# Fractionalization and its experimental consequences in spin liquids

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## Outline

1. Signatures of fractionalization in U(1) spin liquid?

**GC** PRB 94,205107 (2016) **GC** PRB 96,085136 (2017) **GC** arxiv1706.04333(2017)

2. Spin quantum number fractionalization in YbMgGaO4? Is it spinon Fermi surface spin liquid?

> YD Li, XQ Wang, **GC**\*, YD Li, XQ Wang, **GC**\*, YD Li, Y Shen, YS Li, J Zhao, **GC**\*, YD Li, YM Lu, **GC**\*, YD Li, **GC**\*,

YS Li, **GC**\*, .., QM Zhang\*, Y Shen, YD Li, .., **GC**\*, J Zhao\*, Y Shen, YD Li, .., **GC**\*, J Zhao\*, PRB 94, 035107 (2016) PRB 94, 201114 (2016) arXiv 1608.06445 PRB 96, 054445 (2017) PRB 96, 075105 (2017)

PRL 115, 167203 (2015) Nature, 540, 559 (2016) arXiv 1708.06655

## The odd number "2"









Chenjie Wang (PI, Canada -> City University of Hong Kong, China)

#### Spin ice



#### Lattice gauge theory for U(1) spin liquid



#### One could think more realistically, ...

- Kramers' doublet  $H = \sum_{\langle ij \rangle} \{J_{zz} \mathbf{S}_i^z \mathbf{S}_j^z - J_{\pm} (\mathbf{S}_i^+ \mathbf{S}_j^- + \mathbf{S}_i^- \mathbf{S}_j^+) \\ + J_{\pm\pm} (\gamma_{ij} \mathbf{S}_i^+ \mathbf{S}_j^+ + \gamma_{ij}^* \mathbf{S}_i^- \mathbf{S}_j^-) \\ + J_{z\pm} [\mathbf{S}_i^z (\zeta_{ij} \mathbf{S}_j^+ + \zeta_{ij}^* \mathbf{S}_j^-) + i \leftrightarrow j] \},$ S. H. Curnoe, PRB (2008). Savary, **Balents**, PRL 2012  $H = \sum_{\langle ij \rangle} \{J_{zz} \mathbf{S}_i^z \mathbf{S}_j^z - J_{\pm} (\mathbf{S}_i^+ \mathbf{S}_j^- + \mathbf{S}_i^- \mathbf{S}_j^+) \\ + J_{\pm\pm} (\gamma_{ij} \mathbf{S}_i^+ \mathbf{S}_j^+ + \gamma_{ij}^* \mathbf{S}_i^- \mathbf{S}_j^-)$ S. Dnoda, etc, 2009  $+ J_{\pm\pm} (\gamma_{ij} \mathbf{S}_i^+ \mathbf{S}_j^+ + \gamma_{ij}^* \mathbf{S}_i^- \mathbf{S}_j^-)$ SB Lee, Onoda, **Balents**, 2012
- Dipole-octupole doublet

$$H = \sum_{\langle ij \rangle} J_x S_i^x S_j^x + J_y S_i^y S_j^y + J_z S_i^z S_j^z + J_{xz} (S_i^x S_j^z + S_i^z S_j^x).$$

Y-P Huang, **GC**, M Hermele, PRL 2014 Y-D LI, **GC**, PRB 2017

Nd2Ir2O7, Nd2Sn2O7, Nd2Zr2O7, Ce2Sn2O7 no sign problem for QMC on any lattice. It supports nontrivial phases





Aharonov-Bohm flux experienced by spinon via the 4 translation is identical to the flux in the hexagon.



2-spinon scattering state in an inelastic neutron scattering measurement

 $|a
angle \equiv |\boldsymbol{q}_{a}; z_{a}
angle,$ 

construct another 3 equal-energy states by translating one spinon by 3 lattice vector

$$|b\rangle = T_1^s(1)|a\rangle, \quad |c\rangle = T_2^s(1)|a\rangle, \quad |d\rangle = T_3^s(1)|a\rangle$$

> Xiao-Gang Wen, 2001, 2002, Essin, Hermele, 2014 Gang Chen, 1704.02734

#### Spectral periodicity of the spinon continuum



Lower edge of 2-spinon continuum  $\mathcal{L}(\boldsymbol{q}) = \mathcal{L}(\boldsymbol{q} + 2\pi(100)) = \mathcal{L}(\boldsymbol{q} + 2\pi(010))$ =  $\mathcal{L}(\boldsymbol{q} + 2\pi(001))$ , Upper edge of 2-spinon continuum  $\mathcal{U}(\boldsymbol{q}) = \mathcal{U}(\boldsymbol{q} + 2\pi(100)) = \mathcal{U}(\boldsymbol{q} + 2\pi(010))$ =  $\mathcal{U}(\boldsymbol{q} + 2\pi(001))$ .

