

Superconductor-Correlated metal-Superconductor Josephson junctions for high-speed digital electronics



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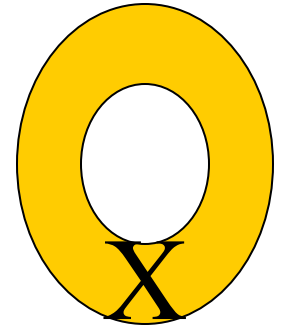
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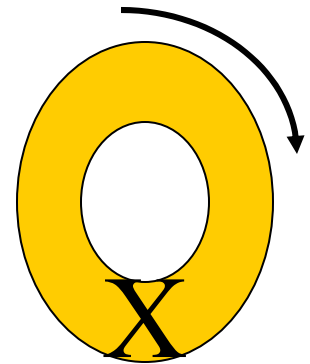
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Digital Electronics and RSFQ logic

- **Rapid single-flux quantum logic** is used for high-speed applications. A loop of superconducting material has one JJ interrupting it. The absence or presence of a flux quantum in the loop is the binary 0 and 1 of the device.
- The flux is changed by generating a **voltage pulse** through the junction, whose time integral is equal to a flux quantum. Since the voltage scale is set by the product $I_c R_n$, which is on the order of a few mV in low- T_c superconductors, **operating speeds of up to 770 GHz** have already been demonstrated.
- New superconducting materials like MgB_2 and novel barriers like Ta_xN show a promise for even higher characteristic voltages, and hence faster operating speeds of circuits.

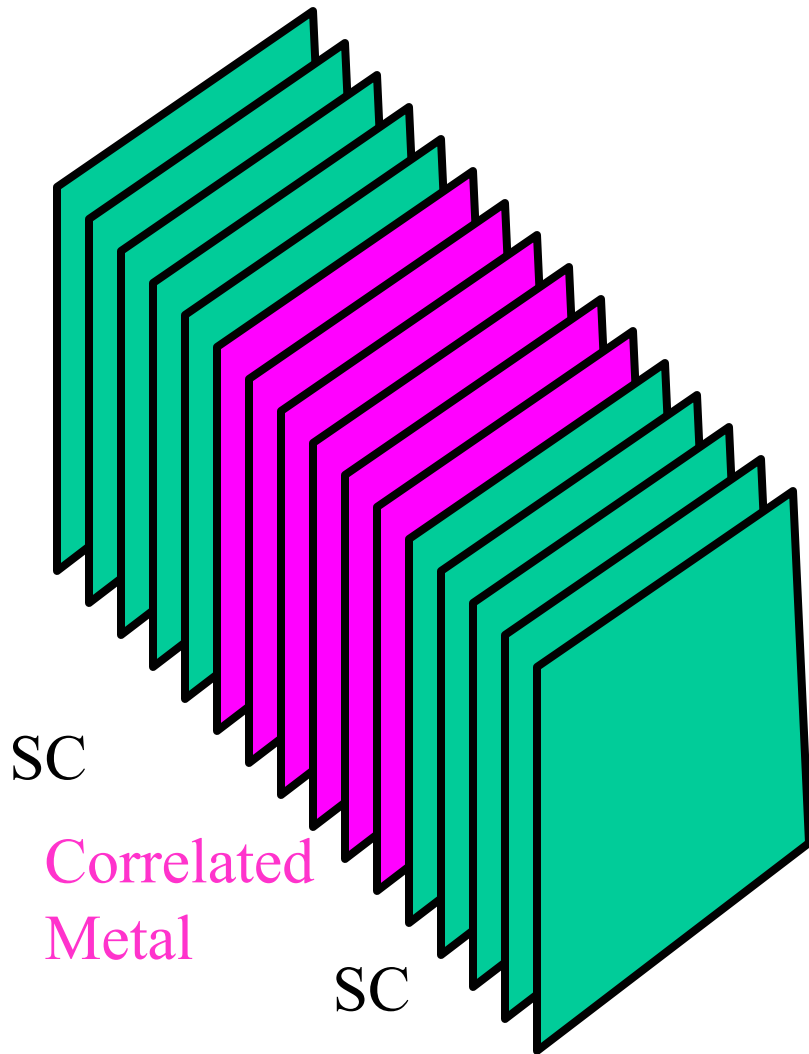


Binary 0, no flux



Binary 1, one flux quantum

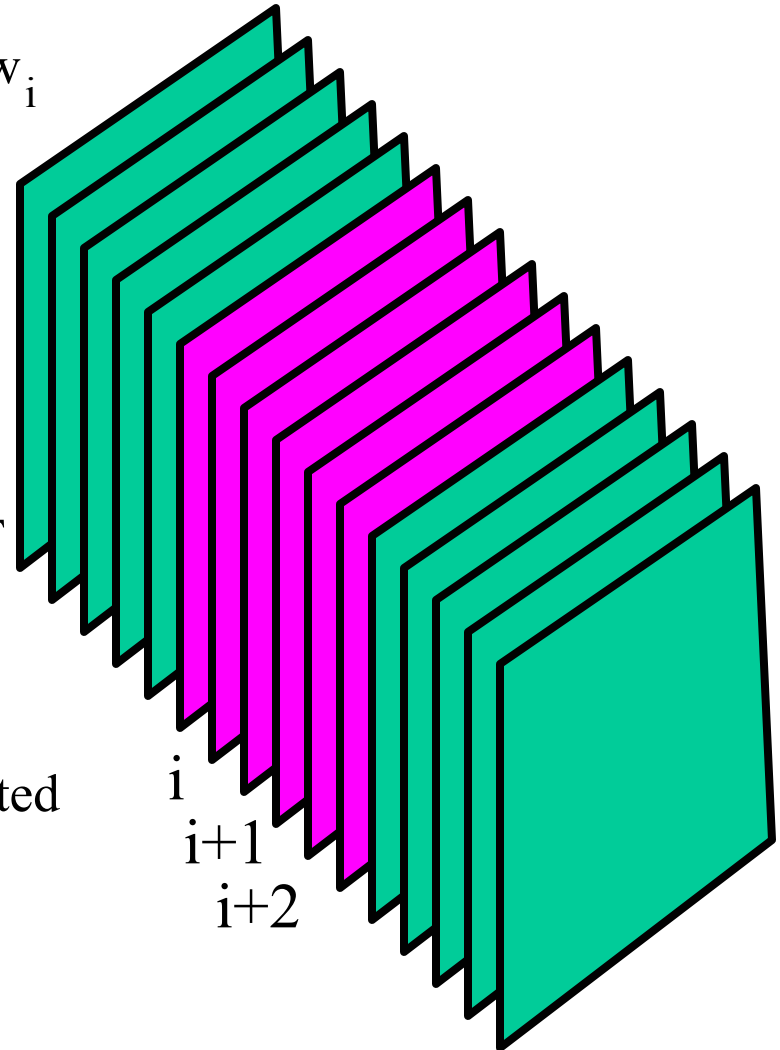
Optimization of the speed of a JJ



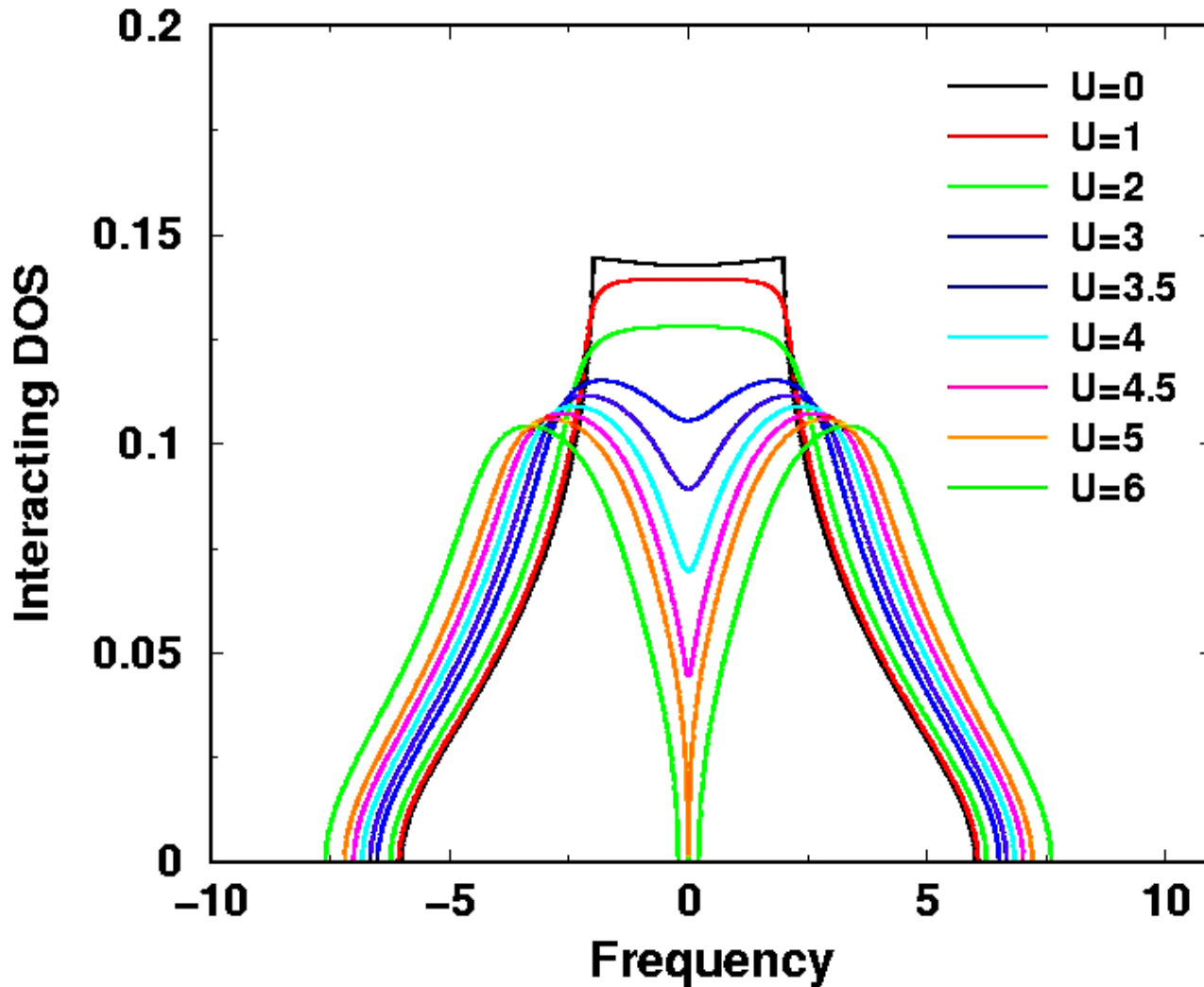
- Three elements are needed for high speed digital electronics based on JJs: (i) a **large figure-of-merit** $I_c R_n$; (ii) **small temperature derivatives** of the characteristic voltage and the critical current within the operating temperature range; and (iii) **nonhysteretic** current-voltage characteristics.
- Can the next generation of JJ technology be built out of a new class of **SCmS junctions** where the correlated metal barrier has its thickness and metallicity tuned to lie **close to the metal-insulator transition**?

Many-Body Formalism

- **Inhomogeneous system, with planes stacked along the z-direction.**
- $H = -\sum_{ij} t_{ij} c_{i\sigma}^* c_{j\sigma} + \sum_i U_i n_{i\uparrow} n_{i\downarrow} + \sum_i U_i^{\text{FK}} (n_{i\uparrow} + n_{i\downarrow}) w_i$
- Local dynamical correlations are explicitly included for each plane via the **dynamical mean field theory**. The self-consistency relation is now modified to include effects that couple the effective medium between the planes.
- The superconductor is described by the H-F approximation, which is identical to a **self-consistent solution** of the Bogoliubov-deGennes equations for a short-coherence length, s-wave superconductor. The correlated metal is described by an exact form of the **coherent-potential approximation** which displays a metal-insulator transition.

