"If it looks like Kondo, acts like Kondo, tastes like Kondo..."

# Is it Kondo?

(with deep apologies to Jun Kondo)

Joshua Folk, UBC

Postdocs and students:

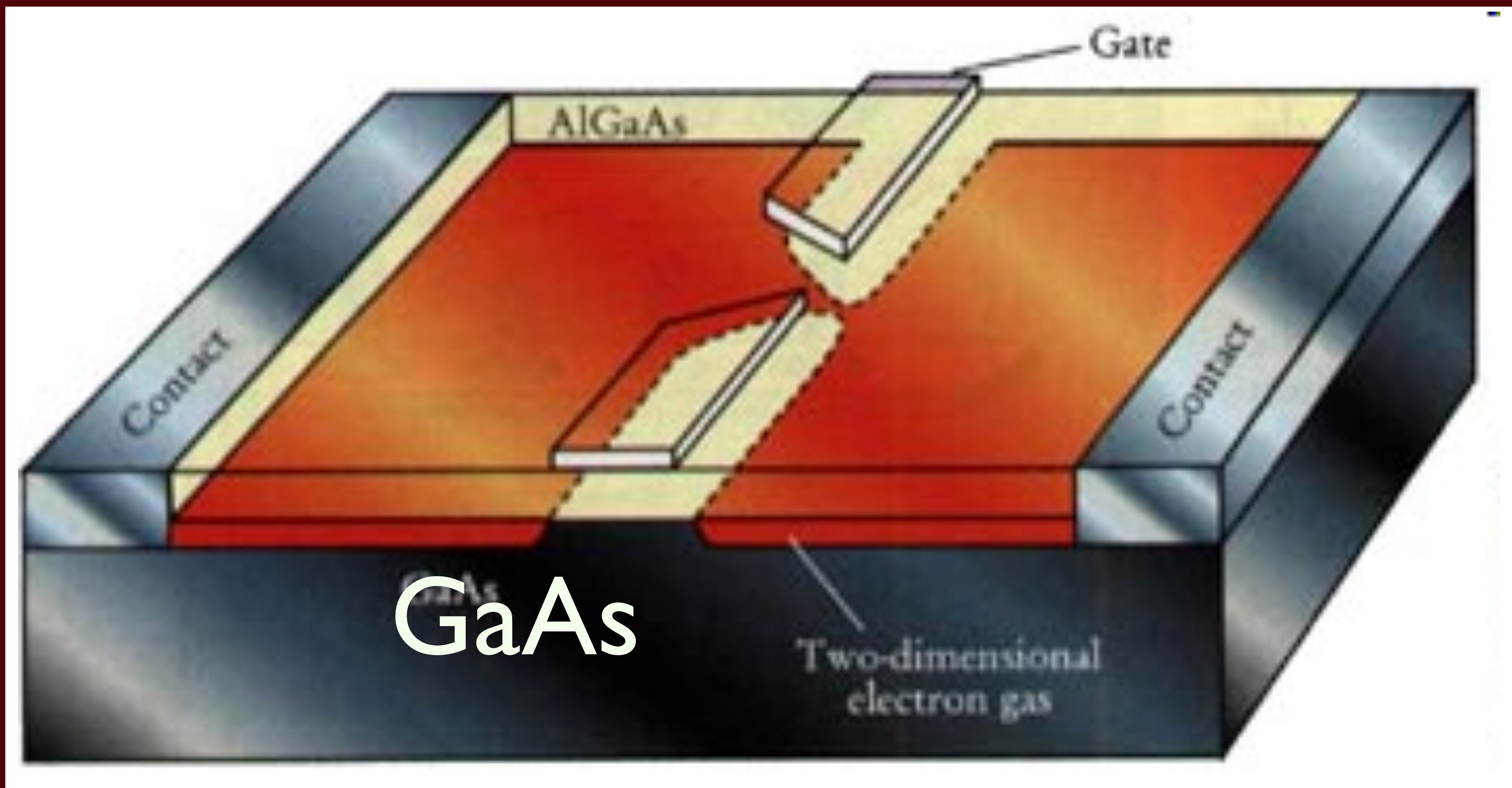
<u>Yuan Ren</u>
Wing Wa Yu
Sergey Frolov (ex)
Ananth Venkatesan (ex)

