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Strain manipulation of multi-component order parameters

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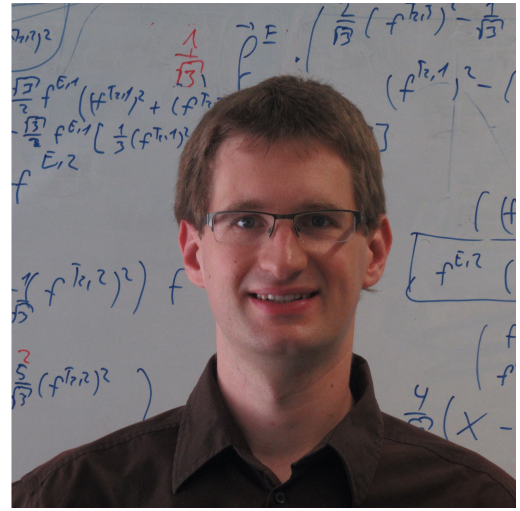
Deutsche Forschungsgemeinschaft
German Research Foundation
CRC– TRR 288
Elasto-Q-Mat

collaborators

Matthias Hecker (KIT)



Roland Willa (KIT)

Rafael M. Fernandes (Minnesota)

Rolf Lortz (Hong-Kong UST)

Outline

Karlsruhe Institute of Technology

- brief recap: vestigial order in iron-based systems
- vestigial order in doped Bi_2Se_3

  with Matthias Hecker (theory) + Rolf Lortz (experiment)

  Matthias Hecker and J.S., npj Quantum Mater. **3**, 26 (2018)

  C.-w. Cho, et al., Nature Comm. **11**, 3056 (2020)

- proposal for (non) TRS-breaking in Sr_2RuO_4

  with Roland Willa and Rafael Fernandes

  unpublished

Landau theory of phase transitions: 1937

Lev D. Landau
(1908-1968)

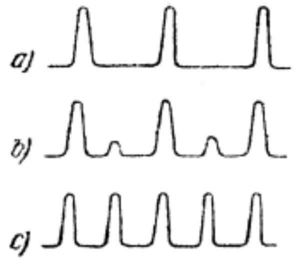


Fig. 1

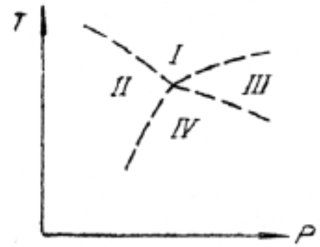


Fig. 3

$$\delta\rho(\mathbf{r}) = \sum_n \sum_\mu \eta_\mu^{(n)} \varphi_\mu^{(n)}(\mathbf{r})$$

- expand w.r.t. the irreducible representations of the symmetry group
- Schur's orthogonality relations →

$$f = \sum_n r_n \sum_\mu \eta_\mu^{(n)} \eta_\mu^{(n)} + \cdots$$

L. D. Landau, Zh. Eksp. Teor. Fiz. **7**, 19 (1937)

symmetry breaking fluctuations:

fluctuating field η_μ with multiple components $\mu = 1, \cdots, d_{\text{irr}}$

$$\varphi = \sum_{\mu,\nu} r_{\mu\nu} \eta_\mu^* \eta_\nu \qquad \varphi = \sum_{\mu,\nu,\lambda} r_{\mu\nu\lambda} \eta_\mu \eta_\nu \eta_\lambda$$

composite order of a fluctuating variable can break a symmetry

$$\langle \varphi \rangle \neq 0$$

fluctuations or frustration

long range order is suppressed

$$\langle \eta_\mu \rangle = 0$$

a liquid of spins,
of Cooper pairs etc.
forms

composite order
(condensation of fluctuations)

$$\langle \eta_\mu \eta_\nu \rangle \neq 0 \qquad \langle \eta_\mu \eta_\nu \eta_\lambda \rangle \neq 0$$

symmetry: must be a nontrivial combination
energetics: less fluctuations or frustration

vestigial order

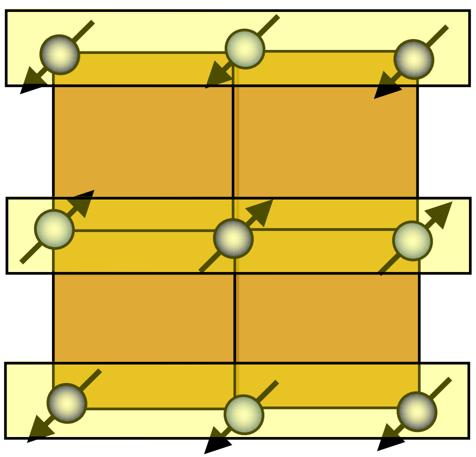
VOLUME 64, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 1990

Ising Transition in Frustrated Heisenberg Models

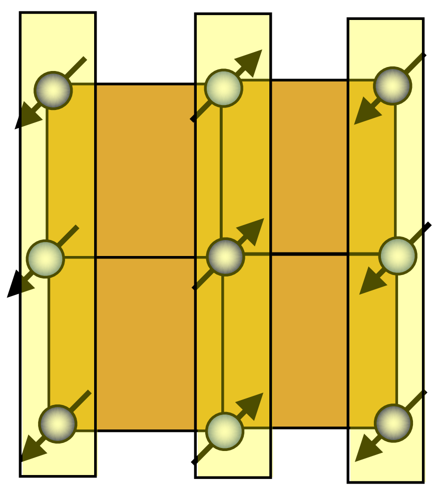
P. Chandra
Corporate Research Science Laboratories, Exxon Research and Engineering Company, Annandale, New Jersey 08801

P. Coleman and A. I. Larkin[(a)]
Serin Physics Laboratory, Rutgers University, P.O. Box 849, Piscataway, New Jersey 08854
(Received 5 June 1989)

J_1–J_2 Heisenberg model



$\varphi < 0$



$\varphi > 0$

additional Z_2 degeneracy

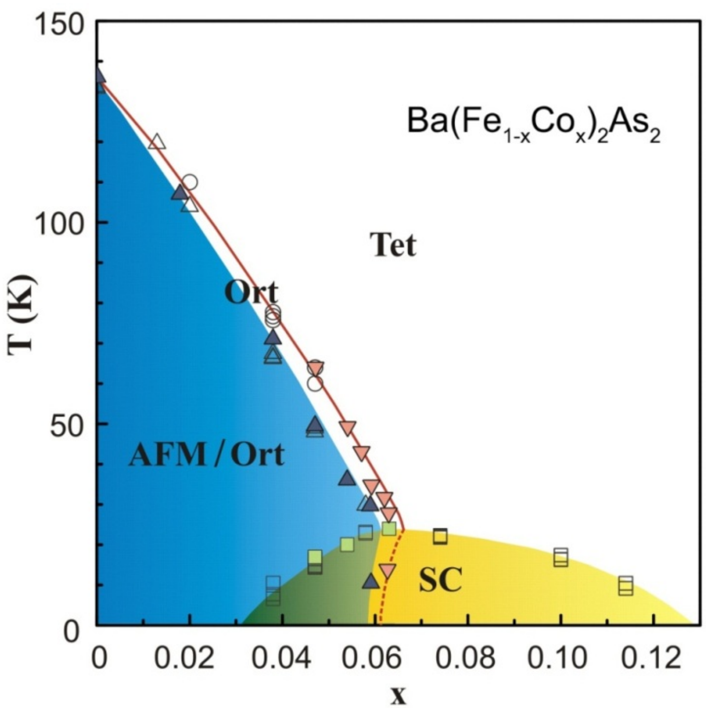
$$\mathbf{S}(\mathbf{r}) = \mathbf{S}_x(\mathbf{r})\, e^{i\mathbf{Q}_x\cdot\mathbf{r}} + \mathbf{S}_y(\mathbf{r})\, e^{i\mathbf{Q}_y\cdot\mathbf{r}}$$

emergent Ising order parameter

$$\varphi = \langle \mathbf{S}_x^2 - \mathbf{S}_y^2 \rangle$$

vestigial nematicity in iron-based systems

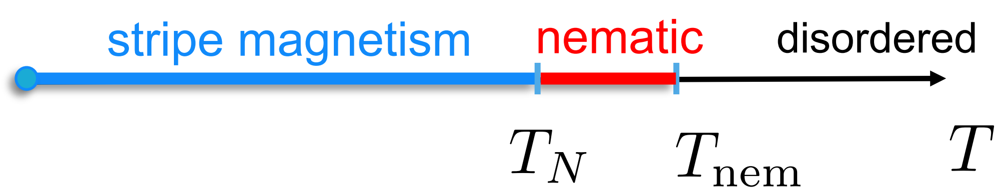
time-reversal symmetry and rotational symmetry are separately broken



C. Xu, M. Müller, and S. Sachdev, PRB **78**, 020501(R) (2008)

C. Fang, H. Yao, W.-F. Tsai, J. P. Hu, and S. A. Kivelson, PRB **77**, 224509 (2008)

$$\varphi = \langle \mathbf{S}_x^2 - \mathbf{S}_y^2 \rangle$$



Ni et al, PRB (2008), Fernandes et al, PRB (2010)

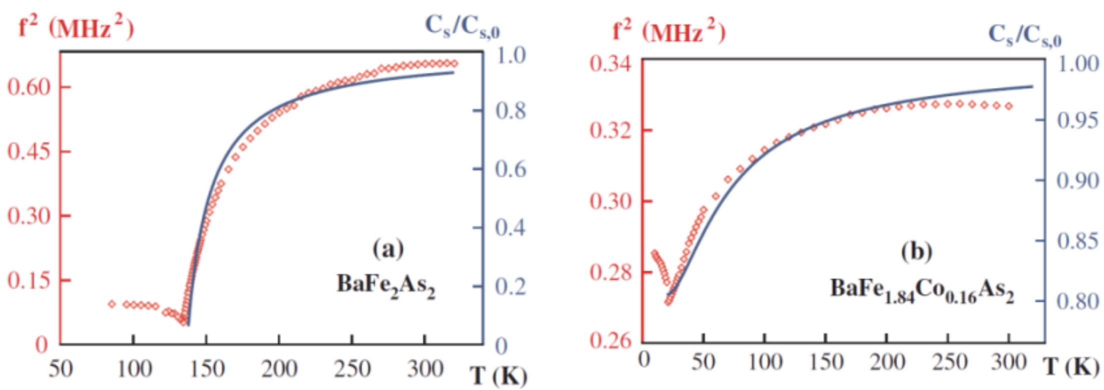
nematic susceptibility: elastic constants

coupling to the lattice $$H_{mag.-elast.} = -\lambda \int_x \varepsilon_{66}(x)\,\varphi(x)$$

renormalization of the elastic constants

$$C_{66}^{-1} = C_{66,0}^{-1} + \lambda^2 C_{66,0}^{-2} \chi_{\text{nem}}$$

elastic constants measure the static nematic susceptibility



R. M. Fernandes, L. H. VanBebber, S. Bhattacharya, P. Chandra, V. Keppens, D. Mandrus, M. A. McGuire, B. C. Sales, A. S. Sefat, and J. S., PRL **105**, 157003 (2010)

