High-T_c superconductivity in 2D ruthenates: Relation to CDW/SDW

Sci. Rep. **10**, 3462 (2020)

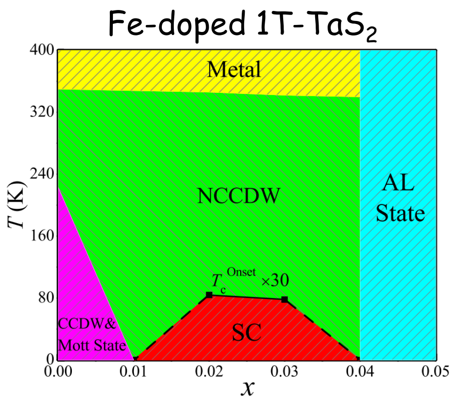
Hiroyoshi Nobukane

K. Yanagihara, Y. Kunisada, Y. Ogasawara, K. Isono, K. Nomura, K. Tanahashi, T. Nomura and S. Tanda

HOKKAIDO UNIVERSITY

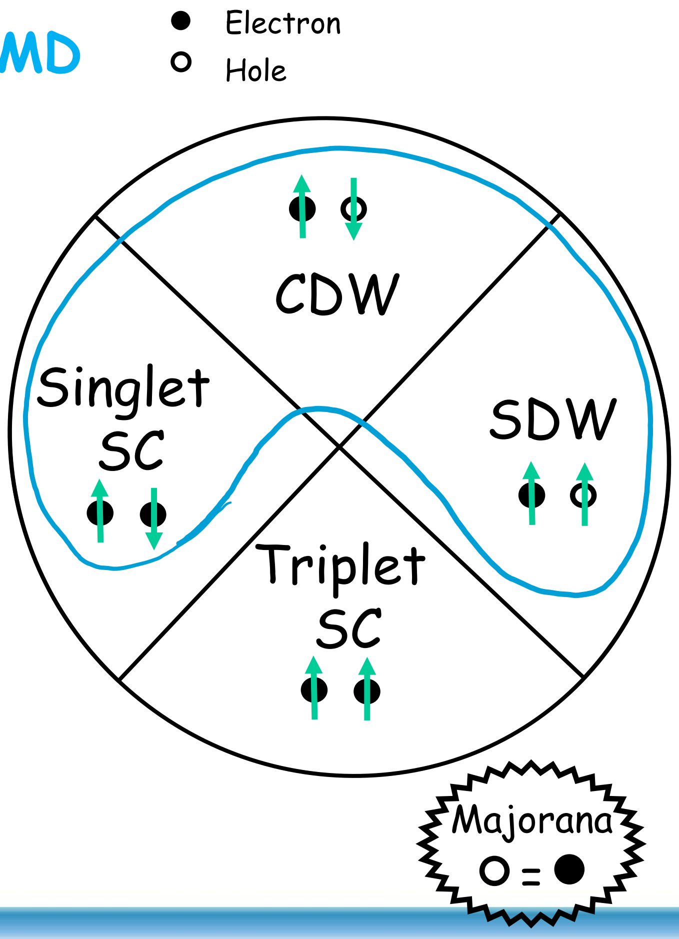
nobukane@sci.hokudai.ac.jp

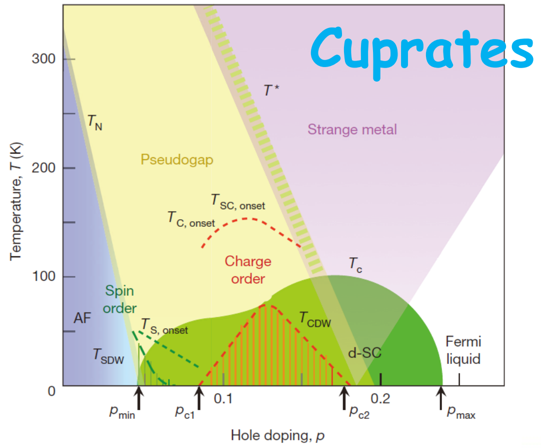
2D layered materials: TMD and cuprates



L. J. Li, *et al.*, EPL 97 67005 (2012)

TMD

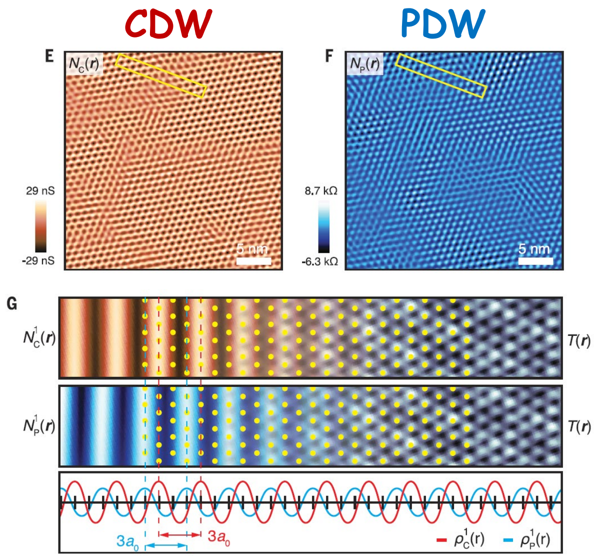




B. Keimer *et al.*, Nature (2015)

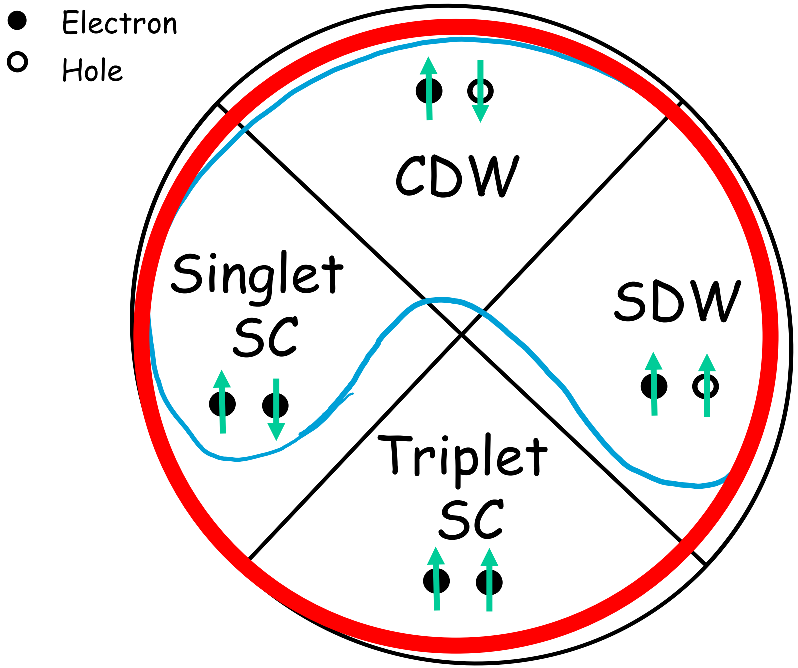
Cooper-pair density wave (PDW) and CDW in $NbSe_2$

T = 290mK



X. Liu et al., Science **372**, 1447 (2021)

2D materials: Triplet SC and DWs !?

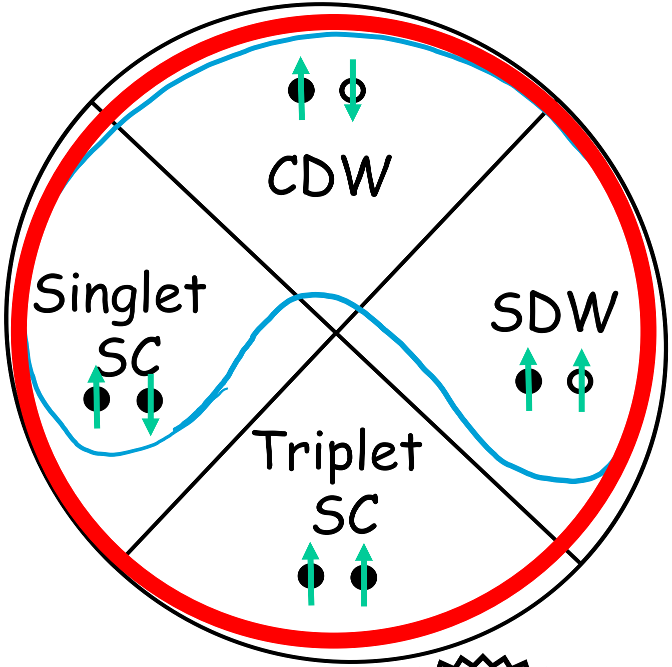


Are there any two-dimensional materials in which triplet SC and DWs can be studied?

