Spin thermopower in the overscreened Kondo model

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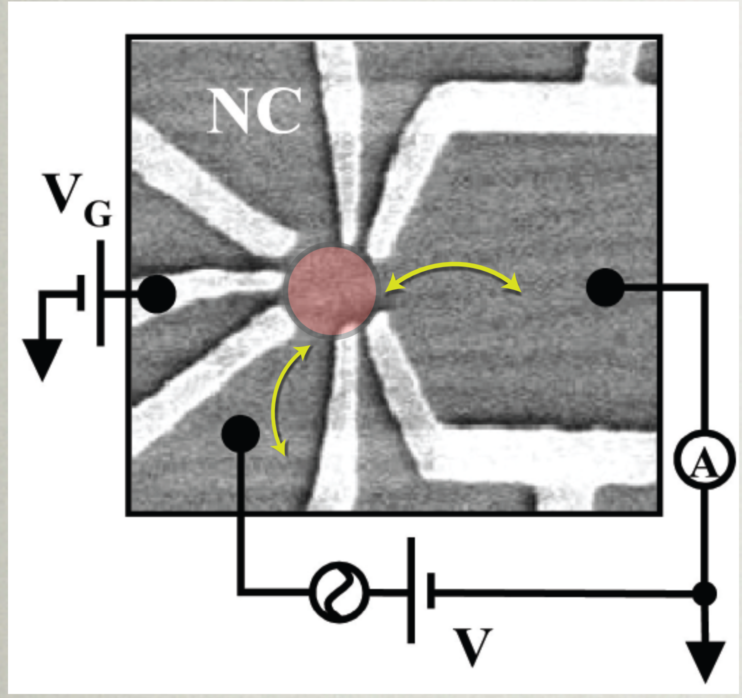
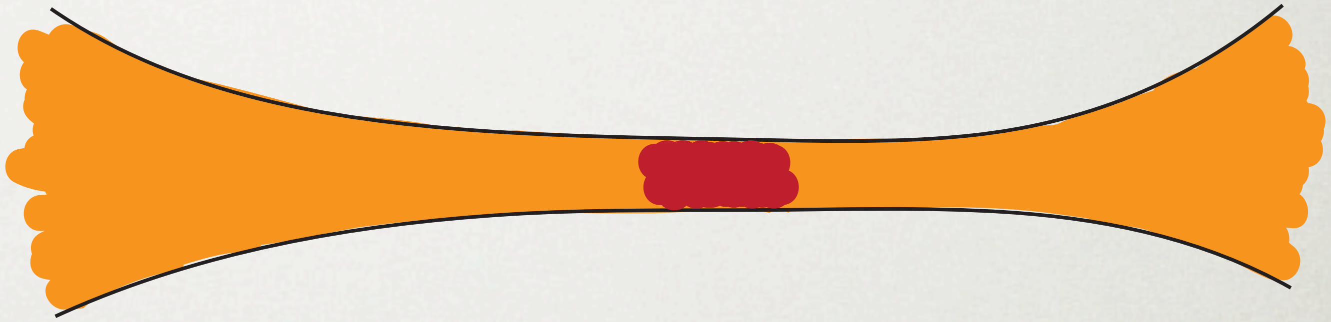
Transport in Nanostructures



Grobis et al., PRL 100, 246601 (2008)



transmission coefficient, T(ϵ)

Landauer formula: $$G = \frac{e^2}{h} \sum_\sigma T_\sigma(E_F)$$

$$G = \left.\frac{\mathrm{d}I}{\mathrm{d}V}\right|_{V=0}$$

Conductance quantum: $$G_0 = \frac{2e^2}{h} = 1/12.906\,\mathrm{k}\Omega$$

Single-Impurity Anderson Model

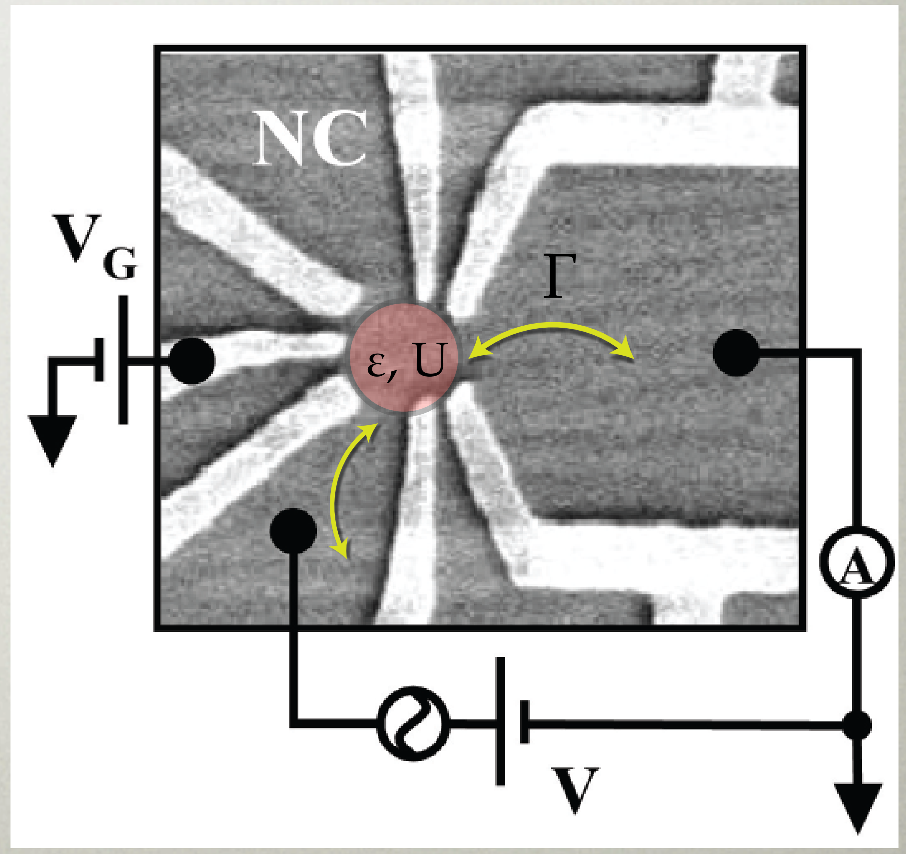
$$H = H_{\text{imp}} + H_{\text{band}} + H_{\text{hyb}}$$

$$H_{\text{imp}} = \sum_{\sigma} \epsilon\, n_\sigma + U\, n_\uparrow n_\downarrow \qquad n_\sigma = d_\sigma^\dagger d_\sigma$$

$$H_{\text{band}} = \sum_{\mathbf{k},\sigma} \epsilon_k\, c_{\mathbf{k},\sigma}^\dagger c_{\mathbf{k},\sigma}$$

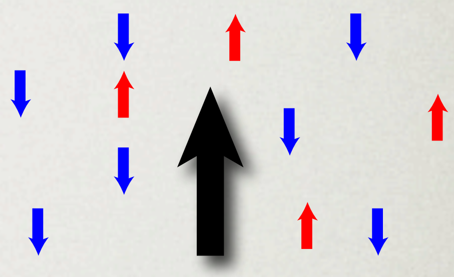
$$H_{\text{hyb}} = \sum_{k,\sigma} \left(V_k\, c_{k,\sigma}^\dagger d_\sigma + \text{H.c.} \right)$$

$$\Delta(\omega) = \sum_k \frac{|V_k|^2}{\omega - \epsilon_k} \approx i\Gamma$$



Kondo Model

$$H = H_{\text{band}} + H_{\text{exch}}$$



$$H_{\text{band}} = \sum_{\mathbf{k},\sigma} \epsilon_k \, c^\dagger_{\mathbf{k},\sigma} c_{\mathbf{k},\sigma}$$

Fermi sea: gas of non-interacting electrons

$$H_{\text{exch}} = J \, \mathbf{S} \cdot \mathbf{s}$$

exchange coupling

$$\mathbf{S} = \frac{1}{2}\boldsymbol{\sigma}$$ quantum-mechanical spin operator

$$\mathbf{s} = \sum_{\mathbf{k},\alpha,\beta} c^\dagger_{\mathbf{k},\alpha} \left(\frac{1}{2} \boldsymbol{\sigma}_{\alpha\beta} \right) c_{\mathbf{k},\beta}$$ spin-density (at **r**=0)

Schrieffer-Wolff transformation: $\rho J = \dfrac{8\Gamma}{\pi U}$

THE FAMILY OF KONDO IMPURITY MODELS

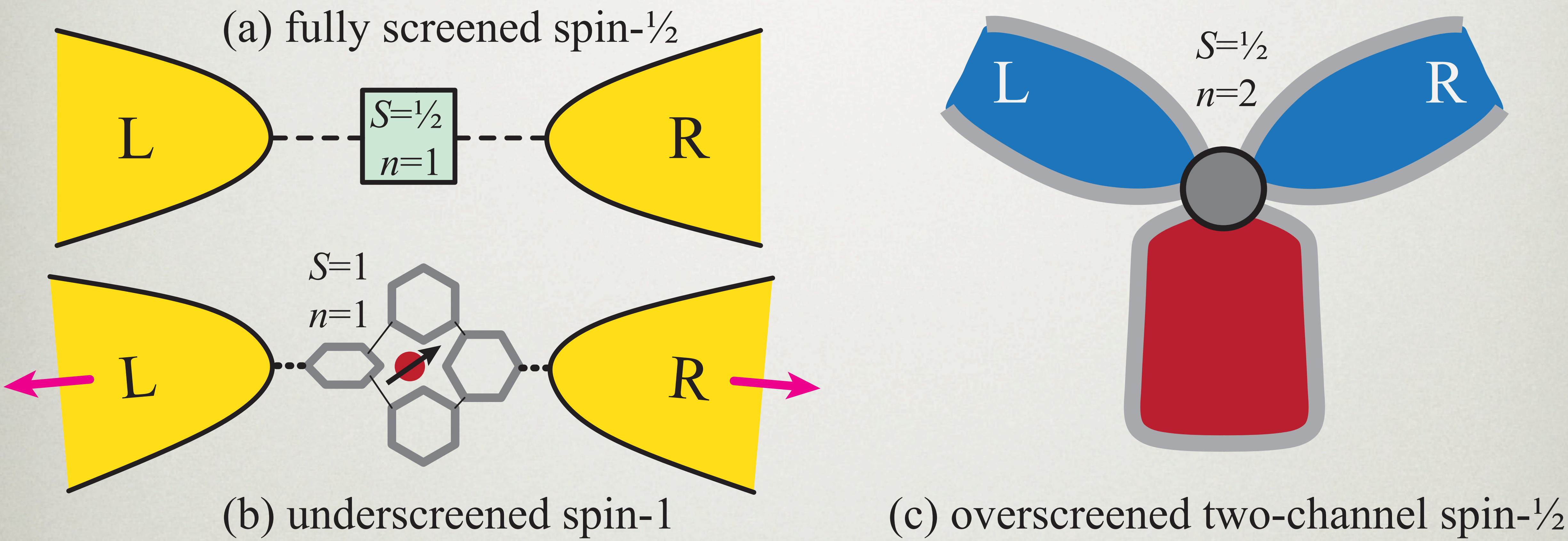
$$H = \sum_{\mathbf{k},\sigma,i} \epsilon_k c^\dagger_{\mathbf{k},\sigma,i} c_{\mathbf{k},\sigma,i} + \sum_i J \mathbf{s}_i \cdot \mathbf{S} + \mathbf{B} \cdot \mathbf{S}$$ $i=1,\ldots,N_{\text{channels}}$

