Physics seminar at 清華大学　高等研究院

Quantum `spin-metal' phase in an organic Mott insulator with two-dimensional triangular lattice

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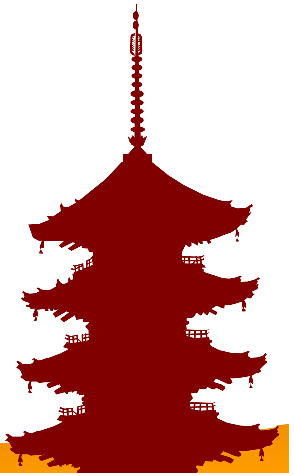
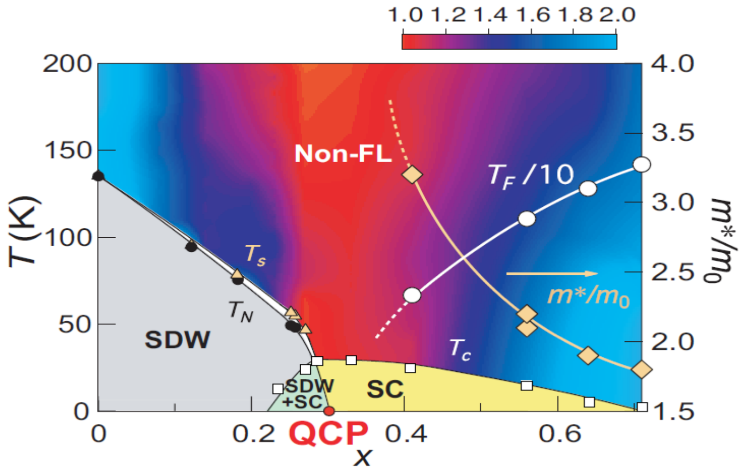


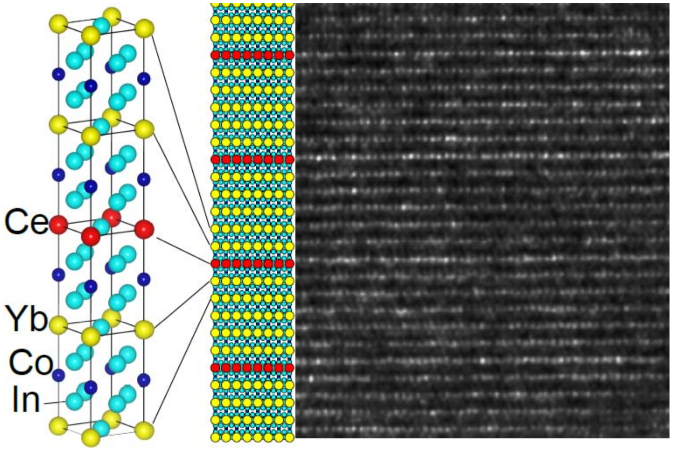
Current projects in Matsuda-Shibauchi group in Kyoto

Iron-pnictide superconductivity



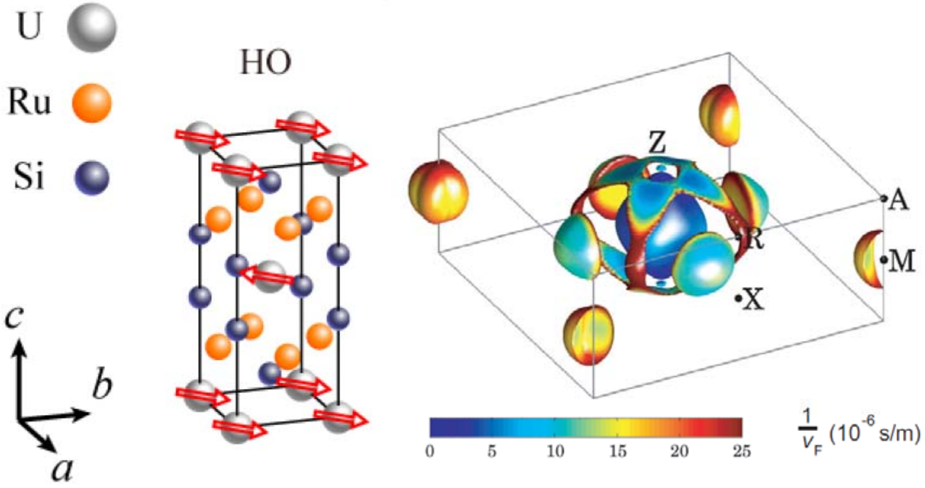
Nature (2012); Science (2012); PRLs (2009-12).

Heavy-fermion superlattices



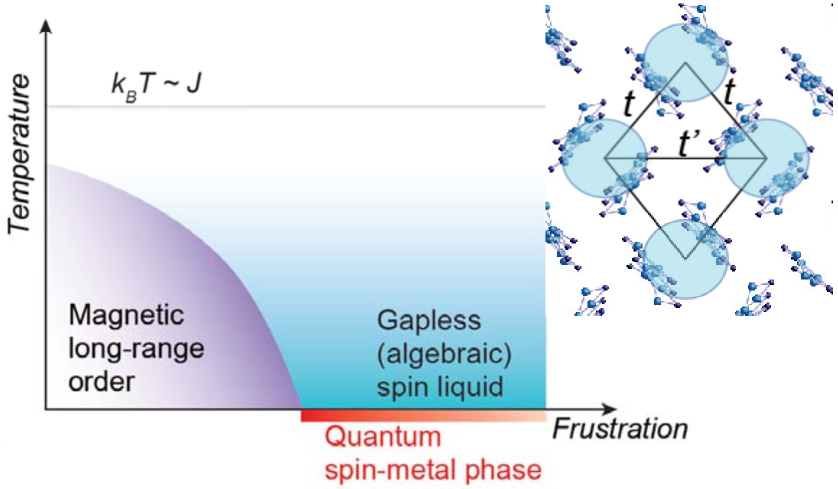
Science (2011); Nature Phys. (2012); PRL (2012).

Hidden-order mystery in URu_2Si_2



Science (2011); Nature Phys. (2012); PRL (2012).

Quantum spin liquids in triangular lattices



Nat. Phys. (2009); Science (2010); Nat. Commun. (2012).

Collaborators

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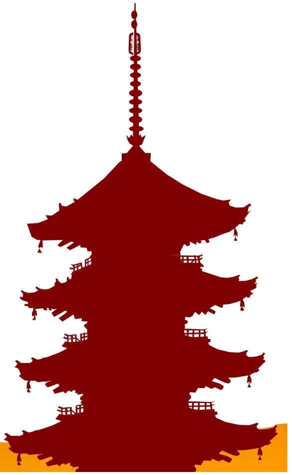
Acknowledgement: N. Kawakami, Yong-Baek Kim, P. A. Lee, T. Senthil, and N. Nagaosa for discussions



Outline

1. Introduction

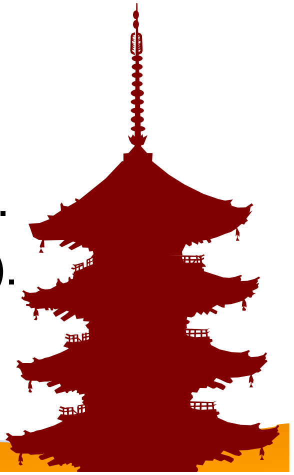
2. A quantum spin liquid state in 2D organic Mott insulator $\mathrm{EtMe_3Sb[Pd(dmit)_2]_2}$ with triangular lattice

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

4. Quantum spin metal: a novel phase in the Mott Insulator

5. Summary

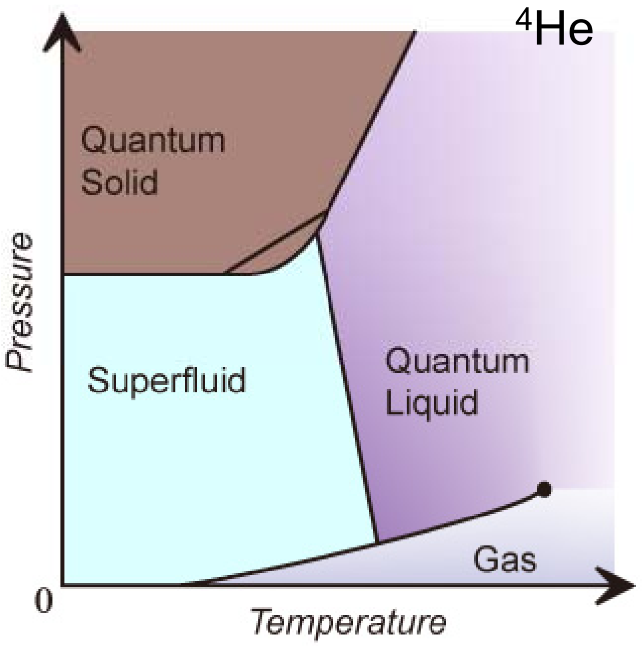
M.Yamashita *et al.*, Nature Phys. **5**, 44 (2009).
M. Yamashita *et al.*, Science **328**, 1246 (2010).
D. Watanabe *et al.*, Nature Commun. (2012).

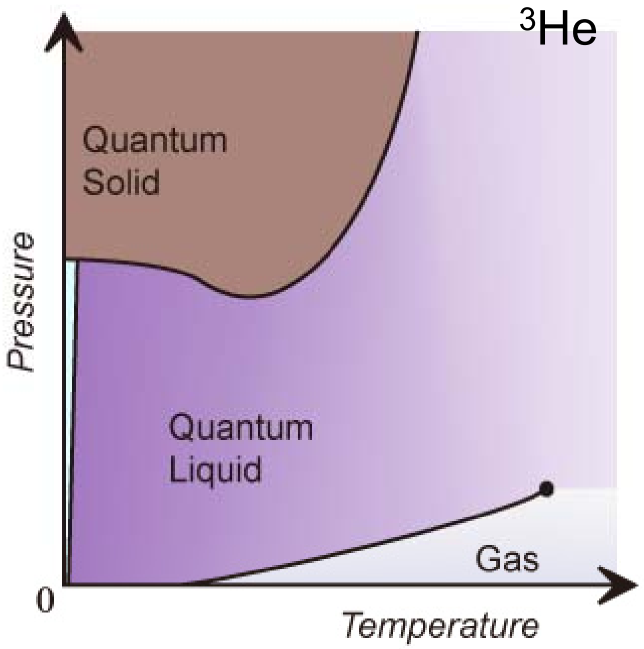


Introduction

Quantum Liquid

Quantum fluctuation prevents conventional ordering





Introduction

Quantum spin liquid (QSL)

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

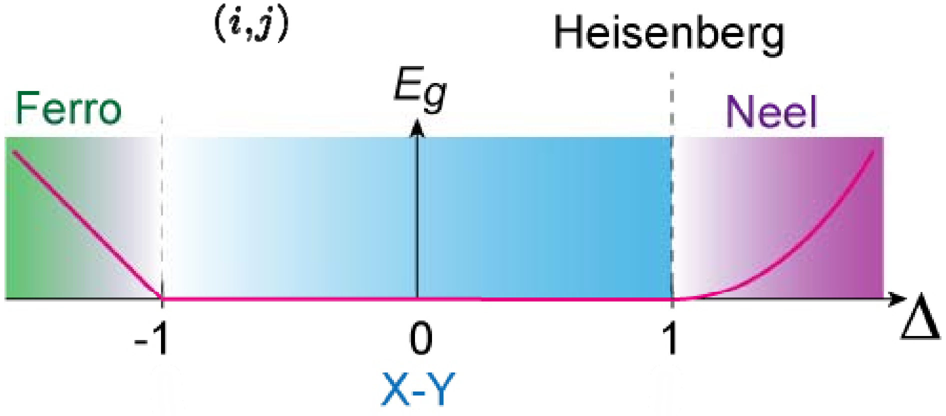
Spin Liquids are states which do not break any simple symmetry: neither spin-rotational symmetry nor lattice symmetry.

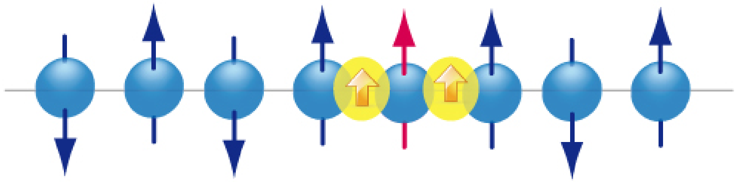
P. W. Anderson, Mater. Res. Bull (1973), Science (1987).

Notion of QSL is firmly established in 1D

1D XXZ chain (S = 1/2)

$$\mathcal{H} = J\sum_{(i,j)} \left(S_i^x \cdot S_j^x + S_i^y \cdot S_j^y + \Delta S_i^z \cdot S_j^z\right)$$





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

QSL
- ☐ No LRO
- ☐ Gapless
- ☐ Algebraic spin correlation (critical phase)

$$\langle S(r)S(0)\rangle \sim r^{-\nu}$$

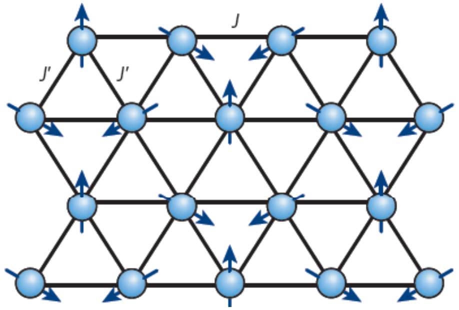
QSLs in two and three dimensions

Geometrical frustrations are required

Classical	A large ground-state degeneracy
Quantum	Quantum fluctuation lifts the degeneracy and a QSL ground state may appear

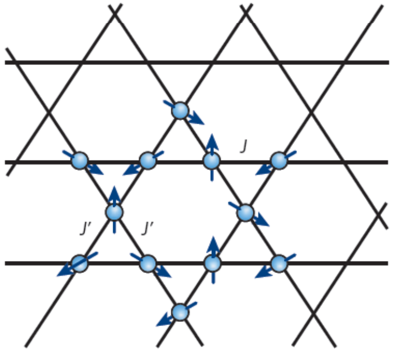
Only a few candidate materials exist.

Triangular lattice



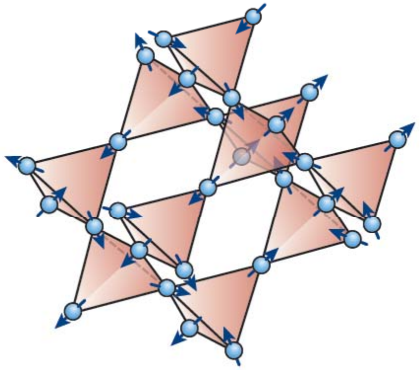
^{3}He on graphite
Organic compounds

Kagome lattice



$ZnCu_3(OH)_6Cl_2$ (Herbertsmithite)
$BaCu_3V_2O_8(OH)_2$ (Vesigniete)

Pyrochlore lattice



$Na_4Ir_3O_8$
·
·

Introduction

QSLs in two and three dimensions

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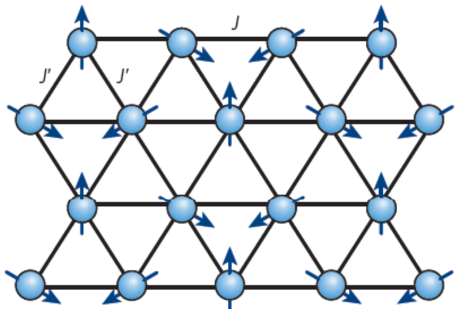
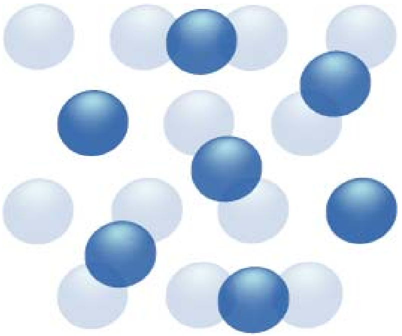
Only a few candidate materials exist.

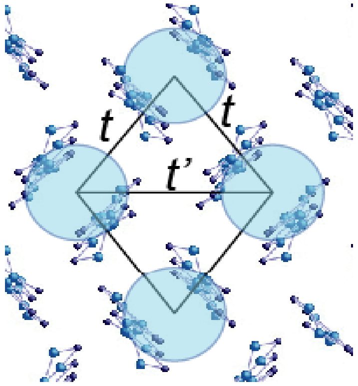
Triangular lattice





^{3}He on graphite

surface

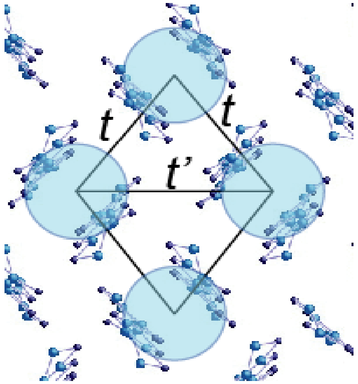


Organic compounds

bulk

Introduction

Organic Mott insulators with trianglar lattice



κ-(B<u>E</u>DT-<u>T</u>TF)$_2$Cu$_2$(CN)$_3$	**ET**
EtMe$_3$Sb[Pd(<u>dmit</u>)$_2$]$_2$	**dmit**

Strong candidates that host a QSL state

What kind of QSL is realized?

