

Probing Kitaev spin liquids with resonant inelastic X-ray scattering

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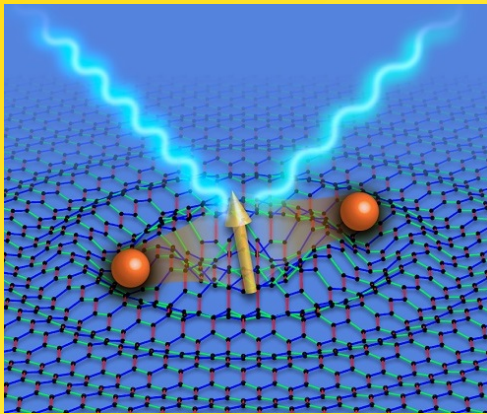
Brent Perreault
(U. of Minnesota)



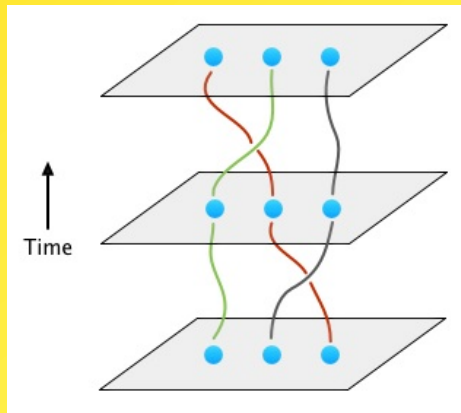
Jeroen van den Brink
(IFW Dresden)

Quantum spin liquids

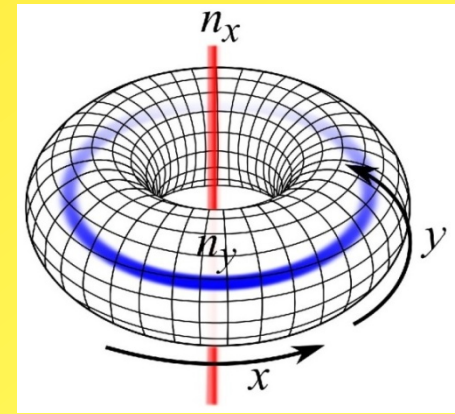
Magnetic phases with long-range quantum entanglement



Fractionalization
into nonlocal
quasiparticles



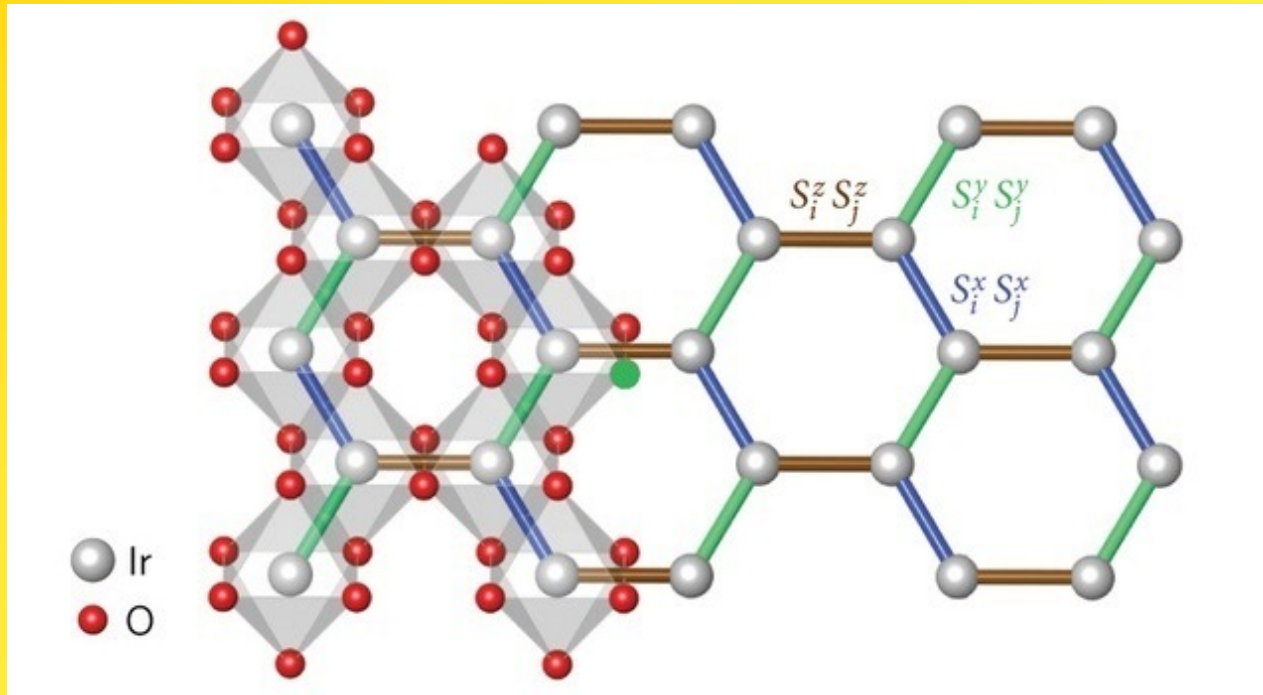
Anyonic
quasiparticle
statistics



Topological order
and ground-state
degeneracy

Problem: No "smoking-gun" experimental signatures

Kitaev spin liquids

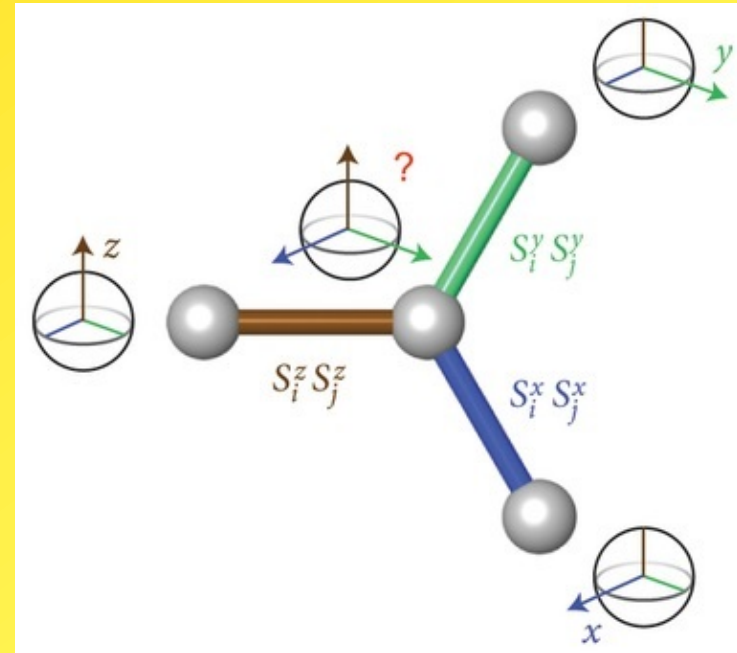
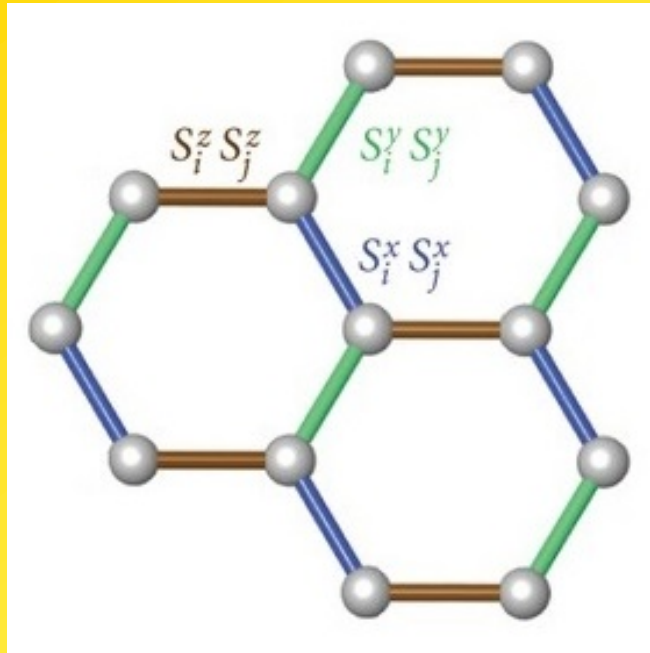


