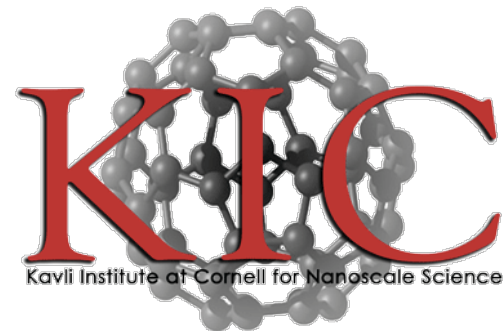
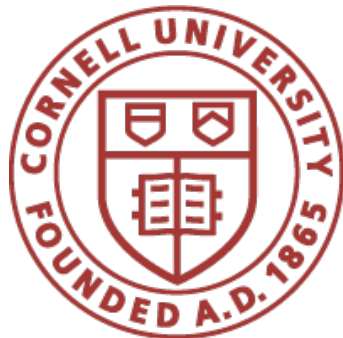


Probing and controlling spins in 2D CrI₃

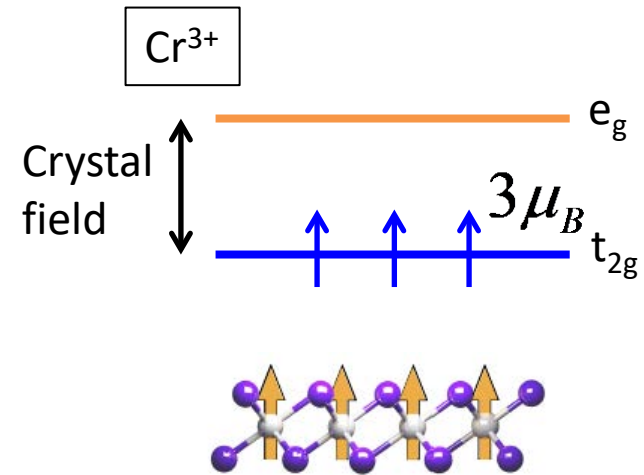
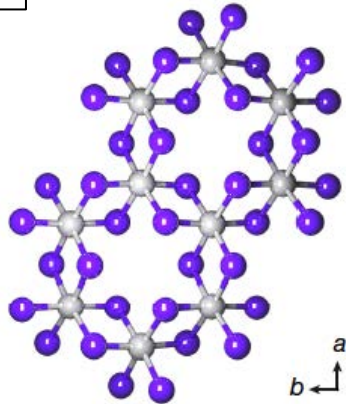
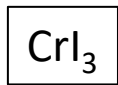
Kin Fai Mak

Departments of Physics and Applied & Engineering Physics

Kavli Institute at Cornell for Nanoscale Science

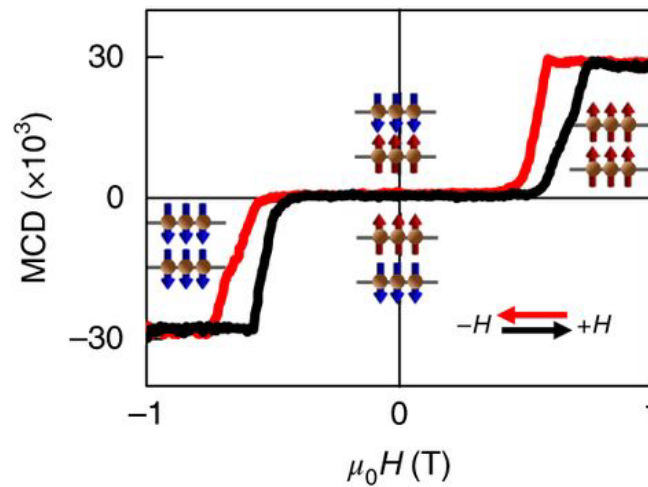
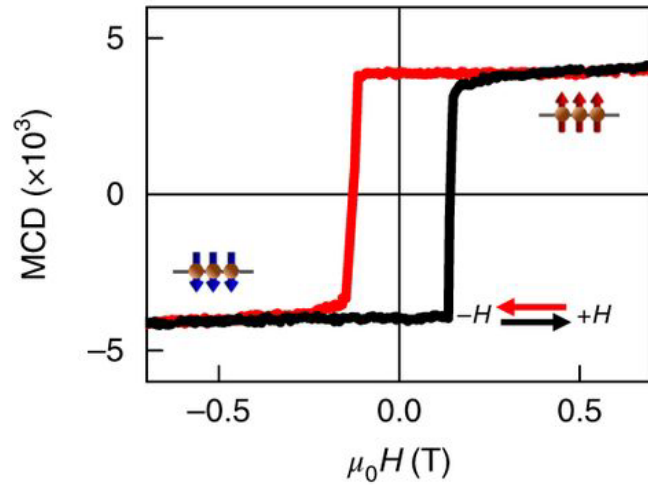