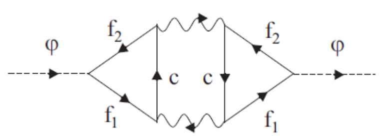
nematic dynamics: Raman scattering

$$\chi_{\mathrm{nem}}(q,\omega) \propto \left\langle \rho^{B_{1g}}_{q,\omega}\, \rho^{B_{1g}}_{-q,-\omega} \right\rangle$$

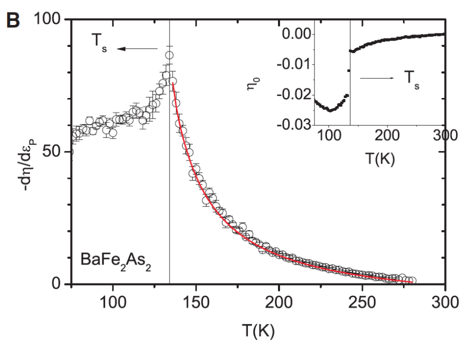
Y. Gallais et al. Phys. Rev. Lett. **111**, 267001 (2013)

$$\chi_{\mathrm{nem}} = \frac{\chi^0_{\mathrm{nem}}}{1 - g\chi^0_{\mathrm{nem}}}$$

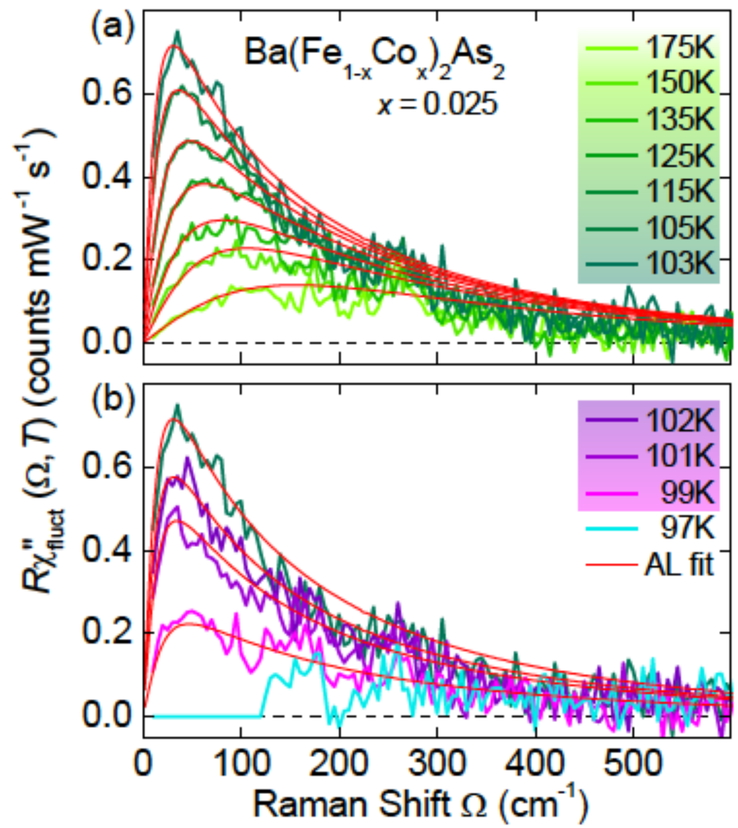
χ^0_{nem}



low-frequency slope = elasto-resistivity



J.H. Chu, H.-H. Kuo, J. G. Analytis, I. R. Fisher
Science **337**, 710 (2012)



F. Kretzschmar et al.
Nature Physics **12**, 560 (2016)

spin-driven composite order?

using NMR to probe the origin of lattice softening

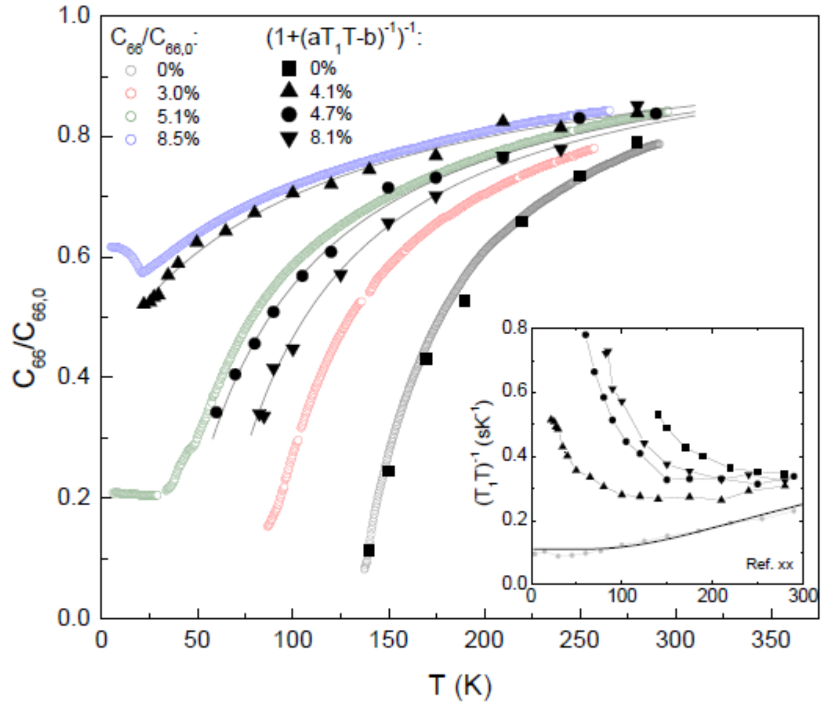
$$\varphi = \langle \mathbf{S}_x^2 - \mathbf{S}_y^2 \rangle$$

$$\frac{1}{T_1 T} \Longleftrightarrow \chi_{\text{nem}} \Longleftrightarrow C_{66}$$

assume overdamped spin response

$$\chi_{\text{spin}}\left(q,\omega\right) \propto \frac{1}{\epsilon(q) - i\omega/\Gamma}$$

D. S. Inosov, et al. Nature Phys. **6**, 178 (2010)



R. M. Fernandes, A. E. Böhmer, C. Meingast, J. S., Phys. Rev. Lett. **111**, 137001 (2013)

primary and vestigial order

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order parameter expansion $\delta f = a(T) \sum_{\mu=1}^{n_{\mathrm{irr}}} \eta_\mu^* \eta_\mu + \cdots$

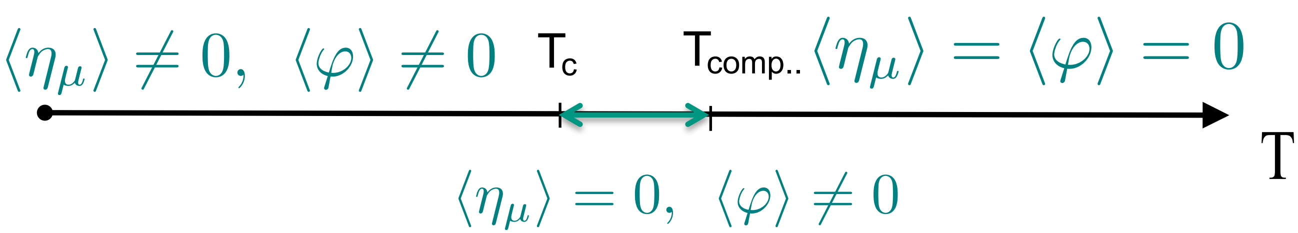
form bilinear combinations
that transform non-trivially

$$\varphi = \sum_{\mu\nu} r_{\mu\nu} \eta_\mu^* \eta_\nu$$

$$\Gamma^* \otimes \Gamma = E \oplus \Gamma_1 \oplus \cdots \oplus \Gamma_n$$

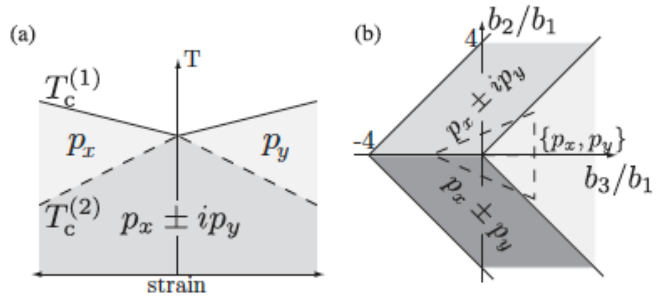
nontrivial bilinear forms
=
intertwined symmetry breakings

order made from fluctuations



R. M. Fernandes, P. P. Orth, and J. S., Ann. Rev, of Cond. Mat. Phys. **10**, 133 (2019)

Vestigial phases in multi-component superconductors



M. H. Fischer and Erez Berg PRB **93**, 054501 (2016)

charge-4e superconductivity

E.Berg, E. Fradkin, and S.A.Kivelson, Nat. Phys. **5**, 830 (2009)
D. F. Agterberg and H. Tsunetsugu, Nat. Phys. **4**, 639 (2008)
L. Radzihovsky and A. Vishwanath, PRL**103**, 010404 (2009)

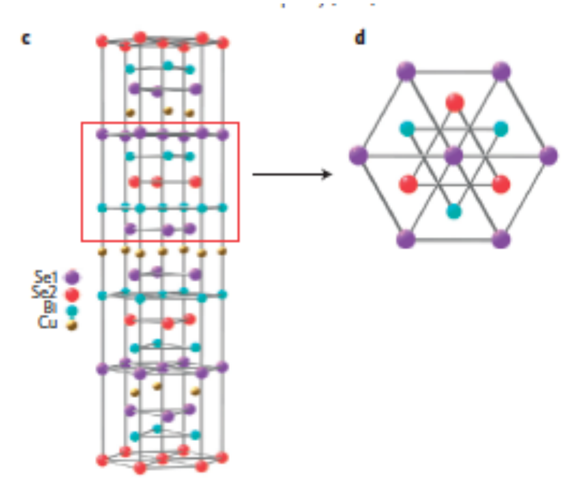
Notice: superconductors don't fluctuate very much!

