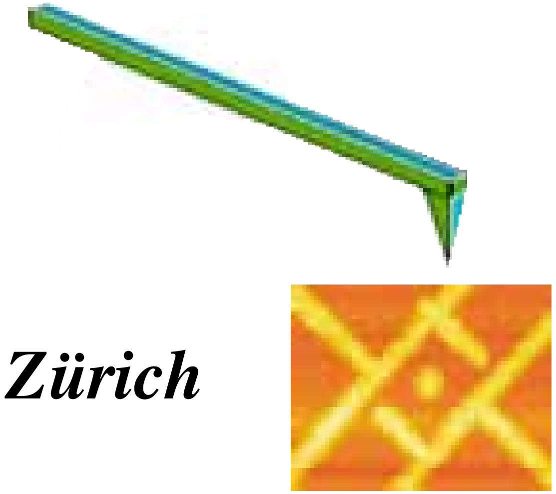
Spin states in quantum rings

Klaus Ensslin



Solid State Physics **Zürich**

in collaboration with

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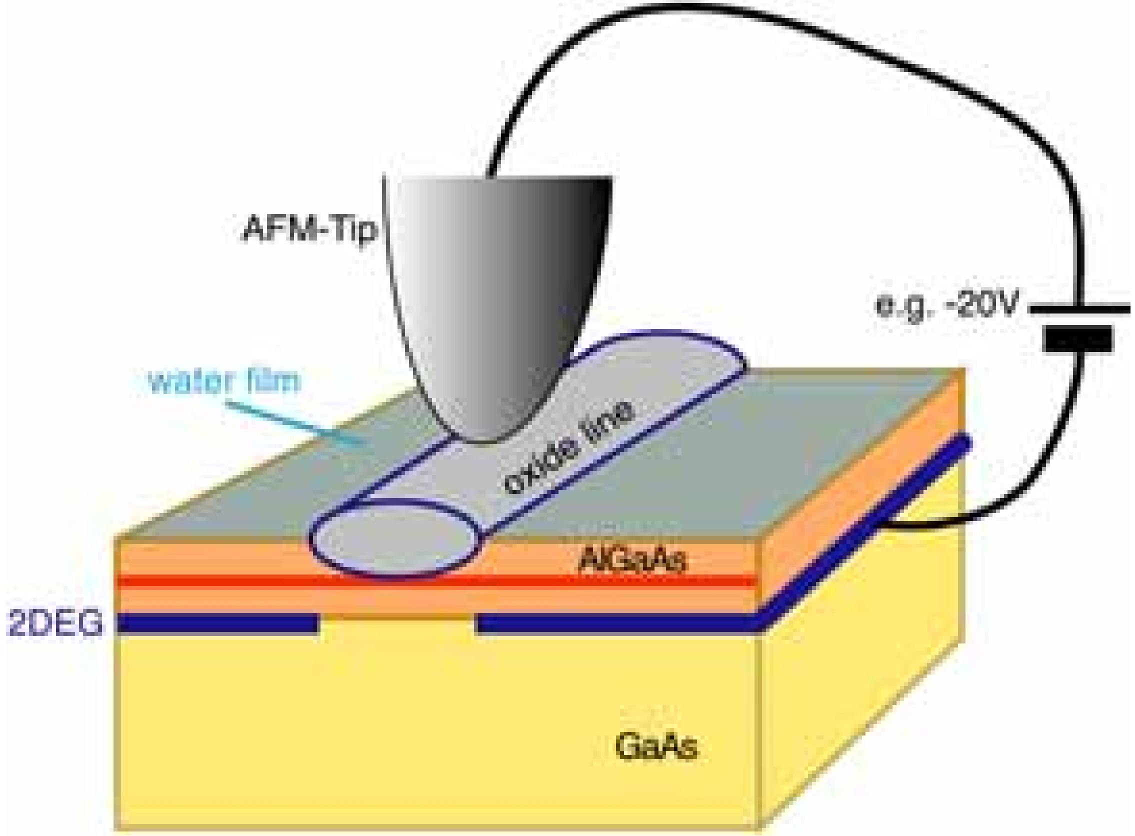
T. Ihn	ETH Zürich
T. Heinzel	Univ. Freiburg
W. Wegscheider	Univ. Regensburg
M. Bichler	TU München

coherence
energy spectra
and
spin states
in dots/rings

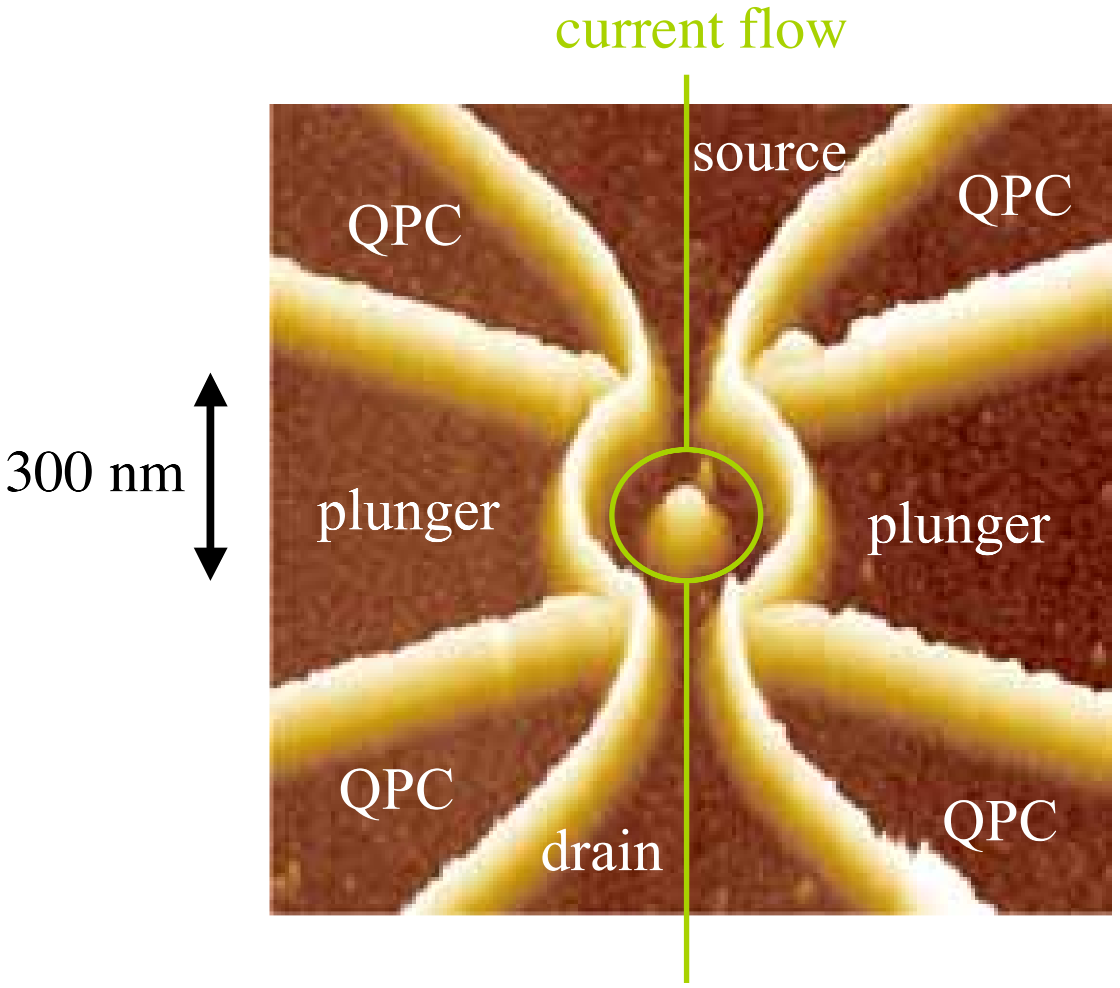
direct patterning of AlGaAs/GaAs



high mobility two-dimensional electron gas (2DEG)
below sample surface

Matsumoto et al., APL **68**, 34 (1996)
Held et al., APL **73**, 262 (1998)

AFM defined quantum ring



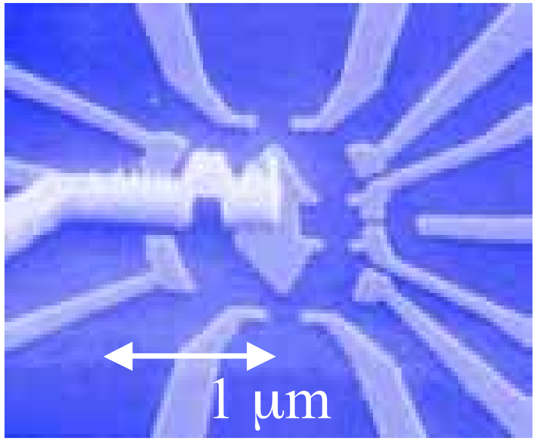
Kekulé
Bull. Soc. Chim.
Fr. 3, 98 (1865)
-> benzene

Aharonov & Bohm
Phys. Rev. **115**,
485-491 (1959)
-> magnetic flux

Büttiker, Imry,
& Landauer
Phys. Lett. 96A,
365-367 (1983)
-> persistent currents

