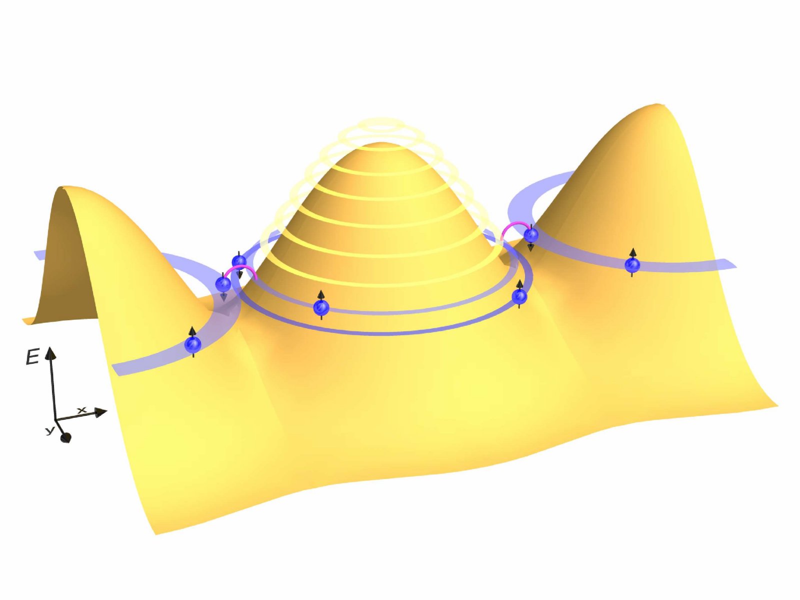
Semiconductor Physics Group

Cavendish Laboratory

University of Cambridge

Charging and Kondo Effects in an Antidot in the Quantum Hall Regime



M. Kataoka

C. J. B. Ford

M. Y. Simmons†

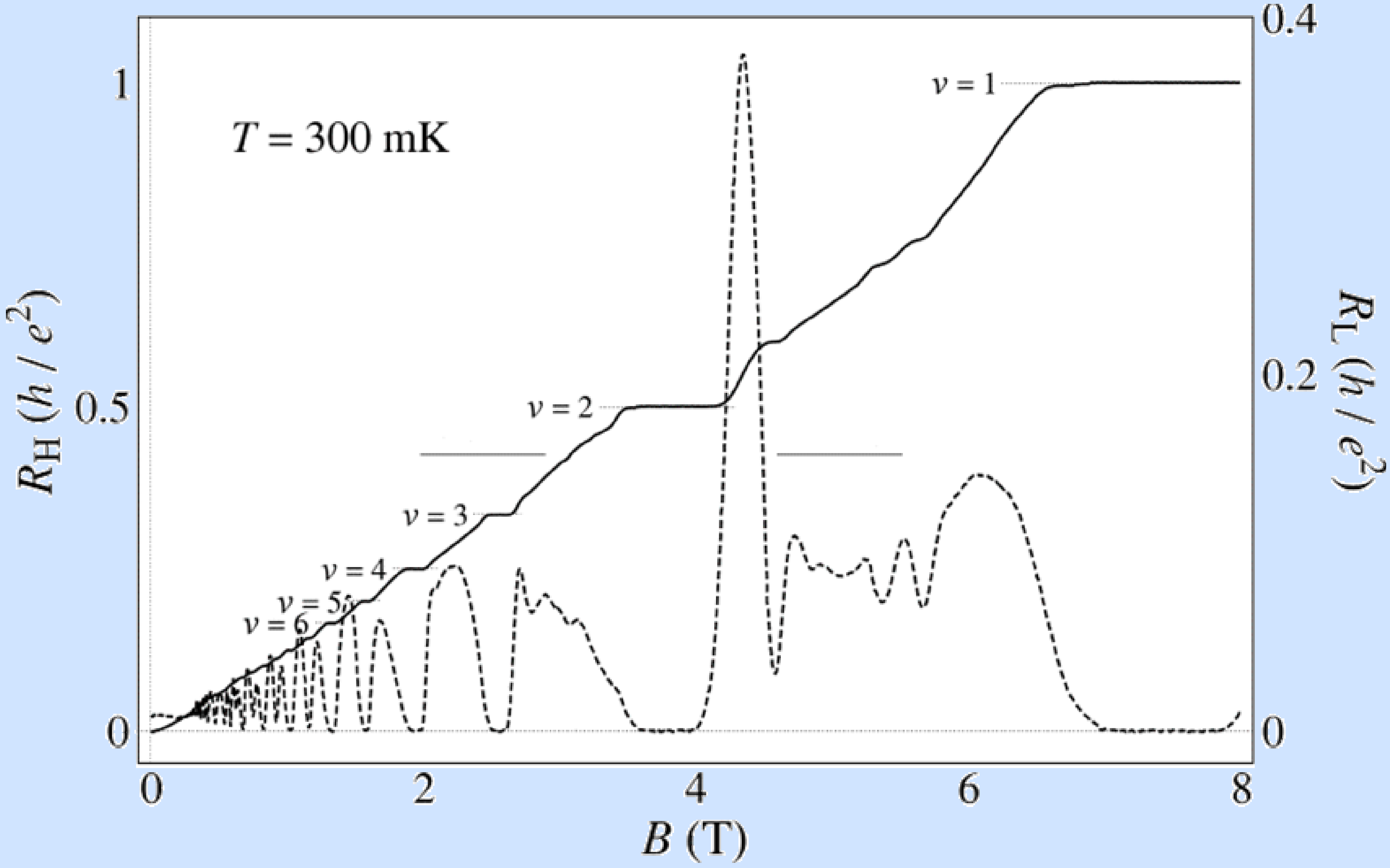
D. A. Ritchie

†University of New South Wales, Sydney, Australia

Outline

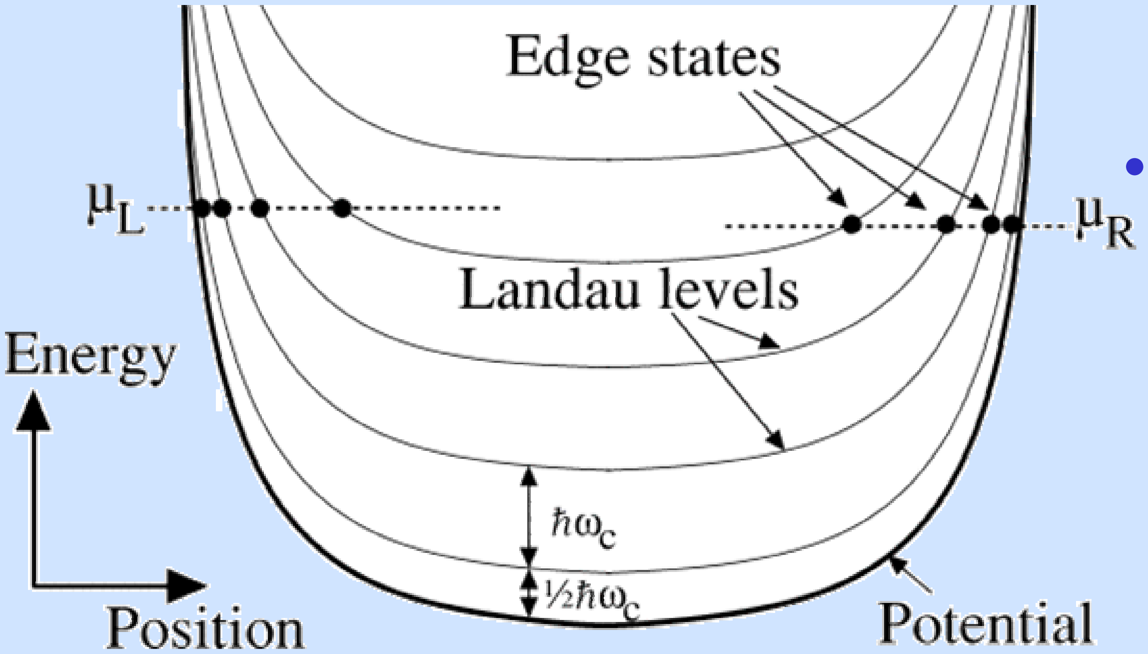
• **Introduction**	Quantum Hall effect Antidots
• **Aharonov-Bohm oscillations**	Spin-splitting Double-frequency AB
• **Charging of an antidot**	Detector How does an antidot charge up?
• **Double-frequency AB**	Compressible & incompressible regions
• **Kondo effect**	Many-body effects at intermediate B
• **Injection of just one spin**	Non-equilibrium injection into edge state
• **Conclusion**	

