Coulombic Quantum Liquids in Spin-1/2 Pyrochlores

Lucile Savary

Lausanne, June 27th, 2012

Collaborators

Leon Balents
(KITP)

$Yb_2Ti_2O_7$ project

Kate Ross

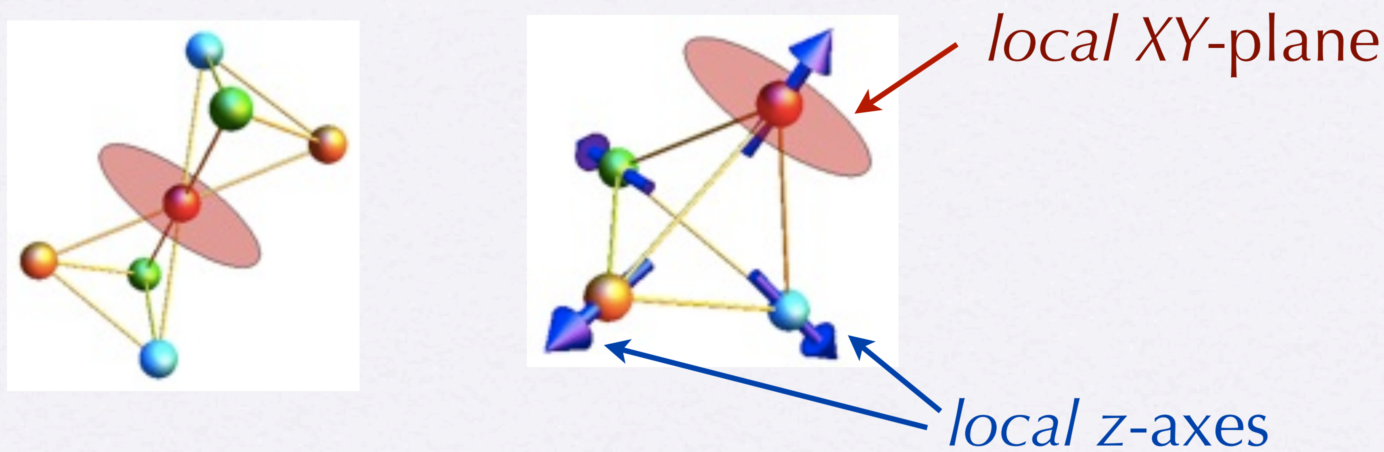
Bruce Gaulin

(experiments, McMaster)

Special thanks to Benjamin Canals and Peter Holdsworth.

Reminder

- the pyrochlore lattice



- spin ice (cf. Michel's talk)

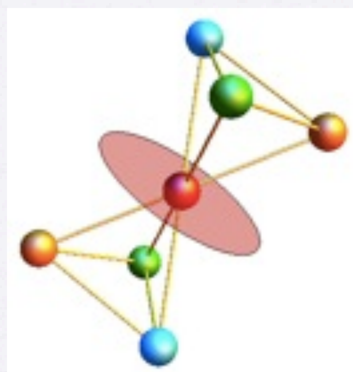
in local bases

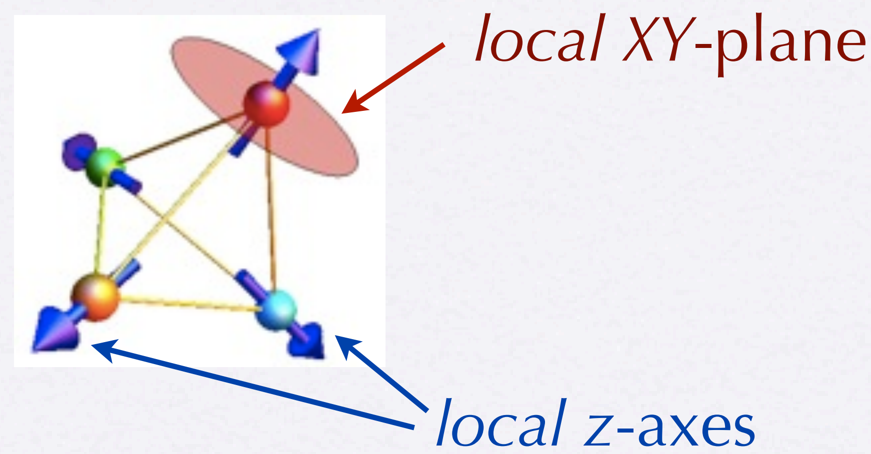
$$H_{\mathrm{SI}} = J_{zz} \sum_{\langle i,j \rangle} \mathsf{S}_i^z \mathsf{S}_j^z \qquad J_{zz} > 0$$

$$H_{\mathrm{SI}} \sim \frac{J_{zz}}{2} \underbrace{(\mathsf{S}_0^z + \mathsf{S}_1^z + \mathsf{S}_2^z + \mathsf{S}_3^z)^2}_{= 0}$$

Reminder

- the pyrochlore lattice

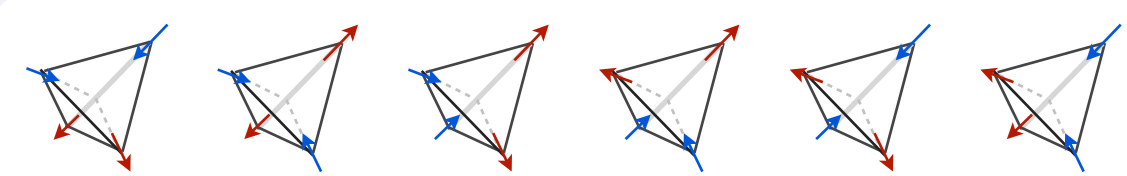




- spin ice (cf. Michel's talk)

in local bases

$$H_{\mathrm{SI}} = J_{zz} \sum_{\langle i,j \rangle} \mathsf{S}_i^z \mathsf{S}_j^z \qquad J_{zz} > 0$$



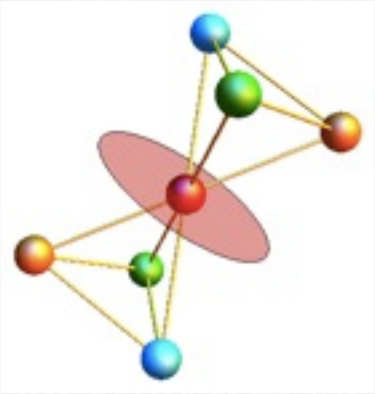
two-in-two-out states for *one* tetrahedron

extensive degeneracy $\longrightarrow$ classical spin liquid with monopole excitations

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: $CdEr_2S_4$, $CdEr_2Se_4$, $CdYb_2S_4$, $CdYb_2Se_4$, $MgYb_2S_4$, $MgYb_2S_4$, $MnYb_2S_4$, $MnYb_2Se_4$, $FeYb_2S_4$, $CdTm_2S_4$, $CdHo_2S_4$, $FeLu_2S_4$, $MnLu_2S_4$, $MnLu_2Se_4$, ...



lots of room for diverse behaviors!

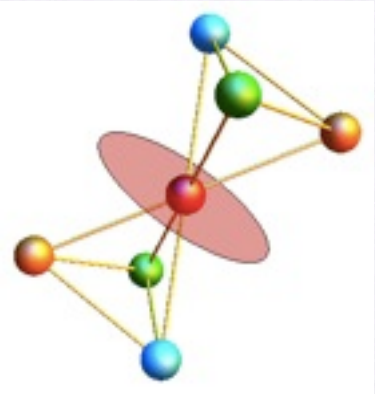
Gardner, Gingras, Greedan, RMP 2010, Lago *et al.* PRL 2010, Savary *et al.* 2012

Rare-earth pyrochlores

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

spin ices

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



lots of room for diverse behaviors!

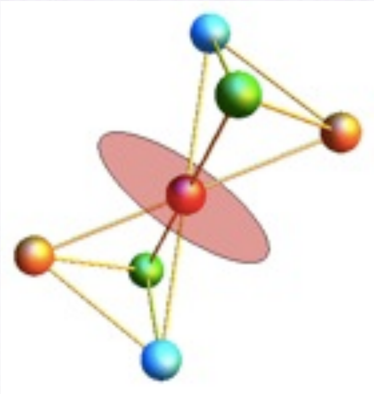
Gardner, Gingras, Greedan, RMP 2010, Lago *et al.* PRL 2010, Savary *et al.* 2012

Rare-earth pyrochlores

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

quantum AFM, order by disorder

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



lots of room for diverse behaviors!

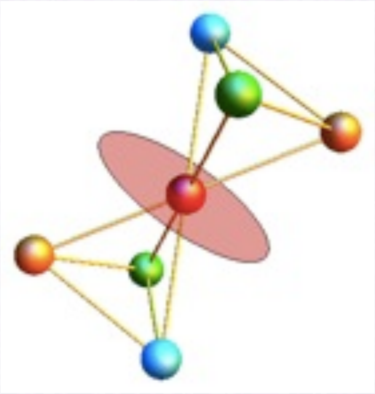
Gardner, Gingras, Greedan, RMP 2010, Lago *et al.* PRL 2010, Savary *et al.* 2012

Rare-earth pyrochlores

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

quantum spin liquids ?

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



lots of room for diverse behaviors!

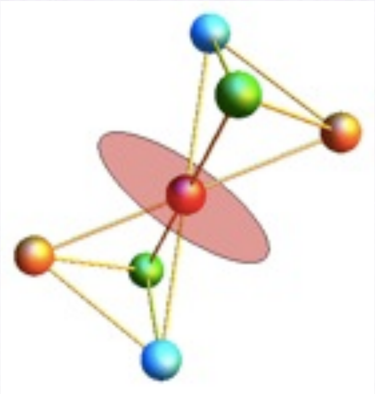
Gardner, Gingras, Greedan, RMP 2010, Lago *et al.* PRL 2010, Savary *et al.* 2012

Rare-earth pyrochlores

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

spin ice ?

