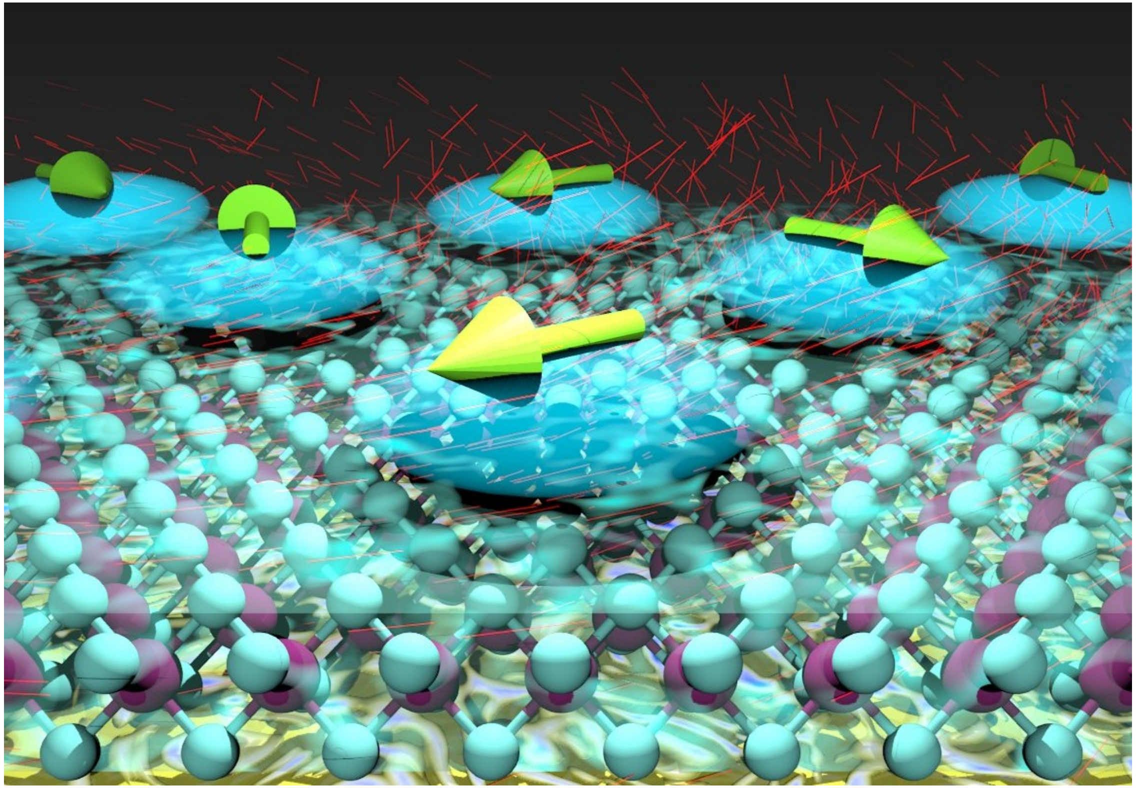
Magnetism, magnons, quantum magnetism and spinons



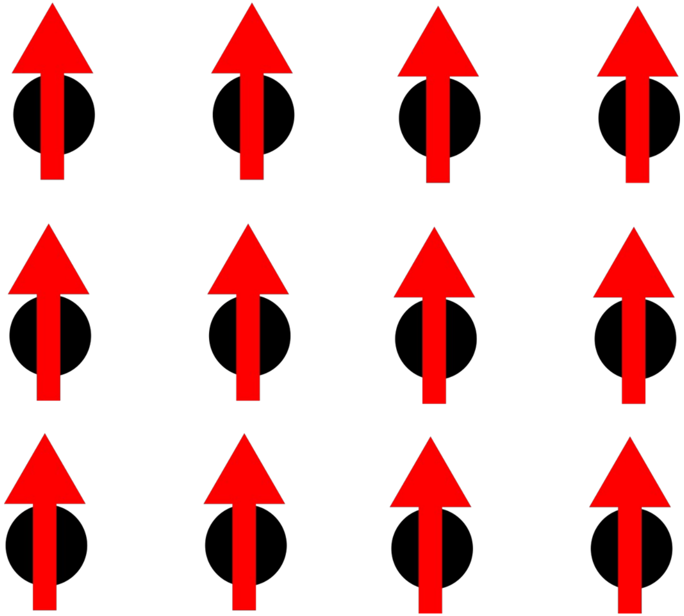
May 2nd 2023

Today's learning outcomes

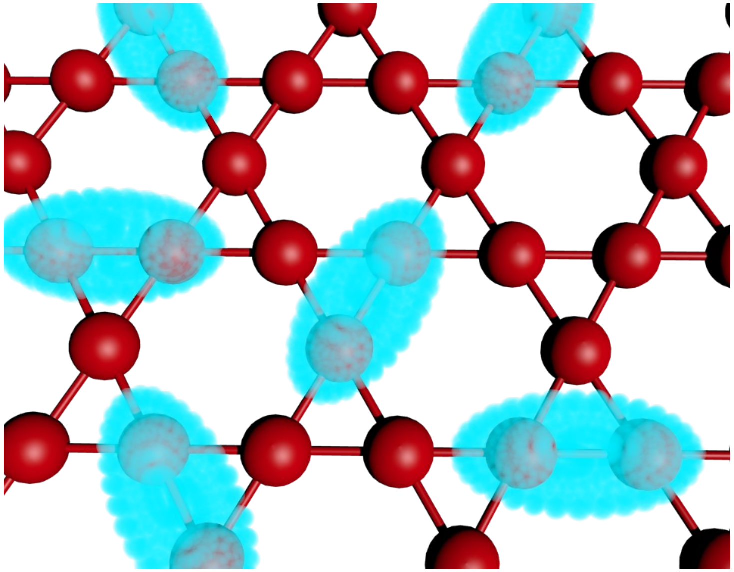
- Derive minimal models for magnetism
- Identify the quantum excitations of ordered magnets
- Identify the quantum excitations of quantum spin-liquids
- Identify the fundamental physics of Kondo lattice models

Today’s materials

Ferromagnet & antiferromagnets

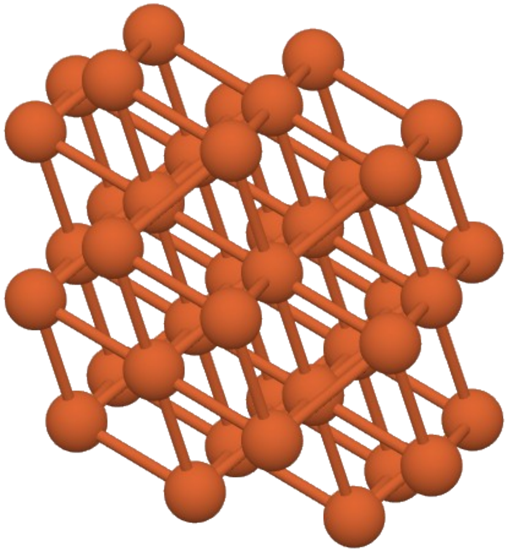


Quantum spin-liquids



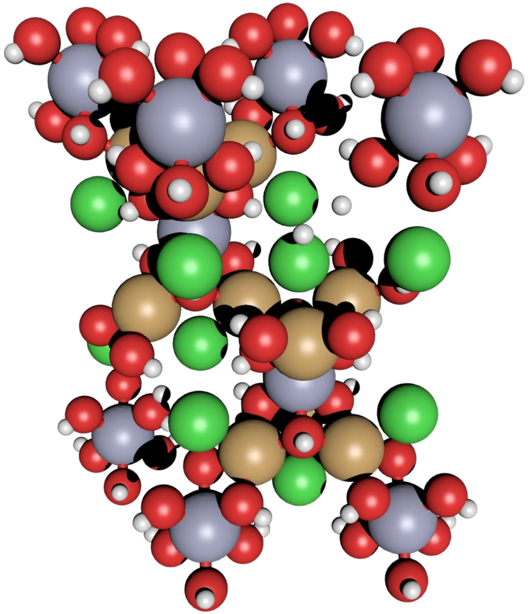
Today's materials

Ferromagnet & antiferromagnets



Iron

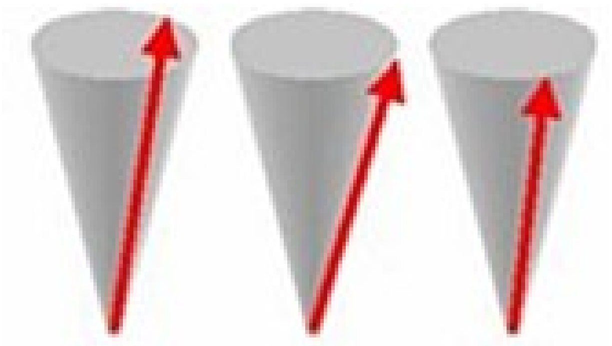
Quantum spin-liquids



Herbertsmithite

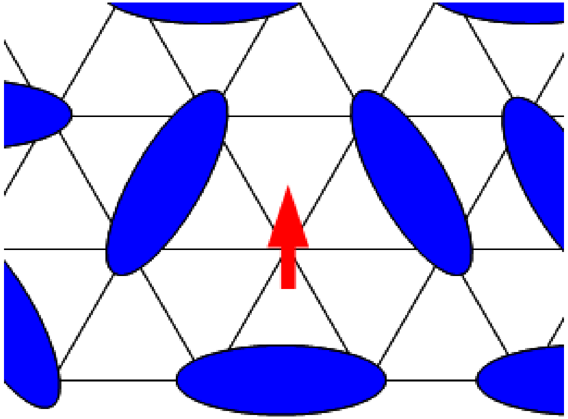
Today’s quasiparticles

Magnons



S=1
No charge

Spinons



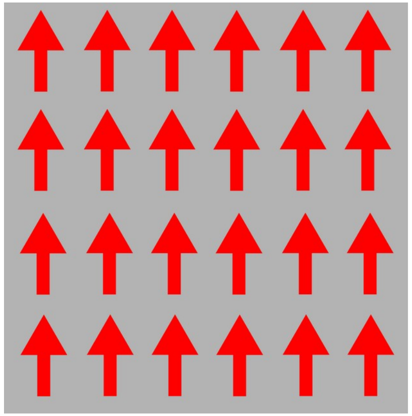
S=1/2
No charge

A reminder from previous sessions

Electronic interactions are responsible for symmetry breaking

Broken
time-reversal symmetry

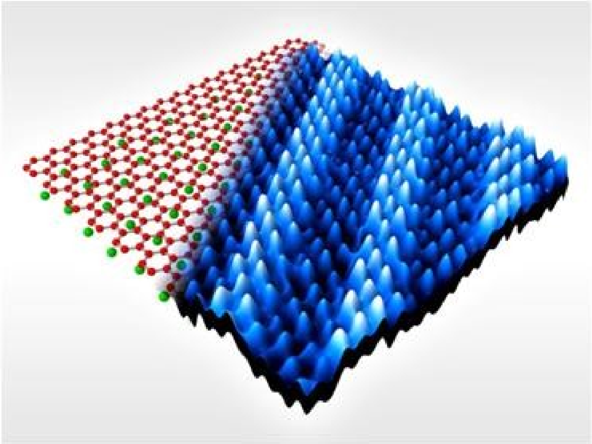
Classical magnets



$$\mathbf{M} \rightarrow -\mathbf{M}$$

Broken
crystal symmetry

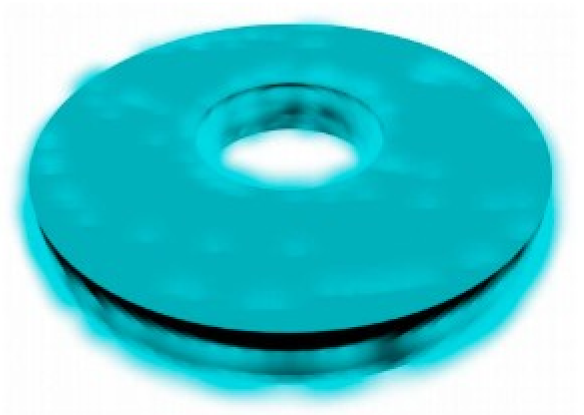
Charge density wave



$$\mathbf{r} \rightarrow \mathbf{r} + \mathbf{R}$$

Broken
gauge symmetry

Superconductors



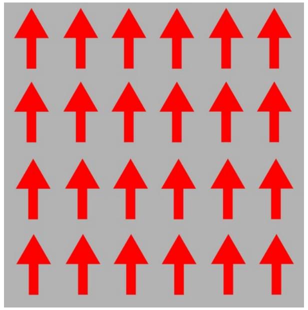
$$\langle c_\uparrow c_\downarrow \rangle \rightarrow e^{i\phi} \langle c_\uparrow c_\downarrow \rangle$$

