Title: Disorder-induced zero bias anomalies in strongly correlated systems

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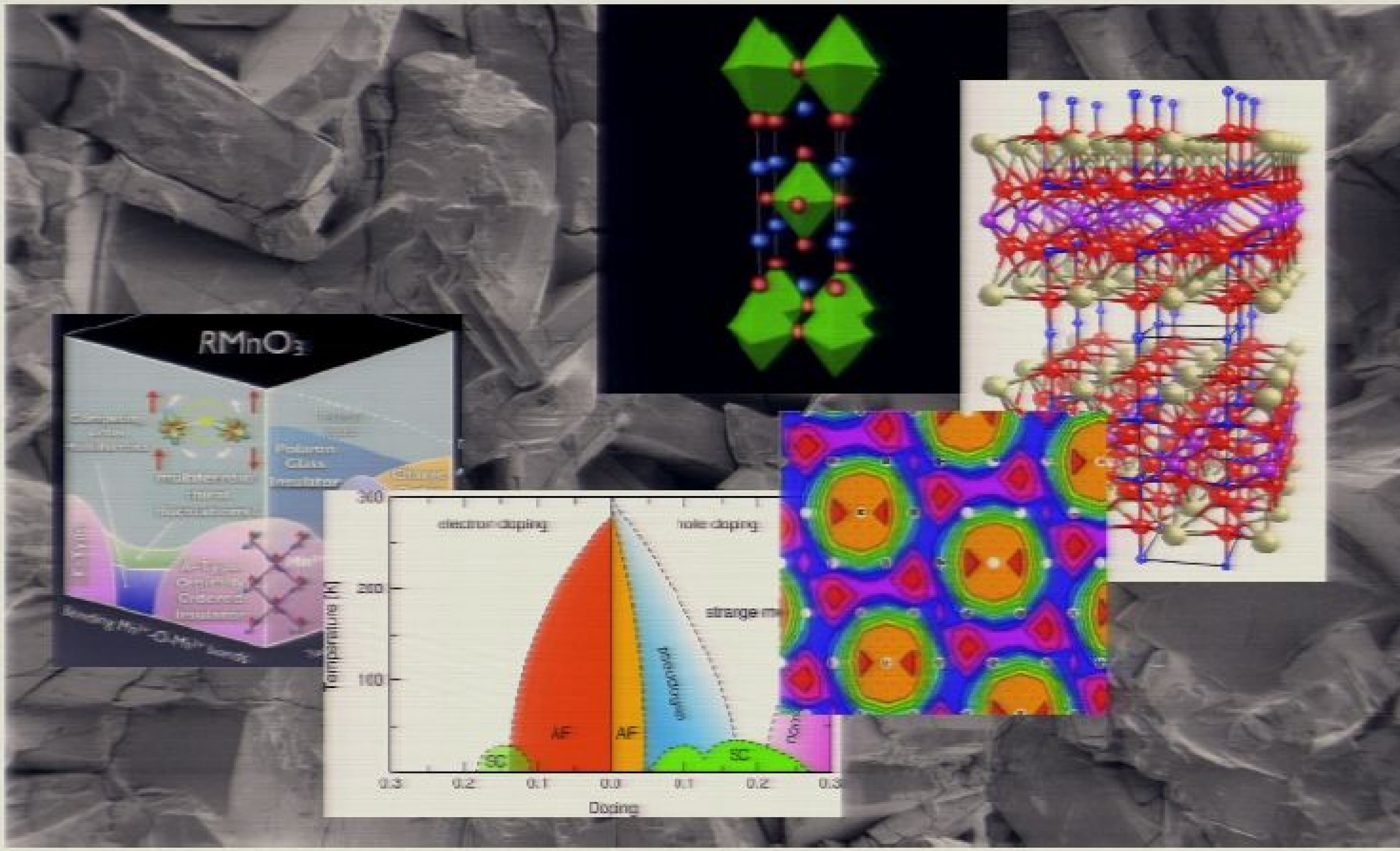
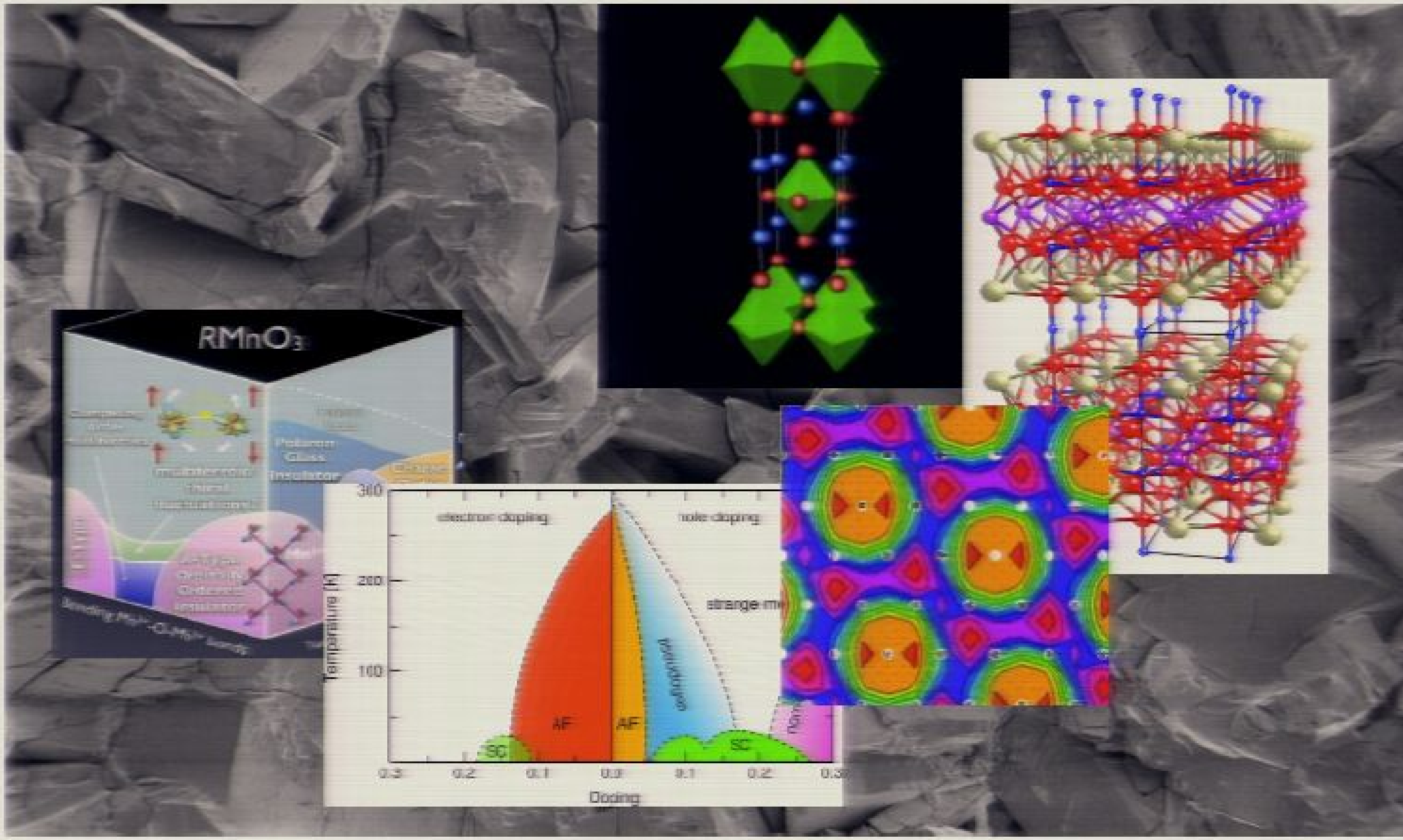
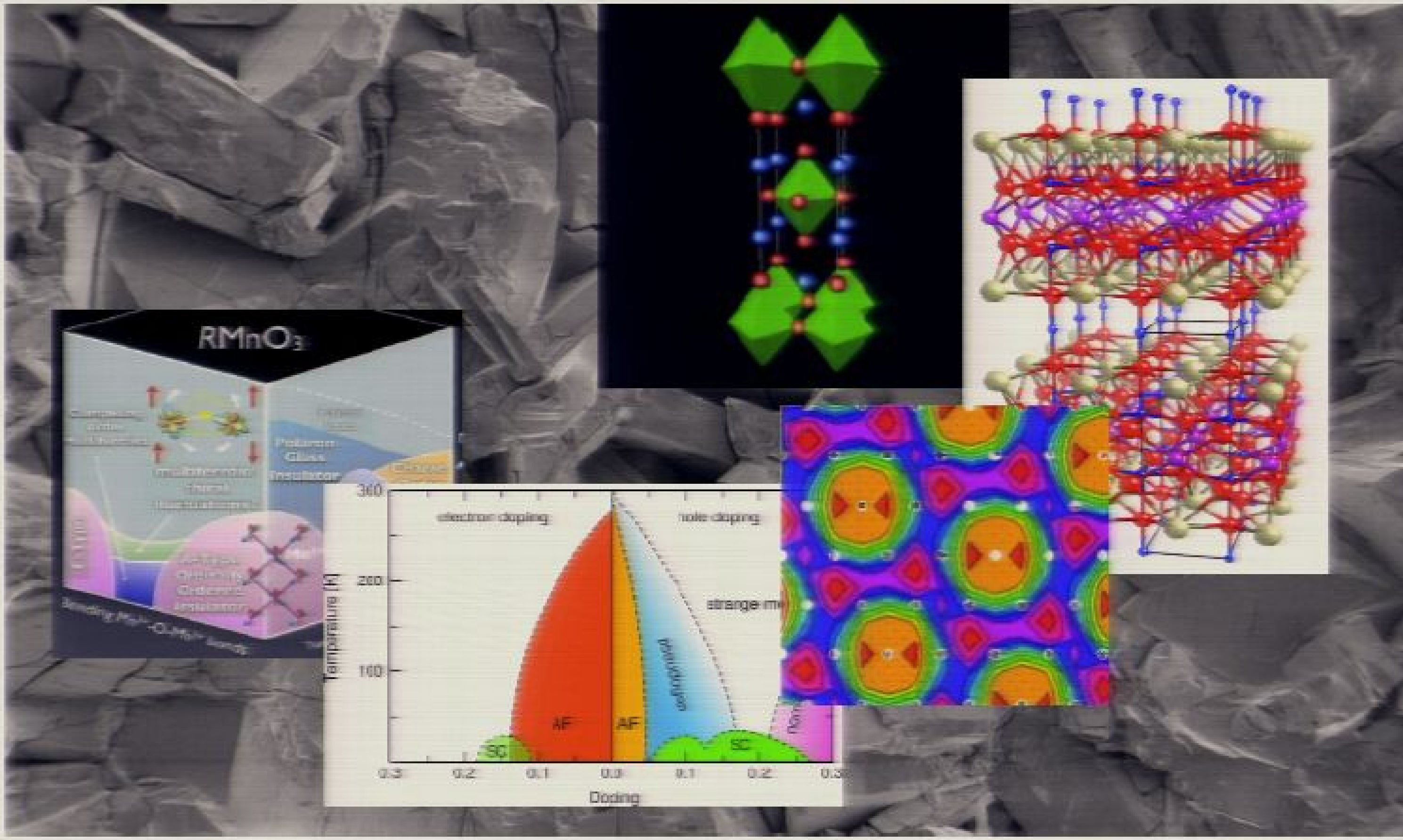
Abstract: Many of the most interesting electronic behaviors arise in materials with strong electron-electron correlations. Many of these same materials are disordered either intrinsically or due to doping. The combination of disorder and interactions generally gives rise to a feature in the density of states at the Fermi level, with two of the most influential examples being the Altshuler-Aronov anomaly and the Efros-Shklovskii Coulomb gap. Experiments on strongly correlated materials and recent numerical results on the Anderson-Hubbard model, however, show behavior which is inconsistent with both of these frameworks. This talk will present some of the features of the zero bias anomaly in strongly correlated systems, both in the case of a purely on-site interaction and in the presence of nearest-neighbor interactions, and it will describe the physical origin of some of these features.