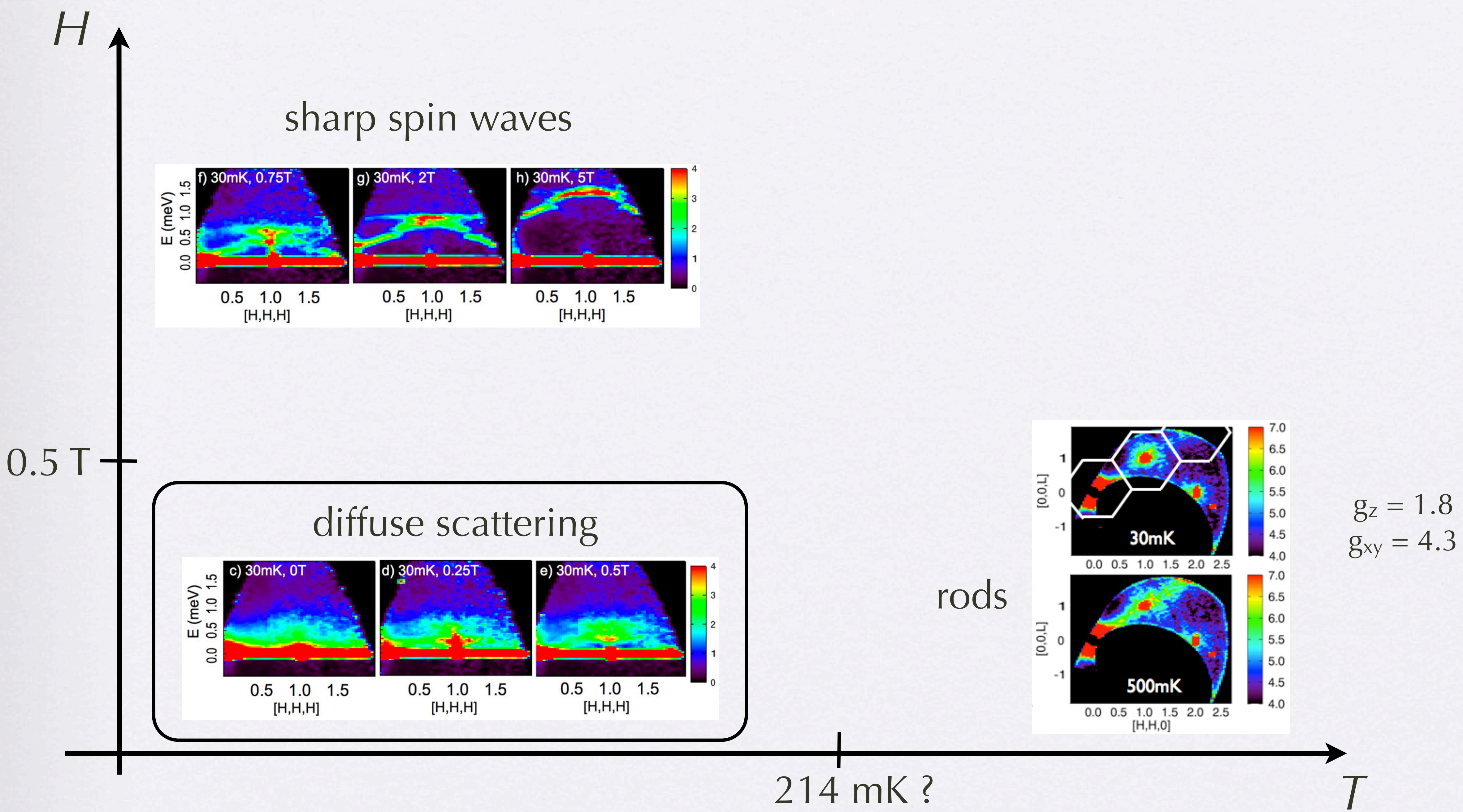
- grown rare-earth B-site spinels: $CdEr_2S_4$, $CdEr_2Se_4$, $CdYb_2S_4$, $CdYb_2Se_4$, $MgYb_2S_4$, $MgYb_2S_4$, $MnYb_2S_4$, $MnYb_2Se_4$, $FeYb_2S_4$, $CdTm_2S_4$, $CdHo_2S_4$, $FeLu_2S_4$, $MnLu_2S_4$, $MnLu_2Se_4$, ...



lots of room for diverse behaviors!

Gardner, Gingras, Greedan, RMP 2010, Lago *et al.* PRL 2010, Savary *et al.* 2012

$Yb_2Ti_2O_7$: puzzling experimental features



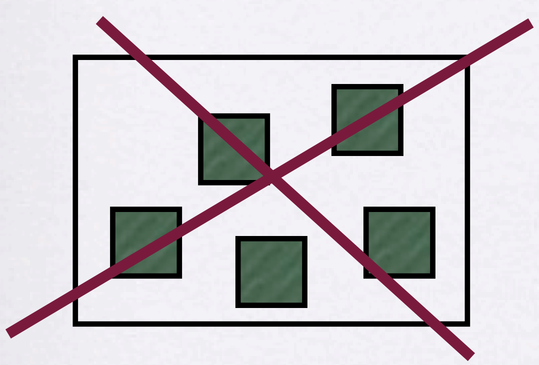
quantum spin liquid regime?

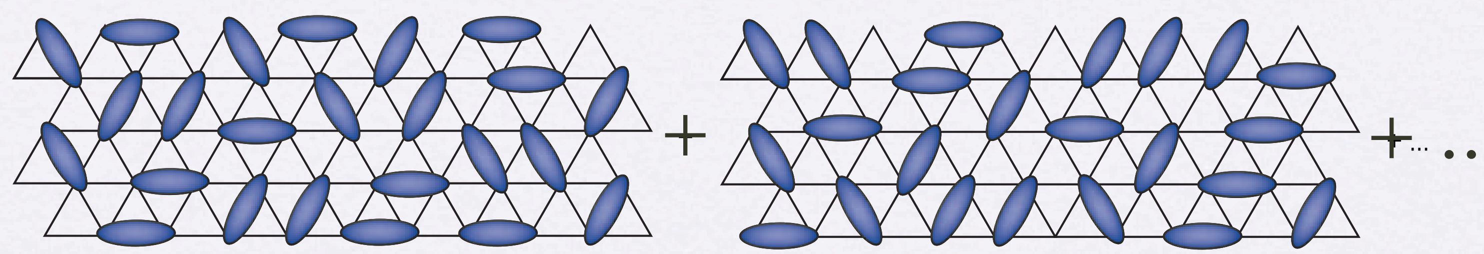
Ross *et al.*, PRL 2009, PRB 2011

What Is a Quantum Spin Liquid (QSL)?

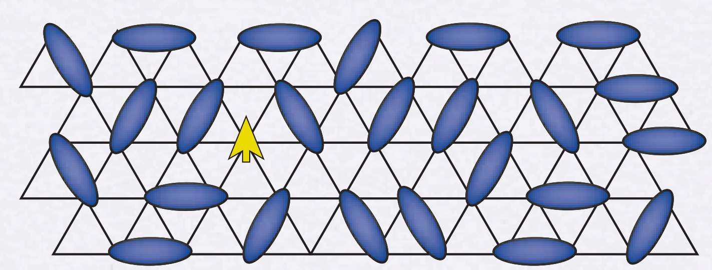
- history: $\langle \mathbf{S} \rangle = \mathbf{0}$ - too restrictive

- **long-range entangled**: a state which cannot be written or approximated as a product of any finite blocks





- consequence: **exotic properties**, e.g. **fractional particles**



note: {$\langle \mathbf{S} \rangle = \mathbf{0}$ & exotic properties} requires long-range entanglement

Balents 2010

What Is a Quantum Spin Liquid?

- first prediction: Anderson 1973
- would be *really* nice to find one in nature!
- good place to look: frustrated magnets
  - organics (triangular lattice), J_1-J_2 models, pyrochlores...

Outline

- method
- results
- experimental signatures
- materials

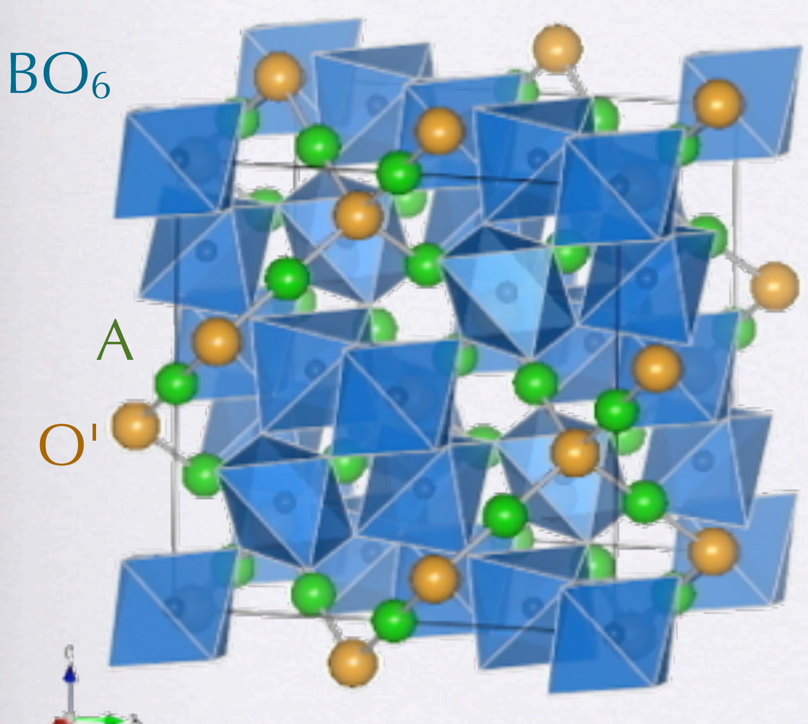
based on Savary and Balents PRL **108**, 037202 (2012)

Symmetries of the Hamiltonian

rare-earths : intrinsic strong spin-orbit coupling

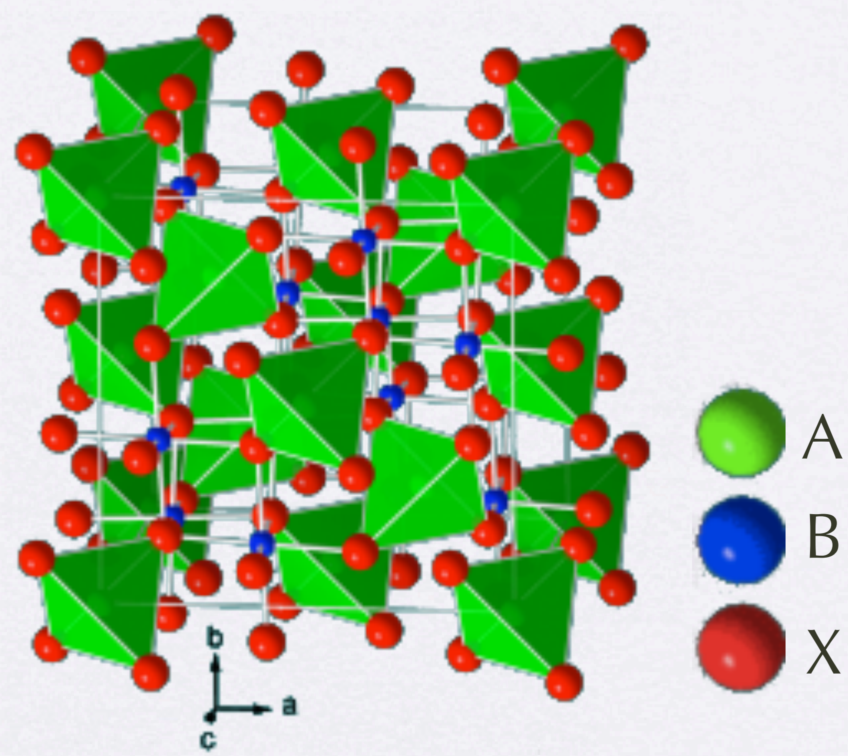
$\longrightarrow$ *discrete* cubic symmetries *only*

space group: Fd-3m, i.e. #227 :



$\mathbf{A}_2B_2O_7$

"pyrochlore oxides"