Many types of QSL proposed

- Resonating-valence-bond liquid
- Chiral spin liquid
- Quantum dimer liquid
- Z_2 spin liquid
- Algebraic spin liquid
- Spin Bose Metal
- etc…

Elementary excitations

Spinon with Fermi surface

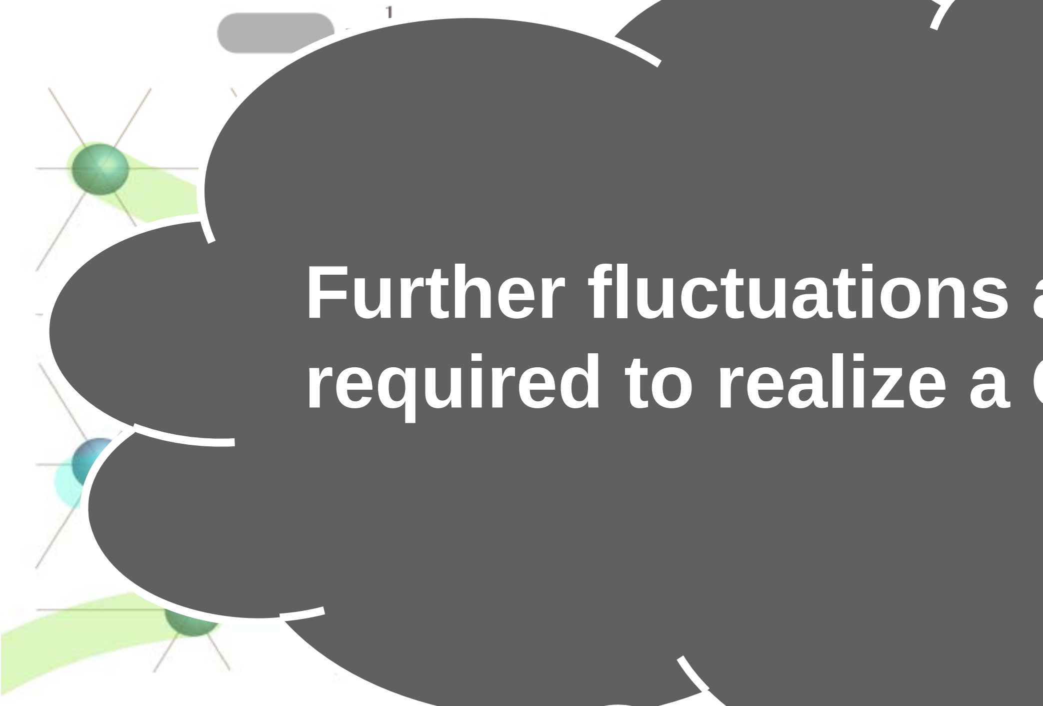
- Vison
- Majorana fermions
- etc…

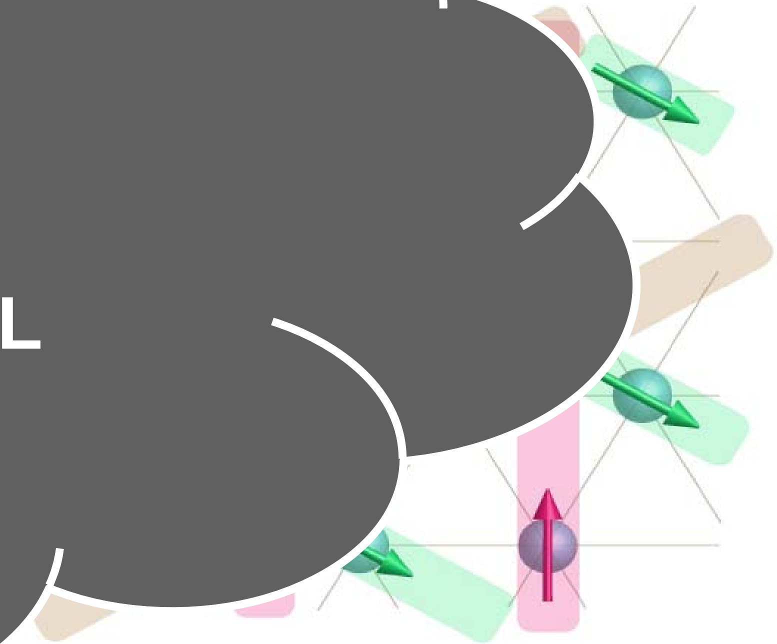
Heisenberg spins on 2D triangular lattice

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

Resonating Valence Bond (RVB) Liquid

Long-range order





Further fluctuations are required to realize a QSL

Superposition of differe nfigura

Resonance between h degenerated spin configurations lea to a liquid-like wavefunction.

P. Fazekas and P. W. Anderson, Philos. Mag. (1974).

3-sublattice Néel order (120° structure)

D. Huse and V. Elser, PRL (1988).
L. Caprioti, A. E.E. Trumper, S. Sorella, PRL (1999).
B. Bernu, C. Lhuillier, L. Pierre, PRL (1992).

Quantum spin liquid on a 2D triangular lattice

Heisenberg model for a triangular lattice

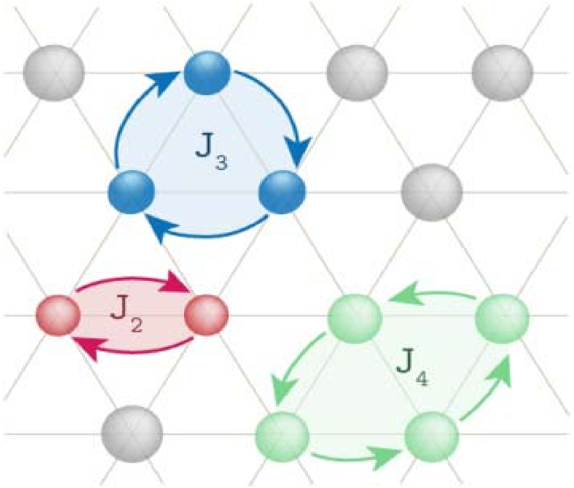
4 spin ring exchange model

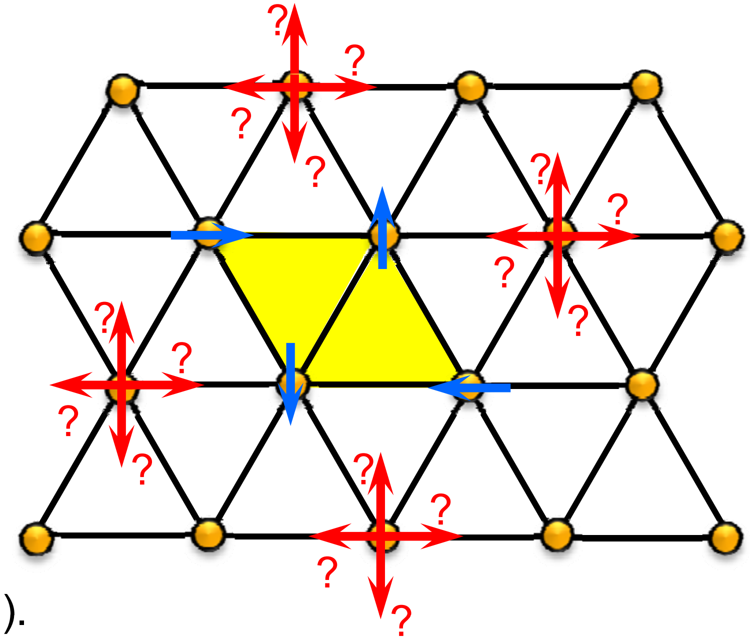
$$\hat{H}_{\text{ring}} = J_2 \sum_{\bullet\!-\!\bullet} P_{12} + J_4 \sum_{\lozenge} \left(P_{1234} + P_{1234}^{\dagger} \right)$$

$$P_{1234} = (\mathbf{s}_1 \cdot \mathbf{s}_2)(\mathbf{s}_3 \cdot \mathbf{s}_4) + (\mathbf{s}_1 \cdot \mathbf{s}_4)(\mathbf{s}_3 \cdot \mathbf{s}_2) - (\mathbf{s}_1 \cdot \mathbf{s}_3)(\mathbf{s}_2 \cdot \mathbf{s}_4)$$

When $J_4 > 0$

$$\theta_1 - \theta_2 + \theta_3 - \theta_4 = \pi$$





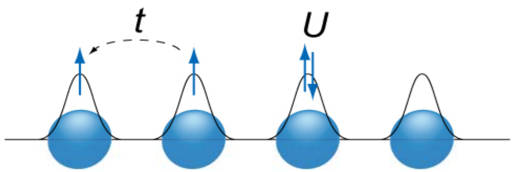
4-spin ring exchange yields a strong frustration

G. Misguich *et al*., PRB (1999).

W. LiMing, G. Misguish, P. Sindzingre, C. Luhuiller, PRB (2000).

QSL with gapped excitations

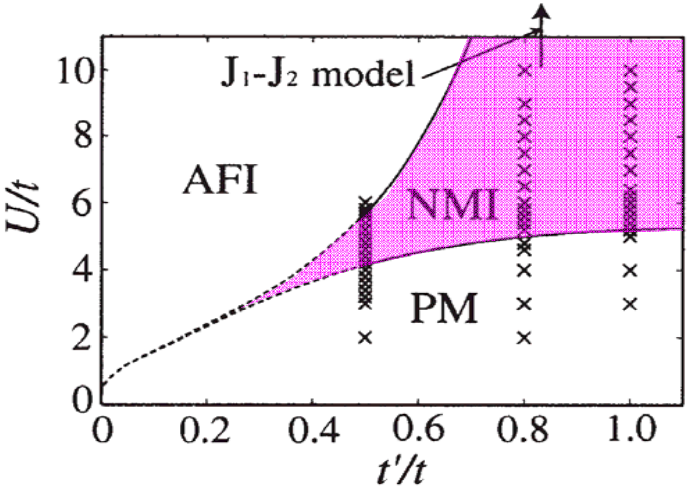
Quantum spin liquid on a 2D triangular lattice



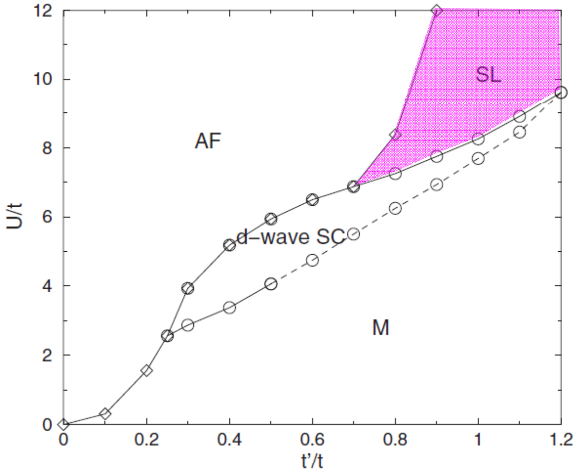
Hubbard model

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

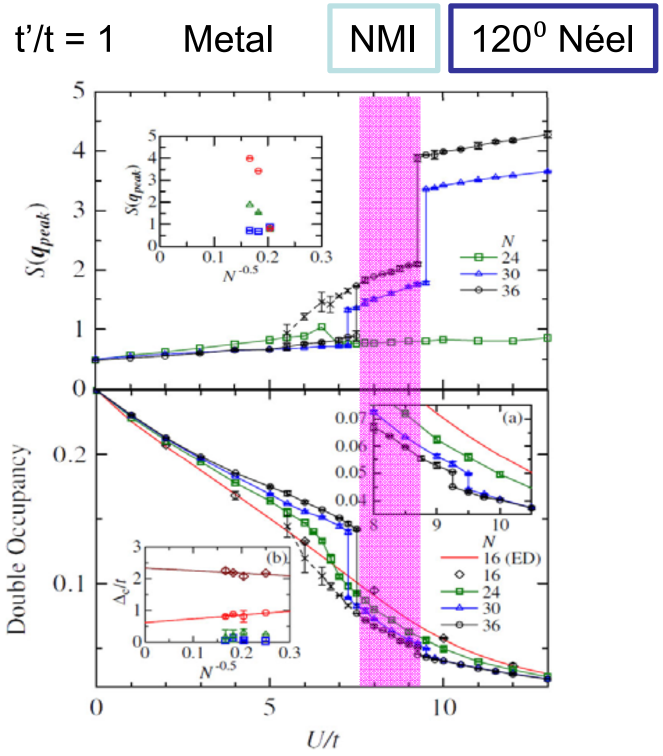
Non-Magnetic Insulating phase near M-I transition
(Quantum spin liquid)



Morita-Watanabe-Imada, JPSJ (2002).



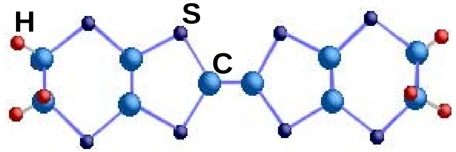
Kyung-Tremblay, PRL (2006).



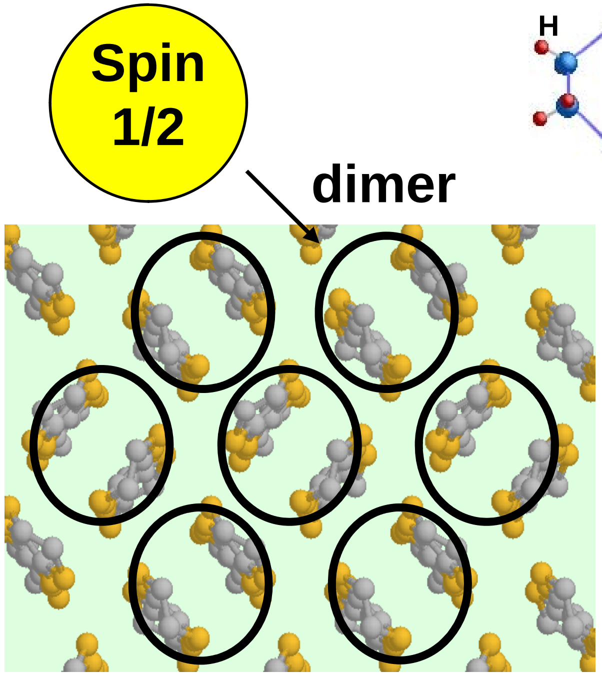
Yoshioka-Koga-Kawakami, PRL (2010).

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

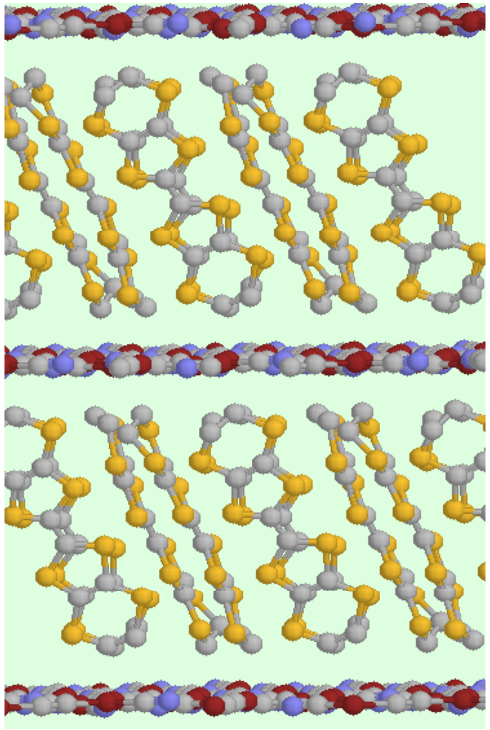
$\kappa\text{-(B}\underline{\text{E}}\text{DT-}\underline{\text{T}}\text{TF)}_2\text{Cu}_2\text{(CN)}_3$



BEDT-TTF molecule
bis(ethylendithio)-tetrathiafulvalence

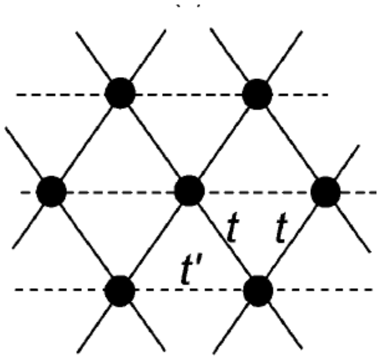


Viewed from the top



Layer of BEDT-TTF

Layer of anion (nonmagnetic)

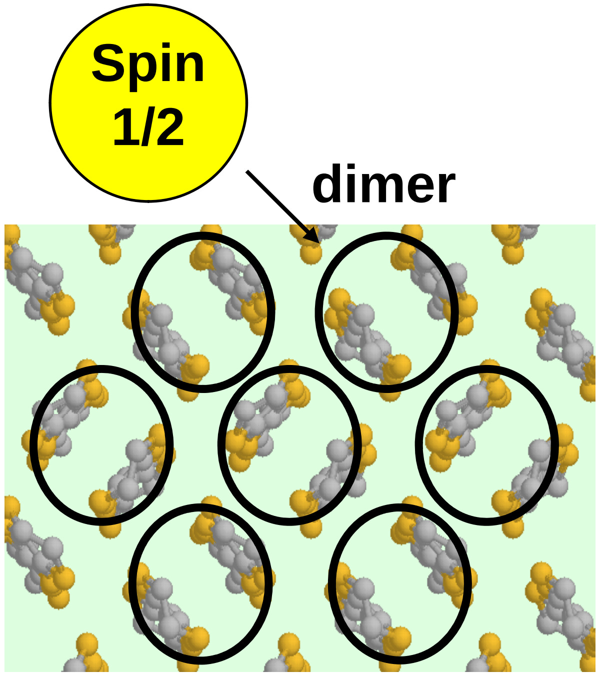


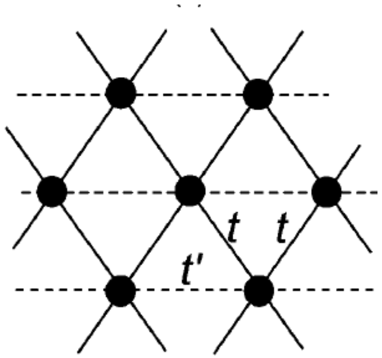
J~250 K

$t'/t = 1.06$
(Hückel Method)