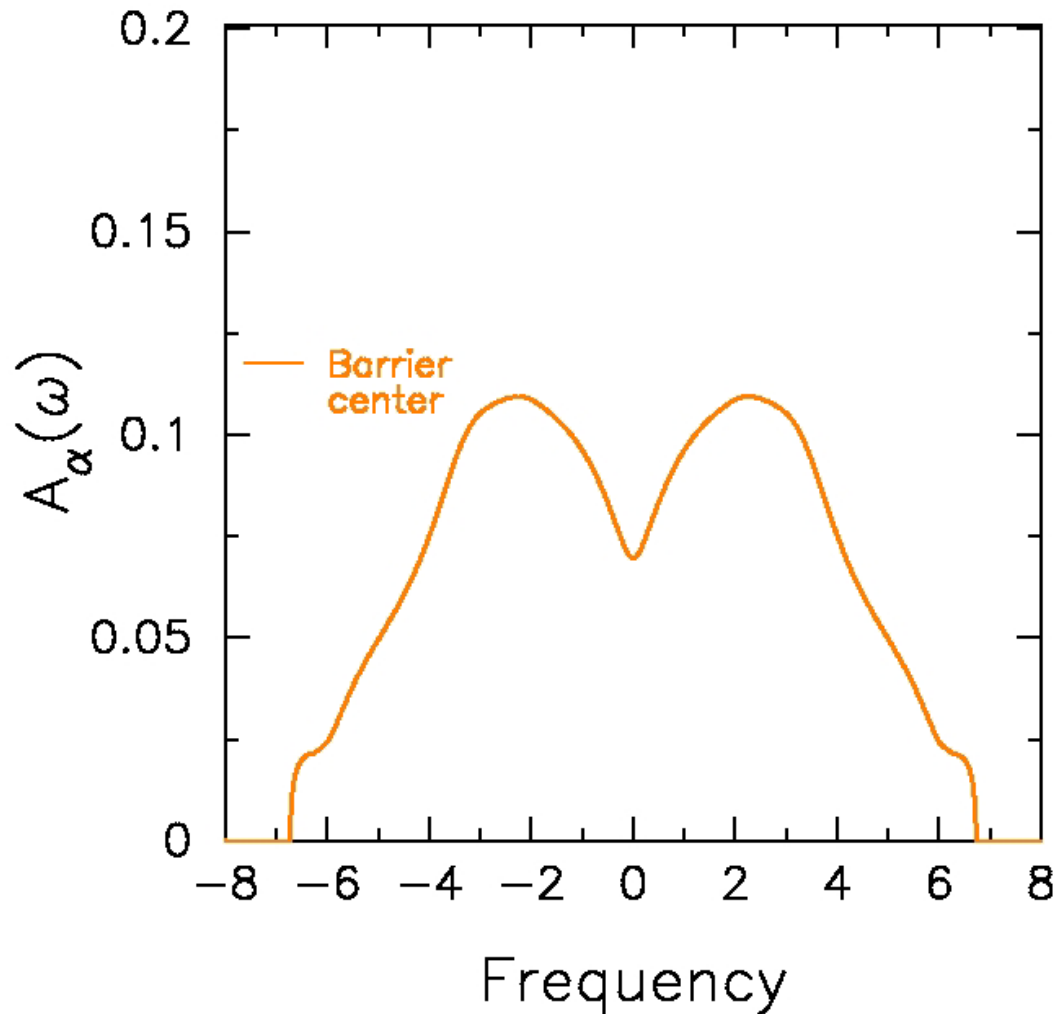


Metal-insulator transition



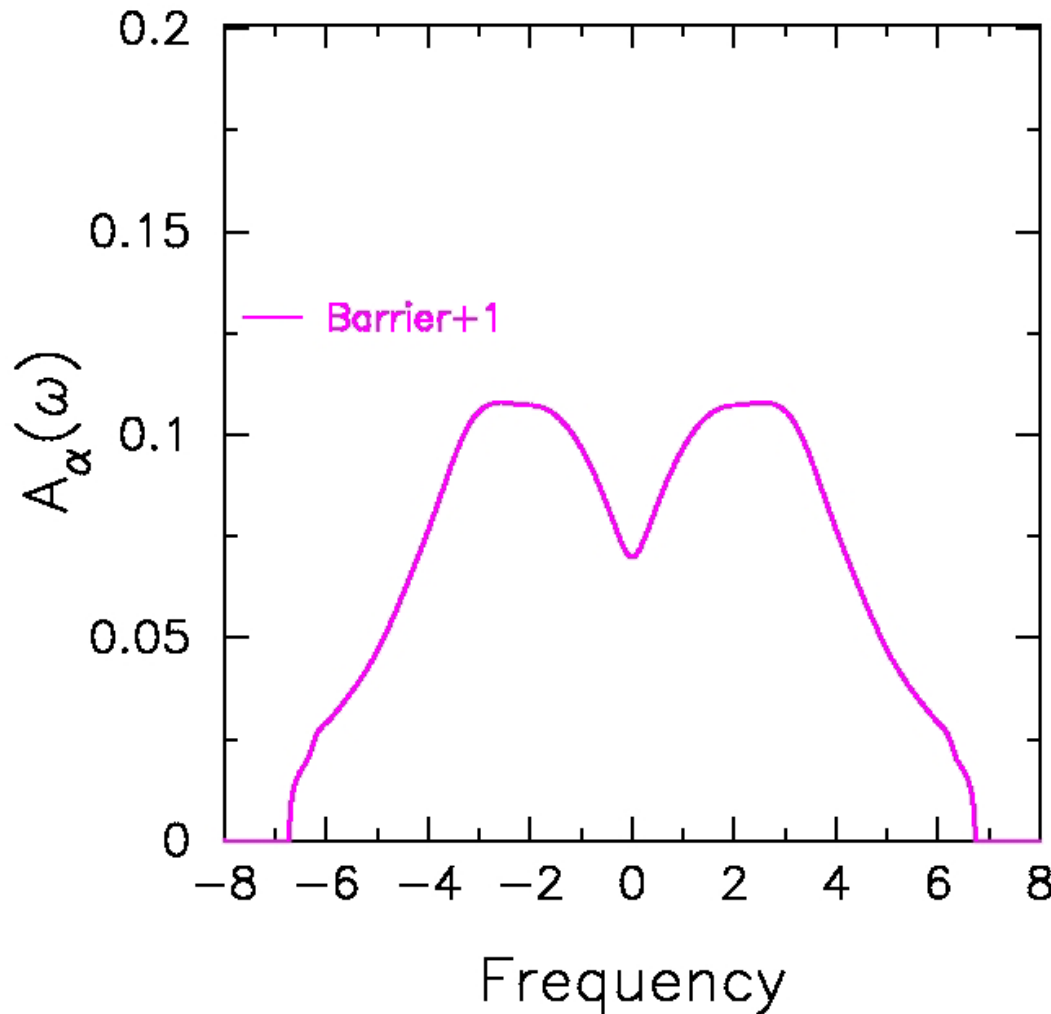
The Falicov-Kimball model has a **metal-insulator transition** that occurs as the correlation energy U is increased. The bulk interacting DOS shows that a **pseudogap** phase first develops followed by the opening of a **true gap** above $U=4.9$ (in the bulk). Note: the FK model is **not a Fermi liquid** in its metallic state since the lifetime of excitations is always finite.

Local DOS in a correlated metal



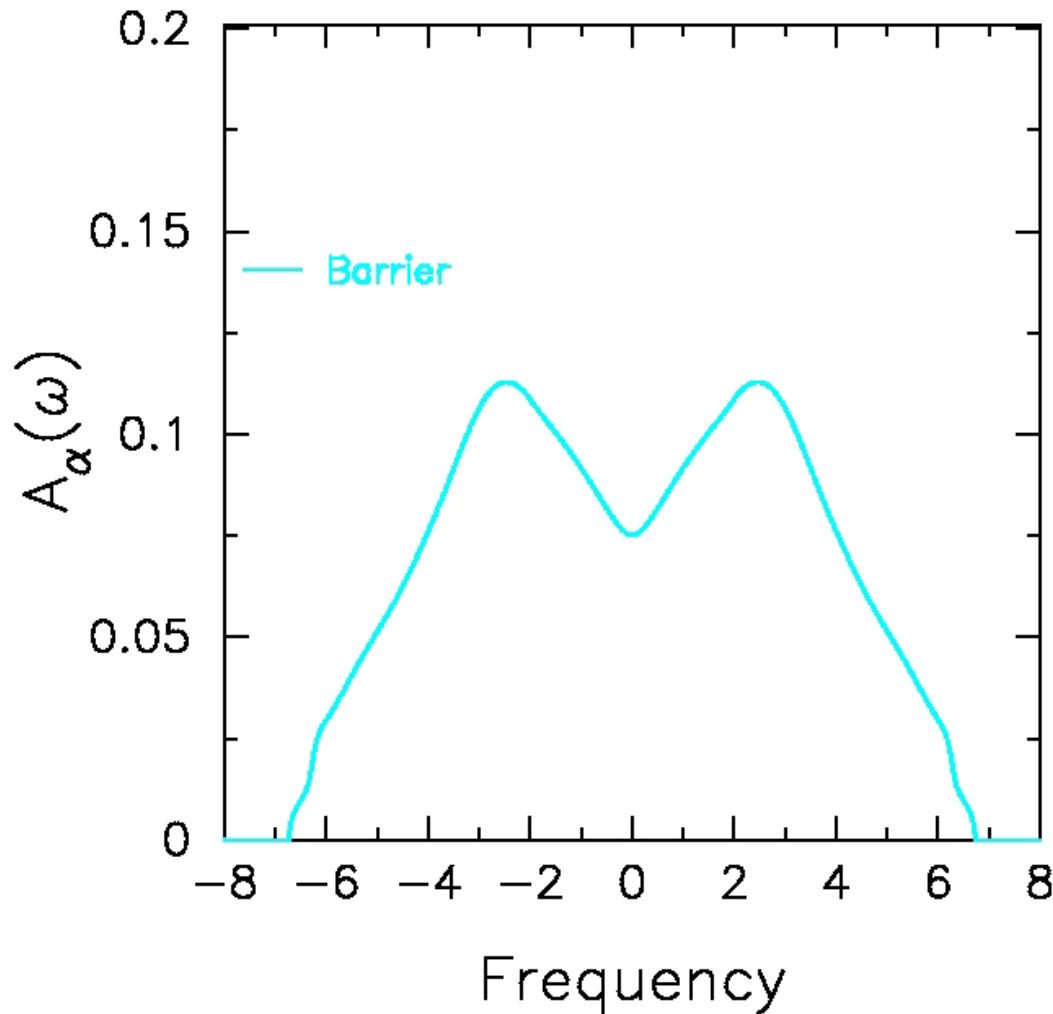
The dos in the barrier of a moderately thick ($N=5$) junction in the normal state is essentially the same as in the bulk. Note the pseudogap suppression of the dos and the separation into two peaks. But there is a “bump” at the band edge.

Local DOS in a correlated metal



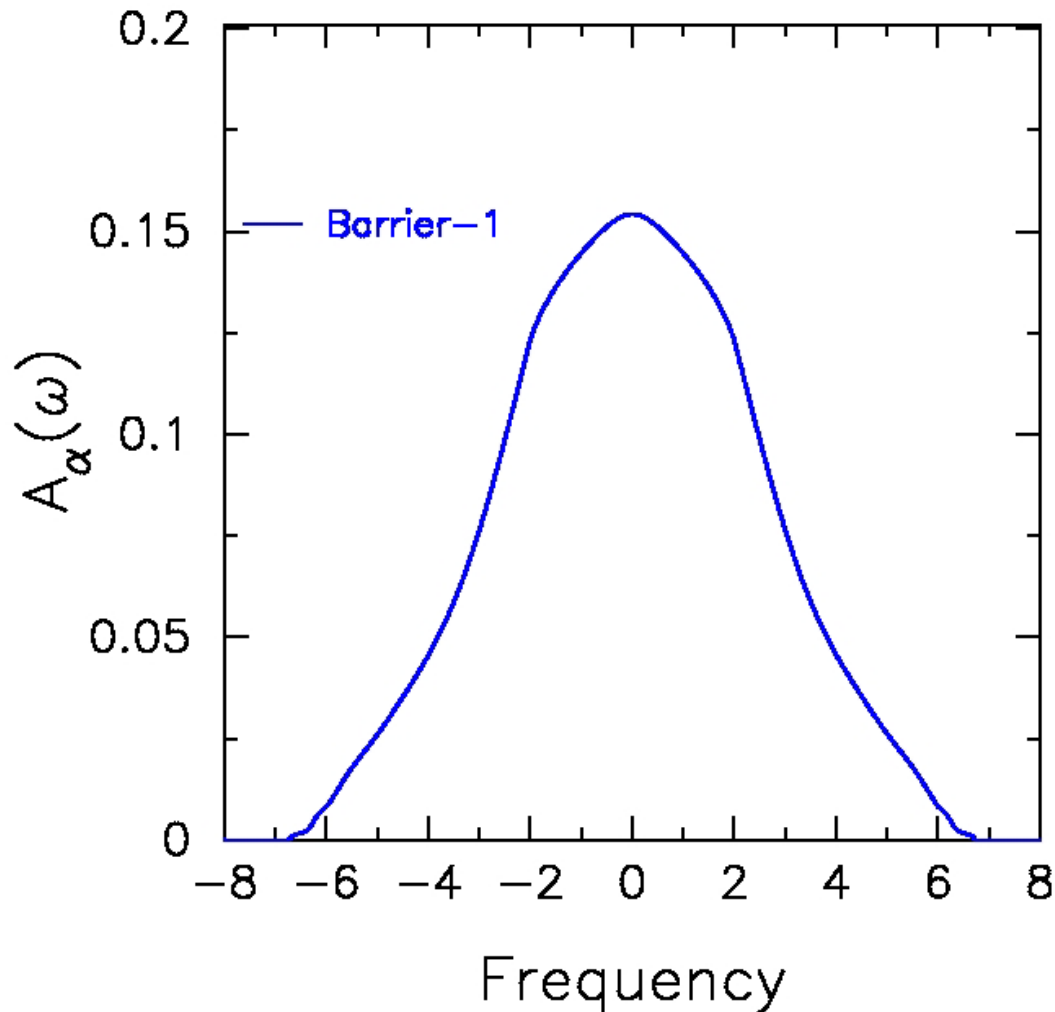
As we move from the center of the junction toward the barrier interface, the dos flattens at the peak and oscillations develop toward the band edge.

