Mottness and Holography: A Discrete Marriage

Thanks to:
NSF, EFRC (DOE)

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emergent

gravity

spectral
weight
transfer
2-particle probe

YBa$_2$Cu$_3$O$_{y}$
E//CuO$_2$

$\sigma(\omega)$
$\Omega^{-1} \text{cm}^{-1}$

$y=6.6$
$y=6.1$
spectral weight transfer

2-particle probe

\[ \sigma(\omega) \Omega^{-1}\text{cm}^{-1} \]

- YBa\(_2\)Cu\(_3\)O\(_y\)
- E\(/\)CuO\(_2\)

\(y = 6.6\)

\(y = 6.1\)

1-particle

NORMALIZED FLUORESCENCE YIELD

\[ \text{PHOTON ENERGY (eV)} \]

- La\(_{2-x}\)Sr\(_x\)CuO\(_4\)
- La\(_2\)CuO\(_4\)0.05

- \(x = 0.15, 0.10, 0.07, 0.04, 0.02, 0.00\)
skeletal weight transfer

2-particle probe

[Graph showing spectral weight transfer for YBa$_2$Cu$_3$O$_y$ in E//CuO$_2$]

$\sigma(\omega)$

$\Omega^{-1}\text{cm}^{-1}$

$\nu=6.6$

$\nu=6.1$

1-particle

[Graph showing normalized fluorescence yield for La$_2$O$_2$,CuO$_4$, La$_2$CuO$_4$,005, and La$_2$CuO$_{0.05}$]

SC state

non-BCS
spectral weight transfer

2-particle probe
YBa$_2$Cu$_3$O$_y$
El/CuO$_2$

\[ \sigma(\omega) \Omega^{-1}\text{cm}^{-1} \]

\[ y = 6.6 \]

\[ y = 6.1 \]

1-particle

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

non-BCS

SC state

\[ 8\hbar^2 A_{\text{D}}(\text{eV}^2) \]

\[ 8\hbar^2 A_{\text{H}}(\text{eV}^2) \]

\[ T^2(10^4 \text{K}^2) \]
spectral weight transfer

2-particle probe

YBa$_2$Cu$_3$O$_y$

El/CuO$_2$

$\sigma(\omega)$

$\Omega^{-1}$cm$^{-1}$

$\nu=6.6$

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1-particle

physics of a non-rigid band:

UV-IR mixing

non-BCS

SC state

Wilsonian program

holography
Is spectral weight transfer important?
Fermi Arcs

P. Johnson, PRL 2011

Na-CCOC
(Shen, Science 2006)
Fermi Arcs

P. Johnson, PRL 2011

Na-CCOC
(Shen, Science 2006)
Fermi Arcs

$\epsilon(k)$ seen

not seen zeros (incoherence)

Na-CCOC
(Shen, Science 2006)

P. Johnson, PRL 2011
Fermi Arcs

can we explain this?

seen

not seen

zeros (incoherence)

meaning?

can we explain this?
Where do the zeros come from?

\[ G(\omega, k) = \frac{\cos^2 \theta}{\omega - \omega_+} + \frac{\sin^2 \theta}{\omega - \omega_-} = \frac{Z}{\omega - \epsilon_k - \Sigma(\omega, k)} \]

Mixing between two bands
Where do the zeros come from?

\[ G(\omega, k) = \frac{\cos^2 \theta}{\omega - \omega_+} + \frac{\sin^2 \theta}{\omega - \omega_-} = \frac{Z}{\omega - \epsilon_k - \Sigma(\omega, k)} \]

Mixing between 'two' bands
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Mixing between two bands

phenomenology: YRZ, Norman, Sachdev, Imada,...
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Mixing between two bands

Mott Problem

density of states

not rigid bands: spectral weight transfer

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Mixing between two bands

Mott Problem

-density of states

not rigid bands: spectral weight transfer

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UV-IR mixing

LHB

UHB
zeros of Hubbard model: Exact Results
zeros of Hubbard model: Exact Results

\[ G(\omega, k) = \frac{1 + x}{\omega - \mu + U/2} + \frac{1 - x}{\omega - \mu - U/2} \]
zeros of Hubbard model: Exact Results

\[ \omega = \mu \]
\[ x = 0 \]

atomic limit

static spectral weight

\[ G(\omega, k) = \frac{1 + x}{\omega - \mu + U/2} + \frac{1 - x}{\omega - \mu - U/2} \]
zeros of Hubbard model: Exact Results

atomic limit
static spectral weight

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

\[\omega = \mu \quad x = 0\]

