united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR 1232 - 34

XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

KONDO EFFECT IN A GaAs QUANTUM DOT SYSTEM

D.J. GOLDHABER-GORDON
Harvard University - Dept. of Physics
MA-02138 Cambridge, USA

The Kondo Effect in a Single-Electron Transistor

David Goldhaber-Gordon, MIT/Harvard

Collaborators:

Weizmann Institute, Israel

Hadas Shtrikman

Diana Mahalu

Udi Meirav

MIT

David Abusch-Magder

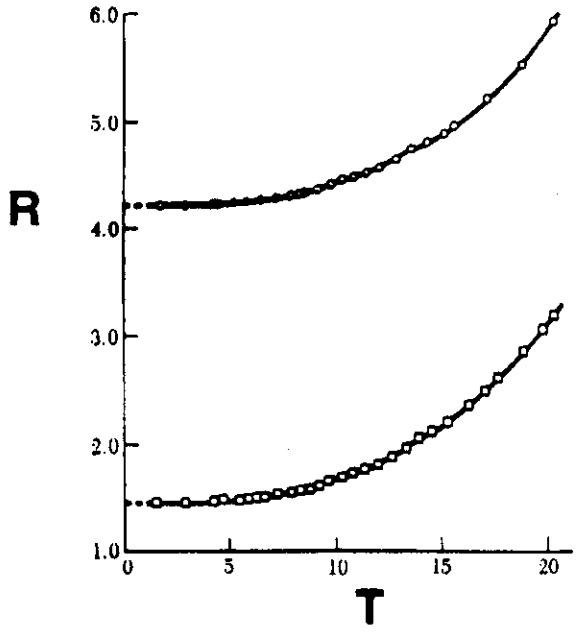
Marc Kastner

Joern Goeres

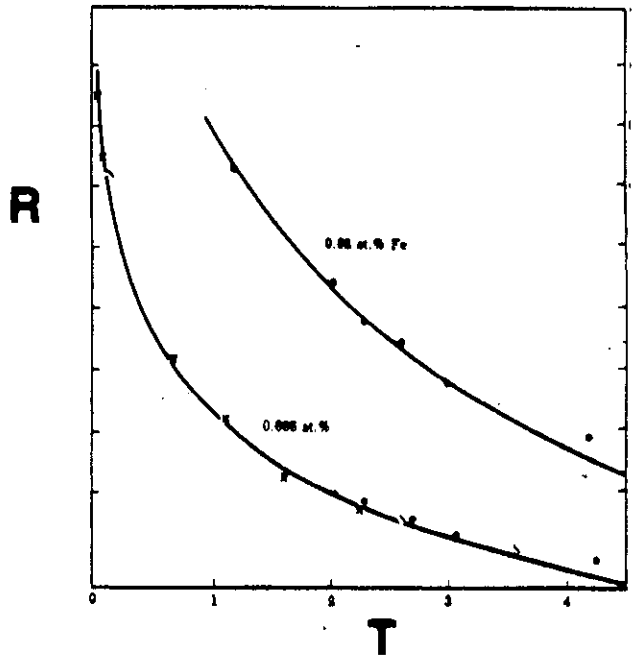
Theoretical background: **Ned Wingreen and Yigal Meir**

