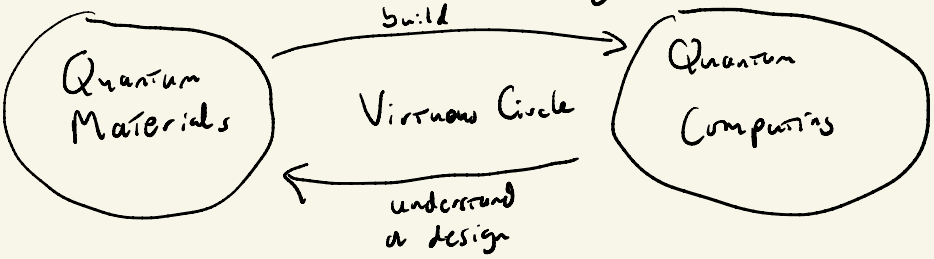
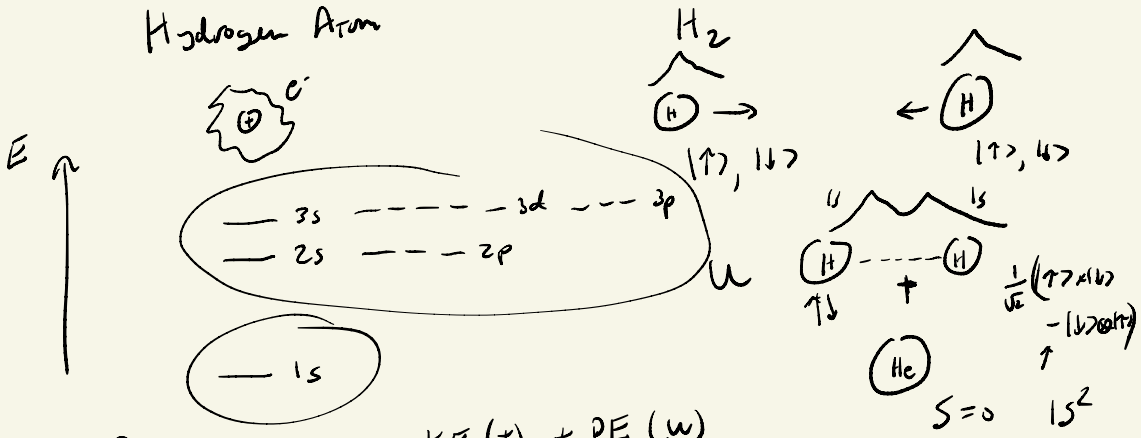
Welcome to the Era of Quantum Materials





Competition between KE (t) + PE (U)

Many degrees of freedom : Hydrogen chain PRX 2020

Simons Foundation : DMRG, QMC

Phase transition at $R \to 0$

"Emergent Property"

