PAUL SCHERRER INSTITUT

PSI

Laboratory for Neutron and Muon INstrumentation

Gediminas Simutis :: Paul Scherrer Institute

High Pressure Techniques for Neutrons, X-rays and muons

Sample Environment Training School

January 19th – 23rd 2026, Lund, Sweden

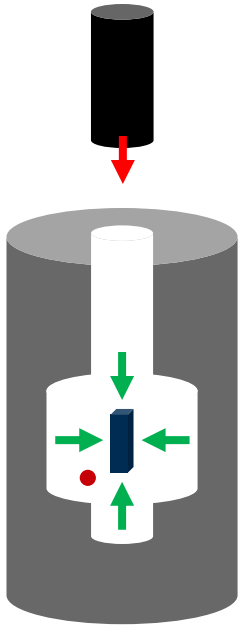
Plan for the lectures

- **Lecture 1:**

1. **Why are we doing high pressure experiments?**
2. **What are the constituent parts?**
3. **How do we build the cells?**
4. **Different designs of the cells**
5. **How to measure pressure?**
6. **How do we transmit the pressure?**

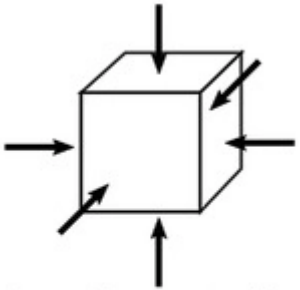
- **Lecture 2:**

1. **Uniaxial pressure: different methods**
2. **Uniaxial pressure: tips and tricks**
3. **Pressure and background**
4. **Computing background**
5. **Combining pressure and field.**
6. **MuSR experiments at high pressure**

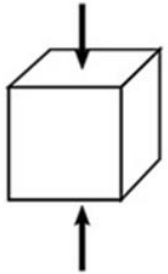


Uniaxial Pressure Experiments

Hydrostatic versus uniaxial



hydrostatic pressure

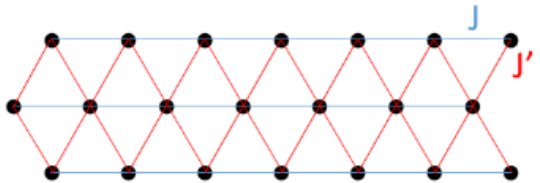


uniaxial pressure

- No explicit symmetry breaking
- Volume reduction
- Multiple couplings modified
- Compression only

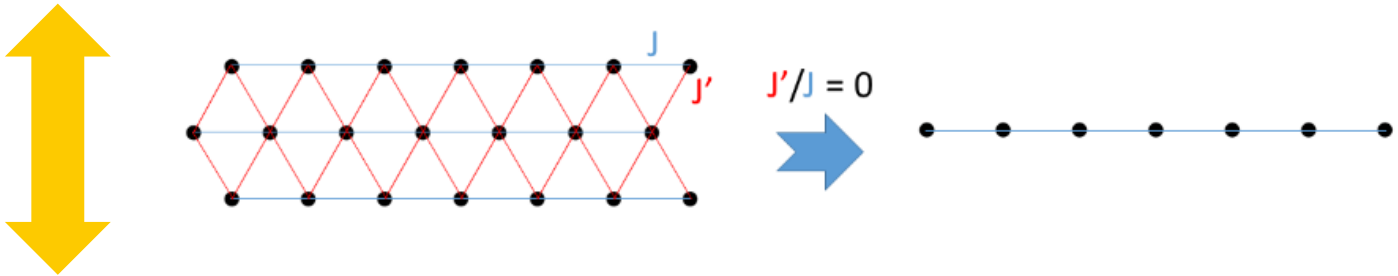
- Explicit symmetry breaking
- Volume redistribution
- Targeted tuning of couplings
- Tension also possible

Tuning quantum matter



$$\mathcal{H} = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + J' \sum_{\langle ij \rangle'} \mathbf{S}_i \cdot \mathbf{S}_j$$

Tuning quantum matter



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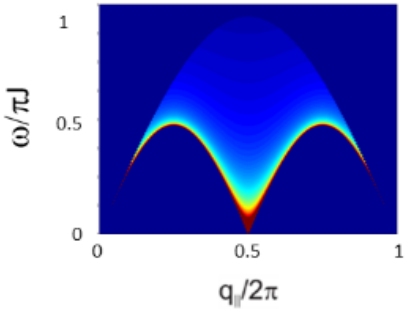
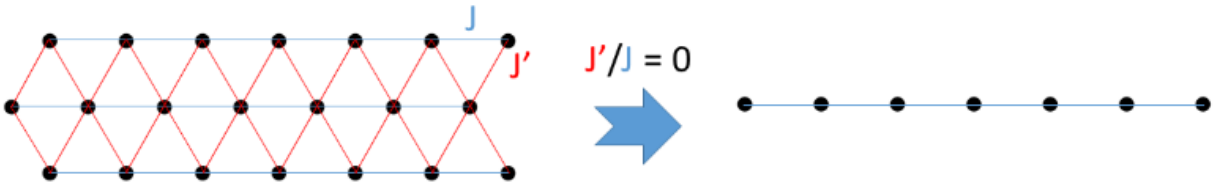
Tuning quantum matter





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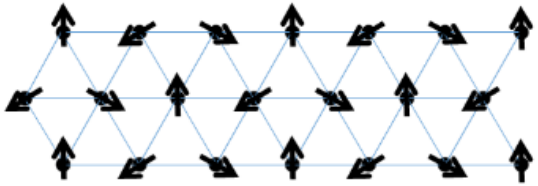
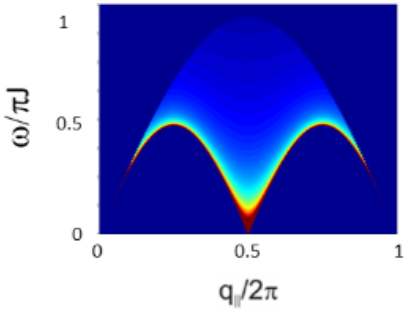
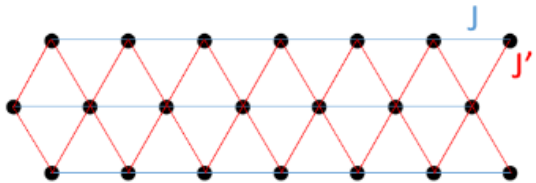
Tuning quantum matter



J′/J = 1



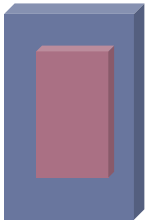


J′/J = 0

$$\mathcal{H} = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + J' \sum_{\langle ij \rangle'} \mathbf{S}_i \cdot \mathbf{S}_j$$

Different ways to do uniaxial pressure

Differential thermal contraction



+ Simple

- Stress transfer?
- One Stress value
- Background
- Zero Stress?
- Value?

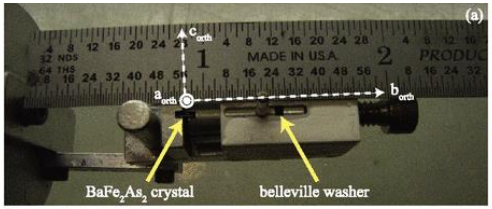
Simple press

+ Simple
+ Background

- Value ?
- Ex-situ

Choi, J. et al.
PRL **128**, 207002 (2022)

press with a spring

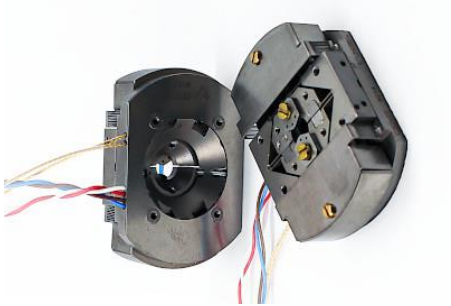


+ Simple ish
+/- Value (T-dep?)

- Ex-situ

Dhital, C. et al.
PRL **108**, 087001 (2012)

Piezo-electric devices



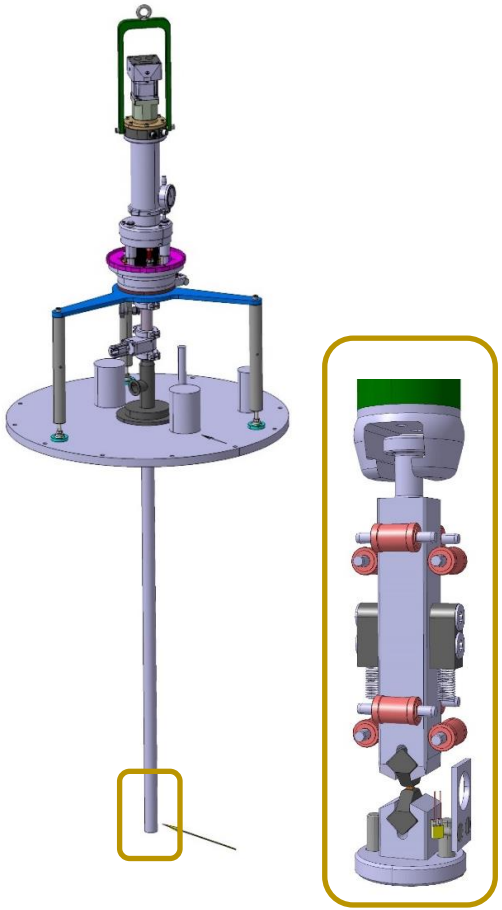
+ Push-pull
+ In-situ
+ Value

- Background?
- Zero Stress?
- Complexity

I. Vinograd et al.,
NComms, **15**, 3277 (2024)

Implementation with a motor

In-situ uniaxial pressure device



Tuning in-situ

Push-pull capabilities

Separate F, T readout

Thermal expansion decoupling

Large distance motion

In-situ uniaxial pressure device. Implementation

stepper motor control

Disc spring packages for fine precision

Load cell

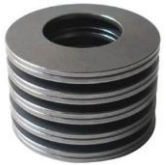
Efficient force transfer

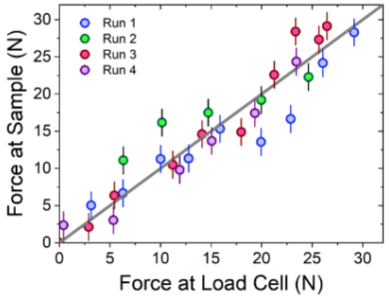
Feedback to maintain force

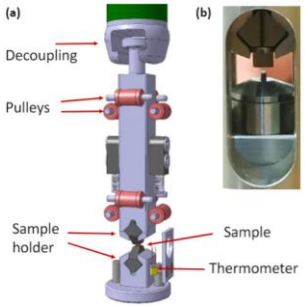
Control integrated into PSI and DESY beamlines

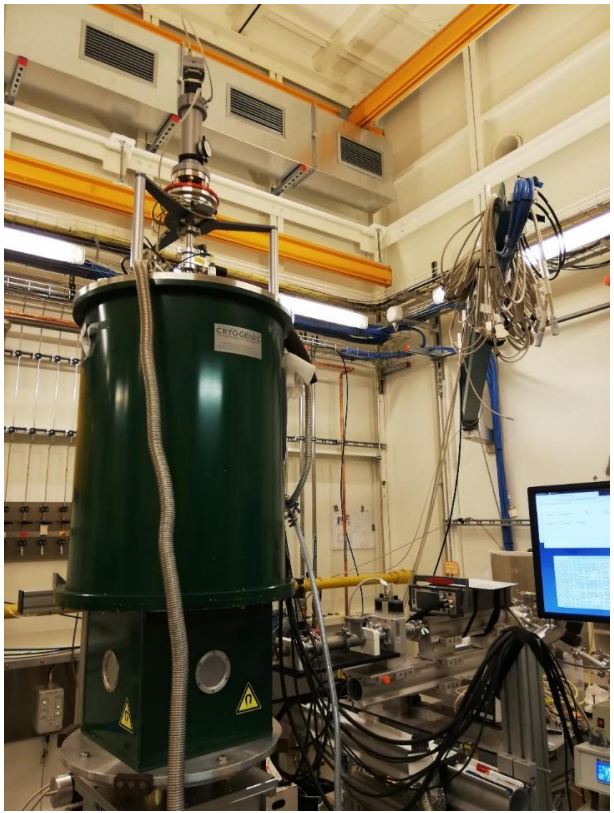
Separate thermometer

Easy switching between prepared samples



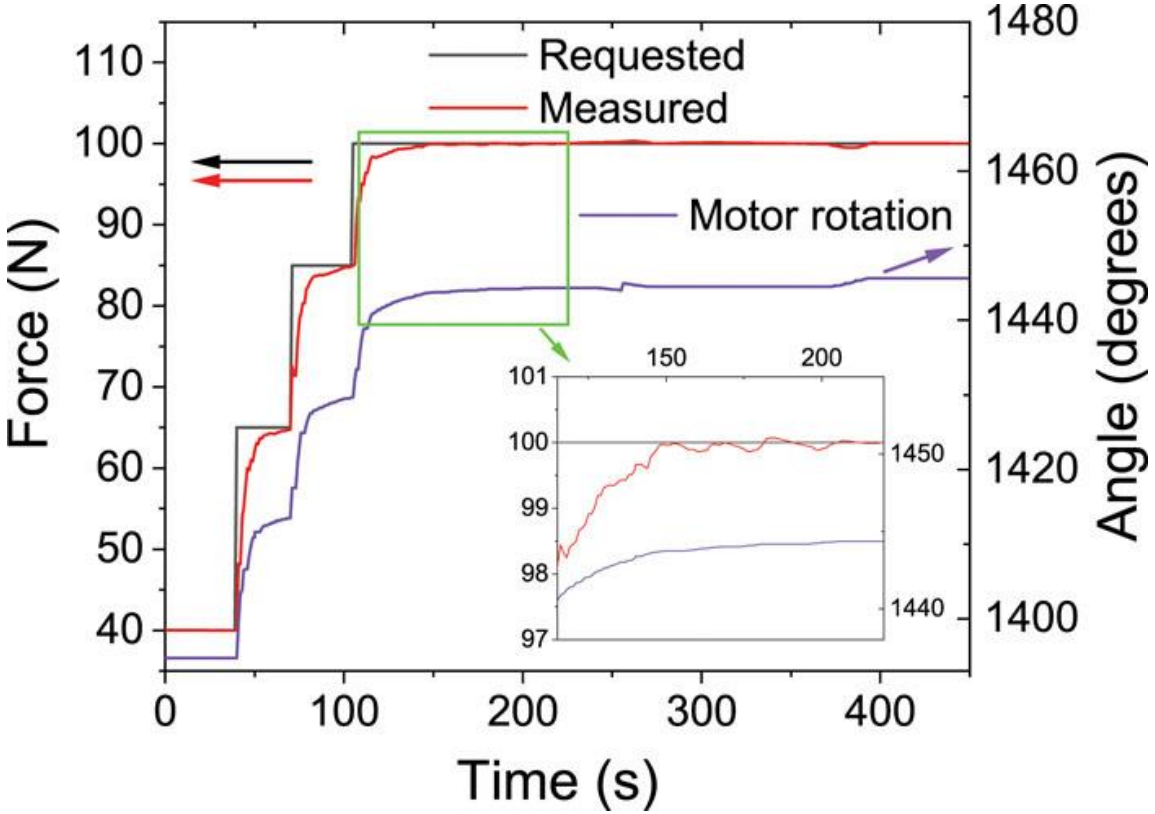


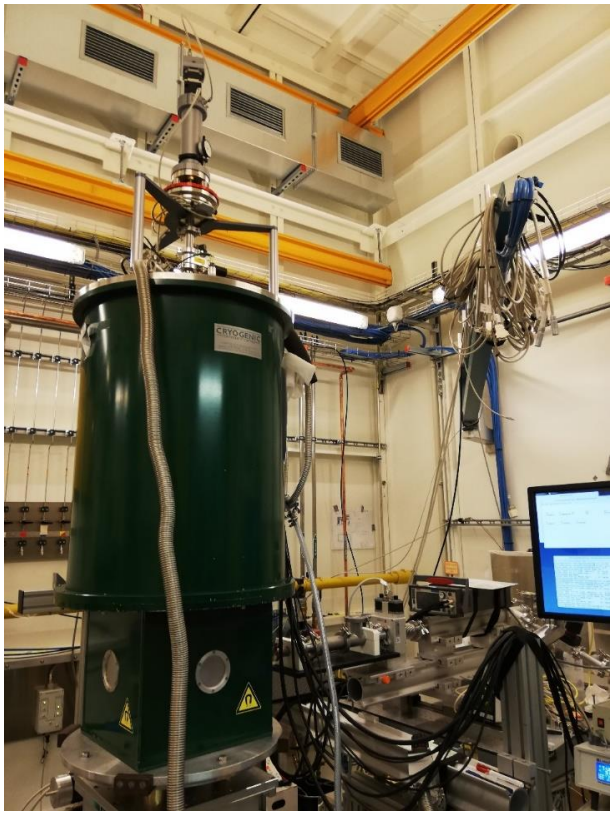




Review of Scientific Instruments **94**, 013906 (2023)

