What lurks below the last plateau

15+ years of 0.7: What have we learned and where to next?

What
you see…
isn't
always
what
you get.

Lecture 3: The Kondo effect in films, quantum dots… and QPCs?

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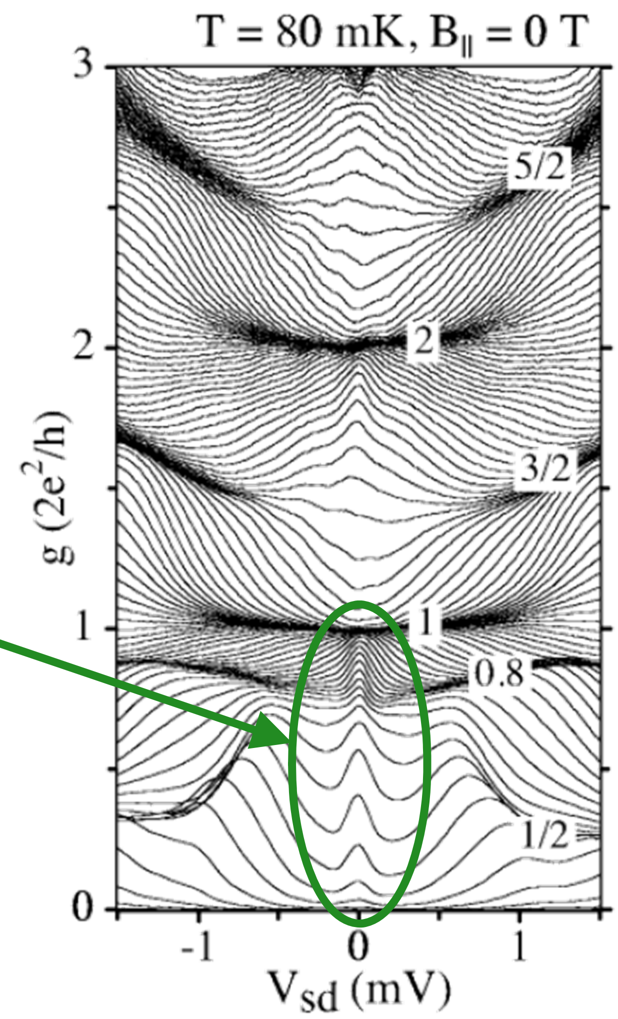
Let's start again with the differential conductance

This peak is called the 'zero bias anomaly'

It was interpreted as a sign of quantum dot Kondo physics within the QPC, possibly linked to the 0.7 anomaly.



S.M. Cronenwett *et al.,* PRL 88, 226805 (2002).

Primer on Kondo Physics

- **A key characteristic of a metal is an decreasing resistivity as *T* is reduced.**

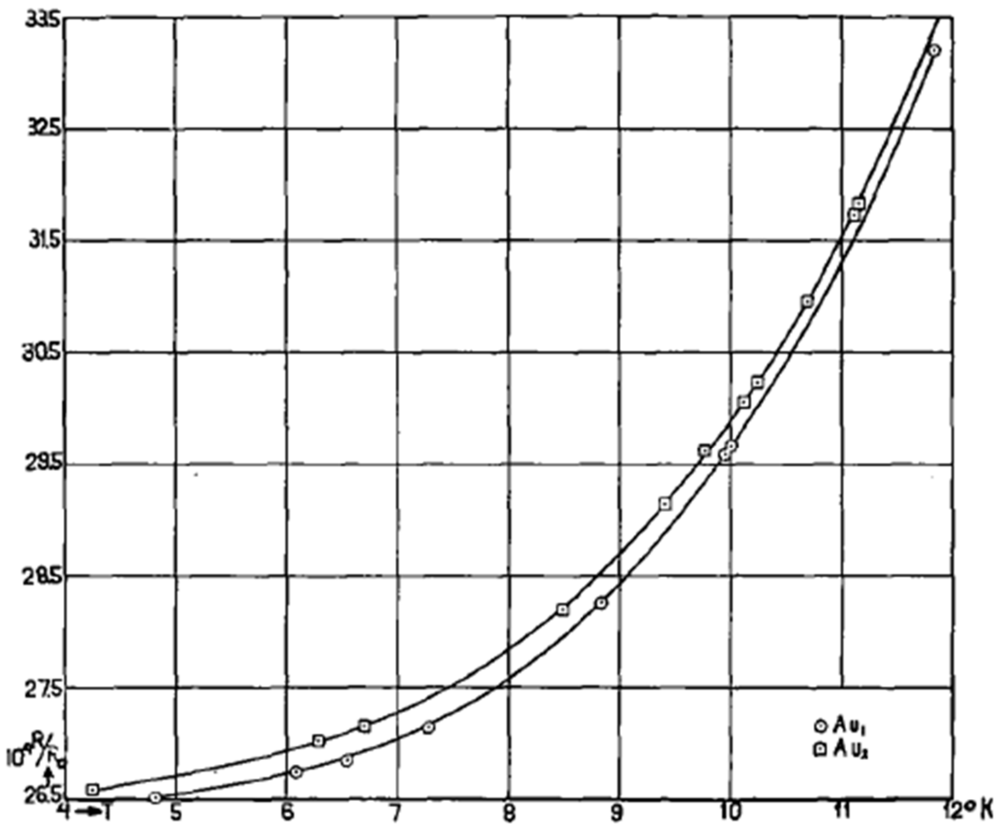
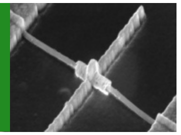


Fig. 2. Resistance of *Au* between 4°K. and 12°K.

W.J. de Haas *et al.*, Physica 1, 1115 (1934).



Primer on Kondo Physics

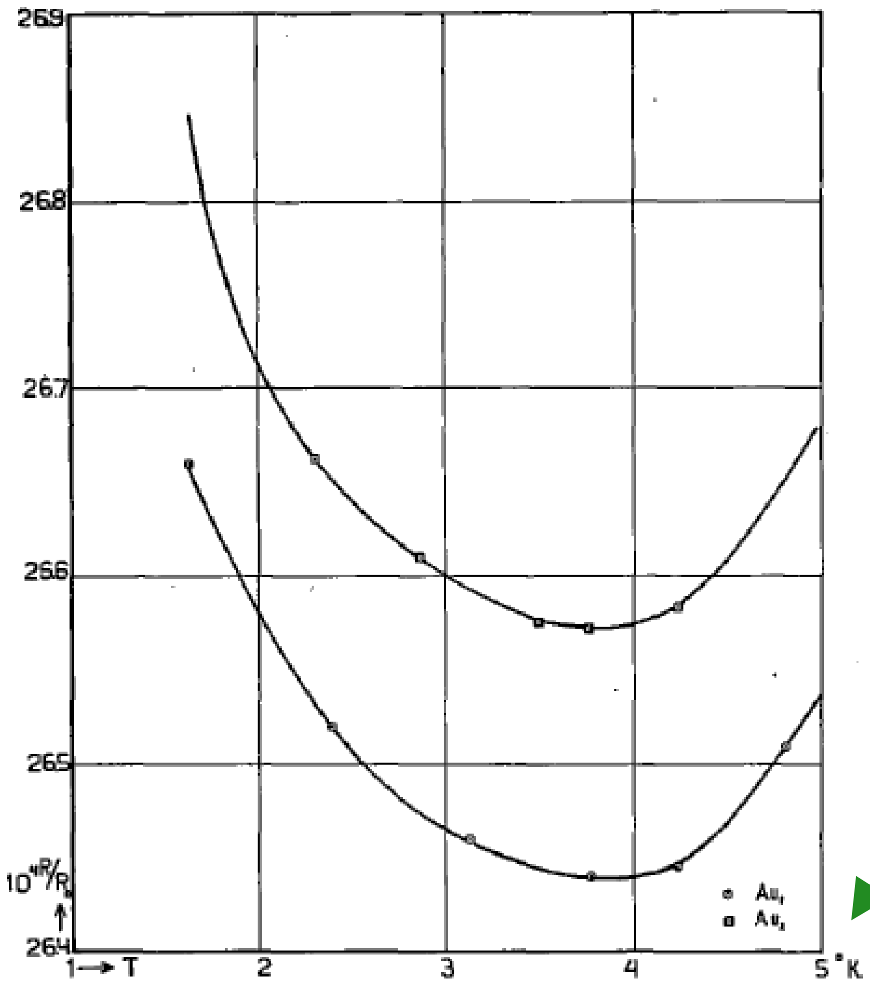


Fig. 1. Resistance of *Au* between 1°K. and 5°K.

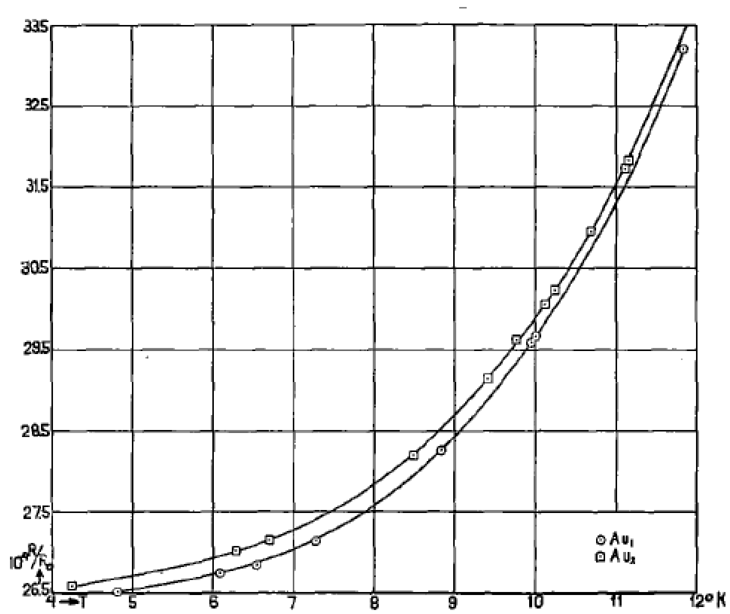


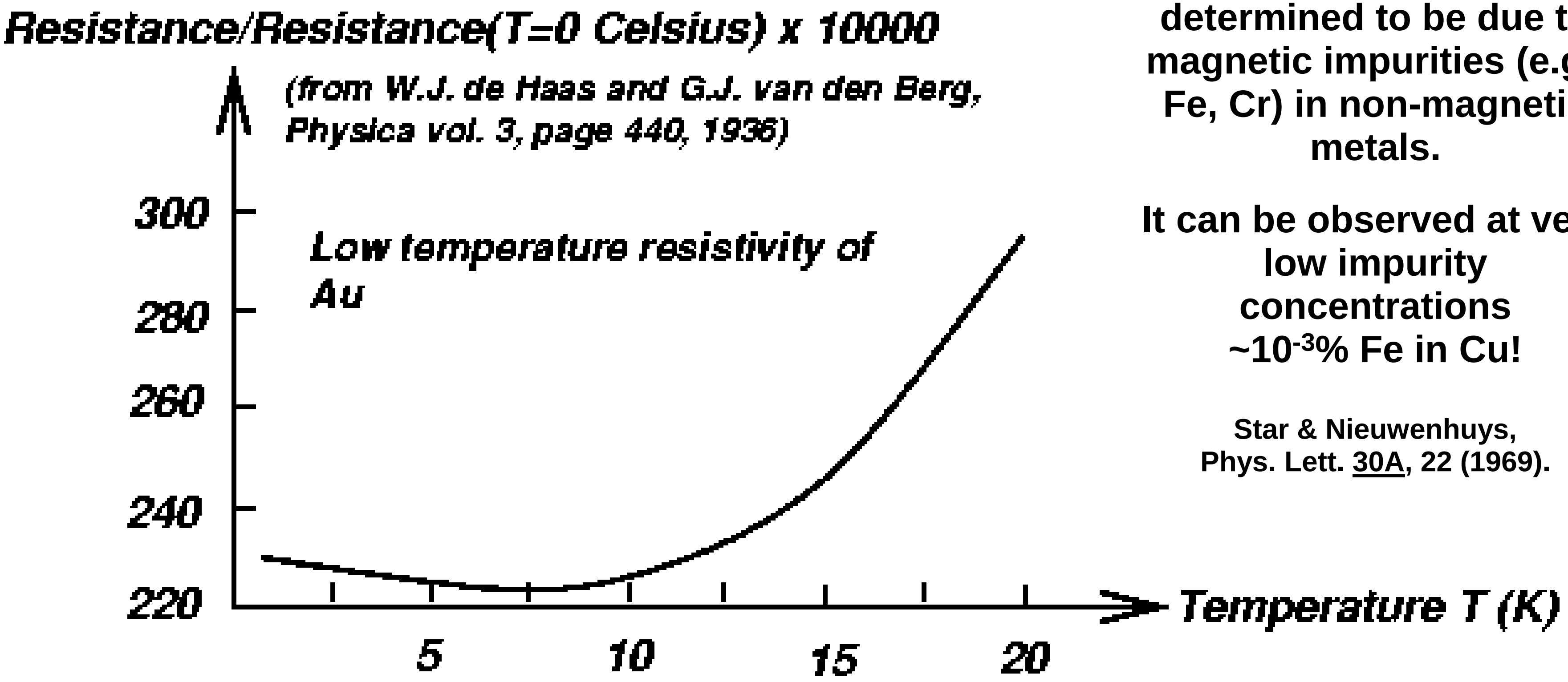
Fig. 2. Resistance of *Au* between 4°K. and 12°K.

But at low enough *T*, the resistance starts to rise again. This was a mystery for many years.

W.J. de Haas *et al.,* Physica 1, 1115 (1934).

Primer on Kondo Physics

- **Just to make sure I'm not being deceptive, let's plot on one graph. It's not a very large upturn in reality.**

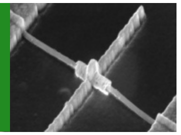


Wikipedia: Kondo Physics

The effect was eventually determined to be due to magnetic impurities (e.g., Fe, Cr) in non-magnetic metals.

It can be observed at very low impurity concentrations ~10^{-3}% Fe in Cu!

Star & Nieuwenhuys, Phys. Lett. 30A, 22 (1969).



Primer on Kondo Physics

- **The resistance minimum was first explained by Jun Kondo in 1964 as an effect arising from s.d exchange interaction between the localized spins of magnetic impurities and the conduction electrons.**

See: J. Kondo, Prog. Theor. Phys. 28, 846 (1962); Prog. Theor. Phys. 32, 37 (1964).

- **The Kondo effect is an important many-body problem, the electrons cannot be treated independently.**

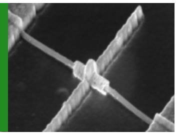
To see why, imagine two spin-up electrons attempting to undergo spin-flip scattering with a spin-down impurity. The first electron interacts with the impurity, becoming spin-down and making the impurity spin-up. The second electron now can't undergo spin-flip scattering with the impurity as both the electron and the impurity have spin-up.

$\Rightarrow$Scattering of electron 2 is influenced by spin of electron 1 (and all others).

$\Rightarrow$No independent treatment possible.

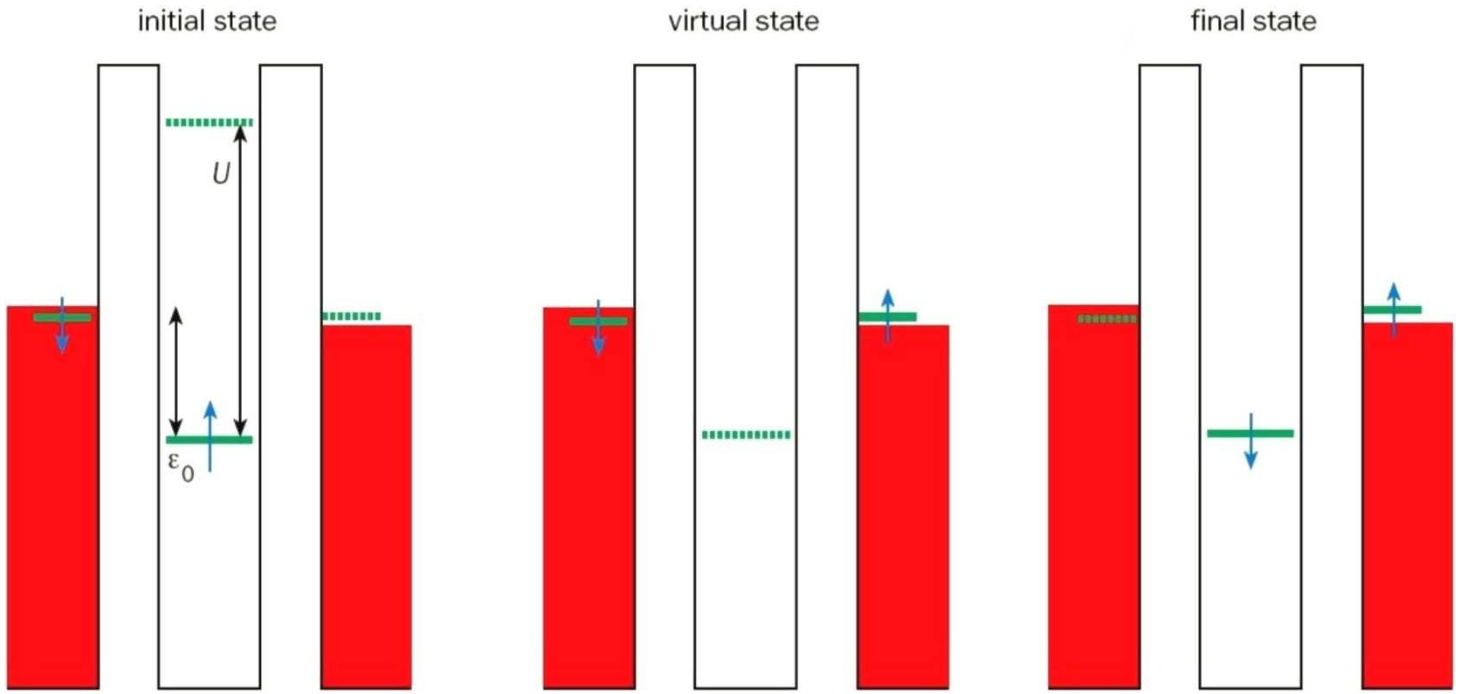
- **Ultimately the electron's local to the impurity cooperate to screen the localized spin from the rest of the electron sea at temperatures below the 'Kondo temperature' T_K.**

See: K.G. Wilson, Rev. Mod. Phys. 47, 773 (1975).



Anderson model of a magnetic impurity

- **This simple model for a magnetic impurity has a single electron level with energy ε_0. The electron can tunnel off the impurity provided the level sits above the Fermi energy E_F, otherwise the electron is trapped, giving the impurity a fixed spin $\pm$½.**

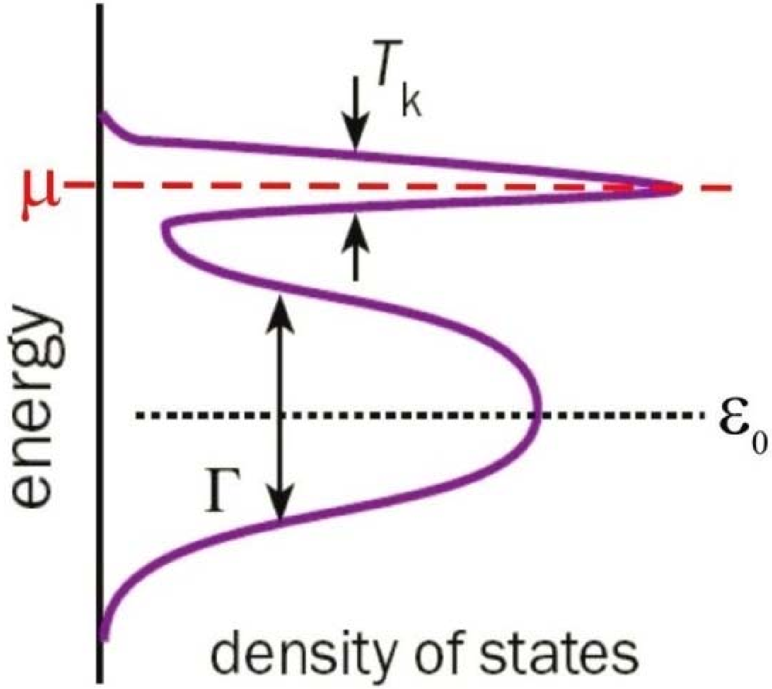


- **Since ε_0 is 1-10 meV below E_F, the process above can only occur via a virtual state if it is complete within a timescale $h/|\varepsilon_0|$, leading to a flip of the spin on the impurity.**

See: P.W. Anderson, Phys. Rev. 124, 41 (1961); Kouwenhoven & Glazman, Physics World 14(1), 33 (2001).

The Kondo density of states peak

- **The Kondo state leads to an additional peak in the density of states centered at the Fermi energy (i.e., the chemical potential μ).**



- **The Kondo peak is always centered at μ, irrespective of ε_0, hence the Kondo state is usually referred to as always 'on resonance'.**

Kouwenhoven & Glazman, Physics World <u>14(1)</u>, 33 (2001).

The Kondo temperature

- The Kondo temperature T_K is related to the parameters of the Anderson model, it is given by:

$$T_K = \tfrac{1}{2}(\Gamma U)^{1/2} \exp[\pi\varepsilon_0(\varepsilon_0 + U)/\Gamma U]$$

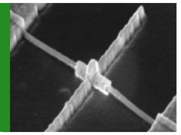
where Γ is the width of the impurity level and U is the Coulomb repulsion energy between two electrons sitting on the impurity. The broadening of the impurity level comes about due to electrons tunneling to/from it.

- Due to the exponential dependence above, the Kondo temperature can vary from as low as 1 K to around 100 K.

- In metals, the resistance ratio R/R_0 depends only on the ratio T/T_K, where R_0 is the resistance at absolute zero, irrespective of the nature of the system. In other words, $R/R_0 = f(T/T_K)$.

- The Kondo temperature T_K is a single parameter that can be used instead of U, Γ and ε_0 to characterize the system.

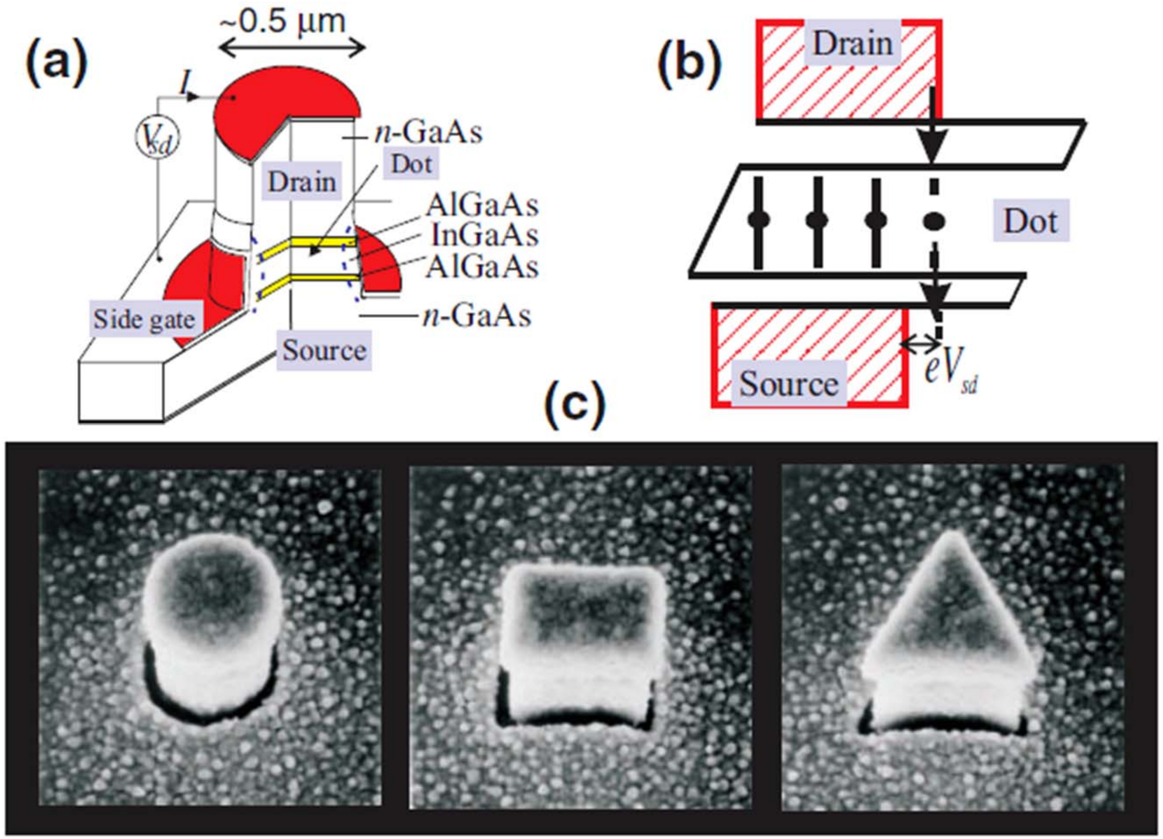
F.D.M. Haldane, PRL 40, 416 (1978).



