Coulombic Quantum Liquids in Spin-1/2 Pyrochlores

Lucile Savary

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Collaborators

Leon Balents
(KITP, UCSB)

$Yb_2Ti_2O_7$ project

Kate Ross

Bruce Gaulin

(experiments, Mc Master)

Special thanks to Benjamin Canals and Peter Holdsworth.

Rare-earth pyrochlores

- grown rare-earth pyrochlores: $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$, $Ho_2Sn_2O_7$, $Dy_2Sn_2O_7$, $Er_2Ti_2O_7$, $Yb_2Ti_2O_7$, $Tb_2Ti_2O_7$, $Er_2Sn_2O_7$, $Tb_2Sn_2O_7$, $Pr_2Sn_2O_7$, $Nd_2Sn_2O_7$, $Gd_2Sn_2O_7$, ...

- grown rare-earth B-site spinels: $CdEr_2S_4$, $CdEr_2Se_4$, $CdYb_2S_4$, $CdYb_2Se_4$, $MgYb_2S_4$, $MgYb_2S_4$, $MnYb_2S_4$, $MnYb_2Se_4$, $FeYb_2S_4$, $CdTm_2S_4$, $CdHo_2S_4$, $FeLu_2S_4$, $MnLu_2S_4$, $MnLu_2Se_4$, ...

behaviors:

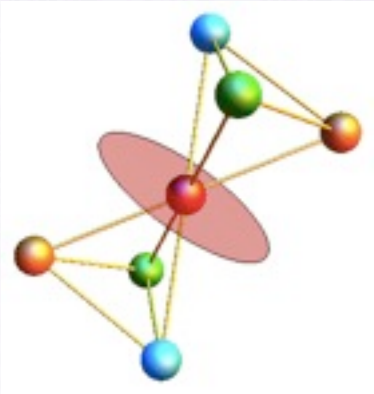
spin ices

quantum AFM

quantum spin liquids ?

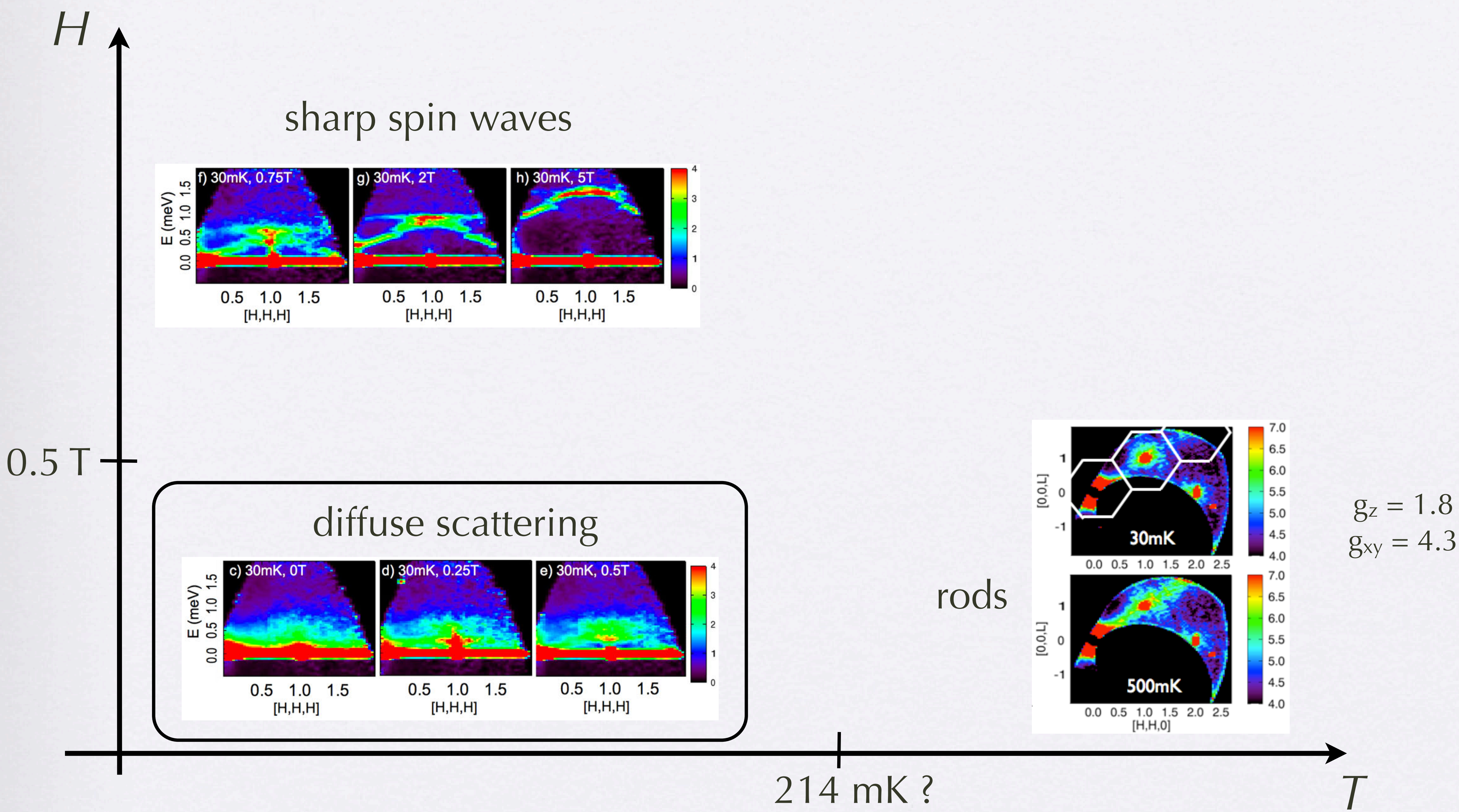
spin ice ?