Control

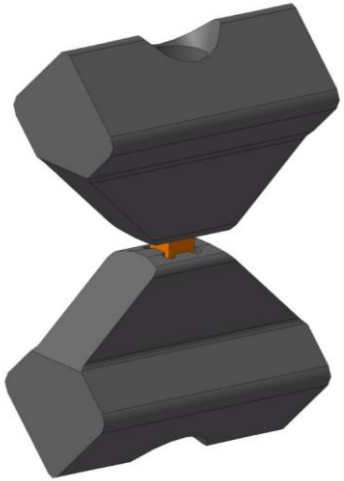


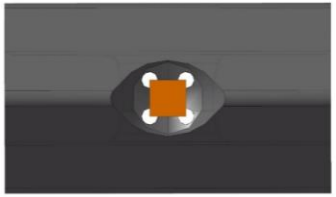


Review of Scientific Instruments **94**, 013906 (2023)

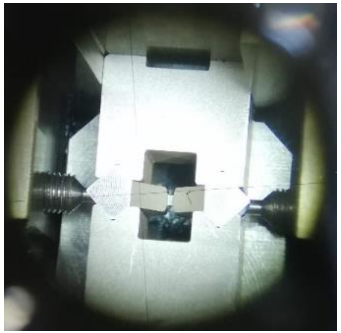
Sample holders – push and pull

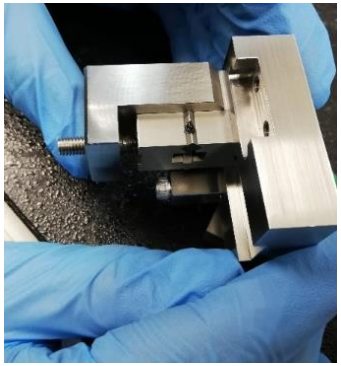
Push and Pull holder





Gluing





Positioned in the device

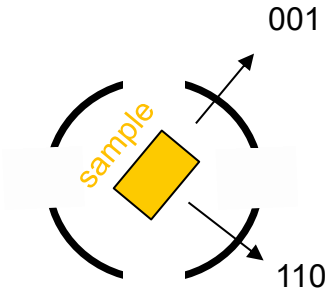
Advantage – very well controlled push/pull. Drawbacks – long samples needed, more complex

Challenge – where to look?

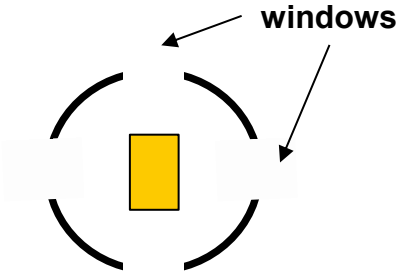
Only +- 5 degrees available from the magnet

Tilt is only +- 5 degrees

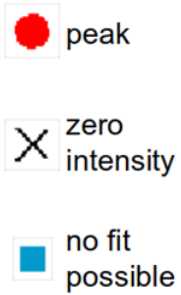
Need careful mounting
of the crystal

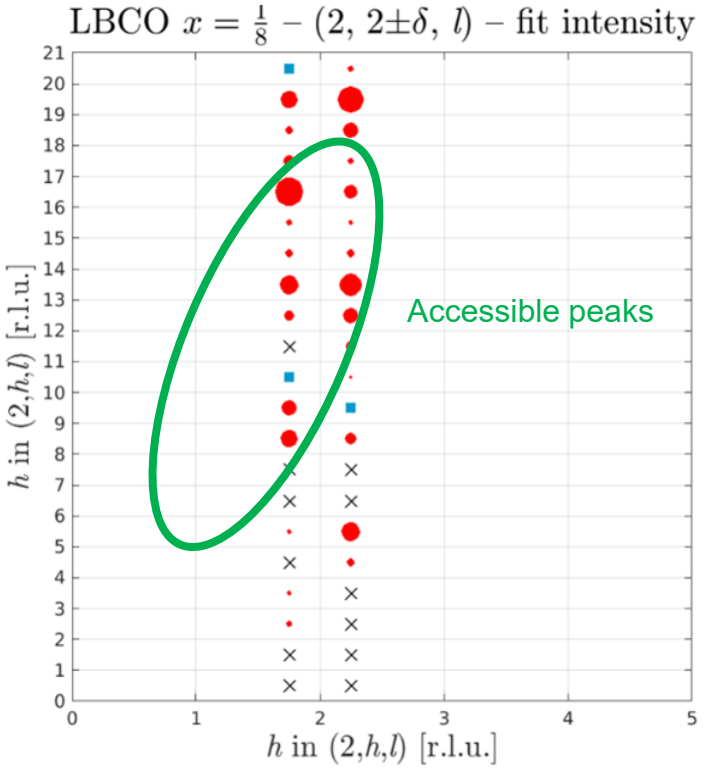


CDW study



Structure study

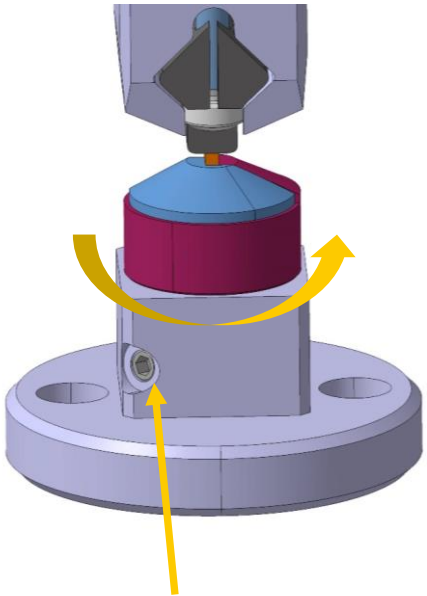




Oleh Ivashko and
Martin von Zimmermann
(unpublished)

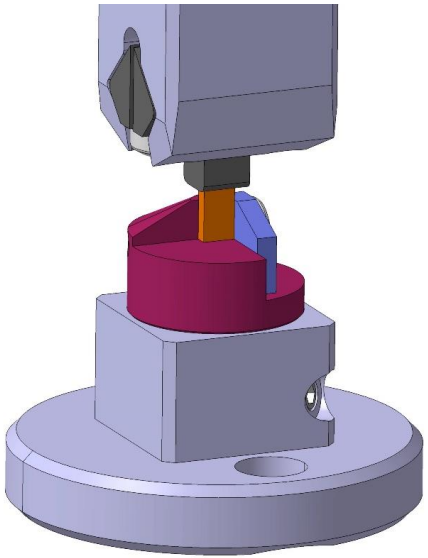
Push only sample holders – allows for arbitrary rotation!

Version 1 – more forgiving for non-ideal samples by putting more stycast inside



Enables rotation and fixation

Version 2 – better alignment, assuming perfectly parallel sample



Challenges – thermal effects

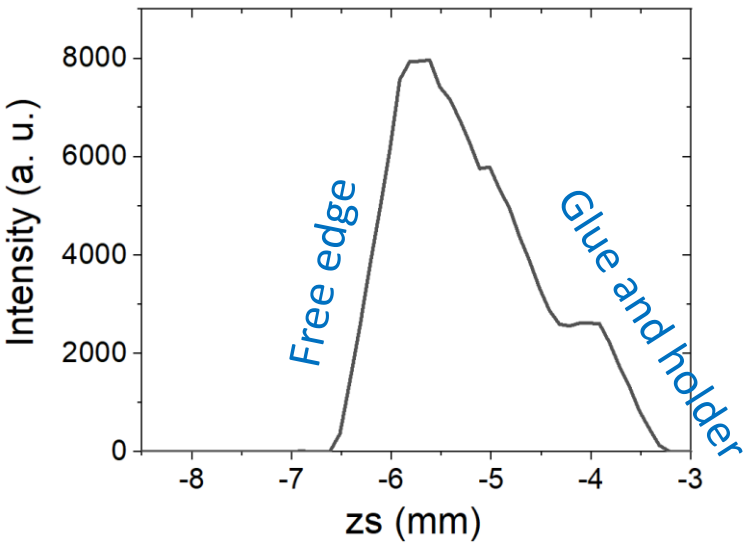
- Long rod of 130 cm. Top at 300 K. Bottom at sample T

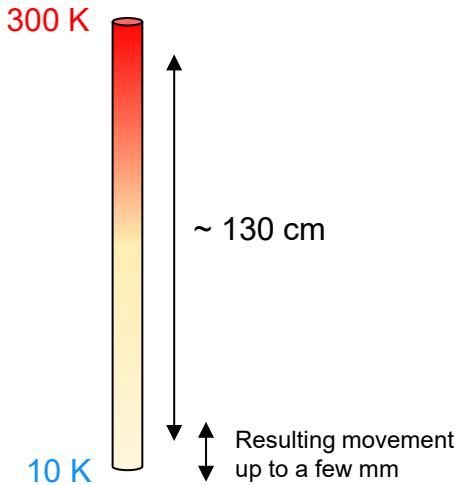
Spurious signals can be observed:

- High-energy X-rays shoot through the sample holder

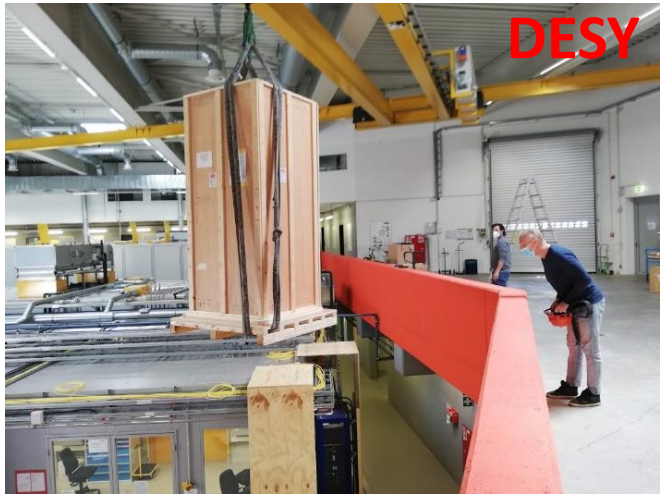
Can observe sample inside the glue

- **Solution** – Make use of the **different timescales** for measurement and equilibration
- **Implementation**: **Scan Height** before and after the real measurement



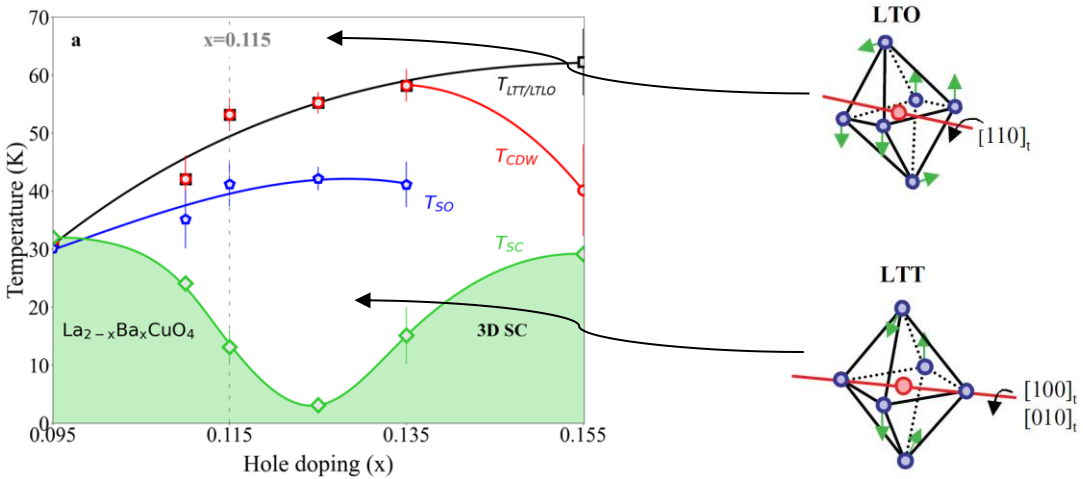


Challenge – Logistics



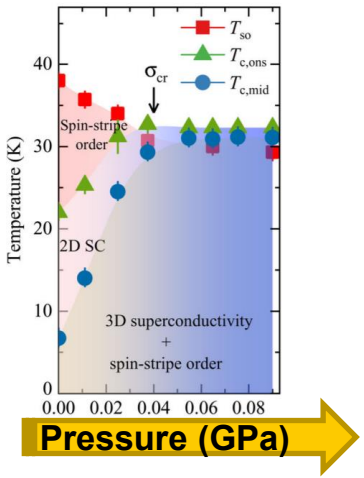
Application 1: High-Tc Cuprate Superconductors

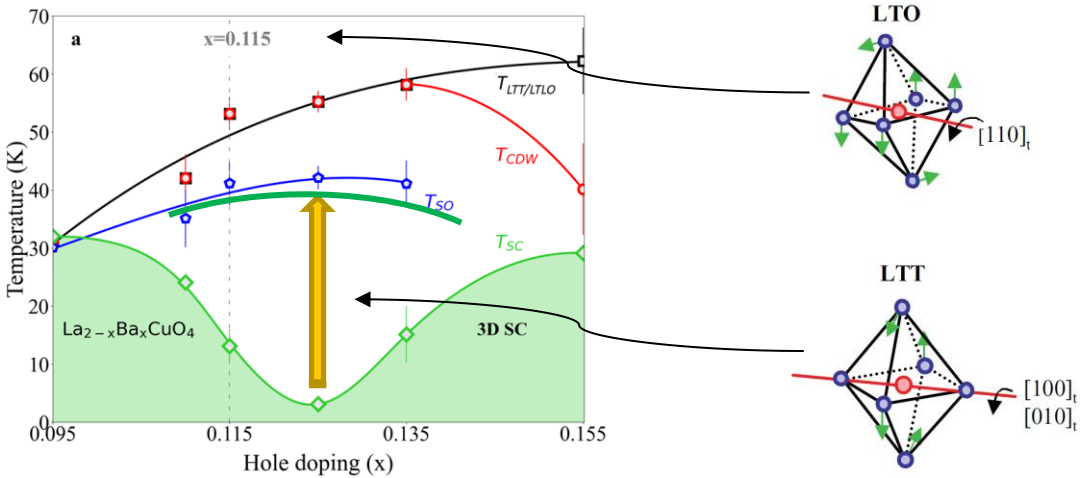
Uniaxial pressure effects on structure



PNAS, e2303423120 (2023)

