Some Frontier Topics in Frustrated Magnets

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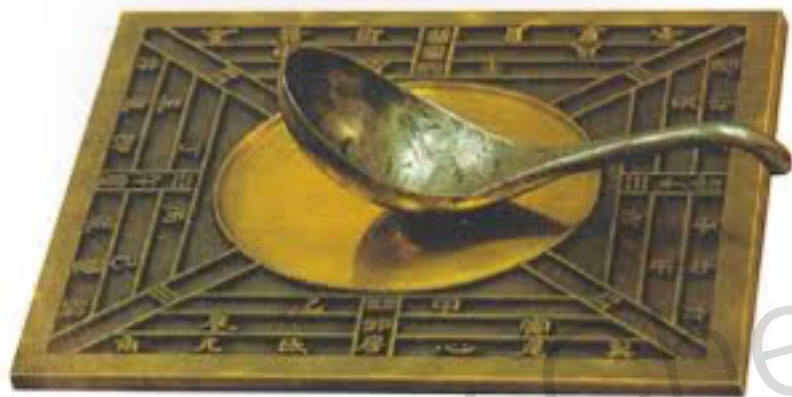
Outline
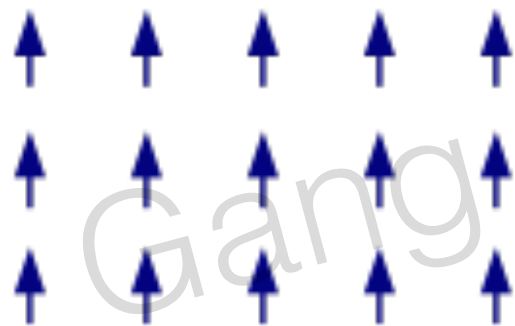
- 自旋有序态的新物理：理论，现象，机制，材料

- 自旋无序态的新发展：理论，现象，机制，材料

- 总结

自旋的有序态

在自旋体系中，有序态一般被认为是没有意思的。
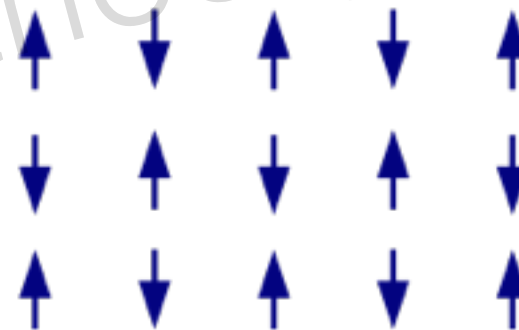

司南

Louis Neel

铁磁（500BC,中国、古希腊）

反铁磁 (Nobel Prize, 1970)
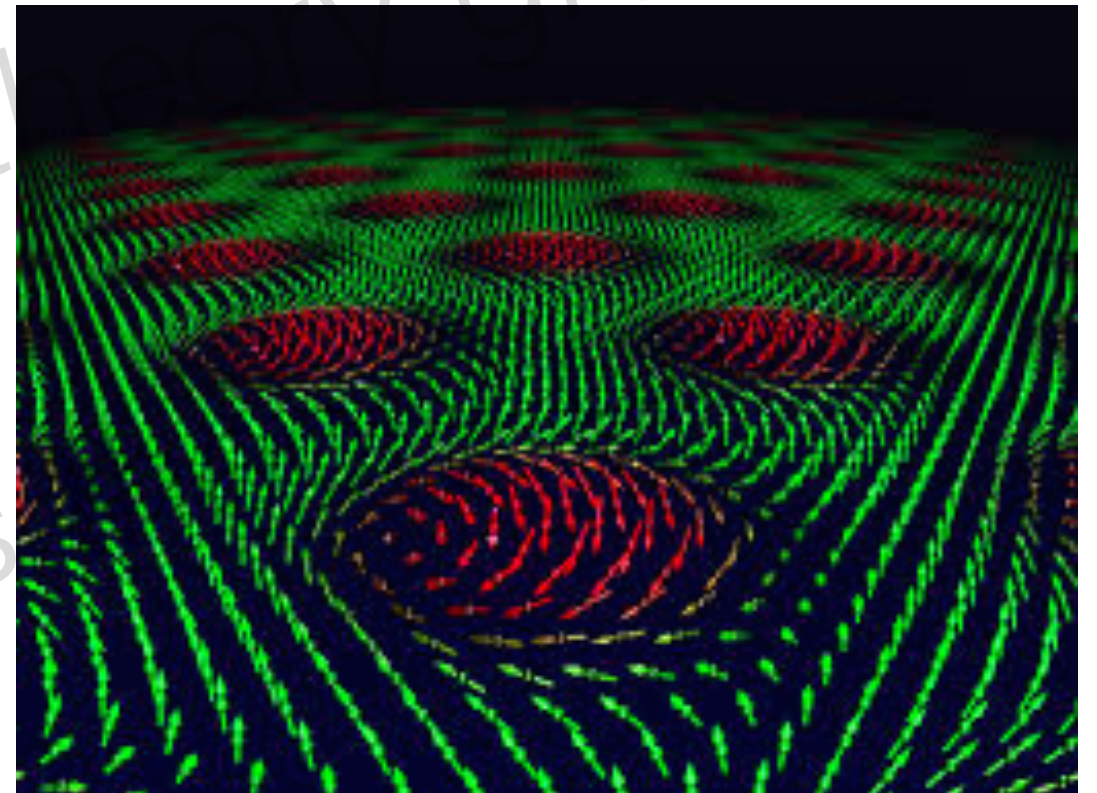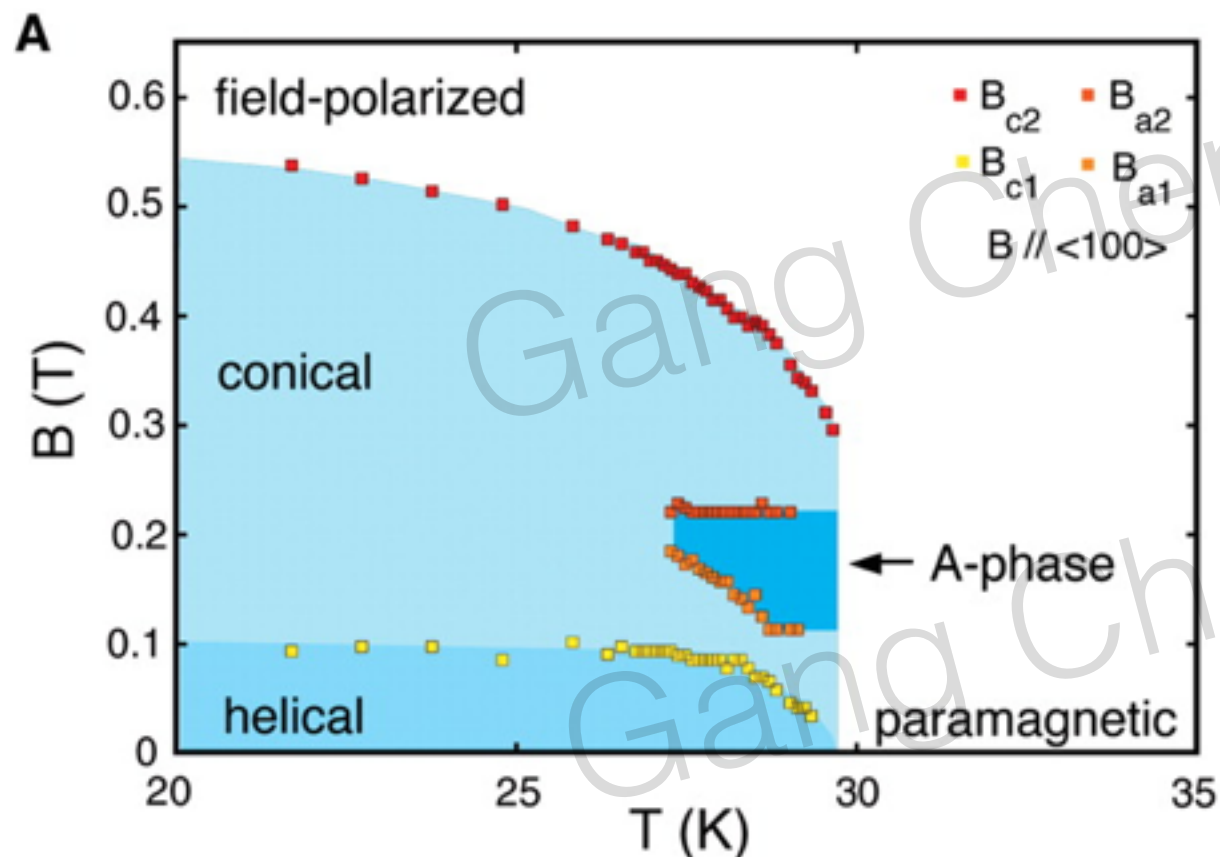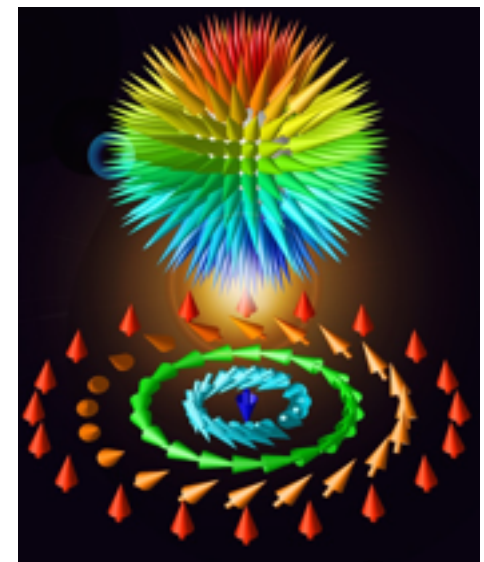
用传统的朗道对称性破缺的序参量理论来描述

目前什么才是有意义的自旋有序态？

我肤浅地认为自旋有序态至少可以在四个层面上有意义：

1. 非平庸的自旋结构

2. 自旋有序态对其他自由度的影响和调控

3. 自旋有序态非平庸的元激发

4. 非传统的自旋序

1. 非平庸的自旋结构
（Non-trivial / topological spin texture）
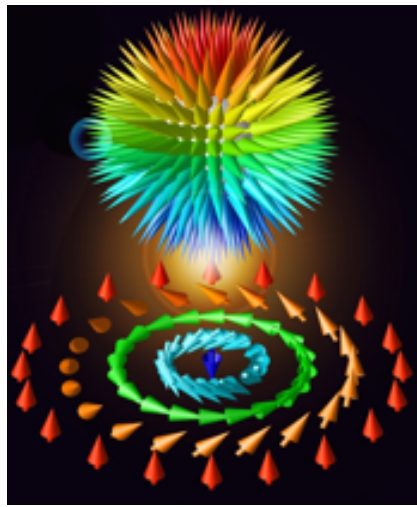
例： Skyrmion 晶格 in MnSi (B20 结构)

Mühlbauer, etc, Science 2009

田明亮group也从事这方面的工作。
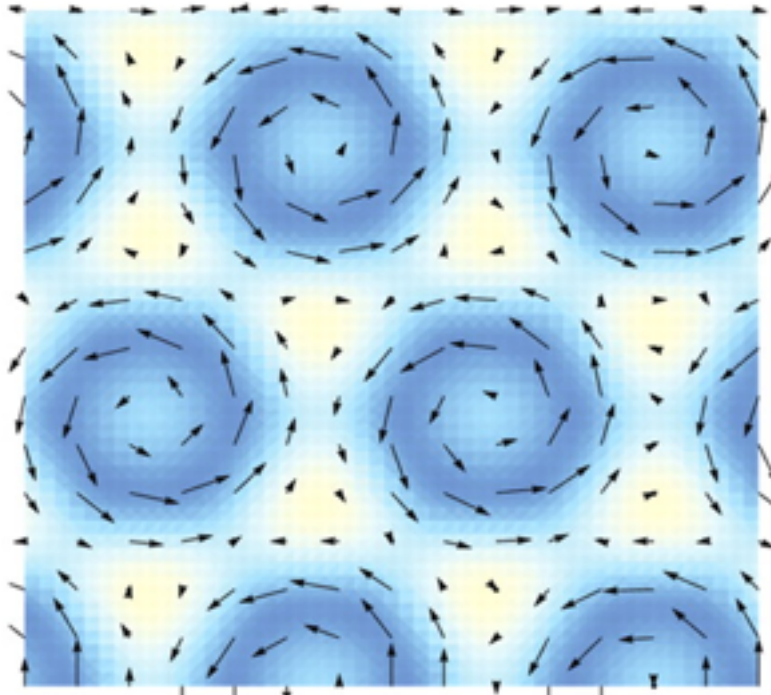
Skyrmion 晶格

Skyrmion是磁序的**拓扑缺陷**

可以类比第二类超导体的vortex晶格

带有Skyrmion晶格的磁性体系

Table 2.1 List of materials hosting skyrmion spin texture. Magnetic ordering temperature T_c and spin modulation period λ_m are also indicated

Category	Material	T_c (K)	λ_m (nm)	Conductivity	Ref.
Chiral-lattice ferromagnets	MnSi	30	18	Metal	[6, 10]
	$Fe_{1-x}Co_xSi$	<36	$40 \sim 230$	Semiconductor	[11, 12]
	MnGe	170	3	Metal	[18]
	FeGe	278	70	Metal	[15]
	Cu_2OSeO_3	59	62	Insulator	[19, 22]
Centrosymmetric ferromagnets	$Y_3Fe_5O_{12}$	560	>500	Insulator	[32]
	$RFeO_3$	>600	>100,000	Insulator	[32]
	$BaFe_{11.79}Sc_{0.16}Mg_{0.05}O_{19}$	>300	200	Insulator	[40]
	$La_{1.37}Sr_{1.63}Mn_2O_7$	100	160	Insulator	[41]
Interface	Fe/Ir(111)	(>300)	1	Metal	[43]
	FePd/Ir(111)	(>300)	7	Metal	[44]

物理机制

Skyrmion 晶格

一般要有自旋轨道相互作用(or Dzyaloshinskii-Moriya 相互作用)，也可以是阻挫的自旋相互作用。

Skyrmion晶格对电输运和自旋输运都会有影响和调制，有潜在的spintronics方面的应用。

Q: Skyrmion晶格是一个经典的自旋构型，如果有量子效应,

    对skyrmion晶格和skyrmion本身有什么影响？
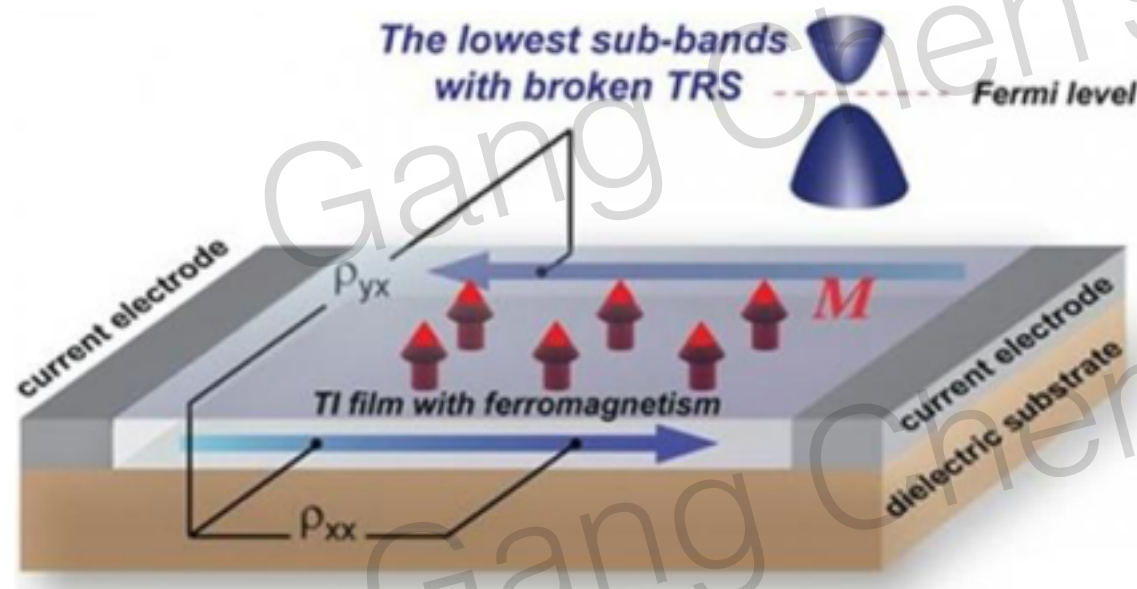
如果quantum disorder skyrmion晶格，会有什么可能的新的量子力学态？

量子skyrmion？晶格被破坏了但保留topology, 出现skyrmion液体？
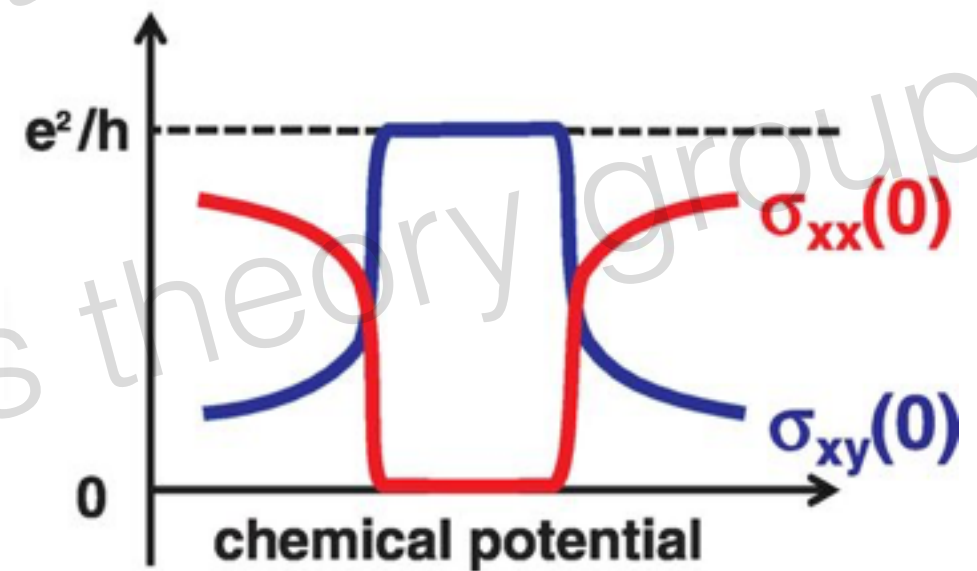
有没有其他的类似拓扑缺陷，或者其他自由度的拓扑缺陷？
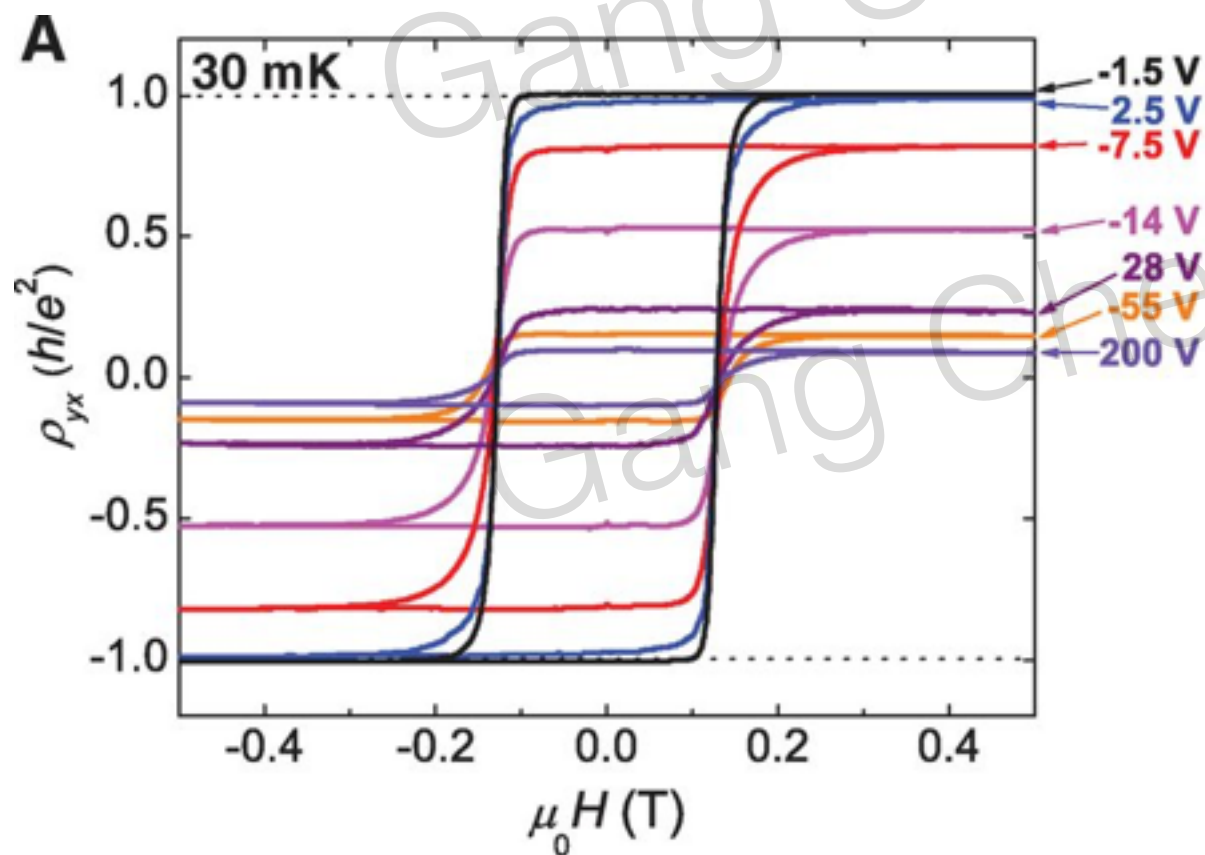
2. 自旋有序态对其他物理自由度的影响和调控

自旋和传导电子耦合,自旋的有序调制了传导电子能带的拓扑性质.

