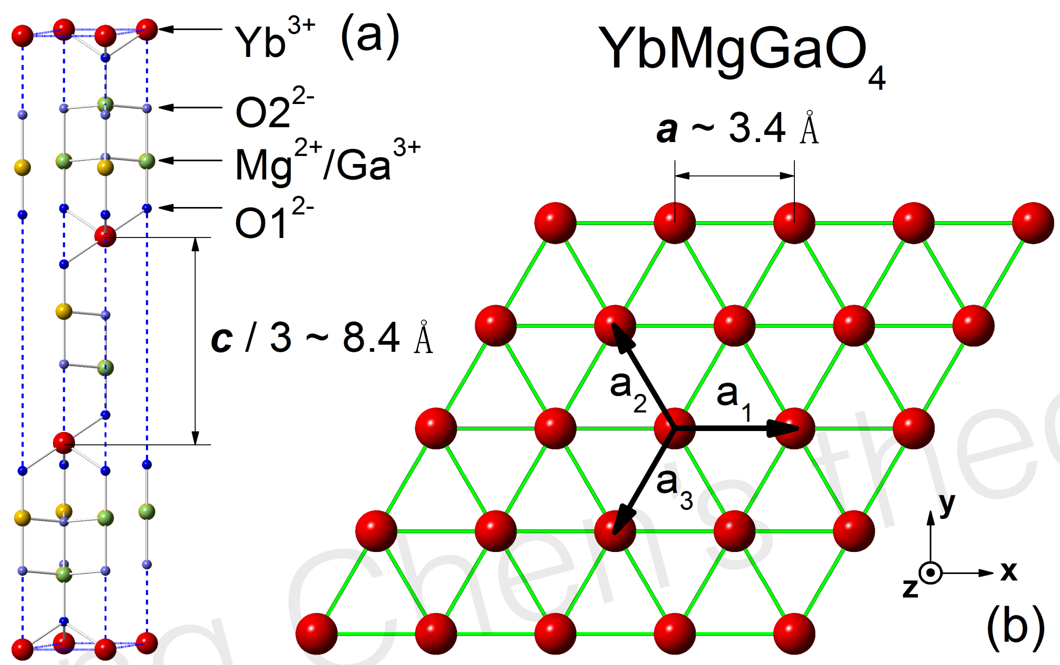
Signatures of fractionalization in spin liquid candidate

Gang Chen
Fudan University
Shanghai, China

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



Qingming Zhang
(Renmin Univ of China)

- Hastings-Oshikawa-Lieb-Shultz-Mattis theorem.
- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2015).
- This is likely the **first strong spin-orbit coupled QSL with odd electron filling** and effective spin-1/2.
- It is the first clear observation of $T^{2/3}$ heat capacity. (needs comment.)
- Inelastic neutron scattering is consistent with spinon Fermi surface results.
- We think it is a spinon Fermi surface U(1) QSL.

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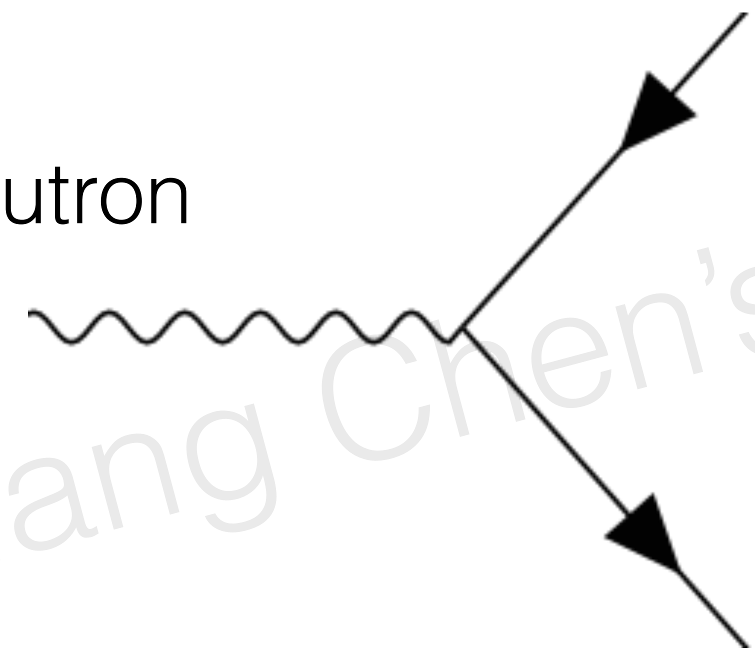
Inelastic neutron scattering

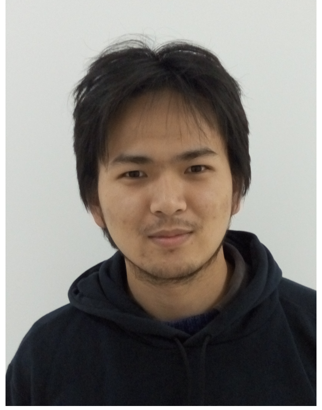
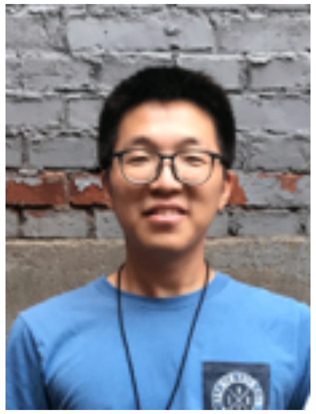


