Quantum spin liquid:
—A novel quantum state of matter—

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OUTLINE

1. Introduction

2. A possible quantum spin liquid state in the 2D organic Mott insulators with triangular lattice

3. Elementary excitations and phase diagram of the quantum spin liquid

4. A novel quantum phase in the Mott Insulator
   Can insulators have Fermi surface ?

5. Summary

M.Yamashita *et al*., Nature Phys. **5**, 44 (2009).
M. Yamashita *et al*., Science **328**, 1246 (2010).
D. Watanabe *et al*., Nature Commun. **3**, 1090 (2012).

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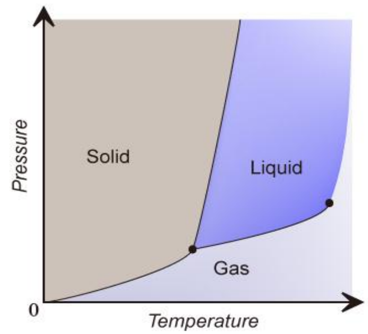
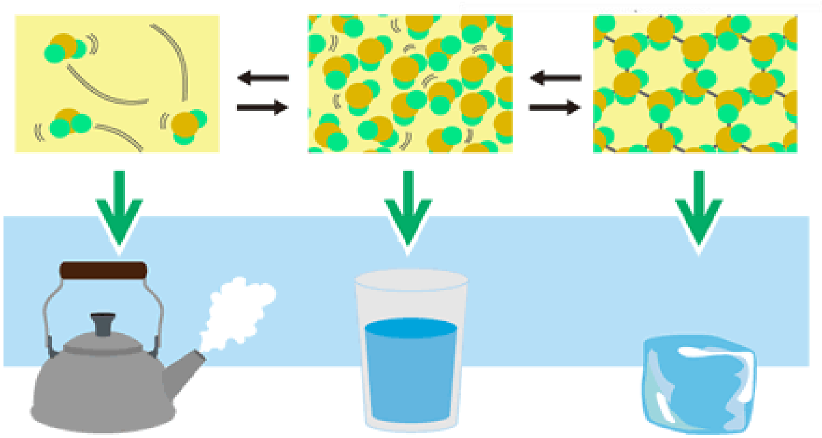
Quantum Liquid

Classical Liquids

- ✓ Frozen at the absolute zero temperature
- ✓ Ordering in conventional way

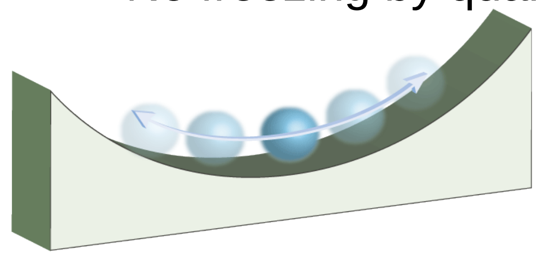
e.g. crystallization





Quantum Liquids

- No freezing by quantum fluctuation

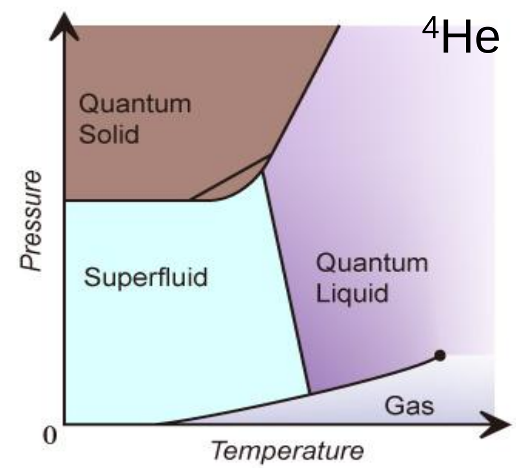


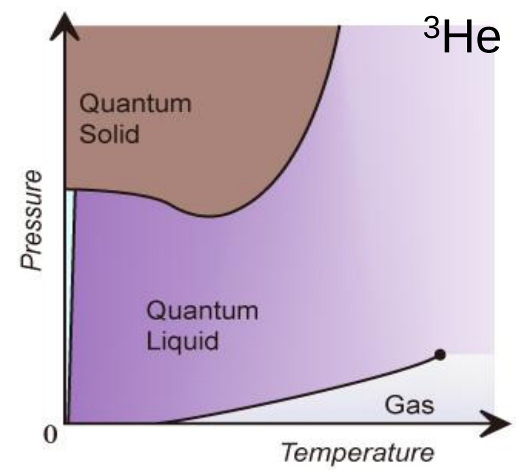
Zero point oscillation
> Interaction

Difference of quantum statics explicitly emerges

Bose statics
BEC, superfluid ^{4}He

Fermi statics
Fermi liquid, Cooper pairing





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Classical Liquids

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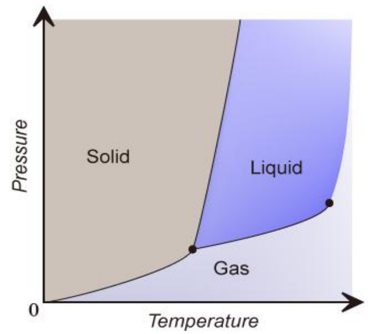

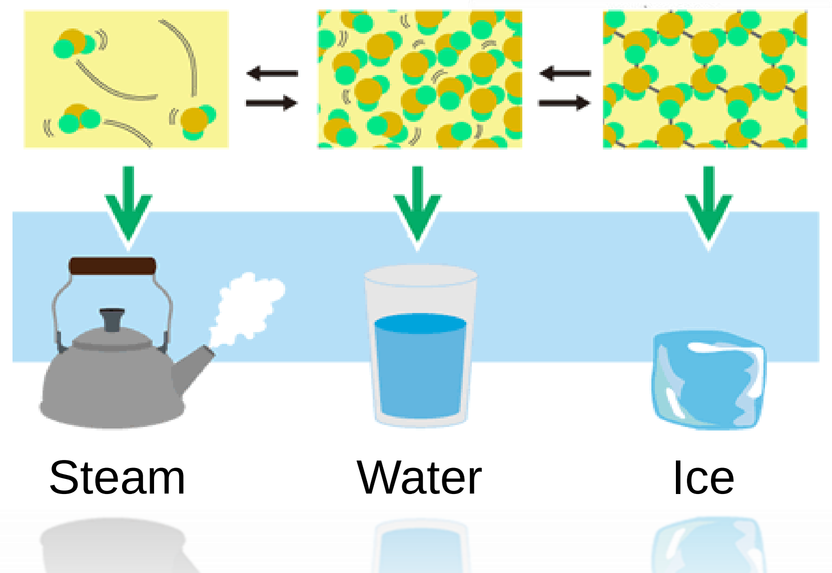

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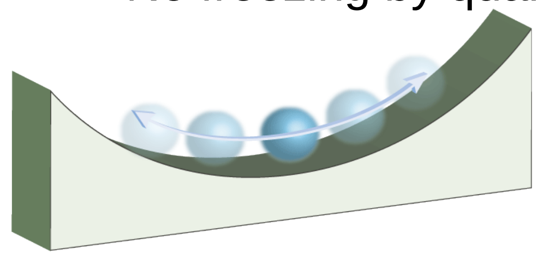
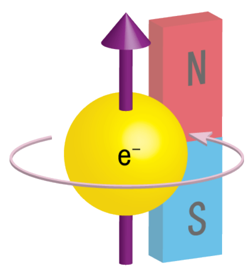
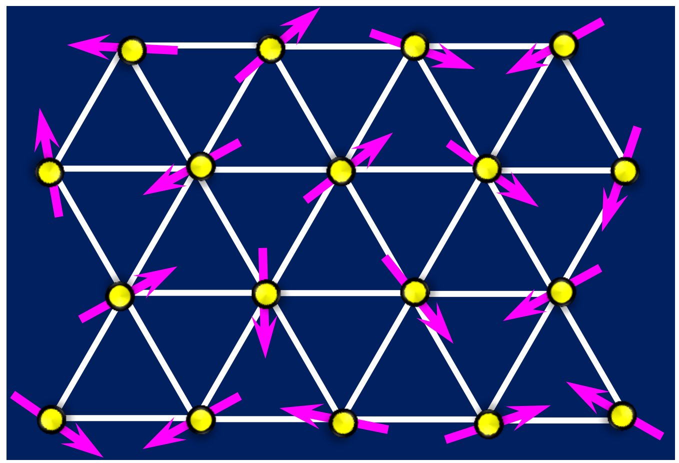


Zero point oscillation
> Interaction

Quantum Spin Liquids

A state of matter where strong quantum fluctuations melt the long-range magnetic order even at absolute zero temperature.



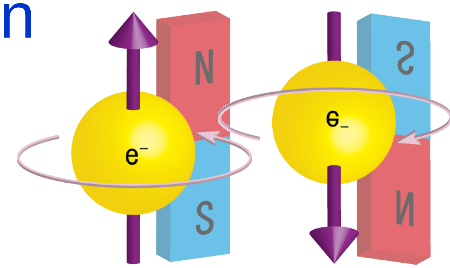


Introduction

A spin pair of *S*=1/2 spins coupled by the Heisenberg interaction

$$J\boldsymbol{S_1}\cdot\boldsymbol{S_2} \qquad J>0$$

Antiferromagnetic interaction



$$\boldsymbol{S_1}\cdot\boldsymbol{S_2} = S_{1x}S_{2x} + S_{1y}S_{2y} + S_{1z}S_{2z}$$
$$= \frac{1}{2}(S_{1+}S_{2-} + S_{1-}S_{2+}) + S_{1z}S_{2z}$$

Classical spin

$$\uparrow\downarrow \qquad < S_{1z}S_{2z} > \qquad E_N = -\frac{1}{4}J$$

Quantum spin (no classical analogue)

$$|s> = \frac{1}{\sqrt{2}}(|\uparrow\downarrow> - |\downarrow\uparrow>)$$ singlet

$$< S_{1x}S_{2x} >, < S_{1y}S_{2y} >, < S_{1z}S_{2z} >$$

$$E_{sx} = E_{sy} = E_{sz} = -\frac{1}{4}J$$ Quantum fluctuation

$$E_s = -\frac{3}{4}J < E_N$$

1D spin-1/2 Heisenberg antiferromagnet

$$\mathcal{H} = J \sum_{i<j}^{N} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Ground state $S=0$

(1) Classical Neel state

↑ ↓ ↑ ↓ ↑ ↓

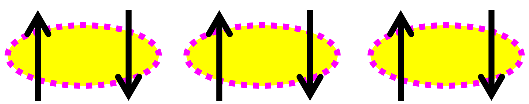
Long range order

$$E_{Neel} = -\frac{1}{4}JN = -0.25JN$$

Spin rotational symmetry: **Broken**

Translational symmetry: **Broken**

(2) Dimer state (Valence Bond Soild State)



$$E_{singlet} = -\frac{3}{8}JN = -0.375JN$$

Spin singlet $|s>= \frac{1}{\sqrt{2}}(|\uparrow\downarrow> - |\downarrow\uparrow>)$

Long range order of singlet pairs

Spin rotational symmetry: **Unbroken**

Translational symmetry: **Broken**

(3) Exact solution (Quantum Spin Liquid State)

$$E_0 = -(\ln 2 - 1/4)JN = -0.4431JN$$

No long range order

Spin rotational symmetry: **Unbroken**

Translational symmetry: **Unbroken**

Spin Liquids states do not break any simple symmetry: neither spin-rotational symmetry nor lattice symmetry.

1D spin-1/2 Heisenberg antiferromagnet

Ground state

Tomonaga-Luttinger liquid

Quantum spin liquid (No long range order)

Spin-spin correlation function $|<\boldsymbol{S}_i \cdot \boldsymbol{S}_j>| \sim |i-j|^{-1} \sim r^{-1}$

Algebraic spin correlation (critical phase)

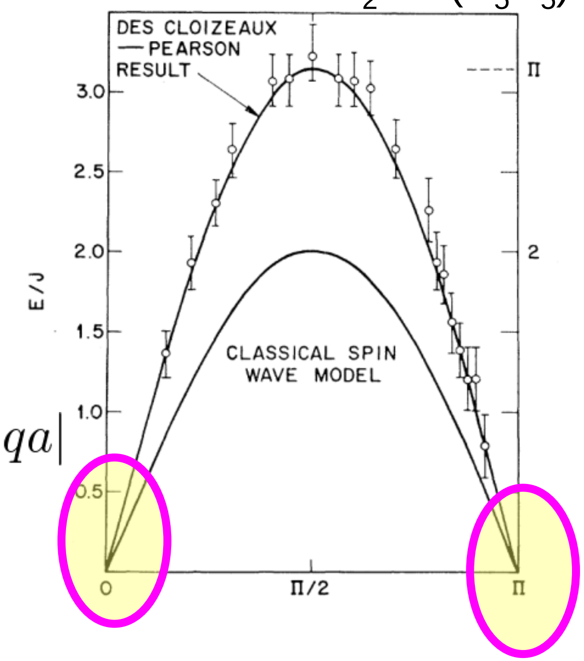
Excitation

Gapless (magnetic)

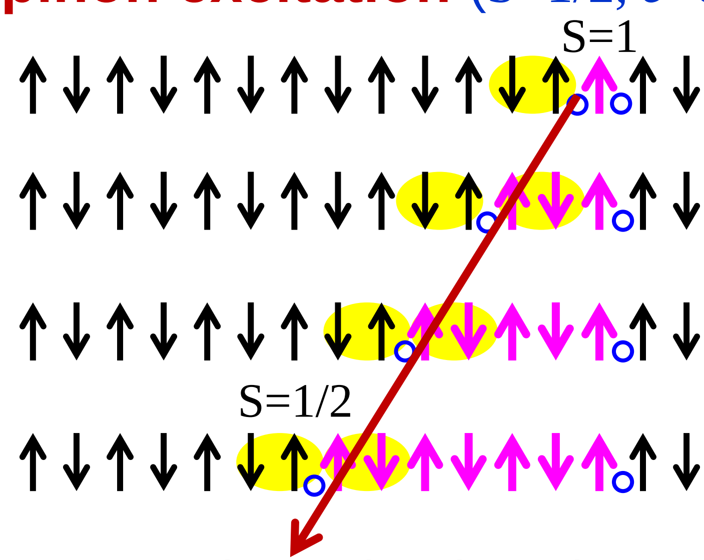
J.des Cloizeaux and J.J. Pearson

$$\Delta E_1(q) = \frac{\pi}{2} J |\sin qa|$$

$CuCl_2 \bullet 2N(C_5D_5)$



Spinon excitation (S=1/2, *e*=0)



No energy cost in moving the spinons far apart.

Notion of QSL is firmly established in 1D. How about in higher dimensions?

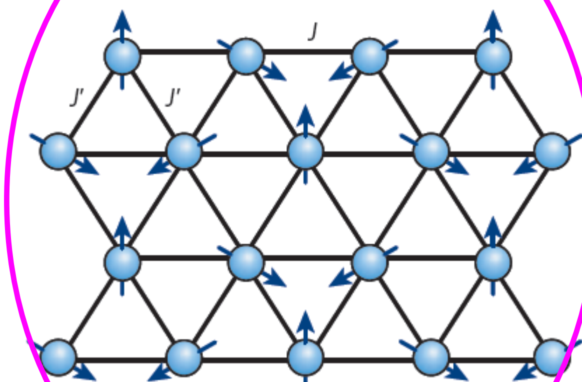
QSLs in two and three dimensions

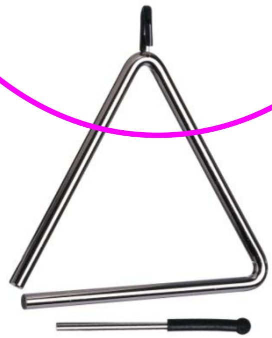
Geometrical frustrations are required

Classical — A significant ground-state degeneracy

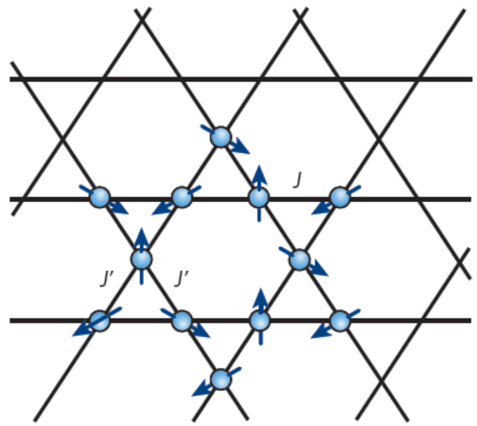
Quantum — Quantum fluctuation lifts the degeneracy. It may lead to a QSL ground state.