Cr-doped $(Bi,Sb)_2Te_3$
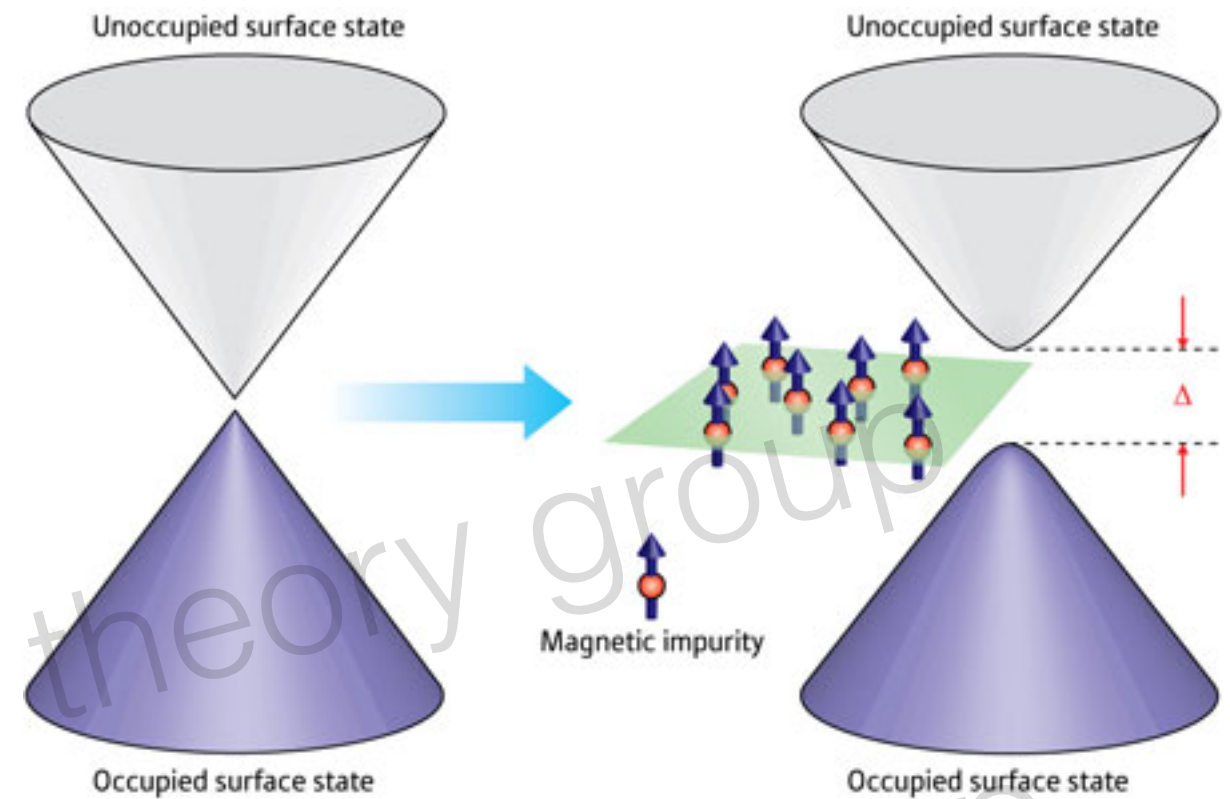

QAHE (Prof Xue的重大发现)

Prof Xue's group

Unoccupied surface state

Occupied surface state

Magnetic impurity
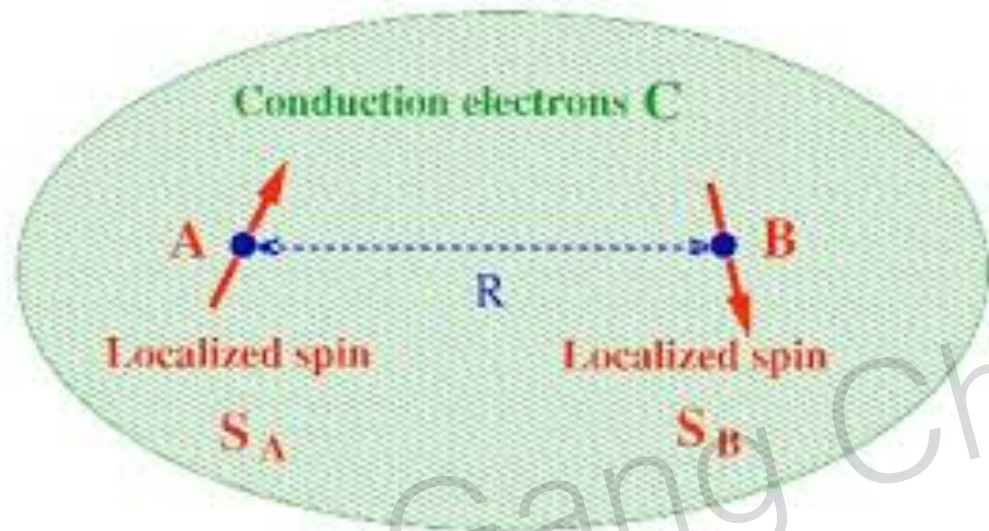
这里的自旋有序态
是简单的铁磁态.

QAHE是局域磁矩和Dirac电子(更普遍的是带强自旋轨道相互作用的巡游电子)的相互作用和影响的一个具体的例子.

局域磁矩 & 巡游电子

巡游电子和局域磁矩的相互耦合拥有很丰富的物理。

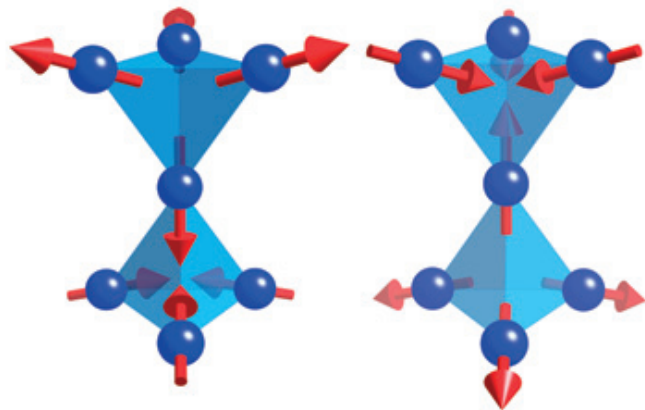通过传导电子改变局域磁矩的相互作用决定局域磁矩的状态，
局域磁矩的状态又反过来影响传导电子。

如何在实验上调控？

RKKY + 超交换

1. 改变传导电子
2. 改变局域磁矩（例：
Nd2Ir2O7 field-driven
metal-insulator transition (田召明老师))

Q: 能否超越一般的磁偶极序，磁多极矩和巡游电子的耦合？理论、模型、实验、材料？
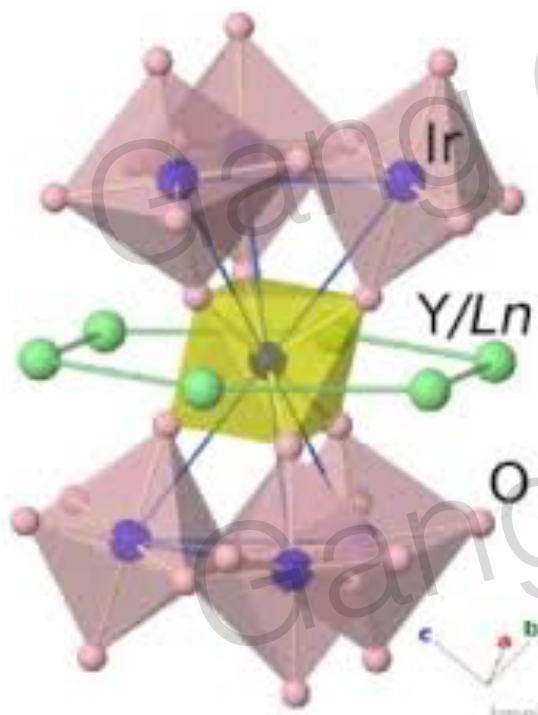因为自旋轨道的纠缠，4f/5f电子的磁矩拥有更加丰富的局域磁矩的结构和自由度！

复旦大学和绵阳9院在4f/5f电子开展合作研究,
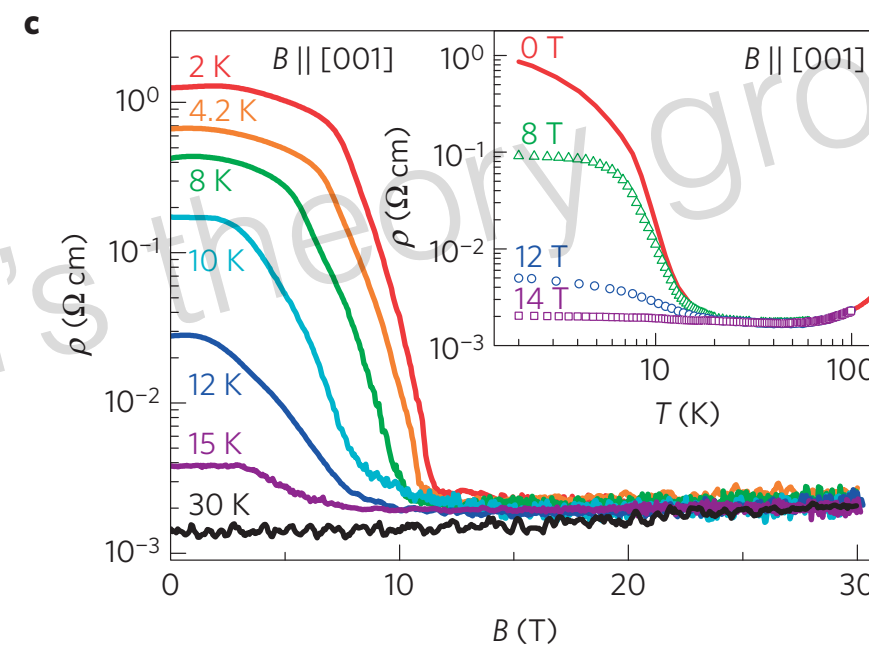我们期待李世燕他们有exciting的发现。
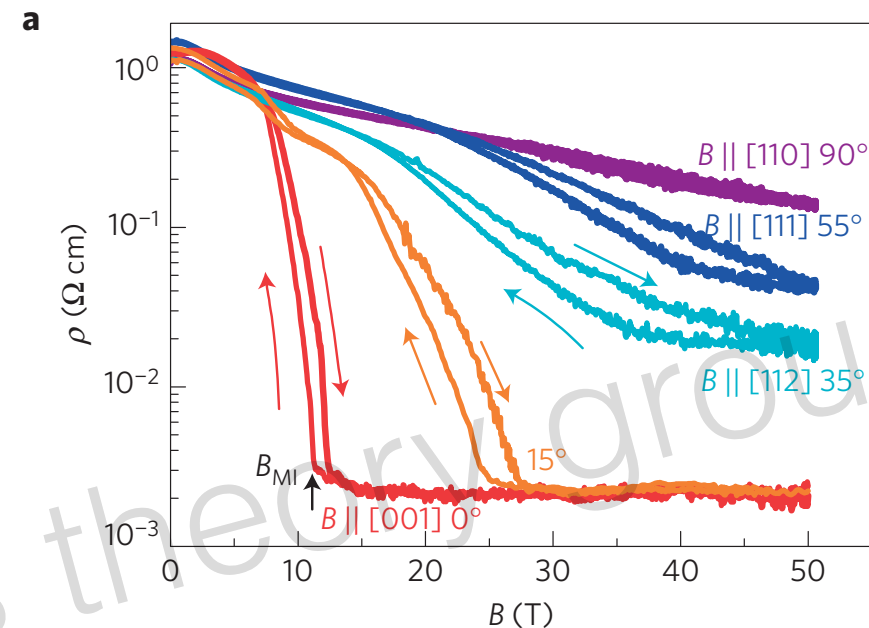
磁场诱导的金属绝缘体相变

Nd ordering in Nd2Ir2O7

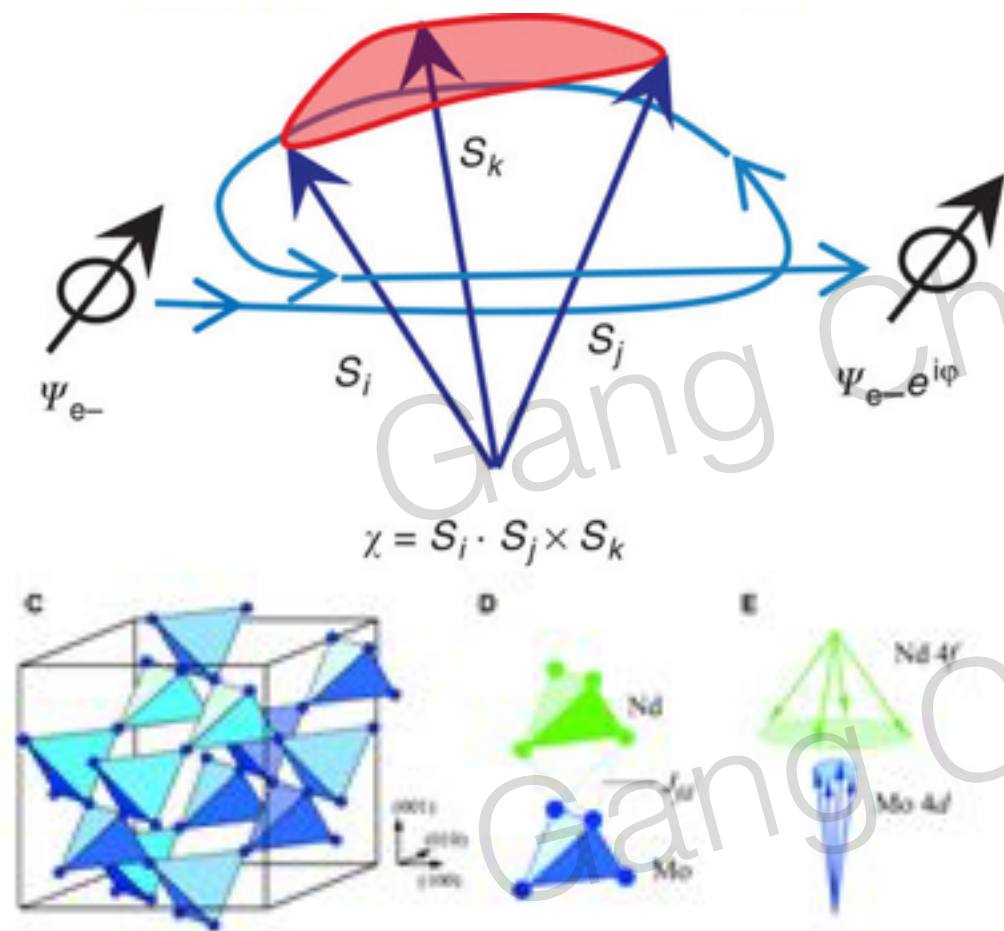

外场主要和局域磁矩耦合，
进而影响传导电子能带结构
和载流子浓度

ZM Tian, etc, NatPhys
电阻改变近600倍！

这样的物理应该会比较普遍，很多的体系
都应该有，这个显然会有很大的应用价值.

自旋结构的Berry相以及拓扑霍尔效应

阻挫的相互作用 -> non-collinear的自旋结构 -> 非平凡的Berry相 -> 几何/拓扑霍尔效应

$$\chi = S_i \cdot S_j \times S_k$$

Taguchi et al
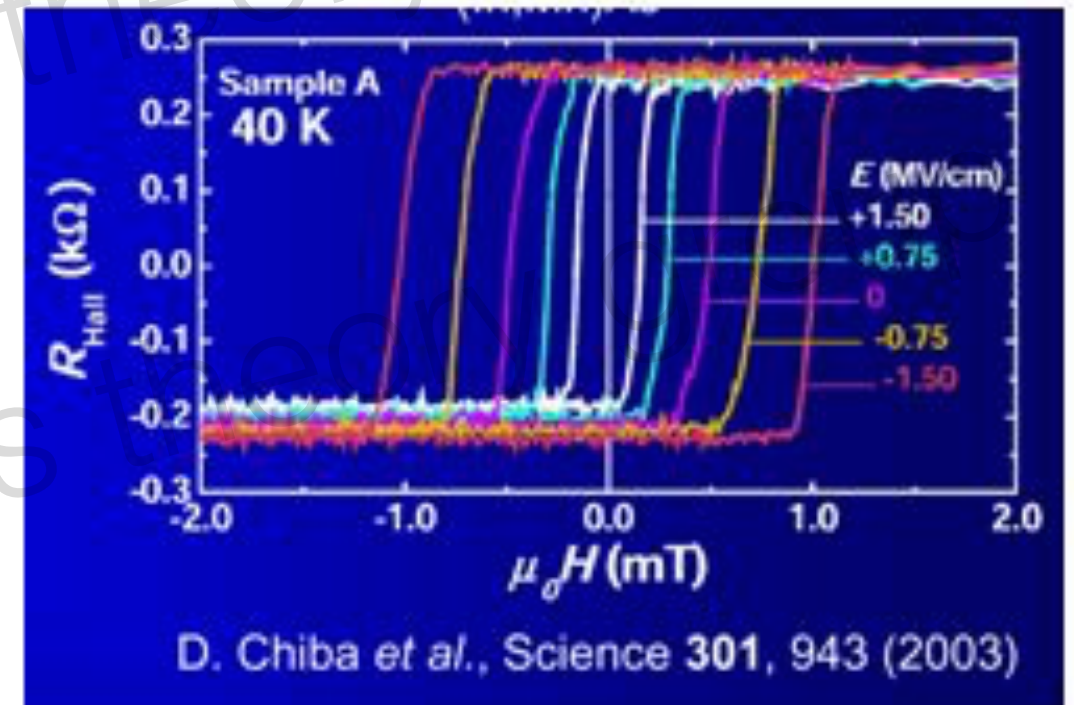
AHE in $Nd_2Mo_2O_7$

外磁场诱导调制spin chirality (Berry phase)