GaAs Heterostructures

W. Wegscheider

Funding: CIFAR, CFI, NSERC

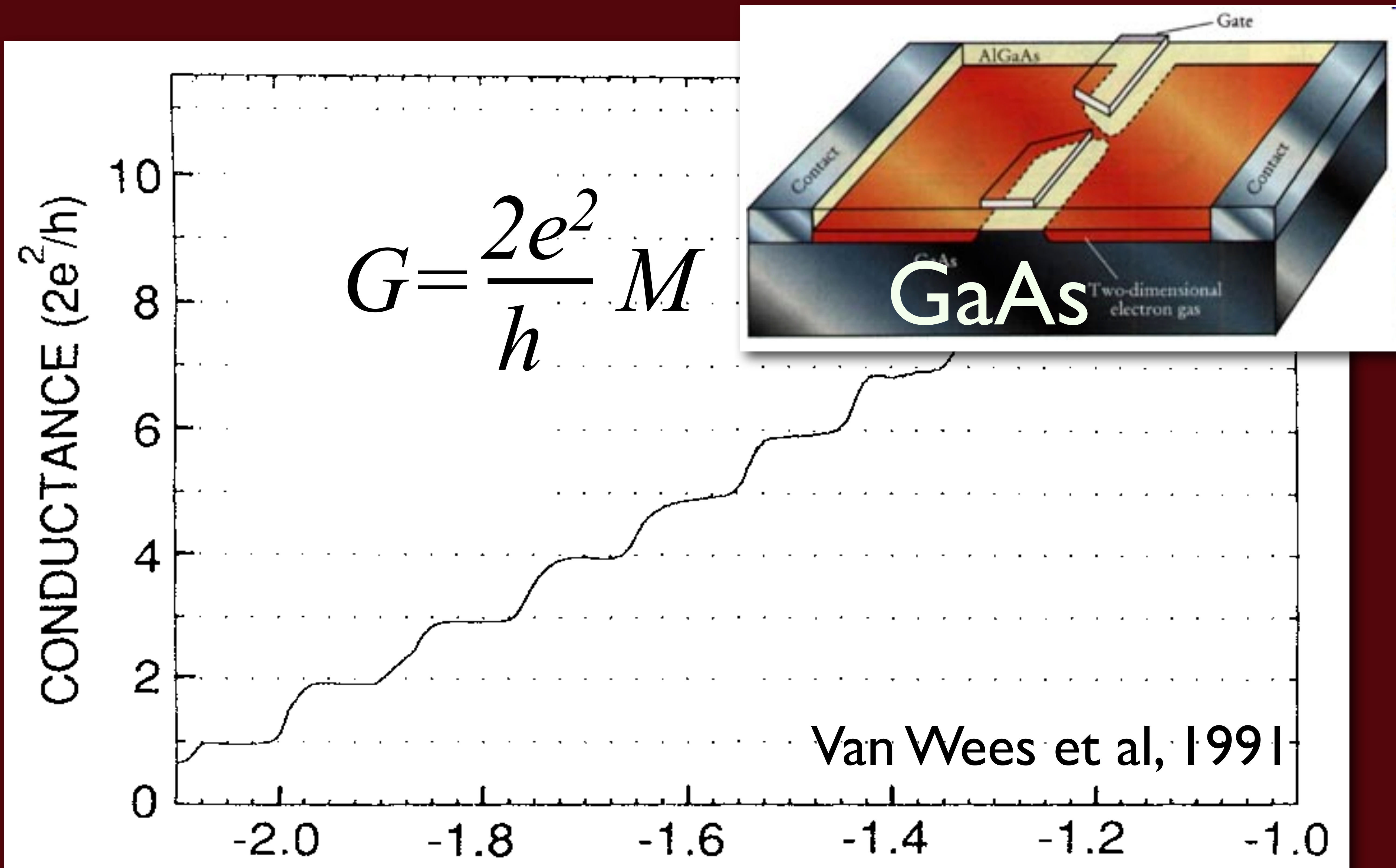
# Quantum point contacts




Constriction width ~ $\lambda_F$ $\Rightarrow$

Waveguide transmission modes

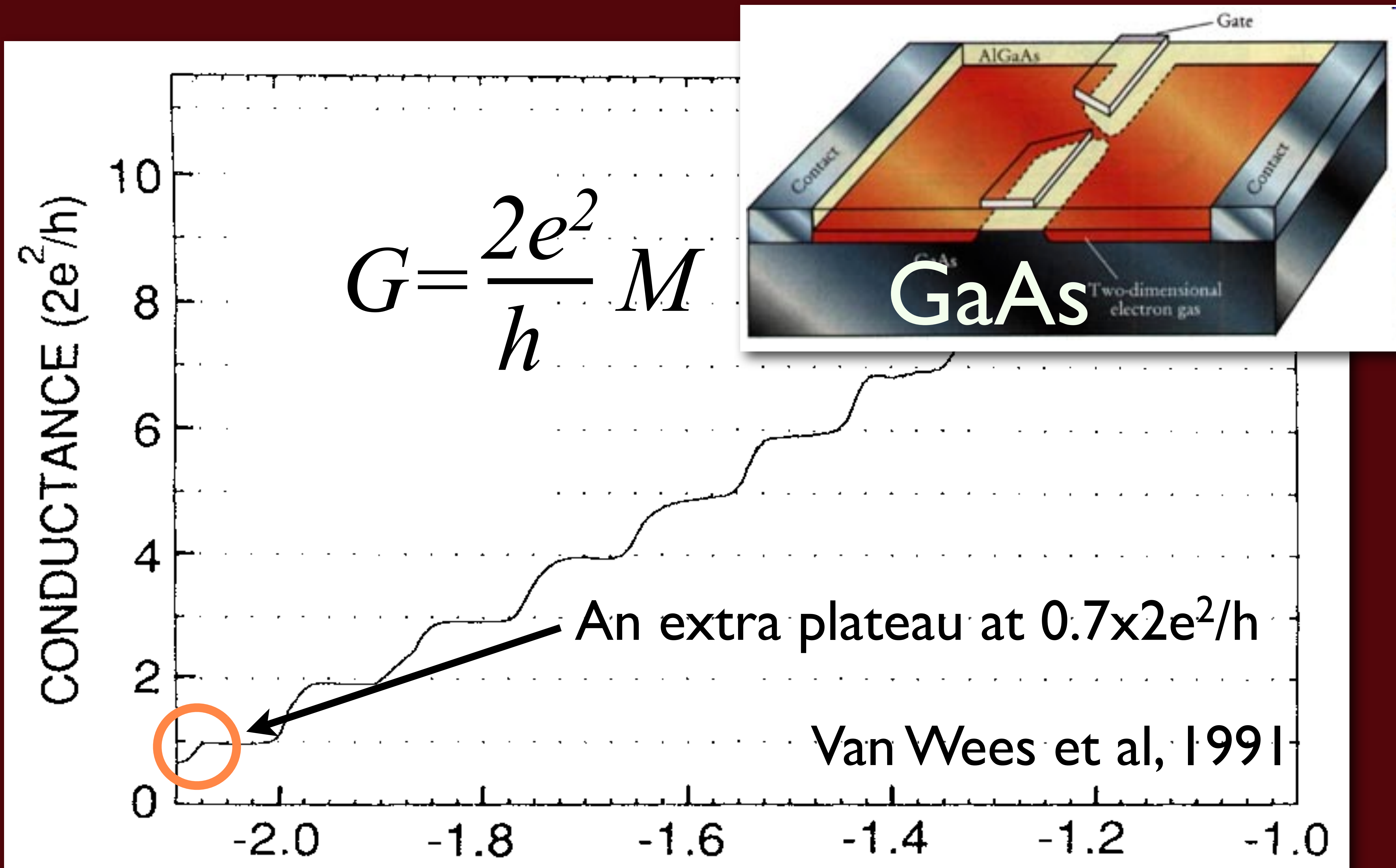
# Quantum point contacts




$$G = \frac{2e^2}{h} M$$

Van Wees et al, 1991

# A clue that something subtle is going on...

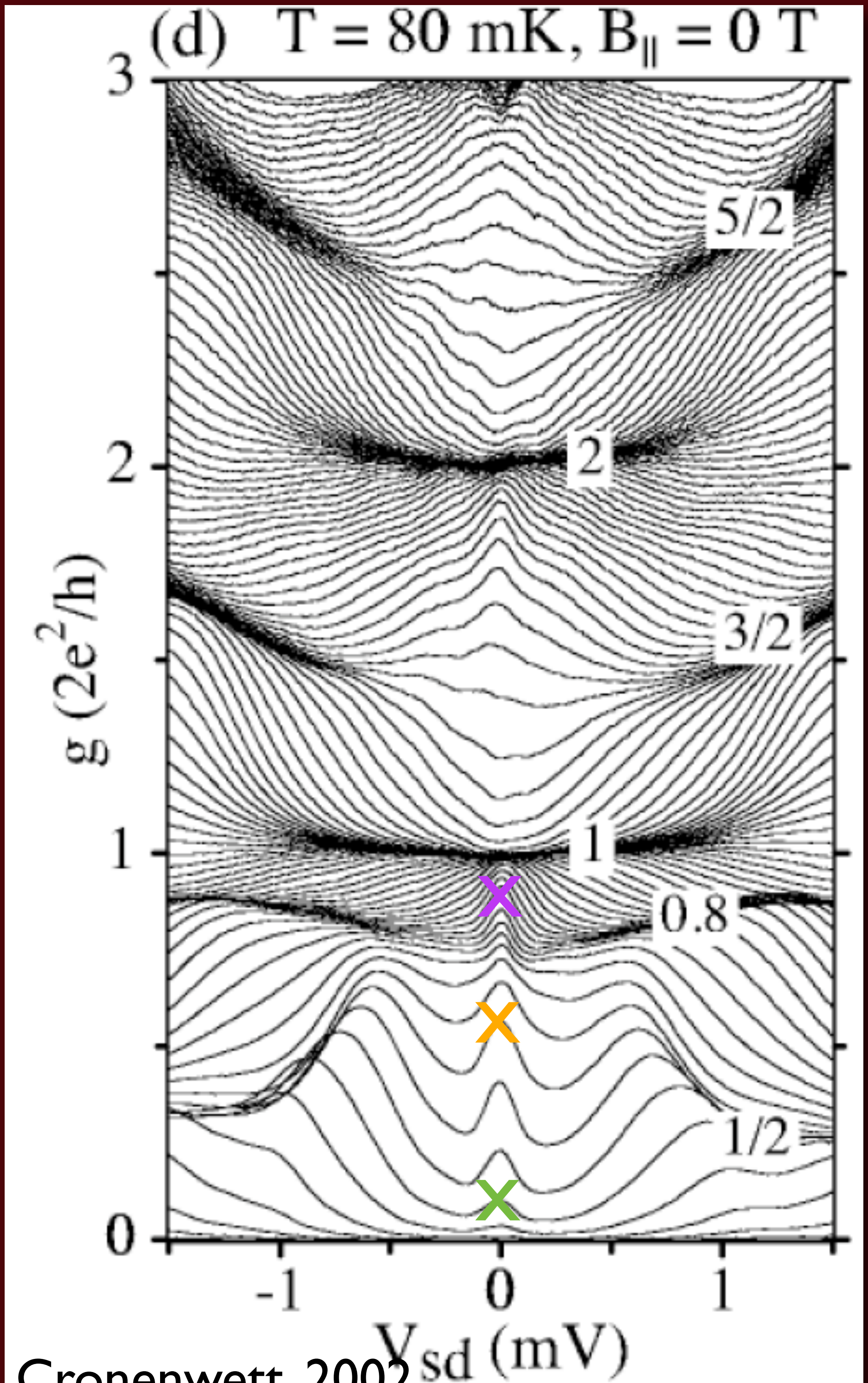



$$G = \frac{2e^2}{h} M$$

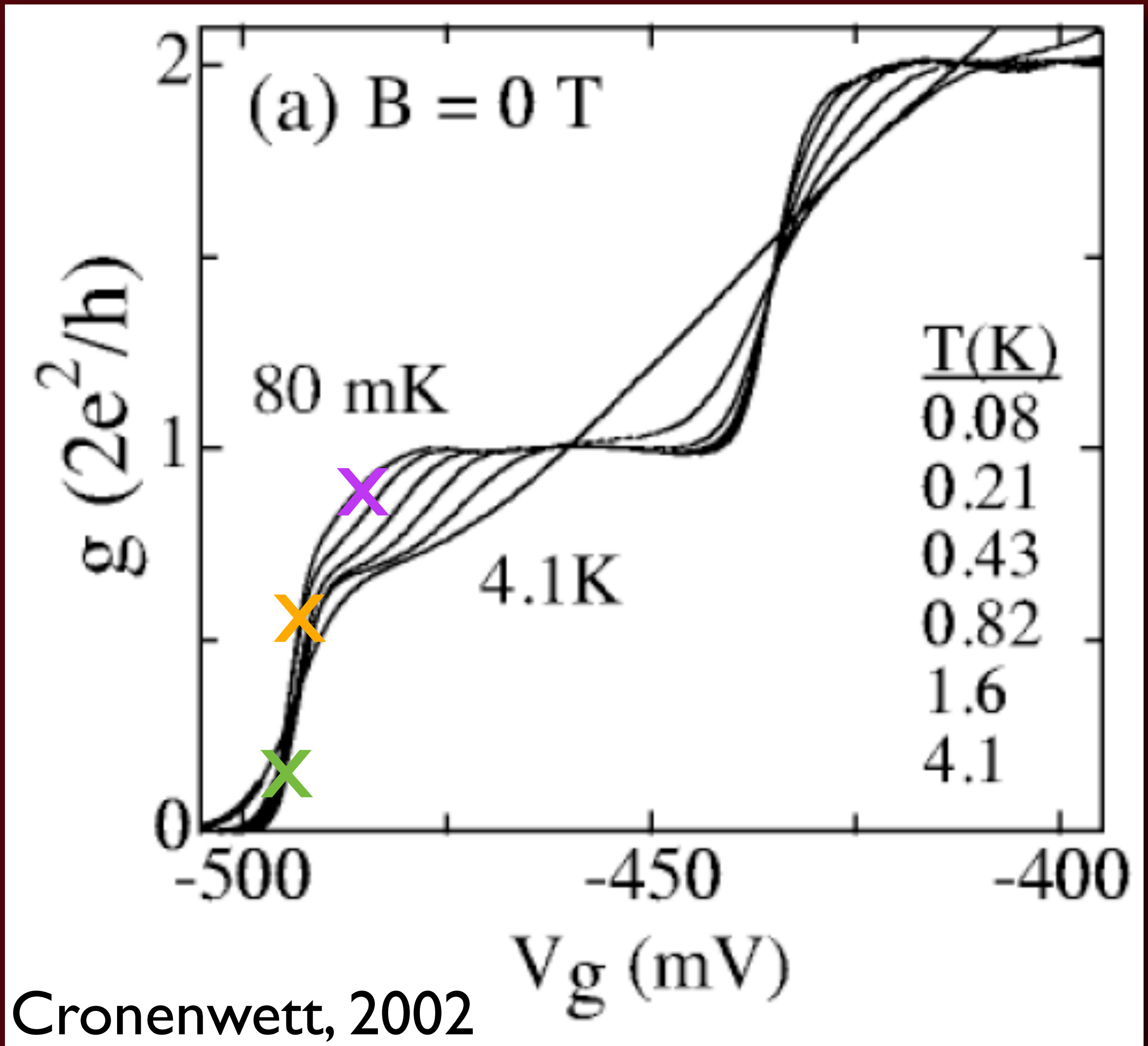
An extra plateau at $0.7 \times 2e^2/h$

Van Wees et al, 1991

# Low energy features: the zero bias anomaly




Cronenwett, 2002




Cronenwett, 2002

# A multitude of explanations

## Possible Spin Polarization in a One-Dimensional Electron Gas

K. J. Thomas, J. T. Nicholls, M. Y. Simmons, M. Pepper, D. R. Mace, and D. A. Ritchie
*Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE, United Kingdom*
(Received 4 March 1996)

In zero magnetic field, conductance measurements of clean one-dimensional (1D) constrictions defined in GaAs/AlGaAs heterostructures show up to 26 quantized ballistic plateaus, as well as a structure close to $0.7(2e^2/h)$. In an in-plane magnetic field all the 1D subbands show linear Zeeman splitting, and in the wide channel limit the $g$ factor is $|g| = 0.4$, close to that of bulk GaAs. For the last subband, spin splitting originates from the structure at $0.7(2e^2/h)$, indicating spin polarization at $B = 0$. The measured enhancement of the $g$ factor as the subbands are depopulated suggests that the "0.7 structure" is induced by electron-electron interactions. [S0031-9007(96)00520-0]

## Spin-Incoherent Transport in Qu

W. K. Hew, K. J. Thomas, M. Pepper, I. Farrer, D. Anderson
*Cavendish Laboratory, J. J. Thomson Avenue, Cambridge*
(Received 22 December 2007; published

When a quantum wire is weakly confined, a conductance plat
carrier density in zero magnetic field accompanied by a gradual suppression of the $2e^2/h$ plateau.
Applying an in-plane magnetic field $B_{\|}$ does not alter the value of this quantization; however, the $e^2/h$
plateau weakens with increasing $B_{\|}$ up to 9 T, and
restores the $2e^2/h$ plateau. Our results are consiste
wire.

## Low-Temperature Fate of the 0.7 Structure in a Point Contact: A Kondo-like Correlated State in an Open System

S. M. Cronenwett,[1,2] H. J. Lynch,[1] D. Goldhaber-Gordon,[1,2] L. P. Kouwenhoven,[1,3] C. M. Marcus,[1] K. Hirose,[4] N. S. Wingreen,[5] and V. Umansky[6]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138*
[2]*Department of Physics, Stanford University, Stanford, California 94305-4060*
[3]*Department of Applied Physics and ERATO, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands*
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[5]*NEC Research Institute, 4 Independence Way, Princeton, New Jersey 08540*
[6]*Braun Center for Submicron Research, Weizmann Institute of Science, Rehovot 76100, Israel*
(Received 31 January 2002; published 20 May 2002)

Besides the usual conductance plateaus at multiples of $2e^2/h$, quantum point contacts typically show an extra plateau at $\sim 0.7(2e^2/h)$, believed to arise from electron-electron interactions that prohibit the two spin channels from being simultaneously occupied. We present evidence that the disappearance of the 0.7 structure at very low temperature signals the formation of a Kondo-like correlated spin state. Evidence includes a zero-bias conductance peak that splits in a parallel field, scaling of conductance to a modified Kondo form, and consistency between peak width and the Kondo temperature.

## Ferromagnetic Spin Coupling as

*Department of Physic*
(Received 17

We study one-dimensional itinera
origin of the 0.7 anomaly in quantum point contacts. Linear conductance calculations from the quantum
Monte Carlo technique for spin interactions of different spatial range suggest that $0.7(2e^2/h)$ anomaly results from a strong interaction of low-density conduction electrons to ferromagnetic fluctuations formed across the potential barrier. The conductance plateau appears due to the strong incoherent scattering at high temperature when the electron traversal time matches the time scale of dynamic ferromagnetic excitations.

# A multitude of explanations

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- Explains extra conductance plateau, but does not address zero bias anomaly.
- Spin current measurements detect no polarization at zero magnetic field (our group).

# A multitude of explanations

Possible Spin Polarization in a One-Dimensional Electron Gas

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K. Aryanpour and J. E. Han
*Department of Physics, SUNY at Buffalo, Buffalo, New York 14260, USA*
(Received 17 October 2008; published 5 February 2009)

We study one-dimensional itinerant electron models with ferromagnetic coupling to investigate the origin of the 0.7 anomaly in quantum point contacts. Linear conductance calculations from the quantum Monte Carlo technique for spin interactions of different spatial range suggest that $0.7(2e^2/h)$ anomaly results from a strong interaction of low-density conduction electrons to ferromagnetic fluctuations formed across the potential barrier. The conductance plateau appears due to the strong incoherent scattering at high temperature when the electron traversal time matches the time scale of dynamic ferromagnetic excitations.

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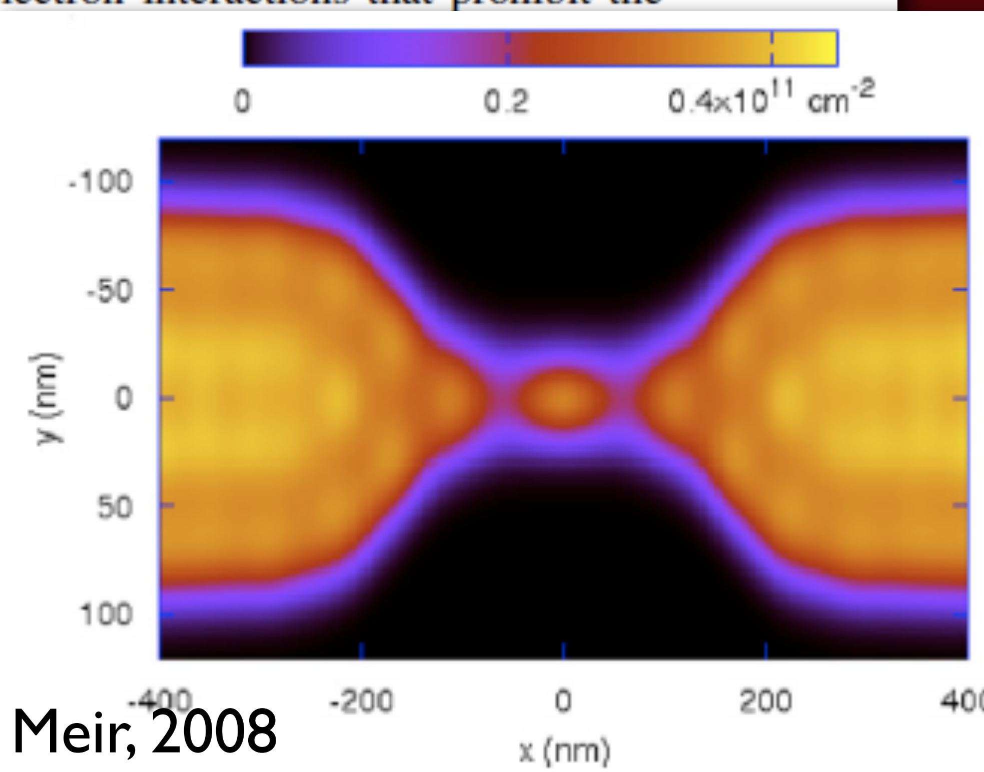
Density functional calculations justify "localized state" in clean point contact due to interactions