Large-R : Insulator

Small-R : Metal

Hubbard-Model 1-band (1s) : Insulator at all R

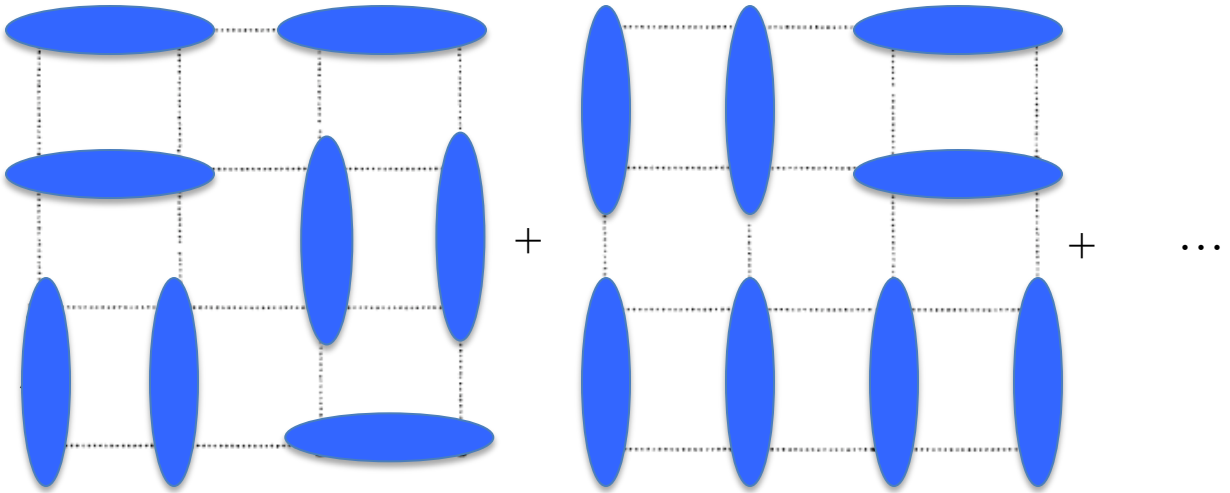
Real Materials

Slides courtesy Prof. Jaime Merino (Madrid)

Anderson's RVB idea (1973)

Ground state of the Heisenberg antiferromagnet on a 2-D triangular lattice is a RVB spin liquid.

$$\mathcal{H} = J \sum_{\langle j,k \rangle} \vec{S}_j \cdot \vec{S}_k$$

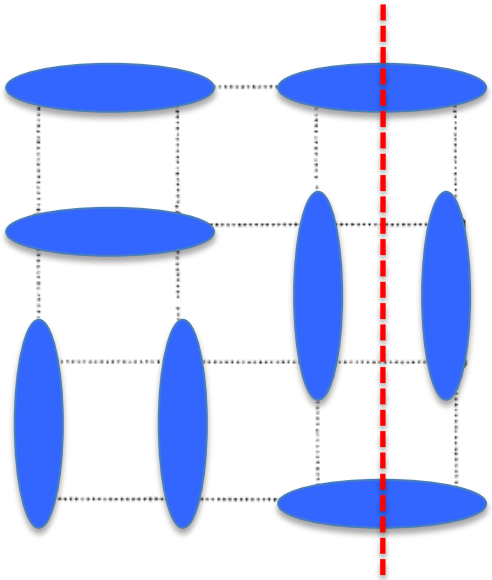
$|RVB\rangle =$  $+ \quad + \quad \cdots$

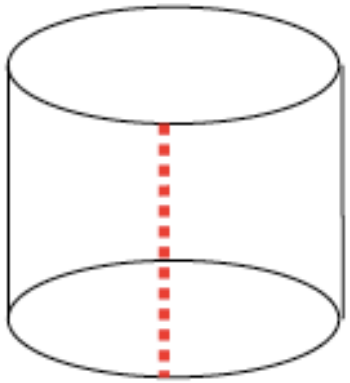
 $= (ij) = 1/\sqrt{2}(|i\uparrow j\downarrow\rangle - |i\downarrow j\uparrow\rangle) = -(ji)$

Valence Bond/ Singlet

Topological order in RVB

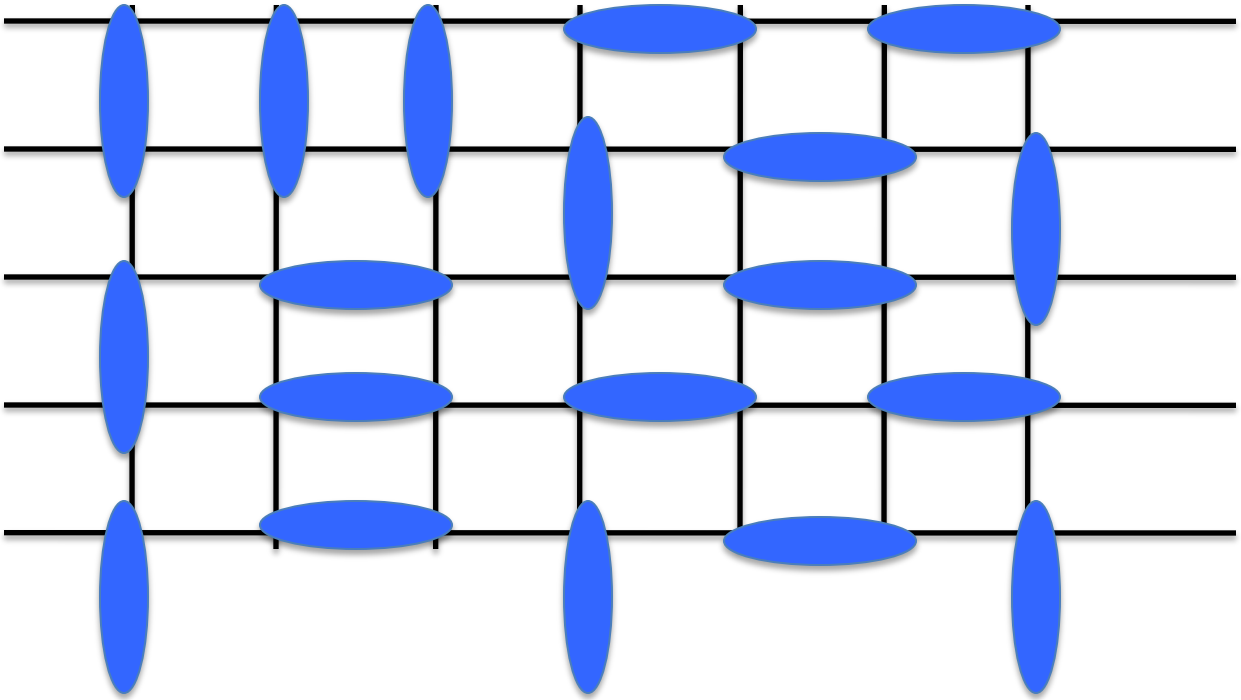
- The RVB is different from a conventional quantum paramagnet: it has “hidden” or topological order.
- Parity of the number of valence bonds in the cut is conserved: even/odd topologies.