Uniaxial pressure effects on structure





PNAS, e2303423120 (2023)

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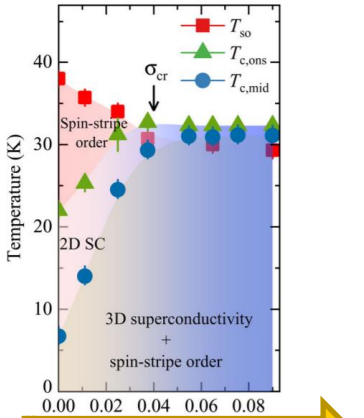
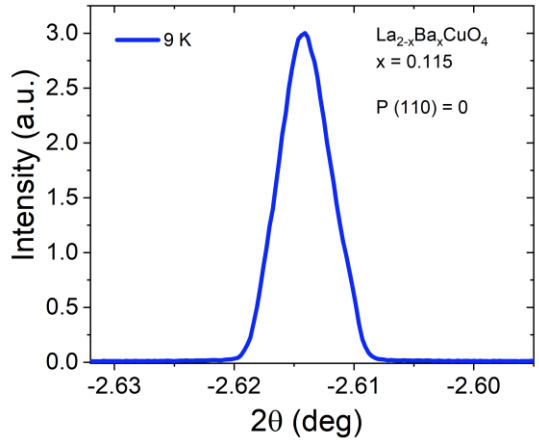
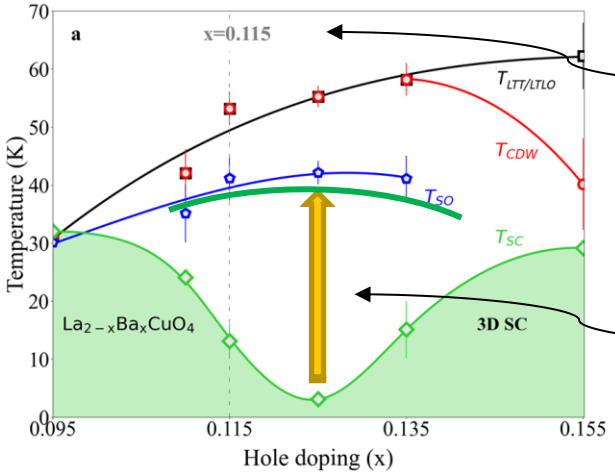
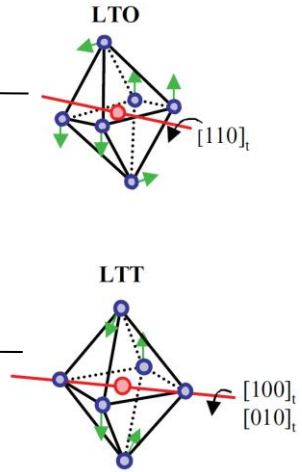


Pressure (GPa)







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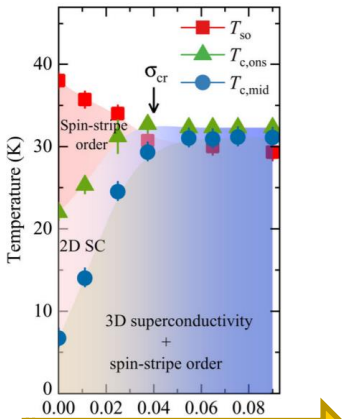

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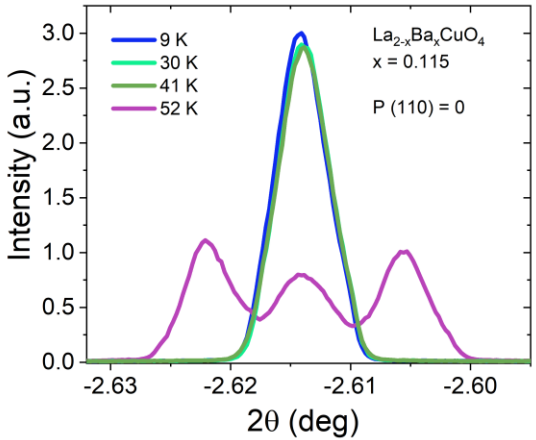

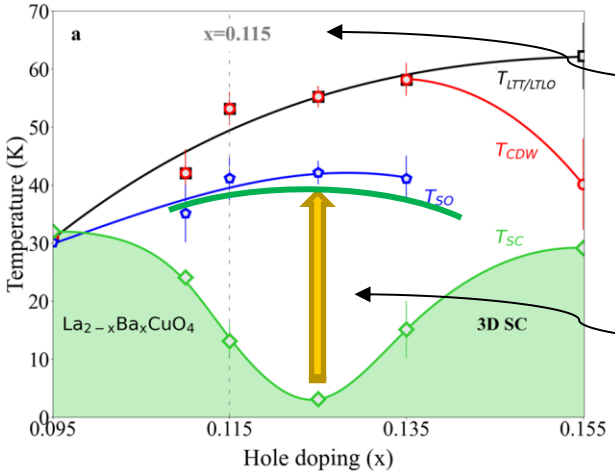

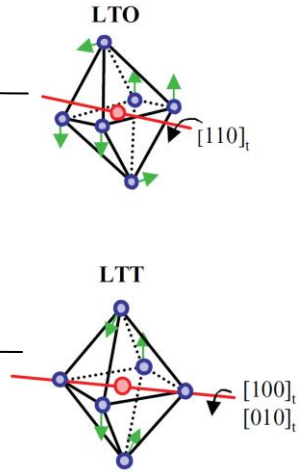

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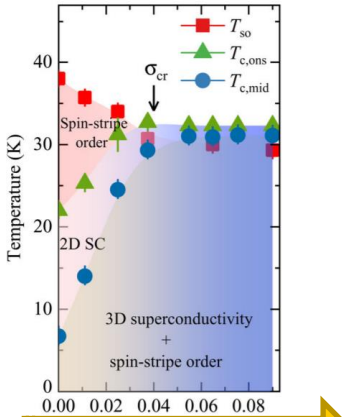

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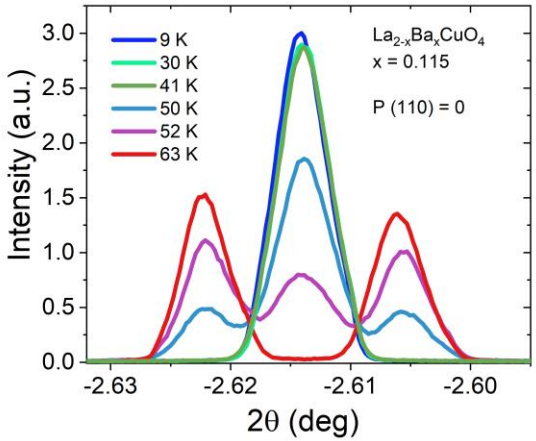

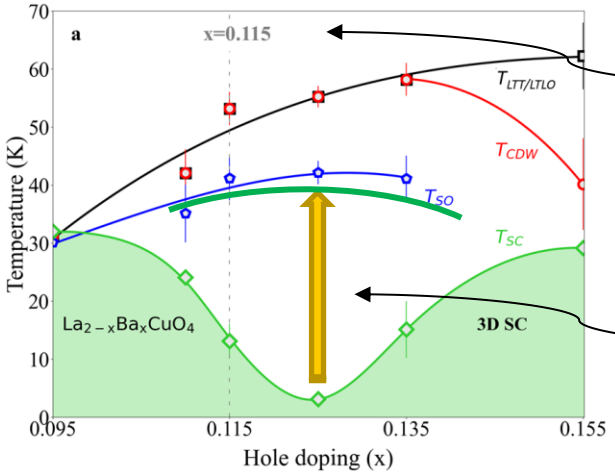

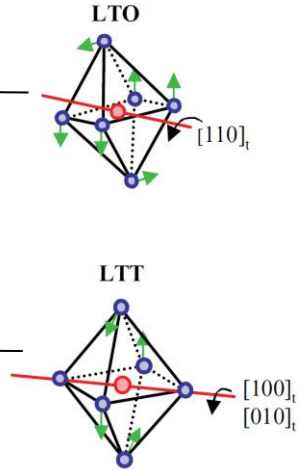

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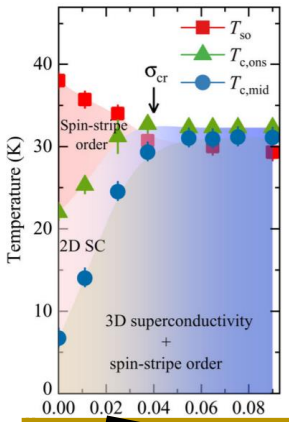

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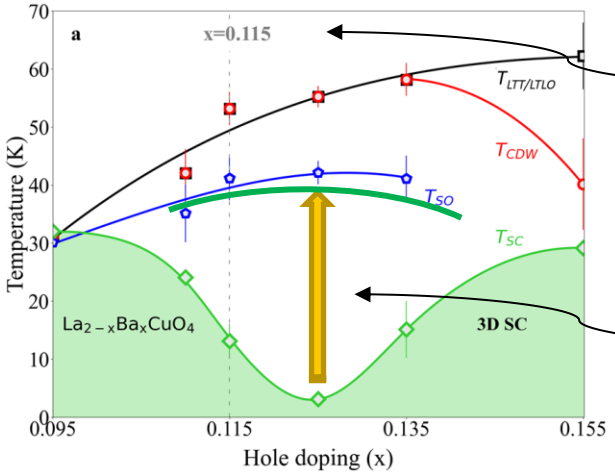
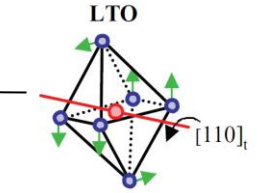
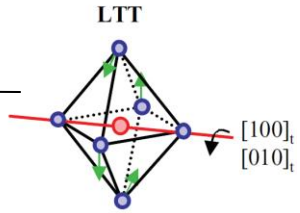
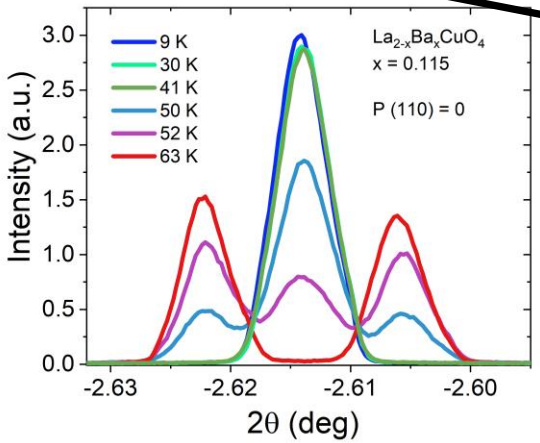
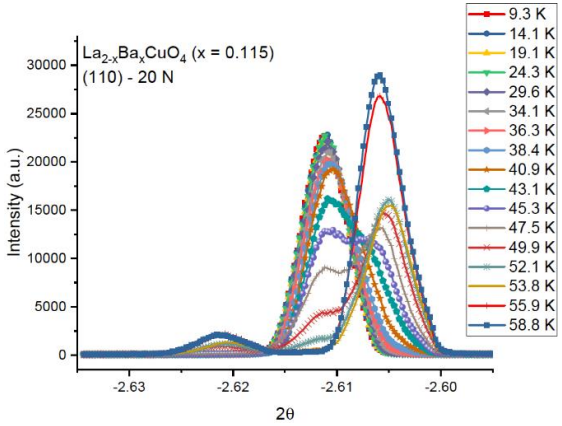


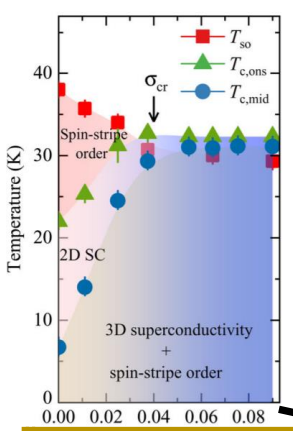




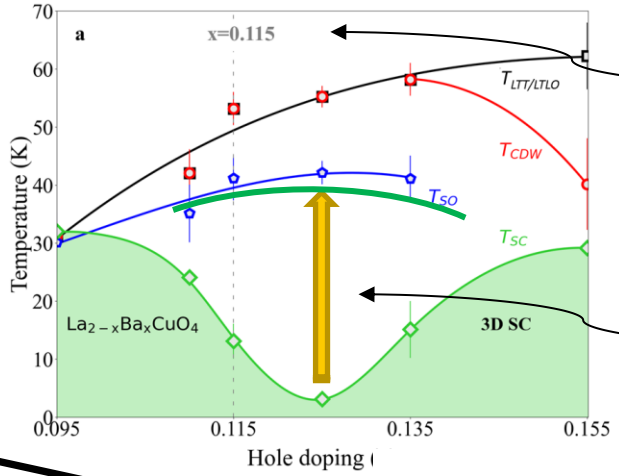


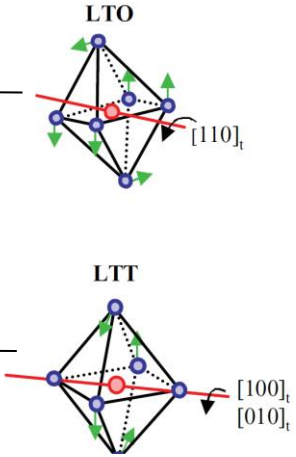


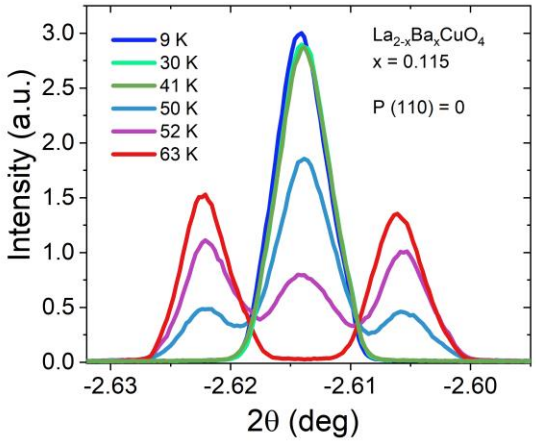
Uniaxial pressure effects on structure



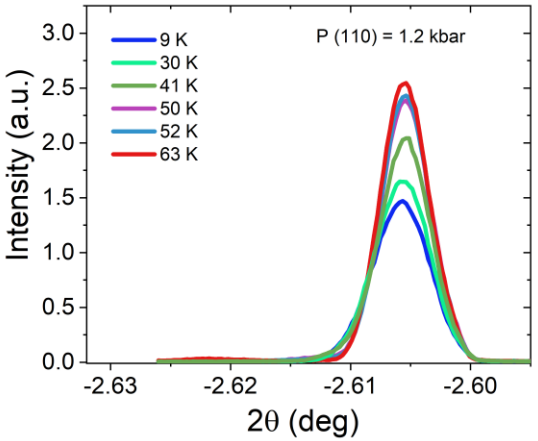
Pressure (GPa)





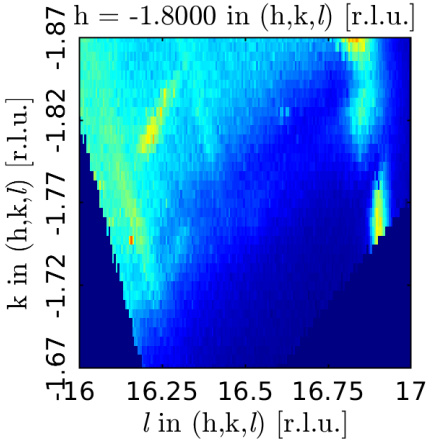


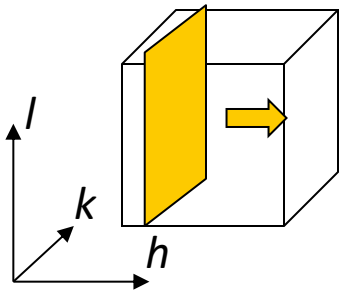
Uniaxial Pressure (GPa)



