SubCourse A4: Experimental Condensed Matter Physics

Hiroshi FUKUYAMA
(1998-)
Low-Temperature Physics
Quantum Liquid/Solid

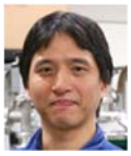
Shuji HASEGAWA
(1994-)
Surface Physics

Toru OKAMOTO
(2000-)
2D Electron Physics

Masamitsu HAYASHI
(2016-)
Spintronics, Magnetism

Kensuke KOBAYASHI
(2019-)
(Inst Phys Inteligence, CA; Osaka Univ)
Solid-State Device Physics

Hidenori TAKAGI (CA: Max Planck Inst)
Kentaro KITAGAWA
(2011-)
Strongly Correlated Electron Physics,
Quantum Critical Phenomena



Satoru NAKATSUJI
(2019-)
(CA; Inst Solid State Phys; Johns Hopkins Univ)
Topological Physics, Superconductivity,
Spintronics

Ryo SHIMANO
(2004-)
(Cryogenic Res Center)
Laser and Terahertz Spectroscopy Physics

Major Topics in Condensed Matter Physics

1980 1990 2000 2010 2020

Okamoto(2000-)

Quantum Hall effect (1980) 1985 Nobel Prize

2D Physics

1998 Nobel Prize

Dirac electrons in Graphene (2004) 2010 Nobel Prize

Kosterlitz–Thouless Transition (1973)

Berry Phase (1984)

Haldane Gap (1983) 2017 Nobel Prize

Topological Insulator (2005)

Topological Physics

Nakatsuji(2019-)

Hayashi (2016-)

Spintronics

Giant Magneto Resistance (1987) 2007 Nobel Prize

Spin Hall effect (2003)

Takagi/Kitagawa (2011-)

Correlated electron physics

High-Tc Superconductivity (1986) 1987 Nobel Prize

Scanning Tunneling Microscopy STM (1983) 1986 Nobel Prize

Hasegawa(1994-)

Surface Physics

Atom(spin) manipulation

2003 Nobel Prize

^{3}He Superfluidity (1973) 1996 Nobel Prize

Fukuyama(1998-)

ULT physics

Cold atom (1996) 2001 Nobel Prize

Quantum Technology

Non-equilibrium Physics

Kobayashi(2019-)

Advanced photon sources

Shimano(2004-)

Experimental CMP Group

1. Policy
   - Diversity: cover various branches of CMP - "Alps type", not "Mt. Fuji type"
     wide choices for students, excellence at each field
   - Presence in University of Tokyo -among other materials-related Dpts and Inst
     - fundamentals
     - education
       new faculties; Kobayashi and Nakatsuji (2019), Hayashi (2016)
2. Collaboration/Synergy
   - Internal collaborations — orthogonal, but collaborative
     - facilities for common uses (PPMS, MPMS, LT-STM, e-beam litho…)
     - joint project, sample-fabrication and measurements, theory groups
   - External collaborations
     - Collaborative Institute of Trans-scale Quantum Science (with ISSP, IPMU, CRC)
     - MPI-UBC-UTokyo; exchange undergraduates, carrying credits
     - Cross-appointments; ISSP, Inst Phys Intelligence, CRC, Osaka Univ. JHU, …
3. Issues
   - attract good students (many good students prefer theory…)
   - female/foreign faculties…
   - common facilities

Fukuyama Group

Hiroshi FUKUYAMA
(1998-)
Low-Temperature Physics
Quantum Liquid/Solid

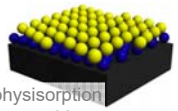
Activities of Hiroshi FUKUYAMA (2012-2020)

Review of Dept. of Phys., Feb. 13, 2020

Quantum liquids and solids in 2D (monolayers of ^{3}He and ^{4}He)

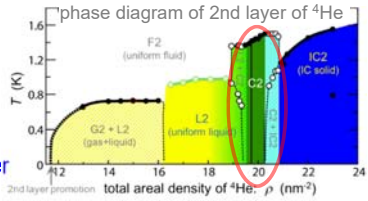
1. **Quantum liquid crystal** (QLC) phase in ^{4}He monolayers

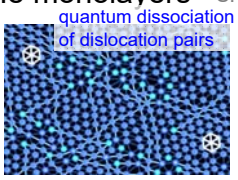
S. Nakamura et al., PRB **94**, 180501 (2016)



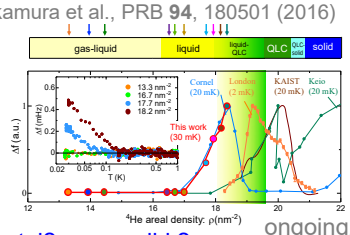
physisorption on graphite

new state of matter





quantum hexatic phase

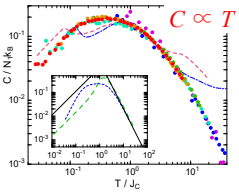


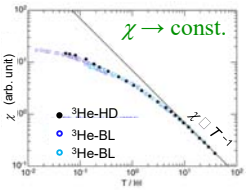
ongoing!

super liquid-crystal? supersolid ?

2. Fluctuation induced gapless **spin liquid** (SL) state in ^{3}He-QLC phase

M. Kamada et al., in preparation

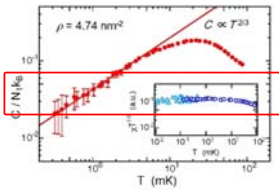




density (charge) fluctuations

ubiquitous mechanism for SLs?

cf. K. Ishida *et al.*, (1997)



new SL !

$C \propto T^{2/3}$

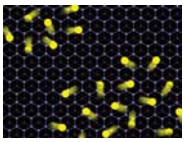
$\chi \propto T^{-1/3}$

$\to \varepsilon \propto k^3$

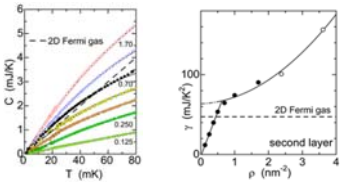
exotic magnetic excitations

3. **Many-body condensation** (liquefaction) **of ^{3}He in 2D**

D. Sato et al., PRL **109**, 235306 (2012)



theoretically unexpected



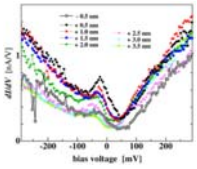
Activities of Hiroshi FUKUYAMA (2012-2020)

Review of Dept. of Phys., Feb. 13, 2020

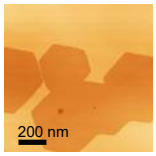
Zigzag Graphene Nano Ribbon (zGNR) (search for spin-polarized edge state)

1. Synthesis of high-density **zigzag edges** on graphite by **H-plasma etching**

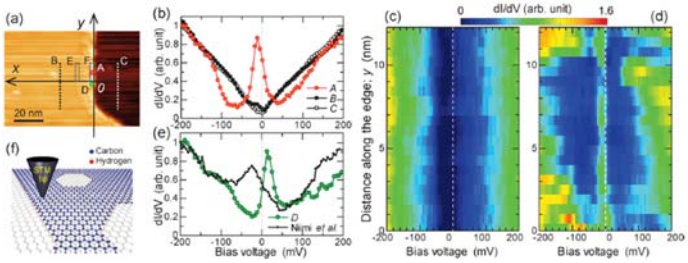
T. Matsui et al., J. Phys. Chem. C **123**, 22665 (2019)



hexagonal nanopits of ML depth with zigzag edges



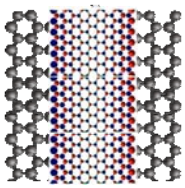
Y. Niimi *et al.*, (2005) (2006)

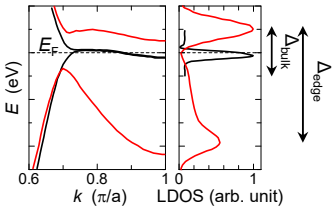


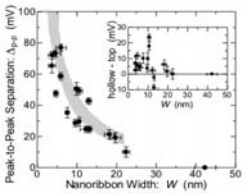
2. STS observation of **spin-polarized edge states on zGNR**

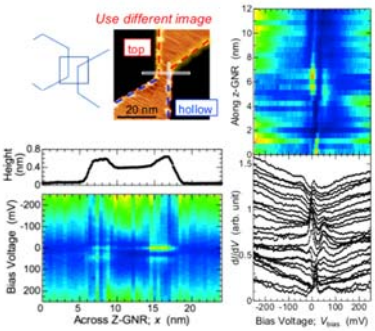
T. Matsui et al., in preparation

found split of single DOS peak into two









Hasegawa Group

Shuji HASEGAWA
(1994-)
Surface Physics

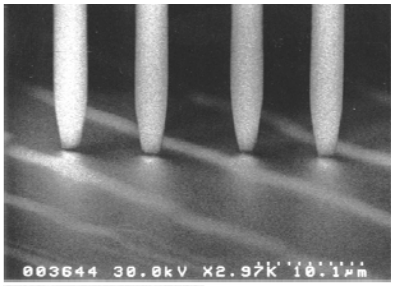
Hasegawa Group ：Surface Physics

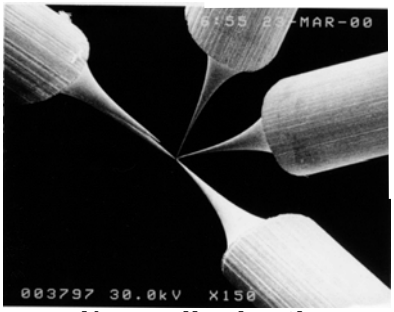
Target：Structures and Charge/Spin Transport at Crystal Surfaces/Atomic Layers

Low-D＋Symmetry breaking

Methods：

- ***in-situ* measurements in UHV with MBE growth**
  - **Four-Tip STM**
  - **Micro-Four-Point Probes**
- **combined with conventional methods**
  - **ED, ARPES, STM, PPMS, MPMS, …**





