Nematic superconductivity in the doped topological insulators $M_xBi_2Se_3$

SPICE Mainz

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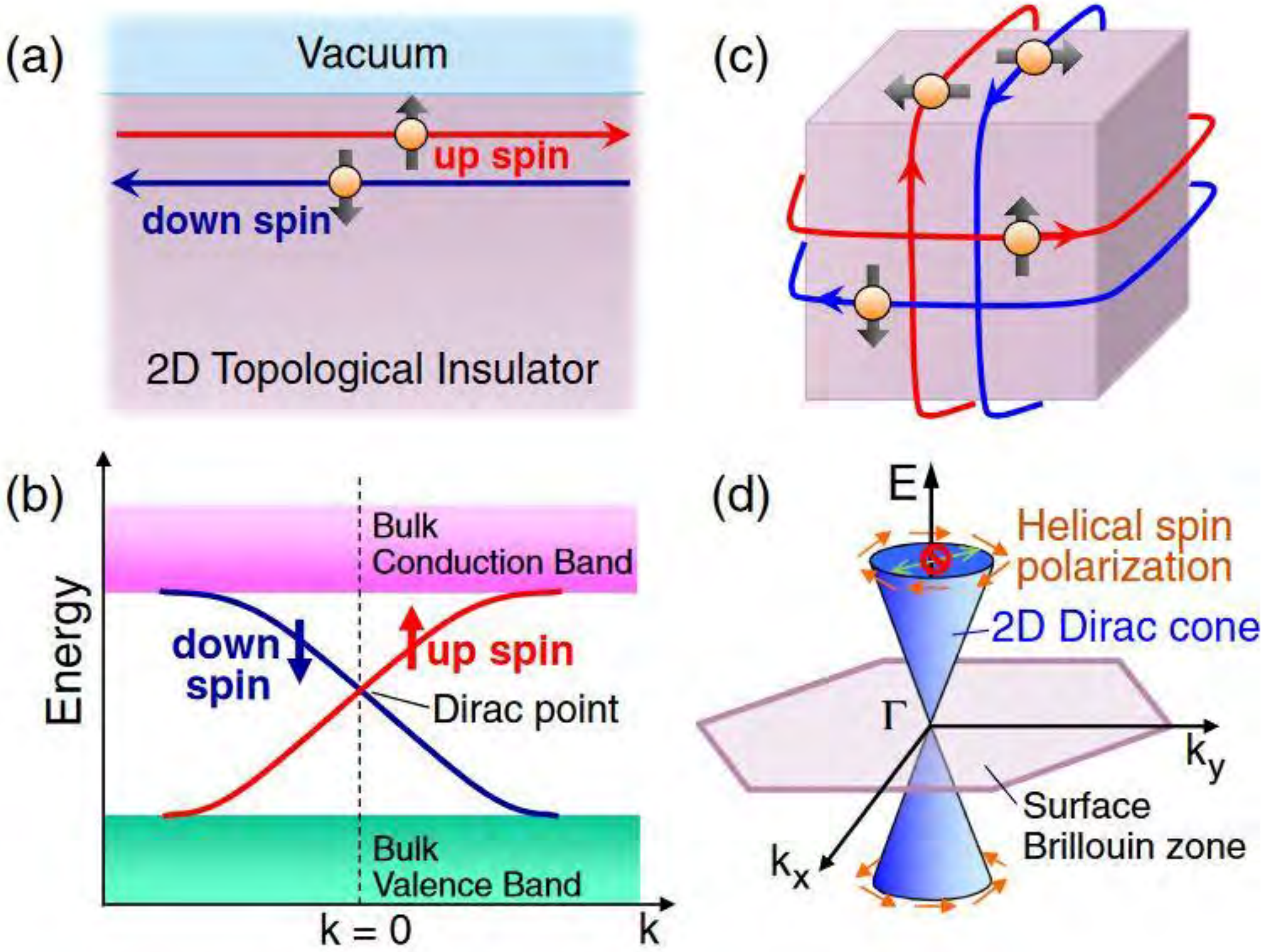
Topological insulators



gap less, symmetry protected, spin-momentum locked surface states

What would happen if we could induce superconductivity in these surface states?

Superconducting surface states or vortex cores could host zero energy bound states: so called Majorana states.

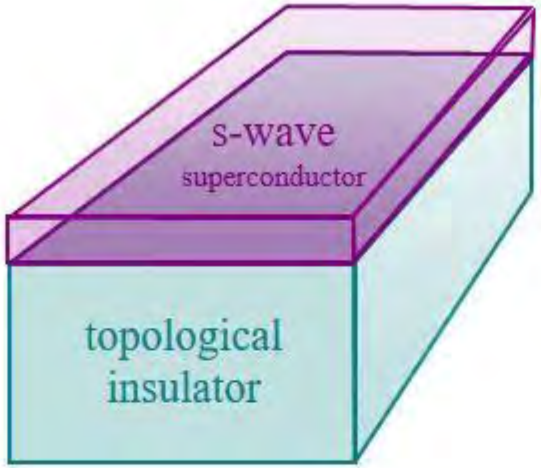
This would allow for topologically protected quantum computations that are free from decoherence.

Kitaev, Phys.-Usp. **44**, 131 (2001) Sato, PLB **575**, 126-30 (2003) Kitaev, AIP Conf. Proc. **1134**, 22-30 (2009) Ando, JPSJ **82**, 102001 (2013)

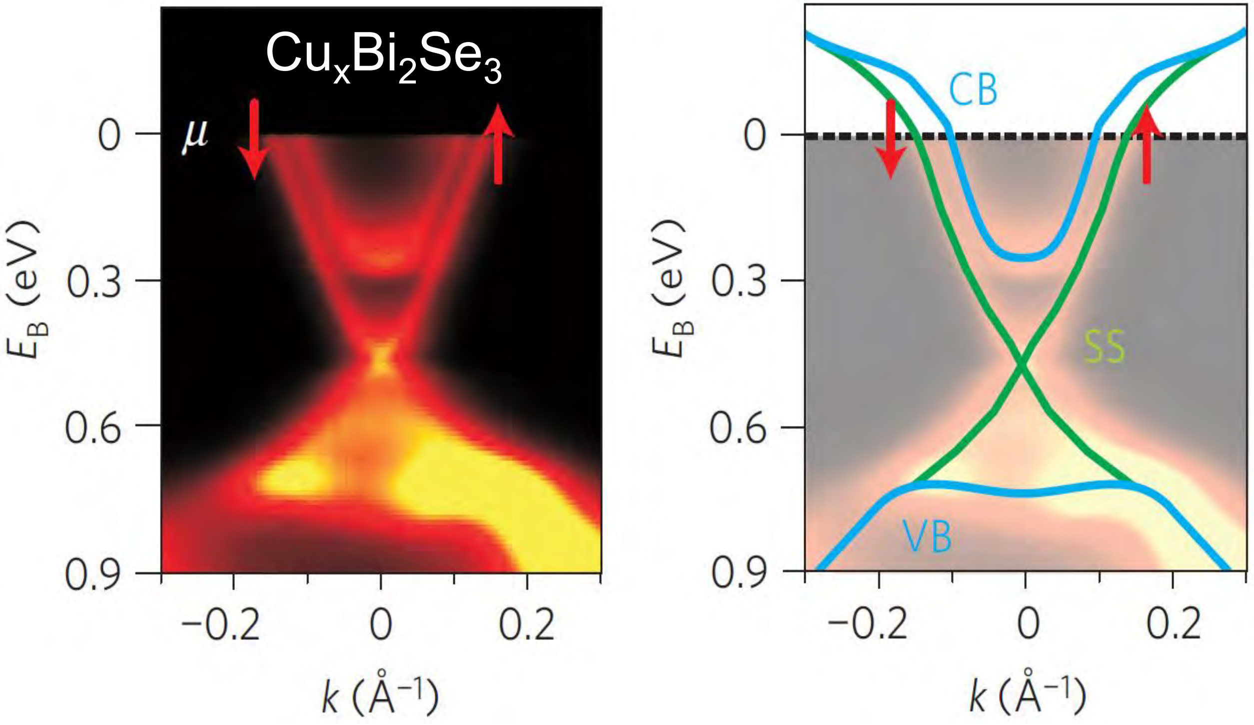
Topological superconductors

How can we get topological superconductors?

Proximity effect



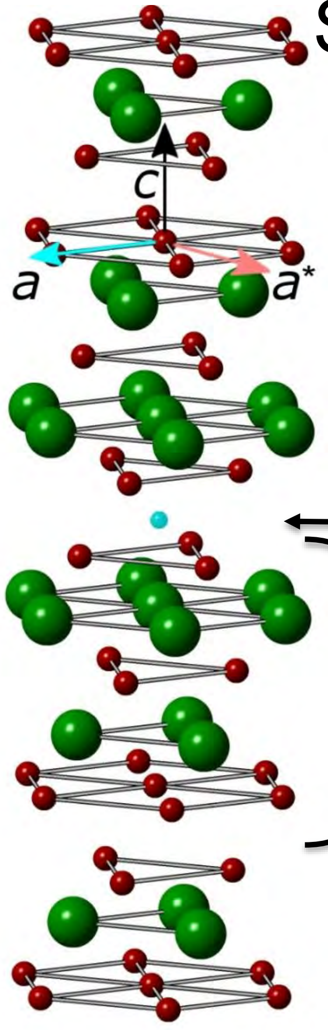
Doping bulk topological insulators



Wray et al., Nat Phys **6**, 855–859 (2010)

Doped topological insulator Bi_2Se_3

Se



Bi

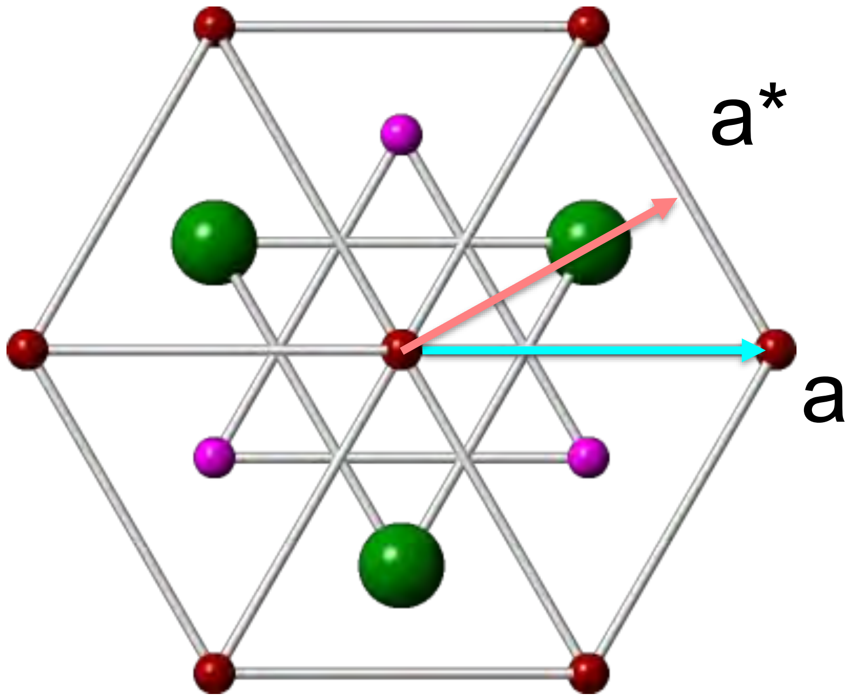
Trigonal crystal structure

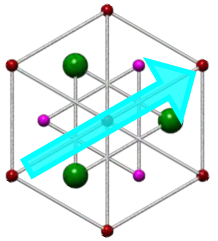
→ 6-fold symmetry
in the plane

Van-der-Waals gap

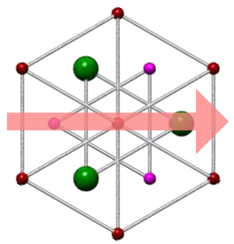
Doping achieved with Cu, Nb, Sr

Quintuple layers





no mirror symmetry
in the a-c plane



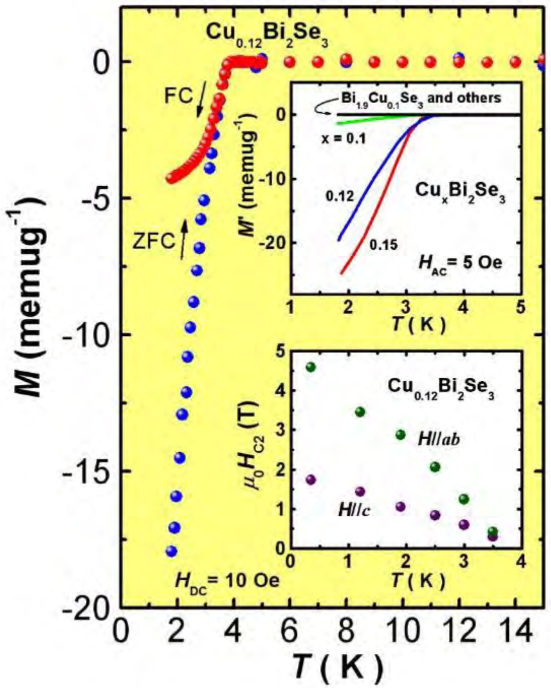
mirror symmetry
in the a*-c plane

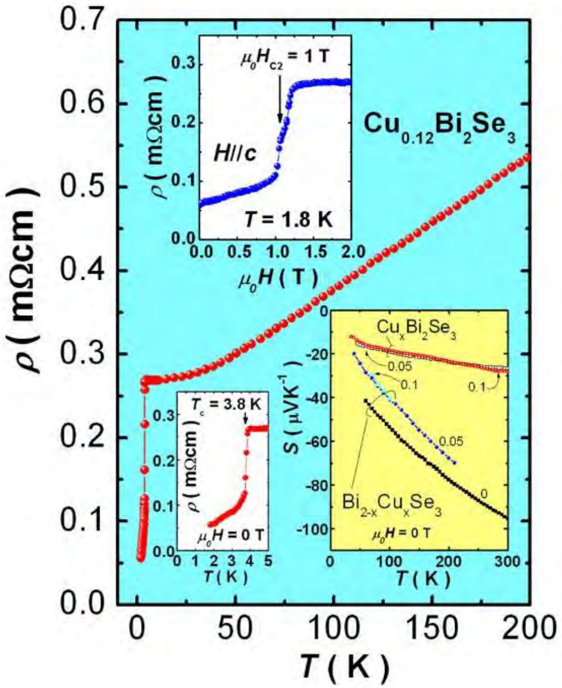
Superconductivity in doped Bi_2Se_3

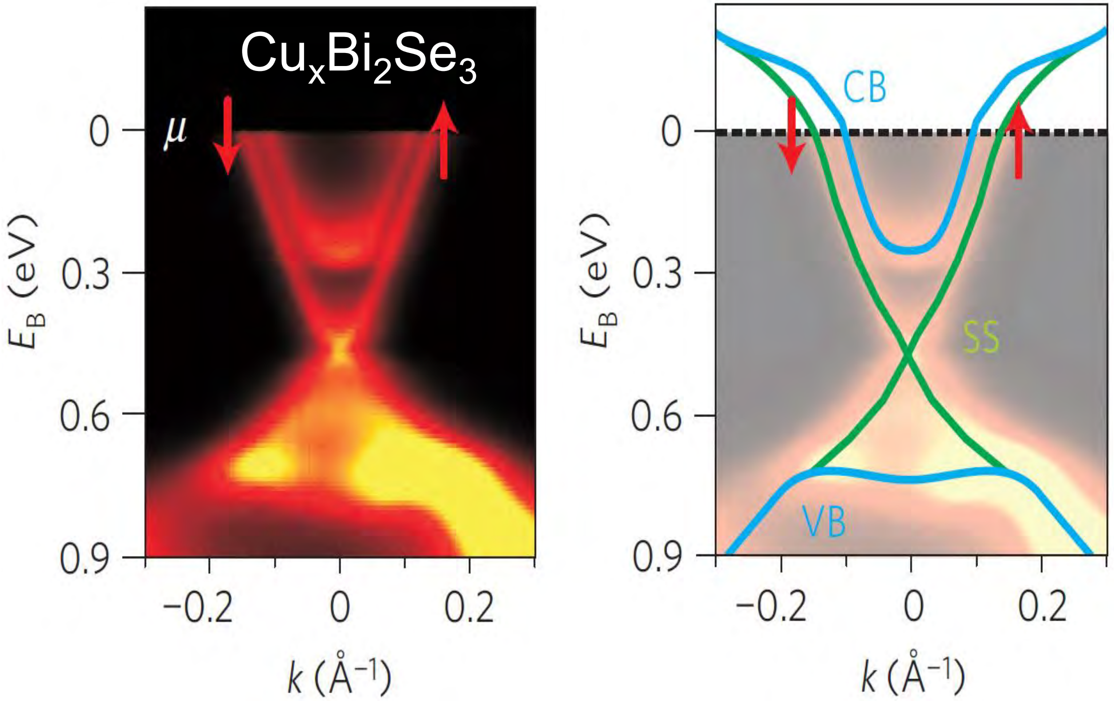
First report of superconductivity in Cu doped Bi_2Se_3

Doping of about 10% necessary

Topological nature of the surface states preserved







T_c=3.5K

→ Doping with Nb or Sr also leads to superconductivity at around 3K

Hor et al., PRL104,057001 (2010)

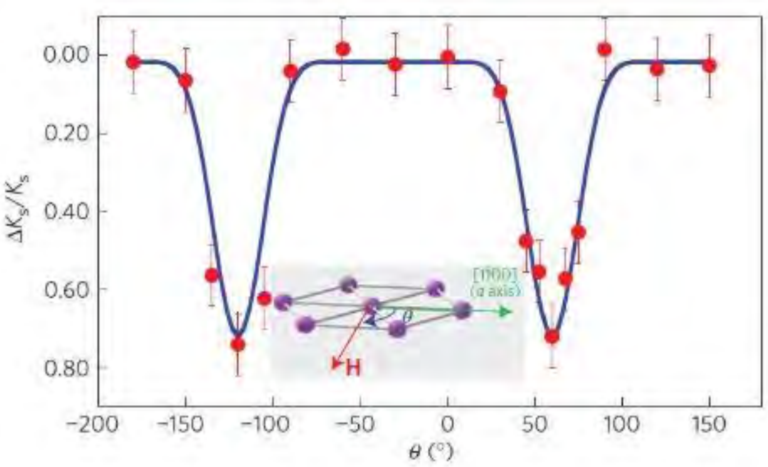
Kriener et al., PRL106,127004 (2011)

Wray et al., Nat Phys **6**, 855–859 (2010)

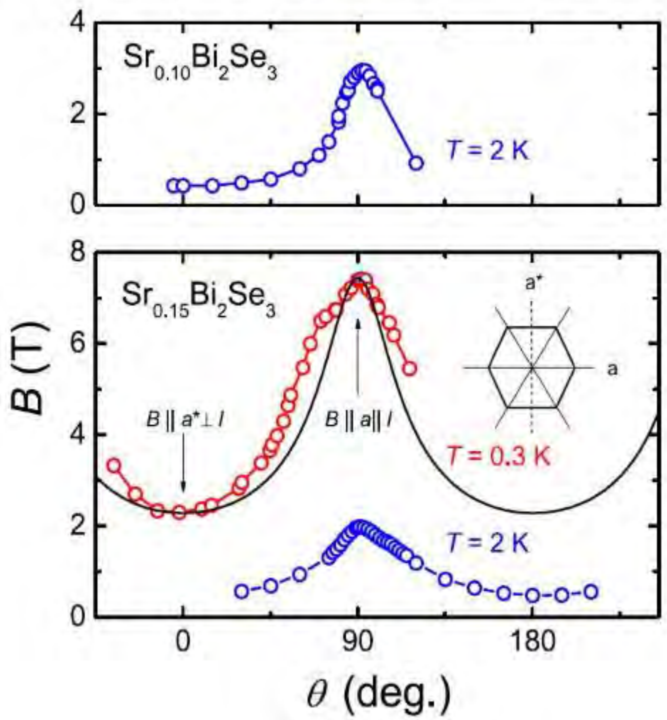
First indications of nematic superconductivity

2-fold symmetry in the superconducting state despite trigonal crystal structure

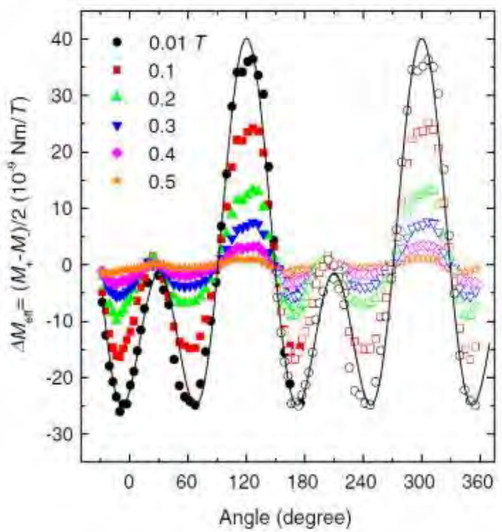
(a) $Cu_xBi_2Se_3$, NMR



(c) $Sr_xBi_2Se_3$, H_{c2} from resistivity



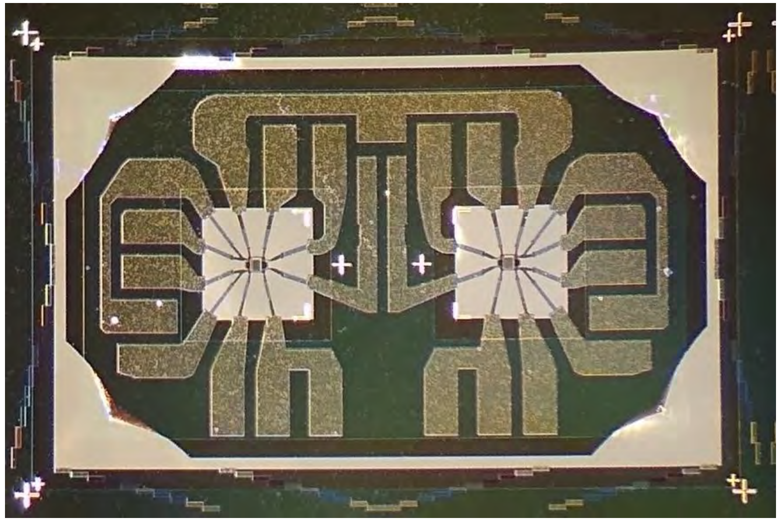
(d) $Nb_xBi_2Se_3$, magnetic torque



Is this a sign of the superconducting gap structure or are there external or more conventional sources responsible for this two fold symmetry?

