Two Channel Kondo in a Modified SET

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http://www.weizmann.ac.il/condmat/oreg_group.html

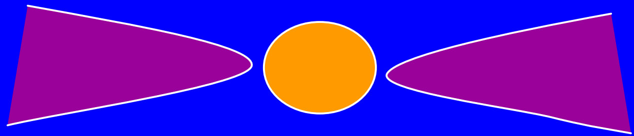
Outline

- Fermi liquid vs. non Fermi Liquids (NFL).
- Fermi edge singularity (FES).
- Single channel Kondo effect – Schrieffer-Wolff and Coulomb gas.
- Multi-channel Kondo effect an academic exercise (Nozieres ,Blandin and Zawadowski).
- Realization of multi-channel Kondo effect (MCK) in a single electron transistor (SET).
- Possible measurements of MCK in a SET.
- Summary.

2-Channel Vs 1-Channel Kondo

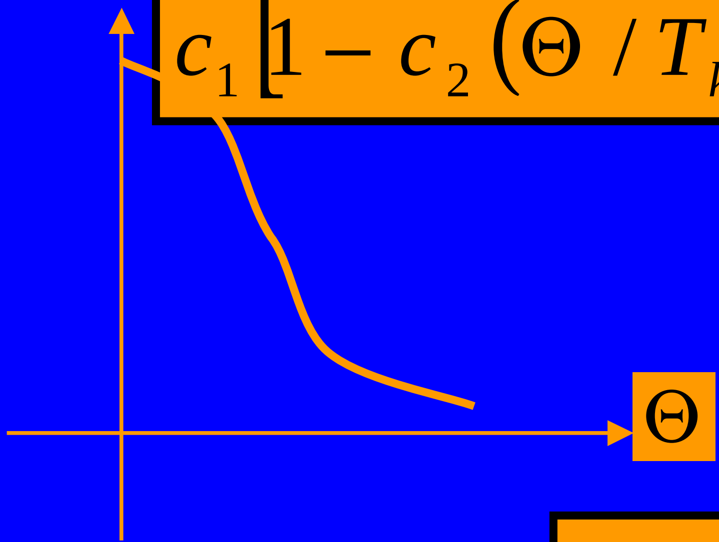
$T << T_K$	Single Channel	Two Channel
Entropy	$a\frac{T}{T_K}\underset{T\to 0}{\to} 0 = Log[1]$	$\frac{1}{2} Log[2]$
Spin Susceptibility	$b\frac{(g\mu_B)^2}{T_K}$	$\beta\frac{(g\mu_B)^2}{T_K} Log\left(\frac{T_K}{T}\right)$
Specific Heat	$a\frac{T}{T_K}$	$\alpha\left(\frac{T}{T_K}\right) Log\left(\frac{T_K}{T}\right)$
Conductance	$c_1 - c_2\left(\frac{T}{T_K}\right)^2$	$\gamma_1 \pm \gamma_2\sqrt{\frac{T}{T_K}}$

Fermi Liquid (FL)	***Non FL***
Single Channel Kondo	**Two-Channel Kondo**



dI/dV$_{sd}$

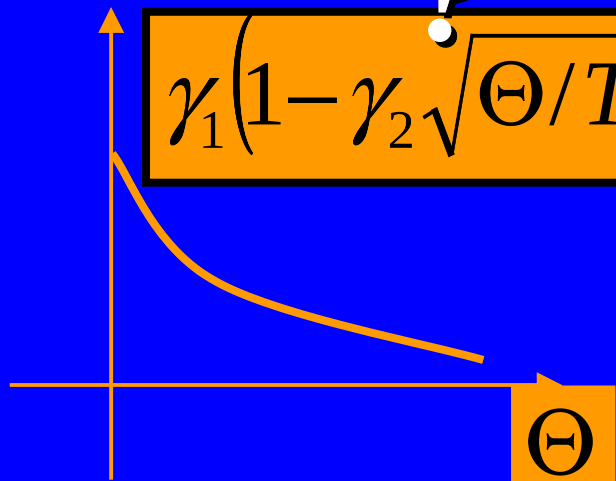
$$c_1\left[1 - c_2\left(\Theta / T_k\right)^2\right]$$



dI/dV$_{sd}$

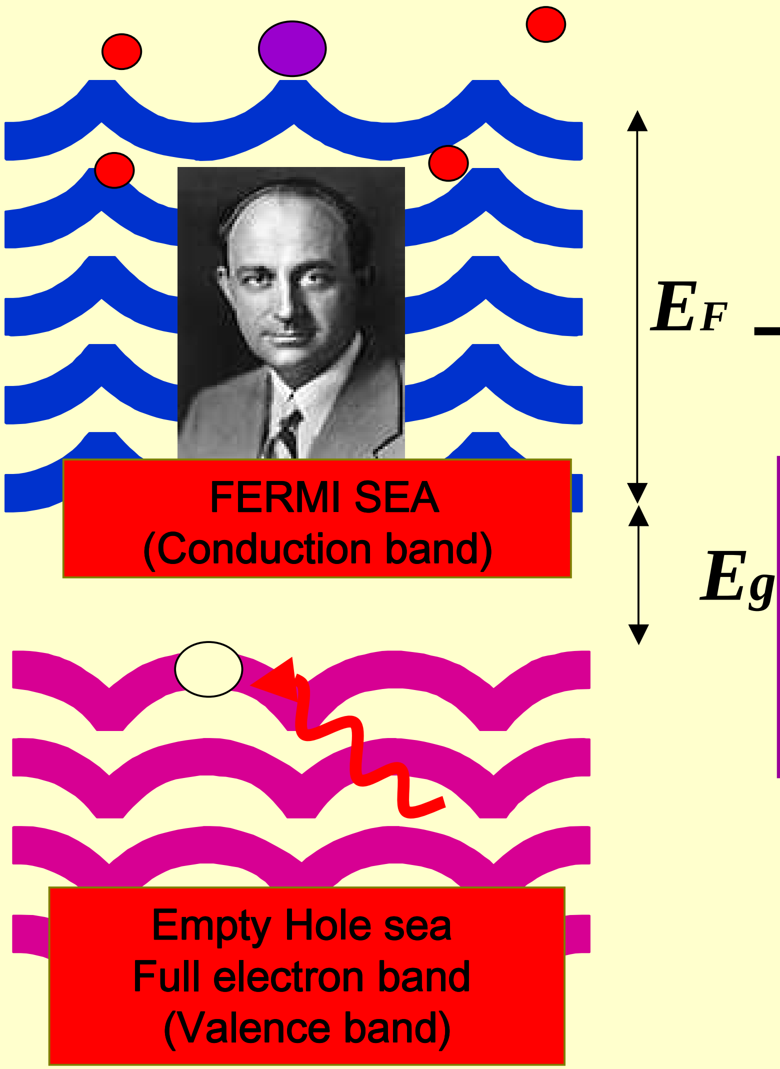
$$\gamma_1\left(1-\gamma_2\sqrt{\Theta/T_k}\right)$$

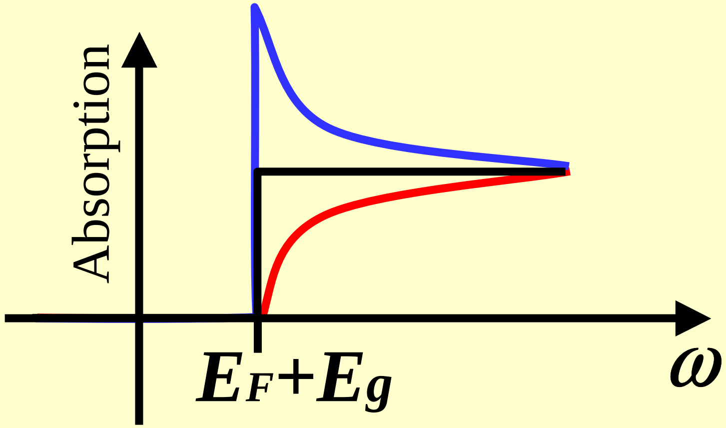
?