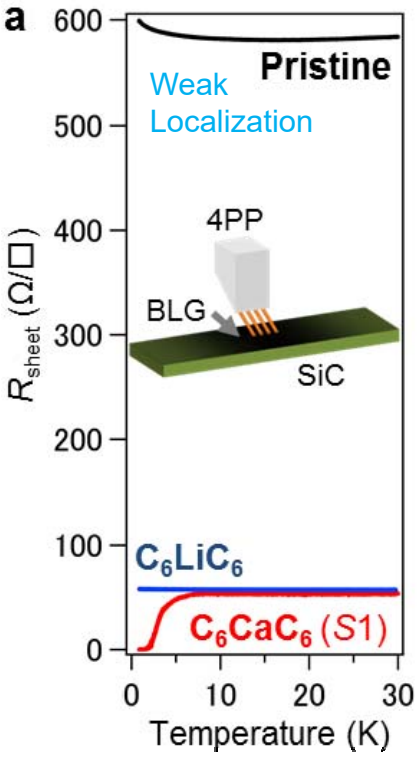
Recent Topics

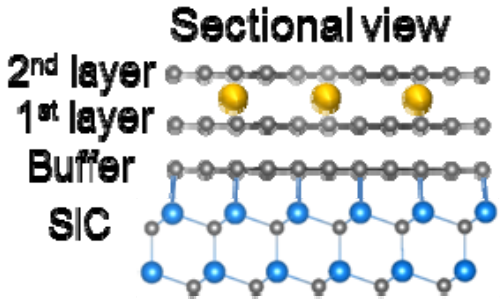
- **Atomic-Layer Superconductors**
- **Transport at Topological Surface States**
  - **spin-polarized, pure spin current, non-reciprocal/non-dissipation**

AP	PD	D3	D3	D2	D1	D1	M2	M2	M1	M1	M1
Akiyama	Hobara	Endo	Fan	Huang	Toyama	Liu	Takashiro	Watanabe	Guo	Hiwatari	Jung

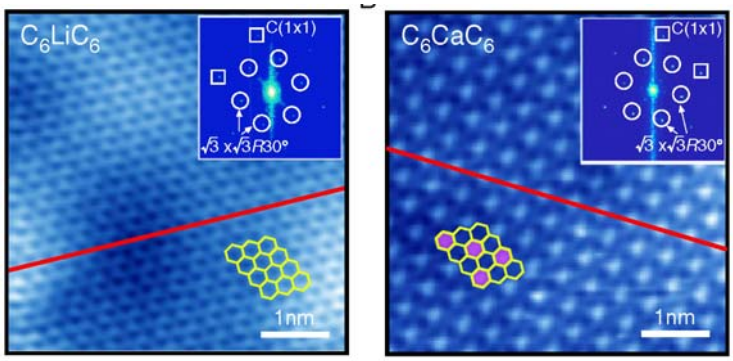
Resistance of Bilayer Graphene w/wo Ca/Li Intercalation

S. Ichinokura, K. Sugawara, A. Takayama, T. Takahashi, and S. Hasegawa:
"*Superconducting Calcium-Intercalated Bilayer Graphene*" , ACS Nano **10**, 2761-2765 (Jan, 2016)

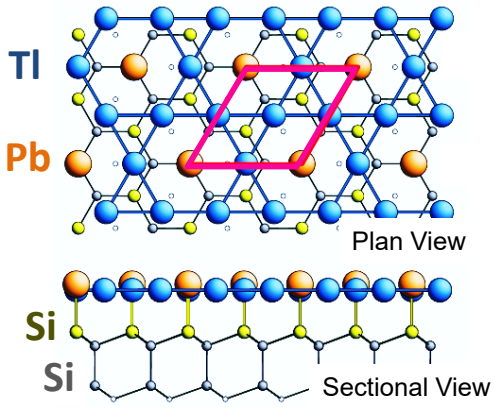




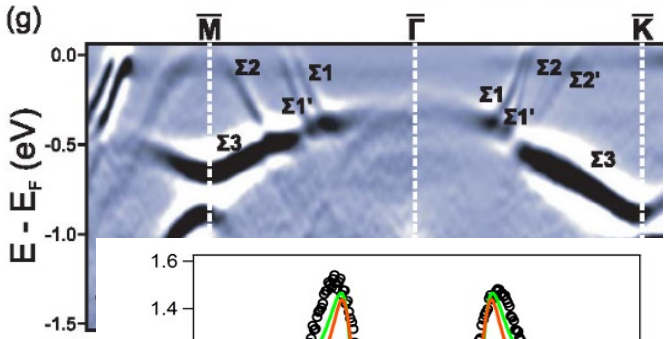
STM images

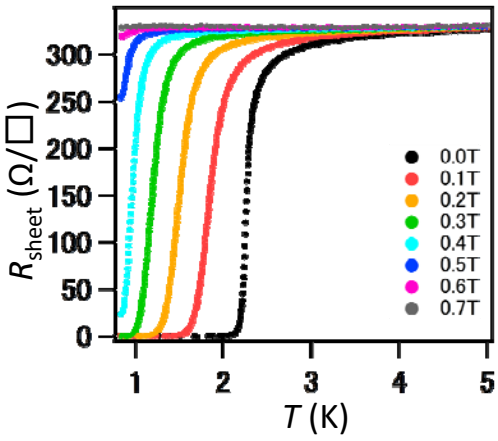


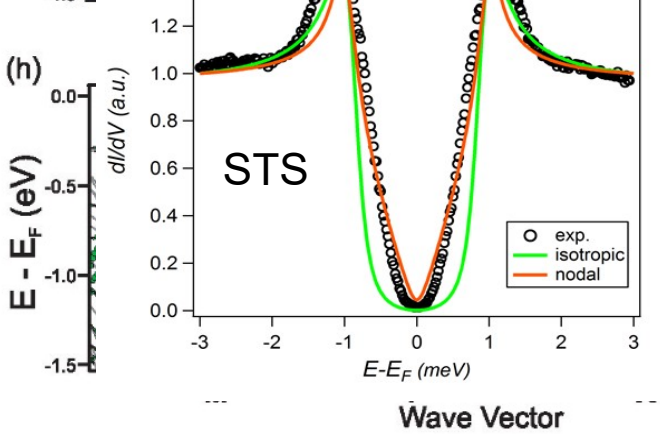
Rashba Superconductor: Si(111)–√3x√3-(Tl, Pb) Surface



A.V. Matetskiy, S. Ichinokura, et al.,
Phys. Rev. Lett. **115**, 147003 (2015).

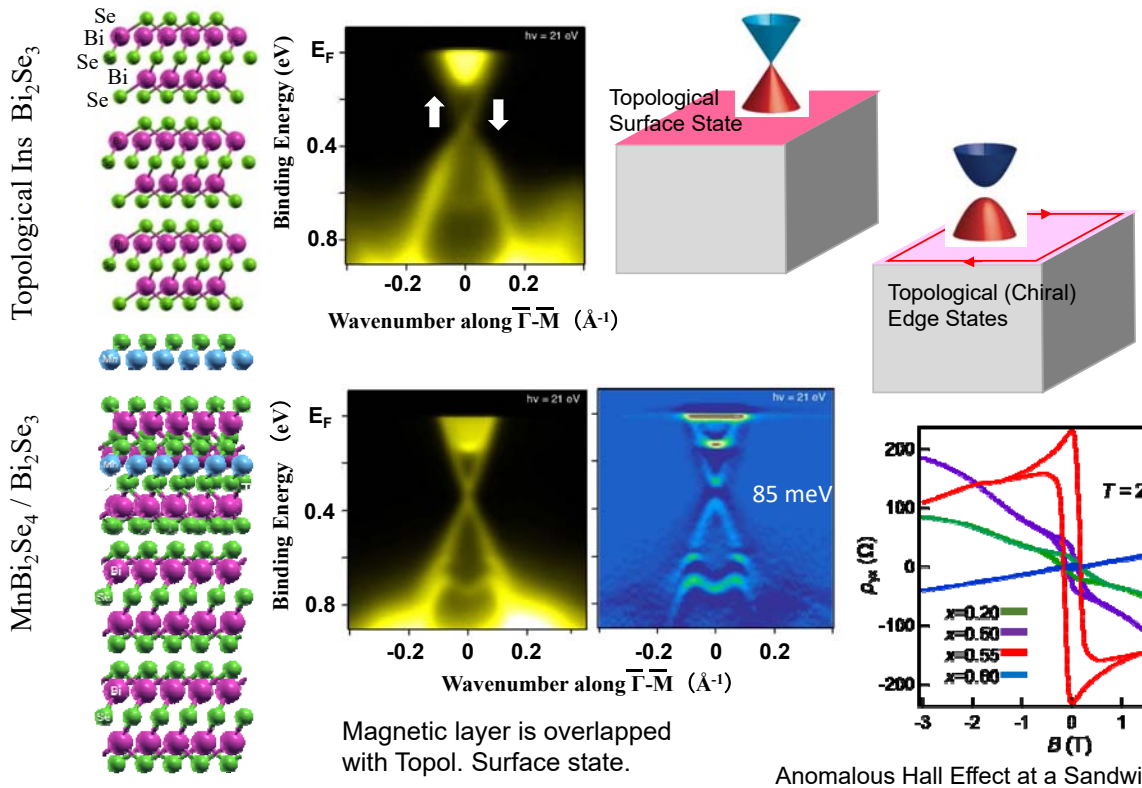






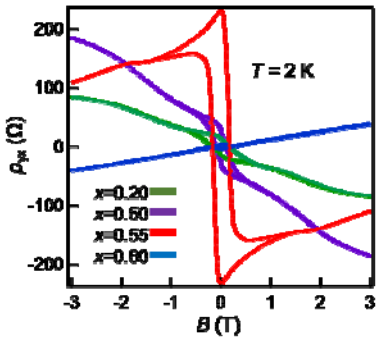
Magnetic Layer / Topological Insulator Hetrostructure

T. Hirahara, et al., Nano Letters **17**, 3493 (2017)



Magnetic layer is overlapped with Topol. Surface state.