The Bulk Kondo Effect

Normal Metal



Magnetic Impurities

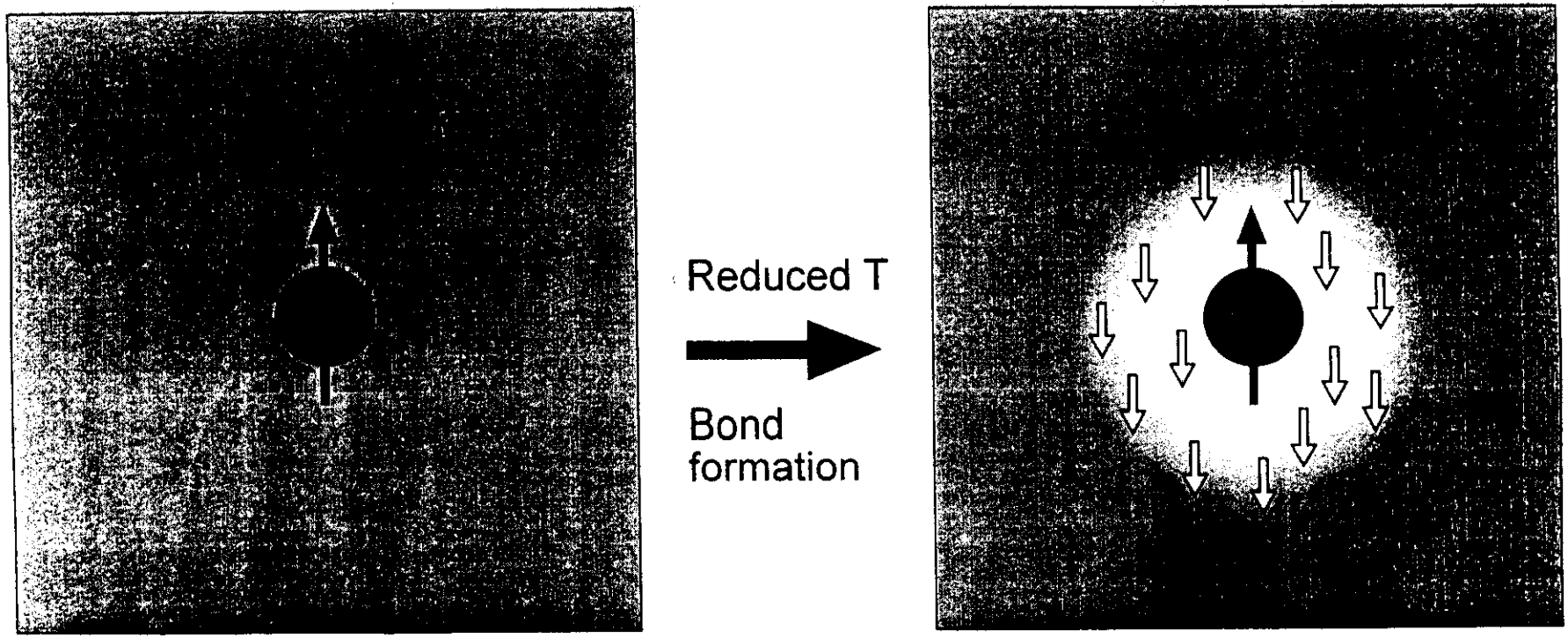


Kittel

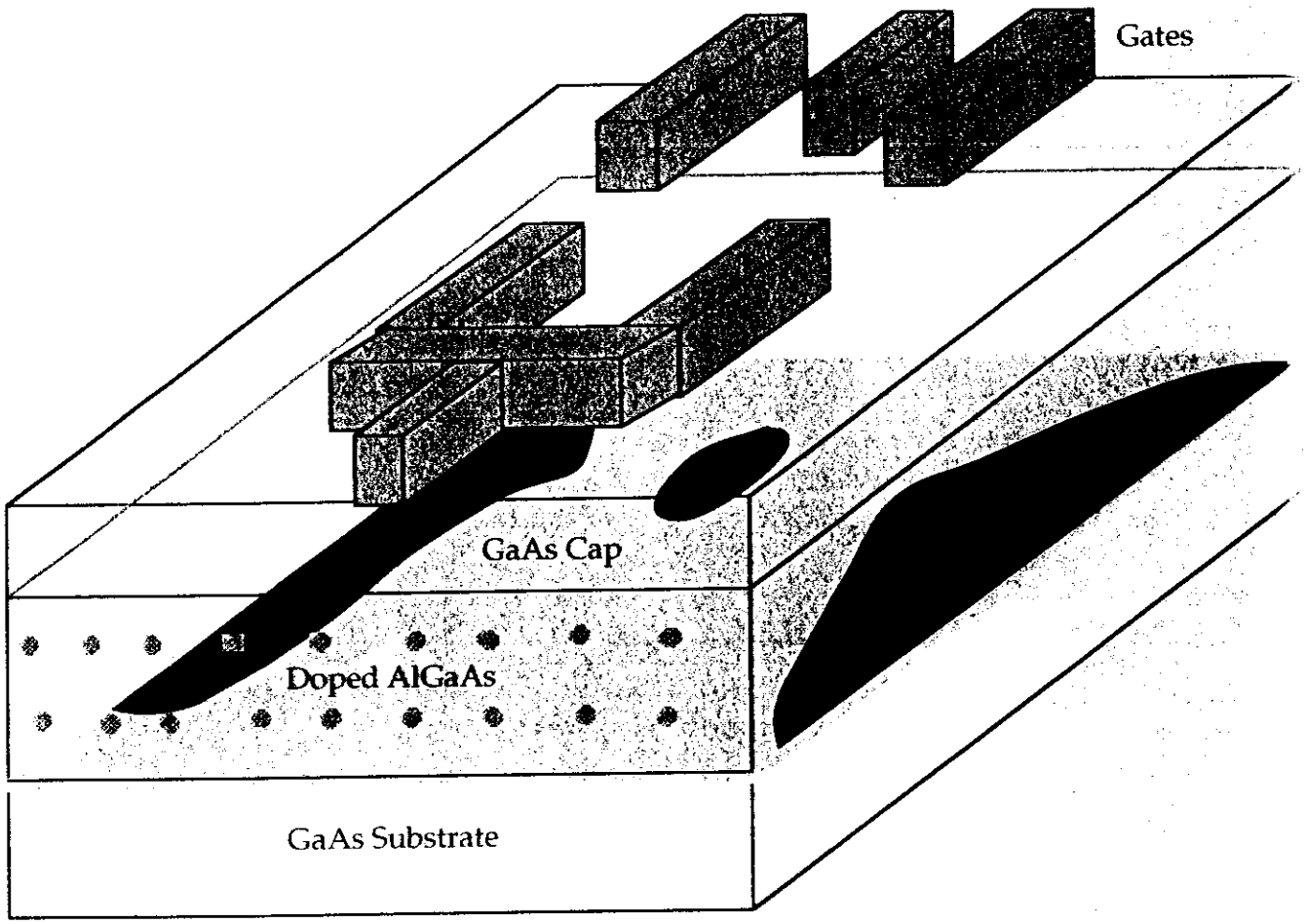
- $T \downarrow \Rightarrow R \downarrow$
- **Magnetic impurities: R ↑ again at low T**
- **Bond between localized and mobile electrons**

a

b



Lateral Quantum Dot Structure



Artificial atom as Kondo impurity

- **Anderson Hamiltonian:**

Leads / Metal

Electron droplet/ Impurity atom

$$\mathcal{H} = \sum_{\sigma;k\epsilon \mathrm{L,R}} \epsilon_{k\sigma} c^{\dagger}_{k\sigma} c_{k\sigma} + \sum_{\sigma} \epsilon_{\sigma} d^{\dagger}_{\sigma} d_{\sigma}$$

$$+ \frac{1}{2} U n_{\sigma} n_{\sigma'} + \sum_{\sigma;k\epsilon \mathrm{L,R}} t_{k\sigma} c^{\dagger}_{k\sigma} d_{\sigma} + \mathrm{H.c.}$$

