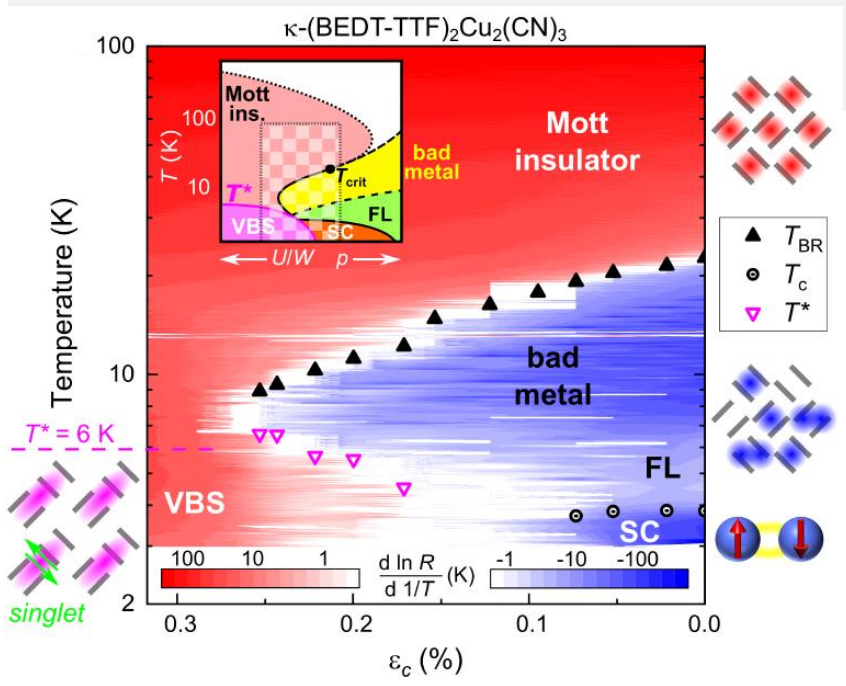
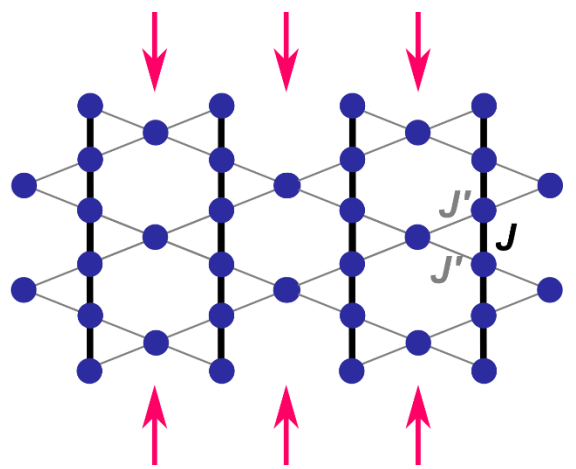


Spectroscopy Under Strain: New Spin on Correlated Electrons

Stress Reduces Frustration



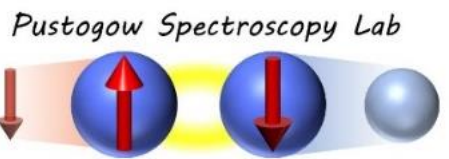
Science **372**, 276-279 (2021)
Solids **3**, 93-110 (2022)
Nat. Commun. **14**, 1960 (2023)



Phys. Rev. Lett. **131**, 256501 (2023)



Andrej Pustogow
Institute of Solid State Physics
TU Wien, Austria

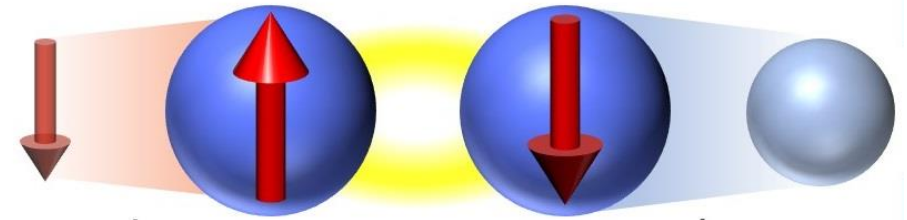


Ass. Prof. Andrej Pustogow

INSTITUT FÜR FESTKÖRPERPHYSIK
INSTITUTE OF SOLID STATE PHYSICS

Technische Universität Wien Vienna University of Technology

Correlated Electron Systems



spin

charge

Nuclear Magnetic Resonance

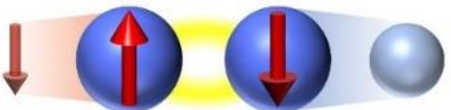
Optical Spectroscopy



Karlsplatz
Vienna, Austria

my office

Pustogow Spectroscopy Lab



2024-0/-23

Andrej Pustogow

Y. Kawasugi
H. Sakurakoji
N. Tajima



- Toho University, Japan
 - RIKEN, Japan

Fabian Jerzembeck
Dmitry Sokolov
Clifford W. Hicks
Andrew P. Mackenzie



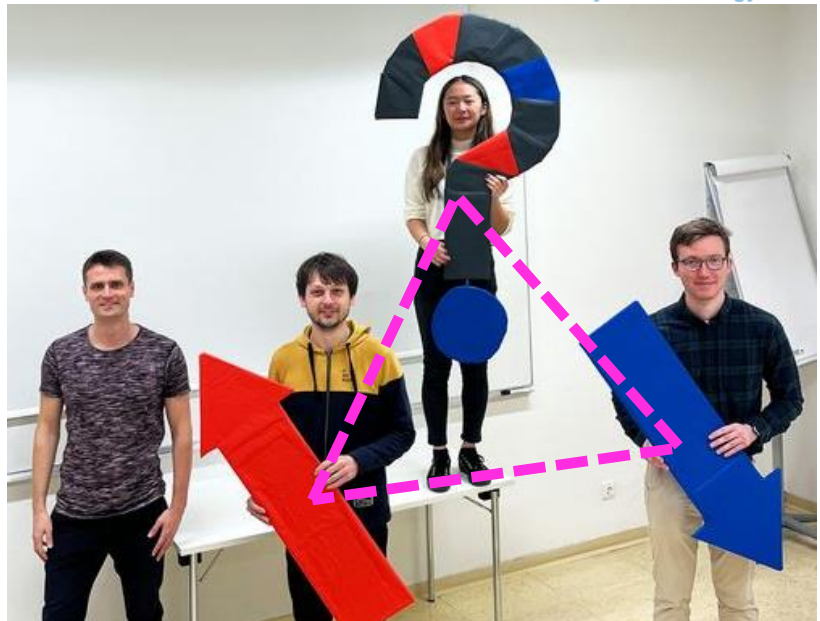
Max-Planck-Institute for
 Chemical Physics of Solids
 Dresden, Germany



Pascal Puphal
 MPI Stuttgart, Germany

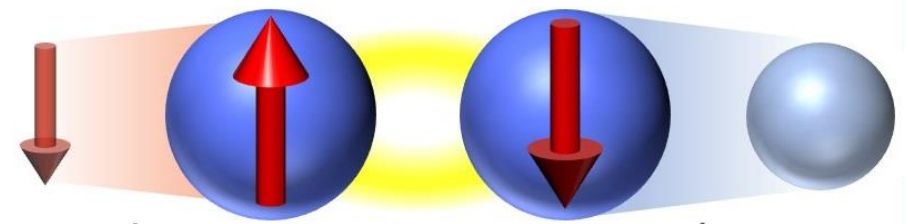
INSTITUT FÜR FESTKÖRPERPHYSIK
INSTITUTE OF SOLID STATE PHYSICS

Technische Universität Wien Vienna University of Technology



Cornelius Krellner
 Universität Frankfurt

Correlated Electron Systems



spin

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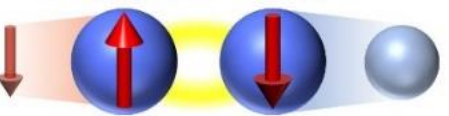
Alexander von Humboldt
 Stiftung/Foundation



Yongkang Luo
Aaron Chronister
Yue-Shun Su
Stuart E. Brown

UC Los Angeles, USA

Pustogow Spectroscopy Lab

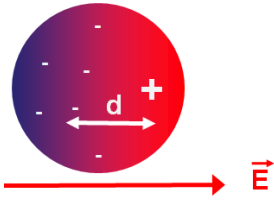


2024-08-23

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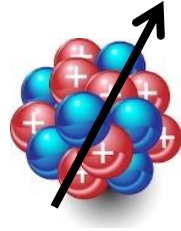


dipole reorientation



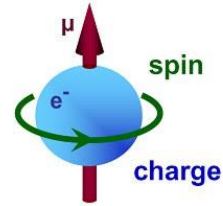
audio

nuclear spins

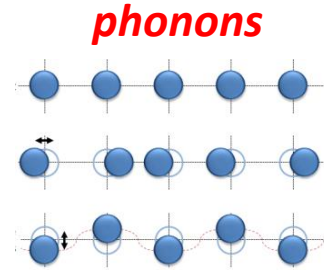


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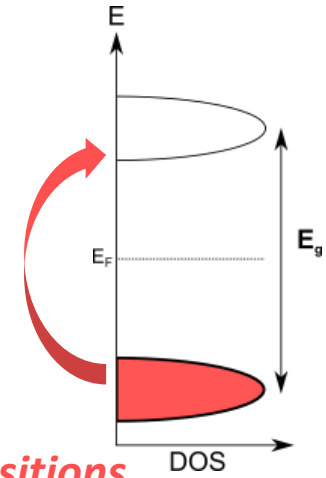
electron spins



microwave



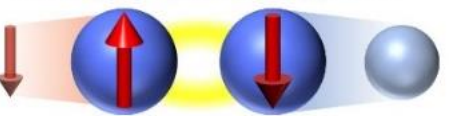
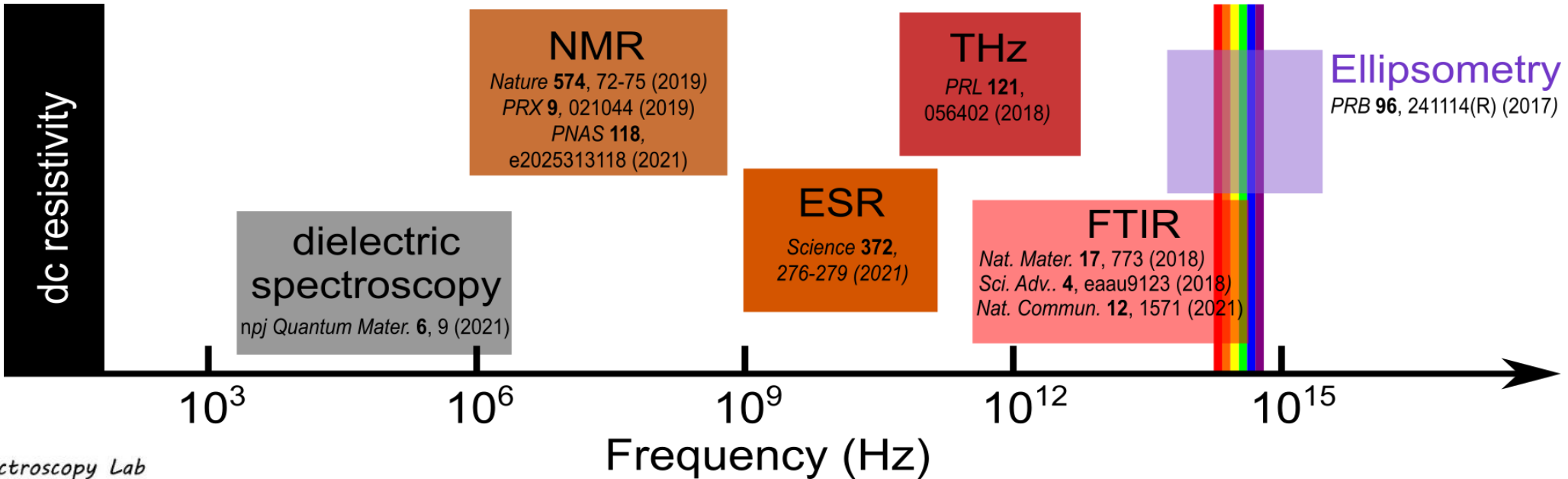
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electronic transitions

VIS

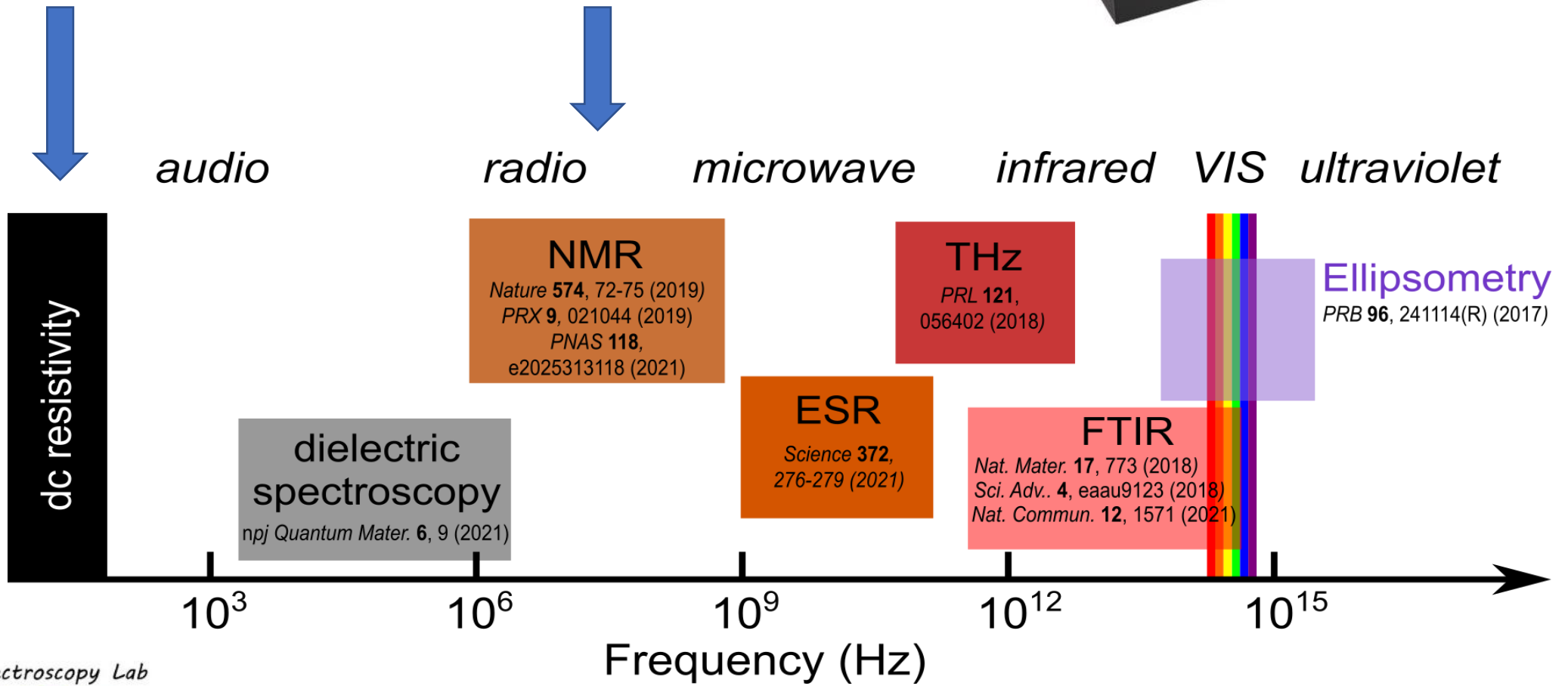
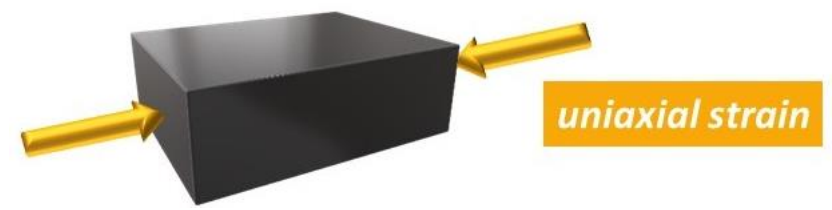
ultraviolet



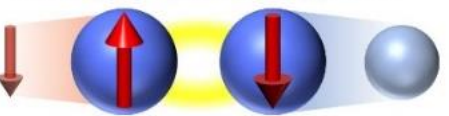
Experiments at TU Wien

J. Phys. Soc. Jpn. **92**, 065001 (2023)
Nat. Commun. **14**, 1960 (2023)

PRL **131**, 256501 (2023)



Pustogow Spectroscopy Lab



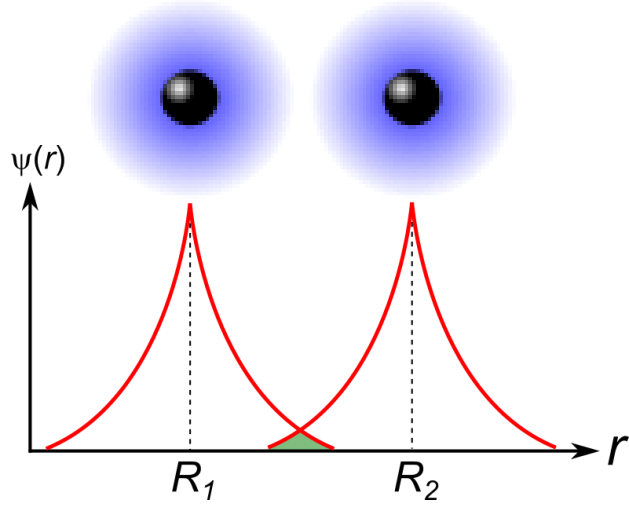
2024-08-23

Andrej Pustogow

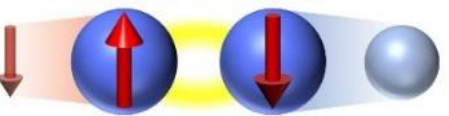
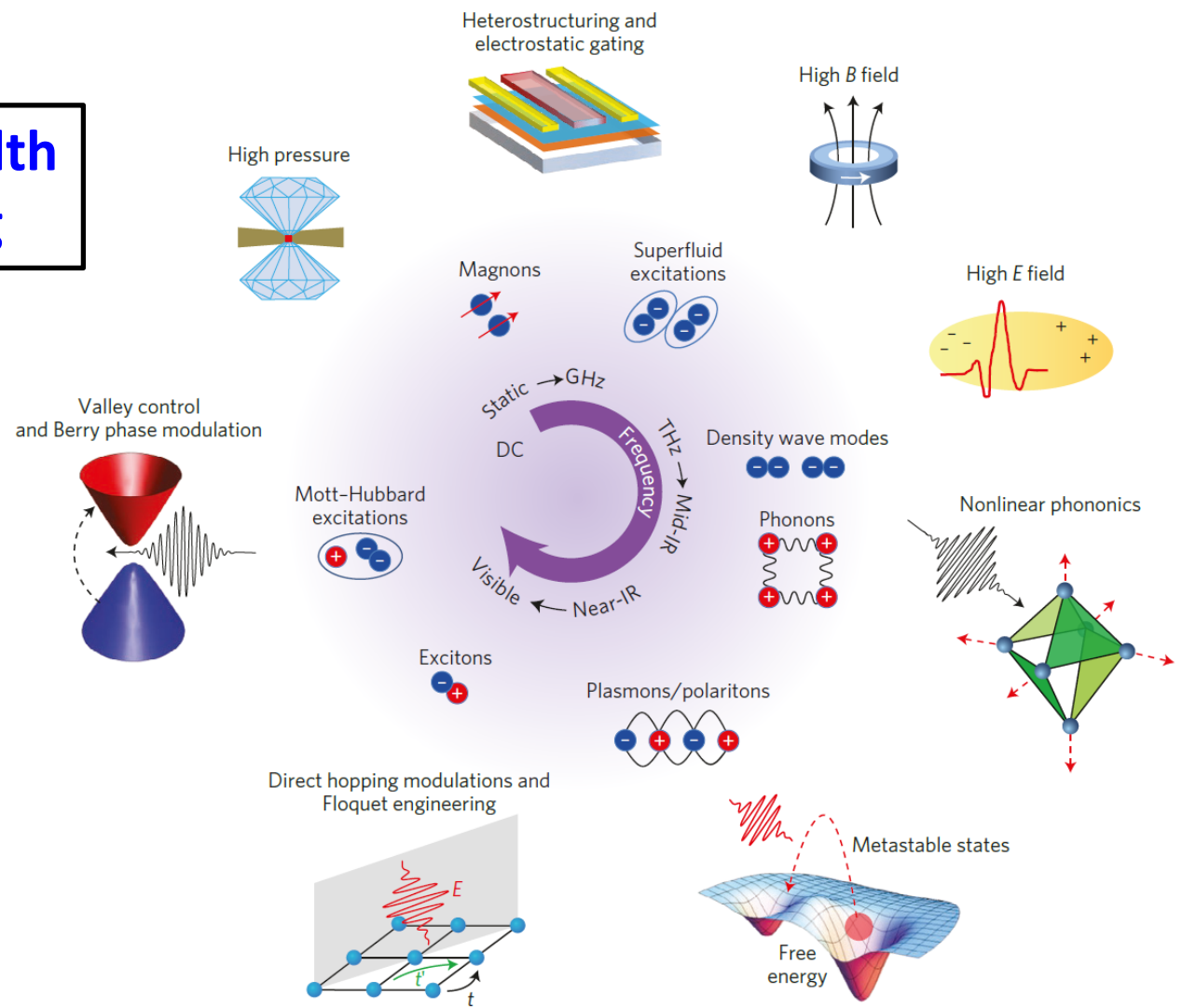
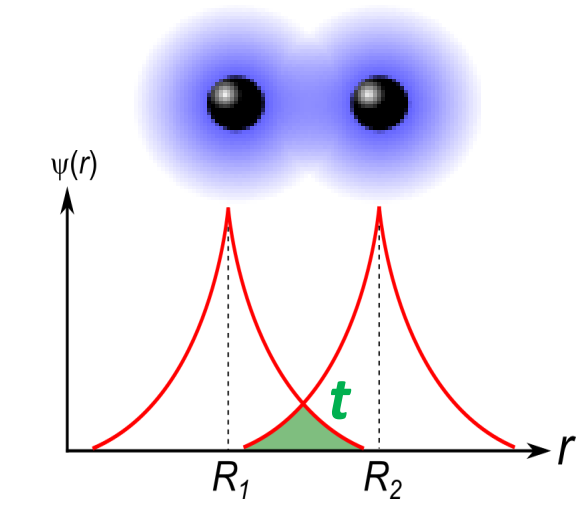
Towards properties on demand in quantum materials

Nat. Mater. **16**, 1077-1088 (2017)

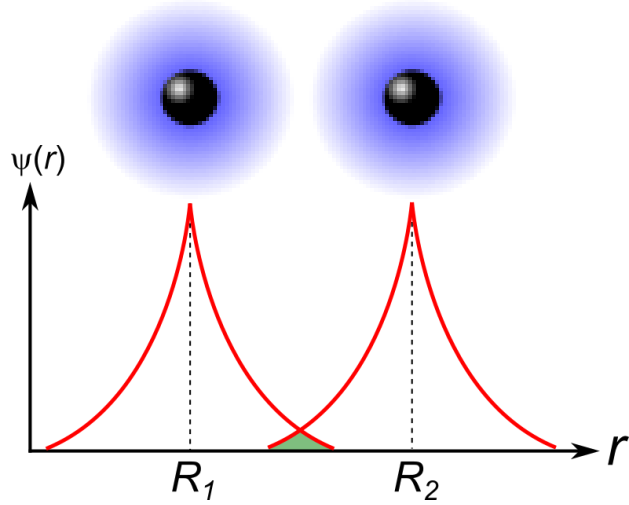
D. N. Basov^{1*}, R. D. Averitt^{2*} and D. Hsieh^{3*}



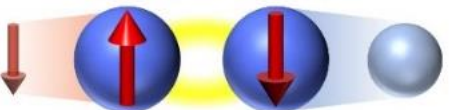
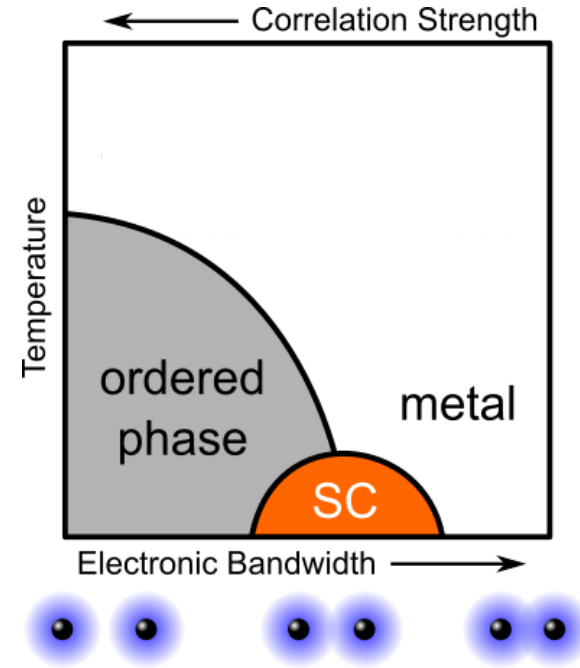
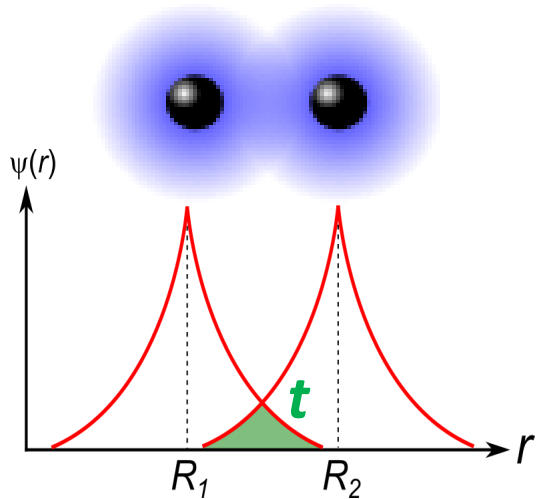
bandwidth tuning