The Quantum Hall Effect



- Quantised Hall resistance R_H and zeroes in longitudinal resistance R_L

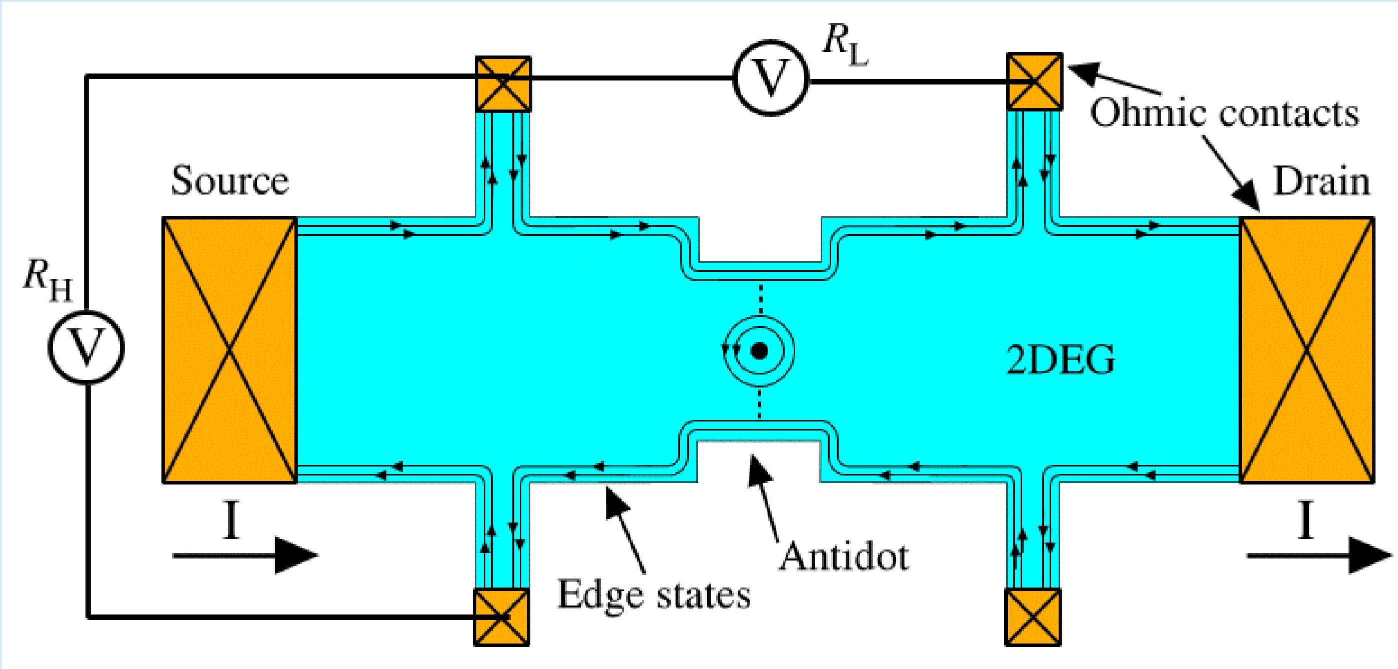
The Quantum Hall Effect



- Magnetic field ***B*** is perpendicular to two-dimensional electron gas (2DEG) $\Rightarrow$ **Landau levels**

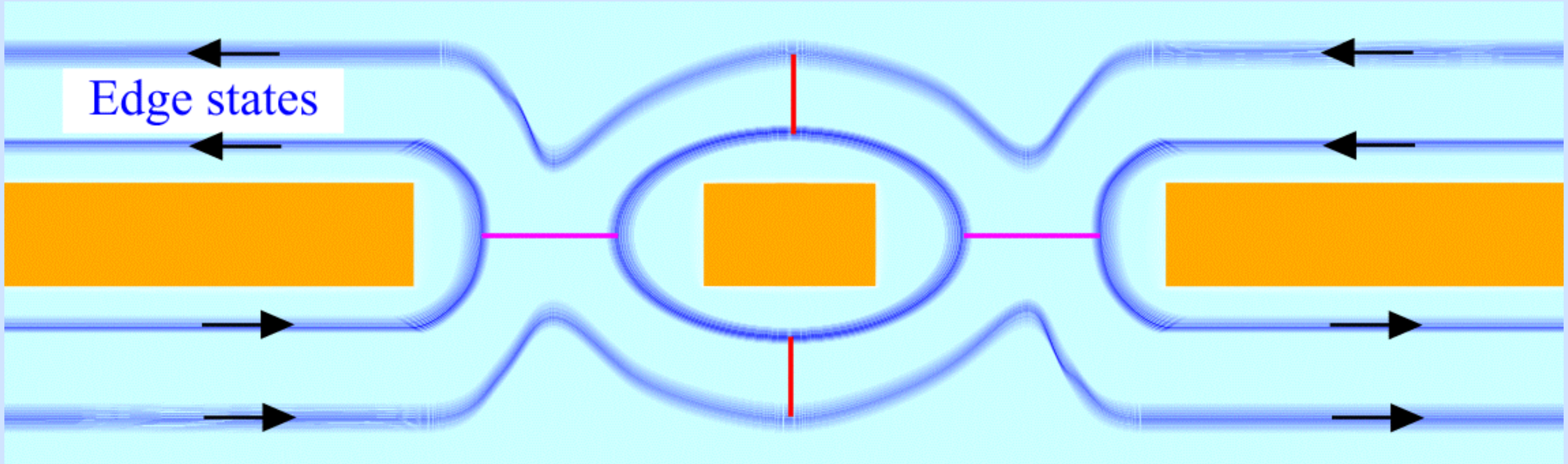
- Transport is via edge states at the chemical potential (μ_L and μ_R on left and right edges respectively)

A Hall Bar with an Antidot

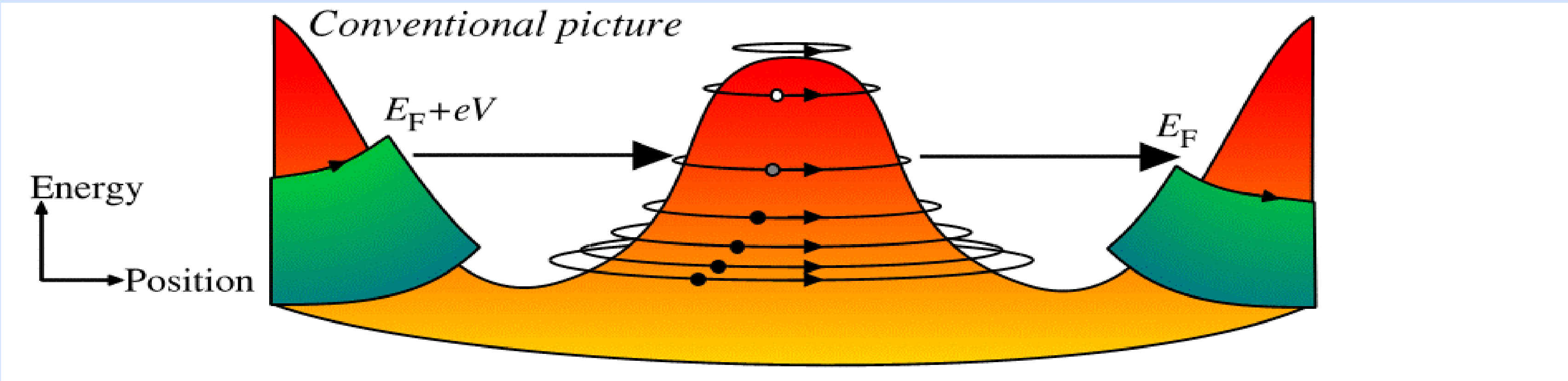


- Opposite edges too far apart for backscattering
  $\Rightarrow$ no dissipation $\Rightarrow R_L = 0$ (Quantum Hall Effect)
- **Antidot** (*a bump in potential*) brings edges close together
- Overlap $\Rightarrow$ tunnelling, backscattering
- Confinement is produced by the magnetic field ***B***