lots of room for diverse behaviors!



Gardner, Gingras, Greedan, RMP 2010, Lago *et al.* PRL 2010

$Yb_2Ti_2O_7$: puzzling experimental features



quantum spin liquid regime?

Ross *et al.*, PRL 2009, PRB 2011

Outline

- method
- results
- experimental signatures
- materials

based on Savary and Balents, PRL **108**, 037202 (2012)

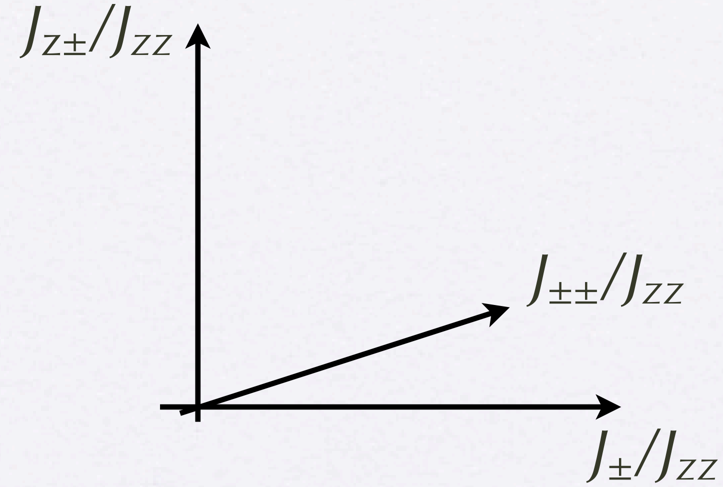
General NN exchange Hamiltonian for effective spins 1/2

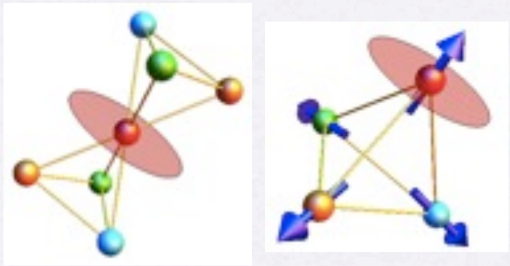
$$H = \sum_{\langle ij \rangle} \Big[\quad J_{zz} \mathsf{S}_i^z \mathsf{S}_j^z \qquad \text{(spin ice)}$$

$$- J_{\pm} (\mathsf{S}_i^+ \mathsf{S}_j^- + \mathsf{S}_i^- \mathsf{S}_j^+)$$

$$+ J_{z\pm} \left[\mathsf{S}_i^z (\zeta_{ij} \mathsf{S}_j^+ + \zeta_{ij}^* \mathsf{S}_j^-) + i \leftrightarrow j \right]$$

$$+ J_{\pm\pm} \left[\gamma_{ij} \mathsf{S}_i^+ \mathsf{S}_j^+ + \gamma_{ij}^* \mathsf{S}_i^- \mathsf{S}_j^- \right] \Big]$$