Correlated Electron Systems

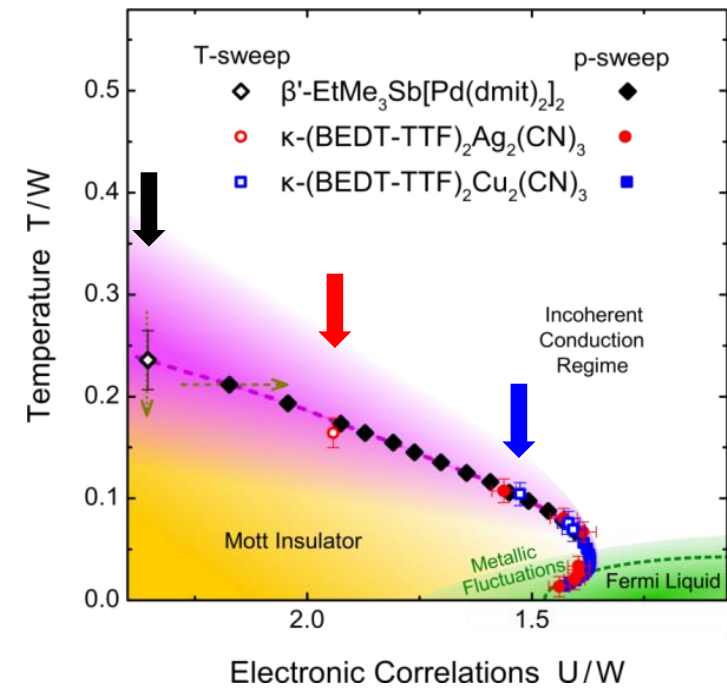


bandwidth tuning

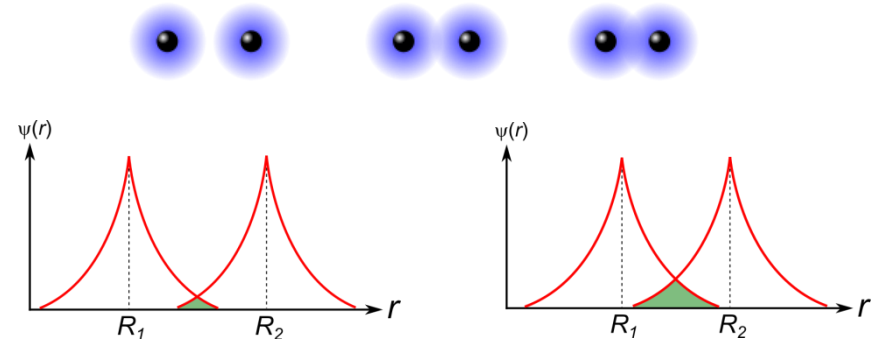
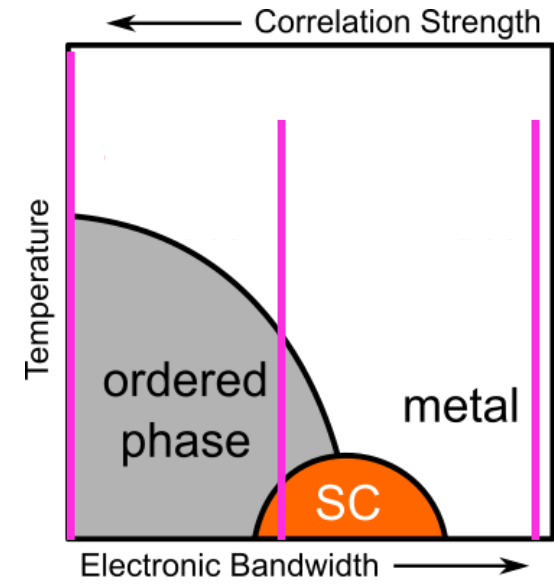


Chemical Tuning

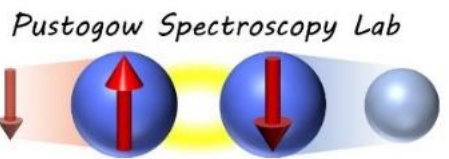
- synthesize samples at different positions in phase diagram



Quantum spin liquids unveil the genuine Mott state
 Pustogow *et al.*, *Nat. Mater.* **17**, 773-777 (2018)



Pustogow *et al.*, *Nat. Mater.* **17**, 773-777 (2018)
Nat. Commun. **12**, 1571 (2021)
npj Quantum Mater. **6**, 9 (2021)
 Saito *et al.*, *J. Mater. Chem. C* **9**, 10841 (2021)
Crystals **11**, 817 (2021)



2024-08-23

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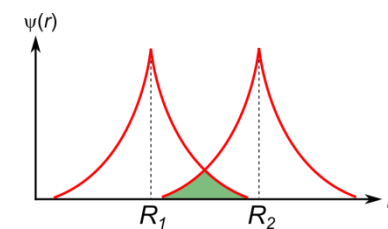
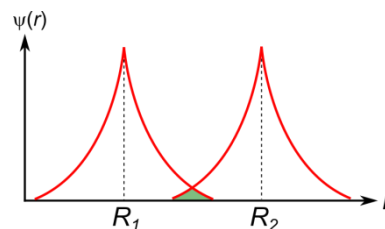
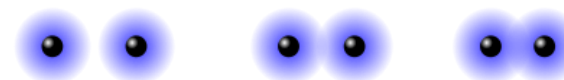
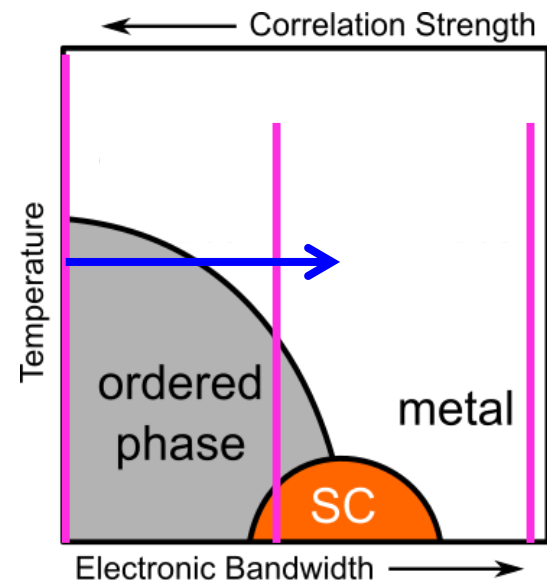
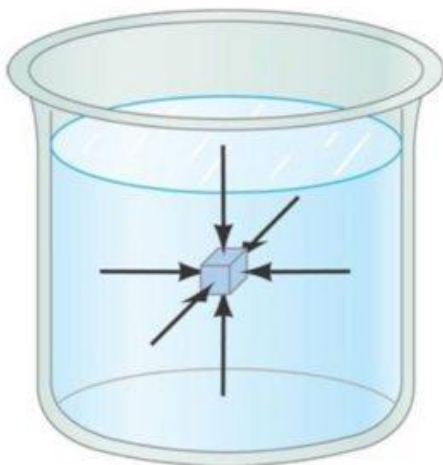
Correlated Electron Systems

Chemical Tuning

- synthesize samples at different positions in phase diagram

Hydrostatic Pressure Tuning

- difficult to combine with spectroscopy
- no ‚negative pressure‘ ($p > 0$)



Pustogow *et al.*, *Nat. Mater.* **17**, 773-777 (2018)
Nat. Commun. **12**, 1571 (2021)
npj Quantum Mater. **6**, 9 (2021)
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Crystals **11**, 817 (2021)



Correlated Electron Systems

Chemical Tuning

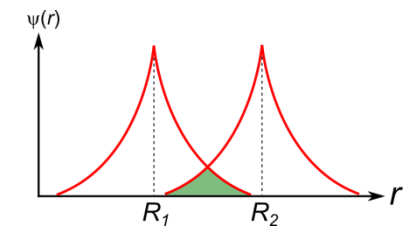
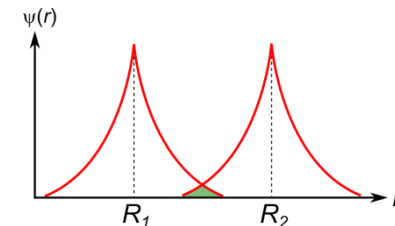
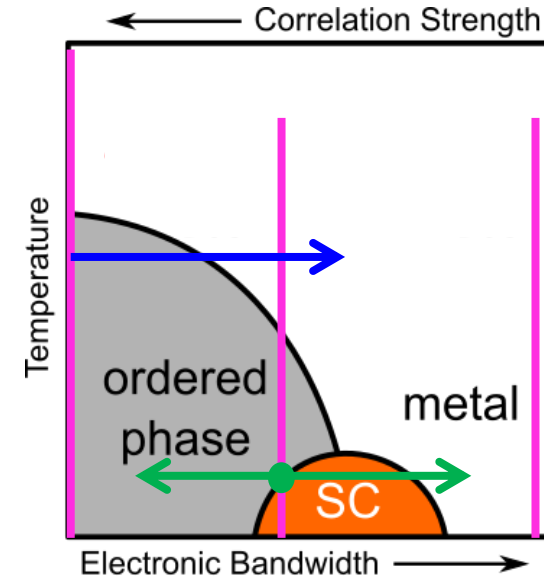
- synthesize samples at different positions in phase diagram

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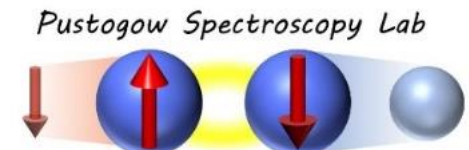
Uniaxial Strain Tuning

- positive and ‚negative‘ pressure
- *in situ* control by piezoelectric strain cells at millikelvin temperatures

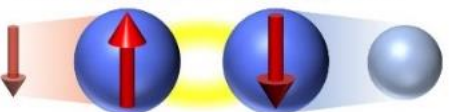
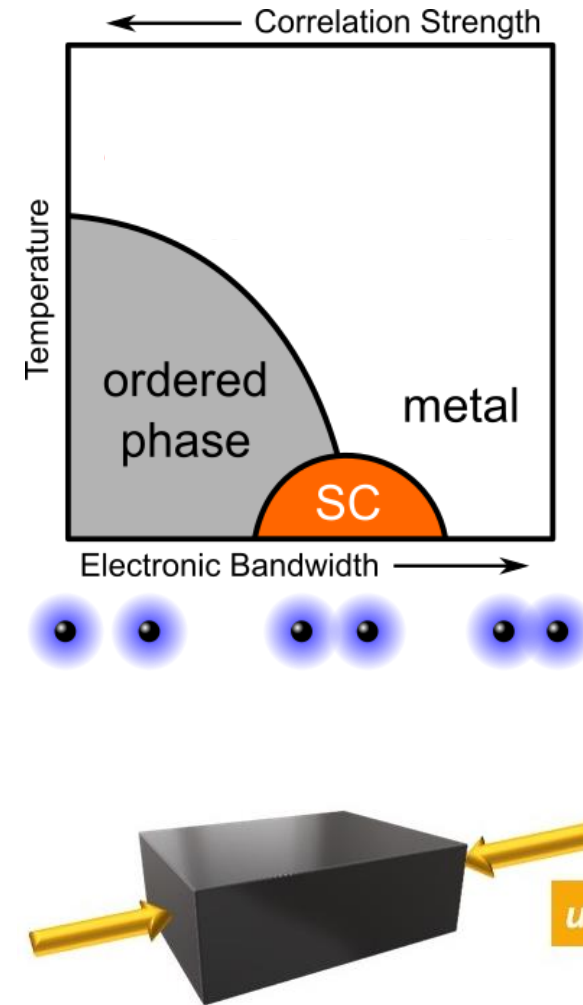
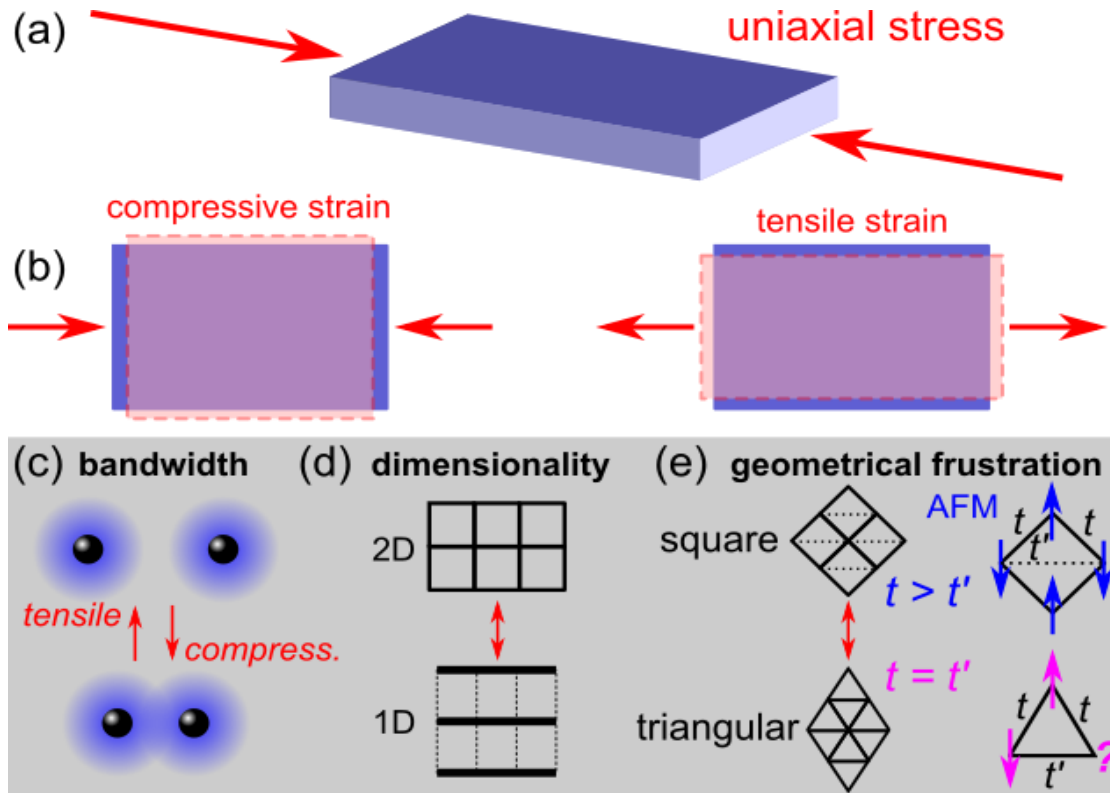


Pustogow *et al.*, *Nat. Mater.* **17**, 773-777 (2018)
Nat. Commun. **12**, 1571 (2021)
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Crystals **11**, 817 (2021)

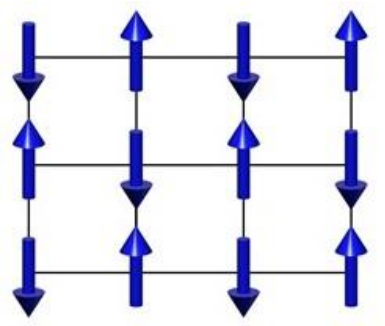
Pustogow *et al.*,
Nature **574**, 72–75 (2019)
Phys. Rev. X **9**, 021044 (2019)
npj Quantum Mater. **7**, 113 (2022)
Nat. Commun. **14**, 1960 (2023)
Phys. Rev. Lett. **131**, 256501 (2023)



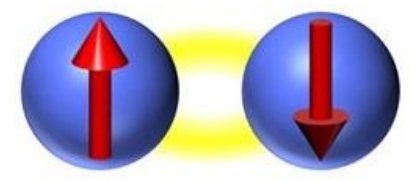
New Spin on Correlated Electrons



New Spin on Correlated Electrons



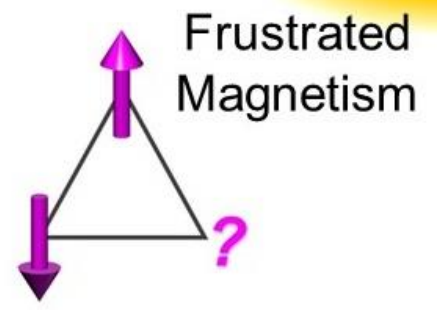
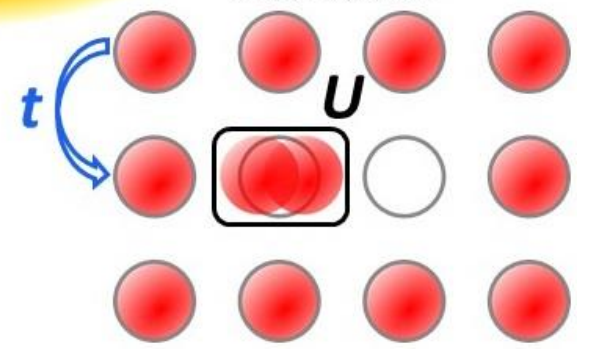
Magnetic Order



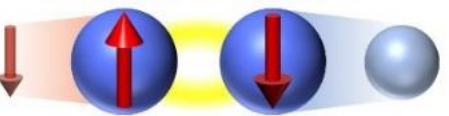
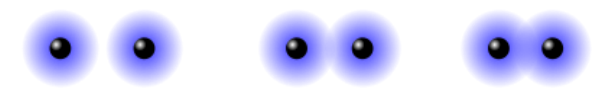
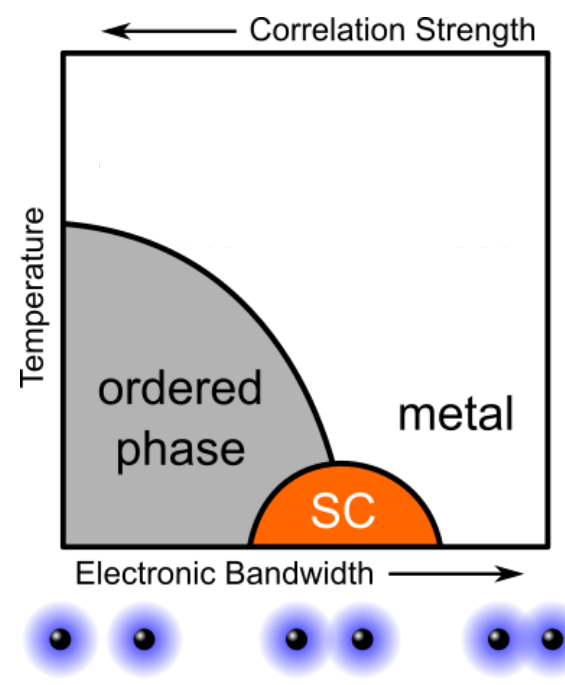
Unconventional Superconductivity

Correlated Electron Systems

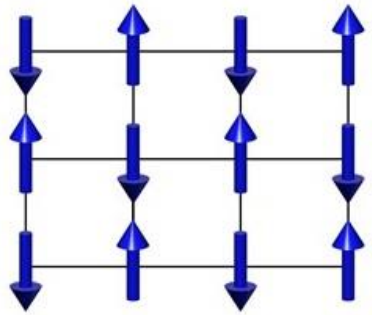
Mott Metal-Insulator Transition



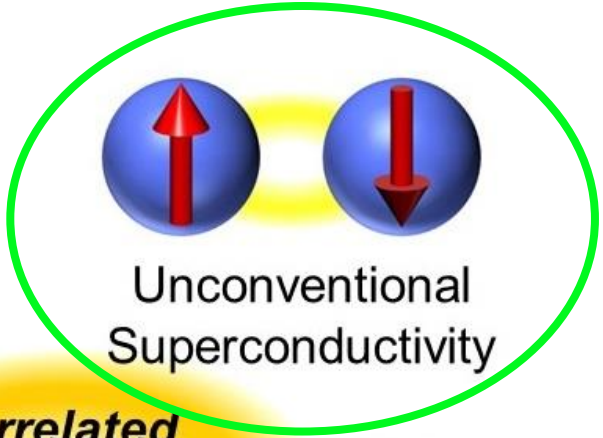
Frustrated Magnetism



New Spin on Correlated Electrons



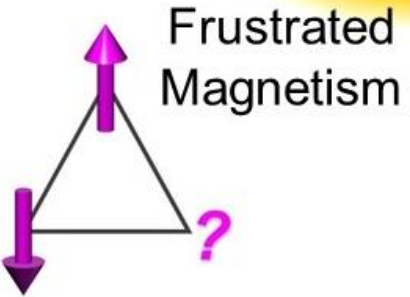
Magnetic Order



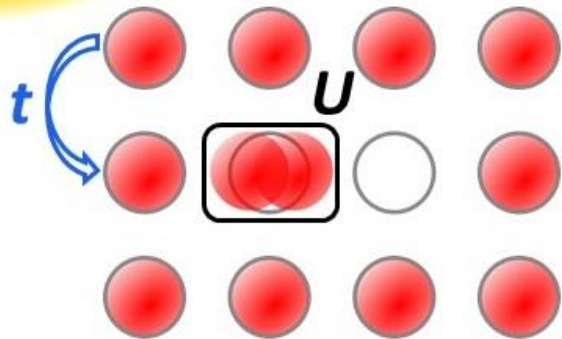
Unconventional Superconductivity

Correlated Electron Systems

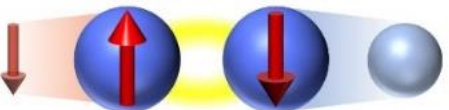
Mott Metal-Insulator Transition



Frustrated Magnetism

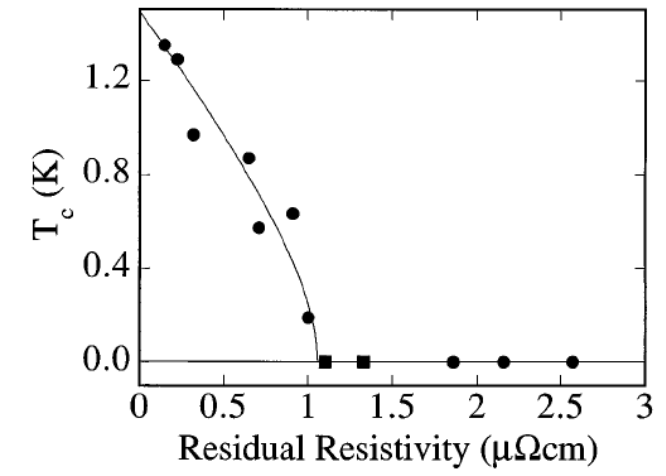
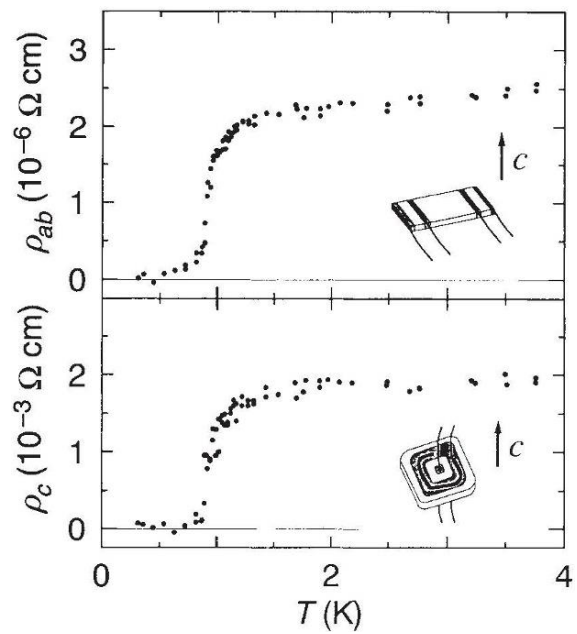
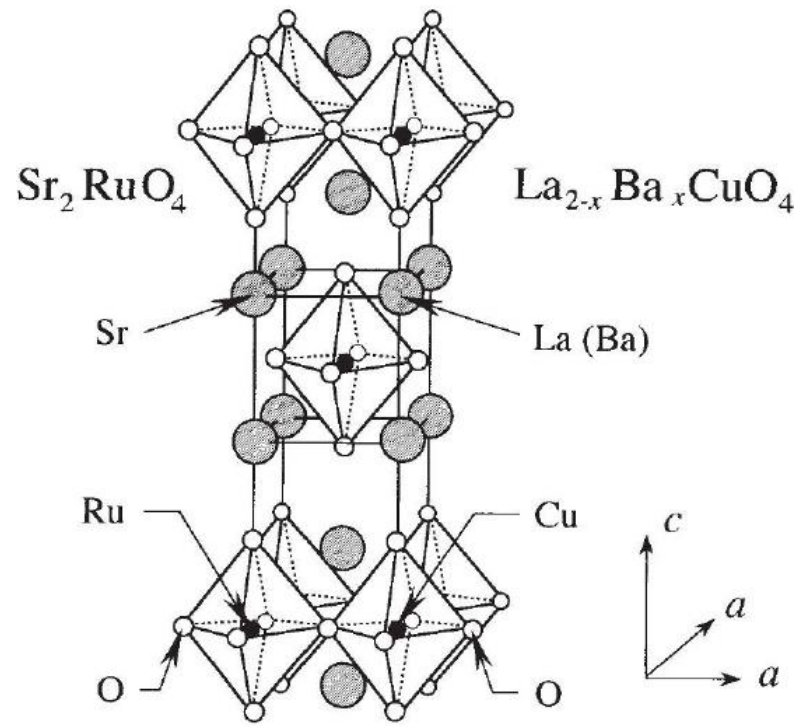


Part 1: Sr_2RuO_4 under strain
An unexpected discovery



Sr₂RuO₄: Unconv. Superconductivity

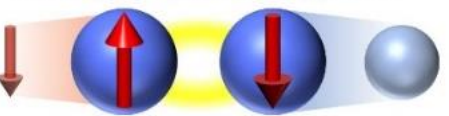
Superconductivity in a layered perovskite without copper
 Y. Maeno*, H. Hashimoto*, K. Yoshida*,
 S. Nishizaki*, T. Fujita*, J. G. Bednorz†
 & F. Lichtenberg†‡
Nature **372**, 532–534 (1994)



VOLUME 80, NUMBER 1 PHYSICAL REVIEW LETTERS 5 JANUARY 1998

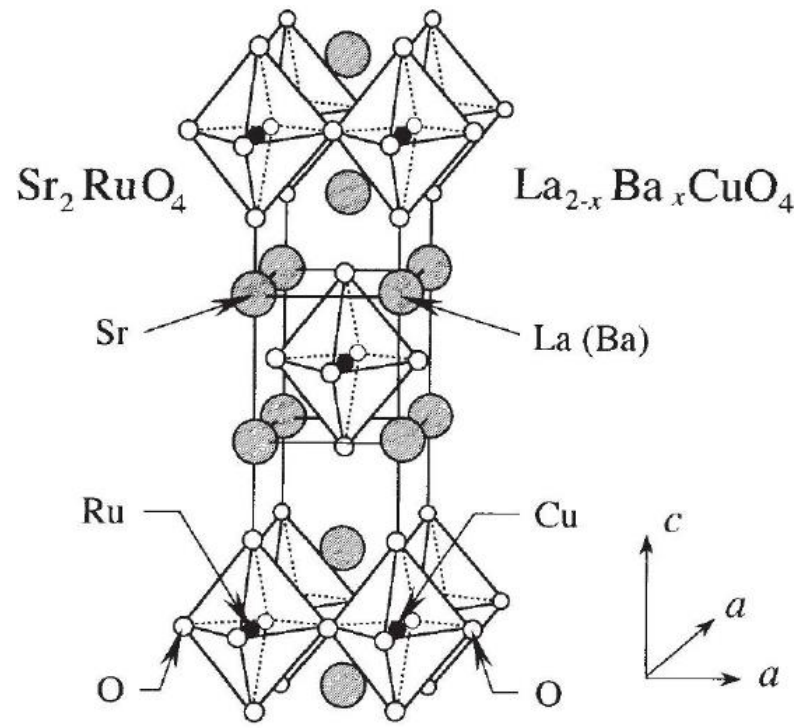
Extremely Strong Dependence of Superconductivity on Disorder in Sr₂RuO₄

A. P. Mackenzie,^{1,*} R. K. W. Haselwimmer,² A. W. Tyler,^{1,*} G. G. Lonzarich,² Y. Mori,³ S. Nishizaki,³ and Y. Maeno³