Enough metals, what’s this got to do with QPCs?

Quantum dots as atoms

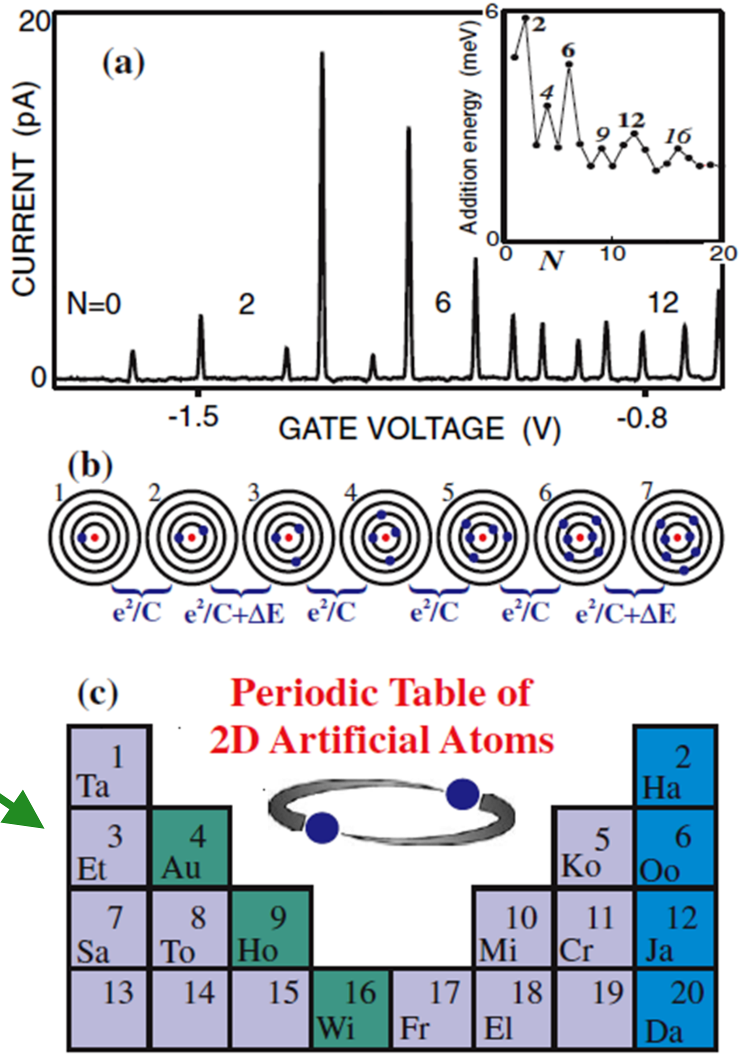
- **Around the mid 90s it became possible to make 'few electron' quantum dots; dots sufficiently small and with precise enough control to count down to the last electron.**



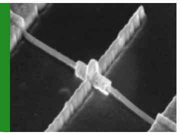
L.P. Kouwenhoven *et al.*, Rep. Prog. Phys. 64, 701 (2001).

Quantum dots as atoms

Can essentially make a 'magnetic impurity atom' using ultra-small quantum dots.

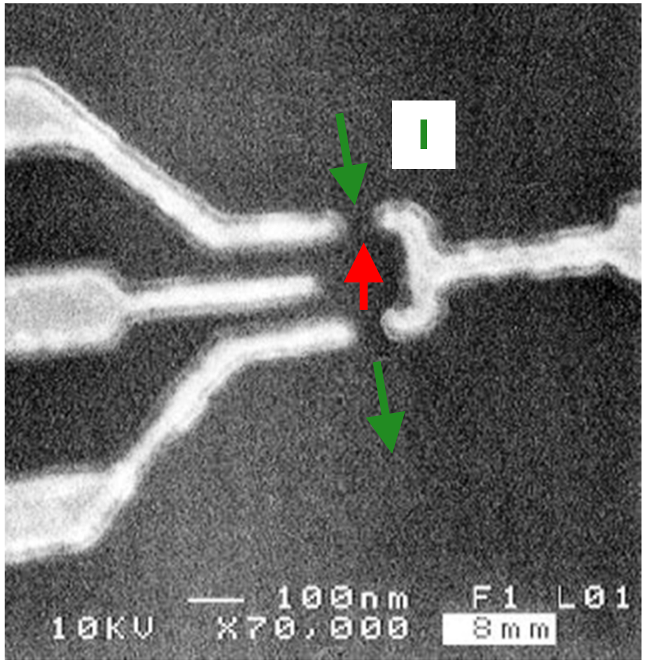


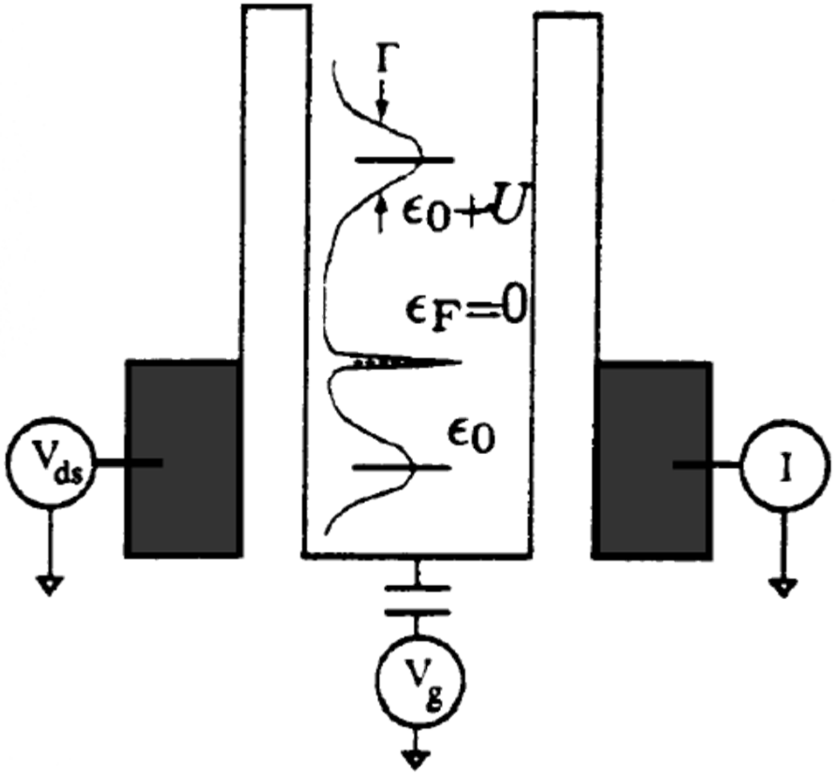
L.P. Kouwenhoven *et al.*, Rep. Prog. Phys. 64, 701 (2001).



The quantum dot Kondo effect

- Can build an analog of the Kondo scenario in metals. A localized spin surrounded by a sea of electrons. Note that there is a difference – here the electrons must go <u>through</u> the impurity to contribute to the current.

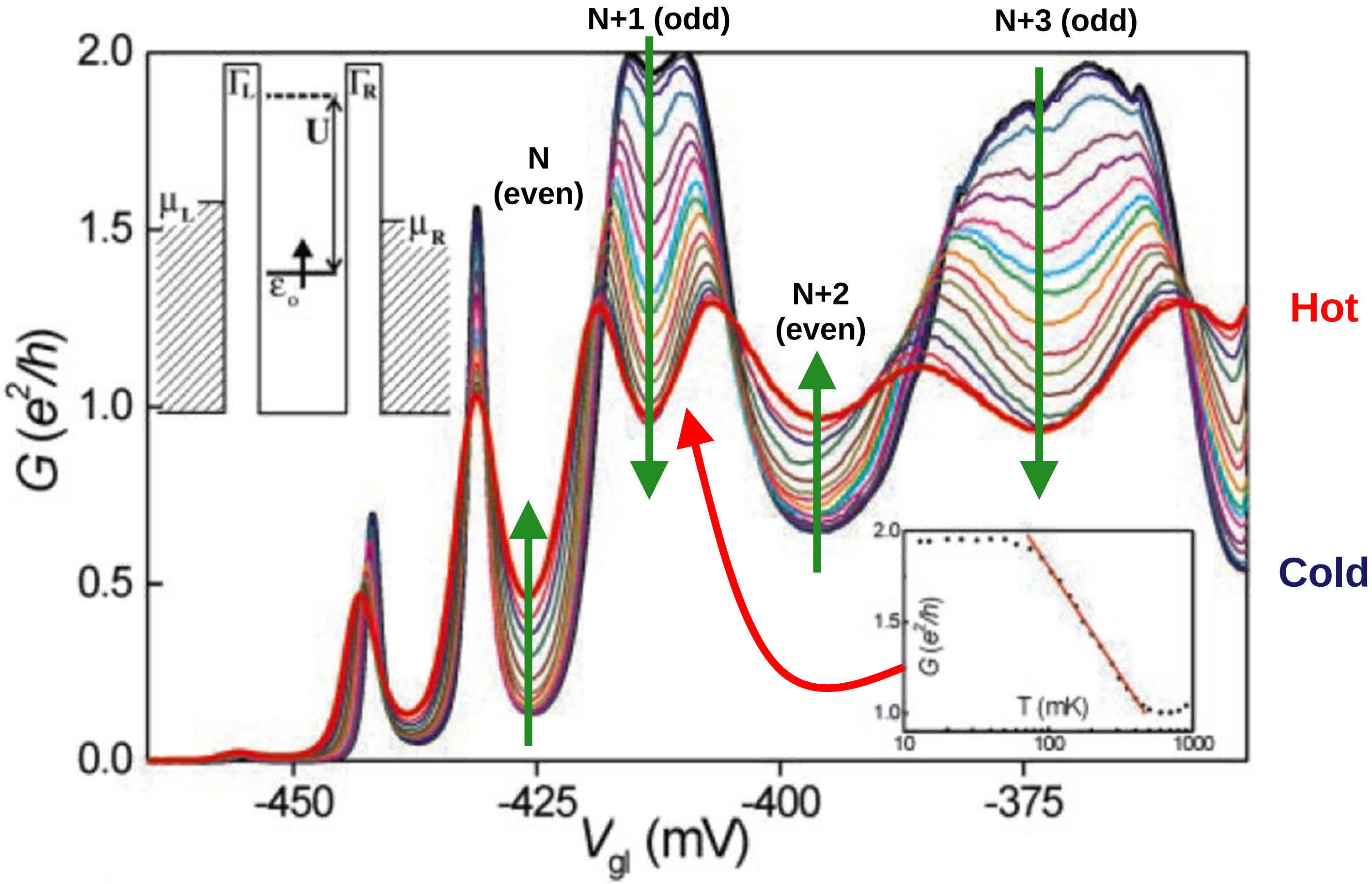




D. Goldhaber-Gordon *et al.*, Nature <u>391</u>, 156 (1998); PRL <u>81</u>, 5225 (1998).

The quantum dot Kondo effect

- **The first key observation is an odd-even temperature dependence in the Coulomb-Blockade oscillations on the dot.**



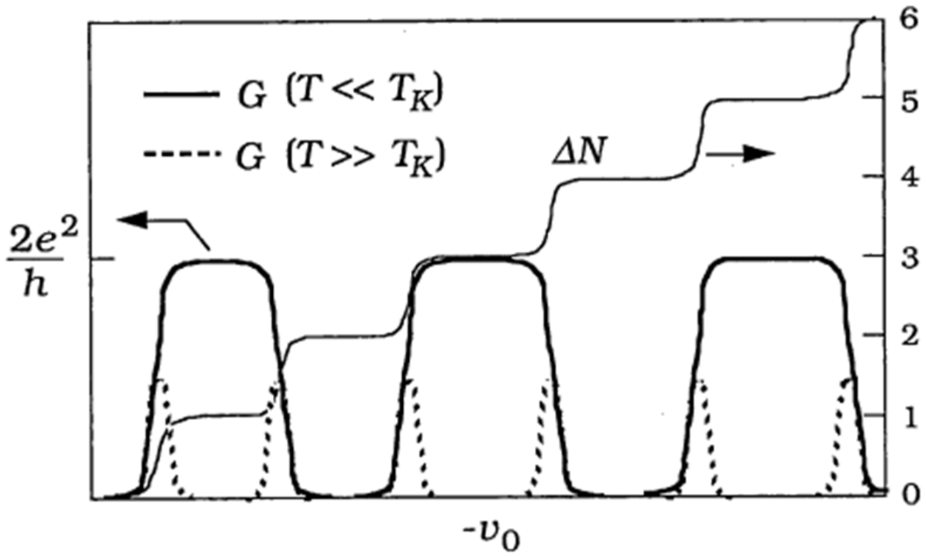
W.G. van der Wiel *et al.*, Science 289, 2105 (2000).

The unitary limit

- **Screening of local spin creates single, extended many-body system throughout the device with a single well-defined Fermi surface.**
- **The quasiparticles at this Fermi surface no longer experience the repulsive barrier potentials defining the dot or the Coulomb repulsion from electrons on the dot.**

⇒ Kondo correlated state drives the dot towards perfect transmission.

Very different to metals, where the Kondo process increases the resistance.

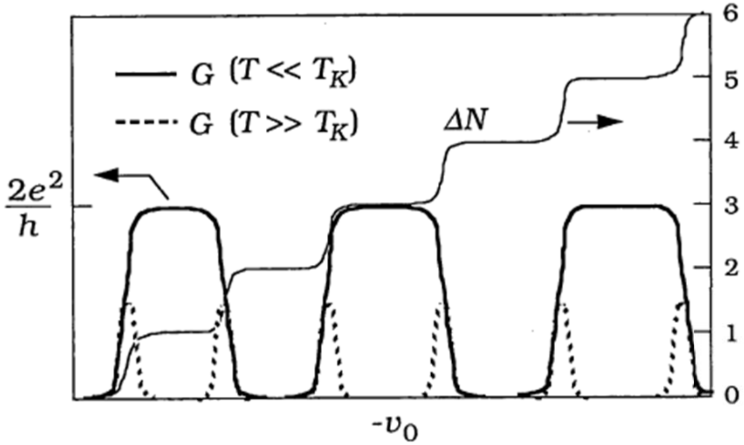


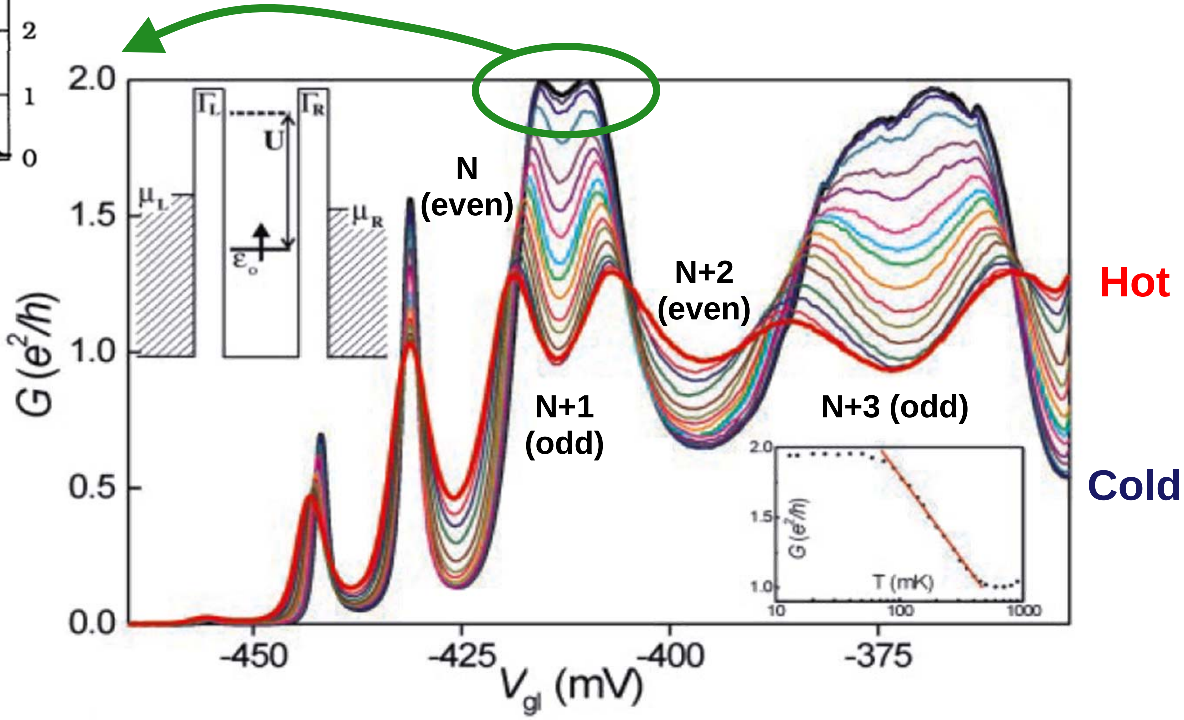
"In conclusion, we predict that in a quasi one-dimensional system the conductance through a quantum dot is close to $2e^2/h$ if a localized moment exists in the dot and the temperature is smaller than the Kondo temperature. This also holds true for in two- or three-dimensional systems if the effective numbers of the channels is one and the system is essentially one-dimensional."

A. Kawabata, J. Phys. Soc. Jpn <u>60</u>, 3222 (1991); T.K. Ng & P.A. Lee, PRL <u>61</u>, 1768 (1988).

The unitary limit

⇒ **Kondo correlated state drives the dot towards perfect transmission.**

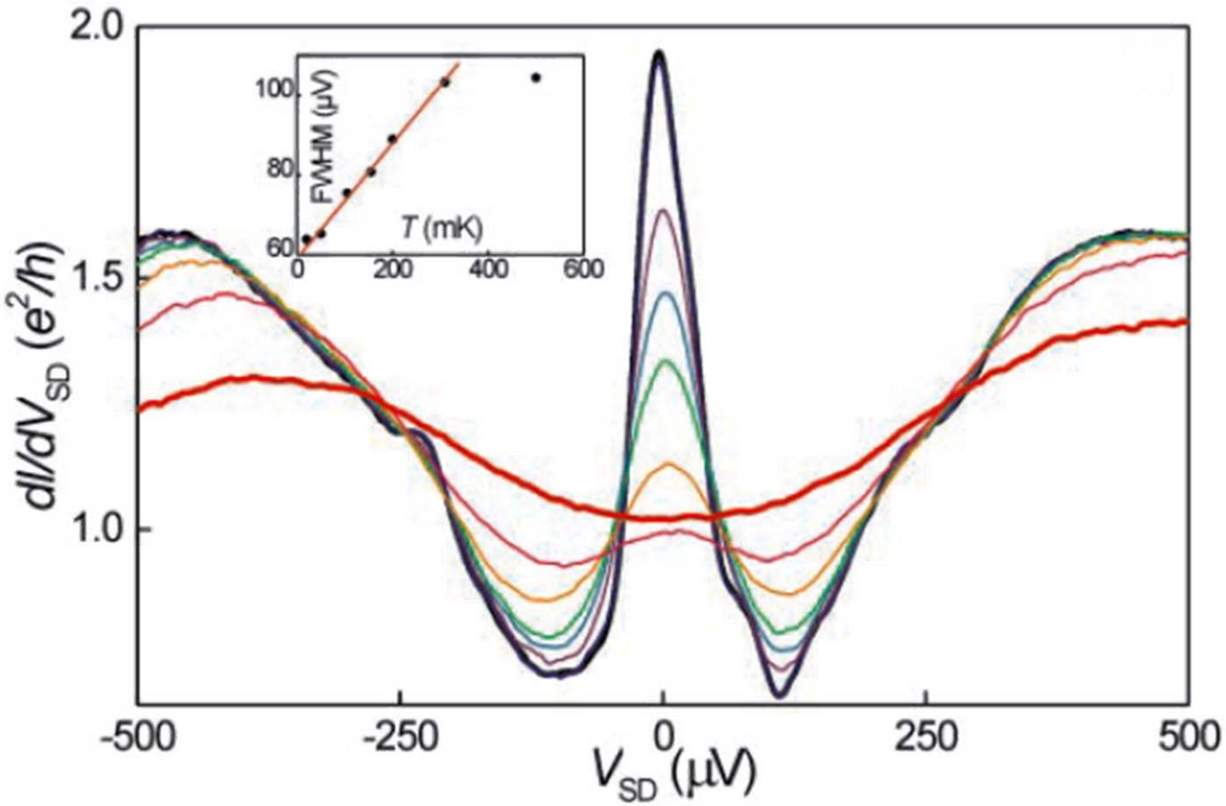




W.G. van der Wiel *et al.*, Science 289, 2105 (2000).

The quantum dot Kondo effect

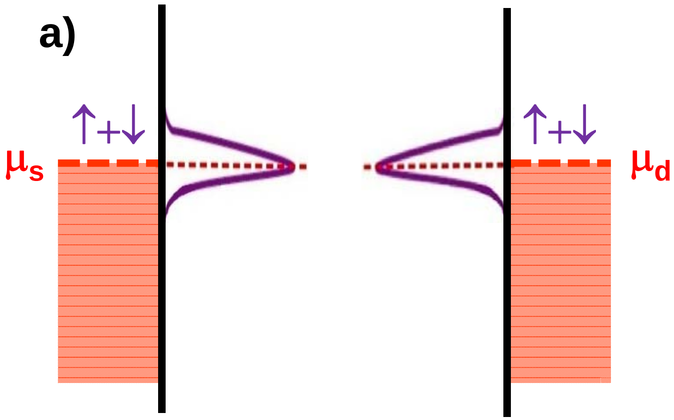
- **The second key observation is a peak at zero bias in the differential conductance $g = dI/dV_{sd}$ as a function of source-drain bias V_{sd}.**

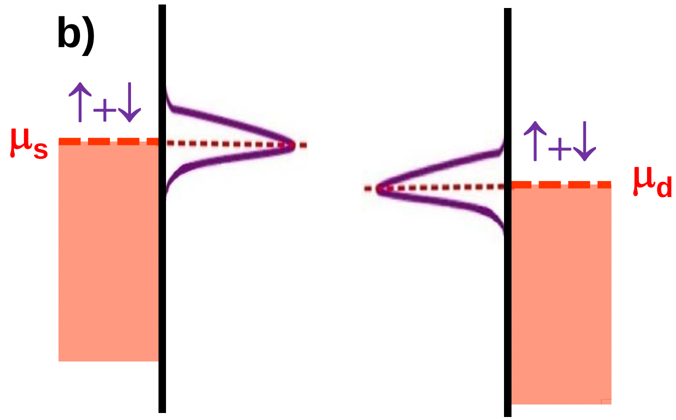


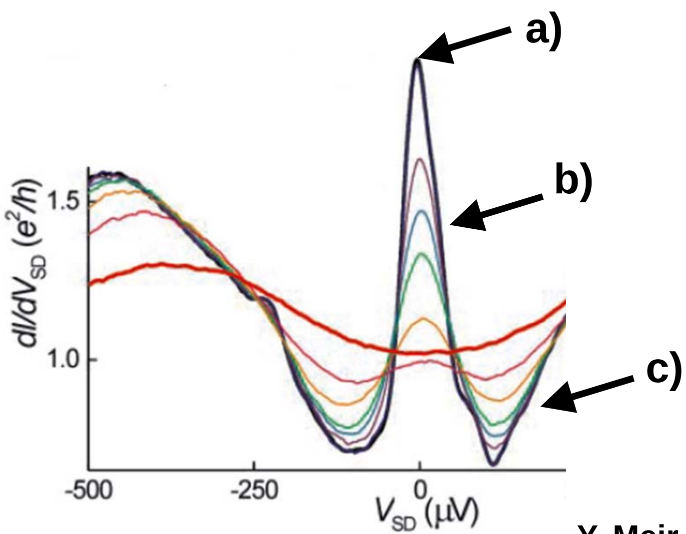
W.G. van der Wiel *et al.*, Science <u>289</u>, 2105 (2000).

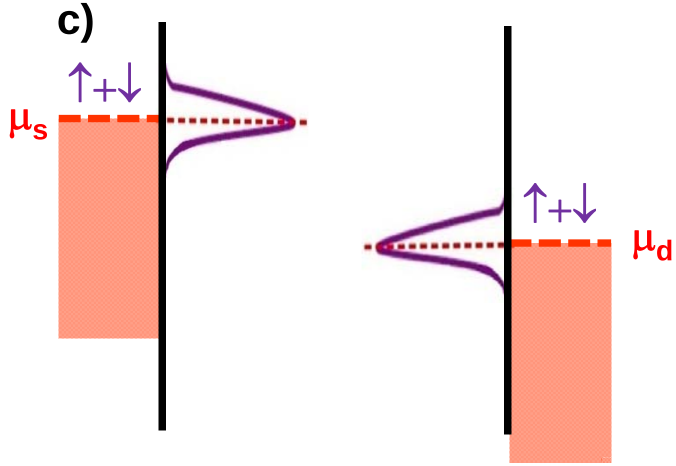
Why a zero bias peak?