local axes, specific local bases

to each material corresponds a set of *J*'s

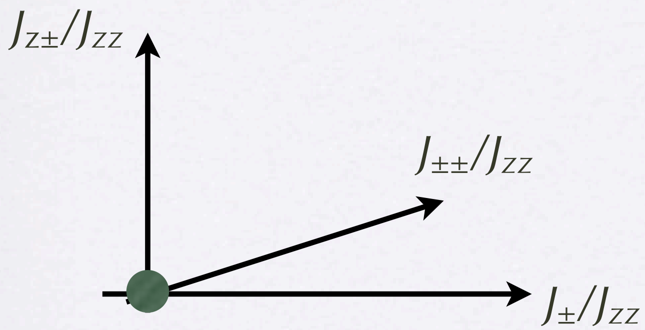
What is the phase diagram ?

Are there any exotic phases there ?

Curnoe PRB 2008, Ross Savary Gaulin Balents PRX 2011

"Known" classical and quantum SLs

classical spin ice

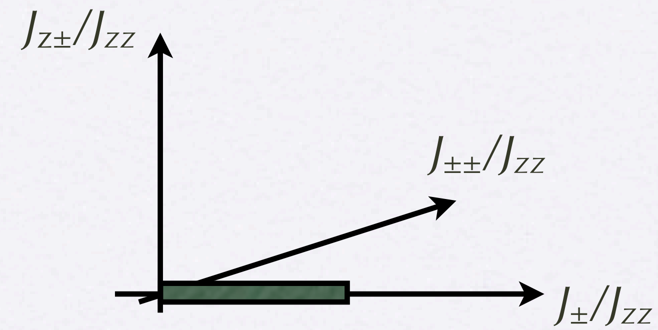


thermal spin liquid

extensively many degenerate ground states

magnetic monopoles
= spinons

U(1) quantum spin liquid



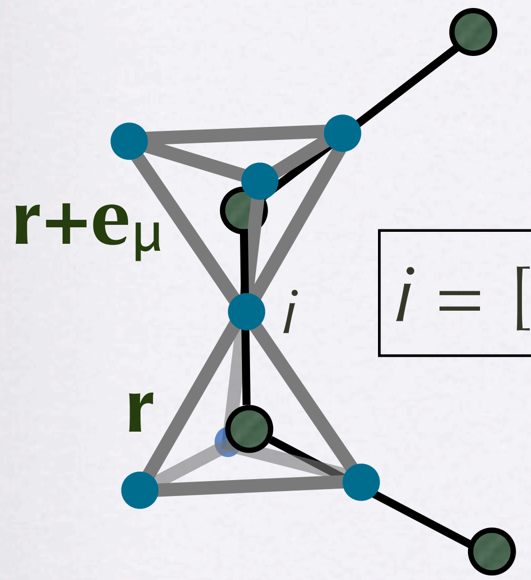
quantum spin liquid

one entangled ground state
(= vacuum)

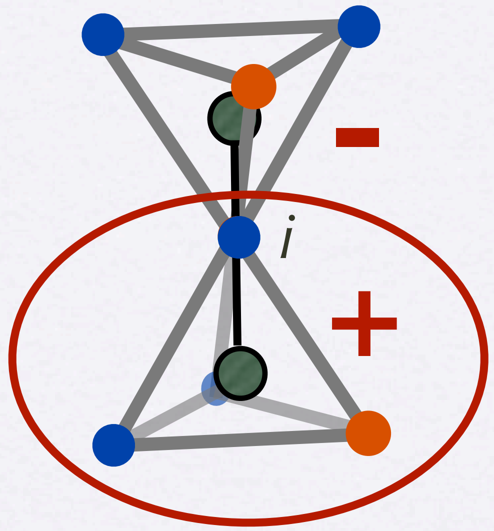
spinons
"electric" monopoles
gapless photon

Gingras, Introduction to Frustrated Magnetism (2011), Hermele Fisher Balents, PRB 2004

How we do this: compact abelian lattice Higgs theory



dual diamond lattice



$$S^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} = \Phi^{\dagger}_{\mathbf{r}}\, \mathsf{s}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu}\, \Phi_{\mathbf{r}+\mathbf{e}_\mu}$$

$$S^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} = \mathsf{s}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu}$$

$$\begin{cases} \Phi_{\mathbf{r}} \to \Phi_{\mathbf{r}}\, e^{-i\chi_{\mathbf{r}}} \\ \mathsf{s}^{\pm}_{\mathbf{r}\mathbf{r}'} \to \mathsf{s}^{\pm}_{\mathbf{r}\mathbf{r}'}\, e^{\pm i(\chi_{\mathbf{r}'}-\chi_{\mathbf{r}})} \end{cases}$$

