Non-Equilibrium FES in Mesoscopic Devices

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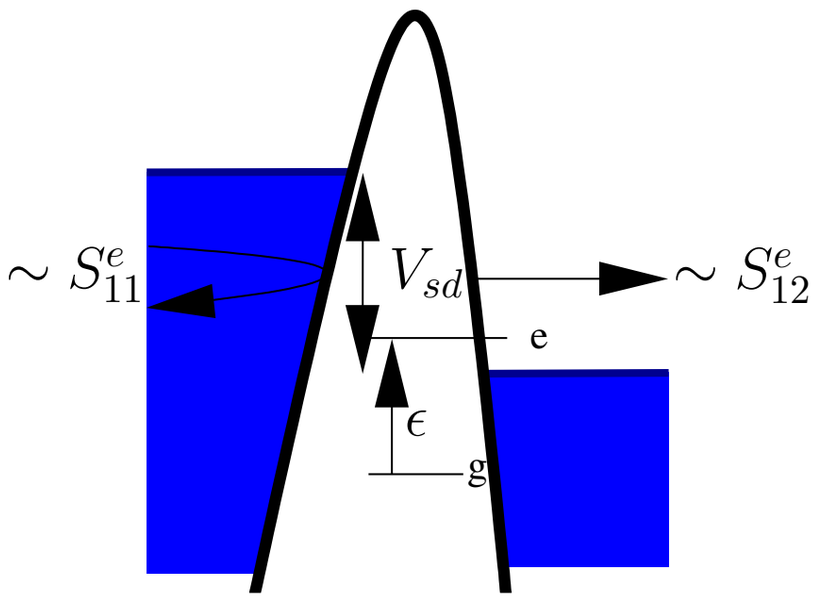
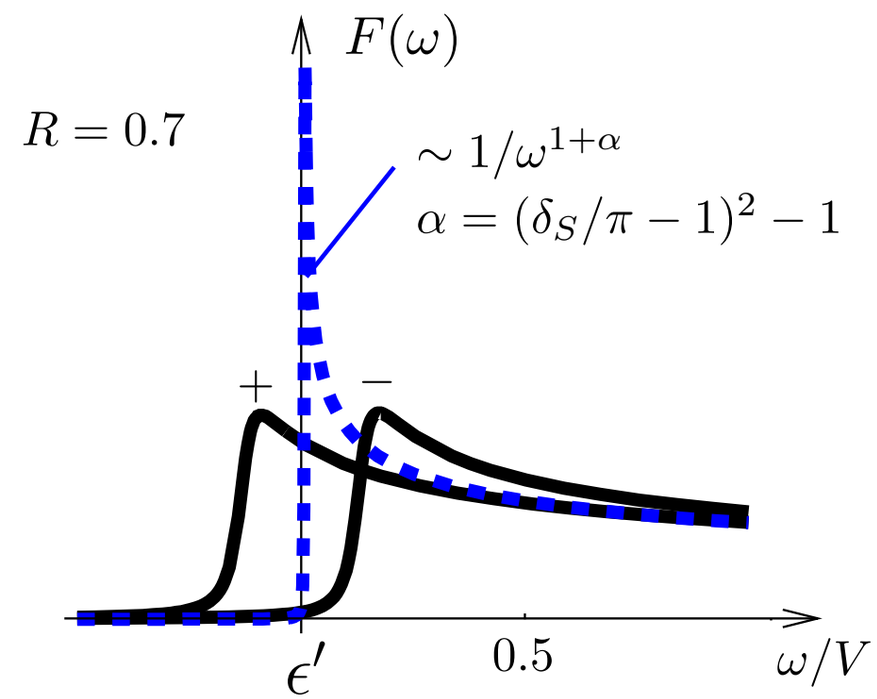
Non-Equilibrium Effects (T=0)





Impurity state change

$$\overbrace{\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}^{S^g} \rightarrow \overbrace{\begin{pmatrix} r & -te^{-i\phi(s)} \\ te^{i\phi(s)} & r^* \end{pmatrix}}^{S^e}$$

$\phi(s) \quad = \quad V_{sd}s$ gauge transformation

s time

BM+NdA, 2005, PRB

FES effects:

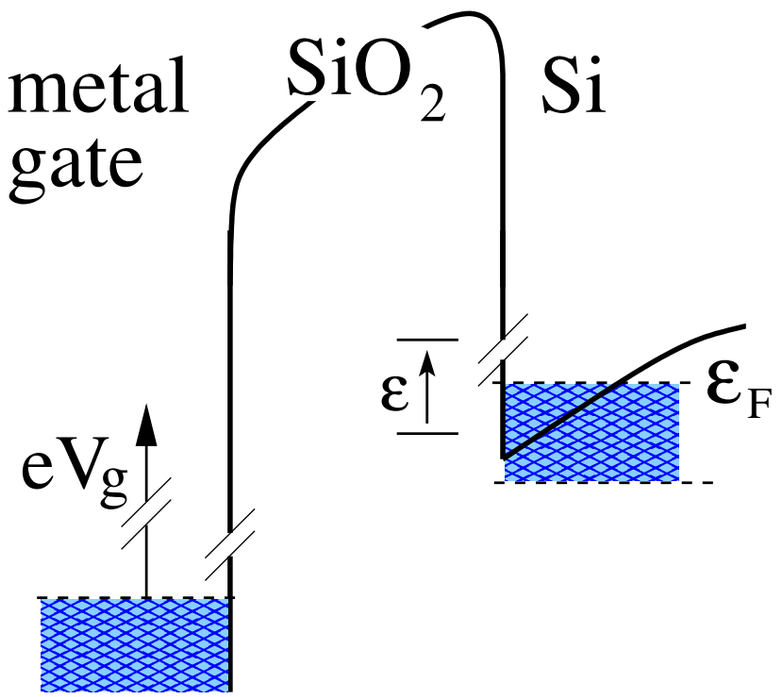
i) Exponent, Friedel sum rule

ii) Fumi shift

$$\epsilon' = \epsilon + \int^{E_F} dE \frac{\delta(E)}{\pi}$$

iii) Non-eqm broadening and shifting

RTS in a dirty MOSFET I

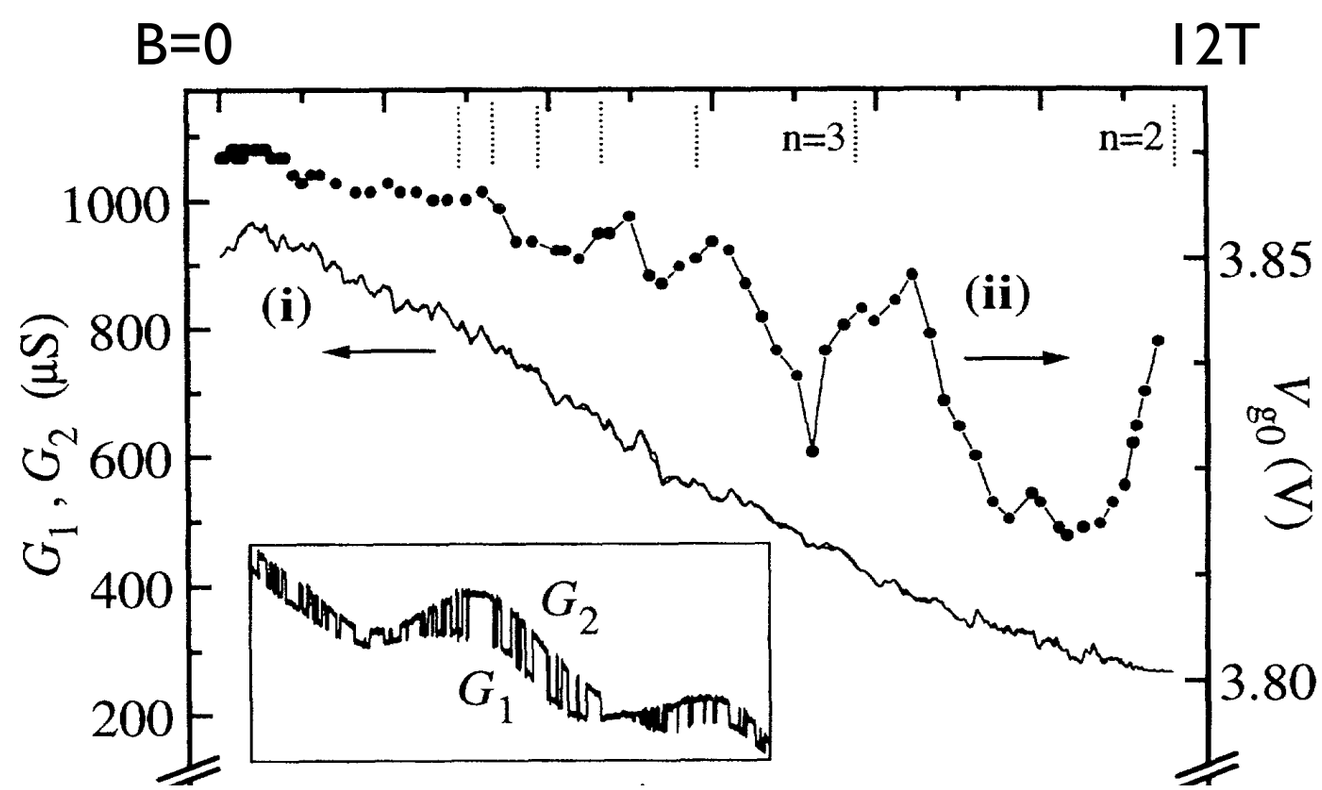


2 Regimes:

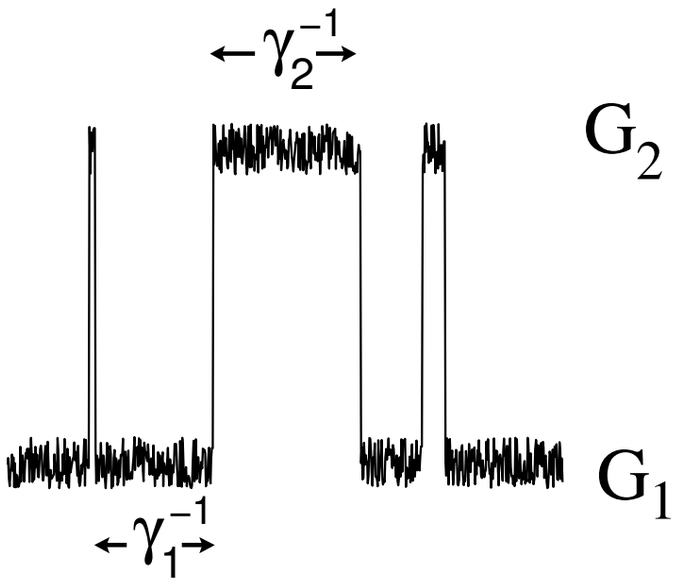
i) UCF weak localization
ii) Quantum Hall regime