Mott insulator : t~54.5 meV, t'~57.5 meV and U~448 meV (U/t~8.2)

κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$





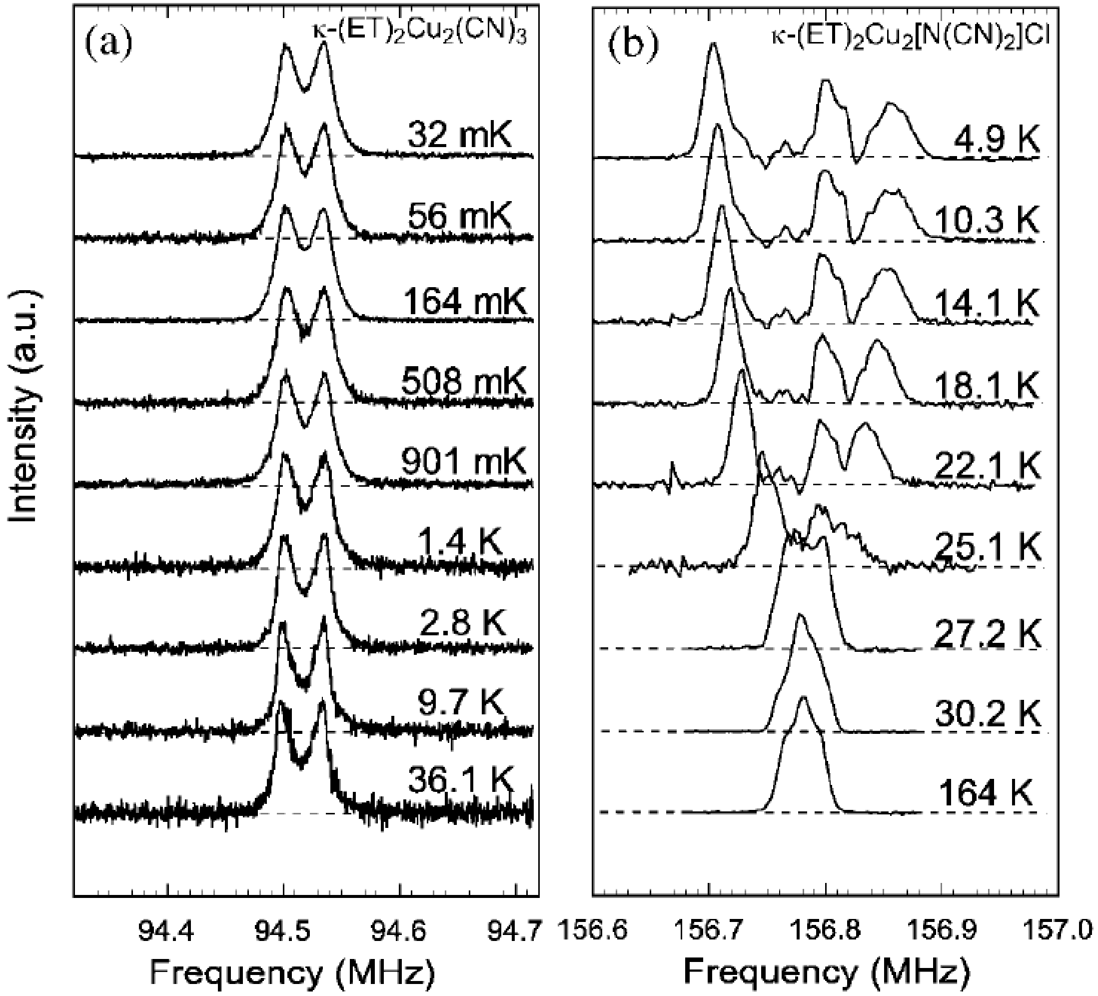
J~250 K

$t'/t = 1.06$
(Hückel Method)

^{1}H NMR

No internal magnetic field

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



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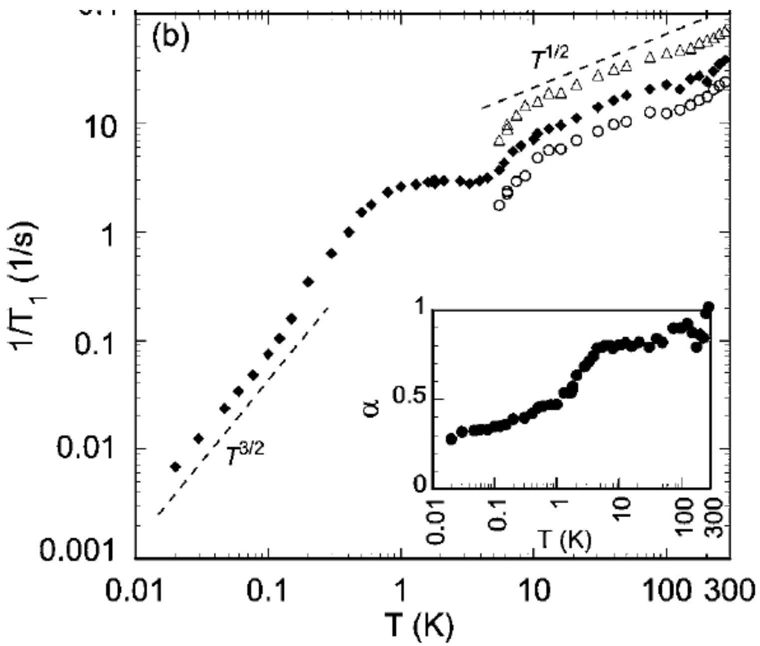
μSR F. L. Pratt *et al.*, Nature (2011).

κ-$(ET)_2Cu_2(CN)_3$: inhomogeneity or phase separation

^{13}C NMR

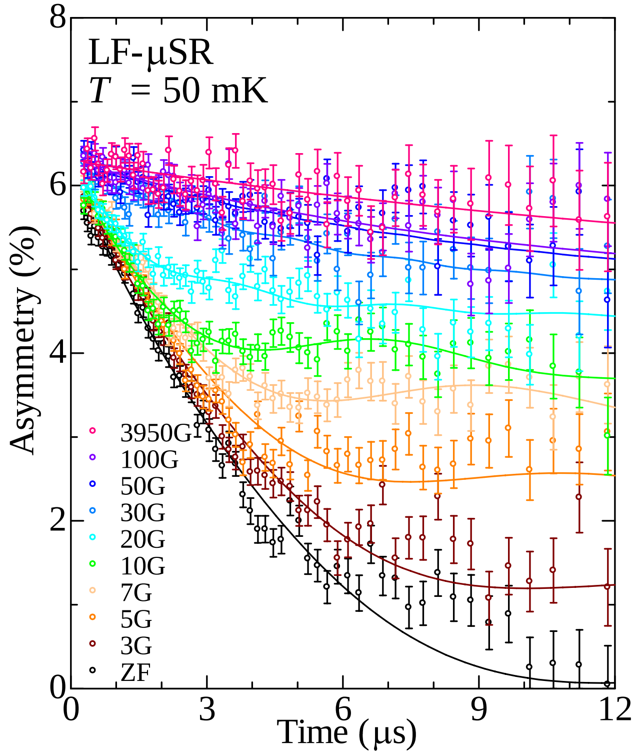


$$-M(t)/M(\infty)=\exp[-(t/T_1)^{\alpha}]$$

Y. Shimizu *et al*. PRB **73**, 140407 (2006).

NMR recovery curve shows stretched exponential

α<0.5 below 1K



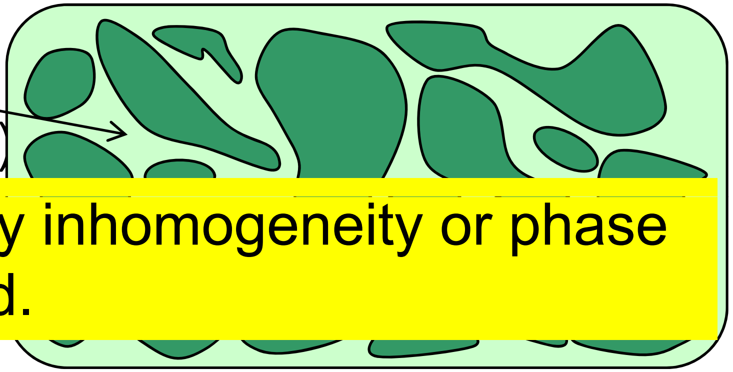
Relaxation curve below 300 mK

two components

S. Nakajima *et al*.
ArXiv 1204.1785

Microscopic phase separation between gapped and gapless regions

singlet region
(non-magnetic gapped)



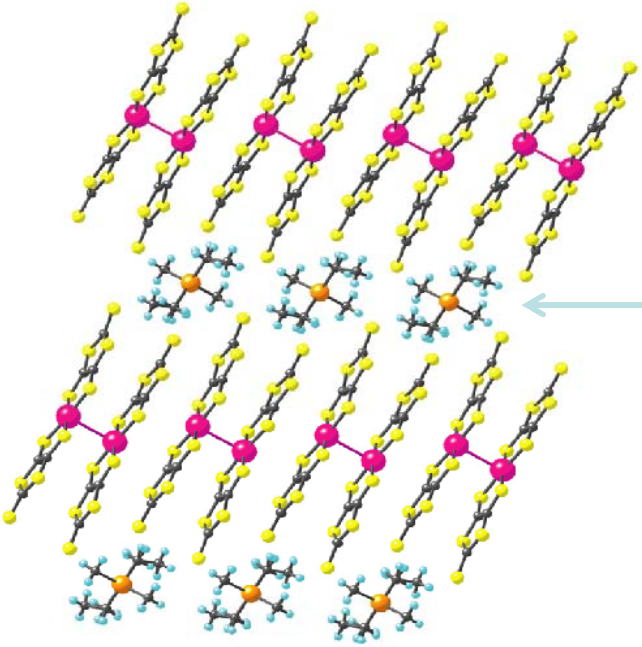
The genuine feature of the QSL may be masked by inhomogeneity or phase separation. More homogeneous system is required.

β’- $\mathrm{EtMe_3Sb[Pd(\underline{dmit})_2]_2}$

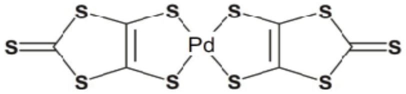
2D spin system

S = ½ Triangular lattice

SIDE VIEW

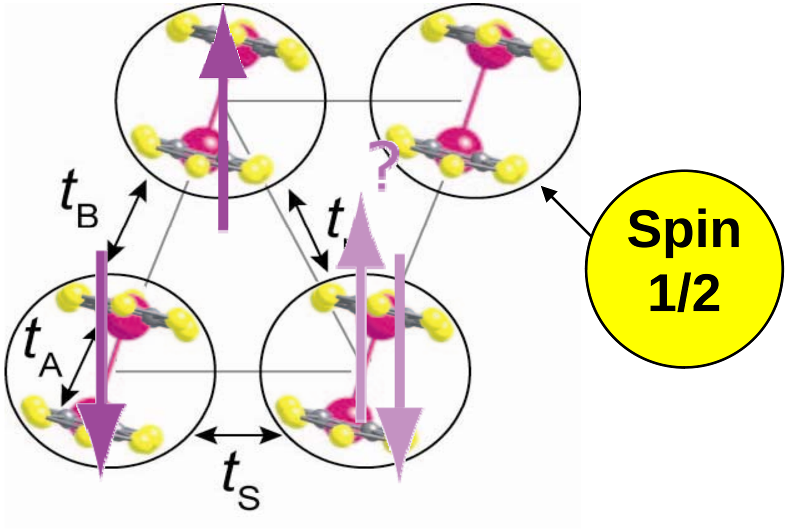


2D layer of
$\mathrm{Pd(dmit)_2}$ molecule



Cation layer
Non-magentic
X = $\mathrm{EtMe_3Sb}$,
$\mathrm{Et_2Me_2Sb}$,
etc.

TOP VIEW

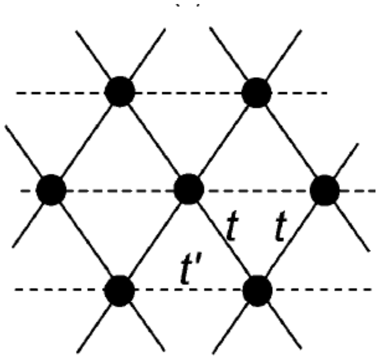


$$t_A \sim 0.5\ \mathrm{eV} \gg t_B, t_S, t_r \sim 30\ \mathrm{mV}$$

Dimerization → Half-filled Mott insulator

$t_S:t_B:t_r$ = 1:1.02:0.93

t'/t =0.93



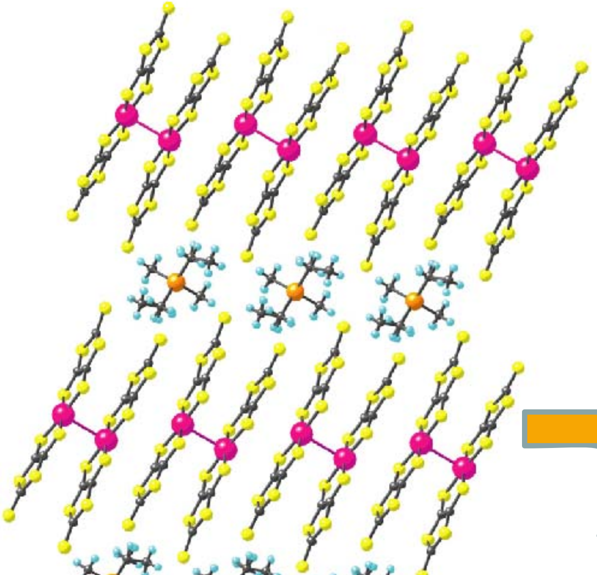
✓Very clean single crystals are available
✓Many material variants are available

R. Kato’s group at RIKEN

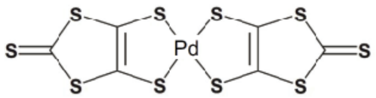
Quantum spin liquid state in β'- $EtMe_3Sb[Pd(d\underline{mit})_2]_2$

Two-dimensional Mott system with a quasi-triangular lattice

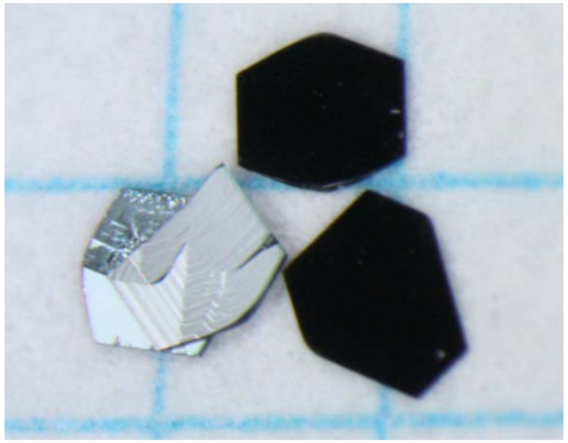
Clean system with small defects



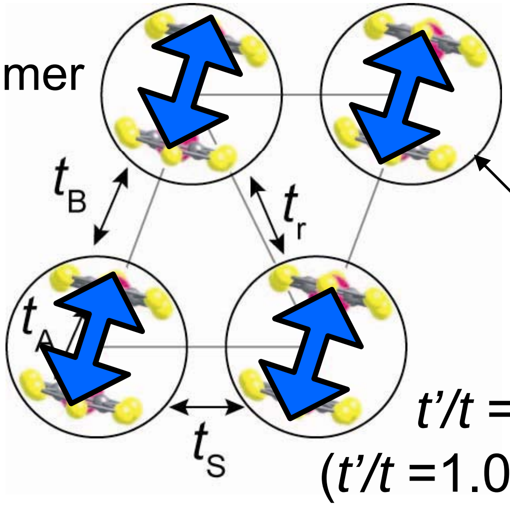
2D layer of
$Pd(dmit)_2$ molecule



Non-magentic layer
X = $EtMe_3Sb$, Et_2Me_2Sb,,,



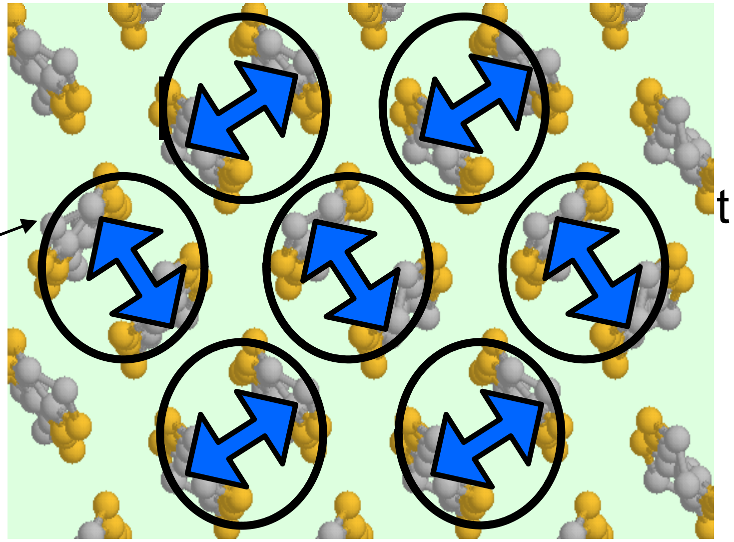
EMe_3Sb
t_S:t_B:t_r = 1:1.02:0.93



t'/t =0.93
(t'/t =1.06 for ET)