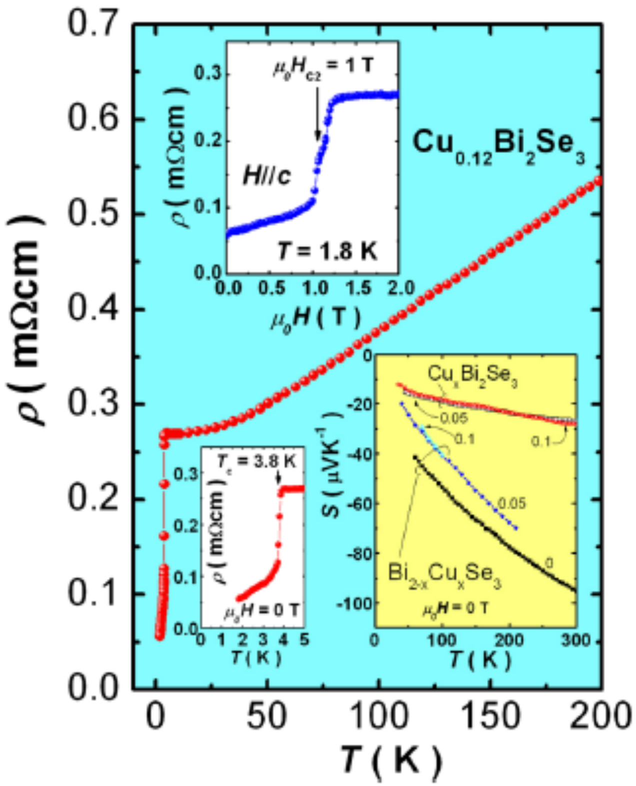
$$\Delta \ll E_F \Longrightarrow \xi_0 \approx v_F/\Delta \gg \lambda_F \approx v_F/E_F$$

doping the 3d topological insulator Bi_2Se_3

superconductivity in $Cu_xBi_2Se_3$

Y. S. Hor, et al. Phys. Rev. Lett. **104**, 057001 (2010)
M. Kriener, et al., Phys. Rev. Lett. **106**, 127004 (2011)





$$T_c \sim 3\mathrm{K}$$

$$n \sim 10^{20}\mathrm{cm}^{-3}$$

low carrier concentration

$$\xi_{ab}/\lambda_F \approx 2-4$$

short coherence length

s.c. fluctuations

Two-component superconducting states

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singlet: E_g $$\Delta_{\mathbf{p}} = \Delta_x \left(p_x p_y + \eta p_y p_z\right) + \Delta_y \left(p_x^2 - p_y^2 + \eta p_x p_z\right)$$

triplet: E_u $$\mathbf{d}_{\mathbf{p}} = \Delta_x \left(\hat{\mathbf{x}} p_z - \eta \hat{\mathbf{z}} p_x\right) + \Delta_y \left(\hat{\mathbf{y}} p_z - \eta \hat{\mathbf{z}} p_y\right)$$

two options: **nematic** or **chiral** (TRS-breaking)

candidate for topological superconductivity

L. Fu and E. Berg, Phys. Rev. Lett. **105**, 097001 (2010)

J. W. F. Venderbos, V. Kozii, and L. Fu, B **94**, 180504(R) (2016)

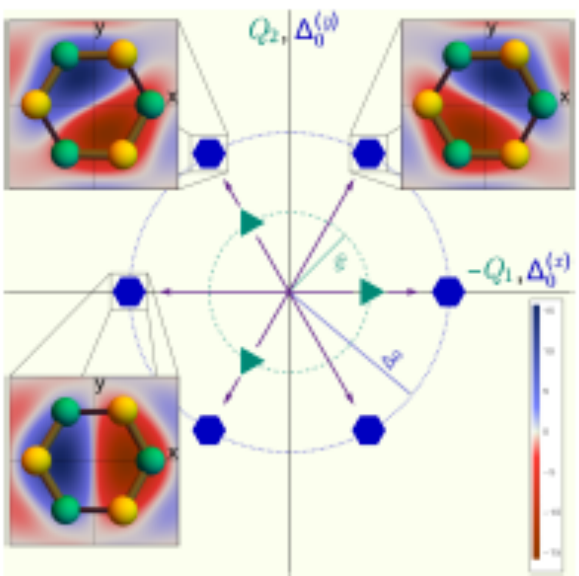
Two-component superconducting states

singlet: E_g $\quad \Delta_{\mathbf{p}} = \Delta_x \left(p_x p_y + \eta p_y p_z \right) + \Delta_y \left(p_x^2 - p_y^2 + \eta p_x p_z \right)$

triplet: E_u $\quad \mathbf{d}_{\mathbf{p}} = \Delta_x \left(\hat{\mathbf{x}} p_z - \eta \hat{\mathbf{z}} p_x \right) + \Delta_y \left(\hat{\mathbf{y}} p_z - \eta \hat{\mathbf{z}} p_y \right)$

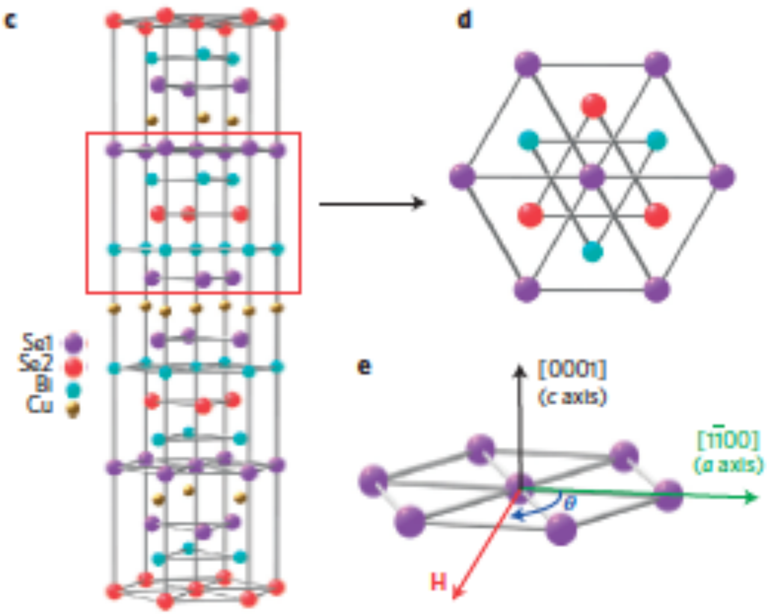
two options: **nematic** or chiral (TRS-breaking)

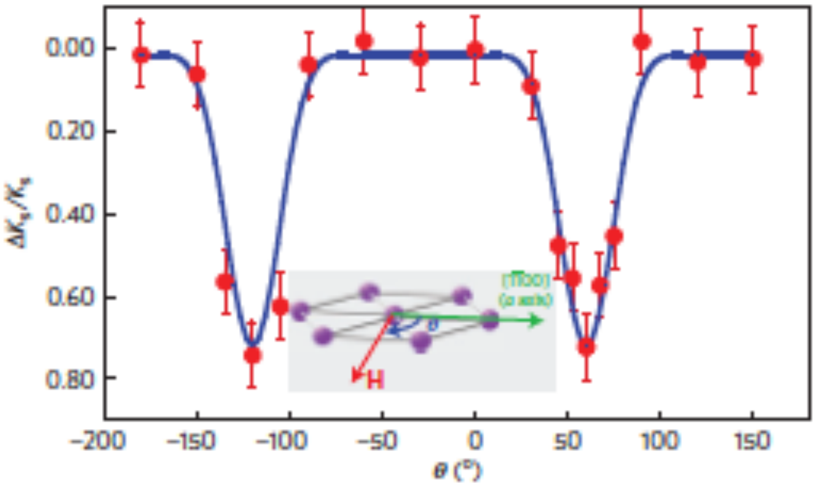
$d_{\mathbf{p},z}$



nematic state:
superconductor breaks rotation symmetry

rotational symmetry breaking





nematic superconductor: either E_g or E_u

K. Matano, M. Kriener, K. Segawa, Y. Ando, and Guo-qing Zheng, Nature Physics **12**, 852 (2016)

anisotropic thermodynamic response

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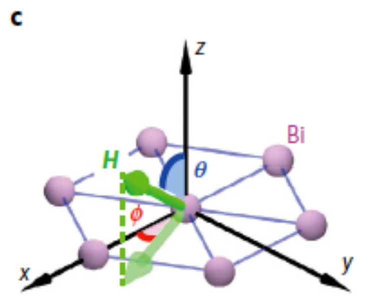
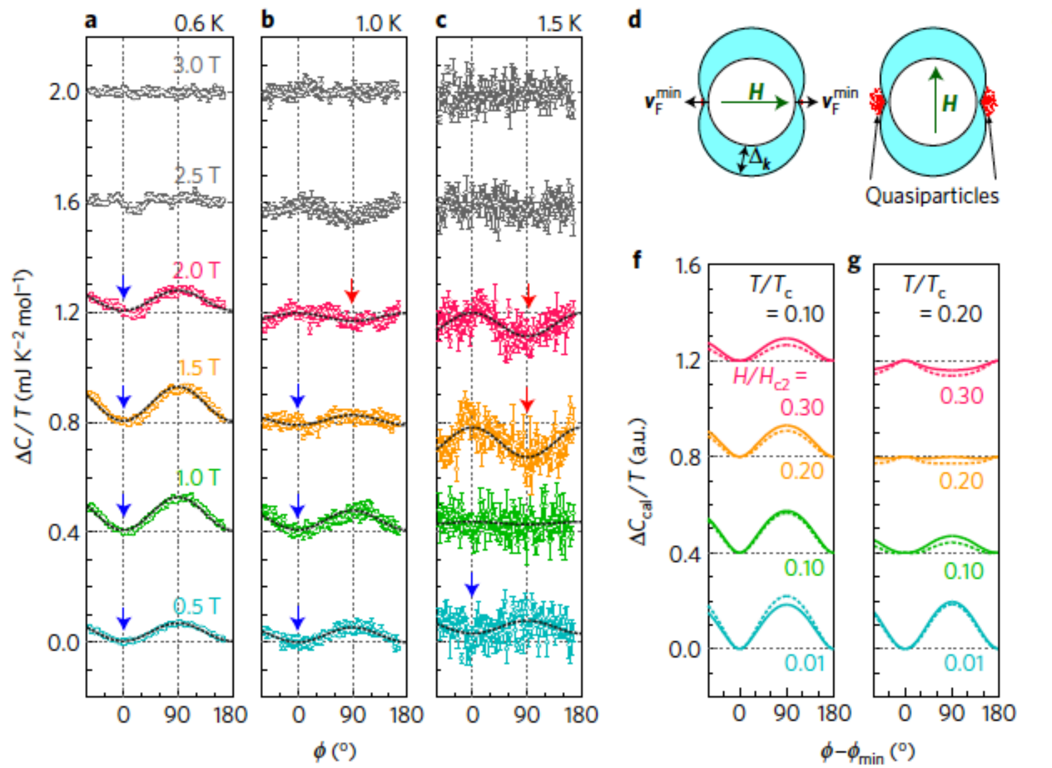


heat capacity as function of in-plane magnetic field



Shingo Yonezawa, Kengo Tajiri, Suguru Nakata, Yuki Nagai, ZhiweiWang, Kouji Segawa, Yoichi Ando, and Yoshiteru Maeno Nat. Phys. **13**, 123 (2017)

vestigial order in $Cu_xBi_2Se_3$

the symmetry group (trigonal) = $D_{3d} \otimes U(1)$

$$E_u^* \otimes E_u = A_{1g} \oplus A_{2g} \oplus E_g$$

time reversal symmetry

possibly relevant for thin films
L. Chirolli, PRB **98**, 014505 (2018)