U(1) gauge symmetry

the slave particles have a simple interpretation

gauge Mean Field Theory (gMFT)

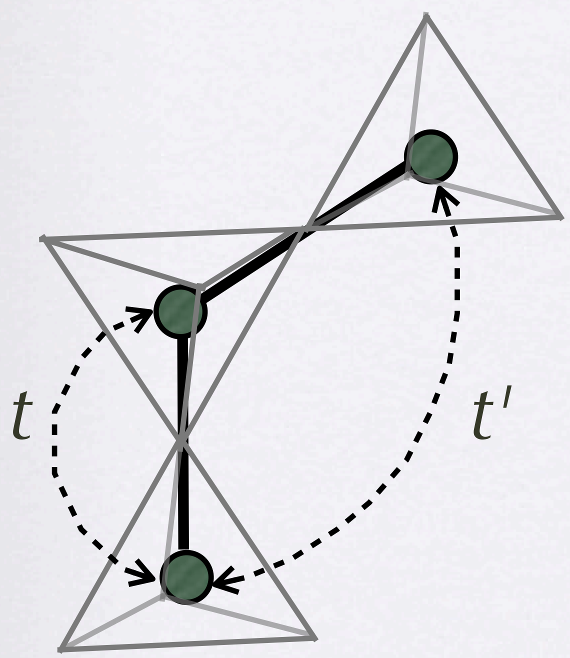
$$\Phi^\dagger \Phi\, \mathsf{s}\, \mathsf{s} \to \Phi^\dagger \Phi \langle \mathsf{s} \rangle \langle \mathsf{s} \rangle + \langle \Phi^\dagger \Phi \rangle \mathsf{s} \langle \mathsf{s} \rangle + \langle \Phi^\dagger \Phi \rangle \langle \mathsf{s} \rangle \mathsf{s} - 2 \langle \Phi^\dagger \Phi \rangle \langle \mathsf{s} \rangle \langle \mathsf{s} \rangle$$

$$H_{\mathsf{s}}^{\mathrm{MF}} = -\sum_{\mathbf{r}} \sum_{\mu} \vec{\mathsf{h}}^{\mathrm{MF}}_{\mathrm{eff},\mu} \cdot \vec{\mathsf{s}}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu}$$

free (but self-consistent) "spins"

$$H_{\Phi}^{\mathrm{MF}} = -\sum_{\mathbf{r}} \sum_{\mu \neq \nu} \left[t_{\mu}^{\mathrm{MF}} \Phi^\dagger_{\mathbf{r}} \Phi_{\mathbf{r}+\mathbf{e}_\mu} + t'^{\mathrm{MF}}_{\mu\nu} \Phi^\dagger_{\mathbf{r}} \Phi_{\mathbf{r}+\mathbf{e}_\mu-\mathbf{e}_\nu} + \mathrm{h.c.} \right]$$