$$\Theta \equiv \max[T, V_{sd}]$$

Fermi Edge singularity

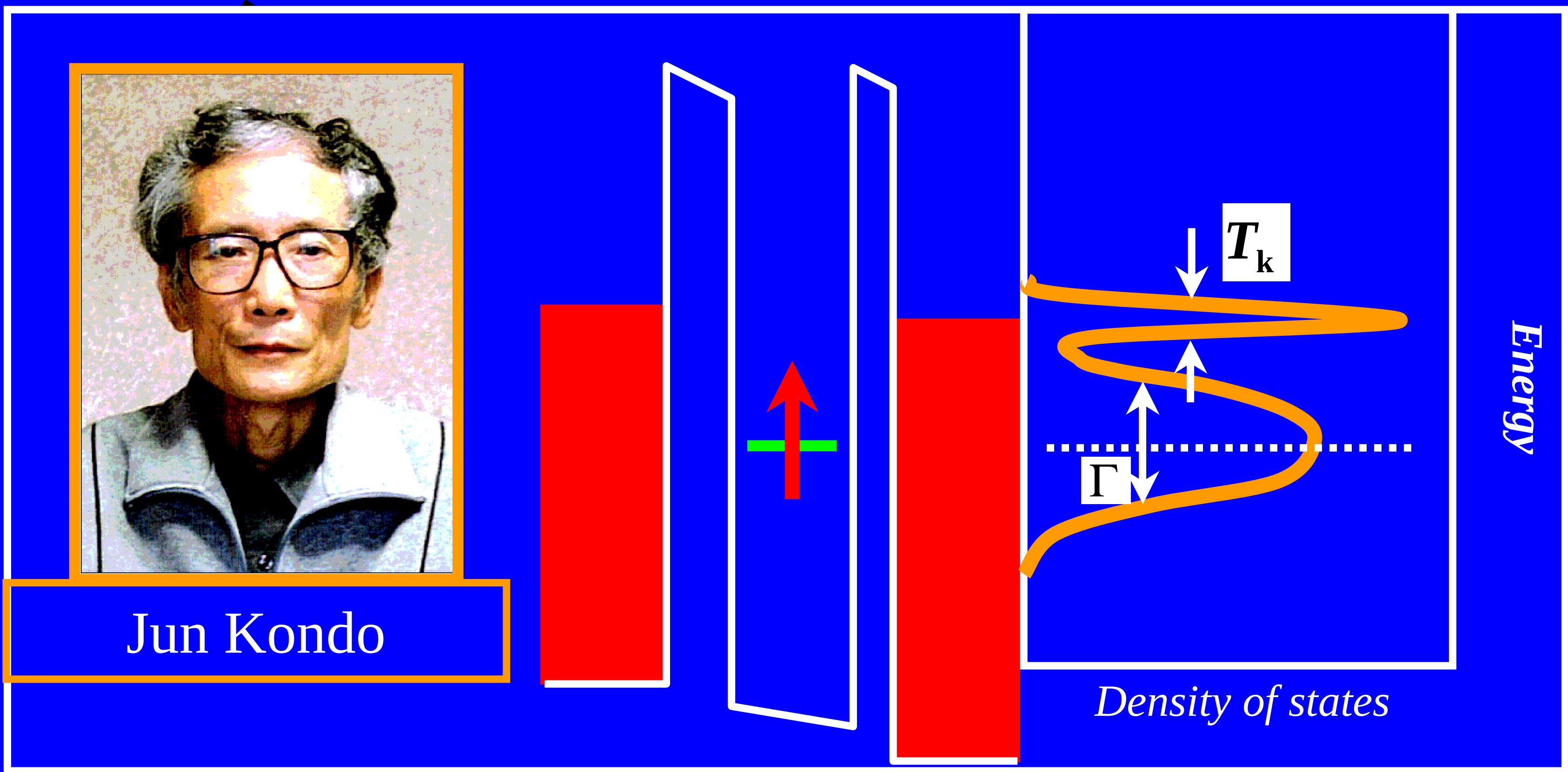




- Attraction between valance hole and conduction electrons.
- Orthogonality "catastrophe"