$$P = q_1 + q_2$$

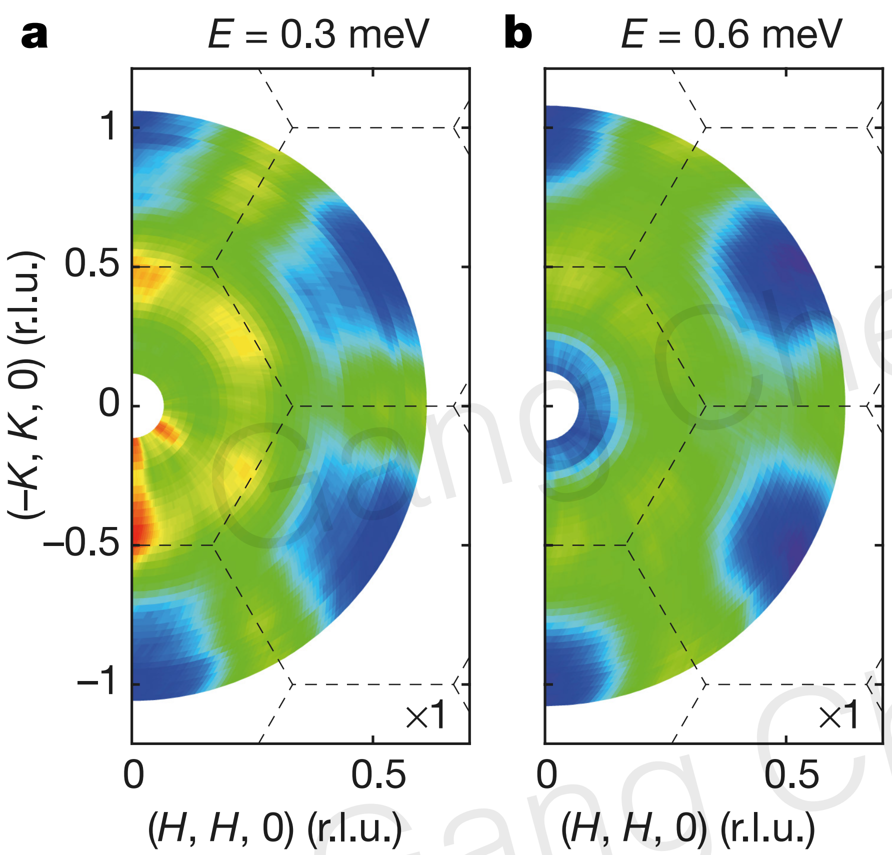
$$E = \omega(q_1) + \omega(q_2)$$

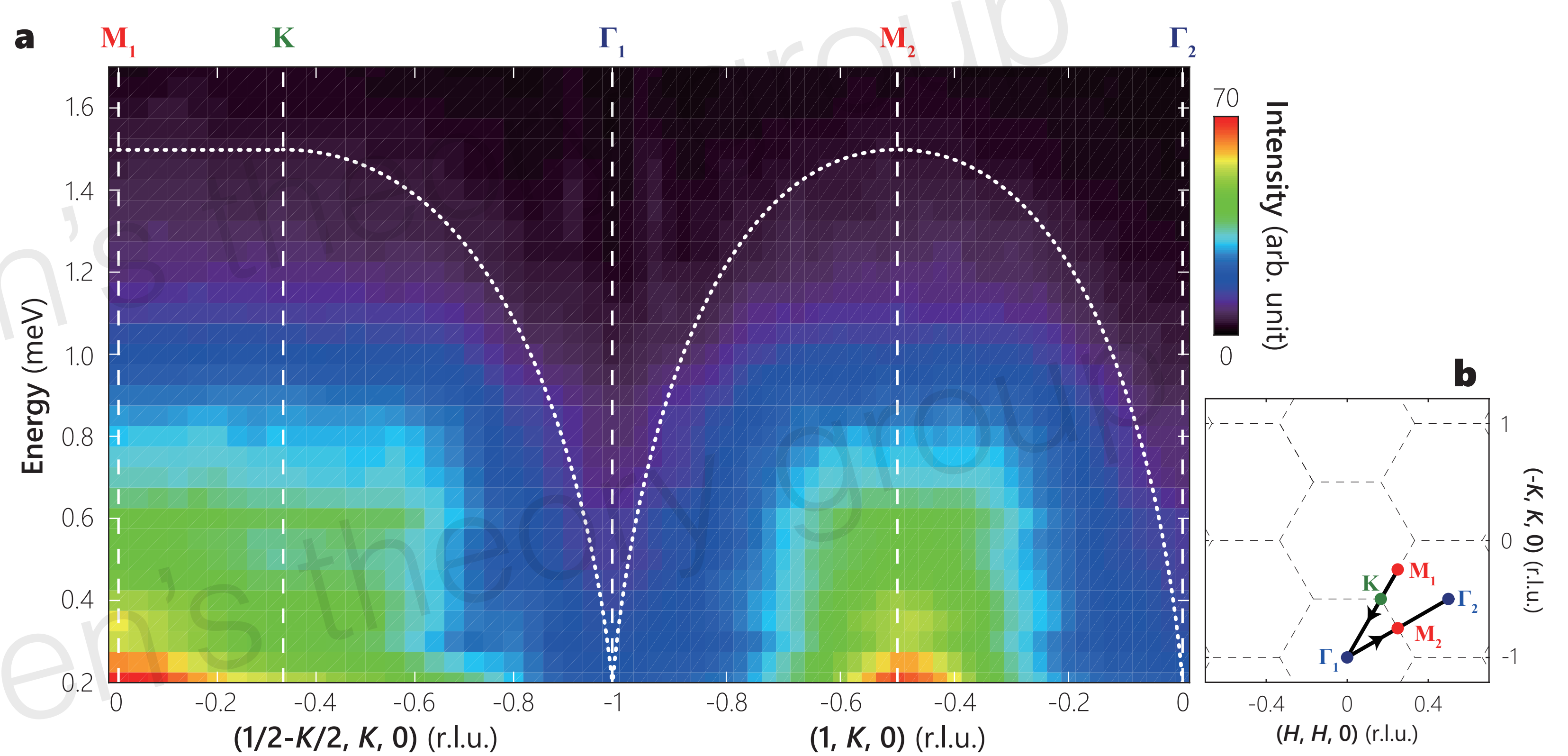
A consequence of fractionalization is the broad continuum in the inelastic neutron scattering.