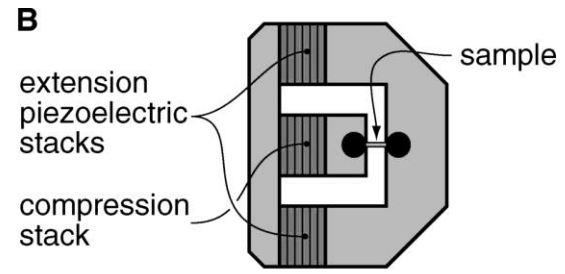


Sr₂RuO₄: Unconv. Superconductivity

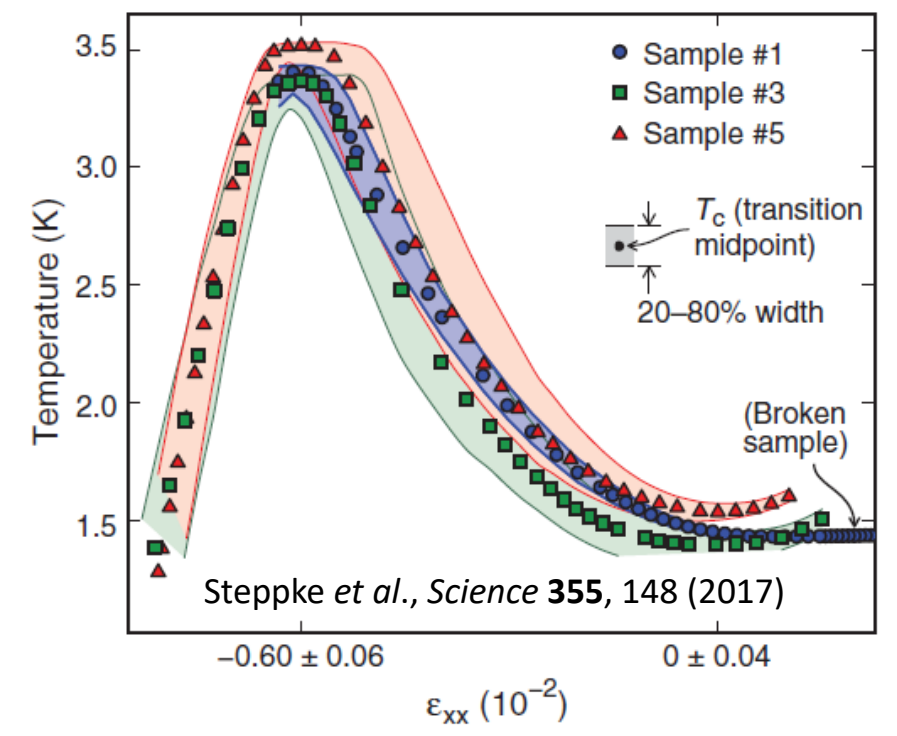
Superconductivity in a layered perovskite without copper
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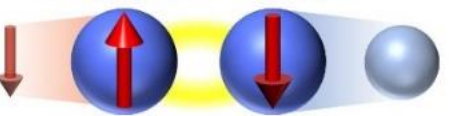
Hicks *et al.*, *Science* **344**, 283 (2014)



- *superconductivity tuned by strain*
- *250% increase of T_c upon ε = 0.6%*



Steppe *et al.*, *Science* **355**, 148 (2017)

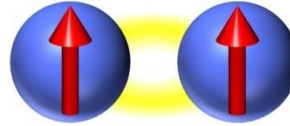


Spin-Triplet Superconductivity

Superconductivity in a layered perovskite without copper

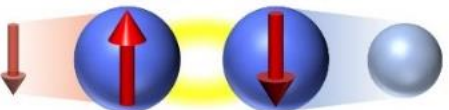
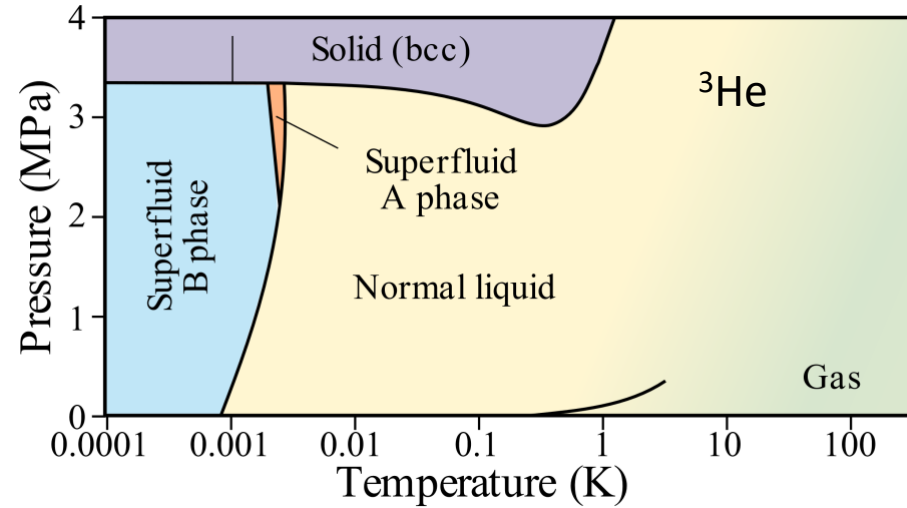
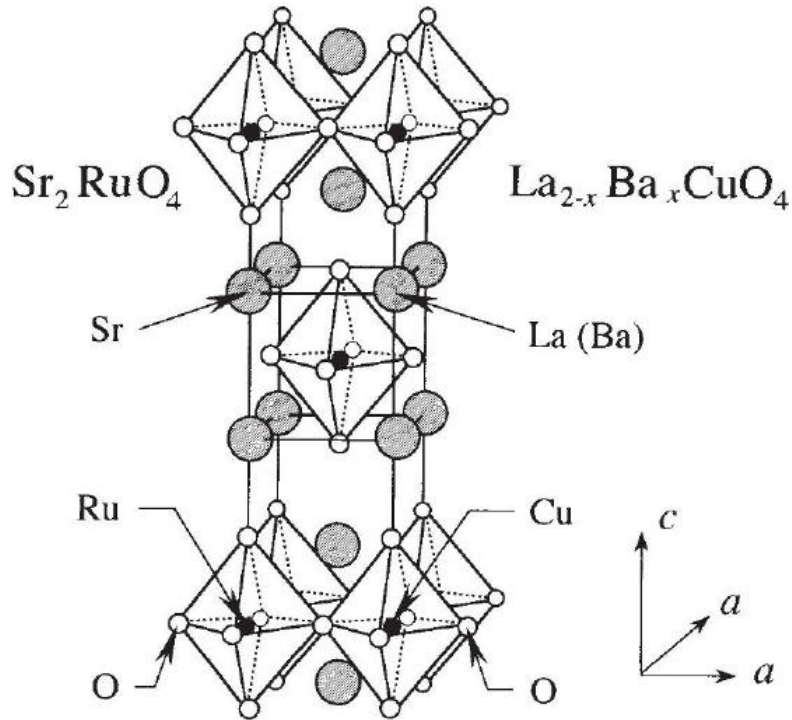
Y. Maeno*, H. Hashimoto*, K. Yoshida*,
 S. Nishizaki*, T. Fujita*, J. G. Bednorz†
 & F. Lichtenberg†‡

Nature **372**, 532–534 (1994)



Sr₂RuO₄: an electronic analogue of ³He?

T M Rice†‡ and M Sigrist§
J. Phys.: Condens. Matter **7**, L643-L648 (1995)

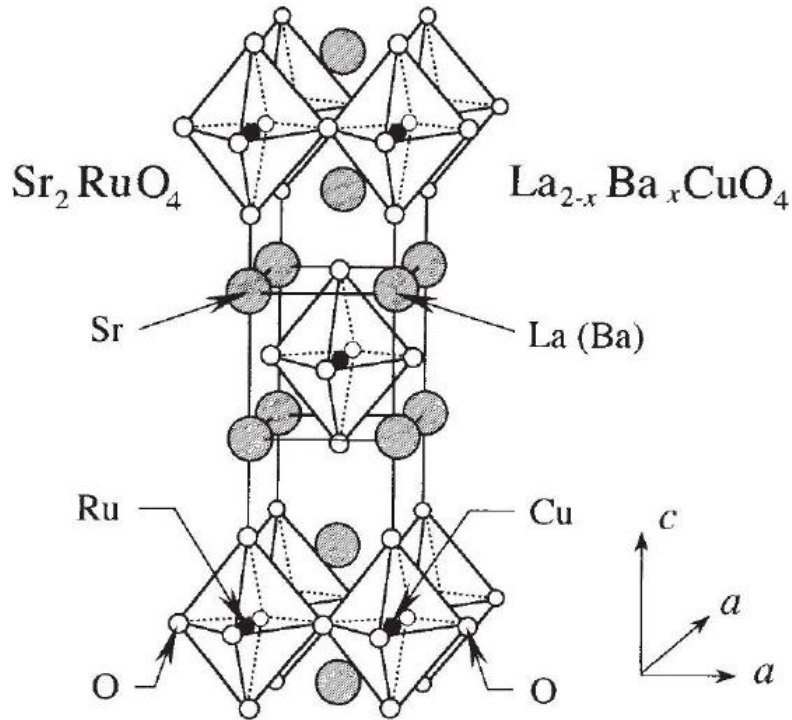


Spin-Triplet Superconductivity

Superconductivity in a layered perovskite without copper

Y. Maeno*, H. Hashimoto*, K. Yoshida*,
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Nature **372**, 532–534 (1994)



Sr₂RuO₄: an electronic analogue of ³He?

T M Rice†‡ and M Sigrist§
J. Phys.: Condens. Matter **7**, L643-L648 (1995)

Spin-triplet superconductivity in Sr₂RuO₄ identified by ¹⁷O Knight shift

K. Ishida*, H. Mukuda*, Y. Kitaoka*, K. Asayama*,
 Z. Q. Mao†‡, Y. Mori† & Y. Maeno†‡
Nature **396**, 658–660 (1998)

Time-reversal symmetry-breaking superconductivity in Sr₂RuO₄

G. M. Luke*, Y. Fudamoto*, K. M. Kojima*, M. I. Larkin*,
 J. Merrin*, B. Nachumi*, Y. J. Uemura*, Y. Maeno†,
 Z. Q. Mao†, Y. Mori†, H. Nakamura‡ & M. Sigrist§
Nature **394**, 558–561 (1998)

PRL **97**, 167002 (2006)

PHYSICAL REVIEW LETTERS

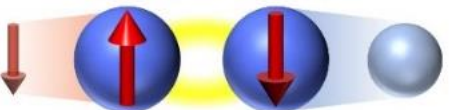
High Resolution Polar Kerr Effect Measurements of Sr₂RuO₄: Evidence for Broken Time-Reversal Symmetry in the Superconducting State

Jing Xia,¹ Yoshiteru Maeno,² Peter T. Beyersdorf,³ M. M. Fejer,⁴ and Aharon Kapitulnik^{1,4}

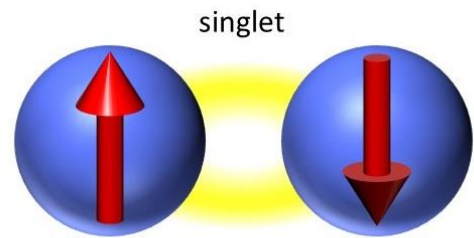
REVIEWS OF MODERN PHYSICS, VOLUME 75, APRIL 2003

The superconductivity of Sr₂RuO₄ and the physics of spin-triplet pairing

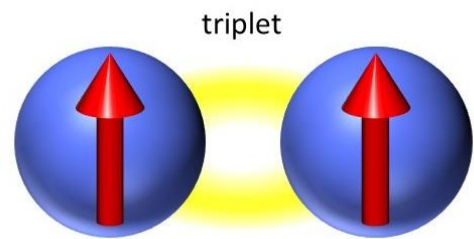
Andrew Peter Mackenzie Yoshiteru Maeno



Spin-Triplet Superconductivity



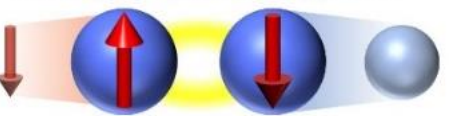
$$M_{sc} \approx 0$$



condensate magnetization

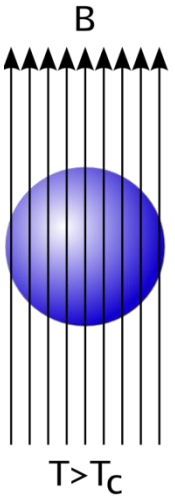
$$M_{sc} \approx M_n$$

Cooper pairs

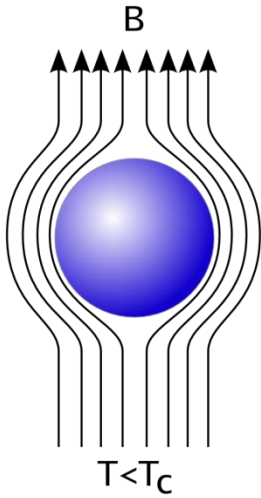


Spin-Triplet Superconductivity

normal metal

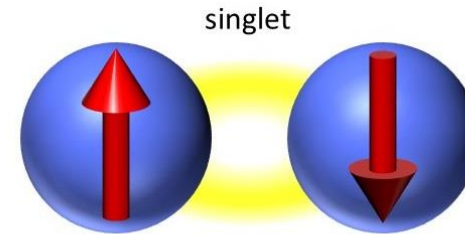


superconductor

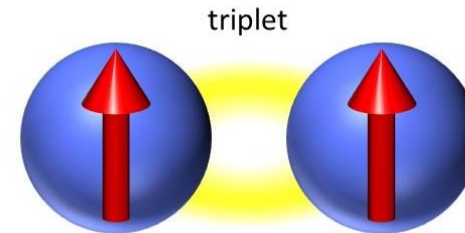


Meissner effect
perfect diamagnet

Pauli susceptibility is small compared to diamagnetic response of SC

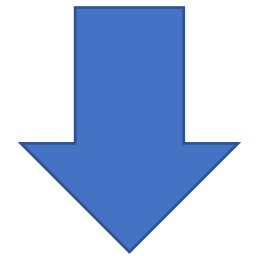


$$M_{sc} \approx 0$$

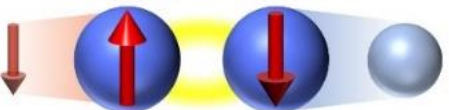


condensate magnetization
 $M_{sc} \approx M_n$

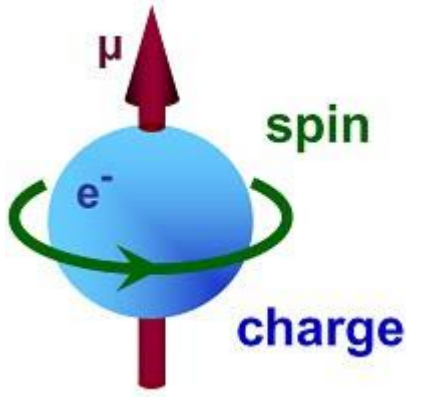
Cooper pairs



probe local magnetization by Nuclear Magnetic Resonance (NMR)



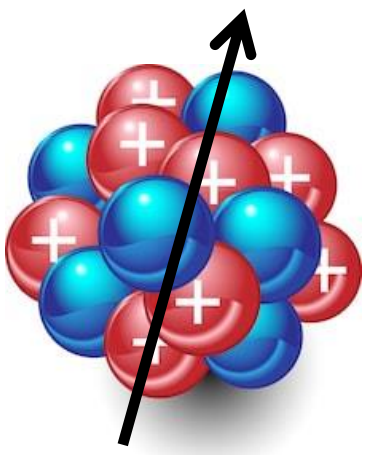
Magnetic Resonance



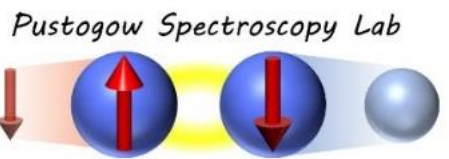
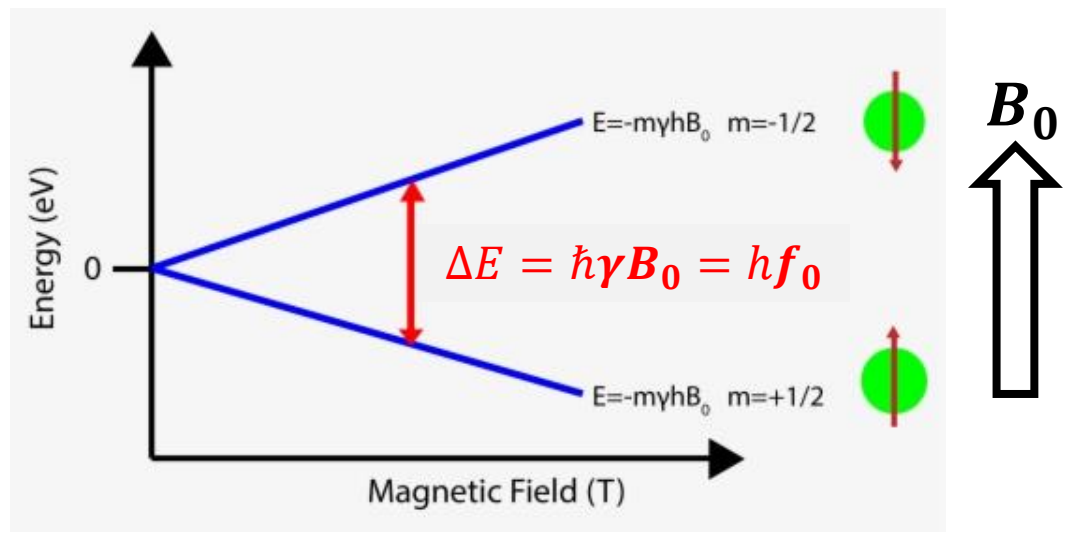
electron
 $\gamma_e = 28 \text{ GHz/T}$

gyromagnetic ratio

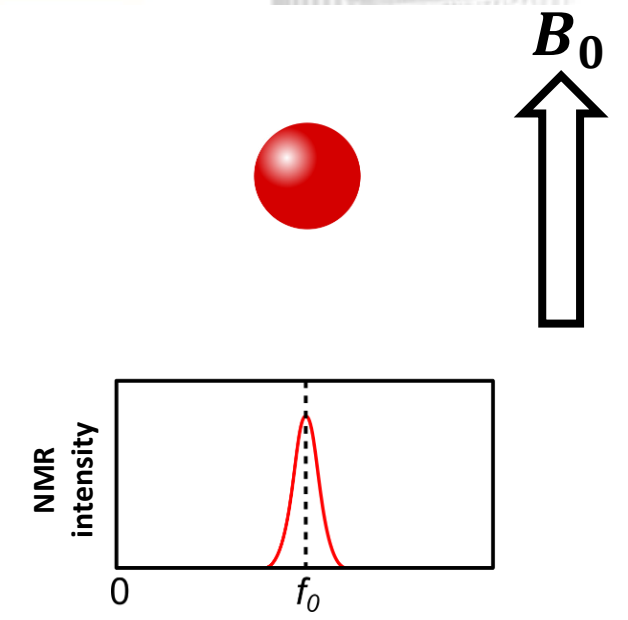
$$\gamma_e = g_e \frac{\mu_B}{\hbar} = \frac{e}{2m} g_e$$



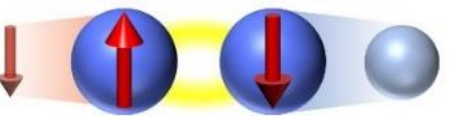
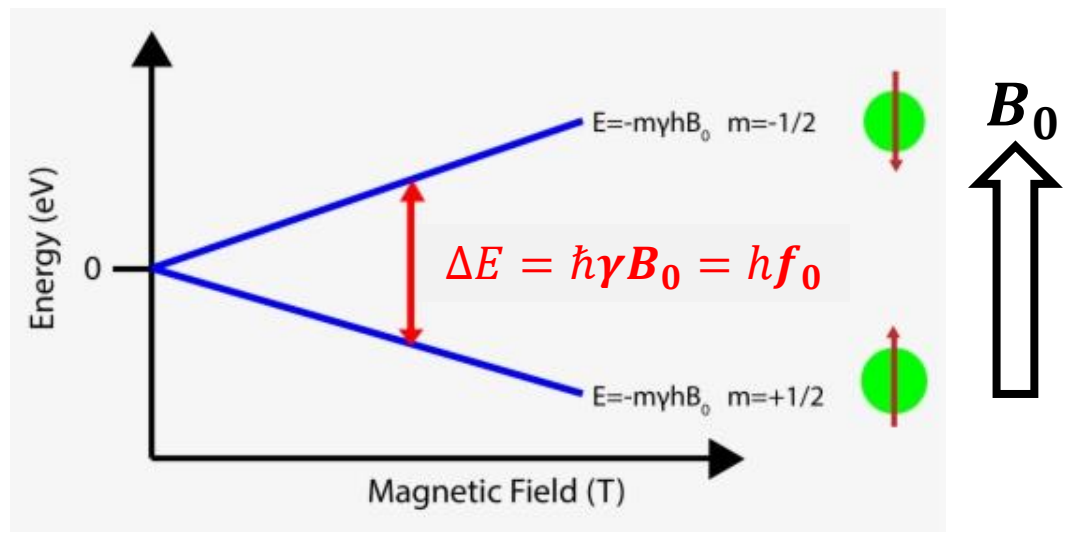
nucleus
 $\gamma_n = 0 - 45 \text{ MHz/T}$



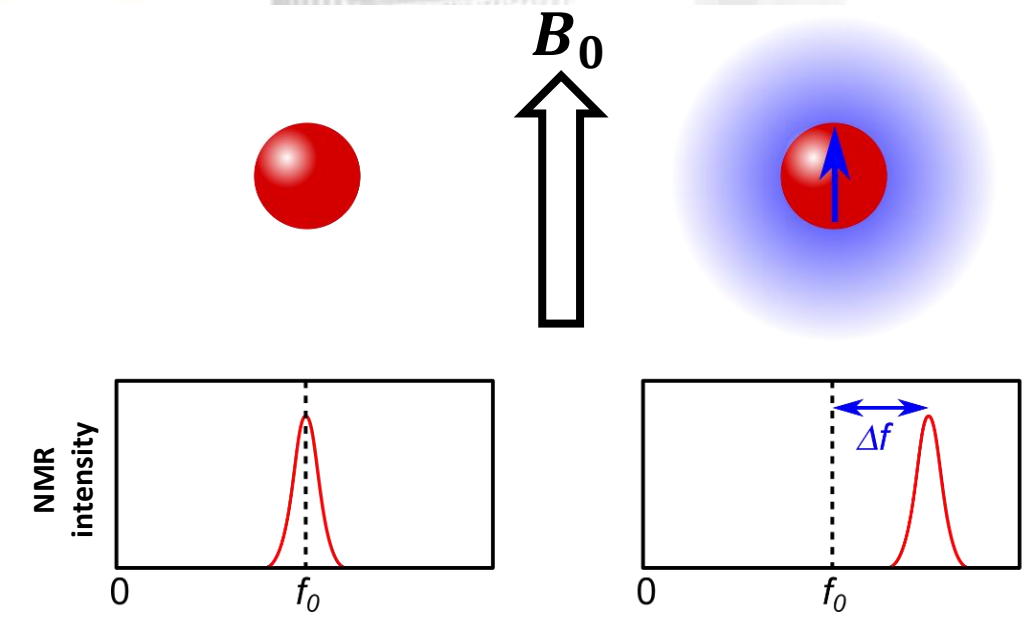
Nuclear Magnetic Resonance (NMR)



$$f = f_0 = \gamma B_0$$



Nuclear Magnetic Resonance (NMR)



$$f = f_0 = \gamma B_0$$

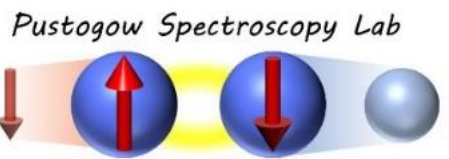
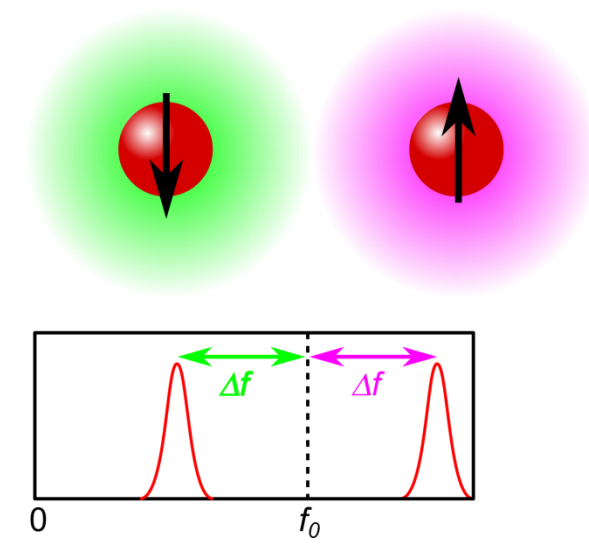
$$f = f_0 + \Delta f = \gamma(B_0 + \Delta B)$$

Nuclear Magnetic Resonance

- Spin of conduction electrons creates magnetic field at nucleus
- Knight shift $K = \Delta f / f_0 \propto M_s / B_0$

Magnetic Materials

- Local field on probed nucleus comparable to B_0 or even larger
- Line broadening
- Antiferromagnetism: line splitting

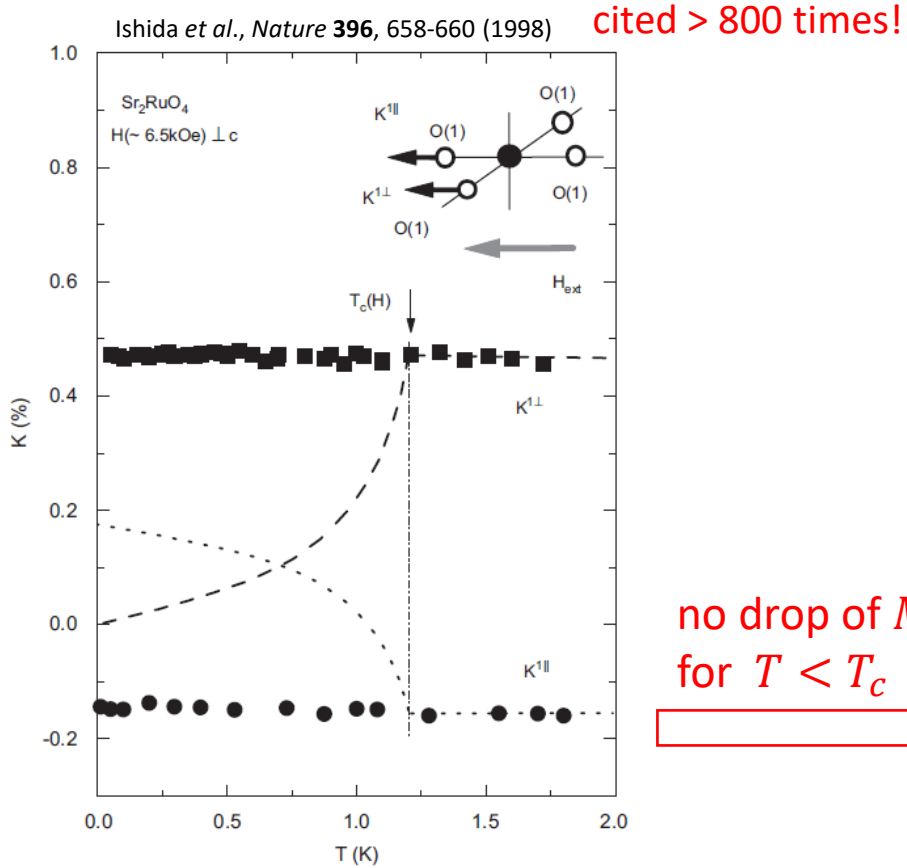


Sr₂RuO₄: Triplet Superconductivity?


1998

Sr₂RuO₄: an electronic analogue of ³He?