Sudden potential +
Many body effects

Single Channel Kondo and Anderson Model: Many FES

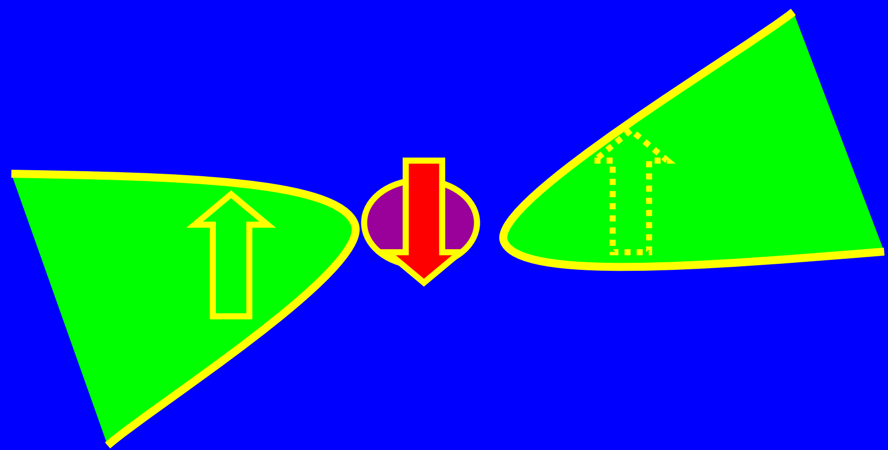


Spin –Charge Separation

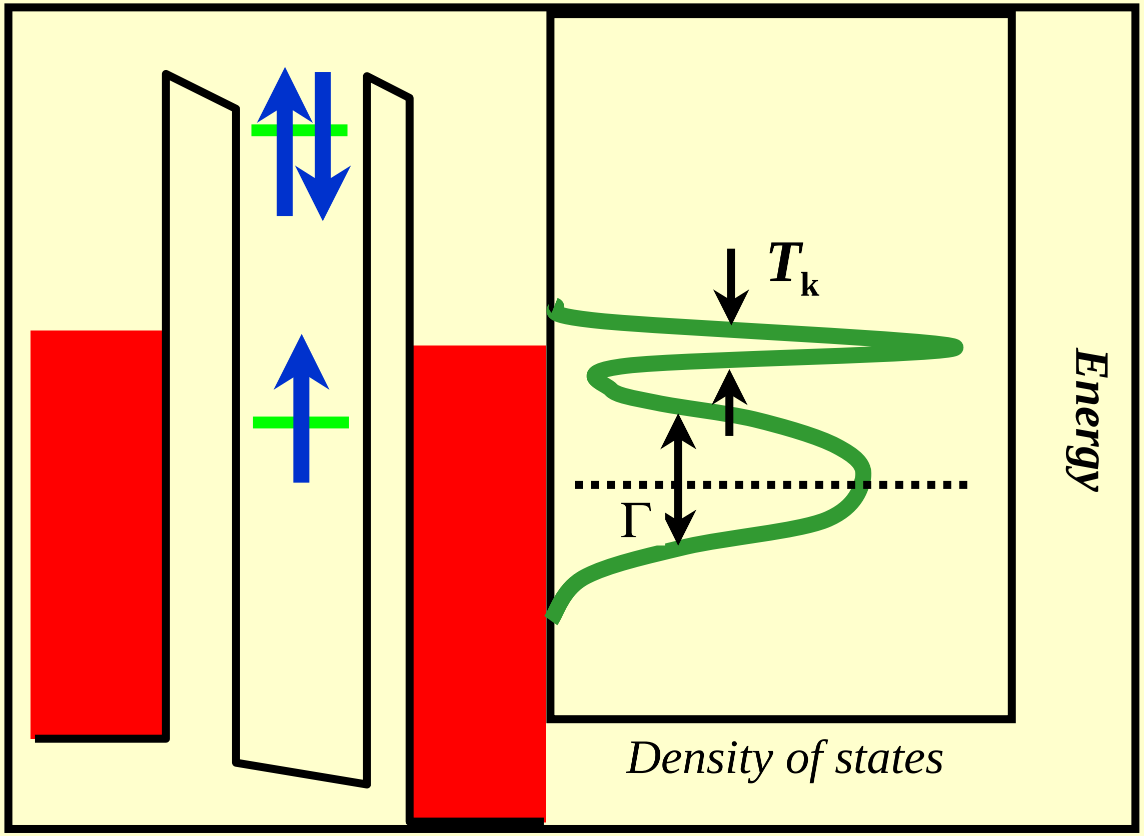
Conduction spin

Dot spin

$$J\,\vec{\sigma}\cdot\vec{S}, \quad J>0$$



Anderson → Haldane → Schrieffer-Wolff → Kondo → Resonance



Anderson Model

$$H = \sum_{ks} \varepsilon_{ks} l_{ks}^{+} l_{ks} + \sum_{s} \varepsilon_{d}^{0} d_{s}^{+} d_{s} + U n_{d\uparrow} n_{d\downarrow}$$

$$+ \sum_{ks} \left(V_{lk}^{*} l_{ks}^{+} d_{s} + V_{lk} d_{s}^{+} l_{ks} \right)$$

Schrieffer-Wolff

$$H = \sum_{ks} \varepsilon_{ks} l_{ks}^{+} l_{ks} + \sum_{kq} J^{kq} \left[S^{+} s^{-kq} + S^{-} s^{+kq} + 2 S^{z} s^{zkq} \right]$$

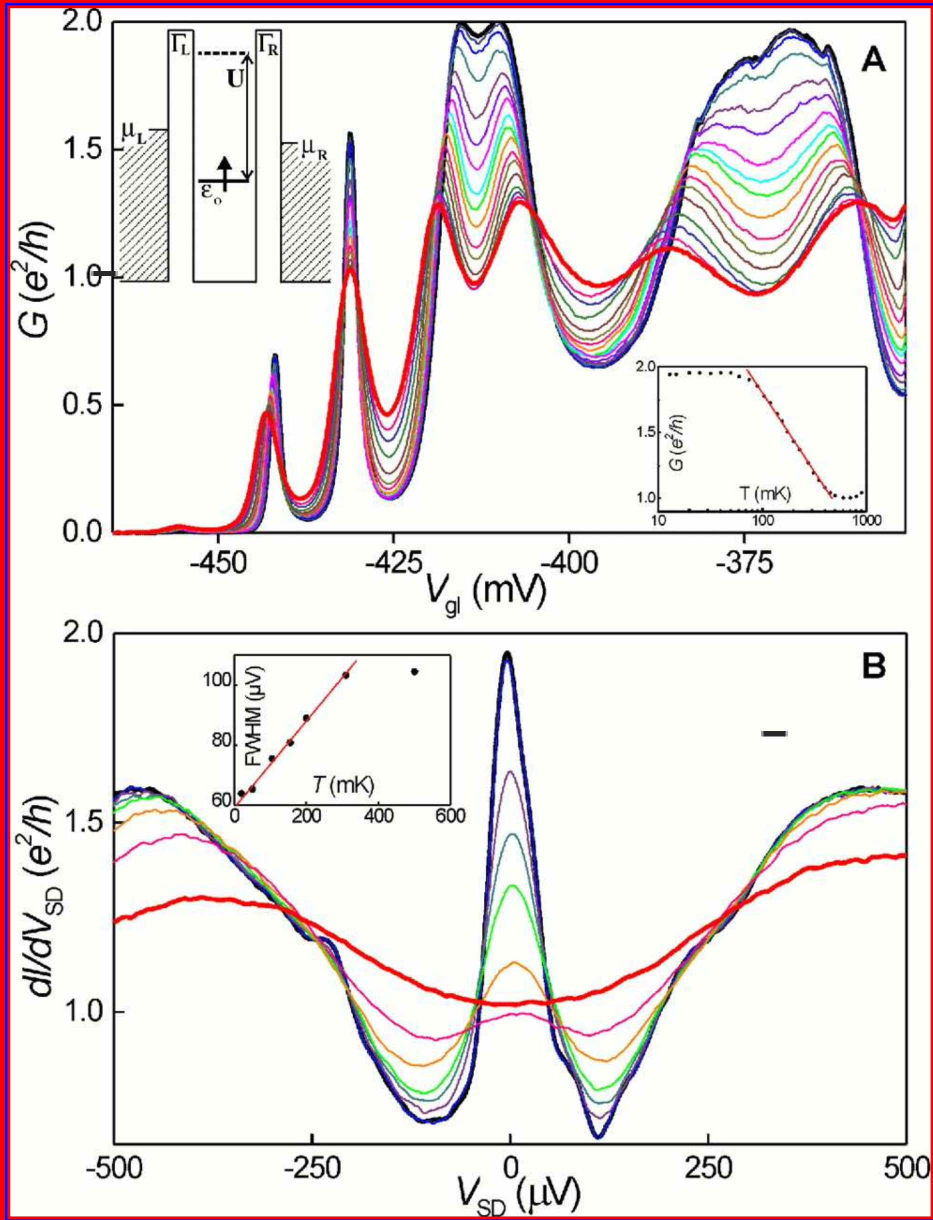
$$S^{+} = d_{\uparrow}^{+} d_{\downarrow}, S^{-} = d_{\downarrow}^{+} d_{\uparrow}, S^{z} = \tfrac{1}{2}\left(d_{\uparrow}^{+} d_{\uparrow} - d_{\downarrow}^{+} d_{\downarrow} \right),$$