Transition metal trihalides



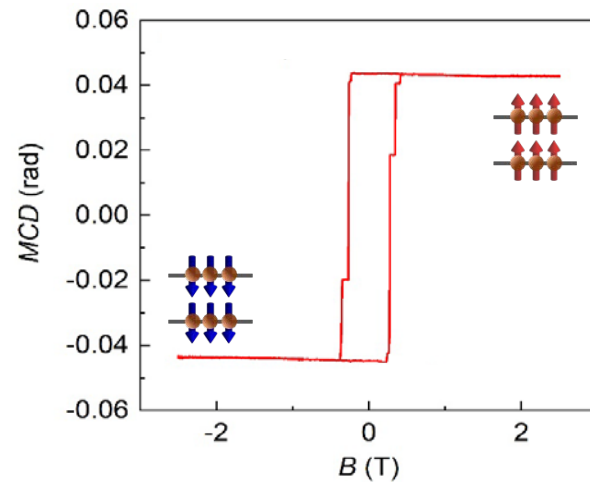
Effective 2D Ising magnet

Layer- and structure-dependent magnetism



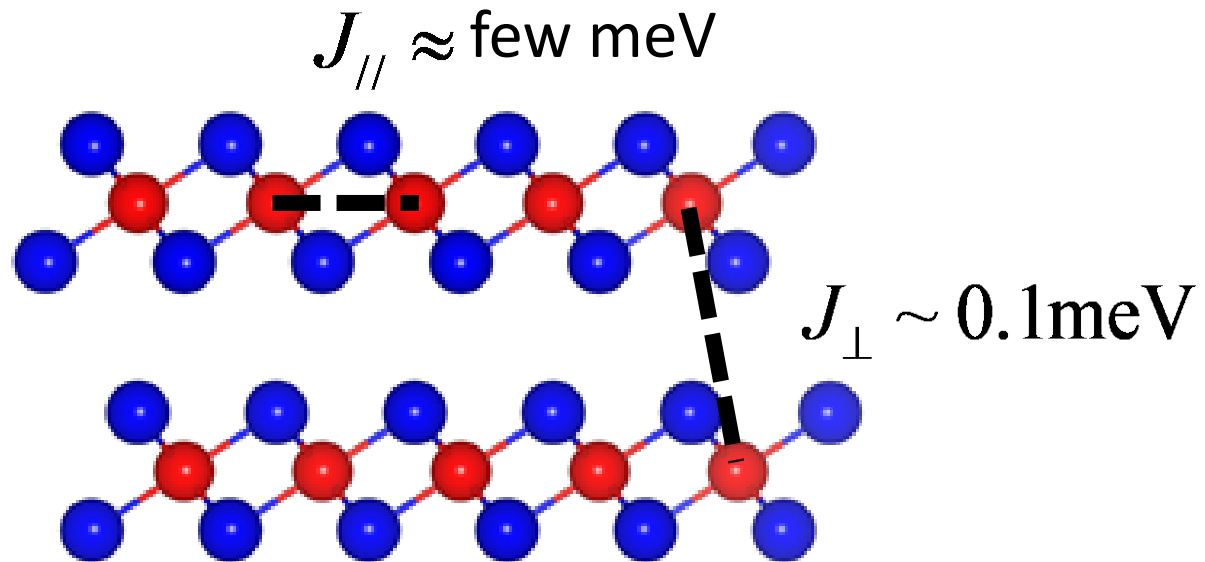
Monoclinic (AF)

- Huang et al. Nature (2017)
- Jiang et al. Nature Nano. (2018)
- Li et al. Nature Mater. (2019)
- Song et al. Nature Mater. (2019)



Rhombohedral (FM)

Weak interlayer exchange interaction



Outline

- Control of magnetism by electric fields
- Directly see critical spin fluctuations in 2D
- Mechanical probes of 2D magnetism

Jiang, Shan, Mak, Nat. Mater. (2018)

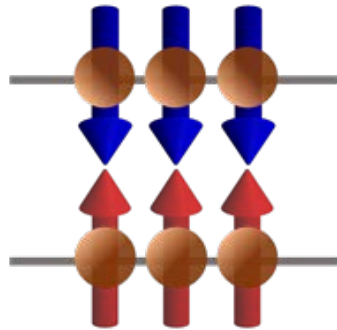
Jiang, Li, Wang, Shan, Mak, Nat. Nano. (2018)

Jin, Tao, Kang, Mak, Shan, Nature Mater. (2020)

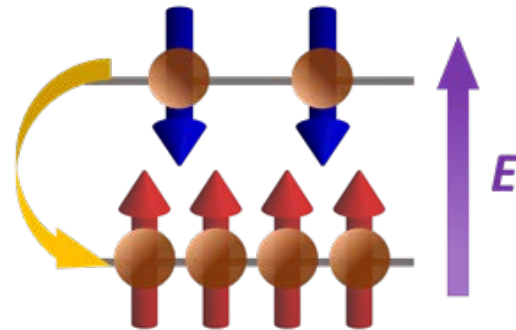
Jiang, Xie, Shan, Mak, Nature Mater. (2020)

Magnetoelectric effect

2-layer CrI₃



*Broken inversion and
time-reversal symmetries*

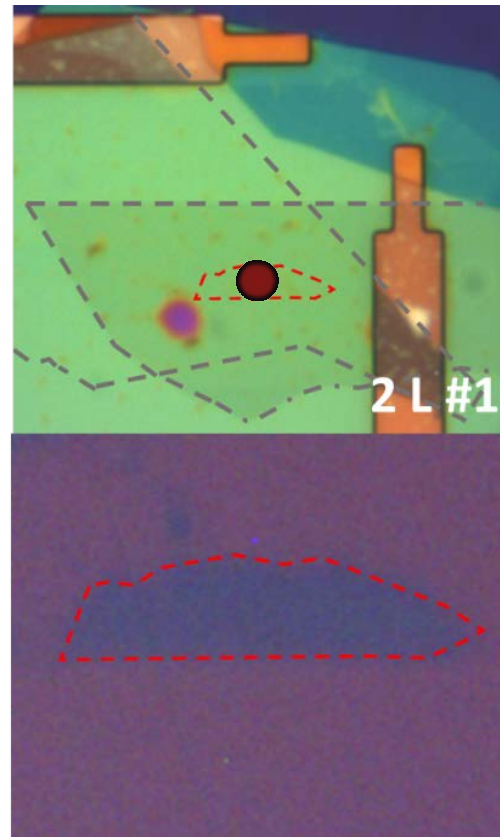
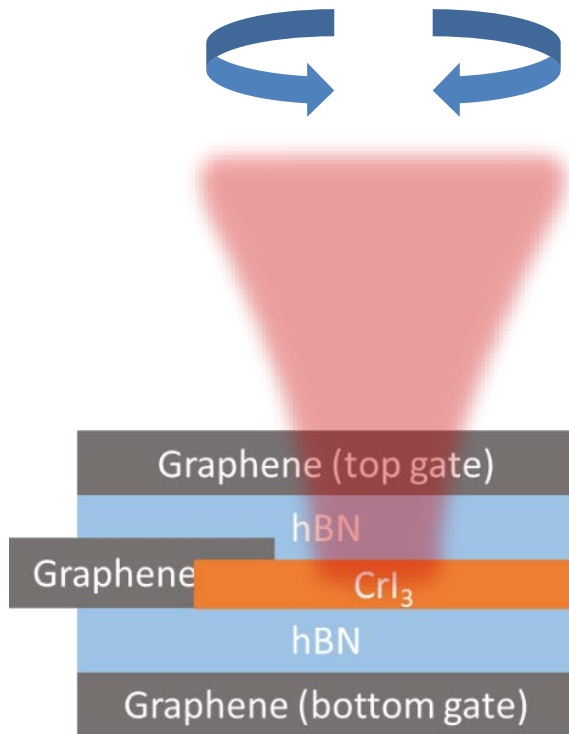


