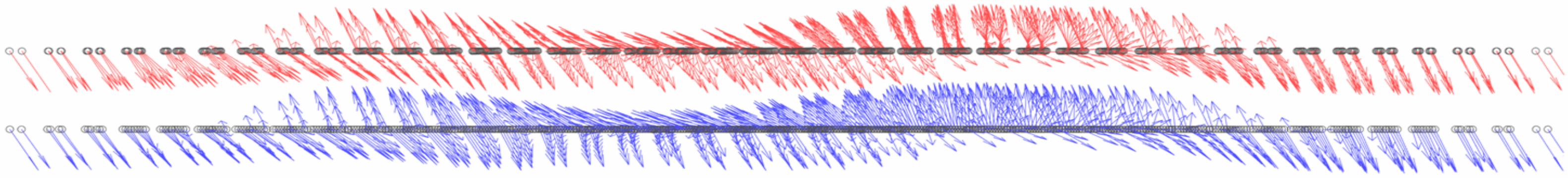
Twisted Bilayer Magnet CrI_3



Moon Jip Park

PCS-IBS

IBS-APCTP Conference

09. 22.

research center theoretical physics of complex systems

asia pacific center for theoretical physics

Acknowledgements

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Twisted Magnets CrI_3

Kyoung-Min Kim (PCS-IBS)

Grigory Bednik (PCS-IBS)

Do Hun Kim (KAIST)

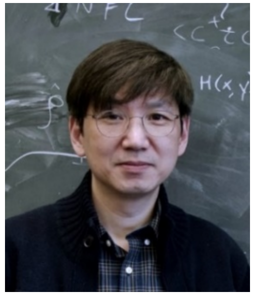
Myung Joon Han (KAIST)

Ref: K.-M. Kim, D. H. Kiem, G. Bednik, M. J. Han, MJP, arXiv:2206.05264 (2022)

3D Twisted Superconductivity & Quasicrystal

SungBin Lee (KAIST)

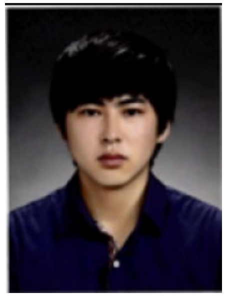
Yong Baek Kim (Toronto)



Twisted Bilayer Graphene

Youngkuk Kim (SKKU)

Sunam Jeon (SKKU)

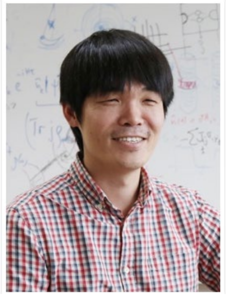


Gil Young Cho (Postech)

Moire Photonics

ChangHwan Yi (PCS-IBS)

Hee Chul Park (PCS-IBS)

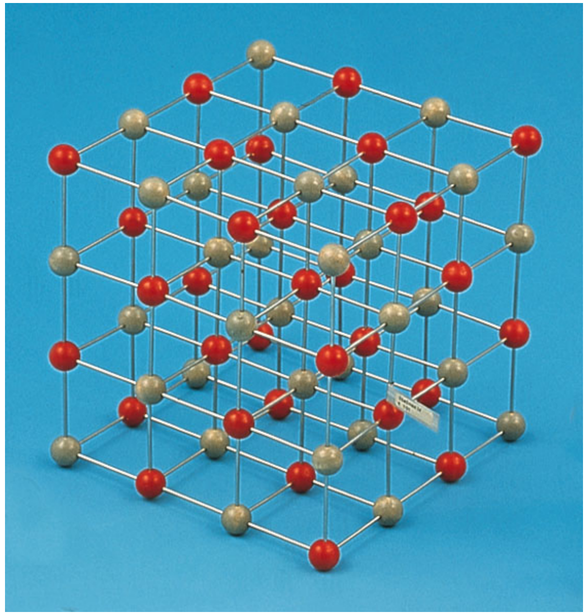


Hofstadter Moire Replica HOTI

Sun-Woo Kim (KAIST/SKKU BRL→Cambridge)

Physics of Length Scale

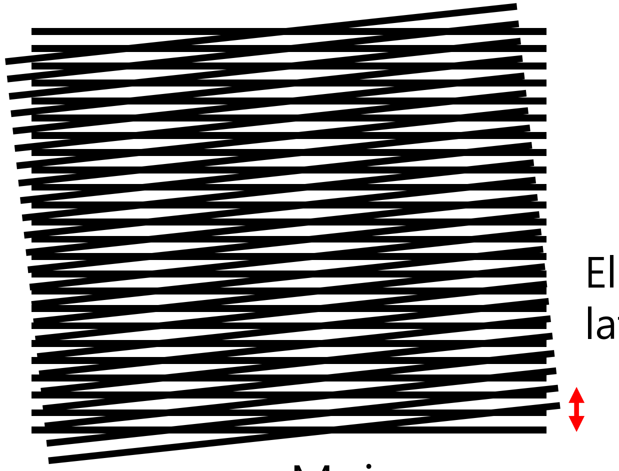
Solid state lattice



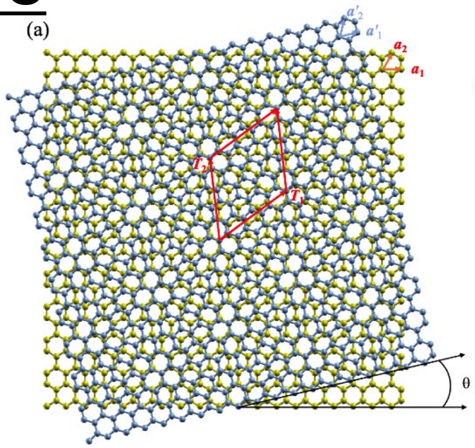
Magnetic Domains

Complex Network

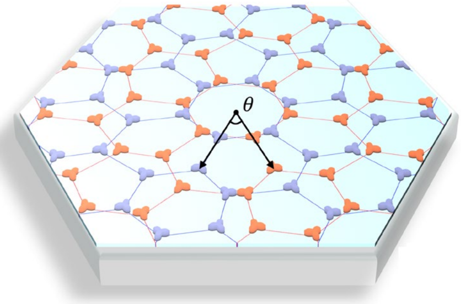
Length Scale in solid state



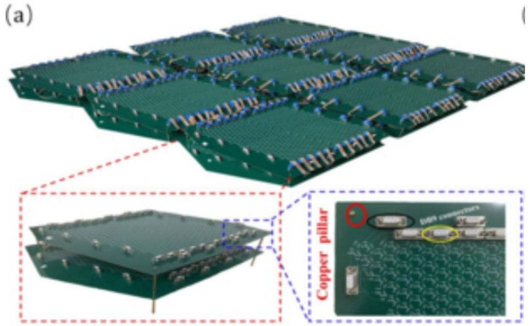
Graphene



Photonic Crystals

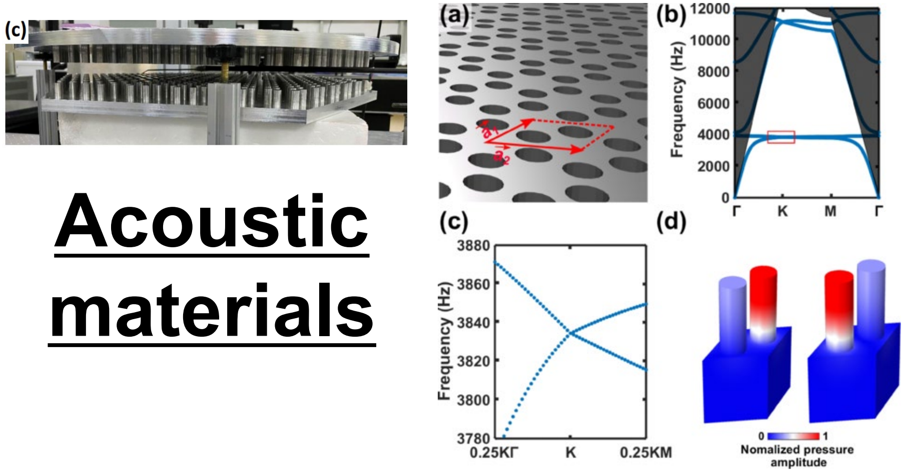


Moire circuit



Xiangdong Zhang group

Acoustic materials



Yun Jing group

In this talk, we generalize moire materials to spin systems,
"**twisted bilayer magnetism**"

Experimental progress

Letter | Published: 29 November 2021

Coexisting ferromagnetic–antiferromagnetic state in twisted bilayer CrI_3

Yang Xu, Ariana Ray, Yu-Tsun Shao, Shengwei Jiang, Kihong Lee, Daniel Weber, Joshua E. Goldberger, Kenji Watanabe, Takashi Taniguchi, David A. Muller, Kin Fai Mak & Jie Shan

Nature Nanotechnology **17**, 143–147 (2022) | Cite this article

REPORT | MAGNETISM

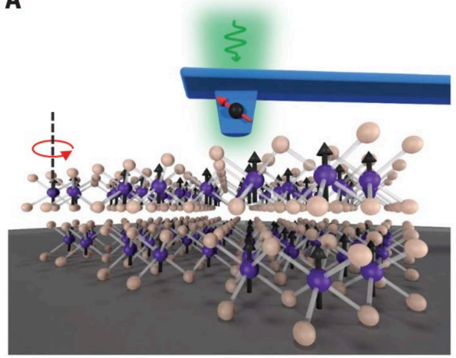
Direct visualization of magnetic domains and moiré magnetism in twisted 2D magnets

TIANCHENG SONG, QI-CHAO SUN, ERIC ANDERSON, CHONG WANG, JIMIN QIAN, TAKASHI TANIGUCHI, KENJI WATANABE, MICHAEL A. MCGUIRE, RAINER STÖHR, [...] XIAODONG XU +4 authors Authors Info & Affiliations

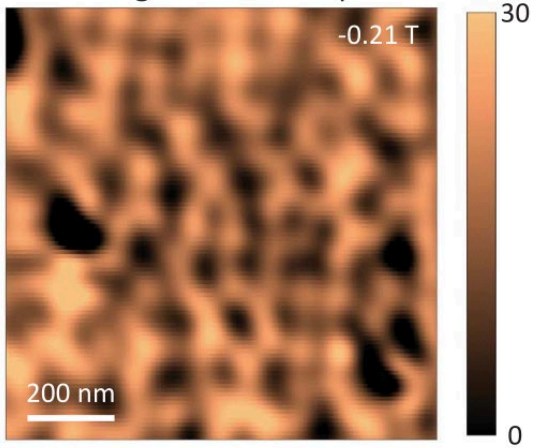
SCIENCE • 25 Nov 2021 • Vol 374, Issue 6571 • pp. 1140-1144 • DOI: 10.1126/science.abj7478

Local (AFM) measurement

A



C Magnetization map m_z (μ_B/nm^2)

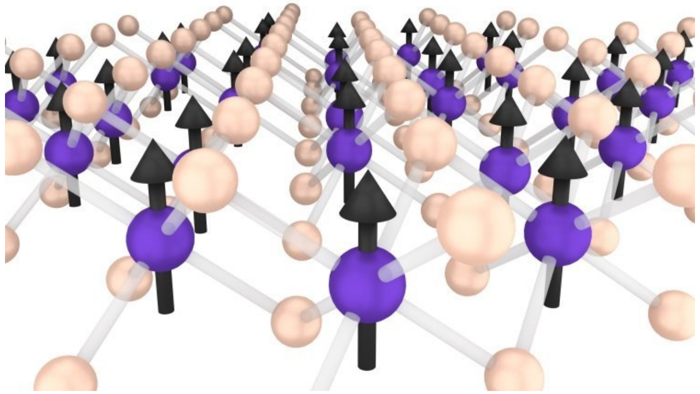


Song et al. Science (2021)