What does disorder do to strongly correlated systems?



What does disorder do to strongly correlated systems?

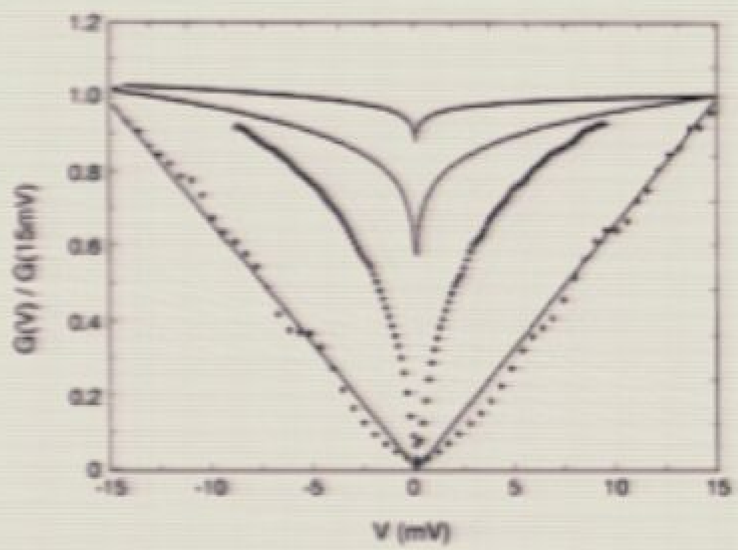


What does disorder do to strongly correlated systems?