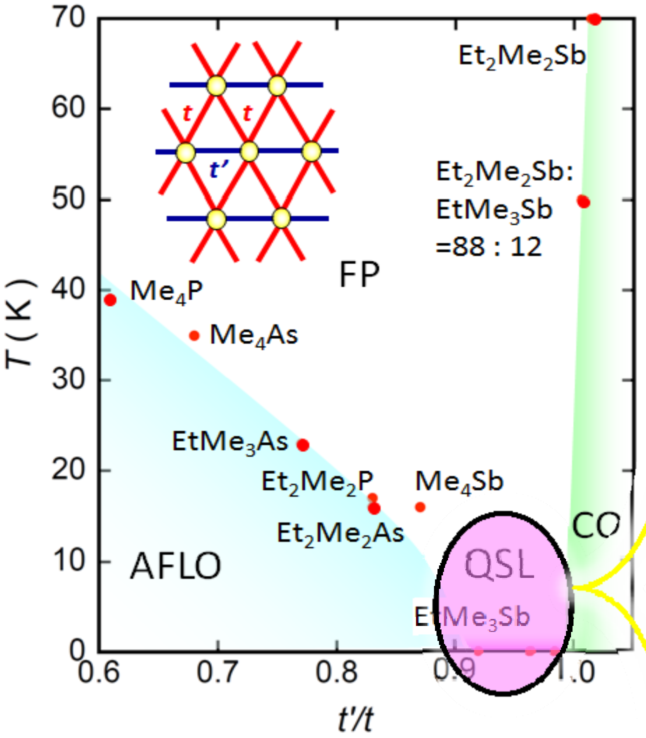
Spin 1/2

κ-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$



New QSL system $EtMe_3Sb[Pd(\underline{dmit})_2]_2$

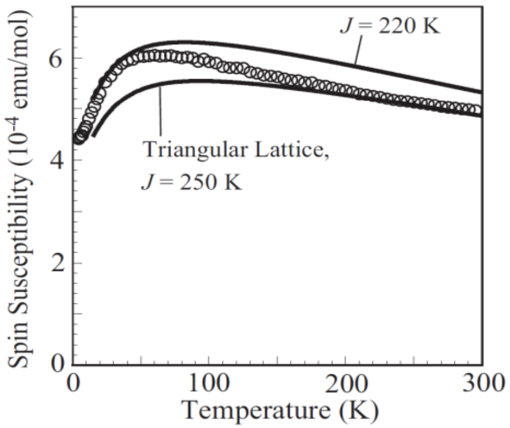
β'-(Cation)$[Pd(dmit)_2]_2$



Frustration

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

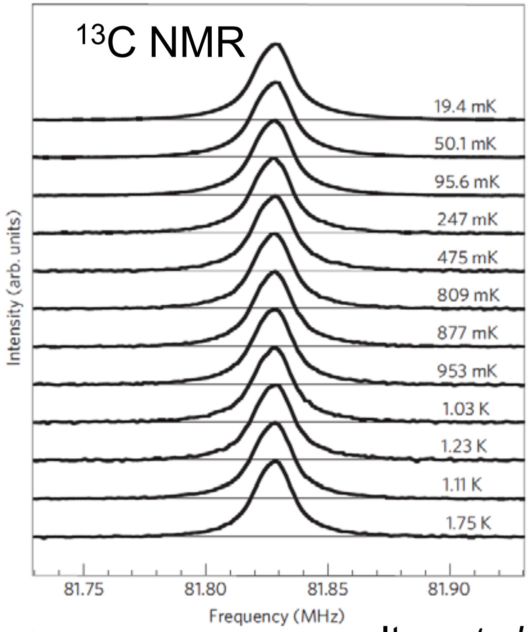
No magnetic order down to ~*J*/10,000



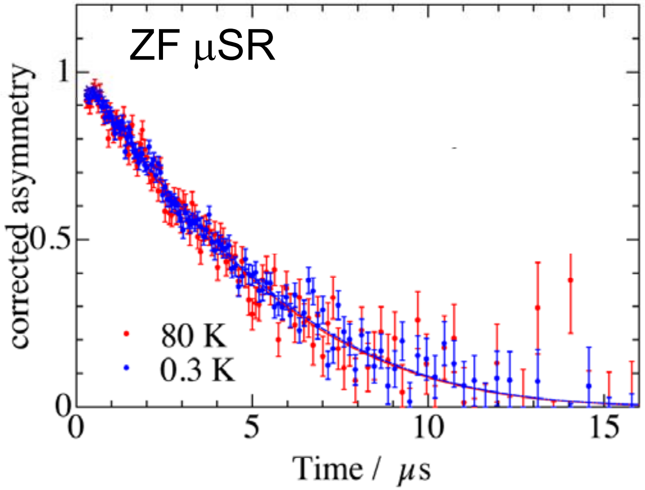
χ(T) : 2D triangular

J = 220 ~ 250 K

No internal magnetic field



No muon spin rotation

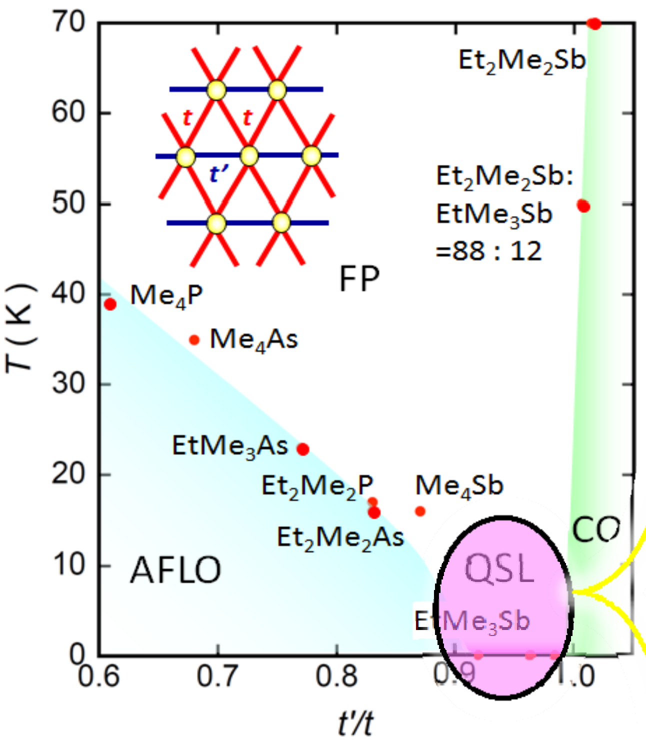


Y. Ishii *et al*.

Itou *et al*., Nature Phys. (2010).

New QSL system $EtMe_3Sb[Pd(\underline{dmit})_2]_2$

β'-(Cation)$[Pd(dmit)_2]_2$

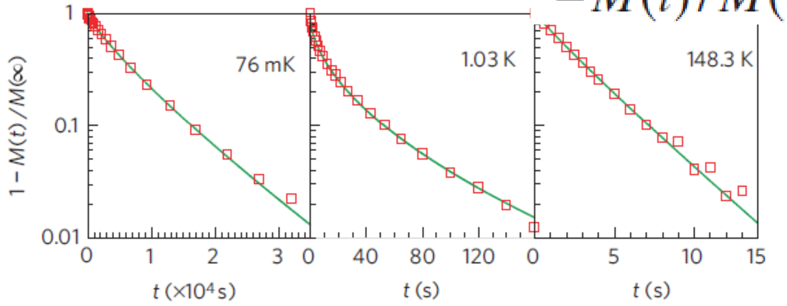


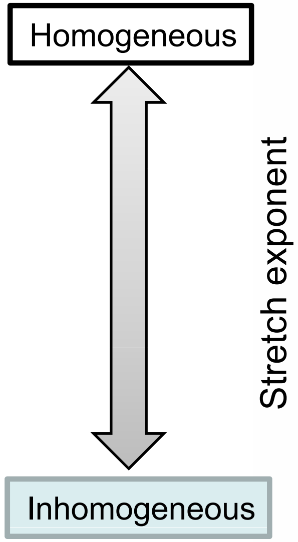
Frustration

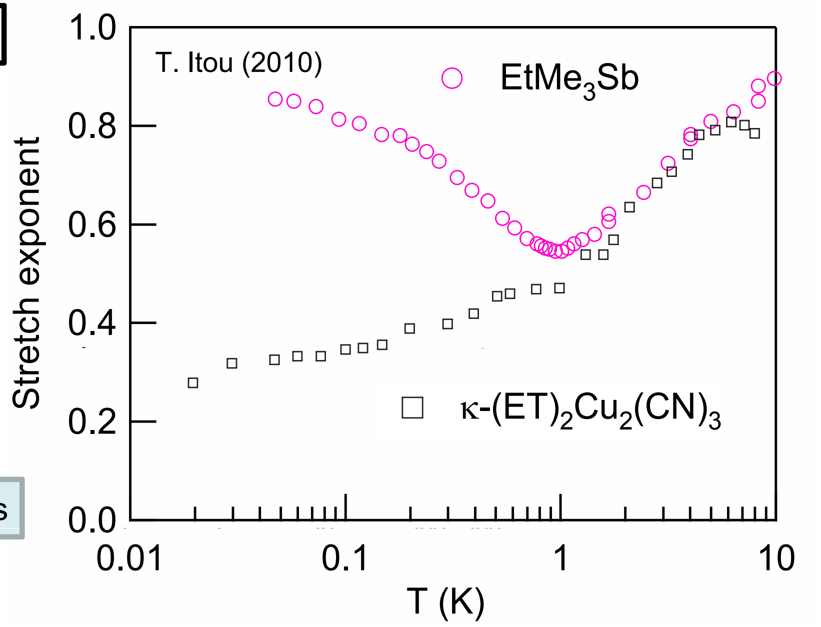
K. Kanoda and R. Kato
Annu. Rev. Condens. Matter Phys.
(2011).

NMR relaxation curve

$$-M(t)/M(\infty)=\exp[-(t/T_1)^{\alpha}]$$







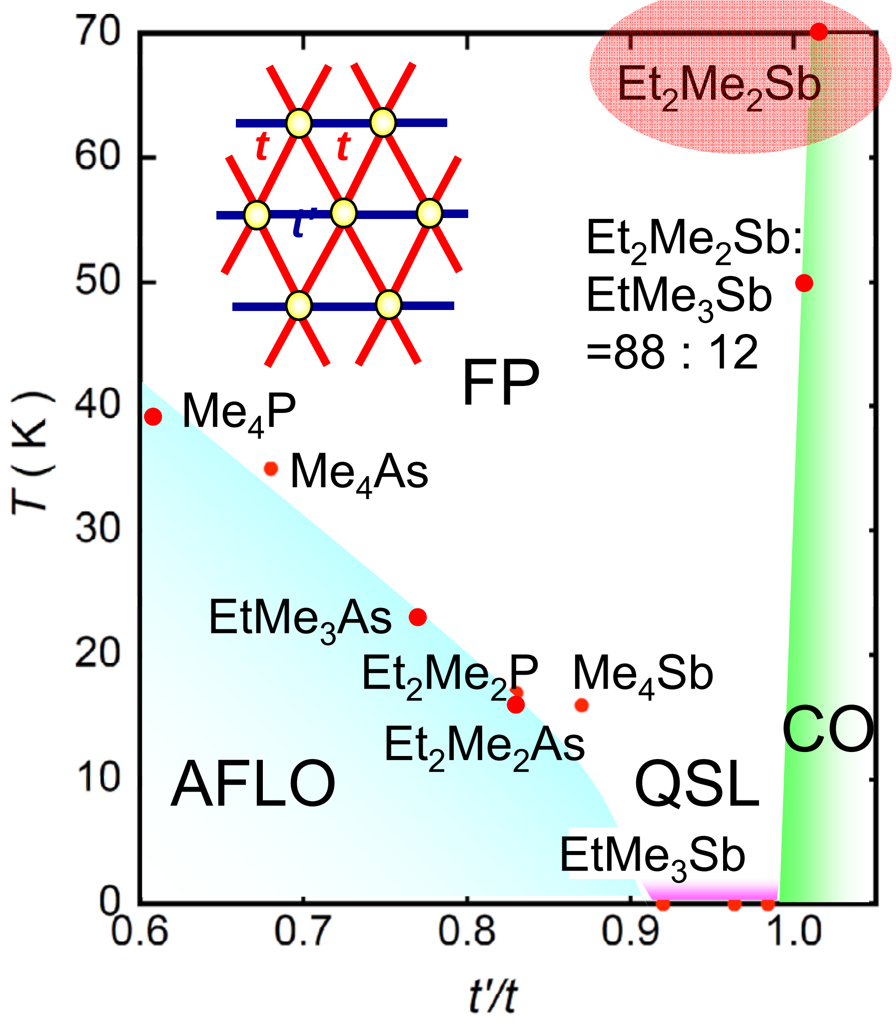
Homogeneous spin liquid state at low temperatures.

Itou *et al*., Nature Phys. (2010).

Supported by μSR

Y. Ishii *et al*. (unpublished).

β'-(Cation)[Pd(dmit)$_2$]$_2$



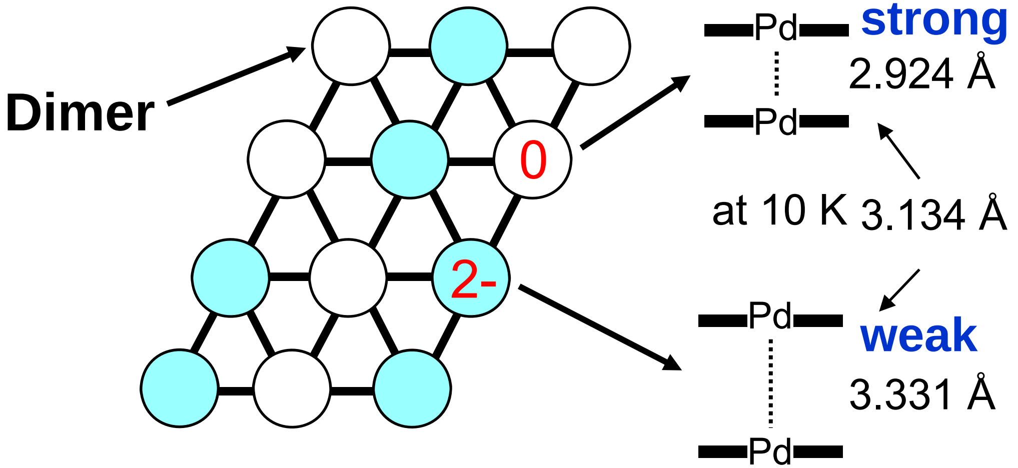
FP: Frustrated paramagnetic state

AFLO: Antiferromagnetic ordered state

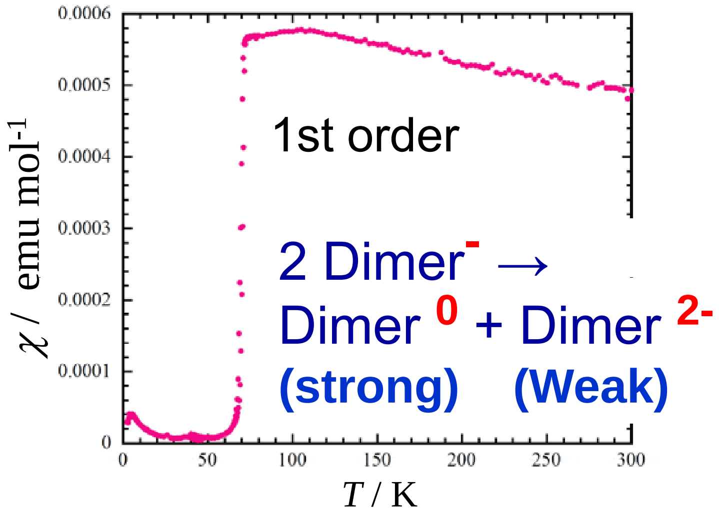
CO: Charge ordered state

QSL: Quantum spin liquid state

Et$_2$Me$_2$Sb (t'/t = 1.01)



Charge Order (CO)



2 Dimer$^-$ → Dimer ^{0} + Dimer $^{2-}$
(strong) **(Weak)**

CPL, **411** (2005) 133 / *JPSJ*, **74** (2005) 2754

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

Two key questions

Elementary excitations

Gapped or gapless?

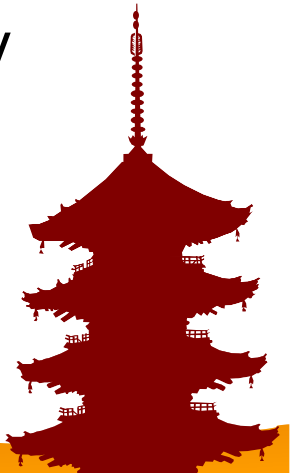
Magnetic or nonmagnetic?