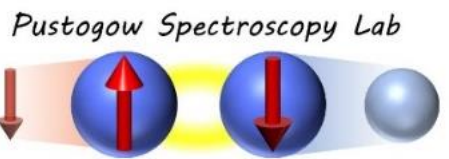
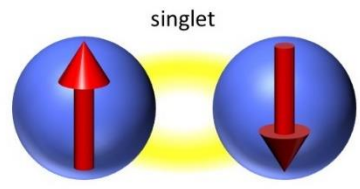
T M Rice†† and M Sigrist§
J. Phys.: Condens. Matter **7**, L643-L648 (1995)



no drop of M_S for $T < T_c$

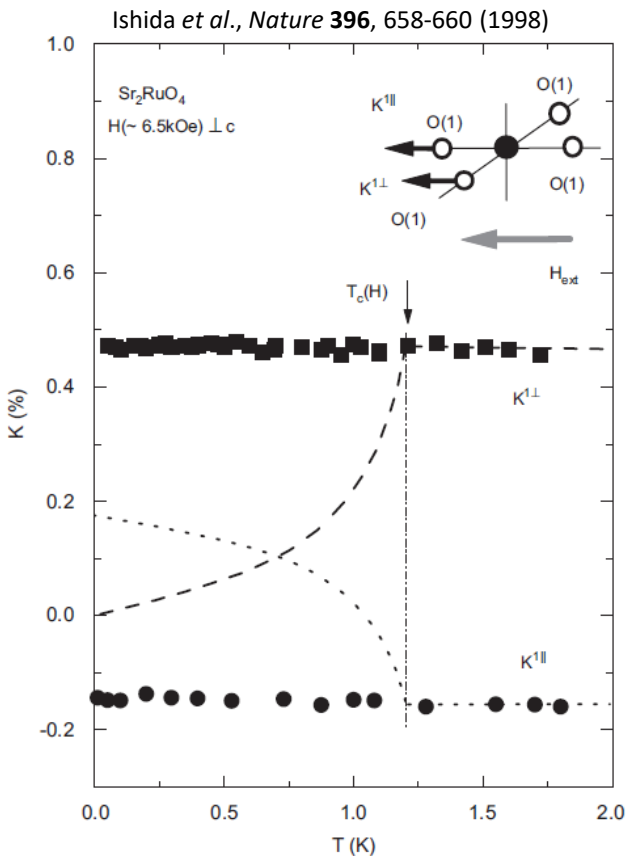


$M_{sc} \approx 0$



Sr₂RuO₄: Triplet Superconductivity?

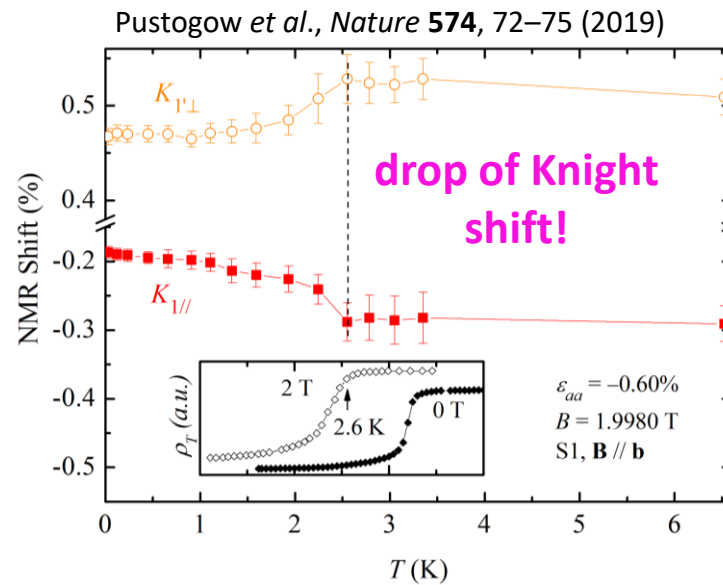
1998



2019

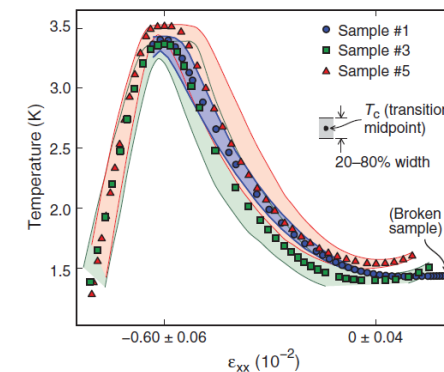
ONCE UPON A TIME IN...
HOLLYWOOD

strikingly different

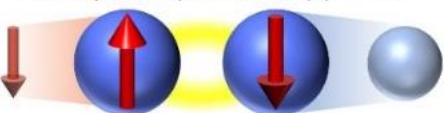



higher T_c & H_{c2}
under strain

$$\epsilon_{aa} = \epsilon_v$$



Pustogow Spectroscopy Lab



2024-08-23

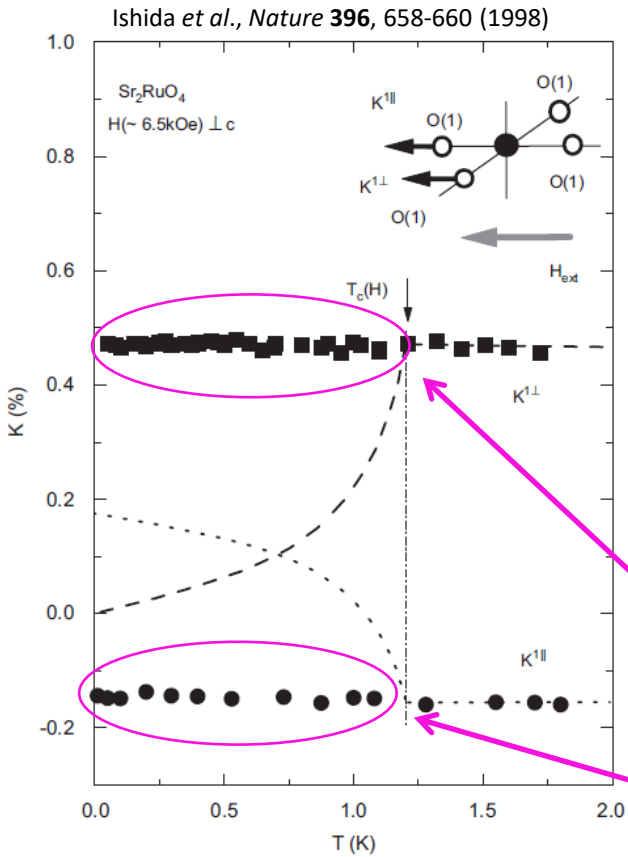
Andrej Pustogow

Steppe et al., *Science* **355**, 148 (2017)

24

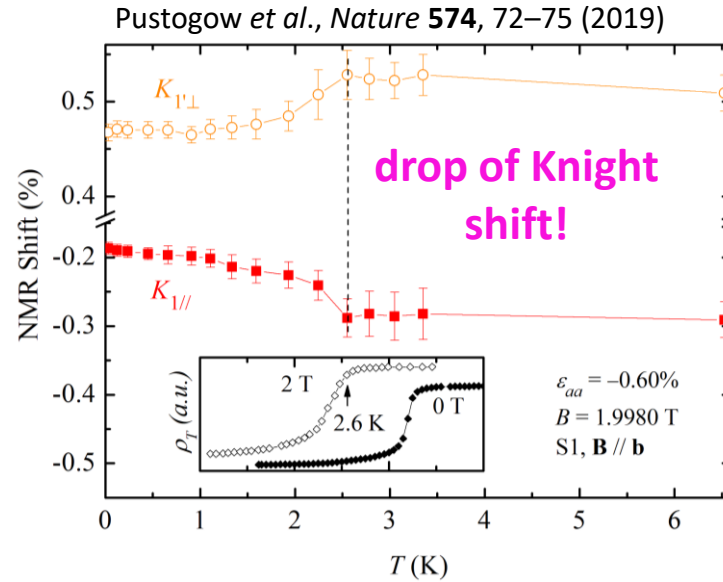
Sr₂RuO₄: Triplet Superconductivity?

1998



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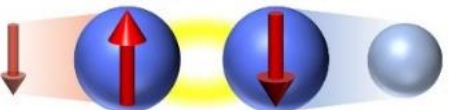
strikingly different



higher T_c & H_{c2}
under strain

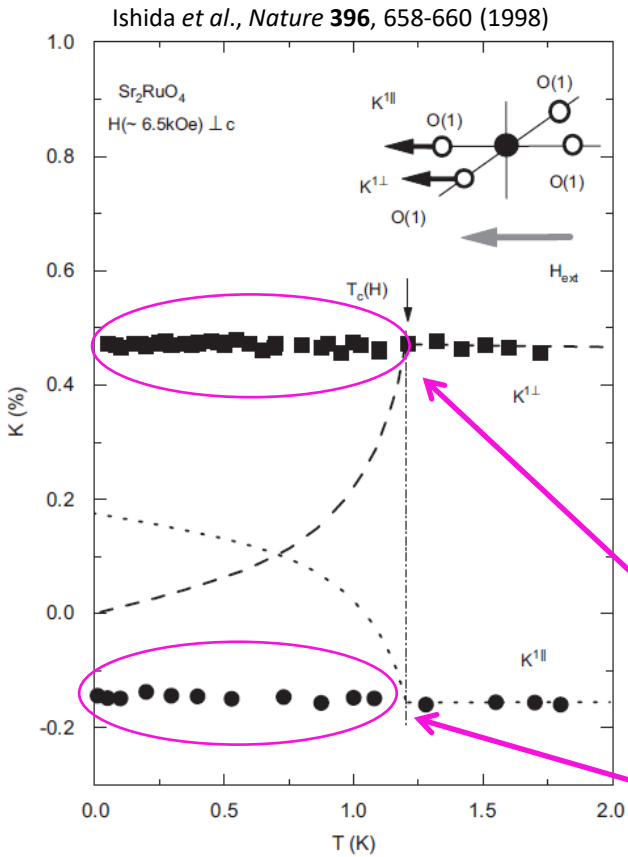
$$\epsilon_{aa} = \epsilon_v$$

$T_{sample} > T_c$

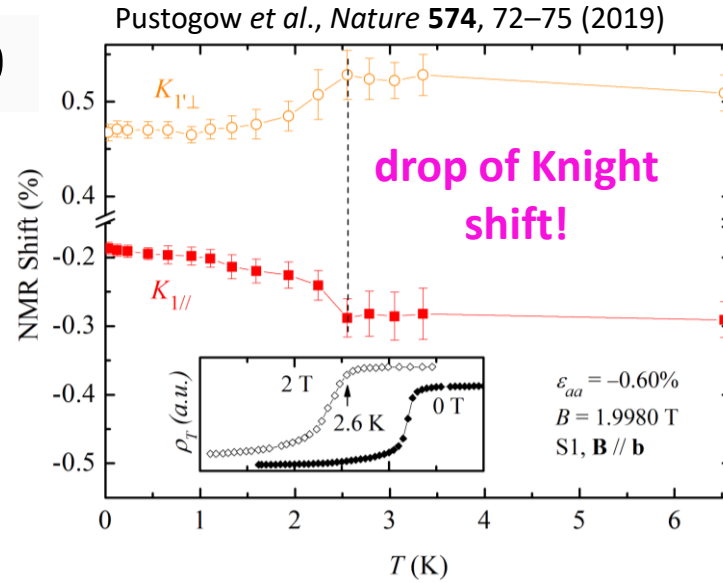


Sr₂RuO₄: Triplet Superconductivity?

1998



2019



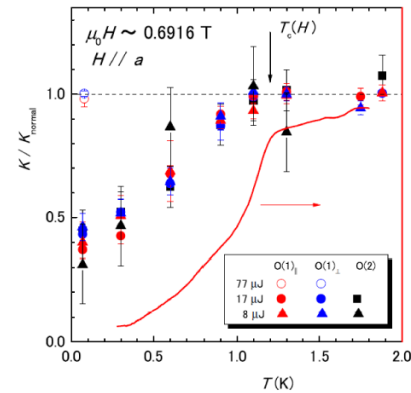
strikingly different



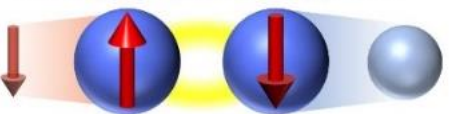
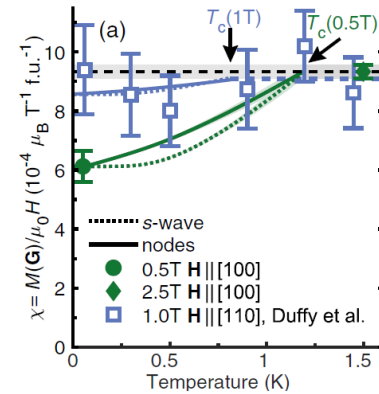
$T_{sample} > T_c$

Heating by NMR pulses!

2020

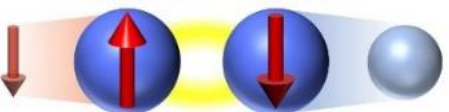
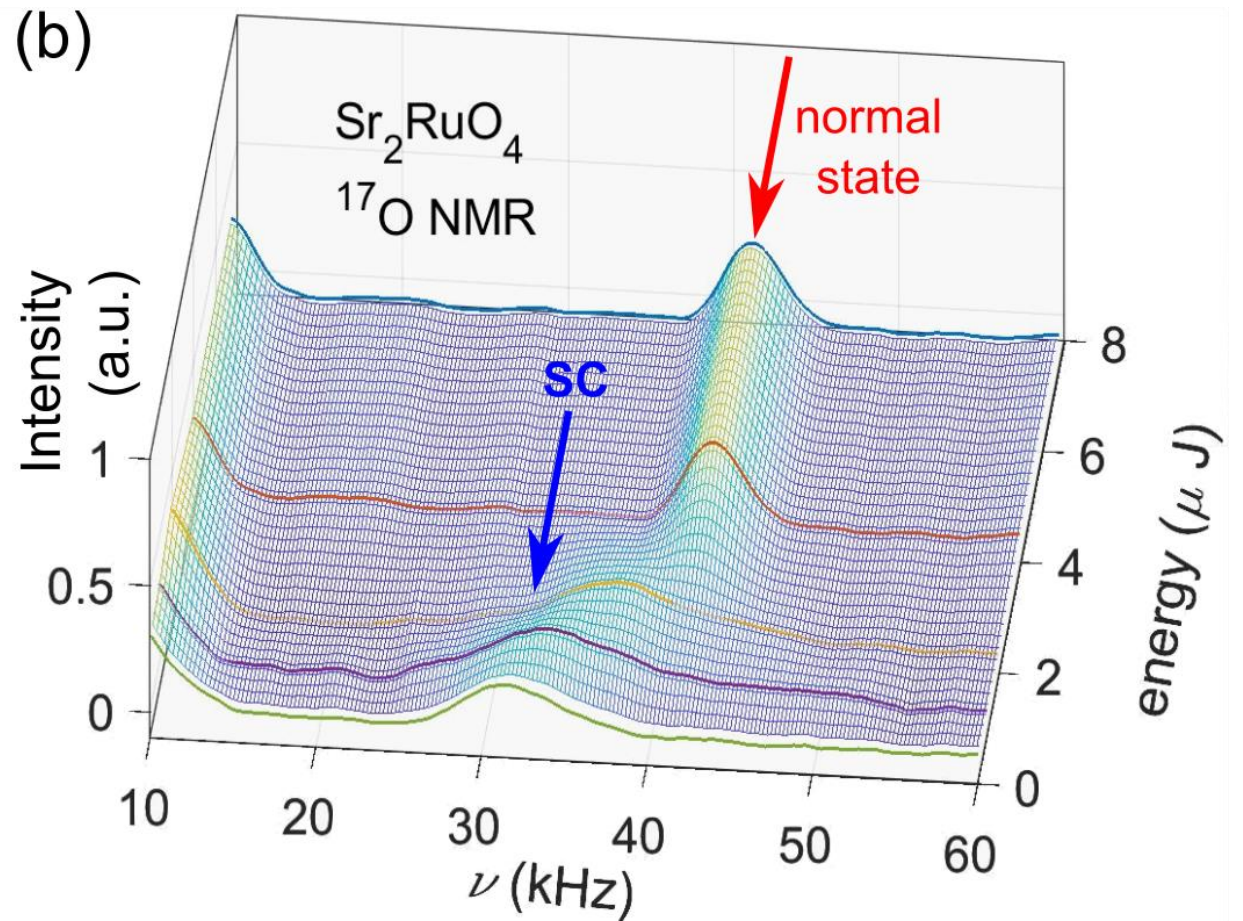
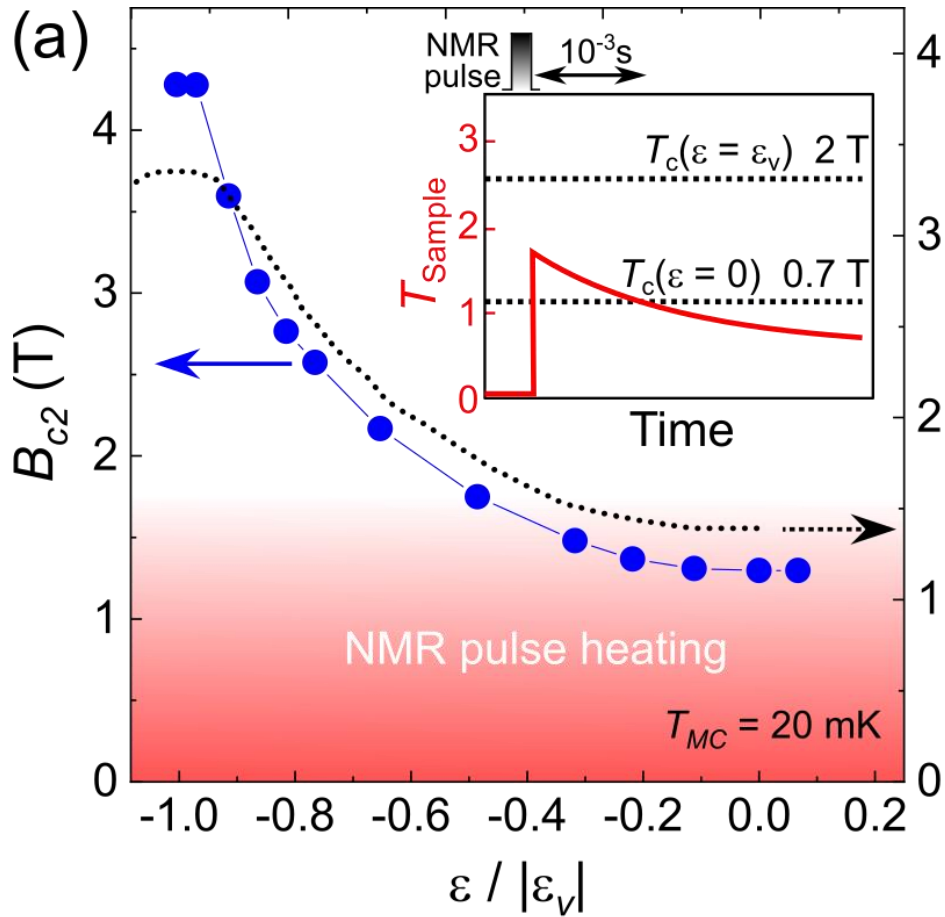


New result confirmed!



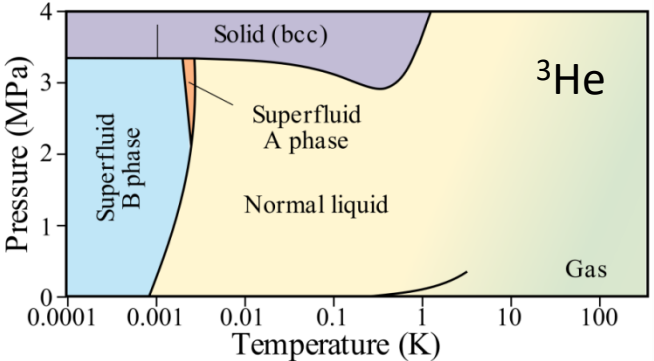
Heating from NMR Pulses

Pustogow et al., *Nature* **574**, 72–75 (2019)

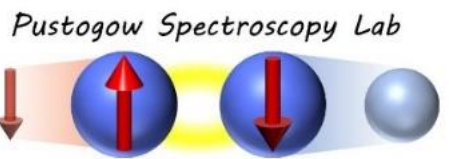


Sr₂RuO₄: Even Parity Superconductivity

1995
Sr₂RuO₄: an electronic analogue of ³He?
 T M Rice†‡ and M Sigrist§
J. Phys.: Condens. Matter **7**, L643-L648 (1995)



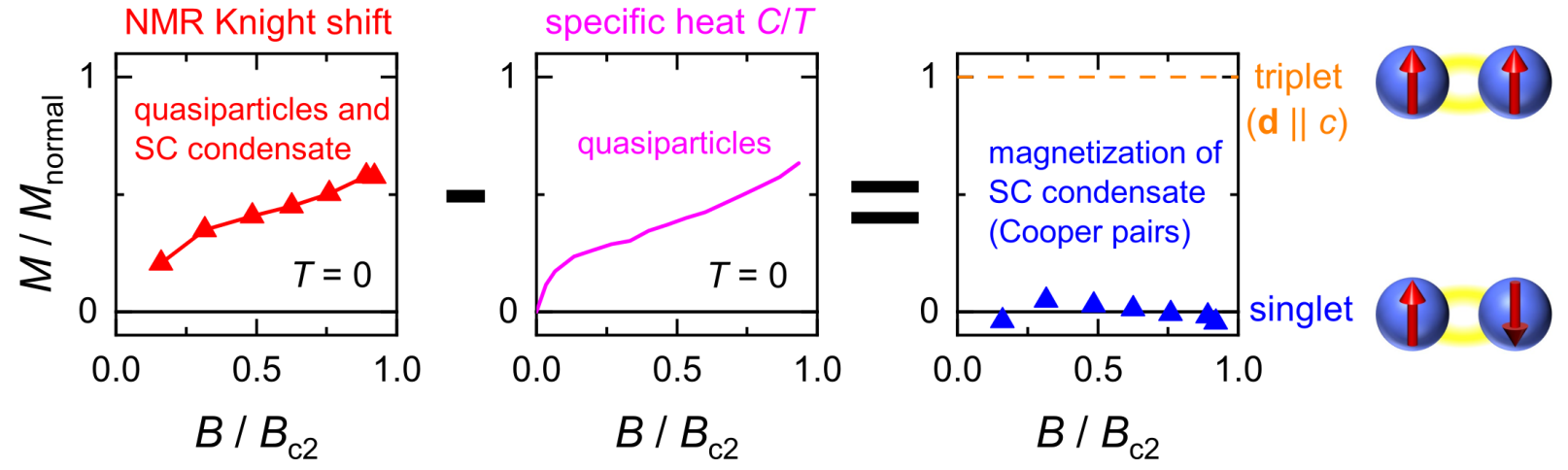
Answer for Sr₂RuO₄: no!
 Is there an electronic analogue of ³He?



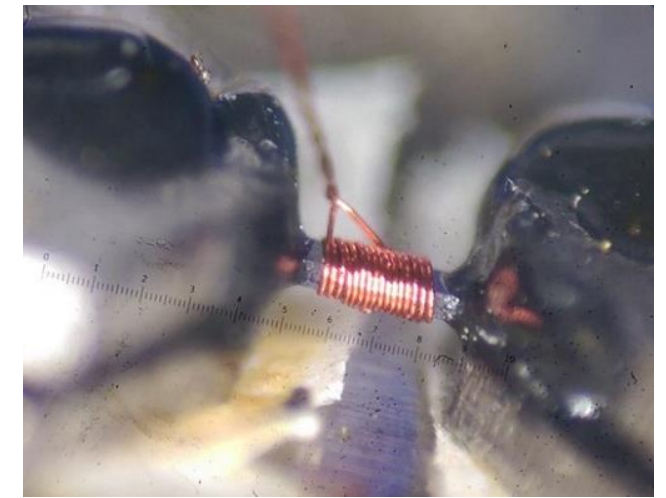
1998
Spin-triplet superconductivity in Sr₂RuO₄ identified by ¹⁷O Knight shift
 K. Ishida*, H. Mukuda*, Y. Kitaoka*, K. Asayama*, Z. Q. Mao†‡, Y. Mori† & Y. Maeno†‡
Nature **396**, 658-660 (1998)

experimental data wrong!!

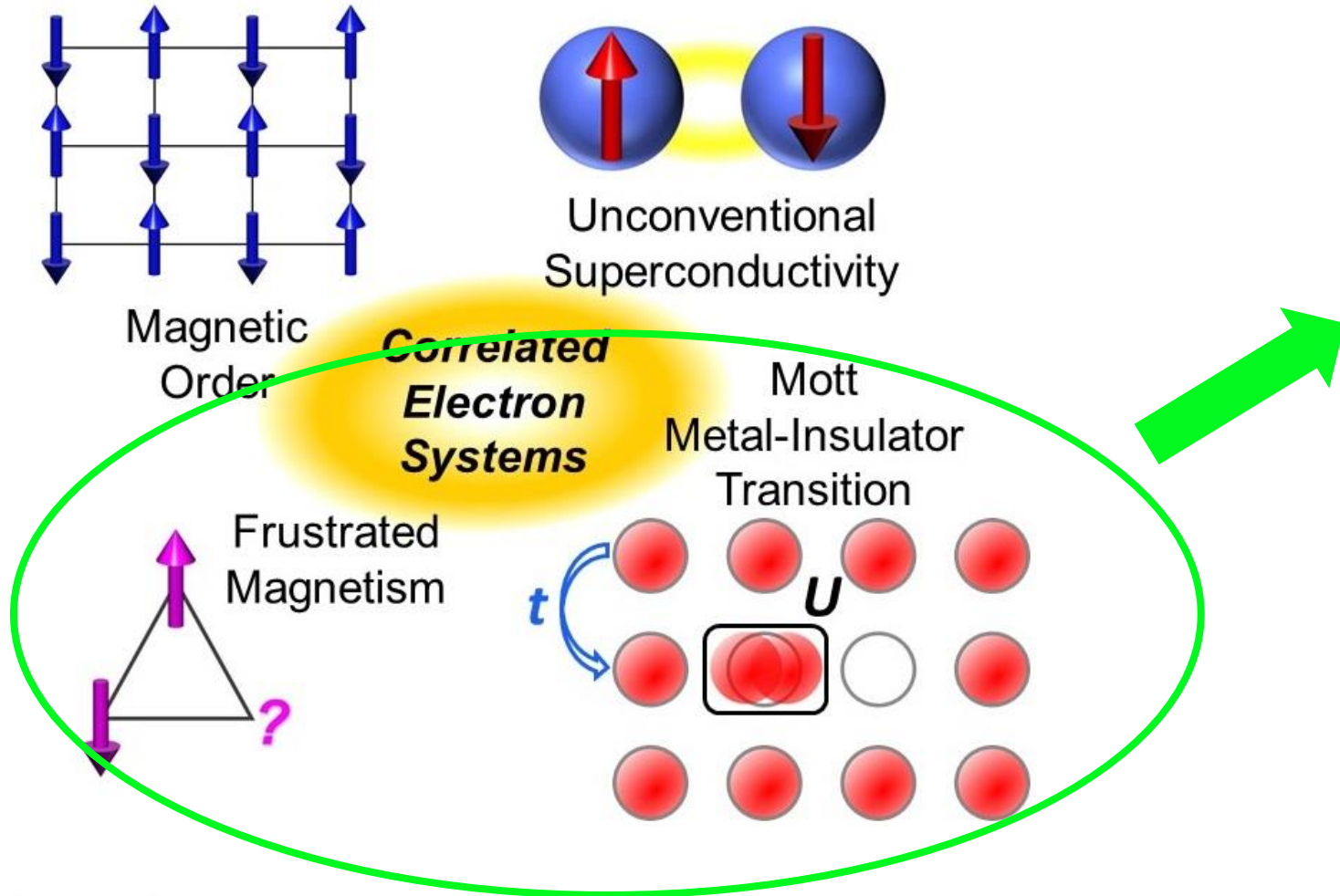
2021 *PNAS* **118**, e2025313118 (2021)



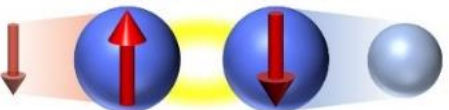
2019 Pustogow *et al.*, *Nature* **574**, 72–75 (2019)



New Spin on Correlated Electrons



Part 2: A frustrated Mott insulator under strain
The true electronic analogue of ^3He