Correlations and mean field

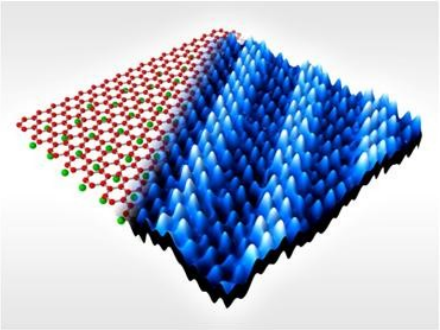
Many quantum states can be approximately described by mean field theories

$$H = \sum_{ij} t_{ij} c_i^\dagger c_j + \sum_{ijkl} V_{ijkl} c_i^\dagger c_j c_k^\dagger c_l$$

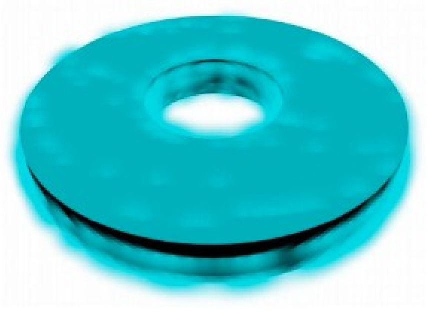
Magnets



Charge density waves



Superconductors



Interactions and mean field

Free Hamiltonian ***Interactions***

$$H = \sum_{ij} t_{ij} c_i^\dagger c_j + \sum_{ijkl} V_{ijkl} c_i^\dagger c_j c_k^\dagger c_l$$

What are these interactions coming from?

- Electrostatic (repulsive) interactions
- Mediated by other quasiparticles (phonons, magnons, plasmons,...)

The net effective interaction can be attractive or repulsive

<u>Magnetism is promoted by repulsive interactions</u>

A simple interacting Hamiltonian

Free Hamiltonian

Interactions (Hubbard term)

$$H = \sum_{ij} t_{ij} [c^\dagger_{i\uparrow} c_{j\uparrow} + c^\dagger_{i\downarrow} c_{j\downarrow}] + \sum_i U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}$$

What is the ground state of this Hamiltonian?

$U < 0$ Superconductivity

$U > 0$ Magnetism

The mean-field approximation

Mean field: *Approximate four fermions by two fermions times expectation values*

Four fermions
(not exactly solvable)

Two fermions
(exactly solvable)

$$U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow} \approx U \langle c^\dagger_{i\uparrow} c_{i\uparrow} \rangle c^\dagger_{i\downarrow} c_{i\downarrow} + ... + h.c.$$

$$U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow} \approx M \sigma^z_{ss'} c^\dagger_{i,s} c_{i,s'} + h.c.$$

For $U > 0$
i.e. repulsive interactions

Magnetic order

$$M \sim \langle c^\dagger_{i\uparrow} c_{i\uparrow} \rangle - \langle c^\dagger_{i\downarrow} c_{i\downarrow} \rangle$$

The mean-field approximation

The non-collinear mean-field Hamiltonian

$$U c^\dagger_{n\uparrow} c_{n\uparrow} c^\dagger_{n\downarrow} c_{n\downarrow} \approx M^\alpha_n \sigma^\alpha_{ss'} c^\dagger_{n,s} c_{n,s'} + h.c.$$

Non-collinear magnetic order

$$M^z_n \sim \langle c^\dagger_{n\uparrow} c_{n\uparrow} \rangle - \langle c^\dagger_{n\downarrow} c_{n\downarrow} \rangle$$

$$M^x_n \sim \langle c^\dagger_{n\uparrow} c_{n\downarrow} \rangle + \langle c^\dagger_{n\downarrow} c_{n\uparrow} \rangle$$

$$M^y_n \sim i\langle c^\dagger_{n\uparrow} c_{n\downarrow} \rangle - i\langle c^\dagger_{n\downarrow} c_{n\uparrow} \rangle$$

A Hamiltonian for a weakly correlated magnet

Free Hamiltonian **_Exchange term_**

$$H = \sum_{ij} t_{ij} [c^\dagger_{i\uparrow} c_{j\uparrow} + c^\dagger_{i\downarrow} c_{j\downarrow}] + M \sum_i \sigma^z_{s,s'} c^\dagger_{i,s} c_{i,s'}$$

Her we assume that interactions are weak (in comparison with the kinetic energy)

What if interactions are much stronger than the kinetic energy?

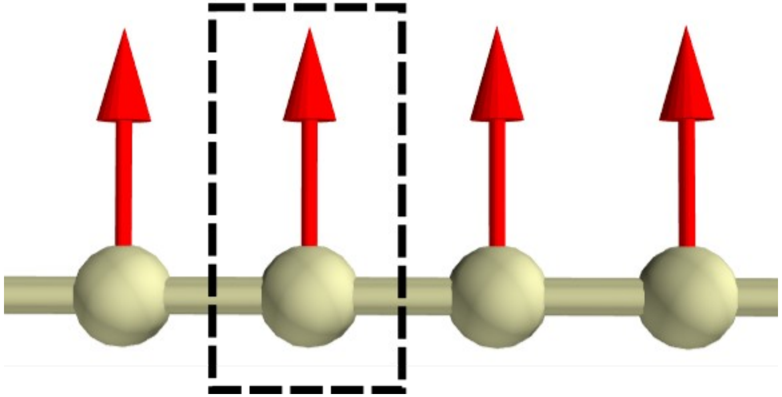
Solving the interacting model at the mean-field level in a 1D chain

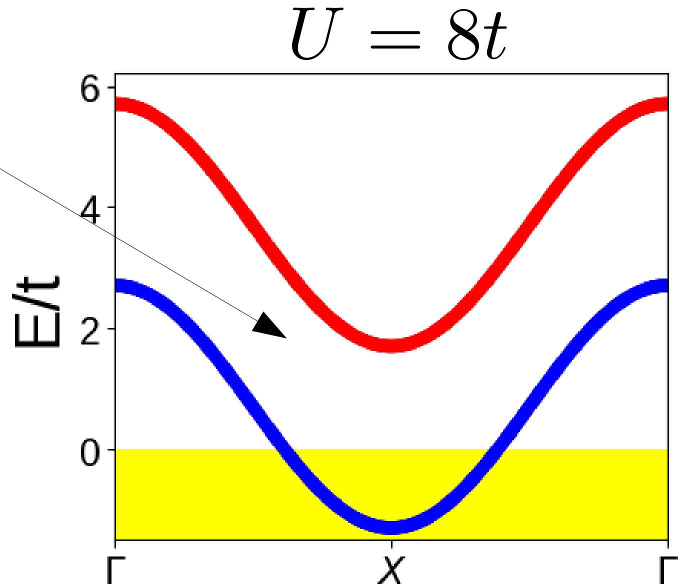
We will take the interacting model and solve it at the mean field level

$$H = \sum_{ij} t_{ij}[c^\dagger_{i\uparrow}c_{j\uparrow} + c^\dagger_{i\downarrow}c_{j\downarrow}] + \sum_i U c^\dagger_{i\uparrow}c_{i\uparrow}c^\dagger_{i\downarrow}c_{i\downarrow}$$

Filling 0.2 (full would be 1)

Interaction-induced splitting

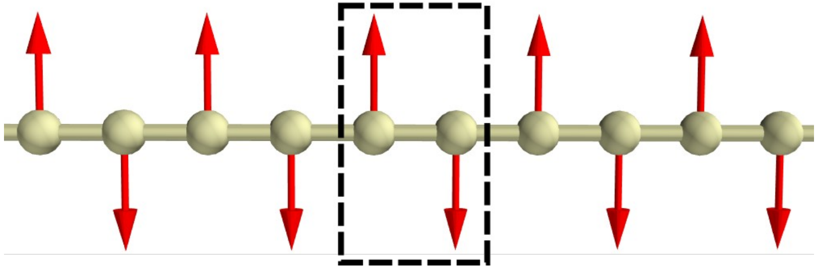


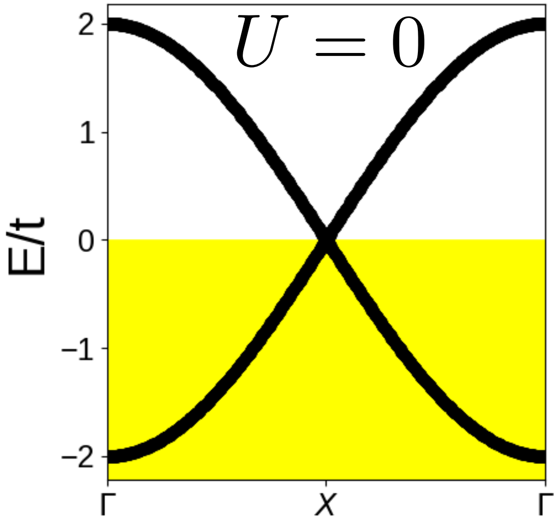


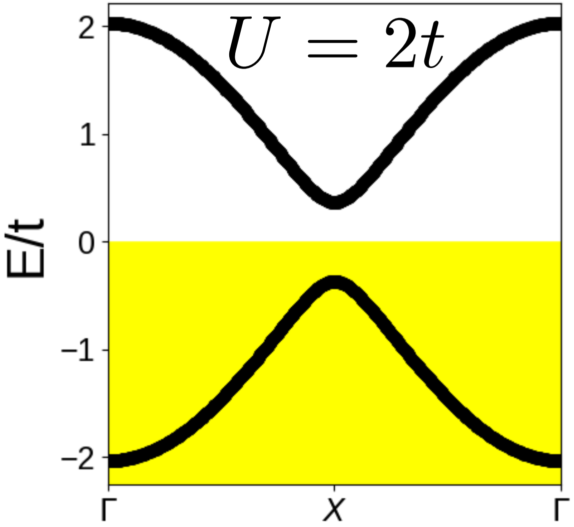
Solving the interacting model at the mean-field level in a 1D chain

Let us do again a 1D, but now with 2 sites per unit cell and at half filling

$$H = \sum_{ij} t_{ij} [c^\dagger_{i\uparrow} c_{j\uparrow} + c^\dagger_{i\downarrow} c_{j\downarrow}] + \sum_i U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}$$

