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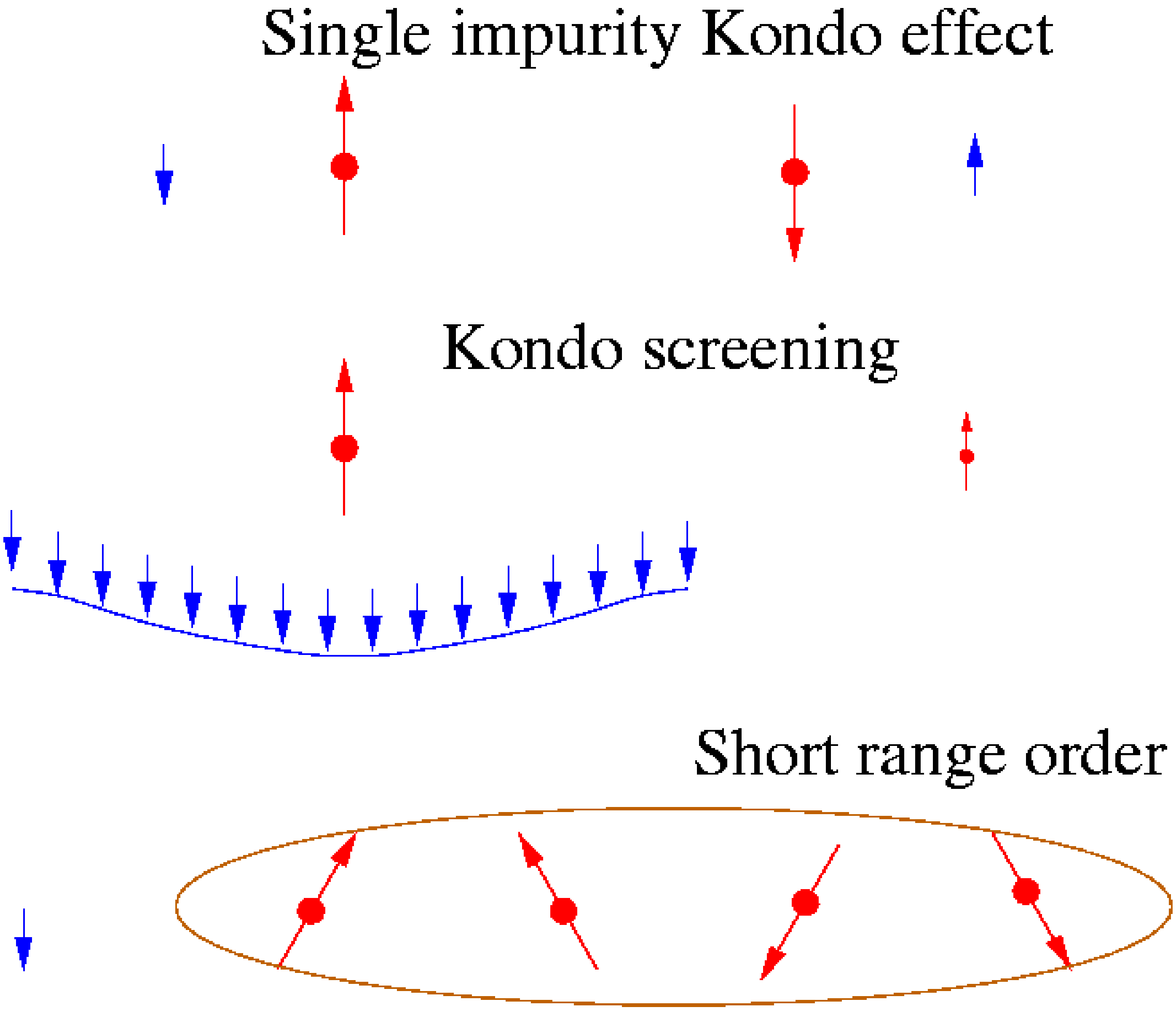
Kondo Lattice without Nozieres Exhaustion Effect

Outline

- Kondo impurity. Kondo chains and lattices
- Nozieres Exhaustion Effect in Kondo Lattices
- Hybrid Magnetic/Conducting Materials
- Conducting Layers and Spin Chains
- Random AFM quantum spin chains
- Conclusions, open questions and perspectives

Collaboration: K.Kikoin, Beer Sheva, Israel

see K.Kikon, M.N.Kiselev, cond-mat/0504339


Single impurity Kondo effect
Kondo screening
Short range order

What is Nozieres Exhaustion Effect?

Example: Strong coupling regime

$$N_{el} \gg N_{spin}$$

Singlet formation proceeds freely.
Remaining electrons provide the low temperature
Fermi Liquid.

Many times repeated Single Kondo Impurity

$$N_{el} \ll N_{spin}$$

Magnetic screening is necessarily collective effect

Ground state: mixture of N_{el} magnetically inert singlets and (N_{spins}-N_{el}) “bachelor” spins

Bachelor spins behave like fermions and form isotropic singlet liquid state

P.Nozieres,1985

Nozieres Exhaustion Effect in Kondo Lattices

$$H = \frac{J}{N_L} \sum_{i}^{N_{spins}} \sum_{k,k'} \overrightarrow{S_i} c^+ \overrightarrow{\sigma} c \exp\left[i\left(\vec{k} - \vec{k}'\right)\overrightarrow{R_i} \right]$$

$$T_K \ll E_F$$

"weak coupling"

However, only electrons with energy ~ T_K provide Kondo screening

Measure of "exhaustion" $$p_N = \frac{N_{spins}}{\rho T_K}$$ $$T_K = E_F \exp\left[-\frac{1}{\rho J} \right]$$

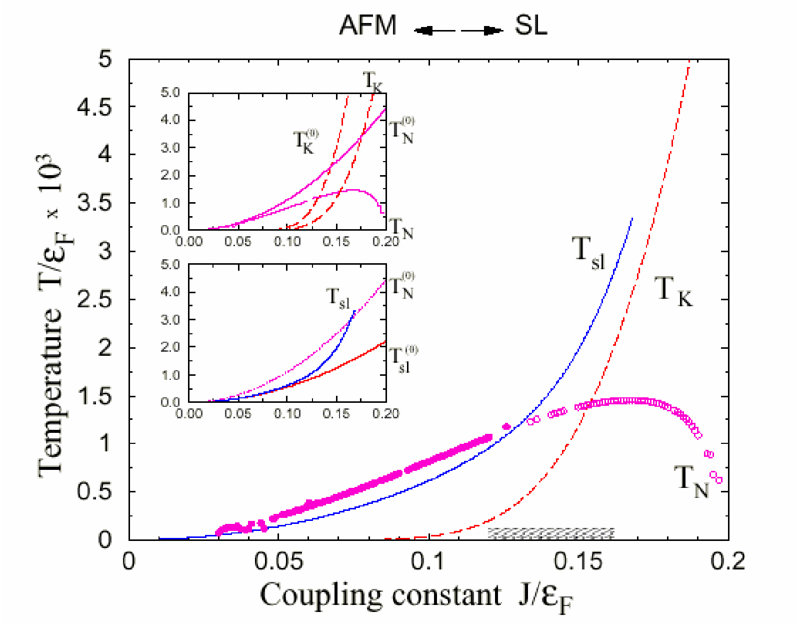
Exhaustion appears if $$1 \ll p_N \ll \left(\frac{E_F}{J}\right)^2$$ $$J_{RKKY} < T_K$$

Magnetic order wins if $$p_N \gg \left[\frac{E_F}{J}\right]^2$$ $$J_{RKKY} > T_K$$

