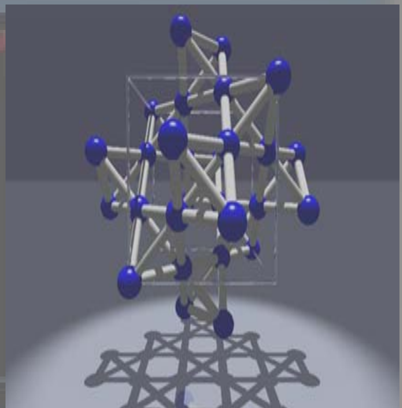
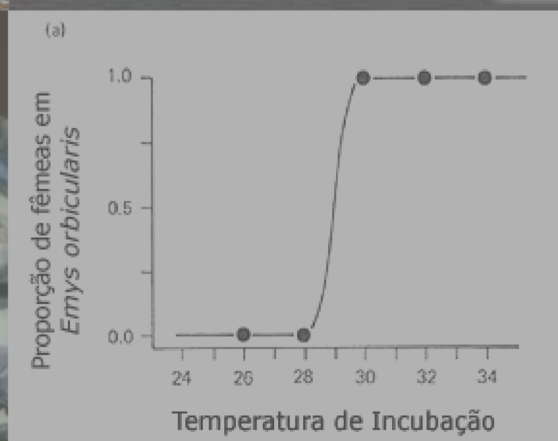
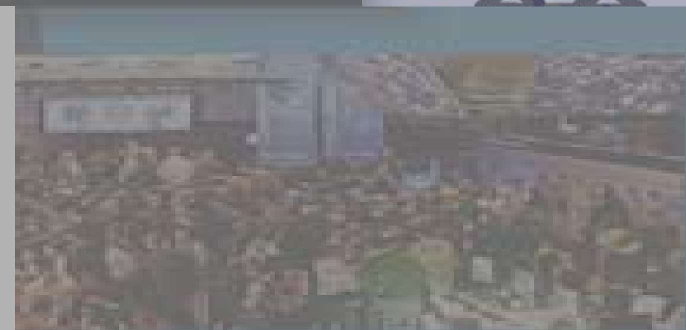
Estado *Líquido de Spin* em Modelos de spins Localizados



José Ricardo de Sousa
(UFAM/INCT-SC)





Rio de Janeiro, Março-2009

Grupo de Mecânica Estatística

UFAM

UNIVERSIDADE FEDERAL DO AMAZONAS

IN UNIVERSA SCIENTIA VERITAS

DF

Pesquisadores

- José Roberto Viana
- João Cabral Neto
- Denilson Borges
- Rita Cassia Mota
- Angsula Ghosh
- Minos Neto (Pos-Doc)

Estudantes

- Márcio Amazonas (doutorando-UFAM/UFSCar)
- Fabian Litaiff (doutorando-UFAM/UFSCar)
- Rosana dos Anjos (doutorando-UFAM/UFSCar)
- Wagner Nunes (doutorando-UFAM/UFSCar)
- Griffith Mendonça (mestrando-UFAM)
- Rodrigo Lapa (mestrando-UFAM)
- Emanuel Costabile Bezerra (PIBIC-UFAM)
- Lilian Rodrigues de Oliveira (PIBIC-UFAM)
- Patrícia Paula Fernandes Oliveira (PIBIC-UFAM)

Apoio:

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

FAPEAM
Fundação de Amparo à Pesquisa do Estado do Amazonas

Sumário

1- Motivações e Questões Básicas

2- Estados Magnéticos não convencionais

3- Resultados

4- Problemáticas

1- Motivações e Questões Básicas

Motivações:

1) Experimental:

- *Supercondutividade em altas temperatura*

- Materiais magnéticos frustrados

2) Teórica:

Propor um modelo realístico que tenha um estado **líquido de spin** (*Degenerescência topológica)*

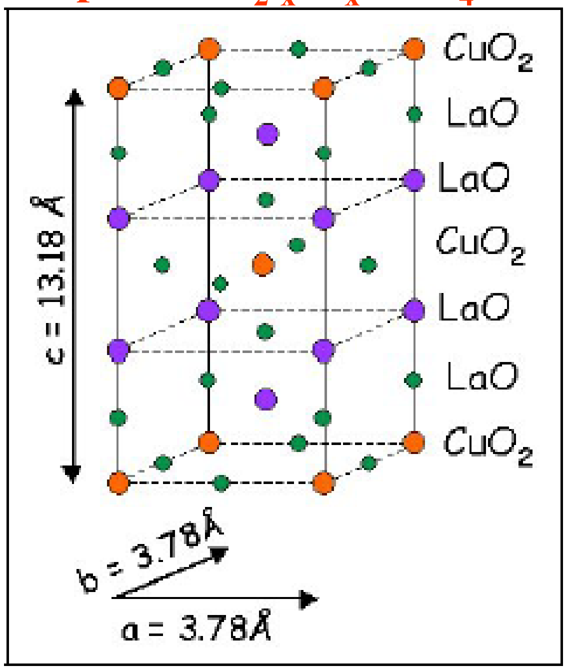
Questões:

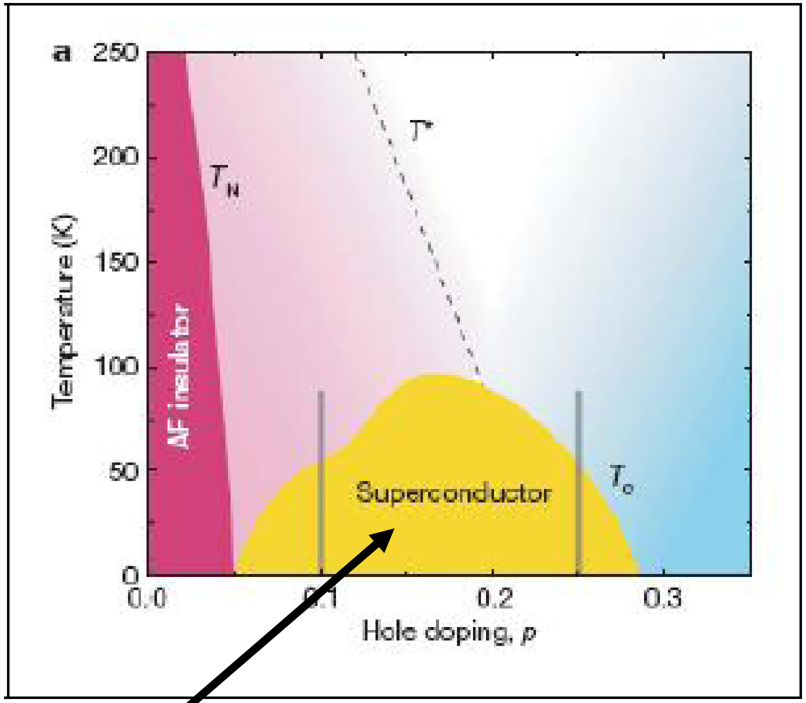
1) O que é o estado **líquido de spin**?

2) Como obter o **estado líquido** de spin (exp)?

Estado SC X Estado Líquido de Spin

Composto $La_{2-x}Sr_xCuO_4$





Sachdev, 2000

- x>0.05 estado SC
- Planos de CuO_2

Estado Líquido de Spin

$k_BT_c \sim \Delta \sim J$(GAP)!!

Sistemas Magnéticos Frustrados

VOLUME 93, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 9 JULY 2004

Direct Determination of the Magnetic Ground State in the Square Lattice $S = 1/2$ Antiferromagnet Li_2VOSiO_4

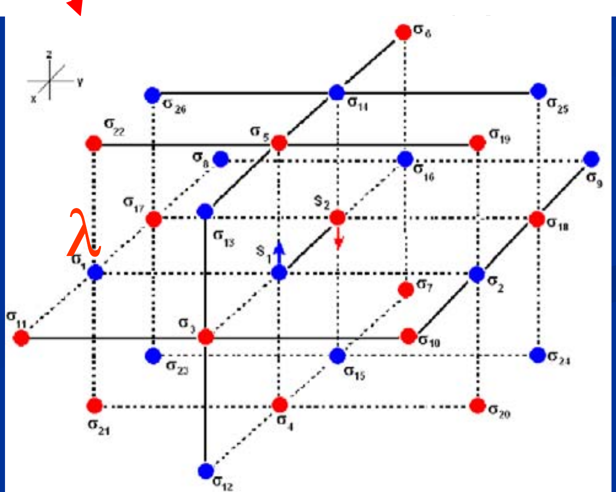
A. Bombardi,[1] J. Rodriguez-Carvajal,[2] S. Di Matteo,[3,4] F. de Bergevin,[1] L. Paolasini,[1] P. Carretta,[5] P. Millet,[6] and R. Caciuffo[7]

[1]European Synchrotron Radiation Facility, BP 220, 38043 Grenoble Cedex 9, France
[2]Laboratoire Léon Brillouin, CEA-SACLAY, 91191 Gif sur Yvette Cedex, France
[3]Laboratori Nazionali di Frascati-INFN, via E. Fermi 40, I-00044 Frascati (Roma), Italy
[4]Dipartimento di Fisica "E. Amaldi," Università di Roma III, via della Vasca Navale 84, I-00146 Roma, Italy
[5]Istituto Nazionale per la Fisica della Materia and Dipartimento di Fisica, Università di Pavia, Via Bassi 6, I-27100 Pavia, Italy
[6]Centre d'Elaboration des Matériaux et d'Etudes Structurales, CNRS, 31055 Toulouse Cedex, France.
[7]Istituto Nazionale per la Fisica della Materia and Dipartimento di Fisica ed Ingegneria dei Materiali, Università Politecnica delle Marche, Via Brecce Bianche, I-60131 Ancona, Italy

(Received 15 December 2003; published 7 July 2004)

Powder neutron diffraction and resonant x-ray scattering measurements from a single crystal have been performed to study the low-temperature state of the 2D frustrated, quantum-Heisenberg system Li_2VOSiO_4. Both techniques indicate a collinear antiferromagnetic ground state, with propagation vector $k = (\frac{1}{2}\ \frac{1}{2}\ 0)$, and magnetic moments in the a-b plane. Contrary to previous reports, the ordered moment at 1.44 K, $m = 0.63(3)\mu_B$, is very close to the value expected for the square lattice Heisenberg model ($\simeq 0.6\mu_B$). The magnetic order is three dimensional, with antiferromagnetic a-b layers stacked ferromagnetically along the c axis. Neither x-ray nor neutron diffraction shows evidence for a structural distortion between 1.6 and 10 K.