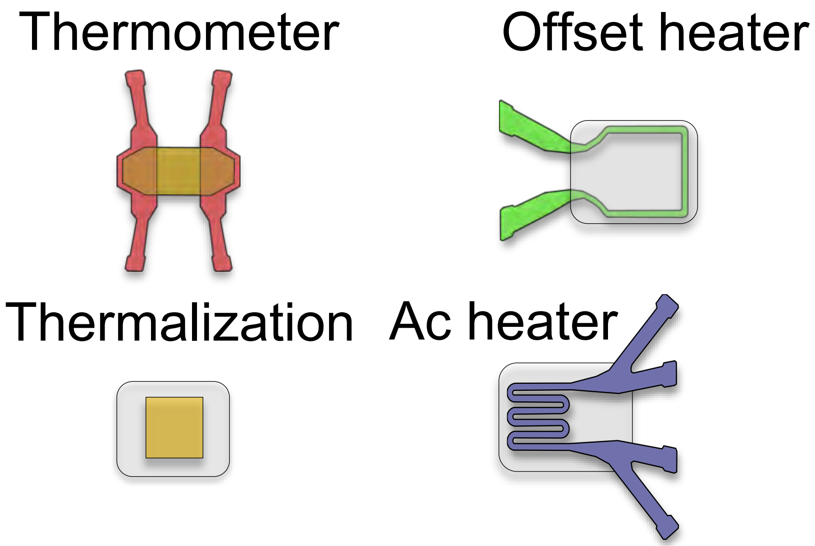
 Matano et al, Nat. Phys., **12**, 852 (2016) Pan et al, Sci. Rep., **6**, 28632 (2016) Asaba et al, Phys. Rev. X, **7**, 011009 (2017)

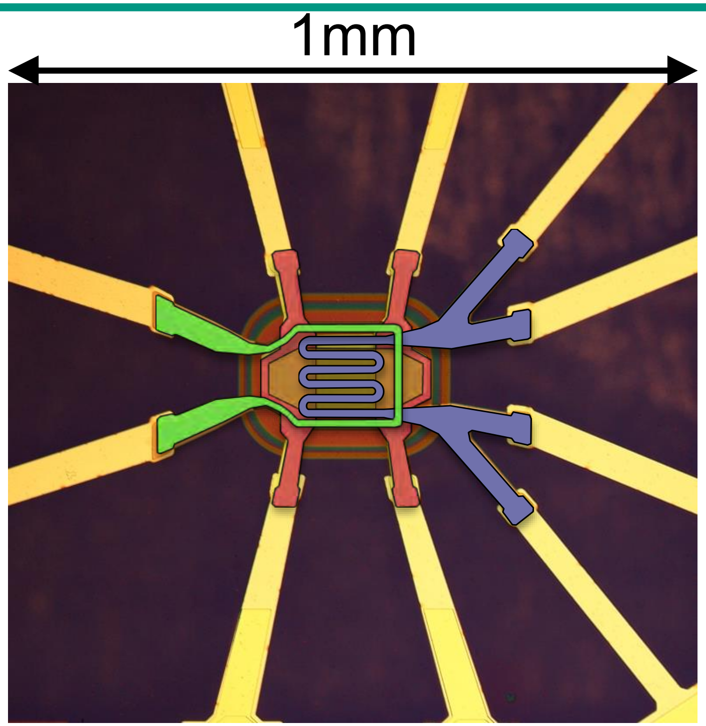
Nanocalorimetry setup



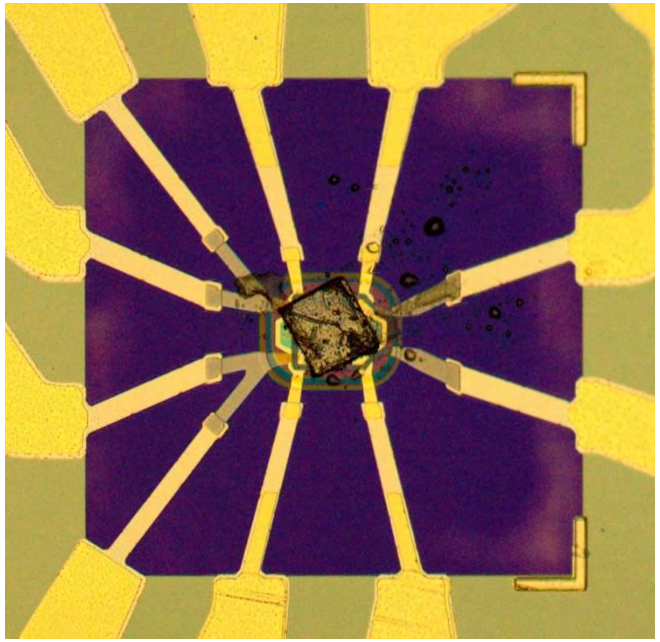
Specifications:

- GeAu thermometer
- Ti+Au thermometer pads
- Ti ac/dc heater
- **150nm** SiN membrane
- High-sensitive differential calorimetry
- RT to mK with mK temperature stability
- very small samples





µg samples



Willa et al, Review of Scientific Instruments **88**, 125108 (2017)

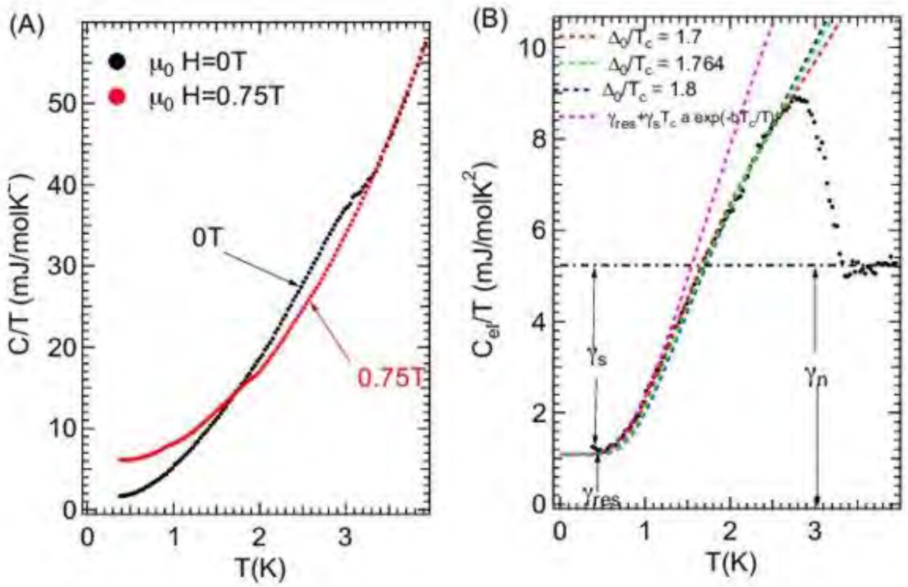
Specific heat of doped Bi_2Se_3

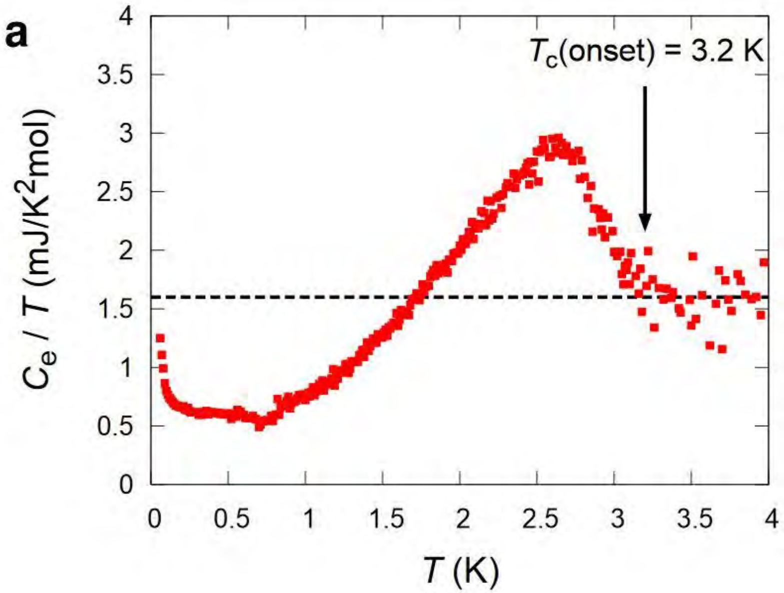
Superconducting transition in

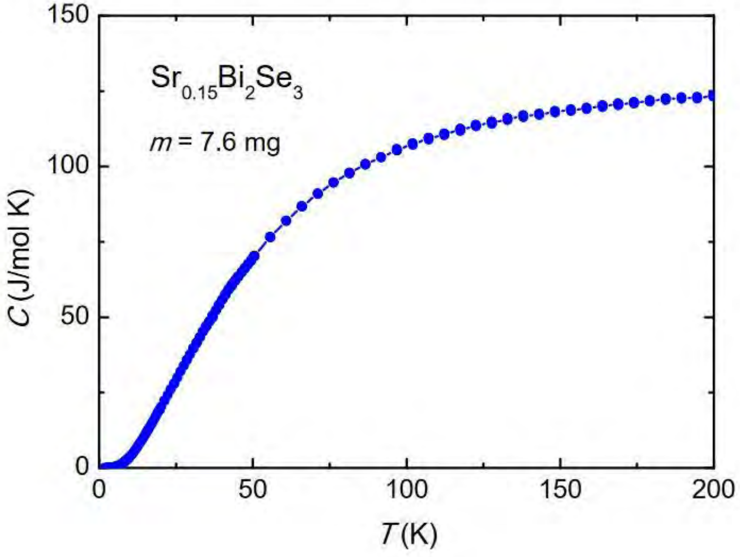
$Nb_xBi_2Se_3$

$Cu_xBi_2Se_3$

$Sr_xBi_2Se_3$?





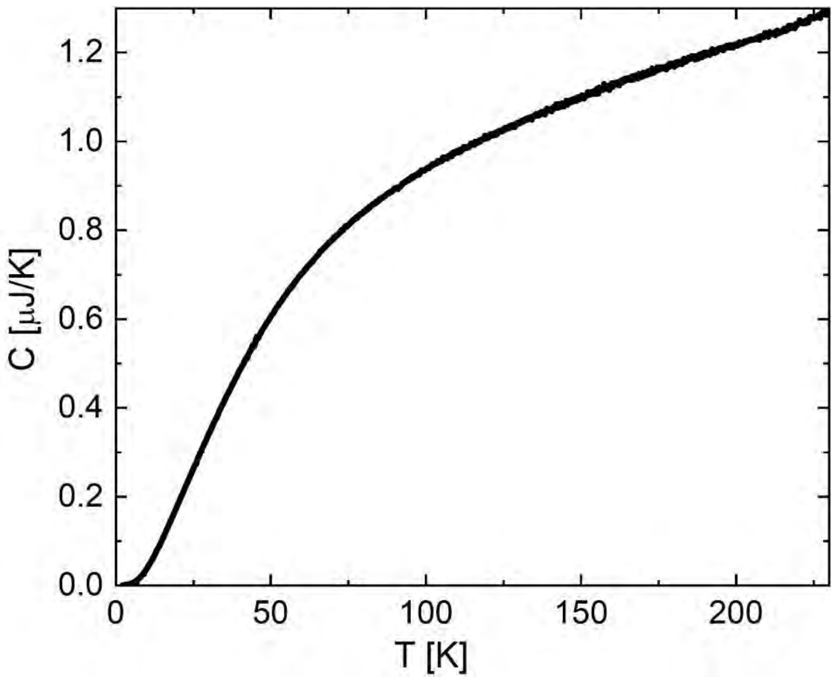


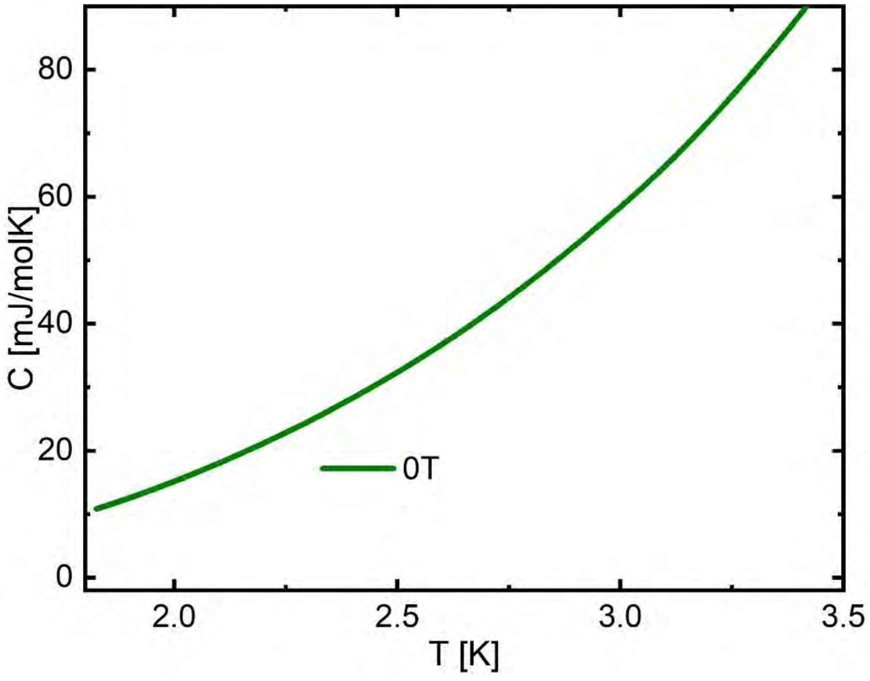
Asaba et al., PRX **7**, 1 (2016)

Yonezawa et al., Nat Phys **13**, 123–126 (2017)

Pan et al., Sci. Rep. **6**, 28632 (2016)

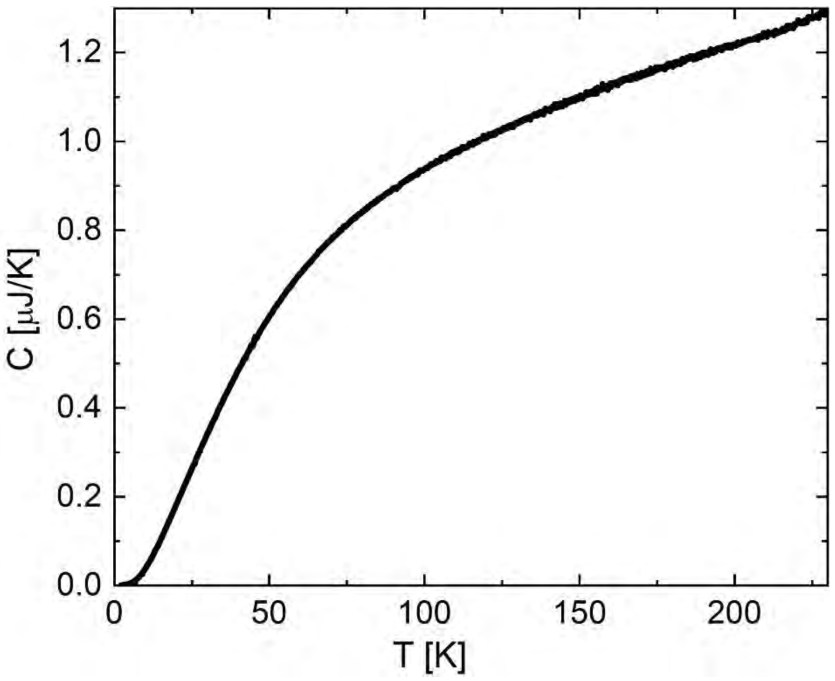
Specific heat of $Sr_xBi_2Se_3$

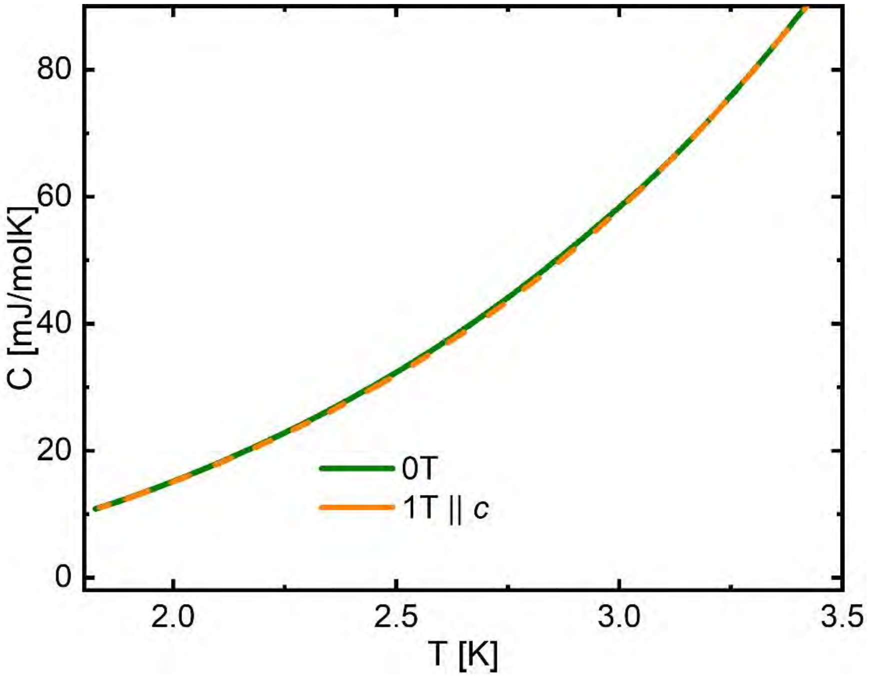




Willa et al., PRB **98**, 184509 (2018)

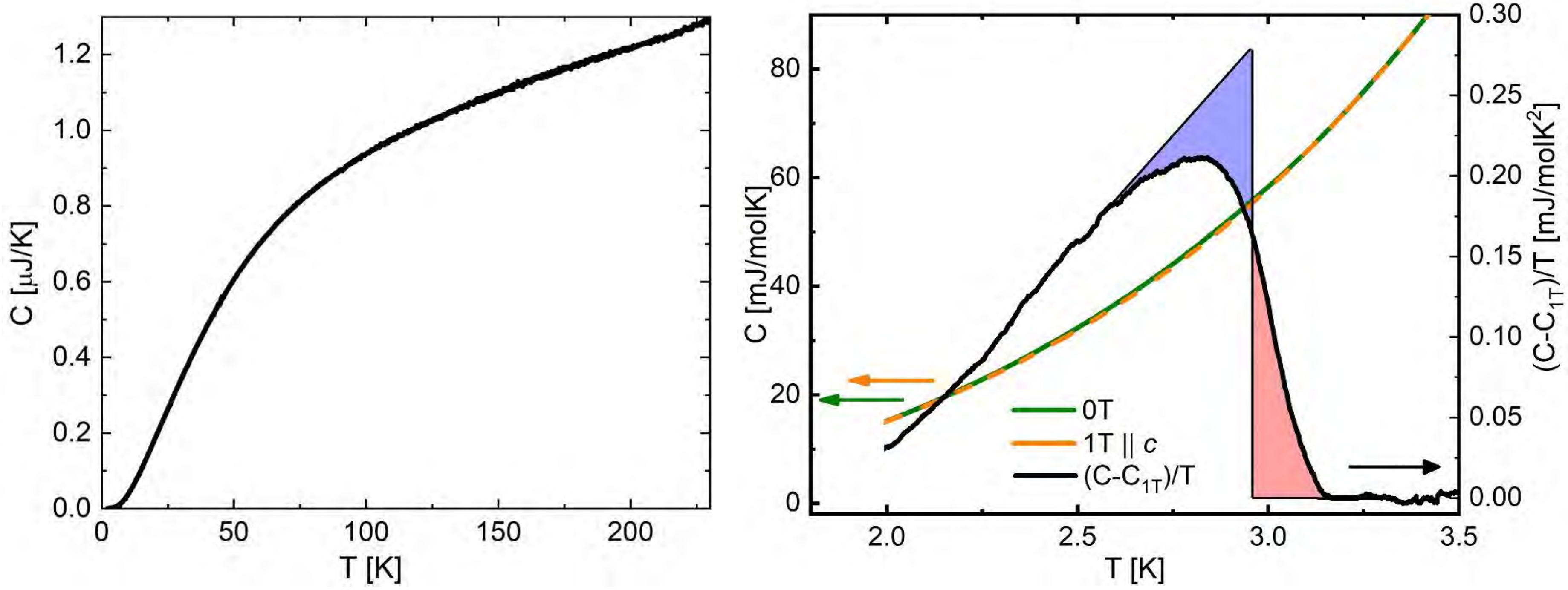
Specific heat of $Sr_xBi_2Se_3$





 Willa et al., PRB **98**, 184509 (2018)

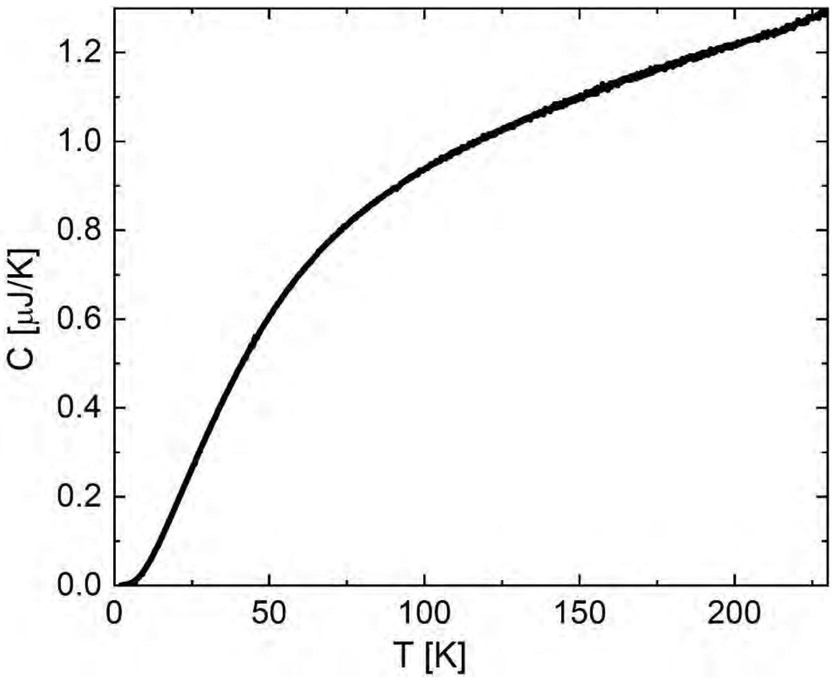
Specific heat of $Sr_xBi_2Se_3$

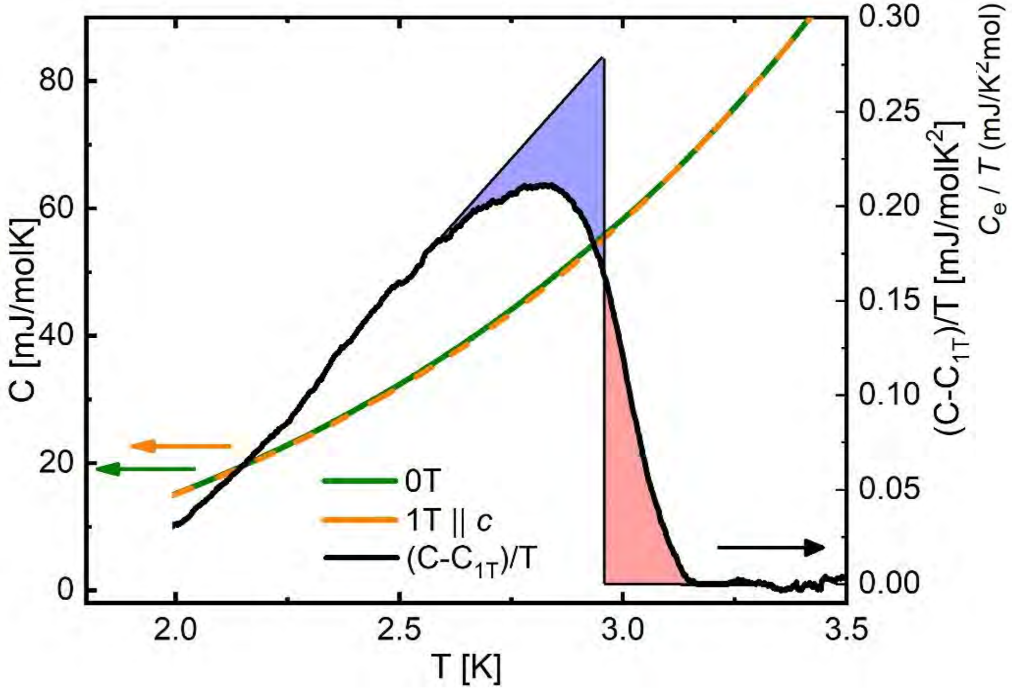


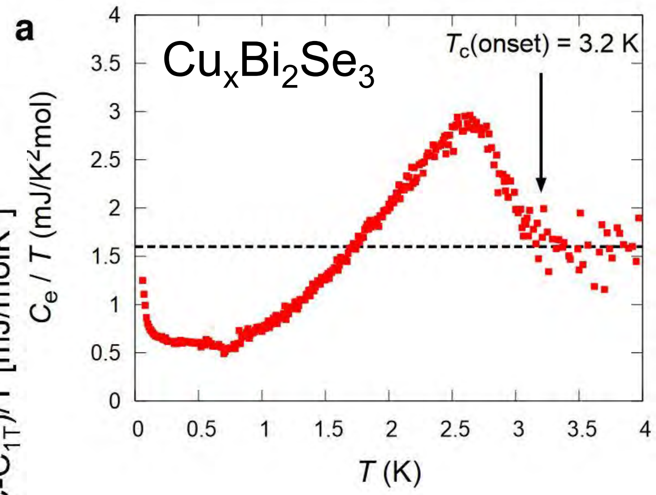
$\Delta C/T = 0.27\ mJ/molK^2$

Bulk superconductivity?