[Picture credit: Gegenwart & Trebst, Nat. Phys. 2015]

Experimental relevance:
(Na,Li)₂IrO₃, α -RuCl₃

Exactly solvable limit:
Kitaev models

Kitaev honeycomb model



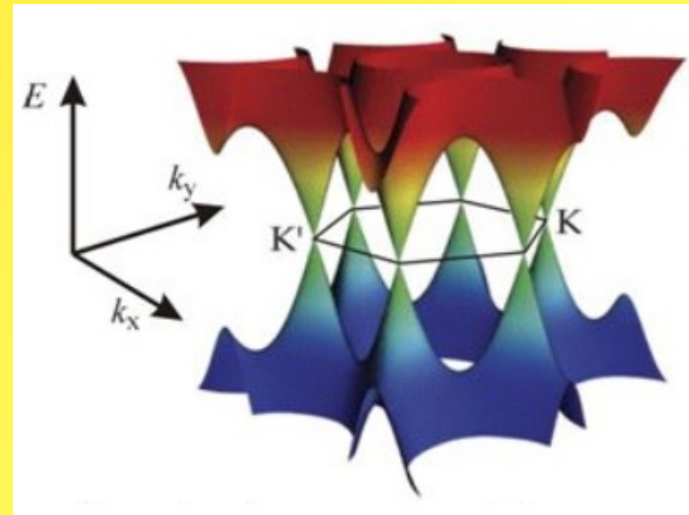
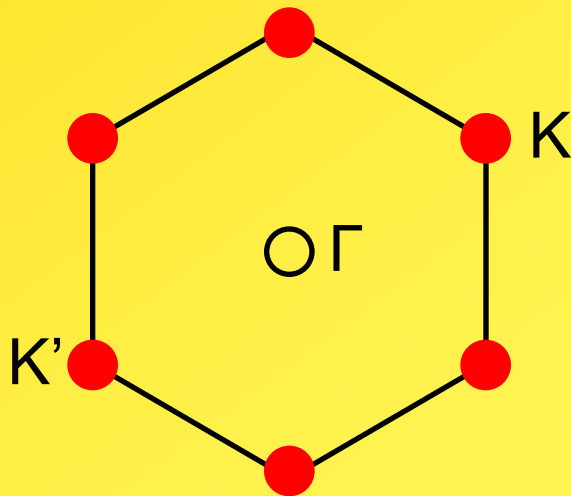
[Picture credit: Gegenwart & Trebst, Nat. Phys. 2015]

$$H_K = -J_K \sum_{\langle i,j \rangle_x} \sigma_i^x \sigma_j^x - J_K \sum_{\langle i,j \rangle_y} \sigma_i^y \sigma_j^y - J_K \sum_{\langle i,j \rangle_z} \sigma_i^z \sigma_j^z$$

Kitaev honeycomb model

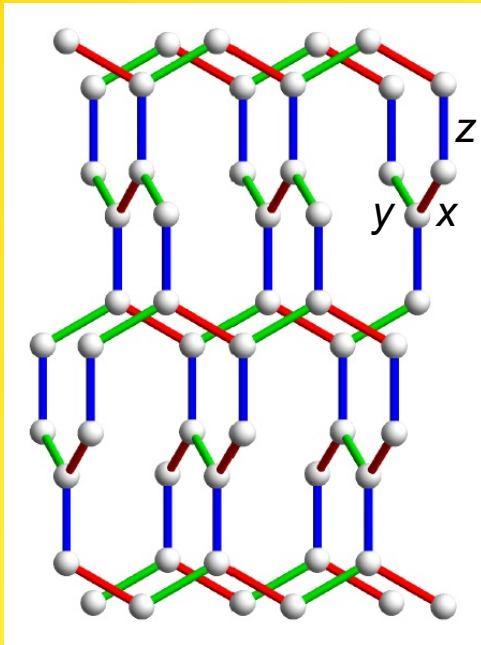
Quantum spin liquid with fractionalized excitations:

- Gauge fluxes (ϕ): gapped & localized
- Majorana fermions: gapless at Dirac points

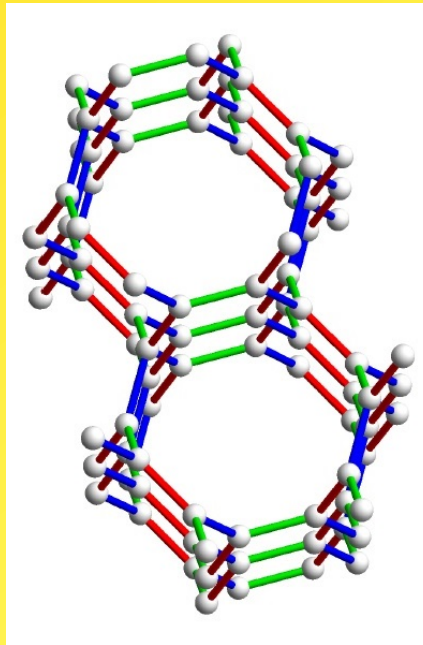


3D Kitaev models

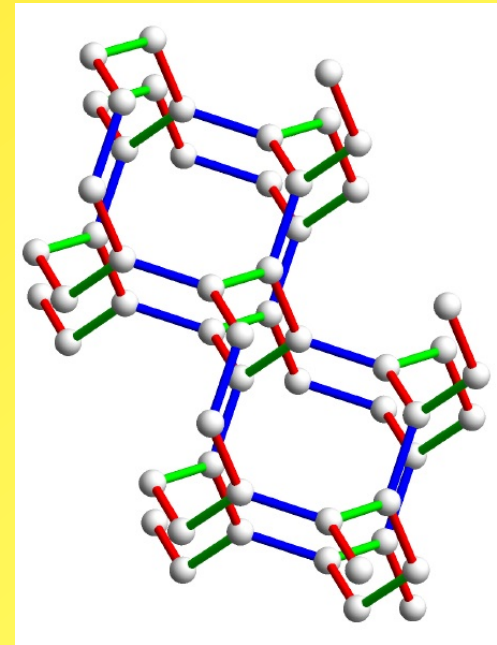
Hyperhoneycomb
model



Hyperhexagon
model



Hyperoctagon
model



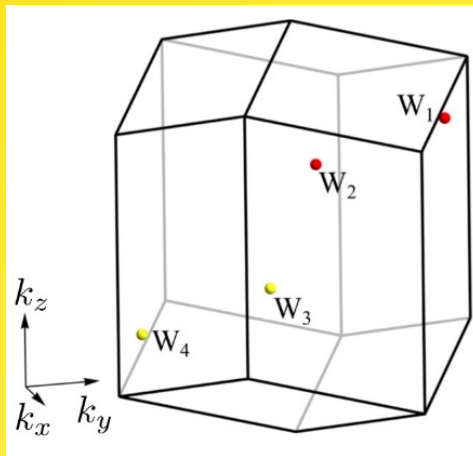
$$H_K = -J_K \sum_{\langle i,j \rangle_x} \sigma_i^x \sigma_j^x - J_K \sum_{\langle i,j \rangle_y} \sigma_i^y \sigma_j^y - J_K \sum_{\langle i,j \rangle_z} \sigma_i^z \sigma_j^z$$

3D Kitaev models

Nodal structures of the gapless Majorana fermions:

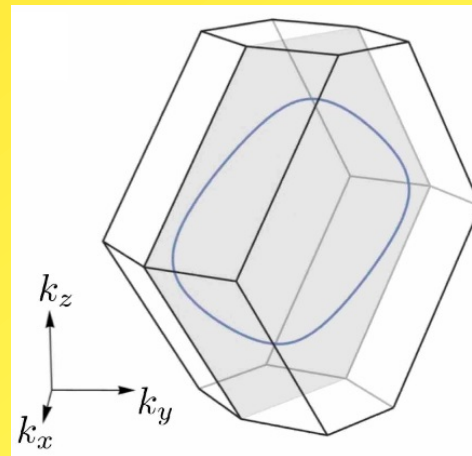
[O'Brien, Hermanns, Trebst, PRB 2016]

