Quest for Novel Kondo Nano systems

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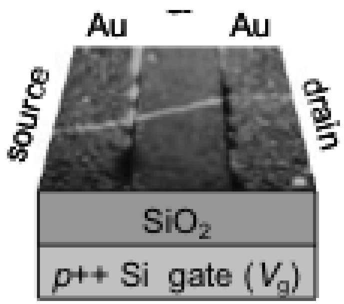
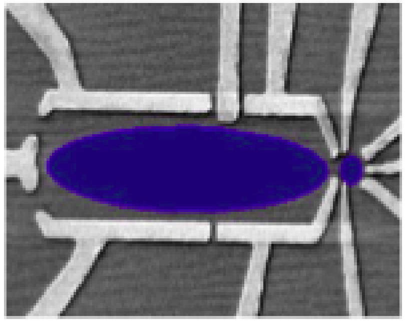
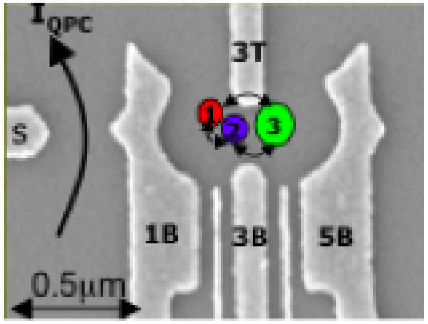
Yale University

Duke, 9th of November 2006







The resistance minimum…

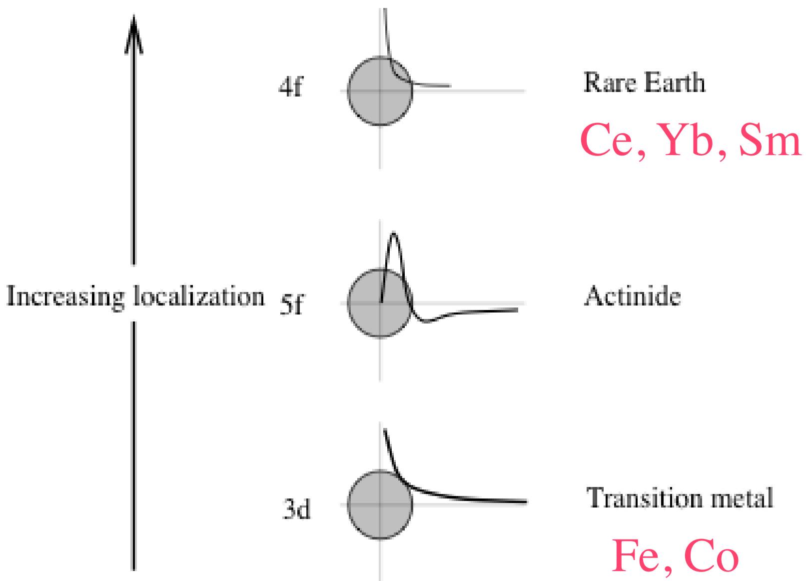


FIGURE 1. Depicting localized 4*f*, 5*f* and 3*d* atomic wavefunctions.

At Leiden, 1934, the resistance minimum
de Haas, Von de Boer, Van den Berg
Physica **1**, 1115 (1934)

1936: Casimir joined Leiden

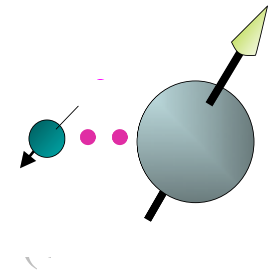
Casimir and Van den Berg worked on the Kondo effect. In 1938, based on an earlier suggestion by Peierls, Casimir worked on heat conductivity of pure single crystals…

« zero-point fluctuations of phonons »

« The resistance minimum was first observed in noble metals containing small concentration of 3d transition metals (such as iron or manganese) »
Jun Kondo, « 40 years after discovery », JPS of Jpn (2005)

Leiden group, 1930s
Sarachik, 1960s

Summary

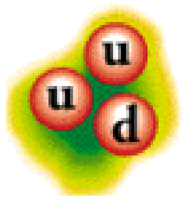


-*Kondo effect definition:*

Involves a magnetic impurity and conduction electrons

A standard « confinement » problem

(meV instead of GeV for quark confinement…)



-Physical observables: universal functions of the confinement scale

-Why Nanotechnology is useful:

« Artifical spin qubit », building block for quantum computing, but also

Engineer some « toy » models and check for fundamental physics

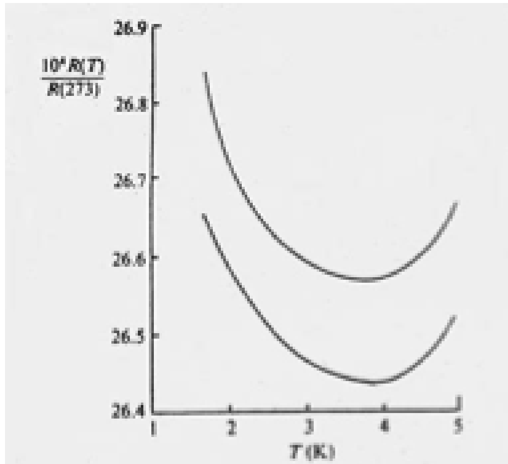
Explore new confinement phenomena

Explore quantum phase transitions through the Kondo effect

Kondo model: impurity spin in metal

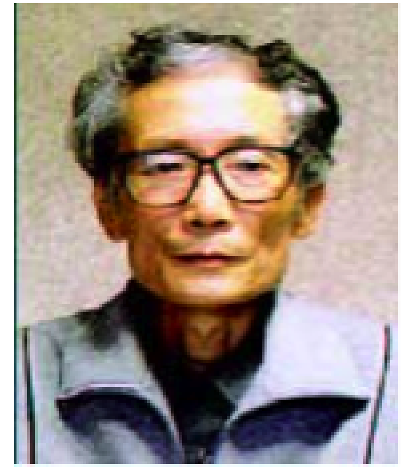
$\rho_O \sim 0.1\Omega\text{cm}$

Good metal:
$\rho \sim 10^{-5}\Omega\text{cm}$



'34: Resistivity minimum of Au

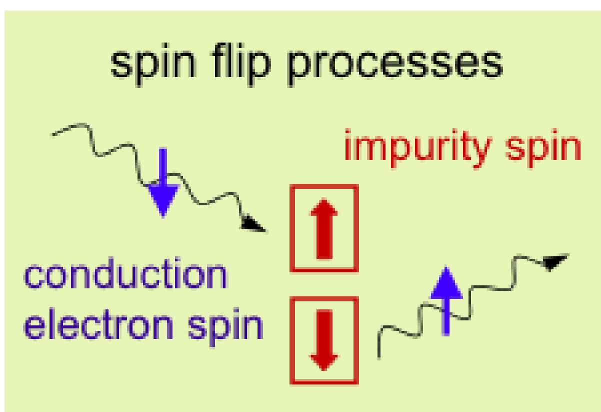
De Haas et al., Physica 1,1115



'62: Explanation by J. Kondo

Electron spin operator:

$$\mathbf{S}^e(\mathbf{x}=\mathbf{0}) = \sum_{\substack{\mathbf{k},\mathbf{k}' \\ \alpha,\beta}} c_{\mathbf{k}\alpha}^{\dagger} \frac{\boldsymbol{\sigma}_{\alpha\beta}}{2} c_{\mathbf{k}'\beta}$$



$$J_\perp[S_+^{(imp)}S_-^{(e)} + h.c.] + J_z S_z^{(imp)} S_z^{(e)}$$

Kondo singlet $\frac{1}{\sqrt{2}}\left(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle\right)$

at $T < T_K$ (Kondo temperature)

Many-body strong-coupling picture

The renormalization group equations tell us that at scales of the order of T_K the Kondo coupling becomes of the order of bandwidth

Anderson, 1970

Precursor of renormalization group for interacting fermions: Shankar, Rev. Mod. Phys. 94

Strong-coupling stable

Wilson (1975): Numerical Renormalization Group method

$$C_v = \gamma T$$

$$\gamma = \frac{\pi}{3} \frac{0.4128 \pm 0.002}{8 T_K}$$

$$W = \frac{\chi/\chi^o}{\gamma/\gamma^0} = \frac{\chi}{\gamma} \frac{\pi^2 k_B^2}{3 \mu_B^2} = 2$$

