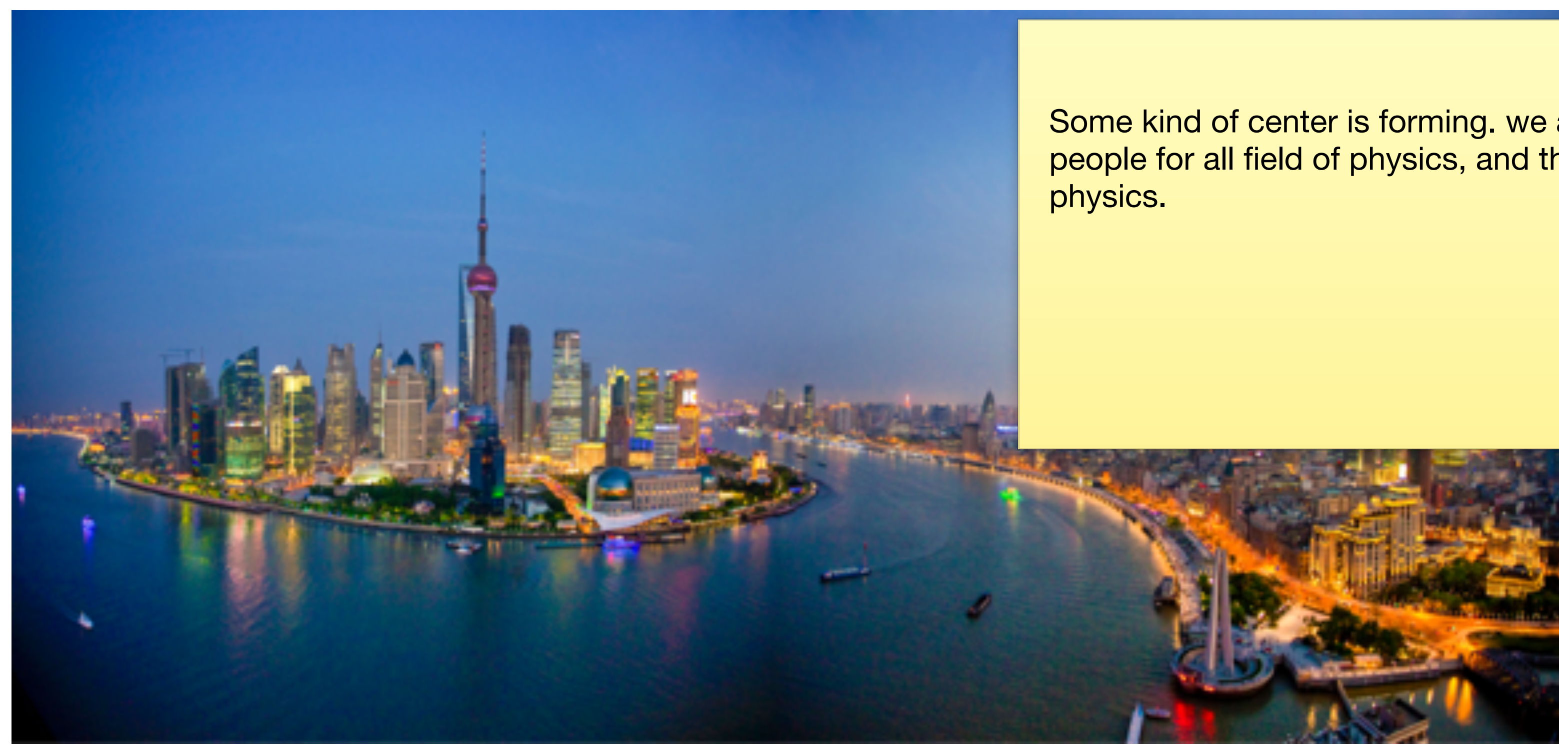
Recent development of quantum spin liquids

Gang Chen (陈 钢)
Fudan University

Opportunity for students and postdocs

- My research group is looking for graduate students and postdocs
- Our **postdocs and visiting professors** are generously funded.



Some kind of center is forming. we are hir
people for all field of physics, and theoreti
physics.

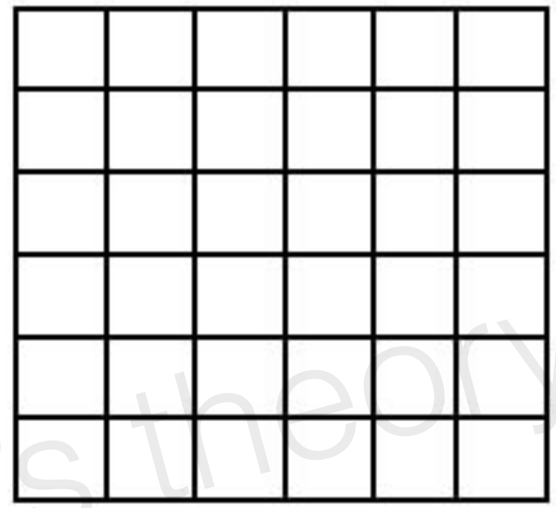
FUDAN UNIVERSITY

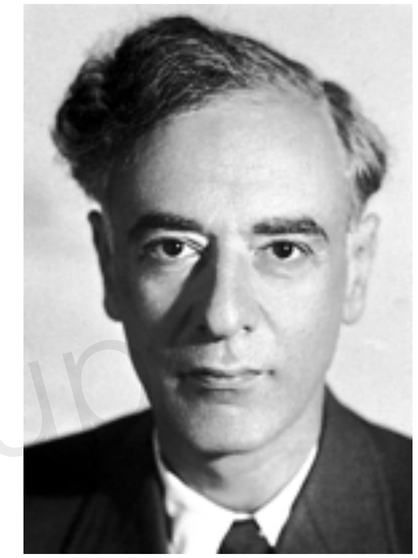
Outline

- A general introduction to quantum spin liquids
- Spinon Fermi surface U(1) quantum spin liquid
- Rare earth triangular lattice quantum spin liquid and experiment prediction
- Control spinons in a quantum spin ice U(1) quantum spin liquid

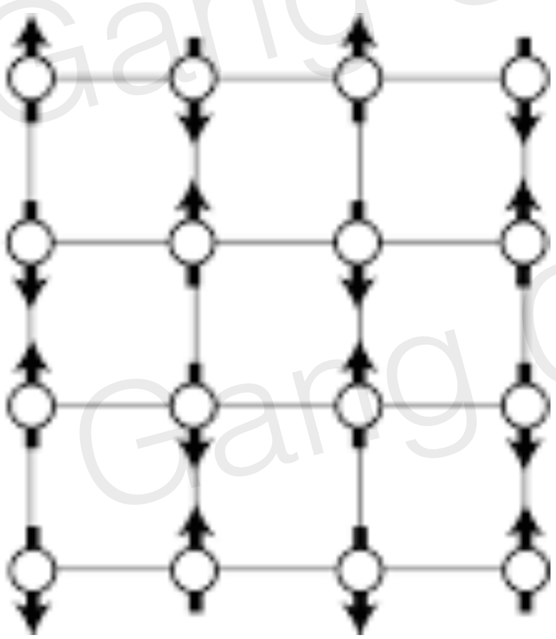
Neel vs Landau (1930-40s)

Neel





Landau



$$H = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

$$\text{Spin singlet} = \frac{1}{\sqrt{2}} \left[\uparrow\!\!-\!\!\downarrow \; - \; \downarrow\!\!-\!\!\uparrow \right]$$

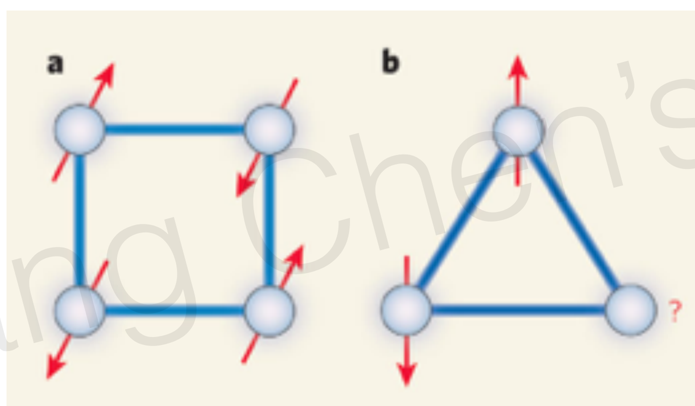
P. W. Anderson

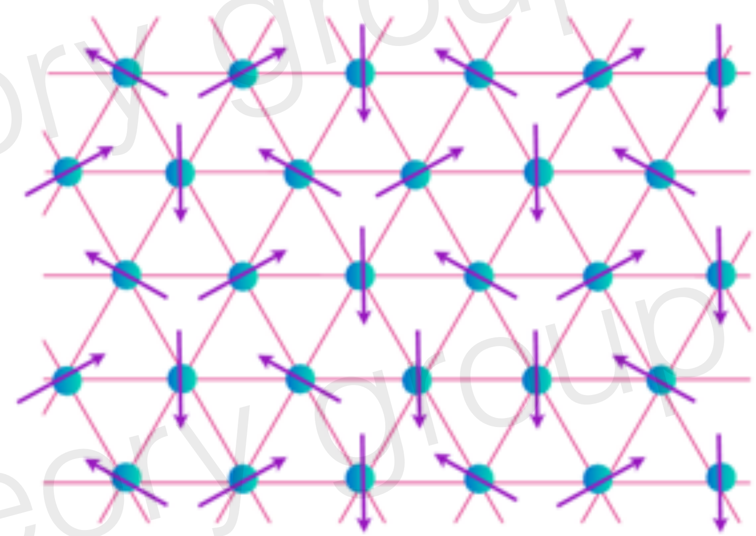
The idea of quantum spin liquid (1973)

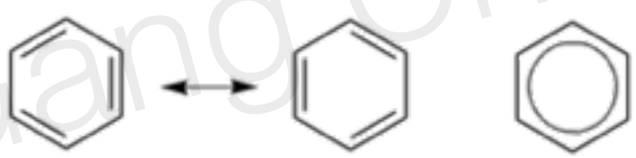
RESONATING VALENCE BONDS: A NEW KIND OF INSULATOR?*

P. W. Anderson

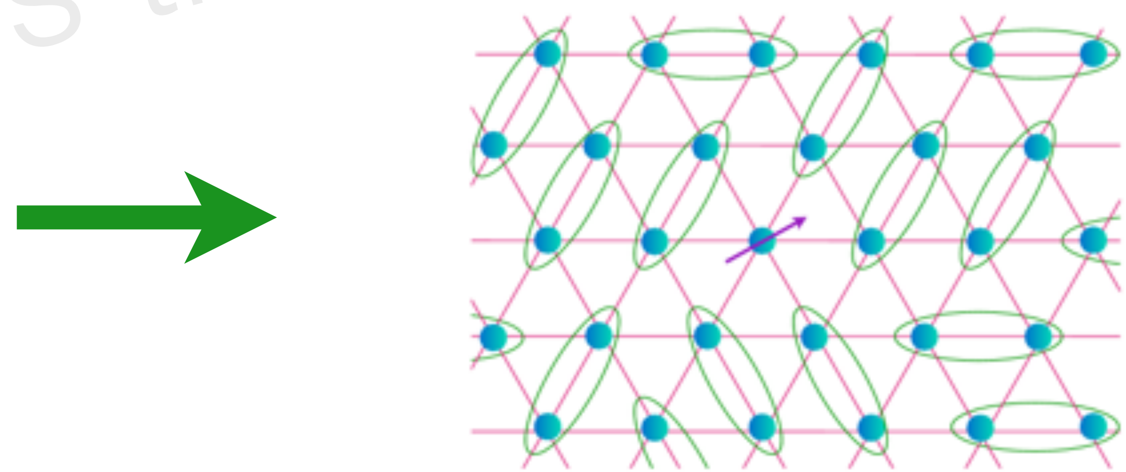
type would be insulating; it would represent an alternative state to the Néel antiferromagnetic state for S = 1/2. An estimate of

