

RUB

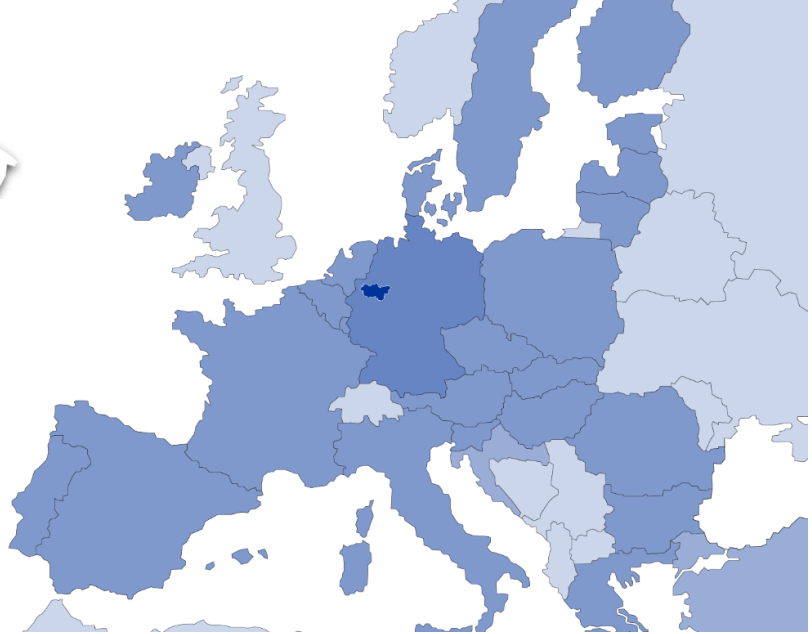
RUHR-UNIVERSITÄT BOCHUM

“Strain in topological quantum materials”

Physik und Astronomie
from matter to materials

Anna Böhmer, Lehrstuhl für Experimentalphysik IV | Festkörperphysik





RUB

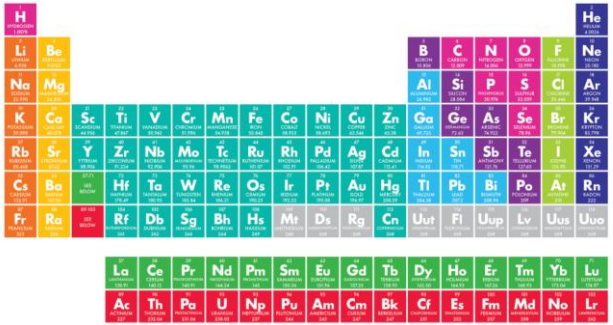
RUHR-UNIVERSITÄT BOCHUM

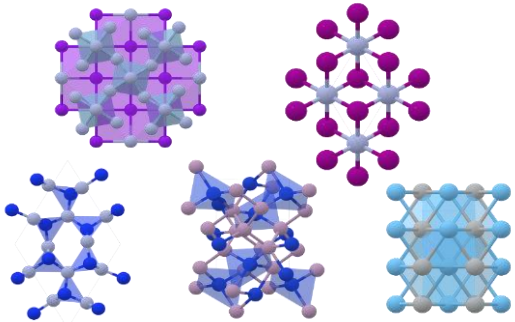
Physik und Astronomie
from matter to materials

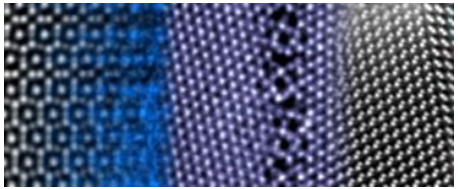
“Strain in topological quantum materials”
Pursuits from crystal growth

Anna Böhmer, Lehrstuhl für Experimentalphysik IV | Festkörperphysik

Design, create, tune and understand quantum materials

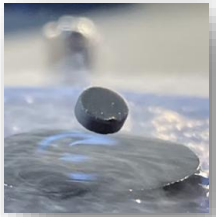


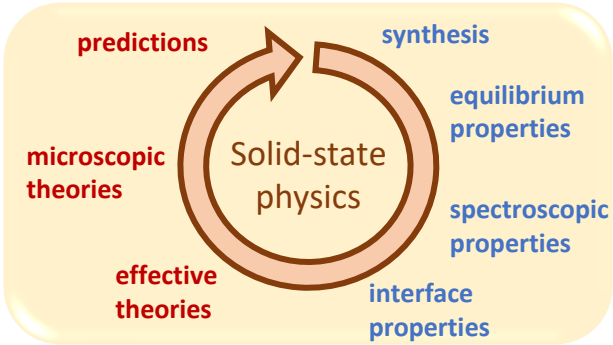




Quantum phenomena

- correlations between electrons
- exotic magnetism
- superconductivity
- some structural transitions
- topology

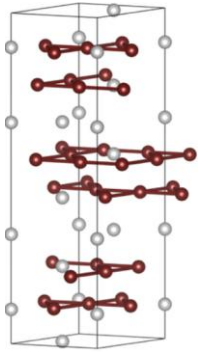


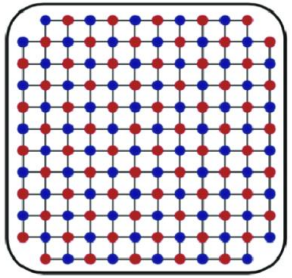


Why single crystals?

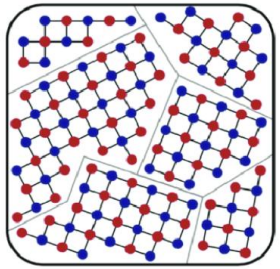
- **Higher phase purity**
- **Anisotropic properties**
- **No grain boundaries**
- **Clearer physical features**



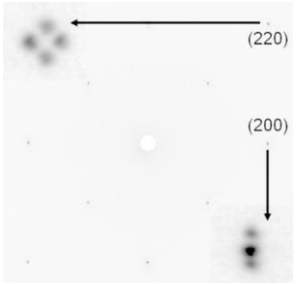


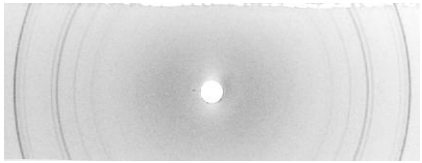


Crystalline

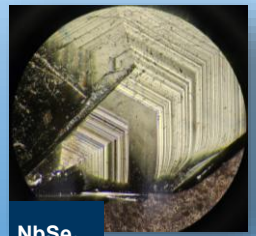


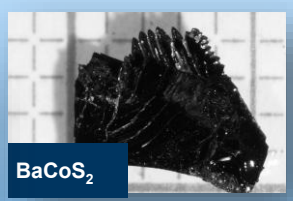
Polycrystalline





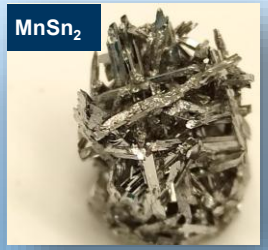
Beauty



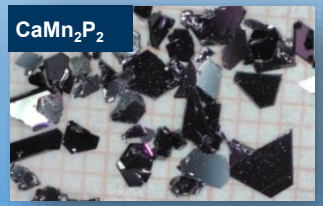


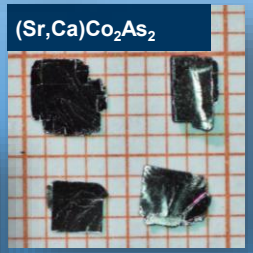


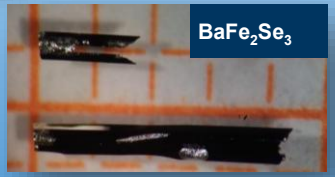


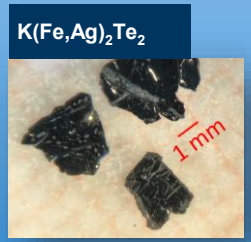


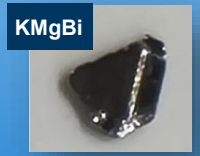










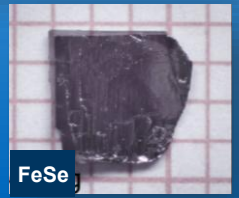




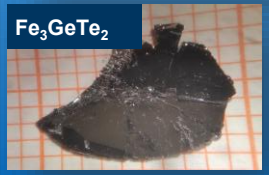














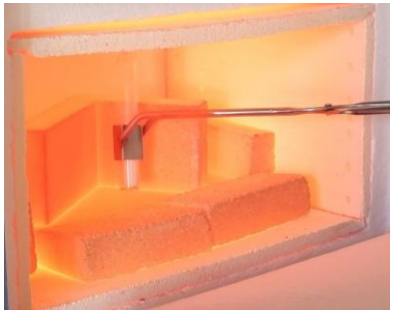
Haneen Abushamalla, Ashiwini Balodhi, Max Brückner, Fatih Cetin, Chelsea Ehigiator, Maik Golombiewski, Jule Kirschke, Martin Kostka, Andreas Kreyssig, Matthias Kroll, Luqman Mustafa, Jutta Püttmann, N. S. Sangeetha, Maximilian van de Loo, participants of the Blockpraktikum 513, and others

RUB
UNIVERSITÄT BOCHUM

There are two kinds of experimental groups….