$T \ll T_K$

Renormalized density of states

$N^*(0) = 1/T_K \Rightarrow$ Heavy Mass $\propto 1/T_K$

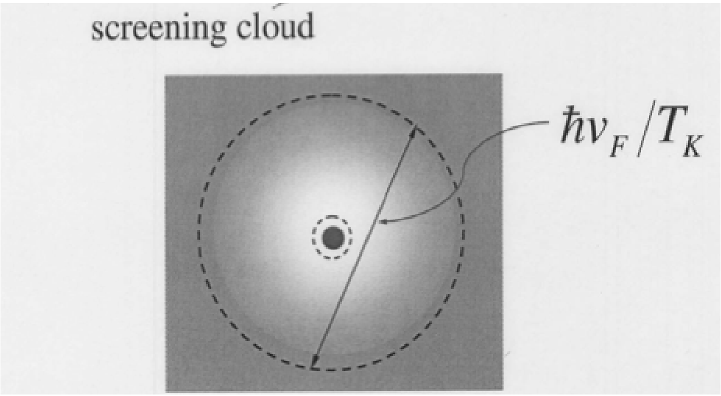
agree with Bethe-Ansatz calculations

N. Andrei; P. Wiegmann (1980)

Emergence of heavy fermions

Real-space picture:
Nozières, 1974

BCFT Spectroscopy:
Affleck & Ludwig

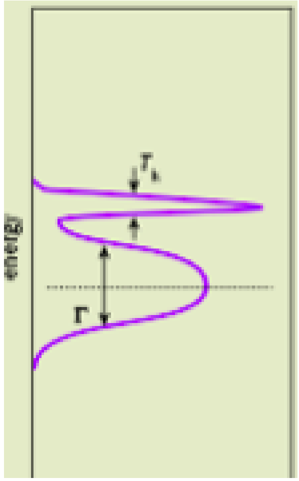


Key point: $T \ll T_K$
Spin induces interactions between electrons $\approx 1/T_K$

⇓

« Emergence of heavy Mass »

Large-N theory
(N. Read & Newns 1983)

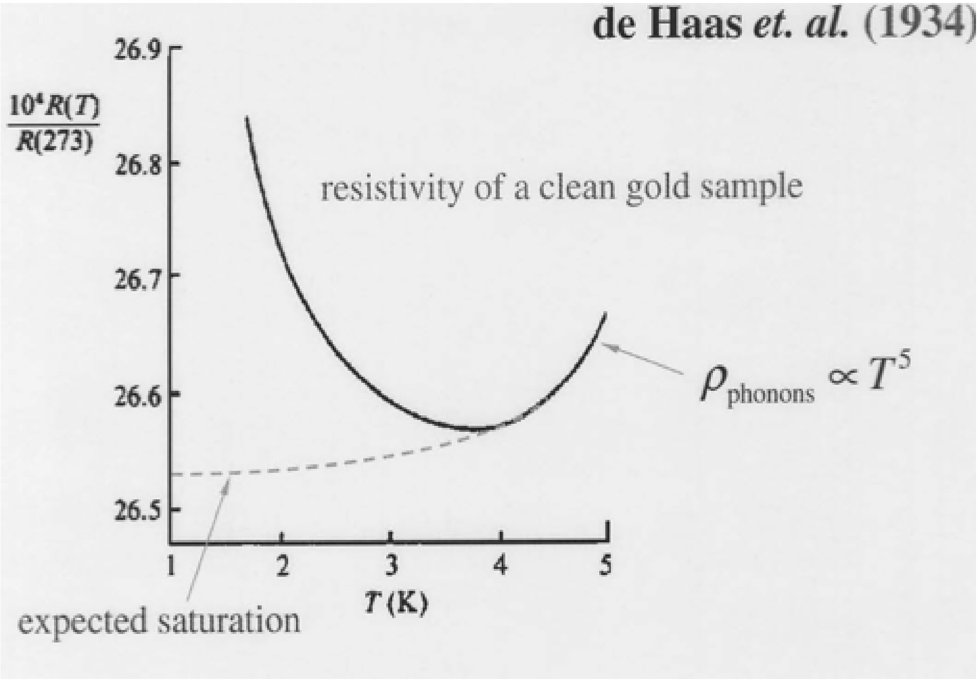


Density of states

Another approach: $T \ll T_K$
Spin behaves itinerantly & formation of an Abrikosov-Suhl resonance of width T_K

Landau quasiparticles with $N^*(0) = 1/T_K \Rightarrow$ Sommerfeld cst, $\gamma^* \propto 1/T_K$

Resistivity Summary



T >> T_K then λ=JN(0)<<1

Poor man scaling: Anderson 1970

$$d\,\lambda/[d\ln(E_F/T)] \approx \lambda^2 - \ldots$$

$\lambda[T_K] \approx 1$ Strong coupling realm

$\Rightarrow T_K \approx E_F \exp -1/\lambda$

Few K   1eV

Kondo 1964

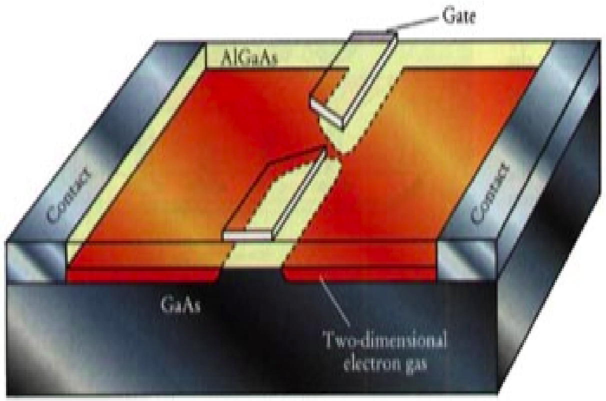
$T \approx T_K \quad \Delta\rho \approx \lambda^2 + \lambda^3 \ln(E_F/T)$

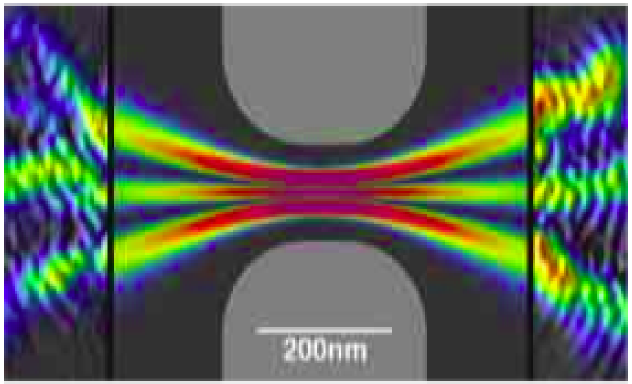
$T \ll T_K \quad \Delta\rho \approx \rho_o - (T/T_K)^2$

Nozières 1974

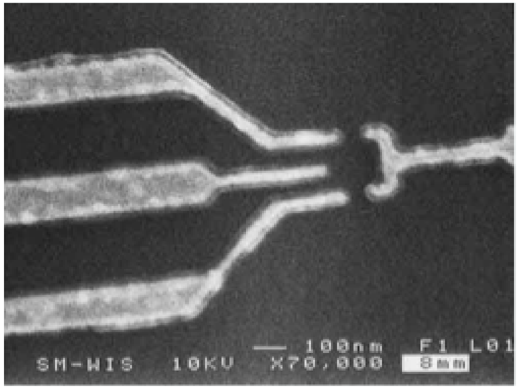
Energy relaxation in Ag, Cu, Au wires:
F. Pierre, H. Pothier, D. Esteve, M. Devoret, N. Birge, JLTP 118, 437 (2000)