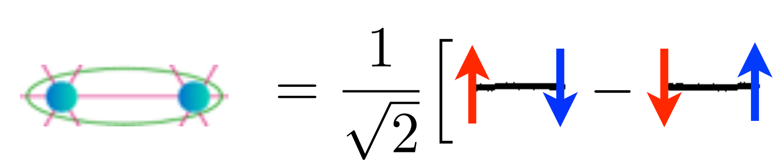






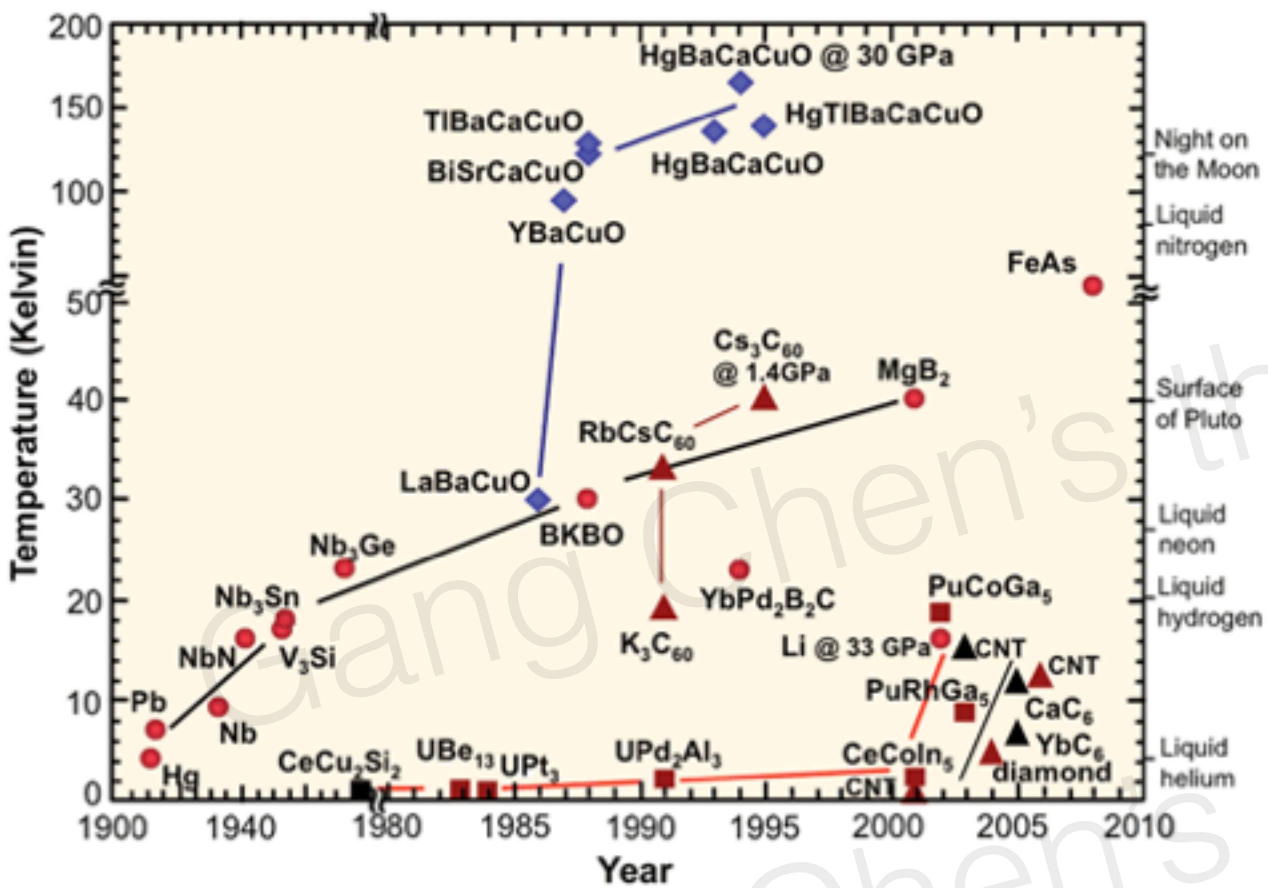
Pauling's RVB wavefunction
for Benzene molecule

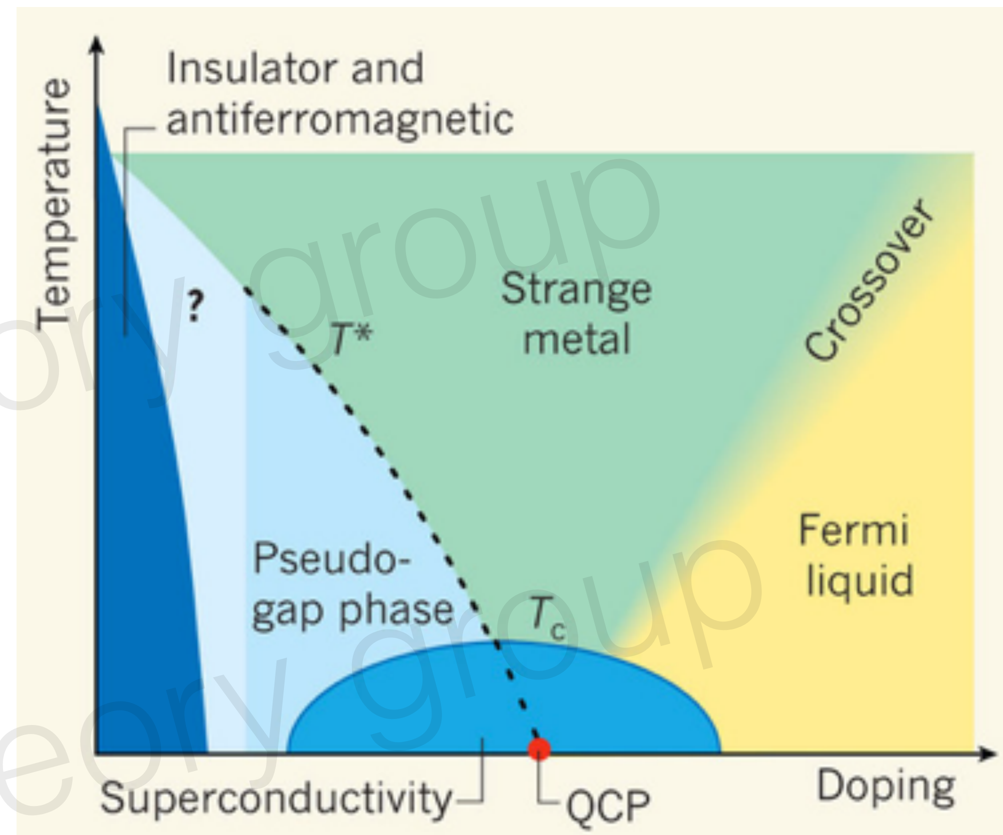




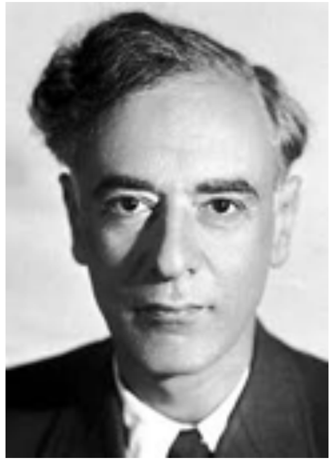
it is very i
motivatio

High temperature superconductivity (1986)



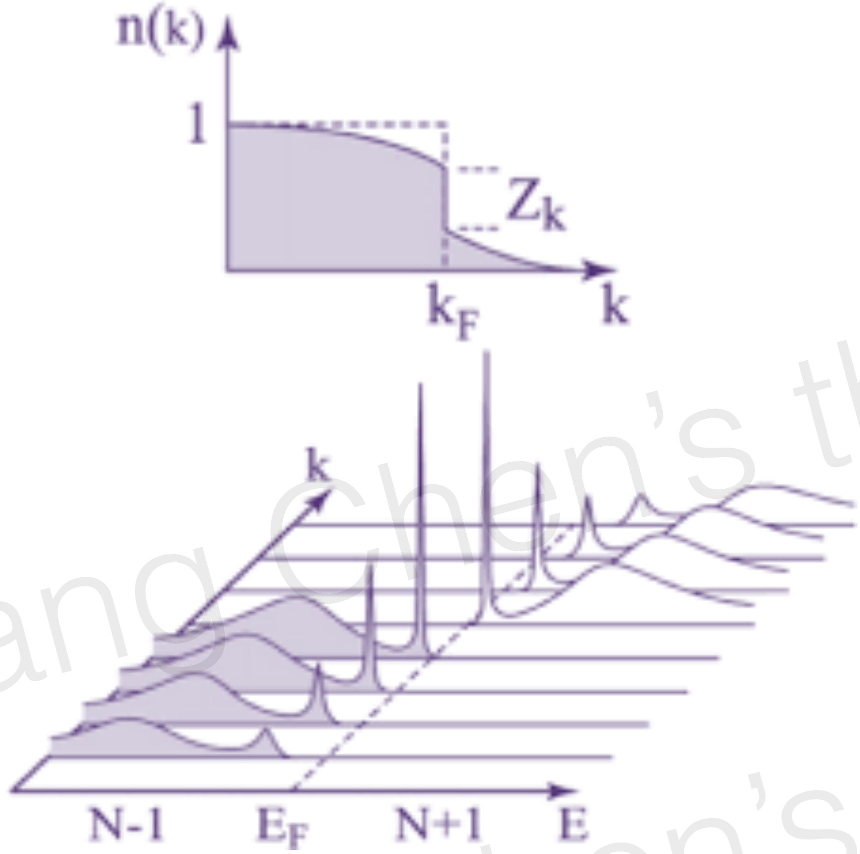


The idea is to view Mott insulator (QSL) as the parent state of high-temperature superconductor. In the QSL, there are preformed Cooper pairs. Doping it allows to Cooper pairs to condense and lead to superconductivity.

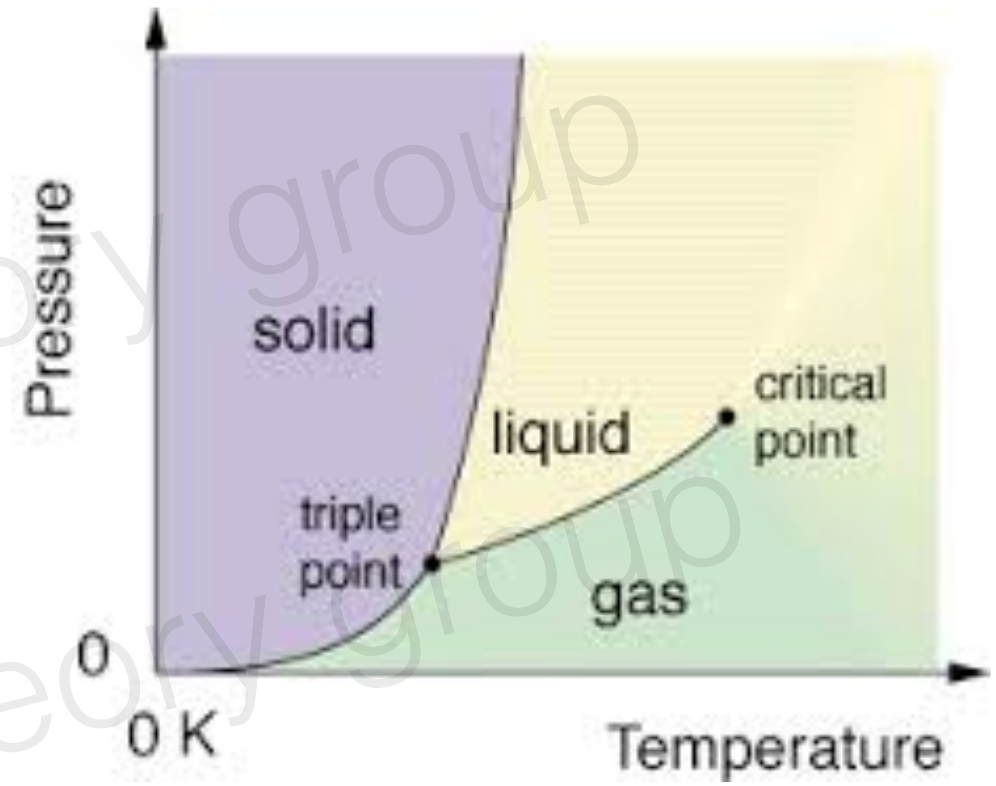


Landau

Two milestones of 20th century condensed matter physics



Landau Fermi liquid theory



Landau symmetry breaking theory

These two paradigms break down after the discovery of fractional quantum Hall effect in 1980s.