What is a zero bias anomaly?

A feature in the single-particle density of states
at the Fermi level

(usually associated with disorder)



tunneling conductance of Be films
Butko, DiTusa and Adams, PRL **84** 1543 (2000)

Outline

Background

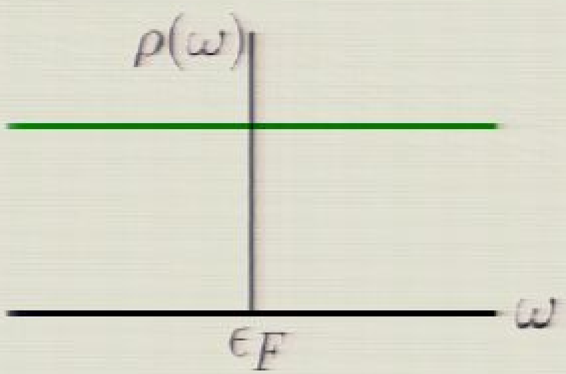
- weakly correlated metals (Altshuler & Aronov)
- atomic limit (Efros & Shklovskii)

Anderson-Hubbard model

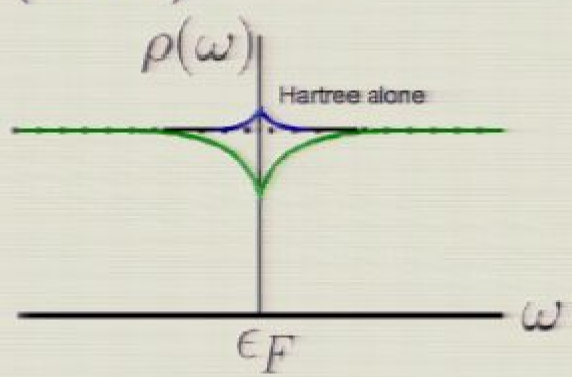
- numerical results
- physical picture
- temperature dependence
- extended interactions

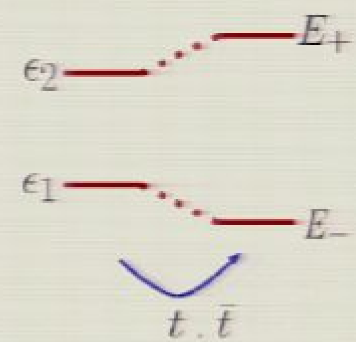
The Altshuler-Aronov zero-bias anomaly

either disorder
or interactions



both disorder
and interactions
(weak)

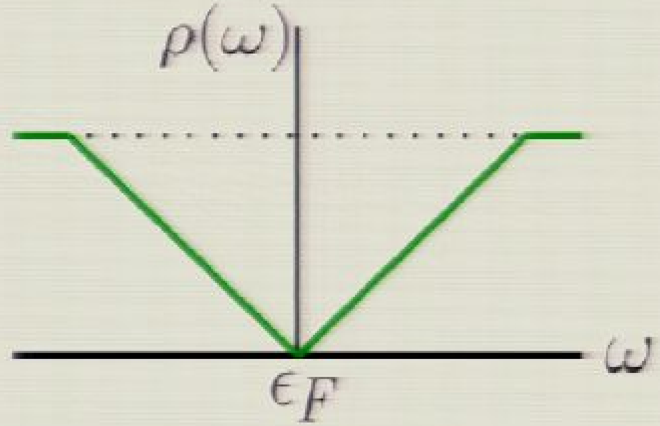




$$g(\epsilon) \propto \begin{cases} |\epsilon - \epsilon_F|^{1/2} & d = 3 \\ \ln|\epsilon - \epsilon_F| & d = 2 \end{cases}$$

The Efros-Shklovskii Coulomb gap

arbitrary disorder
1/r interactions
atomic limit

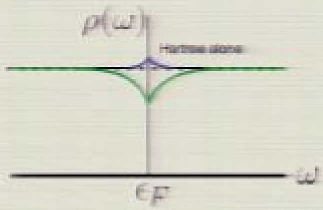


$$\Delta E_{-\epsilon/2}^{+\epsilon/2} > 0$$

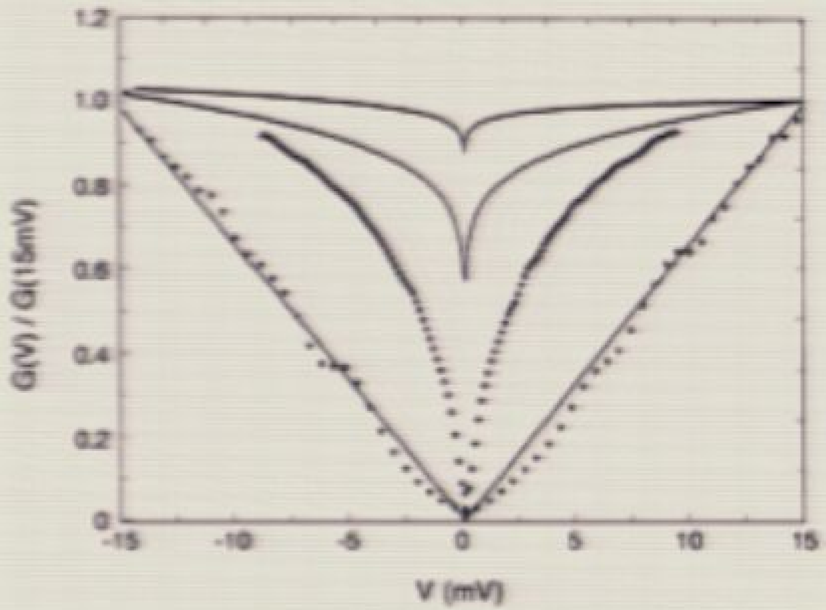
$$g < C\epsilon^{d-1}$$

$$g(\epsilon) \propto |\epsilon - \epsilon_F|^{d-1}$$

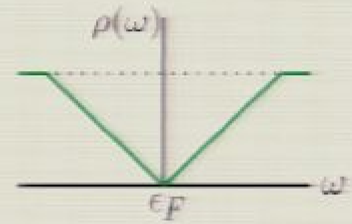
Smooth crossover in weakly interacting systems