Classification according to 2S vs. N_{channels}

	fully screened Kondo model	underscreened Kondo model	overscreened Kondo model
impurity spin, S	1/2	1	1/2
N_{channels}	1	1	2
fixed point	Fermi liquid	singular Fermi liquid	non-Fermi liquid

P. Nozières and A. Blandin. J. Physique 41, 193 (1980)

Physical realizations



D. Goldhaber-Gordon, H. Shtrikman, D. Mahalu, D. Abusch-Magder, U. Meirav, M. A. Kastner, Nature 391, 156 (1998)

N. Roch, S. Florens, V. Bouchiat, W. Wernsdorfer, F. Balestro, Nature (London) 453, 633 (2008)

J. J. Parks, A. R. Champagne, T. A. Costi, W. W. Shum, A. N. Pasupathy, E. Neuscamman, S. Flores-Torres, P. S. Cornaglia, A. A. Aligia, C. A. Balseiro, G. K.-L. Chan, H. A. Abruna, and D. C. Ralph. Science 328, 1370 (2010)

R. M. Potok, I. G. Rau, Hadas Shtrikman, Yuval Oreg, and D. Goldhaber-Gordon, Nature 446, 167 (2007)

Fermi Liquids

- Excitations are "quasiparticles": same charge, spin and statistics as electrons, but different *effective* mass; "dressed" fermions.
- Residual interactions between quasiparticles go to zero as the Fermi level is approached.
- Specific heat $\propto$T, scattering rate $\propto\omega^2$

$$\langle b, \mathrm{out}|a, \mathrm{in}\rangle \equiv \langle b, \mathrm{in}|\hat{S}|a, \mathrm{in}\rangle$$

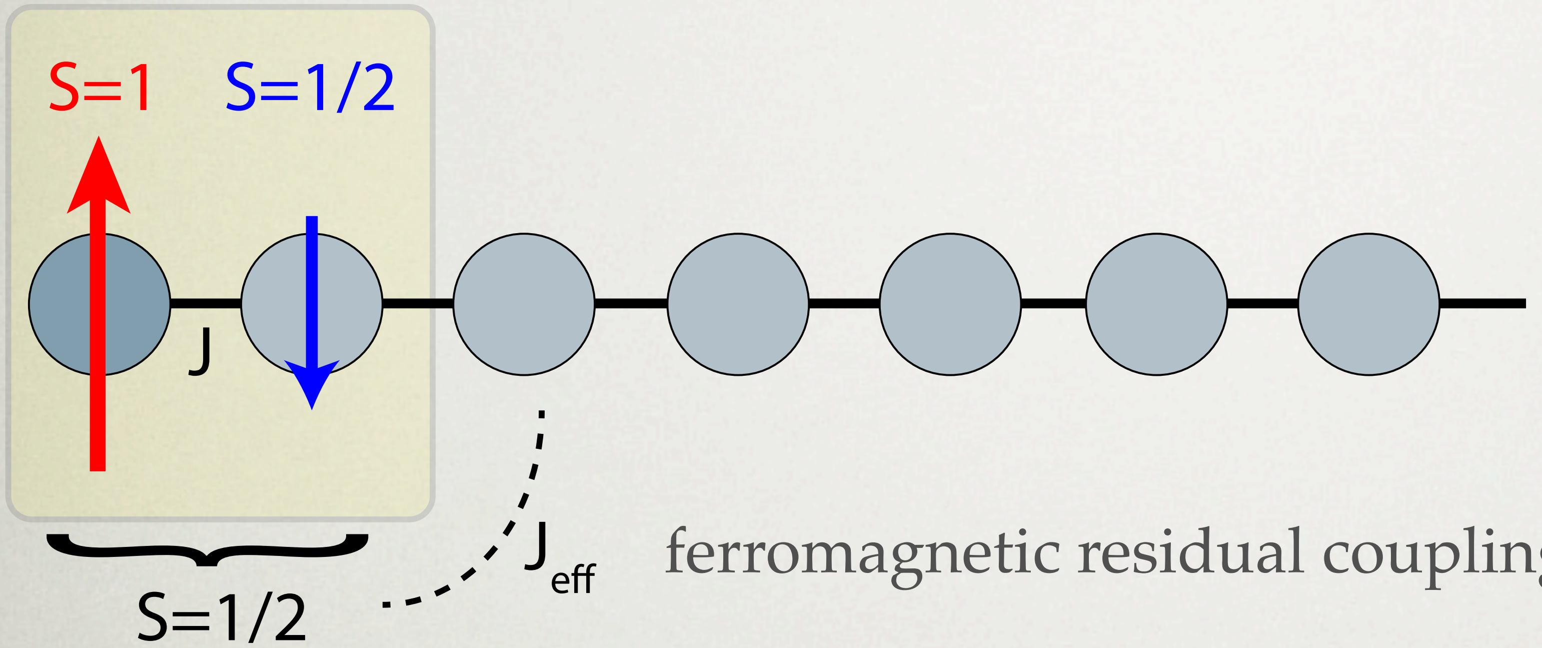
$$\langle k\sigma, \mathrm{in}|\hat{S}|k'\sigma', \mathrm{in}\rangle = 2\pi\delta(k-k')\delta_{\sigma\sigma'}S(\omega)$$

$|S(\omega=0)| = 1$ S(ω) analytic around ω=0

P. Nozieres, J. Low. Temp. Phys., 17, 31 (1974)

P. Mehta et al., Phys. Rev. B **72**, 014430 (2005)

Underscreened Kondo Effect for S=1 Model



$$J_{\mathrm{eff}} = \frac{1}{\ln(\omega/T_0)}$$

$|S(\omega = 0)| = 1$ S(ω) singular around ω=0

$1/\ln^2(\omega/T_0)$ cusps in spectral functions

This is a singular Fermi liquid!

W. Koller et al., Phys. Rev. B **72**, 045117 (2005)
P. Mehta et al., Phys. Rev. B **72**, 014430 (2005)

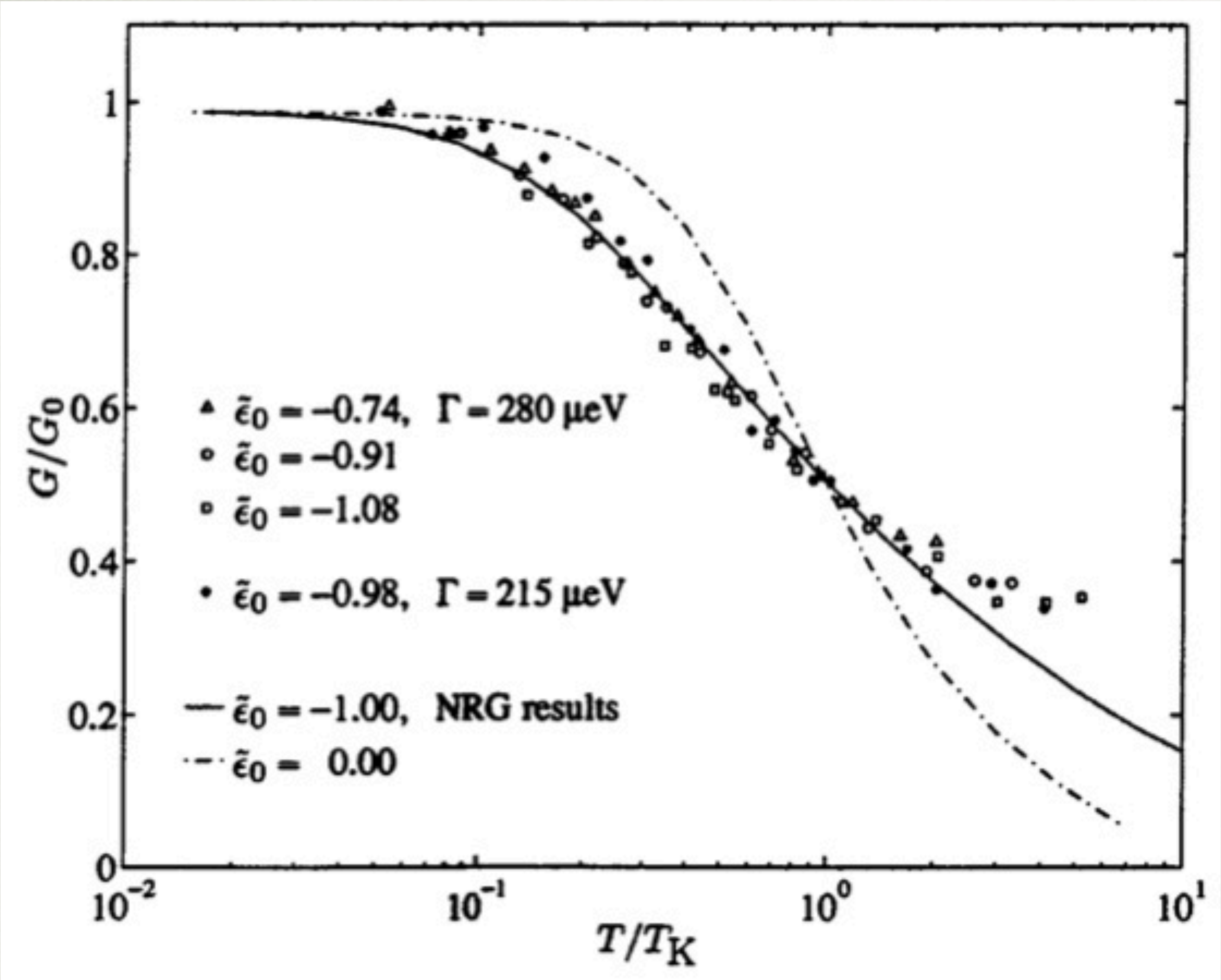
OVERSCREENED KONDO EFFECT FOR TWO-CHANNEL S=1/2 MODEL

- |S(ω=0)|=0, incoming electrons scatters into particle-hole excitations
- Non-interacting fixed point, but in terms of Majorana fermions non-Fermi liquid
- √ω cusps in spectral functions