Local DOS in a correlated metal



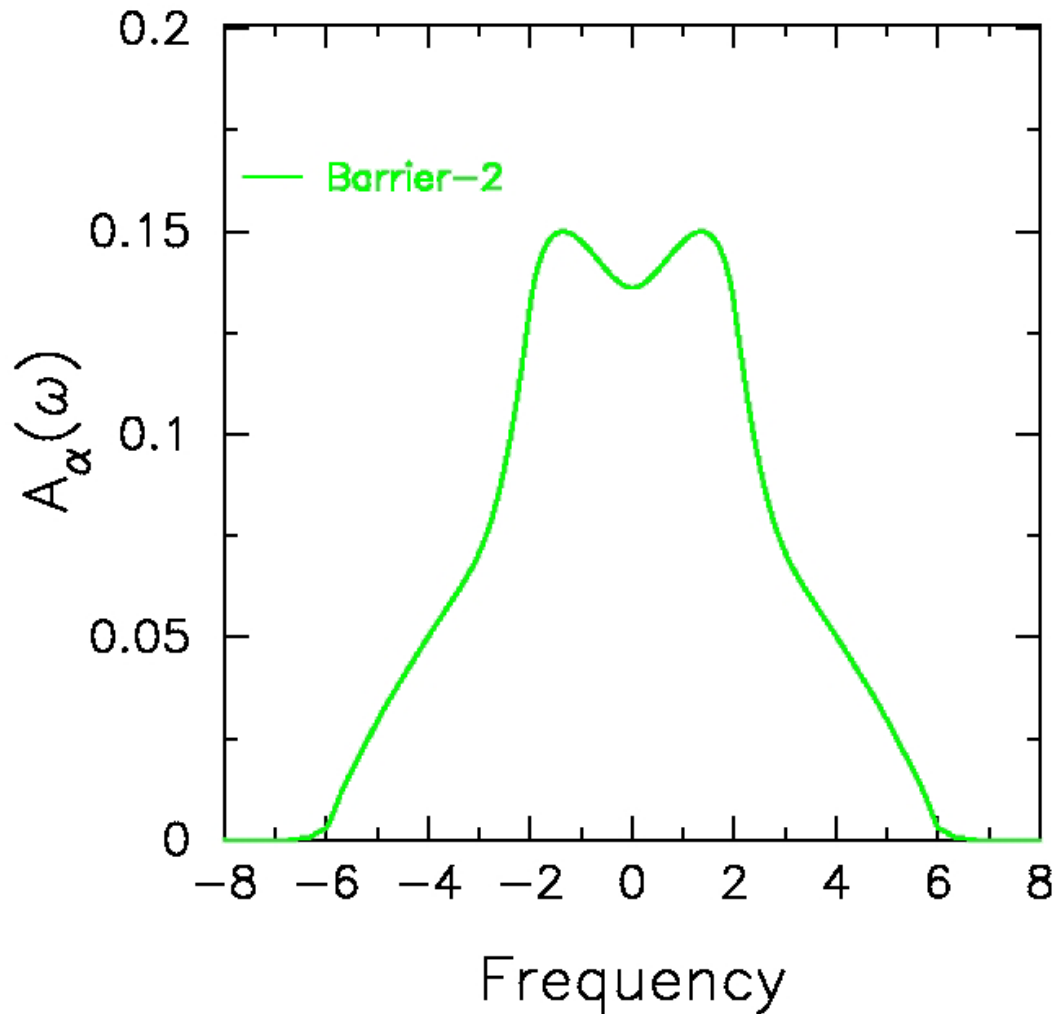
At the interface, the dip increases.

Local DOS in a correlated metal



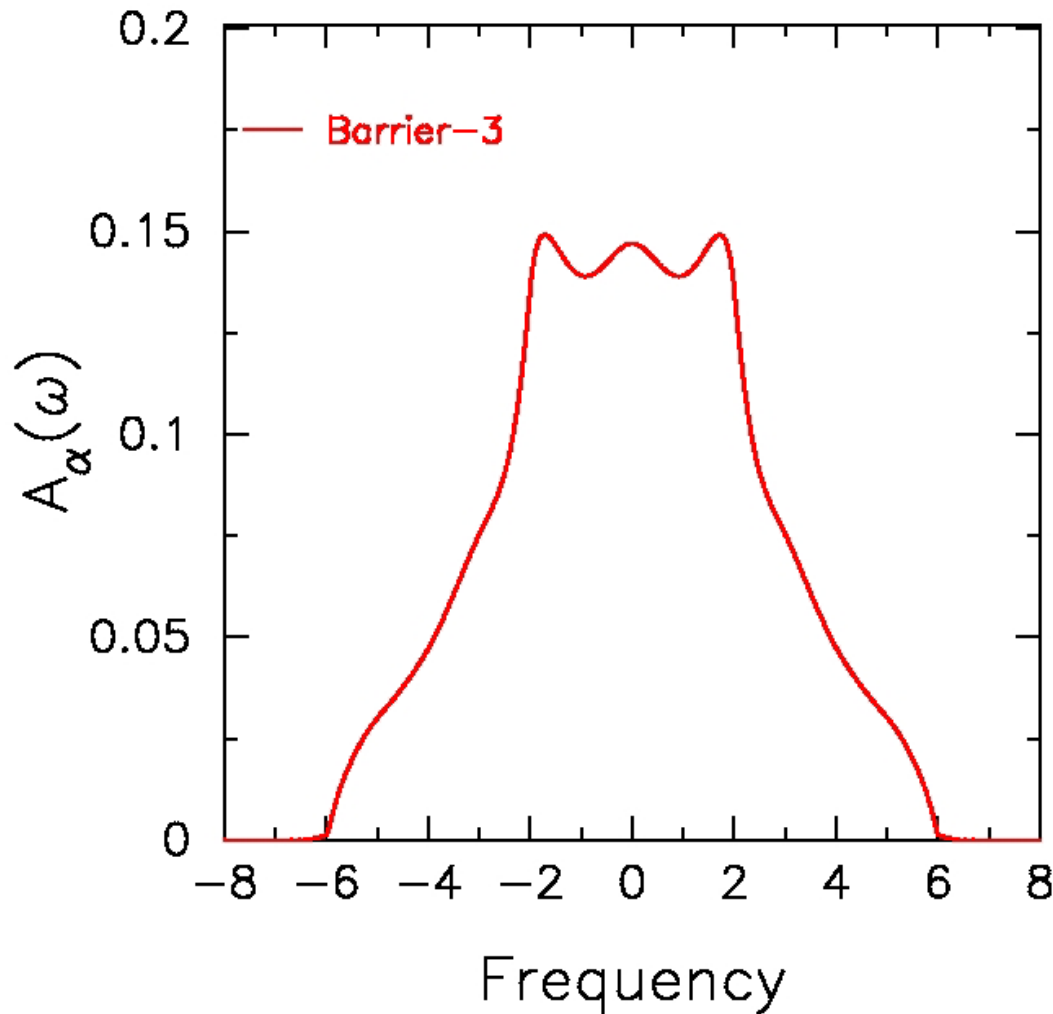
In the metallic lead, the pseudogap disappears and the dos is rather smooth. The dos leaks beyond the bulk metal band edge at 6.

Local DOS in a correlated metal



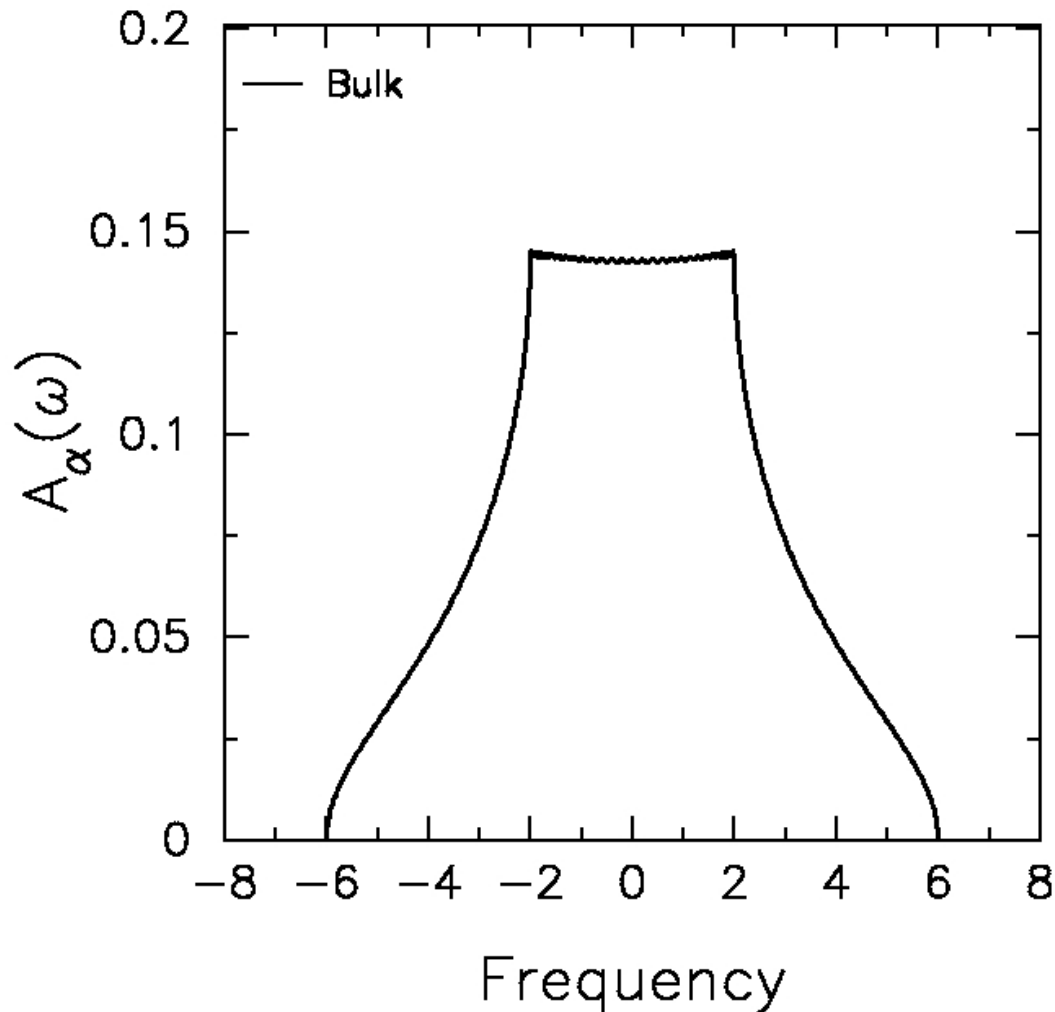
Moving one more plane out and the bulk simple cubic dos starts to emerge but with Friedel-like oscillations superimposed.

Local DOS in a correlated metal



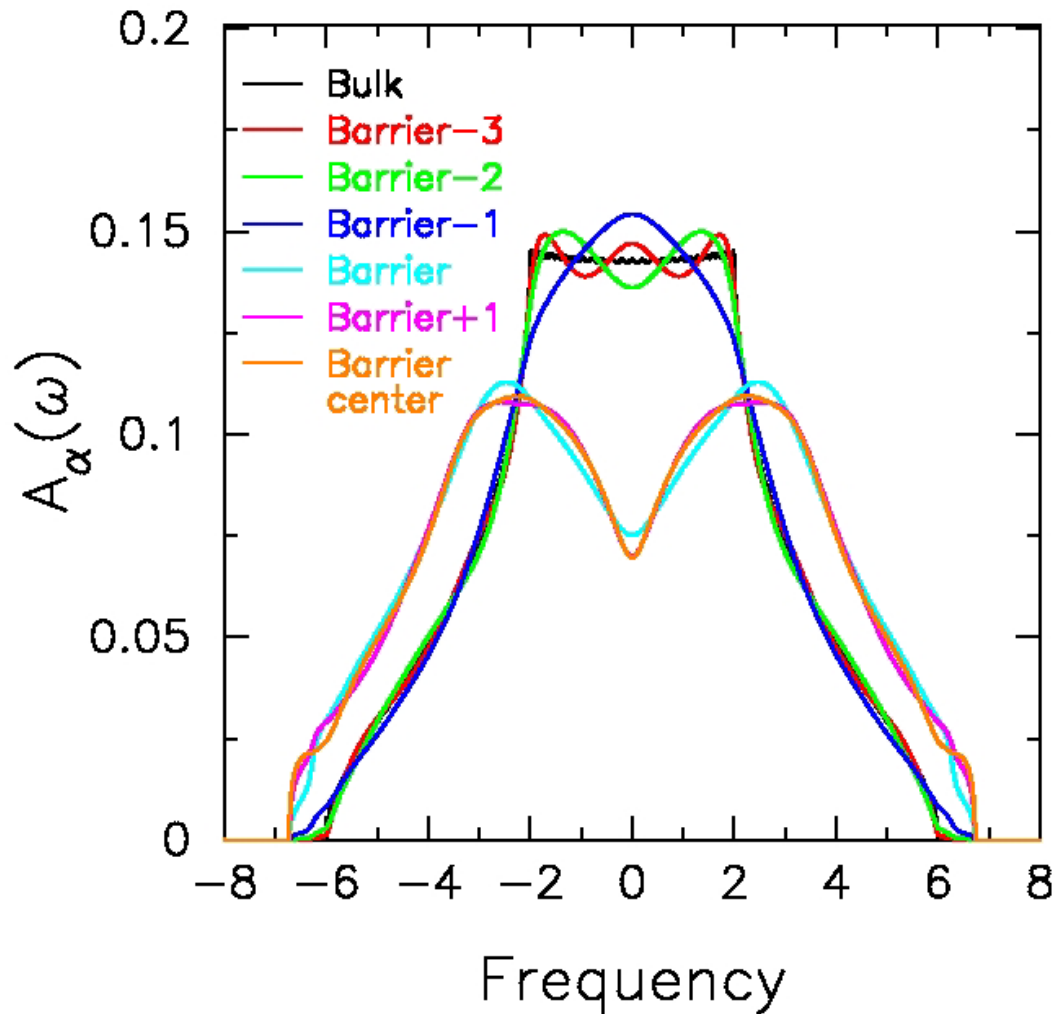
The oscillations continue as we move further out.