Antidots



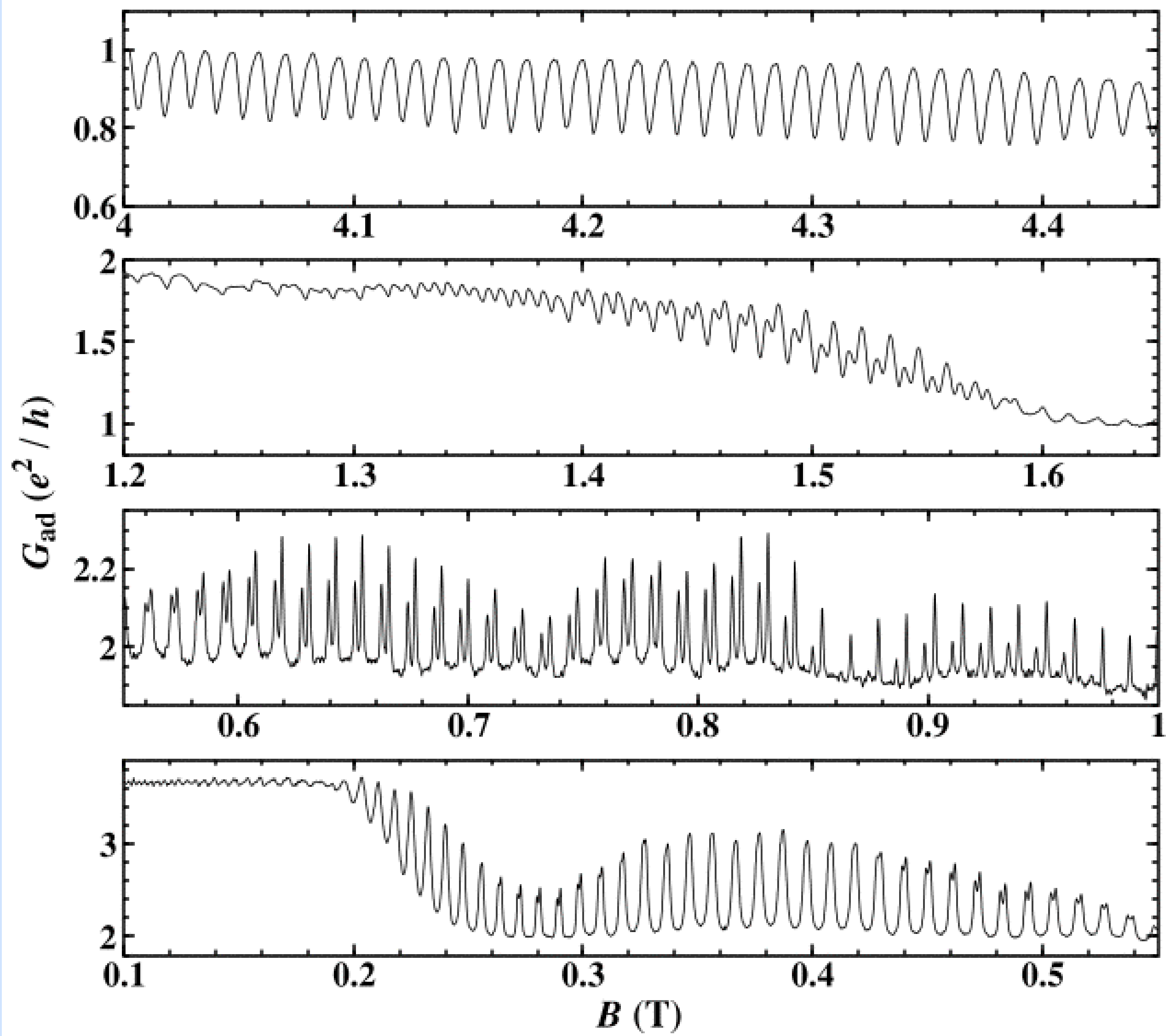
•Three separate gates tune tunnelling across two constrictions



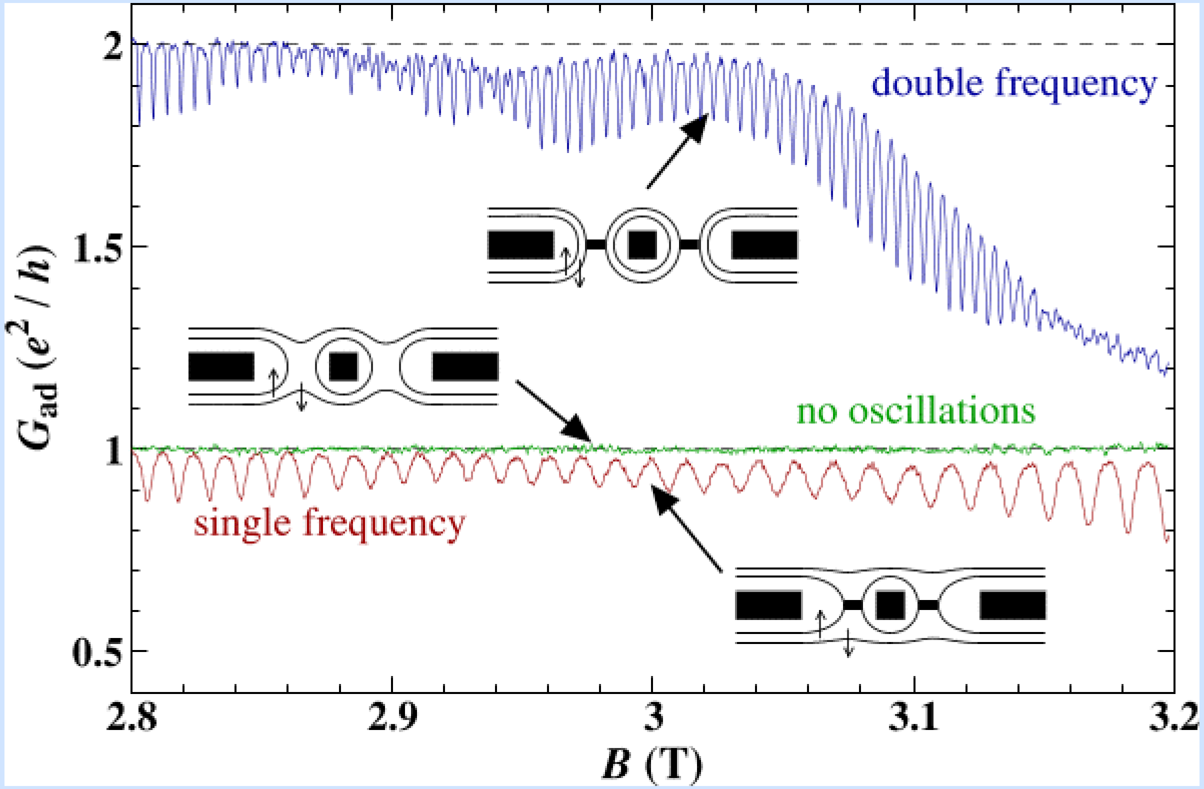
- **Aharonov-Bohm Effect** → States enclose multiples of *h*/*e* in flux
- Tunnelling → resonant **backscattering** (dips) or **transmission** (peaks)

Aharonov-Bohm Effect

- Fully spin-split at high *B*
- Spin splitting at intermediate *B*
- No AB oscillations below 0.2 T since no edge states yet

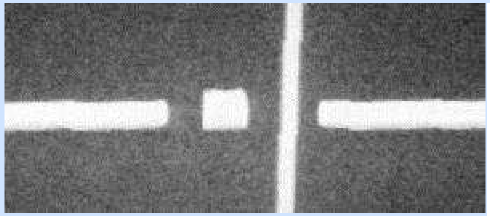


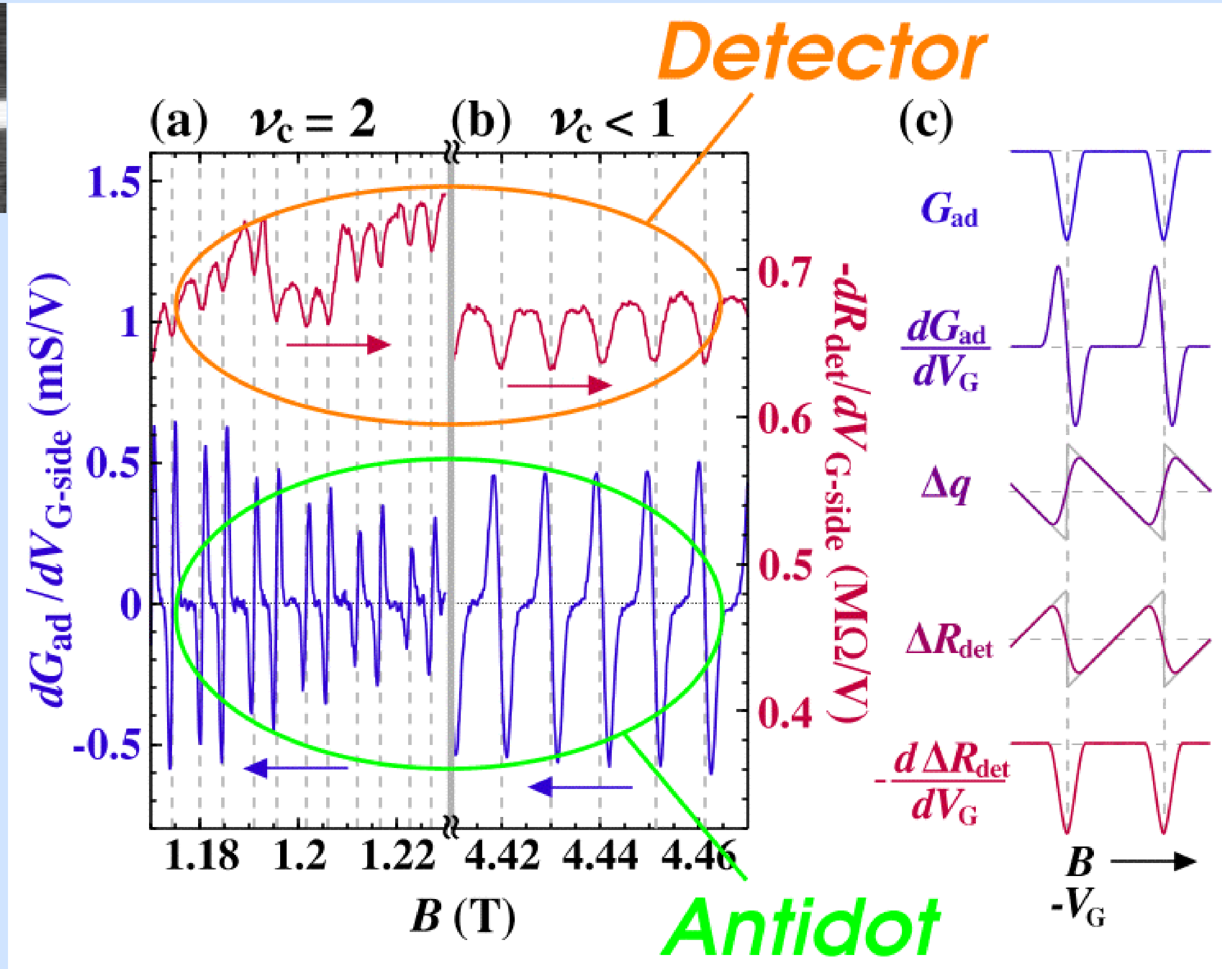
h/2*e* oscillations only from outer spins



- Squeeze constrictions symmetrically ⇒ *h*/2*e* oscillations die
- Then $\nu_c = 1$ plateau gives way to *h*/*e* oscillations
- Proof that *h*/2*e* resonances are only through *outer* spin state
- But how can resonances occur twice per *h*/*e* period?