Hyperhexagon
model



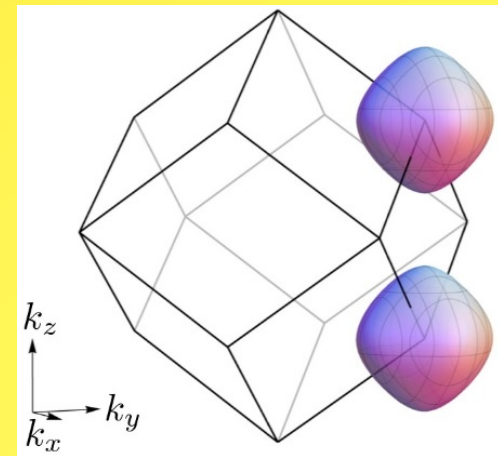
Weyl points

Hyperhoneycomb
model



Nodal line

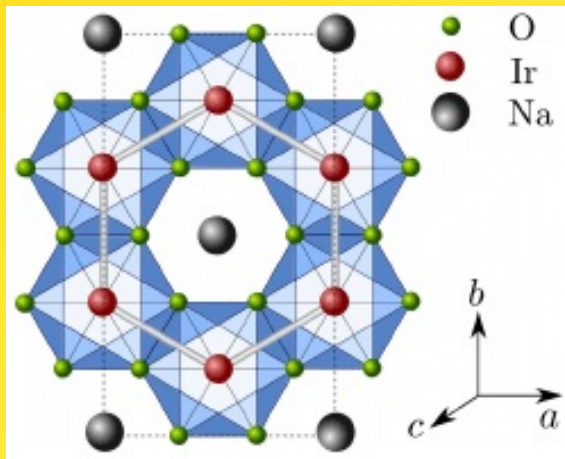
Hyperoctagon
model



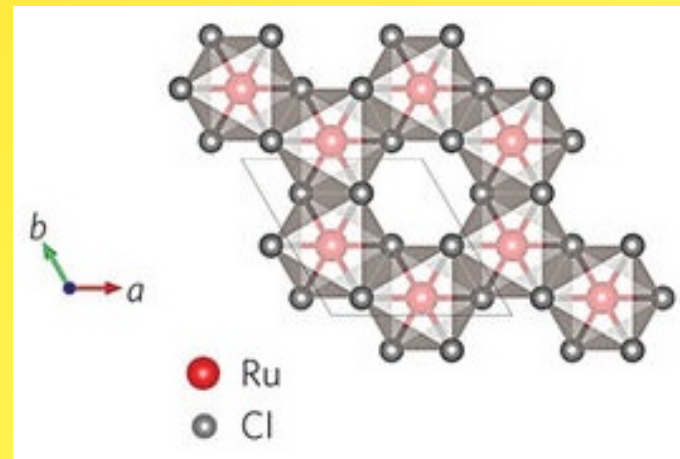
Fermi surfaces

Kitaev materials

Two-dimensional (layered) honeycomb systems:



[Picture credit: Das *et al.*]

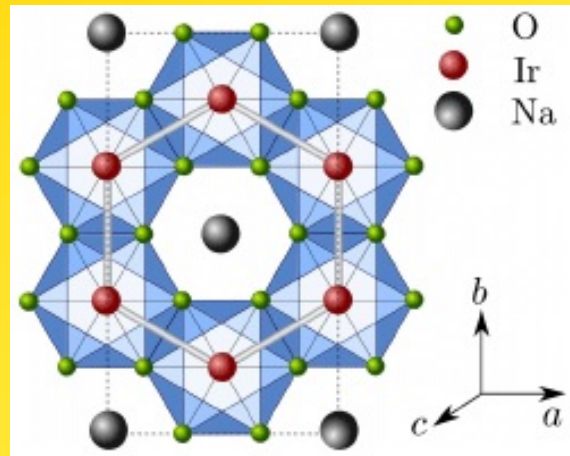


[Picture credit: Banerjee *et al.*]

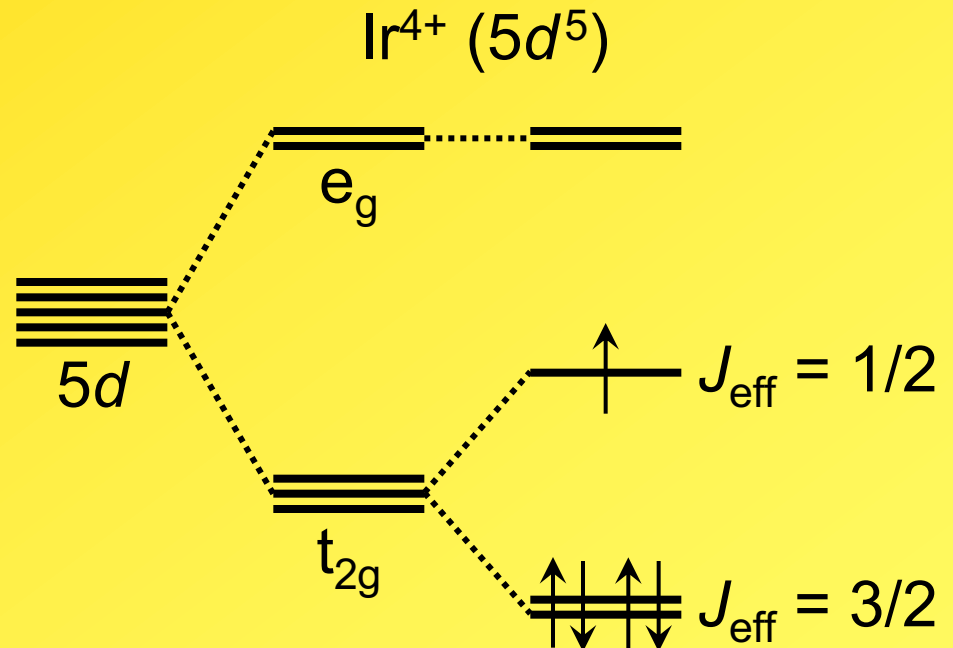
Three-dimensional harmonic-honeycomb systems:



Kitaev materials



[Picture credit: Das *et al.*]