Meir, 2008

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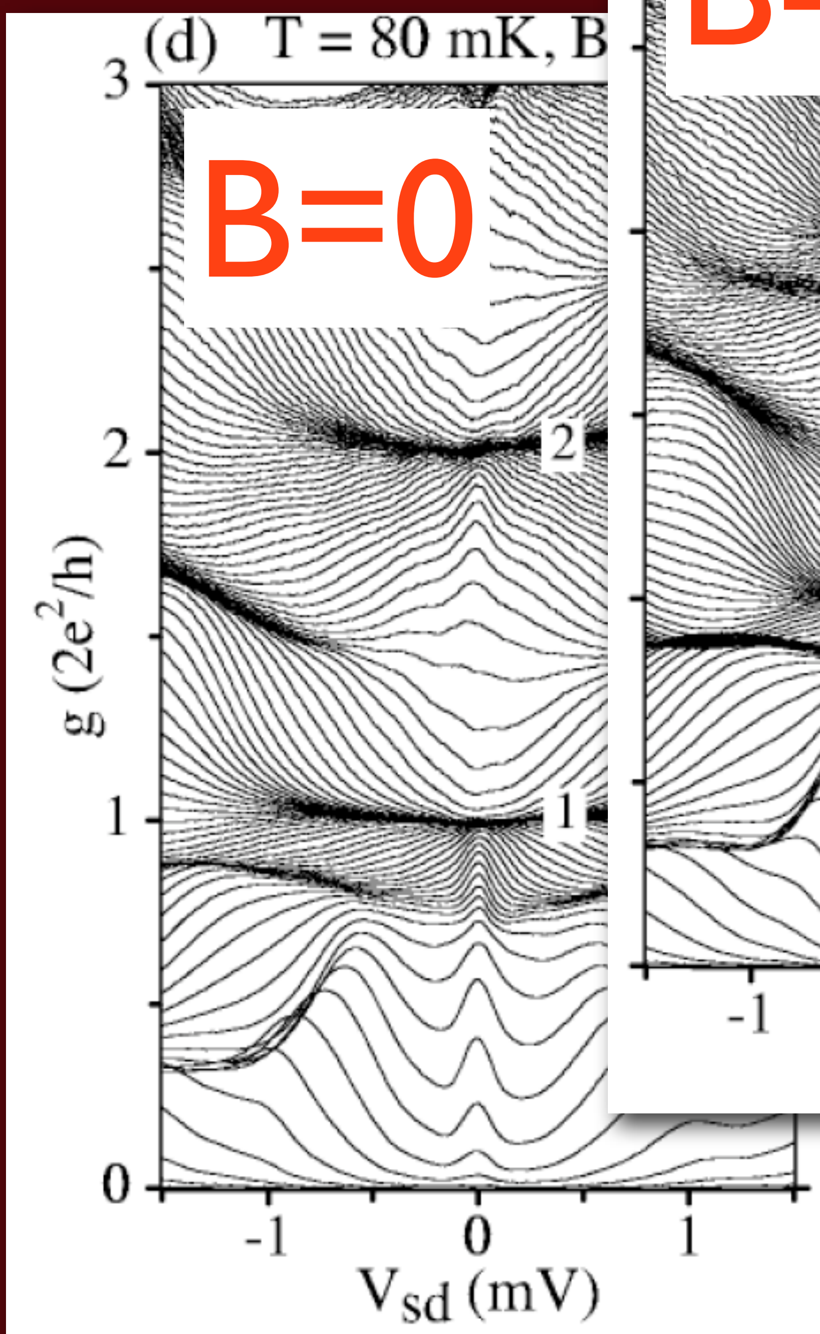
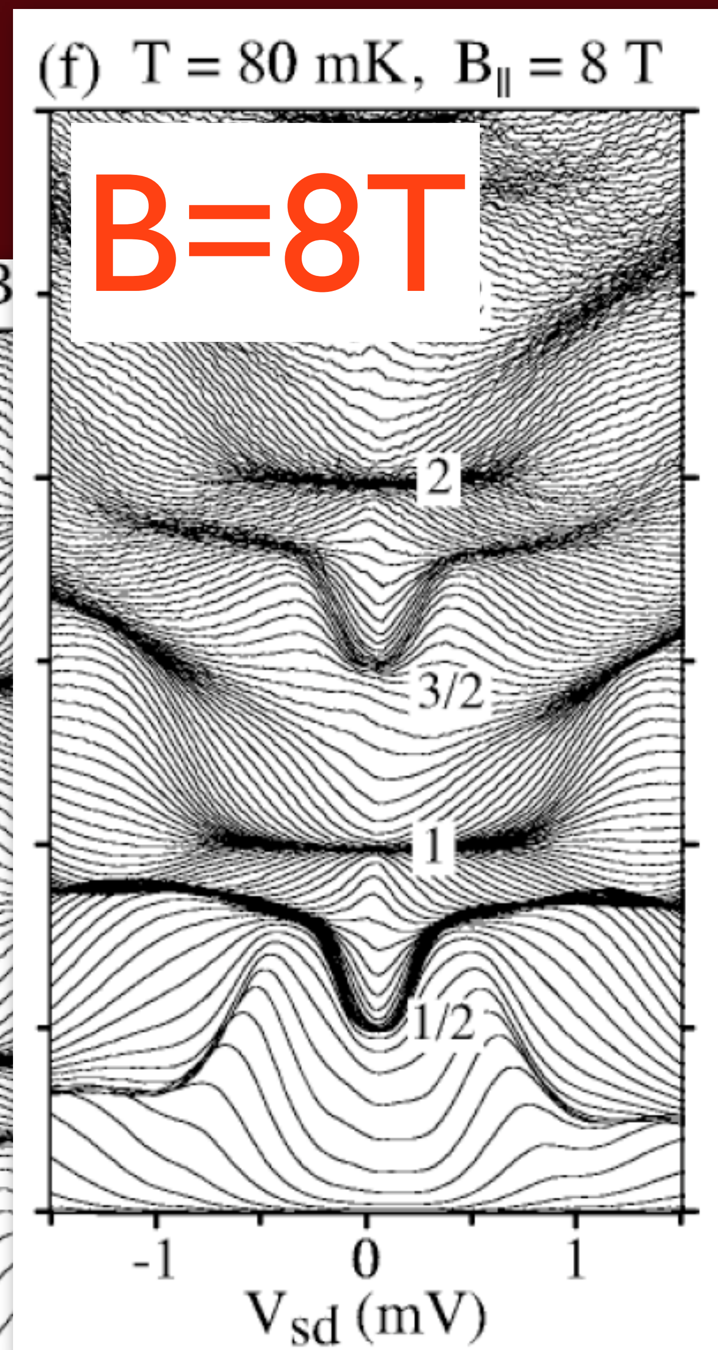
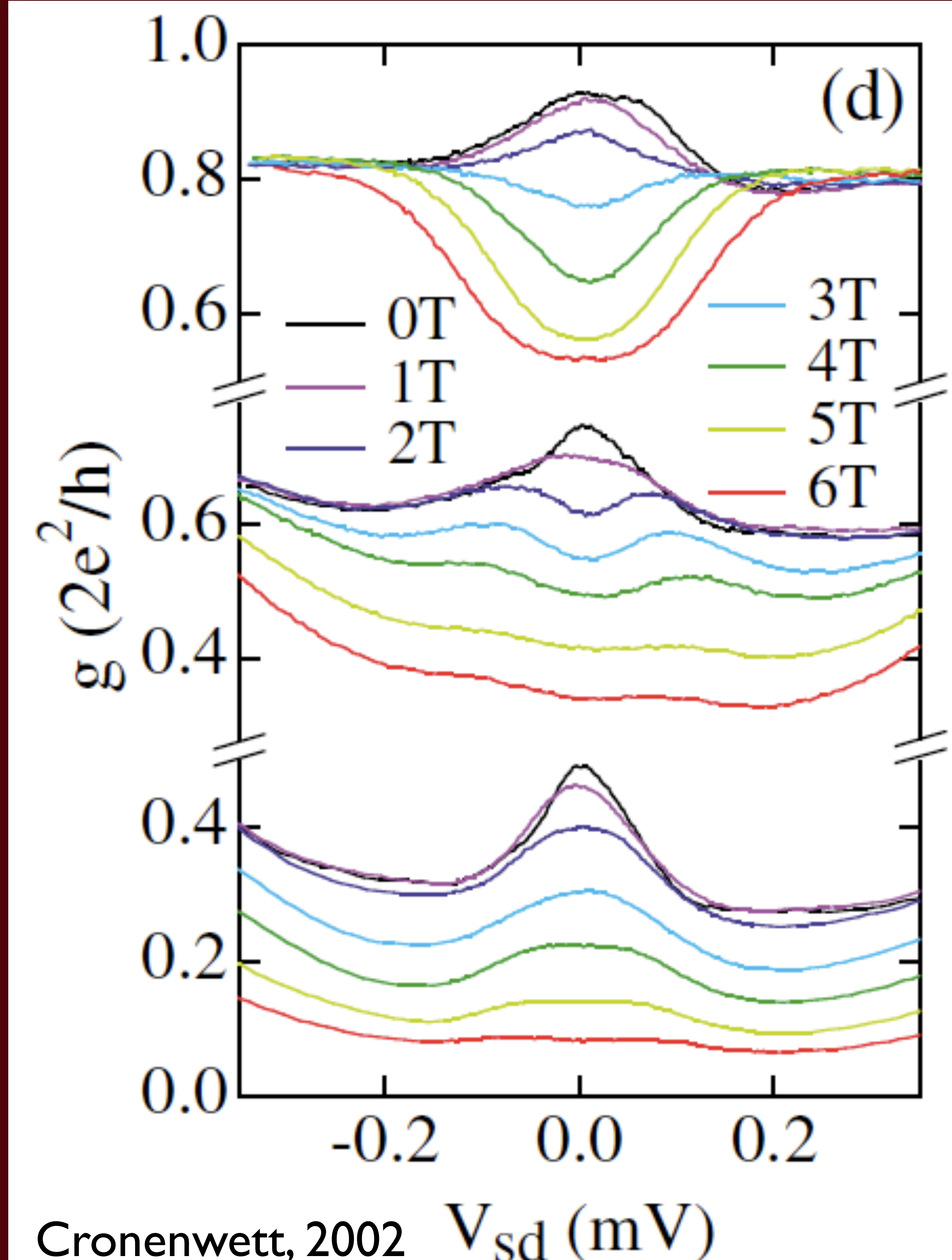
- Explains zero bias anomaly and extra plateau
- ZBA splits with field***
- Most popular theory for many years