⇒ Large gap opening



Anomalous Hall Effect at a Sandwitch Structure
$Mn(Bi_{1-x}Sb_x)_2Te_4/(Bi_{1-x}Sb_x)_2Te_3/Mn(Bi_{1-x}Sb_x)_2Te_4$

Okamoto Group

Toru OKAMOTO
(2000-)
2D Electron Physics

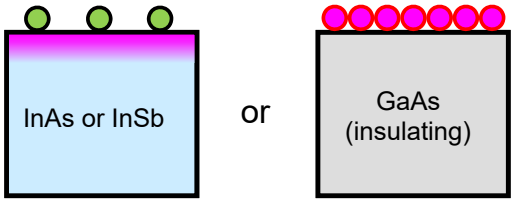
Okamoto group: Two dimensional systems

T. Okamoto (assoc. prof.)
R. Masutomi (assist. prof.)

Two dimensional systems
- low temperatures
- high magnetic fields

1. Quantum wells
(conventional 2D electron gas in semiconductor heterostructures)

2. Cleaved surfaces



2D electron gas induced by adatoms

ultrathin films on the cleaved surface

⇨ transport measurements
(electric resistance, Hall resistance)

Development of an experimental system

transport measurements | STM/STS

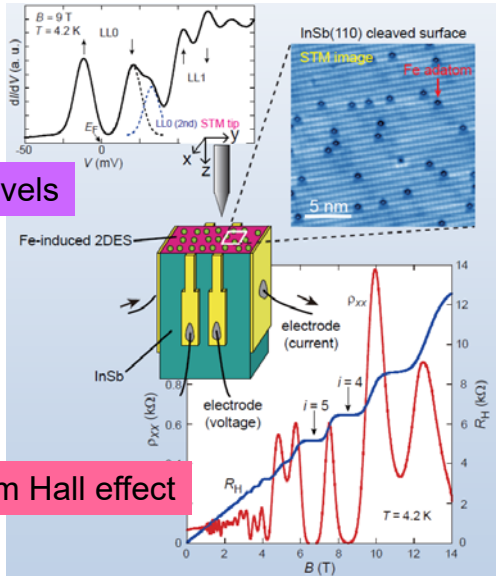
⇩ ⇩

2D electron gas at cleaved surface

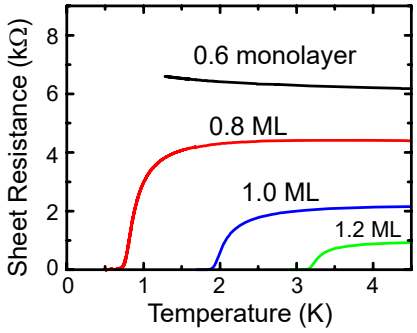
Masutomi et al., Appl. Phys. Lett. ***106****, 251602 (2015)*
(Editor's pick)

STS ⇩ Landau levels

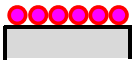
transport ⇩ Quantum Hall effect



Two dimensional Rashba superconductor



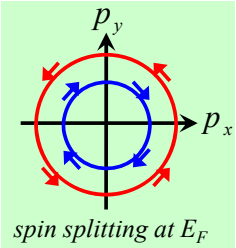
Pb monolayer



GaAs(110)
(insulating)

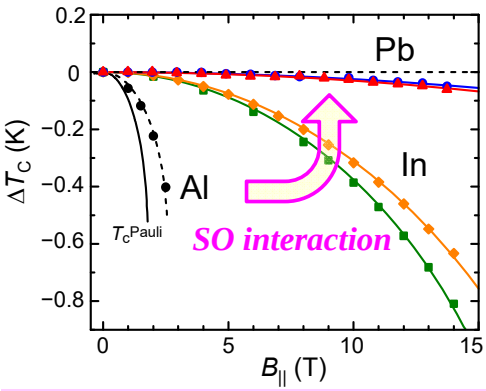
atomically flat substrate of cleaved surface
⇒ R = 0 is observed in monolayer films

surface electric field
×
spin-orbit interaction
⇩
Rashba effect

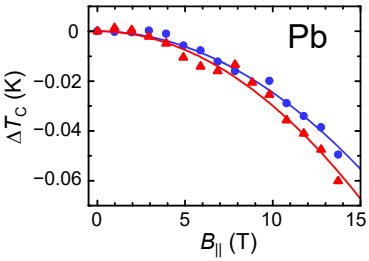


$$H_{Rashba} = \alpha\left(\vec{E}\times\vec{p}\right)\cdot\vec{s}$$

$\vec{E}$: surface electric field (// z)
$\vec{p}$: momentum (⊥ z)
$\vec{s}$: spin



Pb → robust superconductor in parallel magnetic field



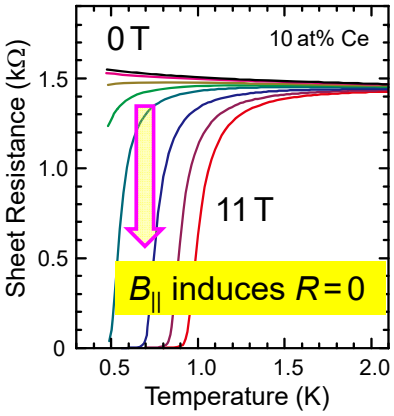
Theory for 2D Rashba superconductor
⇩
reproduces $\Delta T_c(B_{||})$

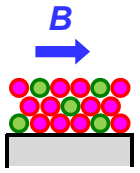
This work is the first experimental study on the Rashba-type 2D superconductors in monolayer metal films.

Sekihara et al.: Phys. Rev. Lett. **111**, 057005 (2013).
Sekihara et al.: J. Phys. Soc. Jpn. **84**, 064710 (2015).
Okamoto & Masutomi: 表面科学 **36**, 118 (2017)
Okamoto & Masutomi : 固体物理 **52**, 97 (2017)

Magnetic-field-induced superconductivity

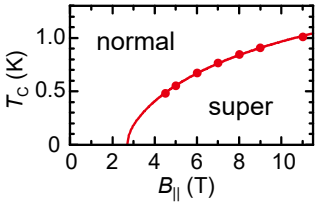
Conventional wisdom:
B suppresses superconductivity





Pb-Ce alloy
(d ~ 3 ML)

Niwata et al.:
Phys. Rev. Lett.
119, 257001 (2017).



Previous works on B-induced superconductivity

1. $Eu_{0.75}Sn_{0.25}Mo_6S_{7.2}Se_{0.8}$
   H.W. Meul et. al., PRL **53**, 497 (1984)
2. $CePb_3$
   C.L. Lin et. al., PRL **54**, 2541 (1985)
3. λ-$(BETS)_2Fe_{0.47}Ga_{0.53}Cl_4$
   S. Uji et. al., Nature **410**, 908 (2001)
4. κ-$(BETS)_2FeBr_4$
   T. Konoike et. al., PRB **70**, 094514 (2004)

Jaccarino-Peter mechanism (1962)

(*compensation of B_{int} by B_{ext}*)

our results

suppression of the spin-exchange scattering rate in magnetic fields

A new type of magnetic-field-induced superconductivity was demonstrated.

Hayashi Group

Masamitsu HAYASHI
(2016-)
Spintronics, Magnetism

THE UNIVERSITY OF TOKYO

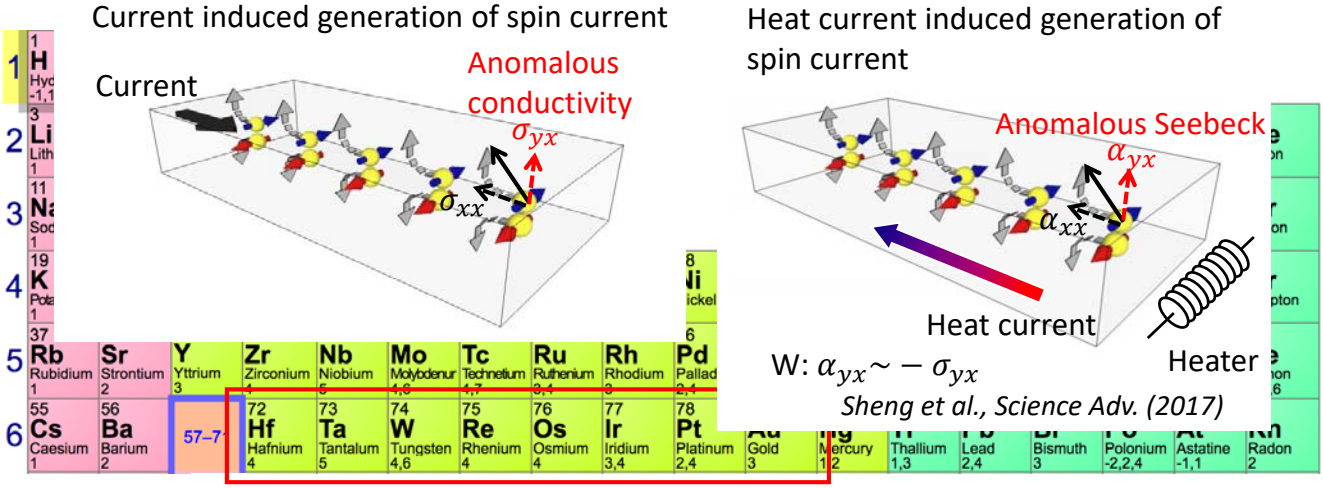
Spin conversion effects in spin orbit materials

