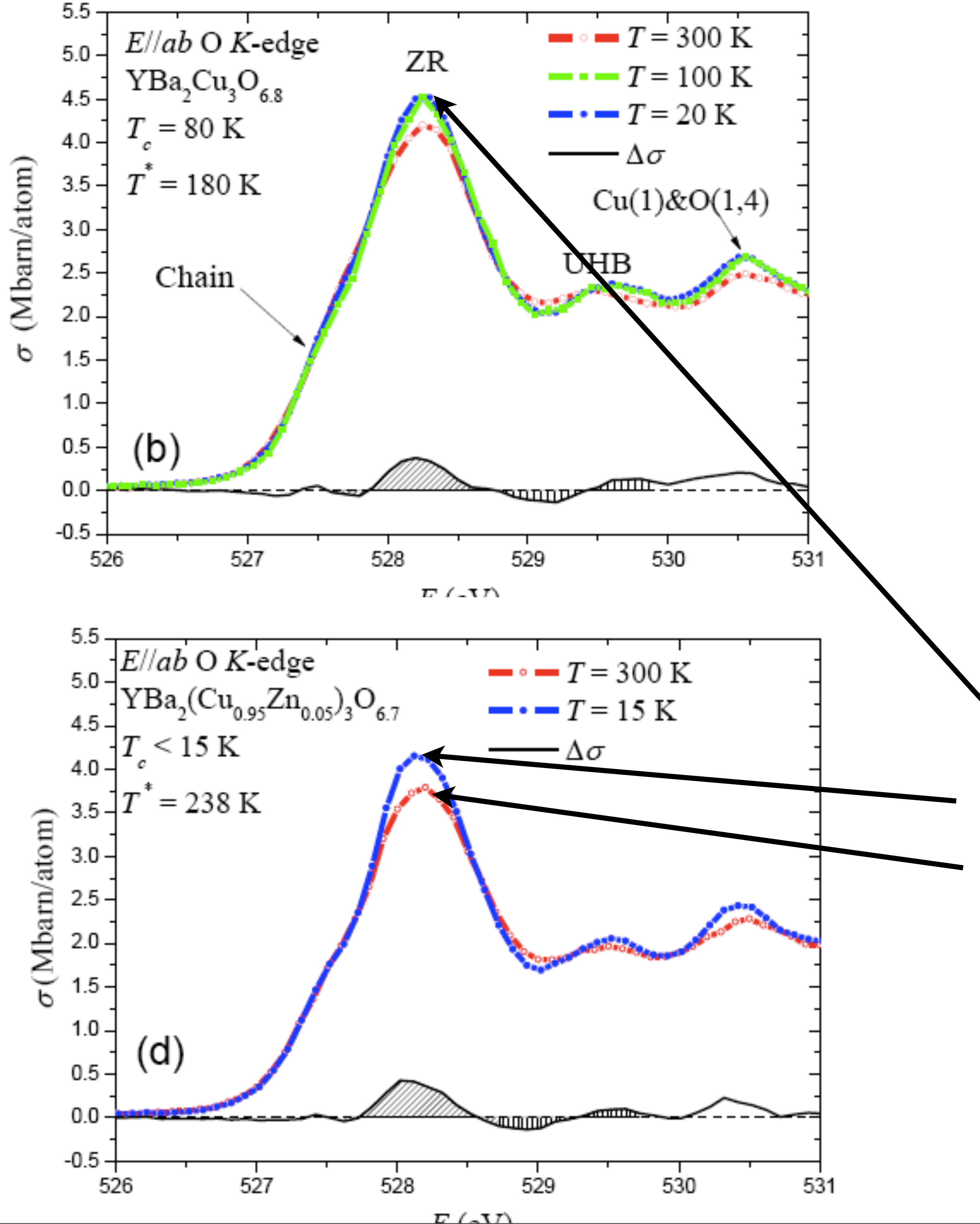
Pseudogap=`confinement'

More `e' states at lower temperature

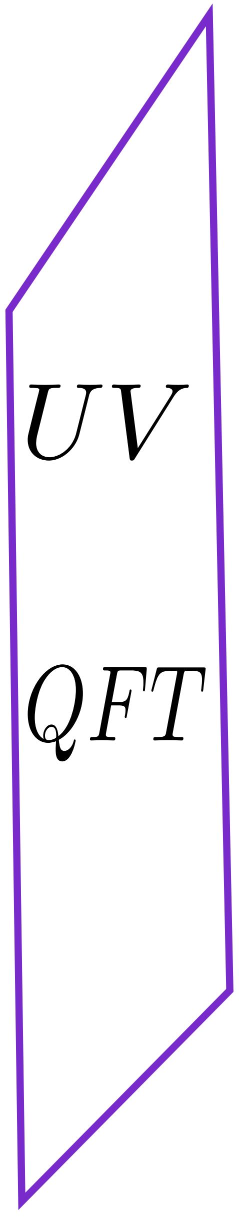


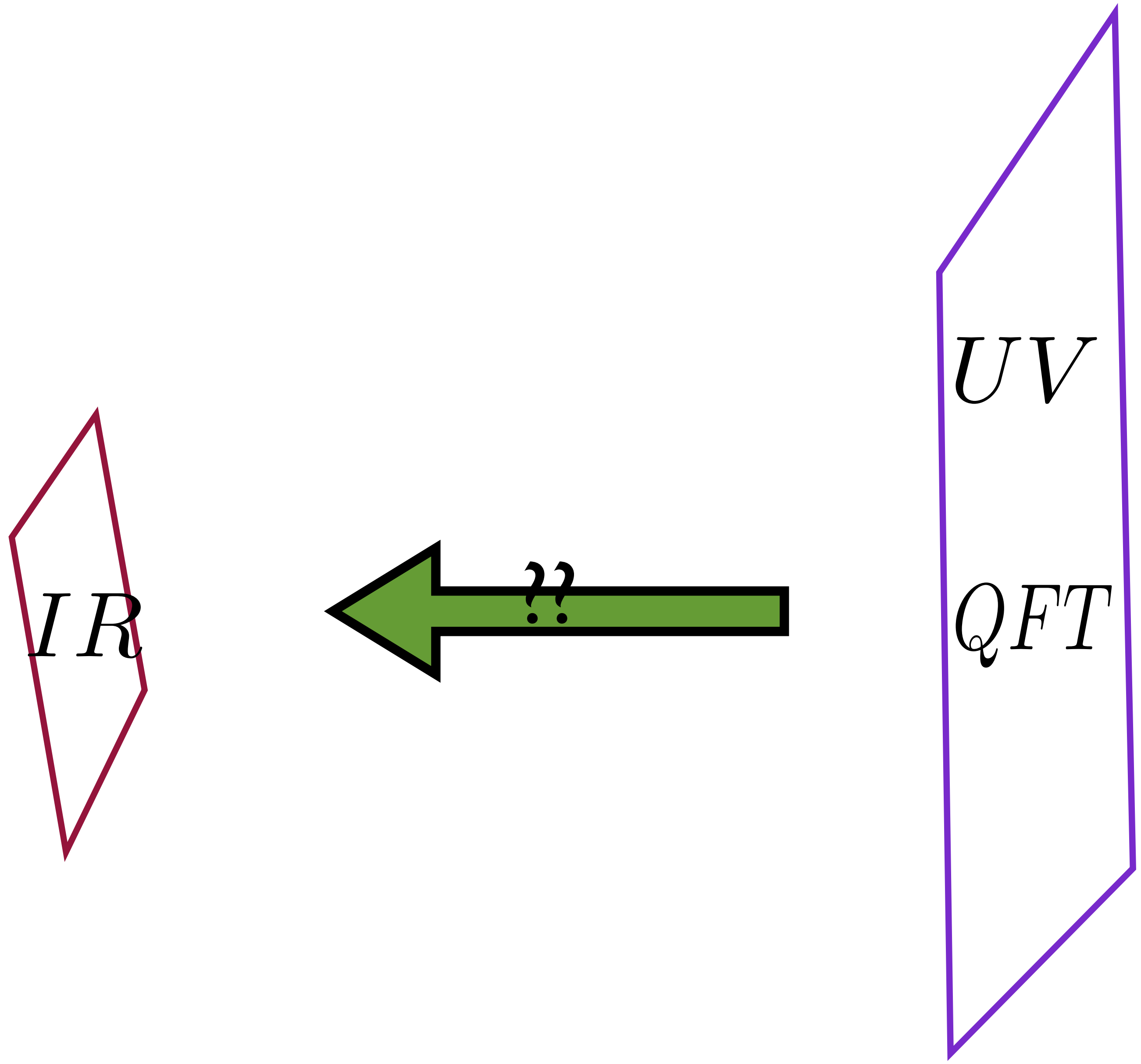
composite or bound states not in UV theory

Jiunn-Yuan Lin, et al. (Taiwan)

