The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1855-11

School and Workshop on Highly Frustrated Magnets and Strongly Correlated Systems: From Non-Perturbative Approaches to Experiments

30 July - 17 August, 2007

Mobile holes in frustrated quantum magnets

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Mobile holes in frustrated quantum magnets

An Introduction

To be covered in the book chapter:

Covered in this Lecture

- Mobile holes in frustrated quantum magnets
- Ordering phenomena at commensurate fermion densities on frustrated geometries
- Doping Quantum Dimer Models

OUTLINE

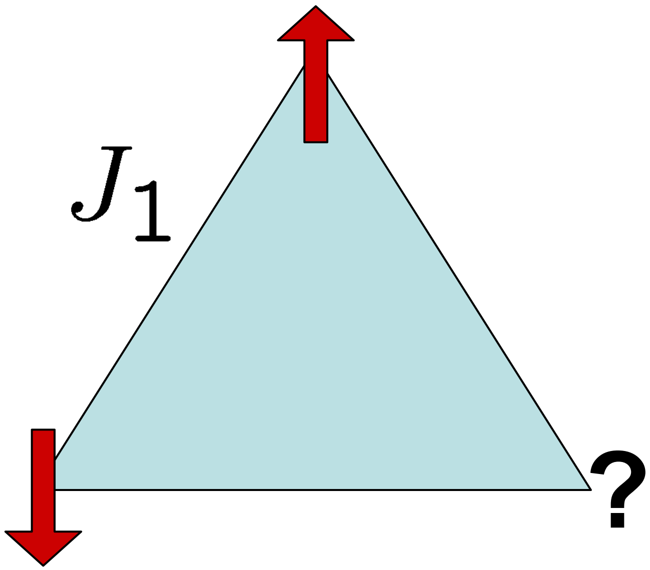
- Basic notions on frustration

  - Some frustrated lattices

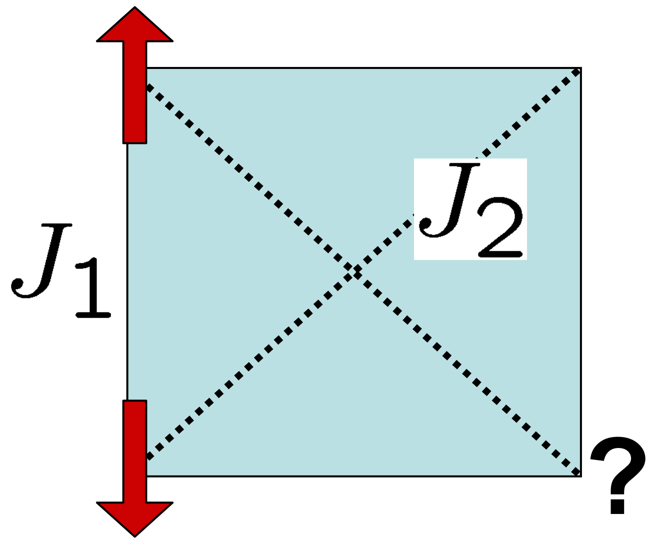
  - Quantum disordered phases (VBC & spin liquids)

- Some doping issues – Impurities and mobiles holes in VBC & spin-liquid hosts

The concept of frustration



Topological origin



Extended range interaction

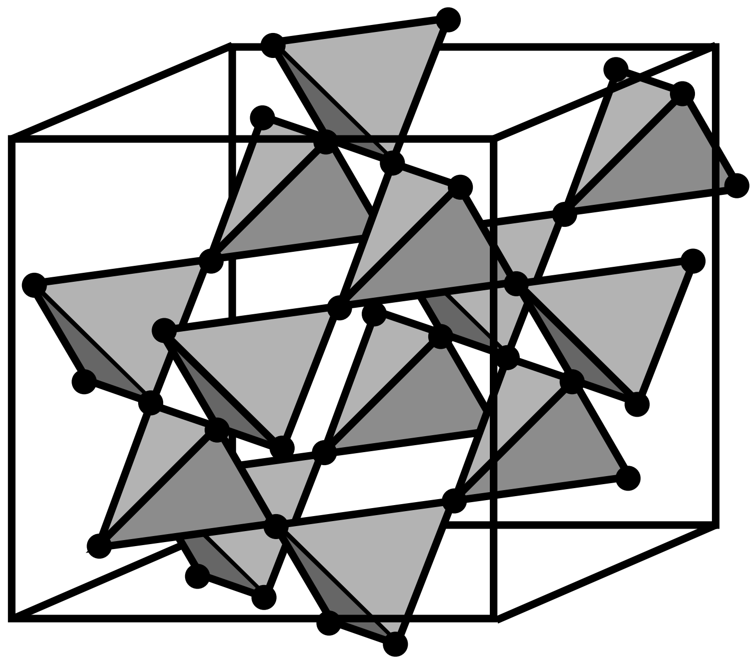
For classical spins, one cannot minimize independently all bond (AF) interactions