Inelastic neutron scattering

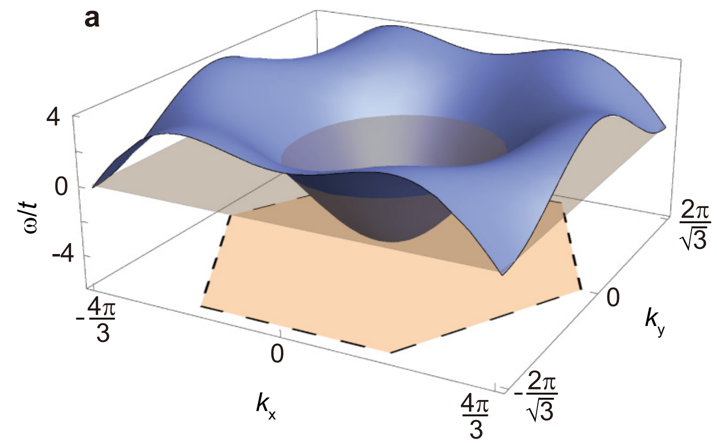

Yao-Dong Li (Fudan -> UCSB) **Yao Shen (Fudan)** **Jun Zhao (Fudan)**





Y Shen, YD Li …GC*, J Zhao* **Nature** 2016

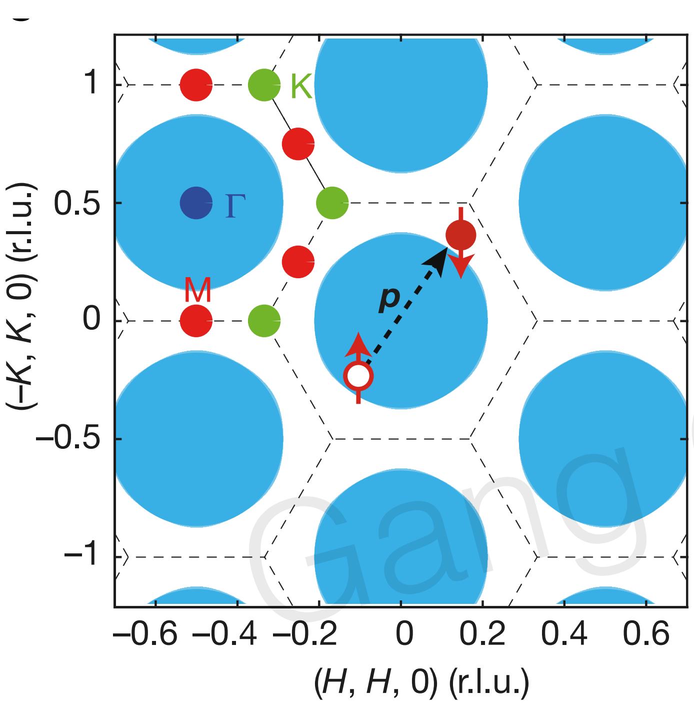
Consistent neutron results from Martin Mourigal's group, Nature Physics

