QIMP11, May 29th – June 10th, 2011, Dresden

Far from equilibrium

and time-dependent phenomena

for electron transport in quantum dots

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Part II
Kondo effect in quantum dots

1. Signatures of Kondo effect in quantum dots
2. Single parameter scaling and Kondo temperature
3. Out-of-equilibrium Kondo effect
4. “Exotic” Kondo effects
5. Ferromagnetic and superconducting reservoirs
6. Quantum criticality

reviews: L. Kouwenhoven & L. Glazman, Physics World 14, 33 (2001)
M. Grobis *et al.*, in Handbook of Magnetism and Advanced Magnetic Materials, Vol. 5, Wiley
arXiv:cond-mat/0611480

1. Signature of Kondo effect in quantum dots

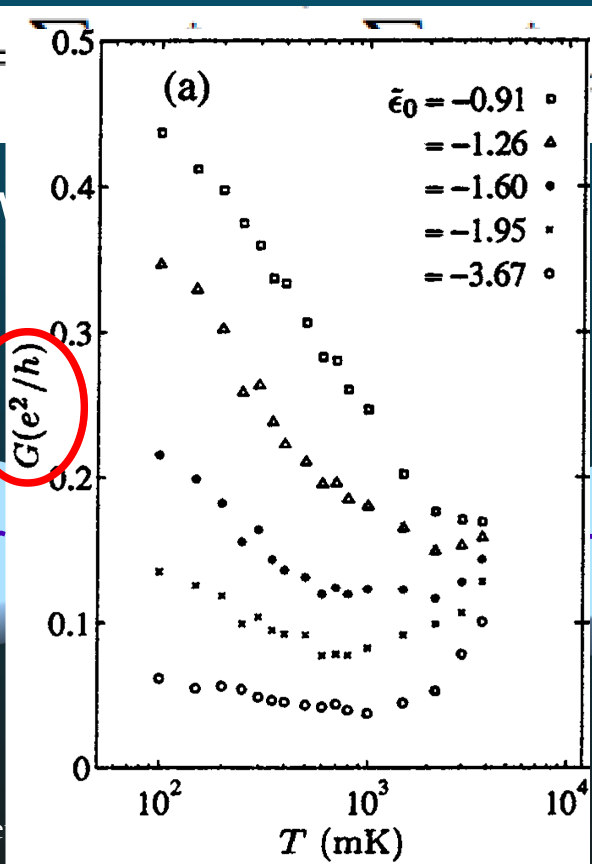
- Single impurity coupled to Fermi leads ⇔ Kondo problem
  L. I. Glazman & M. E. Raikh, JETP Lett. 47, 452 (1988)
  T. K. Ng & P. A. Lee, PRL 61, 1768 (1988)
  – due to on-site Coulomb interaction in the quantum dot

$$H = \sum \ldots + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow + \sum_{k,\sigma} \big(v_k \ldots$$

  – w… effect (U, ε_0, ν_k… T_K … 1961)

conductance

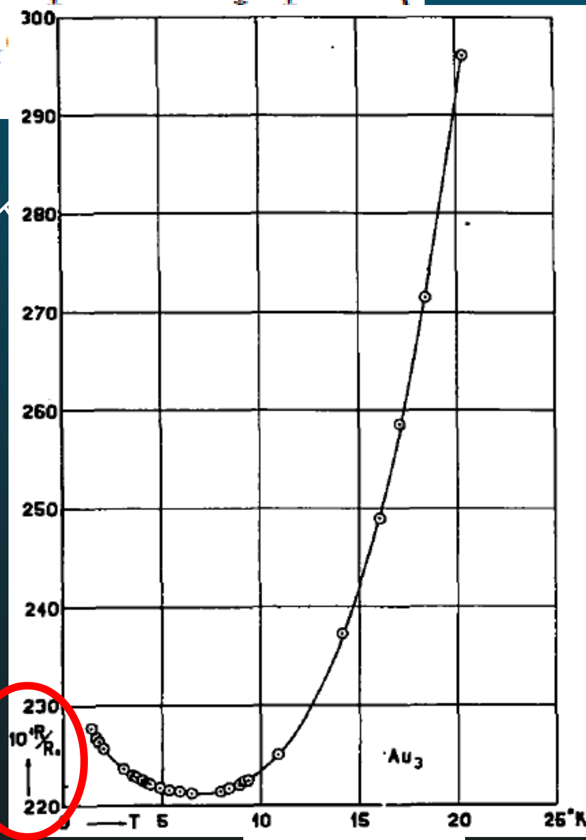
source … drain



D. Goldhaber-Gordon … PRL 81, 5225 (1998)

⇔

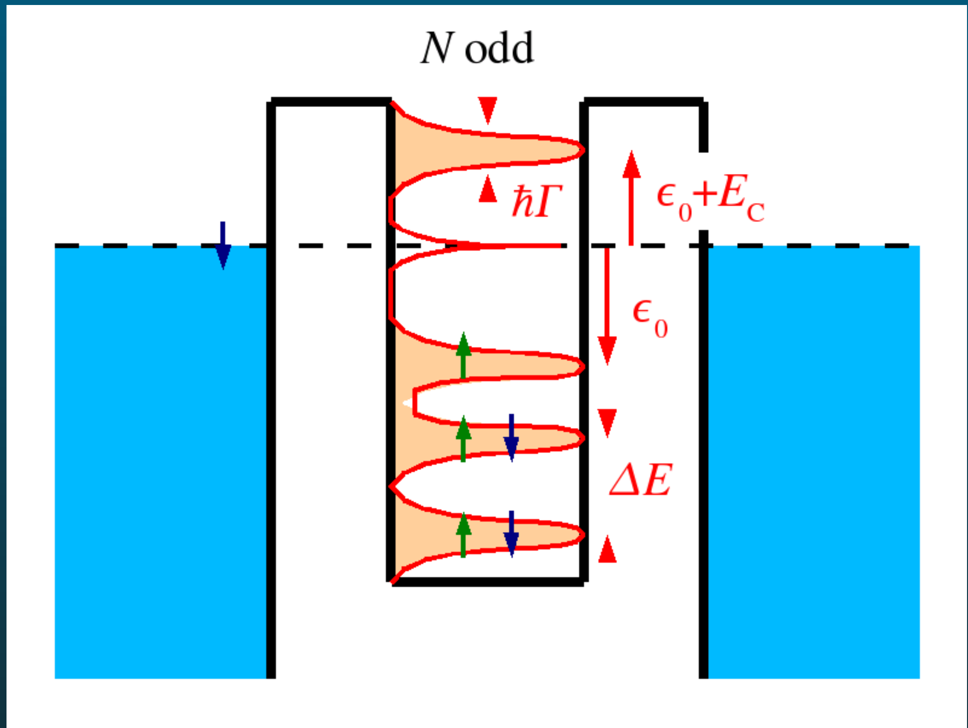
resistance



W. J. De Haas & G. J. Van Den Berg, Physica 3, 440 (1936)

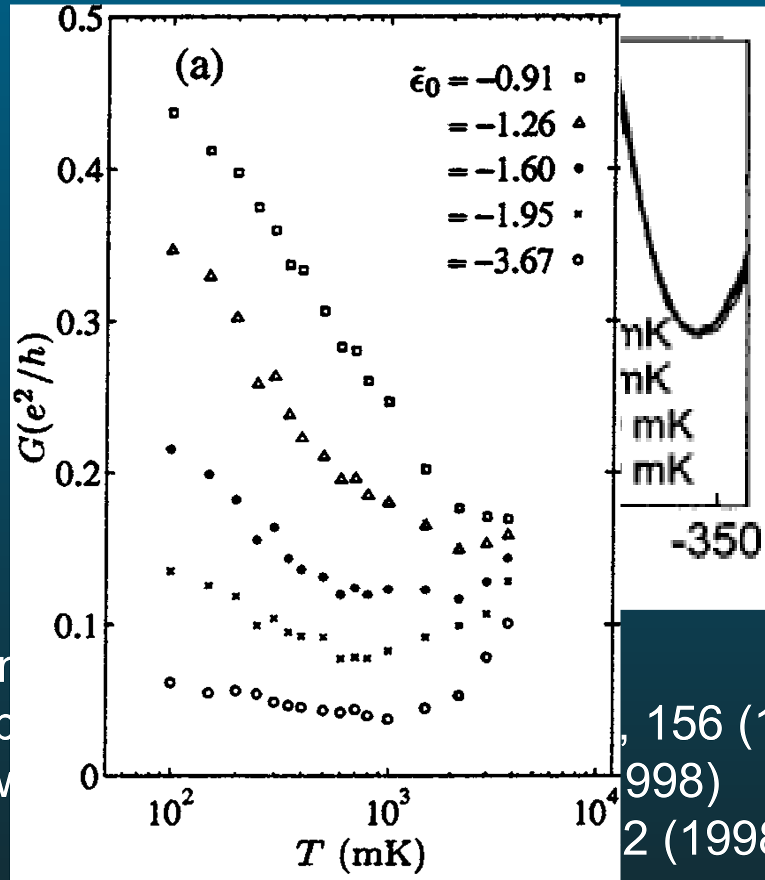
Kondo effect in quantum dots

- Singlet state due to exchange interaction
- Transport allowed by co-tunneling (virtual intermediate state)
- Enhanced density of states aligned with the chemical potential of the leads



Kondo effect in quantum dots

- Singlet state due to exchange interaction
- Transport allowed by co-tunneling (virtual intermediate state)
- Enhanced density of states aligned with the chemical potential of the leads
- Enhanced conductance in the Coulomb blockaded region at low temperature

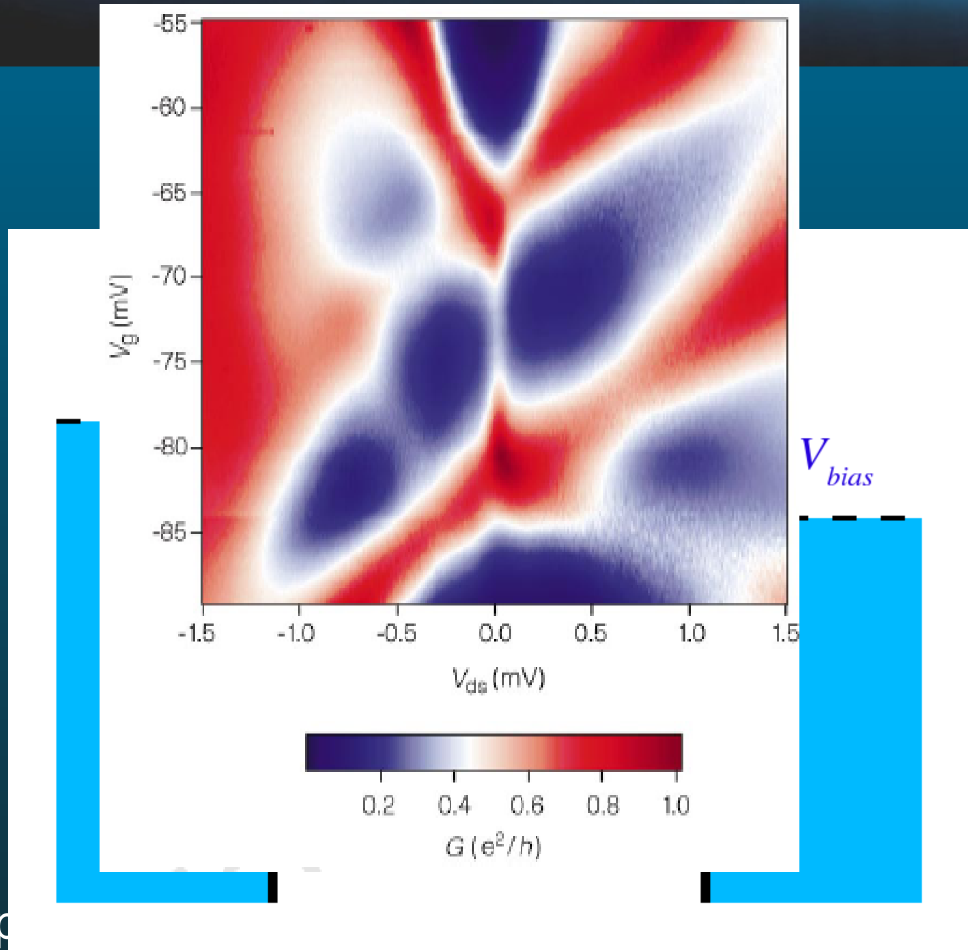


- experir
Goldhab , 156 (1998)
Cronenw 998)
Schmid 2 (1998)

D. Goldhaber-Gordon *et al.*, PRL **81**, 5225 (1998)

Zero bias anomaly

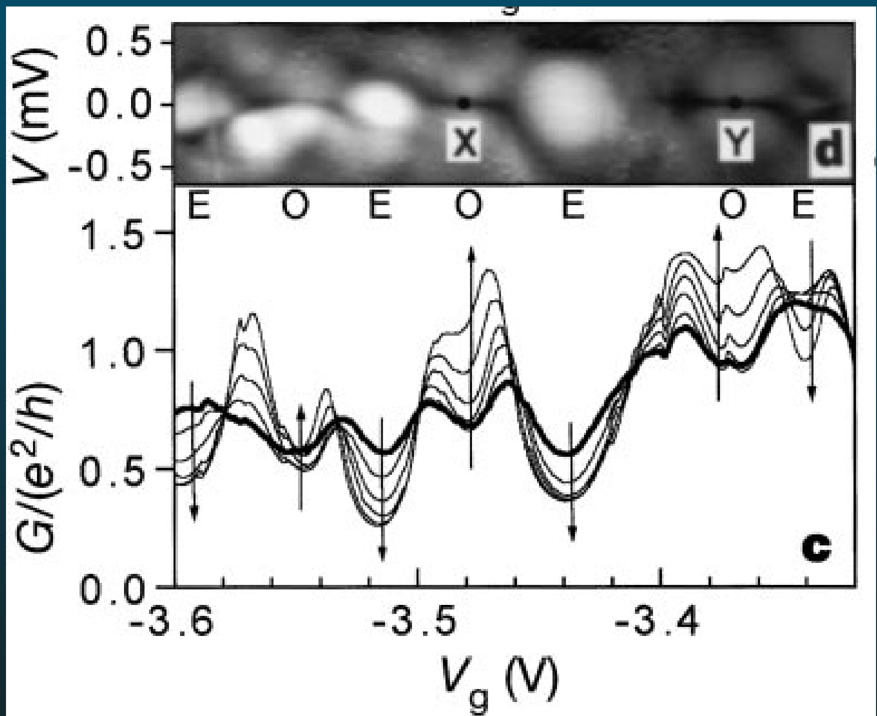
- High bias voltage ⇒ double peak in the DOS expected at finite bias
- Two-terminal experiment: suppression of the conductance at high bias (zero bias anomaly)