P. Nozieres and A. Blandin. J. Physique 41, 193 (1980)

Maldacena, Affleck: bosonization, conformal field theory

Standard Kondo effect



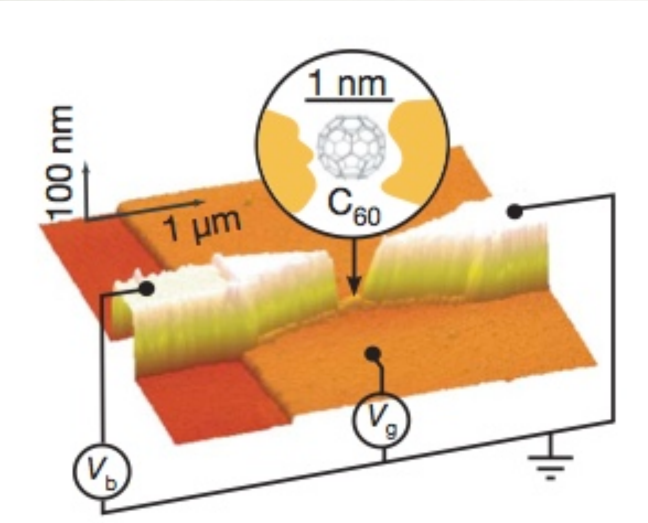
$$G(T) = G_0 \left(\frac{T_K^2}{T^2 + T_K^2} \right)^s$$

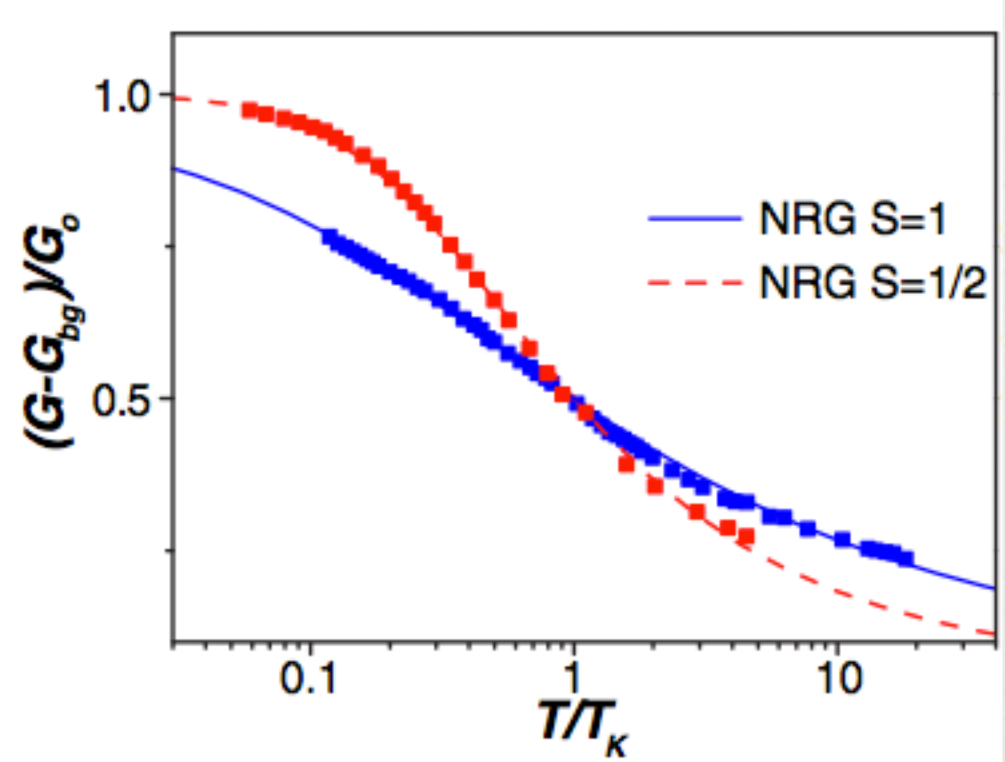
s=0.22

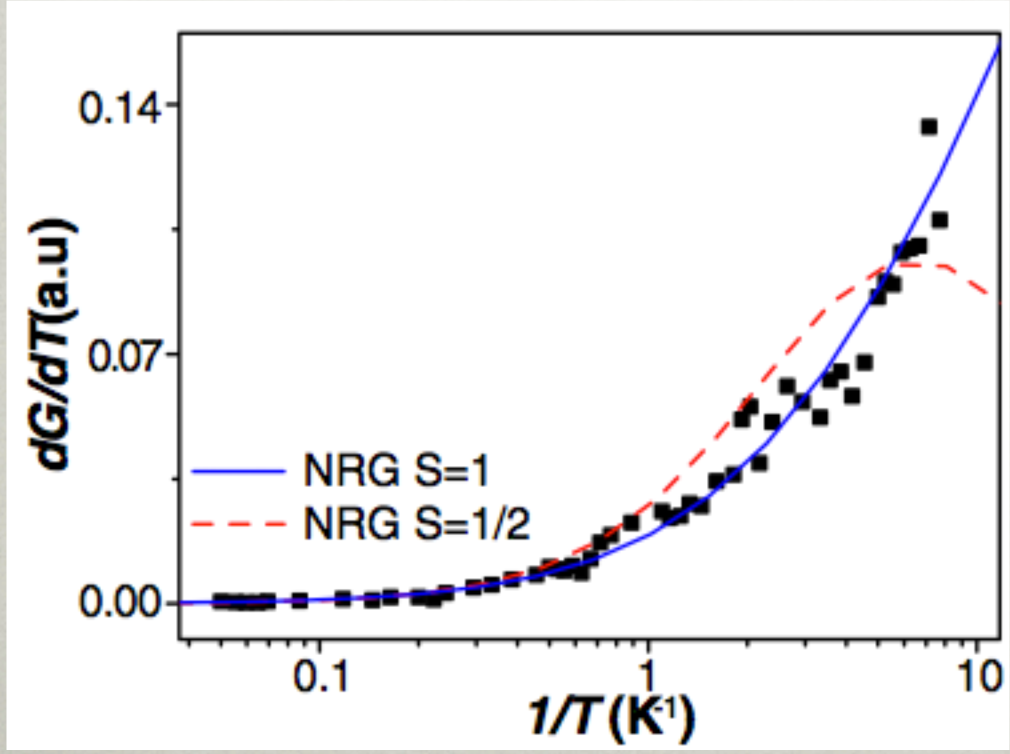
Goldhaber-Gordon et al., Phys. Rev. Lett. 81, 5225 (1998)