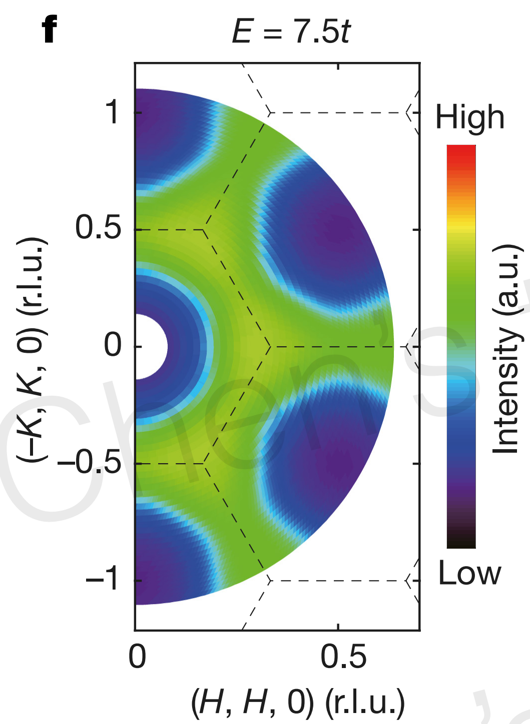


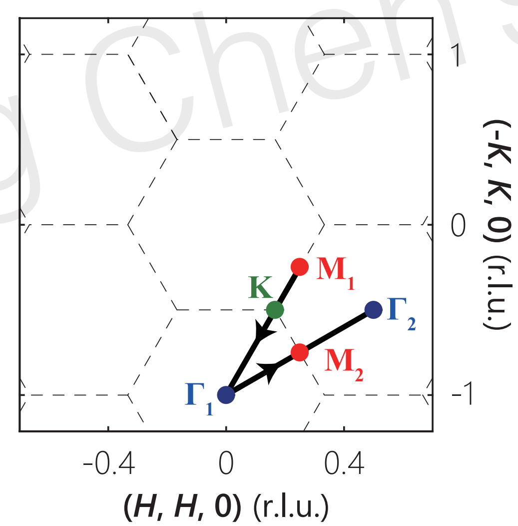
Spinon Fermi surface state

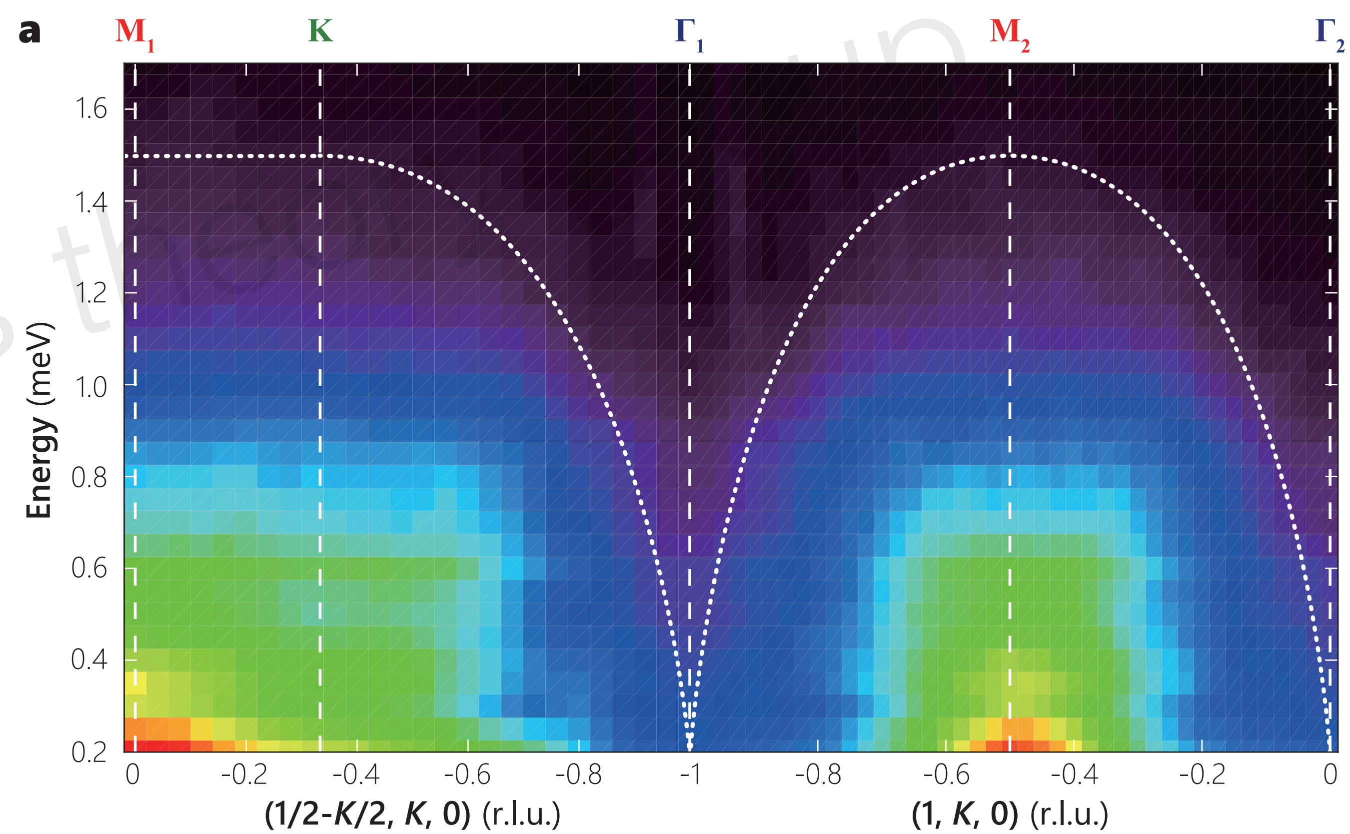
$$\boldsymbol{S}_{\boldsymbol{r}} = \frac{1}{2} \sum_{\alpha,\beta} f^{\dagger}_{\boldsymbol{r}\alpha} \boldsymbol{\sigma}_{\alpha\beta} f_{\boldsymbol{r}\beta},$$

$$H_{\mathrm{MFT}} = -t \sum_{\langle ij \rangle} (f^{\dagger}_{i\alpha} f_{j\alpha} + \mathrm{h.c.}) - \mu \sum_{i} f^{\dagger}_{i\alpha} f_{i\alpha}$$









Y Shen, YD Li **...GC*, J Zhao*** **Nature** 2016
YD Li, YM Lu, GC, PRB 2017

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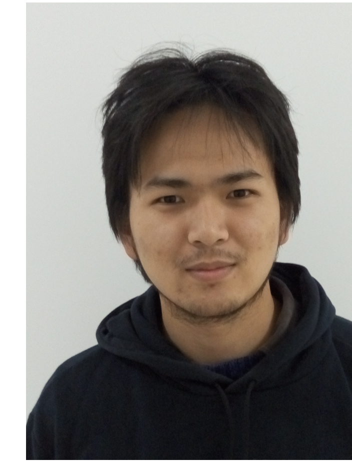
The experiments are inconsistent with a Dirac QSL nor a Z2 QSL.