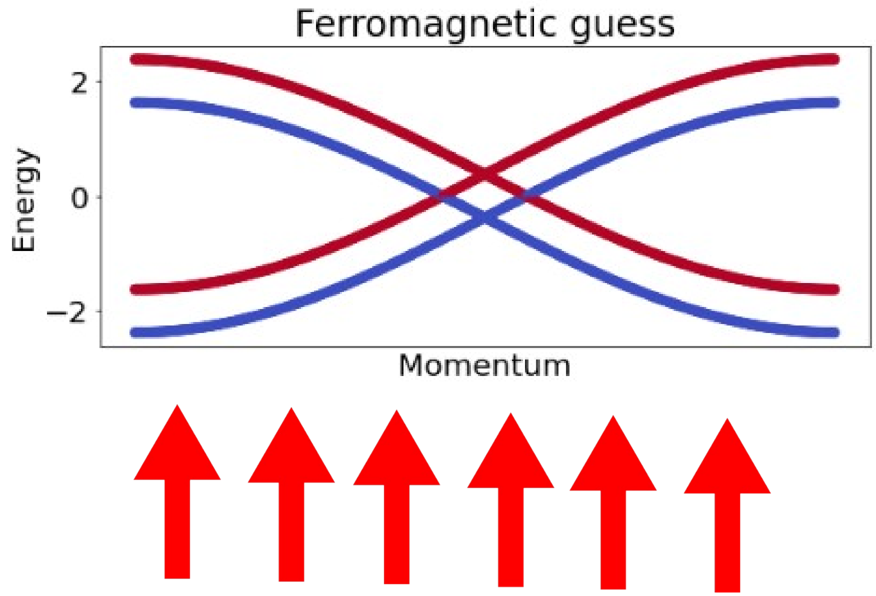


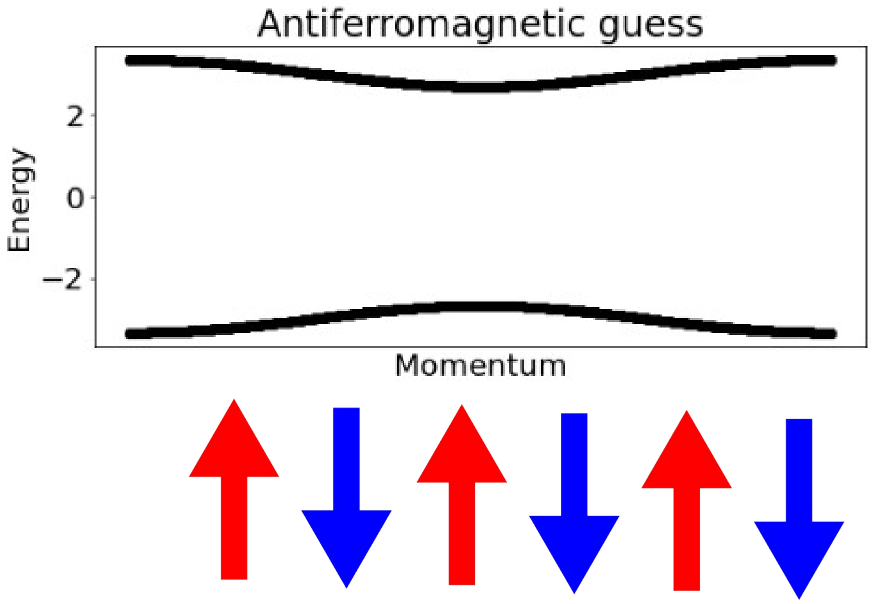




Competing solutions for a magnetic state

Let us now consider two selfconsistent solutions for the interacting model

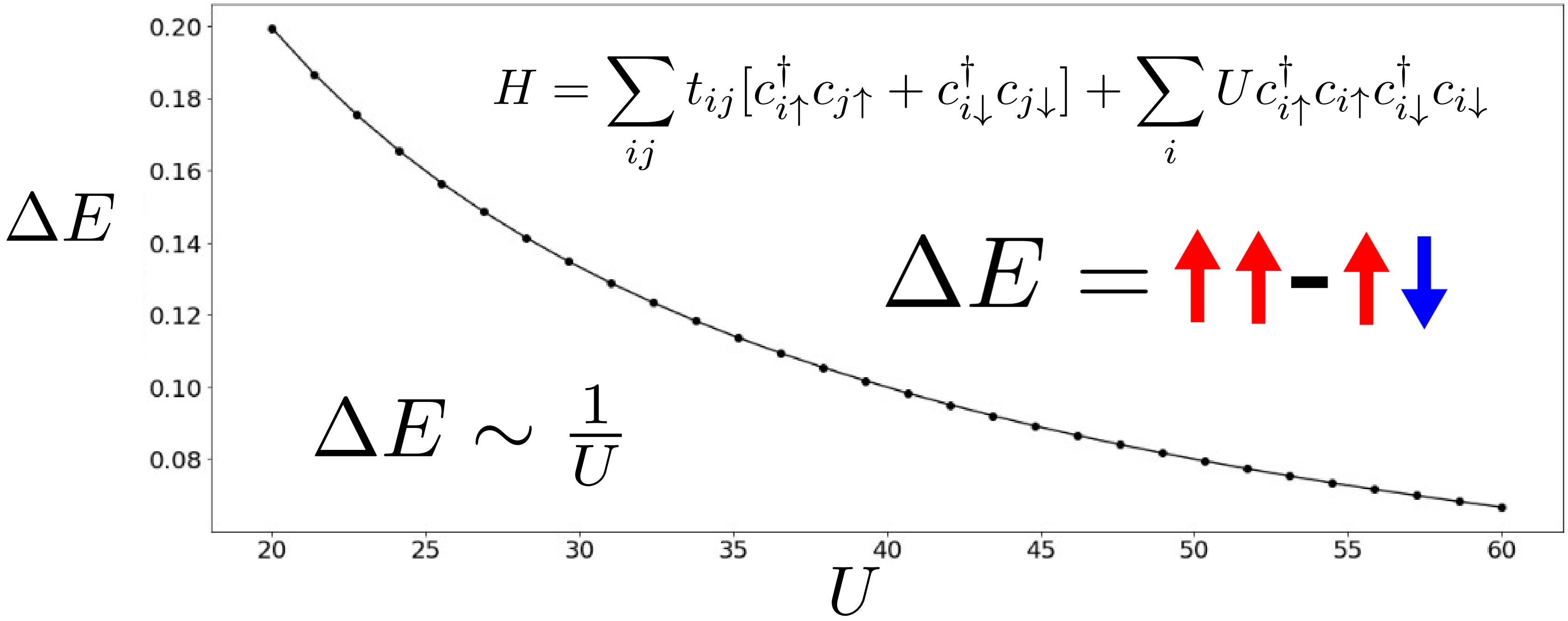




Only once of them is the true ground state, but which one it is?

Competing solutions for a magnetic state

Let us now compute the energy difference between the two configurations



For strong interactions, the AF configuration always has lower energy

The critical interaction for magnetic ordering

Lets take the Hamiltonian

$$H = \sum_{ij} t_{ij} [c^\dagger_{i\uparrow} c_{j\uparrow} + c^\dagger_{i\downarrow} c_{j\downarrow}] + \sum_i U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}$$

Do we have magnetism for any value of U? $\langle S_z \rangle \neq 0$

In general, in the weak coupling limit magnetism appears when

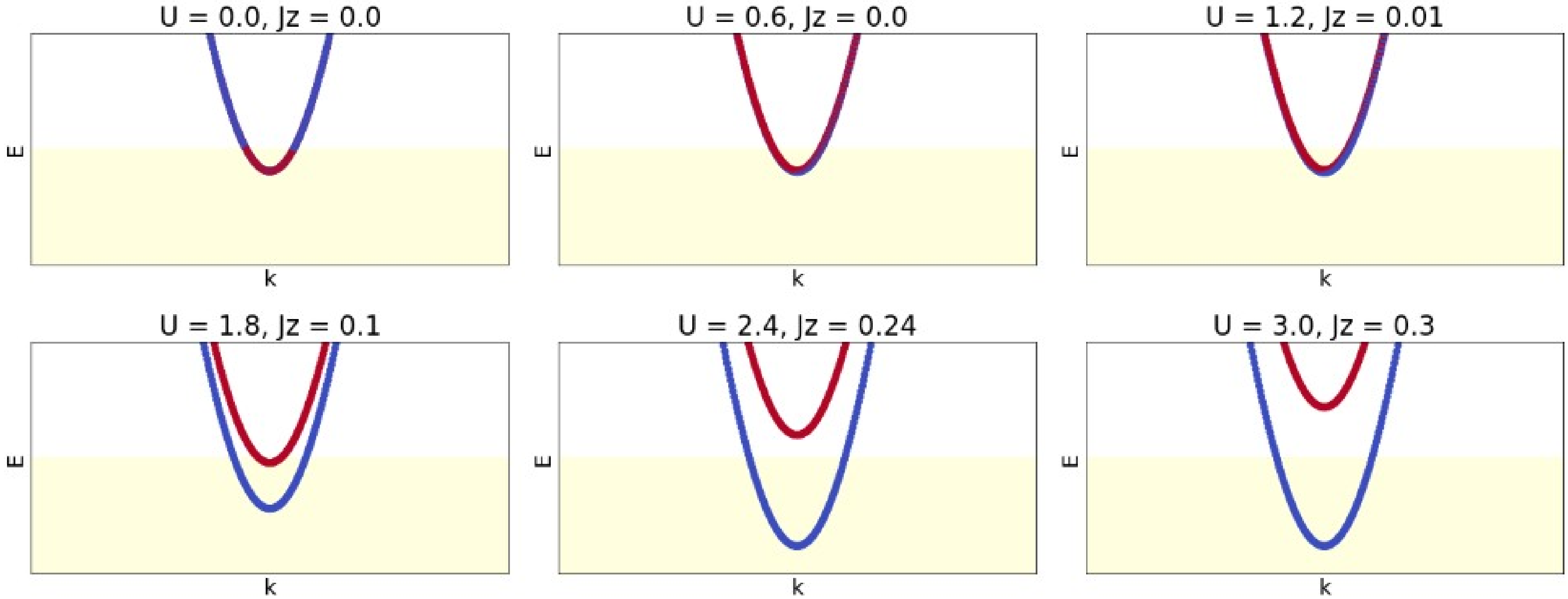
$$U D(\omega) > 1$$

Repulsive interaction

Density of states

The critical interaction for magnetic ordering

Magnetic instabilities occur once interactions are strong enough



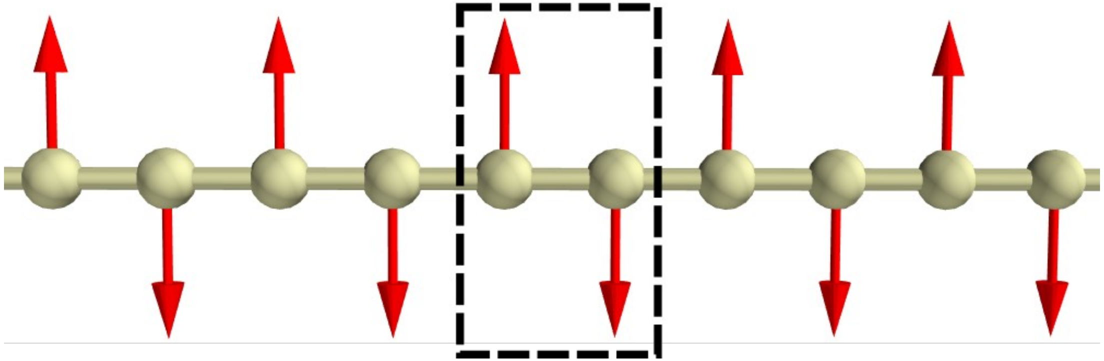
For interactions below a threshold, no magnetic order occurs

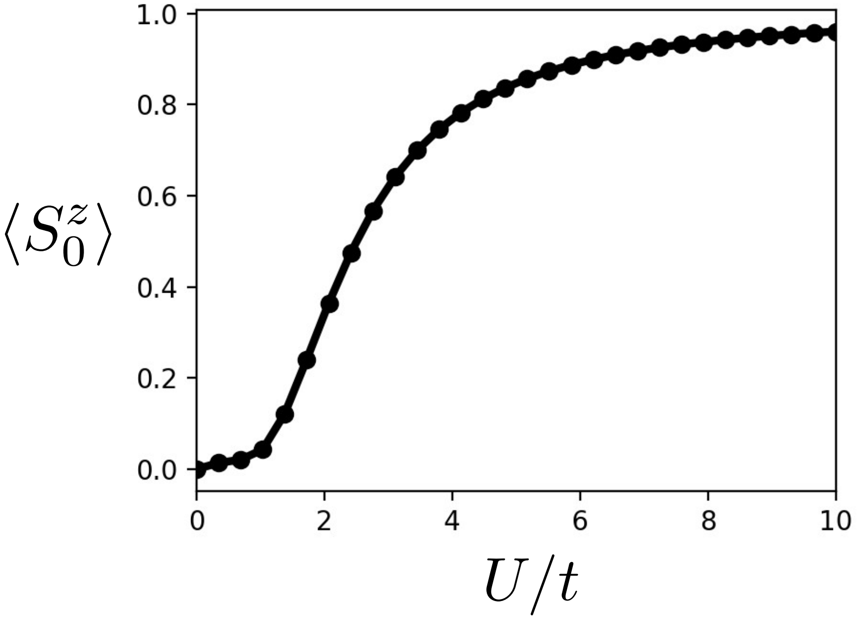
The strongly localized limit and the Heisenberg model