- **There are two independent electron seas here, one on either side of the localised spin. There will be a Kondo peak in the density of states associated with each of them.**

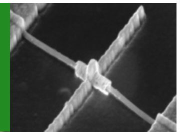






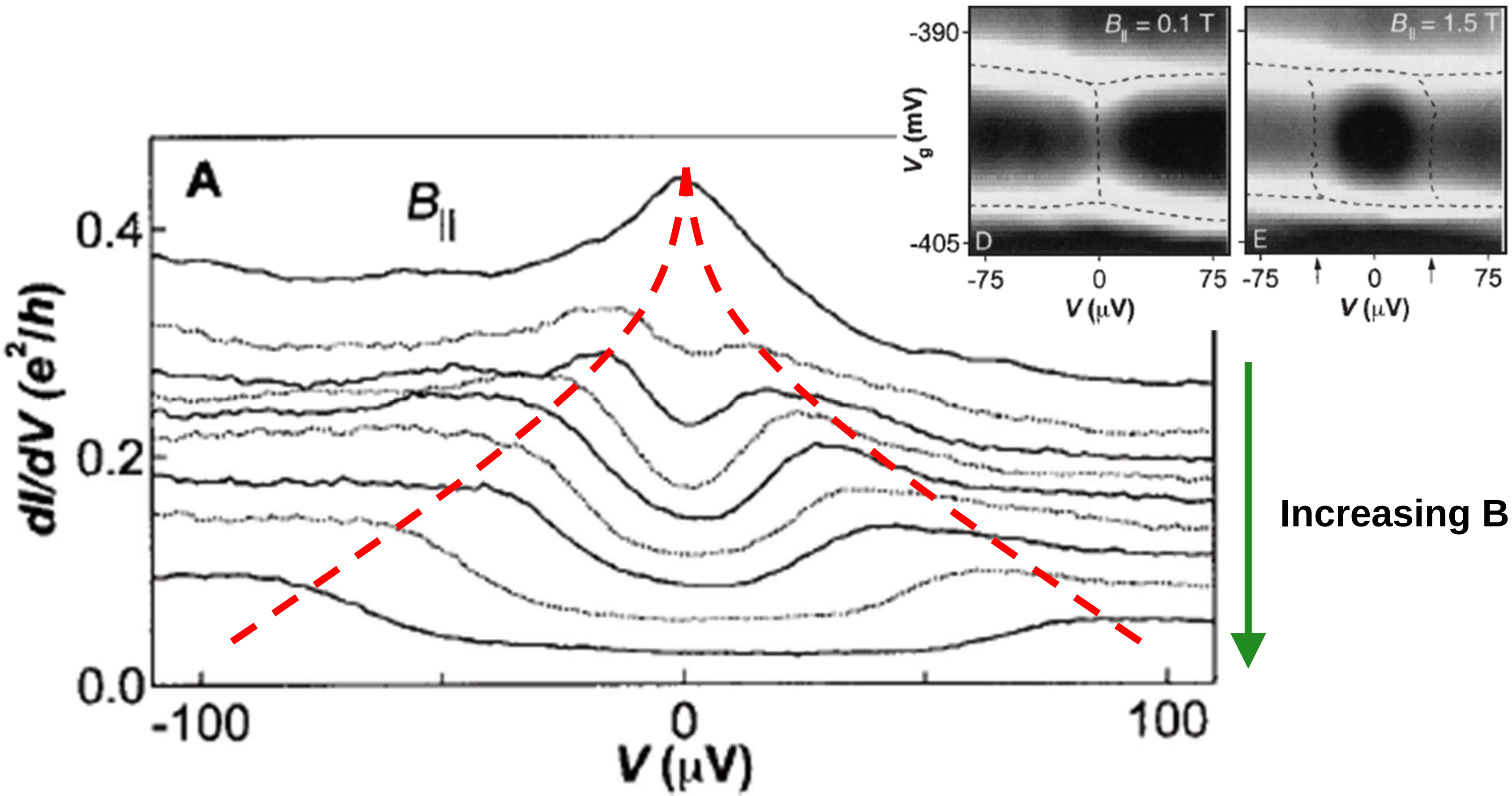


Y. Meir *et al.*, PRL 70, 2601 (1993).

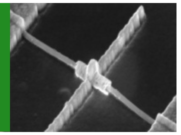


The quantum dot Kondo effect

- **The third key observation is that the zero bias peak in g vs V_{sd} splits with magnetic field.**

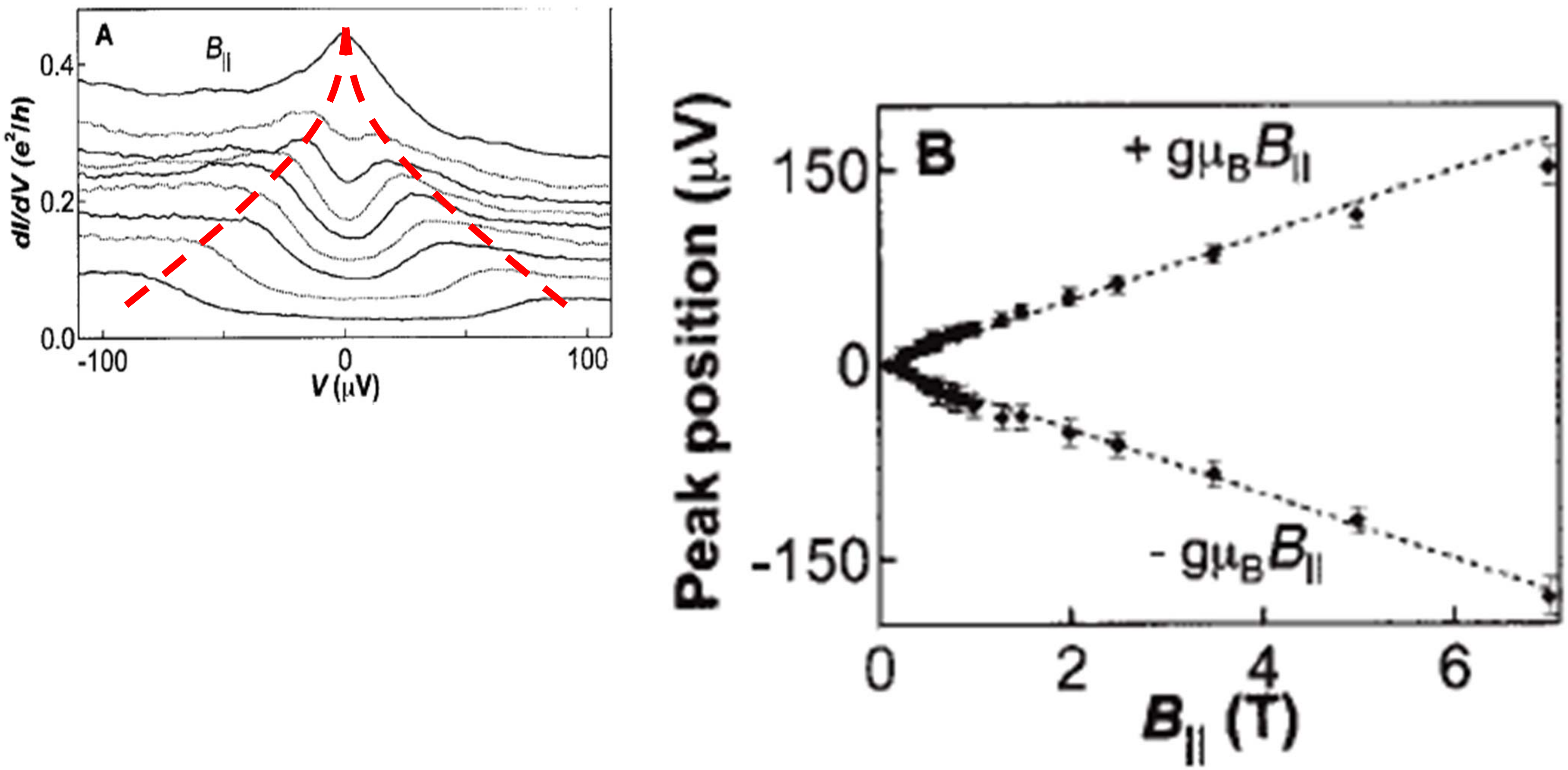


S.M. Cronenwett *et al.*, Science <u>281</u>, 540 (1998).



The quantum dot Kondo effect

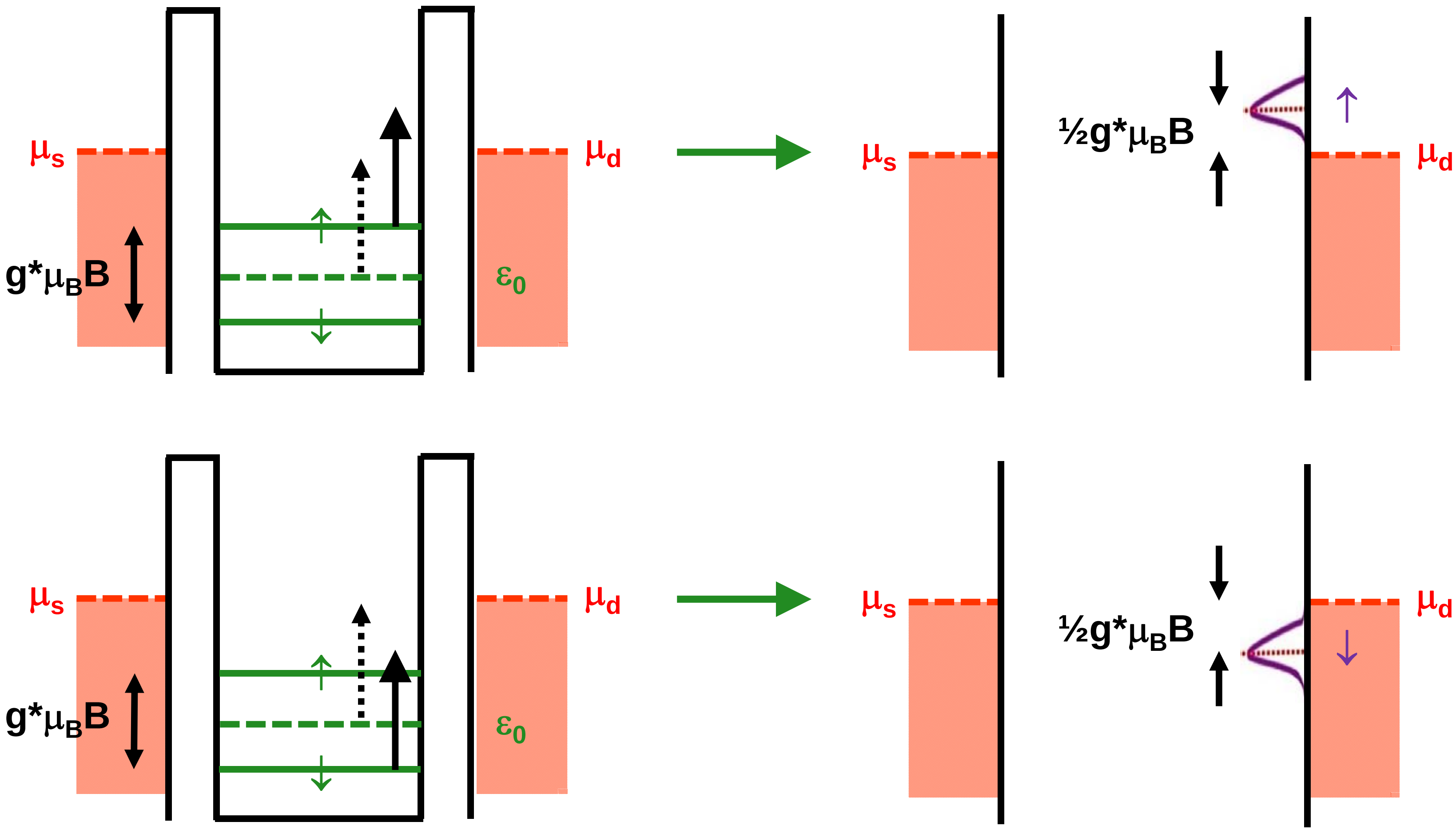
- **This field splitting is very particular, as it goes as $2g^*\mu_B B$ rather than $g^*\mu_B B$.**



S.M. Cronenwett *et al.*, Science 281, 540 (1998).

Why is the peak splitting $2g^*\mu_B B$?

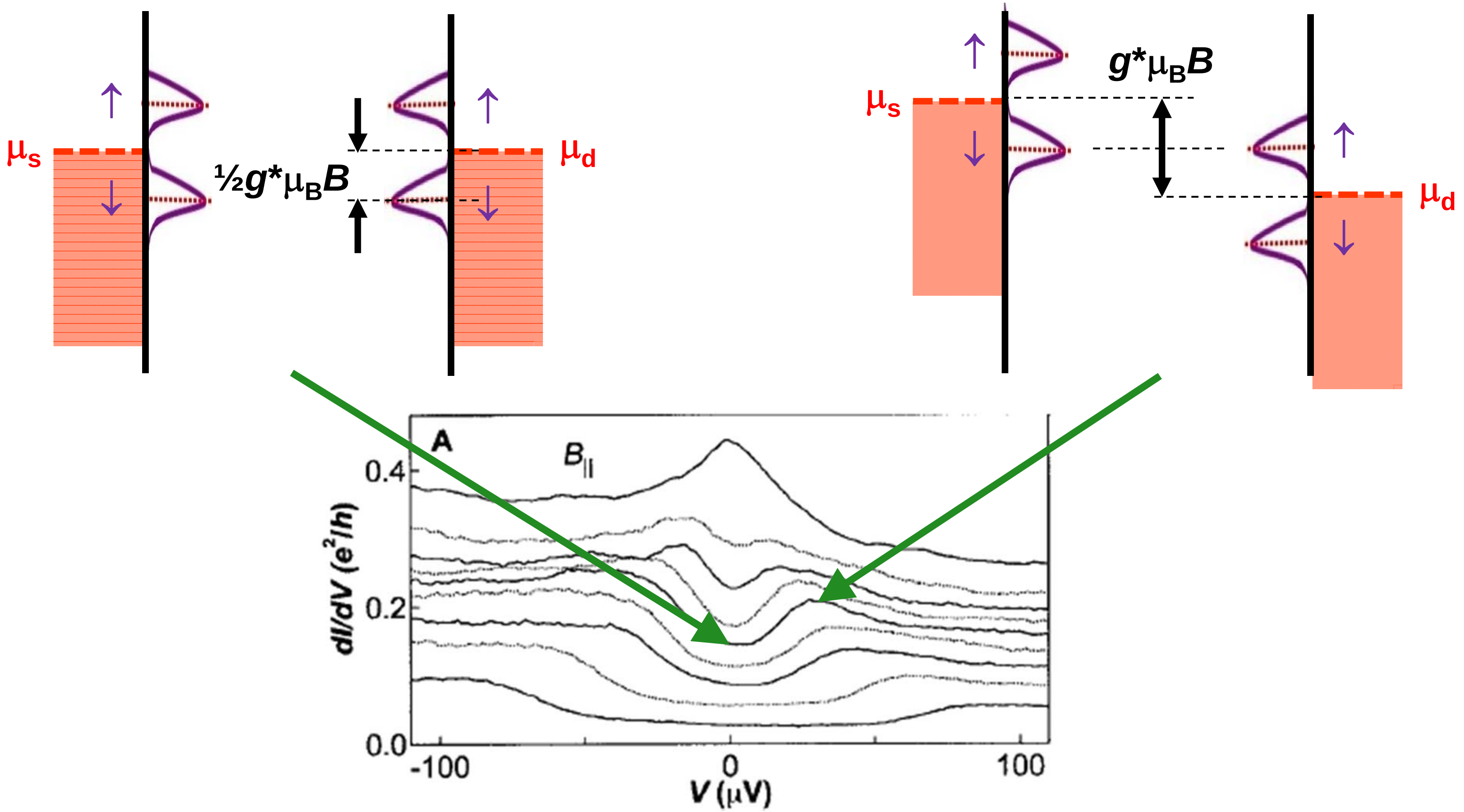
- **Due to the spin-dependent nature of the Kondo mechanism, an applied magnetic field Zeeman splits the Kondo density of states peak.**



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

Why is the peak splitting $2g^*\mu_B B$?

- The Kondo process is quenched at $V_{sd} = 0$ because the ↑ Kondo DOS in the source doesn't align with the ↓ Kondo DOS in the drain. We need $V_{sd} = \pm g^*\mu_B B$ to align them.

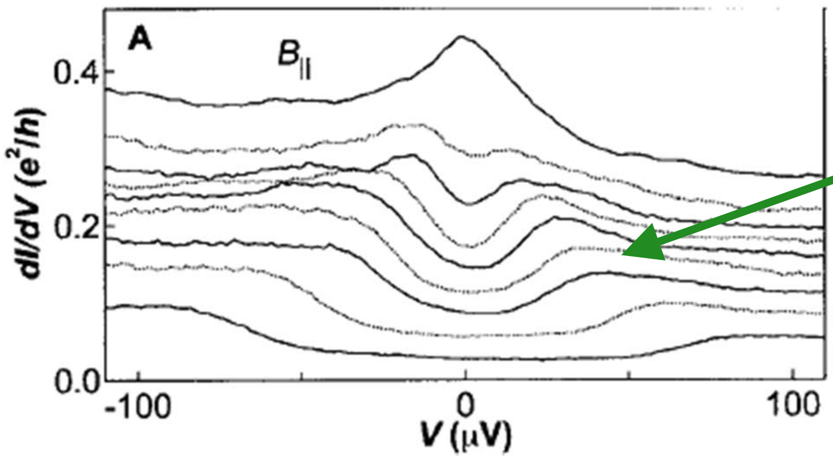


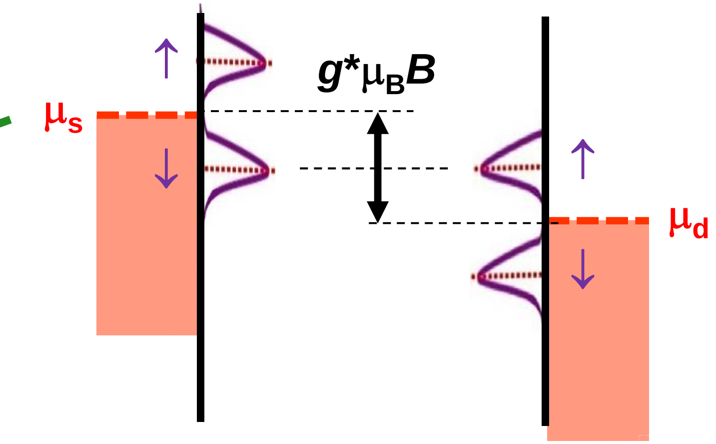
Y. Meir *et al.*, PRL 70, 2601 (1993).

The smoking gun

"Experimentally, observation of peaks in the differential conductance at $\Delta\mu = \Delta\varepsilon$ **[at** ***B*** **> 0]** ***would provide a "Smoking gun" for the presence of Kondo physics in transport through a quantum dot."***

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





Kondo scaling

- **The fourth key observation is Kondo scaling – the ratio of the conductance to the zero temperature conductance G_0 is a function only of the ratio of T to T_K, i.e., $G/G_0 = f(T/T_K)$.**

- **The functional form for quantum dots is:**

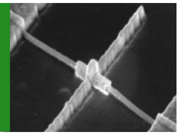
$$G(T) = G_0\left(\frac{T_K'^2}{T^2 + T_K'^2}\right)^s$$

where $T_K' = T_K/(2^{1/s} - 1)^{1/2}$ so that $G(T_K) = G_0/2$.

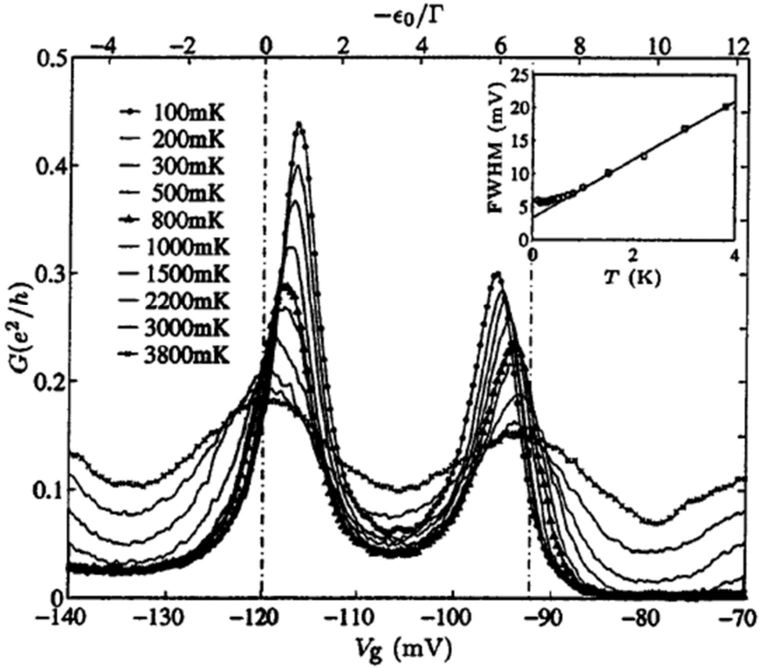
D. Goldhaber-Gordon *et al.*, PRL <u>81</u>, 5225 (1998).

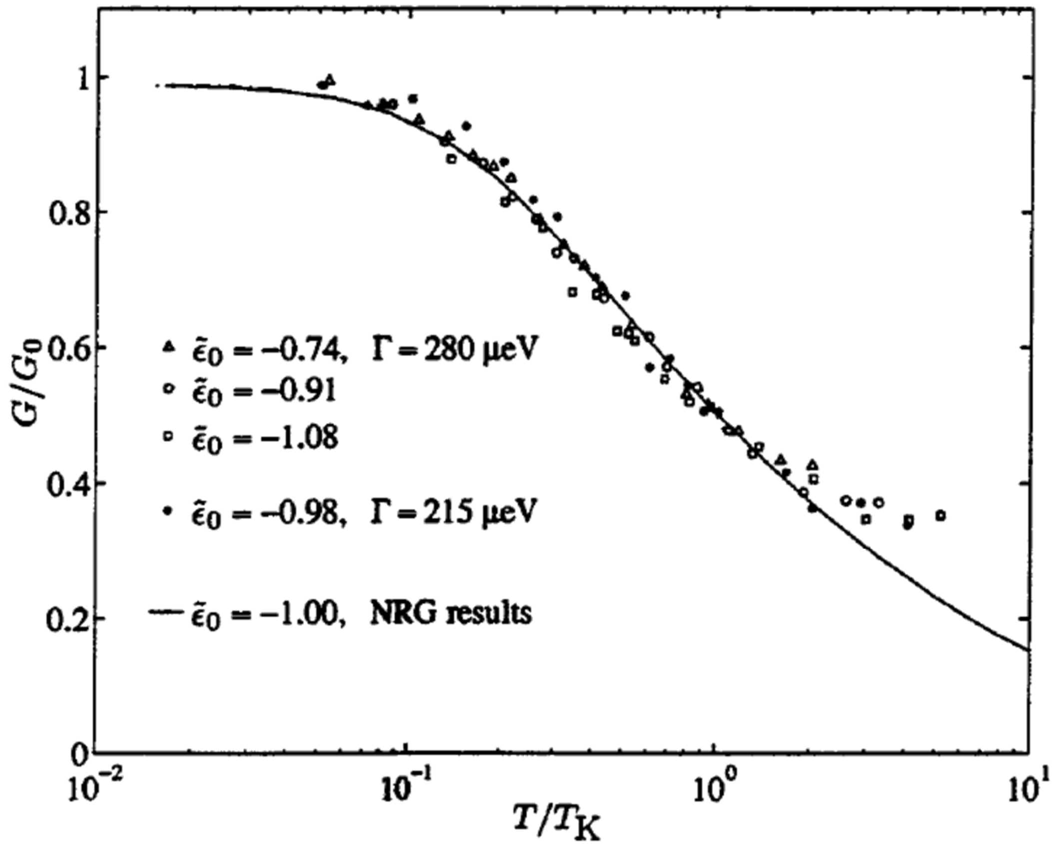
- **The parameter s depends on the spin-state of the localised spin. For spin ½ it is expected to be $s = 0.22 \pm 0.01$ based on Numerical Renormalization Group (NRG) theory calculations.**

T.A. Costi & A.C. Hewson, J. Phys. Condens. Matter <u>6</u>, 2519 (1994).



Kondo scaling





ε_0, *U* and Γ can be measured from the CB data (above). *G* vs *T* data is fit with the Kondo scaling equation to get G_0 and T_K. This is then plotted to the right, along with calculations based on NRG theory.