Phase Transitions

well-known example: H_2O



$T > 650\text{ K}$
 $p > 220\text{ bar}$



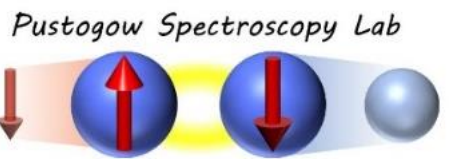
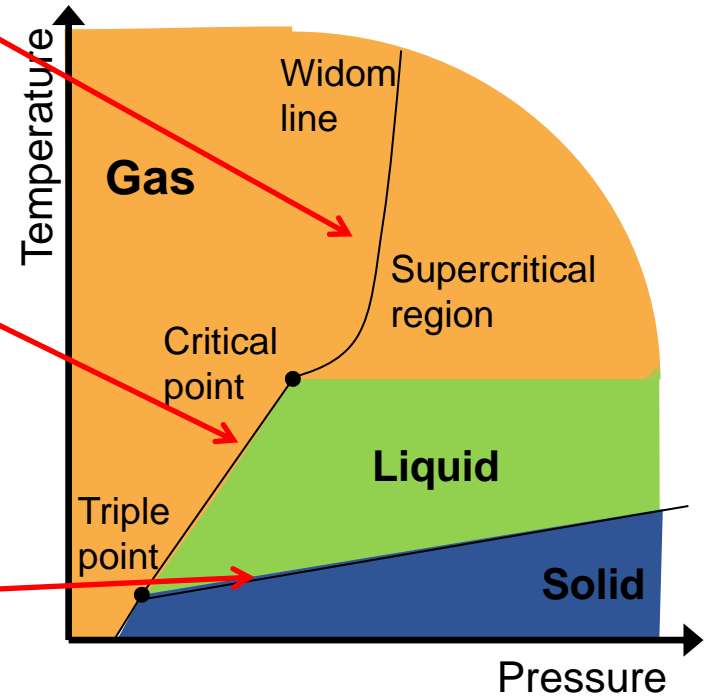
$T = 100^\circ\text{C}$
 $p = 1\text{ bar}$



$T = 0^\circ\text{C}$
 $p = 1\text{ bar}$

Liquid-Gas Transition

- no symmetry breaking
- first-order transition below critical point
- Widom line in supercritical region



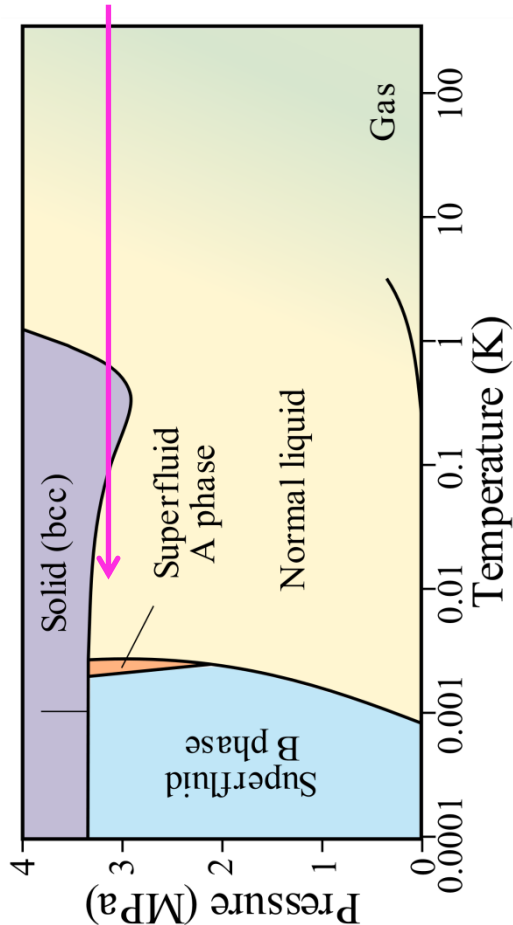
Quantum Phase Transitions

Pomeranchuk effect in ^3He
solid melts upon cooling

Clausius-Clapeyron

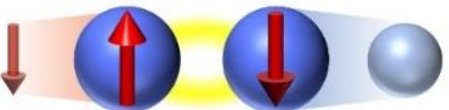
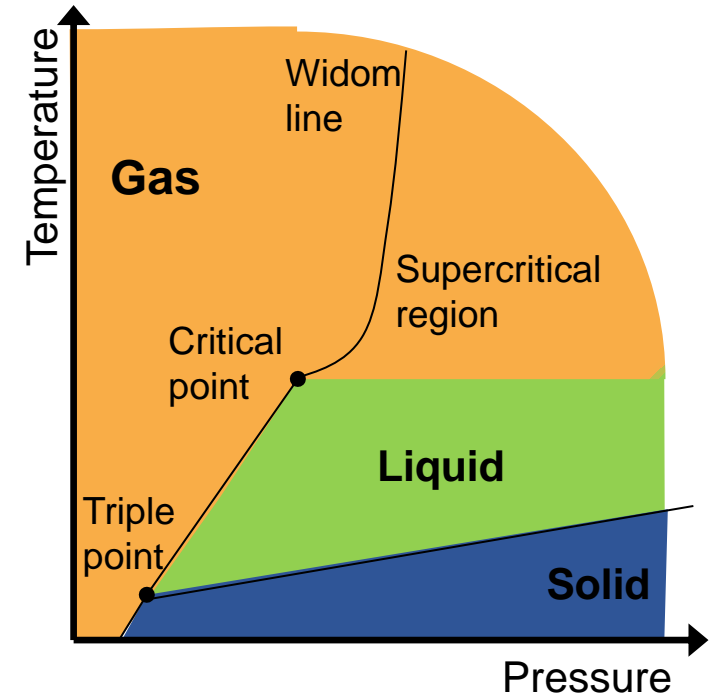
$$\frac{dT}{dp} = \frac{\Delta V}{\Delta S}$$

- ^3He nucleus has $S = \frac{1}{2}$ (*fermion*)
- nuclear spins in solid ^3He have larger entropy than liquid phase



Liquid-Gas Transition

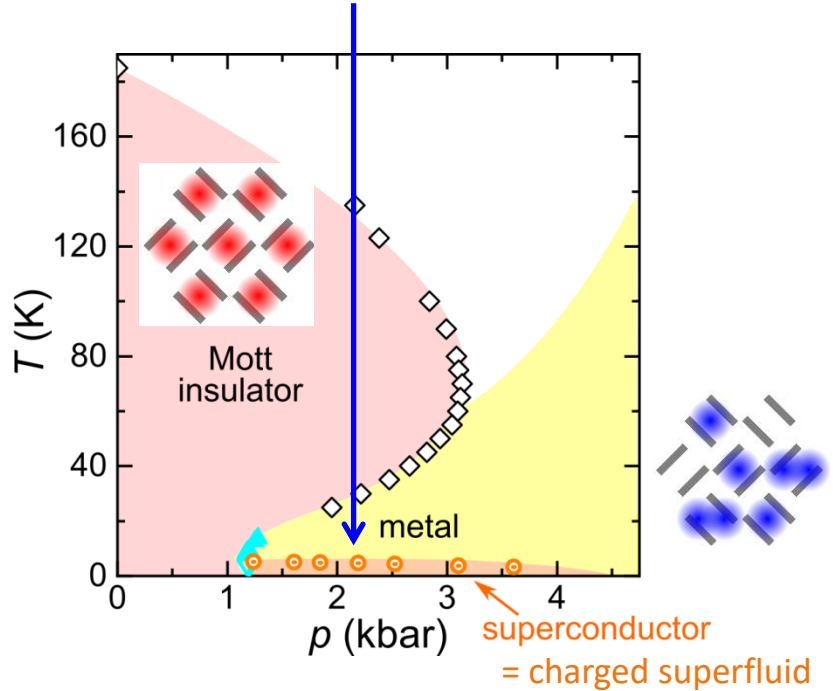
- no symmetry breaking
- first-order transition below critical point
- gradual crossover in supercritical region



Electronic Analogue of ^3He

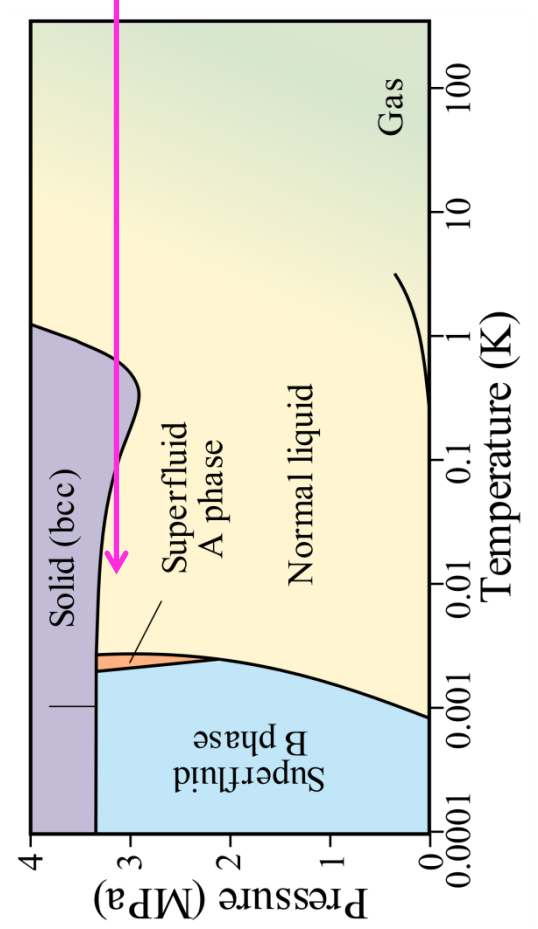
Mott insulator

charge solid (insulator) melts into charge liquid (metal) upon cooling



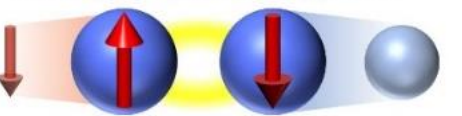
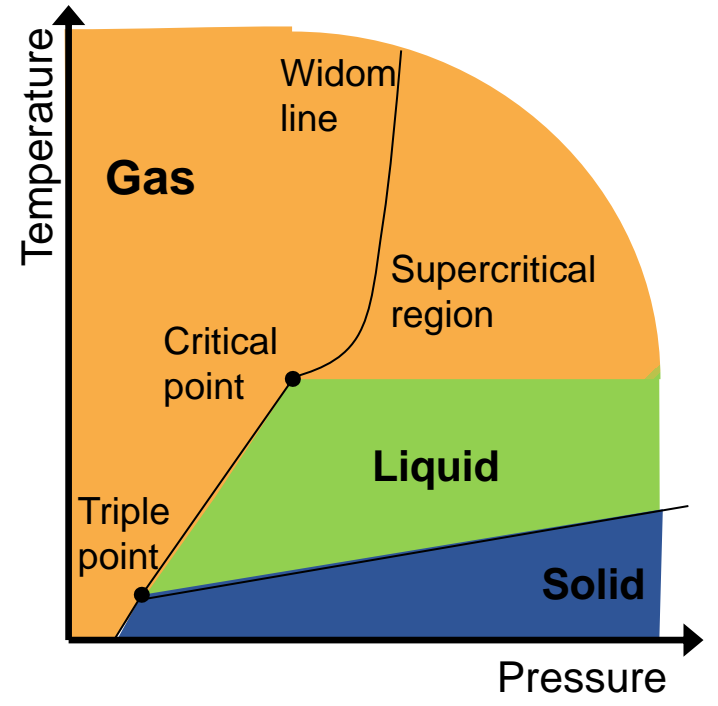
Pustogow et al., *Nat. Commun.* **12**, 1571 (2021)
Nat. Commun. **14**, 1960 (2023)
 Pustogow Spectroscopy Lab

Pomeranchuk effect in ^3He solid melts upon cooling



Liquid-Gas Transition

- no symmetry breaking
- first-order transition below critical point
- gradual crossover in supercritical region

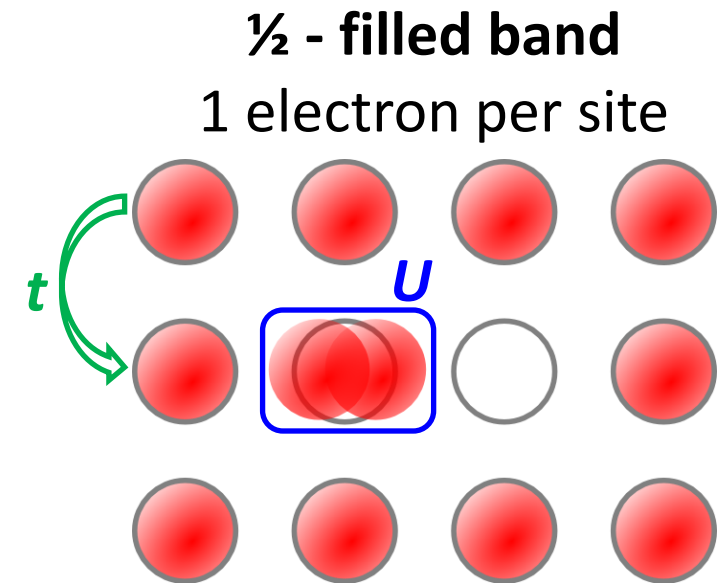
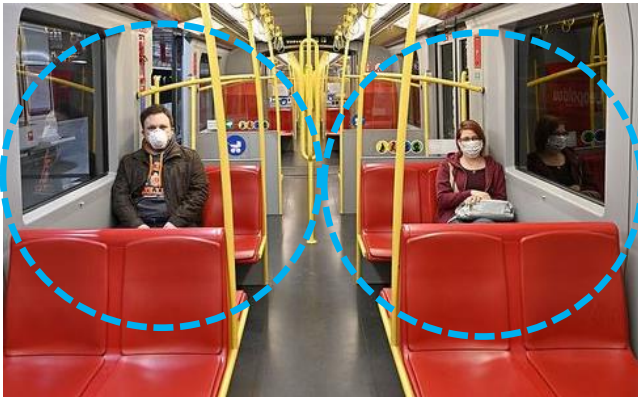


Mott Metal-Insulator Transition

Hubbard Model
$$H = -t \sum_{\langle ij \rangle, \sigma} (c_{i\sigma}^\dagger c_{j\sigma} + H.c.) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

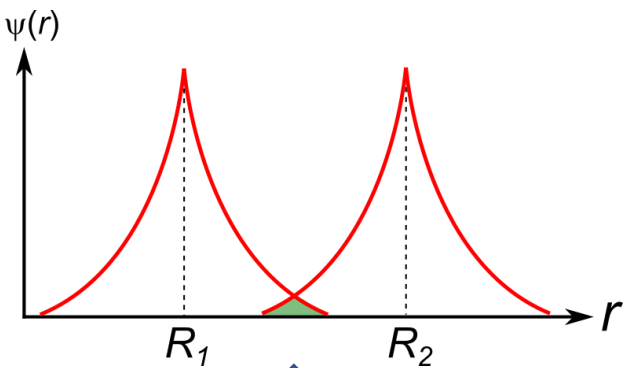
- periodic arrangement
- 1 particle per site

on-site Coulomb repulsion

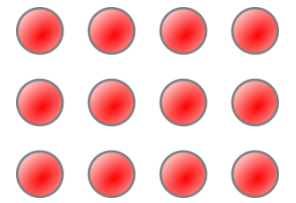


Mott Metal-Insulator Transition

Hubbard Model $H = -t \sum_{\langle ij \rangle, \sigma} (c_{i\sigma}^\dagger c_{j\sigma} + H.c.) + U \sum_i n_{i\uparrow} n_{i\downarrow}$

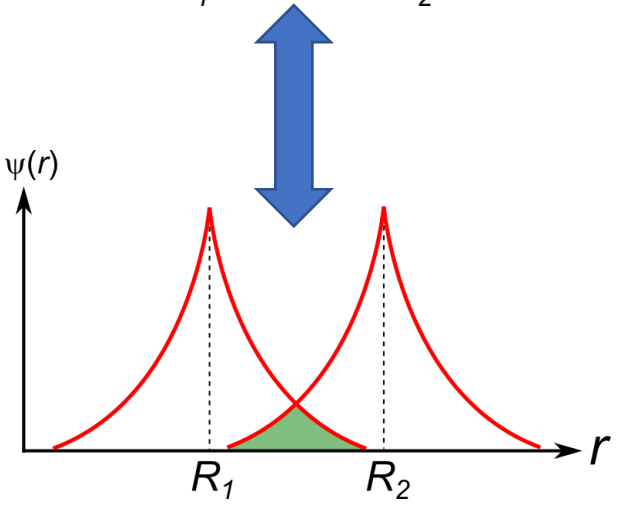


$U > t$

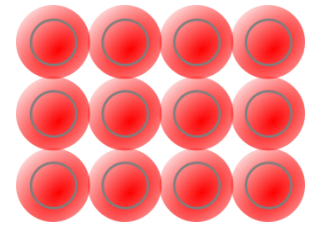


Mott Insulator

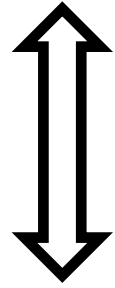
- electrons localized
- no current can flow



$U < t$

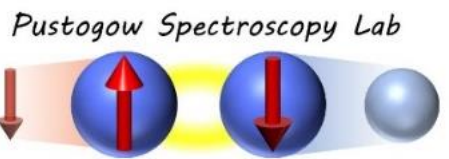


metal-insulator transition



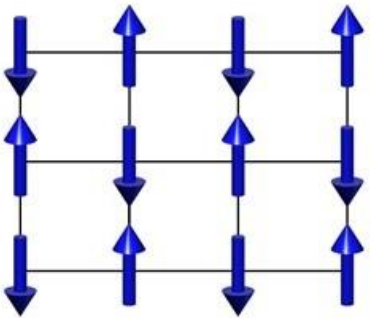
Metal

- large wave function overlap
- delocalized, mobile electrons

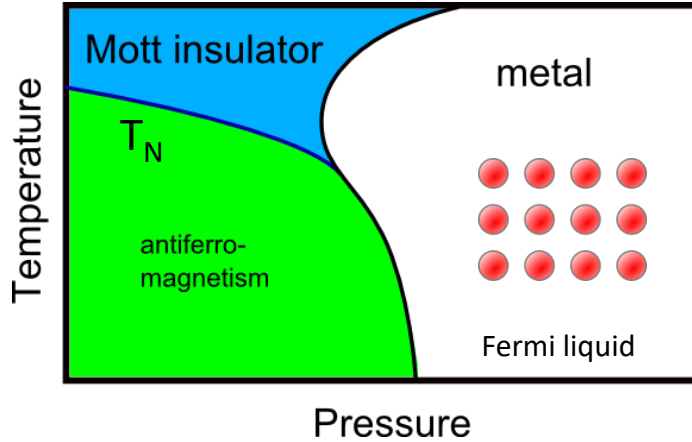


Mott Insulator - Magnetism

Magnetic Order



Mott-Heisenberg insulator

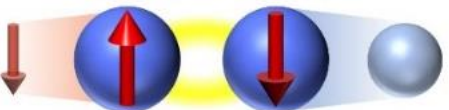
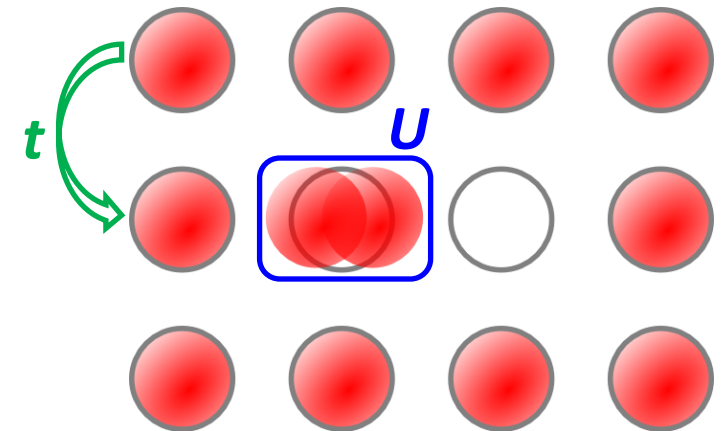


antiferromagnetic interactions

itinerant exchange mechanism

$$J \propto \frac{t^2}{U}$$

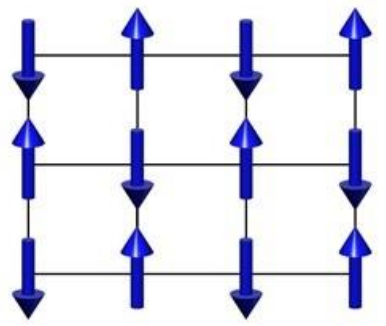
½ - filled band
1 electron per site



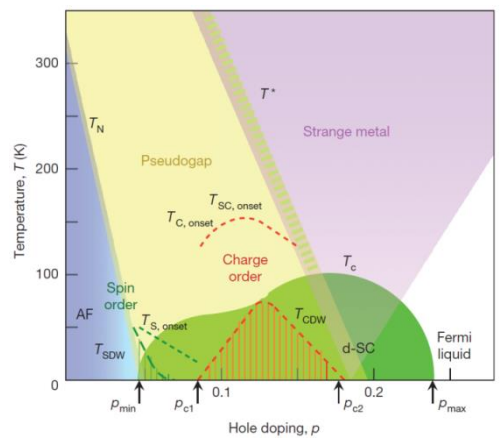
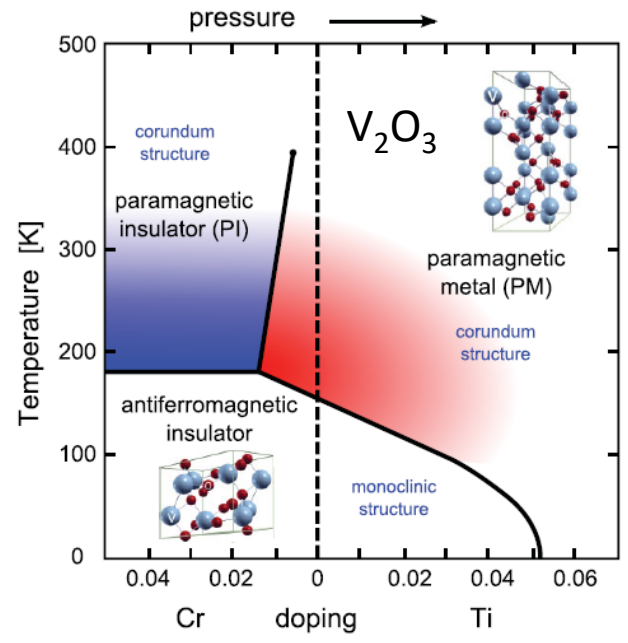
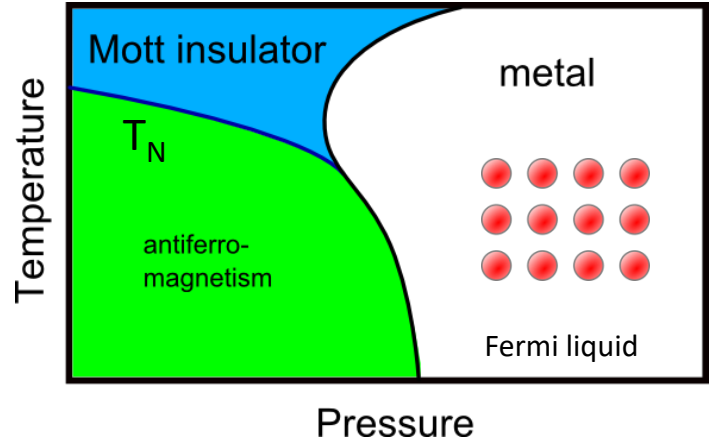
Mott Insulator - Magnetism

Hansmann *et al.*, *Phys. Status Solidi B* **250**, 1251–1264 (2013)

Magnetic Order



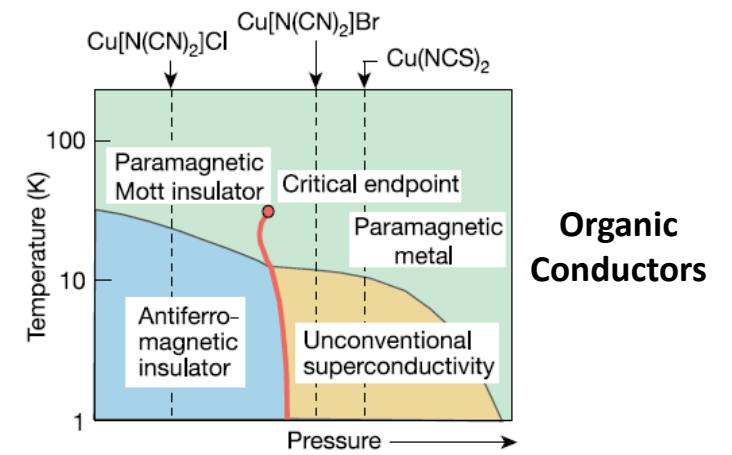
Mott-Heisenberg insulator



High-T_c Cuprates

Keimer *et al.*, *Nature* **518**, 179 (2015)

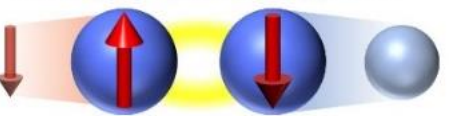
$$J \propto \frac{t^2}{U}$$



Organic Conductors

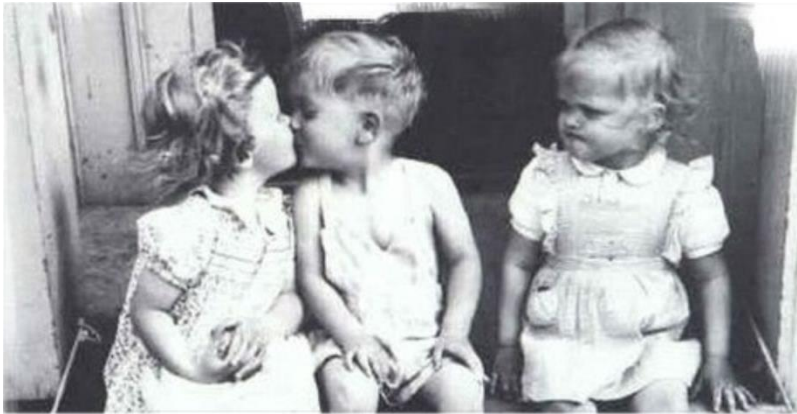
Kagawa *et al.*, *Nature* **436**, 534 (2005)

Pustogow Spectroscopy Lab



Geometrical Frustration

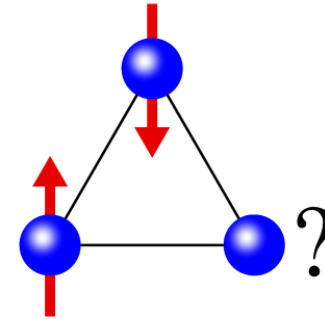
frustration in real life



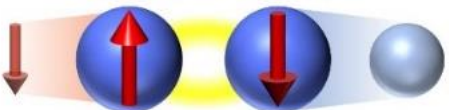
(picture from **Simone Fratini's** talk at ECRYS 2014)



geometrical frustration in physics

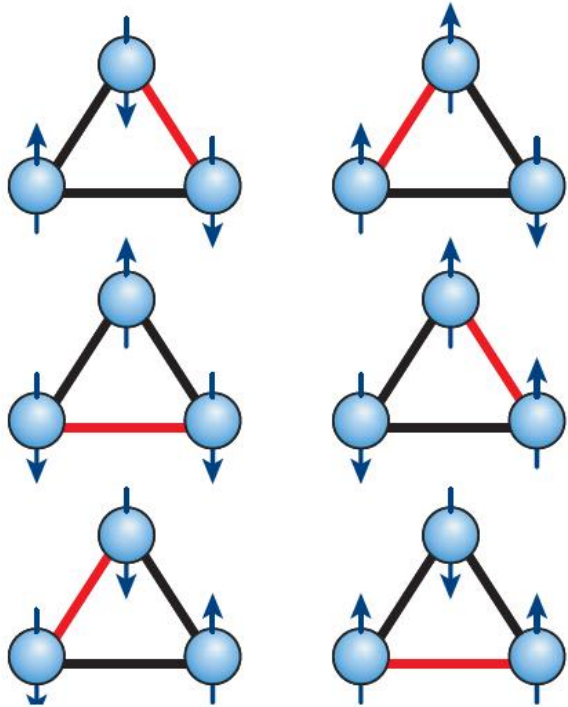


- suppression of magnetic order
- quantum spin liquid
- exotic excitations (spinons)