Detection of Antidot Charging

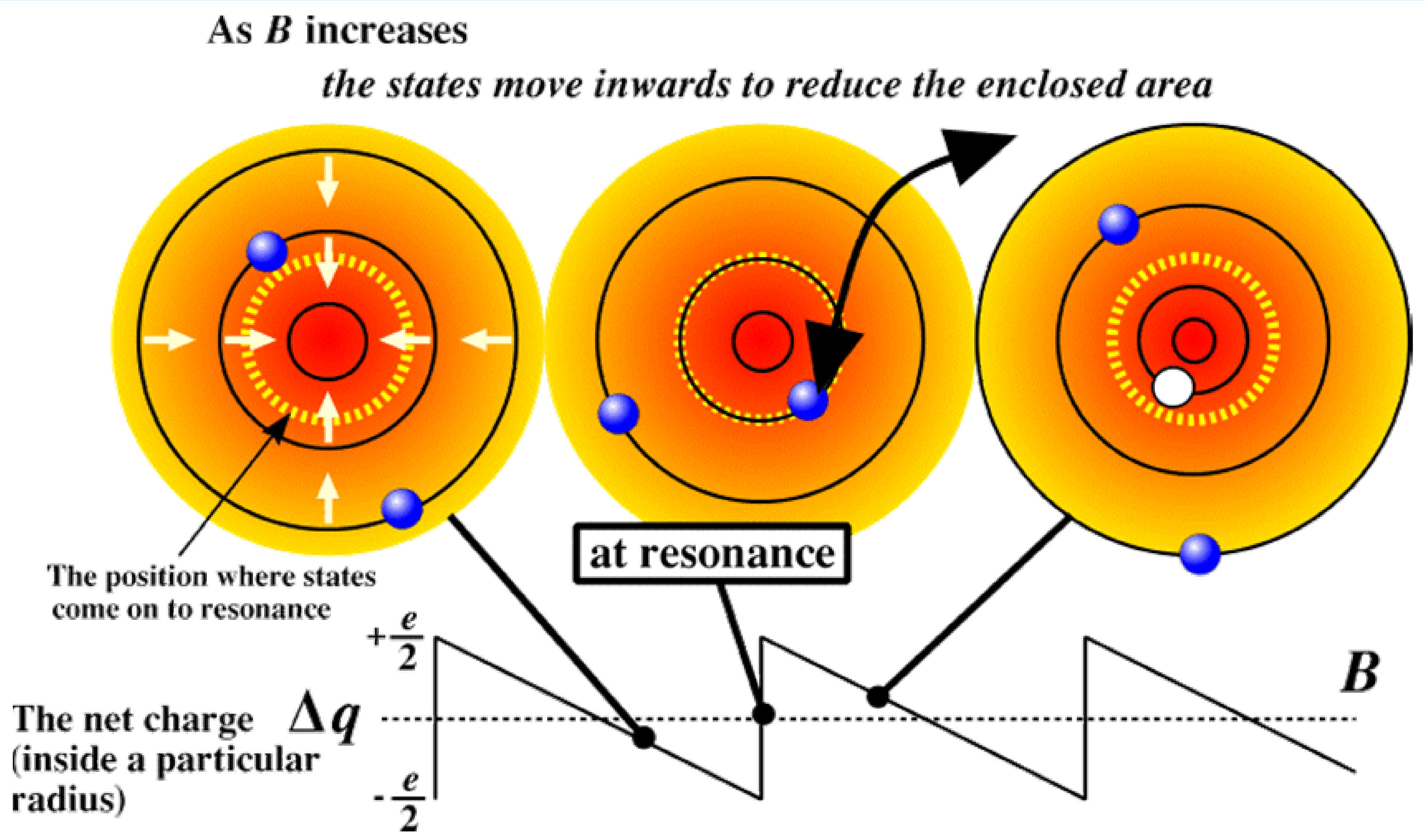




- Transresistance dips match transconductance oscillations
- Net charge Δq around antidot shows saw-tooth oscillations

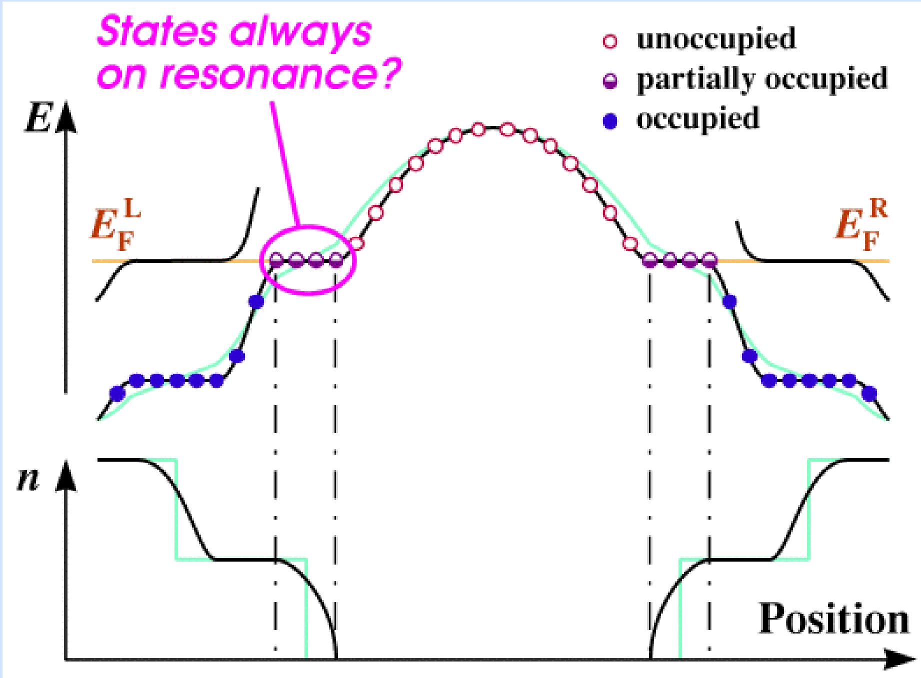
M. Kataoka *et al.*, *Phys. Rev. Lett.* **83**, 160 (1999)
(Samples made by G. Faini, D. Mailly, LPN - CNRS, Bagneux, France)

How does an antidot charge up?



- Very like CB in a dot, but sweep *B* not gate voltage
- Squeezing comes from change in area of quantum-mechanical states

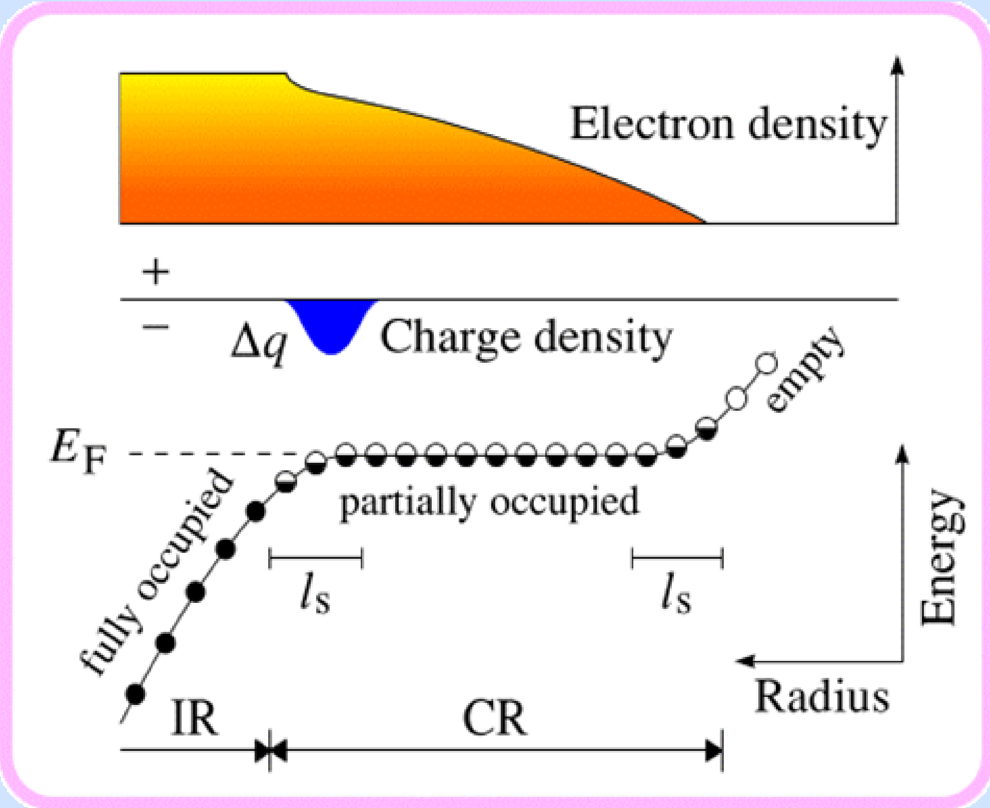
Self-consistent potential – compressible regions



