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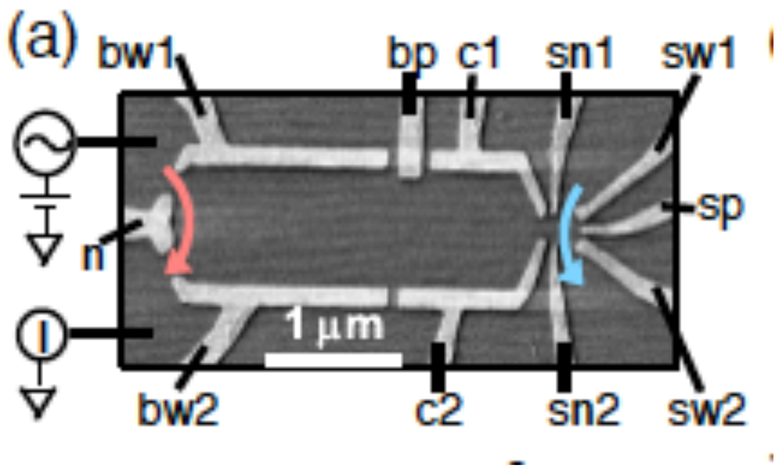
M.N.Kiselev

Thermoelectric transport through Kondo nano-devices



T.K.T. Nguyen, MK and V.E. Kravtsov, PRB 82, (2010)
MK and Z. Ratiani (2013)

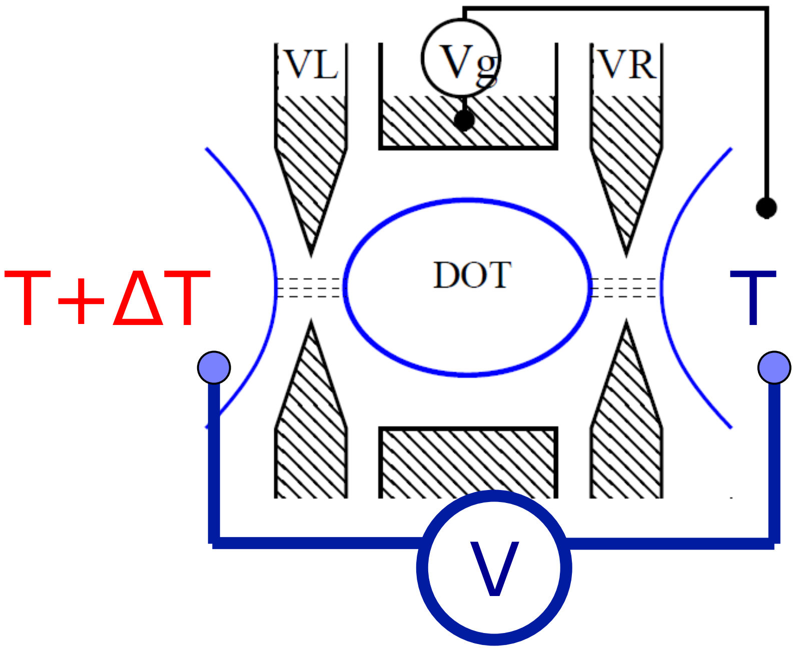
KITP, November 21 2013

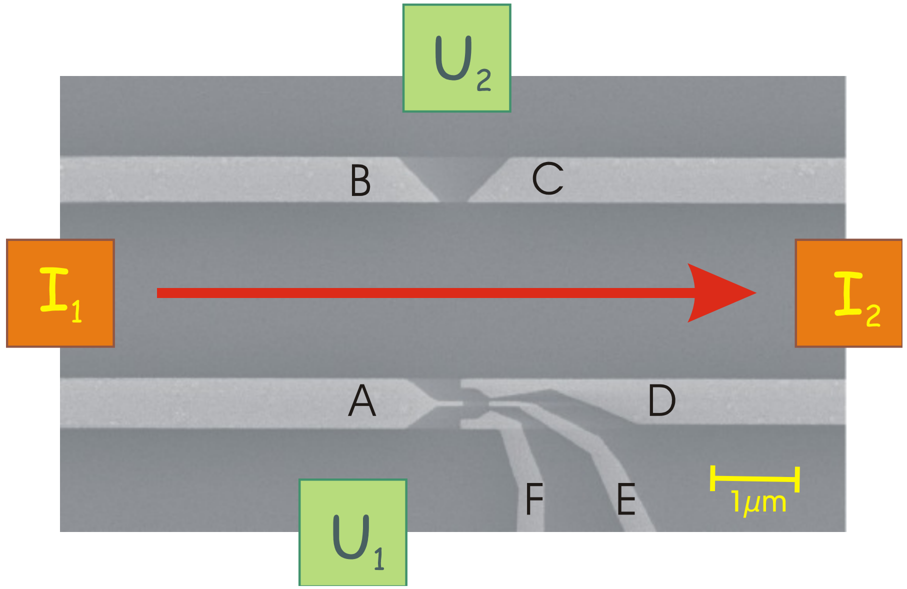
Thermoelectric transport through nanostructures

thermopower

$$S = -\frac{V}{\Delta T} = \frac{G_{12}}{G}$$

thermovoltage





$$I = G \cdot V + G_{12} \cdot \Delta T = 0$$

Thermoelectric transport: FL description

Bulk metals (Fermi Liquid Theory):

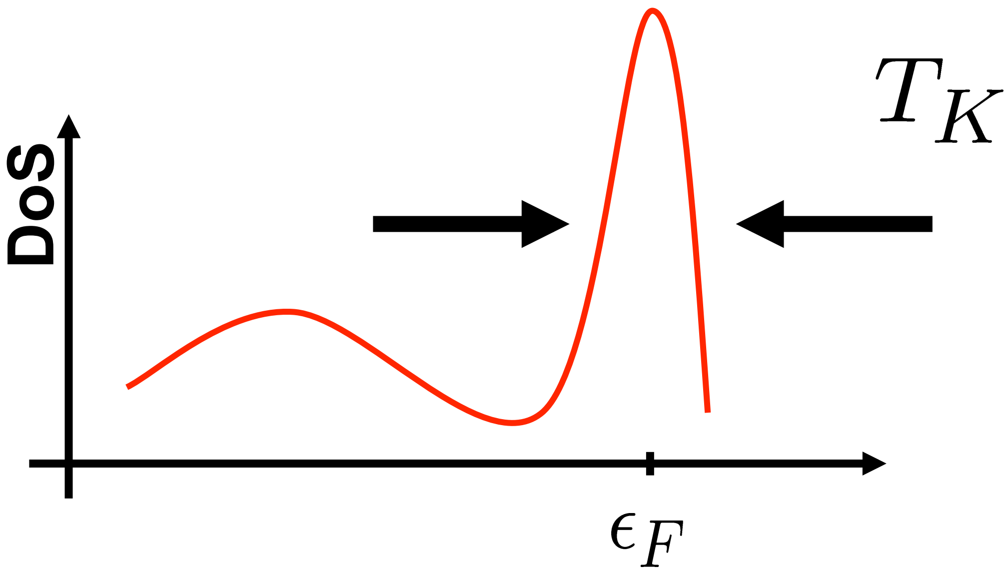
$S \sim T/\epsilon_F$ → (strongly correlated metals) → $S \sim T/T^*$

$T^* \ll \epsilon_F$

strong electron-electron interaction

resonance scattering effects

Example: Kondo effect



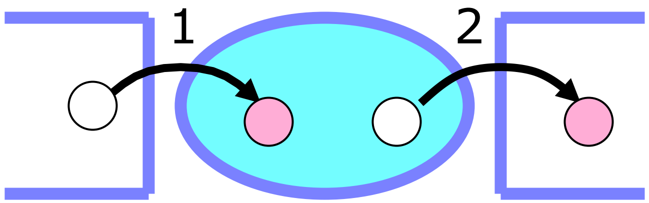
$S \sim T/T_K$

Q: How do the effects of strong electron correlations manifest themselves in the thermoelectric transport through the nanostructures?

Q: What are possible mechanisms for enhancement of the thermoelectric power?

Q: Is the thermo-transport through nanostructures always characterized by the Fermi-Liquid concept?

Sequential tunneling at Coulomb blockade

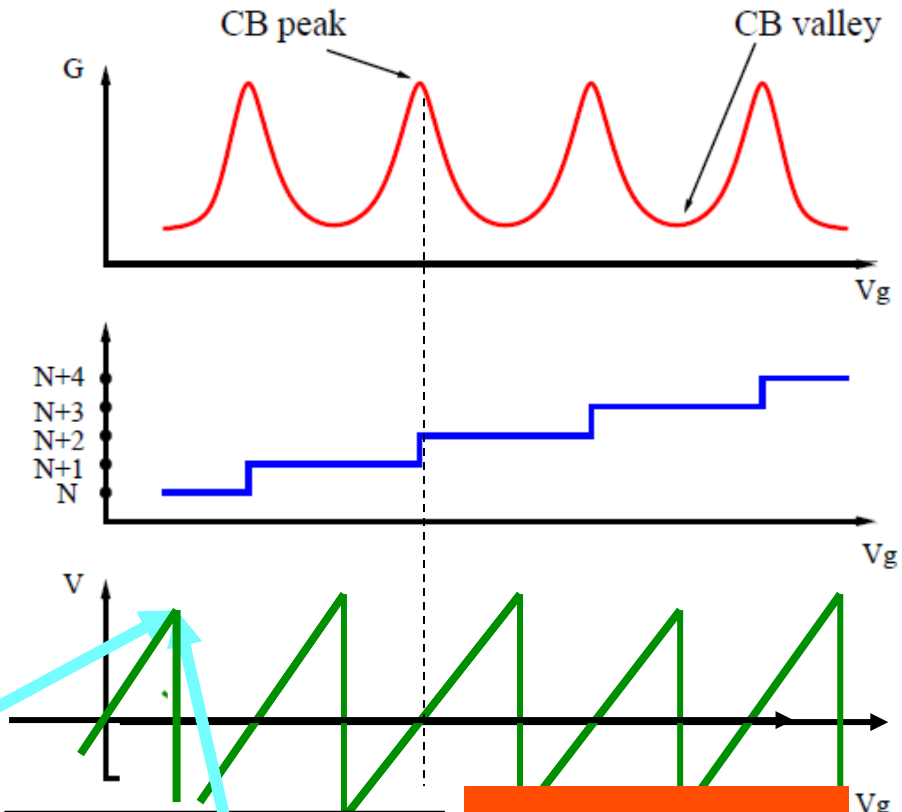


$$S_{\mathrm{Mott}} \equiv -\frac{\pi^2}{3}\frac{k}{e}kT\frac{d\ln G}{dE_F}$$

For a bulk metal
$eS \sim T/E_F << 1$

Mott's rule would give for sequential tunneling
$eS \sim 1$

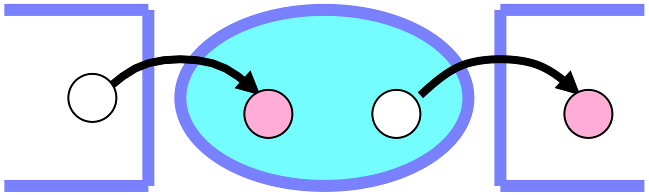
Beenakker & Staring 1992



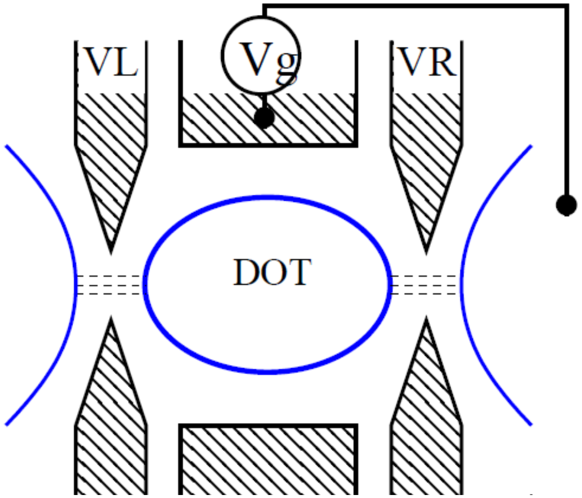
Beenakker & Staring
$eS \sim E_C / T >> 1$

Too large??