Specific heat of $Sr_xBi_2Se_3$







$\Delta C/T$ = 3 mJ/molK^2

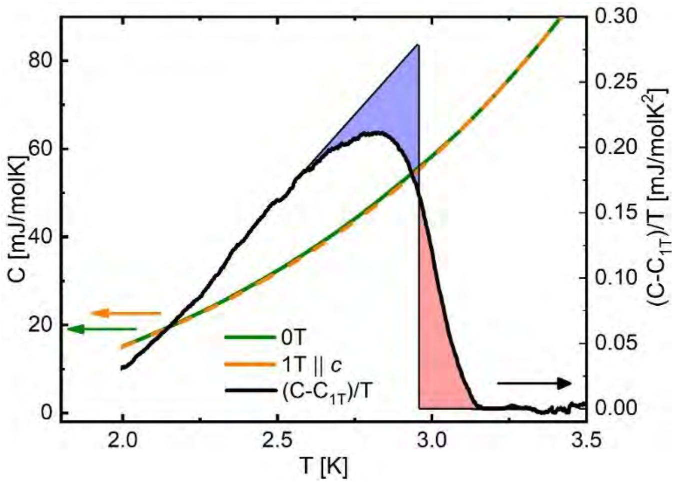
n ≈ 10^{-20}cm^{-3}

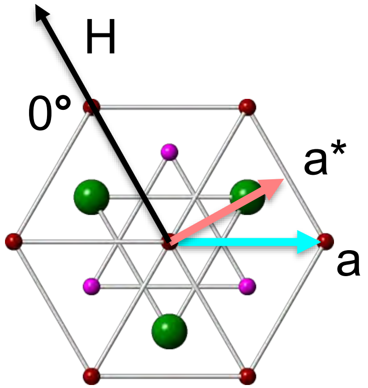
$\Delta C/T$ = 0.27 mJ/molK^2

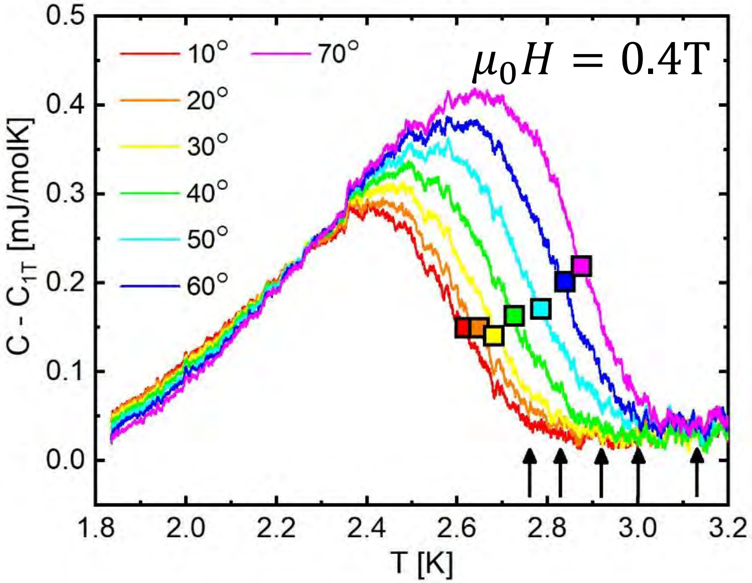
n ≈ 10^{-19}cm^{-3}

Difference in $\Delta C/T$ due to difference in carrier concentration

Specific heat of $Sr_xBi_2Se_3$

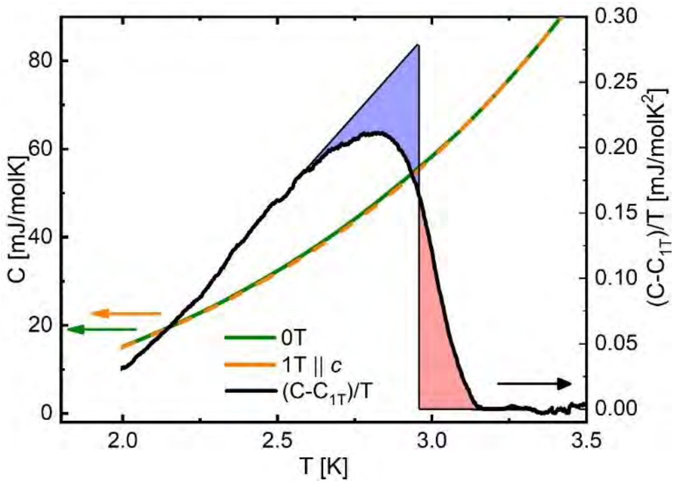


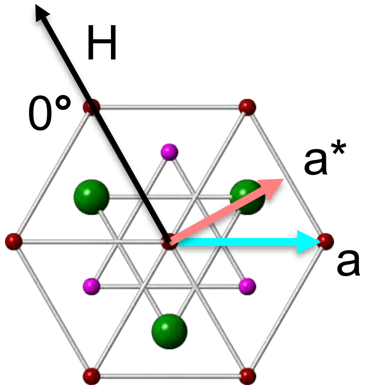


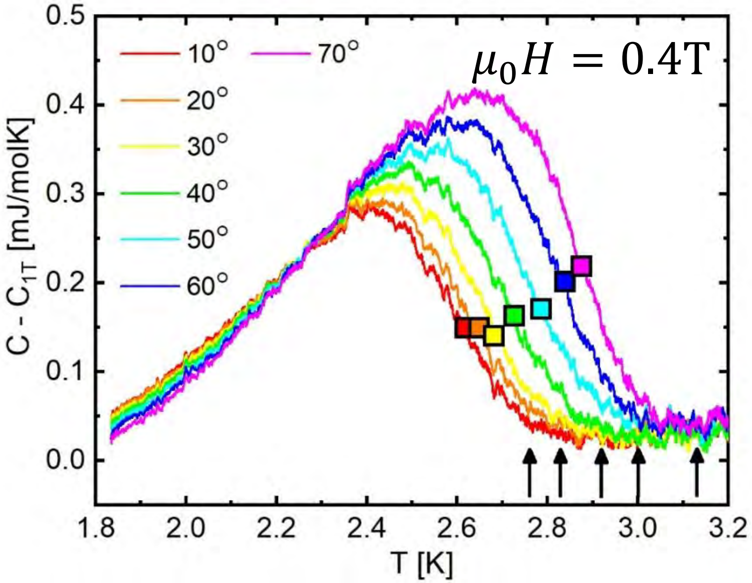


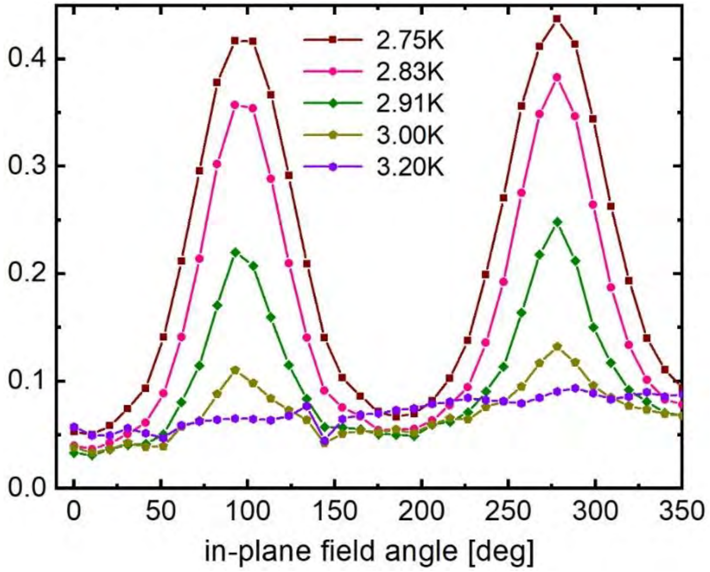
Willa et al., PRB **98**, 184509 (2018)

Specific heat of $Sr_xBi_2Se_3$



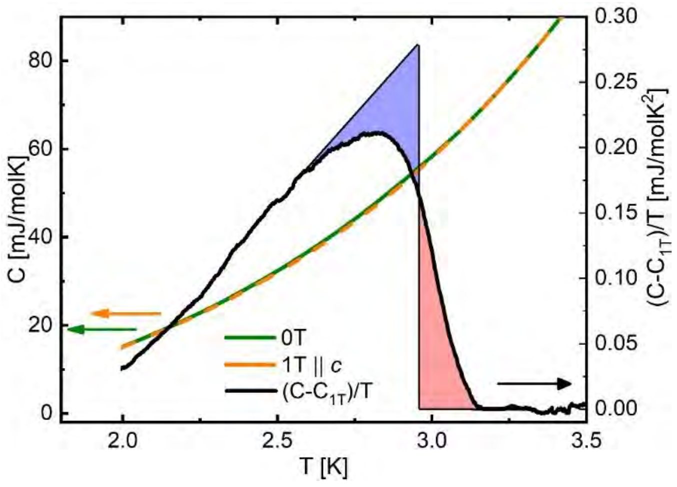


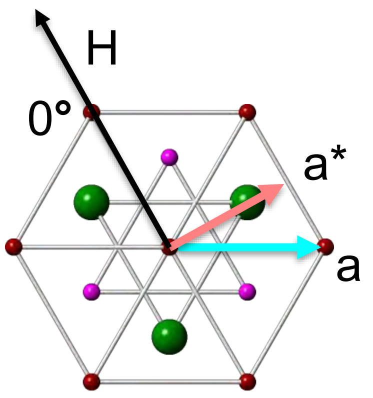


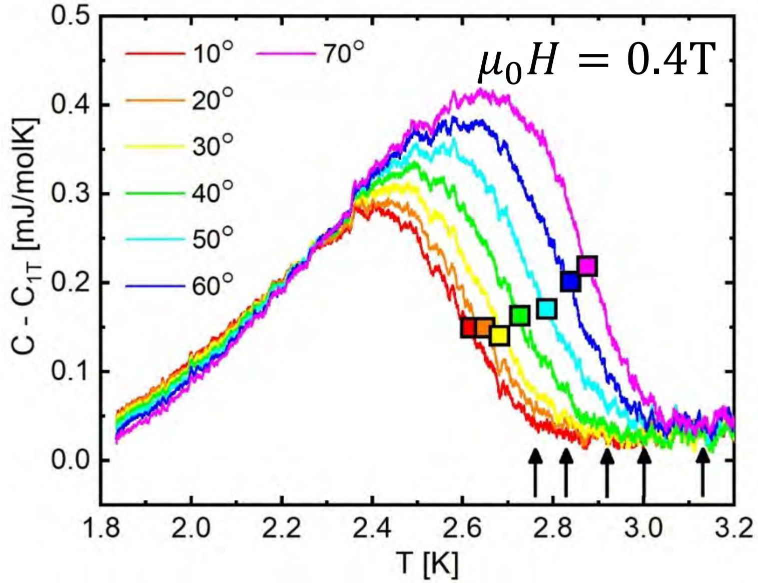


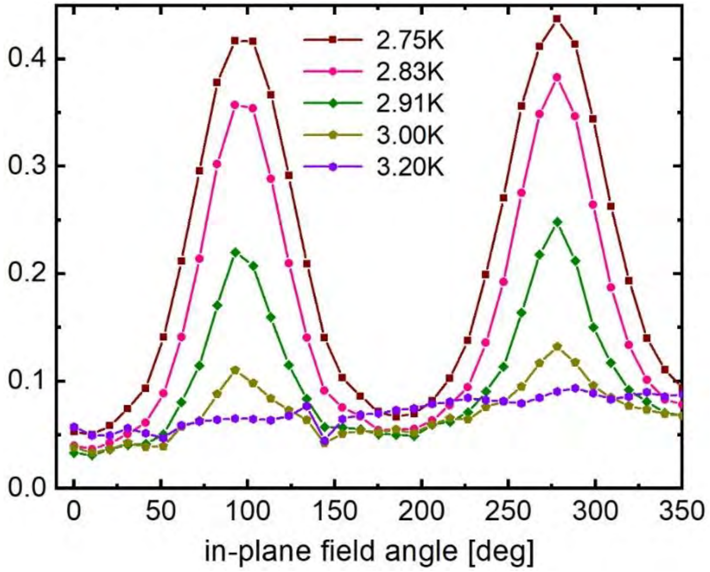
 Willa et al., PRB **98**, 184509 (2018)