2D ruthenates: SC and FM

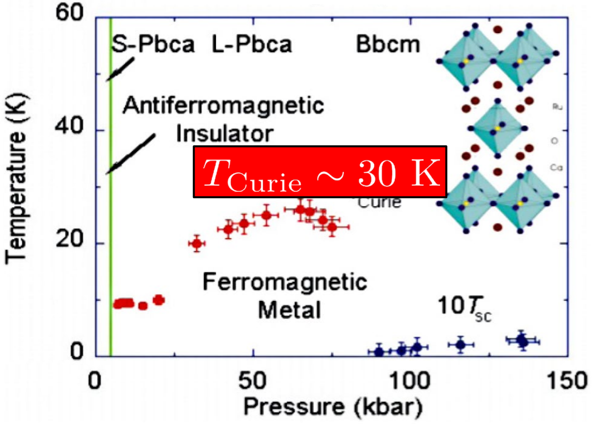
● Electron
○ Hole

Ruthenates



Ca_2RuO_4 (CRO)

Experiment



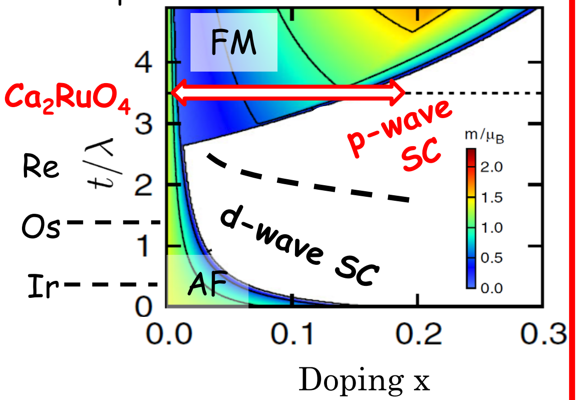
$T_{SC} \sim 0.4$ K

P. L. Alireza *et al.*,
J. Phys. Condens. Matter (2010)

Pressure

Theory

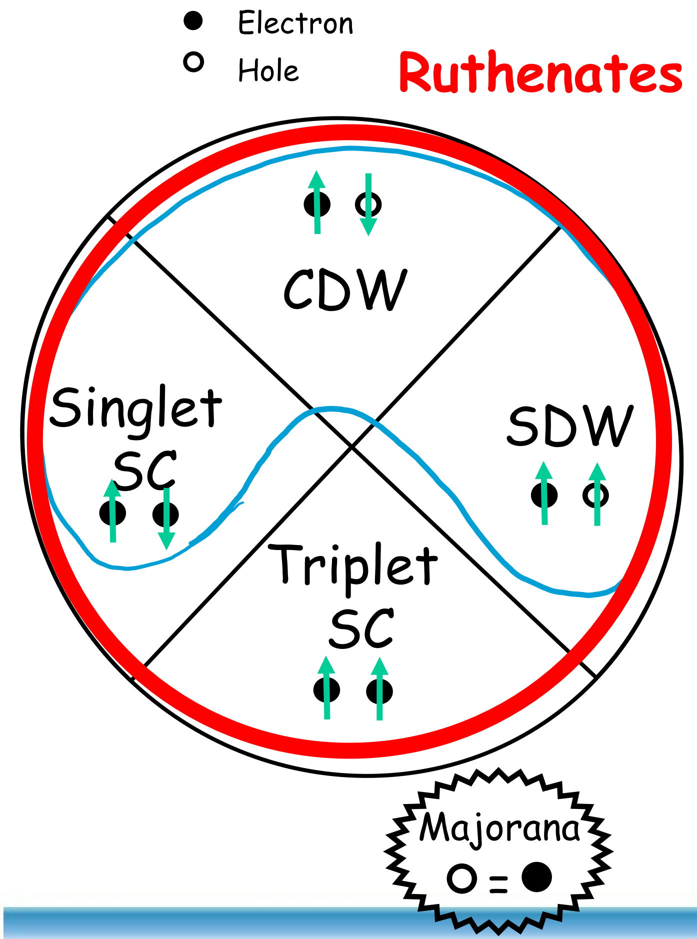
λ : spin-orbit interaction

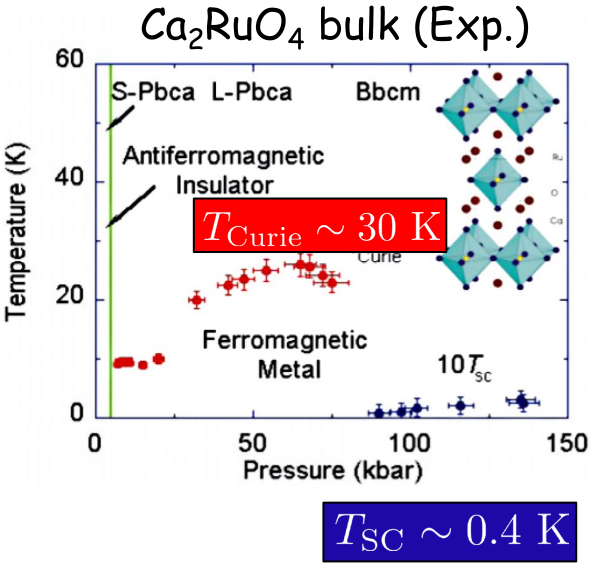


Chaloupka *et al.*,
PRL 116, 017203 (2016)

Carrier doping

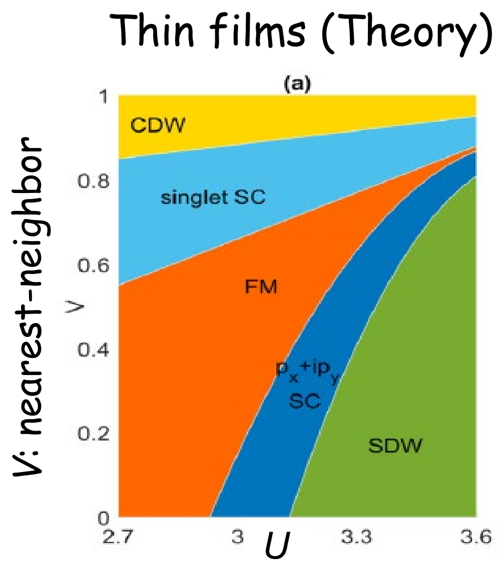
2D ruthenates: DWs





P. L. Alireza *et al.*, J. Phys. Condens. Matter (2010)

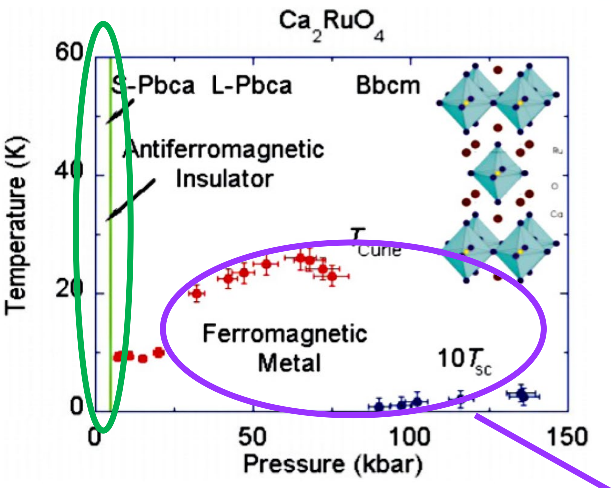
Pressure



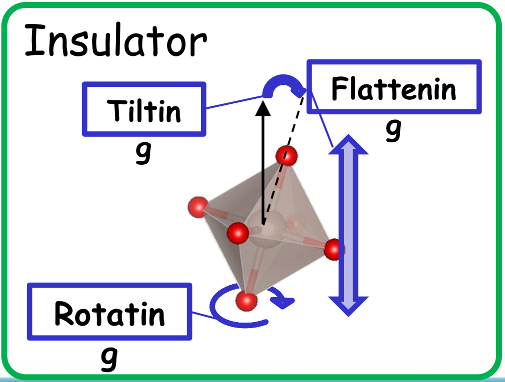
Y. Liu et al., PRB 97, 224522 (2018)

Tuning Fermi surface under strain to the RuO_6

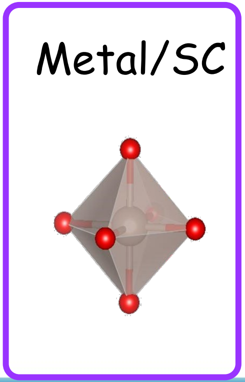
Layer number control in ruthenates



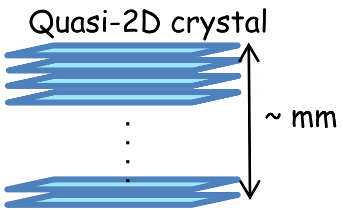
P. L. Alireza *et al.*, J. Phys. Condens. Matter (2010)



Released distortions



Bulk



Layer number control

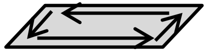
2D ruthenates

The emergence of novel quantum states!

