The theory of cluster Mott insulators:
charge fluctuations and quantum spin liquids

GANG CHEN
(Univ of Toronto)

ArXiv 1402.5425 (**PRL 2014**),
1408.1963 (**unpublished**).

Collaborators: Hae-Young Kee, Yong-Baek Kim

Outline

- Motivation and introduction
- Cluster Mott insulator in 2D: theory and experiments
- Cluster Mott insulator in 3D: theory and experiments
- Summary

Sung-Sik Lee

T Senthil

Mott insulator and Mott transition
"Conventional"

O Motrunich

P Lee

Triangular lattice Hubbard model at half filling

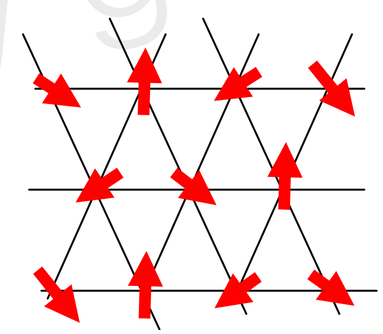
$$H = -t \sum_{\langle ij \rangle, \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + h.c. + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

weak Mott regime | **strong** Mott regime

Fermi liquid metal | U(1) quantum spin liquid with spinon Fermi surface | 120-degree magnetic order → U/t

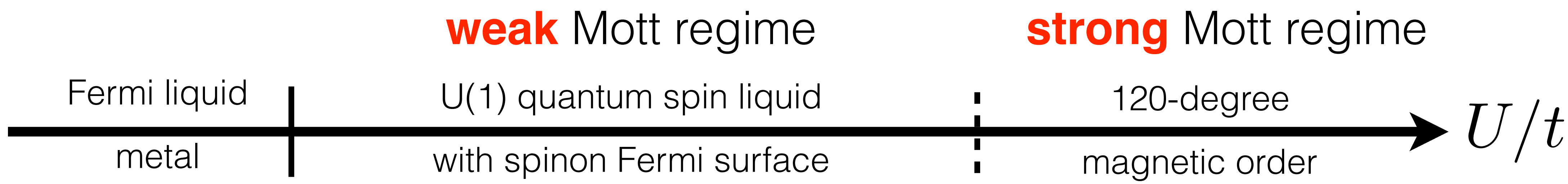
Mott transition

such a disordered regime is supported by various and different numerical studies



Low EFT of QSL: spinon Fermi surface coupled with a fluctuating U(1) gauge field. It is a strong coupled theory, no controlled method!

Many properties of spinon metal are "similar" to electron metal but with **subtle and important** differences !



Remark (on the mechanism NOT the properties of QSL):

1. There is no sharp distinction between the charge fluctuations in the weak and strong Mott regimes.
2. Strong charge fluctuation in the weak Mott regime is a quantitative description.

Question / observation:

1. What if the change fluctuation is very strong, and in the most extreme case, the charge sector forms a **quantum charge liquid**? Spin sector is even more likely to be in a QSL.
2. What if the charge fluctuation leads to **some structure in the charge** sector? Spin sector is surely to be influenced in a non-trivial way. This would lead to a **striking experimental** consequence. If it is observed, it gives us confidence on the theoretical framework that we are developing.

Cluster Mott Insulator: a new class of Mott insulators

Electrons (or bosonic particles) are localized on some cluster units instead of the lattice sites. These cluster units build the lattice.

My Goal Of This Talk

1. Introduce the notion of cluster Mott insulator (they are interesting and they exist in nature, actually quite a lot, not studied)
2. Develop a **new theoretical framework** to understand the **novel charge fluctuation** and spin fluctuation
3. Apply to illustrative examples and explain the puzzling experiments.

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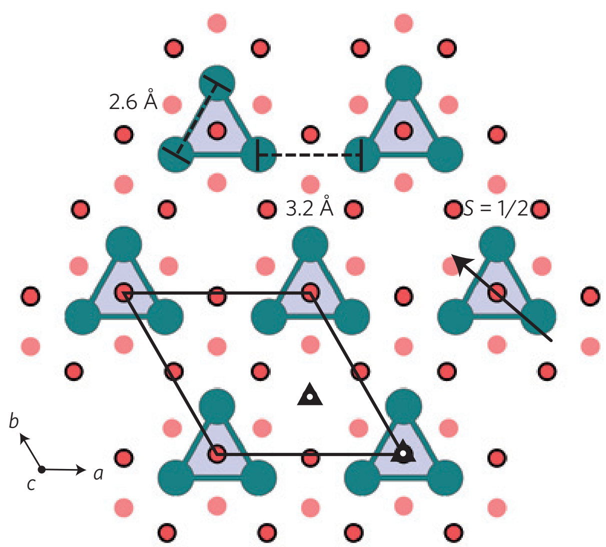
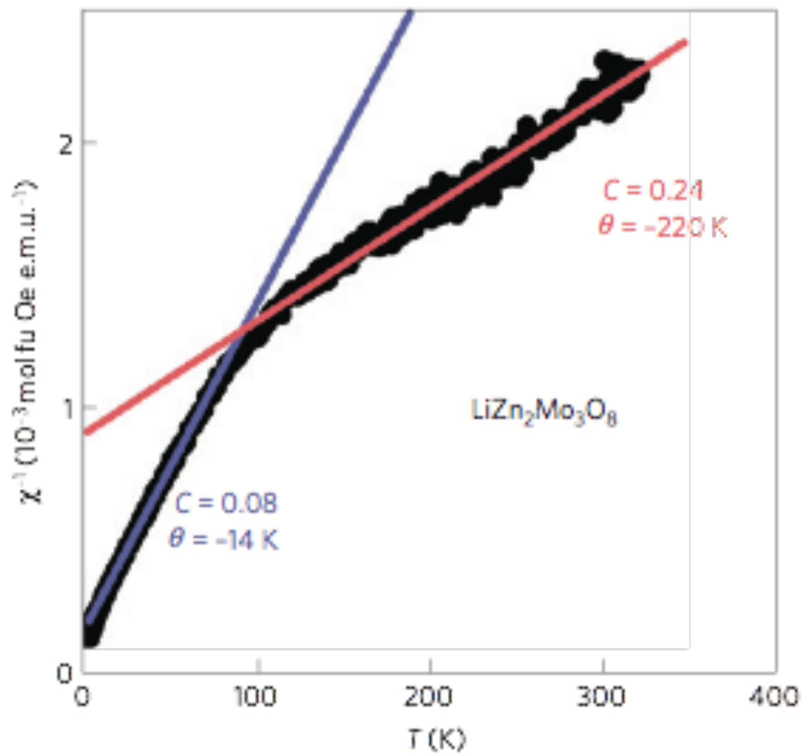
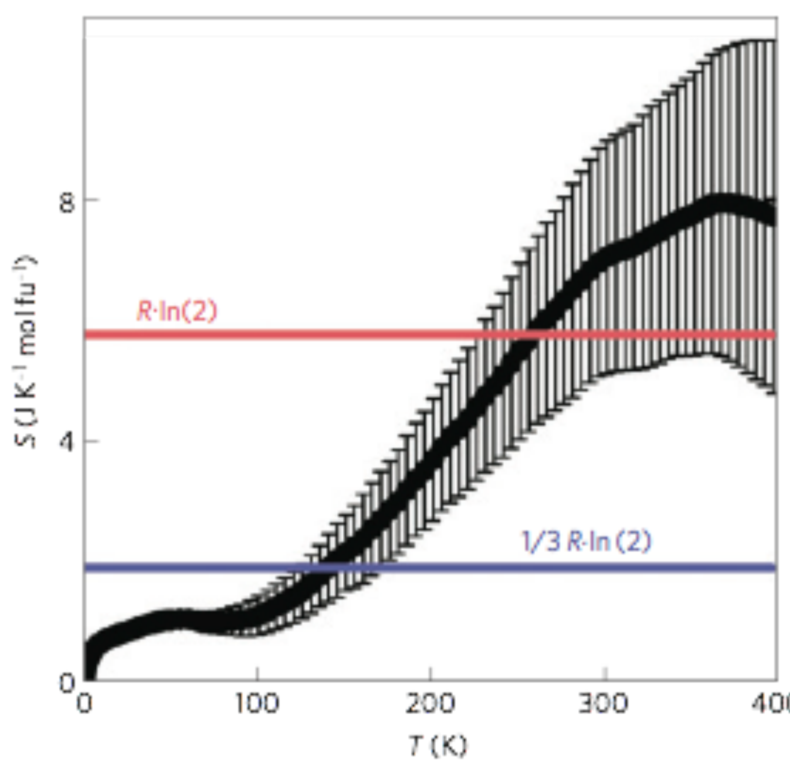
One striking experiment on $LiZn_2Mo_3O_8$

T. McQueen @ JHU



Nature Materials 2012





Why striking and difficult?

1. Triangular lattice Heisenberg model
2. Triangular lattice Hubbard model at 1/2 filling

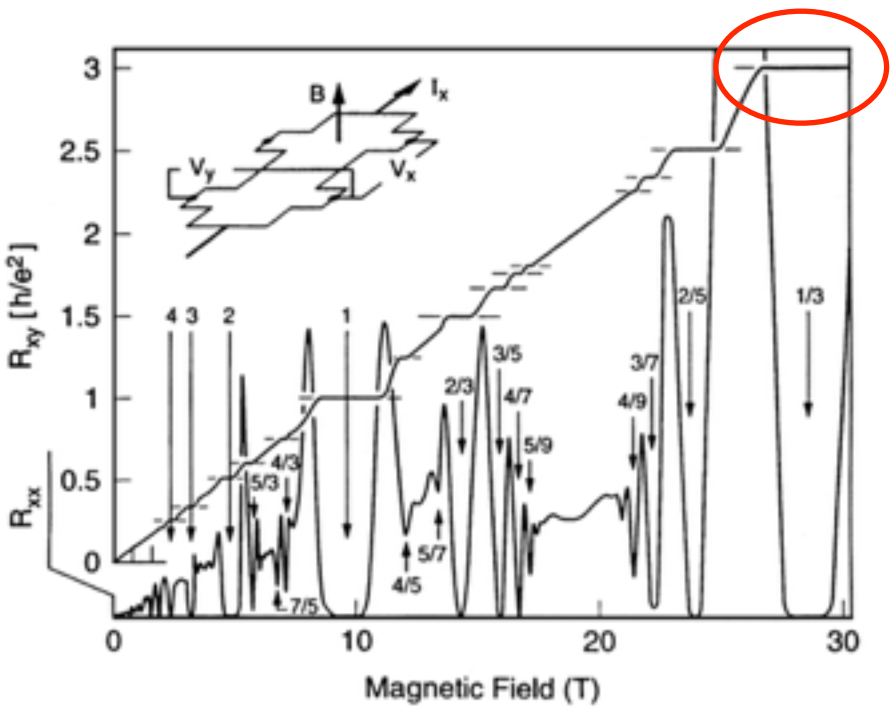
Neither model works.