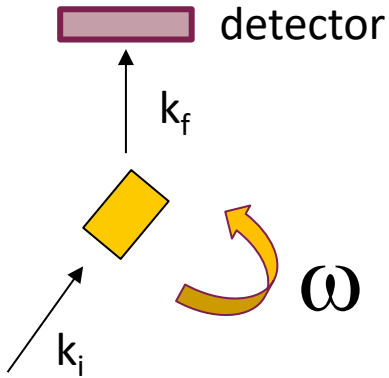
Uniaxial pressure effects on charge order

Uniaxial pressure effects on charge order

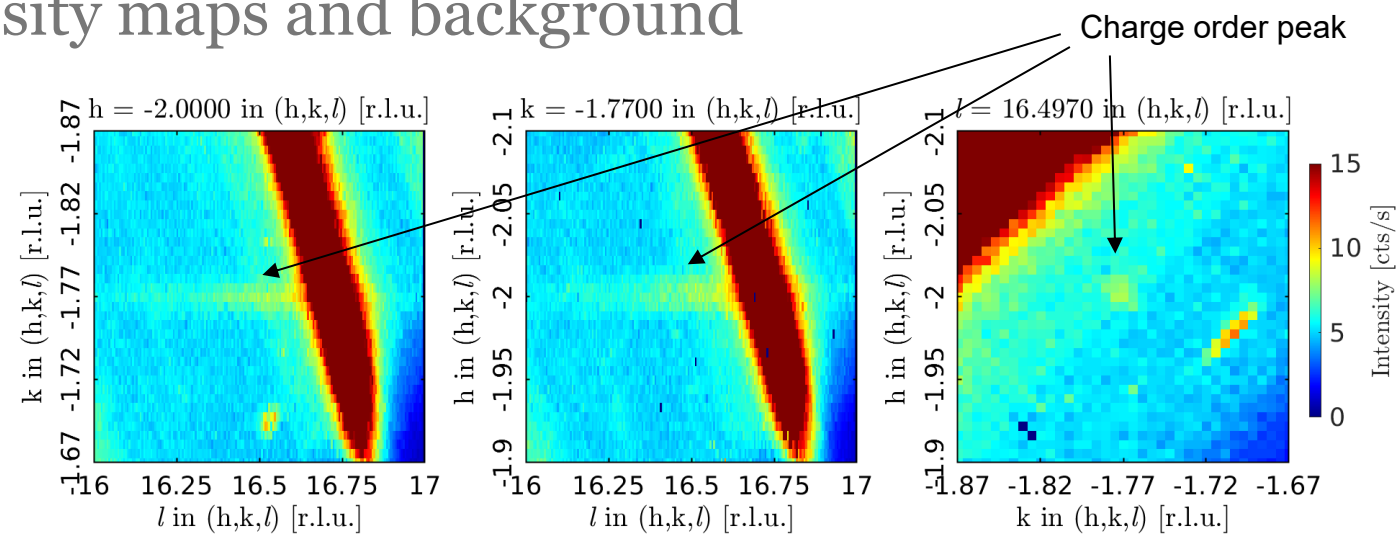


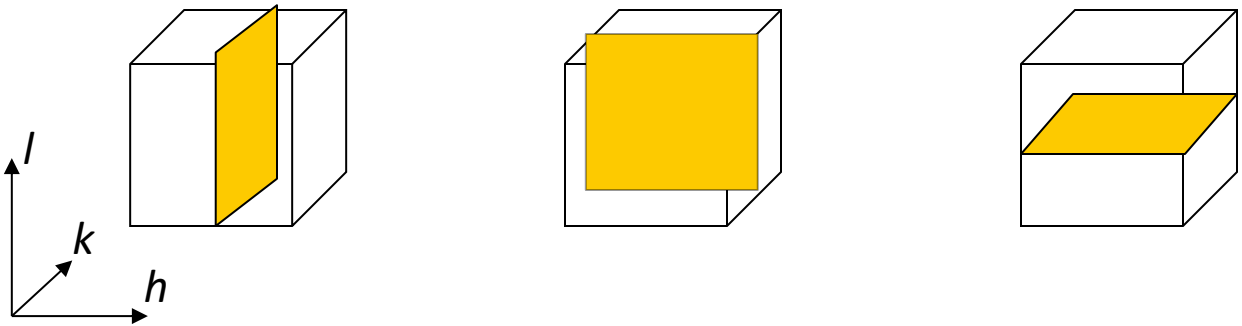


- Broad peaks in k-space
- 3D map through area detector and rotation

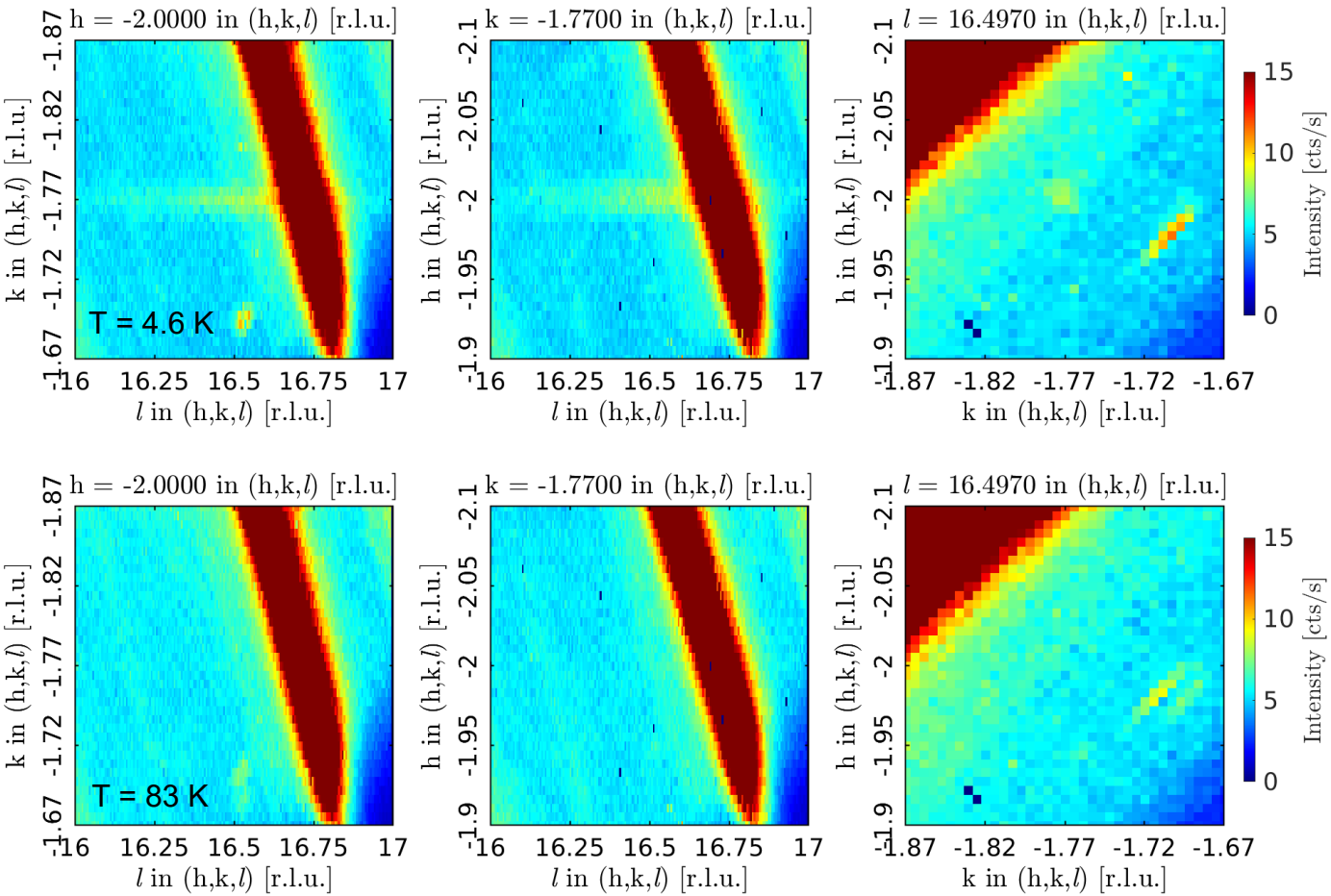


Intensity maps and background



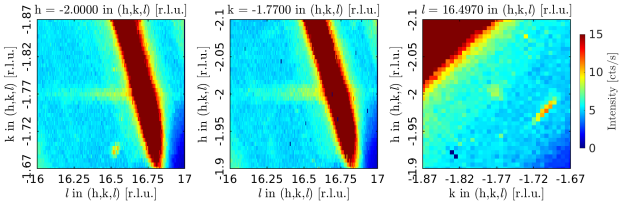


Intensity maps and background



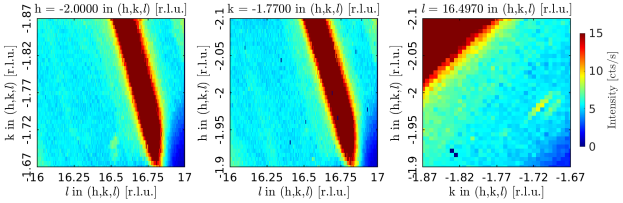
Intensity maps and background

T = 4.6 K



−

T = 83 K



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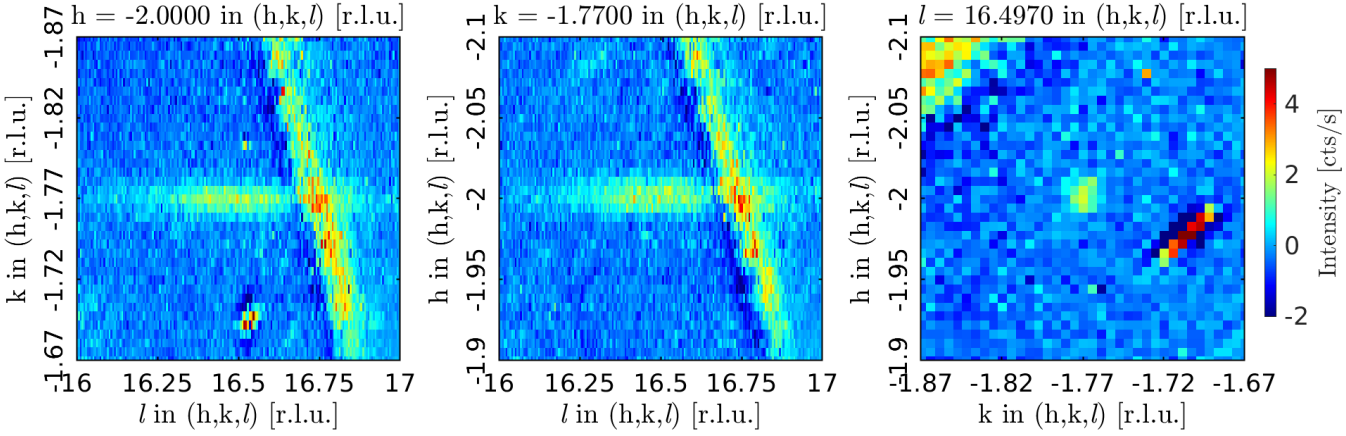
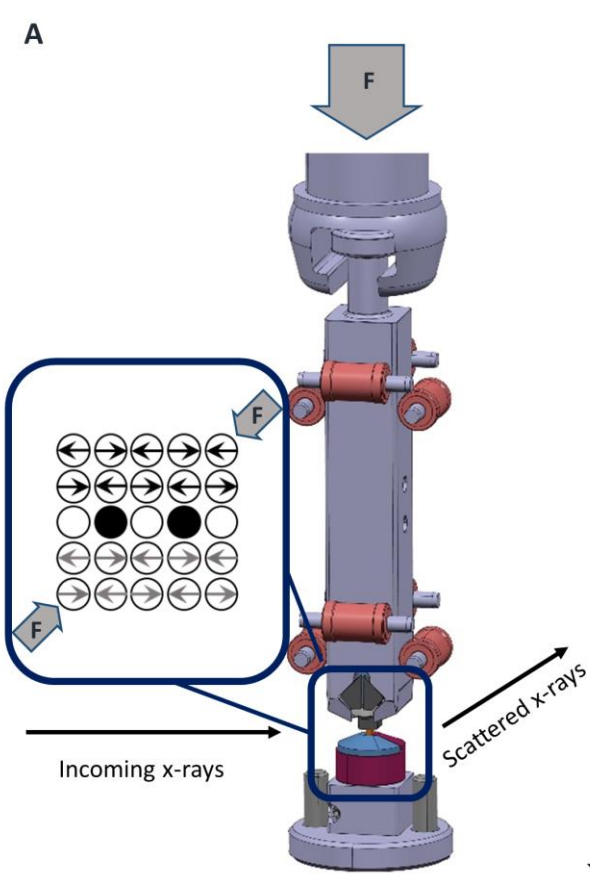
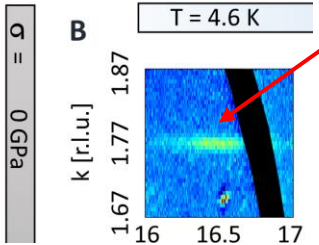


