Higgs Modes in Condensed Matter and Quantum Gases
Yukawa Institute for Theoretical Physics June 23, 2014

Higgs mode in quantum spin systems

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Outline

- Higgs mode in quantum spin systems

- Low-dimensional system

- Spin dimer system

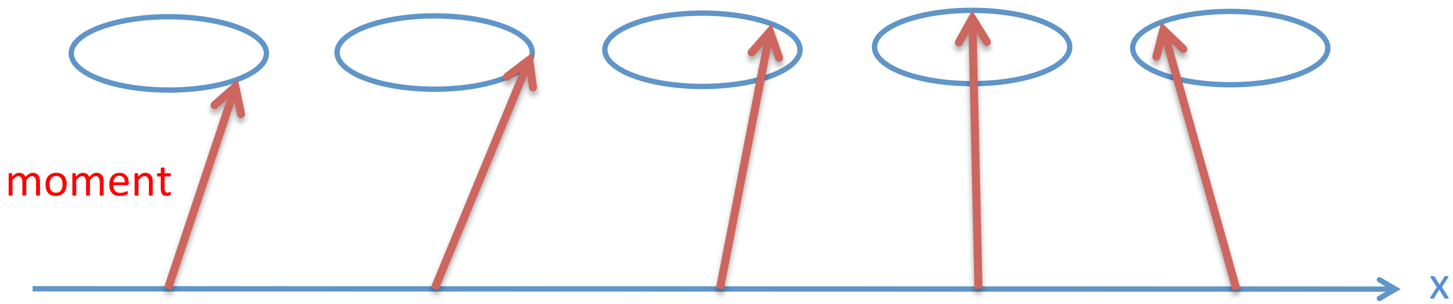
Extended spin-wave theory
describing both Nambu-Goldstone and Higgs modes

- Rerated system and optical property

Higgs mode in quantum spin systems

Nambu-Goldstone mode (transverse mode)

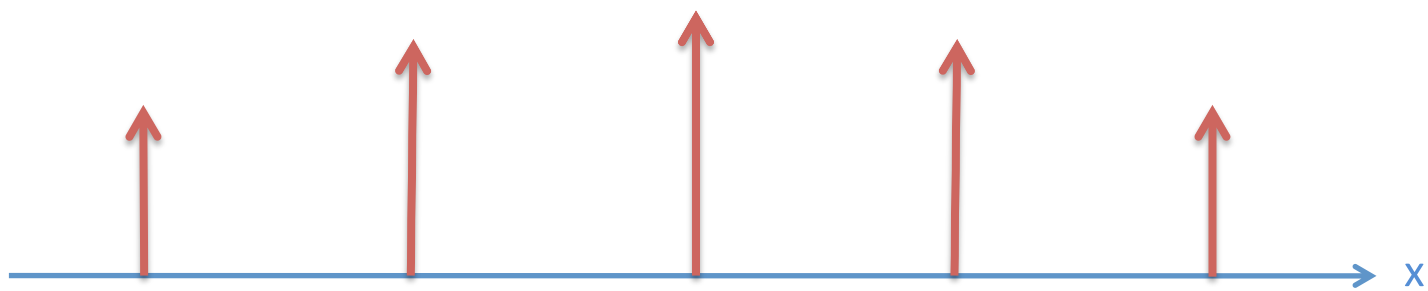
direction fluctuation



Higgs mode (longitudinal mode)

Amplitude fluctuation

Sachdev and Keimer, Physics Today (2001)



To have the Higgs mode

Longitudinal fluctuation

⇩

Moment size changes easily (soft moment)

⇩

Quantum critical point
Moment reduction

Affleck and Wellman PRB (1992)

Quantum phase transition

- Low dimensionality — quasi 1-dimensional S=1 system — **Affleck, PRL (1989)**
- Local quench of spin — spin dimer system; easy-plane single-ion anisotropy $D(S^z)^2$

Quasi 1-dimensional S=1 system

Hamiltonain

$$H_3 = J \sum_{\langle i,j \rangle}^{\text{chains}} \mathbf{S}_i \cdot \mathbf{S}_j + J' \sum_{\langle i,j \rangle}^{\text{planes}} \mathbf{S}_i \cdot \mathbf{S}_j$$

Affleck, PRL (1989)
Affleck and Wellman, PRB (1992)

Low-energy effective mode (σ model)

mass (Haldane gap)

$$L = \sum_i [(\partial \boldsymbol{\phi}_i/\partial t)^2/2v - v(\partial \boldsymbol{\phi}_i/\partial z)^2/2 - (\Delta^2/2v)\boldsymbol{\phi}_i^2 - 2Ds(\phi_i^z)^2 - (\lambda/4)(\boldsymbol{\phi}_i \cdot \boldsymbol{\phi}_i)^2]$$

intra-chain

$$-2J's \sum_{\langle i,j \rangle} \boldsymbol{\phi}_i(z) \cdot \boldsymbol{\phi}_j(z)$$

inter-chain

Intersite-interaction-induced quantum phase transition

$$J_c' = \Delta^2/16vs$$

critical vaule

Higgs

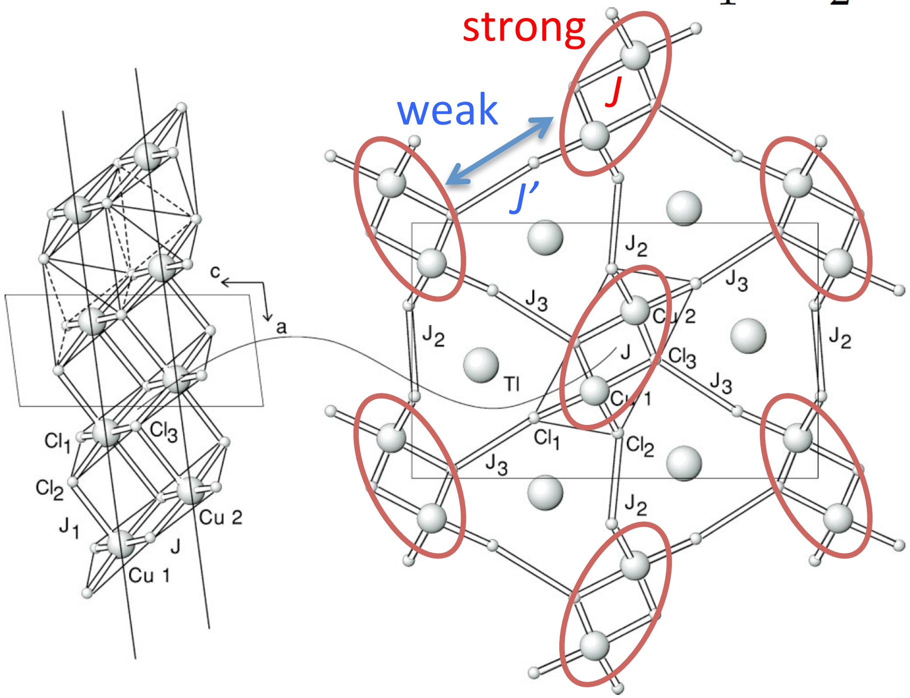
$$\boldsymbol{\phi} = (\phi_x, \phi_y, \phi_0 + \phi_z)$$

Nambu-Goldstone classical

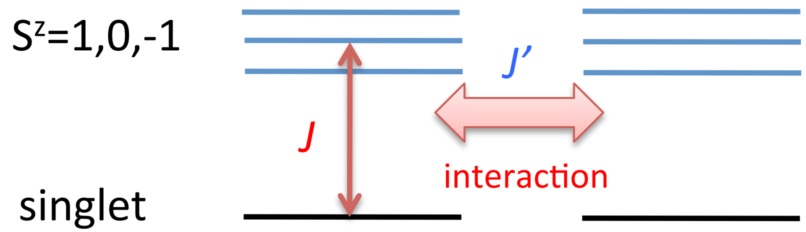
Spin dimer system $TlCuCl_3$

$TlCuCl_3$

$$J\boldsymbol{S}_1 \cdot \boldsymbol{S}_2$$

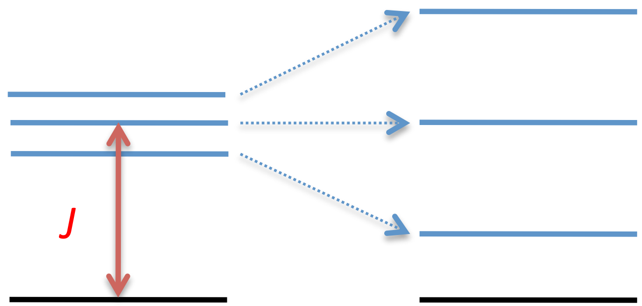


$$J\boldsymbol{S}_1 \cdot \boldsymbol{S}_2$$



Competition J ⟺ J'