Masamitsu Hayashi

Department of Physics, The University of Tokyo

Spin Hall effect

Current induced generation of spin current

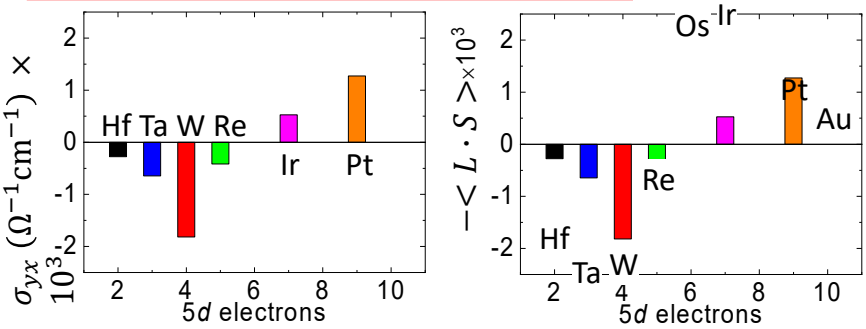


- Spin Nernst effect

Heat current induced generation of spin current

W: $\alpha_{yx} \sim -\sigma_{yx}$

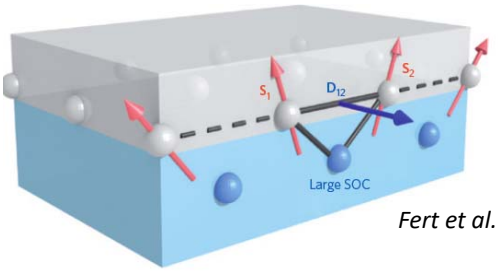
Sheng et al., Science Adv. (2017)



Kim et al., PRL (2016), Liu et al., APL (2015), Kawaguchi et al., APL (2018), Ishikuro et al., PRB (2019)

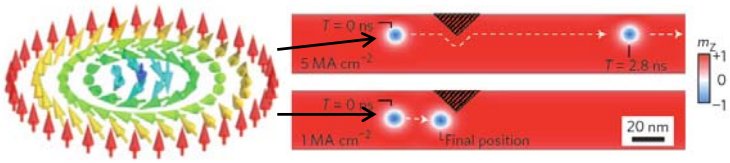
Chiral magnetism: Dzyaloshinskii-Moriya interaction (DMI)

- Interfacial Dzyaloshinskii-Moriya interaction

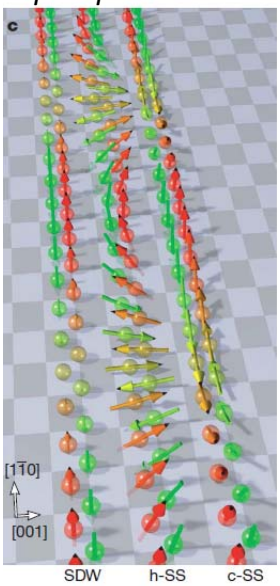


Fert et al. Nat. Nanotechnol. ***8****, 152 (2013)*

- *Skyrmions*

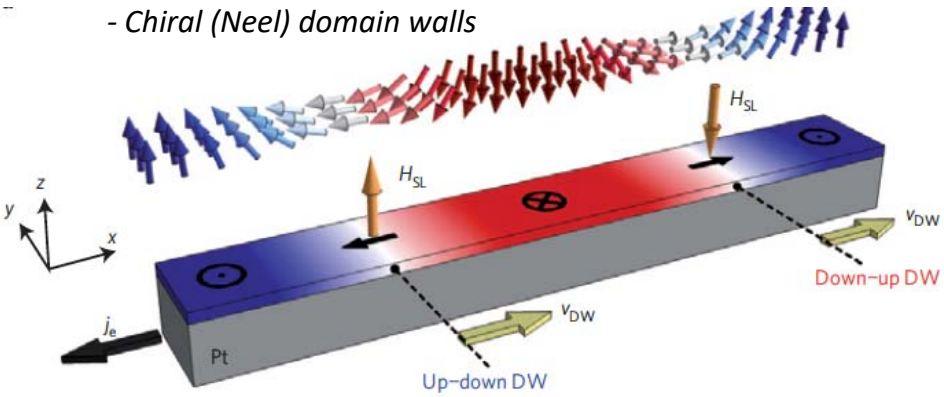


- *Spin spirals*



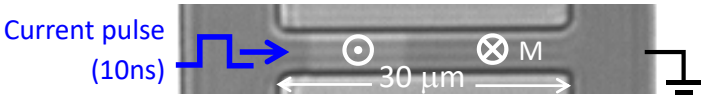
Bode et al., Nature 447, 190 (2007)

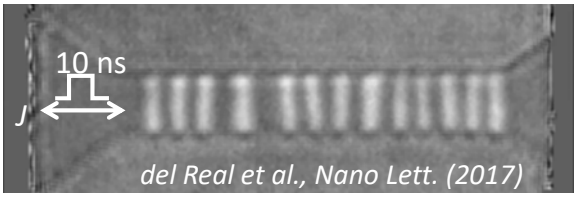
- *Chiral (Neel) domain walls*



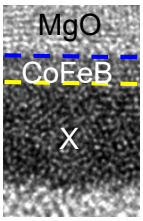
Emori et al. Nat. Mater. 12, 611 (2013)

Current induced motion of magnetic domains

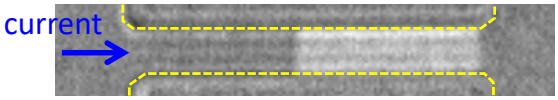




del Real et al., Nano Lett. (2017)

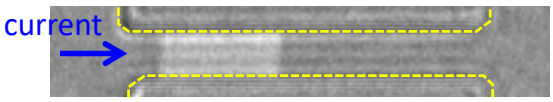


Hf/CoFeB/MgO

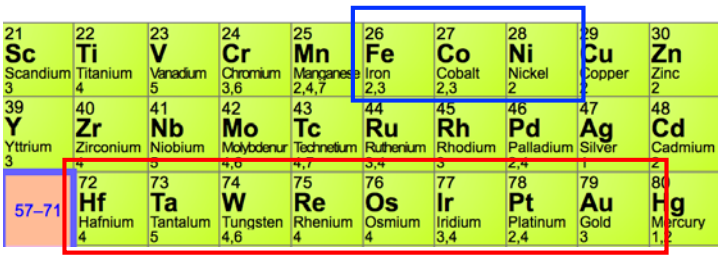


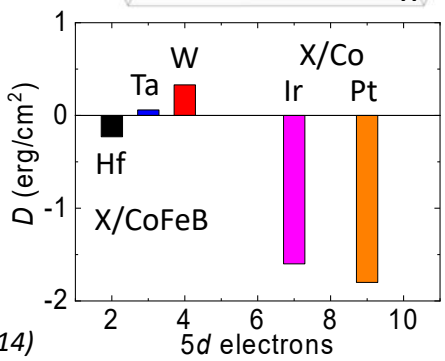
Left handed Neel wall

W/CoFeB/MgO



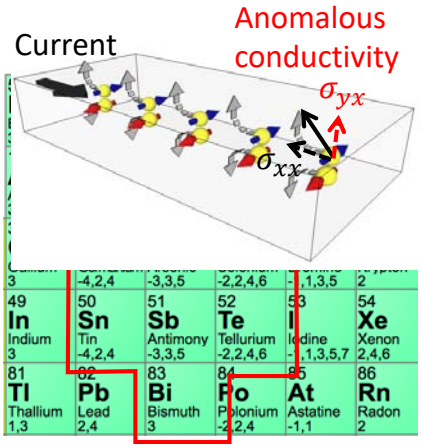
Right handed Neel wall

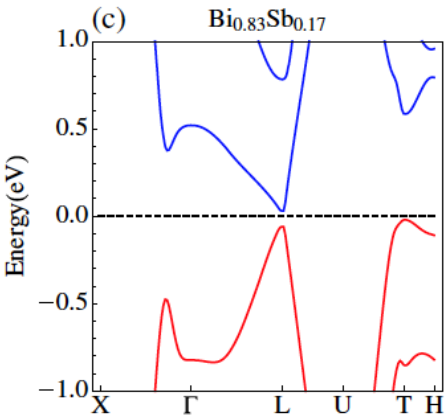




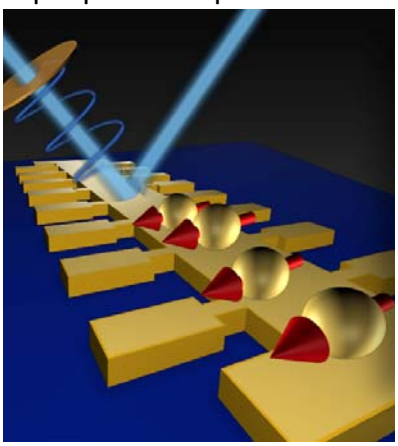
Kim et al., Natuer Mater. (2013), Torrejon et al. Nature Comm. (2014)
Torrejon et al., Nature Comm. (2016), Ishikuro et al., PRB (2019)

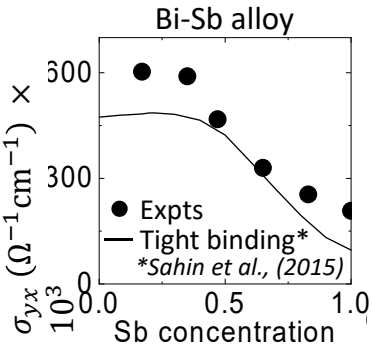
Dirac materials

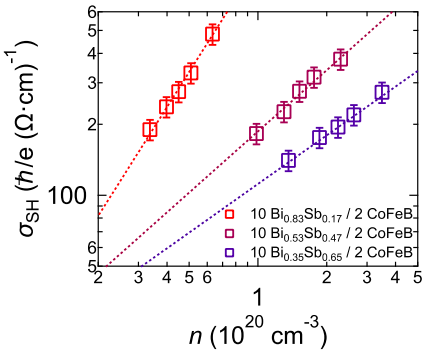


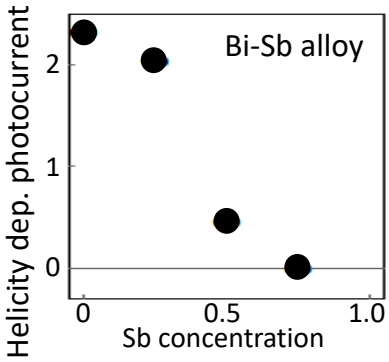


Circularly polarized light
→ Spin polarized photocurrent









Chi et al., Science Adv. in press

Hirose et al., APL (2018), in prep.