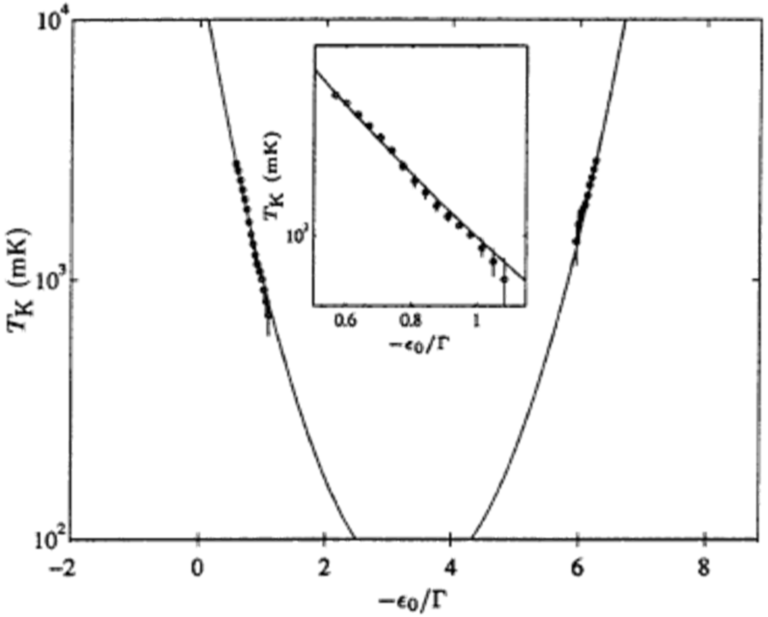
D. Goldhaber-Gordon *et al.*, PRL 81, 5225 (1998).

Kondo scaling

- **Bearing in mind the equation for T_K:**

$$T_K = \frac{\sqrt{\Gamma U}}{2} e^{\pi \epsilon_0(\epsilon_0 + U)/\Gamma U}$$

If U is finite, then ln T_K should be quadratic in ε_0, and ultimately in V_g.



D. Goldhaber-Gordon *et al.*, PRL <u>81</u>, 5225 (1998).

OK, that's great, but isn't this course about QPCs?

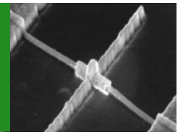
Interesting hypothesis: Can Kondo also explain 0.7?

"Although the QPC is an open (almost adiabatic) system to the surrounding 2DEG, the inverted harmonic potential may create an isolated spin ½ bound state in the middle of the constriction. The electrons may form a symmetric state around the constriction middle. The state with two electrons bound around the potential maximum we anticipate is the ground state whereas the situation with a single electron riding on top of the potential maximum is a high energy isomer of the system. It carries an isolated spin."

"The high energy isomer is a spin ½ state (but not magnetically ordered), and will not directly contribute to the transmission unless temperature is high or the biasing allows a Kondo-like resonant transmission. The resonant transmission represents a reduction in conduction from the fully quantized value, $2e^2/h$."

"The optimum coupling comes about because the spin ½ induces a Kondo state with the source (or drain), while the electron may still be fairly localized in the middle of the constriction. The situation is similar to the observations in quantum dots and carbon nanotubes, but the QPC constitutes an anti-dot configuration where the electrons are bound to a maximum in the potential."

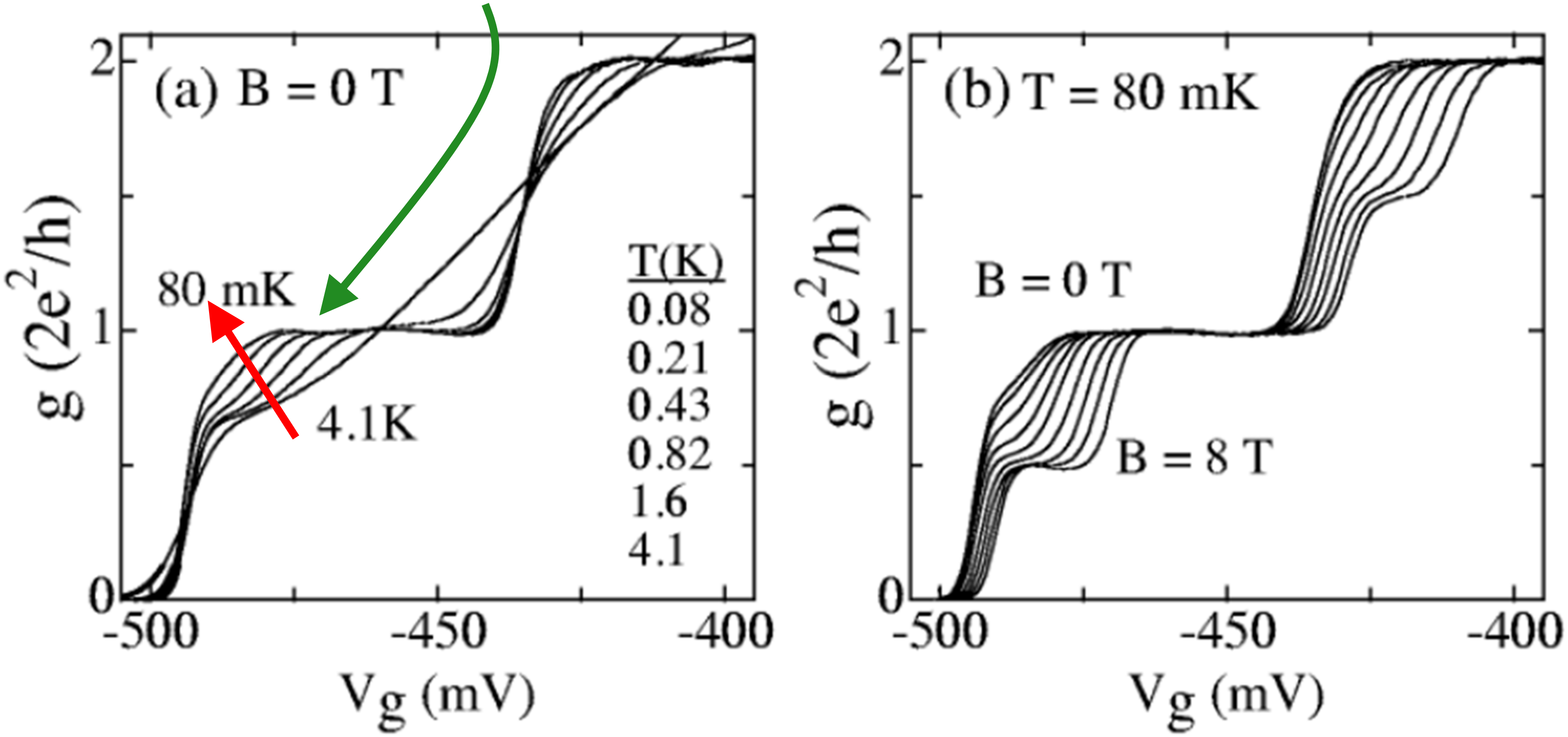
P.E. Lindelof, Proc. SPIE 4415, 77 (2001).



First data for Kondo in QPCs

- **Cronenwett *et al.* suggested that the disappearance of the 0.7 structure at very low temperature signals the formation of a Kondo-like correlated spin state.**

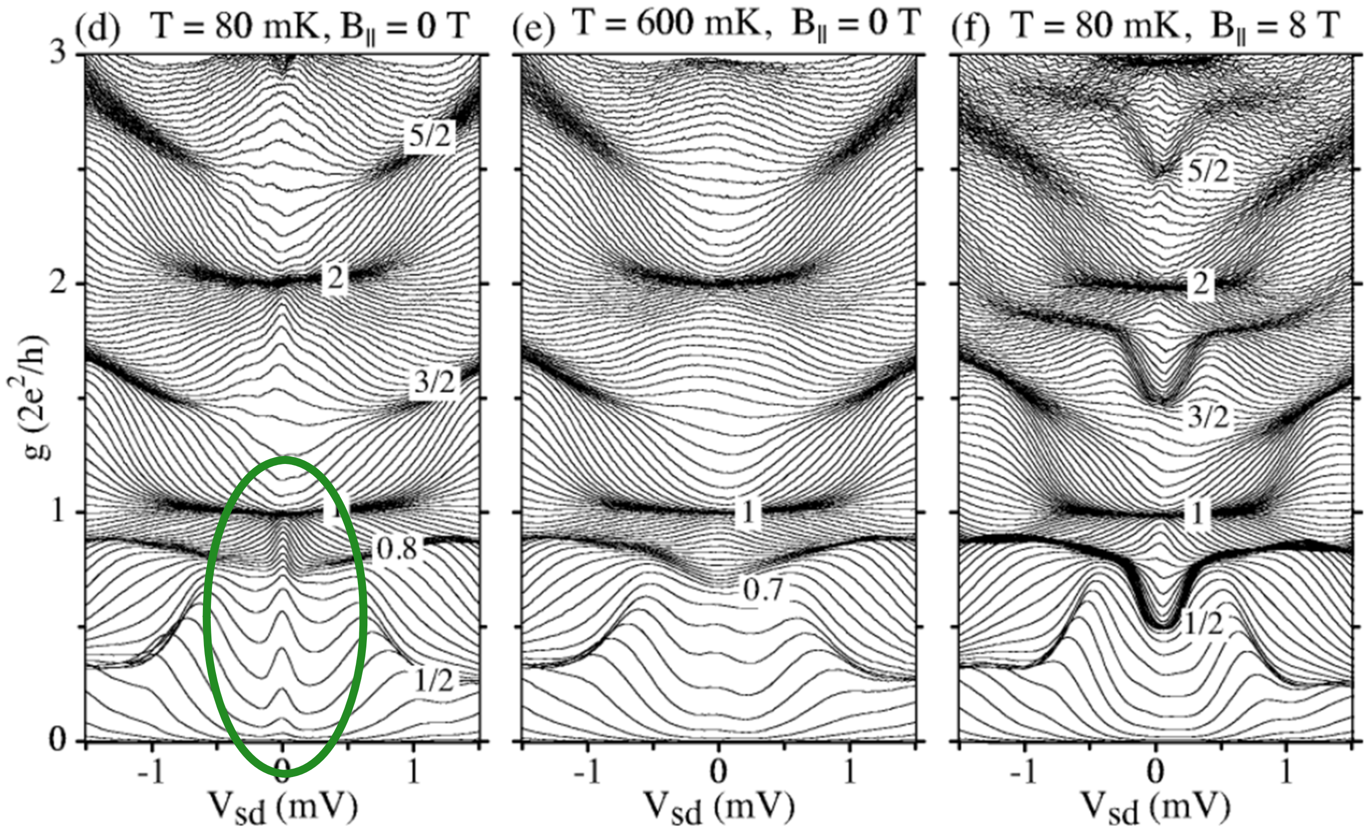
Note in particular how conductance is restored towards the unitary value at low *T*



S.M. Cronenwett *et al*., PRL <u>88</u>, 226805 (2002).

First data for Kondo in QPCs

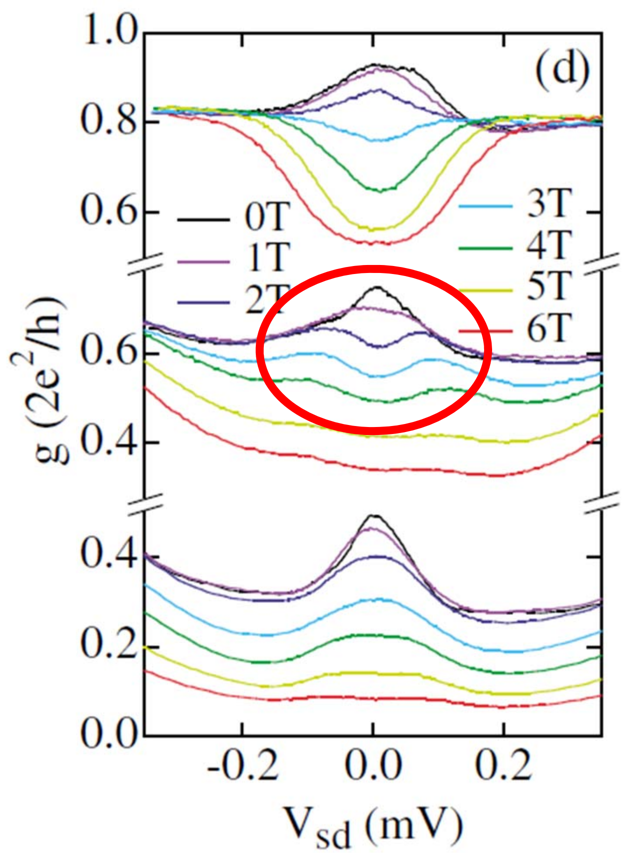
- **The initial clue is a zero-bias peak in the differential conductance at $G < G_0$ that disappears at higher temperatures and at higher magnetic fields.**



S.M. Cronenwett *et al*., PRL <u>88</u>, 226805 (2002).

Zeeman splitting of the zero-bias peak

- **The zero-bias peak clearly splits as a function of magnetic field, but do we have the smoking gun of 2$g^*\mu_B B$?**



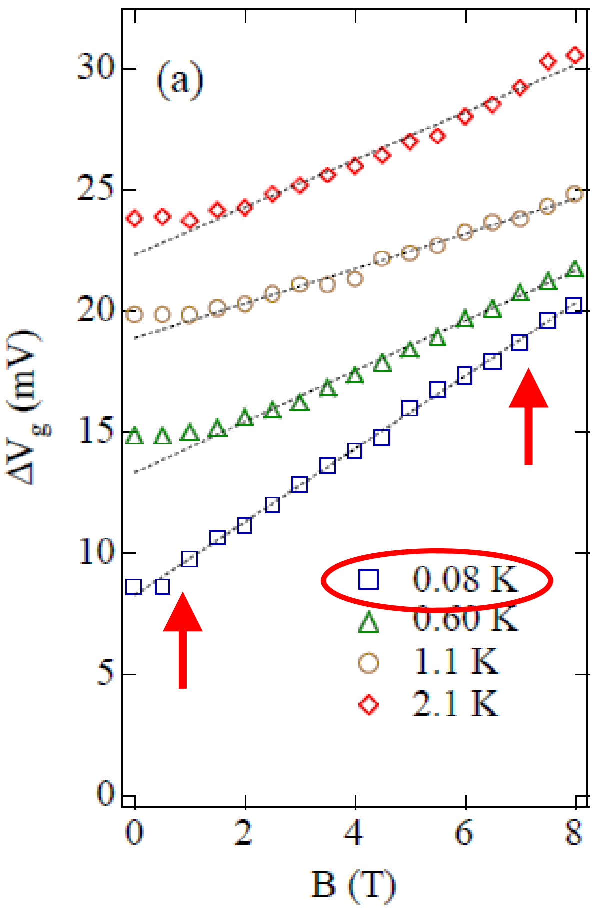
"A characteristic feature of the Kondo regime ($T < T_K$) in quantum dots is that the ZBA peak is split by $2g^*\mu_B B$ upon application of an in-plane magnetic field when $g^*\mu_B B > \sim T_K$. In the QPC, we find the ZBA peak does not split uniformly over the full range $0 < g < 2e^2/h$, as seen to the left. Near g ~ 0.7 clear splitting is seen, consistent with $2g^*\mu_B B$ (i.e., splitting roughly linear in field for B < ~3T, consistent with a g-factor ~1.5 times the bulk value)."

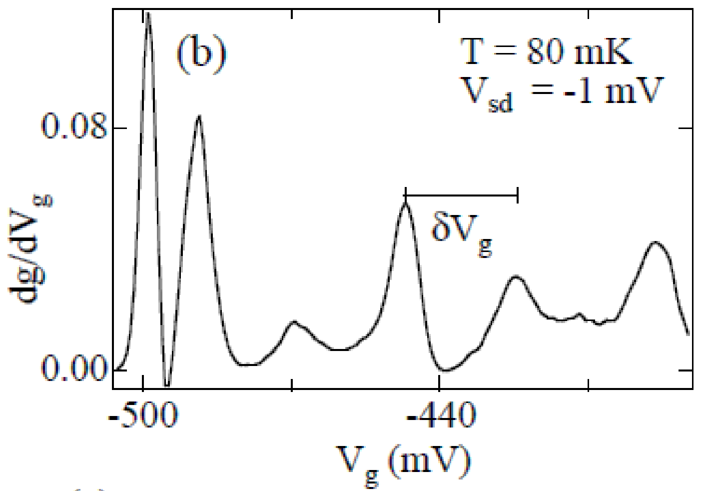
In other words, you get 2$g^*\mu_B B$ if g^* is 1.5 × 0.44 = 0.66, <u>but is it?</u>

S.M. Cronenwett *et al*., PRL <u>88</u>, 226805 (2002).

Is the gun really smoking?

- **First, measurements of transconductance peak splitting with magnetic field.**





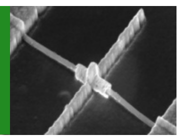
(c)

T (K)	0.08	0.67	1.3	3.1
$\eta \left(\frac{\mu eV}{mV_g}\right)$	43.0	38.7	38.4	41.0
g^*	1.12	0.68	0.51	0.65

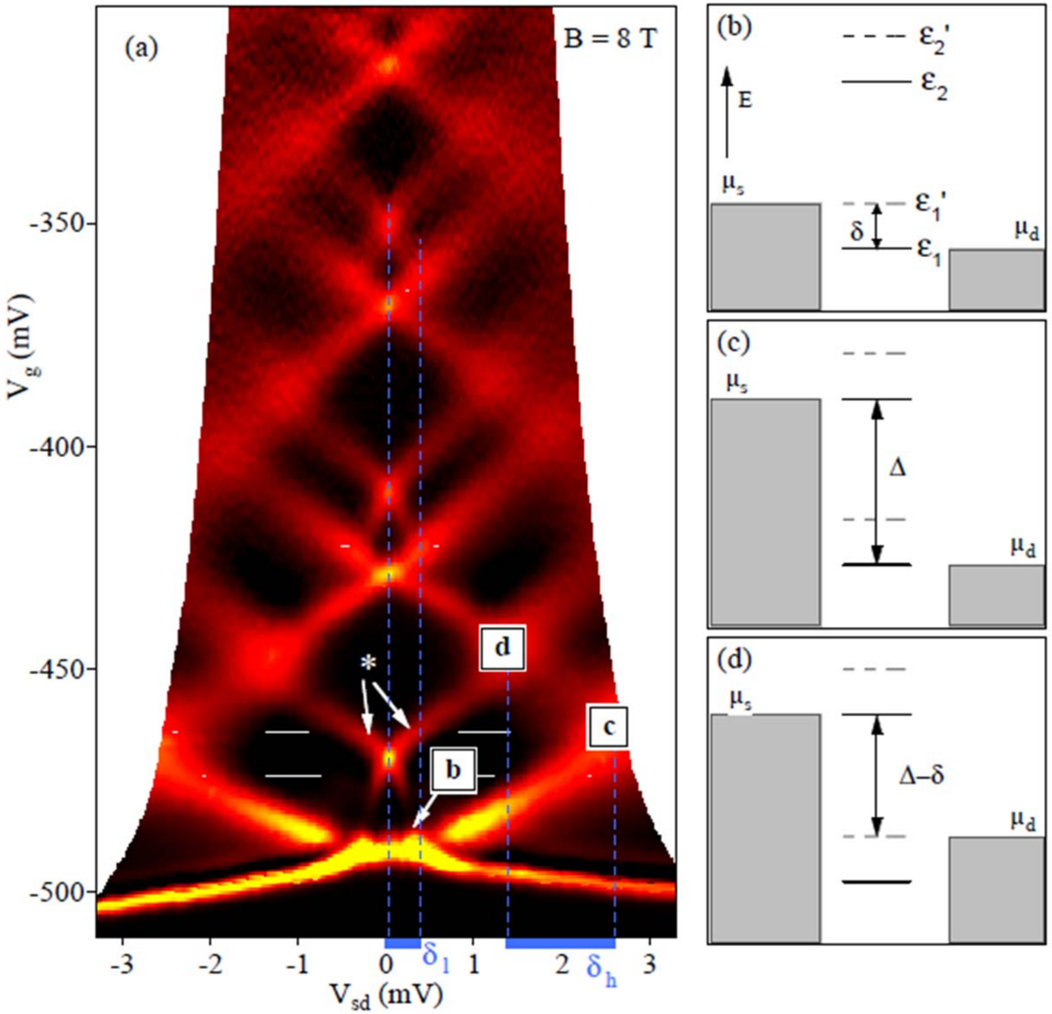
Under identical conditions Cronenwett measures g^* = 1.12 for the lowest subband.

This would mean a splitting of $1.18g^*\mu_B B$ and not $2g^*\mu_B B$.

S.M. Cronenwett, Ph.D. Thesis, Stanford University (2001).



Is the gun really smoking?



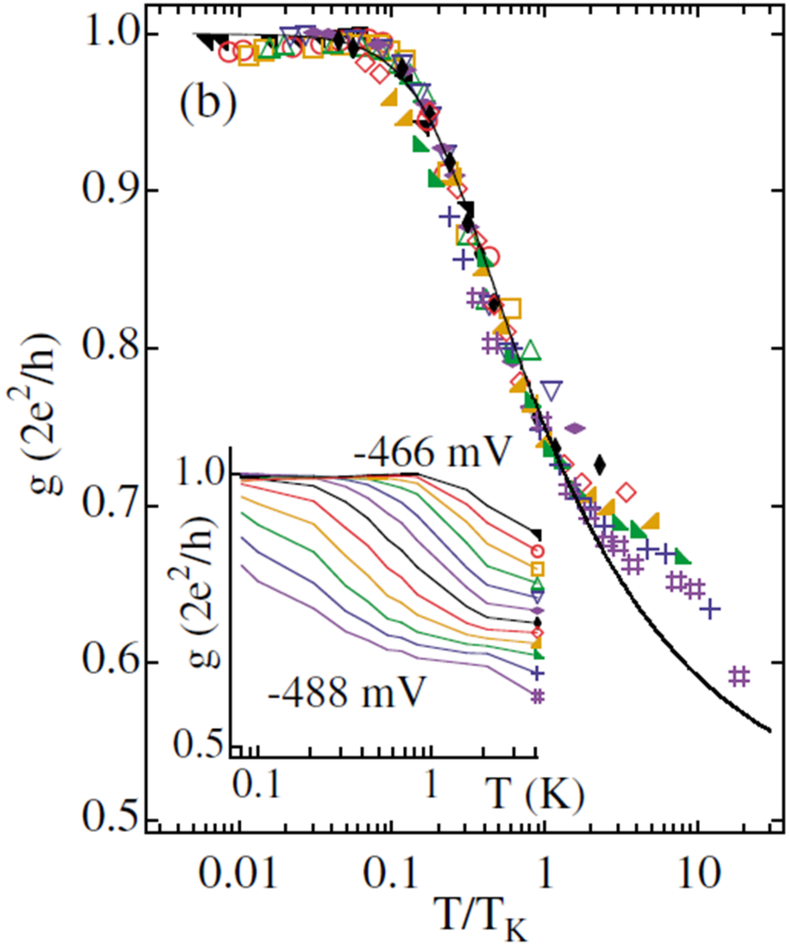
Measurements from the transconductance at high magnetic field give two other estimates of *g**.

The first at low V_{sd} gives g^* = 0.76, which corresponds to $1.74g^*\mu_B B$.

The second at high V_{sd} gives g^* = 2.62, which corresponds to $0.5g^*\mu_B B$.

S.M. Cronenwett, Ph.D. Thesis, Stanford University (2001).