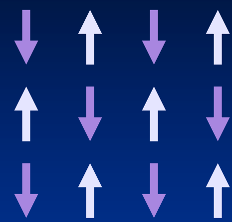
$$\mathcal{H} = J_1 \sum_{nn} \mathbf{S}_i \cdot \mathbf{S}_j + J_2 \sum_{nnn} \mathbf{S}_i \cdot \mathbf{S}_j$$



2- Estados magnéticos não convencionais

- **Fase de Néel** (AF)

  (Neel, Landau 1933; Pomeranchuk - Férmions neutrons 1941)



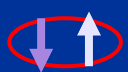
magnetização alternada

$$\langle S_r^z \rangle \neq 0$$

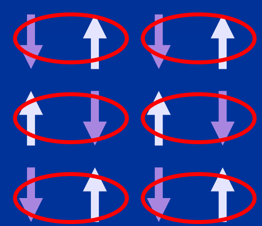
- ***Valence bond solid*** (VBS)

  (Sachdev, Read 1990)

Cristal de singletos



$$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$$



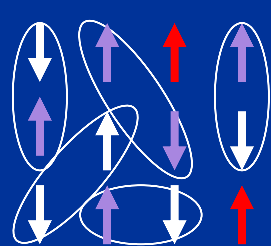
$$\langle S_r^z \rangle = 0$$

Ordem de longo-alcance com dímero

Quebra de simetria translacional

- ***Spin liquid***

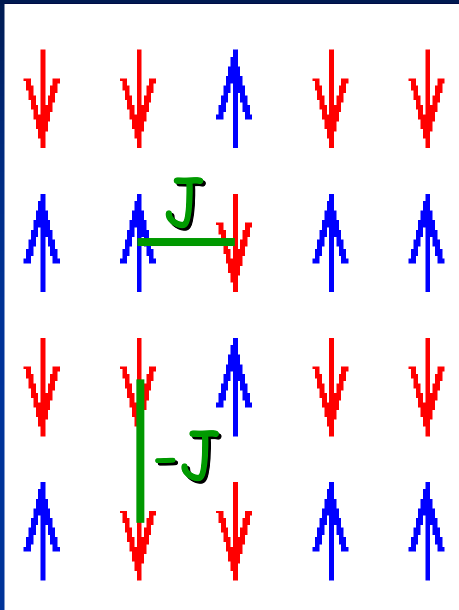
  (Anderson 1973,1987)



$$\langle S_r^z \rangle = 0$$

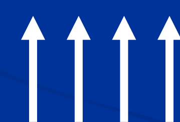
Parâmetro de ordem não local

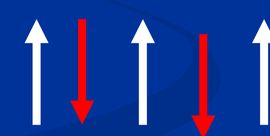
Modelagem teórica-Rede de spins



- **Cada configuração tem uma energia**
- **A energia é a soma da energia de cada par de spins vizinhos**
- **Hamiltoniano de Heisenberg (modelo localizado)**

$$\mathcal{H} = -\sum_{\langle i,j \rangle} J_{ij} \vec{S}_i . \vec{S}_j$$

$J_{ij}>0$ estado ferromagnético 

$J_{ij}<0$ estado antiferromagnético 

WORKSHOP: ***The Heisenberg Model: past, present and future***

LOCAL: CIFMC, Brasília (<u>20 a 27 de julho de 2009</u>)

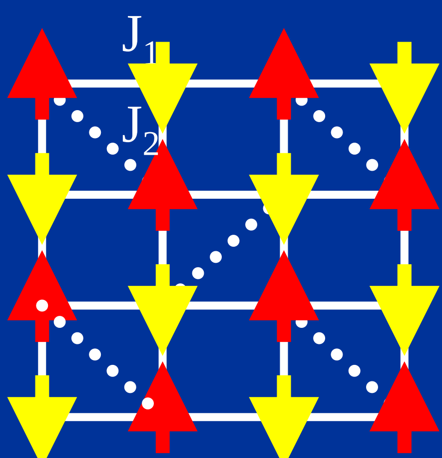
3- Resultados

Modelo J_1-J_2 2D

$$\mathcal{H} = J_1 \sum_{nn} \mathbf{S}_i \cdot \mathbf{S}_j + J_2 \sum_{nnn} \mathbf{S}_i \cdot \mathbf{S}_j$$

$\alpha = J_2/J_1 < \alpha_{1c}$

Ordem AF

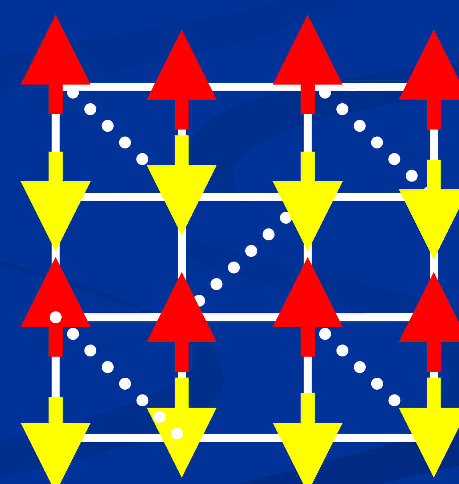


$\alpha_{1c} < \alpha < \alpha_{2c}$

→ **Estado desordenado ?** →

$\alpha > \alpha_{2c}$

Ordem colinear-SAF

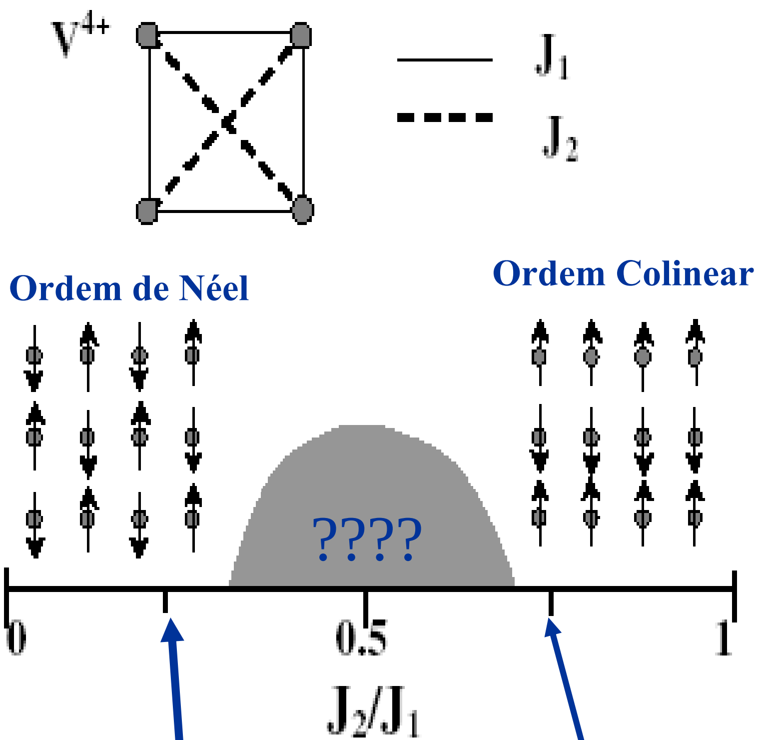


Existe um ponto crítico QUÂNTICO $\alpha_{1c} = (J_2/J_1)_c$?, Qual a ordem da transição?,...

VOLUME 85, NUMBER 6 PHYSICAL REVIEW LETTERS 7 AUGUST 2000

$Li_2VO(Si,Ge)O_4$, a Prototype of a Two-Dimensional Frustrated Quantum Heisenberg Antiferromagnet

R. Melzi,[1] P. Carretta,[1] A. Lascialfari,[1] M. Mambrini,[2] M. Troyer,[3] P. Millet,[4] and F. Mila[2]



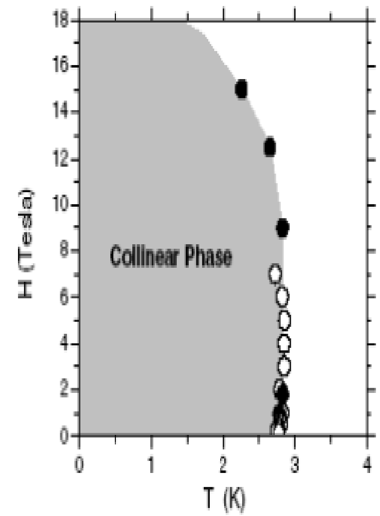
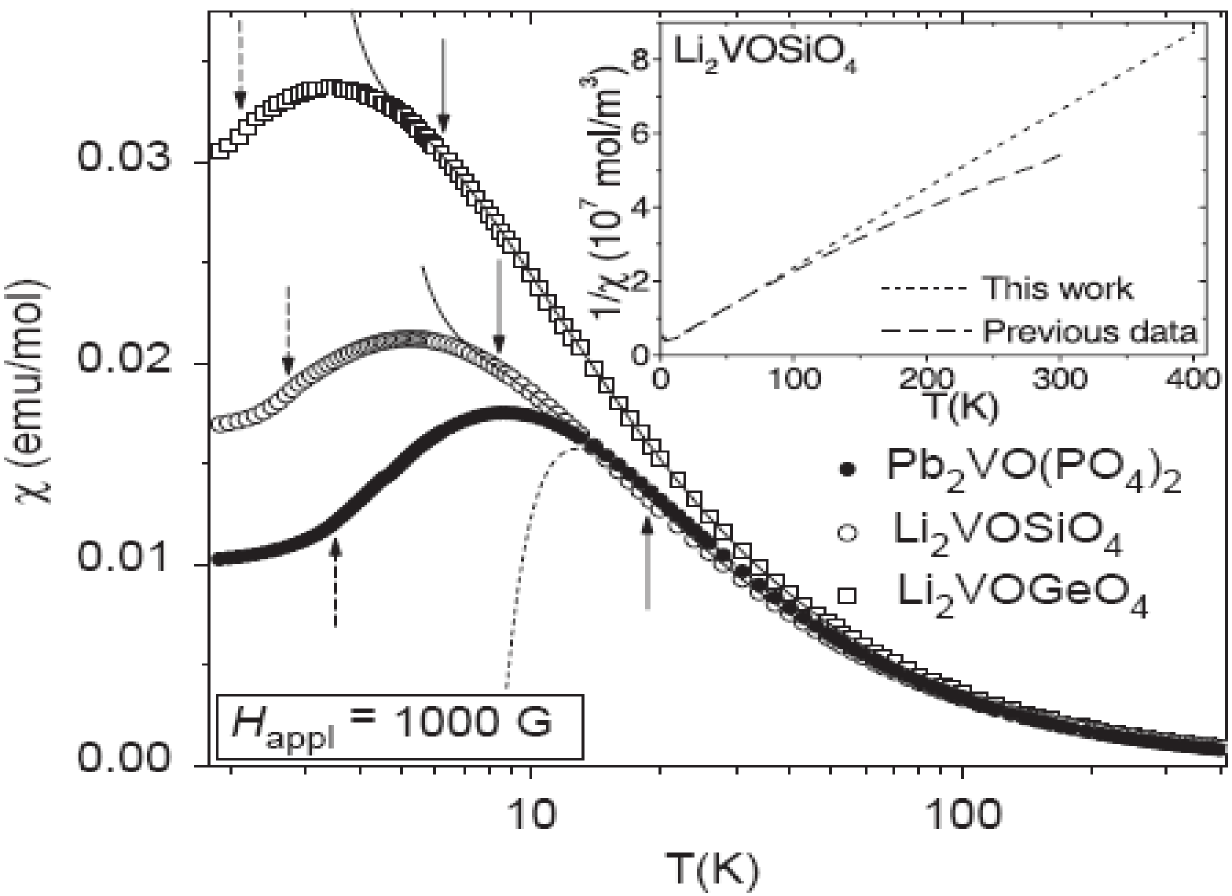