Field-induced order

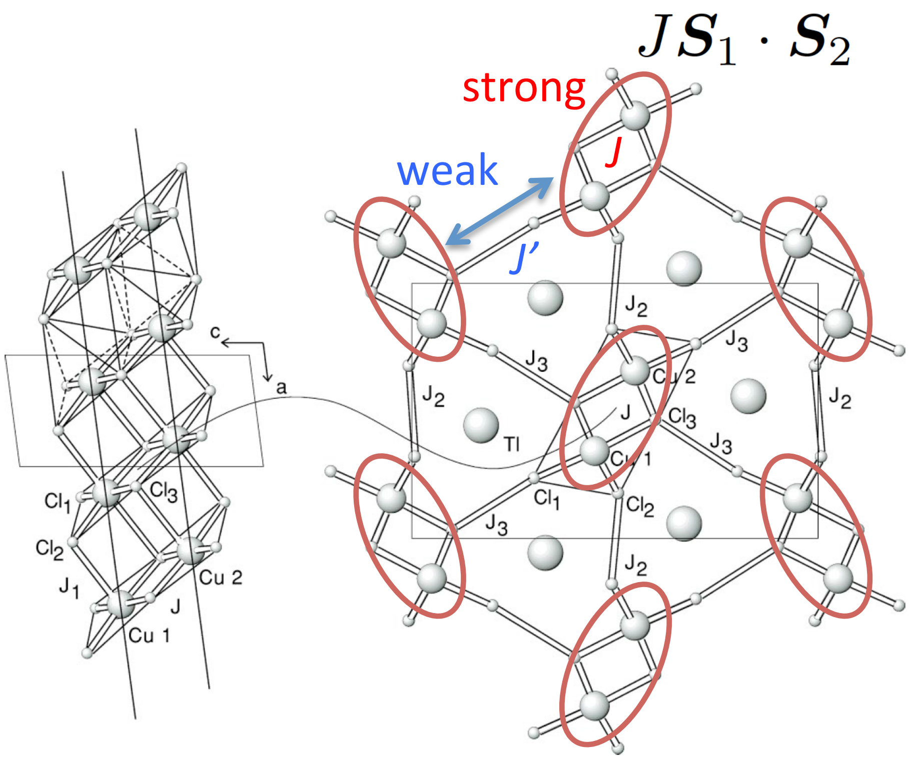


J ⇨ weakened

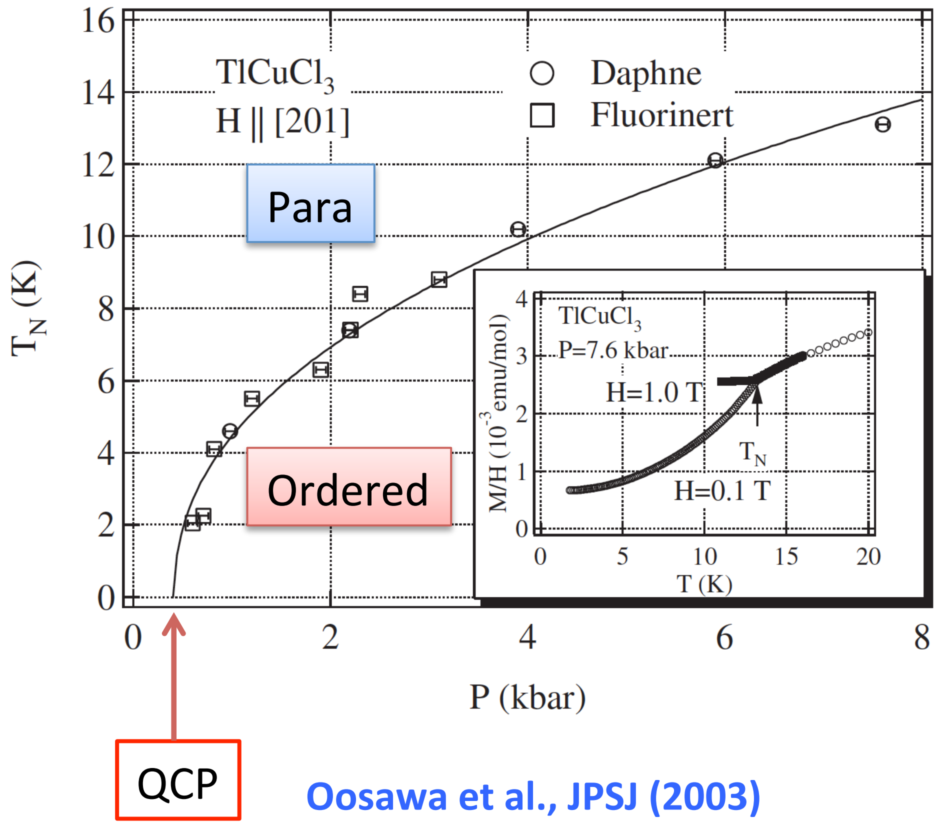
Magnon BEC
Nikuni et al., PRL (2000)