How to further ensure the fractionalization?



Yao-Dong Li
(Fudan -> UCSB)

An idea: explore the weak field regime

1. Under a weak field, the spin liquid state would be preserved, and the fractionalized spinon remains to be a good description of the magnetic excitations.

2. Due to the small energy scale of rare-earth moments, this proposal can be realized.

3. We can predict the spectral weight shift under the field and predict the evolution of the continuum.

Realizable and Predictable.

Yao-Dong Li, **GC**, PRB 96, 075105 (2017)

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Spinon excitations with external field: One dimensional systems

Zeeman splitting in Spinon band with field

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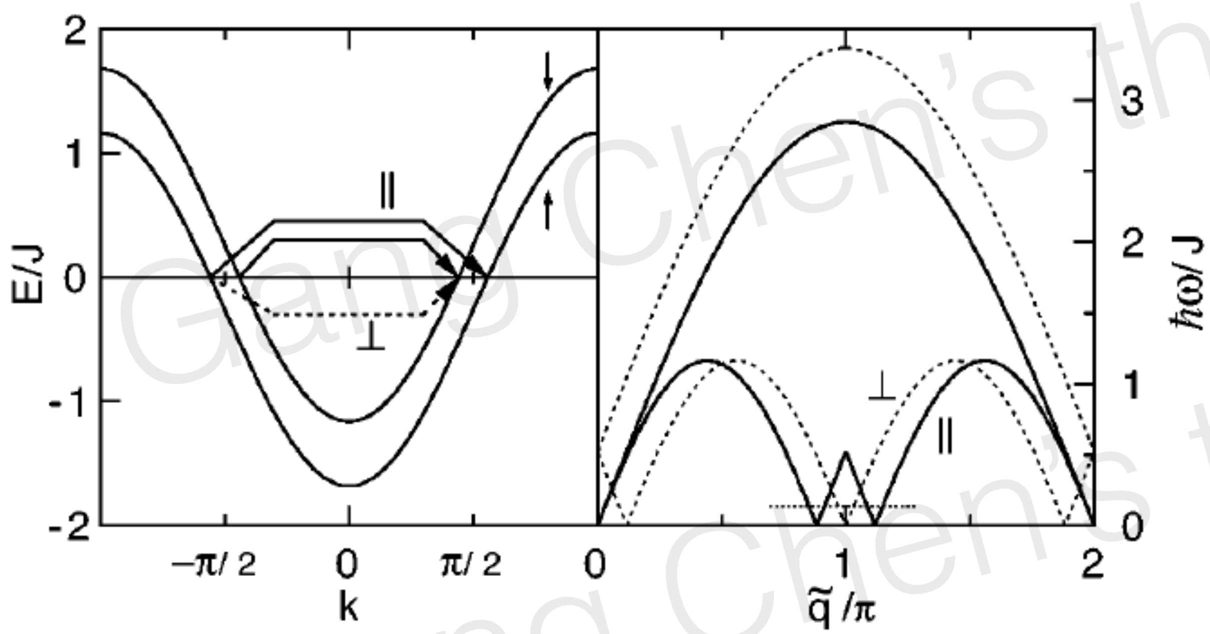
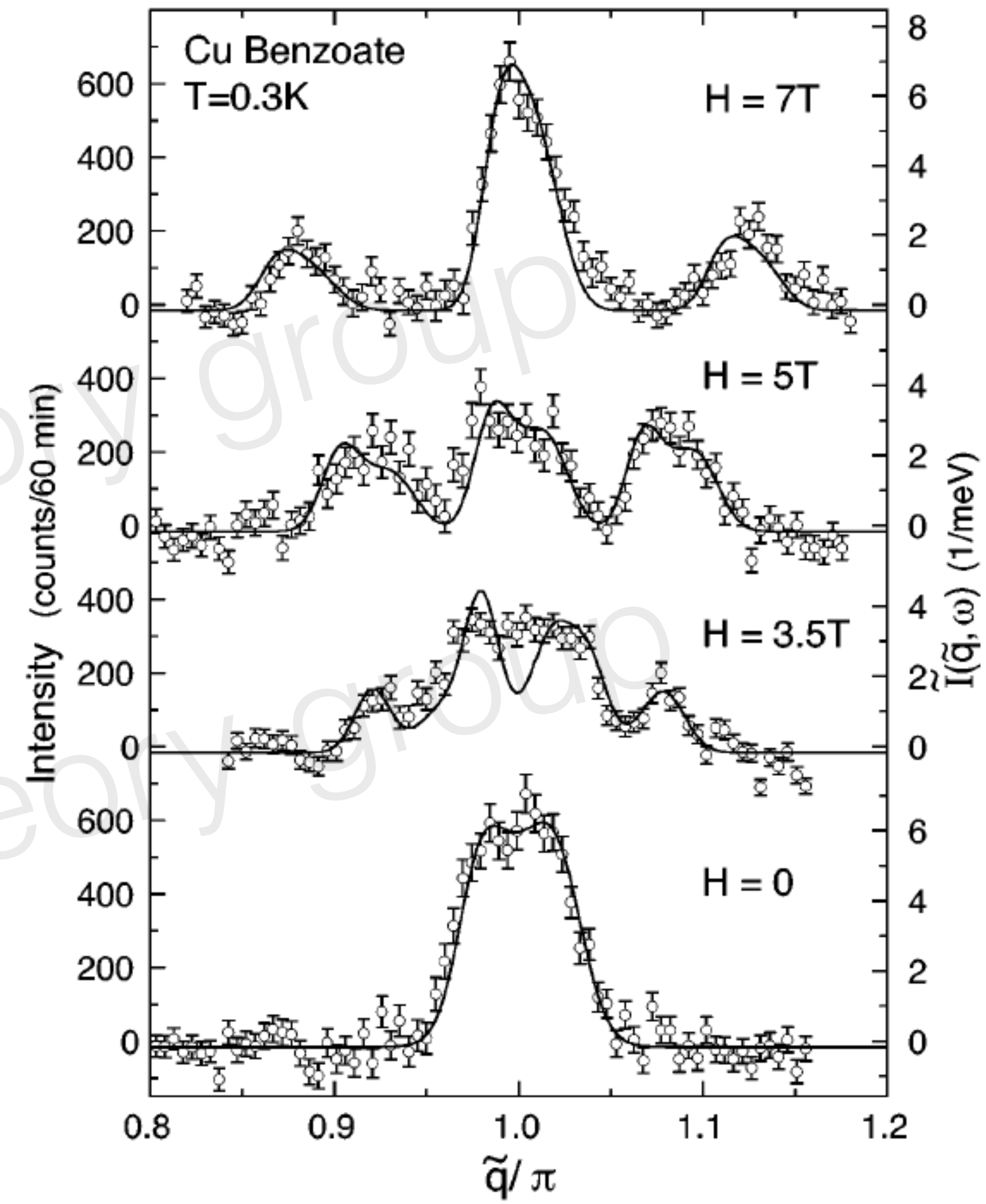
Corresponding modulation on neutron spectra