Figura 4.7: Diagrama de fase no plano $T-H$ para o composto Li_2VOSiO_4. A temperatura crítica T_c foi estimada da medida susceptibilidade (circulos brancos) ou da relaxaç ão de RMN (círculos pretos) [29].

2ª ordem α_{1c}~0.40?

1ª ordem α_{2c}~0.60?

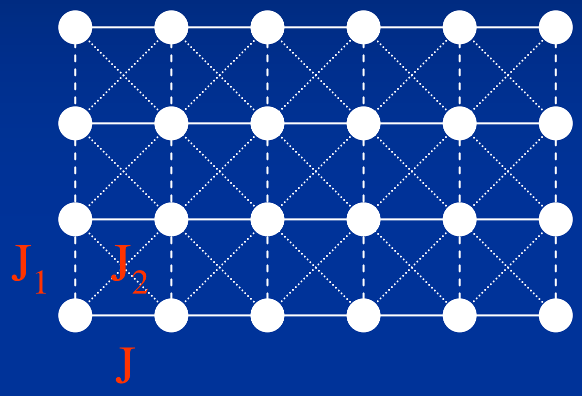


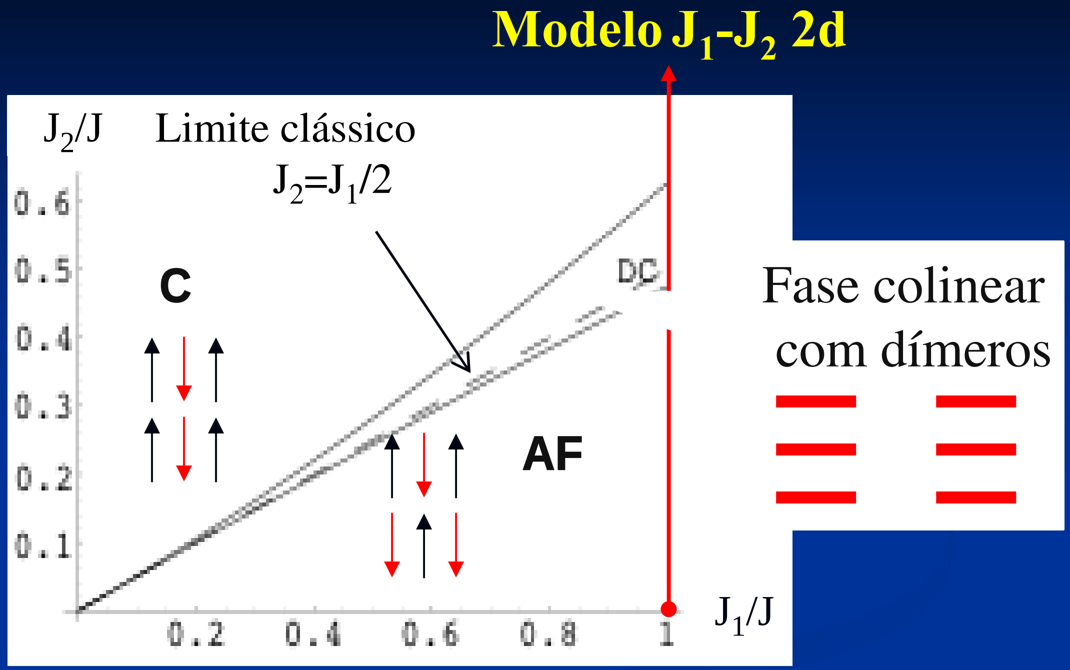
	Li_2VOSiO_4	Li_2VOGeO_4	$Pb_2VO(PO_4)_2$
J_1 (K)	0.56	0.82	−6
J_2 (K)	6.3	4.1	9.8
J_2/J_1	11	5	1.64
$J_1 + J_2$ (θ_{CW}) (K)	6.9	4.9	3.8
T^{χ}_{max} (K)	5.34	3.5	8.67
T_N (K)	2.7	2.1	3.5
T^{χ}_{max}/T_N	1.98	1.7	2.48

Kaul, et al. **JMMM** 272-276, 922 (2004)

Diagrama de fase do modelo 2d

Rede quadrada frustrada AFM





- **Fase ordenada magneticamente**: AF ou C

- **Fase colinear com dímeros (LS)**

$$\frac{J_1}{J} - \frac{J_1^2}{4\pi^2 J^2} < \frac{2J_2}{J} < \frac{J_1}{J} + \frac{5J_1^2}{4\pi^2 J^2}$$

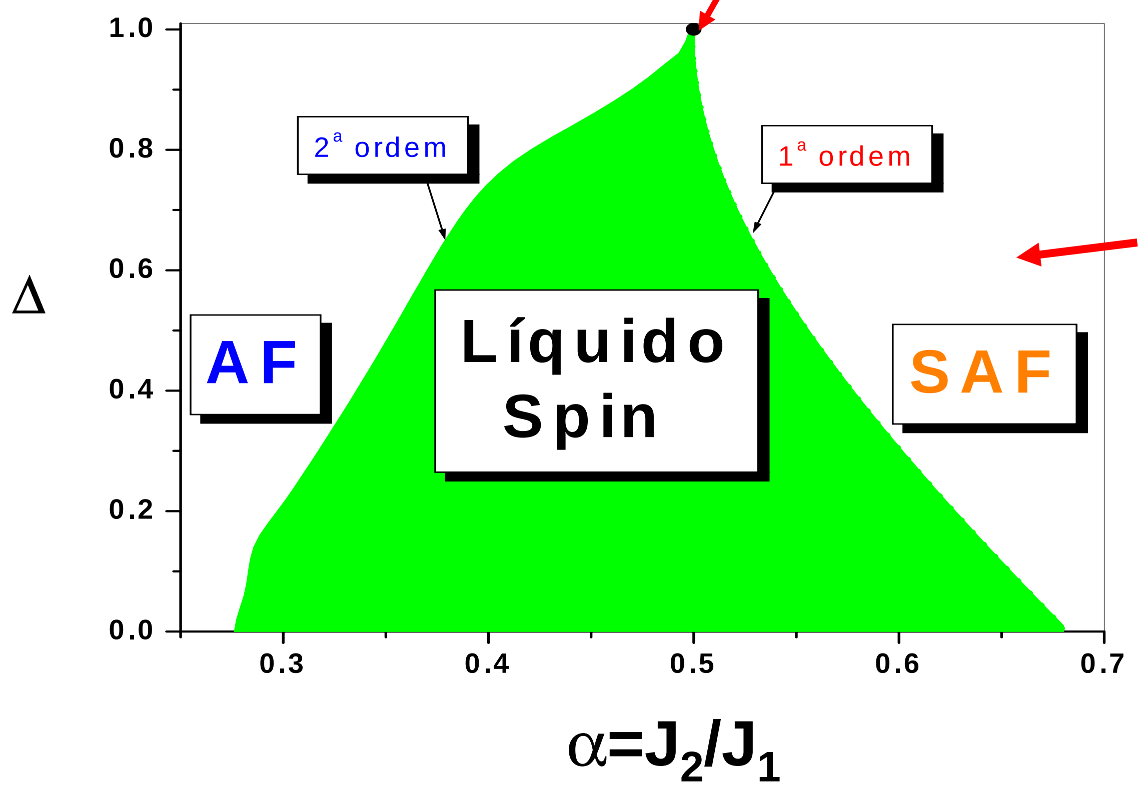
Dimerização alternada $\langle \varepsilon \rangle \approx 0.15 J_2/J$ GAP $\Delta \approx 0.21 (J_2/J)^2$

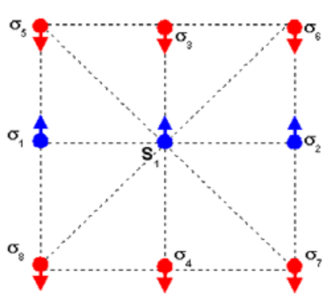
- Diagrama de fase de acordo com Expansão em N (Sachdev,Read 1990, 1991)[J_1=J]
  Expansão em séries (Singh 1990) [J_1=J],
  Diagonalização exata (Sindzingre 2003) [J_1 < J]

Modelo J_1-J_2 anisotrópico 2d

Não existe o estado líquido de spin para modelos clássicos

Viana e **JRS**, **PRB** 75, 052403 (2007)





$$\mathcal{H} = J_1 \sum_{nn} \left[(1-\Delta)\left(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y\right) + \sigma_i^z \sigma_j^z \right] + J_2 \sum_{nnn} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j,$$

Modelo J_1-J_2 anisotrópico 3d

dos Anjos, Viana, **JRS** e Plascak, **PRE** 76, 022103 (2007)

Viana, **JRS** e Continentino, **PRB** 77, 172412 (2008)