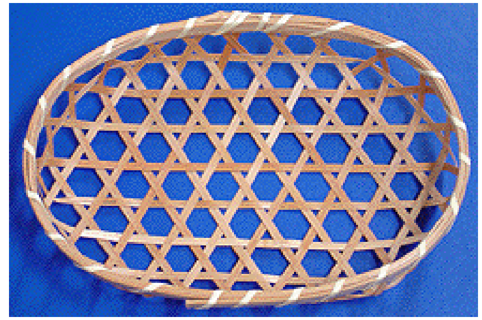
Triangular lattice



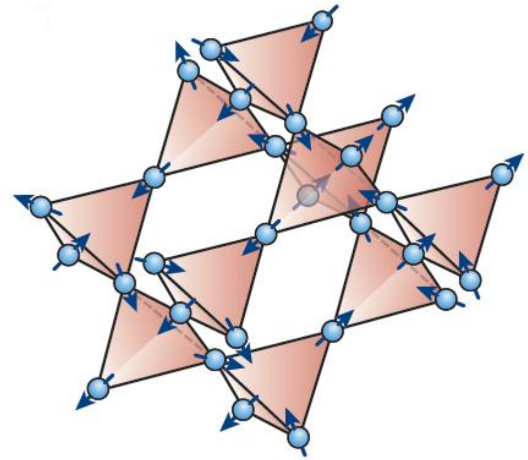


Kagome lattice





Pyrochlore lattice

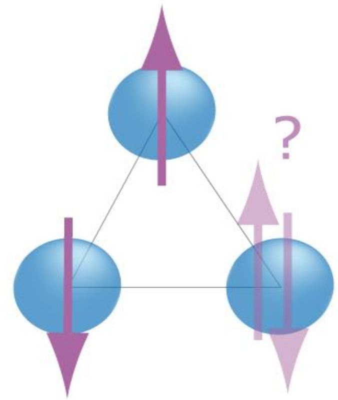


Quantum spin liquid state in 2D triangular lattice

2D triangular lattice

P.W. Anderson (1973)

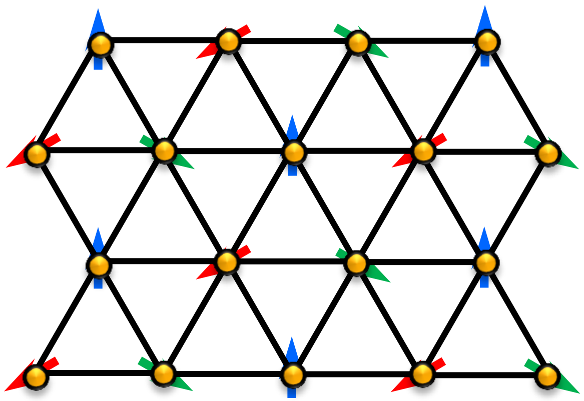
A triangle of AF interacting Ising spins, all spins cannot be antiparallel.

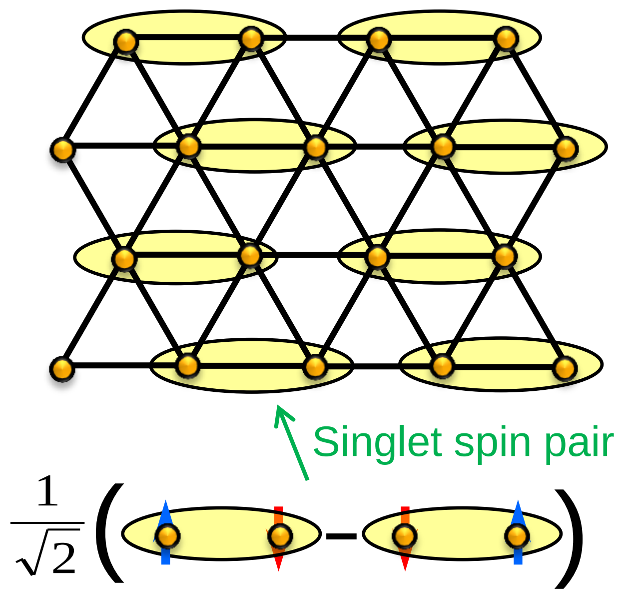


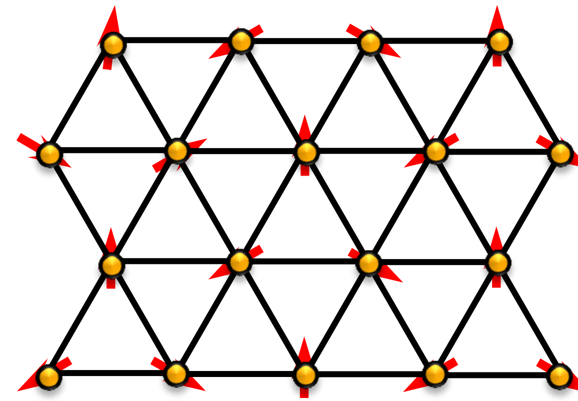
Frustration

What is the ground state of 2D triangular lattice ?

Néel order ?	Valence Bond Solid ?	Spin Liquid ?







Broken spin-rotational symmetry
Broken translational symmetry

3-sublattice Néel order
(120° structure)

Unbroken spin-rotational
Broken translational

Long range order of singlet

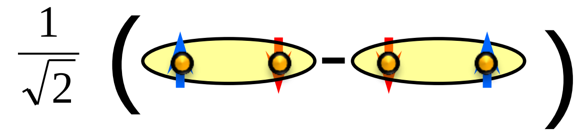
Unbroken spin-rotational
Unbroken translational

No simple symmetry breaking

Quantum spin liquid state in 2D triangular lattice

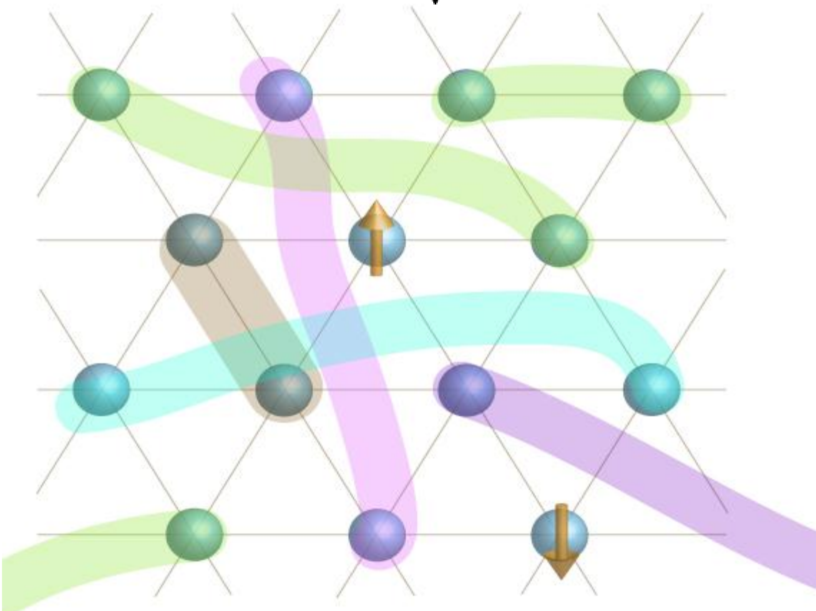
$$\mathcal{H} = J \sum_{(i,j)=\Delta} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

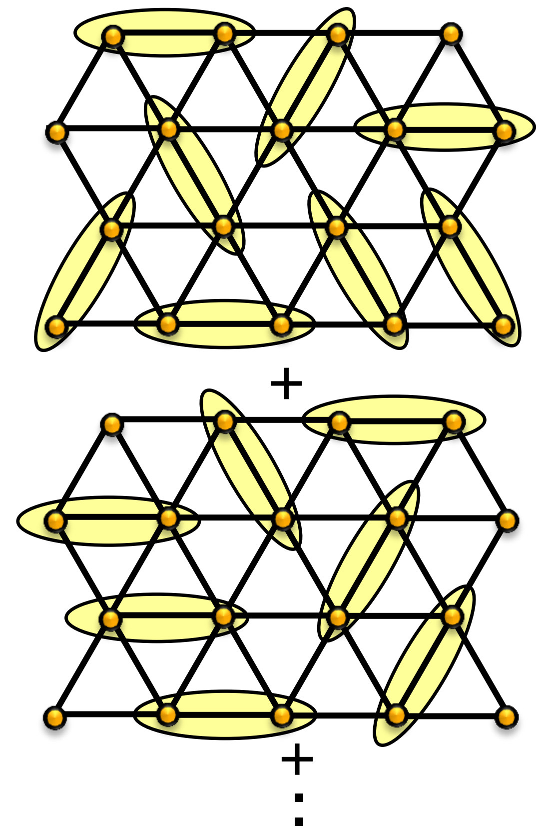
Heisenberg model with nearest-neighbor interaction



Resonating Valence Bond (RVB) Liquid

$$= \frac{1}{\sqrt{2}}(|\uparrow\downarrow> - |\downarrow\uparrow>)$$





Superposition of different configurations

Resonance between highly degenerated spin configurations leads to a liquid-like wavefunction.

P. Fazekas and P.W. Anderson, Philos. Mag. (74)

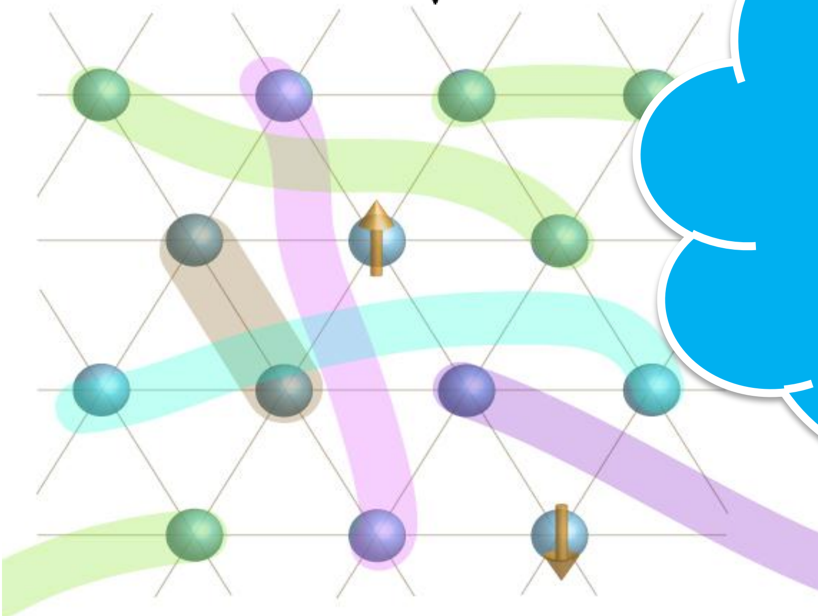
Quantum spin liquid state in 2D triangular lattice

$$\mathcal{H} = J \sum_{(i,j)=\Delta} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

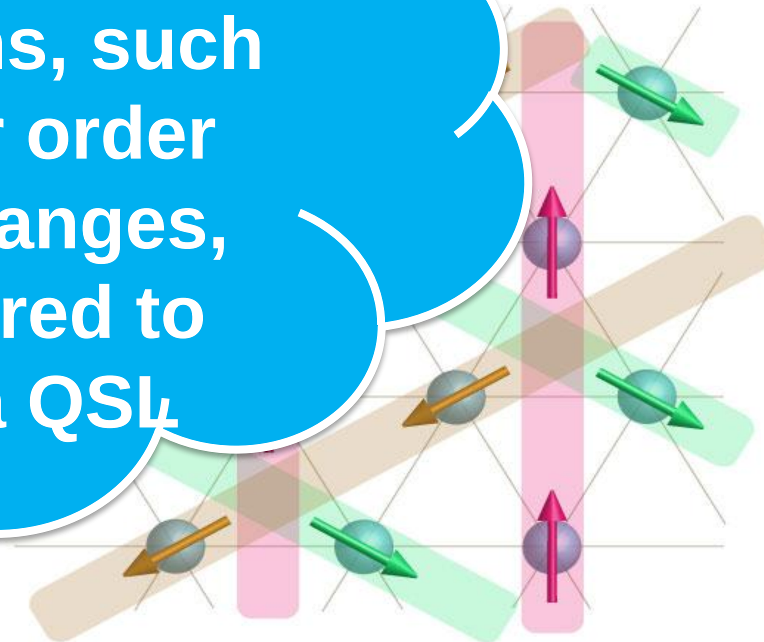
Heisenberg model with nearest-neighbor interaction

Resonating Valence Bond (RVB) Liqui… order

$$= \frac{1}{\sqrt{2}}(|\uparrow\downarrow> -| \ldots$$



Further fluctuations, such as higher order ring exchanges, are required to realize a QSL



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3-sublattice Néel order (120° structure)

L. Caprioti, A. E.E. Trumper and S. Sorella, PRL (99)

B. Bernu, C. Lhuillier and L. Pierre, PRL (92)

Quantum spin liquids in two and three dimensions

Order or not order?

- geometrical frustration plays important rule

Many theories proposed

- Resonating-valence-bond liquid
- Chiral spin liquid
- Quantum dimer liquid
- Z_2 spin liquid
- Algebraic spin liquid
- Spin Bose Metal
- Etc.,,

New quantum condensed-state may be realized!!

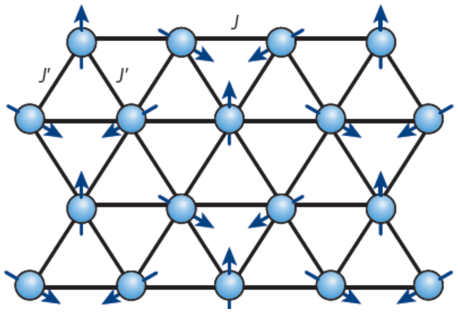
Elementary excitaion not yet identified

- Spinon with Fermi surface
- Vison
- Majorana fermions

Quantum spin liquid on a 2D triangular lattice

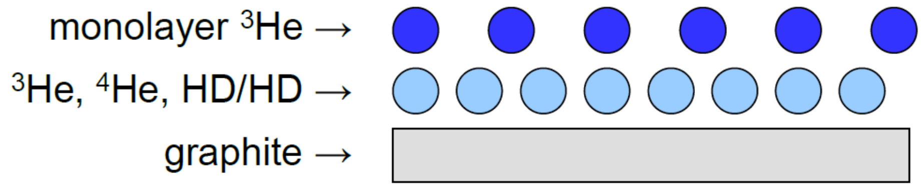
Only a few candidate materials exist.

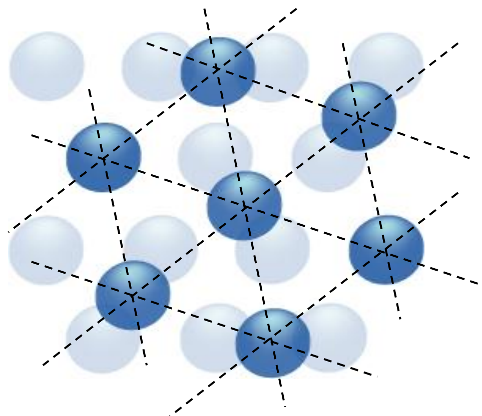
Triangular lattice



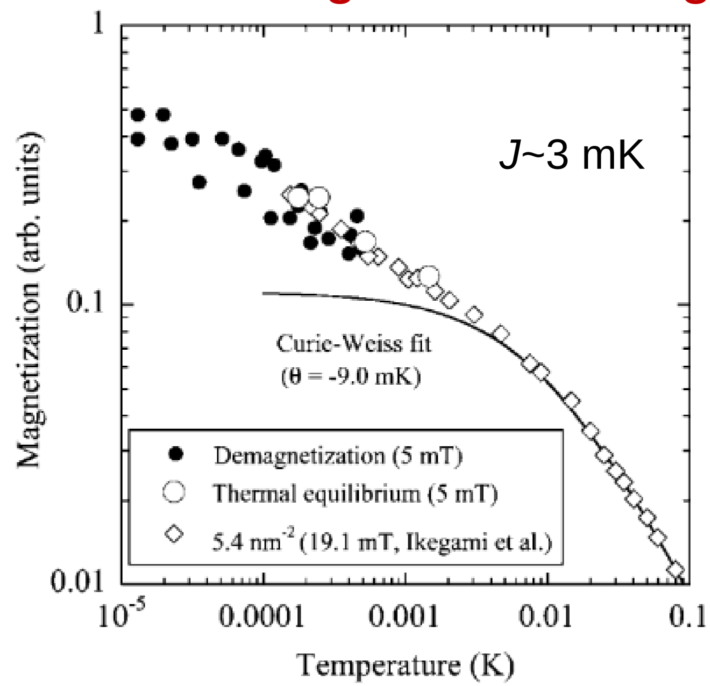
^{3}He on graphite

Organic compounds





No magnetic ordering



R. Masutomi *et al*., PRL 92, 025301 (04)

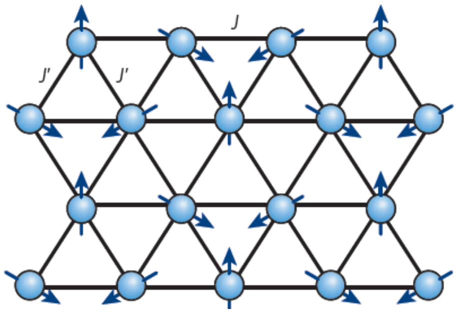
Specific heat

K. Ishida *et al*. PRL 79, 3451 (97)

Quantum spin liquid on a 2D triangular lattice

Only a few candidate materials exist.

Triangular lattice



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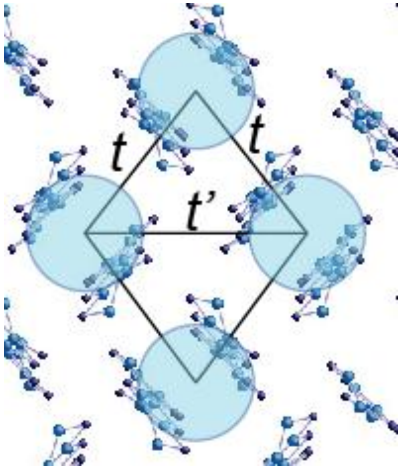


κ-[bis(ethylenedithio)tetrathiafulvalene]$_2$-Cu$_2$-(CN)$_3$

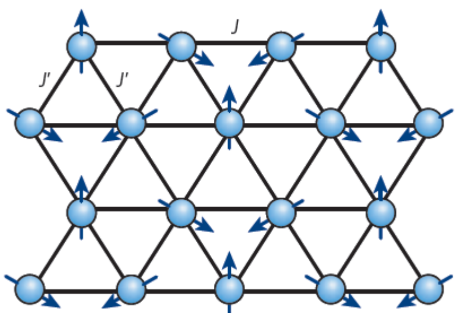
$C_2H_5[CH_3]_3$Sb[Pd(1,3-dithiole-2-thione-4,5-dithiolate)$_2$]$_2$

catechol-fused ethylenedithiotetrathiafulvalene

Quantum spin liquid on a 2D triangular lattice

Only a few candidate materials exist.