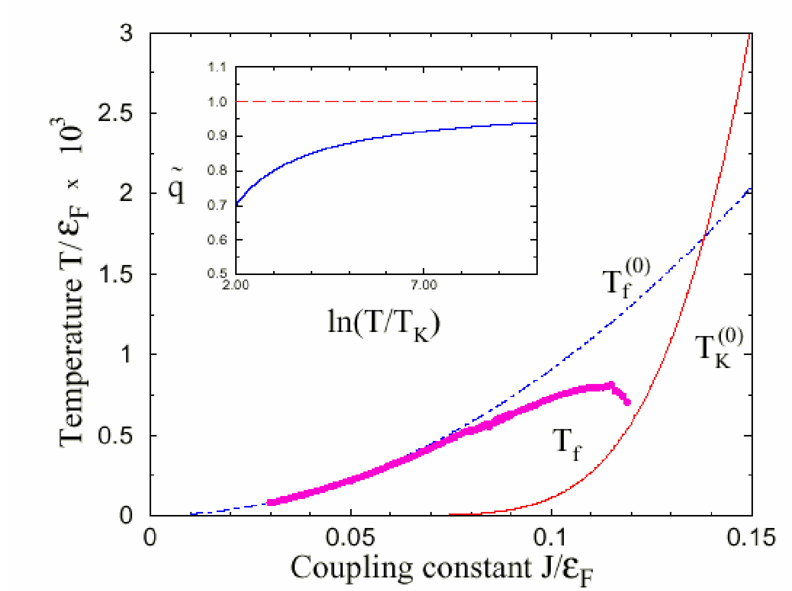
Doniach’s Diagram

Competition between magnetic order and Kondo effect

Antiferromagnet



Spin Glass



S.Doniach, 1977

MNK, K.Kikoin, R.Oppermann, 2002

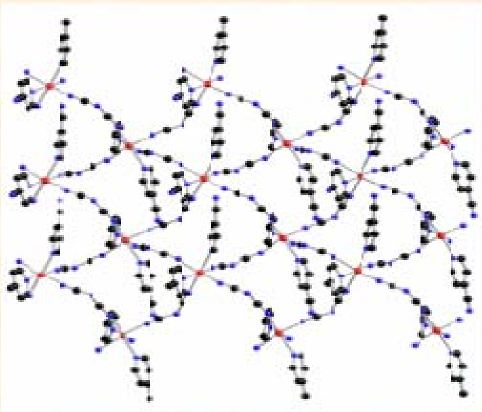
How to avoid Nozieres exhaustion effect?

How to kill magnetic (spin glass) transition?

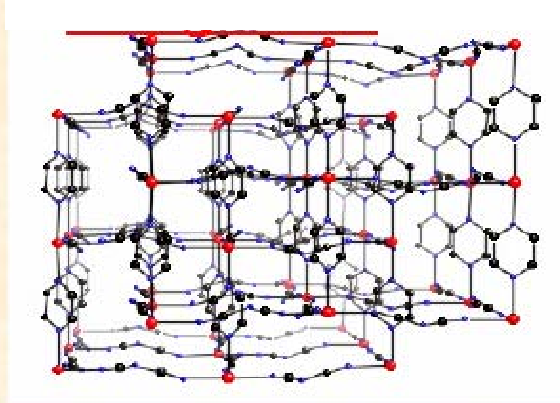
Idea: Hybrid Conducting/Magnetic compounds with spatially separated charges + spins (planes) and spin (chains)

- **different "capacities" of spin and charge reservoirs**
- **no long range order in 1D spin subsystem**