Kondo scaling



The *g* vs *T* is measured for different V_g (i.e., different points on the drop down from the G_0 plateau. They are fit with a slightly different, empirical Kondo scaling formula:

$$g = 2e^2/h[1/2f(T/T_K) + 1/2]$$

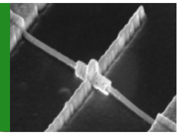
where:

$$f(T/T_K) \sim [1 + (2^{1/s} - 1)(T/T_K)^2]^{-s}$$

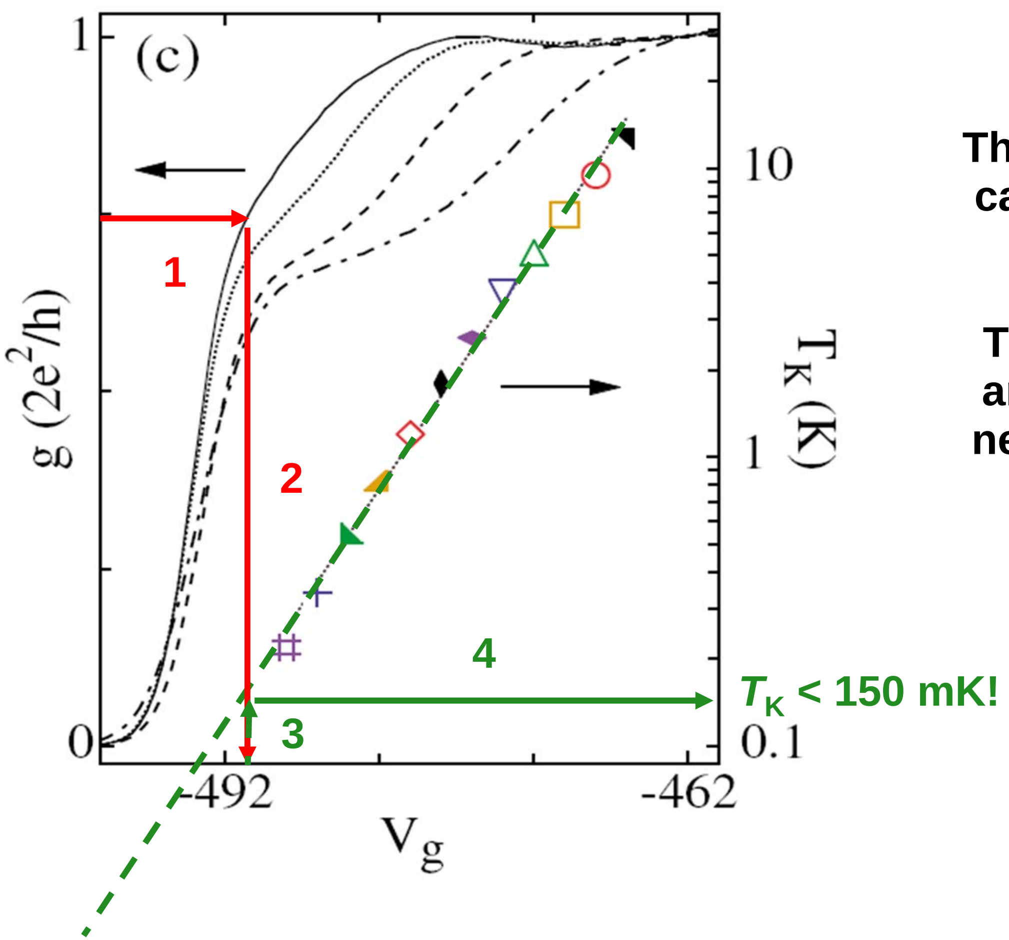
with *s* = 0.22, as per earlier.

This analysis enables the Kondo temperature T_K to be extracted as a function of V_g, just as for quantum dots.

S.M. Cronenwett *et al*., PRL 88, 226805 (2002).



Kondo scaling



The Kondo temperature plot takes some careful reading, but essentially, ln T_K is linear in V_g rather than quadratic.

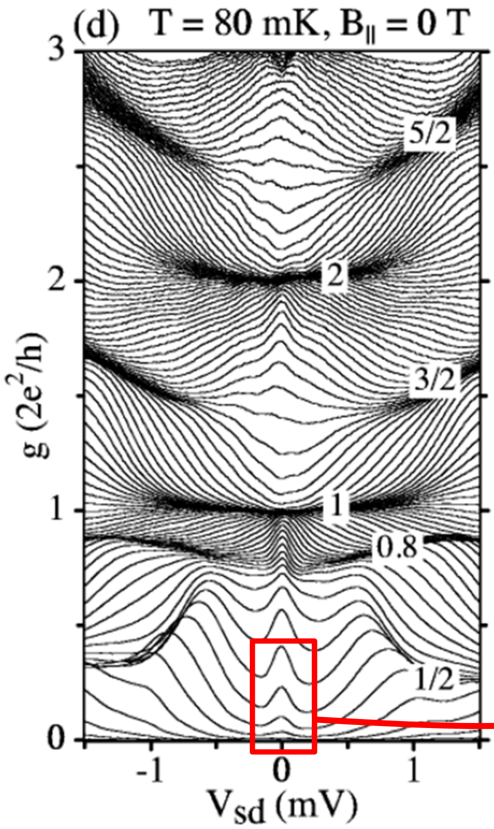
This may not be so surprising, as ε_0, Γ and *U* will not be as tuneable in a QPC near pinch-off as they are in a quantum dot at Coulomb blockade.

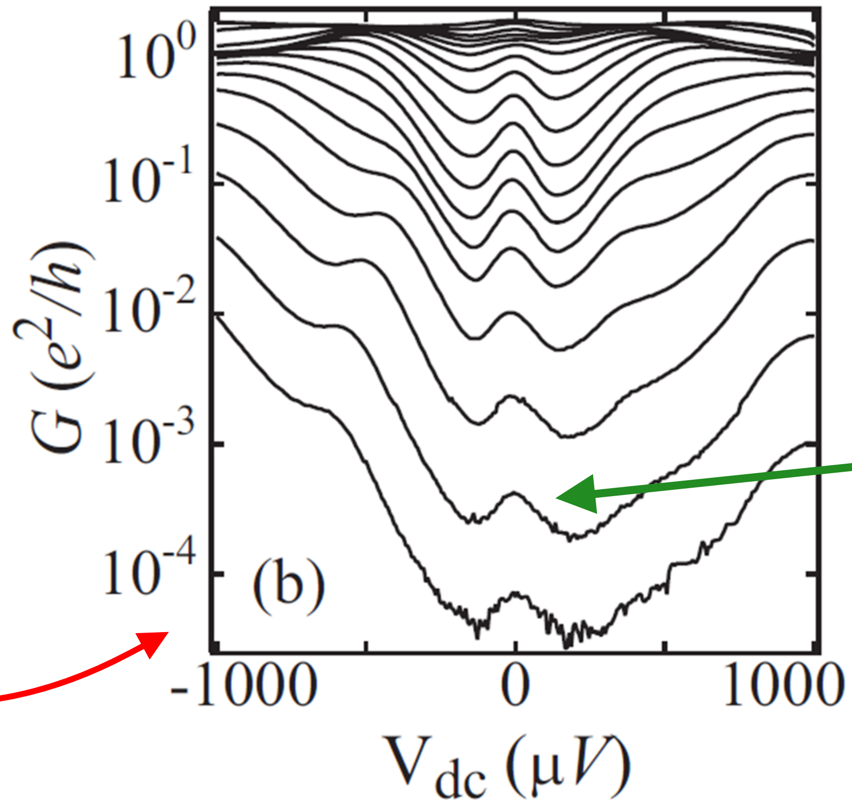
What is concerning is how low the T_K values get at g << 0.5, because....

S.M. Cronenwett *et al*., PRL 88, 226805 (2002).

Kondo scaling

- … the electron temperature rarely gets below 50 mK (never mind the thermometry), and the zero-bias peak is observed right down to 10^{-4} G_0, where according to Cronenwett's data, T_K should be miniscule.





T_K should be tiny compared to T down here.

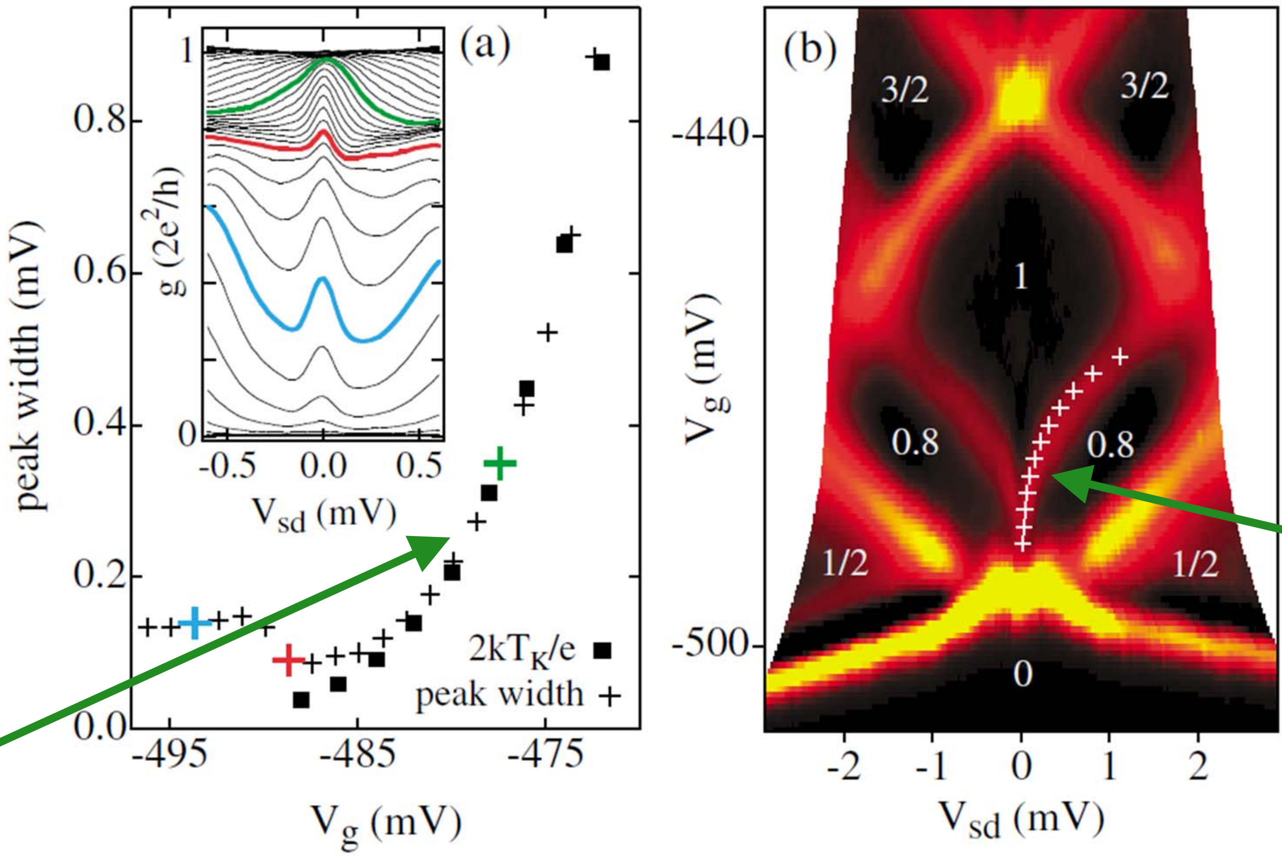
S.M. Cronenwett *et al.*, PRL 88, 226805 (2002).

Y. Ren *et al.*, PRB 82, 045313 (2010).

Kondo scaling

- The final piece of data is FWHM measurements of the zero-bias peak, these should (in principle) be equal to $2k_BT_K/e$, where the T_K here is obtained from Kondo scaling fits.

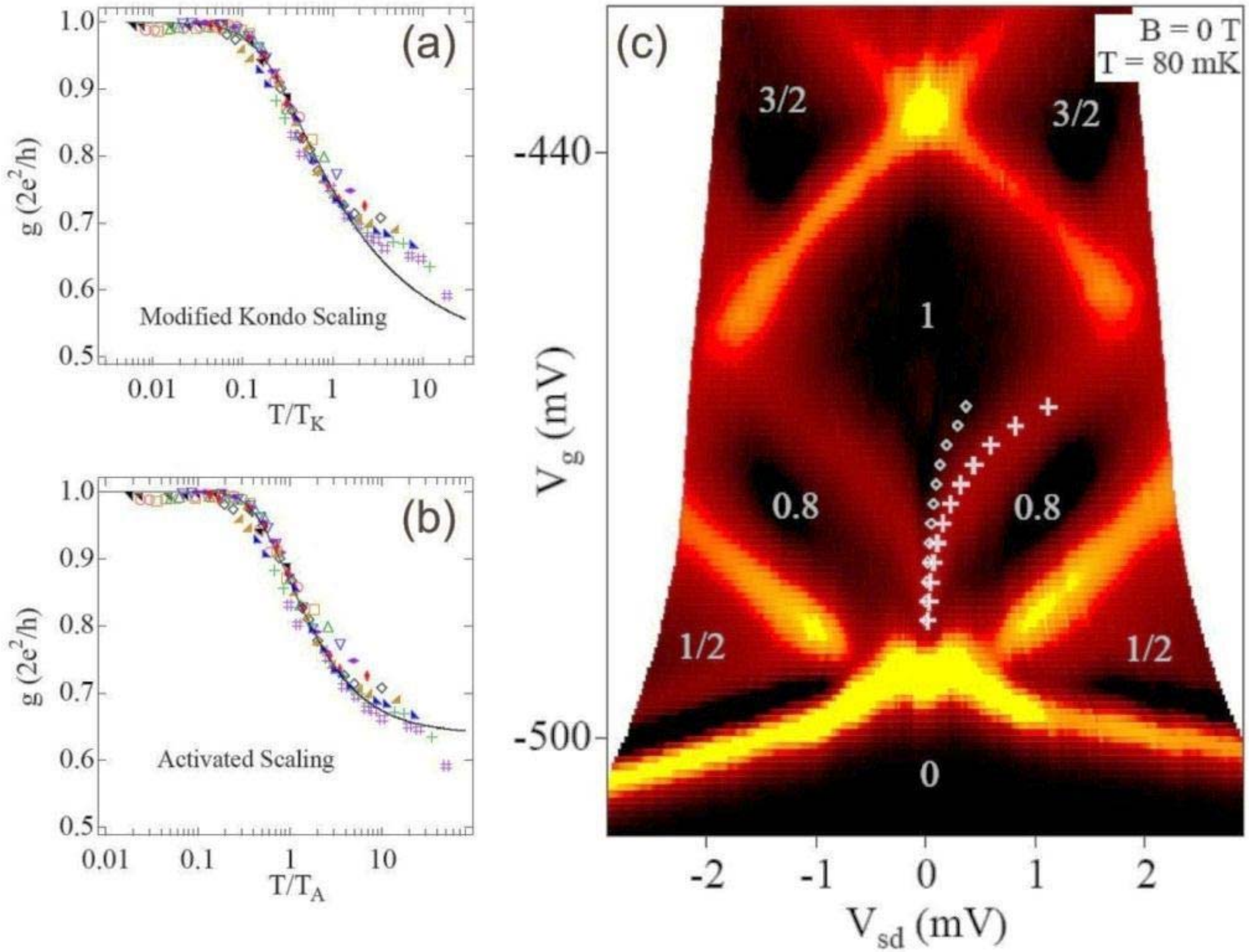
The agreement between scaling T_K and FWHM-derived T_K is remarkably good.



This plot will look familiar from last lecture. Kristensen *et al.* did something similar with activation data.

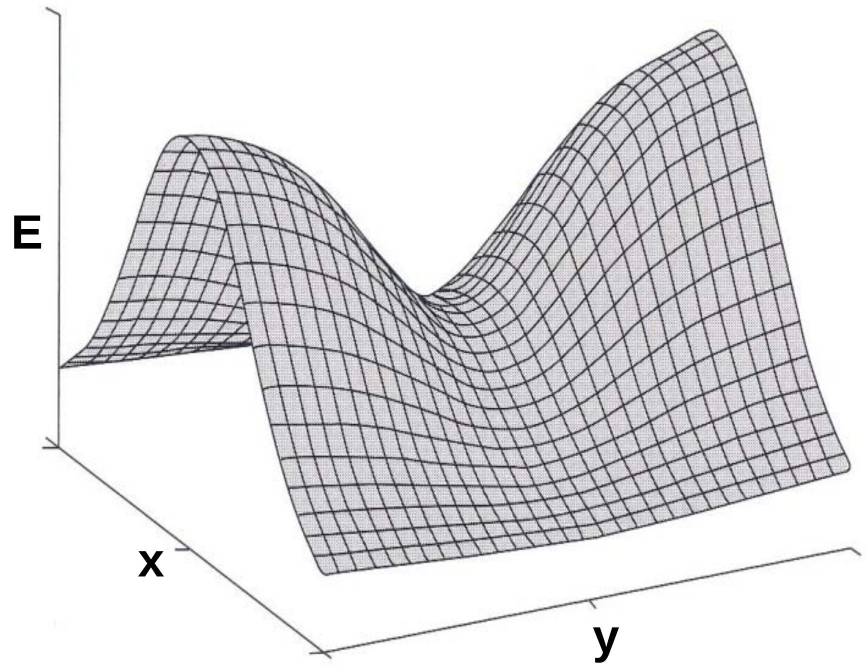
S.M. Cronenwett *et al*., PRL 88, 226805 (2002).

Kondo scaling



S.M. Cronenwett, Ph.D. Thesis, Stanford University (2001).

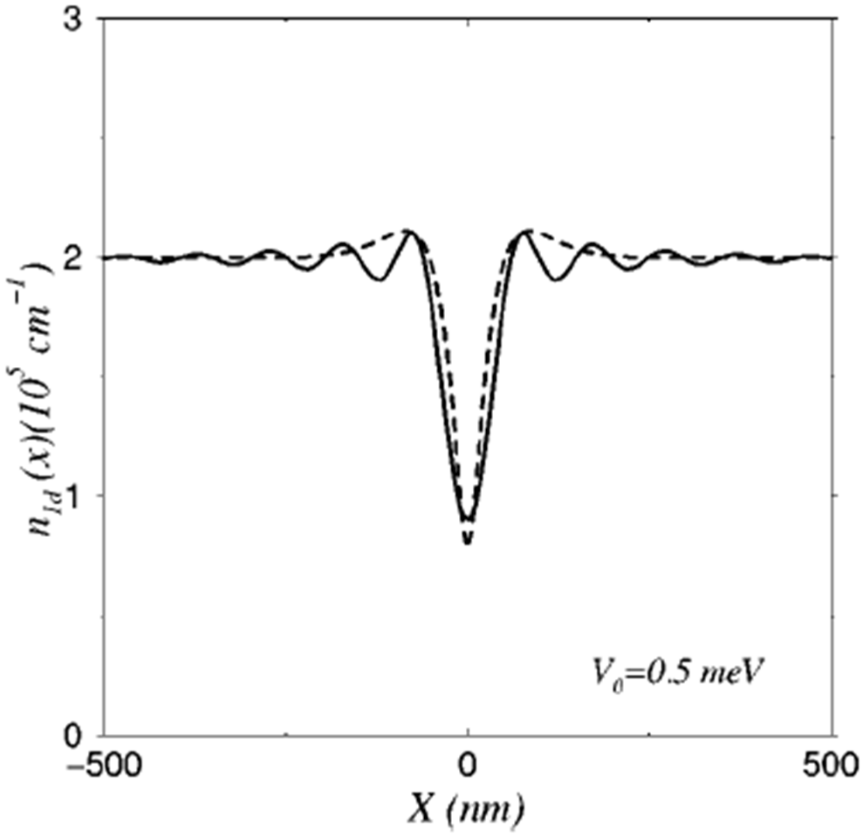
Why would you expect Kondo in QPCs at all?



- **In other words, why would you get a bound state from a saddle point potential?**

DFT results for a realistic QPC

- **Back in Lecture 1 we saw that an approximation taken in the DFT calculations took away the Friedel oscillations. They are a crucial part of the Kondo hypothesis…**



solid lines = exact
dotted lines = n_{1D} approx

C.K. Wang *et al.,* PRB 57, 4552 (1998).

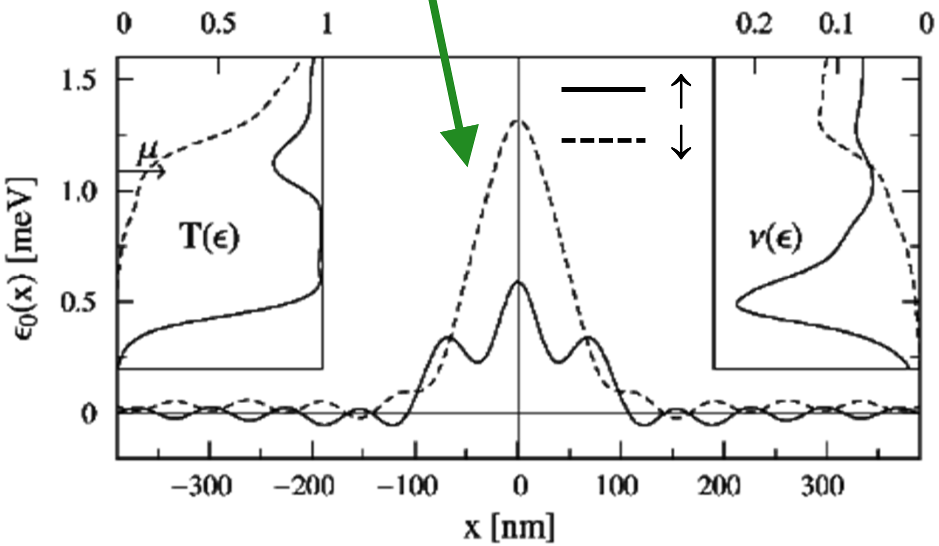
More spin DFT calculations for a QPC

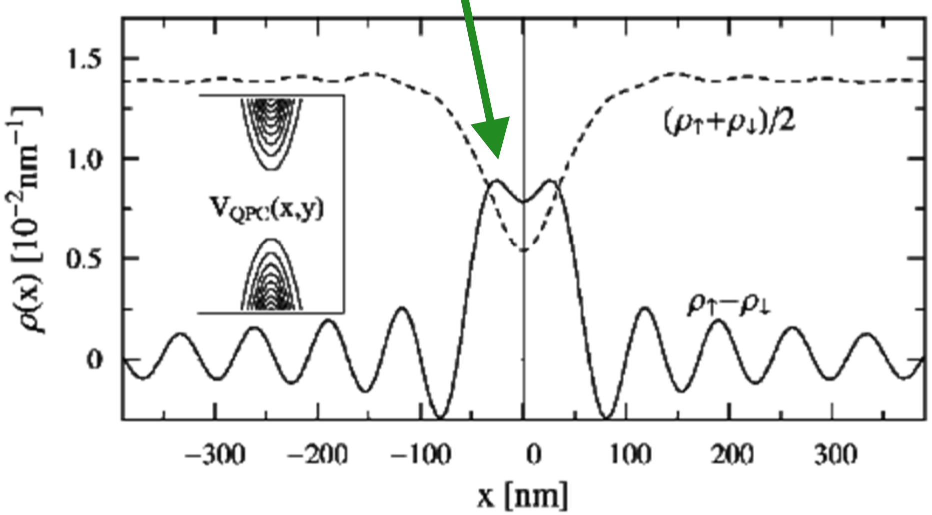
- Meir *et al*. also performed spin DFT calculations for a QPC, again using the Kohn-Sham equations using the local density approximation. The differences are mostly in the details: potential, implementation of the calculations, etc.

  But, the results are quite different (and debated by the SDFT community, as we'll see).

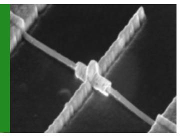
Strong barrier to ↓ but less for ↑

Integrated ↑ density at QPC center is 0.96 electrons ⇒ bound spin?



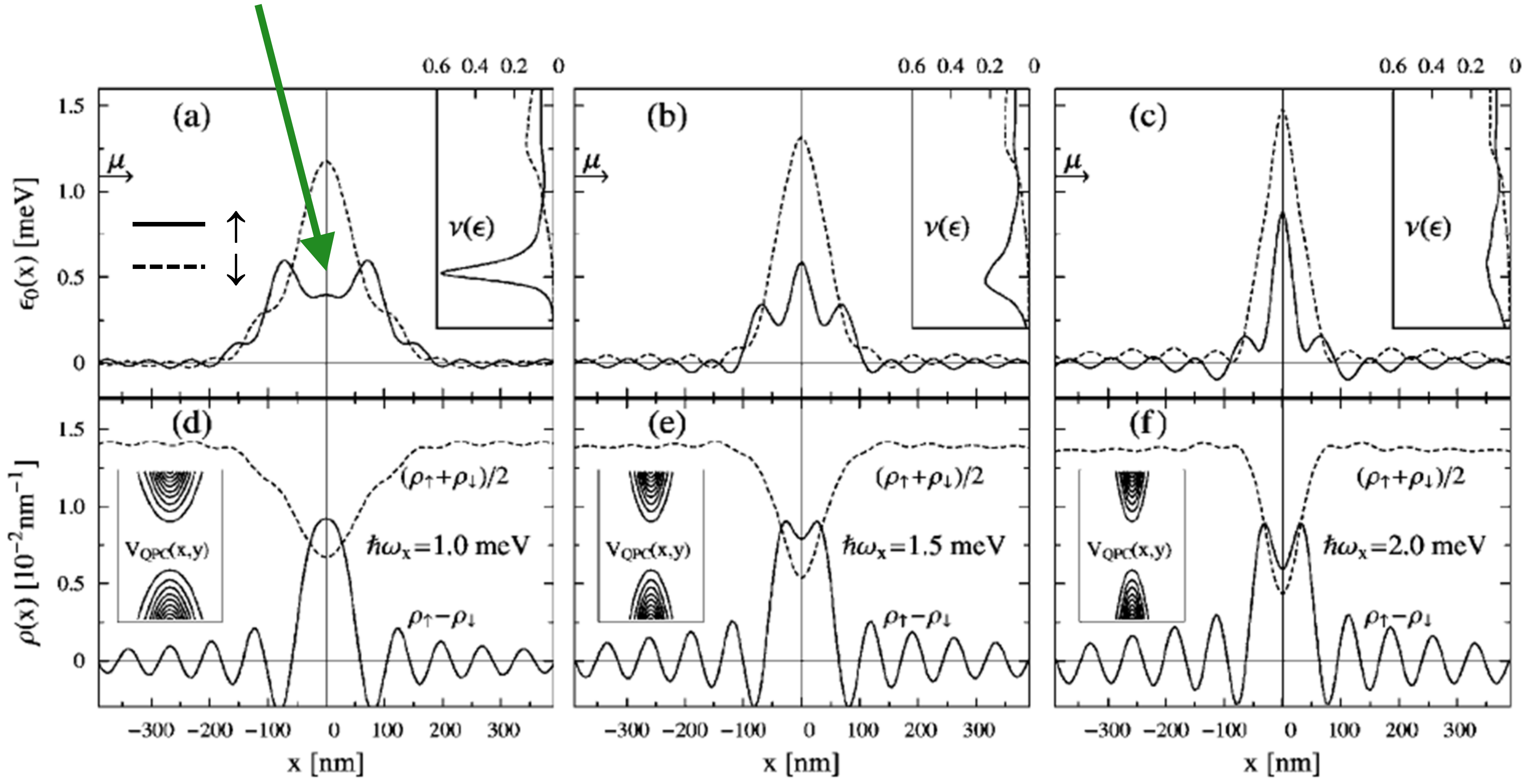


Y. Meir *et al*., PRL 89, 196802 (2002).



More spin DFT calculations for a QPC

In some instances there is even a minimum at the centre of the QPC for ↑



K. Hirose *et al*., PRL 90, 026804 (2003).

Extending the Anderson model to QPCs

- Meir *et al.* extended the Anderson model applied to quantum dot Kondo to QPCs, motivated in part by spin DFT calculations we will talk about soon, and the data that follows.