$$\mathrm{s}^{+\mathrm{kq}} = l_{k\uparrow}^{+} l_{q\downarrow}, \mathrm{s}^{-\mathrm{kq}} = l_{k\downarrow}^{+} l_{q\uparrow}, \mathrm{s}^{\mathrm{zkq}} = \tfrac{1}{2}\left(l_{k\uparrow}^{+} l_{q\uparrow} - l_{k\downarrow}^{+} l_{q\downarrow} \right)$$

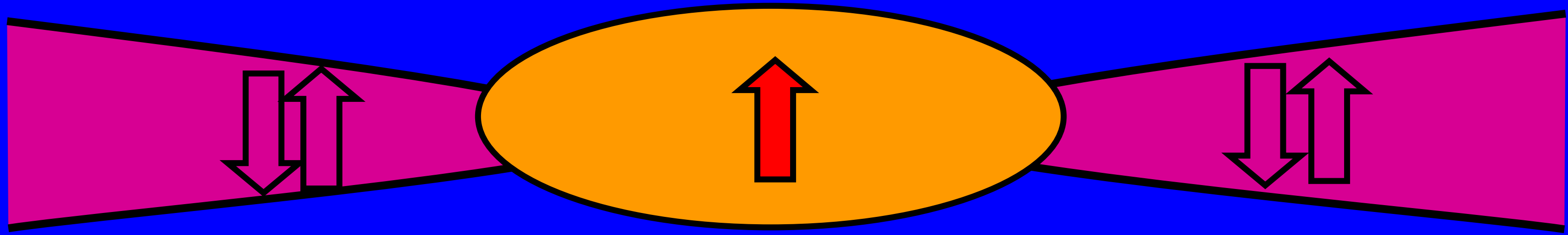
$$J^{kq} = V_k V_q^{*} \left[\frac{1}{E_{\mathrm{elec}} - E_{\mathrm{init}}} + \frac{1}{E_{\mathrm{hole}} - E_{\mathrm{init}}} \right]$$

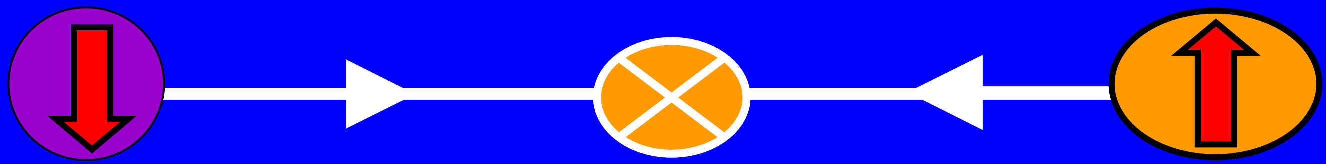
(A) Coulomb oscillations in G versus V_{gl} at B = 0.4 T for different temperatures. T ranges from 15 mK (thick black trace) up to 800 mK (thick red trace). V_{gr} is fixed at 448 mV. The red line in the right inset highlights the logarithmic T dependence between ~90 and ~500 mK for V_{gl} = -413 mV. The left inset explains the variables used in the text with $\Gamma = \Gamma_L + \Gamma_R$. ε_0 is negative and measured from the Fermi level in the leads at equilibrium.