# Magnetic field dependence of ZBA

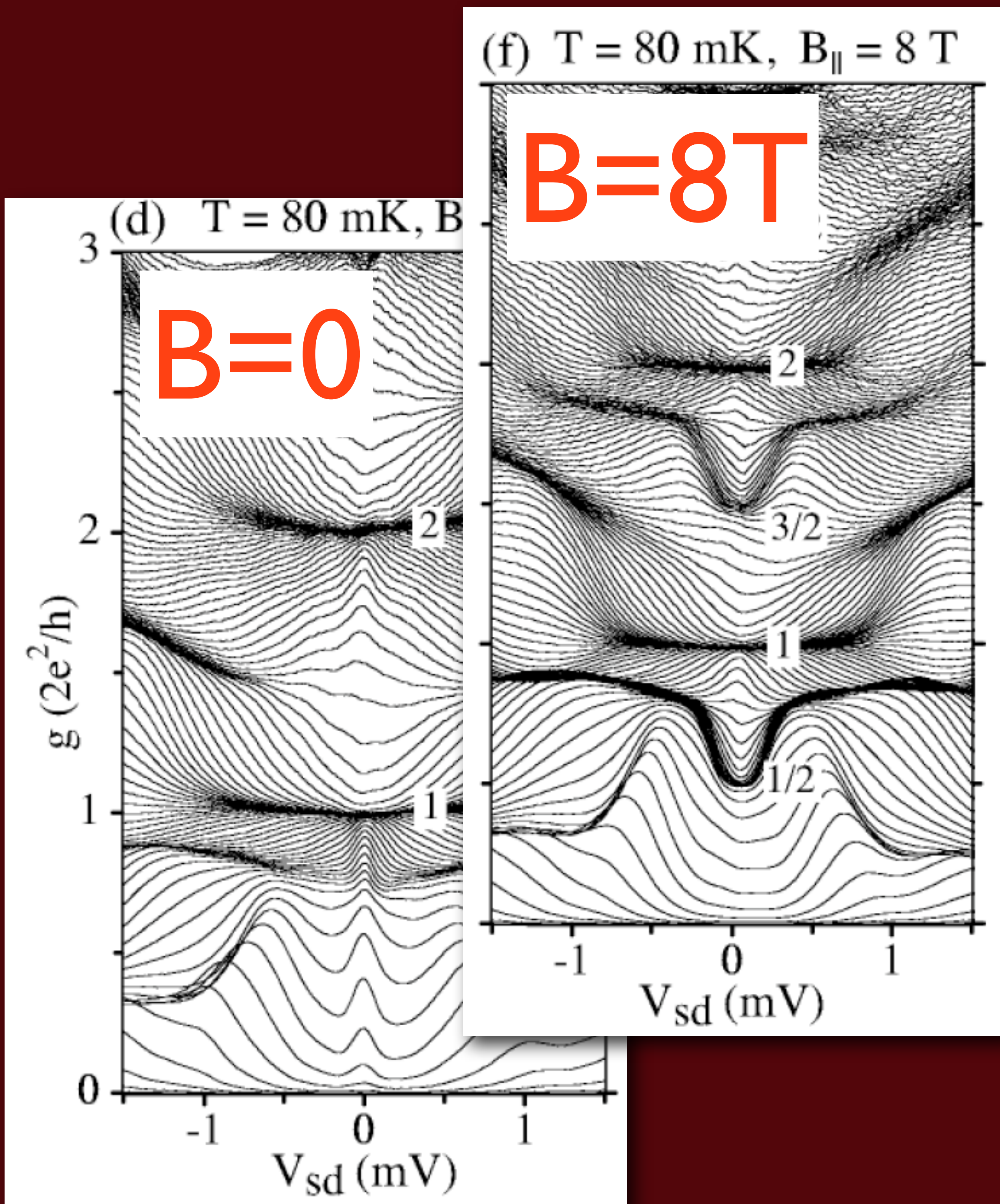


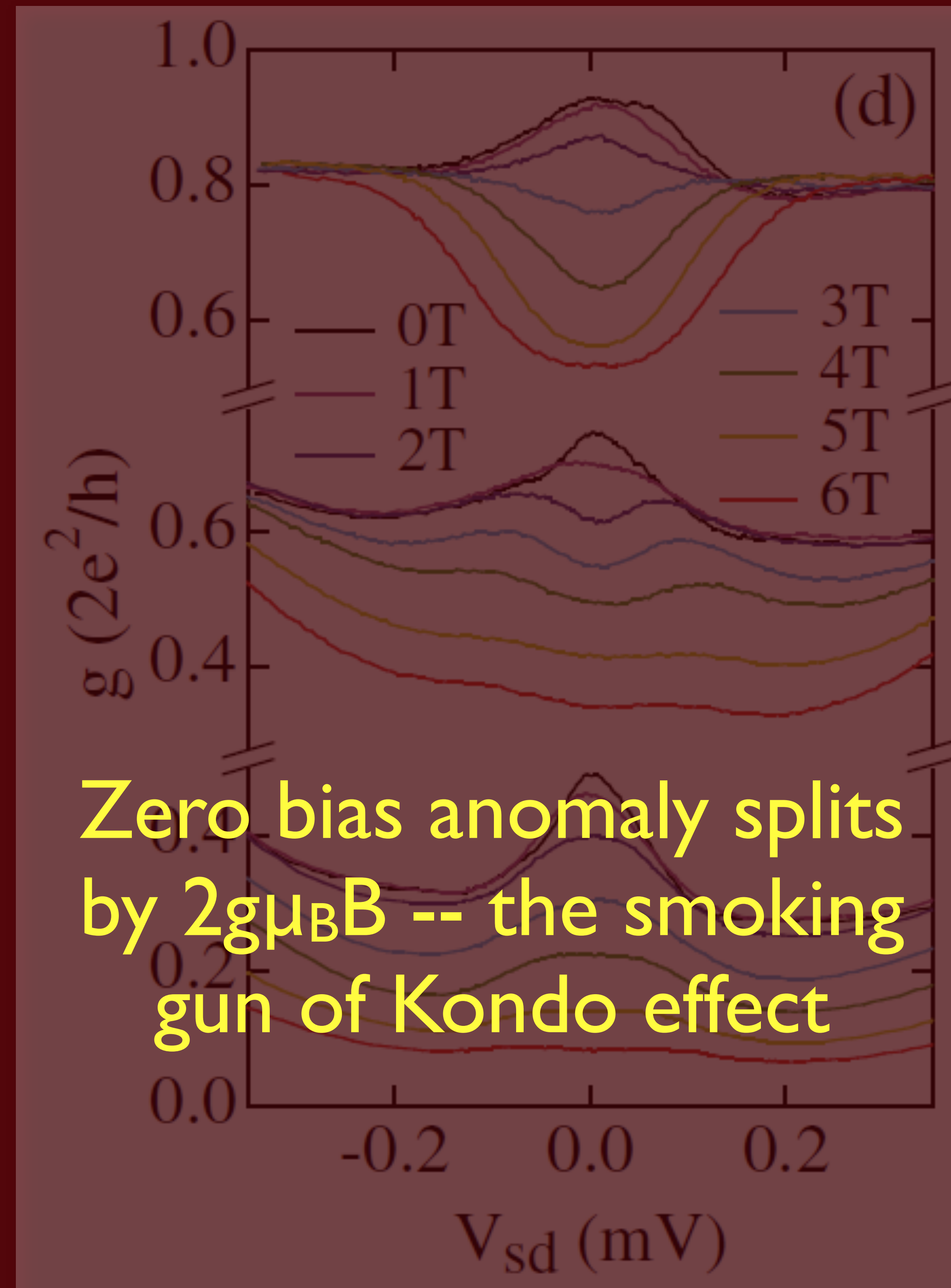




Cronenwett, 2002

# Magnetic field dependence of ZBA

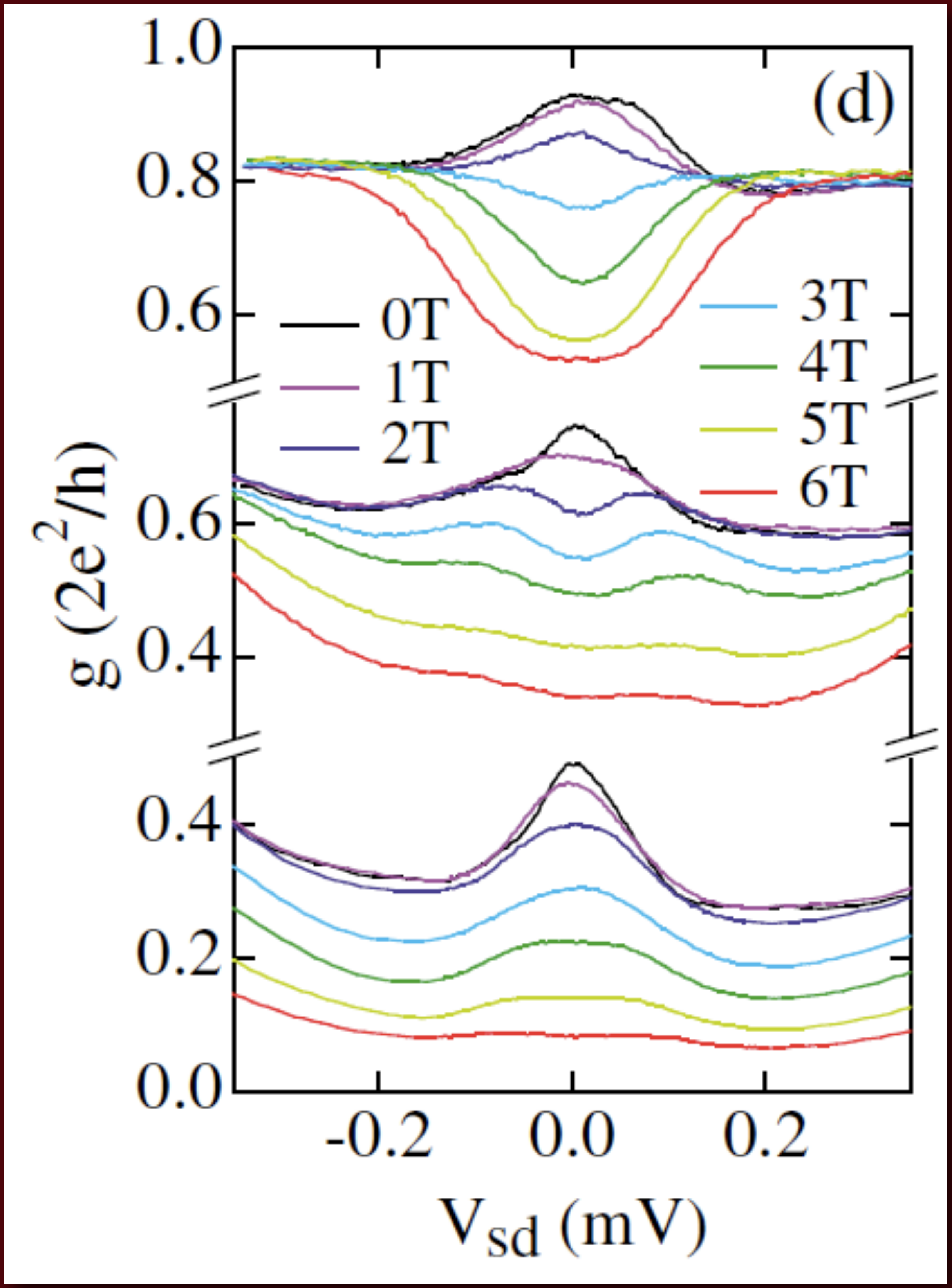


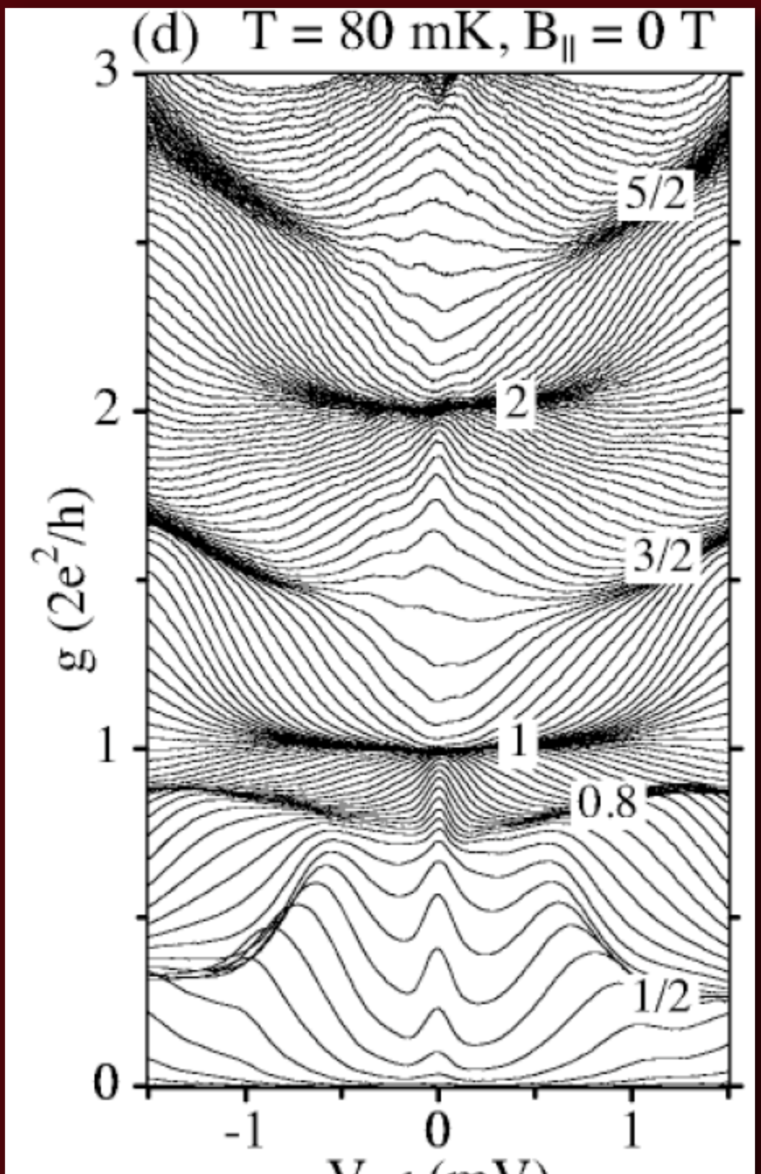
# Is the splitting real?

- "Splitting" is obvious only within a narrow range of conductance
- Observed g-factor is higher than the bulk g=0.44, closer to the exchange-enhanced splitting of 2DEG

Still --- a zero-bias anomaly that splits by $2g\mu_B B$ must be Kondo.