The Anderson Hamiltonian for the problem looks like:

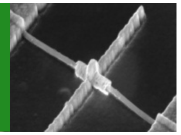
$$H = \underbrace{\sum_{\sigma;k\in L,R} \varepsilon_{k\sigma}\mathbf{c}^{\dagger}_{k\sigma}\mathbf{c}_{k\sigma}}_{\text{leads}} + \underbrace{\sum_{\sigma} \varepsilon_{\sigma}\mathbf{d}^{\dagger}_{\sigma}\mathbf{d}_{\sigma} + U\mathbf{n}_{\uparrow}\mathbf{n}_{\downarrow}}_{\text{“site”}} + \sum_{\sigma;k\in L,R} [\underbrace{V^{(1)}_{k\sigma}(1-\mathbf{n}_{\bar{\sigma}})\mathbf{c}^{\dagger}_{k\sigma}\mathbf{d}_{\sigma}}_{0\leftrightarrow 1} + \underbrace{V^{(2)}_{k\sigma}\mathbf{n}_{\bar{\sigma}}\mathbf{c}^{\dagger}_{k\sigma}\mathbf{d}_{\sigma}}_{1\leftrightarrow 2} + \mathrm{H.c.}]$$

where $c_{k\sigma}^{\dagger}$($c_{k\sigma}$) creates (destroys) an electron with momentum k and spin σ in lead L or R, $d_{k\sigma}^{\dagger}$($d_{k\sigma}$) creates (destroys) a spin-σ electron on 'the site', which is a quasibound state at the centre of the QPC, and $n_{\sigma} = d_{\sigma}^{\dagger}d_{\sigma}$.

The matrix elements $V_{k\sigma}^{(1)}$ and $V_{k\sigma}^{(2)}$, which relate to transitions between 0 and 1 and 1 and 2 electrons on the site respectively, are taken to be step-like functions in *E*.

It is expected that $V_{k\sigma}^{(2)} < V_{k\sigma}^{(1)}$ as the Coulomb potential of the 1st electron should reduce the tunnel probability for the 2nd, but the Kondo effect will enhance the contribution of the second channel with decreasing *T*, such that the conductance becomes $2e^2/h$ at zero temperature.

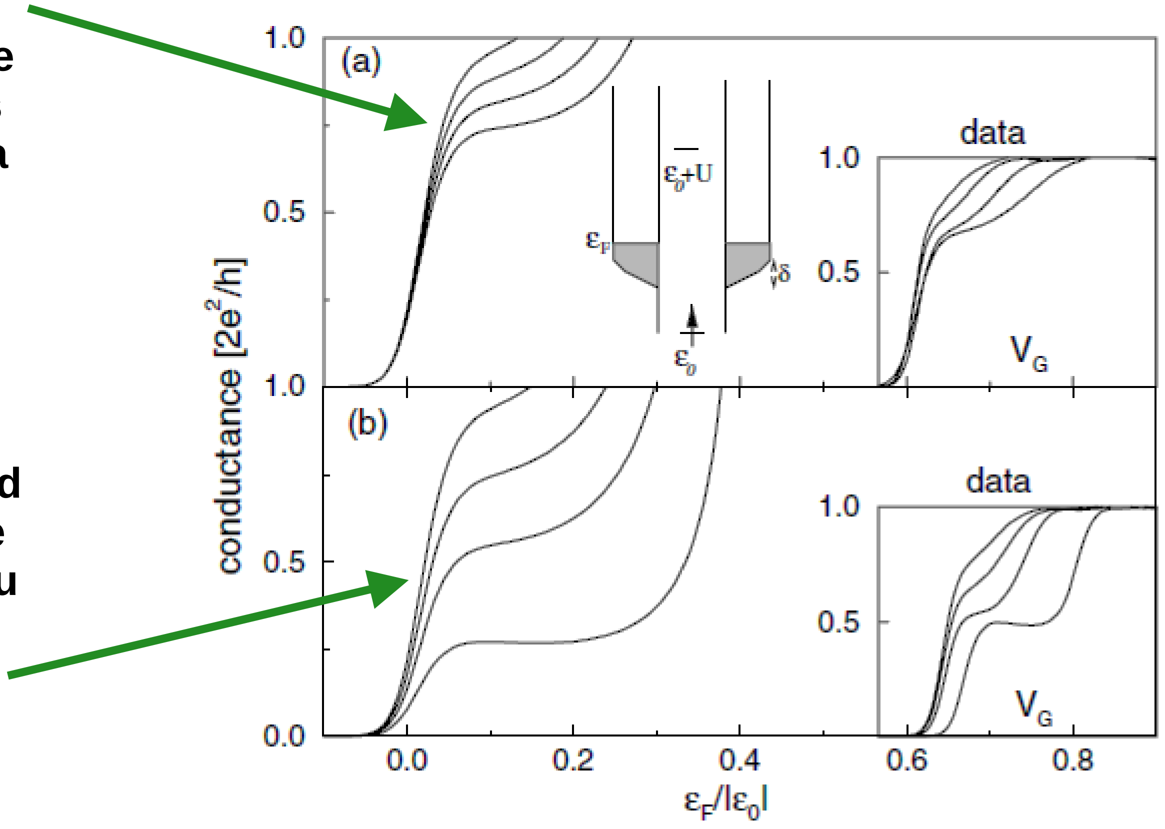
Y. Meir *et al*., PRL 89, 196802 (2002).



Extending the Anderson model to QPCs

Kondo model does a good job with the temperature dependence of the 0.7 anomaly, it its not clear there's a plateau at $2e^2/h$.

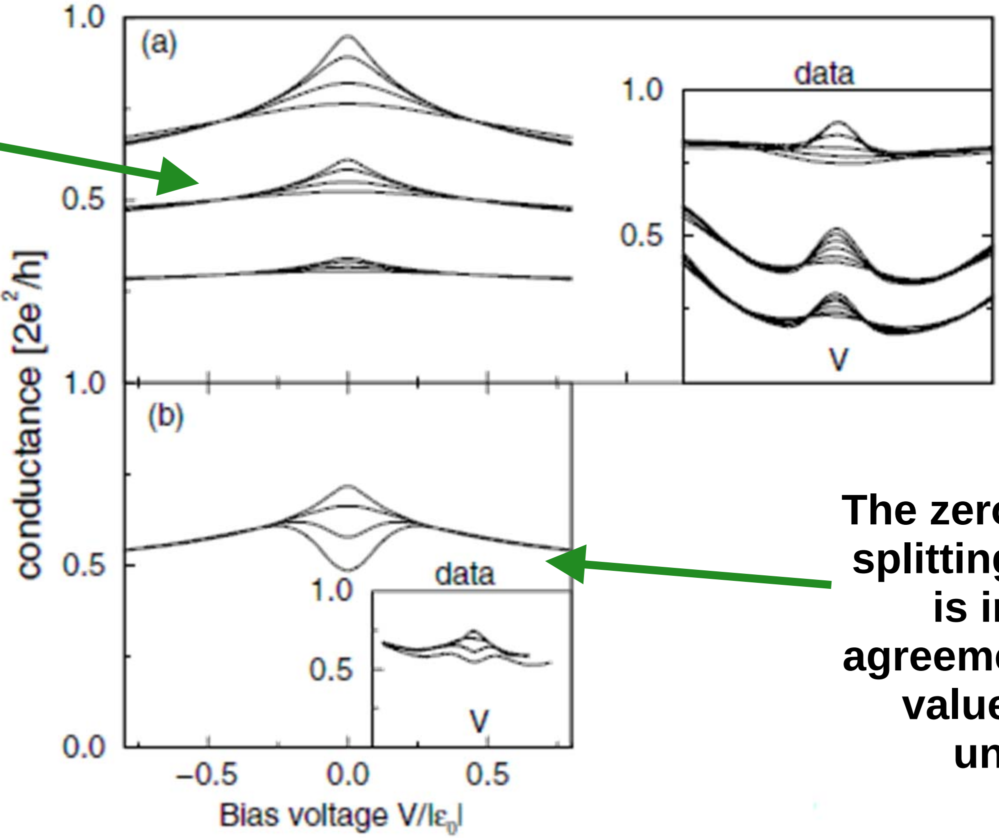
The trend with field is correct, but the drop of the plateau to $0.25G_0$ is not observed experimentally.



Y. Meir *et al*., PRL 89, 196802 (2002) with exp. data from S.M. Cronenwett *et al*., PRL 88, 226805 (2002).

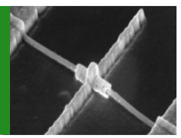
Extending the Anderson model to QPCs

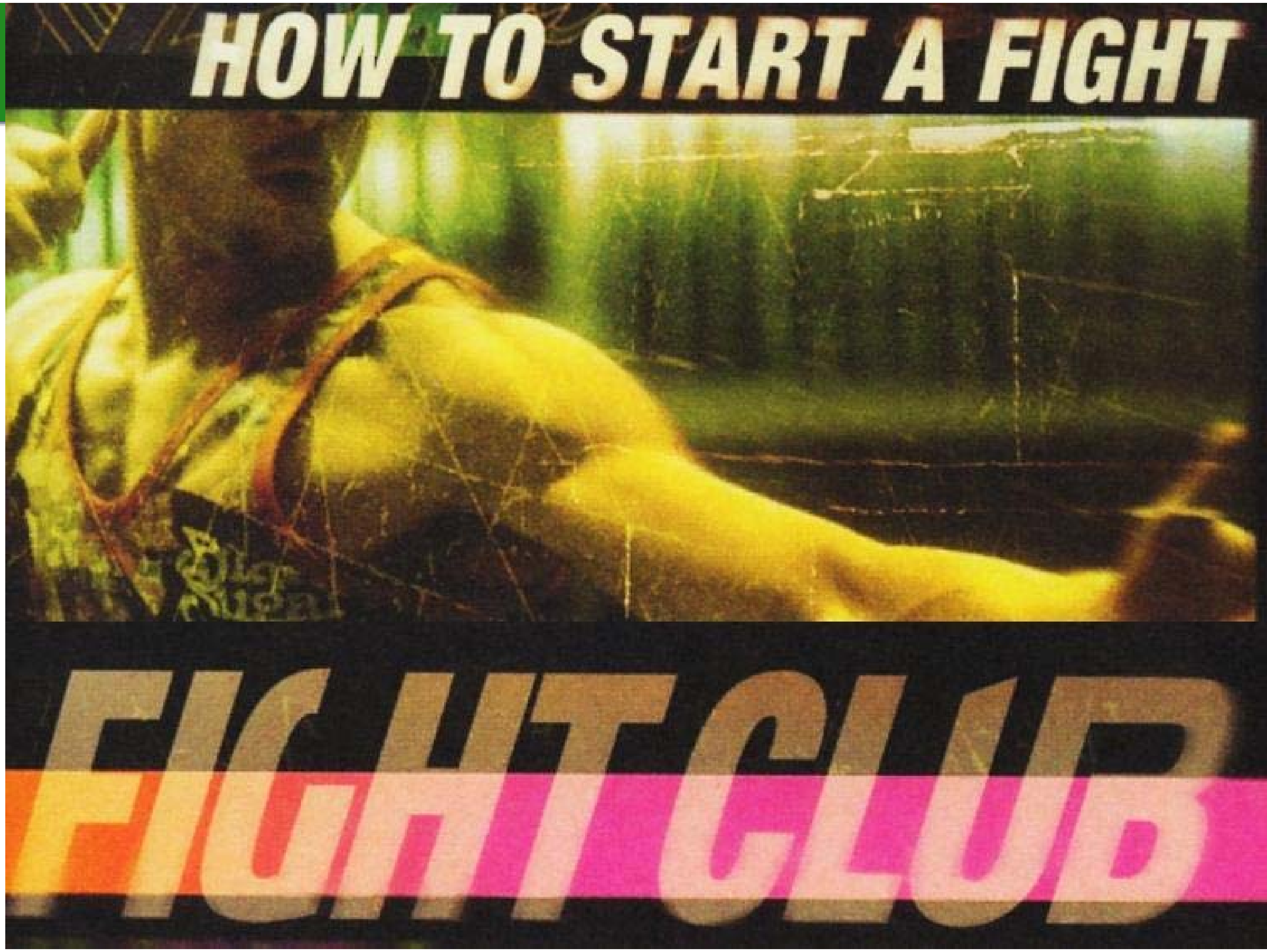
Predicts a zero-bias peak that weakens at lower *G*. This is consistent with C'wett, but not with other data.



The zero-bias peak splitting with field is in good agreement, but the value of g^* is unclear.

Y. Meir *et al*., PRL <u>89</u>, 196802 (2002) with exp. data from S.M. Cronenwett *et al*., PRL <u>88</u>, 226805 (2002).





- **There are two areas of significant debate when it comes to Kondo and QPCs:**

  1. Does the data really behave like you'd expect it to for Kondo? – Today

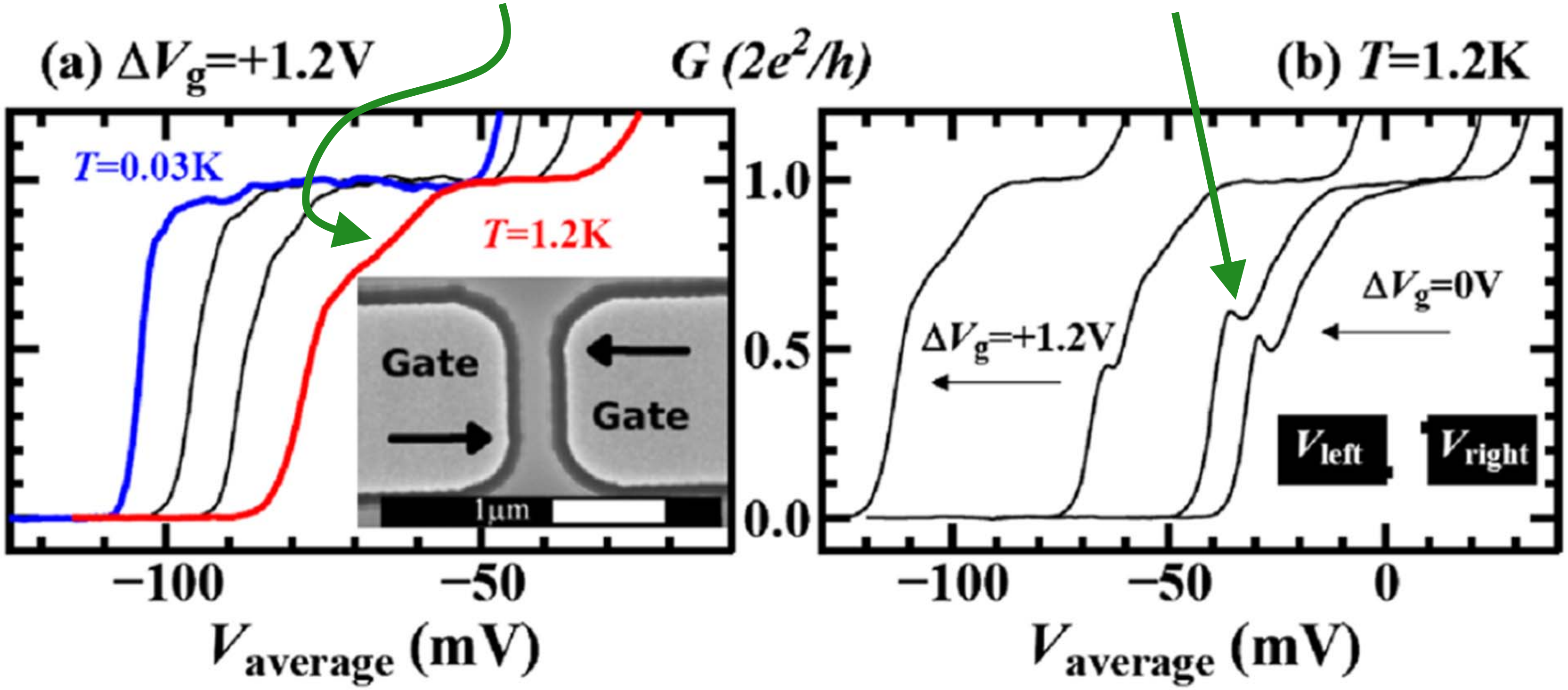
  2. Is there really a bound-state inside a QPC? – Tomorrow

Deliberately inducing a bound-state

- **Sfigakis *et al.* studied a QPC with microconstrictions that induce a bound-state. The device shows both classic 0.7 behavior and Kondo.**

Classic 0.7 *T* dependence in displaced channel

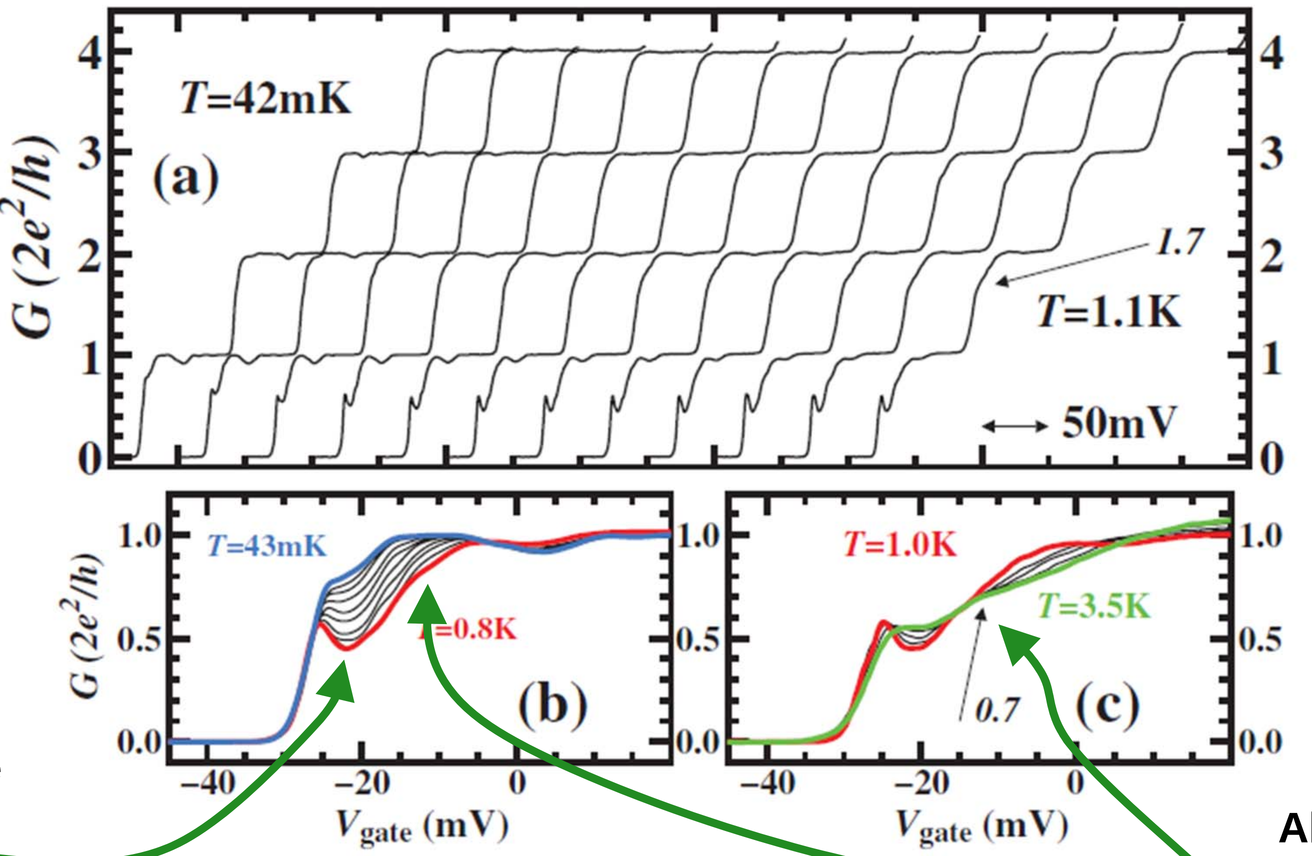
Undisplaced channel shows a CB peak.



F. Sfigakis *et al.*, PRL 100, 026807 (2008).

Deliberately inducing a bound-state

All $\Delta V_g = 0$



Kondo restores the CB valley towards unitary *G*

All the while, 0.7 does its thing above it.

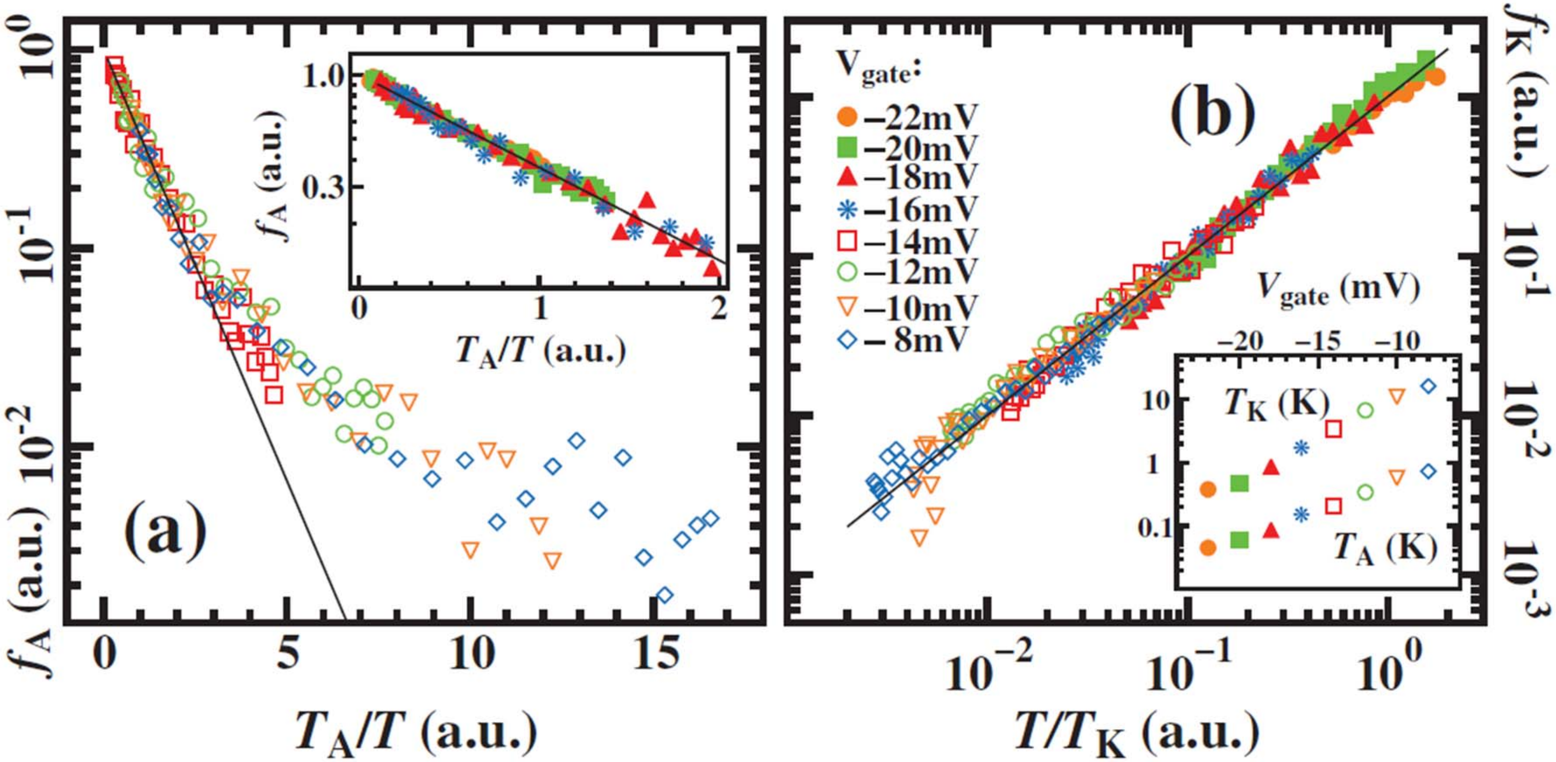
F. Sfigakis *et al.*, PRL 100, 026807 (2008).