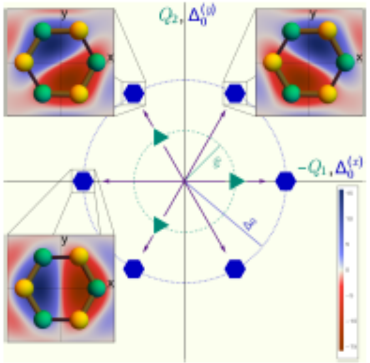
nematic superconductivity

$$q_1 = \Delta_x^* \Delta_x - \Delta_y^* \Delta_y$$
$$q_2 = \Delta_x^* \Delta_y + \Delta_y^* \Delta_x$$

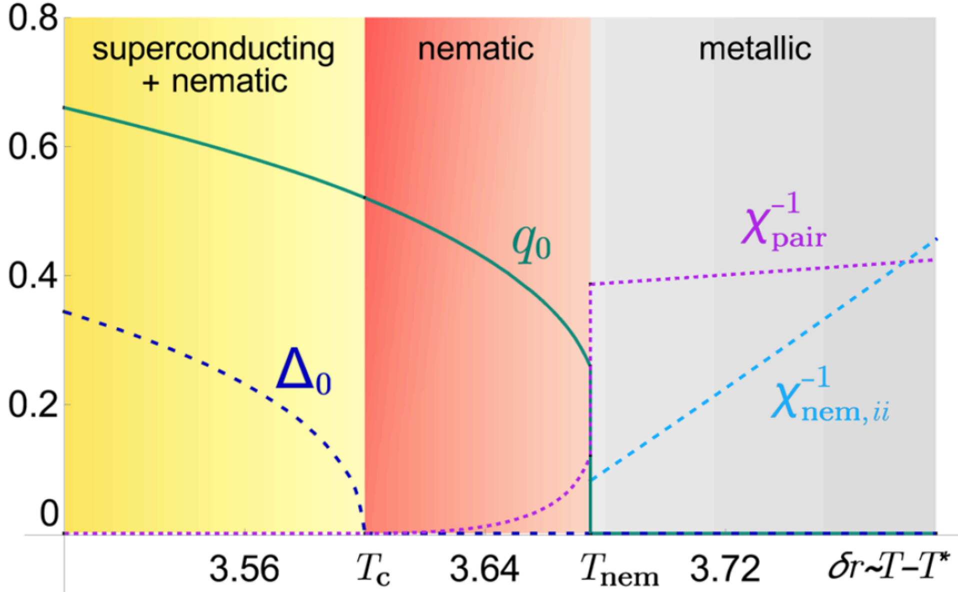
$$\hat{Q} = \begin{pmatrix} q_1 & q_2 \\ q_2 & -q_1 \end{pmatrix}$$

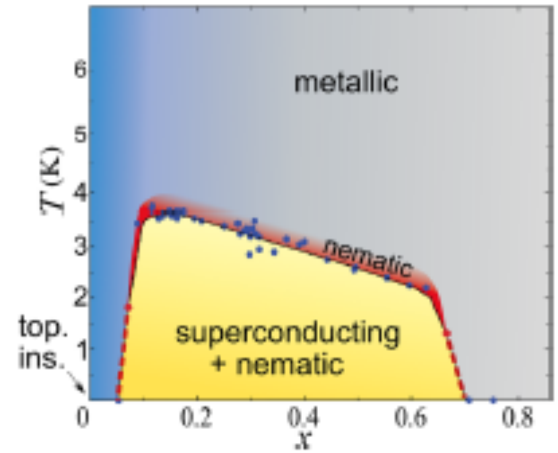
$$f = \frac{r}{2}\left(q_1^2 + q_2^2\right) - \frac{g}{3} q_1 \left(q_1^2 - 3q_2^2\right) + \frac{u}{4}\left(q_1^2 + q_2^2\right)^2$$

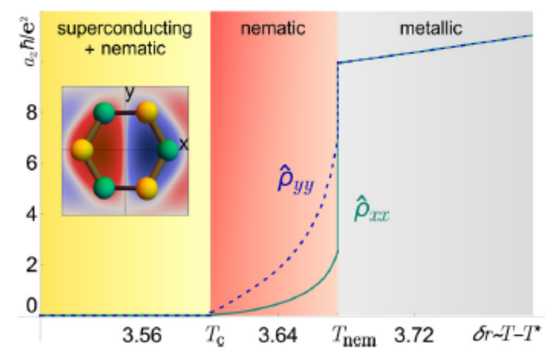
3-state Potts model
three degenerate
solutions that break
rotation invariance



vestigial order in $Cu_xBi_2Se_3$

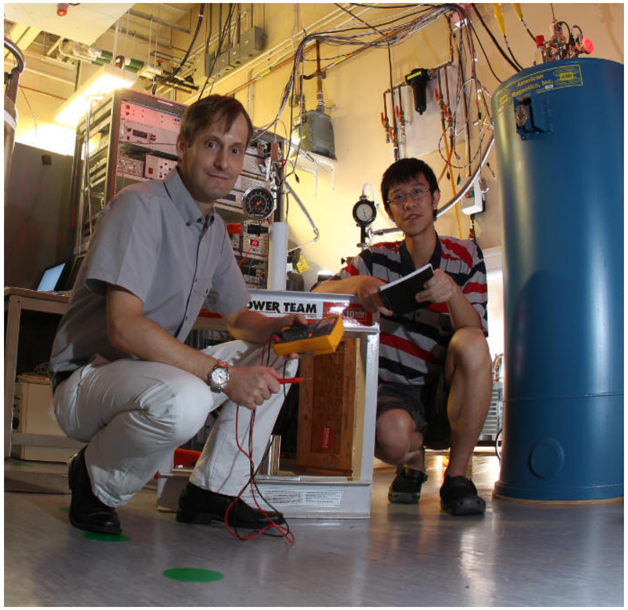






→ large anisotropic para-conductivity
→ coupling to the lattice
→ Raman anomaly

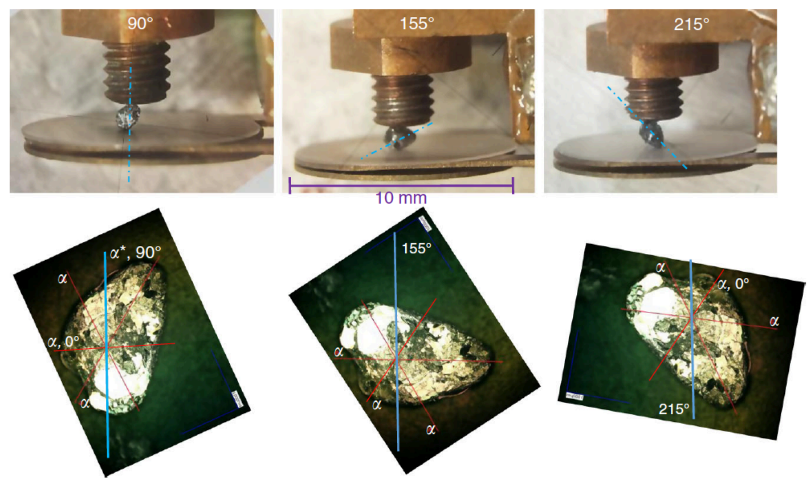
Matthias Hecker and J.S., npj Quantum Mater. **3**, 26 (2018)



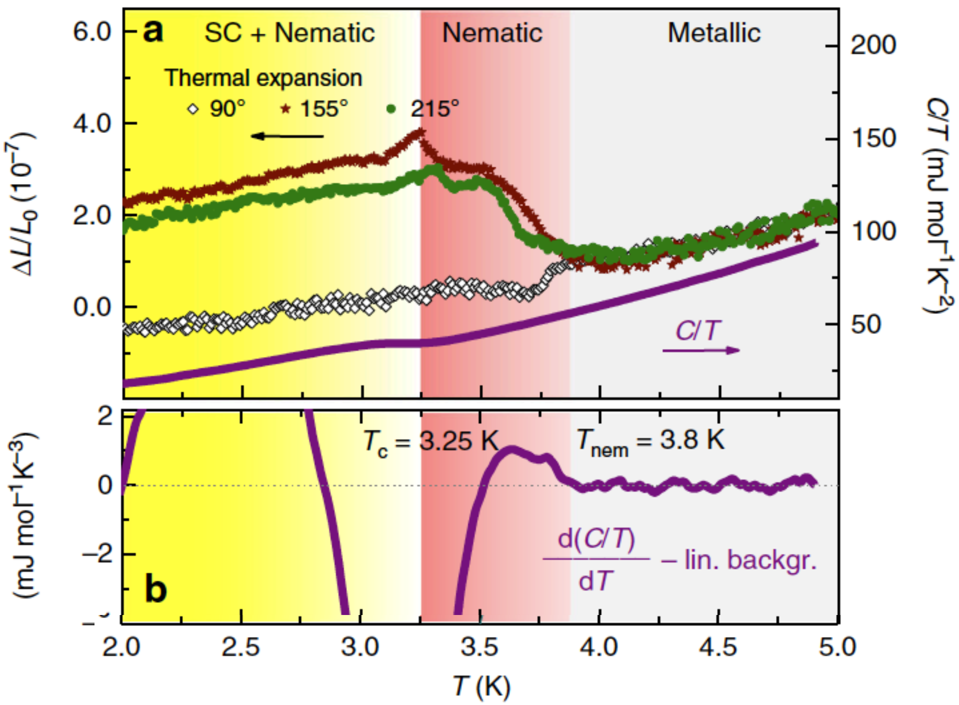
Rolf Lortz
The Hong Kong University
of Science & Technology