1/2-filling
p-h symmetry

\[\Re G^R > 0\]

\[\Re G^R < 0\]
zeros of Hubbard model: Exact Results

atomic limit

static spectral weight

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

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\[ \Re G^R < 0 \]
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No Fermi arcs
zeros of Hubbard model: Exact Results

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1/2-filling
p-h symmetry

No Fermi arcs

dynamical spectral weight transfer
quantum Mottness: $U$ finite

$U \gg t$

double occupancy in ground state!!

$W_{\text{PES}} > 1 + x$
beyond the atomic limit: any real system

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

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

$1 - x - \alpha$

density of states

dynamical spectral weight transfer

Harris & Lange, 1967
Beyond the atomic limit: any real system

\[ 1 + x + \alpha(t/U, x) \]

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

Intensity $> 1 + x$

Density of states

Harris & Lange, 1967

Dynamical spectral weight transfer
$1 + x + \alpha(t/U, x)$

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

Beyond the atomic limit: any real system

Density of states

Dynamical spectral weight transfer

Intensity $> 1 + x$

# of charge e states

Harris & Lange, 1967
Beyond the atomic limit: any real system

\[ 1 + x + \alpha(t/U, x) \]

\[ \alpha = \frac{t}{U} \sum_{ij} \langle c_i^{\dagger} c_j \sigma \rangle > 0 \]

1 - x - \alpha

Intensity \(>1+x\)

# of charge e states

# of electron states in lower band

Harris & Lange, 1967

dynamical spectral weight transfer

density of states
Beyond the atomic limit: any real system

\[ 1 + x + \alpha(t/U, x) \]

\[ \alpha = \frac{t}{U} \sum_{ij} \langle c_i^{\dagger} c_j \rangle > 0 \]

Intensit\textgreater;\textasciitilde;1+x

\# of charge e states

\# of electron states in lower band

not exhausted by counting electrons alone?

Density of states

Harris & Lange, 1967

dynamical spectral weight transfer
Low-energy physics ala Wilson

\[ 1 + x + \alpha(t/U, x) \]

\[ \int \] d(UHB)
Low-energy physics ala Wilson

1 + x + α(t/U, x) charge 2e stuff

Density of states

∫

d(UHB)

produces zeros in lower band
Key Idea: Extended Hilbert Space \( \mathcal{H}_C \otimes \mathcal{H}_D \) + Integrate out D’s

Fermionic (one per site)

Unphysical Hilbert space

\[ \delta(D - \theta c_\uparrow c_\downarrow) \]
Key Idea: Extended Hilbert Space \( \mathcal{H}_C \otimes \mathcal{H}_D \) + Integrate out D's

Fermionic (one per site)

Unphysical Hilbert space

\[ \delta(D - \theta c^\uparrow c^\downarrow) \]

\[ \theta \varphi_i^\dagger \]

charge 2e boson
$1 + x$

$$\mathcal{L} = \mathcal{L}_{\text{projected}}(c) + \mathcal{L}_{\text{spin}} + \mathcal{L}_{\text{charge}}(\varphi, c, c^{\dagger})$$

$t$-$J$ model
charge dynamics due to mixing

\[ L = L_{\text{projected}}(c) + L_{\text{spin}} + L_{\text{charge}}(\varphi, c, c^\dagger) \]

\[ 1 + x + \alpha \quad \text{t-J model} \quad 1 - x - \alpha(t/U, x) \]
charge dynamics due to mixing

\[ 1 + x + \alpha - (t/U, x) - \alpha(t/U, x) \]

\[ L = L_{\text{projected}}(c) + L_{\text{spin}} + L_{\text{charge}}(\varphi, c, c^\dagger) \]

\[ 1 + x \]

\[ \mu \]

spectral function

quadratic
charge dynamics due to mixing

\[
1 + x + \alpha
\]

\[
1 - x - \alpha \left( \frac{t}{U}, x \right)
\]

\[
L = L_{\text{projected}}(c) + L_{\text{spin}} + L_{\text{charge}}(\varphi, c, c^\dagger)
\]

spectral function

quadratic
The t-J model is given by:

\[ \mathcal{L} = \mathcal{L}_{\text{projected}}(c) + \mathcal{L}_{\text{spin}} + \mathcal{L}_{\text{charge}}(\varphi, c, c^\dagger) \]

\[ F = -\frac{1}{\beta} \ln Z = \sum_{\mathbf{q}} \sum_{\varphi_0} F[\varphi_0 e^{i\mathbf{q} \cdot \mathbf{r}}] \]