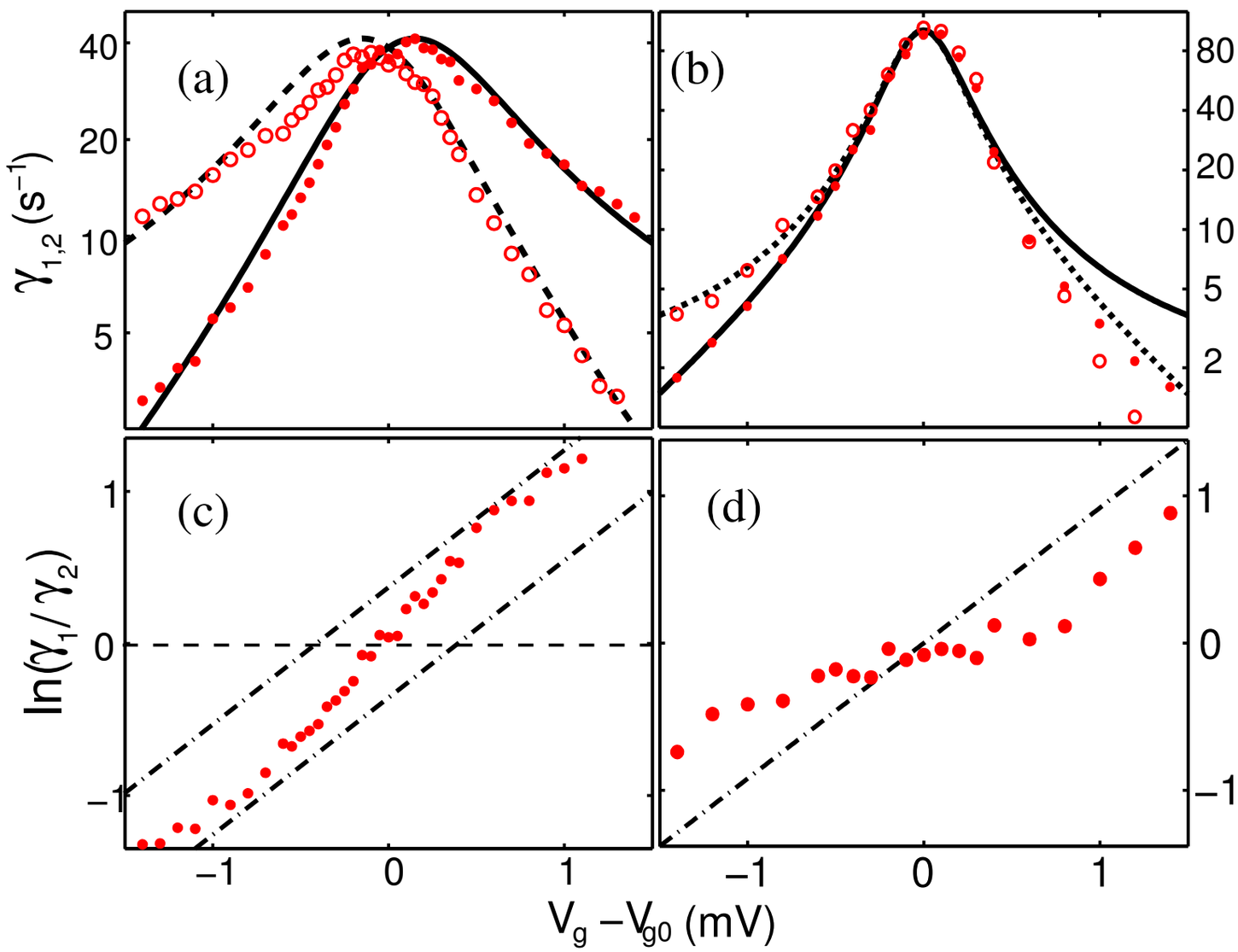
$T = 100$mK,
Channel 0.6-0.8μm
$l \sim 300$Å

Cobden, Muzyk. 1995



RTS in a dirty MOSFET II





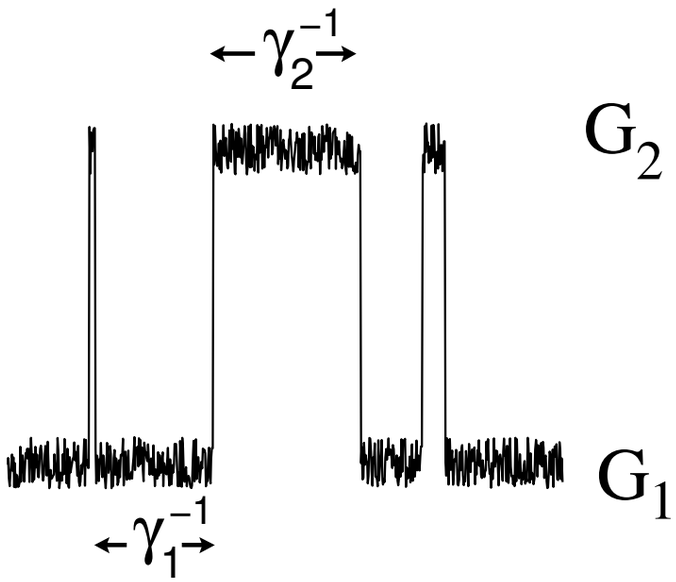
Detailed Balance:

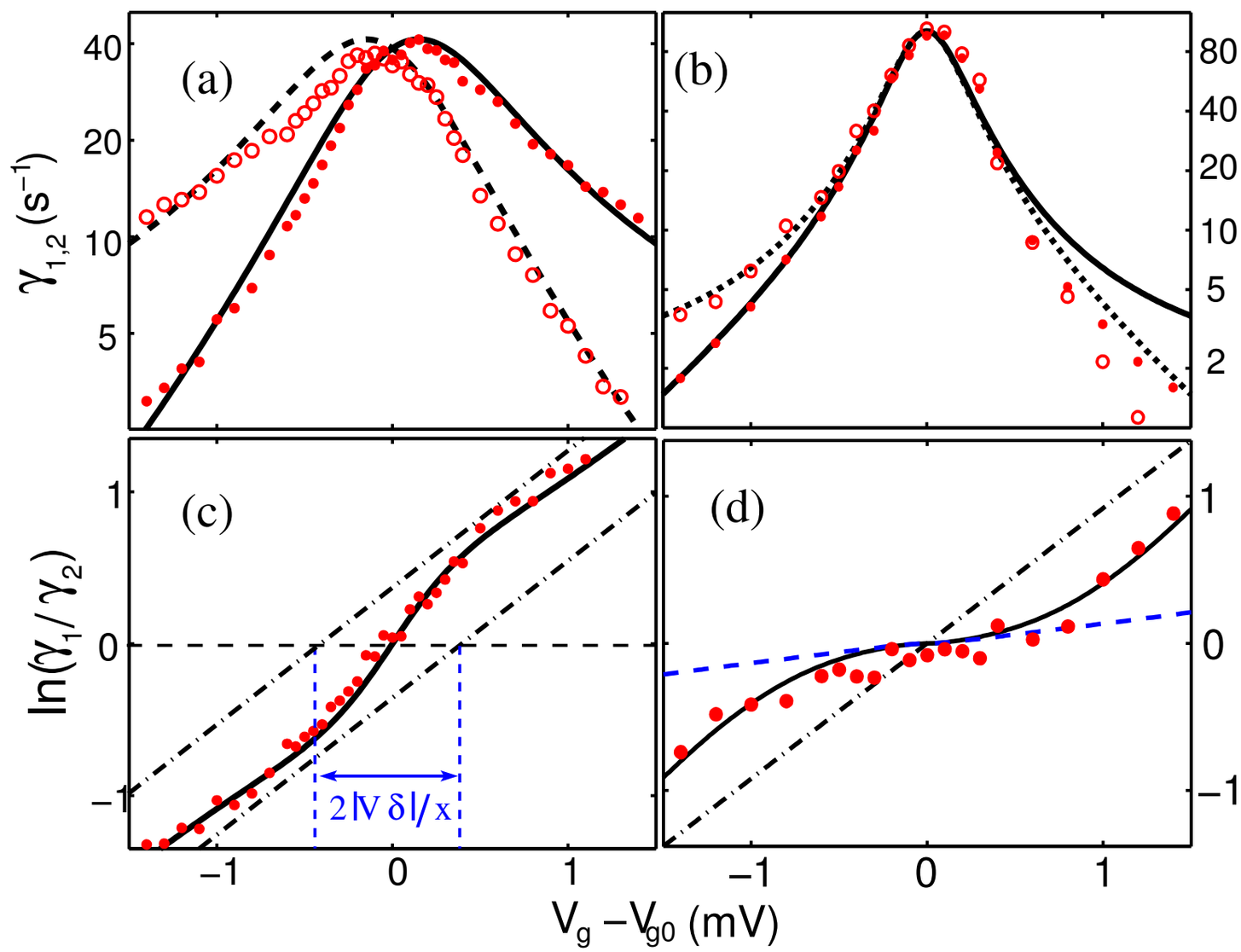
$$\gamma_2/\gamma_1 = \exp \epsilon/kT$$

$$\begin{aligned}
\sigma_{12} &\approx 3.6\mu\mathrm{S} \approx 0.1\frac{e^2}{h} \\
\sigma_1 &\approx 10\mu\mathrm{S} \\
\frac{\sigma_{12}}{\sigma_1} &\approx \left(\frac{A_\phi}{A}\right)^{1/2} \approx 0.45
\end{aligned}$$

$$V_{sd}^{ac} = 20\mu\mathrm{V},\ \ T = 100\mathrm{mK},\ \ B = 0.06\mathrm{T},\ 10.35\mathrm{T}$$

RTS in a dirty MOSFET II





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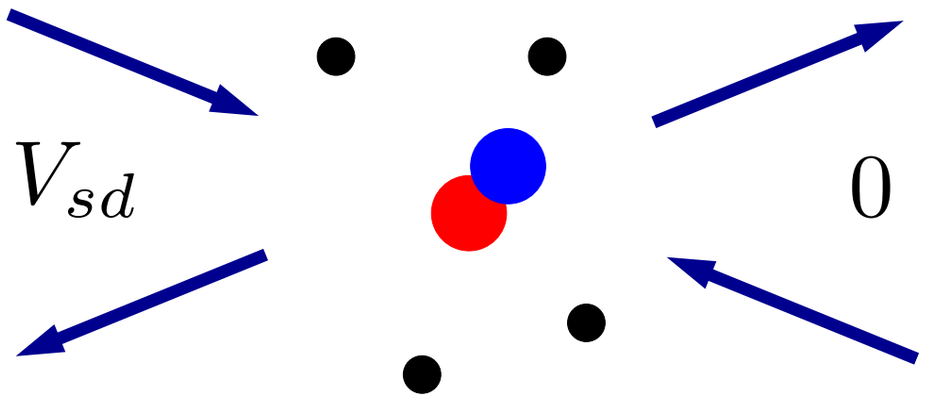
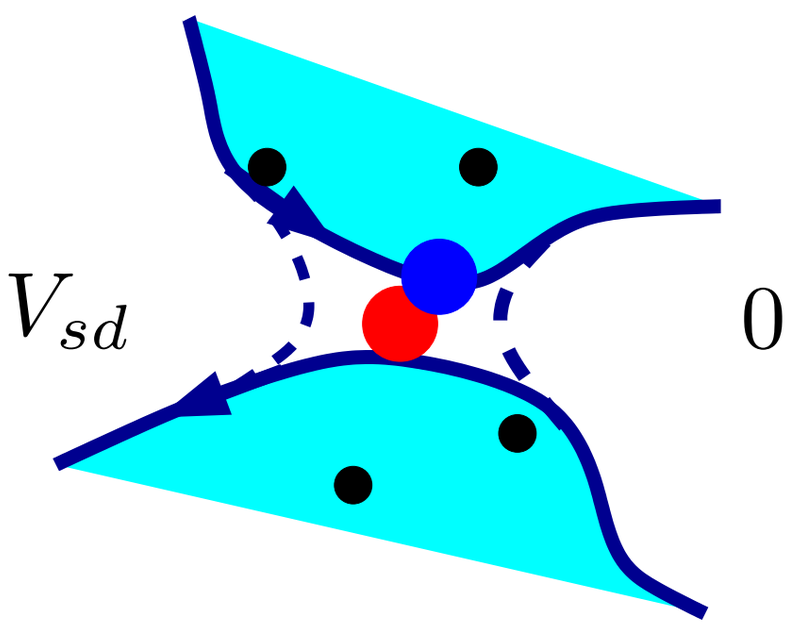
Two Regimes