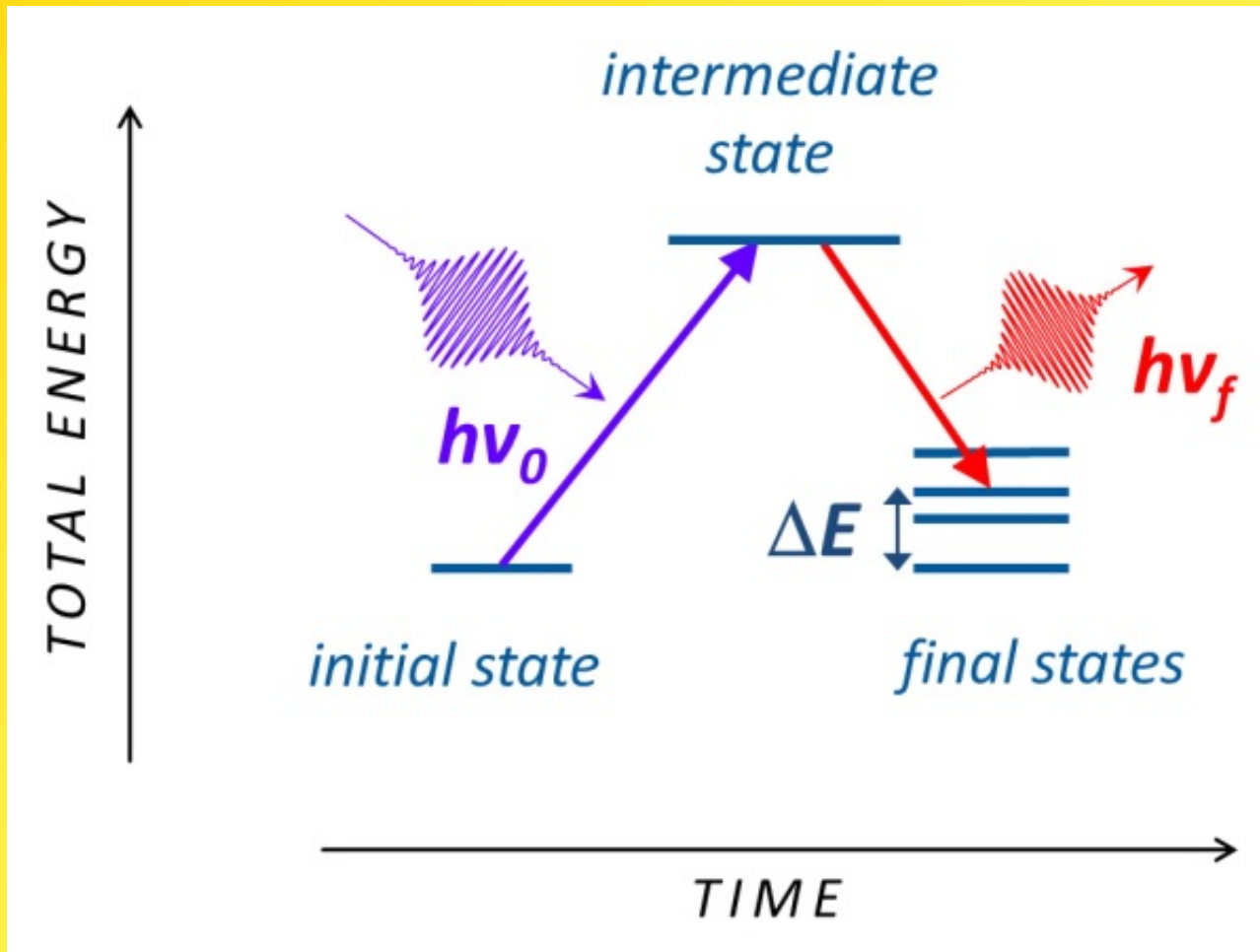


Effective low-energy Hamiltonian for $J_{\text{eff}} = 1/2$ "spins":

$$H = H_K + (\text{other terms})$$

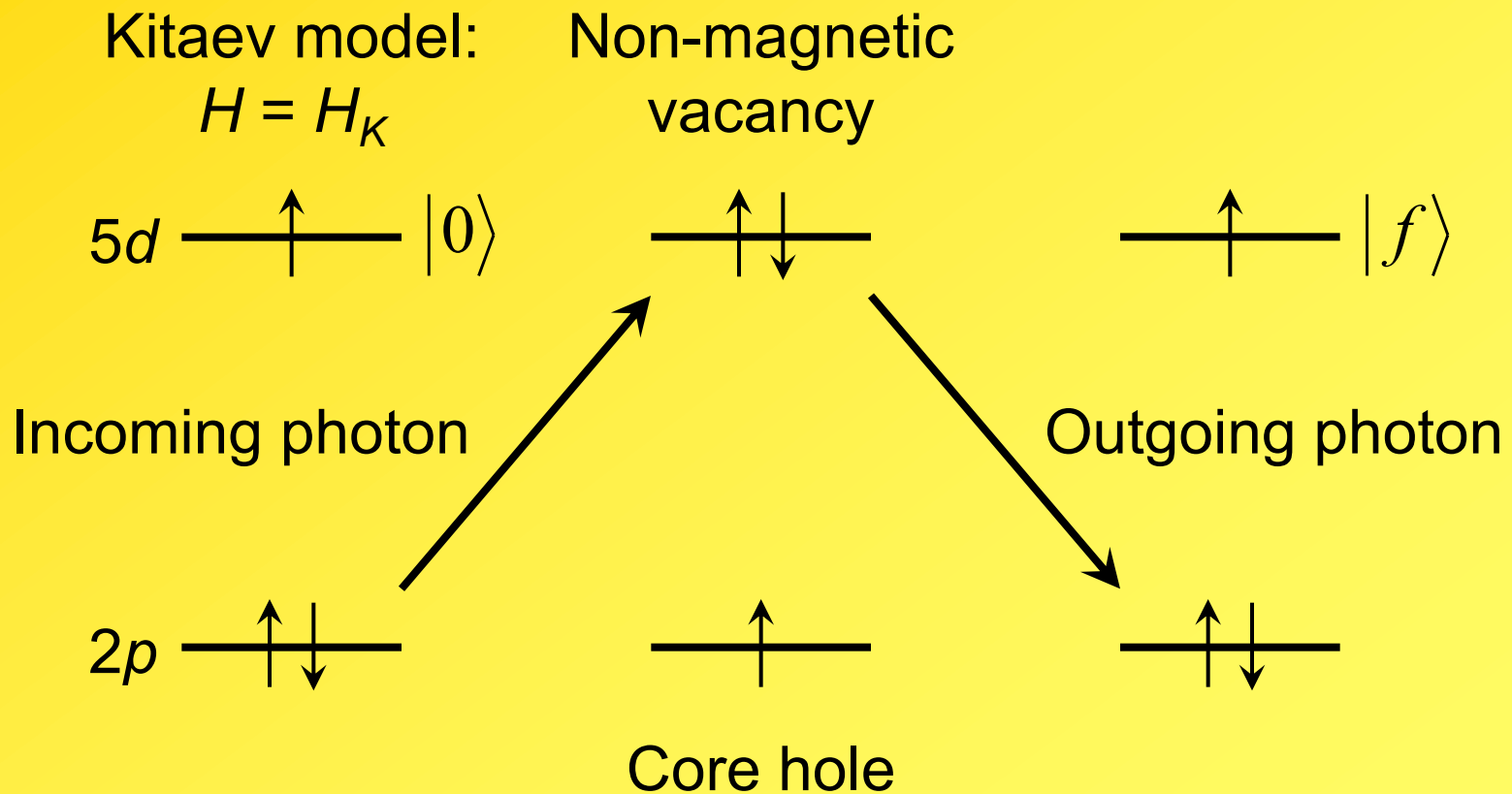
[Jackeli & Khaliullin, PRL 2009]

Resonant inelastic X-ray scattering



Resonant inelastic X-ray scattering

(Na,Li)₂IrO₃ with Ir⁴⁺ in 5d⁵ configuration [*L*₃ edge]:

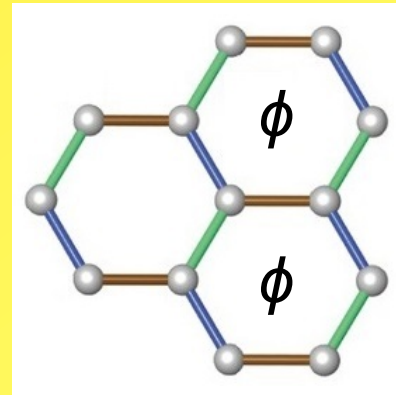
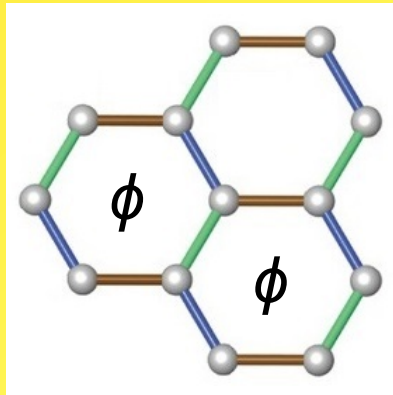
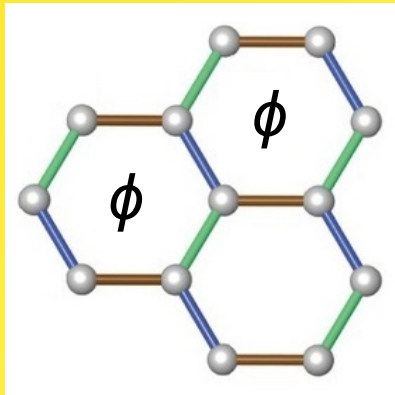