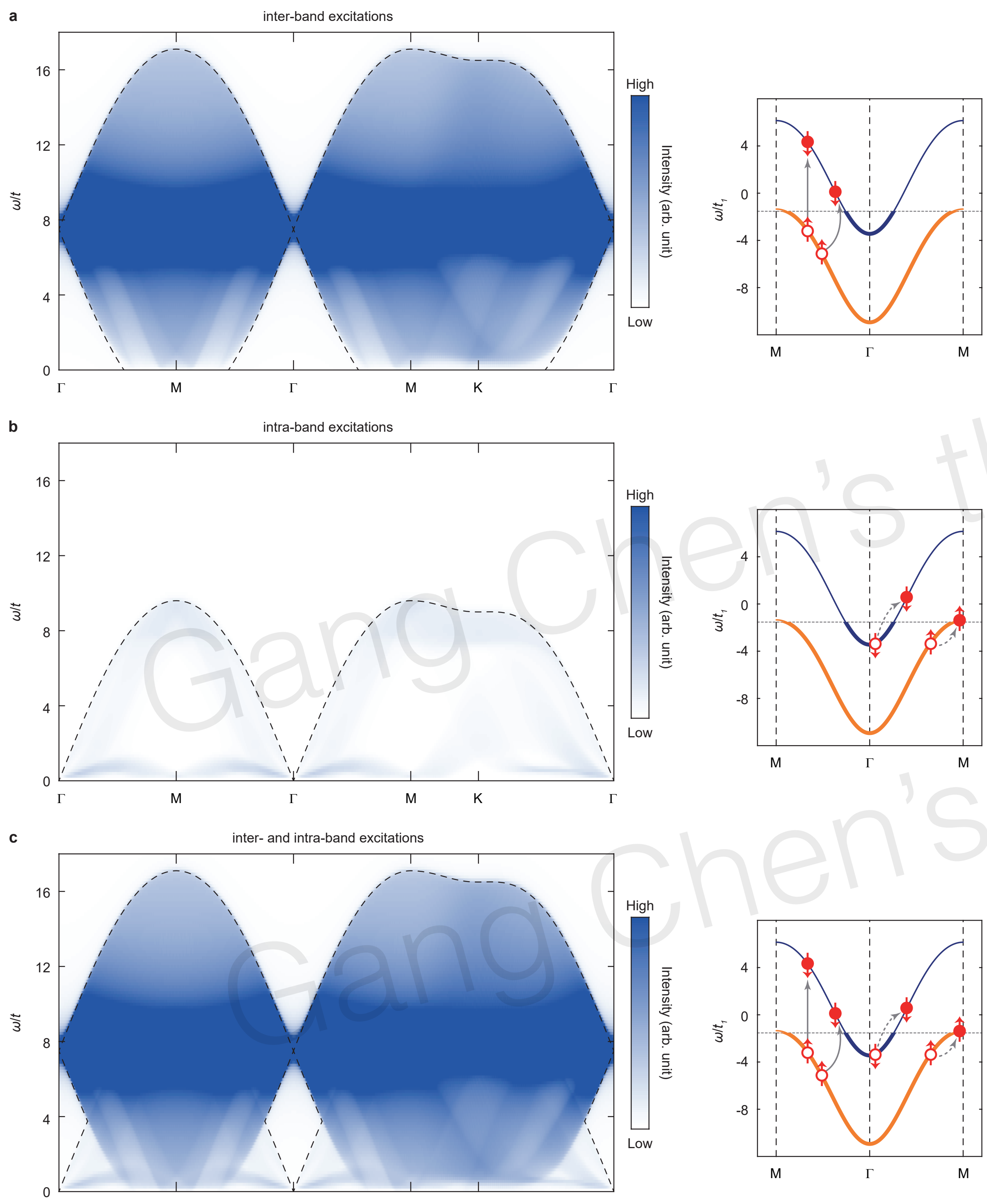


D. C. Dender *et al.*, *Phys. Rev. Lett.* **79**, 1750 (1997).



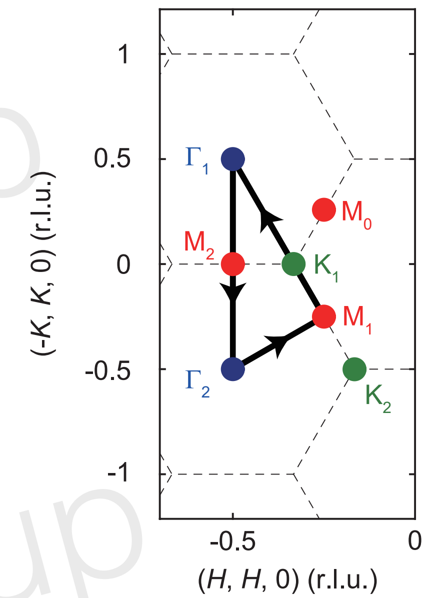
1D spin liquid is simple Luttinger liquid, and
1D spinons are simply domain walls, cannot extend to high dims.

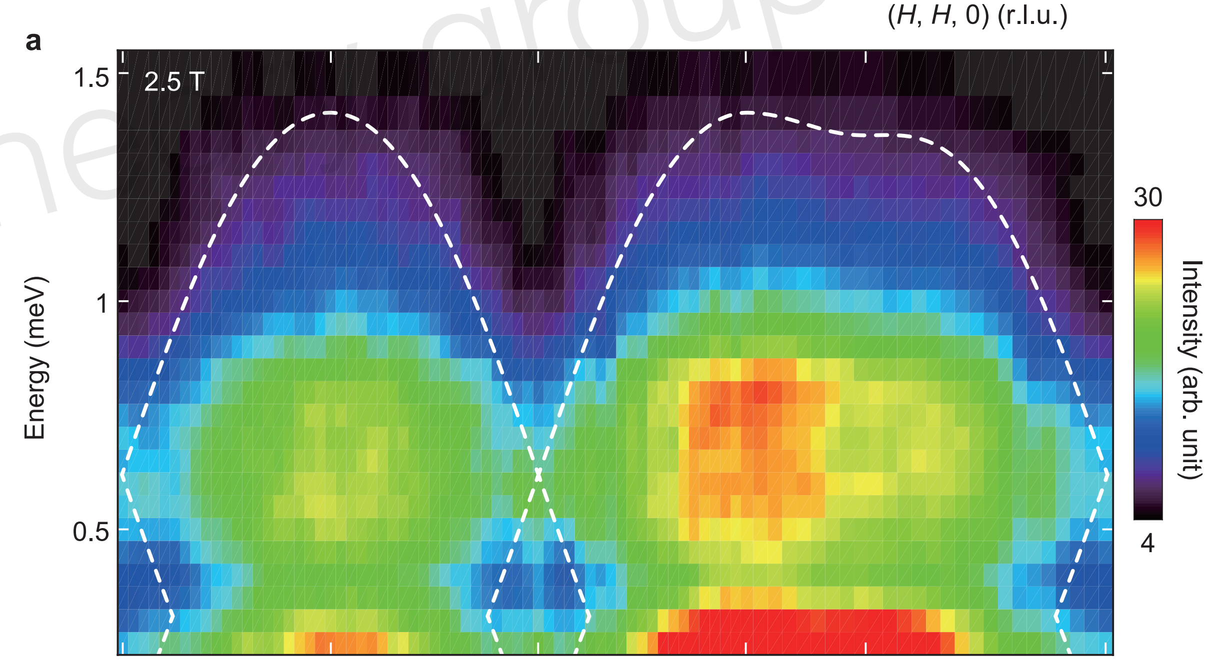
Strong Mott regime: only Zeeman coupling



$$\mathcal{H}_{\rm MFT} = -t_1 \sum_{\langle ij\rangle,\alpha} f^\dagger_{i\alpha} f_{j\alpha} - t_2 \sum_{\langle\langle ij\rangle\rangle,\alpha} f^\dagger_{i\alpha} f_{j\alpha} - \mu \sum_i f^\dagger_{i\alpha} f_{i\alpha}$$

$$- g_z \mu_{\rm B} H \sum_i f^\dagger_{i\alpha} \frac{\sigma^z_{\alpha\beta}}{2} f_{i\beta}$$





Y Shen, YD Li, …, GC*, J Zhao*
arXiv: 1708.06655

Summary

We study both zero and weak field regimes to understand the signatures of fractionalization in a spin liquid candidate.

Further directions:

1. how to detect spinon-gauge coupling?
2. confirm 2kF effect?
3. how to detect gauge field?
4. any other rare-earth magnets with similar properties?