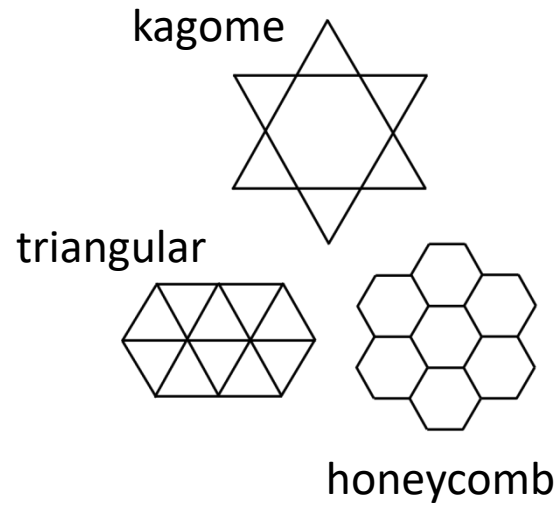


Geometrical Frustration

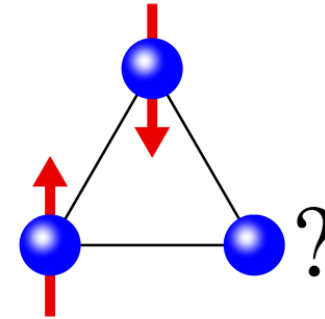
suppression of long-range order



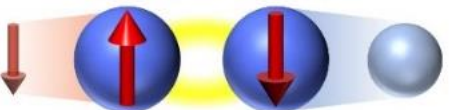
Balents, *Nature* **464**, 199–208 (2010)



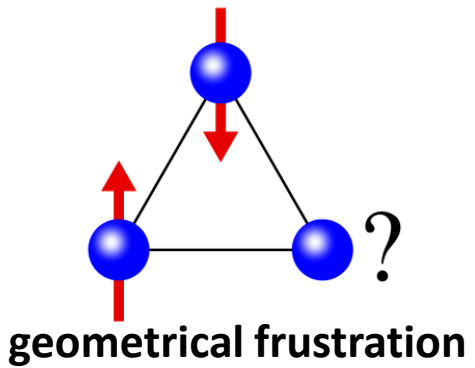
geometrical frustration in physics



- suppression of magnetic order
- quantum spin liquid
- exotic excitations (spinons)

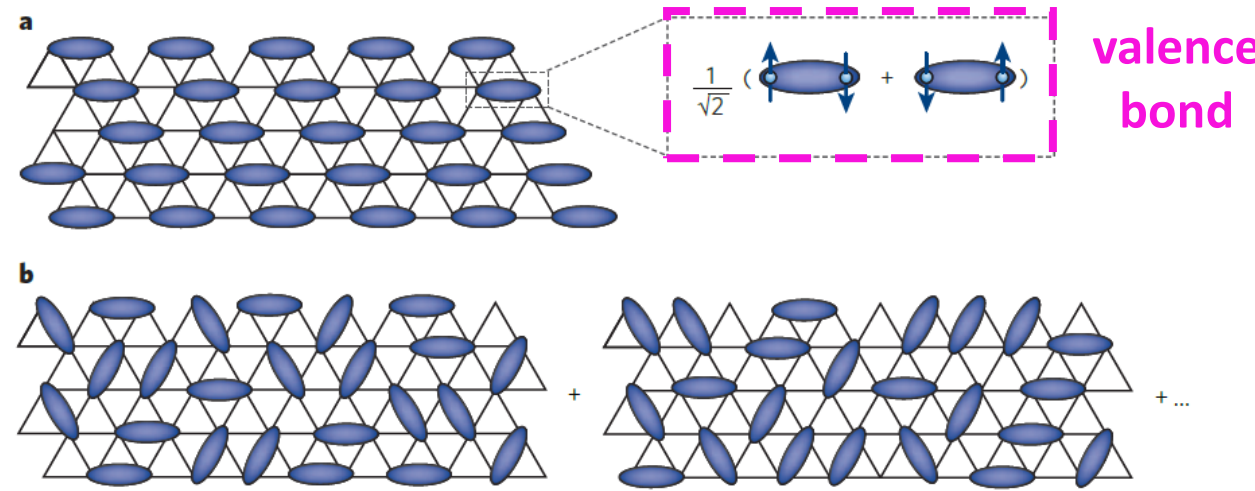


Frustrated Magnetism

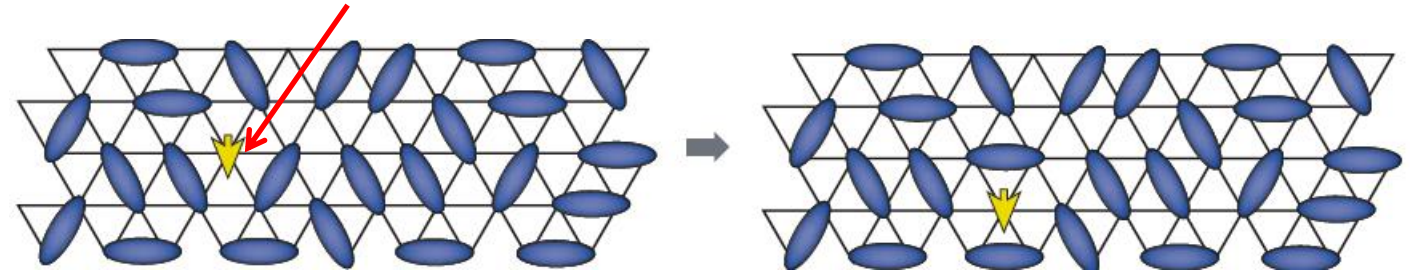


Valence Bond Solid
(e.g. Spin-Peierls in 1D)

Resonating Valence Bond (RVB) State

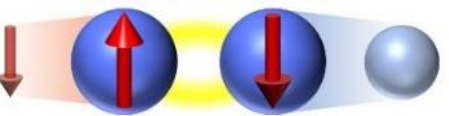


spinon: neutral $S = \frac{1}{2}$ excitation

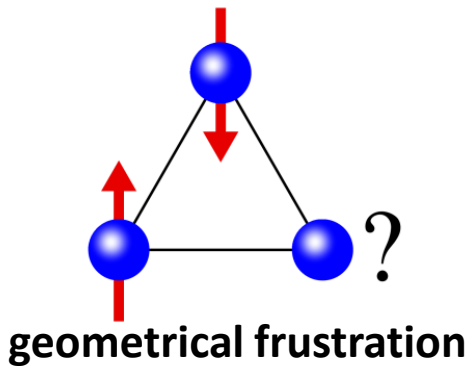


mobile spinons ('gapless')
similar to electrons in a metal,
but without charge

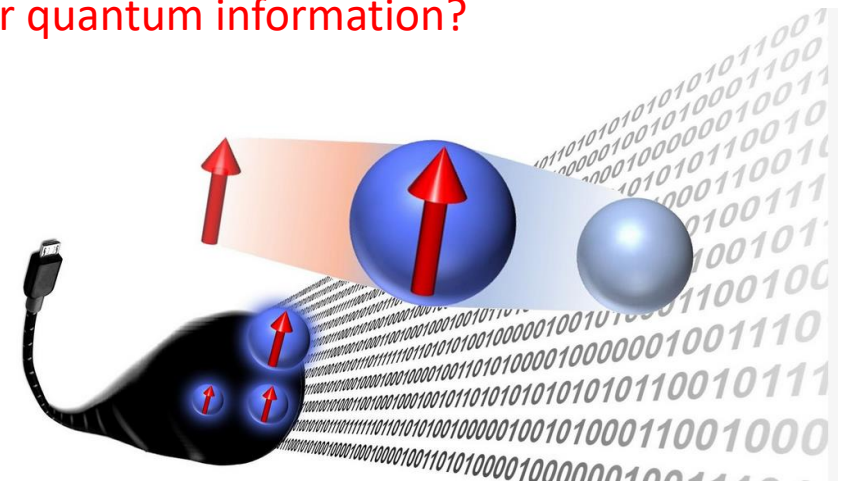
Balents, *Nature* **464**, 199–208 (2010)



Frustrated Magnetism

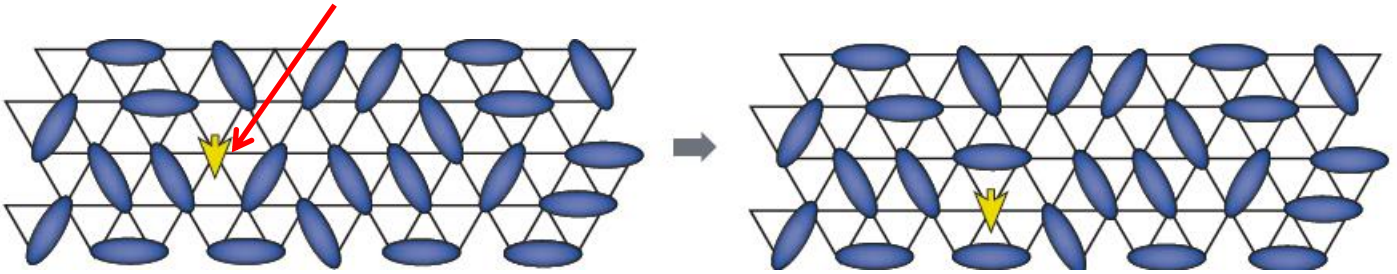


Useful for quantum information?



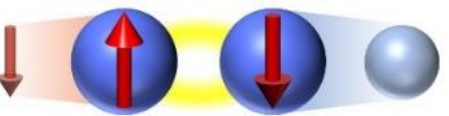
<https://www.tuwien.at/en/tu-wien/news/news/neue-messungen-stellen-spin-fluessigkeiten-in-frage>

spinon: neutral $S = \frac{1}{2}$ excitation

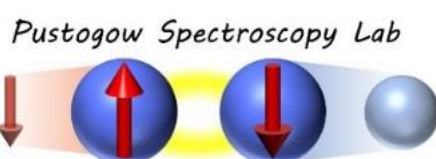
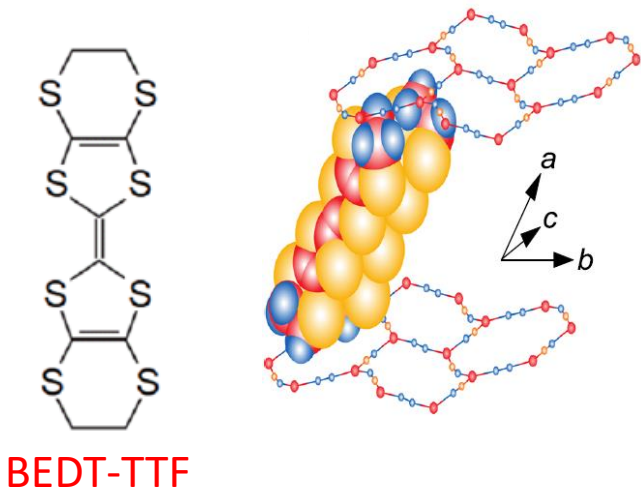
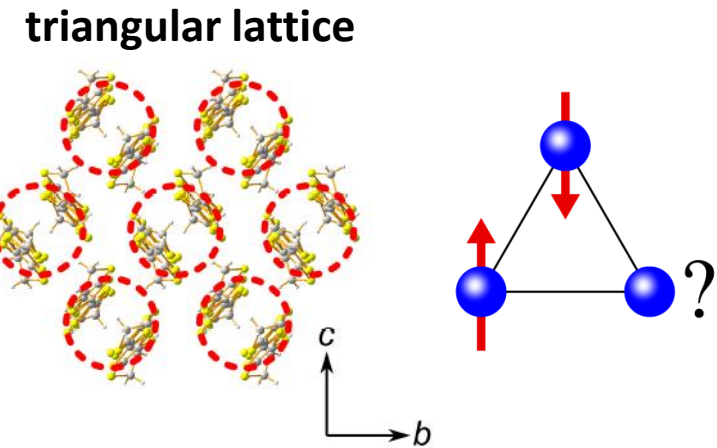
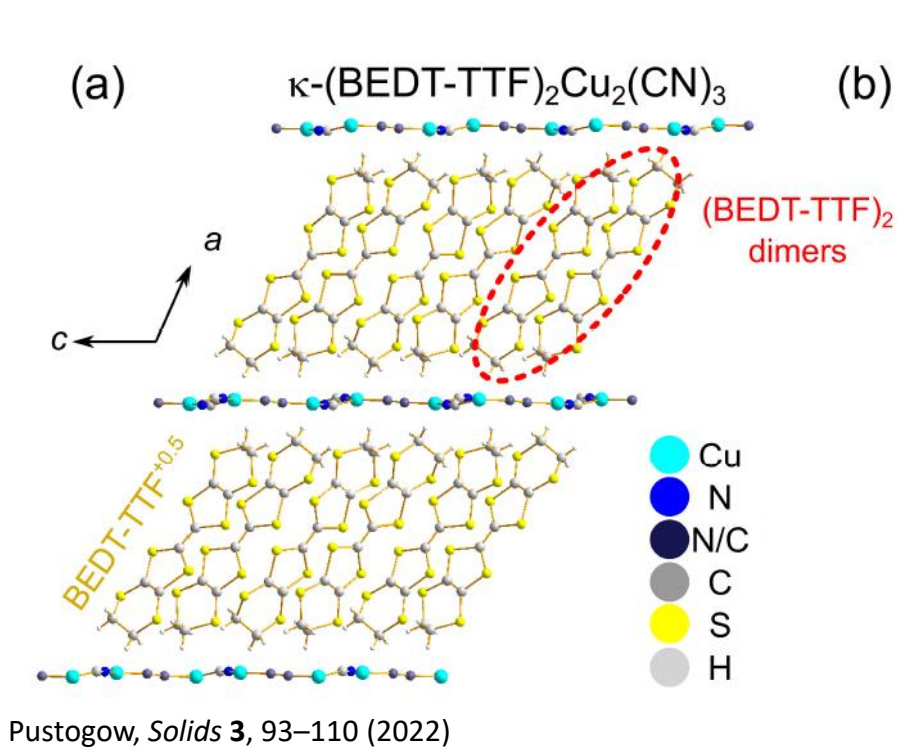


Balents, *Nature* **464**, 199–208 (2010)

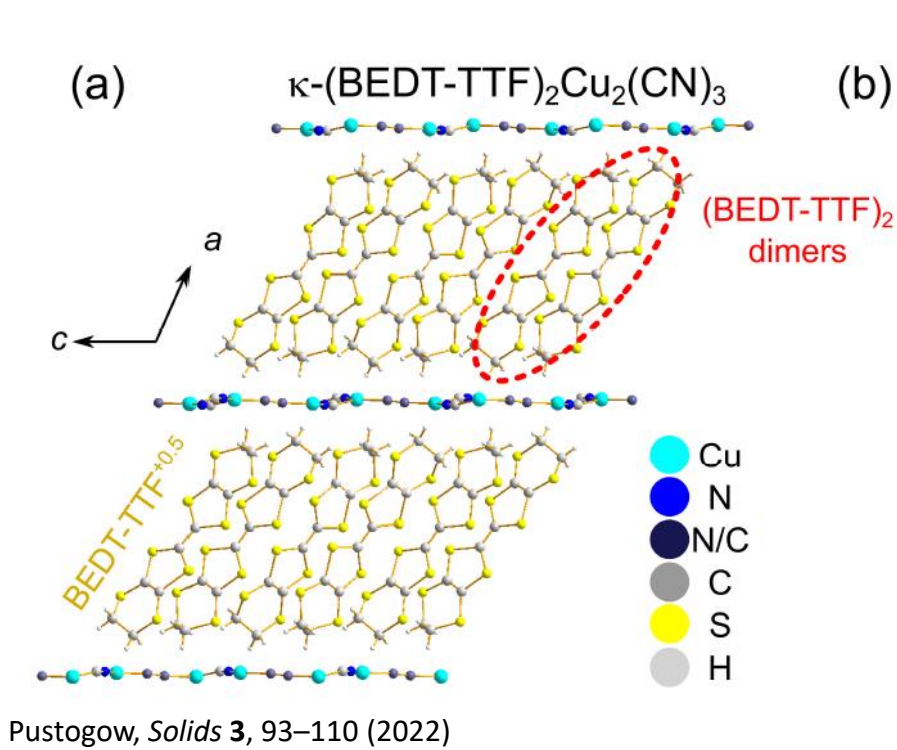
mobile spinons ('gapless')
similar to electrons in a metal,
but without charge



κ -(BEDT-TTF)₂Cu₂(CN)₃



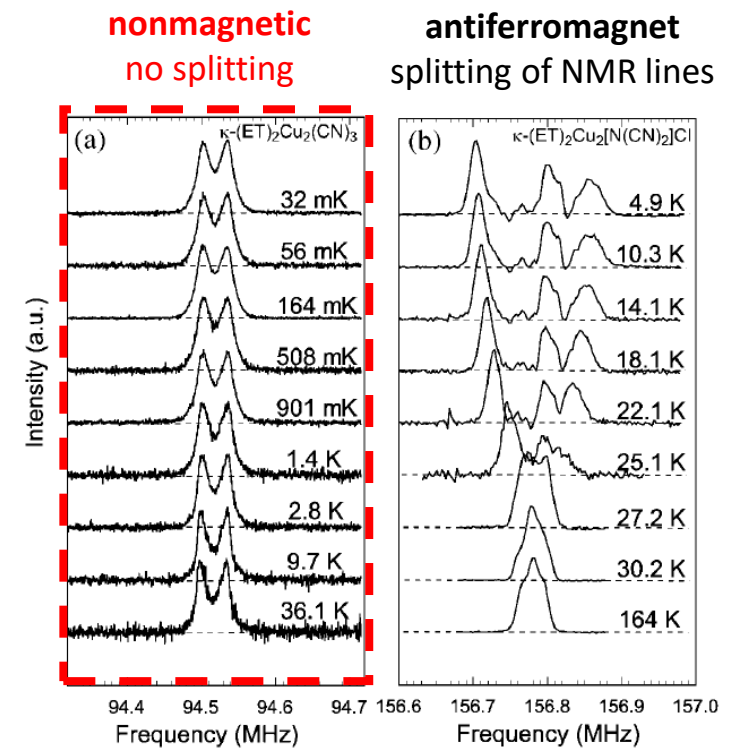
$\kappa\text{-(BEDT-TTF)}_2\text{Cu}_2(\text{CN})_3$



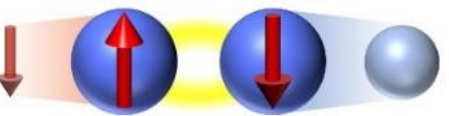
Nat. Phys. **4**, 459 (2008)
Science **328**, 1246 (2010)

Gapless quantum spin liquid?

- **no antiferromagnetism**



Shimizu *et al.*, *PRL* **91**, 107001 (2003)



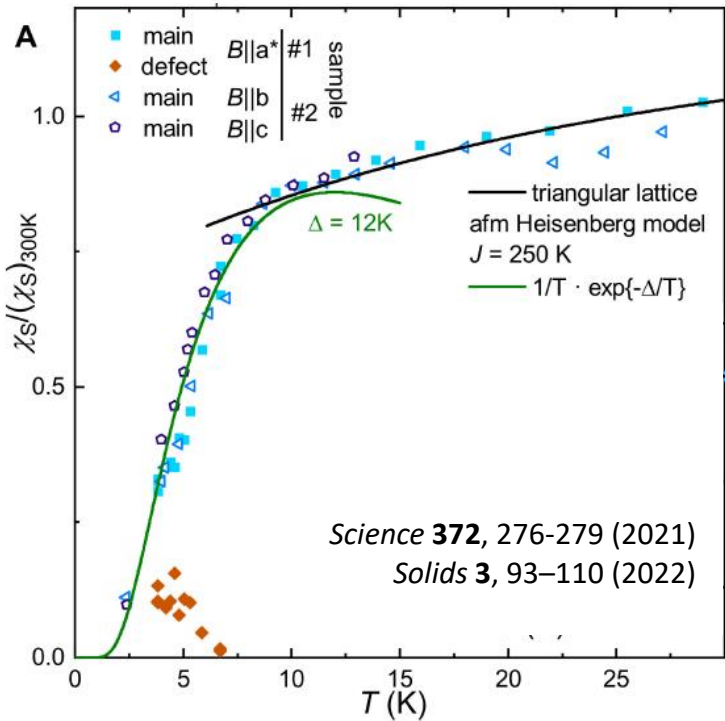


REPORT

MAGNETISM

Gapped magnetic ground state in quantum spin liquid candidate $\kappa\text{-(BEDT-TTF)}_2\text{Cu}_2(\text{CN})_3$

Björn Miksch¹, Andrej Pustogow^{1,2}, Mojtaba Javaheri Rahim¹, Andrey A. Bardin³, Kazushi Kanoda⁴,
 John A. Schlueter^{5,6}, Ralph Hübner¹, Marc Scheffler¹, Martin Dressel^{1*}

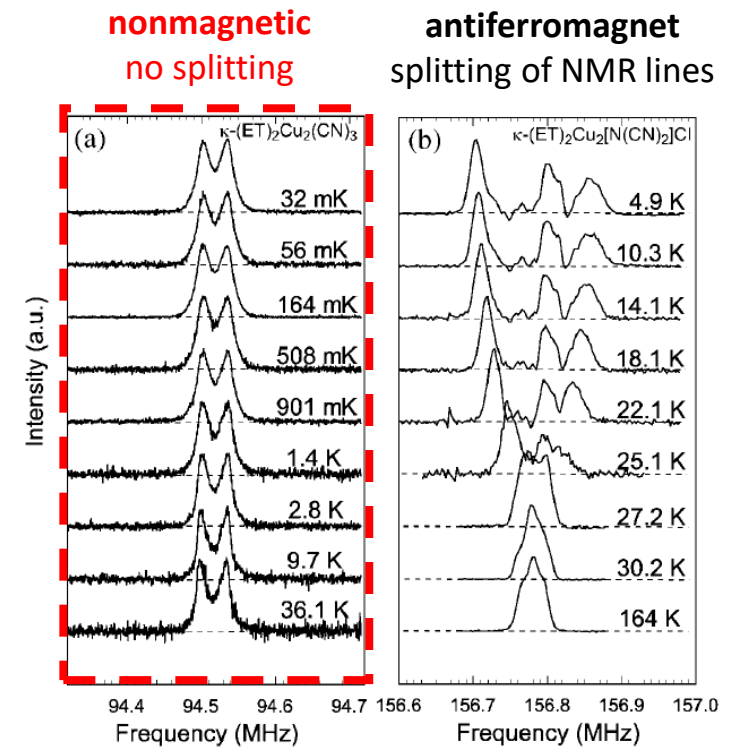


Nat. Phys. **4**, 459 (2008)
Science **328**, 1246 (2010)

~~Gapless quantum spin liquid?~~

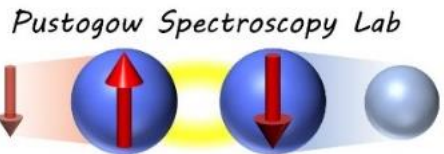
- no antiferromagnetism
- spin gap below 6 K

Gapless spin liquid state ruled out.
What is the magnetic ground state?



Shimizu et al., *PRL* **91**, 107001 (2003)

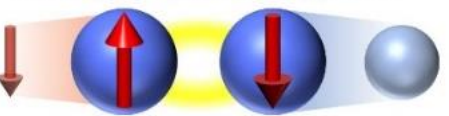
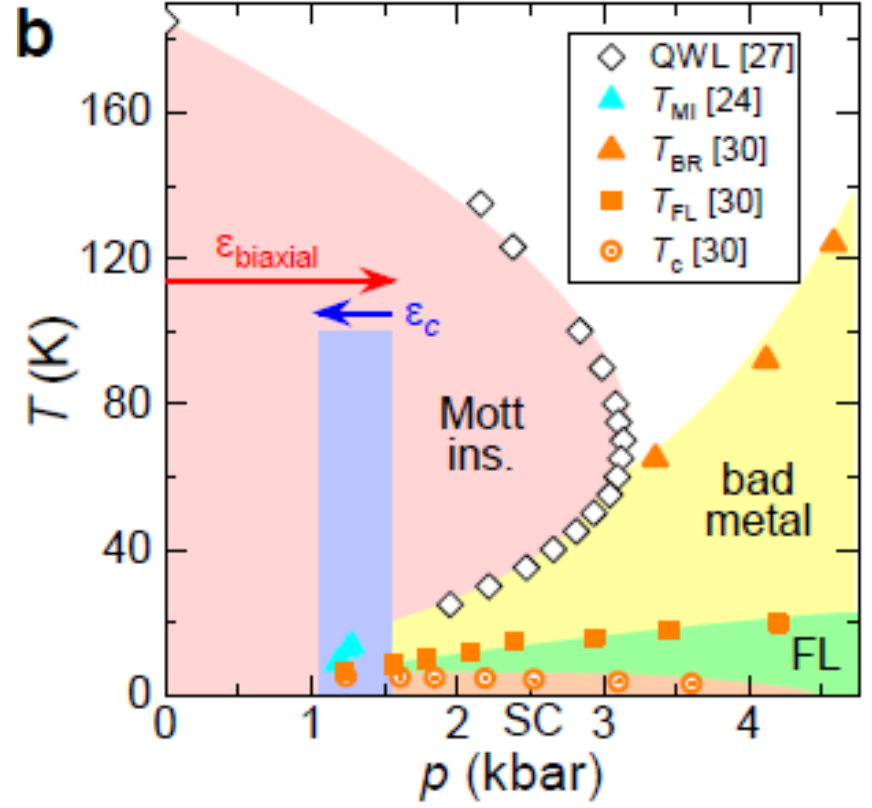
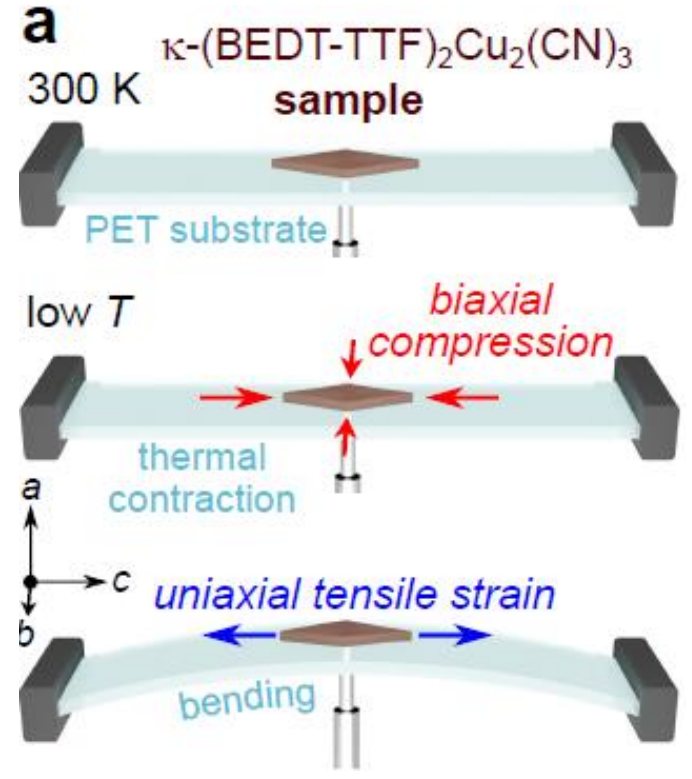
Tune spin gap through phase diagram