Triangular lattice



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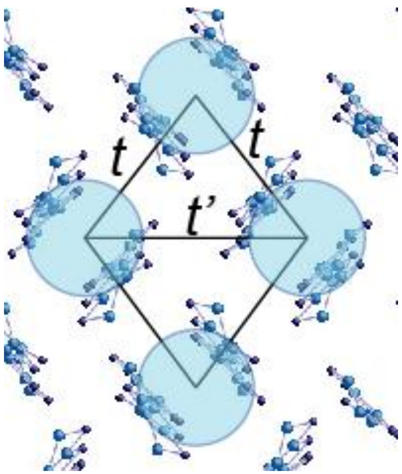
Organic compounds



κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$

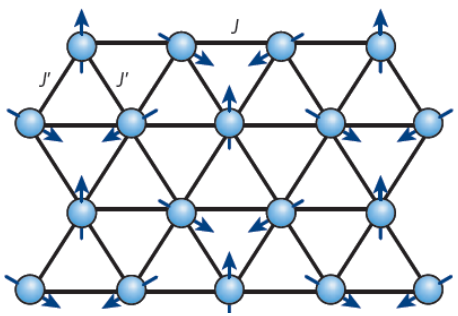
EtMe$_3$Sb[Pd(dmit)$_2$]$_2$

κ-H$_3$(Cat-EDT-TTF)$_2$

Quantum spin liquid on a 2D triangular lattice

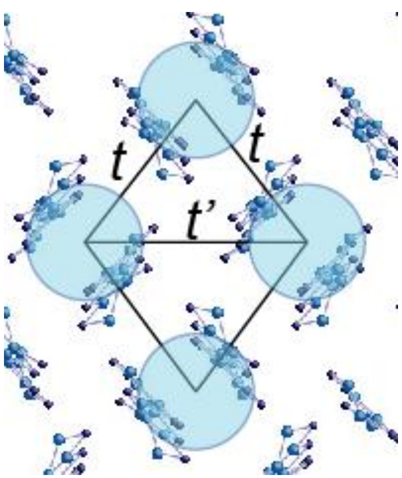
Only a few candidate materials exist.

Triangular lattice



^{3}He on graphite

Organic compounds



κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$

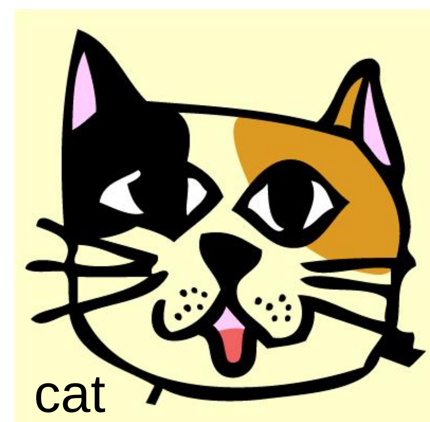
κ-ET

EtMe$_3$Sb[Pd(dmit)$_2$]$_2$

dmit

k-H$_3$(Cat-EDT-TTF)$_2$

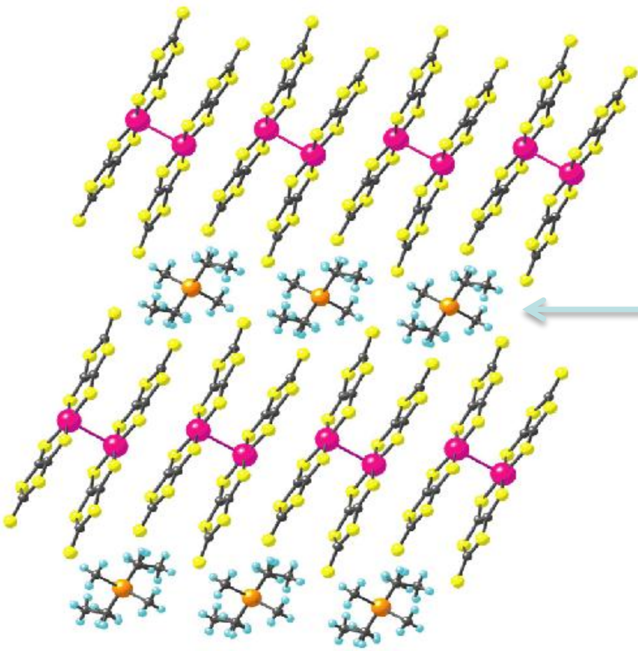
cat



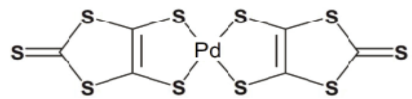
$EtMe_3Sb[Pd(dmit)_2]_2$

2D spin system

SIDE VIEW



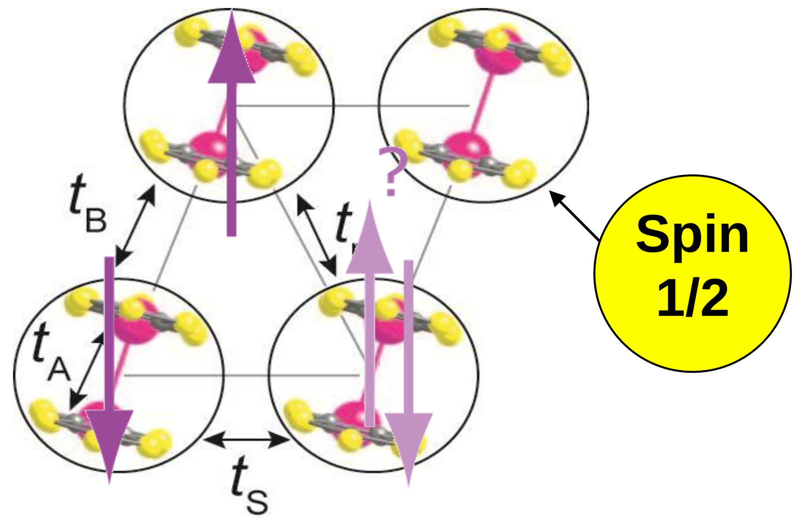
2D layer of
$Pd(dmit)_2$ molecule



Cation layer
Non-magnetic
X = $EtMe_3Sb$,
Et_2Me_2Sb,
etc.

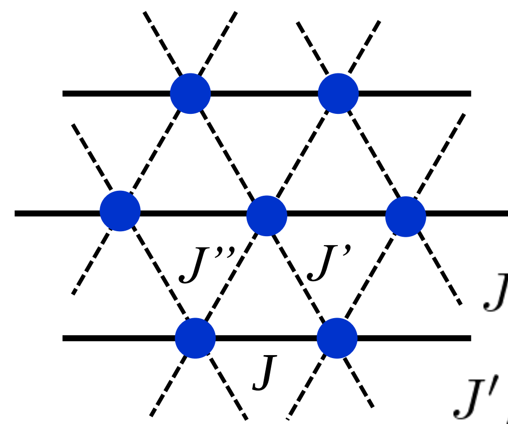
S = ½ Triangular lattice

TOP VIEW



$$t_A \sim 0.5\ \mathrm{eV} \gg t_B, t_s, t_r$$
$$t_B \sim 55\ \mathrm{meV},\ t_s \approx t_r \sim 45\ \mathrm{meV}$$

Dimerization → Half-filled Mott insulator



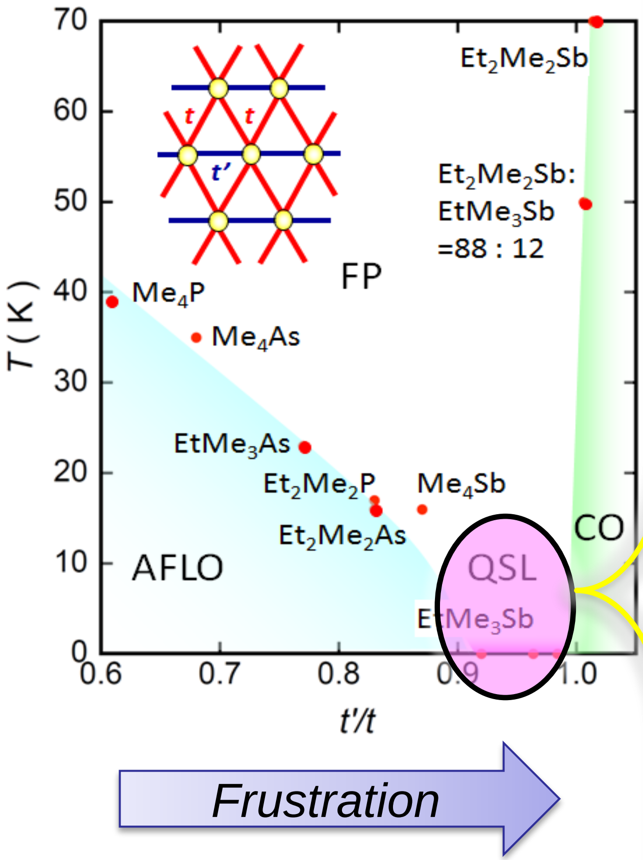
$J > J' \approx J''$

$J'/J \approx 0.83$

✓Very clean single crystals are available
✓Many material variants can be prepared.

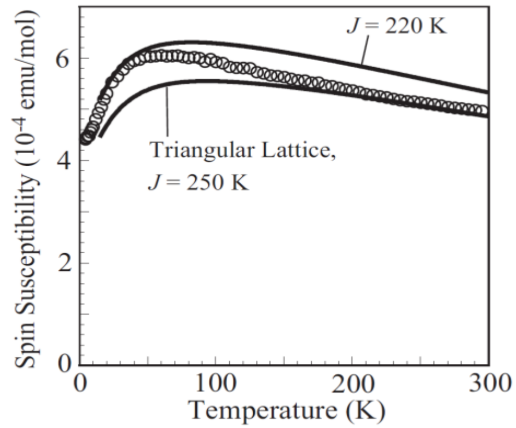
A new QSL system $EtMe_3Sb[Pd(dmit)_2]_2$

β'-(Cation)[Pd(dmit)$_2$]$_2$



K. Kanoda and R. Kato
Annu. Rev. Condens. Matter Phys.
(2011)

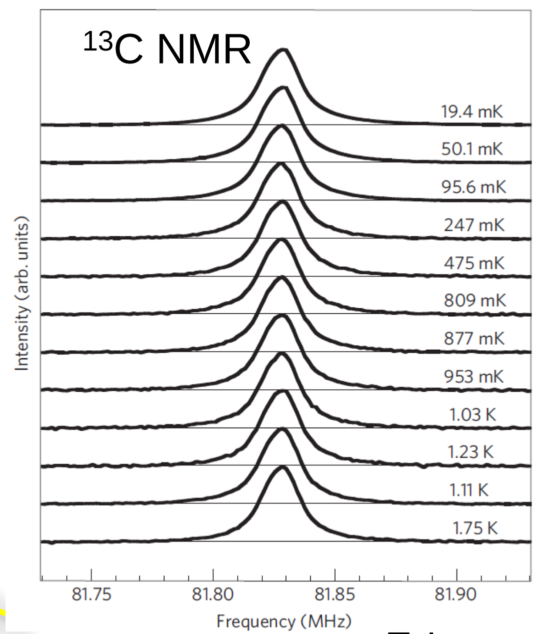
No magnetic order down to ~J/10,000



χ(T) : 2D triangular

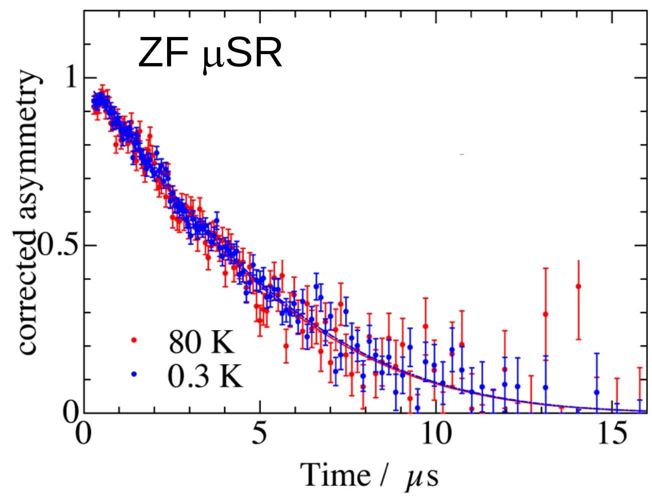
J = 220 ~ 250 K

No internal magnetic field



T. Itou *et al*., Nature Phys. (10)

No muon spin rotation



Y. Ishii *et al*.

What kind of QSL state in $EtMe_3Sb[Pd(dmit)_2]_2$?

Two key questions

Elementary excitations

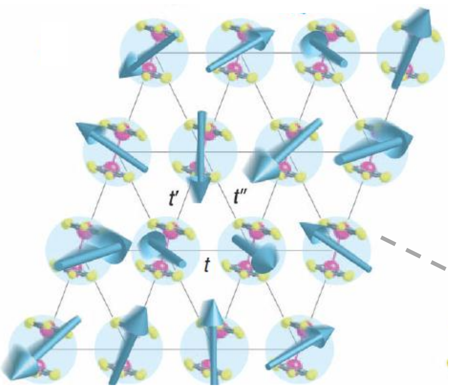
Gapped or gapless?

Magnetic or nonmagnetic?

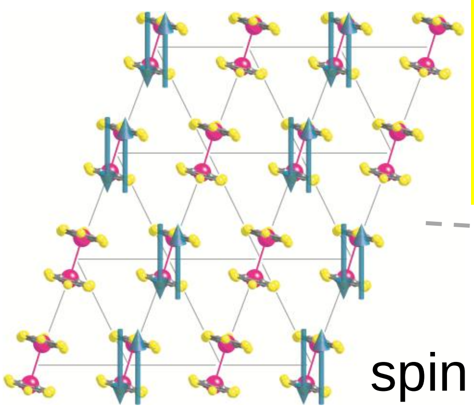
Phase diagram

How the nature of the QSL varies when tuned by non-thermal parameters, such as degree of frustration?

Elementary excitations in $EtMe_3Sb[Pd(dmit)_2]_2$



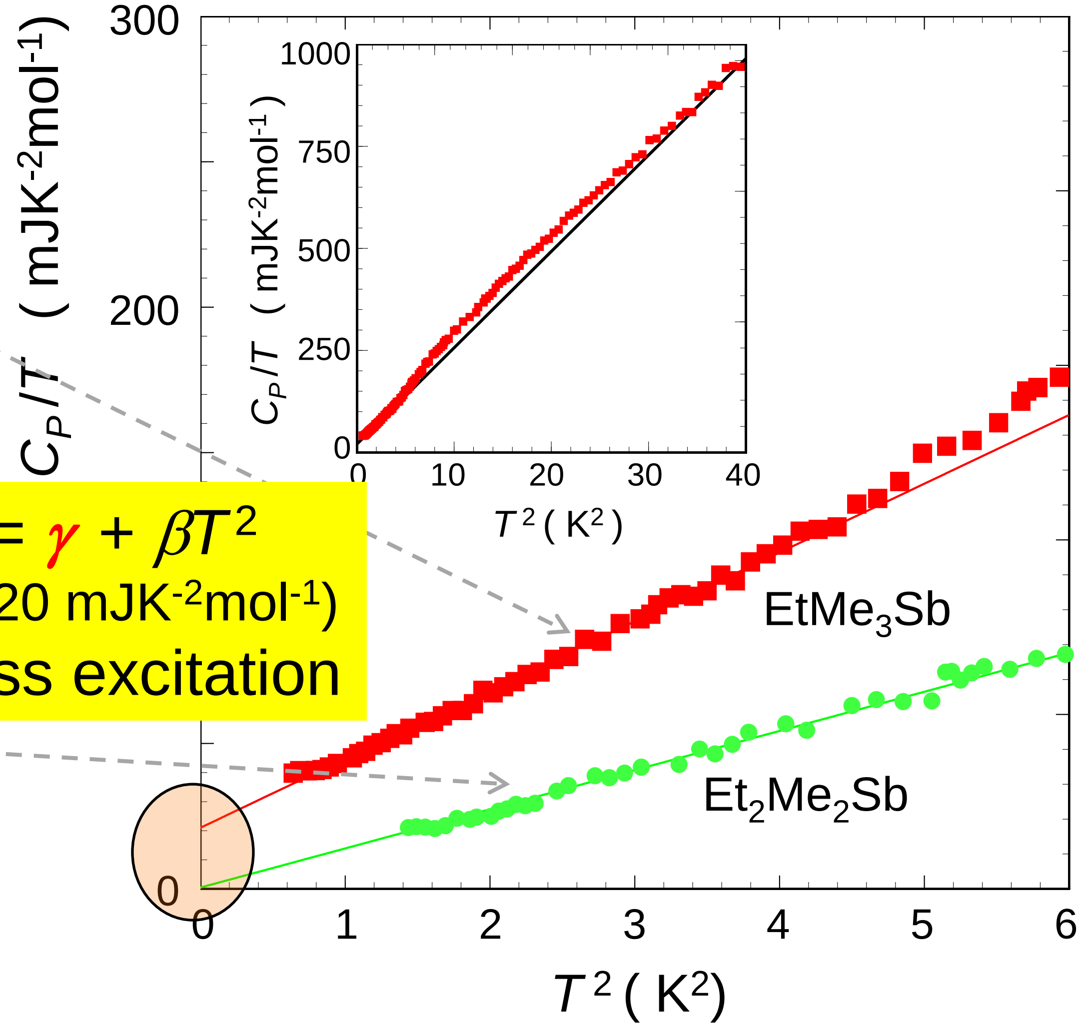
Spin liquid



Charge order

Specific heat

S. Yamashita *et al*. Nature Commun. (11)



$C_P T^{-1} = \gamma + \beta T^2$

($\gamma \approx$ 20 $mJK^{-2}mol^{-1}$)

Gapless excitation

Contaminated by large Schottky contribution at low temperatures

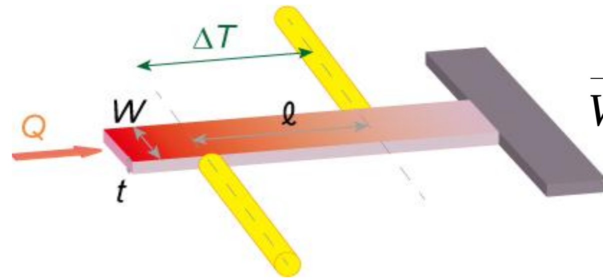
Elementary excitations in $EtMe_3Sb[Pd(dmit)_2]_2$

Thermal conductivity

Can probe elementary excitations at low temperature very reliably.