Resonant inelastic X-ray scattering

Four fundamental channels \rightarrow No interference

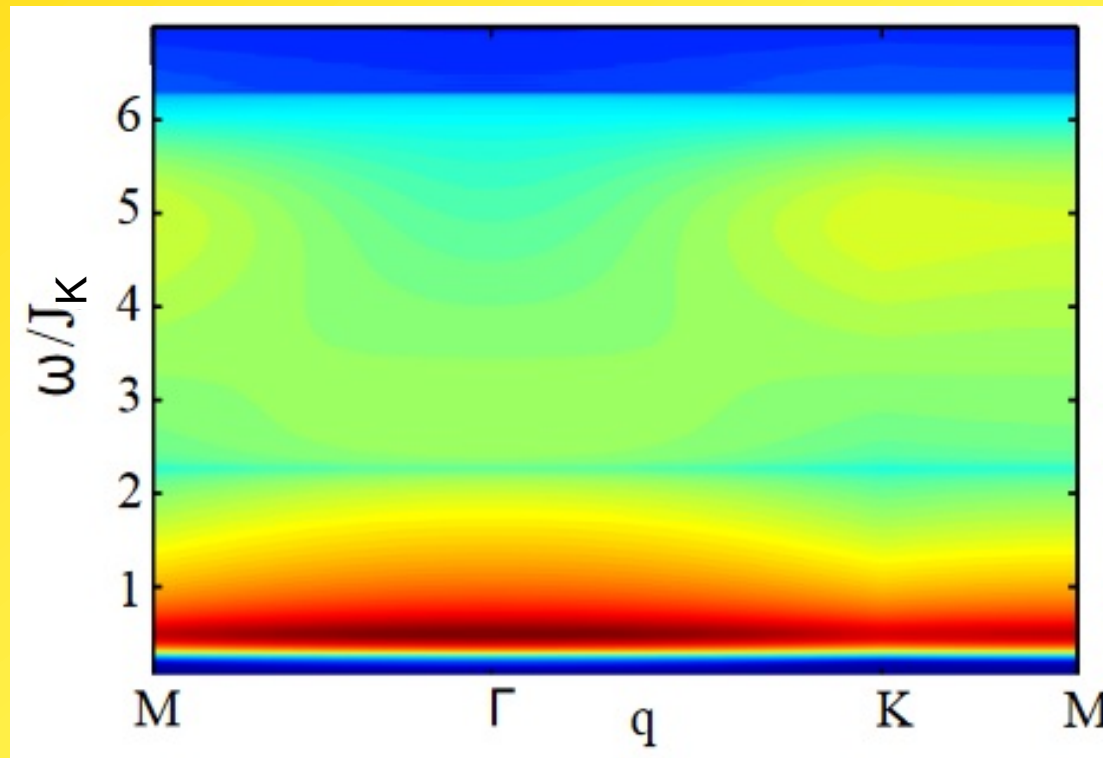
Spin-conserving (SC) channel creates two fermions

Three non-spin-conserving (NSC) channels create two fluxes and one fermion:



Honeycomb model

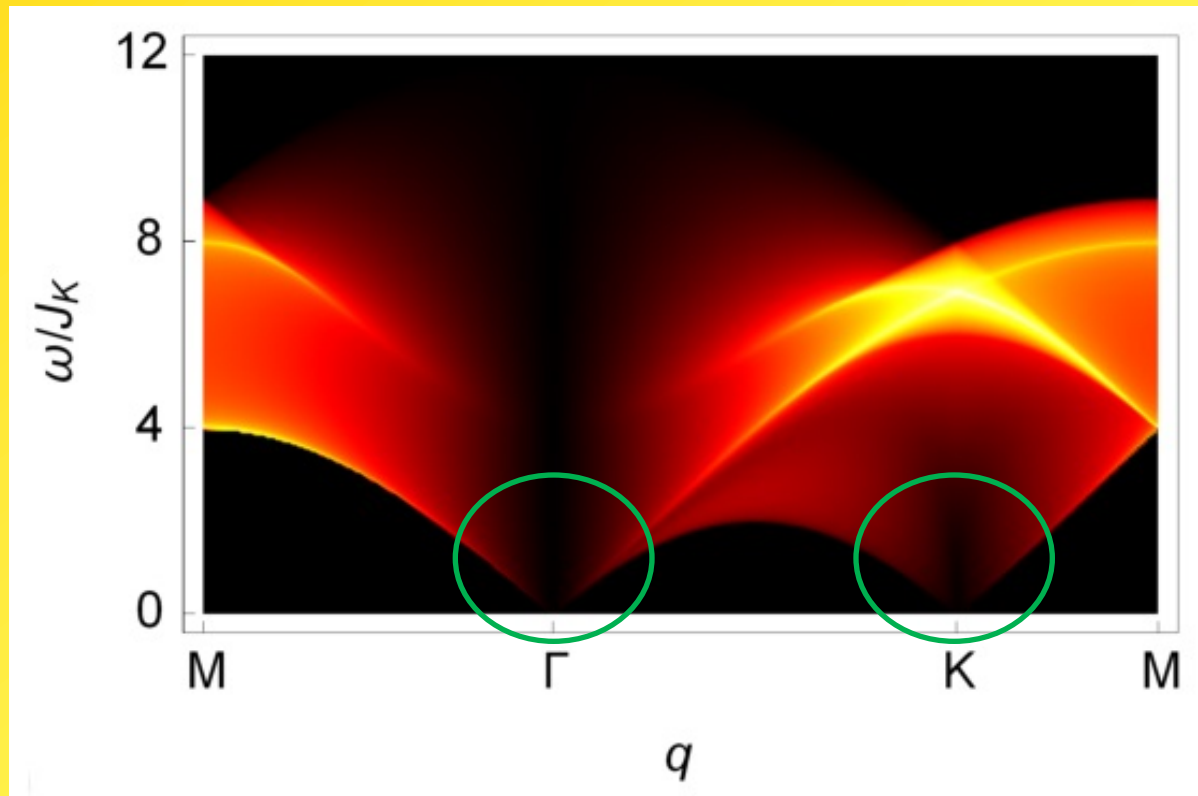
NSC channels ~ Inelastic neutron scattering response:



Knolle, Kovrizhin, Chalker, Moessner, PRL 2014

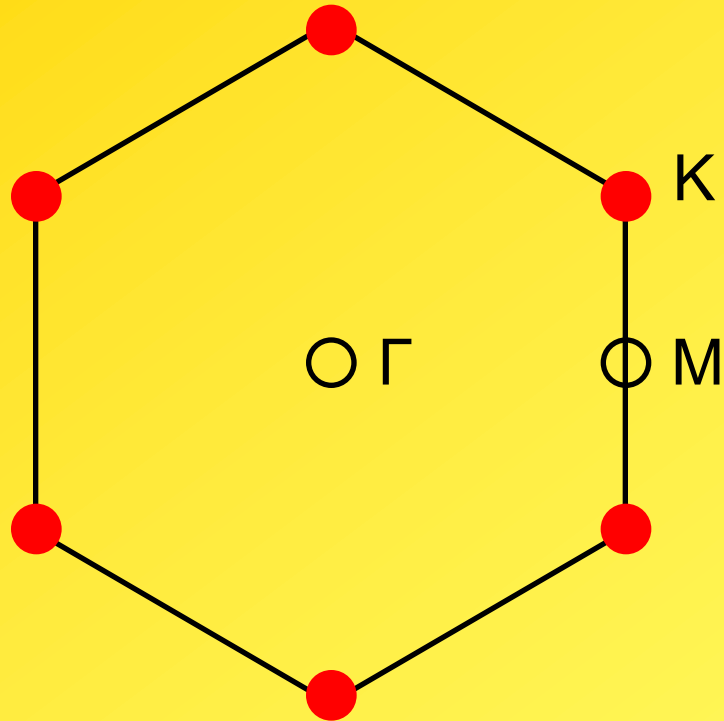
Honeycomb model

SC channel \rightarrow Lowest-order inelastic response:



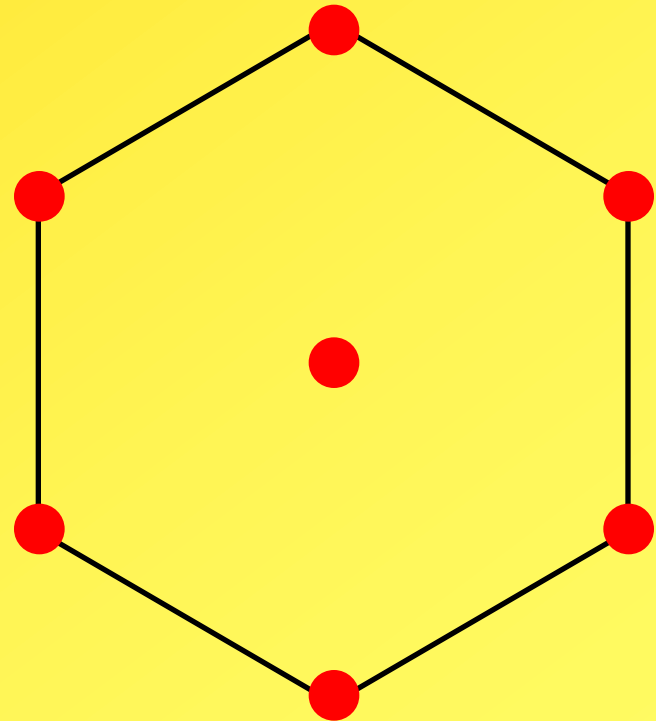
Honeycomb model

Dirac points



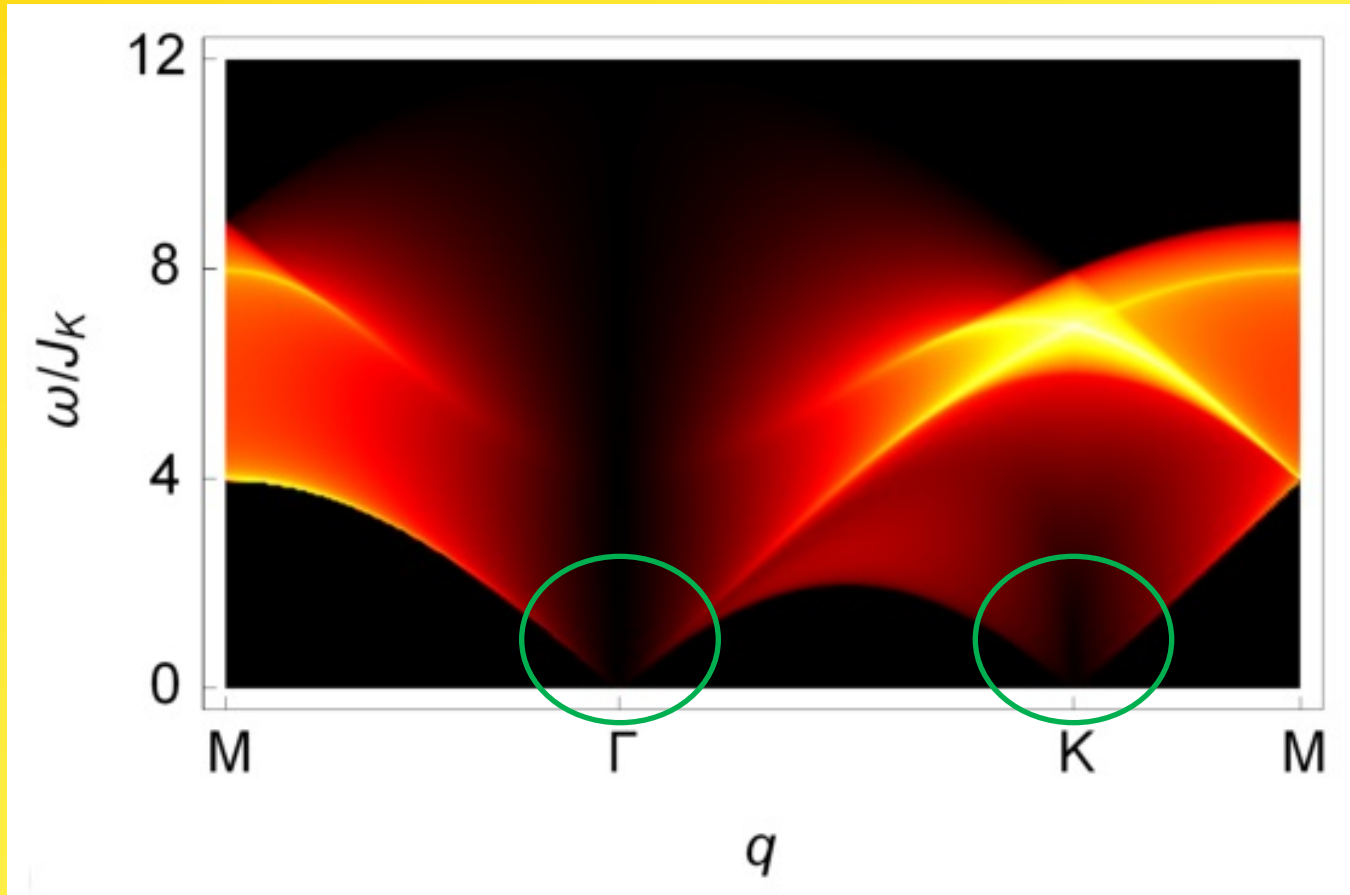
K points

Gapless response



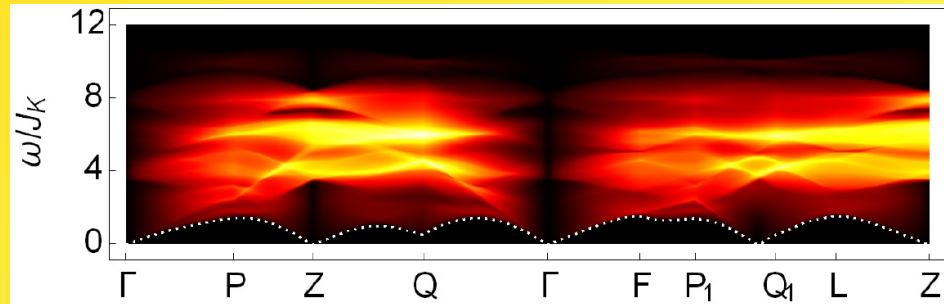
Γ and K points

Honeycomb model

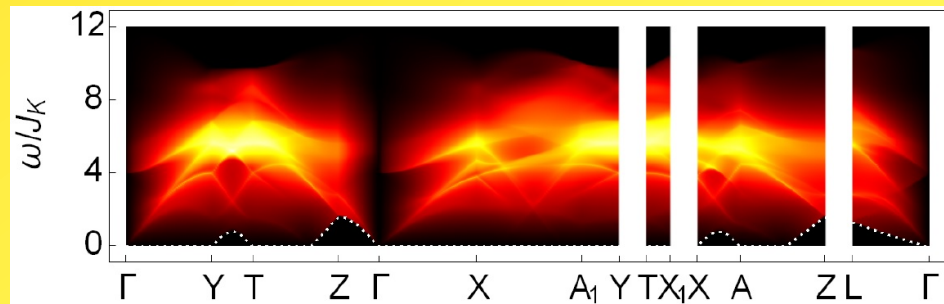


3D Kitaev models

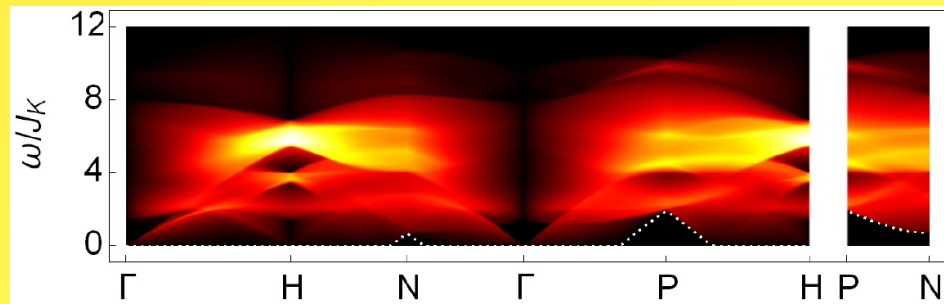
Hyperhexagon
model:



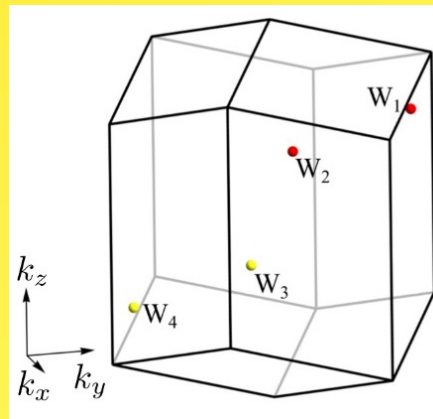
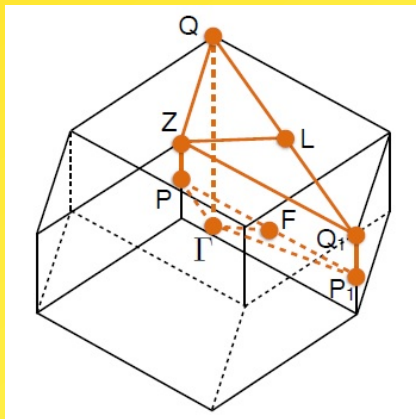
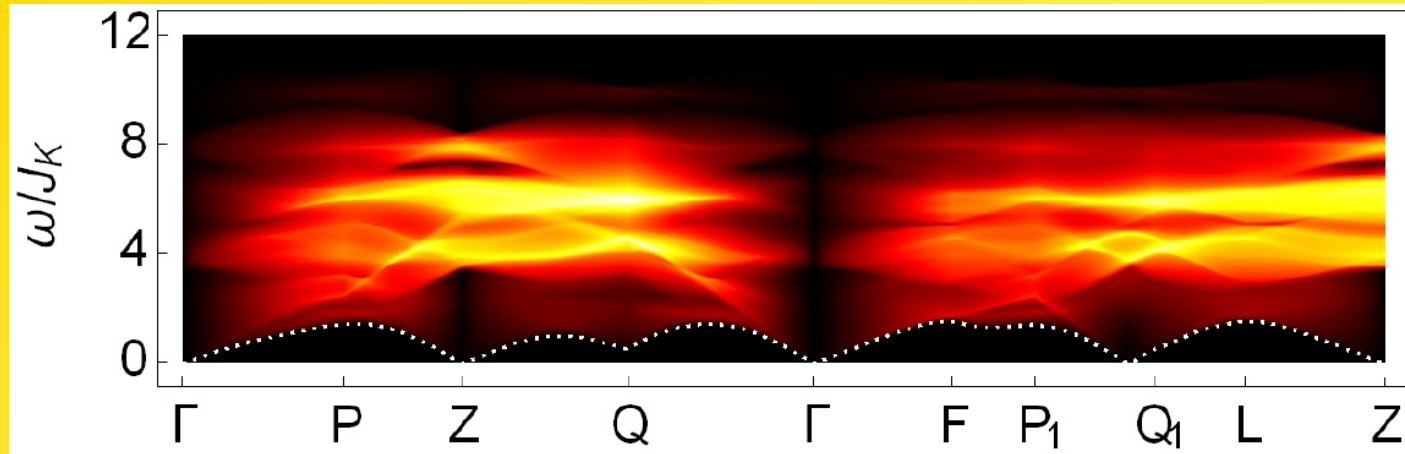
Hyperhoneycomb
model:



Hyperoctagon
model:



Hyperhexagon model

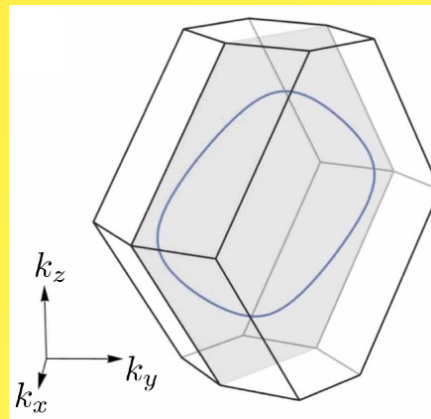
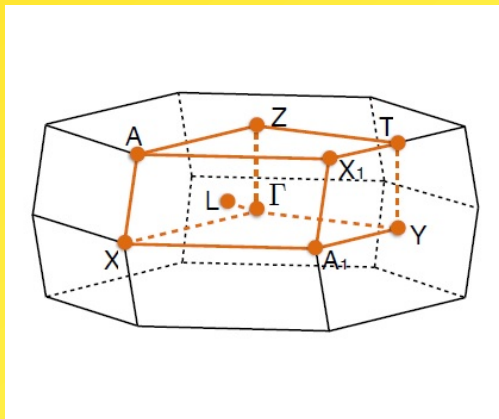
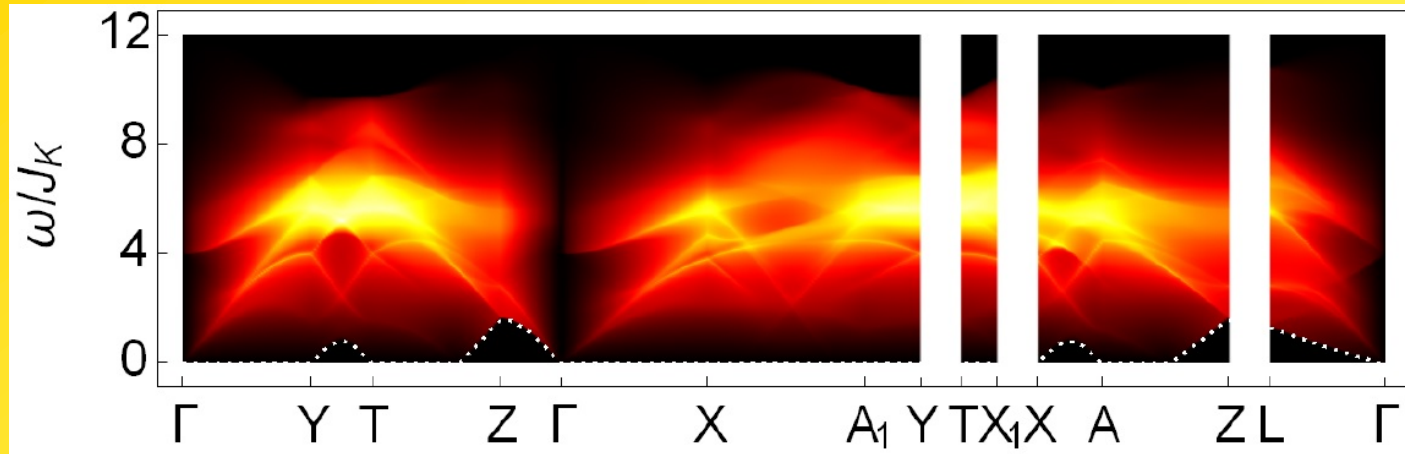


Weyl points



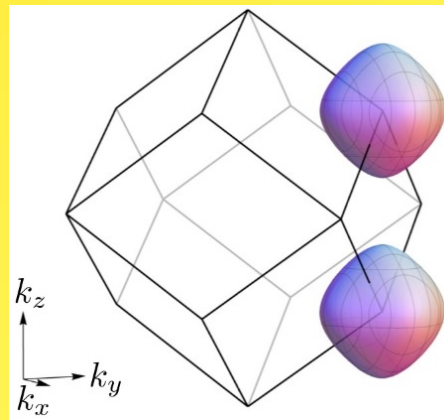
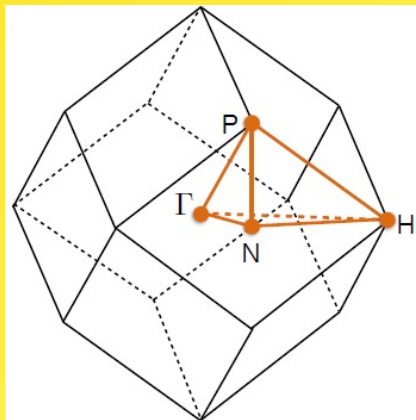
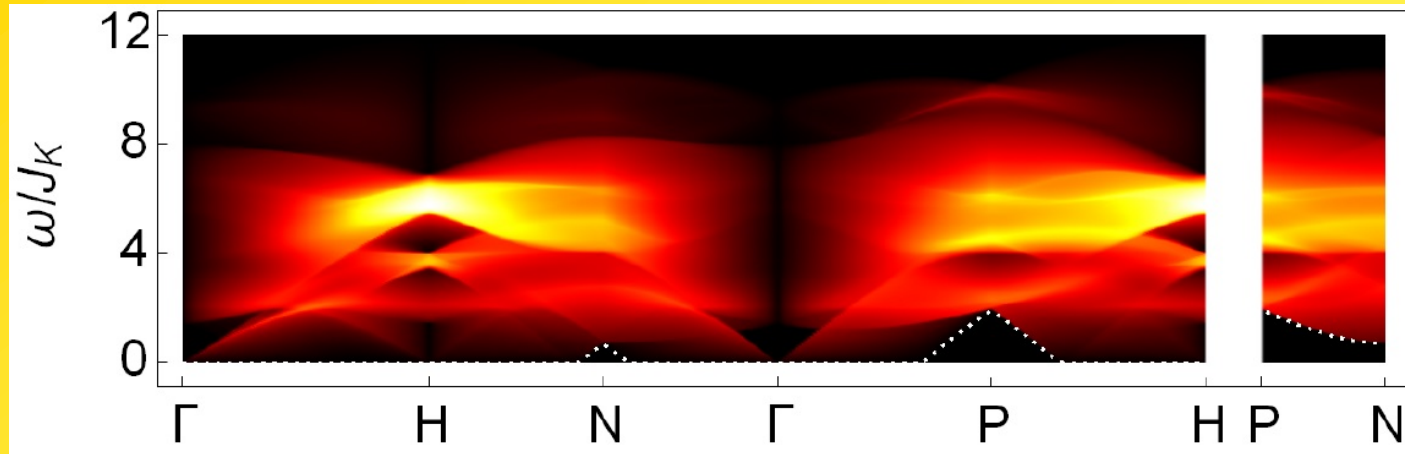
Gapless response
at discrete points