Laughlin

FQHE (Tsui, Stormer, and Gossard)

First exotic phenomenon known to us

Wen

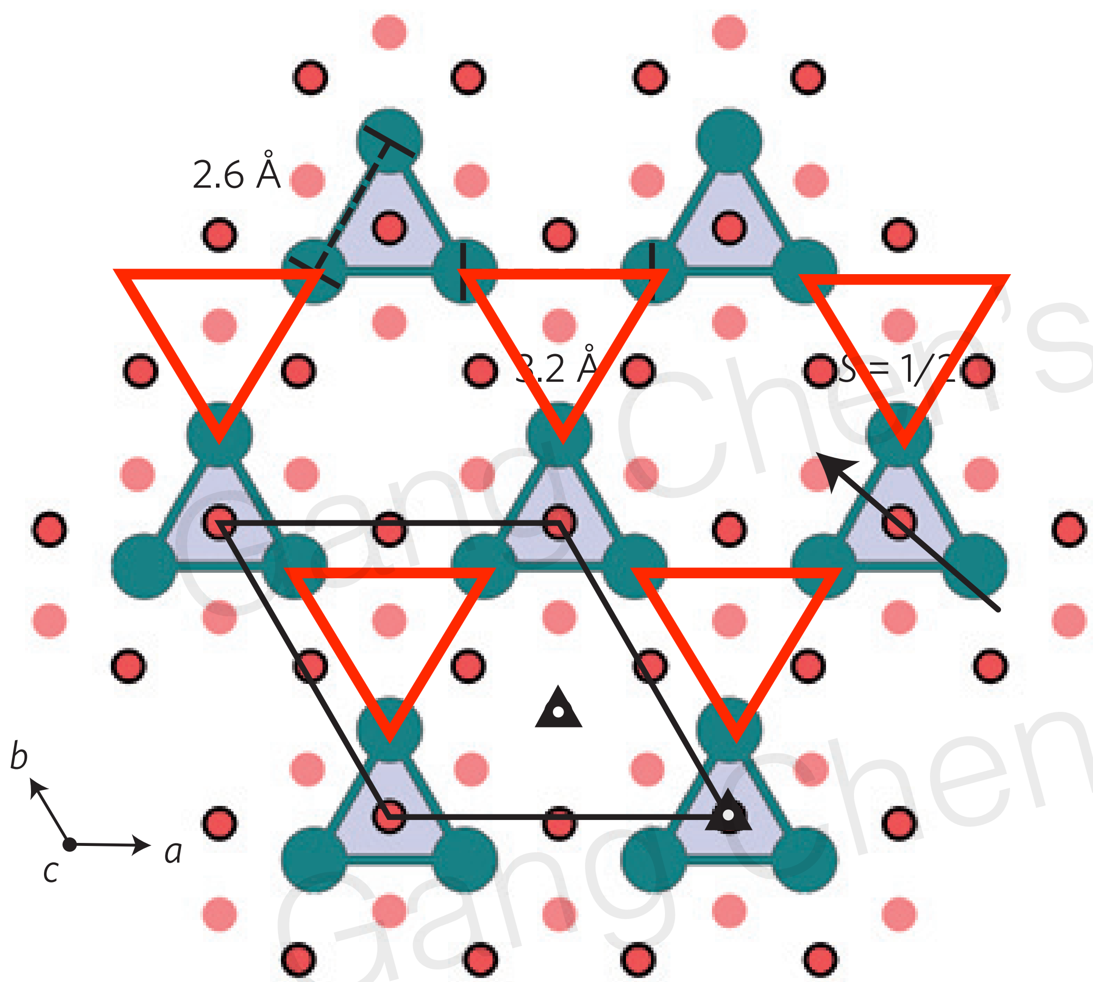


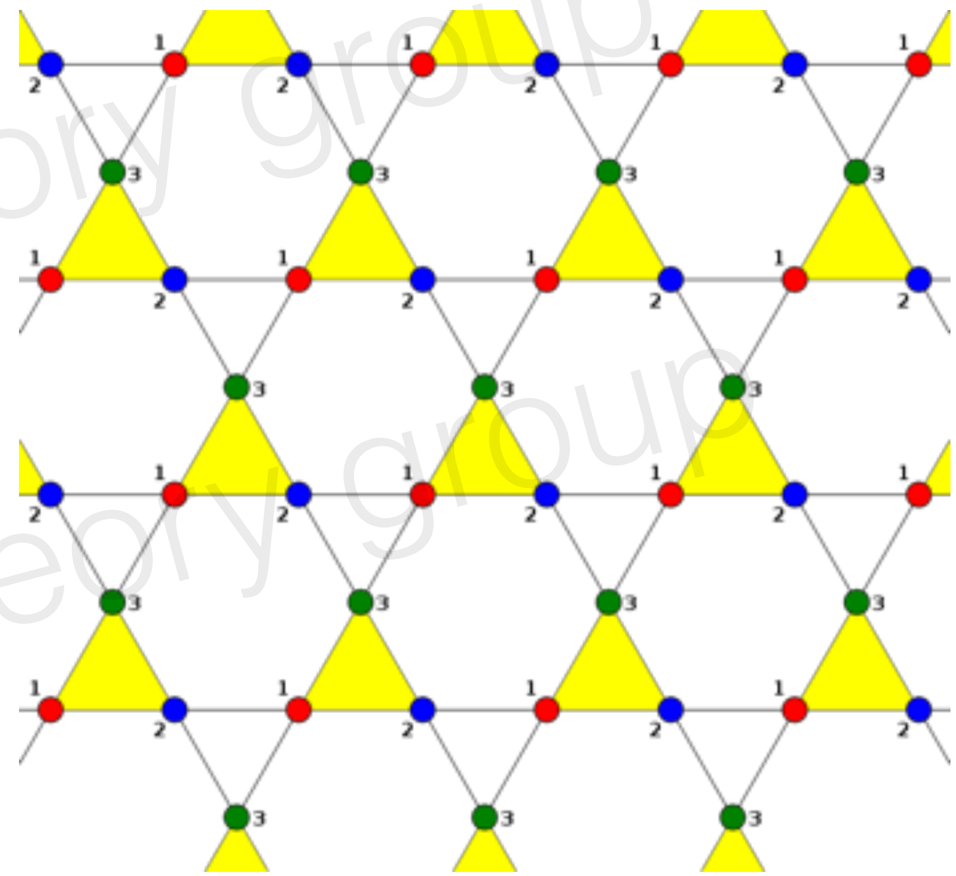
Wen: all the electrons in the Laughlin state dance collectively.

What do electrons do in $LiZn_2Mo_3O_8$?

Collective behaviours? Actually there are similarities.

$LiZn_2Mo_3O_8$ structure



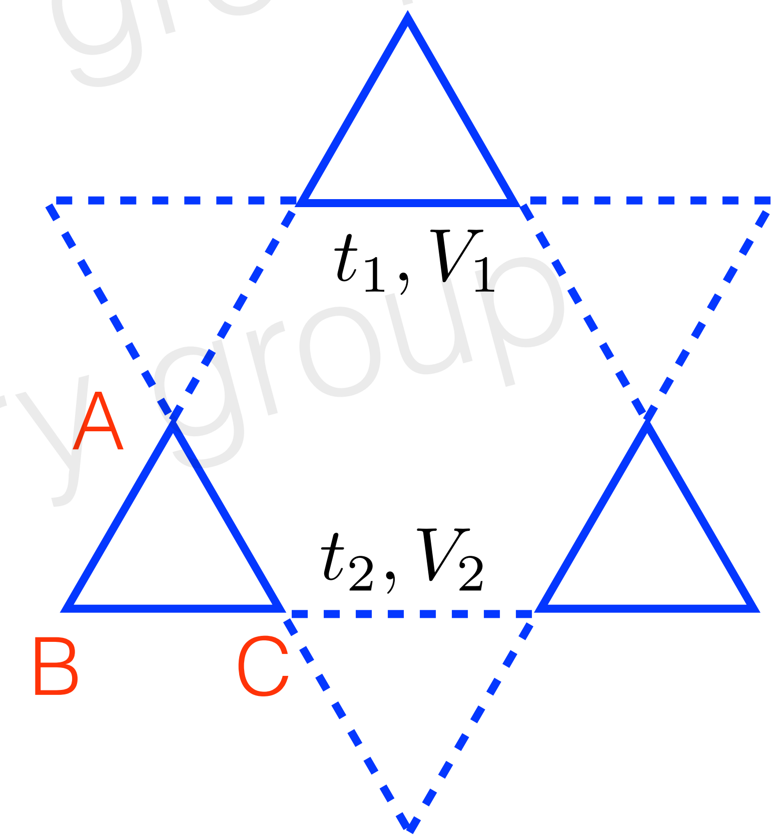


Model

Claim: a single-band extended Hubbard model on an anisotropic Kagome lattice with **1/6 electron filling.**

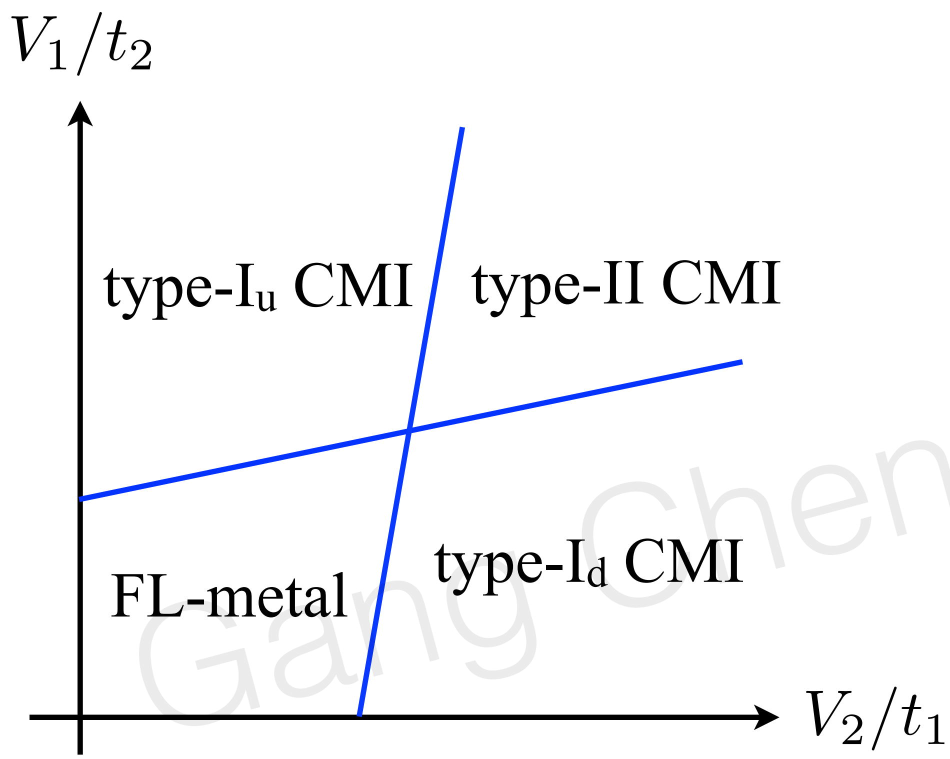
Minimal model allowed by symmetry

$$H = \sum_{\langle ij\rangle \in \mathrm{u}} [-t_1(c^\dagger_{i\sigma} c_{j\sigma} + h.c.) + V_1 n_i n_j]$$
$$+ \sum_{\langle ij\rangle \in \mathrm{d}} [-t_2(c^\dagger_{i\sigma} c_{j\sigma} + h.c.) + V_2 n_i n_j]$$
$$+ \sum_i \frac{U}{2}(n_i - \frac{1}{2})^2,$$



Large U alone **cannot** localize the electron.
V_1 and V_2 are needed: because it is 4d orbital,
and also to localize the electron in the clusters.