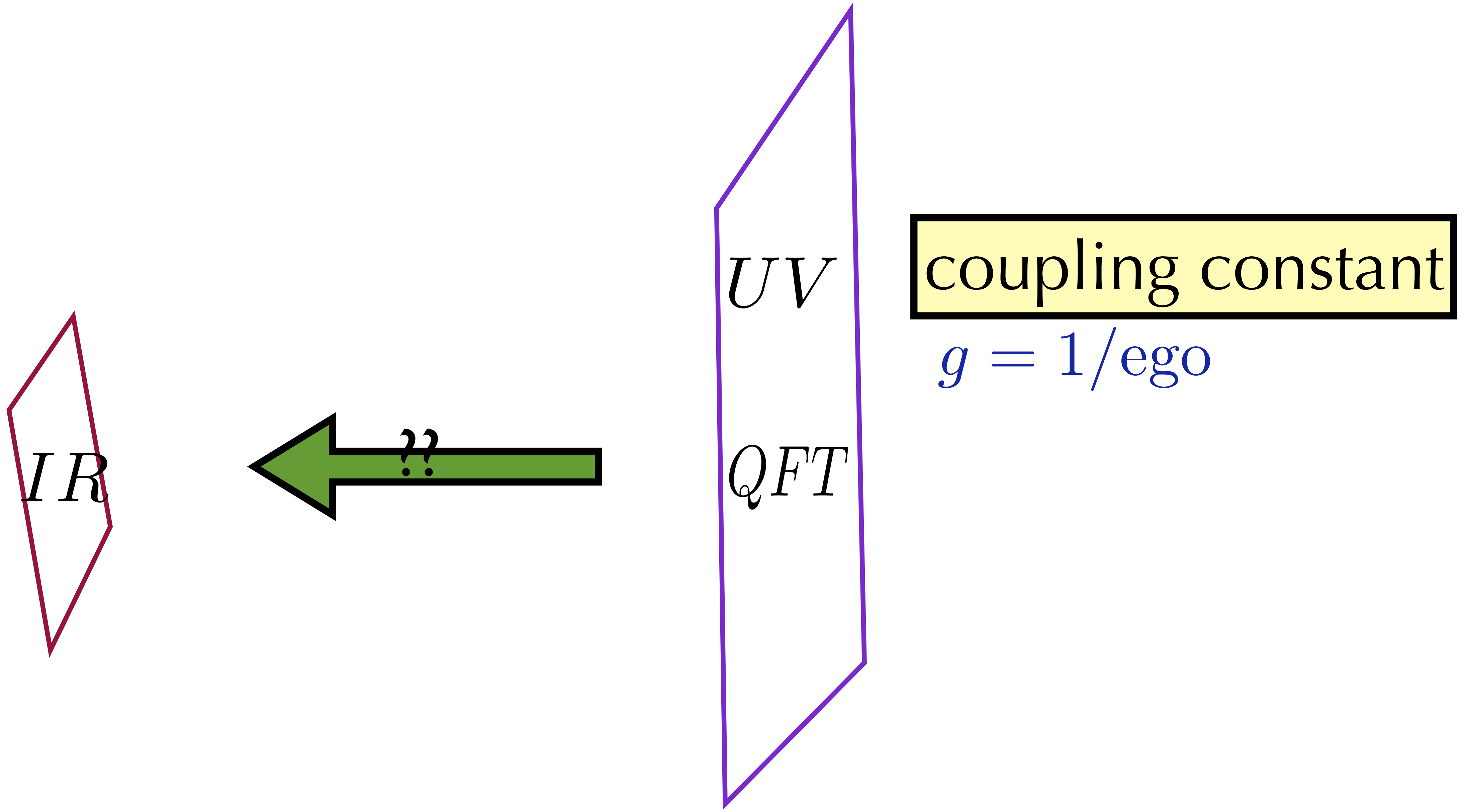


More addition states in PG: new charge e states

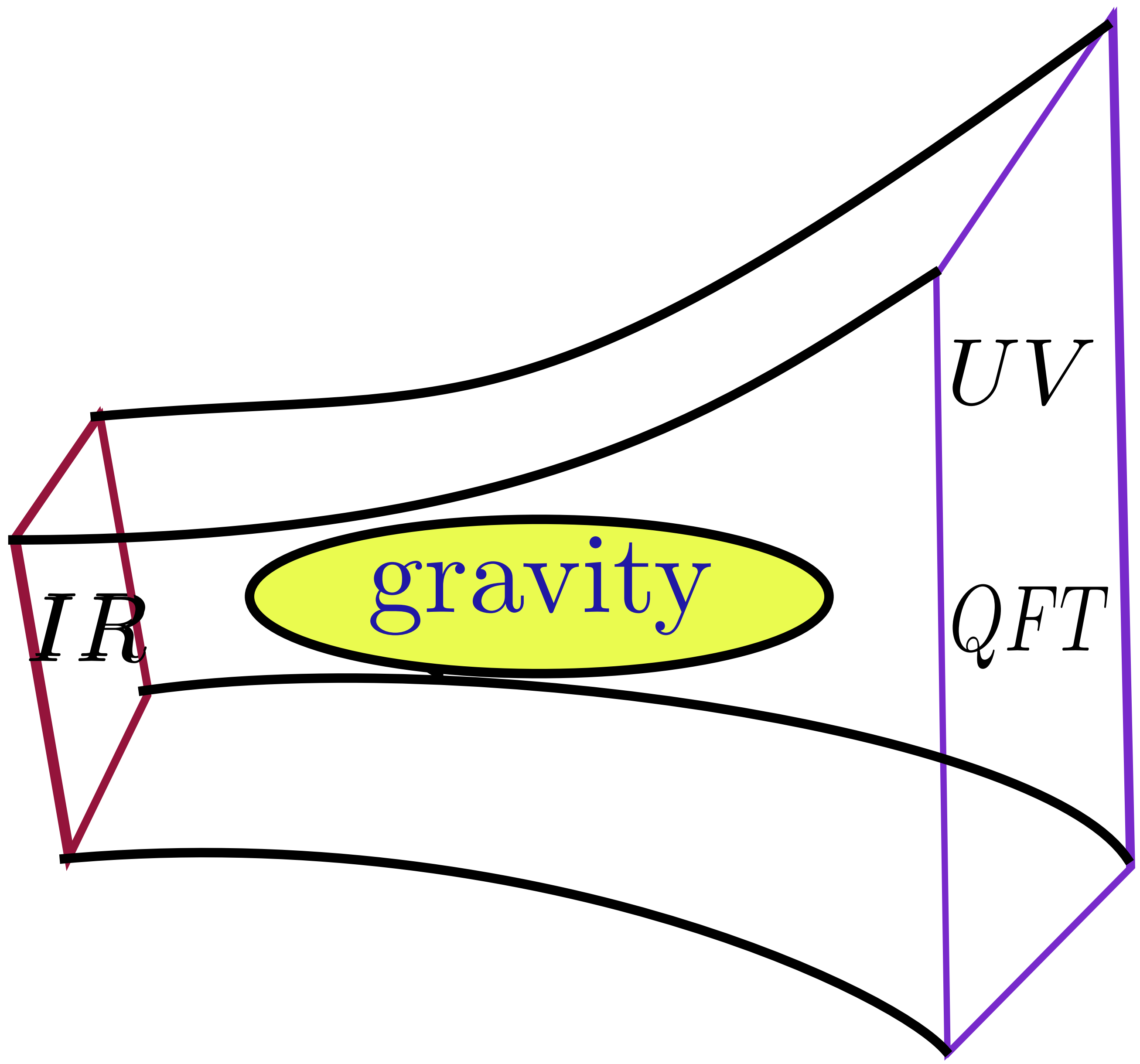

UV
QFT



IR
??
UV
QFT


IR
??
UV
QFT
coupling constant
g = 1/ego

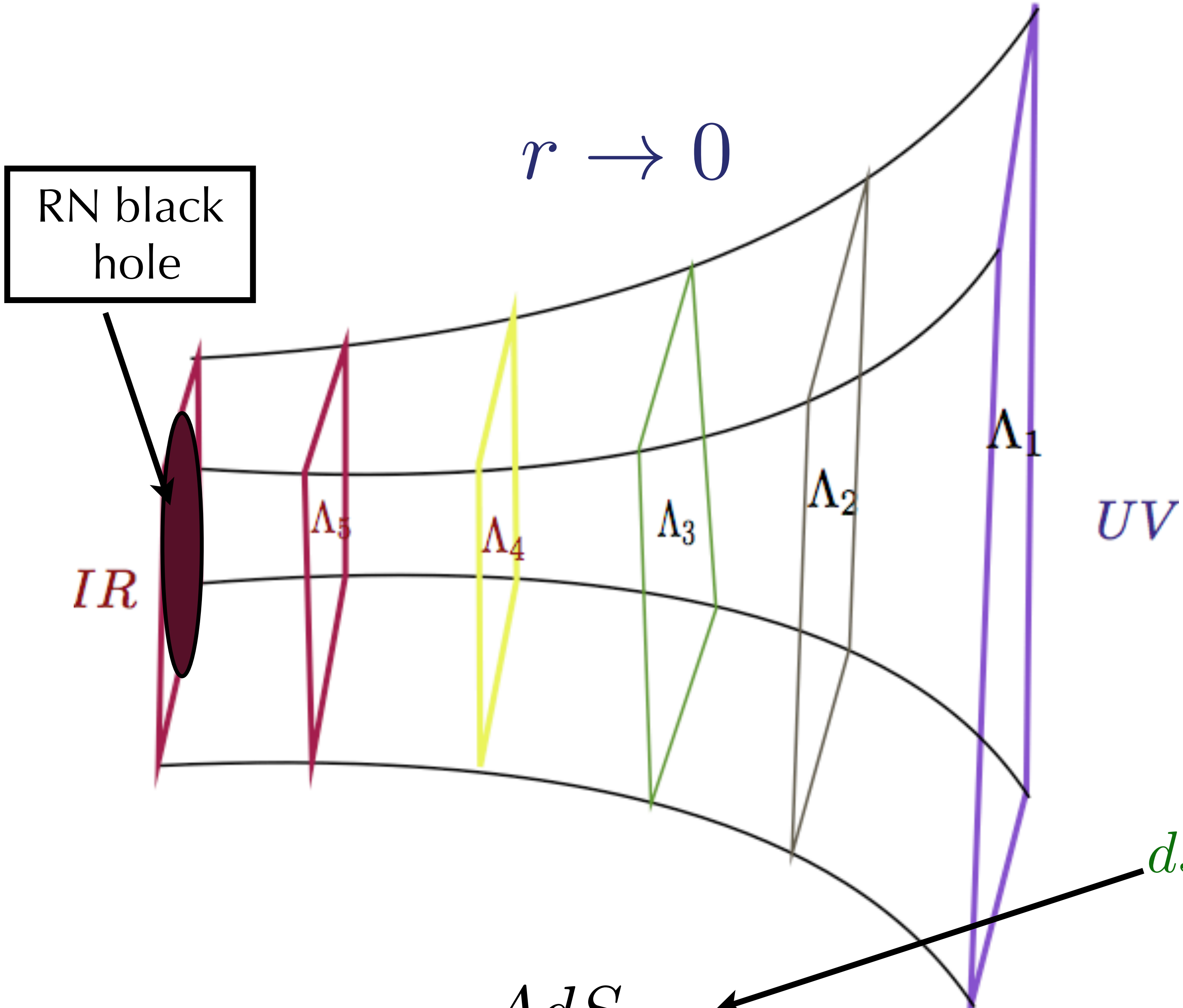
gauge-gravity duality
(Maldacena, 1997)



coupling constant

$g = 1/\text{ego}$

`Holography'



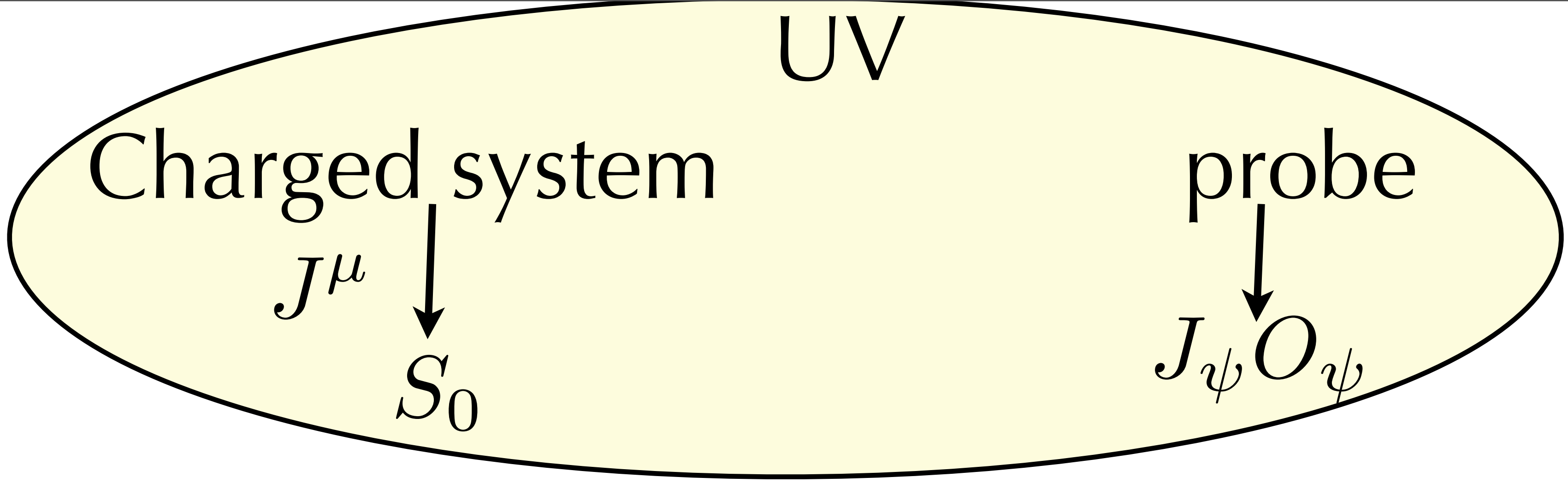
$$ds^2 = L^2\left(\frac{-dt^2}{r^2} + \frac{d\vec{x}^2}{r^2} + \frac{dr^2}{r^2}\right)$$