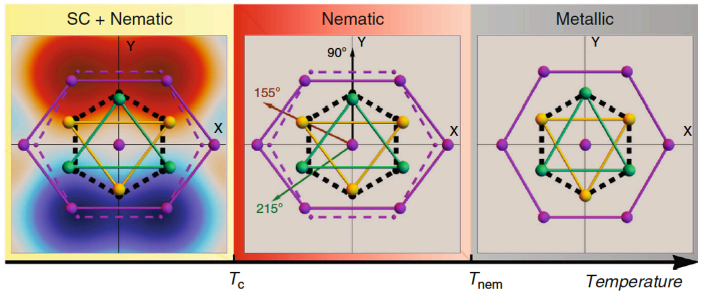
Karlsruhe Institute of Technology

$Nb_{0.25}Bi_2Se_3$ single crystal mounted in the capacitive dilatometer along the three orientations
(similar results for $Cu_xBi_2Se_3$)



High-precision thermal expansion measurements

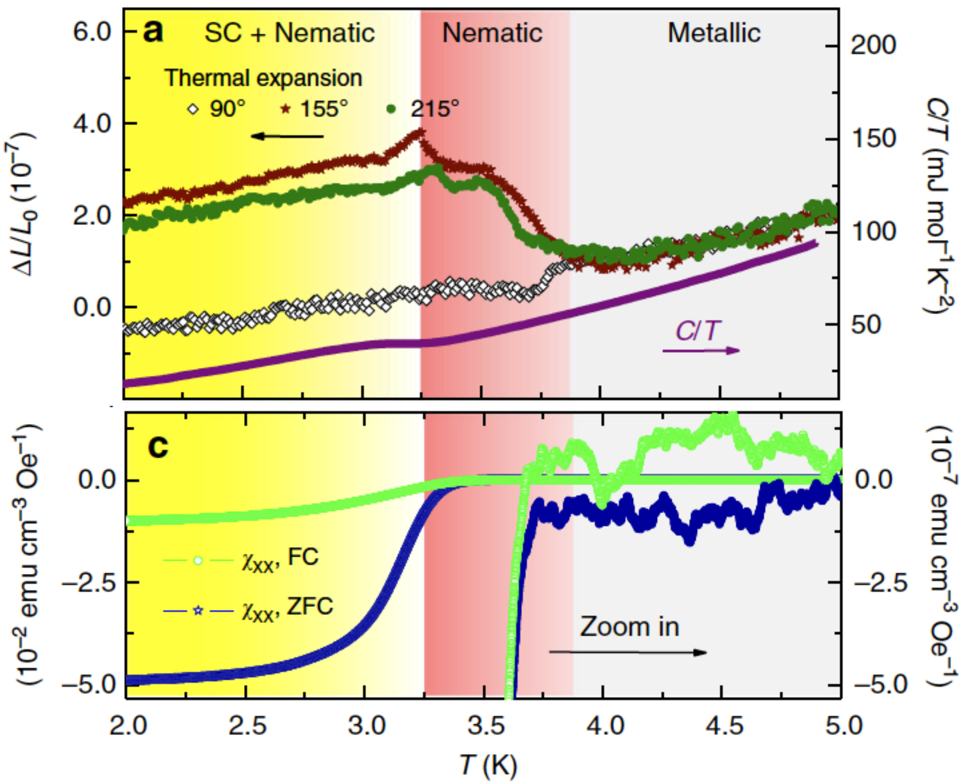


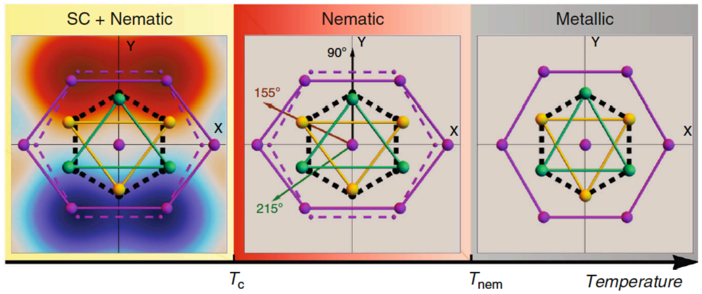


Z_3-Potts symmetry breaking slightly above T_c

C.-w. Cho, J. Shen, J. Lyu, O. Atanov, Q. Chen, S. H. Lee, Y. S. Hor, D. J. Gawryluk, E. Pomjakushina, M. Bartkowiak, M. Hecker, J. S., and R. Lortz, Nature Comm. **11**, 3056 (2020)

High-precision thermal expansion measurements

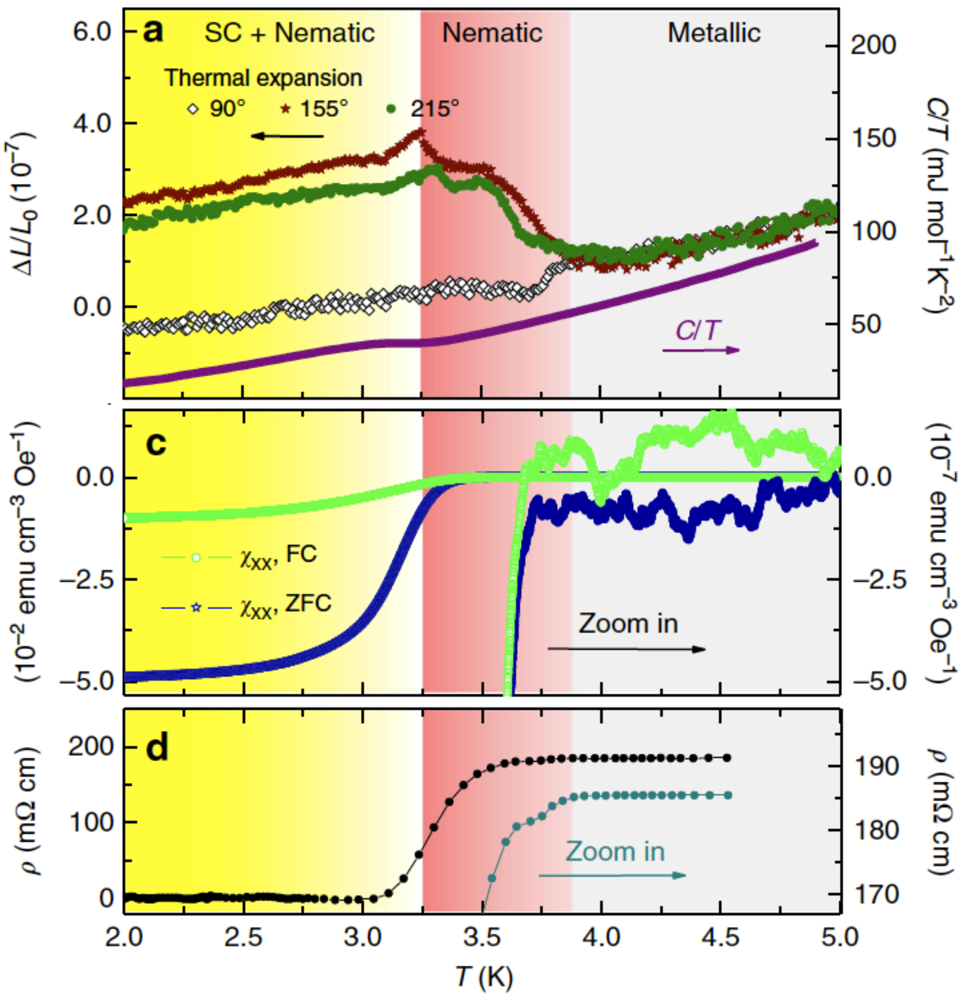


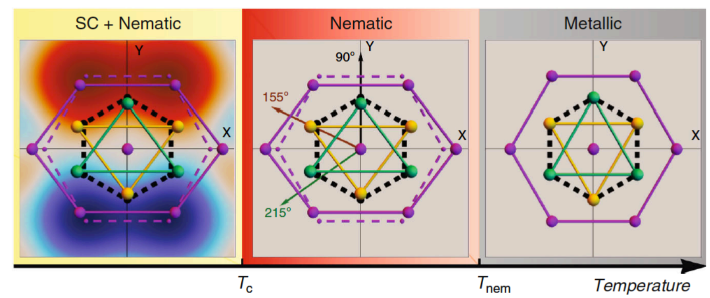


susceptibility: onset of diamagnetic fluctuations at T_{nem}

C.-w. Cho, J. Shen, J. Lyu, O. Atanov, Q. Chen, S. H. Lee, Y. S. Hor, D. J. Gawryluk, E. Pomjakushina, M. Bartkowiak, M. Hecker, J. S., and R. Lortz, Nature Comm. **11**, 3056 (2020)

High-precision thermal expansion measurements



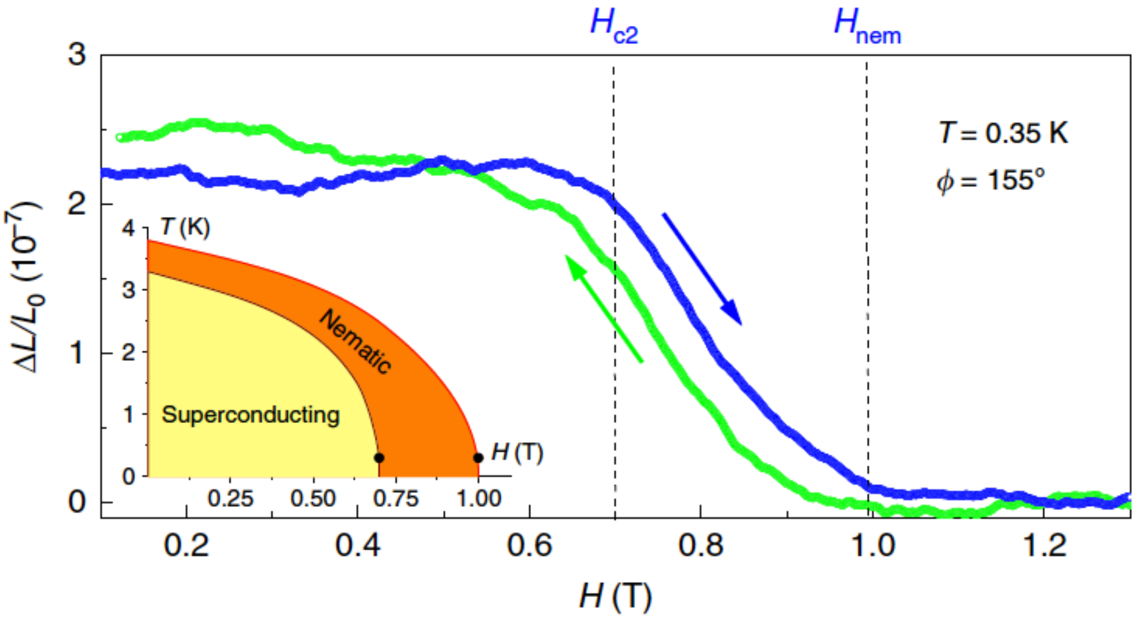


susceptibility: onset of diamagnetic fluctuations at T_{nem}

transport: onset of paraconductivity at T_{nem}

C.-w. Cho, J. Shen, J. Lyu, O. Atanov, Q. Chen, S. H. Lee, Y. S. Hor, D. J. Gawryluk, E. Pomjakushina, M. Bartkowiak, M. Hecker, J. S., and R. Lortz, Nature Comm. **11**, 3056 (2020)

magnetostriction measurements



- nematic order is tied to superconductivity
- possibility of an isolated Z_3 quantum Potts transition

strong evidence for vestigial superconducting phase !