Magnetoelectric effect
from *electron transfer*



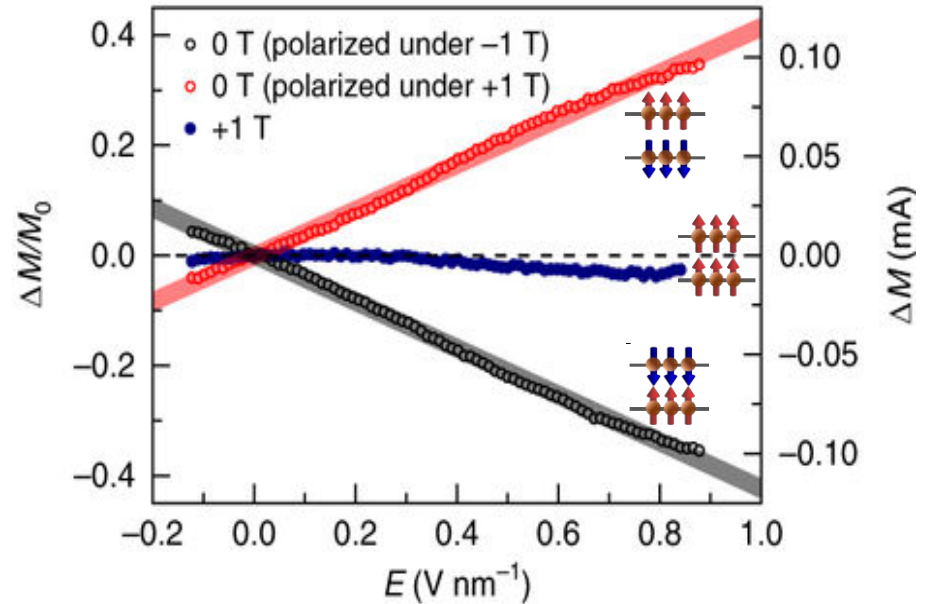
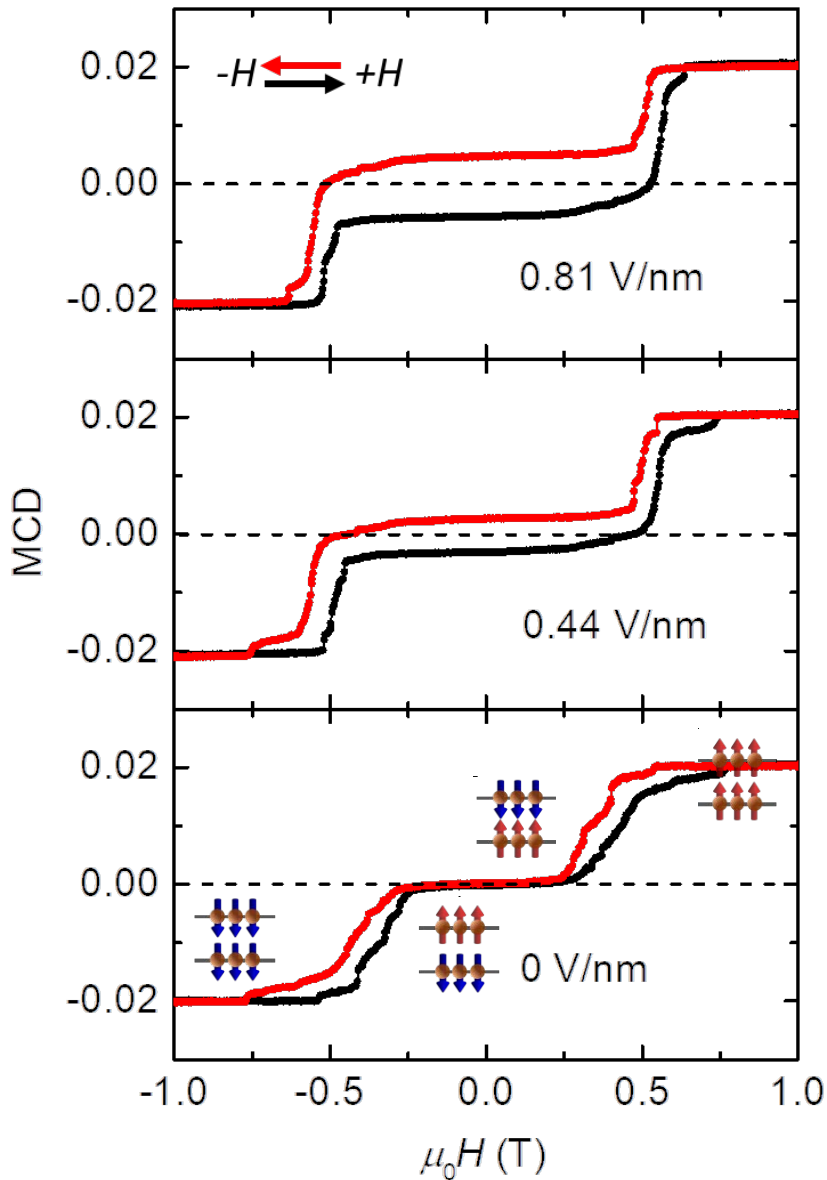
Shengwei Jiang