Dot as an artificial atom



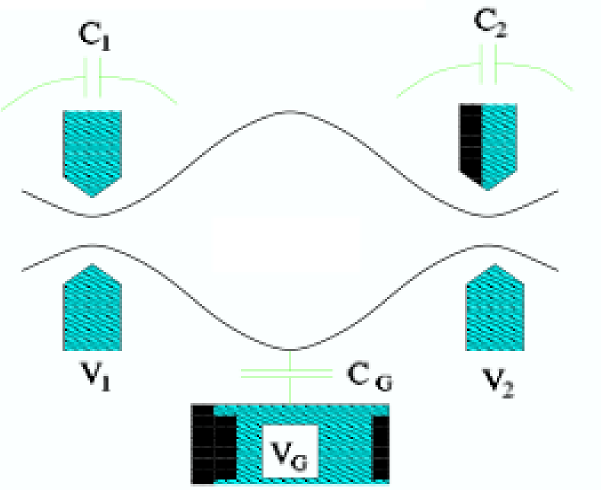


Imaging Coherent Electron Flow
Westervelt, Heller and Gossard



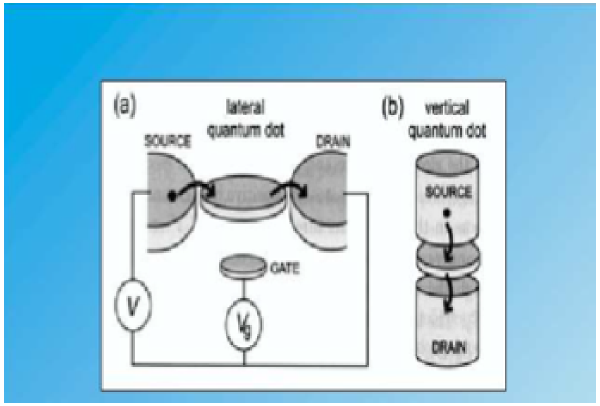
D. Goldhaber-Gordon, Nature 1998

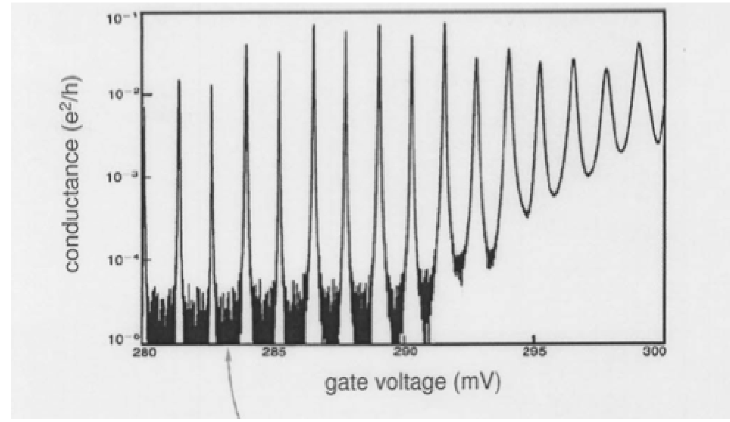
$R \gg R_K$ $R = h/(2e^2\,T)$
Quantum of resistance
$h/2e^2 = 12.9k\Omega s$



« Single-Charge Tunneling »

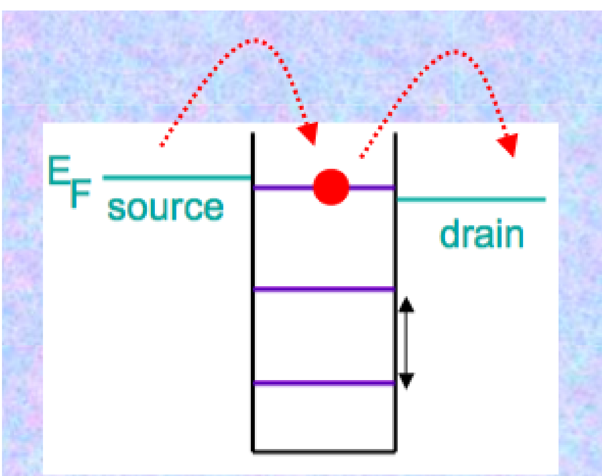
Edited by Hermann Grabert and Michel Devoret, 1992, Plenum Press, NY





M. Kastner, Physics Today (1993)

Resonant tunneling case

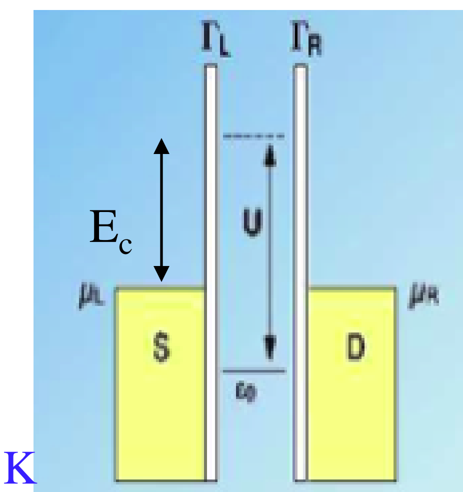


Charging energy $E_c = U + \varepsilon_o$ blocks transport

$G \propto e^{-E_c/T}$

Ultraviolet cutoff: E_c few K

Coulomb valley

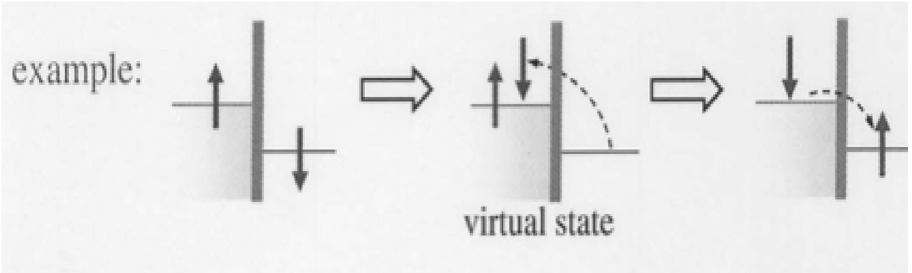


Universal Kondo physics…

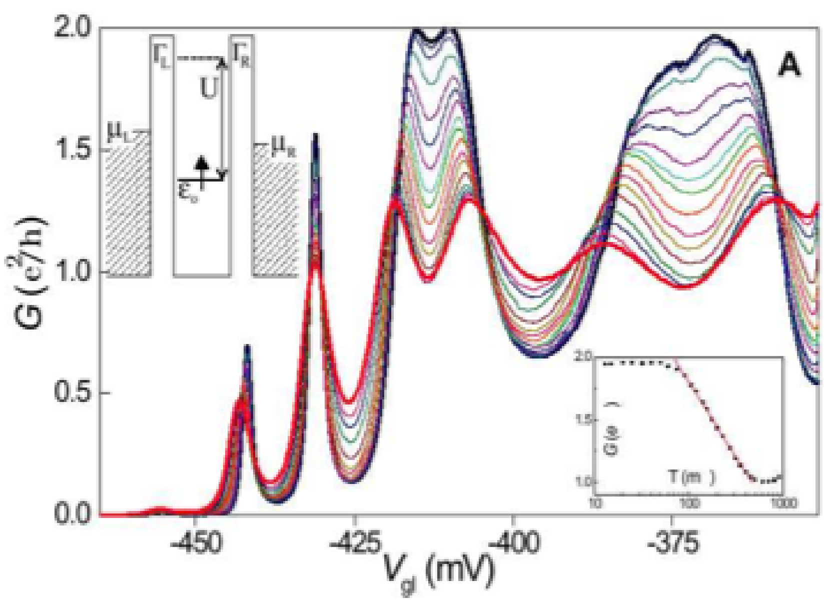
Details of Coulomb peaks depend on shape and size

R. Jalabert, D. Stone, Y. Alhassid Phys. Rev. Lett. **68**, 3468 (1992)

Universal features for small dots (200nm & few tens of electrons)



E_c=10K from 800mK to 15mK



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

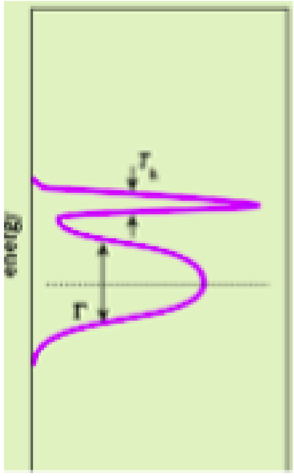
Glazman & Raikh, 1988
Ng & P. Lee, 1988

$$G(\varepsilon) = (2e^2/h)\sin^2 \delta(\varepsilon)$$

$$\delta(\varepsilon=0)=\pi/N$$

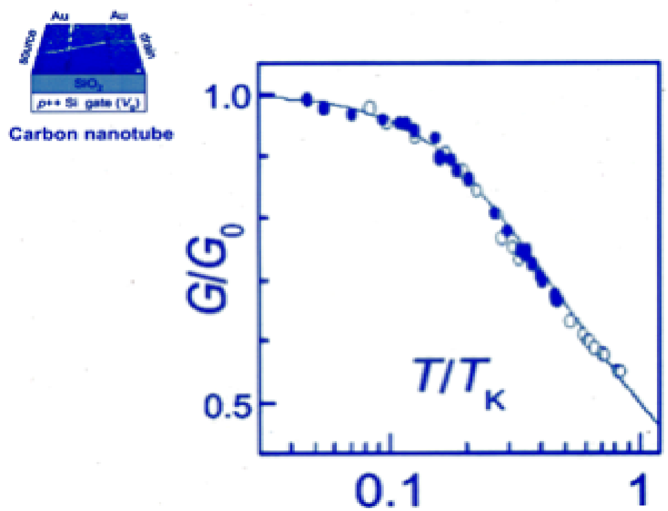
N=2 screening electrons

« Friedel sum rule for unitary diffusion, 1952 »