Spin dimer system $TlCuCl_3$

$TlCuCl_3$

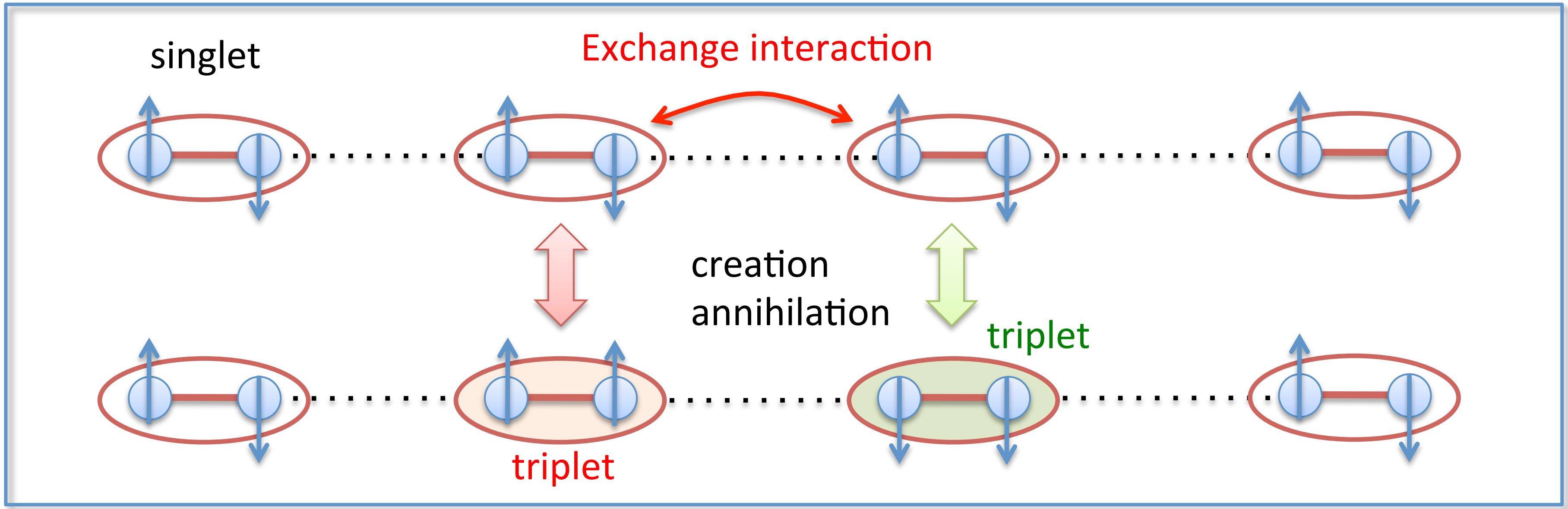


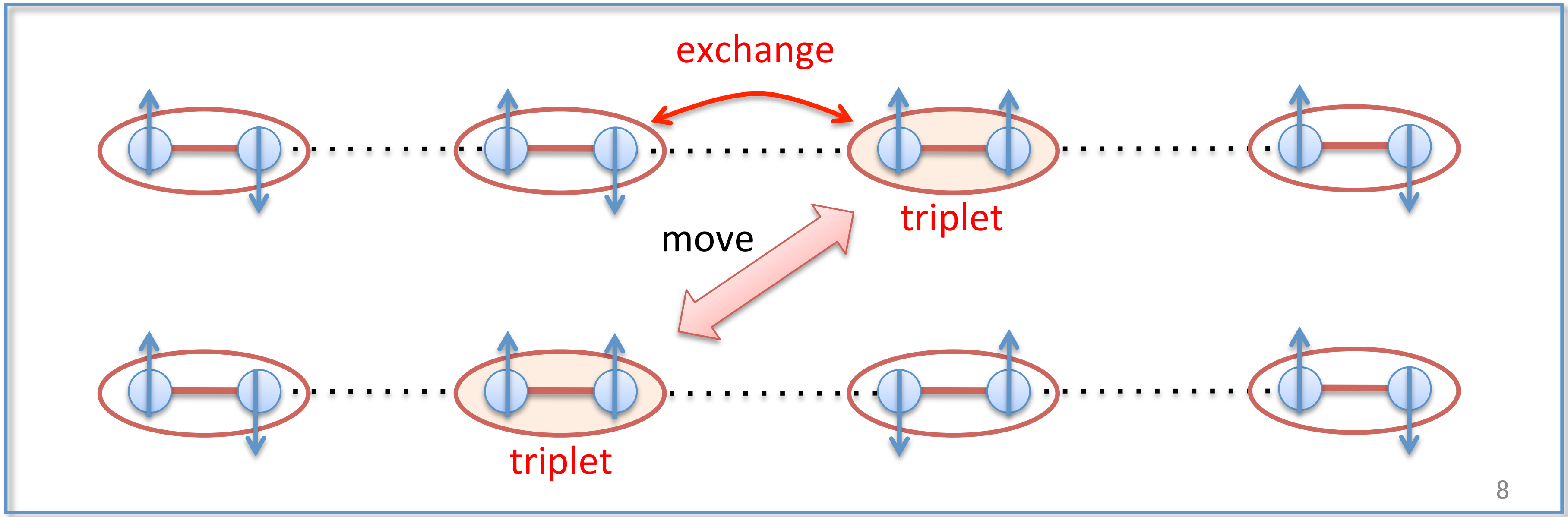
Pressure-induced order



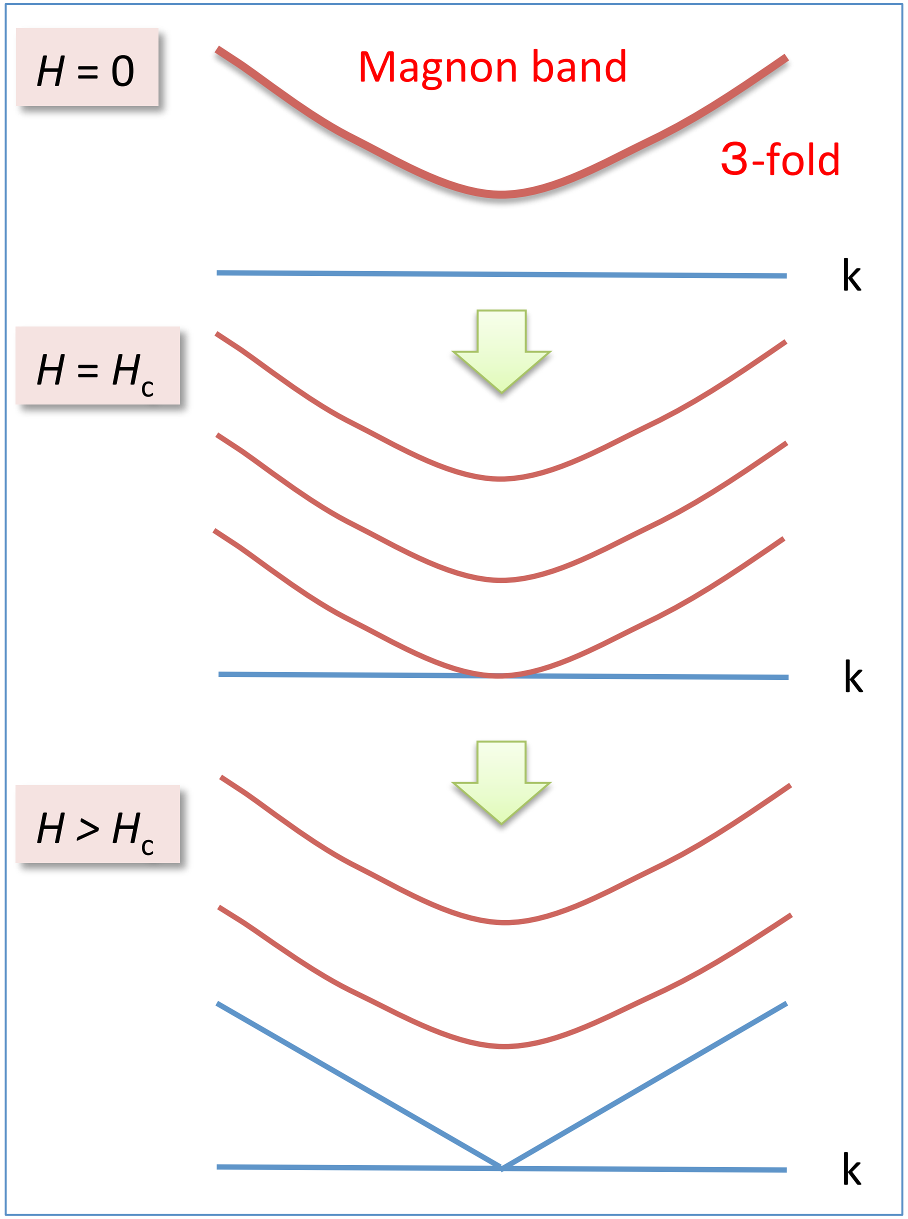
Oosawa et al., JPSJ (2003)
Goto et al., JPSJ 73 (2004)