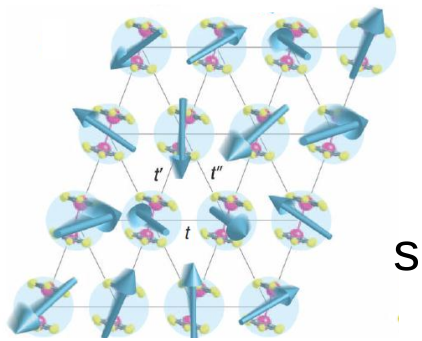
Not affected by localized impurities

Not contaminated by Schottky contribution



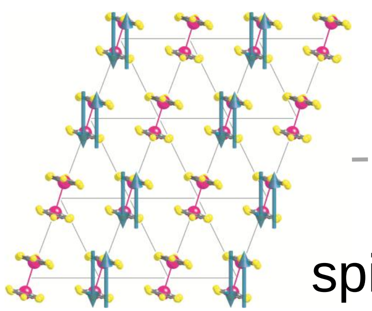
$$\frac{1}{Wt}Q = \kappa\frac{\Delta T}{\ell}$$

$EtMe_3Sb[Pd(dmit)_2]_2$ Spin liquid

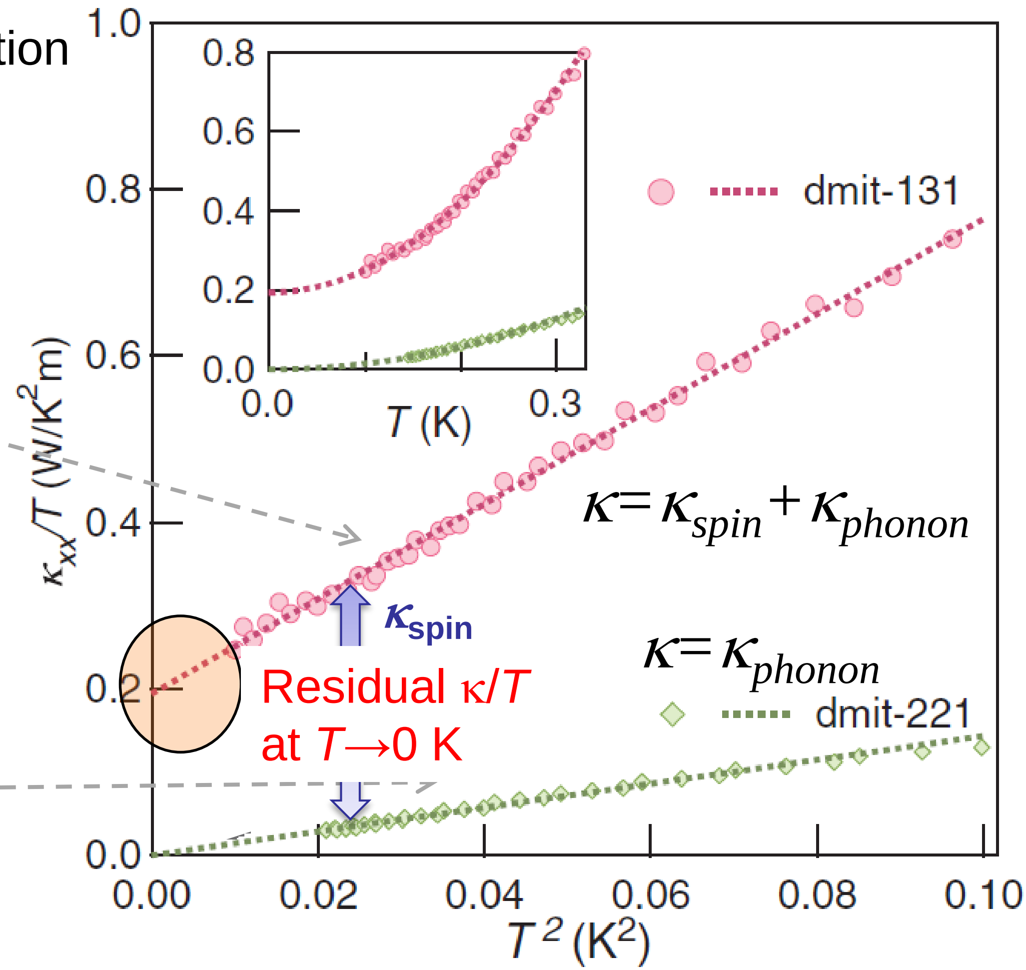


spin 1/2

$Et_2Me_2Sb[Pd(dmit)_2]_2$ Charge order



spin 0



M. Yamashita *et al*. Science 328, 1246 (2010)

Elementary excitations in $EtMe_3Sb[Pd(dmit)_2]_2$

Thermal conductivity

Clear residual of κ_{xx}/T
$\kappa_{xx}/T\,(T\rightarrow 0)$ = 0.19 W/K^{2}m
Evidence for a ***gapless excitation***.

$$\kappa_{xx} = C v_s \ell$$

Estimation of mean free path

$$C/T \sim 20\text{mJ}/\text{K}^2\text{mol}$$

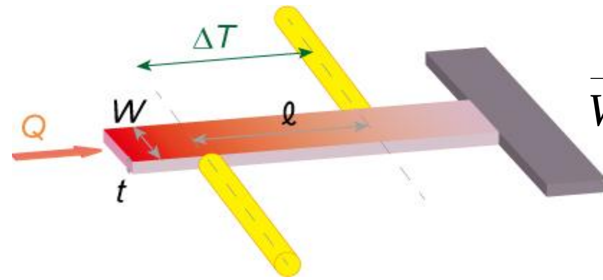
$$\Rightarrow \ell = 0.5\ \mu\text{m} \gg a \sim 1\ \text{nm}$$

More than 500 times longer than the interspin distance!!

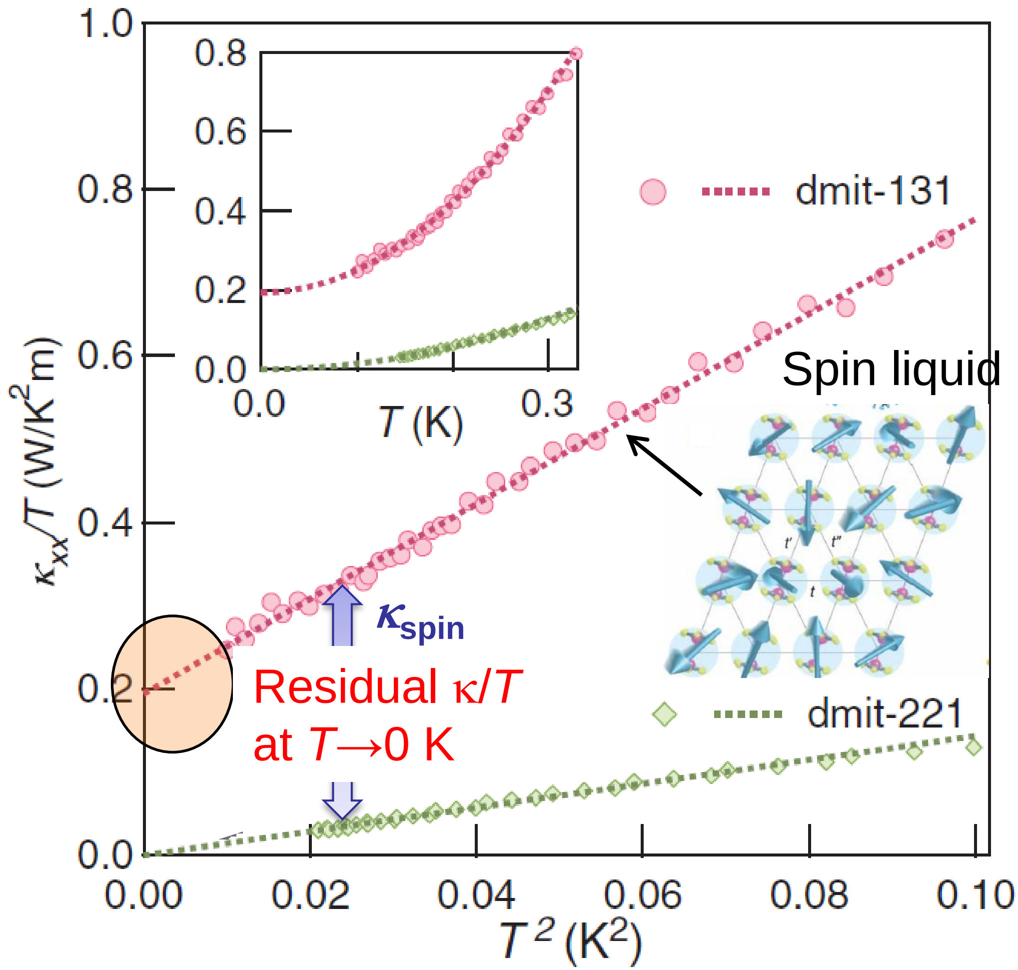
Itinerant excitation

Homogeneous

Extremely long correlation length



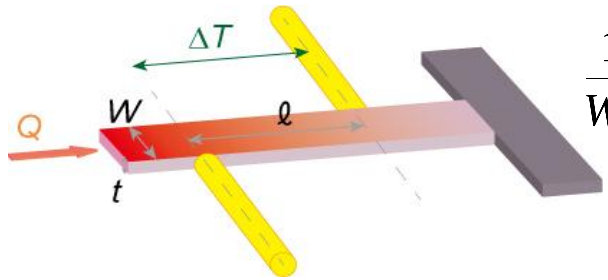
$$\frac{1}{Wt}Q = \kappa\frac{\Delta T}{\ell}$$



M. Yamashita *et al*. Science 328, 1246 (10)

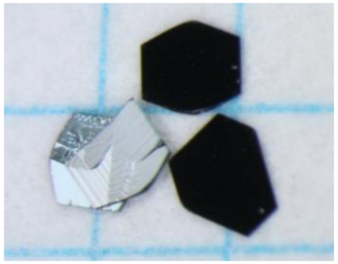
Elementary excitations in $EtMe_3Sb[Pd(dmit)_2]_2$

Thermal conductivity

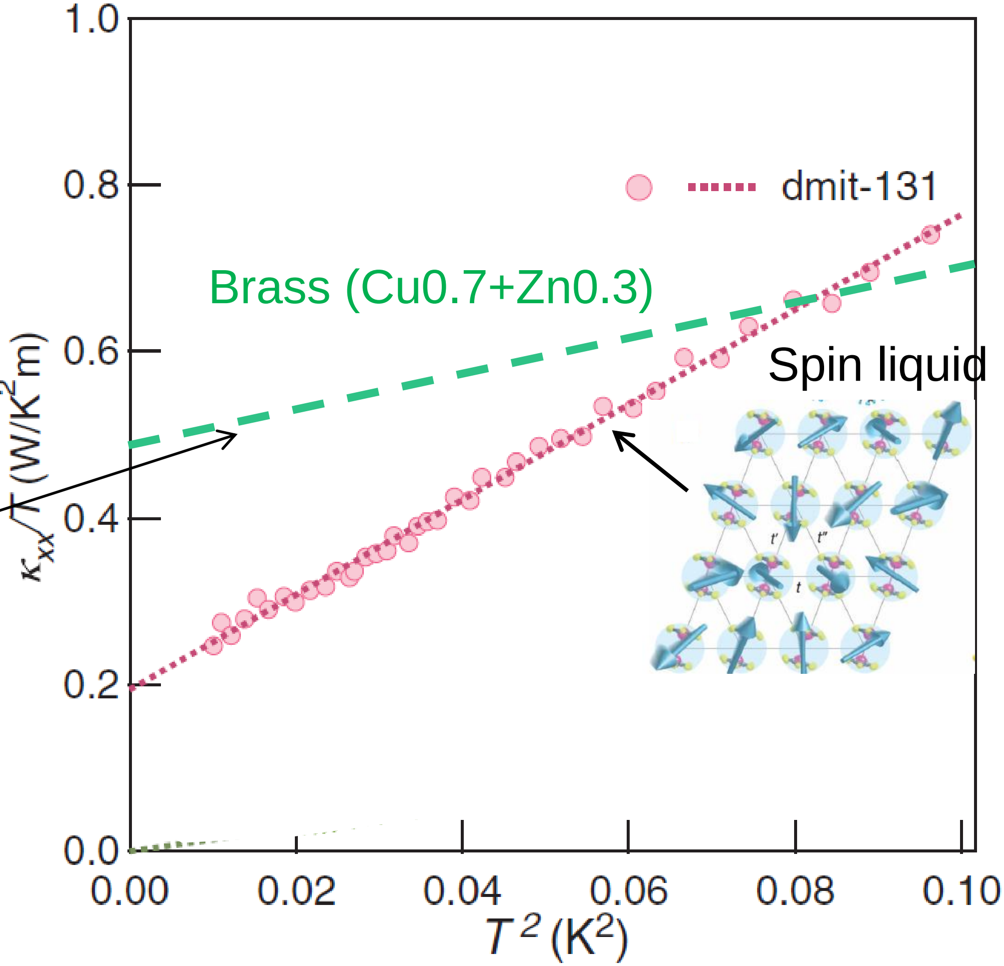


$$\frac{1}{Wt}Q = \kappa\frac{\Delta T}{\ell}$$

Quantum spin liquid conducts heat very well, as good as brass.



Brass

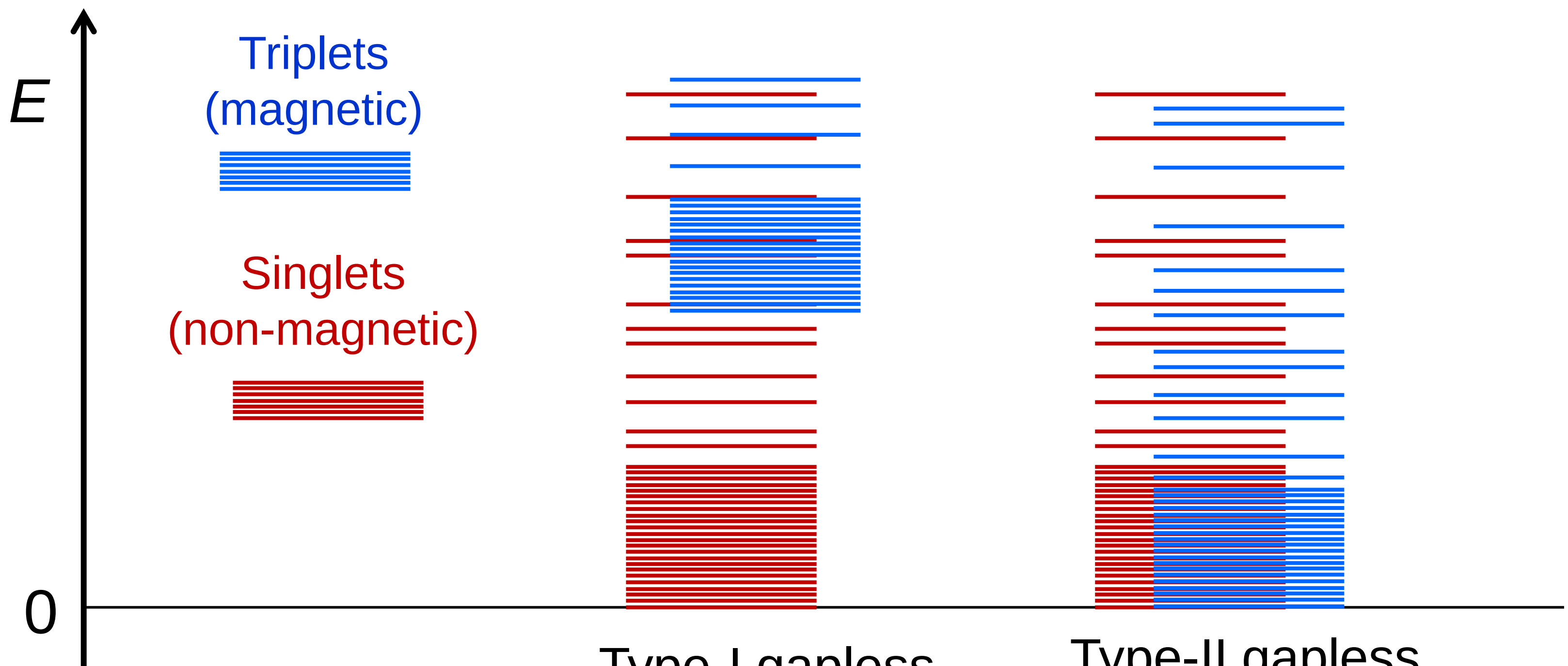


M. Yamashita *et al*. Science 328, 1246 (10)

Elementary excitations in $EtMe_3Sb[Pd(dmit)_2]_2$

Elementary excitations contain a gapless component

Next important question: Are they magnetic?