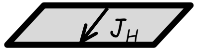
Triplet pairing, CDW/SDW

Sr_2RuO_4 thin films

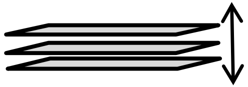
1D Edge



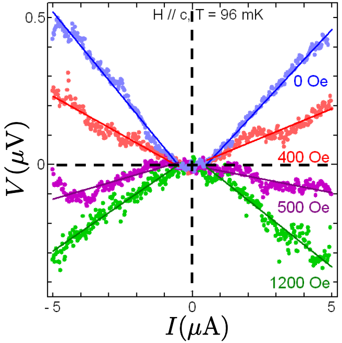
2D Hall



3D Bulk

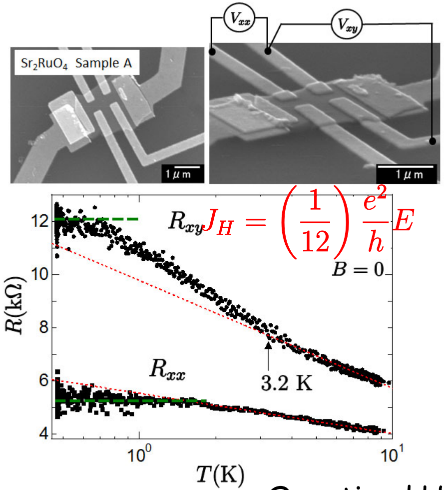


Parity violation of *I-V*



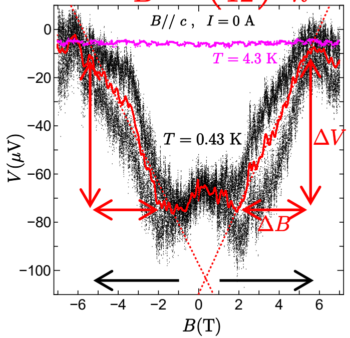
Chiral Majorana fermions

H. Nobukane et al., PRB **83**, 144502 (2011)
H. Nobukane et al., JJAP **49**, 020209 (2010)
H. Nobukane et al., SSC **149**, 1212 (2009)



Quantized Hall

$$\frac{P}{B} \sim \left(\frac{1}{12}\right)\frac{e^2}{h}$$

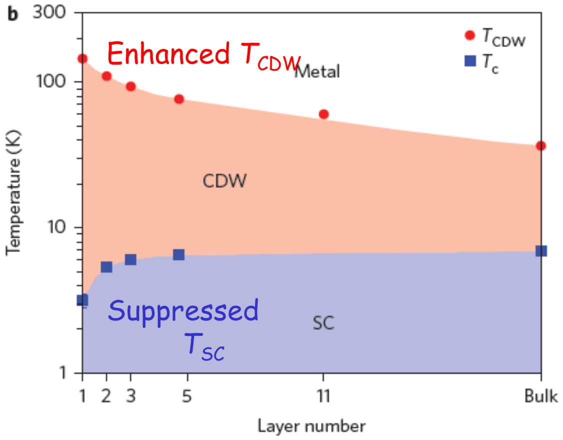


Topological Magneto-electric effect

H. Nobukane et al., Sci. Rep. **7**, 41291 (2017)

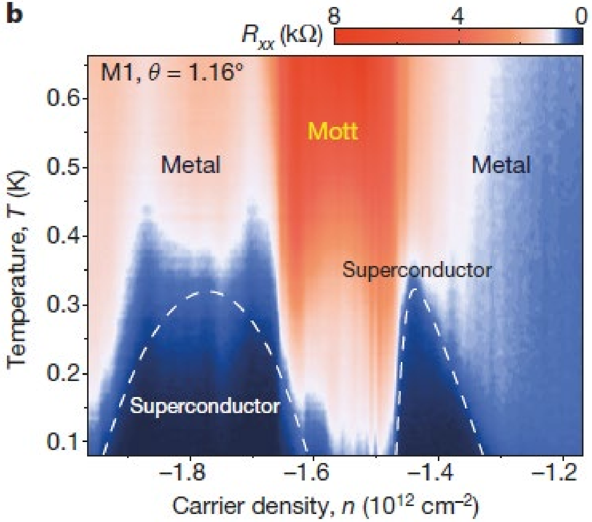
Layer number control in $NbSe_2$ and graphene

$NbSe_2$ films



X. Xi *et al.*, n.nano **10**, 765 (2015)

Magic-angle twisted bilayer graphene



Y. Cao *et al.*, Nature **556**, 43 (2018)

Exotic states
due to a negative pressure!

2D layer play a key part for studying ruthenate physics.

Our purpose

To study electric states from Mott insulator to superconductivity in Ca_2RuO_4 nanocrystals by reducing the number of layers

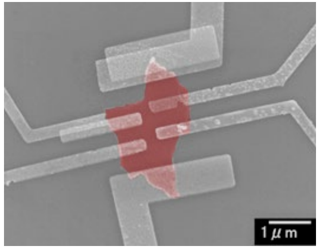
Experimental

Nano-crystal

Synthesized nanoscale crystals with a solid phase reaction.

Electric transport

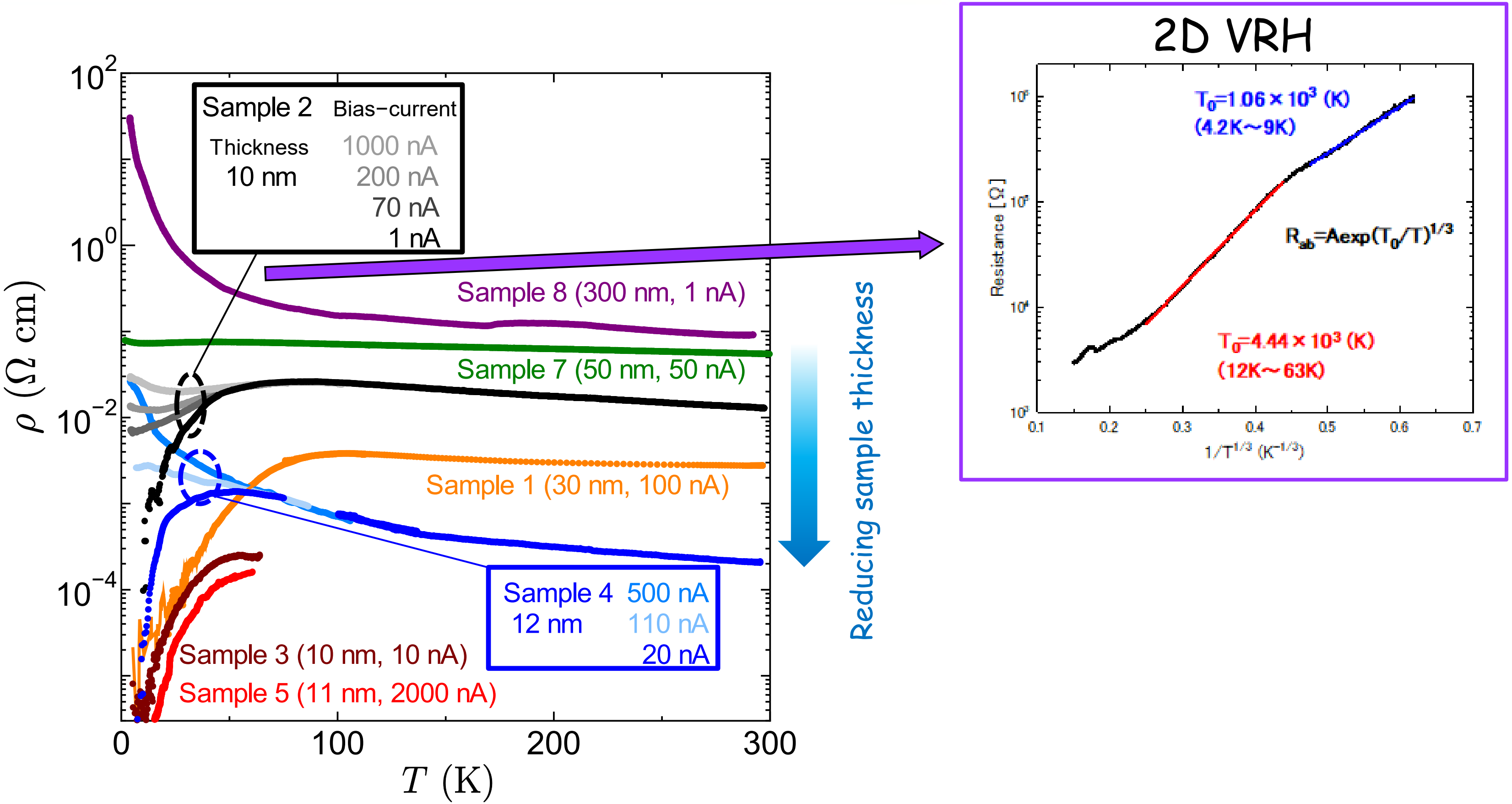
Attached gold electrodes by EB lithography