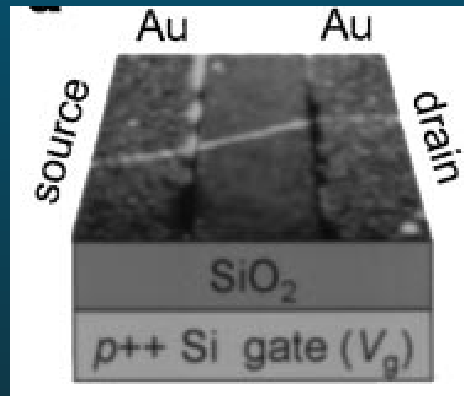


- p
Meir *et al.*, PRL **70,** 2601 (1993)
- experiments:
Goldhaber-Gordon *et al.*, Nature **391**, 156 (1998)
Cronenwett *et al.*, Science **28**, 540 (1998)
Schmid *et al.*, Physica B **256-258**, 182 (1998)

Origin of the Kondo effect

- Is it related to the electron spin?
  - observed (mainly) for odd electron filling (odd-even behavior)
  - splitting of the resonance at finite magnetic field

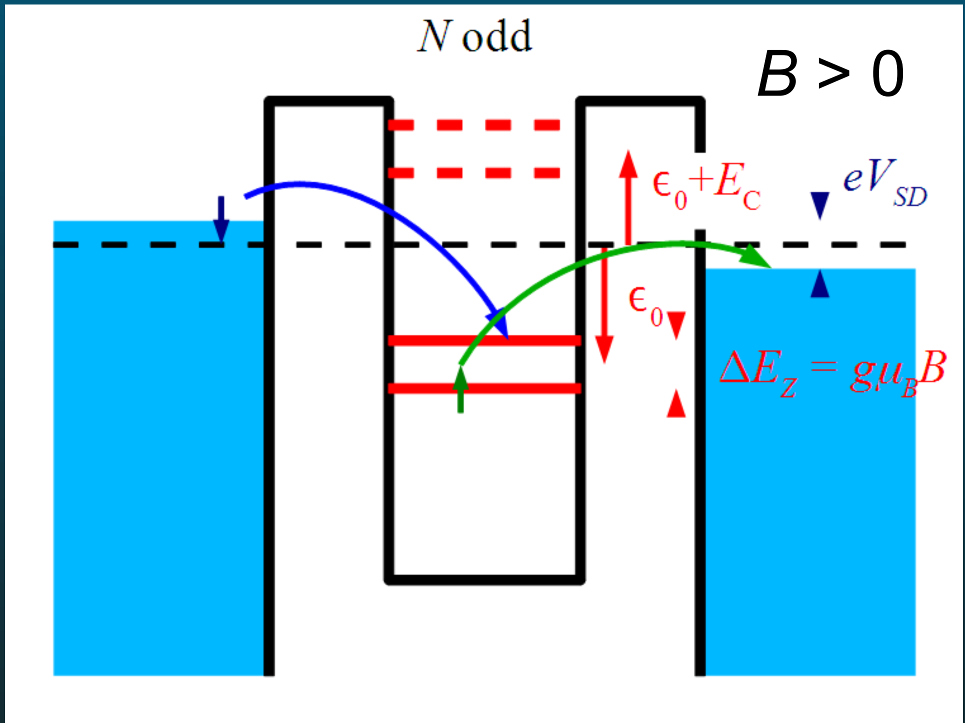


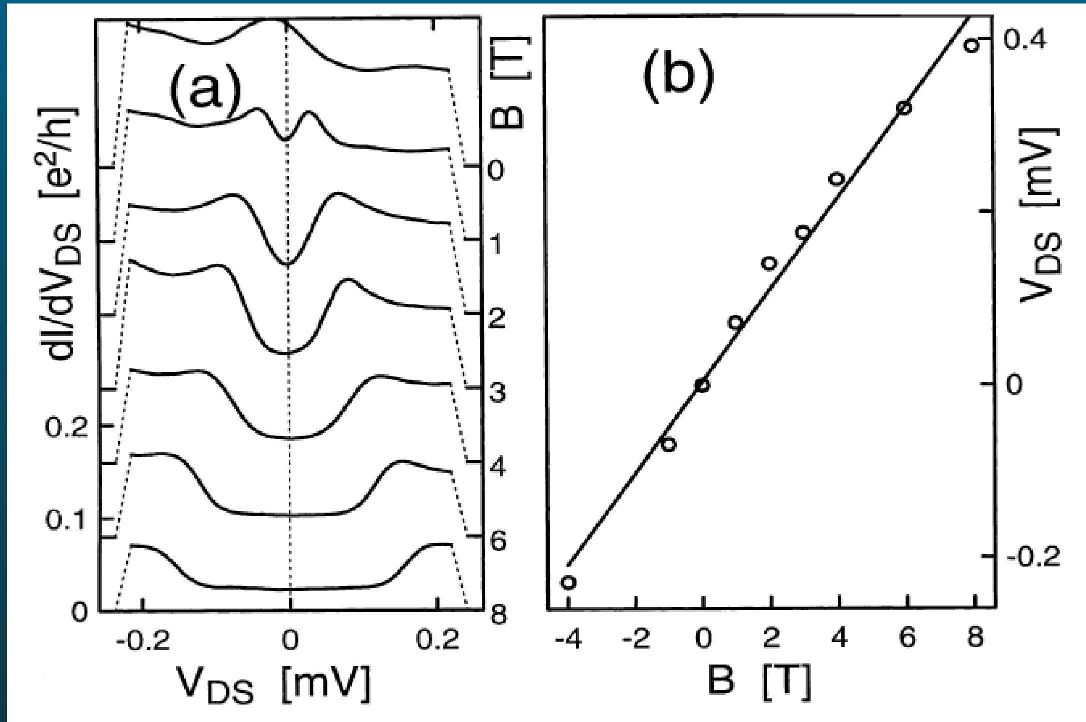


J. Nygard *et al.*, Nature **408**, 342 (2000)

Magnetic field dependence

- Splitting of the resonance at finite magnetic field





- prediction:
Meir *et al.*, PRL **70,** 2601 (1993)
- experiments:
Goldhaber-Gordon *et al.*, Nature **391**, 156 (1998)
Cronenwett *et al.*, Science **28**, 540 (1998)
Schmid *et al.*, Physica B **256-258**, 182 (1998)

Take-away message (1)

Kondo effect in quantum dots lead to an enhanced condutance

opposite to metals

fits to expectation in ideal cases (constant interaction model)

next: quantitative analysis of the enhanced conductance

2. Single parameter scaling and Kondo temperature

- Temperature dependence of the conductance

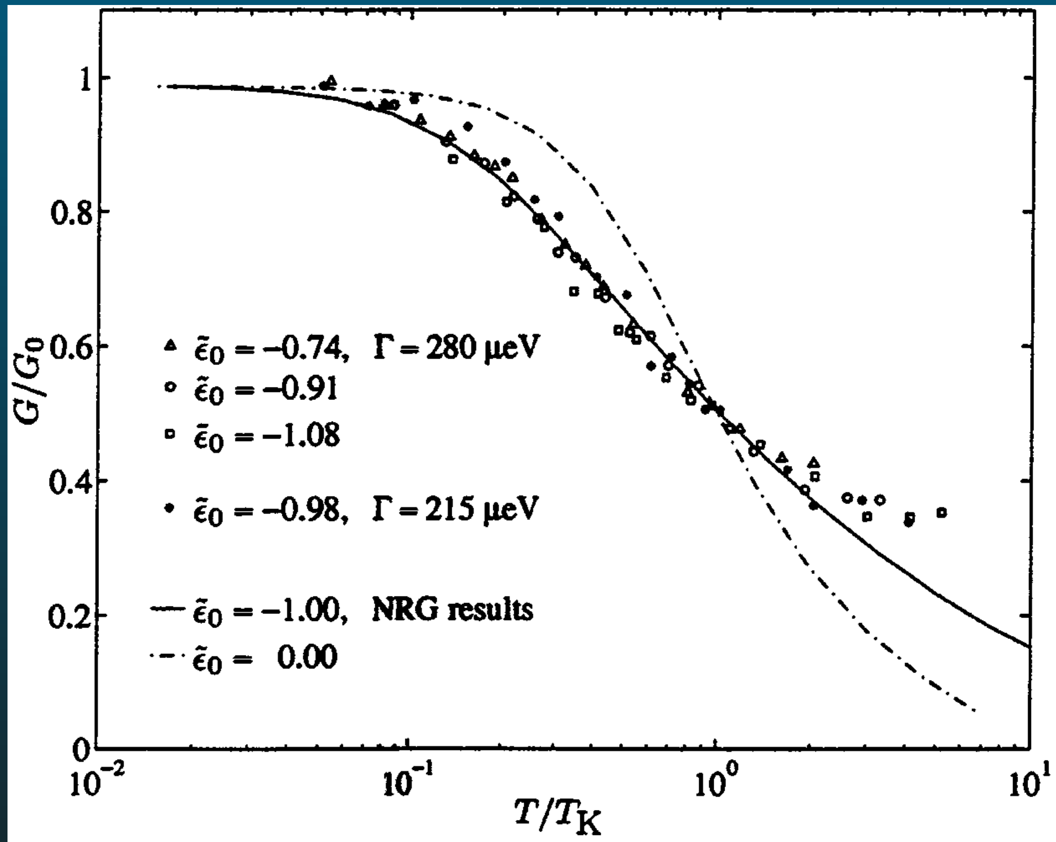
$$G(T) = G_0 \left(\frac{T_K'^2}{T_K'^2 + T^2} \right)^s$$

$$T_K' = \frac{T_K}{\sqrt{2^{1/s} - 1}}$$

$$T_K = \frac{\sqrt{\Gamma U}}{2} e^{\pi \varepsilon_0 (\varepsilon_0 + U)/\Gamma U}$$

$s \approx 0.2$

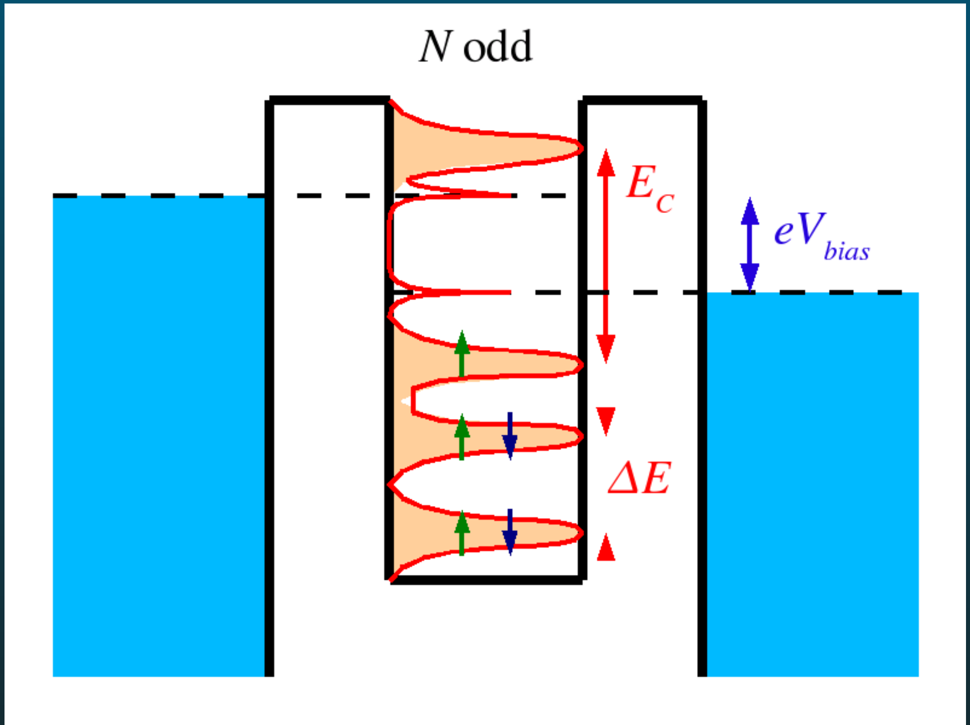
T. A. Costi & A. C. Hewson,
J. Phys. Condens. Matter **6**, 2519 (1994).

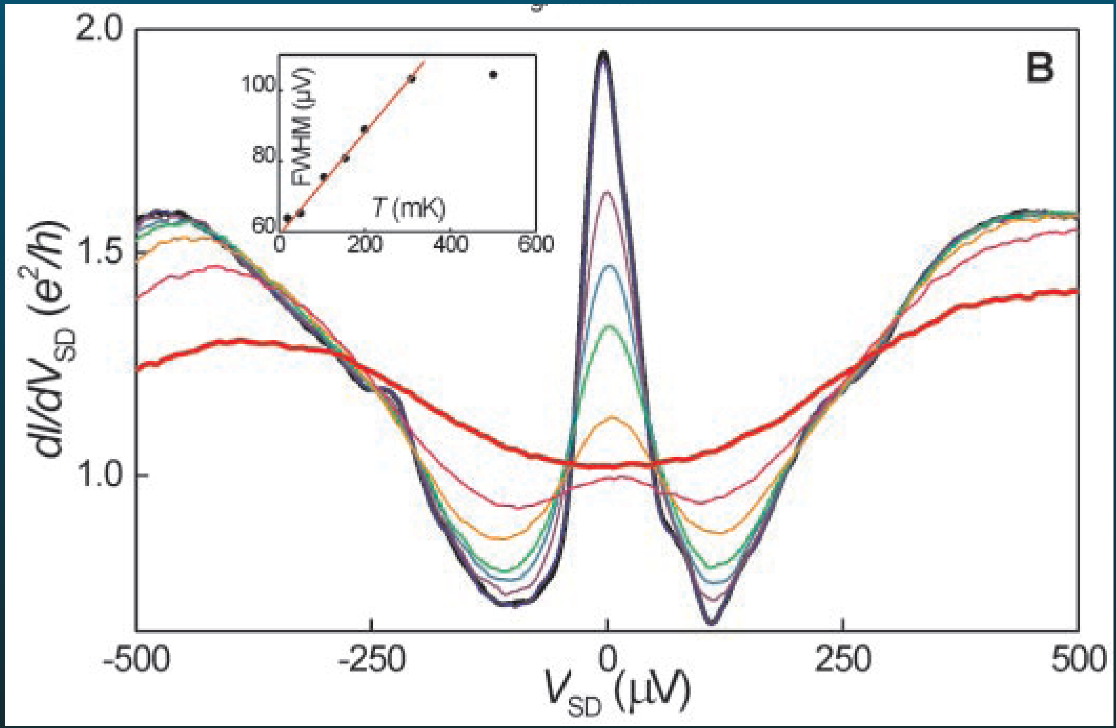


D. Goldhaber-Gordon *et al.*, PRL **81**, 5225 (1998)

Width of the Kondo resonance

- Width of the Kondo resonance related to the Kondo DOS
  - width at zero temperature = $\alpha\, k_B T_K$?