Charging energy

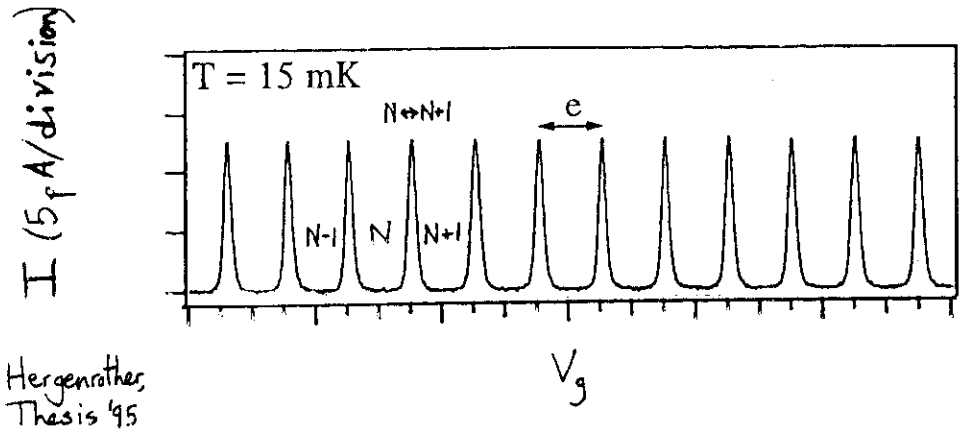
Tunneling

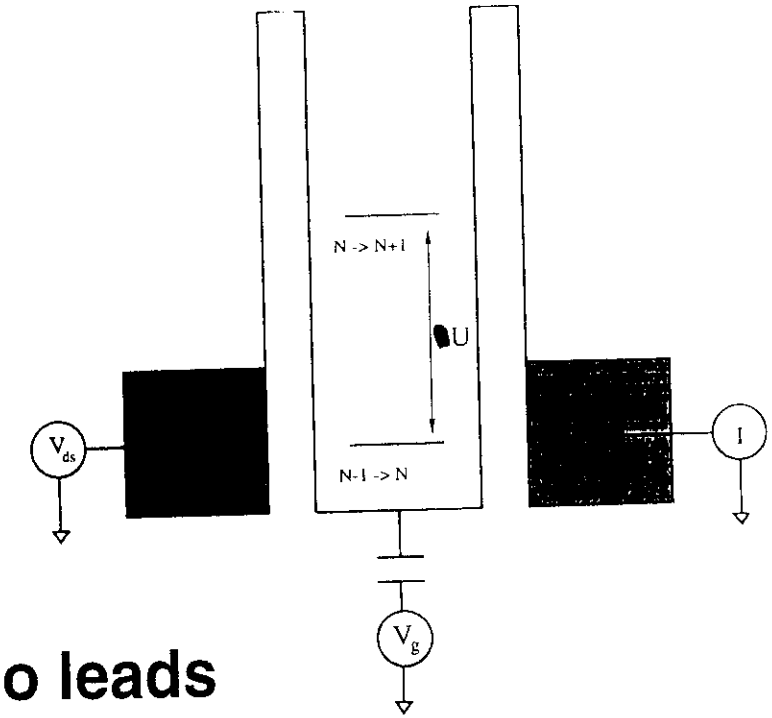
Ng & Lee, Glazman & Raikh `88

Consequences

- Have seen all predicted aspects of Kondo effect in an SET
- Anderson model works remarkably well for SETs
- Exploring regimes inaccessible in bulk

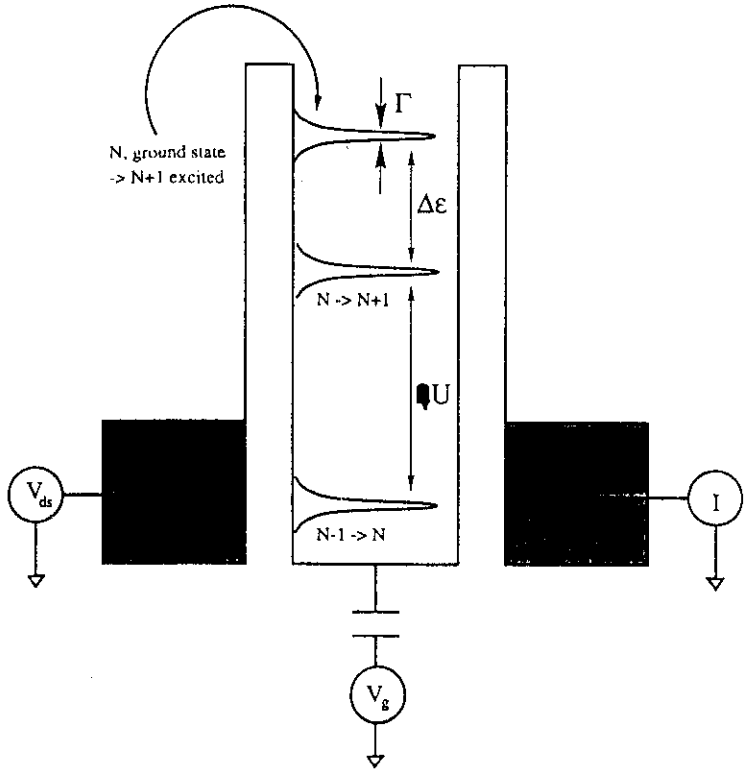
The Single-Electron Transistor



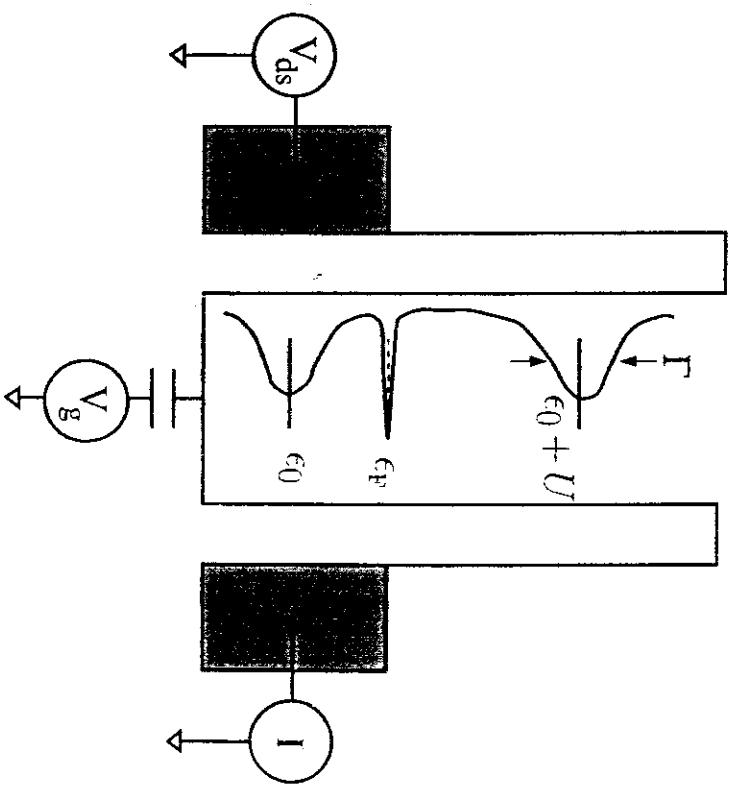


- An artificial atom coupled to leads
- Current turns on and then off each time an electron is added: Coulomb blockade

Important energy scales



- **Want Γ >> kT, $\Gamma/\Delta\varepsilon$ < 1 --▷ need small AA**
- **How is Γ tuned?**