Effect of co-tunneling at weak coupling



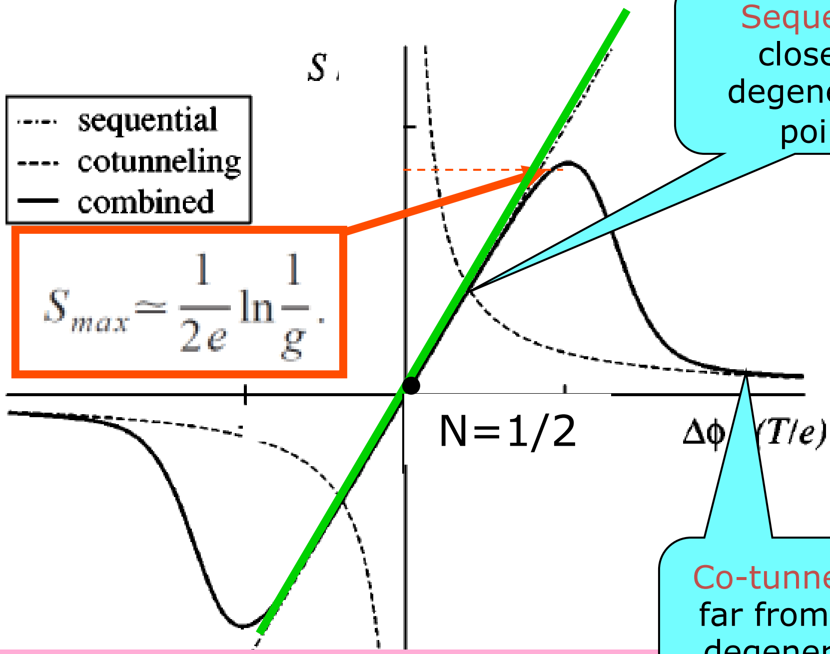
Turek & Matveev, 2002



Weak coupling

$$g = \frac{\hbar(G_l + G_r)}{2\pi e^2} << 1$$

No Coulomb energy is payed



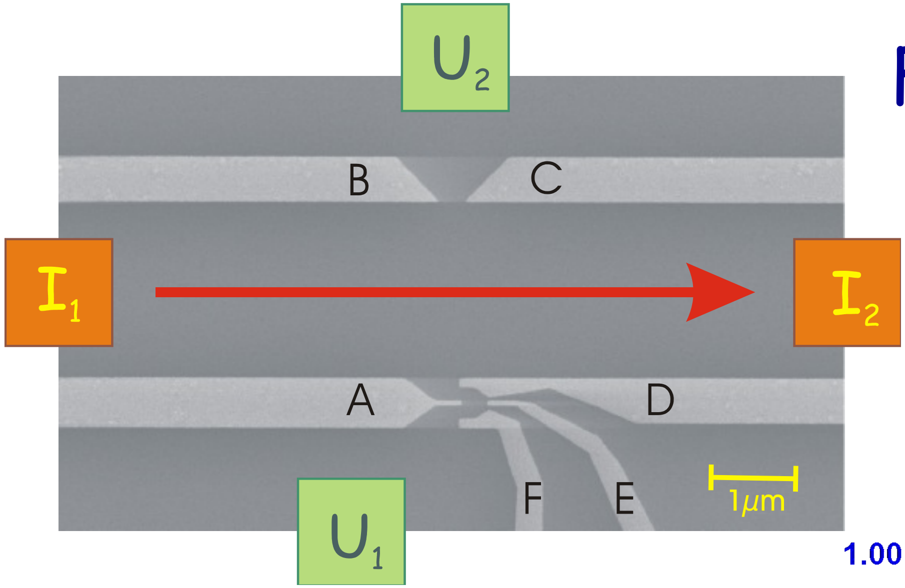
$$S_{max} \simeq \frac{1}{2e} \ln \frac{1}{g}.$$

Sequential close to degeneracy point

Co-tunneling far from the degeneracy point

S_{max} is much smaller than Beenakker&Staring estimation, more consistent with the Mott's rule result eS~1 but enhanced compared to bulk eS~T/E_F<<1

From weak to strong coupling



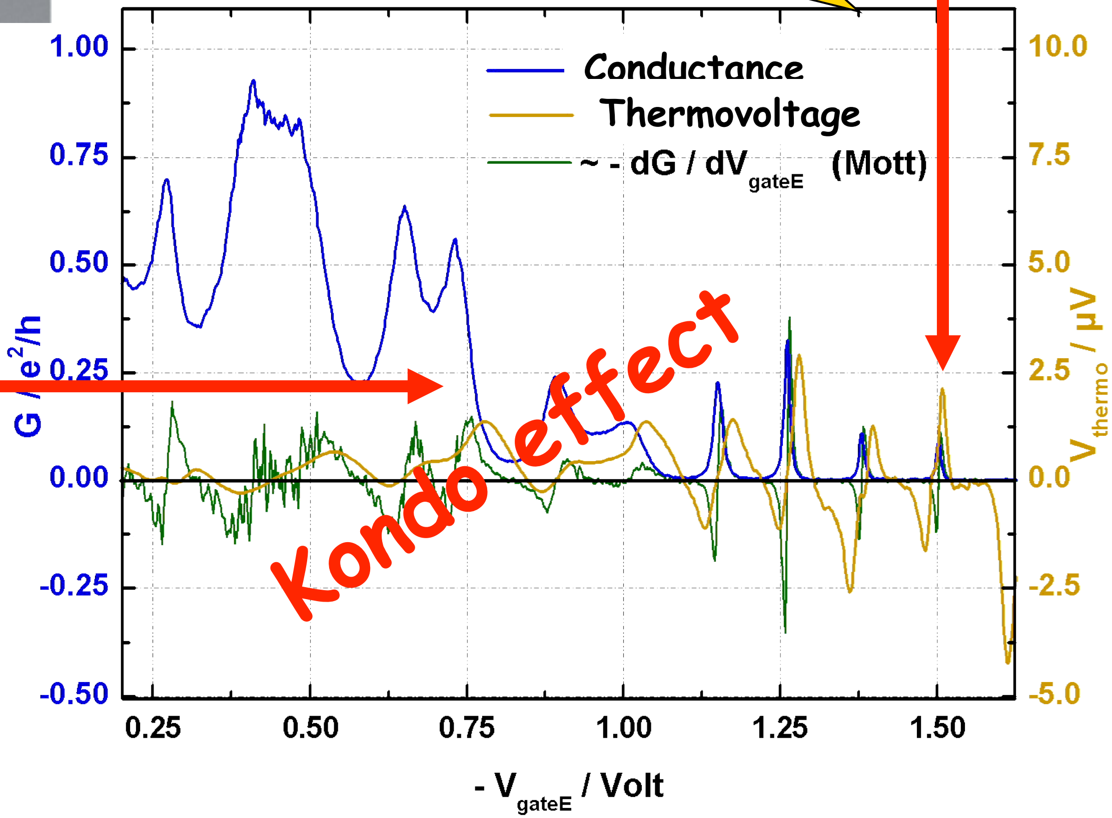
$$S \sim \frac{\partial \ln G}{\partial V_g}$$

Strong coupling

Mott law is violated

Weak coupling

Mott law is obeyed



Molenkamp, MK et al, 2005

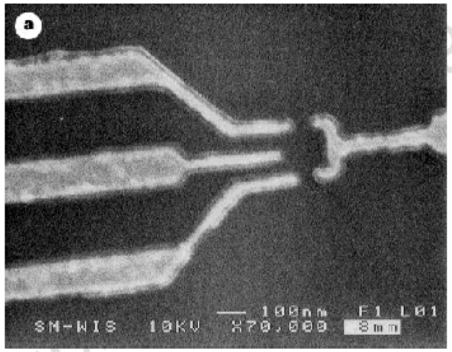
Q1: How does the Kondo effect influence a thermoelectric transport through the nano-structures?

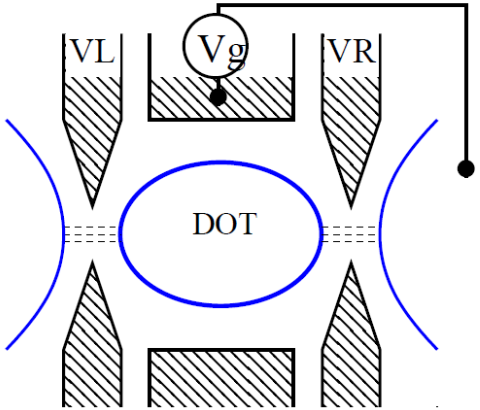
Q2: What are the manifestations of Kondo effect in the thermoelectric transport through the nanostructures?

Q3: Is there a room for NFL enhancement of thermopower in the nanostructures?