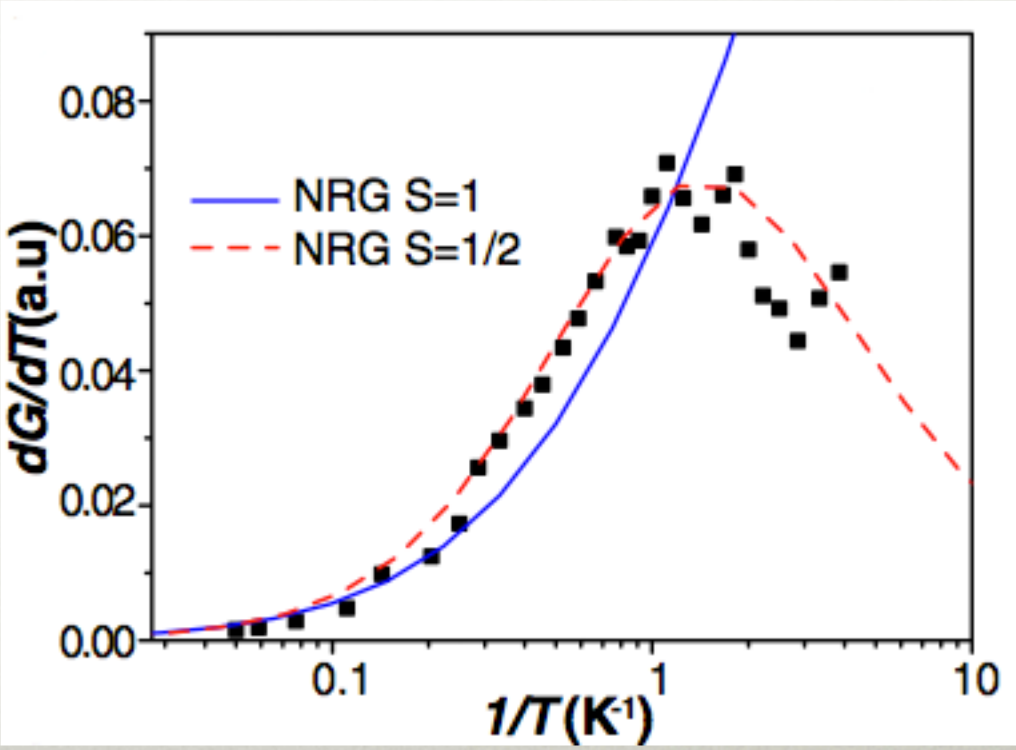
Underscreened Kondo Effect

C_{60} molecule

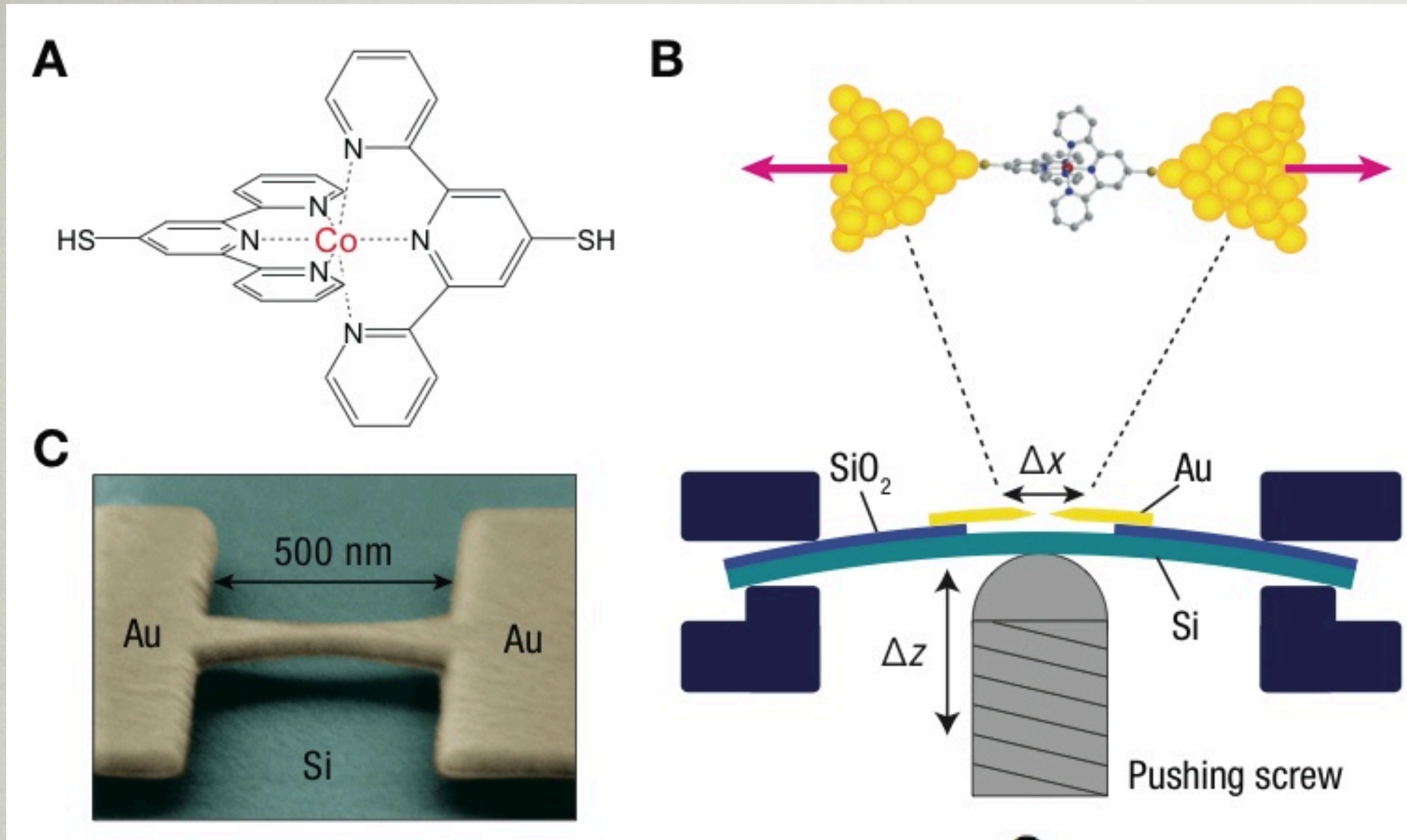


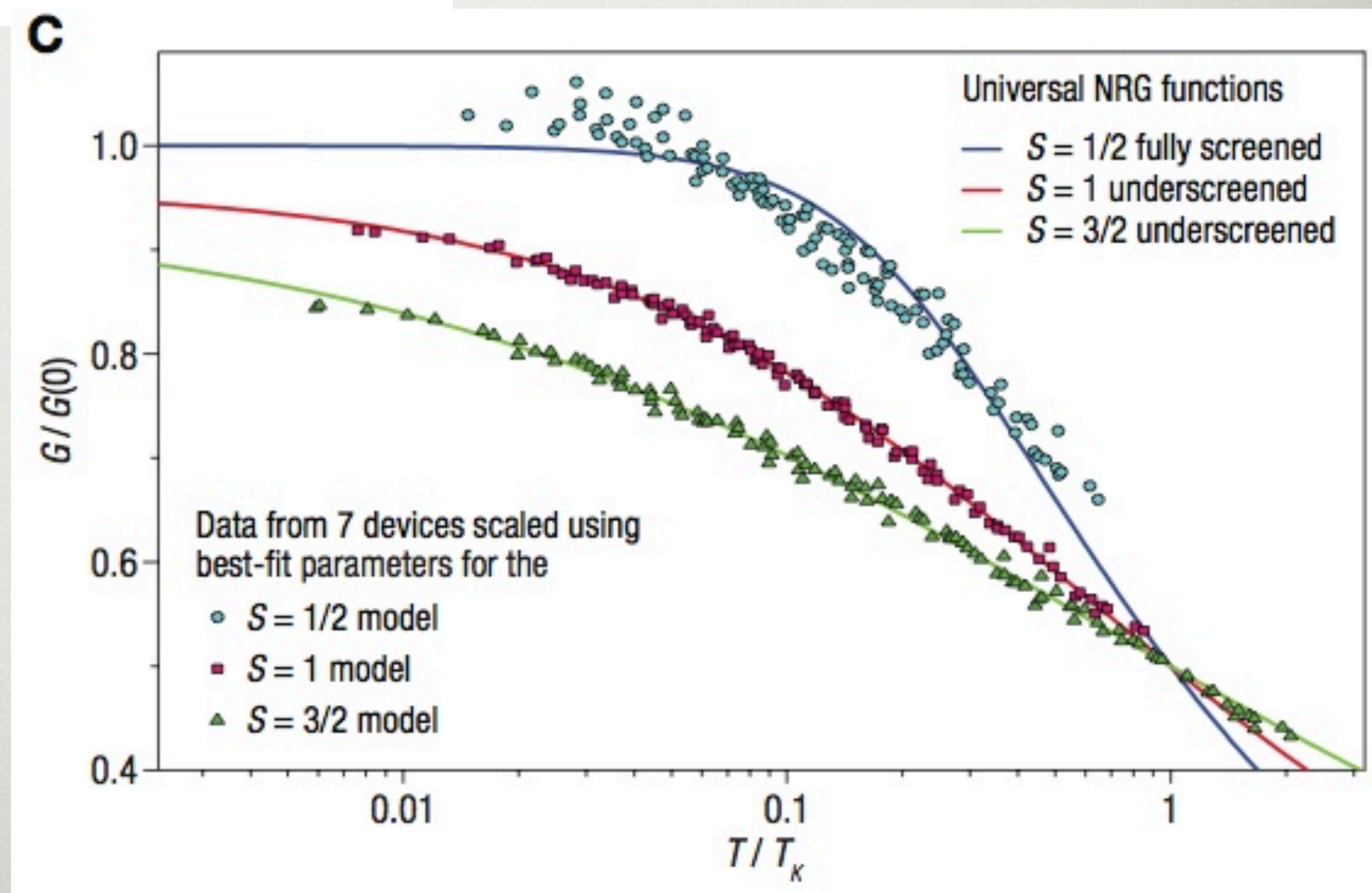






N. Roch, S. Florens, T. A. Costi, W. Wernsdorfer, F. Balestro, PRL 103, 197202 (2009)





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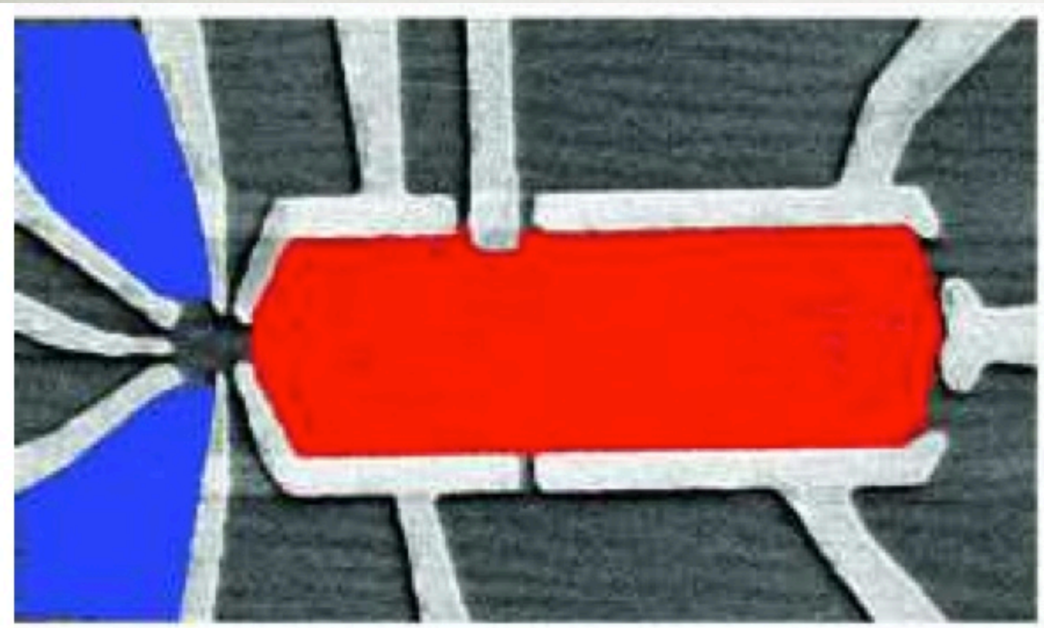
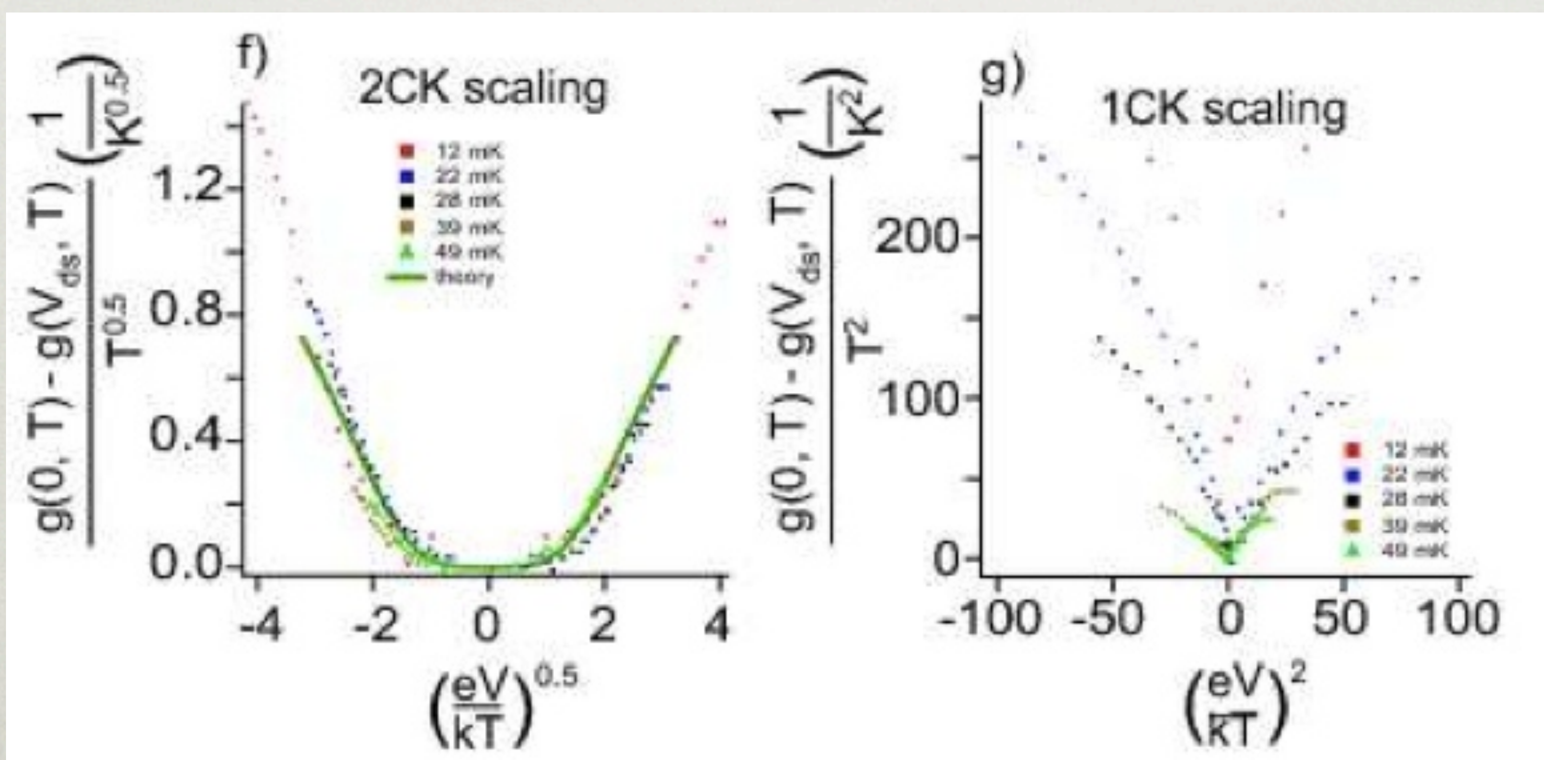
Two-Channel Kondo effect



$$\frac{g(0,T) - g(V_{\mathrm{sd}},T)}{T^{0.5}} \propto Y\left(\frac{eV_{\mathrm{ds}}}{k_B T}\right)$$

$$Y(x) \approx \begin{cases} \frac{3}{\pi}\sqrt{x} - 1 & \text{for } x \gg 1 \\ cx^2 & \text{for } x \ll 1 \end{cases}$$