Uniaxial pressure effects on charge order

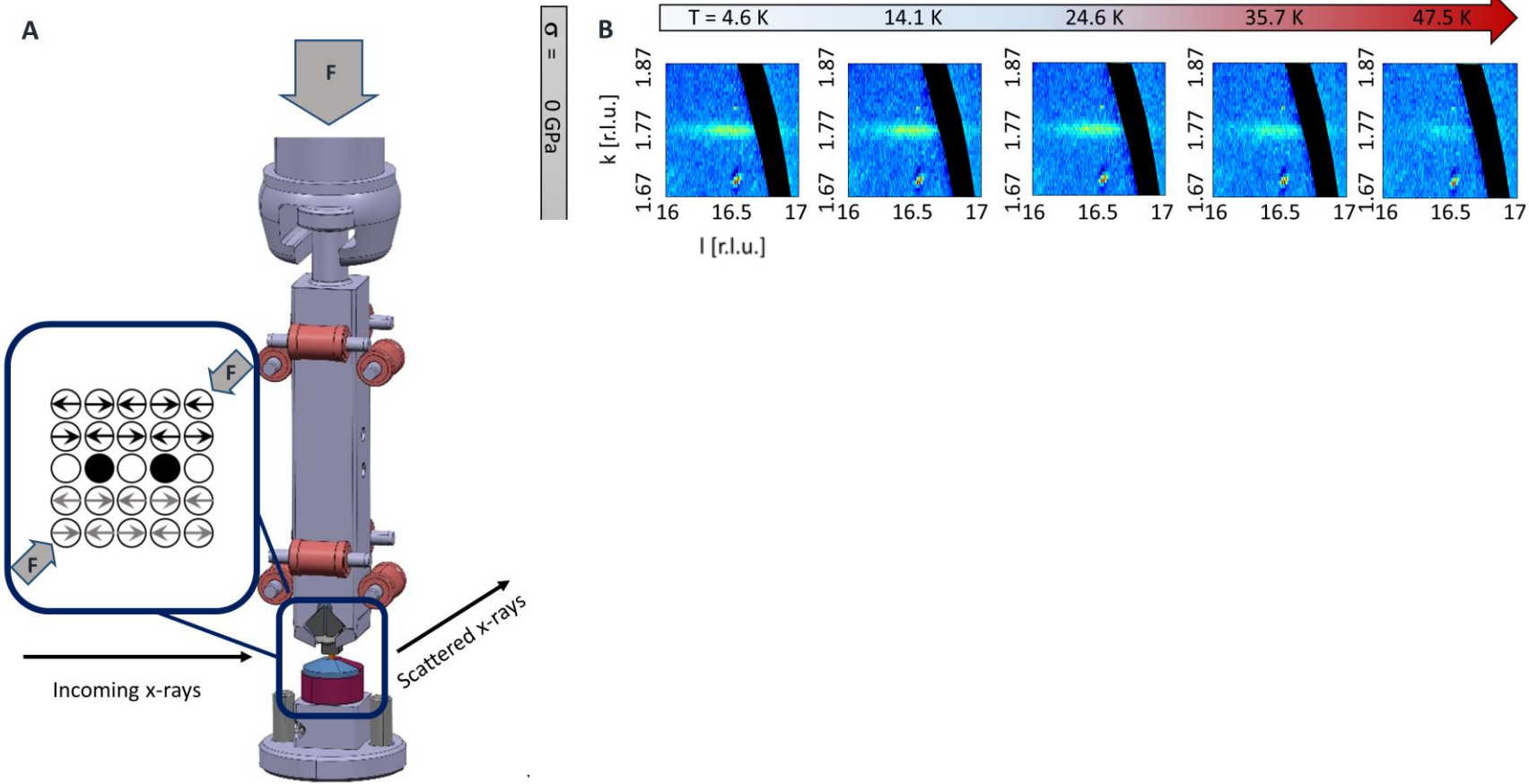




Charge – order peak

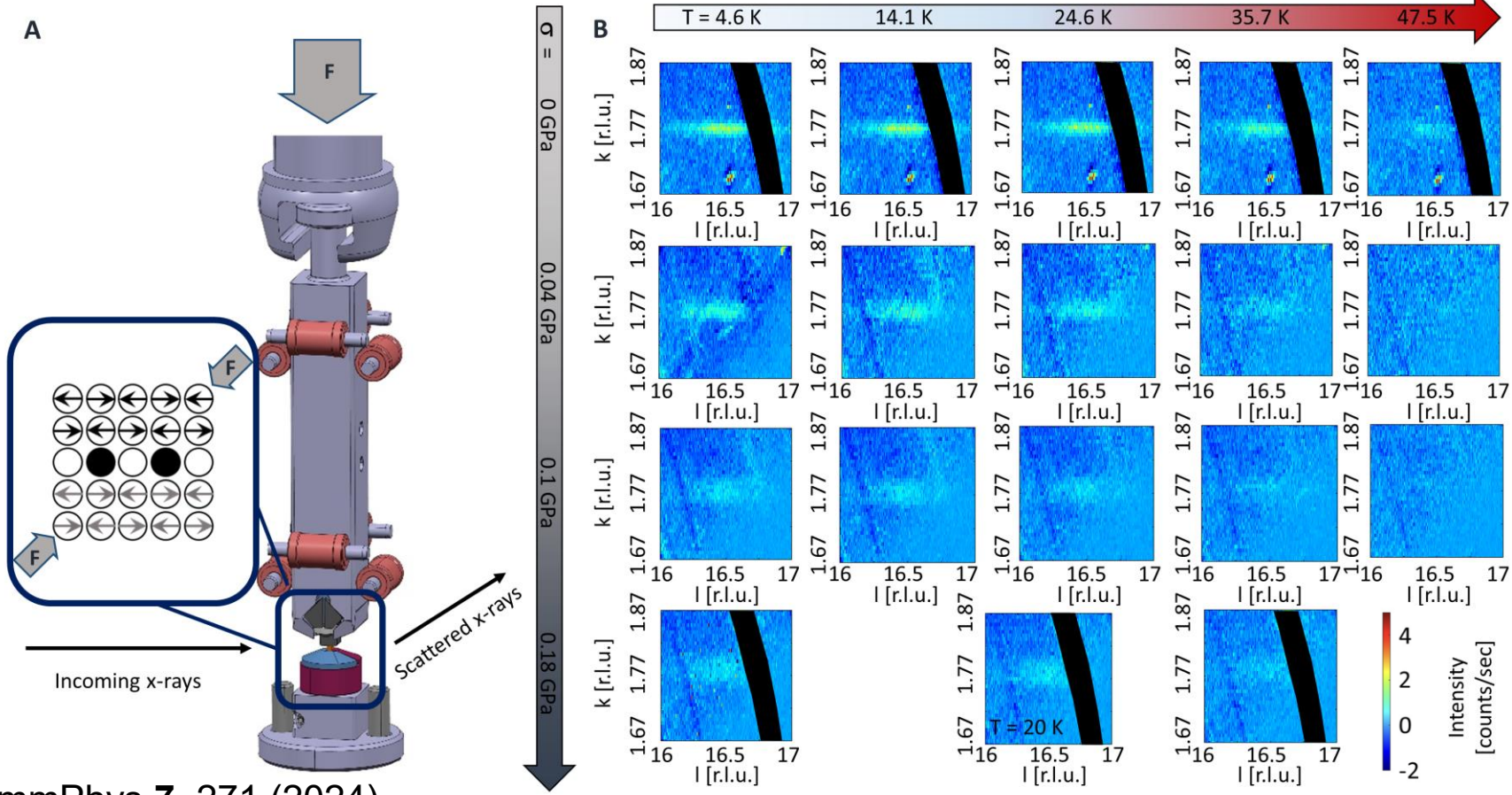
NCommPhys **7,** 271 (2024)

Uniaxial pressure effects on charge order



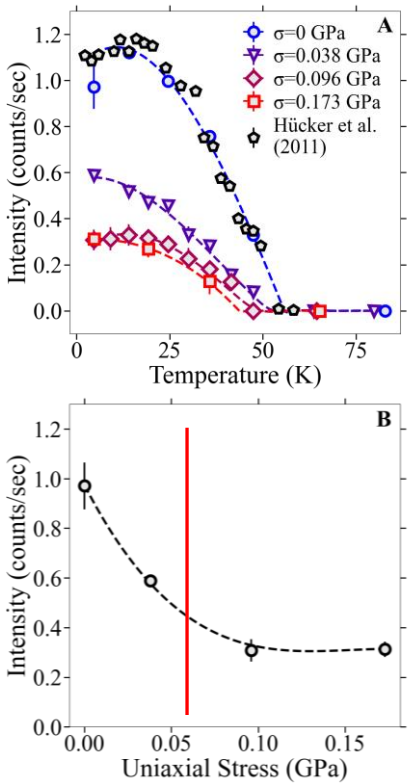
NCommPhys **7,** 271 (2024)

Uniaxial pressure effects on charge order



NCommPhys **7,** 271 (2024)

CDW evolution

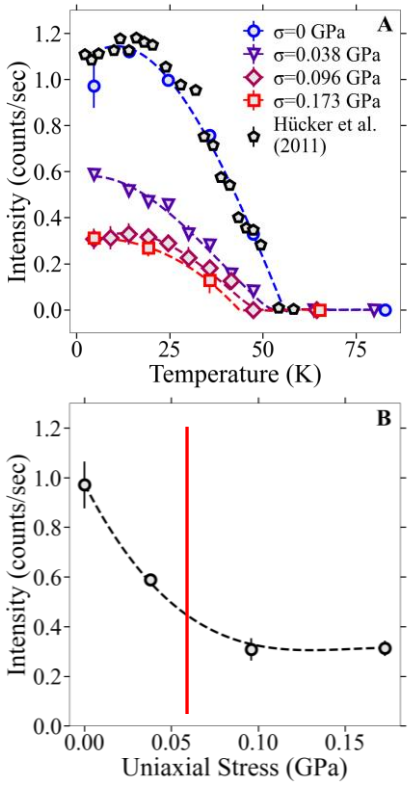


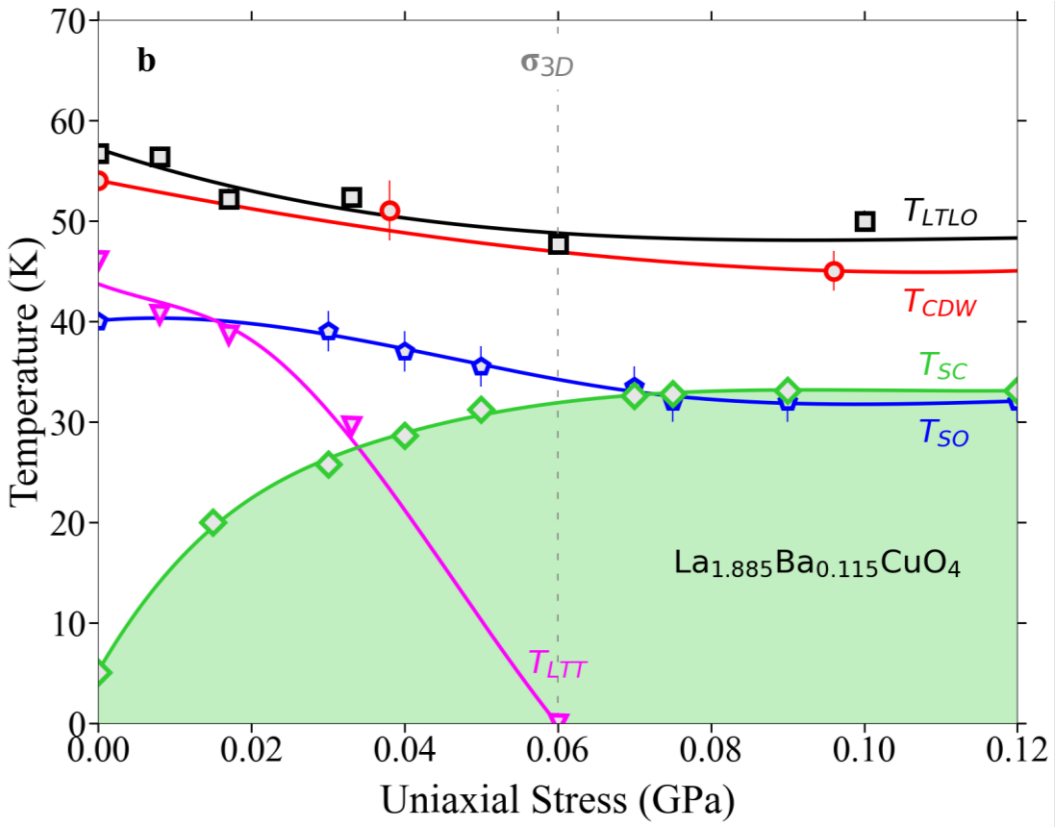
NCommPhys **7,** 271 (2024)

Full Phase Diagram

CDW is suppressed with uniaxial stress, but remains constant above critical value

Optimally-sized charge order islands lead to the highest T_C





NCommPhys **7,** 271 (2024)

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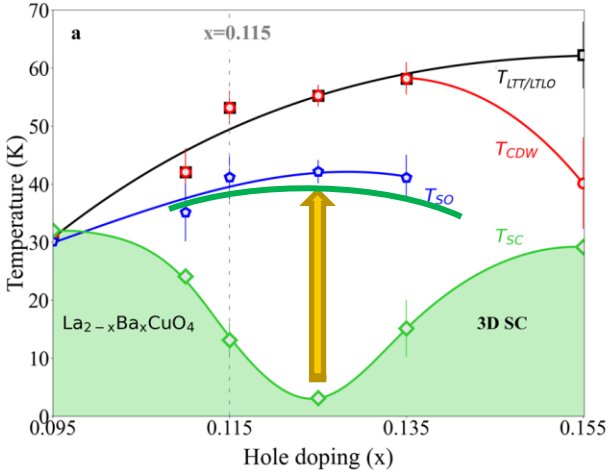
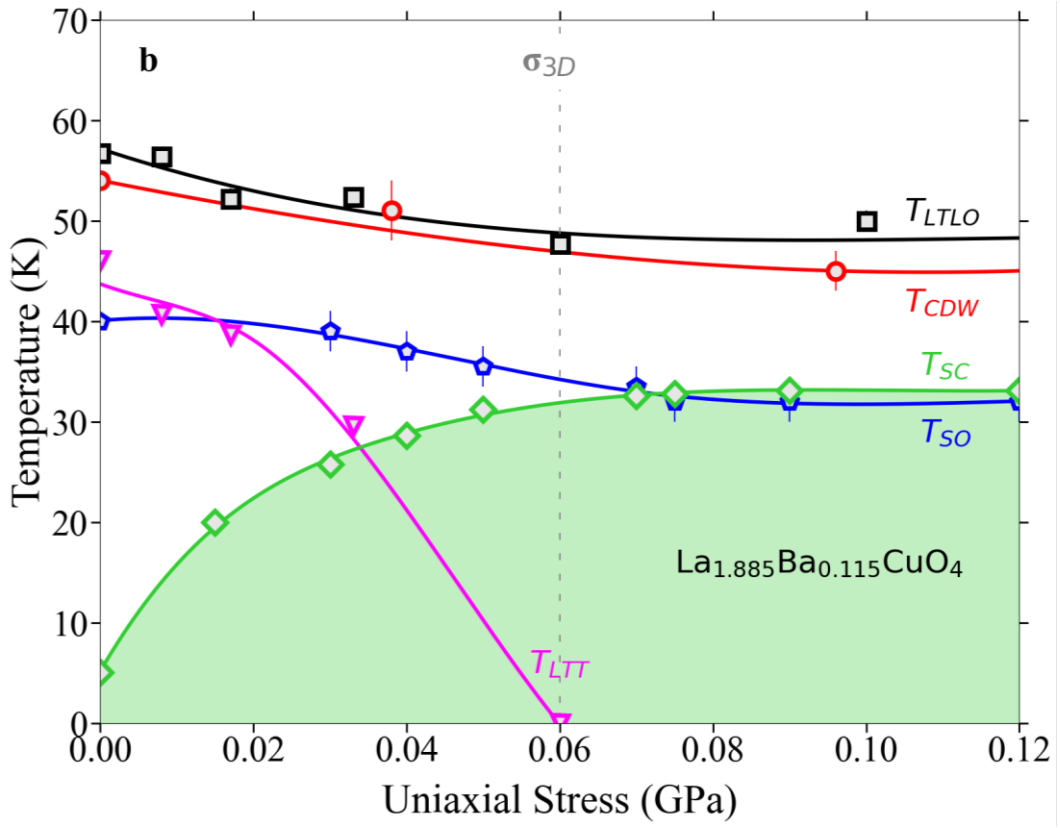
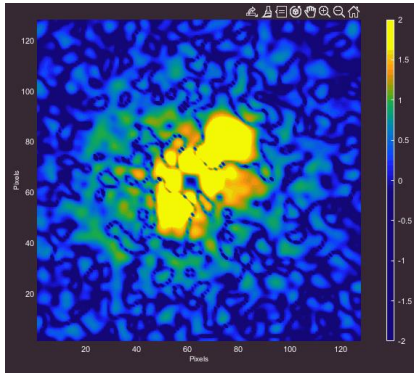


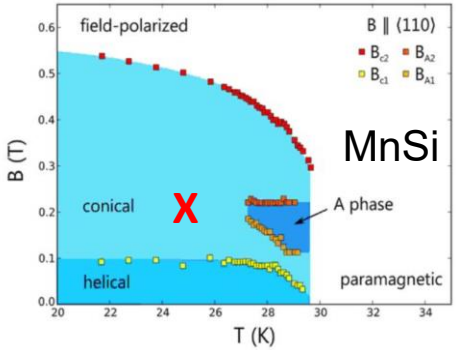


NCommPhys **7,** 271 (2024)