From a weak magnet to the strongly localized limit

$$H = \sum_{ij} t_{ij} [c^\dagger_{i\uparrow} c_{j\uparrow} + c^\dagger_{i\downarrow} c_{j\downarrow}] + \sum_i U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}$$

For large interaction strength, the system develops a local quantized magnetic moment





The strongly localized limit

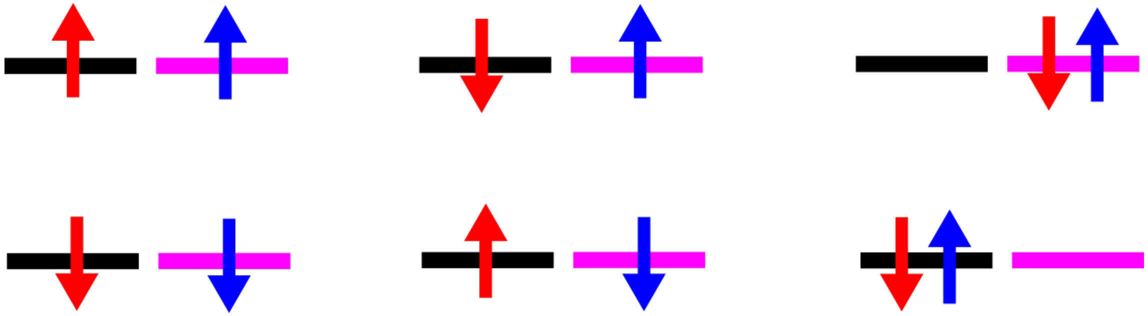
Let us start with a Hubbard model dimer

$$H = t[c^\dagger_{0\uparrow}c_{1\uparrow} + c^\dagger_{0\downarrow}c_{1\downarrow}] + \sum_i U c^\dagger_{i\uparrow}c_{i\uparrow}c^\dagger_{i\downarrow}c_{i\downarrow} + h.c.$$

Now in the limit $U \gg t$

Levels 

The full Hilbert space at half filling is

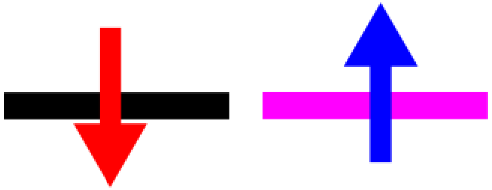


The strongly localized limit

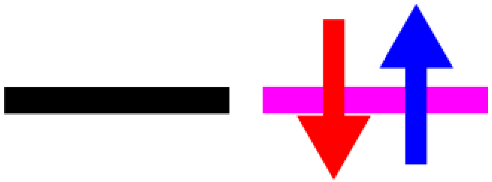
Let us start with a Hubbard model dimer

$$H = t[c^\dagger_{0\uparrow}c_{1\uparrow} + c^\dagger_{0\downarrow}c_{1\downarrow}] + \sum_i U c^\dagger_{i\uparrow}c_{i\uparrow}c^\dagger_{i\downarrow}c_{i\downarrow} + h.c.$$

The energies in the strongly localized limit are $U \gg t$



~ 0



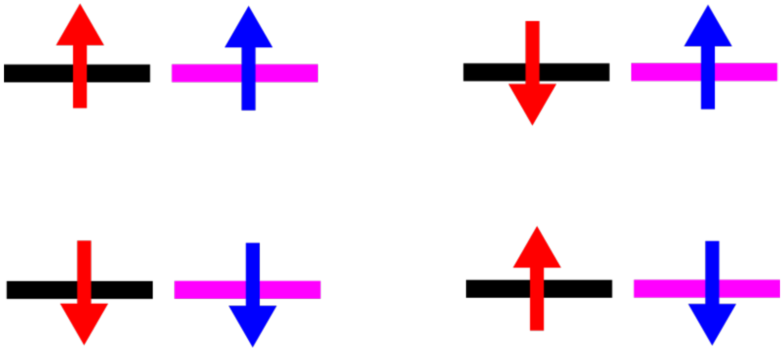
$\sim U$

The strongly localized limit

Let us start with a Hubbard model dimer

$$H = t[c^{\dagger}_{0\uparrow} c_{1\uparrow} + c^{\dagger}_{0\downarrow} c_{1\downarrow}] + \sum_i U c^{\dagger}_{i\uparrow} c_{i\uparrow} c^{\dagger}_{i\downarrow} c_{i\downarrow} + h.c.$$

The low energy manifold is



Just one electron in each site for $U \gg t$

Local S=1/2 at each site

The strongly localized limit

Effective Heisenberg model in the localized limit $\mathcal{H} = J\vec{S}_0 \cdot \vec{S}_1$

We can compute J using second order perturbation theory

$$H = H_0 + V$$

$$H_0 = \sum_i U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}$$

“pristine” Hamiltonian
(Hubbard)

$$V = t[c^\dagger_{0\uparrow} c_{1\uparrow} + c^\dagger_{0\downarrow} c_{1\downarrow}] + \text{h.c.}$$

“perturbation” Hamiltonian
(hopping)

The strongly localized limit

Effective Heisenberg model in the localized limit $$\mathcal{H} = J\vec{S}_0 \cdot \vec{S}_1$$

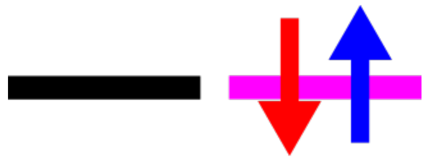
We can compute J using second order perturbation theory

$$H = H_0 + V$$

$$J \sim \frac{t^2}{U}$$

Ground state

Virtual state



The Heisenberg model

For a generic Hamiltonian in a generic lattice

$$H = \sum_{ij} t_{ij} [c^\dagger_{i\uparrow} c_{j\uparrow} + c^\dagger_{i\downarrow} c_{j\downarrow}] + \sum_i U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow}$$

In the strongly correlated (half-filled) limit we obtain a Heisenberg model

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

$$J_{ij} \sim \frac{|t_{ij}|^2}{U}$$

The Heisenberg model

Non-Hubbard (multiorbital) models also yield effective Heisenberg models

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

In those generic cases, the exchange couplings can be positive or negative

$$J_{ij} > 0$$

Antiferromagnetic coupling

$$J_{ij} < 0$$

Ferromagnetic coupling

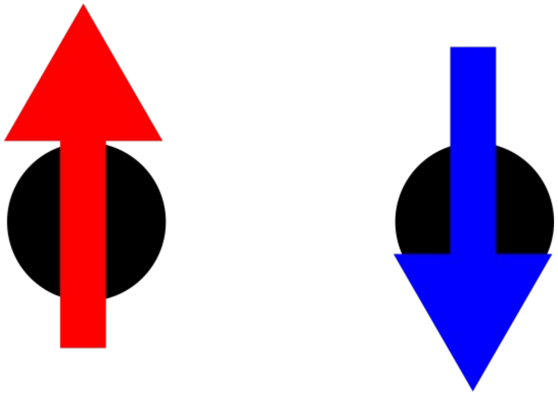
Spin-orbit coupling introduces anisotropic couplings

$$\mathcal{H} = \sum_{ij} J_{ij}^{\alpha\beta} S_i^{\alpha} S_j^{\beta}$$

The Heisenberg model

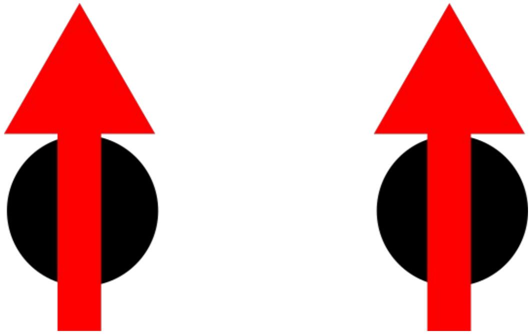
$$J_{ij} > 0$$

Antiferromagnetic coupling



$$J_{ij} < 0$$

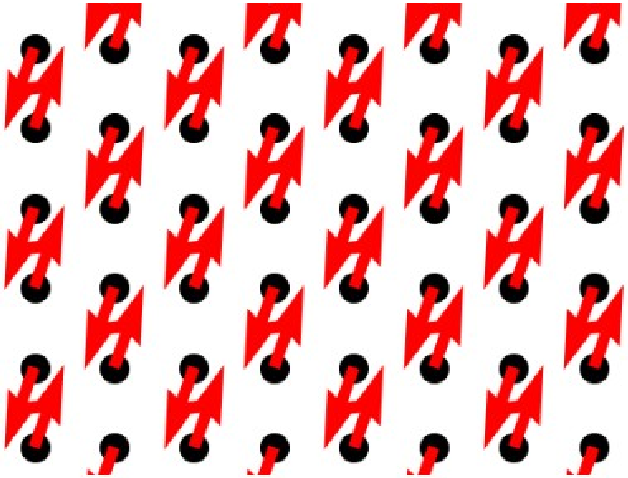
Ferromagnetic coupling



Classical ground states

Antiferromagnetism driven by superexchange

In the square lattice



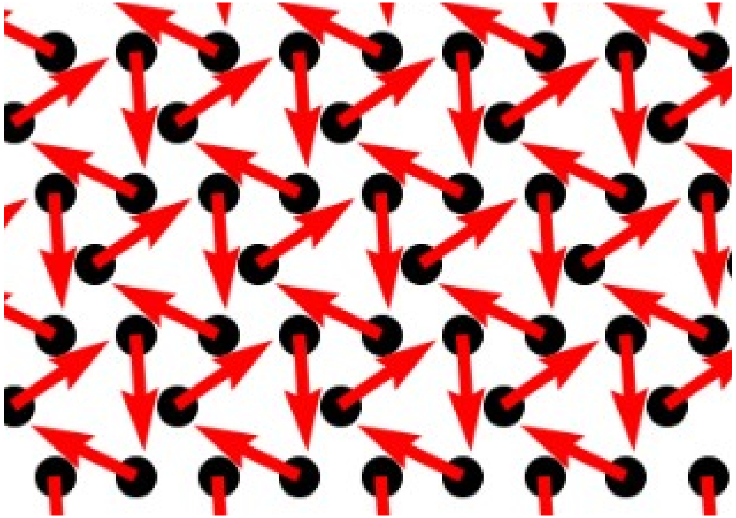
In the honeycomb lattice

$$H = \sum_{ij,s} t_{ij} c^\dagger_{i,s} c_{j,s} + \sum_i U c^\dagger_{i\uparrow} c_{i\uparrow} c^\dagger_{i\downarrow} c_{i\downarrow} + h.c.$$

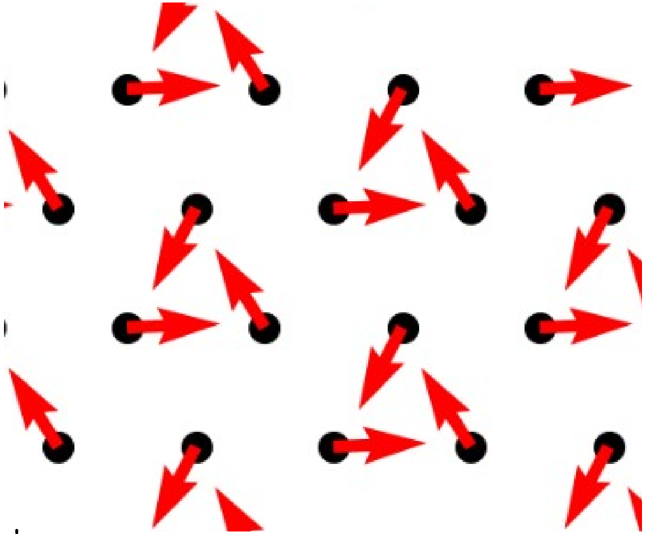
In bipartite lattices, the magnetization is collinear