$A\mathbf{B}_2X_4$

spinels

strong crystal fields

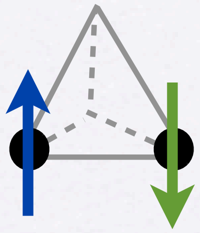
General NN exchange Hamiltonian for effective spins 1/2

$$H = \sum_{\langle ij \rangle} \Big[\quad J_{zz} \mathsf{S}_i^z \mathsf{S}_j^z$$

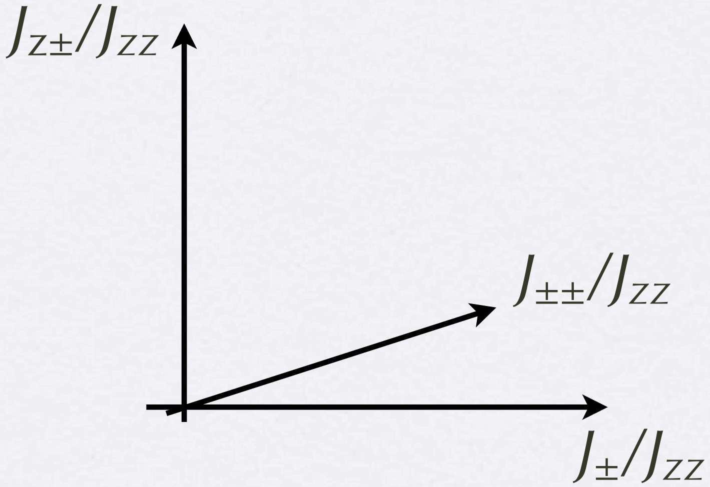
$$-J_{\pm} (\mathsf{S}_i^+ \mathsf{S}_j^- + \mathsf{S}_i^- \mathsf{S}_j^+)$$

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

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



to each material corresponds a set of J's

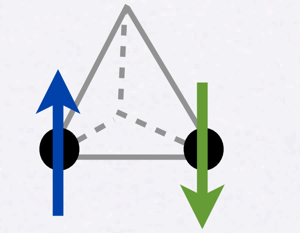


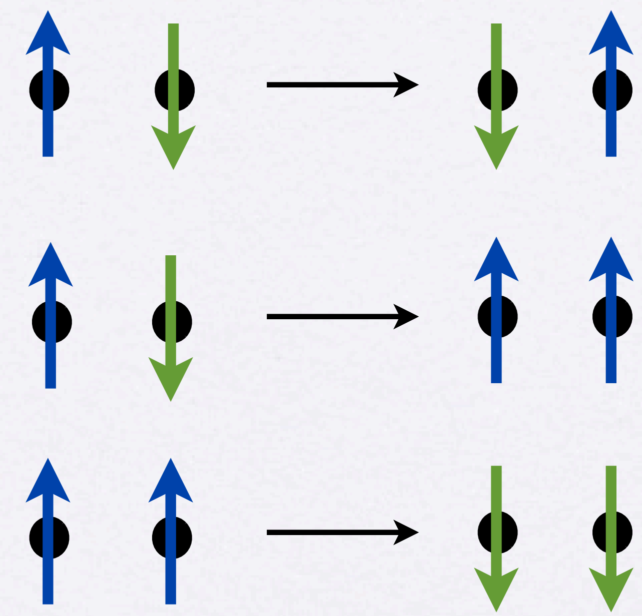
Curnoe PRB 2008, Ross Savary Gaulin Balents PRX 2011

General NN exchange Hamiltonian for effective spins 1/2

$$
\begin{aligned}
H = \sum_{\langle ij \rangle} \Big[\quad & J_{zz} \mathsf{S}_i^z \mathsf{S}_j^z \\
& - J_{\pm} (\mathsf{S}_i^+ \mathsf{S}_j^- + \mathsf{S}_i^- \mathsf{S}_j^+) \\
& + J_{z\pm} \left[\mathsf{S}_i^z (\zeta_{ij} \mathsf{S}_j^+ + \zeta_{ij}^* \mathsf{S}_j^-) + i \leftrightarrow j \right] \\
& + J_{\pm\pm} \left[\gamma_{ij} \mathsf{S}_i^+ \mathsf{S}_j^+ + \gamma_{ij}^* \mathsf{S}_i^- \mathsf{S}_j^- \right] \Big]
\end{aligned}
$$

spin ice

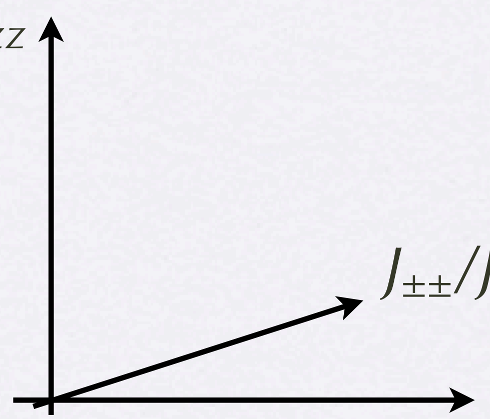




to each material corresponds a set of *J*'s

What is the phase diagram ?

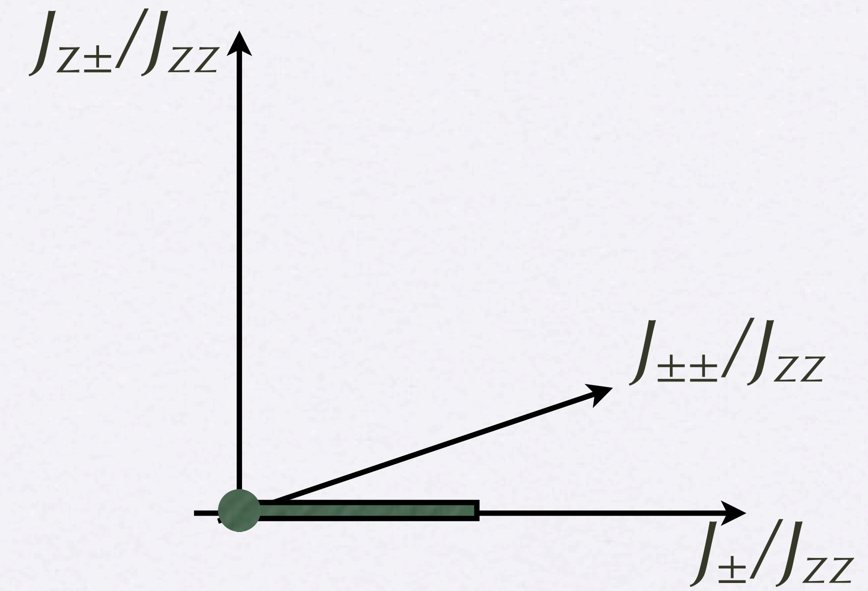
Are there any exotic phases there ?



Curnoe PRB 2008, Ross Savary Gaulin Balents PRX 2011

The Hermele *et al*. QSL

$$H = \sum_{\langle ij \rangle} \Big[\quad J_{zz} \mathsf{S}_i^z \mathsf{S}_j^z - J_{\pm} \left(\mathsf{S}_i^+ \mathsf{S}_j^- + \mathsf{S}_i^- \mathsf{S}_j^+ \right) \Big]$$



$\xrightarrow{\text{perturbation theory in } J_\pm/J_{zz}}$ quantum electrodynamics $H \sim H_{\mathrm{QED}} \sim E^2 + B^2$

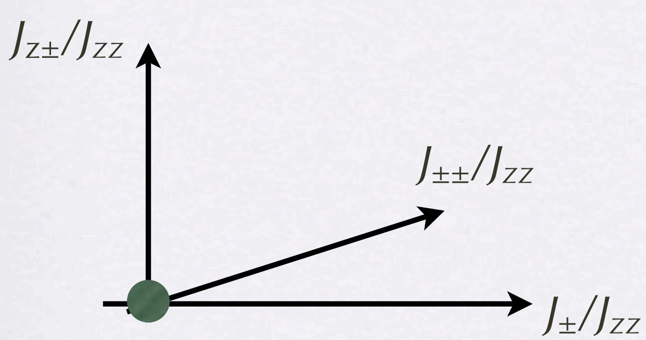
$\Longrightarrow$ photon (gapless and linear)

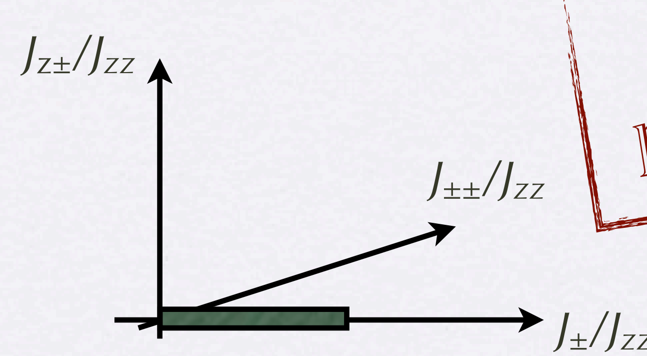
particle-hole excitations (gapped)

Hermele Fisher Balents, PRB 2004

Relation to classical spin ice

classical spin ice	U(1) quantum spin liquid
thermal spin liquid	quantum spin liquid
extensively many degenerate ground states	*one* entangled ground state (= vacuum)
magnetic monopoles = spinons	spinons "electric" monopoles gapless photon