(B) Differential conductance dI/dV_{SD} versus dc bias voltage between source and drain contacts V_{SD} for T ranging from 15 mK (thick black trace) up to 900 mK (thick red trace), at V_{gl} = *413 mV* and B = 0.4 T. The inset shows that the width of the zero-bias peak, measured from the FWHM, increases linearly with T. The red line indicates a slope of 1.7 k_B/e. At 15 mK, the FWHM = 64 μV, and it starts to saturate around 300 mK.



Multi - Channel Kondo

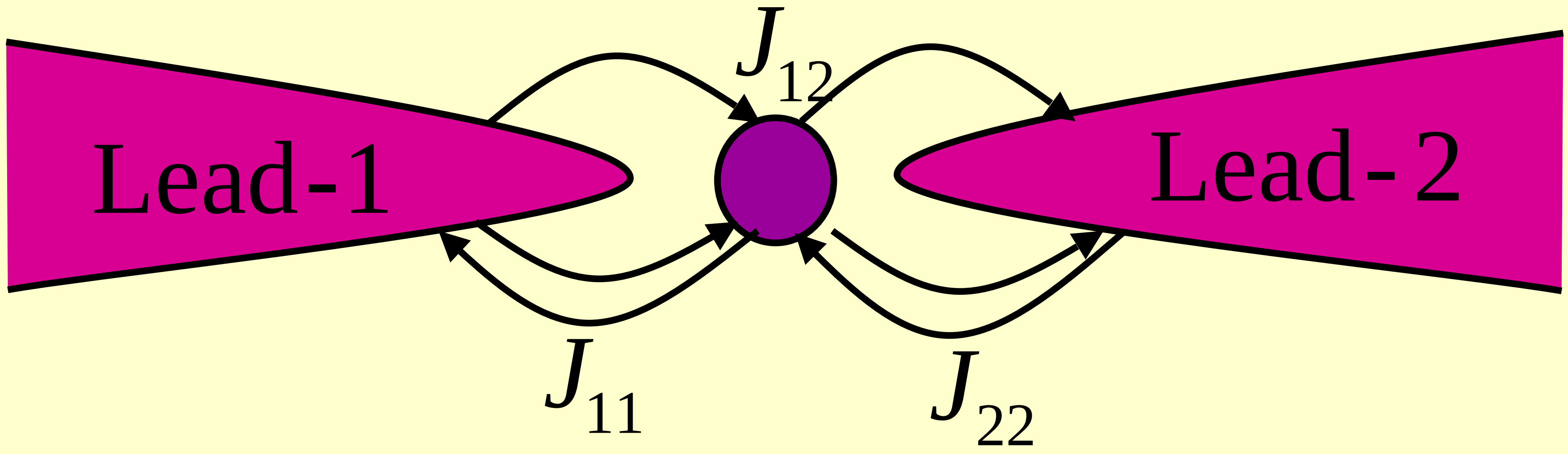




- RG, NRG
- Bethe Ansatz (Andrei, Wiegmann-Tsvelik)
- Conformal Field Theory (Affleck - Ludwig)
- “Pseudo Particle” or “Slave Bosons”

  (Read - Coleman, Ruckenstein - Cox)
- Bosonization (Kivelson - Emery)

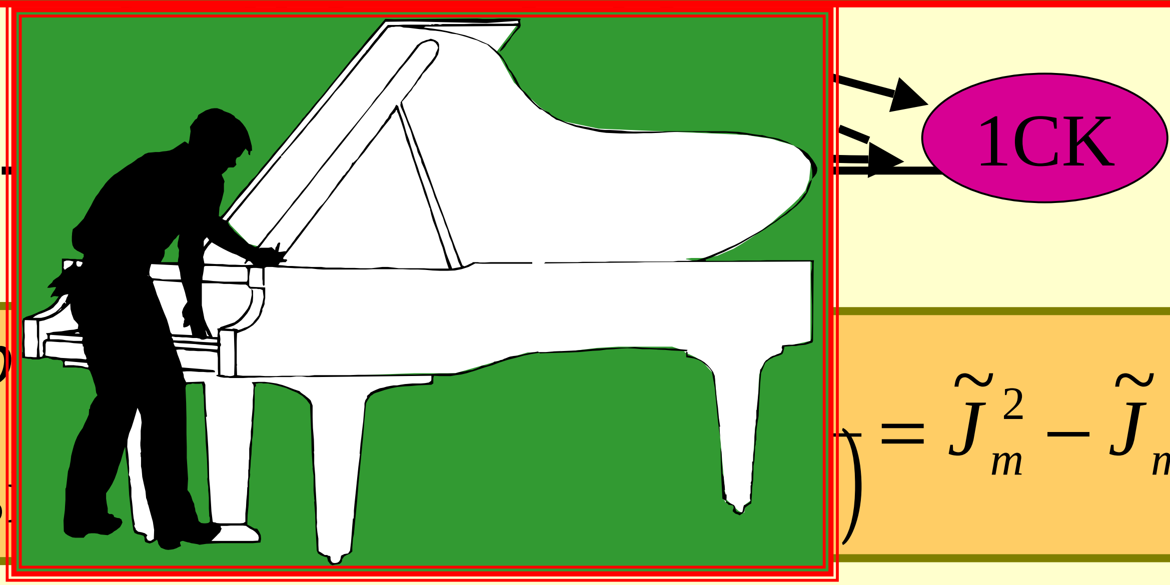
Channel anisotropy



$$\begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} \Rightarrow \begin{pmatrix} J_1 & 0 \\ 0 & J_2 \end{pmatrix} =$$

$$\frac{1}{2}\begin{pmatrix} J_{11}-J_{22}+\sqrt{(J_{11}-J_{22})^2+4J_{12}J_{21}} & 0 \\ 0 & J_{11}-J_{22}-\sqrt{(J_{11}-J_{22})^2+4J_{12}J_{21}} \end{pmatrix}$$

In Quantum dots we can tune $J_1 = J_2$



$m = 1{,}2$ and p

$\tilde{J} = J \bullet \text{Dens}$

$= \tilde{J}_m^2 - \tilde{J}_m \sum_p \tilde{J}_p^2.$

Suggestions for 2CK Realizations:

~100 Publications/attempts to realize MCK

- Two level systems, "spins are isotropic channels"
  - Theo: Zawadowski, von Delft et al,
  - Exp: Dan Ralph and Burman.
- Coulomb blockade peak is a degenerate state
  - The. Matveev et al. (Requires a large dot, and smooth contacts)
  - Exp. Devoret et al. $\Delta << T_k \approx \sqrt{E_c \Gamma} e^{-E_c/\Gamma} << E_c$ Hard in real systems.
  - Schiller et al.
- Quadruple 2CK (Cox)
- Non equilibrium (Wen)
- Luttinger leads (Kim)