Motion of triplet excitation

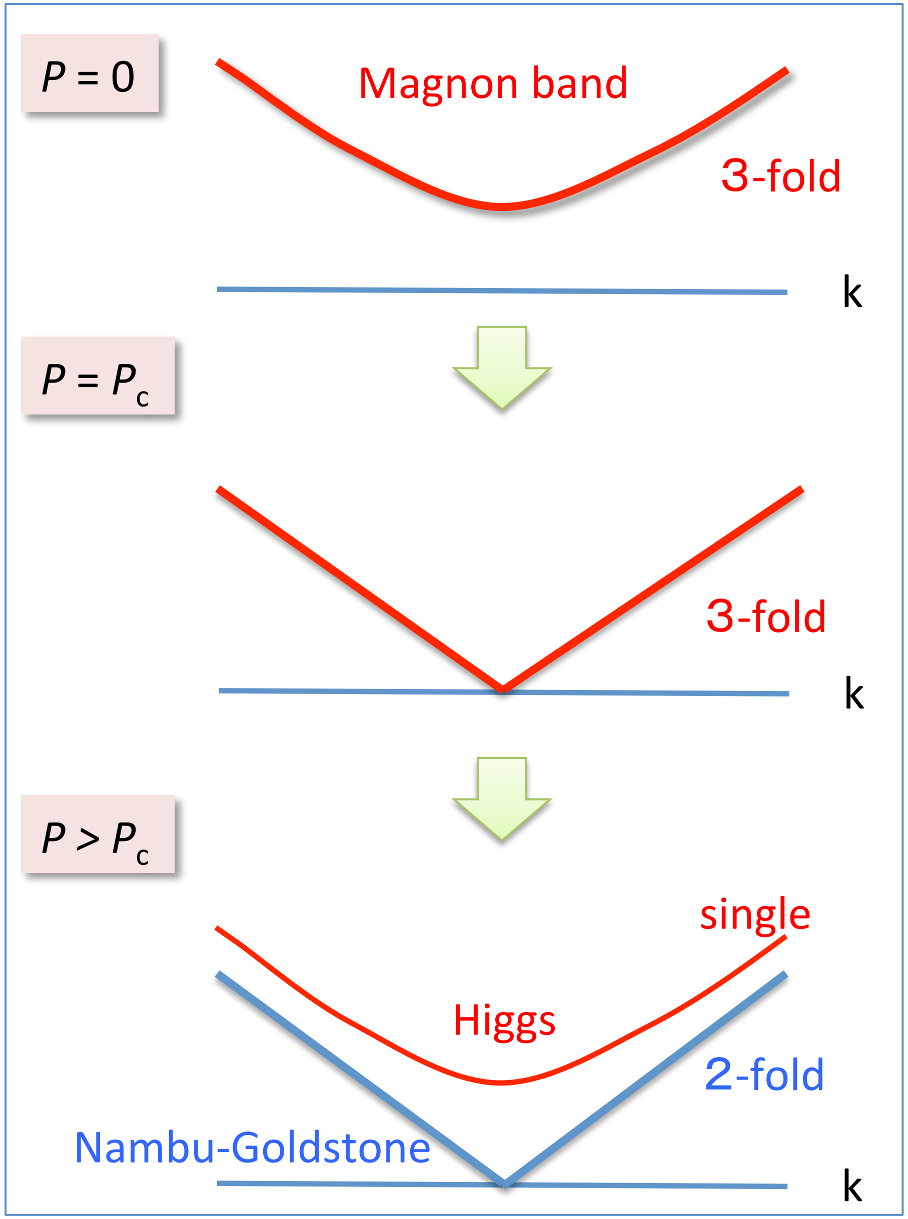




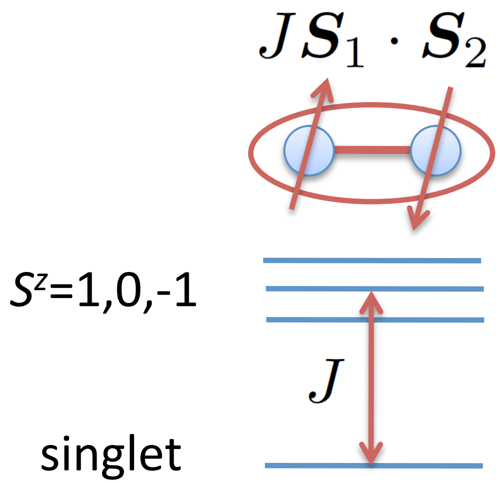
Field-induced order

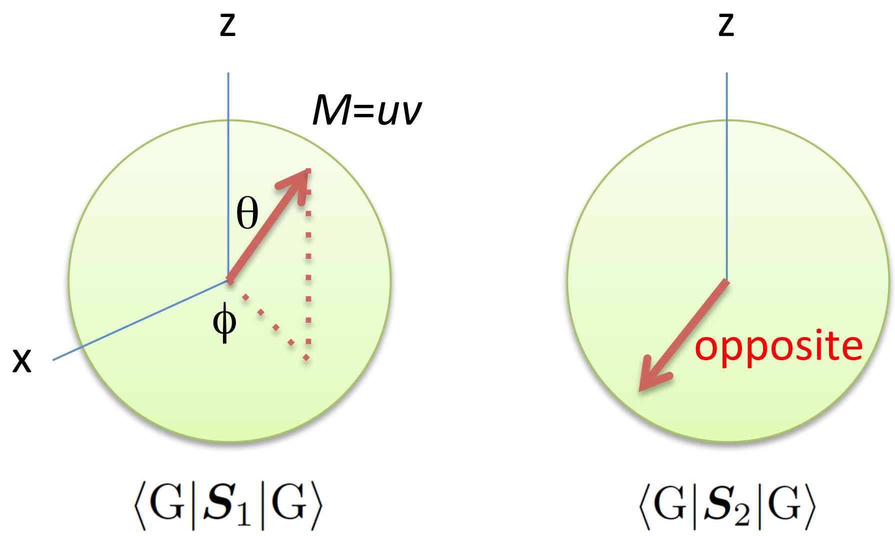


Pressure-induced order



Classical energy for pressure-induced order





Local groundstate

$$|\mathrm{G}\rangle = u|s\rangle + v\left[\frac{\sin\theta}{\sqrt{2}}\left(-e^{-i\phi}|1\rangle + e^{i\phi}|-1\rangle\right) + \cos\theta|0\rangle\right]$$
$$= u|s\rangle + v\left(\sin\theta\cos\phi|x\rangle + \sin\theta\sin\phi|y\rangle + \cos\theta|z\rangle\right)$$

$$|x\rangle = \frac{1}{\sqrt{2}}\left(-|1\rangle + |-1\rangle\right)$$
$$|y\rangle = \frac{i}{\sqrt{2}}\left(|1\rangle + |-1\rangle\right)$$
$$|z\rangle = |0\rangle$$

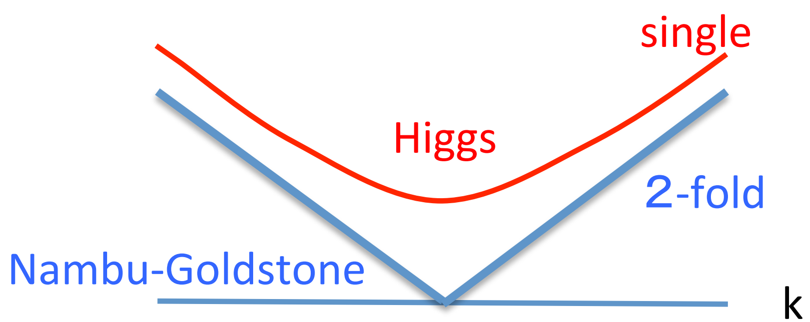
Classical energy

Higgs potential

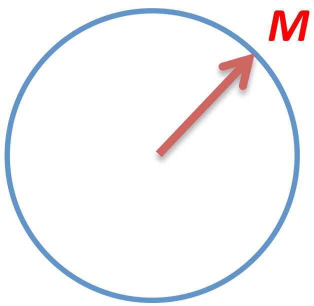
$$E_{\mathrm{MF}}(v,\theta,\phi) = -\frac{3}{4}J + (J - J_{\mathrm{eff}})v^2 + J_{\mathrm{eff}}v^4$$

Interdimer interaction

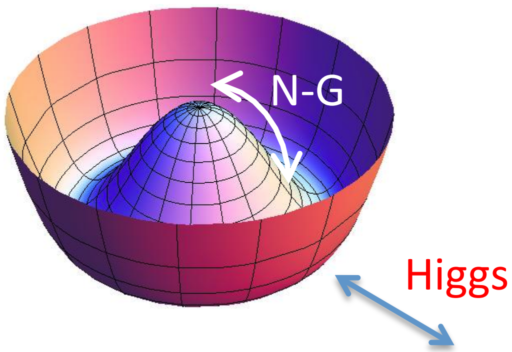
Classical energy for pressure-induced order



Magnetic moment



Classical energy



Classical energy

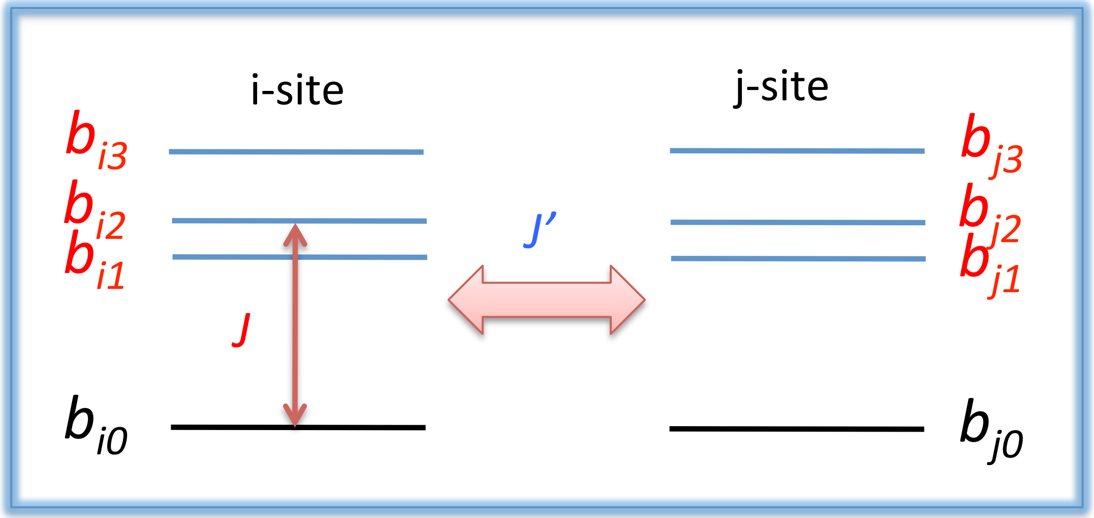
Higgs potential

$$E_{\mathrm{MF}}(v, \theta, \phi) = -\frac{3}{4}J + (J - J_{\mathrm{eff}})v^2 + J_{\mathrm{eff}}v^4$$

Interdimer interaction

Extended spin-wave theory

Introduce bosons for mean-field states



Sachdev et al. (1990)
Chubukov et al. (1995)
Sommer et. al. (2001)
Matsumoto et al. (2002)
Shiina et al. (2003)

Local constraint

$$\sum_{m=0}^{3} b_{im}^{\dagger} b_{im} = 1$$

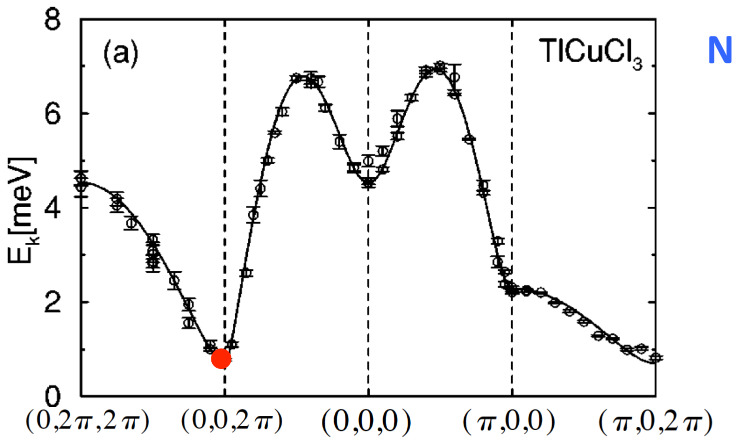
Boson for GS

$$b_{i0} \to \left(1 - \sum_{m=1}^{3} b_{im}^{\dagger} b_{im}\right)^{1/2} \qquad b_{i0}^{\dagger} \to \left(1 - \sum_{m=1}^{3} b_{im}^{\dagger} b_{im}\right)^{1/2}$$

Hamiltonian

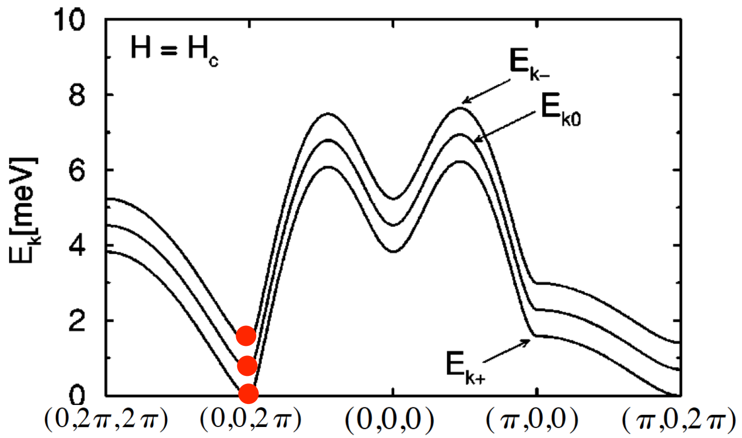
Retain quadratic terms of $b_{\boldsymbol{k}m}$ and $b_{\boldsymbol{k}m}^{\dagger}$ $(m = 1, 2, 3)$