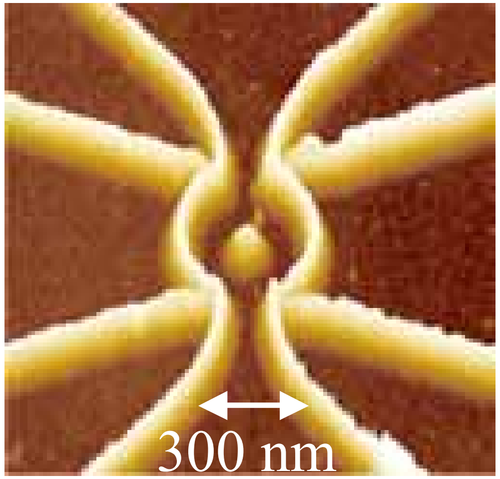
coherence

measure the phase of an electronic system



quantum dot in an
Aharonov-Bohm interferometer

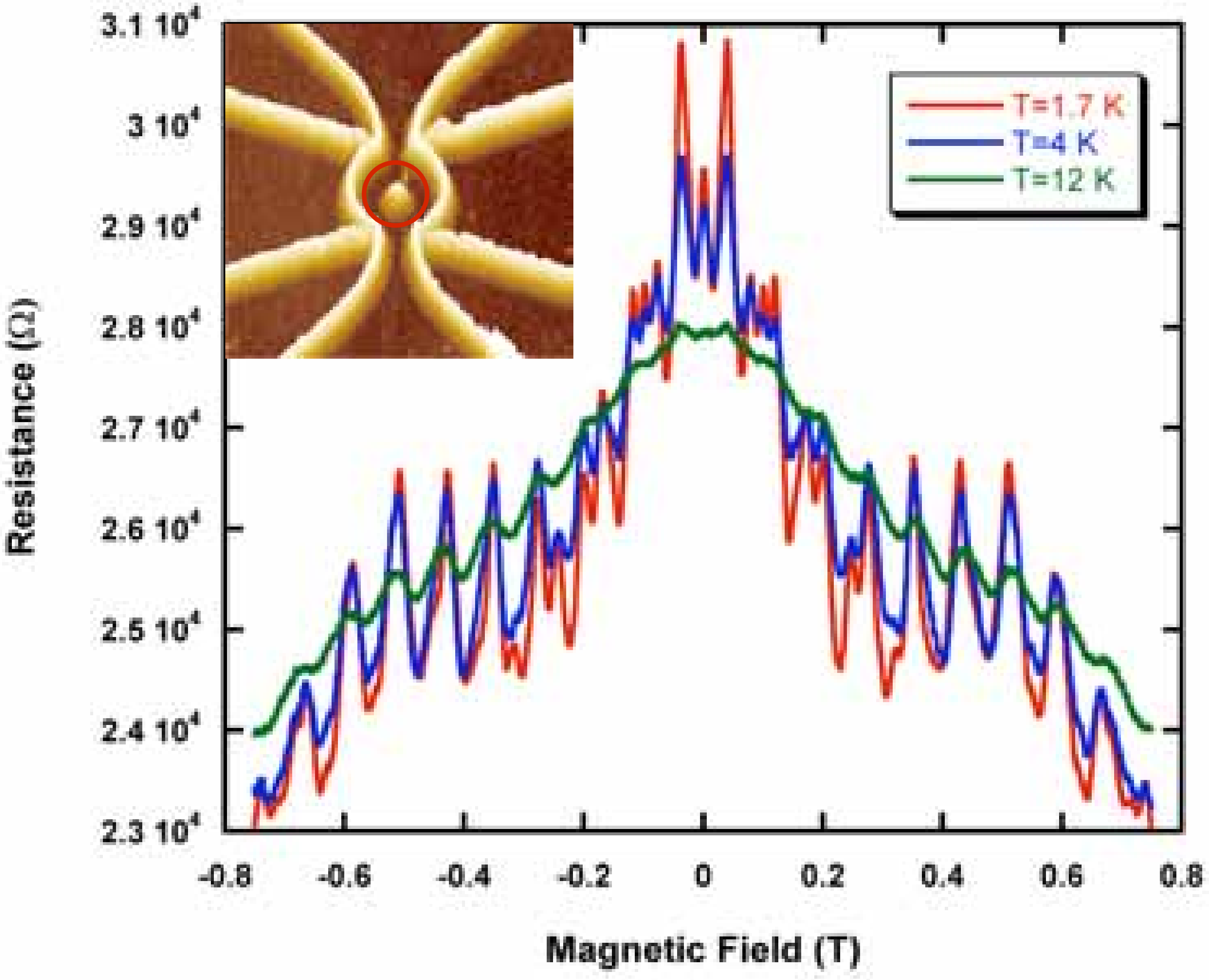
Heiblum et al @ Weizmann
Nature 391, 871 (1998)



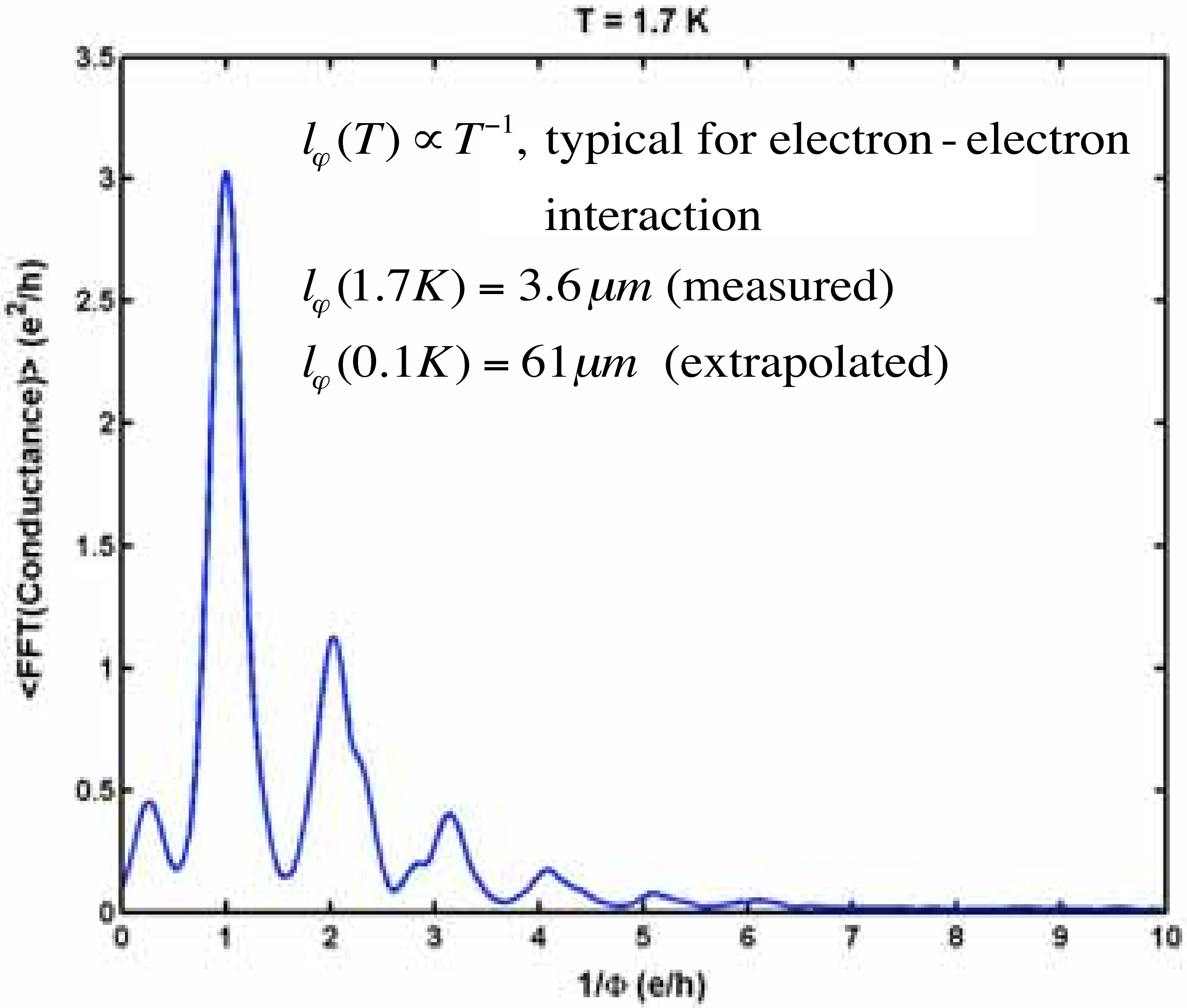
Coulomb blockaded
quantum ring

-> Aharonov-Bohm effect
and Coulomb blockade ?