Type-I gapless spin liquid	Type-II gapless spin liquid
$\Delta_s = 0, \ \Delta_t > 0$	$\Delta_s = 0, \ \Delta_t = 0$
$\langle S(r)S(0)\rangle \sim e^{-r/\xi}$	$\langle S(r)S(0)\rangle \sim r^{-\nu}$
Exponential	Power law (algebraic)

Elementary excitations in $EtMe_3Sb[Pd(dmit)_2]_2$

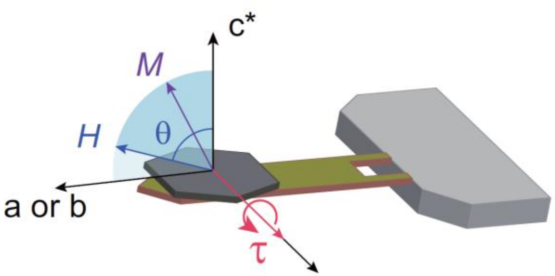
Elementary excitations contain a gapless component

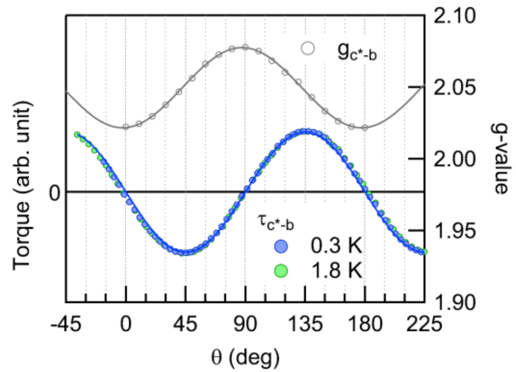
Next important question: Are they magnetic?

Uniform susceptibility and magnetization at low temperatures

SQUID (Only down to ~4 K due to large Curie contribution)

Magnetic torque+ESR (down to 30 mK up to 32 T)





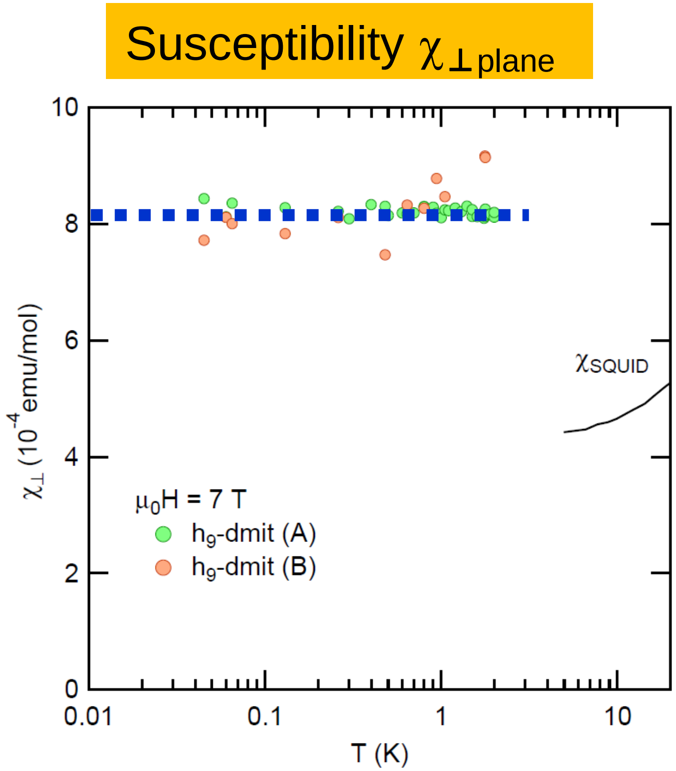
$$\tau_{c^*-a} = \frac{1}{2}\mu_0 H^2 V \Delta\chi_{c^*-a} \sin 2\theta$$

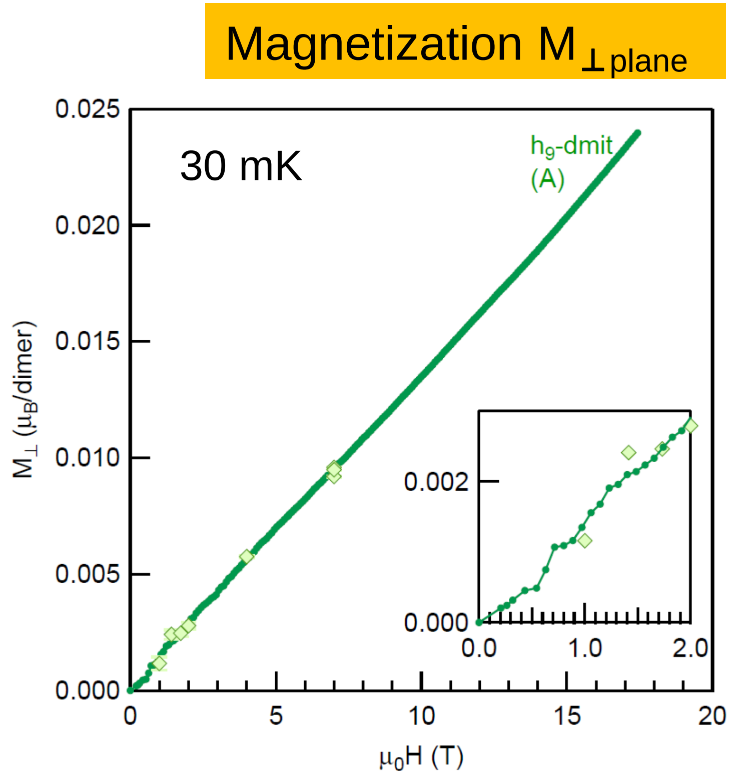
- Torque picks up only anisotropic components

  Isotropic contribution from impurities is cancelled.
- High sensitivity.

  Measurements on a tiny single crystal are possible.

Elementary excitations in $EtMe_3Sb[Pd(dmit)_2]_2$





T-independent and remains finite at T→0K

increases linearly with *H*

⇨ *Gapless excitations are magnetic (absence of spin gap)*

$\Delta \propto \xi^{-1}$ (ξ: magnetic correlation length, Δ: spin gap)

⇨ Divergence of ξ, i.e. QSL is in *a critical state*

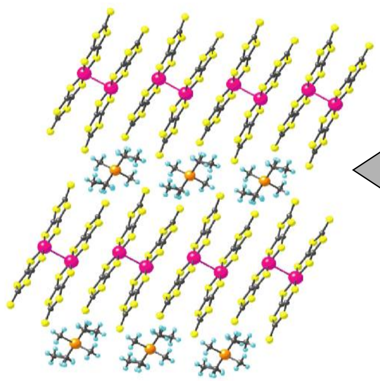
$$\langle S^z(r) S^z(0) \rangle \propto r^{-\eta}$$

Algebraic

How the QSL changes when the degree of frustration varies?

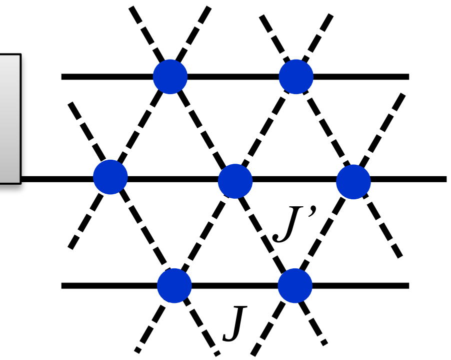
Next important question: **Phase diagram of the QSL**

Deuteration

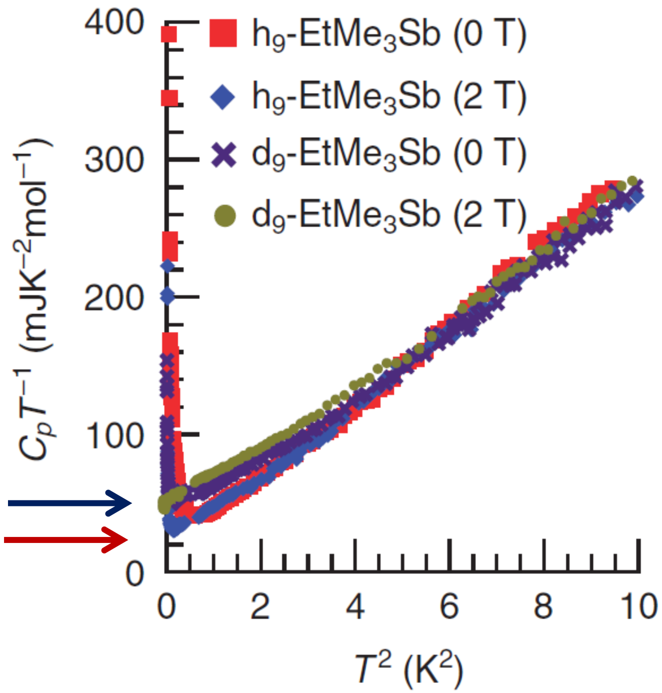


Cation layer X = $EtMe_3Sb$,
Three Me groups are deuterated

h_9-dmit: pristine
d_9-dmit :deuterated



$J'/J \approx 0.83$ (pristine)



d_9-dmit:
h_9-dmit:

h_9-dmit: $C_p/T(T \to 0\ \mathrm{K}) \sim 20\ \mathrm{mJ/K^2mol}$

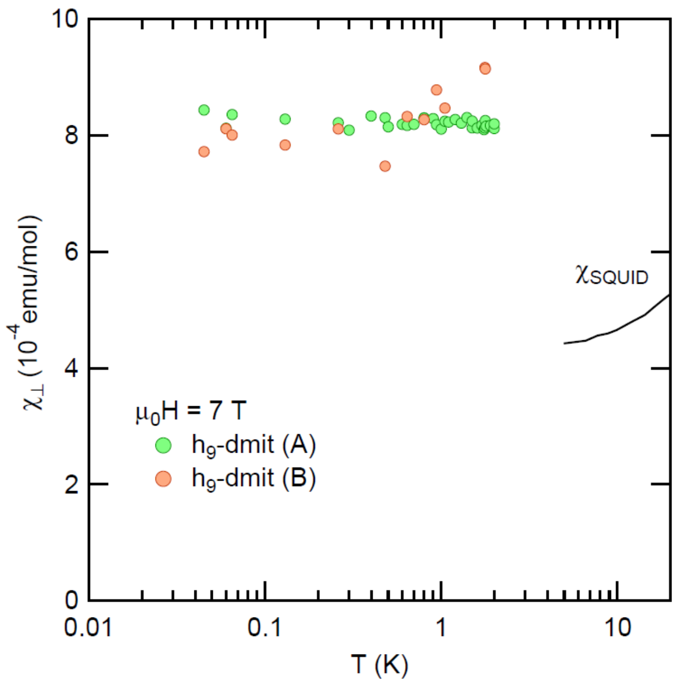
d_9-dmit : $C_p/T(T \to 0\ \mathrm{K}) \sim 40\ \mathrm{mJ/K^2mol}$

Deuteration changes the low temperature specific heat. Presumably it reduces *J'/J.*

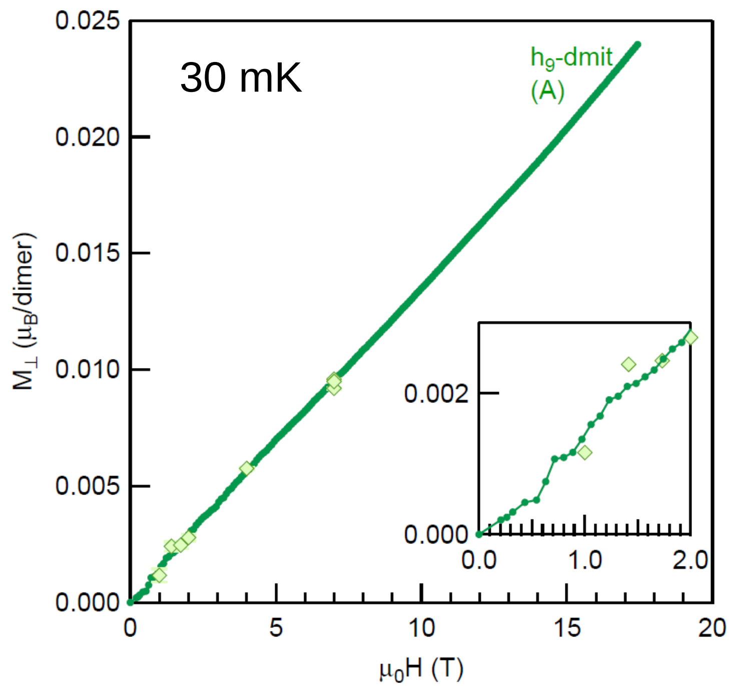
S. Yamashita *et al*. Nature Commun. (11)

How the QSL changes when the degree of frustration varies?

Susceptibility $\chi_{\perp plane}$

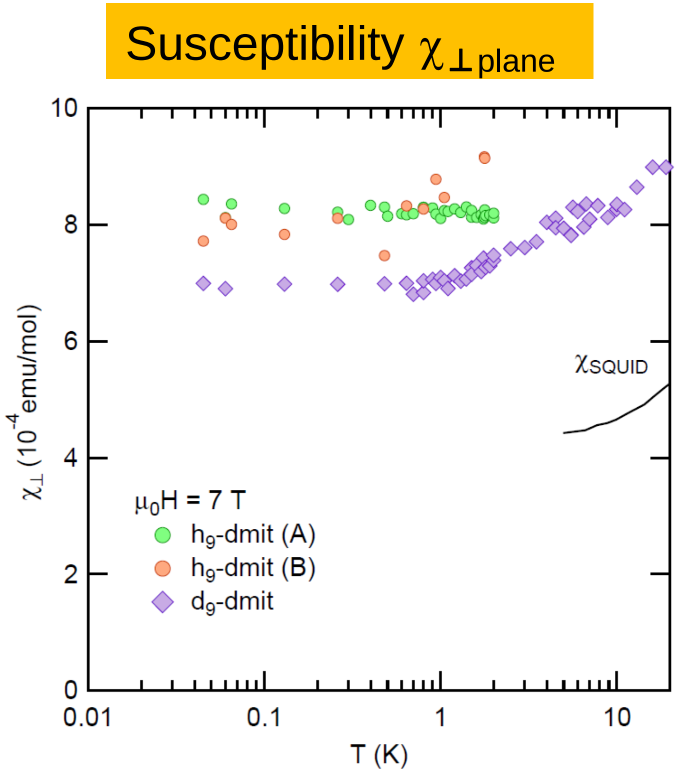


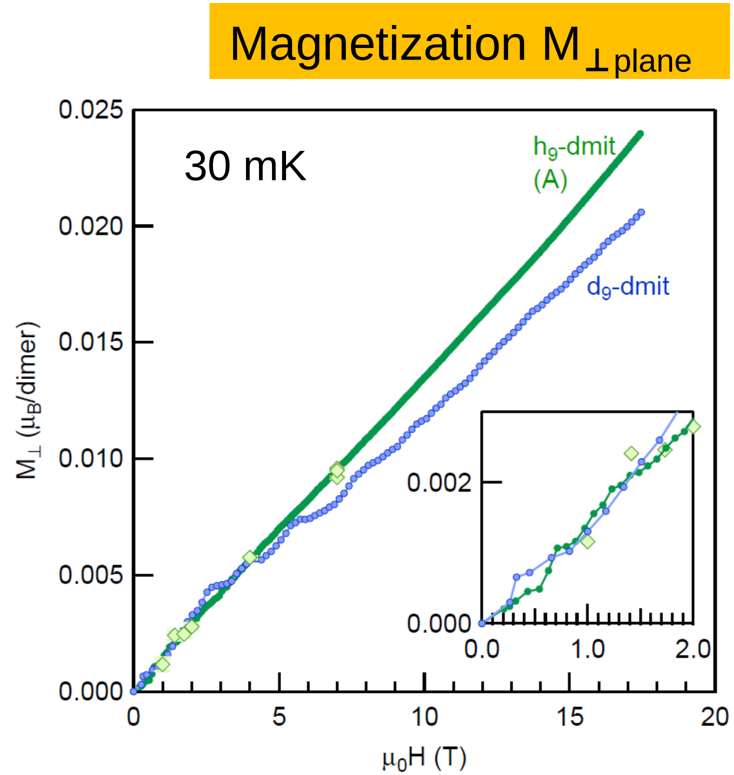
Magnetization $M_{\perp plane}$



Deuteration changes the degrees of geometrical frustration.

How the QSL changes when the degree of frustration varies?