Realization of Kondo-effect in nanostructures I

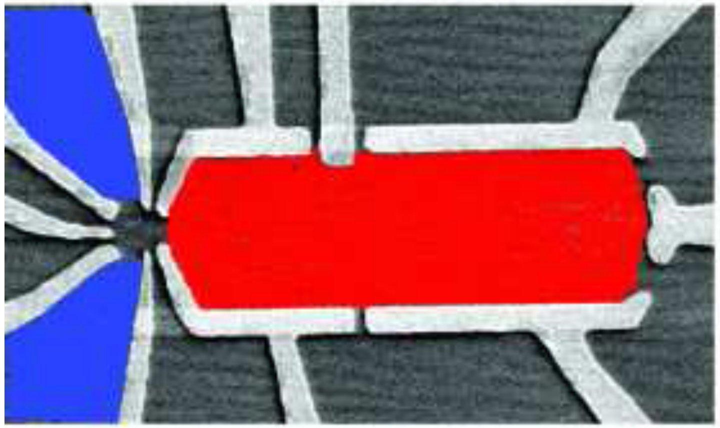
1CK

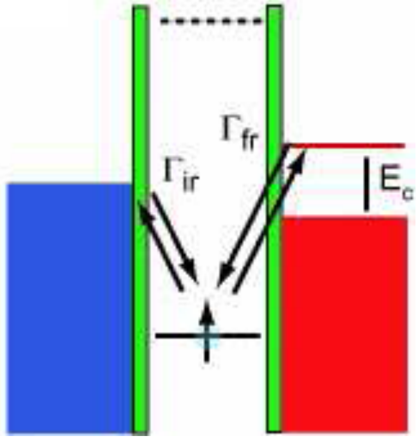




2CK

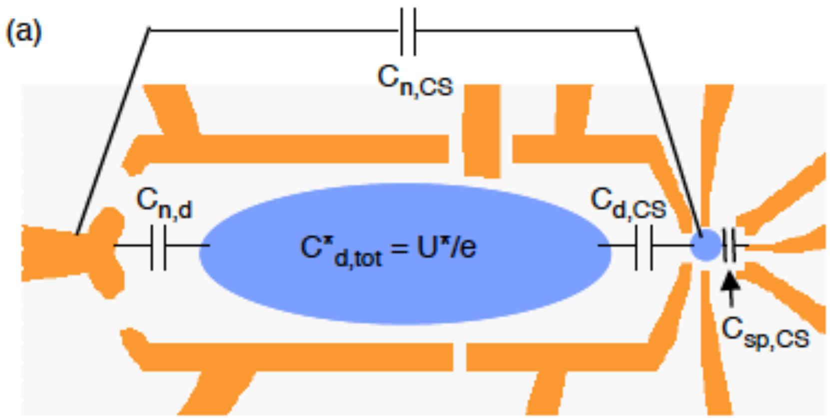
D.Goldhaber-Gordon et al, Nature, 1998

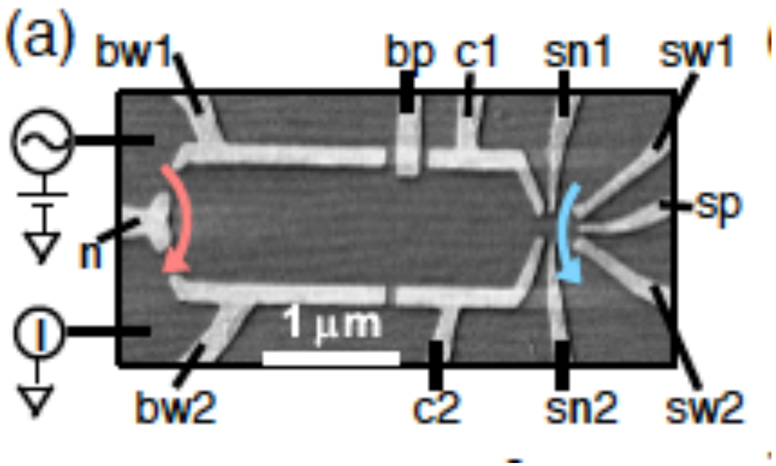


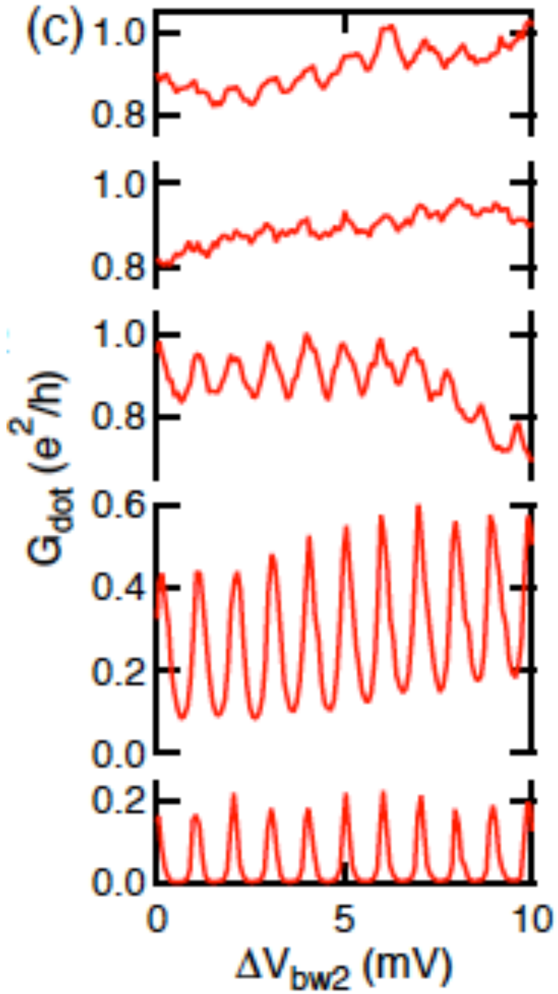


R.M. Potok et al, Nature, 2007

Realization of Kondo-effect in nanostructures II

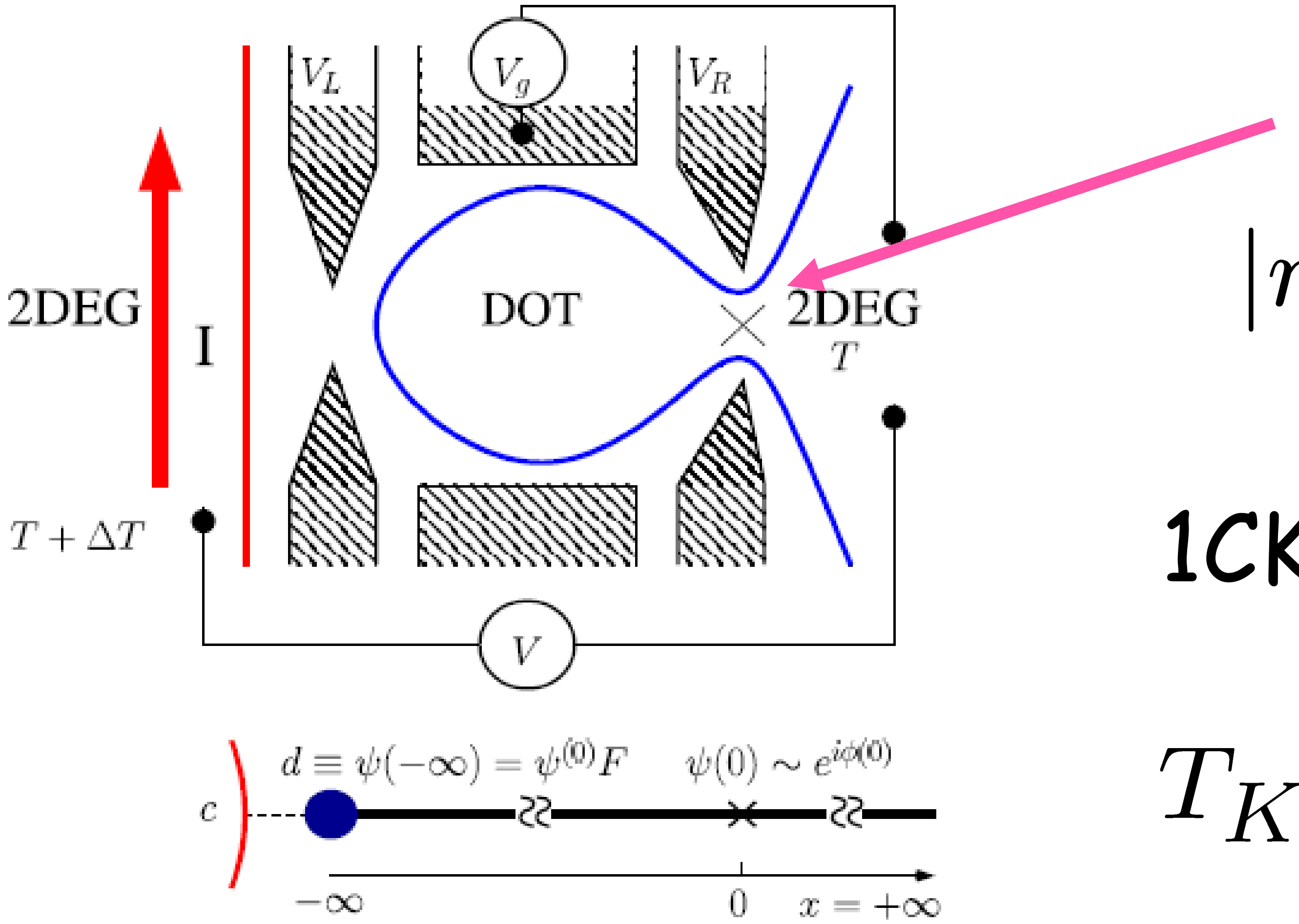






S.Amasha et al, PRL 2011

Flensberg - Matveev – Furusaki setup



QPC

$$|r| \ll 1$$

1CK - 2CK

$$T_K \sim E_C$$

Flensberg 1993, Matveev 1995, Furusaki, Matveev 1996

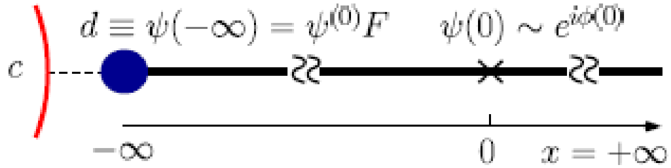
Strong coupling limit and effective model

Model →

$$H = H_0 + H_L + H_R + H_C$$

$$H_0 = \sum_{k,\alpha} \epsilon_{k,\alpha} c^\dagger_{k,\alpha} c_{k,\alpha} + \sum_\alpha \epsilon_\alpha d^\dagger_\alpha d_\alpha +$$

$$+ \sum_\alpha \frac{v_{F,\alpha}}{2\pi} \int_{-\infty}^{\infty} \left\{ [\Pi_\alpha(x)]^2 + [\partial_x \phi_\alpha(x)]^2 \right\} dx$$



$$H_L = \sum_{k,\alpha} (t_{k,\alpha} c^\dagger_{k,\alpha} d_\alpha + hc)$$

$$H_R = -\frac{D}{\pi} \sum_\alpha |r_\alpha| \cos[2\phi_\alpha(0)]$$

$$H_C = E_C \left[\hat{n} + \frac{1}{\pi} \sum_\alpha \phi_\alpha(0) - N(V_g) \right]^2$$

Assumptions:

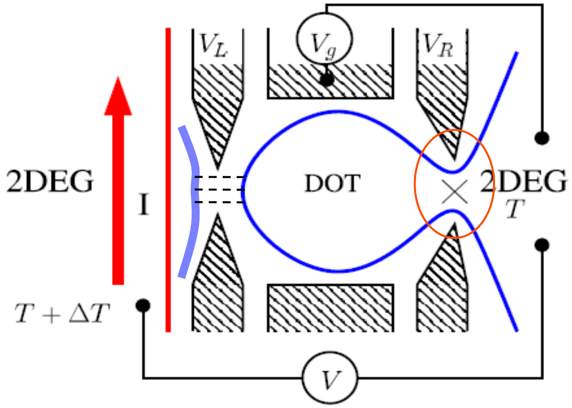
Strong coupling regime $\quad T \ll E_C$