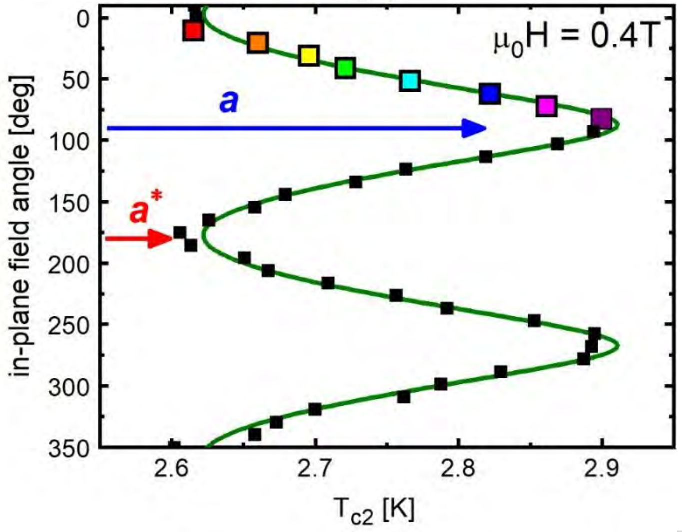
Specific heat of $Sr_xBi_2Se_3$



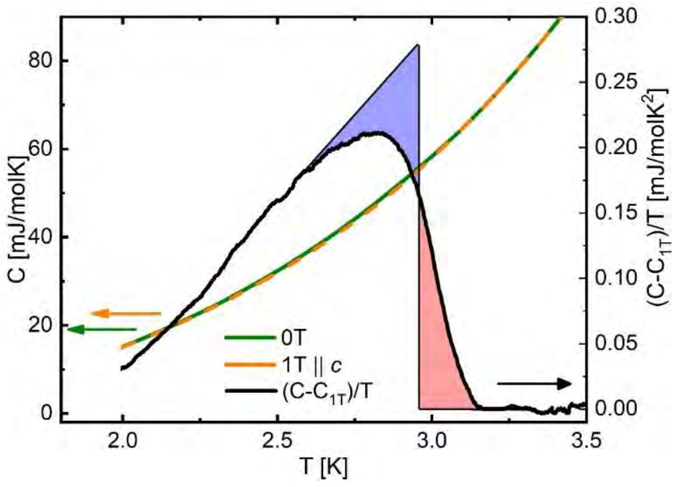


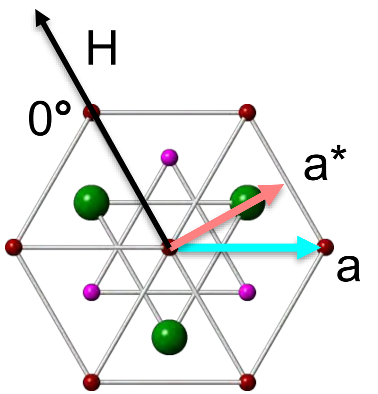




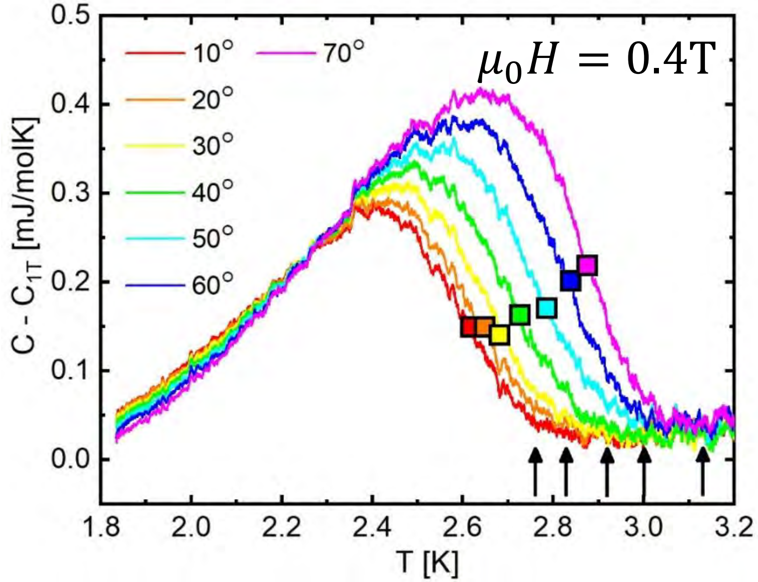


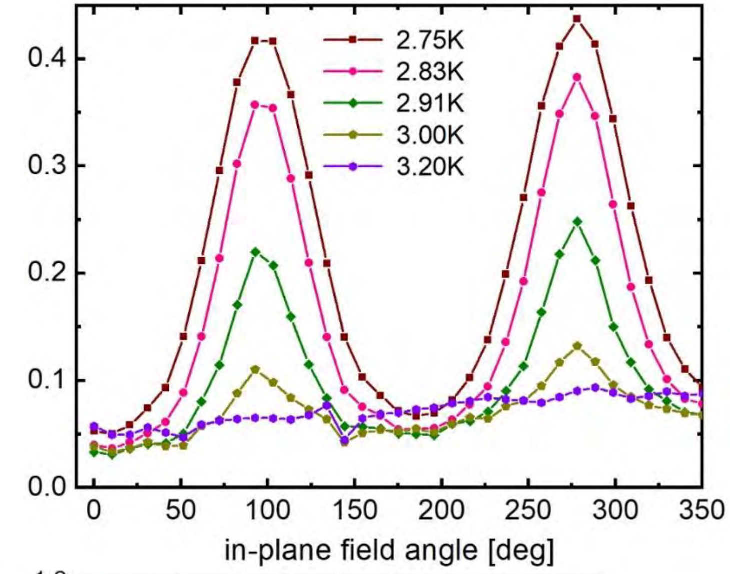
Specific heat of $Sr_xBi_2Se_3$

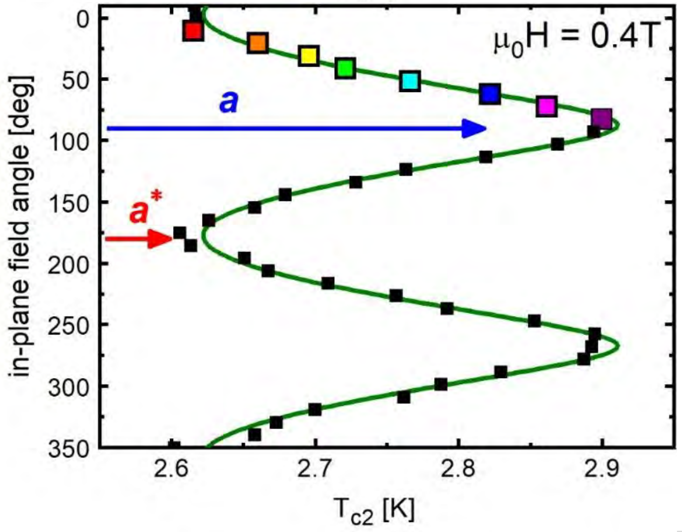


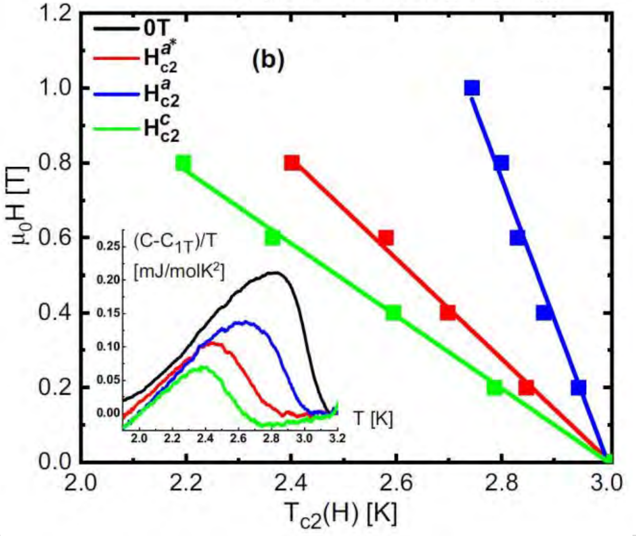


$$\Gamma_{\text{exp}} = H_{c2}^{a} / H_{c2}^{a^*} = 3.5$$

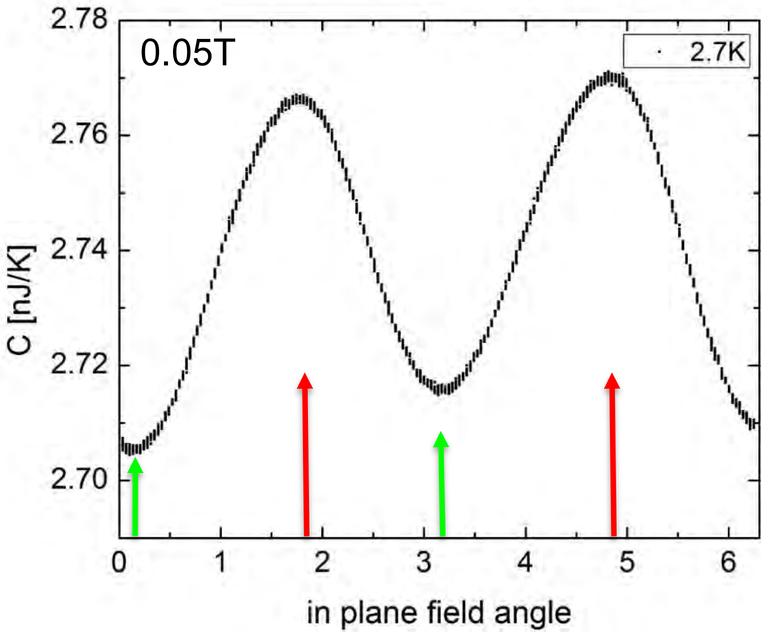


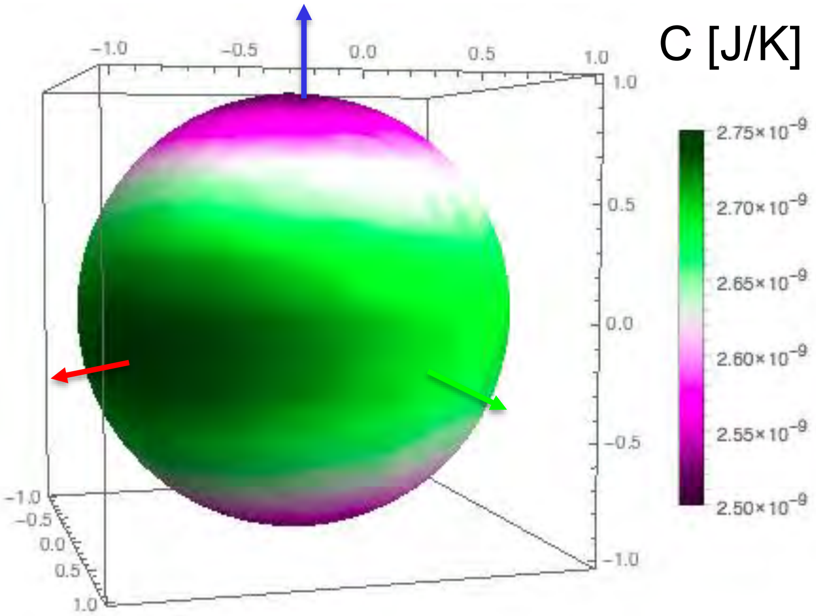




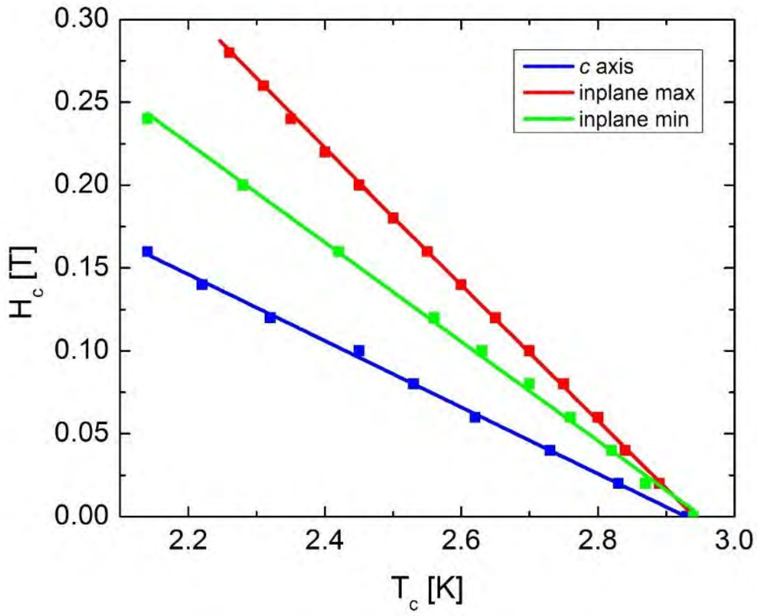


Nematic superconductivity in $Nb_xBi_2Se_3$



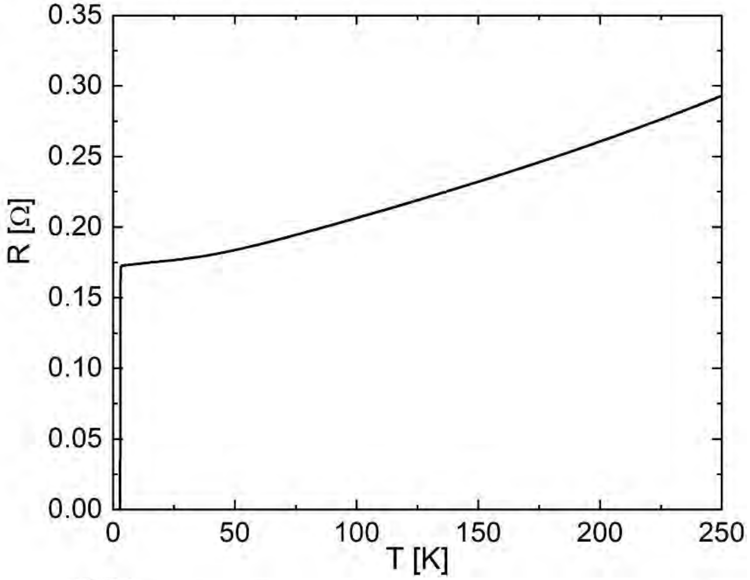


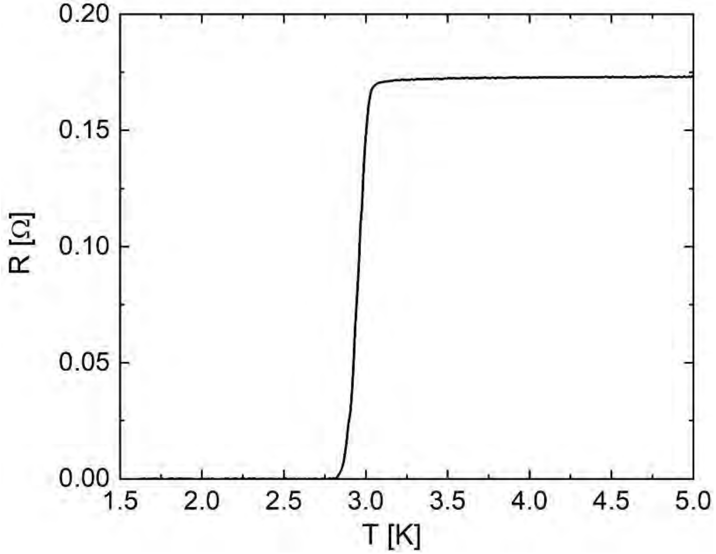
Two-fold anisotropy in the a-a*plane



Phase diagram

Transport measurements of $Sr_xBi_2Se_3$





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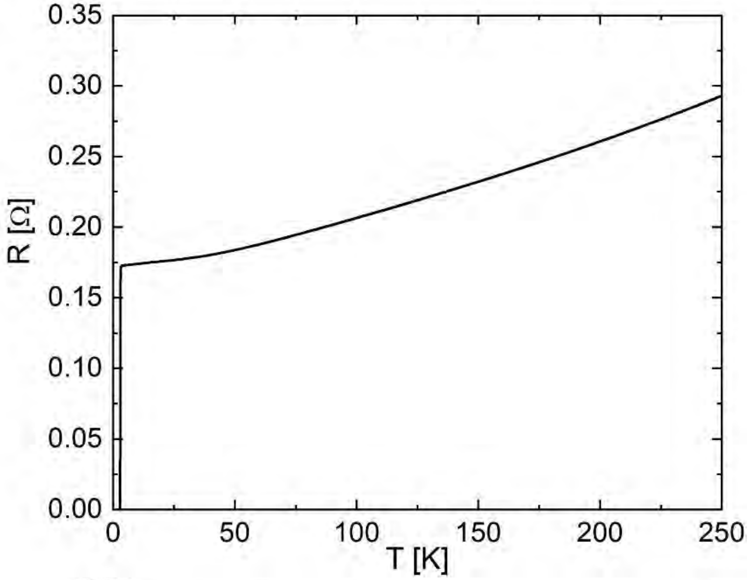
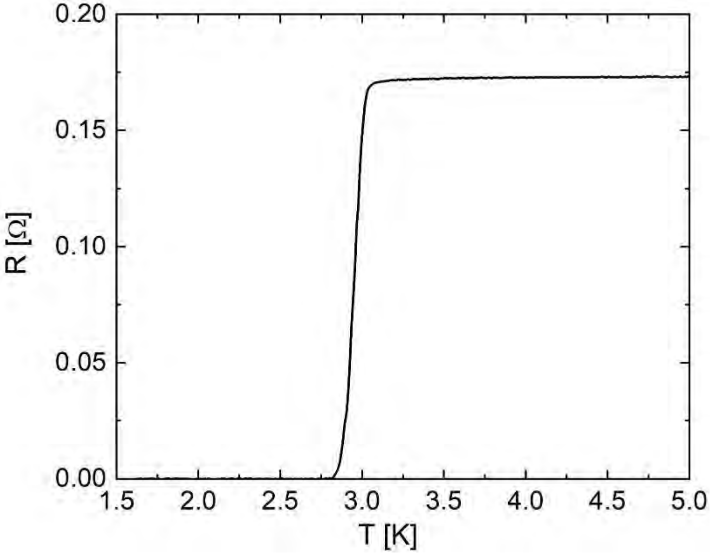
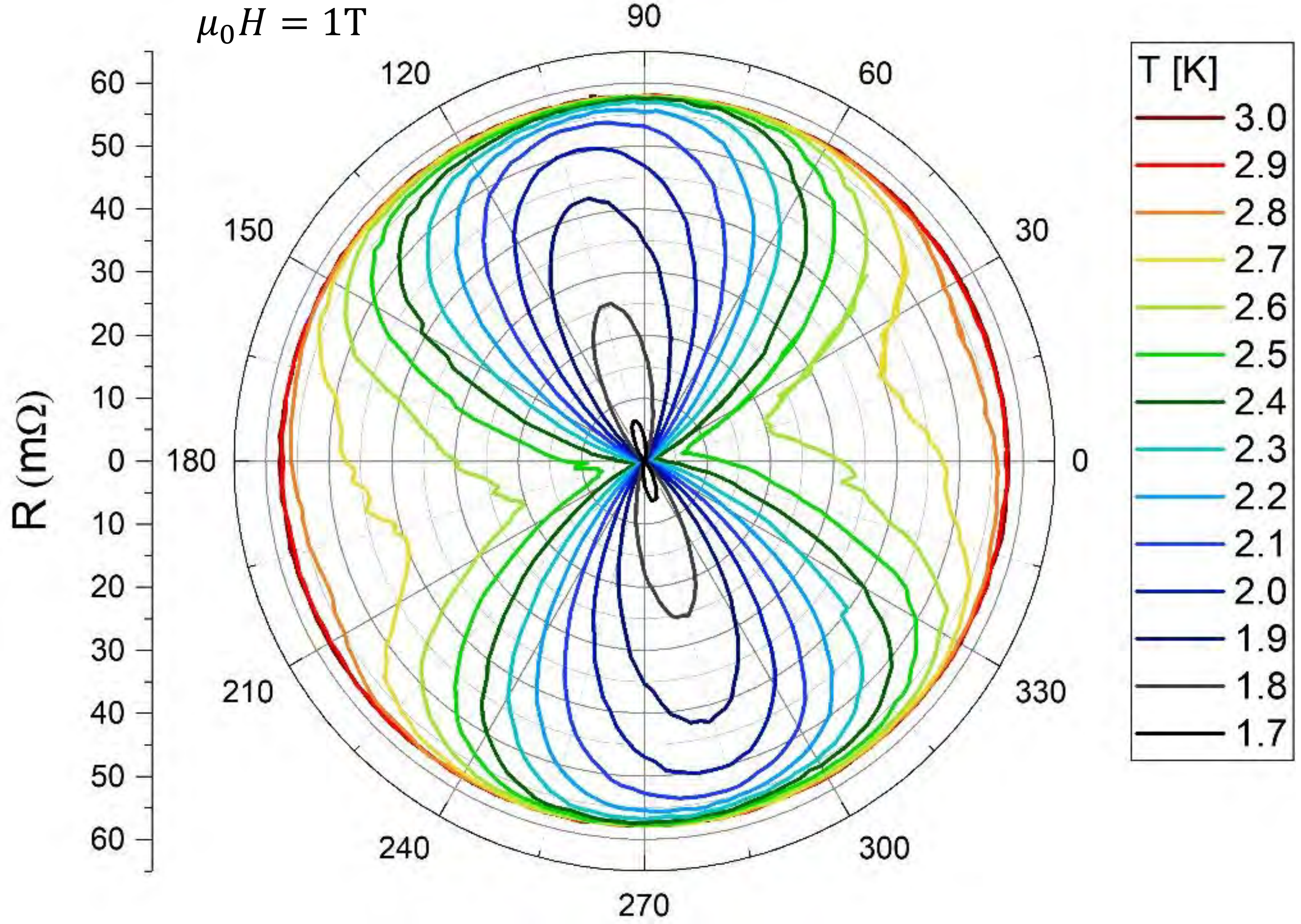




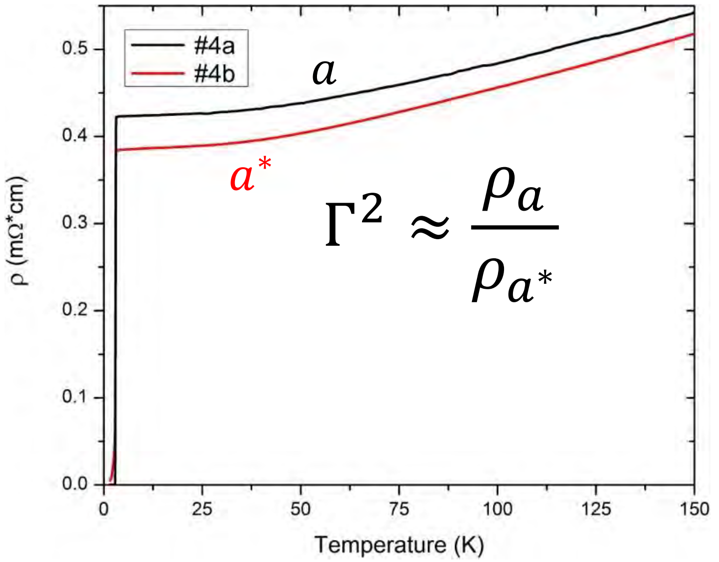


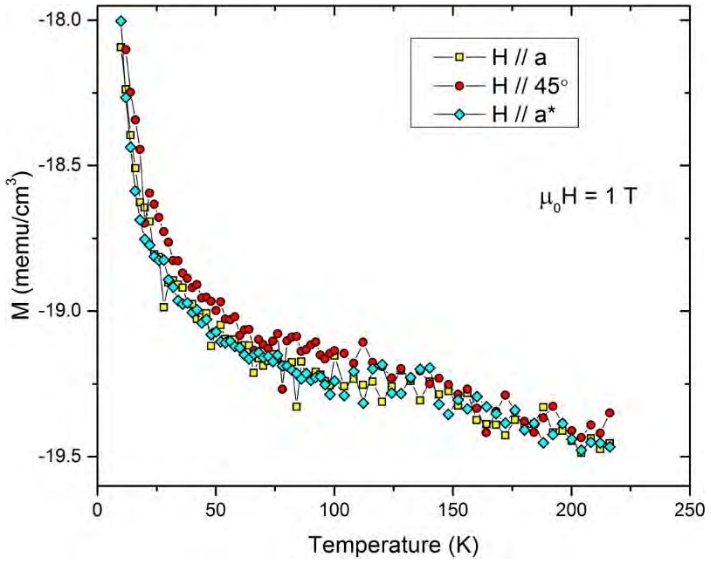
Could there be conventional causes?

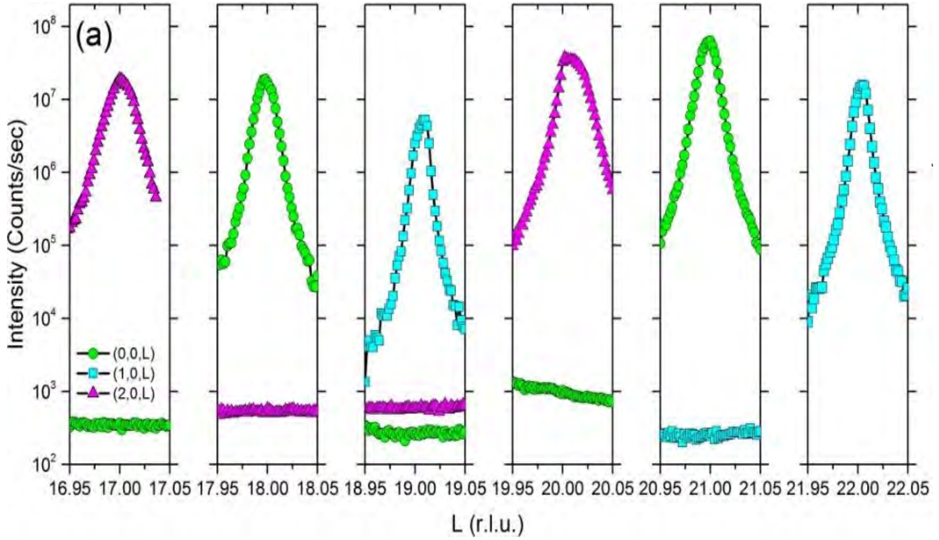
Effective mass anisotropy?

Magnetic anisotropy?

Structural distortions?

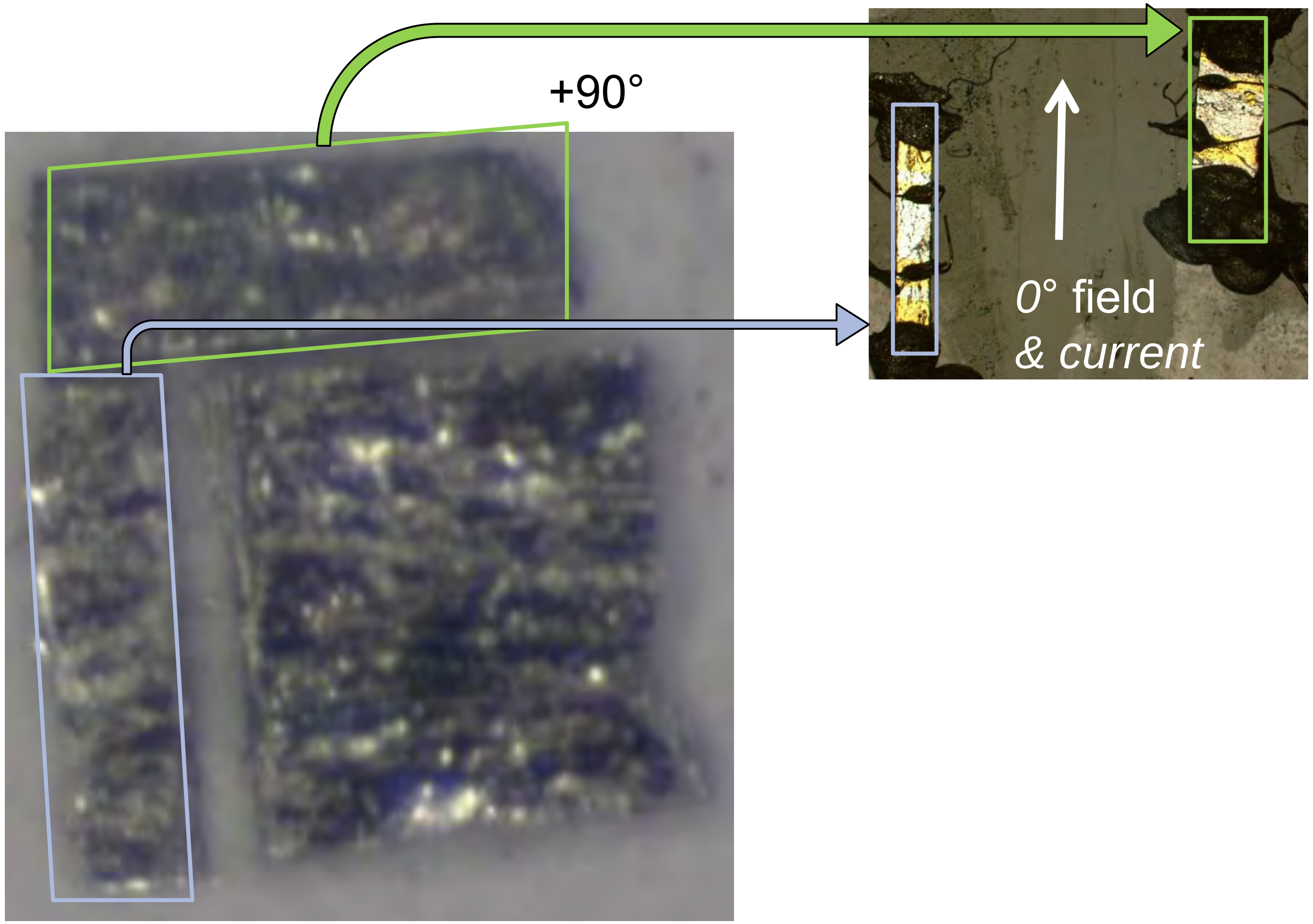






Smylie, **Willa** et al., Sci. Rep. **8**, 7666 (2018)

Could there be conventional causes?