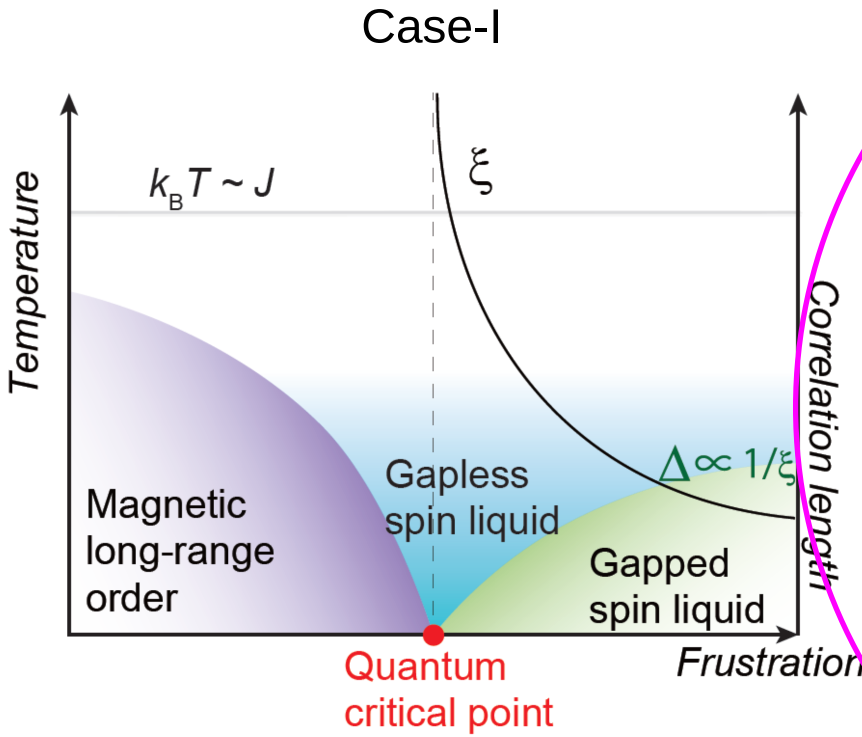


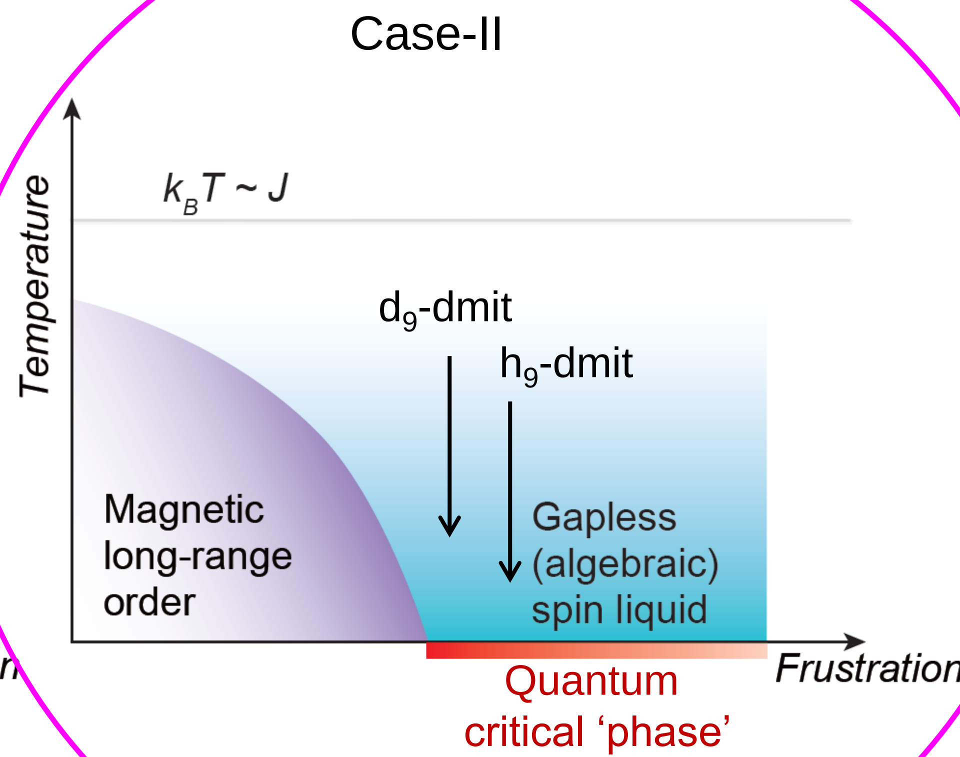
Deuteration changes the degrees of geometrical frustration.

Both h_9- and d_9-dmit systems exhibit essentially the same paramagnetic behavior ***with gapless magnetic excitations***.

Both systems are in the critical state down to $k_BT\sim J/10{,}000$

Phase diagram of the QSL

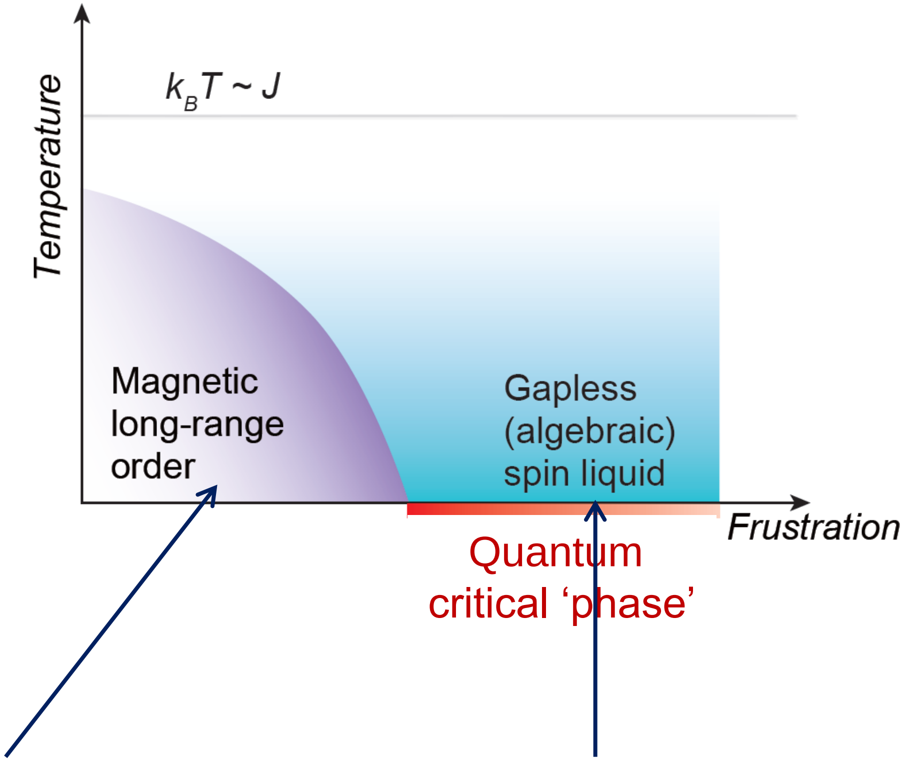




Both pristine (h_9-dmit) and deuterated (d_9-dmit) samples with different degrees of frustration exhibit essentially the same paramagnetic behavior with *gapless* magnetic excitations.

An extended quantum critical phase, rather than a QCP.

Are the excitations in the QSL fermionic or bosonic?

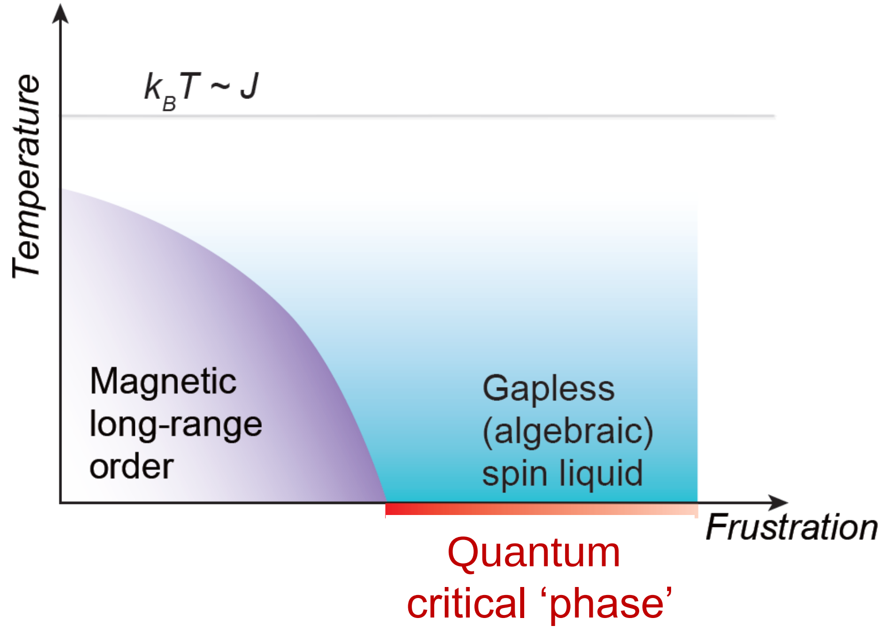


Gapless Nambu-Goldstone boson

Appearance of another gapless bosonic excitations seems unlikely

Fermionic excitations appear to be more likely

Are the excitations in the QSL fermionic or bosonic?



A simple thermodynamic test assuming 2D Fermion with Fermi surface

Pauli susceptibility

$$\chi_\perp = \frac{1}{4} g_{c^*}^2 \mu_B^2 D(\varepsilon_F)$$

$$\chi_\perp = 8.0(5) \times 10^{-4} \text{ emu/mol}$$

$$D(\varepsilon_F) = n/\varepsilon_F$$

Specific heat coefficient C/T

$$\gamma = \frac{1}{3}\pi^2 k_B^2 D(\varepsilon_F) = \frac{1}{3}\pi^2 k_B^2 \frac{4\chi_\perp}{g_{c^*}^2 \mu_B^2} \sim 56 \text{ mJ/K}^2 \text{ mol}$$

$\gamma \sim 20 \text{mJ/K}^2$ mol (experimental value)

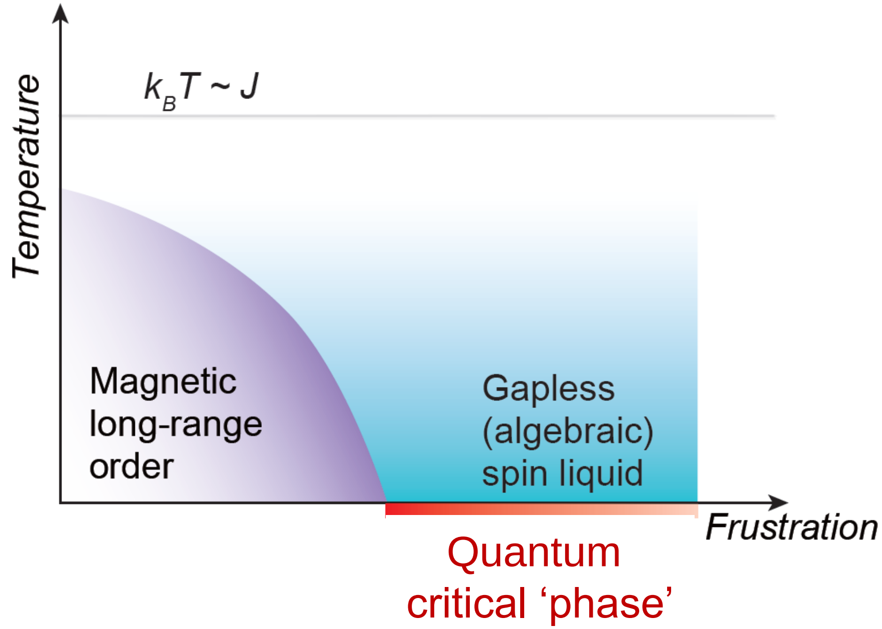
Fermi temperature

$$T_F = \varepsilon_F / k_B = \frac{g_{c^*}^2 \mu_B^2}{4\chi_\perp k_B} \sim 480 \text{ K} \quad J/k_B \sim 250 \text{ K (exp. value)}$$

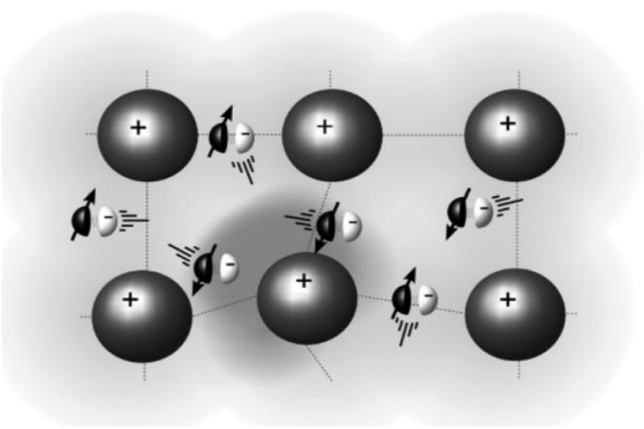
Wilson ratio $R_W = \chi_\perp / \gamma = 2.83(1.41)$ for pristine (deuterated) sample

Elementary excitations behave like Fermi liquid

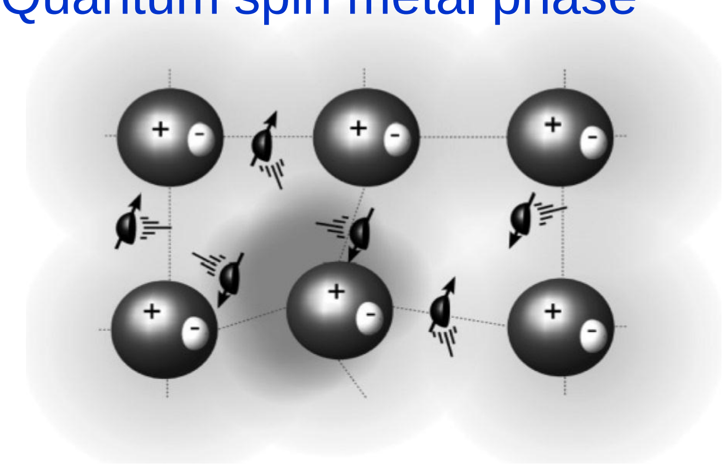
A new phase in a Mott insulator



Metal



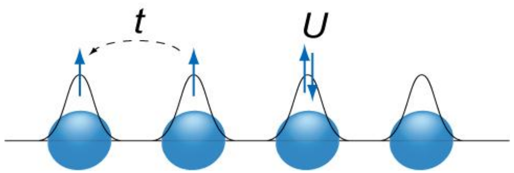
Quantum spin metal phase



D.F. Mross and T. Senthil, PRB (11)

Spin excitations behave as in Pauli paramagnetic metals with Fermi surface, even though the charge degrees of freedom are frozen.

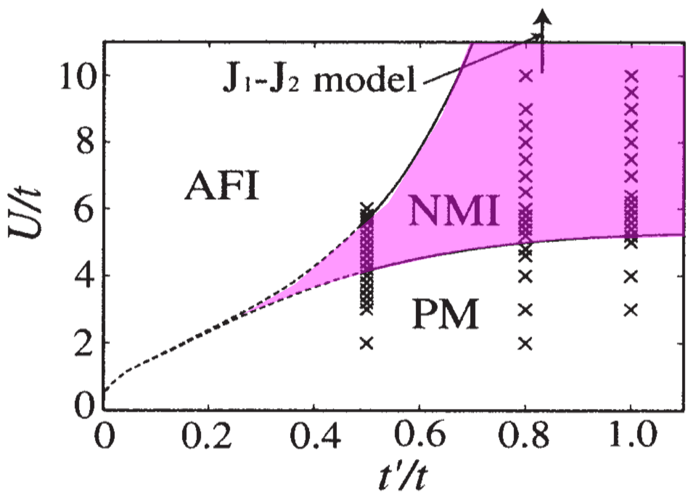
A new phase in a Mott insulator



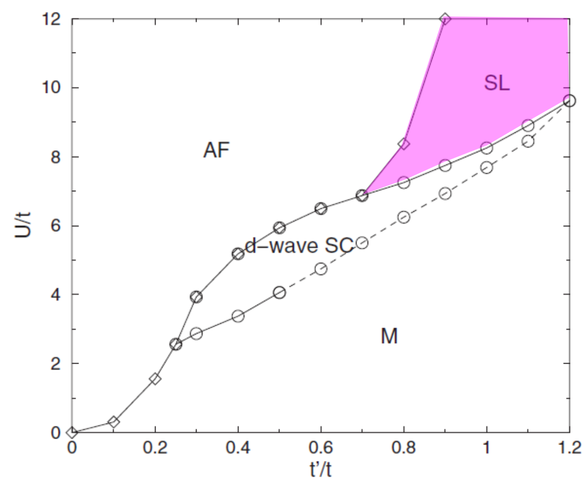
Hubbard model

$$\mathcal{H} = -\sum_{(i,j),\sigma} t\left(c_{i\sigma}^{\dagger}c_{j\sigma} + \mathrm{H.C.}\right) + U\sum_{i=1}^{N} n_{i\uparrow}n_{i\downarrow}$$

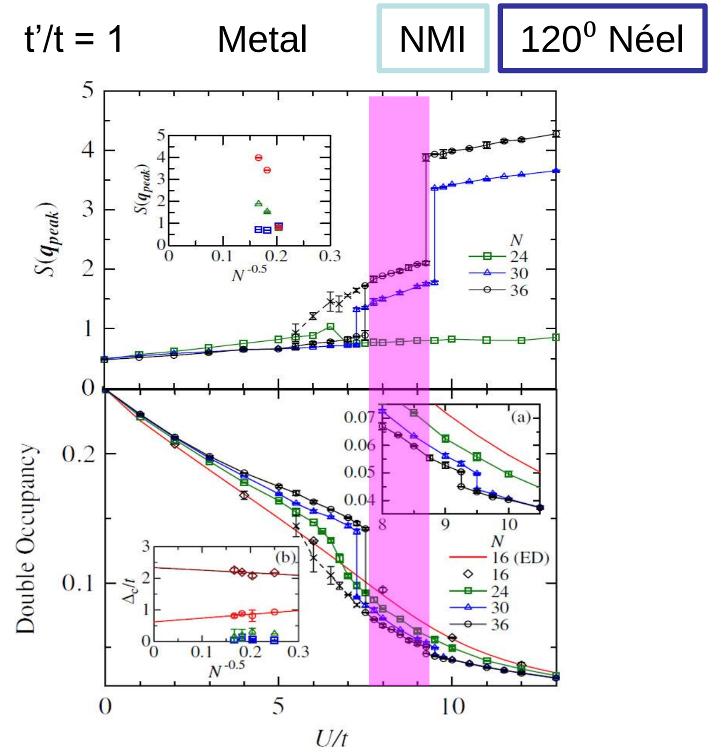
Non-Magnetic Insulating phase near M-I transition
(Quantum spin liquid)



Morita-Watanabe-Imada,JPSJ (02)



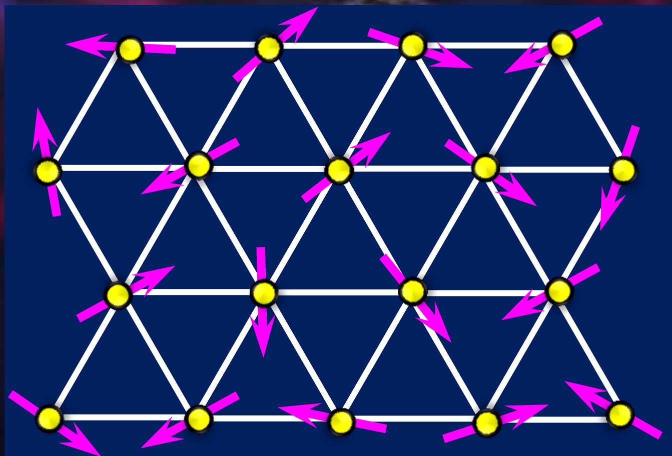
Kyung-Tremblay, PRL (06)