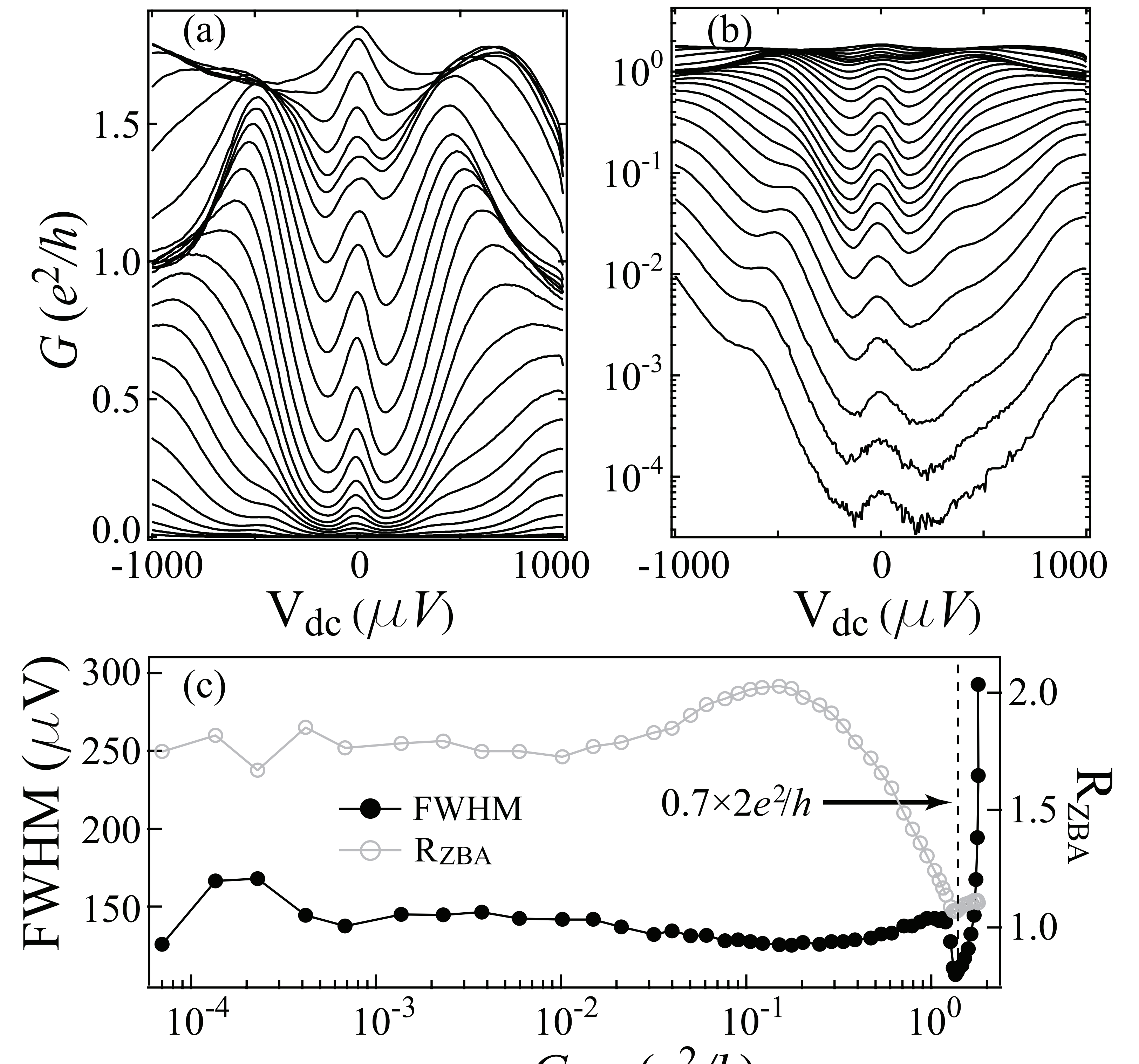


# Cracks in the Kondo argument:
# 1. ZBA at very low conductance




Cronenwett, 2002

Compare to Sarkozy et al, PRB 2009




Ren, 2009

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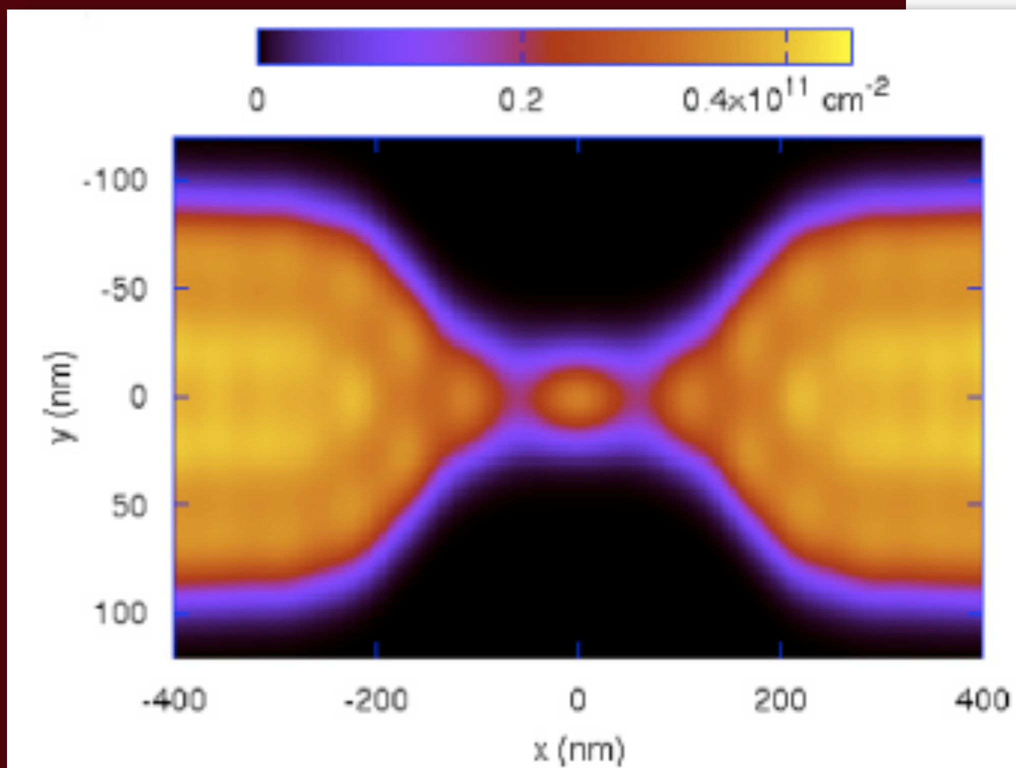
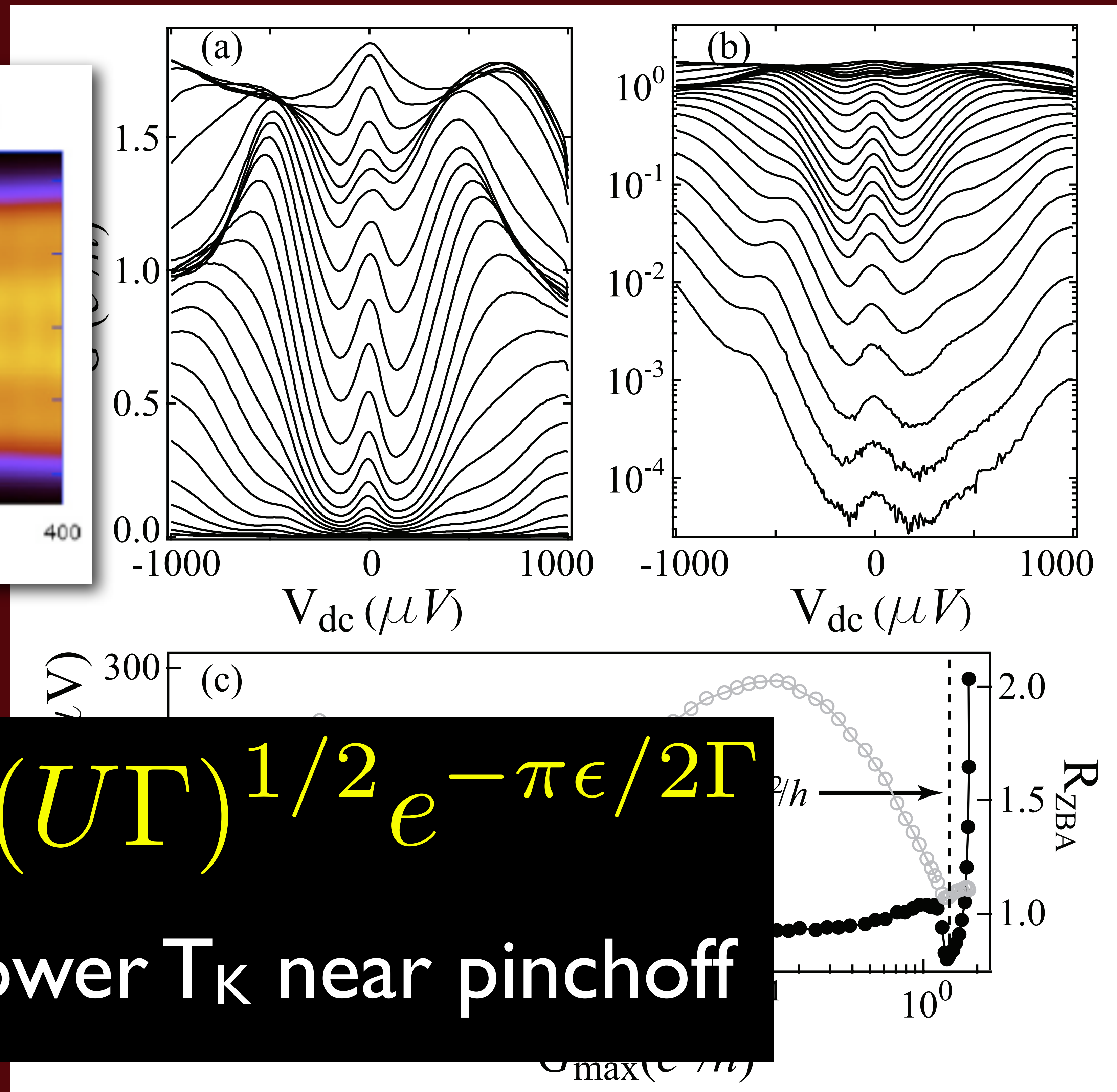
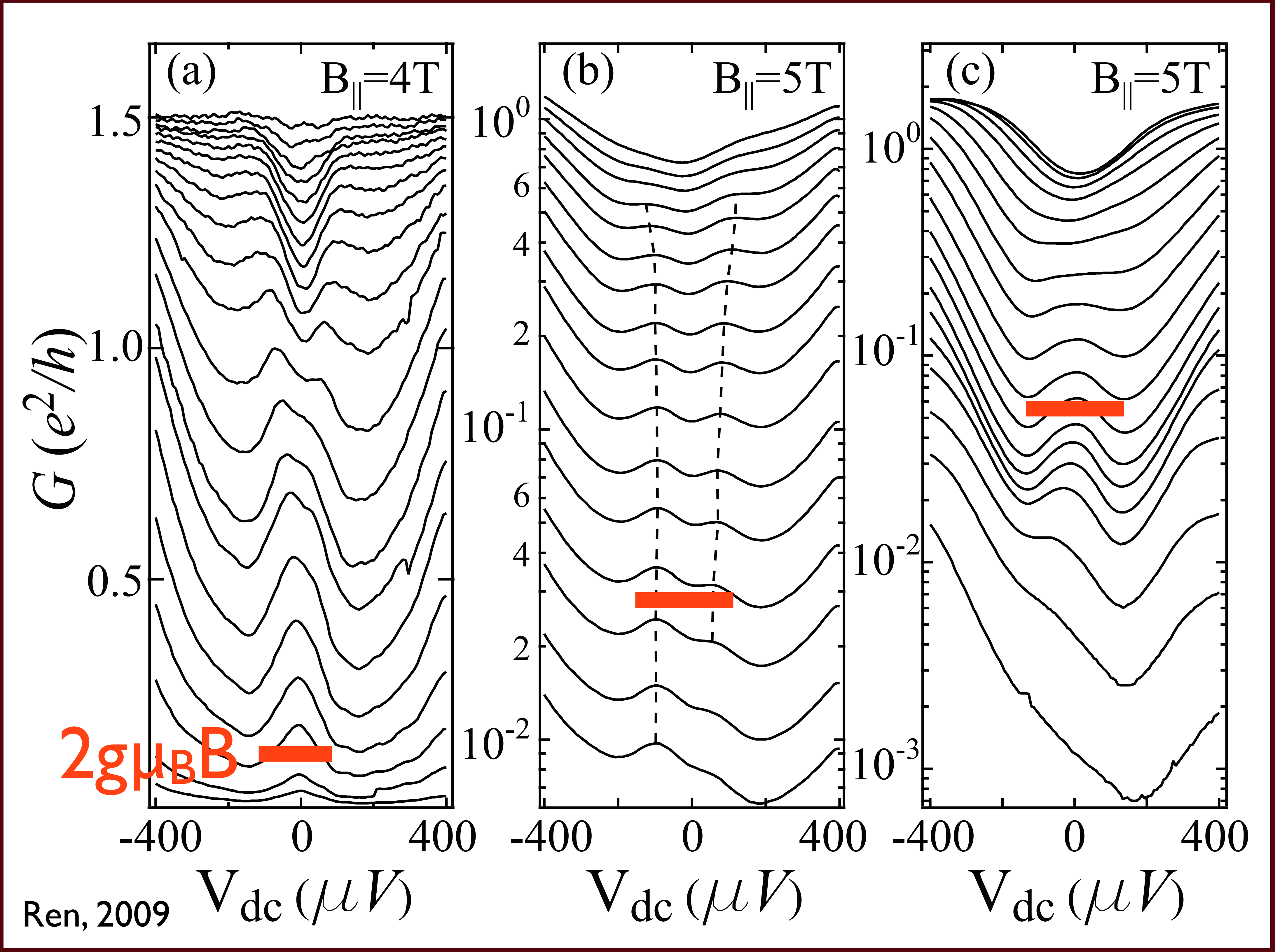