open ring: AB effect



Fourier trafo amplitude

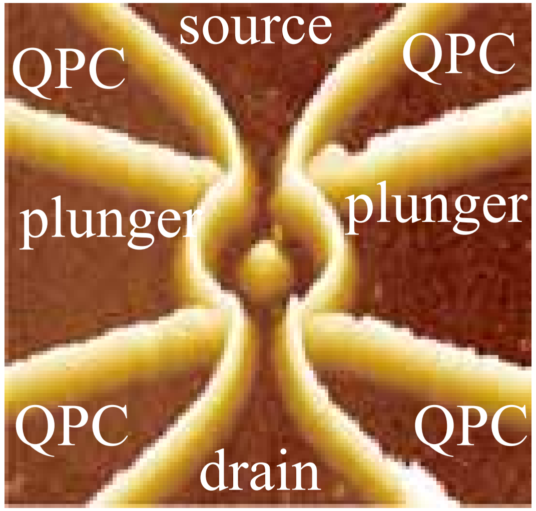


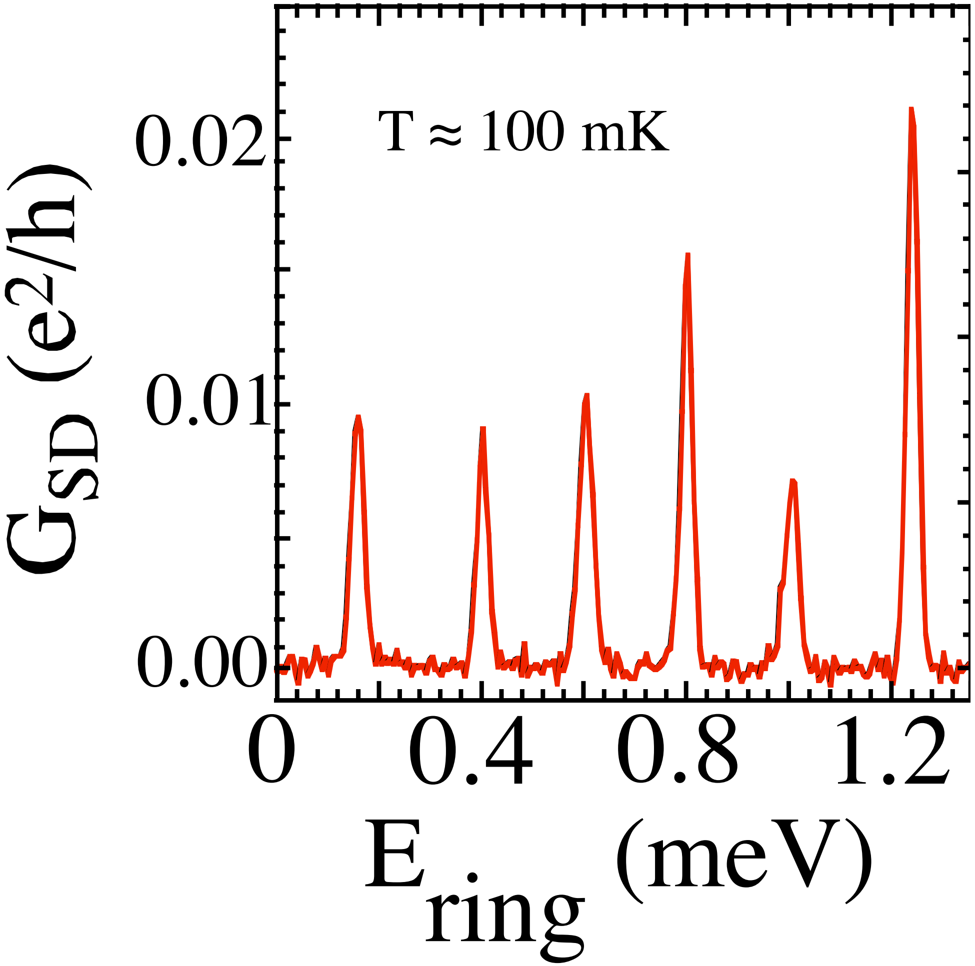
$l_\varphi(T) \propto T^{-1}$, typical for electron - electron interaction

$l_\varphi(1.7K) = 3.6\mu m$ (measured)

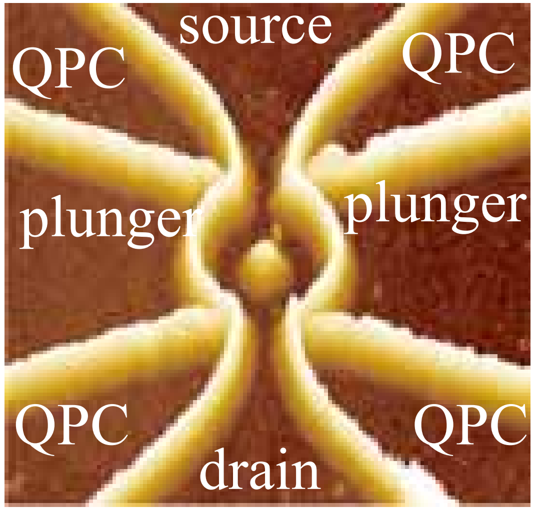
$l_\varphi(0.1K) = 61\mu m$ (extrapolated)