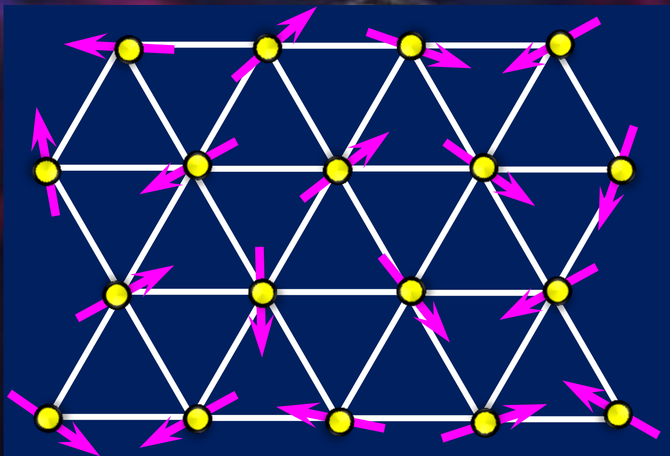
Yoshioka-Koga-Kawakami, PRL (10)

Energy resolutions of these calculations are not enough to discuss low energy excitations (E~J/100)

Question

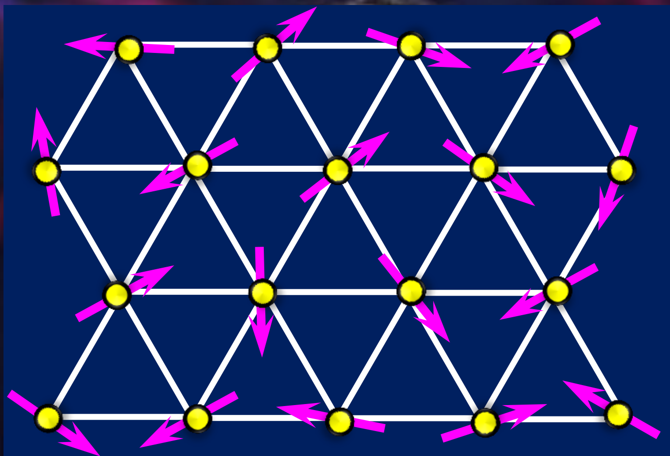


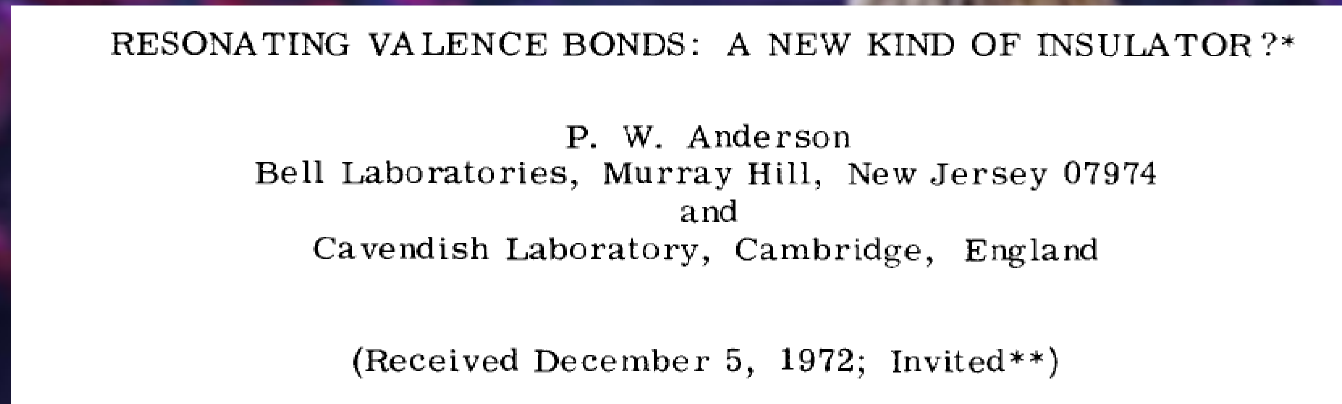
Question



What is the theory known to describe 2D QSL?

Question





RESONATING VALENCE BONDS: A NEW KIND OF INSULATOR?*

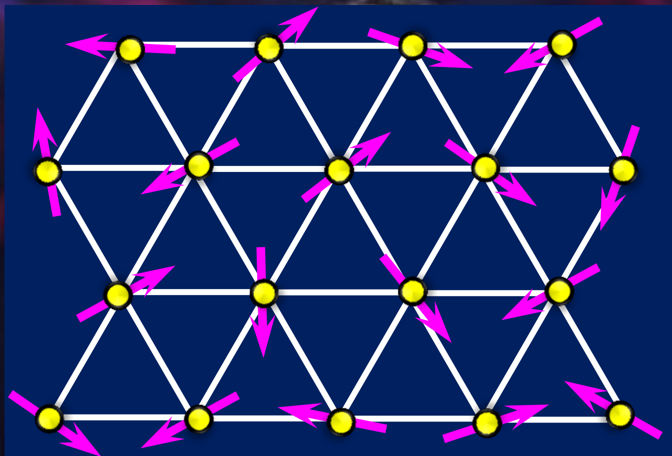
P. W. Anderson
Bell Laboratories, Murray Hill, New Jersey 07974
and
Cavendish Laboratory, Cambridge, England

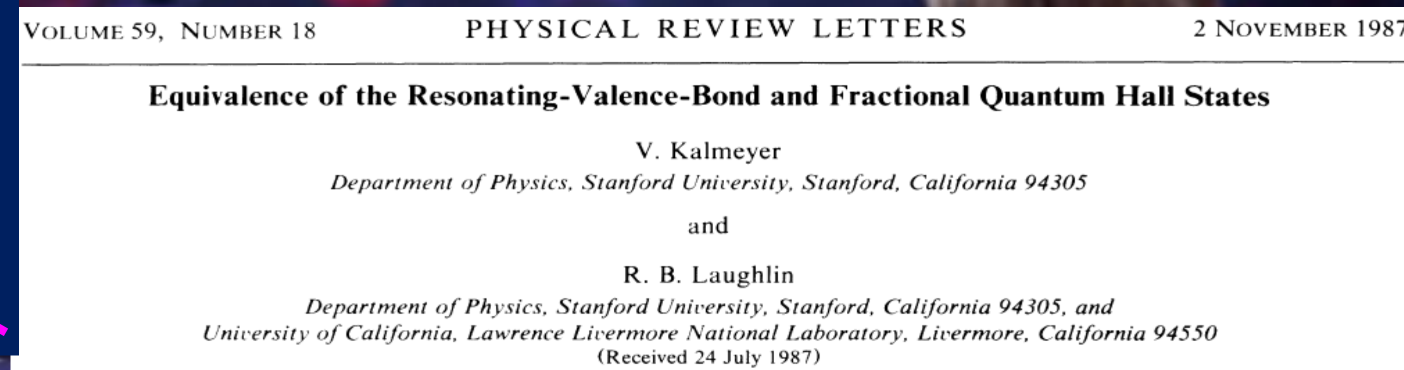
(Received December 5, 1972; Invited**)

What is the theory known to describe 2D QSL?

- **A:** resonating-valence-bond

Question





VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Equivalence of the Resonating-Valence-Bond and Fractional Quantum Hall States

V. Kalmeyer
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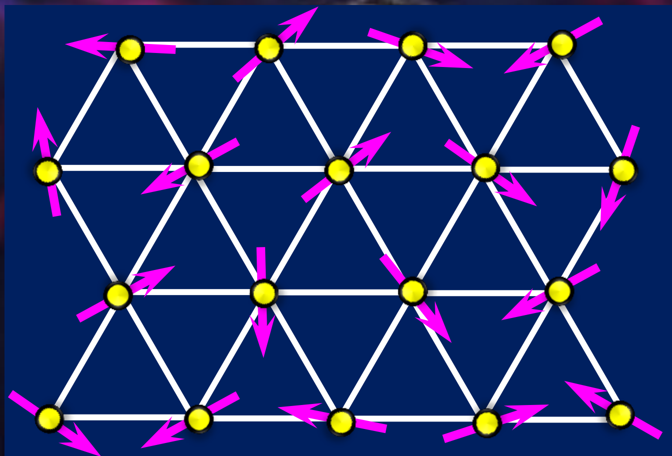
and
R. B. Laughlin
Department of Physics, Stanford University, Stanford, California 94305, and University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 24 July 1987)

What is the theory known to describe 2D QSL?

- **A:** resonating-valence-bond
- **B:** chiral spin liquid

Question



VOLUME 86, NUMBER 9 PHYSICAL REVIEW LETTERS 26 FEBRUARY 2001

Resonating Valence Bond Phase in the Triangular Lattice Quantum Dimer Model

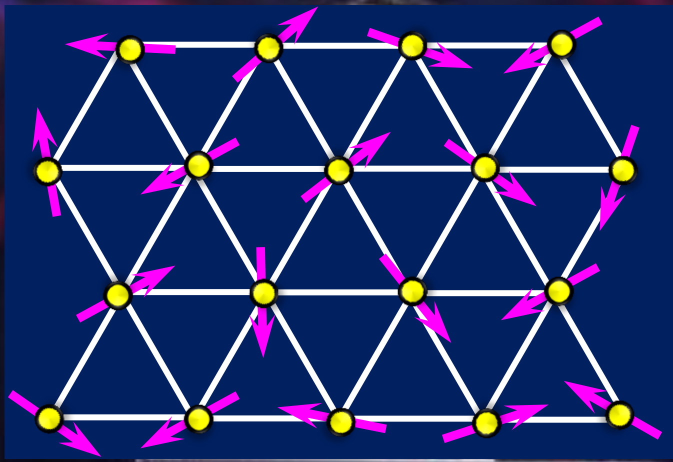
R. Moessner and S. L. Sondhi
Department of Physics, Princeton University, Princeton, New Jersey 08544
(Received 3 August 2000)

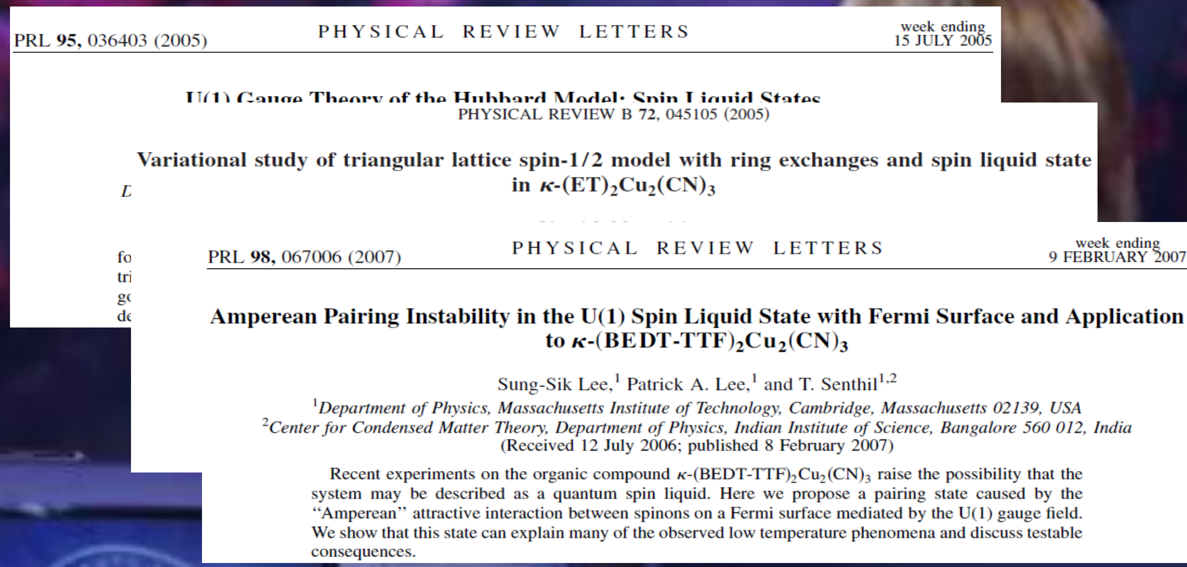
We study the quantum dimer model on the triangular lattice, which is expected to describe the singlet dynamics of frustrated Heisenberg models in phases where valence bond configurations dominate their physics. We find, in contrast to the square lattice, that there is a truly short ranged resonating valence bond phase with no gapless excitations and with deconfined, gapped, spinons for a *finite* range of parameters. We also establish the presence of crystalline dimer phases.

What is the theory known to describe 2D QSL?

- **A:** resonating-valence-bond
- **B:** chiral spin liquid
- **C:** Quantum dimer liquid

Question





PRL **95,** 036403 (2005) PHYSICAL REVIEW LETTERS week ending 15 JULY 2005

PHYSICAL REVIEW B 72, 045105 (2005)

Variational study of triangular lattice spin-1/2 model with ring exchanges and spin liquid state in κ-(ET)$_2$Cu$_2$(CN)$_3$

PRL **98,** 067006 (2007) PHYSICAL REVIEW LETTERS week ending 9 FEBRUARY 2007

Amperean Pairing Instability in the U(1) Spin Liquid State with Fermi Surface and Application to κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$

Sung-Sik Lee,[1] Patrick A. Lee,[1] and T. Senthil[1,2]

[1]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Center for Condensed Matter Theory, Department of Physics, Indian Institute of Science, Bangalore 560 012, India*

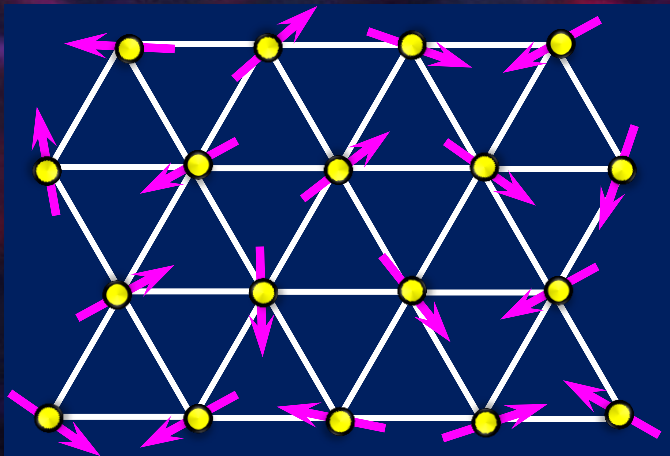
(Received 12 July 2006; published 8 February 2007)

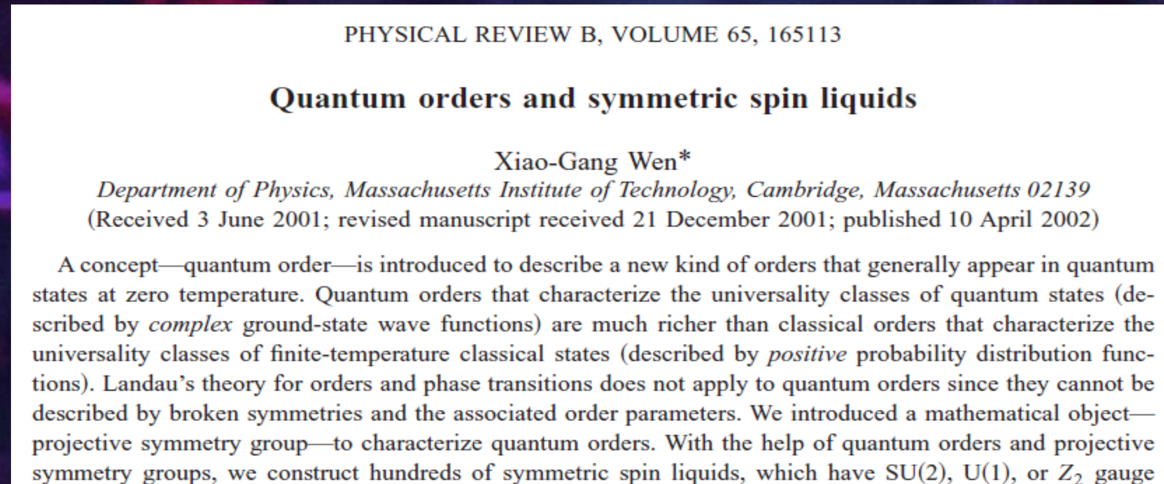
Recent experiments on the organic compound κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ raise the possibility that the system may be described as a quantum spin liquid. Here we propose a pairing state caused by the "Amperean" attractive interaction between spinons on a Fermi surface mediated by the U(1) gauge field. We show that this state can explain many of the observed low temperature phenomena and discuss testable consequences.

What is the theory known to describe 2D QSL?

- **A:** resonating-valence-bond
- **B:** chiral spin liquid
- **C:** Quantum dimer liquid
- **D:** QSL with spinon Fermi surface

Question





PHYSICAL REVIEW B, VOLUME 65, 165113

Quantum orders and symmetric spin liquids

Xiao-Gang Wen*
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 3 June 2001; revised manuscript received 21 December 2001; published 10 April 2002)

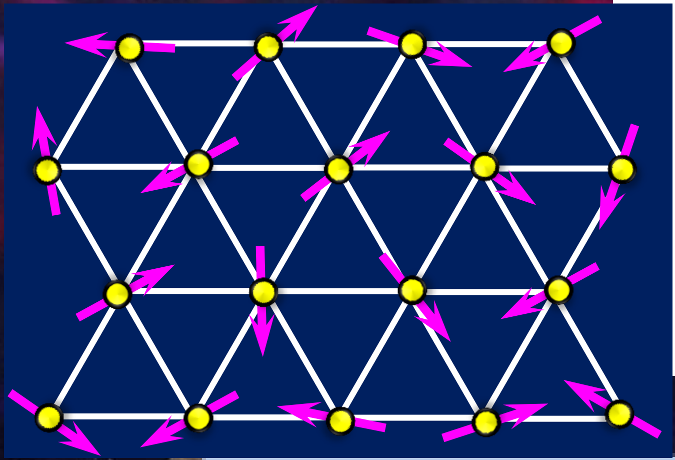
A concept—quantum order—is introduced to describe a new kind of orders that generally appear in quantum states at zero temperature. Quantum orders that characterize the universality classes of quantum states (described by *complex* ground-state wave functions) are much richer than classical orders that characterize the universality classes of finite-temperature classical states (described by *positive* probability distribution functions). Landau's theory for orders and phase transitions does not apply to quantum orders since they cannot be described by broken symmetries and the associated order parameters. We introduced a mathematical object—projective symmetry group—to characterize quantum orders. With the help of quantum orders and projective symmetry groups, we construct hundreds of symmetric spin liquids, which have SU(2), U(1), or Z_2 gauge

What is the theory known to describe 2D QSL?