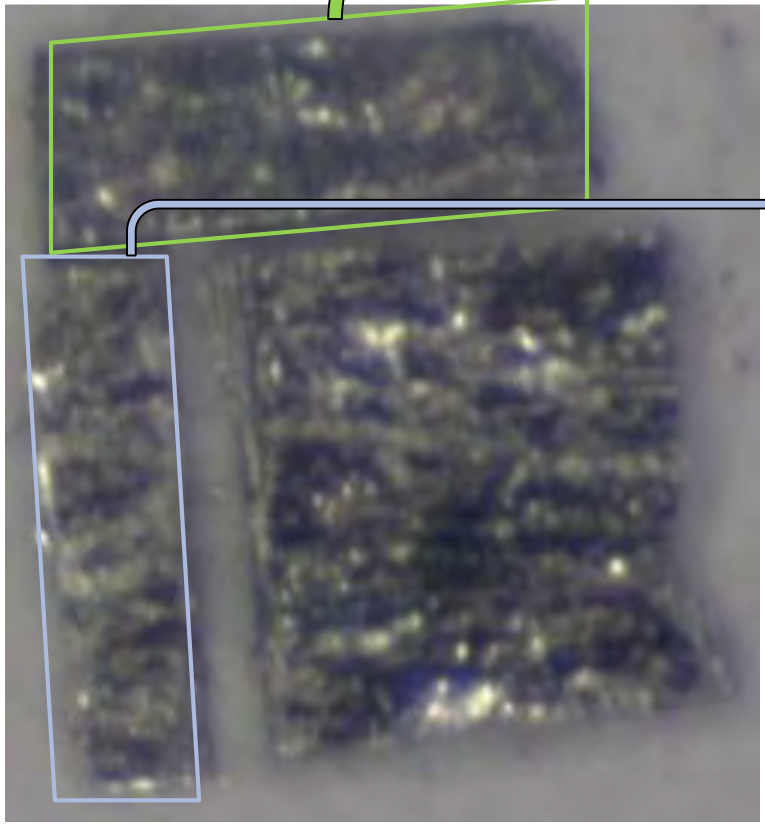


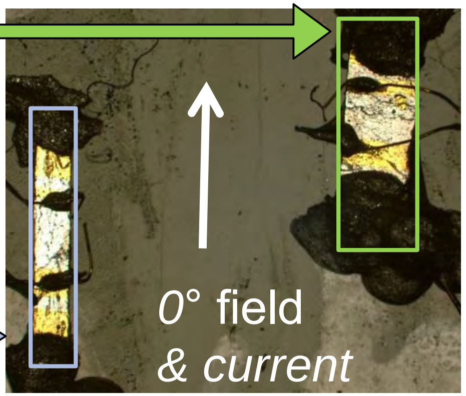
Crystal shape?
Vortex motion?
Misalignment of the magnetic field?

Smylie, **Willa** et al., Sci. Rep. **8**, 7666 (2018)

Could there be conventional causes?

+90°





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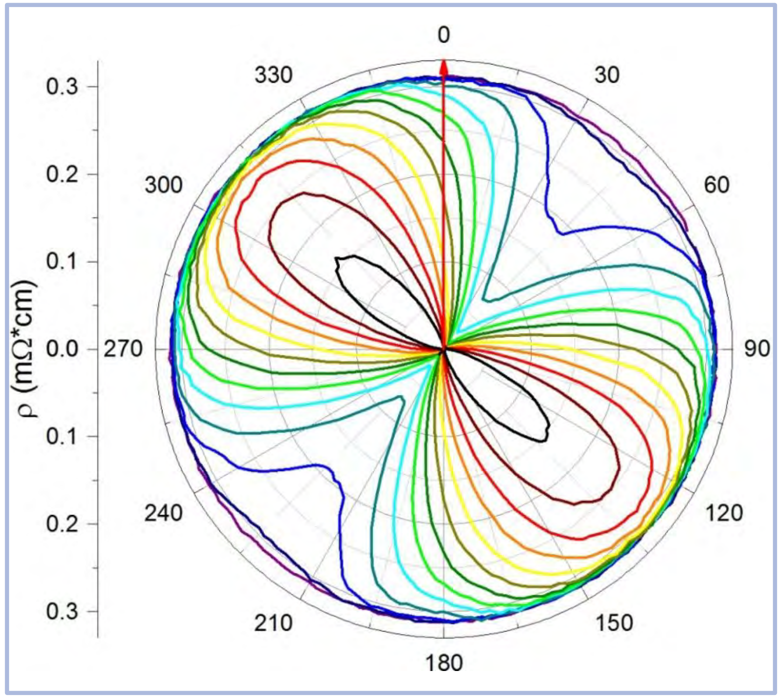

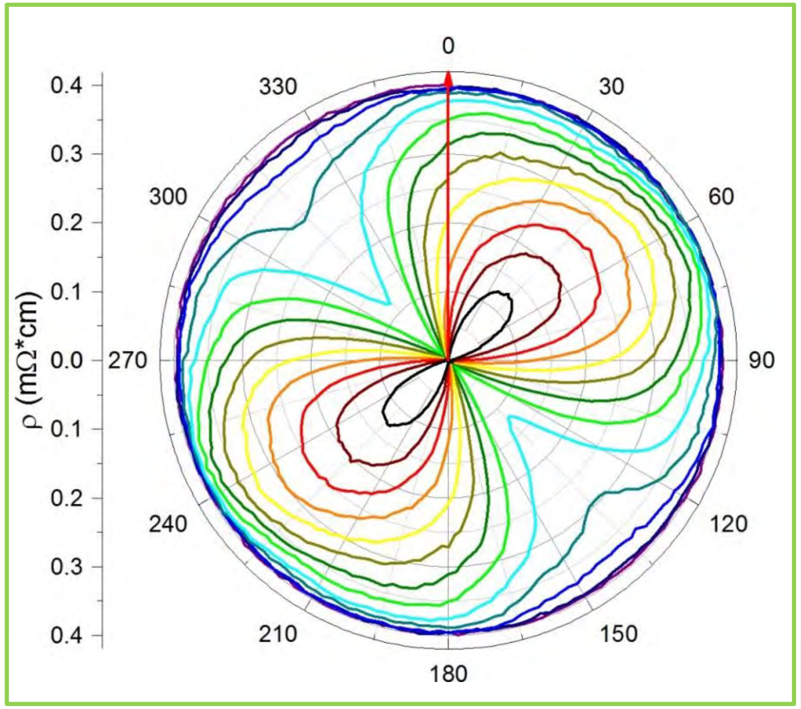

Smylie, **Willa** et al., Sci. Rep. **8**, 7666 (2018)

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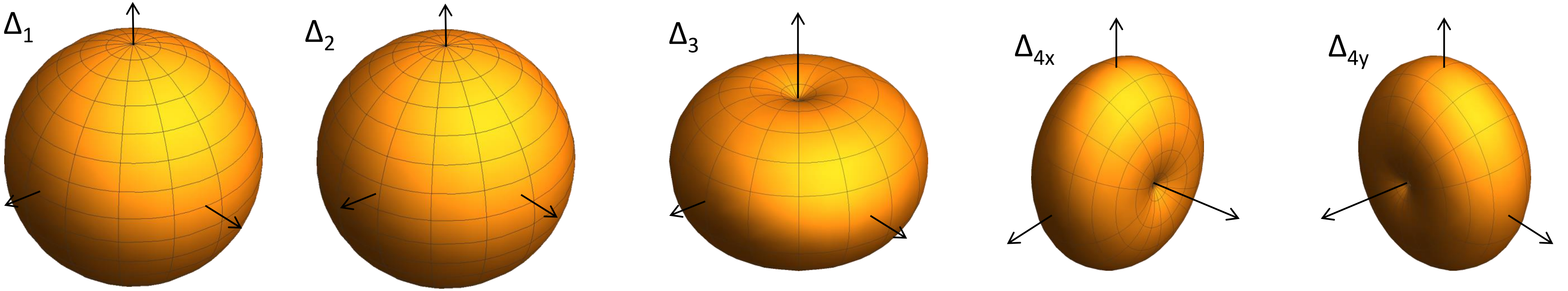
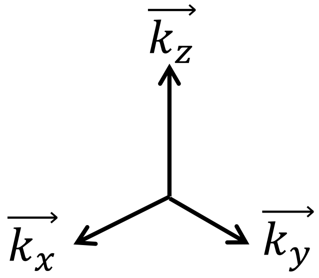
Possible gap structures

Karlsruhe Institute of Technology

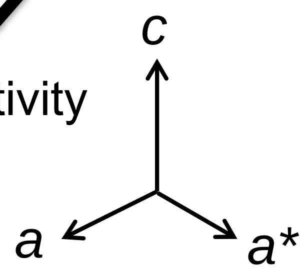
One component order parameter			two component order parameter	



Full gap	Full gap	Point node on $\overrightarrow{\mathrm{k}_z}$	Point node on $\overrightarrow{\mathrm{k}_y}$	Gap minimum on $\overrightarrow{\mathrm{k}_x}$
A_{1g}	A_{1u}	A_{2u}	E_u	E_u

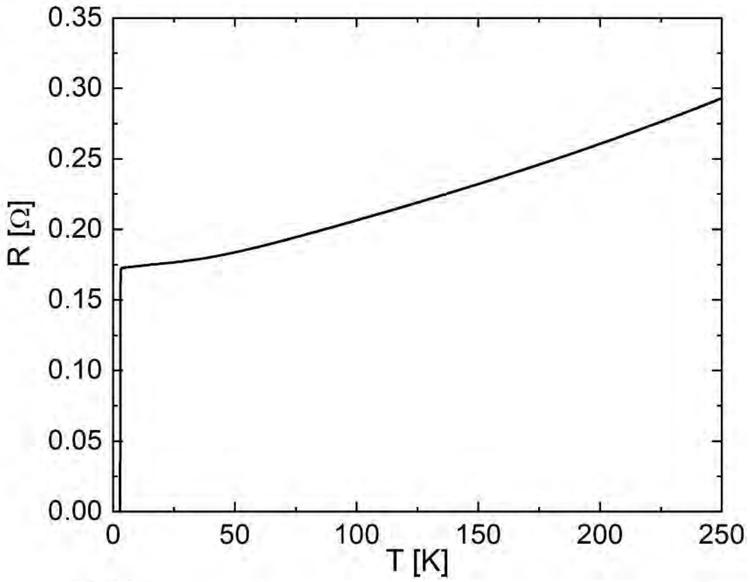


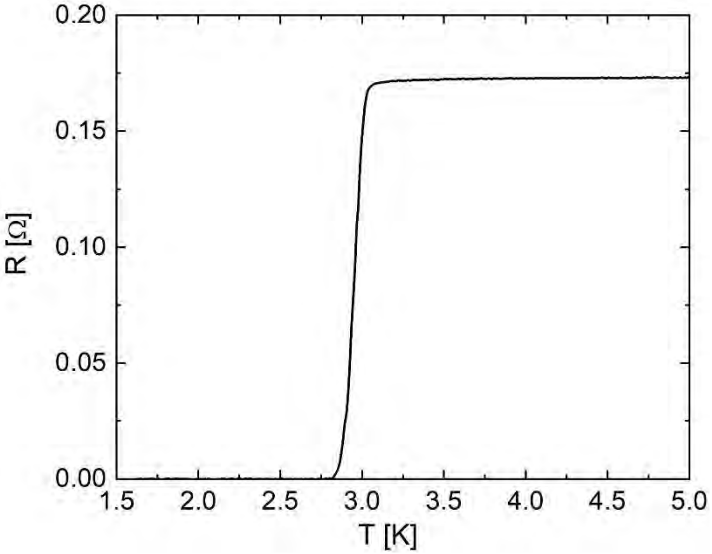
Nematic superconductivity



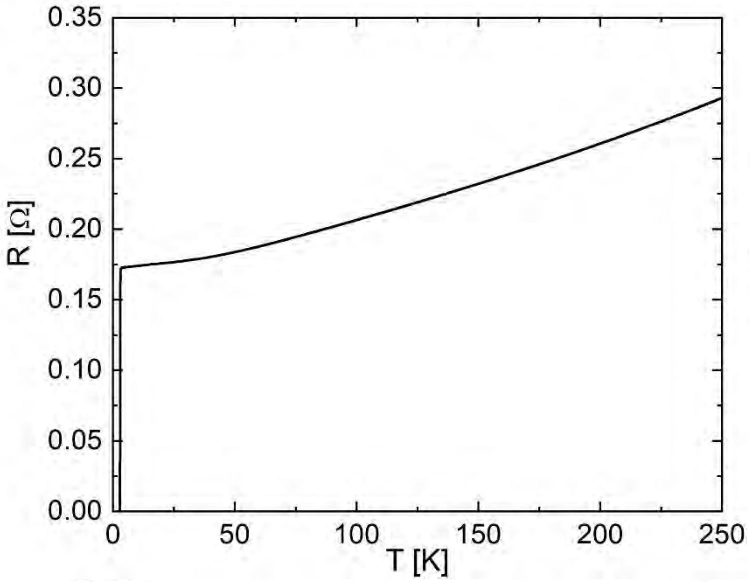
L. Fu & E. Berg, PRL **105**, 097001 (2010) L. Fu, PRB **90**, 100509(R) (2014) J. W. F. Venderbos et al., PRB **94**, 094522 (2016)

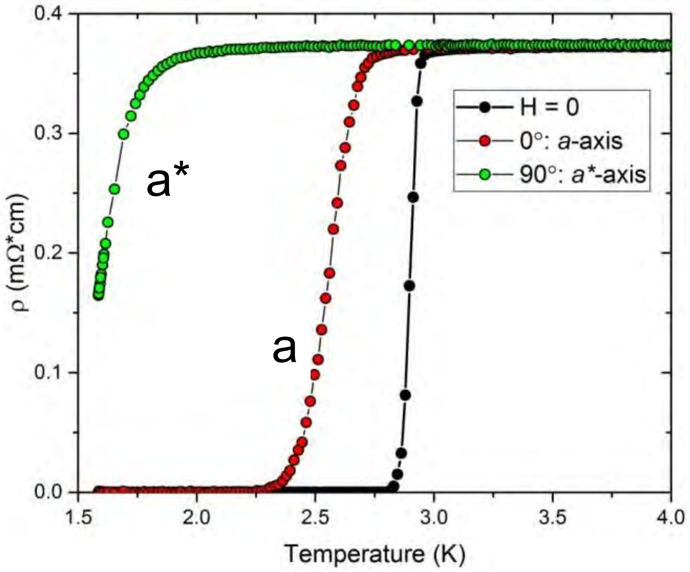
Transport measurements on $Sr_xBi_2Se_3$

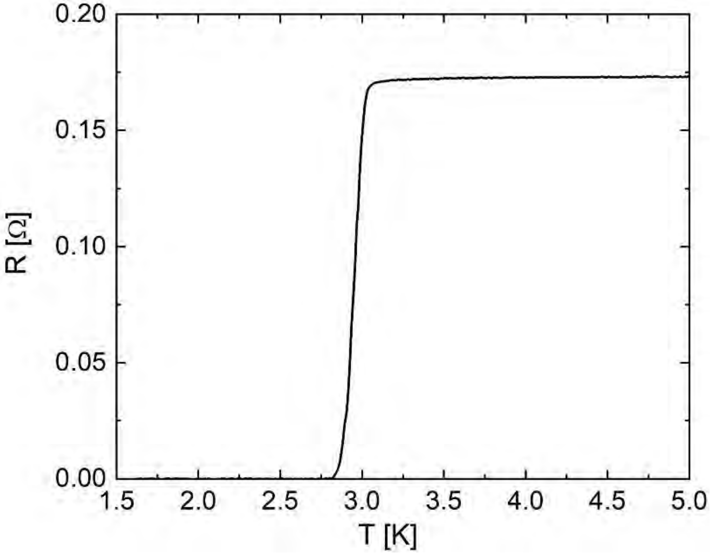


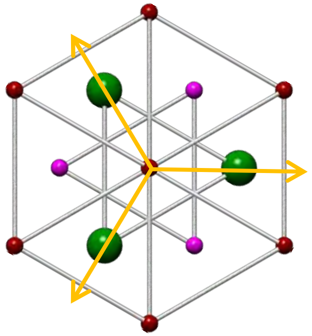


Transport measurements on $Sr_xBi_2Se_3$

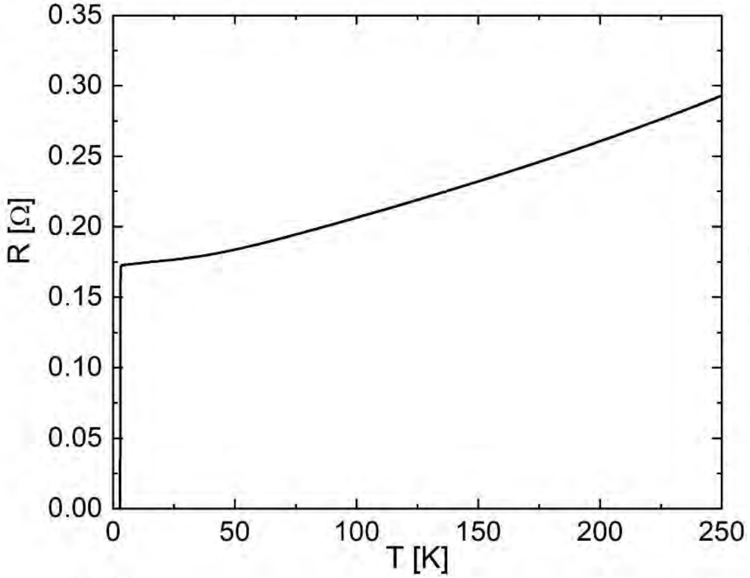


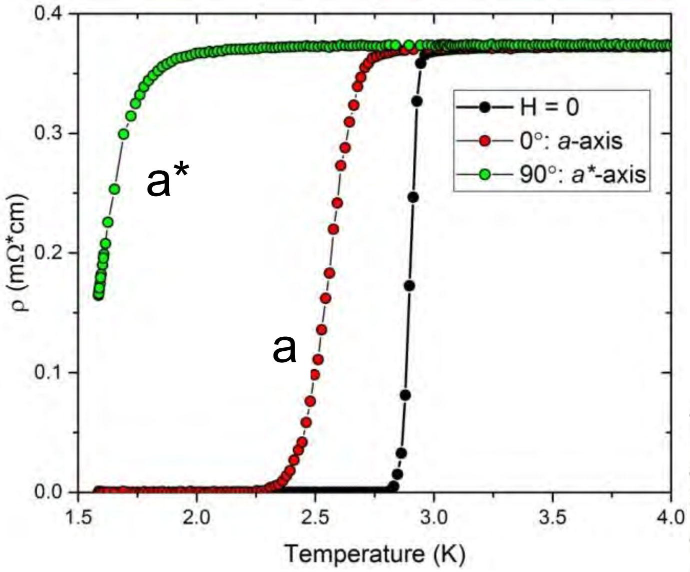


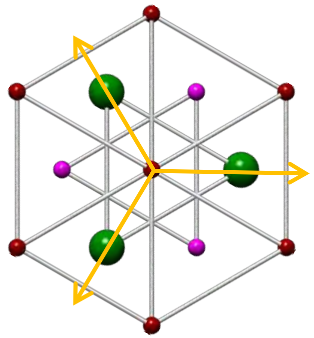


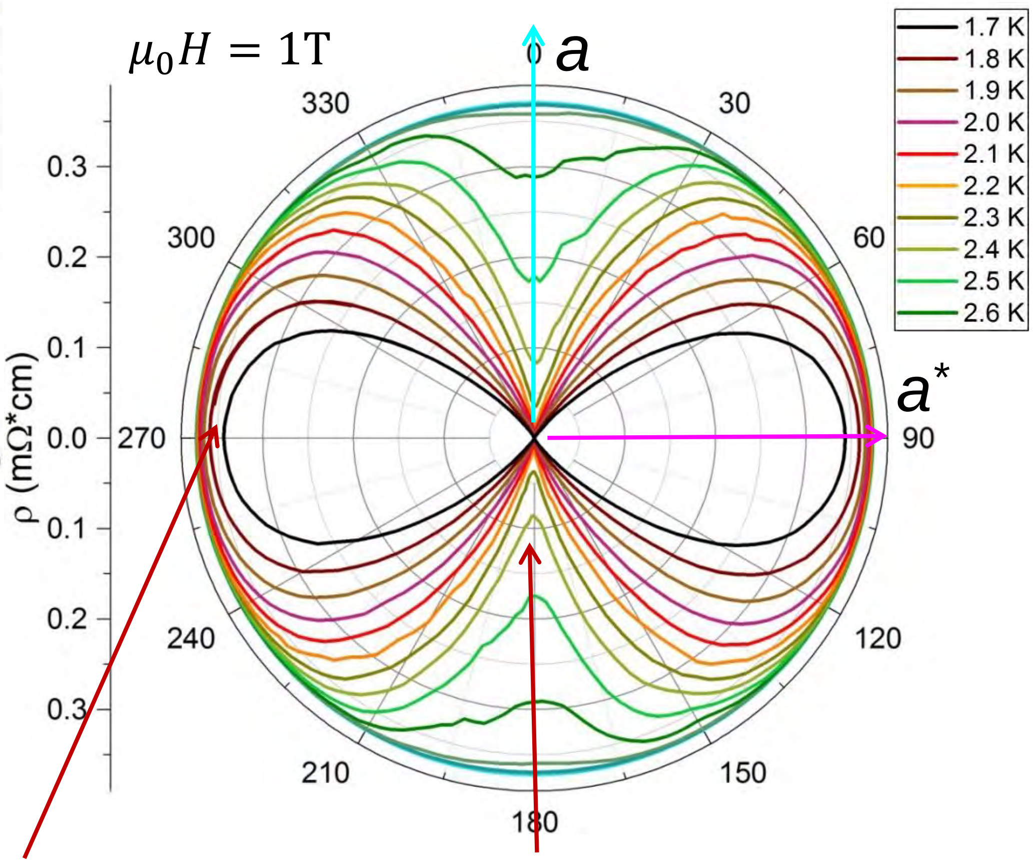


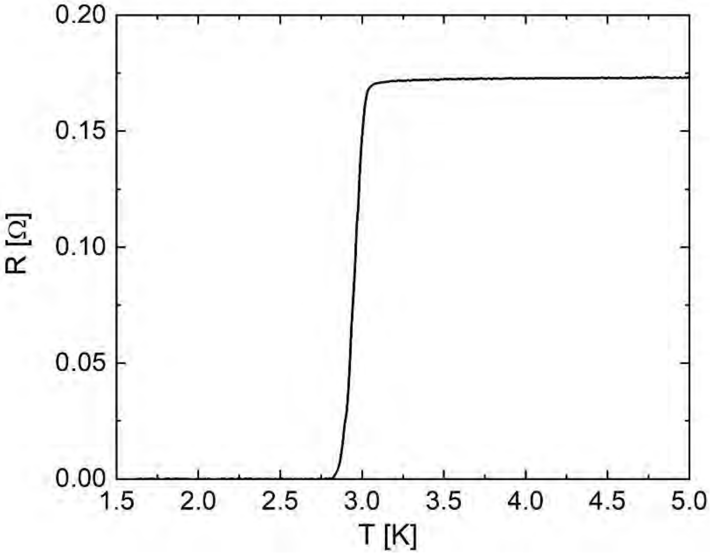
Transport measurements on $Sr_xBi_2Se_3$