Charge dynamics due to mixing is described by the spectral function approach, where:

\[ \varphi_i \rightarrow |\varphi_0| e^{i\mathbf{q} \cdot \mathbf{r}_i} \]
Free energy minimization

\[ \varphi_i \rightarrow |\varphi_0| e^{i\mathbf{q} \cdot \mathbf{r}_i} \]

\[ F[\varphi_0 e^{i\mathbf{q} \cdot \mathbf{r}}] - F[\varphi_0] \]

Probability \((\pi, \pi)\) is most likely

\[ \mathcal{L}_{\text{charge}}(\varphi, c, c^\dagger) \sim \varphi c_\uparrow^\dagger c_\downarrow^\dagger + \text{c.c.} \]
\[ G(i\omega_n, k) = \int d|\varphi||\varphi| P(\varphi) G(i\omega_n, k)|_{\varphi_q=\delta_q,\pi} |\varphi| \]

\[ G(i\omega_n, k) = \frac{\tilde{g_t}}{i\omega_n - \mu - \tilde{g_t}\epsilon_k - \Sigma_\pm(i\omega_n, k)} \]

\[ \Sigma_\pm(i\omega_n, k) = \frac{s_{k,q}^2 \varphi_q \varphi_q^*}{i\omega_n - \mu \pm \tilde{g_t}\epsilon_{q-k}} , \]
Green Function and Self Energy

\( \varphi_i \rightarrow |\varphi_0| e^{i\mathbf{q} \cdot \mathbf{r}_i} \quad \mathbf{q} = (\pi, \pi) \)

\[
G(\omega, \mathbf{k}) = -\text{FT} \left\langle \mathcal{T}_\tau \tilde{c}_{i\sigma}(\tau) \tilde{c}^\dagger_j(0) \right\rangle = \frac{g_t}{\omega - \epsilon_{\mathbf{k}} - \Sigma_{\mathbf{k}}} + O(t/U)
\]
Green Function and Self Energy

\[ \varphi_i \rightarrow |\varphi_0| e^{i\mathbf{q} \cdot \mathbf{r}_i} \quad \mathbf{q} = (\pi, \pi) \]

\[ G(\omega, \mathbf{k}) = -\text{FT} \langle \mathcal{T}_\tau \tilde{c}_{i\sigma}(\tau) \tilde{c}_{j}^\dagger(0) \rangle = \frac{g_t}{\omega - \epsilon_{\mathbf{k}} - \Sigma_{\mathbf{k}}} + O(t/U) \]

Self energy (particle - particle)

\[ \varphi \mathbf{c}_{\uparrow} \mathbf{c}_{\downarrow} \rightarrow \langle \varphi \rangle \mathbf{c}_{\uparrow} \mathbf{c}_{\downarrow} \]

\[ \Sigma_{\mathbf{k}} = \frac{|\varphi_0|^2}{\omega + \epsilon_{\mathbf{q} - \mathbf{k}}} \]

No Fermi Arcs

Fermi Arcs Incoherent feature
Green Function and Self Energy

\[ \varphi_i \rightarrow |\varphi_0| e^{i\mathbf{q} \cdot \mathbf{r}_i} \quad \mathbf{q} = (\pi, \pi) \]

\[ G(\omega, \mathbf{k}) = -\text{FT} \left\langle T_\tau \tilde{c}_{i\sigma}(\tau) \tilde{c}_{j}^\dagger(0) \right\rangle = \frac{g_t}{\omega - \epsilon_{\mathbf{k}} - \Sigma_{\mathbf{k}}} + O(t/U) \]