最初的理论: Jinwu Ye, etc PRL 1999

多铁材料: 自旋对电子密度的耦合和影响
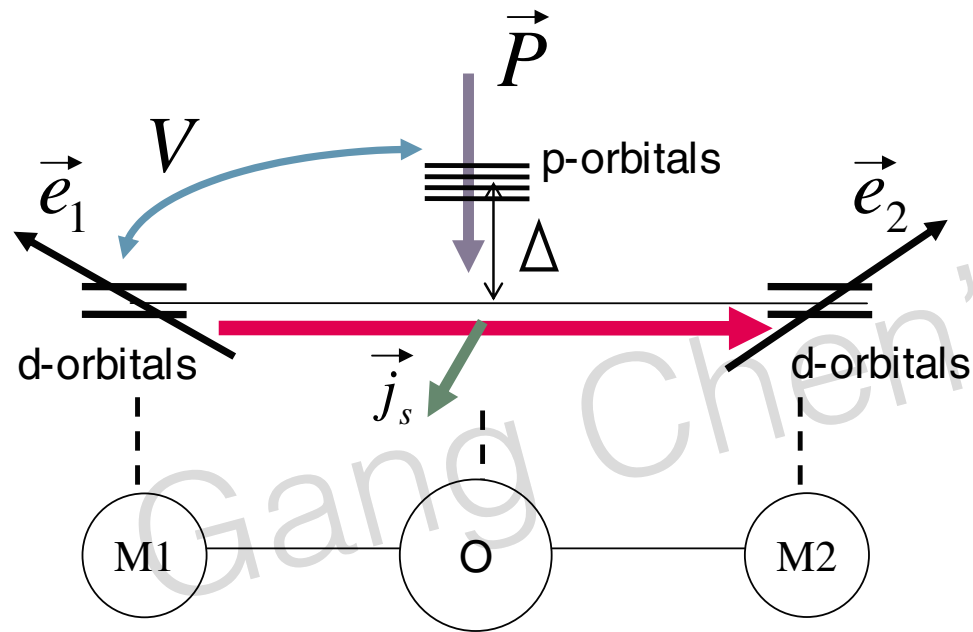
Inverse Dzyaloshinskii-Moriya effect

$$\vec{P} \cong -\frac{eV}{3\Delta} I \frac{\vec{e}_{12} \times (\vec{e}_1 \times \vec{e}_2)}{|\cos\frac{\theta_{12}}{2}|}$$
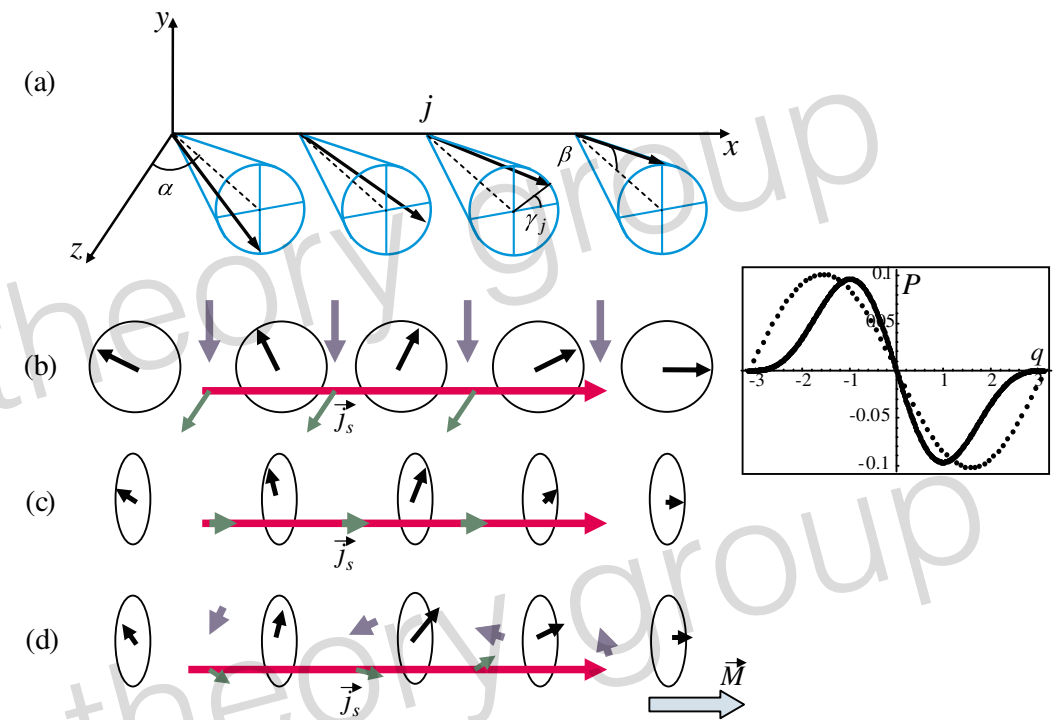
Nagaosa, etc PRL 2006

阻挫相互作用 -> 非共线性的磁有序 -> 电极化矢量

3. 自旋有序态非平庸的元激发

如前所诉，有序态一般可能是平庸的, 但是基态的平庸并不代表激发态也是平庸的.
磁有序态的激发可以有非平庸的拓扑能带结构。
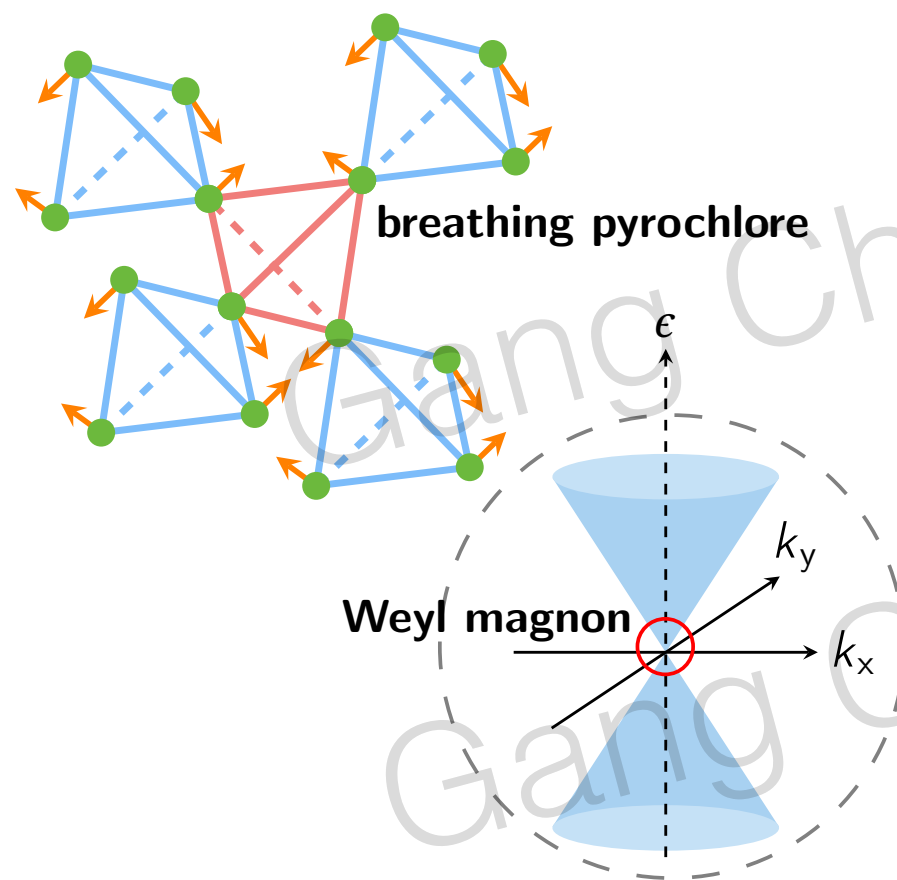
三维威尔磁子(Weyl Magnon)
FY Li,YD Li, … **GC**,
Nature Comm 2016
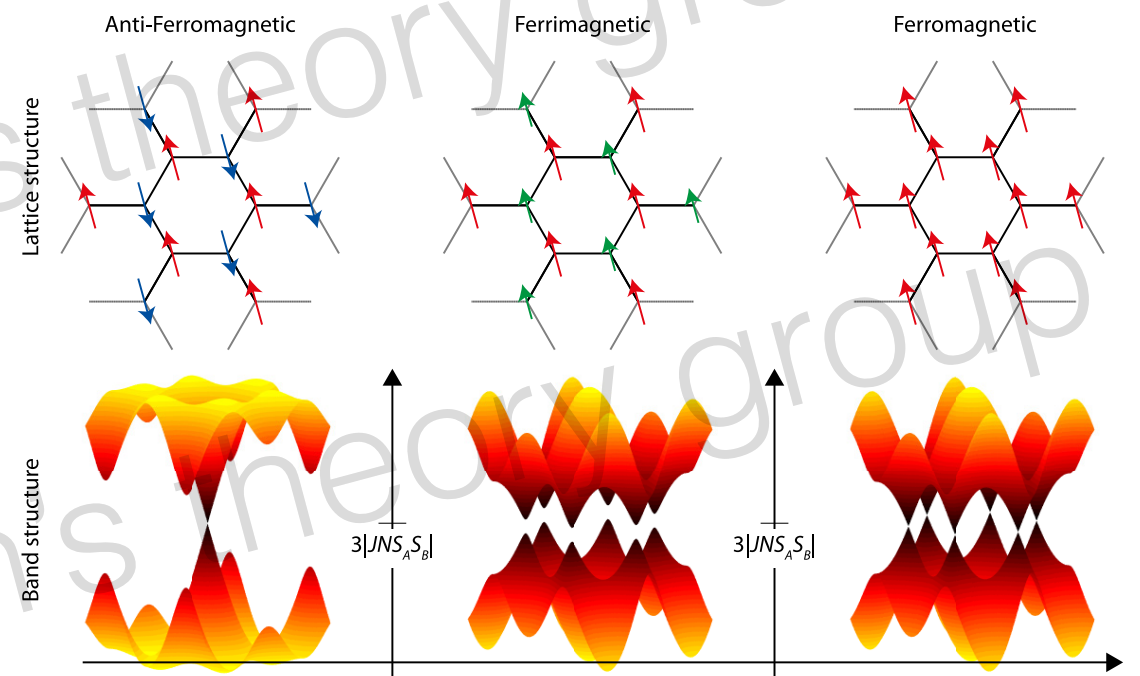
二维狄拉克磁子(Dirac magnon)
Fransson, Black-Schaffer, Balatsky, PRB, 2016

威尔磁子(Weyl Magnon)
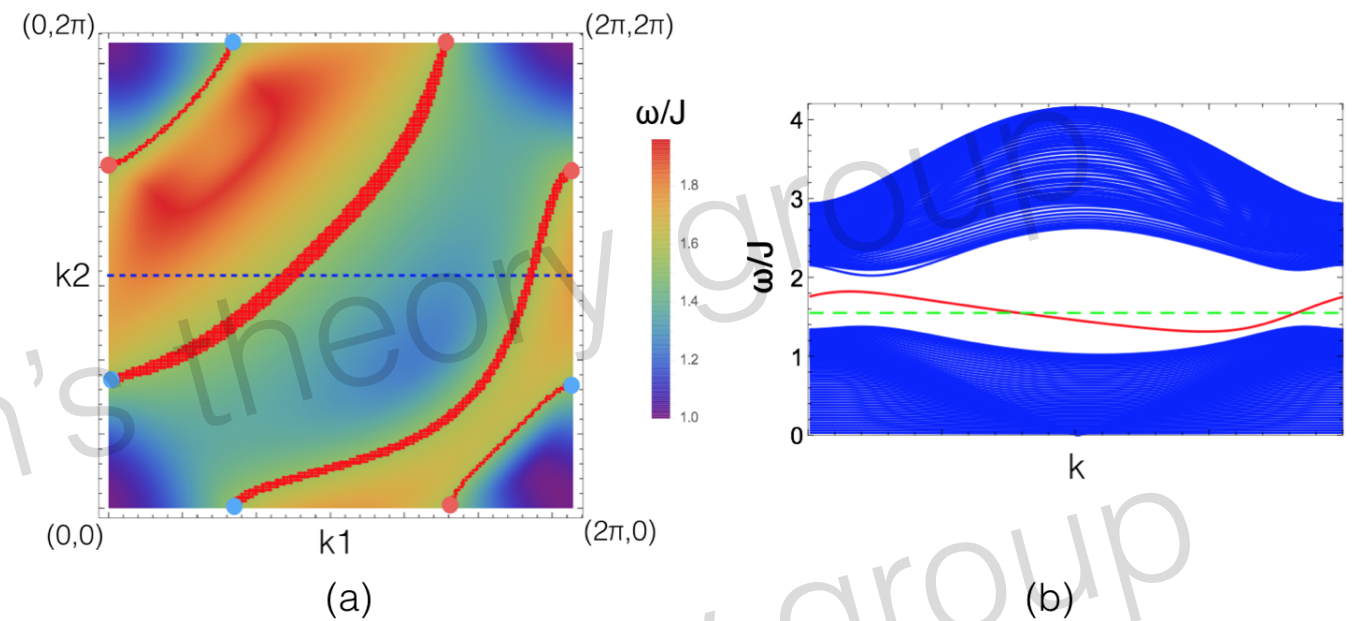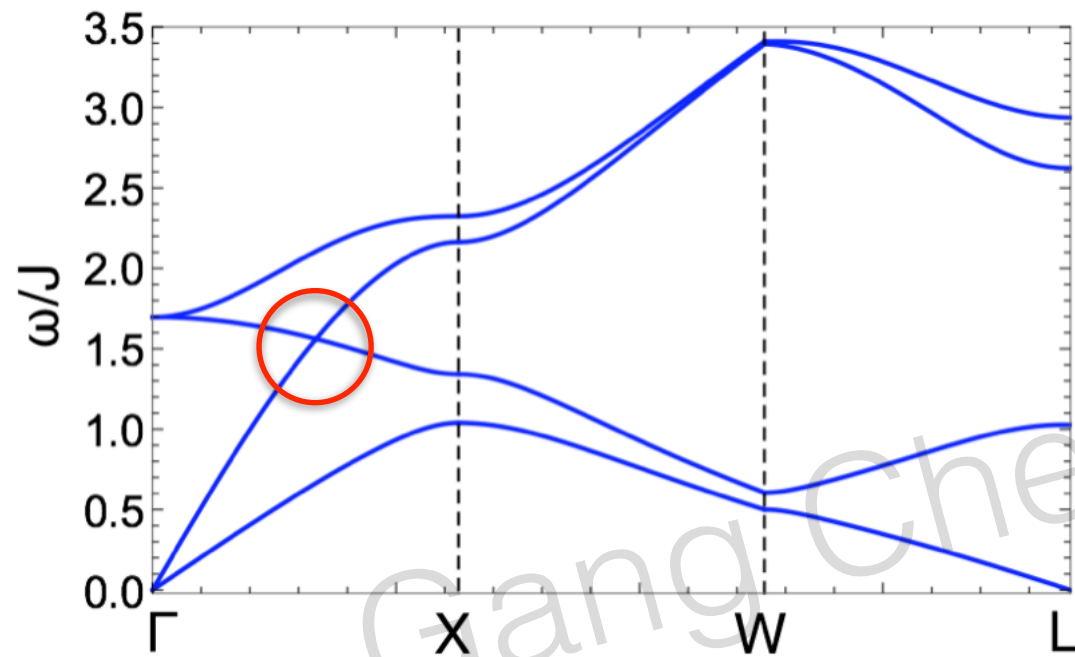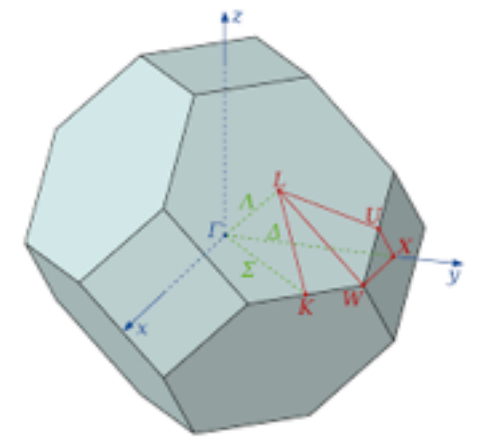
拓扑保护的表面弧
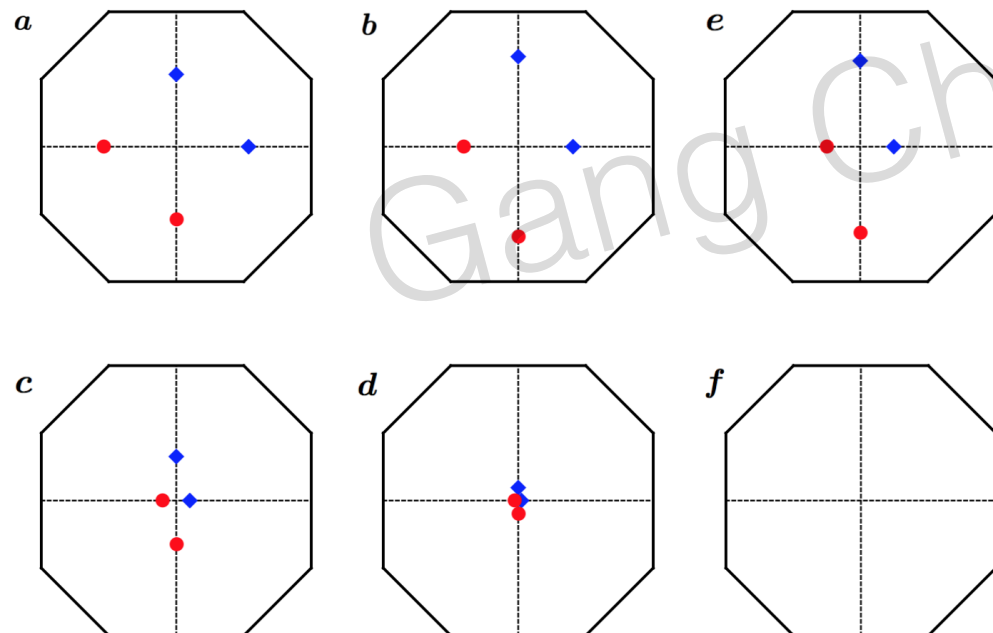
可以通过外场来调控威尔点，
这是威尔磁子的独特的地方！

FY Li,YD Li, Kim, Balents, Yue Yu, **GC**,
Nature Comm 2016

拓扑自旋波理论

一般的理论目前并不存在，需要我们去发展它。

一些特殊的feature: Magnon的能带是由自旋的相互作用Hamiltonian和自旋序共同决定，这个和以前电子能带的理论是不一样的。

实验： Magnon不带电，所以磁场很好地可以调控它 -> **Magnonics**
　　　　Hall热输运的后果。
　　　　中子散射直接测量。

FY Li,YD Li, Kim, Balents, Yue Yu, **GC**, Nature Comm 2016

4. 非传统的自旋序

由于自旋轨道作用，4f, 5f的电子拥有相当丰富的磁矩结构
磁多极矩相当普遍，高阶磁矩不好直接测量 (hidden order)

Moments	Operators
Dipoles	J_x
	J_y
	J_z
Quadrupoles	$\frac{1}{2}(2J_z^2 - J_x^2 - J_y^2) \equiv O_2^0$
	$\frac{\sqrt{3}}{2}(J_x^2 - J_y^2) \equiv O_2^2$
	$\frac{\sqrt{3}}{2}\overline{J_y J_z} \equiv O_{yz}$
	$\frac{\sqrt{3}}{2}\overline{J_z J_x} \equiv O_{zx}$
	$\frac{\sqrt{3}}{2}\overline{J_x J_y} \equiv O_{xy}$

Octupoles	
	$\frac{\sqrt{15}}{6}\overline{J_x J_y J_z} \equiv T_{xyz}$
	$\frac{1}{2}(2J_x^3 - \overline{J_x J_y^2} - \overline{J_z^2 J_x}) \equiv T_x^\alpha$
	$\frac{1}{2}(2J_y^3 - \overline{J_y J_z^2} - \overline{J_x^2 J_y}) \equiv T_y^\alpha$
	$\frac{1}{2}(2J_z^3 - \overline{J_z J_x^2} - \overline{J_y^2 J_z}) \equiv T_z^\alpha$
	$\frac{\sqrt{15}}{6}(\overline{J_x J_y^2} - \overline{J_z^2 J_x}) \equiv T_x^\beta$
	$\frac{\sqrt{15}}{6}(\overline{J_y J_z^2} - \overline{J_x^2 J_y}) \equiv T_y^\beta$
	$\frac{\sqrt{15}}{6}(\overline{J_z J_x^2} - \overline{J_y^2 J_z}) \equiv T_z^\beta$