R. M. Potok, I. G. Rau, Hadas Shtrikman, Yuval Oreg, and D. Goldhaber-Gordon, Nature 446, 167 (2007)

(SPIN) THERMOPOWER

$$I_\sigma = \frac{e}{h}\int \mathrm{d}\omega\,[f_{L\sigma}(\omega) - f_{R\sigma}(\omega)]\mathcal{T}_\sigma(\omega)$$

$$\Delta T = T_L - T_R$$

$$eV = \mu_L - \mu_R$$

$$eV_s = (\mu_{L\uparrow} - \mu_{L\downarrow}) - (\mu_{R\uparrow} - \mu_{R\downarrow})$$

$$I_C = \frac{e}{h}\left[(\mathcal{I}_{1\uparrow} + \mathcal{I}_{1\downarrow})\frac{\Delta T}{T} + (\mathcal{I}_{0\uparrow} + \mathcal{I}_{0\downarrow})eV + \frac{1}{2}(\mathcal{I}_{0\uparrow} - \mathcal{I}_{0\downarrow})eV_s\right]$$

$$I_S = \frac{e}{h}\left[(\mathcal{I}_{1\uparrow} - \mathcal{I}_{1\downarrow})\frac{\Delta T}{T} + (\mathcal{I}_{0\uparrow} - \mathcal{I}_{0\downarrow})eV + \frac{1}{2}(\mathcal{I}_{0\uparrow} + \mathcal{I}_{0\downarrow})eV_s\right]$$

$$\mathcal{I}_{n\sigma} = \int \mathrm{d}\omega\,\omega^n[-f'(\omega)]\mathcal{T}_\sigma(\omega)$$

(SPIN) THERMOPOWER

Particle-hole symmetric point: $A_\uparrow(\omega) = A_\downarrow(-\omega)$

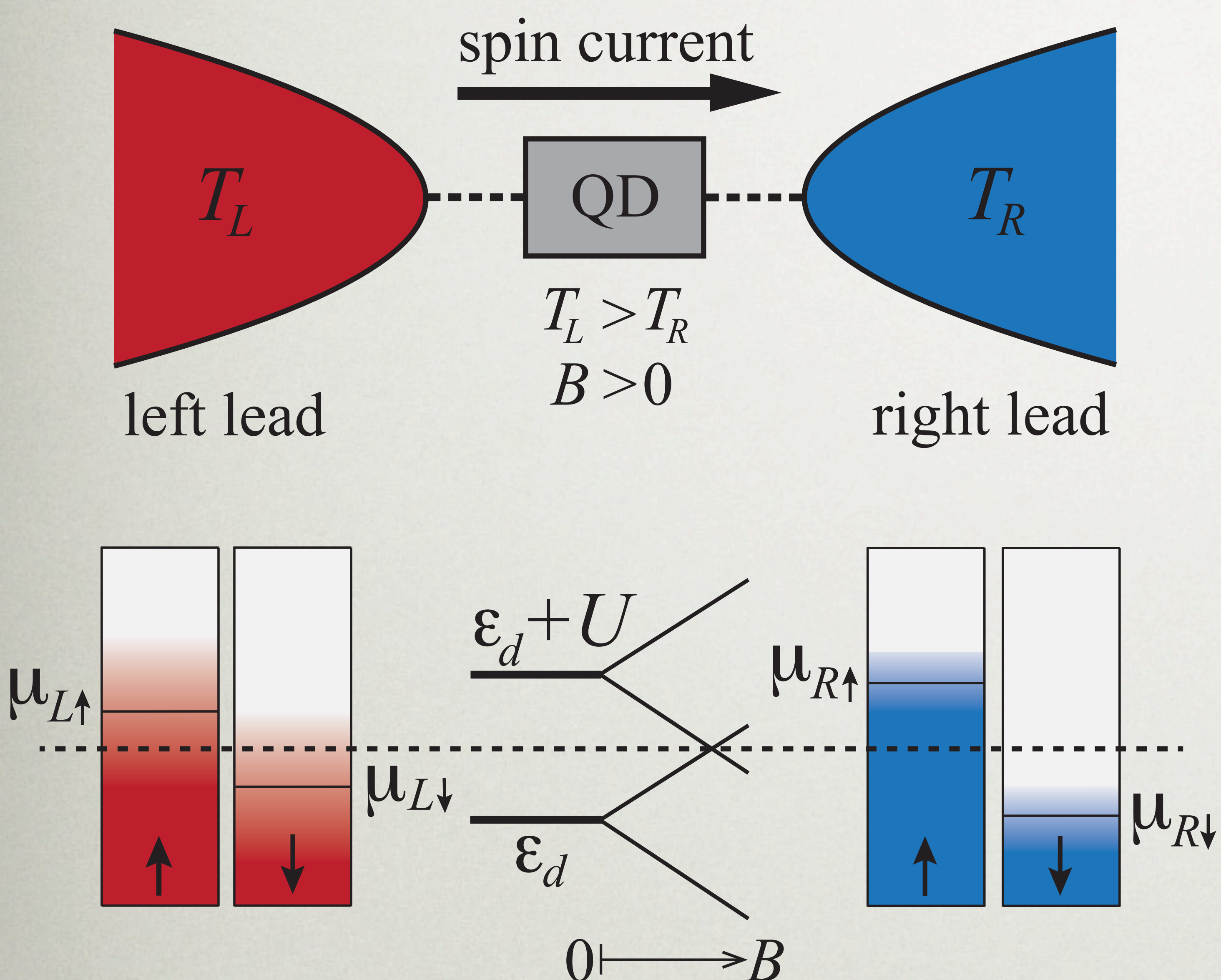
$$\mathcal{I}_{0\uparrow} = \mathcal{I}_{0\downarrow} \equiv \mathcal{I}_0$$

$$\mathcal{I}_{1\uparrow} = -\mathcal{I}_{1\downarrow} \equiv \mathcal{I}_1$$

$$I_C = \frac{2e}{h}\mathcal{I}_0 eV$$

$$I_S = \frac{2e}{h}\left(\mathcal{I}_1 \frac{\Delta T}{T} + \frac{1}{2}\mathcal{I}_0 eV_s\right)$$

(SPIN) THERMOPOWER



Spin Seebeck coefficient:

$$S_s = -\frac{V_s}{\Delta T}\Big|_{I_s=0}$$

$$S_s = \frac{2}{T}\frac{\mathcal{I}_1}{\mathcal{I}_0}$$

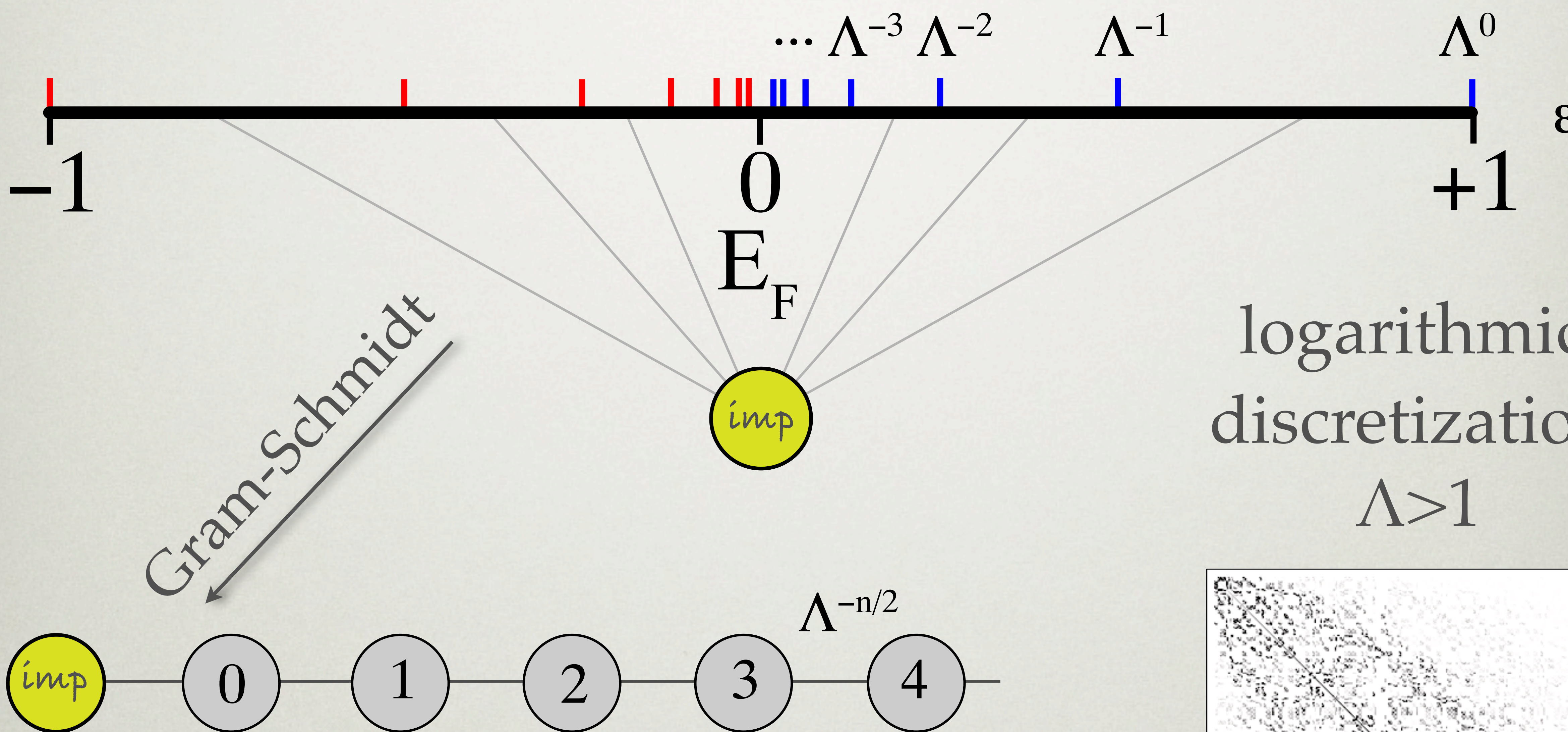
Tomaž Rejec, Rok Žitko, Jernej Mravlje, and Anton Ramšak, Phys. Rev. B 85, 085117 (2012)