Local DOS in a correlated metal



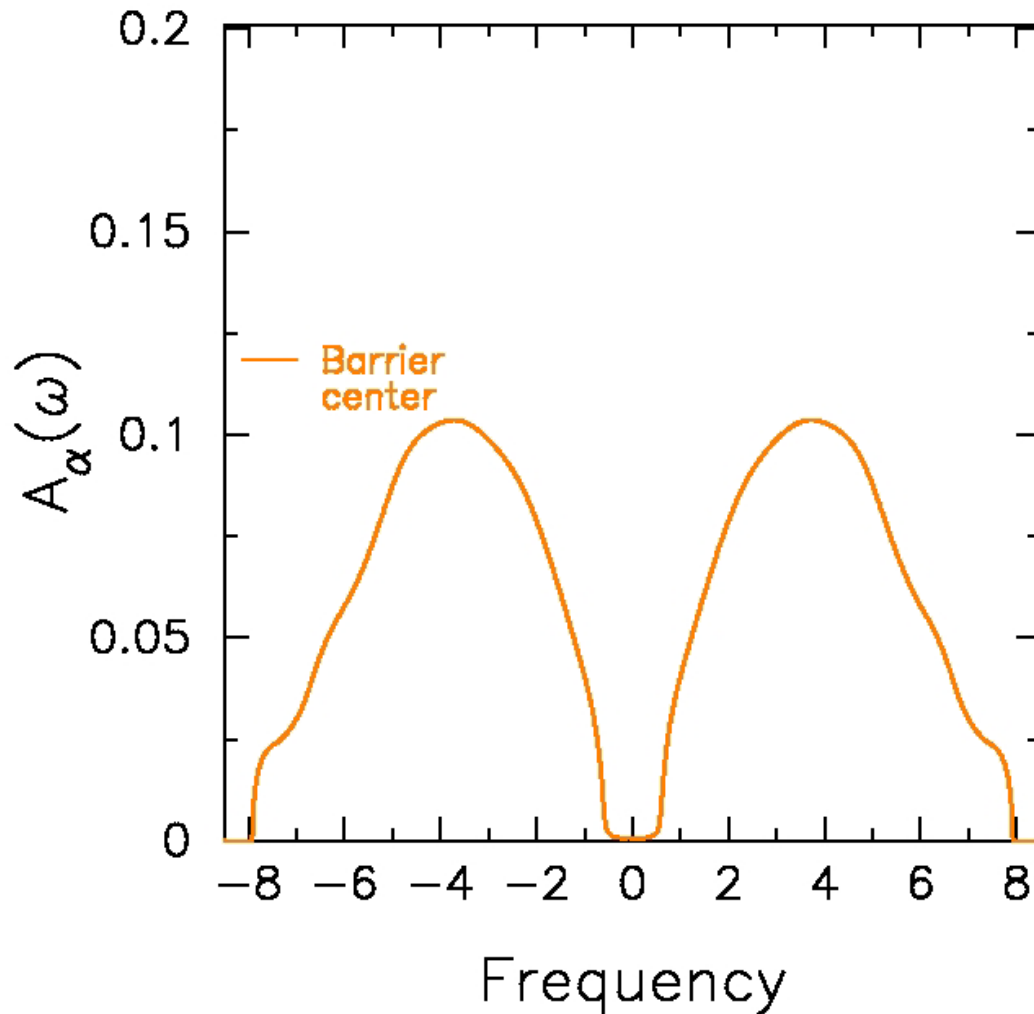
By the time we go thirty planes away, the simple-cubic dos is clear, but some low-amplitude oscillations remain.

Local DOS in a correlated metal



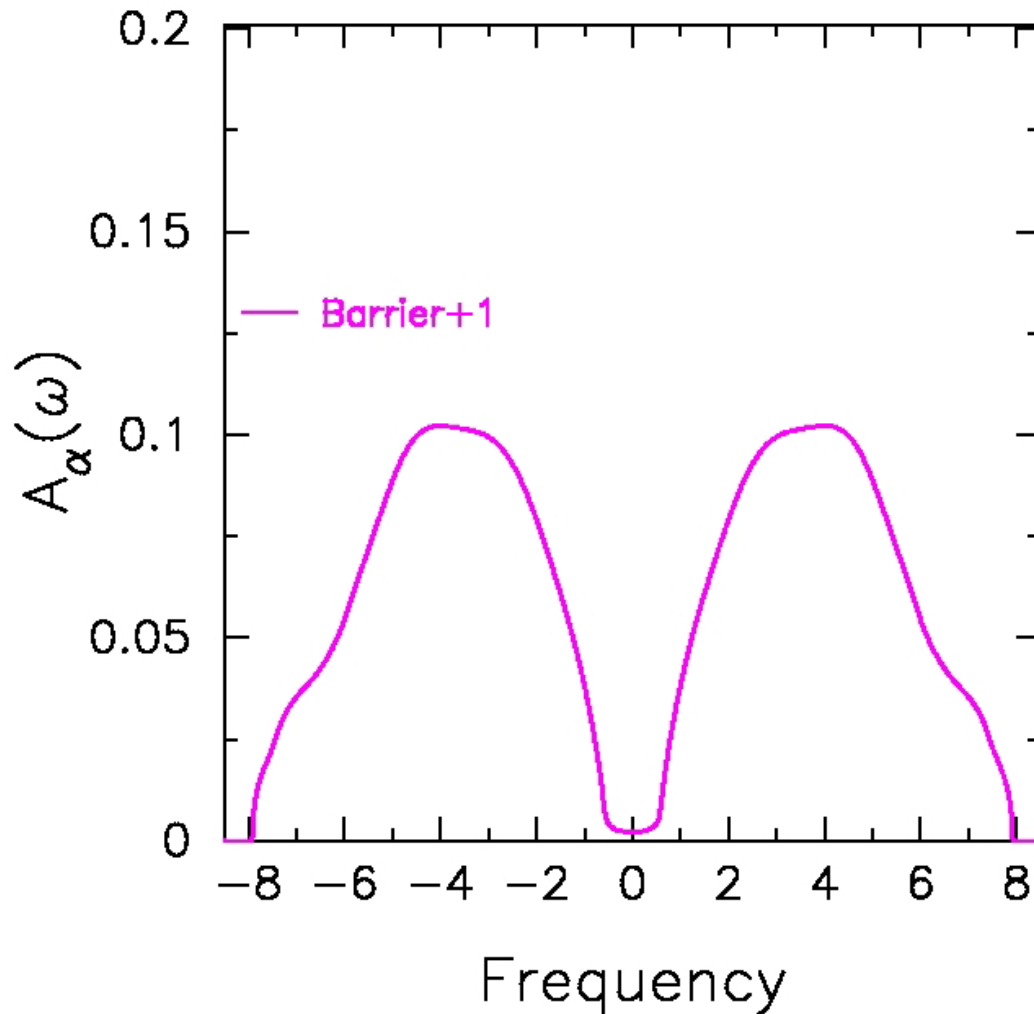
In summary, we can see tremendous structure to the local dos that are generated by the nanoscale barrier.

Local DOS in a correlated insulator



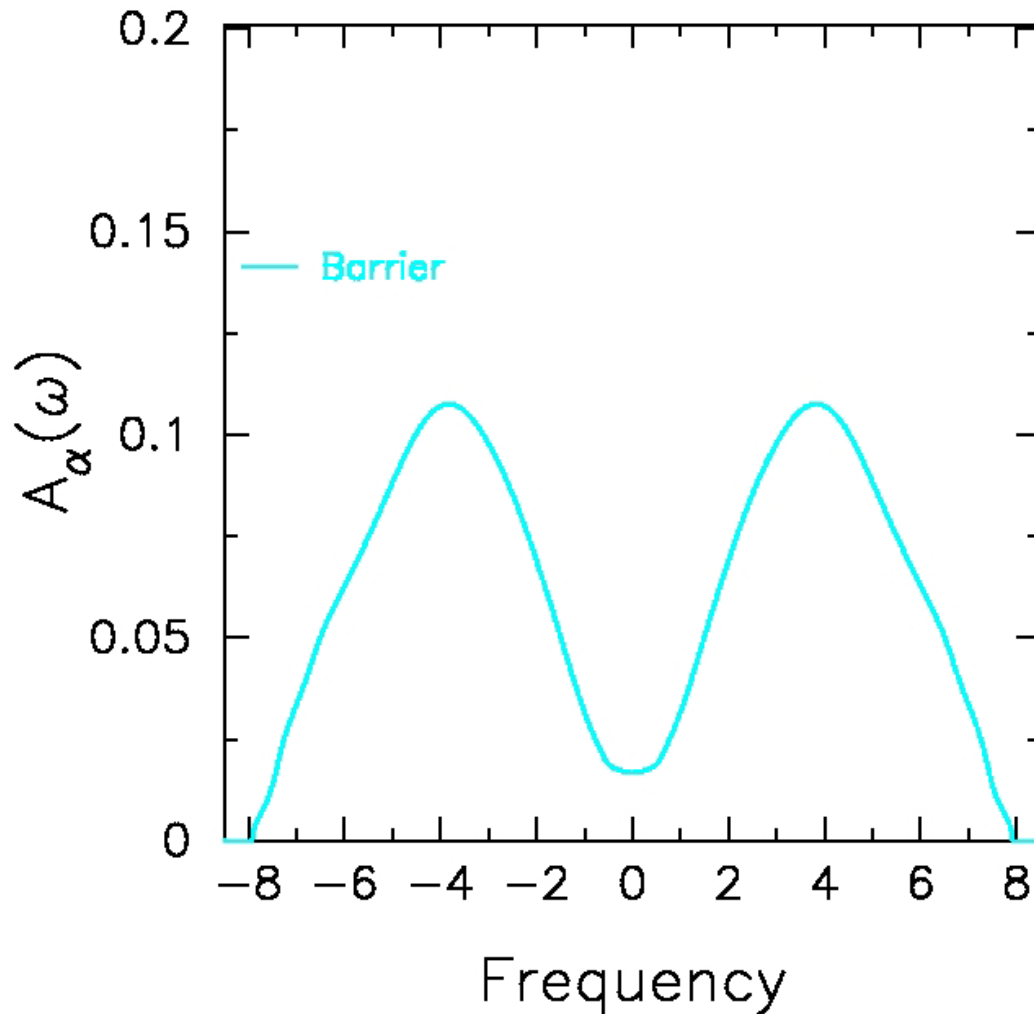
The insulator, at first, looks much like the bulk, but the dos does not go to zero in the “gap region”.

Local DOS in a correlated insulator



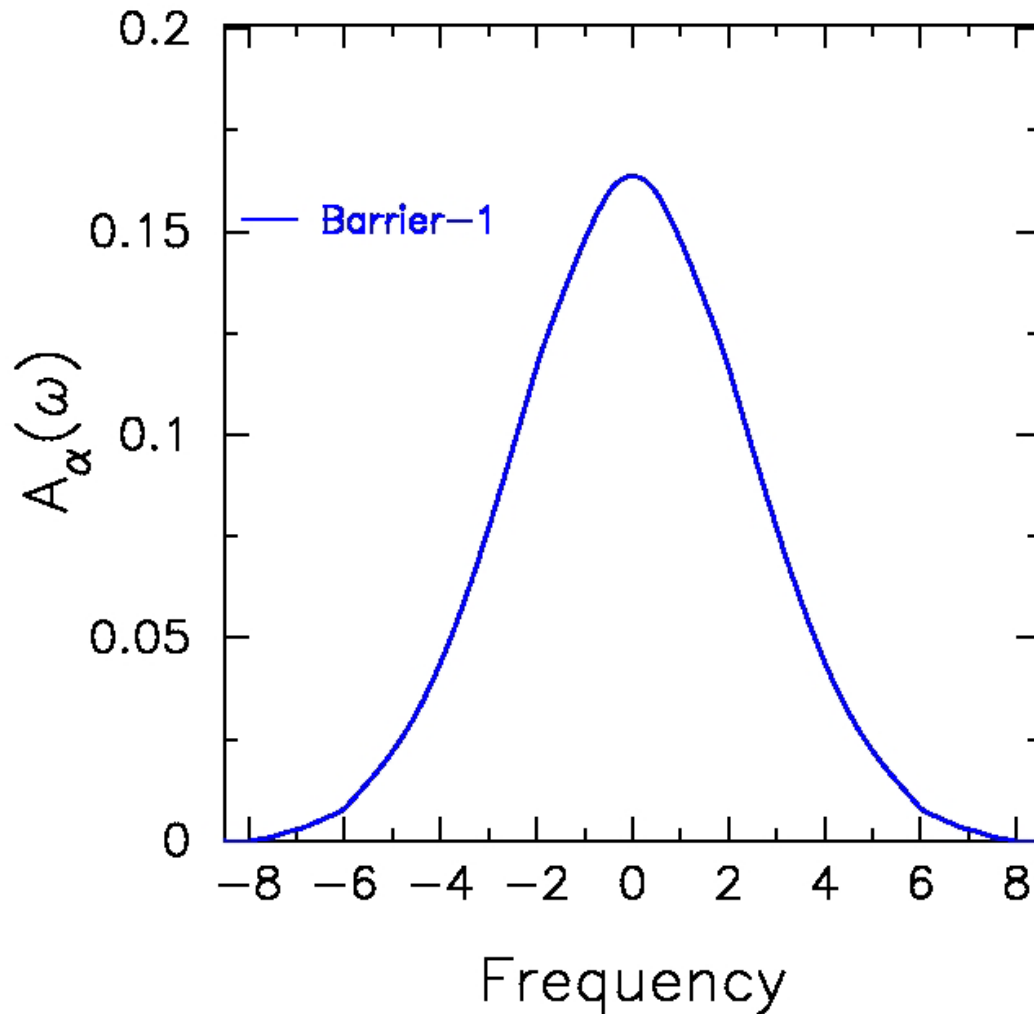
Moving one plane away lifts the “subgap” dos significantly.