Quantum spin liquid

- Quantum spin liquid is a new quantum phase of matter, and cannot be characterized by Landau symmetry breaking, instead by emergent gauge structure and deconfined fractionalized excitations.

- QSL, its existence, is very clear, at least at the level of theory.

  - Exactly solvable model with QSL ground state: e.g. Kitaev model and extension.
  - Classification of QSLs: many distinct symmetry enriched QSLs (XG Wen etc).
  - Numerical solutions: DMRG, QMC, exact diagonalization, etc.

QSL is **robust** against any local perturbation. So it should exist in Nature **!**

QSL: existing experiments

- 2D triangular and Kagome lattice

organics: kappa-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$, EtMe$_3$Sb[Pd(dmit)$_2$]$_2$, κappa–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, etc

- 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

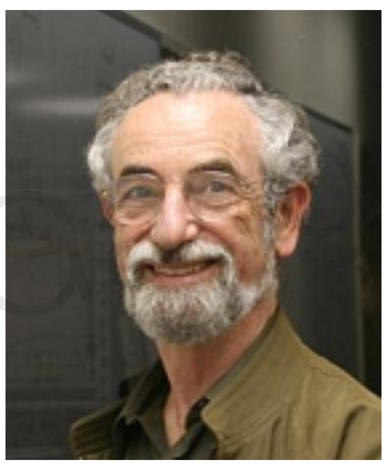
- Ultracold atom and molecules on optical lattices: temperature is too high now.

Some candidate materials have already been ruled out.
Not being a QSL does not necessarily mean the physics is not interesting !

- Spinon Fermi surface U(1) quantum spin liquid

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: **$YbMgGaO_4$**

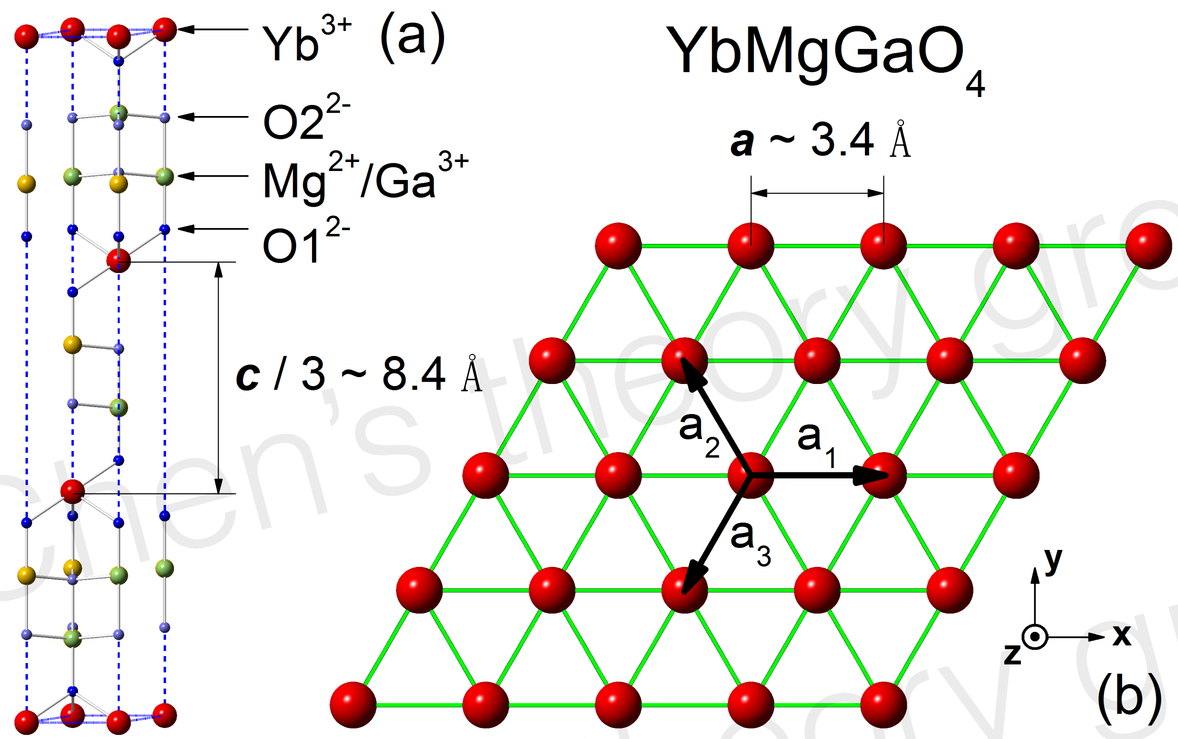
Dr. Yuesheng Li
Renmin Univ -> MPI, Germany

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)

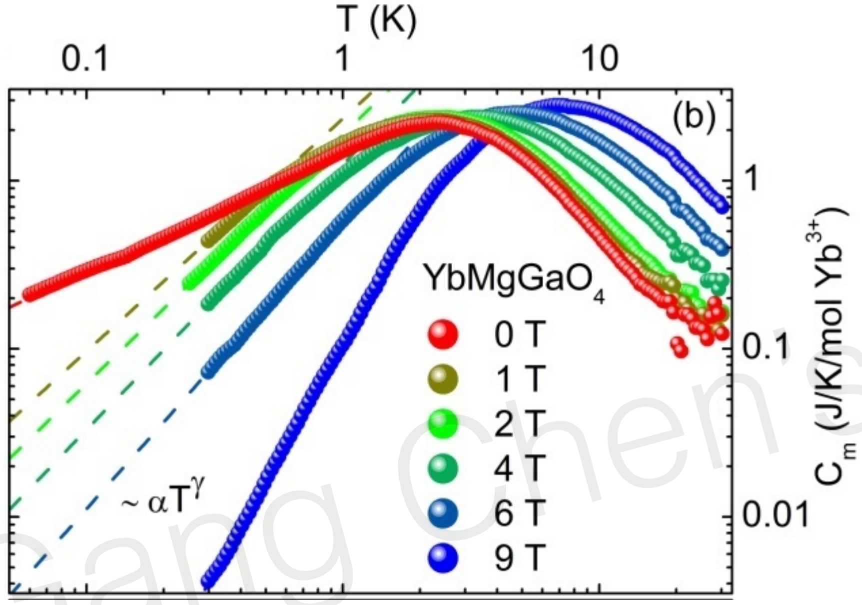
YS Li, **GC***,…., QM Zhang*
PhysRevLett 2015

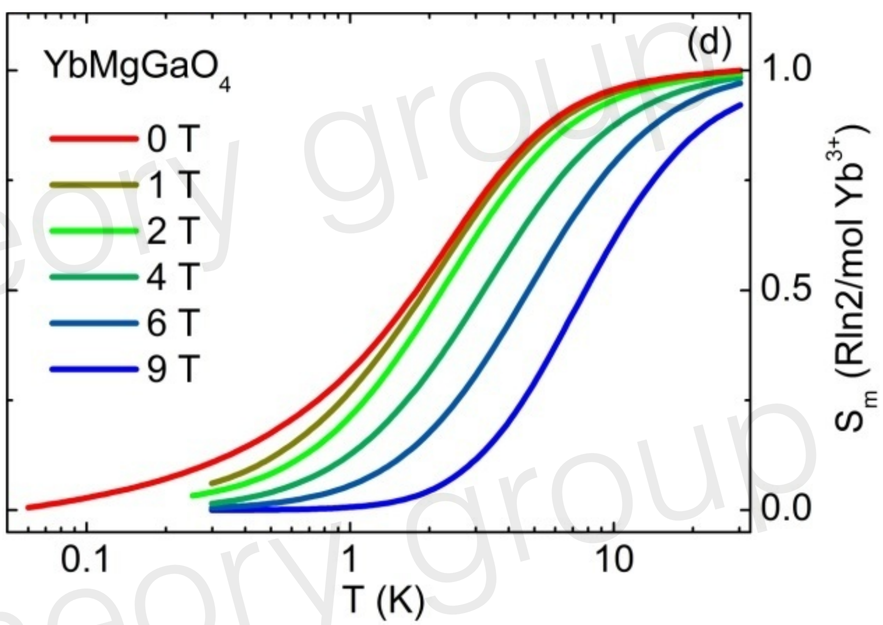
A rare-earth triangular lattice quantum spin liquid: **$YbMgGaO_4$**



- 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$_4$



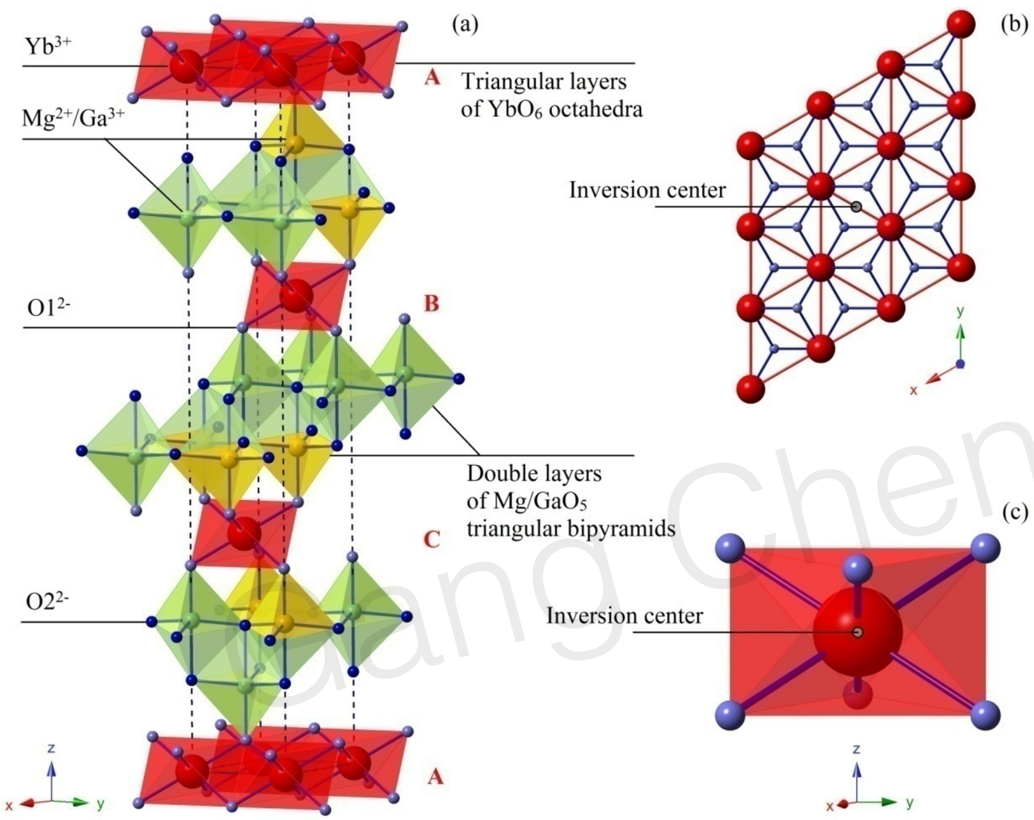


- observation of $T^{2/3}$ heat capacity
- Entropy: effective spin-1/2 local moments

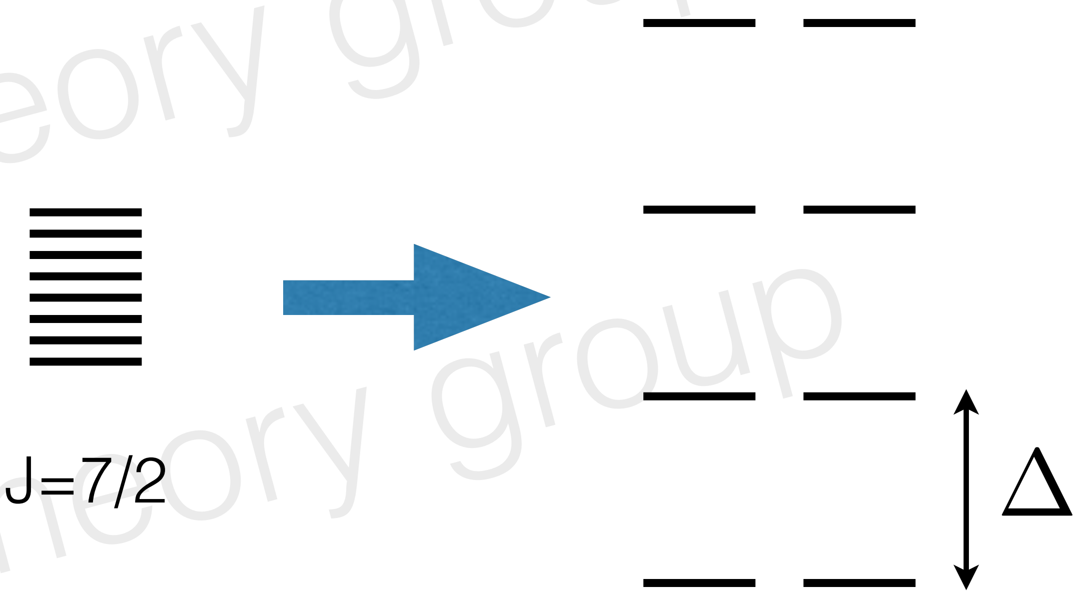
My proposal for ground state: spinon Fermi surface U(1) QSL.