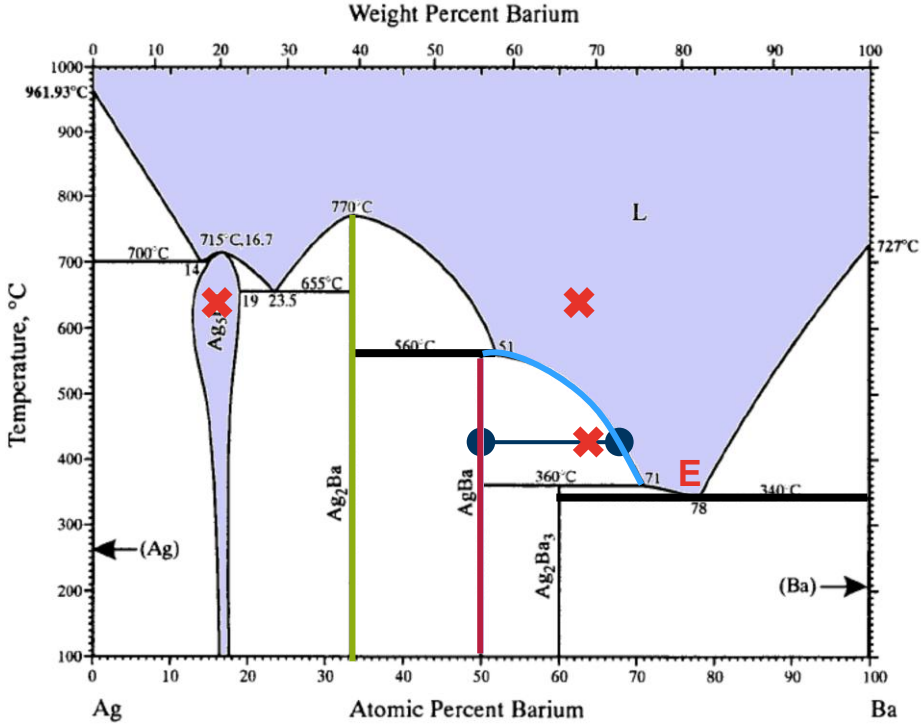


Receive *N* samples by mail



Make *x* samples on demand

Phase diagrams: maps to guide a growth



Purple areas: single phase regions (liquid or solid)

White areas: two-phase regions

Vertical lines: compounds (see as narrow purple areas)

Horizonal lines: something is changing on crossing it

Liquidus lines separate liquid from solid+liquid regions

Eutectic points: minimum melting temperatures

Some compounds are **congruently melting,** other compounds melt **incongruently**

Our crystal growth lab

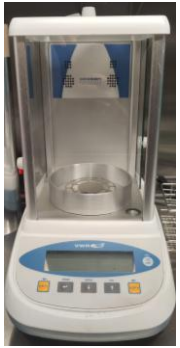


P. C. Canfield, I. R. and Fisher, *High-temperature solution growth of intermetallic single crystals and quasicrystals*, Journal of Crystal Growth, 225, 155 (2001)

Canfield, P. C., & Fisk, Z. (1992). Growth of single crystals from metallic fluxes. Philosophical Magazine B, 65(6), 1117–1123.

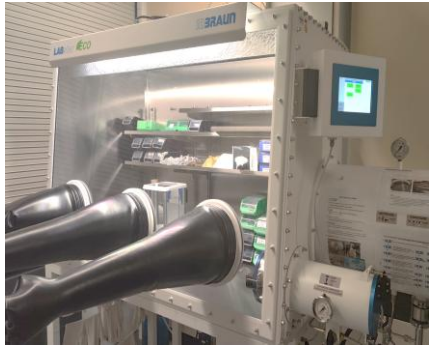
M. Tachibana, *Beginner's Guide to Flux Crystal Growth*. Springer. 2001

Solution growth in practice („Prof. Canfield‘s style“)

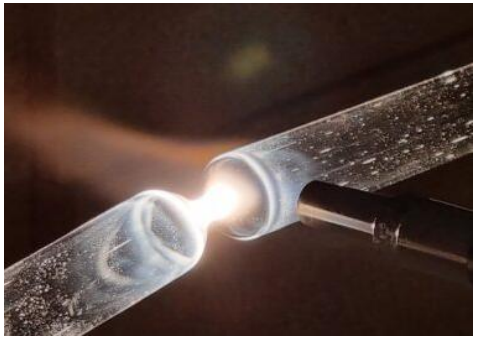


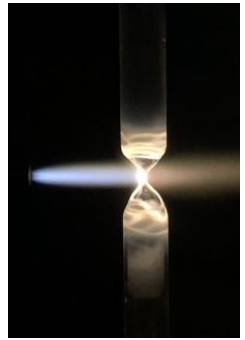


Weigh elements into Al_2O_3 crucibles



in the glovebox (if elements are air-sensitive or toxic)





Seal everything in protective atmosphere (Ar) in a heat resistance ampoule (quartz/ fused silica) using a really hot flame (H_2-O_2)

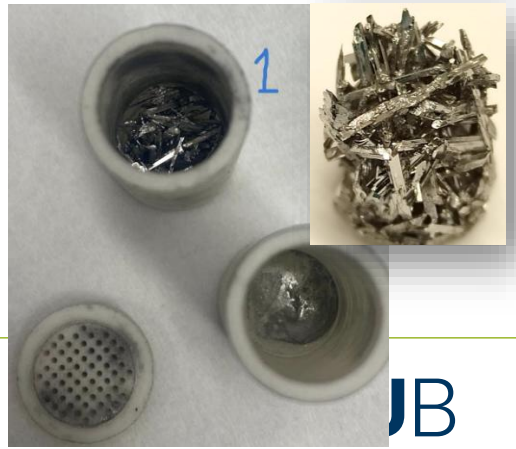




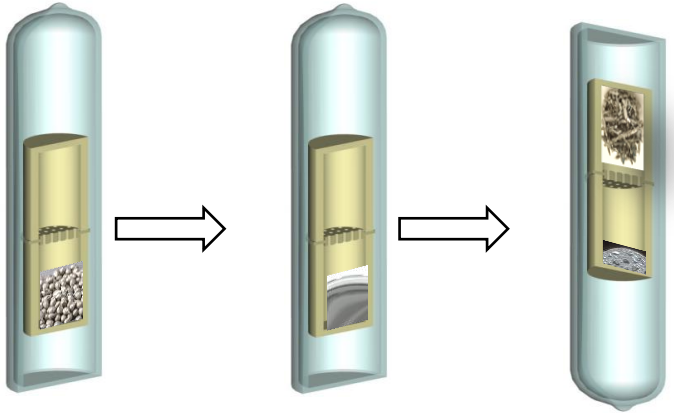
Place in a furnace, heat to create a melt, cool slowly for crystallization



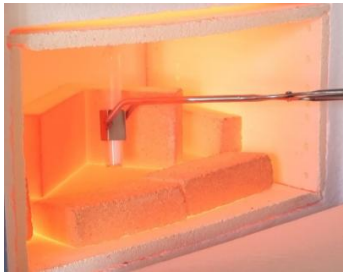
„Decant“ remaining melt using a centrifuge