Altshuler & Aronov



tunneling conductance of Be films
Butko, DiTusa and Adams,
PRL **84** 1543 (2000)



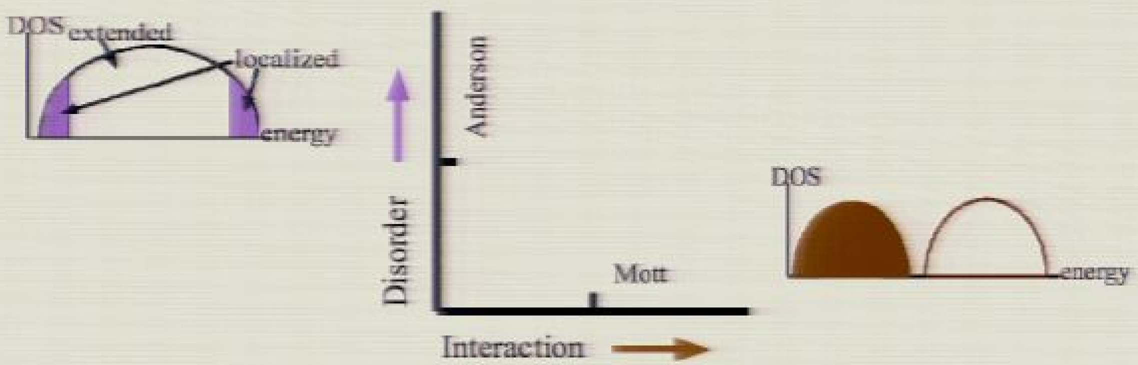
Efros & Shklovskii

The Anderson-Hubbard Model

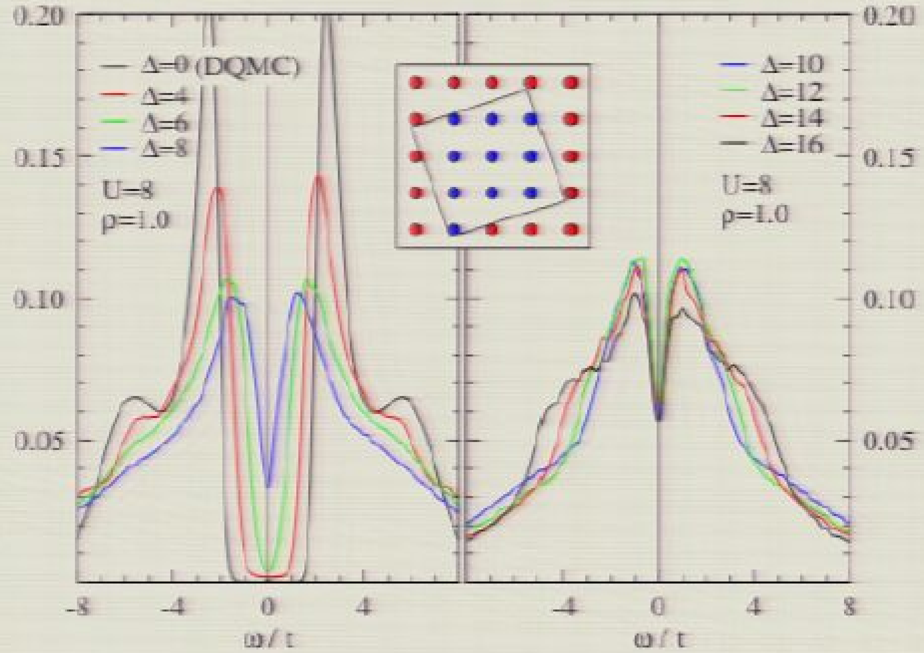
hopping, interactions, and disorder

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

$$P(\epsilon_i) = \frac{1}{\Delta} \Theta\left(\frac{\Delta}{2} - |\epsilon_i|\right)$$



Density of States of the Anderson-Hubbard model



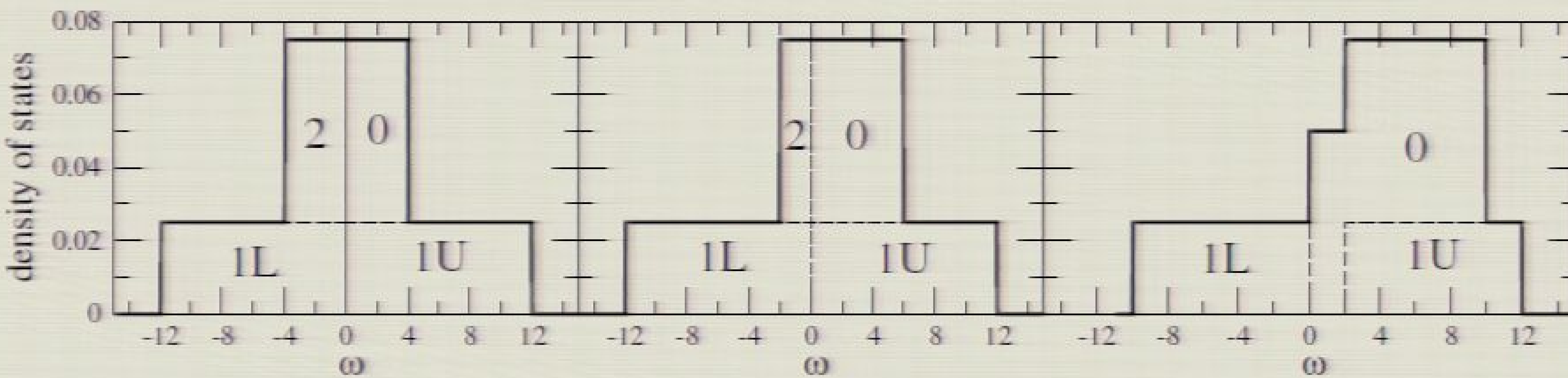
Chiesa, Chakraborty, Pickett and Scalettar, PRL **101**, 086401 (2008).