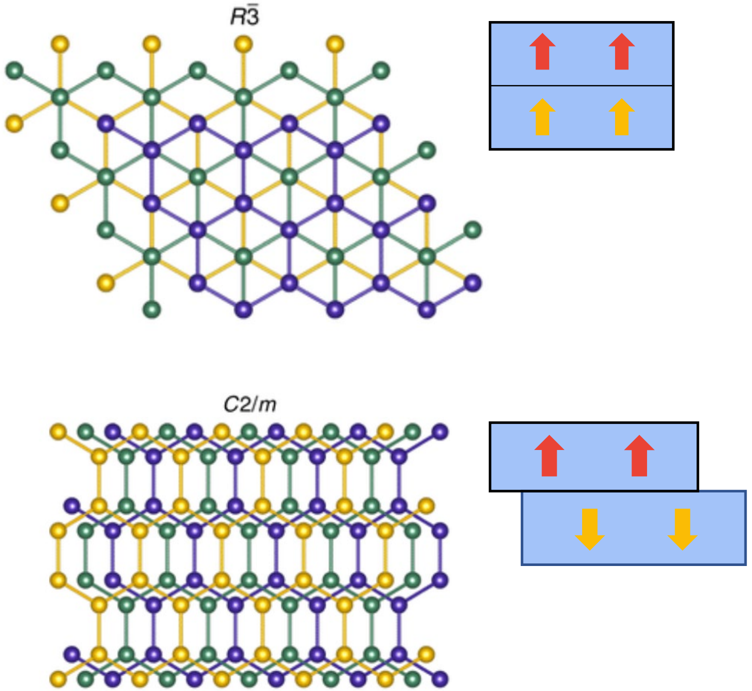
Twisted bilayer magnet

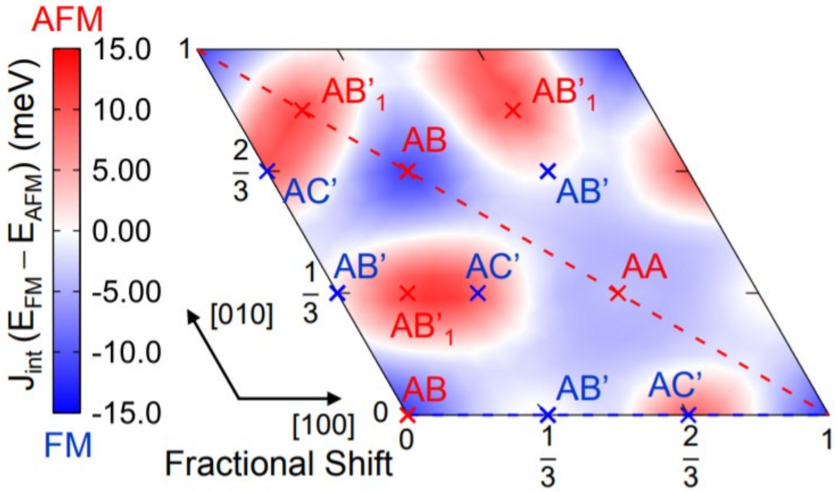
Transition metal trihalides

- **Honeycomb magnet CrI3**



- **Stacking dependent magnetism**



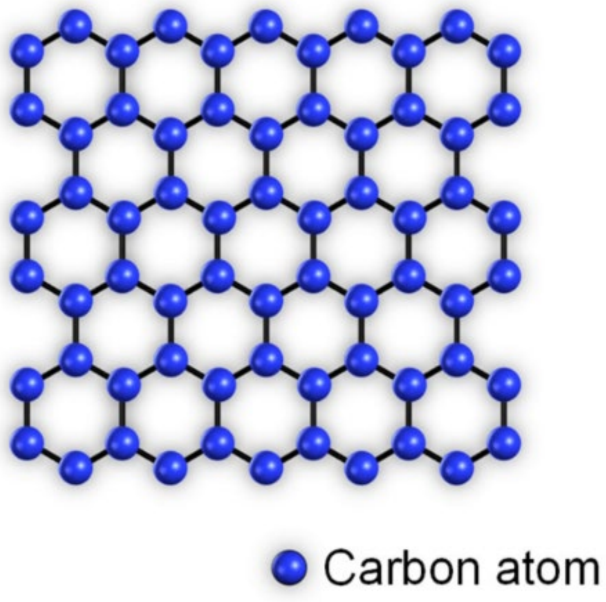


$$H = \sum_{\langle i,j\rangle} J\mathbf{S}_i \cdot \mathbf{S}_j + \sum_{z_j = z_i + d} J^{\perp}_{ij}\mathbf{S}_i \cdot \mathbf{S}_j + D_z \sum_i (S_i^z)^2$$

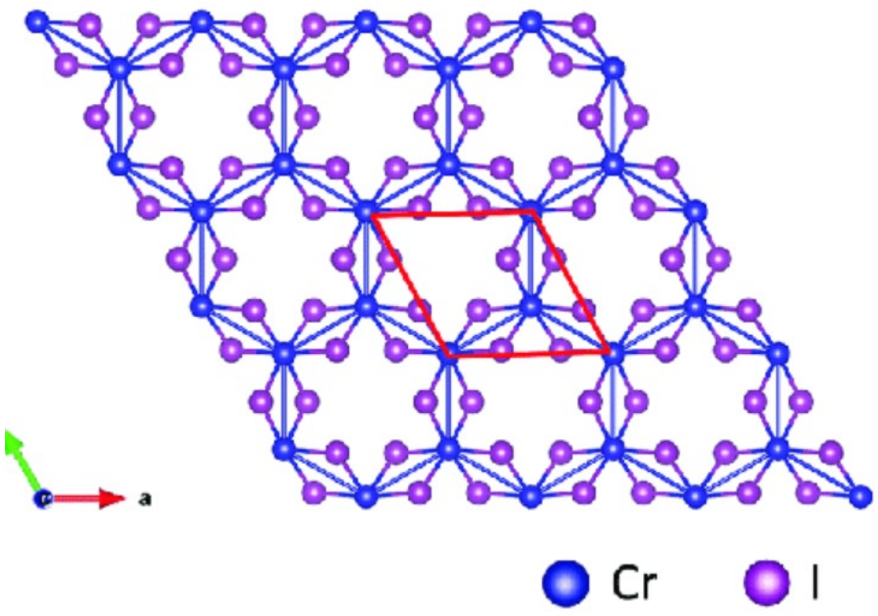
Sivadas et al. Nano Letters (2018)

Symmetry of Twisted CrI_3

- **Graphene**



- **CrI_3**



- Monolayer preserves $\mathbf{C_{2z}}$ and **P** symmetry
- $\mathbf{C_{2z}}$ is preserved in twisted bilayer
- Point group D_6

- Non-magnetic I atoms break $\mathbf{C_{2z}}$
- Twisted bilayer breaks both $\mathbf{C_{2z}}$ and **P** symmetry
- Point group D_3

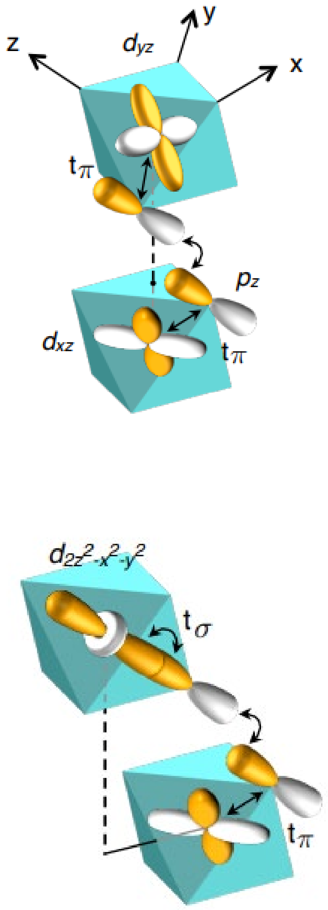
Ab-initio model construction

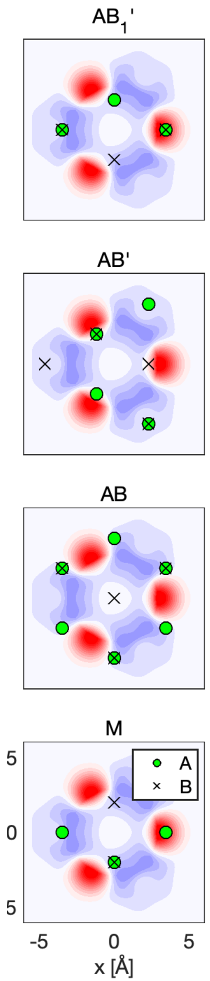
Ab-initio DFT calculations

Atomic-level calculations

Effective spin model approach
$$H = \sum J_{ij} S_i \cdot S_j$$

Analytical methods





Do Hun Kim (KAIST)

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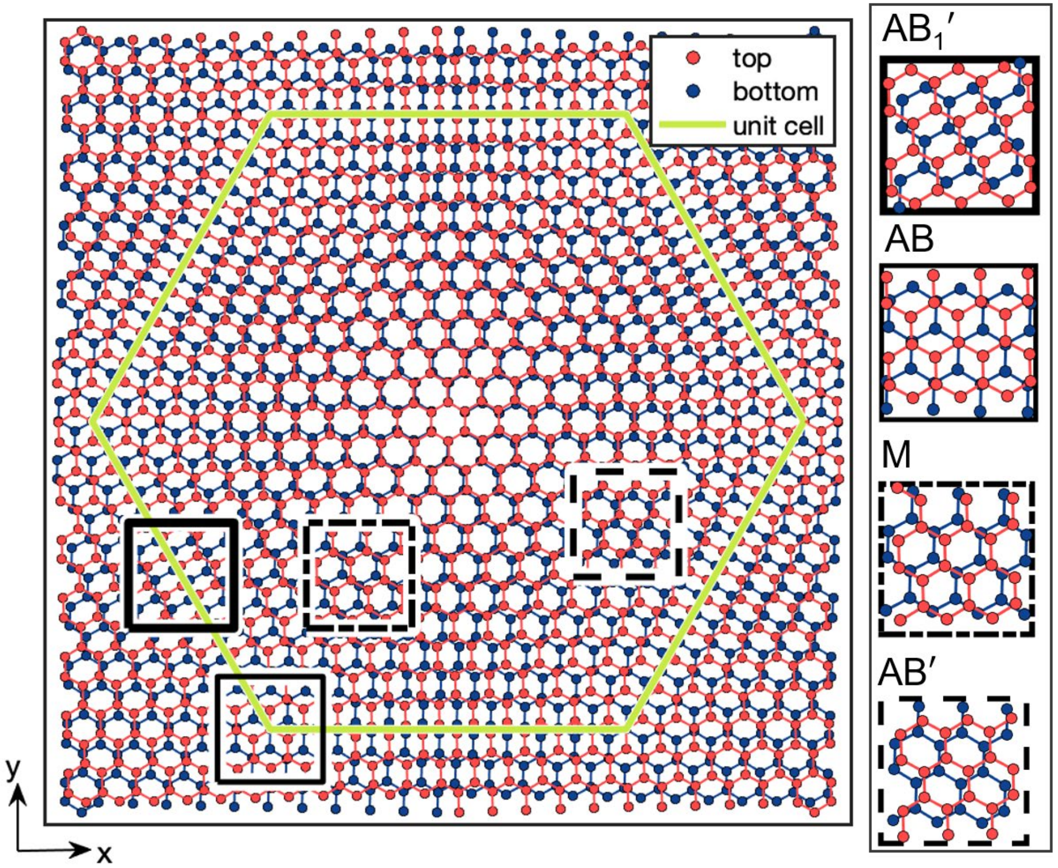
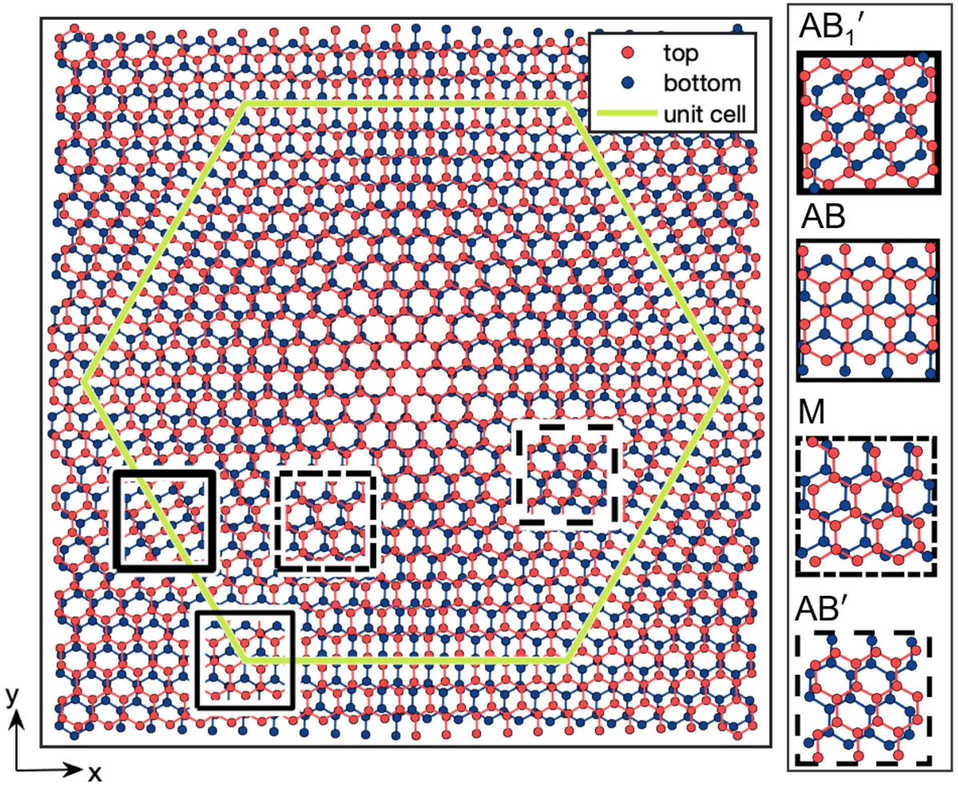
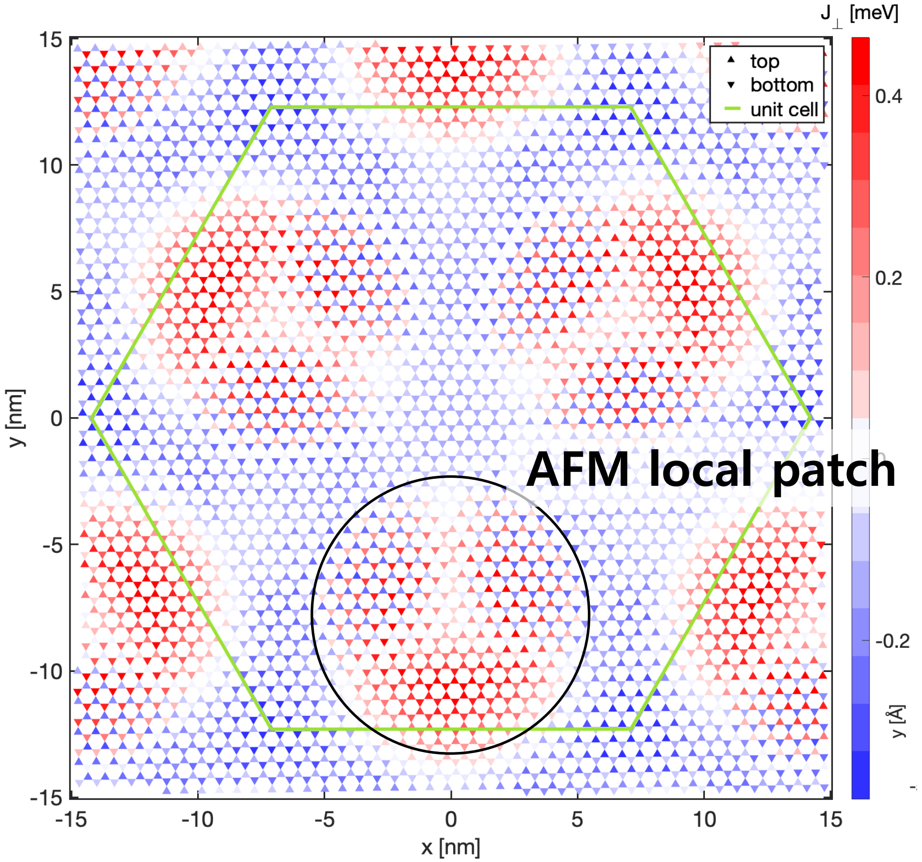
Kyoung-Min Kim (PCS-IBS)