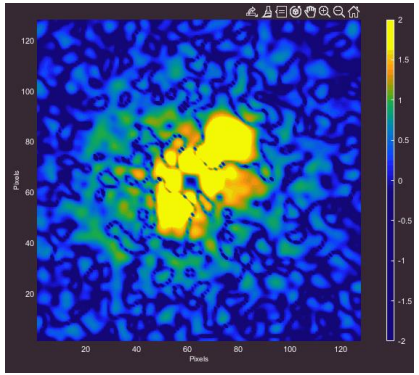
Neutron application: Skyrmion lattices

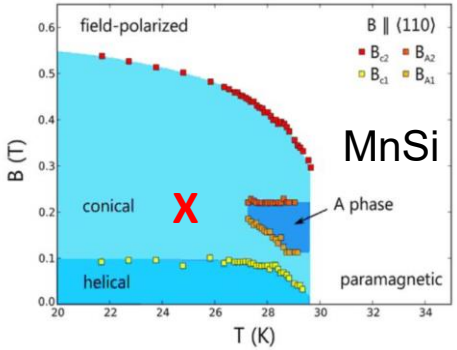
In-situ uniaxial pressure device. Example 2: SANS





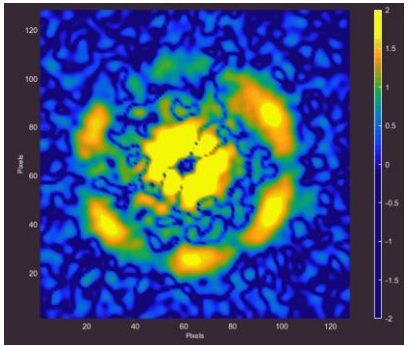
In-situ uniaxial pressure device. Example 2: SANS





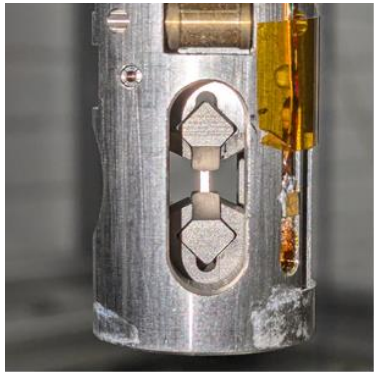
Force

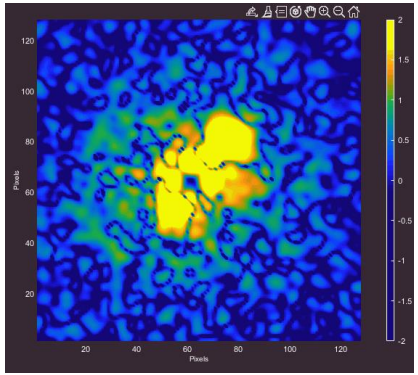
- Created Skyrmion lattice with strain !

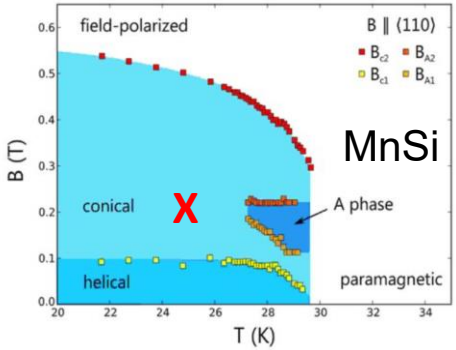


- Following Chacon 2015, but we keep T and B constant and just apply uniaxial pressure

In-situ uniaxial pressure device. Example 2: SANS





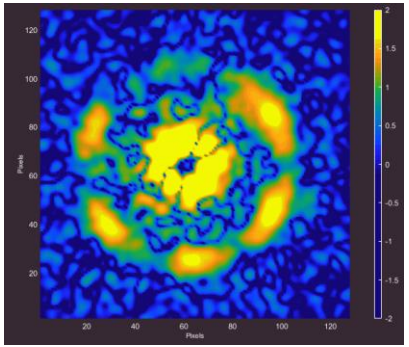


Force

- Created Skyrmion lattice with strain !

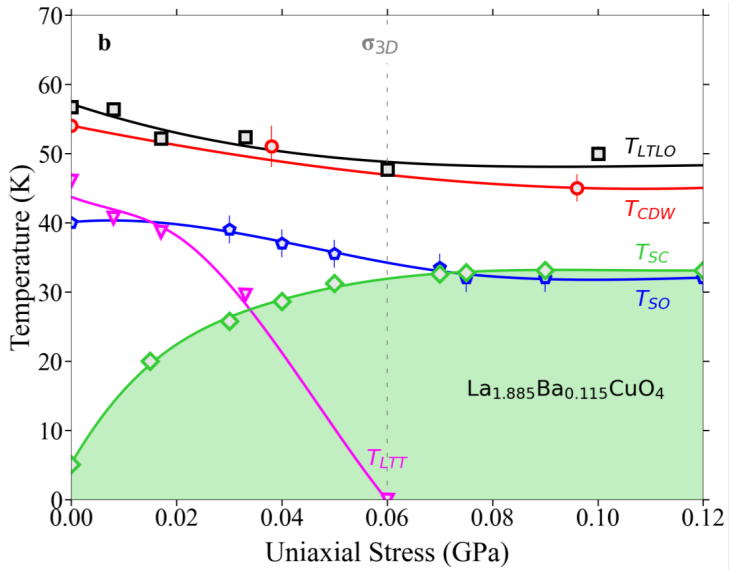
Cd shielding

Gd2O3 paint



- Following Chacon 2015, but we keep T and B constant and just apply uniaxial pressure

Uniaxial Control



Uniaxial pressure is a precise tool to tune competing phases

Combination with scattering enables microscopic understanding

In LBCO, uniaxial pressure:
- maximizes TC
- suppresses LTT phase
- reduces charge-order volume
- charge order persists

New devices available for the user program at PSI

NCommPhys **5**, 296 (2022)
RSI **94**, 013906 (2023)
PNAS, e2303423120 (2023)
NCommPhys **7,** 225 (2024)
NCommPhys **7,** 271 (2024)

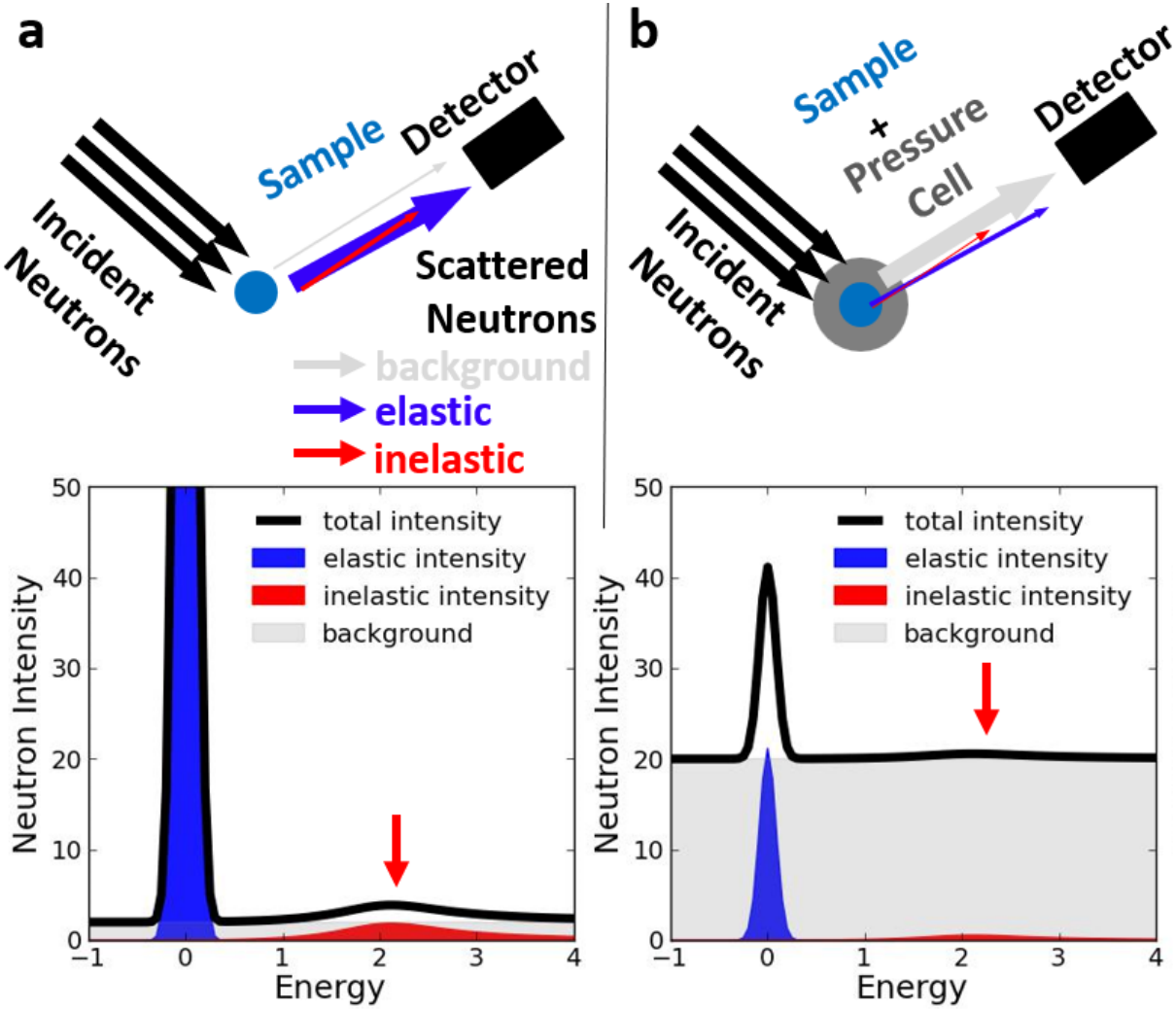
High Pressure and background management

Sometimes very weak signals (especially inelastic)

Effect of P-cell:

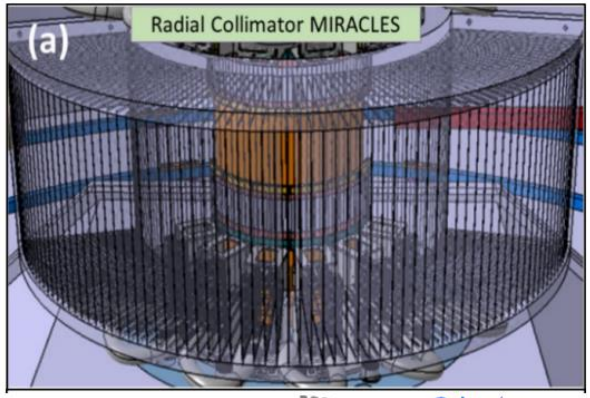
1. reduced transmission
   -> smaller signal

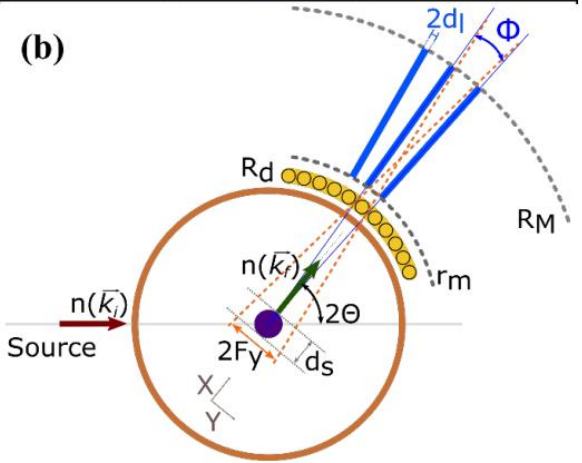
2. scattering of the untransmitted neutrons
   -> increased noise



Figures from Marc Janoschek

Collimation, shielding and material choice





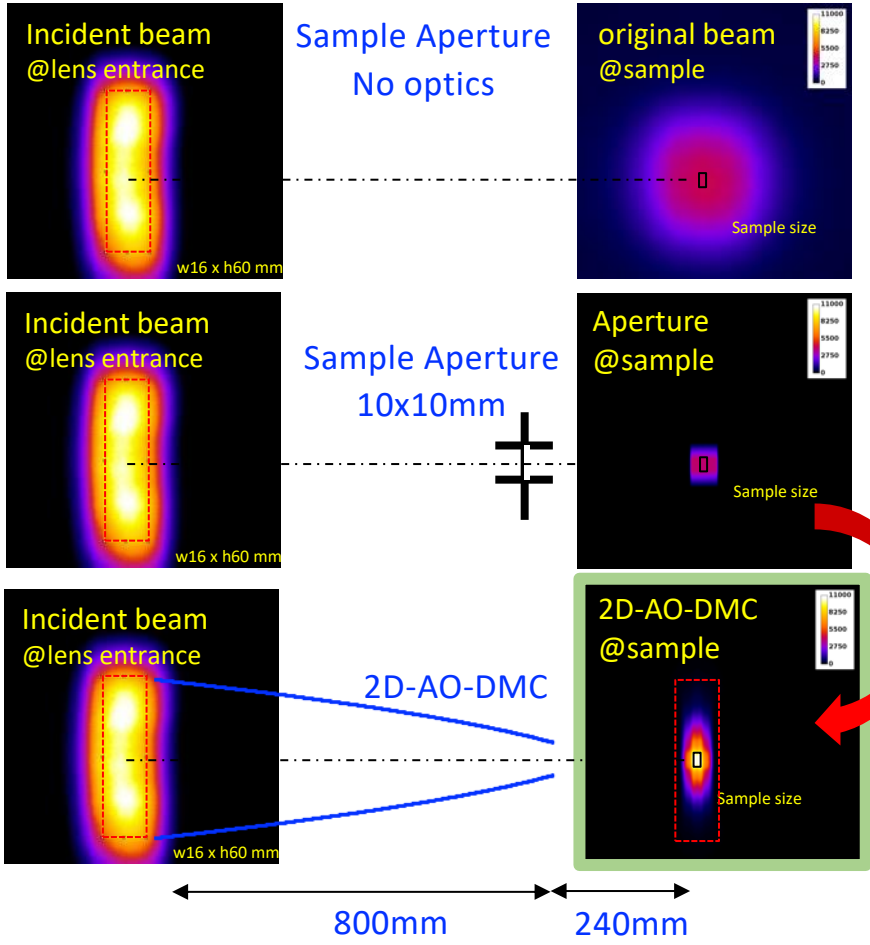
Cd shielding

Gd2O3 paint

Table 1. Neutron transmission and mechanical yield strength of various materials used for high-pressure cells in neutron scattering.

Material	Yield Strength (kbar)	Transmission (1 cm)
CuBe	15	37 %
NiCrAl	20	27 %
TiZr	12	**65 %**
Alumina	25	**68 %**

Adaptive neutron optics



Beam flux gain x2.4!