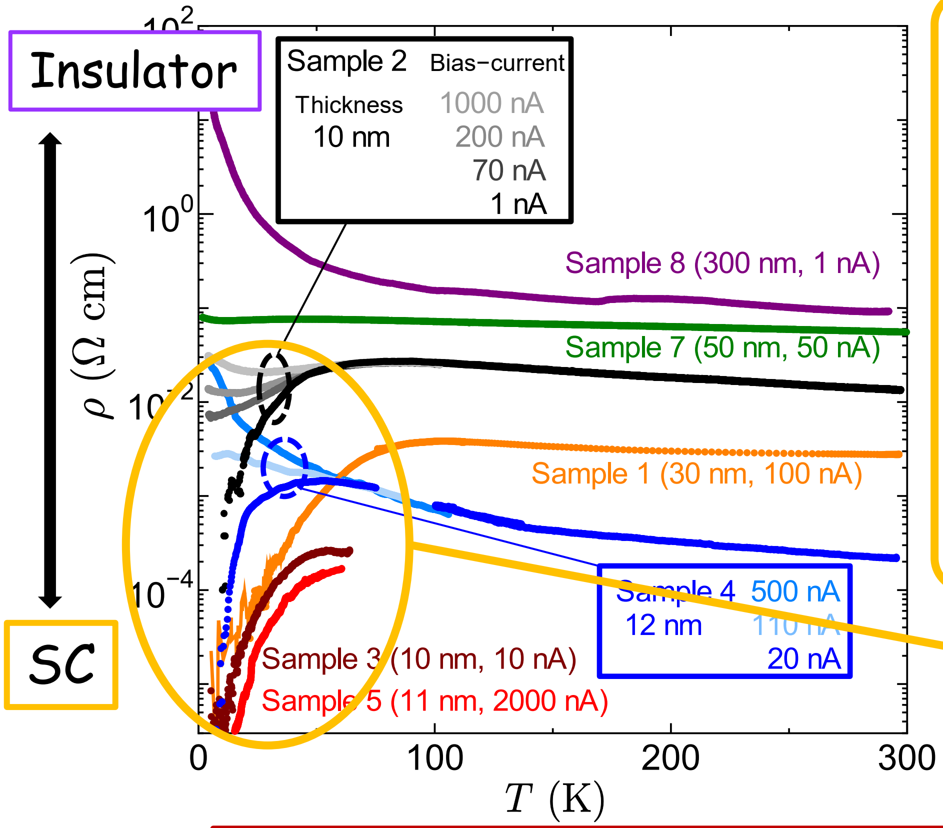
Magnetization

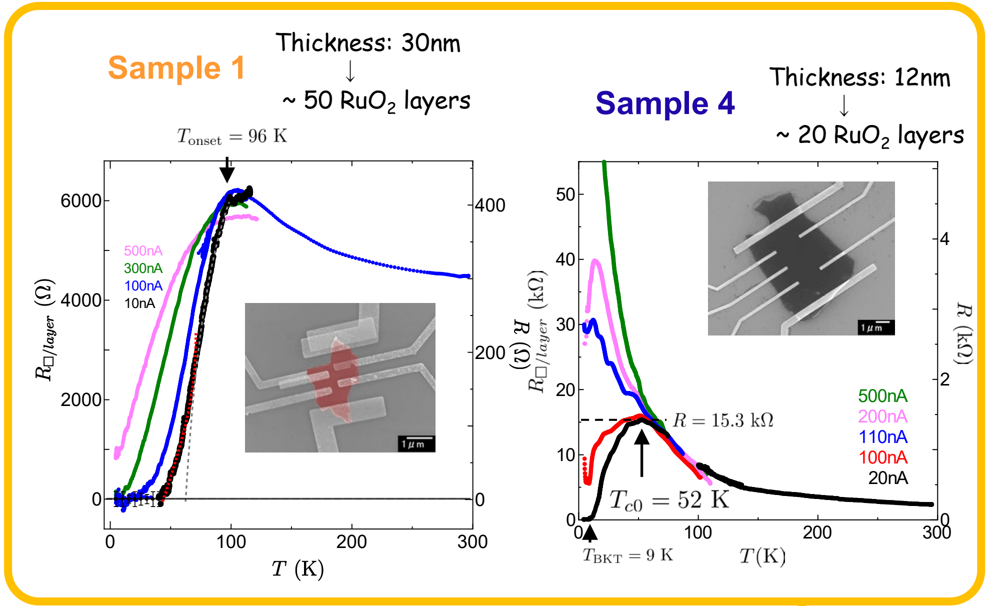
Powder consisting of nanoscale crystals

$\rho - T$ for different thicknesses



Thickness-tuned SIT



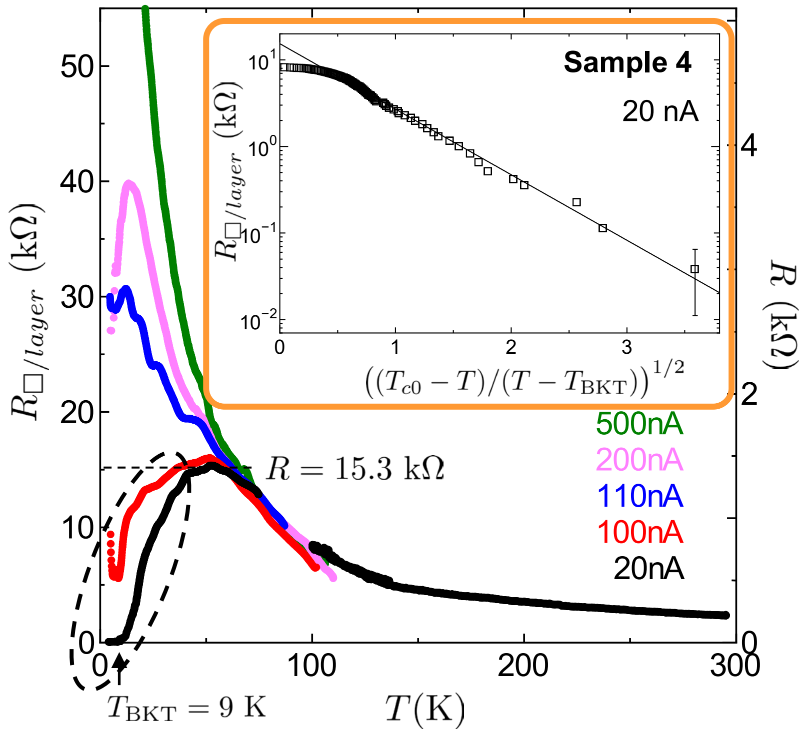


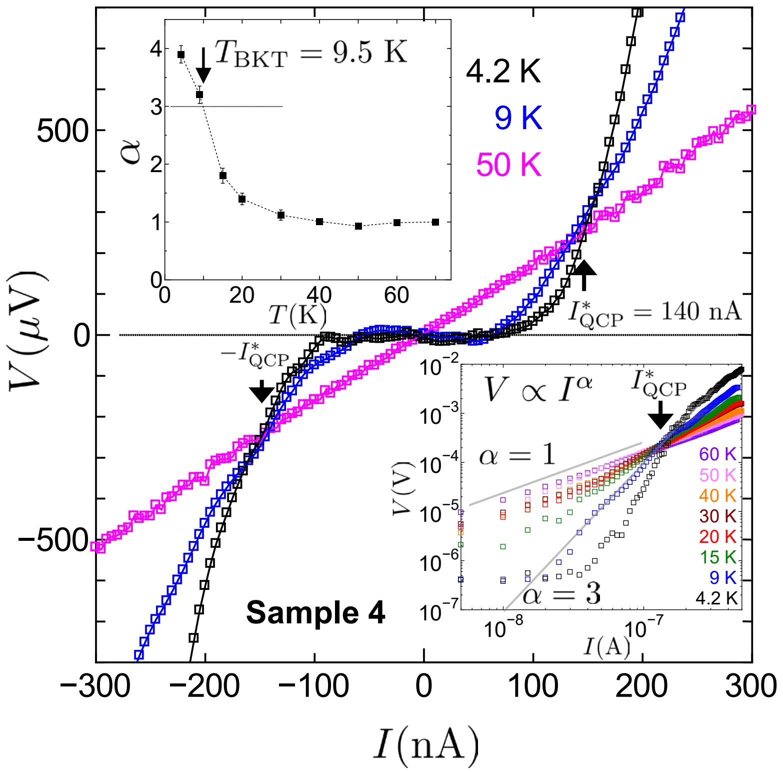
Resistivity drop
Zero resistivity

We found the thickness-tuned SIT in nanoscale Ca_2RuO_4.

BKT transition in nano-Ca_2RuO_4

$$R_{xx} \propto R_{xx}^{N} \exp\left[-2\left(b\frac{T_{c0}-T}{T-T_{\mathrm{KT}}}\right)\right]^{1/2}$$

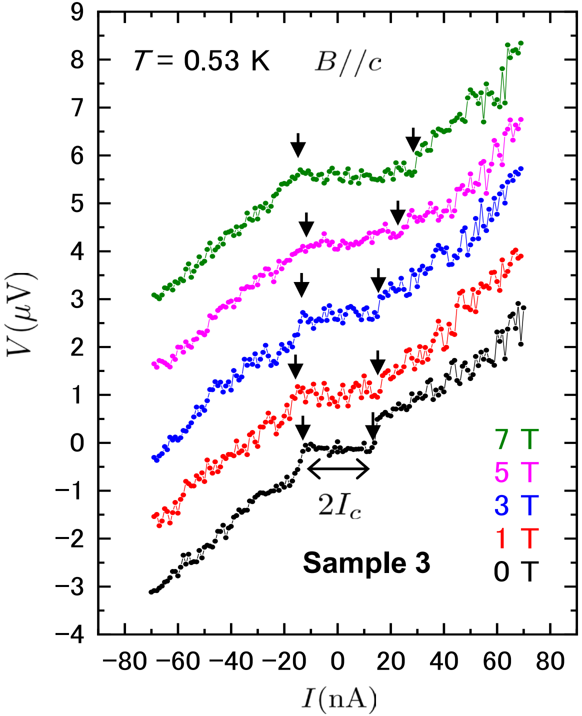




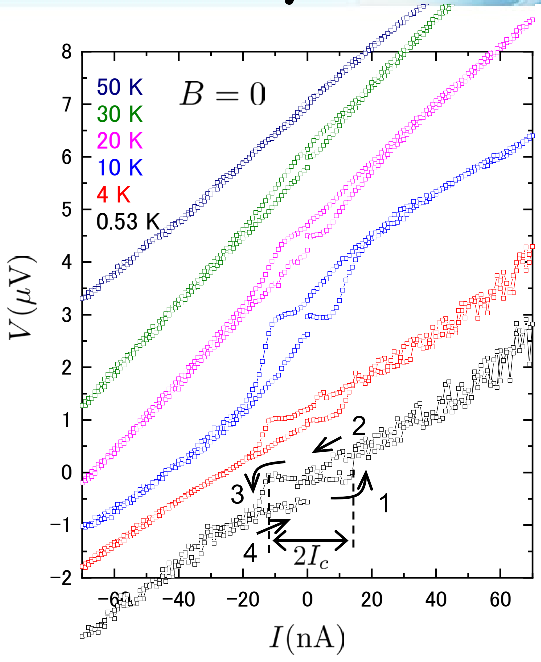
Universal jump of $V \propto I^{\alpha}$