Density of states

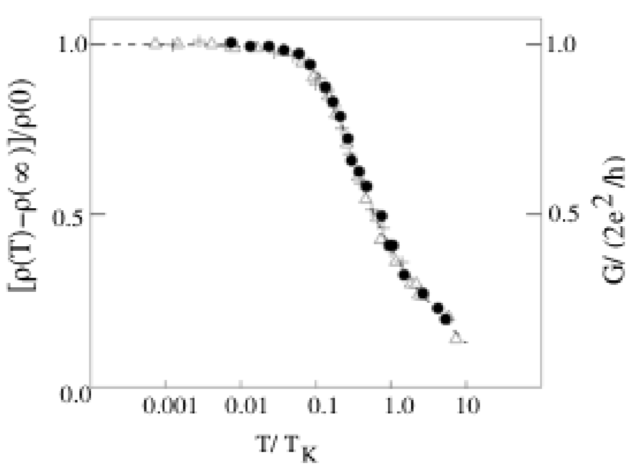
Interesting remarks



GaAs dot ⟶ Carbon nanotube dot

Features are « dot-independent »

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



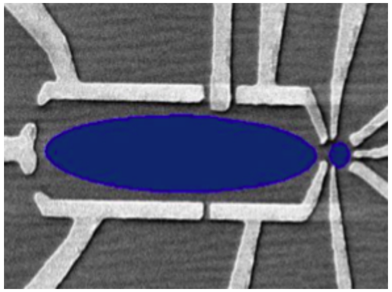
Same Kondo anomaly as in metals: $\ln(E_c/T)$ but ultraviolet much smaller

$Nb_{1-x}Mo_x$ alloys, Sarachik et al. (1964)

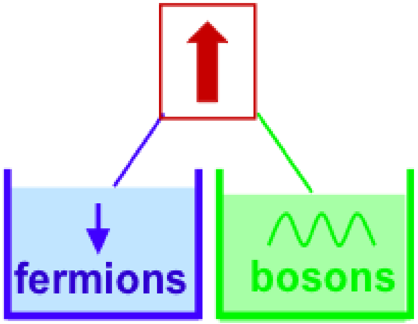
P. Coleman, cond-mat/0206003

Quest for novel Nano Kondo liquids

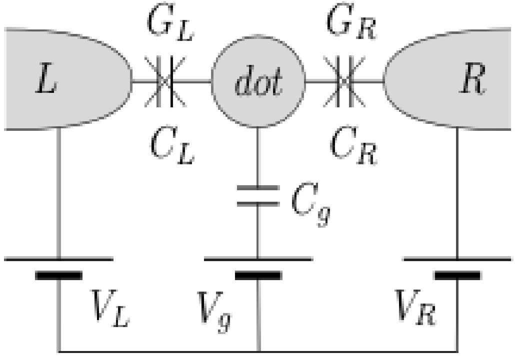
« Competing channels: Destruction of confinement? »



2 channels of fermions
Intermediate fixed point
Nozières-Blandin (1980)

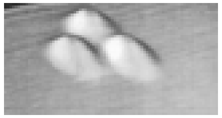


D. Goldhaber-Gordon & Y. Oreg



K. Le Hur, Phys. Rev. Lett. 92, 196804 (2004)
M.-R. Li, K. Le Hur, W. Hofstetter, PRL 95, 086406 (2005)

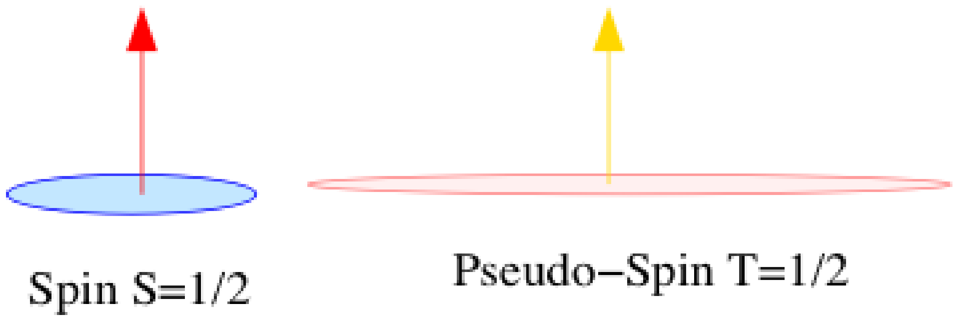
« Charge-Spin » entanglement
Quantum Phase Transitions
Artificial Trimer



« Out of equilibrium »

A. Rosch & P. Woelfle

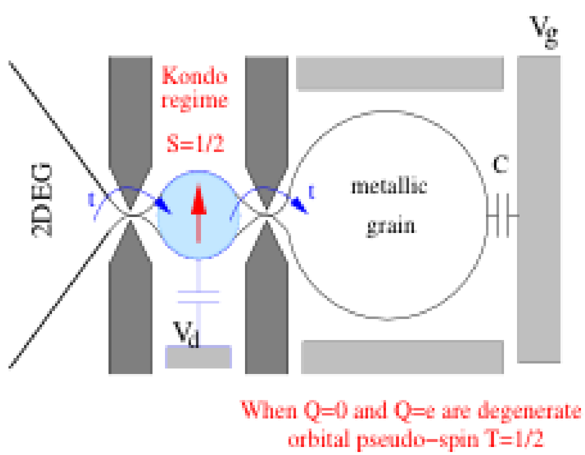
« Qubits of different types »

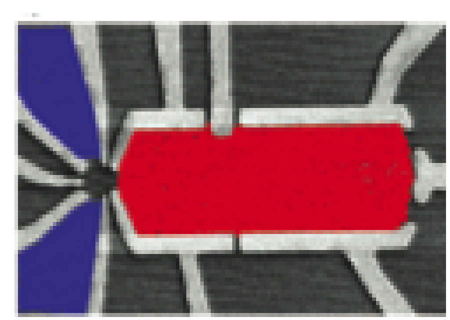


Large dot at resonance: « charge object »
↑= occupied
↓= unoccupied

Spins are coupled through a magnetic interaction: Heisenberg, Ising…
Charges are coupled through Coulomb forces or Capacitances

Confinement mechanisms to couple spin & charge? Kondo effect?





K. Le Hur & P. Simon, PRB 67, R201308 (2003)

Curtesy of D. Goldhaber-Gordon

Which condition to have entanglement?

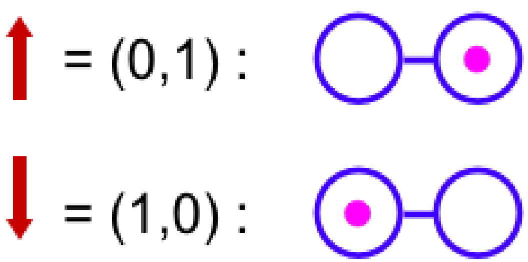
SU(4) symmetry

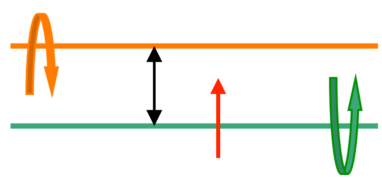
$$H_K = J \sum_A \psi^\dagger t^A \left[\sum_{\alpha,\beta} \left(S^\alpha + \frac{1}{2} \right) \left(T^\beta + \frac{1}{2} \right) \right]^A \psi$$

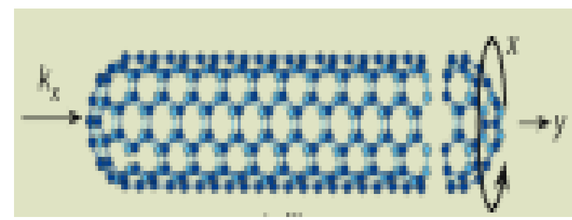
$$= \frac{J}{4} \sum_A M^A \sum_{\mu,\nu} \psi^\dagger_\mu t^A_{\mu\nu} \psi_\nu ,$$

4 screening channels…

Other Proposals for « charge » and « spin »



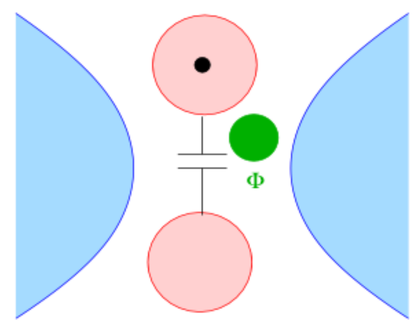




Orbital & Spin Kondo: Kouwenhoven et al., Nature 2006

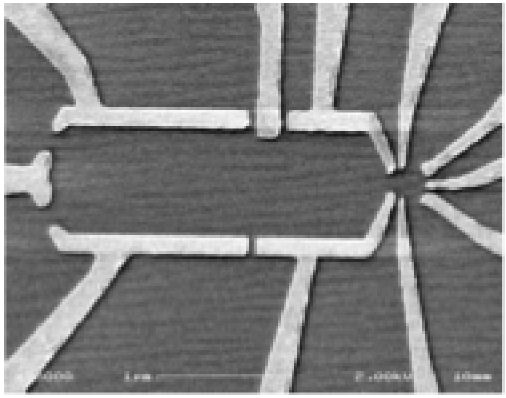
Halperin, et al. PRL 90, 026602 (2003)
M.-R. Li & K. Le Hur, PRL 93, 176802 (2004)