铁基超导 (FeSe)中也可能有类似的magnetic quadrupolar order
(四极矩) / spin nematic order（向列序）

RXS 与 RIXS 探测隐藏序

Resonant X-ray 散射

Resonant inelastic X-ray 散射

是一个二阶过程，可以
有选择enhanced某些channel
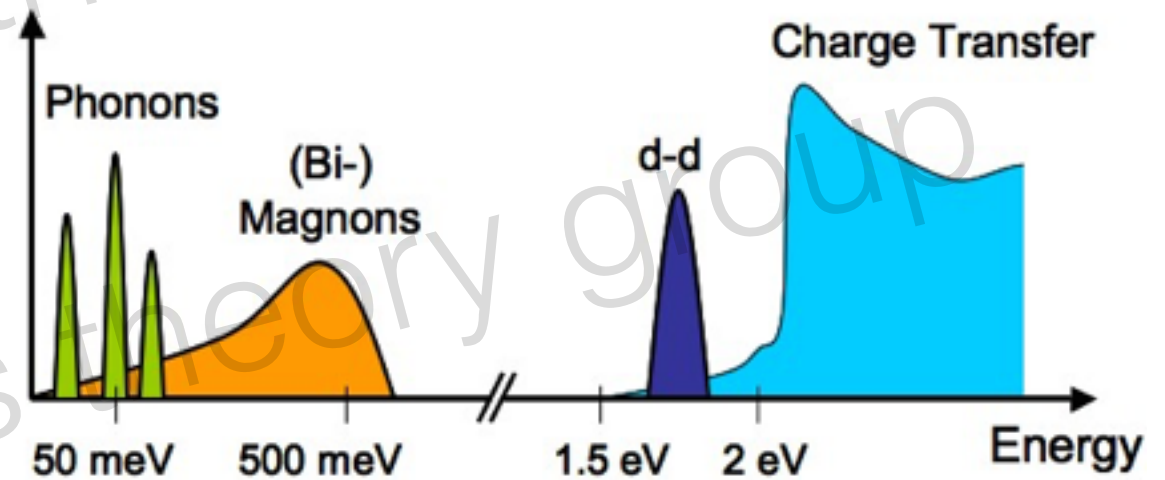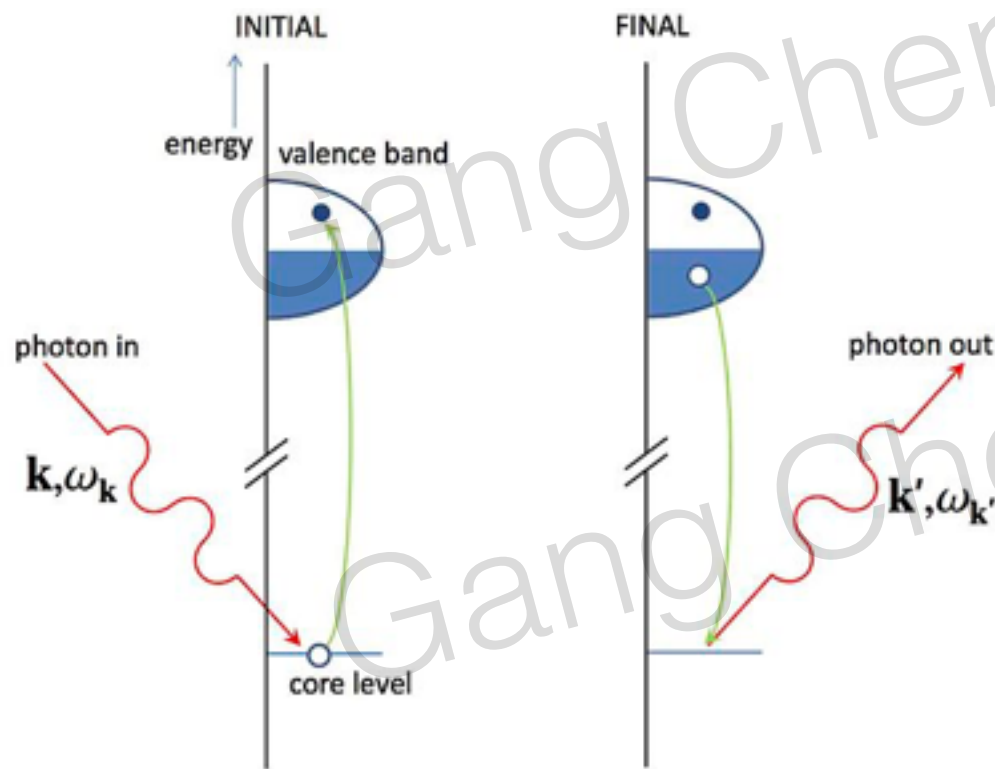
既可以测量static order，
也可以测量元激发

隐藏序, 轨道序等等
目前的限制在能量的分辨率

自旋的无序态

这里不讨论spin glass这些东西

1. 接近量子临界点的量子顺磁态

2. 拓扑顺磁态：Haldane S=1 chain, spin SPT, topological paramagnet

3. 量子自旋液体

这里应该还有其他的无序态。

1. 接近量子临界点的量子顺磁态

BaCuSi2O6

"中国紫"

a Cu²⁺ Cl⁻ Tl⁺

b J_1 J_0 J_2 t_1 t_2
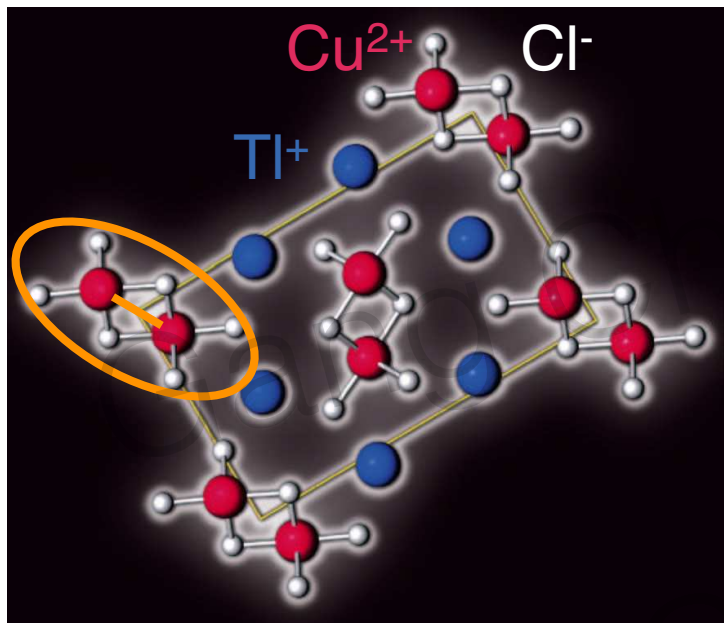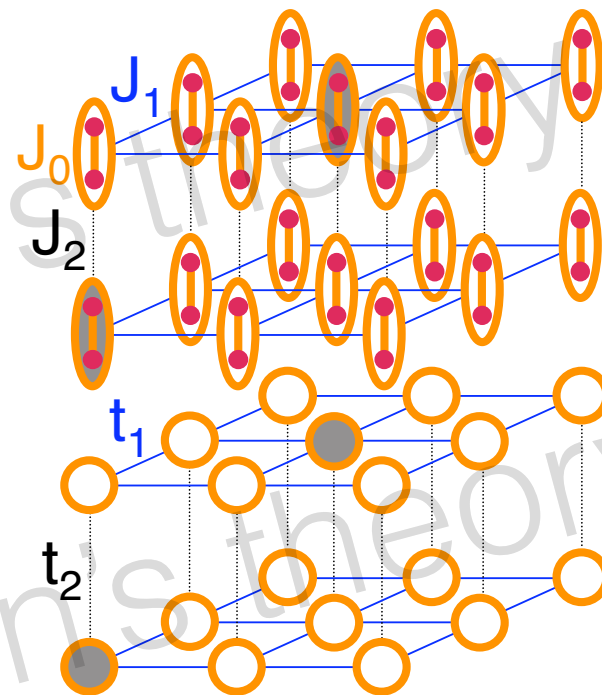
$\Longrightarrow$ 自旋单态

基态就是一些近邻自旋组成的单态，
自旋没有长程序，所以是一个量子顺磁态，
虽然这是一个非常trivial的态。

磁场诱导的量子临界行为
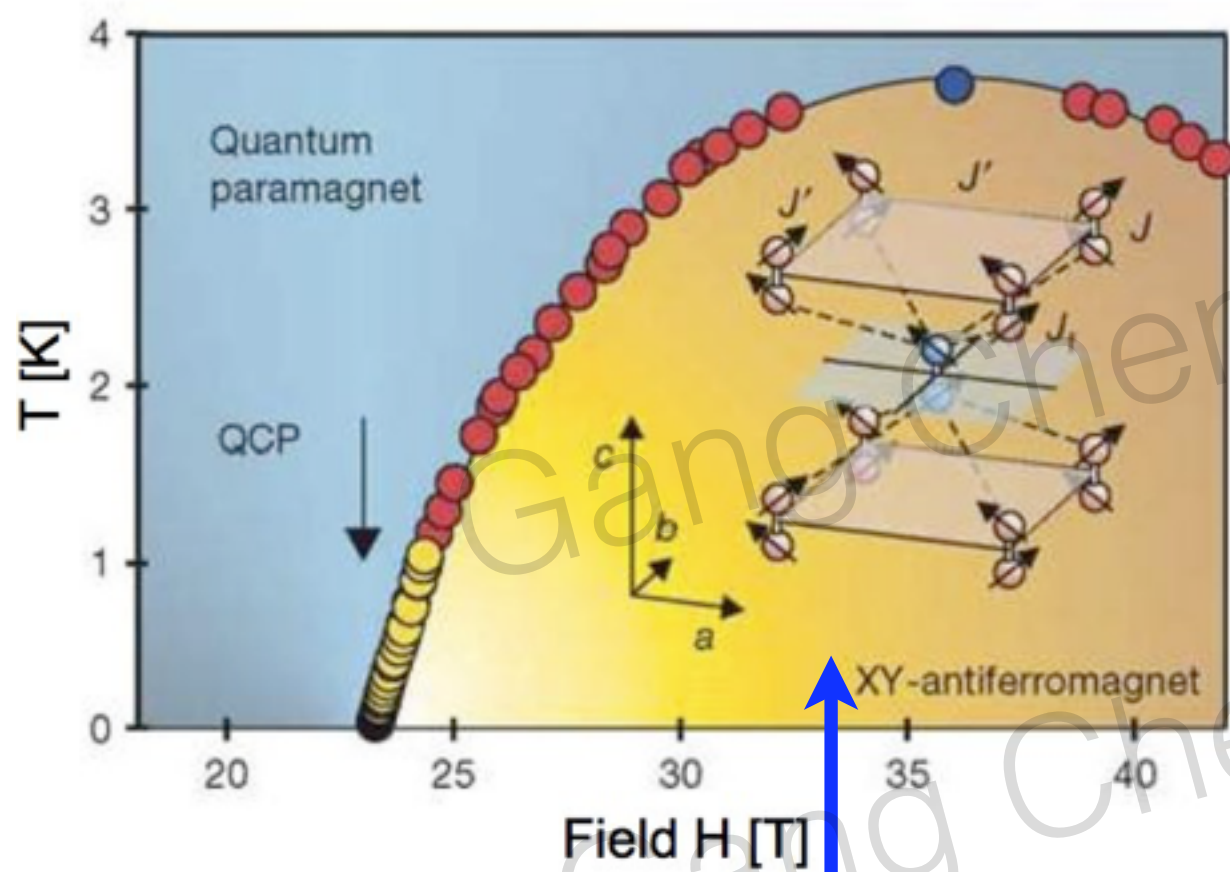
Triplon BEC
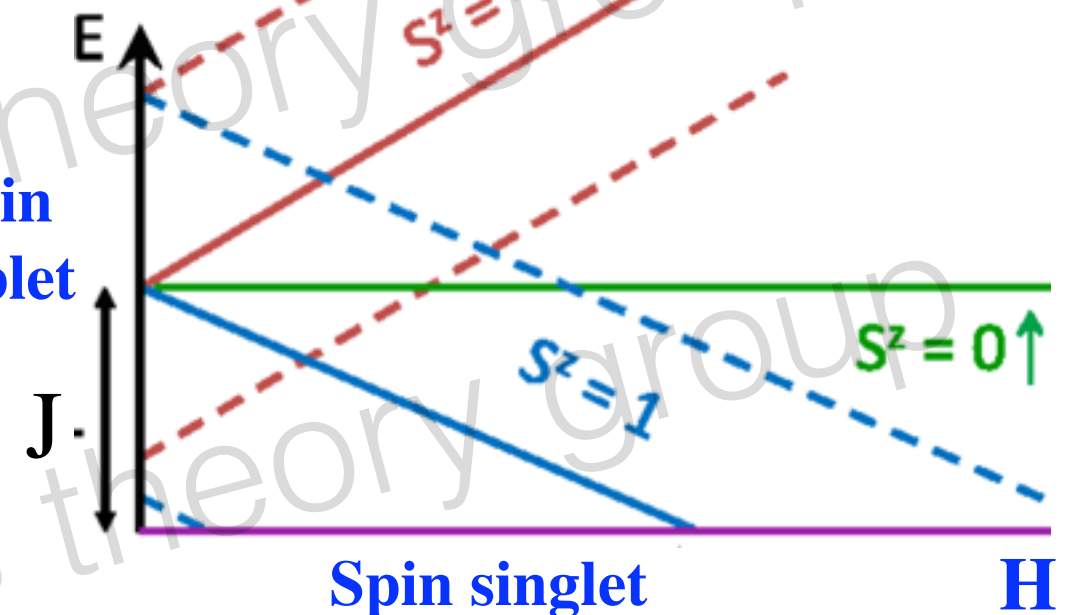
外场把triplet的激发拉下来，可以诱导triplon玻色爱因斯坦凝聚的一个量子相变，可以研究所谓的Higgs模以及量子临界现象等物理。

自然界中的perfect量子临界体系并不很多

1. 接近量子临界点的量子顺磁态

Competition between magnetic exchange and spin-orbit interaction, J/λ
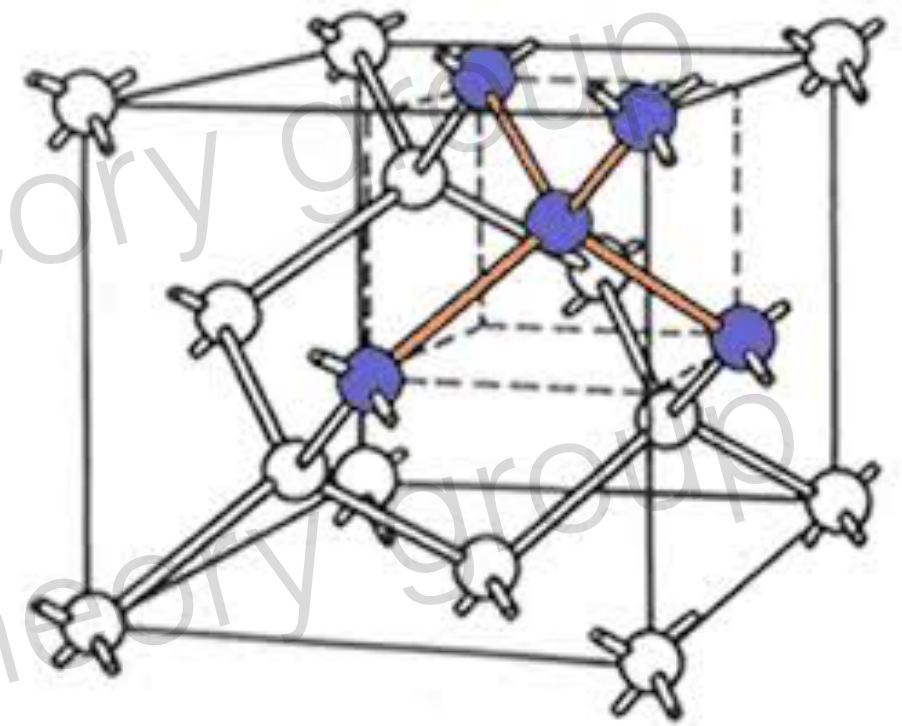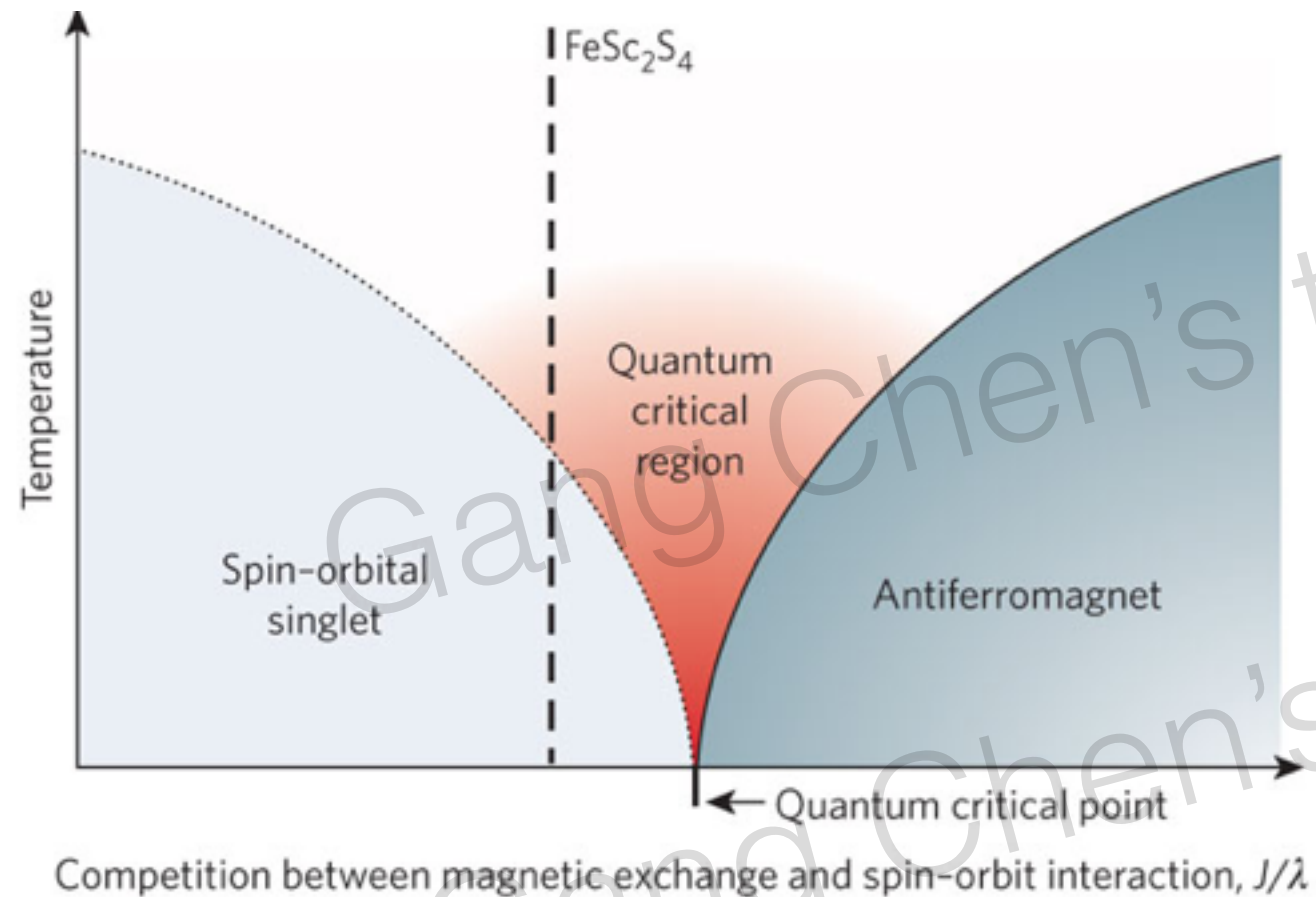
FeSc2S4的金刚石晶格