$$T_K \sim (U\Gamma)^{1/2} e^{-\pi\epsilon/2\Gamma}$$

Expect lower $T_K$ near pinchoff

# Cracks in the Kondo argument:
# 2. ZBA splitting is too small near pinchoff



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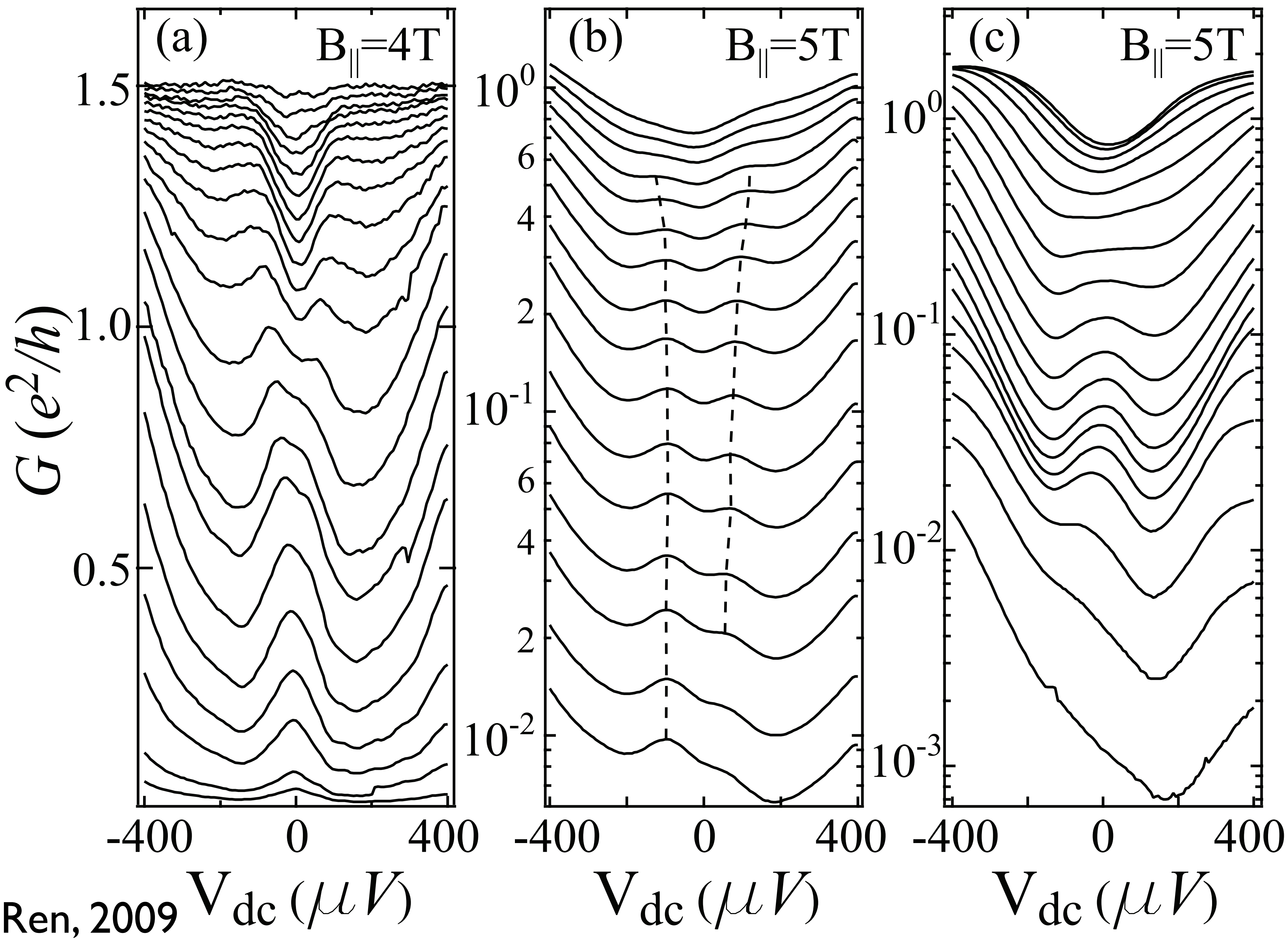
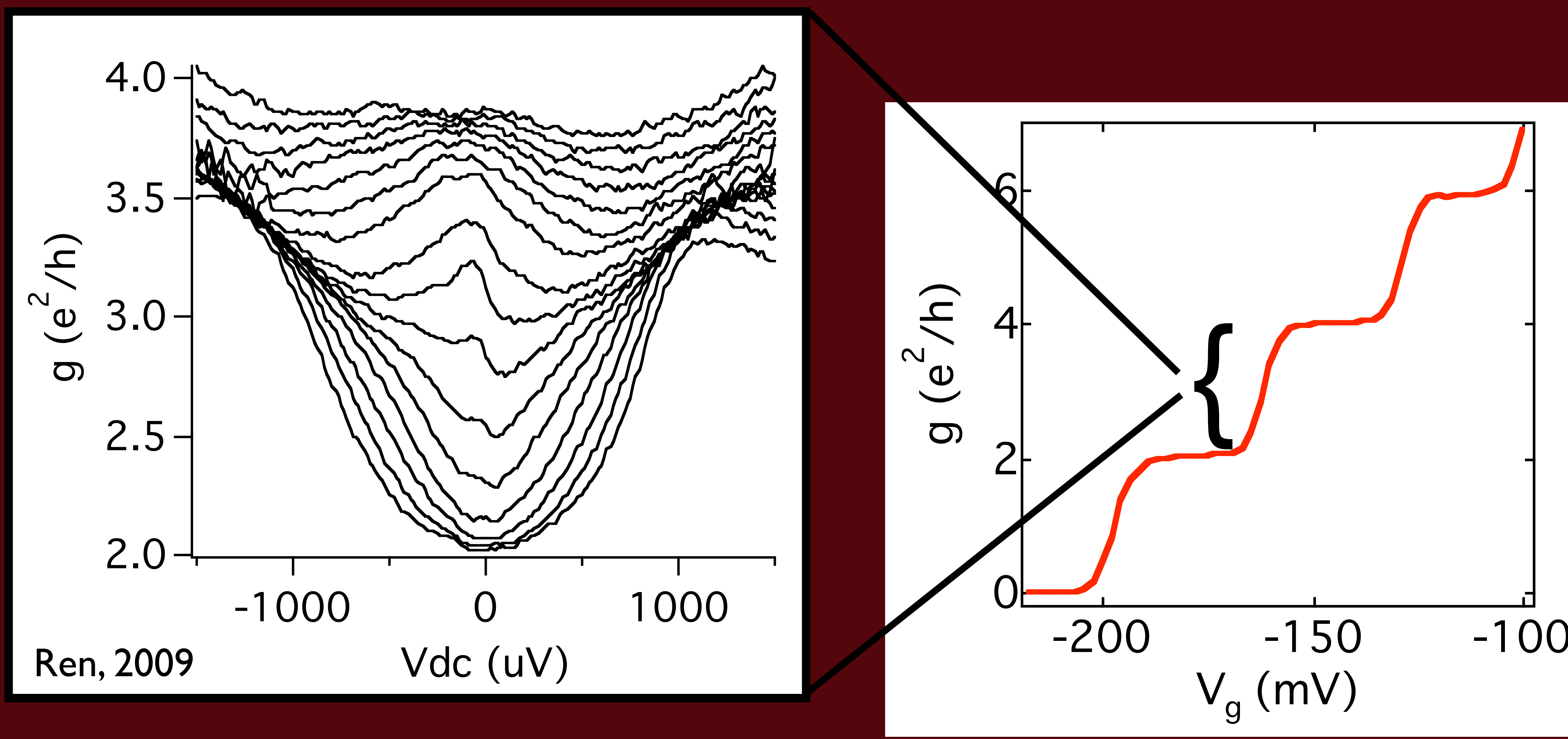



Ren, 2009

and depends on microscopic potential in device

# Cracks in the Kondo argument:
# 3. Similar ZBA above $2e^2/h$
## (where's the localized state?)



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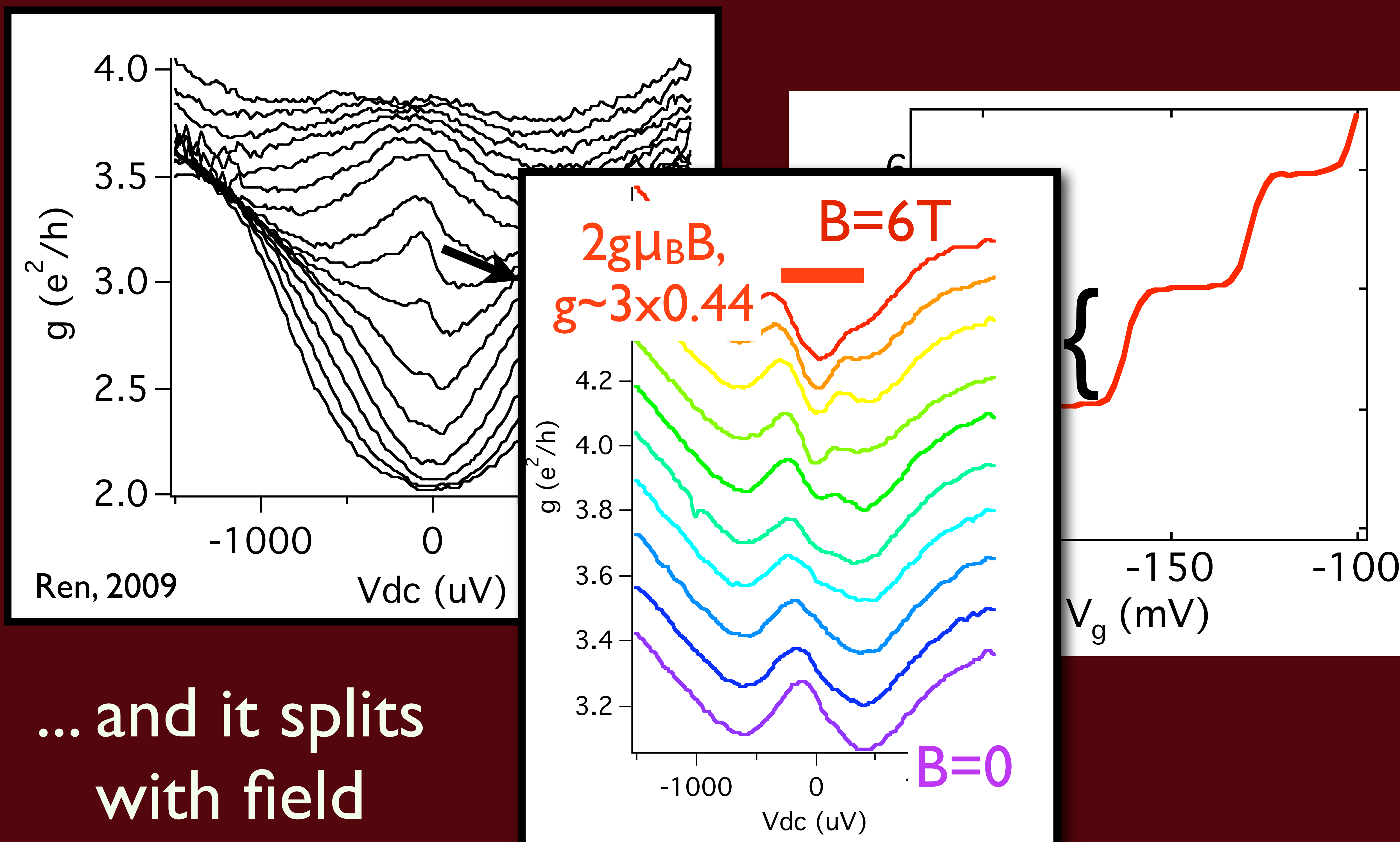



... and it splits with field

# Cracks in the Kondo argument:
# 4. Transmission through saddle point splits by $2g\mu_B B$ with no many-body physics!

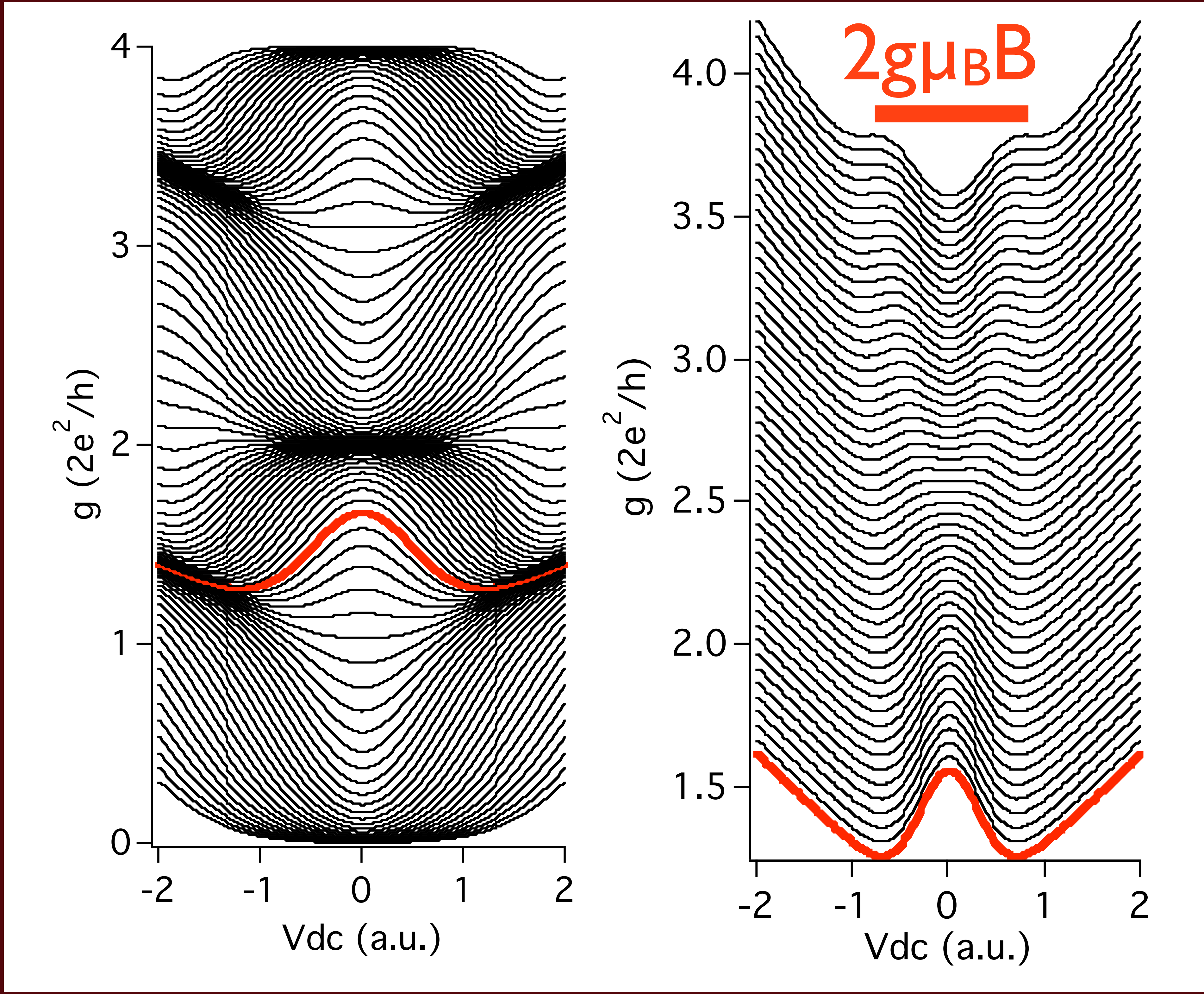
## Non-linear conductance of a saddle-point constriction

L Martín-Moreno, J T Nicholls, N K Patel and M Pepper
Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

Received 13 November 1991

**Abstract.** We present calculations of the differential conductance, $G$, of a constriction, defined by a saddle-point potential in a two-dimensional electron gas, in the non-linear regime of transport as a function of Fermi energy, source–drain voltage and magnetic field. The manner in which the potential is dropped along the device is considered phenomenologically. The dependence of $G$ on the parameters that define the potential drop is investigated, extending the model proposed by Glazman and Khaetskii. A method for measuring the sub-band energies and spin-splitting energies in a bottle-neck of the constriction is also proposed. Finally, a comparison between experimental data and theoretical calculations is presented.