Zero bias anomaly: proportional to t; independent of U, Δ and filling

The atomic limit

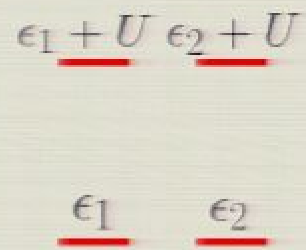
Individual sites:

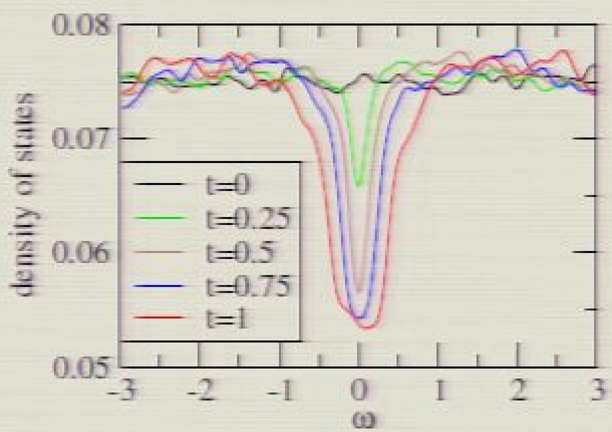
Ensemble of sites:

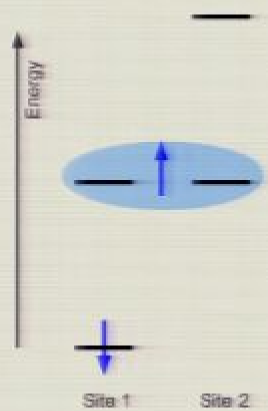


$t = 0$, $U = 12$, $\Delta = 20$, $\mu = U/2,\ U/3$, and 0

What hopping does in an ensemble of two-site systems

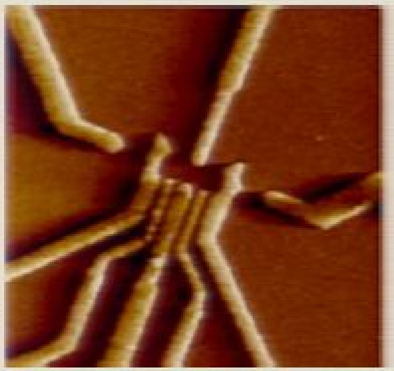


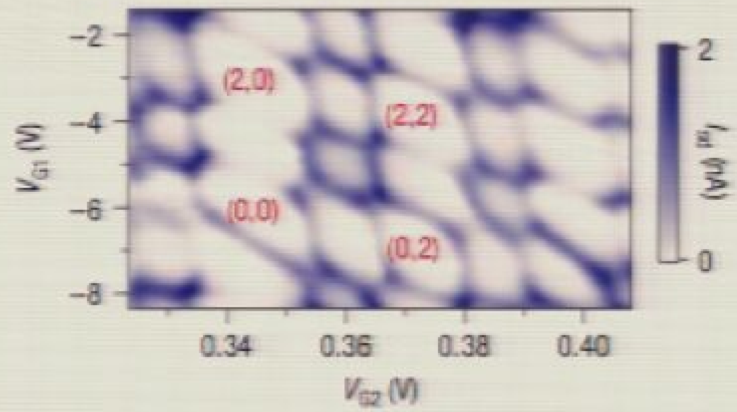




Kinetic-energy-driven zero bias anomaly.

Observable in double quantum dots?

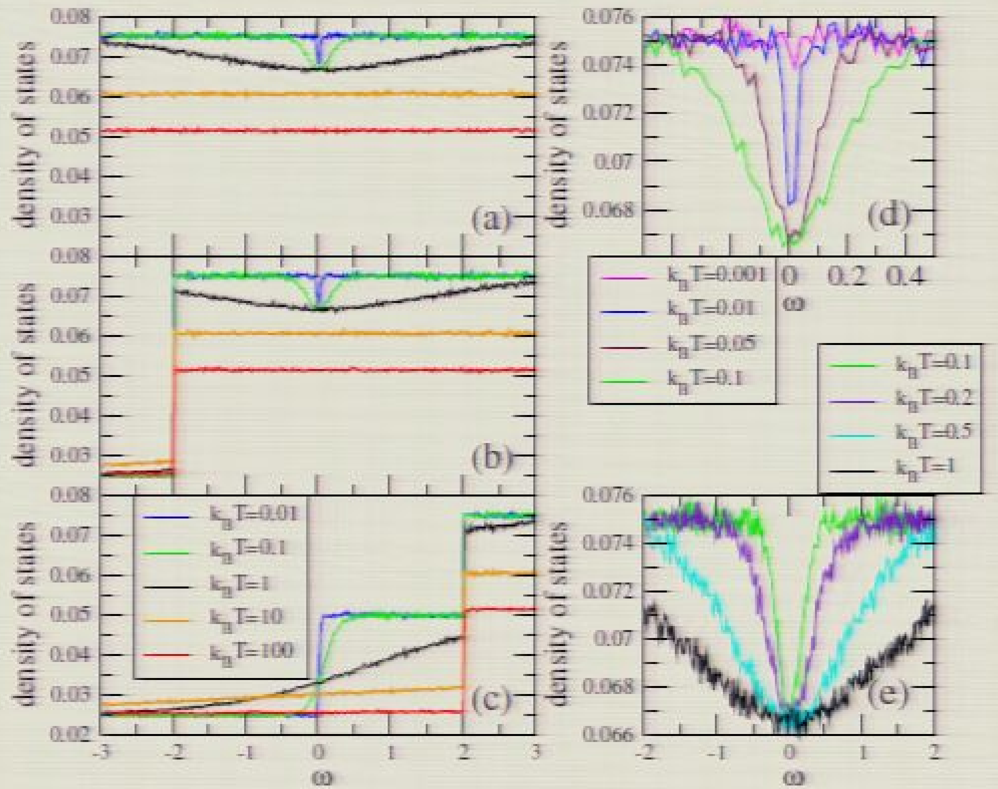




Jorgensen, et al, Nature Physics 4, 536 (2008)

Atomic limit $T > 0$ density of states

$t = 0$, $U = 12$, $\Delta = 20$, $\mu = U/2$, $U/3$, and 0



Thermally-driven zero bias anomaly.