Expts: M. Pioro-Ladrière & A. Sachrajda, PRB (2005)
J. Petta, C. Marcus, et al. PRL (2004)



PRB 71, 115312 (2005)

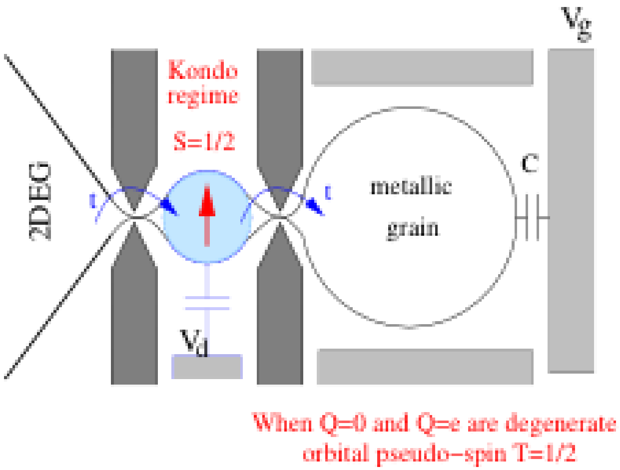
Hybrid Large dot - Small dot



Collaborators: Pascal Simon & Laszlo Borda

K. Le Hur & P. Simon, PRB 67, R201308 (2003)
K. Le Hur, P. Simon, L. Borda, PRB 69, 045326 (2004)

David Goldhaber-Gordon & Ron Potok



Metallic grain: level spacing ⇒ 0
continuum of fermions $c_{kg\alpha}$

At the resonant condition:

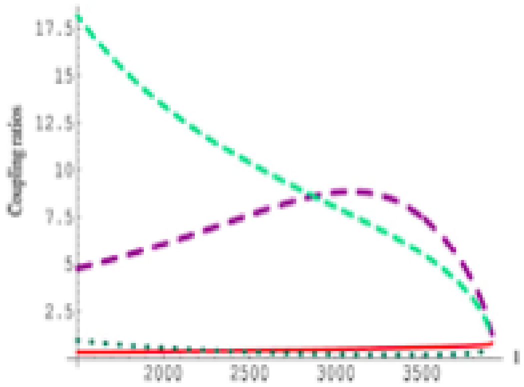
T matrix embodies the two-given charge states

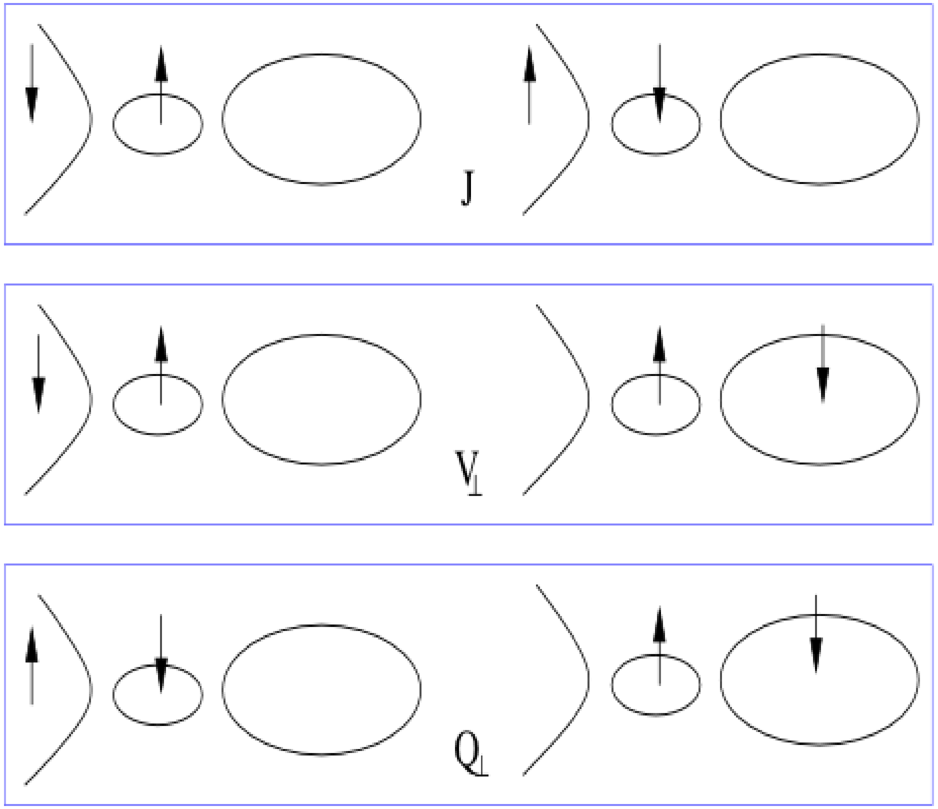
ψ_μ with $\mu=(\tau,\alpha)$

τ: position g or l
α: spin ↑ or ↓

-Asymmetric bare values

-But for symmetric barriers
 poor man scaling
+ Wilson NRG approach: SU(4)





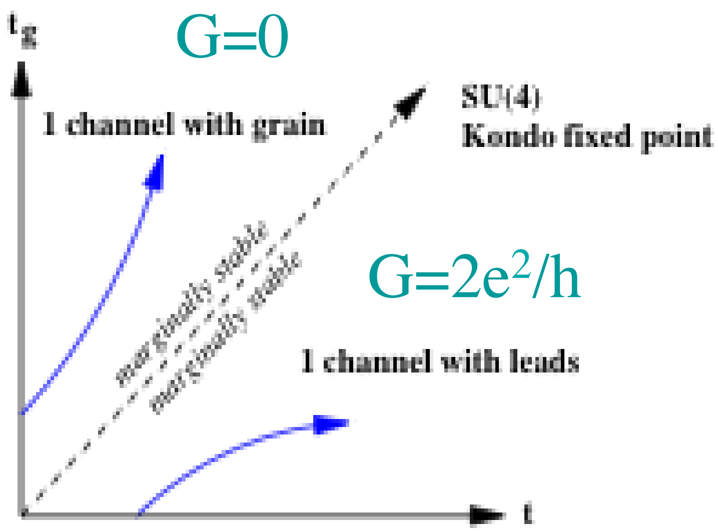
$$
\begin{aligned}
H_K &= \frac{J}{2}\vec{S}\cdot(\psi^\dagger\vec{\sigma}\psi) \\
&+ \frac{V_z}{2}T^z(\psi^\dagger\tau^z\psi) + \frac{V_\perp}{2}[T^+(\psi^\dagger\tau^-\psi) + h.c.] \\
&+ Q_z T^z\vec{S}\cdot(\psi^\dagger\tau^z\vec{\sigma}\psi) + Q_\perp\vec{S}\cdot[T^+(\psi^\dagger\tau^-\vec{\sigma}\psi) + h.c.],
\end{aligned}
$$

Experimental consequences

SU(4) strong-coupling fixed point: Marginally stable towards perturbations such as magnetic field or orbital field (grain gate V)

Theory: $\delta(T=0)=\pi/4$ (here, 4 screening channels!)
so $G=e^2/h$ at the fixed point (V,T=0)