Simple frustrated lattices

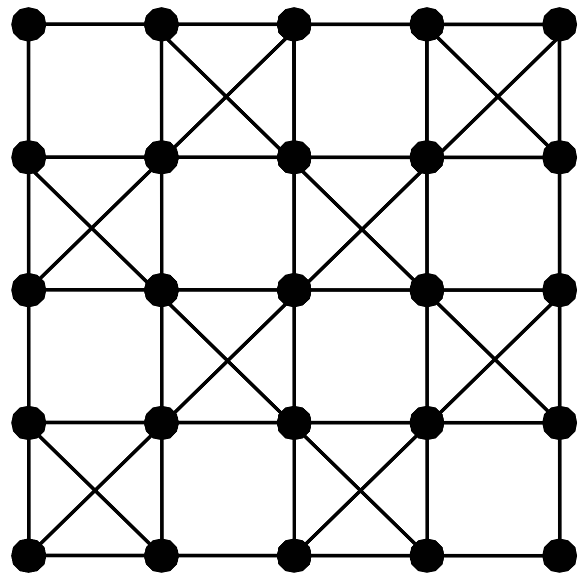
Reminder from previous lectures

Lattices of corner-sharing units

Pyrochlore lattice



Checkerboard lattice

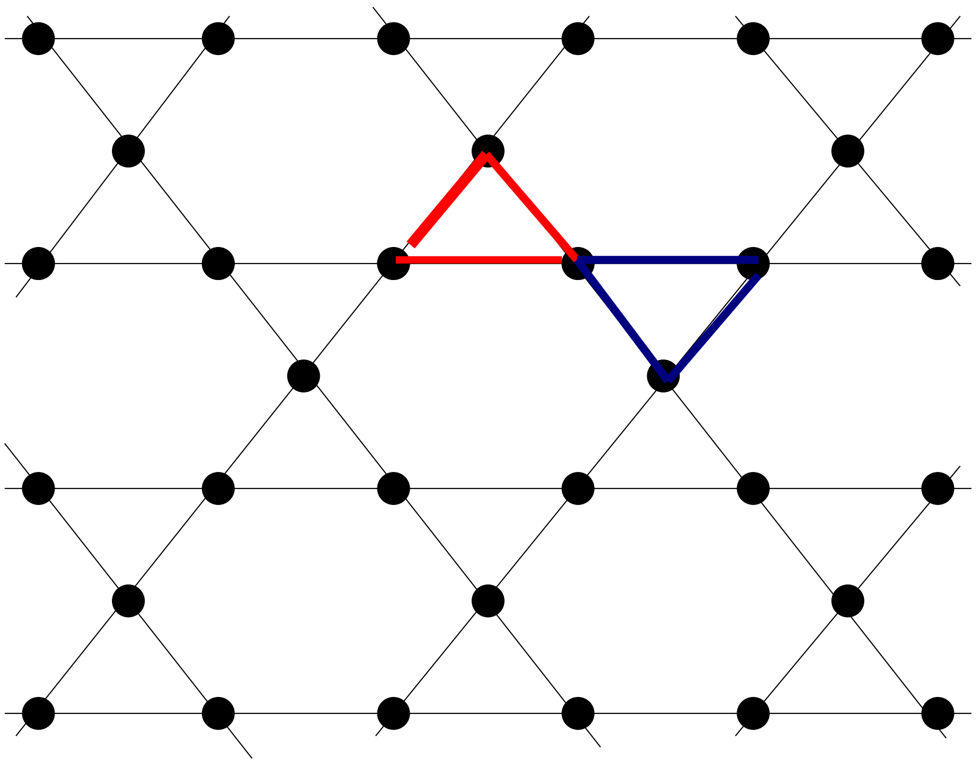


A lattice for theorists !

Corner-sharing tetraedras in 3D & 2D

The Kagome lattice

2D lattice of corner sharing triangles



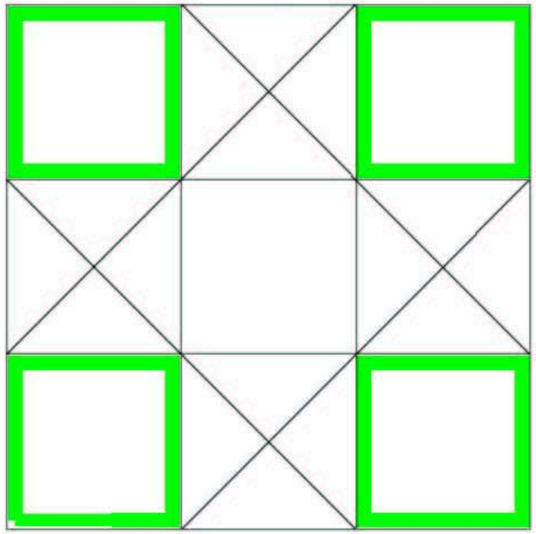
Very high classical degeneracy !!

Quantum disordered phases

& Quantum Critical Point (QCP) scenario

VBC vs SL

Checkerboard lattice

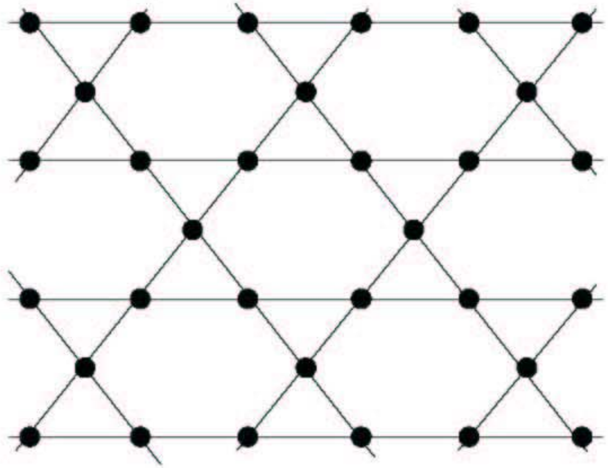


Valence bond crystal

- Finite gaps
- Spontaneous translation symm. breaking

(Fouet al.)