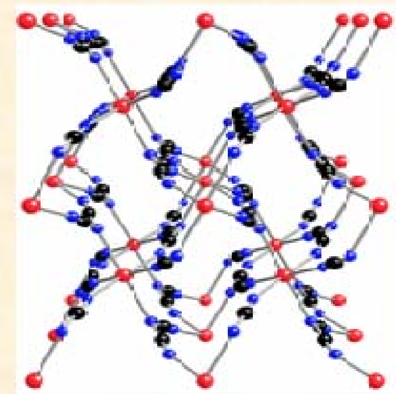
Polymeric Magnets



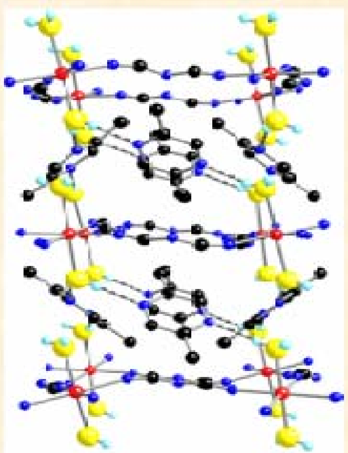
$Mn[N(CN)_2]_2(4\text{-}CNpy)_2$

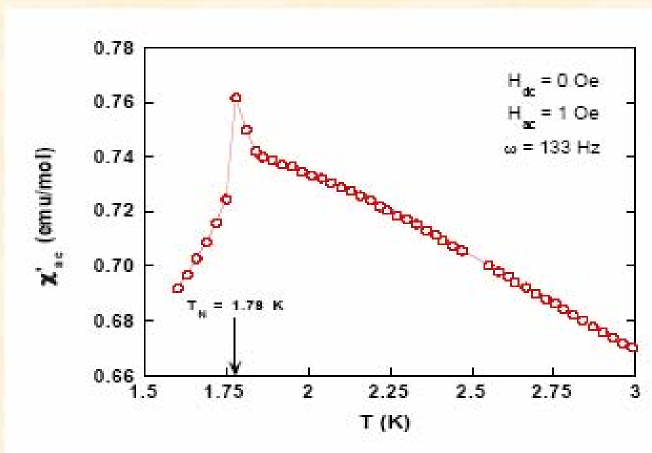


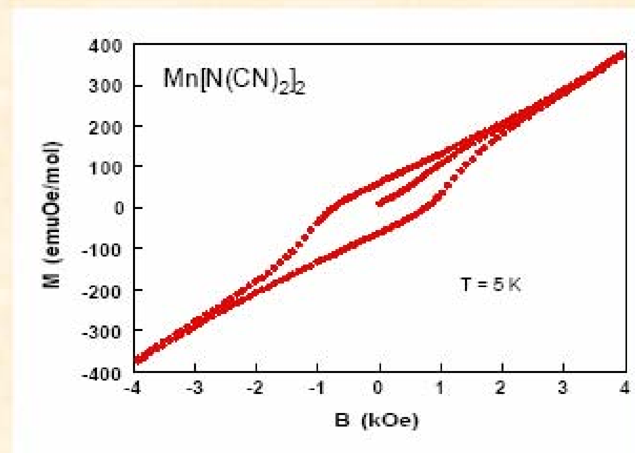
$Mn[N(CN)_2]_2(pyz)$



$Mn[N(CN)_2]_2$



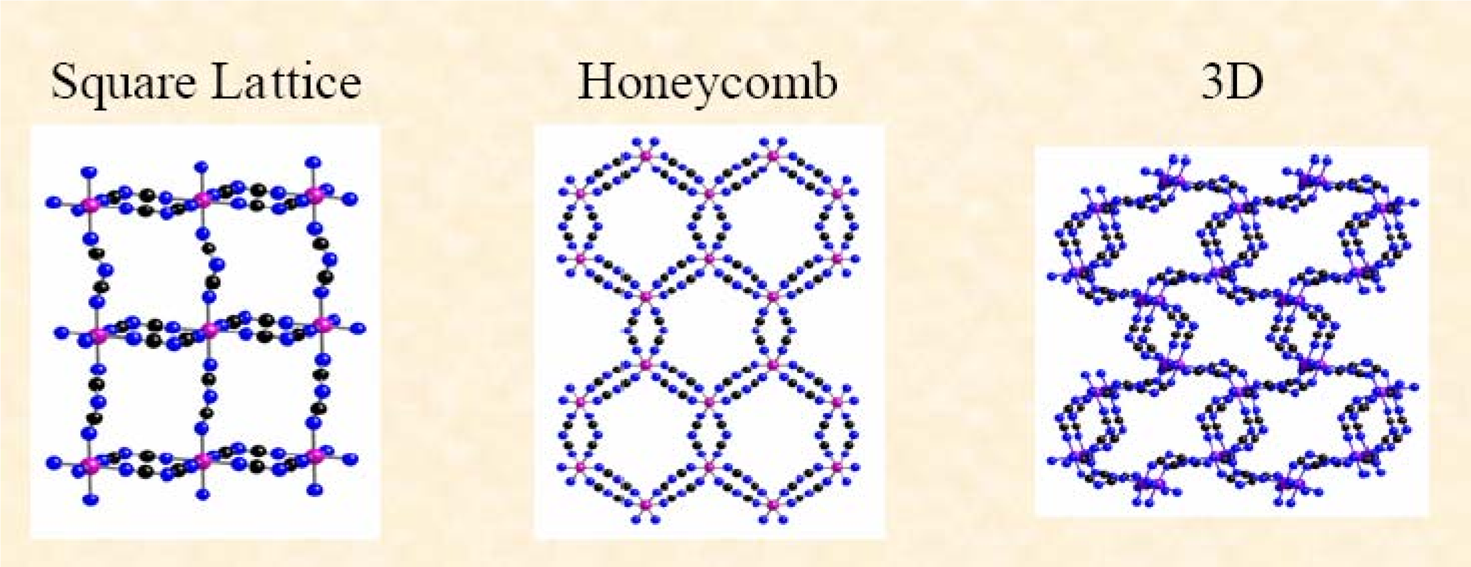




$Mn[N(CN)_2]_2(2,5\text{-}dimepyz)_2(H_2O)_2$

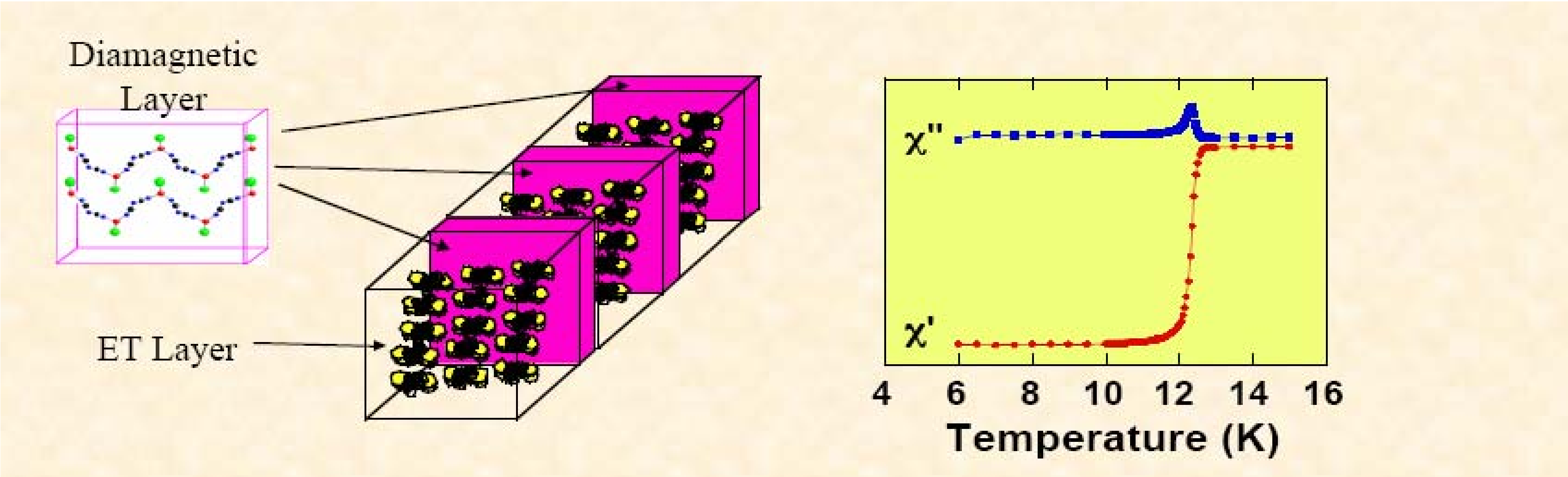
J.A.Schlueter et al, 2004

Anionic Molecular Building Blocks



J.A.Schlueter et al, 2004

Molecular Superconductors

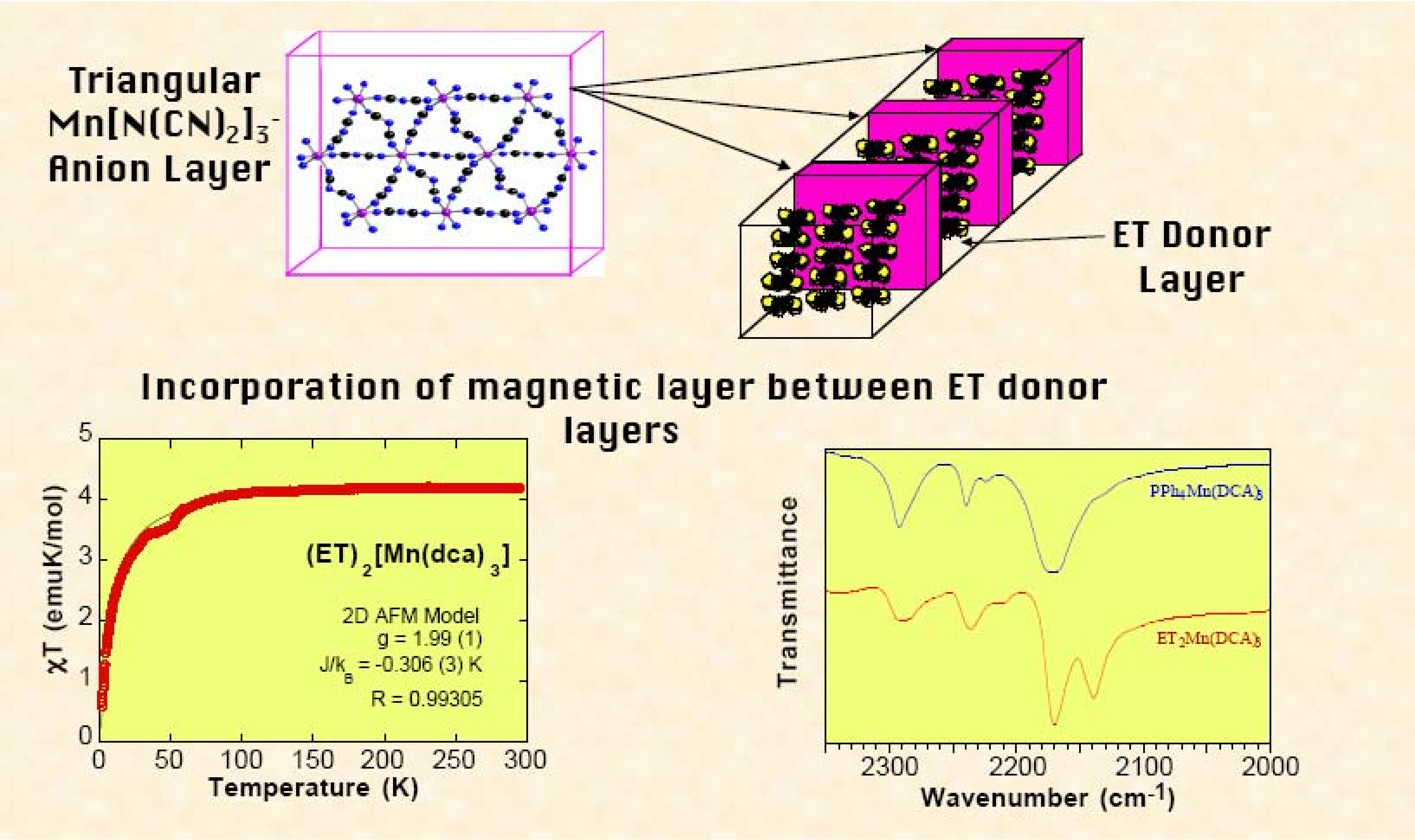


ET=BEDT-TTF

Bis(EthyleneDiThio) TetraThiaFulvalene

J.A.Schlueter et al, 2004

Conducting/Magnetic Hybrid Molecular Solids

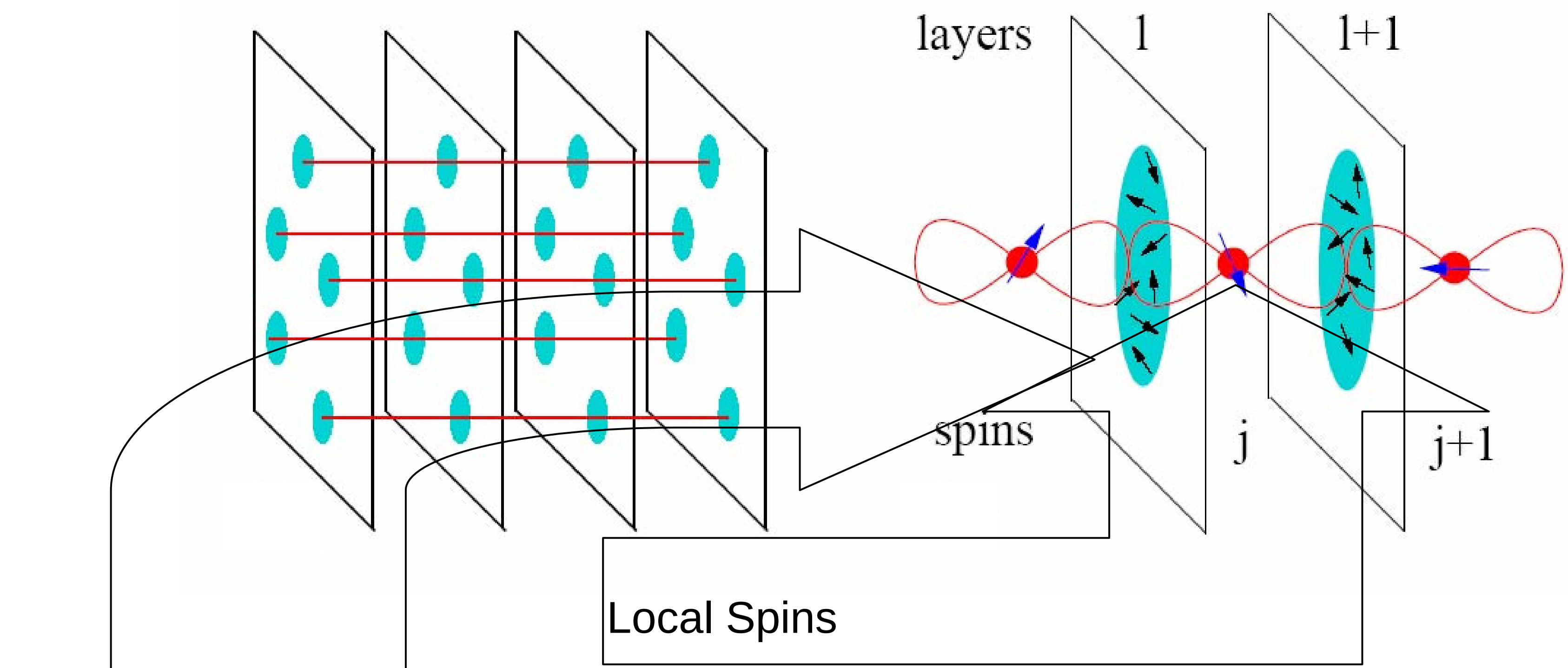


J.A.Schlueter et al, 2004

Possible Compositions of Future Hybrid Materials

Layer 1	Layer 2	Material Properties
Conducting	Non-magnetic, closed shell Fixed valent	2D conductor, Superconductor
Conducting	Open shell, Mixed valent	High T_c superconductors
Conducting	Magnetic	Coupling of electronic and spin lattices: CMR, Spintronics