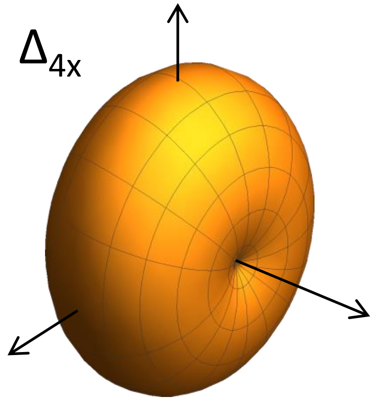


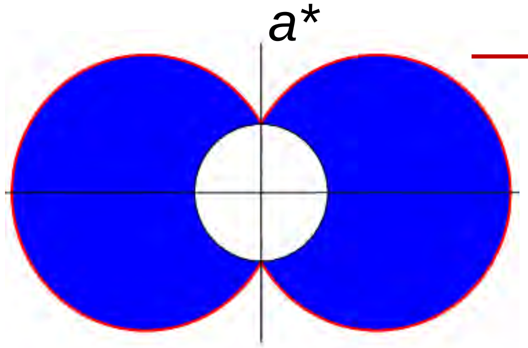
$\rho_{max}: H_{c2}^{min}$

$\rho_{min}: H_{c2}^{max}$

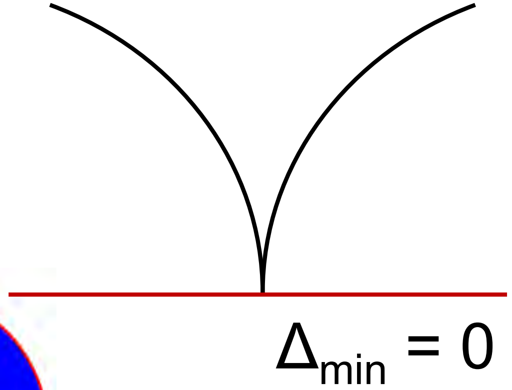
Evidence for Δ_{4x}

Differentiating between deep minima and point nodes in TDO

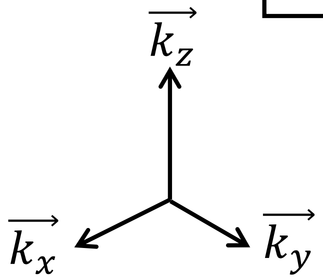




Point Nodes



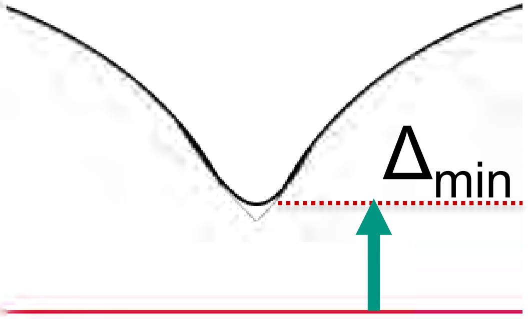
$\lambda(T) \sim T^2$



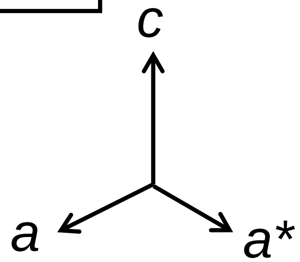
TDO measures the penetration depth λ

Low temperature dependence of λ changes depending on gap structure

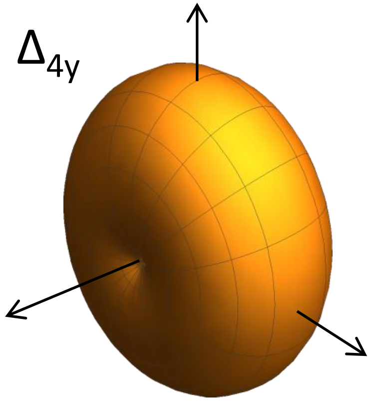
Full gap with deep Minima

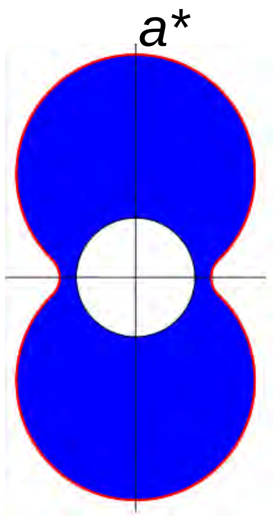


$\lambda(T) \sim \exp\left(-\frac{\Delta_{min}}{T}\right)$

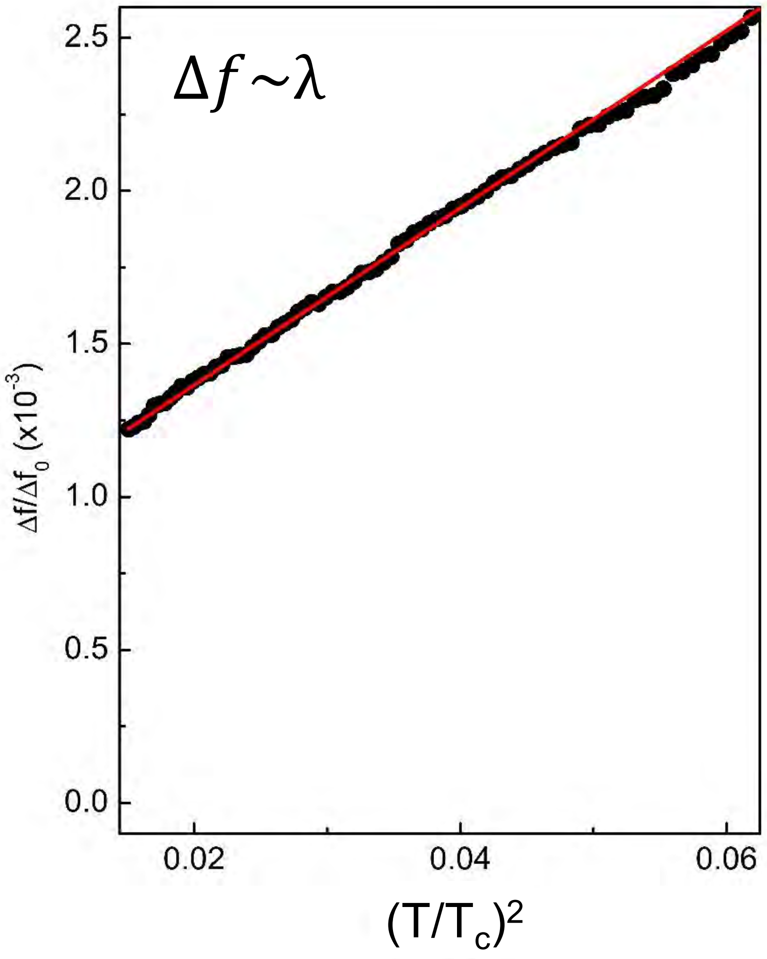


λ can show T^2 dependence if Δ_{min} is below T



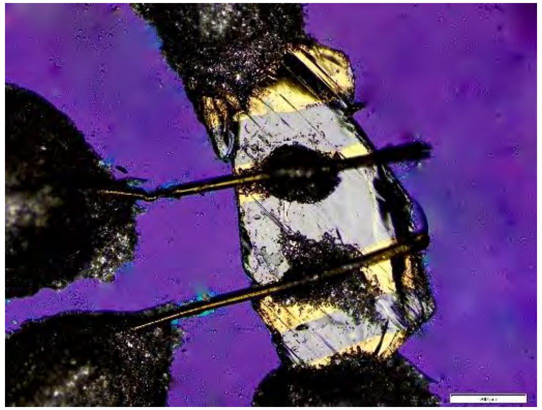


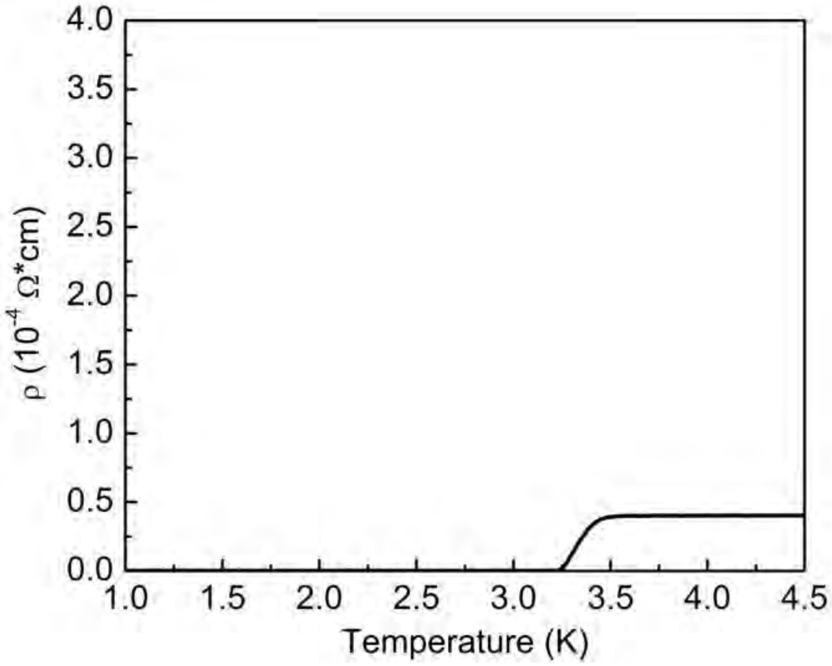
TDO measurements of $Nb_xBi_2Se_3$



- Change in resonator frequency is proportional to the change in penetration depth
- Clear T^2 behavior down to low temperatures for the pristine sample

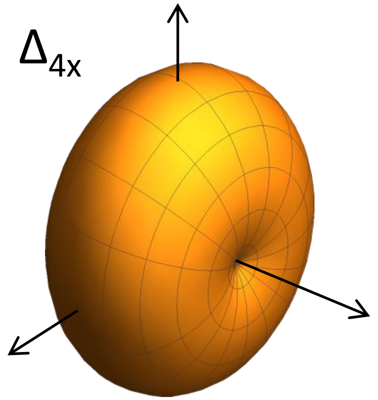
Indication of point nodes

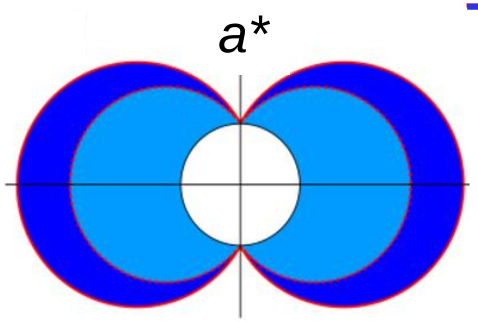




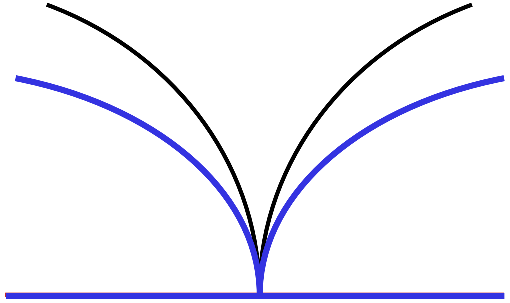
Smylie, **Willa** et al., Phys. Rev. B 94, 180510(R) (2016)

Differentiating between deep minima and point nodes in TDO



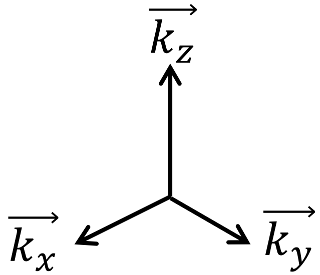


Point Nodes



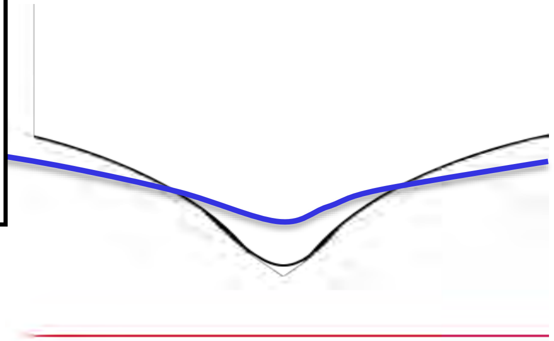
$\Delta_{min} = 0$

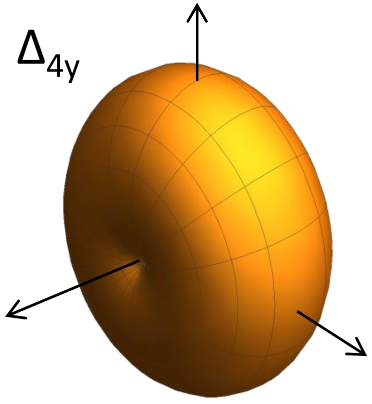
$\lambda(T) \sim T^2$

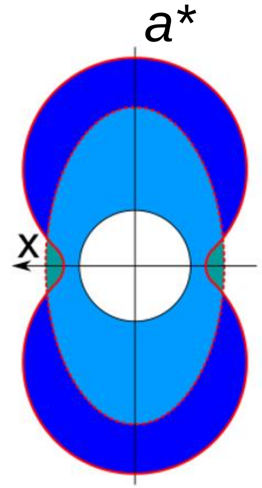


Proton irradiation induces scattering

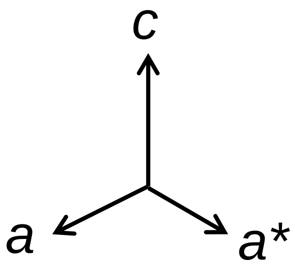
Full gap with deep Minima





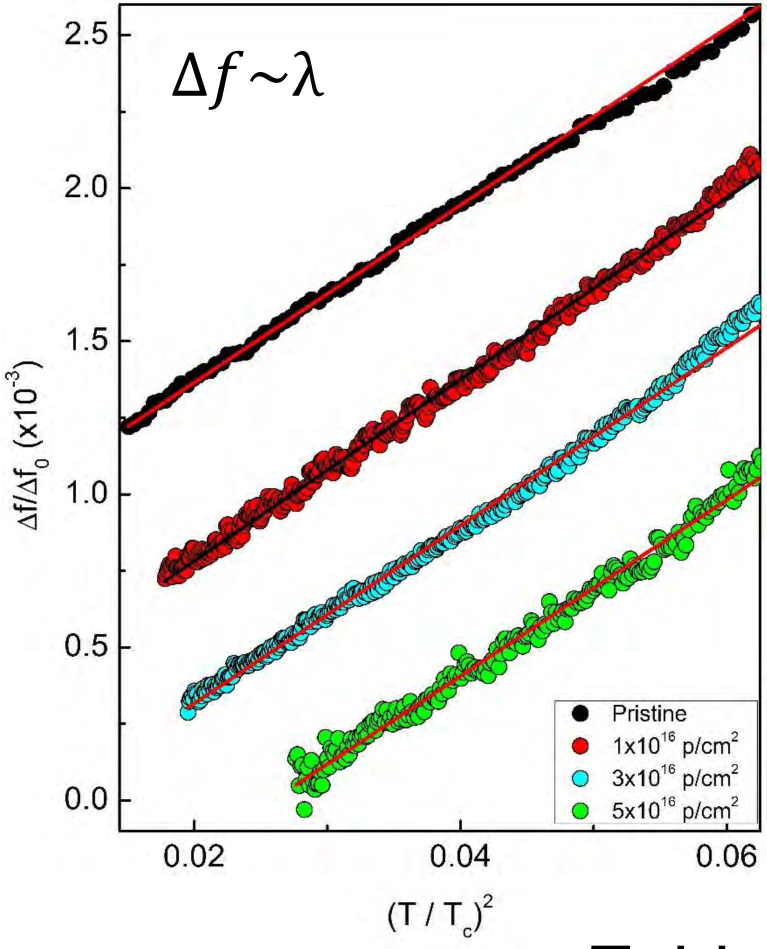


λ dependence will change



[1] F. Gross et al., Phys. B: Condens. Matter **64**, 175 (1986)

TDO measurements of $Nb_xBi_2Se_3$

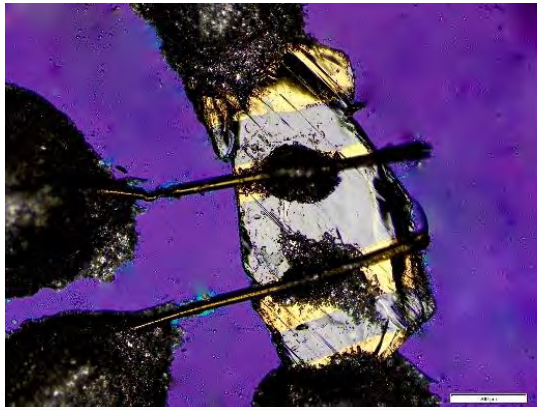


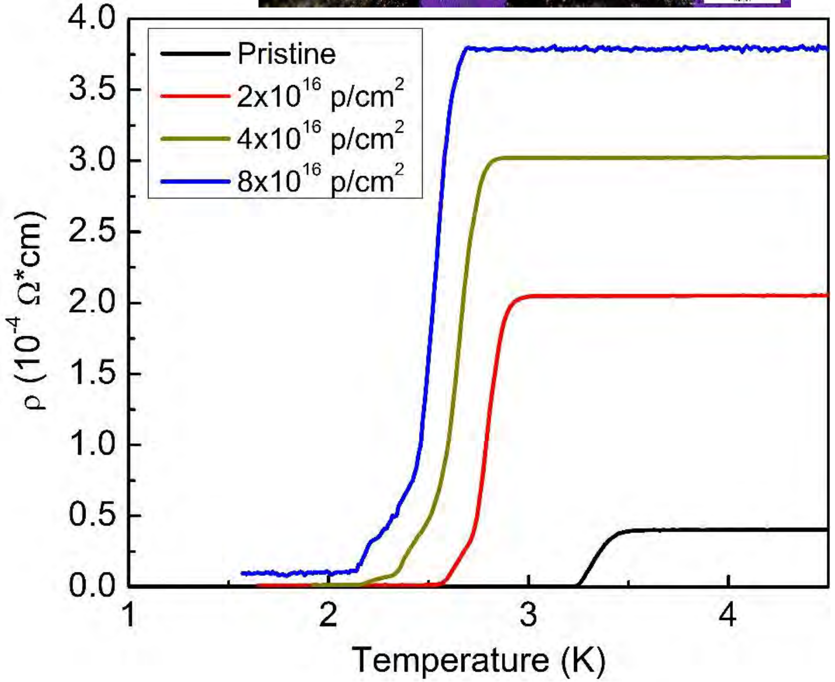
Clear T^2 behavior down to low temperatures for the pristine sample[1]

5 MeV proton irradiation done at the tandem van-de-Graaff accelerator at Western Michigan University

Reduction of T_c and increase in residual resistivity upon increasing the dose of proton irradiation

T^2 behavior survives strong proton irradiation up to 5×10^{16}p/cm^2 (lowering T_c by about 25%)

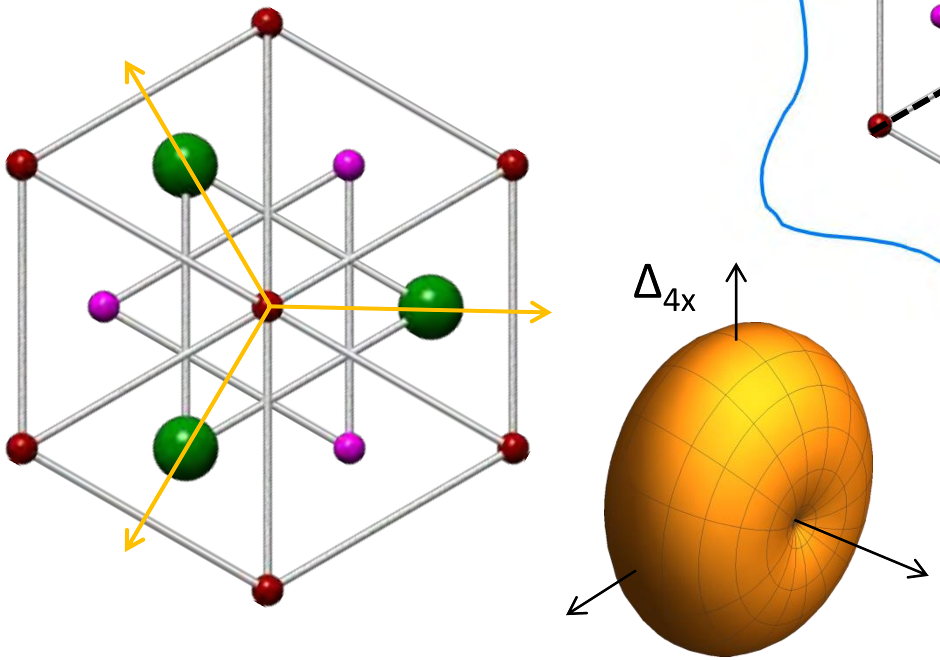


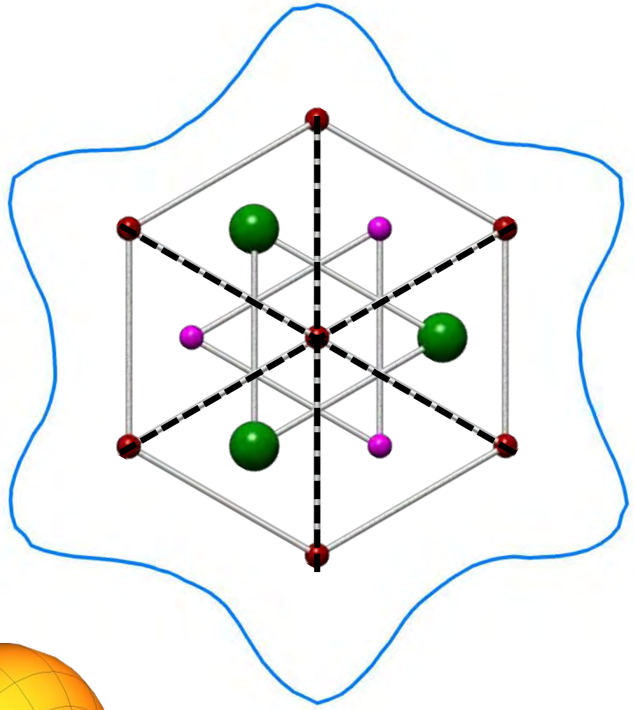


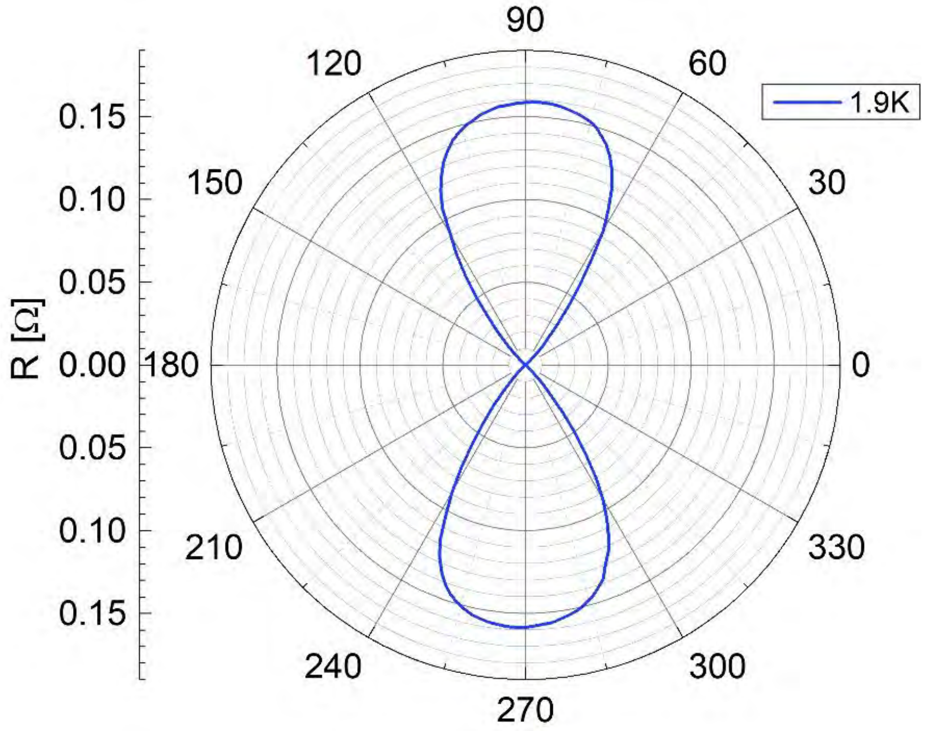
Evidence of point nodes (Δ_{4x})

Orientation of the nematic axis

However, there are three equivalent crystalographic directions!