# Cracks in the Kondo argument: 4. Transmission through saddle point splits by $2g\mu_B B$ with no many-body physics!




Splitting depends on g-factor in leads, enhanced by exchange interaction

# Where does this leave us?
# An assembly of existing literature, informed by recent measurements:

**Conductance of a quantum wire at low electron density**

K. A. Matveev
*Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA and Department of Physics, Duke University, Durham, North Carolina 27708, USA*
(Received 23 May 2004; revised manuscript received 13 October 2004; published 23 December 2004)

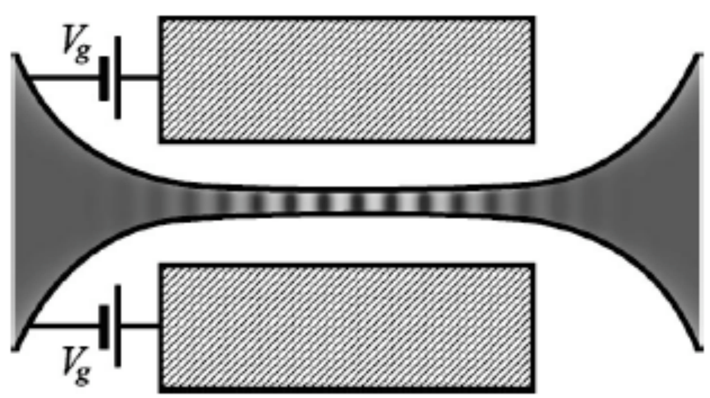
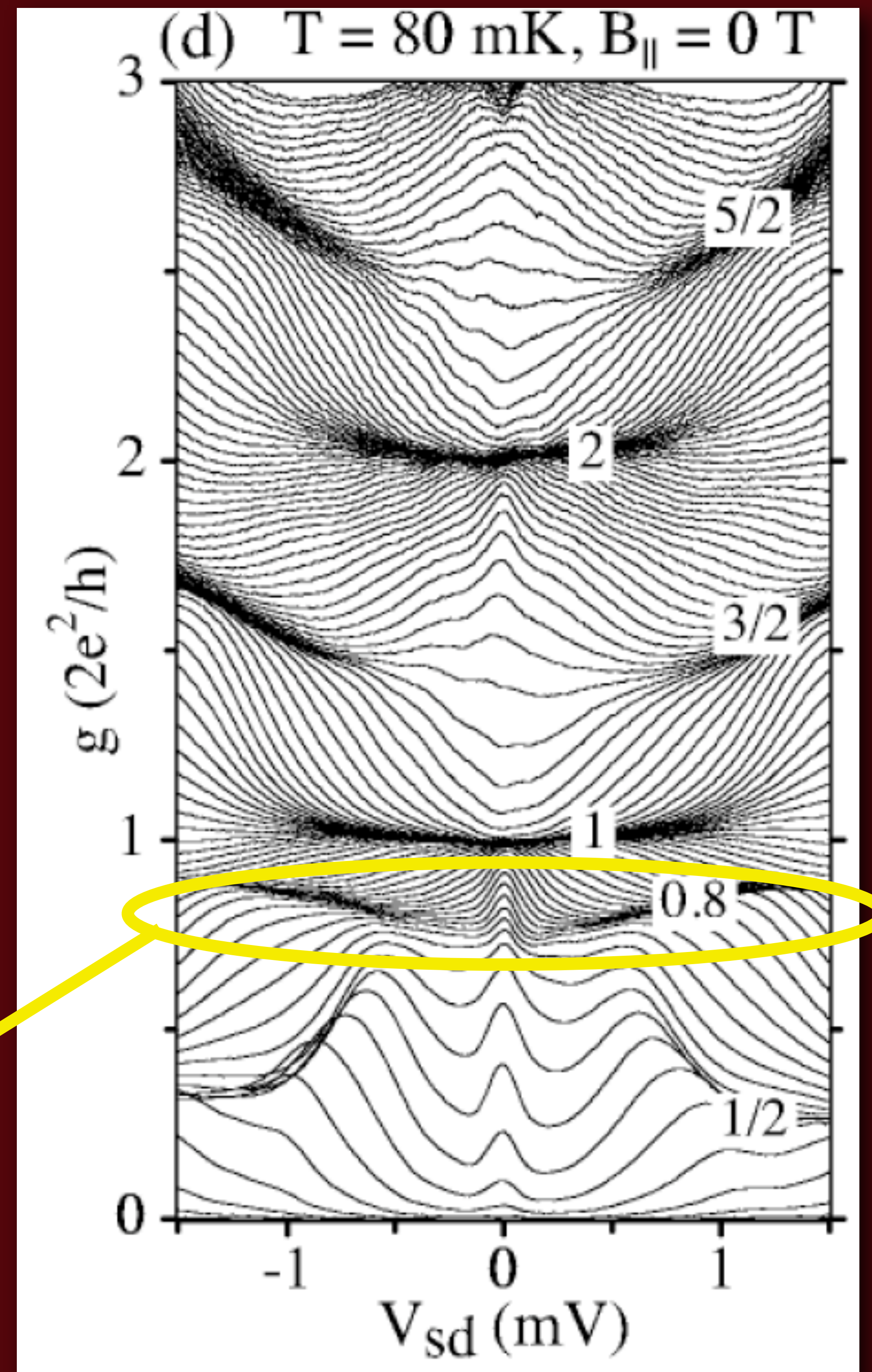



FIG. 1. Sketch of electron density in a quantum wire formed by confining two-dimensional electrons with gates (shaded). The density $n$ of one-dimensional electrons in the wire is controlled by the gate voltage $V_g$. At low density $n \ll a_B^{-1}$ the electrons in the wire form a Wigner crystal.




High energy conductance ~ 0.7x2e2/h comes from spin excitations + e-e interactions

# Where does this leave us?
# An assembly of existing literature, informed by recent measurements:

**Tunneling zero-bias anomaly in the quasiballistic regime**

A. M. Rudin, I. L. Aleiner, and L. I. Glazman
*Theoretical Physics Institute, University of Minnesota, Minneapolis, Minnesota 55455*
(Received 11 December 1996)

We study the tunneling density of states (DOS) of the interacting electron gas beyond the diffusive limit. A strong correction to the DOS persists even at electron energies exceeding the inverse transport relaxation time, which could not be expected from the well-known Altshuler-Aronov-Lee (AAL) theory. This correction origi-
nates from the interference between the electron waves scattere
this impurity creates. Account for such processes also revises
limit. [S0163-1829(97)09615-X]

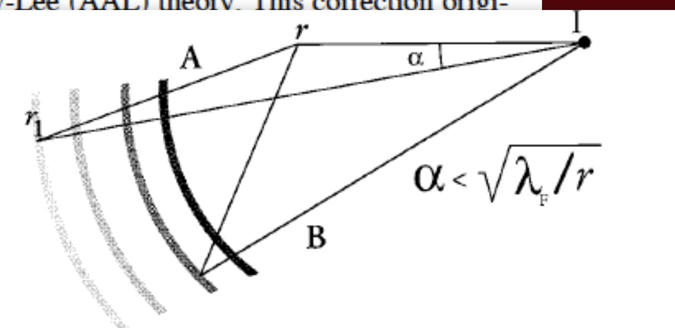
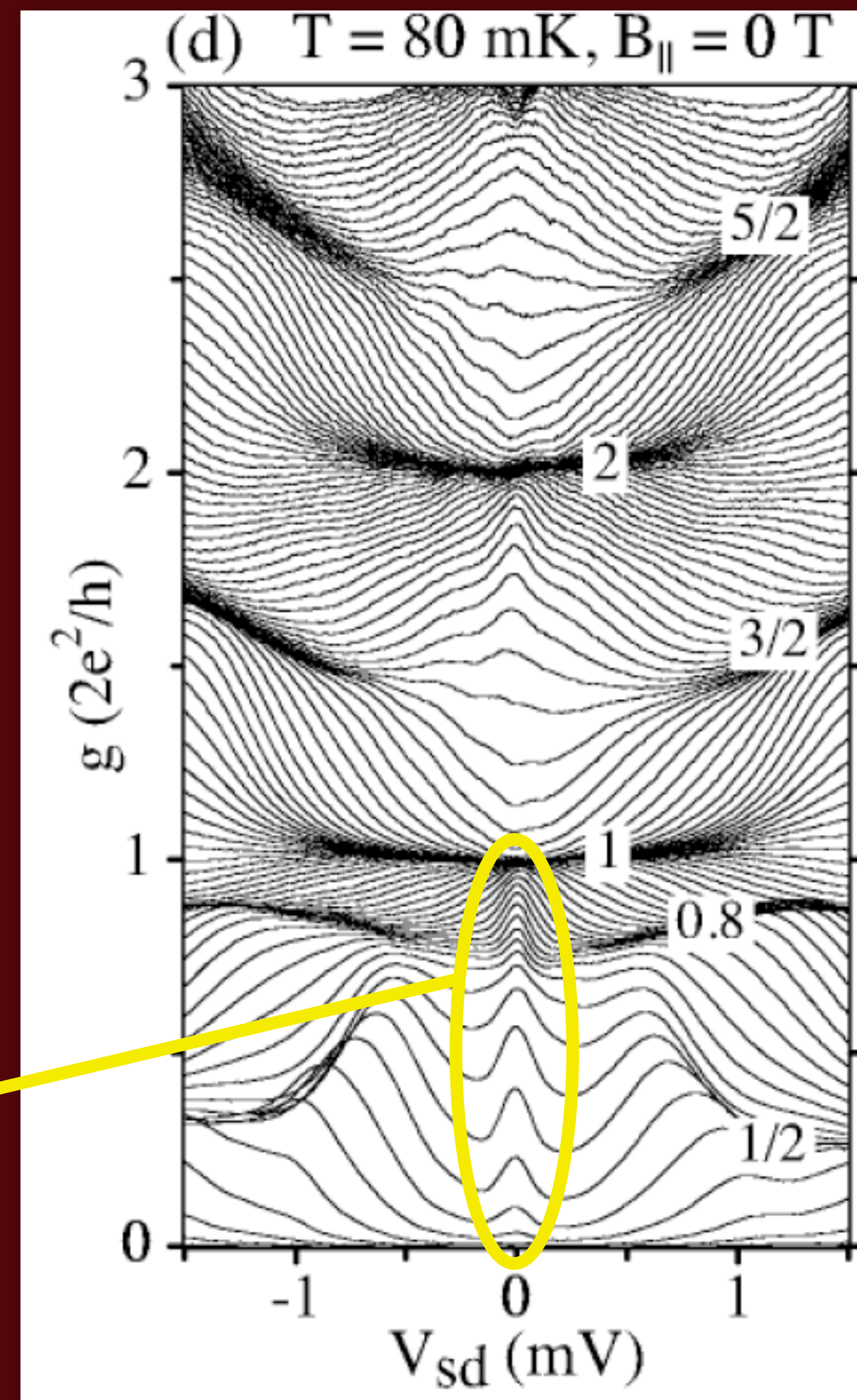


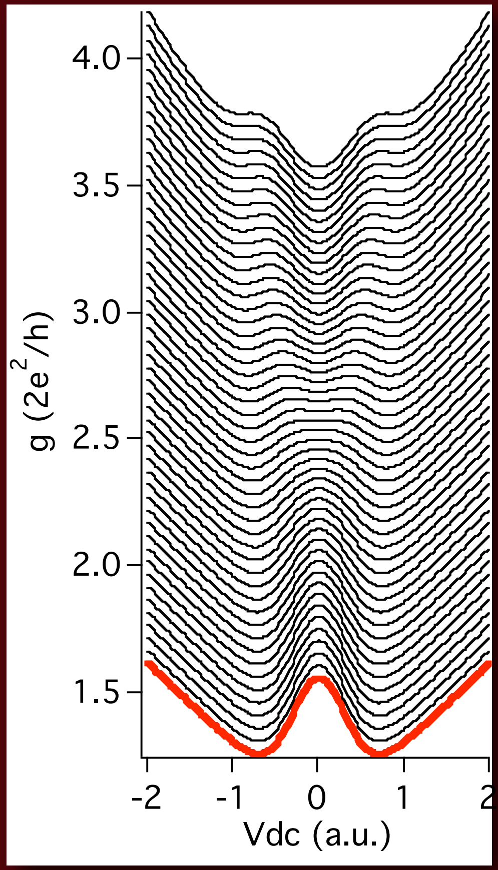

FIG. 1. Two typical trajectories ($A$, $B$) of an electron scattered by an impurity ($I$) and by the corresponding Friedel oscillation (concentric arcs). The correction $\delta\nu(\mathbf{r})$ is dominated by the trajectories of the type $A$, for which the electron is almost scattered back at $I$ and $\mathbf{r}_1$.