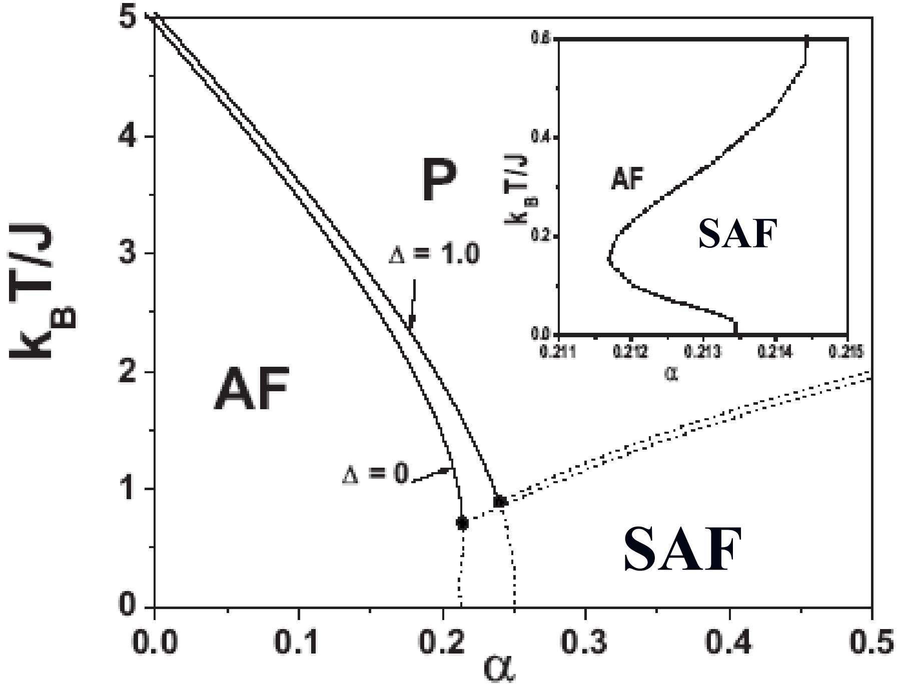


FIG. 2. Phase diagram in the T-α plane for the quantum spin-1/2 anisotropic J_1-J_2 Heisenberg model on a simple cubic lattice for $\Delta=0$ (isotropic Heisenberg limit) and $\Delta=1$ (Ising limit). The first- and second-order transitions are indicated by the dashed and solid lines, respectively. The black points indicate the CEP and α_c at $T=0$ are given by 0.21 and 0.25 for $\Delta=0$ and $\Delta=1$, respectively. The inset shows the re-entrant behavior.

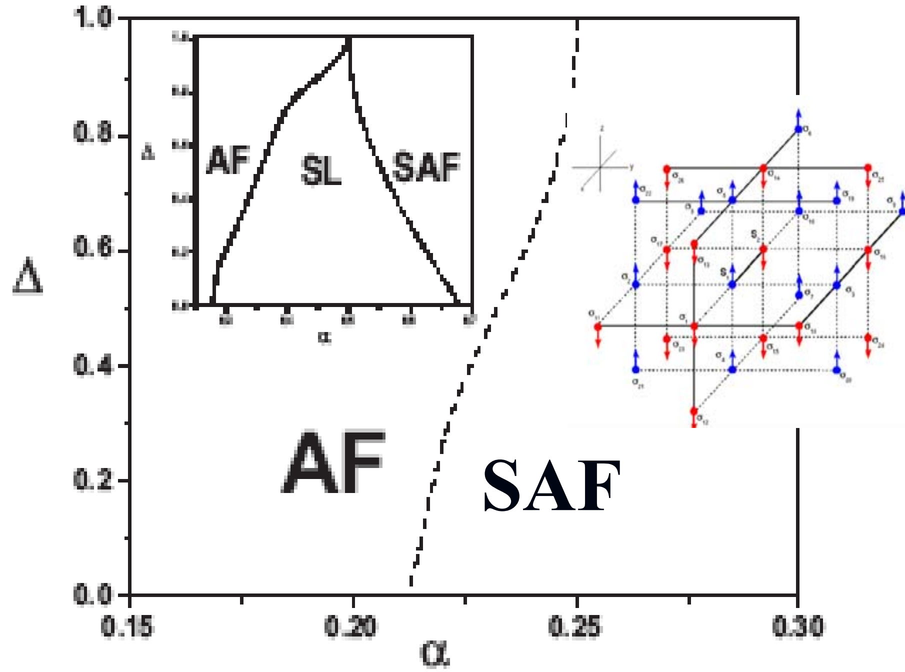
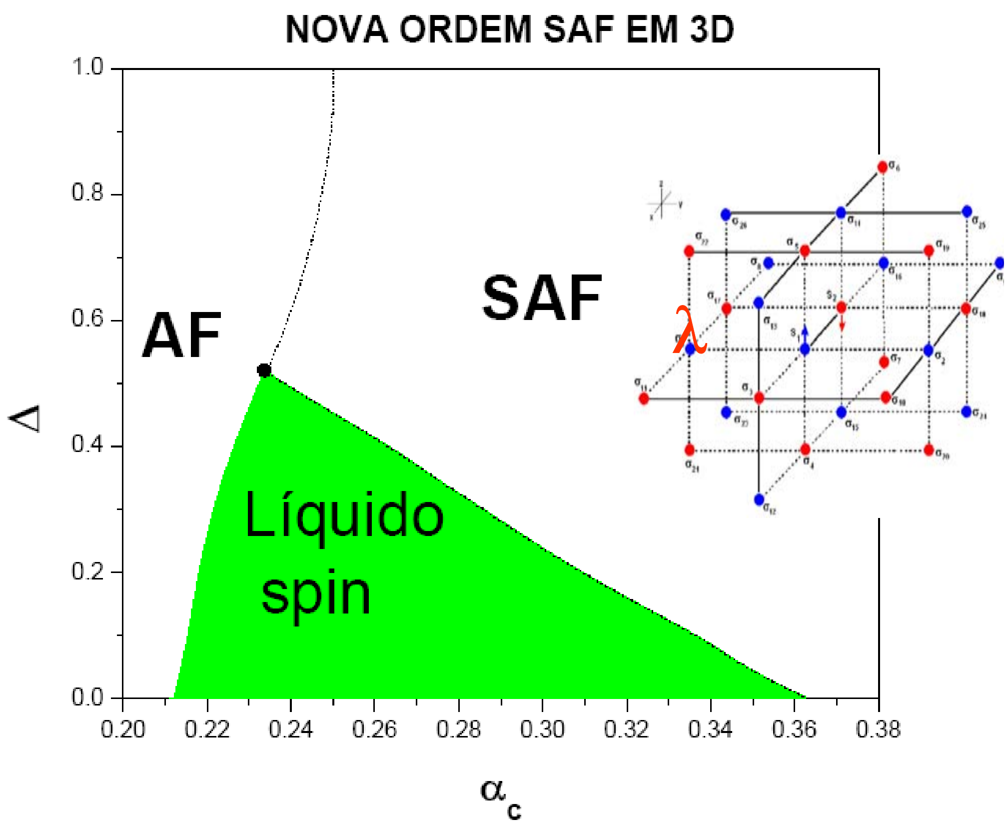


FIG. 3. Ground-state phase diagram in the (α,Δ) plane for the anisotropic quantum spin-1/2 J_1-J_2 Heisenberg model on a simple cubic lattice. The dashed line corresponds to the first-order phase boundaries. In the inset, we present the phase diagram of the model on a square lattice (Ref. 22). The notations indicated by AF, SL, SAF, and L correspond to the antiferromagnetic, spin-liquid, super-antiferromagnetic, and lamellar phases, respectively.

Modelo J_1-J_2 3d

$$\mathcal{H} = J_1 \sum_{nn} \left[(1-\Delta)\left(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y\right) + \sigma_i^z \sigma_j^z \right] + J_2 \sum_{nnn} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j,$$



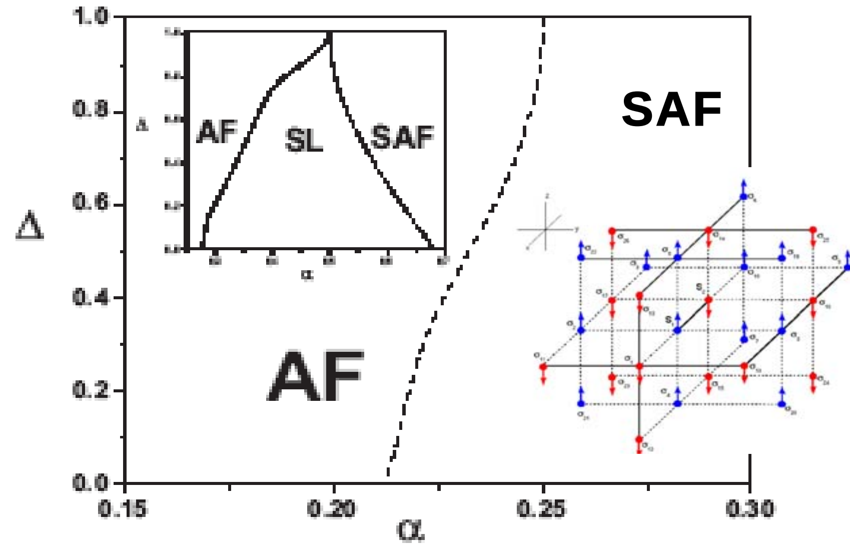


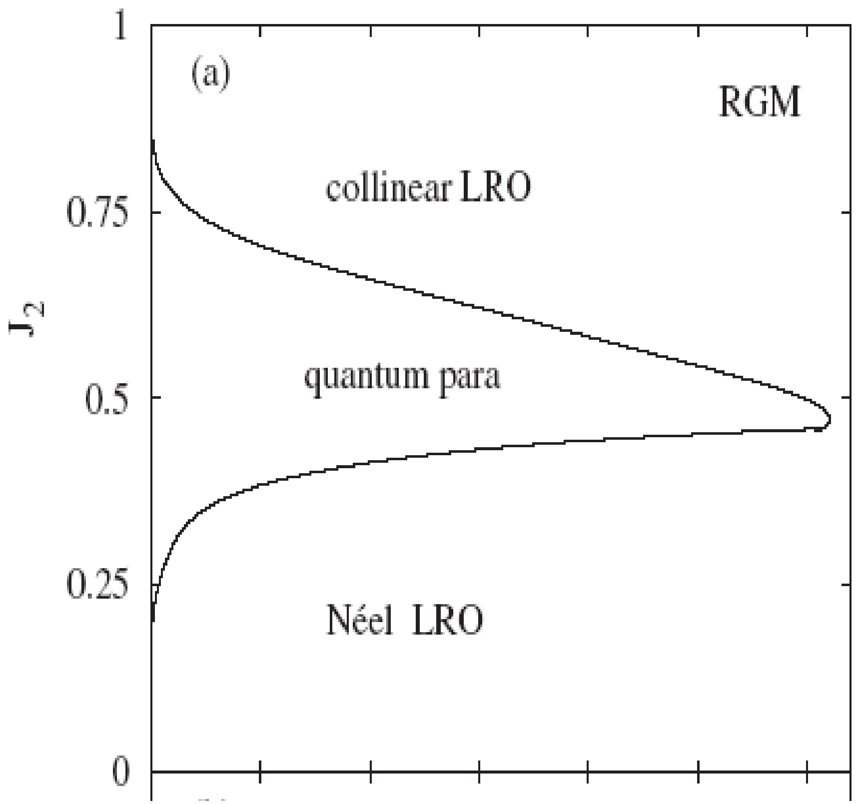
FIG. 3. Ground-state phase diagram in the (α, Δ) plane for the anisotropic quantum spin-1/2 J_1-J_2 Heisenberg model on a simple cubic lattice. The dashed line corresponds to the first-order phase boundaries. In the inset, we present the phase diagram of the model on a square lattice (Ref. 22). The notations indicated by AF, SL, SAF, and L correspond to the antiferromagnetic, spin-liquid, super-antiferromagnetic, and lamellar phases, respectively.