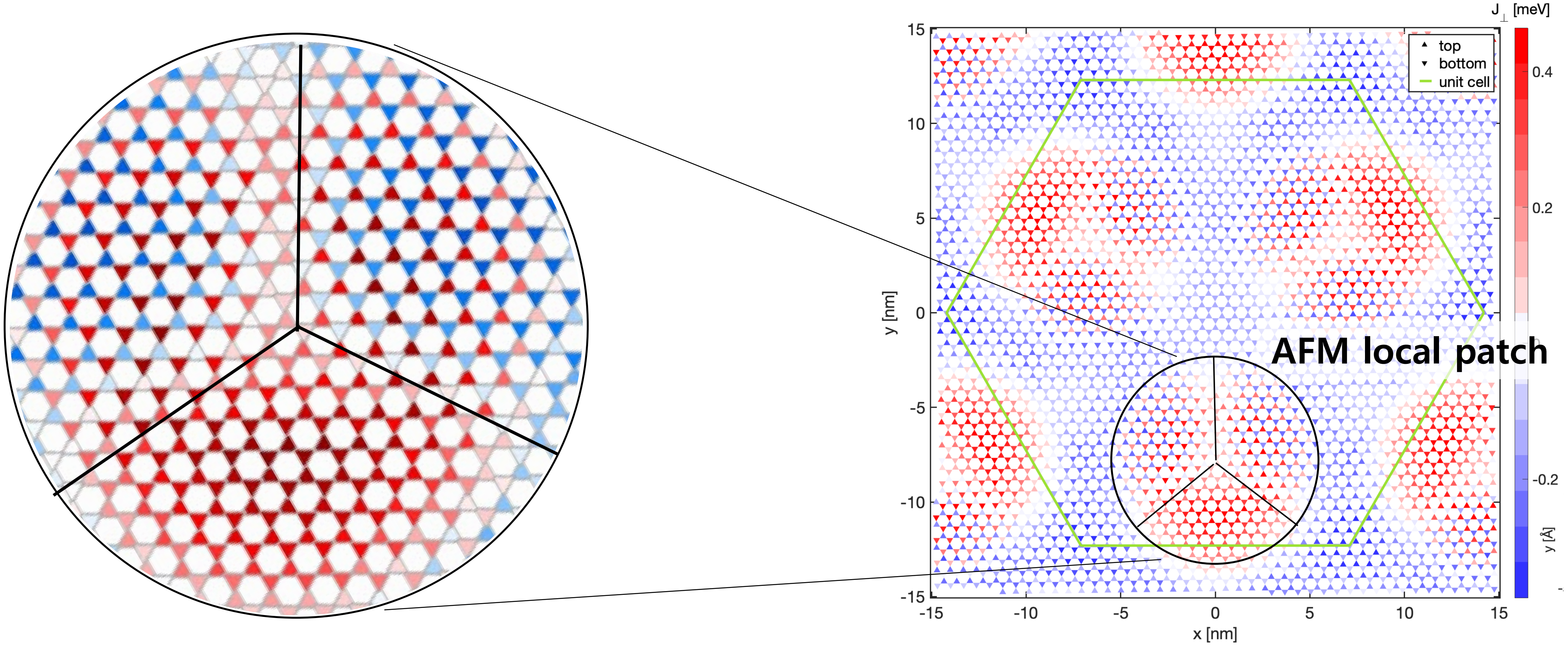


Local stacking structure





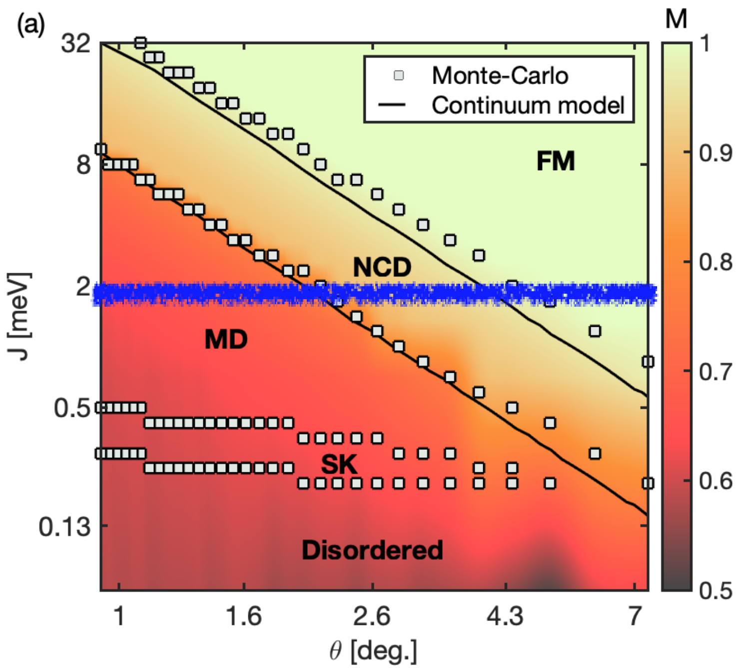
Local stacking structure

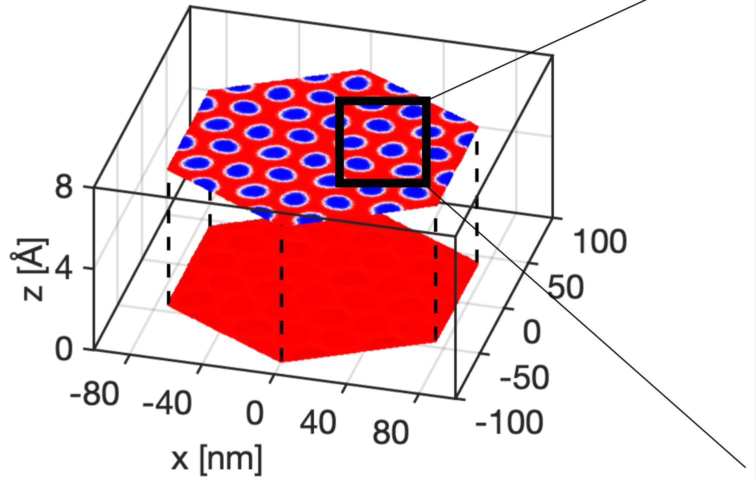


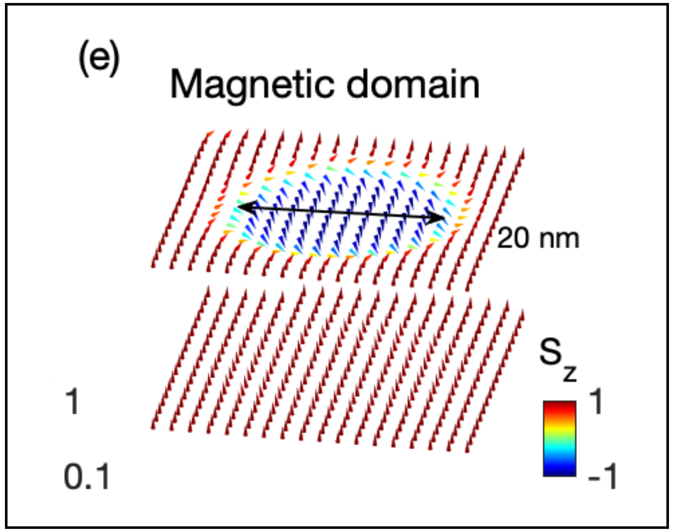
- **<u>Local FM and AFM interlayer coupling coexists.</u>**
- **<u>AB sublattice symmetry breaking.</u>**

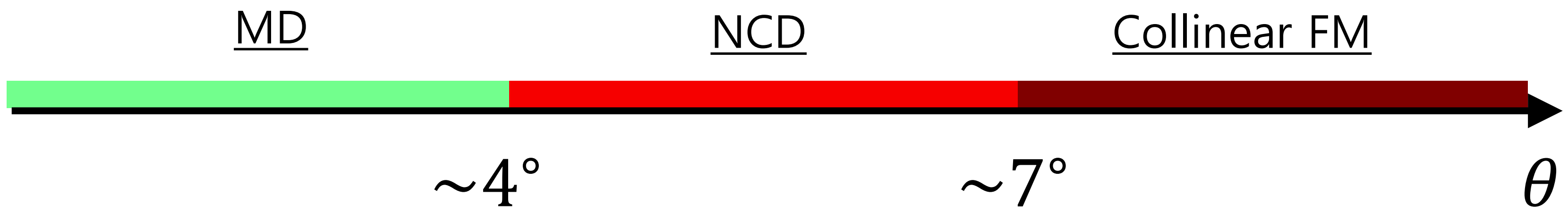
Monte Carlo Simulations

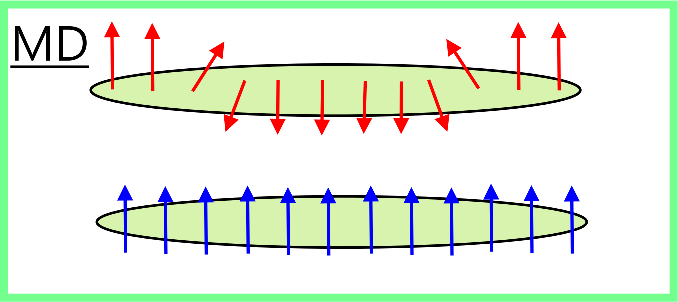
➢ Atomistic level Monte-Carlo simulations