Zero-bias anomaly comes from physics in the leads: scattering from Friedel oscillations (this is why it does not depend on QPC conductance)

# Where does this leave us?
# An assembly of existing literature, informed by recent measurements:

## <u>ZBA splitting by $2g\mu_B B$</u>




Saddle point potential (one-body physics)

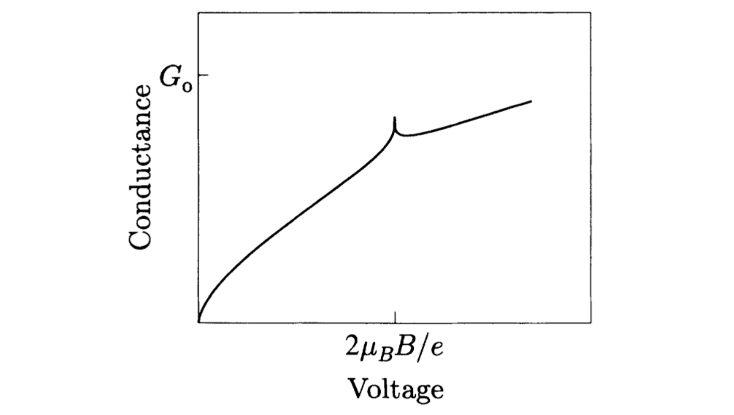
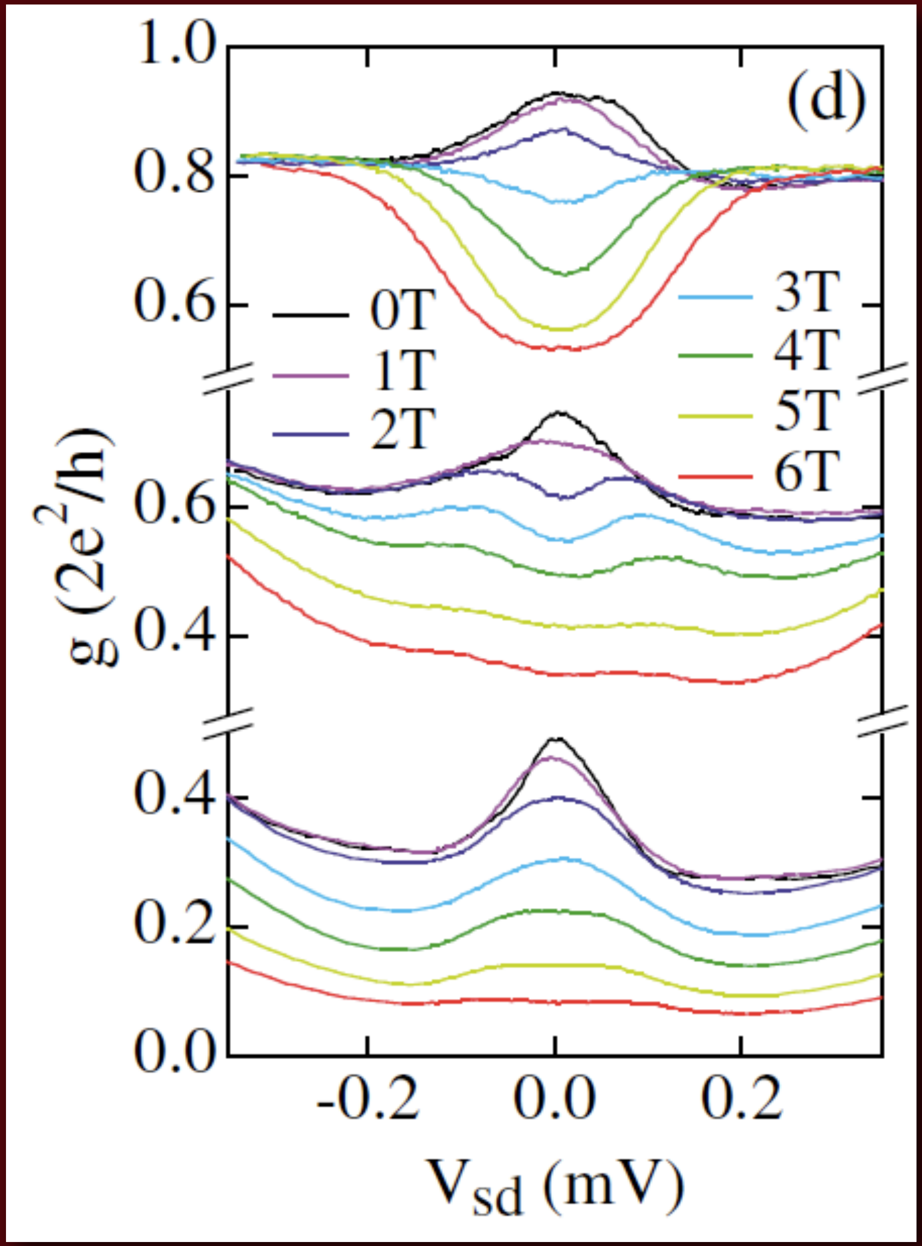
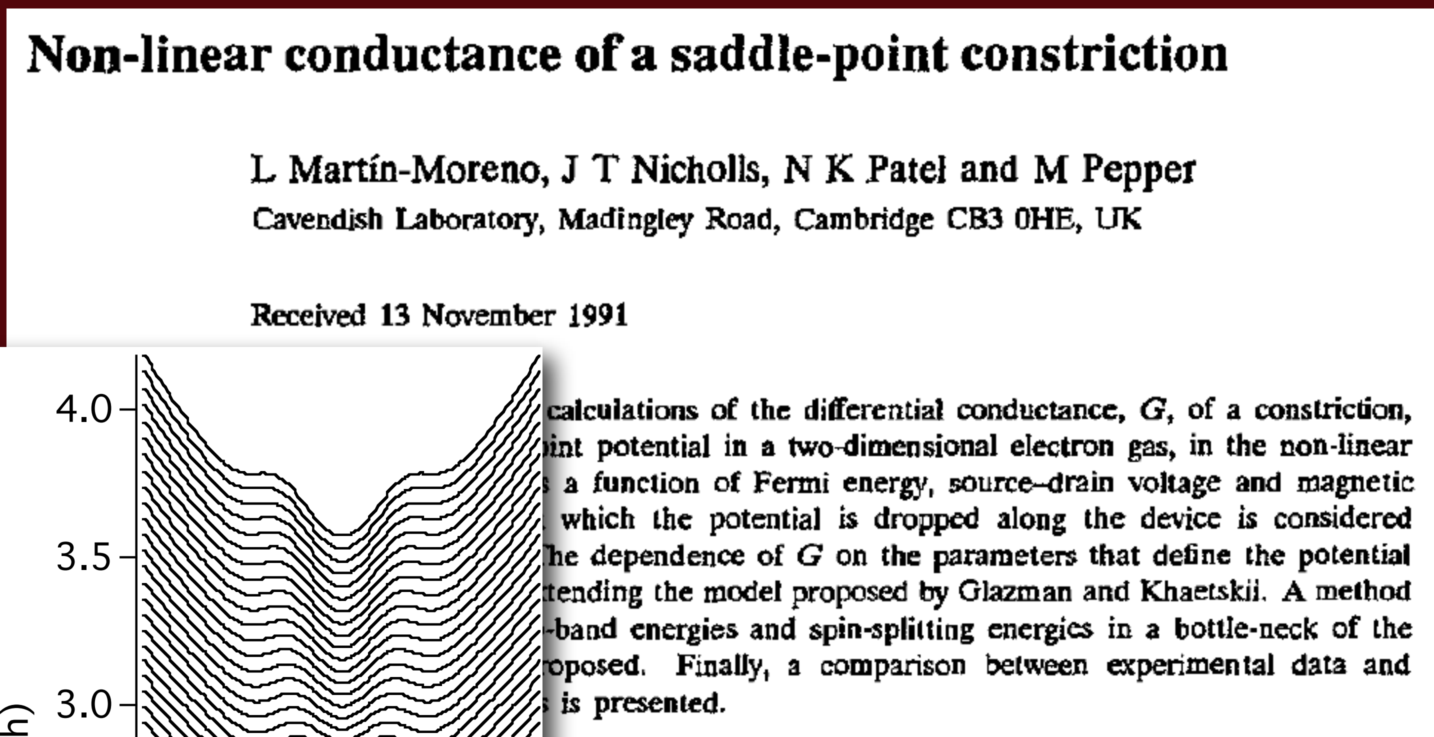



FIG. 3. The differential conductance $G(V) = dI/dV$ of a quantum wire with a strong barrier in the presence of magnetic field $B$. The power-law behavior at $V \to 0$ is consistent with the Luttinger-liquid theory (Ref. 10). The power-law peak (47) at $V = 2\mu_B B/e$ is due to the scattering of electrons on the Friedel oscillation produced by the opposite-spin electrons. The curve was calculated for $\alpha_1 = 1/16$, $\alpha_2 = 3/8$.

Scattering from Friedel oscillations (Yue, Glazman, Matveev 2004)



# Where does this leave us?
# An assembly of existing literature, informed by recent measurements:


**Non-linear conductance of a saddle-point constriction**

L Martín-Moreno, J T Nicholls, N K Patel and M Pepper
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Received 13 November 1991

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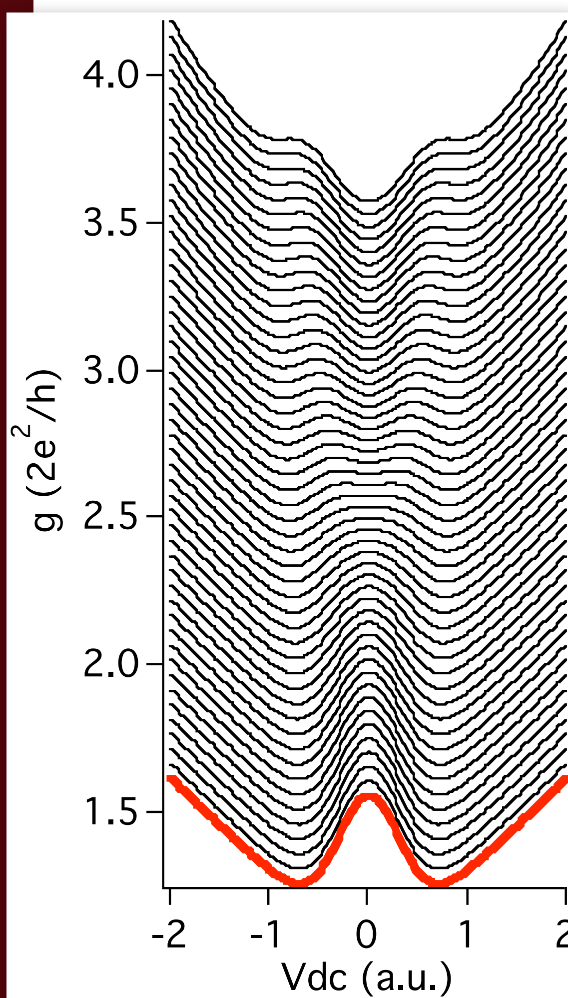
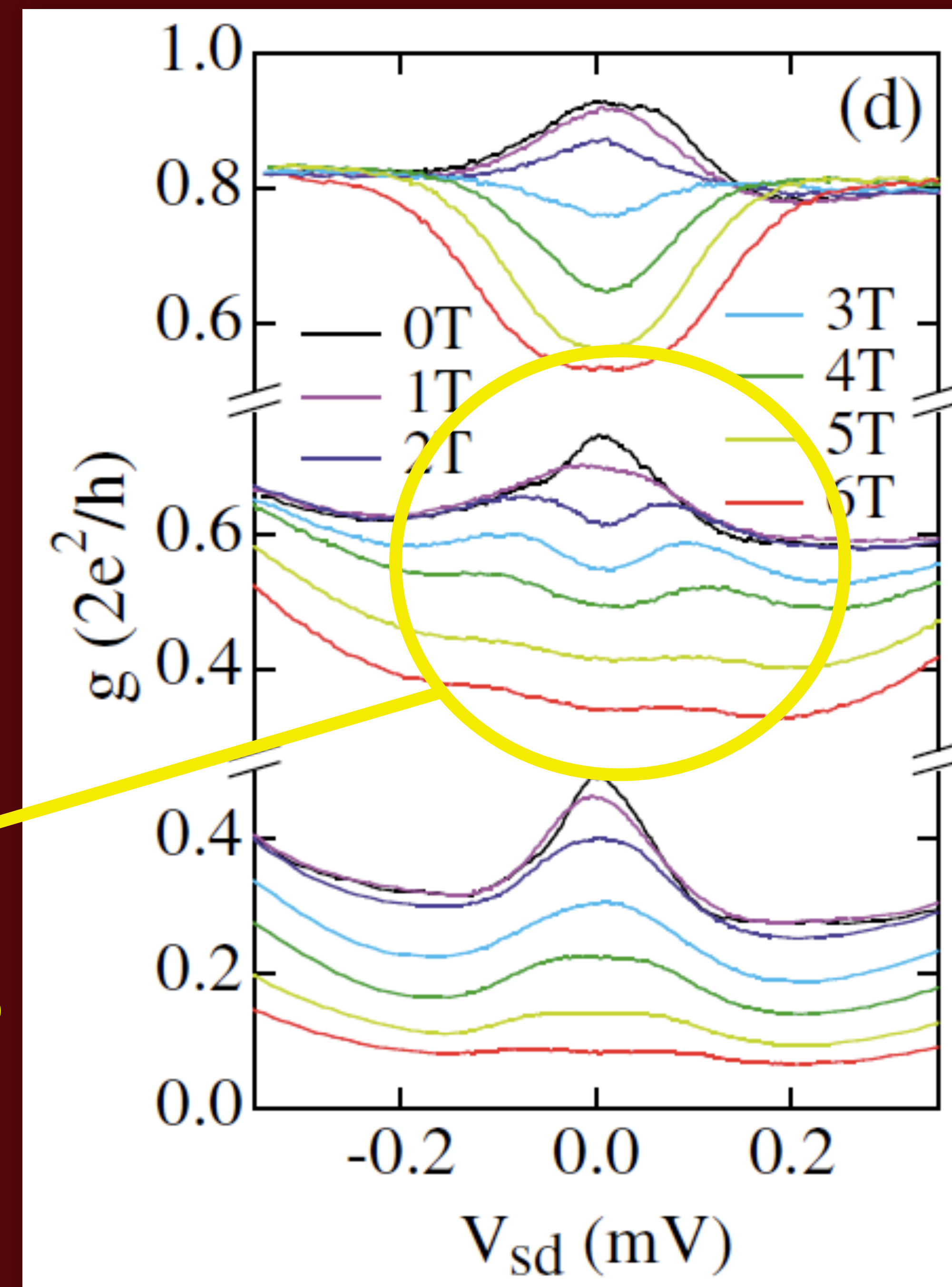



Splitting of zero-bias anomaly at high conductance by $2g\mu_B B$ was a red herring--can result simply from saddle-point model



# Conclusions

What looks like Kondo, acts like Kondo, tastes like Kondo...

isn't always Kondo