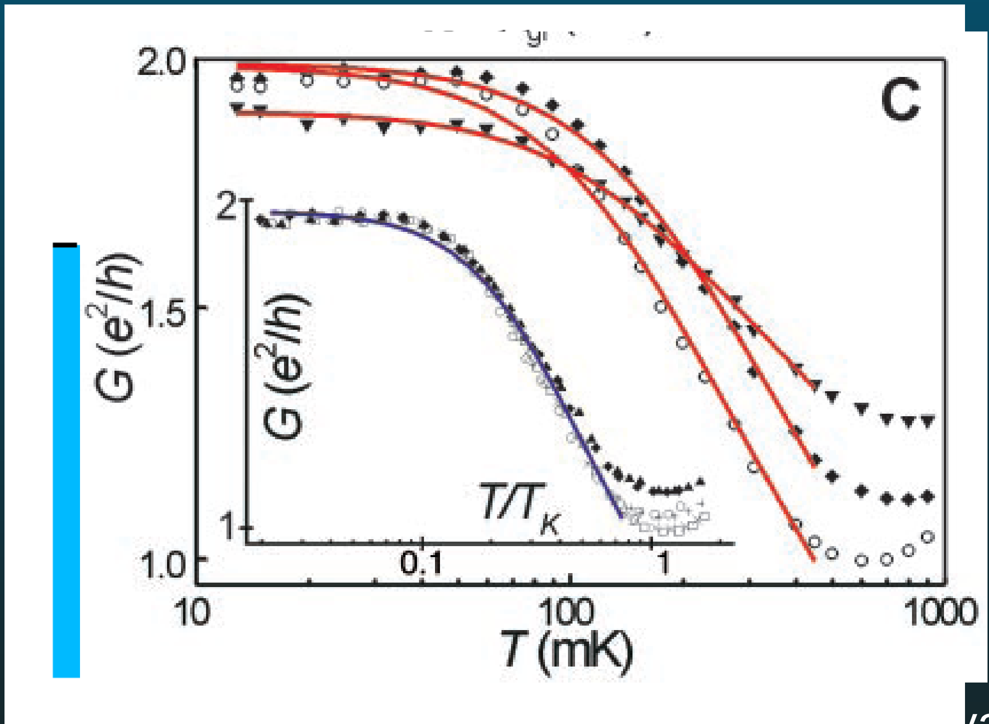


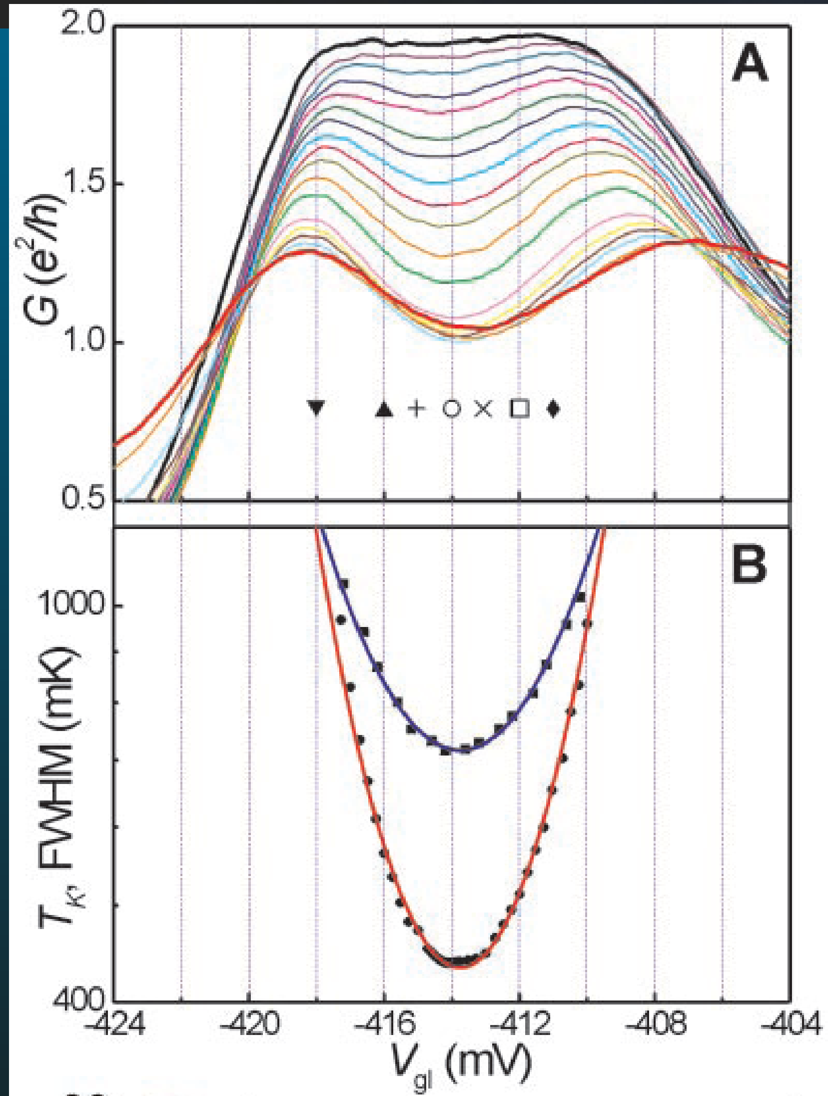
W. G. van der Wiel *et al.*, Science **289**, 2105 (2000)

Transition to the mixed valence regime

- Tuning $\varepsilon_0 \Rightarrow$ control of T_K

$$T_K = \frac{\sqrt{\Gamma U}}{2} e^{\pi \varepsilon_0 (\varepsilon_0 + U)/\Gamma U}$$





W. G. van der Wiel *et al.*, Science **289**, 2105 (2000)

Take-away message (2)

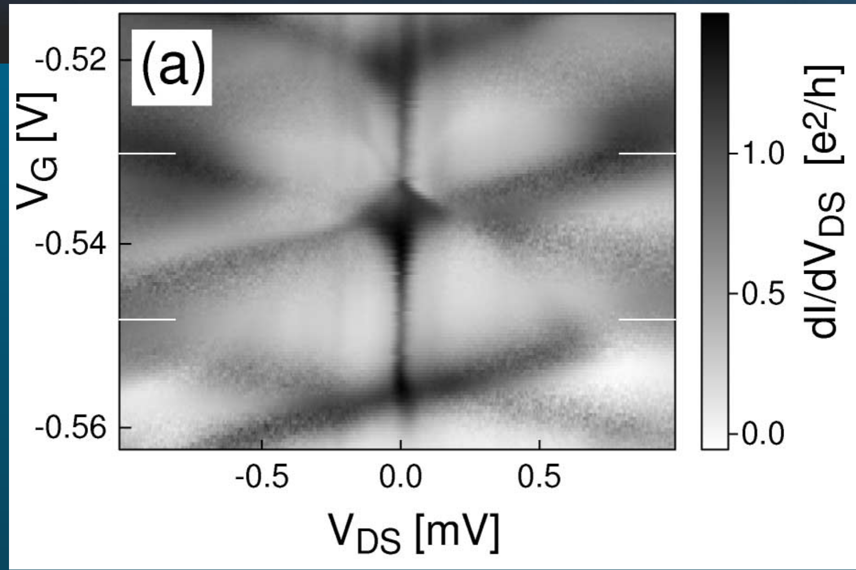
The Kondo effect in quantum dots follows the single parameter scaling as in metals

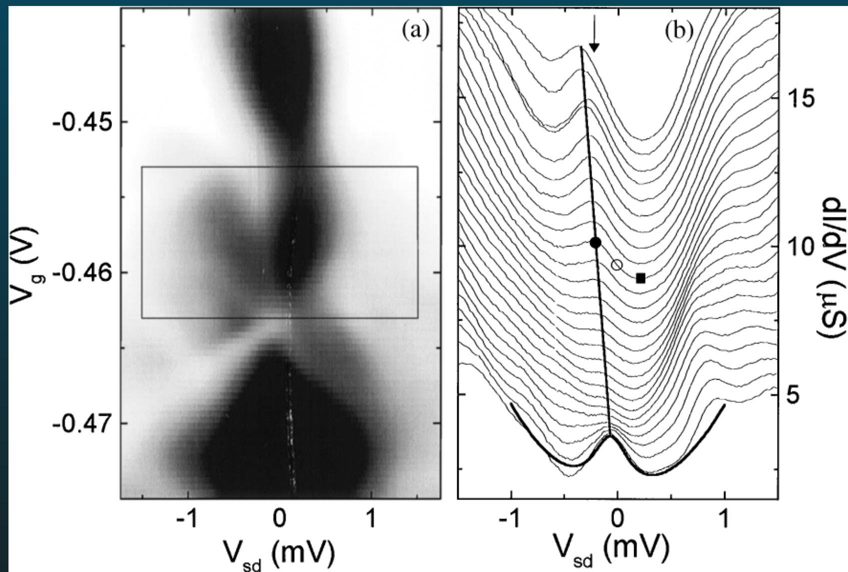
Control of the Kondo temperature using external parameters (gate voltage)

next: Can we learn more about the Kondo effect using quantum dots?

Quantum dots are non-ideal systems

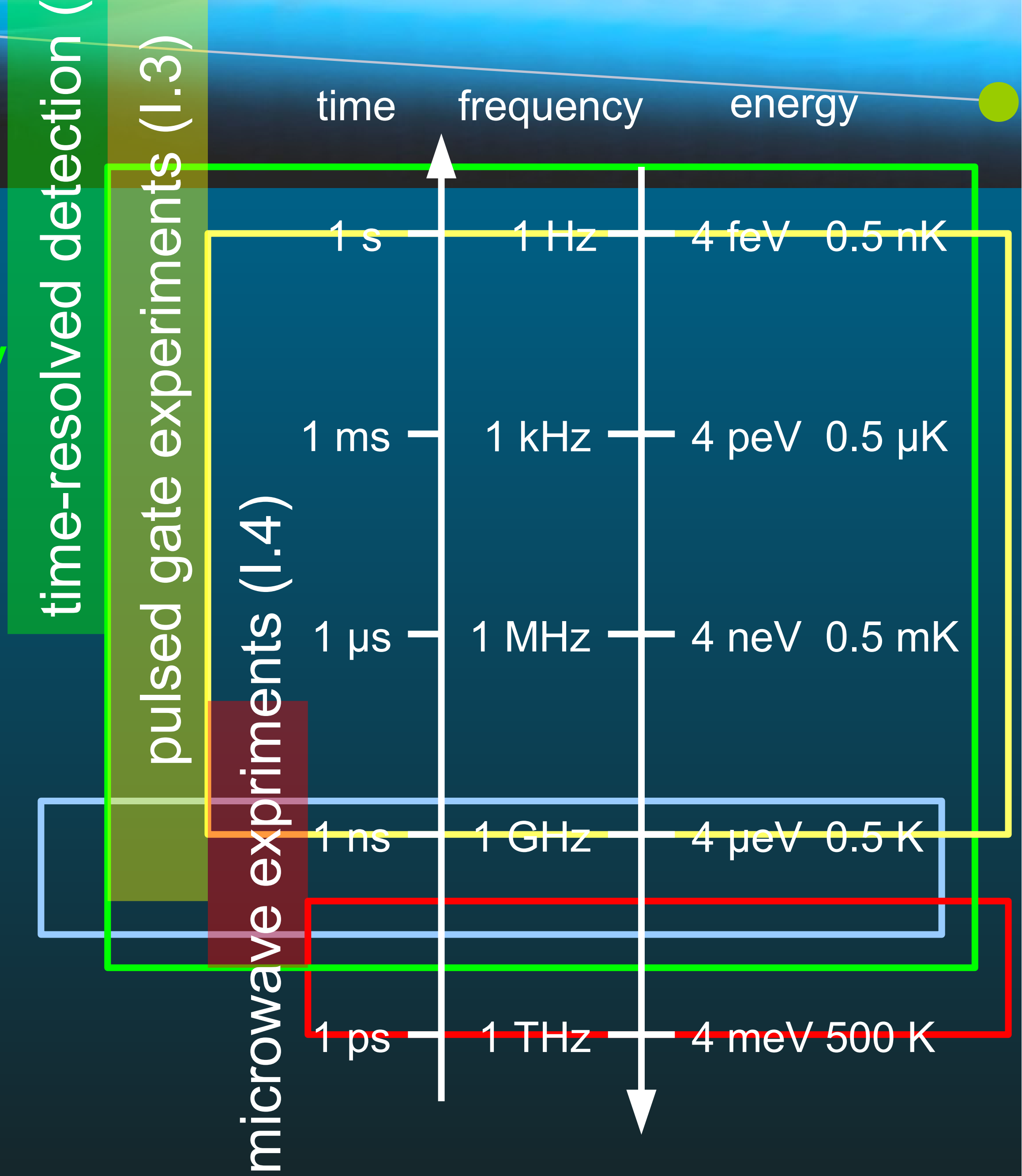
- Absence of odd-even behavior
  J. Schmid et al., PRL 84, 5824 (2000)
  – deviation to the constant interaction model
- Finite-bias Kondo resonance F. Simmel *et al.*, PRL **83**, 804 (1999)
  – due to asymmetric coupling to the leads





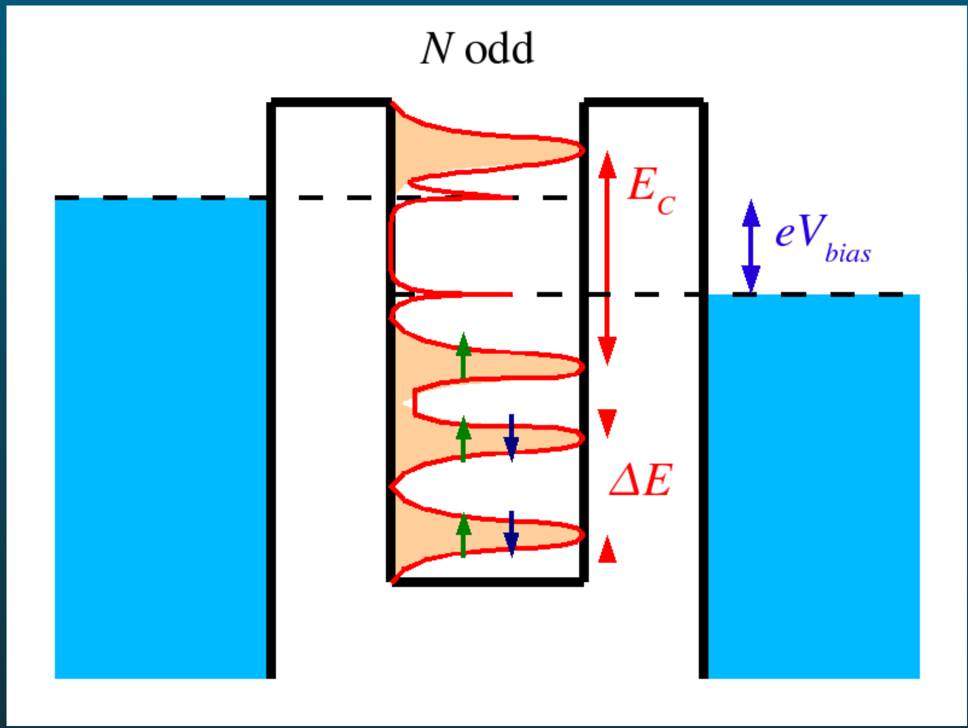
Time scales for single electron transport

- Inverse tunneling rates
  $1/\Gamma_S$, $1/\Gamma_D$ = 10 ps – infinity
  - time scale for a trapped electron to escape
- Charge or spin decay time
  $1/\Gamma_d$ = few ns – 1 second
  - coherent manipulation
- h/E_C, h/Δ = 1 – 100 ps
  - non-adiabatic transistion
- $k_B T_K$ = 0.1 – 10 K