Weak Coulomb Blockade $\quad |r_\alpha| \ll 1$

Metallic regime $\quad \delta \ll T$

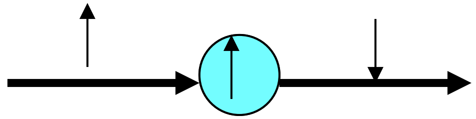
Strong coupling and the Kondo physics

(Matveev & Andreev, 2002)



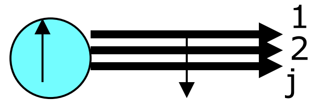
Ordinary (one-channel) Kondo

$$Jc^+_{\sigma}\vec{\sigma}_{\sigma\sigma'}c_{\sigma'}\vec{S}$$

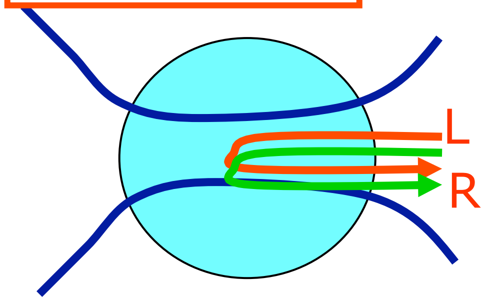


N-channel Kondo: spin-1/2 impurity +N orbital channels

$$J\sum_j c^+_{j\sigma}\vec{\sigma}_{\sigma\sigma'}c_{j\sigma'}\vec{S}$$



Reflection plays a role of spin-flip

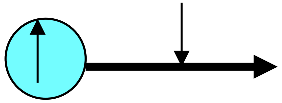


QPC is a quasi-spin-1/2 orbital “impurity” + two spin ↑ and ↓ channels: 2-channel Kondo. Symmetry of channels is protected by TRS

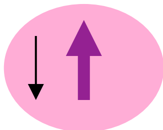
FL and non-FL behavior

Enhancement by non-Fermi-liquid effects

$$Jc^{+}_{\sigma}\vec{\sigma}_{\sigma\sigma'}c_{\sigma'}\vec{S}$$



Kondo screening of the impurity spin



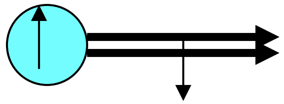
Complete screening below Tk

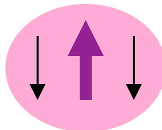
Fermi-liquid behavior

Magnetic susceptibility
χ=const as T->0

eS~T/Tk

$$\sum_j J_j c^{+}_{j\sigma}\vec{\sigma}_{\sigma\sigma'}c_{j\sigma'}\vec{S}$$





overscreening

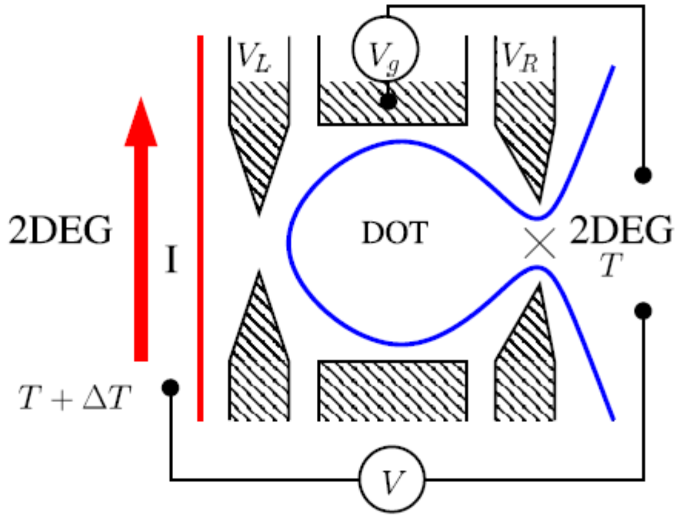
Non-Fermi-liquid behavior

Magnetic susceptibility
χ~ ln(Tk/T)

eS~(T/Tk)$^{1/2}$ ln(Tk/T)

Matveev&Andreev, 2002

Two Kondo regimes



Spinless fermions:
QPC is fully spin-polarized: 1CK
Fermi liquid behavior:

$$S \propto -\frac{T}{E_C}|r|\sin(2\pi N)$$

Enhancement of thermopower by electron-electron interaction !

Spinful fermions:
QPC is non-polarized:
isotropic 2CK
Non Fermi liquid behavior:

$$S \propto -|r|^2 \ln\frac{E_C}{T}\sin(2\pi N)$$

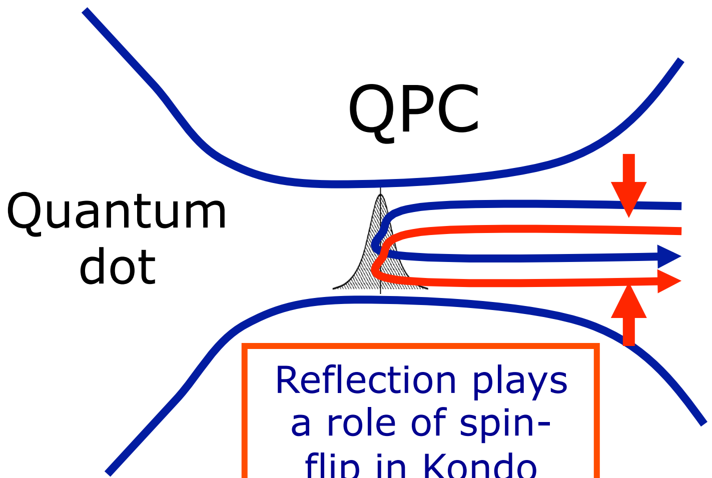
Enhancement by non-Fermi-liquid effects

Q1: How does one regime crossover to another one?

Matveev, Andreev, 2001-2002

How does magnetic field influence two Kondo regimes?

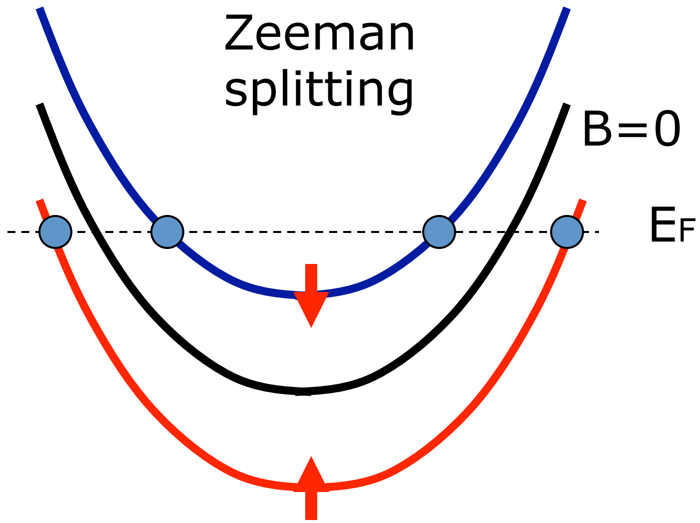
Parallel to the plane magnetic field



Reflection plays a role of spin-flip in Kondo problem

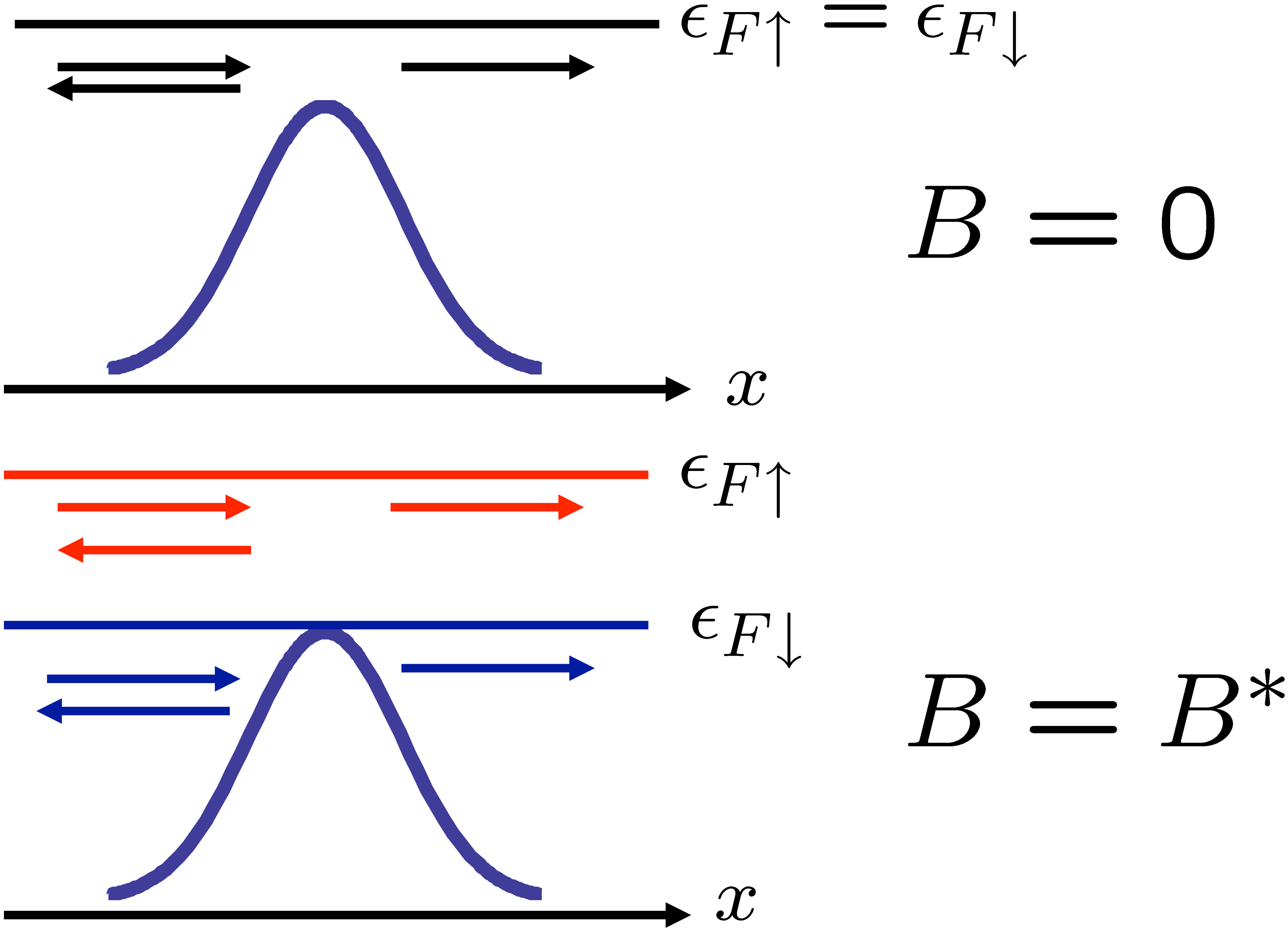
$|r| \Leftrightarrow J$

$T_{\max} \sim |r|^2 E_C, \quad E_C = e^2/(2C)$



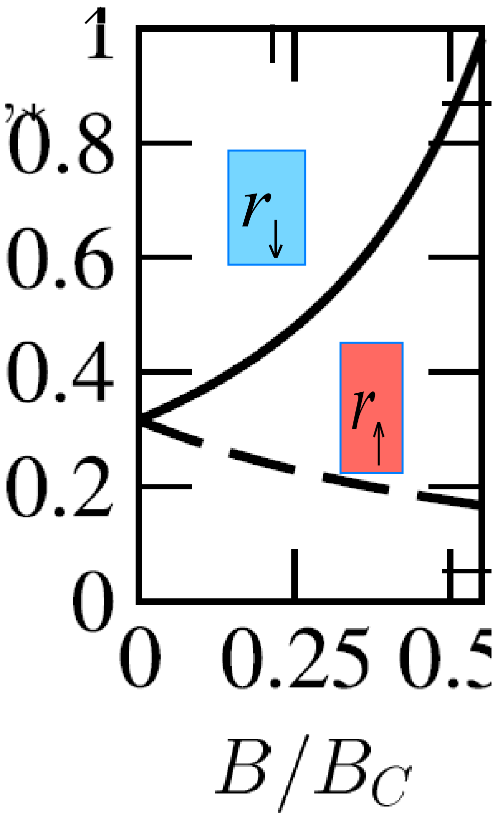
$$B \neq 0: \quad k_{F\uparrow} \neq k_{F\downarrow} \Rightarrow r_\uparrow \neq r_\downarrow$$

$$J_1 \neq J_2$$



$\epsilon_{F\uparrow} = \epsilon_{F\downarrow}$
$B = 0$
x
$\epsilon_{F\uparrow}$
$\epsilon_{F\downarrow}$
$B = B^*$
x