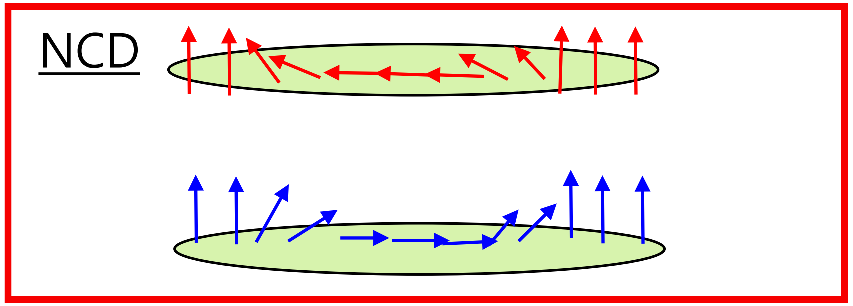


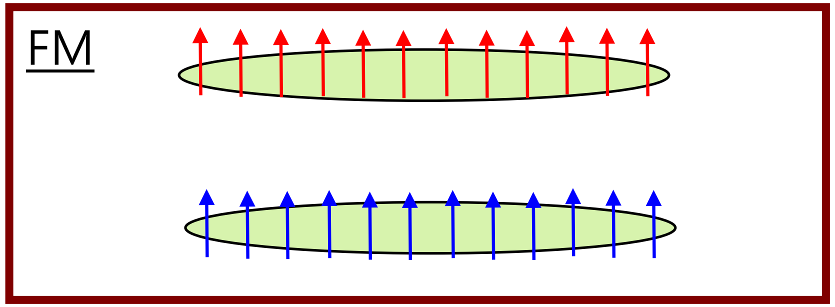






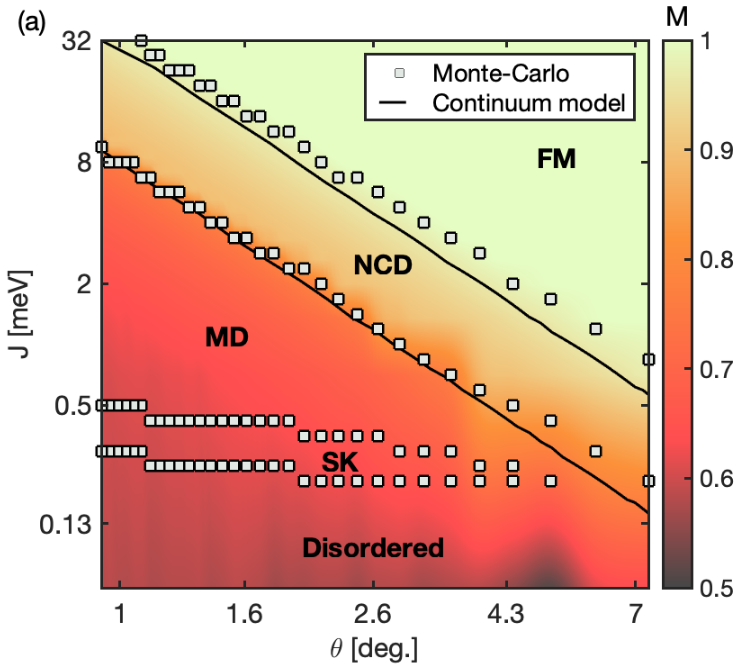


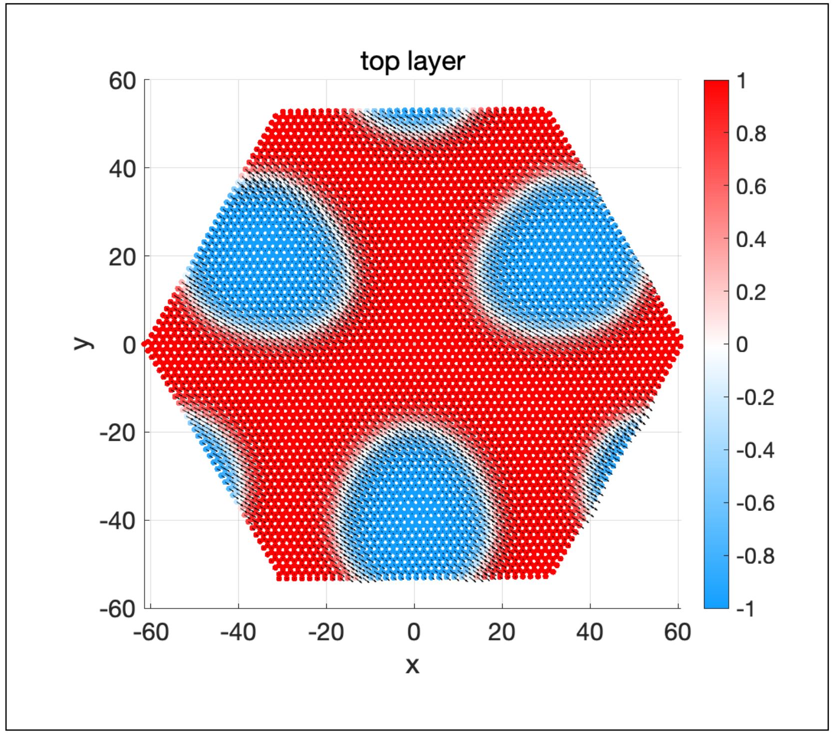


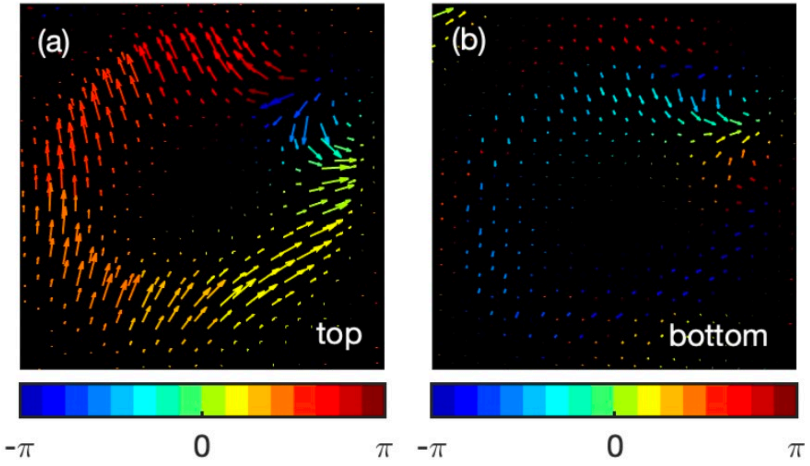


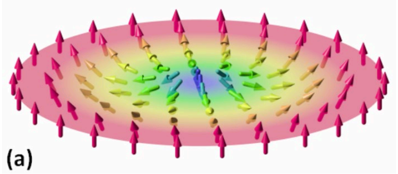
Skyrmion without DMI

➢ Skyrmions in moire superlattice









Standard recipe for skyrmion :

Exchange + DMI + Magnetic field

In twisted bilayer magnets :

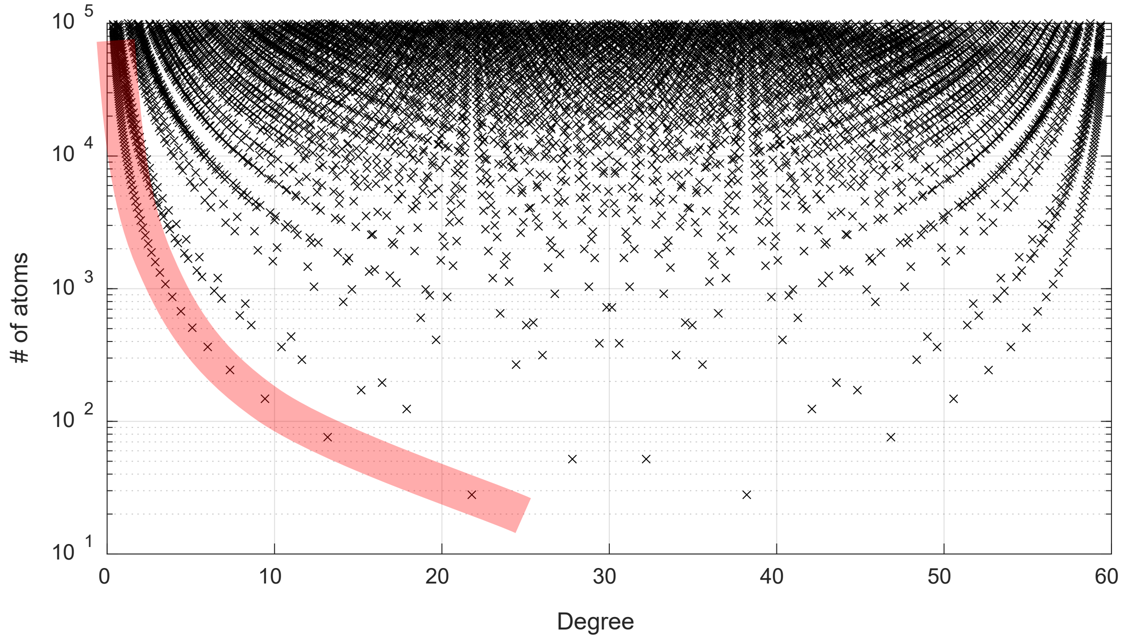
Exchange + Modulating interlayer coupling(sublattice breaking)

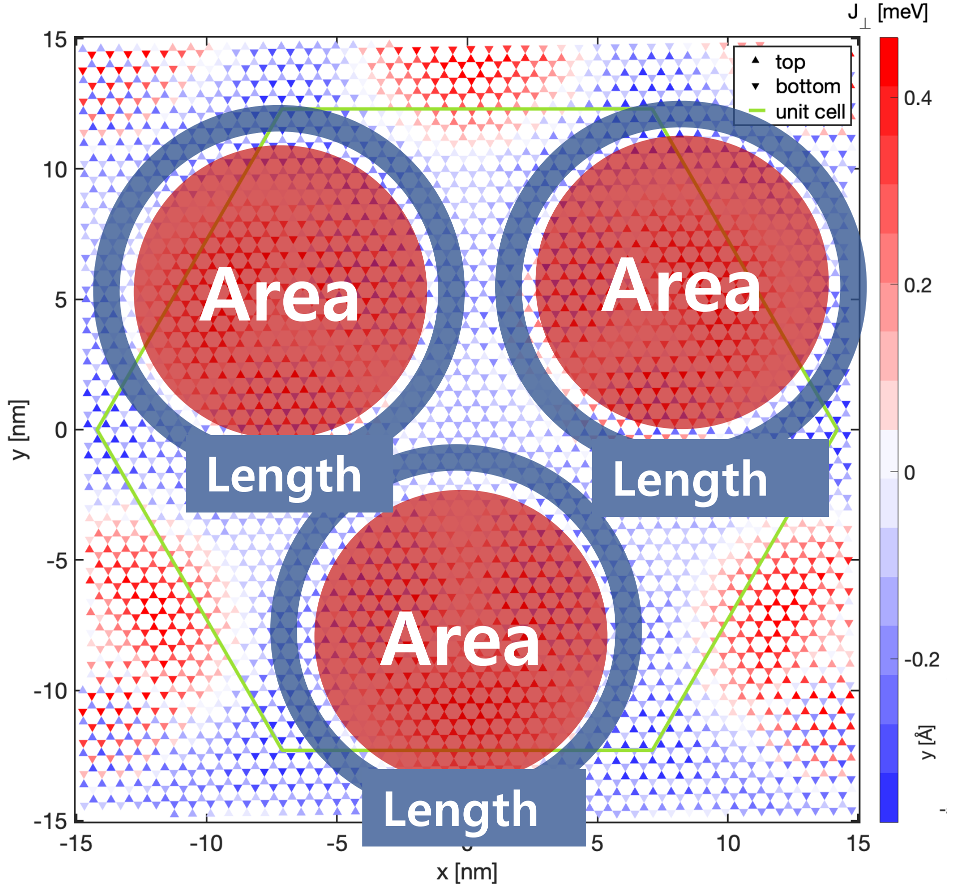
$$N = \int \vec{n} \cdot \left(\frac{\partial \vec{n}}{\partial x} \times \frac{\partial \vec{n}}{\partial y} \right) dA$$

Small-angle limit

research center theoretical physics of complex systems

Moire size as a function of angle





Central observation of moire pattern

"as $\theta \to 0$, moire size diverges"

(Interlayer coupling) X (Area) VS **(Intralayer coupling) X (Length)**

~Spin gradient **~Collinear order**

Magnetic phase transition

research center
theoretical physics of complex systems

➢ Landau theoretical description

Free energy functional:

$$F[\mathbf{n}_t,\mathbf{n}_b] = \sum_{l=t,b}\int d^2\mathbf{x}\left\{\frac{3a_0^2}{2}J[\nabla_{\mathbf{x}}\mathbf{n}_l(\mathbf{x})]^2 - D_z[n_l^z(\mathbf{n}_l)]^2\right\} + \int d^2\mathbf{x}\,\bar{J}_\perp\ \mathbf{n}_t(\mathbf{x})\cdot\mathbf{n}_b(\mathbf{x}),$$

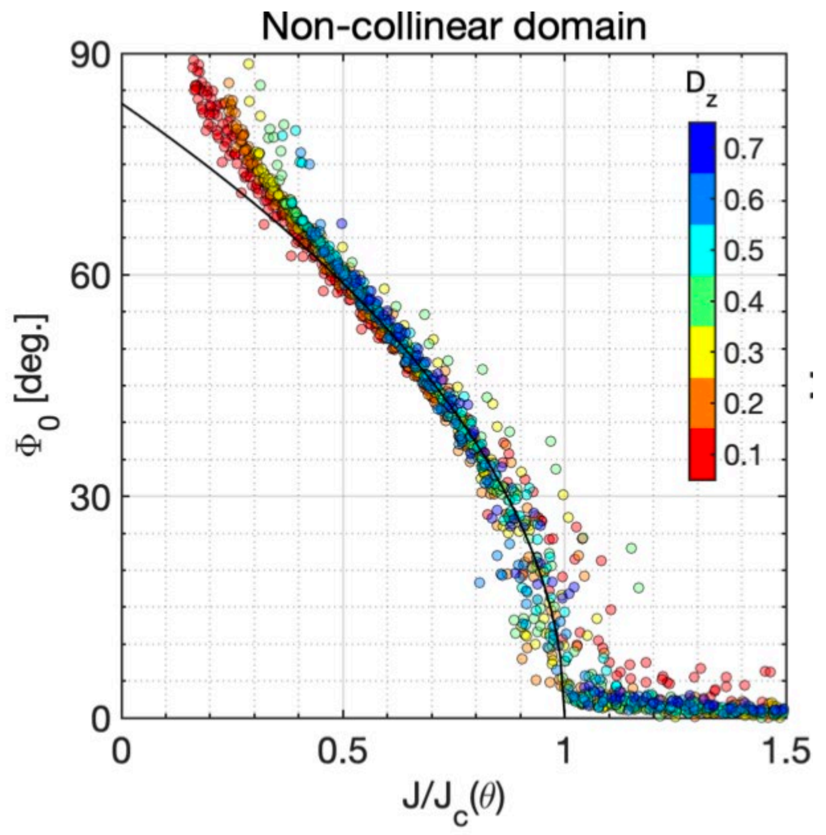
Continuum Ansatz:

$$\mathbf{n}_t = \left(\sin\Phi_t, 0, \cos\Phi_t\right),$$
$$\mathbf{n}_b = \left(-\sin\Phi_t, 0, \cos\Phi_t\right),$$

Expansion:

$$F[\Phi_0] = N_{\rm ncd}(\theta)(\bar{J}_\perp - 2D_z) + \frac{a}{2}[J - J_c(\theta)]\Phi_0^2 + \frac{b}{4}J_c(\theta)\Phi_0^4 + \mathcal{O}(\Phi_0^6)$$

$$\Phi_0 = \pm\sqrt{(a/b)[1 - J/J_c(\theta)]}$$



Conventional second order phase transitions as a function of tilt angle

Magnetic phase transition II

research center
theoretical physics of complex systems

➢ Landau theoretical description

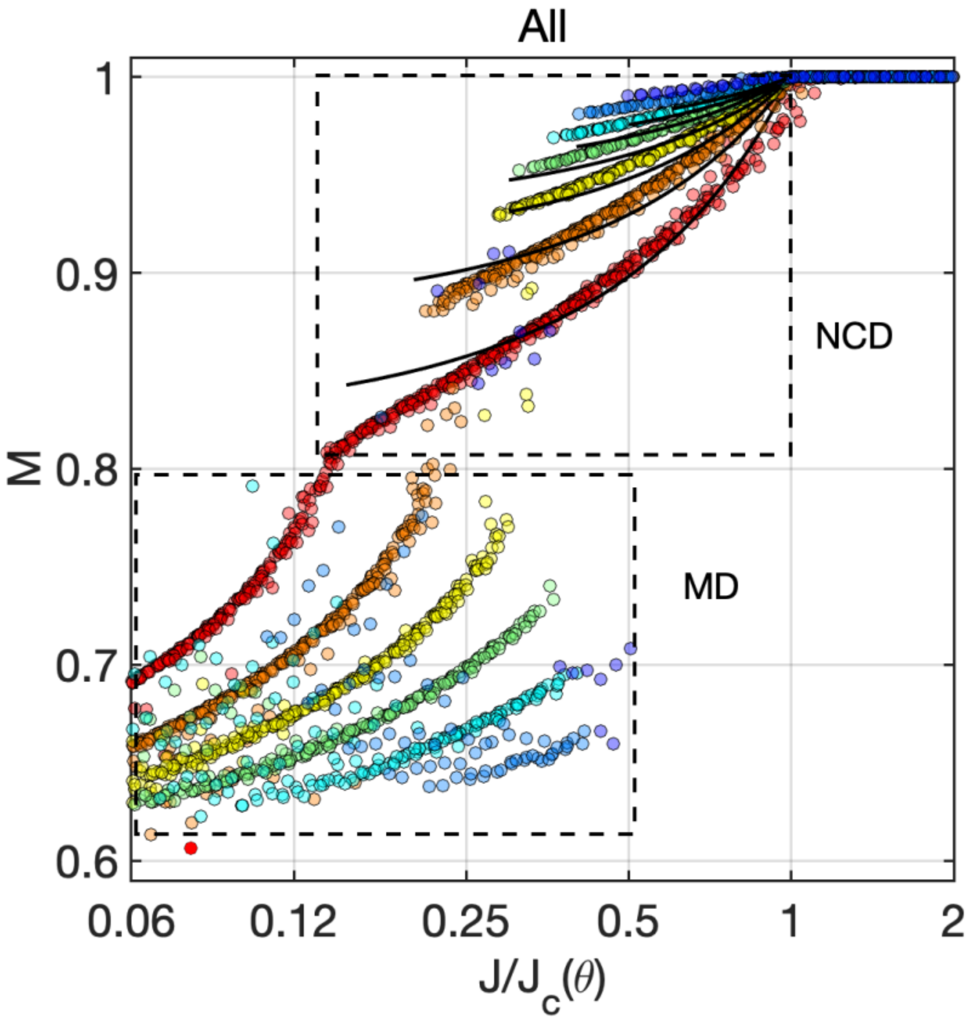
Continuum Ansatz:

$$\mathbf{n}_t = \left(\sin\Phi_\mathrm{t}, 0, \cos\Phi_\mathrm{t}\right), \qquad \mathbf{n}_t = \left(\sin\Phi_\mathrm{t}, 0, \cos\Phi_\mathrm{t}\right),$$
$$\mathbf{n}_b = \left(-\sin\Phi_\mathrm{t}, 0, \cos\Phi_\mathrm{t}\right), \qquad \mathbf{n}_b = \left(0, 0, 0\right),$$