Spin-spin correlation function

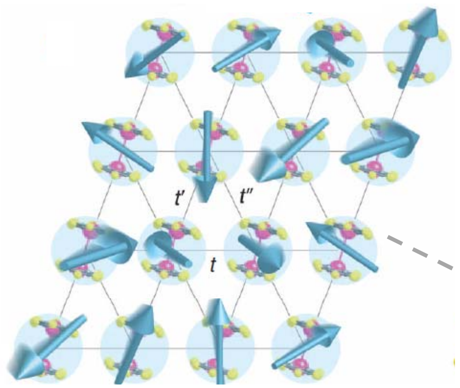
Phase diagram

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

Quantum critical nature of the QSL



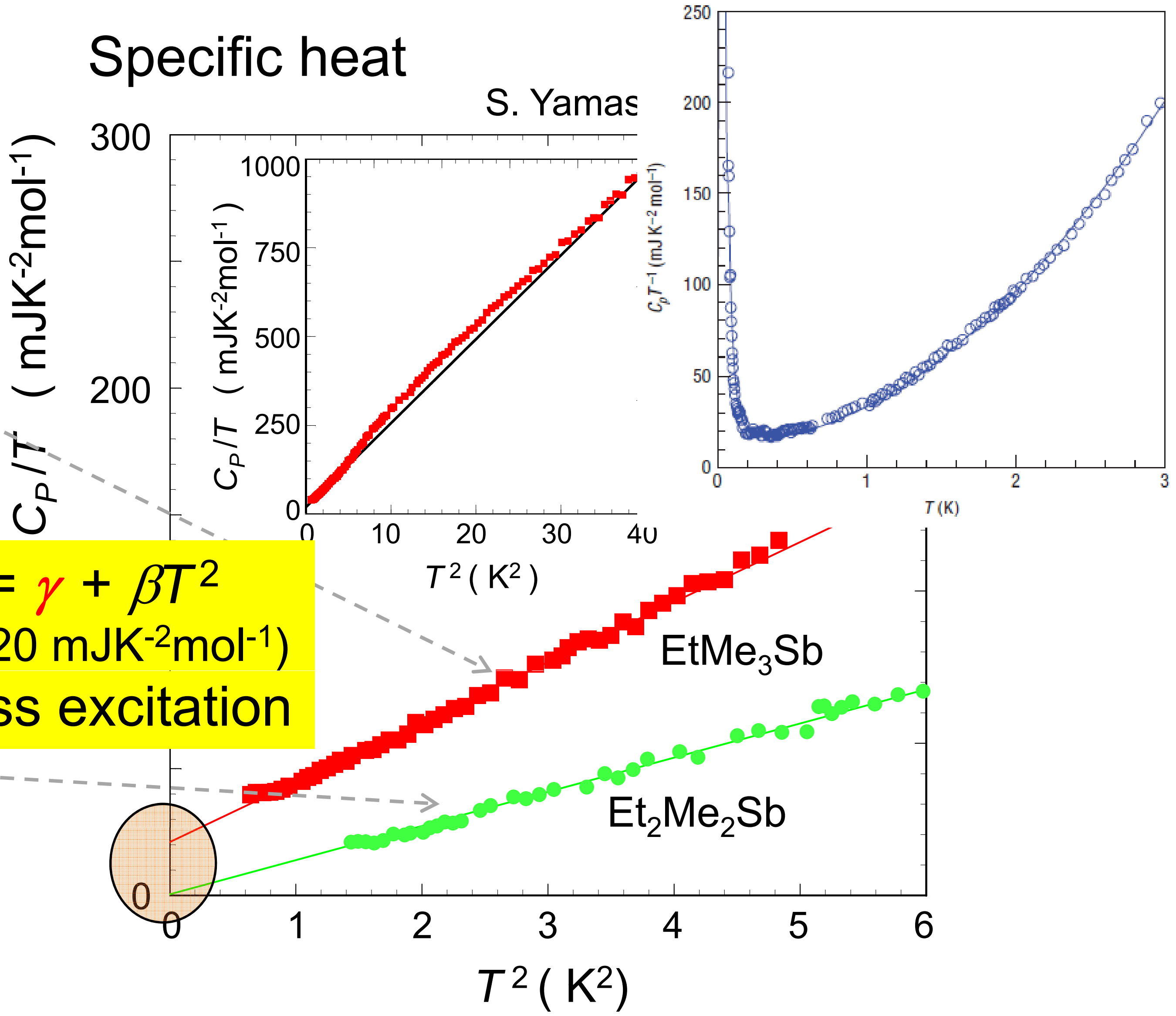
Elementary excitations : gapless or gapped?



spin 1/2

Spin liquid

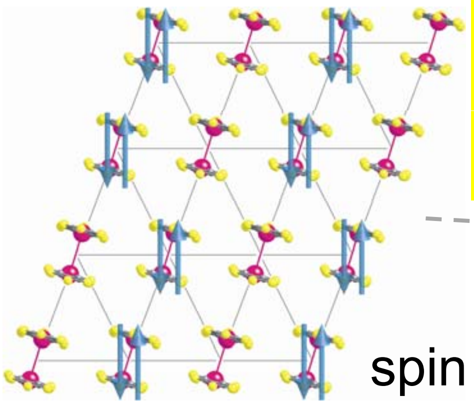
Specific heat



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

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

Gapless excitation



spin 0

Charge order

Contaminated by large Schottky contribution at low temperatures

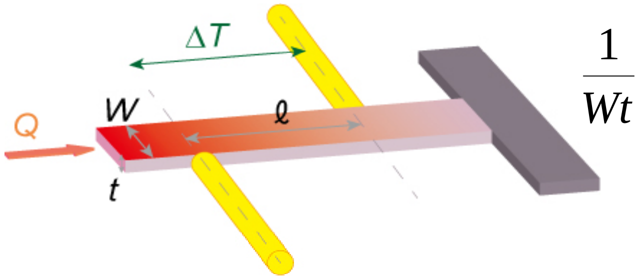
Elementary excitations : gapless or gapped?

Thermal conductivity

Not affected by localized impurities

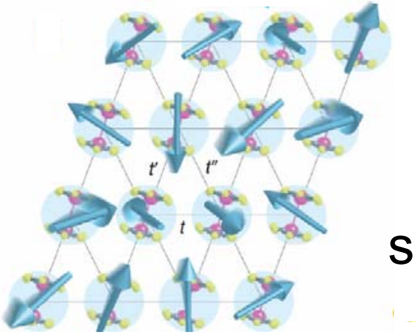
No Schottky contribution

Very low temperature measurements are available.



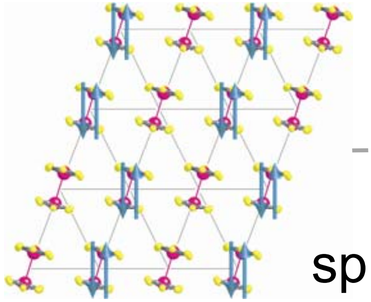
$$\frac{1}{Wt}Q = \kappa\frac{\Delta T}{\ell}$$

$\mathrm{EtMe_3Sb[Pd(dmit)_2]_2}$ Spin liquid

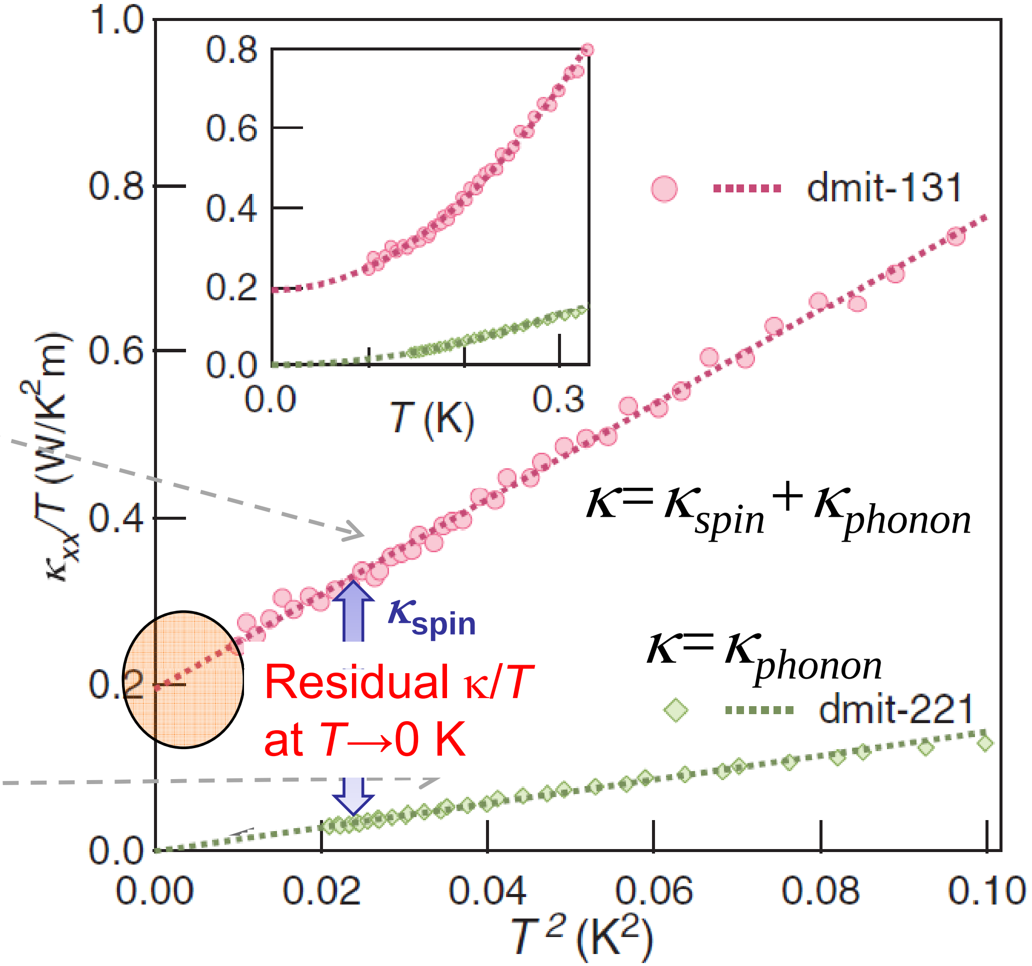


spin 1/2

$\mathrm{Et_2Me_2Sb[Pd(dmit)_2]_2}$ Charge order



spin 0

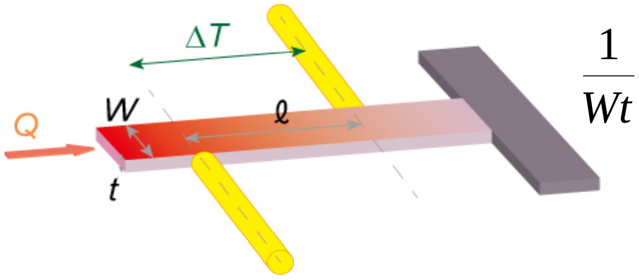


M. Yamashita *et al*., Science **328**, 1246 (2010).

Elementary excitations : gapless or gapped?

Thermal conductivity

$$\kappa = C \cdot \upsilon_s \cdot \ell$$



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

Clear residual of κ/T

κ/T ($T \to 0$) = 0.19 W/K^{2}m

Evidence for a ***gapless excitation***,
like electrons in normal metals.

Estimation of mean free path

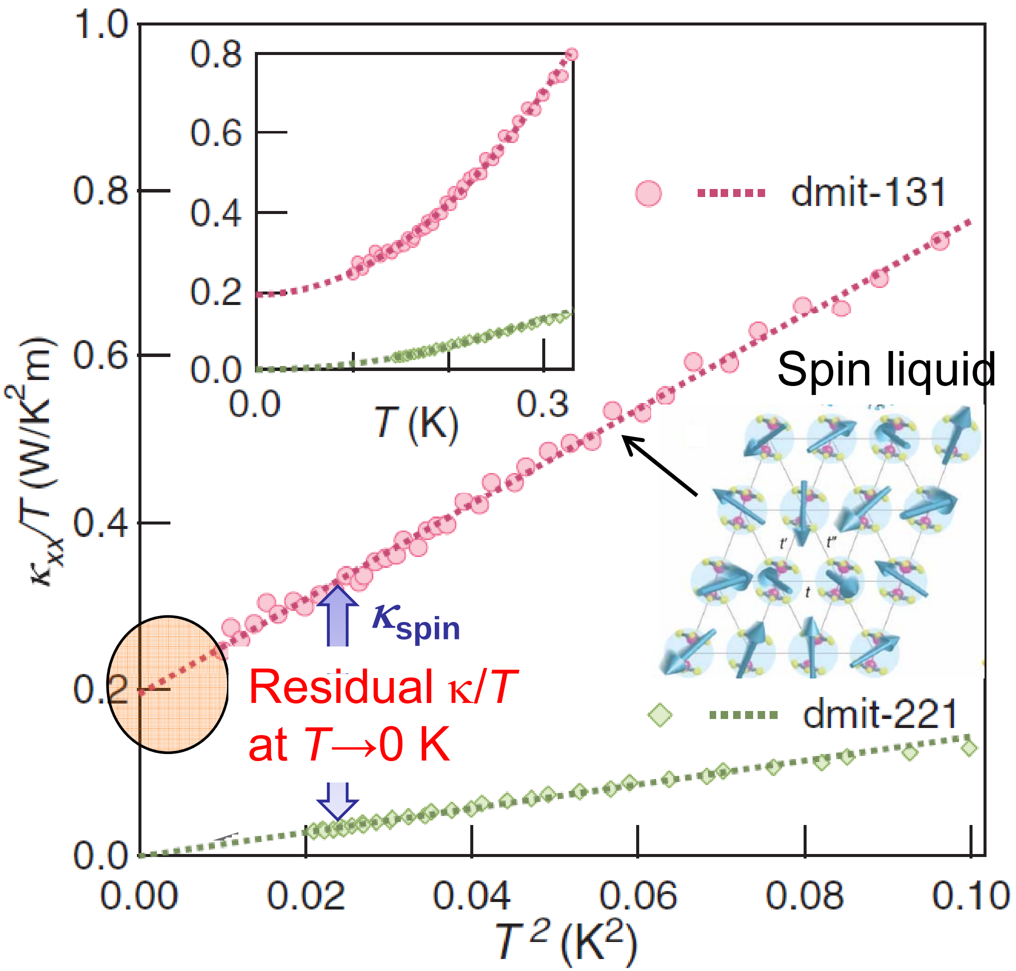
$$C/T \sim 20\mathrm{mJ/K^2mol}$$

$$\ell = 1.2\ \mu\mathrm{m} \gg a \sim 1\,\mathrm{nm}$$

More than 1000 times longer than the interspin distance!!

Itinerant excitation

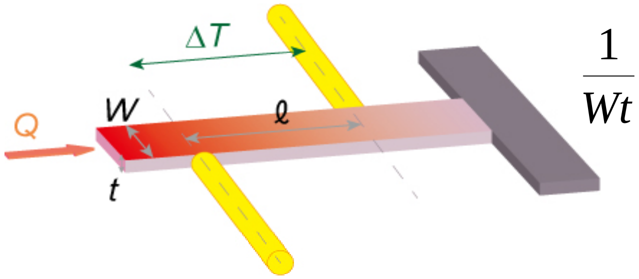
Homogeneous
Extremely long correlation length



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

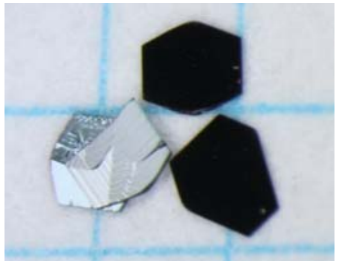
Elementary excitations : gapless or gapped?