#### But elastic neutron scattering will NOT see extra Bragg peak.

Xiao-Gang Wen, 2001, 2002, Essin, Hermele, 2014 Gang Chen, 1704.02734



FIG. 3. (Color online.) The lower excitation edge of the spinon continuum in U(1)<sub>0</sub> and U(1)<sub> $\pi$ </sub> QSLs. Here,  $\Gamma_0\Gamma_1 = 2\pi(\bar{1}11), \Gamma_0\Gamma_2 = 2\pi(1\bar{1}1)$ . We set  $J_{\perp} = 0.12J_{zz}$  for U(1)<sub>0</sub> QSL in (a) and  $J_{\perp} = -J_{zz}/3$  for U(1)<sub> $\pi$ </sub> QSL in (b).

Lower excitation edge of spinon continuum within the gauge MFT calculation

#### How to observe the "magnetic monopole"?



at higher energy, detect monopole continuum

Gang Chen, arXiv 1706.04333 (2017)

Suggestion 1: combine thermal transport with inelastic neutron



#### Suggestion 2: effect of the external magnetic field



The weak magnetic field polarizes Sz slightly, and thus modifies the background electric field distribution. This further modulates monopole band structure, creating "**Hofstadter**" monopole band, which may be detectable in inelastic neutron.

### Summary 1

- We point out the existence of "magnetic monopole continuum" in the U(1) quantum spin liquid, and monopole is purely quantum origin.
- We point out that the "magnetic monopole" always experiences a Pi flux, and thus supports enhanced spectral periodicity with **folded** Brillouin zone, while spinons most of the time experience Pi flux.

In fact, continuum has been observed in Pr2Hf2O7 (R. Sibille, et al, arXiv 1706.03604).



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PRL 115, 167203 (2015) Nature, 540, 559 (2016) arXiv 1708.06655 A rare-earth triangular lattice quantum spin liquid: YbMgGaO4







Qingming Zhang (Renmin)

Yuesheng Li (Renmin)

- 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.
- I think it is a spinon Fermi surface U(1) QSL. •

## The microscopics



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



#### anisotropic both in spin space and in real space !

YD Li, XQ Wang, GC, arXiv1512, PRB 2016 YD Li, Y Shen, YS Li, J Zhao, GC\*, arXiv 1608.06445

> DMRG: Chernyshev, White, 2017 Jize Zhao, XQ Wang, 2017

#### Polarized neutron scattering

## Strong exchange anisotropy in YbMgGaO $_4$ from polarized neutron diffraction

Sándor Tóth,<sup>1,\*</sup> Katharina Rolfs,<sup>2</sup> Andrew R. Wildes,<sup>3</sup> and Christian Rüegg<sup>1,4</sup>

 <sup>1</sup>Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
 <sup>2</sup>Laboratory for Scientific Developments and Novel Materials, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
 <sup>3</sup>Institut Max von Laue-Paul Langevin, 38042 Grenoble 9, France
 <sup>4</sup>Department of Quantum Matter Physics, University of Geneva, 1211 Genève, Switzerland (Dated: May 17, 2017)

We measured the magnetic correlations in the triangular lattice spin-liquid candidate material YbMgGaO<sub>4</sub> via polarized neutron diffraction. The extracted in-plane and out-of-plane components of the magnetic structure factor show clear anisotropy. We found that short-range correlations persist at the lowest measured temperature of 52 mK and neutron scattering intensity is centered at the M middle-point of the hexagonal Brillouin-zone edge. Moreover, we found pronounced spin anisotropy, with different correlation lengths for the in-plane and out-of-plane spin components. When comparing to a self-consistent Gaussian appoximation, our data clearly support a model with only first-neighbor coupling and strongly anisotropic exchanges.



arXiv 1705.05699







Yao Shen (Fudan)

Yao-Dong Li (Fudan->here)

Jun Zhao (Fudan)



#### Inelastic neutron scattering



#### Particle-hole continuum of the spinon Fermi surface $\Gamma_2$ K M, а - 1/3 70 1.6 Intensity (arb. unit) $\frac{2\pi}{\sqrt{3}}$ $\frac{4\pi}{3}$ 0 b СГ (-*K*, *K*, 0) (r.l.u.) -0.5 -0.6 -0.4 -0.8 -0.8 -0.6 -0.4 -0.2 0.2 -1 -0.4 0.4 0 0 (1/2-K/2, K, 0) (r.l.u.) (H, H, 0) (r.l.u.) (1, K, 0) (r.l.u.) -1 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 (H, H, 0) (r.l.u.)