- Chklovskii *et al.* ⇒ compressible and incompressible strips along 2DEG edges
- In antidots, perhaps no compressible regions because (in non-interacting picture) conductance resonances not possible if always more than one state at E_F
- Smooth potential (green) was usually assumed
- If there *is* Coulomb blockade due to charging, such a potential is possible

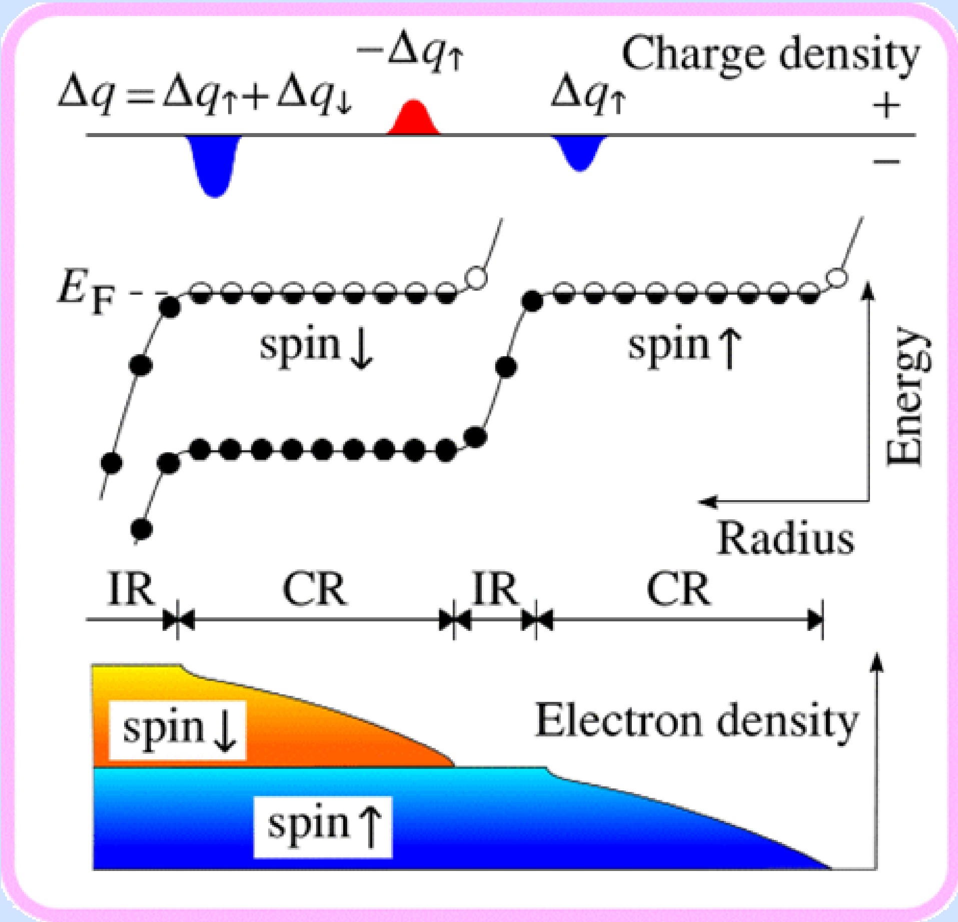
  — A compressible region is *likely* since it minimises electrostatic energy

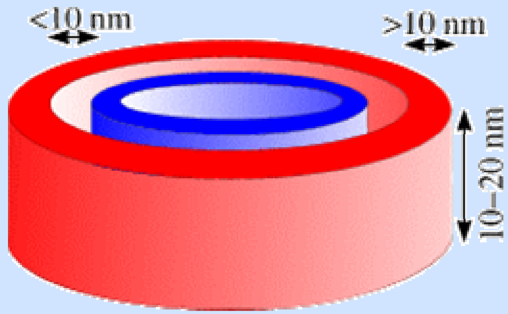
Charging of a compressible ring



- Because of ring shape, net charge should form only at *outer* edge of compressible region (CR) — electric field inside CR should be zero
- Ignore electric field out of plane (reasonable assumption)

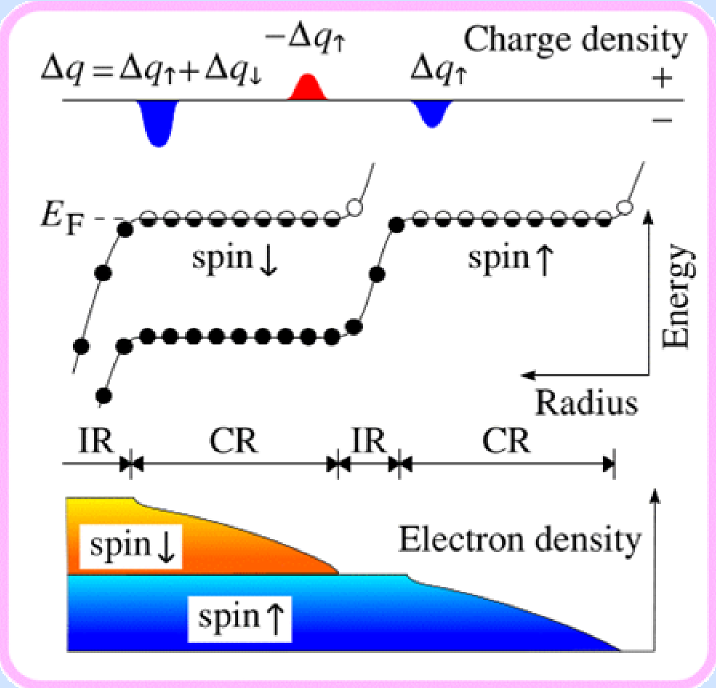
Charging of *two* compressible rings





- *Two* **compressible** regions separated by a narrow $\nu_c = 1$ **incompressible** region
- Act as the *parallel plates of a capacitor* (approximate them as two cylinders)

Mechanism of *h*/2*e* AB oscillations



Mechanism of *h*/2*e* AB oscillations:

Consider the *outer* edge of the *outer* ring:

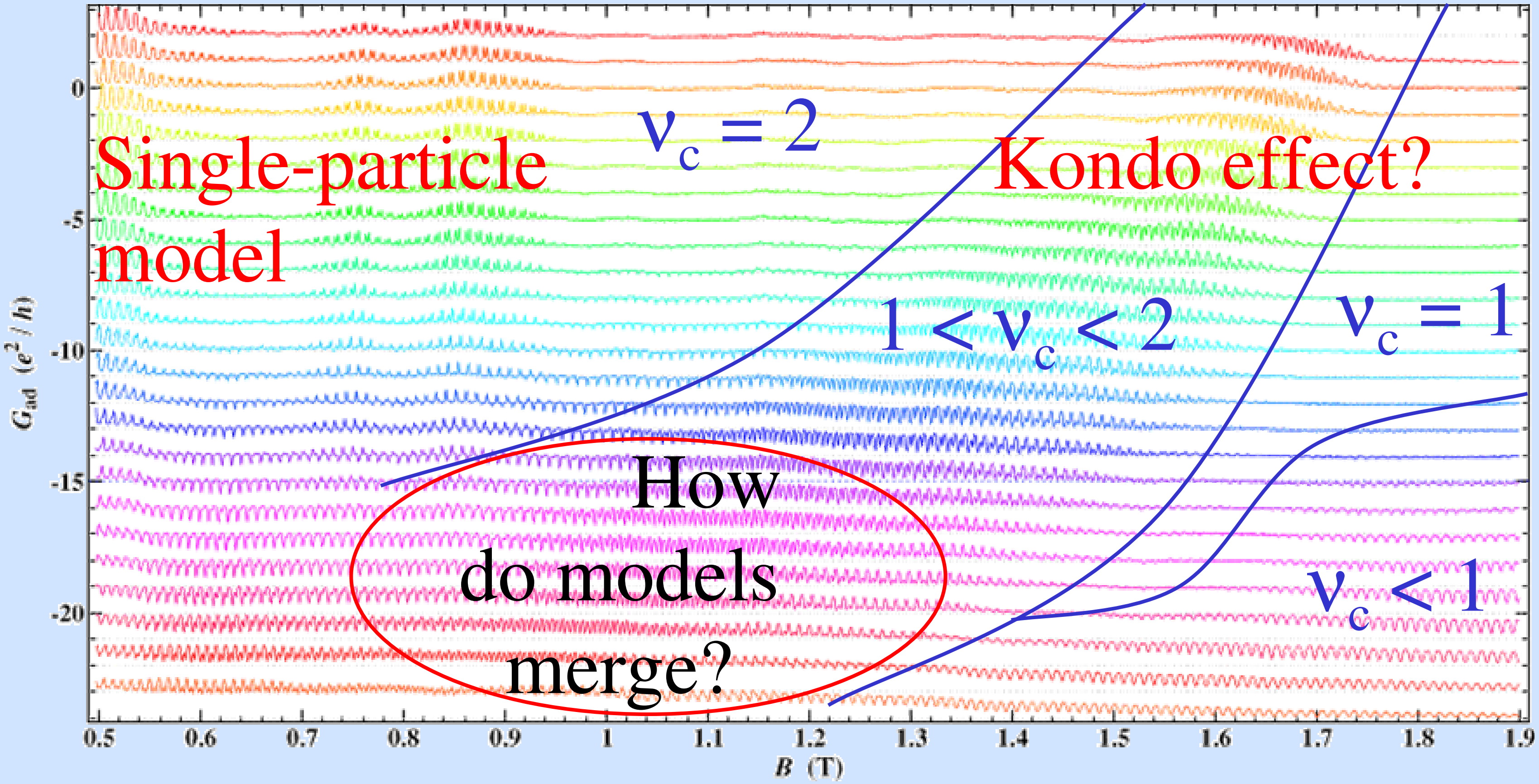
- Increase *B* so extra ½ *h*/*e* of flux is enclosed