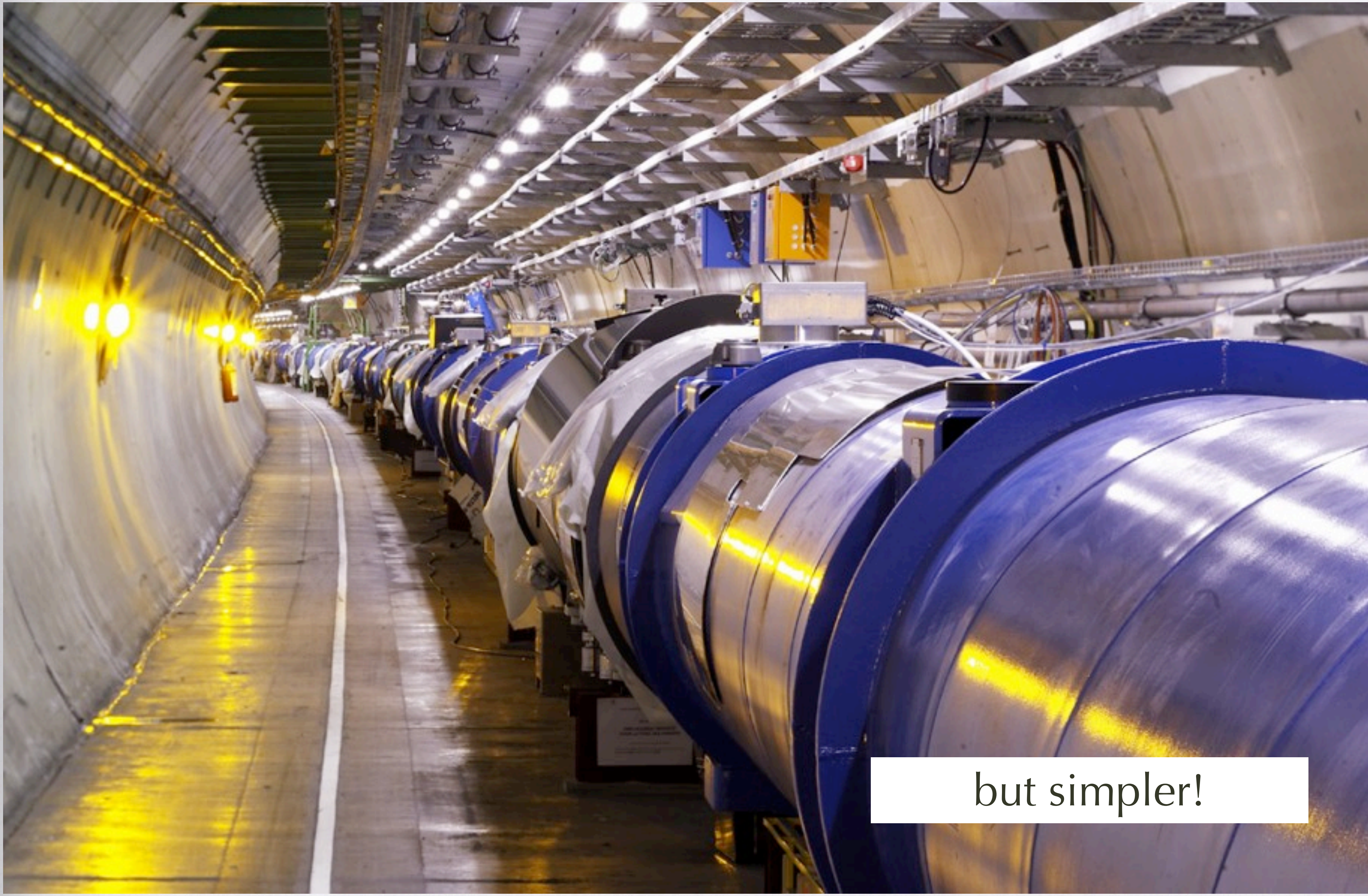




stable to all perturbations

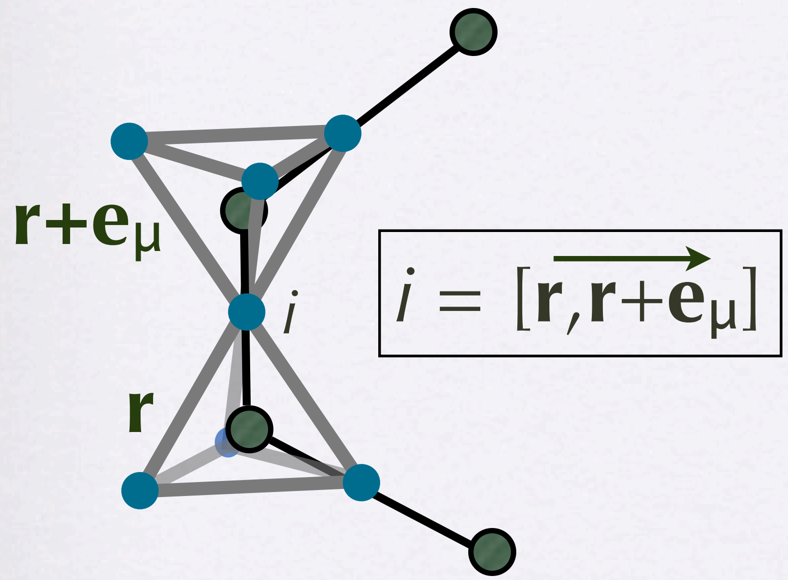
Gingras, Introduction to Frustrated Magnetism (2011), Hermele Fisher Balents, PRB 2004

How we do this: compact abelian lattice Higgs theory

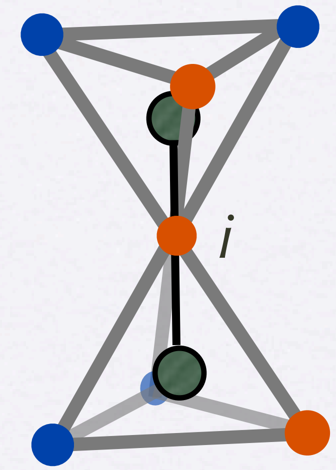


but simpler!

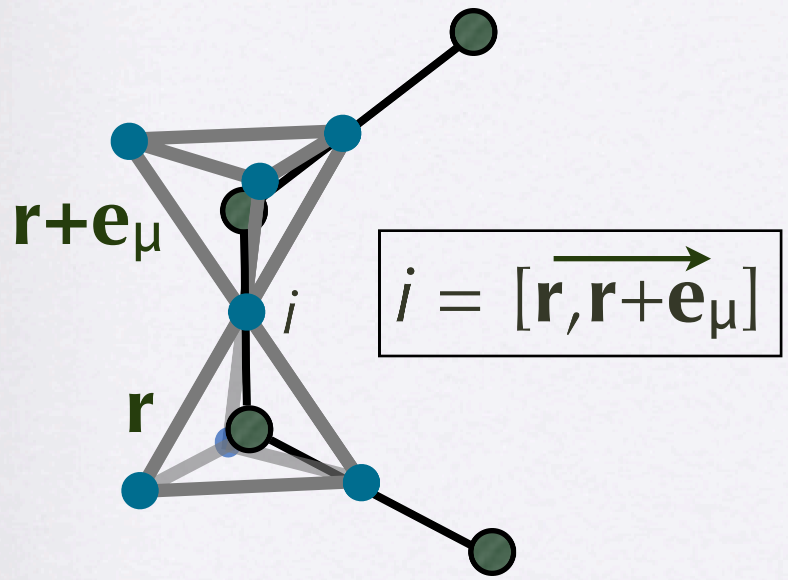
How we do this: compact abelian lattice Higgs theory



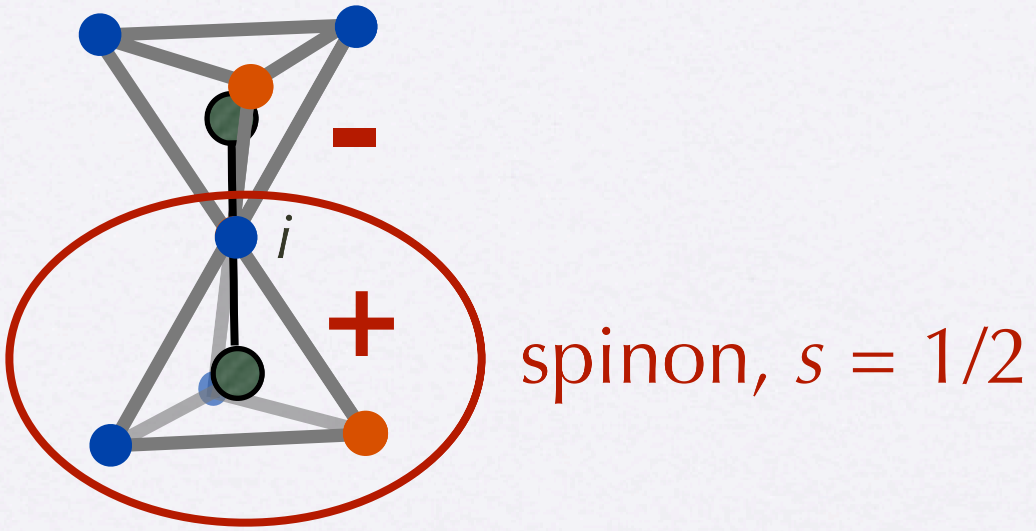
dual diamond lattice



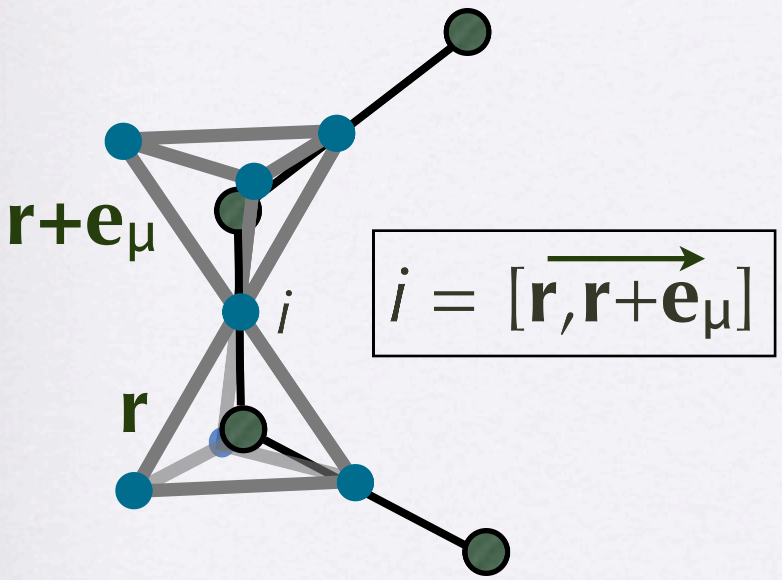
How we do this: compact abelian lattice Higgs theory



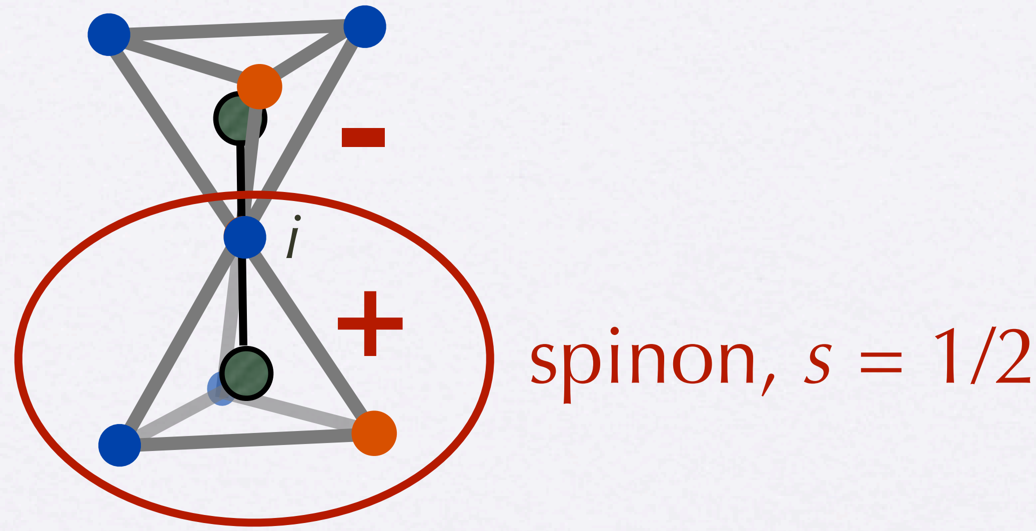
dual diamond lattice



How we do this: compact abelian lattice Higgs theory



dual diamond lattice



$$\boxed{\begin{aligned} \mathsf{S}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \Phi^{\dagger}_{\mathbf{r}}\, \mathsf{s}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu}\, \Phi_{\mathbf{r}+\mathbf{e}_\mu} \\ \mathsf{S}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \mathsf{s}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \end{aligned}}$$