Kagome lattice

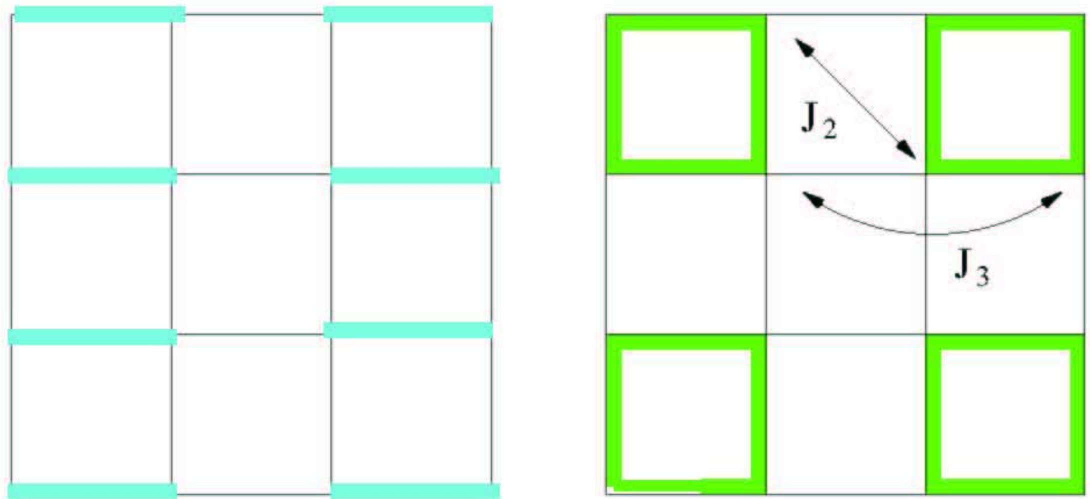


Spin liquid (SL)

- No symmetry breaking
- Large # of low energy singlets

(Mila et al.)

VBC candidates for the AF square lattice

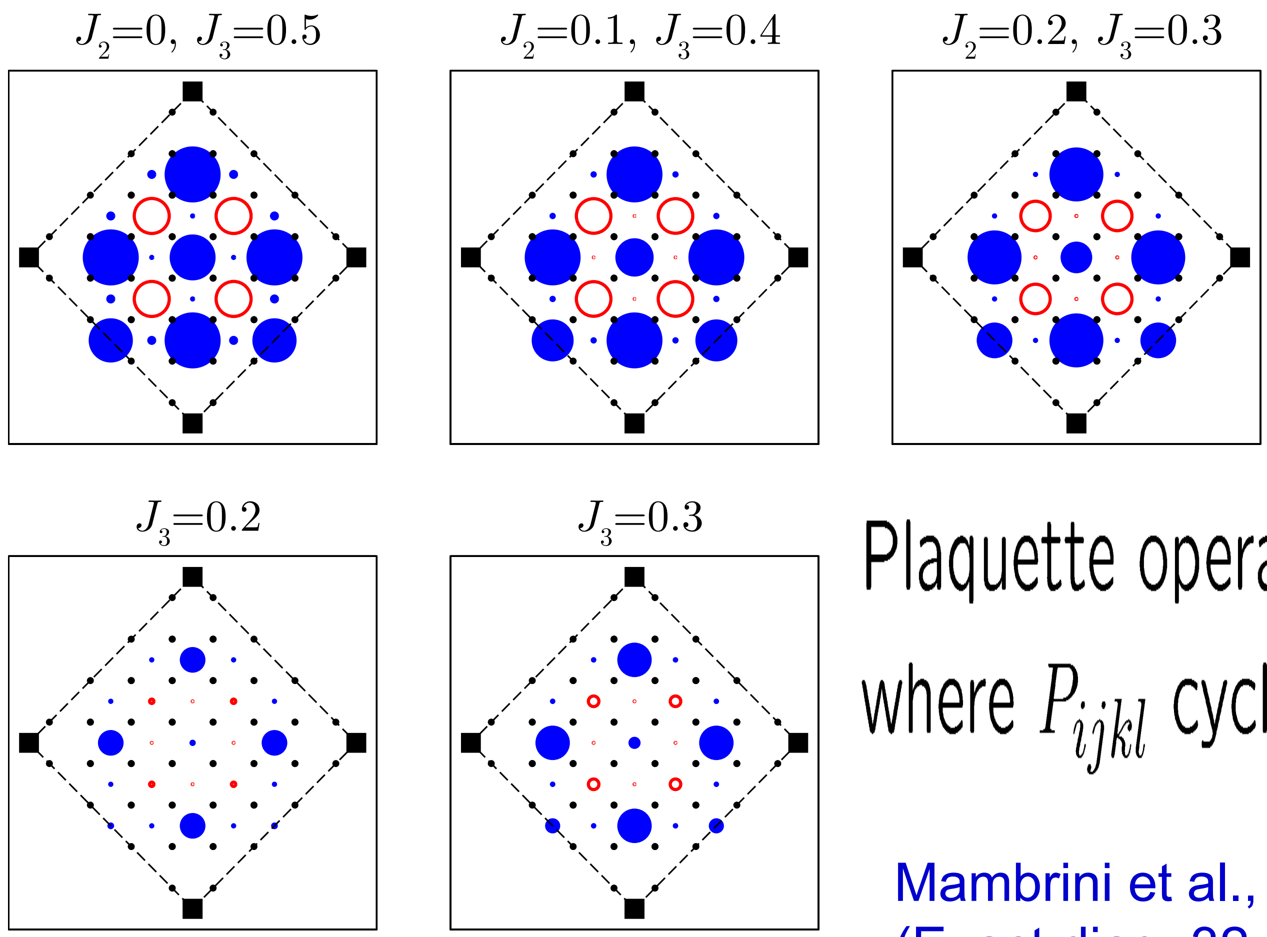


(a) (b)

Next-nearest-neighbor J_2 and N.N.N.N J_3 stabilize 4-fold deg. plaquette VBC phase