hopping Hamiltonian for spinons in fixed (but self-consistent) background



Solve the consistency equations

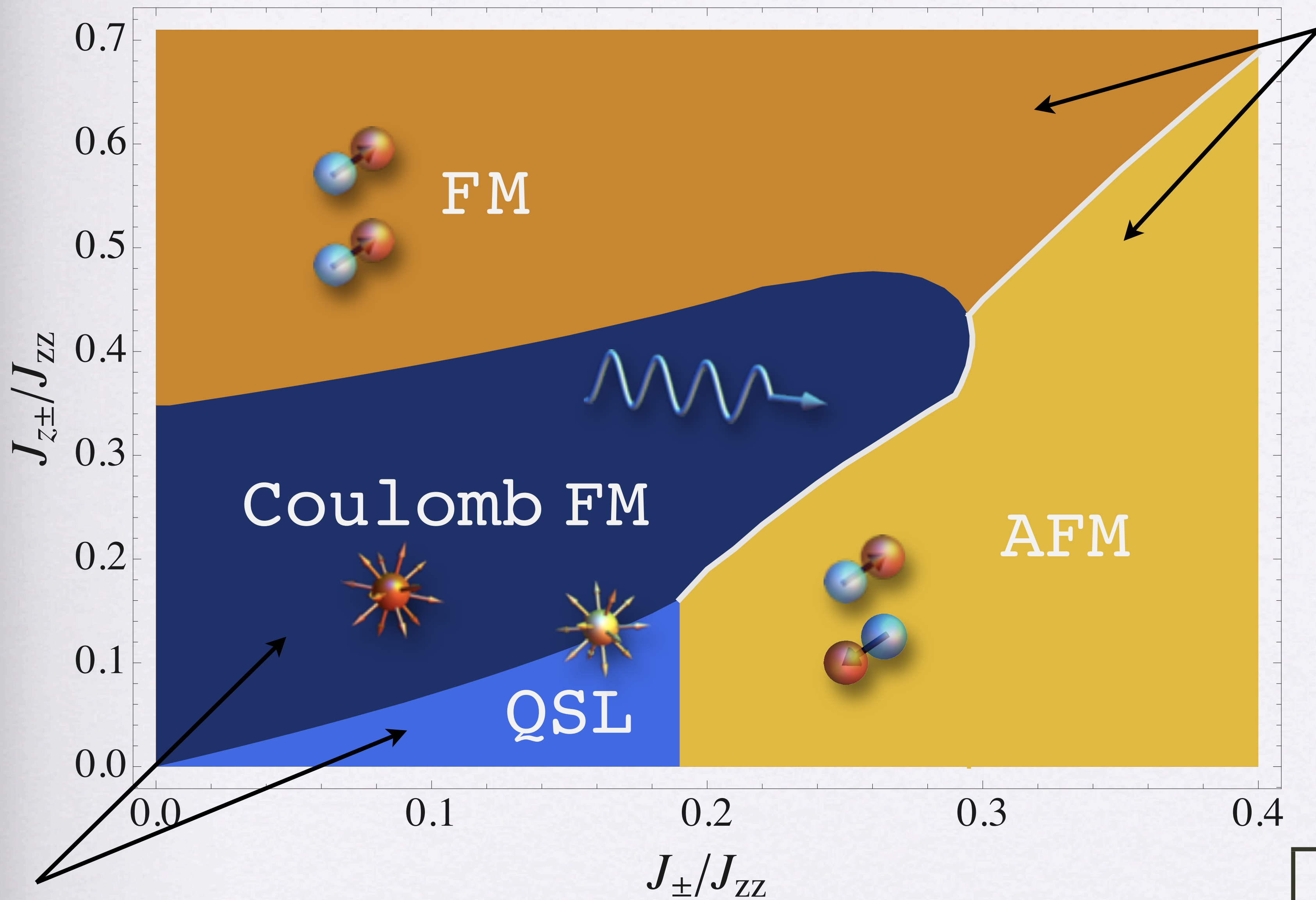
our spinons are bosons

$\Longrightarrow$ they can condense

$\langle \Phi \rangle$	phase
$\neq 0$	conventional
$= 0$	exotic

Phase diagram

$J_{\pm\pm} = 0$



Higgs
= gauge symmetry breaking
= condensed
= **conventional phases**

$\langle \Phi \rangle \neq 0$

deconfined
= uncondensed
= **exotic**

$\langle \Phi \rangle = 0$

$\langle \Phi \rangle$	$\langle S^z \rangle$	phase
$\neq 0$	$= 0$	AFM
$\neq 0$	$\neq 0$	FM
$= 0$	$= 0$	QSL
$= 0$	$\neq 0$	CFM

Insight into the exotic phases

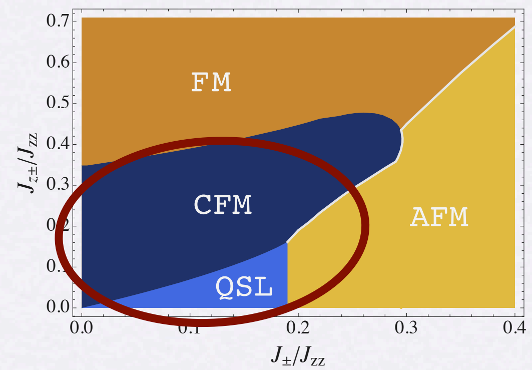
- superposition of states

$$|\psi\rangle \sim \text{equal-weight quantum superposition of 2-in-2-out states}$$