  ⇒ extra *e*/2 of charge moves inside this ring from each spin
- This charge can only go into the *upper* spin level, since the lower one is **incompressible** (full), and *Gauss's law forces the charge to stay as far away from the centre as possible*, because the outer CR is a conductor

- Charge *e* enters outer CR when flux changes by ½ *h*/*e* (so periodicity is ½ *h*/*e*)

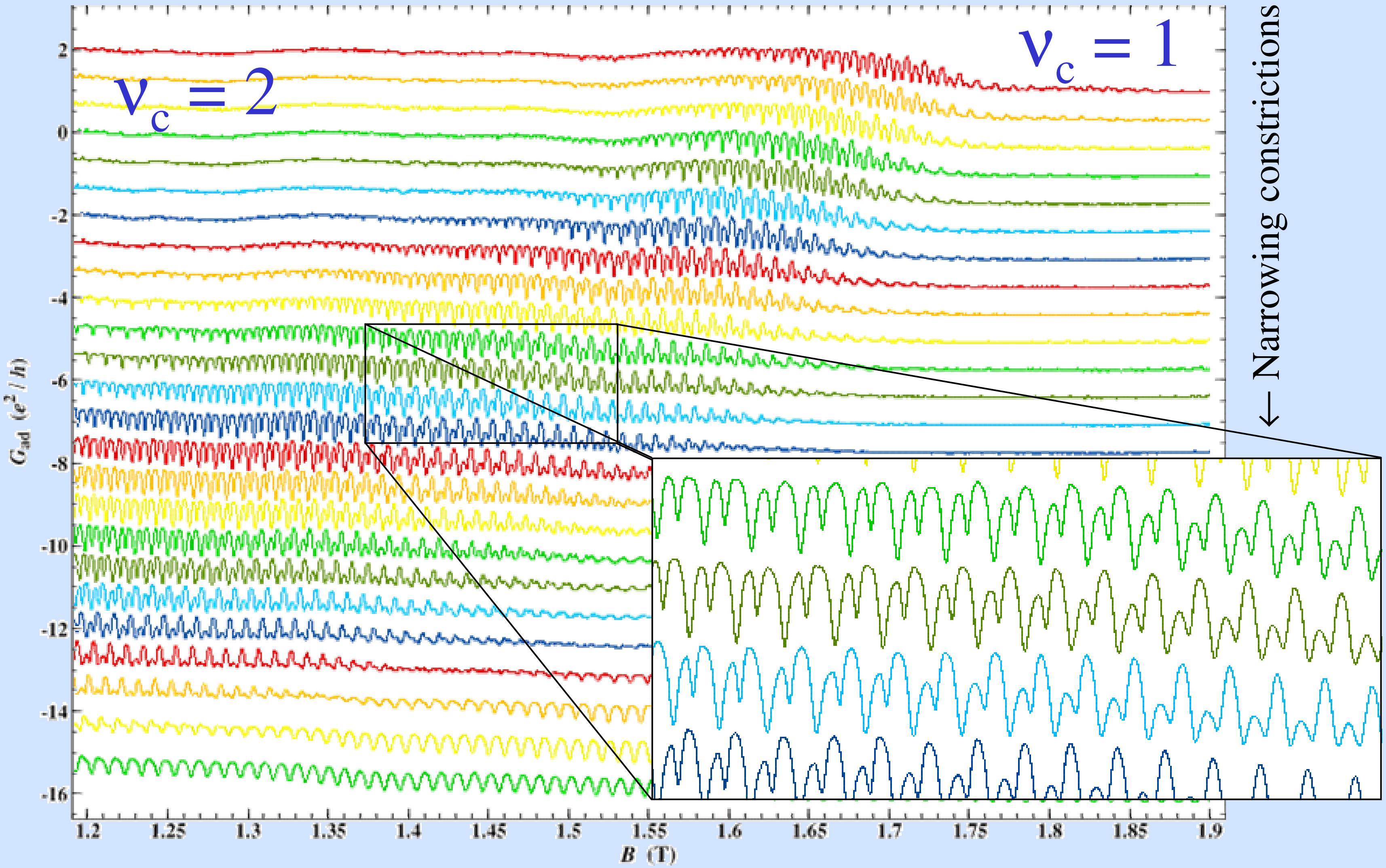
  ⇒ **"Double-frequency" Aharonov-Bohm oscillations**

The Big Picture – Varying Antidot Gate

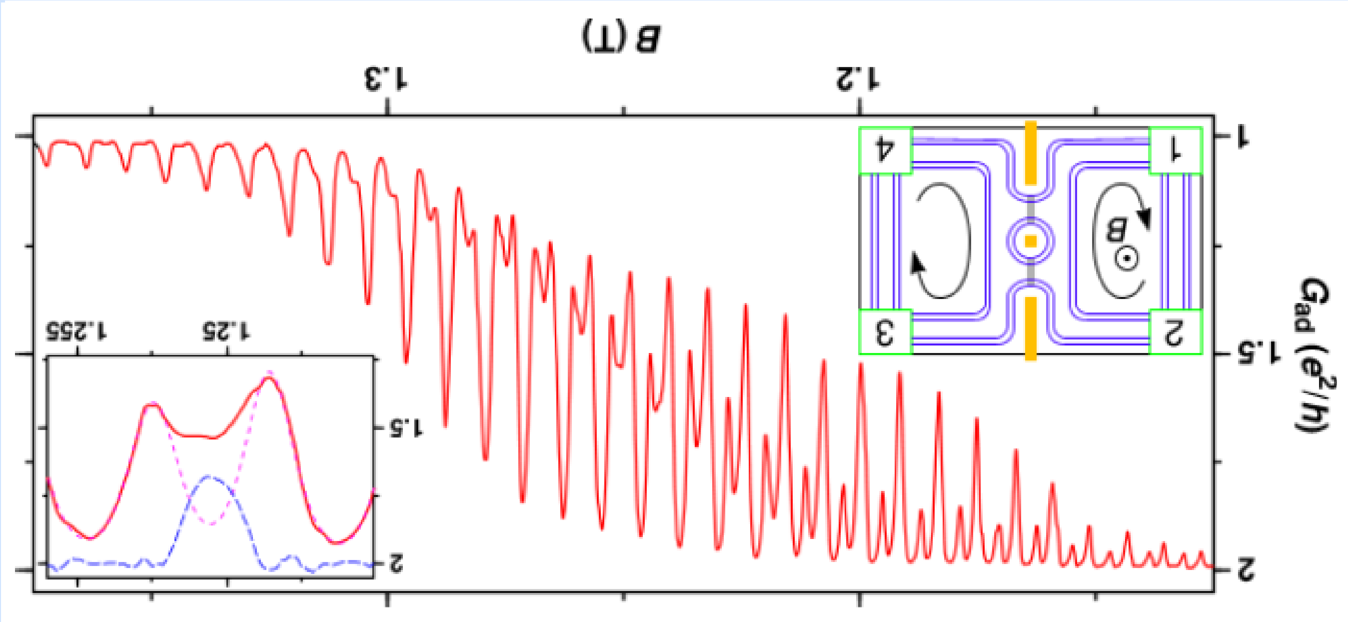


- Study of the line-shapes and temperature and DC-bias dependences can reveal the nature of the system in each region