Antiferromagnetism driven by superexchange

In the Kagome lattice



In the triangular lattice



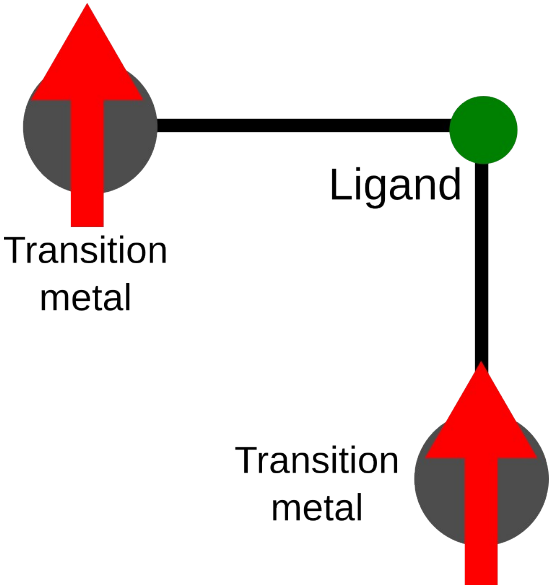
$$H = \sum_{ij,s} t_{ij} c^{\dagger}_{i,s} c_{j,s} + \sum_{i} U c^{\dagger}_{i\uparrow} c_{i\uparrow} c^{\dagger}_{i\downarrow} c_{i\downarrow} + h.c.$$

Geometric frustration promotes non-collinear order at the mean-field level

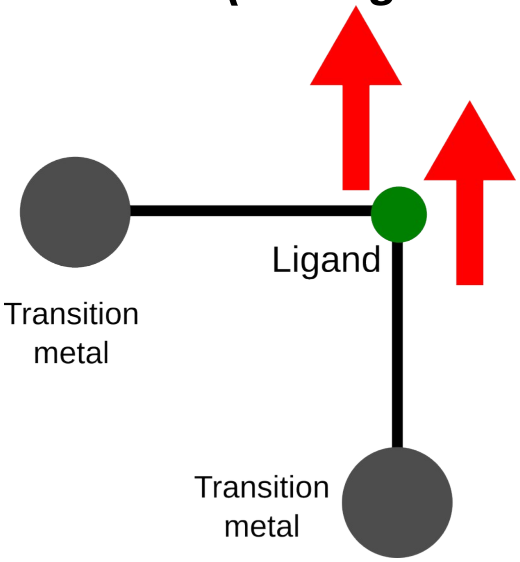
The origin of ferromagnetic coupling

Exchange interactions can be ferromagnetic if mediated by an intermediate site

Low energy manifold



Virtual state (among others)



The sign of the coupling depends on the filling of the d-shell and the angle

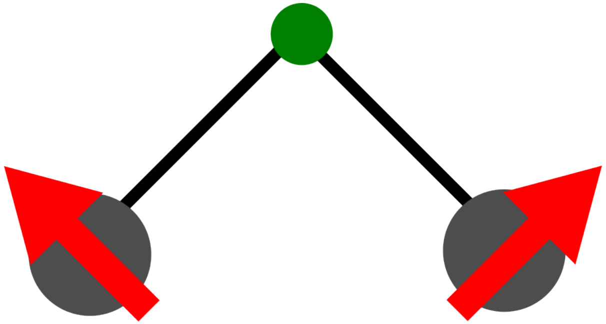
Goodenough-Kanamori rules

Non-isotropic exchange coupling

In the presence of spin-orbit coupling, new terms can appear in the Hamiltonian

Antisymmetric exchange

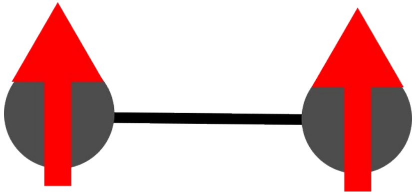
$$(\mathbf{r}_{ik} \times \mathbf{r}_{kj}) \cdot \vec{S}_i \times \vec{S}_j$$



Promotes
non-collinear order

Anisotropic exchange

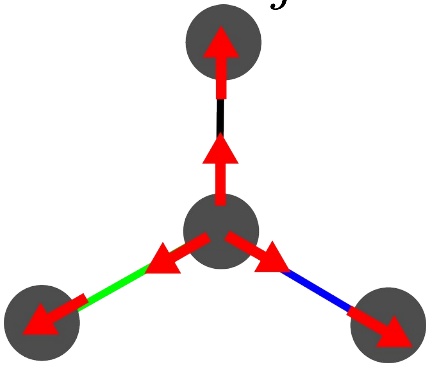
$$S_i^z S_j^z$$



Promotes
easy axis/plane

Kitaev interaction

$$S_i^{\alpha(i)} S_j^{\alpha(j)}$$



Promotes
frustration

Break

10-15 min break

(optional) to discuss during the break

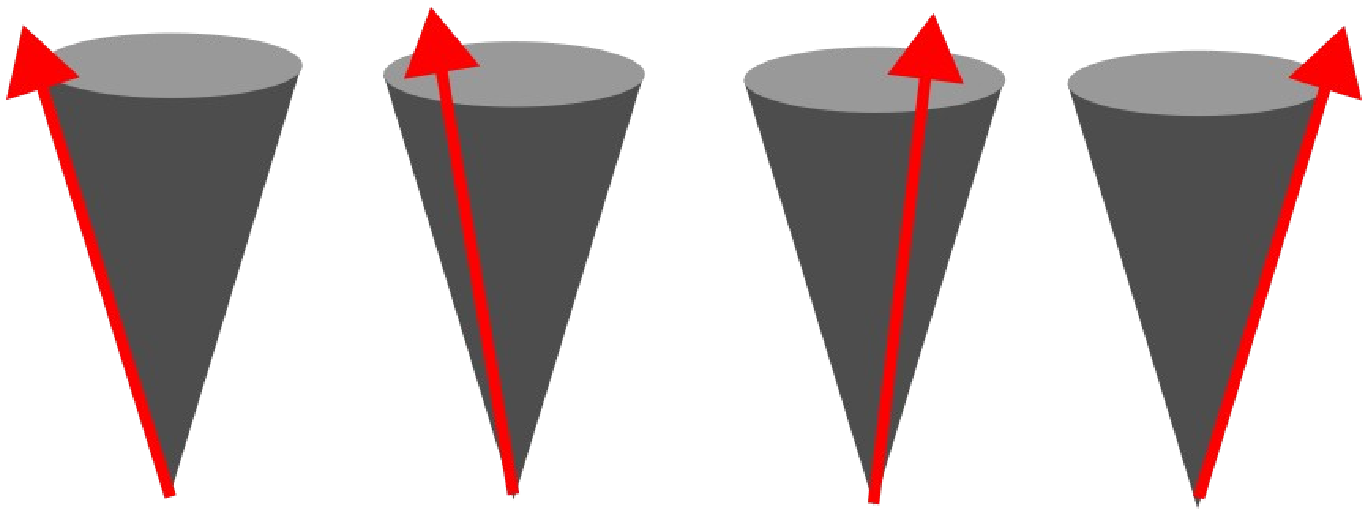
Which type of magnetic order fulfills

$$\langle c^\dagger_{n\uparrow} c_{n\downarrow} \rangle \neq 0 \qquad Im\left[\langle c^\dagger_{n\uparrow} c_{n\downarrow} \rangle\right] = 0 \qquad Re\left[\langle c^\dagger_{n\uparrow} c_{n\downarrow} \rangle\right] = 0$$

Magnons

Excitations in a ferromagnet

Qualitatively, magnons are the fluctuations of the order parameter



Excitations in the Heisenberg model

The Heisenberg model is a full-fledged many-body problem

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

Algebraic commutation relations $$[S_j^\alpha, S_j^\beta] = i\epsilon_{\alpha\beta\gamma} S_j^\gamma$$

$$S = 1/2, 1, 3/2, 2, ...$$

How do we compute its many-body excitations?

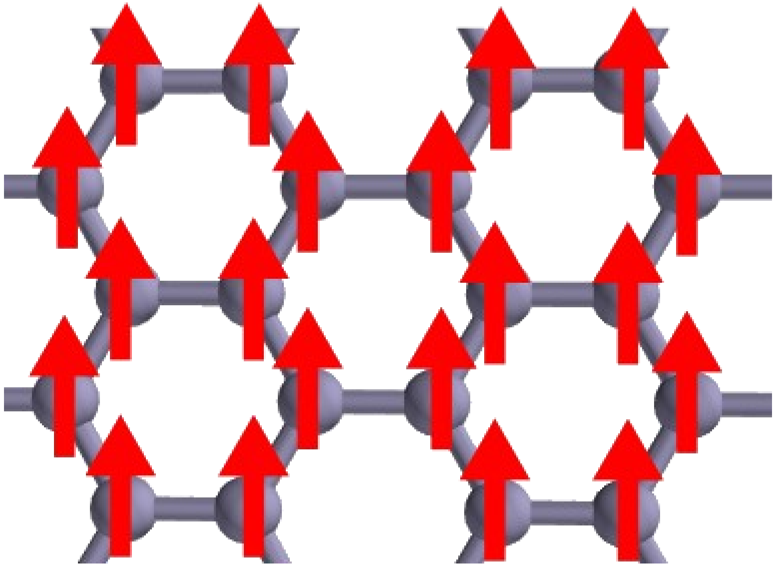
The ferromagnetic Heisenberg model

In the case of a ferromagnetic Heisenberg model, we know the ground state

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

$$J_{ij} < 0$$

$$|GS\rangle = |\uparrow\uparrow\uparrow\uparrow\uparrow ....\rangle$$



But how do we compute the excitations?

The Holstein–Primakoff transformation

Replace the spin Hamiltonian by a bosonic Hamiltonian

$$S_+ = \sqrt{2s}\sqrt{1-\frac{a^\dagger a}{2s}}\,a, \quad S_- = \sqrt{2s}a^\dagger\sqrt{1-\frac{a^\dagger a}{2s}}, \quad S_z = (s - a^\dagger a)$$

Make the replacement and decouple with mean-field assuming $\langle a_i^\dagger a_i \rangle \ll s$

$$\mathcal{H} = \sum_{ij} J_{ij}\vec{S}_i \cdot \vec{S}_j \longrightarrow \mathcal{H} = \sum_{ij} \gamma_{ij} a_i^\dagger a_j$$

Spins **Magnon**

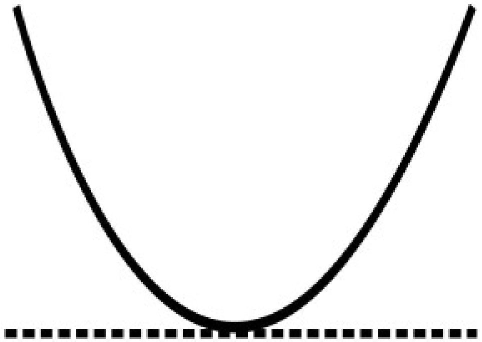
Magnons in a nutshell

Increase the spin	$S_i^+ \sim a_i$	Destroy a magnon
Decrease the spin	$S_i^- \sim a_i^\dagger$	Create a magnon
Net magnetization	$\langle S_i^z \rangle = S - \langle a_i^\dagger a_i \rangle$	Maximal minus the magnons

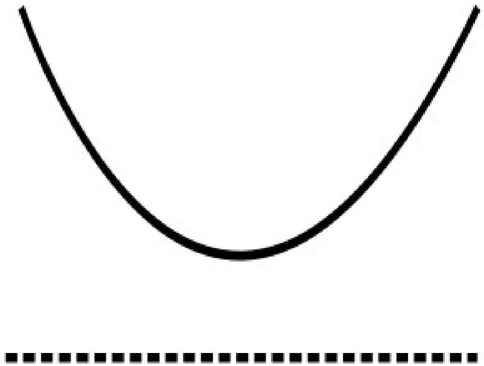
Magnons are S=1 excitations that exist over the symmetry broken state