Self energy (particle - particle)

\[ \varphi c_{\uparrow}^{\dagger} c_{\downarrow}^{\dagger} \rightarrow \langle \varphi \rangle c_{\uparrow}^{\dagger} c_{\downarrow}^{\dagger} \]

\[ \Sigma_{\mathbf{k}} = \frac{|\varphi_0|^2}{\omega + \epsilon_{\mathbf{q} - \mathbf{k}}} \]

Self energy (particle - hole)

\[ \varphi c_{\uparrow}^{\dagger} c_{\downarrow}^{\dagger} \rightarrow (\varphi c_{\uparrow}^{\dagger}) \cdot c_{\downarrow}^{\dagger} \]

\[ \Sigma_{\mathbf{k}} = \frac{|\varphi_0|^2}{\omega - \epsilon_{\mathbf{q} - \mathbf{k}}} \]

No Fermi Arcs

Fermi Arcs Incoherent feature
Results

Fermi Arc

\[(1 - n_{\bar{\sigma}}) c_{\sigma}\]

Shadow band

\[\varphi c_{\uparrow}^{\dagger} c_{\downarrow}^{\dagger} \rightarrow (\varphi c_{\uparrow}^{\dagger}) \cdot c_{\downarrow}^{\dagger}\]

Pocket size \(\sim x\)

Electron pocket?
Fermi arcs

composite or bound states not in UV theory
Fermi arcs

composite or bound states not in UV theory

What computational tools do we have for spectral functions for strongly correlated electron systems?
why does this work at long wavelengths?
why does this work at long wavelengths?

the only difference between this and a theory is that this is not a theory
\[ \frac{dg(E)}{dlnE} = \beta(g(E)) \]

locality in energy
implement E-scaling with an extra dimension

\[ \frac{dg(E)}{d\ln E} = \beta(g(E)) \]

locality in energy
gauge-gravity duality (Maldacena, 1997)

implement E-scaling with an extra dimension

\[ \frac{dg(E)}{d \ln E} = \beta(g(E)) \]

locality in energy
what’s the geometry?
what's the geometry?

$$\frac{dg(E)}{dlnE} = \beta(g(E)) = 0$$

scale invariance (continuous)
what’s the geometry?

\[ \frac{dg(E)}{d\ln E} = \beta(g(E)) = 0 \]

scale invariance (continuous)

\[ E \rightarrow \lambda E \]
\[ x^\mu \rightarrow x^\mu / \lambda \]
what’s the geometry?

\[
\frac{dg(E)}{dlnE} = \beta(g(E)) = 0
\]

scale invariance (continuous)

\[
E \rightarrow \lambda E
\]
\[
x^\mu \rightarrow x^\mu / \lambda
\]

solve Einstein equations
what’s the geometry?

\[
\frac{dg(E)}{d\ln E} = \beta(g(E)) = 0
\]

scale invariance (continuous)

\[E \rightarrow \lambda E\]
\[x^\mu \rightarrow x^\mu / \lambda\]

solve Einstein equations

\[
ds^2 = \left(\frac{u}{L}\right)^2 \eta_{\mu\nu} dx^\mu dx^\nu + \left(\frac{L}{E}\right)^2 dE^2
\]

anti de-Sitter space
fields \( \phi \) 

operators \( O \)
Claim: \[ Z_{\text{QFT}} = e^{-S_{\text{on-shell}}^{\text{ADS}}} (\phi (\phi \partial_{\text{ADS}} = J_\mathcal{O})) \]
\[ Z_{\text{QFT}} = e^{-S_{\text{on-shell}}^{\text{ADS}}(\phi(\phi \partial_{\text{ADS}} = J_\mathcal{O}))} \]
\[ Z_{\text{QFT}} = e^{-S_{\text{on-shell}}^{\text{ADS}}(\phi(\phi \partial_{\text{ADS}} = J_\mathcal{O}))} \]
What gravitational theory gives rise to a gap in $\text{Im} G$ without spontaneous symmetry breaking?

dynamically generated gap: Mott gap (for probe fermions)
what has been done?
MIT, Leiden, McMaster,...
Charged system

$J^\mu$

$S_0$

$\psi$

$O_\psi$

RN-AdS

$ds^2, A_t$

UV

probe

what has been done?