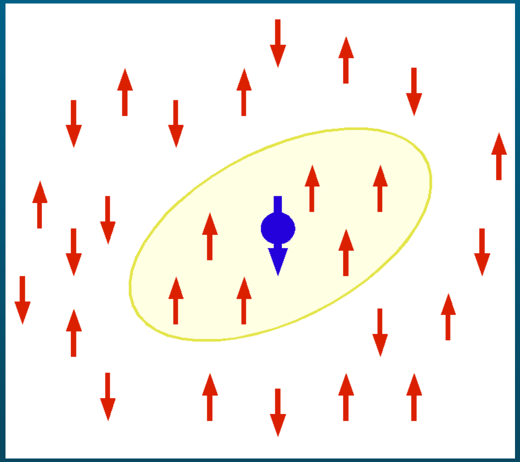
3. Out-of-equilibrium Kondo effect

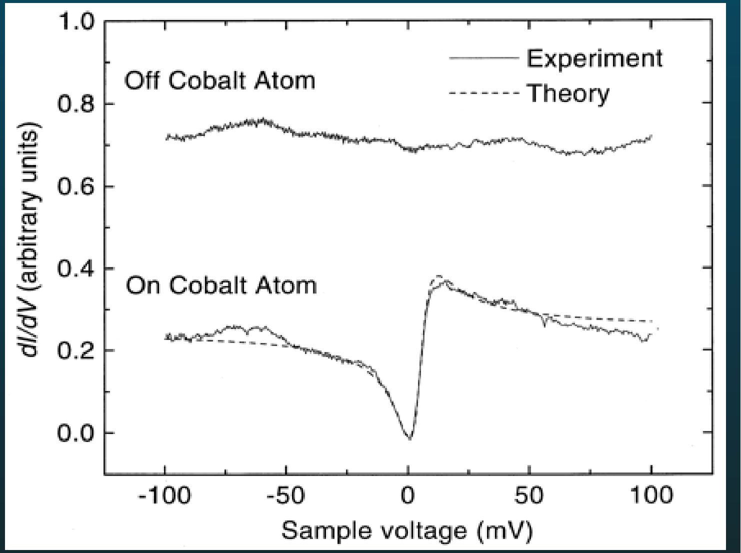
- Validity of the common picture of double peak structure?
  - finite life time of the excited state?
  - decoherence at finite bias?



Kondo density of states in metals

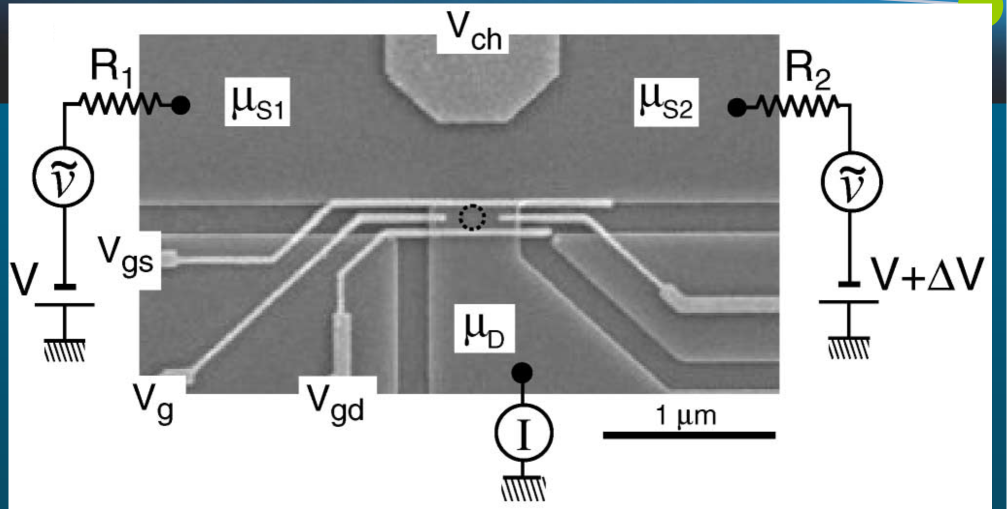
- Increased resistivity due to the screening of magnetic impurities by conduction electrons
- STM experiments on single magnetic impurities: towards probing the local density of states
  Li *et al.*, PRL **80,** 2893 (1998)
  Madhavan *et al.*, Science **280,** 567 (1998)
- Out-of-equilibrium density of states?

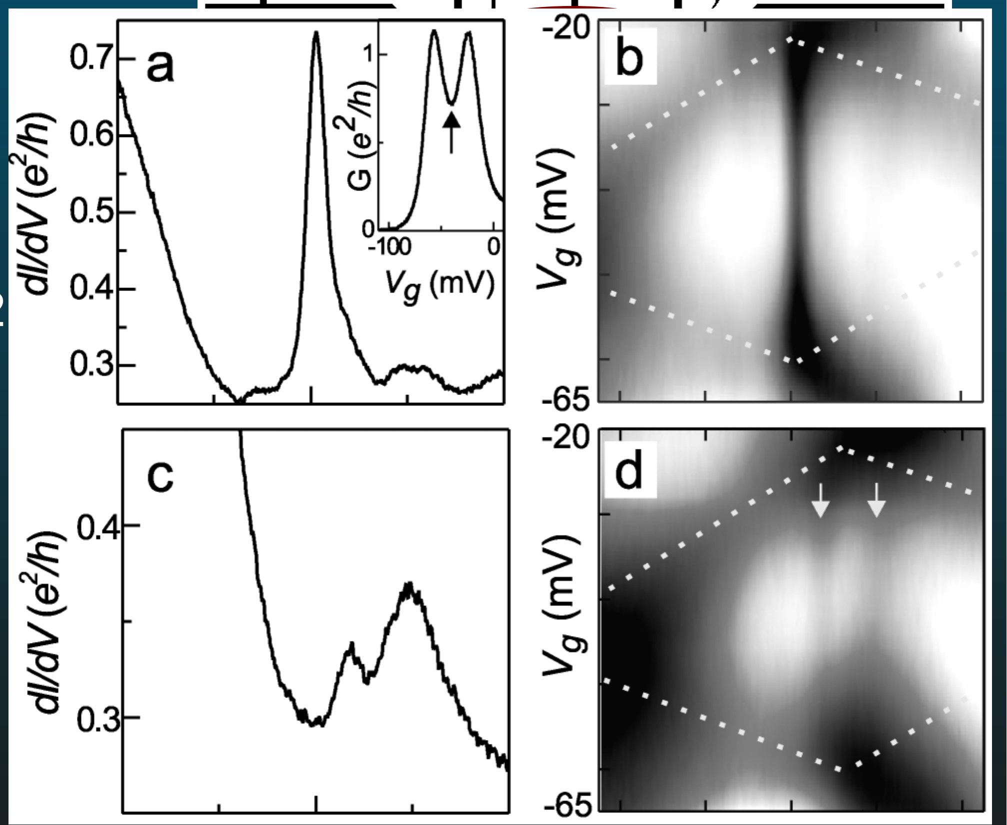


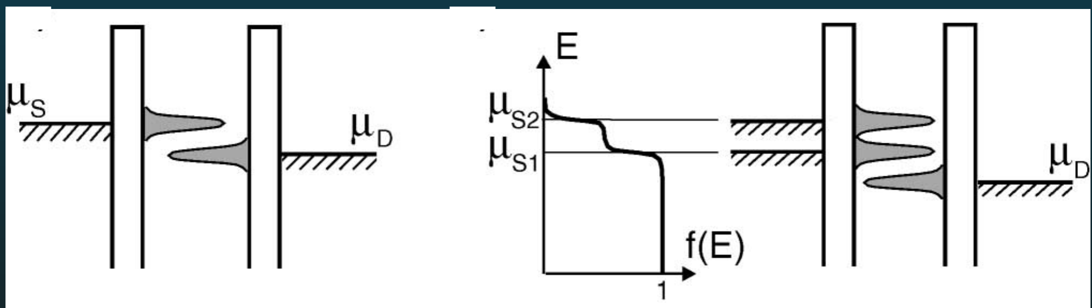


Out-of-equilibrium Kondo density of states

- Three-terminal quantum dot to measure the DOS
  Sun & Guo, PRB **64,** 153306 (2001)
  Lebanon & Schiller, PRB **65,** 035308 (2001)
  Sánchez & López, PRB **71,** 035315 (2005)
- First experiment: quantum dot connected to a wire
  – no direct access to the DOS
    De Franceschi *et al.*, PRL **89,** 156801 (2002







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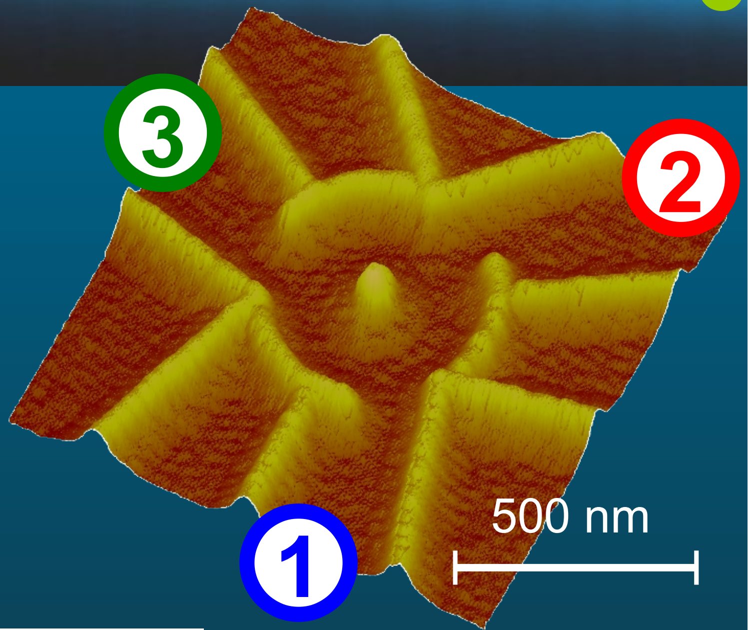
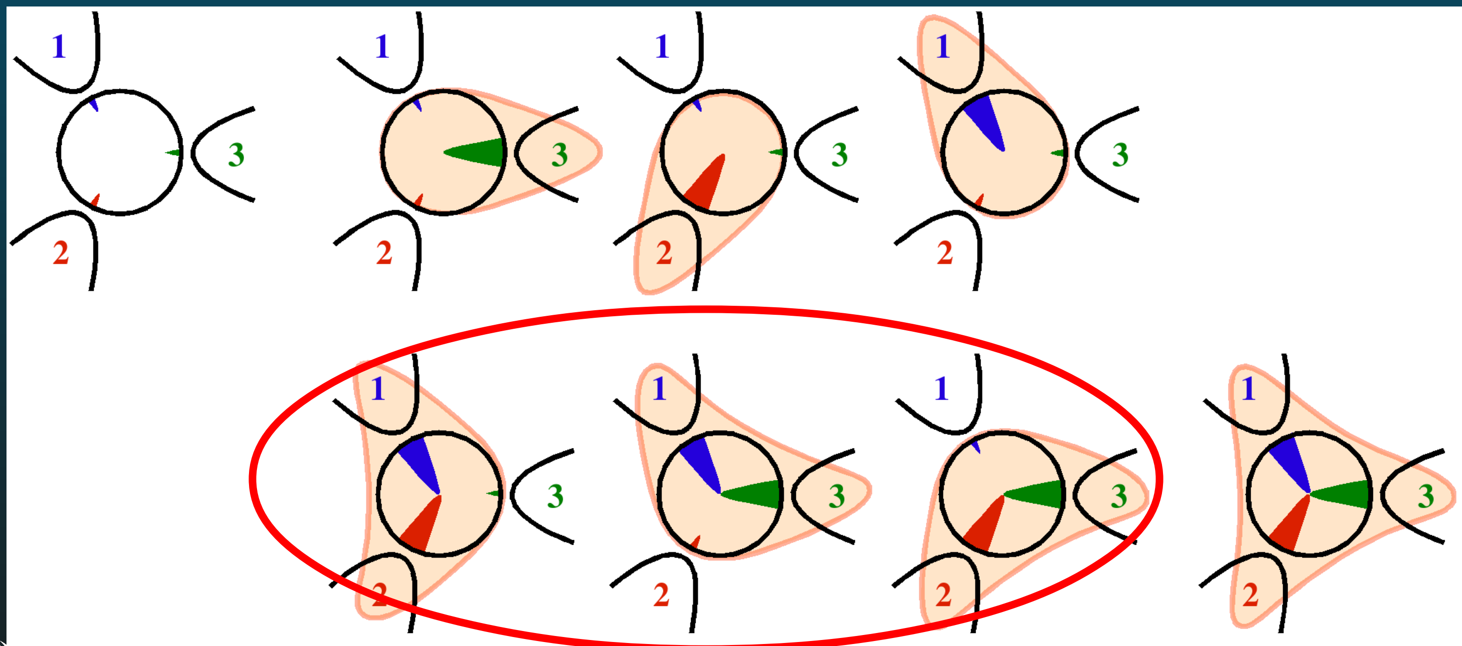
Out-of-equilibrium Kondo density of states

- Three-terminal quantum dot
- Expected configurations
  - with three separate terminals, it is possible to discriminate between different configurations