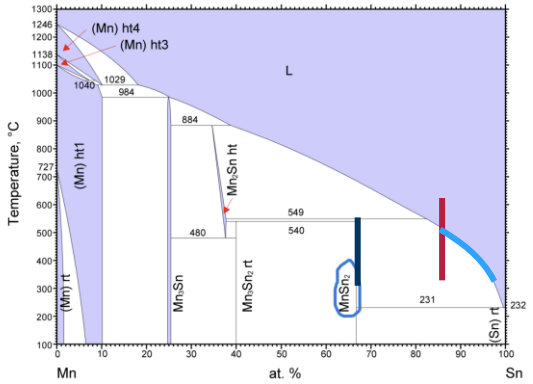
Solution growth – in short

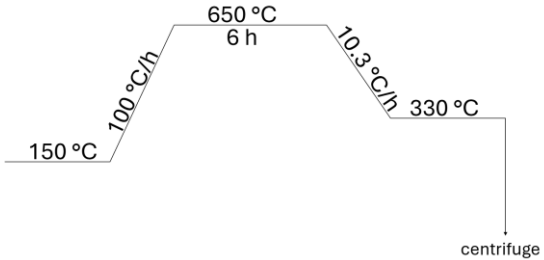




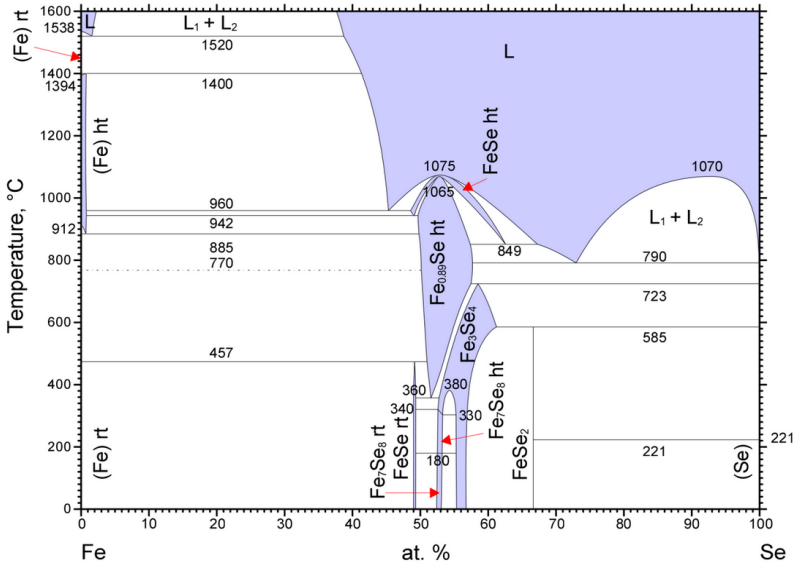


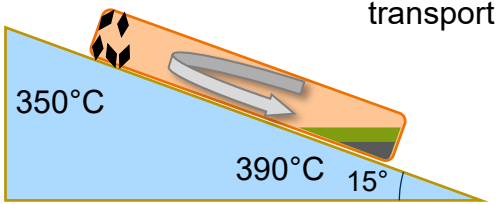




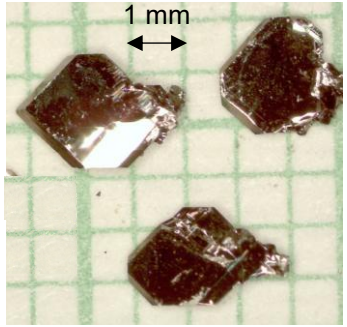


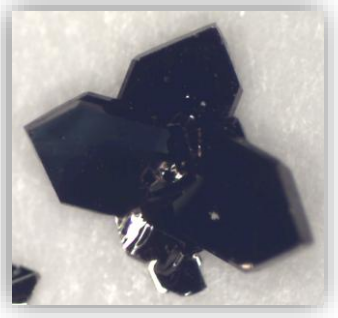
Vapor transport growth





Elements +
transport agent





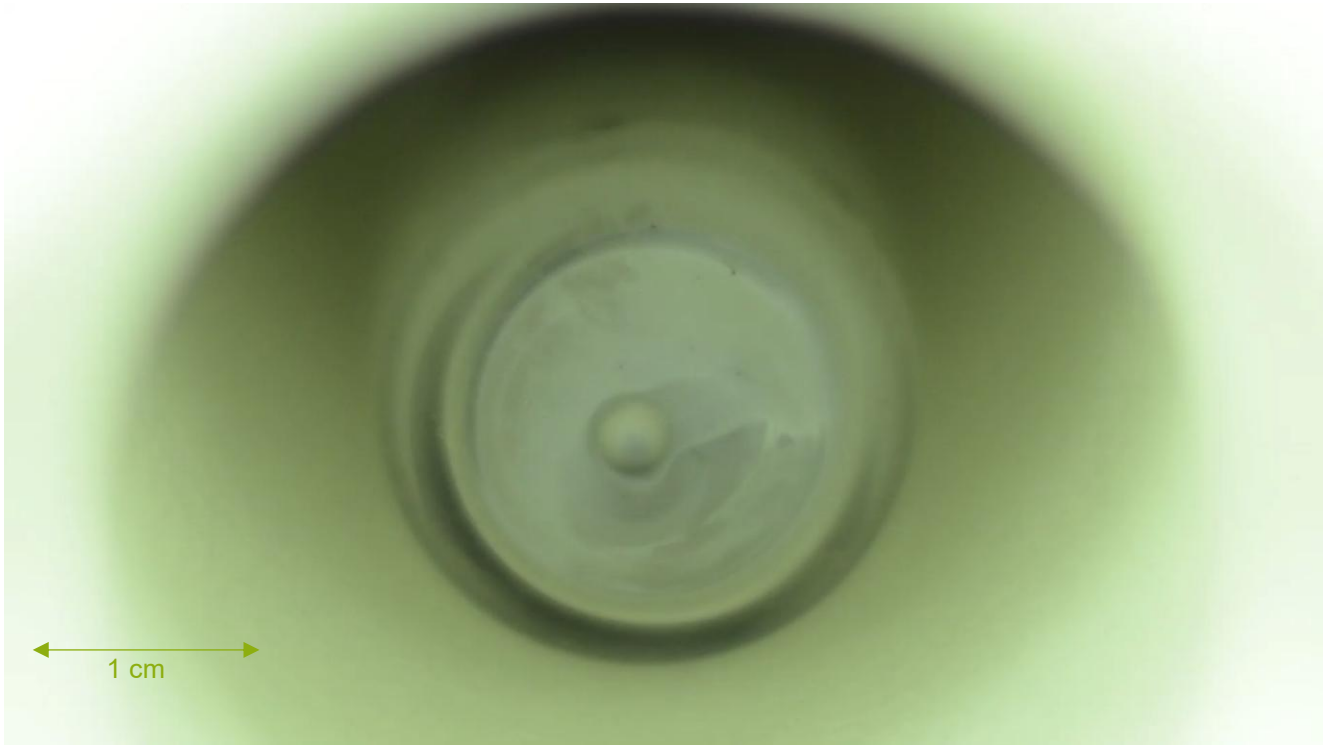
Böhmer et al., PRB **87**, 180505 (2013); Phys. Rev. B **94**, 024526 (2016)
See also: Chareev et al., Cryst Eng Comm, **15**, 1989 (2013)

RUHR UNIVERSITÄT BOCHUM RUB

Growth video of FeSe

Fe + Se + $AlCl_3$ + KCl
in a quartz ampoule

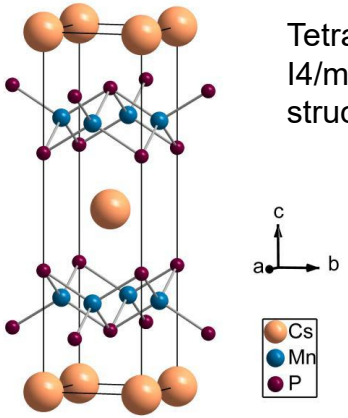




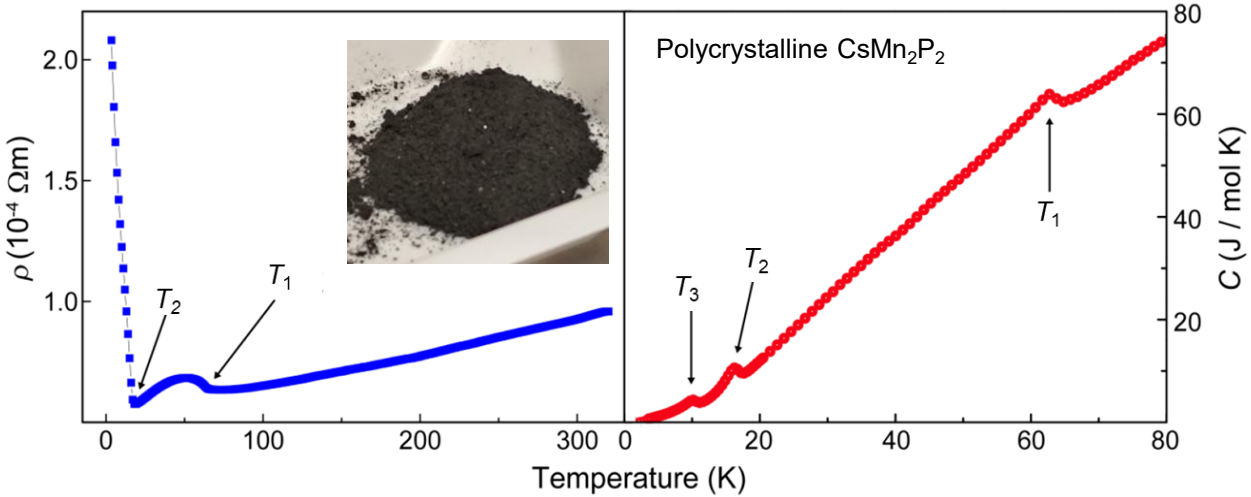
Outline

- Pursuit of the new single crystalline compound $CsMn_2P_2$
- Pursuit of the CDW phase transition in $NbSe_2$
- Pursuit of superconductivity in topological Bi_2Se_3