FUDAN UNIVERSITY 1905 復旦大學 FUDAN UNIVERSITY

Microscopics



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



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

復旦大學 FUDAN UNIVERSITY 1905

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-

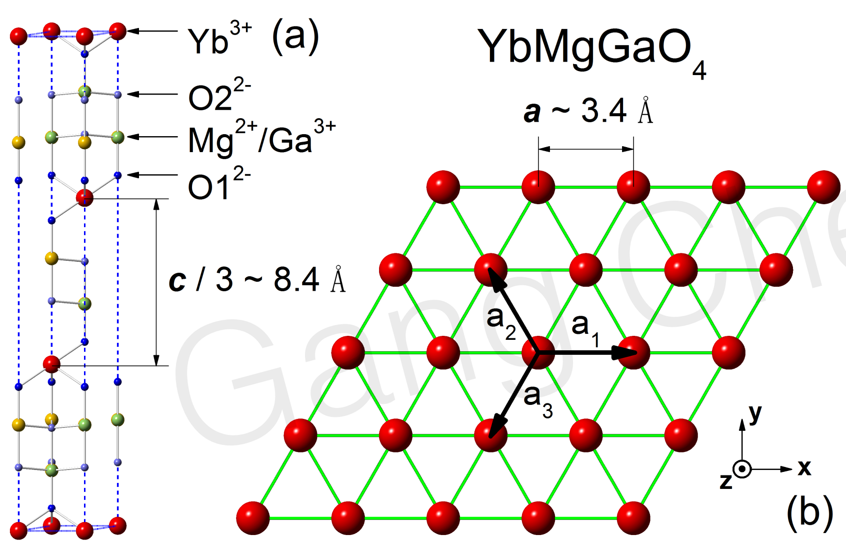
tirely different theoretical approaches are needed. We argue that if a spin-orbit coupled insulator at odd filling is time-reversal symmetric, its ground state must, in a precise sense, be exotic. We introduce two theoreti-

"this kind of system" means effective spin-1/2, spin-orbi
coupling, odd number of electron per cell.

as you may know, there are many theoretical works tryin
constrain the possible states from being exisitg .

What is the physical origin of the QSL?

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



PhysRevLett, 2015

$$\mathcal{H} = \sum_{\langle ij \rangle} \big[J_{zz} S_i^z S_j^z + J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+)$$
$$+ J_{\pm\pm}(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-)$$
$$- \frac{i J_{z\pm}}{2}(\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle)\big], \quad (1)$$

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-

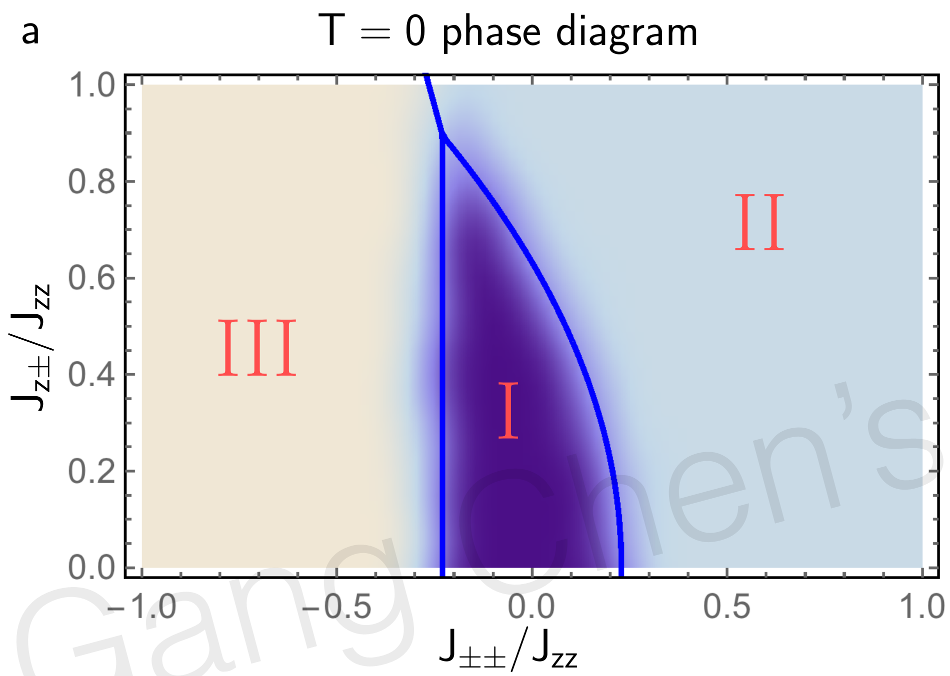
The spin-1/2 XXZ model supports conventional order.

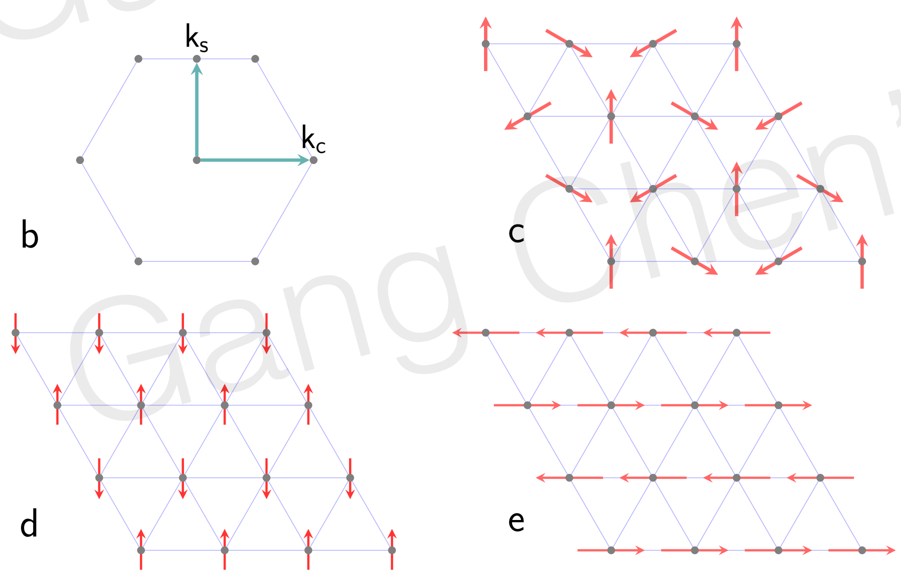
(Yamamoto, etc, PRL 2014)

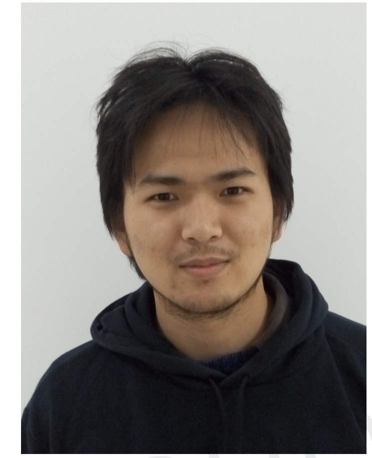
This will makes George happy.

This model

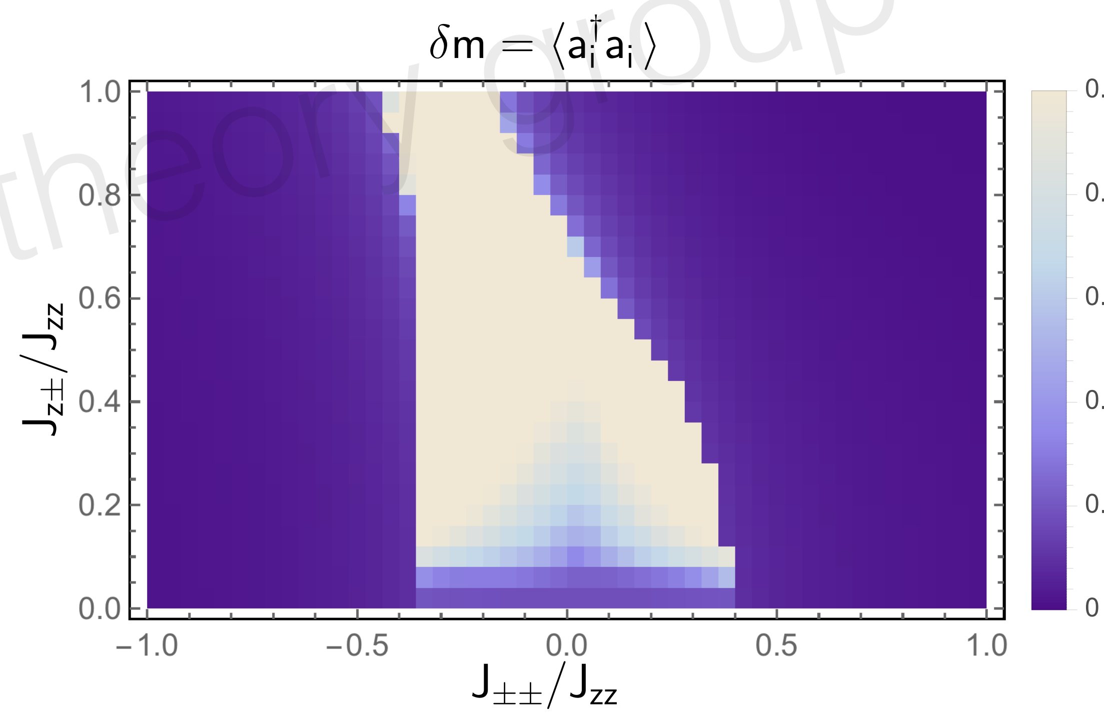
Anisotropic spin interaction could potentially stabilize QSL.