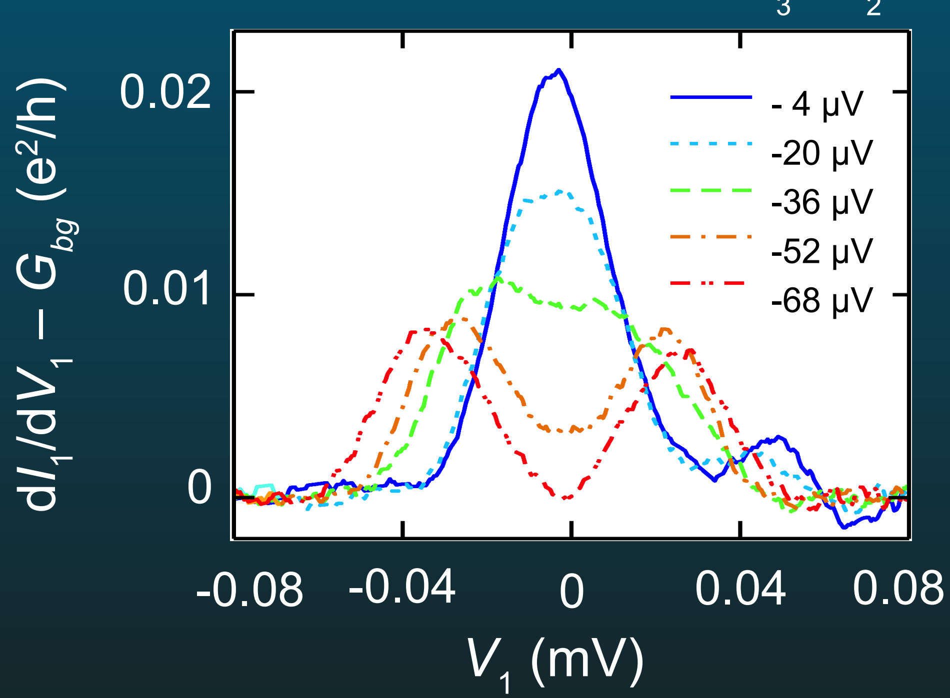


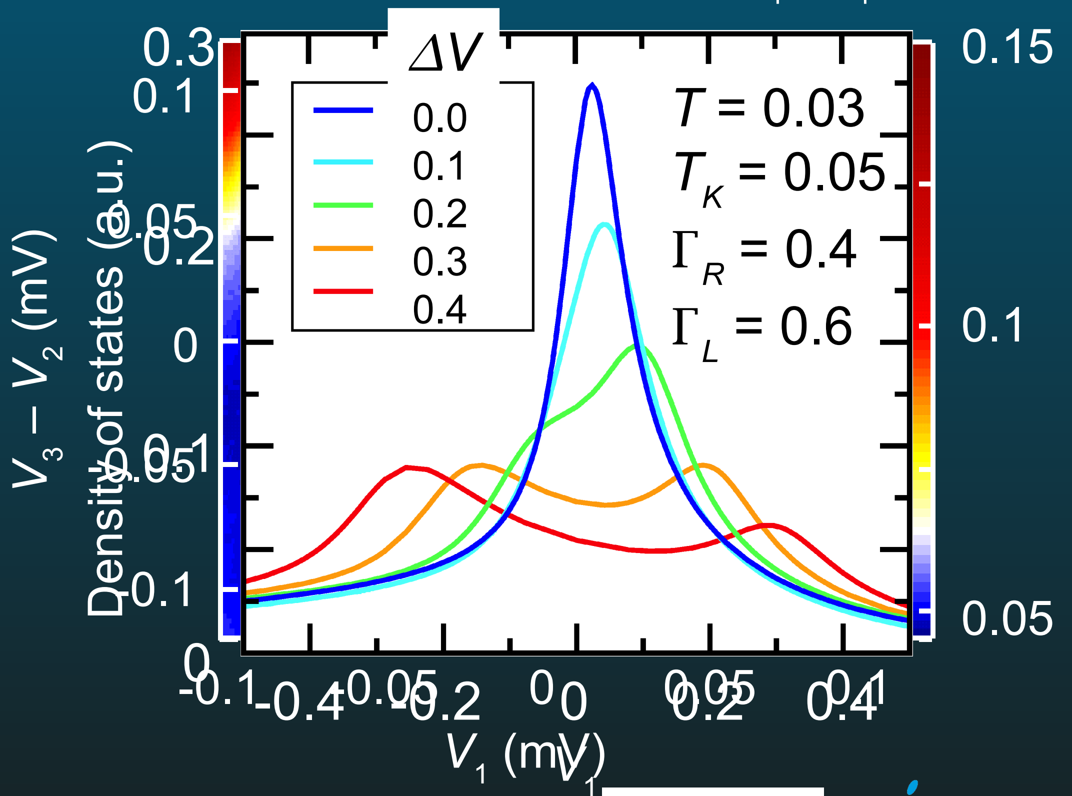


Out-of-equilibrium Kondo density of states

R. Leturcq *et al.*, PRL **95,** 126603 (2005)

- Direct evidence of the splitting of the out-of-equilibrium Kondo resonance → density of states?
  - qualitative agreement with theoretical calculation (noncrossing approximation)





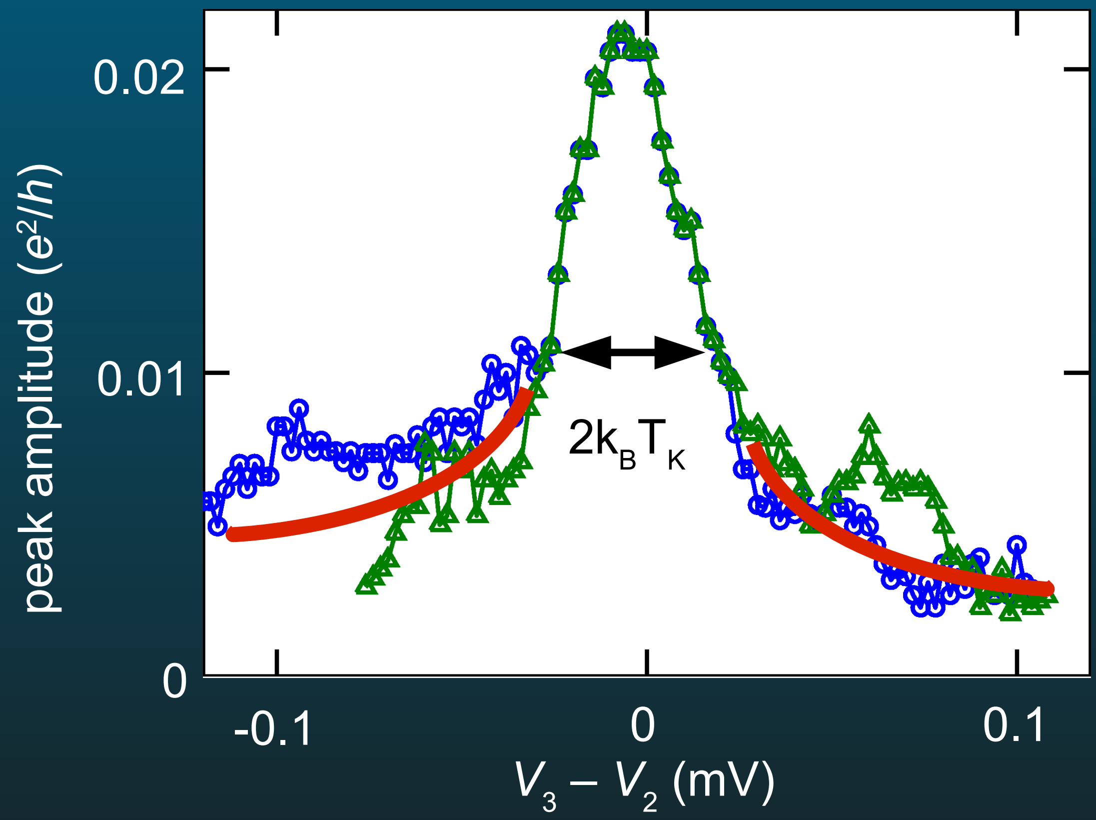
Out-of-equilibrium Kondo density of states

- Exponential decay of the satellite peaks at large bias voltage
  - related to decoherence?

    Meir *et al.*, PRL **70,** 2601 (1993)

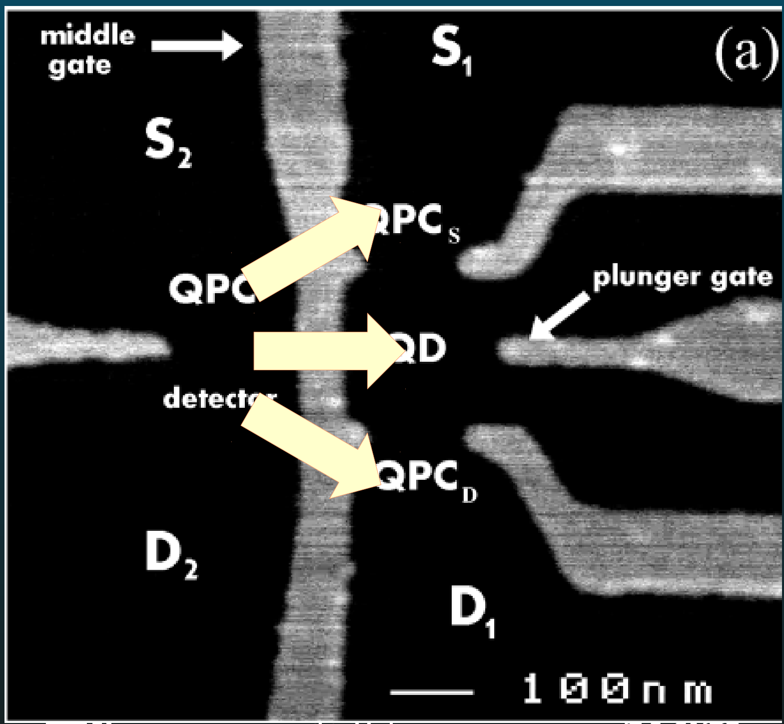
    Kaminski *et al.*, PRL **83,** 384 (1999)

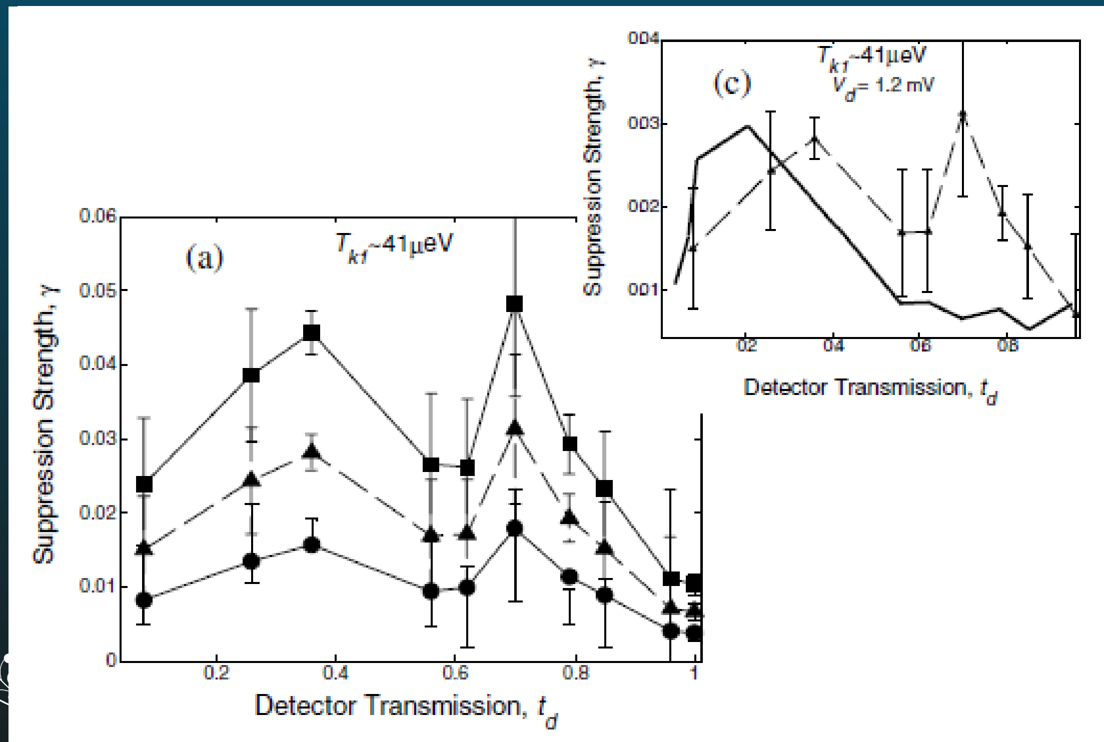
    Paaske *et al.*, PRB **70,** 155301 (2004)



Decoherence by a noise source

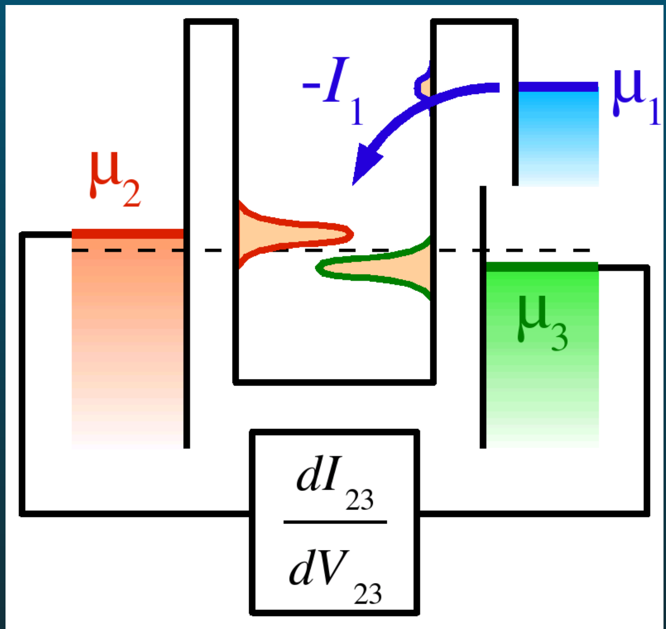
- Shot noise from a nearby quantum point contact
  M. Avinun-Kalish *et al.*, PRL **92**, 156801 (2004)
  - quantitative discrepancy with model of capacitively coupled qantum point contact   A. Silva & S. Levit, Europhys. Lett. 62, 103 (2003)
  - signature of the Kondo cloud extended to the leads?

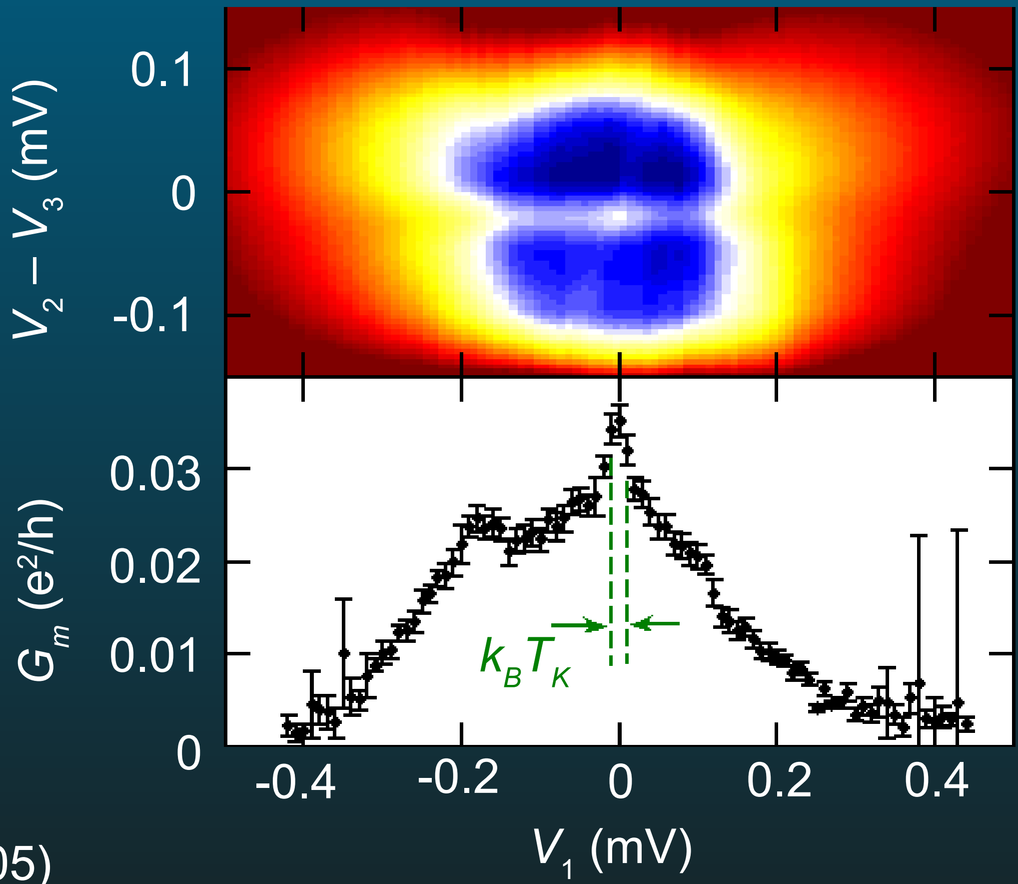




Decoherence of the Kondo resonance

- Large bias applied on the probing lead (weakly coupled)