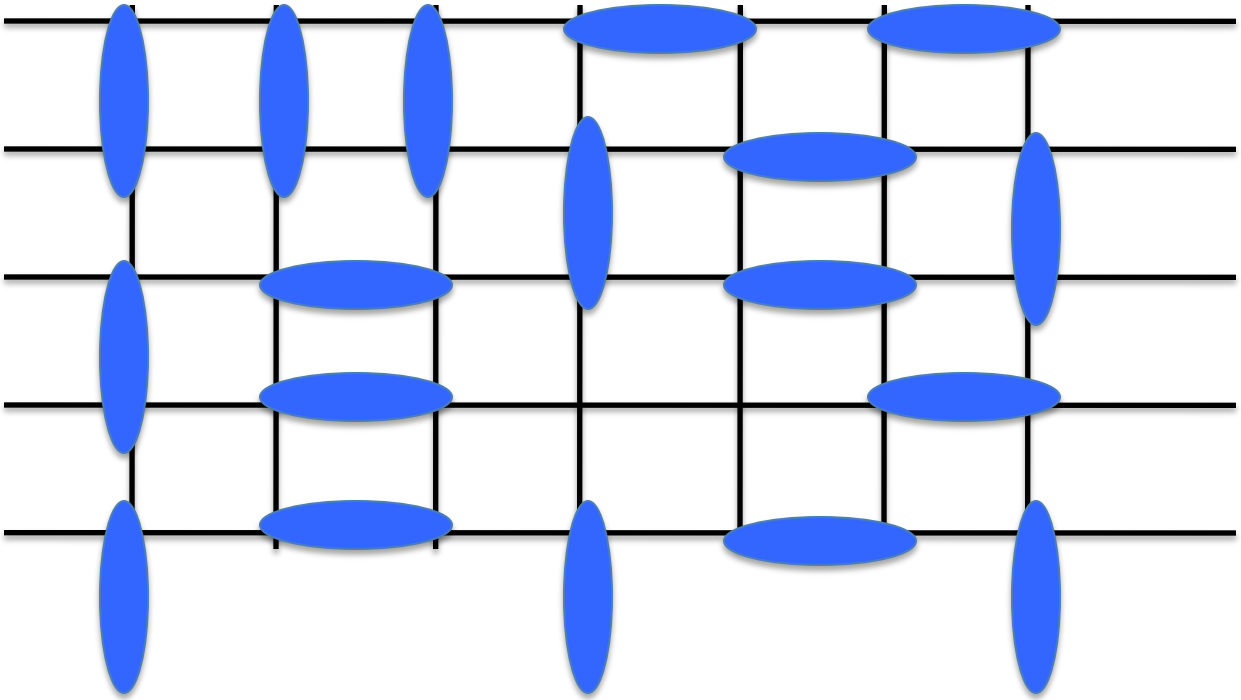
- RVB ground state is 2-fold degenerate on a cylinder and 4-fold degenerate on a torus.
- The RVB sustains fractional excitations (spinons).