Experimental approach

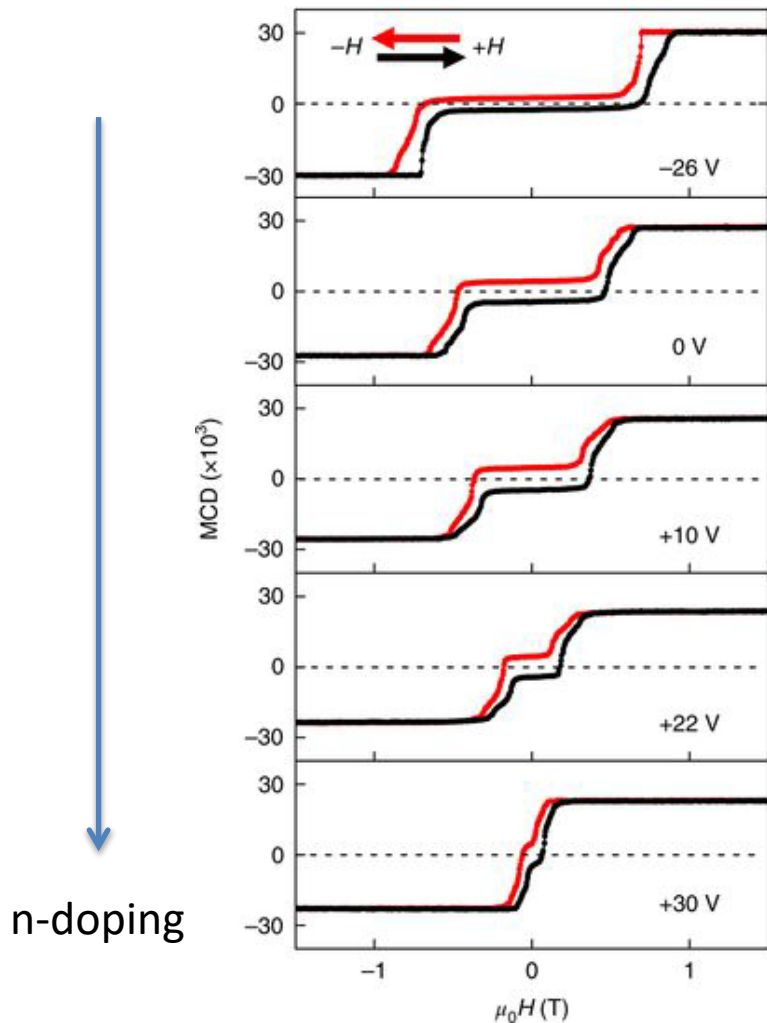


Magnetic circular dichroism
Signal proportional to magnetization

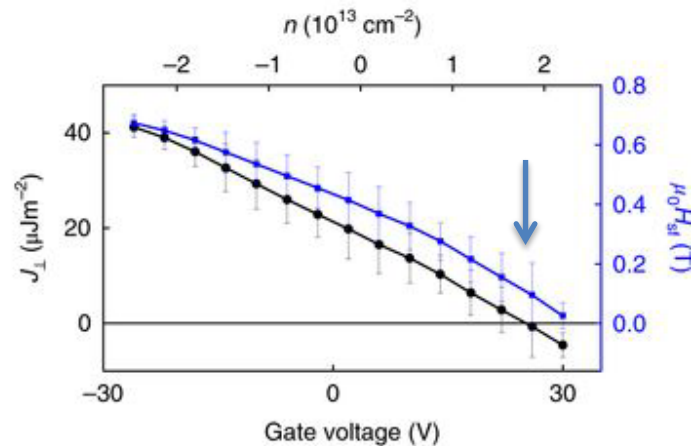
Electrical control of magnetism



Doping control of magnetism in 2lay CrI₃



Gate-induced transition to an FM!



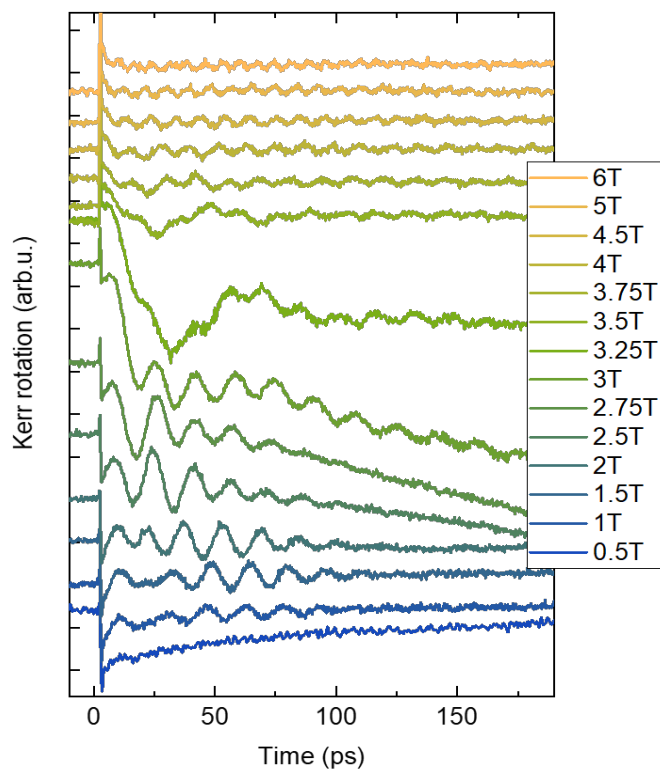
Exchange inverse transition

Gate-tunable exchange interaction



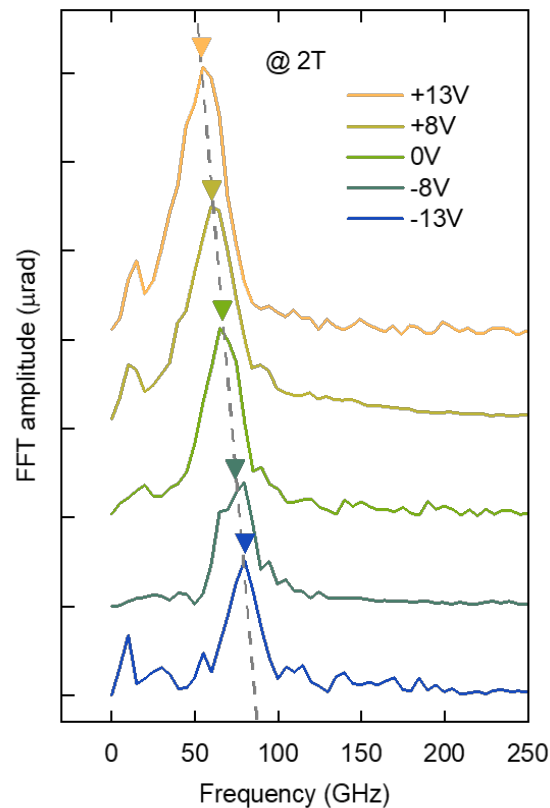
Gate tunable THz spin dynamics

Xiaoxiao Zhang



Initiation of coherent spin precessions
by pulsed laser pumping

Antiferromagnetic resonance

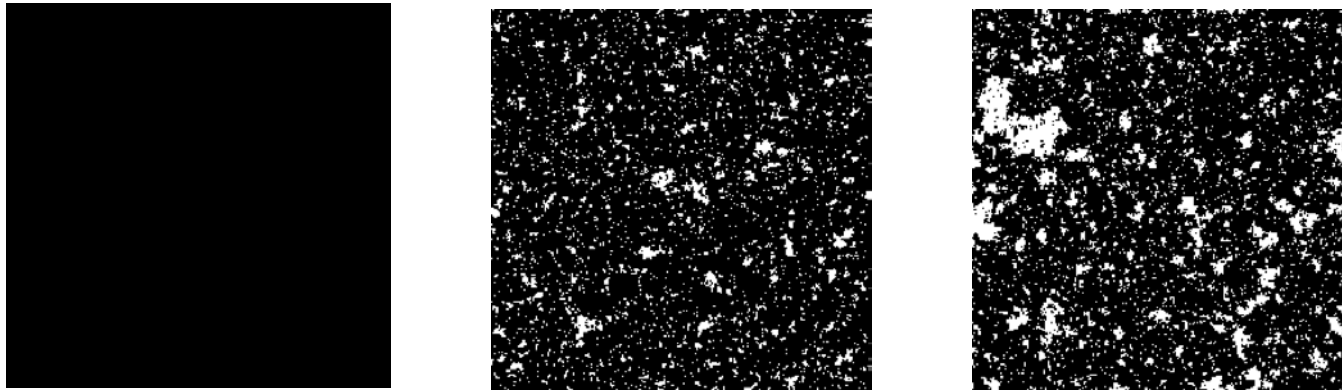


Zhang, Mak, Shan et al. Nature Mater. (2020)