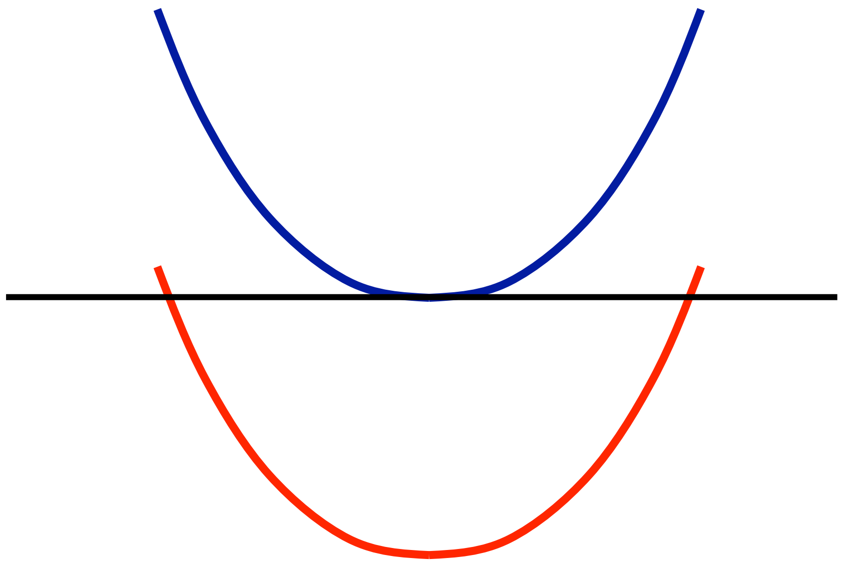
Characteristic scales of magnetic field



Field B*< B_C where spin-down electron is fully reflected

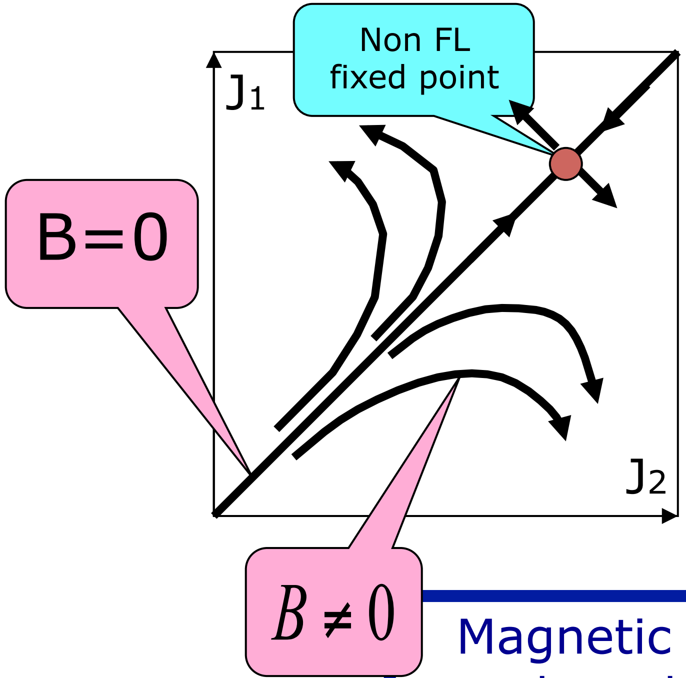
(model dependent)

$$E_{\uparrow,\downarrow}(B) - E_{\uparrow,\downarrow}(0) = \pm\frac{1}{2}g\mu_B B$$



Field of full polarization B_C

Instability of non-FL fixed point



$$\sum_j J_j c^+_{j\sigma} \vec{\sigma}_{\sigma\sigma'} c_{j\sigma'} \vec{S}$$

The symmetric state $J_1=J_2$ and the non-FL fixed point is only stable if protected by the basic symmetry (Time Reversal Symmetry)

Magnetic field breaks TRS and drives system to the 1-channel Kondo with decreasing the temperature T

Suppression of thermopower by magnetic field

The main result

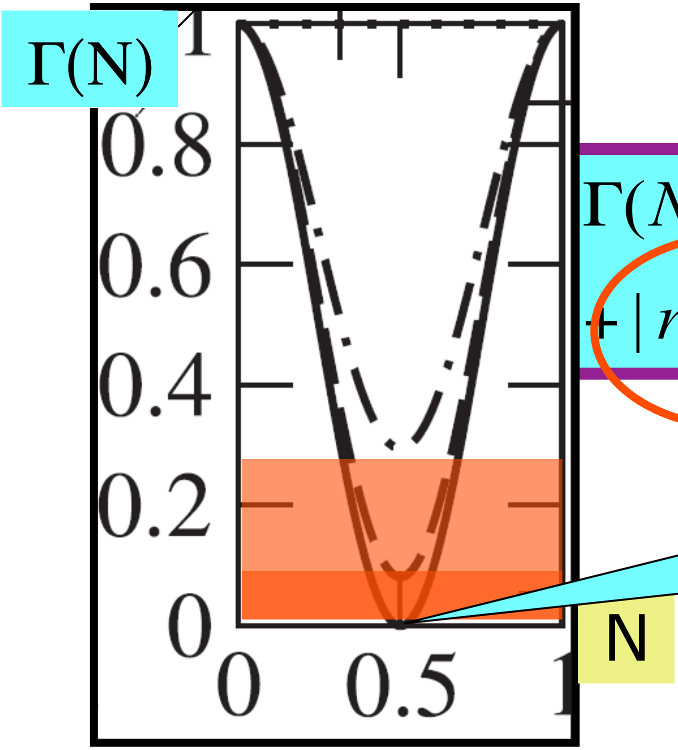
At a finite B a gap in Γ(N) opens up at the degeneracy point N=1/2

$$eS \sim -|r_\uparrow r_\downarrow| \left(\frac{T}{\Gamma(N)}\right) \ln\left(\frac{E_C}{T+\Gamma(N)}\right) \sin(2\pi N) F\left(\frac{\Gamma(N)}{T}\right)$$

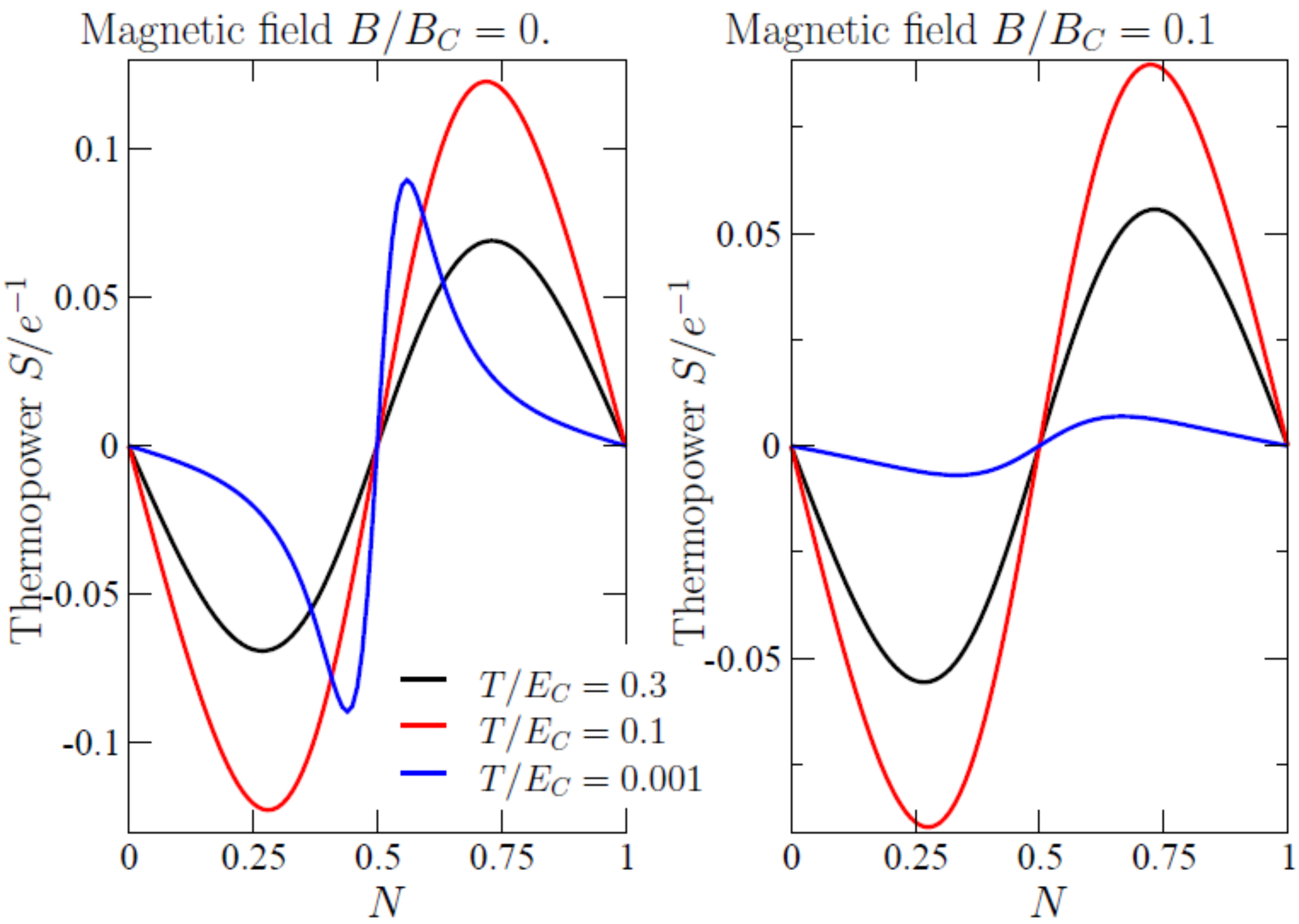
$$F(x) = \begin{cases} x, & x << 1 \\ const, & x >> 1 \end{cases}$$

$$\Gamma(N) \sim E_C[|r_\uparrow + r_\downarrow|^2 \cos^2(\pi N) + |r_\uparrow - r_\downarrow|^2 \sin^2(\pi N)]$$