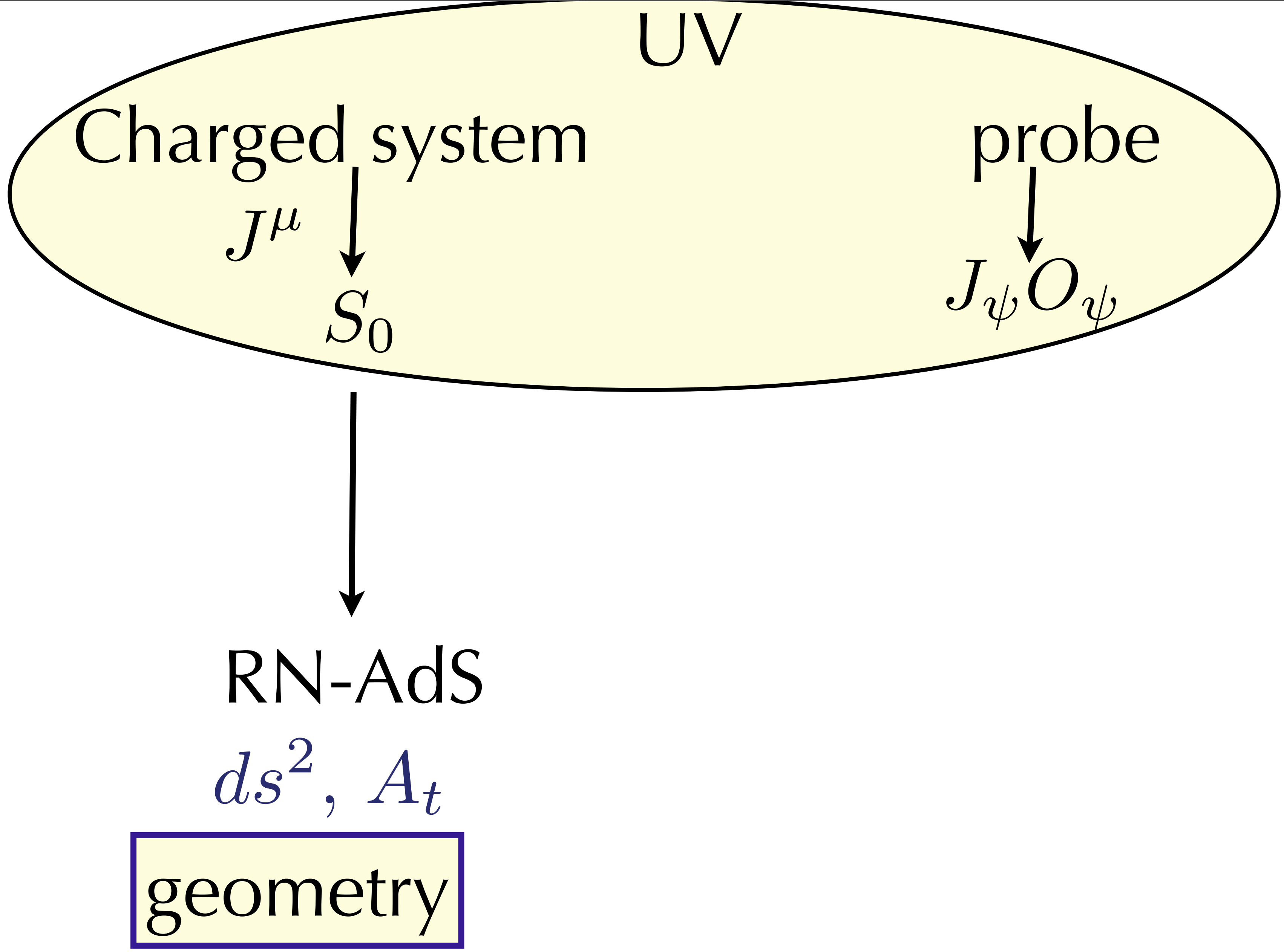
AdS_{d+1}

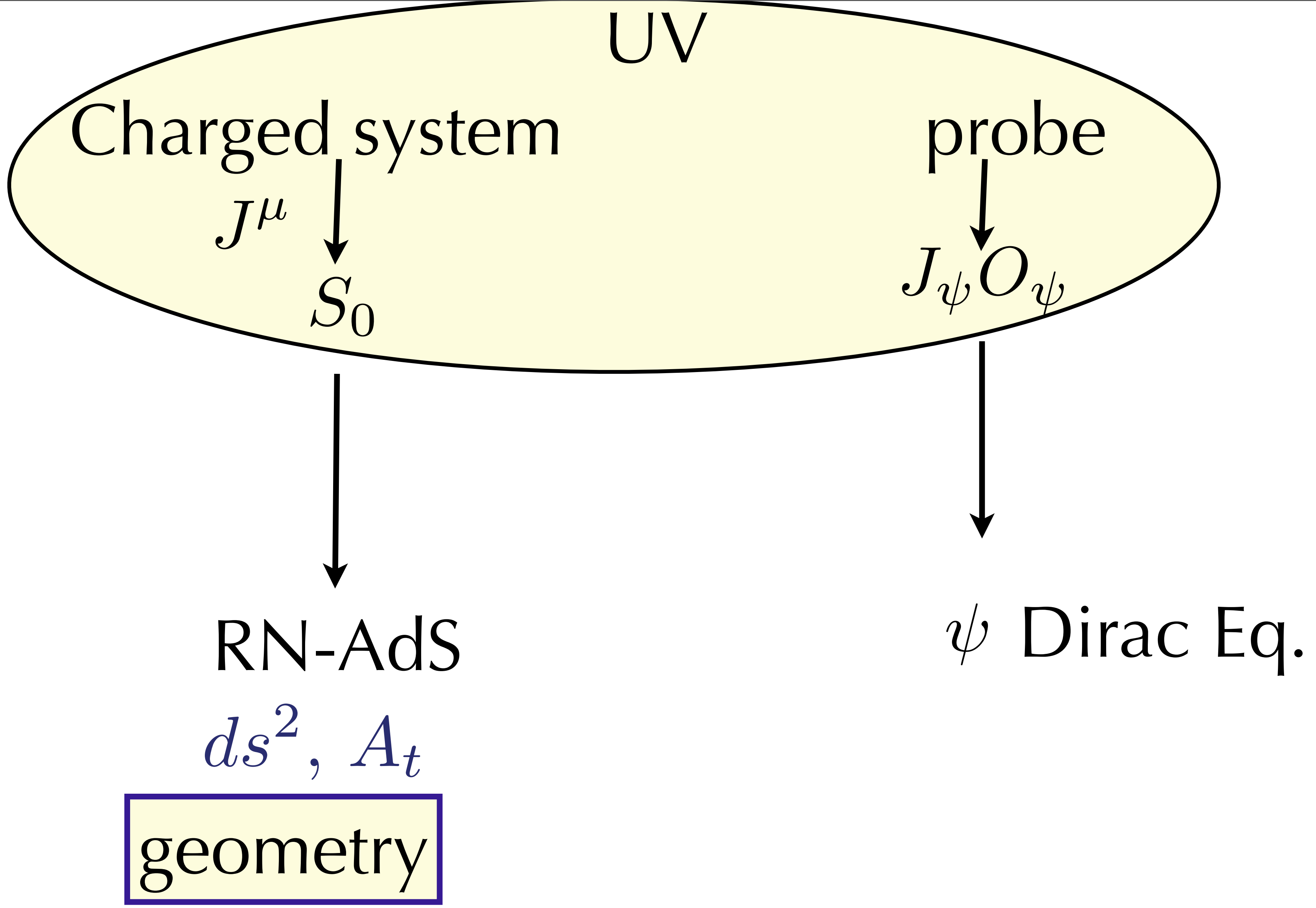
$\beta(g)$ is local
geometrize RG flow

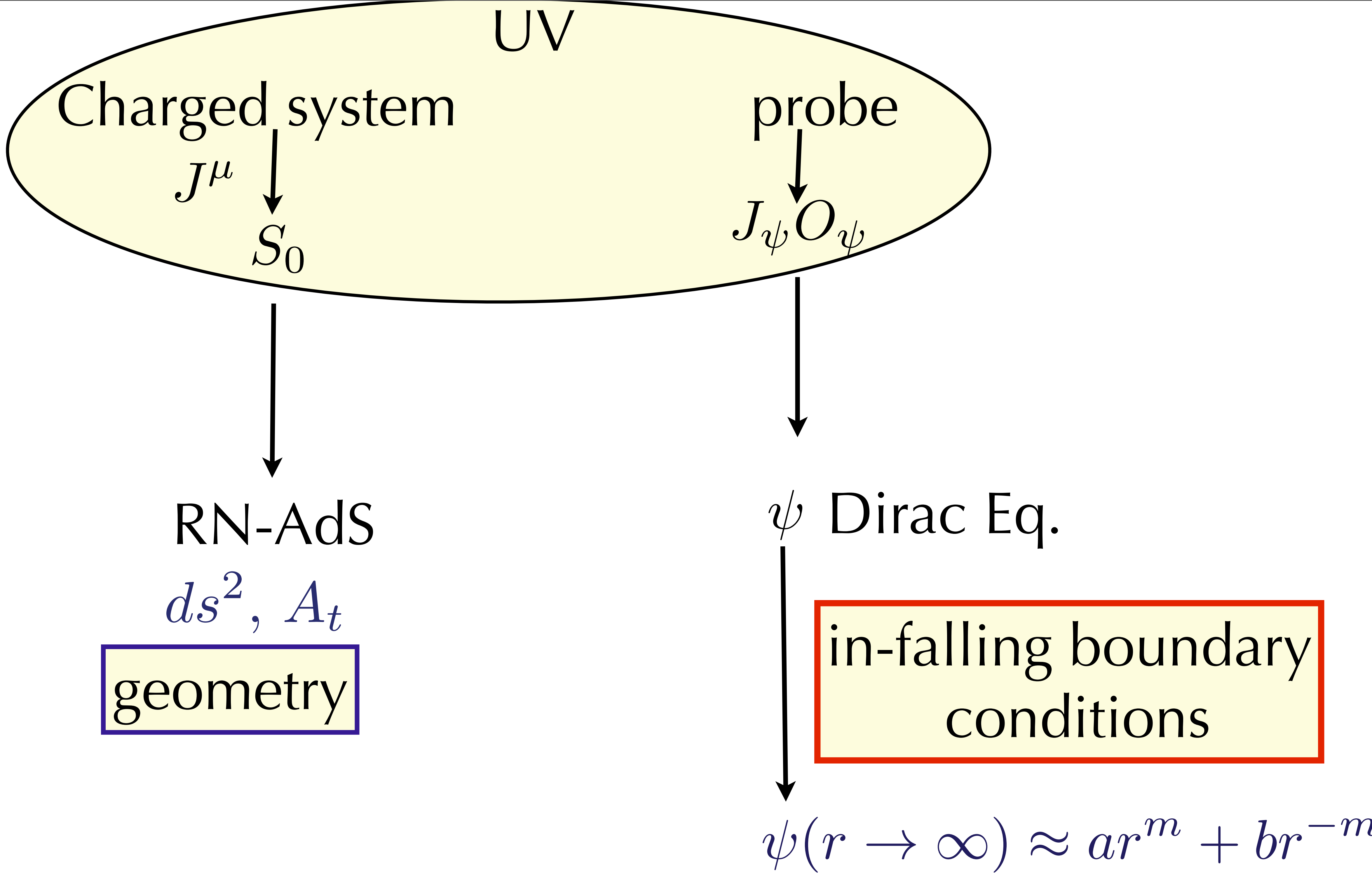
symmetry:

$\{t, \vec{x}, r\} \to \{\lambda t, \lambda \vec{x}, \lambda r\}$


UV
Charged system
probe
J^μ
S_0
$J_\psi O_\psi$


UV
Charged system
probe
J^μ
S_0
$J_\psi O_\psi$
RN-AdS
$ds^2,\ A_t$
geometry


UV
Charged system
probe
J^μ
S_0
$J_\psi O_\psi$
RN-AdS
ψ Dirac Eq.
$ds^2,\ A_t$
geometry



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

What gravitational theory gives rise to a gap in ImG without spontaneous symmetry breaking?

↓

dynamically generated gap: Mott gap (for probe fermions)

bottom-up schemes

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

AdS-RN
MIT, Leiden group

→ `non-Fermi liquids'

bottom-up schemes

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

AdS-RN
MIT, Leiden group

→ `non-Fermi liquids'

??

→ Mott Insulator

bottom-up schemes

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

AdS-RN
MIT, Leiden group

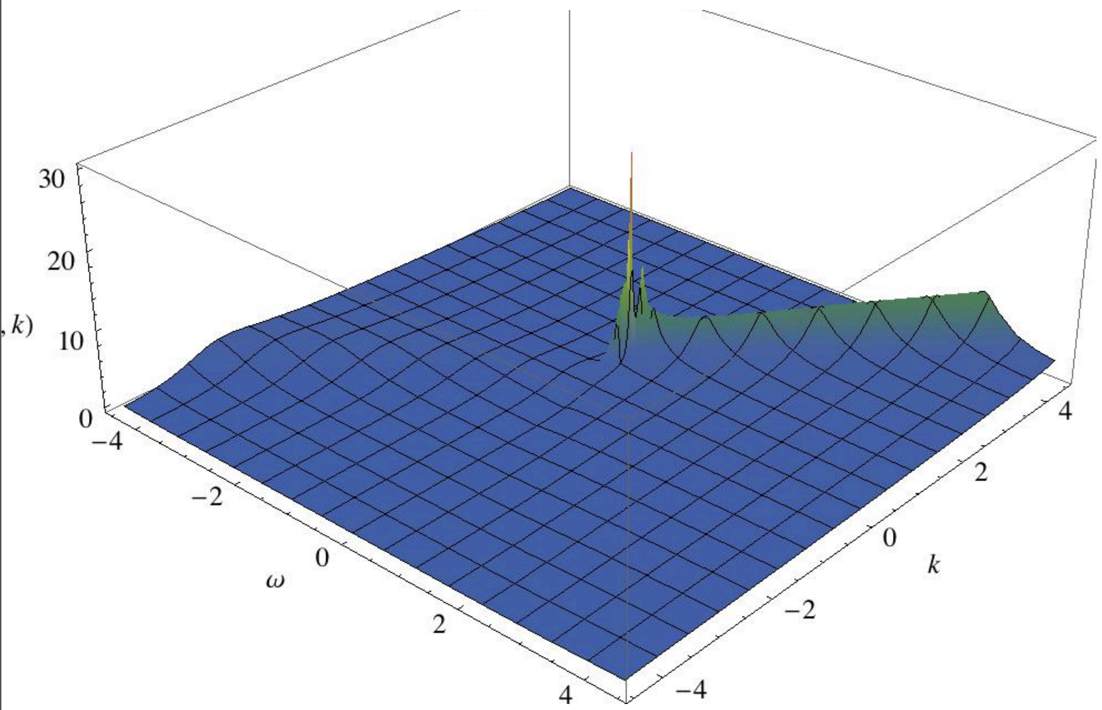
?? → Mott Insulator

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

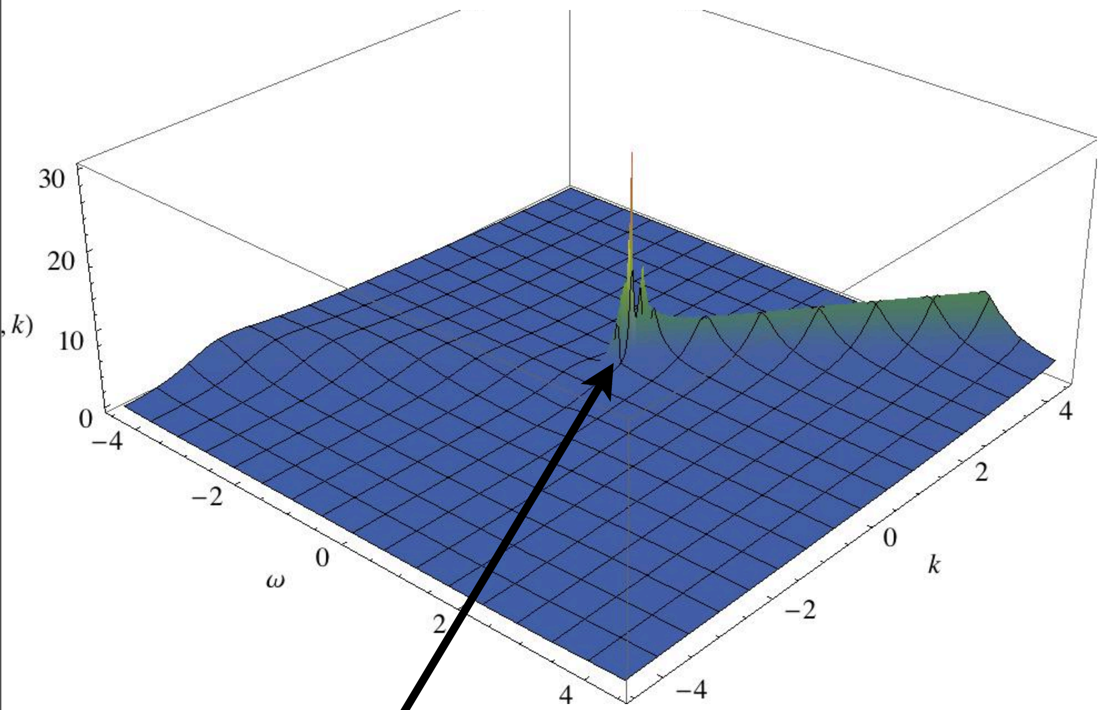
How is the spectrum modified?