Magnon dispersions

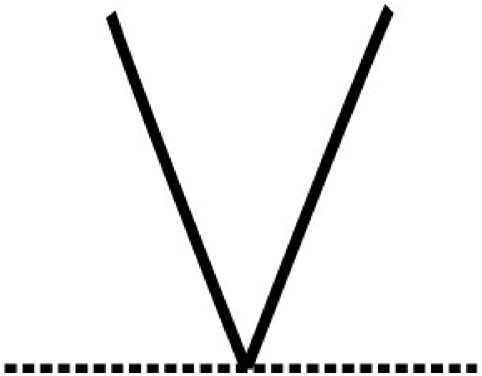
Gapless magnons



Gapped magnons



Dirac magnons



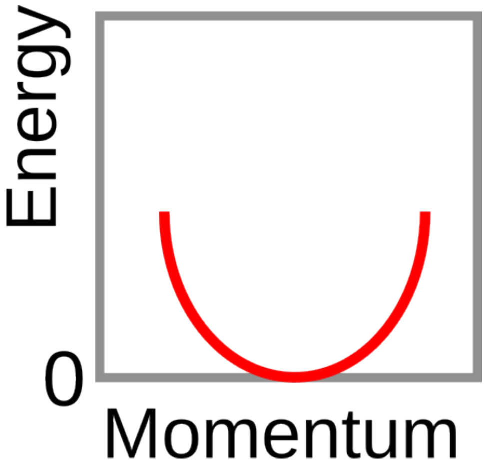
$$\mathcal{H} = \sum_{ij} \gamma_{ij} a_i^\dagger a_j$$

$$\mathcal{H} = \sum_{\mathbf{k}} \epsilon(\mathbf{k}) a_{\mathbf{k}}^\dagger a_{\mathbf{k}}$$

Magnons in the presence and absence of anisotropy

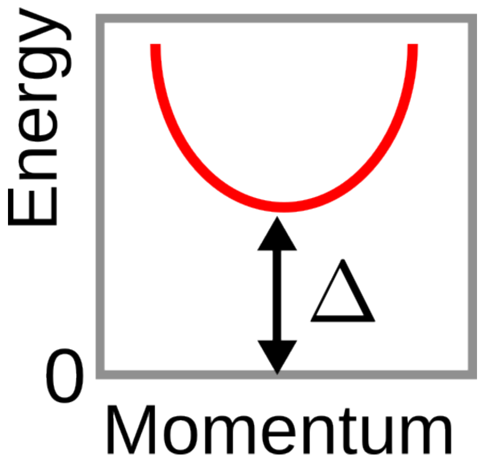
Without anisotropy

$$\mathcal{H} = -\sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



With anisotropy

$$\mathcal{H} = -J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j - K \sum_{\langle ij \rangle} S_i^z S_j^z$$



$$\Delta \sim K$$

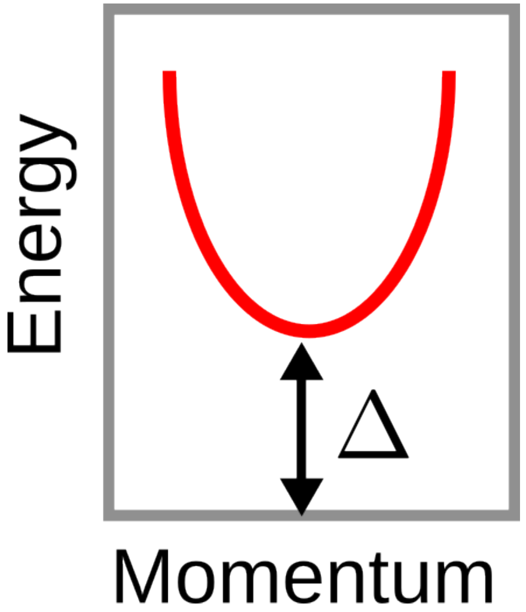
Anisotropy in the spin model generates a magnon gap

The role of magnons in 2D magnets

$$S_z = s - a^\dagger a$$

Correction from magnon population

$$\delta M_z = \langle a^\dagger a \rangle$$



Magnons renormalize the total magnetization

$$\delta M_z \sim T \int_0^{k_c} \frac{k\,dk}{\Delta + k^2}$$

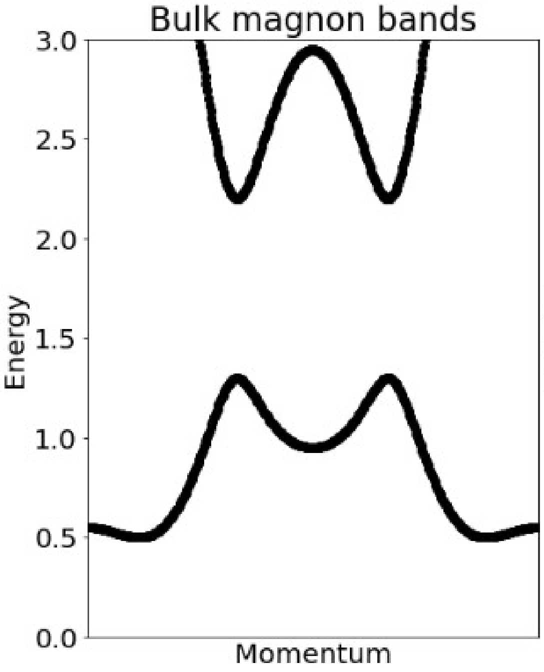
Temperature

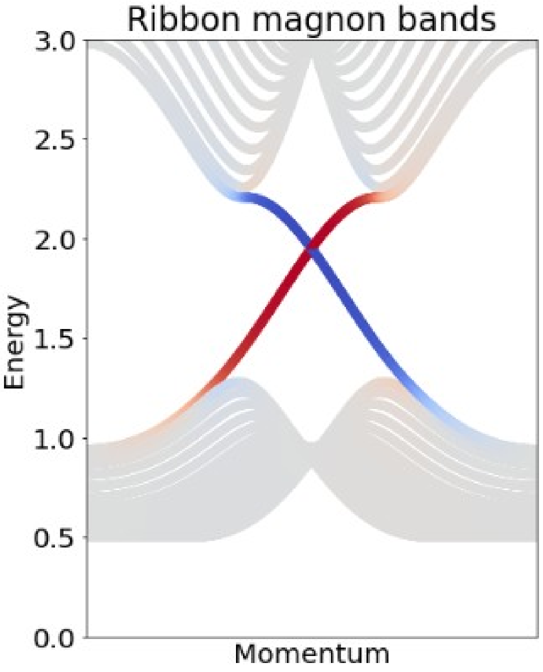
In the absence of a magnon gap, the correction to the magnetization is infinite

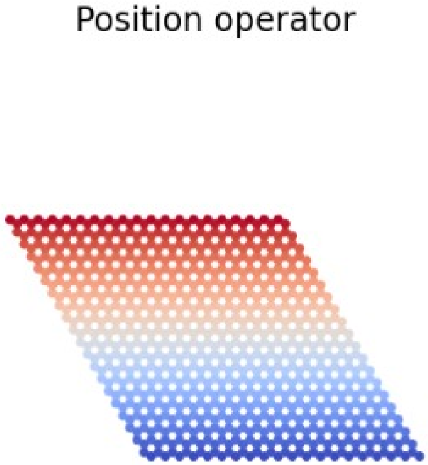
$$\delta M_z \sim T \int_0^{k_c} \frac{dk}{k} \to \infty$$

Topological magnons

A magnon dispersion can have topological gaps at high energies, leading to topological modes







$$\mathcal{H} = \sum_{ij} \gamma_{ij} a_i^\dagger a_j$$

Quantum spin liquids and spinons

The Ising dimer

What is the ground state of this Hamiltonian

$$\mathcal{H} = S_0^z S_1^z$$

The Hamiltonian has two ground states (related by time-reversal symmetry)

$$|GS_1\rangle = |\uparrow\downarrow\rangle \qquad |GS_2\rangle = |\downarrow\uparrow\rangle$$

Each ground state breaks time-reversal symmetry

A symmetry broken antiferromagnet is a macroscopic version of this

The quantum Heisenberg dimer

What is the ground state of this quantum Hamiltonian?

$$\mathcal{H} = \vec{S}_0 \cdot \vec{S}_1$$

The ground state is unique, and does not break time-reversal

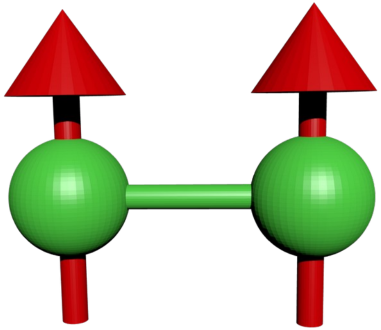
$$|GS\rangle = \frac{1}{\sqrt{2}}\left[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right] \qquad \langle \vec{S}_i \rangle = 0$$

The state is maximally entangled

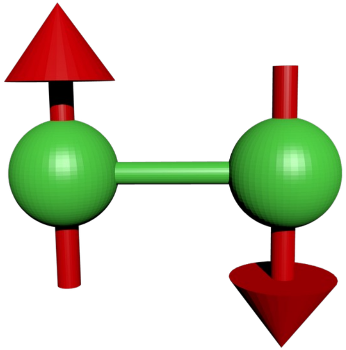
Can we have a macroscopic version of this ground state? $\langle \vec{S}_i \rangle = 0$

Towards quantum-spin liquids

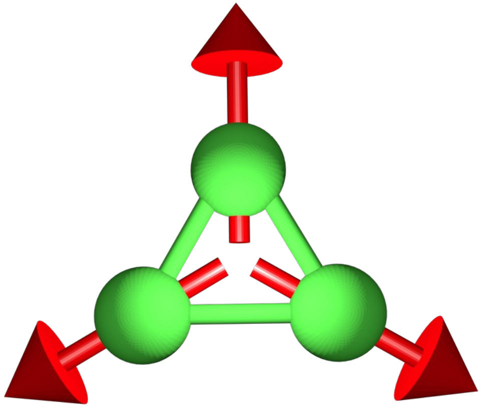
Ferromagnetism



Antiferromagnetism



Frustrated magnetism

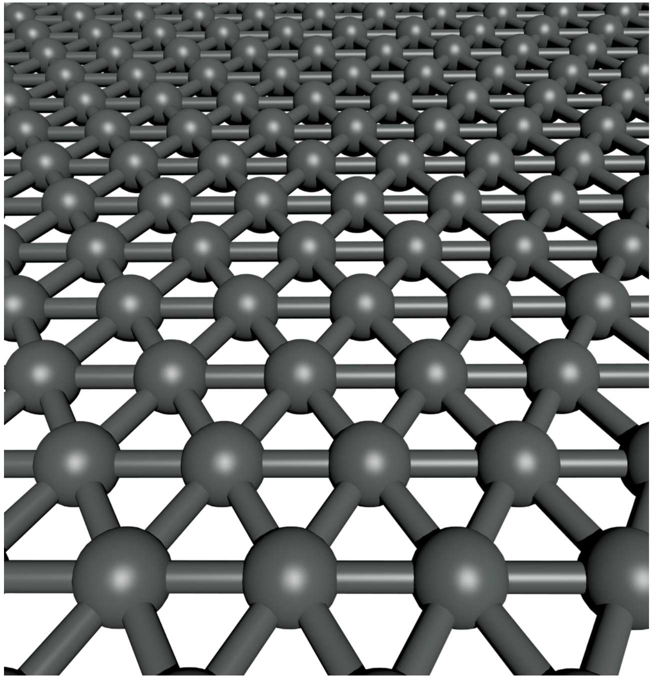


To get a quantum-spin liquid, we should look for frustrated magnetism

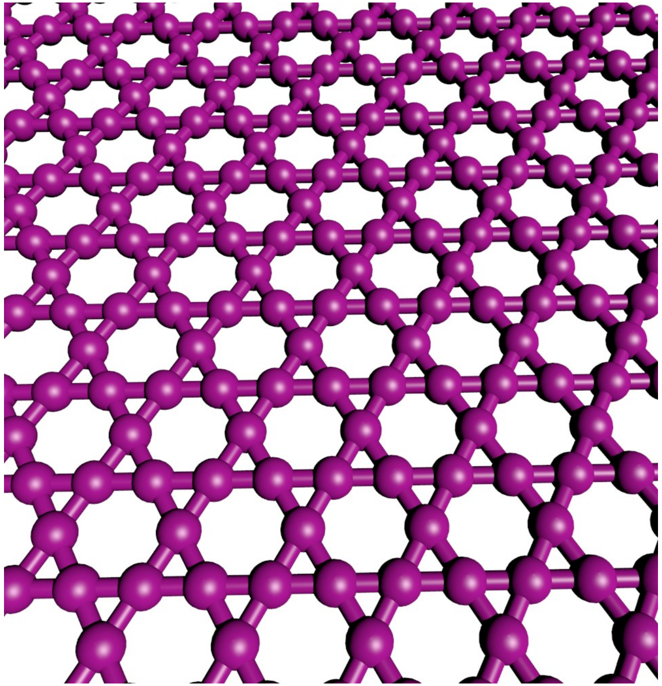
$$\langle \vec{S}_i \rangle = 0$$

Frustrated lattices

Triangular



Kagome



Quasiparticles in a quantum spin-liquid

Let us assume that a certain Hamiltonian realizes a QSL $\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$