Broad transition due to vortex flow

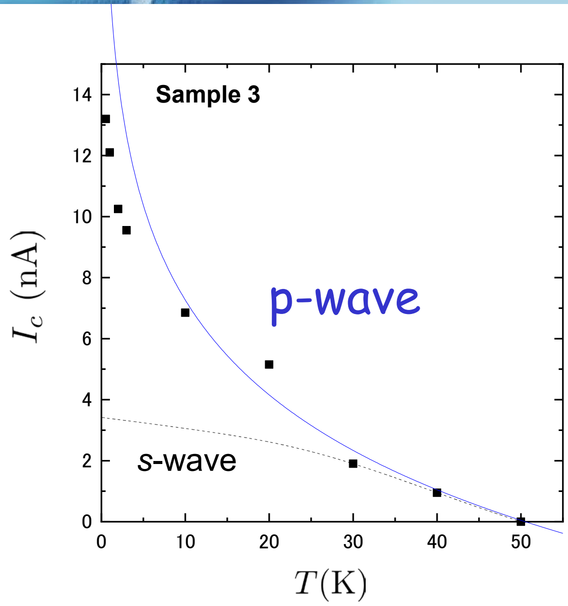
Enhanced superconductivity



- Enhanced supercurrent



- Hysteresis behavior



- I_c anomaly

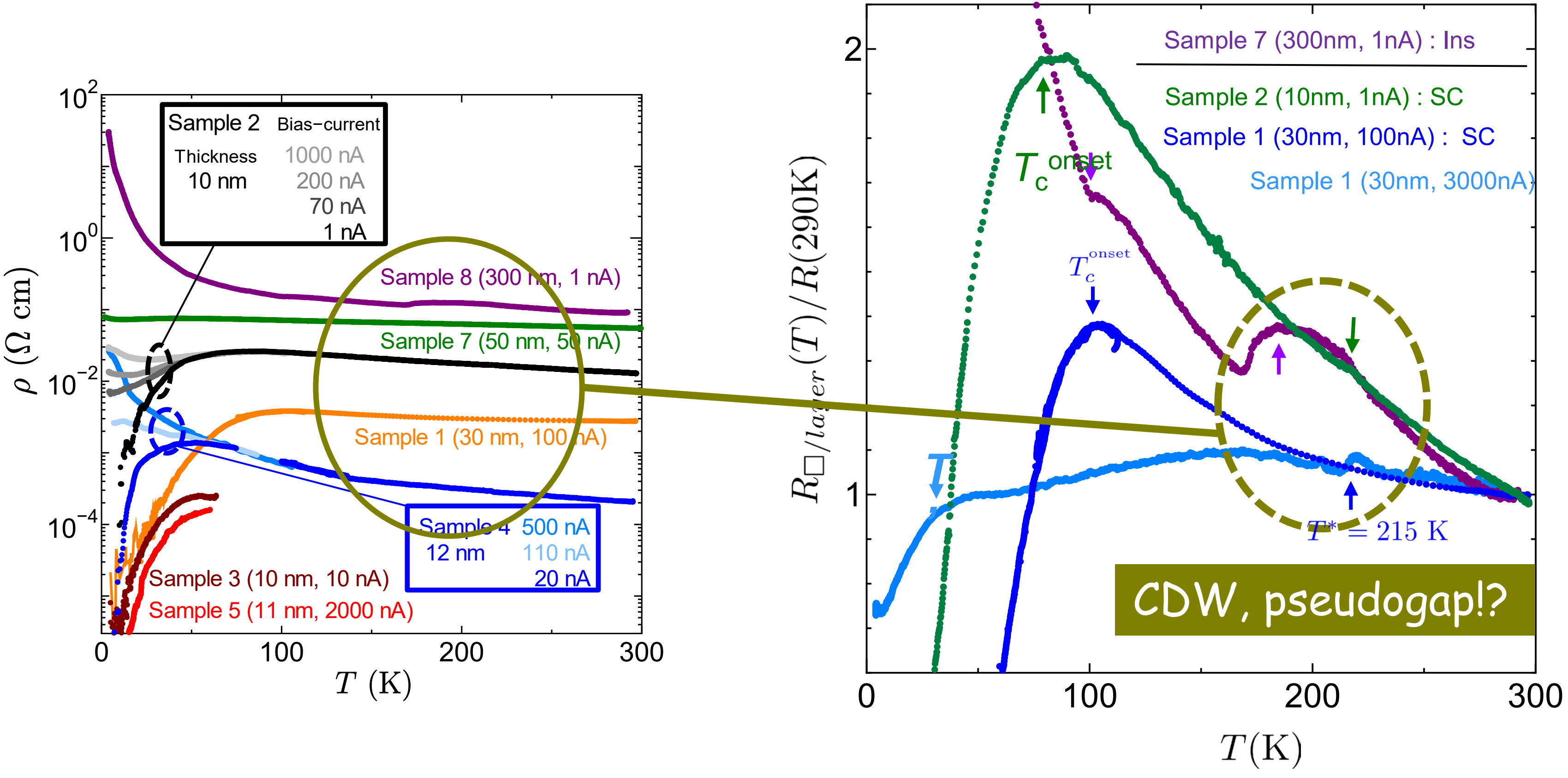
Josephson critical current between chiral *p*-wave SCs

$$I_c(T) = aI_{c0} \ln\left(\frac{b\Delta}{T}\right) \sin\Phi$$

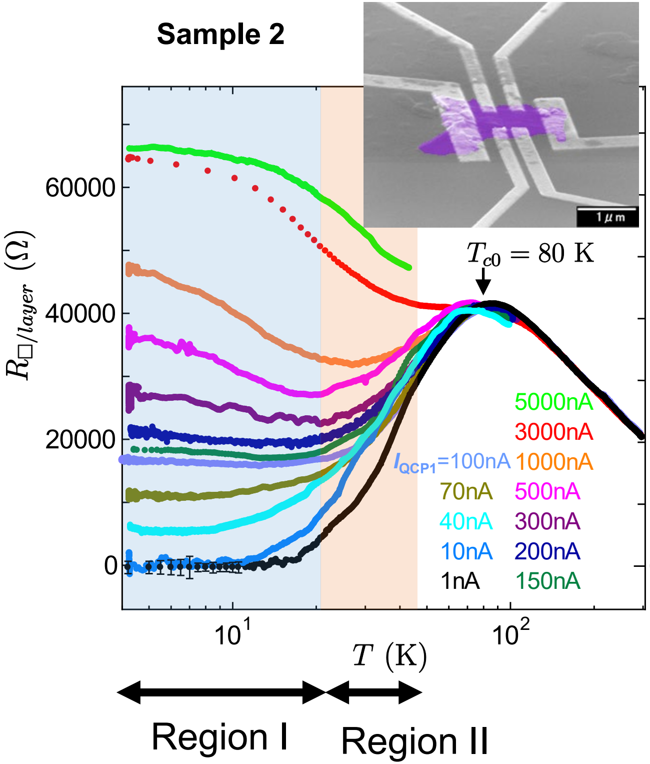
The superconductivity realizes the chiral *p*-wave state.

PSJ (2002)