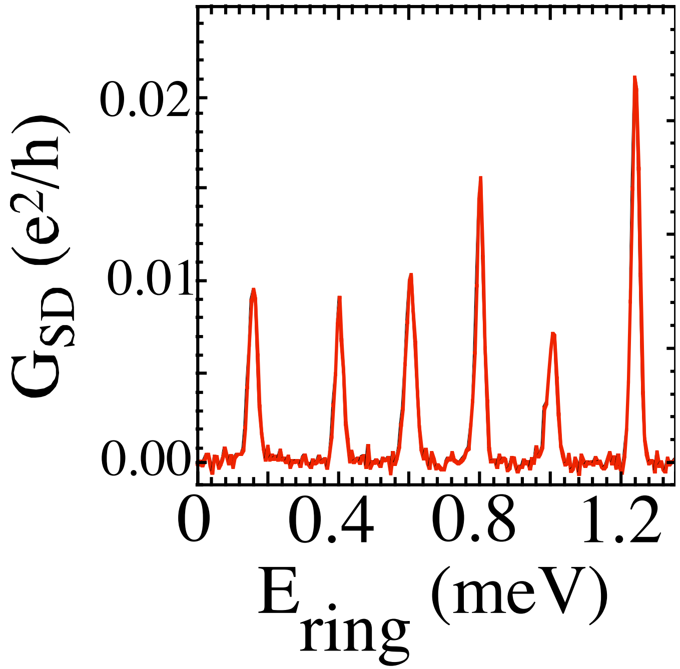
Coulomb blockaded quantum ring

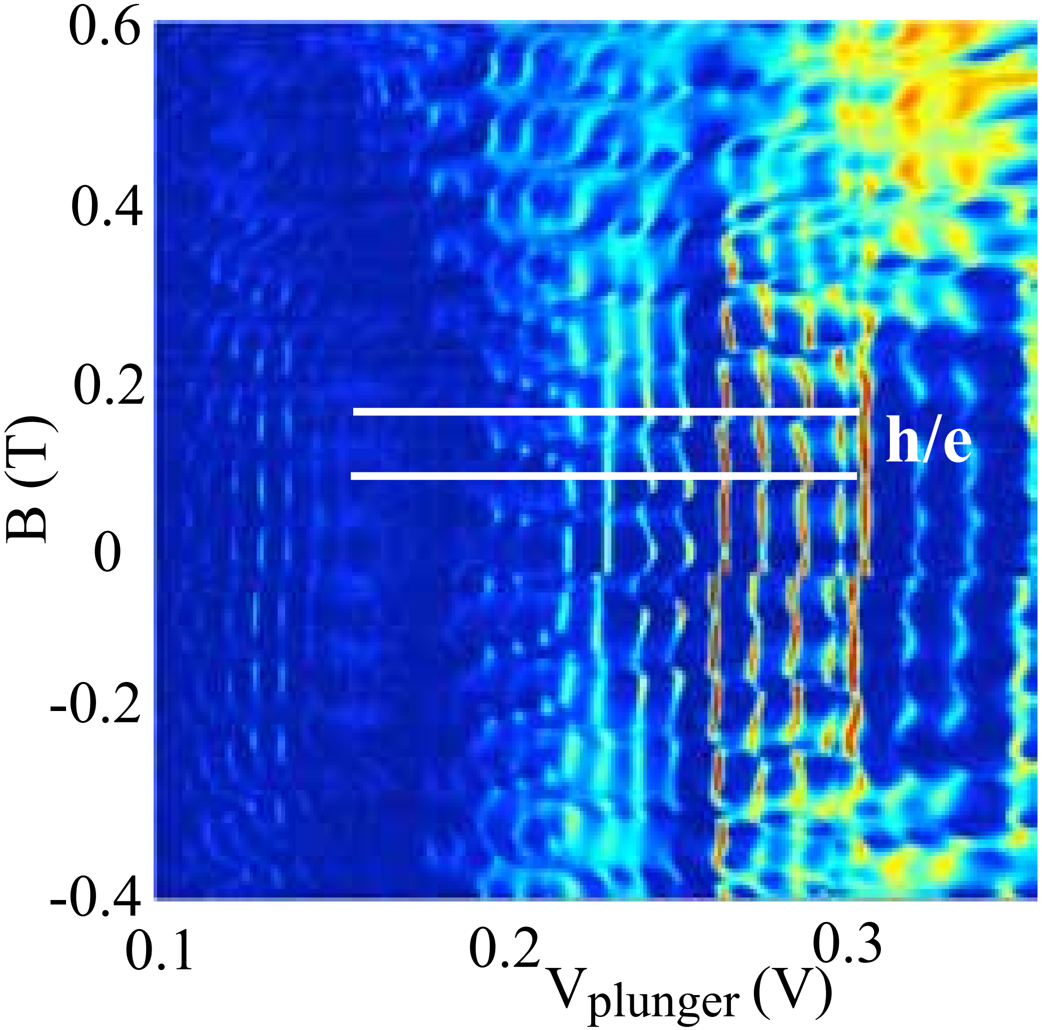




quantum ring

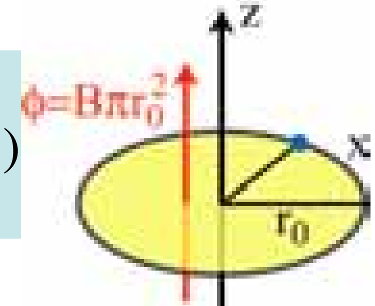


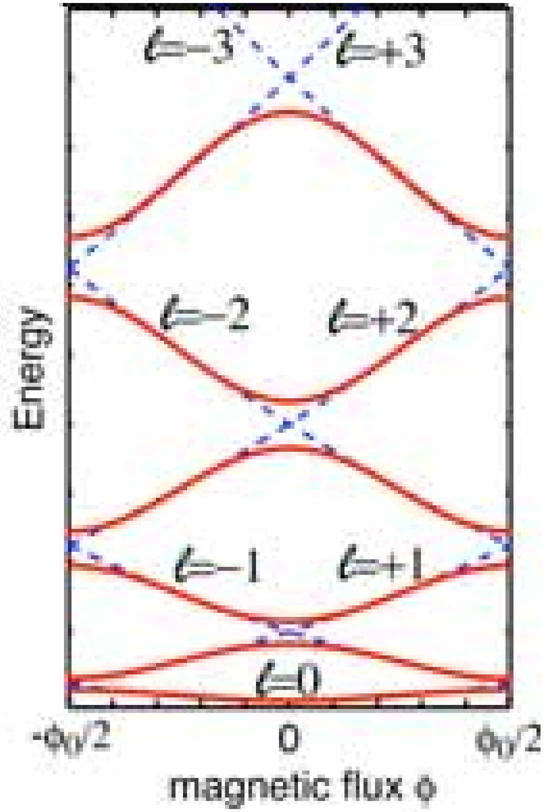


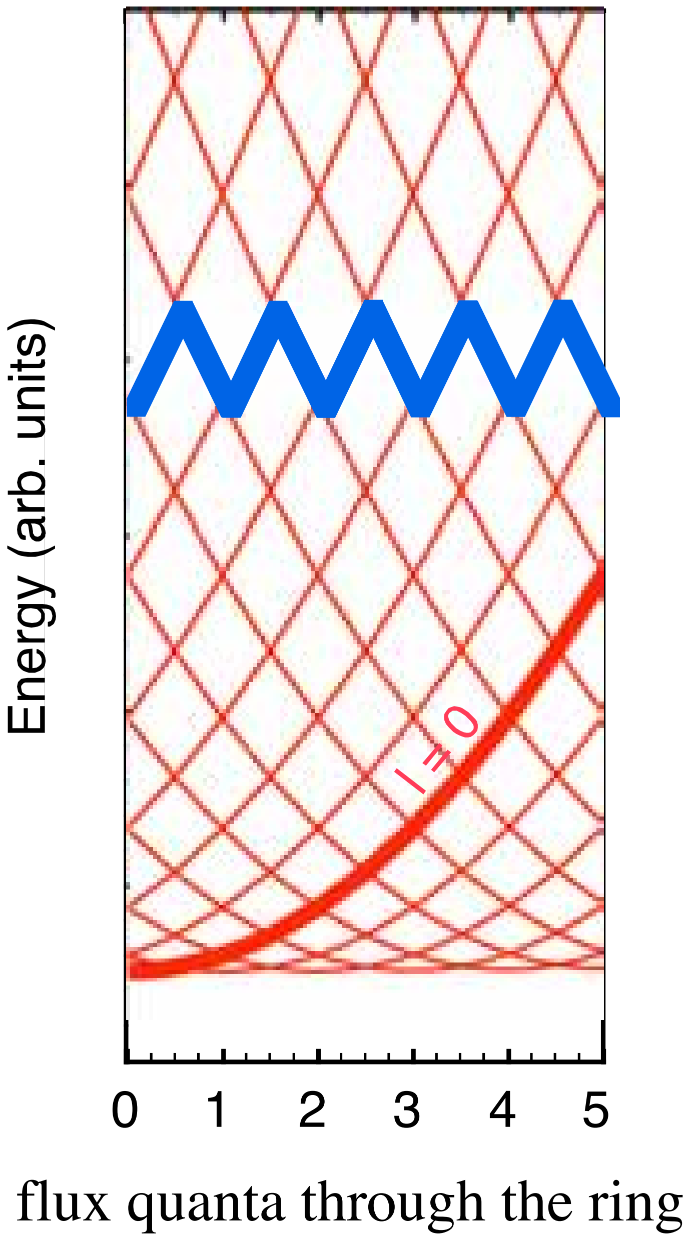


Spectrum of a 1D-Ring

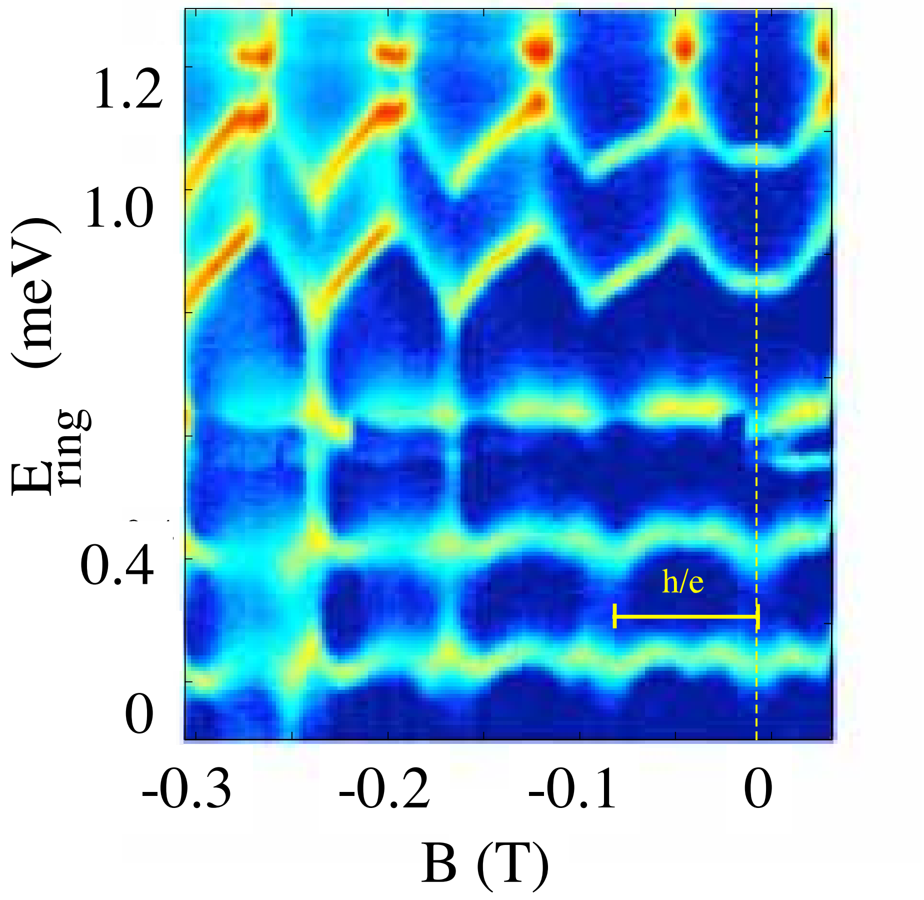
$$\left[\frac{1}{2m}\left(\frac{\hbar}{i}\frac{\partial}{\partial x}+\frac{\hbar}{r_0}\frac{\phi}{\phi_0}\right)^2+\boxed{\hat{V}(x)}\right]u(x)=E(\phi)\cdot u(x)$$