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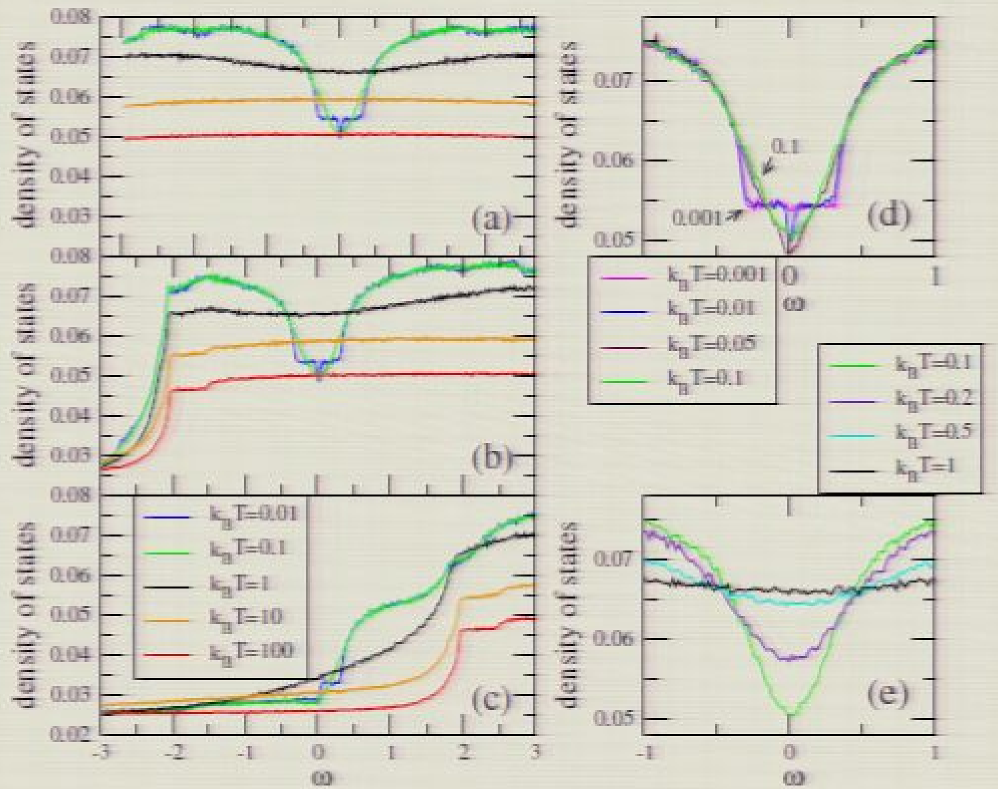
$T > 0$ density of states with hopping

$t = 0$, $U = 12$, $\Delta = 20$, $\mu = U/2$, $U/3$, and 0



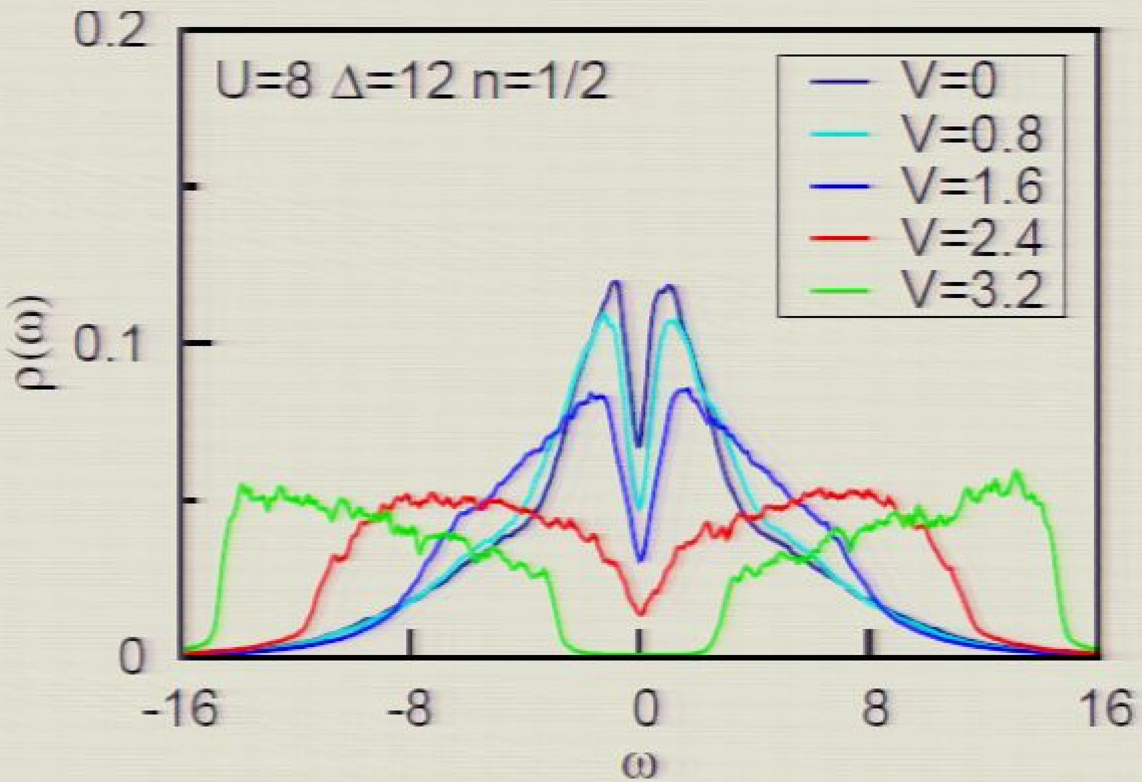
Kinetic and thermal zero bias anomalies add.

The extended Anderson-Hubbard model

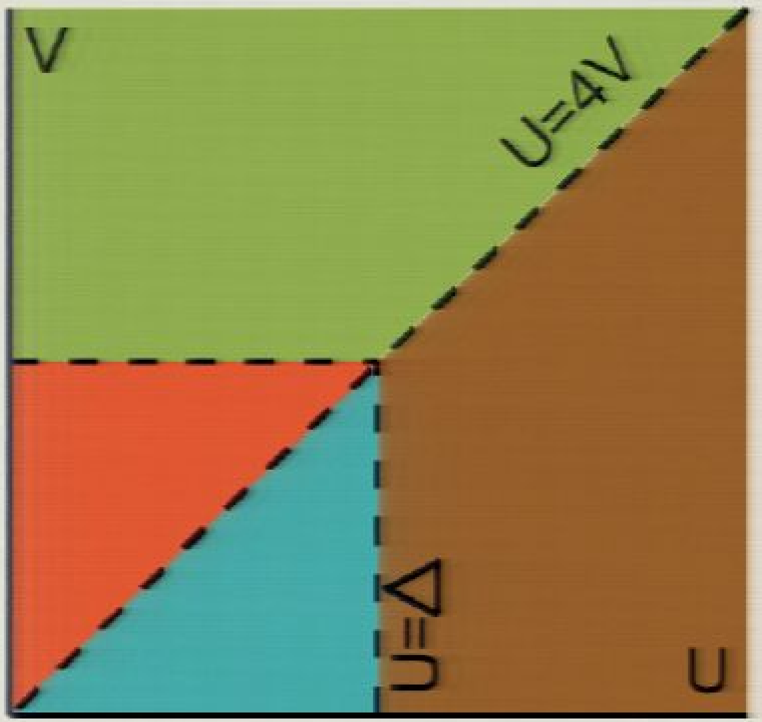
hopping, *local* interactions, disorder
plus nearest-neighbor interactions

$$\mathcal{H} = -t \sum_{\langle i,j \rangle, \sigma} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} + \sum_{i,\sigma} \epsilon_i n_{i\sigma} + \sum_{\langle i,j \rangle} V n_i n_j$$