Nunes, **JRS** e Viana, **PRB** (2009) # Viana, **JRS** e Continentino, **PRB** 77, 172412 (2008)

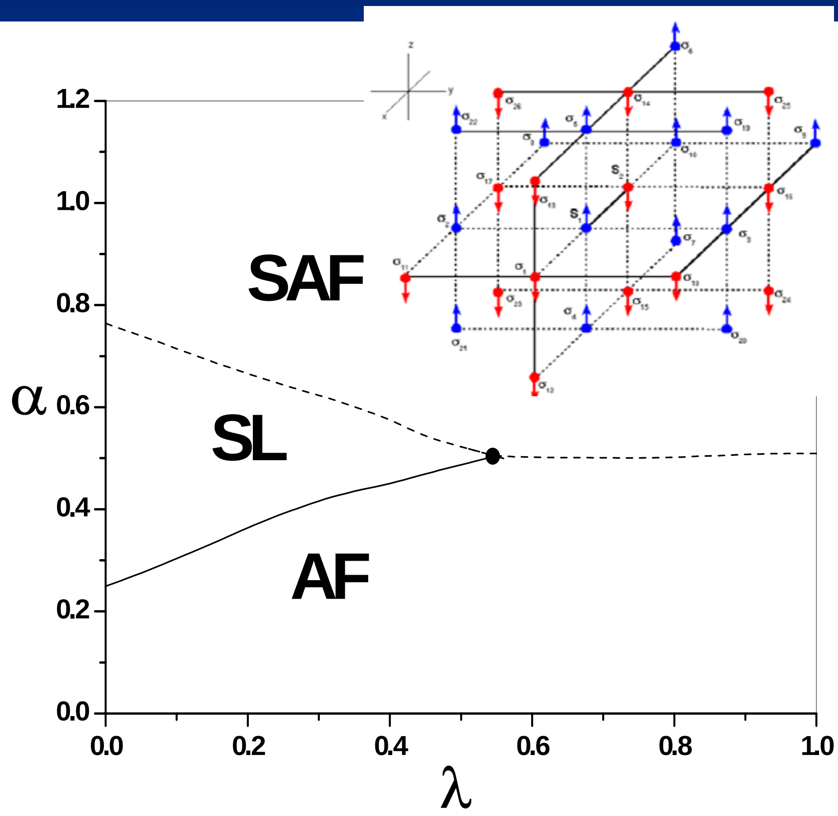
Existência do estado líquido de spin em 3D

Efeito da interação entre planos

$$H=\sum_n\left(J_1\sum_{\langle ij\rangle}\mathbf{s}_{i,n}\cdot\mathbf{s}_{j,n}+J_2\sum_{[ij]}\mathbf{s}_{i,n}\cdot\mathbf{s}_{j,n}\right)+J_\perp\sum_{i,n}\mathbf{s}_{i,n}\cdot\mathbf{s}_{i,n+1},$$

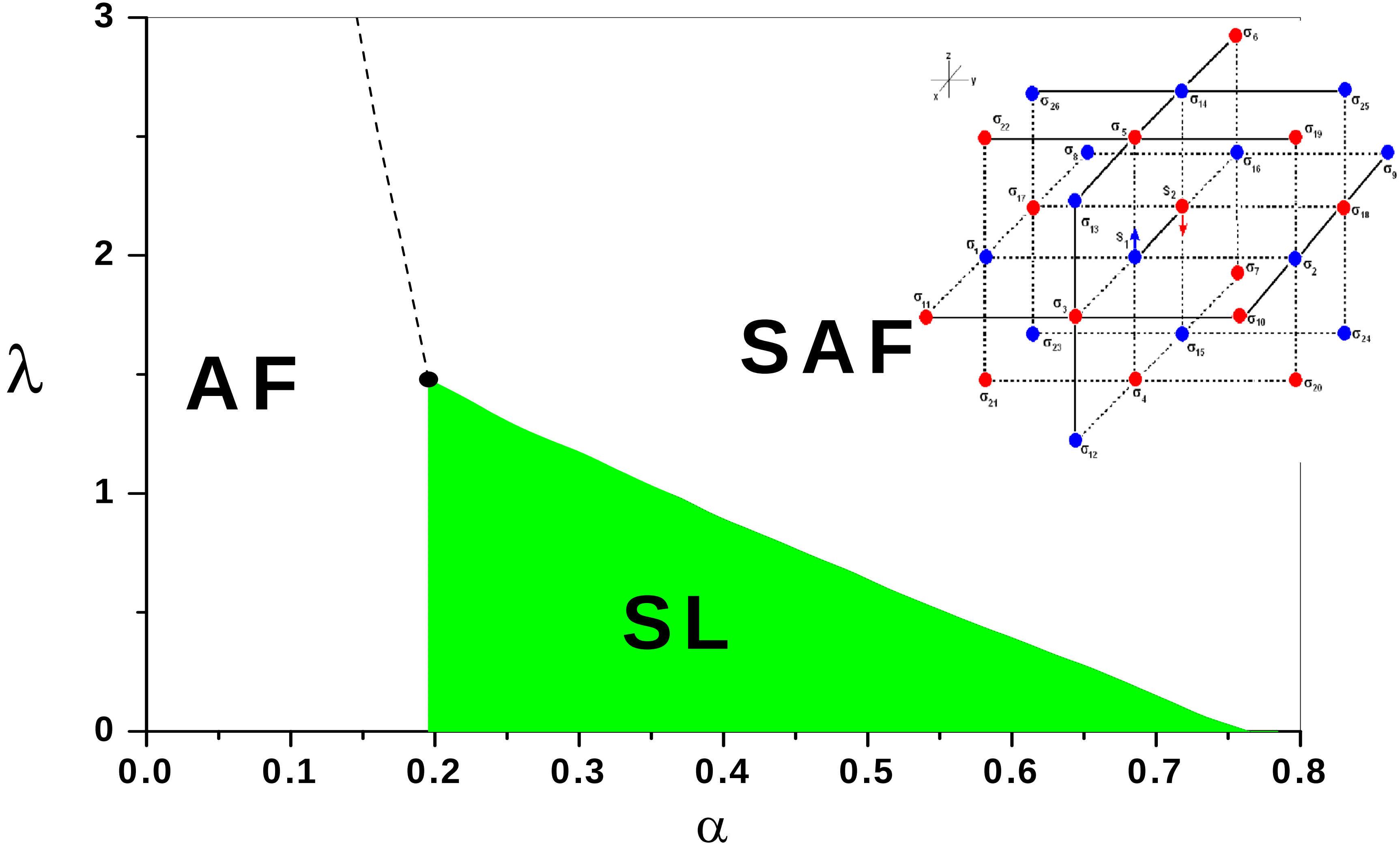


Schmalfub, Darradi e Richter, **PRL** 97, 157201 (2006)



Nunes, Viana, **JRS** e Richter, **PRB** (2009)

Caso $J_2' > 0$



Nunes, **JRS** e Viana, **J. Phys. Cond. Matter** (2009)