Plaquette correlations in J1-J2-J3

$$C_{\mathsf{plaquette}}(p,q) = \langle Q_p Q_q \rangle$$

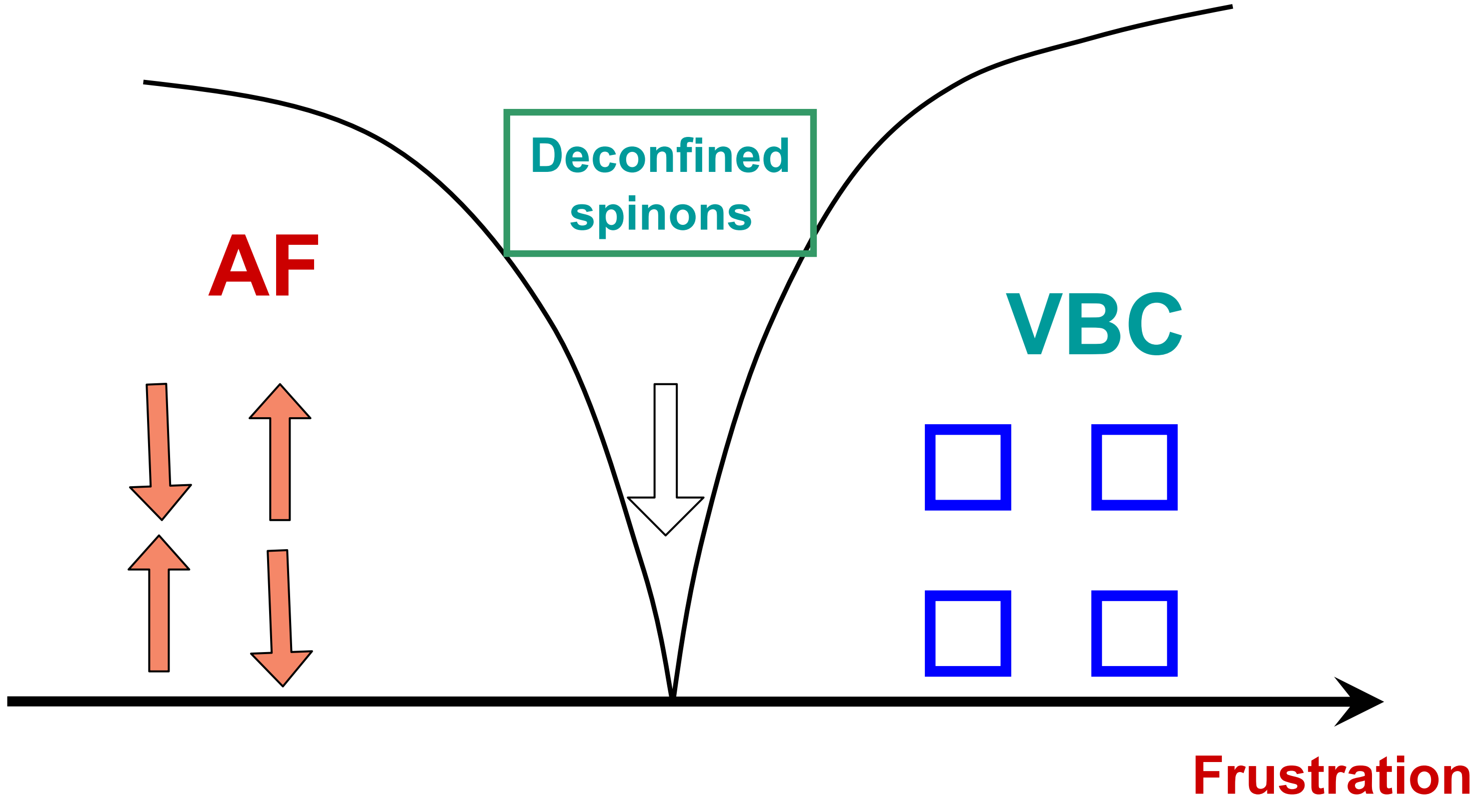


Plaquette operator $Q_{ijkl} = P_{ijkl} + P_{ijkl}^{-1}$

where P_{ijkl} cyclic permutation

Mambrini et al., PRB **74**, 144422 (2006)
(Exact diag. 32 sites cluster)

Deconfined Critical Point



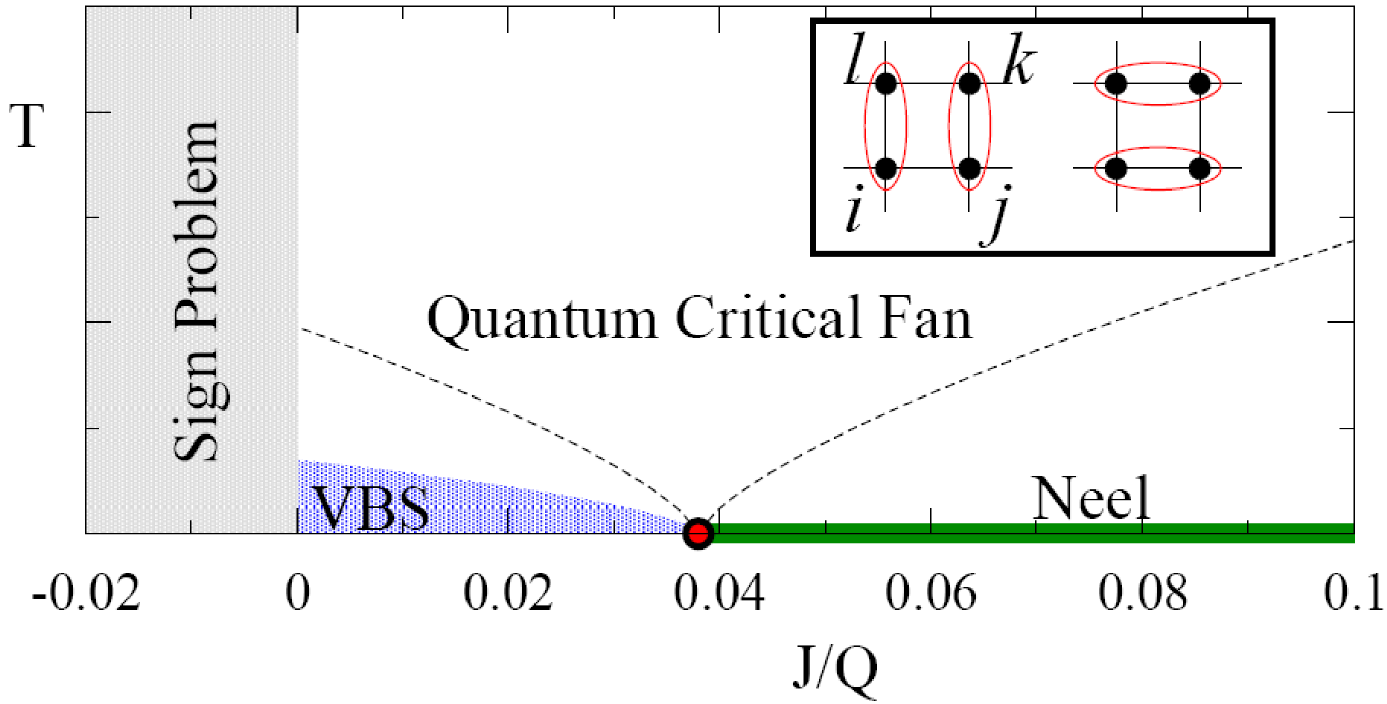
Beyond Ginzburg-Landau paradigm of phase transitions !
Senthil, Sachdev, Fisher et al.