Thermal conductivity



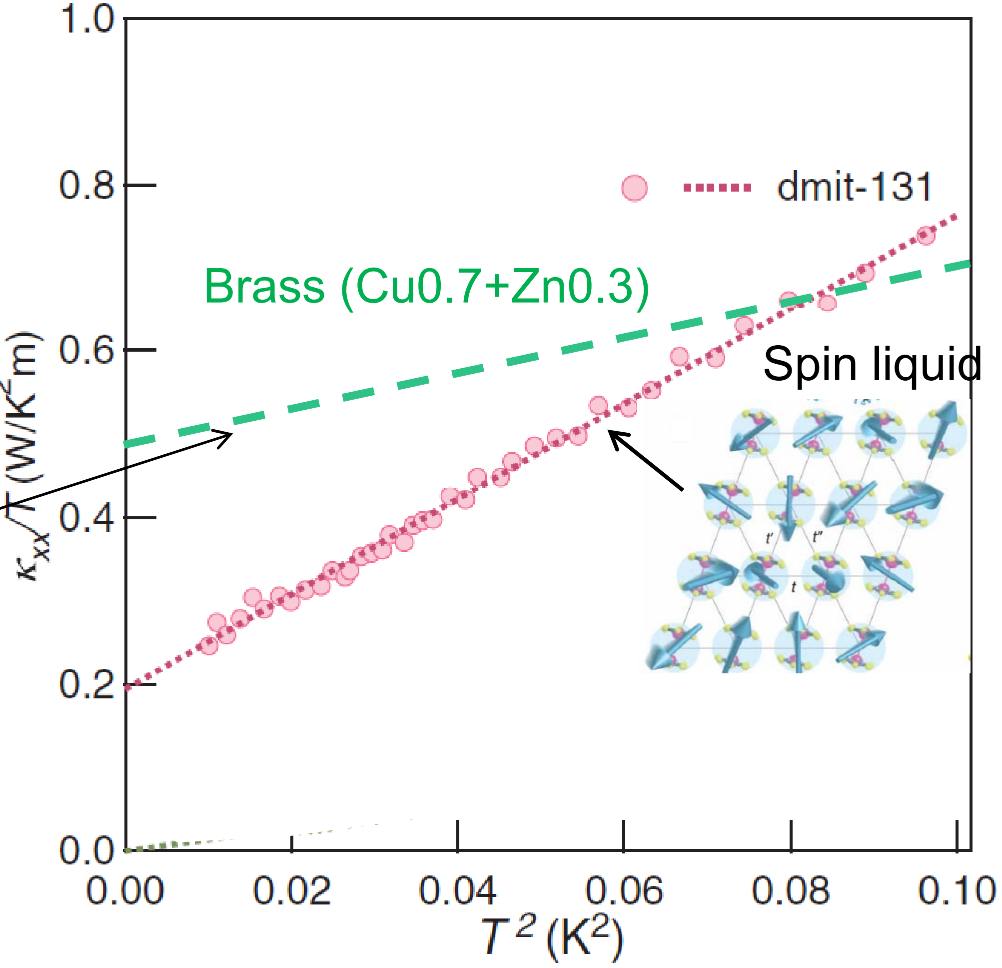
$$\frac{1}{Wt}Q = \kappa\frac{\Delta T}{\ell}$$

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



5 yen coin

Brass



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

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

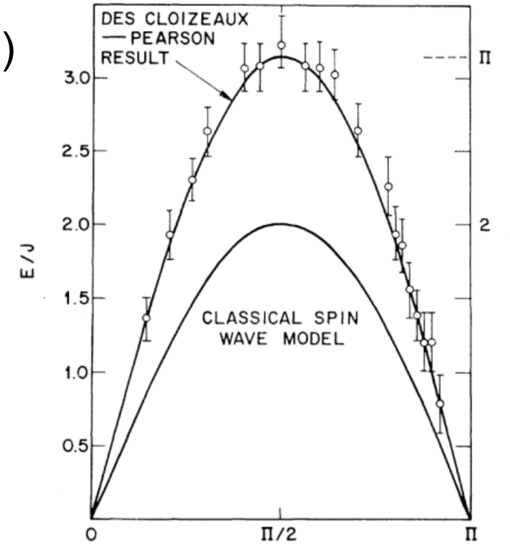
Gapless elementary excitations

Remaining key question   Are they magnetic?

Spin-spin correlation function

1D S=1/2 Heisenberg

$CuCl_2 \bullet 2N(C_5D_5)$

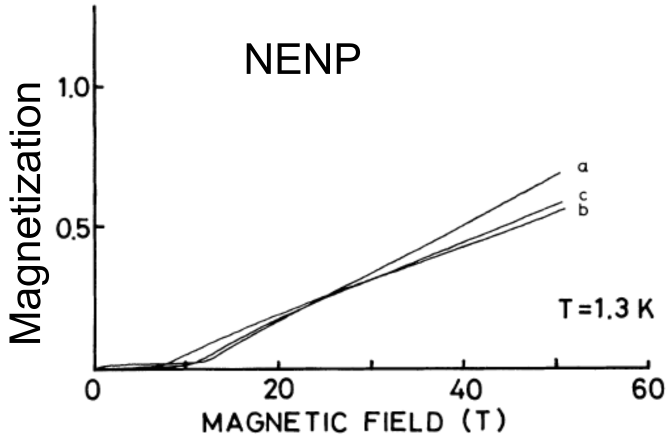


Gapless

Power law (algebraic)

$$\langle S(r)S(0)\rangle \sim r^{-\nu}$$

Haldane system (S = 1)



Gap

Exponential

$$\langle S(r)S(0)\rangle \sim e^{-r/\xi}$$

What kind of QSL state in EtMe$_3$Sb[Pd(dmit)$_2$]$_2$?

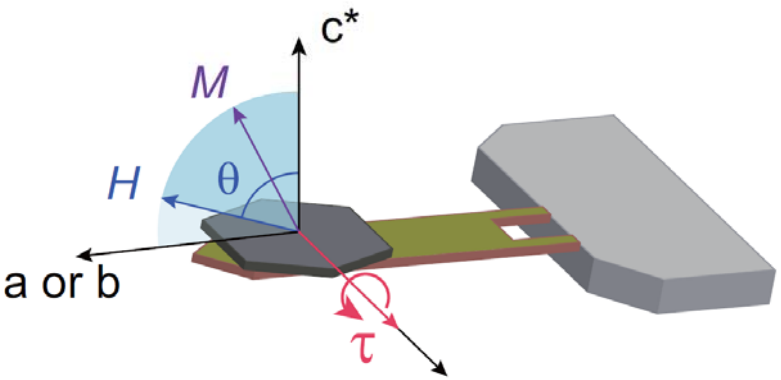
Gapless elementary excitations

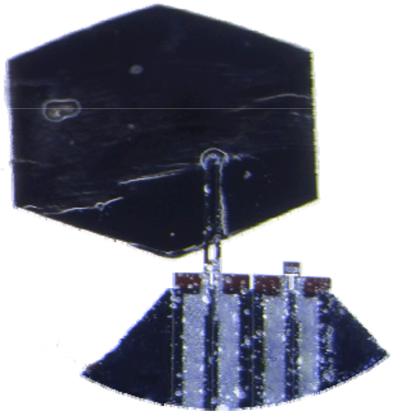
Remaining key question **Are they magnetic?**

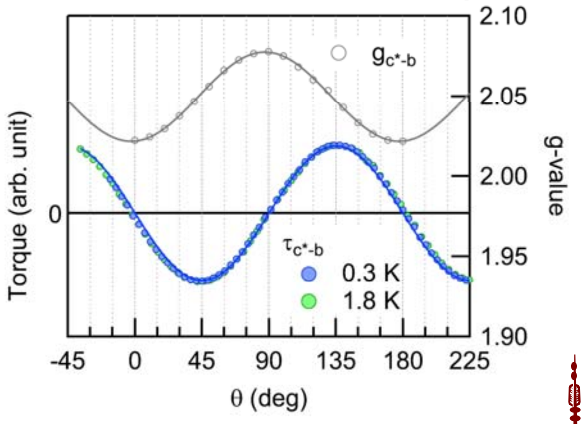
Uniform susceptibility and magnetization at low temperatures

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

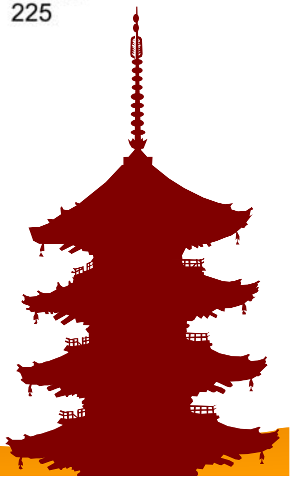
SQUID (Only down to ~4 K due to Curie contribution)



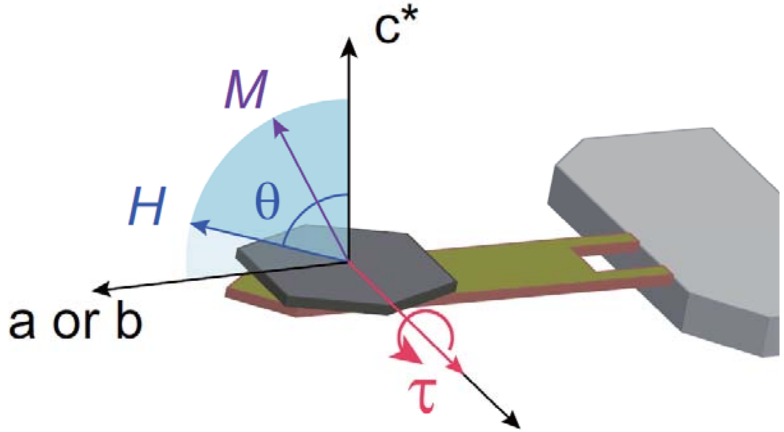


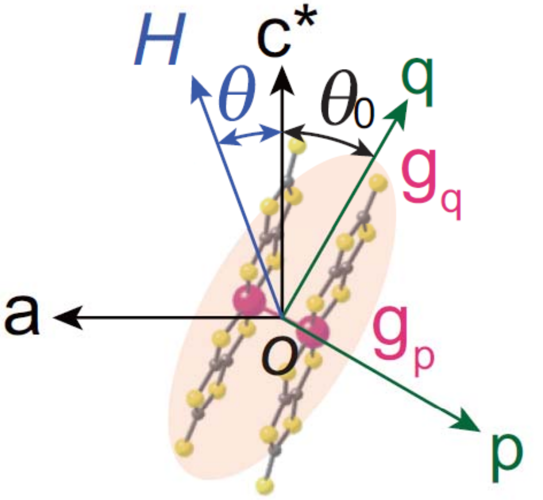


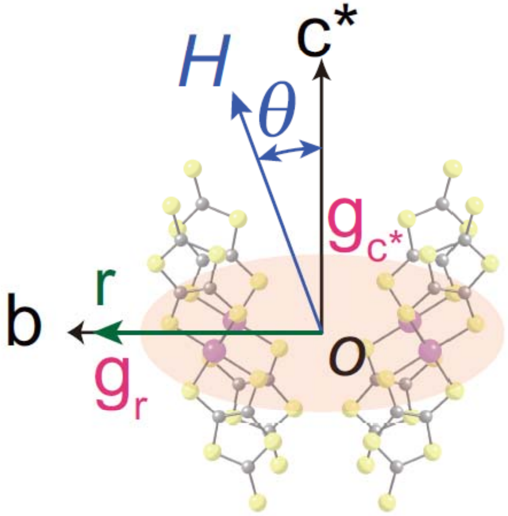
- •Isotropic contribution from impurities is cancelled.
  Torque picks up only anisotropic components.
- •High sensitivity.
  Measurements on a tiny single crystal are possible.



Magnetic torque measurements in EtMe$_3$Sb[Pd(dmit)$_2$]$_2$





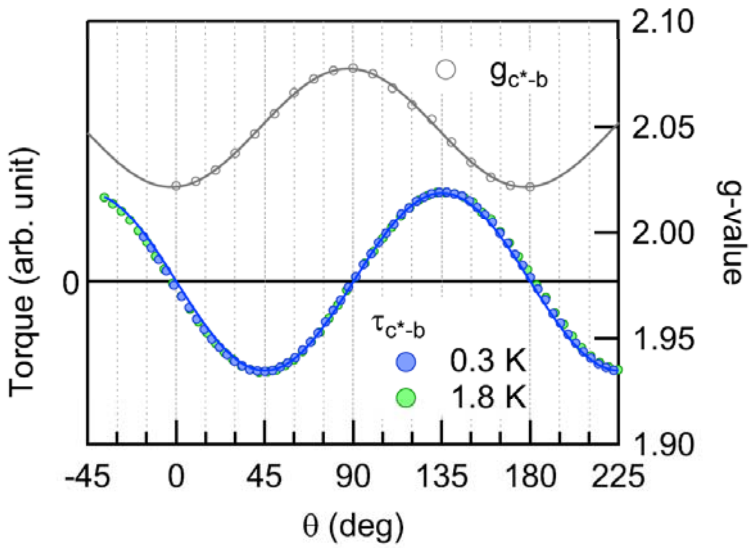


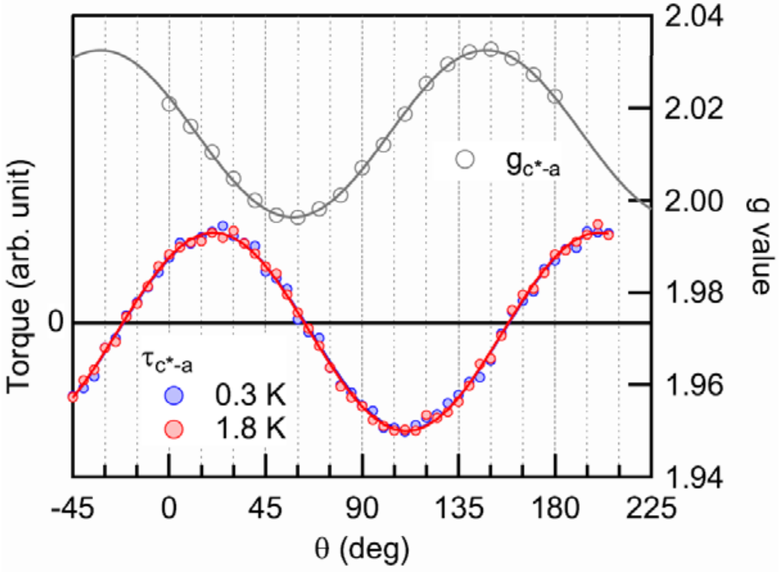
$$M = \begin{pmatrix} \chi_{pp} & 0 & 0 \\ 0 & \chi_{qq} & 0 \\ 0 & 0 & \chi_{rr} \end{pmatrix} H \qquad \chi_{ii} = g_{ii}^2 \tilde{\chi}$$

$$\tau_{c^*-a}(\theta) = \frac{1}{2}\mu_0 H^2 V (g_{qq}^2 - g_{pp}^2)\tilde{\chi}\sin 2(\theta + \theta_0)$$

$$\tau_{c^*-b}(\theta) = \frac{1}{2}\mu_0 H^2 V (g_{pp}^2 \sin^2\theta_0 + g_{qq}^2 \cos^2\theta_0 - g_{rr}^2)\tilde{\chi}\sin 2\theta$$

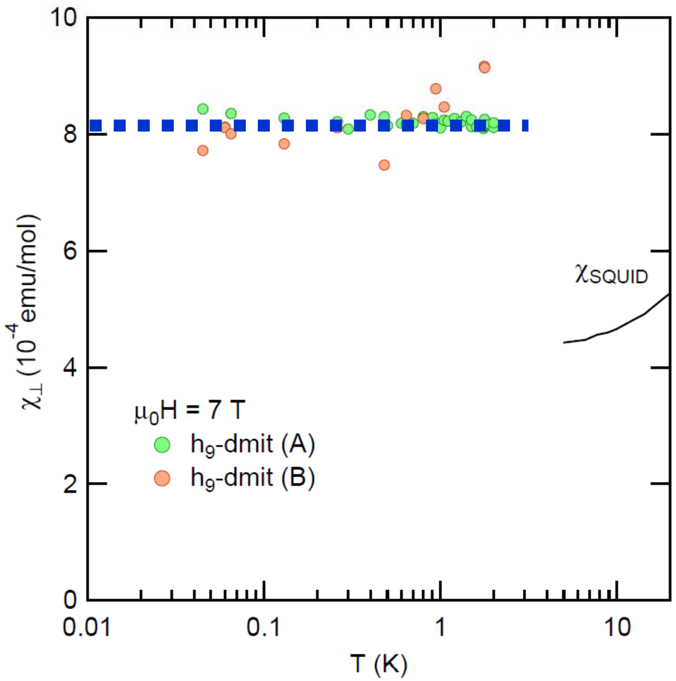
$$\chi_{\perp} = g_{c^* c^*}^2 \tilde{\chi}$$



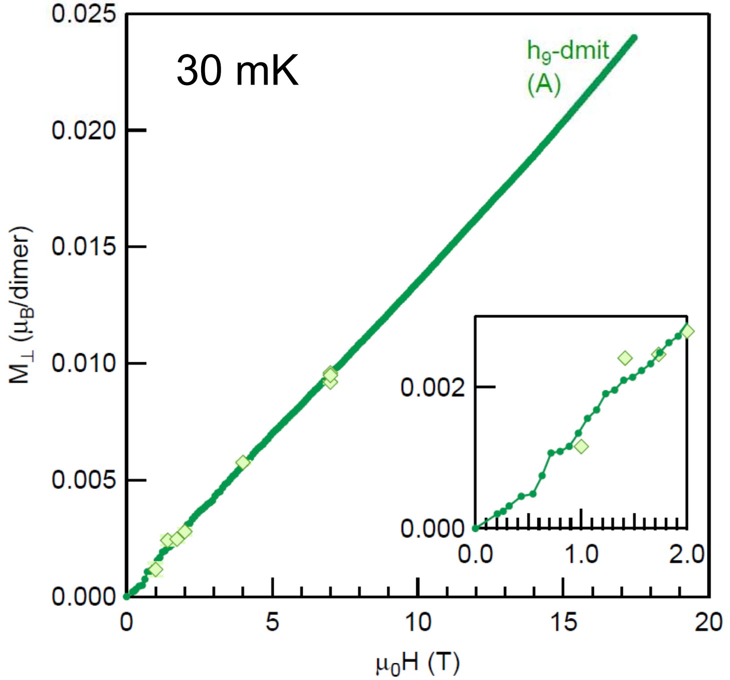


Uniform susceptibility and magnetization of QSL

Susceptibility $\chi_{\perp \text{plane}}$



Magnetization $M_{\perp \text{plane}}$



T-independent and remains finite at T→0K

increases linearly with *H*

Gapless magnetic excitations (absence of spin gap)

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

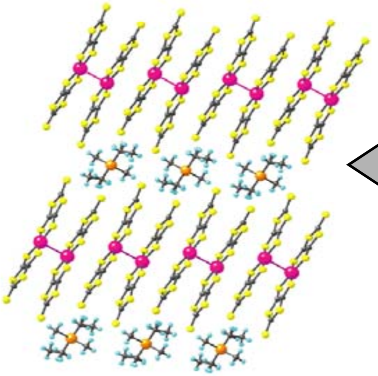
Divergence of ξ, i.e. QSL is in **a critical state**

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

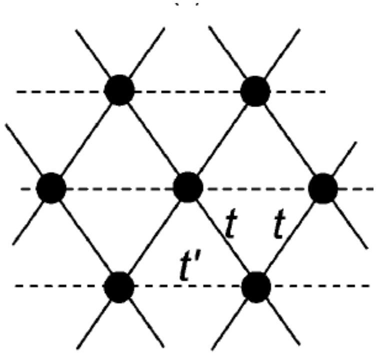
Uniform susceptibility and magnetization of QSL

How the QSL changes when the degree of frustration varies?