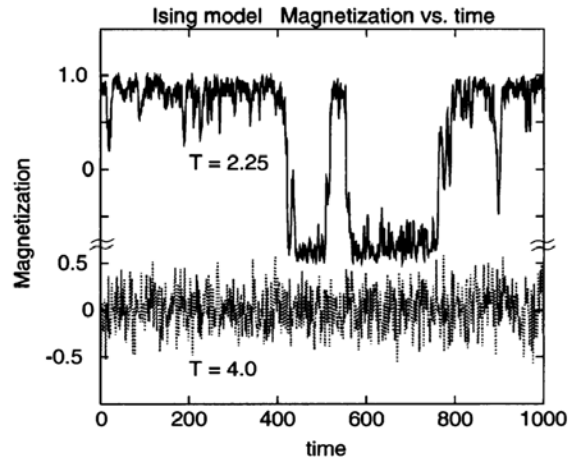
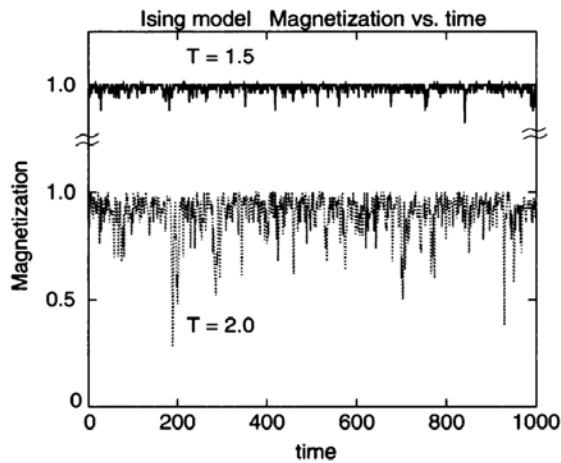
Outline

- Control of magnetism by electric fields
- **Directly see critical spin fluctuations in 2D**
- Mechanical probes of 2D magnetism

Critical spin fluctuations in 2D Ising model



$T \ll T_c$ \longrightarrow $T \sim T_c$



Divergent correlation
time and length

Imaging a single layer of spins

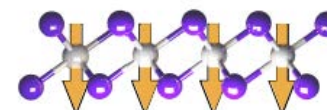
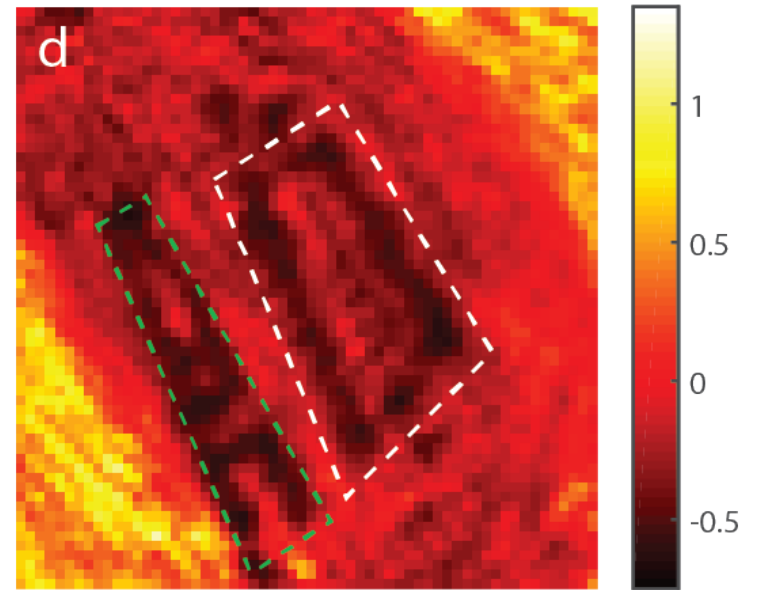
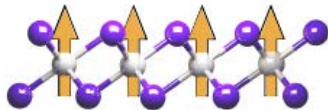
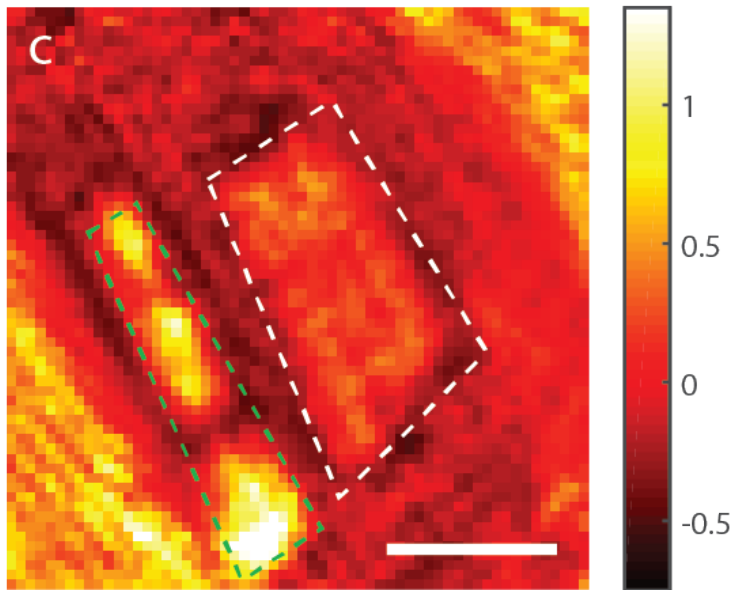