GC, Schnyder, Balents, PhysRevLett 2009

有时候这些量子顺磁态就不是十分明显，但它们代表一类自旋的无序态
这里的是自旋轨道耦合导致的单态。

2. 拓扑顺磁态: spin SPT beyond Haldane S=1链

Haldane
Nobel Prize 2016

Haldane链是一个1维的拓扑顺磁态：
由SO(3)对称保护的s=1/2 边缘态

Haldane 链的材料
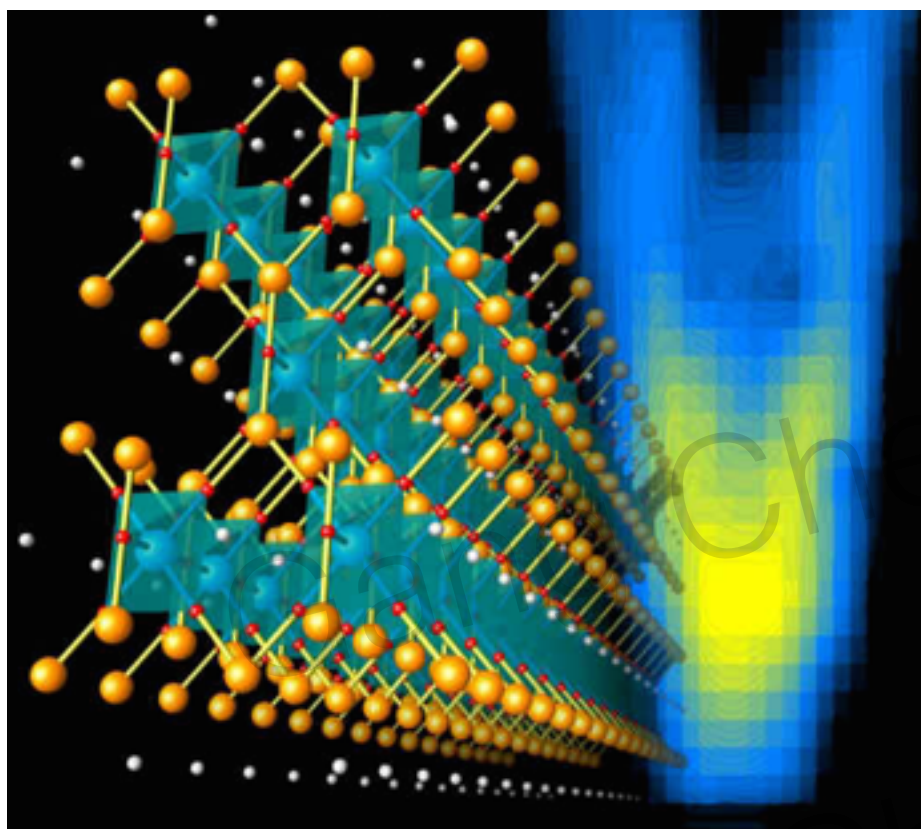
1维有机材料

Nd₂BaNiO₅
realization of Haldane chain

S. Maslov's group UIUC

$$Ni$$
$$O$$
$$N$$
$$C$$

(a) NINO

(b) NENP

$Ni(C_3H_{10}N_2)_2NO_2ClO_4$

$Ni(C_2H_8N_2)_2NO_2ClO_4$

孙学锋 研究组

玻色子体系的对称保护的拓扑相

文小刚

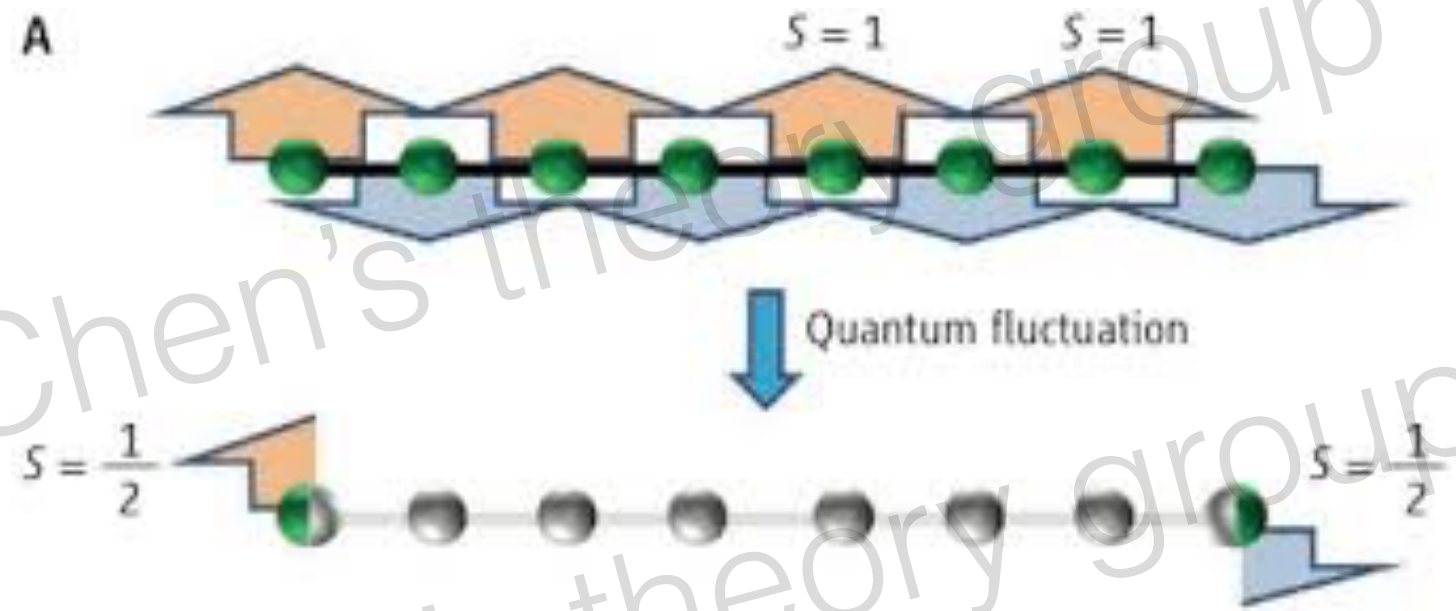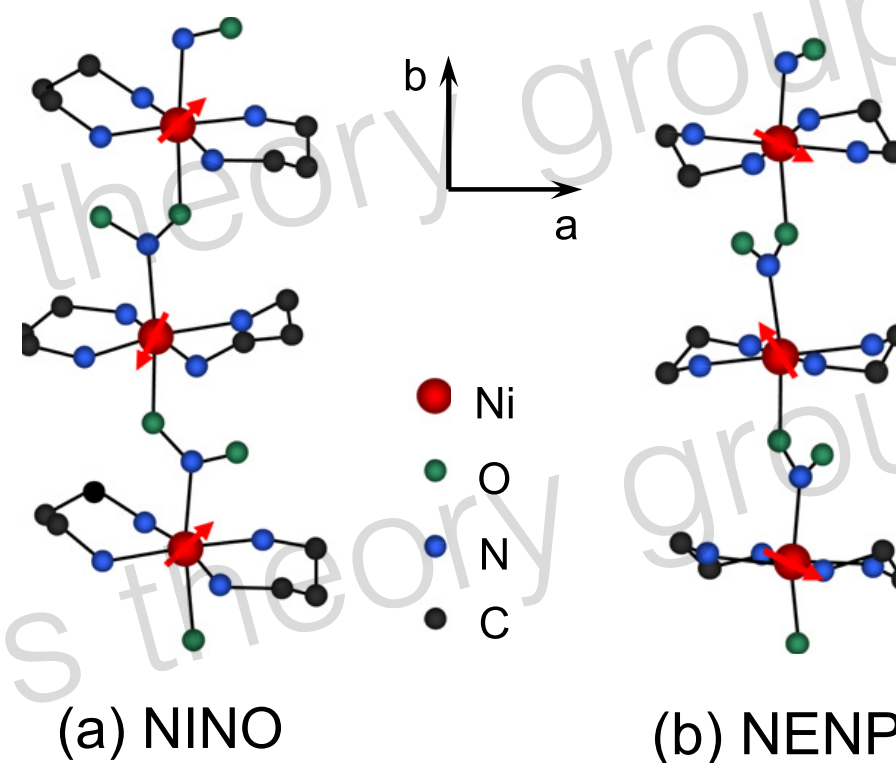| Symmetry	$d = 0$	$d = 1$	$d = 2$	$d = 3$
$U(1) \rtimes Z_2^T$	Z	Z_2	Z_2	Z_2^2
Z_2^T	Z_1	Z_2	Z_1	Z_2
$U(1)$	Z	Z_1	Z	Z_1
$SO(3)$	Z_1	Z_2	Z	Z_1
$SO(3) \times Z_2^T$	Z_1	Z_2^2	Z_2	Z_2^3
Z_n	Z_n	Z_1	Z_n	Z_1
$Z_2^T \times D_2 = D_{2h}$	Z_2^2	Z_2^4	Z_2^6	Z_2^9

这里的物理问题：

1. 什么自由度可以支持这些新的拓扑相？

2. 什么物理机制(相互作用模型)可以导致这些新的拓扑相？

3. 什么材料能实现？

4. 如果可以实现，实验如何测量和验证？因为SPT的bulk是完全gap的，
   有趣的物理几乎都是出现在表面上。

3. 量子自旋液体 – 第三种磁的相

P. W. Anderson

RVB idea,1973
High Tc, 1987
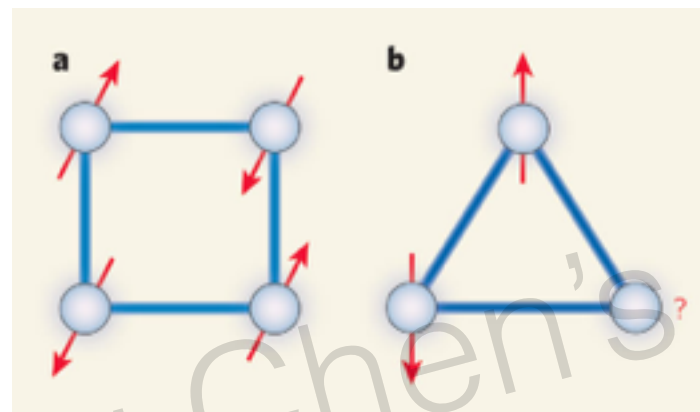
Pauling's RVB 波函数
for Benzene molecule
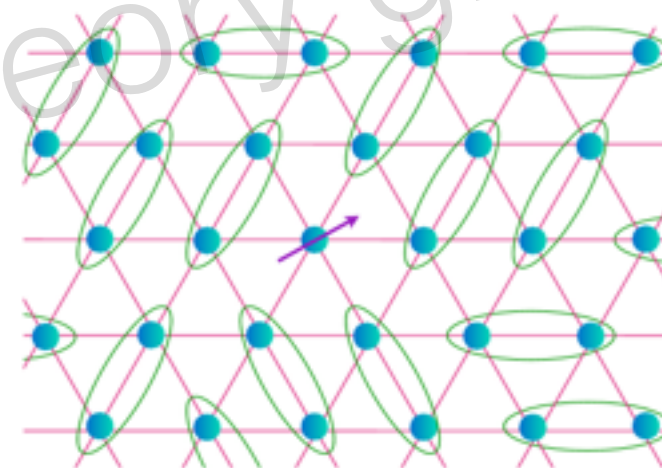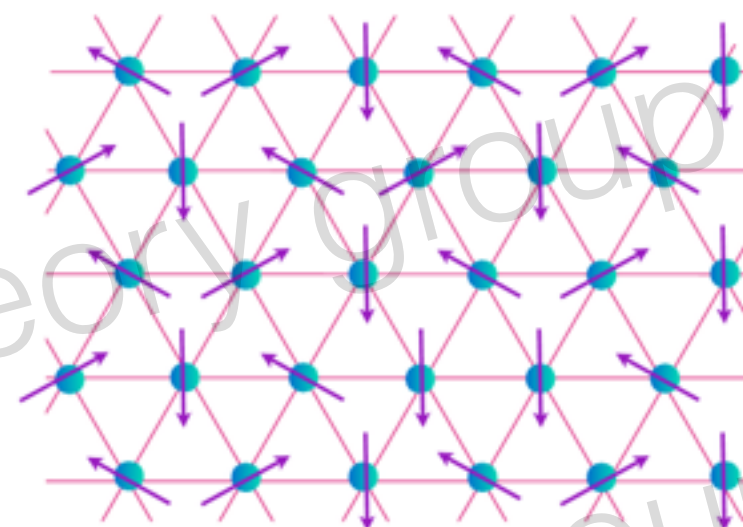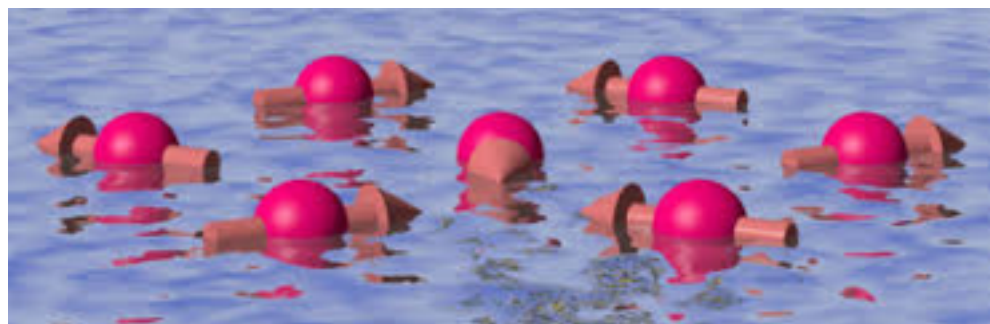
$$= \frac{1}{\sqrt{2}} \left[\uparrow \rule{1em}{0.4pt} \downarrow - \downarrow \rule{1em}{0.4pt} \uparrow \right]$$

Consequence 2: monopoles

- 量子自旋液体是物质的
  之以演生的规范结构和
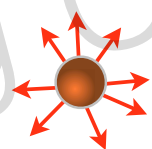
分数化的
spinon

规范场

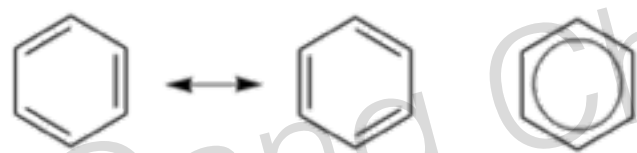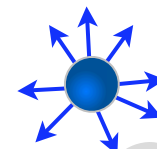分数化的
spinon

- 量子自旋液体在理论上
  各种分类(文小刚)，各和

量子自旋液体对任何局地

Gauss' law for magnetic charge

$$\sum_{i \in tet} S_i^z = \rho_m$$

现有的实验

- 2D triangular and Kagome lattice

  organics: kappa-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$, EtMe$_3$Sb[Pd(dmit)$_2$]$_2$, кappa−H$_3$(Cat-EDT-TTF)$_2$
  herbertsmithite (ZnCu$_3$(OH)$_6$Cl$_2$), Ba$_3$NiSb$_2$O$_9$, Ba$_3$CuSb$_2$O$_9$, LiZn$_2$Mo$_3$O$_8$, ZnCu$_3$(OH)$_6$Cl$_2$
  volborthite (Cu$_3$V$_2$O$_7$(OH)$_2$), BaCu$_3$V$_2$O$_3$(OH)$_2$, [NH$_4$]$_2$[C$_7$H$_{14}$N][V$_7$O$_6$F$_{18}$], Na$_2$IrO$_3$, CsCu$_2$Cl$_4$,
  CsCu$_2$Br$_4$, NiGa$_2$S$_4$, He-3 layers on graphite, **YbMgGaO4 (张清明，沈瑶)**

- 3D pyrochlore, hyperkagome, FCC lattice, diamond lattice, etc

  Na$_4$Ir$_3$O$_8$, IrO$_2$, Ba$_2$YMoO$_6$, Yb$_2$Ti$_2$O$_7$, Pr$_2$Zr$_2$O$_7$, Pr$_2$Sn$_2$O$_7$, Tb$_2$Ti$_2$O$_7$, Nd$_2$Zr$_2$O$_7$, FeSc$_2$S$_4$, etc

- Ultracold atom and molecules on optical lattices: temperature is too high now.

关键的问题在于：如何把这些实验和前沿理论发展联系起来？
既能理论上描述这个态，又能理解形成这个态的物理机制！
如何直接或者间接去confirm 量子自旋液体？

周毅老师的报告已经回答了很多这方面的问题。

一类量子自旋液体材料的理论模型

量子自旋冰体系 (tons of these materials！)

1. rare-earth pyrochlores: $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$, $Ho_2Sn_2O_7$, $Dy_2Sn_2O_7$, Er_2Ti_2O7, $Yb_2Ti_2O_7$, $Tb_2Ti_2O_7$, $Er_2Sn_2O_7$, $Tb_2Sn_2O_7$, $Pr_2Sn_2O_7$, $Nd_2Sn_2O_7$, $Gd_2Sn_2O_7$, ……

2. rare-earth B-site spinel: $CdEr_2S_4$, $CdEr_2Se_4$, $CdYb_2S_4$, $CdYb_2Se_4$, $MgYb_2S_4$, $MgYb_2S_4$, $MnYb_2S_4$, $MnYb_2Se_4$, $FeYb_2S_4$, $CdTm_2S_4$ $CdHo_2S_4$, $FeLu_2S_4$, $MnLu_2S_4$, $MnLu_2Se_4$, ….
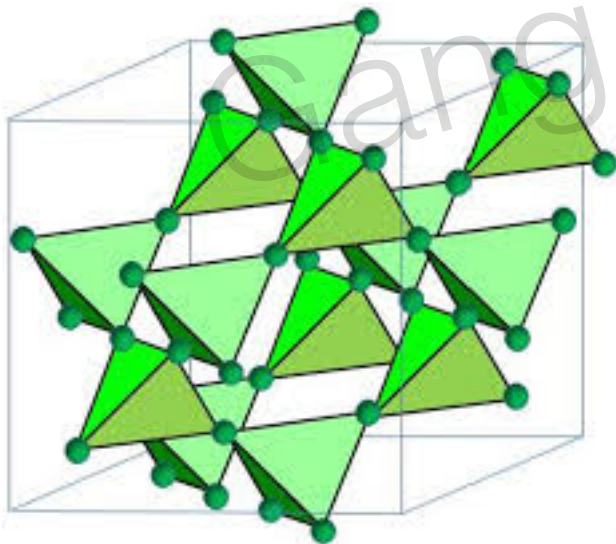
Many have not been carefully explored.

直接 "confirm" 量子自旋液体的实验

Candidate Quantum Spin Liquid in the Ce^{3+} Pyrochlore Stannate Ce$_2$Sn$_2$O$_7$

Romain Sibille,[1,*] Elsa Lhotel,[2] Vladimir Pomjakushin,[3] Chris Baines,[4] Tom Fennell,[3,†] and Michel Kenzelmann[1]
[1]Laboratory for Scientific Developments and Novel Materials, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
[2]Institut Néel, CNRS, and Université Joseph Fourier, BP 166, 38042 Grenoble Cedex 9, France
[3]Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
[4]Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
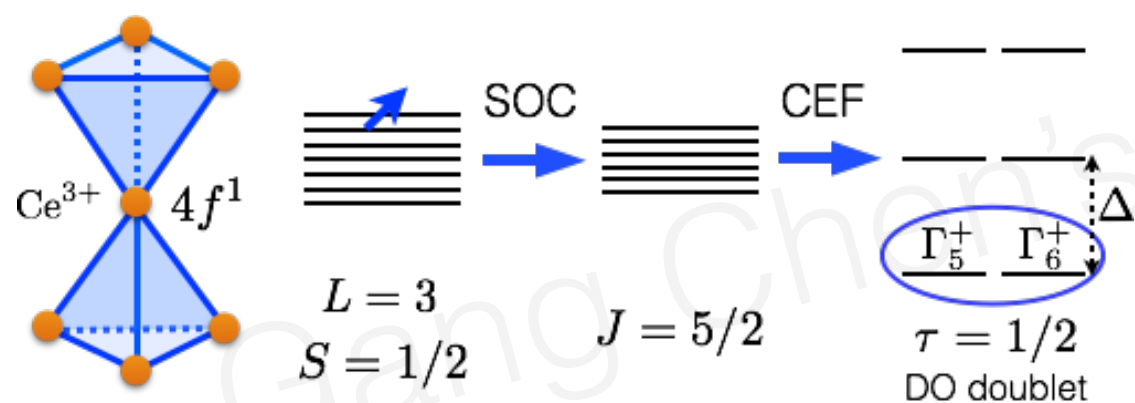
$$H = \sum_{\langle ij \rangle} \sum_{\mu=x,y,z} \tilde{J}_\mu \tilde{\tau}_i^\mu \tilde{\tau}_j^\mu - \sum_i h \left(\hat{n} \cdot \hat{z}_i \right) \tau_i^z,$$

YD Li, **GC**, 2016

FIG. 1. The electron configuration and the D$_{3d}$ crystal electric field (CEF) splitting of the Ce^{3+} ion in Ce$_2$Sn$_2$O$_7$. The