MIT, Leiden, McMaster,...
what has been done?  
MIT, Leiden, McMaster,...
Charged system \( J^\mu \rightarrow S_0 \) probe \( J_\psi O_\psi \)

RN-AdS \( ds^2, A_t \)

UV \( \psi \) Dirac Eq.

in-falling boundary conditions

\[ \psi(r \rightarrow \infty) \approx ar^m + br^{-m} \]

Retarded Green function: \( G = \frac{b}{a} = f(UV (k_F), IR (q,m)) \)

\( a=0 \) defines FS

what has been done? MIT, Leiden, McMaster,...
what has been done?

MIT, Leiden, McMaster,...

in-falling boundary conditions

Retarded Green function:

\[ G = \begin{cases} a & \psi(r \to \infty) \\ \approx & ar^m + br^{-m} \\ = f(UV(k_F), IR(q,m)) \end{cases} \]

\( a = 0 \) defines FS
Charged system

\[ J_\mu \]

\[ S_0 \]

probe

\[ J_\psi O_\psi \]

RN-AdS

\[ ds^2, A_t \]

Dirac Eq.

\[ \psi \]

\[ \psi(r \to \infty) \approx ar^m + br^{-m} \]

in-falling boundary conditions

Retarded Green function:

\[ G = \frac{b}{a} = f(\text{UV (k_F), IR (q,m)}) \]

a=0 defines FS

what has been done?

MIT, Leiden, McMaster,...
\[ S_{\text{probe}}(\psi, \bar{\psi}) = \int d^d x \sqrt{-g} i \bar{\psi} (\Gamma^M D_M - m + \cdots) \psi \]
\[ S_{\text{probe}}(\psi, \bar{\psi}) = \int d^d x \sqrt{-g} i \bar{\psi} (\Gamma^M D_M - m + \cdots) \psi \]

what is hidden here?
\[ S_{\text{probe}}(\psi, \bar{\psi}) = \int d^d x \sqrt{-g} i \bar{\psi}(\Gamma^M D_M - m + \cdots) \psi \]

Consider \[ \sqrt{-g} i \bar{\psi}(\not{D} - m - i\rho F) \psi \]

What is hidden here?
QED anomalous magnetic moment of an electron
(Schwinger 1949)

\[ S_{\text{probe}}(\psi, \bar{\psi}) = \int d^d x \sqrt{-g} i \bar{\psi}(\Gamma^M D_M - m + \cdots) \psi \]

consider \[ \sqrt{-g} i \bar{\psi}(\mathcal{D} - m - ipF) \psi \]

what is hidden here?

\[ F_{\mu \nu} \Gamma^{\mu \nu} \]
QED anomalous magnetic moment of an electron
(Schwinger 1949)

$S_{\text{probe}}(\psi, \bar{\psi}) = \int d^d x \sqrt{-g} i \bar{\psi} (\Gamma^M D_M - m + \cdots) \psi$

what is hidden here?

consider

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

what happens at the boundary?
How is the spectrum modified?

P=0, MIT, Leiden, McMaster

Fermi surface peak
How is the spectrum modified?

P=0, MIT, Leiden, McMaster

Fermi surface peak
How is the spectrum modified?

P=0, MIT, Leiden, McMaster

Fermi surface peak

$P > 4.2$
How is the spectrum modified?

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How is the spectrum modified?

Fermi surface peak

dynamically generated gap:

$P > 4.2$
How is the spectrum modified?

P=0, MIT, Leiden, McMaster

Fermi surface peak

spectral weight transfer

dynamically generated gap:

$P > 4.2$
How is the spectrum modified?

Gubser, Gauntlett, 2011 ‘similar’ results

Fermi surface peak

dynamically generated gap:

spectral weight transfer

$P = 0$, MIT, Leiden, McMaster

$P > 4.2$
Sonner, 2011 (top-down gravitino model)
Mechanism?

\[ \psi \propto ar^\Delta + br^{-\Delta} \]
\[ \psi \propto ar^\Delta + br^{-\Delta} \]
$\psi \propto ar^\Delta + br^{-\Delta}$

Operators where is $k_F$
Mechanism?