Resistance anomalies near 200 K



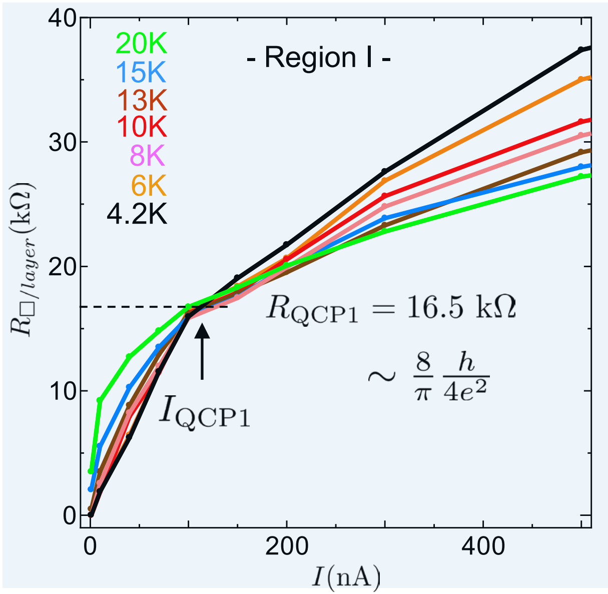
Current-driven SIT

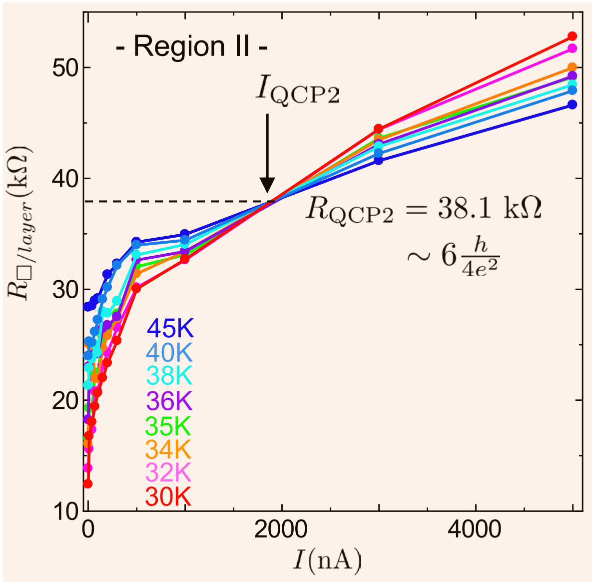


Thickness: 10 nm
↓
16 RuO_2 layers

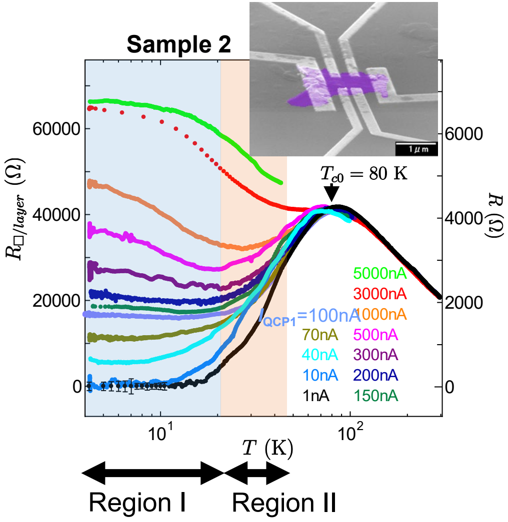
Universal scaling analysis

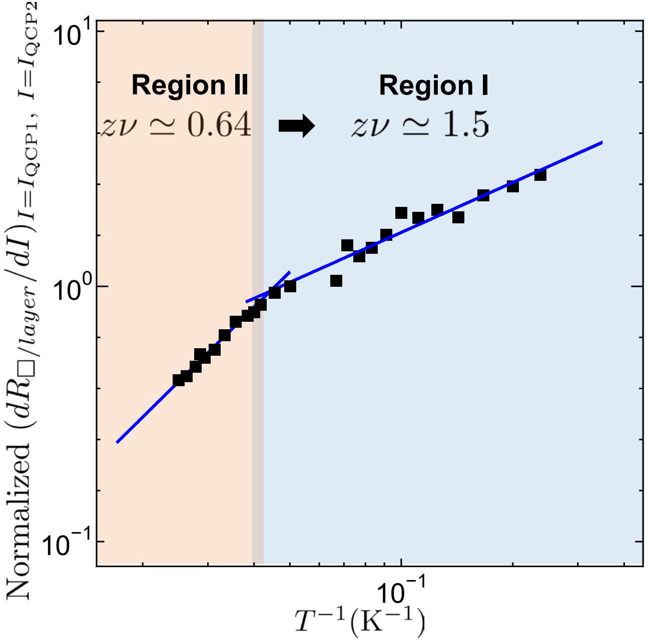
$$R_\square(I,T) = \frac{h}{4e^2} f\left[\frac{c_0(I-I_c)}{T^{1/z\nu}}\right]$$

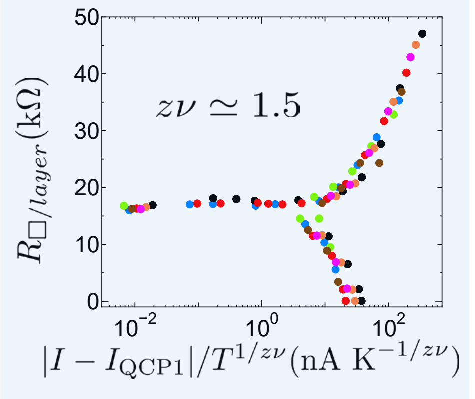


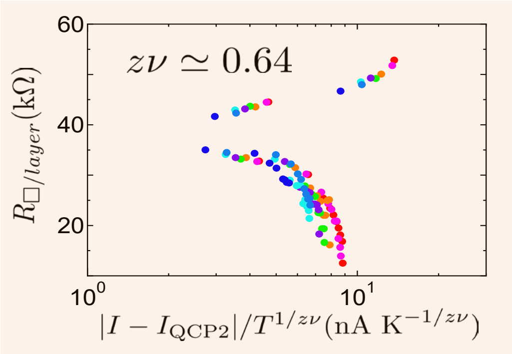


Two-stage quantum criticality







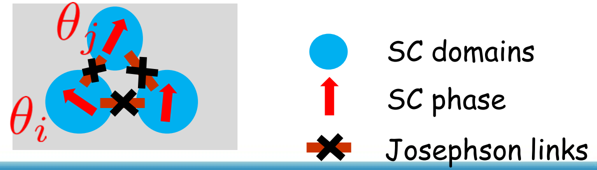


High T $z\nu = 2/3$ (2+1)D XY model in the clean limit

⇩

Low T $z\nu = 3/2$ Intrinsic inhomogeneities (quantum disorder) in strongly correlated systems

"Phase fluctuations"

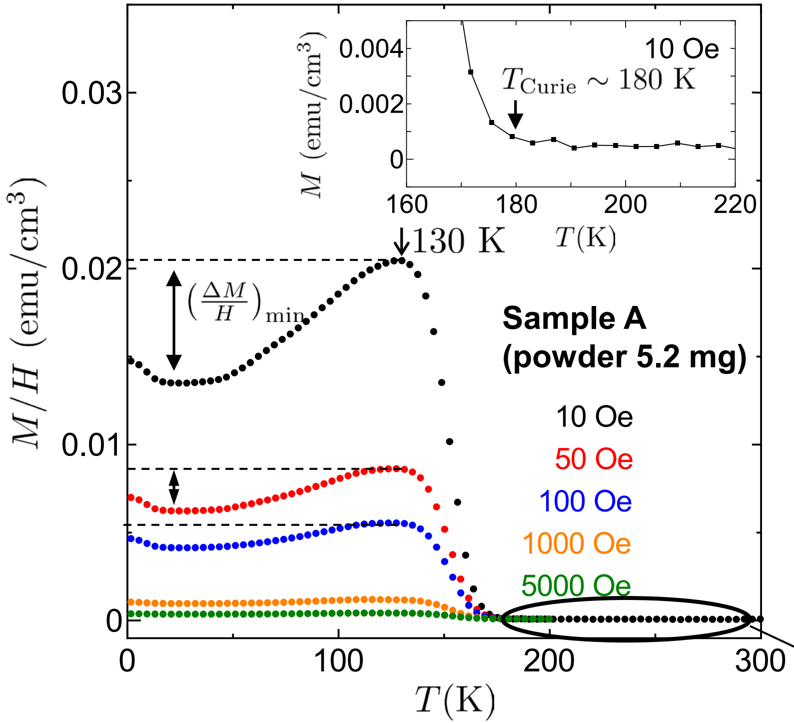


To clarify the diamagnetism,
we performed magnetic measurements
for powders consisting of nanoscale crystals.

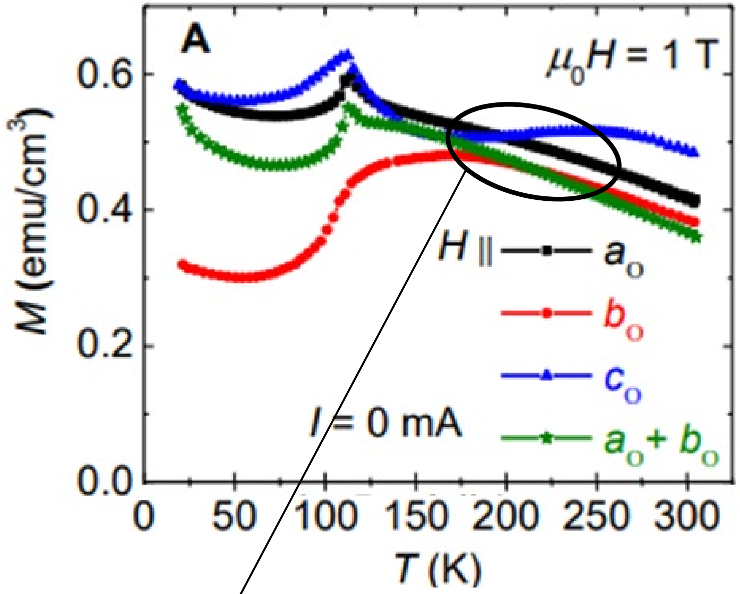
Sample A : 5.2 mg
Sample B : 2.6 mg

Temperature: 2K～300K
Magnetic field :-7T～+7T
Performed by MPMS3

Magnetic properties



Bulk Ca_2RuO_4 (AF insulator $T_N = 113$K)



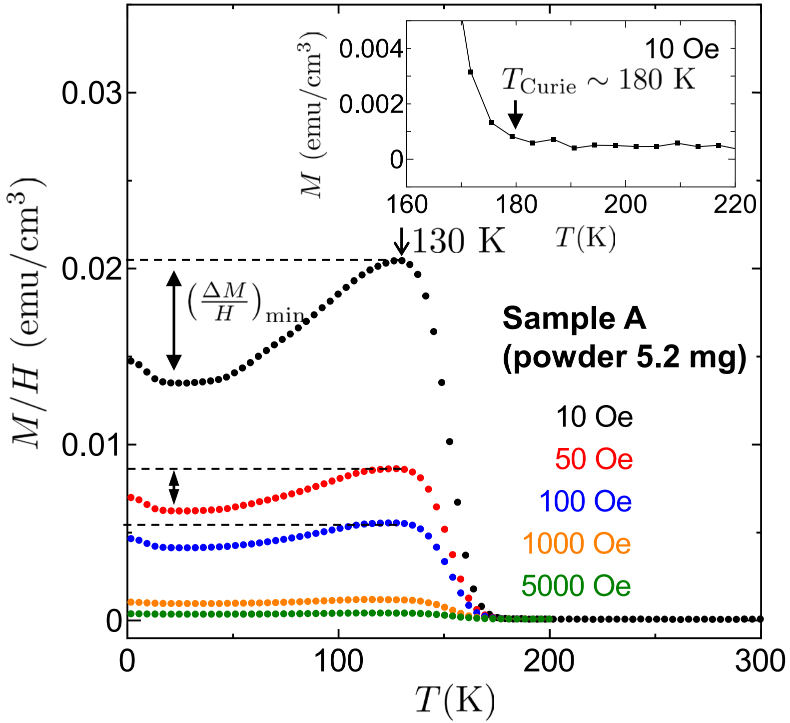
C. Sow *et al.*, Science. **358**.1084(2017)