Other proposal …

Sandvik, Phys. Rev. Lett. **98**, 227202 (2007)

Melko & Kaul, arXiv:0707.2961

$$H_{\mathrm{JQ}} = J\sum_{\langle ij\rangle} \mathbf{S}_i\cdot\mathbf{S}_j - Q\sum_{\langle ijkl\rangle}(\mathbf{S}_i\cdot\mathbf{S}_j - 1/4)(\mathbf{S}_k\cdot\mathbf{S}_l - 1/4)$$



SSE-QMC

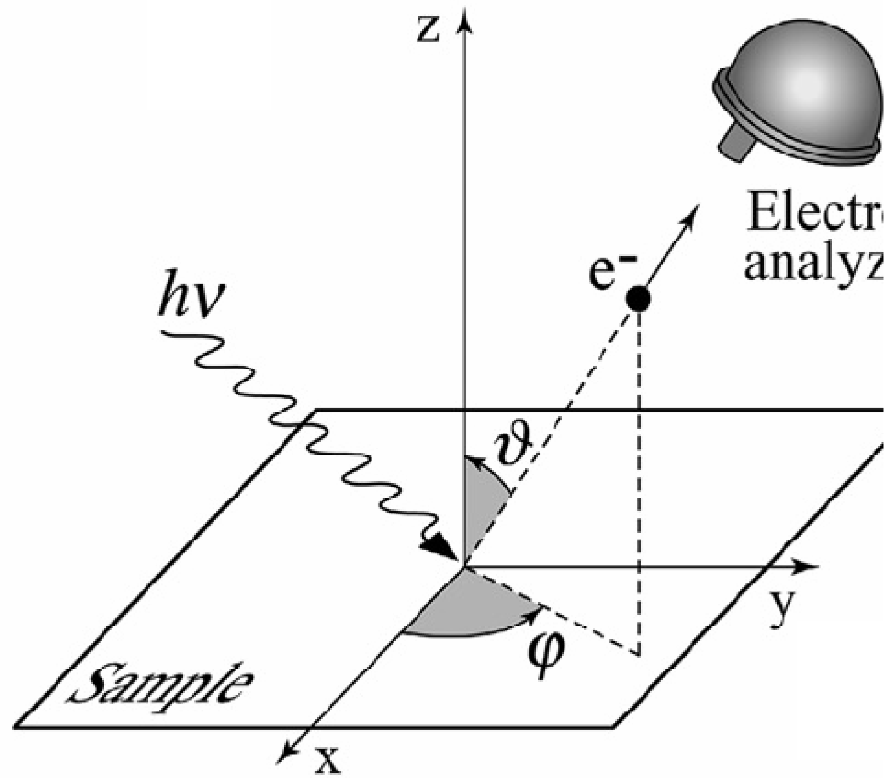
Doping frustrated magnets

Itinerant frustrated systems

- spinel oxide $LiTi_2O_4$
  Sun et al., PRB **70**, 054519 (2004)
- 5d transition-metal pyrochlores as $Cd_2Re_20_7$ or KOs_2O_6
  Hanawa et al., PRL **87**, 187001 (2001)
  Hiroi et al., JPSJ **73**, 1651 (2004)
- CoO triangular layer based compound
  Takada et al., Nature **422**, 53 (2003)

All superconducting with T_c up to 13.7 K !