Local DOS in a correlated insulator



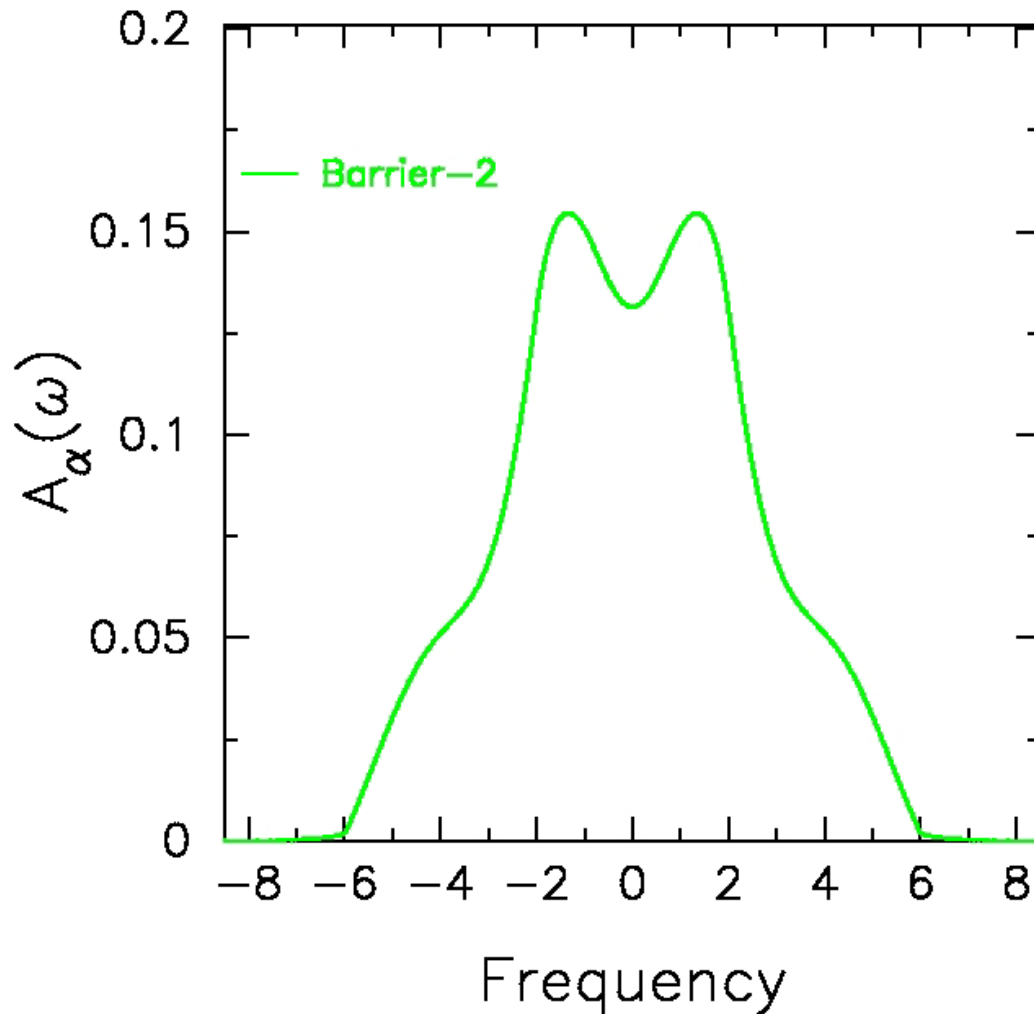
By the time the barrier is reached, the dos looks like a pseudogap.

Local DOS in a correlated insulator



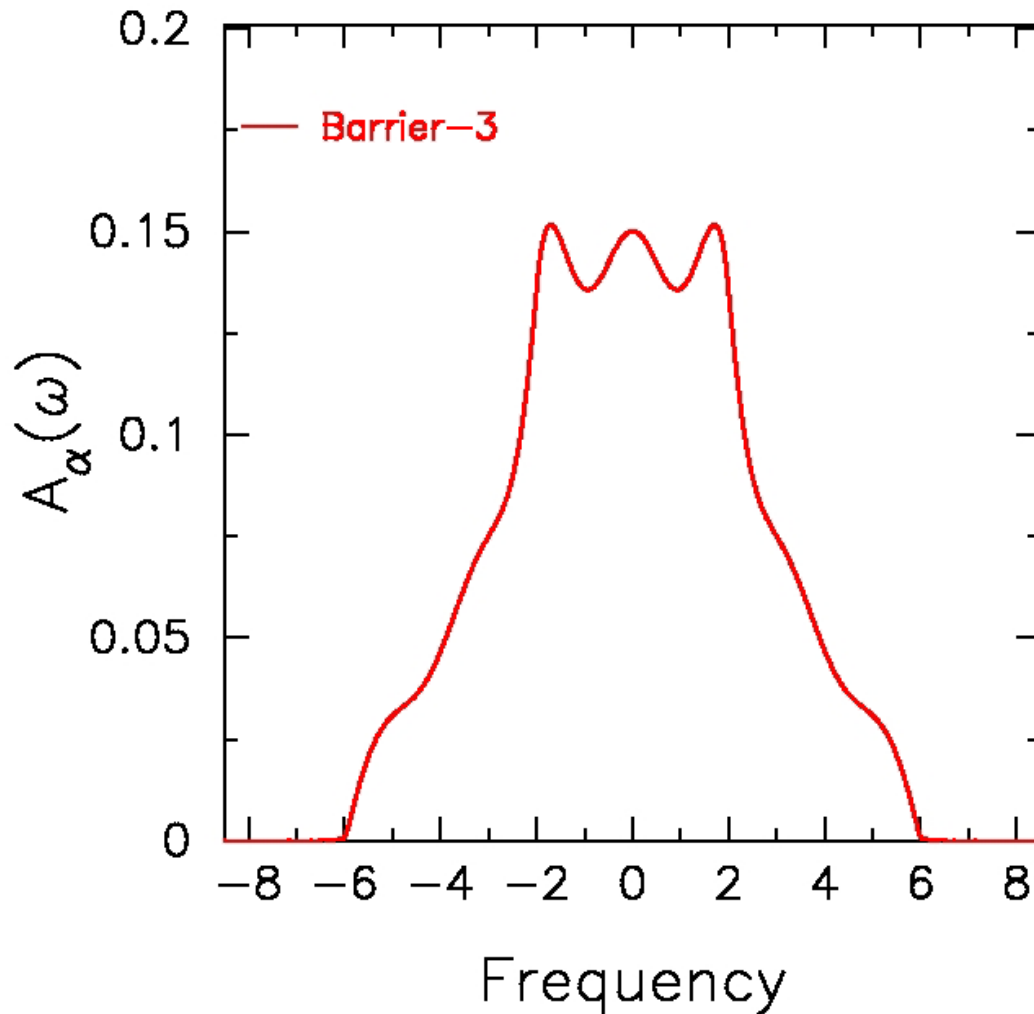
In the metallic lead, the dos looks similar to the correlated metal case.

Local DOS in a correlated insulator



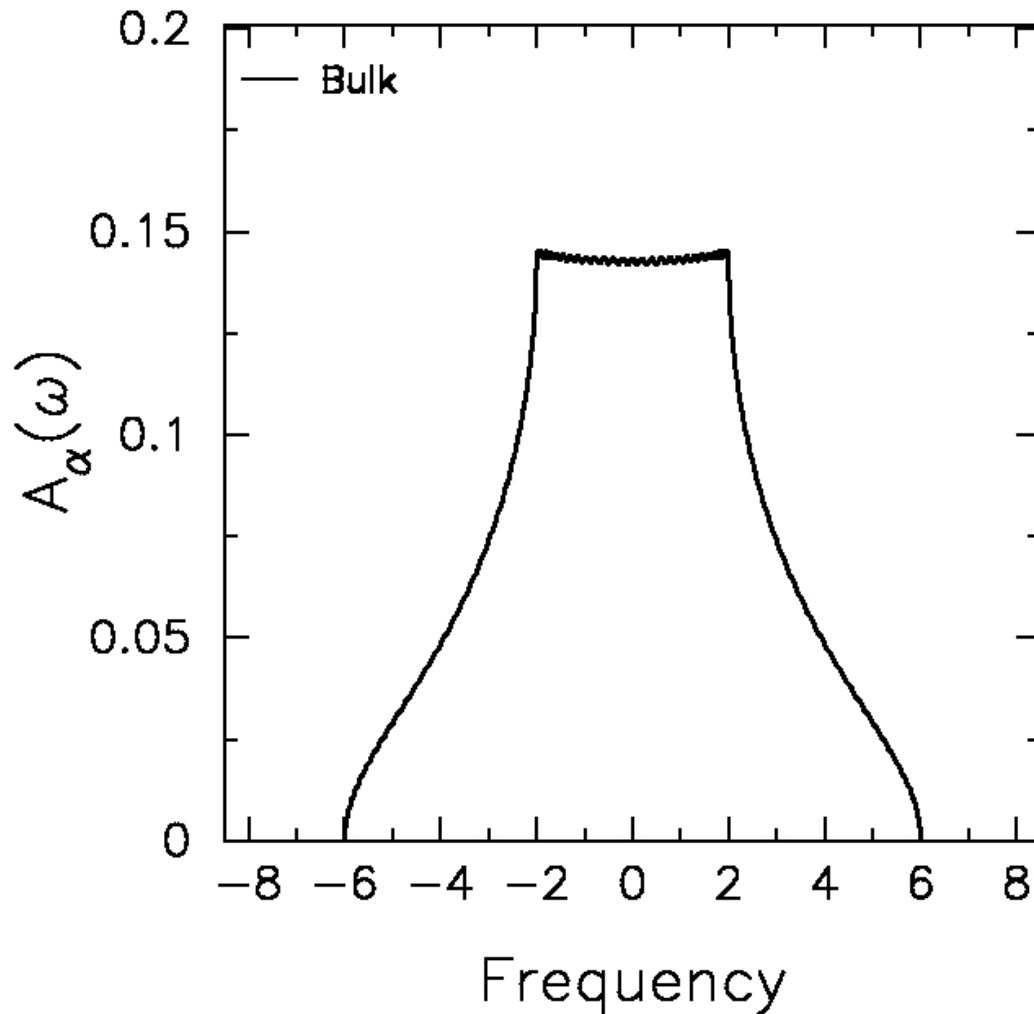
Oscillations develop as we move further away.

Local DOS in a correlated insulator



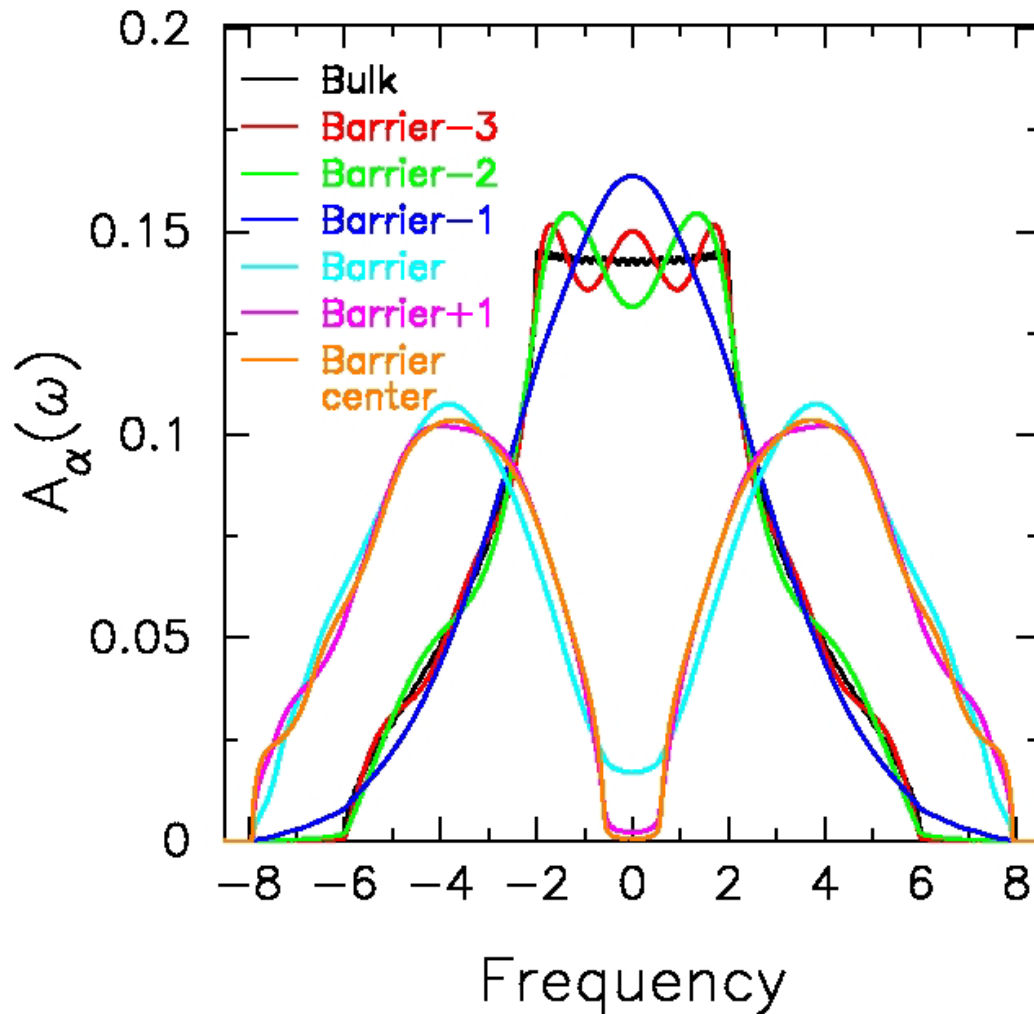
Oscillations continue
as we move further
away.