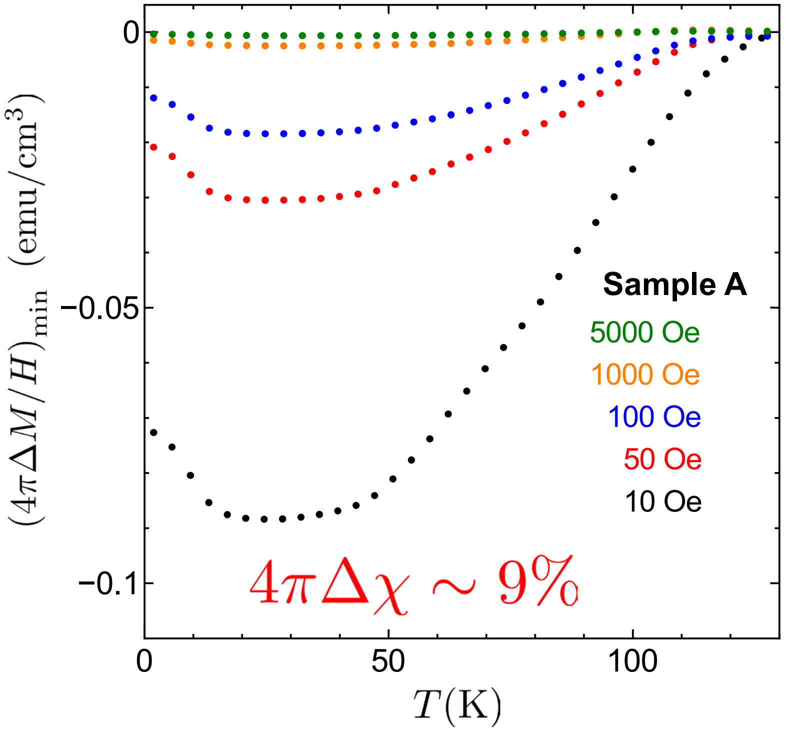
- T_{Curie} = 180 K
- **Diamagnetic component**

$\chi \sim 5.0 \times 10^{-5}$emu/cm^3

Paramagnetic state

Diamagnetism



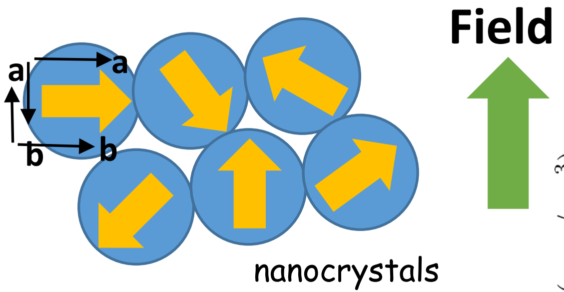


- $T_{Curie} = 180$ K
- **Diamagnetic component**

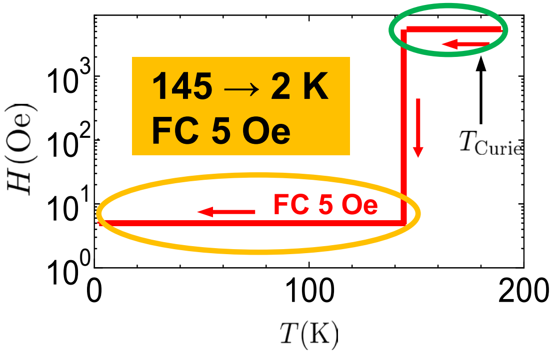
There are no phenomena that show such a giant diamagnetism other than superconductivity.

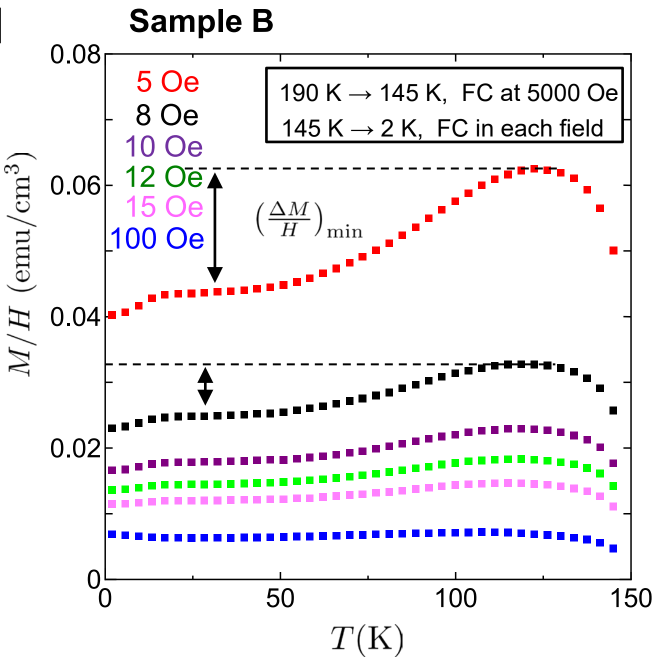
Enhanced diamagnetic components

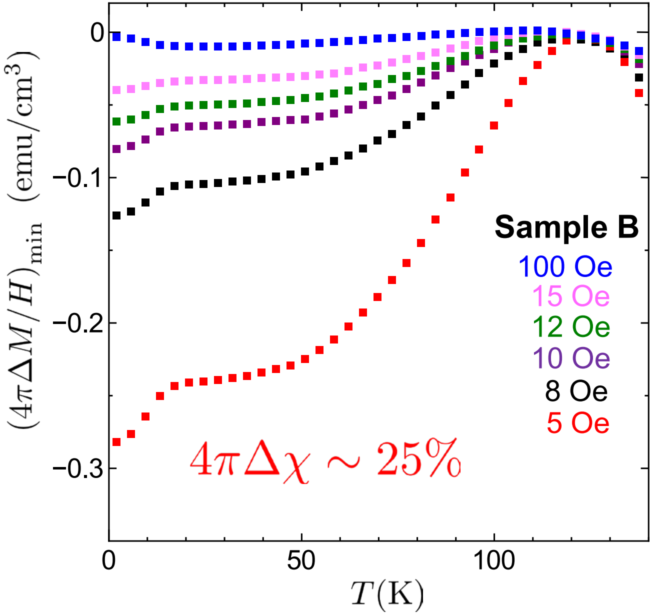
Aligned magnetic domain



190 → 145 K
FC 5000 Oe

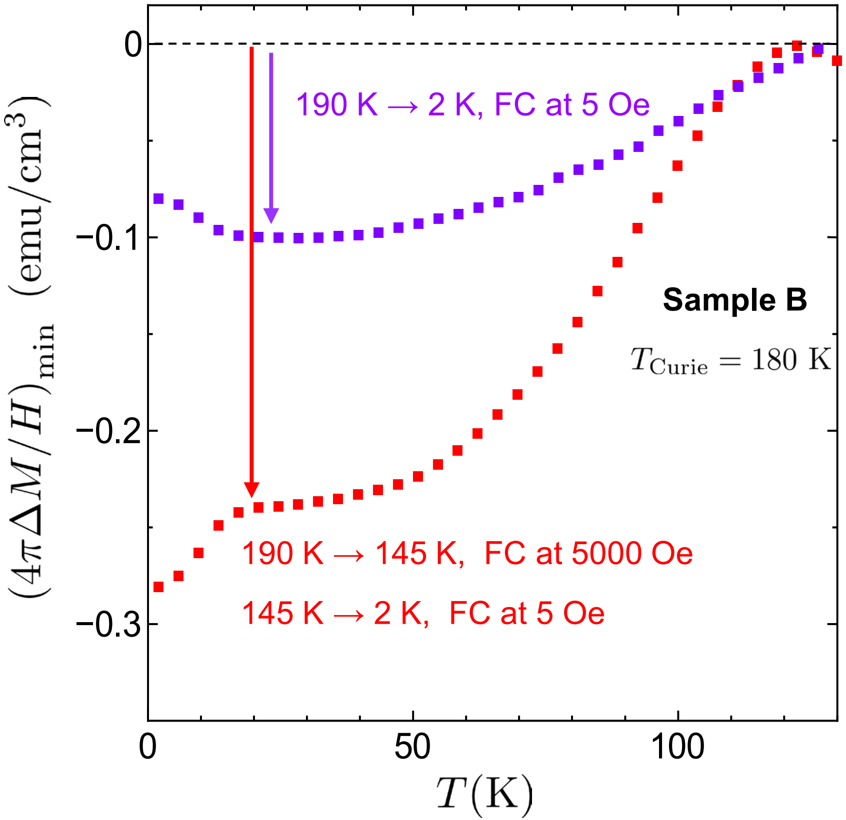


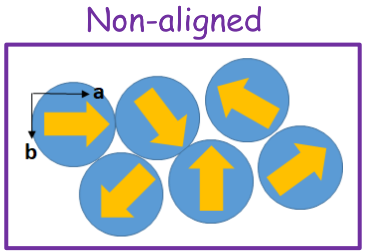


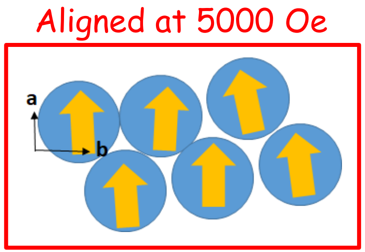


The diamagnetic components is enhanced by ferromagnetic ordering.