Injecting a hole by ARPES



Photoemission geometry

Andrea Damascelli

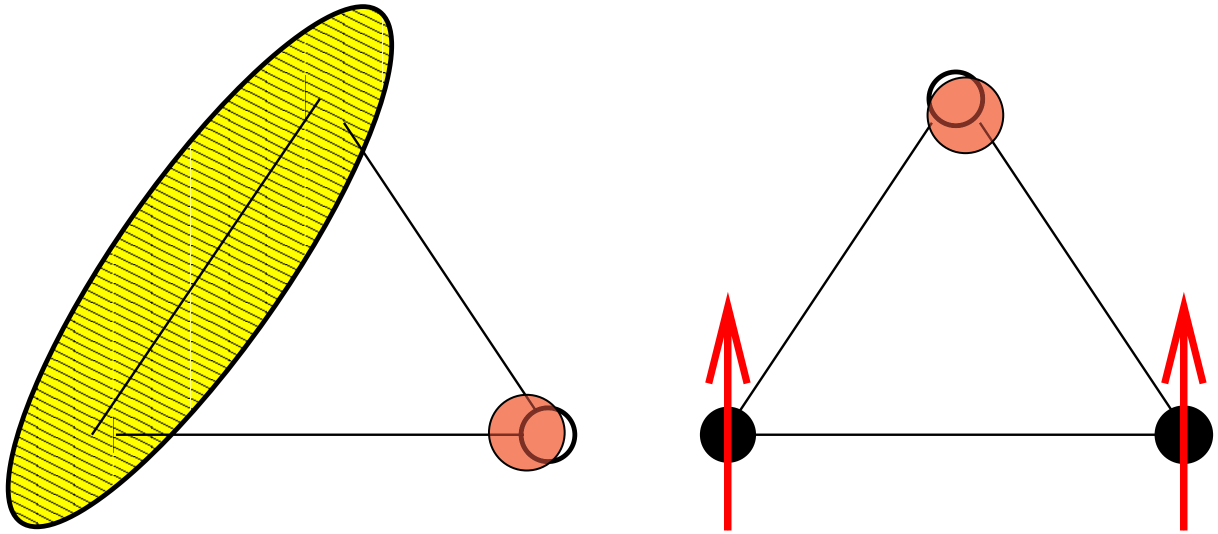
Physica Scripta. Vol. T109, 61–74, 2004

$$A(\boldsymbol{k},\omega) = A^{+}(\boldsymbol{k},\omega) + A^{-}(\boldsymbol{k},\omega) = -(1/\pi)\,\mathrm{Im}\,G(\boldsymbol{k},\omega)$$

Kinetic frustration

t-J model not particle-hole symmetric => sign of t matters !

J=0

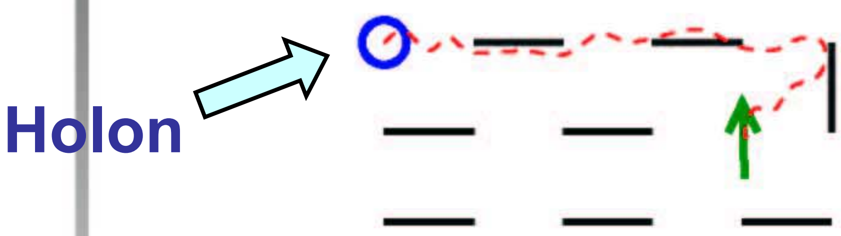


	singlet	triplet
t>0 :	E=-2t	E=-t
t<0 :	E=-|t|	E=-2|t|

Nagaoka

Confinement vs deconfinement

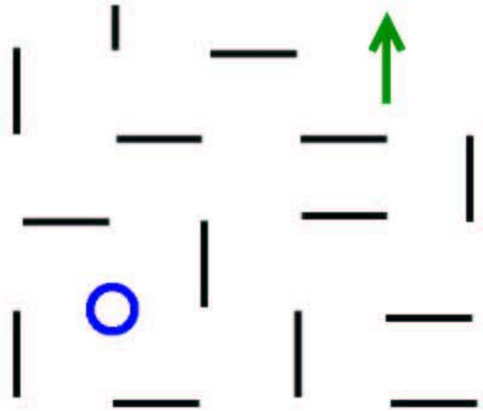
See Sachdev



(a)

"string potential"

Checkerboard ??

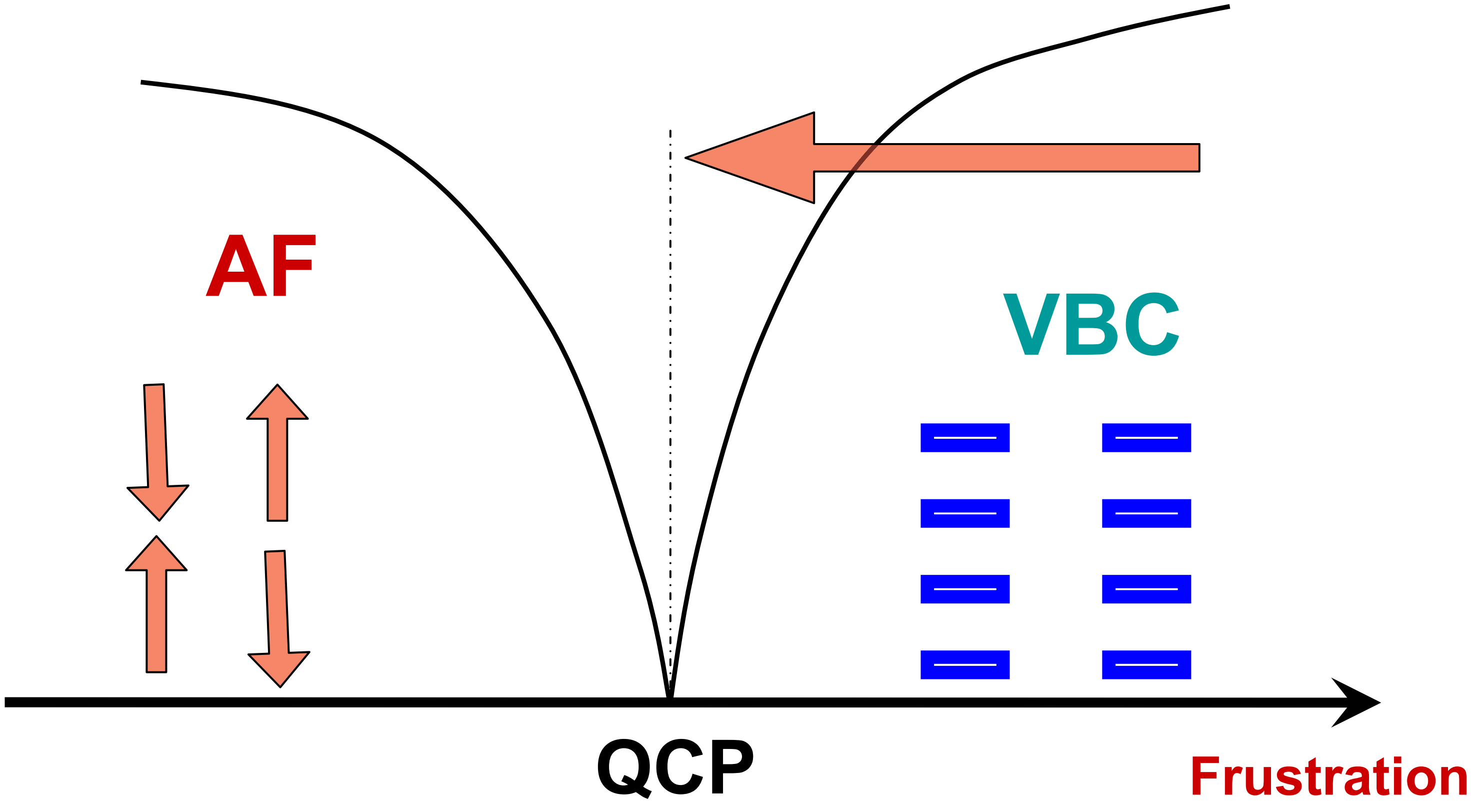


(b)

"deconfined" spinon

Kagome ??