Deliberately inducing a bound-state

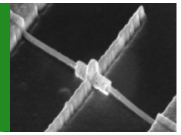
- **Considering the scaling, the data for this device is best fit using the quantum dot Kondo formula, with activated behaviour being a reasonable fit. The QPC Kondo expression cannot be fit to the data at all.**

Activated

Quantum dot Kondo

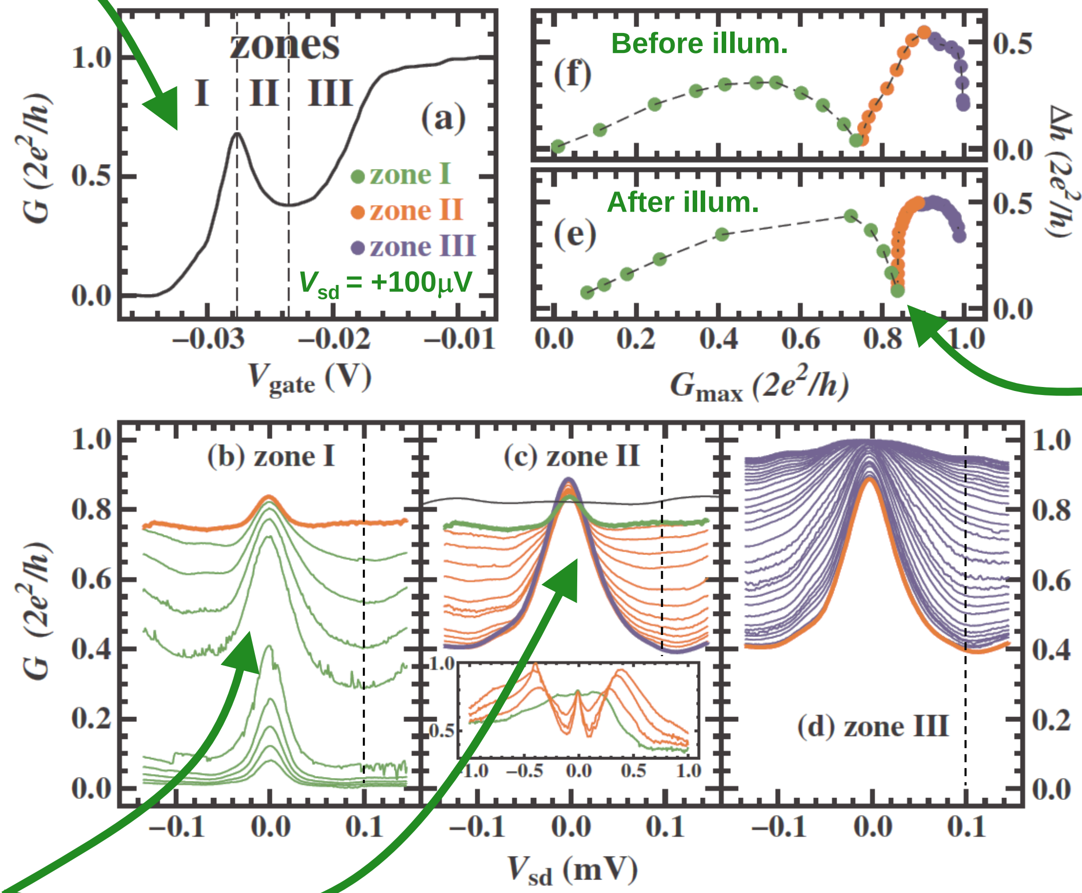


F. Sfigakis *et al.*, PRL 100, 026807 (2008).



A deeper analysis of the zero-bias peak

Look at the ZBP at different parts of the sub-G_0 conductance



Δh defined as G_{max} minus G at the local minimum on the RHS of the ZBP.

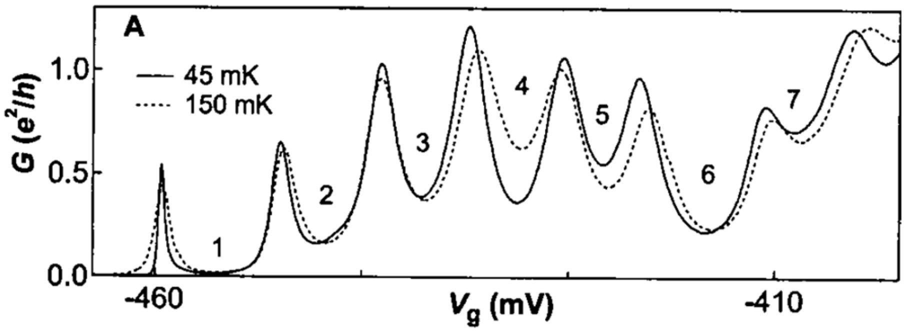
There is a local minimum at the apex of the CB peak.

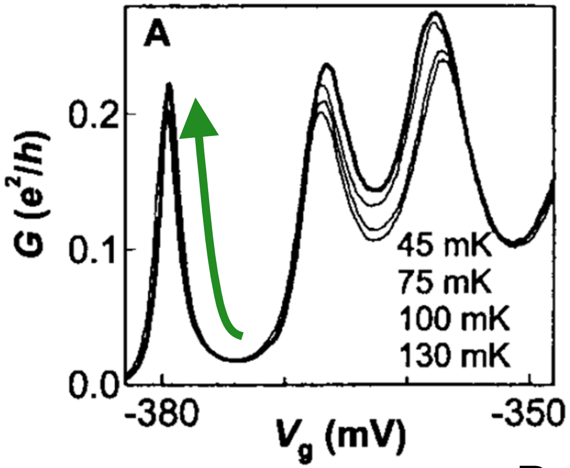
The zero-bias peak appears on both sides of the CB peak, would violate odd/even parity rule for Kondo.

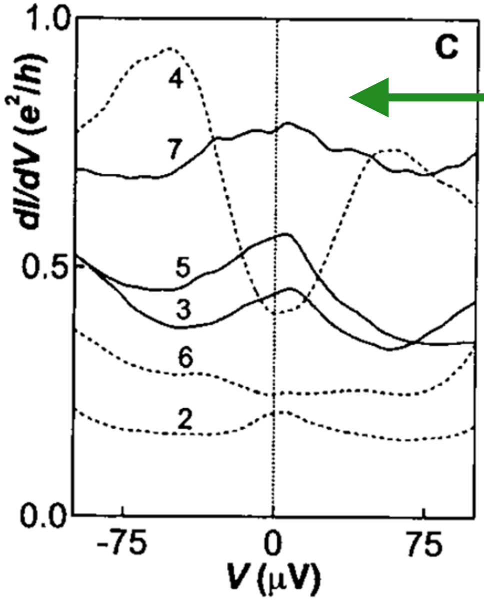
F. Sfigakis *et al.*, PRL 100, 026807 (2008).

A deeper analysis of the zero-bias peak

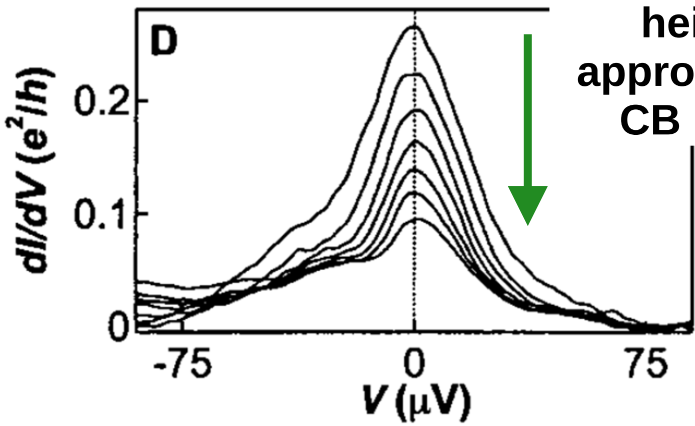
- **Odd/even parity and the apex minimum are also seen in dots.**





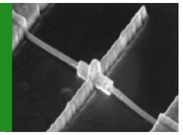


Odd valleys all have pronounced ZBPs, the even valleys don't.



Reduced ZBP height approaching CB peak

S.M. Cronenwett *et al.*, Science 281, 540 (1998).

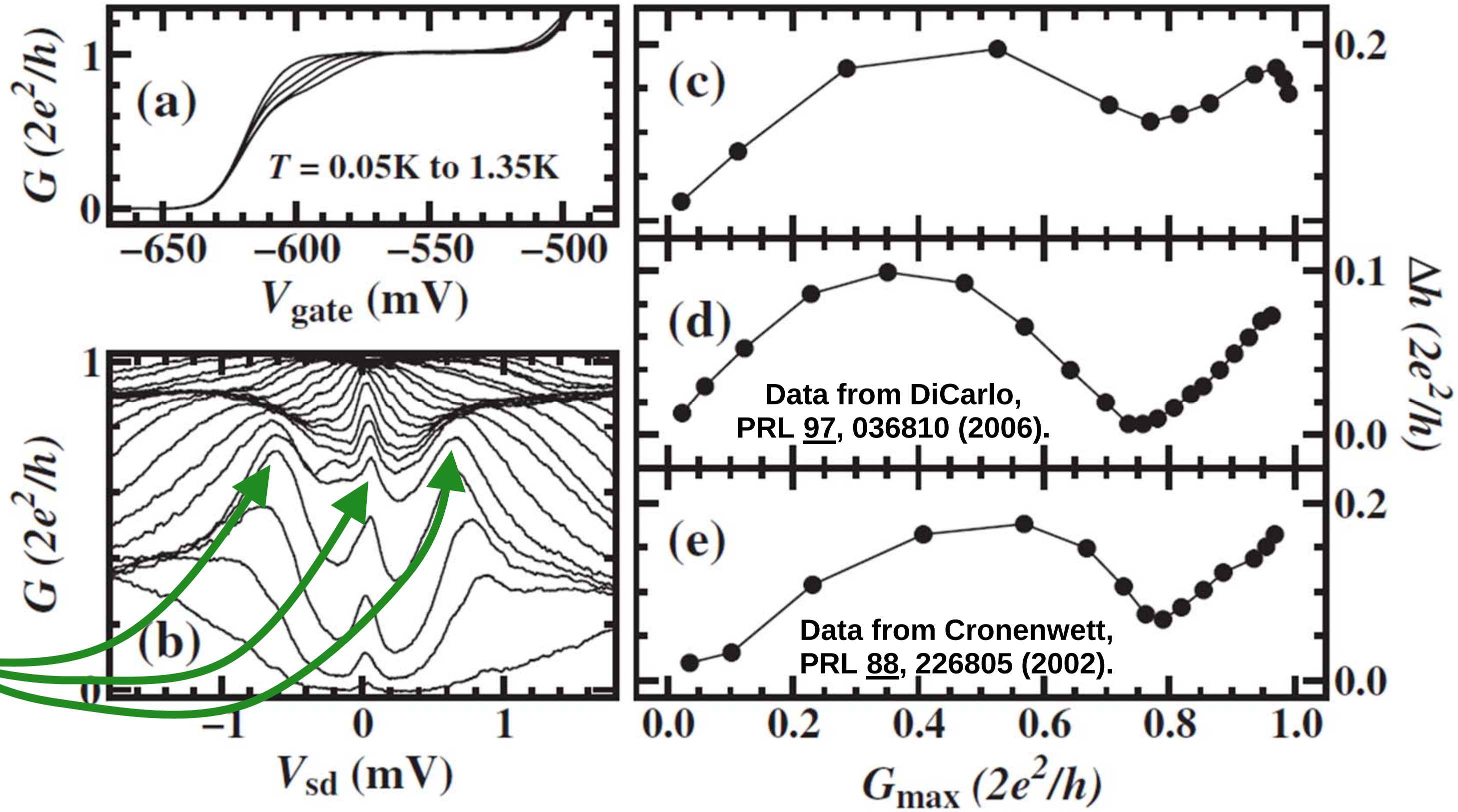


And a sample without a CB peak?

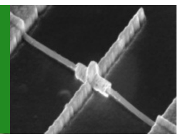
- **Data from a sharp QPC, not a quantum wire, with no CB peak… … little has changed here really. Suggests that the ZBP in QPCs might not be related to Kondo at all.**

Note the triple peak structure.

Sfigakis *et al.* suggest it might be resonant tunnelling via a bound or only partially extended state ε_{1D} due to exchange.

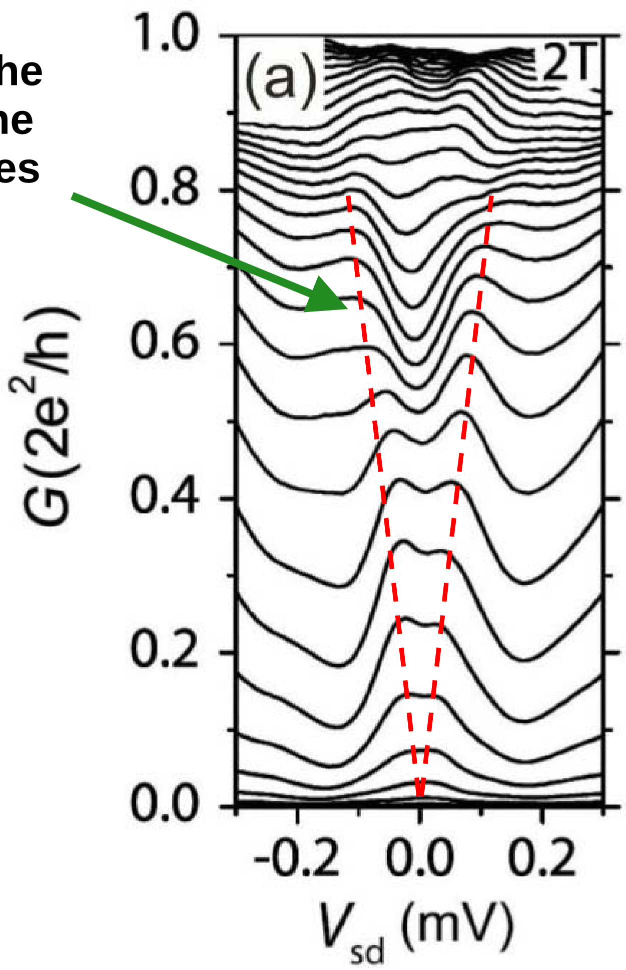


F. Sfigakis *et al.*, PRL 100, 026807 (2008).



Another look at the Zeeman splitting

Even at a fixed field, the Zeeman splitting of the zero-bias peak changes with *G*.



Considering that $\Delta E \propto g^{*}\mu_{B}B$, this can't simply be exchange enhancement, as *g should increase with decreasing density, forcing the Zeeman split ZBP further apart.**

Something more is going on here.

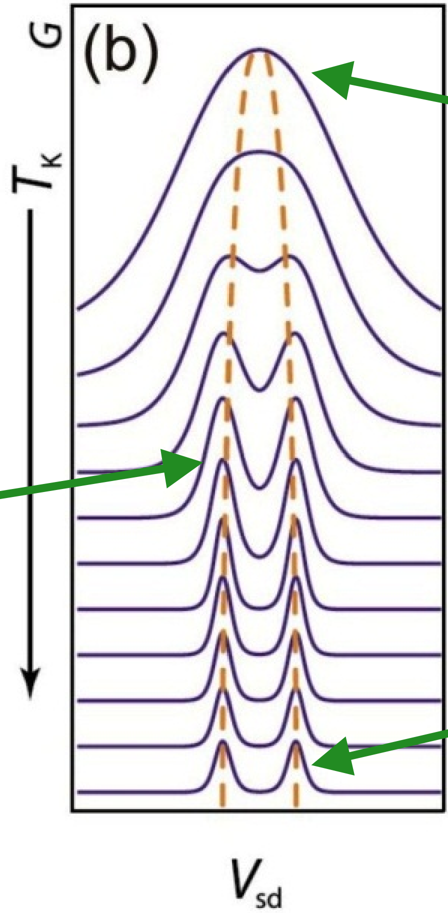
S. Sarkozy *et al.*, PRB 79, 161307 (2009).

What should happen?

- The schematic illustrates how the ZBP should evolve with T_K at fixed B and T. Essentially, the peak splitting is gate voltage independent at fixed B.

These traces would, in principle, overlay. They are offset vertically for clarity

At intermediate $T_{K,}$ where $g^*\mu_B B > k_B T_K > k_B T$, the ZBP is strong and the spin-splitting is resolved.



At large T_K, where $k_B T_K > g^*\mu_B B > k_B T$, the Zeeman splitting cannot be resolved (Kondo DOS width exceeds Zeeman splitting).

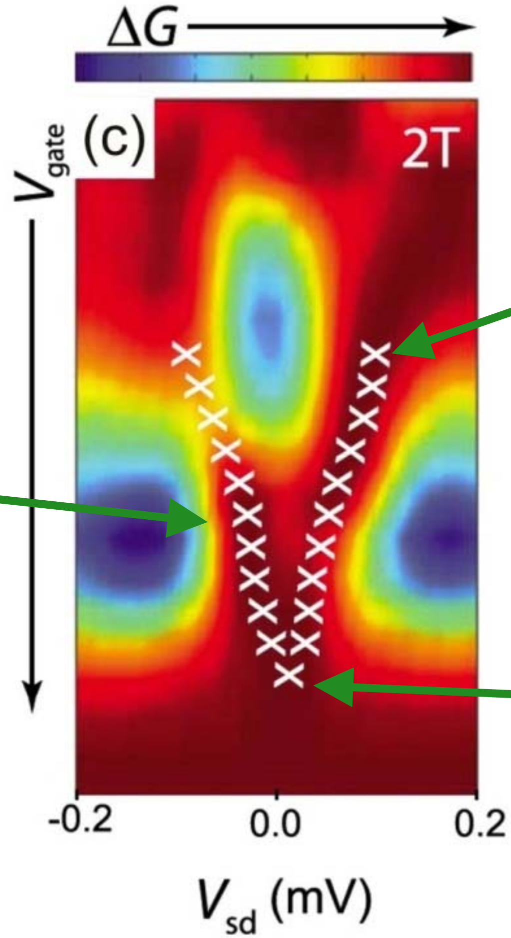
At small $T_{K,}$ where $g^*\mu_B B > k_B T > k_B T_K$, the Kondo correlations fail, and the ZBP weakens rapidly.

S. Sarkozy *et al.*, PRB 79, 161307 (2009).

What does happen?

- We know from earlier that T_K is V_g-dependent and decreases as V_g becomes more negative.

At intermediate $T_{K,}$ the ZBP should be strong and the spin-splitting is resolved. Most importantly, down here, the splitting should not change, only the strength of the ZBP.



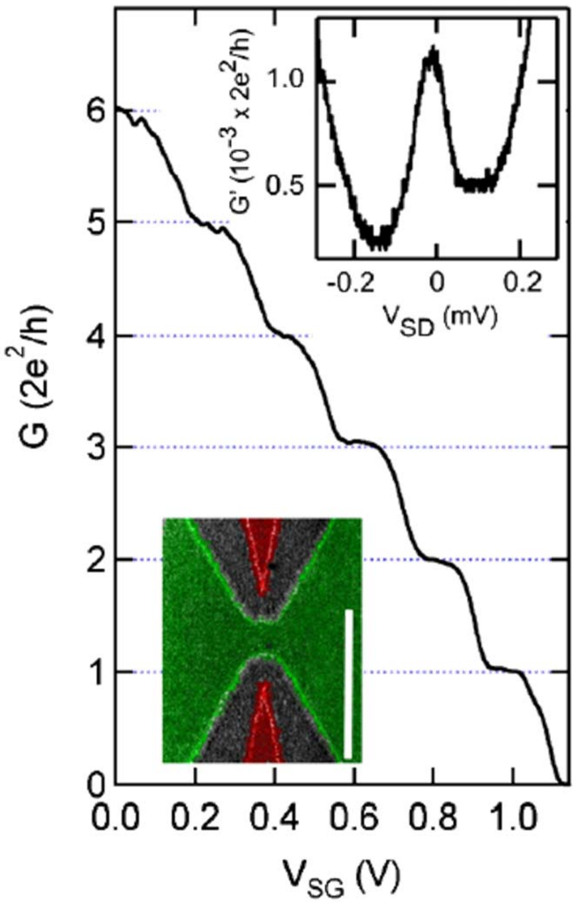
At large T_K, the Zeeman splitting should not be resolvable, but it is. It's more resolvable than anywhere else.

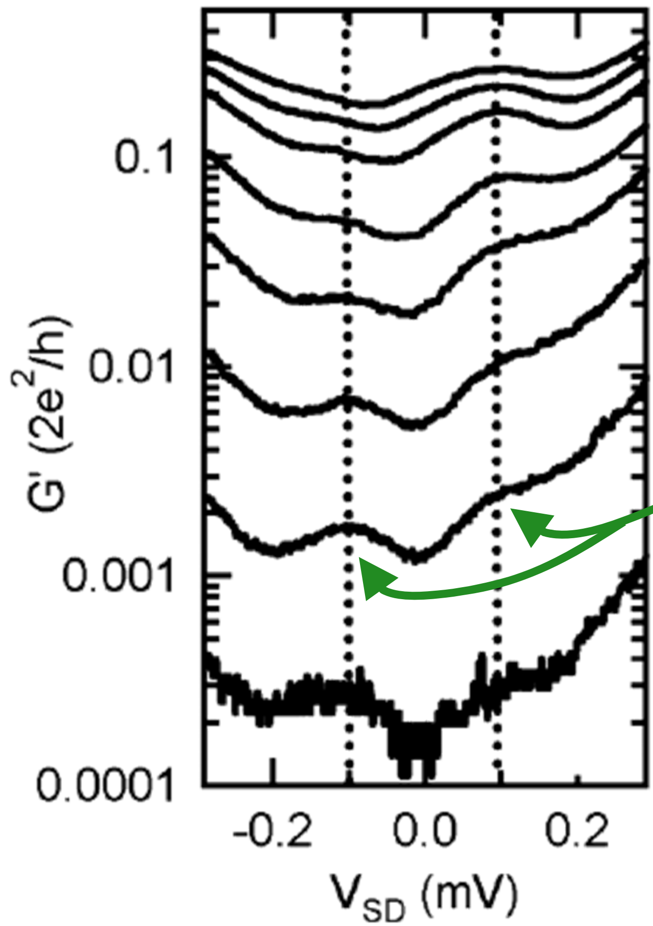
At small $T_{K,}$ the ZBP should be weak and the splitting resolved, it is not.

S. Sarkozy *et al.*, PRB 79, 161307 (2009).

To show that the prediction with T_K is true…

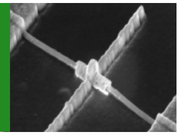
- **Data taken from an undoped QPC with holes rather than electrons (spin physics is slightly different).**





Splitting is constant at fixed *B* over >3 orders.