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

U(1) gauge symmetry

the slave particles have a simple interpretation

How we do this: compact abelian Higgs U(1) lattice gauge theory

$$\boxed{\begin{aligned} \mathsf{S}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \Phi^{\dagger}_{\mathbf{r}}\, \mathsf{s}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu}\, \Phi_{\mathbf{r}+\mathbf{e}_\mu} \\ \mathsf{S}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \mathsf{s}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \end{aligned}}$$

$$|\Phi_{\mathbf{r}}| = 1$$
$$Q_{\mathbf{r}} = \pm \sum_{\mu} \mathsf{s}^{z}_{\mathbf{r},\mathbf{r}\pm\mathbf{e}_\mu}$$

$$\mathsf{s}^{z}_{\mathbf{r}\mathbf{r}'} = E_{\mathbf{r}\mathbf{r}'}$$
$$\mathsf{s}^{\pm}_{\mathbf{r}\mathbf{r}'} = e^{\pm i A_{\mathbf{r}\mathbf{r}'}}$$

our spinons are bosons $\Longrightarrow$ they can condense

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

How we do this: compact abelian Higgs U(1) lattice gauge theory

$$\boxed{\begin{aligned} \mathsf{S}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \Phi^\dagger_{\mathbf{r}}\, \mathsf{s}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \Phi_{\mathbf{r}+\mathbf{e}_\mu} \\ \mathsf{S}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \mathsf{s}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \end{aligned}}$$

$$|\Phi_{\mathbf{r}}| = 1$$
$$Q_{\mathbf{r}} = \pm \sum_\mu \mathsf{s}^z_{\mathbf{r},\mathbf{r}\pm\mathbf{e}_\mu}$$

$$\mathsf{s}^z_{\mathbf{r}\mathbf{r}'} = E_{\mathbf{r}\mathbf{r}'}$$
$$\mathsf{s}^\pm_{\mathbf{r}\mathbf{r}'} = e^{\pm i A_{\mathbf{r}\mathbf{r}'}}$$

our spinons are bosons $\Longrightarrow$ they can condense

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

$$H = \sum_{\mathbf{r}\in \mathrm{I,II}} \frac{J_{zz}}{2} Q_{\mathbf{r}}^2 - J_\pm \left\{ \sum_{\mathbf{r}\in\mathrm{I}} \sum_{\mu,\nu\neq\mu} \Phi^\dagger_{\mathbf{r}+\mathbf{e}_\mu} \Phi_{\mathbf{r}+\mathbf{e}_\nu} \mathsf{s}^-_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \mathsf{s}^+_{\mathbf{r},\mathbf{r}+\mathbf{e}_\nu} + \sum_{\mathbf{r}\in\mathrm{II}} \sum_{\mu,\nu\neq\mu} \Phi^\dagger_{\mathbf{r}-\mathbf{e}_\mu} \Phi_{\mathbf{r}-\mathbf{e}_\nu} \mathsf{s}^+_{\mathbf{r},\mathbf{r}-\mathbf{e}_\mu} \mathsf{s}^-_{\mathbf{r},\mathbf{r}-\mathbf{e}_\nu} \right\}$$
$$-J_{z\pm} \left\{ \sum_{r\in\mathrm{I}} \sum_{\mu,\nu\neq\mu} \left(\gamma^*_{\mu\nu} \Phi^\dagger_{\mathbf{r}} \Phi_{\mathbf{r}+\mathbf{e}_\nu} \mathsf{s}^z_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \mathsf{s}^+_{\mathbf{r},\mathbf{r}+\mathbf{e}_\nu} + \text{h.c.}\right) + \sum_{\mathbf{r}\in\mathrm{II}} \sum_{\mu,\nu\neq\mu} \left(\gamma^*_{\mu\nu} \Phi^\dagger_{\mathbf{r}-\mathbf{e}_\nu} \Phi_{\mathbf{r}} \mathsf{s}^z_{\mathbf{r},\mathbf{r}-\mathbf{e}_\mu} \mathsf{s}^+_{\mathbf{r},\mathbf{r}-\mathbf{e}_\nu} + \text{h.c.}\right) \right\} + \text{const.}$$

$\boxed{J_{\pm\pm} = 0}$

How we do this: compact abelian Higgs U(1) lattice gauge theory

$$\boxed{\begin{aligned} \mathsf{S}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \Phi^{\dagger}_{\mathbf{r}}\, \mathsf{s}^{+}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \Phi_{\mathbf{r}+\mathbf{e}_\mu} \\ \mathsf{S}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} &= \mathsf{s}^{z}_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \end{aligned}}$$

$$|\Phi_{\mathbf{r}}| = 1$$
$$Q_{\mathbf{r}} = \pm \sum_{\mu} \mathsf{s}^{z}_{\mathbf{r},\mathbf{r}\pm\mathbf{e}_\mu}$$

$$\mathsf{s}^{z}_{\mathbf{r}\mathbf{r}'} = E_{\mathbf{r}\mathbf{r}'}$$
$$\mathsf{s}^{\pm}_{\mathbf{r}\mathbf{r}'} = e^{\pm i A_{\mathbf{r}\mathbf{r}'}}$$

our spinons are bosons $\Longrightarrow$ they can condense

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

vacuum: quantum superposition of two-in-two-out states

H = hopping Hamiltonian for spinons in fluctuating background

gauge Mean Field Theory (gMFT)

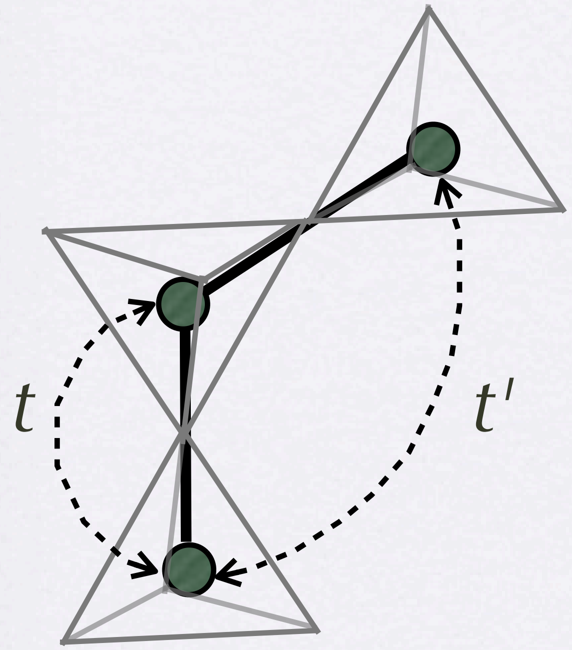
$$\Phi^\dagger \Phi\, \mathsf{s}\, \mathsf{s} \to \Phi^\dagger \Phi \langle \mathsf{s} \rangle \langle \mathsf{s} \rangle + \langle \Phi^\dagger \Phi \rangle \mathsf{s} \langle \mathsf{s} \rangle + \langle \Phi^\dagger \Phi \rangle \langle \mathsf{s} \rangle \mathsf{s} - 2 \langle \Phi^\dagger \Phi \rangle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

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

free (but self-consistent) "spins"

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

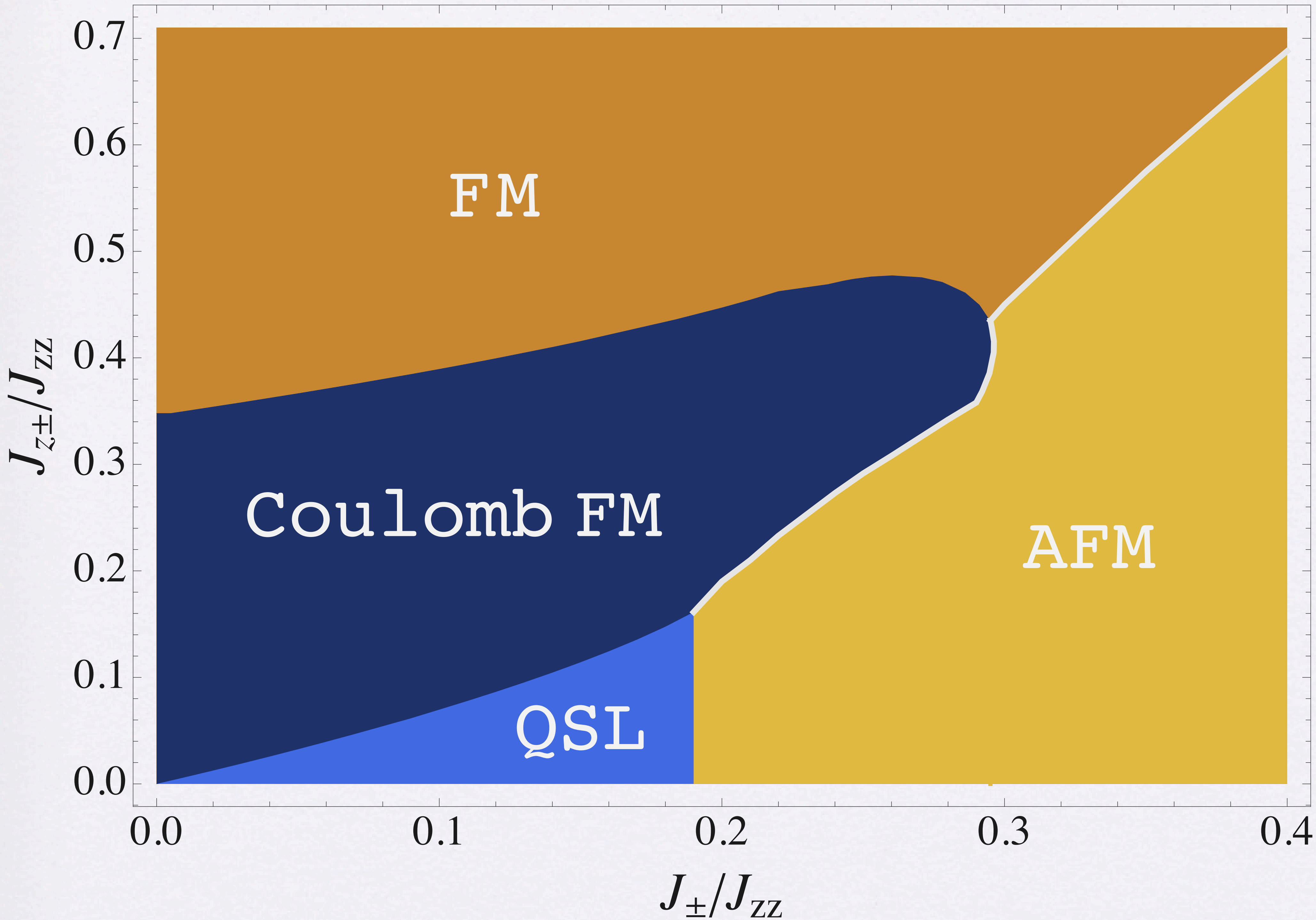
hopping Hamiltonian for spinons in fixed (but self-consistent) background