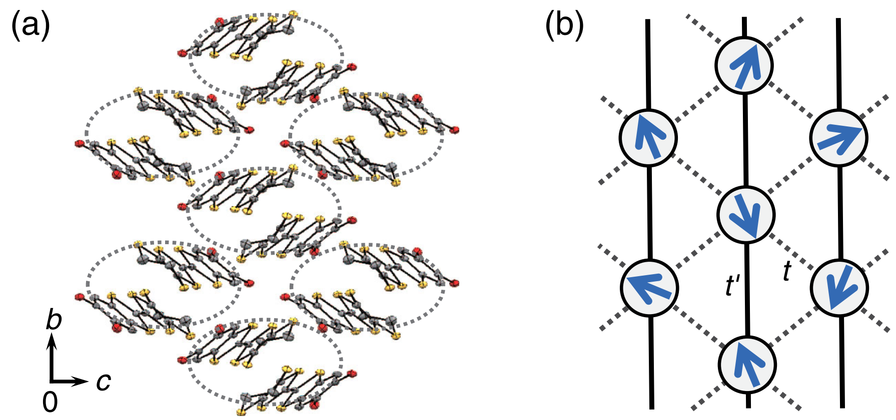


Yao-Dong Li
Dept of Computer Sciences
Fudan University

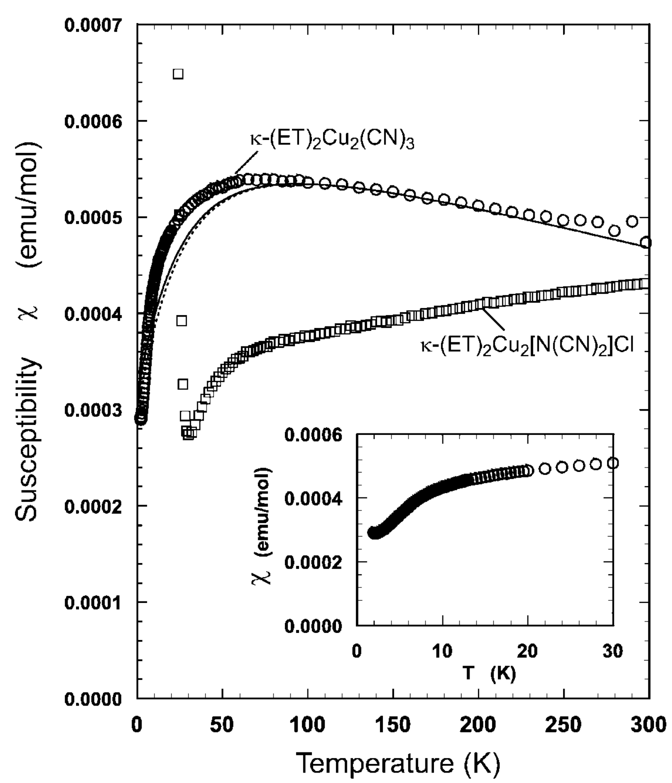


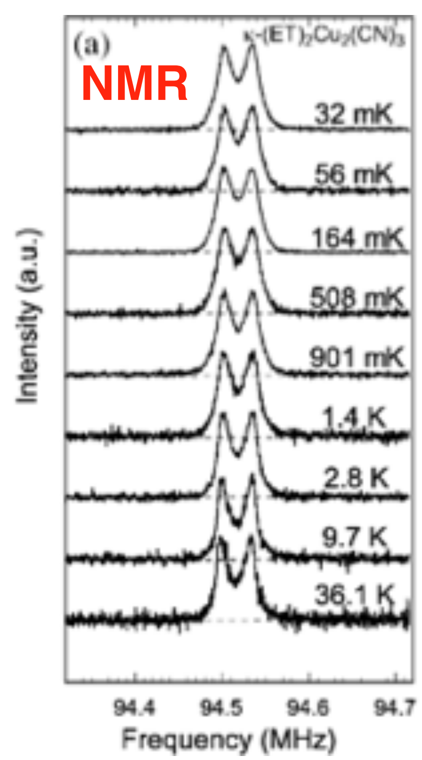
Spinon Fermi surface U(1) QSL in organic magnets?

Kanoda



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!**





* 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.


Sung-Sik Lee

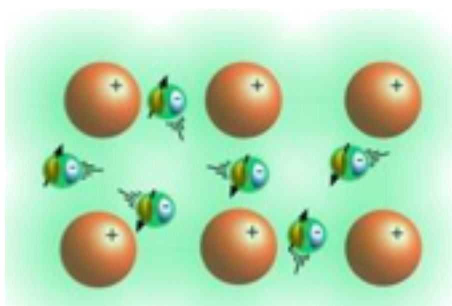

T Senthil


Patrick Lee

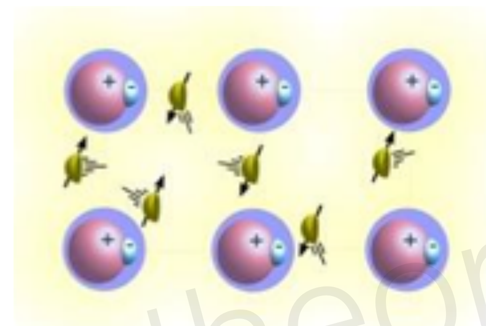
- Theoretical understanding: expected phase diagram

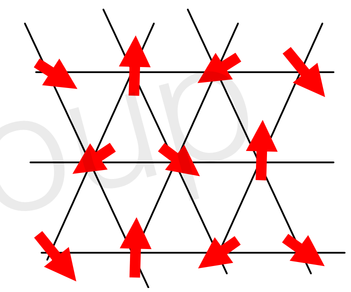
$$H = -t \sum_{\langle ij \rangle, \sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + h.c. + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

Senthil's cartoon



Mott transition





Fermi liquid | **weak** Mott regime | **strong** Mott regime → U/t

metal

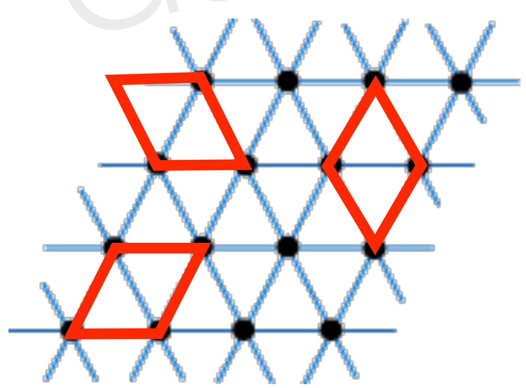
U(1) QSL with spinon Fermi surface

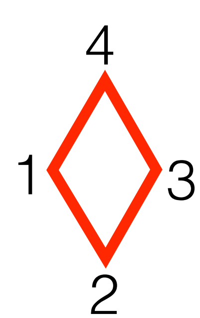
supported by various different numerics

120-degree order

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

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



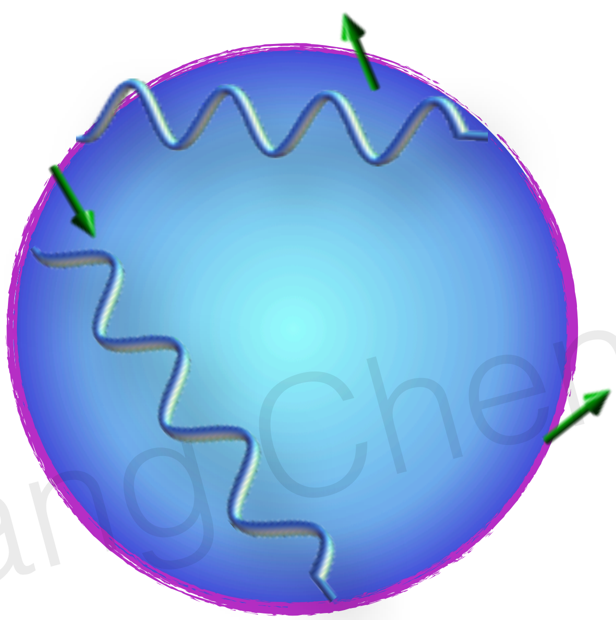


4-site ring exchange

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


Motrunich

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

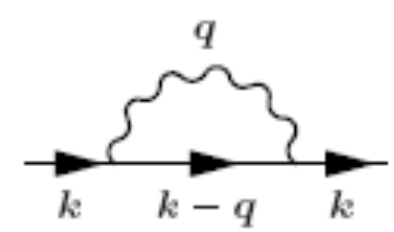


Spinon Fermi surface coupled with dynamical U(1) gauge field: instanton event is suppressed.

dual to extremal/charged black hole?

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

gauge photon is overly Landau-damped.

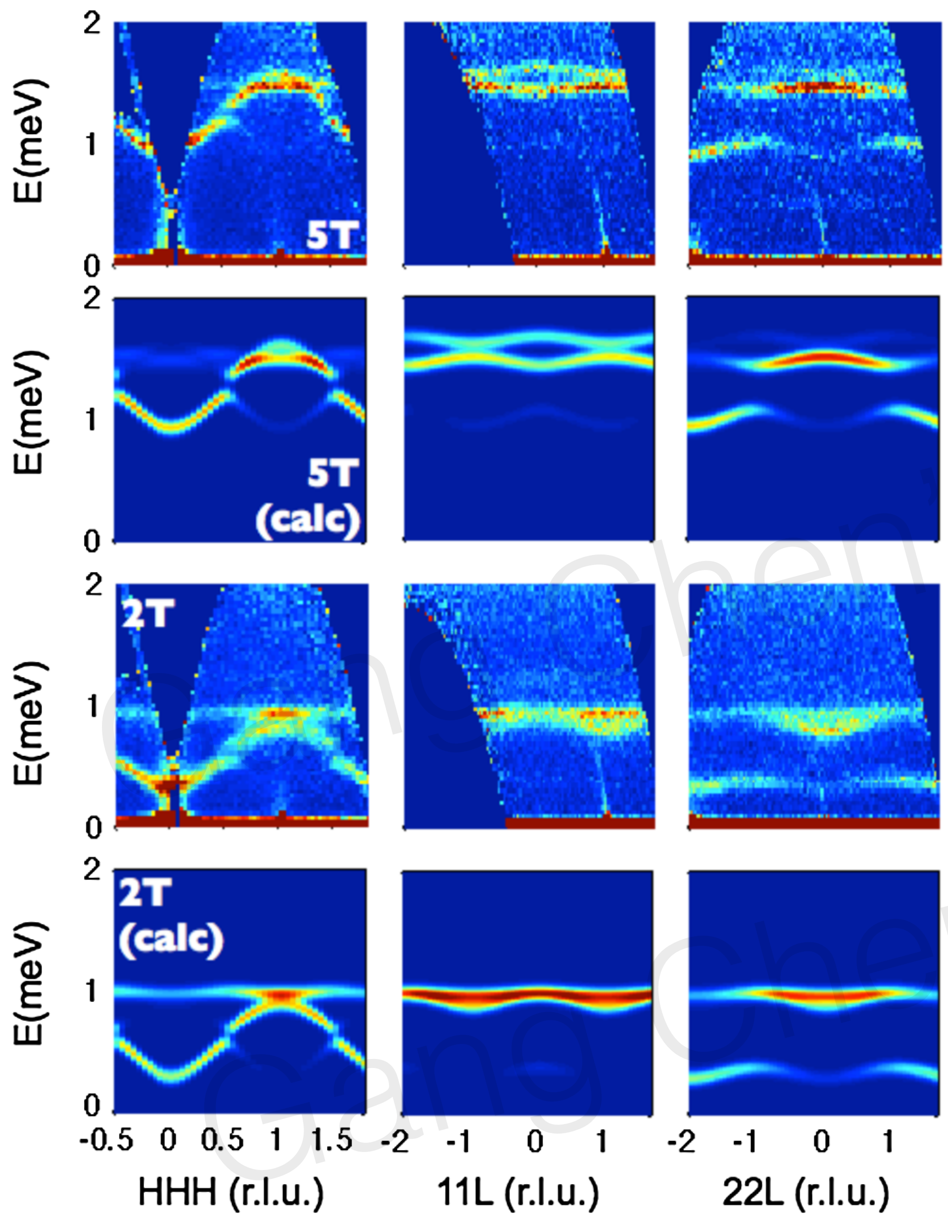


$$Re\Sigma\sim Im\Sigma\sim\omega^{2/3}$$

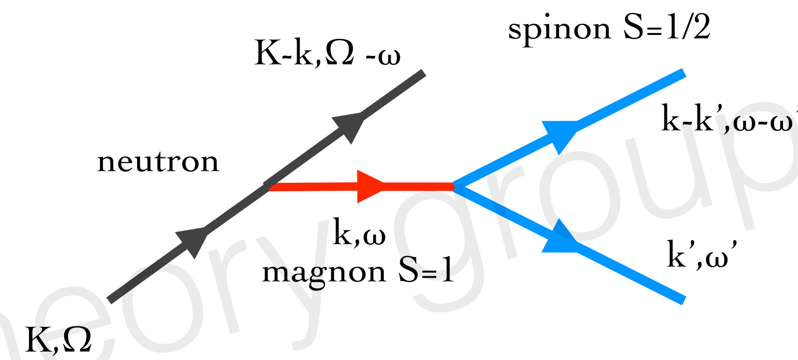
Hermele et al., PRB 70, 214437 (04)