Fractionalization in RVB spin liquid



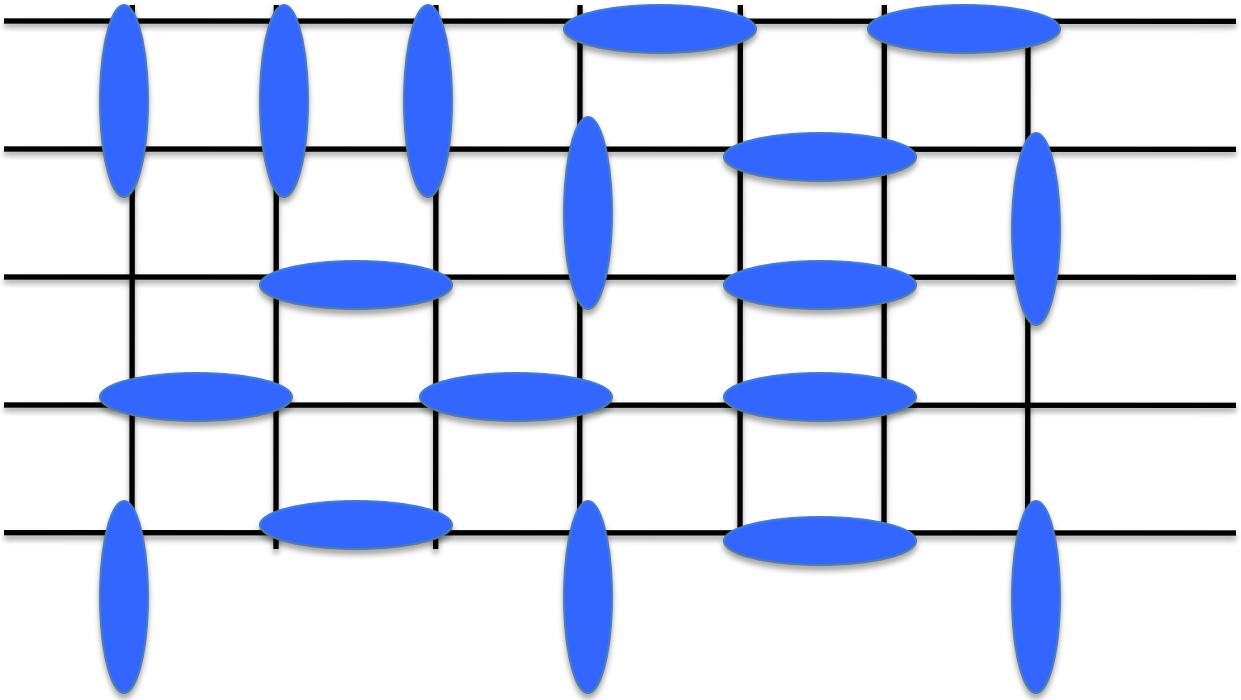
Breaking a valence bond in the spin liquid leads to two s=1/2 half-dimer excitations (spinons).