T. A. Costi and V. Zlatić, Phys. Rev. B 81, 235127 (2010), S. Andergassen, T. A. Costi, V. Zlatić, Phys. Rev. B, 84:241107(R), 2011

P. S. Cornaglia, G. Usaj, and C. A. Balseiro, Phys. Rev. B 86, 041107(R) (2012)

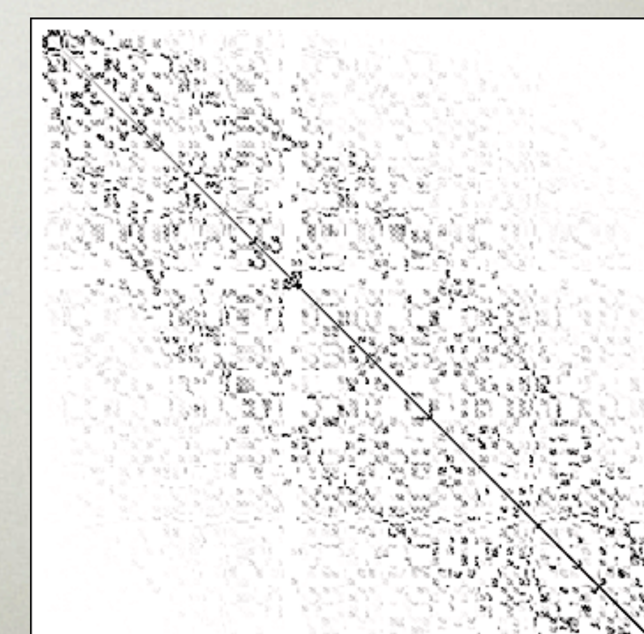
Numerical Renormalization Group

K. G. Wilson, Rev. Mod. Phys. **47**, 773 (1975)



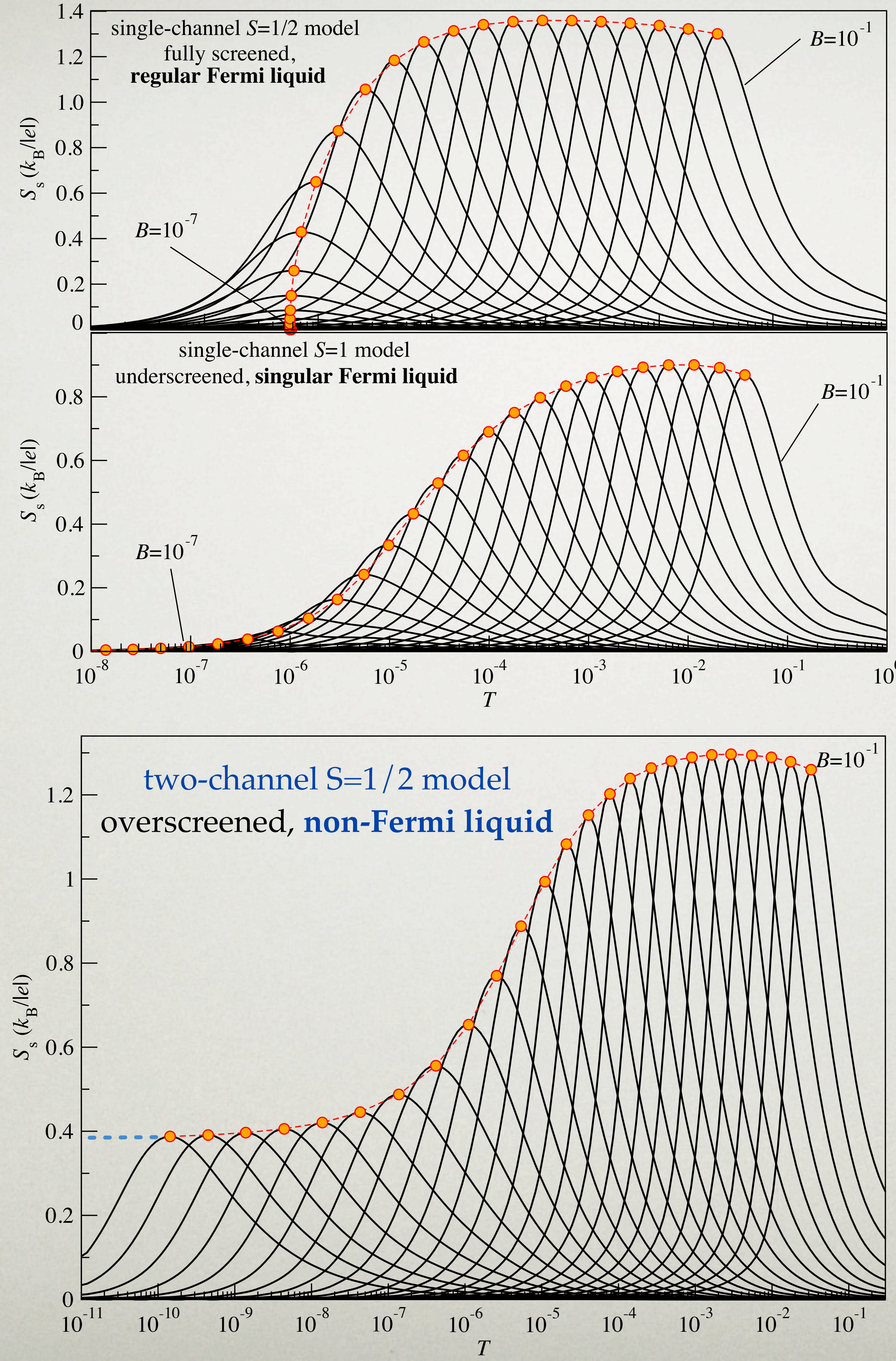
Wilson's chain