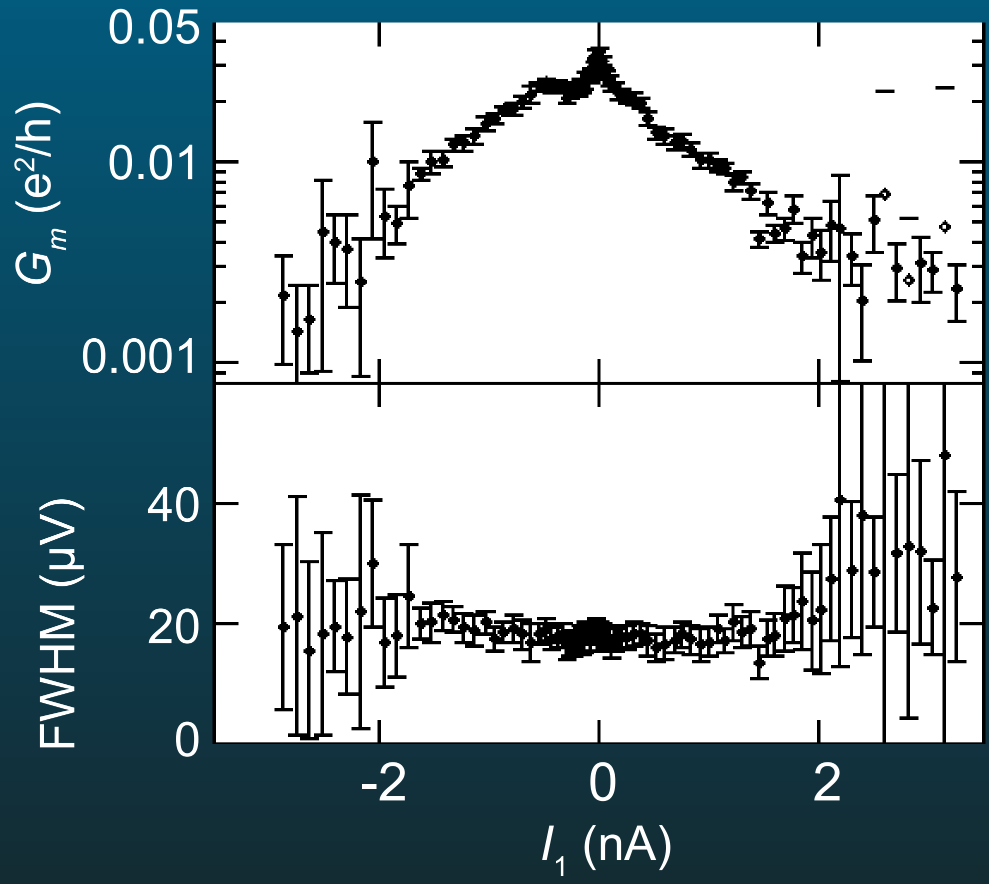




R. Leturcq *et al.*, PRL **95,** 126603 (2005)

Decoherence of the Kondo resonance

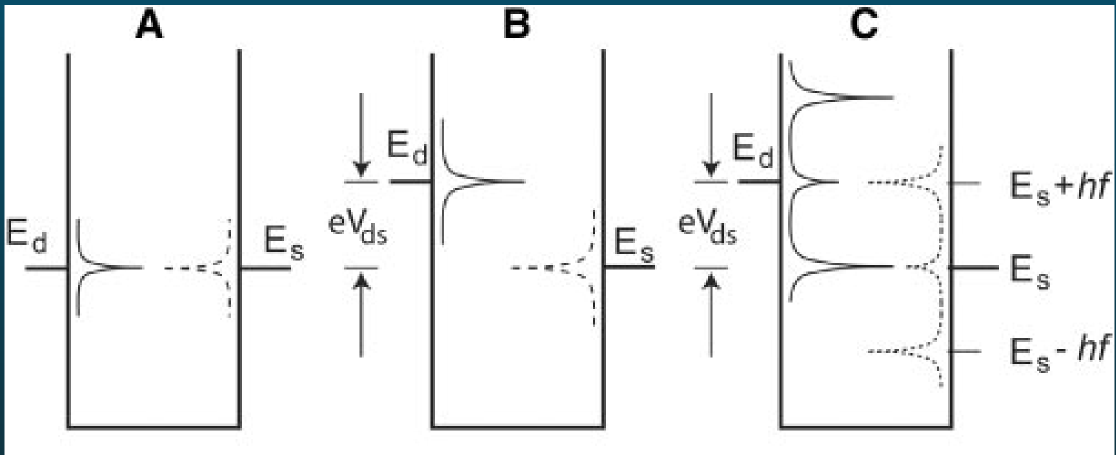
- Strong decrease of the Kondo resonance
- BUT dephasing should lead to an increase of the peak width!



R. Leturcq *et al.*, PRL **95,** 126603 (2005)

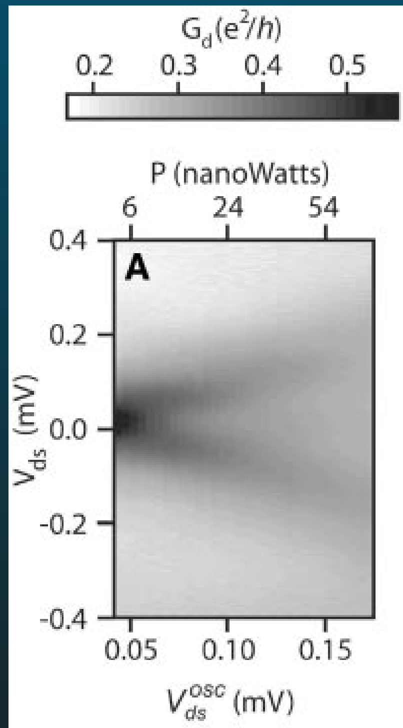
Photon-assisted tunneling in the Kondo regime

- From the adiabatic to the non-adiabatic regime
  - change of the Kondo temperature

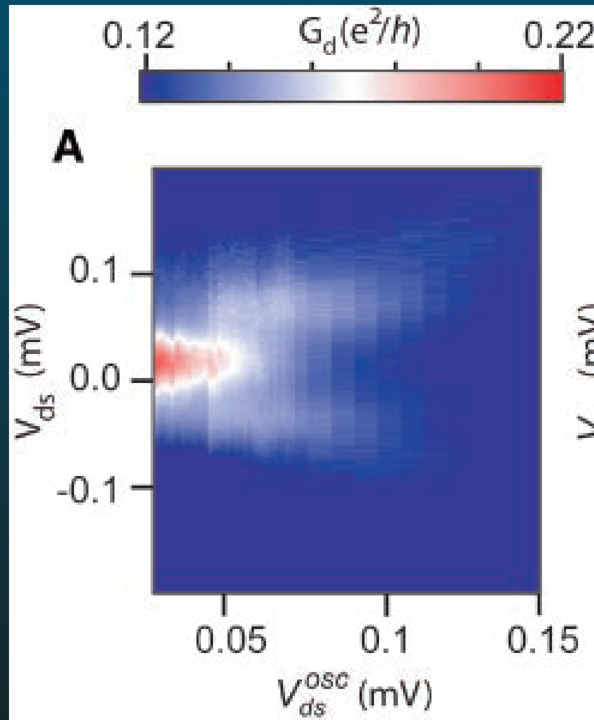


A. Kogan *et al.*, Science **304**, 1293 (2004)
+ talk on Tuesday, June 7th

adiabatic regime
$f \ll k_B T_K/h$



non-adiabatic regime
$f \approx k_B T_K/h$



Take-away message (3)

Out-of-equilibrium Kondo effect probed by large bias voltage or high frequency

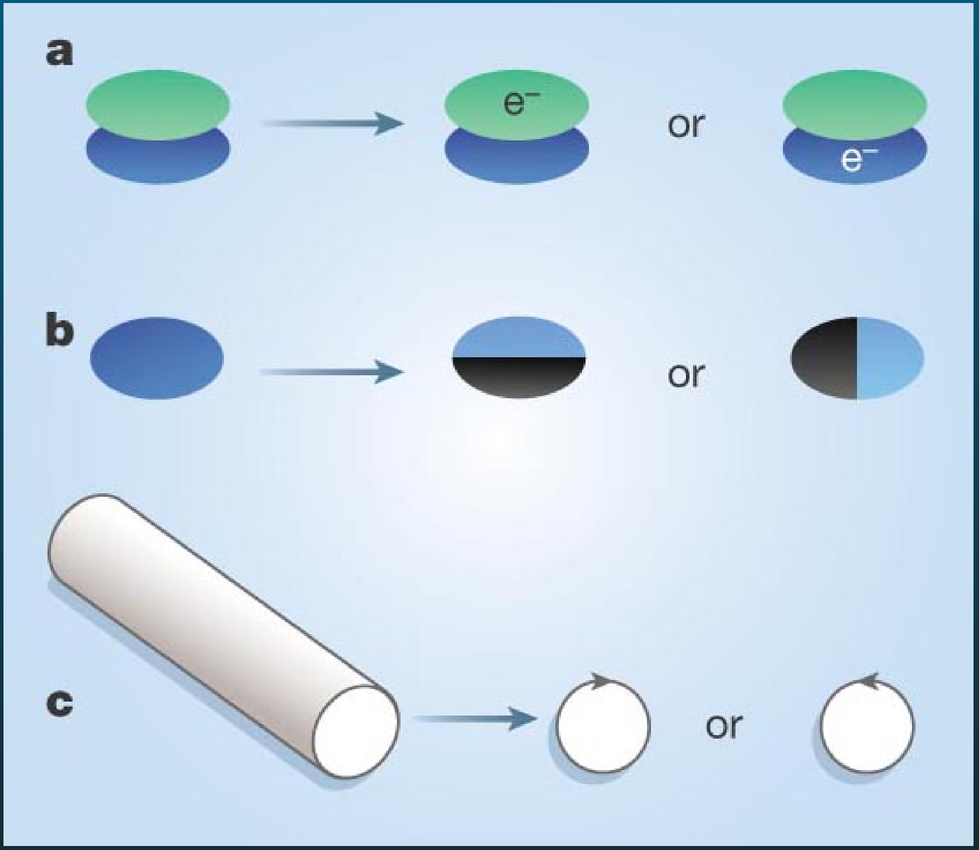
direct evidence of the splitting of the Kondo resonance

probing the effect of dephasing

next: up to now, spin ½ Kondo effect... are there other types of Kondo effect?

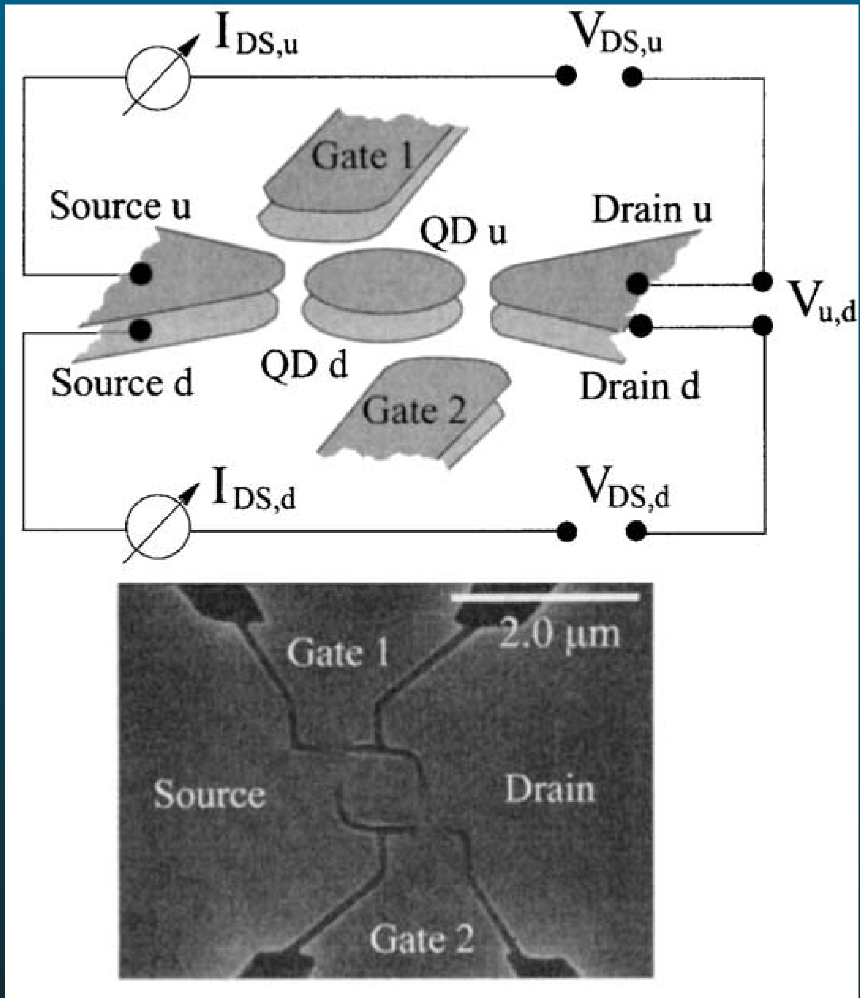
4. “Exotic” Kondo effects

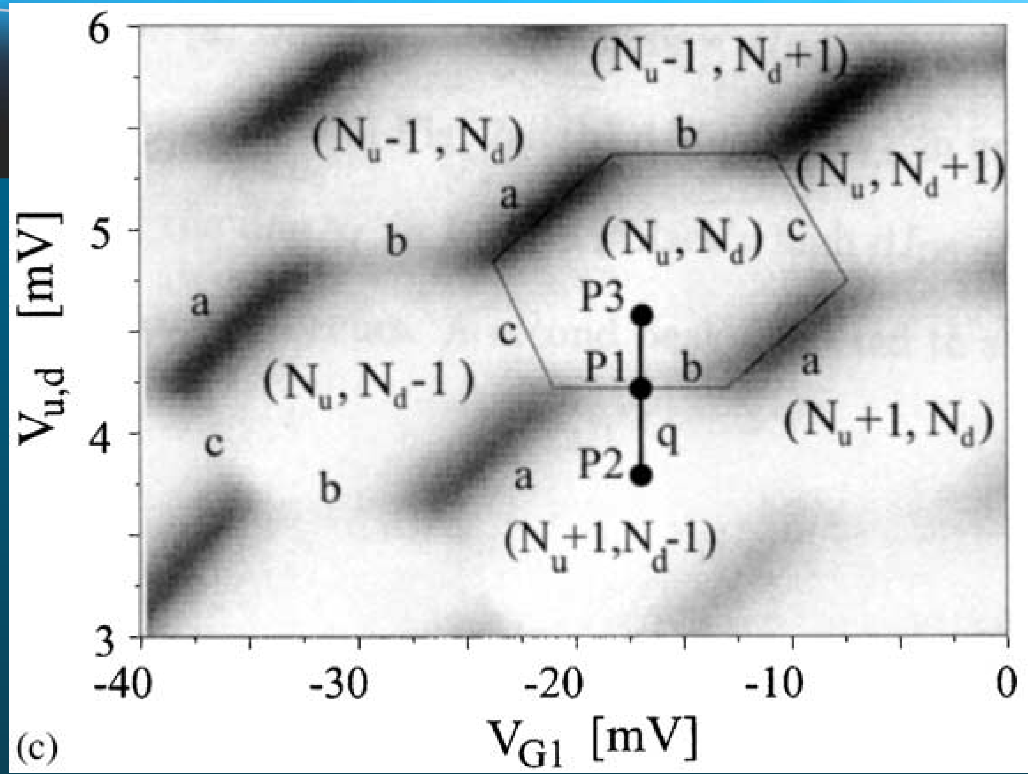
- Requirements for the Kondo effect to occur
  - localized degenerate level
  - electron reservoir with the same quantum number
- In quantum dots, other degeneracies than spin
  a) one-site degeneracy
  b) orbital degeneracy
  c) orbital degeneracy in a carbon nanotube