Desired compound: $CsMn_2P_2$



Tetragonal
I4/mmm
structure



The only metallic Mn-based
122 pnictide

Antiferromagnetic ordering at room temperature + three magnetic transitions

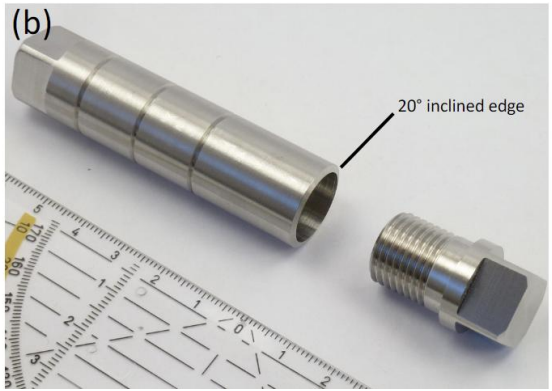
Hummel, F. Diss. LMU, 2015

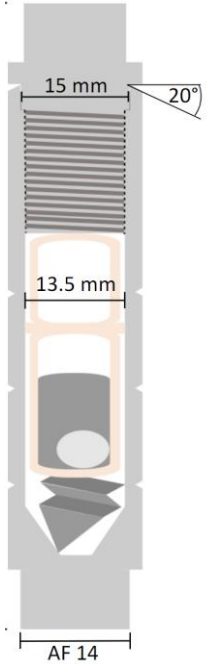
How to safely contain alkali elements such as Cs

Alkali-elements react violently with quartz.

Extra sealing in tantalum tubes (or similar) necessary



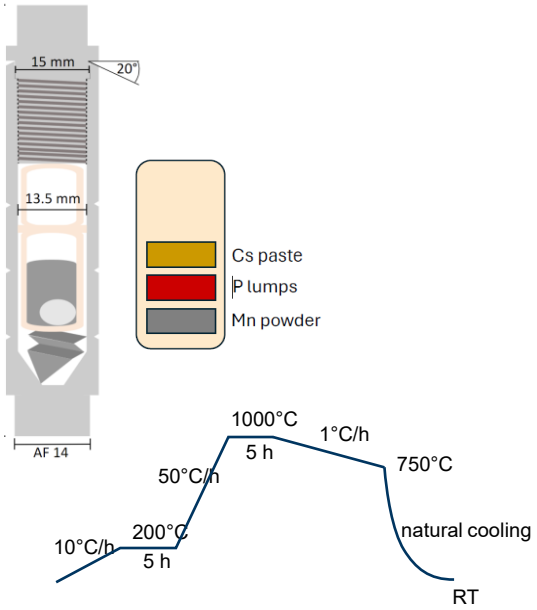




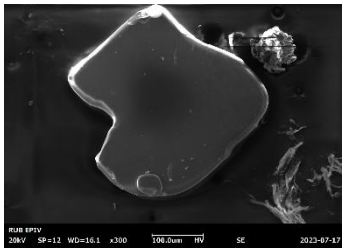
Püttmann, J., Sangeetha, N. S., Thomas, T. R., Meermann, J., Kreyssig, A., & Böhmer, A. E. (2023). Robust Conveniently Sealable Container for High-Temperature Single-Crystal Growth Out of Reactive Melts with High Vapor Pressure. Crystals, 13(9), 1332.

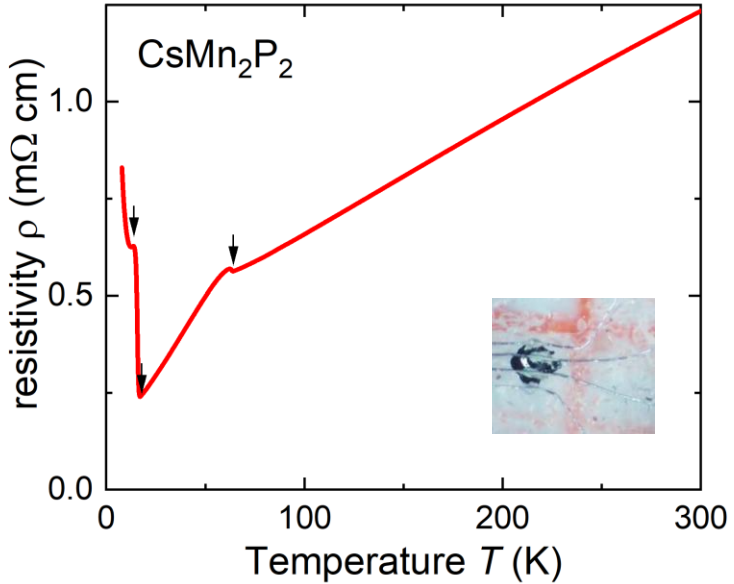
Paul C. Canfield, Tai Kong, Udhara S. Kaluarachchi & Na Hyun Jo (2016), Philosophical Magazine, 96:1, 84-92
T. J. Slade, P. C. Canfield, *Z. Anorg. Allg. Chem.* **2022**, *648*, e202200145
A. Jesche & P.C. Canfield (2014), Philosophical Magazine, **94**:21, 2372-2402

$CsMn_2P_2$ has intriguing transport behavior





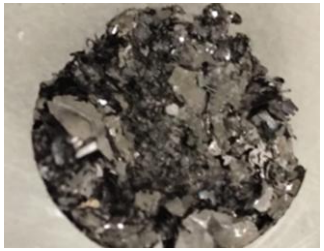




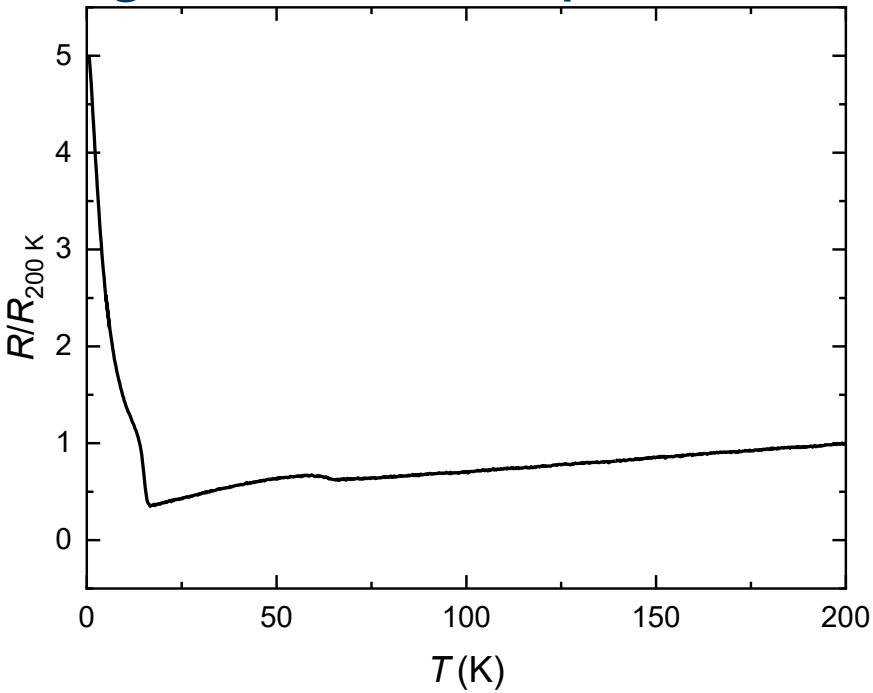
N. S. Sangeetha, RUB

See: Hummel, Franziska. *Magnetism and superconductivity in layered manganese and iron pnictides*. Diss. LMU, 2015.