Local DOS in a correlated insulator



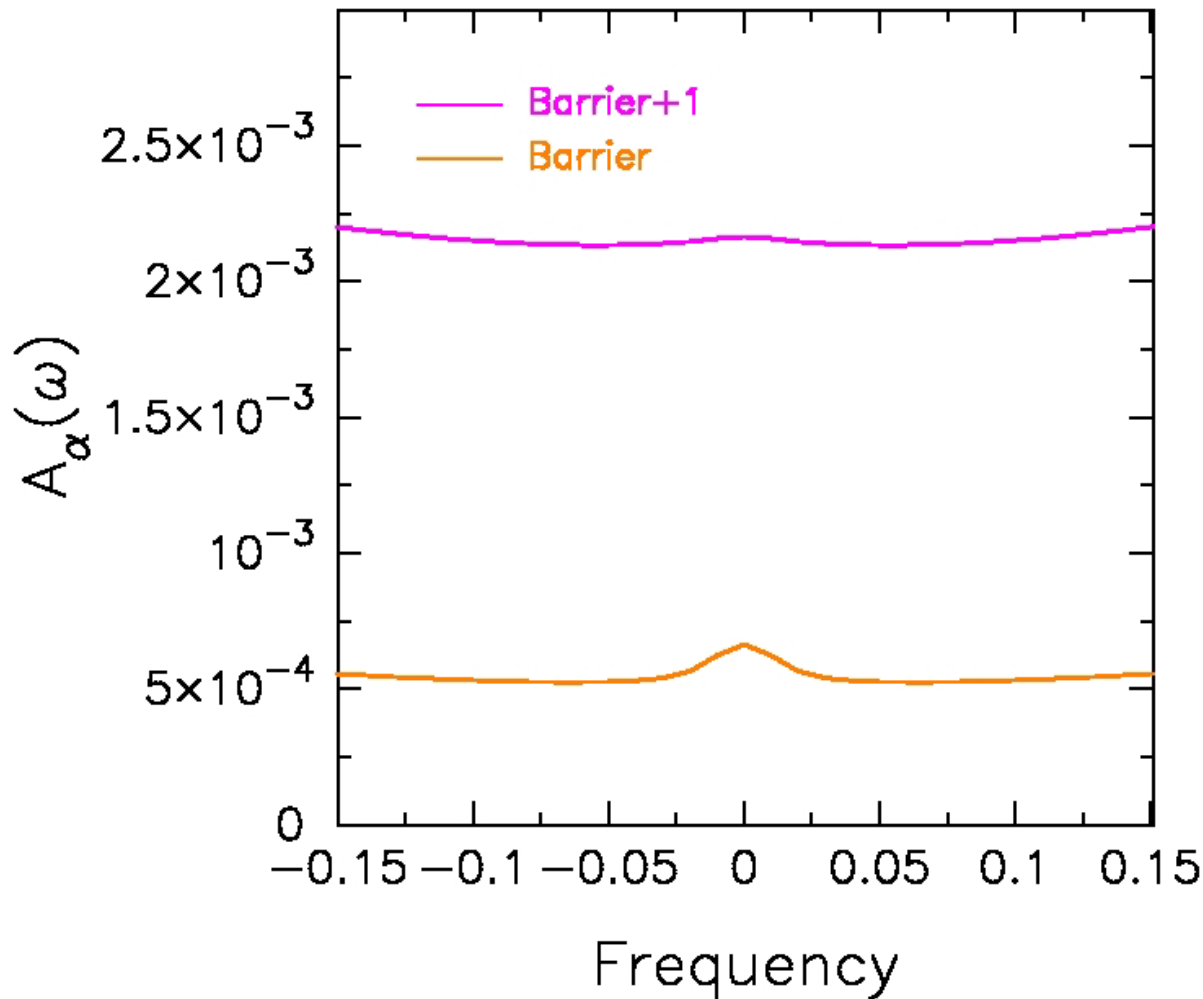
Thirty planes away, the bulk looks similar to before.

Local DOS in a correlated insulator



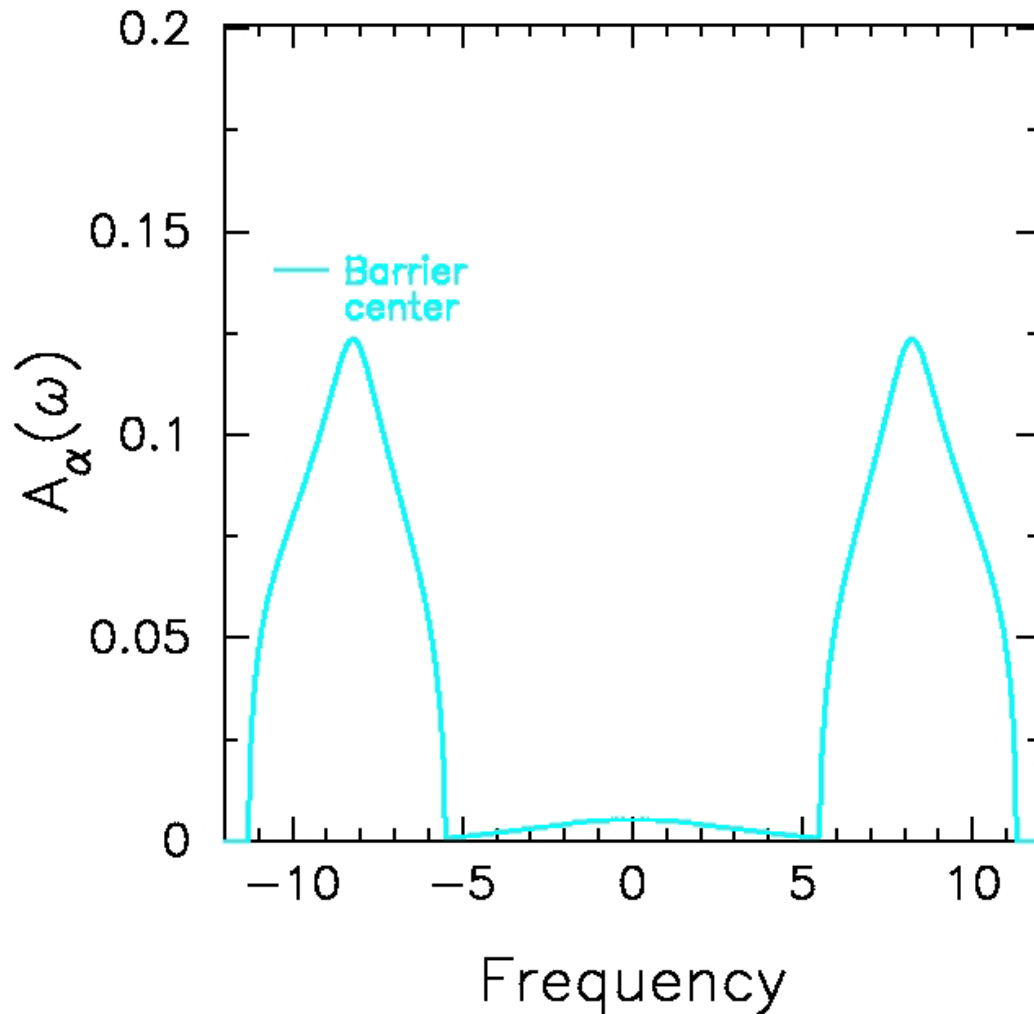
The evolution shows how the dos fills in and eventually becomes simple cubic like.

Local DOS in a correlated insulator



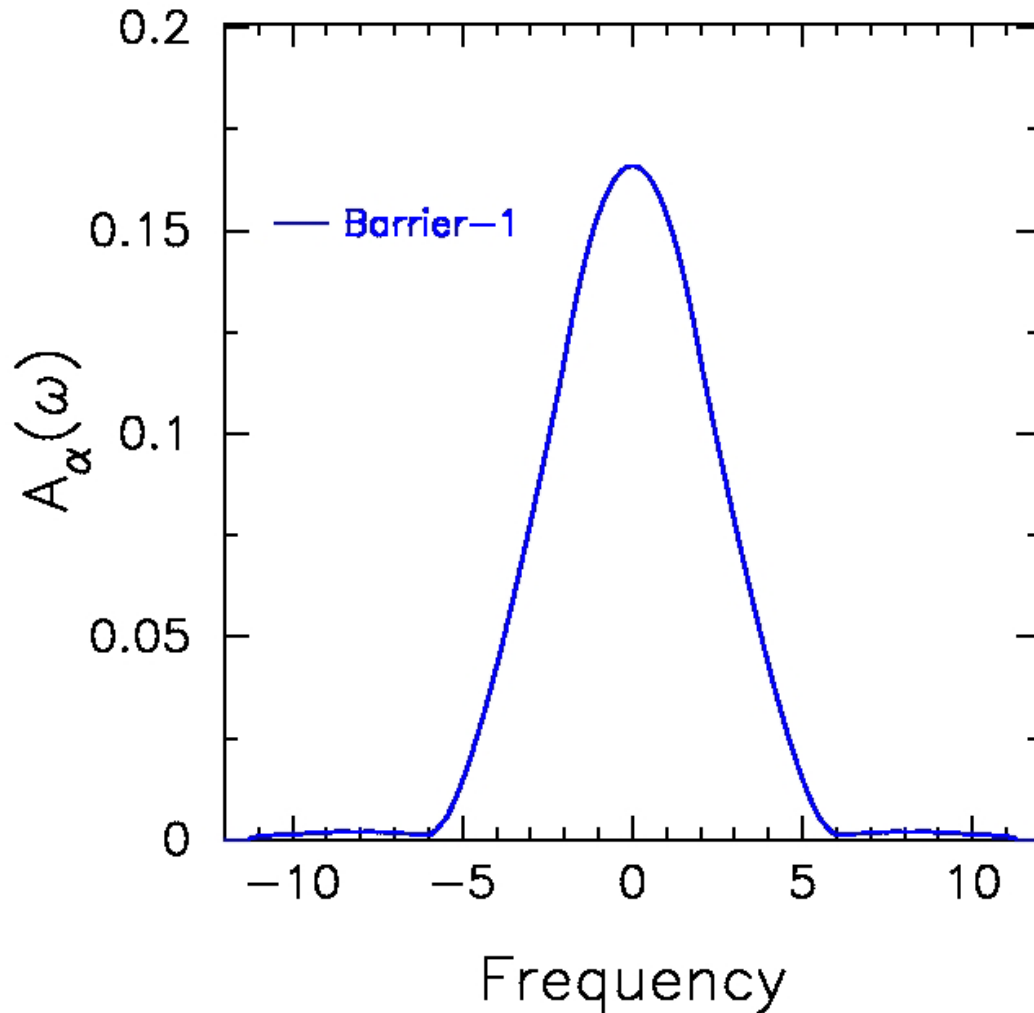
A blow up of the “subgap region” shows a flat metal-like dos inside the gap, that even has a small peak at zero energy. This feature is critical for determining the junction resistance.

Local DOS in a tunnel junction



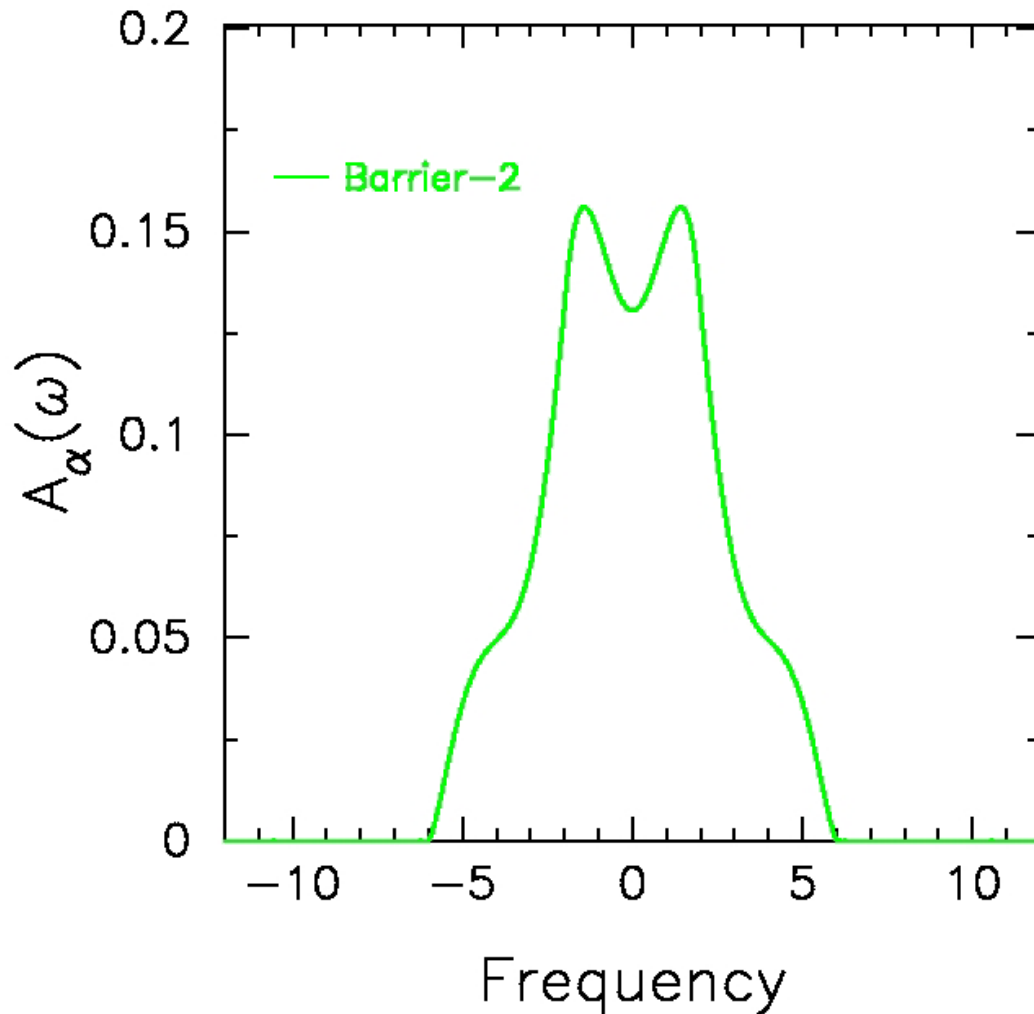
Trying to squeeze a correlated insulator into a single-plane nanostructure results in a “squeezing out” of the correlations, as the subgap dos develops a strong metallic character.