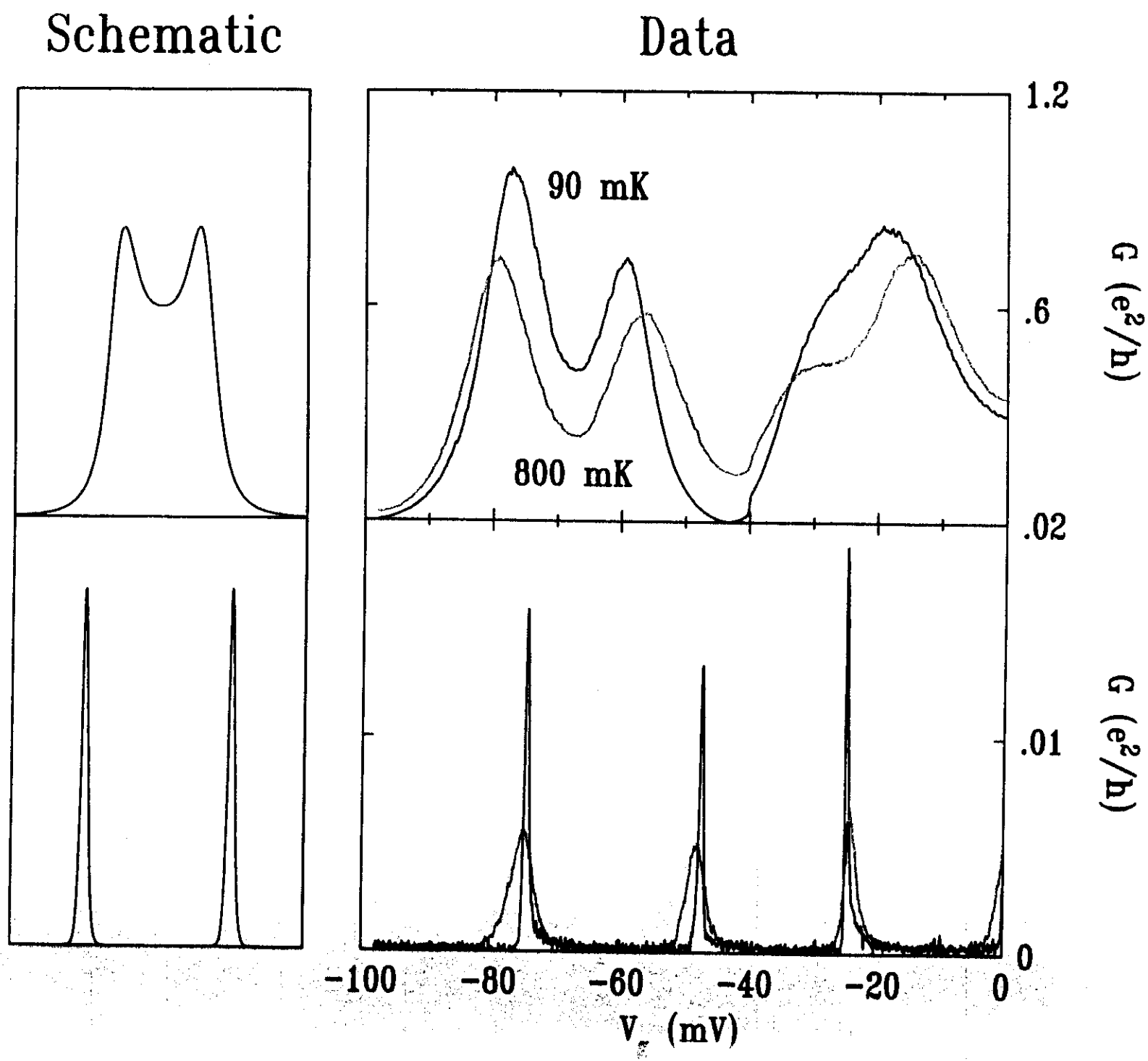

V_ds
V_g
I
ε0
εf
U + ε0
Γ


100nm F1 L01
SM-WIS 10KV X70,000 R5mm

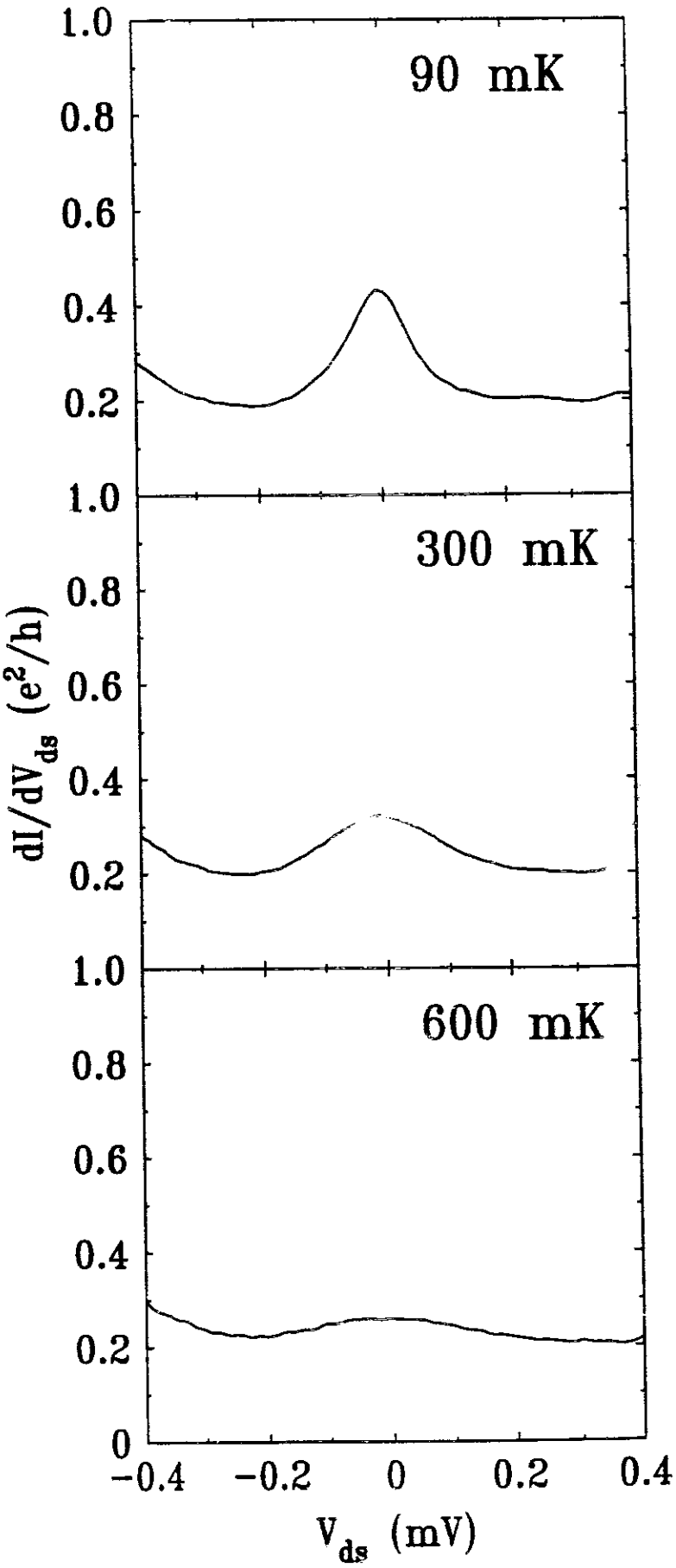
Fabrication Requirements

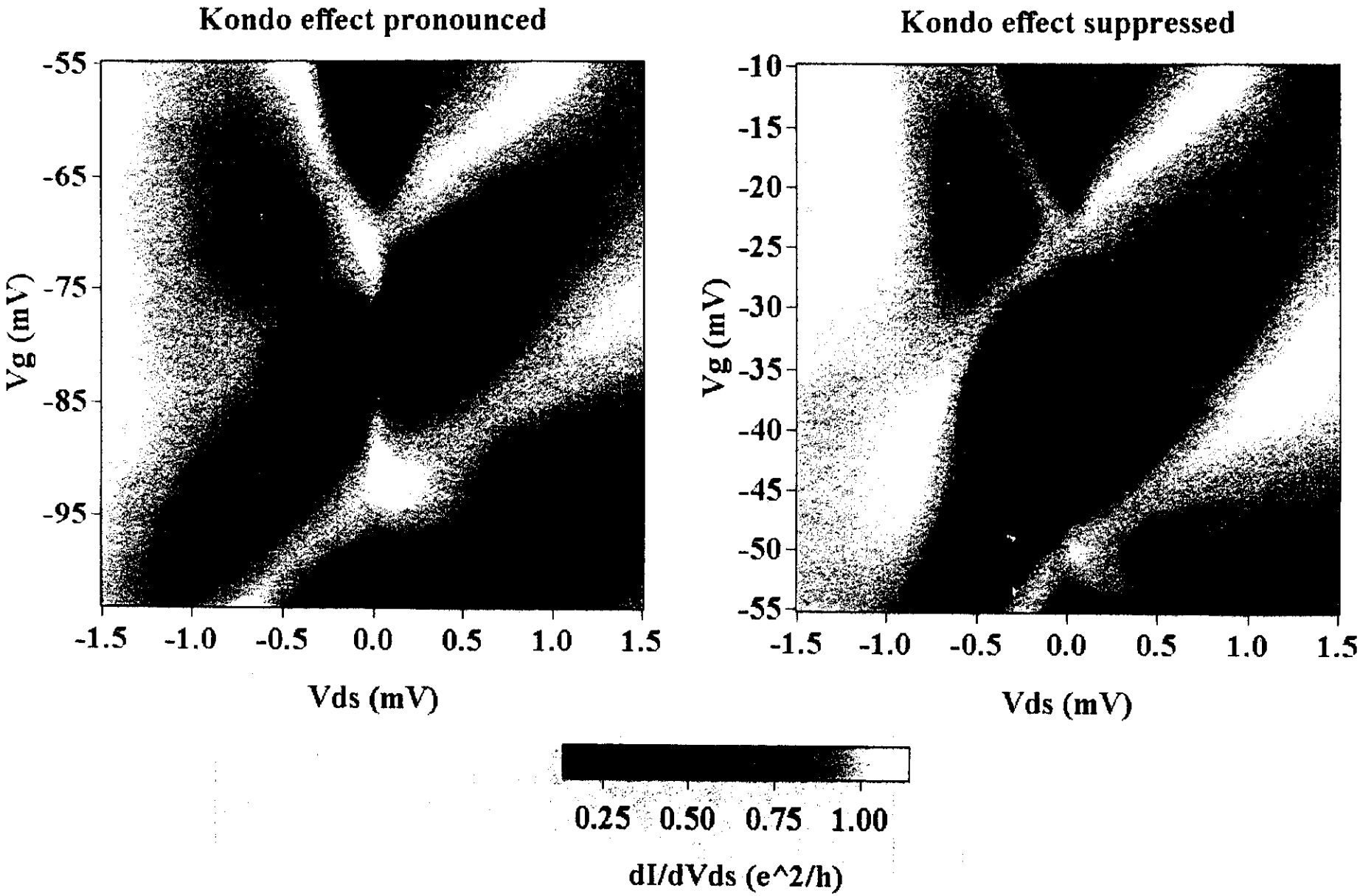
- Large $\Delta E \Rightarrow$ Small dot
  - Fine lithography
  - Shallow 2DEG
  - High density 2DEG
- Decent mobility

Mahalu
Shtrikman


Schematic
Data
90 mK
800 mK
1.2
.6
.02
.01
0
G (e²/h)
G (e²/h)
-100
-80
-60
-40
-20
0
V_c (mV)

Zero-bias peak in dI/dV




Kondo effect pronounced
-55
-65
-75
-85
-95
Vg (mV)
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Vds (mV)
Kondo effect suppressed
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
Vg (mV)
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Vds (mV)
0.25
0.50
0.75
1.00
dI/dVds (e^2/h)