Generic phase diagram



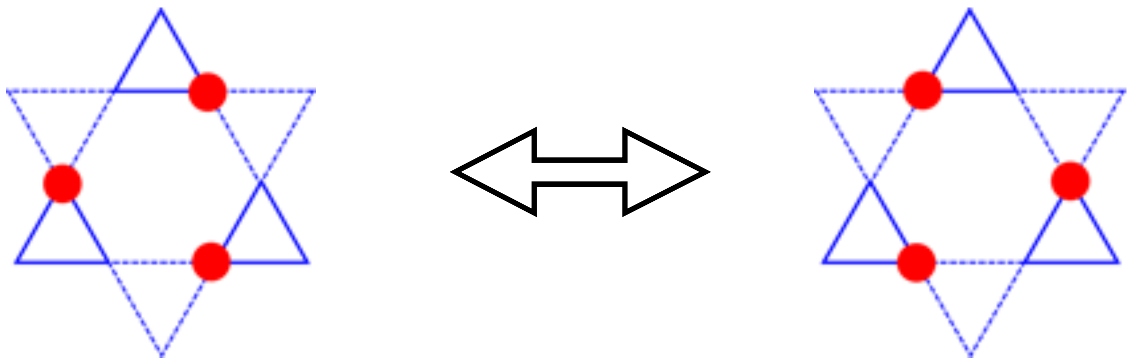
spin sector is spin liquid

no qualitative difference
for different t1/t2

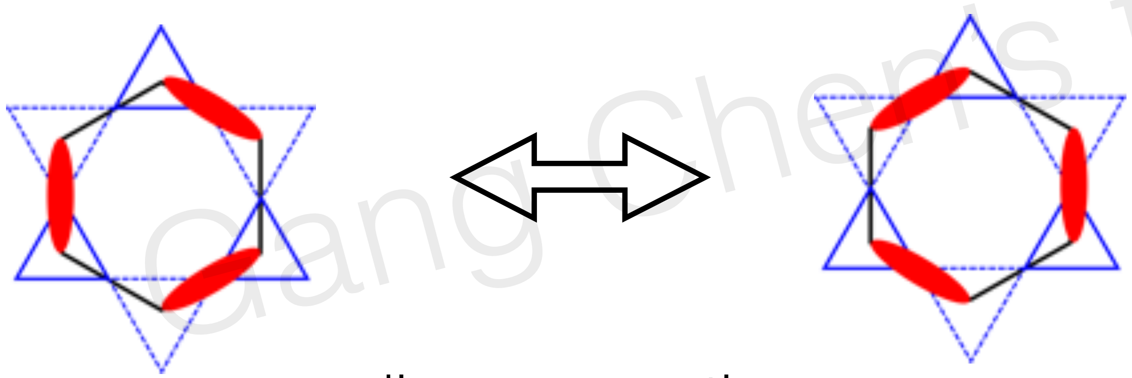
snapshots of electron occupation in type-I CMI
V_2 is small, V_1 is large

A “simple” understanding:
electrons are localized in **one** type of triangles in type-I CMI;
electrons are localized in **both** types of triangles in type-II CMI.

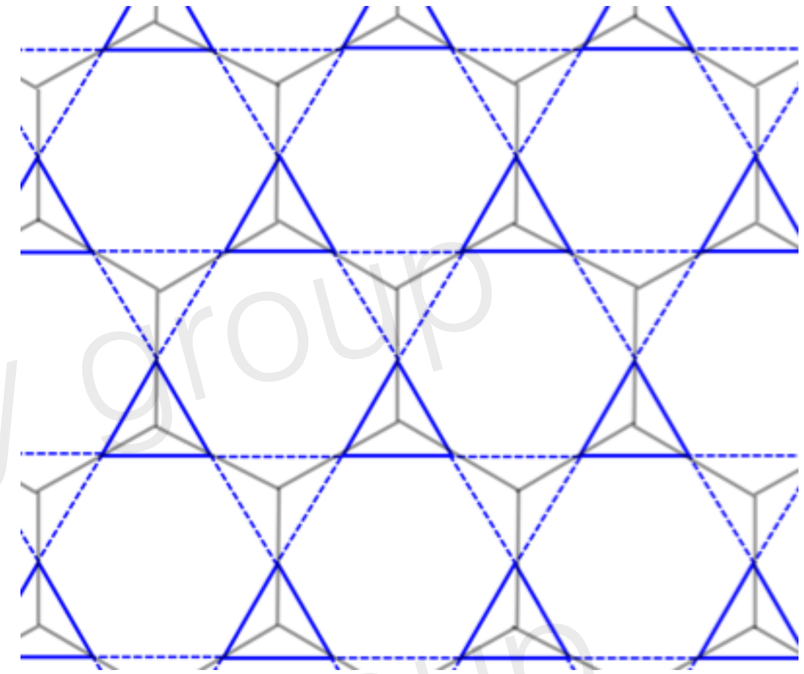
type-II CMI: **correlated** electron motion



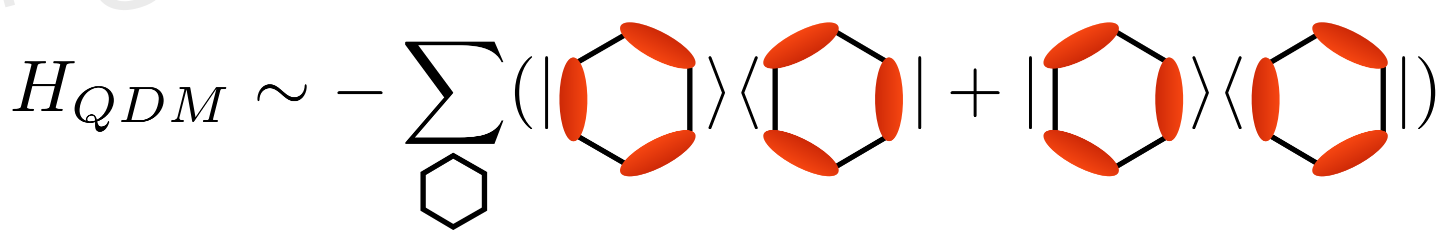
3rd order process in type-II CMI



dimer resonating

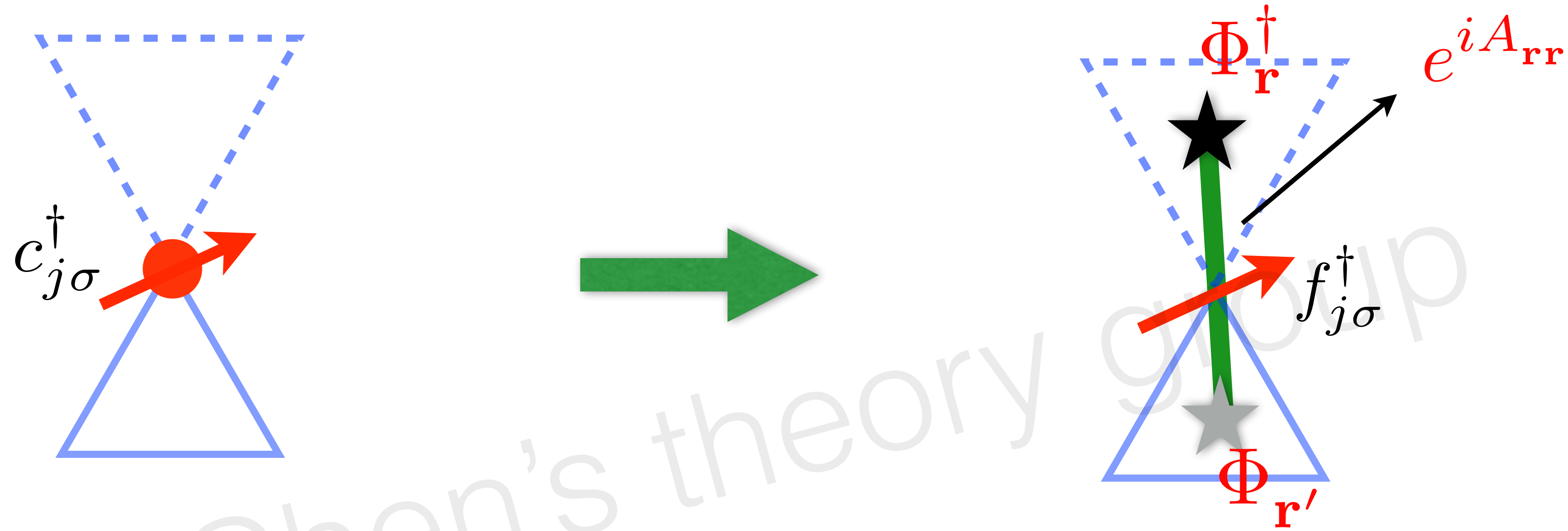


Dual honeycomb lattice and
Kagome lattice



Charge sector is described by a compact U(1) gauge theory on the dual honeycomb lattice.

A new parton gauge construction



$$c_{i\sigma} = \underbrace{e^{-i\theta_i}}_{\text{charge-}q_e \text{ spinless boson}} \underbrace{f_{i\sigma}}_{\text{charge-neutral spin-1/2 fermion}}$$

$$\boxed{c^{\dagger}_{j\sigma} \sim f^{\dagger}_{j\sigma} \Phi^{\dagger}_{\mathbf{r}} \Phi_{\mathbf{r}'} e^{iA_{\mathbf{r}\mathbf{r}'}}}$$

Original slave rotor construction works for the conventional Mott insulator

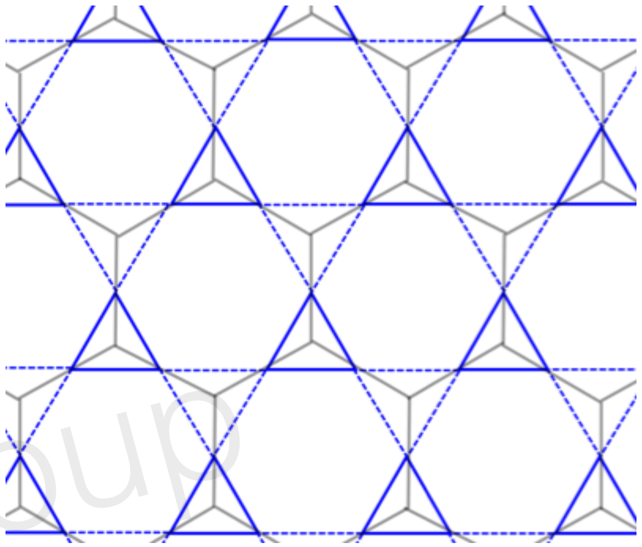
A new parton gauge construction is required for cluster Mott insulators.

Gauge structure

	$U(1)_{sp}$	$U(1)_{\rm c} \times U(1)_{sp}$
	one U(1) gauge field	two U(1) gauge fields

A formalism

$$
\begin{aligned}
H = & -t_1 \sum_{\mathbf{r}\in \mathrm{u}} \sum_{\mu\neq\nu} l^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} l^{-}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\nu} f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma} \bar{\Phi}^\dagger_{\mathbf{r}+\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}+\mathbf{e}_\nu} \\
& -t_2 \sum_{\mathbf{r}\in \mathrm{d}} \sum_{\mu\neq\nu} l^{+}_{\mathbf{r}-\mathbf{e}_\mu,\mathbf{r}} l^{-}_{\mathbf{r}-\mathbf{e}_\nu,\mathbf{r}} f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma} \bar{\Phi}^\dagger_{\mathbf{r}-\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}-\mathbf{e}_\nu} \\
& + \frac{V_1}{2} \sum_{\mathbf{r}\in \mathrm{u}} Q^2_{\mathbf{r}} + \frac{V_2}{2} \sum_{\mathbf{r}\in \mathrm{d}} Q^2_{\mathbf{r}},
\end{aligned} \tag{12}
$$