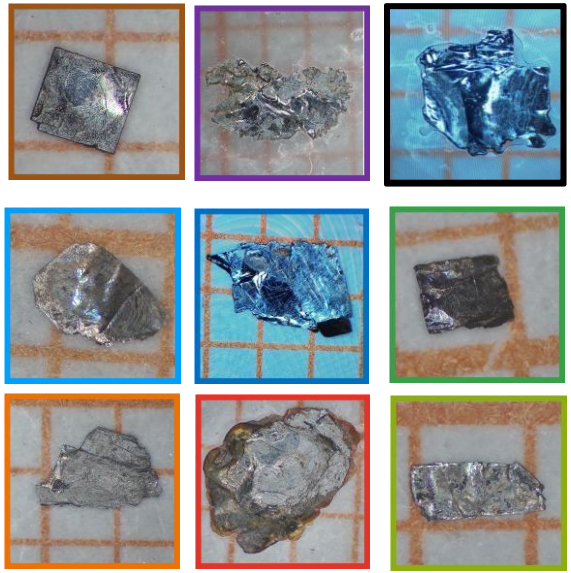
Crystals from Cs-P-rich self-flux growth technique

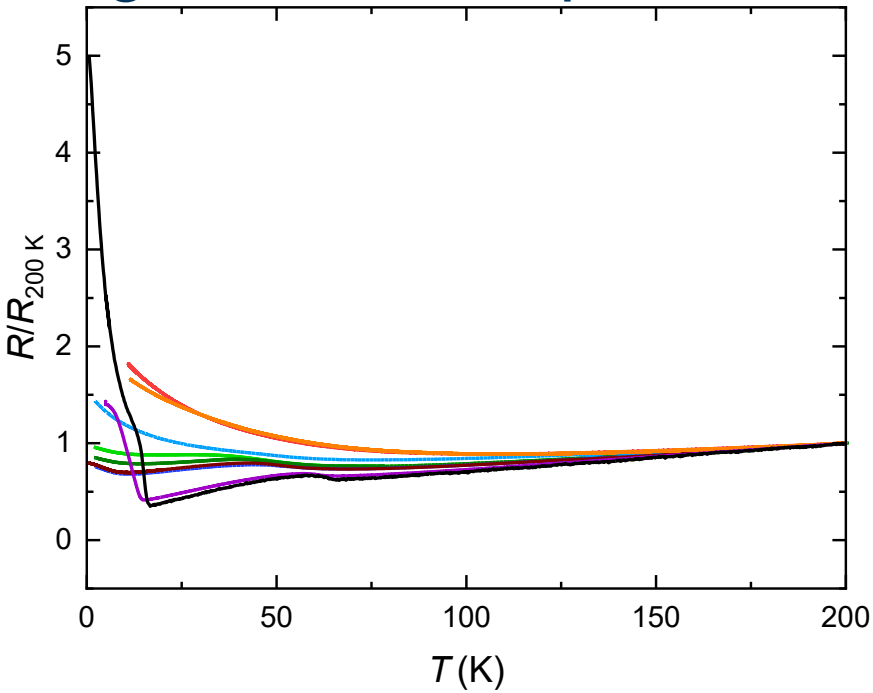






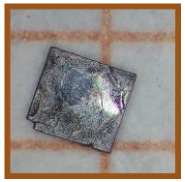
Crystals from Cs-P-rich self-flux growth technique

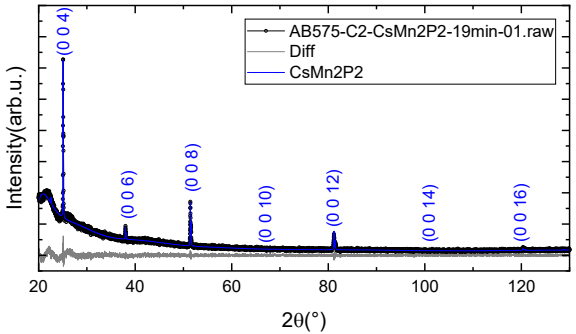


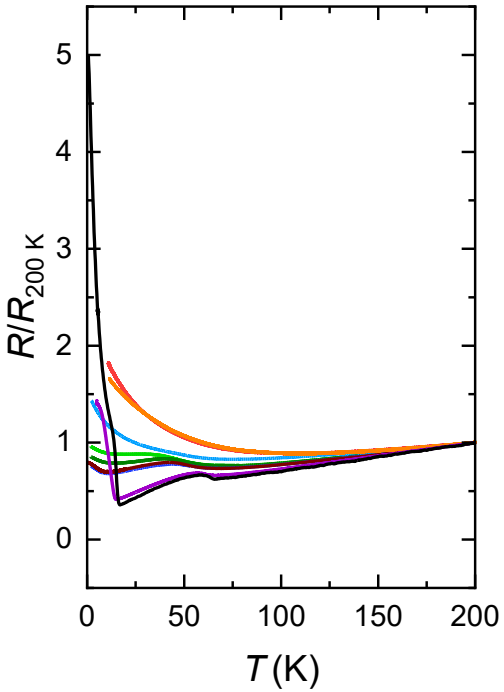


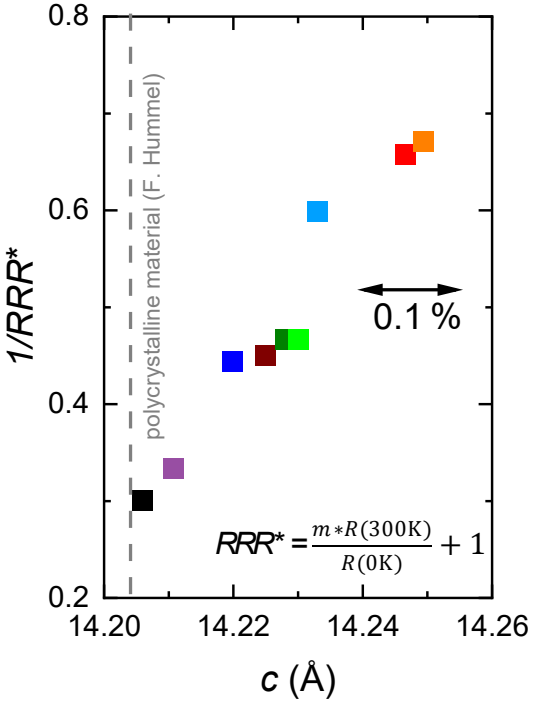
Tunable transport properties. Detailed nature of the phase transitions remains to be identified.

Correlation with *c* lattice parameter: strain tuning?









Outline

- Pursuit of the new single crystalline compound $CsMn_2P_2$
- **Pursuit of the CDW phase transition in $NbSe_2$**
- Pursuit of superconductivity in topological Bi_2Se_3

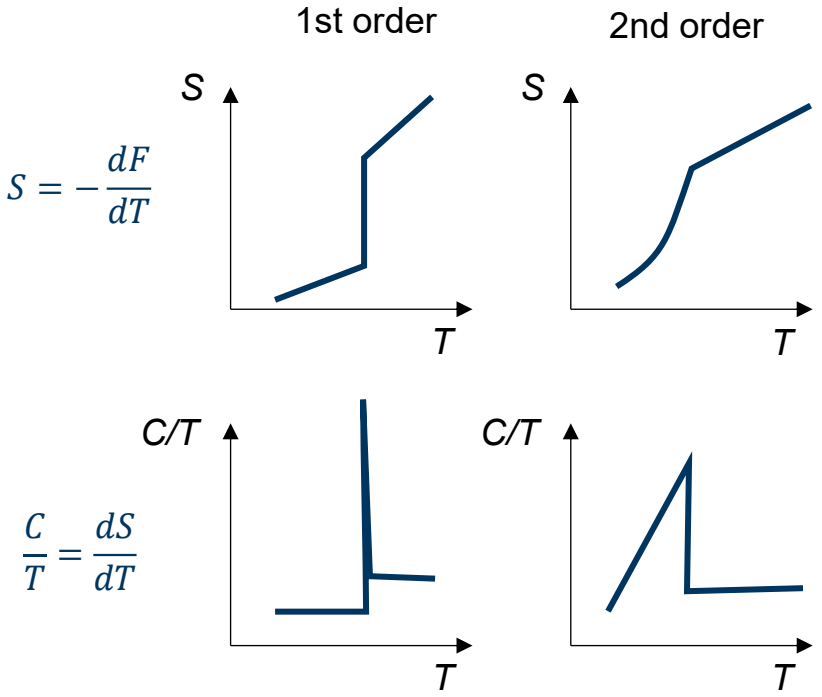
Phase transitions

What is a phase transition?