4/

Related experimental work

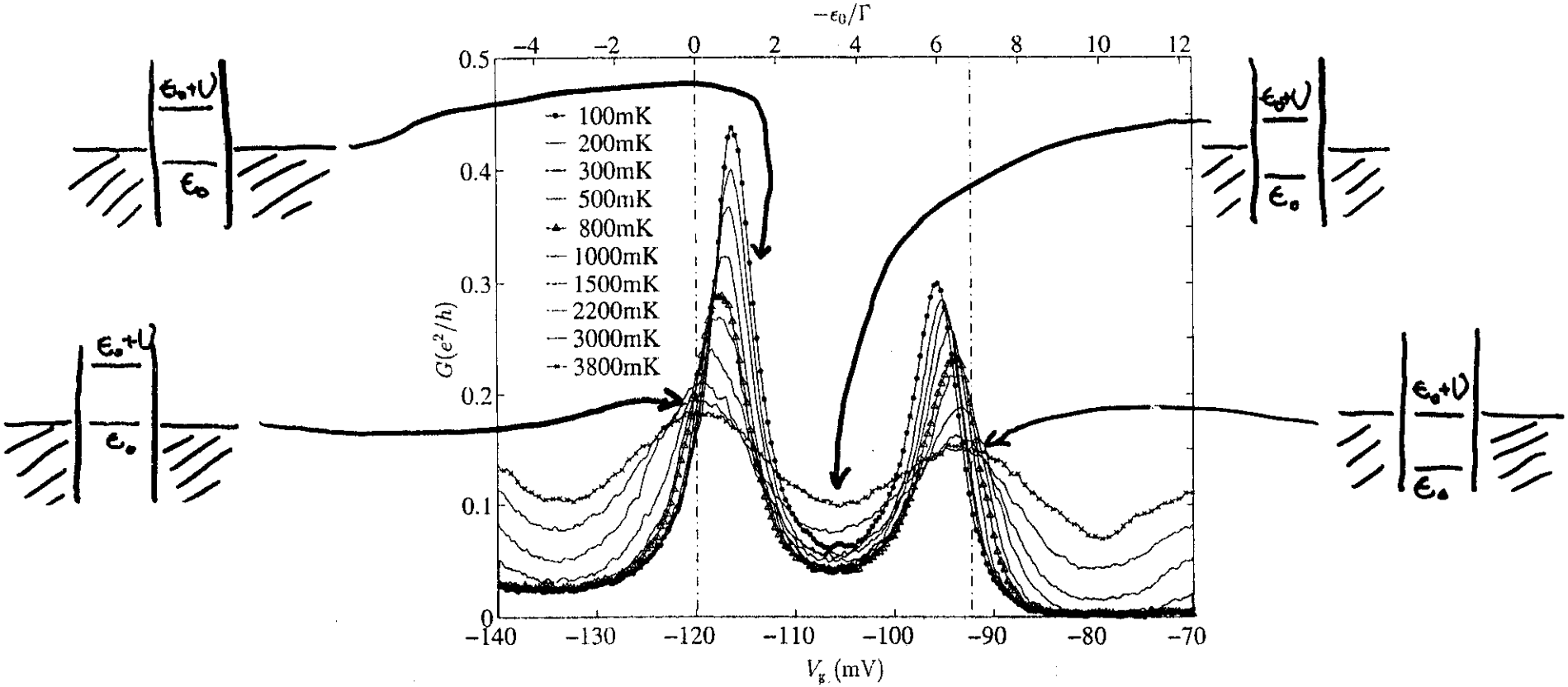
- Ralph
  - Tunneling through single magnetic impurity
- Crommie
  - STM study of Co atoms on Au
- Cronenwett, Oosterkamp, Kouwenhoven
  - SET study of B field splitting
- Schmid et al.
- Simmel et al.

Parameters

- **U** 1.9 meV
- Γ 0.2 to 0.3 meV
- $\Delta\varepsilon$ 0.4 meV
- ε_0 Γ to -8 Γ
- **kT** 0.008 meV to 0.3 meV
- kT_K 0.003 meV to 0.25 meV

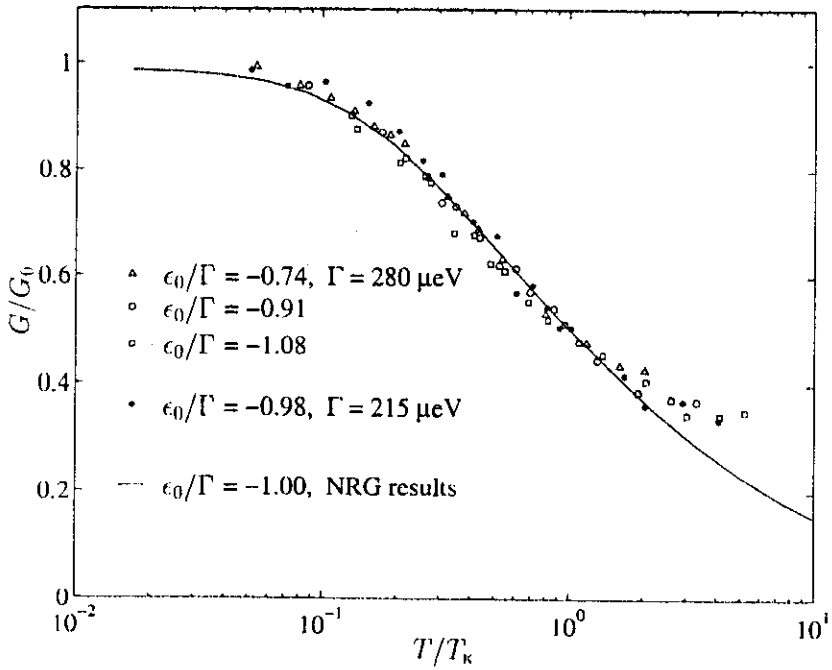
Göres

Varying ε_0 and T in an SET



- ε_0 controlled by V_g
- Conductance peak shifts with T (due to Kondo)