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

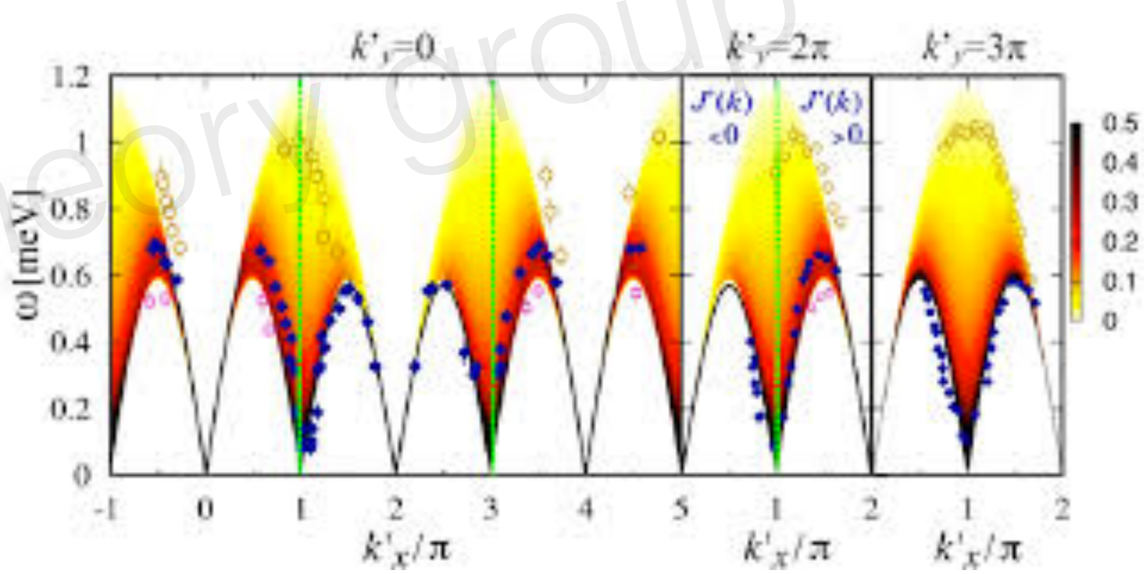
Spin wave vs (fractionalized) spinon continuum



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

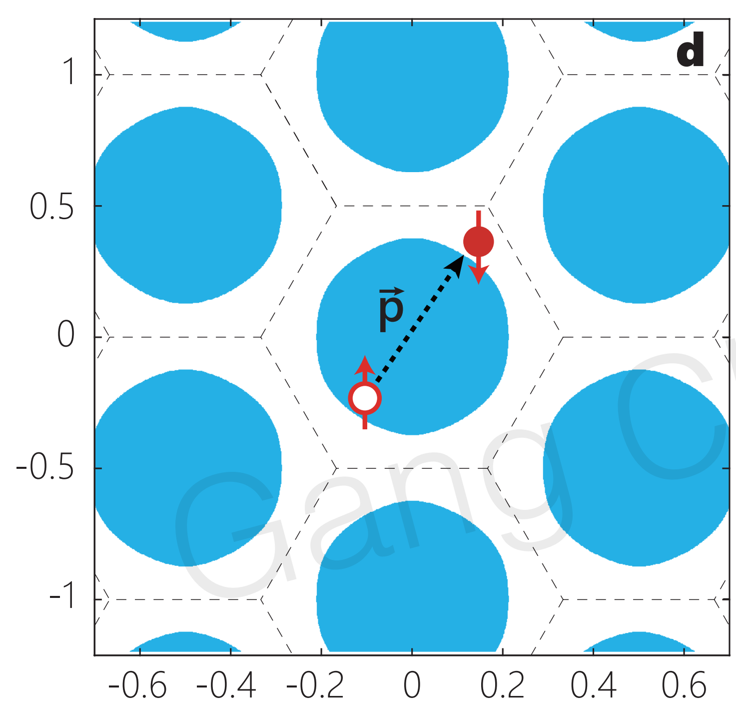


broad peak with
$\omega = \varepsilon(k') + \varepsilon(k-k')$

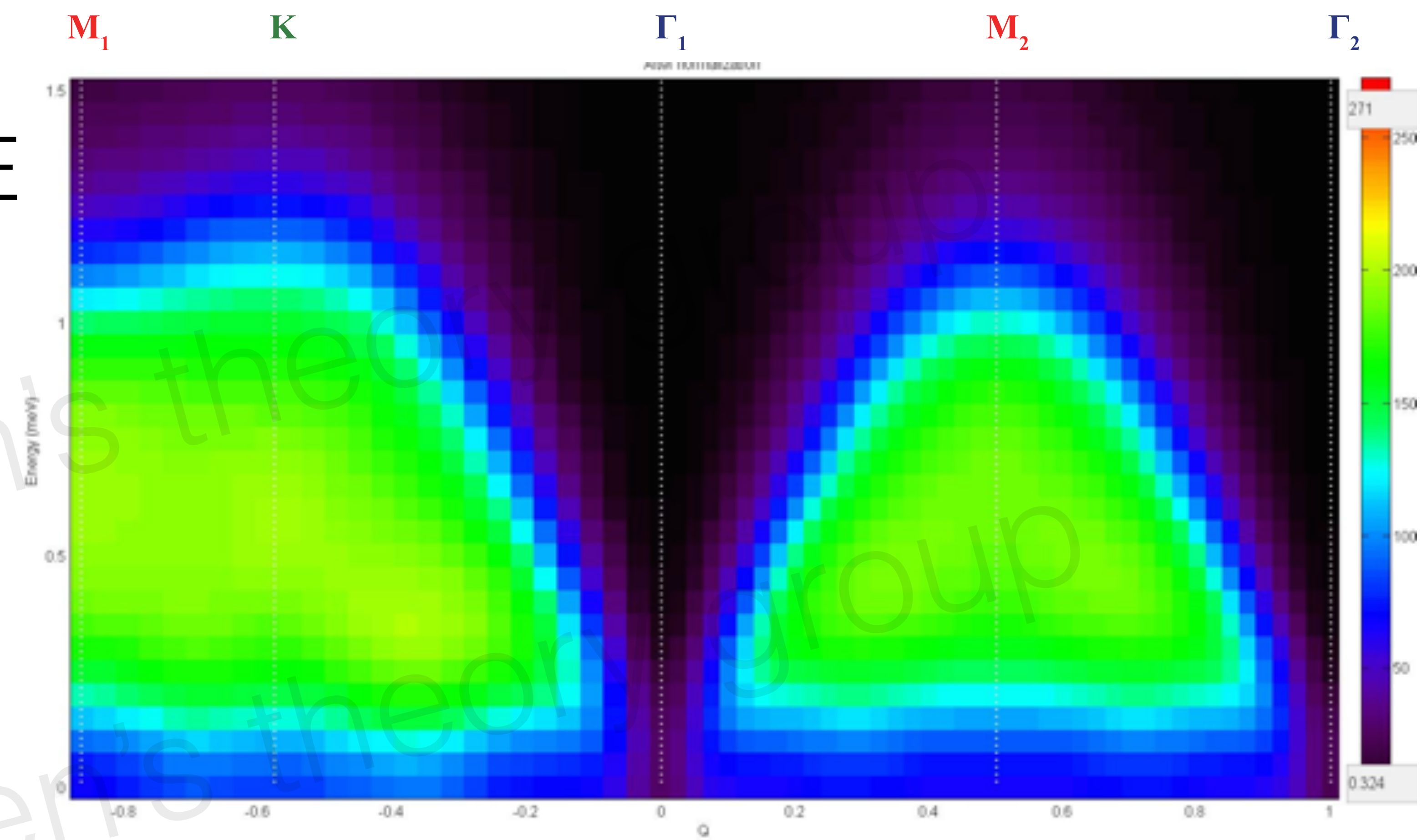


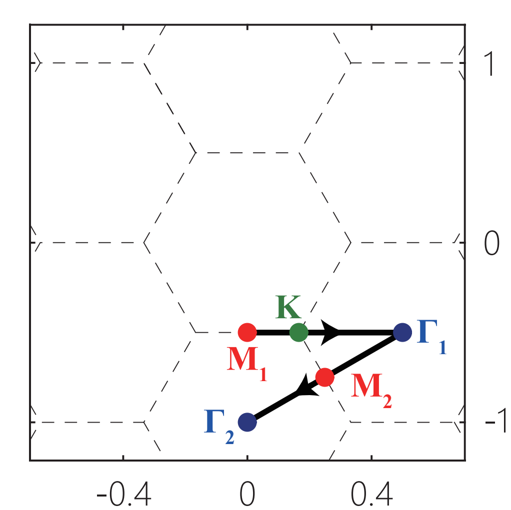
spinon continuum in Cs2CuCl4
Masanori, etc NatPhys 2009
but these are **1d spinons** !

Huge spinon continuum at all energies



E





Summary

1. QSL is a field that bridges the fundamental ideas with the frontier experiments, it provides exciting opportunities for both theorists and experimentalists.

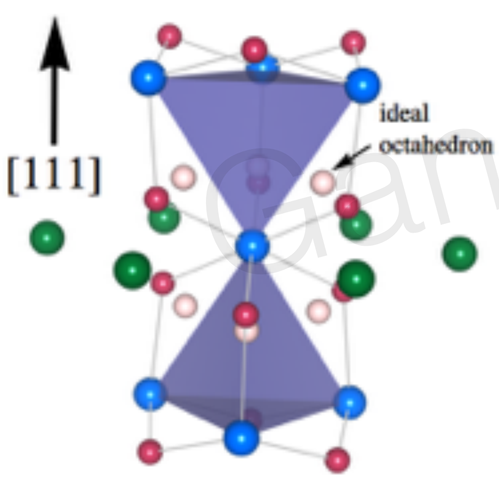
2. Rare-earth triangular lattice quantum spin liquid: **$YbMgGaO_4$**

- To our best knowledge, this is the **first strong spin-orbit coupled** quantum spin liquid candidate with odd number of electrons per unit cell and effective spin-1/2 moment.

Dipole-octupole doublet

- Why is this Kramers doublet so special ?

ONE-dimensional representations of the point gro



$$R(2\pi/3)|J^z = \pm 3/2\rangle = -|J^z = \pm 3/2\rangle$$

$$R(2\pi/3) \equiv e^{-i\frac{2\pi}{3}J^z} = e^{-i\frac{2\pi}{3}\times(\pm\frac{3}{2})} = e^{\mp i\pi} = -1$$

$$|J^z = +3/2\rangle \xrightarrow{\text{time reversal}} |J^z = -3/2\rangle$$

YP Huang, GC*, Hermele, **Phys. Rev. Lett**.112,167203 (2014)

why special,

they are one dimensional rep of po
group.

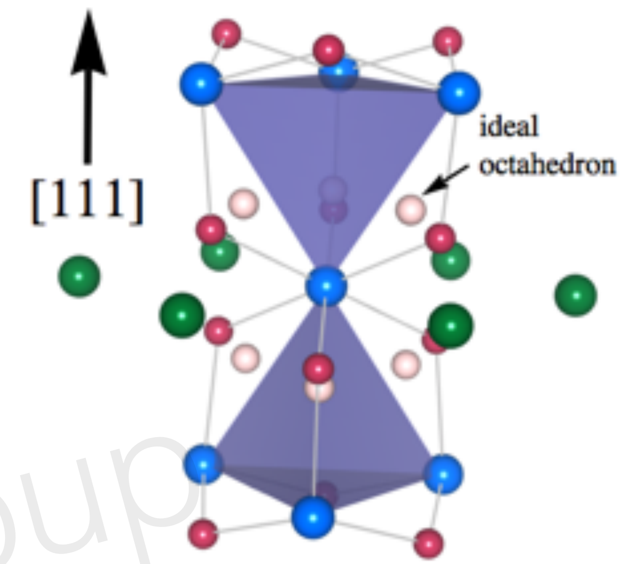
in particular, if you look at the 3-fol
rotation operation, under this rotati
ech state stay invariant, except a m
sign. they do not transform into ea
other under the point group
transfomation.

simple algebar

this is very different from 2-dim irep
where these two states of the doub
are mixed.