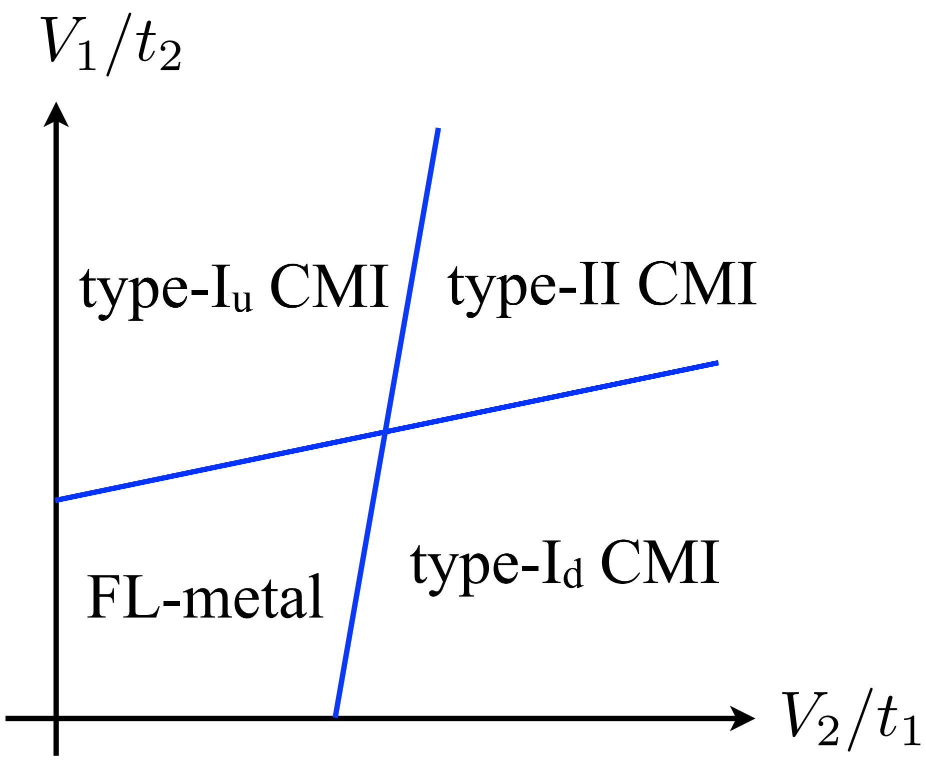


Self-consistent mean field theory: charge, spin, gauge sectors

$$
\begin{aligned}
H^{\mathrm{u}}_{\mathrm{ch}} &= -\bar{J}_1 \sum_{\mathbf{r}\in \mathrm{d}} \sum_{\mu\neq\nu} \bar{\Phi}^\dagger_{\mathbf{r}-\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}-\mathbf{e}_\nu} + \frac{V_1}{2} \sum_{\mathbf{r}\in \mathrm{u}} Q^2_{\mathbf{r}}, \\
H^{\mathrm{d}}_{\mathrm{ch}} &= -\bar{J}_2 \sum_{\mathbf{r}\in \mathrm{u}} \sum_{\mu\neq\nu} \bar{\Phi}^\dagger_{\mathbf{r}+\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}+\mathbf{e}_\nu} + \frac{V_2}{2} \sum_{\mathbf{r}\in \mathrm{d}} Q^2_{\mathbf{r}}, \\
H_{\mathrm{sp}} &= -\sum_{\mu\neq\nu} [\bar{t}_1 \sum_{\mathbf{r}\in \mathrm{u}} f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma} + \bar{t}_2 \sum_{\mathbf{r}\in \mathrm{d}} f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma}], \\
H_A &= -\sum_{\mu\neq\nu} \big[\bar{K}_1 \sum_{\mathbf{r}\in \mathrm{u}} l^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} l^{-}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\nu} \\
& \qquad + \bar{K}_2 \sum_{\mathbf{r}\in \mathrm{d}} l^{+}_{\mathbf{r}-\mathbf{e}_\mu,\mathbf{r}} l^{-}_{\mathbf{r}-\mathbf{e}_\nu,\mathbf{r}}\big],
\end{aligned}
$$

$$
\begin{aligned}
\bar{J}_1 &= t_2 \langle l^{+}_{\mathbf{r}-\mathbf{e}_\mu,\mathbf{r}} \rangle \langle l^{-}_{\mathbf{r}-\mathbf{e}_\nu,\mathbf{r}} \rangle \sum_\sigma \langle f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma} \rangle, & \mathbf{r} \in \mathrm{d}, \\
\bar{J}_2 &= t_1 \langle l^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \rangle \langle l^{-}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\nu} \rangle \sum_\sigma \langle f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma} \rangle, & \mathbf{r} \in \mathrm{u}, \\
\bar{t}_1 &= t_1 \langle l^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \rangle \langle l^{-}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\nu} \rangle \langle \bar{\Phi}^\dagger_{\mathbf{r}+\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}+\mathbf{e}_\nu} \rangle, & \mathbf{r} \in \mathrm{u}, \\
\bar{t}_2 &= t_2 \langle l^{+}_{\mathbf{r}-\mathbf{e}_\mu,\mathbf{r}} \rangle \langle l^{-}_{\mathbf{r}-\mathbf{e}_\nu,\mathbf{r}} \rangle \langle \bar{\Phi}^\dagger_{\mathbf{r}-\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}-\mathbf{e}_\nu} \rangle, & \mathbf{r} \in \mathrm{d}, \\
\bar{K}_1 &= t_1 \sum_\sigma \langle f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma} \rangle \langle \bar{\Phi}^\dagger_{\mathbf{r}+\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}+\mathbf{e}_\nu} \rangle, & \mathbf{r} \in \mathrm{u}, \\
\bar{K}_2 &= t_2 \sum_\sigma \langle f^\dagger_{\mathbf{r}\mu\sigma} f_{\mathbf{r}\nu\sigma} \rangle \langle \bar{\Phi}^\dagger_{\mathbf{r}-\mathbf{e}_\mu} \bar{\Phi}_{\mathbf{r}-\mathbf{e}_\nu} \rangle, & \mathbf{r} \in \mathrm{d}.
\end{aligned}
$$

Generic phase diagram from **gauge** theory of charge sector



Phases	$\langle \Phi_\mathbf{r} \rangle, \mathbf{r} \in \mathrm{u}$	$\langle \Phi_\mathbf{r} \rangle, \mathbf{r} \in \mathrm{d}$	$U(1)_\mathrm{c}$	$U(1)_\mathrm{sp}$
FL-metal	$\neq 0$	$\neq 0$	Higgsed	Higgsed
type-I$_\mathrm{u}$ CMI	$\neq 0$	$= 0$	Higgsed	Deconf
type-I$_\mathrm{d}$ CMI	$= 0$	$\neq 0$	Higgsed	Deconf
type-II CMI	$= 0$	$= 0$	Confining?	Deconf

type-II CMI: plaquette charge order via QDM

Moessner, Sondhi, Chandra 2001, also
in several other numerical works

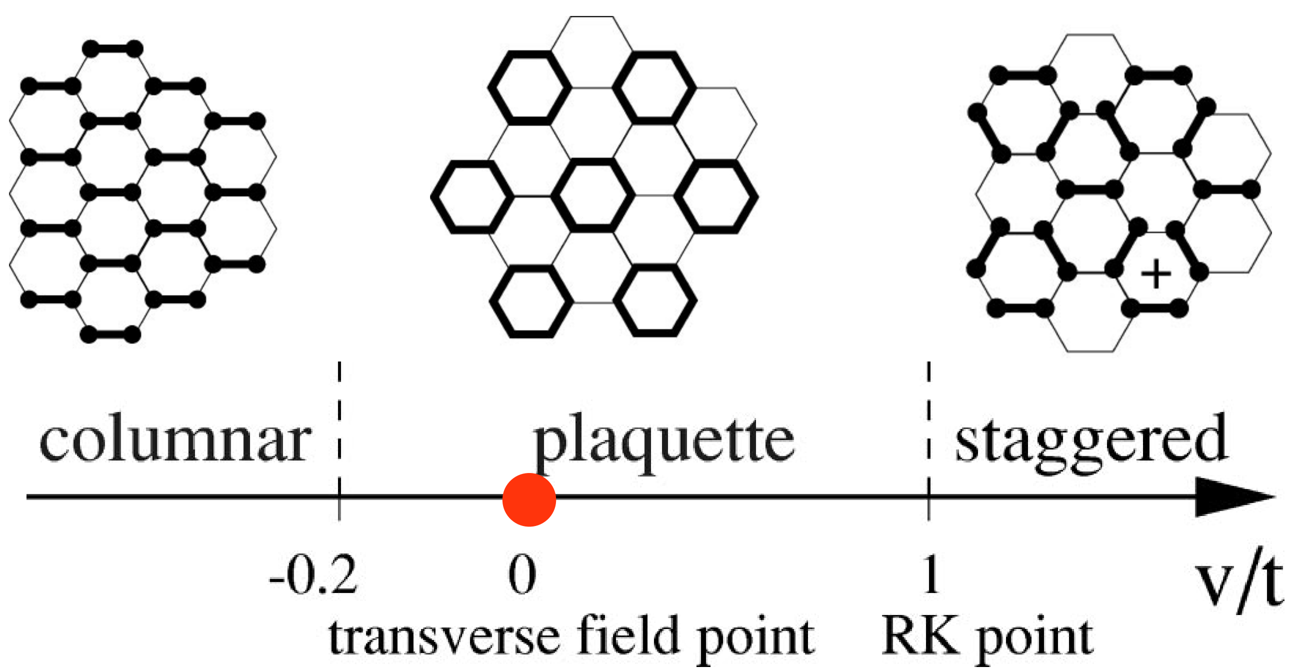
R. Moessner

S. Sondhi

P. Chandra

$$H_{QDM} = -t\hat{T} + v\hat{V}$$

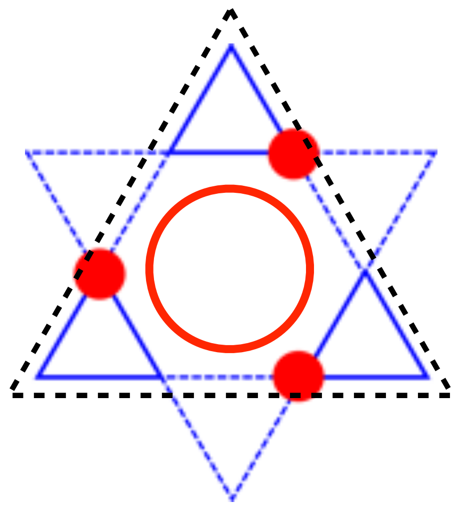
$$= -t\left(|\nabla\rangle\langle\Delta| + \text{H.c.}\right) + v\left(|\nabla\rangle\langle\nabla| + |\Delta\rangle\langle\Delta|\right).$$



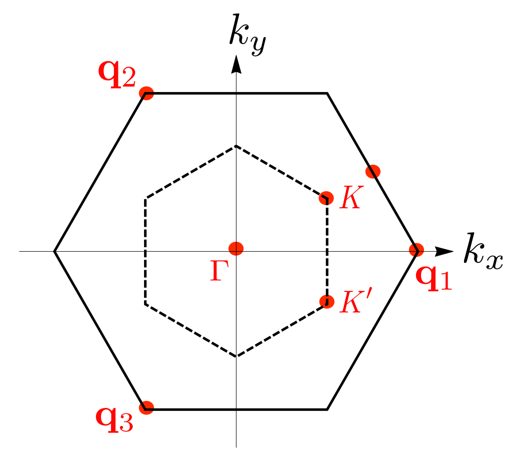
Plaquette charge order:
a local **charge "RVB"**,
a local collective behaviour !
It is a quantum effect.