$$\langle \Delta_{x,y} \rangle = 0$$

$$\langle \Delta_x^* \Delta_x - \Delta_y^* \Delta_y \rangle \neq 0$$

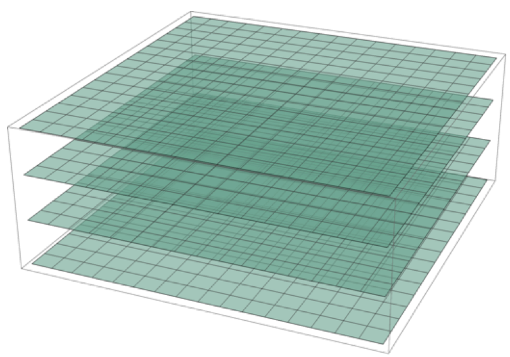
condensation of anisotropic pairing fluctuations

C.-w. Cho, J. Shen, J. Lyu, O. Atanov, Q. Chen, S. H. Lee, Y. S. Hor, D. J. Gawryluk, E. Pomjakushina, M. Bartkowiak, M. Hecker, J. S., and R. Lortz, Nature Comm. **11**, 3056 (2020)

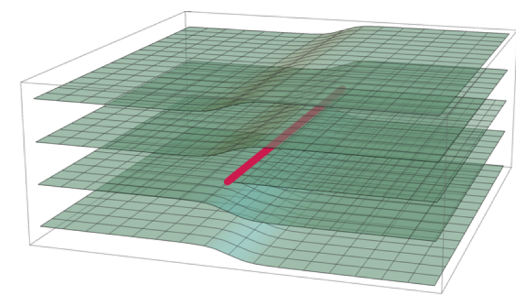
the pairing state of Sr_2RuO_4

(in collaboration with Roland Willa and Rafael Fernandes)

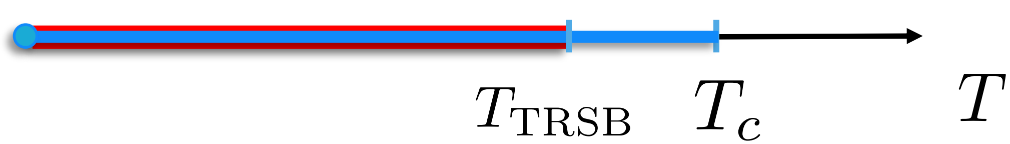
perfect Sr_2RuO_4
time-reversal symmetric, single-component
(d-wave) superconductor



TRS-breaking is no bulk effect but
occurs near edge dislocations



TRSB near the dislocation $d + e^{i\phi(\mathbf{r})} g$



d-wave bulk superconductivity

consistent with quasiparticle
interference data

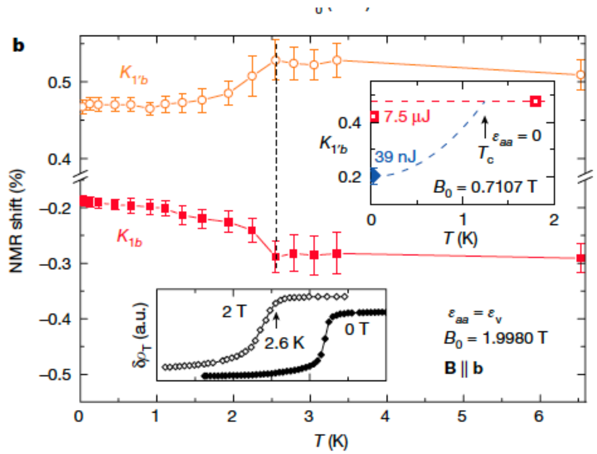
R. Sharma et al., PNAS **117**, 5222 (2020)

the pairing state of Sr_2RuO_4

A. P. Mackenzie, T. Scaffidi, C. W. Hicks , and Y. Maeno, npj Quantum Mat. **2**, 40 (2017)

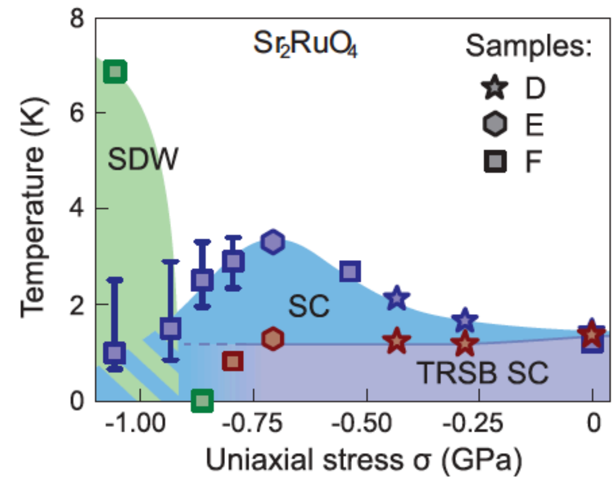
singlet pairing

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



split transitions under strain

V. Grinenko et al., arXiv:2001.08152



$$d_{xz} \pm i d_{yz} \quad ?$$

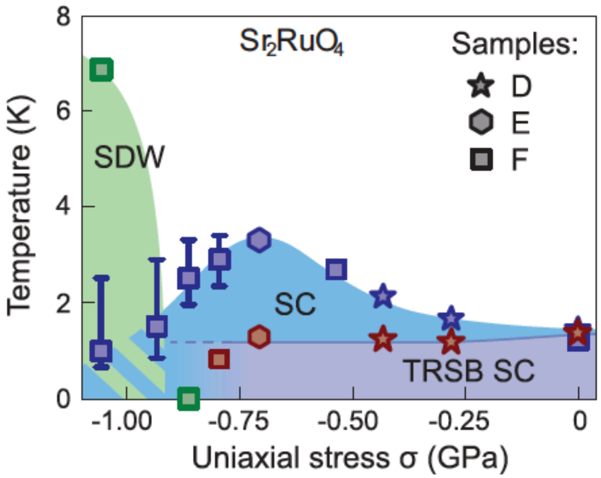
O. Gingras et al. PRL **123**, 217005 (2019)

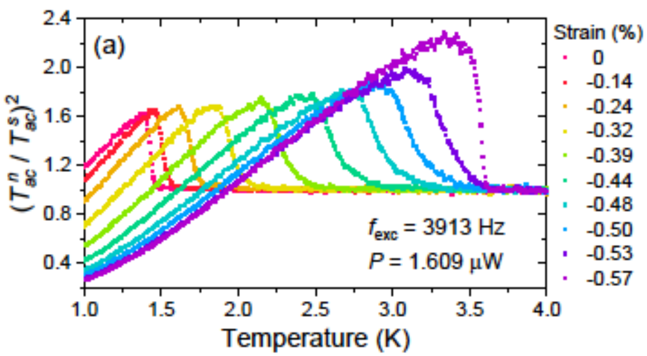
nontrivial orbital pairing ?

A. Ramires and M. Sigrist PRB **100**, 104501 (2019)
W. Huang et al., PRB **100** 134506 (2019)
H.-G. Suh et al., PRR **2**, 032023(R) (2020)

the pairing state of Sr_2RuO_4

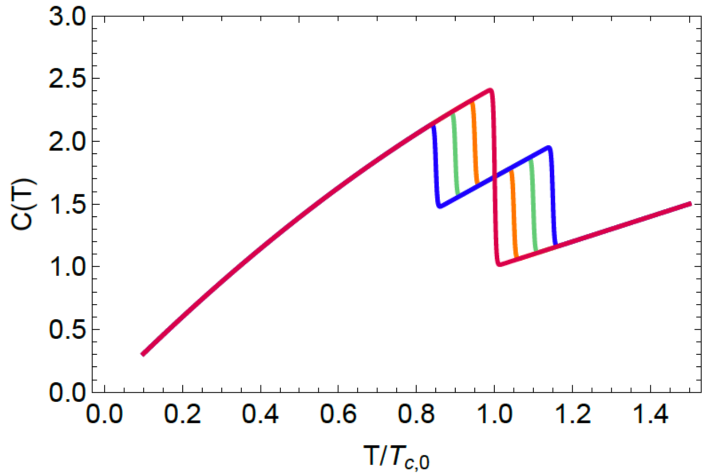
split transitions under strain
V. Grinenko et al. arXiv:2001.08152