Charging energy

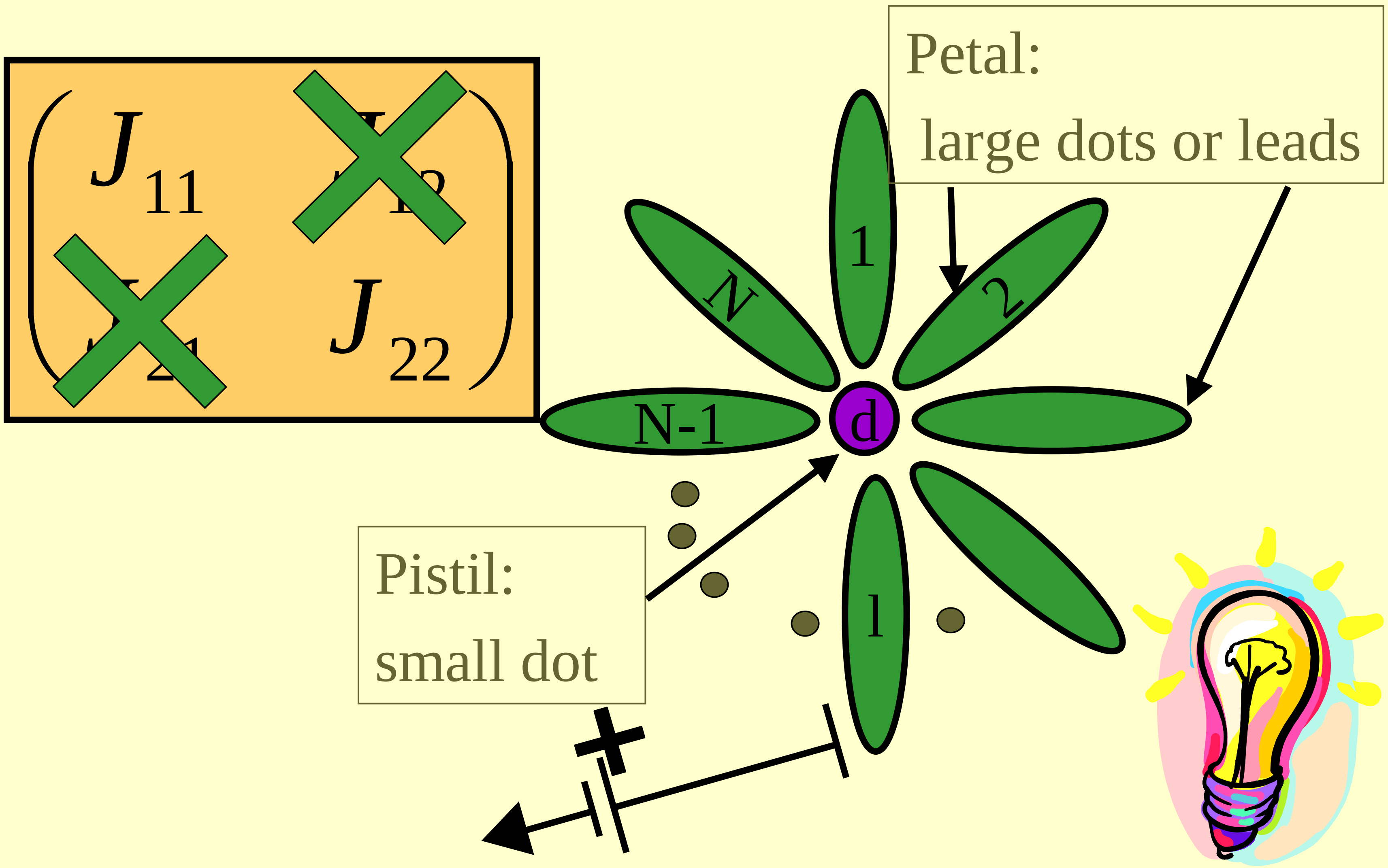
Lead-Dot Coupling const

Kondo temp.

Average level spacing

A simple realization of MCK

YO and David Goldhaber-Gordon



Generalized Anderson Model

$$H = \sum_{kls} \varepsilon_{ks} l^{+}_{ks} l_{ks} + \sum_{s} \varepsilon^{0}_{d} d^{+}_{s} d_{s} + U n_{d\uparrow} n_{d\downarrow}$$

$$+ \sum_{l} E_{cl} \left(n_{l} - N_{l} \right)^{2}$$

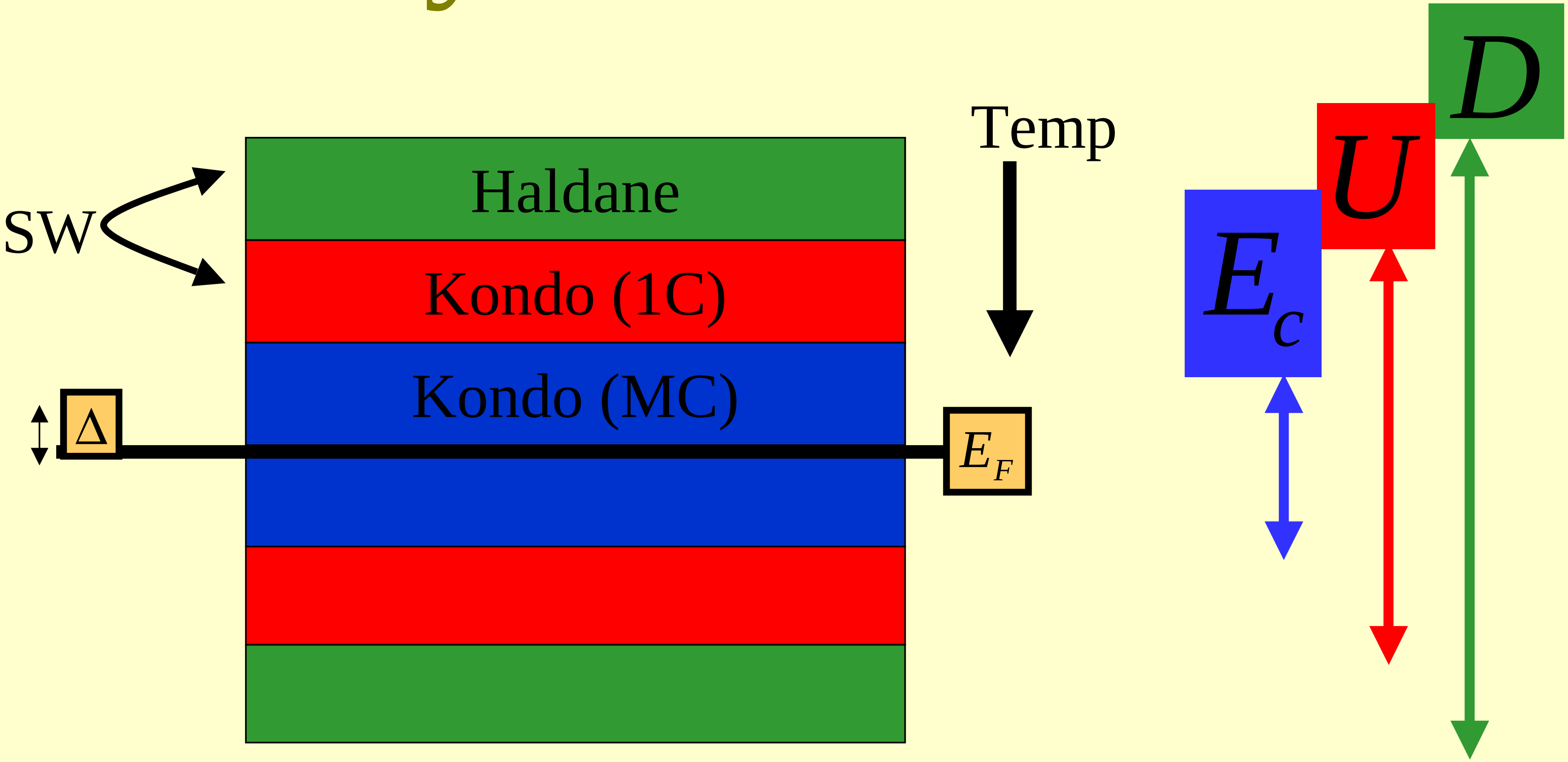
$$+ \sum_{ks} \left(V^{*}_{lk} l^{+}_{ks} d_{s} + V_{lk} d^{+}_{s} l_{ks} \right)$$