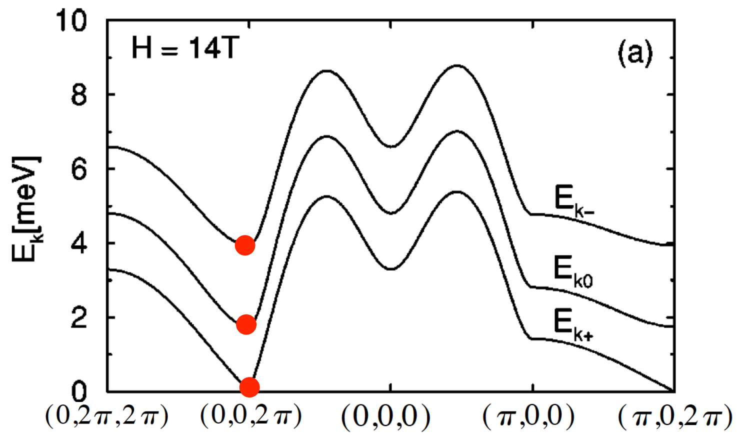
Bogoliubov transformation ⇨ diagonal

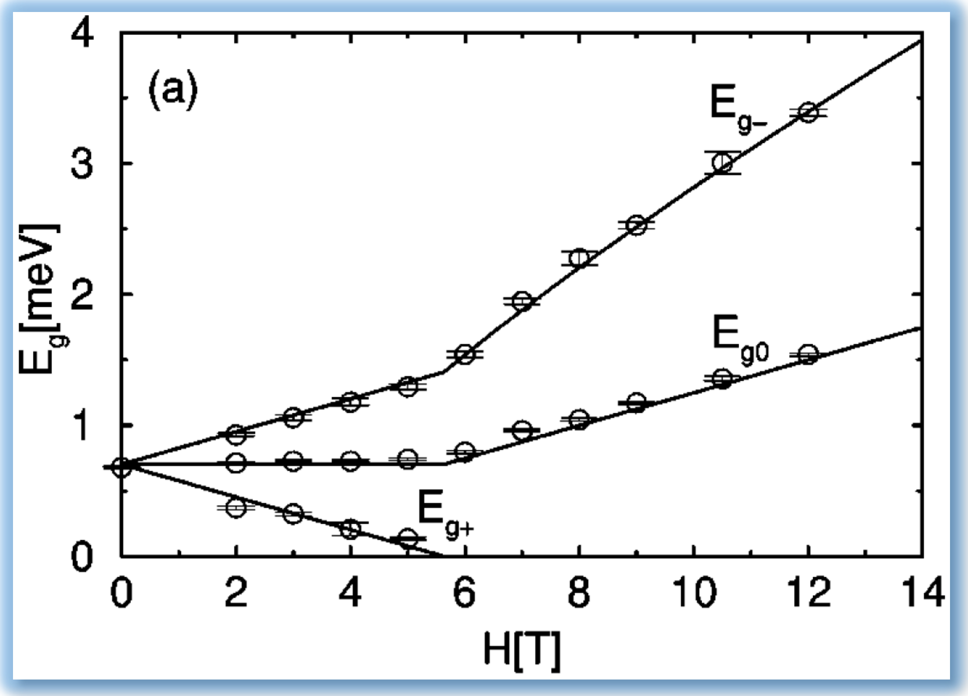


N. Cavadini et al., J. Phys.: Condens. Matter (2000)

Field-induced order





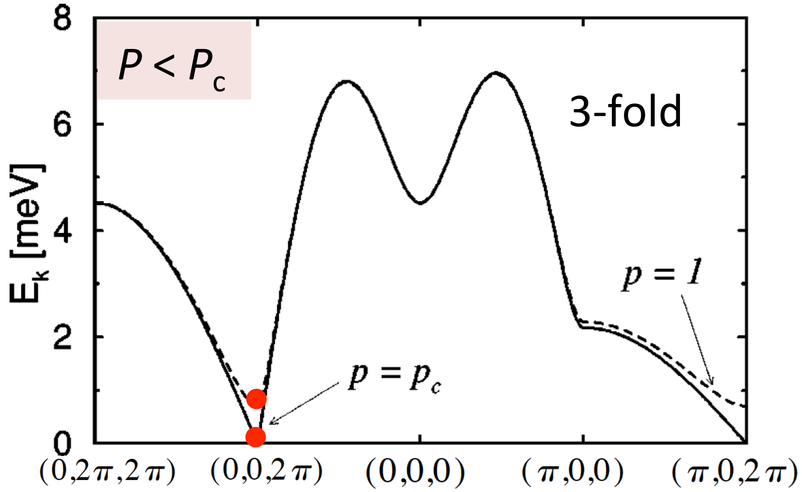


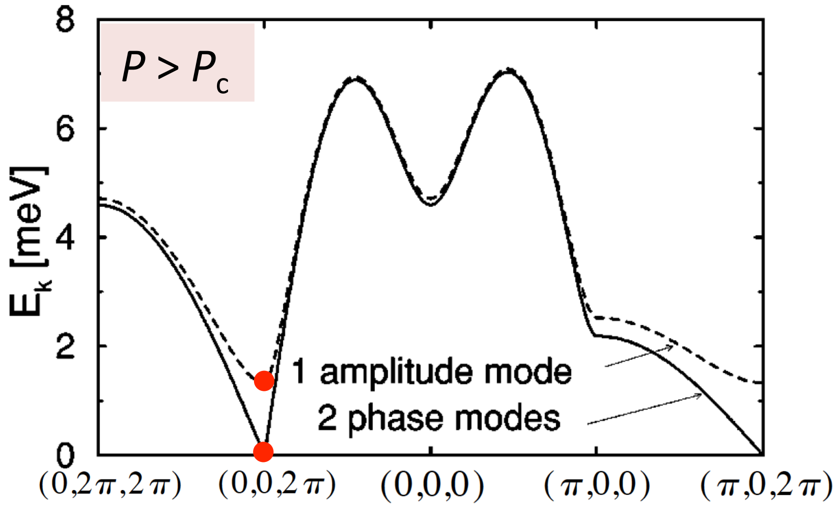
Ch. Rüegg et al., Nature (2003)

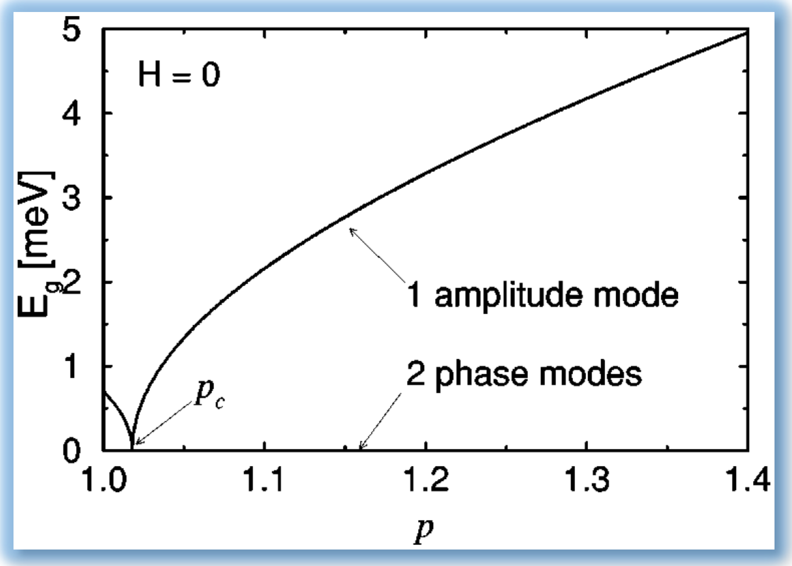
Matsumoto et al., PRB (2004)

Pressure-induced order

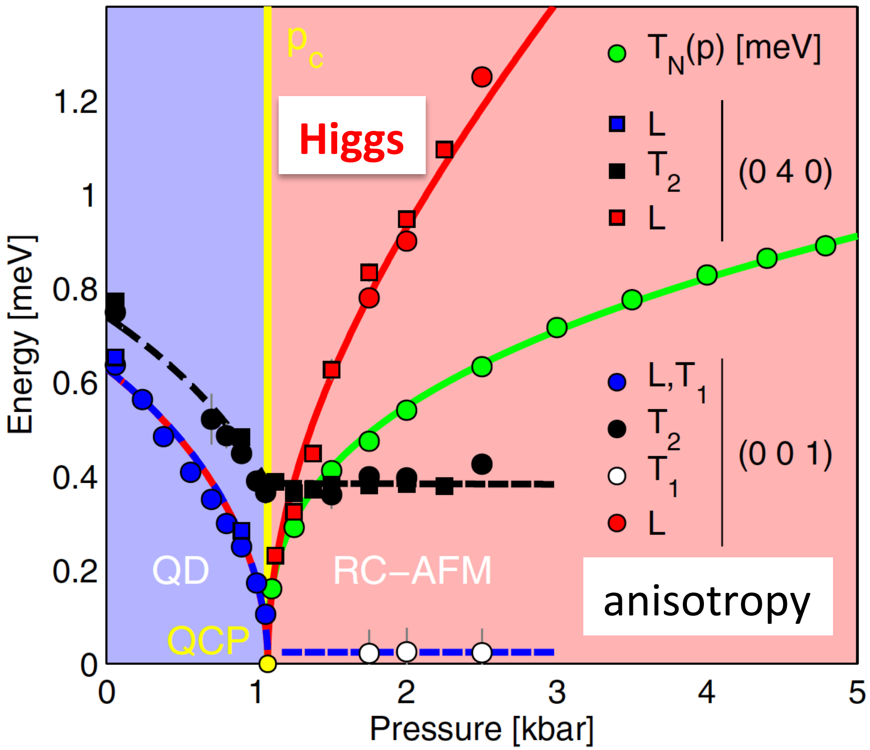
Matsumoto et al., PRB (2004)