Chenhao Jin



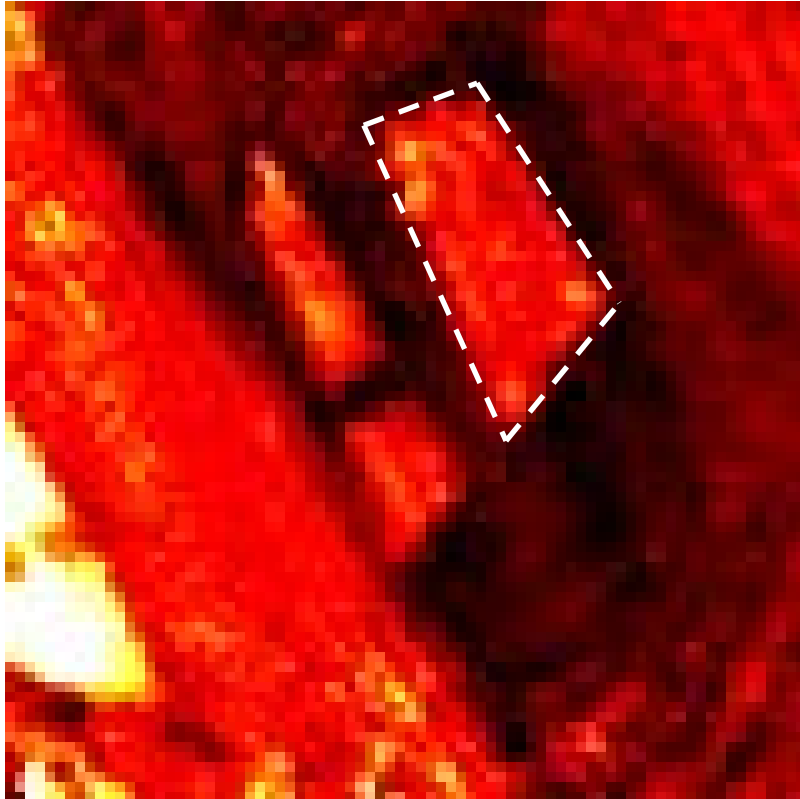
Zui Tao

Magneto-optical contrast

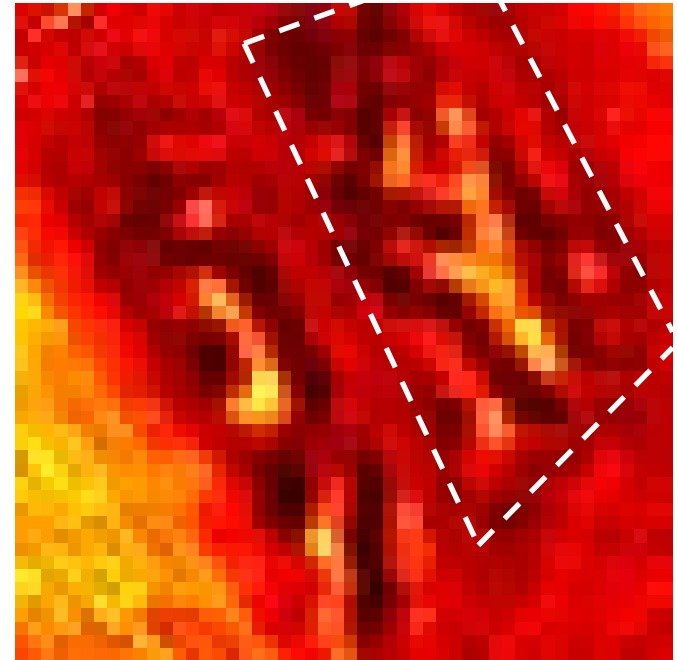


60% contrast for a single layer of spins!
Allow one shot imaging in 10 ms

Direct imaging of critical fluctuations



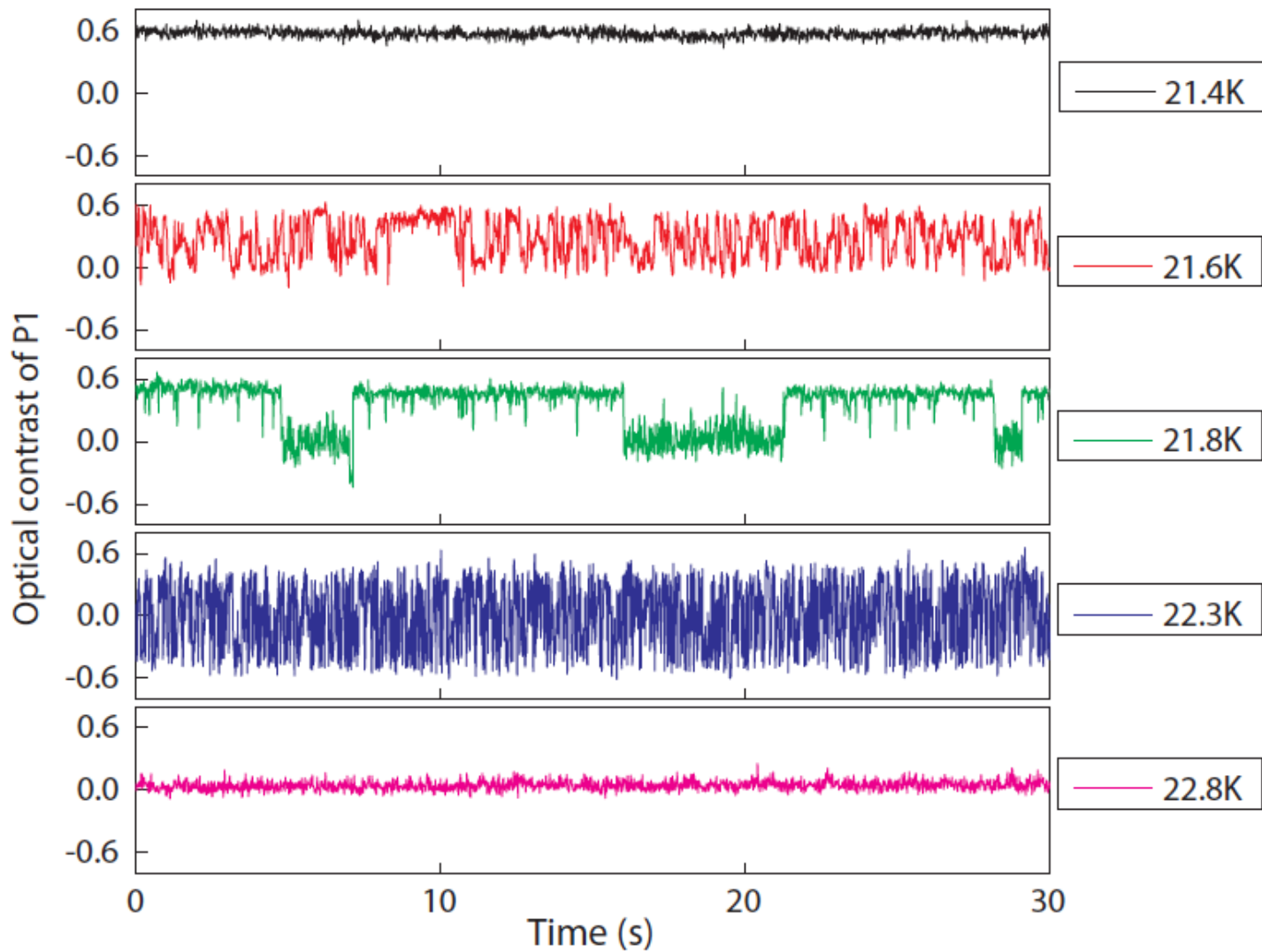
Heating from 18 K to 26 K



Fixed at 22.1 K

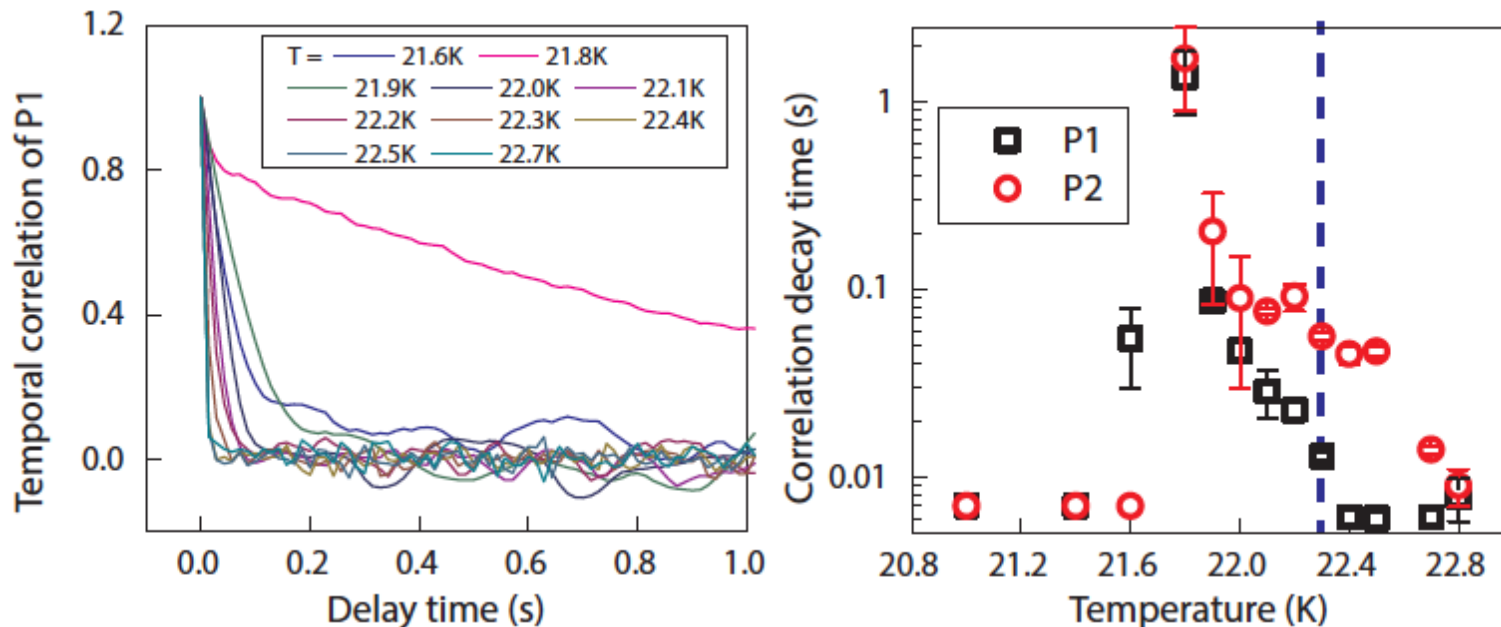