# More assurance from projective symmetry group analysis





Yao-Dong Li (Fudan->UCSB)

Yuan-Ming Lu (OSU)



 $T_1^{-1}T_2T_1T_2^{-1} = T_1^{-1}T_2^{-1}T_1T_2 = 1,$  $C_2^{-1}T_1C_2T_2^{-1} = C_2^{-1}T_2C_2T_1^{-1} = 1,$  $S_6^{-1}T_1S_6T_2 = S_6^{-1}T_2S_6T_2^{-1}T_1^{-1} = 1,$  $(C_2)^2 = (S_6)^6 = (S_6C_2)^2 = 1.$ 
$$\begin{split} \boldsymbol{S}_{\boldsymbol{r}} &= \frac{1}{2} \sum_{\alpha,\beta} f_{\boldsymbol{r}\alpha}^{\dagger} \boldsymbol{\sigma}_{\alpha\beta} f_{\boldsymbol{r}\beta}, \\ \boldsymbol{\Psi}_{\boldsymbol{r}} &= (f_{\boldsymbol{r}\uparrow}, f_{\boldsymbol{r}\downarrow}^{\dagger}, f_{\boldsymbol{r}\downarrow}, -f_{\boldsymbol{r}\uparrow}^{\dagger})^T \end{split}$$
 $oldsymbol{S_r} = rac{1}{4} \Psi^{\dagger}_{oldsymbol{r}}(oldsymbol{\sigma} \otimes I_{2 imes 2}) \Psi_{oldsymbol{r}},$  $\boldsymbol{G_r} = rac{1}{4} \Psi_{\boldsymbol{r}}^{\dagger} (I_{2 \times 2} \otimes \boldsymbol{\sigma}) \Psi_{\boldsymbol{r}},$  $[S^{\mu}_{r}, G^{\nu}_{r}] = 0.$ 

The spin transformation and gauge transformation commute with each other. XG Wen PRB 2002

#### Reduction and simplification: classification mean field states

$$\begin{array}{ll} \text{Mean-field model} & H_{\text{MF}} = -\frac{1}{2} \sum_{(r,r')} \left[ \Psi_{r}^{\dagger} u_{rr'} \Psi_{r'} + h.c. \right], \\ & \Psi_{r} = (f_{r\uparrow}, f_{r\downarrow}^{\dagger}, f_{r\downarrow}, -f_{r\uparrow}^{\dagger})^{T} \\ \text{symmetry transformation } \mathcal{O} & u_{rr'} = \mathcal{G}_{\mathcal{O}(r)}^{\mathcal{O}\dagger} \mathcal{U}_{\mathcal{O}}^{\mathcal{O}(r)\mathcal{O}(r')} \mathcal{U}_{\mathcal{O}} \mathcal{G}_{\mathcal{O}(r')}^{\mathcal{O}}. \\ & \text{spin rotation} & \text{gauge rotation} \\ \\ \text{group relation } \mathcal{O}_{1}\mathcal{O}_{2}\mathcal{O}_{3}\mathcal{O}_{4} = 1 \\ & \mathcal{U}_{\mathcal{O}_{1}}\mathcal{G}_{r}^{\mathcal{O}_{1}}\mathcal{U}_{\mathcal{O}_{2}}\mathcal{G}_{\mathcal{O}_{2}\mathcal{O}_{3}\mathcal{O}_{4}(r)}^{\mathcal{O}_{2}}\mathcal{U}_{\mathcal{O}_{3}}\mathcal{O}_{4}(r)} \mathcal{U}_{\mathcal{O}_{3}}\mathcal{G}_{\mathcal{O}_{3}\mathcal{O}_{4}(r)}^{\mathcal{O}}\mathcal{U}_{\mathcal{O}_{4}}\mathcal{G}_{\mathcal{O}_{4}(r)}^{\mathcal{O}_{4}} \\ & = \mathcal{U}_{\mathcal{O}_{1}}\mathcal{U}_{\mathcal{O}_{2}}\mathcal{U}_{\mathcal{O}_{3}}\mathcal{U}_{\mathcal{O}_{4}}\mathcal{G}_{\mathcal{O}_{2}\mathcal{O}_{3}\mathcal{O}_{4}(r)}\mathcal{G}_{\mathcal{O}_{3}\mathcal{O}_{4}(r)}^{\mathcal{O}_{3}}\mathcal{G}_{\mathcal{O}_{3}\mathcal{O}_{4}(r)}\mathcal{G}_{\mathcal{O}_{4}(r)}^{\mathcal{O}_{4}} \\ & \in \text{IGG}, \\ \\ & \mathcal{U}_{\mathcal{O}_{1}}\mathcal{U}_{\mathcal{O}_{2}}\mathcal{U}_{\mathcal{O}_{3}}\mathcal{U}_{\mathcal{O}_{4}} = \pm I_{4\times 4}, \quad \{\pm I_{4\times 4}\} \subset \text{IGG} \end{array}$$