- inelastic structure factor $\mathcal{S}(\mathbf{k},\omega) = \sum_{\mu,\nu} \left[\delta_{\mu\nu} - (\hat{\mathbf{k}})_\mu (\hat{\mathbf{k}})_\nu\right] \sum_{a,b} \left\langle m_a^\mu(-\mathbf{k},-\omega) m_b^\nu(\mathbf{k},\omega)\right\rangle$

$\langle \mathsf{S}^z \mathsf{S}^z \rangle$ contribution $\longleftrightarrow$ photon mode

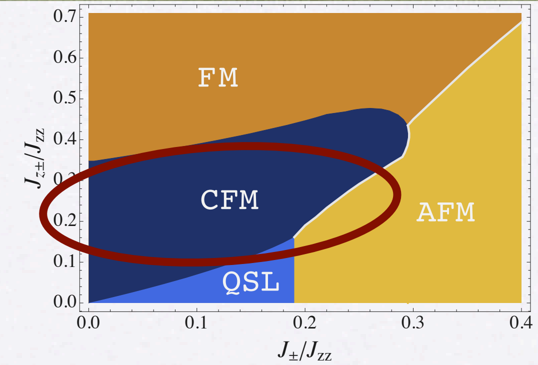
$\langle \mathsf{S}^+ \mathsf{S}^- \rangle$ contribution $\longleftrightarrow$ spinon mode



$$\mathsf{S}^z|\psi\rangle = |1 \text{ photon} + \text{vacuum}\rangle$$

$$\mathsf{S}^+|\psi\rangle = |2 \text{ spinons} + \text{vacuum}\rangle$$

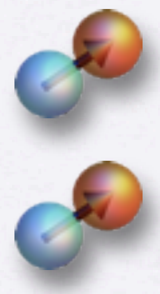
The Coulomb ferromagnet



(secretly a quantum spin liquid!)

- magnetized

$$\langle S^z \rangle \neq 0$$



spins with non-zero expectation value

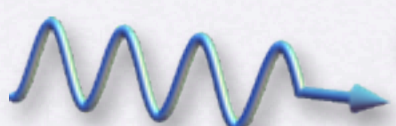
$$\langle S^z \rangle < 1/2$$

$\langle \Phi \rangle$	$\langle S^z \rangle$	phase
$\neq 0$	$= 0$	AFM
$\neq 0$	$\neq 0$	FM
$= 0$	$= 0$	QSL
$= 0$	$\neq 0$	CFM