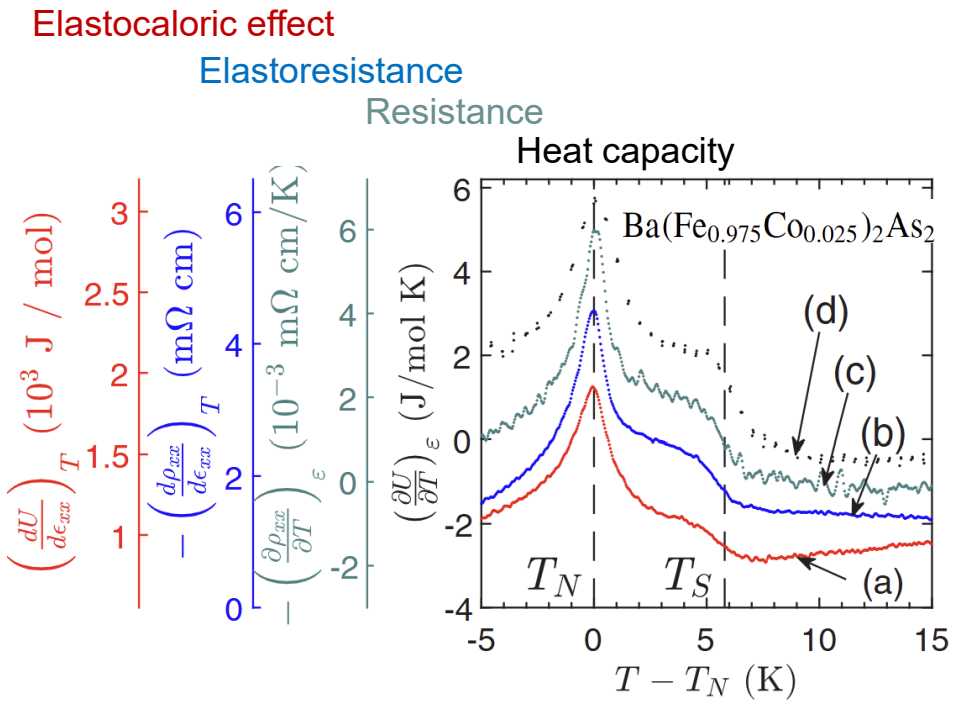
- A discontinuity in the (first/second derivative) of the free energy/thermodynamic potential
- An abrupt change of (at least one) physical property

Experimental methods to identify a phase transition

- *In principle:* anything
- *Typical:* electrical resistance, magnetic susceptbility, heat capacity, …



Scaling of critical behavior of different properties

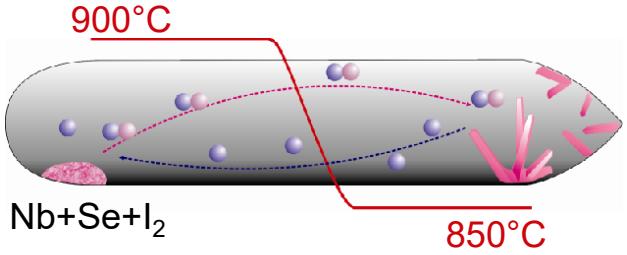


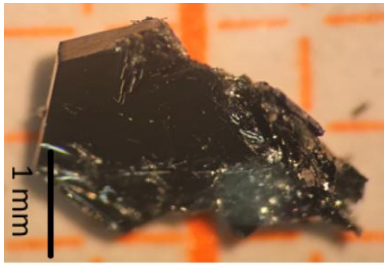
Scaling follows from:

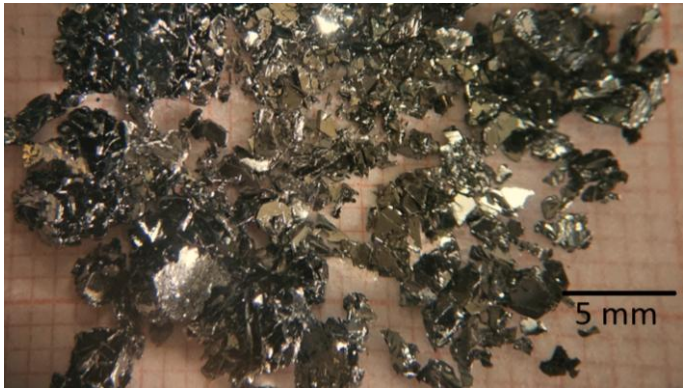
- Fisher-Langer relation: entropy S ~ resistance R or $C = 1/T\mathrm{d}S/\mathrm{d}T \sim \mathrm{d}R/\mathrm{d}T$
- Strain-dependence of transition temperatures

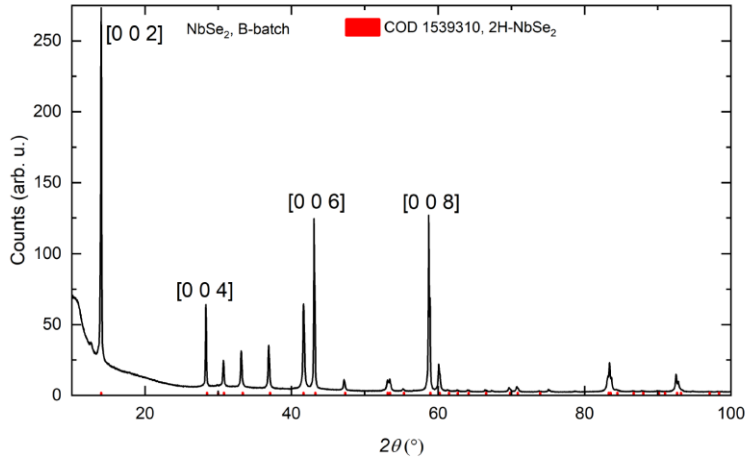
Hristov et al., PRB 99, 100101 (2019)

Chemical vapor transport growth of 2*H*-$NbSe_2$

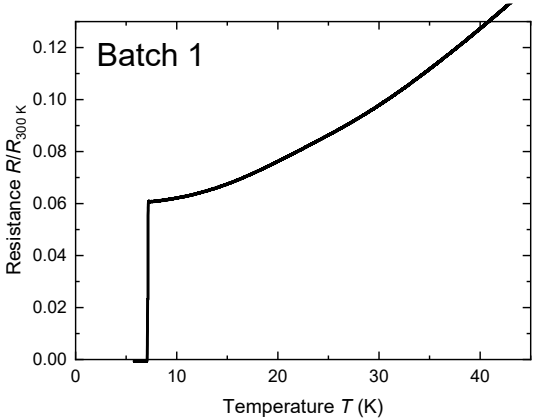


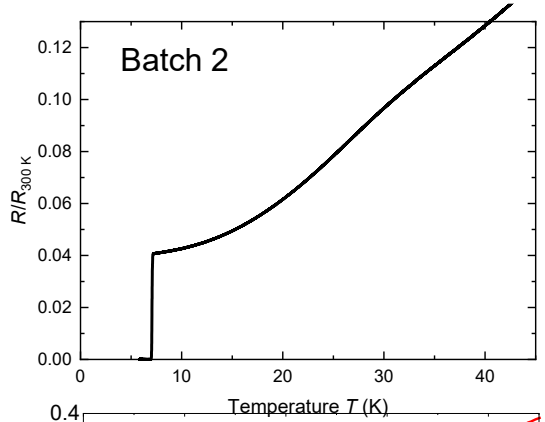


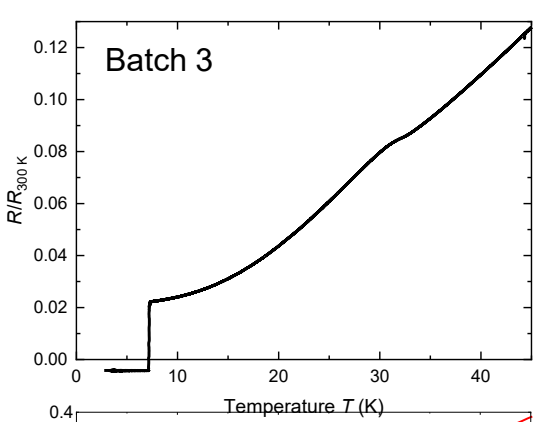


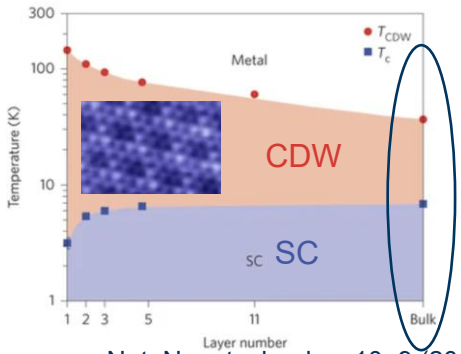


Phase transitions in $NbSe_2$: resistance and heat capacity

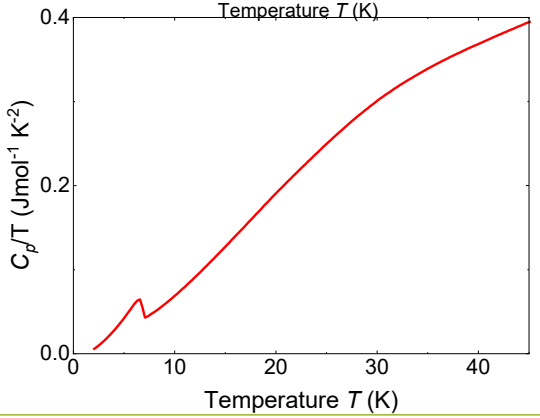


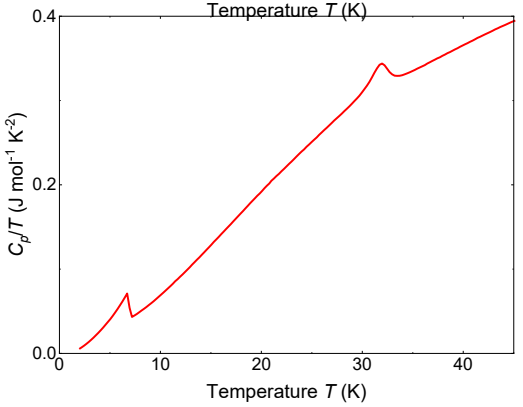






Nat. Nanotechnology10, 9 (2015)