These two state are dgenerate und
time reversal, deg proctected by ti
reversal.

More generally, …



- Also applies to 4*f* electron moments on pyrochlore

$$J = \frac{3}{2}, \frac{9}{2}, \frac{15}{2}, \cdots$$

with the local crystal field Hamiltonian

$$H_{\rm cf} \; = \; 3B_2^0 (J^z)^2 + \cdots \quad \text{if } B_2^0 < 0$$

more generially, it applies to xxxx.
if the local crystal field hamiltnian is easy axis like.

e.g. local doublet wavefunction of Dy^{3+} $(J = \frac{15}{2})$ in $Dy_2Ti_2O_7$

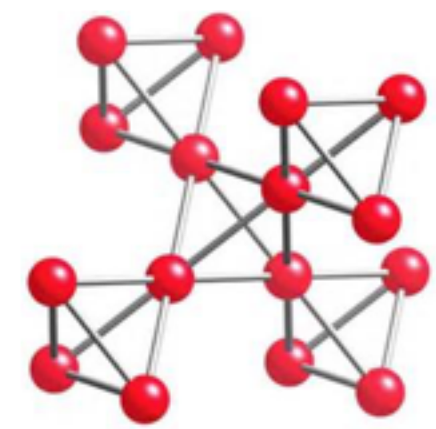
$$|\phi_0^{\pm}\rangle = 0.981|\pm\tfrac{15}{2}\rangle \pm 0.190|\pm\tfrac{9}{2}\rangle - 0.022|\pm\tfrac{3}{2}\rangle \mp 0.037|\mp\tfrac{3}{2}\rangle + 0.005|\mp\tfrac{9}{2}\rangle \pm 0.001|\mp\tfrac{15}{2}\rangle$$

Bertin, etc, J. Phys: cond.mat 2012

Emphasis: what matters is the wavefunction, not the spin value !

- May generally apply to any Kramers' doublets with $J > 1/2$!

e.g, Ce: **$Ce_2Sn_2O_7$**



PRL **115,** 097202 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

Candidate Quantum Spin Liquid in the Ce^{3+} Pyrochlore Stannate $Ce_2Sn_2O_7$

Romain Sibille,[1,*] Elsa Lhotel,[2] Vladimir Pomjakushin,[3] Chris Baines,[4] Tom Fennell,[3,†] and Michel Kenzelmann[1]

$4f^1$ ion in D_{3d} local symmetry to the susceptibility was realized between $T = 1.8$ and 370 K, and the resulting calculation of the single ion magnetic moment is shown in Fig. 2(c). The wave functions of the ground state Kramers doublet correspond to a linear combination of $m_J = \pm 3/2$ states. The fitted coefficients result in energy levels at 50 ±

Ce^{3+} $(4f^1, {}^2F$

$$J = \frac{5}{2}$$

the wavefucntion shou
of states with odd inte
3/2.

this really because of t
they are one-dimensio
even in the YbTiO, suc
the excited doublets.

experimentalists of this paper do not know what they really talk about.

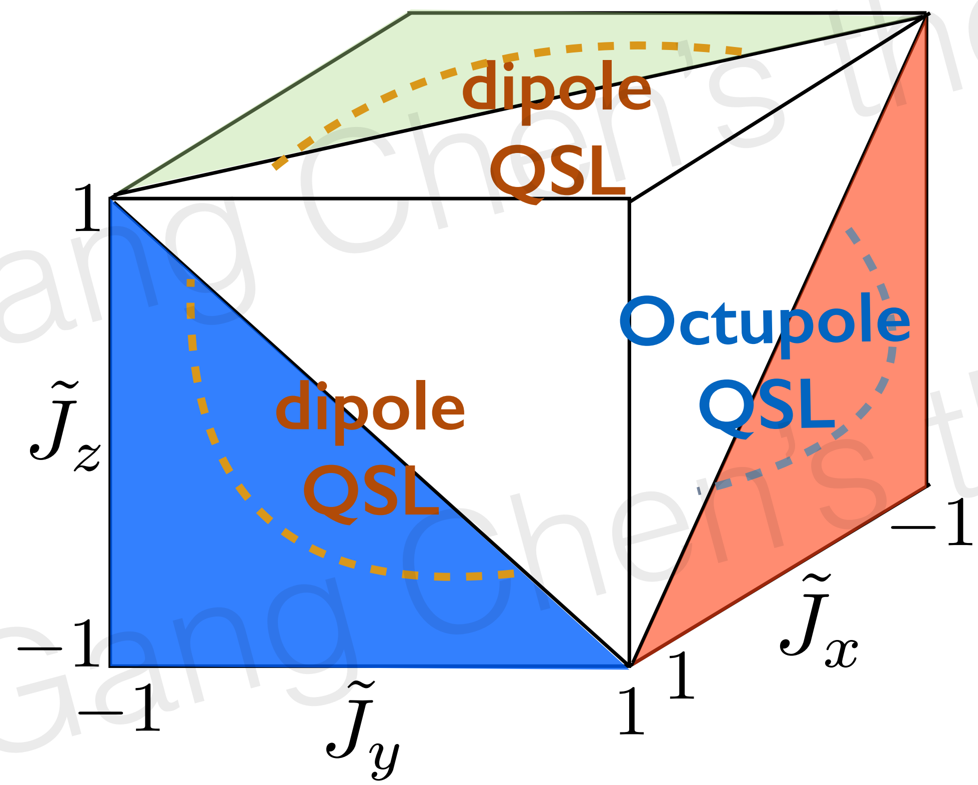
But this sentence means a lot to us. It means that gs doublet is a DO doublet, and the model is described by XX

FUDAN UNIVERSITY 1905 復旦大學 FUDAN UNIVERSITY

XYZ model is the generic model that describes the interaction between DO doublets.

unlike XXZ model, XYZ model is r
richer

$$H_{\mathrm{XYZ}} = \sum_{\langle ij \rangle} \mathcal{J}_x \tau_i^z \tau_j^z + \mathcal{J}_y \tau_i^y \tau_j^y + \mathcal{J}_z \tau_i^z \tau_j^z$$

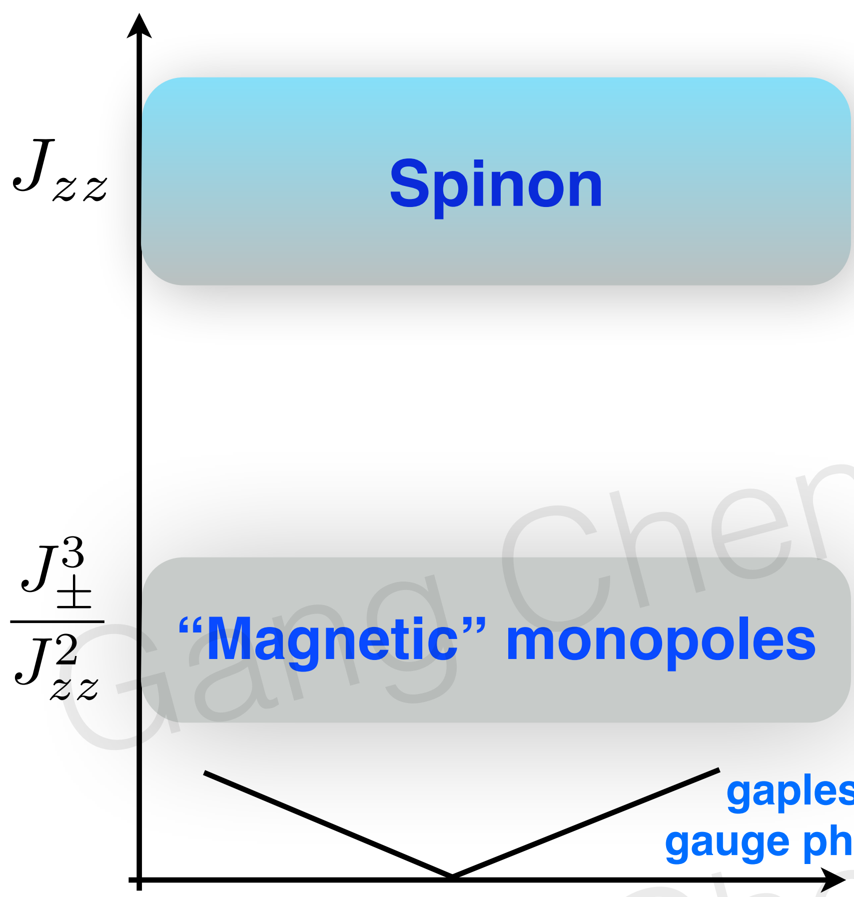


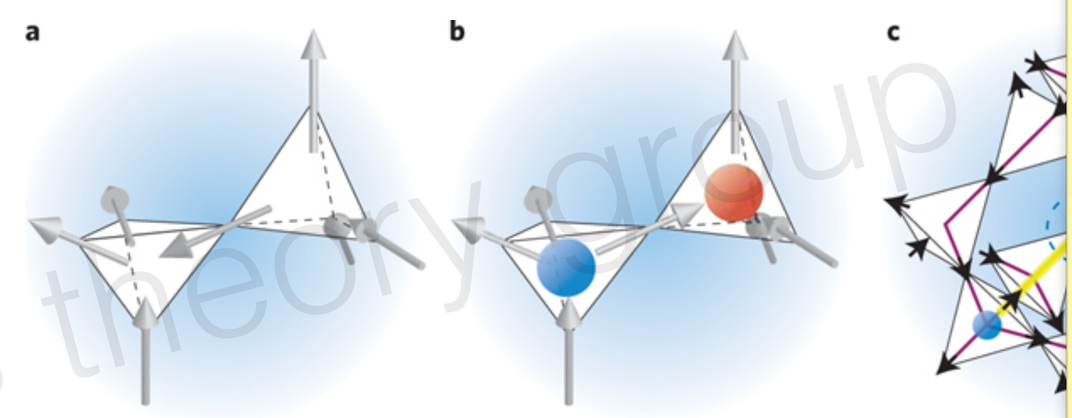
3D phase diagram

Each component (not just Sz) can be emergent electric field, depending on the parameters !

Study phase on a cube: $-1 \leq \tilde{J}_{x,y,z} \leq 1$.

Emergent Quantum Electrodynamics of U(1) Q





Figs from Mo

Spinon deconfinement

Emergent electric field $S^z \sim E$

Emergent vector potential $S^{\pm} \sim e^{\pm iA}$

$$H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z - J_{\pm} \sum_{\langle i,j \rangle} \left(S_i^+ S_j^- + S_i^- S_j^+ \right) + \cdots\cdots$$

as quantum spin ice is a dis
there is no long range order,
a new phase of matter and c
in the landau's paradigm of