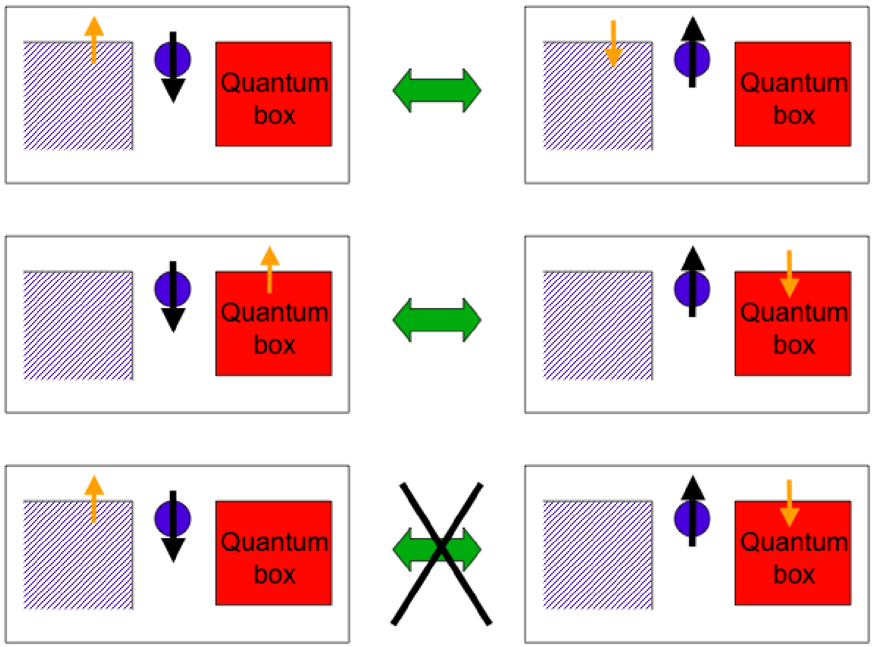
$$G = (2e^2/h)\sin^2\delta$$



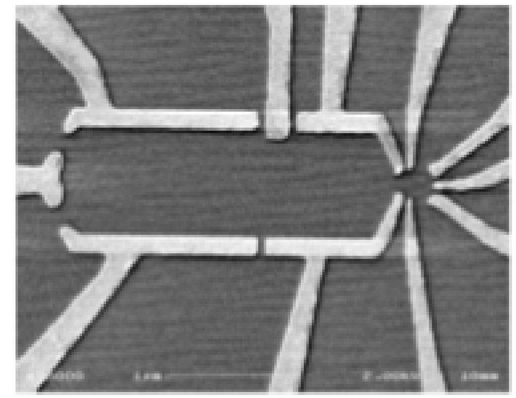
Linear scaling in V/T_K:
Abrikosov-Suhl resonance at $\omega=T_K$

K. Le Hur & P. Simon, PRB 67, R201308 (2003)
K. Le Hur, P. Simon, L. Borda, PRB 69, 045326 (2004)
K. Le Hur, P. Simon, D. Loss, cond-mat/0609298

2-channel Kondo physics?



D. Goldhaber-Gordon & Y. Oreg
PRL **90**, *136602 (2003)*



R. Potok, D. Goldhaber-Gordon et al

$\delta(T=0)=\pi/4$ so $G=e^2/h$

scaling in $(T/T_K)^{1/2}$

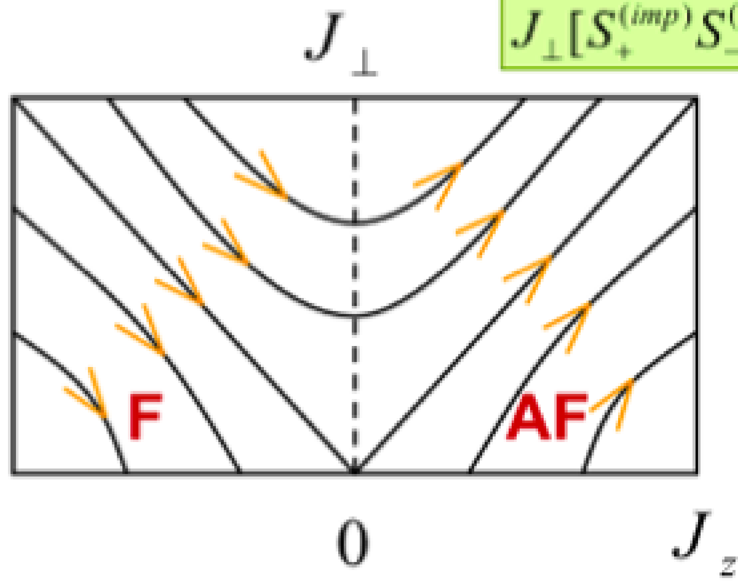
$$H_K = \frac{J_1}{2}\vec{S}.(\psi_1^\dagger \vec{\sigma}\, \psi_1) + \frac{J_g}{2}\vec{S}.(\psi_g^\dagger \vec{\sigma}\, \psi_g)$$

Nozières & Blandin, 1980
Affleck & Ludwig

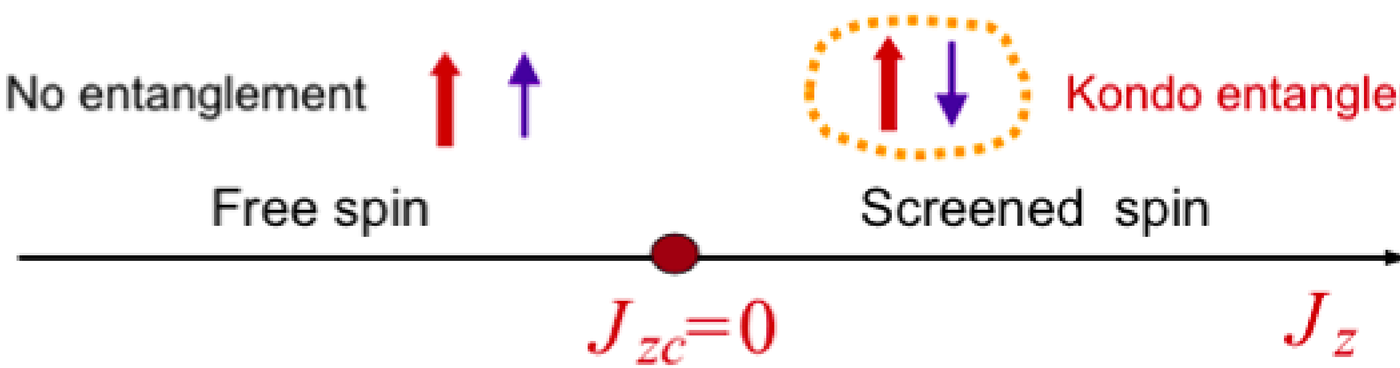
Other 2-channel proposals:
-5/2 plateau of the FQHE
P. Fendley, M. Fisher, C. Nayak
-Orbital Kondo effect
K. Le Hur & G. Seelig (2002),…

Quantum phase transition in Kondo model

$J_{\perp}[S_{+}^{(imp)}S_{-}^{(e)} + h.c.] + J_{z}S_{z}^{(imp)}S_{z}^{(e)}$



Small $J_{\perp}$

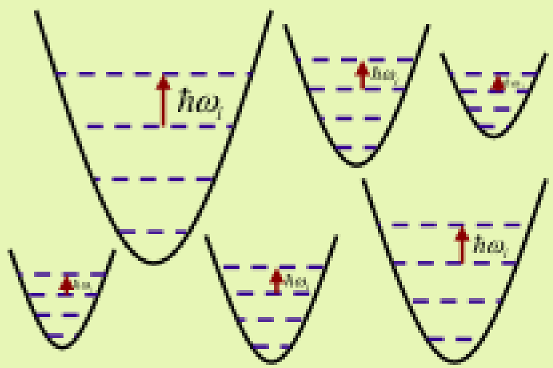


Observability?

Hidden « Caldeira-Leggett » model

S. Chakravarty, PRL 49, 681 (1982)
A.J. Bray & I.A. Moore, PRL, 49, 1545 (1982)

$$H_B = \sum_i \left(\frac{p_i^2}{2m_i} + \frac{m_i \omega_i^2 x_i^2}{2} \right)$$



$$H_{CL} = hS_z + \Delta(S_+ + S_-) + S_z \sum_i \lambda_i x_i + H_B$$

A.J. Leggett et al., Rev. Mod. Phys. 59, 1(1987)

$$J_z \propto 1 - \sqrt{\alpha}$$
$$J_\perp \propto \Delta$$

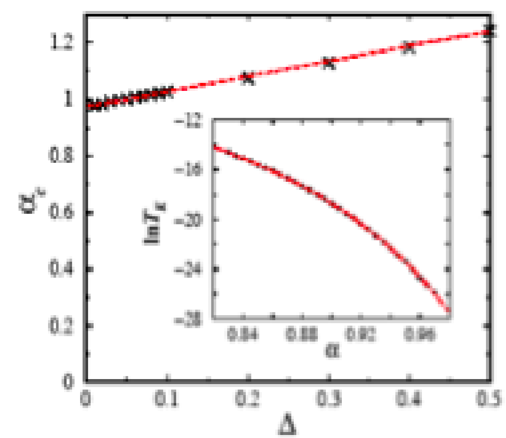
$$\frac{1}{2}\left\langle \sum_i \lambda_i x_i(t) \cdot \sum_i \lambda_i x_i(0) \right\rangle_\omega = \hbar J(\omega) \coth(\omega / 2k_B T)$$