Fractionalization in RVB spin liquid



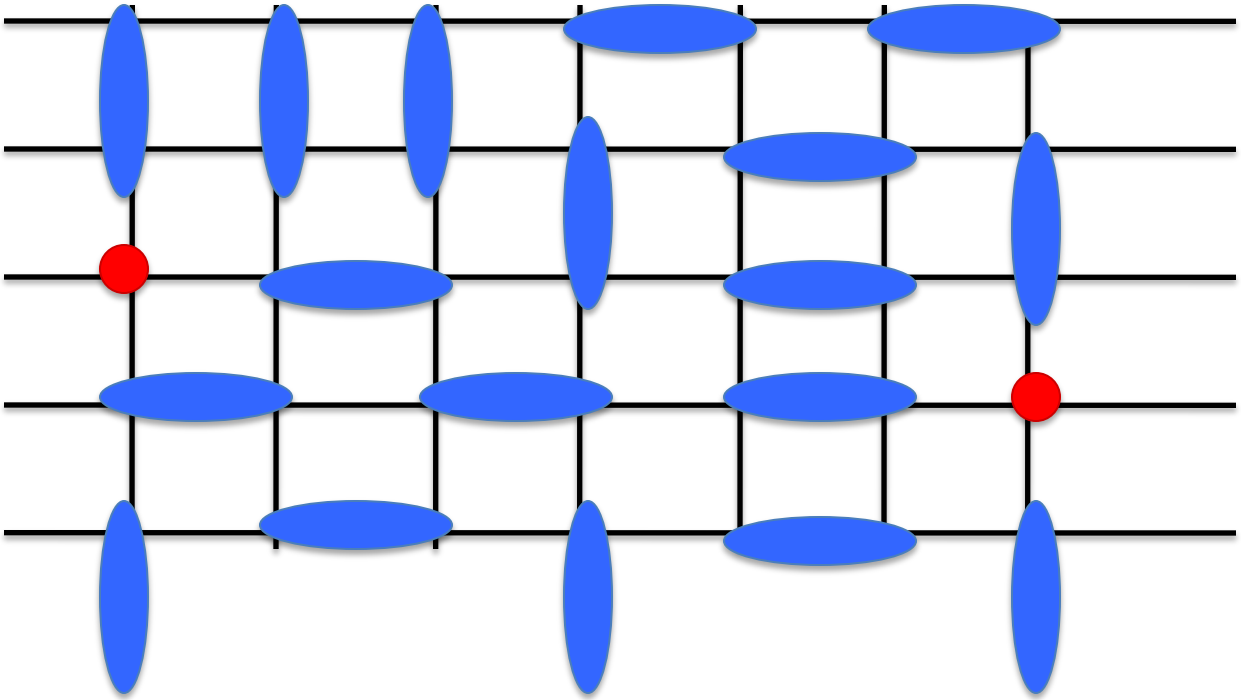
Breaking a valence bond in the spin liquid leads to two s=1/2 half-dimer excitations (spinons).

Fractionalization in RVB spin liquid



Breaking a valence bond in the spin liquid leads to two s=1/2 half-dimer excitations (spinons).

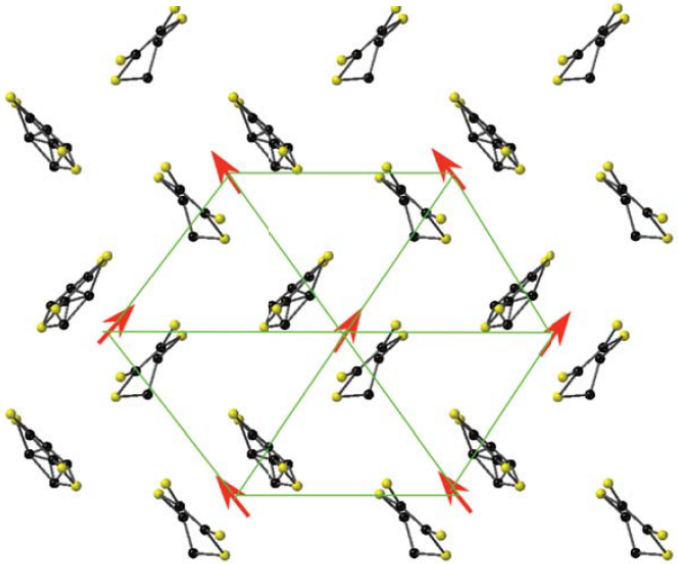
Fractionalization in RVB spin liquid



Breaking a valence bond in the spin liquid leads to two s=1/2 half-dimer excitations (spinons).