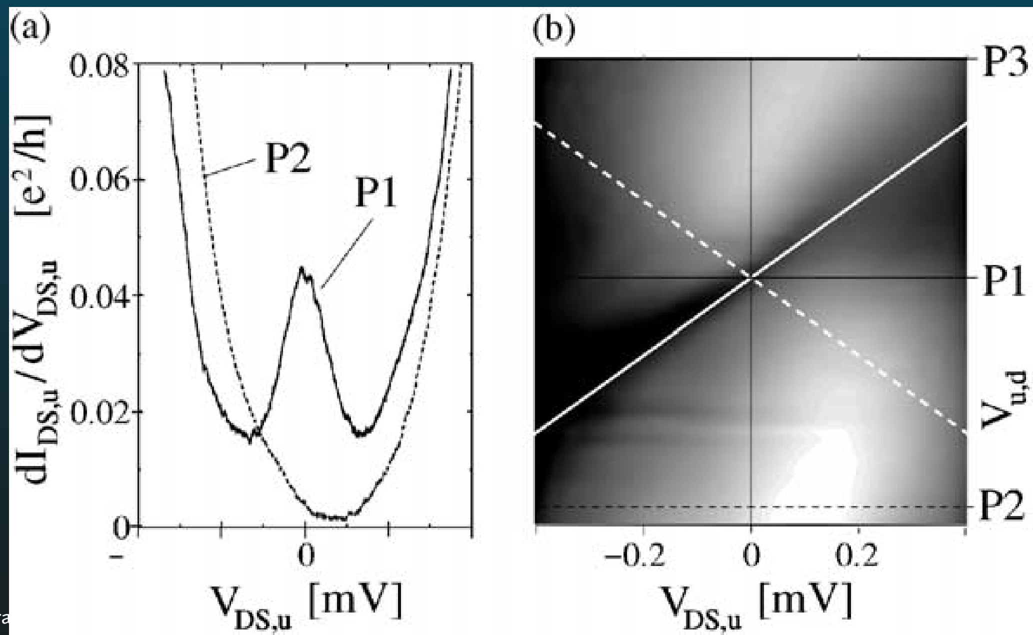


R. M. Potok & D. Goldhaber-Gordon, Nature **434**, 451 (2005)

Orbital Kondo effect in a bilayer system



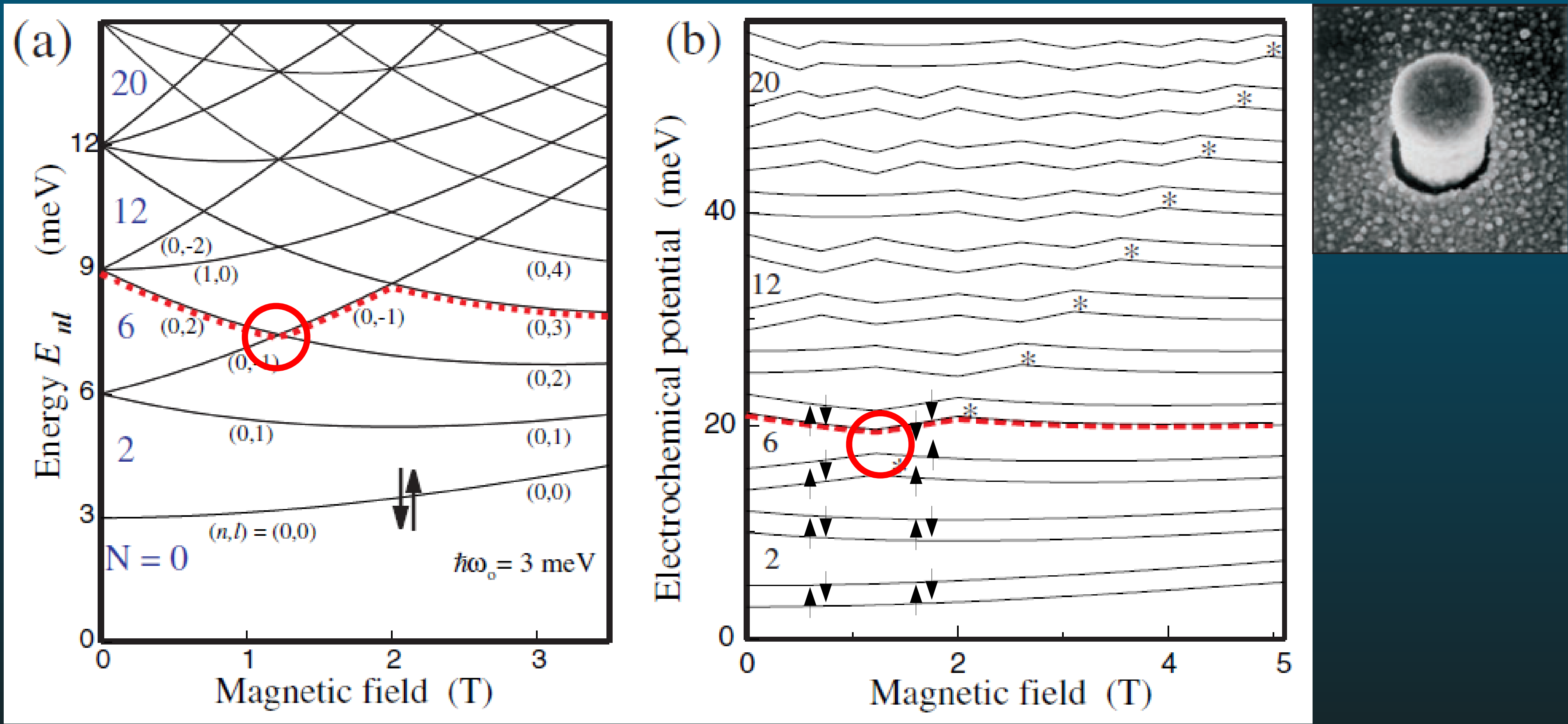




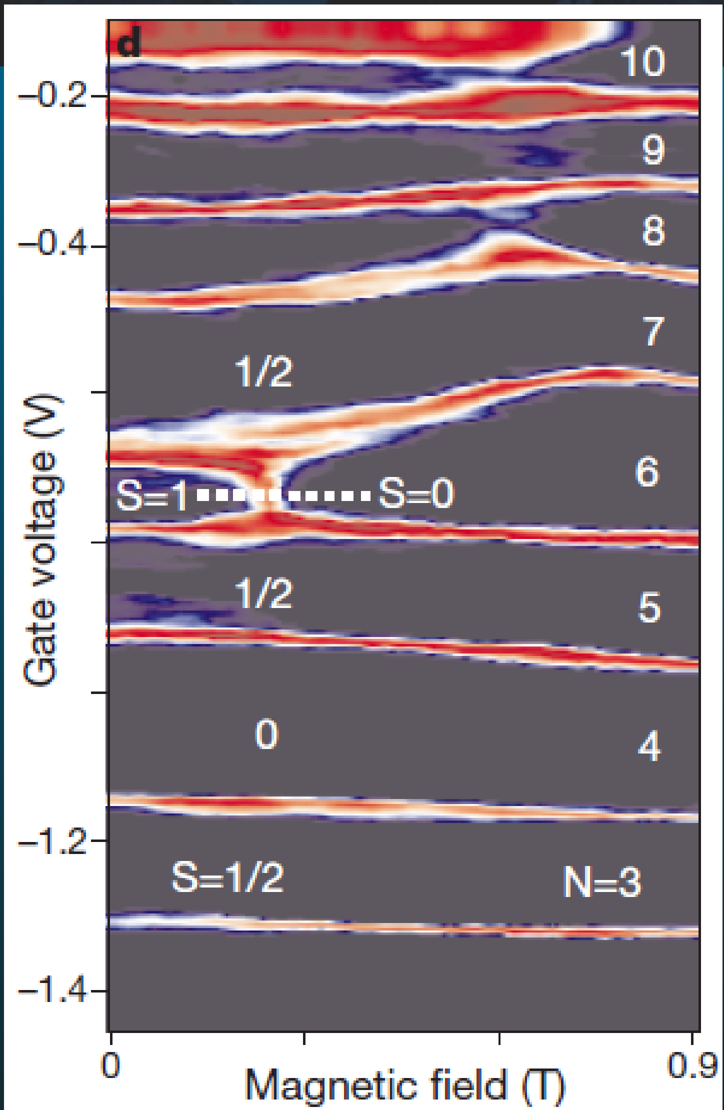
Wilhelm *et al.*, Physica E **14**, 385 (2002)

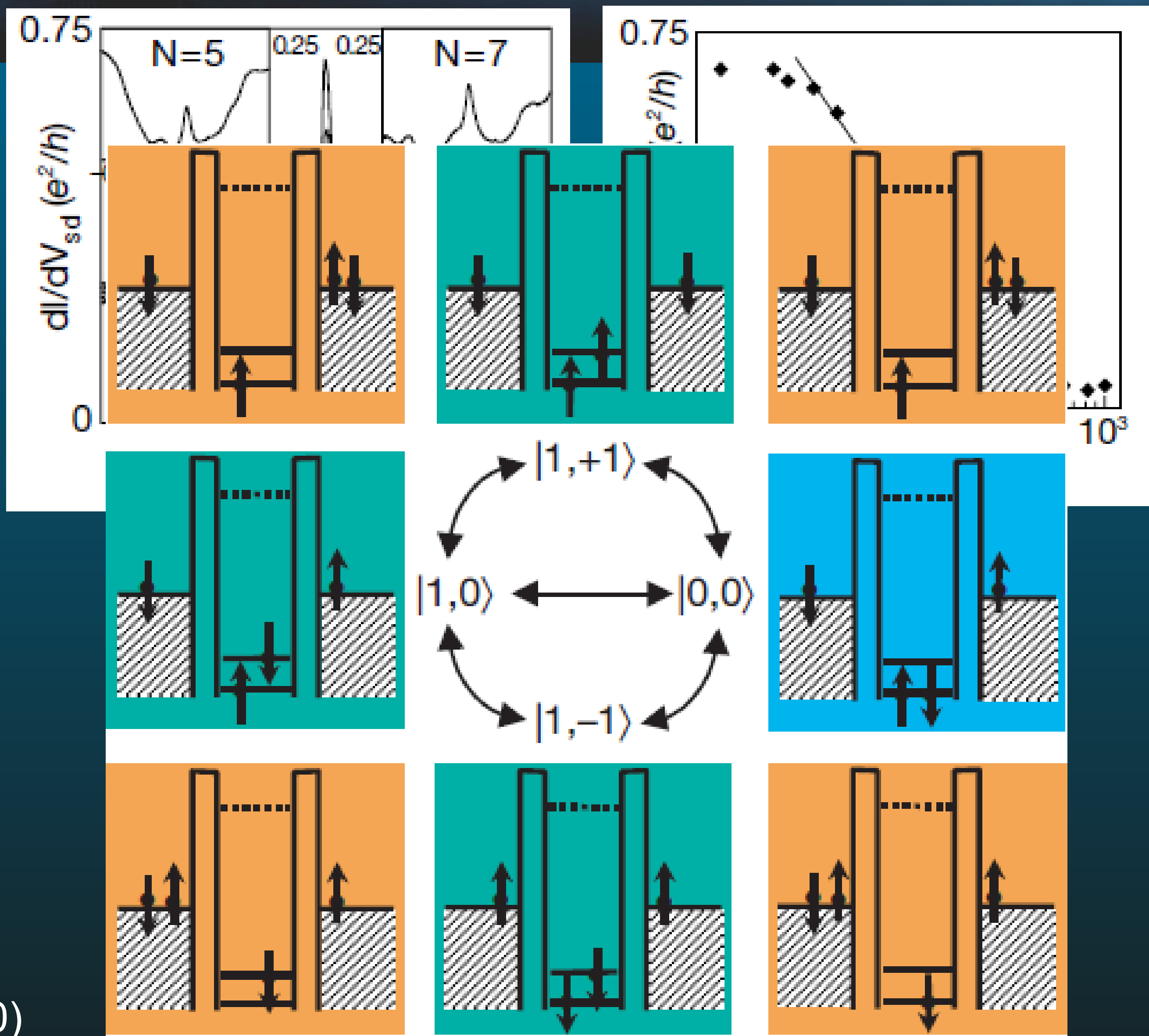
Magnetic-field induced orbital degeneracy

- Magnetic field dependence of orbital energies
  L. P. Kouwenhoven et al., Rep. Prog. Phys. **64**, 701 (2001)