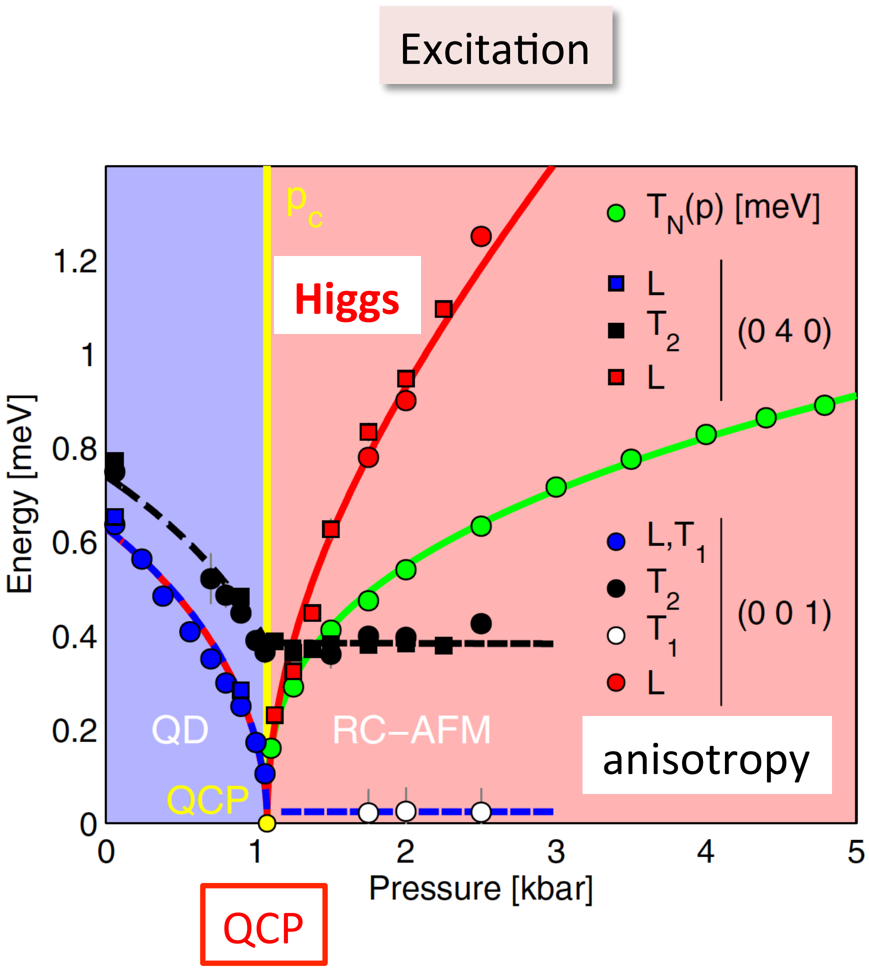


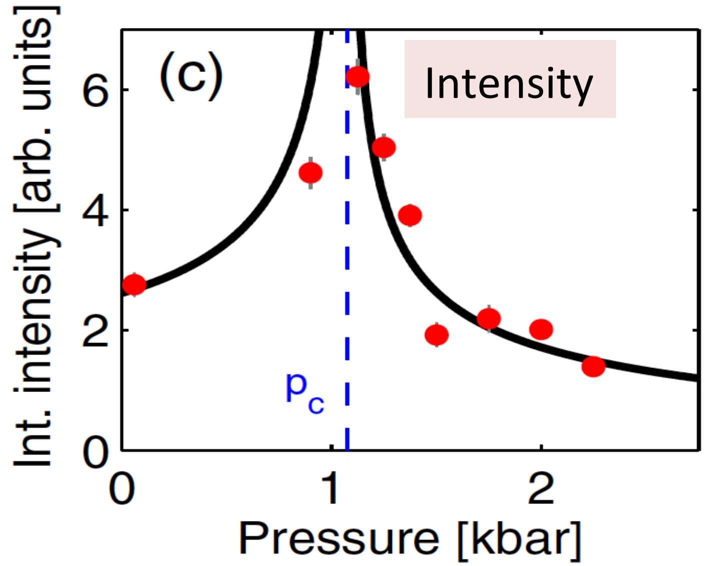


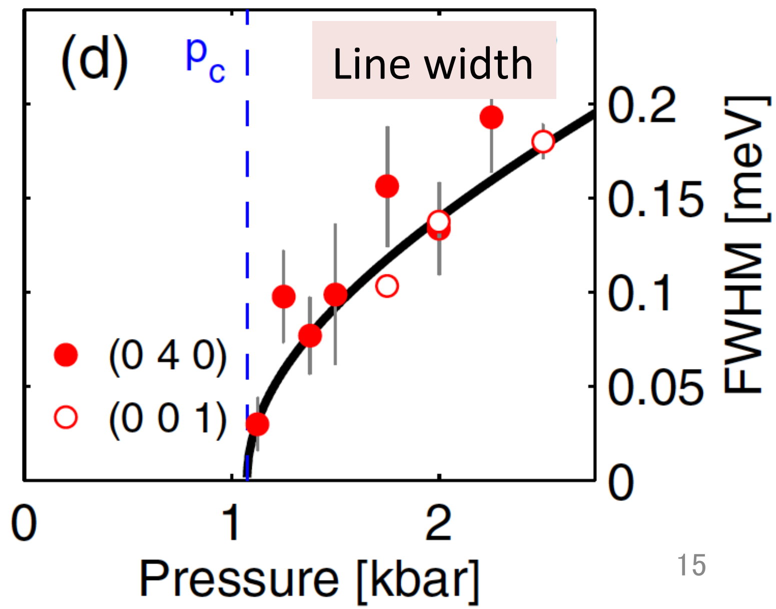
Ch. Rüegg et al., PRL (2008)