Charging energy of large-dot-l

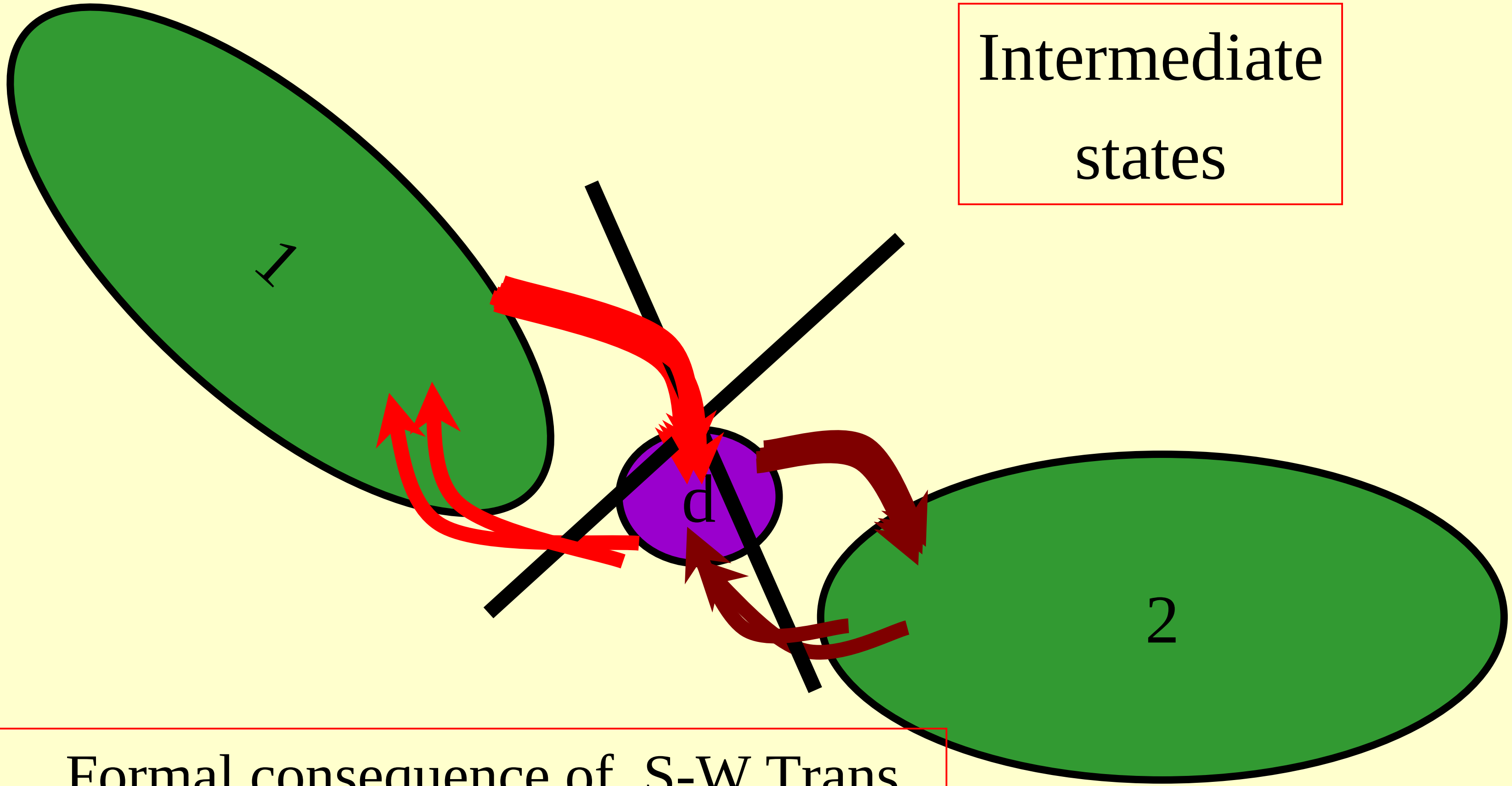
Gate potential on large-dot-l

Number of electrons in large-dot-l

Analysis of the model

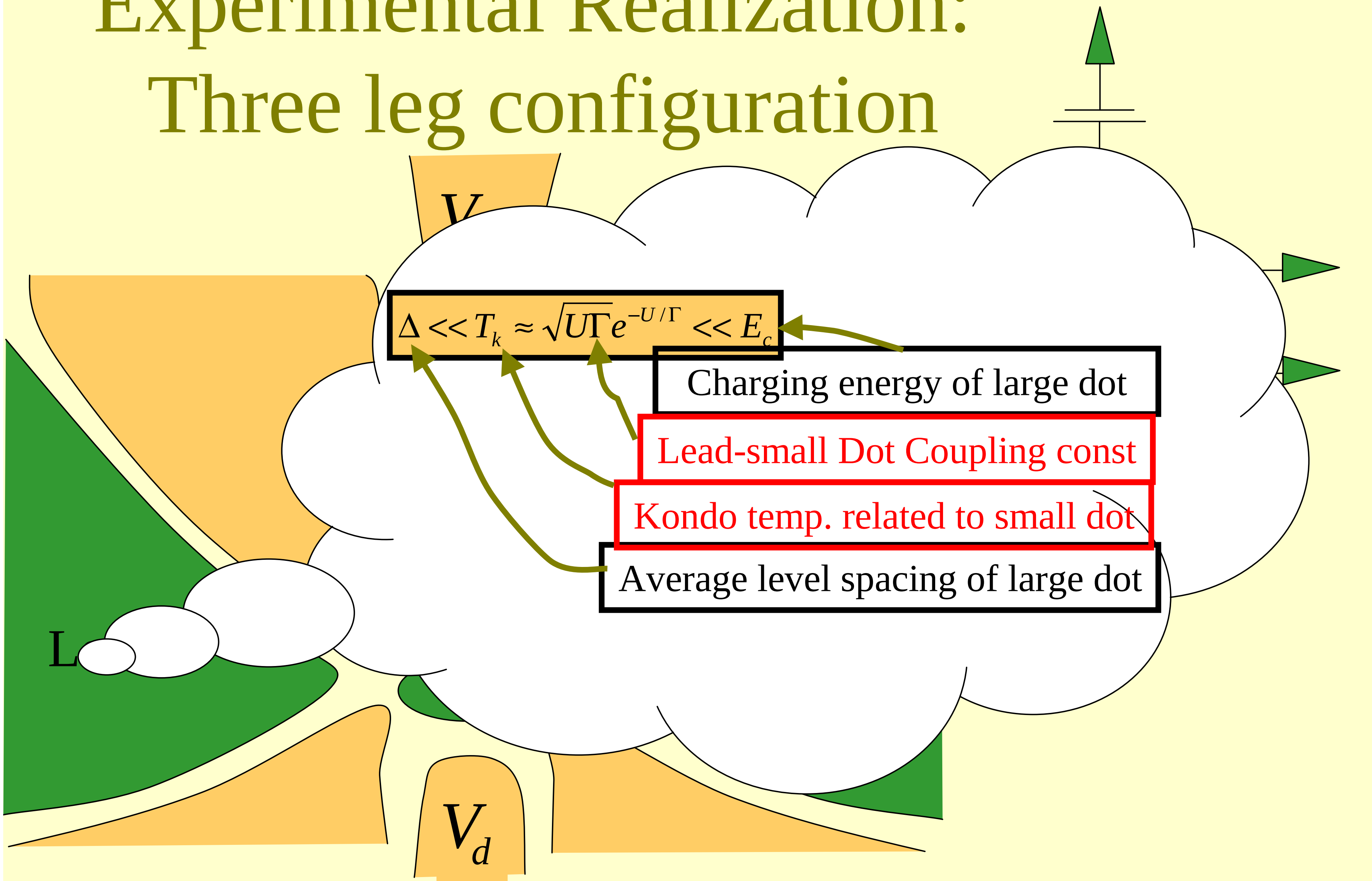


Neglect Higher Orders

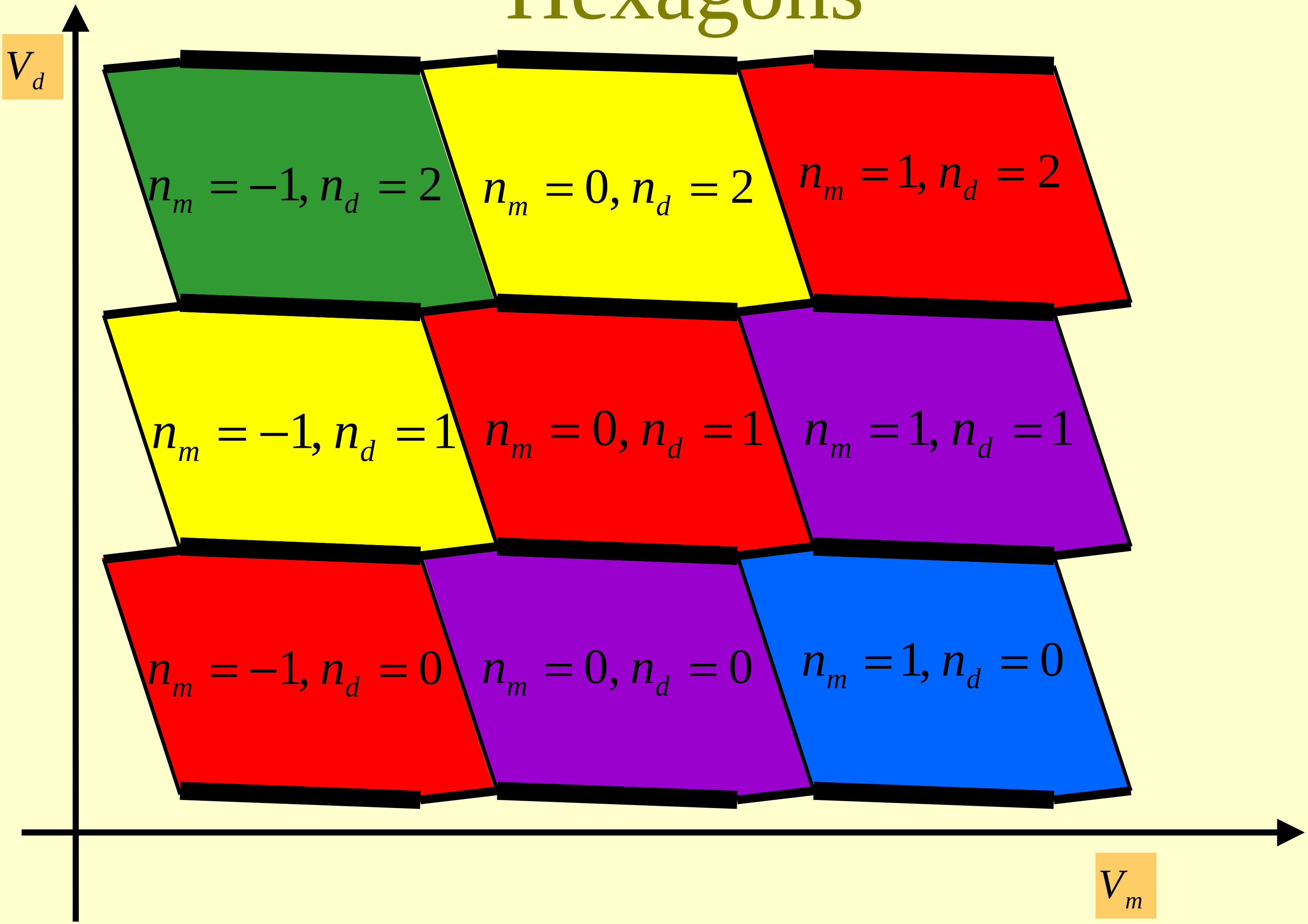


- Formal consequence of S-W Trans Coqblin & Schrieffer (1969)
- Smaller by a Factor U/T compare to two separate hops to the same dot