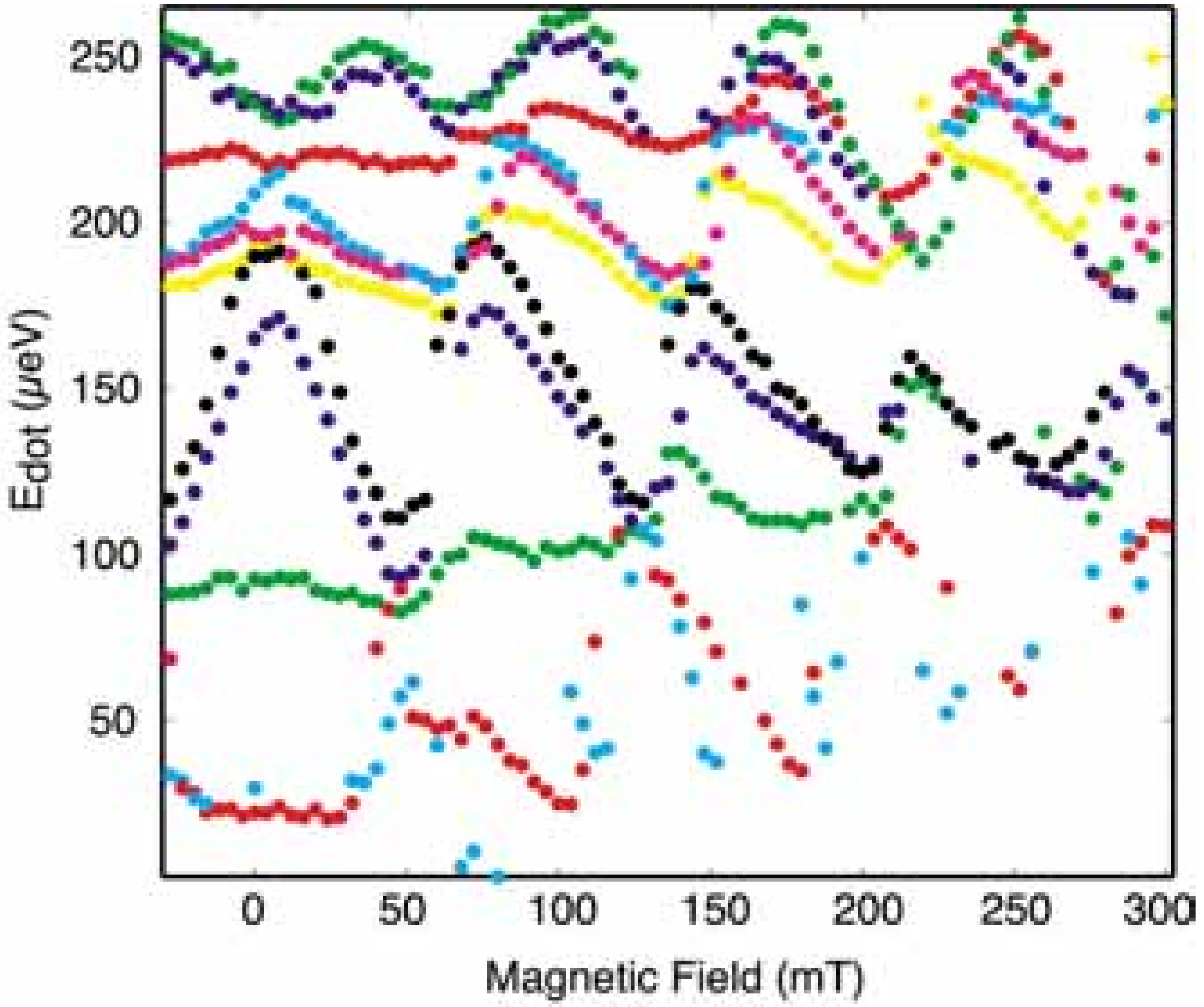
constant number of electrons



$$j = -\frac{\partial F}{\partial \Phi} \approx 5\ \text{nA}$$

F: free energy
Φ: flux

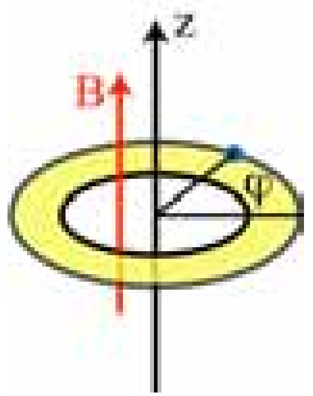
Coulomb peak positions

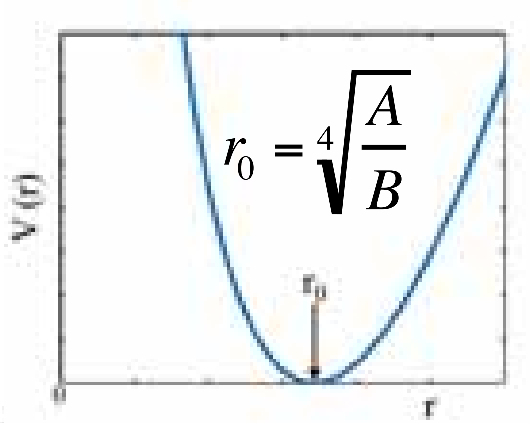


strongly
(weakly)
oscillating
states

-> small
(large)
spin splitting

Model: Ring with finite width



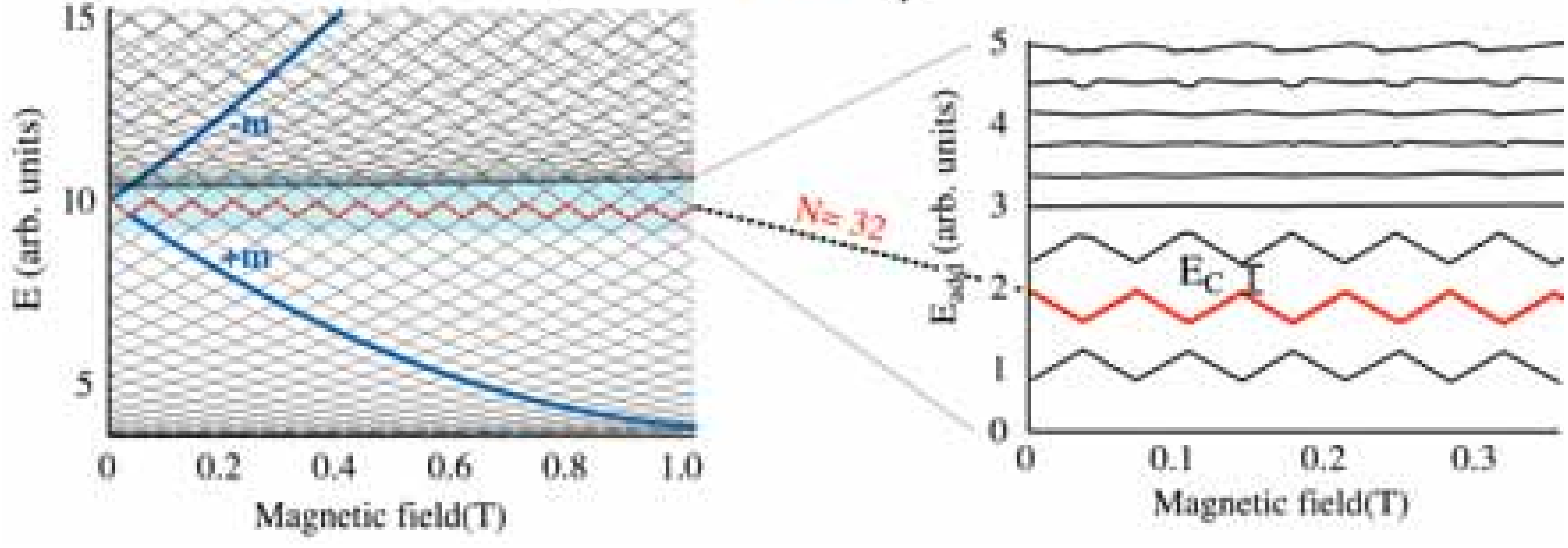


$$r_0 = \sqrt[4]{\frac{A}{B}}$$

Tan & Inkson
PRB **53**, 6947 (1996)

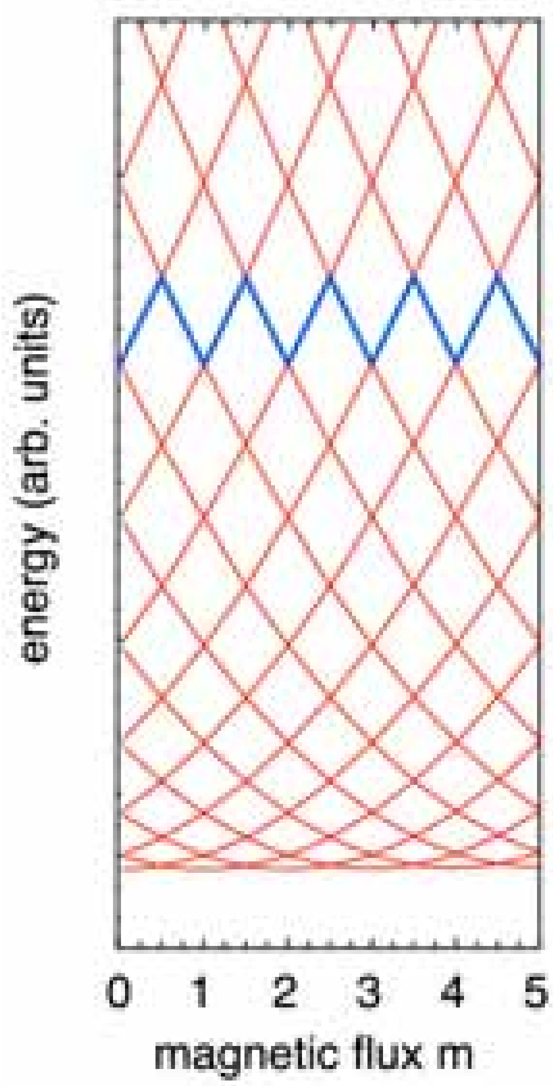
$$V(r) = A \cdot \frac{1}{r^2} + B \cdot r^2$$