Two emerging length scales



$$\xi_{\mathrm{conf}} \sim \xi_{\mathrm{VBC}} \gg \xi_{\mathrm{AF}}$$

Senthil et al.

Injected hole acts like a probe: bare and dressed wavefunctions

$$|\Phi_{\mathrm{bare}}\rangle = c_{O,\downarrow}|\Phi_0\rangle$$

Ground state of the Mott insulator

Remove a spin down at a given site O

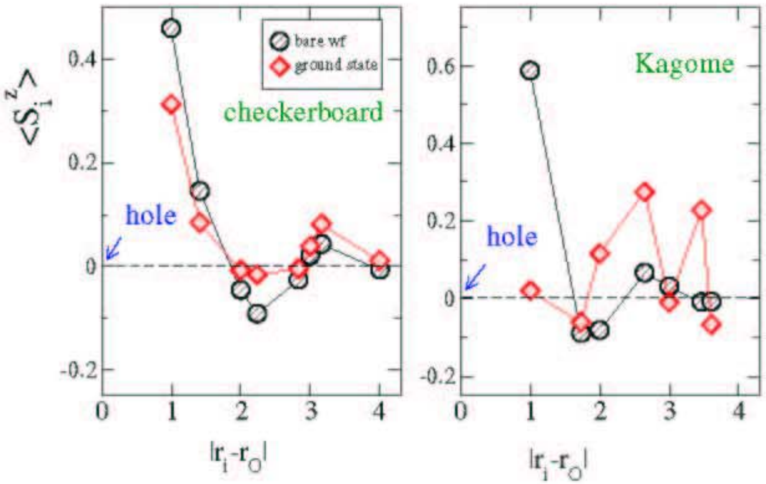
⇒ Leaves behind a spin up polarization at a typical distance ξ_{AF} from site O

$$|\Phi_{\mathrm{GS}}\rangle = \text{"one impurity-one spinon" GS}$$

$\langle S_i^z \rangle_{\mathrm{GS}}$ ⇒ Profile of spinon wavefunction

Spin density around a vacancy

$\langle S_i^z \rangle$ at distance $\mathbf{r} = \mathbf{r_i} - \mathbf{r}_O$ from defect



- $\langle S_i^z \rangle_{\mathrm{bare}} \rightarrow$ spin-spin correlation in host
- $\langle S_i^z \rangle_{\mathrm{gs}} \rightarrow$ "spinon" wavefunction

Kagomé: deconfined

Checkerboard: strongly confined

D.P. et al. PRB (2006)

Quasiparticle weight

Overlap (squared) $Z = |\langle \Phi_{\rm gs} | \Phi_{\rm bare} \rangle|^2$
zero or finite ?

$$Z_{\rm Kagome} = 0$$
$$Z_{\rm checkerboard} \simeq 1$$

Dynamic hole (finite t) $\longrightarrow Z_{\mathbf{k}}$
$A(\mathbf{k}, \omega) = Z_{\mathbf{k}} \delta(\omega - \omega_{\mathbf{k}}) + A_{\rm inc}$??

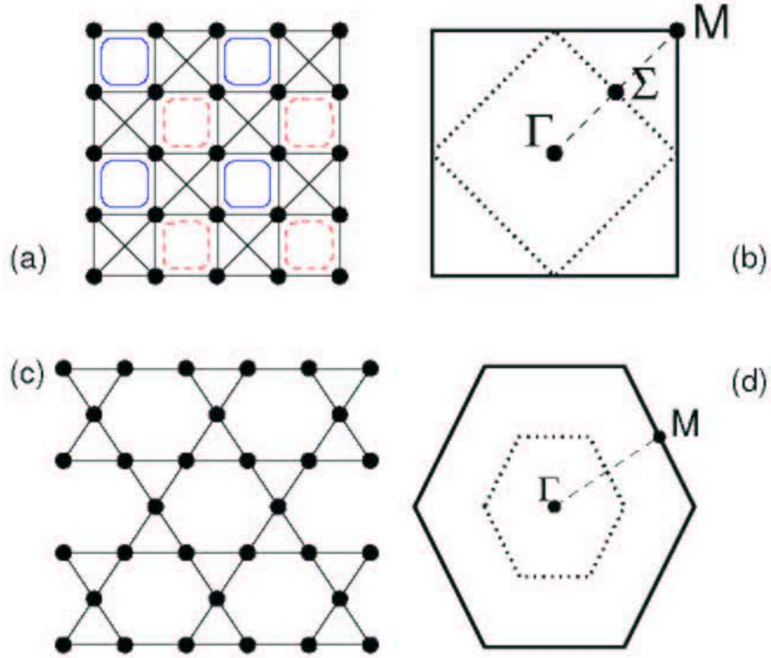
Single hole Green function

$$A(\mathbf{k},\omega) = \mathrm{Im}\{\langle\Phi_0|c^\dagger_{\mathbf{k}\uparrow}\frac{1}{\omega+i\epsilon-H}c_{-\mathbf{k}\downarrow}|\Phi_0\rangle\}$$

"Bare" wavefunction
(Bloch state)