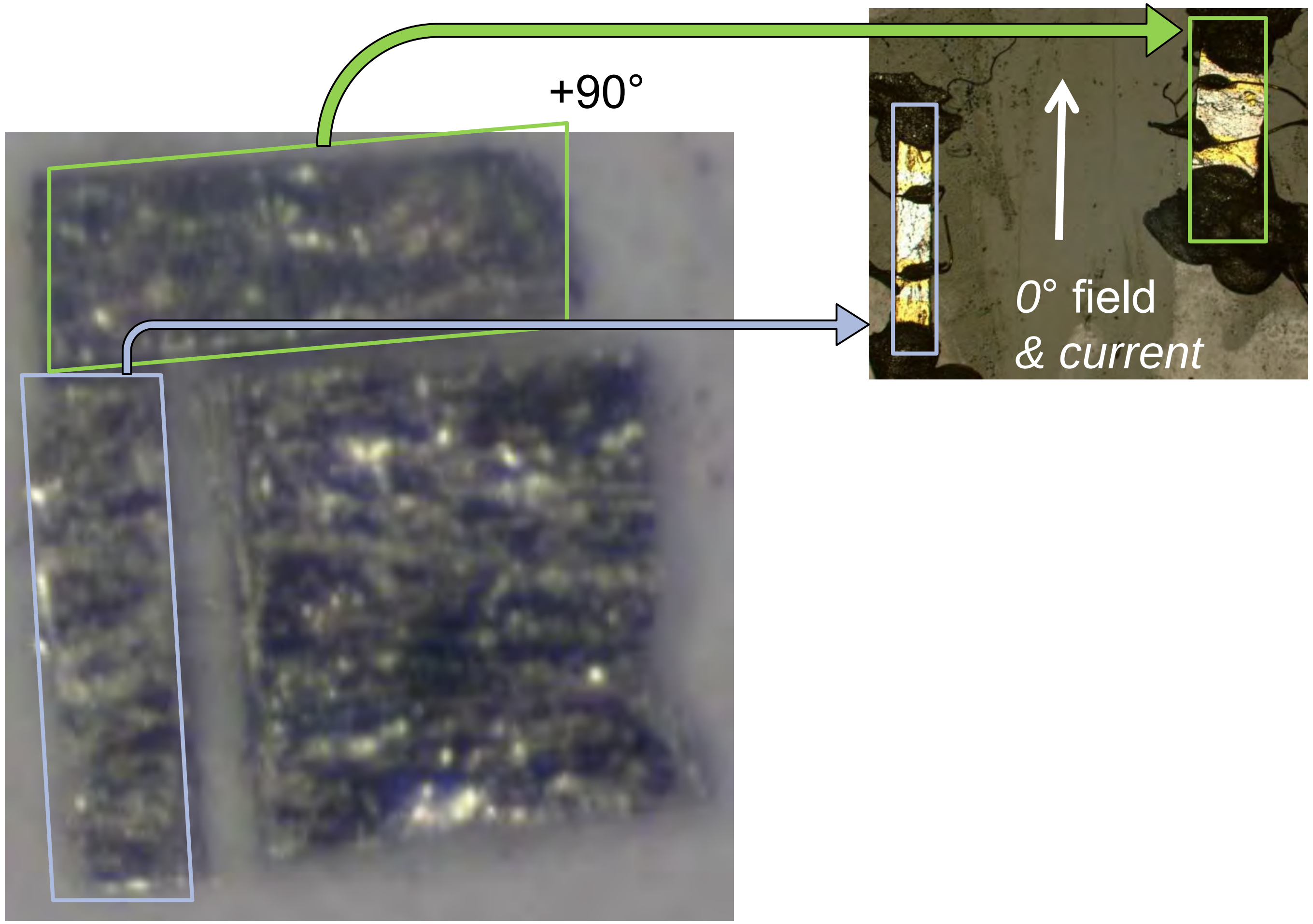




Why are there no signs of domains?

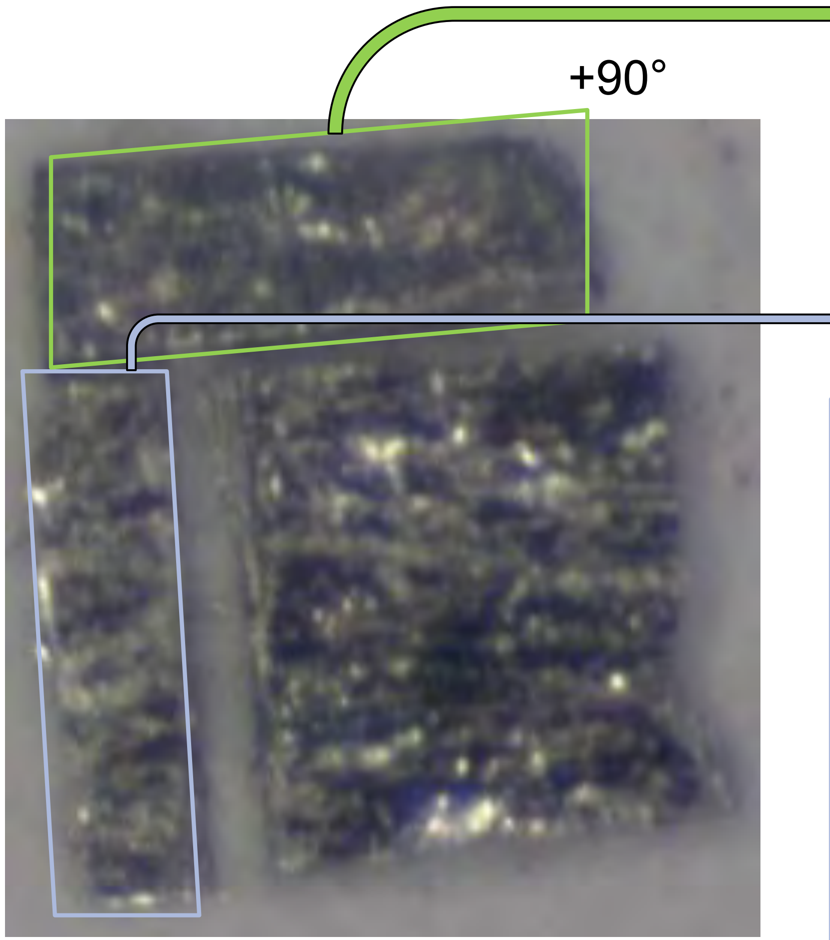
Why do multiple warming and cooling cycles always reproduce the same axis?

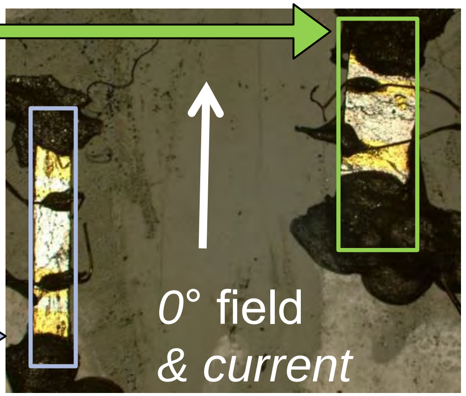
Orientation of the nematic axis



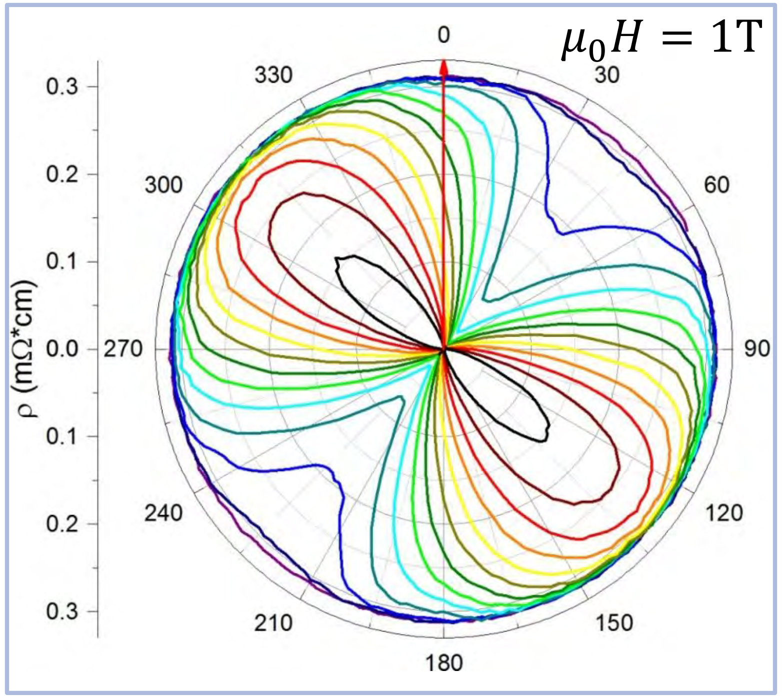
Smylie, **Willa** et al., Sci. Rep. **8**, 7666 (2018)

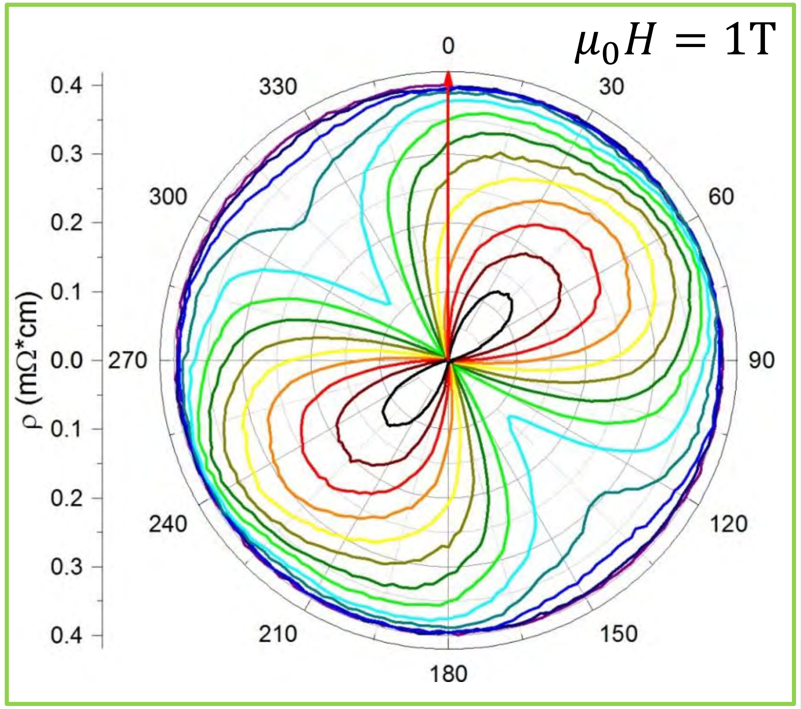
Orientation of the nematic axis





Nematic axis independent of: - crystal shape
- current direction

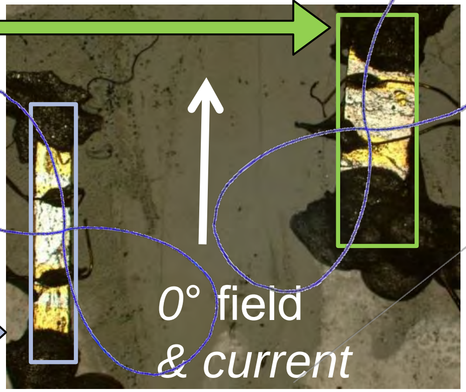




Smylie, **Willa** et al., Sci. Rep. **8**, 7666 (2018)

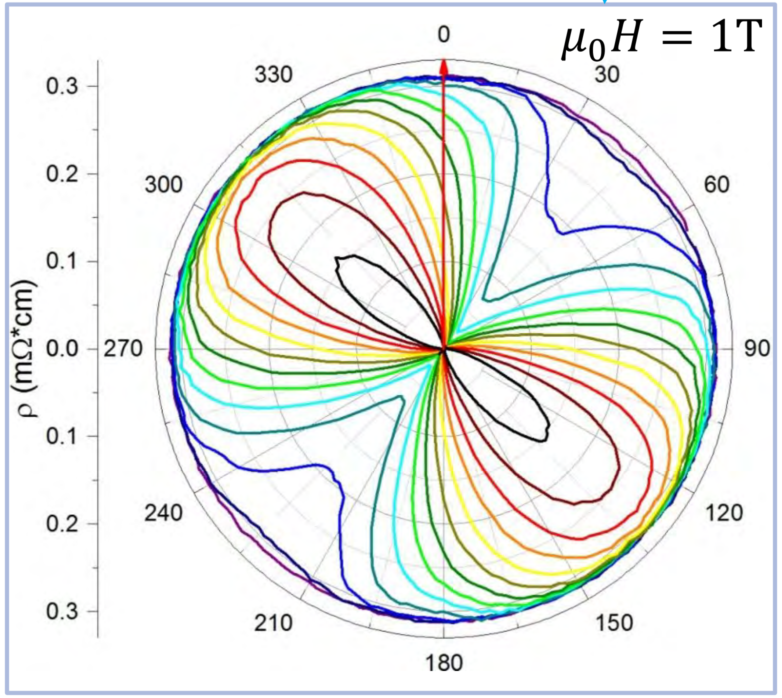
Orientation of the nematic axis

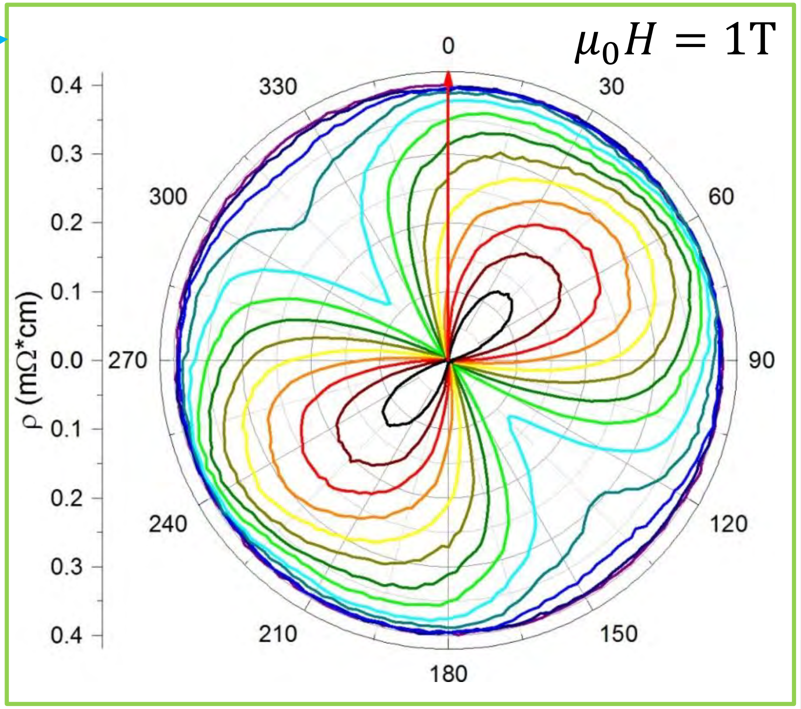
+90°



Nematic axis independent of: - crystal shape
- current direction

≈90°





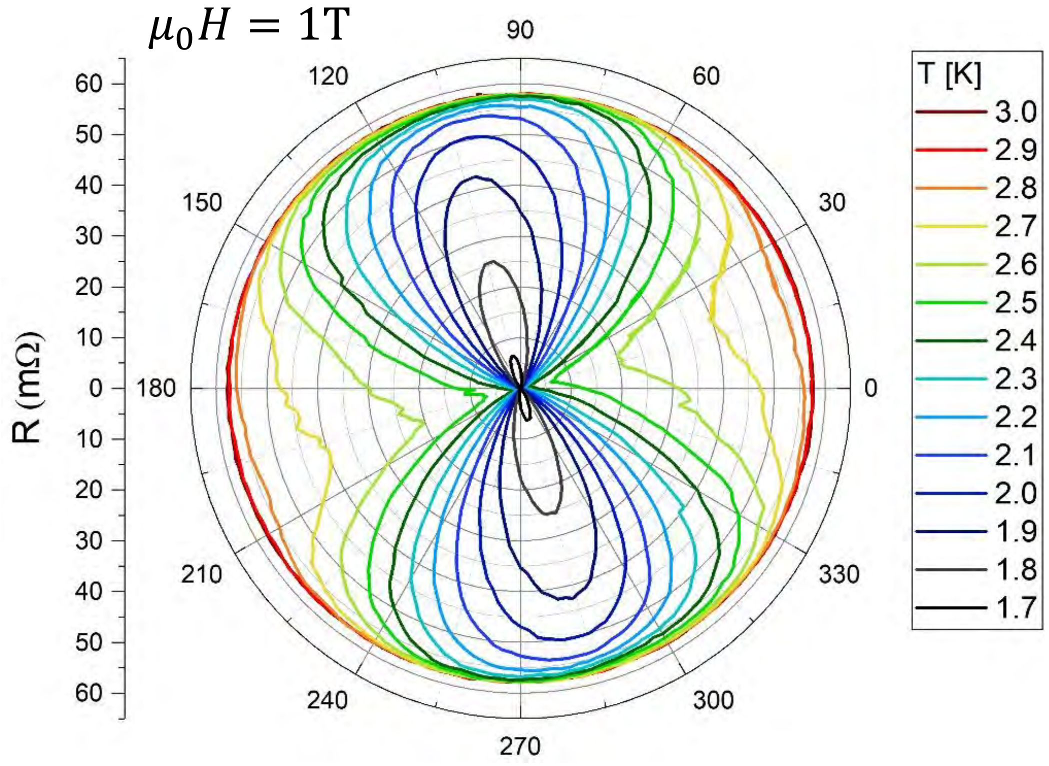
→ Nematic axis prealigned in the original crystal

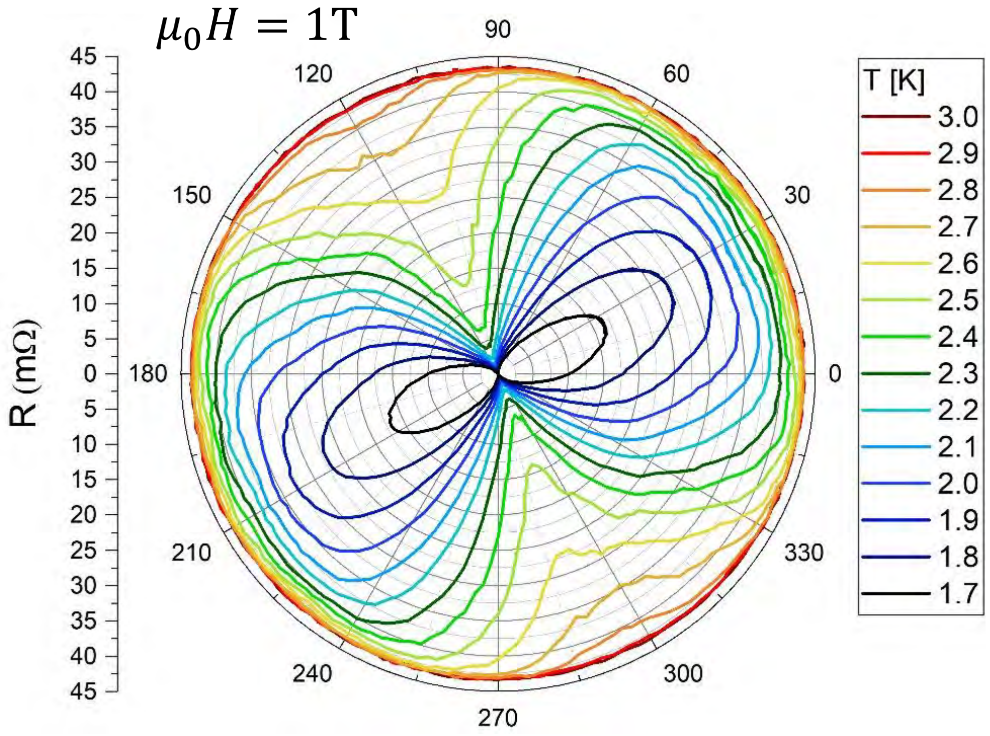
Can we change the direction of the nematic axis?