AB Oscillations at Moderate *B*

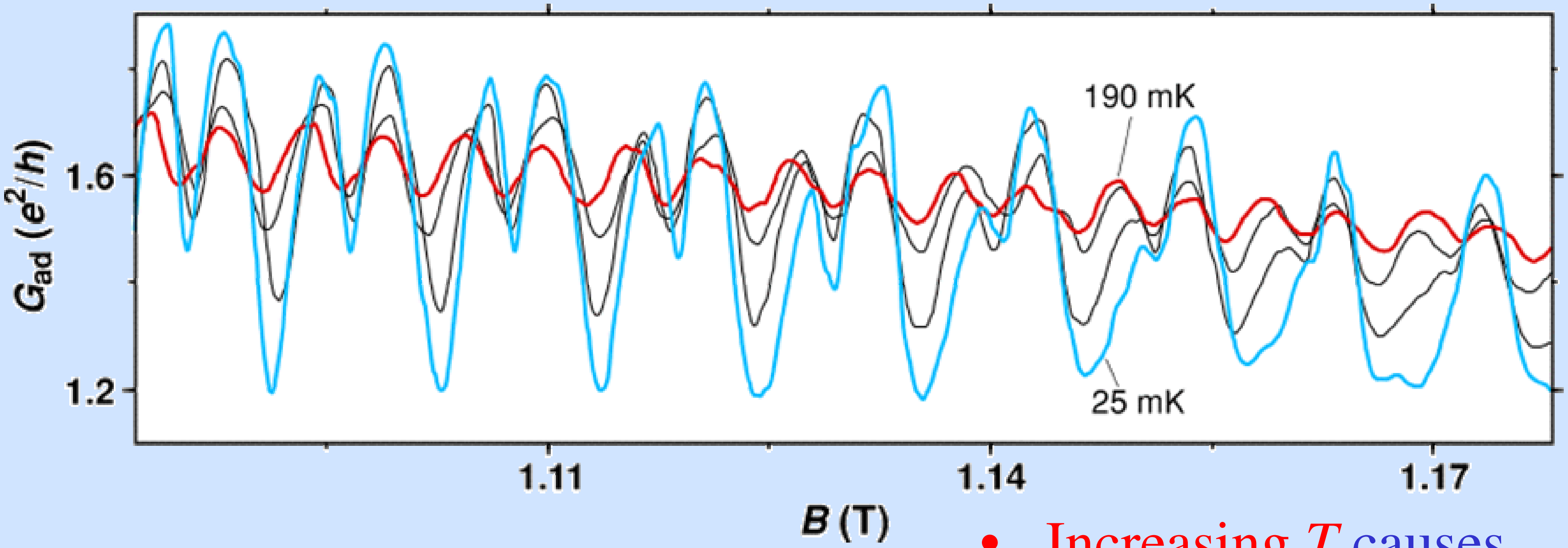


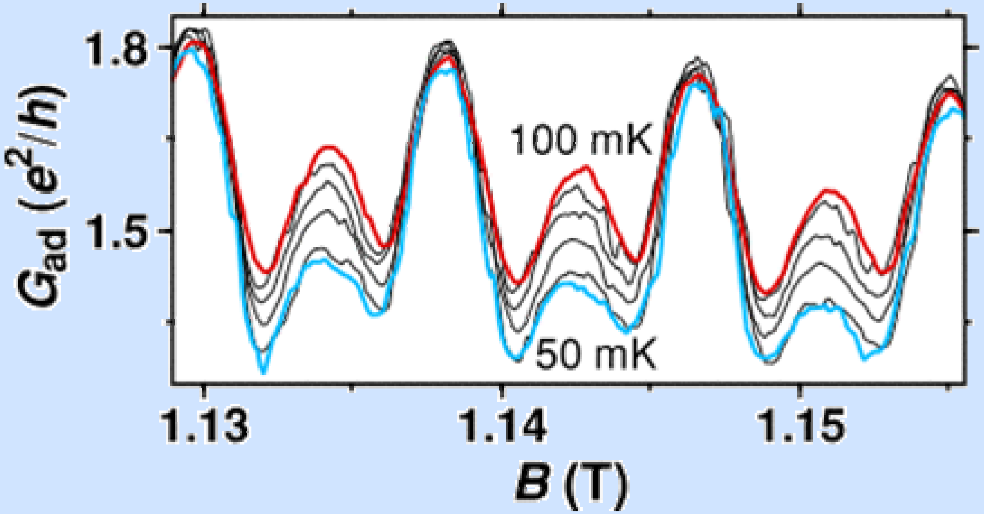
Kondo Effect in an Antidot?



- We can fit a set of dips to model the line-shapes, **but**:
- There is an extra dip in between alternate dips
- This, and *T* and DC-bias dependences, closely resemble the Kondo effect in a quantum dot
- Extra "Kondo" backscattering peak decays as *T* or V_{sd} is increased