Solve the consistency equations

Quantum Spin Liquids in Quantum Spin Ices

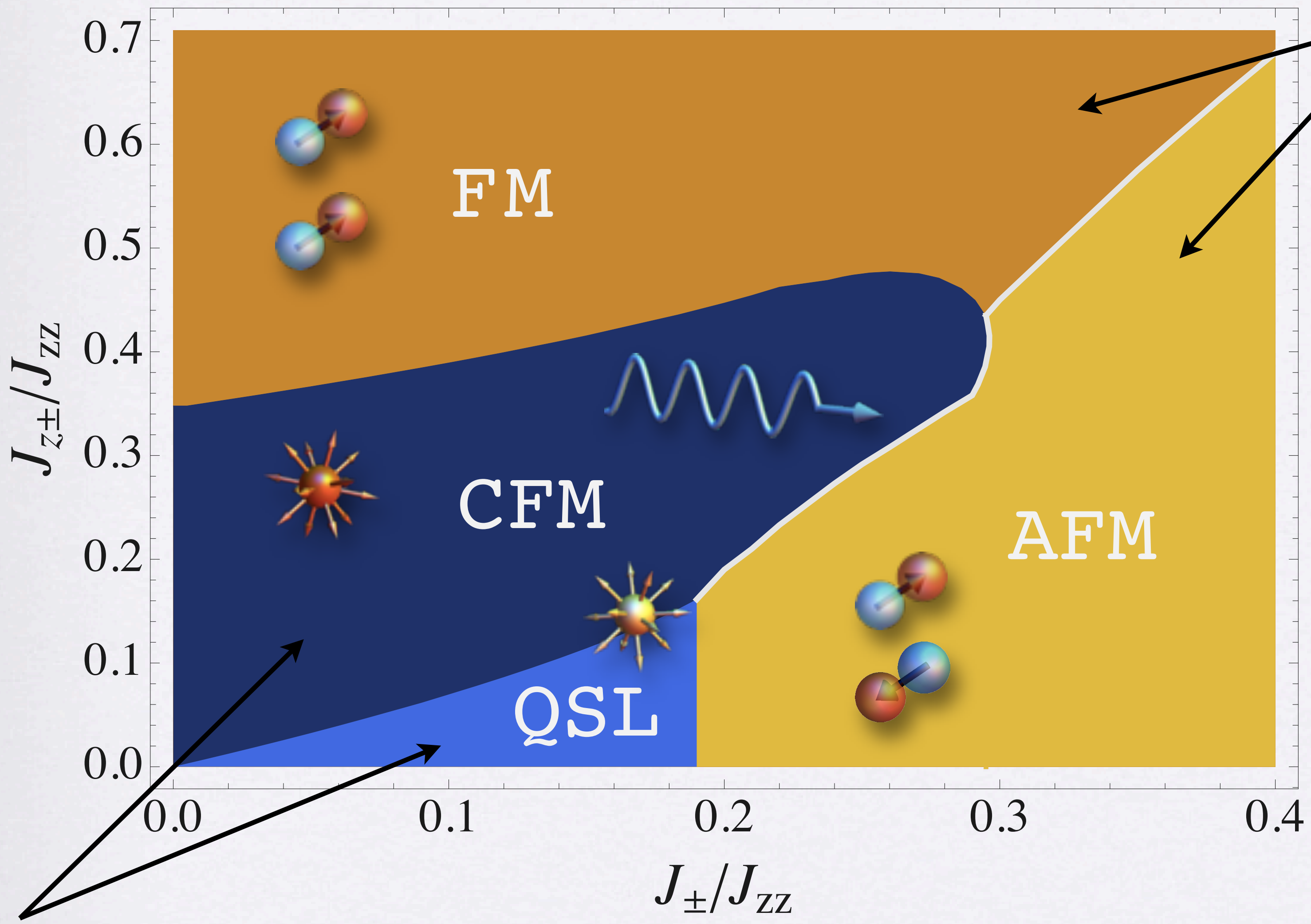
Phase diagram



$J_{\pm\pm} = 0$

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

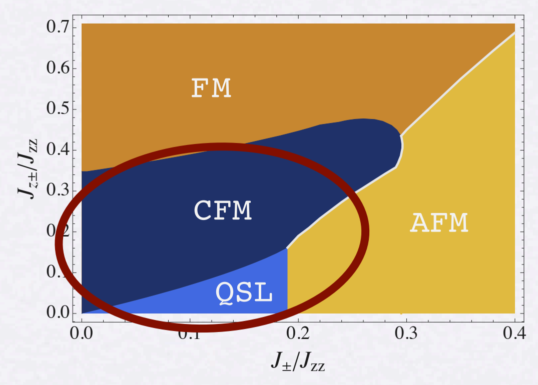
$$|\psi\rangle \sim \text{equal-weight quantum superposition of 2-in-2-out states}$$

- 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

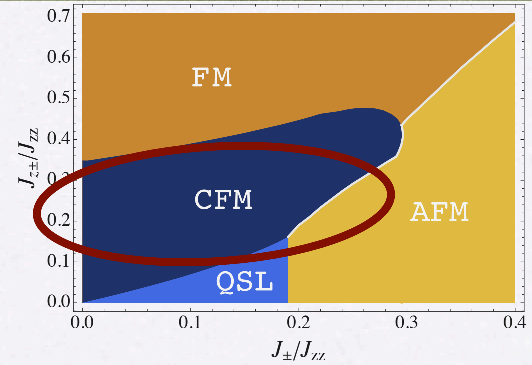
$\langle \mathsf{S}^+\mathsf{S}^-\rangle$ contribution $\longleftrightarrow$ spinon mode

$$\mathsf{S}^z|\psi\rangle = |1 \text{ photon} + \text{vacuum}\rangle$$
$$\mathsf{S}^+|\psi\rangle = |2 \text{ spinons} + \text{vacuum}\rangle$$



The Coulomb ferromagnet

(secretly a quantum spin liquid!)



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

- magnetized

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

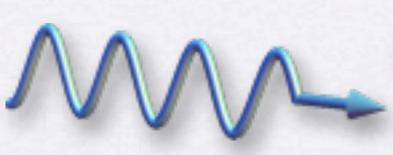
$$\langle S^z \rangle < 1/2$$

spins with non-zero expectation value

- supports exotic excitations

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

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



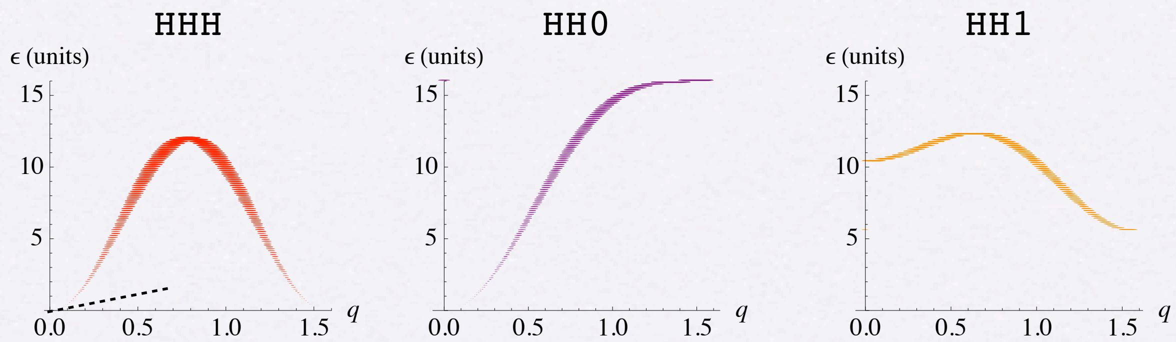
gapless photon

spinon

"electric" monopole

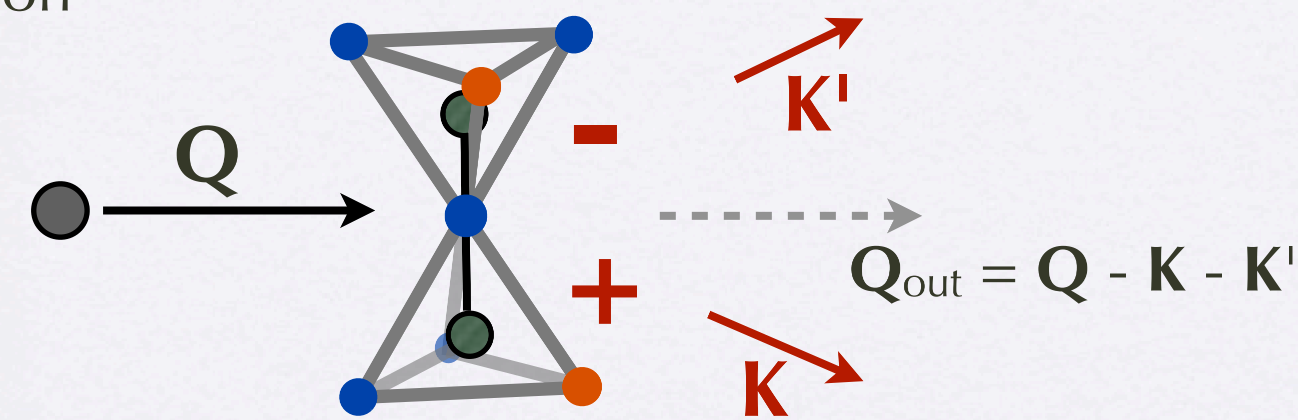
Signatures of the deconfined phases

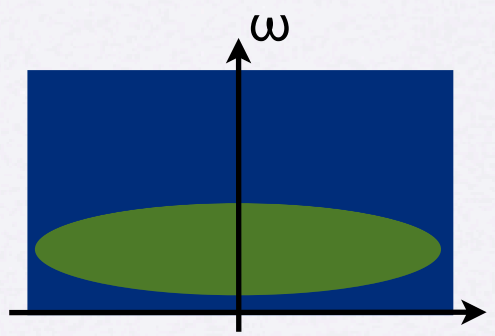
- inelastic neutron scattering:
    - photon