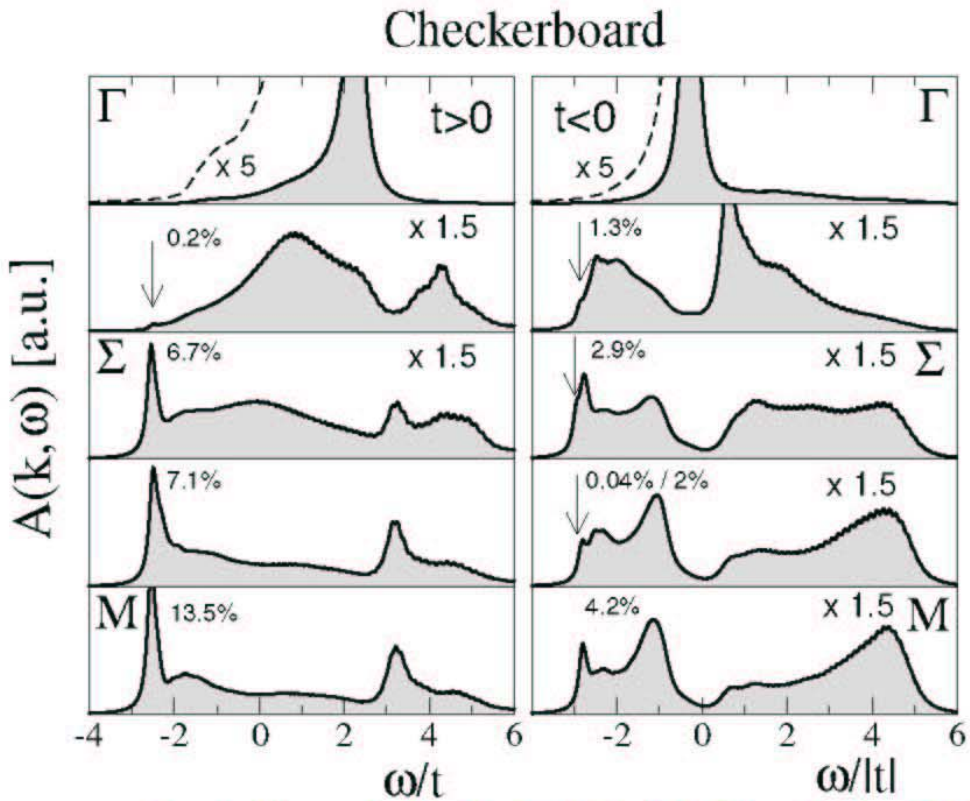
Use Lanczos continued-fraction method

Hole dynamics: t-J model



$$H = -t \sum_{\langle i,j \rangle,\sigma} \mathcal{P} \left(c_{i,\sigma}^{\dagger} c_{j,\sigma} + \text{h.c.} \right) \mathcal{P} + J \sum_{\langle i,j \rangle} S_i \cdot S_j - \frac{1}{4} n_i n_j$$

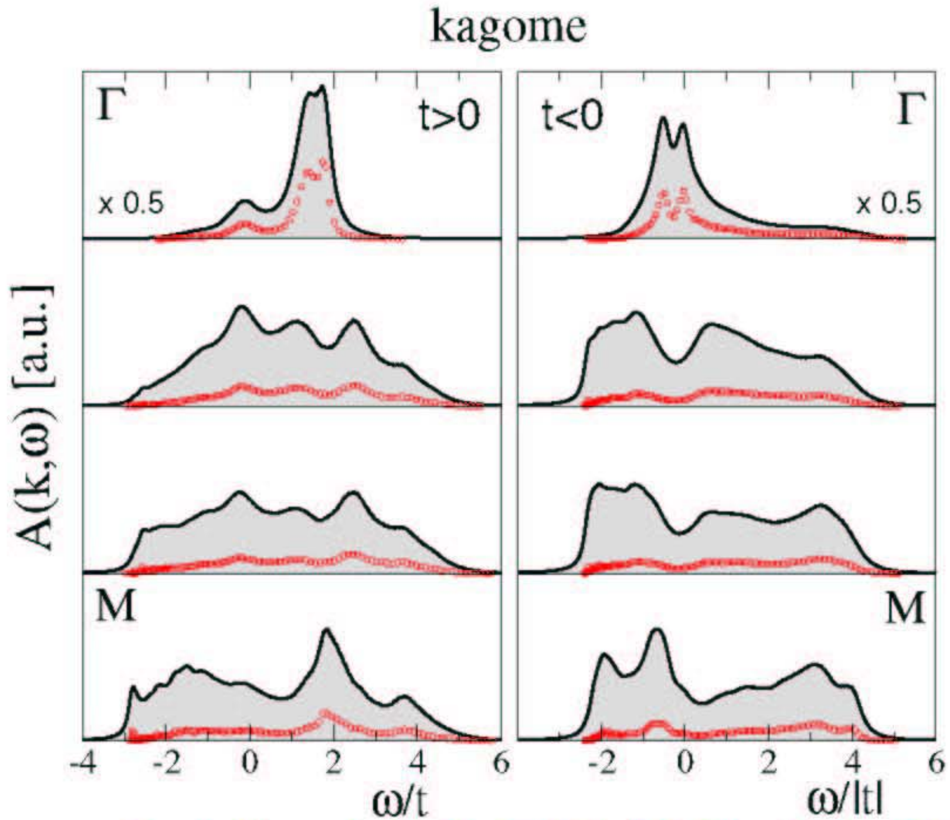
Hole dynamics in the VB Solid



Small quasi-particle peaks: holon-spinon boundstate

A. Läuchli & DP, PRL **92**, 236404 (2004)

Single hole doped in a spin liquid



Incoherent spectrum

Weights distributed on many poles even at low energies

A. Läuchli & DP, PRL **92**, 236404 (2004)

Summary / Conclusions

- Frustration + quantum fluctuations lead to exotic disordered GS (VBC, SL, …)
- Possible realization of exotic physics (Deconfined Critical Points, etc…)
- The doping issue might reserve many surprises but needs further investigations