Conducting	Extended π-systems and dyes	Electron-exciton interactions: Photomodulation of electronic properties
Magnetic	Photochromic	Photomodulation of hysteresis loop.

Model

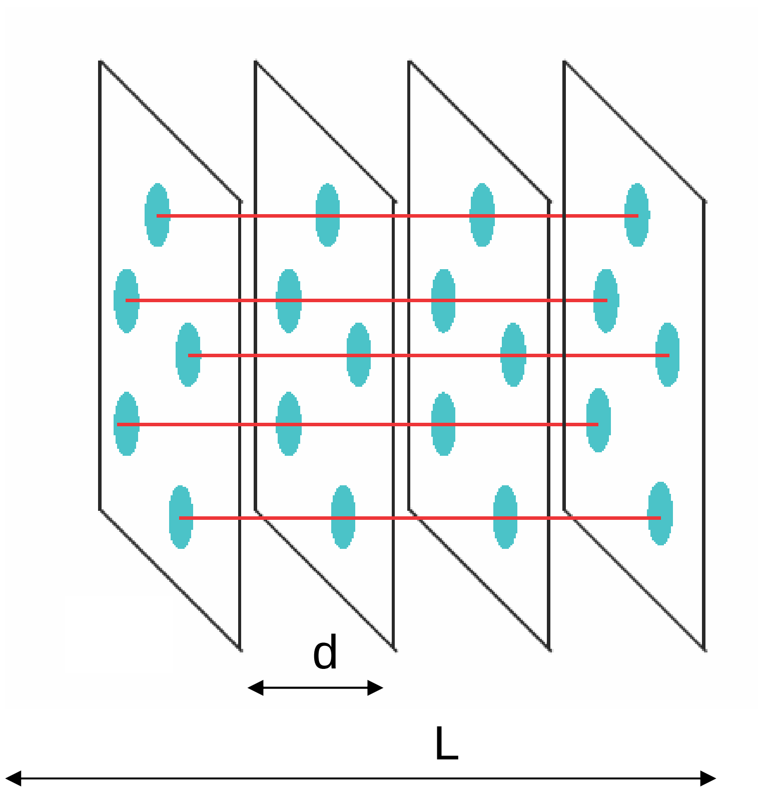


$$H = \sum_{l\mathbf{k}\sigma} \epsilon_k c^{\dagger}_{l\mathbf{k}\sigma} c_{l\mathbf{k}\sigma} + \sum_{j\sigma} \left(\epsilon_d n^d_{j\sigma} + \frac{1}{2} U n^d_{j\sigma} n^d_{j\bar{\sigma}} \right) + \sum_{jl} \sum_{\mathbf{k}\sigma} V_{\mathbf{k}} \left(c^{\dagger}_{l\mathbf{k}\sigma} (d_{j\sigma} + d_{j+1,\sigma}) + h.c \right)$$

Conduction electrons

Interaction

How does Nozieres Exhaustion Principle work?



L/d 2D Fermi reservoirs

$$N_{el} \sim \left(\frac{L}{a_{\parallel}}\right)^2$$ electrons in each layer

$$N_{spins} \sim \left(\frac{L}{d}\right)$$ spins in each chain

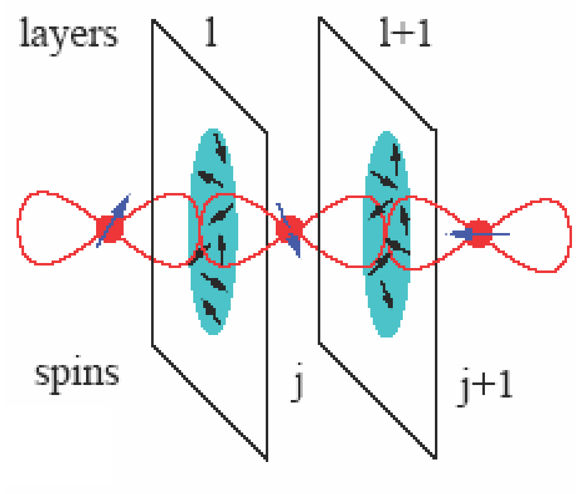
$$p_N \sim N_{chains} \frac{a_{\parallel}^2}{dL} \ll 1$$

Dilute limit. No interaction between chains.

$$p_N \ll 1$$

No exhaustion problem even in strong coupling limit!