场诱导的Higgs相变
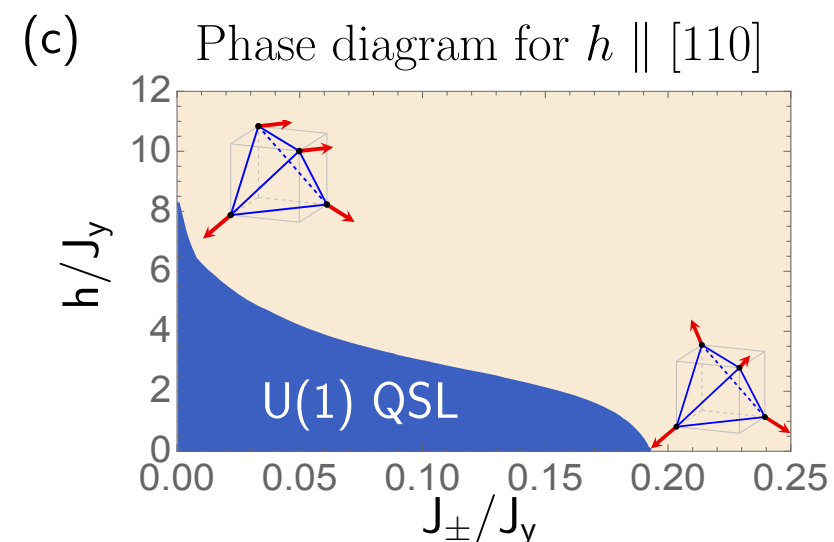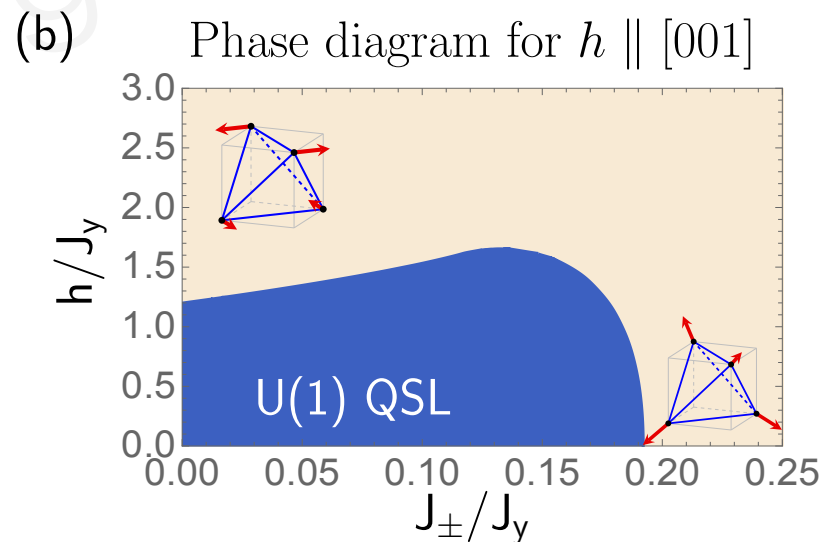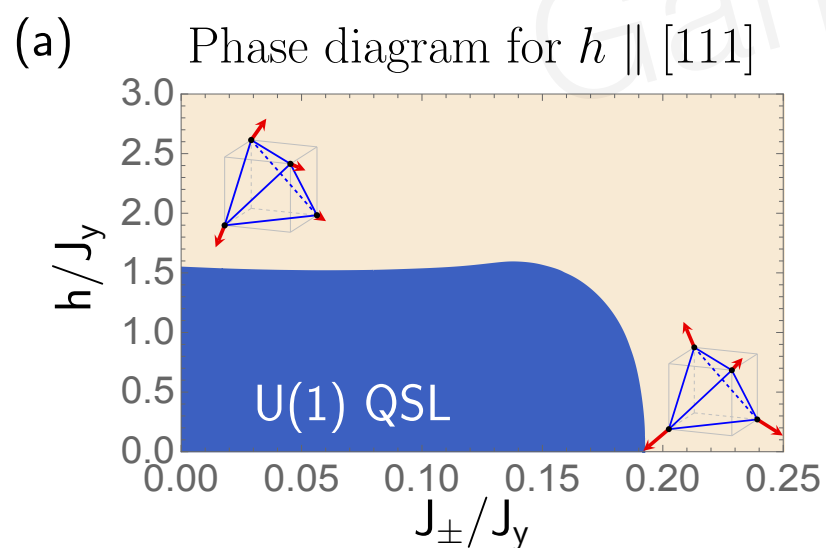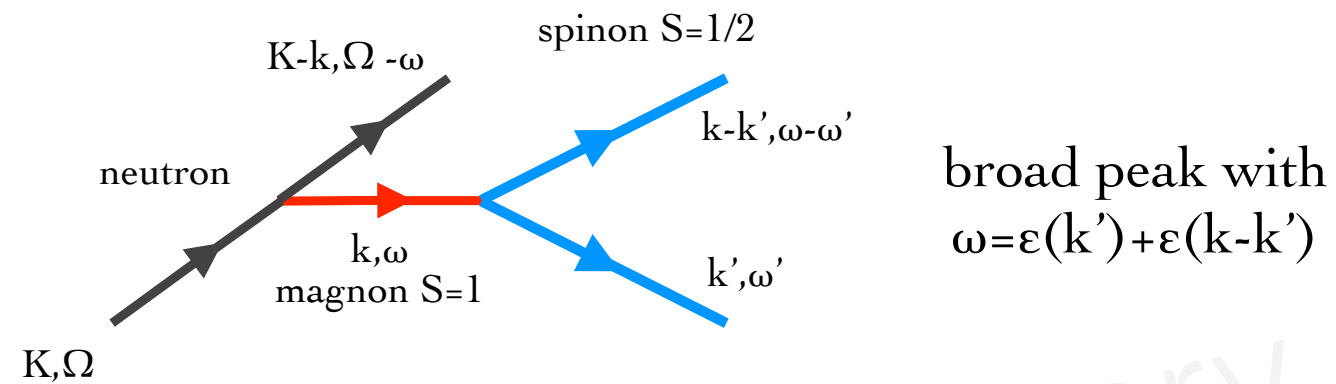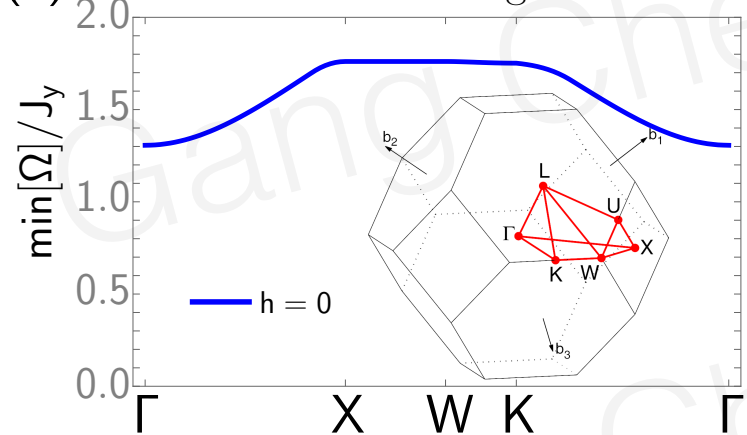
(a) Phase diagram for $h \parallel [111]$

(b) Phase diagram for $h \parallel [001]$

(c) Phase diagram for $h \parallel [110]$

中子散射的连续谱：场控制的连续谱
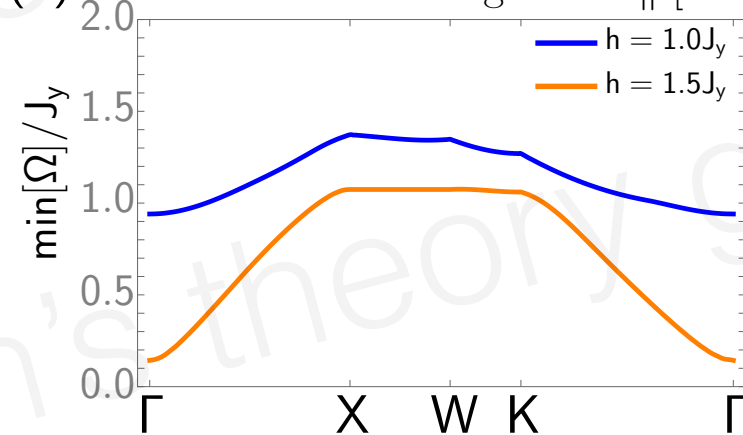
间接 "confirm" 量子自旋液体

Pr2Ir2O7的理论相图, Gang Chen, PRB 2016
Pr 磁矩从一个U(1)量子自旋液体到一个有序态
的相变：类似于夸克紧闭的相变
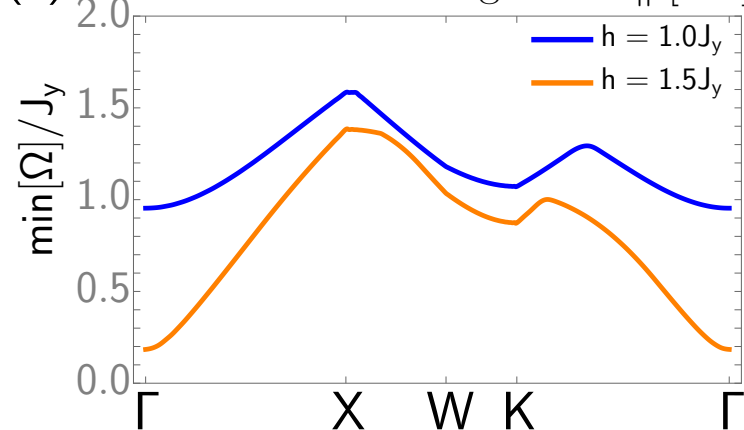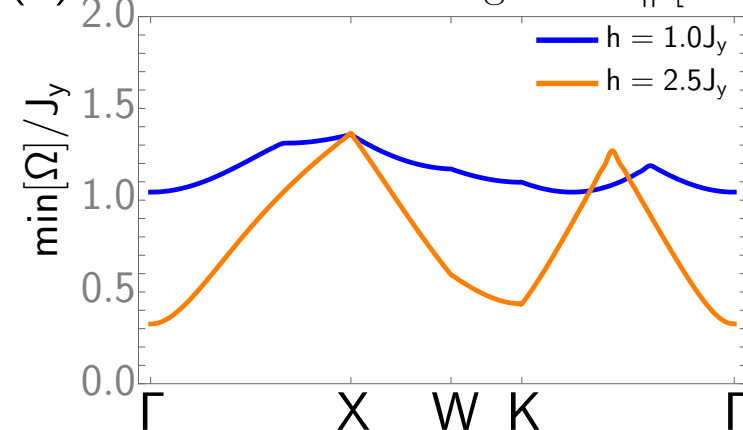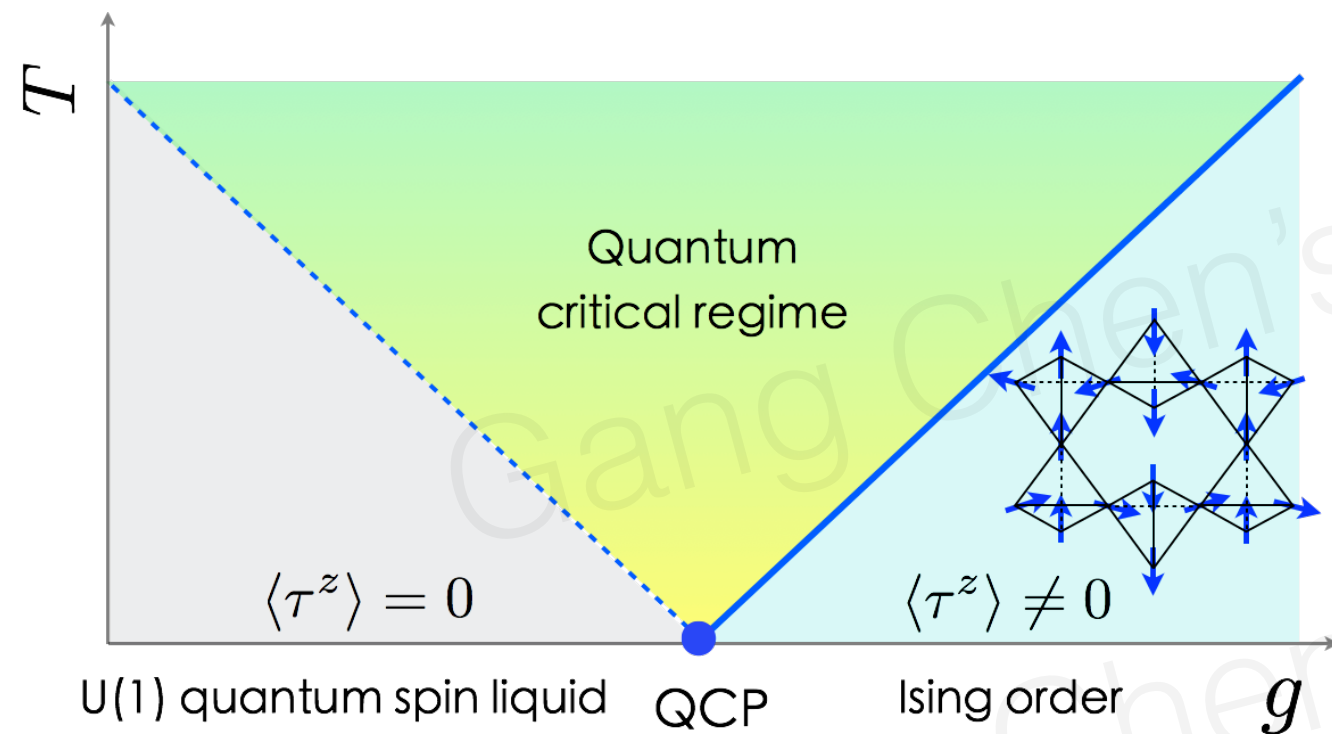
量子自旋液体是物质新的态，
它有特别的性质和元激发。

自旋液体到它附近的一般态的
量子相变也往往是非平庸的。

这些非平庸的量子相变
(比如: **deconfined quantum criticality**)
的行为反应了量子自旋液体的特征。

其他的课题

1. 轨道物理

2. 关联体系中的自旋轨道作用

3. 磁多极矩

   等等
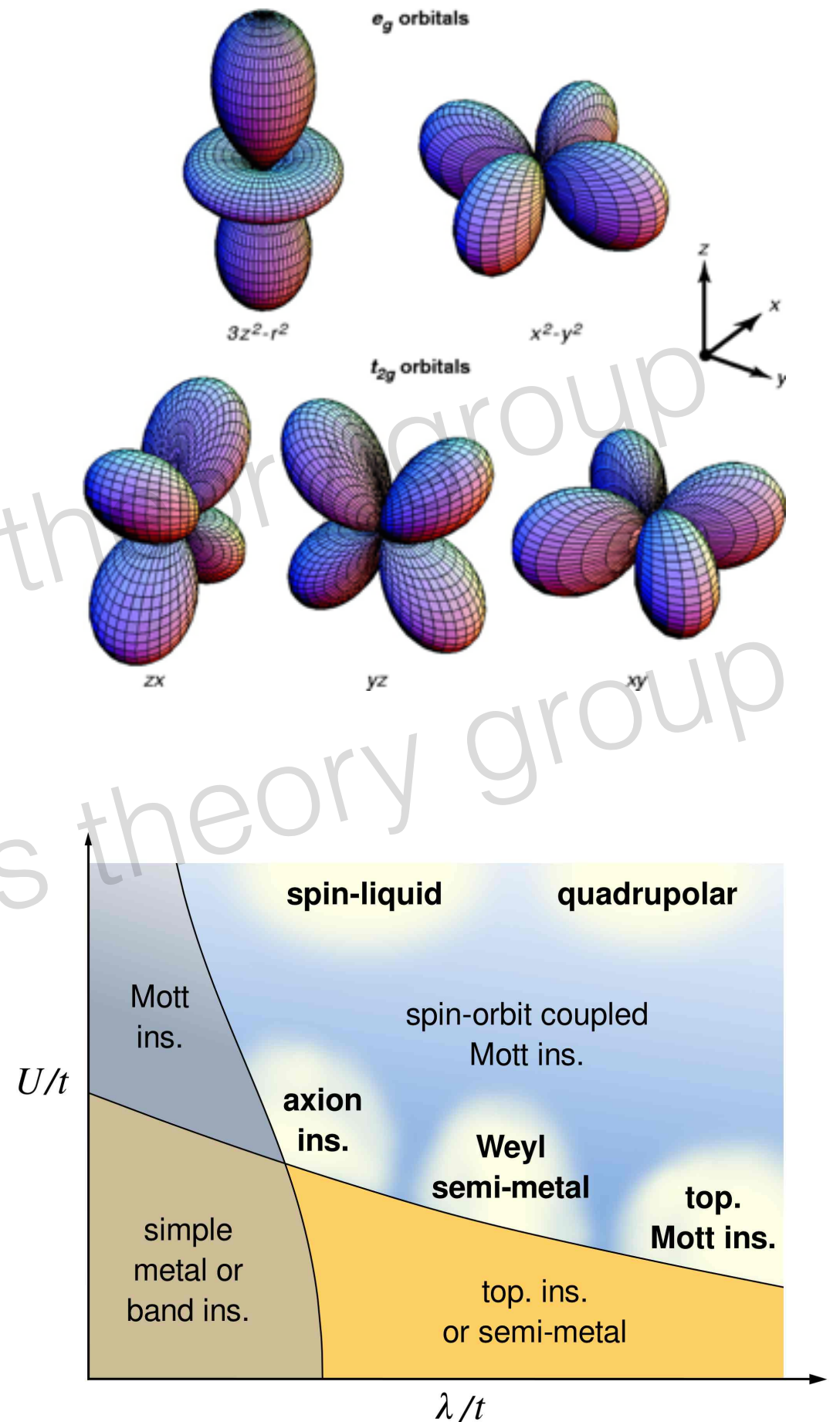
总 结

我这里讲到了有序态的各种新奇的物理和无序态的发展前景。

量子阻挫磁体是一个令人振奋的领域，最前沿的物理理论和实验在这里交汇。

Any guiding rule to find QSL?   Not really.

Frustrated lattice?   Honeycomb Kitaev model.
Frustrated interaction?   We do not really know unless we identify the interaction.
Low dimensionality?   3D lattice also has QSL.
Odd electrons per cell? Many QSLs have even electrons per cell.

Lieb   Oshikawa   Hastings   Vishwanath

- Hastings-Oshikawa-Lieb-Shultz-Mattis theorem.
- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2016).

A rare-earth triangular lattice quantum spin liquid: **YbMgGaO₄**

Dr. Yuesheng Li
Renmin Univ -> MPI, Germany

This part is in collaboration with experimentalists

Dr. Yuesheng Li (Renmin Univ, Beijing)
Prof. Qingming Zhang (Renmin Univ, Beijing)
Wei Tong (High Magnetic field Lab, Hefei)
Pi Li (High Magnetic field Lab, Hefei)
Juanjuan Liu (Renmin Univ, Beijing)
Zhaorong Yang (Institute of Solid-State Physics, Hefei)
Xiaoqun Wang (Renmin, Shanghai Jiaotong)

A rare-earth triangular lattice quantum spin liquid: **YbMgGaO₄**
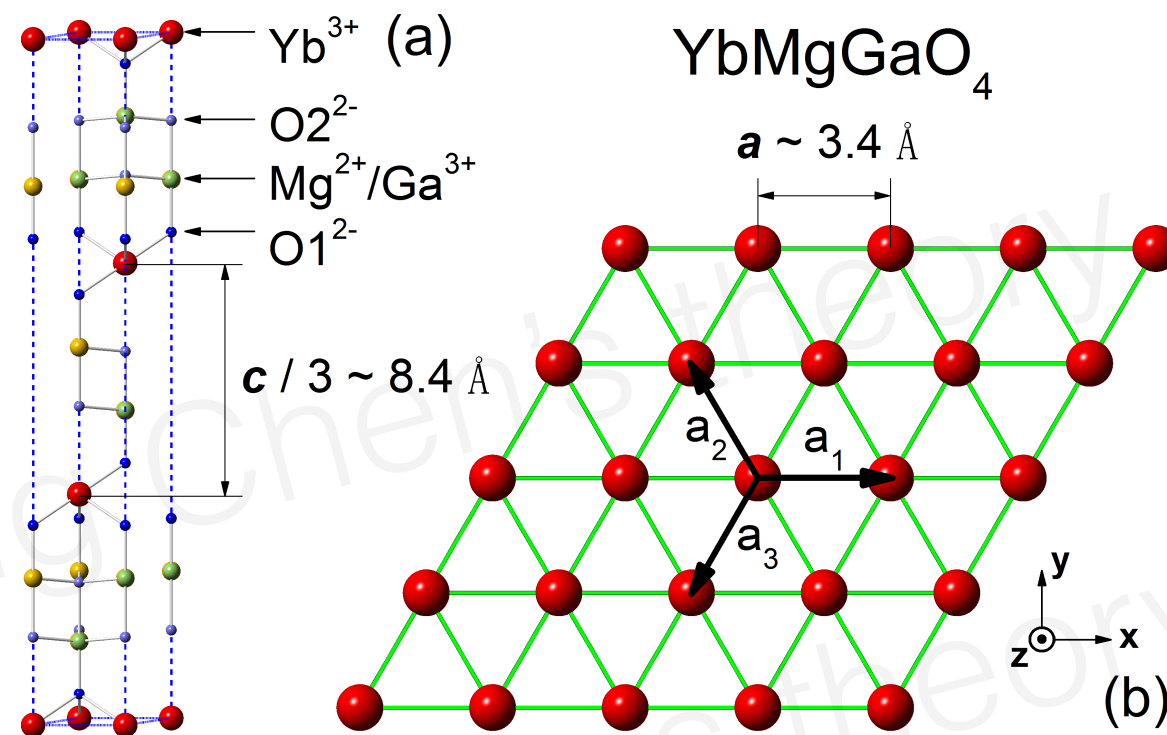
- This is the **first** strong spin-orbit coupled QSL with odd number of electrons and effective spin-1/2.
- It is the **first** clear observation of $T^{2/3}$ heat capacity.
- We understand the microscopic Hamiltonian and the physical mechanism.