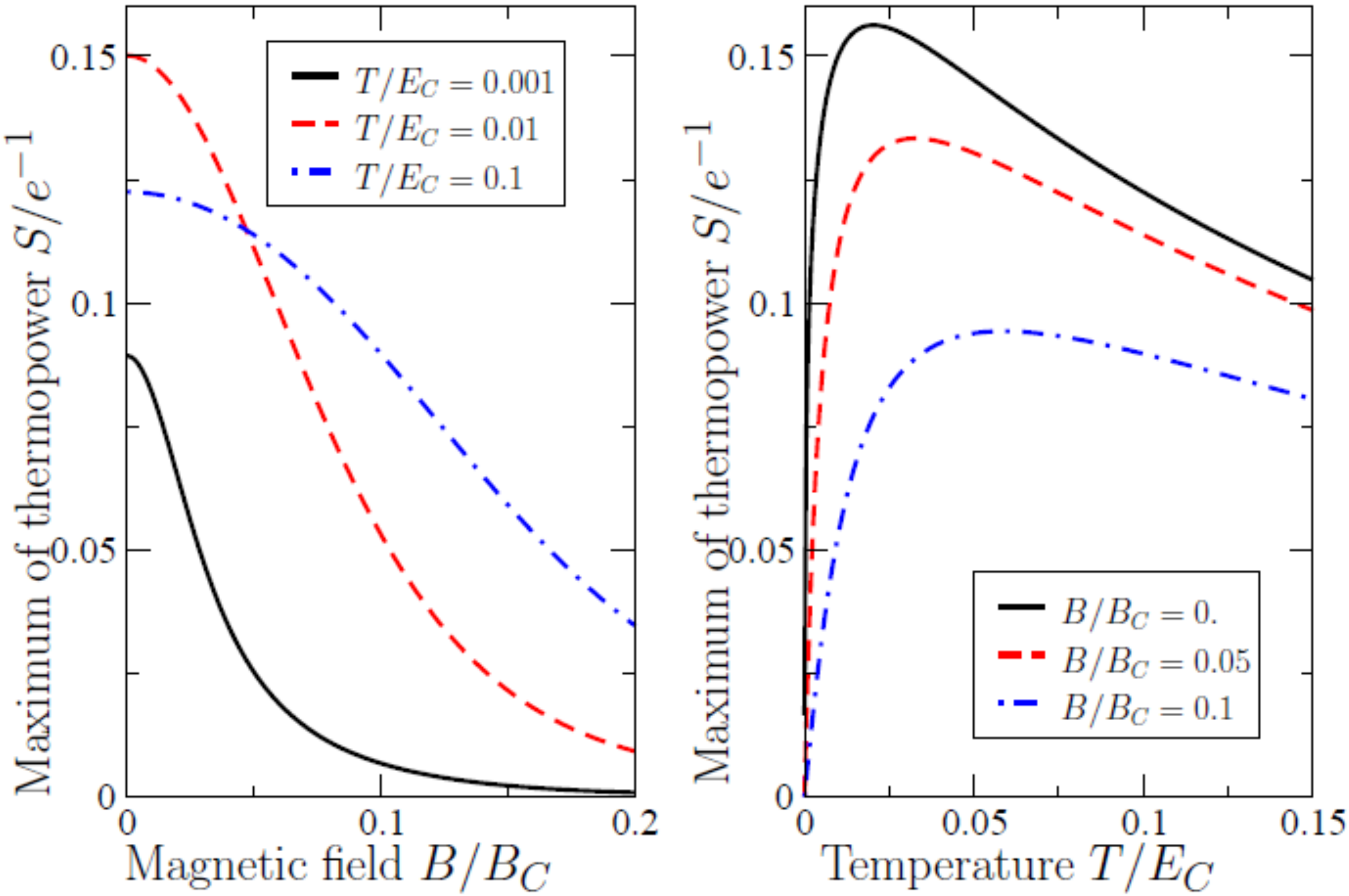
Effect of B



Theoretical predictions: gate voltage dependence

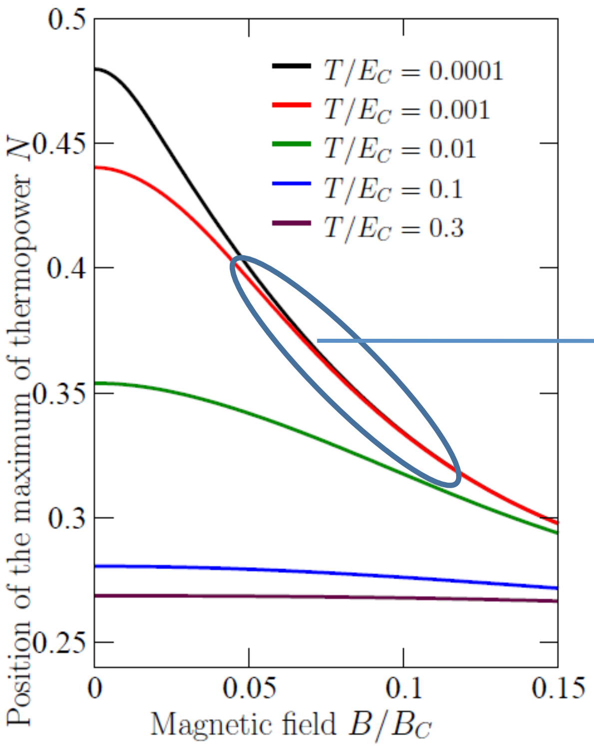


Theoretical predictions: B and T -dependences



Effects of magnetic field on thermopower

$$|r_\downarrow r_\uparrow| \xrightarrow{B\uparrow} |r_\uparrow|$$



For $T << T_{\min}$:

$$S \propto -\frac{1}{e}|r_\uparrow r_\downarrow| \frac{T}{\Gamma(N)} \ln\frac{E_C}{\Gamma(N)} \sin(2\pi N)$$

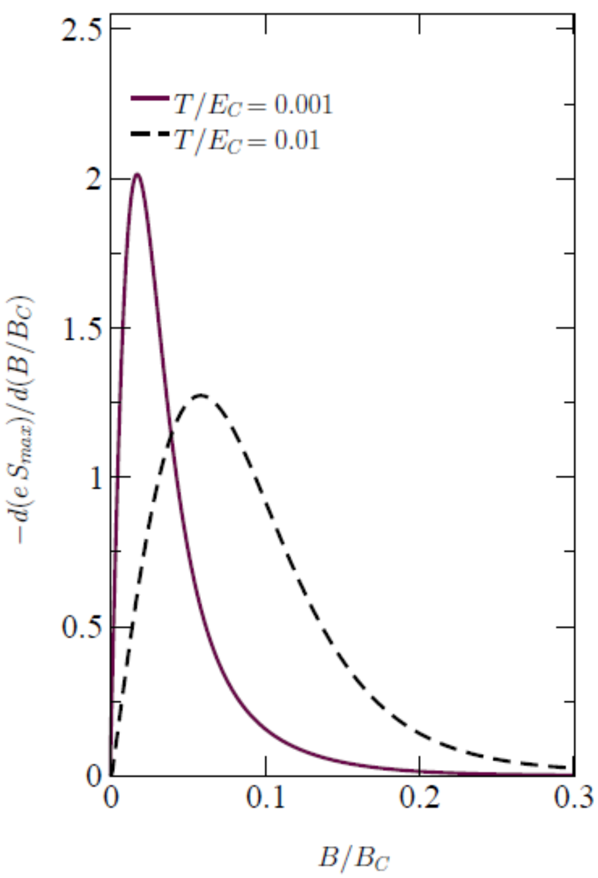
$$eS_{\max} \propto \frac{T}{E_0}$$

$$E_0 = E_C \left|\frac{B}{B_C}\right| \ln^{-1}\left[\frac{B_C}{B|r|}\right]$$

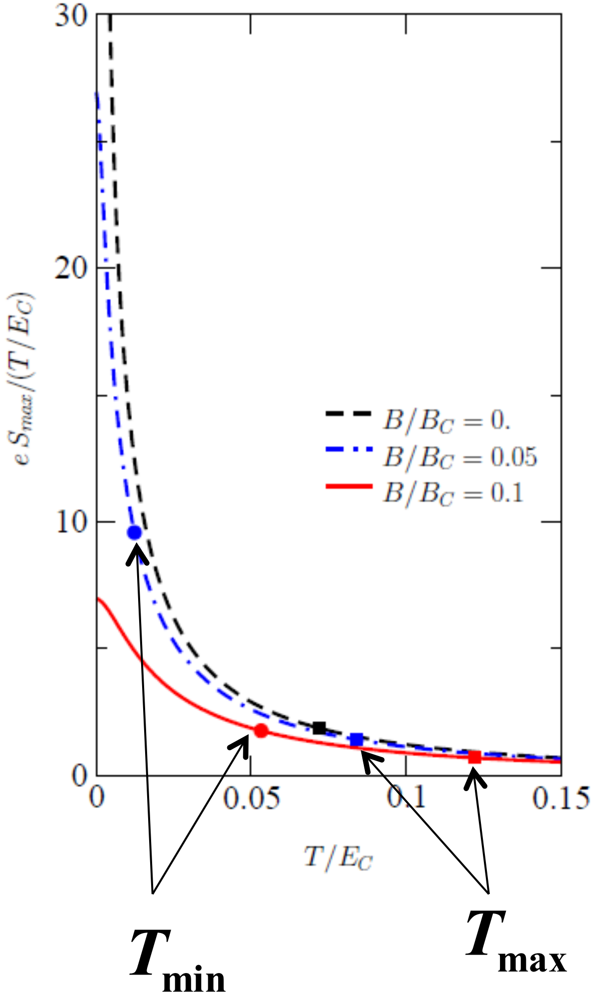
"Giant Fermi energy"

Giant Fermi-liquid behavior in magnetic field

Theoretical predictions: derivatives



Existence of maximum in dS/dB



B=0: S_{max}/T diverges at T = 0;
Finite B: S_{max}/T saturates below T_{min}

Message to take home

$$T_{min} \sim r_0^2 E_C (B/B_c)^2$$

0 — $T_{\min} \sim (|r_\downarrow| - |r_\uparrow|)^2 E_C$ — $T_{\max} \sim (|r_\downarrow| + |r_\uparrow|)^2 E_C$ — E_C — E_F — **T**