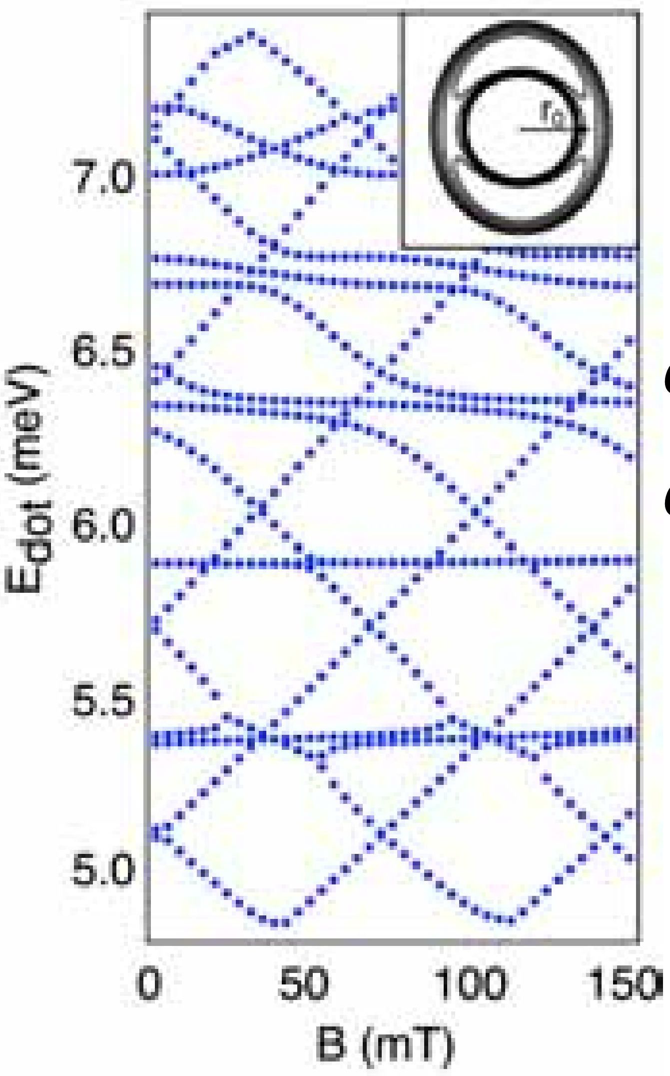
$$\omega_0 = \sqrt{8B/m^*}$$



calculated energy spectra

perfect ring

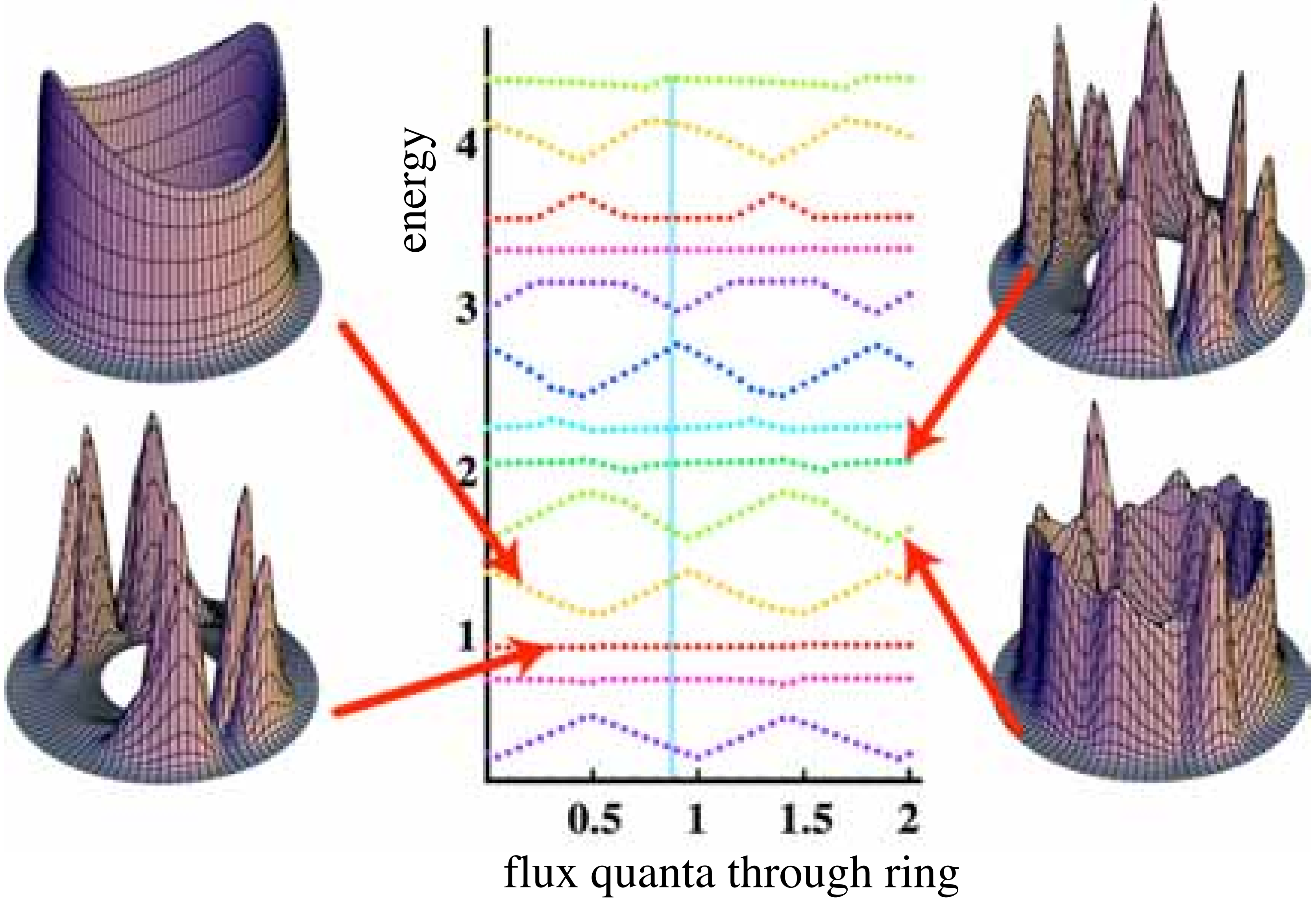




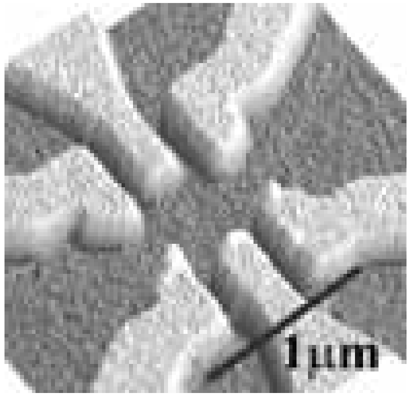
asymmetric ring
with finite width

$$\omega_0 -> \omega_0\left(1-\varepsilon\cos(2\Phi)\right)$$

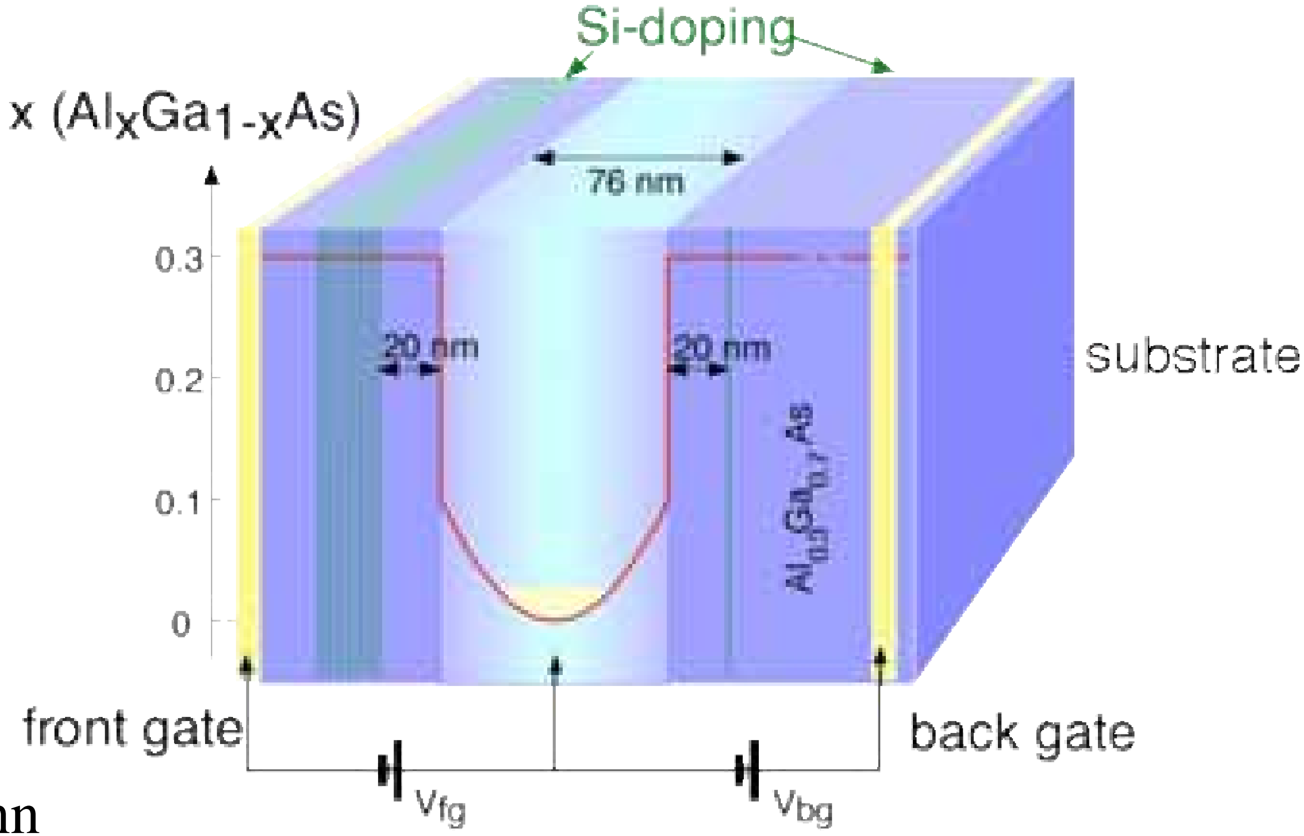
energy levels and wave functions



top gate defined quantum dots



top gates defined by electron beam lithography

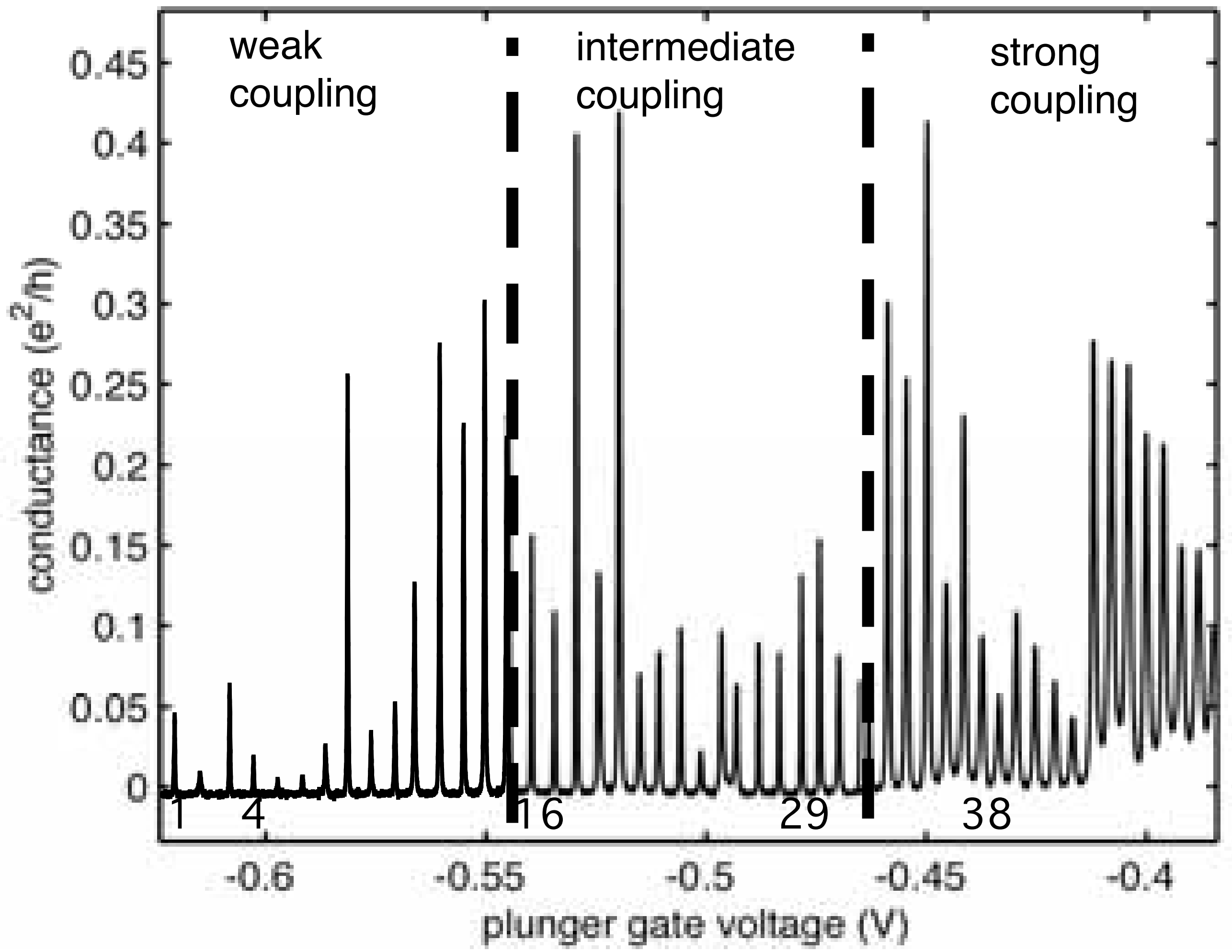


electron gas is
embedded in
a parabolic
quantum well

Stefan Lindemann

Samples: K. Maranowski, A. Gossard

Coulomb blockade in different coupling regimes



Spectroscopy of spin states