Weak localization regime:
1 impurity $\rightarrow$ UCF, Altshuler, Spivak '85

$$\overbrace{\begin{pmatrix} r & -te^{-i\phi(s)} \\ te^{i\phi(s)} & r^* \end{pmatrix}}^{S^e}, r = |r|e^{2i\delta}, t \ll 1$$



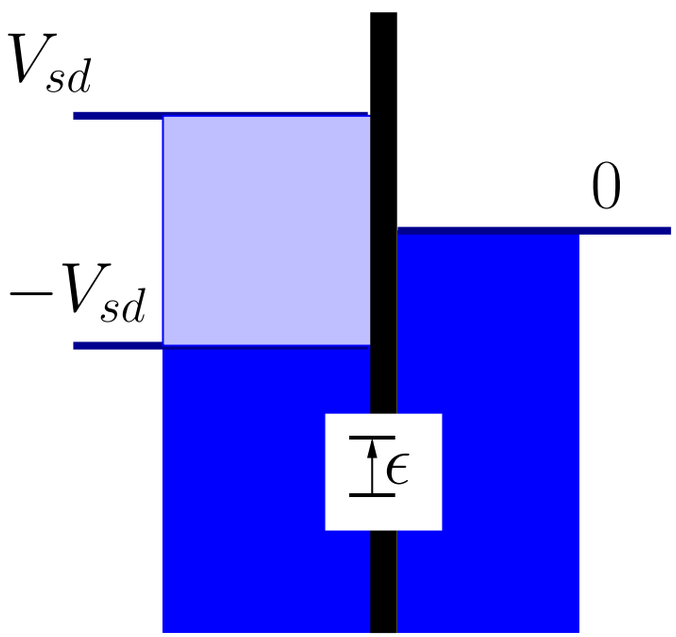
High field regime, saddle points,$(\ell_0 < \ell)$

$$r = |r|e^{2i\delta}, |t| < 1$$

Expect $|t|$ to relate to σ_{12}

Non-equilibrium FES

Core Hole:



$$\epsilon' = \epsilon + \int_0^{E_F+V_{sd}} dE \frac{\delta_l(E)}{\pi} = \epsilon + \Delta(V_{sd})$$

Fumi Shift:

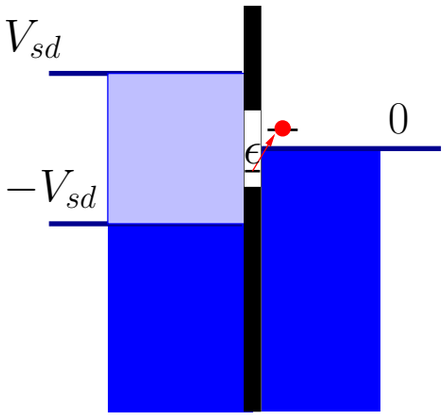
$$\Delta_1(V) = \Delta_2(V)^* = \left(\frac{\delta - i\ln|r|}{2\pi}\right) V$$

Shift $V\delta/2\pi$ and dephasing $V\ln|r|/2\pi$

Line Shape: Fermi Edge Singularity

$$\begin{aligned} G_j(t_f) &= \langle i|U_0^{-1}(t_f)U(t_f)|i\rangle \\ \gamma_j(\epsilon, V, \Delta_j) &\propto \int dt_f\, G_j(t_f) e^{i\epsilon t_f} \end{aligned}$$

Open Line:



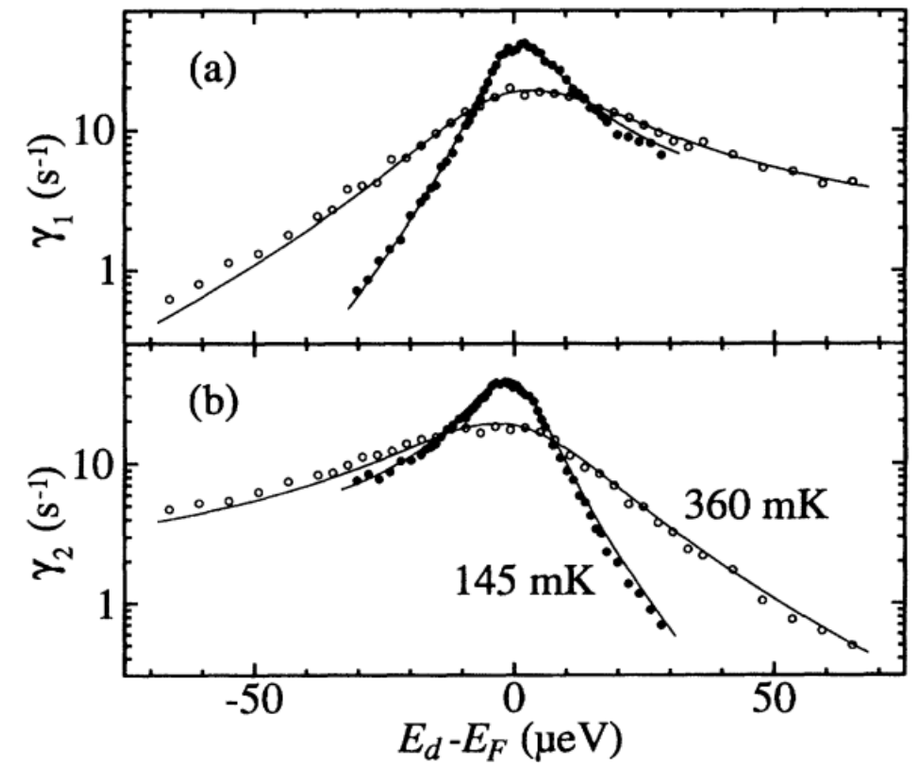
Line-Shape

Equilibrium (no bias voltage):