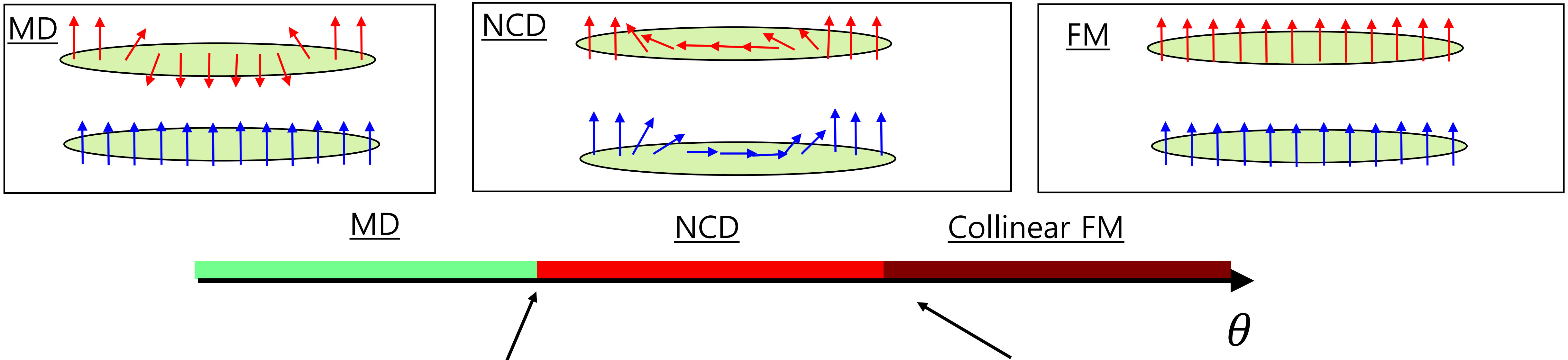
Expansion:

$$F[\Phi_0] = N_{\mathrm{ncd}}(\theta)(\bar{J}_\perp - 2D_z) + \frac{a}{2}[J - J_c(\theta)]\Phi_0^2 + \frac{b}{4}J_c(\theta)\Phi_0^4 + \mathcal{O}(\Phi_0^6)$$

$$F[l] = \frac{aJ\pi^2}{4}\left(\frac{2R}{l} - 1\right) - D_z N_{md}(\theta)\left[1 + \frac{1}{2}\left(1 - \frac{l}{R}\right)^2\right] - \bar{J}_\perp N_{md}(\theta)\left[\left(1 - \frac{l}{R}\right)^2 - \frac{4}{\pi^2}\left(\frac{l}{R}\right)^2\right], \qquad (4.6)$$



Competing scales of moire magnet



Second order phase transition

(Interlayer coupling) X (Area)
~Spin gradient

VS

(Intralayer coupling) X (Length)
~Collinear order

First order phase transition

(Interlayer coupling) X (Area)
~NC2

VS

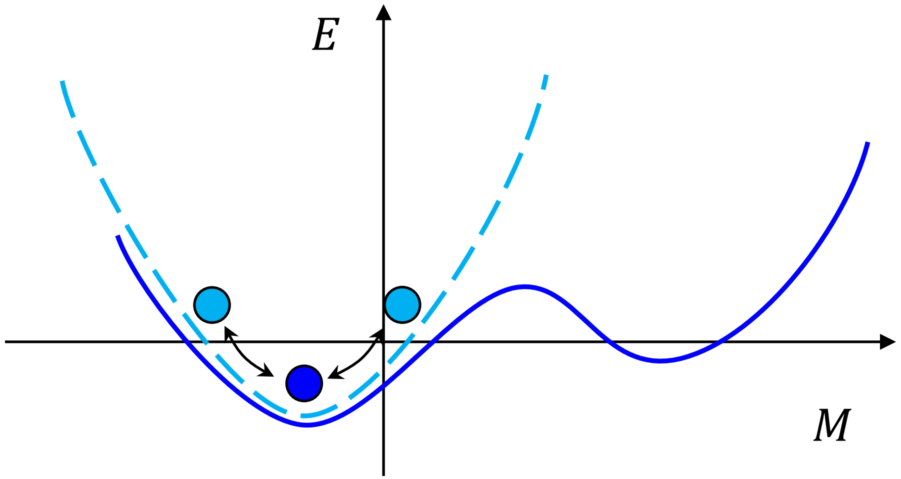
(Single ion anisotropy) X (Area)
~NC1

Outline

- Magnetic phases
- Phase transitions
- Excitations

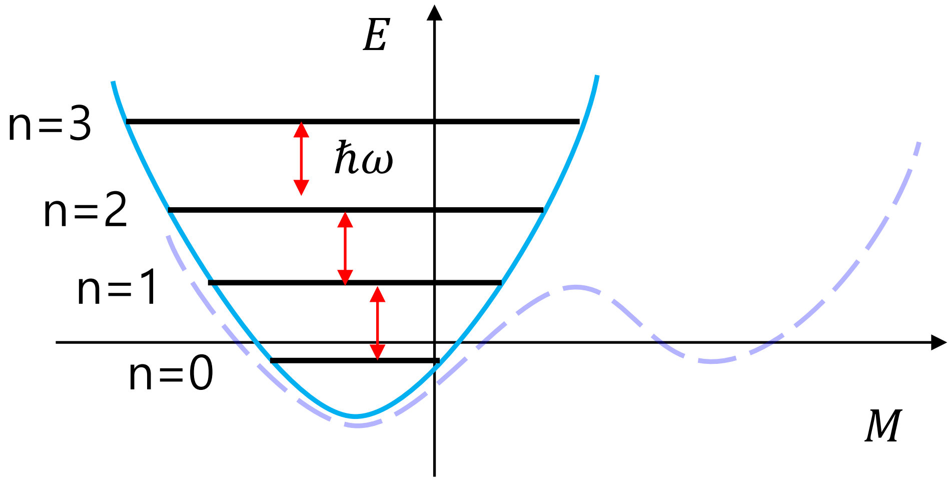
Holestein-Primakoff Boson

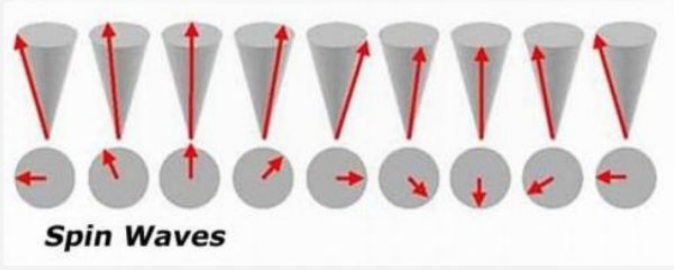
- Global magnetic ground state



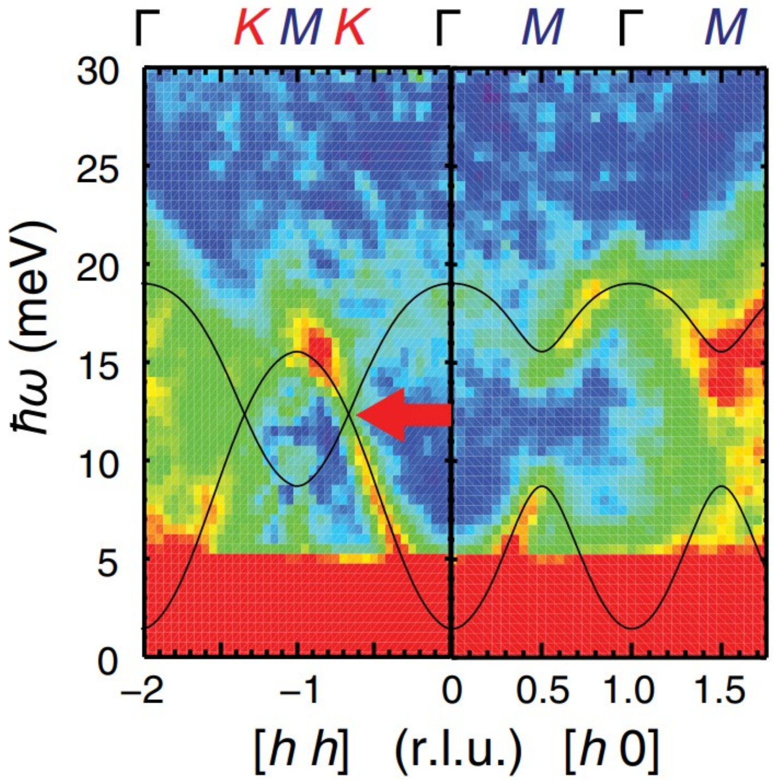
$$
\begin{aligned}
S^{+} &= \hbar\sqrt{2S}a^{+}\sqrt{1-\frac{a^{+}a}{2S}}\,, \\
S^{-} &= \hbar\sqrt{2S}\sqrt{1-\frac{a^{+}a}{2S}}\,a\,, \\
S^{z} &= \hbar(a^{+}a-S)\,,
\end{aligned}
$$

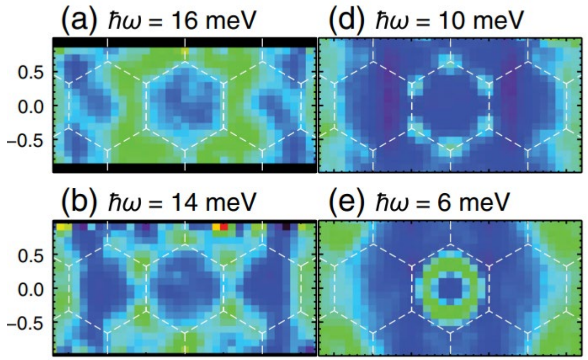
- Local harmonic oscillator

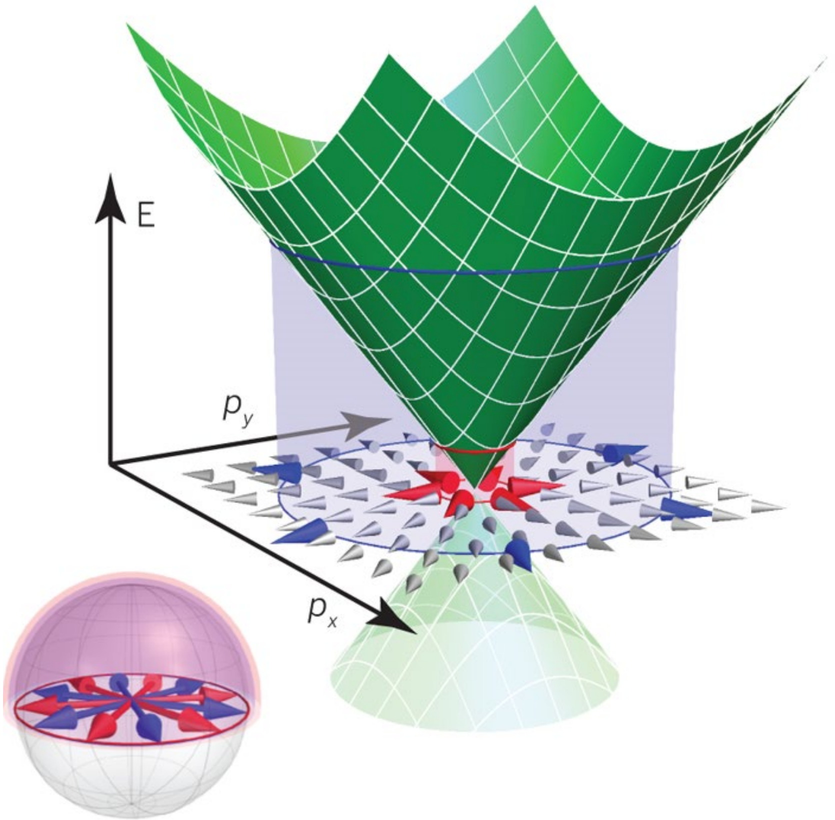




Dirac magnons







Dirac magnons are protected by coexistence of the following three symmetries.