Gang Chen's theory group

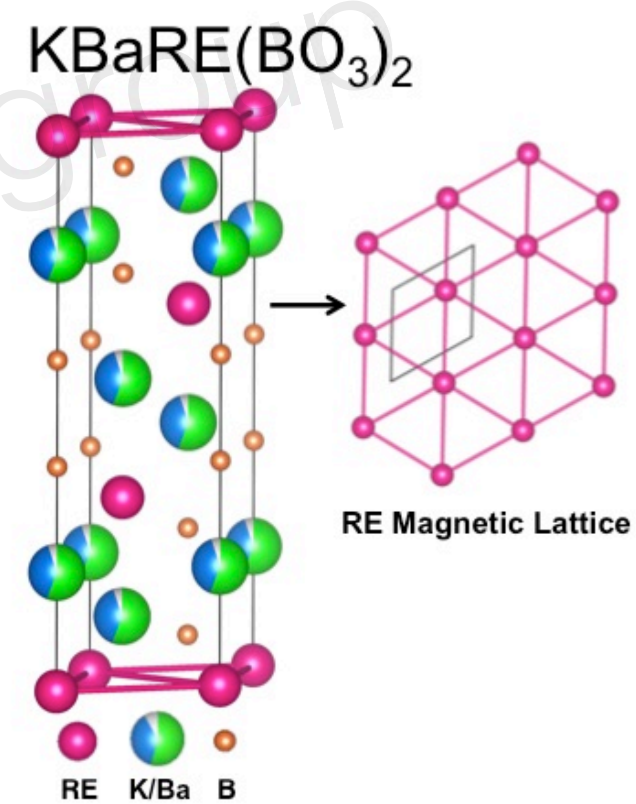
Use new materials to support materials

Compound	Magnetic ion	Space group	Local moment	Θ_{CW} (K)	Magnetic transition	Frustration para. f	Refs.
$YbMgGaO_4$	$Yb^{3+}(4f^{13})$	$R\bar{3}m$	Kramers doublet	-4	PM down to 60 mK	$f > 66$	[4]
$CeCd_3P_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-60	PM down to 0.48 K	$f > 200$	[5]
$CeZn_3P_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-6.6	AFM order at 0.8 K	$f = 8.2$	[7]
$CeZn_3As_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-62	Unknown	Unknown	[8]
$PrZn_3As_3$	$Pr^{3+}(4f^{2})$	$P6_3/mmc$	Non-Kramers doublet	-18	Unknown	Unknown	[8]
$NdZn_3As_3$	$Nd^{3+}(4f^{3})$	$P6_3/mmc$	Kramers doublet	-11	Unknown	Unknown	[8]

YD Li, XQ Wang, GC*, PRB 94, 035107 (2016)

Magnetism in the $KBaRE(BO_3)_2$ (RE=Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) series: materials with a triangular rare earth lattice

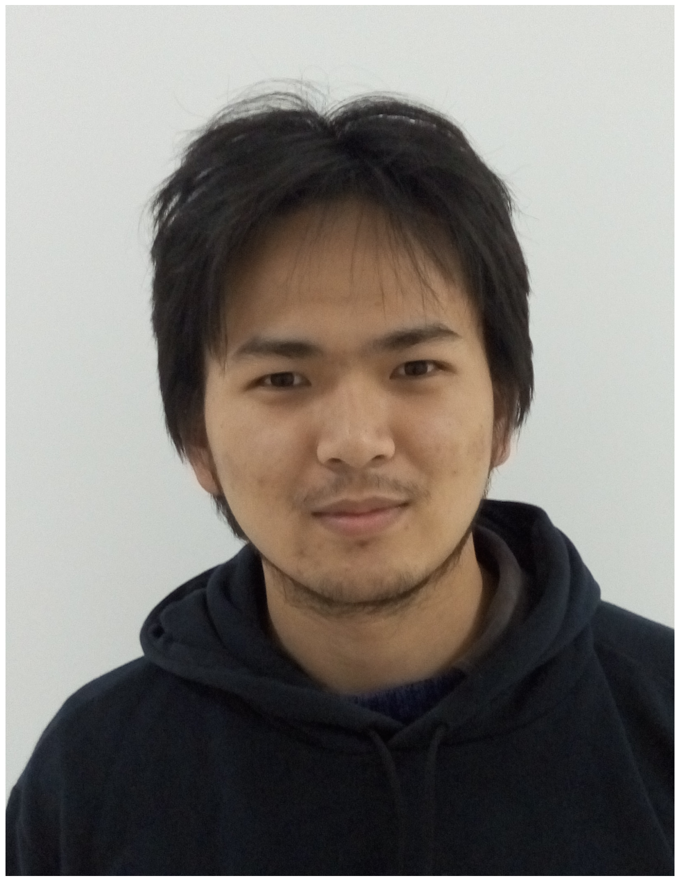
M. B. Sanders, F. A. Cevallos, R. J. Cava
Department of Chemistry, Princeton University, Princeton, New Jersey 08544



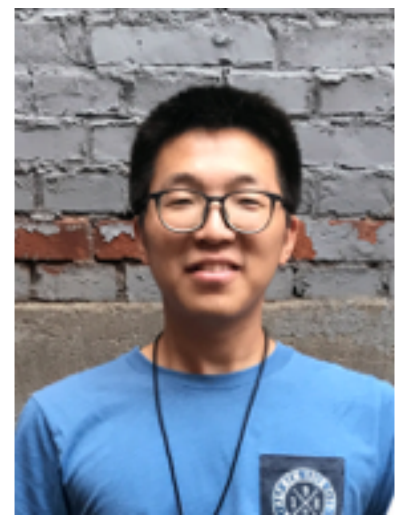
many ternary chalcogenides $NaRES_2$, $NaRESe_2$, $KRES_2$, $KRESe_2$, $KRETe_2$, $RbRES_2$, $RbRESe_2$, $RbRETe_2$, $CsRES_2$, $CsRESe_2$, etc.)

Lots of isostructural materials

Major collaborators for this piece of work



Yaodong Li
(now transferred to UCSB)



Yao Shen
(Fudan)

Jun Zhao
(Fudan)

Others: Yuesheng Li, Qingming Zhang,
Yuan-Ming Lu, etc

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