$$\gamma_{1,2} \quad \propto \quad CT^{\beta-1} \exp\left[\pm\frac{\epsilon-\Delta_0}{kT}\right]\frac{\Gamma[\beta/2+i\epsilon/2\pi kT]^2}{\Gamma[\beta]}$$

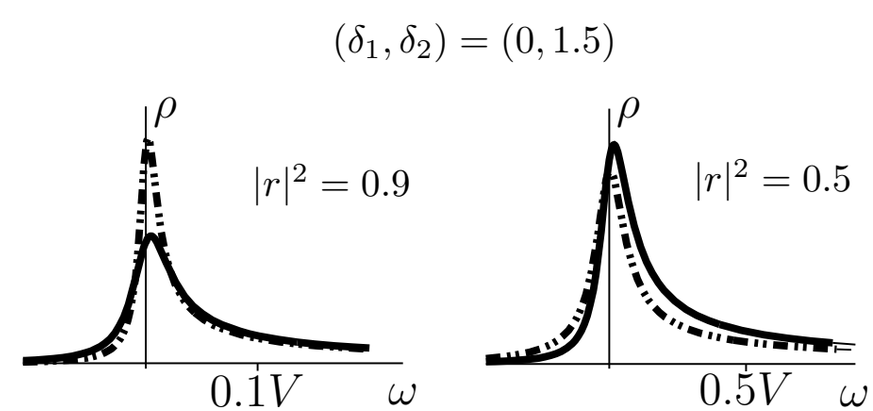
$$\beta = \left(\frac{\delta_1}{\pi}\right)^2 + \left(\frac{\delta_2}{\pi}\right)^2 \quad \text{(diagonalize S)}$$

(Yuval & Anderson '70, Matveev & Larkin '92)



Non-Equilibrium:

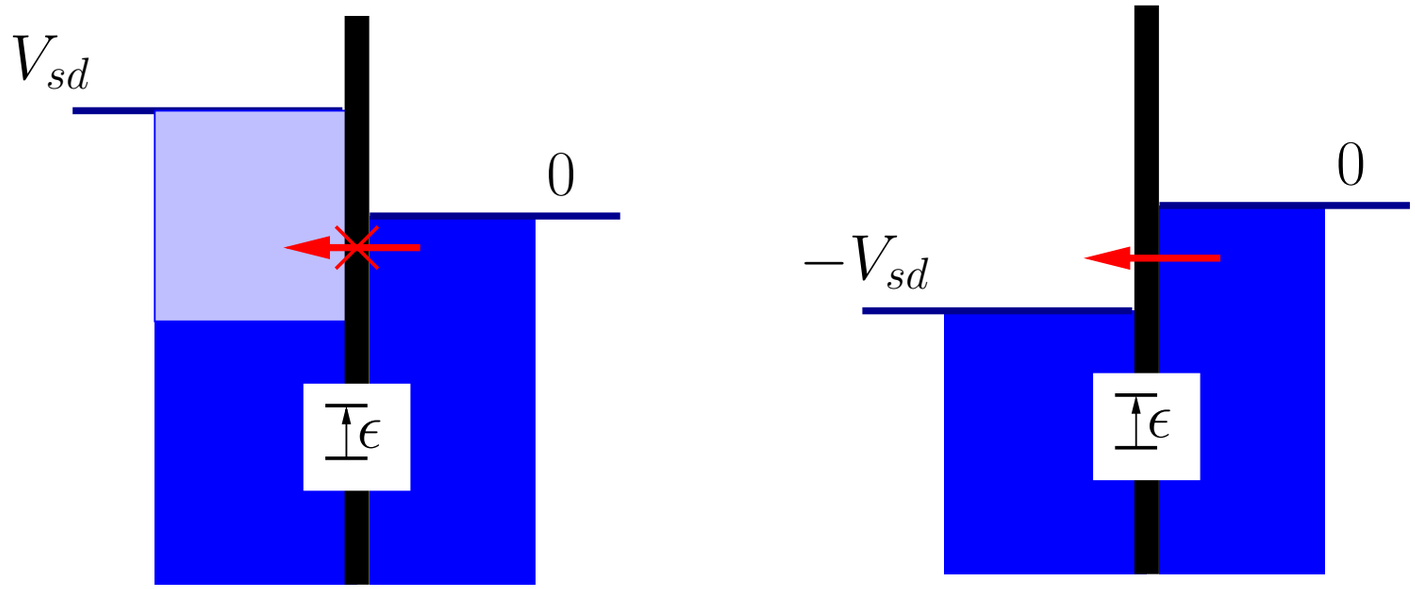
$$\begin{aligned}\beta' &= \left(\frac{\log\left(S^e_{11}\right)}{2\pi i}\right)^2 + \left(\frac{\log\left(1/S^e_{22}\right)^*}{2\pi i}\right)^2 \quad \text{for } \epsilon < V_{sd} \\ &= \beta \ \text{ otherwise}\end{aligned}$$