Lieb-Schultz-Mattis-Oshikawa-Hastings' theorem: apply to type-II CMI

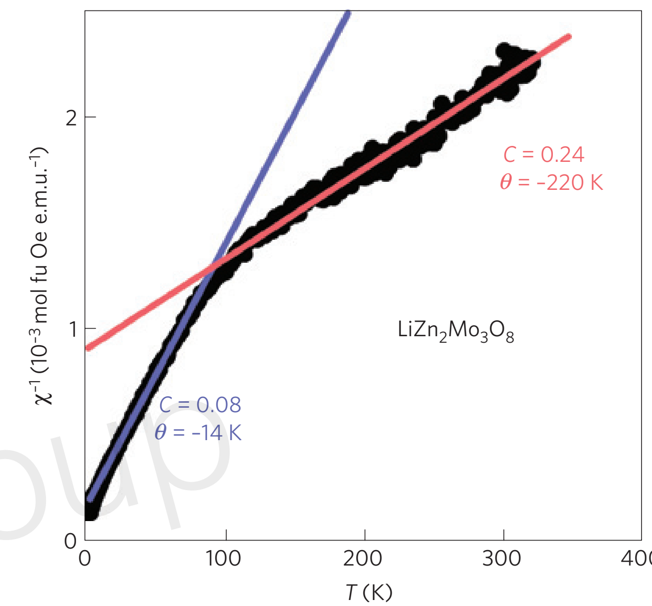
M. Hastings



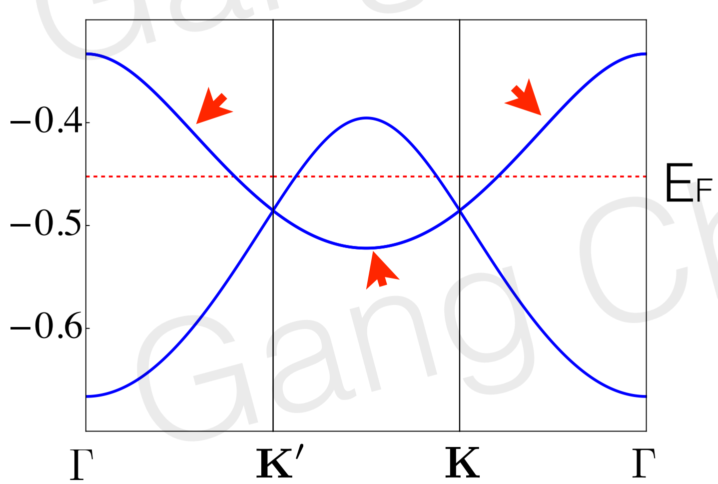
tripled unit cell,
host 3 electrons



BZ of type-I & type-II CMIs

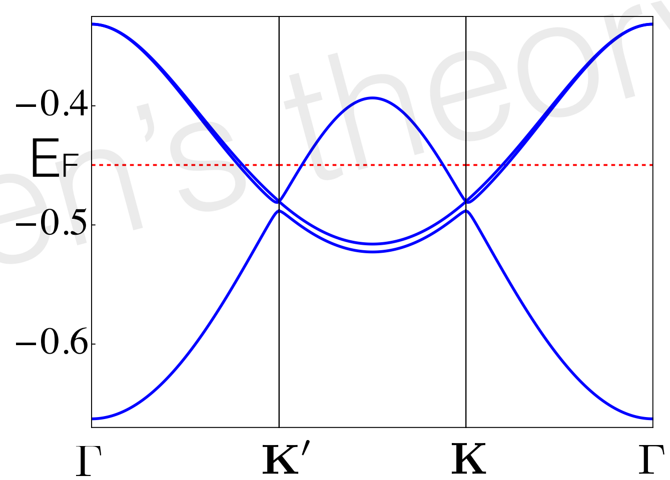


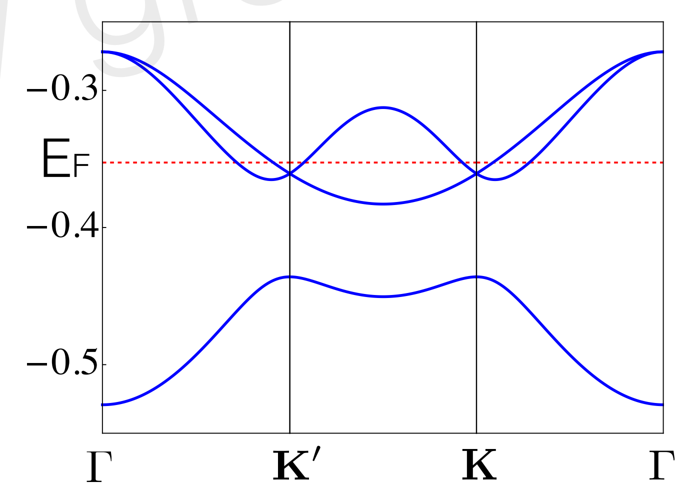
Spinon band reconstruction



type-I CMI: no PCO

folding the lowest spinon band
onto the BZ of type-II CMI



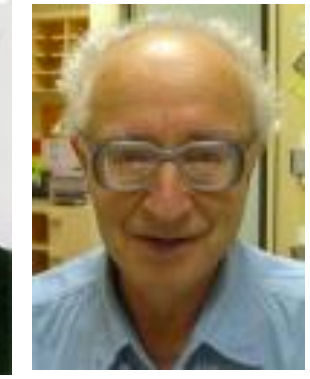


increasing PCO
in type-II CMI

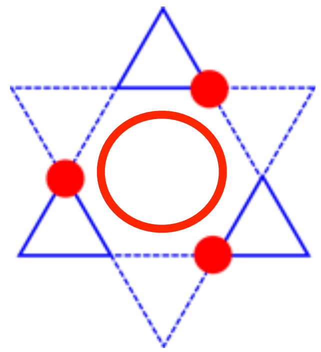
Implication to susceptibility from bandwidth and filling

Another view: **spin state reconstruction**

K. Kugel



D. Khomskii

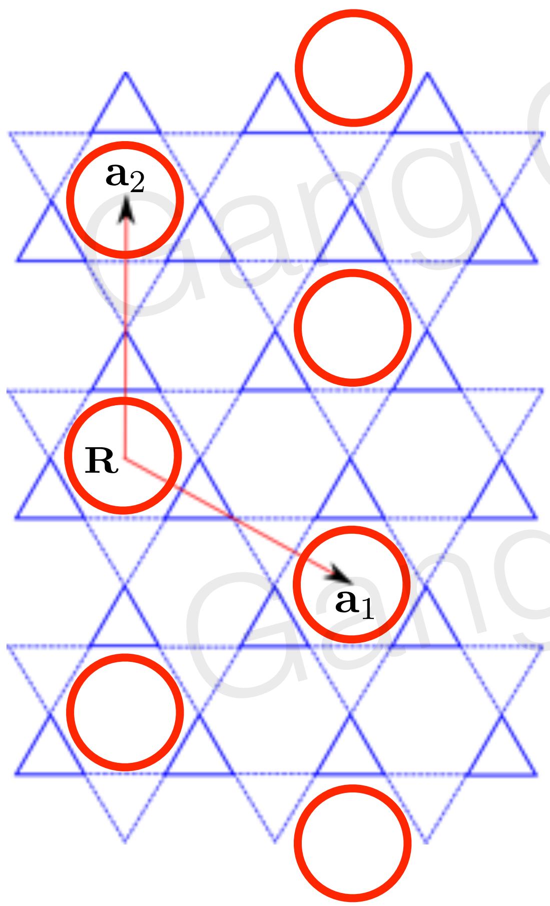


a single resonating hexagon

3 spins act as one effective spin-1/2 and one pseudospin-1/2

$$\frac{1}{2}\otimes\frac{1}{2}\otimes\frac{1}{2}=\frac{1}{2}\oplus\frac{1}{2}\oplus\cancel{\frac{3}{2}}$$

spin s=1/2, pseudospin $\mathcal{T}$=1/2, nonmagnetic



An effective Kugel-Khomskii model on the **emergent triangular lattice**

$$H_{\mathrm{KK}}=\frac{J'}{9}\sum_{\mathbf{R}}\sum_{\mu=x,y,z}\left[\mathbf{s}(\mathbf{R})\cdot\mathbf{s}(\mathbf{R}+\mathbf{a}_\mu)\right]\times[1+4\cancel{\pi^{\mu}}(\mathbf{R})][1-2\pi^{\mu}(\cancel{\mathbf{R}}+\mathbf{a}_\mu)]$$

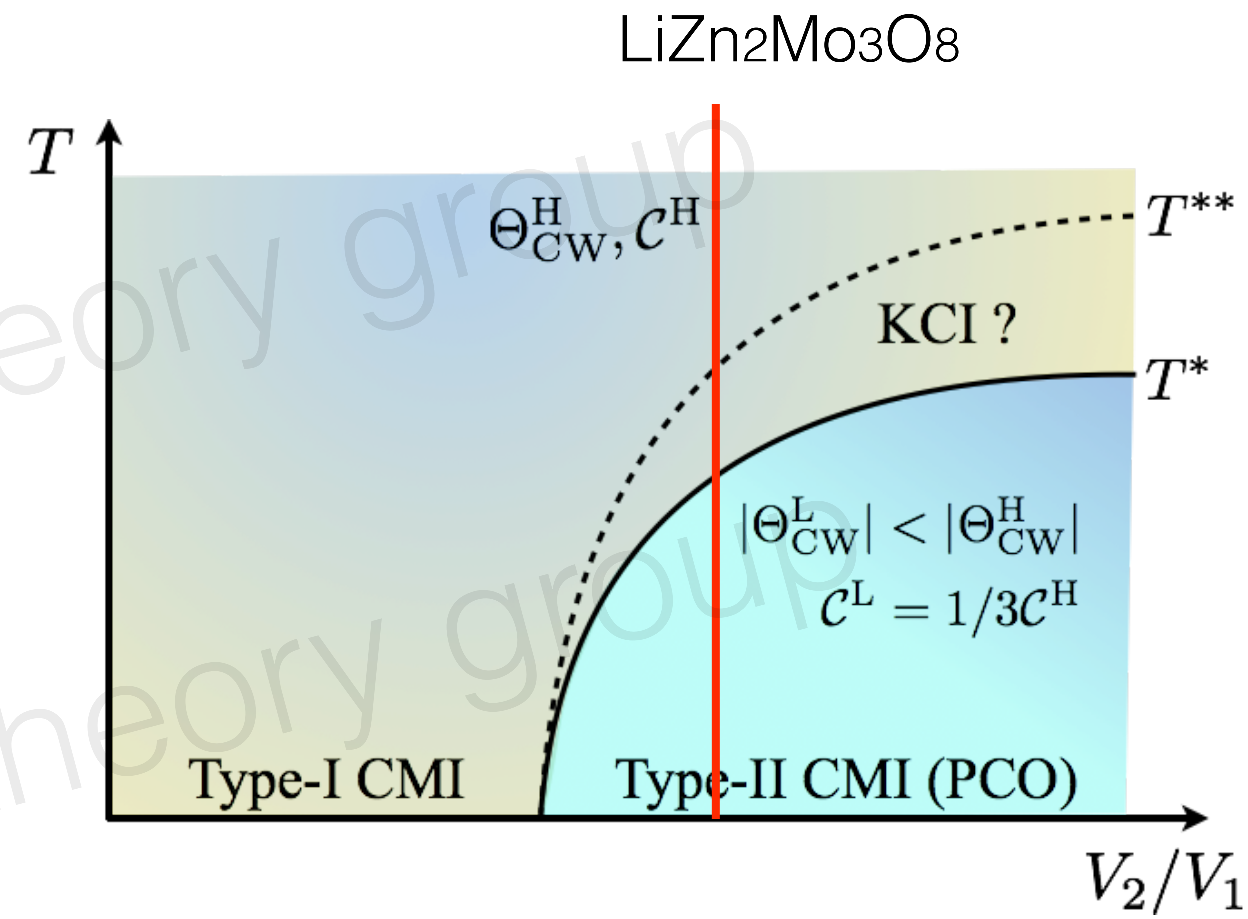
$$\Theta^{\mathrm{L}}_{\mathrm{CW}}=-\frac{z_t s(s+1)}{3}\frac{J'}{9},\ \mathcal{C}^{\mathrm{L}}=\frac{g^2\mu_{\mathrm{B}}^2 s(s+1)}{3k_{\mathrm{B}}}\frac{N_\Delta}{3}$$

due to the reduced probability of spin interaction

1. very frustrated, may also support spin liquid
2. interesting ordering under a strong field

Summary about $LiZn_2Mo_3O_8$

The emergence of PCO is the driving force of the 1/3 susceptibility anomaly. —> "**Short-range quantum entanglement**"
The spin GS of the system is probably a U(1) QSL with spinon Fermi surfaces.—>"**Long-range quantum entanglement**"



