# Decreasing excitation gap in Andreev billiards by disorder scattering

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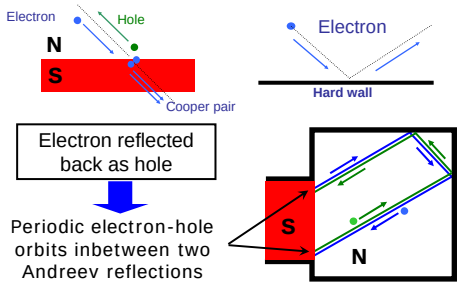
## Andreev billiards

Ballistic quantum billiard (N) in contact with a **superconductor** (S)

Andreev reflection [1] | Normal reflection

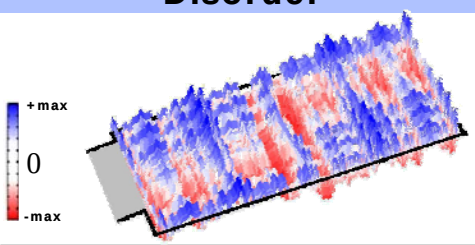



Electron reflected back as hole

Periodic electron-hole orbits inbetween two Andreev reflections




## Disorder

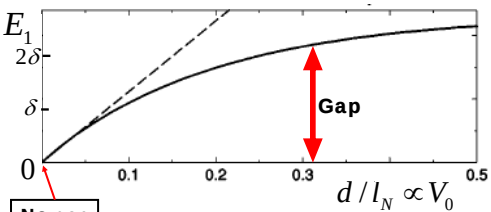



Correlated on-site disorder potential in N-region, characterized by

$$\langle V \rangle = 0 \qquad \sqrt{\langle V^2 \rangle} = V_0 \qquad l_{\text{corr.}} = 0.2\lambda_F$$

## Excitation gap

Result for **SN junctions [3]: Disorder** shifts lowest eigenenergy $E_1$ **away** from Fermi energy



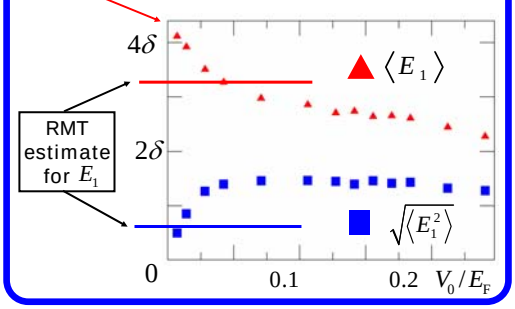

**No** gap at $V_0 = 0.$

Gap **increases** with increasing disorder!

? How to explain reduction of gap size as semiclassics and RMT do **not** work ?

**Largest** gap at $V_0 = 0.$

Gap **decreases** with increasing disorder




## Proper delay times

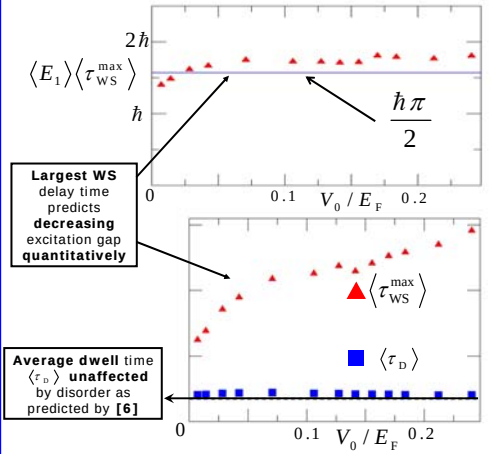
**Eigenenergies** of closed Andreev billiards **[4]**

$$\det\left[1+S(E)S^{\dagger}(-E)\right]=0 \Leftrightarrow E \approx \frac{\hbar\pi}{2\tau_{\text{WS}}}$$

$\tau_{\text{WS}}$: Eigenvalues of the Wigner-Smith delay time matrix $Q = -i\hbar S^{\dagger}\partial_E S$ **[5].**