Effective Model



$$H = H_0 + H^{cd}_{int} + H^{dd}_{int}$$

$$H^{cd}_{int} = \sum_{j=1,k,k'}^{N_i} J_{\mathbf{k}\mathbf{k}'} \vec{s}^{\,l,l'}_{\mathbf{k}\mathbf{k}'} \left(\vec{S}_j + \vec{S}_{j+1}\right)$$

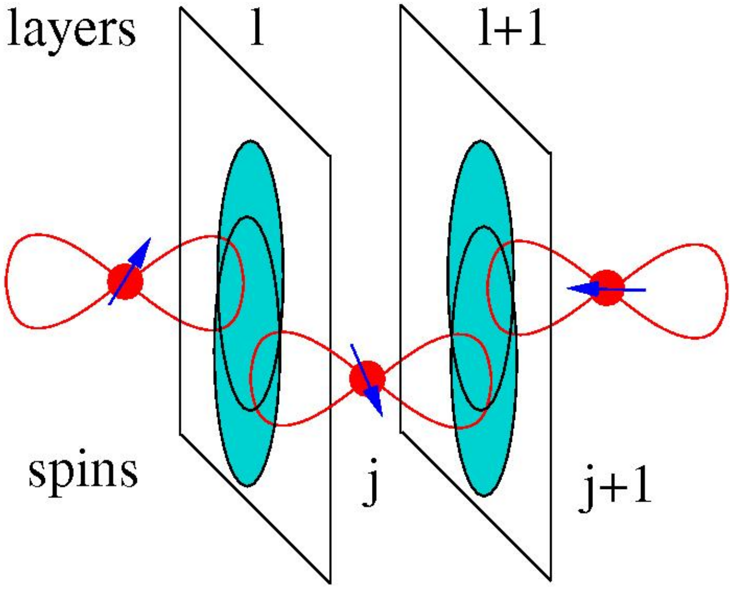
$$\vec{s}^{\,ll'}_{\mathbf{k}\mathbf{k}'} = \frac{1}{2} c^{\dagger}_{l,\mathbf{k}\sigma} \vec{\sigma}_{\sigma\sigma'} c_{l',\mathbf{k}'\sigma'}$$

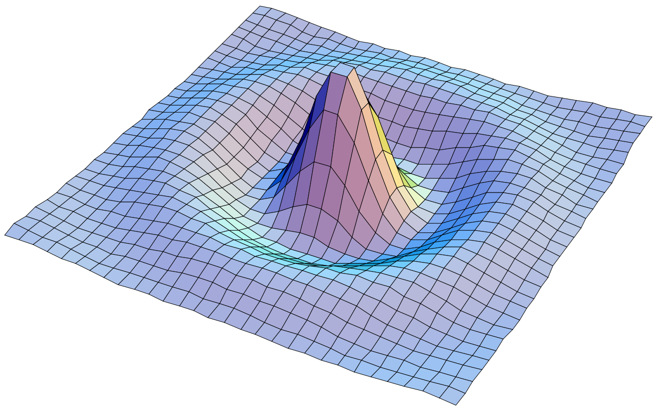
$$\vec{S}_j = \frac{1}{2} d^{\dagger}_{j,\sigma} \vec{\sigma}_{\sigma\sigma'} d_{j\sigma'}$$

$$H^{dd}_{int} = -I \sum_{j,\sigma\sigma'} d^{\dagger}_{j\sigma} d_{j+1,\sigma} d^{\dagger}_{j+1,\sigma'} d_{j\sigma'}$$

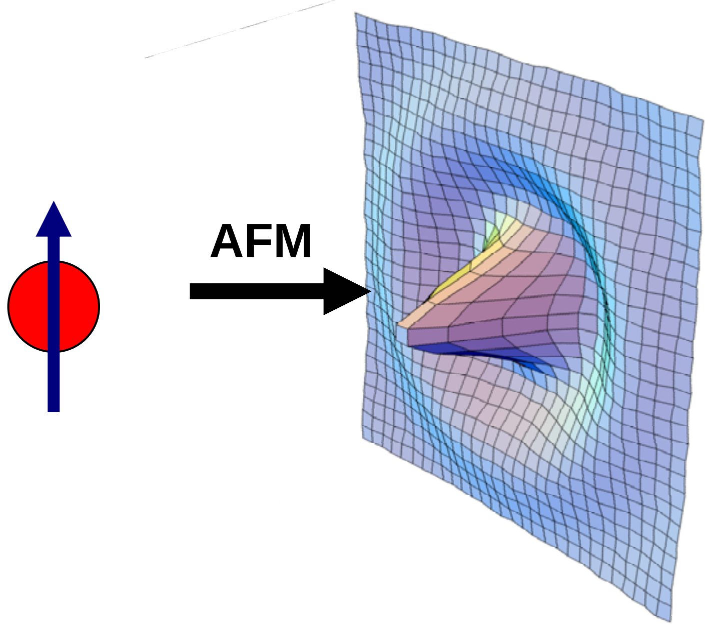
Kondo clouds (shadows) are formed in conducting planes