Intensity of neutron scattering



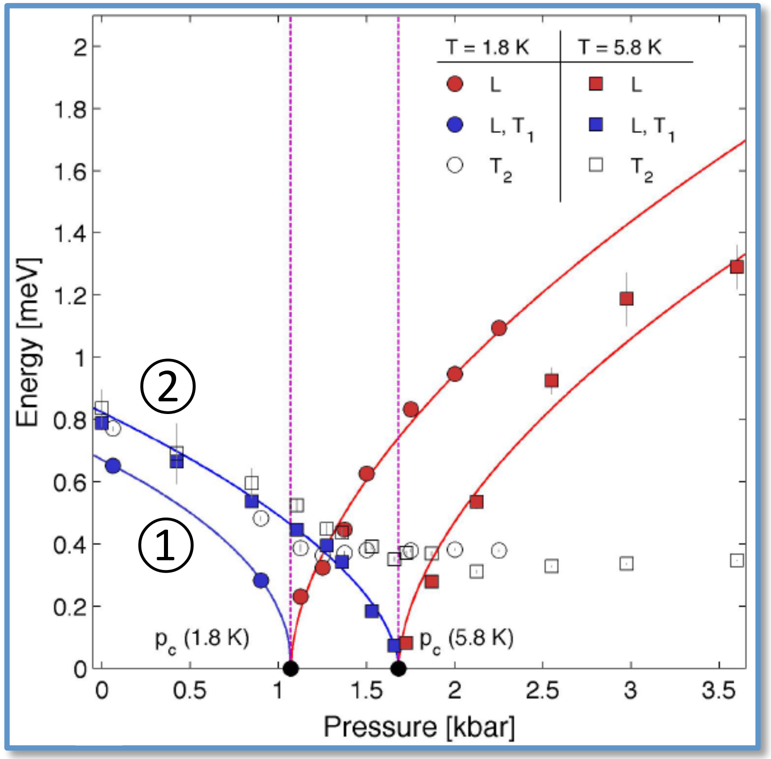


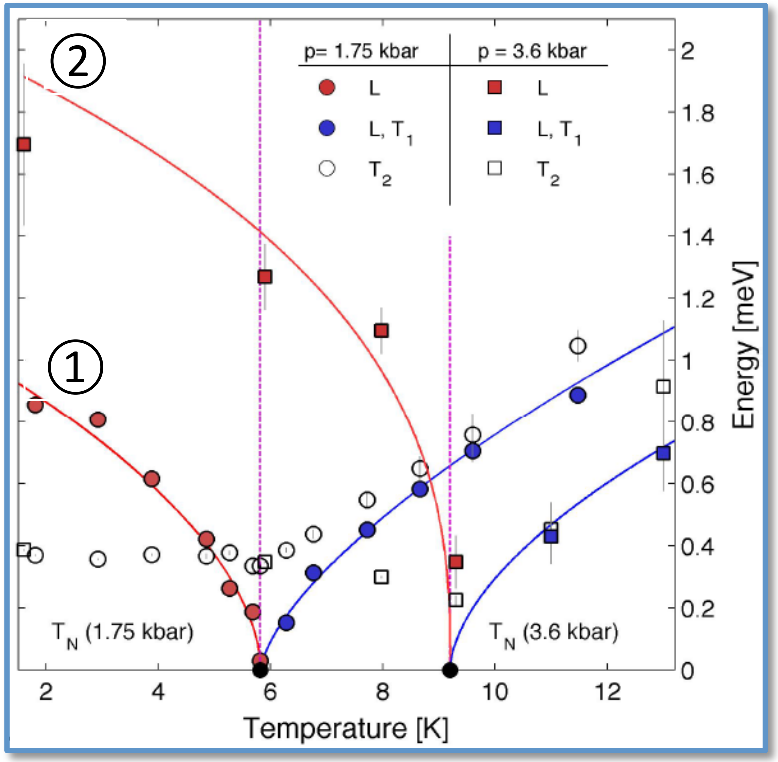


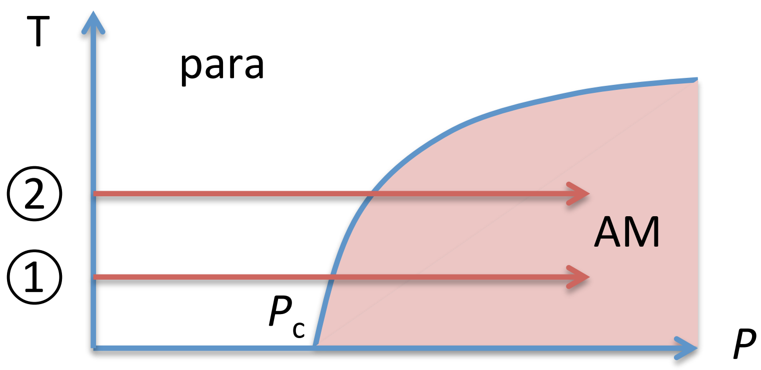
Ch. Ruegg et al., PRL (2008)

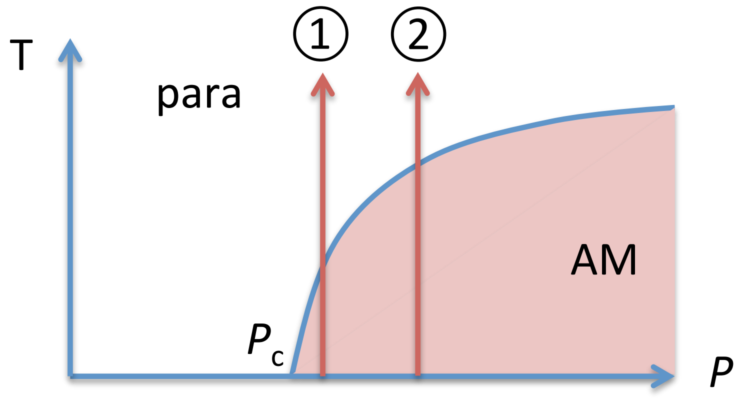
Finite temperature

Merchant et al., Nat. Phys. (2014)

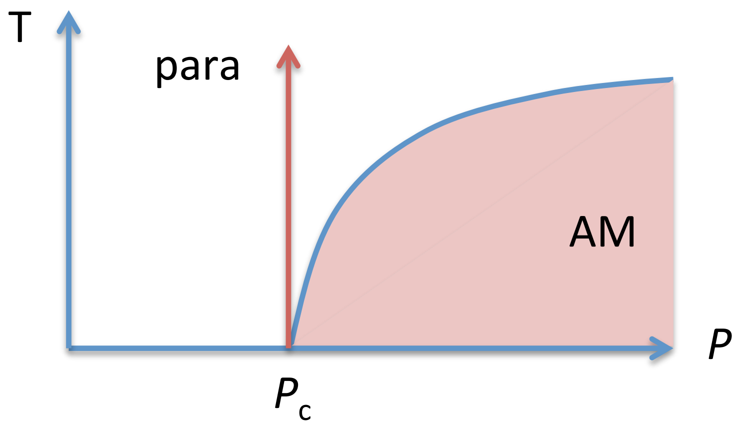


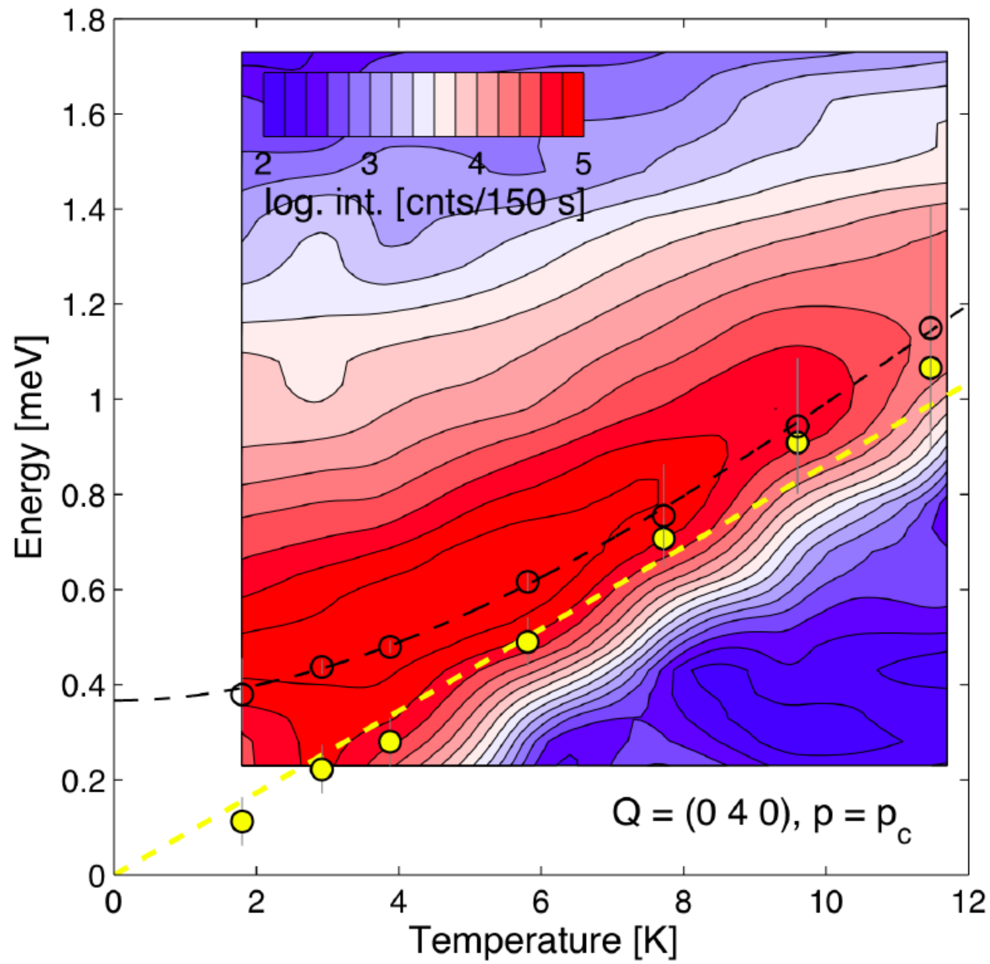






At the critical pressure



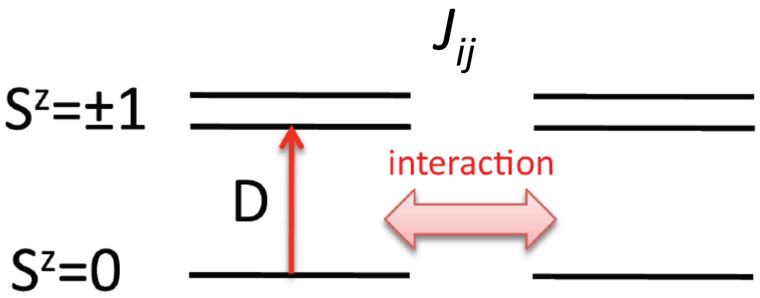


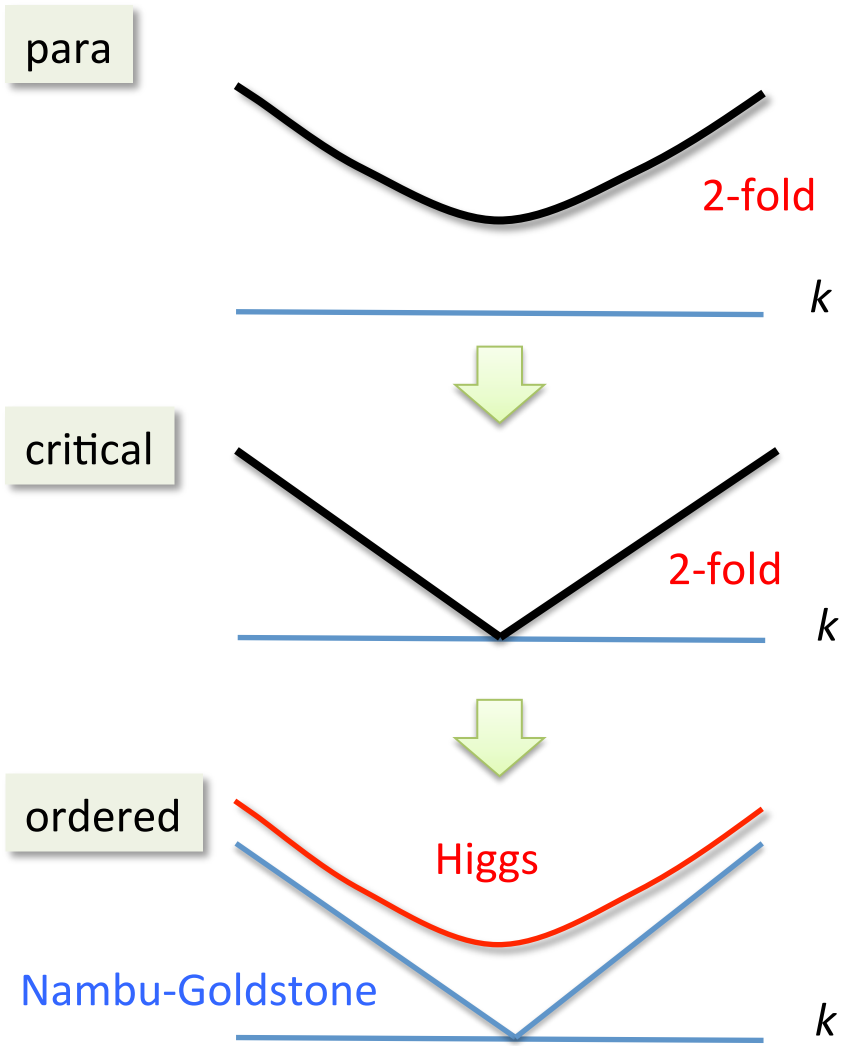
Merchant et al., Nat. Phys. (2014)