Ohmic dissipation

$$J(\omega) = \alpha \pi \hbar \omega / 2$$

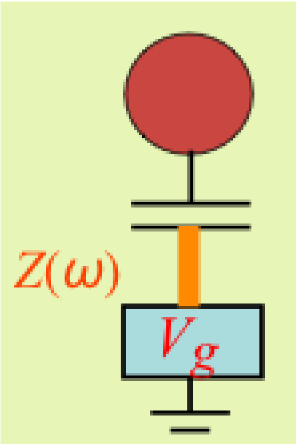
Dissipation strength

Numerical RG for bosons:
M.-R. Li, K. Le Hur, W. Hofstetter
PRL 95, 086406 (2005)



$$\alpha_c = R_c / R_K = 1 + 0.5\Delta/\Lambda$$

Application: Noisy Qubits

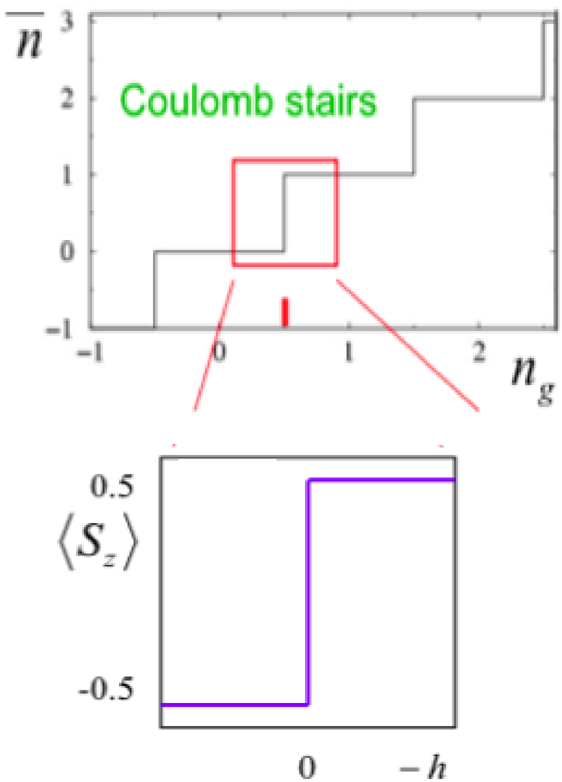


Noisy SC « charge » qubits close to resonance

Schoelkopf, Clerk, Girvin, Lehnert, Devoret, cond-mat/0210347

$$E_{ch} = E_c(n - n_g)^2$$

$$n_g = C_g V_g / e$$



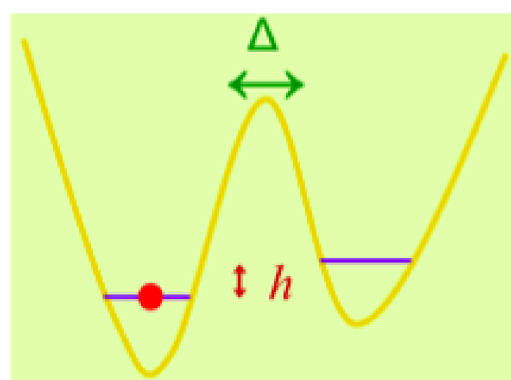
Two-state system

↑ $n = 1$ state

↓ $n = 0$ state

$$E_{ch} = hS_z \qquad h = 2E_c(1/2 - n_g)$$

$$H_S = hS_z + \Delta(S_+ + S_-)$$

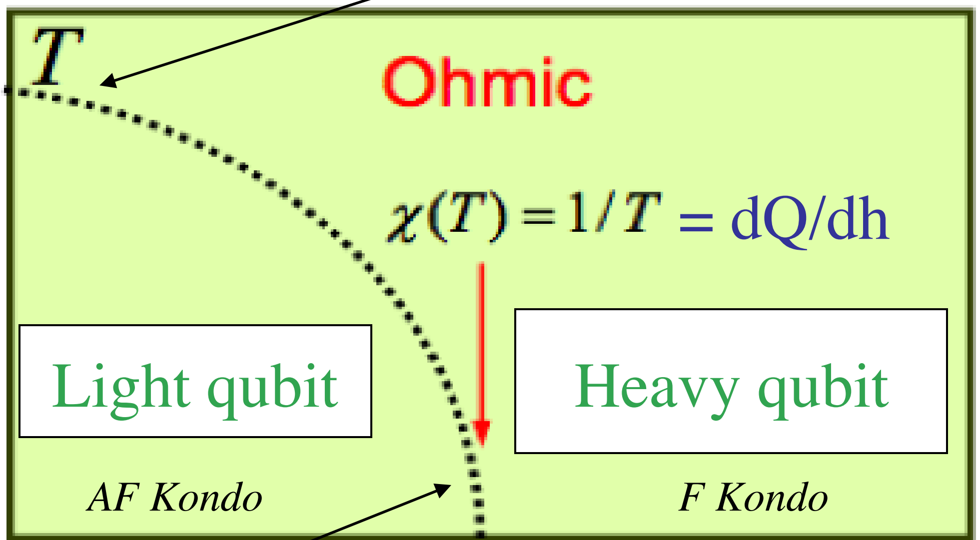


constant

In the SC: ψ = √n exp iθ

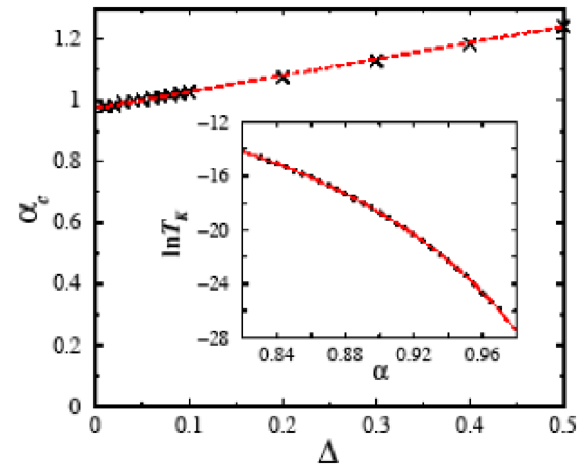
$T_c = \Delta(\Delta/\Lambda)^{\alpha/(1-\alpha)}$

M.-R. Li, K. Le Hur, W. Hofstetter, PRL 95, 086406 (2005)



KT α

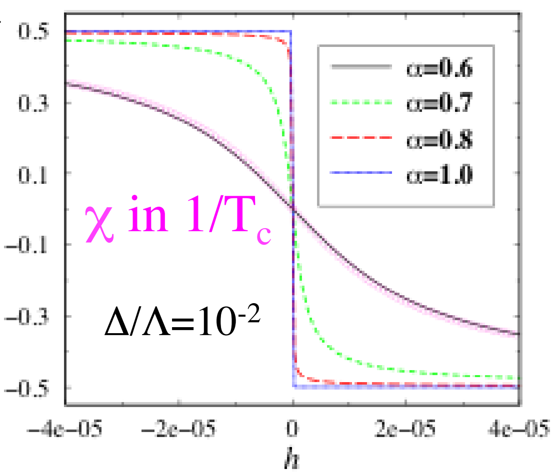
$\ln T_c/\Lambda \approx 1/(\alpha_c - \alpha)$



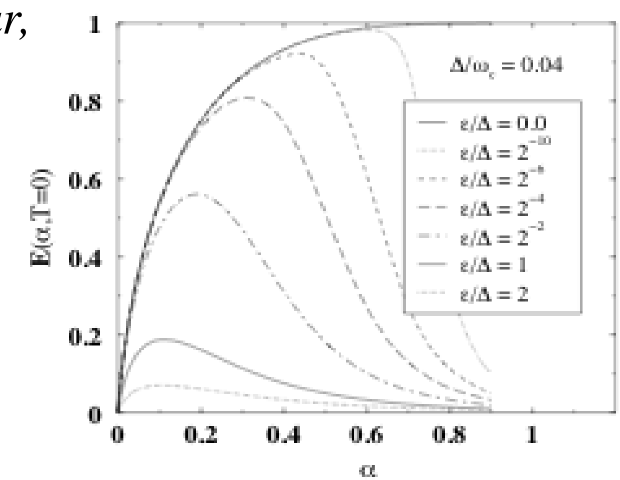
$\alpha_c = R_c/R_K = 1+0.5\Delta/\Lambda$

$\langle S_z \rangle$

α=0.6:
Bethe
Ansatz check



A. Kopp & K. Le Hur, In preparation

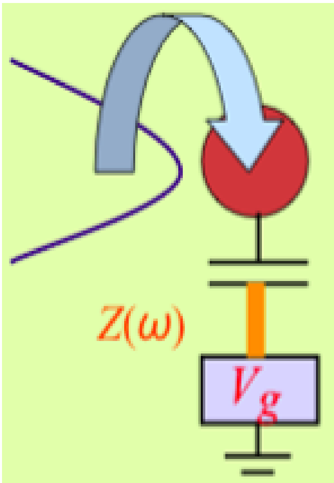


Size of the Jump = $1 - (\Delta/\Lambda)^2 [2(2\alpha-1)(2\alpha-2)]^{-1}$ for $\alpha \gg 1$

T. Costi & R. McKenzie, Phys. Rev. A 68, 034301 (2003)

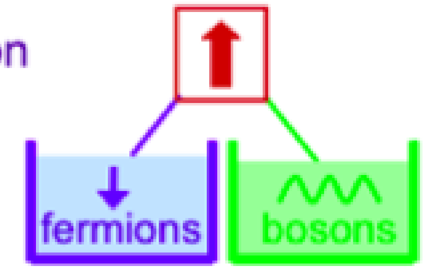
Metallic qubit: Bose-Fermi Kondo model!