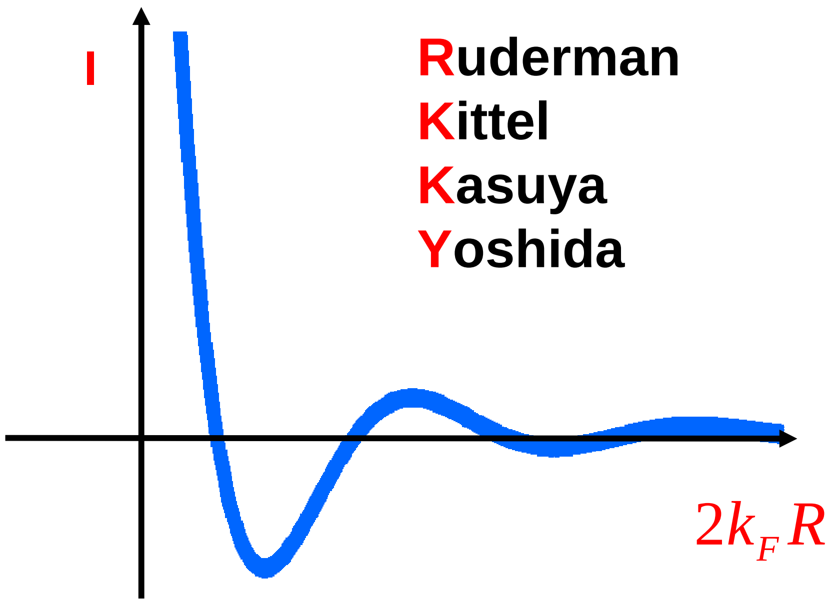
Effective interaction





RKKY interaction

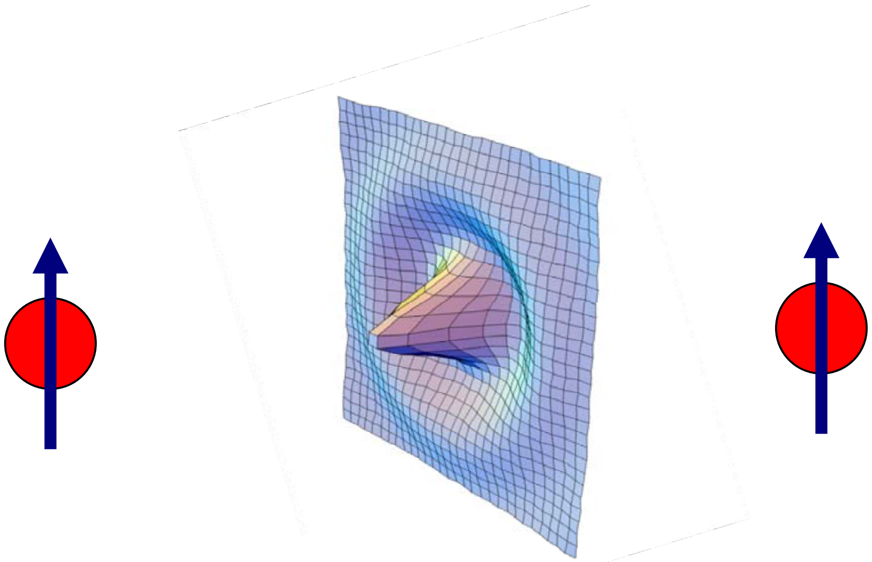




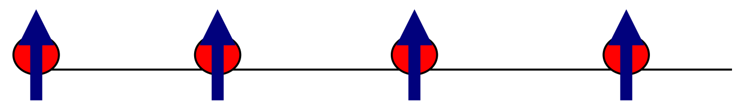
Ruderman
Kittel
Kasuya
Yoshida

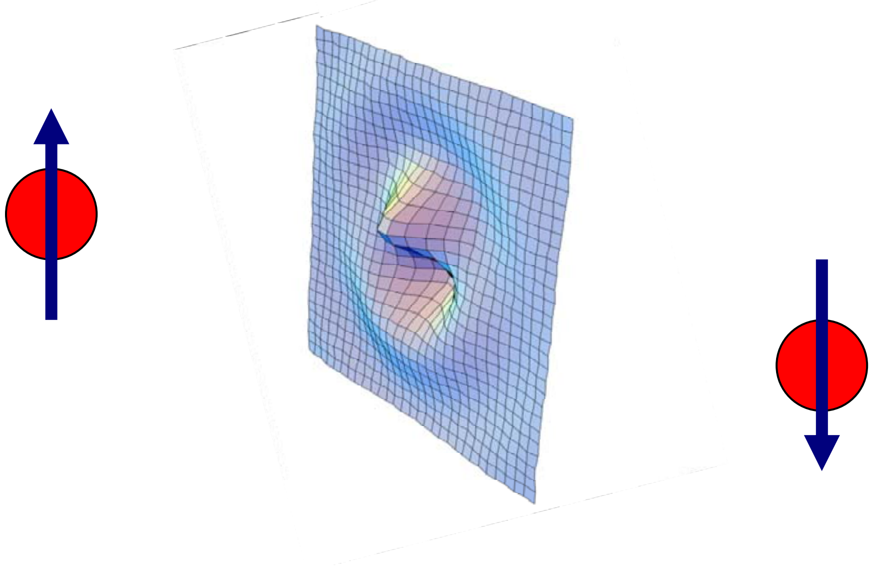
$$I_{ij} = I^{RKKY} = -\left(\frac{J^2}{\varepsilon_F}\right)\frac{\sin\left[2k_F R_{ij}\right]}{(2k_F R_{ij})^2}$$

Ferro or Antiferro?

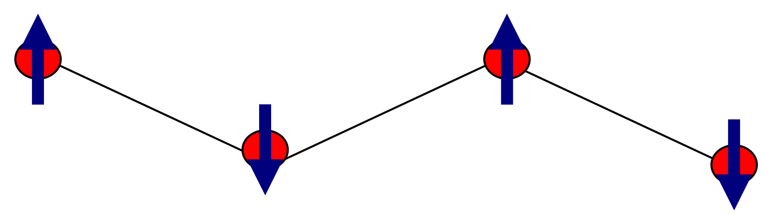


Ferromagnetic exchange





Antiferromagnetic exchange



Effective Model

Local Spins

$$H = \boxed{\sum_{l\mathbf{k}\sigma} \epsilon_k c^\dagger_{l\mathbf{k}\sigma} c_{l\mathbf{k}\sigma}} + \boxed{\sum_{j\sigma} \left(\epsilon_d n^d_{j\sigma} + \frac{1}{2} U n^d_{j\sigma} n^d_{j\bar{\sigma}} \right)} + \boxed{\sum_{jl} \sum_{\mathbf{k}\sigma} V_{\mathbf{k}} \left(c^\dagger_{l\mathbf{k}\sigma} (d_{j\sigma} + d_{j+1,\sigma}) + h.c \right)}$$

Conduction electrons

Interaction

$$H = H_0 + H^{cd}_{int} + H^{dd}_{int}$$

$$H^{cd}_{int} = \sum_{j=1,k,k'}^{N_i} J_{\mathbf{k}\mathbf{k}'} \vec{s}^{\,ll'}_{\mathbf{k}\mathbf{k}'} \left(\vec{S}_j + \vec{S}_{j+1} \right)$$

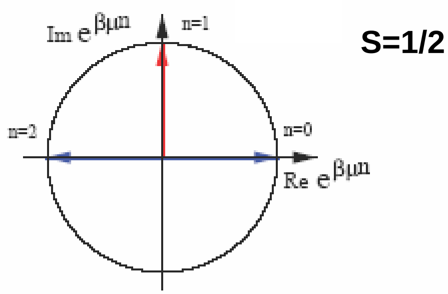
$$J \sim V^*_{\mathbf{k}} V_{\mathbf{k}} / U$$

$$H^{dd}_{int} = -I \sum_{j,\sigma\sigma'} d^\dagger_{j\sigma} d_{j+1,\sigma} d^\dagger_{j+1,\sigma'} d_{j\sigma'}$$

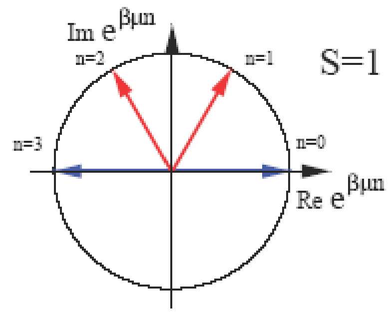
$$I \sim J^2 / \epsilon_F$$

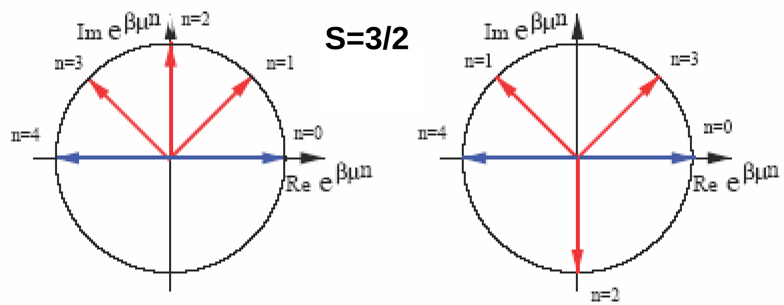
Semi-fermionic spin representation

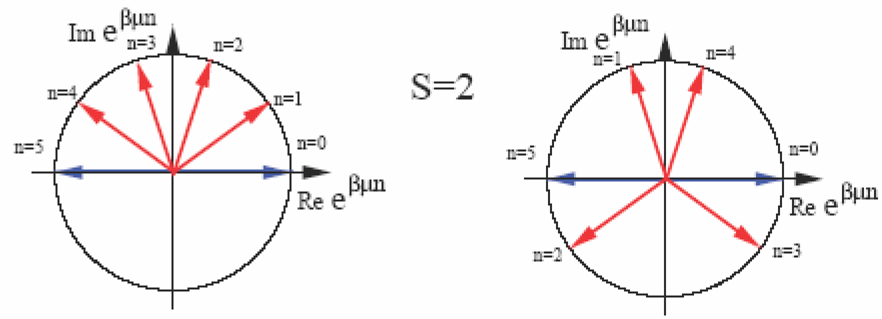
$$\vec{S} = s \cdot d_{\alpha}^{+} \vec{\sigma}_{\alpha\beta} d_{\beta}$$



$$\mu = -i \frac{\pi T}{2S+1}$$







$$\omega = 2\pi T\left(n + 1/4\right) \qquad \omega = 2\pi T\left(n + 1/3\right)$$

$$Z_S = Tr\left[\exp\left(-\beta H_S\right)\right] = A\,Tr\left[\exp\left(-\beta H_F + \beta\mu N_F\right)\right]$$

No local constraint problem

V.N.Popov, S.A.Fedotov, 1988 MNK, R.Oppermann, 2000 MNK, 2002

Effective field theory

$$\mathcal{A} = \int_0^\beta d\tau \left[\sum_j \left(\bar{c}\mathcal{G}_0^{-1}c + \bar{d}\mathcal{D}_0^{-1}d\right) - H_{int}^{cd} - H_{int}^{dd}\right]$$