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

- spinon

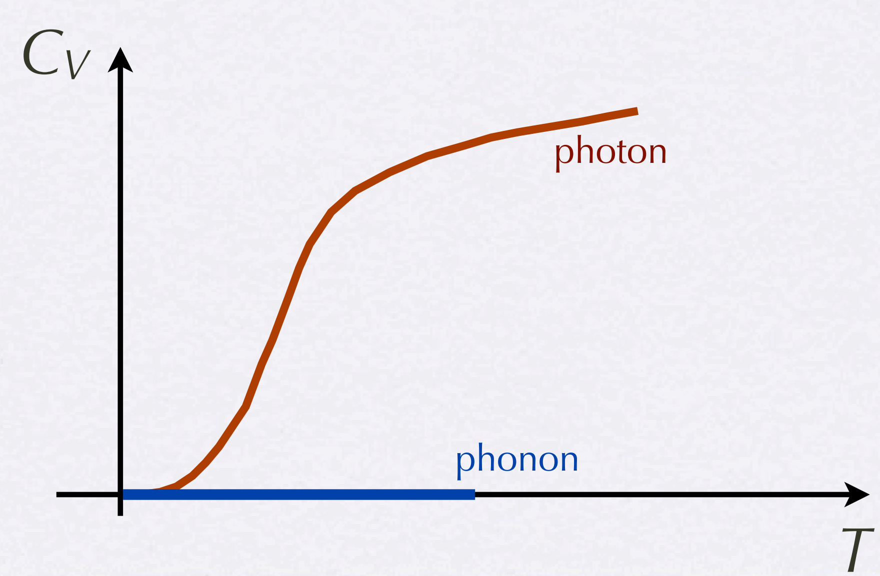




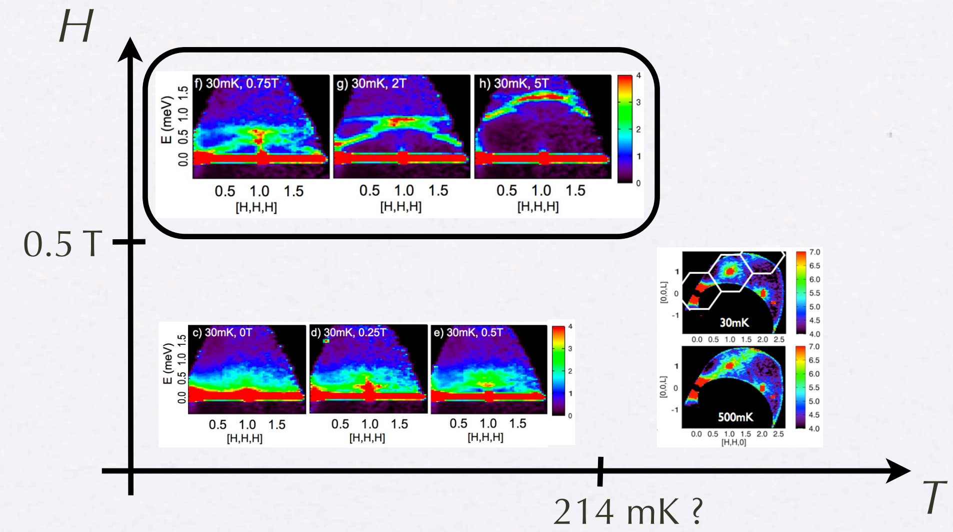
diffuse scattering

- specific heat:
    - photon $\qquad C_v^{T\approx 0} \sim B_{\rm photon} T^3 + B_{\rm phonon} T^3$

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

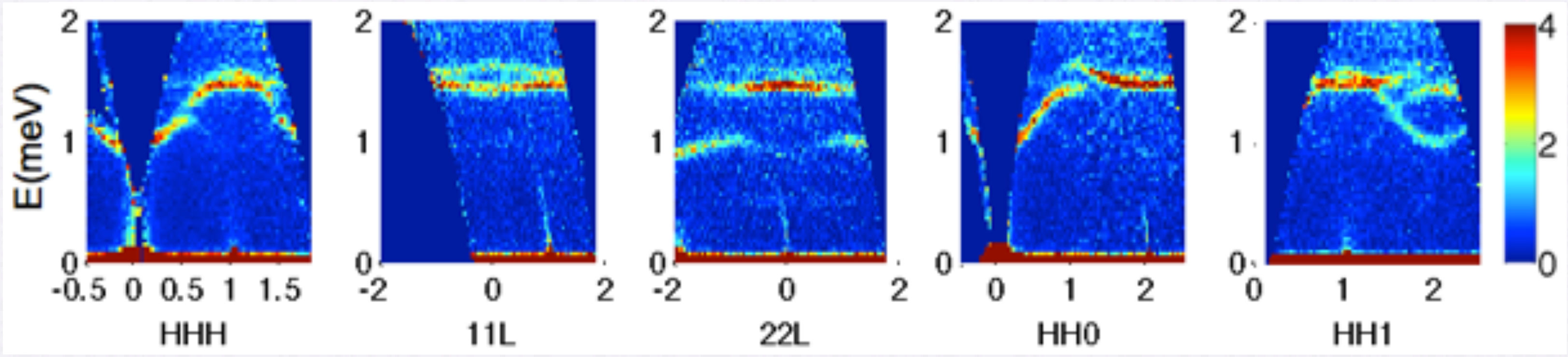


$Yb_2Ti_2O_7$



high field H = 5T

experiment

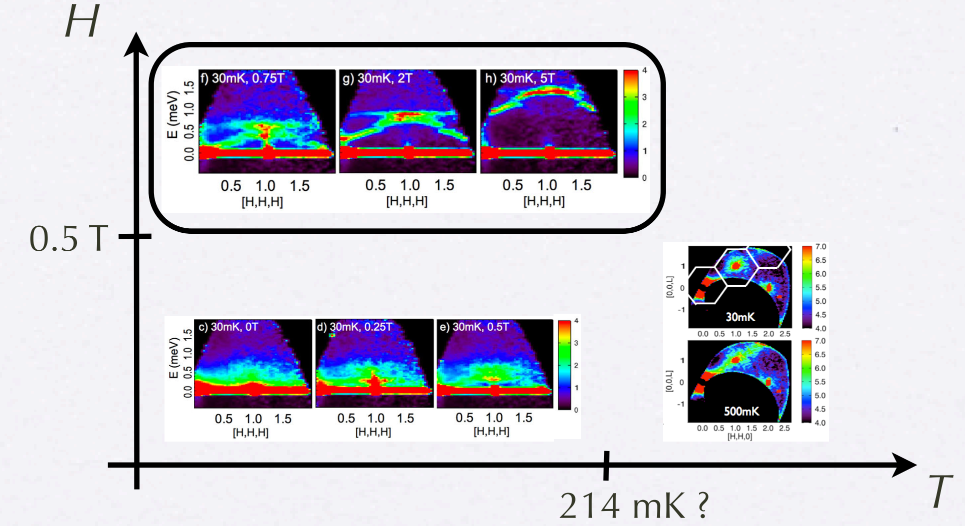


spin wave theory

1. classical high-field ground state
2. Holstein-Primakoff bosons in the spirit of large s
3. calculation of the inelastic structure factor