Broadening + Polarity effects

BM, NdA, Braunecker, 03

Asymmetries in NFES

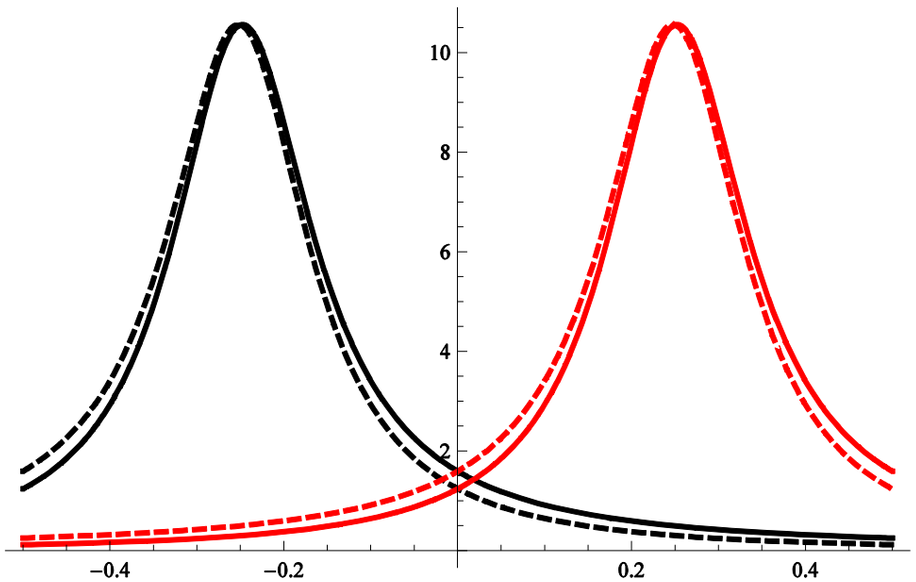


Transition Rates - Low Field

Low frequency ac signal: (5kHz)

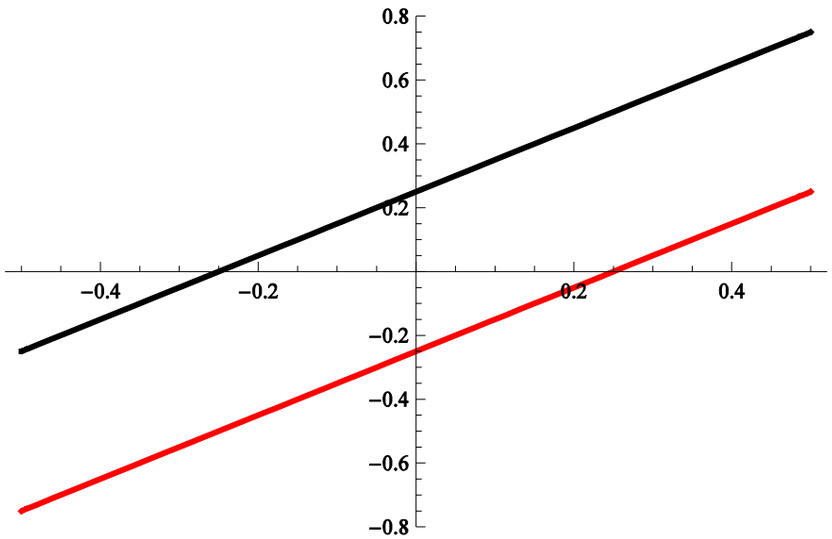
With $|r| \leq 0.99$, $V = 20\mu\text{V}$,

$$-\frac{V \ln |r|}{2\pi} \ll 10\mu\text{s}$$



Average transition rates:

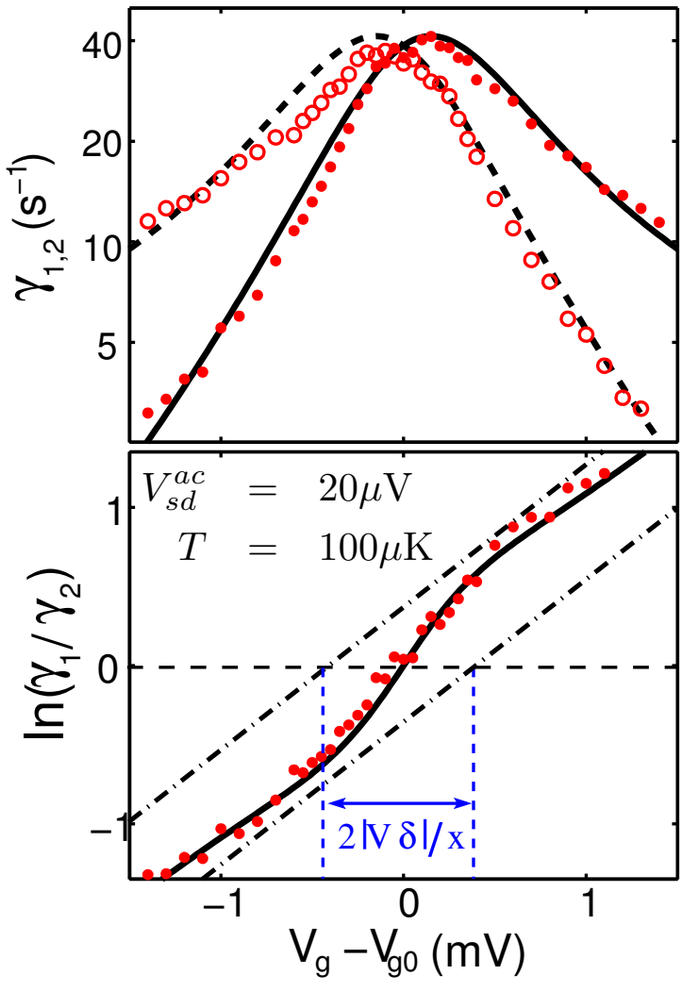
$$\gamma_j^{ac} = \left[\frac{2}{\gamma_j^{-1}(\epsilon, V) + \gamma_j^{-1}(\epsilon, -V)} \right]^{-1}$$