- supports exotic excitations

$$\langle \Phi \rangle = 0$$

$$\langle S^{\pm} \rangle = 0$$



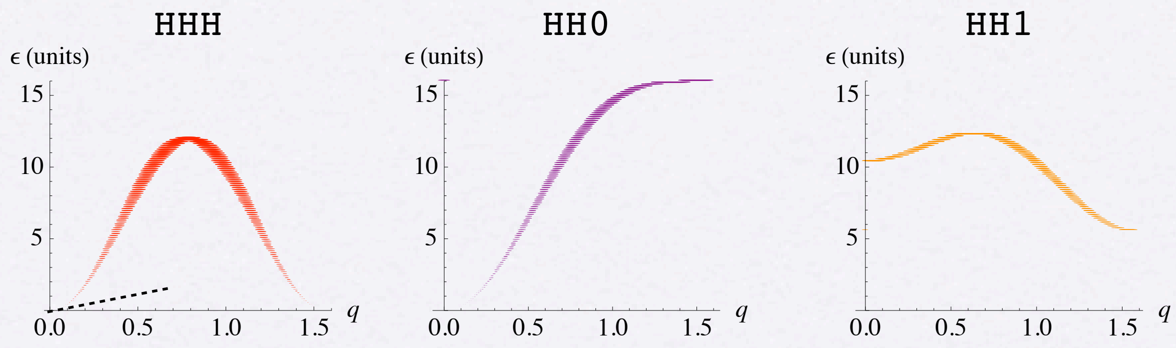
gapless photon

spinon

"electric" monopole

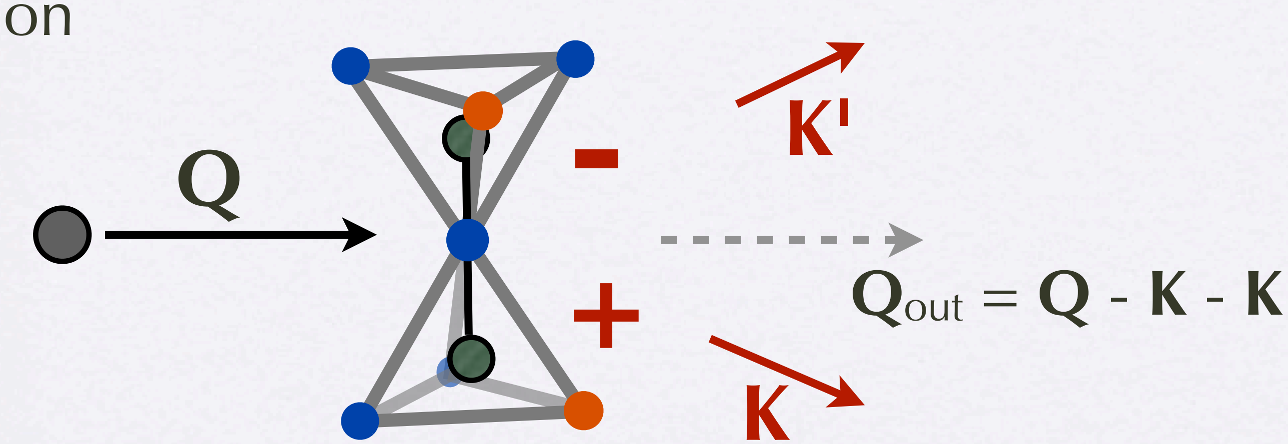
Signatures of the deconfined phases

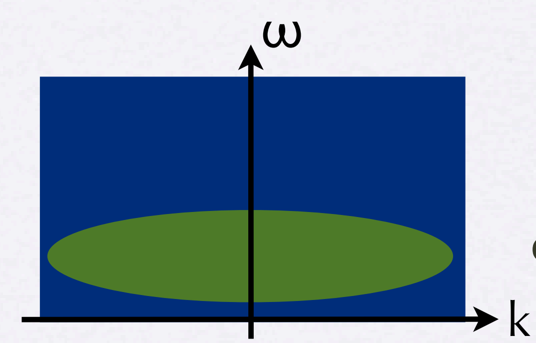
- inelastic neutron scattering:
  - photon



$$\mathcal{S}(\mathbf{k} \sim \mathbf{0}, \omega) \sim \omega\, \delta[\omega - v|\mathbf{k}|]$$