Estrutura cristalina do composto Cs_2CuCl_4

R. Coldea, et al. (PRL 86, 1335 (2001)
Y. Shimizu, et al. PRL 91, 107001(2003)

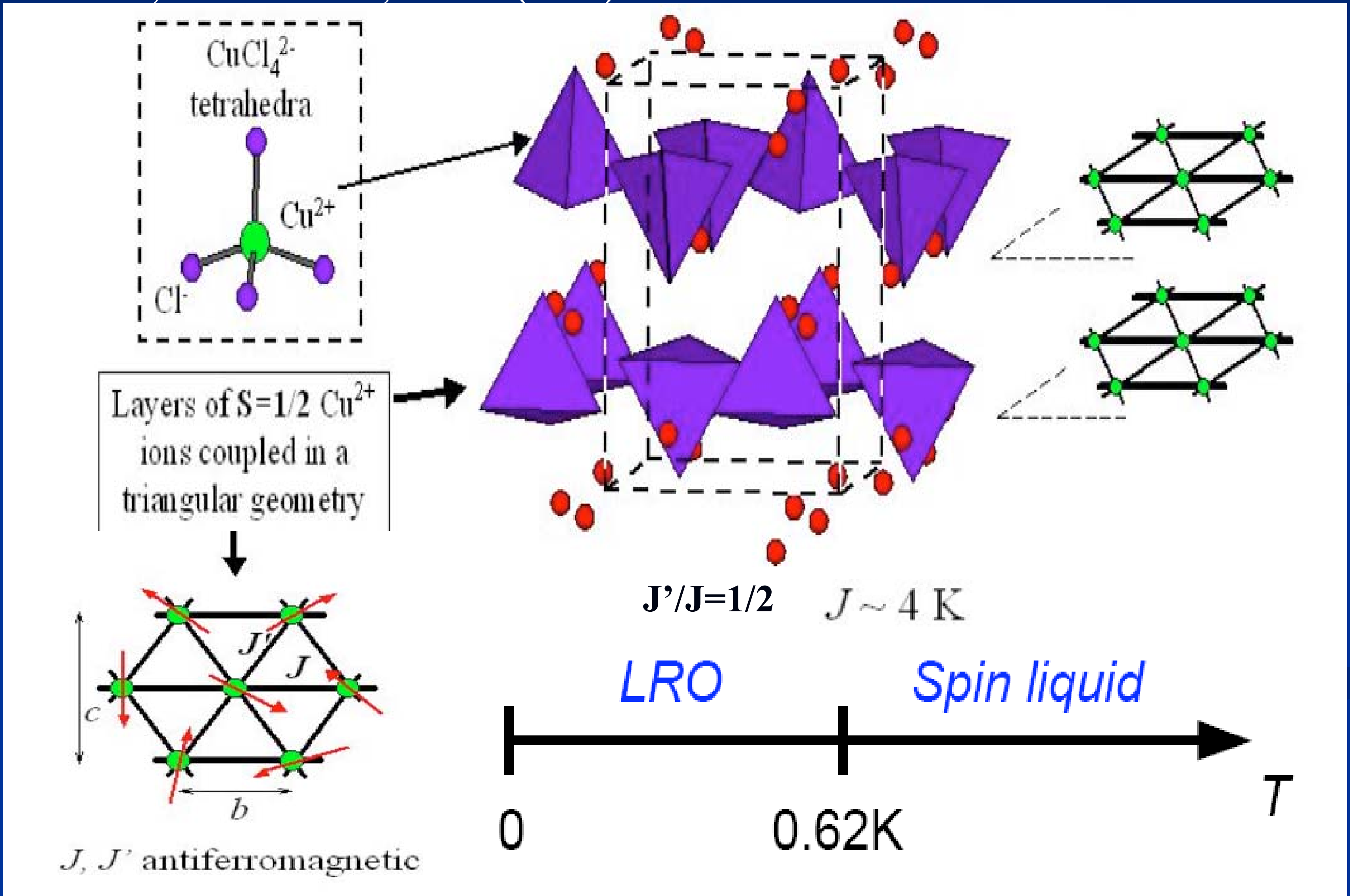
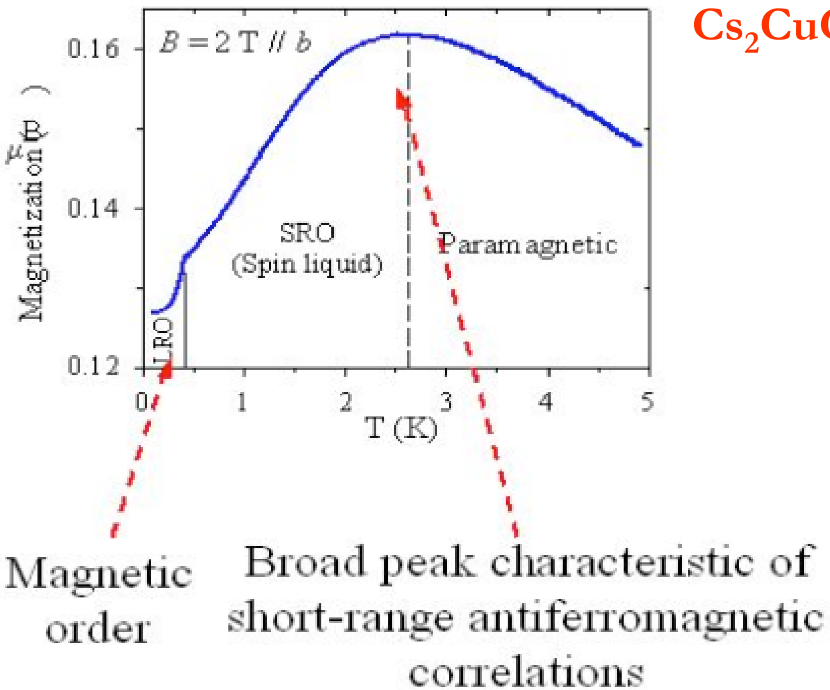
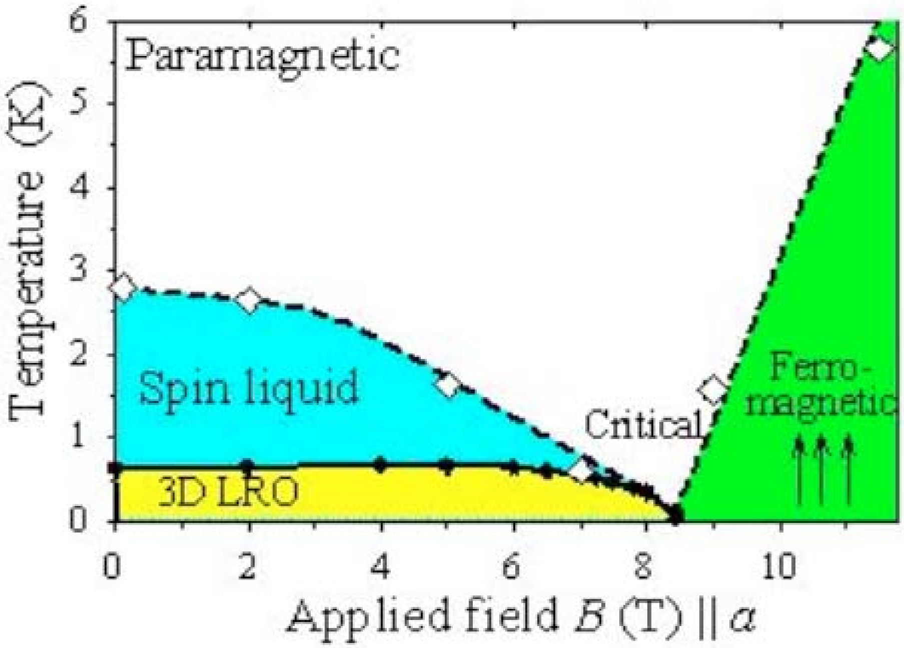
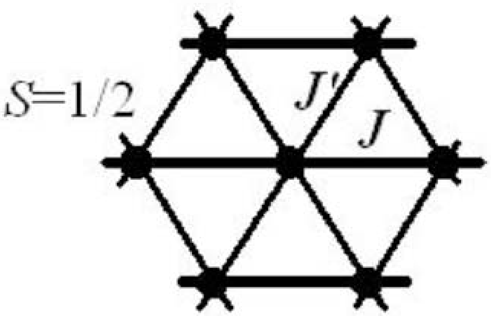


Diagrama de fase com B perpendicular ao plano

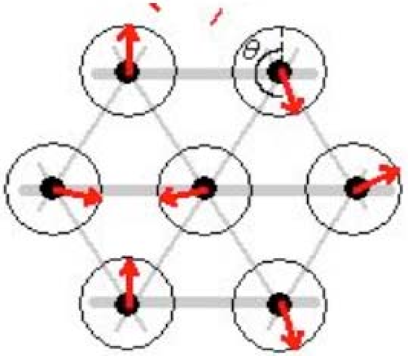


Cs_2CuCl_4

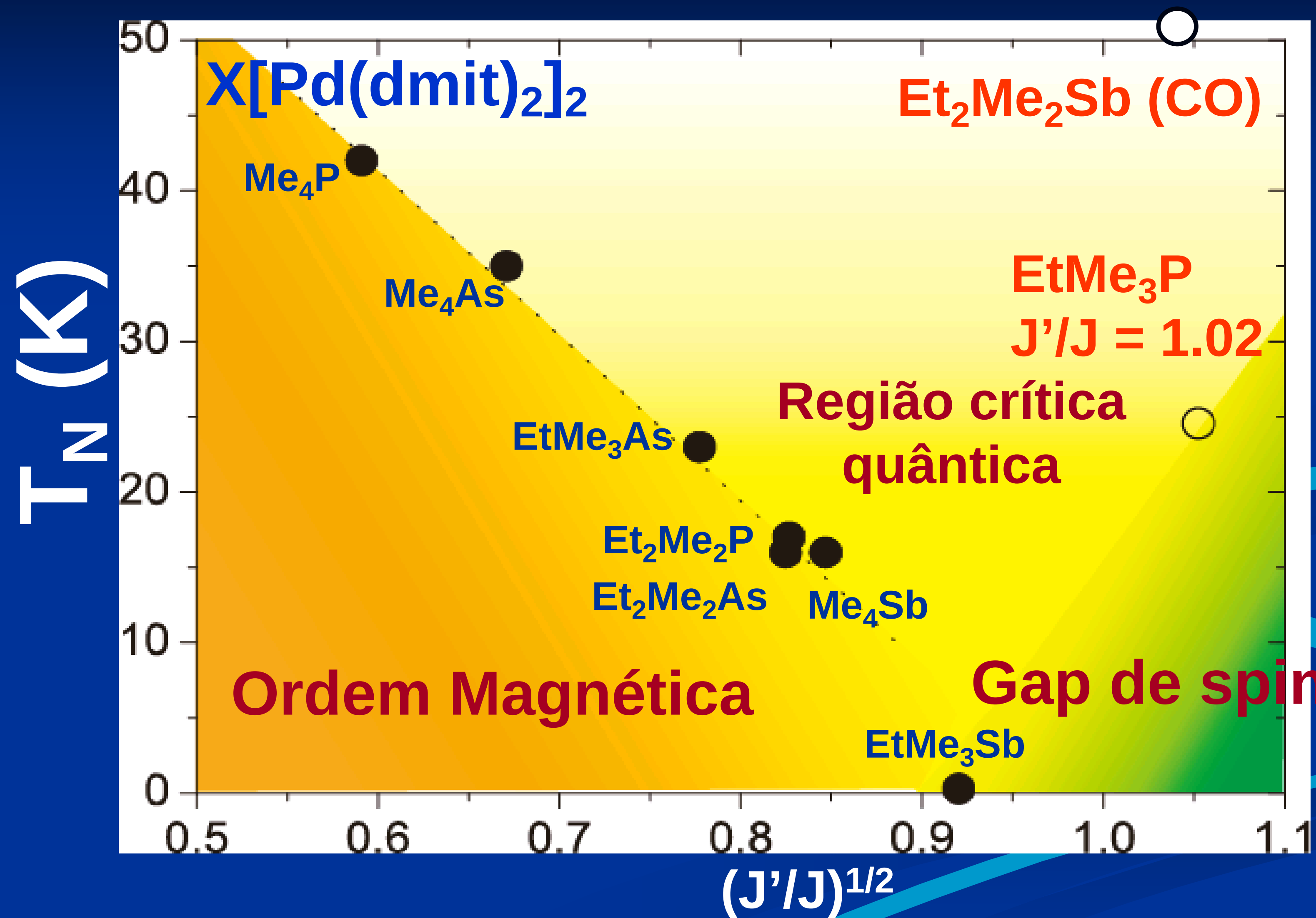




Spiral LRO at
low T



Criticalidade Magnética



Y. Shimizu, et al. , *J. Phys.: Condens. Matter* **19**, 145240 (2007)

PHYSICAL REVIEW B **79**, 060404(R) (2009)