logarithmic discretization $\Lambda>1$

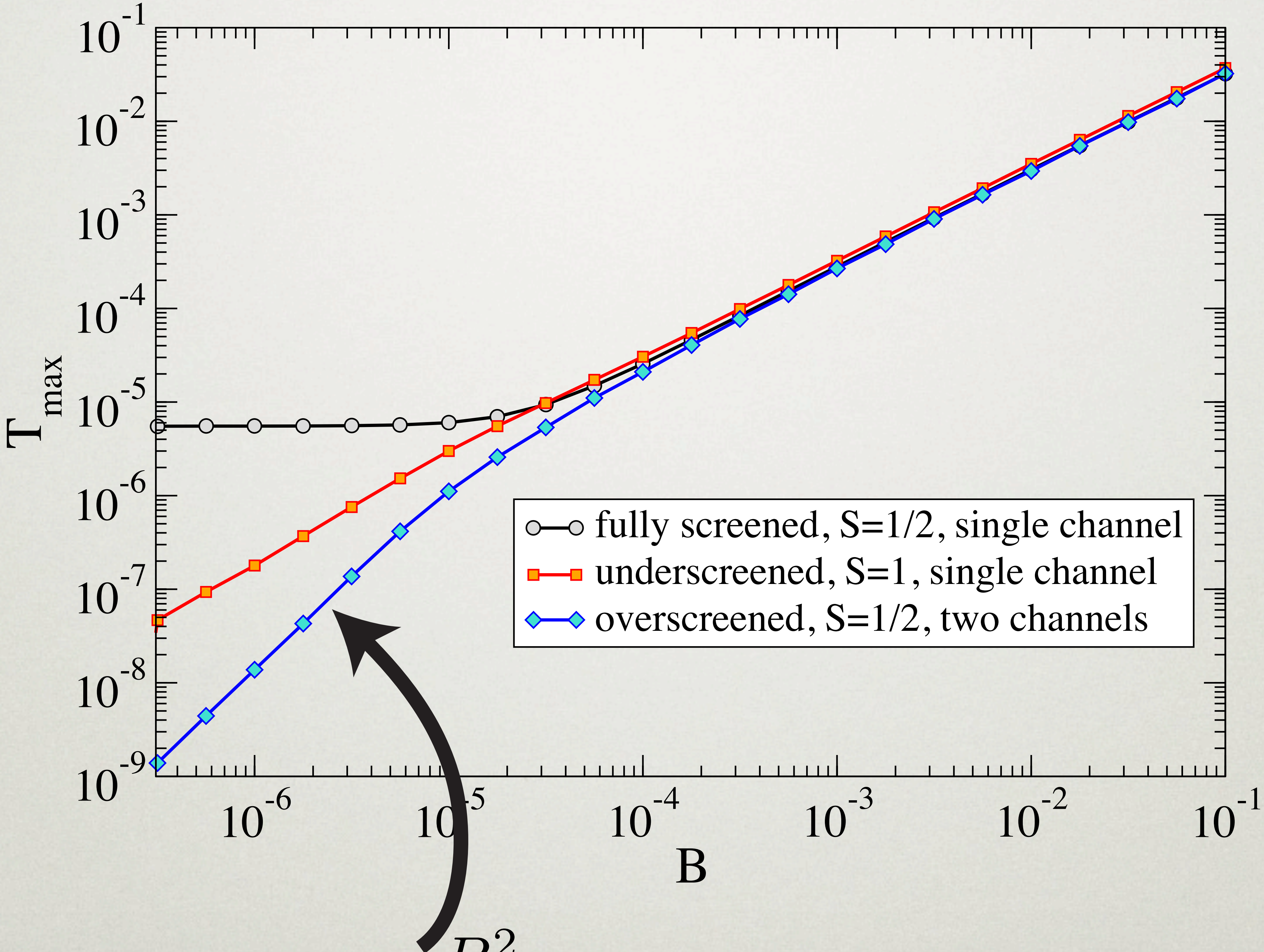


open-source code: http://nrgljubljana.ijs.si/

$T_K = 1.1\times10^{-5}\,D$



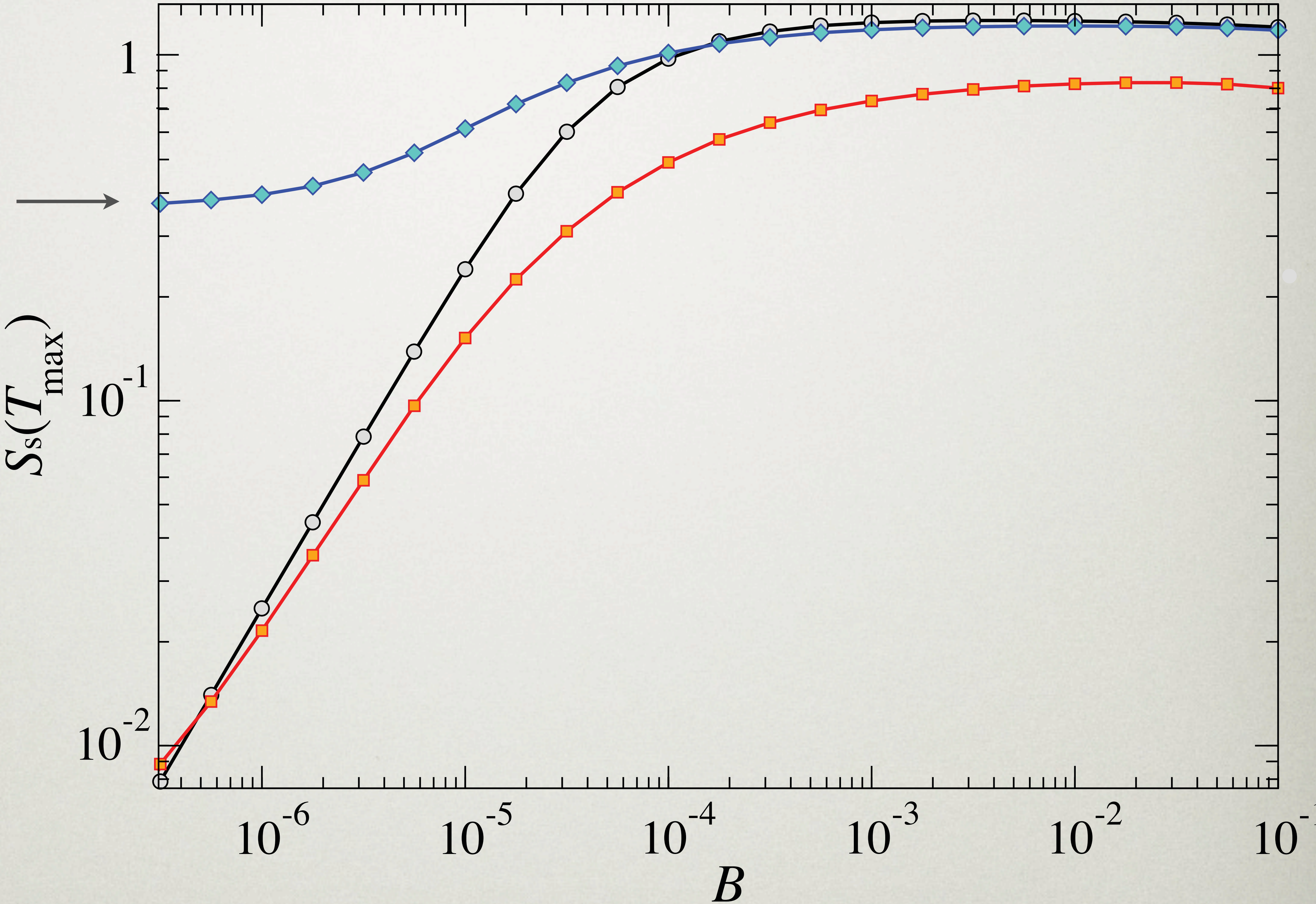
R. Žitko, J. Mravlje,
A. Ramšak, T. Rejec,
to appear in New J. Phys.

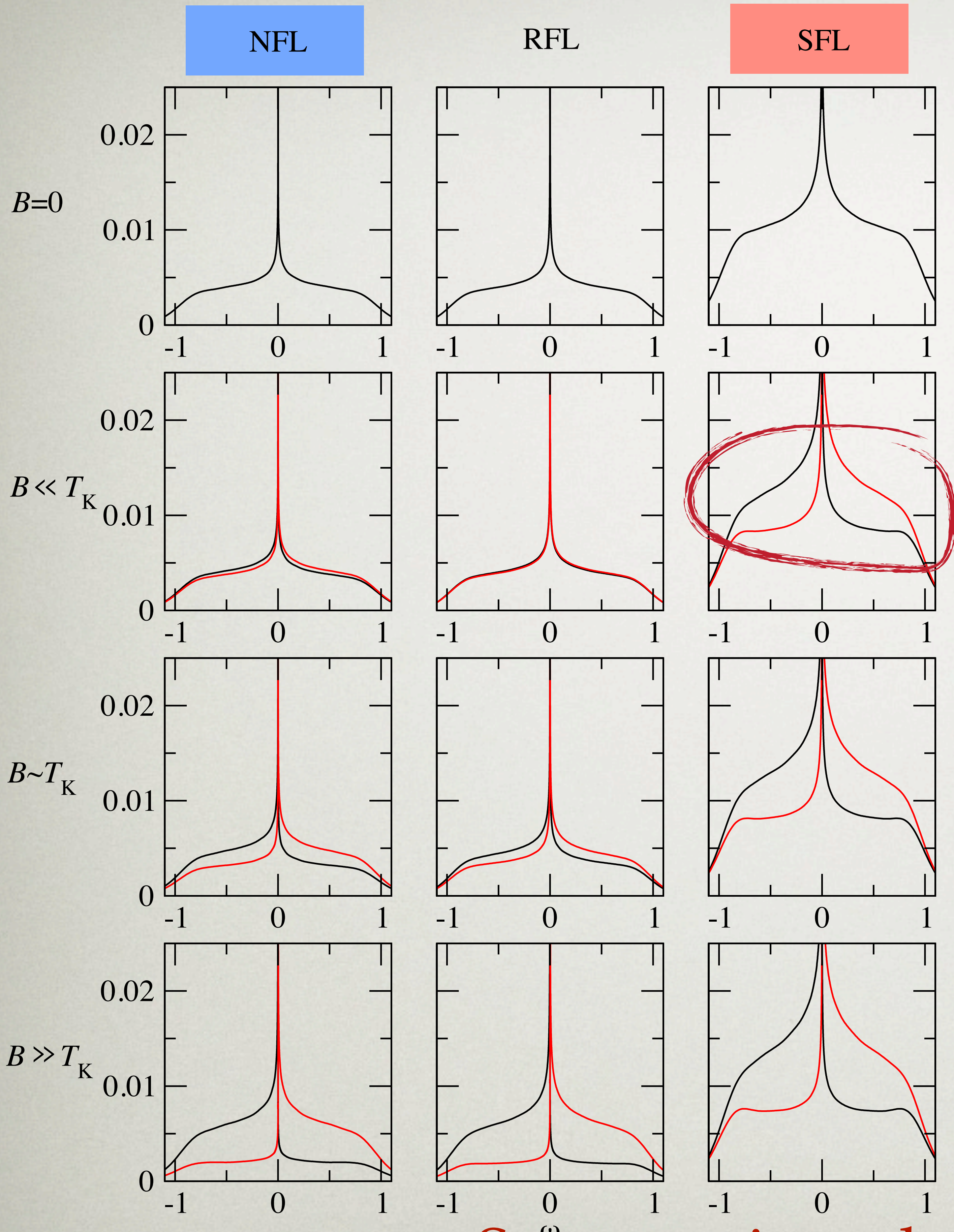


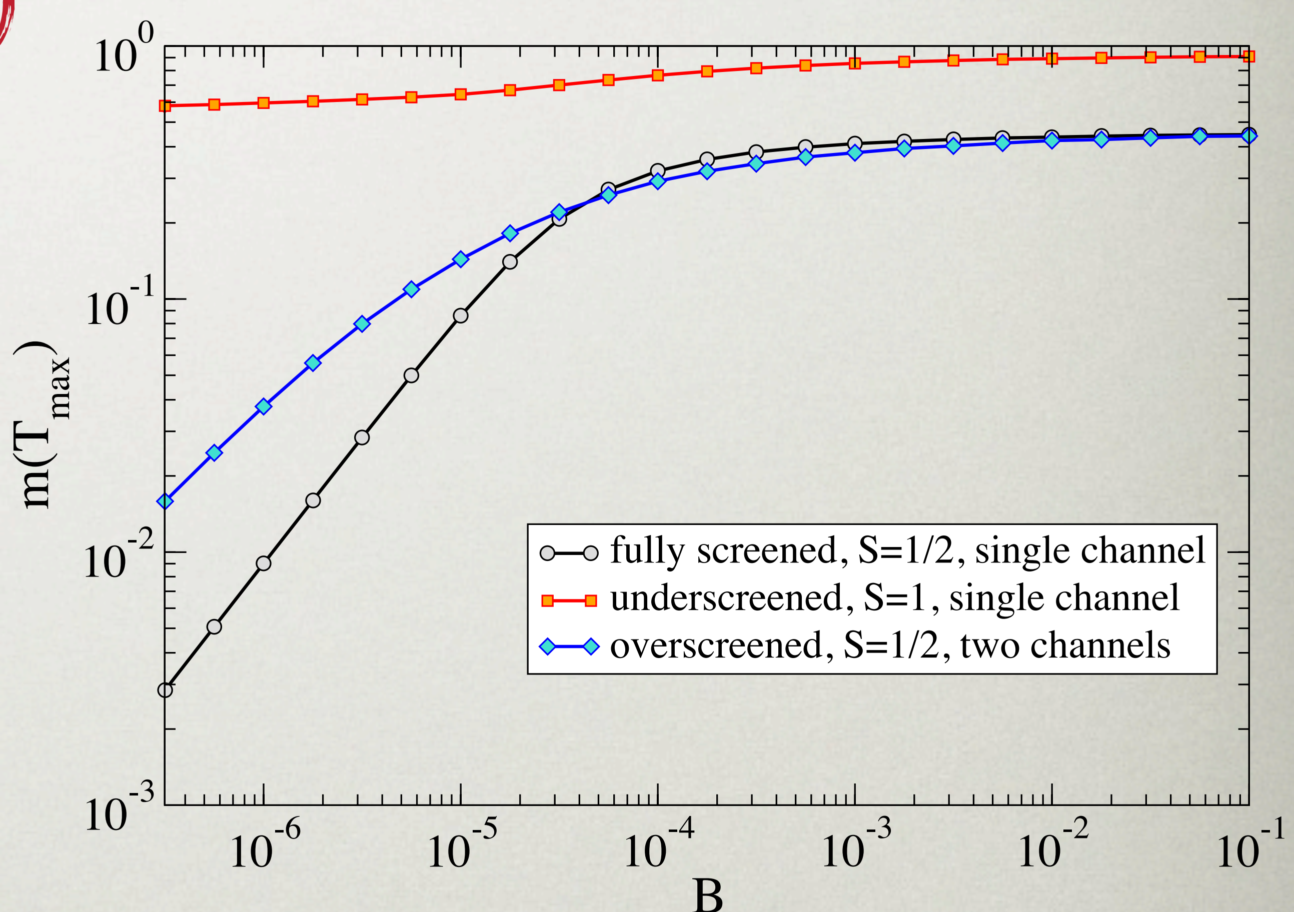
cross-over scale $T^* \sim \frac{B^2}{T_K}$

Saturation!