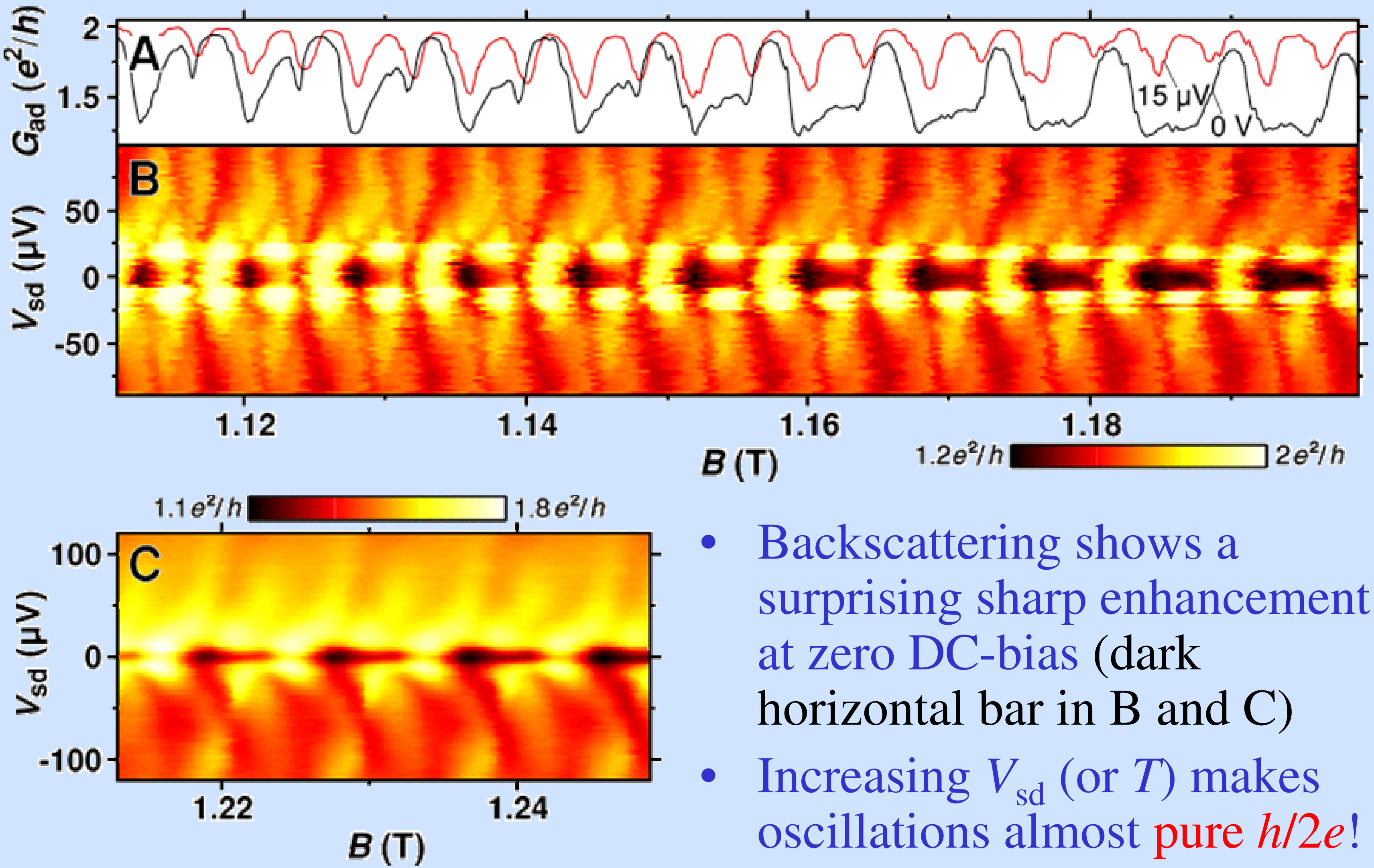
Temperature Dependence





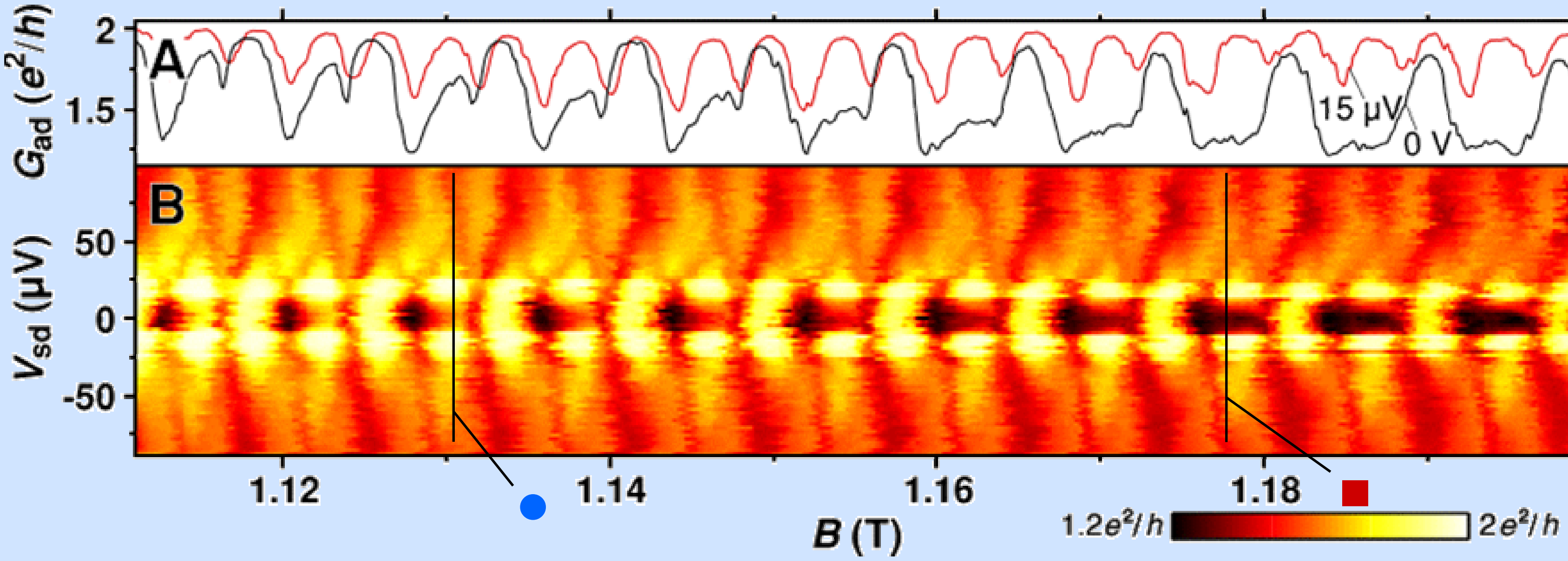
- Increasing *T* causes the splitting of each pair to become *more* pronounced
- Increasing *T* makes oscillations almost pure *h*/2*e*!

Zero-bias Anomaly in DC Bias

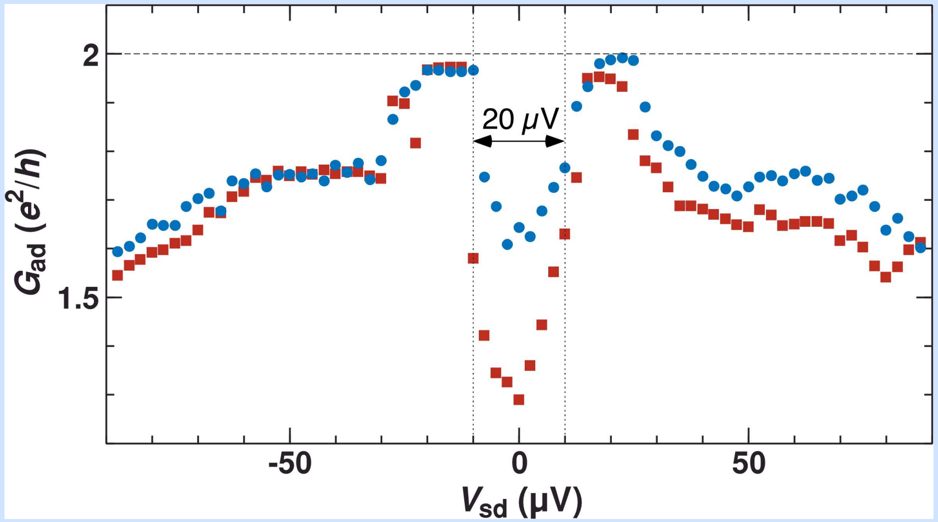


- Backscattering shows a surprising sharp enhancement at zero DC-bias (dark horizontal bar in B and C)
- Increasing V_{sd} (or T) makes oscillations almost pure $h/2e$! (A)

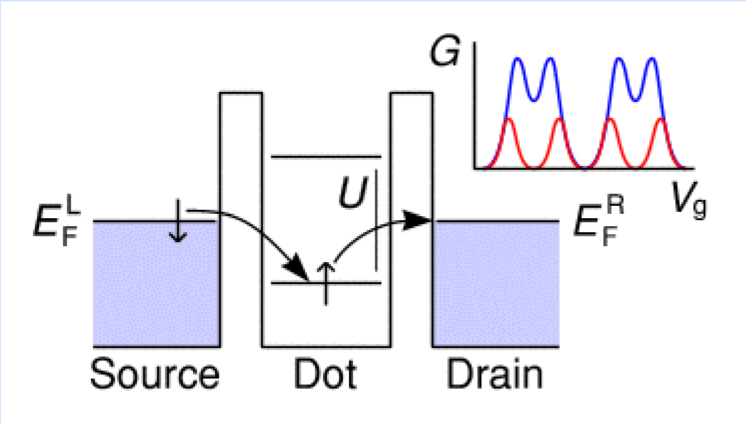
Source-drain Bias

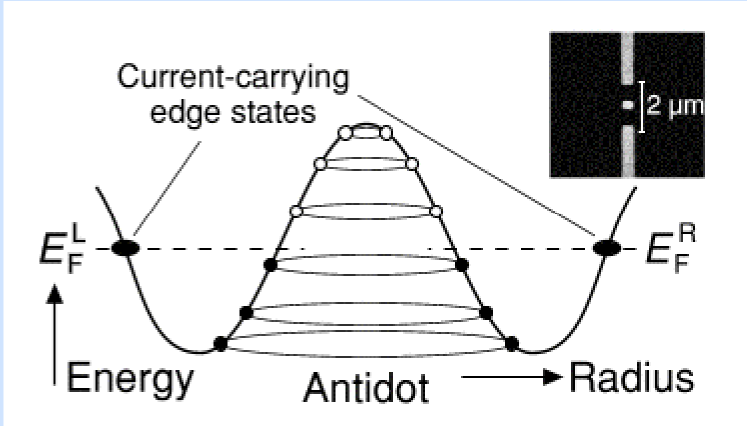


- Stronger zero-bias anomaly with stronger coupling at higher *B*
- Charging energy ~ 60 μeV
- FWHM of zero-bias anomaly ~ 20 μV (< $2E_Z/e$ ~ 60 μV)



The Kondo Effect





In a dot (or in bulk material):

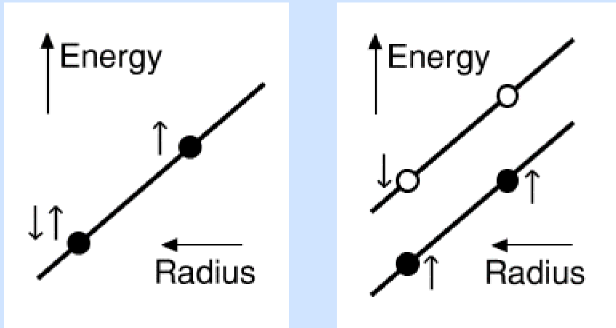
- *If* there is a pair of spin-degenerate states in the dot (or magnetic impurity) *and* one of the states is occupied, *then*

  another electron of opposite spin can tunnel in as the other electron tunnels out

- This is a second-order effect, but when first-order tunnelling is Coulomb blockaded, every electron in the vicinity can try to tunnel in this way, giving a huge enhancement – the Kondo effect
- The anti-parallel configuration must have a lower energy than the parallel one

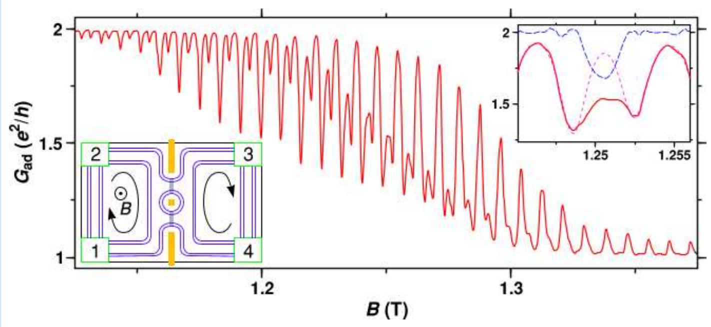
Is the Antidot Spin-degenerate?

- The Fermi energy must be the same in both leads (spin splitting would give a split ZBA) and T must be lower than T_K, which is related to the coupling
- Zeeman splitting has been observed in dots, as a splitting of the zero-bias anomaly
- The Zeeman splitting should be greater than the width of the band in DC-bias plots
- So perhaps it is suppressed [why?] or there is accidental degeneracy [unlikely since we always see this effect]



- Our two compressible regions may be present, but then the tunnelling probability will be different for each spin, which may or may not help… (Igor Smolyarenko and Nigel Cooper, TCM)

Conclusions



- Aharonov-Bohm oscillations in conductance past an antidot show effects very like Kondo effect in quantum dots:
  - Zero-bias anomaly (narrower than the Zeeman splitting!)
  - *T* dependence
  - Extra dip between alternate dips
- Why should Kondo effect occur? (requires spin degeneracy?)
  - Should consider many-body states around antidot
  - Exchange enhancement might align energies?
  - Skyrmion-like edge reconstruction?
  - Compressible regions (as at high *B*) – but tunnelling different?
- Unusual features:
  - Kondo dip saturates at e^2/h, not at $2e^2/h$
  - The two peaks have different amplitudes (anisotropic coupling)