Gang Chen's theory group

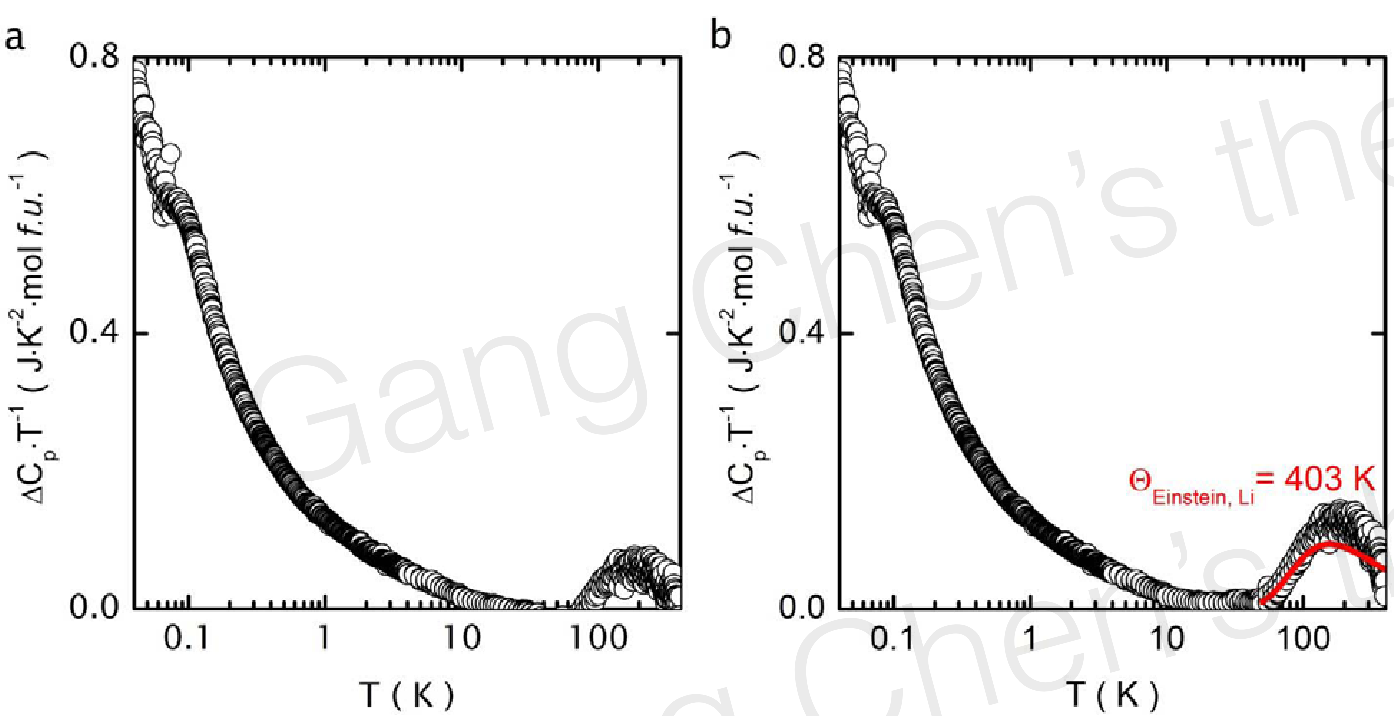
type-II CMI (PCO)

The crossover Kagome charge ice (KCI) regime is probably not sharply defined in $LiZn_2Mo_3O_8$ as it requires V_2 >> T > ring hopping.

KCI: same Curie const as high-T one, slightly different Curie temperature

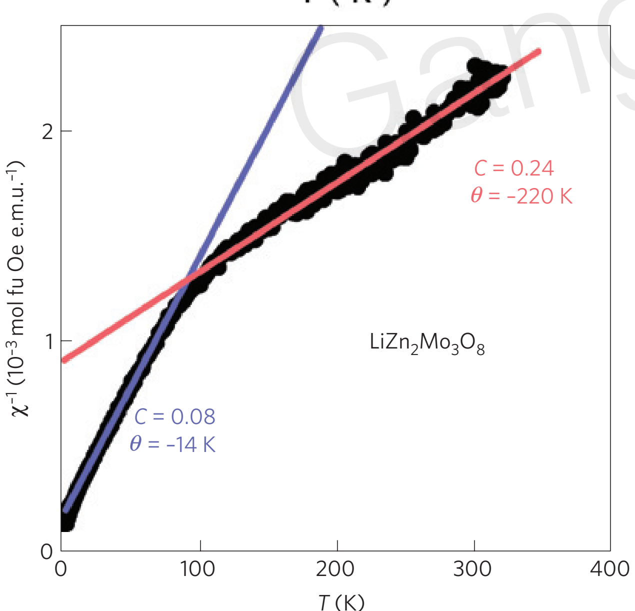
Prediction A : charge sector

1. Expect 1st order finite temperature transition, peak at ~100K, (was interpreted as Li freezing.) smeared out 1st transition?
2. High resolution X-ray, RIXS
3. Nuclear quadrupolar resonance: electric field gradient (suggested to me by Baskaran)



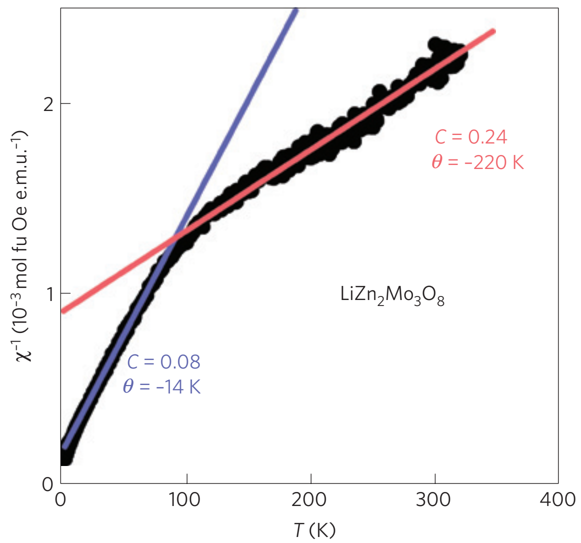
Disorders pin the charge density wave, broaden the phase transition.

W. L. McMillan PRB 1975



coincide with
susceptibility anomaly

Further **prediction B**: low-T QSL

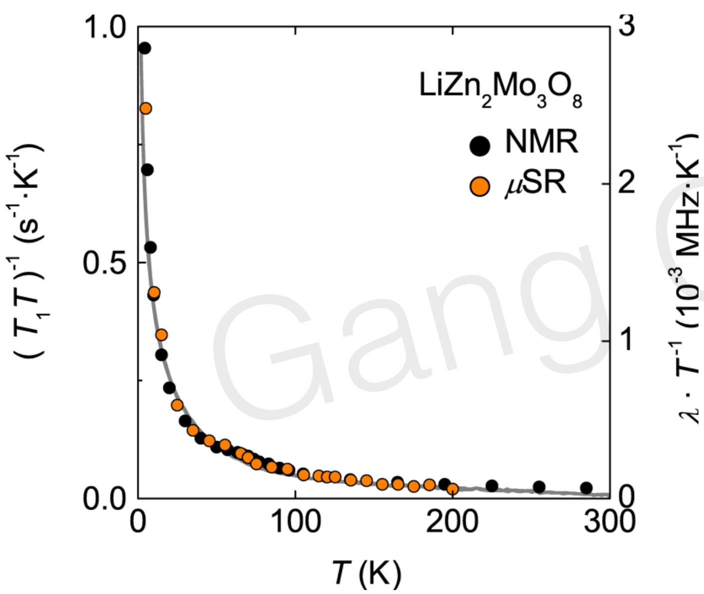


1. thermodynamics

U(1) QSL with spinon Fermi surfaces

$$C_v \sim T^{2/3}, \quad \chi \sim \text{const}$$

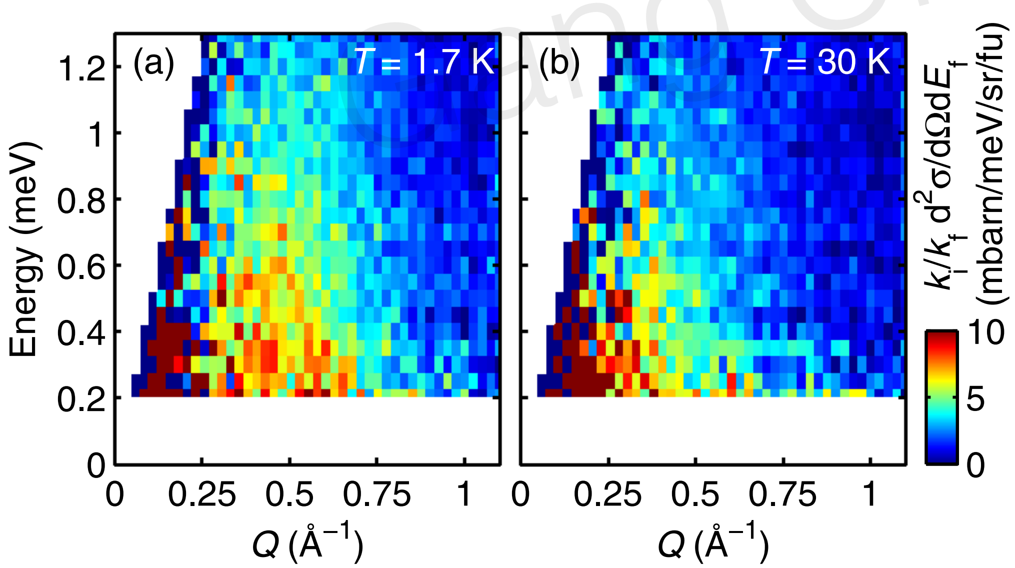
at very low temperature (<1K).



2. spectroscopic

NMR: large density of low-energy spin excitations because of the reduced bandwidth

$$1/(T_1 T) \propto D(E_F)^2$$



Neutron scattering: it would be nice to compare the prediction from the spinon band structure in future work. Single crystal data and better resolution are preferred.

What is type-I CMI?

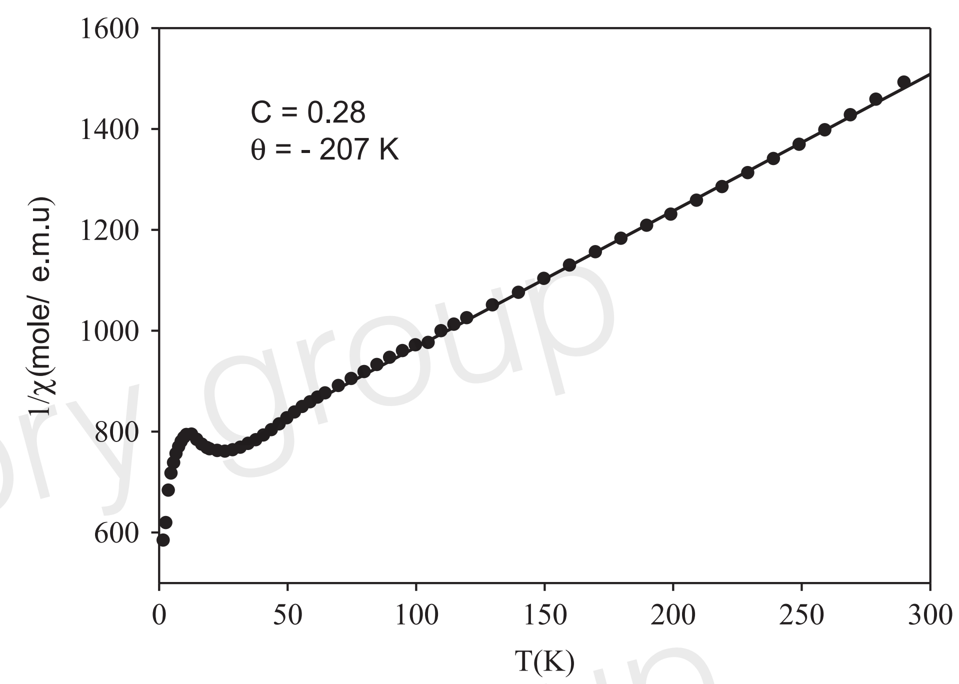


Fig. 5. Inverse magnetic susceptibility as a function of temperature for $Li_2InMo_3O_8$. Data were taken under an applied field of 5000 Oe. Curie–Weiss fit is represented by the solid line.

no susceptibility anomaly !