Kobayashi Group

Kensuke KOBAYASHI
(2019-)
(Inst Phys Inteligence, CA; Osaka Univ)
Solid-State Device Physics

On-chip Condensed-matter Physics

Kensuke KOBAYASHI

Institute for Physics of Intelligence (IPI) & Department of Physics, The University of Tokyo
Department of Physics, Osaka University [cross appointment]

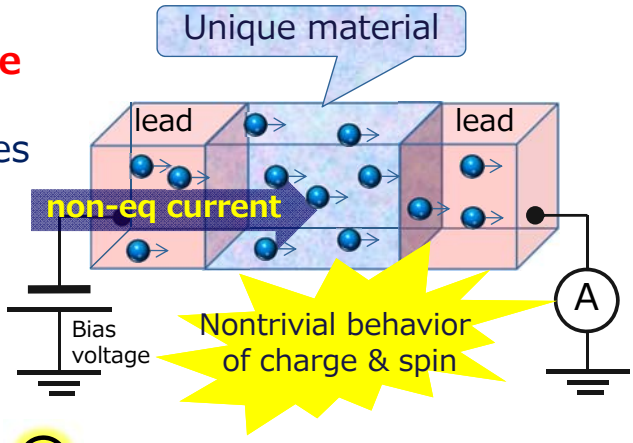
Motivation

Recent progress in **material science** & **nanotechnology** enables us to explore physics on solid state devices ("**on-chip**") as pursued in

- Spintronics
- Strongly correlated systems
- Molecular electronics

We are facing **non-equilibrium quantum many-body systems**.

This leads us to new physics & new technology.



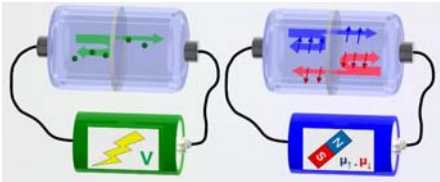
Non-equilibrium = States subject to flow and/or change. It is at the heart of electronics, chemical reactions, life, and so on, and remains unexplored.

Recent achievements

Quantum nano-devices (Mesoscopic systems) combined Precise non-equilibrium fluctuation measurement

Spin shot noise

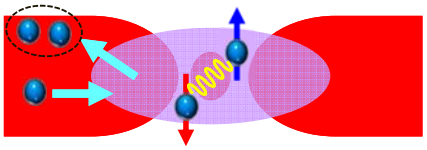
Current fluctuation tells the reality of **spin current**.



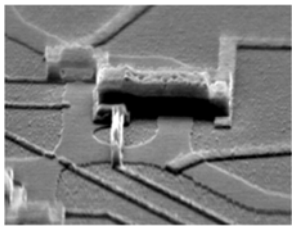
Arakawa *et al.*, *PRL* **114,** 016601 (2015).

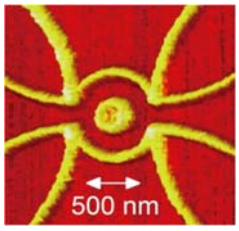
Quantum liquid

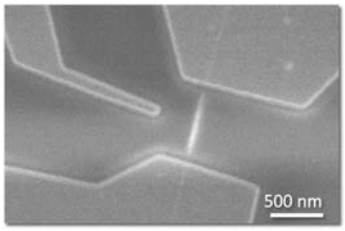
Most strict test of non-eq. quantum many-body theory carried out in **Kondo-correlated quantum dot**.

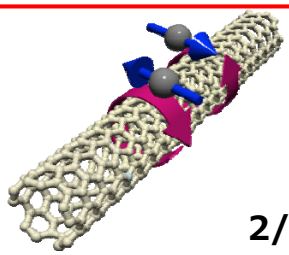


Ferrier *et al.*, *Nat. Phys.* **12**, 230 (2016).
Ferrier *et al.*, *PRL* **118**, 196803 (2017).
Hata *et al.*, *PRL* **121,** 247703 (2018).

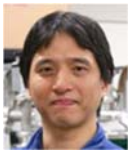








Takagi - Kitagawa Group



Hidenori TAKAGI (CA: Max Planck Inst)
Kentaro KITAGAWA
(2011-)
Strongly Correlated Electron Physics,
Quantum Critical Phenomena

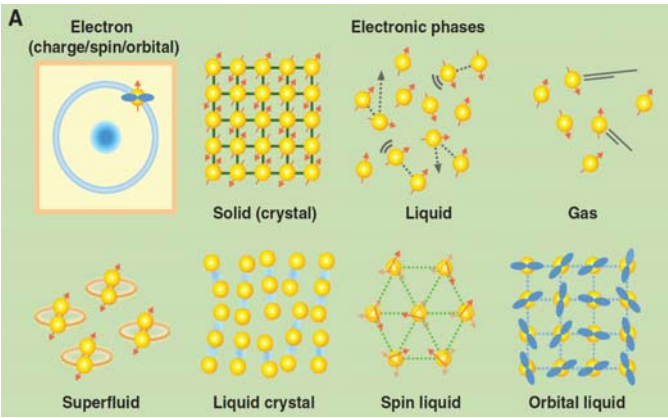
Takagi-Kitagawa Group

Feb 13/2020

Lecturer Kentaro Kitagawa, Res. Assoc. Naoka Hiraoka, 3 PhD and 3 MSc students

Cross appointment with Max Planck Institute, Germany
MPI-UBC-MPI center for quantum materials, sent 8 undergraduate students in 5 yrs

Materials physics
taking materials-based approach rather than probe-based



Takagi & Hwang, Science 327 (2010) 1601.

Exotic phases of correlated *d*-electrons in novel transition metal (TM) compounds

Interacting via Coulomb repulsion U ~eV for d-electrons

From 3d to 4d & 5d with strong spin-orbit coupling

3d U=3-10eV >~ E_F=1-2 eV >> λ_{so}~ a few 10 meV

Large U — Small SO

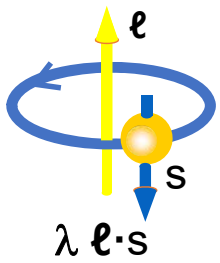
High-Tc Cu oxides

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd
Ln	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg

Small U — Large SO

5d and 4d: spin-orbit coupling $\propto Z^2$, λso~ 0.5 eV

U = ~ 2-3eV, E_F = 1-2eV



Form "spin-orbital entangled" state
Localized: Spin-orbital liquid, exotic spin-orbital order
Itinerant: Correlated topological (semi-)metal

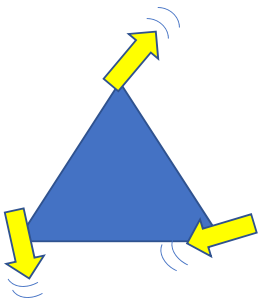
spin-orbital Mott state in Sr_2IrO_4 with $5d^5$ J_{eff}=1/2 (s=1/2 l_{eff}=1)
Science 323, 1329 (2009). Cited 970 times.

Takagi-Kitagawa Group

Major 3 discoveries: 1. Spin–orbital entangled J_{eff}=1/2 quantum liquid on 2D honeycomb $H_3LiIr_2O_6$

A.Kitaev Annals of Physics 2 (2006).

Quantum Spin Liquid

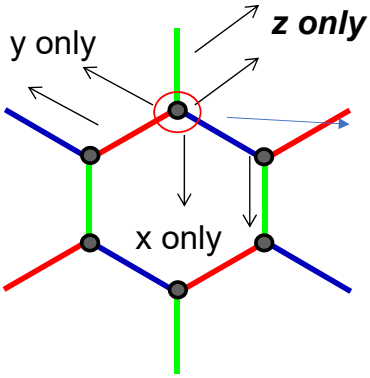


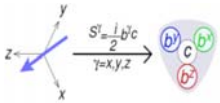
T=0 quantum mechanically fluctuating due to a frustration without magnetic ordering

Concept and realization of Kitaev quantum spin liquids
Hidenori Takagi, Tomohiro Takayama, George Jackeli, Giniyat Khaliullin and Stephen E. Nagler

Nature Rev. Phys. (2019). Cited 37 times

Kitaev Quantum Spin Liquid – holy grail





Spin fractionalize into Majorana fermions (particle =antiparticle)

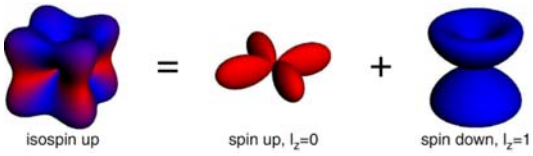
S=1/2 on honeycomb
3 bonds with orthogonal Ising axes *x, y and z*

conflict of 3 bonds-> QSL

Takagi-Kitagawa Group

Major 3 discoveries: 1. spin–orbital entangled J_{eff}=1/2 quantum liquid on 2D honeycomb $H_3LiIr_2O_6$

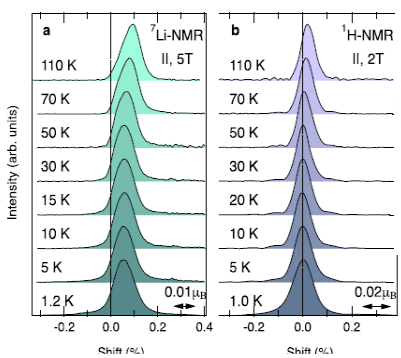
SO entangled J_{eff}=1/2 (s=1/2, l_{eff}=1), $5d^5$ Ir^{4+}