Quantum spin liquids require $\langle \vec{S}_i \rangle = 0$

The approximation used for magnons breaks down

$$\langle S_i^z \rangle = S - \langle a_i^\dagger a_i \rangle$$

$$\langle a_i^\dagger a_i \rangle \ll S$$

We need a new approximation for the quantum excitations

The parton transformation

Transform spin operators to auxiliary fermions (Abrikosov fermions)

$$S_i^\alpha = \frac{1}{2}\sigma^\alpha_{s,s'} f^\dagger_{i,s} f_{i,s'}$$

The fermions f (spinons) have S=1/2 but no charge

This transformation artificially enlarges the Hilbert space, thus we have to put the constraint

$$\sum_s f^\dagger_{i,s} f_{i,s} = 1$$

This transformation allow to turn a spin Hamiltonian into a fermionic Hamiltonian

The spinon Hamiltonian

We can insert the auxiliary fermions $S_i^\alpha \sim \sigma^\alpha_{s,s'} f^\dagger_{i,s} f_{i,s'}$

And perform a mean-field in the auxiliary fermions (spinons)

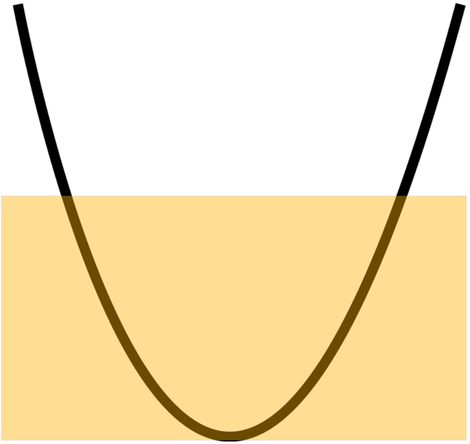
$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j \longrightarrow \mathcal{H} = \sum_{ij,s} \chi_{ij} f^\dagger_{i,s} f_{j,s}$$

Enforcing time-reversal symmetry $\langle \vec{S}_i \rangle = 0$

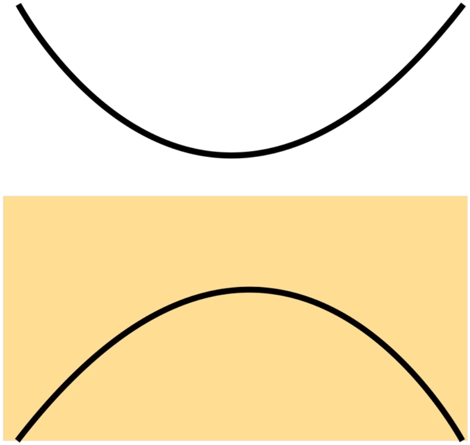
The exitations of the QSL are described by a single particle spinon Hamiltonian

Spinon dispersions

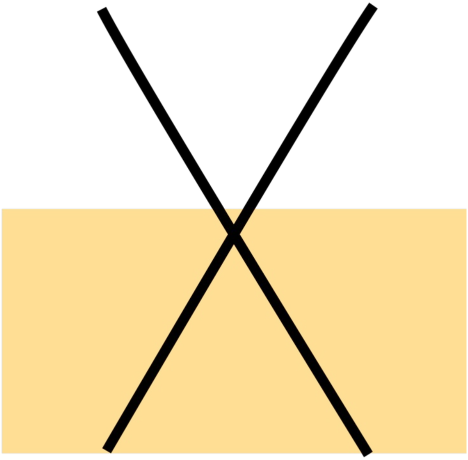
Gapless spinons



Gapped spinons



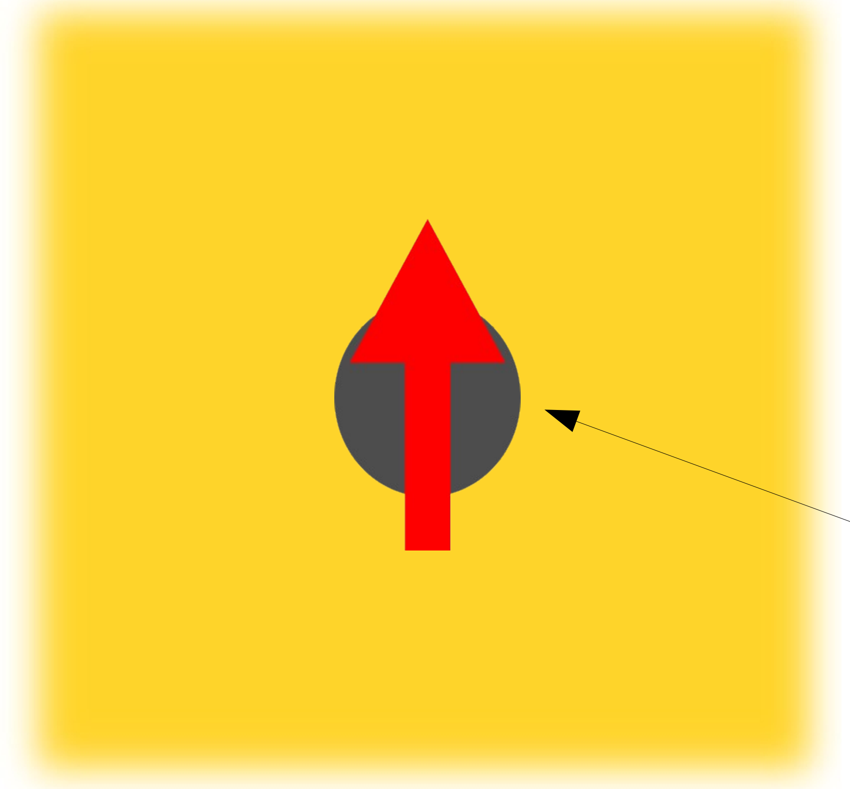
Dirac spinons



$$\mathcal{H} = \sum_{ij,s} \chi_{ij} f^{\dagger}_{i,s} f_{j,s}$$

The Kondo lattice model

The Kondo problem



Conduction electrons

$$H = -t \sum_{(i,j)\sigma} \left(c^{\dagger}_{i\sigma} c_{j\sigma} + \ \mathrm{H.c} \ \right)$$

Kondo coupling

$$H_K = \sum_{\alpha\beta} \left(c^{\dagger}_{0\beta} \vec{\sigma}_{\beta\alpha} c_{0\alpha} \right) \cdot \vec{S}$$

We now take a quantum spin S=1/2

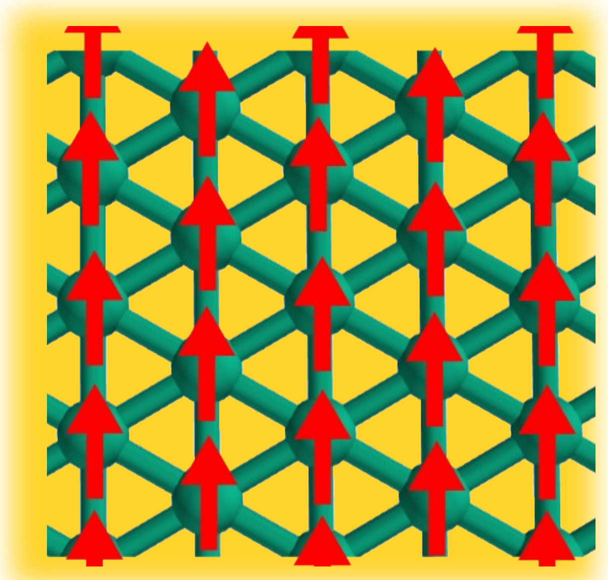
$$|GS\rangle \sim \frac{1}{\sqrt{2}} [| \Uparrow \downarrow \rangle - | \Downarrow \uparrow \rangle]$$

The Kondo lattice problem

The Kondo lattice problem

$$H = -t\sum_{(i,j)\sigma}\left(c^\dagger_{i\sigma}c_{j\sigma} + \text{ H.c }\right) + J\sum_{j,\alpha\beta}\left(c^\dagger_{j\beta}\vec{\sigma}_{\beta\alpha}c_{j\alpha}\right)\cdot\vec{S}_j$$

Conduction electrons

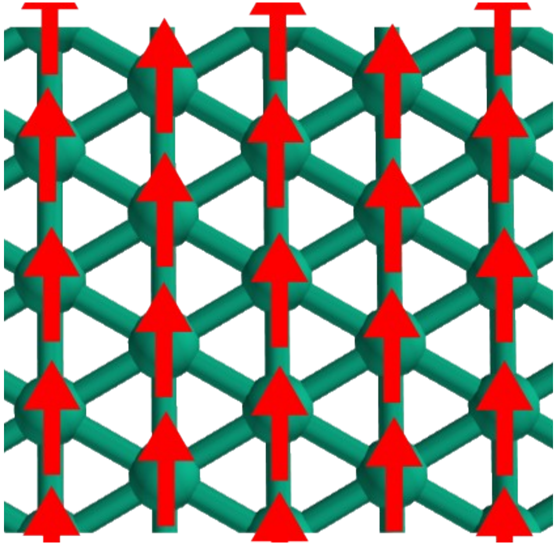


Kondo coupling

Kondo sites

Building an artificial heavy fermion state

Lattice of Kondo impurities



$$J_K$$

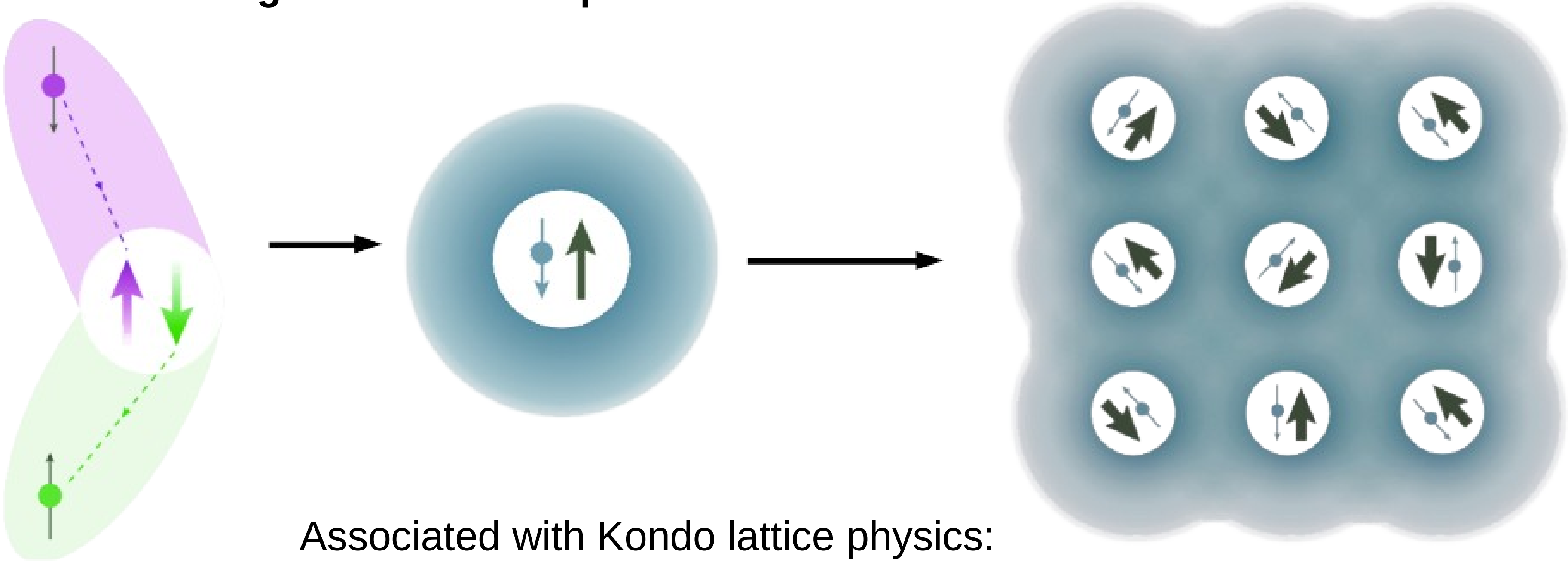
Dispersive electron gas

Both ingredients coupled through Kondo coupling

Building an artificial heavy fermion state

Conduction electrons form Kondo singlets with the impurities

Kondo-lattice model



Associated with Kondo lattice physics:
- Colossal mass enhancement of electrons
- Quantum criticality
- Unconventional (topological) superconductivity