$Li_2InMo_3O_8$ as a type-I CMI ?

quantum spin liquid ?

type-I CMI is a triangular lattice spin liquid

P Gall, etc, J Solid State Chem. 2013

$M_2Mo_3O_8$ (M=Mg,Mn,Fe,Co,Ni,Zn,Cd),

$LiRMo_3O_8$ (R=Sc,Y,In,Sm,Gd,Tb,Dy,Ho,Er,Yb) and many others.

Many materials mean many opportunities to discover new physics there.

Gang Chen's theory group

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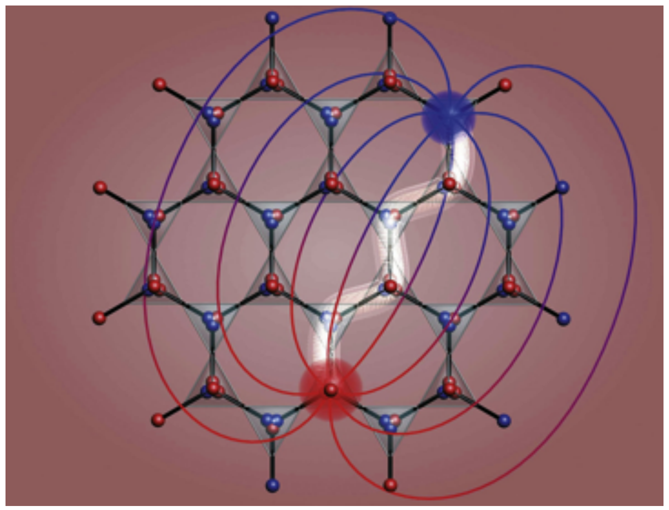
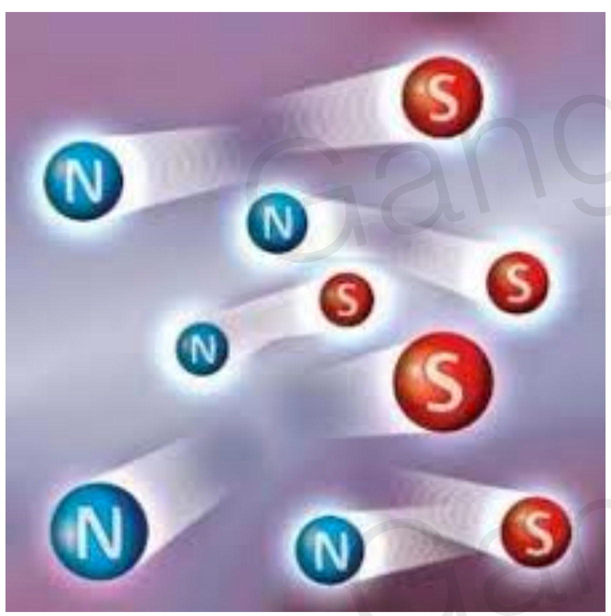
ICE AGE 1: classical spin ice





M. Gingras, R. Melko, C. Castelnovo, R. Moessner,
S. L. Sondhi,O. Tchernyshyov, M. J. Harris,
S. T. Bramwell, D.J.P. Morris, …….

ICE AGE 2: quantum spin ice

stolen from L. Balents and L. Savary

M. Gingras, R. Melko, M Hermele, L. Balents,
M. Fisher, L. Savary, S. Lee, Y. Wan,
O. Tchernyshyov, **G. Chen**, Y.-P. Huang,……..
C. Broholm, K. Ross, B. Gaulin……..

So far, not confirmed experimentally!
Because of very **small energy scale.**
Solution: d electrons, or others ?

lots of materials

A little more about the motivation

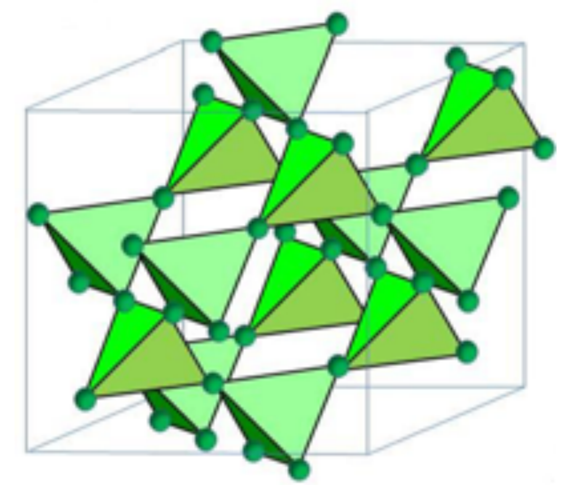
1. Can we use other degrees of freedom to reveal quantum spin ice physics?

electron = spin + charge + orbital (for **condensed matter physicists only!**)

quantum spin ice (most famous !)
quantum charge ice (the rest of the talk)
quantum orbital ice (**Gang Chen**, unpublished)

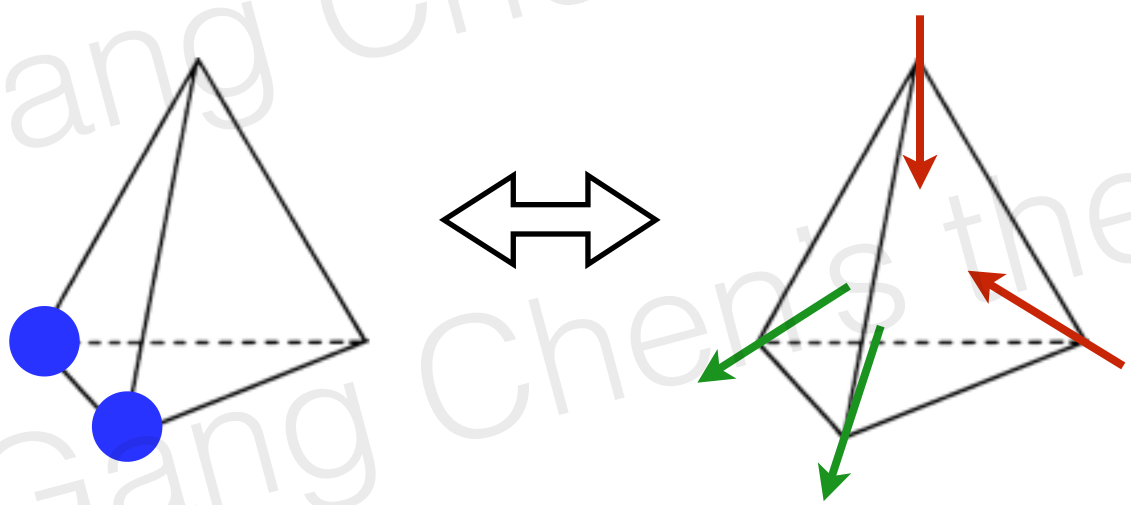
2. Any other physical observables that do not have strong temperature constraint but still manifest the intrinsic properties of quantum spin ice?
Not trivial ! (**Gang Chen**, working in progress !)

3D cluster Mott insulator

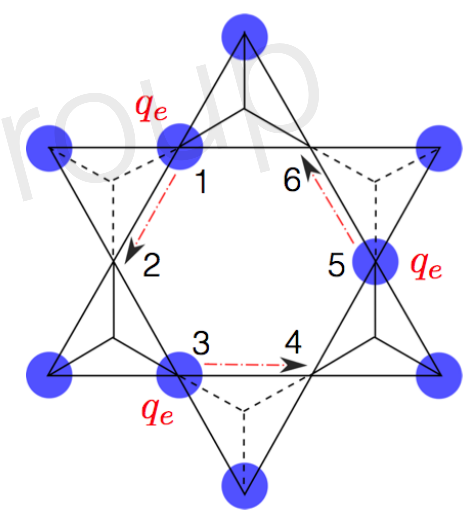


$$H = -t \sum_{\langle ij \rangle, \sigma} (c^\dagger_{i\sigma} c_{j\sigma} + h.c.) - \mu \sum_i n_i$$
$$+V \sum_{\langle ij \rangle} n_i n_j + \frac{U}{2} \sum_i (n_i - \frac{1}{2})^2,$$

1/4 (or 1/8) electron filling



charge ice rule



Charge sector is a **Coulombic charge liquid**.

Charge fractionalization of the Coulombic charge liquid

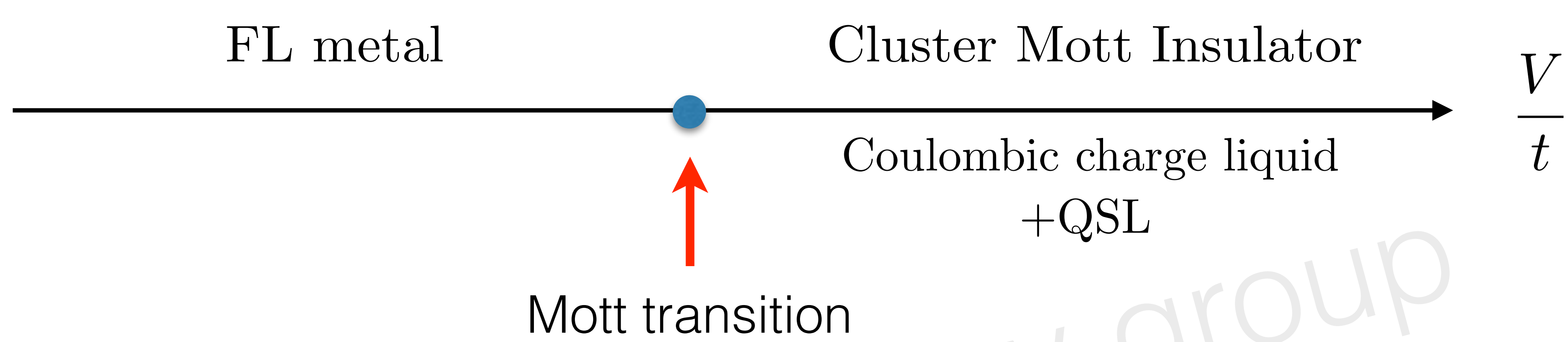
- Low-energy physics in the charge sector is described by an emergent **(compact) quantum electrodynamics** in 3+1D

- Charge excitation carries **1/2 the electron charge** !