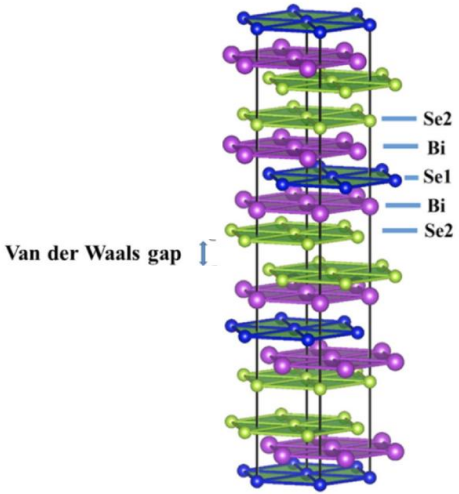


Outline

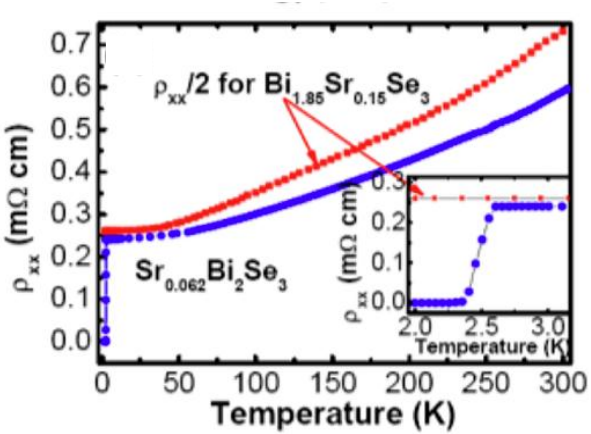
- Pursuit of the new single crystalline compound $CsMn_2P_2$
- Pursuit of the CDW phase transition in $NbSe_2$
- **Pursuit of superconductivity in topological Bi_2Se_3**

Proposed superconductivity in topological insulator

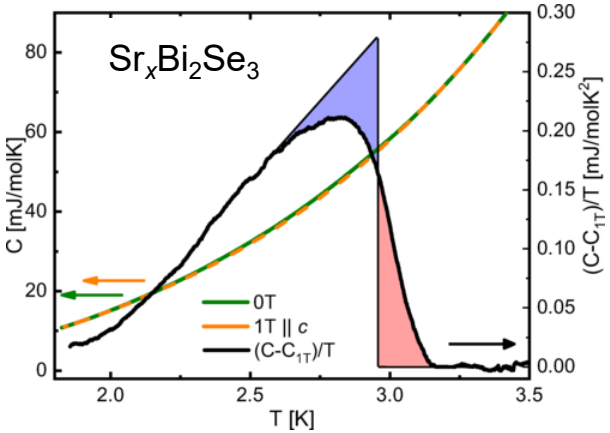
Bi_2Se_3



Topological insulator



Superconductivity

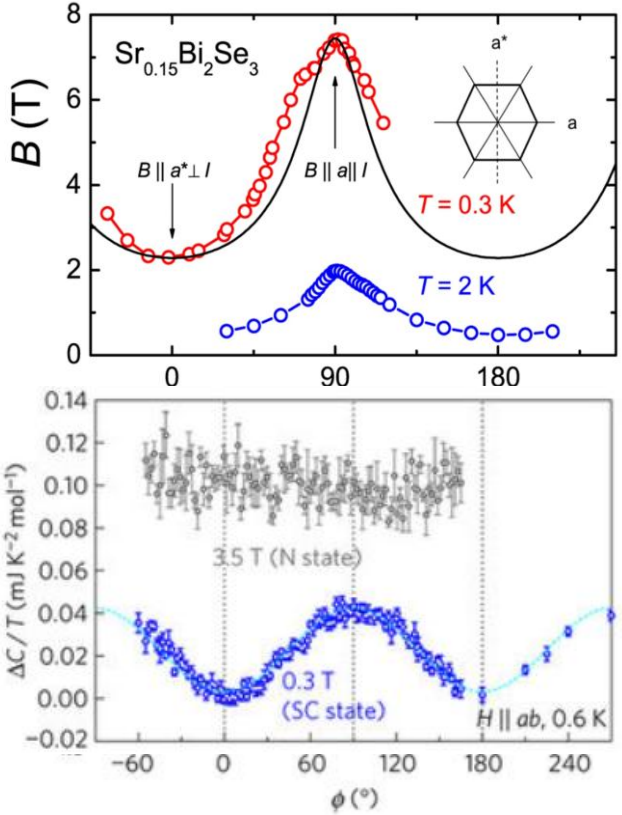


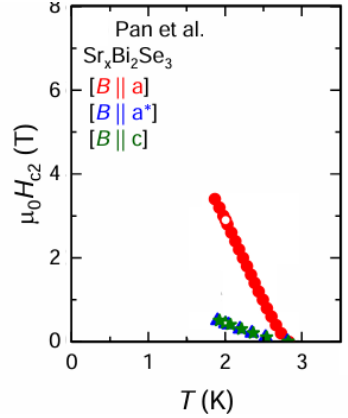
Liu et al., JACS 137, 10512 (2015)
Willa et al., PRB 98, 184509 (2018)

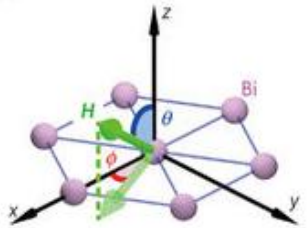
Y. Pan et al., Scientific Reports **6** (2016), 28632
S. Yonewaza, Condens. Matter 2019, 4, 2 (2018) [review]

RUHR UNIVERSITÄT BOCHUM RUB

“Nematic superconductivity in intercalated Bi_2Se_3”

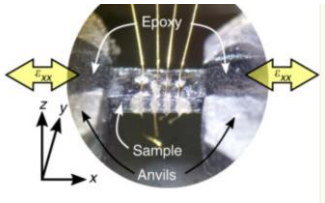


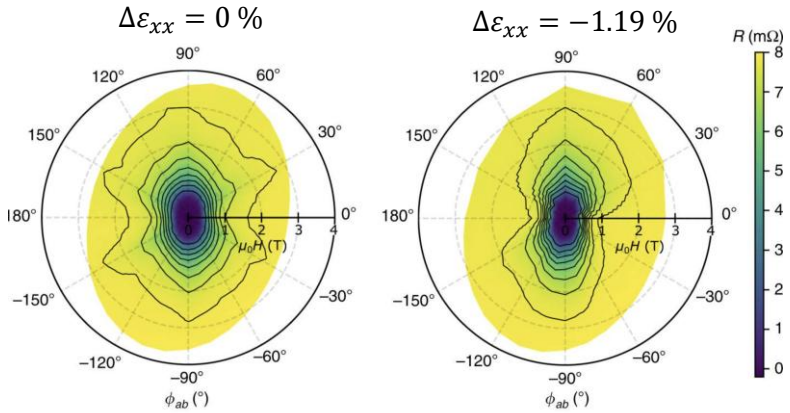




Many open questions, however.

E.g., why no change at >1% strain?