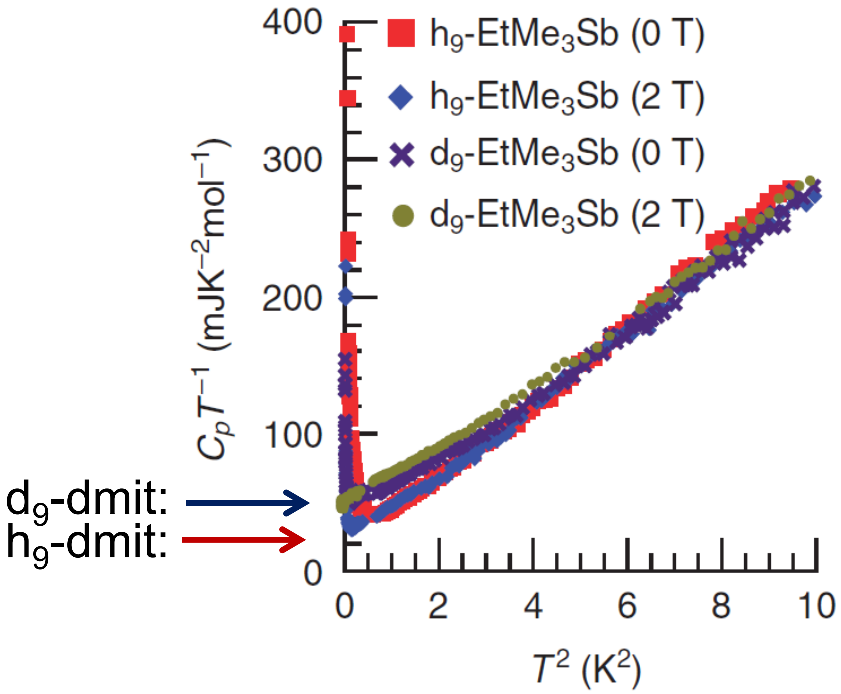
Deuteration



Cation layer X = EtMe$_3$Sb,
Three Me groups are deuterated



h$_9$-dmit: pristine
d$_9$-dmit :deuterated

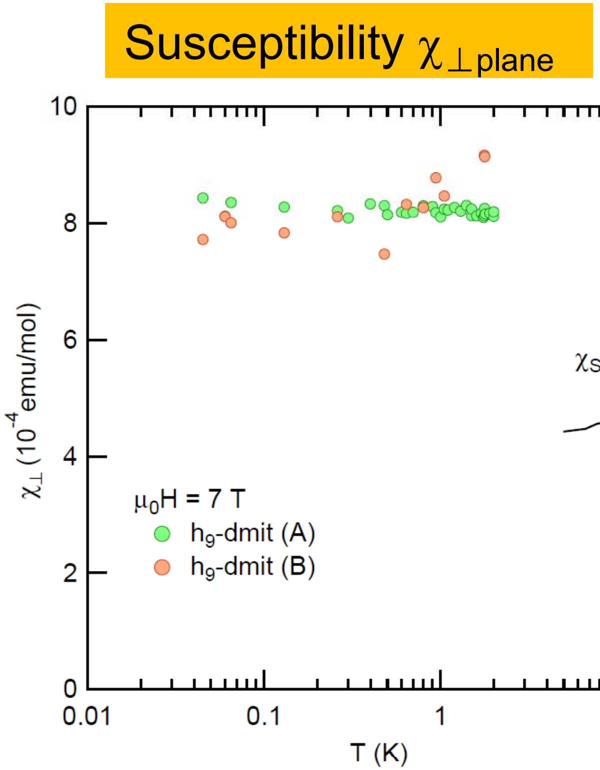


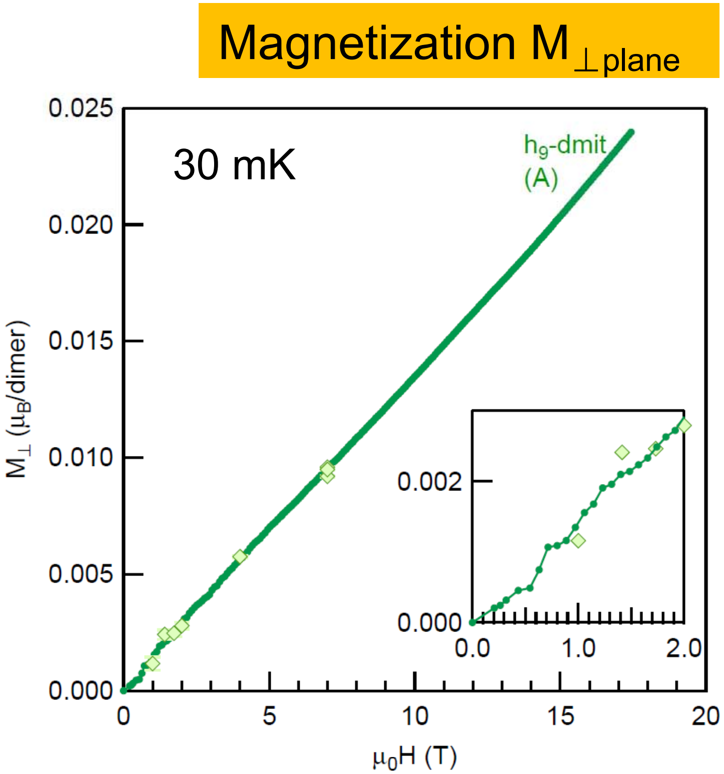
h$_9$-dmit: C_p / T ~ 20 mJ/K^{2}mol
d$_9$-dmit : C_p / T ~ 40 mJ/K^{2}mol

Deuteration changes the low temperature specific heat. Presumably it reduces *t'/t.*

S. Yamashita *et al.*, Nature Commun. (2011).

Uniform susceptibility and magnetization of QSL

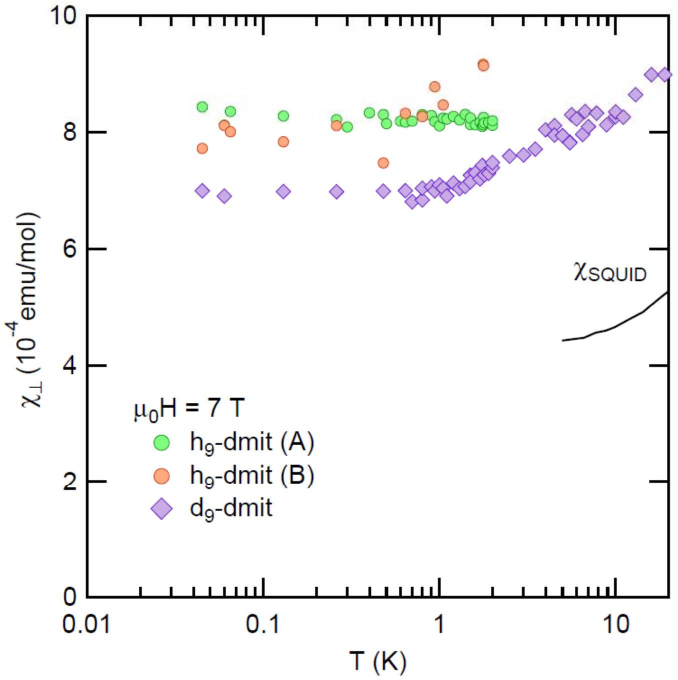




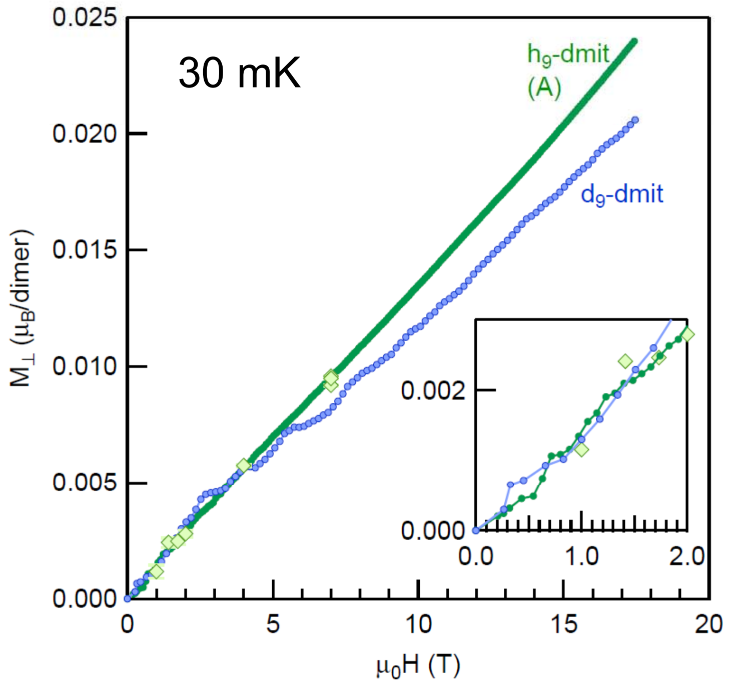
Deuteration changes the degrees of geometrical frustration.

Uniform susceptibility and magnetization of QSL

Susceptibility $\chi_{\perp \mathrm{plane}}$



Magnetization $M_{\perp \mathrm{plane}}$

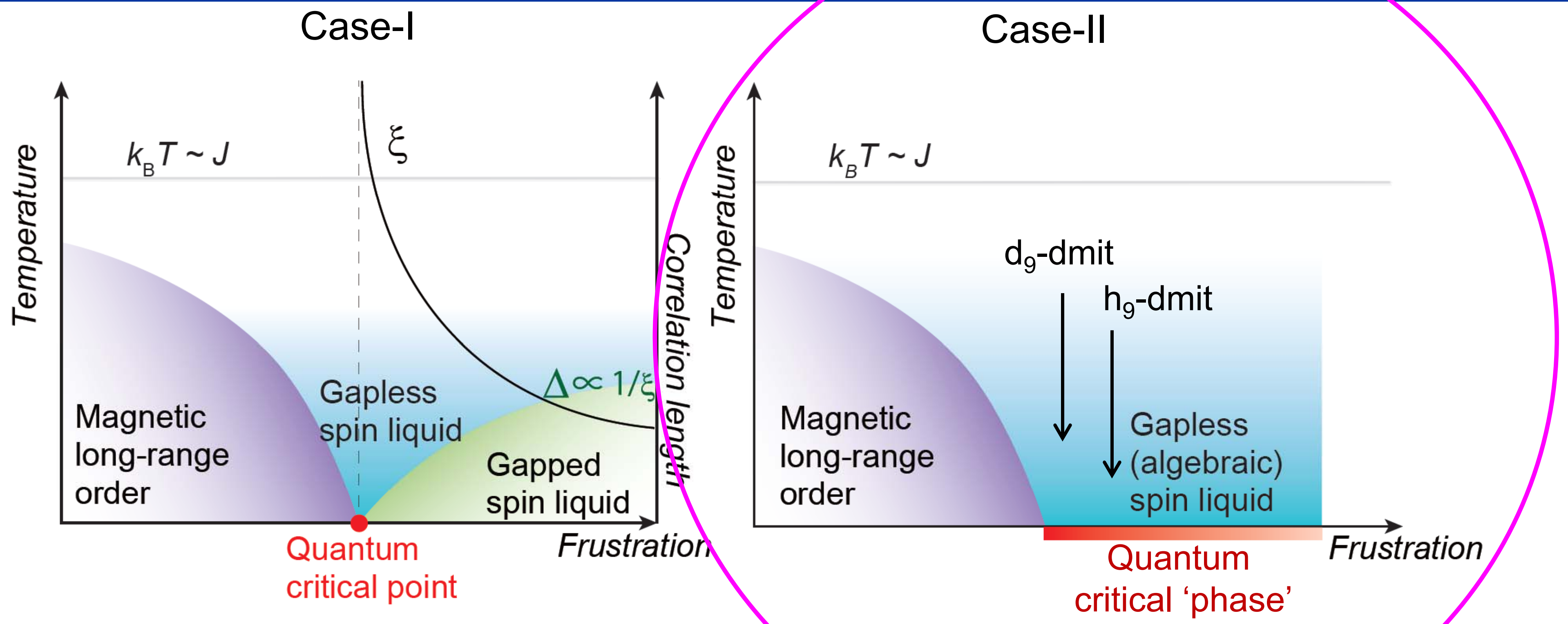


Deuteration changes the degrees of geometrical frustration.

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

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

Phase diagram of the QSL



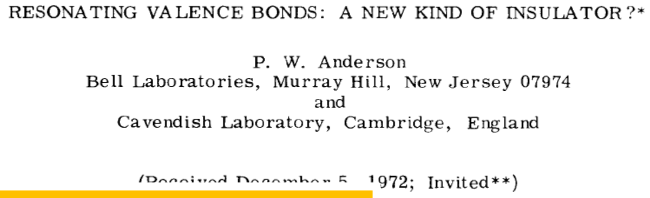
D. Watanabe *et al.*, Nature Commun. **3**, 1090 (2012).

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

An extended quantum critical phase, rather than a QCP.

What kind of spin liquid is realized in dmit?

Resonating-Valence-Bond theory

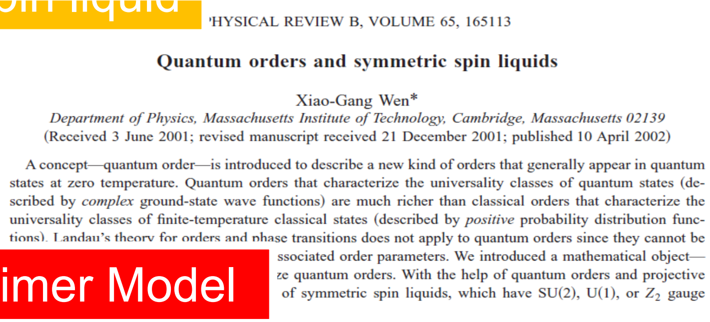


RESONATING VALENCE BONDS: A NEW KIND OF INSULATOR?*

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

1972; Invited**)

Algebraic spin liquid



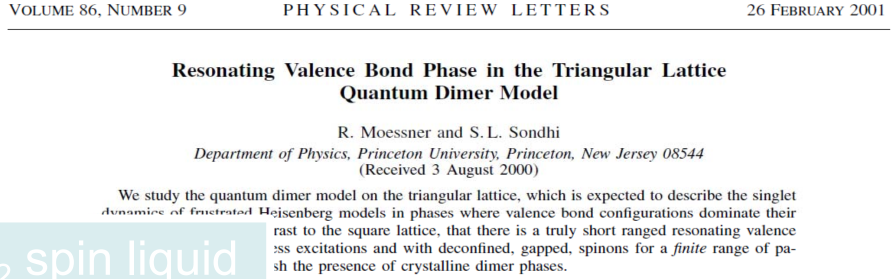
HYSICAL REVIEW B, VOLUME 65, 165113

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
ssociated order parameters. We introduced a mathematical object—
ze quantum orders. With the help of quantum orders and projective
of symmetric spin liquids, which have SU(2), U(1), or Z_2 gauge

Quantum Dimer Model



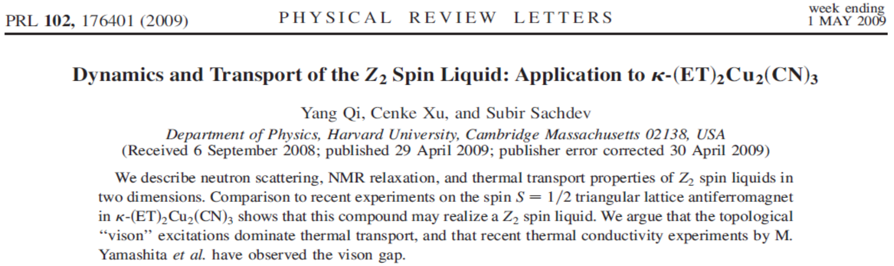
VOLUME 86, NUMBER 9 PHYSICAL REVIEW LETTERS 26 FEBRUARY 2001

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
rast to the square lattice, that there is a truly short ranged resonating valence
ss excitations and with deconfined, gapped, spinons for a *finite* range of pa-
sh the presence of crystalline dimer phases.

Z_2 spin liquid



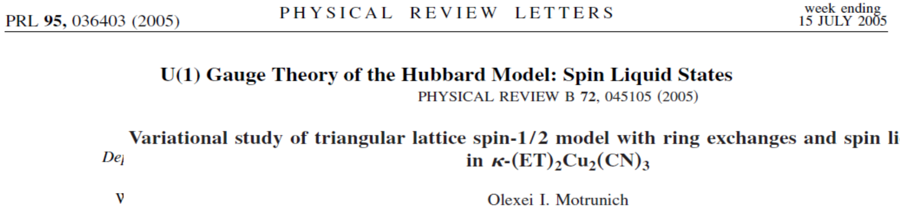
PRL **102,** 176401 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

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.