@ 2.46Å

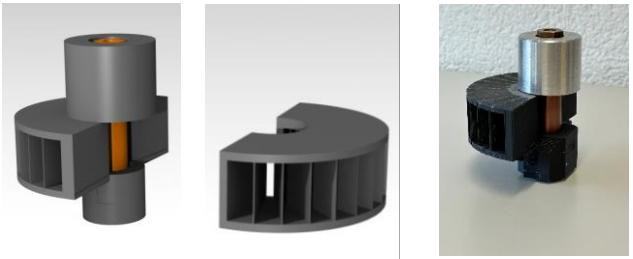





Masako Yamada
Andrea Plank
Christine Klauser
Uwe Filges
Zhanwen Ma
Sascha Thürsam

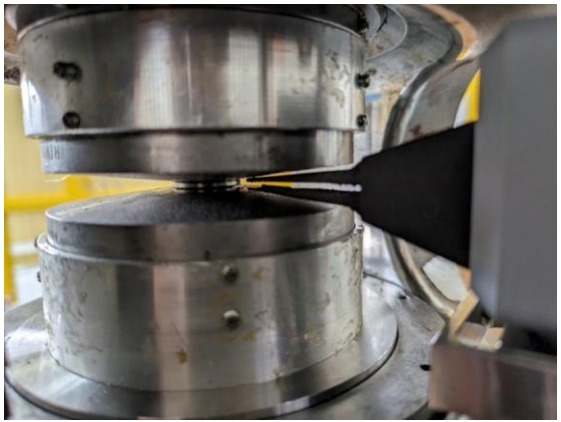
Making the best of what we have

PSI



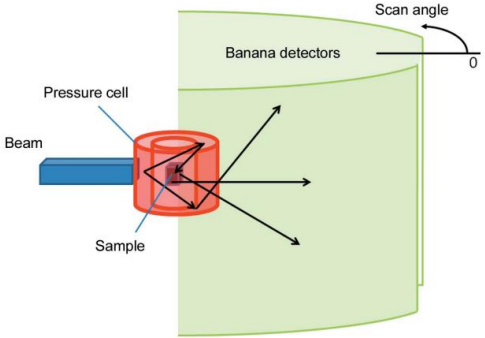
3D-printed neutron-absorbing Collimator
for a clamp cell. Tested at CAMEA

3D-printed neutron-absorbing collimator for PE press



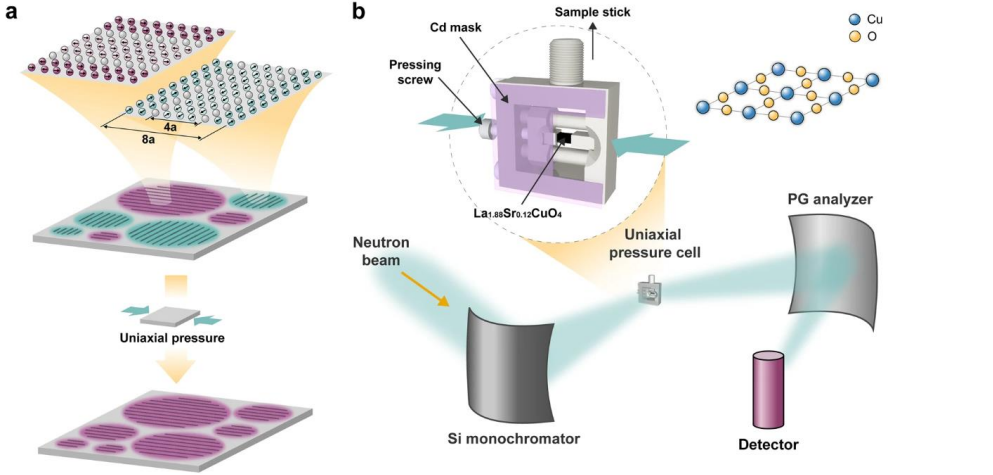
High Pressure and background management

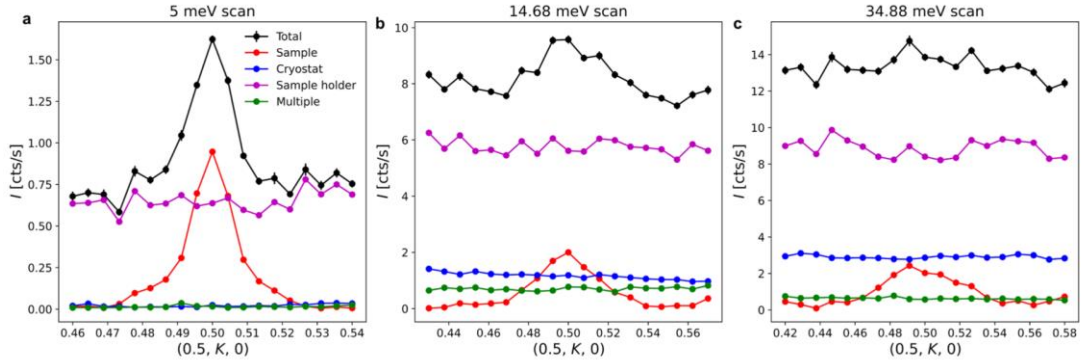
Calculating the response



Neutron ray tracing using McStas Union package

M. Bertelsen, 2017





High Pressure Database and Calculations

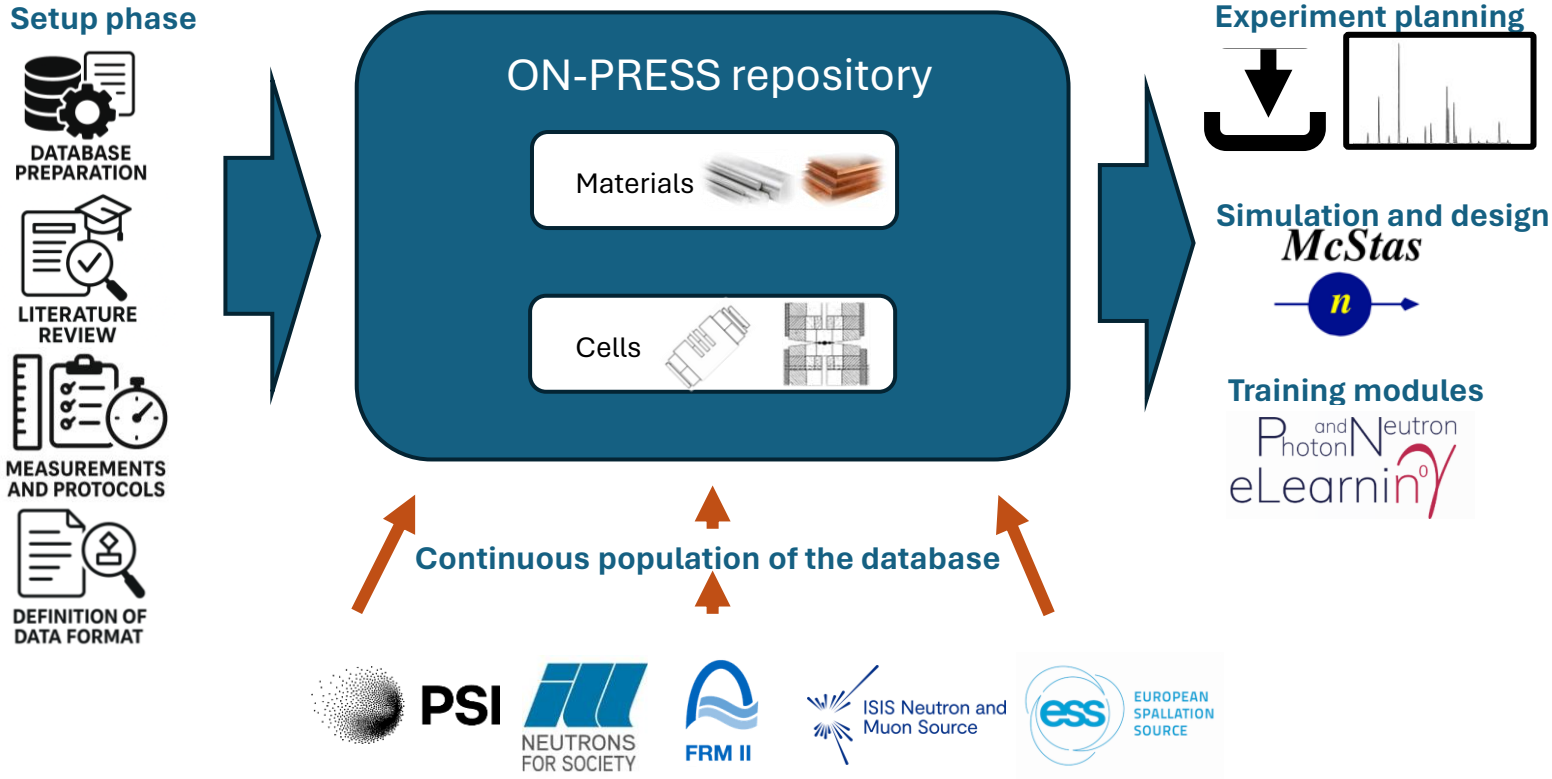
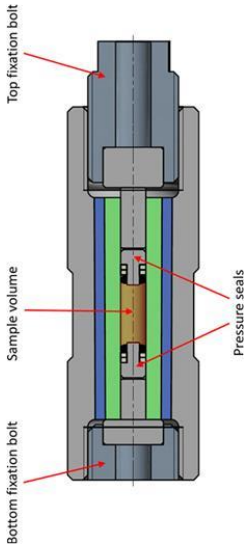


Figure 1. The graphical representation of the ON-PRESS project. The backbone of the database will be the technical preparation for data storage, codes for the instrument-to-database pipeline and the establishment of unified formats and protocols. The repository will then be populated with a series of entries measured by us and gathered from literature. Subsequently, it will be continuously open so that all research infrastructures and individual researchers can upload the data. It will be set up in a way that the important data can be downloaded for experiment planning and evaluation as well as simulation and training purposes.

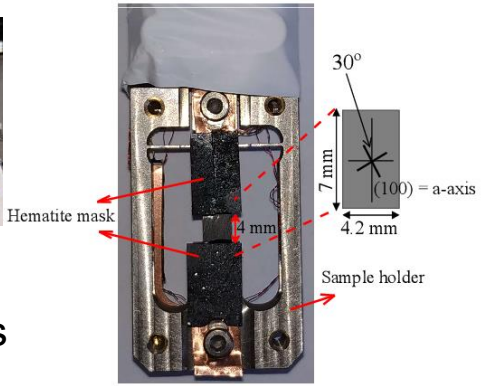
High pressure science with muons

High Pressure Research with Muons



Rustem Khasavov
Matthias Elender

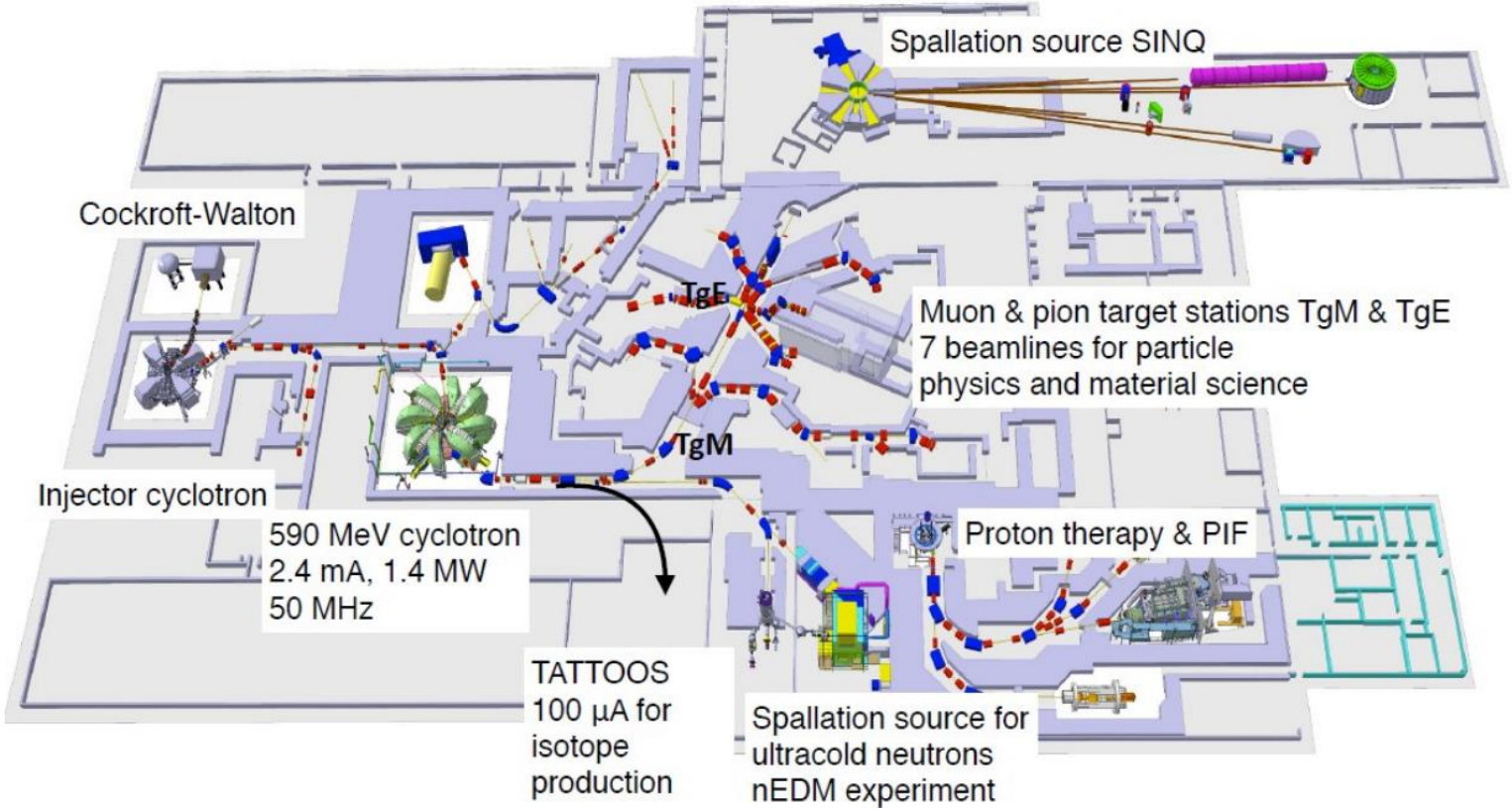
Zurab Guguchia
Hubertus Luetkens
+ TU Dresden



Khasanov, JAppl. Phys. **132**, 190903 (2022)

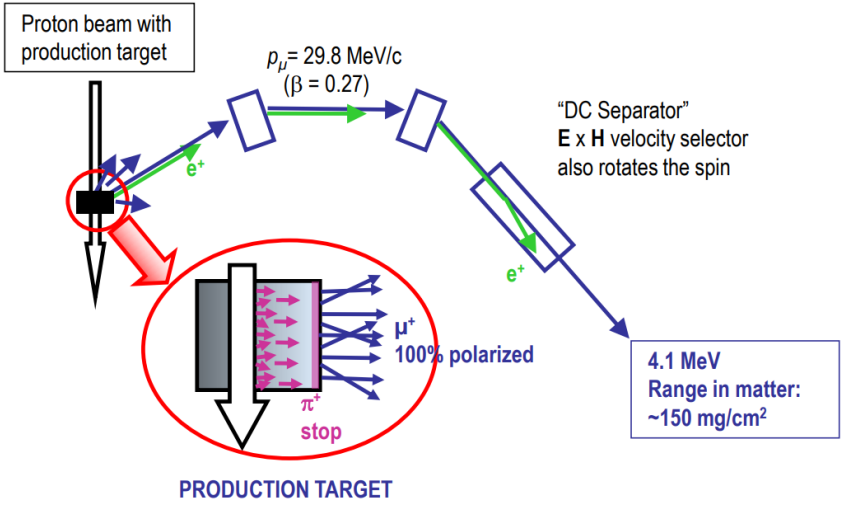
Ghosh et al., RSI **91**, 103902 (2020)

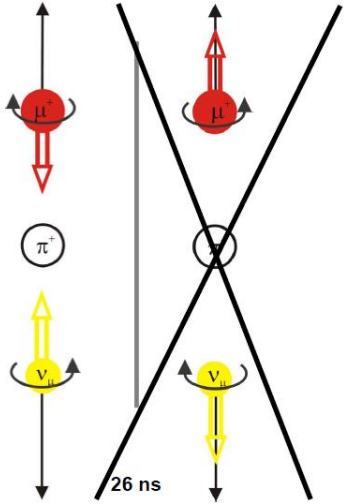
Proton Accelerator



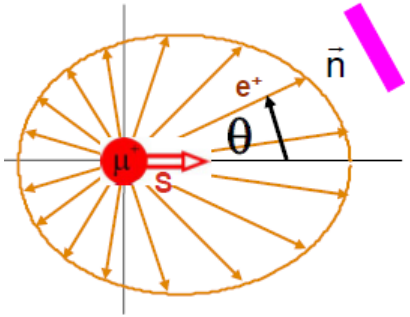
Muon Spin Rotation

Parity violation in pion decay:
only left-handed neutrinos exist
-> Polarized muons!