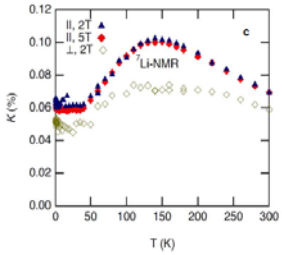


on honeycomb connected by O_2

= "Kitaev" Jackeli et al, PRL

$H_3LiIr_2O_6$





Interacting J_{eff}=1/2 there but
No symmetry breaking to the limit of T=0

A spin–orbital–entangled quantum liquid on a honeycomb lattice

K. Kitagawa[1*], T. Takayama[2*], Y. Matsumoto[2], A. Kato[1], R. Takano[1], Y. Kishimoto[3], S. Bette[2], R. Dinnebier[2], G. Jackeli[2,4] & H. Takagi[1,2,4]

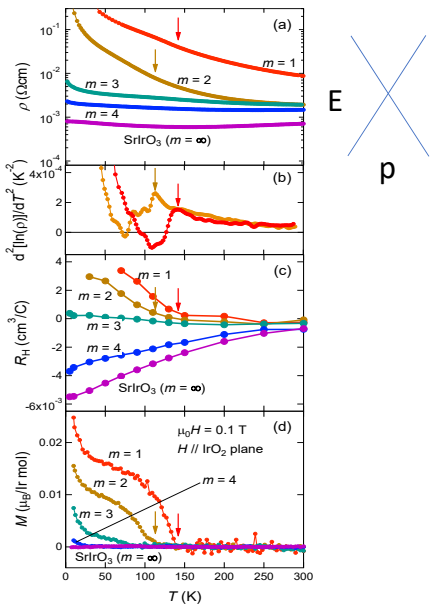
Nature 554, 341(2018), cited 101 times

Discovered also 3D analogue of 2D honeycomb iridate,
"hyperhoneycomb" β-Li_2IrO_3 PRL 114, 077202(2015), cited 248 times

Takagi-Kitagawa Group

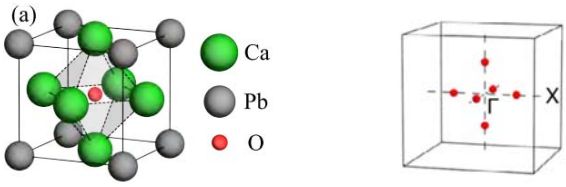
Major 3 discoveries: 2. (Correlated) Dirac Semimetals made of 4d and 5d electrons

Itinerant J_{eff}=1/2 3D $SrIrO_3$ ($5d^5$)
hosts "correlated" Dirac electrons
Dimensionality control to to a magnetic ins.



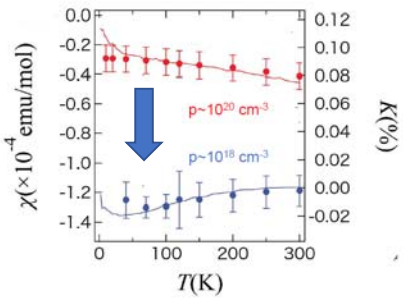
PRL 114 7209 (2015). Cited 115 times

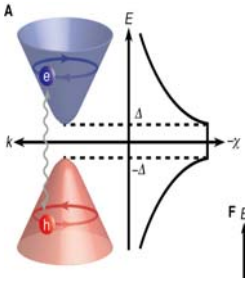
Antiperovskite Sr_3PbO ($4d^0$)
Weakly correlated 3D Dirac electrons
Kariyado & Ogata, JPSJ (2011).



Exp. Quantum oscillation. PRB 98, 115203 (2018).

Orbital origin of giant diamagnetism of Dirac electrons verified by NMR after more than 50 years of history





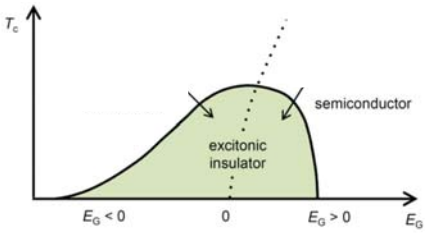
Takagi-Kitagawa Group

Major 3 discoveries: 3. Excitonic Insulator $5d^0$ Ta_2NiSe_5

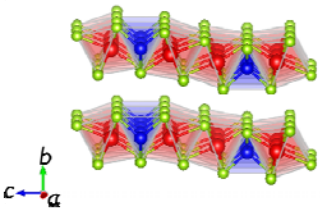
Excitonic Insulator: spontaneous condensation of excitons (e-h pairs) in narrow gap semiconductors/semimetals

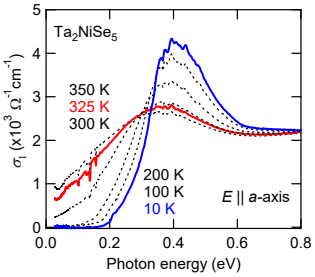
Exciton binding E_B

>
band gap E_G
to create e-h pair



Ta_2NiSe_5 : 1D structure with e & h chain
large carrier mass
-> large E_B~0.2eV





T<Tc=328 K
Excitation gap
= exciton binding E_B
opens

Nature Com. 8, 14408 (2017) Cited 67 times

Many pump & probe studies followed
Science, Nature commun. , PRL….

Magnetic analogue: Excitonic magnetism in $Ag_3LiRu_2O_6$ ($4d^4$)
condensation of J_{eff}=1 excitons

Takagi-Kitagawa Group

Lecturer Kentaro Kitagawa, Res. Assoc. Naoka Hiraoka, 3 PhD and 3 MSc students

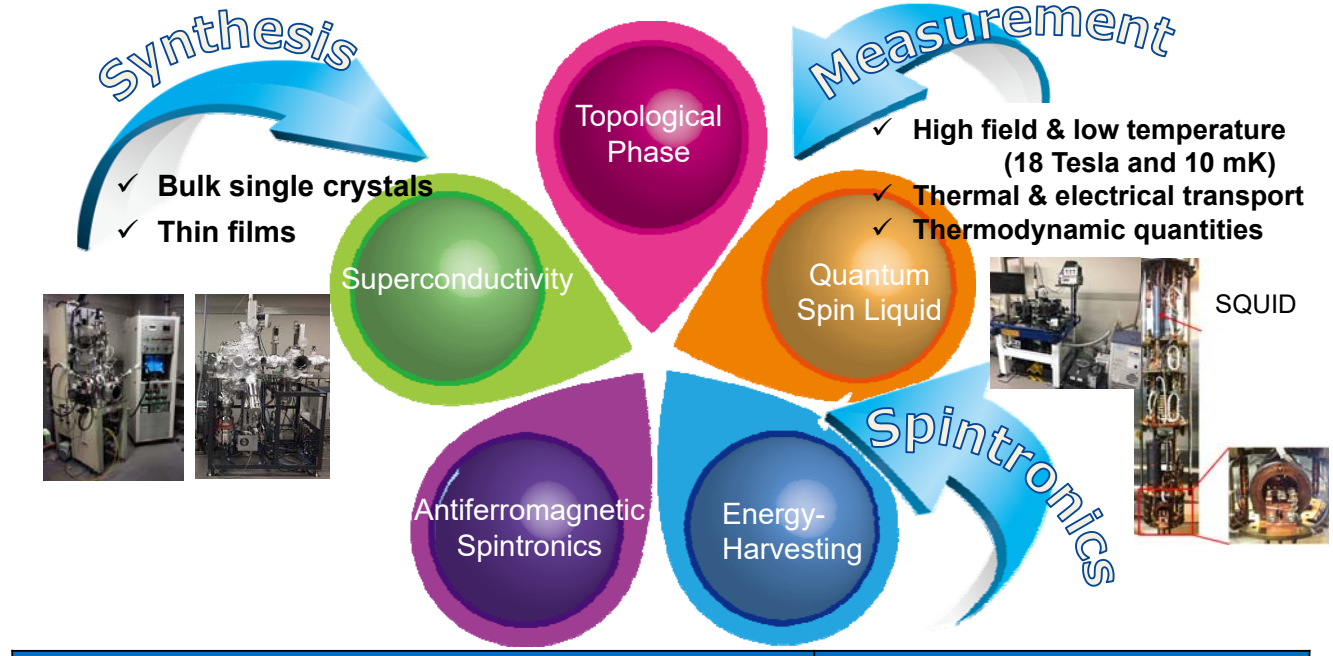
Challenge next 5 years:

Materials discovery beyond Kitaev and excitonic paradigm

Nakatsuji Group

Satoru NAKATSUJI
(2019-)
(CA; Inst Solid State Phys; Johns Hopkins Univ)
Topological Physics, Superconductivity, Spintronics

Nakatsuji Group (June '19 ~)

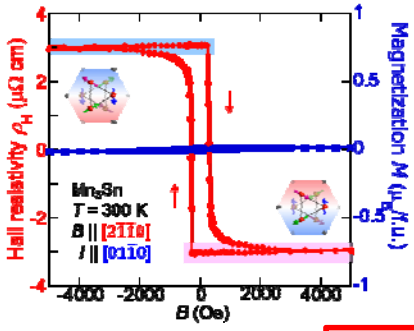


Total 22 Members	Affiliation, Exchange
1 Research Associate	☐ Department of Physics, U. Tokyo
2 Project Research Associates	☐ ISSP, U. Tokyo
1 Visiting Professor	☐ Johns Hopkins University
5 Postdocs, **10** Students, **2** Secretaries	☐ Trans-scale Quantum Science Inst.