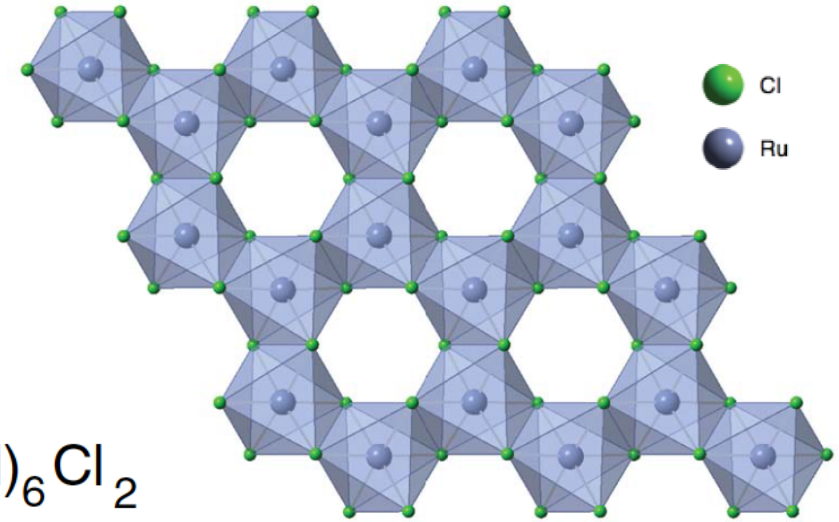
Candidate quantum spin liquid materials

κ-$(ET)_2Cu_2(CN)_3$



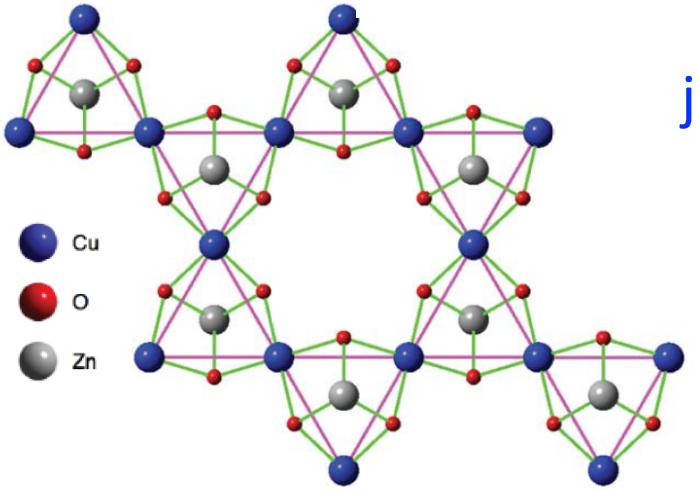
s=1/2, triangular lattice

α-$RuCl_3$



j=1/2, honeycomb

$ZnCu_3(OH)_6Cl_2$

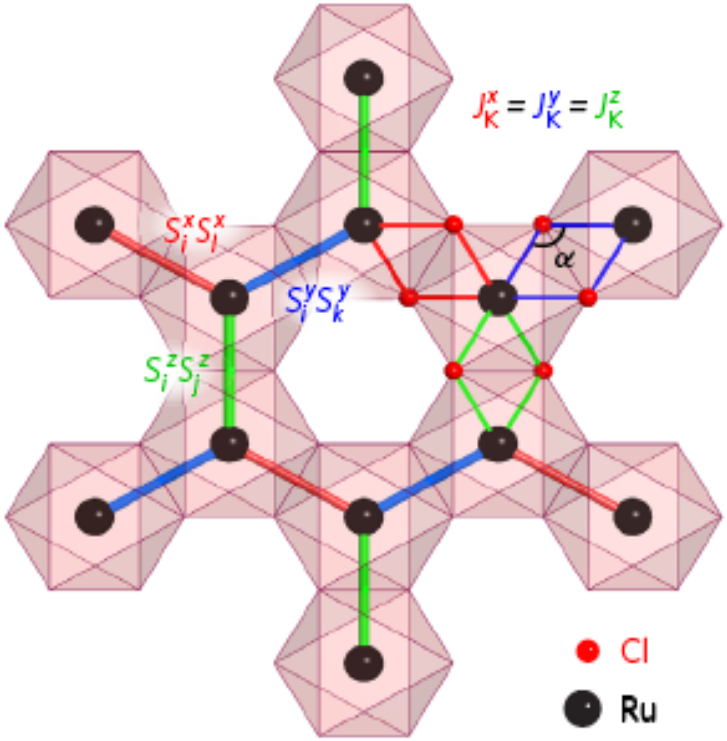


s=1/2, Kagomé

Broholm, et. al., Science (2020)

Kitaev materials

α-$RuCl_3$: $Ru^{3+}(4d^5)$



A_2IrO_3, (A=Na,Li): $Ir^{4+}(5d^5)$