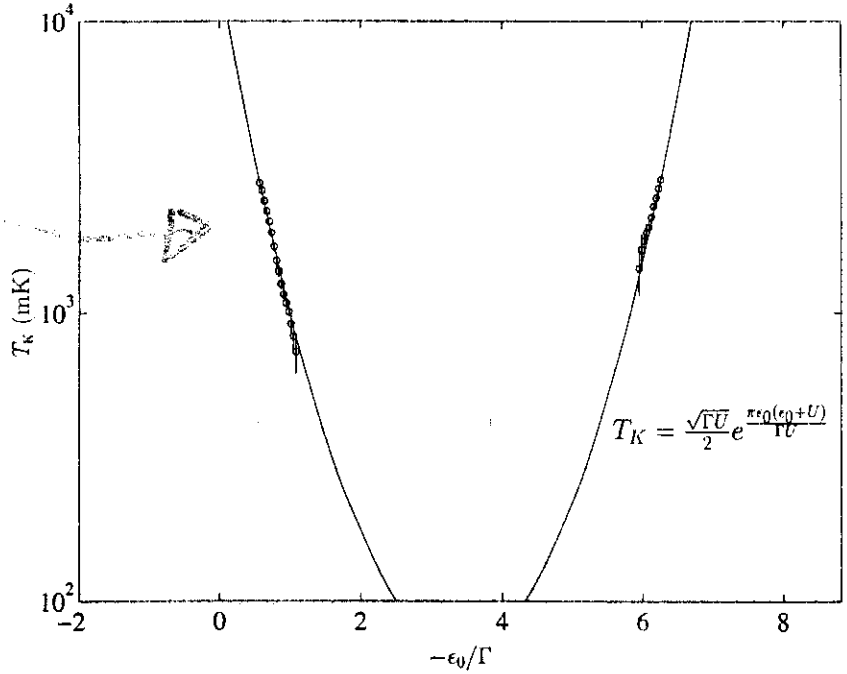
Scaled G(T) in Kondo regime



Costi, Hewson

- Independent of ε_0, Γ
- Matches NRG calculations

Variation of Kondo Temperature



Wilson
Haldane

- T_K exponential in ε_0/Γ
- Matches scaling theory

Contributions

- Smallest lateral quantum dots in GaAs
- 10-year search for Kondo in an SET over
- Experiment probes regimes of Anderson model new to experiment *and* theory
- Physics of strongly-coupled SETs still holds interesting puzzles and surprises

Spin in a Quantum Dot

David Goldhaber-Gordon
Harvard University

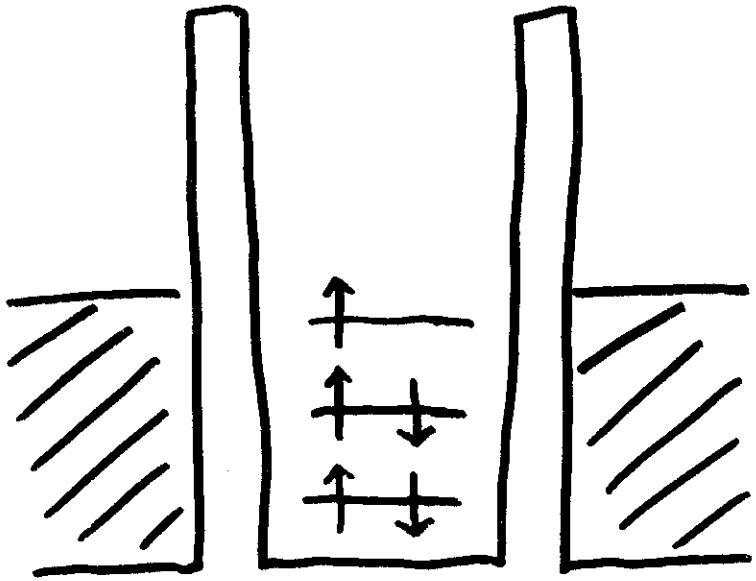
Collaborators:

Harvard	Dave Duncan	UCSB	Kevin Maranowski
	Robert Westervelt		Art Gossard
	Yuval Oreg		
MIT	Joern Goeres	Weizmann	Udi Meirav
	Marc Kastner		Hadas Shtrikman
			Diana Mahalu

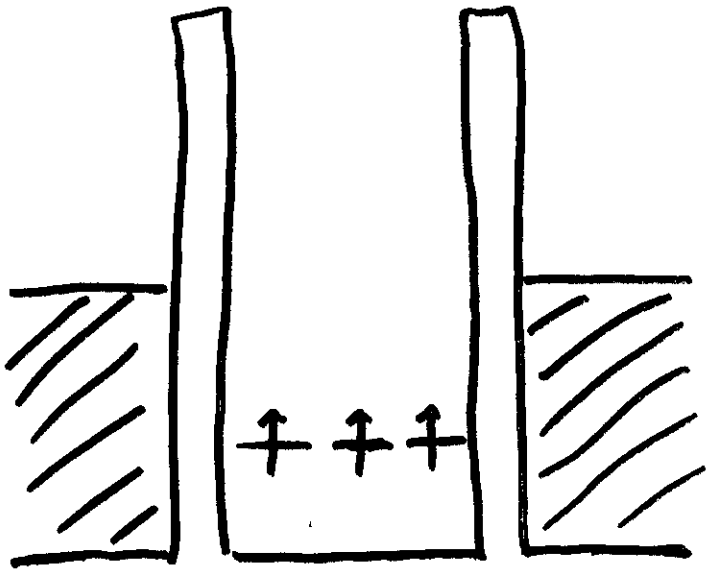
Thanks to: Bert Halperin, Charlie Marcus, Piet Brouwer, Philippe Jacquod, Harold Baranger