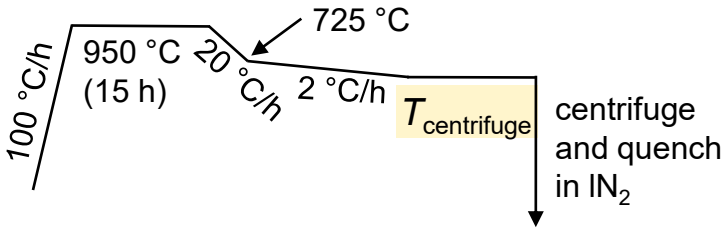


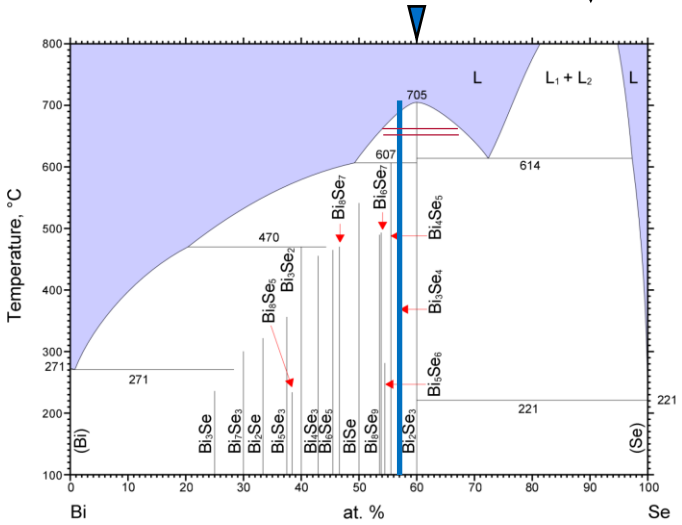


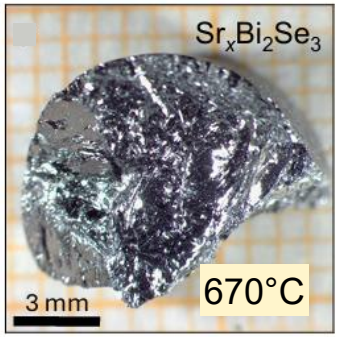
Y. Pan et al., Scientific Reports **6** (2016), 28632
S. Yonewaza, Condens. Matter 2019, 4, 2 (2018) [review]
Kostylev et al, Nat Commun. 11, 4152 (2020)

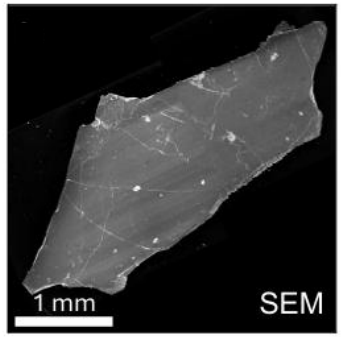
RUHR UNIVERSITÄT BOCHUM RUB

Synthesis from the melt

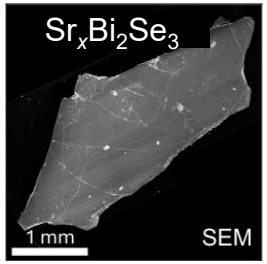


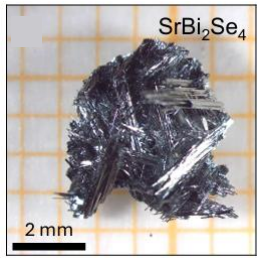


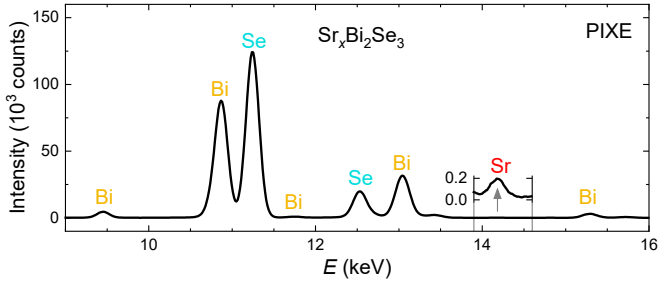


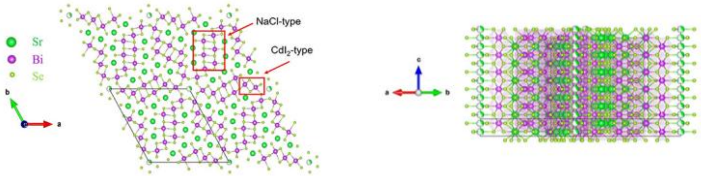


Chemical and crystallographic characterization



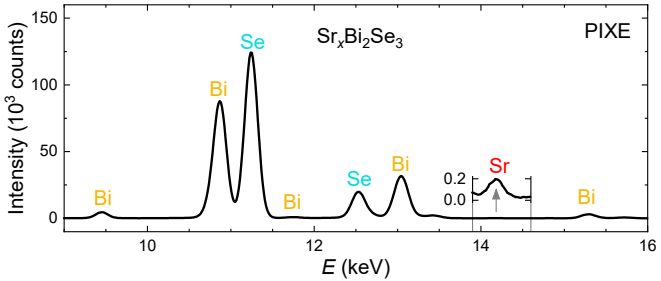


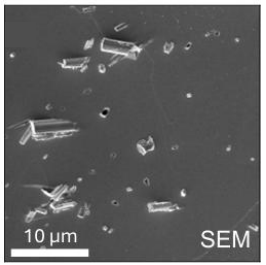




Z. Zhang et al., Chem. Mater. **33** (2021), 6752

Actual Sr content *x* in $Sr_xBi_2Se_3$



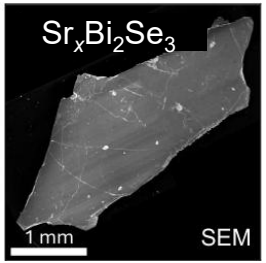


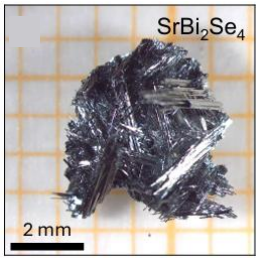
Batch	Sample	PIXE
AB338	C1	$Sr_{0.000983(57)}Bi_2Se_{3.09(18)}$
	C4	$Sr_{0.0000(4)}Bi_2Se_{3.10(18)}$
AB324	C1	$Sr_{0.00286(17)}Bi_2Se_{3.10(18)}$
	C3	$Sr_{0.0000(3)}Bi_2Se_{3.11(18)}$
AB305	C1	$Sr_{0.00314(18)}Bi_2Se_{2.97(17)}$
	C2	$Sr_{0.0926(54)}Bi_2Se_{2.56(15)}$
	C3	$Sr_{0.00296(17)}Bi_2Se_{3.11(18)}$
AB308	C1	$Sr_{0.00205(12)}Bi_2Se_{3.09(18)}$
	C3	$Sr_{0.00570(38)}Bi_2Se_{3.09(18)}$
AB297	C1	$Sr_{0.0038(3)}Bi_2Se_{3.11(18)}$
AB240	C1	$Sr_{0.0220(7)}Bi_2Se_{3.09(18)}$
	C5	$Sr_{0.0159(9)}Bi_2Se_{3.09(18)}$

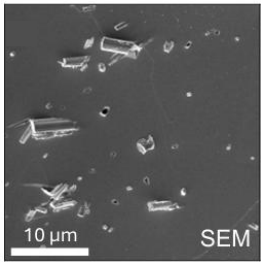
PIXE (beam cross-section 10x10 µm^2):

- $Sr_xBi_2Se_3$, x = 0.0000 - 0.09
- no correlation between x and x_{nom}

Superconducting critical field anisotropy





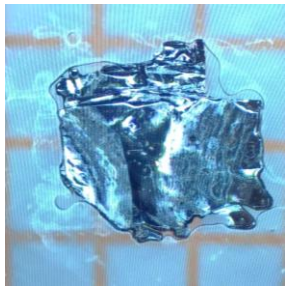


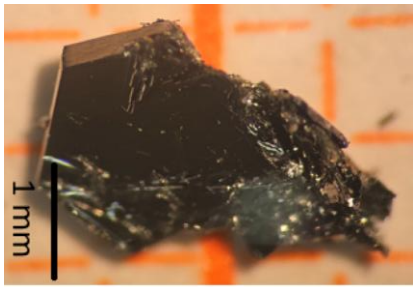
Inclusions of a needle-like superconductor in a topological insulator

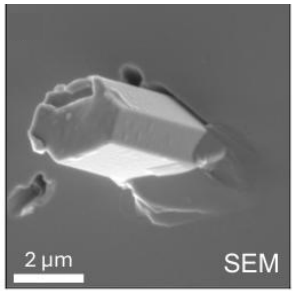
- Can explain the observed „nematic superconductivity“ in Sr-containing Bi_2Se_3
- Optimized crystal growth techniques: might create an even finer network of the superconducting phase embedded in the topological insulator

Summary

- New single crystalline compound $CsMn_2P_2$
- Thermodynamic CDW phase transition in $NbSe_2$
- Clarification of superconductivity in topological Bi_2Se_3







Thanks to

Jutta Püttmann
N.S. Sangeetha
Matthias Kroll
Martin Kostka
Maik Golombiewski
Sven Graus
Teslin Thomas
Jule Stoppacher
Fatih Cetin
Jule Kirschke
Haneen Abushammala
Max Brückner
Andreas Kreyssig



Physik und Astronomie
from matter to materials

Elasto-Q-Mat

RUB

MERCUR
Mercator Research Center Ruhr

erc

DFG

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Chair for experimental physics IV

Ruhr University Bochum

KAPITEL

HERVORHEBUNG