Evolution of DOS with nonlocal interaction V



Parameter space

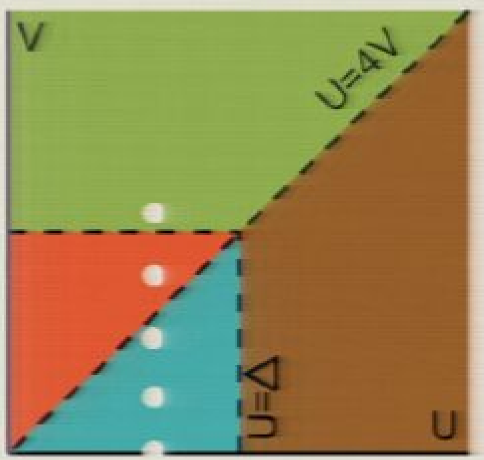


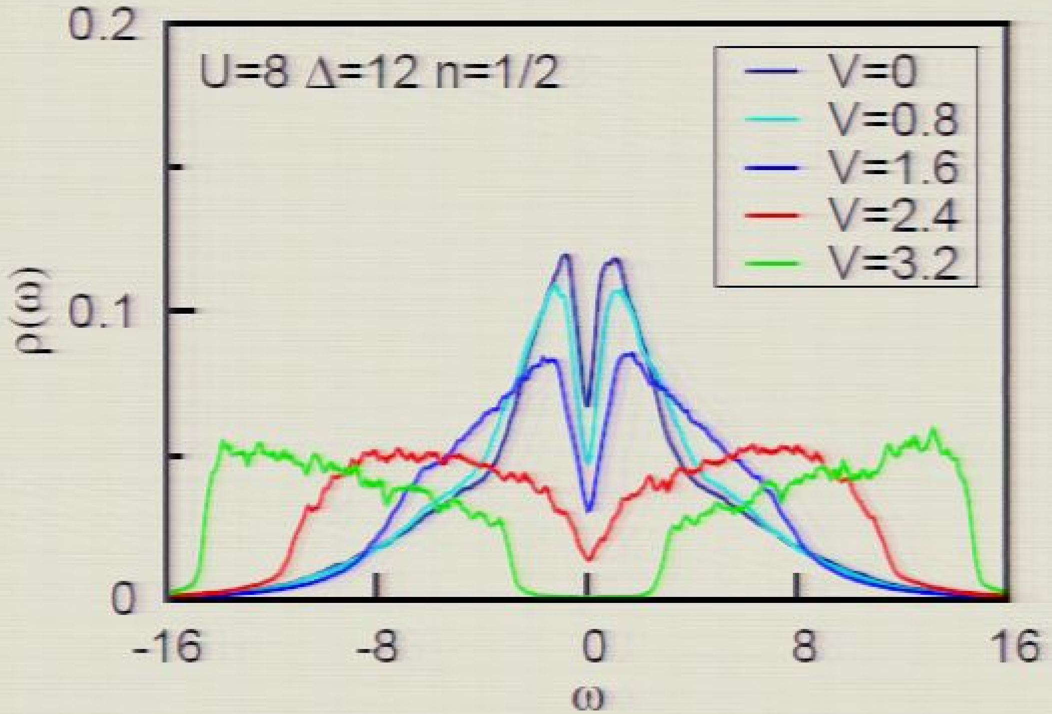
clean 2D EHM

- CDW $U < 4V$
- SDW $U > 4V$

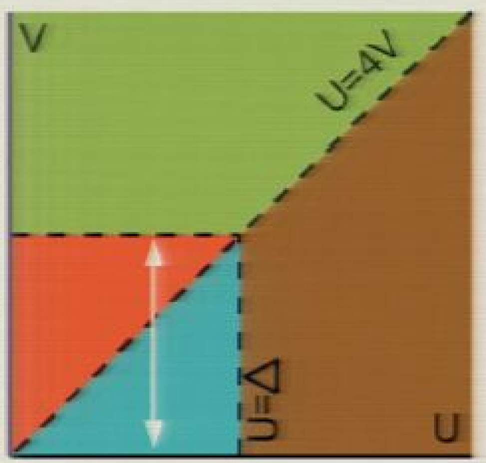
atomic U=0 case analogous to random field Ising model $V \leftrightarrow J$ and $\Delta \leftrightarrow h$

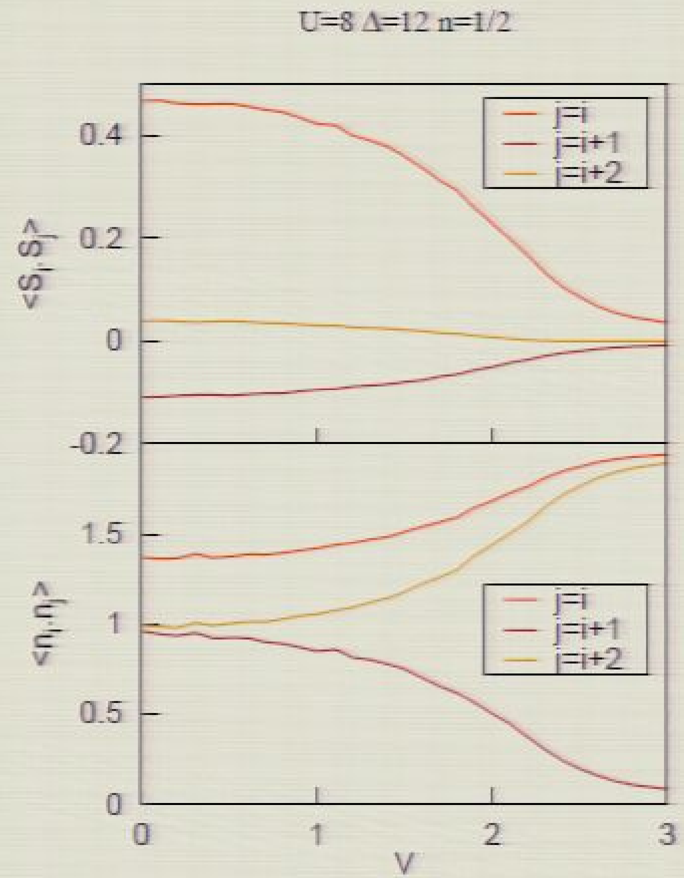
Evolution of DOS with nonlocal interaction V