Fluctuations disappear very quickly
below and above T_c

Critical spin dynamics in real time



Correlation functions

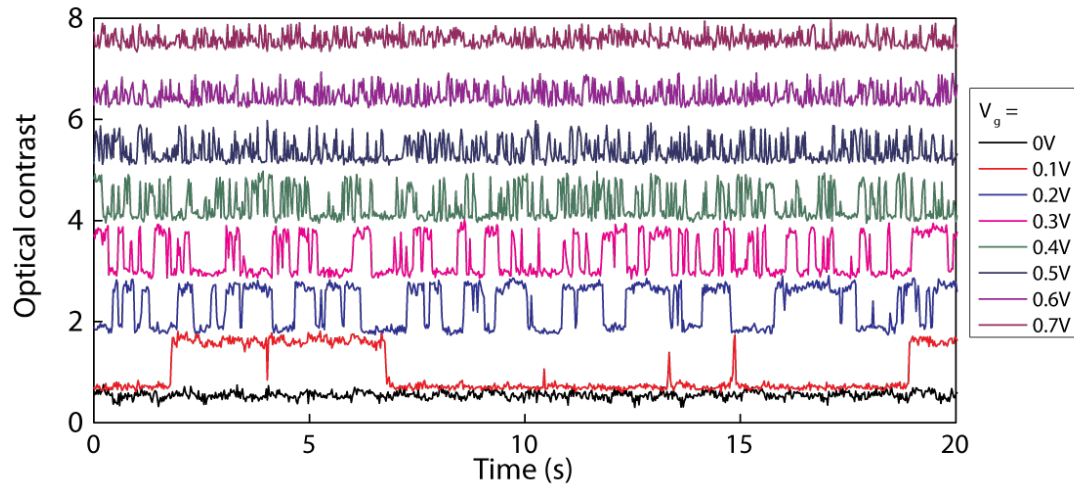
$$\langle M(r_1, t)M(r_2, t + \Delta t) \rangle - \langle M(r_1, t) \rangle \langle M(r_2, t + \Delta t) \rangle$$



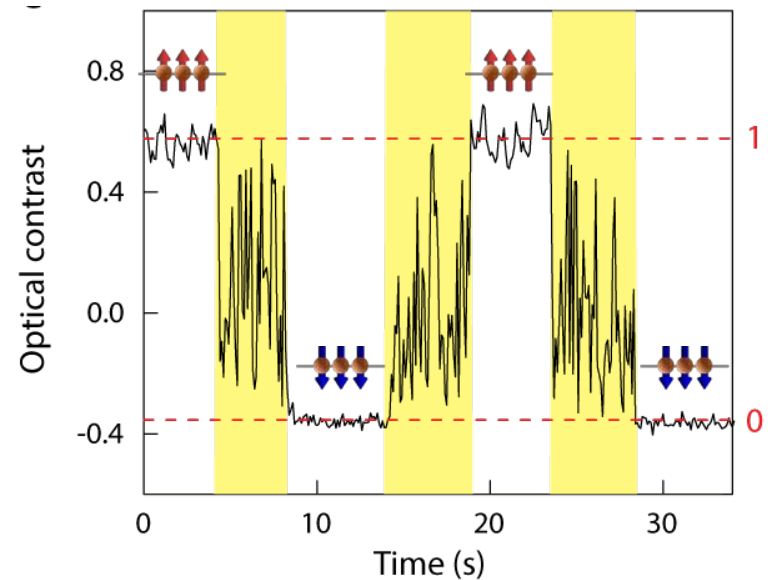
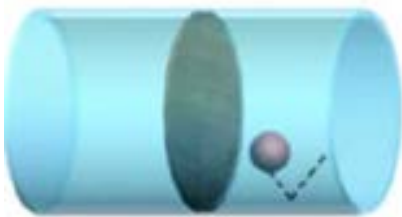
Direct observation of critical slow down