$$\mu_S = \mu_{N+1}(B) = \underbrace{E_{N+1}(B_{\|}) - E_N(B_{\|})}_{\varepsilon_{N+1} + U^H_{N+1} + U^{xc}_{N+1} + \gamma_{N+1} B_{\|}^2 - e\alpha V_{pg}^{N+1}} + (s_z^{N+1} - s_z^N) g \mu_B B_{\|}$$

single-particle energy

Hartree energy

exchange energy

diamagnetic shift

Zeeman-shift

$$V_{pg}^{N+1}(B) = \frac{1}{\alpha e}\left[\varepsilon_{N+1} + U^H_{N+1} + U^{xc}_{N+1} - \mu_S + \gamma_{N+1} B_{\|}^2 + \underbrace{\left(s_z^{N+1} - s_z^N\right)}_{\text{half integer}} g \mu_B B_{\|}\right]$$

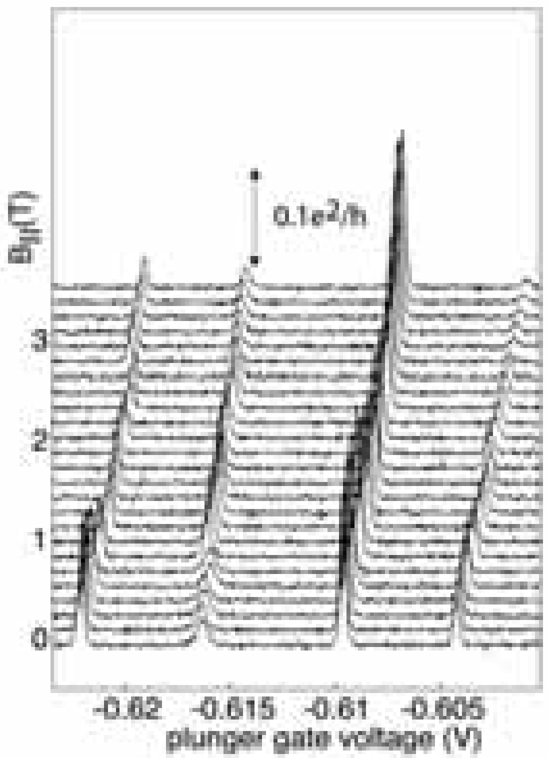
Coupling regimes

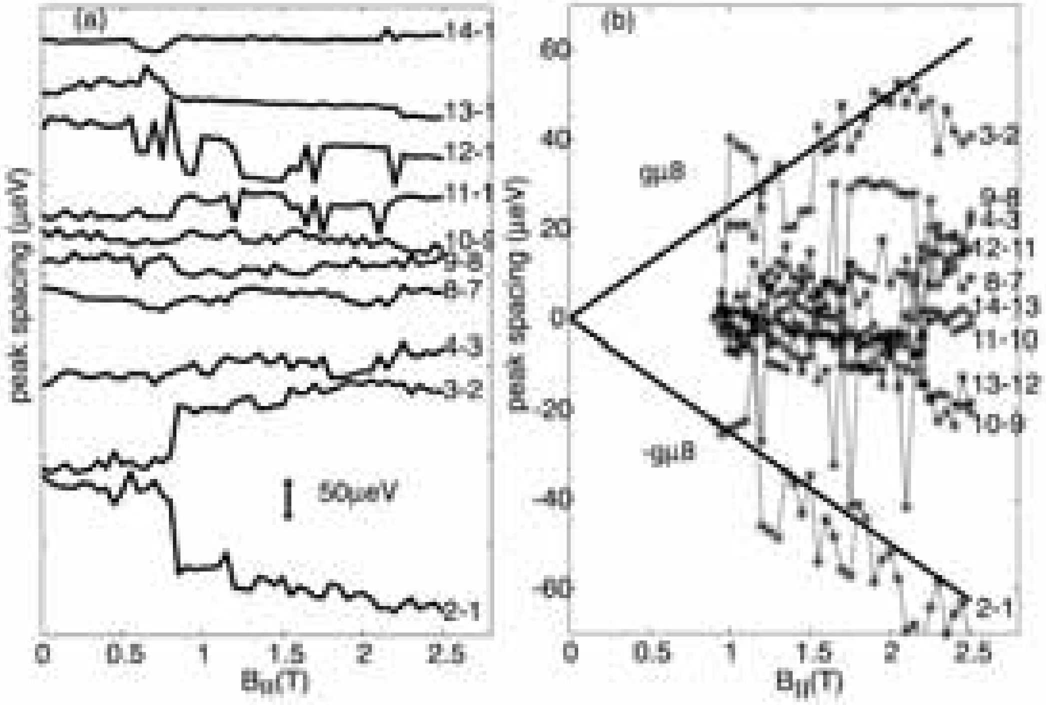
coupling regime	weak	inter-mediate	strong
Conductance [e^2/h]	0.04	0.14	0.18
level width [μeV]	43	52	83
level sepa-ration [μeV]	60 ⟶	⟶	⟶