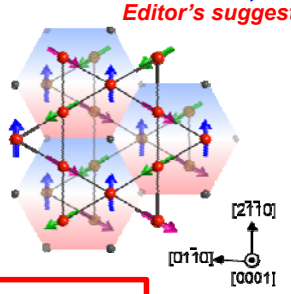
Large Responses in Antiferromagnet

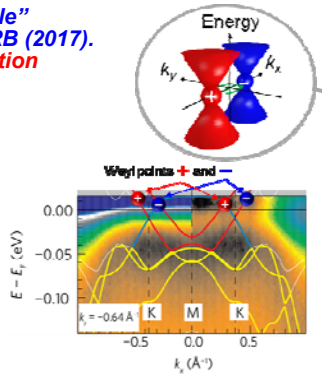
Anomalous Hall effect in the Weyl AFM Mn_3Sn

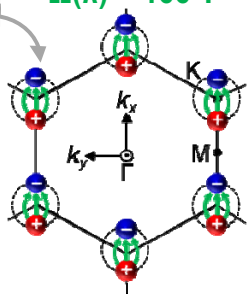
"Mn_3Sn" Nakatsuji et al., Nature (2015).
"Mn_3Ge" Kiyohara et al., PRApplied (2016).
"Mn_3Sn Film" Higo et al., APL (2018). *Featured Articles*



"Cluster octupole"
Suzuki et al., PRB (2017).
Editor's suggestion





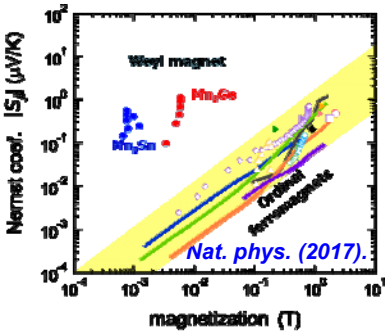


$$\rho_H = R_0 B + R_S \mu_0 M + \rho_H^{AF} = -3\ \mu\Omega\text{cm}$$

~ 0.1 μΩcm

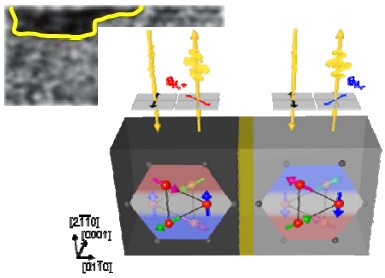
"Magnetic Weyl fermion" Kuroda, Tomita et. al., Nat. Mater. (2017).

Anomalous Nernst



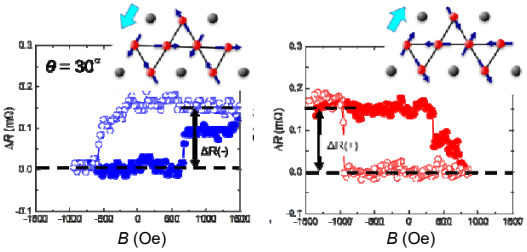
Nat. phys. (2017).

Magneto-optical Kerr



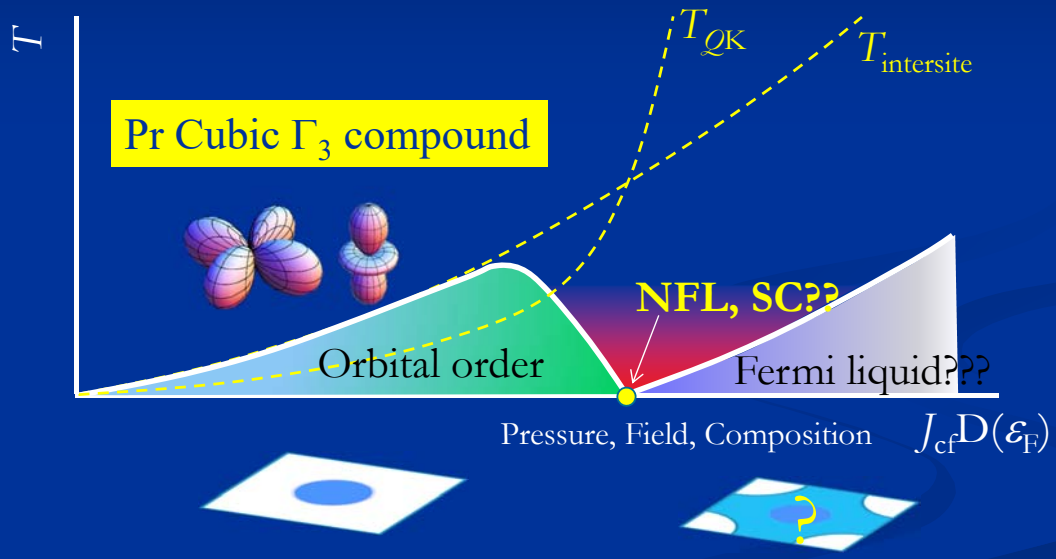
"Imaging of the octupole domain"
Higo et al., Nat. photon. (2018).

Magnetic spin Hall



"AF spin structure dependent SHE"
Kimata et al., Nature (2019).

Quantum Criticality in Quadrupolar Order?



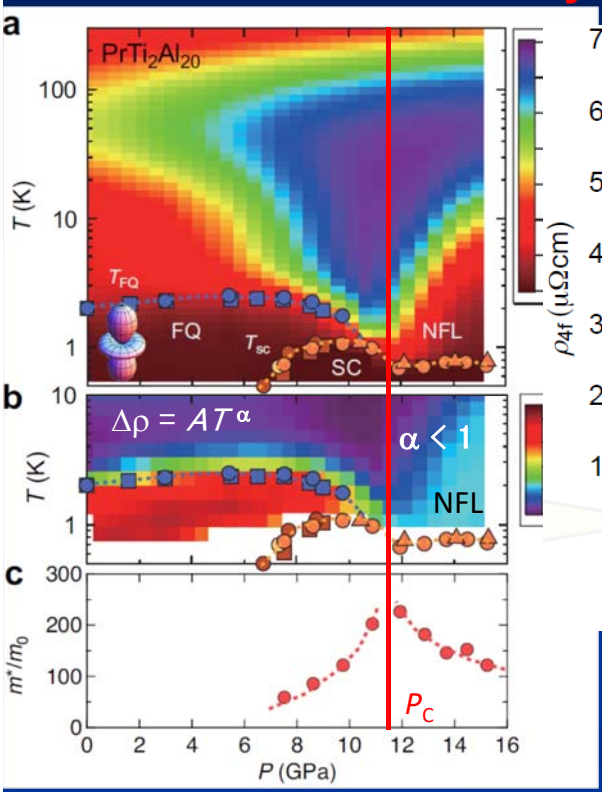
Can we tune the hybridization?

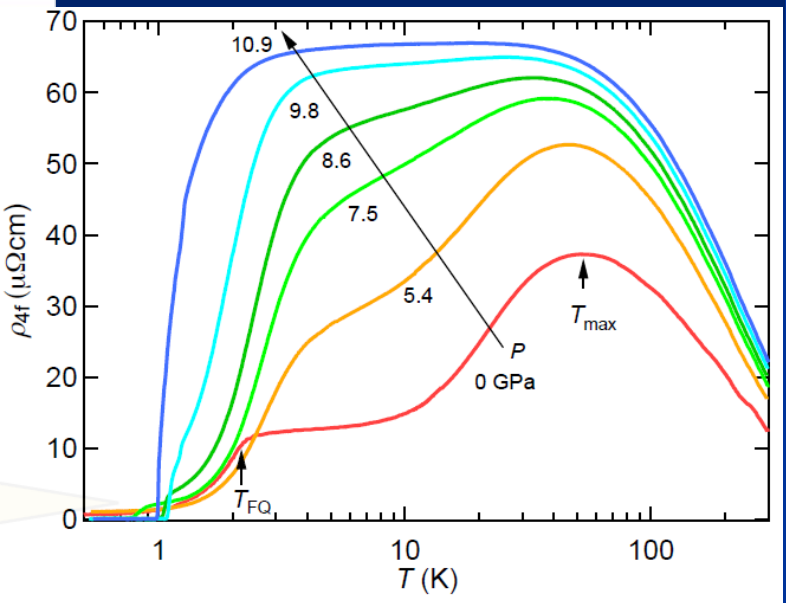
⇔ Pr compounds: Usually Strongly Localized

Multipolar Quantum Criticality in PrT_2Al$_{20}$

Orbital Quantum Criticality

PRL (2014) (2019) Nat. Com. (2019)

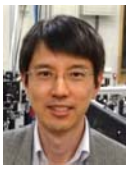




Tc/W ~ 10 %

High Tc Superconductivity

Shimano Group



Ryo SHIMANO

(2004-)

(Cryogenic Res Center)

Laser and Terahertz Spectroscopy Physics

Ryo Shimano

Cryogenic Research Center and Department of Physics

東京大学 THE UNIVERSITY OF TOKYO

Laser and THz spectroscopy of quantum materials

~Understanding and light-control/creation of Macroscopic Quantum States in Matter~

Laser-based time-resolved spectroscopy, THz magneto-optics,
Development of intense THz light source, Nonlinear THz spectroscopy

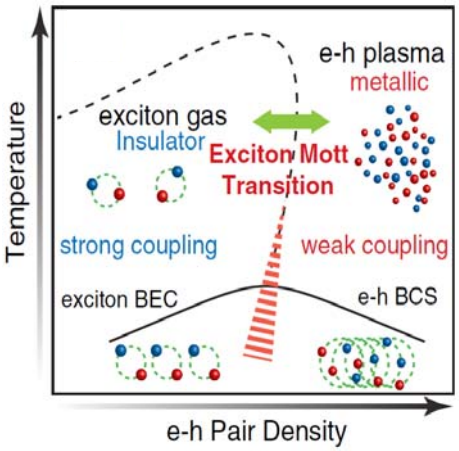
Research Highlights in past 10 years

- Elucidation of Excitonic Mott transition (PRL2012,PRL2017),
  Realization of **e-h BCS state** (Nonequilibrium Ex-Insulator) (PRL2019)
  in a semiconductor
- Quantum Faraday and Kerr rotation (**Optical Quantum Hall Effect**) in 2DEG, graphene (PRL2010,NatCom2013,PRL2018)
- Discovery of spin-current type **electromagnon** in multiferroic material (NatPhsy2012)
- Discovery of **Higgs mode in superconductors**
  s-wave(PRL2013,Science2014,PRL2019), d-wave(PRL2018), multibands