P=0



How is the spectrum modified?

P=0

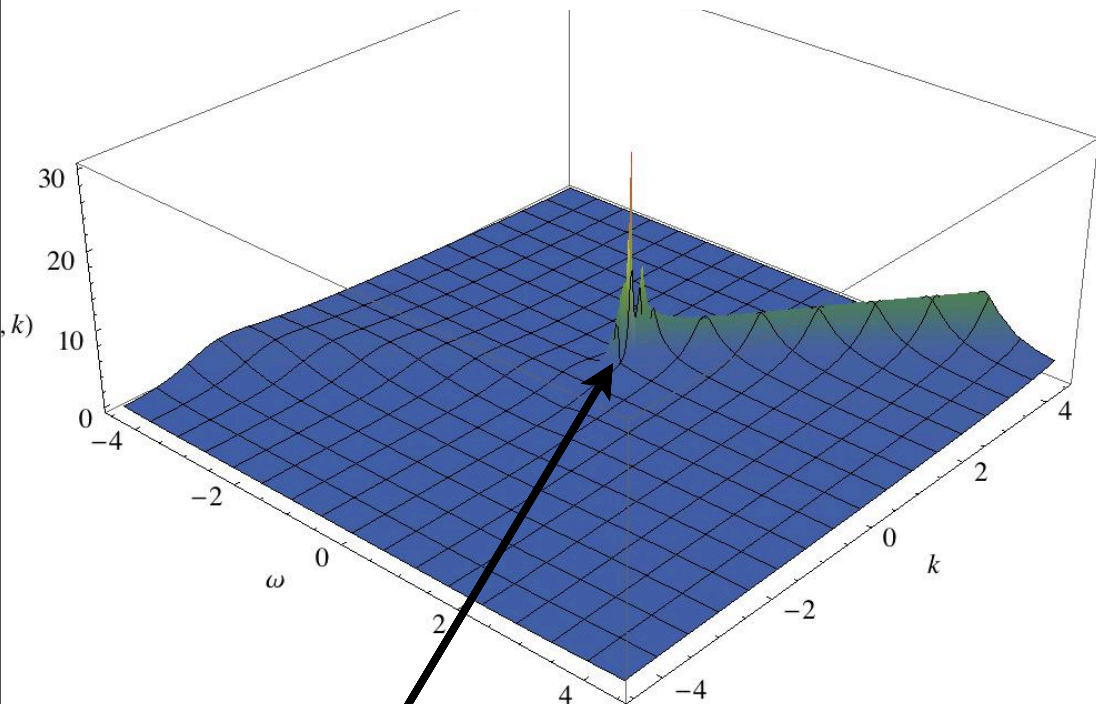


Fermi
surface
peak

How is the spectrum modified?

P=0

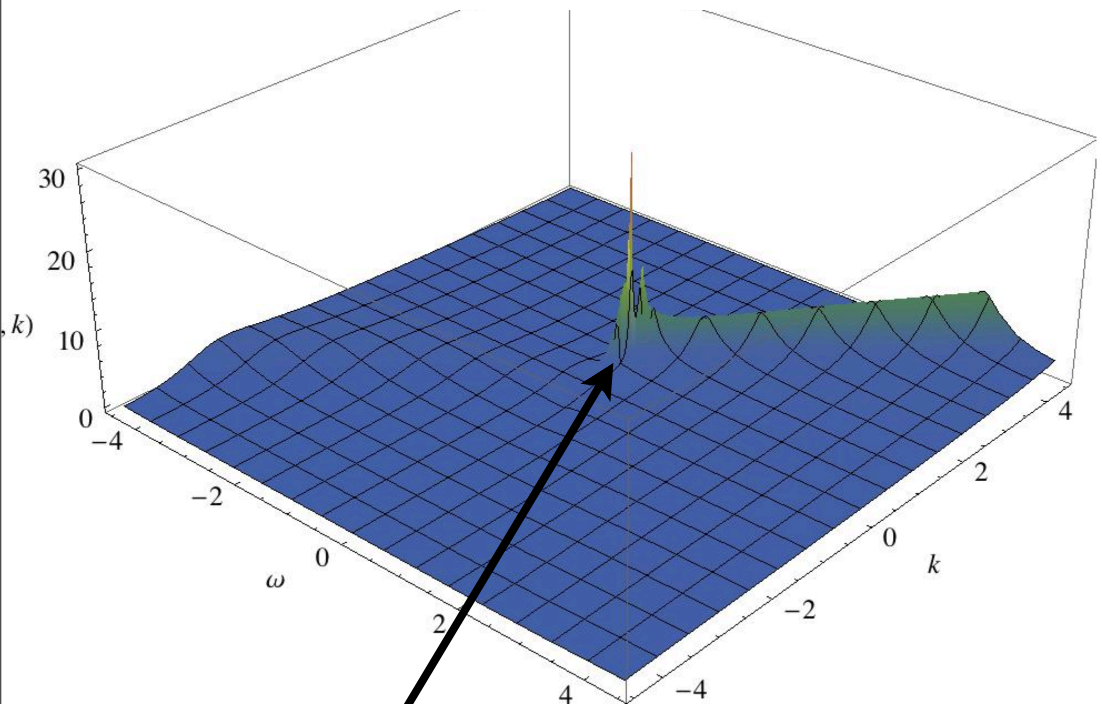
$P > 4.2$



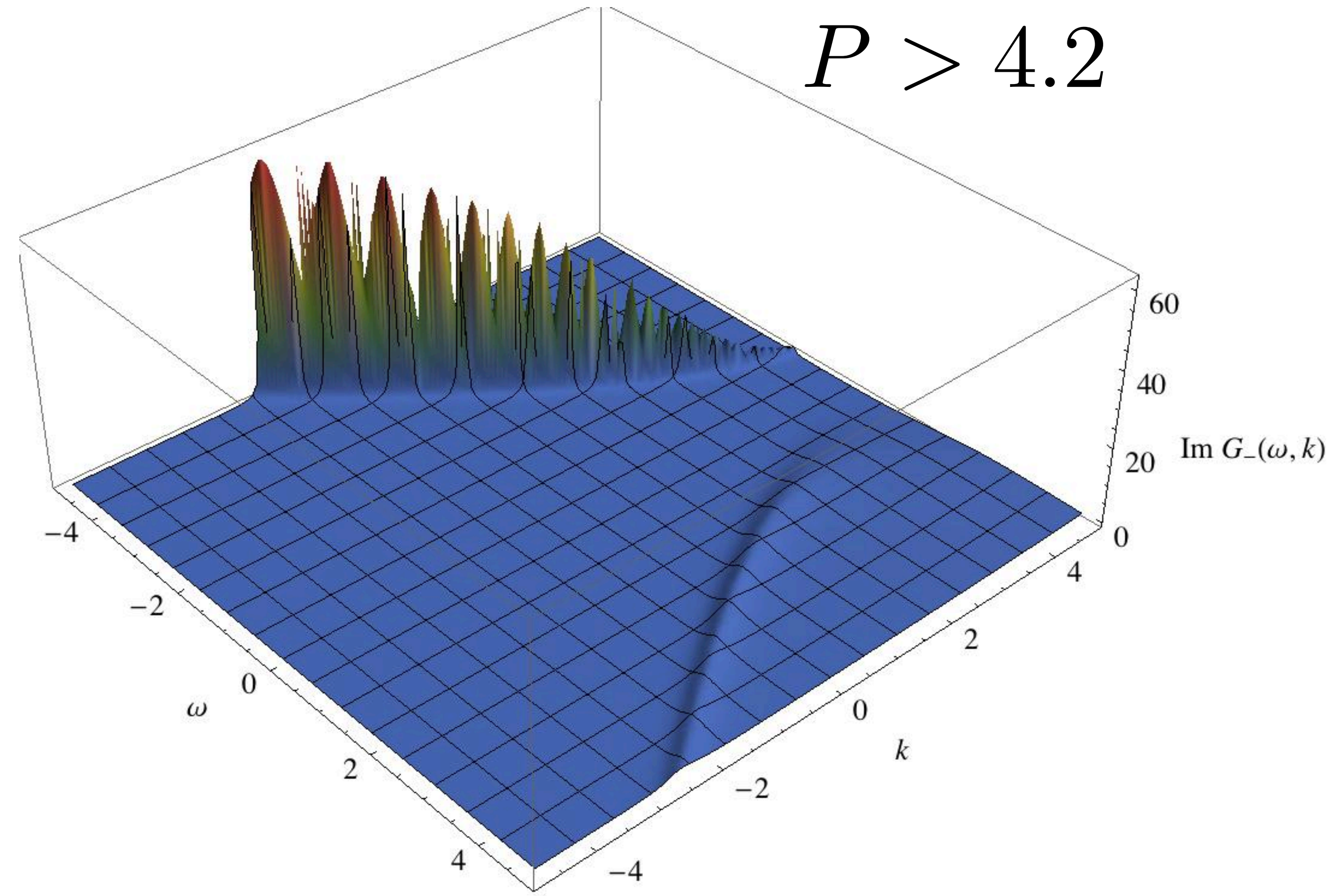
Fermi surface peak

How is the spectrum modified?