O. Klochan *et al.*, PRL 107, 076805 (2011).



Pulling the Sfigakis trick…

PRL 107, 076805 (2011) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2011

Observation of the Kondo Effect in a Spin-$\frac{3}{2}$ Hole Quantum Dot

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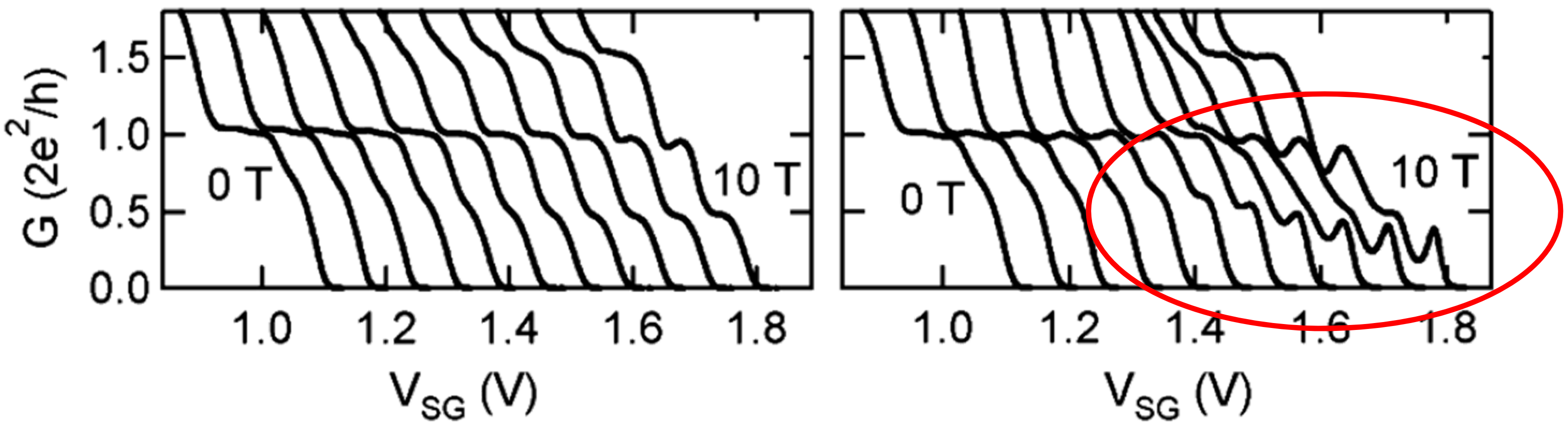
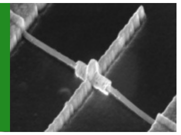
(Received 24 February 2011; published 12 August 2011)

We report the observation of Kondo physics in a spin-$\frac{3}{2}$ hole quantum dot. The dot is formed close to pinch-off in a hole quantum wire defined in an undoped AlGaAs/GaAs heterostructure. We clearly observe two distinctive hallmarks of quantum dot Kondo physics. First, the Zeeman spin splitting of the zero-bias peak in the differential conductance is independent of the gate voltage. Second, this splitting is twice as large as the splitting for the lowest one-dimensional subband. We show that the Zeeman splitting of the zero-bias peak is highly anisotropic and attribute this to the strong spin-orbit interaction for holes in GaAs.

DOI: 10.1103/PhysRevLett.107.076805 PACS numbers: 73.63.Rt, 73.23.Ad, 73.61.Ey, 73.63.Kv

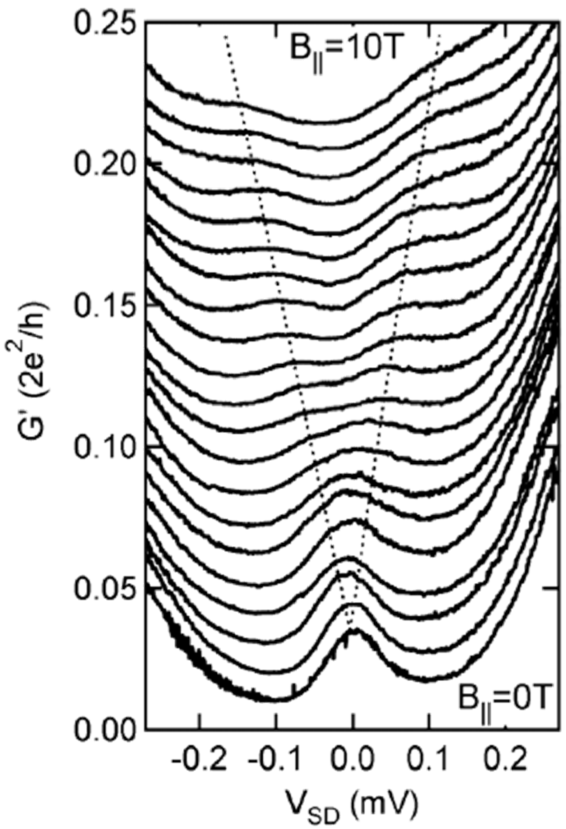




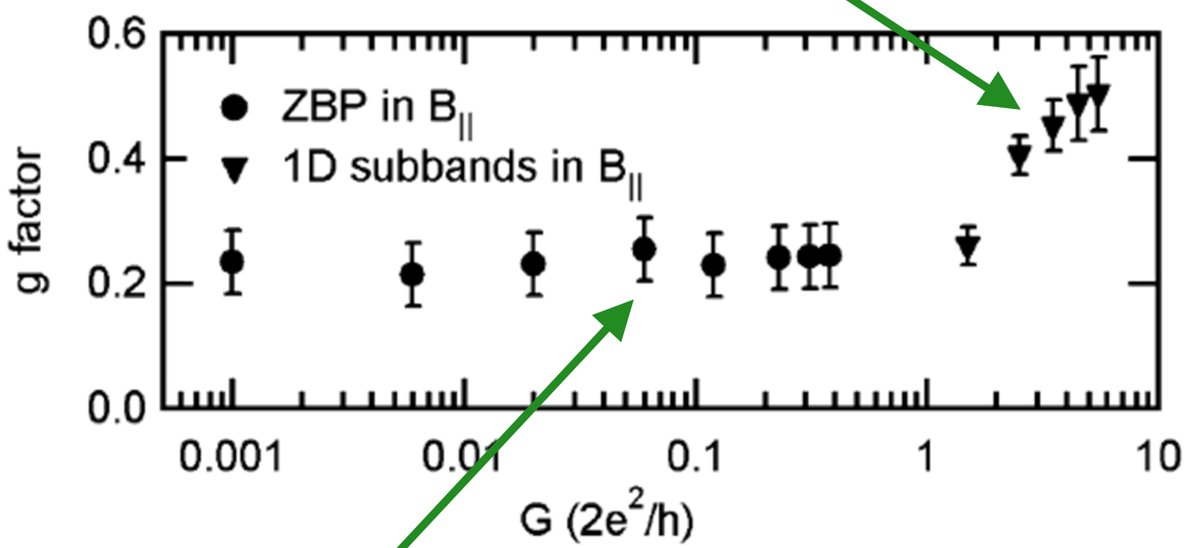
And that the Kondo spin-splitting really is $2g^*\mu_B B$

- **Unlike other experiments, no need for assumptions about *g**, we can measure it!**

Traces offset vertically for clarity

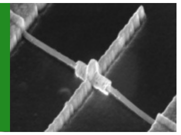


These are 1D *g*-factors, obtained from 1D plateau data using $\Delta E_Z = g^*\mu_B B$. (n.b. there is no exchange enhancement for (100) holes)



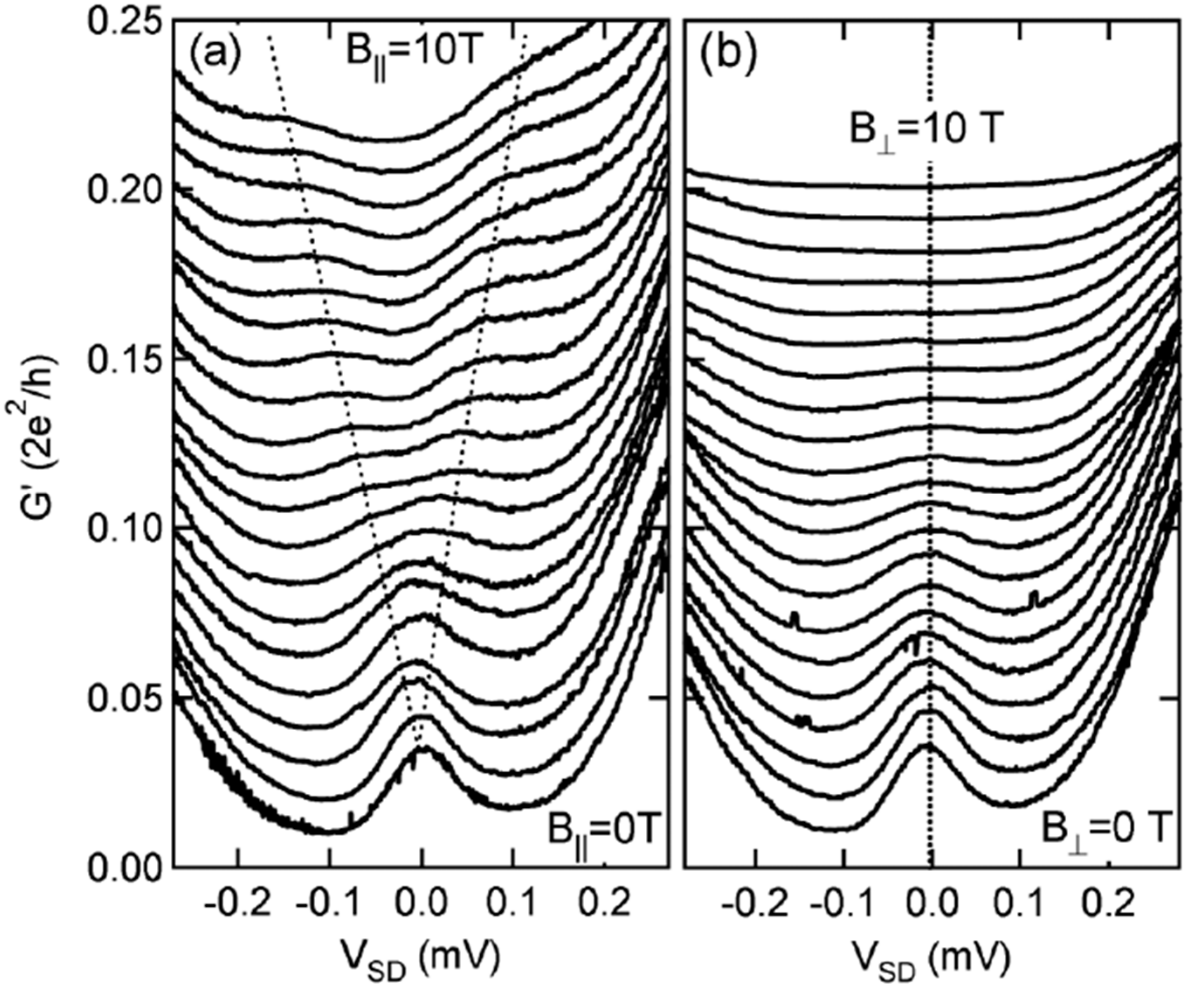
These are Kondo *g*-factors, obtained from ZBP data using $\Delta E_Z = 2g^*\mu_B B$.

O. Klochan *et al.*, PRL 107, 076805 (2011).



Here's where holes get interesting…

Traces offset vertically for clarity

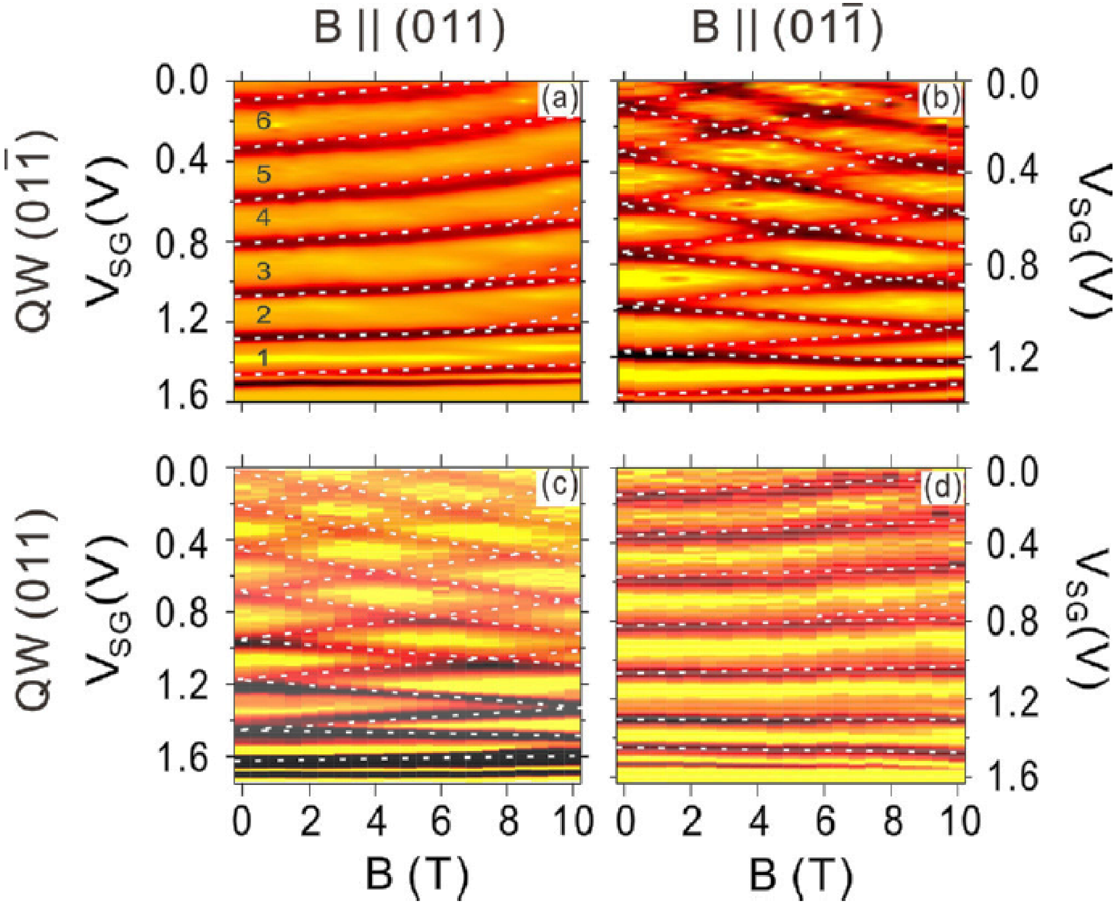


If you rotate the field by 90°, then the Zeeman splitting vanishes!

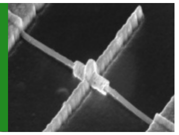
O. Klochan *et al.*, PRL 107, 076805 (2011).

Here's where holes get interesting…

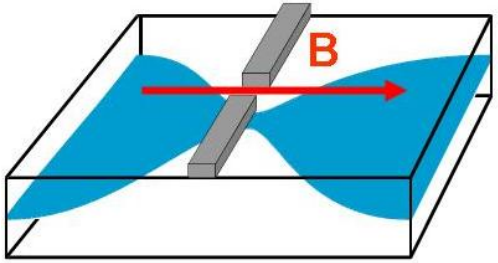
- **The 1D *g** in hole QPCs is strongly anisotropic. This is because holes have a much stronger strong spin-orbit interaction – electric fields affect spin behaviour.**



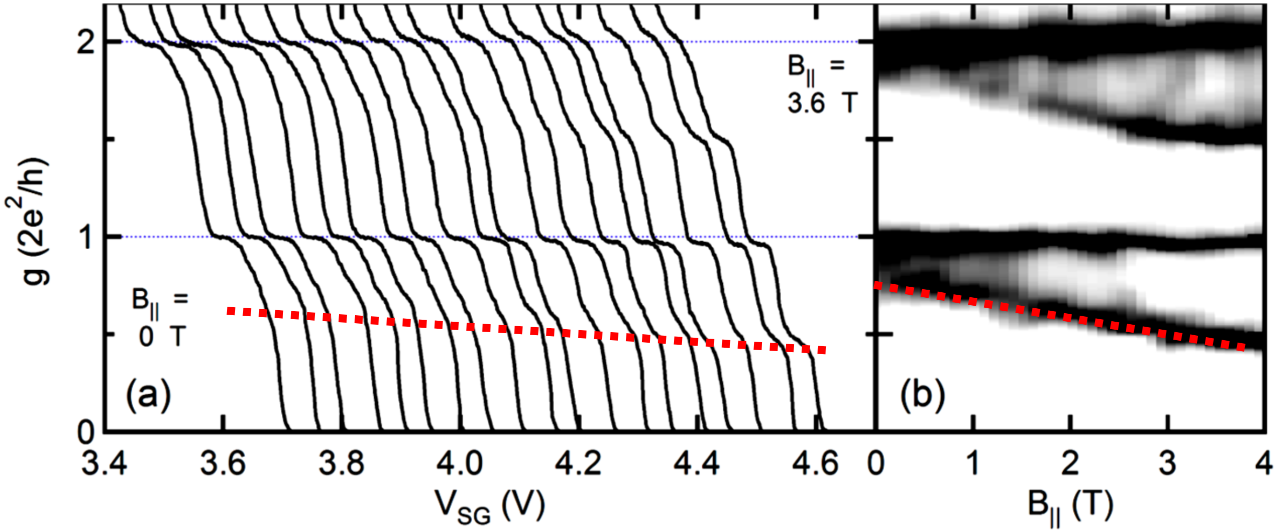
J.C.H. Chen *et al.*, New J. Phys. 12, 033043 (2010).

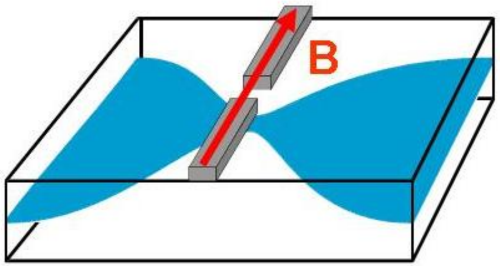


The same anisotropy happens for 0.7.

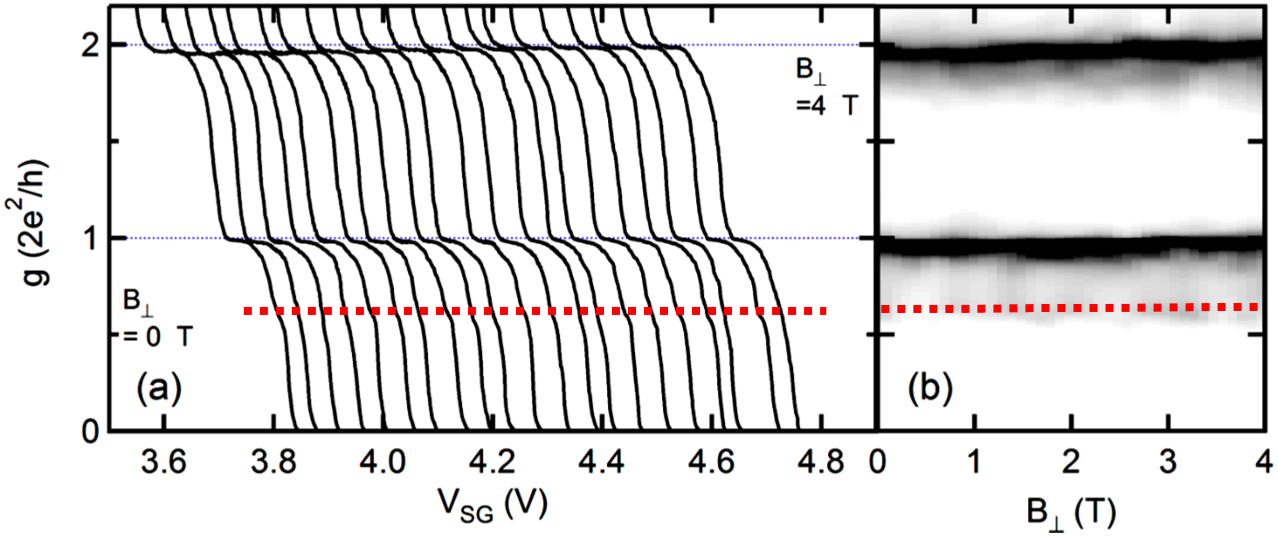


g*$_{||}$ > 0

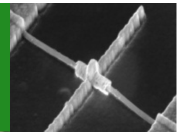




g*$_{\perp}$ ~ 0



R. Danneau *et al.*, PRL <u>100</u>, 016403 (2008).



So where does this get us to?

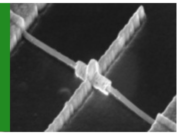
- **It is clear that sometimes quantum dot Kondo can turn up in QPCs, but not always.**

- **There is usually a zero bias peak in QPCs, but it is not always a signature of quantum dot Kondo in its typical manifestation.**

- **It is entirely unclear whether this is some more exotic manifestation of the Kondo phenomenon (e.g. multiple sites), or another effect entirely, or whether the zero bias peak below G_0 is just a natural artifact of QPCs in some way.**

- **It is probably fair to say that 0.7 and Kondo are separate and distinct phenomena, but many would argue that that was clear right from the beginning, and that Kondo is more the reason why you don't see 0.7 at low temperature, with 0.7 being a CB effect.**

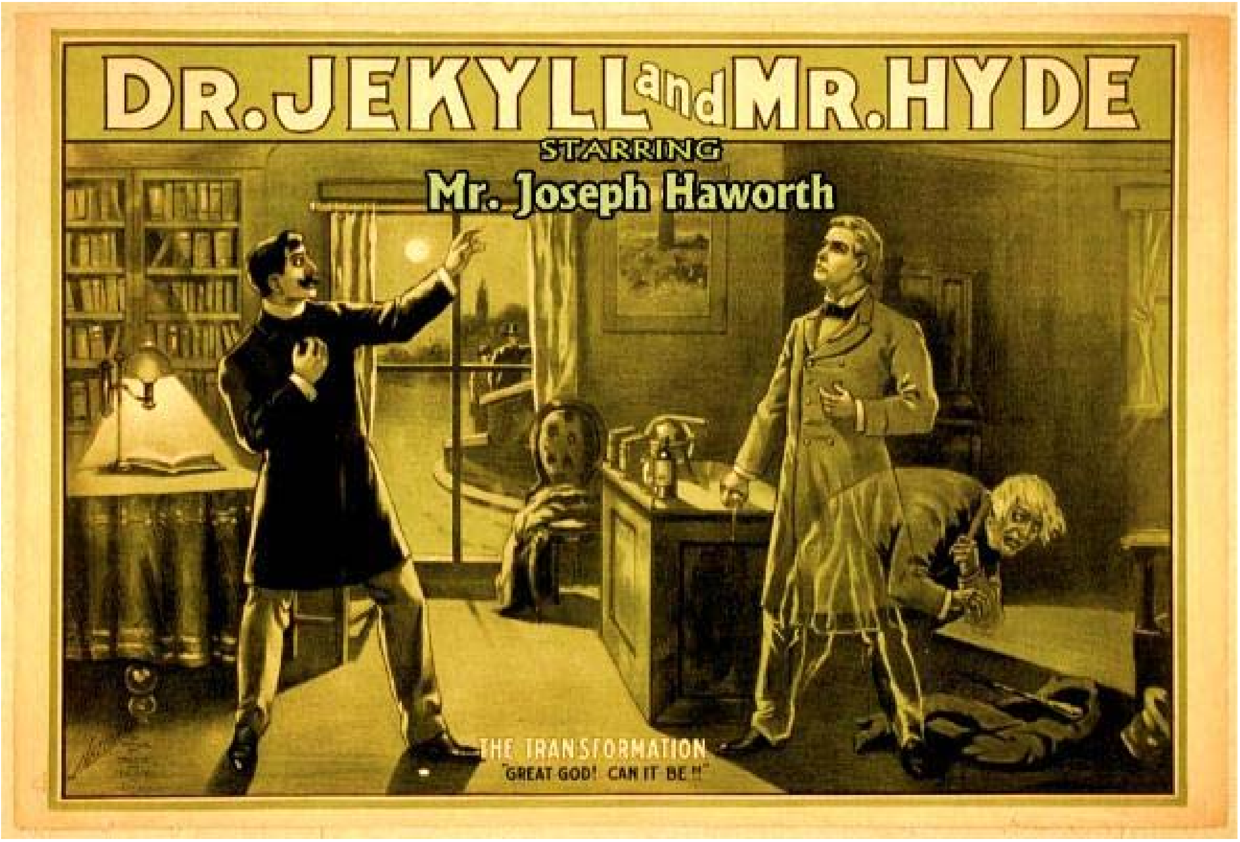
- **My current personal position is that 0.7 and Kondo are coincident phenomena reflecting the non-trivial potential at the center of the QPC. This non-trivial potential isn't just exchange and correlation, I think it also owes something to disorder. I am becoming more and more convinced that quasibound states happen a lot in real QPCs.**



What is the true role of Kondo?

One of the big problems with the field is that it has become somewhat polarized into ‘Kondo’ and ‘non-Kondo’ camps.

I think the truth lies somewhere in between.



What is the true role of Kondo?

One of the big problems with the field is that it has become somewhat polarized into ‘Kondo’ and ‘non-Kondo’ camps.

I think the truth lies somewhere in between.

“*The inferred remnant spin splitting at zero magnetic field is inconsistent with a Kondo model, however, and appears in agreement, instead, with models that predict a static spin polarization in the QPC.*”

Y. Yoon *et al.*, APL 94, 213103 (2009).

PRL **106,** 057203 (2011) PHYSICAL REVIEW LETTERS week ending 4 FEBRUARY 2011

Ferromagnetically Coupled Magnetic Impurities in a Quantum Point Contact

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We investigate the ground and excited states of interacting electrons in a quantum point contact using an exact diagonalization method. We find that strongly localized states in the point contact appear when a new transverse conductance channel opens and longitudinal resonant level is formed due to momentum mismatch. These localized states form magnetic impurity states which are stable in a finite regime of chemical potential and excitation energy. Interestingly, these magnetic impurities have ferromagnetic coupling, which sheds light on the experimentally observed puzzling coexistence of Kondo correlation and spin filtering in a quantum point contact.

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