Spin liquid with spinon Fermi surface



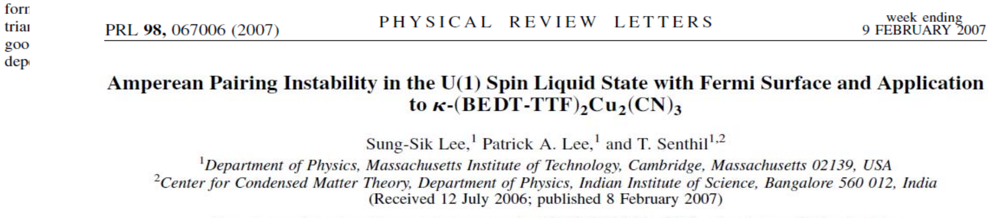
PRL **95,** 036403 (2005) PHYSICAL REVIEW LETTERS week ending 15 JULY 2005

U(1) Gauge Theory of the Hubbard Model: Spin Liquid States

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)$_3$

Olexei I. Motrunich



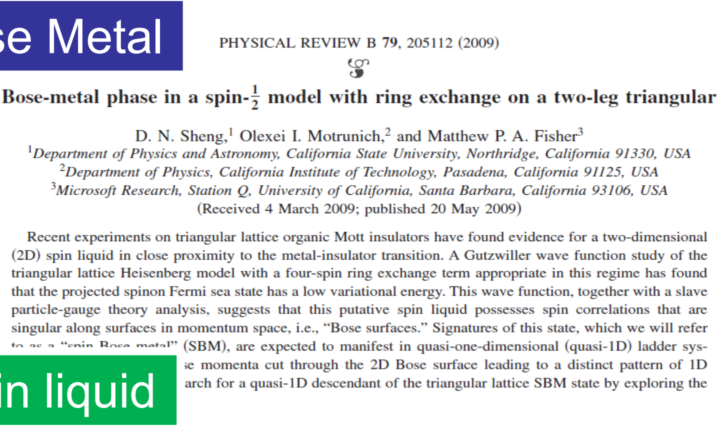
PRL **98,** 067006 (2007) PHYSICAL REVIEW LETTERS week ending 9 FEBRUARY 2007

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

Spin Bose Metal



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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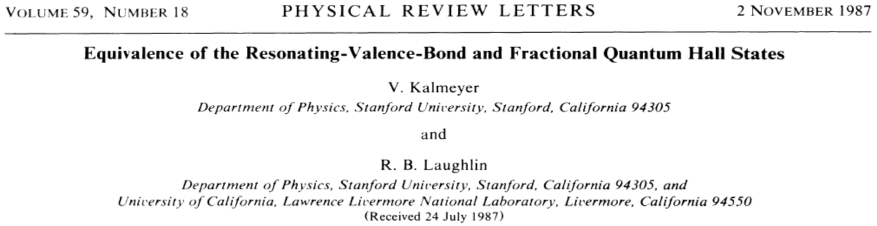
(Received 4 March 2009; published 20 May 2009)

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 sys-
se momenta cut through the 2D Bose surface leading to a distinct pattern of 1D
arch for a quasi-1D descendant of the triangular lattice SBM state by exploring the

Chiral spin liquid



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

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(Received 24 July 1987)

What kind of spin liquid is realized in dmit?

Gapless Spin Liquid

RESONATING VALENCE BONDS: A NEW KIND OF INSULATOR ?*

Resonating-Valence-Bond theory

(Received December 5, 1972; Invited**)

Spin liquid with spinon Fermi surface

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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
d the associated order parameters. We introduced a mathematical object—
racterize quantum orders. With the help of quantum orders and projective
ndreds of symmetric spin liquids, which have SU(2), U(1), or Z_2 gauge

Spin Bose Metal

VIEW LETTERS 26 February 2001

Resonating Valence Bond Phase in the Triangular Lattice Quantum Dimer Model

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(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.

PRL **102,** 176401 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Dynamics and Transport of the Z_2 Spin Liquid: Application to κ-$(ET)_2Cu_2(CN)_3$

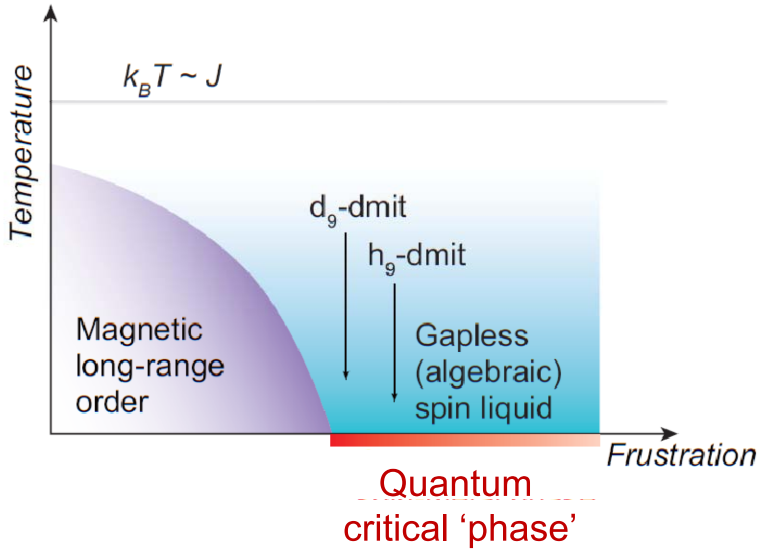
Algebraic spin liquid

usetts 02138, USA

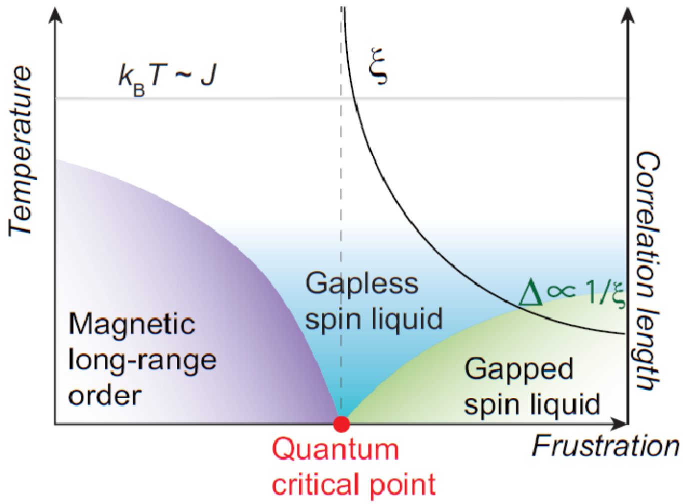
corrected 30 April 2009)

operties of Z_2 spin liquids in two dimensions. Comparison to recent experiments on the spin $S = 1/2$ triangular lattice antiferromagnet in κ-$(ET)_2Cu_2(CN)_3$ 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.

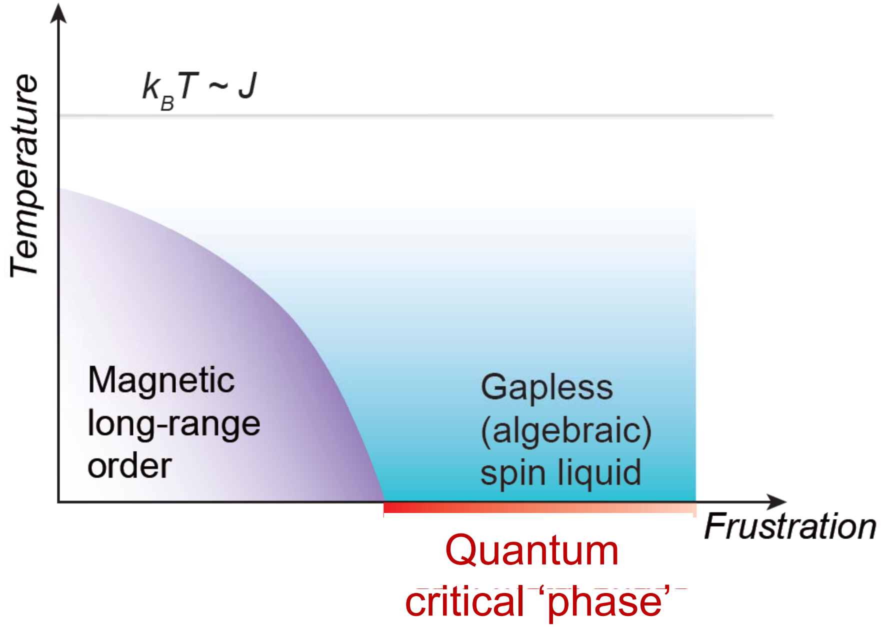
Gapless Fermionic spinon or spin Bose metal



Gapped Bosonic spinon



Spin liquid with spinon Fermi surface?



A simple thermodynamic test assuming 2D Fermion with Fermi surface

Pauli susceptibility → Specific heat coefficient C/T

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

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

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

Specific heat coefficient C/T

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

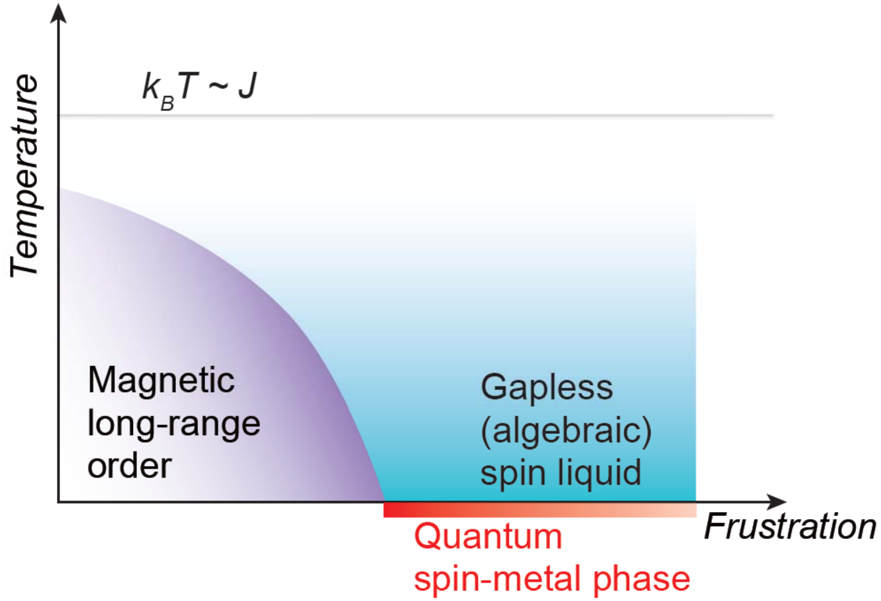
γ~20mJ/K^2 mol (experimental value)

Fermi temperature

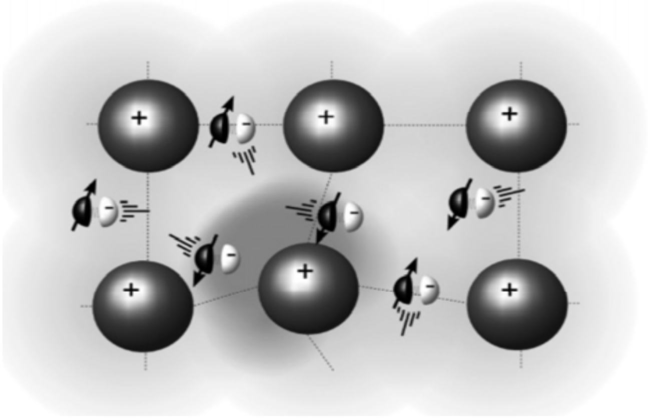
$$T_F = \varepsilon_F/k_B = \frac{g_{c*}^2 \mu_B^2}{4\chi_\perp k_B} \sim 480\,\mathrm{K} \quad J/k_B \sim 250\ \mathrm{K}\ \text{(exp. value)}$$

These values are (semi-)quantitatively consistent with the theory of the QSL that possesses a spinon Fermi surface.

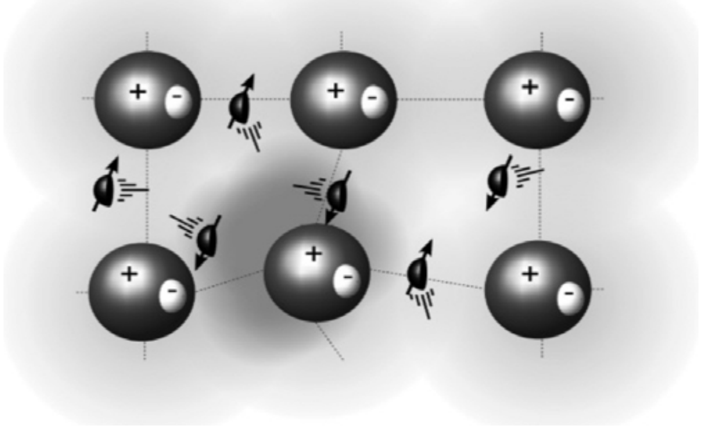
A new phase in a Mott insulator



Metal



Quantum `spin-metal’ phase



D. F. Mross and T. Senthil, PRB (2011).

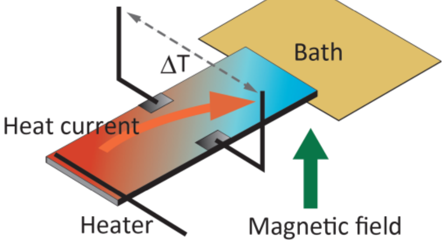
Spin excitation behave as in Pauli paramagnetic metals with Fermi surface, even though the charge degrees of freedom are frozen.

Spin liquid with spinon Fermi surface?

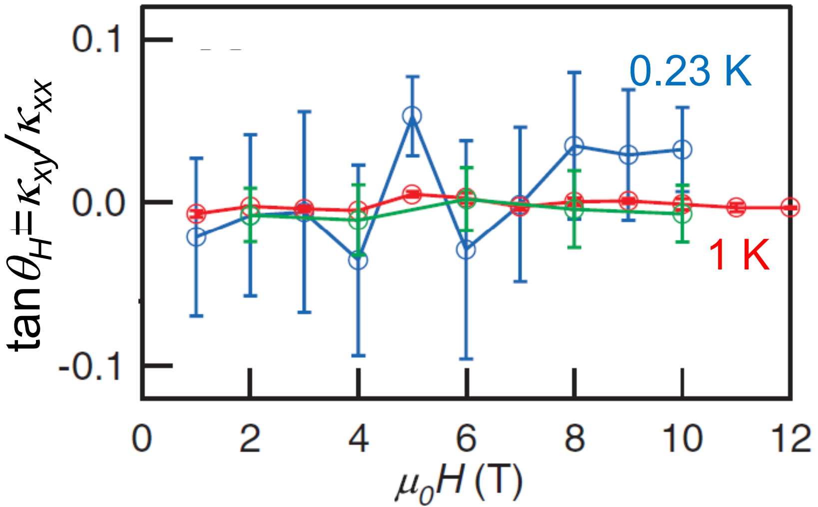
More direct methods to detect the spinon Fermi surface

Thermal Hall effect

H. Katsura, N. Nagaosa and P. A. Lee, PRL (2010).



κ_{xy} thermal Hall conductivity



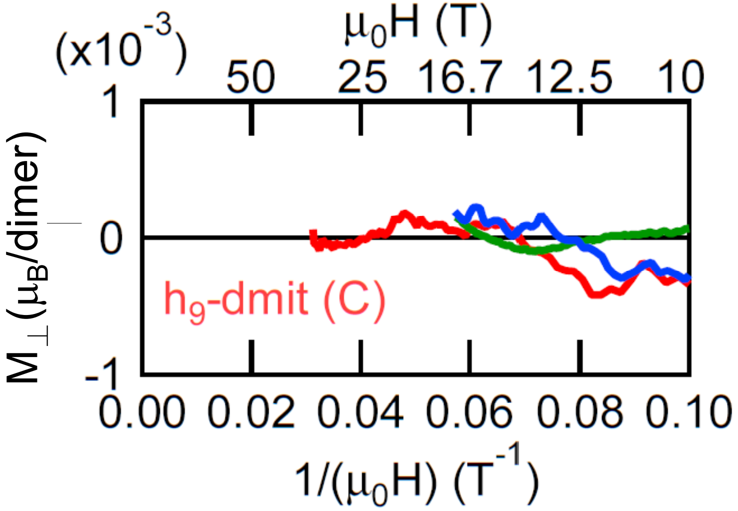
M. Yamashita *et al.*, Science (2010).

No discernible thermal Hall effect

Quantum oscillation

O. I. Mitrunich, PRB (2006).

30 mK up to 35 T



D. Watanabe *et al.*, Nature Commun. (2012).

No discernible oscillation

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

Z_2 spin liquid with pseudo-Fermi surfaces? Barkeshli, Yao, Kivelson (2012).

Summary

Ground state and phase diagram of the QSL in 2D organic Mott insulator $EtMe_3Sb[Pd(dmit)_2]_2$ with triangular lattice

Distinct residual thermal conductivity and paramagnetic susceptibility in the zero temperature limit.

The QSL is an algebraic spin liquid with a magnetically gapless ground state, *i.e.* a critical state with infinite magnetic correlation length.

Essentially the same results in the deuterated sample with a different degree of geometrical frustration

The emergence of an extended `quantum spin-metal phase' in the Mott insulator, in which the low-energy spin excitations behave as in Pauli paramagnetic metals with Fermi surface.

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).