Hyperhoneycomb model



Nodal line
 \downarrow
 Gapless
 response within
 high-symmetry
 planes

Hyperoctagon model

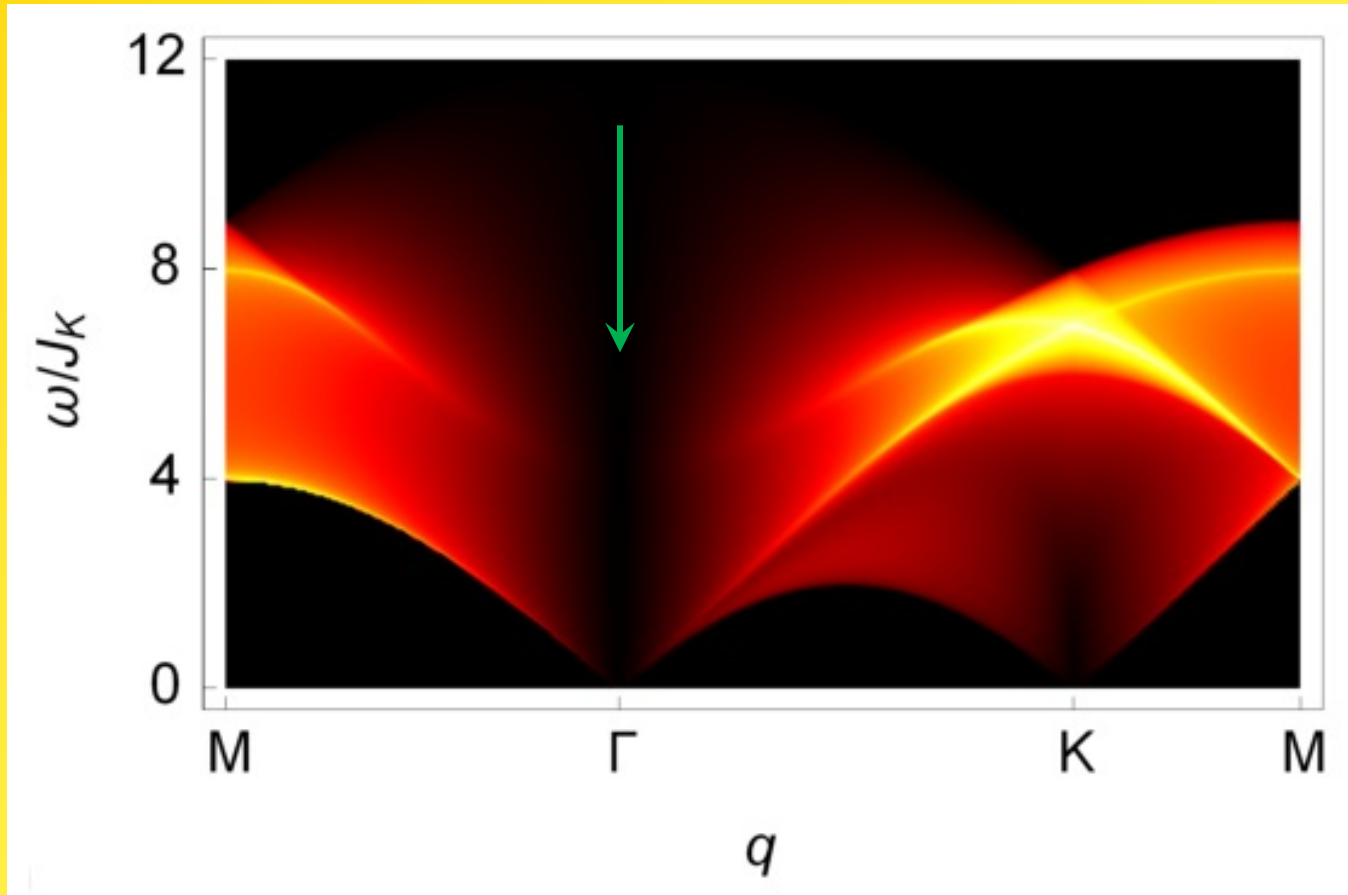


Fermi surfaces



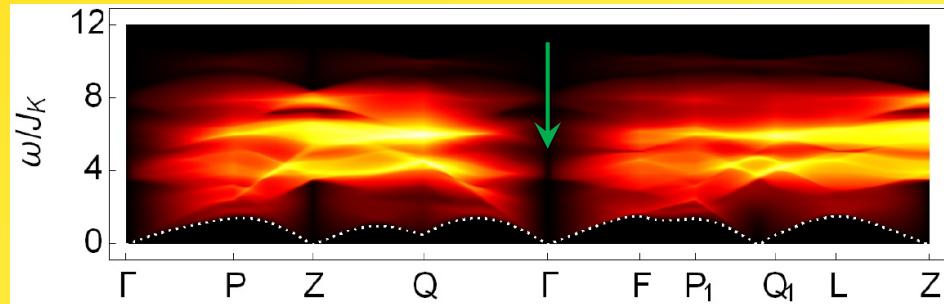
Gapless response
in a finite fraction of
the Brillouin zone

Honeycomb model

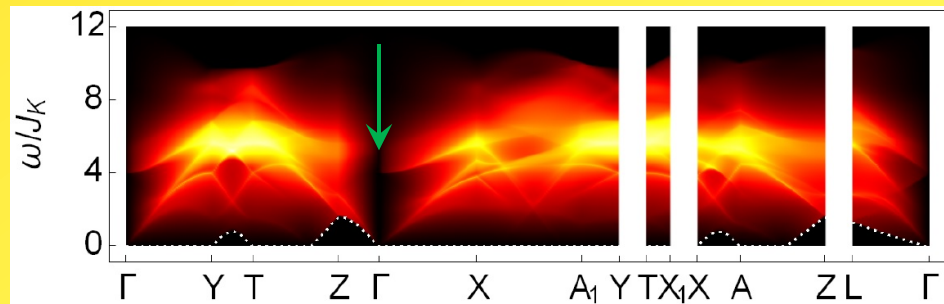


3D Kitaev models

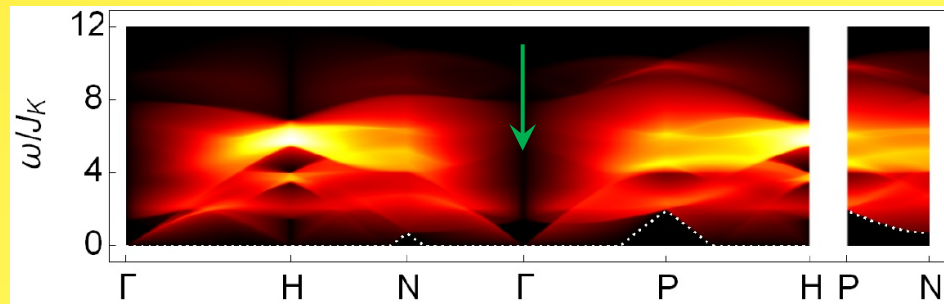
Hyperhexagon
model:



Hyperhoneycomb
model:



Hyperoctagon
model:



Summary

Exact RIXS responses of Kitaev spin liquids

→ Probe fractionalized excitations separately

NSC channels pick up fluxes and recover INS response

SC channel picks up Majorana fermions

→ Pronounced momentum dispersion

→ Distinct fingerprints of different nodal structures

→ Strong suppression around the Γ point



THE END