Decoupling fields:

RVB Luttinger Spin Liquid

$$\Delta_{j,j\pm 1} \to \sum_\sigma \left(d_{j\sigma}^\dagger d_{l\pm 1,\sigma} + c.c\right),$$

Kondo

$$\phi_l \to \sum_{\mathbf{k}\sigma}\left(c_{l-1,\mathbf{k}\sigma}^\dagger (d_{j,\sigma} + d_{j+1,\sigma}) + c.c\right)$$

Green's Functions

Conduction electrons

$$\mathcal{G}_0^{-1} = \partial_\tau - \epsilon(-i\nabla) + \mu$$

Spinons

$$\mathcal{D}_{loc}^{-1} = \partial_\tau - i\pi T/2 \longrightarrow \partial_\tau - \Delta_{j,j\pm 1} - i\pi T/2$$

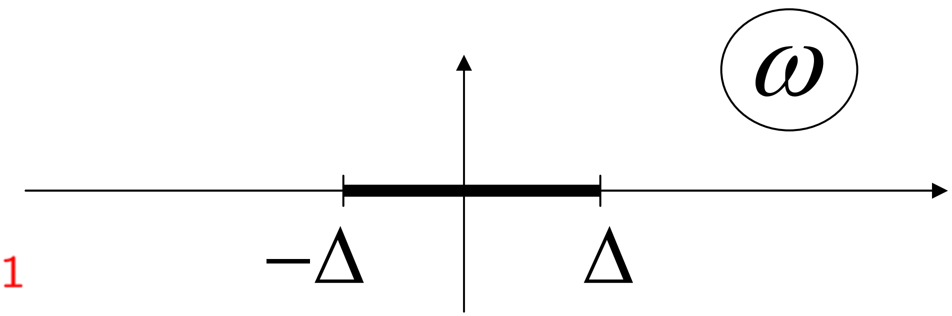
Local Non-local

RVB

$$\bar{\Delta}^2(\beta) = \beta^{-1}\int_0^\beta \Delta(\tau)\Delta(-\tau)d\tau$$

Spinon Green's Function

$$\mathcal{D}^0_{j,j+r}(\omega_n) = \frac{\exp\left(-|r|\left[\ln\left(\frac{\omega_n - \sqrt{\omega_n^2+\bar{\Delta}^2}}{\bar{\Delta}}\right)+i\frac{\pi}{2}\right]\right)}{i\sqrt{\omega_n^2+\bar{\Delta}^2}}.$$



Asymptotic behavior

$$\mathcal{D}^0_{j,j+r}(\omega_n) \sim -\bar{\Delta}^{|r|}/(-i\omega_n)^{|r|+1}$$

Local spinon correlations

$$\mathcal{D}^0_{j,j}(\omega_n) = -i/\sqrt{\omega_n^2+\bar{\Delta}^2}$$

Nearest neighbors

$$\mathcal{D}^0_{j,j\pm 1}(\omega_n) = (\omega_n/\sqrt{\omega_n^2+\bar{\Delta}^2} - 1)/\bar{\Delta}$$

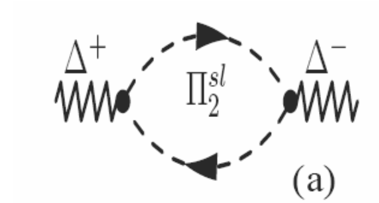
At high temperatures **only local** spinon correlations play role

Non-local effective action

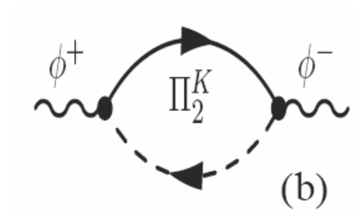
$$\mathcal{A}_{eff} = \sum_{\langle jj' \rangle \omega_n} \left[\frac{|\Delta_{jj'}(\omega_n)|^2}{I} - \Pi_2^{sl} |\Delta_{jj'}(\omega_n) - \bar{\Delta}|^2 \right]$$

$$+ \sum_{jj'l,\omega_n} \left(\frac{1}{\tilde{J}_{jl}} - \Pi_2^K + \Pi_4^K |\Delta_{jj'}(\omega_n)|^2 \right) |\phi_{lj}(\omega_n)|^2$$

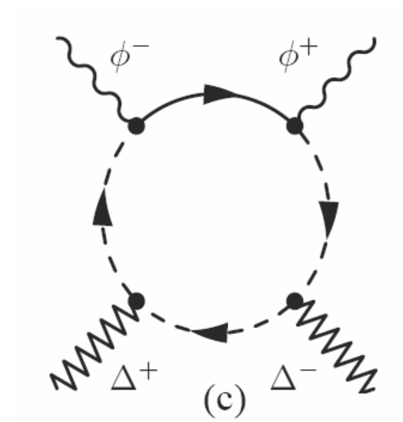
$$+ Tr \log(\mathcal{G}_0^{-1}) + Tr \log[(\mathcal{D}^0)^{-1}] + O(|\phi|^4)$$



Δ **spin liquid**



φ **Kondo clouds**



Kondo-spinon correlations

- If there is a complete screening of spins by Kondo Shadows?
- How is Fermi velocity of spinons renormalized by Kondo effect
- How are Kondo correlations renormalized by spinons

K.Kikoin, MNK, 2005

1D Isotropic Heisenberg - Kondo Chain

Susceptibility

$$\chi(T) = \frac{4\mu_B^2}{\pi^2}\left(1 + \frac{1}{2\ln(T_0/T)}\right)$$

$T_0 \gg T_K$ **even in "critical" Doniach's region!**

Spins form the Spin Liquid at $T < T_0 \sim \overline{\Delta}$

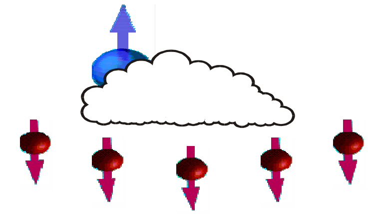
Kondo renormalization stops at T_0 $\Pi_2^K \sim \rho \ln(\bar{\Delta}/T_K)$

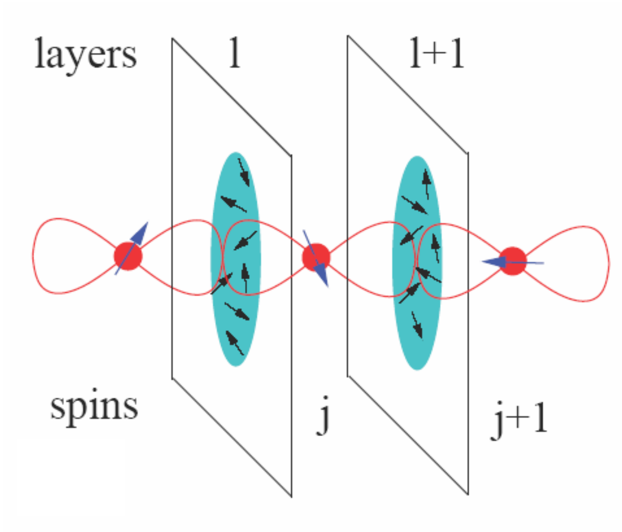
Fermi velocity of spinons $\hbar v_F = I[1 + I/\bar{\Delta}\ln(\bar{\Delta}/T_K)]^{-1}$