Y.-S. Li et al. arXiv:1906.07597

$E_{g,u}$: expect at least comparabe heat capacity jumps at the two transitions



no second heat capacity jump
→ inconsistent with $E_{g,u}$

→ accidental degeneracy

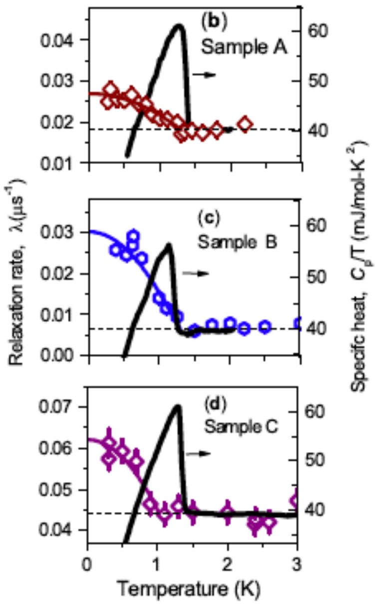
$$d_{x^2-y^2} \pm i g_{xy(x^2-y^2)}$$

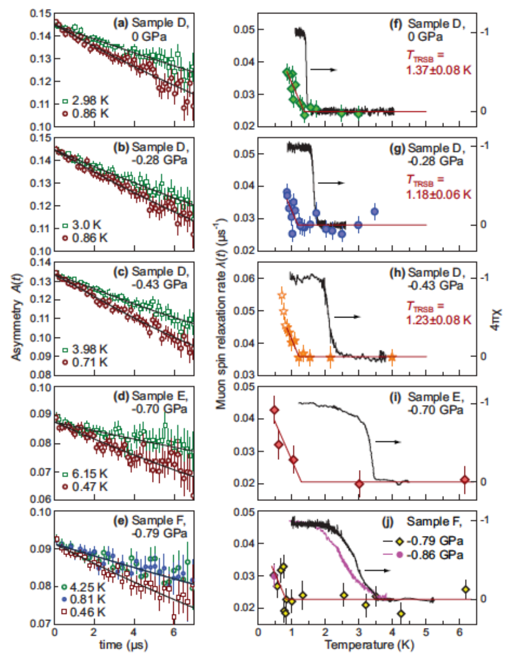
S. A. Kivelson et al. arXiv:2002.00016

μ-SR data under strain

Karlsruhe Institute of Technology

V. Grinenko et al. arXiv:2001.08152

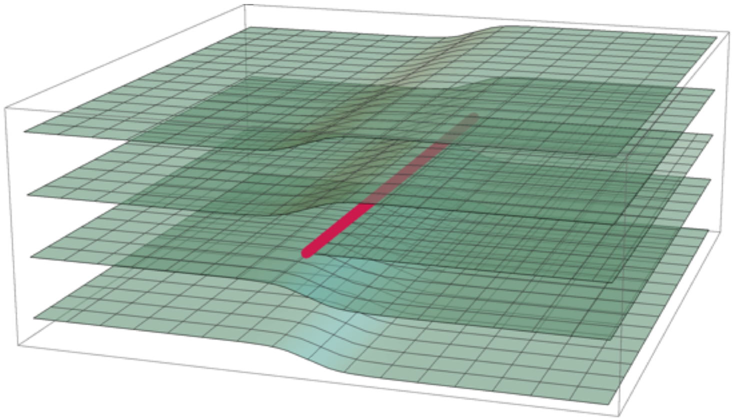


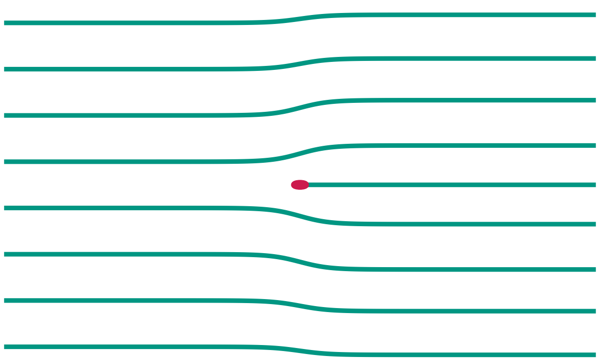


- sample dependence of $T_c - T_{TRSB}$ even at zero strain
- broad distribution of local fields (like spin glasses, only smaller in magnitude)

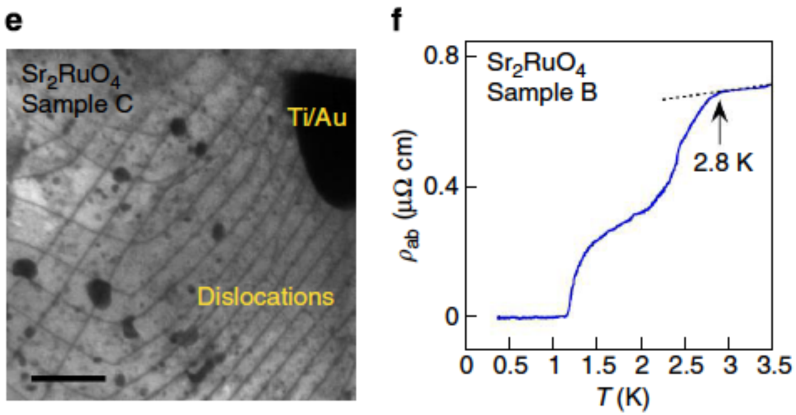
“The internal field is thought to arise at edges, defects, and domain walls …”

edge dislocations in Sr_2RuO_4



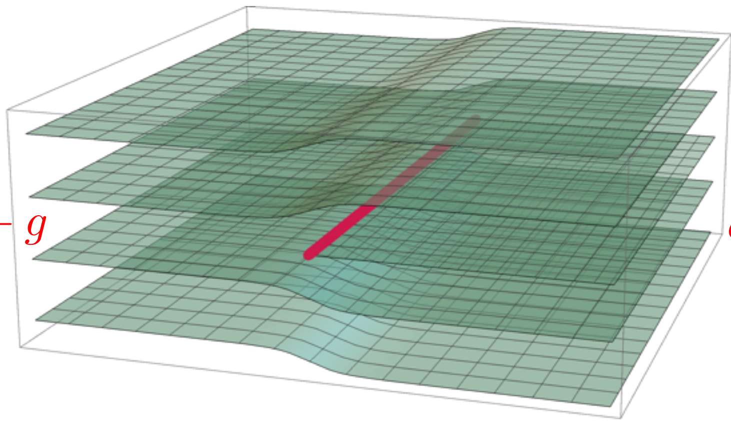


impact of edge dislocations on superconductivity



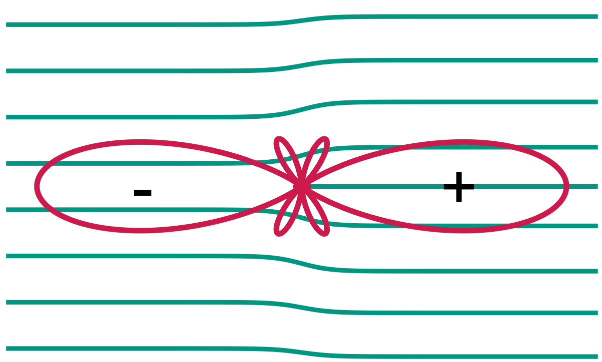
Y.A. Ying, N.E. Staley, Y. Xin, K. Sun, X. Cai, D. Fobes, T.J. Liu, Z.Q. Mao & Y. Liu, Nature Comm. **4**, 2596 (2013)

edge dislocations in Sr_2RuO_4



slowly-decaying
secondary component

strain fields near the dislocation



$$f_c \sim \varepsilon_{xy} \left(\psi_d^* \psi_g + h.c. \right)$$

(strong local mixing of order parameters)

$$+ i H_z \varepsilon_{x^2 - y^2} \left(\psi_d^* \psi_g - h.c. \right)$$

(TRS-breaking: trainable by a magnetic field)

edge dislocations in Sr_2RuO_4

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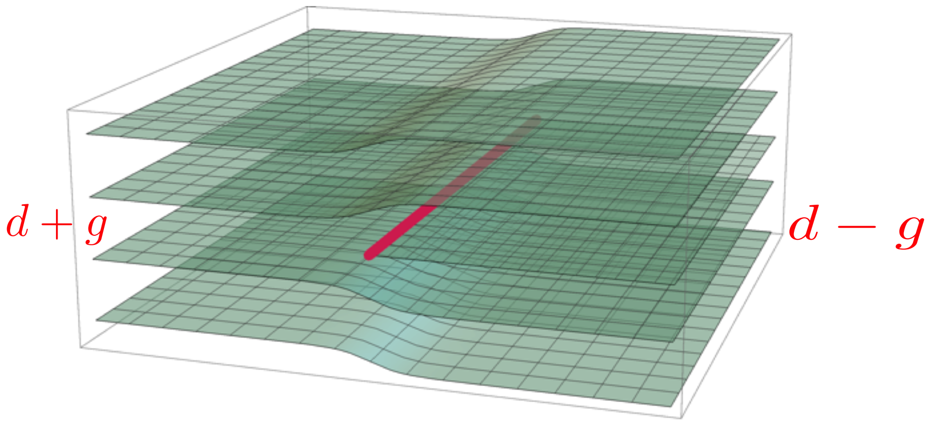
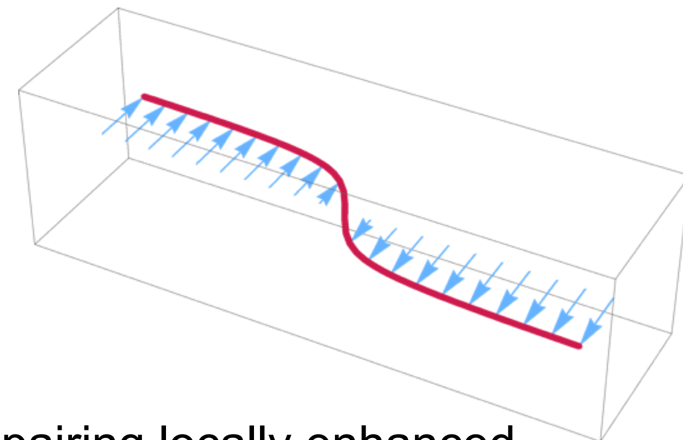
variational ansatz: sign-change through the complex plane

similar to twin boundaries in FeSe: T. Watashige et al. PRX **5**, 031022 (2015)





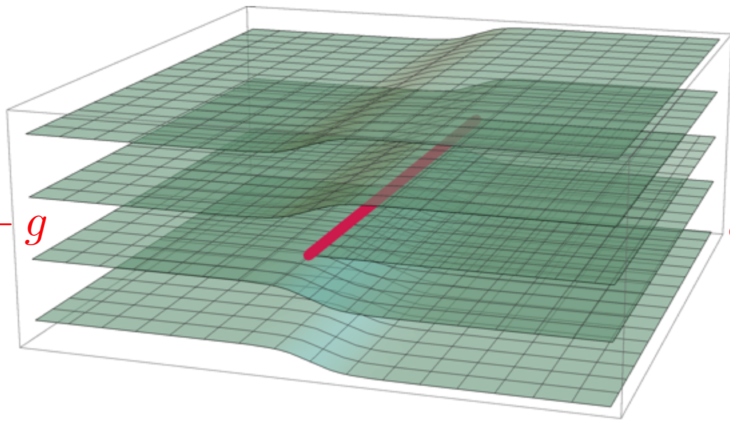
Near T_c : pairing locally enhanced

d-wave bulk superconductivity

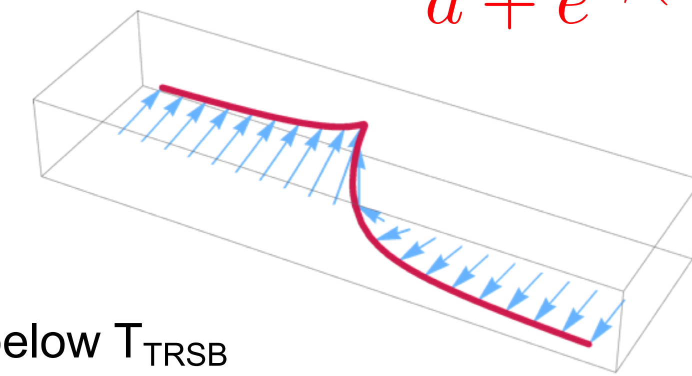
edge dislocations in Sr_2RuO_4

variational ansatz: sign-change through the complex plane

similar to twin boundaries in FeSe: T. Watashige et al. PRX **5**, 031022 (2015)