*K. Le Hur, PRL **92**, 196804 (2004)*
*M.-R. Li & K. Le Hur, PRL **93**, 176802 (2004)*



$$H_t = \underbrace{t\, c^{+}_{dot} c_{lead} S_- + h.c.}_{\text{Spin-fermion}} + \underbrace{\delta V_g S_z}_{\text{Spin-boson}} + H_{noise}$$

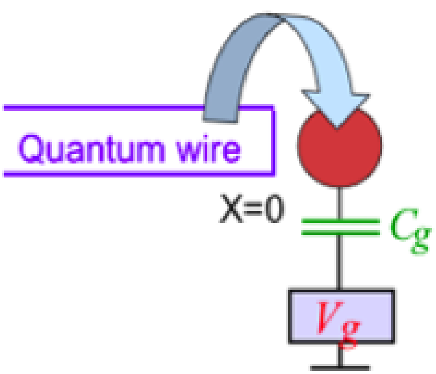
Link to heavy-fermion physics



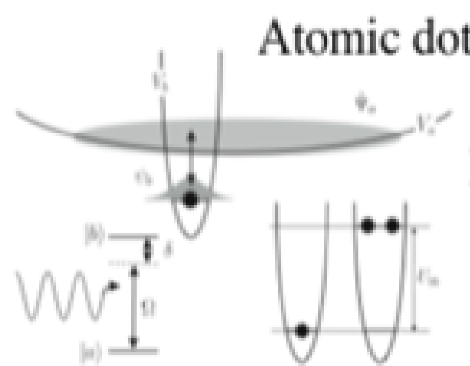
Exact mapping onto Caldeira-Legget model:

All noisy qubits belong to the same universality class

*M.-R. Li, K. Le Hur, W. Hofstetter, PRL **95**, 086406 (2005)*

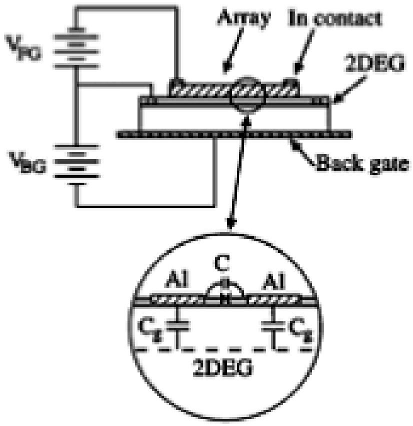


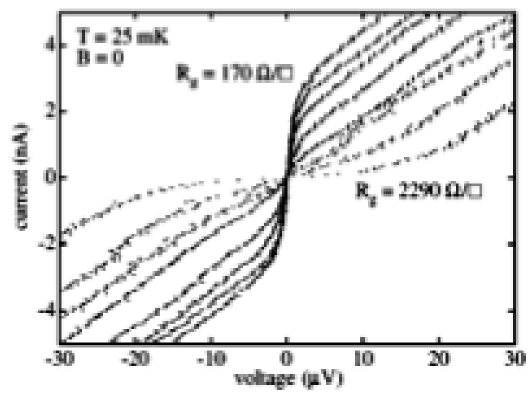
Karyn Le Hur and Mei-Rong Li
PRB 72, 073305 (2005)



P. Zoller

Unification Luttinger physics & em noise





A. Rimberg, J. Clarke et al. PRL 78, 2632 (1997)

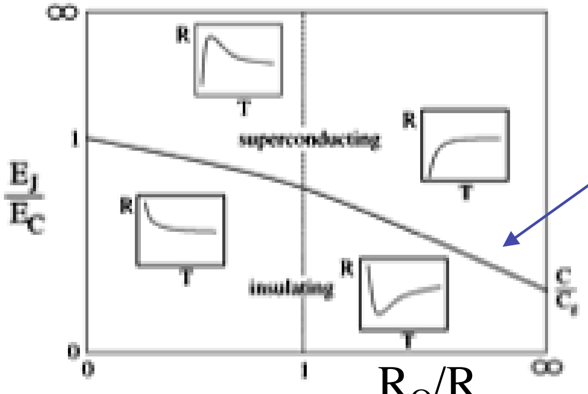
N. Mason & A. Kapitulnik PRL 82, 5341 (1999) (MoGe films)

Bose-Hubbard model in a dissipative environment

The islands are sufficiently large: $C_g >> C$ and $E_c = e^2/C_{tot} = 2.4\ E_J$

$$H = \Sigma_i\ -E_J \cos(\theta_i - \theta_{i+1}) + E_c(\hat{n}_i - n_o)^2$$

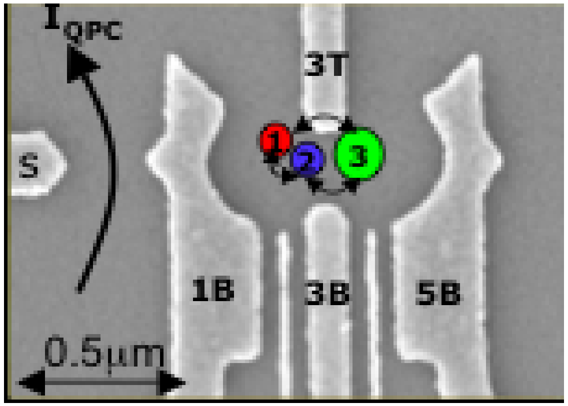
S. Doniach, PRB 24, 5063 (1981)

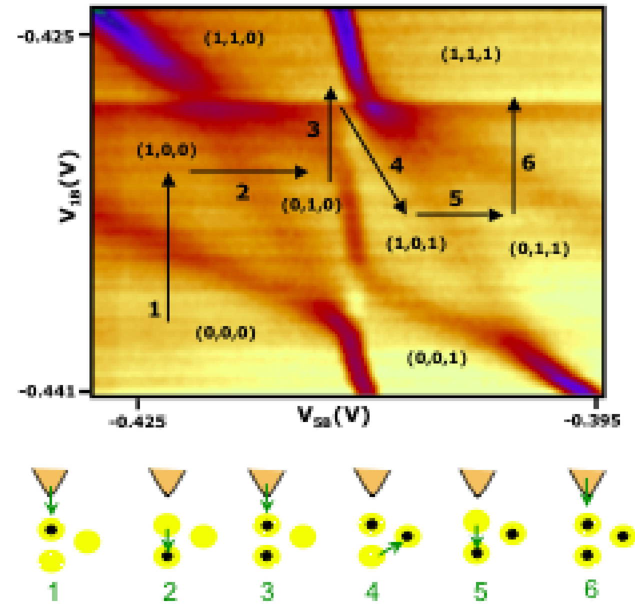


A noise-induced quantum phase transition

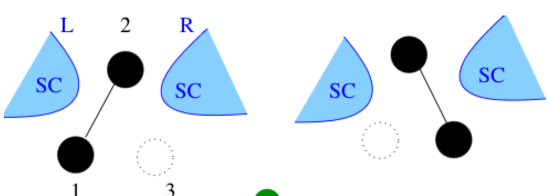
G. Schön et al. PRL 79, 2730 (1997)

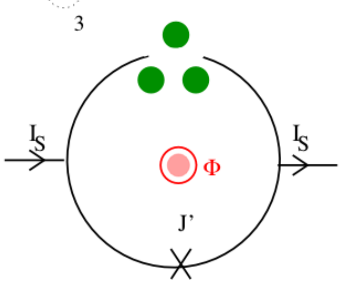
Futurist Ideas: Beyond double dot





Louis Gaudreau
Co-direction: A. Sachrajda (NRC Ottawa)
K. Le Hur





« A Mesoscopic Pendulum »

K. Le Hur, P. Recher, É. Dupont, D. Loss, Phys. Rev. Lett. **96,** 106803 (2006)

« Kondo effect with a trimer »

K. Ingersent, A. Ludwig, I. Affleck, PRL **95**, *257204 (2005)*

Novel Nano-Kondo systems

-Possibility of exploring novel phases: SU(4) Fermi liquid
-Ferro-Antiferro transition of the Kondo model: noisy charge qubits
-Route towards triple dot: Mesoscopic Pendulum, Kondo with Trimer

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Post-Docs: *P. Recher (Stanford), P. Vitushinsky*

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Thank you for your attention !