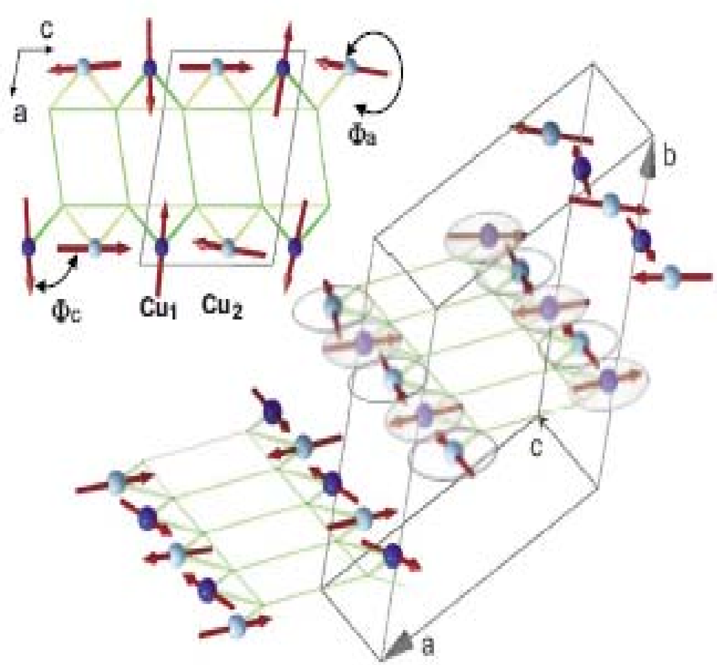
Dimensional crossover in a spin-liquid-to-helimagnet quantum phase transition

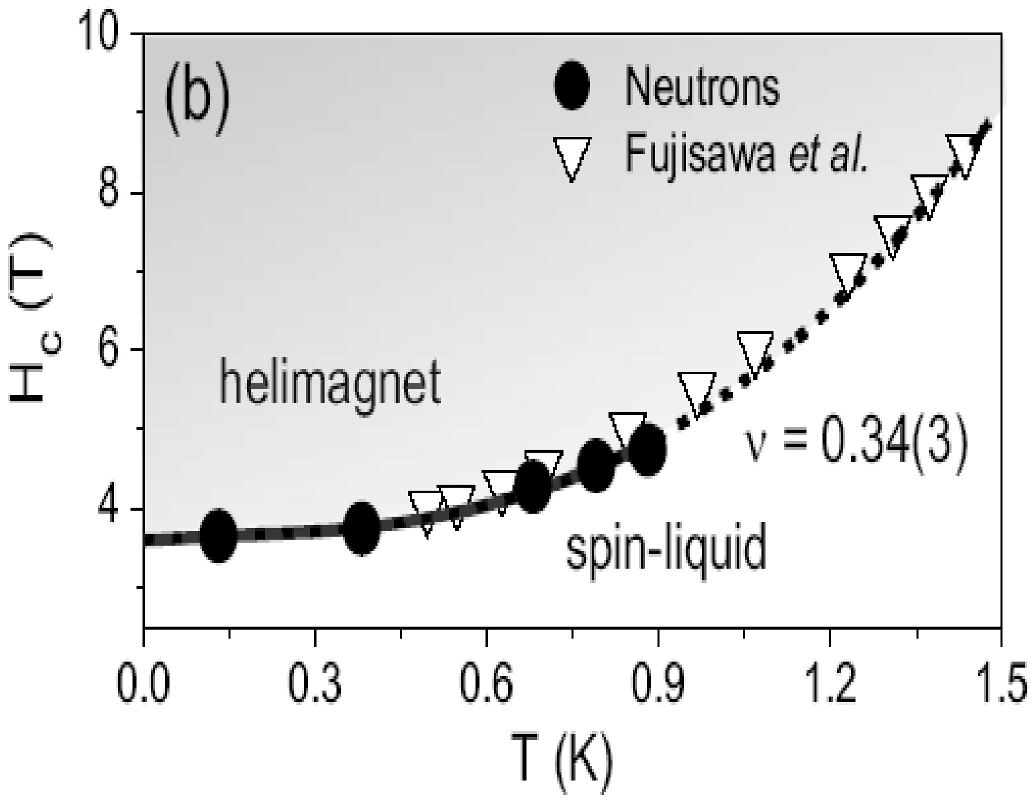
V. O. Garlea* and A. Zheludev
Neutron Scattering Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

K. Habicht and M. Meissner
BENSC, Hahn-Meitner Institut, D-14109 Berlin, Germany

B. Grenier, L.-P. Regnault, and E. Ressouche
CEA-Grenoble, INAC-SPSMS-MDN, 17 Rue des Martyrs, 38054 Grenoble Cedex 9, France
(Received 1 December 2008; published 11 February 2009)

Quase-1D Sul-Cu_2Cl_4

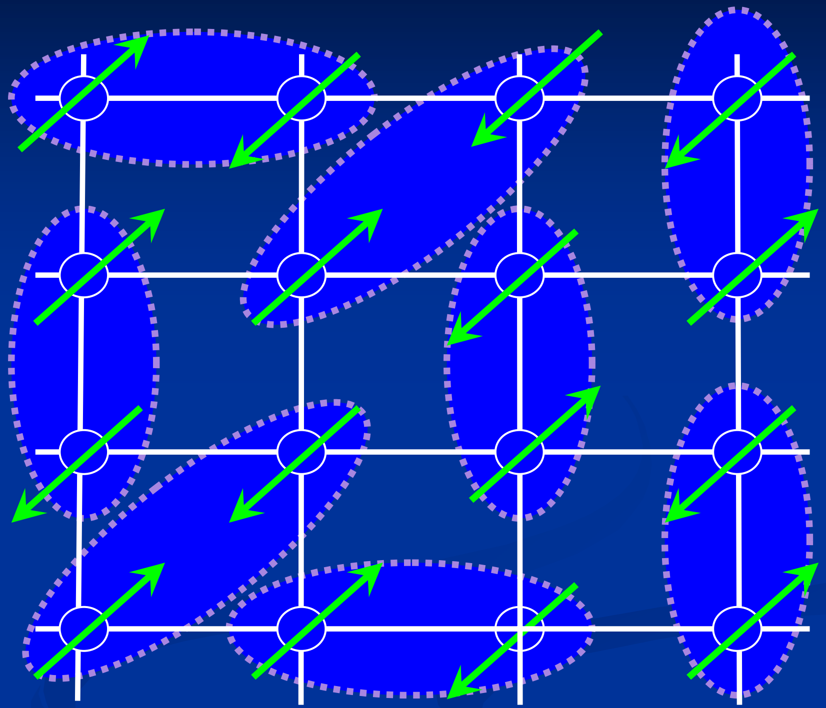




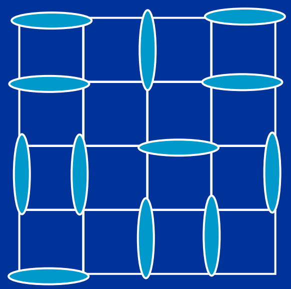
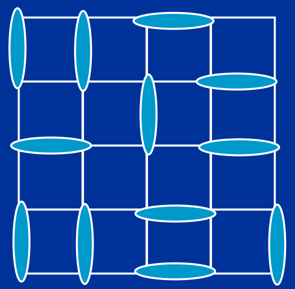
O que é um Líquido de Spin?

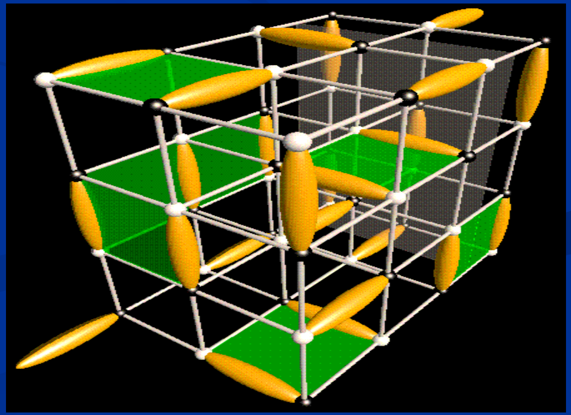
Primeira definição (Shastry-Sutherland, 1981)

Estados singletos distribuídos aleatoriamente



- i) Ausência de ordem de longo alcance
- ii) Ordem topológica (curto alcance)
- iii) **Presença de GAP**

$|\Psi\rangle =$  +  + …



Misguich e Lhuillier, ***Two-dimensional quantum antiferromagnets*** **cond-mat/0310405**