Related system and optical property

3D S=1 system

$$\mathcal{H} = \sum_{\langle ij \rangle} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \sum_i D (S_i^z)^2$$





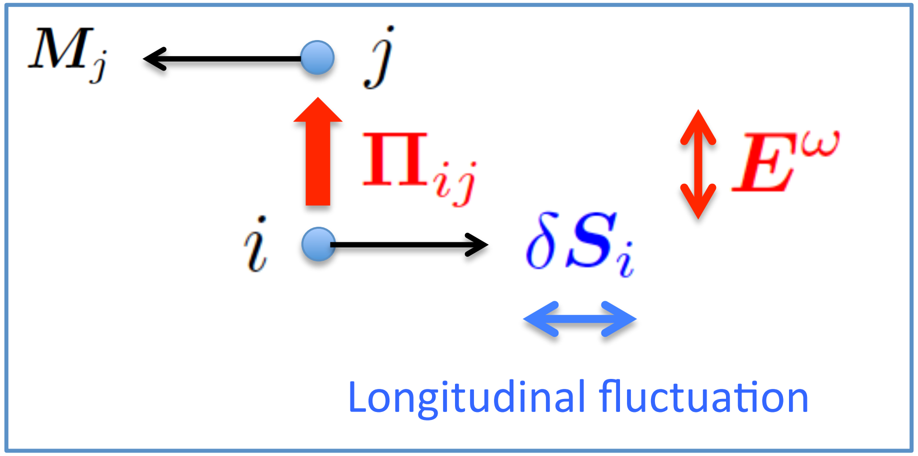
Electromagnon excitation and Higgs mode

Electromagnon

Electric-field-excitable magnon
Multiferroic systems

$$\boldsymbol{S}_i \rightarrow \boldsymbol{M}_i + \delta\boldsymbol{S}_i$$

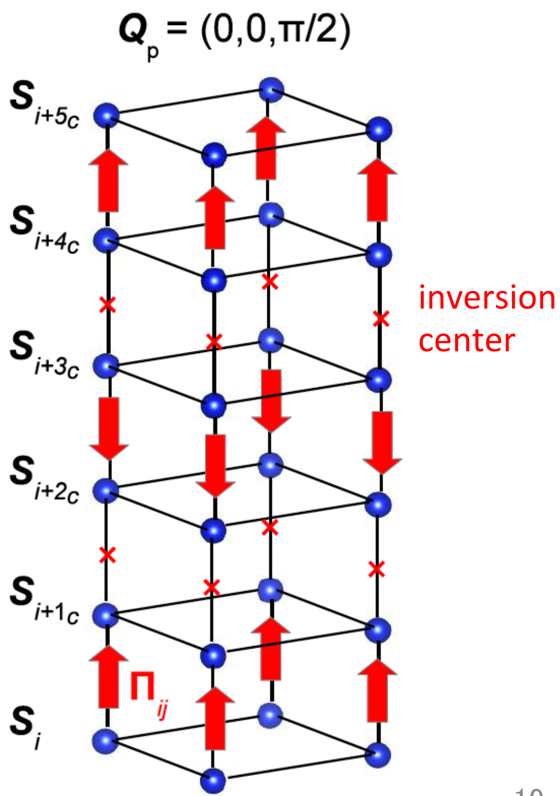
classical fluctuation

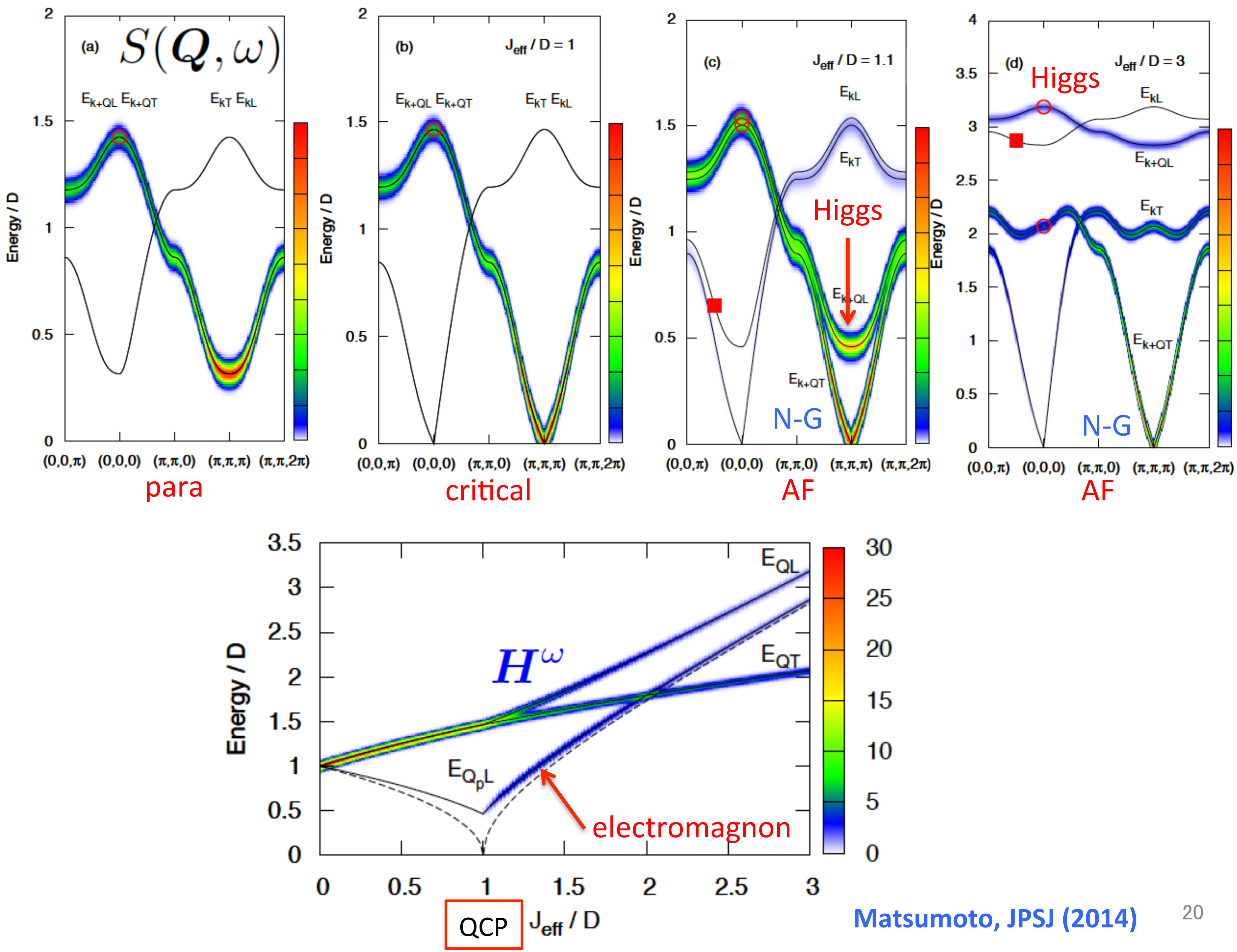


Electric field excites the Higgs mode selectively

Spin-dependent electric polarization

$$\boldsymbol{P} = \sum_{\langle ij \rangle} \boldsymbol{\Pi}_{ij} (\boldsymbol{S}_i \cdot \boldsymbol{S}_j)$$





Matsumoto, JPSJ (2014)

Summary

Higgs mode in quantum spin systems

Detectable in the vicinity of a quantum critical point

Quantum spin systems

various ways to induce QPT
Low-dimensionality
Spin dimer, dimer + monomer, trimer
Easy-plane single-ion anisotropy

↓

Good playground to study Higgs mode

Various ways to detect Higgs mode

Neutron scattering
Light absorption
Raman scattering
ESR

Acknowledgements

Theory

B. Normand

M. Sigrist

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Experiment

Ch. Rüegg

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H. Tanaka

H. Kuroe

T. Sekine

M. Soda

T. Masuda

M. Hase