**Lowest** eigenenergy $E_1$(gap size) determined by **largest** WS delay time value $\tau_{\text{WS}}^{\max}$.

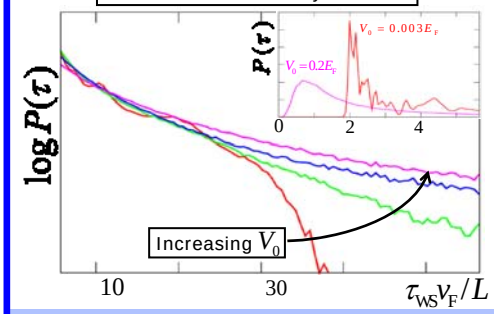
$$E_1\tau_{\text{WS}}^{\max} \approx \frac{\hbar\pi}{2}$$




**Largest WS** delay time predicts **decreasing** excitation gap **quantitatively**

**Average dwell** time $\langle \tau_D \rangle$ **unaffected** by disorder as predicted by **[6]**

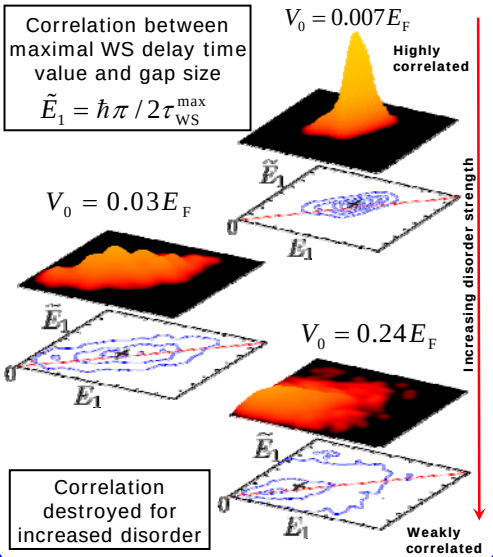
Distribution of delay times




## Correlation

Correlation between maximal WS delay time value and gap size

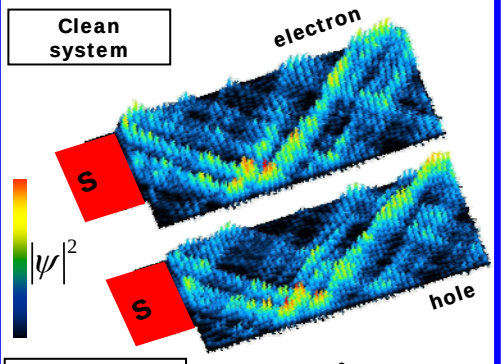
$$\tilde{E}_1 = \hbar\pi/2\tau_{\text{WS}}^{\max}$$



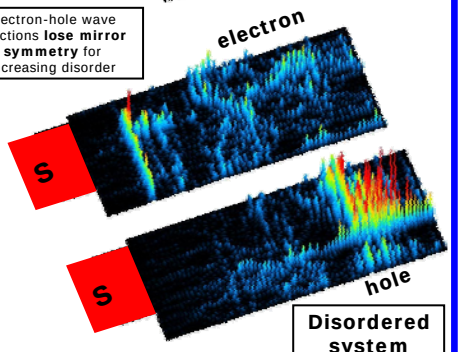

Correlation destroyed for increased disorder

## Wavefunctions

**Clean system**




Electron-hole wave functions **lose mirror symmetry** for increasing disorder




**Disordered system**

## Conclusions

- Gap size **reduced** by disorder
- **Mean delay time** (dwell time) **unrelated** to gap
- Correlation between **maximum** Wigner-Smith delay time and gap size
- Strong disorder breaks correlation between **maximum** Wigner-Smith delay time and gap size

## Future Projects

- Effects of dissipation and decoherence
- Time-dependent Andreev scattering
- Transport through open Andreev billiards

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## References

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