Slowest dynamics occurs slightly below bulk T_c due to $< T_c$ edge fluctuations

Gate control of critical fluctuations



Spin reorientation by
Maxwell's demon



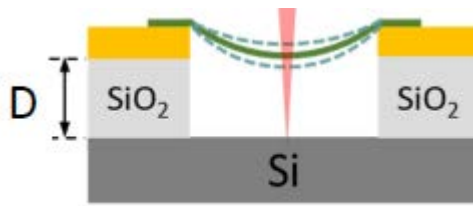
Outline

- Control of magnetism by electric fields
- Directly see critical spin fluctuations in 2D
- Mechanical probes of 2D magnetism

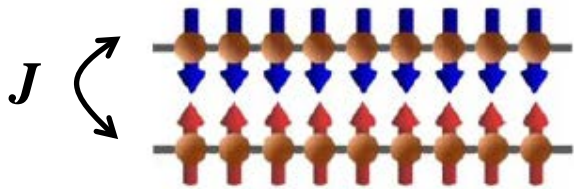
Mechanical detection of magnetic state



Shengwei Jiang

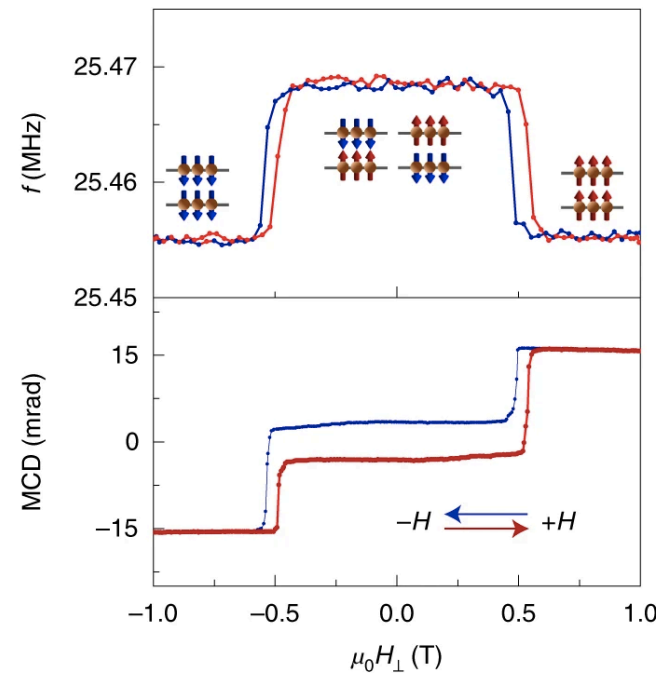


NEMS device



$$\frac{2}{3Y} \frac{\partial J}{\partial \epsilon} \text{ strain}$$

Exchange magnetostriction



Mechanical detection of thermodynamics

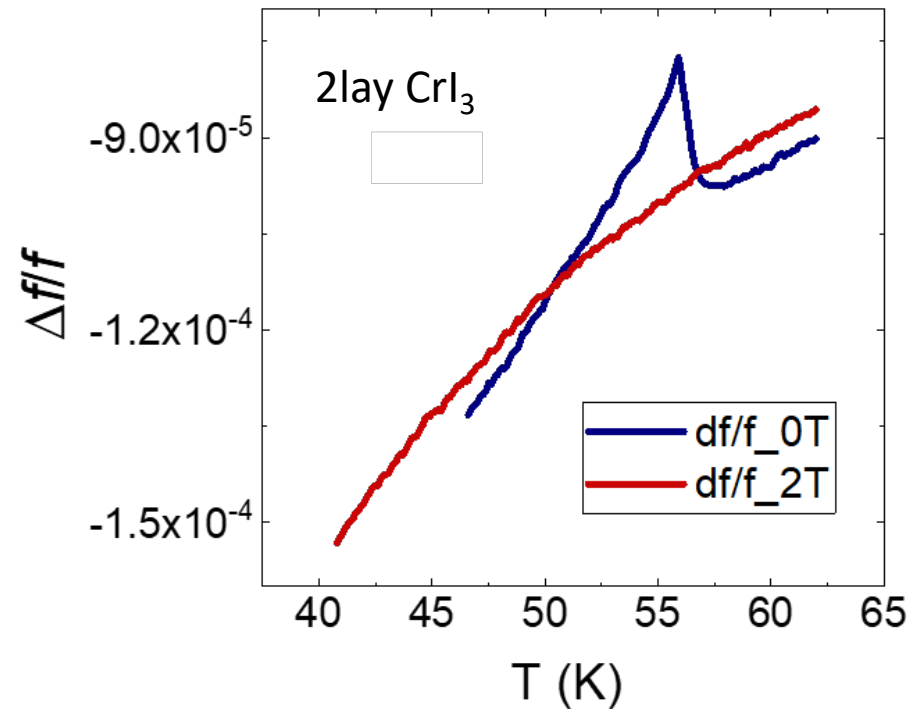
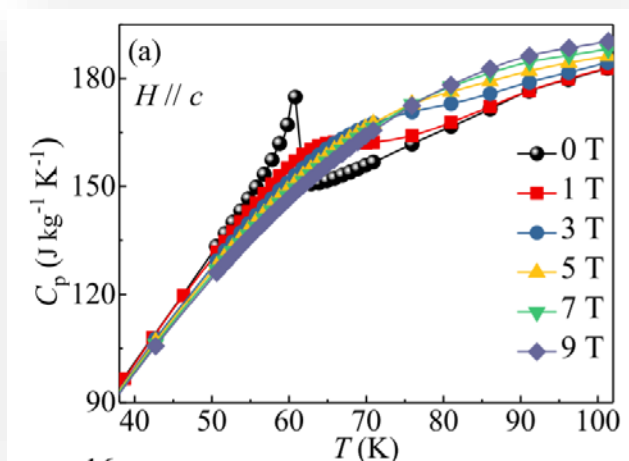


Shengwei Jiang

$$f \propto \sqrt{\frac{Y\varepsilon}{\rho}}$$

$$\frac{d\varepsilon}{dT} = -\Delta\alpha(T) \propto \Delta C_V(T)$$

Thermal expansion coefficient
and specific heat



Jiang, Shan, Mak, In preparation

Acknowledgement



Shengwei Jiang



Lihong Li



Xiao-Xiao Zhang



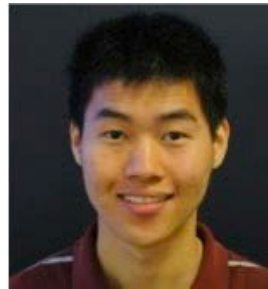
Jie Shan



Chenhao Jin



Zui Tao



Kaifei Kang

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Takashi Taniguchi

CrI_3 : Joshua Goldberger
Daniel Weber (OSU)

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