YbMgGaO$_4$
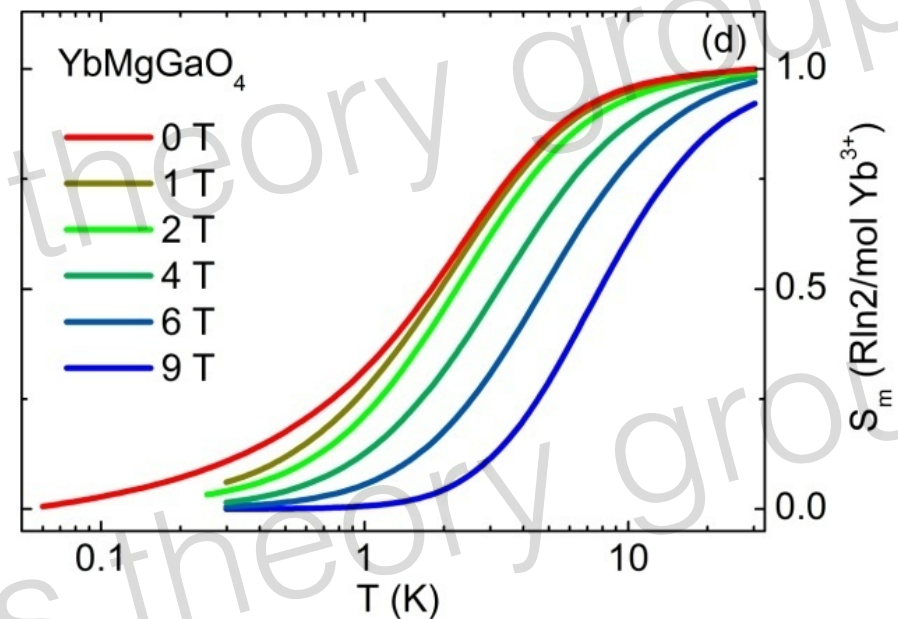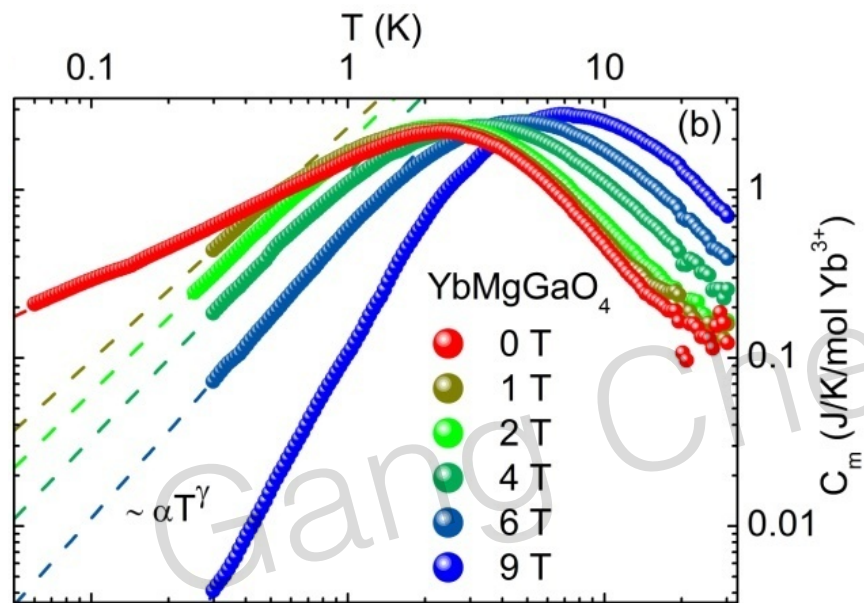
- observation of T$^{2/3}$ heat capacity
- Entropy: effective spin-1/2 local moments

My proposal for ground state: spinon Fermi surface U(1) QSL.

Microscopics
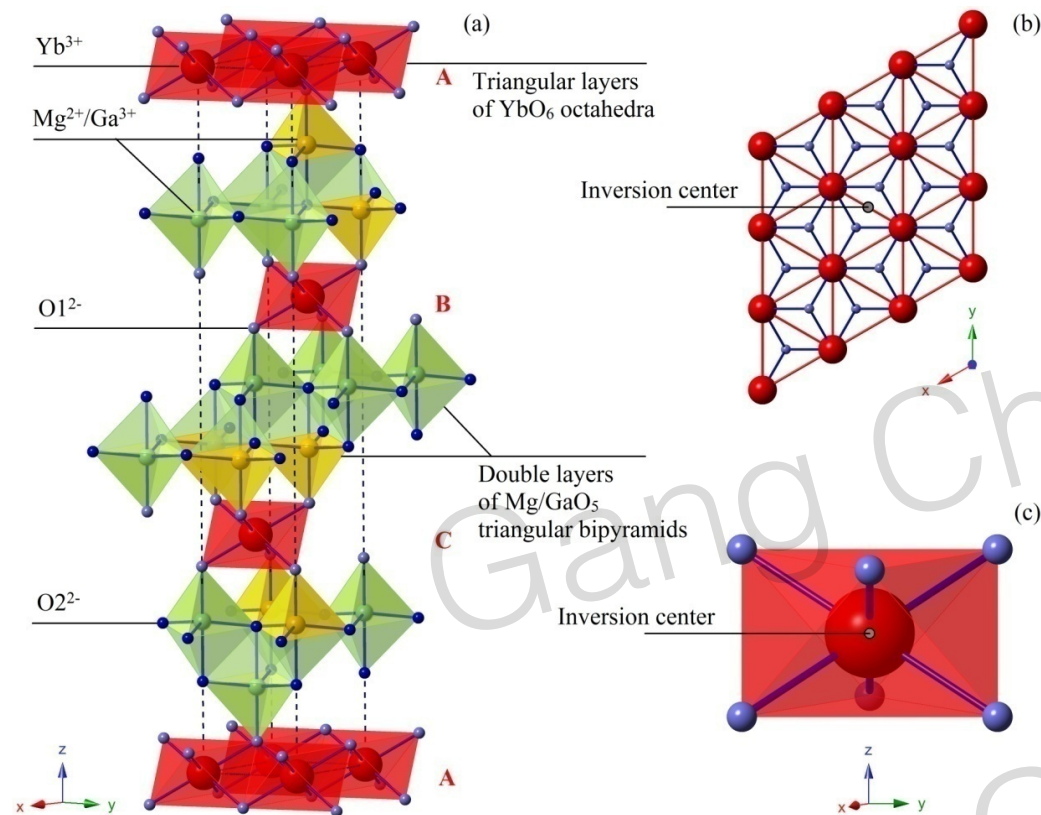
Yb^{3+} ion: 4f^{13} has J=7/2 due to SOC.

J=7/2

Δ
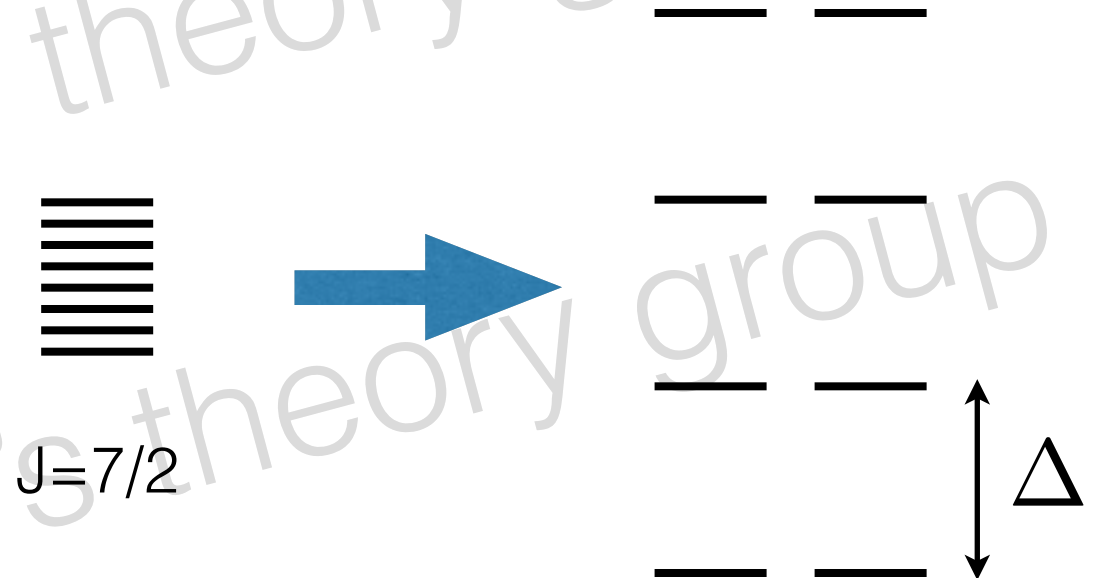
At $T \ll \Delta$, the only active DOF is the ground state doublet that gives rise to an effective spin-1/2.

Can this kind of system support a QSL ground state? Yes.

Filling constraints for spin-orbit coupled insulators in symmorphic and non-symmorphic crystals

Haruki Watanabe,[1] Hoi Chun Po,[1] Ashvin Vishwanath,[1,2] and Michael P. Zaletel[3]

May 2015

and a crystalline lattice or a magnetic field. Mott insulators are a particularly interesting class, with an odd number of electrons in each unit cell. Their low energy physics is captured by a spin model with an odd number of $S = 1/2$ moments in the unit cell. A powerful result due to Lieb, Schultz, and Mattis in 1D[1], later extended to higher dimensions by Hastings and Oshikawa[2,3], holds that if all symmetries remain unbroken, the ground state must be 'exotic' - such as a Luttinger liquid in 1D, or a quantum spin liquid in higher dimensions, with fractional 'spinon' excitations. These exotic states cannot be represented as simple product states, as a consequence of long ranged quantum entanglement. This general re-

tirely different theoretical approaches are needed. We argue that if a spin-orbit coupled insulator at odd filling is time-reversal symmetric, its ground state must, in a precise sense, be exotic. We introduce two theoreti-

What is the physical origin of the QSL?

4f electron is very localized, and dipolar interactions weak.

YbMgGaO$_4$

$a \sim 3.4$ Å

$c / 3 \sim 8.4$ Å
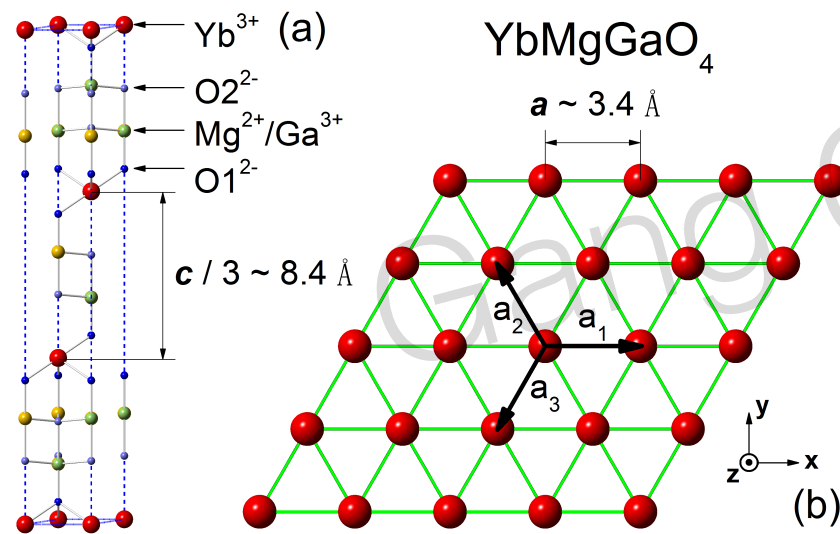
PhysRevLett, 2015

$$\mathcal{H} = \sum_{\langle ij \rangle} \left[J_{zz} S_i^z S_j^z + J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+) \right.$$

$$+ J_{\pm\pm}(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-)$$

$$\left. - \frac{iJ_{z\pm}}{2}(\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle)\right], \quad (1)$$

where $S_i^{\pm} = S_i^x \pm i S_i^y$, and the phase factor $\gamma_{ij} = 1, e^{i2\pi/3}, e^{-i2\pi/3}$ for the bond ij along the $\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3$ direction (see Fig. 1), respectively. This generic Hamil-

The spin-1/2 XXZ model supports conventional order.

(Yamamoto, etc, PRL 2014)

Anisotropic spin interaction could potentially stabilize QSL.
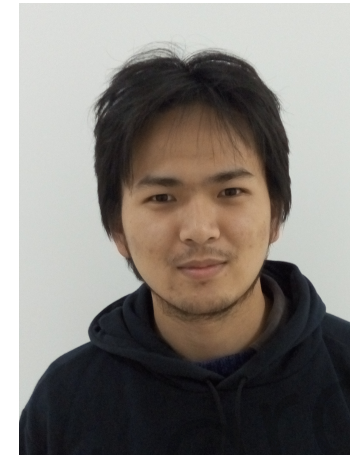
Yao-Dong Li
Dept of Computer Sciences
Fudan University

a T = 0 phase diagram

$\delta m = \langle a_i^\dagger a_i \rangle$

Spinon Fermi surface U(1) QSL
in organic magnets?

Kanoda

(a)

(b)

t' t

kappa-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$,
EtMe$_3$Sb[Pd(dmit)$_2$]$_2$,
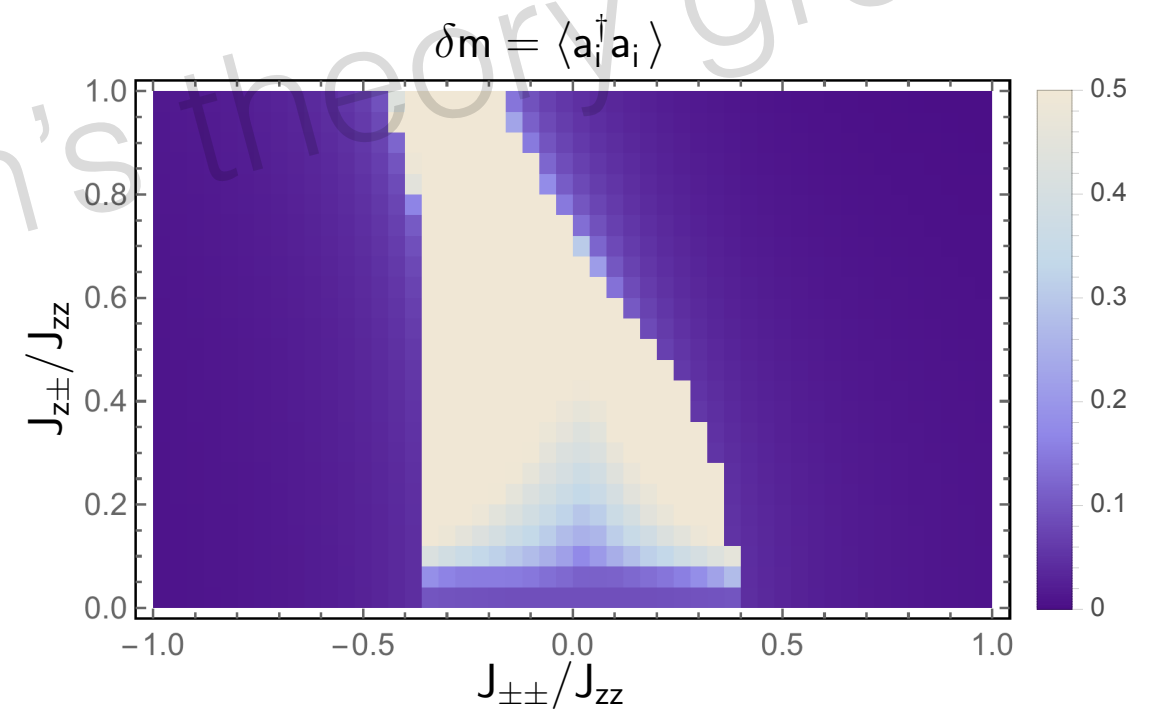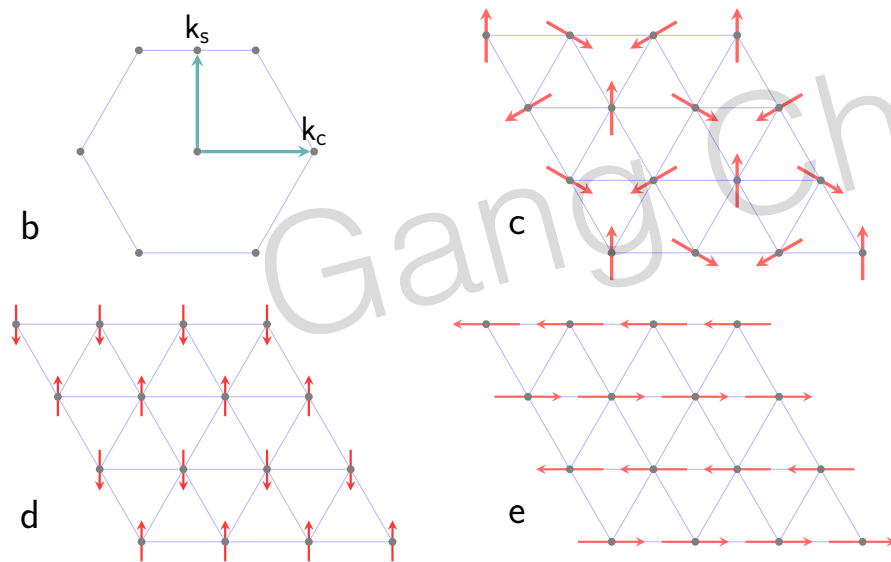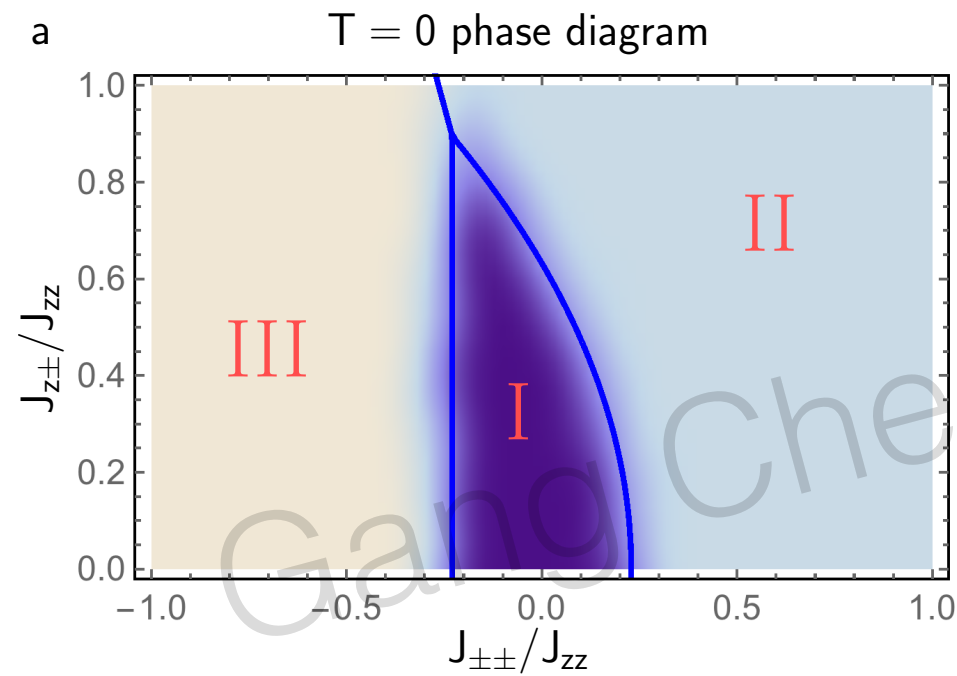kappa−H$_3$(Cat-EDT-TTF)$_2$

a new one!

NMR

κ-(ET)$_2$Cu$_2$(CN)$_3$

32 mK

56 mK

164 mK

508 mK

901 mK

1.4 K

2.8 K

9.7 K

36.1 K
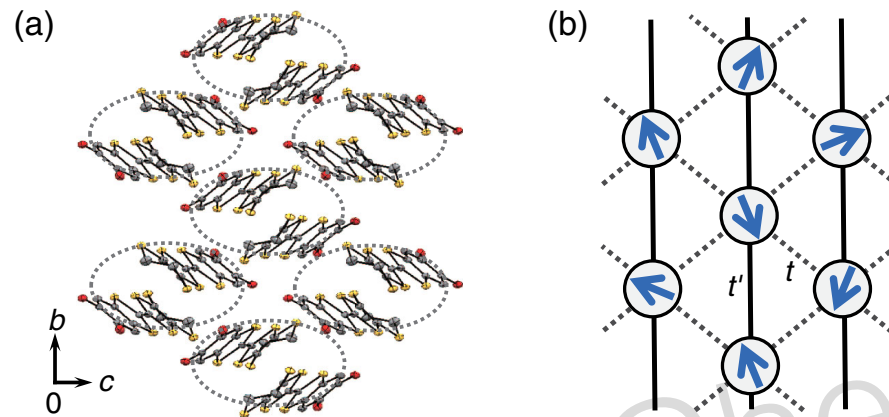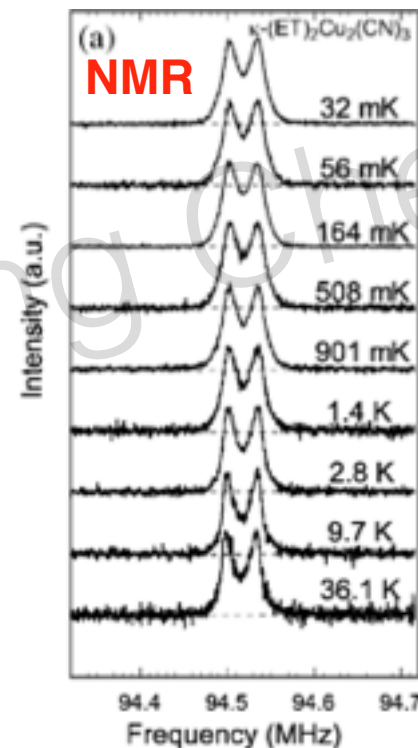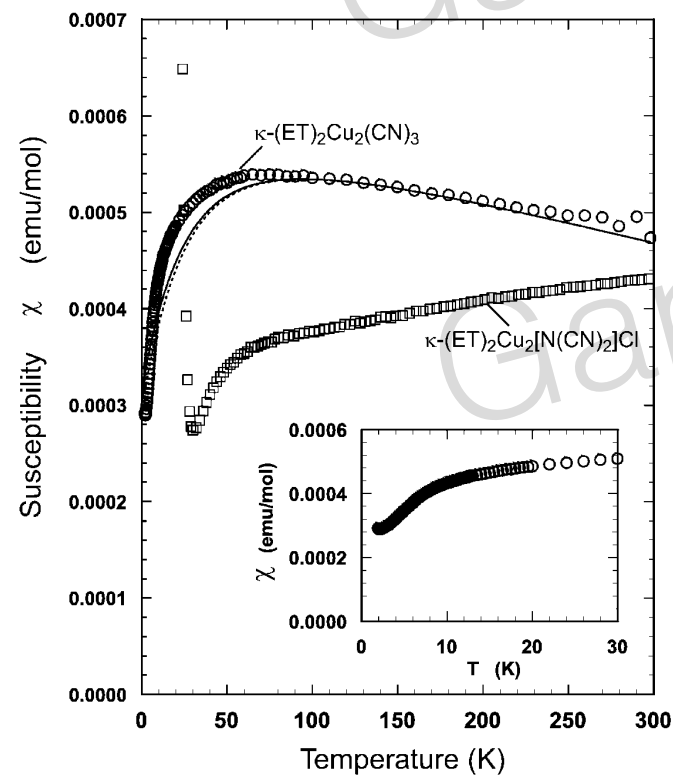
* No magnetic order down to 32mK
* Constant spin susceptibility at zero temperature

Other experiments: transport,
heat capacity, optical absorption, etc,
Unfortunately, **no neutron scattering** so far.