Silvano Di Franceschi, Wilfred van der Wiel, Leo Kouwenhoven

Simple limiting cases



- Noninteracting
  - Double filling
  - Alternating ↑ , ↓

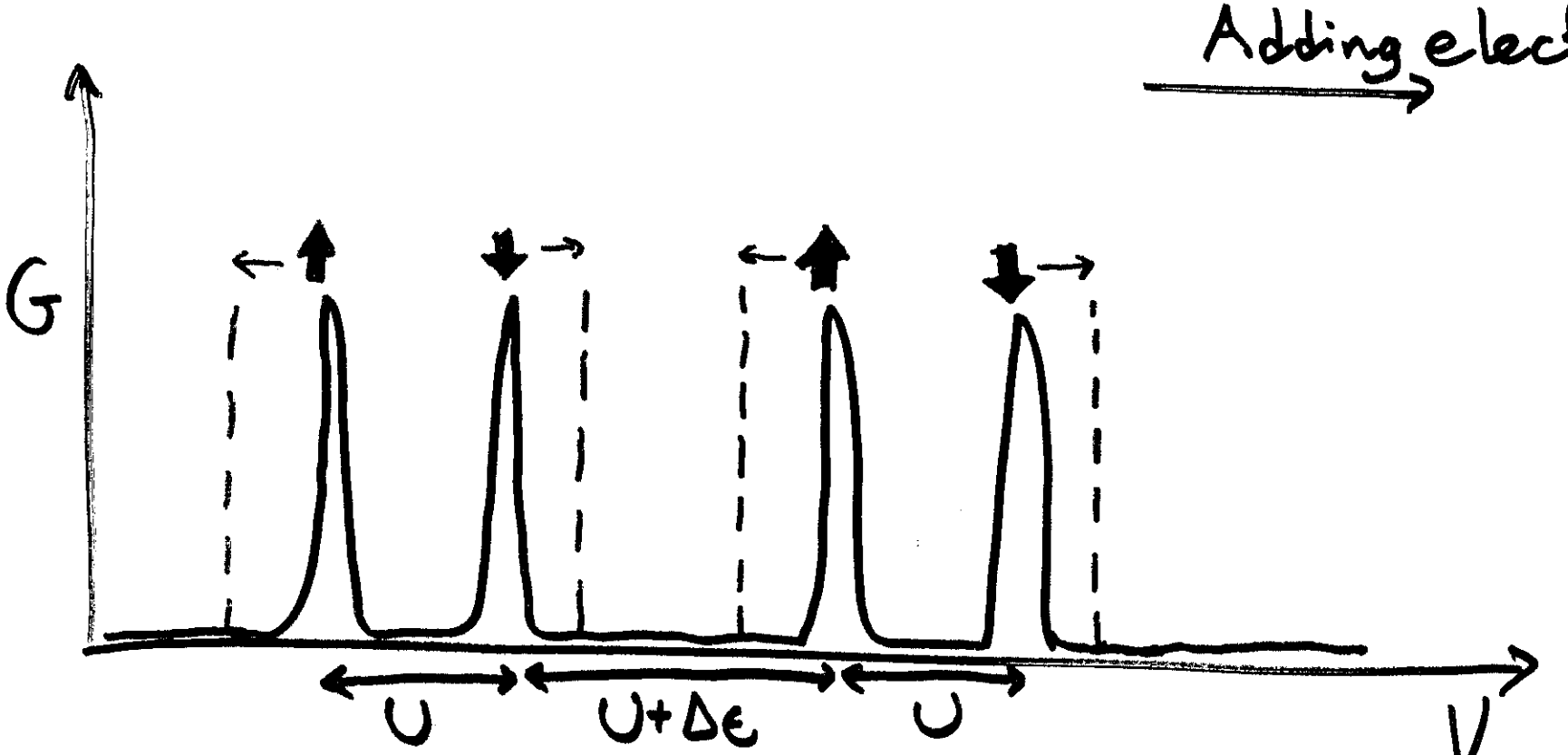


- Interacting plus degeneracies
  - Exchange
  - Hund's rules align spin

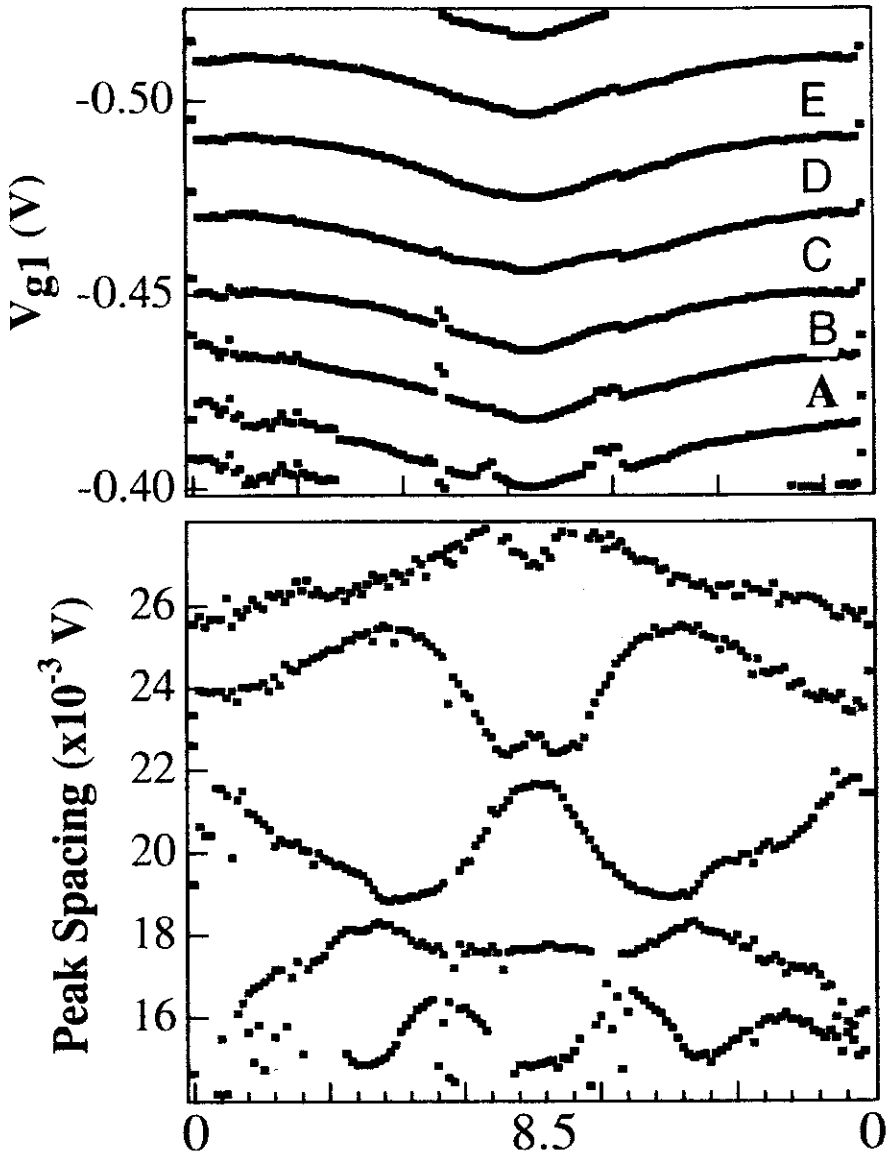
Real situation

- No evidence for spin degeneracy, double filling in typical lateral dots
- Competition between level spacing and interactions
- This work: double filling in small, high-density dots

Influence of B || plane of 2DEG



Peak Spacings vs. B



- Slopes of spacings provide information on changes in the spin of successive ground states
- g-factors comparable to bulk GaAs value at low field

Where from here?

- Spin is a useful tool for probing state filling
- Are single-particle/mean field pictures good enough?
- What parameters drive crossover from simple double occupancy to more complex arrangements (see next talk)