Local DOS in a tunnel junction



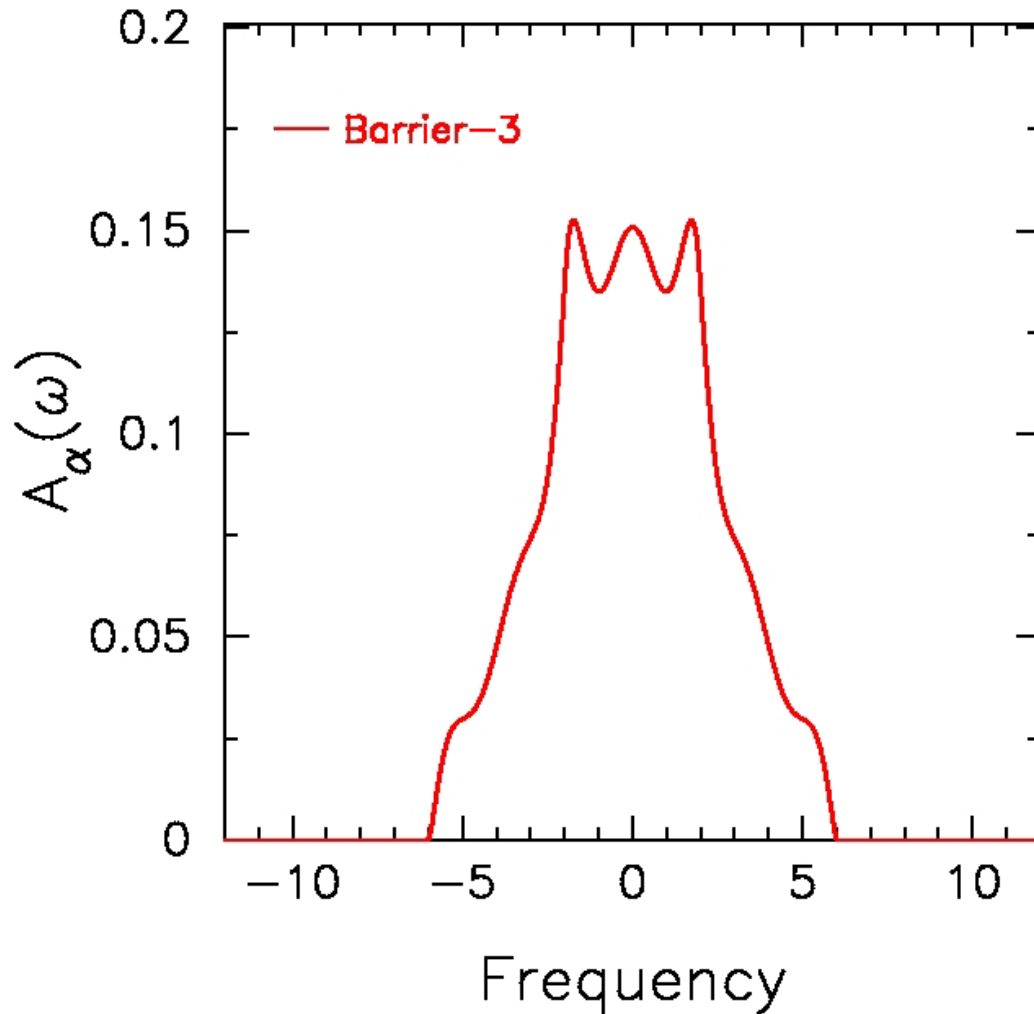
Within the bulk metallic leads, the dos remains similar to what was seen before, except for the large tails at high energy.

Local DOS in a tunnel junction



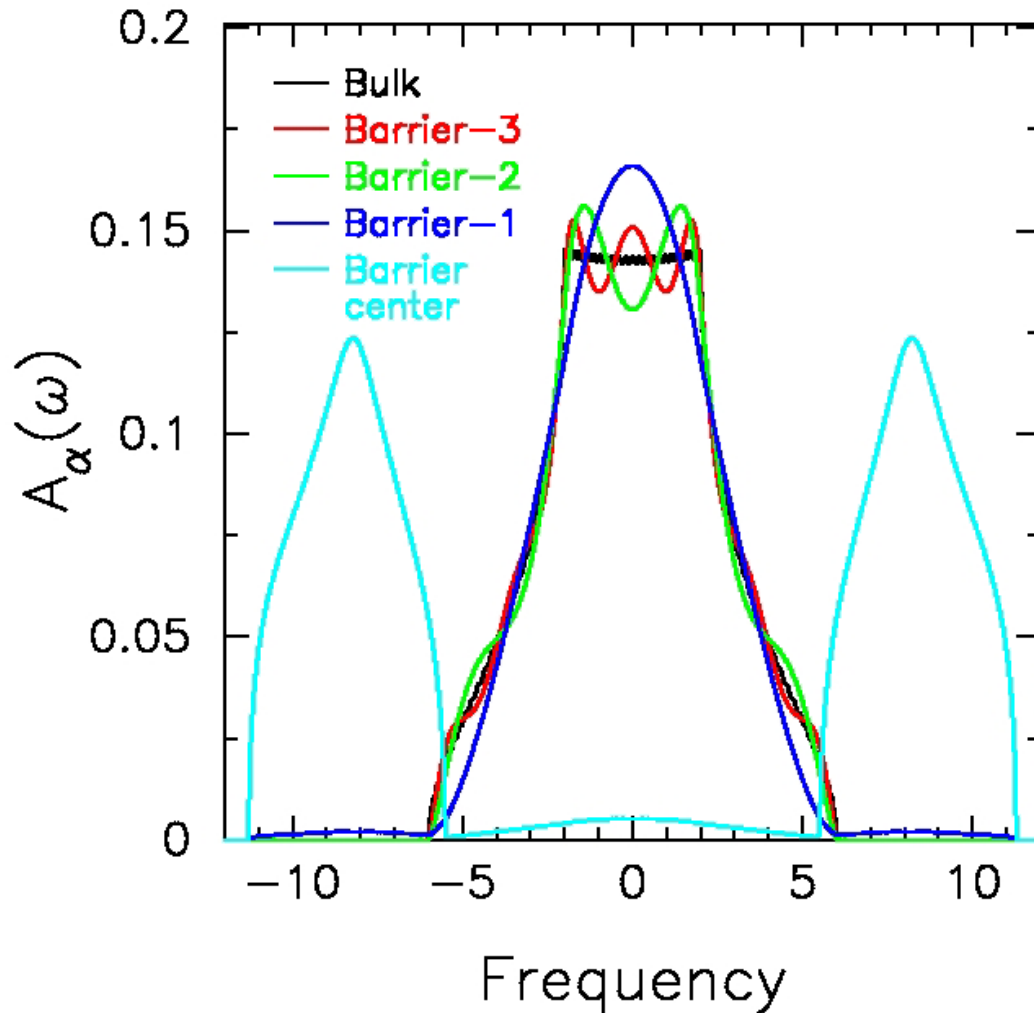
As we move further away from the barrier, we once again see the oscillations. The tails to the dos are strongly suppressed.

Local DOS in a tunnel junction



The oscillations
continue.

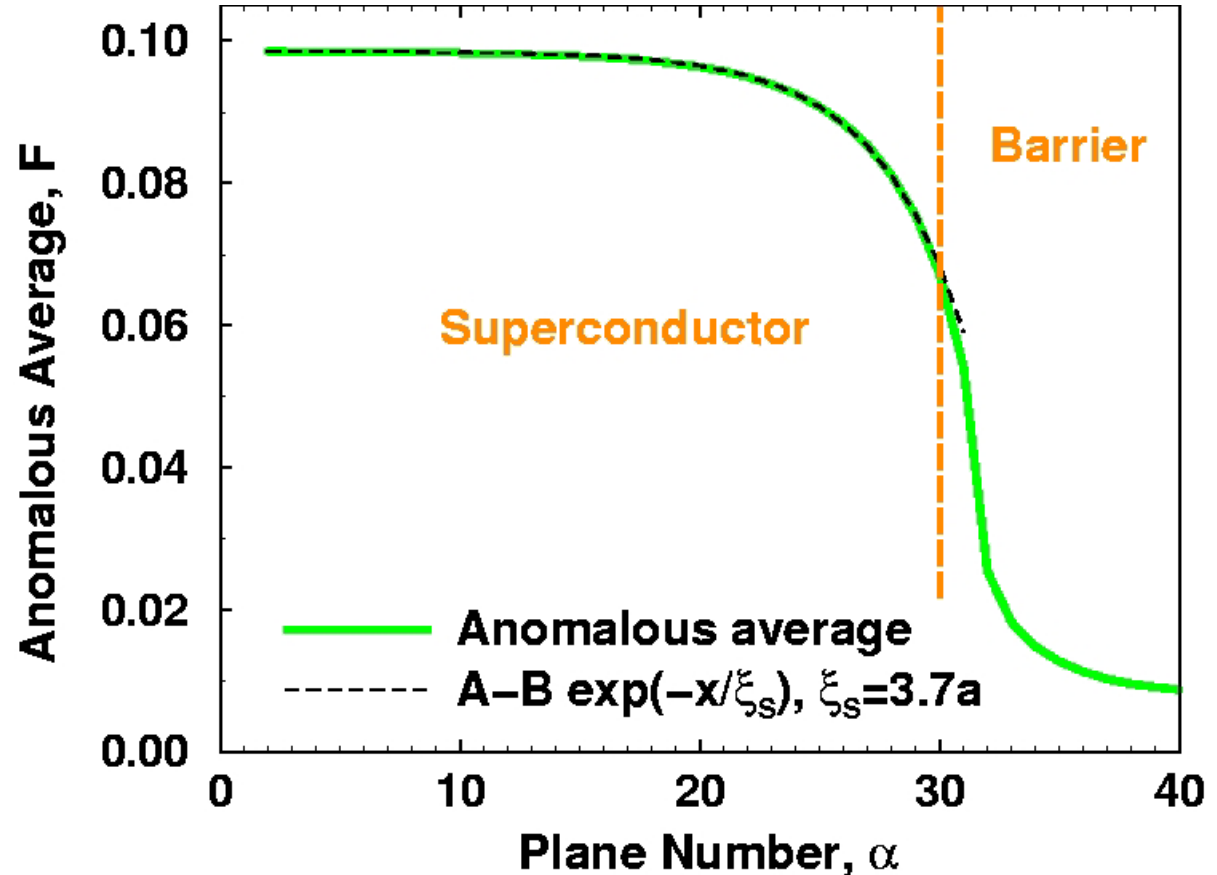
Local DOS in a tunnel junction



In summary, one can see how the nanostructure strongly modifies the insulating character of the correlated insulating plane.

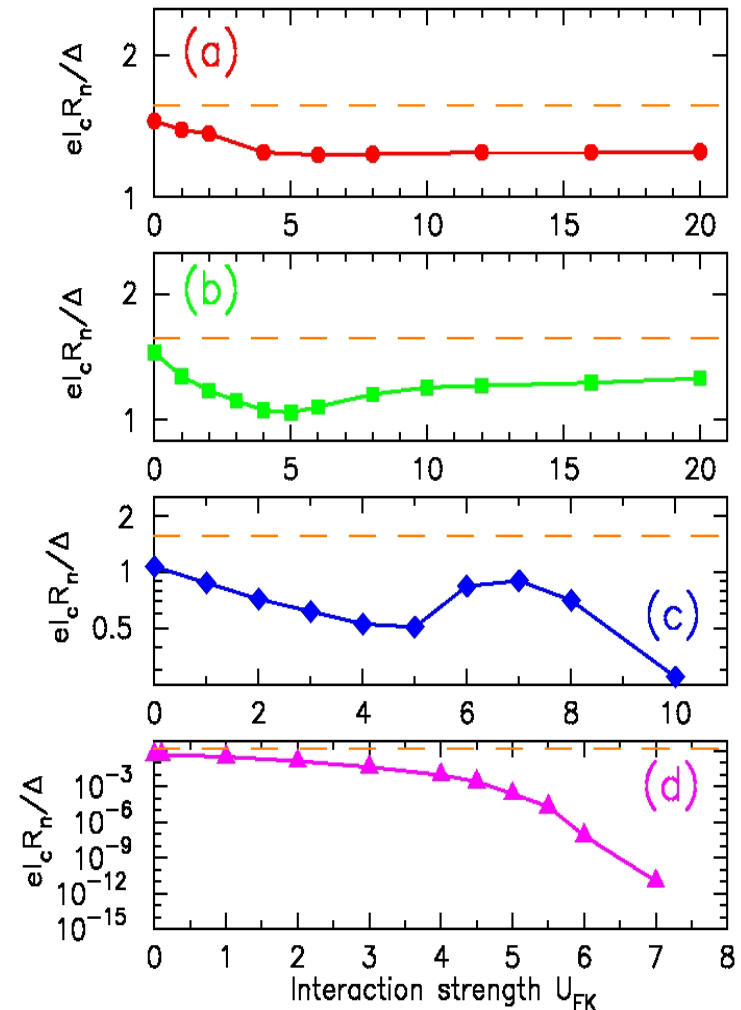
Bulk superconducting properties

- $T_c = 0.112t$,
 $\Delta = 0.198t$,
 $2\Delta/k_B T_c = 3.56$ ---
behaves like a BCS superconductor
- Bulk coherence length $\xi_S = 3.7a = v_F^S / \pi \Delta$ --- **short coherence length superconductor**