Chasing the spin gap through the phase diagram of a frustrated Mott insulator

A. Pustogow , Y. Kawasugi, H. Sakurakoji & N. Tajima

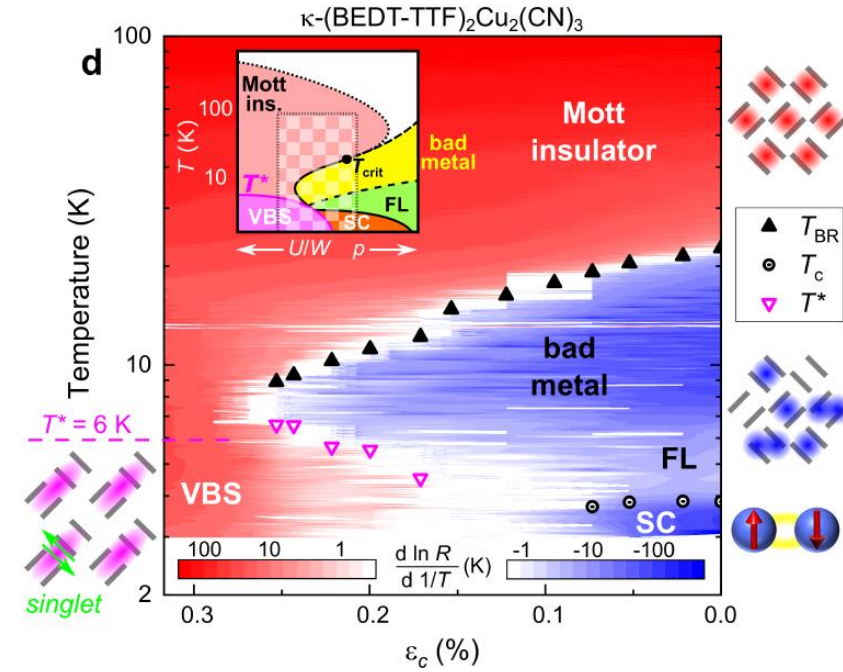
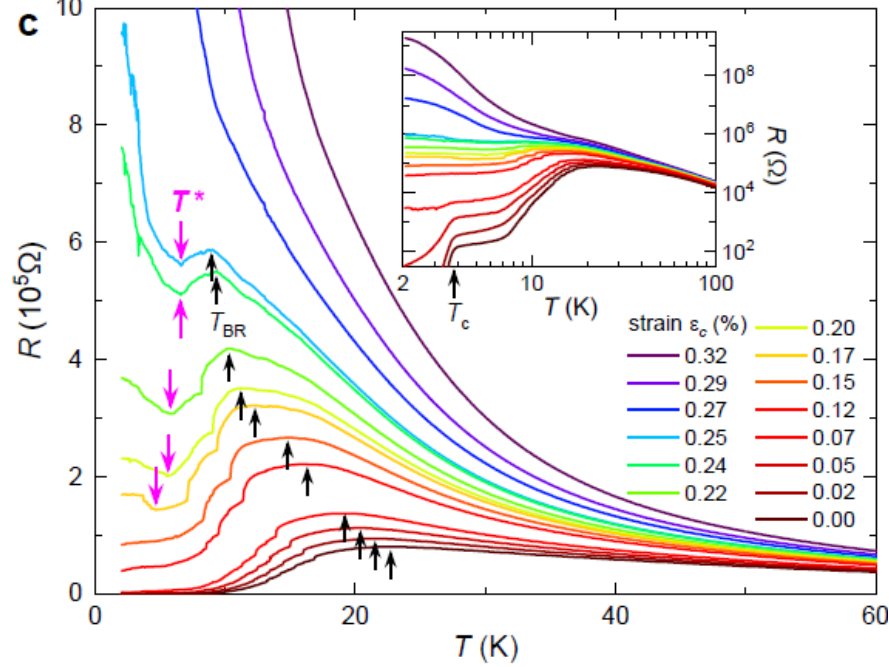
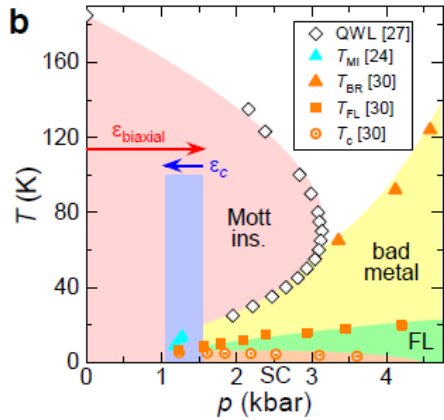
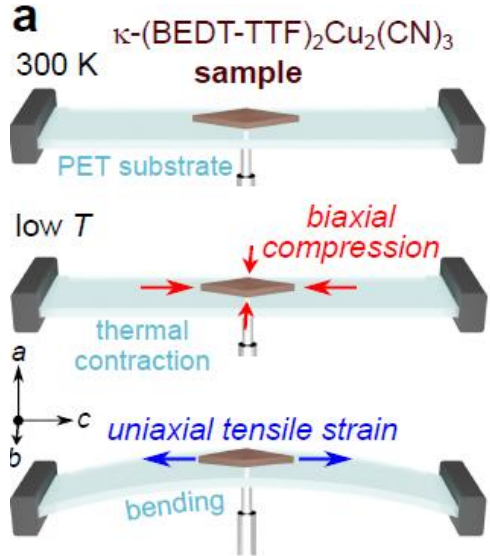
Nat. Commun. **14**, 1960 (2023)
J. Phys. Soc. Jpn. **92**, 065001 (2023)



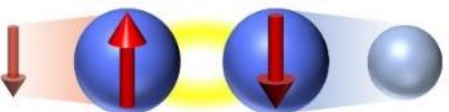
Chasing the spin gap through the phase diagram of a frustrated Mott insulator

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Nat. Commun. **14**, 1960 (2023)
J. Phys. Soc. Jpn. **92**, 065001 (2023)



Pustogow Spectroscopy Lab



2024-08-23

Andrej Pustogow

Chasing the spin gap through the phase diagram of a frustrated Mott insulator

A. Pustogow , Y. Kawasugi, H. Sakurakoji & N. Tajima

Nat. Commun. **14**, 1960 (2023)
J. Phys. Soc. Jpn. **92**, 065001 (2023)

phase diagram identical to valence bond solid

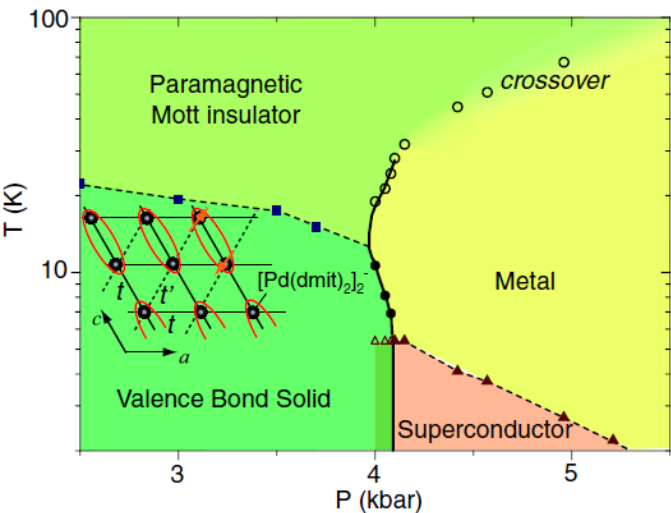
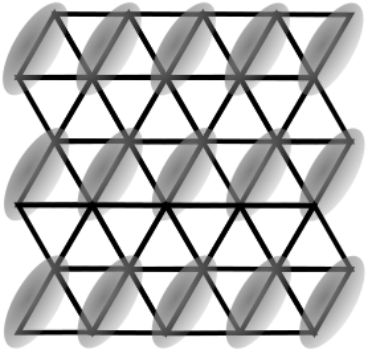
- consistent with
- thermal expansion
 - thermal transport
 - specific heat (6 K)
 - NQR
 - NMR
 - μ -SR
 - ESR

Miksch *et al.*, *Science* **372**, 276–279 (2021)
Pustogow, *Solids* **3**, 93–110 (2022)
Nat. Commun. **14**, 1960 (2023)
J. Phys. Soc. Jpn. **92**, 065001 (2023)

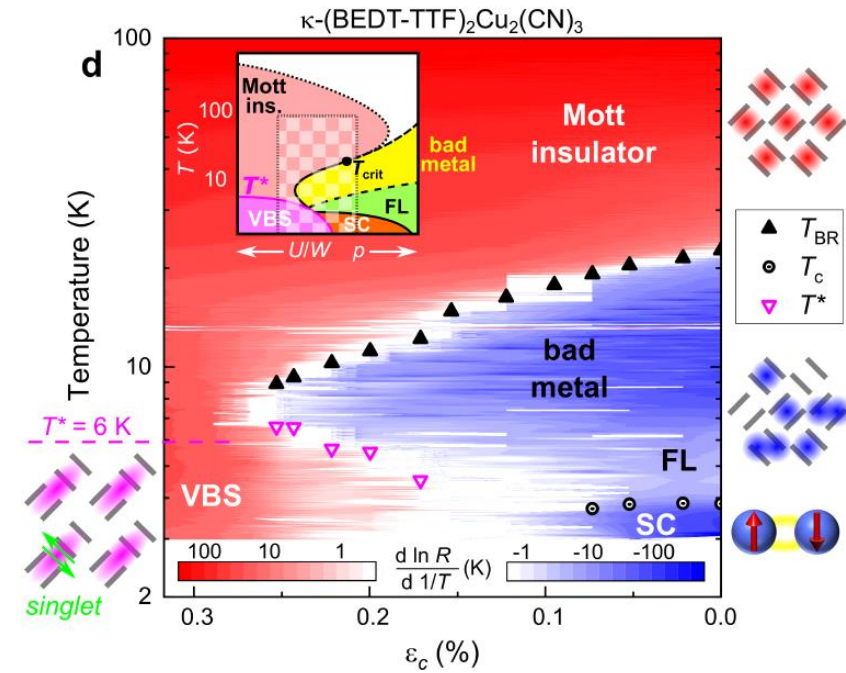
(but: gapped spin liquid phase not ruled out)

Andrej Pustogow

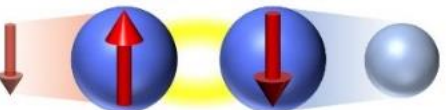
Valence Bond Solid



Shimizu *et al.*, *PRL* **99**, 256403 (2007)
Manna *et al.*, *PRB* **89**, 045113 (2014)

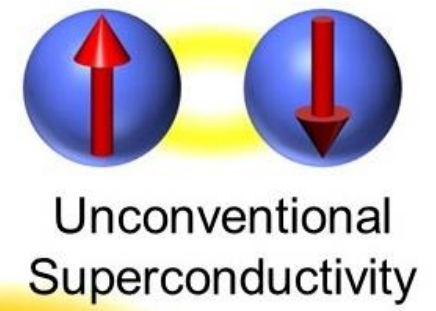
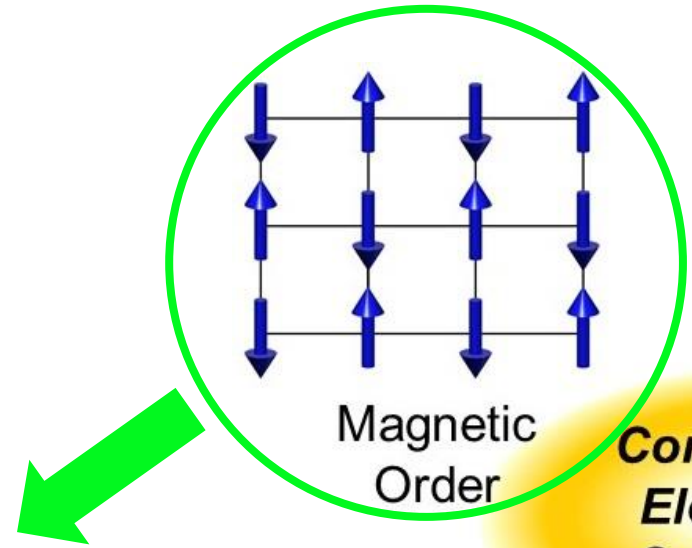
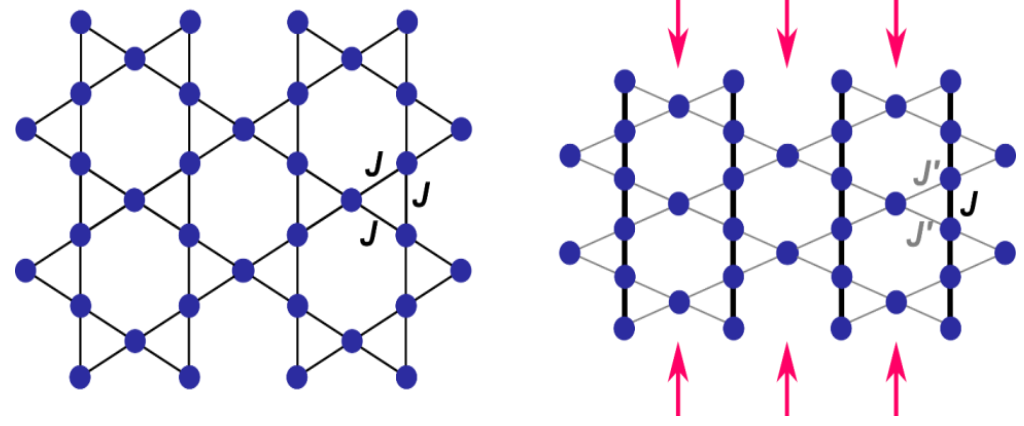


Pustogow Spectroscopy Lab



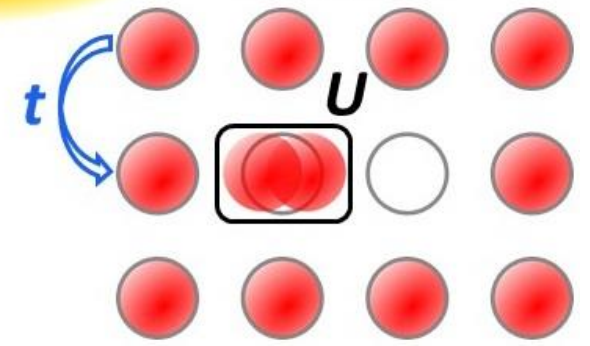
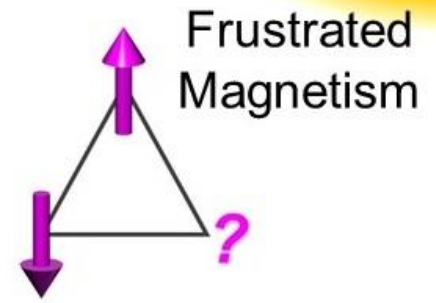
2024-08-23

New Spin on Correlated Electrons



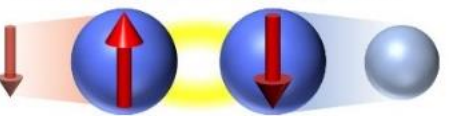
Correlated Electron Systems

Mott Metal-Insulator Transition

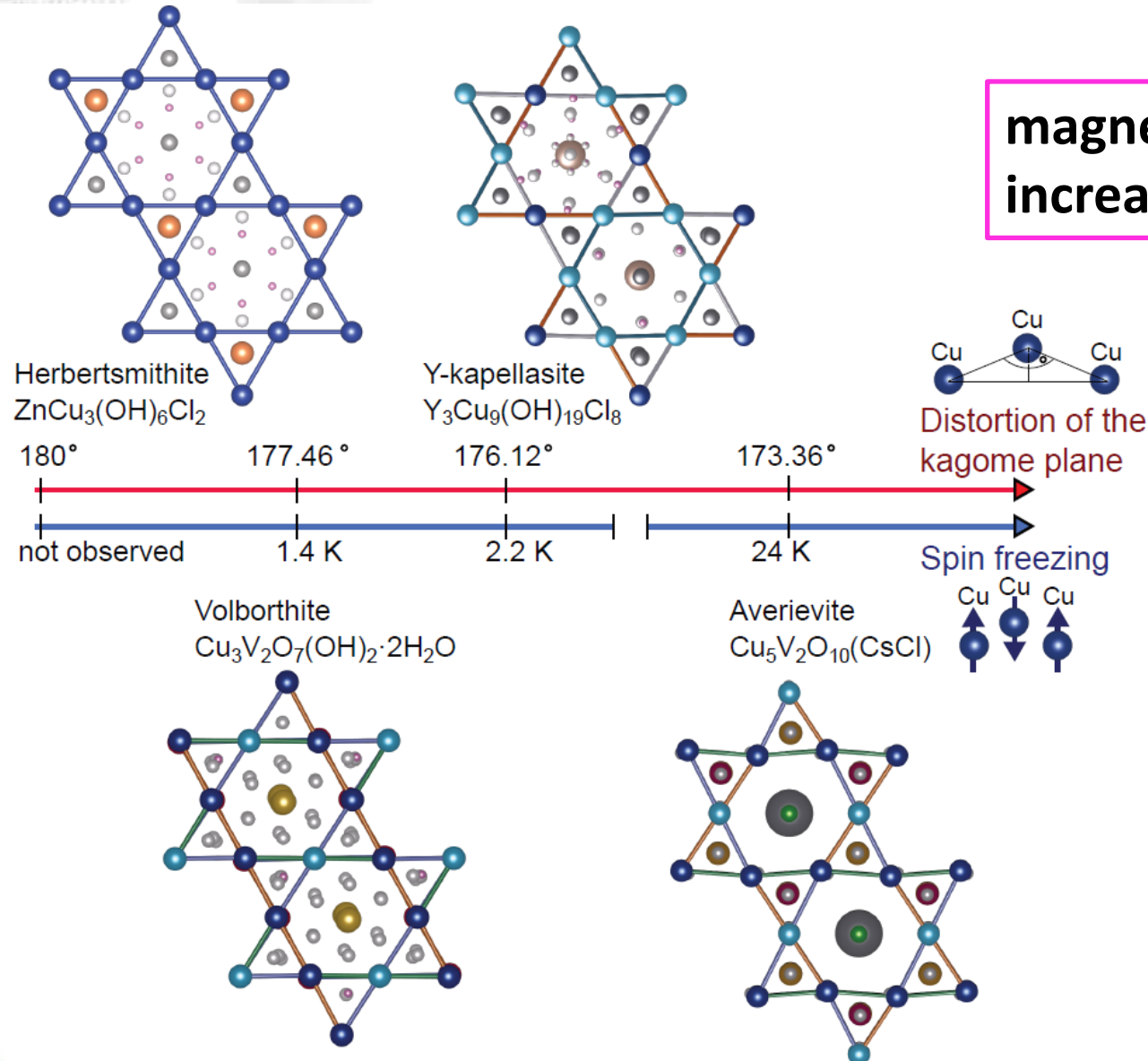


Part 3: strain tuning of a kagome antiferromagnet

Stress reduces frustration!

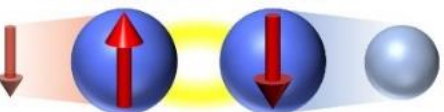


Unfrustrating the Kagome Layer

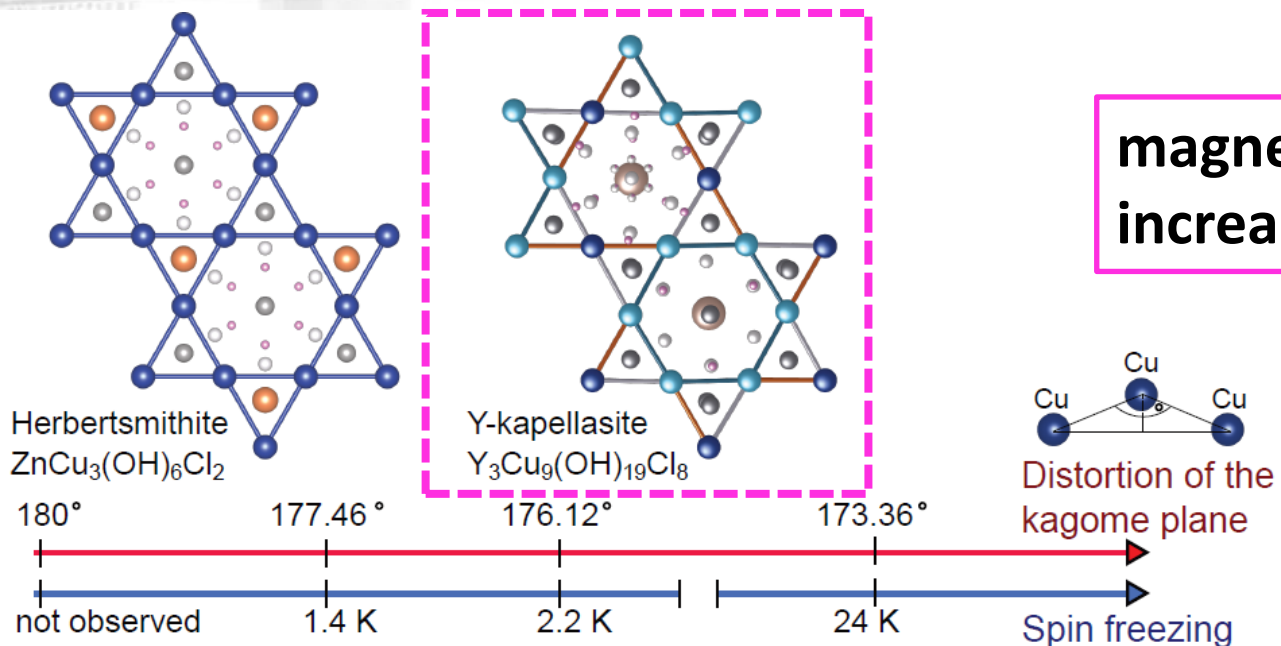


magnetic order stabilized upon increased kagome-plane distortion

Biesner *et al.*, *PRB* **105**, L060410 (2022)
Adv. Quantum Technol. **2022**, 2200023



Unfrustrating the Kagome Layer

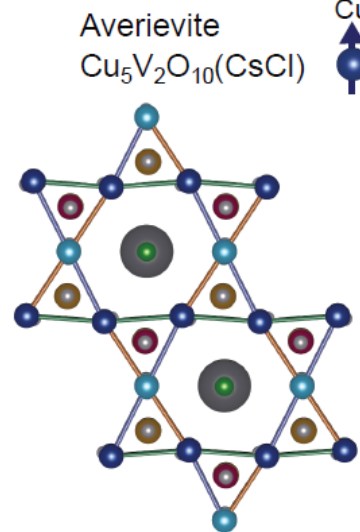
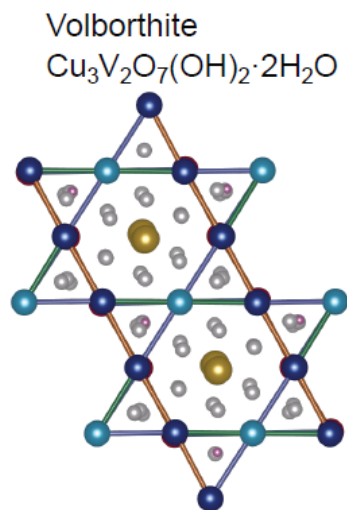


magnetic order stabilized upon increased kagome-plane distortion

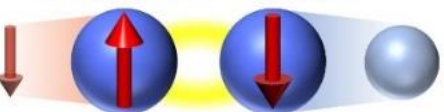


$T_N = 2.2 \text{ K}$

Puphal et al., *J. Mater. Chem. C* 5, 2629 (2017)



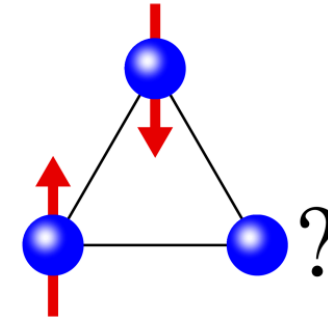
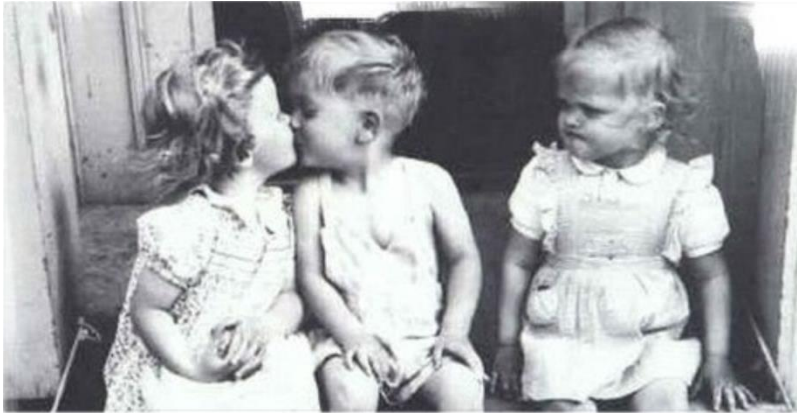
Biesner et al., *PRB* 105, L060410 (2022)
Adv. Quantum Technol. 2022, 2200023



Stress Reduces Frustration

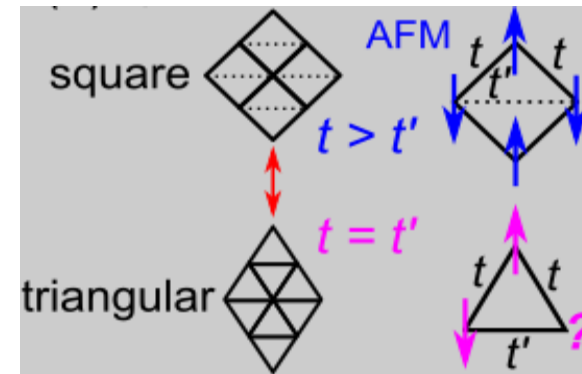
frustration in real life

Both options (left/right) are equivalent

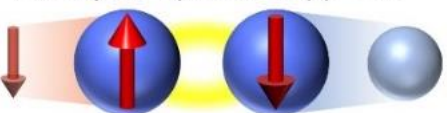


$$J \propto \frac{t^2}{U}$$

- vary t'/t by uniaxial strain
- pull spins apart / closer together



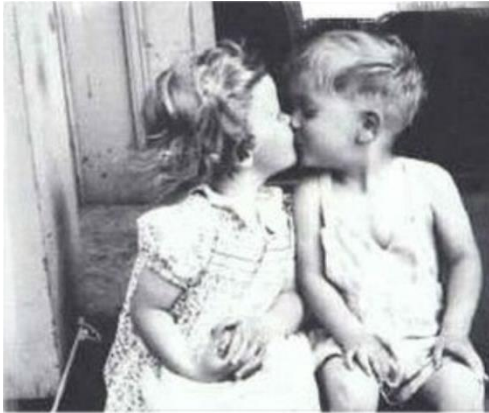
Wang et al., *Phys. Rev. Lett.* **131**, 256501 (2023)