Experimental Realization: Three leg configuration

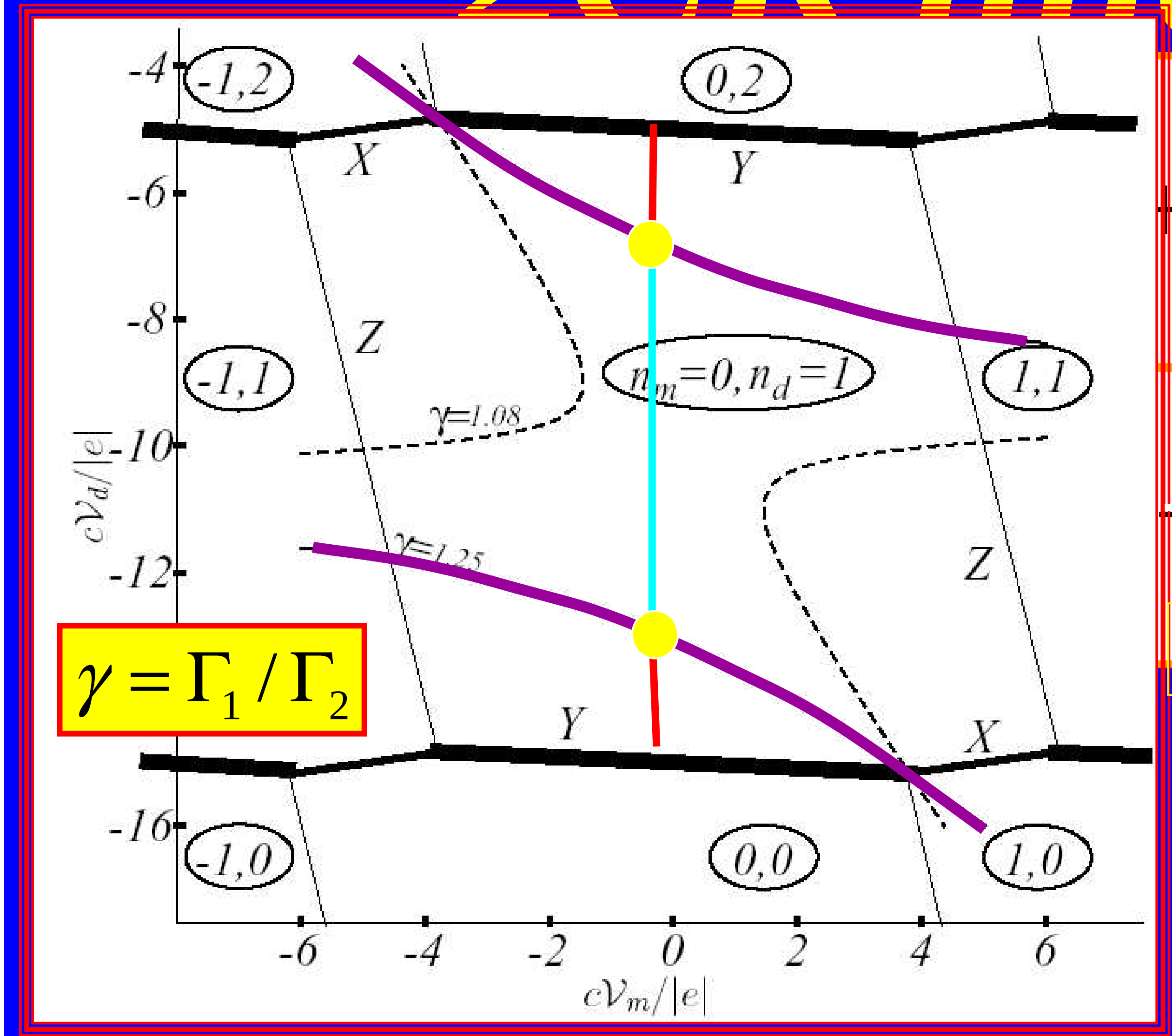


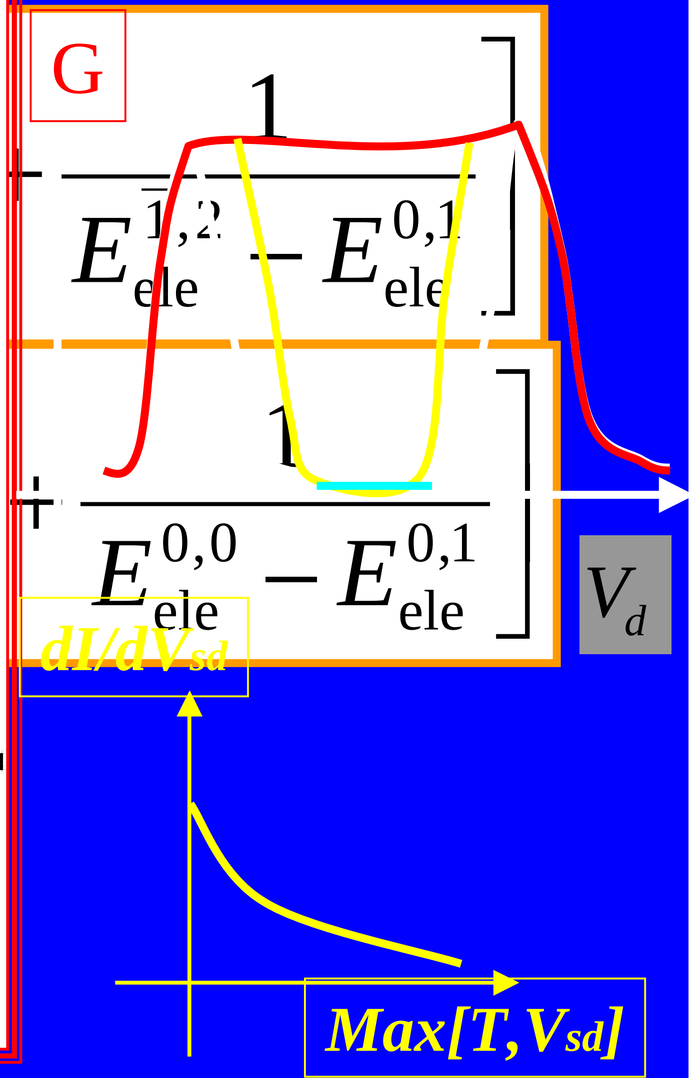
Hexagons



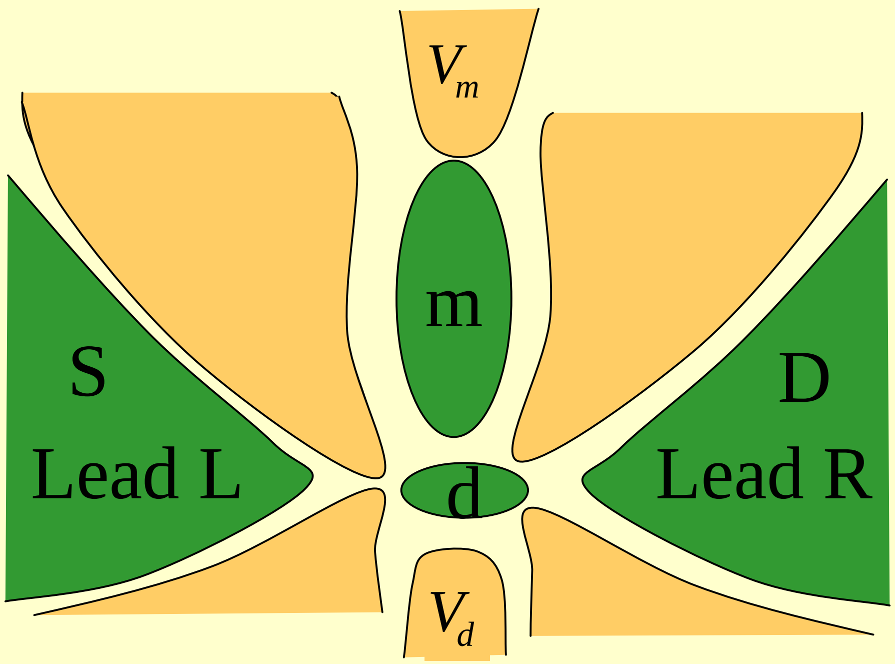
V_d
$n_m = -1, n_d = 2$
$n_m = 0, n_d = 2$
$n_m = 1, n_d = 2$
$n_m = -1, n_d = 1$
$n_m = 0, n_d = 1$
$n_m = 1, n_d = 1$
$n_m = -1, n_d = 0$
$n_m = 0, n_d = 0$
$n_m = 1, n_d = 0$
V_m

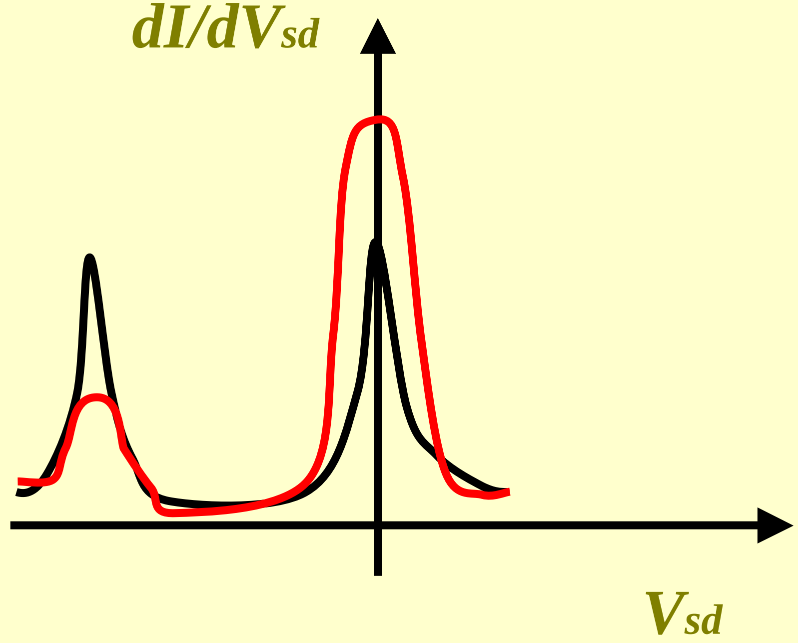
2CK lines


-1,2
0,2
X
Y
Z
-1,1
$n_m=0, n_d=1$
1,1
γ=1.08
γ=1.25
Z
Y
X
-1,0
0,0
1,0
$\gamma = \Gamma_1 / \Gamma_2$
-4
-6
-8
-10
-12
-16
$c\mathcal{V}_d/|e|$
-6
-4
-2
0
2
4
6
$c\mathcal{V}_m/|e|$


G
$\frac{1}{E_{ele}^{-1,2} - E_{ele}^{0,1}}$
$+ \frac{1}{E_{ele}^{0,0} - E_{ele}^{0,1}}$
V_d
dI/dVsd
Max[T,Vsd]

Suggestions for Experiments: Tunneling Density of states





Arcadi Shehter

Summary

- A Realization of ***two (multi) channel Kondo*** in a modified Single Electron Transistor.
  - More theory (Magnetic Field and Anisotropy, dependence on initial physical parameters, De-phasing, noise, pumping, tunneling DOS) and new experiments ...
- Model: small dot + interacting leads (channels):
  - a Generalization in a new direction (each channel have different "electrochemical potential").
  - Generic model: many other types of petals will "do the job":
    - Luttinger liquid, Interacting disordered systems, Two 2D strongly interacting metals (Cuprates?),Environment with large impedance…