Enhanced diamagnetism

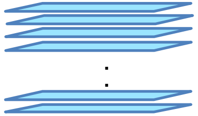
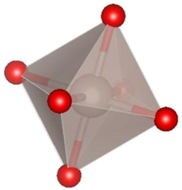
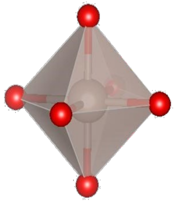






Coexistence of superconductivity and ferromagnetism.

Released distortion in nanocrystals

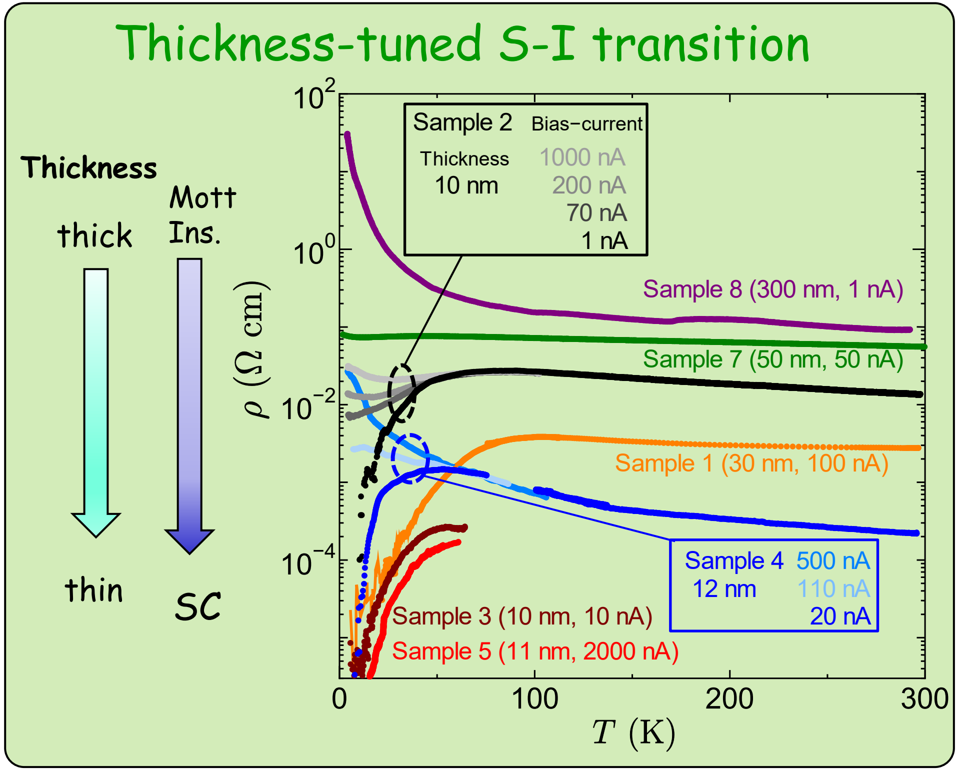
Bulk	Nanofilm
	 By reducing the layer number
 Distortion of RuO_6 by a large number of layers	 Reducing the number of layers releases distortions.
Mott Ins.	**High-Tc SC**

First-principle calculation

	a (Å)	b (Å)	c (Å)	Tilting (°)
Mono-layer	5.806	4.847	—	10.01
Bi-layer	5.719	5.049	11.692	11.06
Tri-layer	5.694	5.128	11.65	11.34
Bulk	5.592	5.253	11.548	11.65

"Flattening" and "tilting" are released in nanofilms.

Emergence of SC with negative pressure



First-principle calculation

	a (Å)	b (Å)	c (Å)	Tilting (°)
Mono-layer	5.806	4.847	—	10.01
Bi-layer	5.719	5.049	11.692	11.06
Tri-layer	5.694	5.128	11.65	11.34
Bulk	5.592	5.253	11.548	11.65

"Flattening" and "tilting" are released in nanofilms.

Suppression of the distortion under the negative pressure is responsible for SC behavior in CRO nanofilms.

Summary

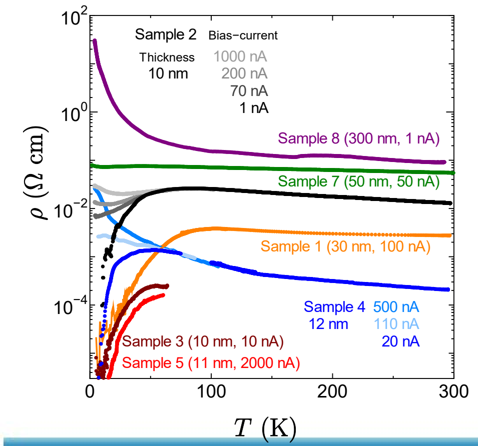
In 2D ruthenates, by reducing the number of layers, we found new ground states not observed in bulk.

Coexistence of high-T_c SC and ferromagnetism in nanoscale Ca_2RuO_4

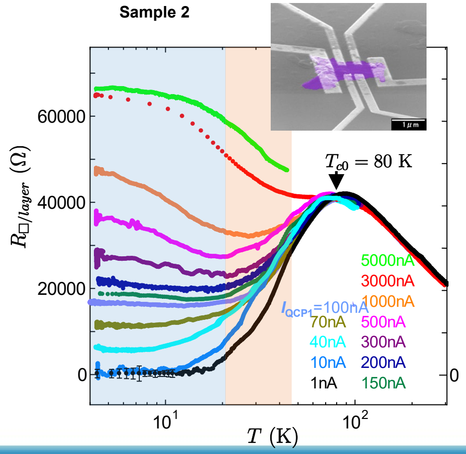
Transport

Magnetism

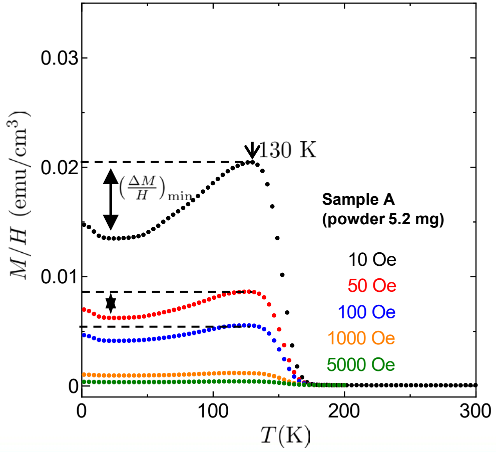
- Thickness-tuned SIT



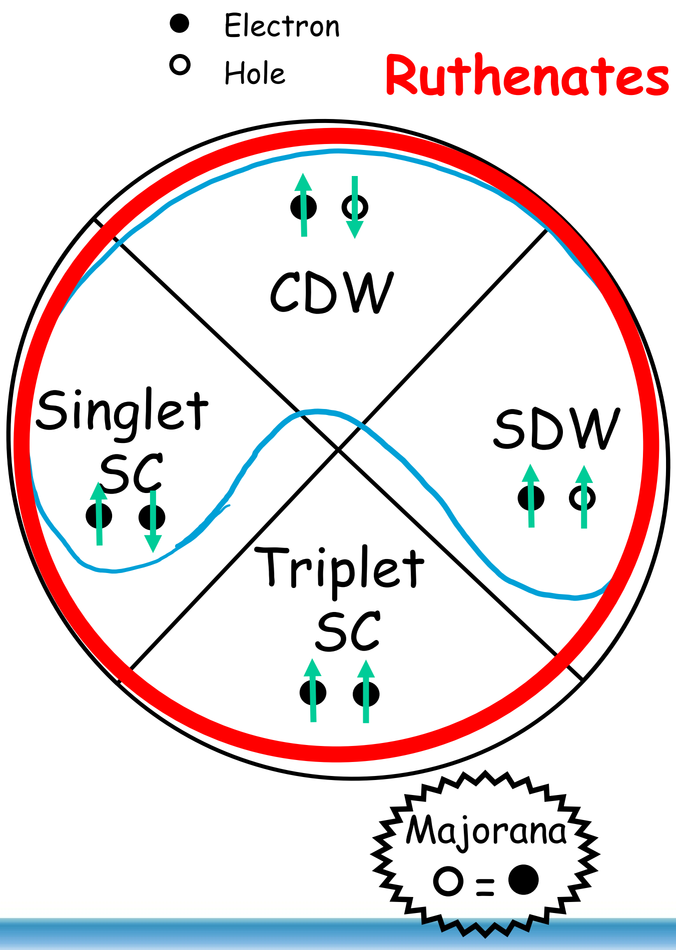
- Current-driven SIT



- SC coexisting with ferromagnetism



Summary



Research for ruthenate thin films reveals that new physics can be explored distinct from in MX_2 and cuprates.

Thank you for your attention.