Stress Reduces Frustration

frustration in real life

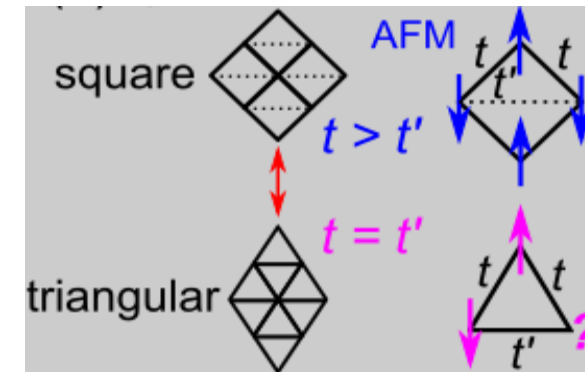
Closer option (left) is obvious



move one option away

$$J \propto \frac{t^2}{U}$$

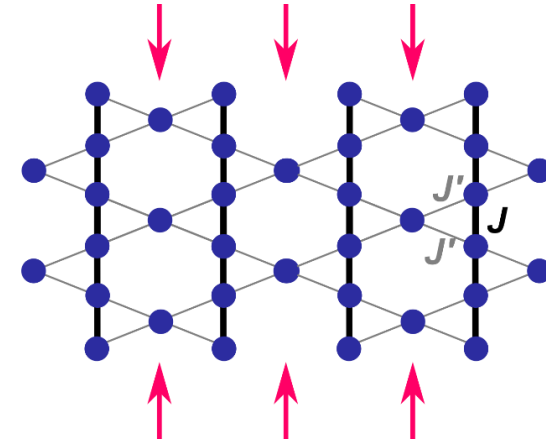
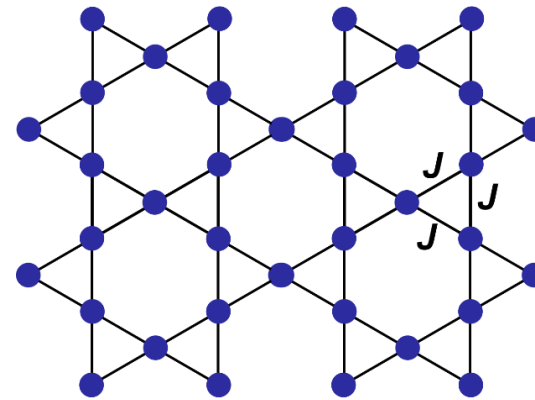
- vary t'/t by uniaxial strain
- pull spins apart / closer together



Wang et al., *Phys. Rev. Lett.* **131**, 256501 (2023)

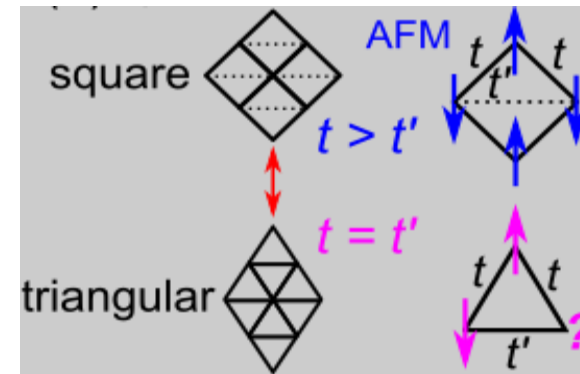


Stress Reduces Frustration

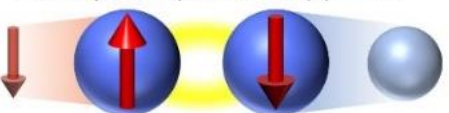


$$J \propto \frac{t^2}{U}$$

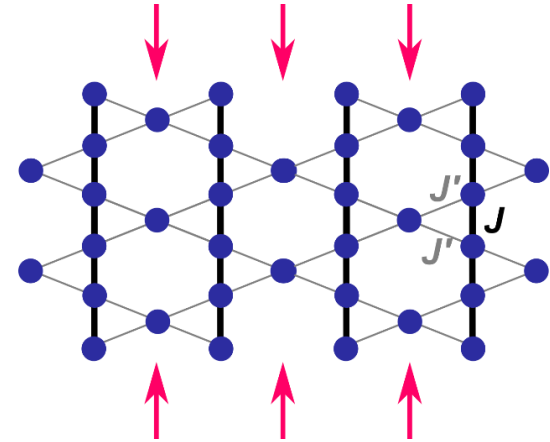
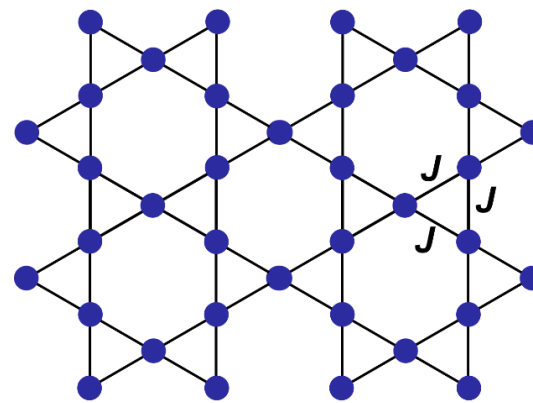
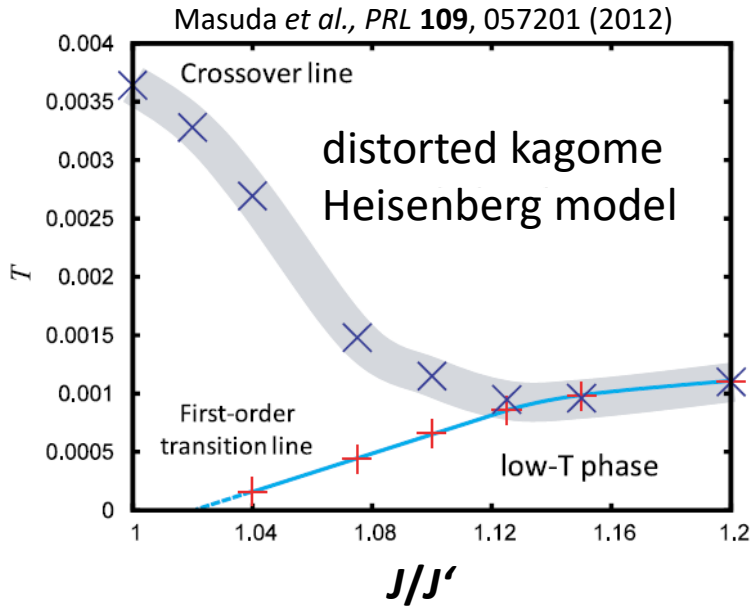
- vary t'/t by uniaxial strain
- pull spins apart / closer together



Wang et al., *Phys. Rev. Lett.* **131**, 256501 (2023)

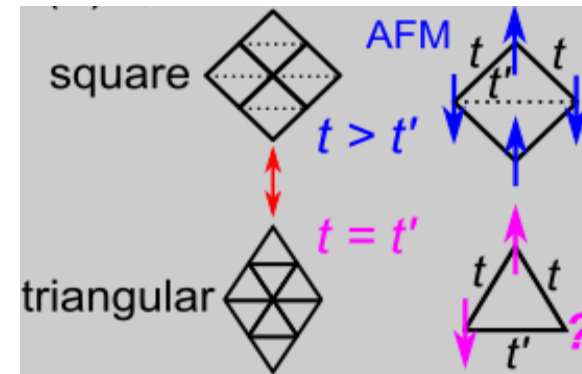


Stress Reduces Frustration

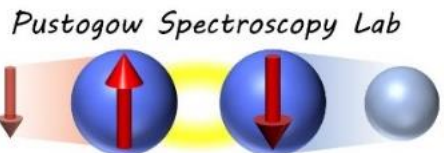


$$J \propto \frac{t^2}{U}$$

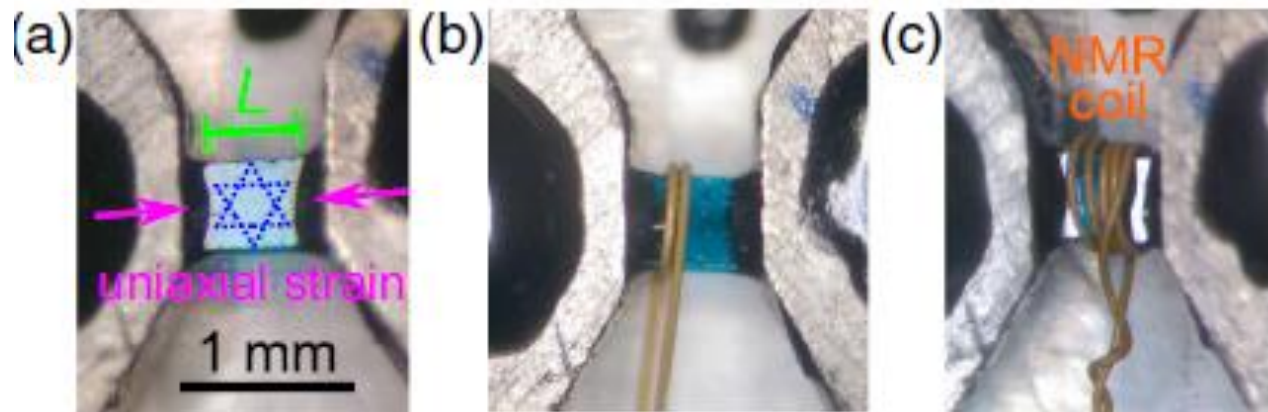
- vary t'/t by uniaxial strain
- pull spins apart / closer together
- **expect linear increase of T_N**



Wang *et al.*, *Phys. Rev. Lett.* **131**, 256501 (2023)



Stress Reduces Frustration

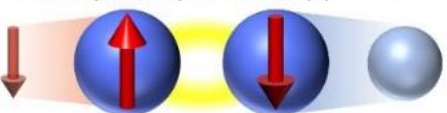
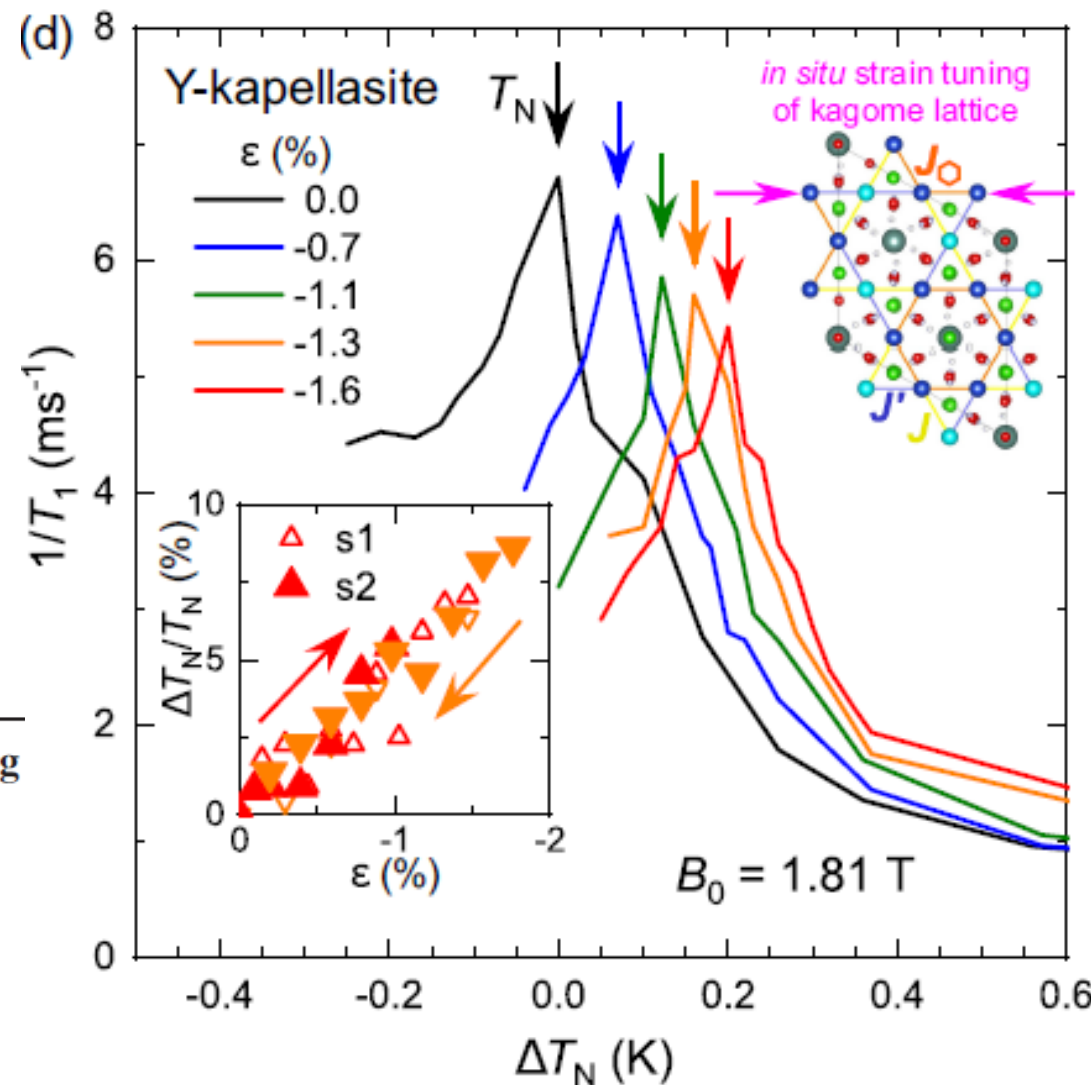


PHYSICAL REVIEW LETTERS 131, 256501 (2023)

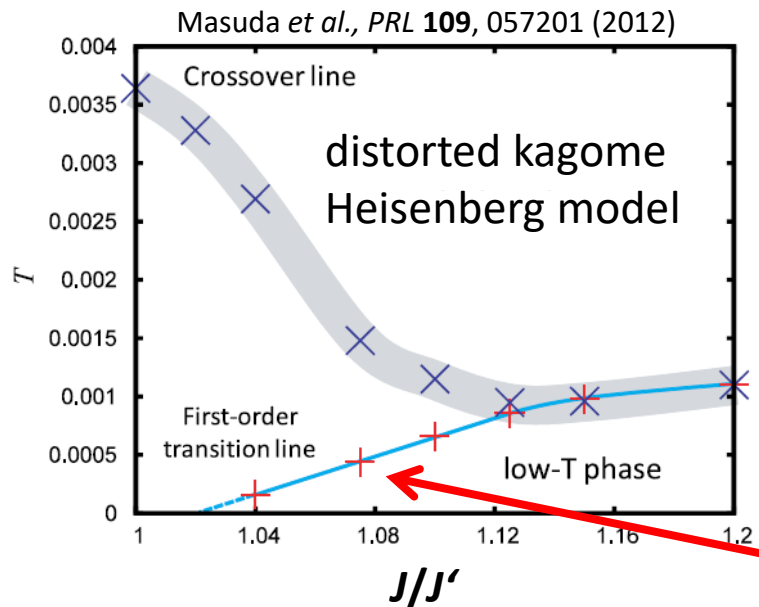
Controlled Frustration Release on the Kagome Lattice by Uniaxial-Strain Tuning

Jierong Wang,¹ M. Spitaler², Y.-S. Su,¹ K. M. Zoch,³ C. Krellner³,
P. Puphal^{3,4}, S. E. Brown,¹ and A. Pustogow^{1,2,*}

in situ strain tuning of J'/J at low T



Stress Reduces Frustration

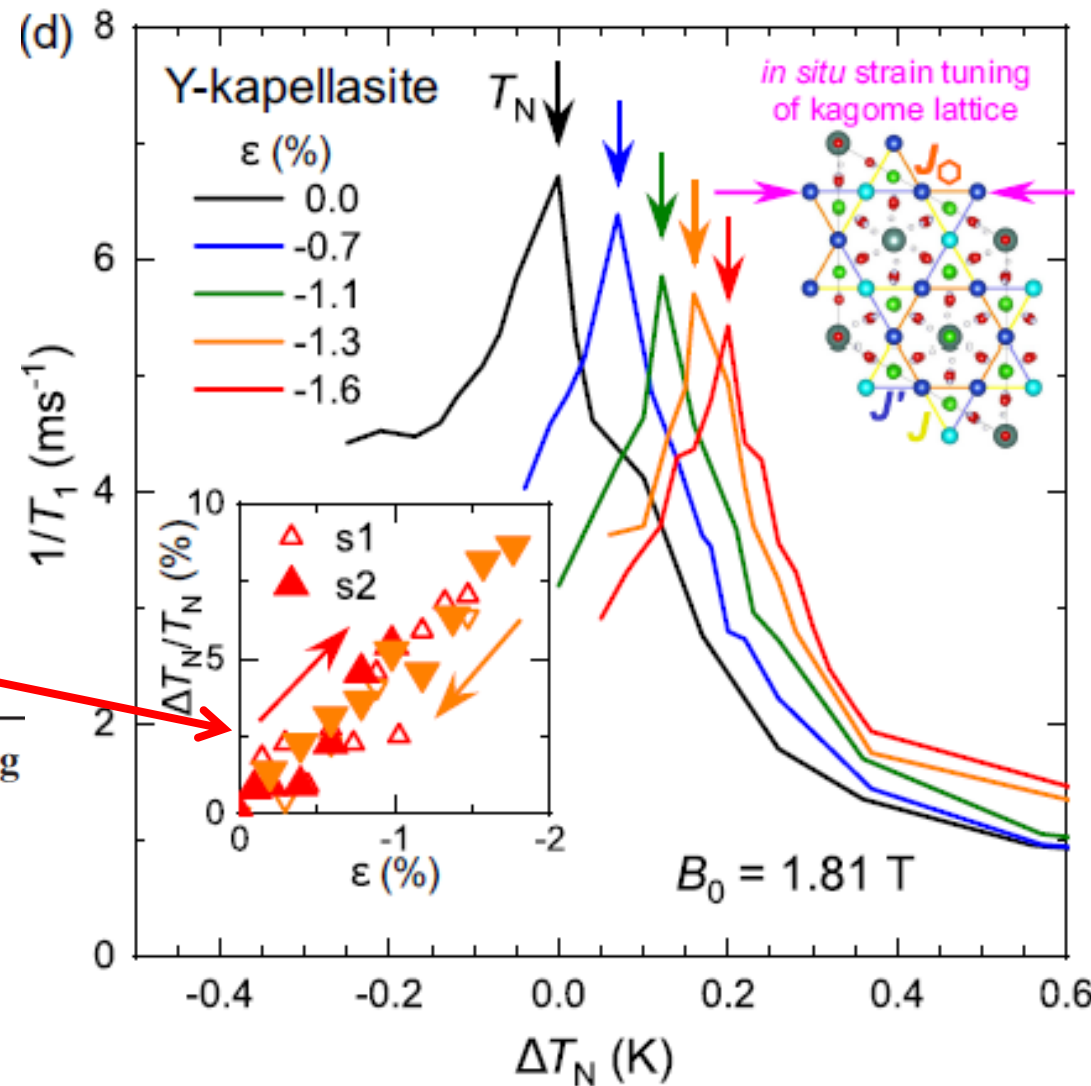


PHYSICAL REVIEW LETTERS **131**, 256501 (2023)

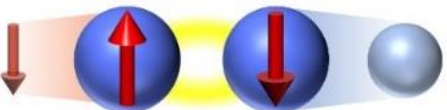
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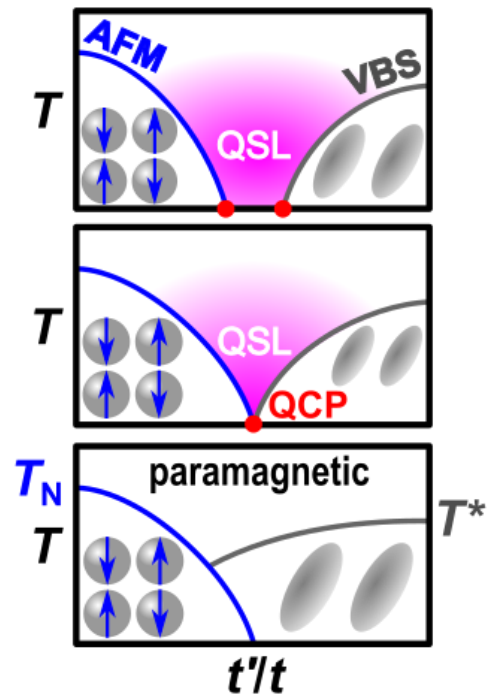
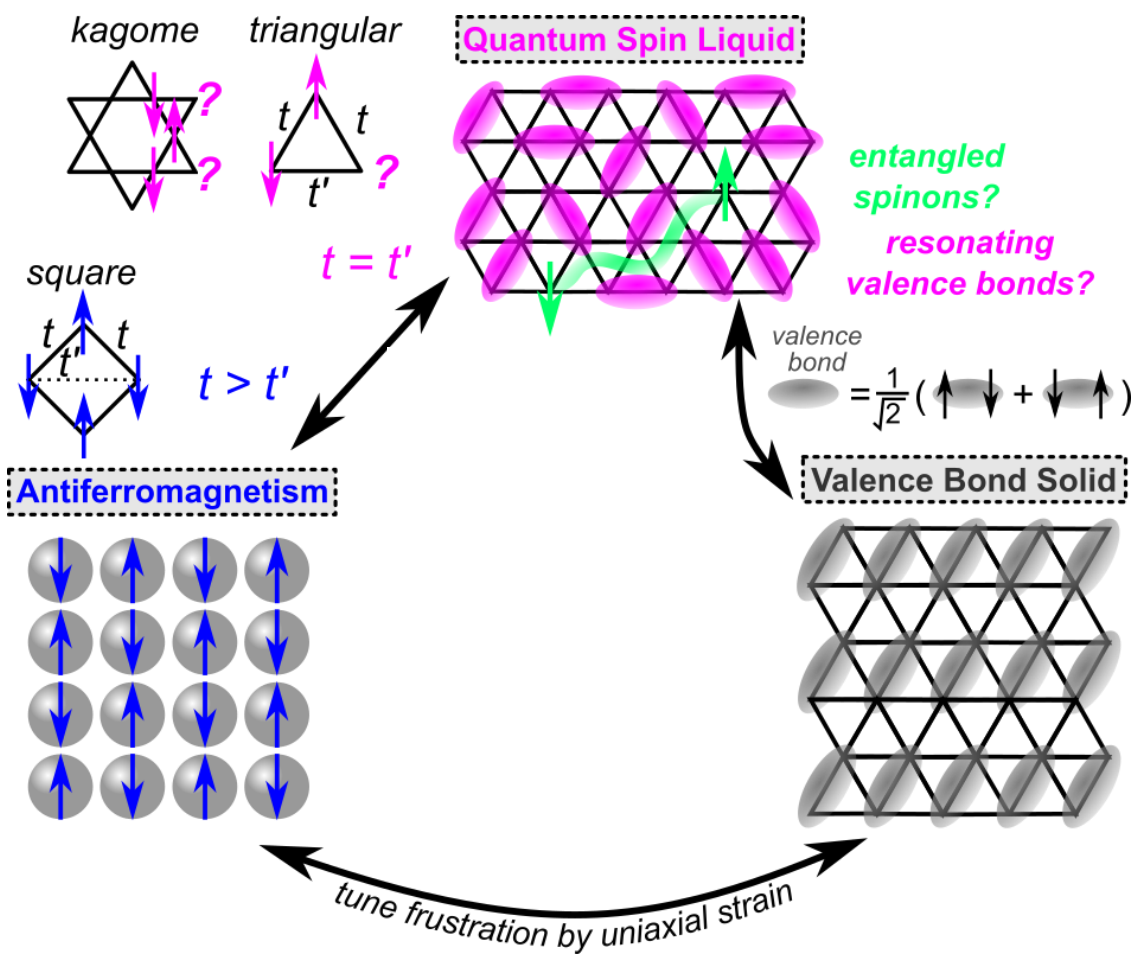
in situ strain tuning of J'/J at low T



linear increase of T_N



Strain Tuning of Frustrated Magnetism



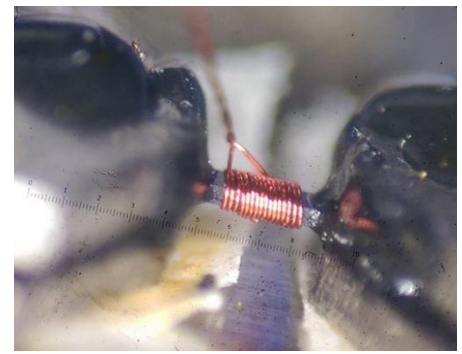
- *in situ* strain tuning of t'/t at low T
- stabilize new phases with t'/t ratios inaccessible to synthesis

Stress Reduces Frustration

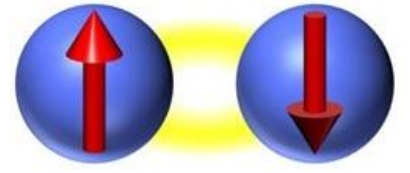
PHYSICS TODAY

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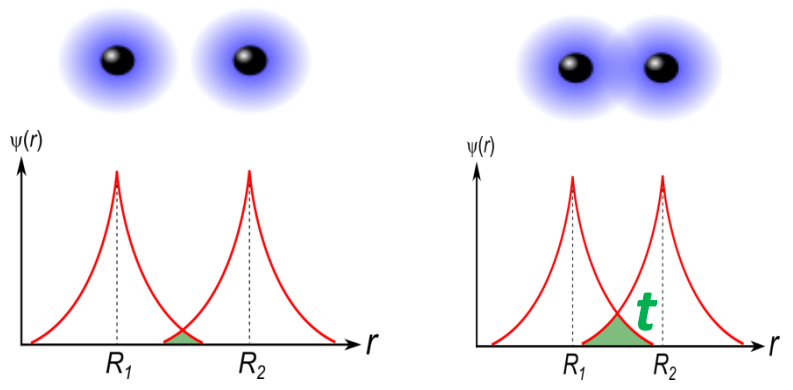
An unconventional superconductor isn't so odd after all



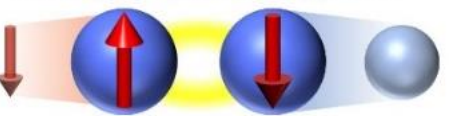
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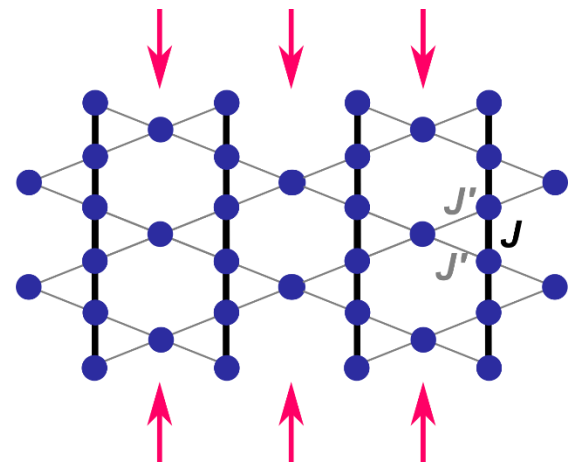
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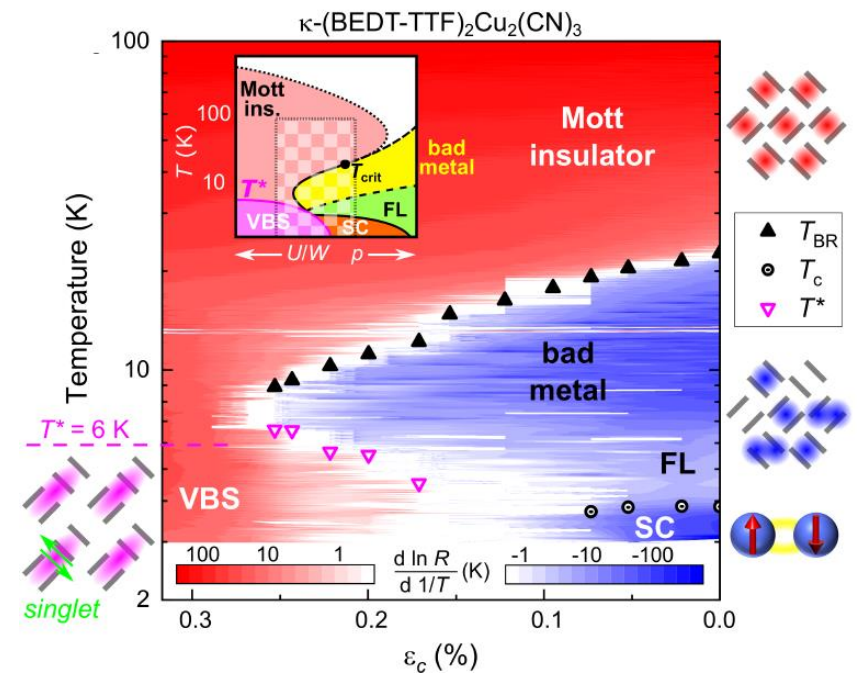


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