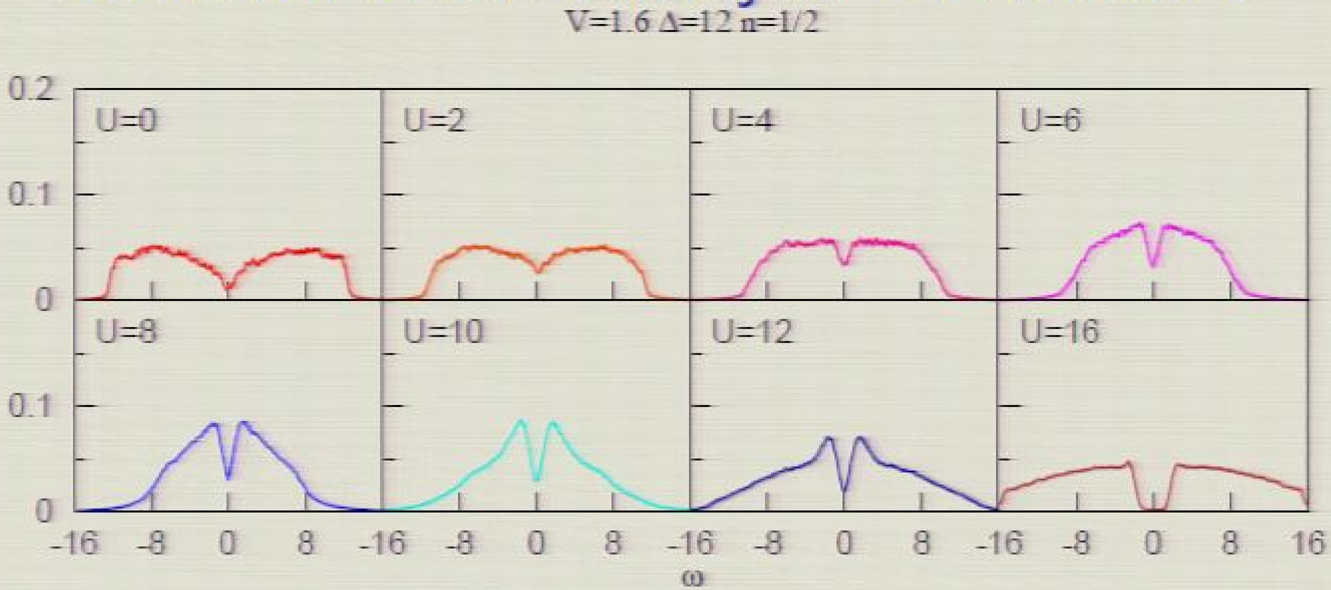


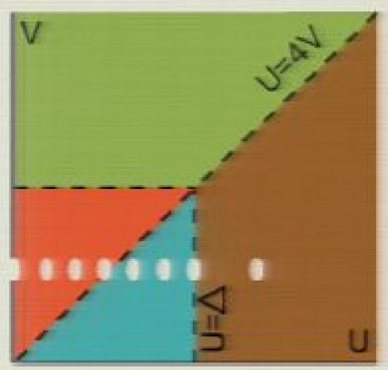
Evolution of spin and charge correlations with V





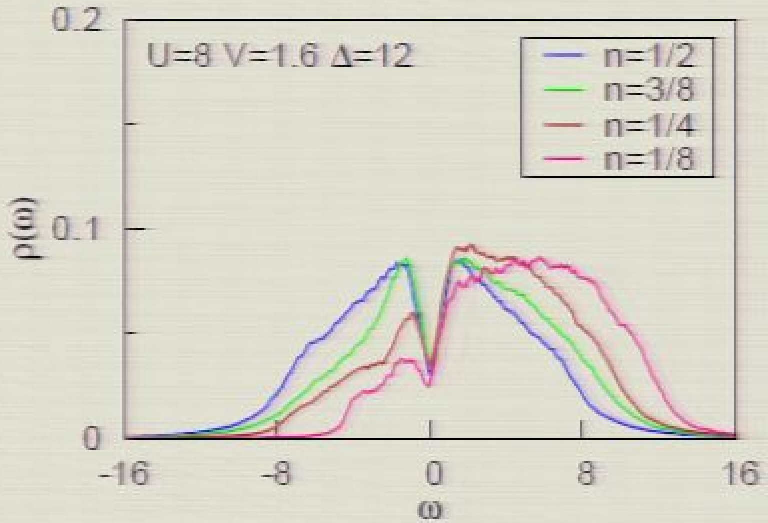
Evolution of the density of states with U



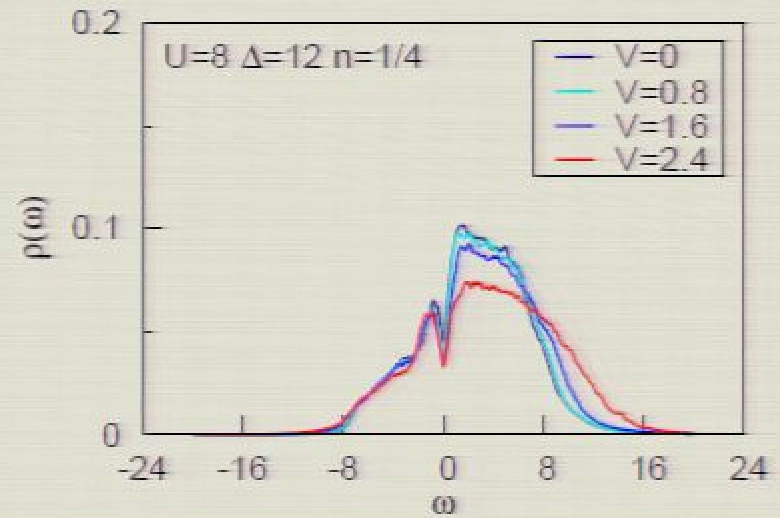


Away from half filling

doping dependence



V dependence
(at quarter filling)



Summary

- Insight into the origin of the disorder-induced ZBA in strongly-correlated electron systems is provided by an ensemble of two-site systems. [PRB **82** 073107 (2010)]

- In strongly correlated systems nonzero temperature can create a zero bias anomaly that wasn't there at $T = 0$. [J. Phys.: Cond. Matt. **23** 094213 (2011)]

- Weak nearest-neighbor interactions simply renormalize the $V = 0$ ZBA, but when $4V > U$ the character of the anomaly changes qualitatively.

Zero bias anomalies can tell us about the interactions in the material in which they are found.