Fumi measures phase shift

Transition Rates

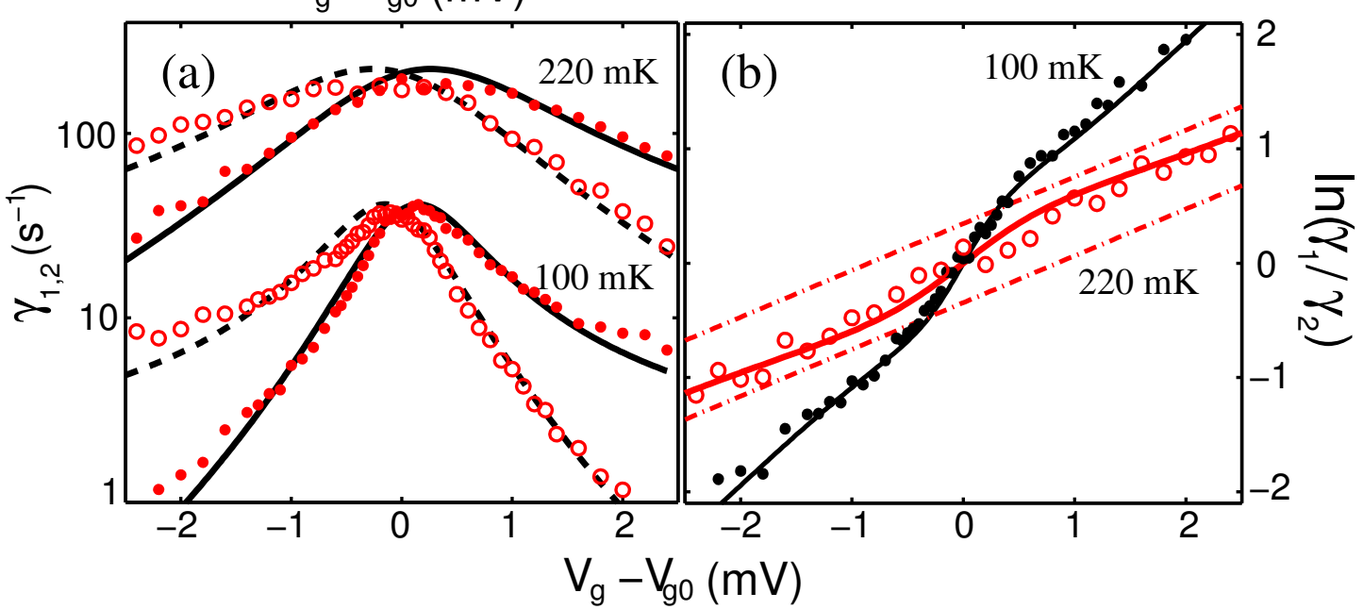
$B = 0.06\mathrm{T}$



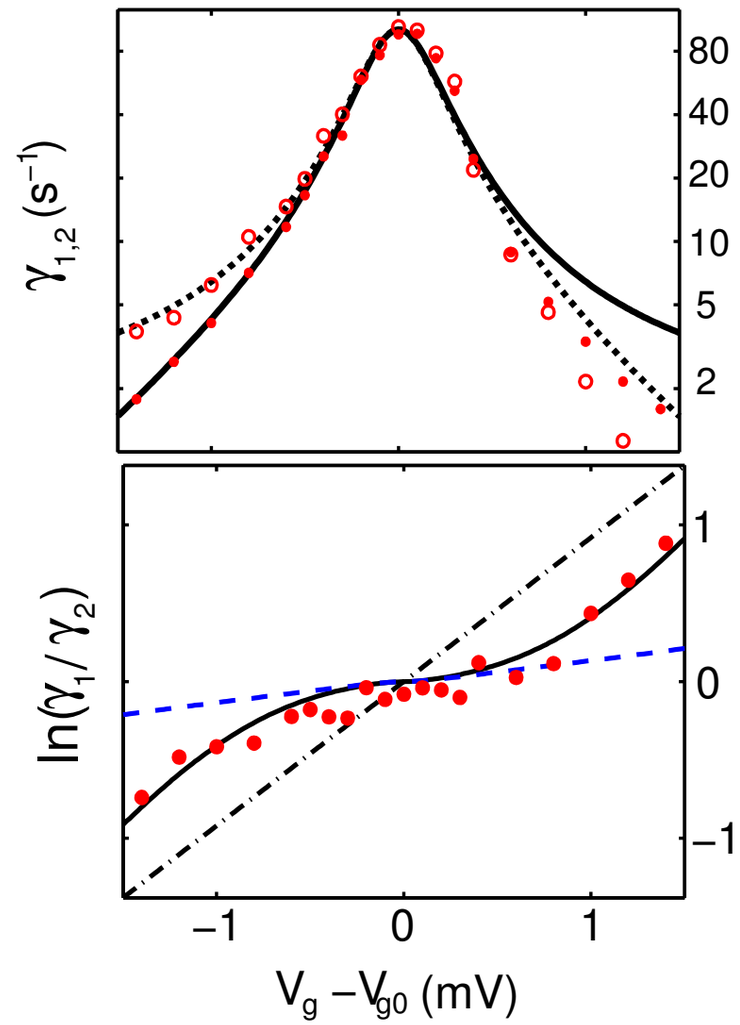
Sensitivity to gate voltage, x, fitted to equilibrium

Access scattering parameters

$r = 0.9, \quad \delta = 0.22$



$B = 10.5\mathrm{T}$



Dephasing: $T_{eff} > T$

+

Asymmetry effects

Conclusions

Non-eqm effects in RTS:

Observation of Altshuler, Spivak prediction

Access scattering parameters, via Fumi shift

NFES effects not just broadening