 $\mathcal{G}_{\boldsymbol{r}}^{\mathcal{O}_1} \mathcal{G}_{\mathcal{O}_2 \mathcal{O}_3 \mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_2} \mathcal{G}_{\mathcal{O}_3 \mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_3} \mathcal{G}_{\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_4} \in \mathrm{IGG}$ 

square lattice by J Alicea's group 2014

#### Projective symmetry group classification

U(1) QSL	$W_{\boldsymbol{r}}^{T_1}$	$W^{T_2}_{m{r}}$	$W^{C_2}_{m{r}}$	$W^{C_6}_{r}$
U1A00	$I_{2 \times 2}$	$I_{2 \times 2}$	$I_{2 \times 2}$	$I_{2 \times 2}$
U1A10	$I_{2\times 2}$	$I_{2 \times 2}$	$i\sigma^y$	$I_{2 \times 2}$
U1A01	$I_{2\times 2}$	$I_{2 \times 2}$	$I_{2 \times 2}$	$i\sigma^y$
U1A11	$I_{2\times 2}$	$I_{2 \times 2}$	$i\sigma^y$	$i\sigma^y$
U1B00	$I_{2 \times 2}$	$(-1)^x I_{2\times 2}$	$(-1)^{xy}I_{2\times 2}$	$(-1)^{xy-\frac{y(y-1)}{2}}I_{2\times 2}$
U1B10	$I_{2 \times 2}$	$(-1)^x I_{2\times 2}$	$i\sigma^y(-1)^{xy}$	$(-1)^{xy-\frac{y(y-1)}{2}}I_{2\times 2}$
U1B01	$I_{2\times 2}$	$(-1)^x I_{2\times 2}$	$(-1)^{xy}I_{2\times 2}$	$i\sigma^y(-1)^{xy-rac{y(y-1)}{2}}$
U1B11	$I_{2\times 2}$	$(-1)^x I_{2\times 2}$	$i\sigma^y(-1)^{xy}$	$i\sigma^y(-1)^{xy-\frac{y(y-1)}{2}}$

TABLE III. The transformation for the spinons under four U1A PSGs that are labeled by  $U1An_{C_2}n_{S_6}$ .

U(1) PSGs	$T_1$	$T_2$		$S_6$
U1A00	$ \begin{array}{ccc} f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow} \\ f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow} \end{array} $	$\begin{array}{c} f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow} \\ f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow} \end{array}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f_{(y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{i\frac{5\pi}{6}} f_{(y,x),\uparrow}$	$f_{(x,y),\uparrow} \to e^{-i\frac{\pi}{3}} f_{(x-y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f_{(x-y,x),\downarrow}$
U1A10	$\begin{array}{c} f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow} \\ f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow} \end{array}$	$\begin{array}{c} f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow} \\ f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow} \end{array}$	$ \begin{array}{c} f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f^{\dagger}_{(y,x),\uparrow} \\ f_{(x,y),\downarrow} \to e^{-i\frac{\pi}{6}} f^{\dagger}_{(y,x),\downarrow} \end{array} $	$f_{(x,y),\uparrow} \to e^{-i\frac{\pi}{3}} f_{(x-y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f_{(x-y,x),\downarrow}$
U1A01	$ \begin{aligned} f_{(x,y),\uparrow} &\to f_{(x+1,y),\uparrow} \\ f_{(x,y),\downarrow} &\to f_{(x+1,y),\downarrow} \end{aligned} $	$\begin{array}{l} f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow} \\ f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow} \end{array}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f_{(y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{i\frac{5\pi}{6}} f_{(y,x),\uparrow}$	$f_{(x,y),\uparrow} \to -e^{-i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\uparrow}$
U1A11	$\begin{array}{ccc} f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow} \\ f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow} \end{array}$	$\begin{array}{c} f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow} \\ f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow} \end{array}$	$ \begin{aligned} f_{(x,y),\uparrow} &\to e^{i\frac{\pi}{6}} f_{(y,x),\uparrow}^{\downarrow\dagger} \\ f_{(x,y),\downarrow} &\to e^{-i\frac{\pi}{6}} f_{(y,x),\downarrow}^{\downarrow\dagger} \end{aligned} $	$f_{(x,y),\uparrow} \rightarrow -e^{-i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\downarrow}$ $f_{(x,y),\downarrow} \rightarrow e^{+i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\uparrow}$