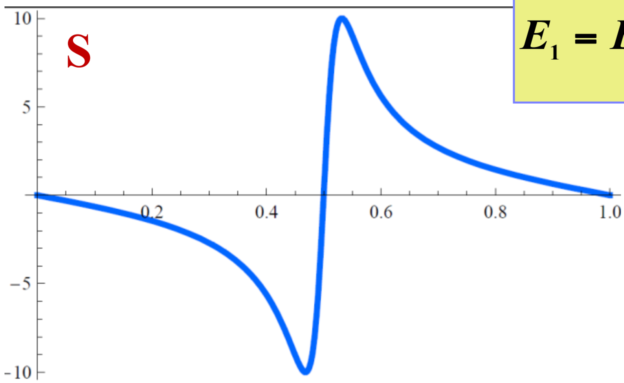
"Giant FL", 1CK

$$eS^{\max} \sim \frac{T}{E_0}$$

Non-perturbative, strong NFL, 2CK

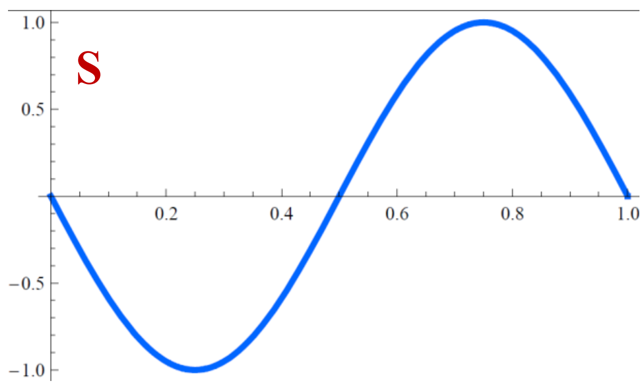
$$eS^{max} \sim \sqrt{\frac{T}{E_1}} \ln\left(\frac{E_C}{T}\right)$$

$$E_1 = E_C\left(\frac{1}{r_\uparrow} + \frac{1}{r_\downarrow}\right)^2$$



Perturbative, weak NFL, 2CK

$$eS^{\max} \sim |r_\uparrow r_\downarrow| \ln\left(\frac{E_C}{T}\right)$$

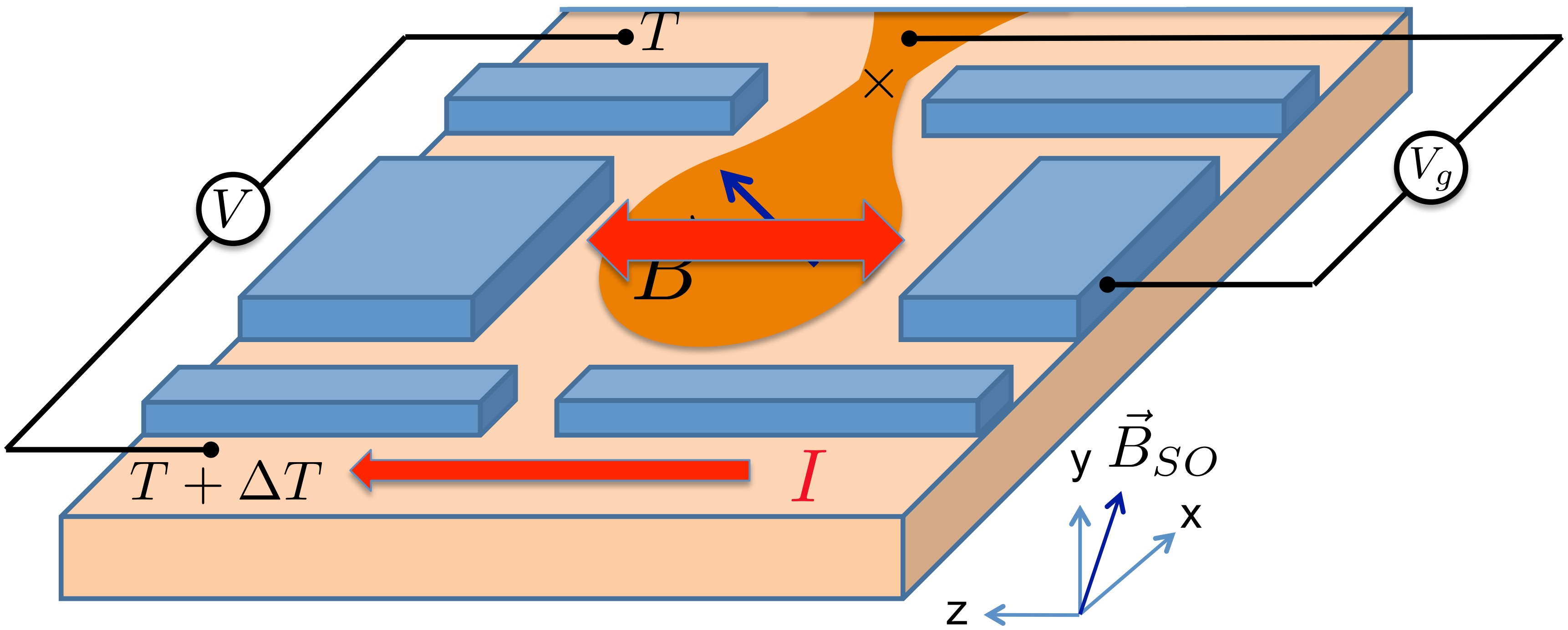


BULK

$$S \sim \frac{T}{E_F}$$

T.K.T. Nguyen, MK and V.E. Kravtsov, PRB 82, (2010)

Flensberg - Matveev - Furusaki setup in external parallel magnetic field in the presence of SOI



$$L \ll l_{SO}$$

Strong Zeeman effect vs strong spin-orbit interaction

$$H = H_0 + H_{LL} + H_{\text{tun}} + H_Z + H_{BS} + H_C + H_{SO}$$

$$H_0 = \sum_{k,\sigma} \epsilon_{p,\sigma} c^\dagger_{p,\sigma} c_{p,\sigma} + \sum_{\sigma} \epsilon_\sigma d^\dagger_\sigma d_\sigma \qquad H_{LL} = i v_F \sum_{\gamma=\pm,\sigma=\uparrow,\downarrow} \gamma \int dx \Psi^\dagger_{\gamma,\sigma} \partial_x \Psi_{\gamma,\sigma}$$

$$H_{\text{tun}} = \sum_{k,\sigma} (t_{k,\sigma} c^\dagger_{k,\sigma} d_\sigma + \text{h.c.}) \qquad H_Z = g\mu_B \vec{B} \cdot \left(\vec{s}_{\text{leads}} + \vec{S}_{\text{dot}}\right)$$

$$H_{BS} = -v_F \sum_{\sigma} |r_\sigma| \left[\Psi^\dagger_{L,\sigma}(0)\Psi_{R,\sigma}(0) + \text{h.c.}\right]$$

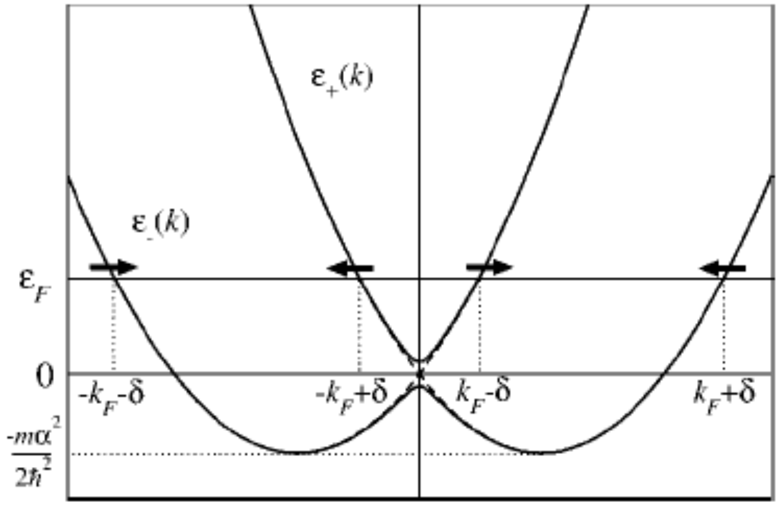
$$H_C = E_C \left[\hat{n} + \int_0^\infty \sum_{\gamma,\sigma} \Psi^\dagger_{\gamma,\sigma}(x)\Psi_{\gamma,\sigma}(x)\, dx - N(V_g)\right]^2$$

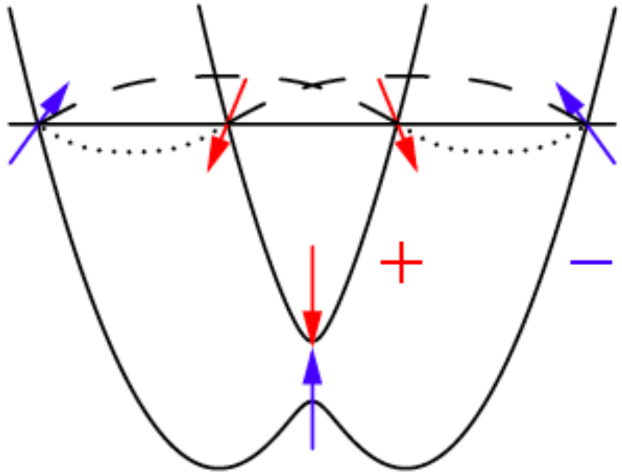
$$H_{SO} = \alpha_R [\vec{p} \times \vec{n}_z] \cdot \vec{\sigma} + \alpha_D p_x \sigma_x$$

$$H_R = i\alpha_R k_F \sum_{\gamma=\pm} \gamma \int dx \left[\Psi^\dagger_{\gamma,\uparrow}\Psi_{\gamma,\downarrow} - \Psi^\dagger_{\gamma,\downarrow}\Psi_{\gamma,\uparrow}\right]$$

$$H_D = \alpha_D k_F \sum_{\gamma=\pm} \gamma \int dx \left[\Psi^\dagger_{\gamma,\uparrow}\Psi_{\gamma,\downarrow} + \Psi^\dagger_{\gamma,\downarrow}\Psi_{\gamma,\uparrow}\right]$$