Ongoing project

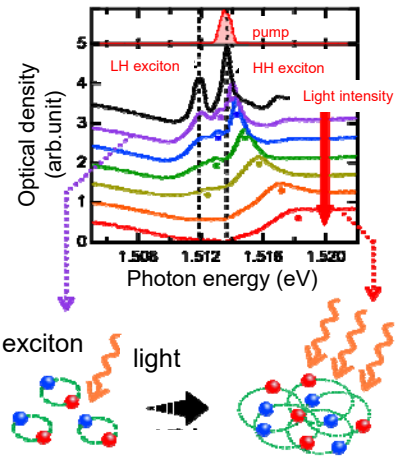
Nonequilibrium superconductivity, Floquet engineering,
Topological nonlinear optics

Matter phases in e-h system in photoexcited semiconductors

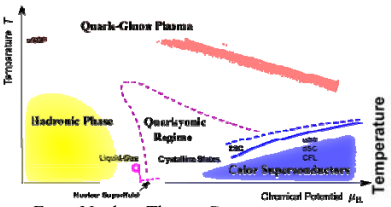


Keldysh&Kopaev (1965)

Murotani et al. PRL2019 (Editor's suggestion)

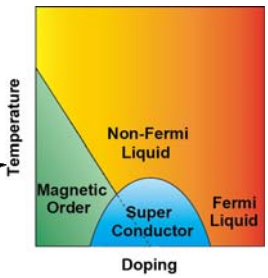


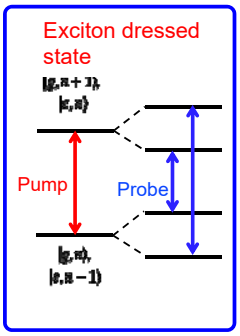
Quark matter

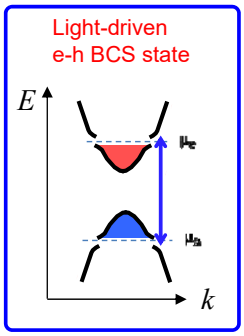


From Nuclear Theory Group
in the Dept. of Physics, UTokyo

High-*Tc* superconducting cuprates

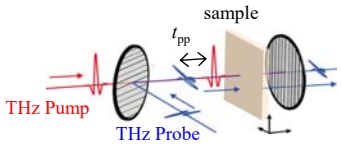




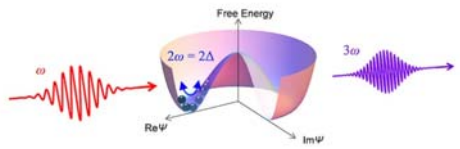


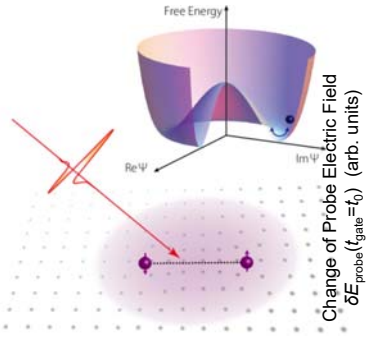
Higgs mode in superconductors

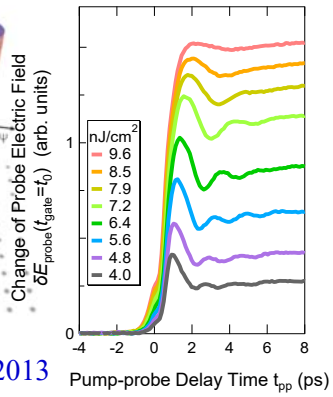
Initial prediction: P.W. Anderson, Physical Review 1958



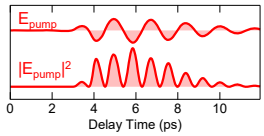
Matsunaga et al, Science2014

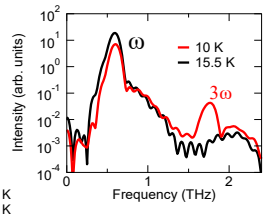


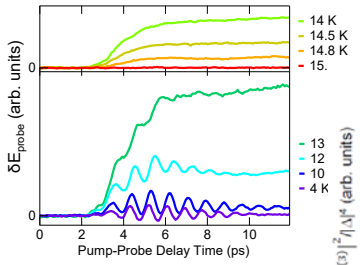


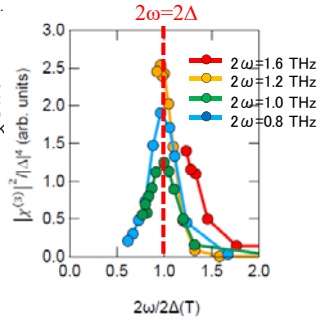


Matsunaga et al., PRL2013

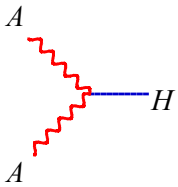








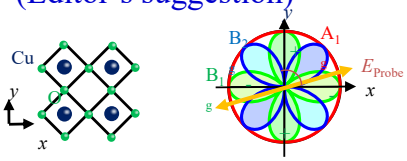
Time-domain observation of Higgs mode oscillation after a sudden quench

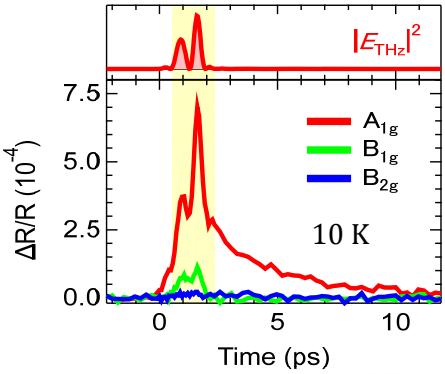


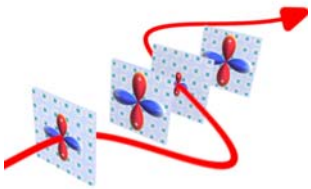
Discovery of two photon coupling with Higgs mode

Higgs mode in high Tc cuprates $Bi_2Sr_2CaCu_2O_x$

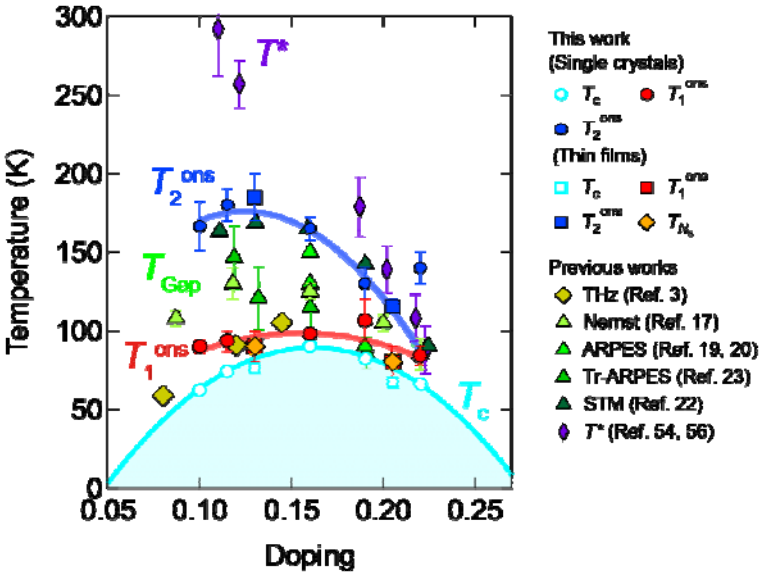
Katsumi et al. PRL2018 (Editor's suggestion)







Two onset temperatures are identified.



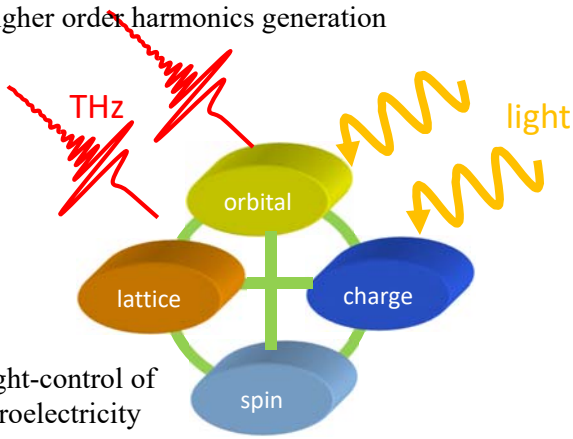
Katsumi et al., arXiv:1910.07695.

Picosecond snapshot of superconducting order parameter.

Toward light-control of quantum matter

Nonequilibrium superconductor
collective modes(Higgs, N-G)
competing order, hidden phase
pairing symmetry（p,d,.. ）
light-induced superconductivity

Floquet Engineering
control of topological number
higher order harmonics generation



Light-control of ferroelectricity

Ultrafast control of multiferroics
electromagnon, skirmion

Light-control of magnetism

International Collaboration

Université de Paris
PRINCETON UNIVERSITY
BROOKHAVEN NATIONAL LABORATORY
MAX PLANCK INSTITUTE FOR SOLID STATE RESEARCH

-Co-director of MPI-UBC-UTokyo Centre for Quantum Materials

MAX PLANCK – UBC – UTokyo CENTRE FOR QUANTUM MATERIALS
STUTTGART • VANCOUVER • TOKYO

- In charge for exchange program between Ecole Normale Superieure (ENS), Paris, and the University of Tokyo (UTokyo) on Physics

Annual Workshop, Student Exchange, Summer/Winter School, etc.