κ-(ET)$_2$Cu$_2$[N(CN)$_2$]Cl

4.9 K

10.3 K

14.1 K

18.1 K

22.1 K

25.1 K

27.2 K

30.2 K

164 K

9.7 K

36.1 K

94.4   94.5   94.6   94.7
Frequency (MHz)

94.4   94.5   94.6   94.7   156.6   156.7   156.8   156.9   157.0
Frequency (MHz)   Frequency (MHz)

κ-(ET)$_2$Cu$_2$(CN)$_3$

κ-(ET)$_2$Cu$_2$[N(CN)$_2$]Cl

Susceptibility   χ   (emu/mol)

Temperature (K)

χ (emu/mol)

T (K)

- Theoretical understanding: expected phase diagram

$$H = -t \sum_{\langle ij \rangle, \sigma} c_{i\sigma}^\dagger c_{j\sigma} + h.c. + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Sung-Sik Lee   T Senthil Patrick Lee

Senthil's cartoon

Mott transition

Fermi liquid metal
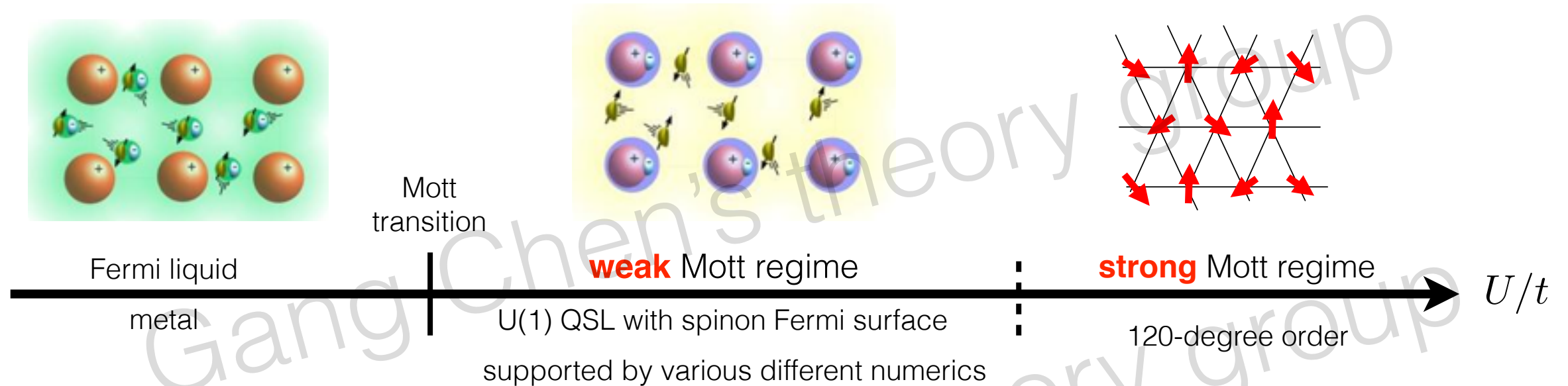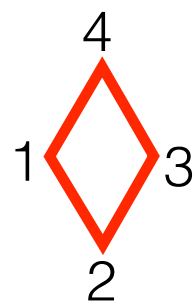
weak Mott regime

U(1) QSL with spinon Fermi surface

supported by various different numerics

strong Mott regime

120-degree order

U/t

- **Physical mechanism** for weak Mott insulator spin liquids: perturbation in t/U

$$H_{\text{pert}} = \sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + K \sum_{1234} (P_{1234} + P_{1234}^{-1}) + \cdots$$
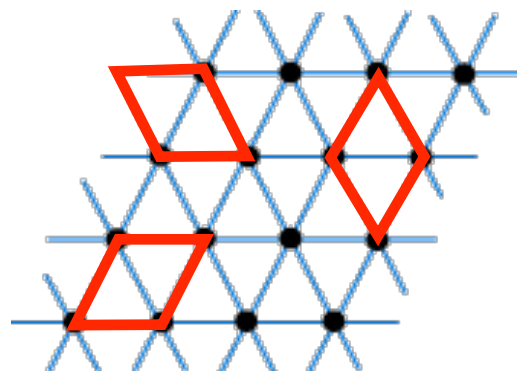
4-site ring exchange

$$(\mathbf{S}_1 \cdot \mathbf{S}_2)(\mathbf{S}_3 \cdot \mathbf{S}_4)$$
$$+(\mathbf{S}_1 \cdot \mathbf{S}_4)(\mathbf{S}_2 \cdot \mathbf{S}_3)$$
$$-(\mathbf{S}_1 \cdot \mathbf{S}_3)(\mathbf{S}_2 \cdot \mathbf{S}_4)$$

4

1   3

2

Motrunich

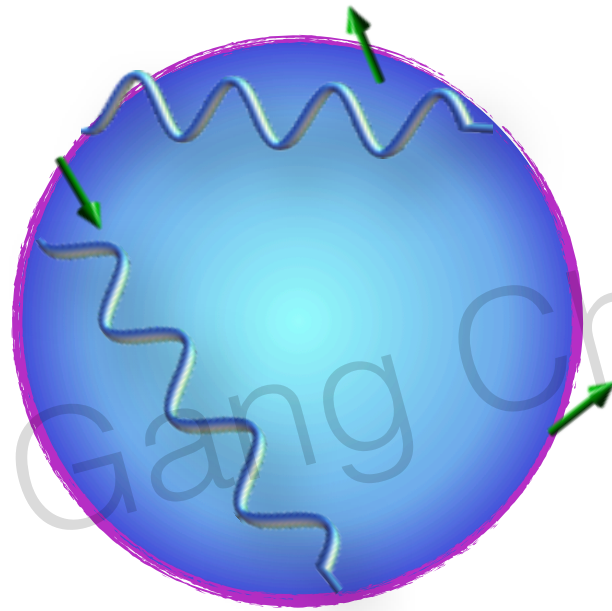# Low energy property of spinon Fermi surface U(1) QSL:
spinon non-Fermi liquid

$$S = \int d^3x \left[\Psi_j^*(\partial_0 - ia_0 - \mu_F)\Psi_j + \frac{1}{2m}\Psi_j^*(-i\nabla - \mathbf{a})^2\Psi_j + \frac{1}{4g^2}f_{\mu\nu}f_{\mu\nu} \right].$$

gauge photon is overly Landau-damped.

Spinon Fermi surface coupled
with dynamical U(1) gauge field:
instanton event is suppressed.
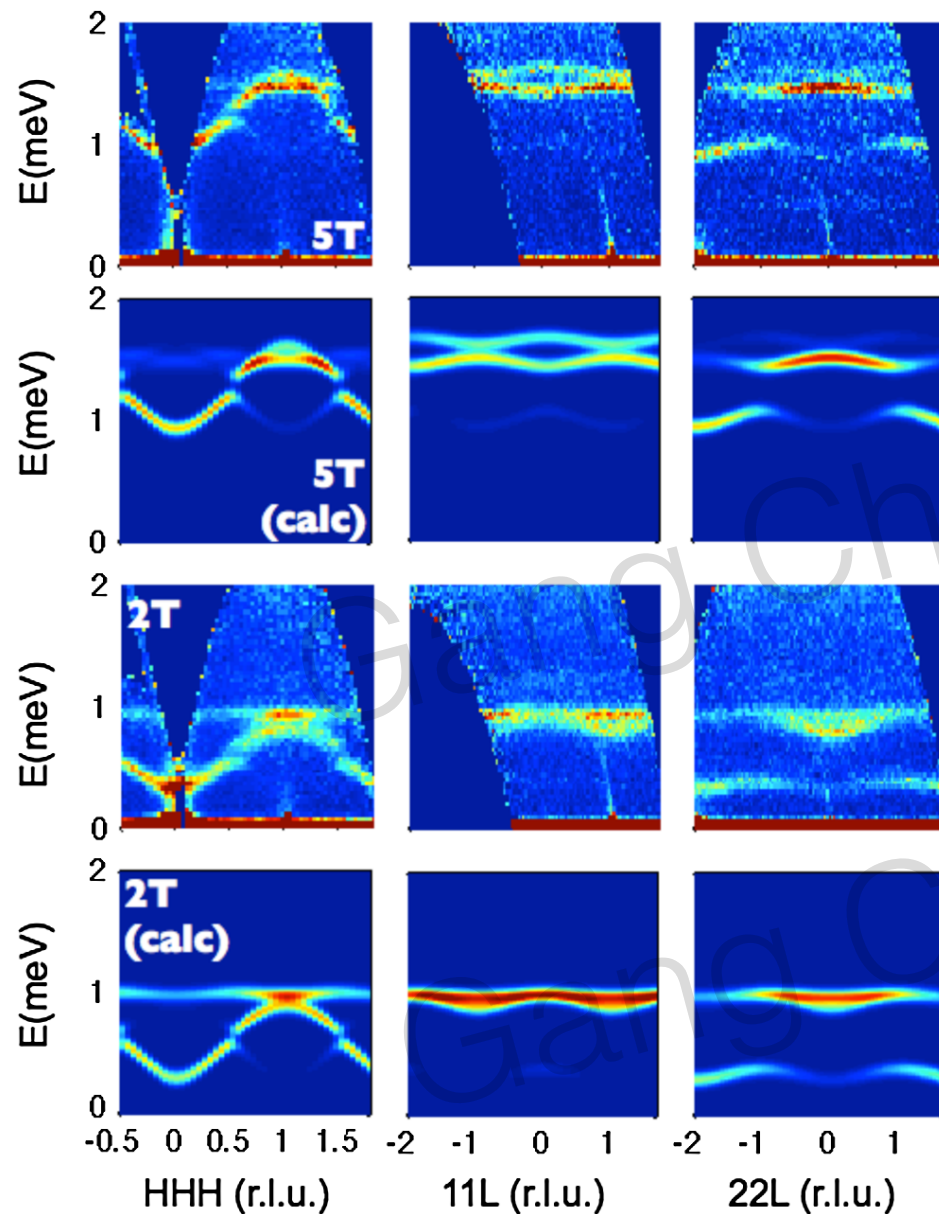
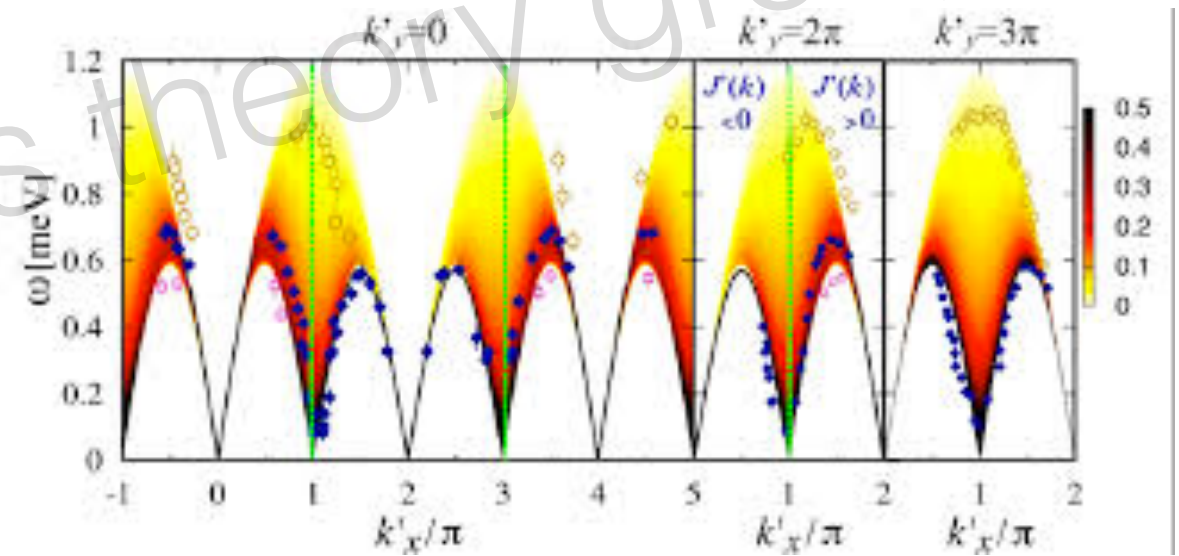dual to extremal/charged black hole?

$$Re\Sigma \sim Im\Sigma \sim \omega^{2/3}$$

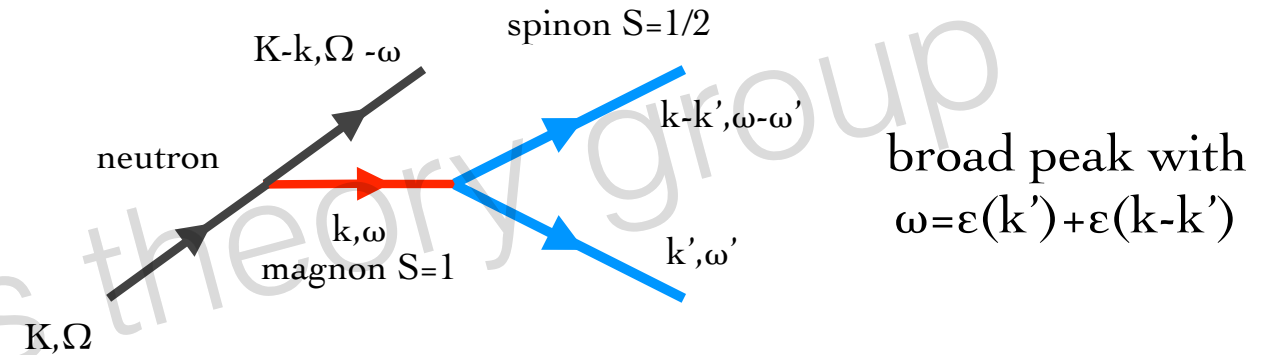Hermele et al., PRB 70, 214437 (04)

Sung-Sik Lee, PRB 78, 085129(08).

Spin wave vs (fractionalized) spinon continuum

spin wave in Yb2Ti2O7
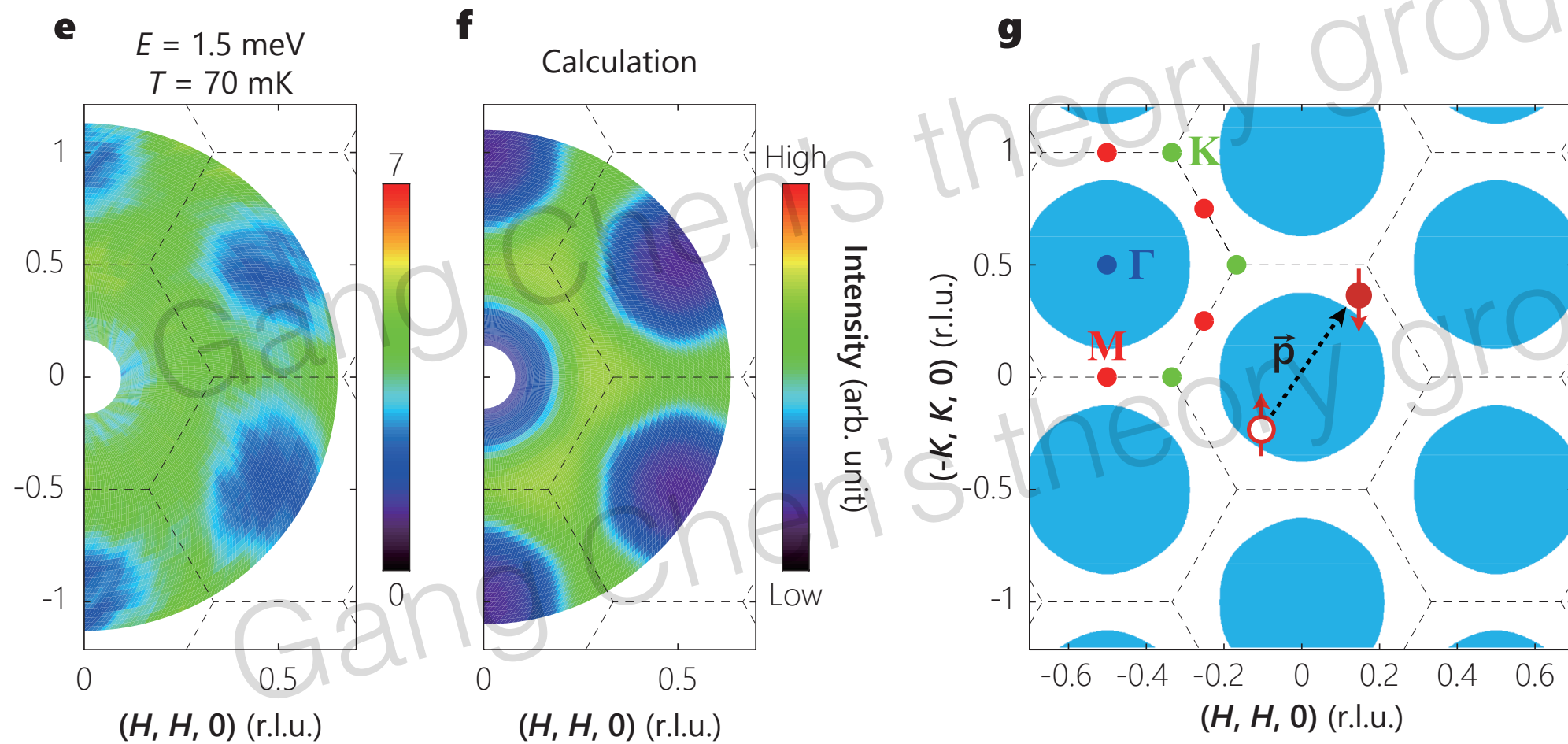L Savary, et al, PRX 2011

broad peak with
$\omega=\varepsilon(k')+\varepsilon(k-k')$

spinon continuum in Cs2CuCl4
Masanori, etc NatPhys 2009
but these are **1d spinons** !

Huge spinon continuum at all energies

Yao Shen, …GC, Jun Zhao arxiv 2016

a

M₁ K Γ₁ M₂ Γ₂

Energy (meV)

Intensity (arb. unit)

(1/2-*K*/2, *K*, 0) (r.l.u.)   (1, *K*, 0) (r.l.u.)

b

(-K, K, 0) (r.l.u.)

K M₁ Γ₂

Γ₁ M₂

(H, H, 0) (r.l.u.)

a

ω/t

k_x

k_y

$-\frac{4\pi}{3}$ 0 $\frac{4\pi}{3}$ $-\frac{2\pi}{\sqrt{3}}$ 0 $\frac{2\pi}{\sqrt{3}}$

Ir

(1/2-*K*/2, *K*, 0) (r.l.u.)   (1, *K*, 0) (r.l.u.)

b

M₁ K Γ₁ M₂ Γ₂

ω/7.5t

High
Low

Intensity (arb. unit)

(1/2-*K*/2, *K*, 0) (r.l.u.)   (1, *K*, 0) (r.l.u.)

Energy (meV)