P=0



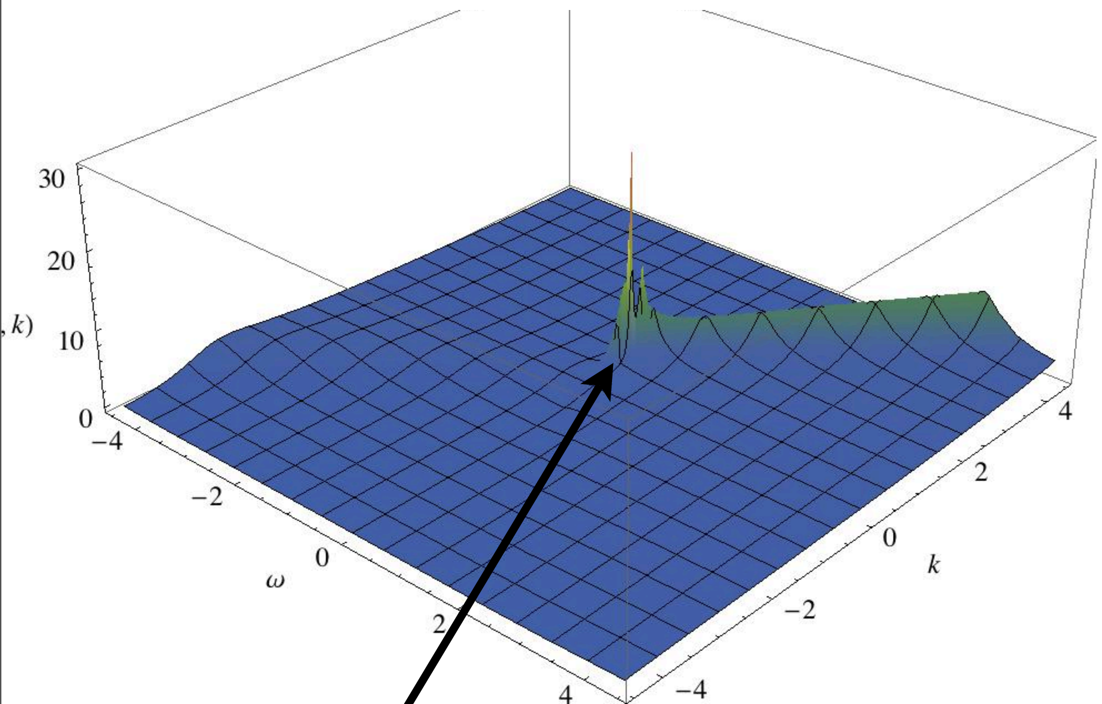
$P > 4.2$



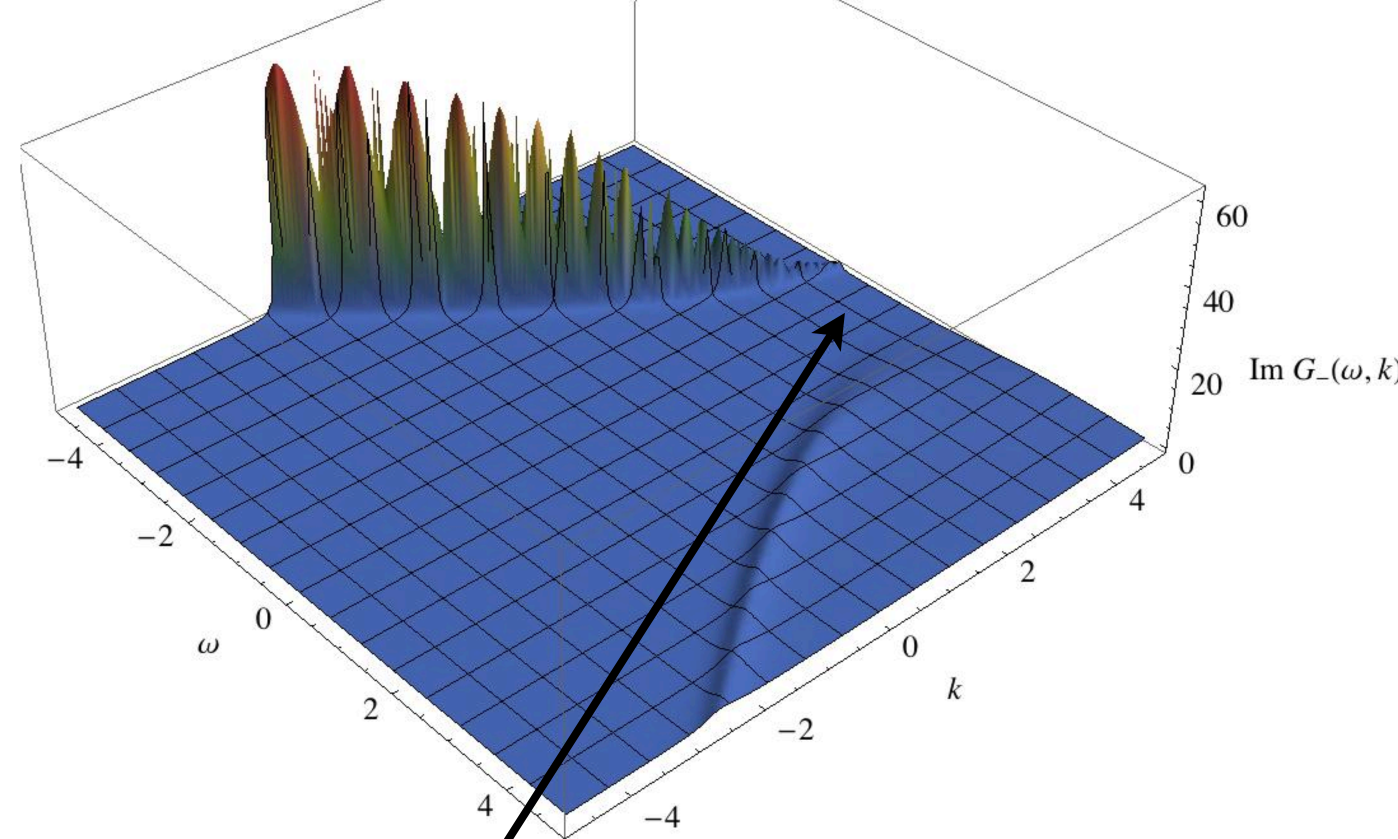
Fermi surface peak

How is the spectrum modified?

P=0



$P > 4.2$

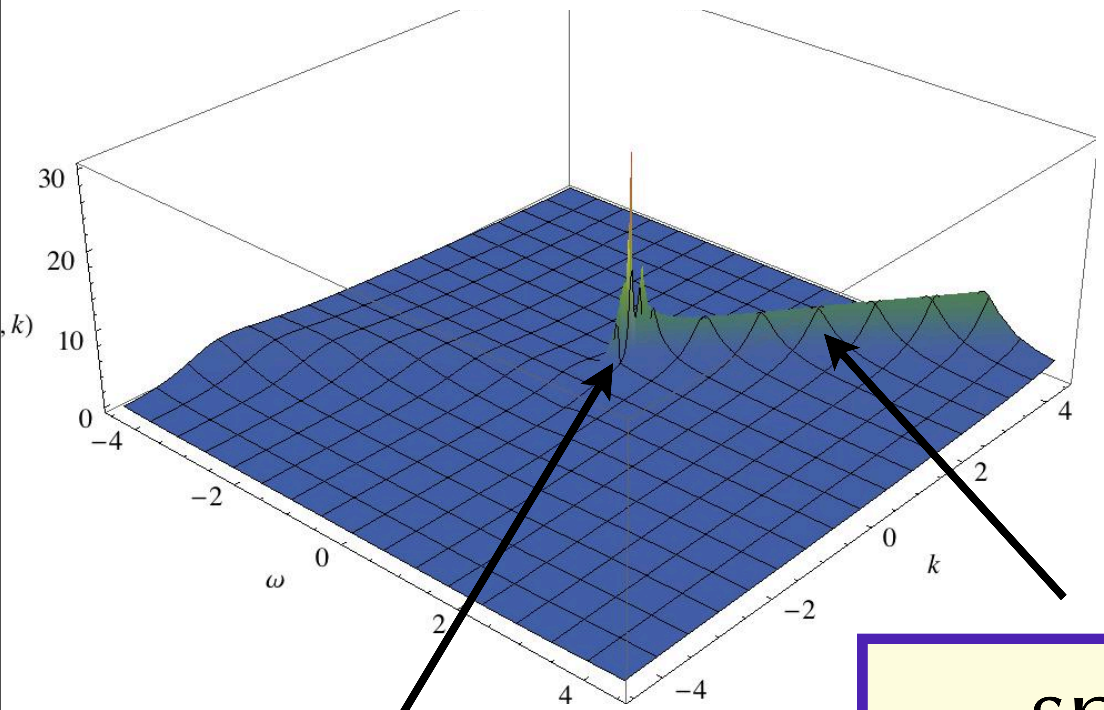


Fermi surface peak

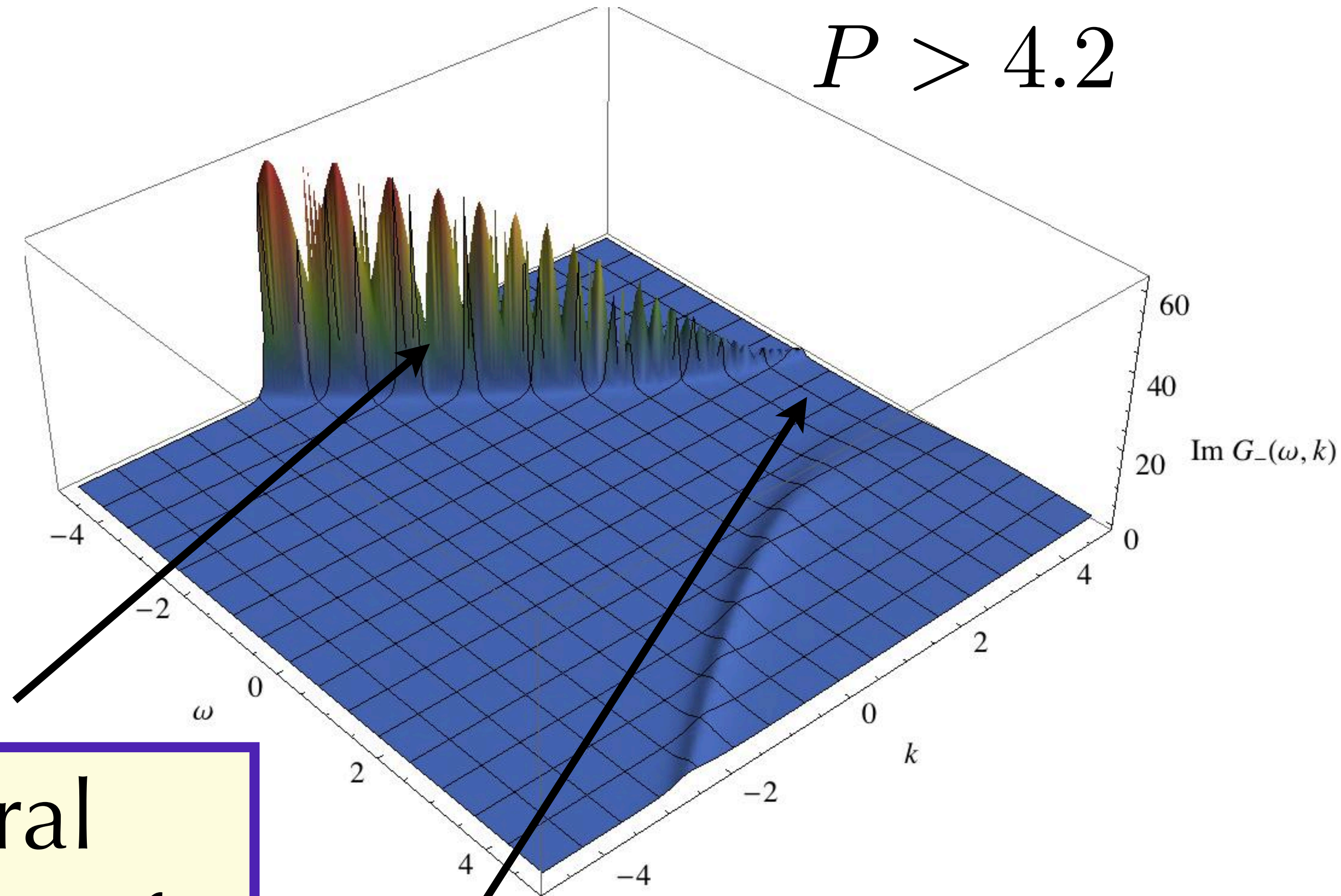
dynamically generated gap:

How is the spectrum modified?

P=0



$P > 4.2$



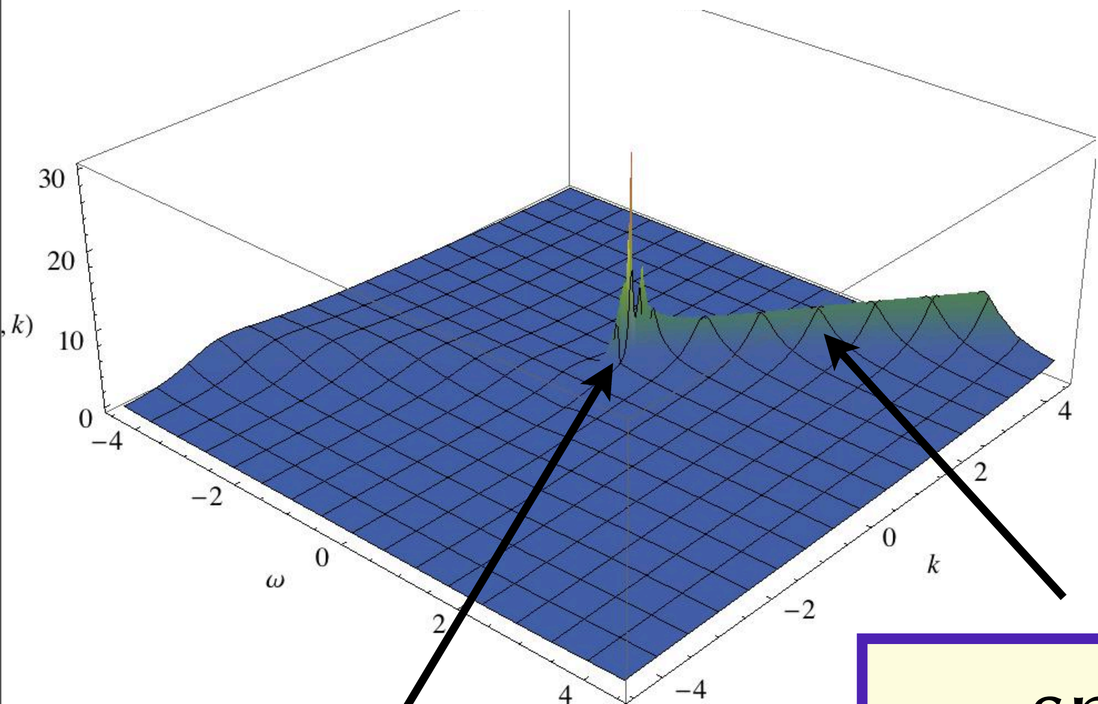
Fermi surface peak

spectral weight transfer

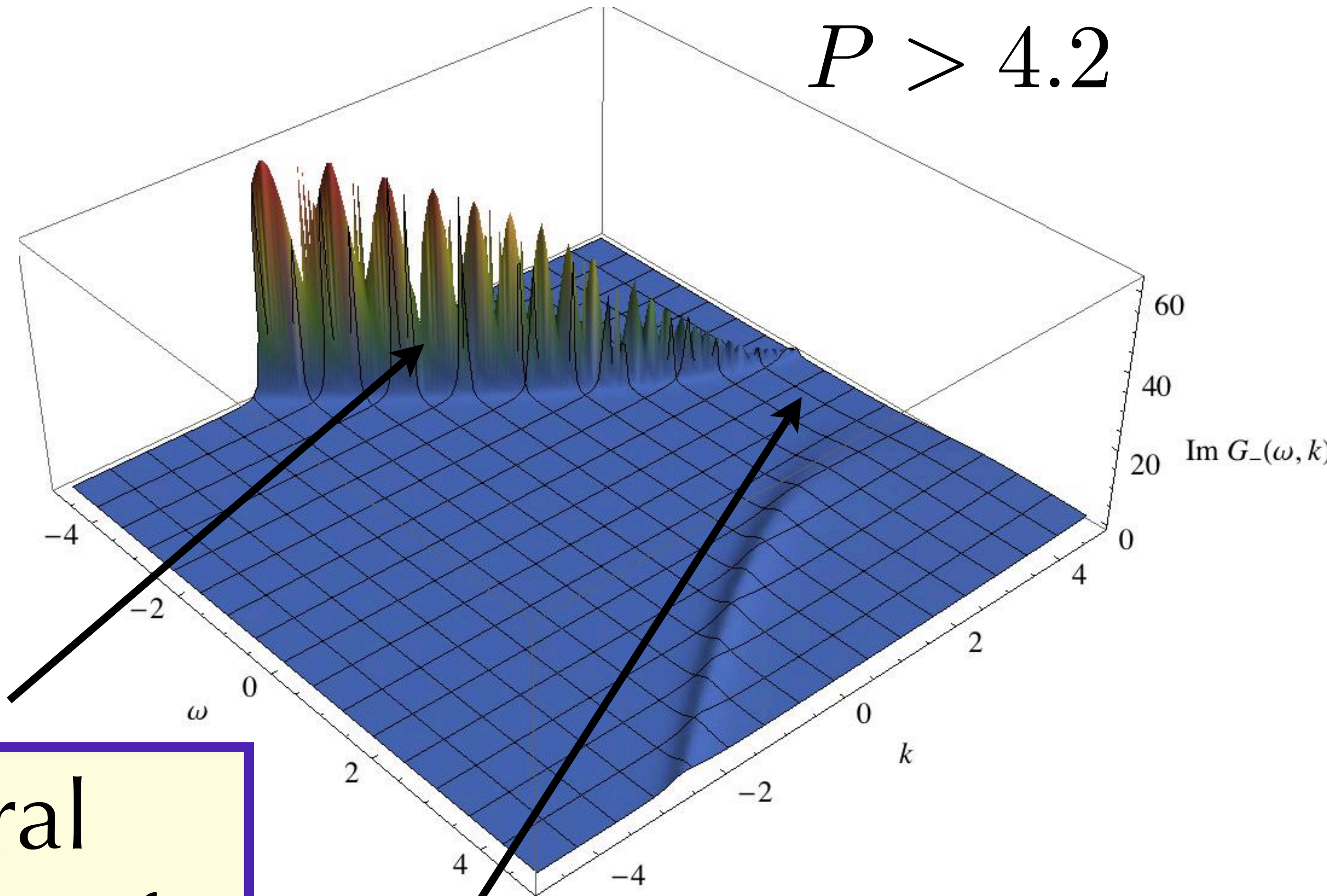
dynamically generated gap:

How is the spectrum modified?