single-level transport | multi-level transport

Weak coupling regime

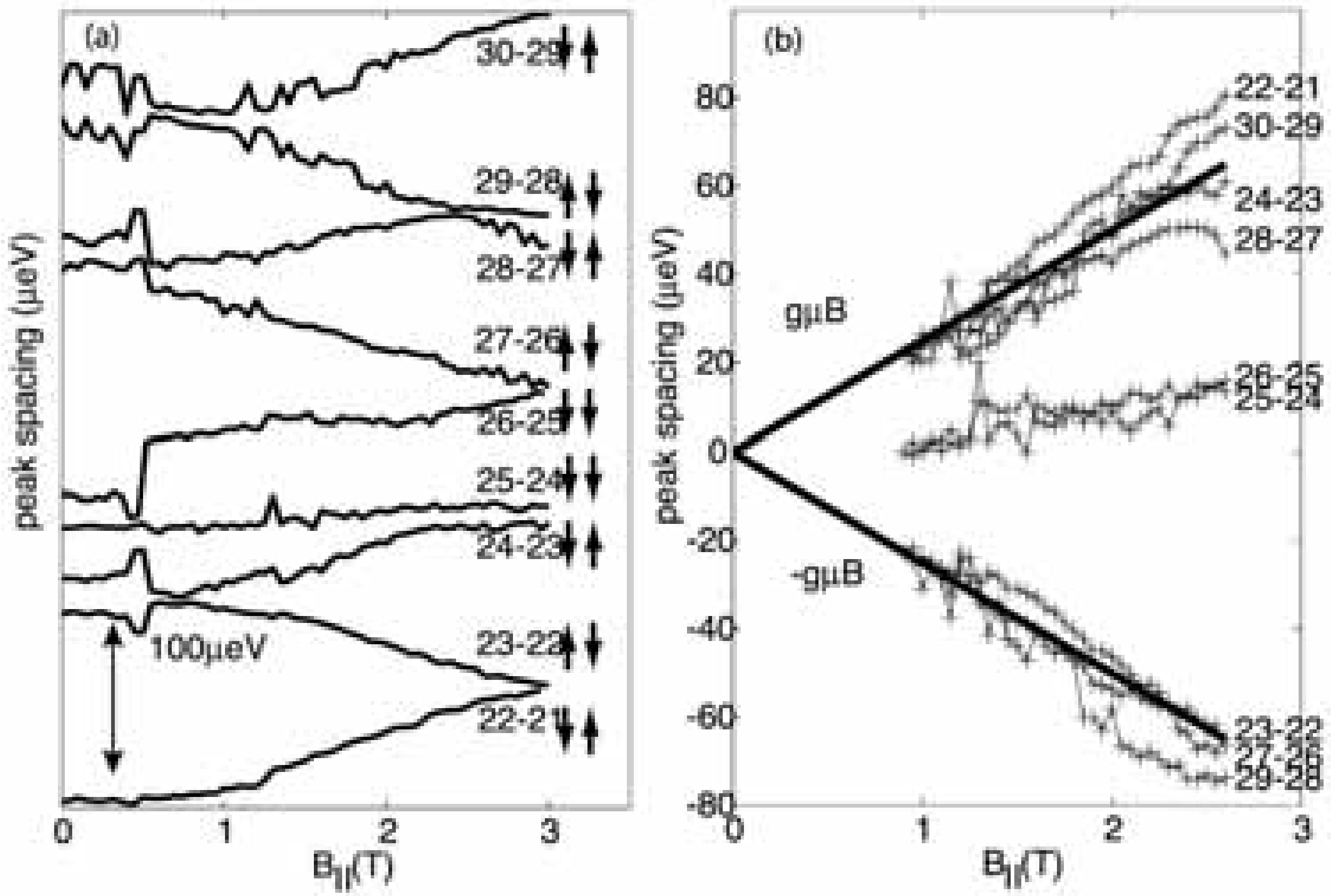
$E_c \approx 10$ K
$\Delta \approx 1$ K
$g\mu_B B$ (1T) ≈ 100 mK





- peak positions fluctuate strongly in B_parallel
- peak separations fall in accordance with Zeeman splitting
- flat peak separation below B ≈ 1T

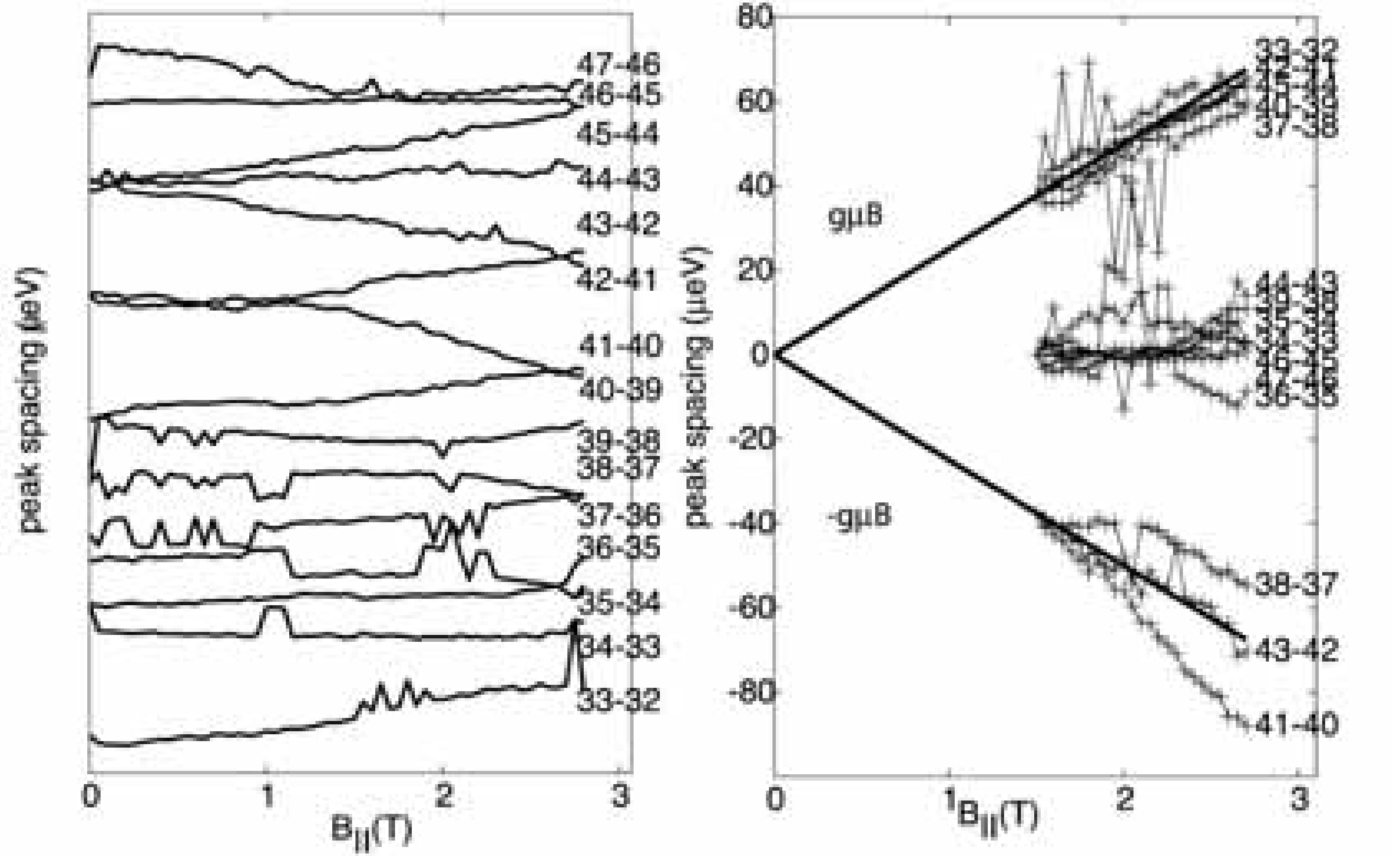
Intermediate coupling regime



see also
Duncan et al,
APL **77**, 2183
(2000).
Folk et al,
Physica Scripta
T **90**, 26(2001).

- peak separations fall into three categories compatible with Zeeman splitting

Strong coupling regime



- peak separations fall into three categories compatible with Zeeman splitting

Zeeman splitting in GaAs quantum dots

- weak coupling (single-level transport):
  peak separations fluctuate and
  generally agree with prediction of Zeeman splitting
- intermediate and strong coupling (multi-level transport):
  peak separations compatible with weakly interacting
  spin 1/2 particles
- spin pairs detected in perpendicular magnetic fields

- spin degrees of freedom in quantum dots are remarkably stable