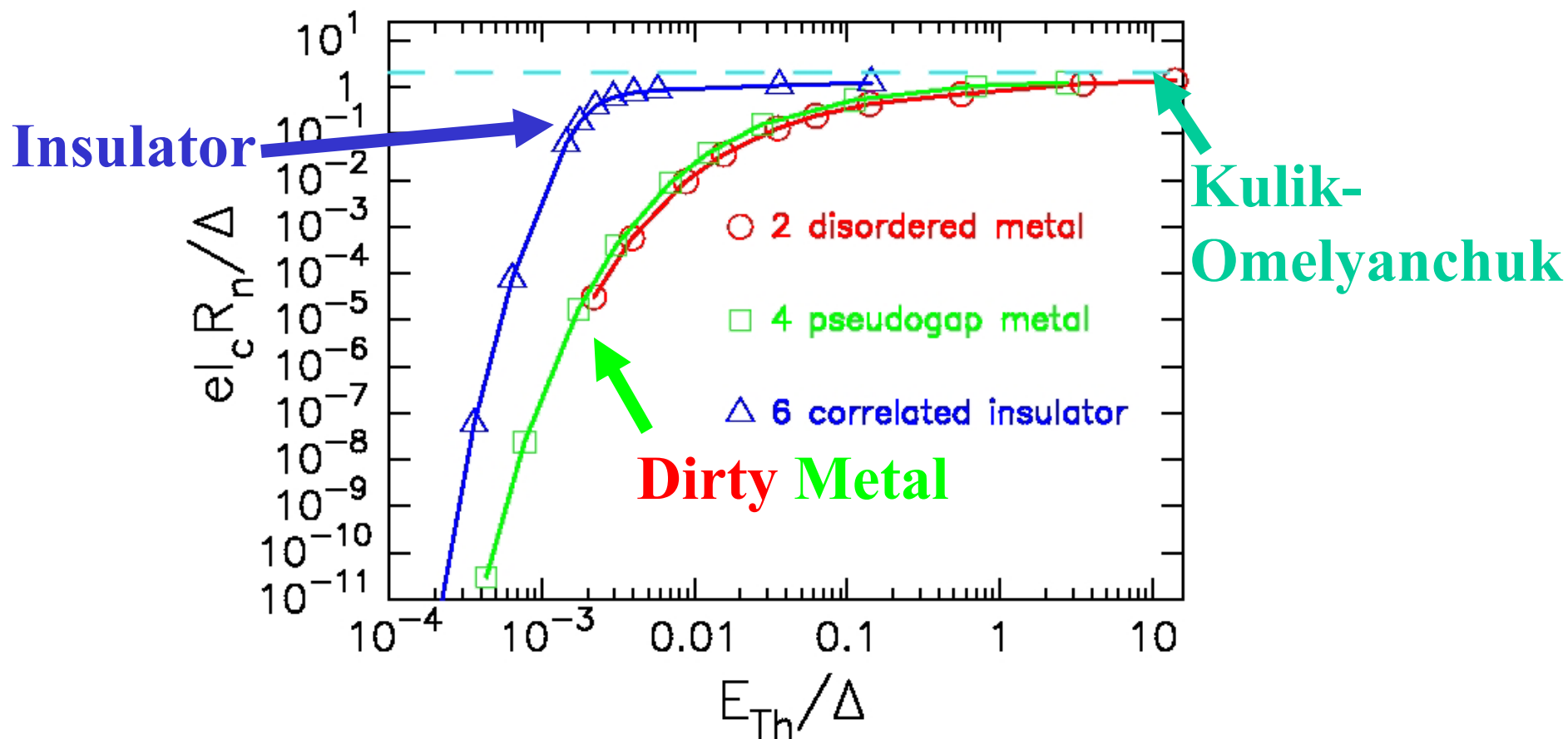


IcRn for different junctions ($T=T_c/11$)

- N=1: Optimization for the metallic junctions, Ambegaokar-Baratoff for the insulator.
- N=2: The SNS junctions are rapidly suppressed as scattering increases, and then Ambegaokar-Baratoff is recovered for the SIS junctions
- N=5: The MIT creates an enhancement to IcRn, but it remains below AB.
- N=20: IcRn decreases rapidly as the scattering increases.



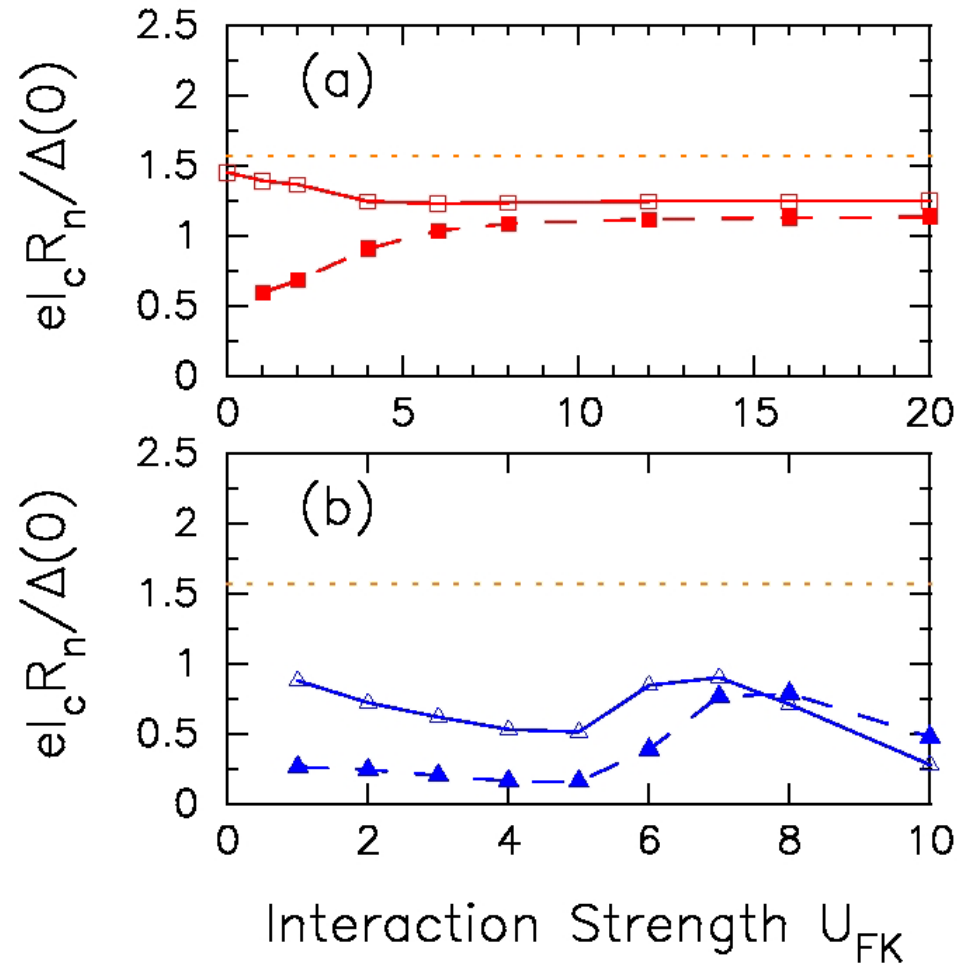
Characteristic voltage versus Thouless energy



- Quasiclassical theory predicts a **universal form for dirty metals**, but we see different behavior for the correlated insulator which predicts a **greater sensitivity to “intrinsic pinholes”**, if the insulator is too thick.

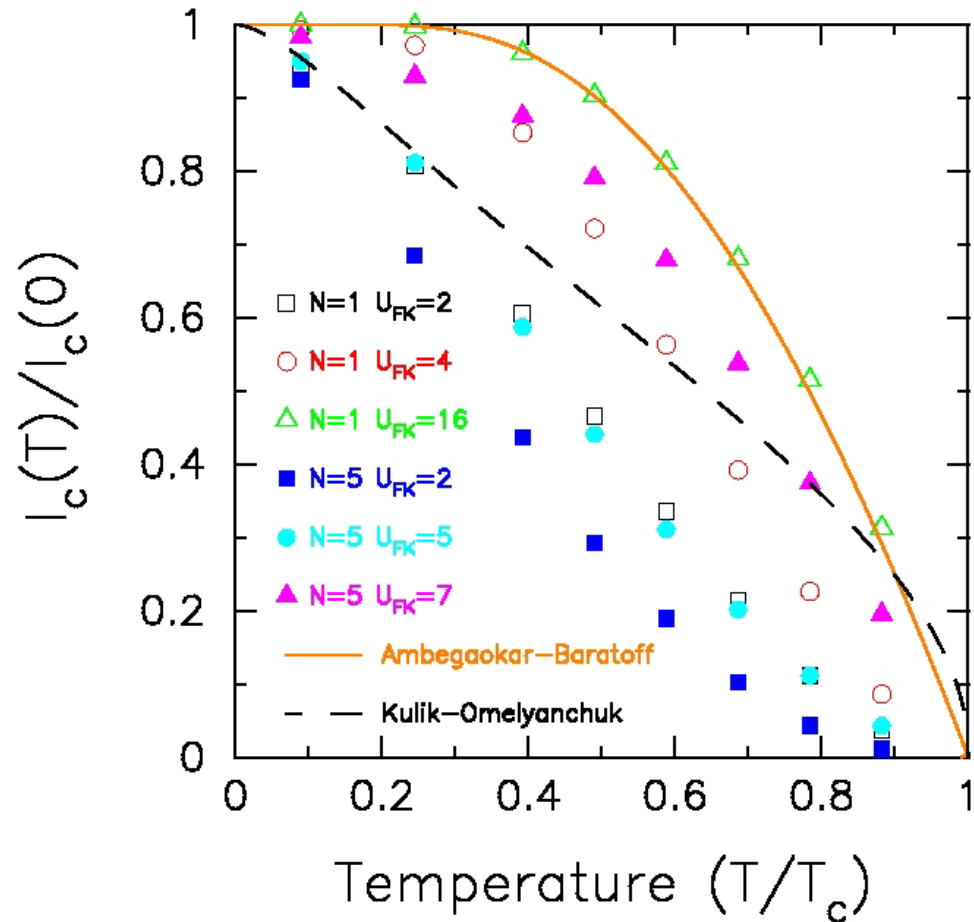
IcRn for different temperatures

- N=1: Open symbols
T=Tc/11, closed symbols
T=Tc/2. Note how the figure of merit is sharply reduced for the SNS junctions.
- N=5: Once again the SNS junctions are sharply reduced with T, but there is **very little temperature dependence** close to the MIT.



$I_c(T)$ for different junctions

- Note how we reproduce the AB result for a SIS tunnel junction, how the temperature dependence of SNS junctions is poor, and how the moderately thick SCmS junction has the same slope as AB in the $0.3 < T/T_c < 0.8$, which is the usual operating range for a junction.



Benefits of SCmS junctions

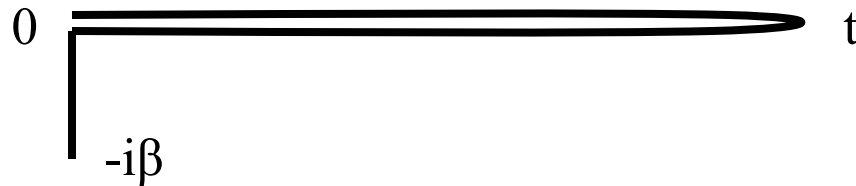
- When properly optimized for thickness and proximity to the MIT, **SCmS junctions have large $I_c R_n$ products.**
- The thermal stability of SCmS junctions over the reasonable operating range of $0.3T_c$ - $0.8T_c$ is **as good as the best case of an SIS junction.**
- **Overall SCmS junctions can have the best properties of any proposed junction type, because we anticipate a smaller junction capacitance, hence they could be self-shunted.**

Potential problems of SCmS junctions

- SCmS junctions may need **fine-tuning** to reach the “optimization zone”.
- Intrinsic pinholes may appear if the JJ coupling is **highly sensitive to the thickness of the junction** (producing dead zones or hot zones that can dominate the JJ effect).
- Fabrication **uniformity would then be difficult** to achieve.

Nonequilibrium formalism

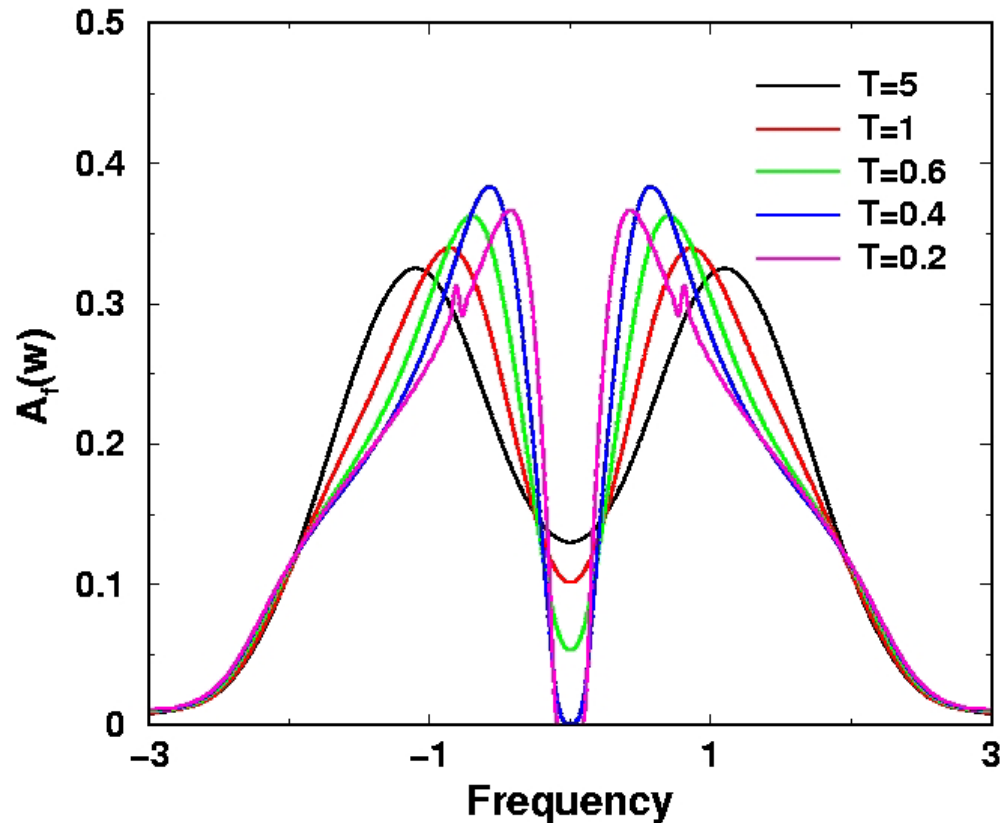
- A nonequilibrium formalism is needed to determine the I-V characteristic.
- A Keldysh-like formalism is used to calculate the so-called contour ordered Green's function.



- The simplest application is to calculating the f -electron spectral function of the bulk FK model, ultimately we hope to calculate I-V curves

F-electron dos

- The f-electron dos requires a nonequilibrium formalism because there is no obvious way to perform the analytic continuation from the imaginary to real axes.
- Here we solve the dos on a Bethe lattice that is a correlated insulator.
- Note how the dos depends on temperature and how a gap opens as T is lowered.



Conclusions

- Examined properties of a Josephson junction **tuned through a metal-insulator transition**.
- Saw that optimization of the characteristic voltage requires a **careful understanding of the correlations, thickness, and operating temperature** of the device.
- Found an **optimization** on the insulating side of the metal-insulator transition for moderately thick barriers in the range $0.3T_c < T < 0.7T_c$.
- Discovered that **temperature effects** are similar to the best case of an SIS junction in the expected operating range for a circuit.
- **Preliminary work on nonequilibrium effects shows promise for calculating IV characteristics.**