$\psi \propto ar^\Delta + br^{-\Delta}$

emergent IR CFT

log-oscillatory

$k_F$ moves into log-oscillatory region: IR $O_{\pm}$ acquires a complex dimension
Schwarzschild (no log-oscillatory region)
finite density of states
\[ G(\omega, k) = G(\omega \lambda^n, k) \]

Discrete scale invariance (DSI)
$G(\omega, k) = G(\omega \lambda^n, k)$

**Discrete scale invariance (DSI)**

$\mathcal{O} = \mu(\lambda) \mathcal{O}(\lambda r)$
\[ G(\omega, k) = G(\omega \lambda^n, k) \]

**Discrete scale invariance (DSI)**

\[ \mathcal{O} = \mu(\lambda) \mathcal{O}(\lambda r) \]

\[ 1 = \mu \lambda^\Delta \]
\[ G(\omega, k) = G(\omega \lambda^n, k) \]

**Discrete scale invariance (DSI)**

\[ \mathcal{O} = \mu(\lambda) \mathcal{O}(\lambda r) \]

\[ e^{2\pi in} = 1 = \mu \lambda^\Delta \]
\[ G(\omega, k) = G(\omega \lambda^n, k) \]

**Discrete scale invariance (DSI)**

\[ \mathcal{O} = \mu(\lambda) \mathcal{O}(\lambda r) \]

\[ e^{2\pi i n} = 1 = \mu \lambda^\Delta \]

\[ \Delta = -\frac{\ln \mu}{\ln \lambda} + \frac{2\pi i n}{\ln \lambda} \]
\[ G(\omega, k) = G(\omega \lambda^n, k) \]

Discrete scale invariance (DSI)

\[ \mathcal{O} = \mu(\lambda) \mathcal{O}(\lambda r) \]

\[ e^{2\pi i n} = 1 = \mu \lambda^\Delta \]

\[ \Delta = -\frac{\ln \mu}{\ln \lambda} + \frac{2\pi i n}{\ln \lambda} \]
\[ G(\omega, k) = G(\omega \lambda^n, k) \]

**Discrete scale invariance (DSI)**

\[ O = \mu(\lambda)O(\lambda r) \]

\[ e^{2\pi i n} = 1 = \mu \lambda^\Delta \]

\[ \Delta = -\frac{\ln \mu}{\ln \lambda} + \frac{2\pi i n}{\ln \lambda} \]

scaling dimension depends on scale

\[ \lambda_n = \lambda^n \]

magnification

n=0: CSI
Finite Temperature Mott transition

\[ T/\mu = 5.15 \times 10^{-3} \]

\[ T/\mu = 3.92 \times 10^{-2} \]
Finite Temperature Mott transition

\[ \Delta \approx 20 \]

\[ \frac{T}{\mu} = 5.15 \times 10^{-3} \]

\[ \frac{T}{\mu} = 3.92 \times 10^{-2} \]

vanadium oxide
Finite Temperature Mott transition

\[ \Delta T \approx 20 \text{ vanadium oxide} \]

\[ \frac{T/\mu}{T_{\text{crit}}} = 5.15 \times 10^{-3} \]

\[ \frac{T/\mu}{T_{\text{crit}}} = 3.92 \times 10^{-2} \]

\[ \frac{\Delta}{T_{\text{crit}}} \approx 10 \]

\[ \frac{\Delta}{T_{\text{crit}}} \approx 20 \text{ vanadium oxide} \]
spectral weight
transfer
UV-IR mixing

\[ \sigma(\omega) \Omega^{-1} \text{cm}^{-1} \]

\[ T \uparrow \]

\[ p_1 \]

\[ p_3 \]
is CSI->DSI the symmetry that is ultimately broken in the Mott problem?
a.) yes

b.) no
holography

a.) yes ⌂

b.) no
a.) yes
b.) no

holography

VO_2, cuprates,...
holography

VO$_2$, cuprates,...

a.) yes ✓

b.) no

Does scaling in VO$_2$ obey: $\Lambda_{IR} = \Lambda_{UV} e^{-\pi/\sqrt{g_c - g}}$
holography

VO\textsubscript{2}, cuprates,...

a.) yes  √  

b.) no  

Does scaling in VO\textsubscript{2} obey: \[ \Lambda_{IR} = \Lambda_{UV} e^{-\pi/\sqrt{g_c-g}} \]

if yes: holography has solved the Mott problem
Holography

Hubbard

dynamical spectral weight transfer