- **U(1)c symmetry**
  (Collinearity)
- **U(1)v symmetry**
  (Valley decoupling)
- **C2z symmetry**
  (Lateral shift)

L Chen et al. PRX (2018)

Park et al. PRB (2021)

Topological magnons

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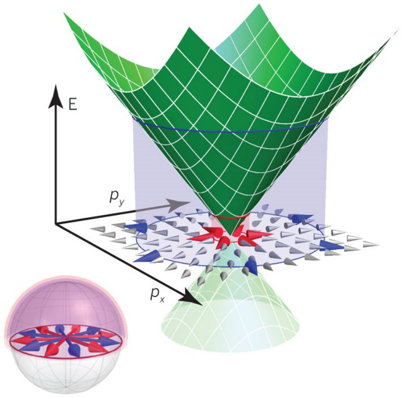
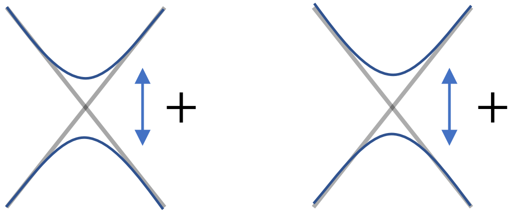
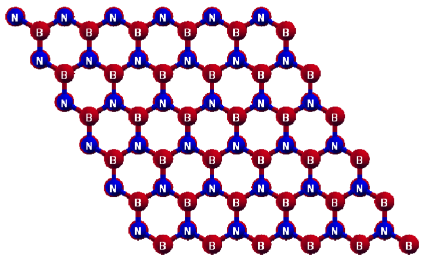
theoretical physics of complex systems

➢ $\{U(1)_c, U(1)_v, C_{2z}\}$ symmetry

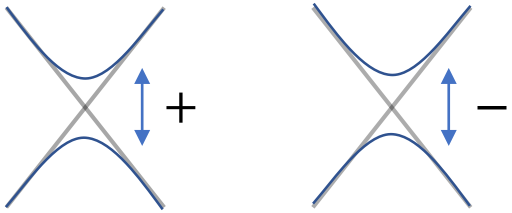


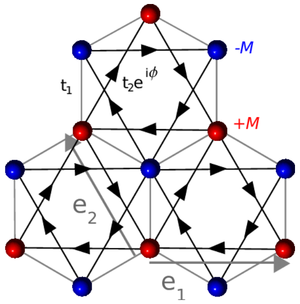
➢ C_{2z} -breaking

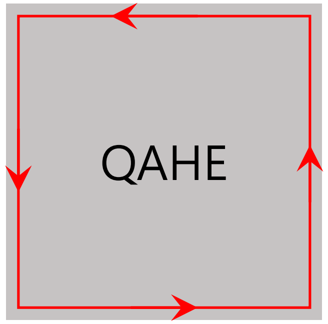




➢ SO(3) breaking
Spin-space group
(DMI)

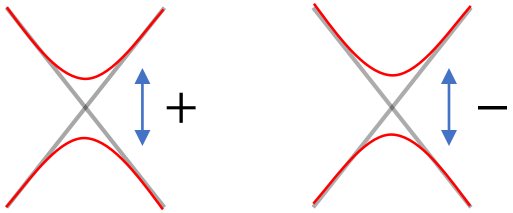




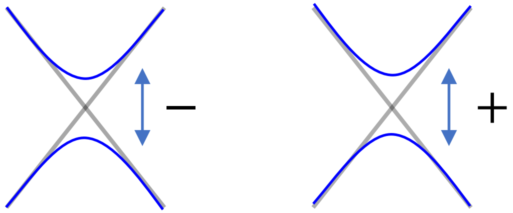


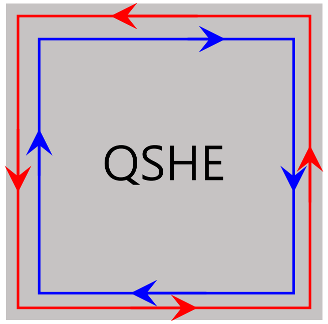
➢ T-preserving
(Spin-orbit coupling)

Spin-up



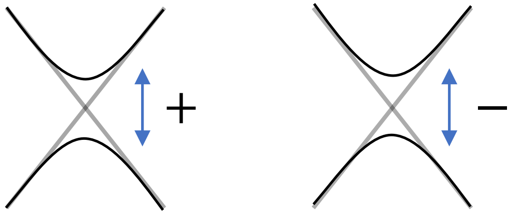
Spin-down



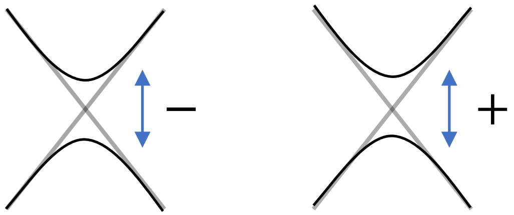


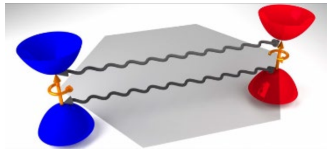
➢ $U(1)_v$ -breaking
(Interlayer coupling)

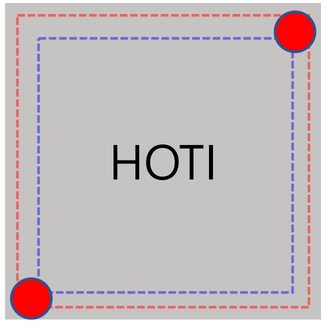
Top-layer



Bottom-layer



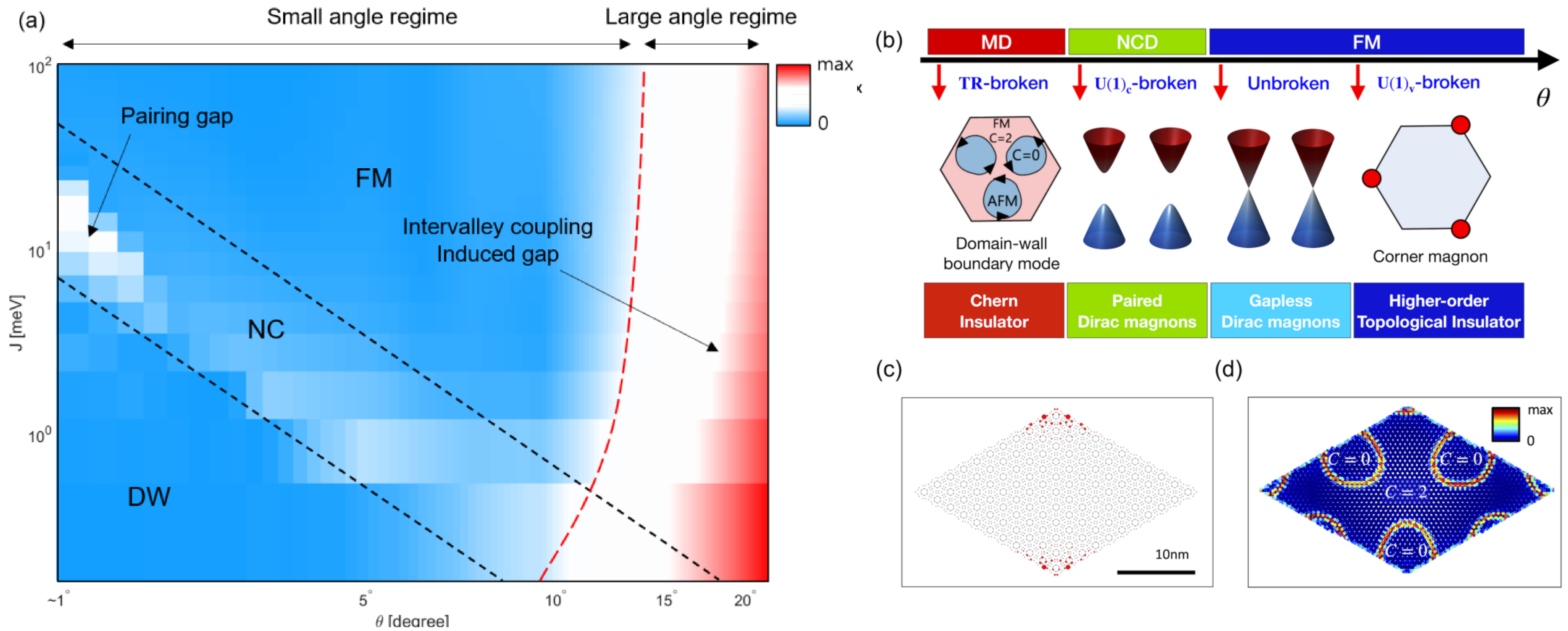




MJP, Youngkuk Kim, Gil Young Cho, SungBin Lee, PRL (2019)

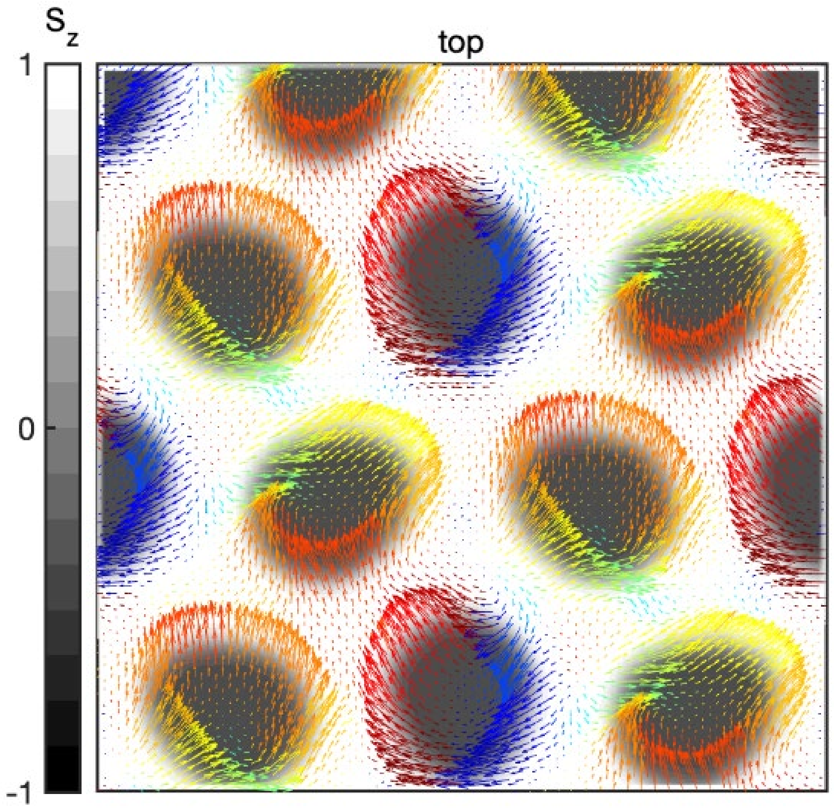
Magnon phase diagram

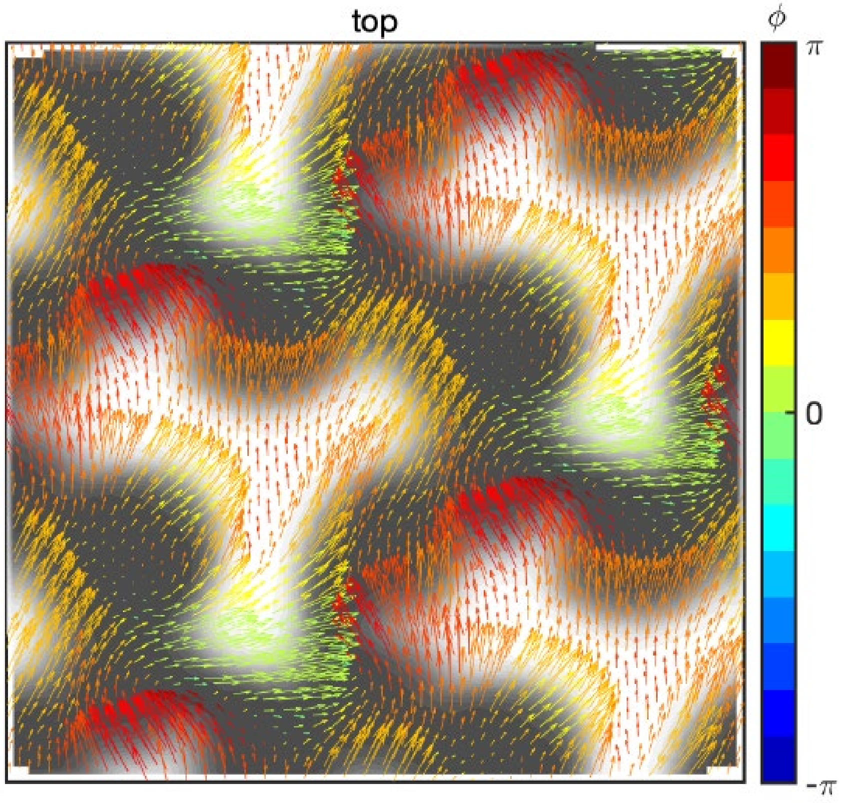
Different magnon gaps are realized as a function of twist angles.