P=0



$P > 4.2$



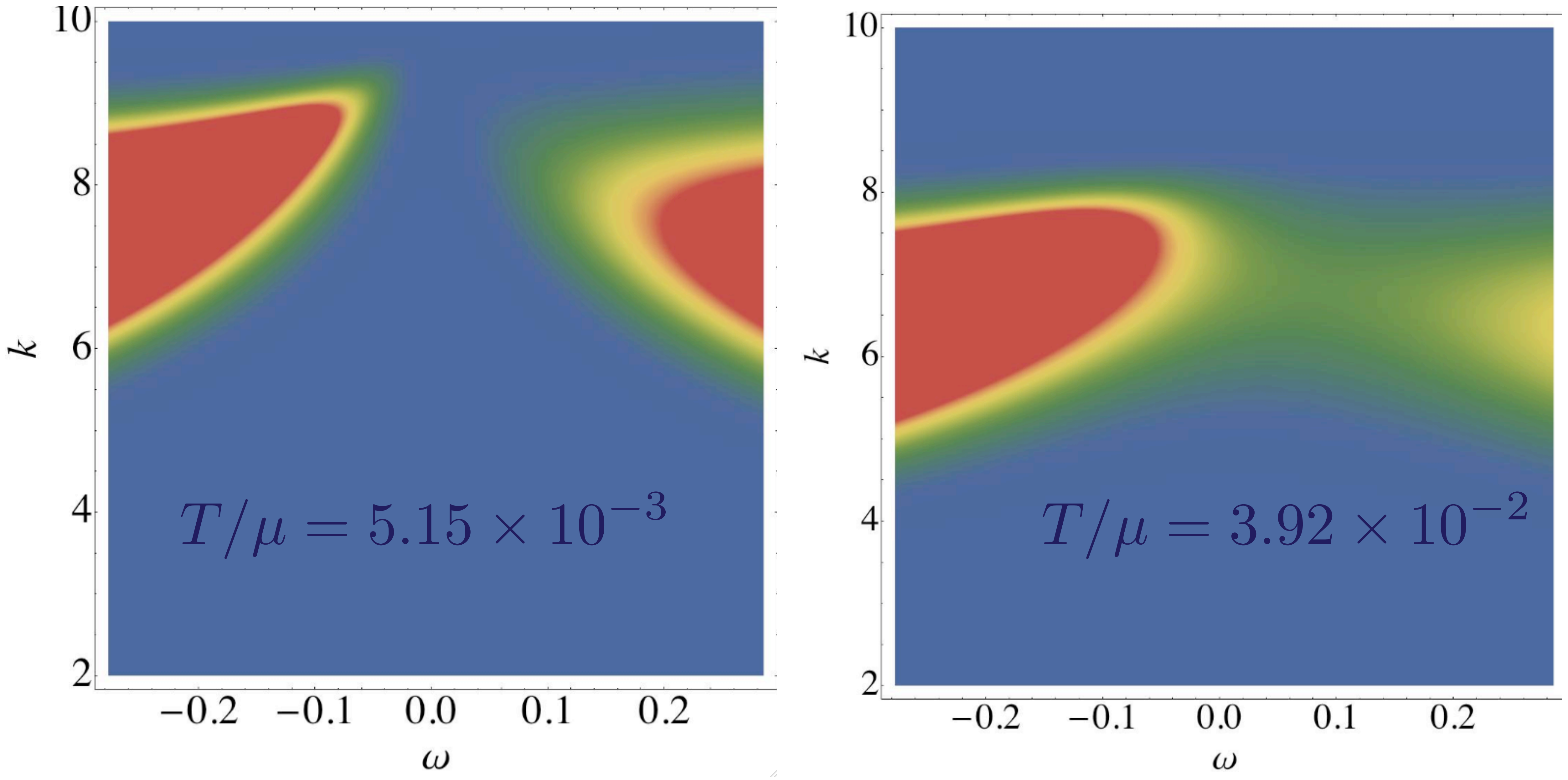
Fermi surface peak

spectral weight transfer

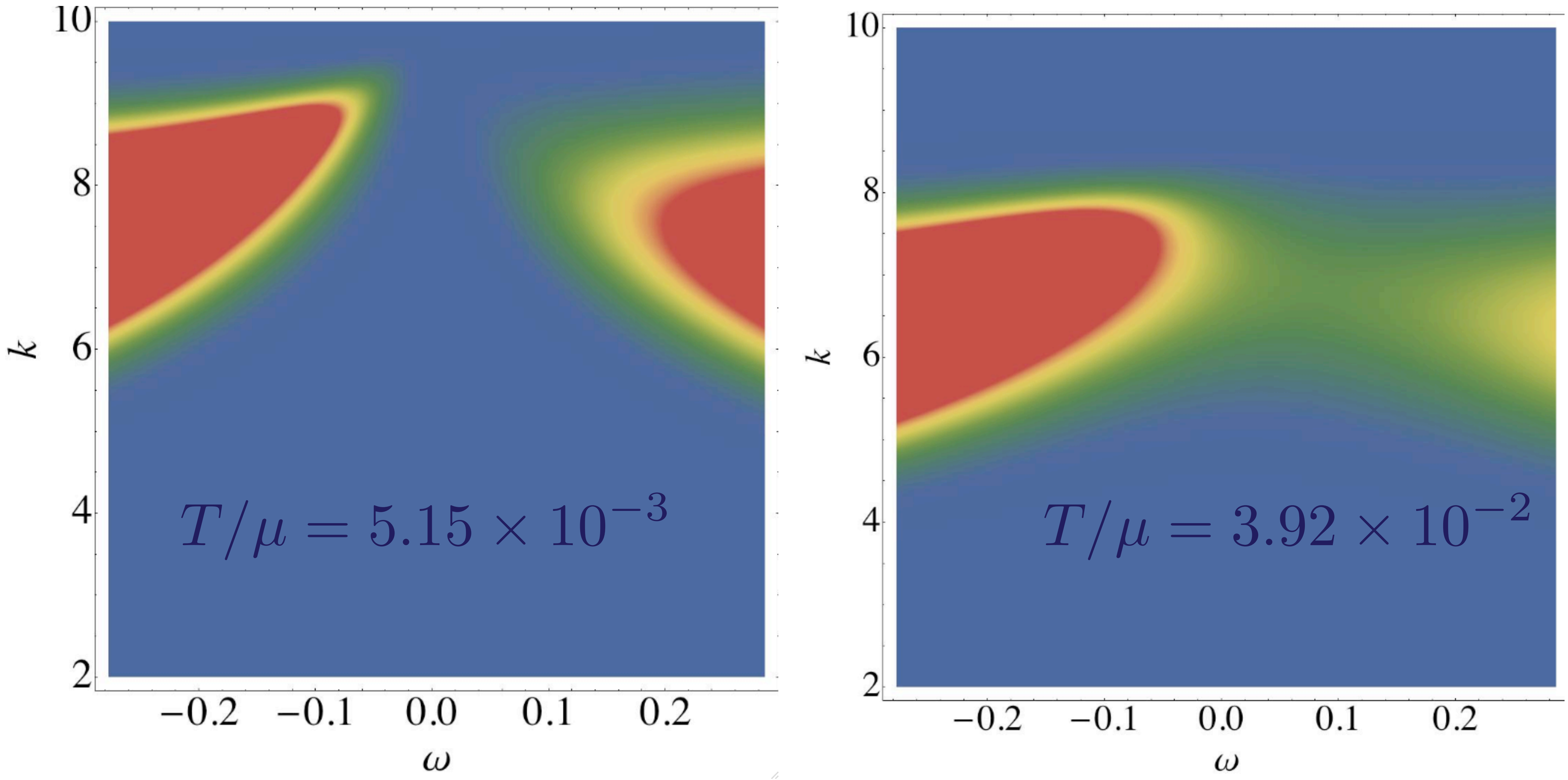
dynamically generated gap:

confirmed by Gubser, Gauntlett, 2011

Finite Temperature Mott transition



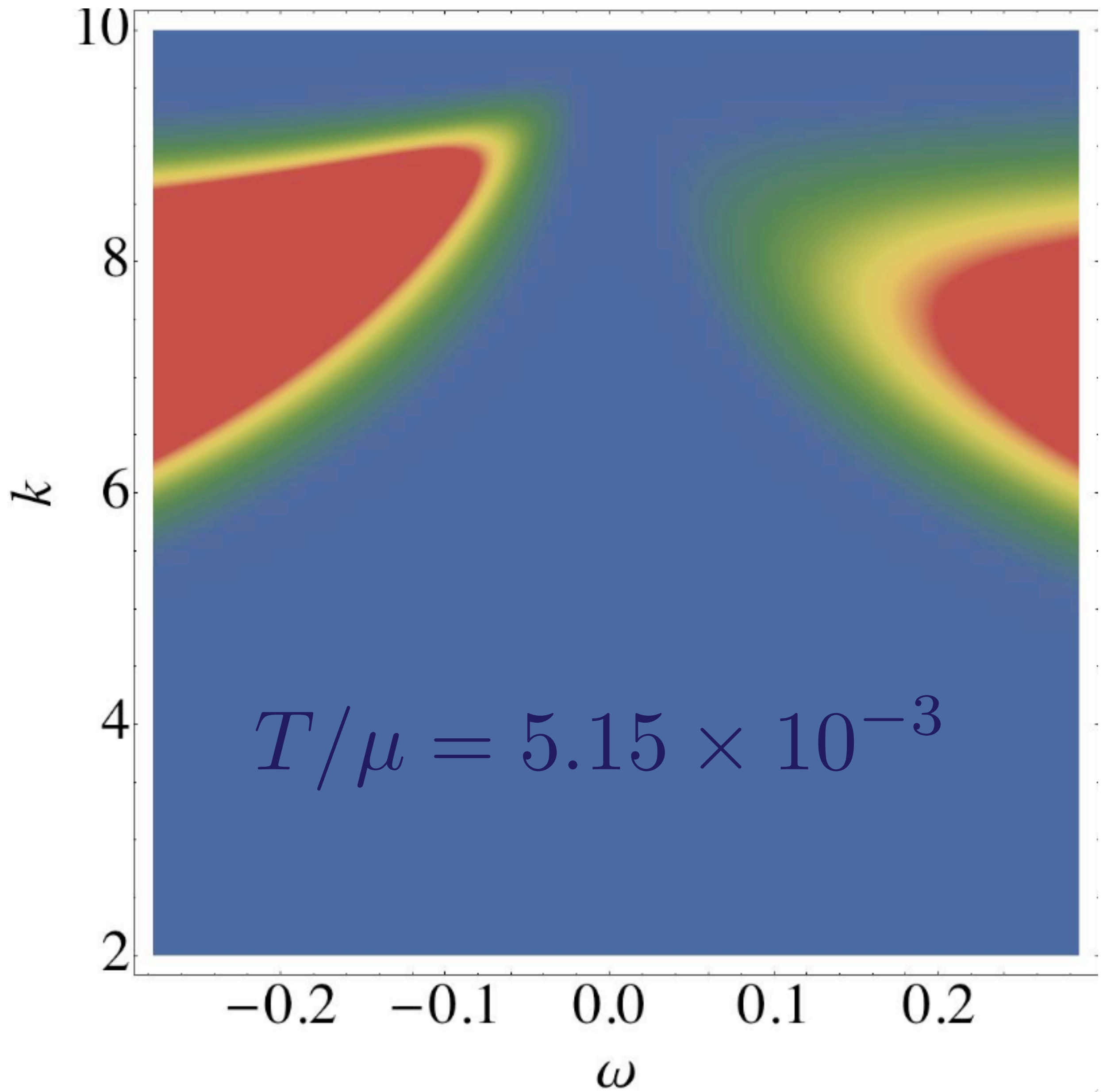
Finite Temperature Mott transition

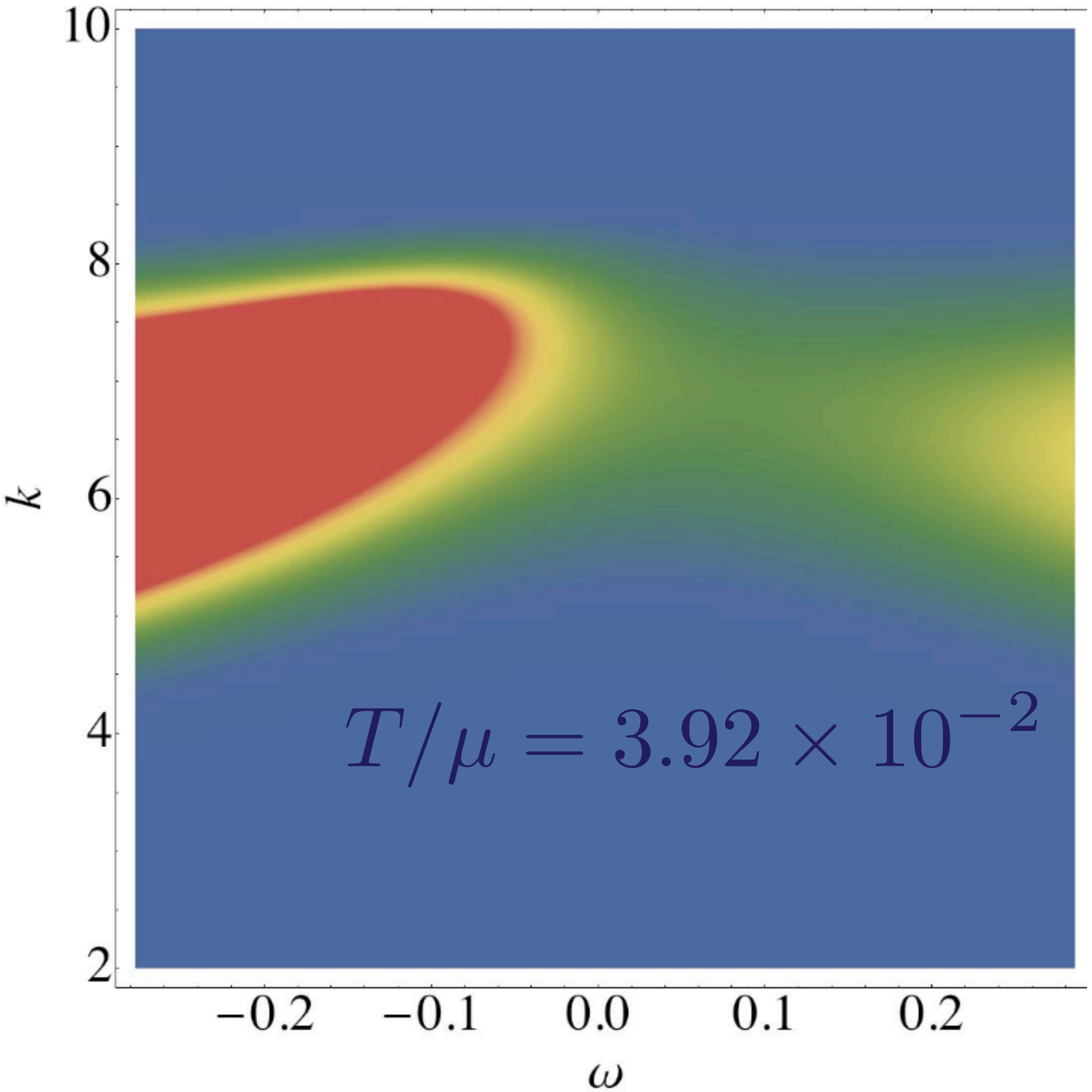


$$\frac{\Delta}{T_{\text{crit}}} \approx 20$$

vanadium oxide

Finite Temperature Mott transition

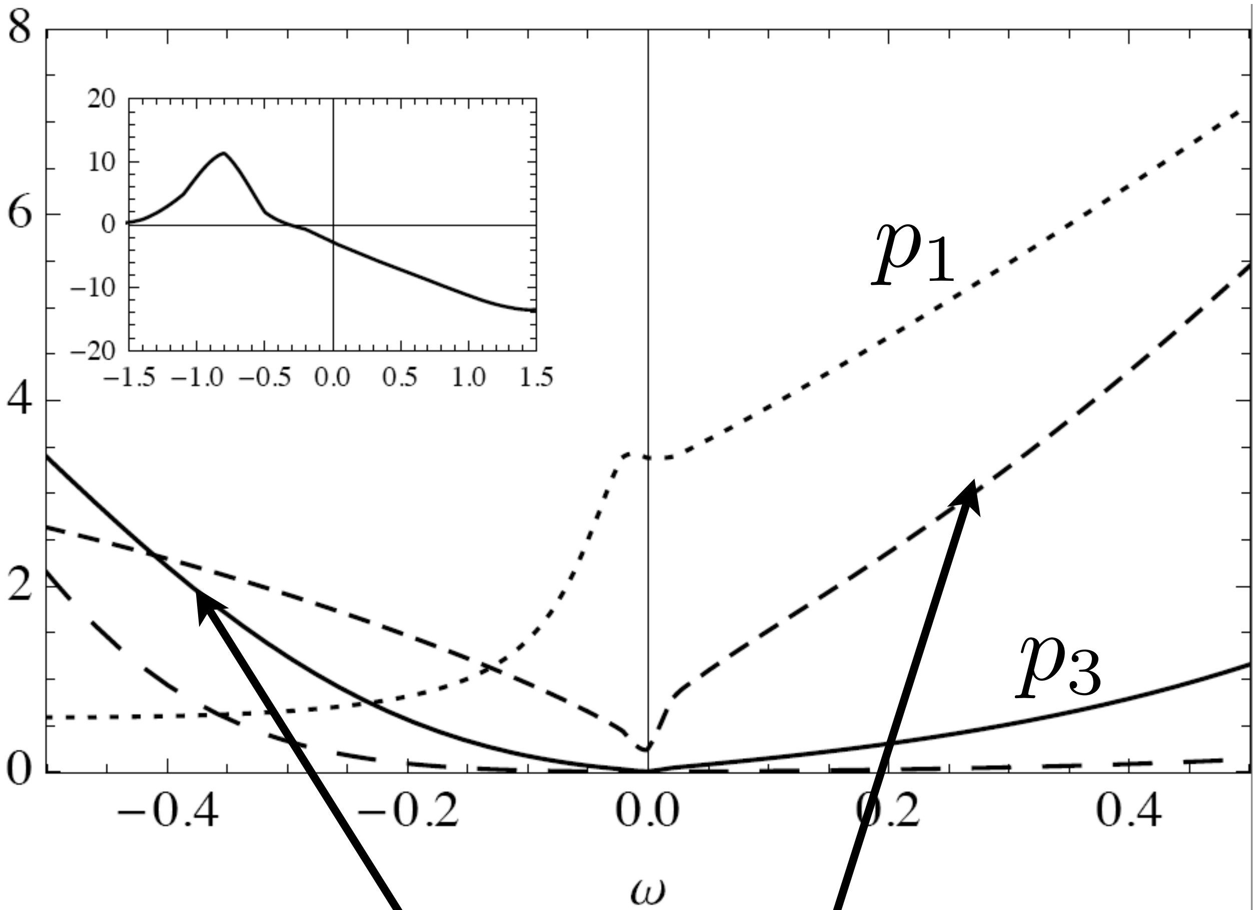


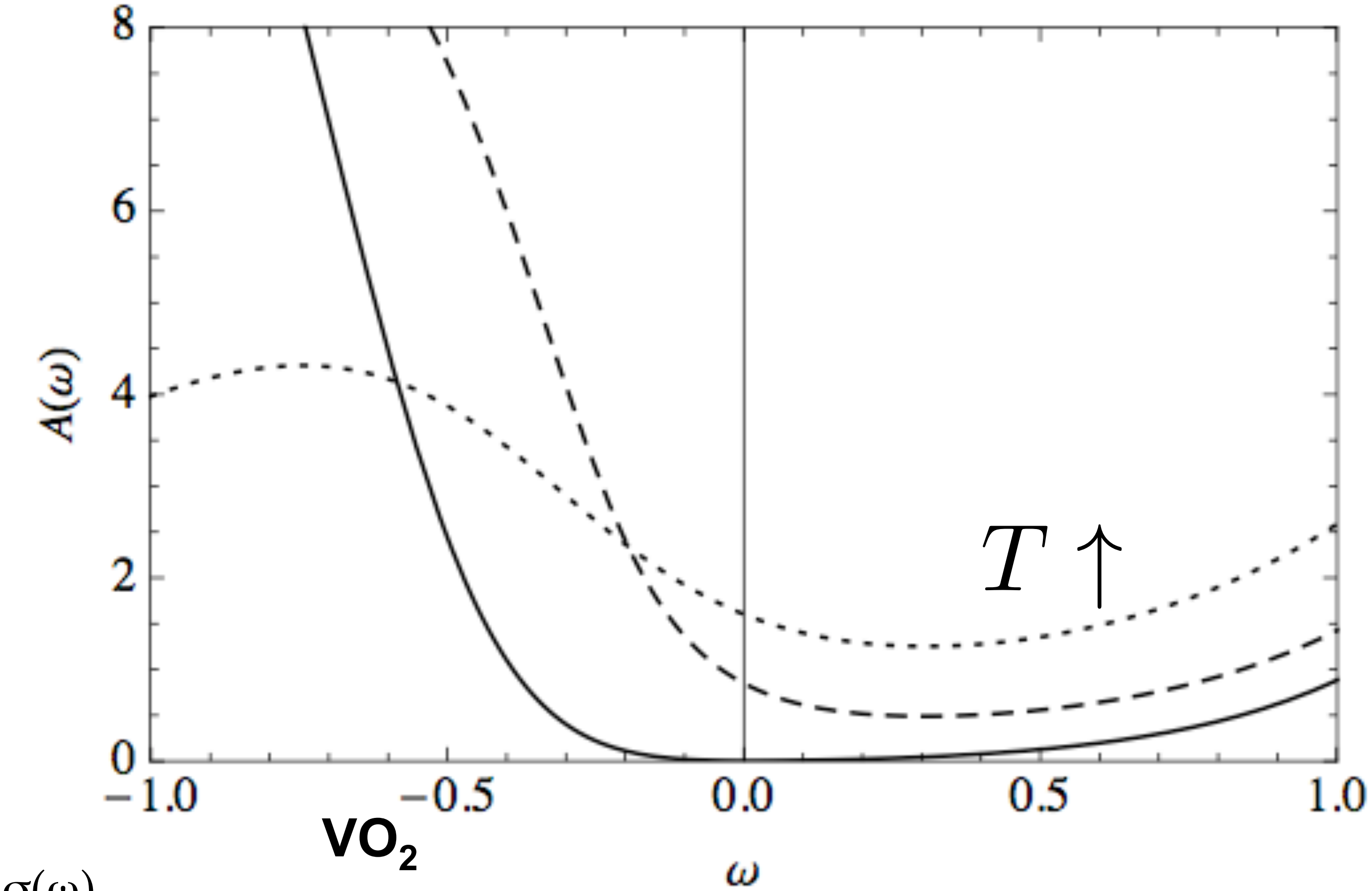


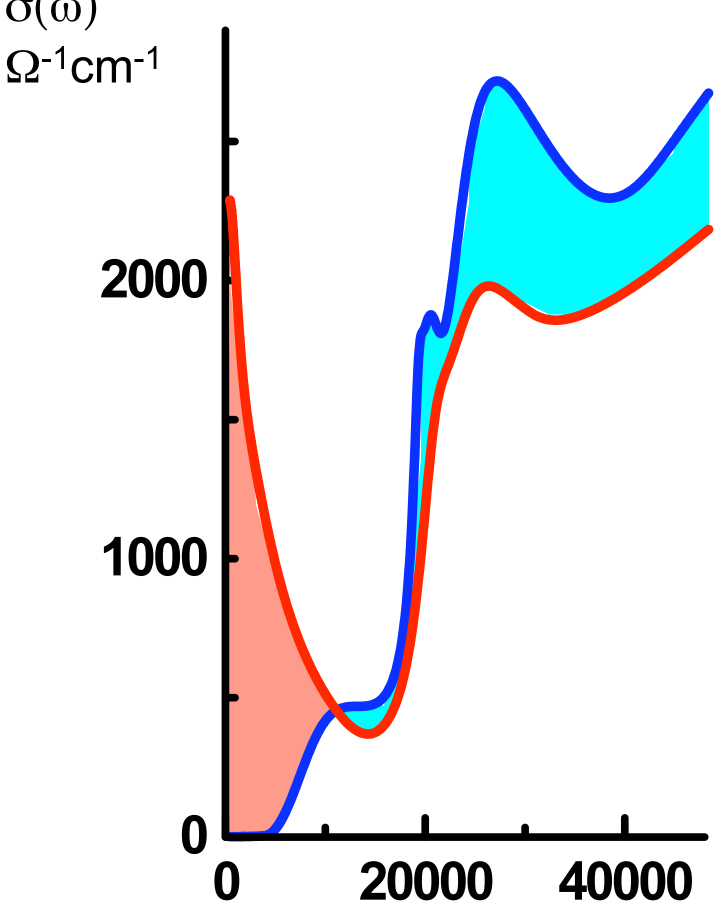
$$\frac{\Delta}{T_{\rm crit}} \approx 10$$