$$c^\dagger_{j\sigma} \sim f^\dagger_{j\sigma} \Phi^\dagger_{\mathbf{r}} \Phi_{\mathbf{r}'} e^{iA_{\mathbf{r}\mathbf{r}'}}$$

fermionic
spinon

Phase diagram and gauge description



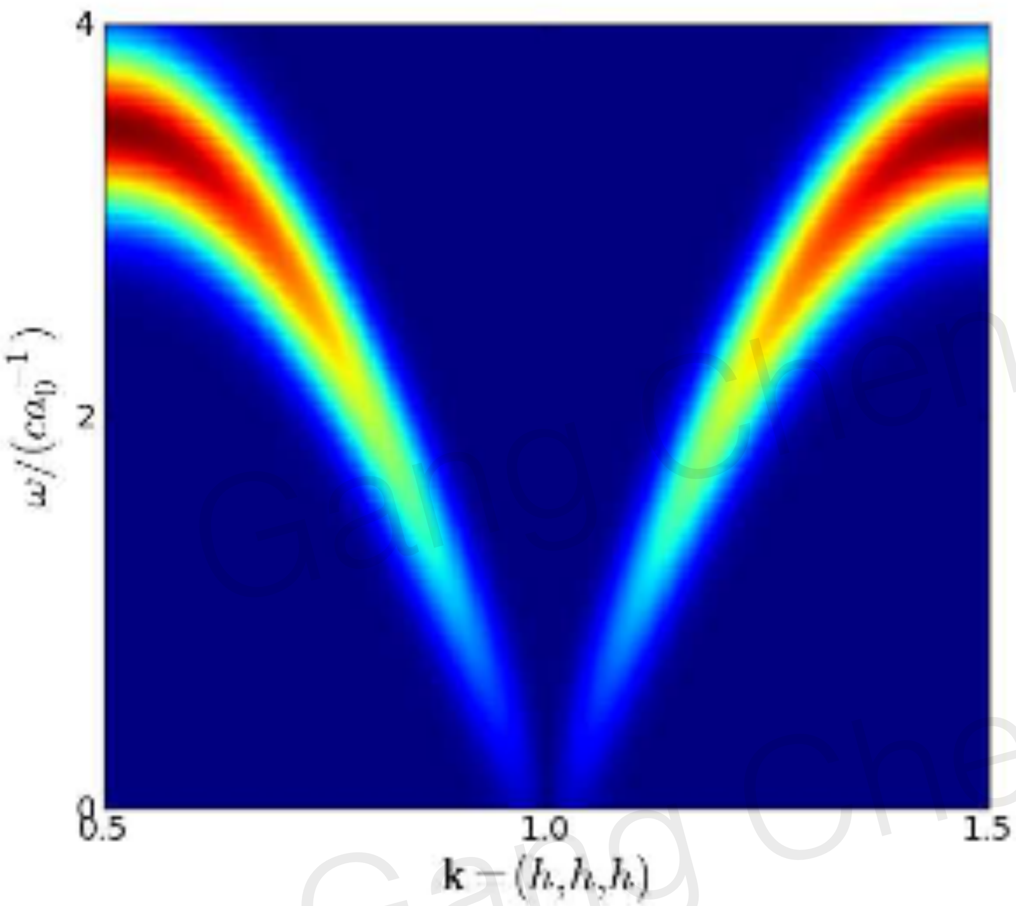
Phases	charge-$\frac{q_e}{2}$ boson	$U(1)_{\rm c}$	$U(1)_{\rm sp}$
FL-metal	Condensed	Higgsed	Higgsed
3D CMI (Coulombic CL + QSL)	uncondensed	Deconf	Deconf

Here charge boson carries both $U(1)_c$ and $U(1)_{sp}$ gauge charge.

- (Inelastic) X-ray scattering measures U(1) gauge field correlation in the charge sector

$$\mathrm{Im}[E^{\alpha}_{-\mathbf{k},-\omega} E^{\beta}_{\mathbf{k},\omega}] \propto [\delta_{\alpha\beta} - \frac{k_\alpha k_\beta}{\mathbf{k}^2}]\,\omega\,\delta(\omega - v|\mathbf{k}|),$$

$$\mathbf{E}_{\mathbf{r}+\frac{1}{2}\mathbf{e}_\mu} \equiv L^z_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \frac{\mathbf{e}_\mu}{|\mathbf{e}_\mu|} = (n_{\mathbf{r}+\frac{1}{2}\mathbf{e}_\mu} - \tfrac{1}{2}) \frac{\mathbf{e}_\mu}{|\mathbf{e}_\mu|}$$



$$I(\omega) \sim \omega$$

emergent light in quantum charge ice !

N Shannon etc 2012,
L Savary etc 2012,
Gingras etc, 2007-now

Byron den Hertog / Science

$$\langle E^{\alpha}_{-\mathbf{k}} E^{\beta}_{\mathbf{k}} \rangle \propto \delta_{\alpha\beta} - \frac{k_\alpha k_\beta}{\mathbf{k}^2}$$

Pinch points in equal-time charge structure factor at T > ring hopping. “classical charge ice”

Mott transition: low-energy field theory

$$\mathcal{L} = \mathcal{L}_\Phi + \mathcal{L}_f + \mathcal{L}_\mathcal{A} + \mathcal{L}_a + \mathcal{L}_{bf} \quad (6)$$

$$\mathcal{L}_\Phi = \big|[\partial_\mu - i(\mathcal{A}_\mu - \frac{a_\mu}{2})]\Phi_{\rm I}\big|^2 + \big|[\partial_\mu - i(\mathcal{A}_\mu + \frac{a_\mu}{2})]\Phi_{\rm II}\big|^2 + m^2[|\Phi_{\rm I}|^2 + |\Phi_{\rm II}|^2] + u[|\Phi_{\rm I}|^4 + |\Phi_{\rm II}|^4] + v|\Phi_{\rm I}|^2|\Phi_{\rm II}|^2$$

$$\mathcal{L}_f = \psi^\dagger_\sigma(\partial_\tau - ia_0 - \mu_f)\psi_\sigma + \frac{1}{2m_f}|(\nabla - i\mathbf{a})\psi_\sigma|^2$$

$$\mathcal{L}_\mathcal{A} = \frac{1}{4g_A^2}(\partial_\mu\mathcal{A}_\nu - \partial_\nu\mathcal{A}_\mu)^2, \quad \mathcal{L}_a = \frac{1}{4g_a^2}(\partial_\mu a_\nu - \partial_\nu a_\mu)^2$$

$$\mathcal{L}_{f\Phi} = \lambda|\psi_\sigma|^2(|\Phi_{\rm I}|^2 + |\Phi_{\rm II}|^2).$$

$\Phi_{\rm I}, \Phi_{\rm II}$ are charge bosons

Ψ_σ are fermionic spinons

$\mathcal{A}_\mu$ is $U(1)_{\rm c}$ gauge field

a_μ is $U(1)_{\rm sp}$ gauge field

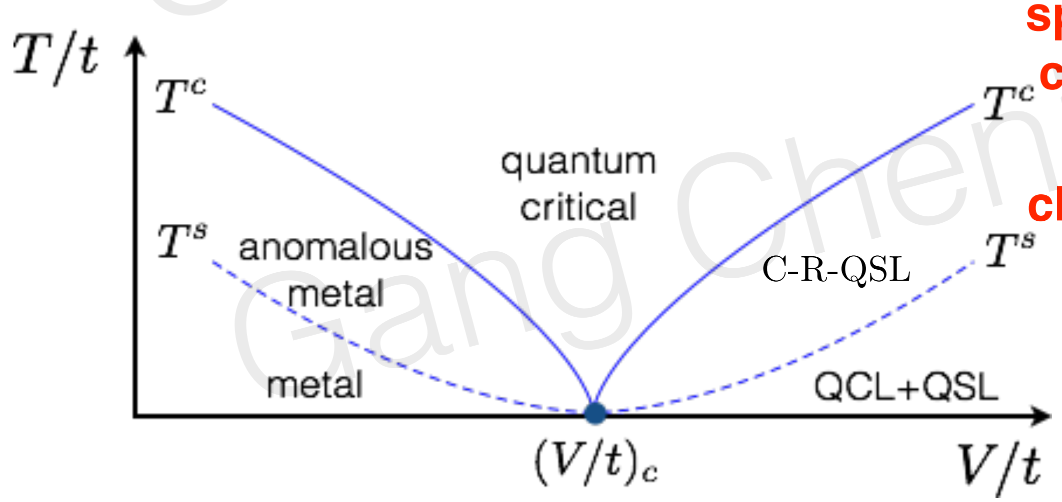


FIG. 2. The finite temperature crossover in the vincinty of the weakly first-order Mott transition.

different dynamical scalings for spin and charge

zc=1, zs=3

Crossover in heat capacity and electric conductivity

1. Heat capacity crossover signals the z_s=3 dynamical exponent

Spinon-U(1)$_{sp}$ gauge sector controls/dominates the thermodynamics

$$C \approx \begin{cases} T \,\mathrm{lnln} 1/T & T > |V - V_c|^{3/2} \quad \text{critical regime} \\ \gamma_1 T \ln 1/T & T < (V - V_c)^{3/2} \quad \text{U(1) QSL} \\ \gamma_2 T & T < (V_c - V)^{3/2} \quad \text{FL metal} \end{cases}$$

2. Electric resistivity signals the z_c=1 dynamical exponent

Ioffe-Larkin composition rule: $\rho_c = \rho_f + (\rho_I^{-1} + \rho_{II}^{-1})^{-1}$

note: the resistivity gap in the Mott regime is single boson gap.

Mott transition itself is insulating. Crossover to metal in the metallic side.

Pyrochlore Mott insulators with fractional electron filling

usually associated with mixed valences

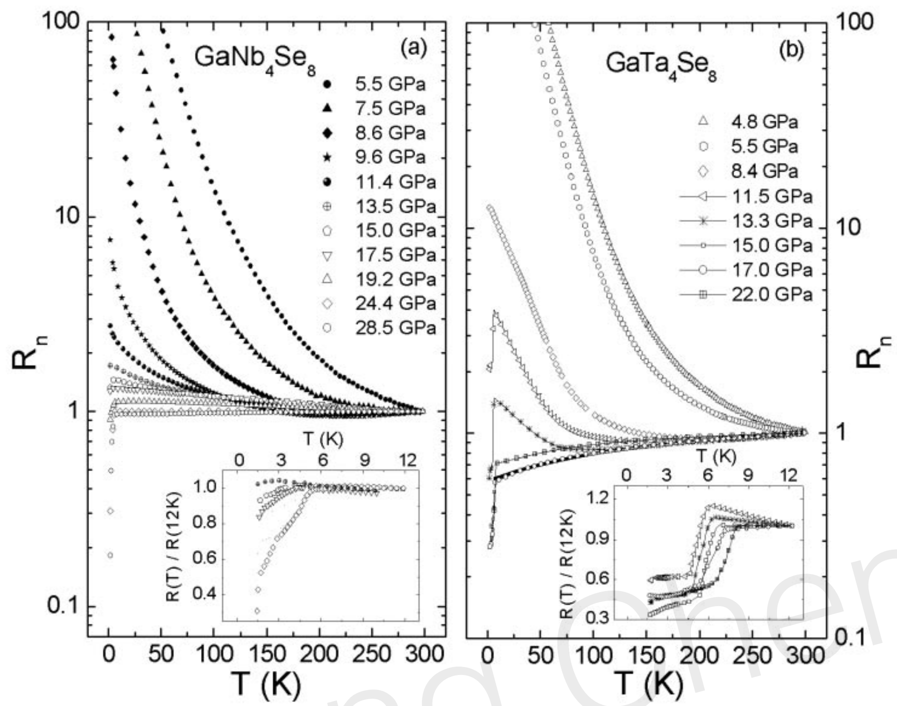


FIG. 2. Temperature dependence of the normalized electrical resistance $R_n = [R(T)/R(297\ \mathrm{K})]$ of $GaNb_4Se_8$ (a) and $GaTa_4Se_8$ (b) at different pressures up to 28.5 GPa. The insets show the drop of R_n at high pressures and low temperatures.

Metal-insulator transition:
but **superconductivity** intervenes!

M.M.Abd-Elmeguid etc, PRL 2004

Superconductivity is actually interesting!

Both U(1)c and U(1)sp gauge fields can be higgsed down to Z2 gauge fields.

The resulting CMI is **Z2 QCL + Z2 QSL**
Gang Chen, YB Kim, HY Kee,
working in progress!

Question / observation:

1. What if the change fluctuation is very strong, and in the most extreme case, the charge sector forms a **quantum charge liquid**? Spin sector is even more likely to be in a QSL.
2. What if the charge fluctuation leads to **some structure in the charge** sector? Spin sector is surely to be influenced in a non-trivial way. This would lead to **striking experimental** consequence. If it is observed, it gives us confidence on the theoretical framework that we are developing.

Summary

Gang Chen's theory group

1. I provide two specific examples about the physics of cluster Mott insulators.
2. There is a very interesting interplay between the charge and spin degrees of freedom in both 2D and 3D cluster Mott insulators.
3. Cluster Mott insulators are new physical systems that may host various emergent and exotic physics.