Ross, Savary, Gaulin, Balents PRX 2011

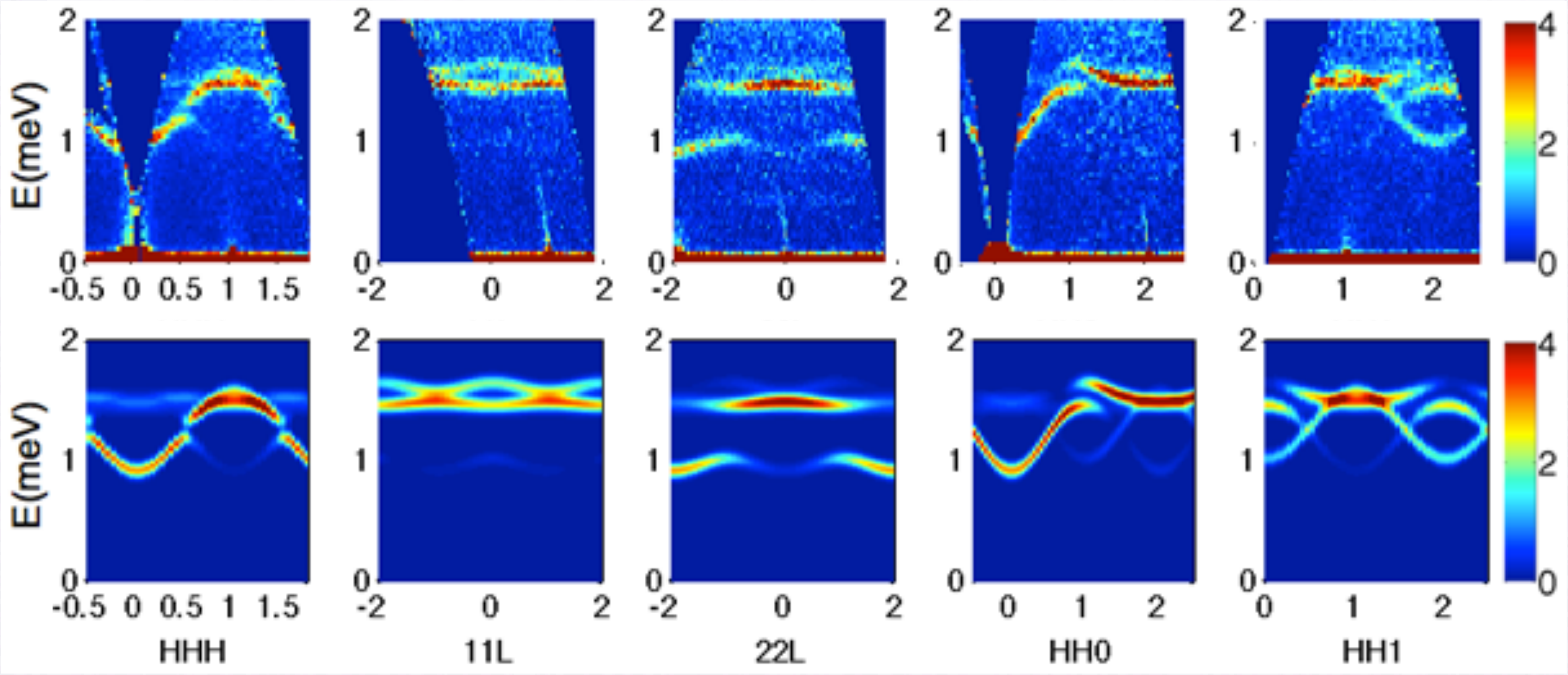
$Yb_2Ti_2O_7$



high field H = 5T

experiment

spin wave theory

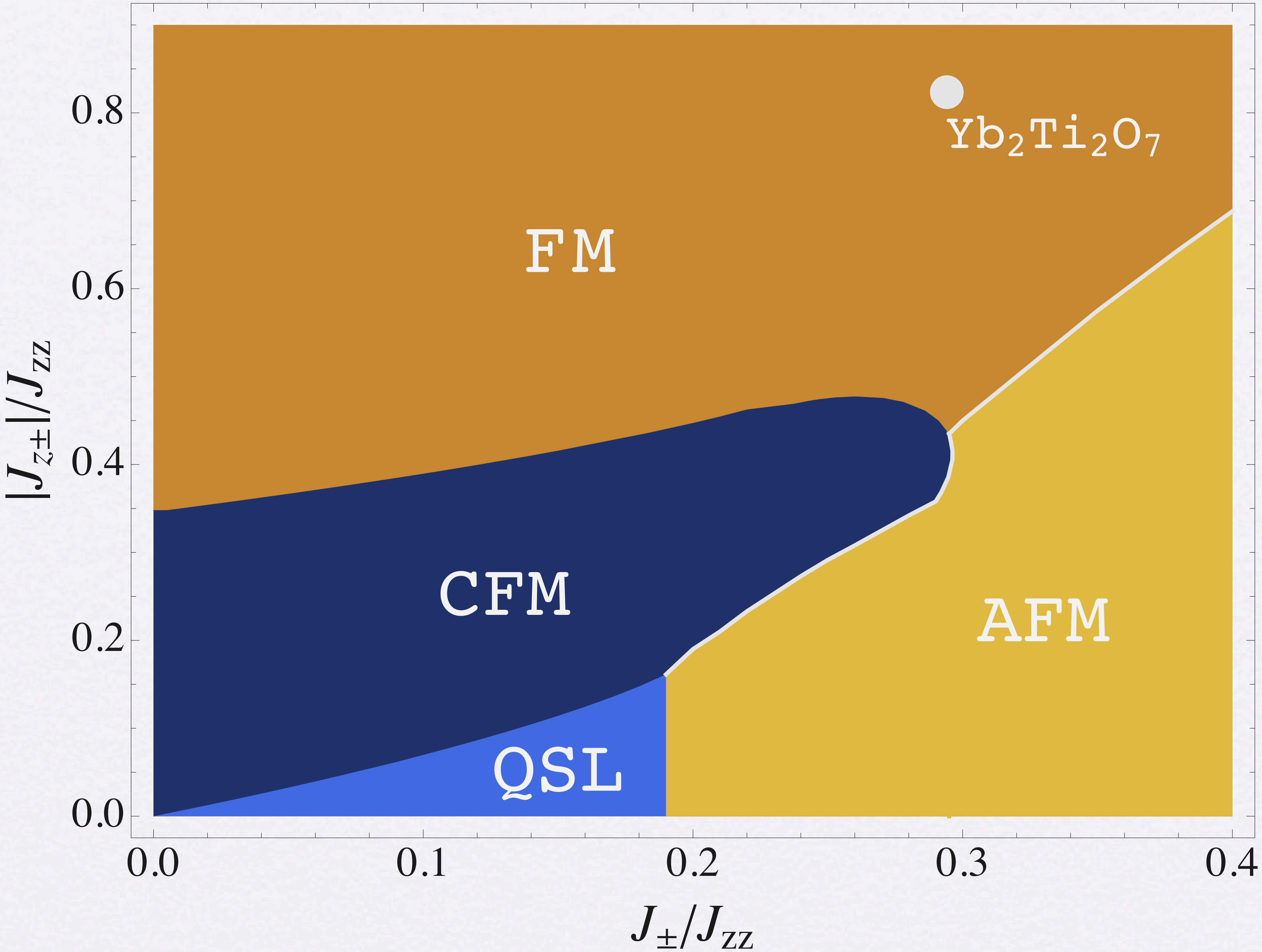


$$J_{zz} = 0.17, \quad J_{\pm} = 0.05, \quad J_{z\pm} = -0.14, \quad J_{\pm\pm} = 0.05 \quad \text{meV}$$

Ross, Savary, Gaulin, Balents PRX 2011

$Yb_2Ti_2O_7$

$$J_{zz} = 0.17, \quad J_{\pm} = 0.05, \quad J_{z\pm} = -0.14, \quad \cancel{J_{\pm\pm} = 0.05} \;\; \text{meV}$$

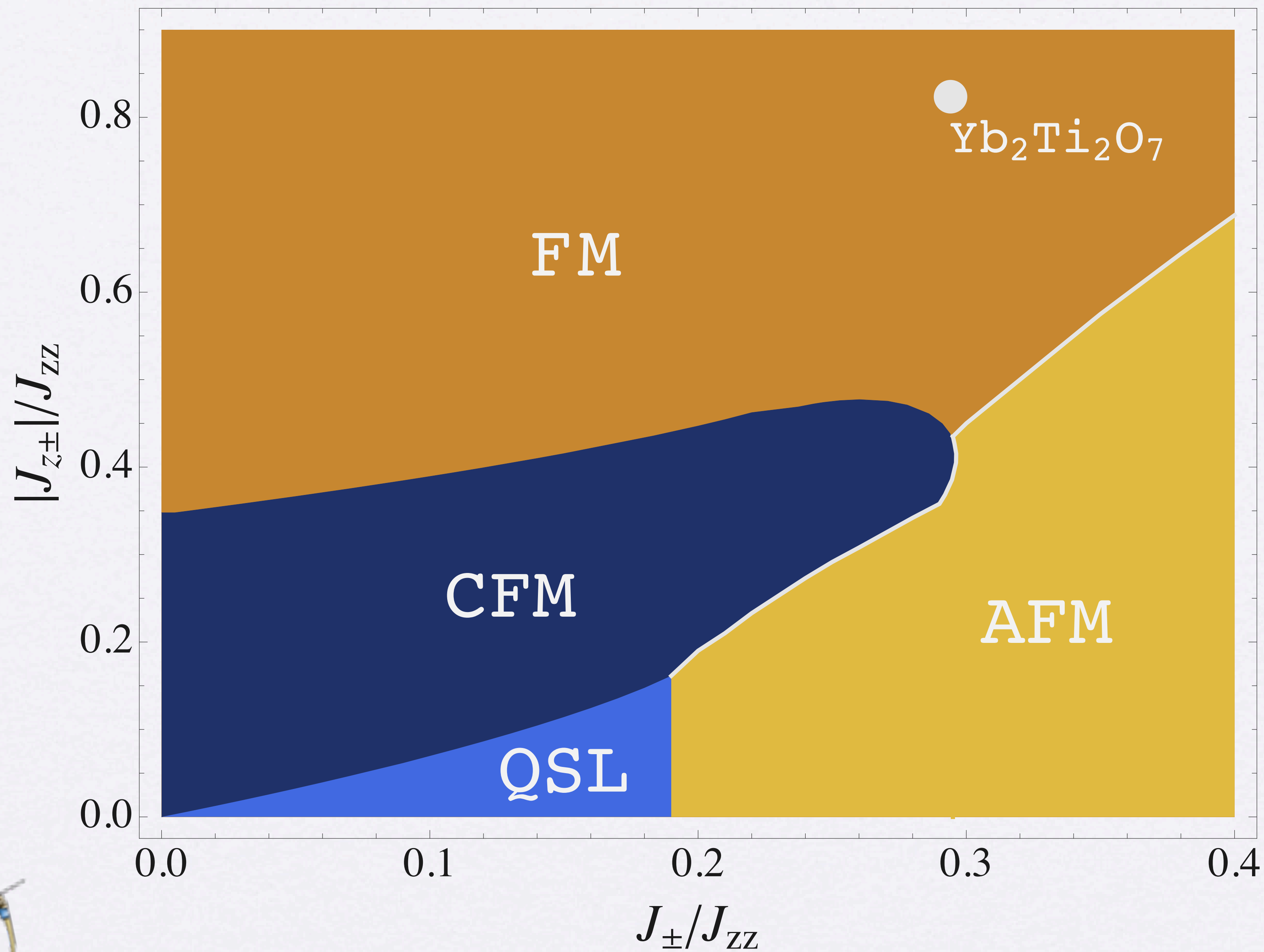


some uncertainties

follow-up work: Ross *et al.* (2011), Chang et al. (2011), Applegate *et al.* (2012)

$Yb_2Ti_2O_7$

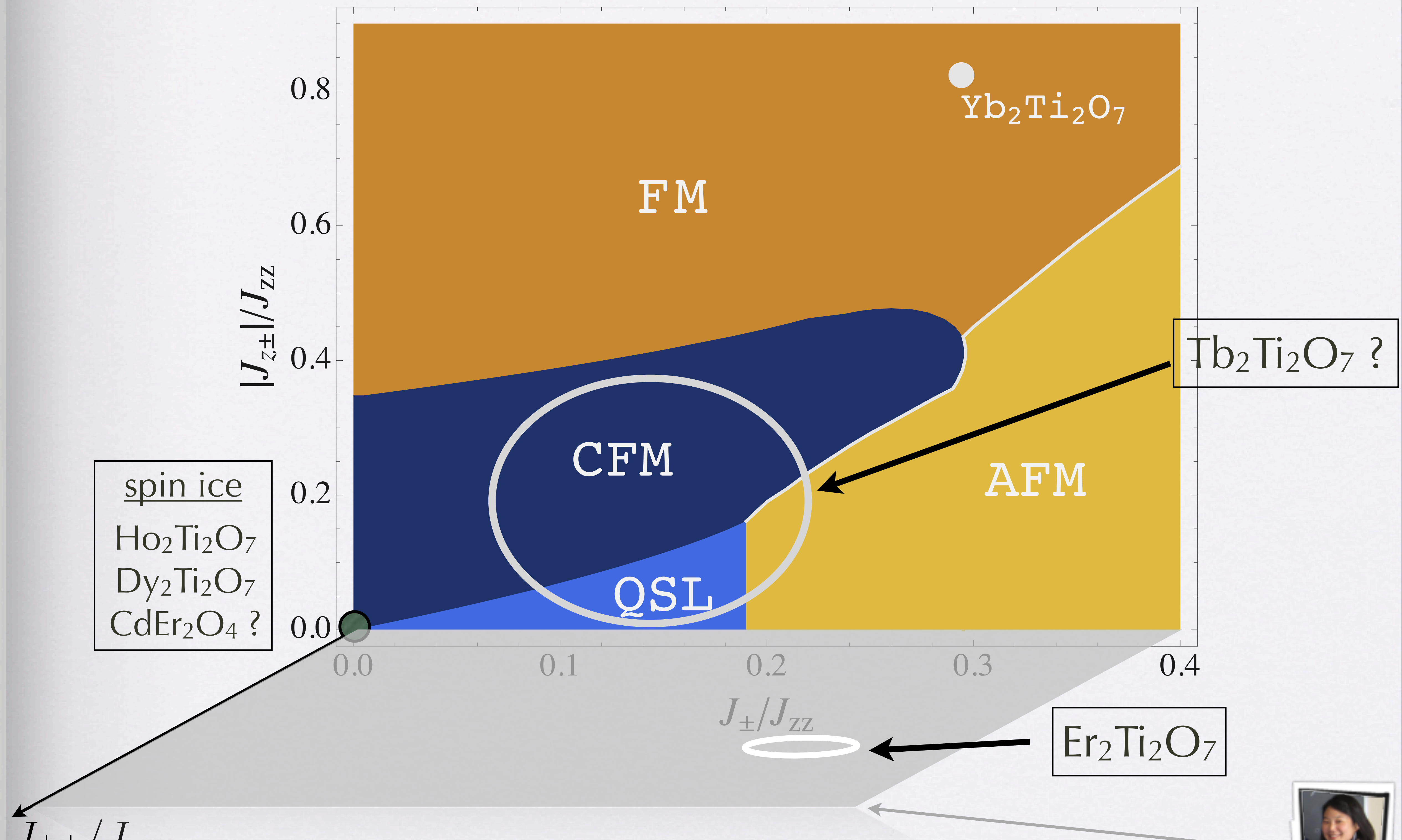
$$J_{zz} = 0.17, \quad J_{\pm} = 0.05, \quad J_{z\pm} = -0.14, \quad \cancel{J_{\pm\pm} = 0.05} \quad \text{meV}$$

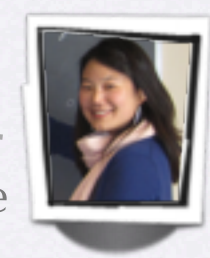


some
uncertainties

$Tb_2Ti_2O_7$? $Er_2Ti_2O_7$? $CdEr_2O_4$? ...

Materials




SungBin Lee

many other materials under investigation (cf. HFM 2012)

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 **low temperature specific heat** data
- Effects of **disorder**
- Effects of **temperature**
- **Longer range** interactions...


Thank you for your attention