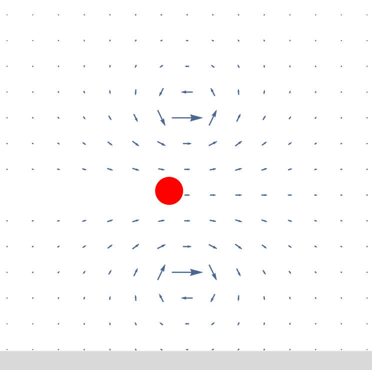


$$d + e^{i\phi(\mathbf{r})} g$$

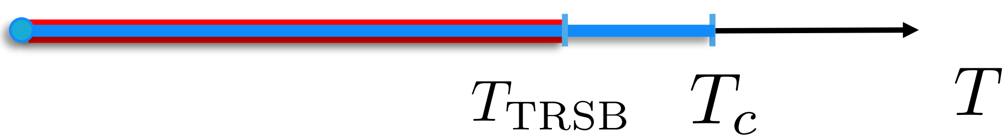


below T_{TRSB}

one-dim. structures with complex current pattern

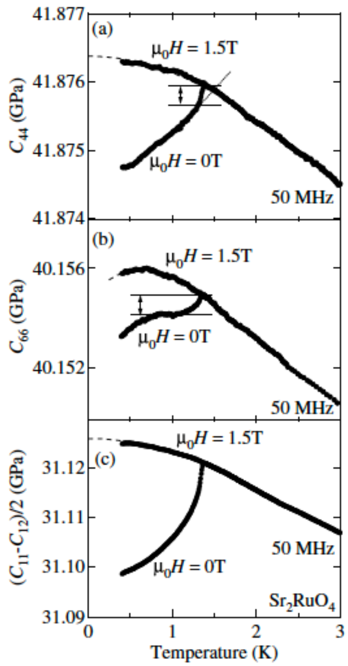


TRSB near the dislocation

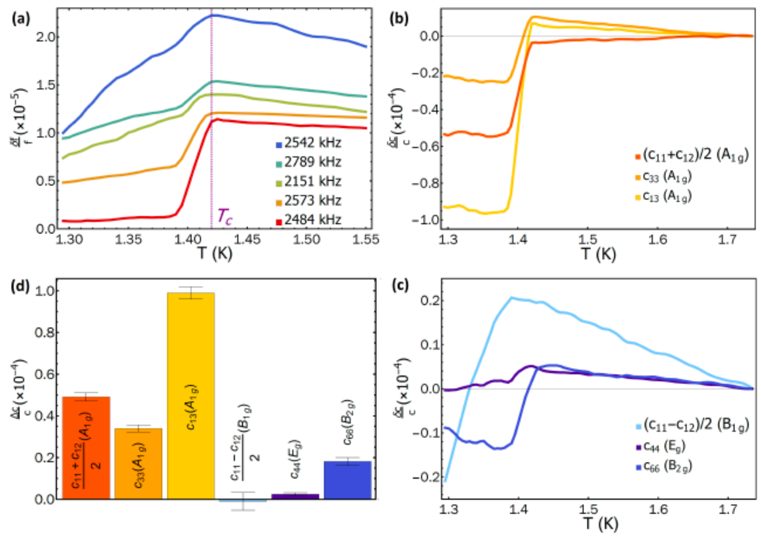


d-wave bulk superconductivity

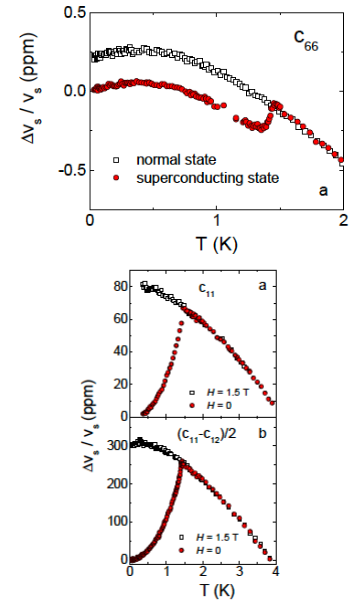
problem: elastic constant discontinuity in C_{66}



N. Okuda et al. JPSJ **71**, 1134 (2002)



S. Ghosh et al. arXiv:2002.06130



S. Benhabib et al. arXiv:2002.05916

dislocation-induced change $$\left.\frac{\delta C}{C}\right|_{\mathrm{disl.}} \sim 0.1\rho_{\mathrm{disl}} l^2 \sim 2-10\% \gg \left.\frac{\Delta C}{C}\right|_{\mathrm{sc.}}$$

G. Grimwall, *Thermophysical properties of materials*, North-Holland (1999)

conclusions

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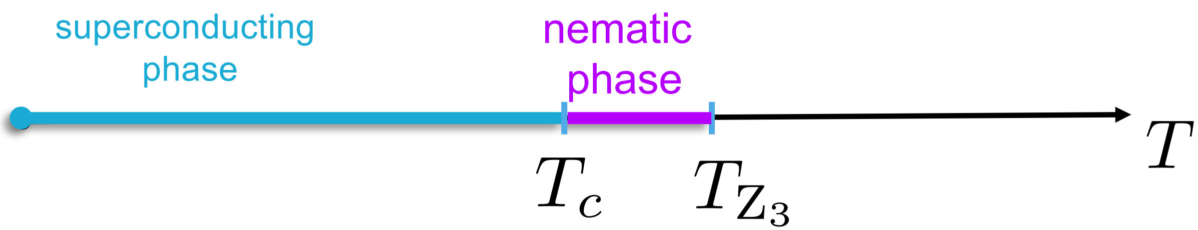
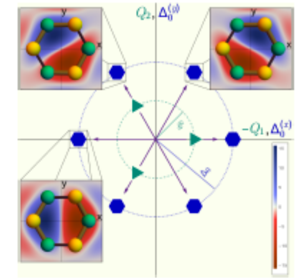
1. doped Bi_2Se_3 Superconducting fluctuations split the superconducting and nematic phase transitions

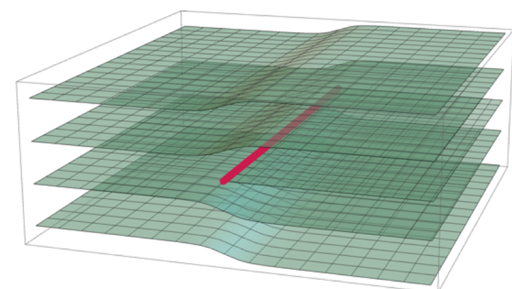


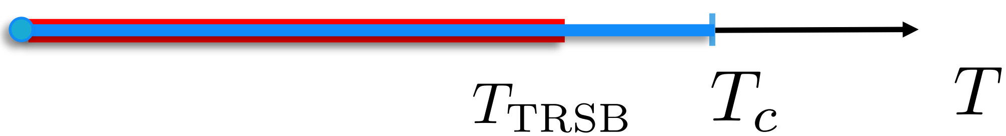


U(1) symmetry and Z_3 rotational symmetry separately broken

2. absence of heat capacity anomaly at TRSB transition + broad distribution of field seen in μ-SR

TRS-breaking only near dislocations
→ one-dimensional structures with complex order parameter and current pattern

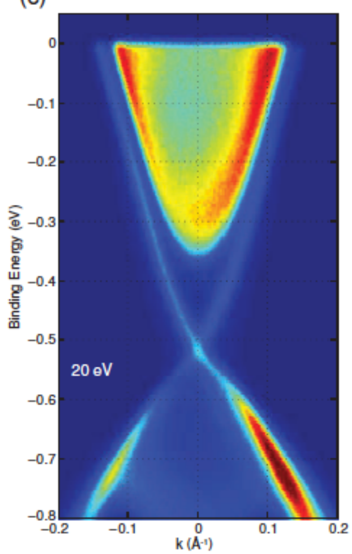




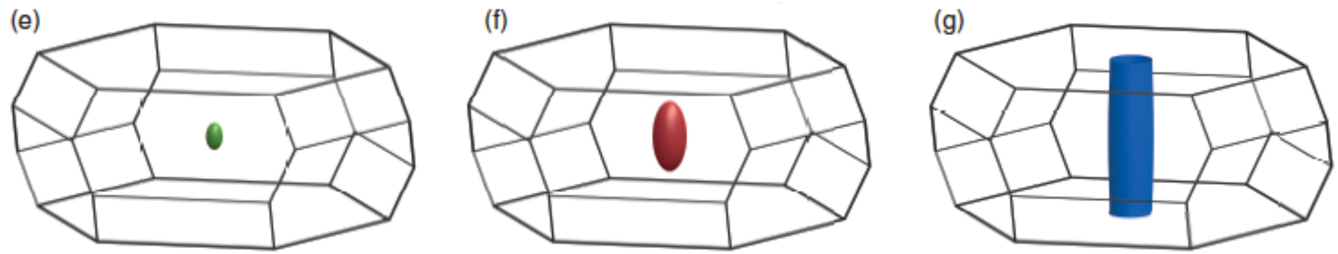
d-wave bulk superconductivity

evolution of the Fermi surface with carrier concentration

ARPES



SdH



$n \sim 10^{17}\mathrm{cm}^{-3}$ $n \sim 10^{19}\mathrm{cm}^{-3}$ $n \sim 10^{20}\mathrm{cm}^{-3}$

electronic structure becomes increasingly anisotropic

E. Lahoud, E. Maniv, M. Shaviv Petrushevsky, M. Naamneh, A. Ribak, S. Wiedmann, L. Petaccia, Z. Salman, K. B. Chashka, Y. Dagan, and A. Kanigel, Phys. Rev. B **88**, 195107 (2013)