Definindo um estado Líquido de Spin

As funções de correlações decaem exponencialmente

Implica no estado com GAP

Isaek, Ortiz e Dukelsky,

PRB 79, 024409 (2009)

$$\Delta \sim \xi^{-z} \sim (\lambda - \lambda_c)^{z\nu}$$

$$\chi_o \simeq e^{-\Delta/T}$$

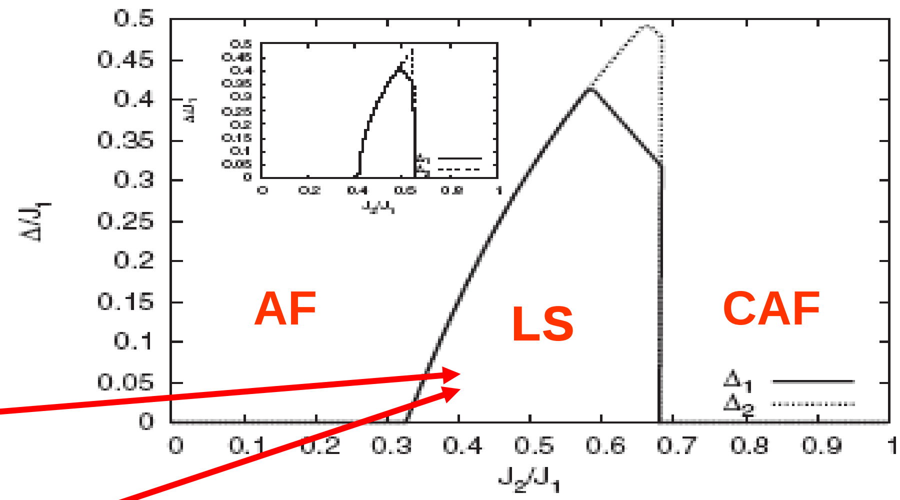
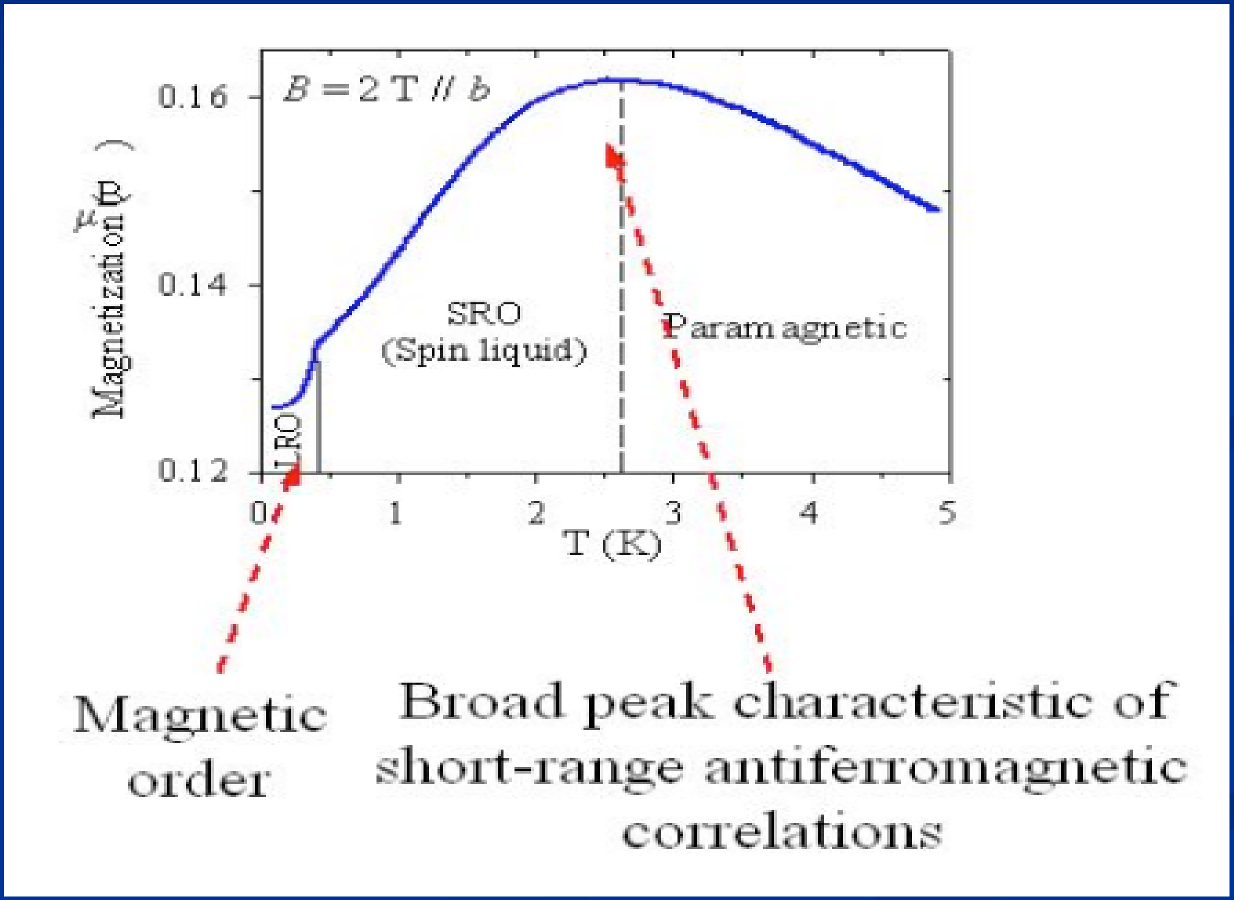


FIG. 11. The two lowest excitation energies taken at the center of the plaquette Brillouin zone. The main panel shows the self-consistent solution to Bogoliubov's equations, while the inset corresponds to the time-dependent Gross-Pitaevskii equation (weak coupling). Since wave functions of collective excitations in the Néel and columnar phases have different symmetries, there are level crossings in the nonmagnetic phase (cusps in the plot).

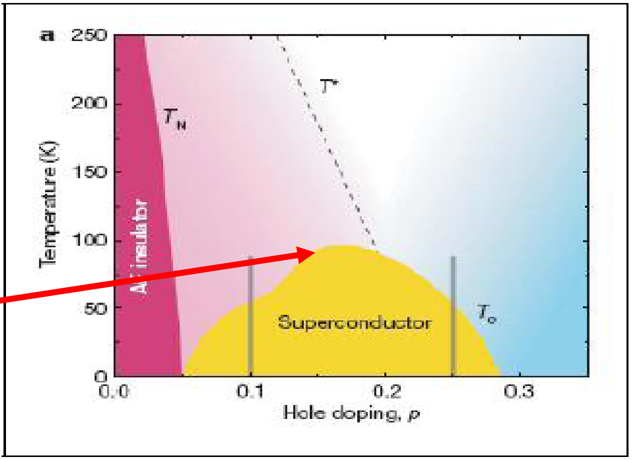
4- Problemáticas

A- Identificação do estado líquido de spin $q_{SL}(T)$?



Y. Shimizu, et al. **PRL** 91, 107001(2003)

B- Conexão com os supercondutores



GAP: $\Delta(T_c)=0$

Chrakravarti, Halperin, e Nelson, **PRB** 39, 2344 (89).

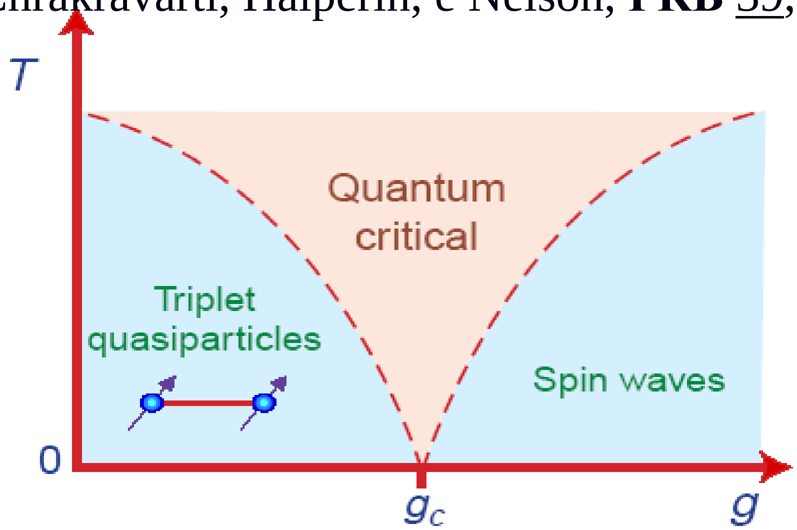


Figure 3: Crossover phase diagram [7] for H_L with the same conventions as Fig 1. The ground state is a paramagnet (Fig. 2B) for $g < g_c$ and the energy cost to create a spin excitation, Δ is finite for $g < g_c$ and vanishes as $\Delta \sim (g_c - g)^{z\nu}$ where $z\nu$ is a critical exponent. There is magnetic Néel order at $T = 0$ for $g > g_c$ (Fig. 2A) and the time-averaged moment on any site, $\vec{N}_0$, vanishes as g approaches g_c from above. Quasiparticle-like dynamics applies in the blue shaded regions. For $g < g_c$, in the cartoon picture of the ground state in Fig 2B, the triplet quasiparticle corresponds to the motion of broken singlet bond in which Fig fig2C is replaced by one of $|\uparrow\uparrow\rangle$, $|\downarrow,\downarrow\rangle$, or $(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$. For $g > g_c$, the quasiparticles are spin-waves representing slow, long-wavelength deformations of the ordered state in Fig 2A.

Imai, et al. **PRL** 70, 1002 (93)

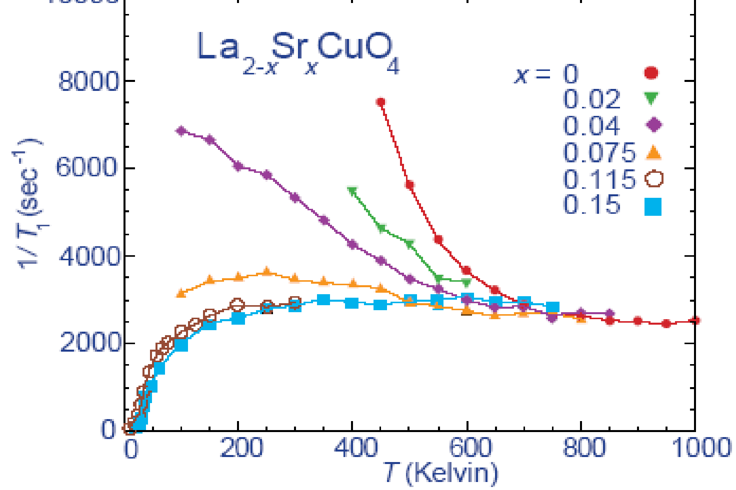


Figure 4: Measurements [21] of the longitudinal nuclear spin relaxation ($1/T_1$) of ^{63}Cu nuclei in the high temperature superconductor $La_{2-x}Sr_xCuO_4$ as a function of x and T. This quantity is a measure of the spectral density of electron spin fluctuations at very low energies. At small x, $1/T_1$ increases rapidly as T is lowered (see red circles): this is also the behavior in the spin-wave regime of Fig 3 ($g > g_c$)—the energy of the dominant thermally excited spin-wave decreases rapidly as T decreases, and so the spin spectral density rises [22]. In contrast, at large x, $1/T_1$ decreases as T is lowered (see blue squares): this corresponds with the triplet quasiparticle regime of Fig 3 ($g < g_c$)—the low energy spectral density is proportionally to the density of thermally excited quasiparticles, and this becomes exponentially small as T is lowered. Finally, at intermediate T, $1/T_1$ is roughly temperature independent for a wide range of T (see orange triangles) and this is the predicted behavior [18, 23] in the quantum critical regime of Fig 3.