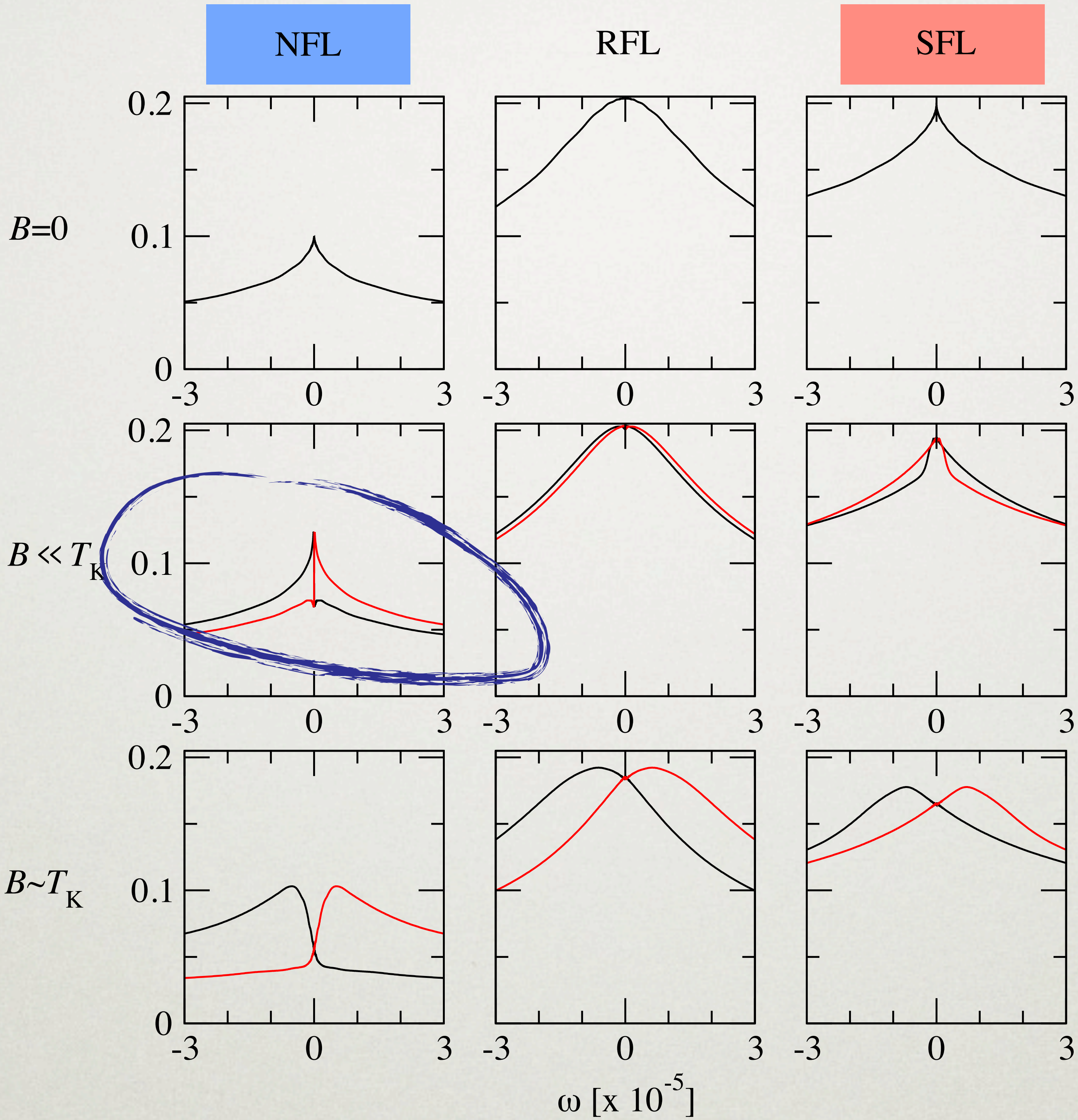
$$0.388\,\frac{k_B}{|e_0|} = 34\,\mu\mathrm{V/K}$$







Strong spin-polarization
of **high**-ω spectral function



Strong spin-polarization
of **low**-ω spectral function

$$\mathcal{T}_\sigma(\omega,T) = \frac{1}{2} + \sigma\frac{1}{\sqrt{8\pi^3}}\int_{-\infty}^{\infty} \mathrm{d}x \frac{\cos\frac{x\omega}{\pi T}}{\tanh\frac{\omega}{2T}\sinh x} \times$$

$$\times\,\mathrm{Re}\left\{\sqrt{\frac{T^*}{T}}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{2\pi}\frac{T^*}{T}\right)}{\Gamma\left(1+\frac{1}{2\pi}\frac{T^*}{T}\right)}\,{}_2F_1\left(\frac{1}{2},\frac{1}{2},1+\frac{1}{2\pi}\frac{T^*}{T},\frac{1-\coth x}{2}\right)\right\}$$

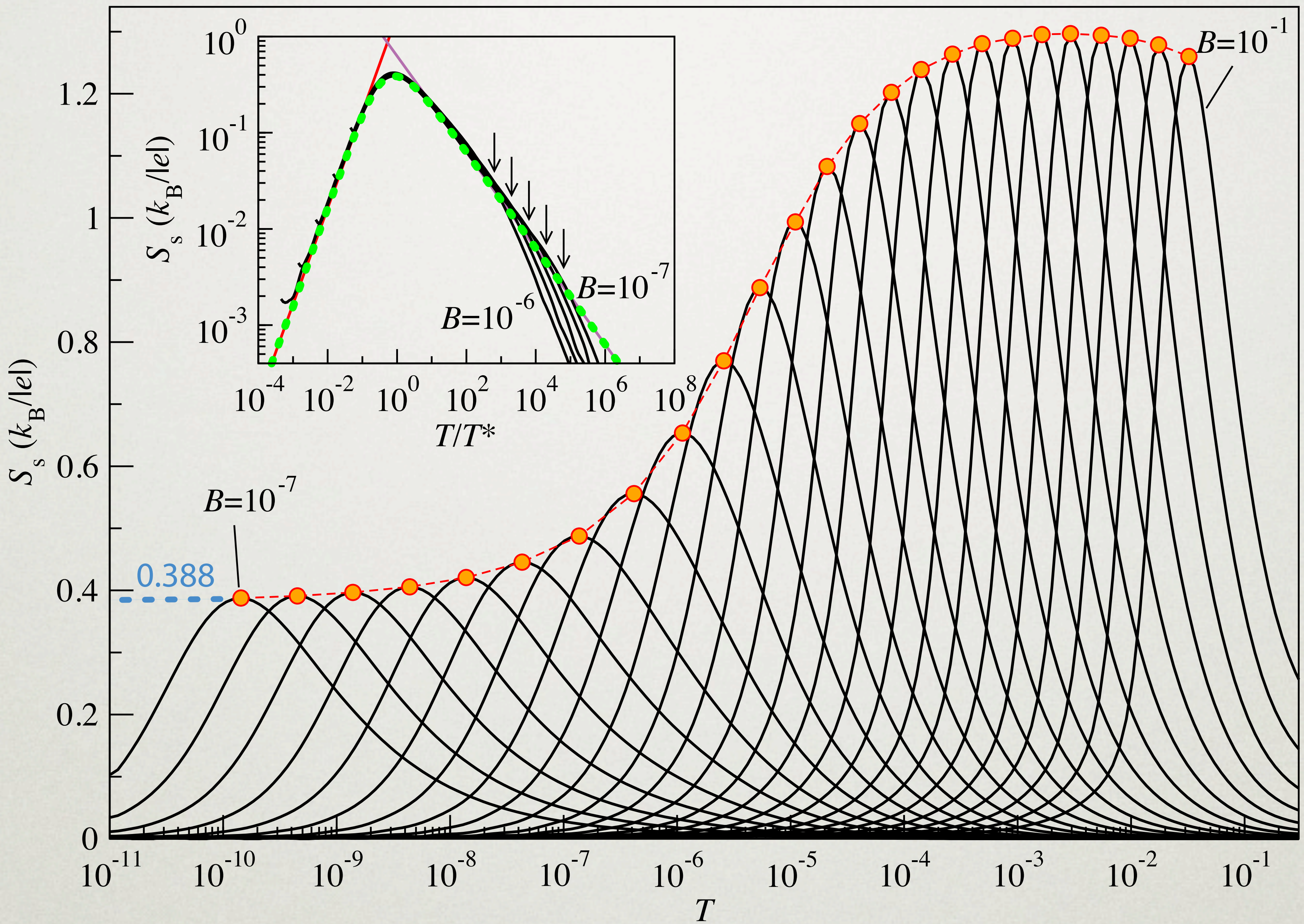
$$S_s = \frac{\sqrt{\pi}}{2\sqrt{2}}\int_{-\infty}^{\infty} \mathrm{d}x \frac{1}{\cosh^2\frac{x}{2}\sinh x} \times$$

$$\times\,\mathrm{Re}\left\{\sqrt{\frac{T^*}{T}}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{2\pi}\frac{T^*}{T}\right)}{\Gamma\left(1+\frac{1}{2\pi}\frac{T^*}{T}\right)}\,{}_2F_1\left(\frac{1}{2},\frac{1}{2},1+\frac{1}{2\pi}\frac{T^*}{T},\frac{1-\coth x}{2}\right)\right\}$$

$$S_s(T_{\max}) = 0.388 \qquad T_{\max} = 0.829T^*$$

Ian Affleck and Andreas W. W. Ludwig, Phys. Rev. B 48, 7297 (1993)

A. K. Mitchell and E. Sella, Phys. Rev. B 85, 235127 (2012)



B=10^{-1}
B=10^{-7}
0.388
S_s (k_B/|e|)
T
T/T^*
B=10^{-6}
B=10^{-7}

Conclusion

- Spin thermopower, measured as a function of B and T, would allow very clear distinction between the different types of the Kondo effect.
- SFL and NFL exhibit strong spin polarization in high and low-ω part of the spectral function, respectively.

Conductance