Strong spin-orbit interaction at $\mathbf{B \ll B_{SO} = \alpha p_F}$





Spectra

R-SOI

$$E_{\pm}(p) = \frac{p^2}{2m} \pm \sqrt{(\alpha_R p)^2 + (g\mu_B B/2)^2}$$

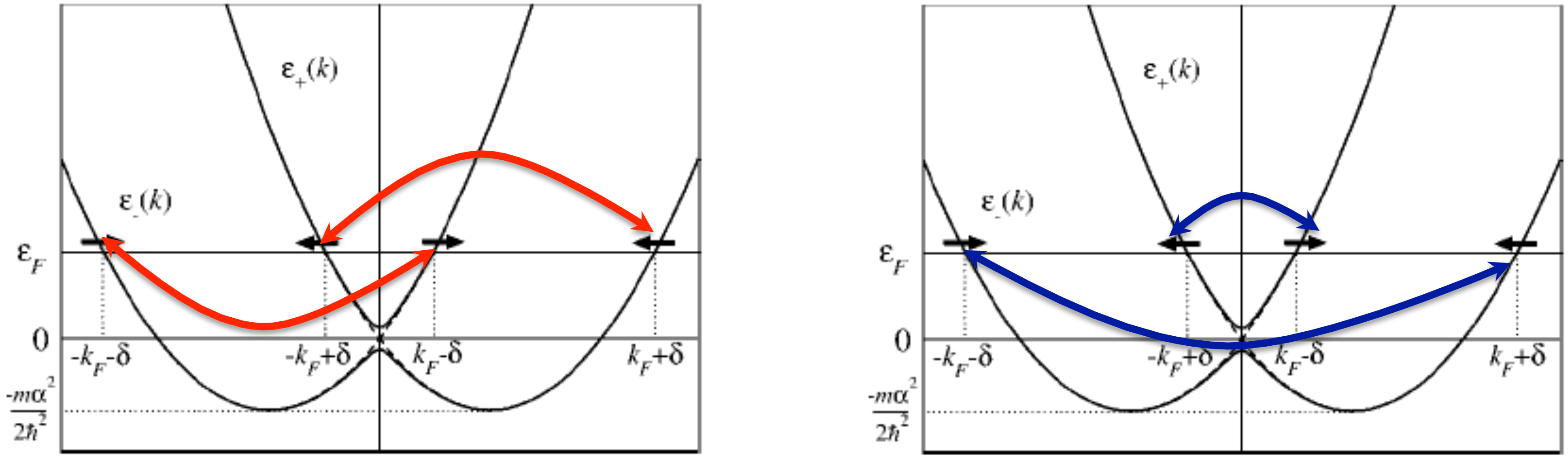
$$E_{\pm}(B) - E_{\pm}(0) = \pm \frac{g\mu_B B^2}{4B_{SO}}$$

D-SOI

$$E_{\pm}(p) = \frac{p^2}{2m} \pm \sqrt{(\alpha_D p)^2 + (g\mu_B B/2)^2 + \alpha_D p g\mu_B B\cos\theta}$$

$$E_{\pm}(B) - E_{\pm}(0) = \pm g\mu_B/2\left(B\cos\theta + \frac{B^2}{2B_{SO}}\sin^2\theta\right)$$

Strong spin-orbit interaction at $\mathbf{B \ll B_{SO} = \alpha p_F}$



Scattering

Spin conserving

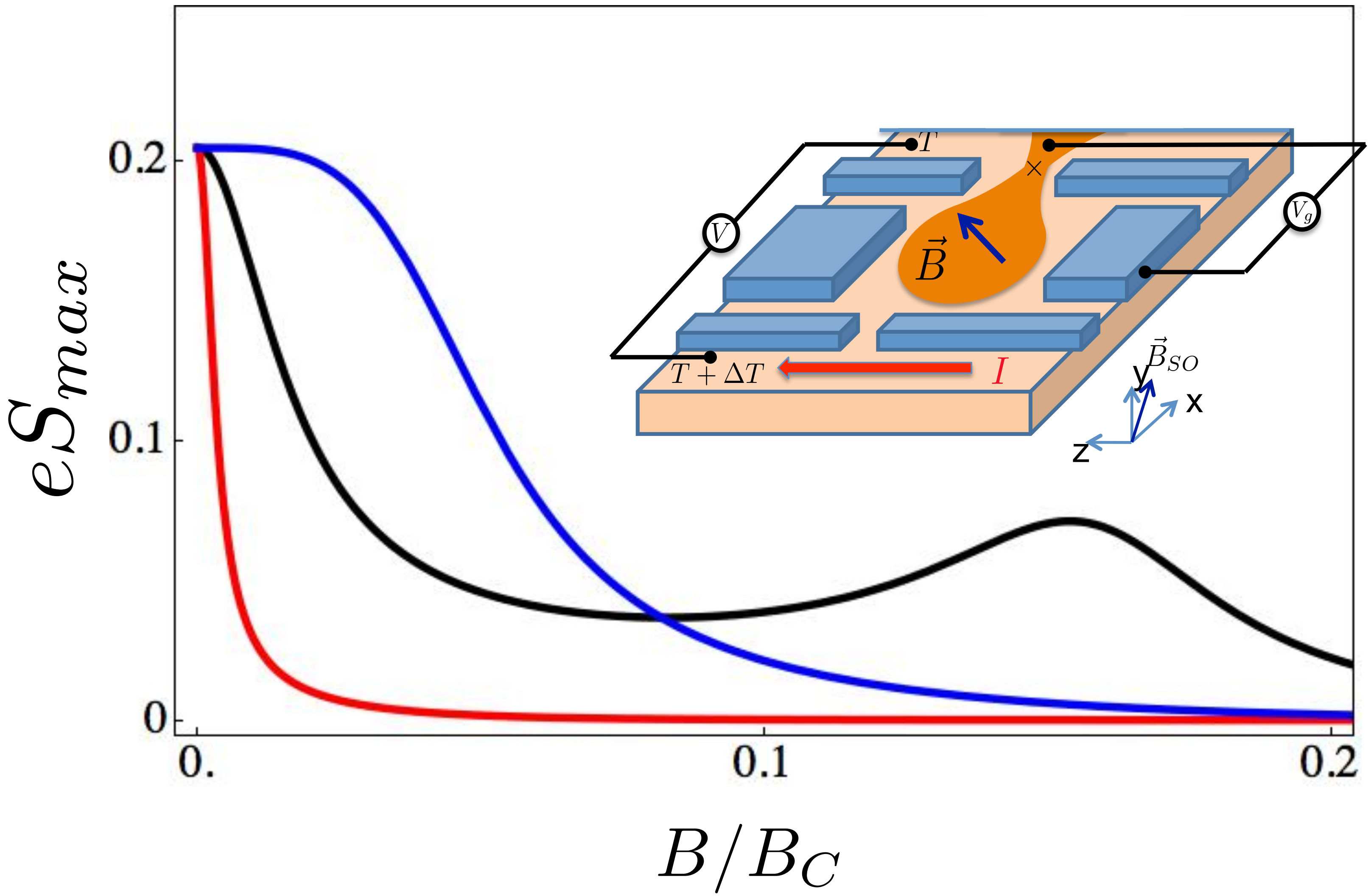
$$H_{BS} = -v_F \sum_{\sigma=\uparrow\downarrow} |r_\sigma| \left[\Psi^\dagger_{L,\sigma}(0)\Psi_{R,\sigma}(0) + \mathrm{h.c.}\right]$$

Spin flip

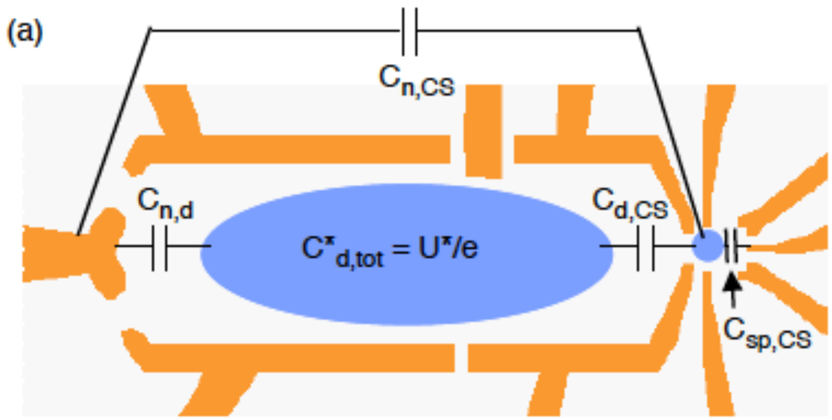
$$H_{BS} = -v_F \sum_{\lambda=\pm} |r_\lambda| \left[\Psi^\dagger_{L,\lambda}(0)\Psi_{R,\lambda}(0) + \mathrm{h.c.}\right]$$

$$|r_\pm| \sim r_0 \frac{B}{\alpha p_{F\pm}}$$

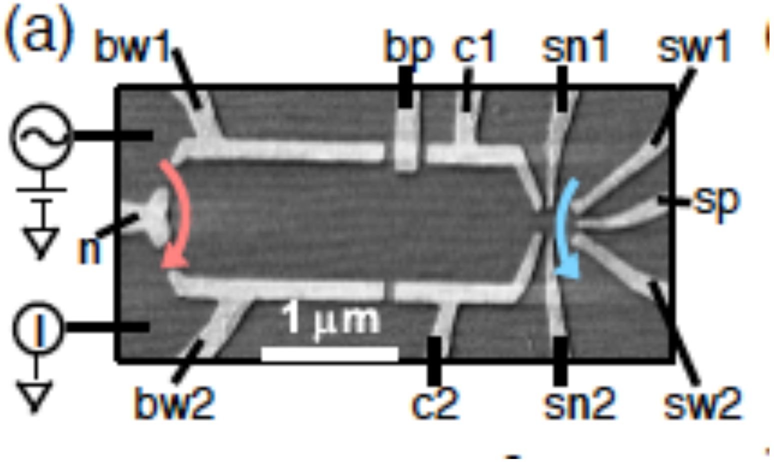
Theoretical predictions: strong spin-orbit

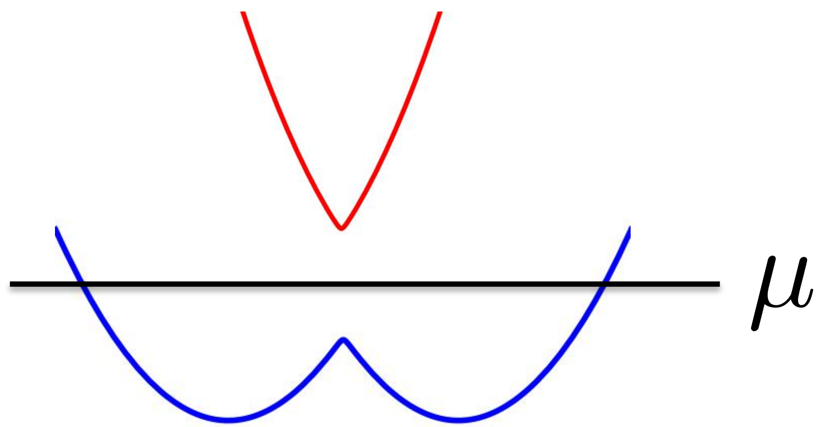


Perspectives:

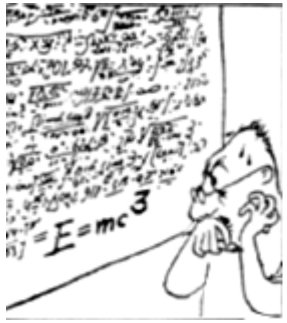


- Multi-channel Kondo effect
- Influence of noise
- Influence of finite s-d voltage
- Quenches with the gate and s-d voltage
- SOI in quantum dot





Conclusions



- Thermopower of a quantum dot can be much larger than in the bulk $eS_{BULK} \sim T/E_F$

- Kondo physics in thermopower of an open dot; magnetic field leads to crossover from 2CK to 1CK

- Magnetic field suppresses thermopower and restores FL behavior at $T < T_{min}$

- Spin – orbit interaction "protects" the NFL at magnetic fields $B < B_{SO}$

- Interplay between linear and quadratic Zeeman effect leads to non-monotonic B- behavior of thermopower

T.K.T. Nguyen, MK and V.E. Kravtsov, PRB 82, (2010)
MK and Z. Ratiani (2013)