- **A:** resonating-valence-bond
- **B:** chiral spin liquid
- **C:** Quantum dimer liquid
- **D:** QSL with spinon Fermi surface
- **E:** Algebraic spin liquid

Question

PRL **102,** 176401 (2009) PHYSICAL REVIEW LETTERS week endi[ng] 1 MAY 20[09]



Dynamics and Transport of the Z_2 Spin Liquid: Application to κ-(ET)$_2$Cu$_2$(CN)$_3$

Yang Qi, Cenke Xu, and Subir Sachdev

Department of Physics, Harvard University, Cambridge Massachusetts 02138, USA

(Received 6 September 2008; published 29 April 2009; publisher error corrected 30 April 2009)

We describe neutron scattering, NMR relaxation, and thermal transport properties of Z_2 spin liquids in two dimensions. Comparison to recent experiments on the spin $S = 1/2$ triangular lattice antiferromagnet in κ-(ET)$_2$Cu$_2$(CN)$_3$ shows that this compound may realize a Z_2 spin liquid. We argue that the topological "vison" excitations dominate thermal transport, and that recent thermal conductivity experiments by M. Yamashita *et al.* have observed the vison gap.

What is the theory known to describe 2D QSL?

- **A:** resonating-valence-bond
- **B:** chiral spin liquid
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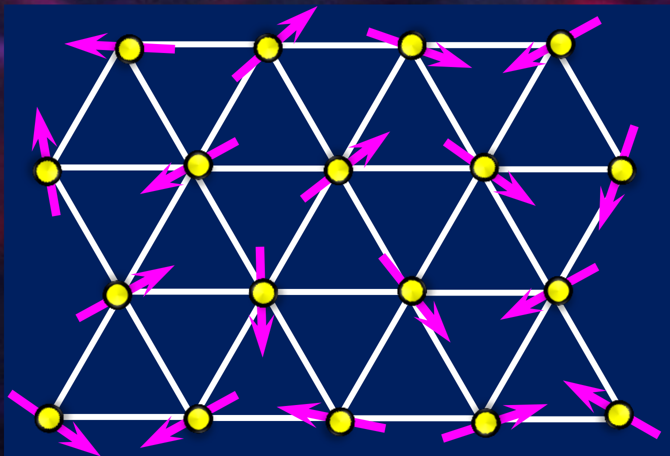
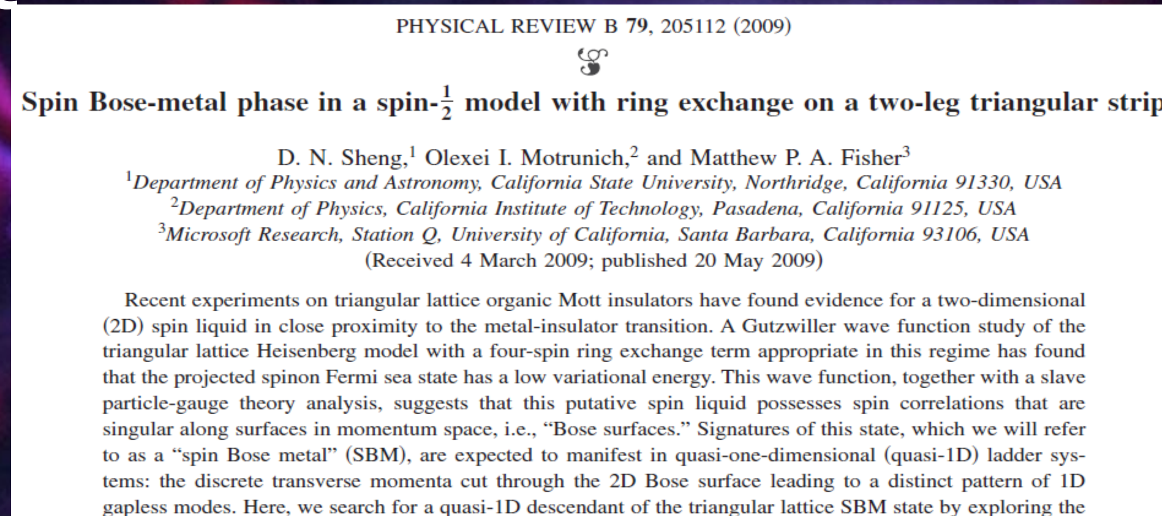
- **D:** QSL with spinon Fermi surface
- **E:** Algebraic spin liquid
- **F:** Z_2 spin liquid

Question





PHYSICAL REVIEW B **79**, 205112 (2009)

Spin Bose-metal phase in a spin-$\frac{1}{2}$ model with ring exchange on a two-leg triangular strip

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(Received 4 March 2009; published 20 May 2009)

Recent experiments on triangular lattice organic Mott insulators have found evidence for a two-dimensional (2D) spin liquid in close proximity to the metal-insulator transition. A Gutzwiller wave function study of the triangular lattice Heisenberg model with a four-spin ring exchange term appropriate in this regime has found that the projected spinon Fermi sea state has a low variational energy. This wave function, together with a slave particle-gauge theory analysis, suggests that this putative spin liquid possesses spin correlations that are singular along surfaces in momentum space, i.e., “Bose surfaces.” Signatures of this state, which we will refer to as a “spin Bose metal” (SBM), are expected to manifest in quasi-one-dimensional (quasi-1D) ladder systems: the discrete transverse momenta cut through the 2D Bose surface leading to a distinct pattern of 1D gapless modes. Here, we search for a quasi-1D descendant of the triangular lattice SBM state by exploring the

What is the theory known to describe 2D QSL?

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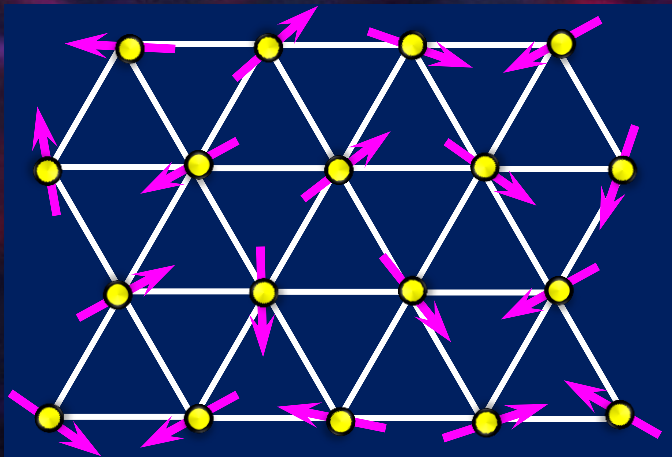
- **G:** Spin-Bose-Metal phase

Question



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- **H:** None of the above

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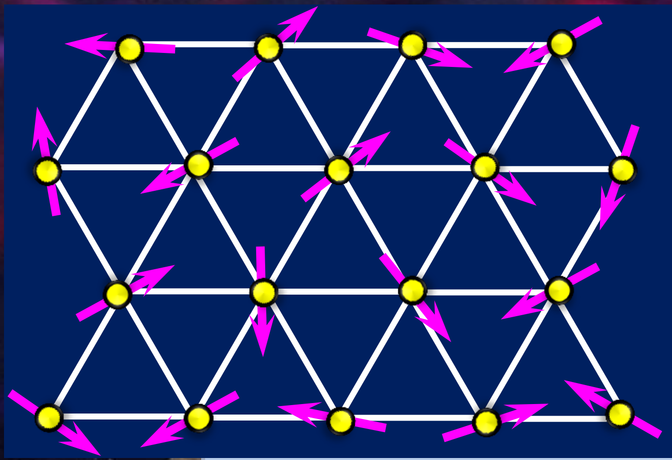

Gapless spin liquid

Gapped spin liquid

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- **H:** None of the above

What kind of spin liquid is realized in $EtMe_3Sb[Pd(dmit)_2]_2$?

Gapless Spin Liquid

Resonating-Valence-Bond theory

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Bell Laboratories, Murray Hill, New Jersey 07974
and
Cavendish Laboratory, Cambridge, England

(Received December 5, 1972; Invited**)

Spin Bose Metal

PHYSICAL REVIEW B 79, 205112 (2009)

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Algebraic spin liquid

PHYSICAL REVIEW B, VOLUME 65, 165113

Quantum orders and symmetric spin liquids

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(Received 3 June 2001; revised manuscript received 21 December 2001; published 10 April 2002)

A concept—quantum order—is introduced to describe a new kind of orders that generally appear in quantum states at zero temperature. Quantum orders that characterize the universality classes of quantum states (described by *complex* ground-state wave functions) are much richer than classical orders that characterize the universality classes of finite-temperature classical states (described by *positive* probability distribution functions). Landau's theory for orders and phase transitions does not apply to quantum orders since they cannot be described by broken symmetries and the associated order parameters. We introduced a mathematical object—projective symmetry group—to characterize quantum orders. With the help of quantum orders and projective symmetry groups, we construct hundreds of symmetric spin liquids, which have SU(2), U(1), or Z_2 gauge

Spin liquid with spinon Fermi surface

PRL 95, 036403 (2005) PHYSICAL REVIEW LETTERS week ending 15 JULY 2005

U(1) Gauge Theory of the Hubbard Model: Spin Liquid States and Possible Application to κ-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$

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(Received 10 February 2005; published 15 July 2005)

We formulate a U(1) gauge theory of the Hubbard model in the slave-rotor representation. From this formalism it is argued that spin liquid phases may exist near the Mott transition in the Hubbard model on triangular and honeycomb lattices at half filling. The organic compound κ-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$ is a good candidate for the spin liquid state on a triangular lattice. We predict a highly unusual temperature dependence for the thermal conductivity of this material.

PHYSICAL REVIEW B 81, 245121 (2010)

Weak Mott insulators on the triangular lattice: Possibility of a gapless nematic quantum spin liquid

Tarun Grover,[1] N. Trivedi,[2] T. Senthil,[1] and Patrick A. Lee[1]
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[2]*Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*
(Received 7 March 2010; revised manuscript received 18 May 2010; published 18 June 2010)

We study the energetics of Gutzwiller projected BCS states of various symmetries for the triangular lattice antiferromagnet with a four-particle ring exchange using variational Monte Carlo methods. In a range of parameters the energetically favored state is found to be a projected $d_{x^2-y^2}$ paired state which breaks lattice rotational symmetry. We show that the properties of this nematic or orientationally ordered paired spin-liquid state as a function of temperature and pressure can account for many of the experiments on organic materials. We also study the ring-exchange model with ferromagnetic Heisenberg exchange and find that among the studied ansätze, a projected *f*-wave state is the most favorable.

Gapless Spin Liquids: Stability and Possible Experimental Relevance

Maissam Barkeshli,[1] Hong Yao,[2,1] and Steven A. Kivelson[1]
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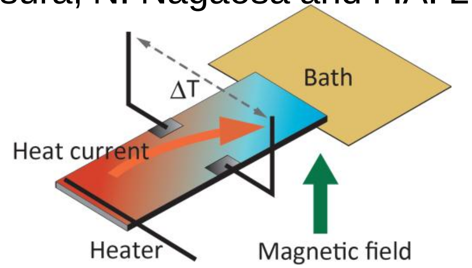
[2]*Institute for Advanced Study, Tsinghua University, Beijing, 100084, China*
(Dated: September 3, 2012)

For certain crystalline systems, most notably the organic compound $EtMe_3Sb[Pd(dmit)_2]_2$, experimental evidence has accumulated of an insulating state with a high density of gapless neutral excitations that produce Fermi-liquid-like power laws in thermodynamic quantities and thermal transport. This has been taken as evidence of a fractionalized spin liquid state. In this paper, we argue that *if the experiments are taken at face value*, the most promising spin liquid candidates are a Z_4 spin liquid with a pseudo-Fermi surface and no broken symmetries, or a Z_2 spin-liquid with a pseudo-Fermi surface and at least one of the following symmetries spontaneously broken: (a) time-reversal and

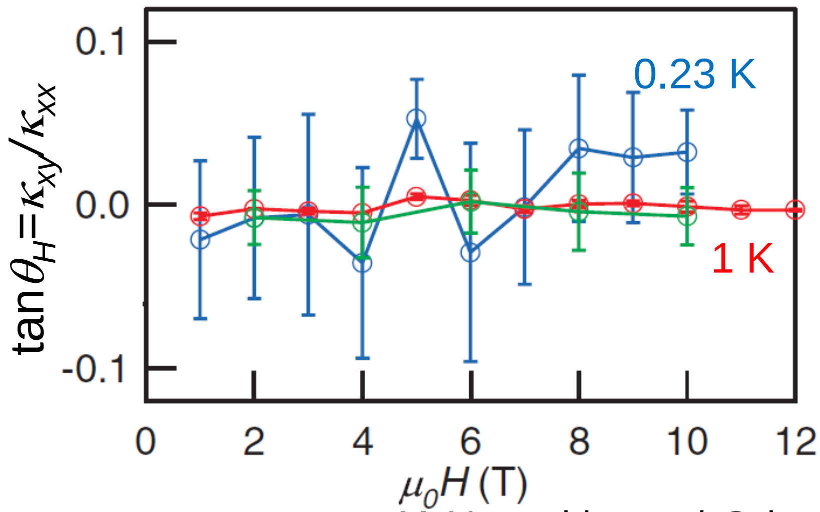
Remaining questions

Thermal Hall effect

H. Katsura, N. Nagaosa and P.A. Lee, PRL (10)



κ_{xy} thermal Hall conductivity



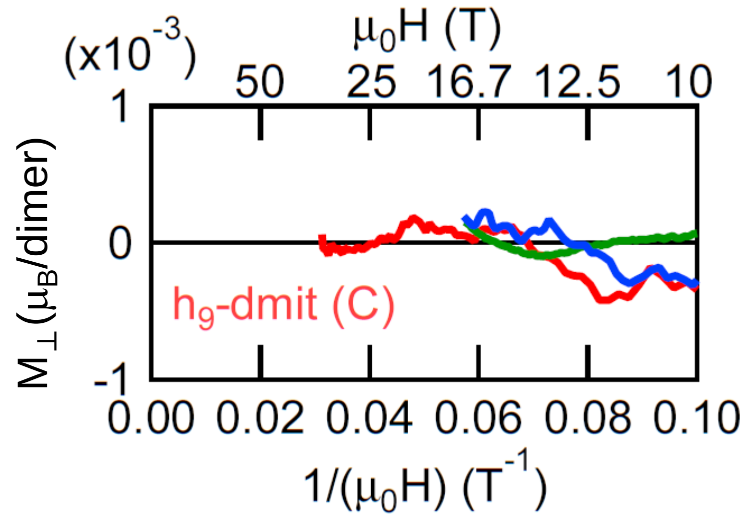
M. Yamashita *et al*. Science (10)

No discernible thermal Hall effect

Quantum oscillation

O.I.Mitrunich, PRB (06)

30 mK up to 35 T



D. Watanabe *et al*. Nature Commu.(2012)

No discernible oscillation

The coupling between the magnetic field and the gauge flux may be weak.

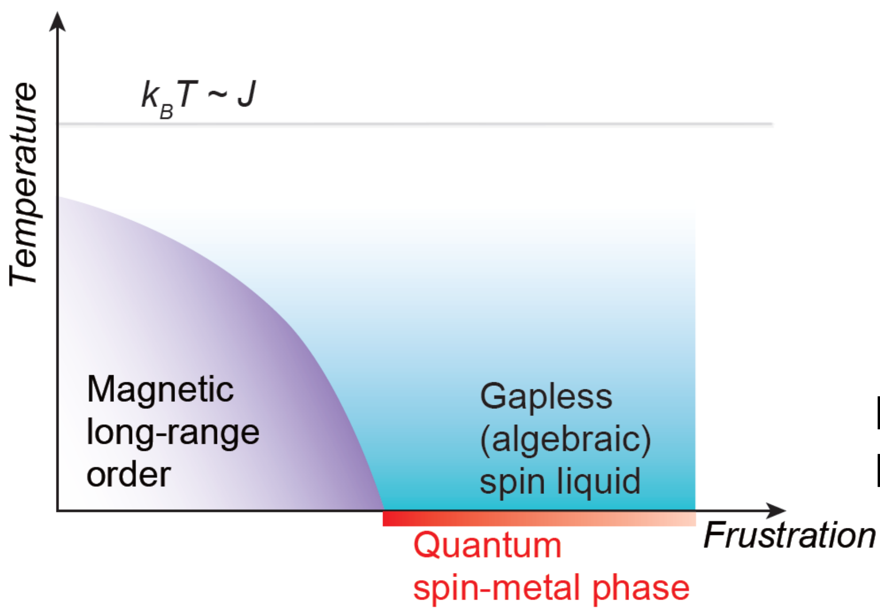
Summary

Elementary excitations and phase diagram of the QSL in $EtMe_3Sb[Pd(dmit)_2]_2$

1. Presence of gapless magnetic excitations.
2. Quantum critical phase, rather than a quantum critical point
3. Character of the excitations: likely to be fermionic

Spin excitations behave as in Pauli paramagnetic metals with Fermi surface, even though the charge degrees of freedom are frozen.

A novel Pauli paramagnetic phase in the Mott insulator



M.Yamashita *et al*., Nature Phys. **5**, 44 (09).

M. Yamashita *et al*., Science **328**, 1246 (10).

D. Watanabe *et al*., Nature Commun. **3**, 1090 (12)