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

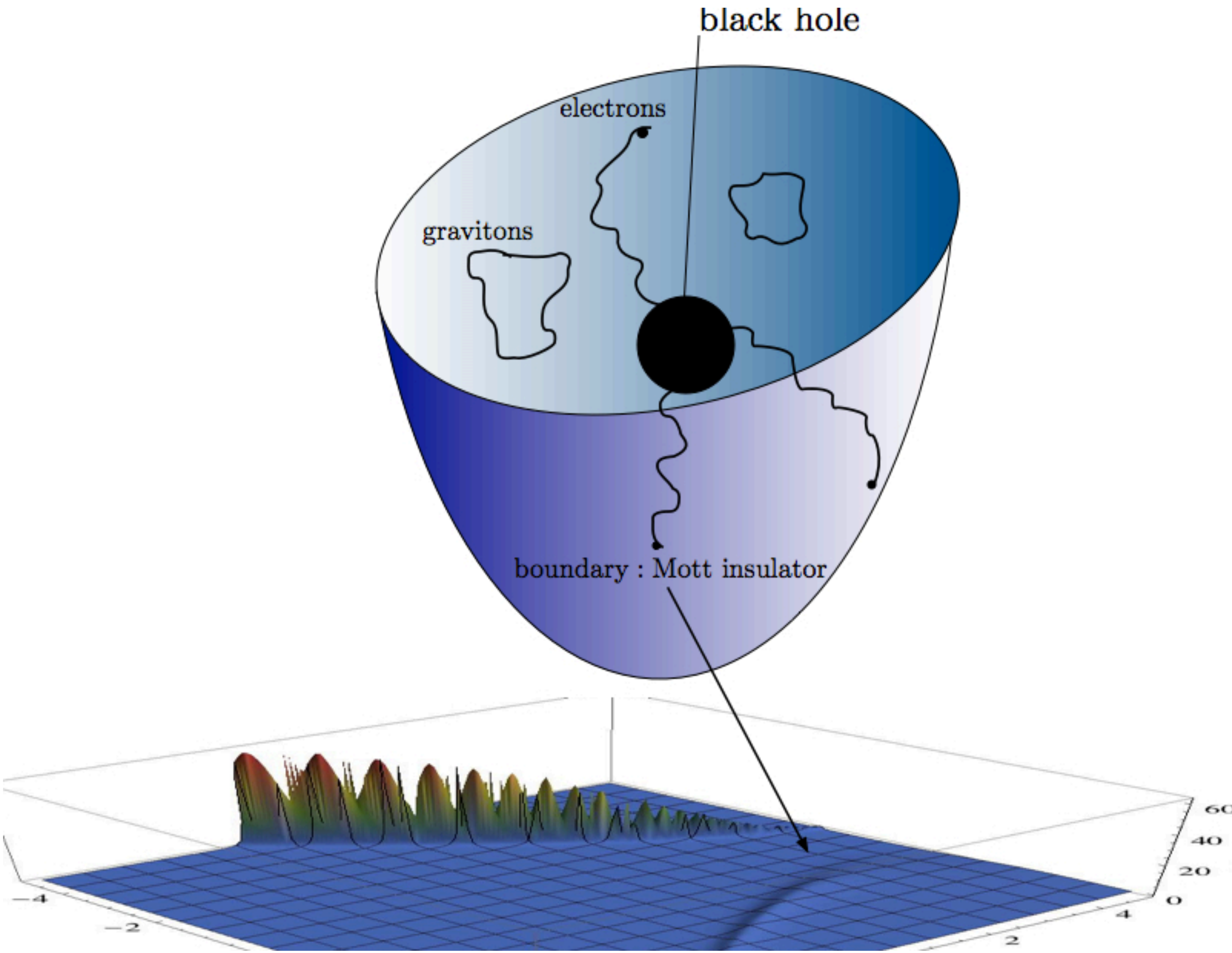
vanadium oxide



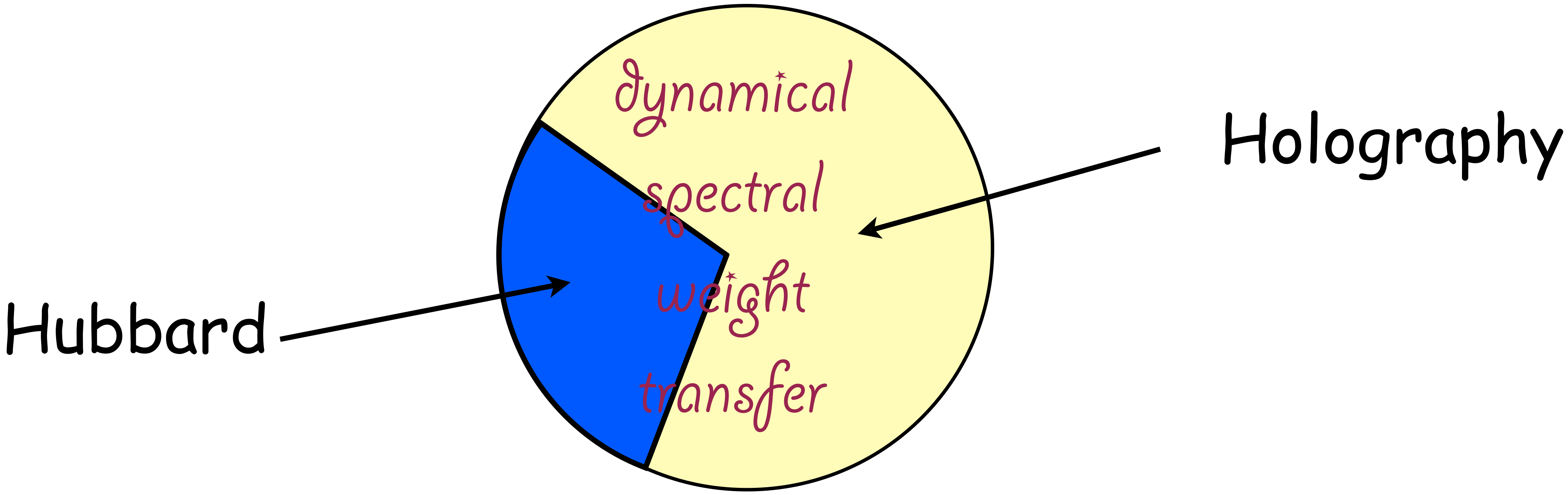


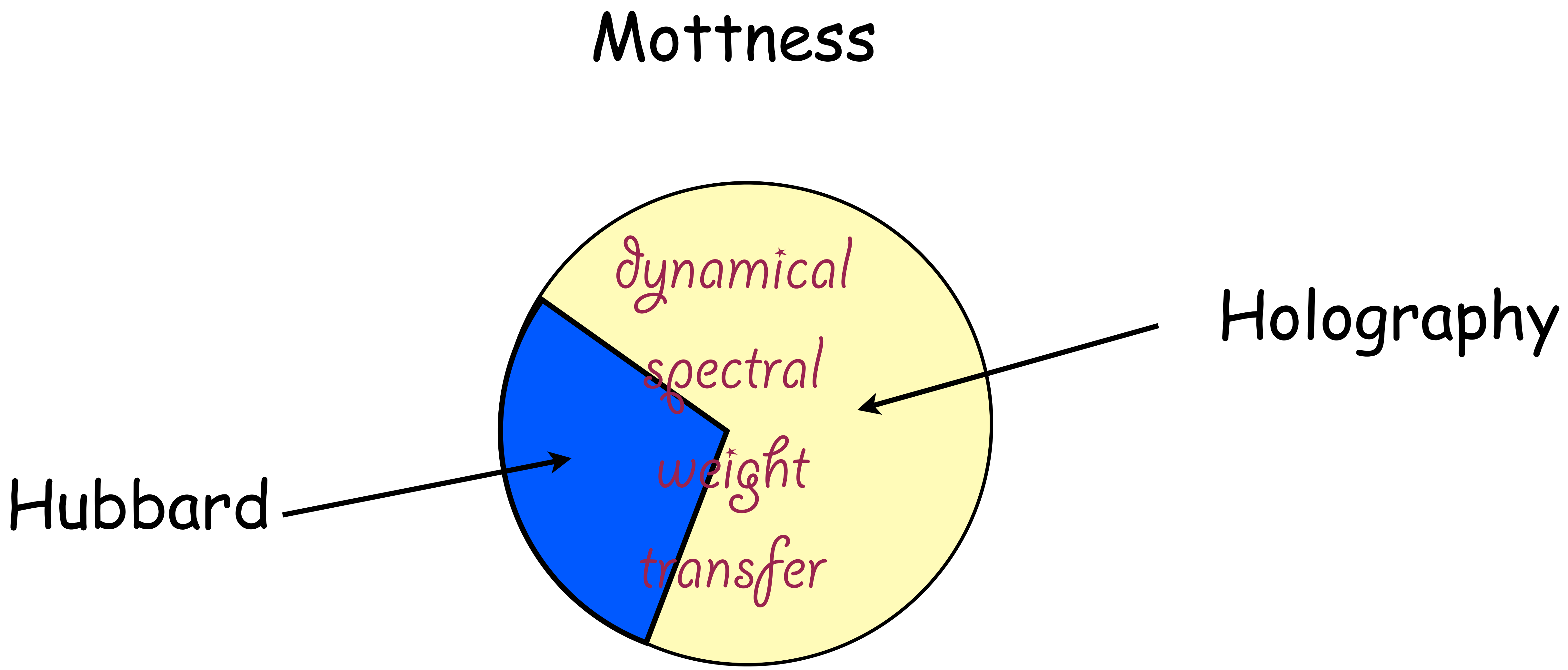


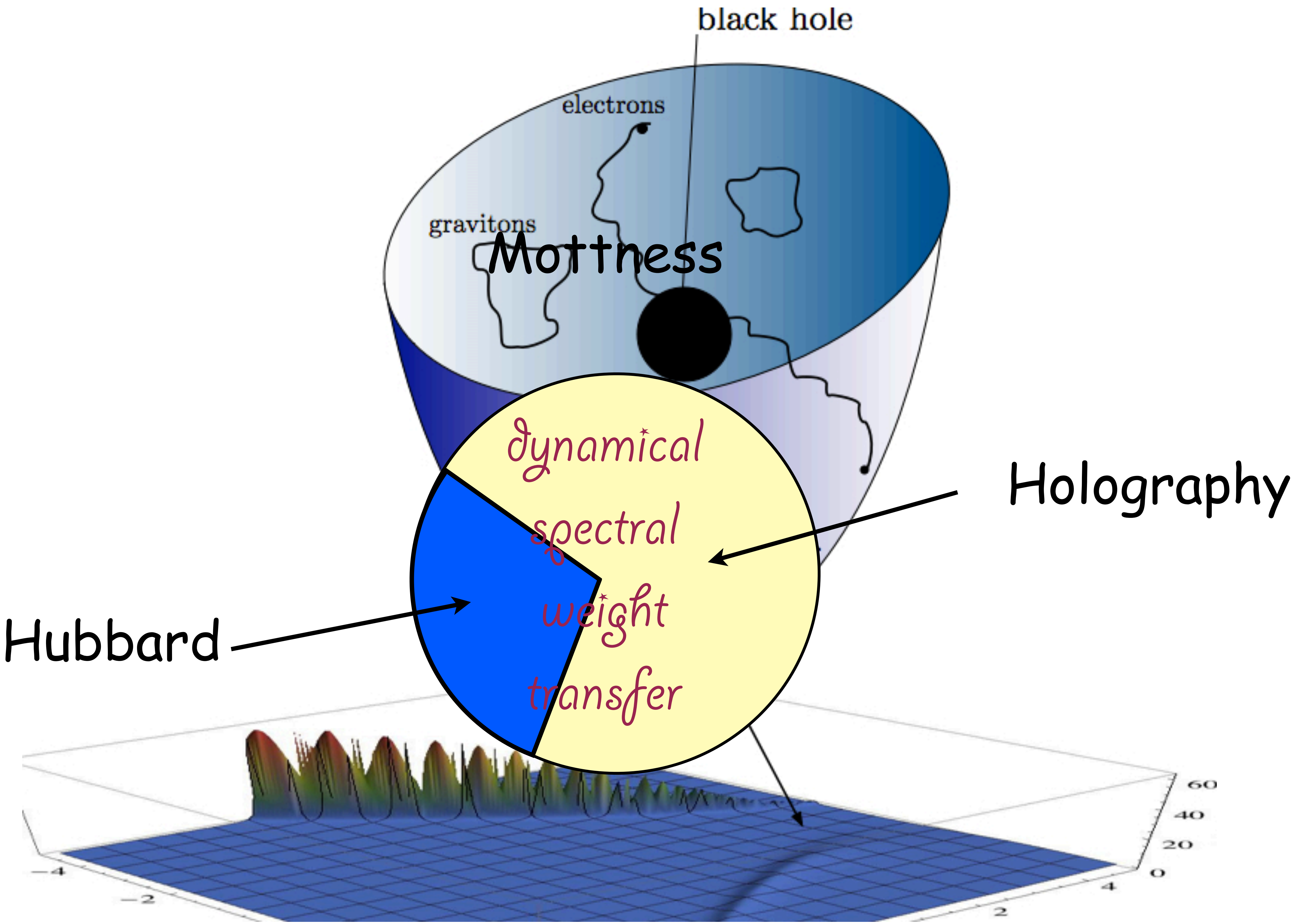
spectral weight
transfer
UV-IR mixing



black hole
electrons
gravitons
boundary : Mott insulator
60
40
20
0
−4
−2
2
4


Holography
Hubbard
dynamical
spectral
weight
transfer


Mottness
dynamical
spectral
weight
transfer
Holography
Hubbard



black hole
electrons
gravitons
Mottness
dynamical
spectral
weight
transfer
Holography
Hubbard
60
40
20
0
−4
−2
2
4