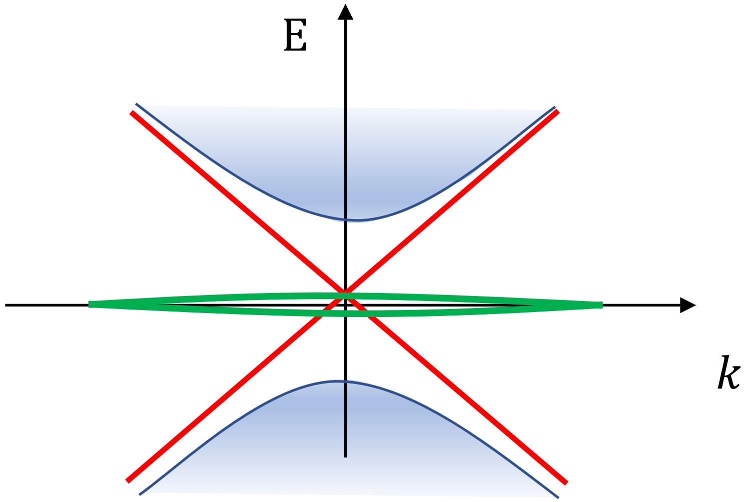


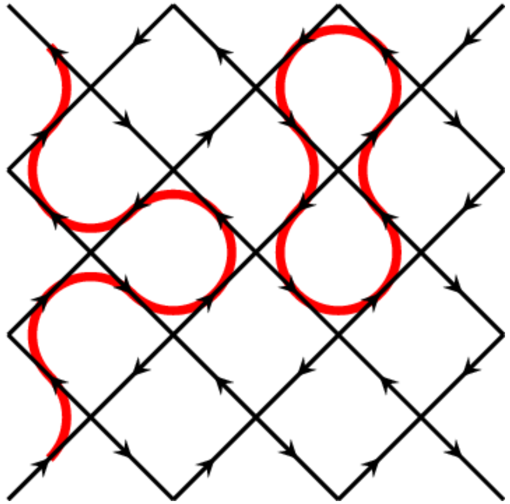
Chalker-Coddington network

- **Localized edge (Large angle)**
- **Delocalized edge (Small angle)**



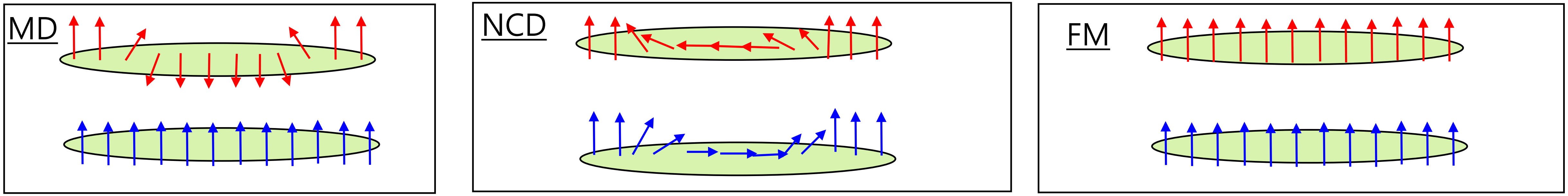






Overall Structure of moire magnets

➢ Magnetic phases



➢ Phase transitions

First order phase transition

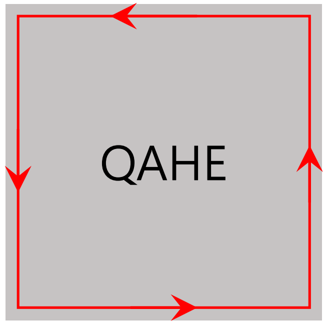
(Interlayer coupling) X (Area) ~NC2 VS (Single ion anisotropy) X (Area) ~NC1

Second order phase transition

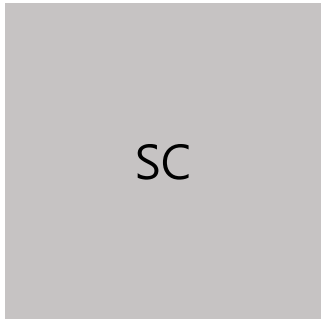
(Interlayer coupling) X (Area) ~Spin gradient VS (Intralayer coupling) X (Length) ~Collinear order

➢ Excitations

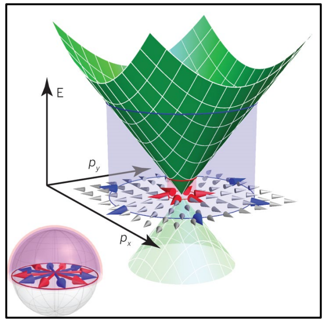
T-broken



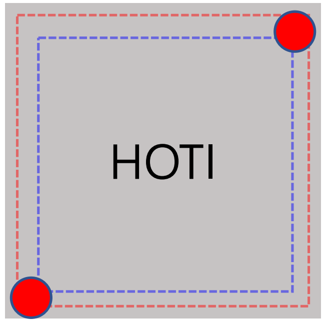
U(1)c broken



Three-symmetry preserved



U(1)v broken

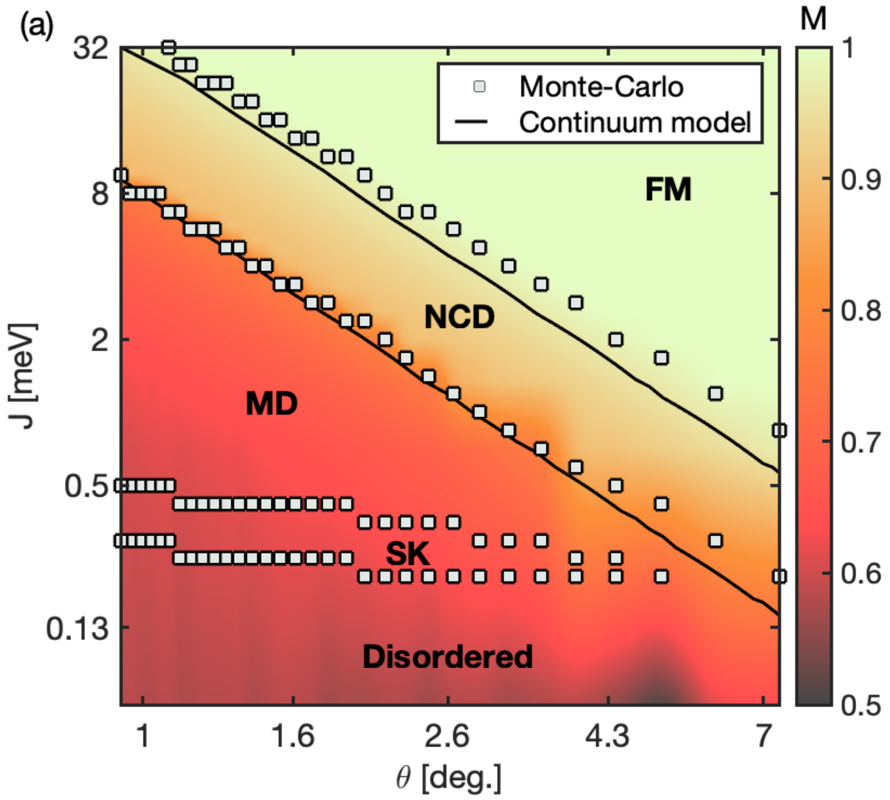


Future Research Directions

research center
theoretical physics of complex systems

We extend theory of moire magnetism to various magnetic materials

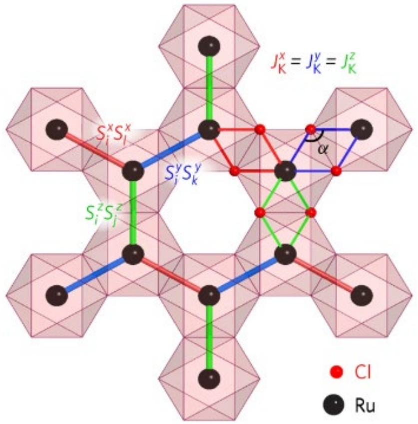
➢ Development of Extensive Monte-Carlo methods

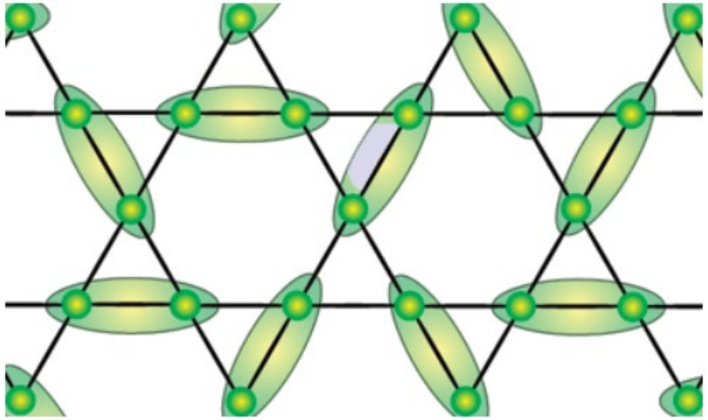


arXiv:2206.05264 (2022)

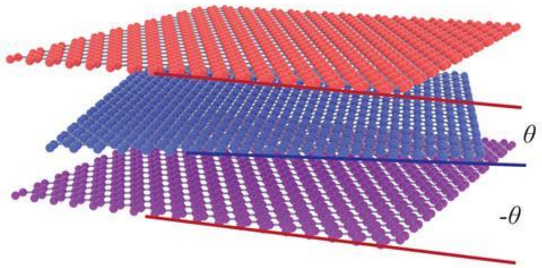
➢ Various magnetic materials :

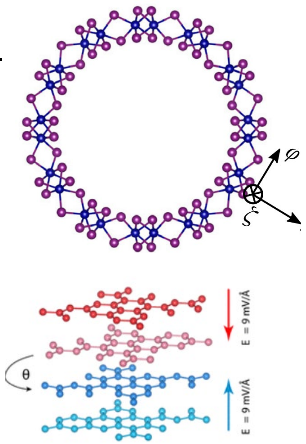
Spin liquid α-$RuCl_3$ Magnetic TMDCs

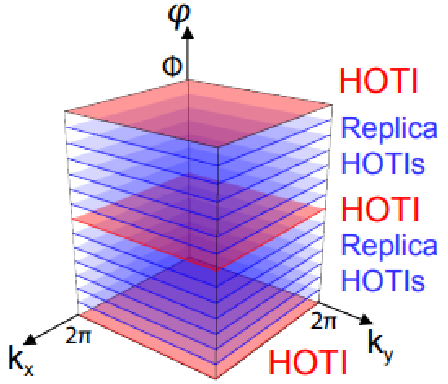




➢ Controlling geometry:

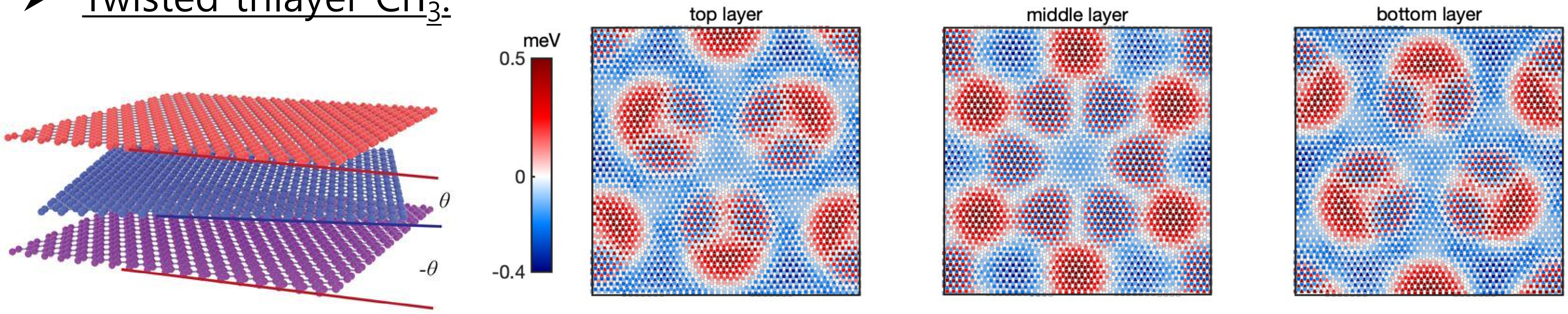




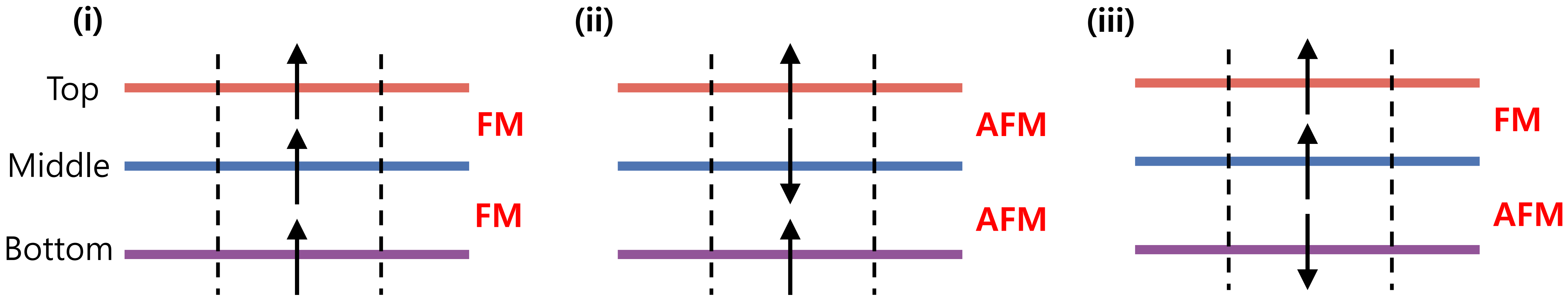


Twisted trilayer Magnet

- Twisted trilayer CrI_3:



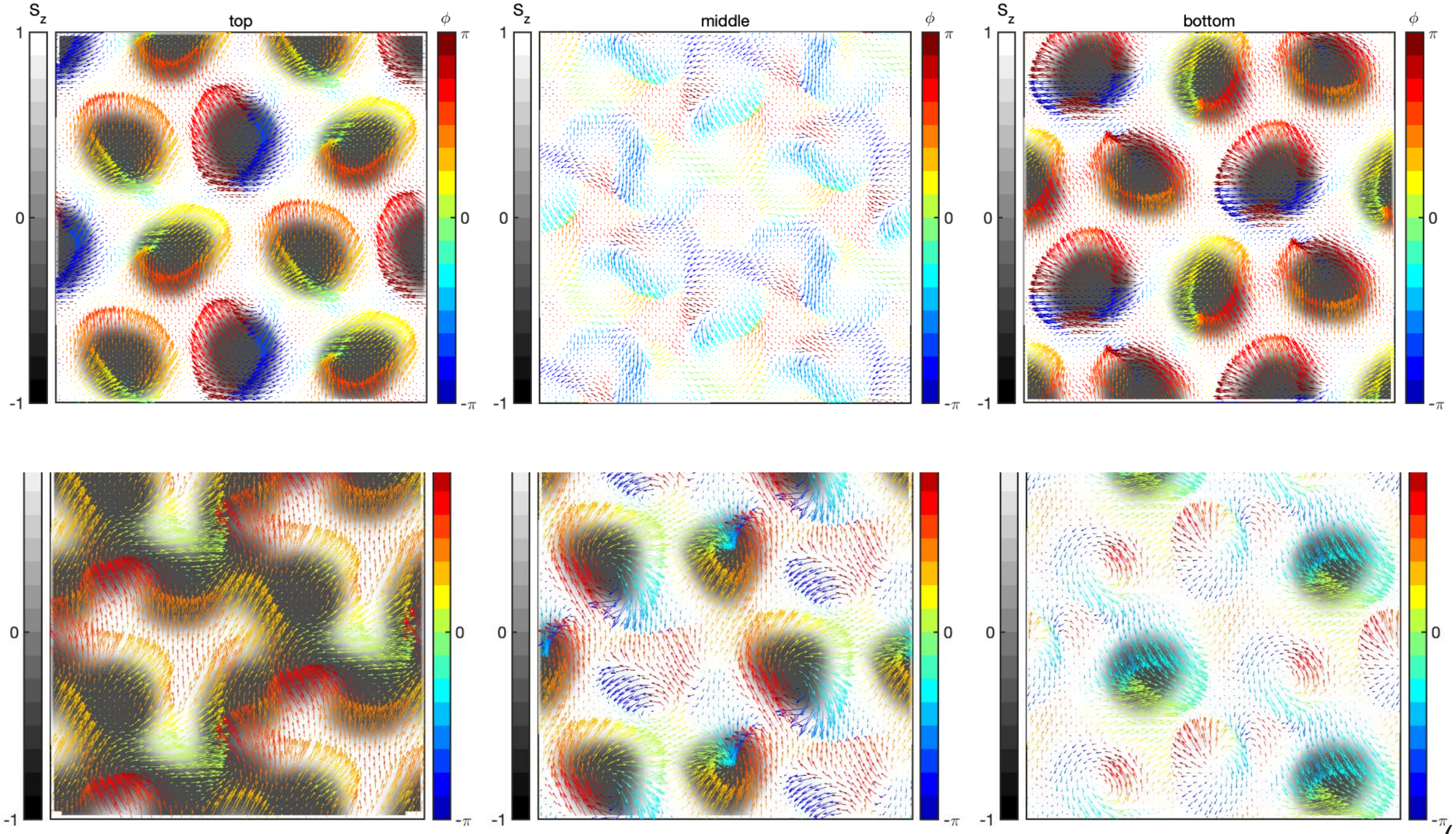
- Stacking dependent couplings



(In preparation)

Twisted triple layer

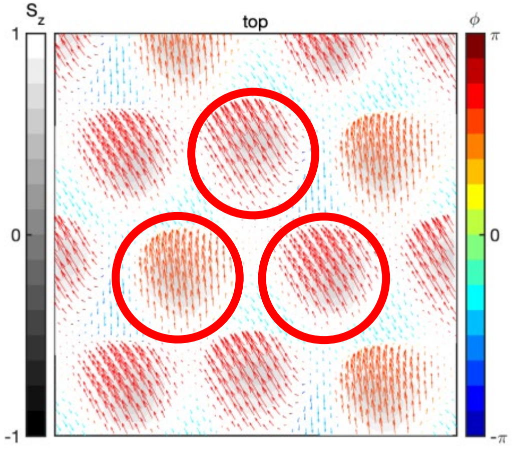
- Controlling geometry:

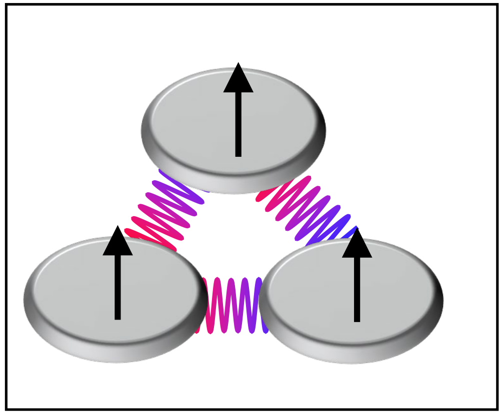


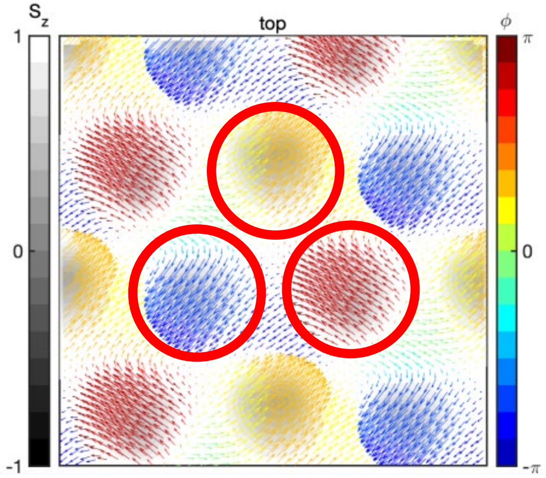
(In preparation)

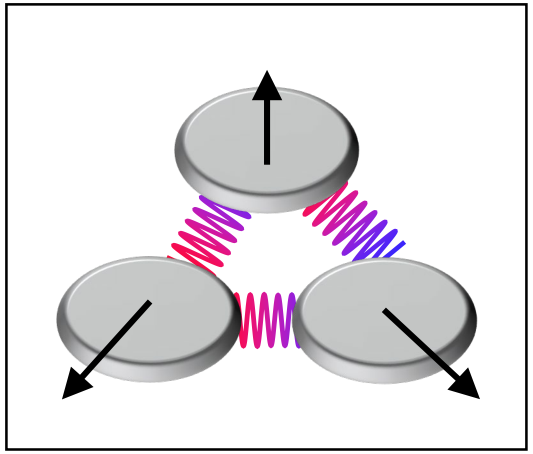
Twisted triple layer

- C3 symmetry breaking order:



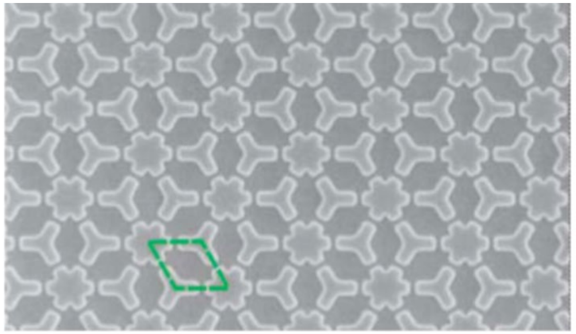


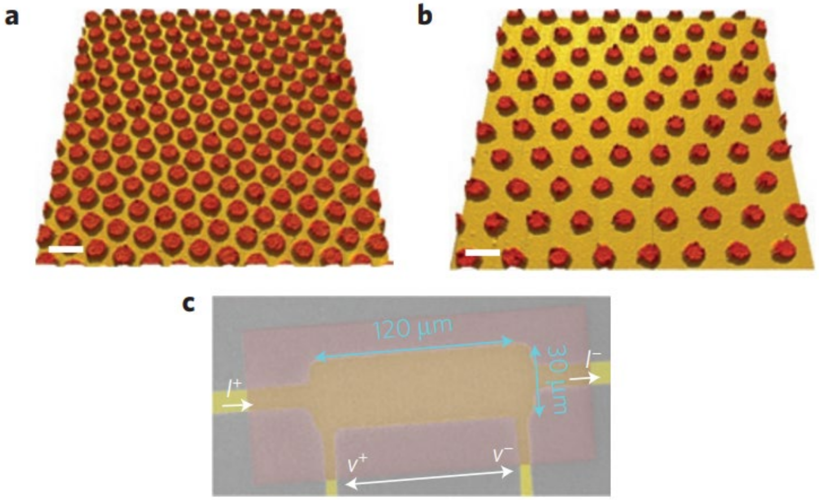


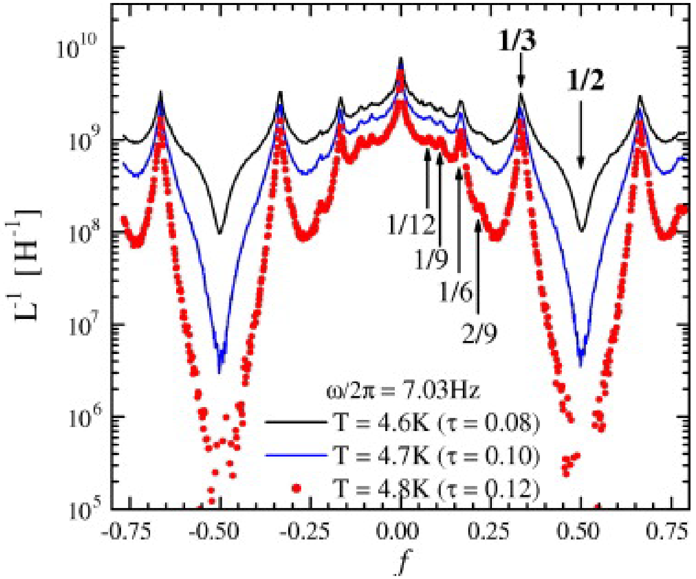


- Analogy with Josephson junction network:

$$H = -J \sum_{p} \sum_{\langle ij \rangle \in p} \cos(\theta_i - \theta_j)$$







Eley et al. Nature Physics (2011)

Summary

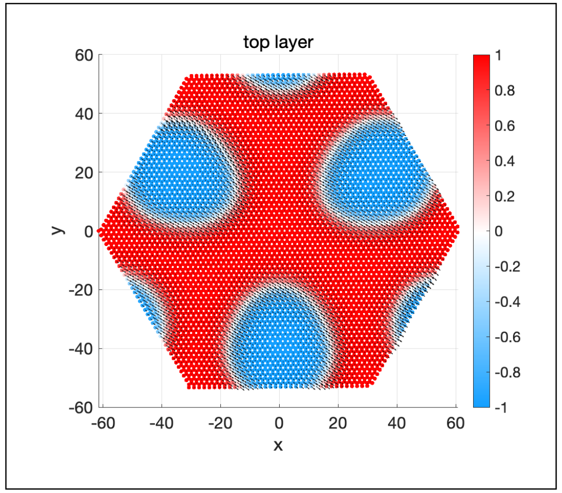
First order phase transition

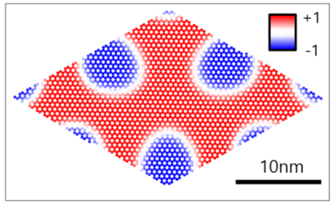
(Interlayer coupling) ~NC2 VS (Single ion anisotropy) ~NC1

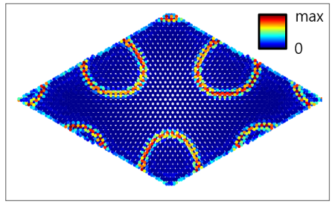
Second order phase transition

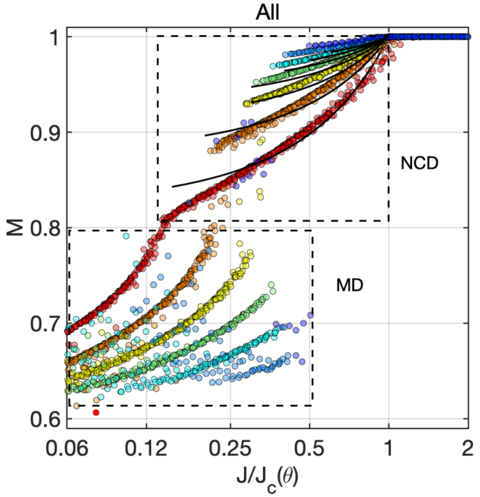
(Interlayer coupling) X (Area) ~Spin gradient VS (Intralayer coupling) X (Length) ~Collinear order

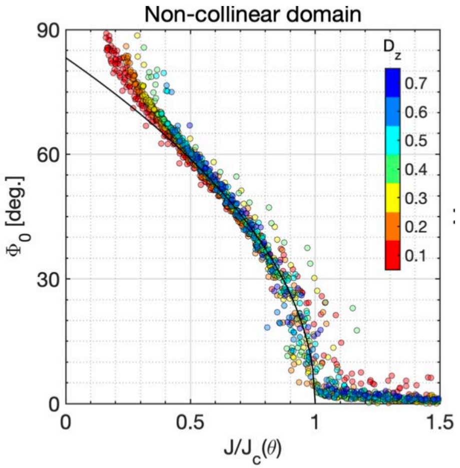
Magnetic domains



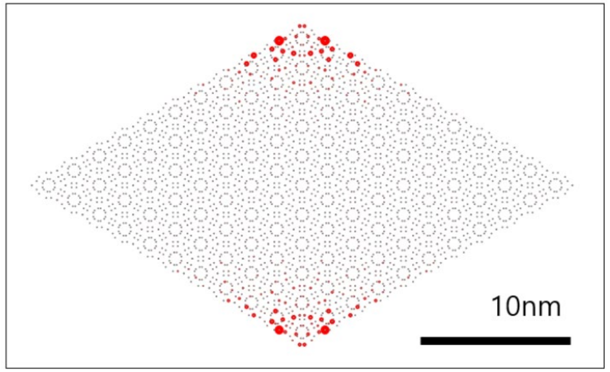




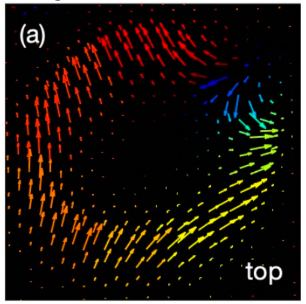


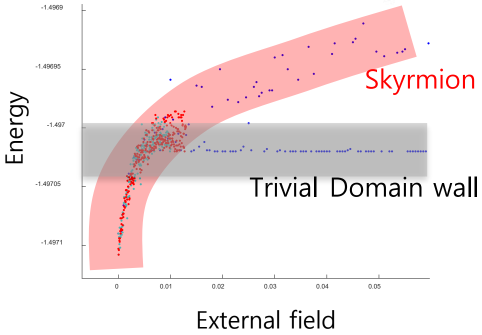


Higher-order topological magnons



Skyrmions





Topological magnon network