Reduction of the Fermi velocity is due to partial Kondo screening

S.Eggert, I.Affleck, M.Takahashi, 1994

Kondo Shadows in conducting planes





$$\langle \phi^{+}\phi^{-}\rangle_{\omega\to 0} = [-i\omega/\Gamma + \alpha q^2 + \ln(\bar{\Delta}/T_K)]^{-1}$$

relaxation mode

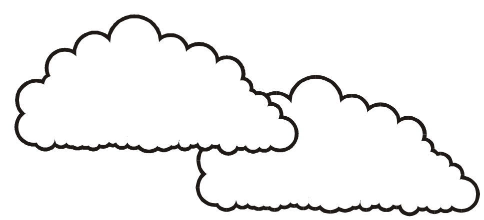
Formation of Kondo Shadows is quenched at

$$T \sim T_0 \sim \bar{\Delta}$$

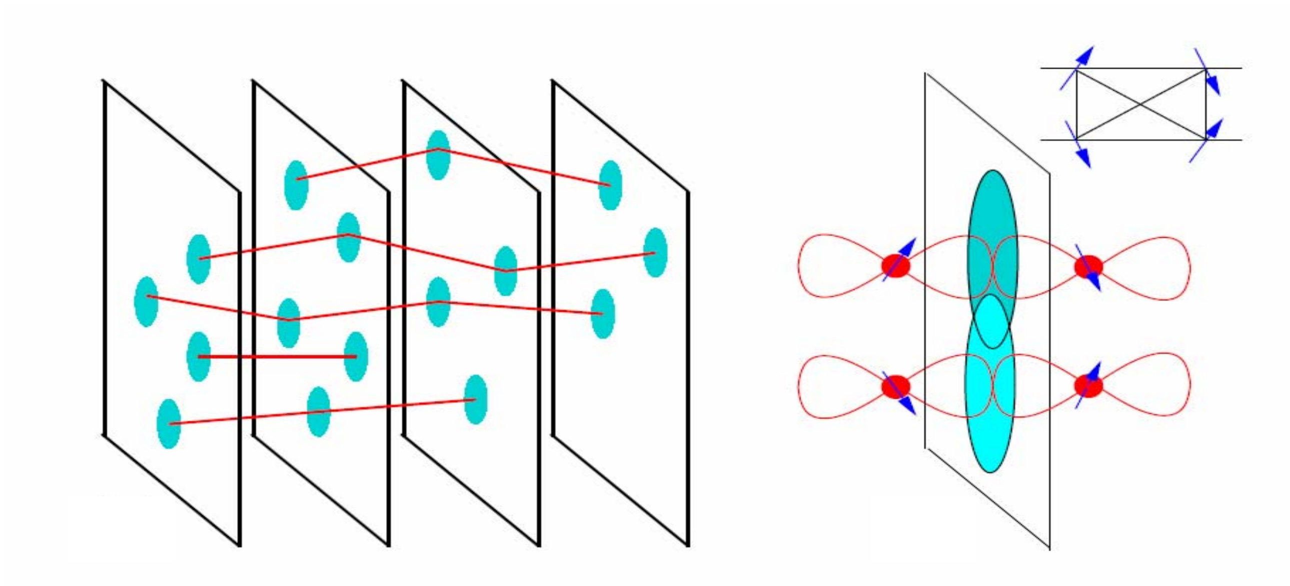
Effective "size" of Kondo Cloud

$$\hbar v_F / R_{Kondo} \sim T_0$$

What happens if Kondo Clouds overlap?



From Order to Disorder



- Chains are distorted and dangled

Distortion: Random RKKY interaction

$$I_j = w_j I$$

Dangling: finite-size effects

Gap in spin excitations

- Chains interact due to overlap of Clouds

Increasing inter-chain interaction restores Nozieres Effect

Random Antiferromagnetic Quantum Spin Chains

$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \vec{S}_j$$

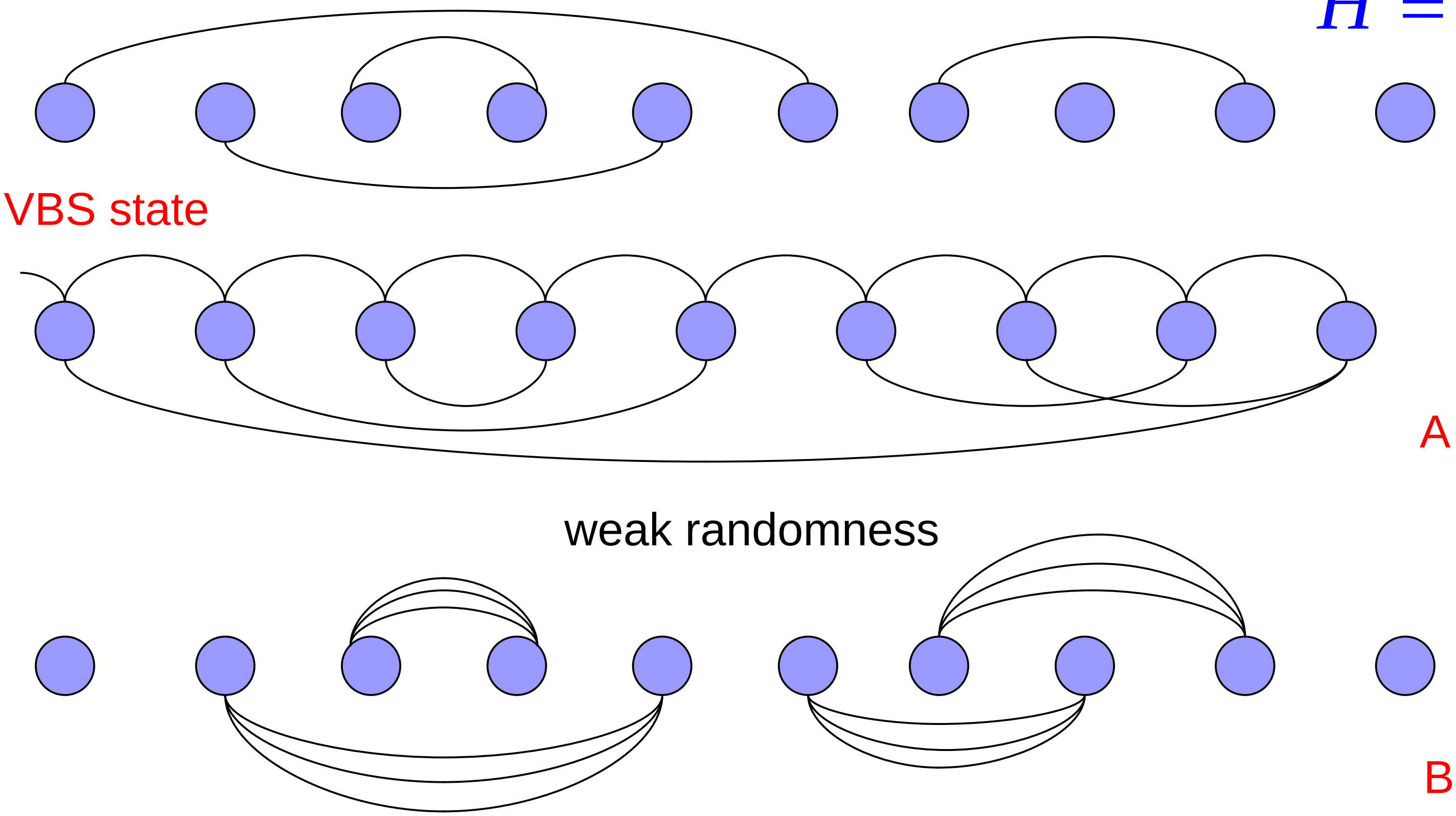
Random singlets

S=1/2

VBS state

S=3/2

S=3/2



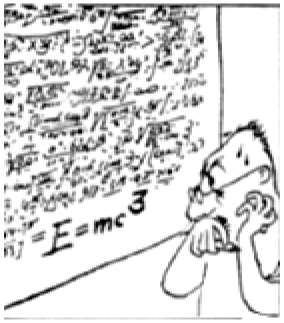
strong randomness

Quantum Phase Transition between A and B phases

D.Fisher, 1994

G.Refael, S.Kehrein, D.Fisher, 2002

Conclusions



• Hybrid Conducting/Magnetic compound is a system with a tunable exhaustion measure. Nozieres Exhaustion Effect does not occur for dilute system

• Hybrid Kondo system is characterized by gapless excitations in both spin and charge sectors

• Effects of disorder do not lead to a formation of the gap in spin excitations spectrum. QPT between different spin gapless phases can be driven by change of randomness