  - spinon

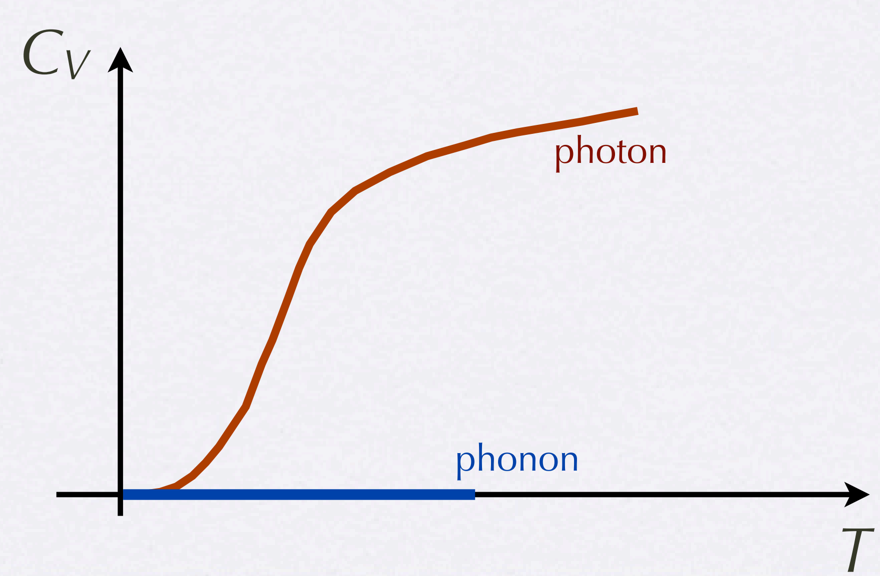




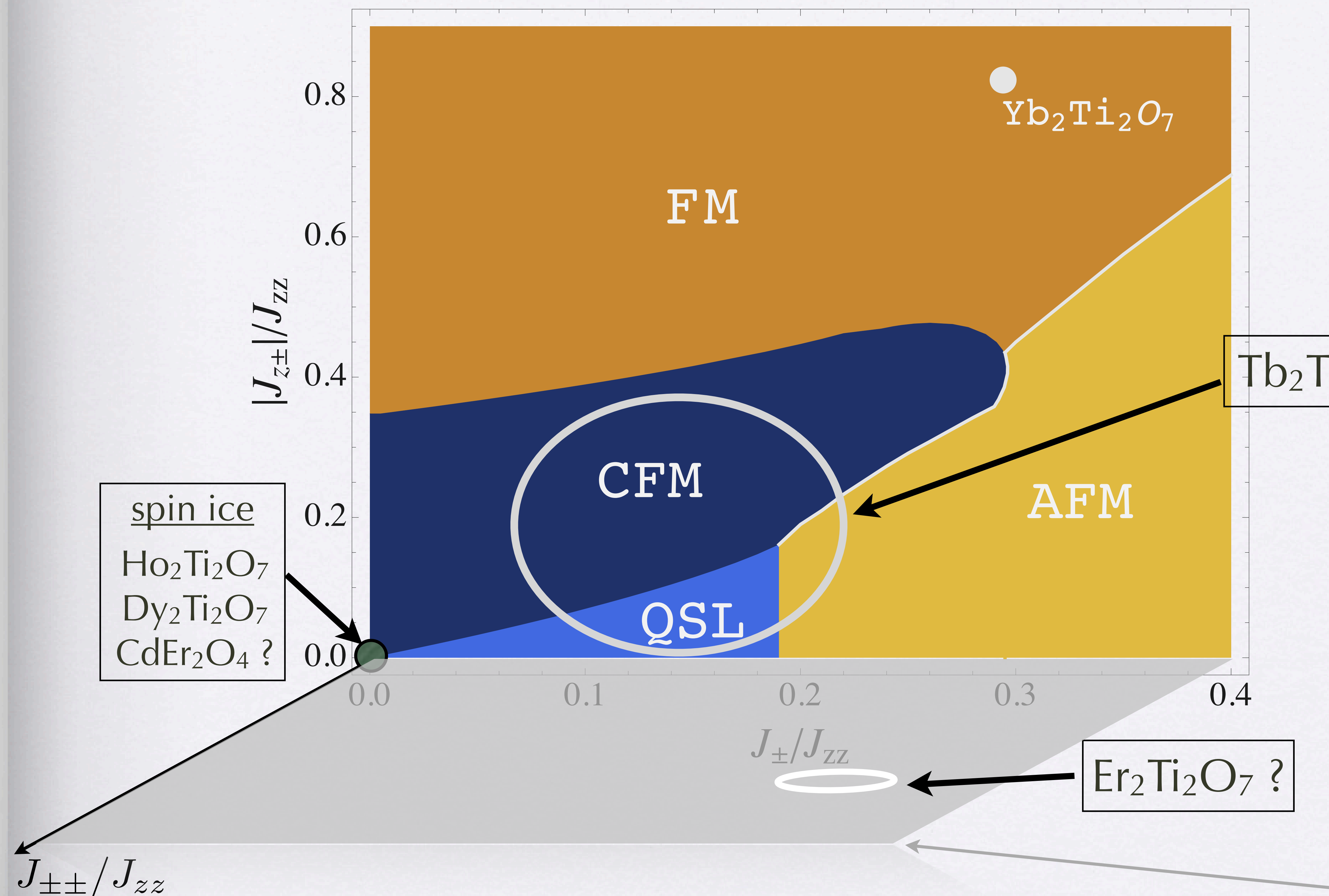
- specific heat:
  - photon

$$C_v^{T\approx 0} \sim B_{\text{photon}} T^3 + B_{\text{phonon}} T^3$$

$$\boxed{B_{\text{photon}} \sim 1000\, B_{\text{phonon}}}$$



Materials



SungBin Lee (QSL I this morning)

Conclusions and perspectives

- Model and phase diagram which should apply to a **wide spectrum of materials**
- Realization of the **U(1) QSL** in a phase diagram for **real materials**
- Existence of a **new phase of matter: the Coulomb FM**
- Need **numerics**
- Need exchange constants of **more materials**
- Need more **very-low temperature specific heat** data
- Effects of **disorder**
- Effects of **temperature**
- **Longer range** interactions...

lsavary@physics.ucsb.edu