Solving the Kondo lattice problem

$$H = -t \sum_{(i,j)\sigma} \left(c^{\dagger}_{i\sigma} c_{j\sigma} + \text{ H.c } \right) + J \sum_{j,\alpha\beta} \left(c^{\dagger}_{j\beta} \vec{\sigma}_{\beta\alpha} c_{j\alpha} \right) \cdot \vec{S}_j$$

Replace the spin sites by auxiliary fermions

$$S_{\alpha\beta}(j) = f^{\dagger}_{j\alpha} f_{j\beta} - \frac{n_f(j)}{N} \delta_{\alpha\beta}$$

This makes the effective Hamiltonian an “interacting” fermionic Hamiltonian

$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} - J \sum_{j,\alpha\beta} \left(c^{\dagger}_{j\beta} f_{j\beta} \right) \left(f^{\dagger}_{j\alpha} c_{j\alpha} \right)$$

Solving the Kondo lattice problem

Now we decouple the fermions with a mean-field approximation

$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} - J \sum_{j,\alpha\beta} \left(c^\dagger_{j\beta} f_{j\beta} \right) \left(f^\dagger_{j\alpha} c_{j\alpha} \right)$$

Obtaining a quadratic Hamiltonian

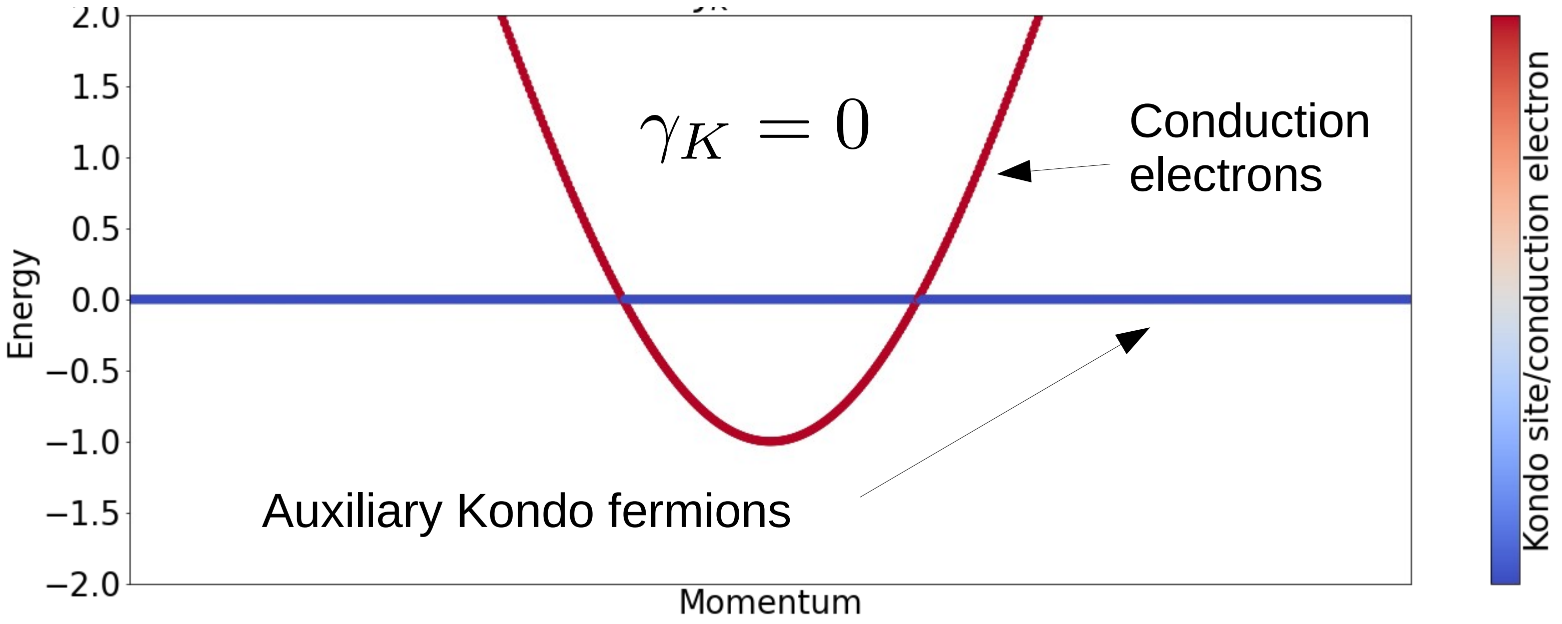
$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k},\alpha\beta} f^\dagger_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} + h.c.$$

Conduction band dispersion

Kondo hybridization

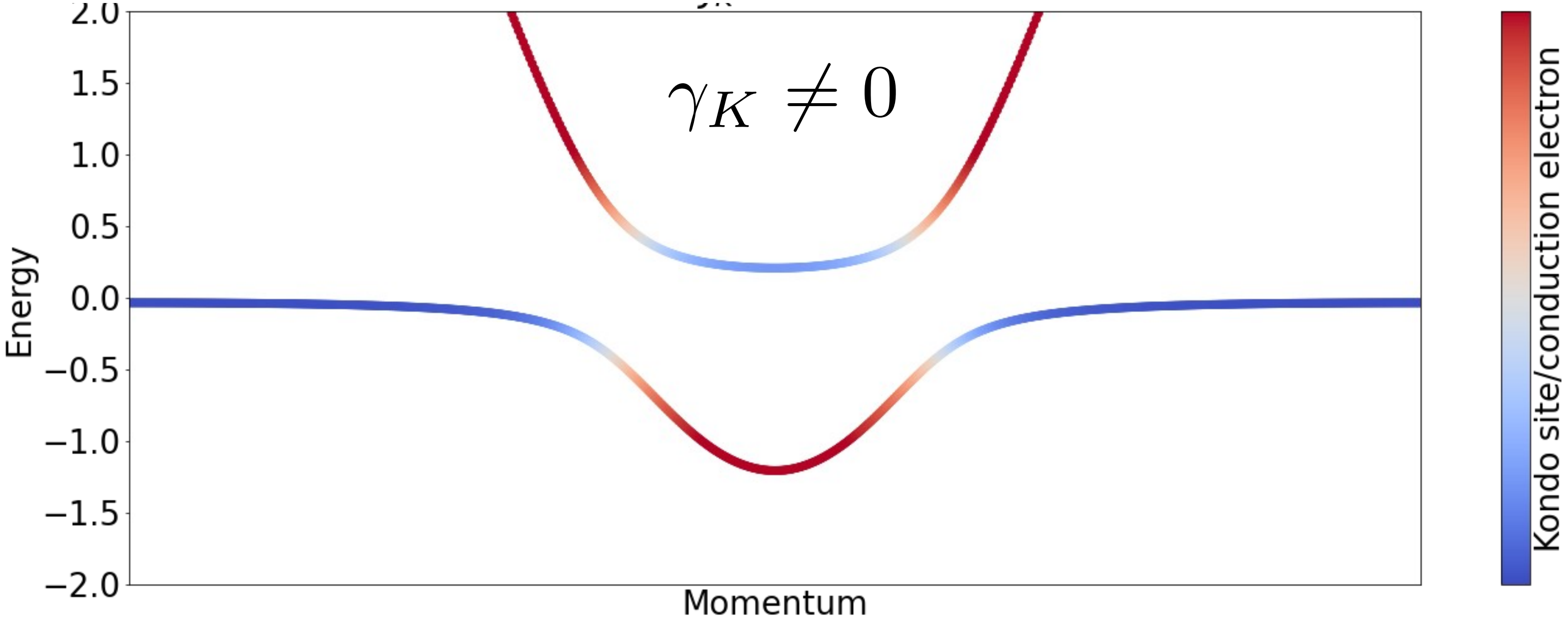
Electronic structure of the Kondo lattice problem

$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k},\alpha\beta} f^\dagger_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} + h.c.$$



Electronic structure of the Kondo lattice problem

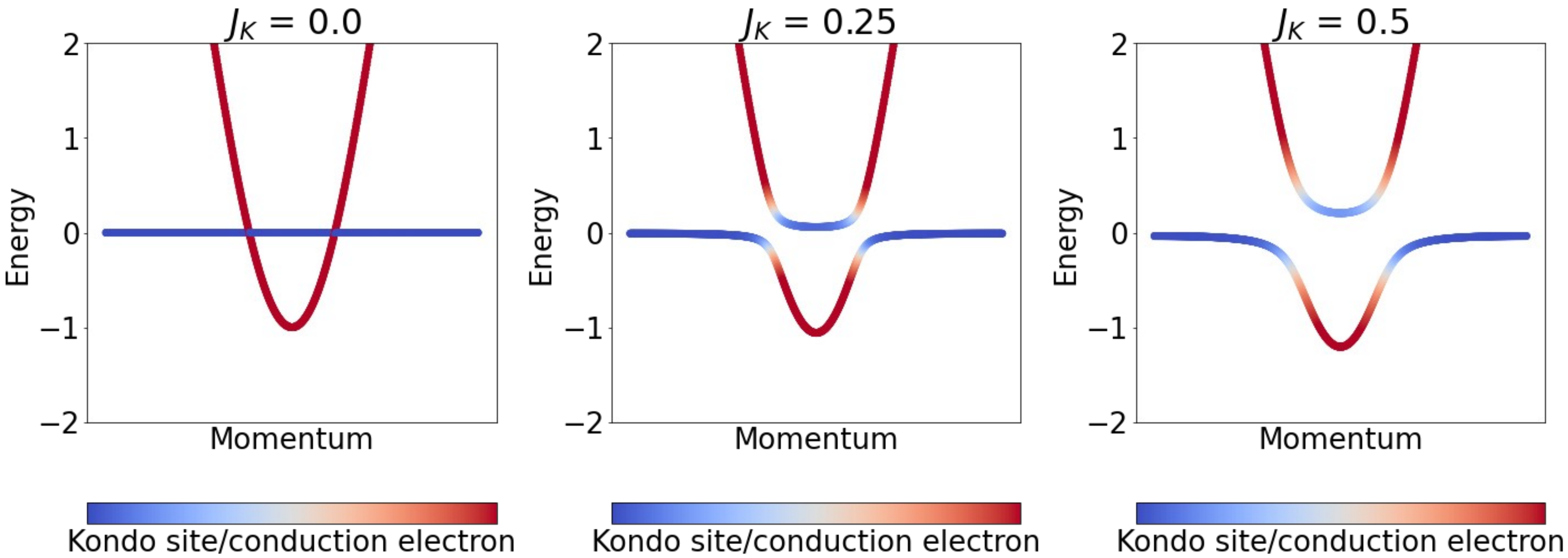
$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k},\alpha\beta} f^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} + h.c.$$



The Kondo coupling opens up a gap in the electronic structure

Dependence on the Kondo coupling

The heavy-fermion gap becomes bigger as the Kondo coupling increases



Take home

- Magnetism arises from repulsive interactions
- The fundamental excitations of magnets are magnons and have S=1
- Frustrated magnetic models can display quantum spin-liquid behavior
- The fundamental excitations of QSL have S=1/2