#### Spectroscopic constraints

#### We use PSG to predict the corresponding spectrum.



The U1A00 state is the spinon Fermi surface state that we proposed in Shen, et al, Nature.

U1A01



**Yao-Dong Li** 

VMC study has been done bty Balents' group

#### Dynamic spin structure factor





#### Explore the weak field regime

Yao-Dong Li (Fudan)

Continuing the recent proposal of the spinon Fermi surface U(1) spin liquid state for YbMgGaO<sub>4</sub> in Yao-Dong Li, *et al*, arXiv:1612.03447 and Yao Shen, *et al*, Nature 2016, we explore the experimental consequences of the external magnetic fields on this exotic state. Specifically, we focus on the *weak field regime* where the spin liquid state is preserved and the fractionalized spinon excitations remain to be a good description of the magnetic excitations. From the spin-1/2 nature of the spinon excitation, we predict the unique features of spinon continuum when the magnetic field is applied to the system. Due to the small energy scale of the rare-earth magnets, our proposal for the spectral weight shifts in the magnetic fields can be immediately tested by inelastic neutron scattering experiments. Several other experimental aspects about the spinon Fermi surface and spinon excitations are discussed and proposed. Our work provides a new way to examine the fractionalized spinon excitation and the candidate spin liquid states in the rare-earth magnets like YbMgGaO<sub>4</sub>.

**Reasonable, Feasible, and Predictabl** 

isotope effect in BCS superconductor

YD Li, **GC**, arXiv: **1703.01876** PhysRevB, 96, 075105

ESR response in a field by Oleg Starykh's group, 2017

#### Organic spin liquids?

(b)

(a)





#### Prediction for dynamic spin structure factor



We predict:

1. The system remains gapless and spinon continuum persists

- 2. spectral weight shifts
- 3. the spectral crossing at Gamma point
- 4. the presence of lower and upper excitation edges

Very different from magnon in the field !!

### Excitation continuum in weakly magnetized YbMgGaQ4



YD Li, **GC**\*, PRB 96, 075105 (2017)

#### Finally, lots of isostructural materials

Compound	Magnetic ion	Space group	Local moment	$\Theta_{\mathrm{CW}}\left(\mathrm{K}\right)$	Magnetic transition	Frustration para. $f$	Refs.
YbMgGaO <sub>4</sub>	$Yb^{3+}(4f^{13})$	R3m	Kramers doublet	-4	PM down to 60 mK	f > 66	[4]
CeCd <sub>3</sub> P <sub>3</sub>	$Ce^{3+}(4f^1)$	$P6_3/mmc$	Kramers doublet	-60	PM down to 0.48 K	f > 200	[5]
CeZn <sub>3</sub> P <sub>3</sub>	$Ce^{3+}(4f^1)$	$P6_3/mmc$	Kramers doublet	-6.6	AFM order at 0.8 K	f = 8.2	[7]
CeZn <sub>3</sub> As <sub>3</sub>	$Ce^{3+}(4f^1)$	$P6_3/mmc$	Kramers doublet	-62	Unknown	Unknown	[8]
PrZn <sub>3</sub> As <sub>3</sub>	$Pr^{3+}(4f^2)$	$P6_3/mmc$	Non-Kramers doublet	-18	Unknown	Unknown	[8]
NdZn <sub>3</sub> As <sub>3</sub>	$Nd^{3+}(4f^{3})$	$P6_3/mmc$	Kramers doublet	-11	Unknown	Unknown	[8]

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

Magnetism in the KBaRE(BO<sub>3</sub>)<sub>2</sub> (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



# Summary

1. We propose YbMgGaO4 to be a spin-orbit-coupled spin liquid.

2. The signature of spin fractionalization has been discovered and interpreted as spinons.

3. Predictions have been made for the weakly magnetized regime. It can be immediately tested by inelastic neutron. It has been **confirmed** in Jun Zhao's recent experiment.