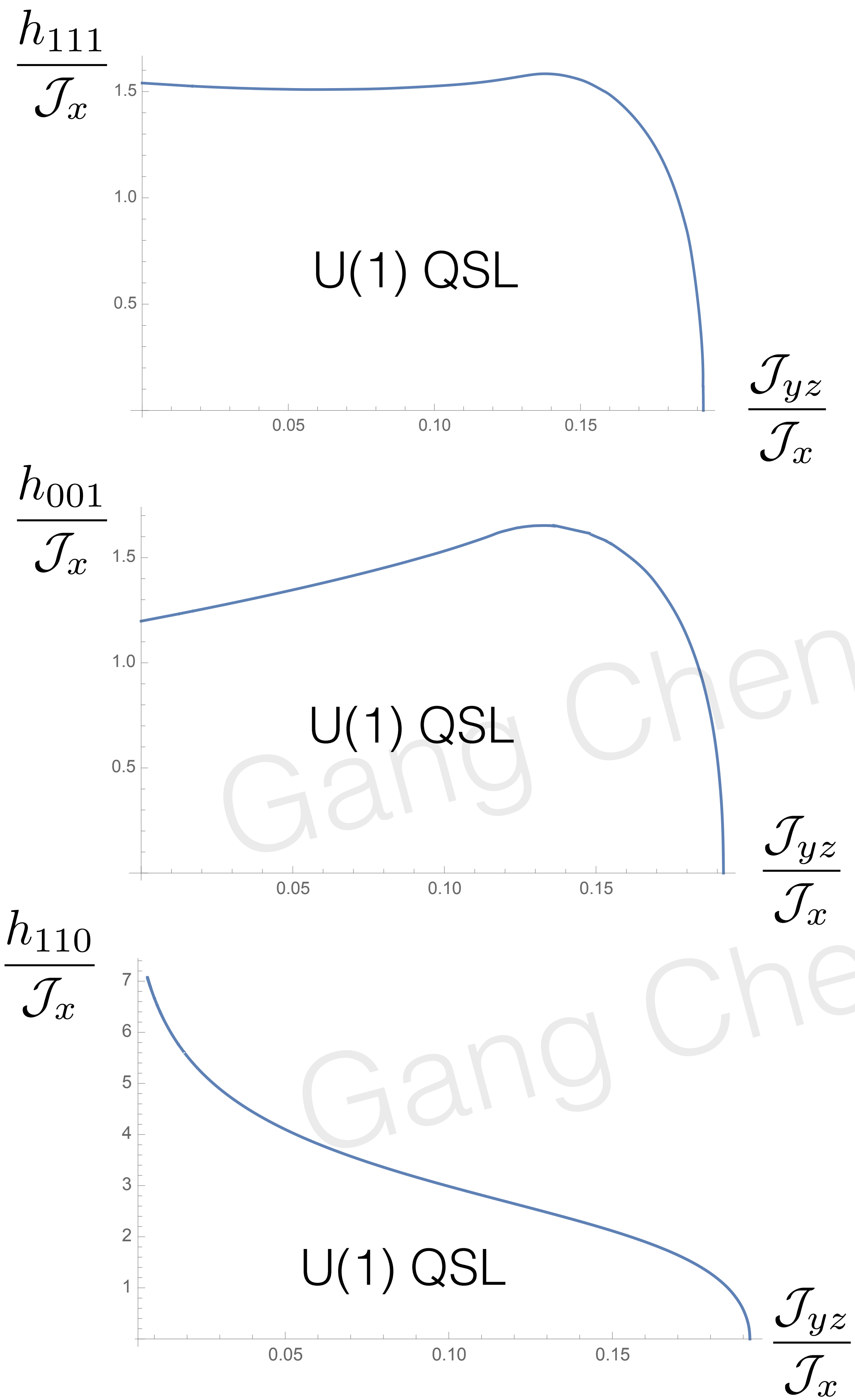
the right description of quan
fractionalization and emerge

there are 3 elementary excit
gauge photon,
it is not goldstone boson, w
breaking, there is no sym br
of emergent gauge structure

there are deconfined spinon
create 2 spinons,
you can flip the further spins
arbitrary distance, it is only o
image there is a string conn
spin is strongly fluting, the s
spinon are decofnined.

the 3rd is magnetic monopo
defect of the emergent U(1)

It is exotic phase of matter, l
propertes as too order.



Field-driven Higgs transition

How to tell if Ce2Sn2O7 is an octupolar U(1) QSL or not ?

The idea to use a little knob that could simply lead to some clear experimental consequence, very much like the isotope effect of BCS supercond.

Here we apply external magnetic field, and expect a field-driven Higgs transition to magnetic ordering as the field only couples to the matter field (spinons).

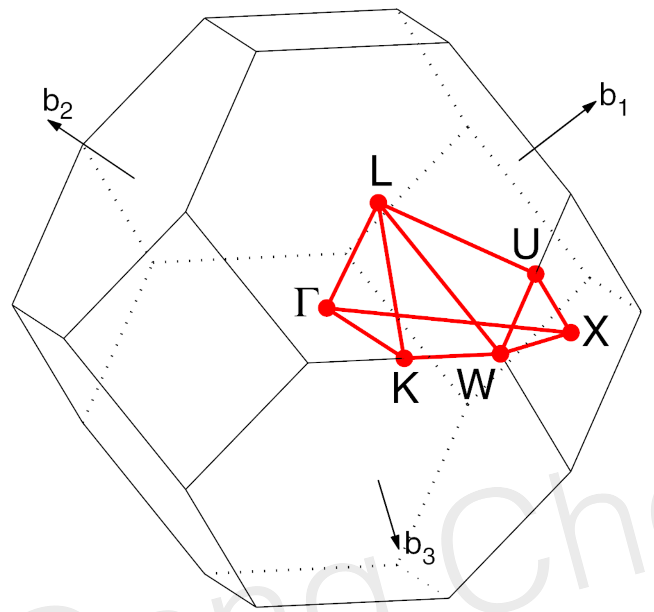
$$H = \sum_{\langle ij \rangle} \mathcal{J}_x \tau_i^x \tau_j^x - \mathcal{J}_{yz}(\tau_i^y \tau_j^y + \tau$$

$$-h \sum_i \tau_i^z (\hat{n}$$

without losing generality

Higgs trnasiton is very much like meisner effect in superconductor

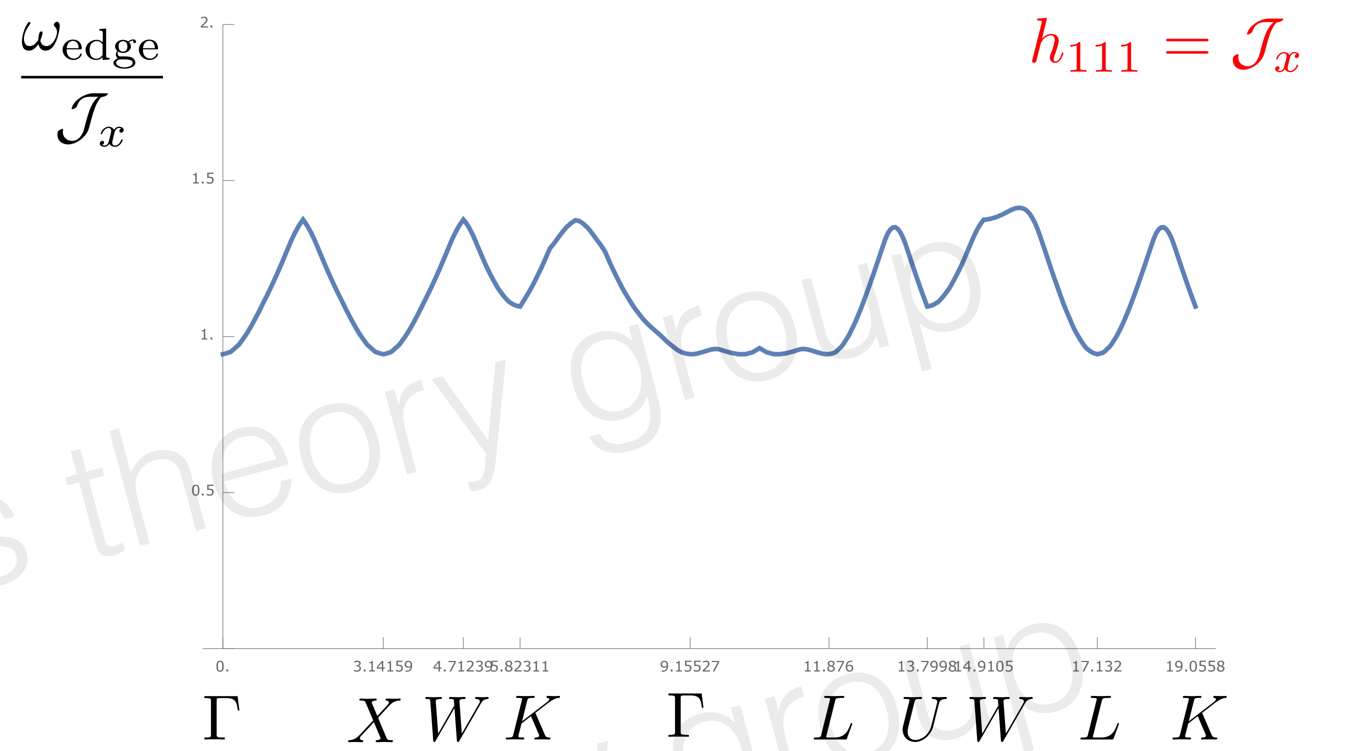
Lower excitation edge

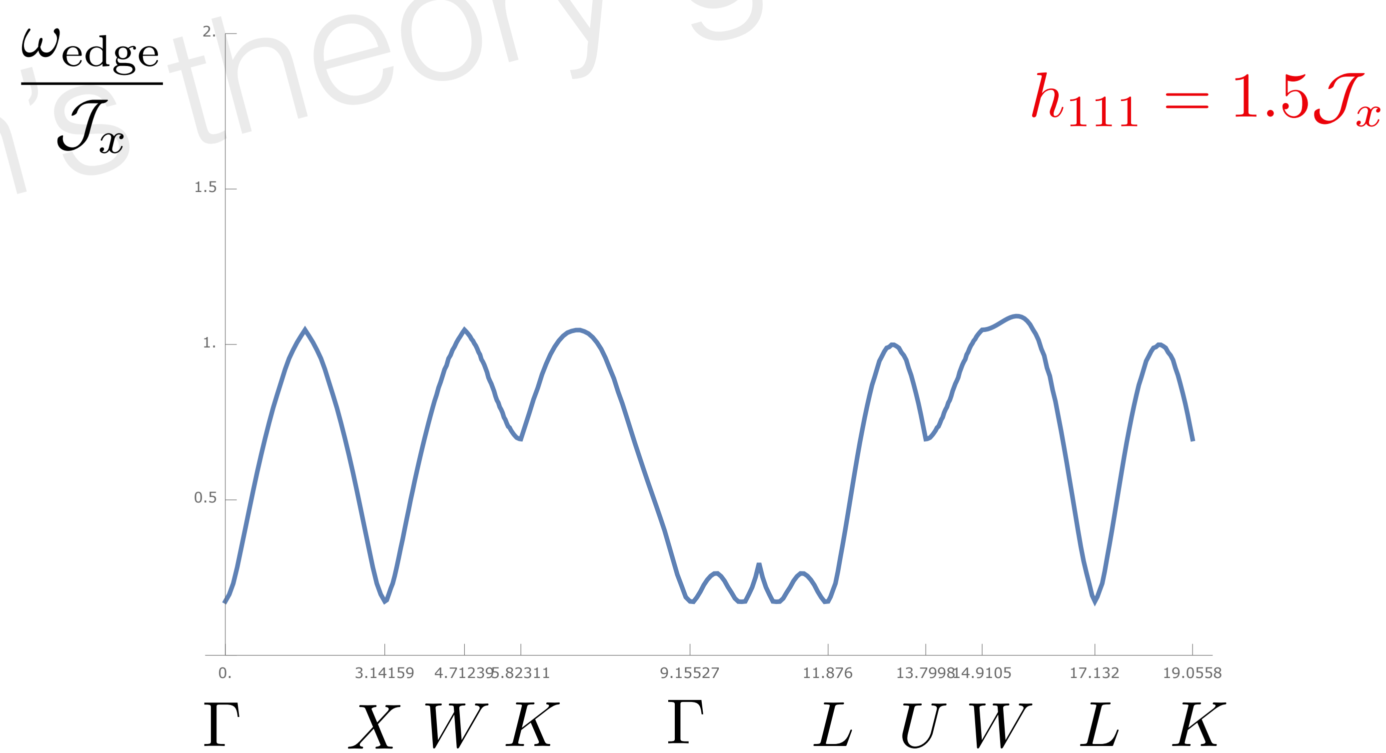


FCC path: Γ-X-W-K-Γ-L-U-W-L-K|U-X

[Setyawan & Curtarolo, DOI: 10.1016/j.commatsci.2010.05.010]

Brioullin zone of FCC lattice





Neutron scattering and thermal transport

Dipolar-U(1) QSL

neutron spin couples to both gauge field and matter field, observe both gapless gauge photon and gapped spinon continnum

Octupolar-U(1) QSL

neutron spin only couples to the matter field (spinons), observes only the gapped spinon continuum. External magnetic field can manipulate the spinon continuum, which can be confirmed by neutron scattering.

Thermal transport

see both contribution, but there is a big separation of energy scales in spinon and gapless photons.

It can be beneficial to observe the low temperature peak in the thermal transport.