Smylie, **Willa** et al., Sci. Rep. **8**, 7666 (2018)

Can strain switch the nematic axis?

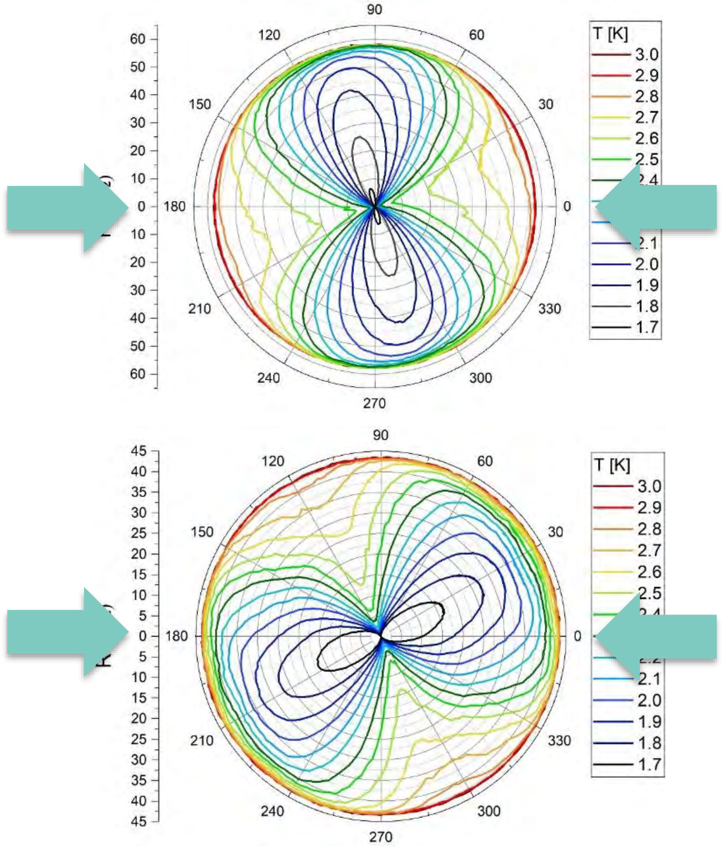
Same procedure – two crystals cut from a larger crystal at 90°

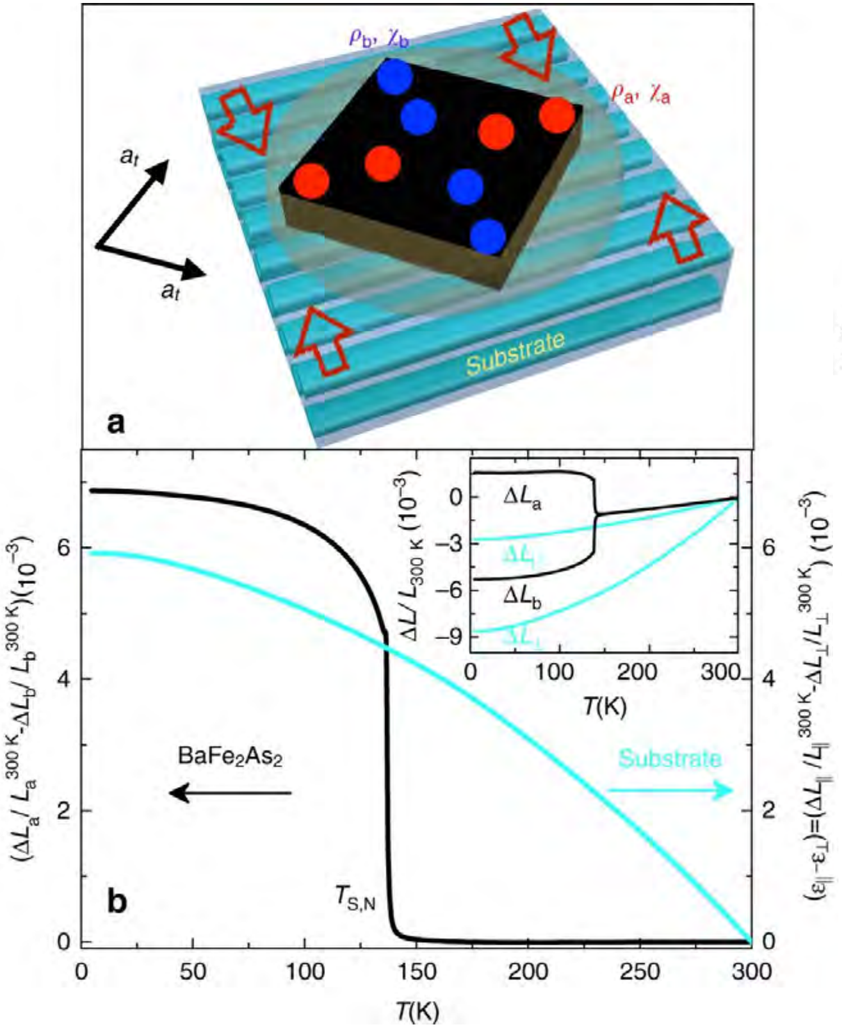


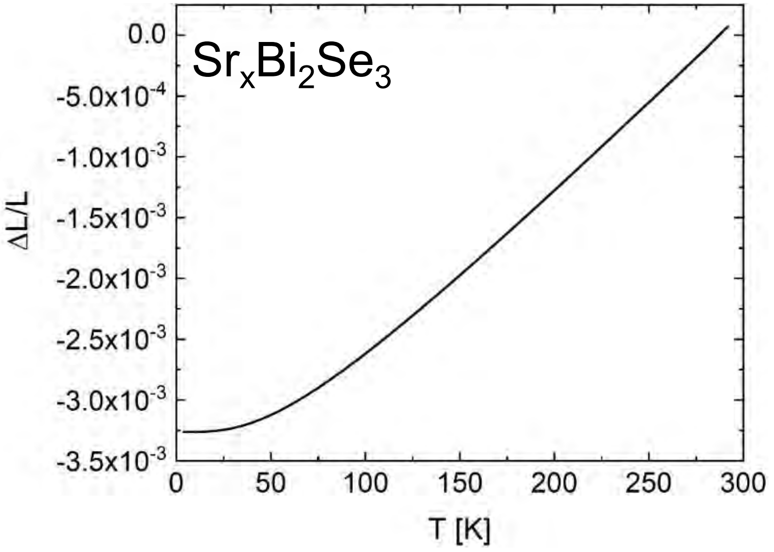


Can strain switch the nematic axis?

Same procedure – two crystals cut from a larger crystal at 90°



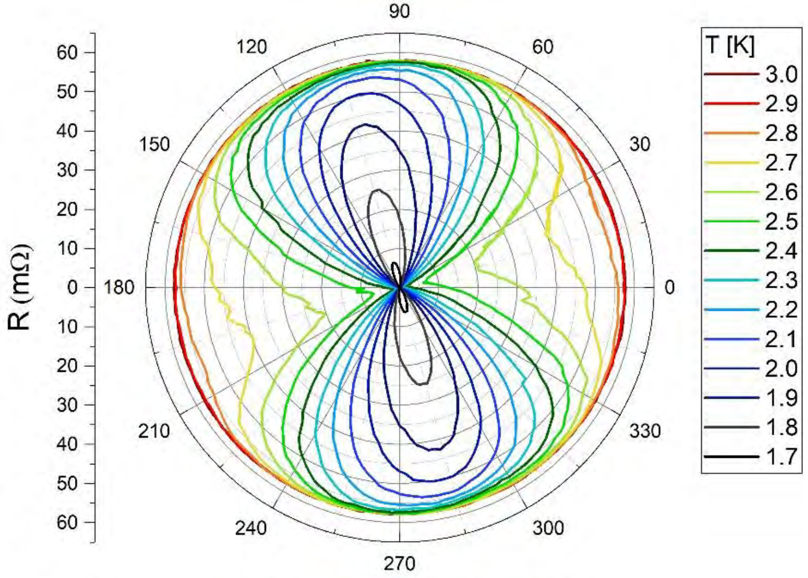


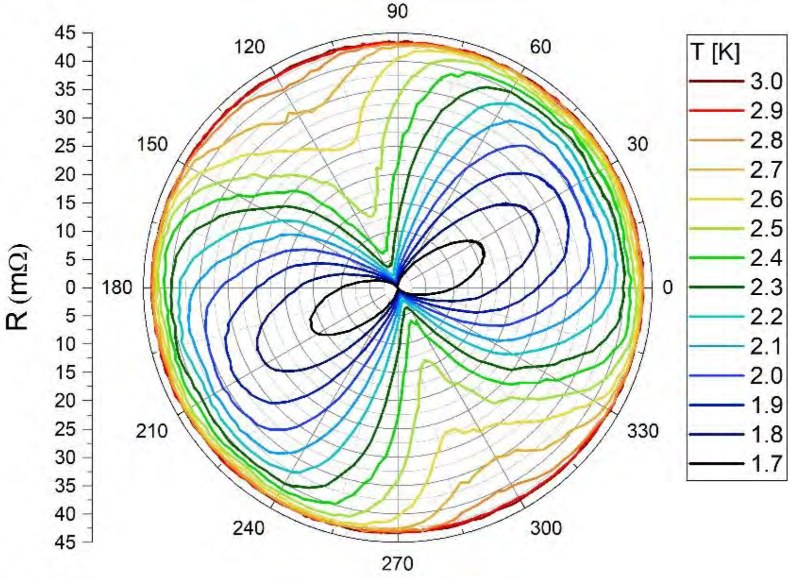


- almost uniaxial strain
- maximal strain $\varepsilon \approx 0.6\%$

He et al., Nat. Comm. 8, 504 (2017)

Can strain switch the nematic axis?

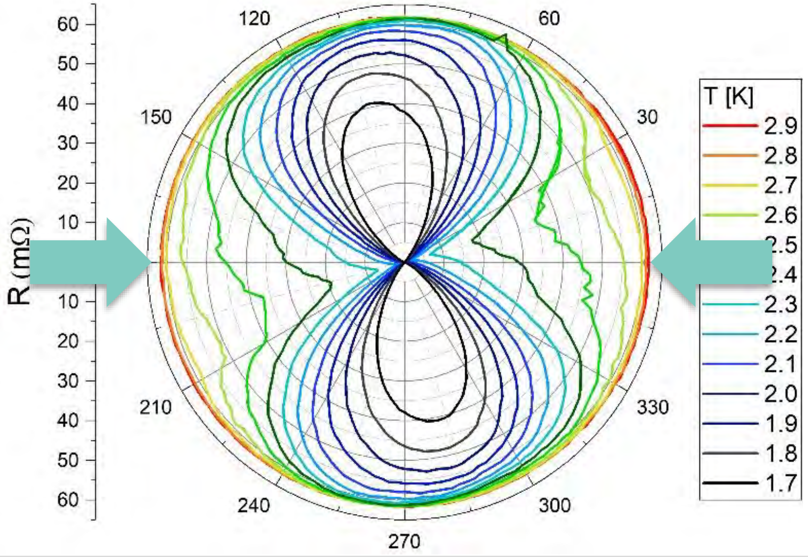


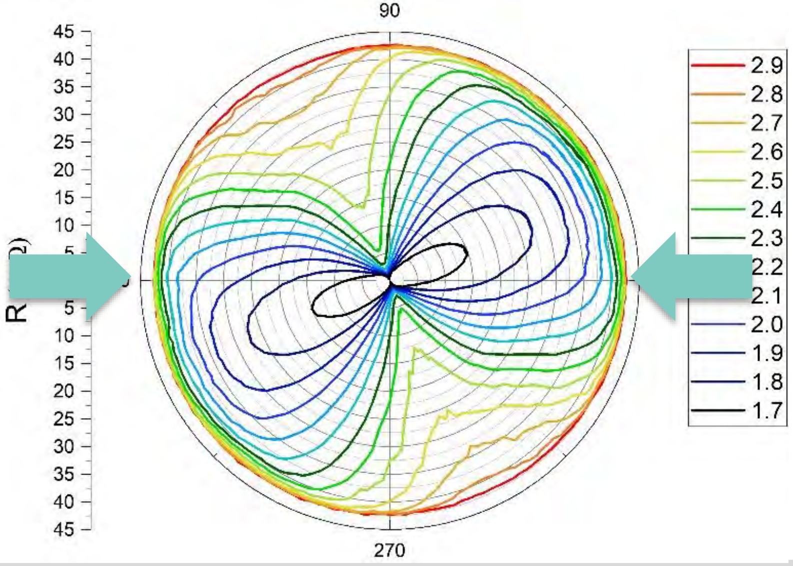


unstrained

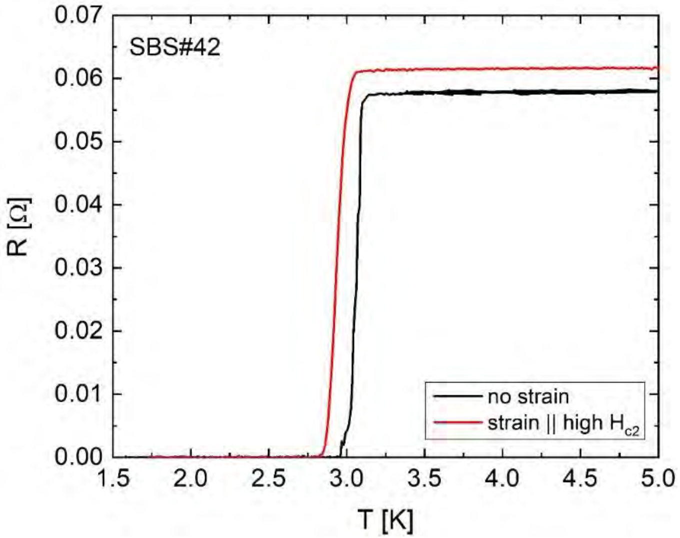
no change in the nematic axis

strained



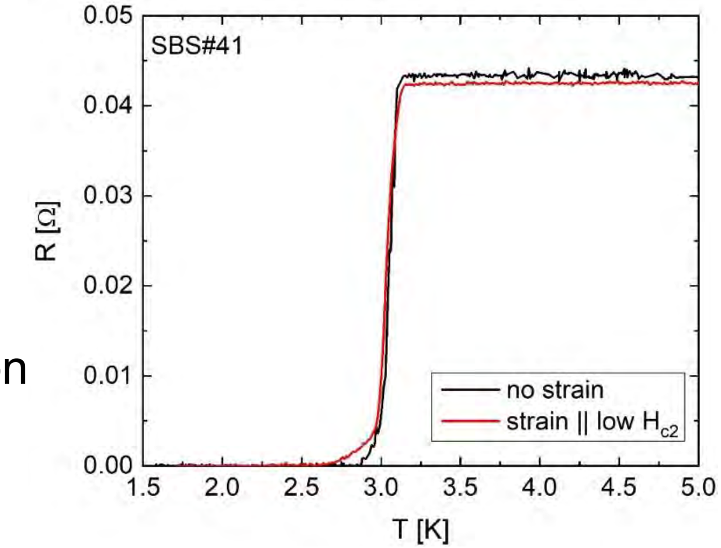


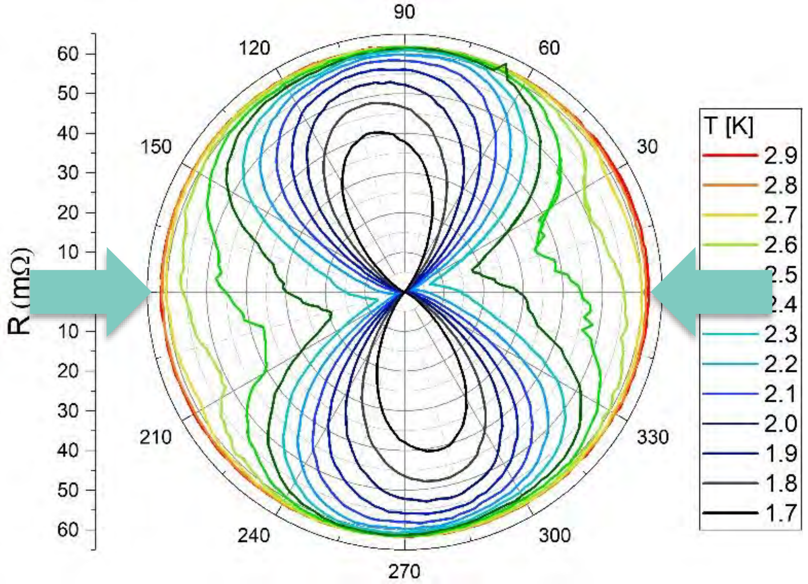
Can strain switch the nematic axis?



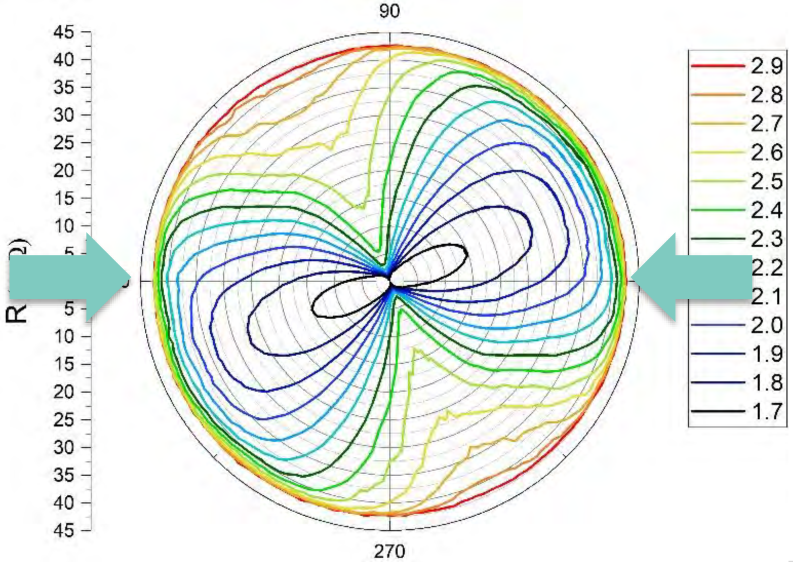
Compressive strain along high H_{c2} direction leads to T_c reduction

Compressive strain along low H_{c2} direction has no effect



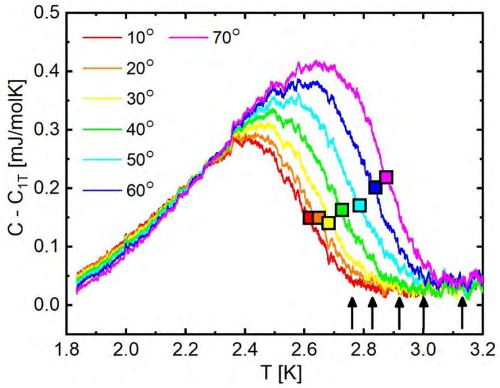


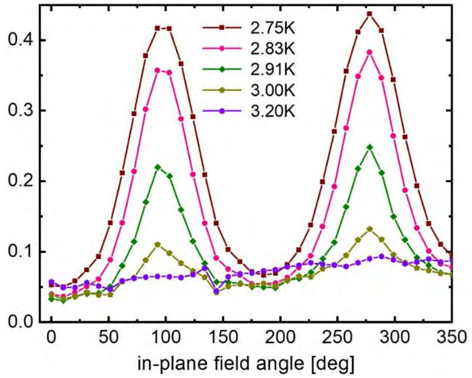
no change in the nematic axis

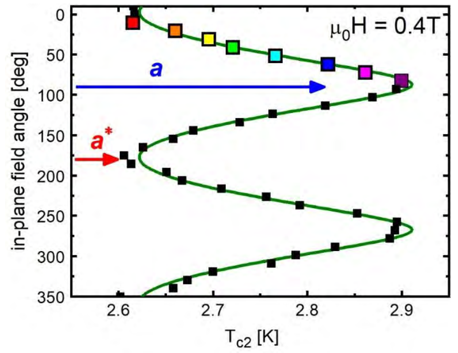


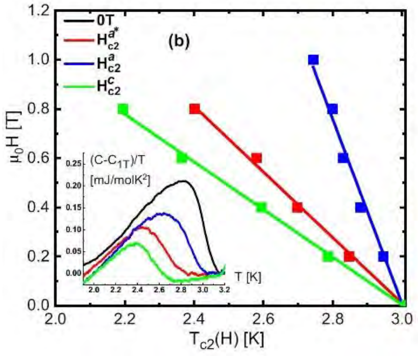
Summary

Rotational symmetry breaking in the superconducting state

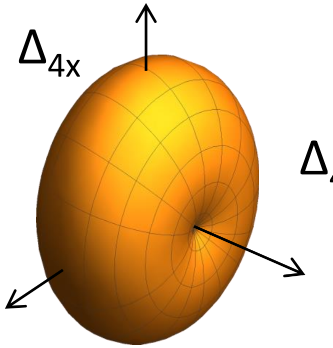




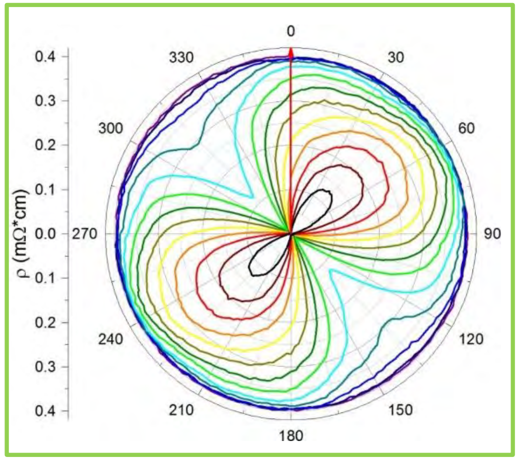


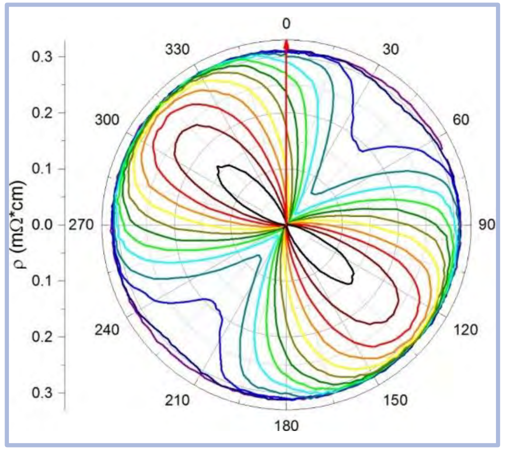


No anisotropy of the normal state



Δ_{4x} state observed





Nematic axis predetermined in each crystal

Strain was not able to switch the nematic axis