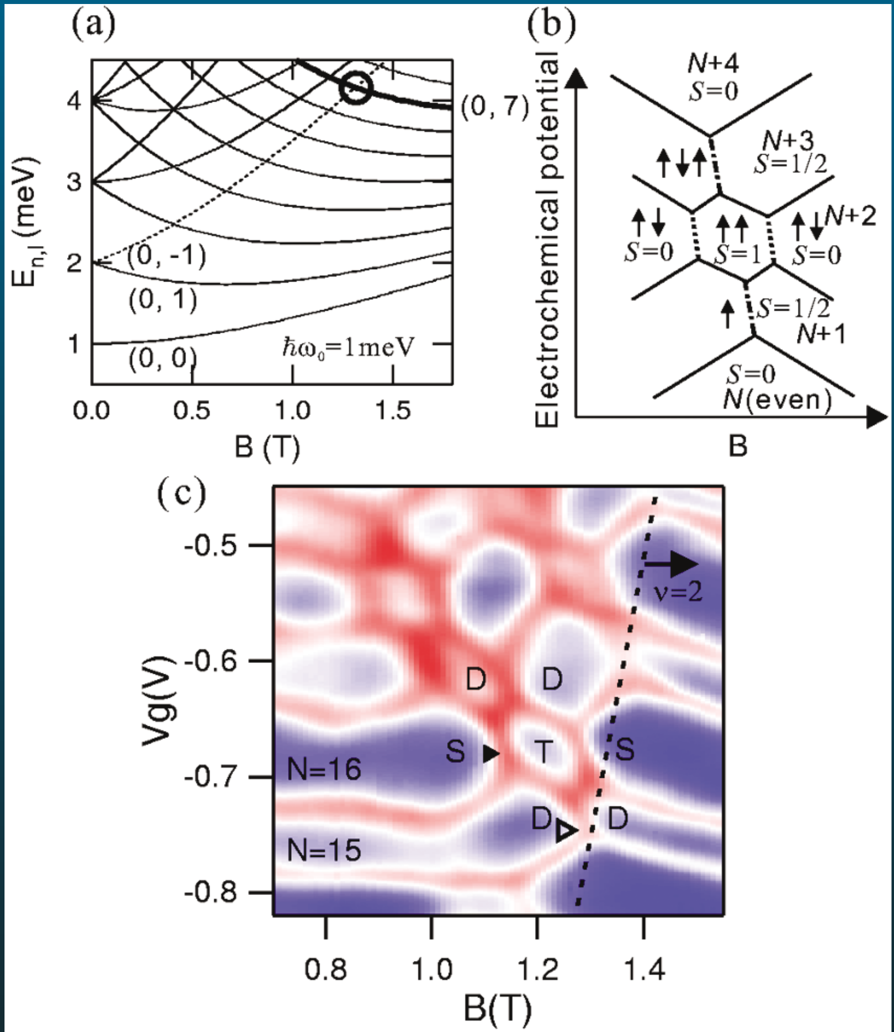
Singlet-triplet Kondo effect



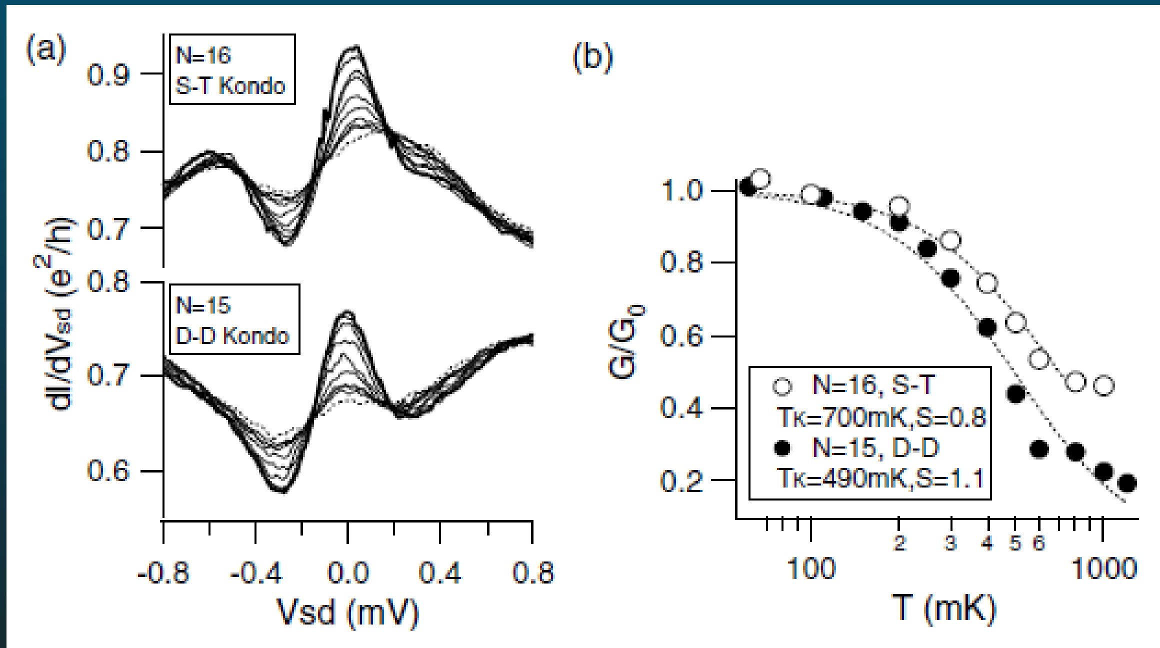


S. Sasaki *et al.*, Nature **405**, 765 (2000)

Orbital Kondo effect



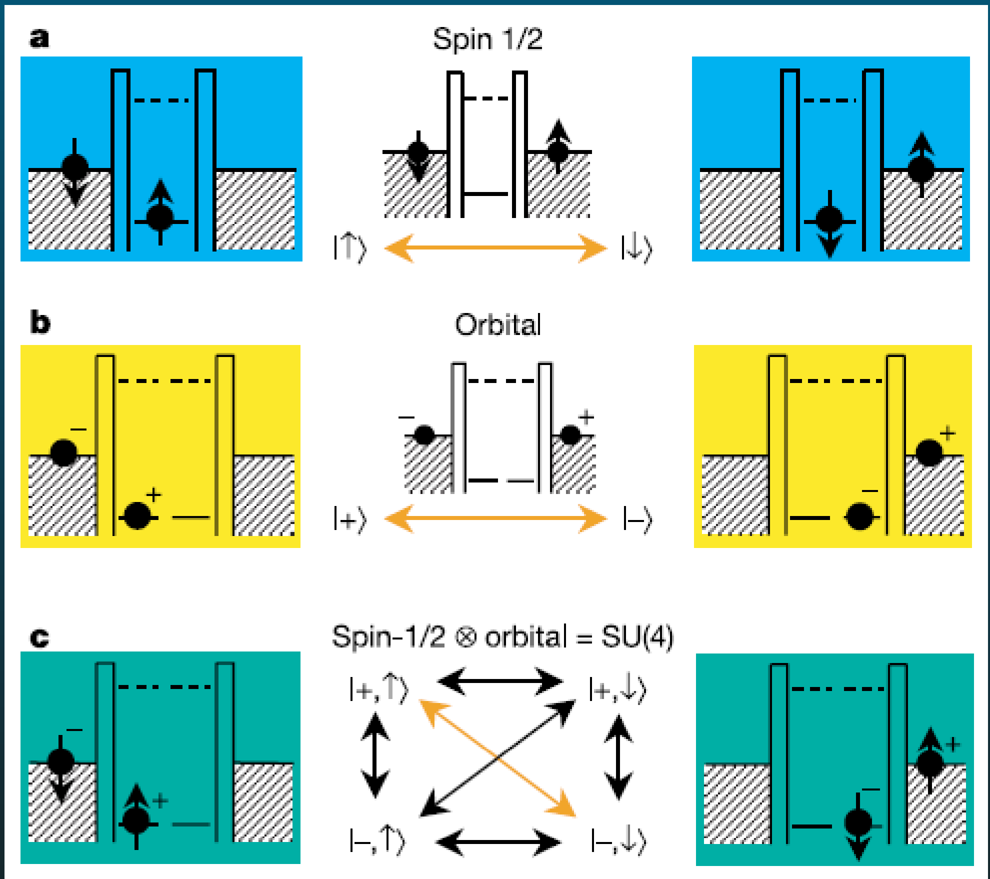
- Doublet-doublet Kondo effect due to orbital degeneracy

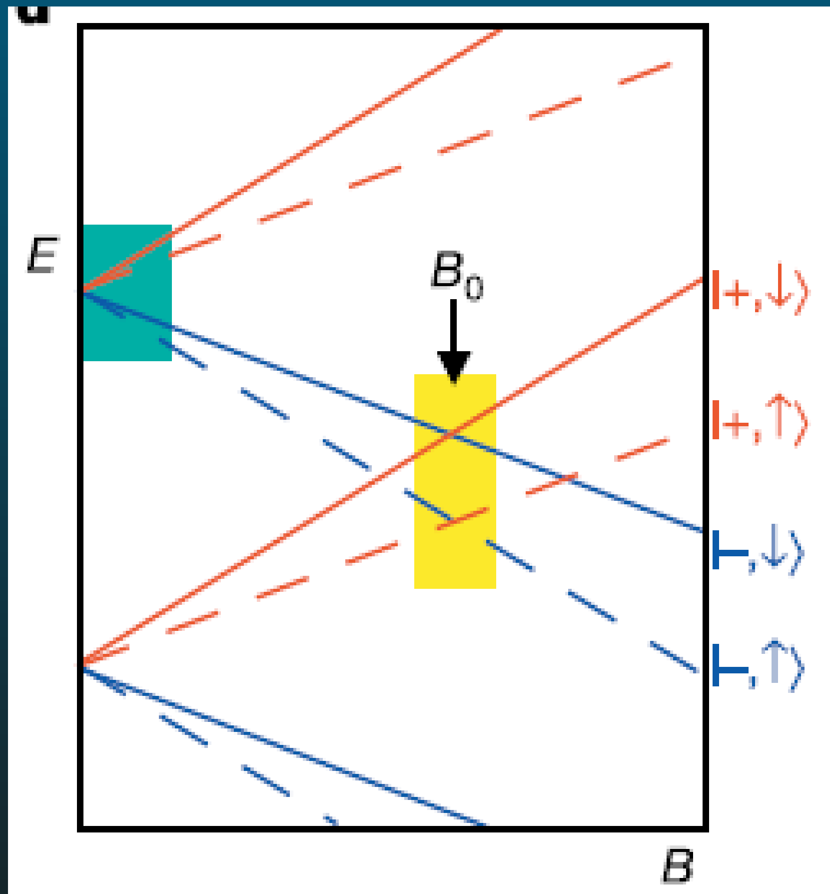


S. Sasaki *et al.*, PRL **93**, 017205 (2004)

SU(4) Kondo effect

- Combine spin and orbital degeneracy in carbon nanotubes   P. Jarillo-Herrero et al., Nature 484, 434 (2005)

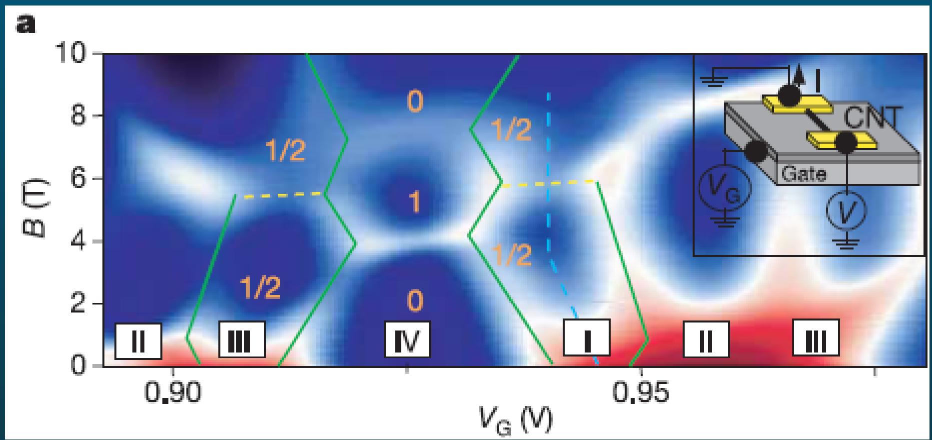


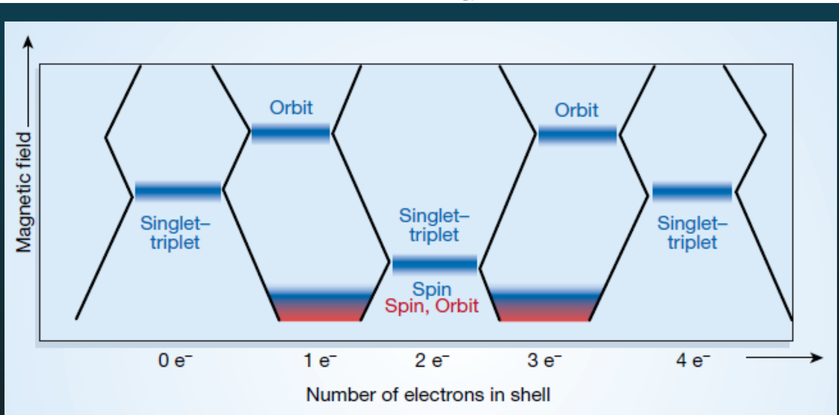


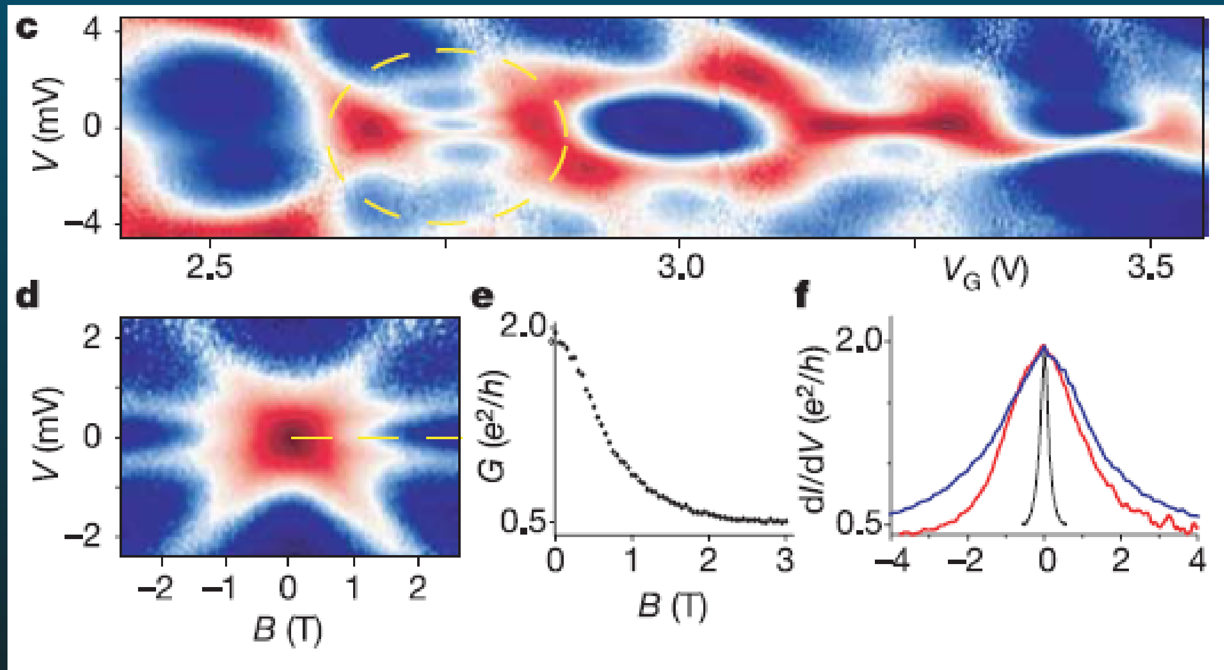
SU(4) Kondo effect

- Combine spin and orbital degeneracy in carbon nanotubes

P. Jarillo-Herrero et al., Nature 484, 434 (2005)







Conclusion – Part II

- Quantum dots for fully tunable Kondo physics
  - from equilibrium to non-equilibrium transport
  - tunable energy and time scales

- Many more experiments already performed
  - superconducting and ferromagnetic contacts
  - Kondo quantum critical point
  - 2-channel Kondo effect

- New ideas for future experiments?

Thanks

Nanophysics group (ETH Zürich)

B. Grbic
S. Gustavsson
A. Pfund

R. Bianchetti
G. Götz
D. Graf
C. Roth
L. Schmid
M. Studer
B. Simovic
R. Schleser
I. Shorubalko
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