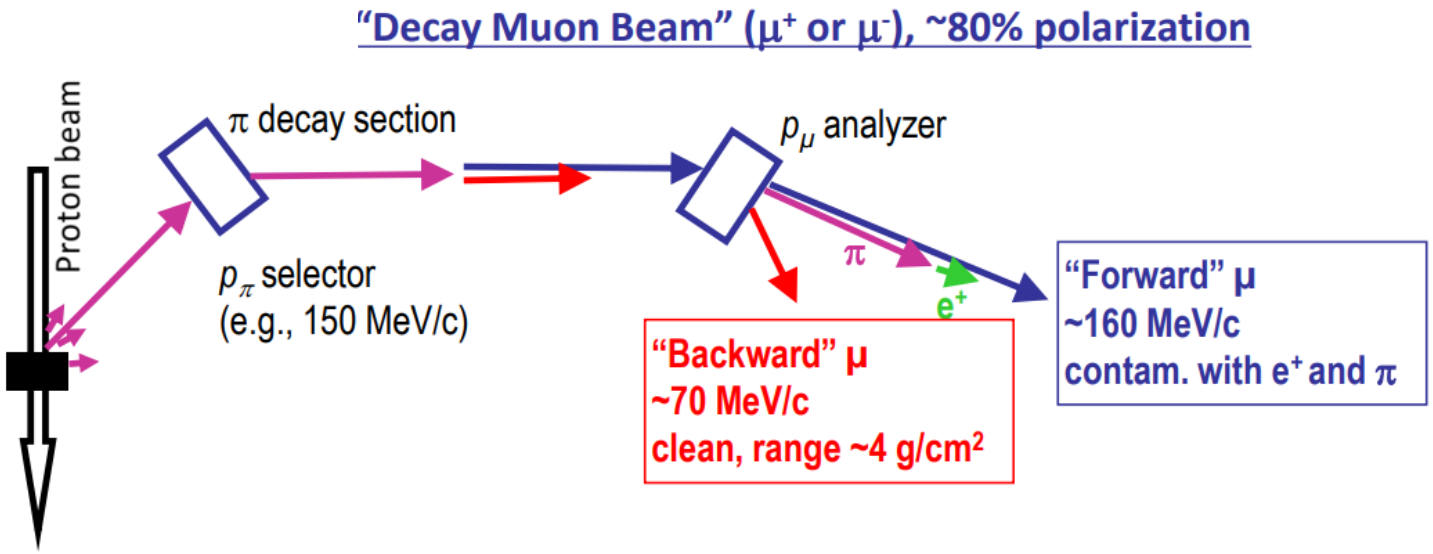


$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

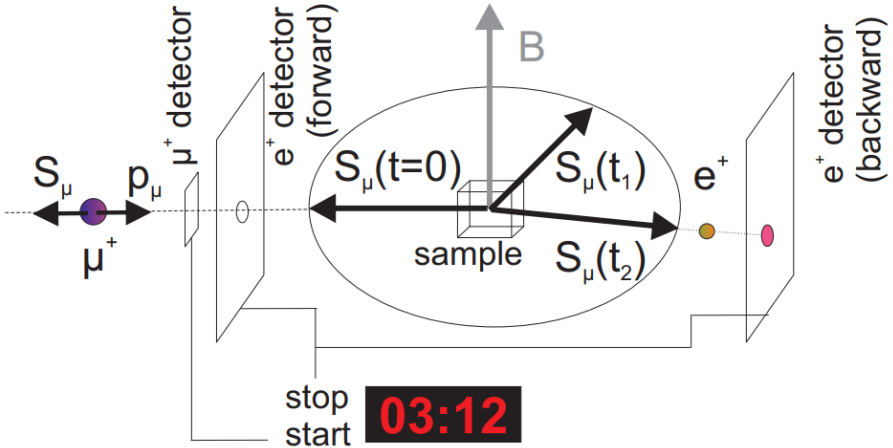


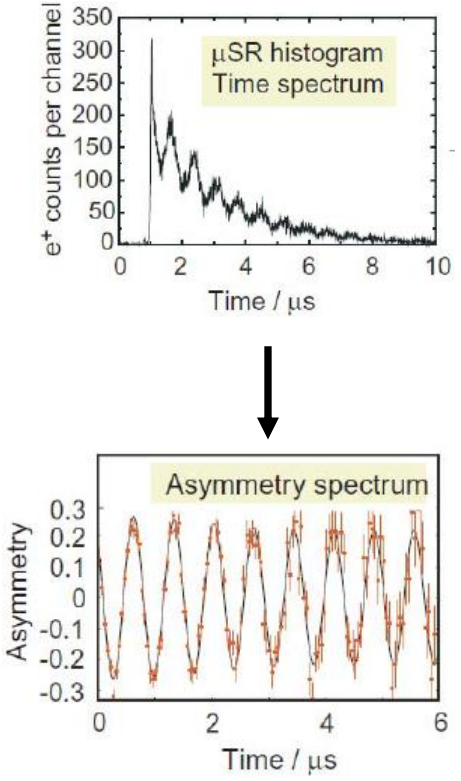
Parity violation in muon decay:
positrons preferentially emitted in the direction of muon spin
-> time evolution of muon spin!

High pressure science with muons

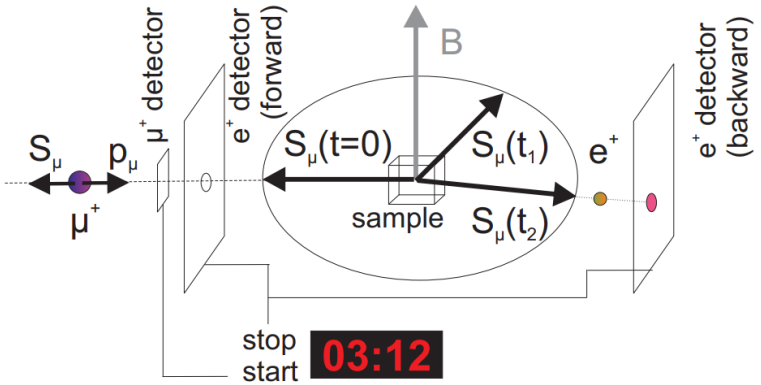


Muon Spin Rotation

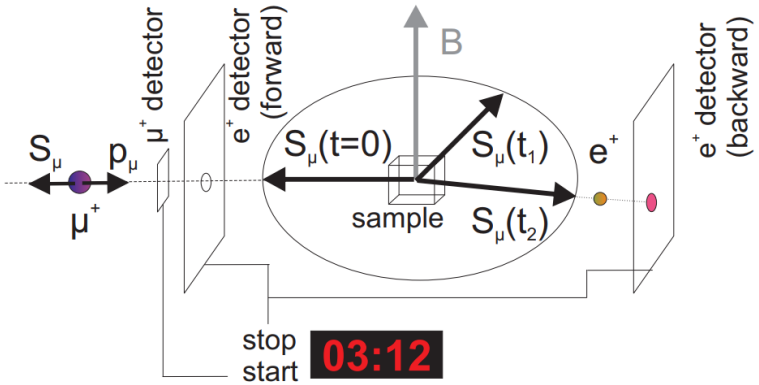


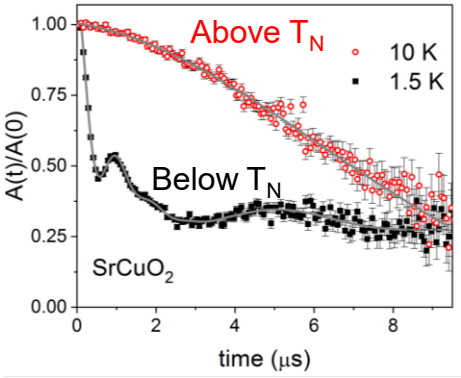


Muon Spin Rotation

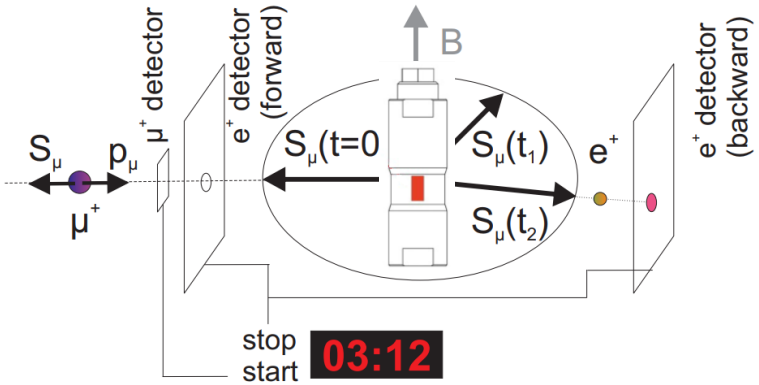


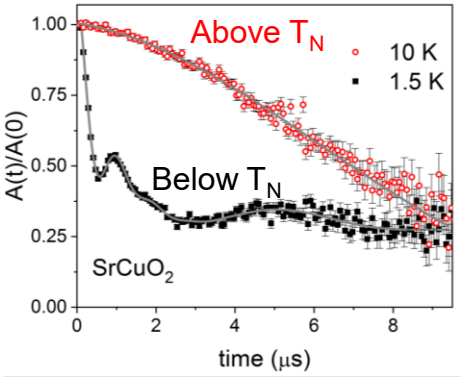
Muon Spin Rotation





Muon Spin Rotation





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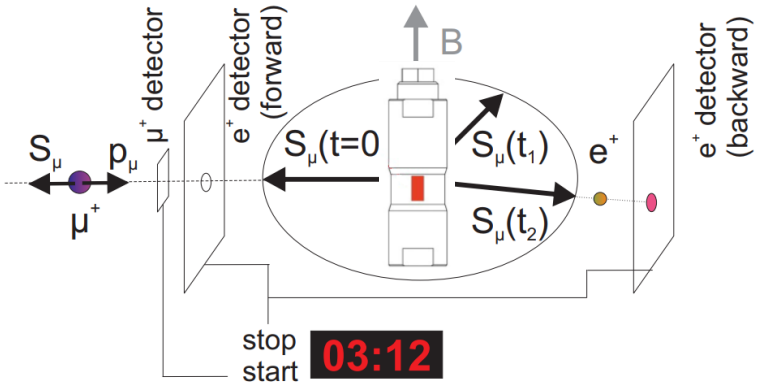

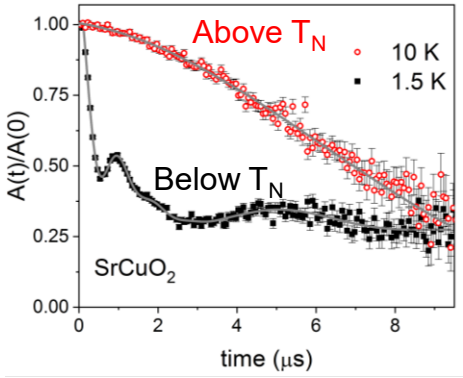

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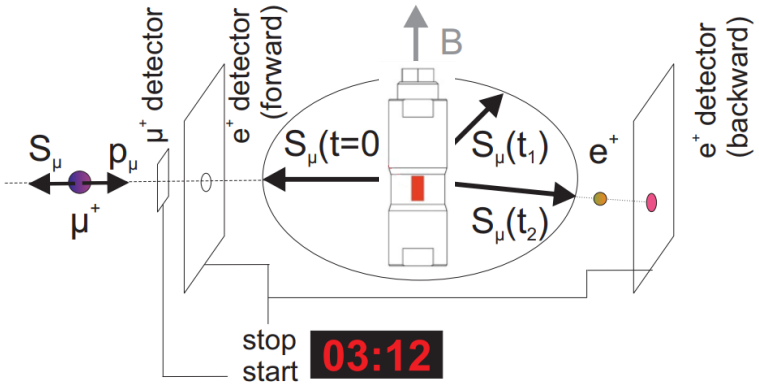
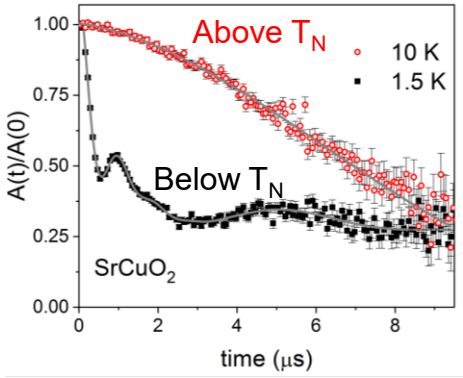
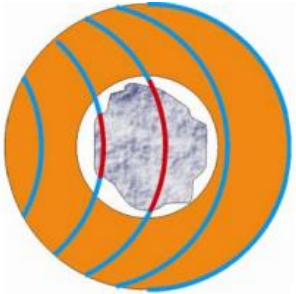
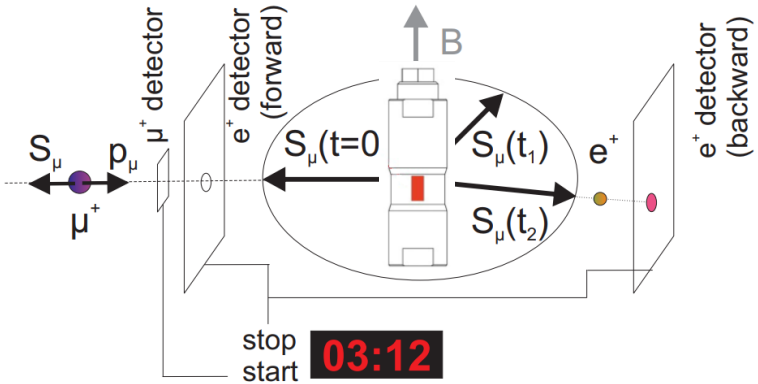


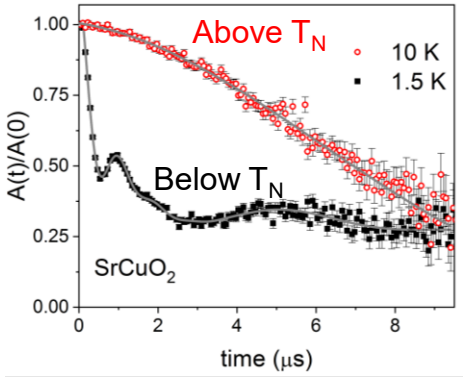


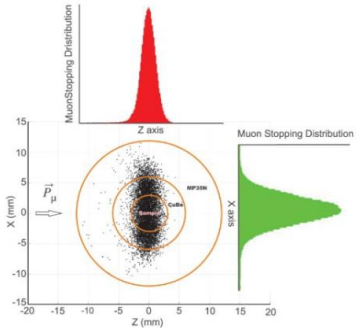


Different energies – different implantation depth

Muon Spin Rotation





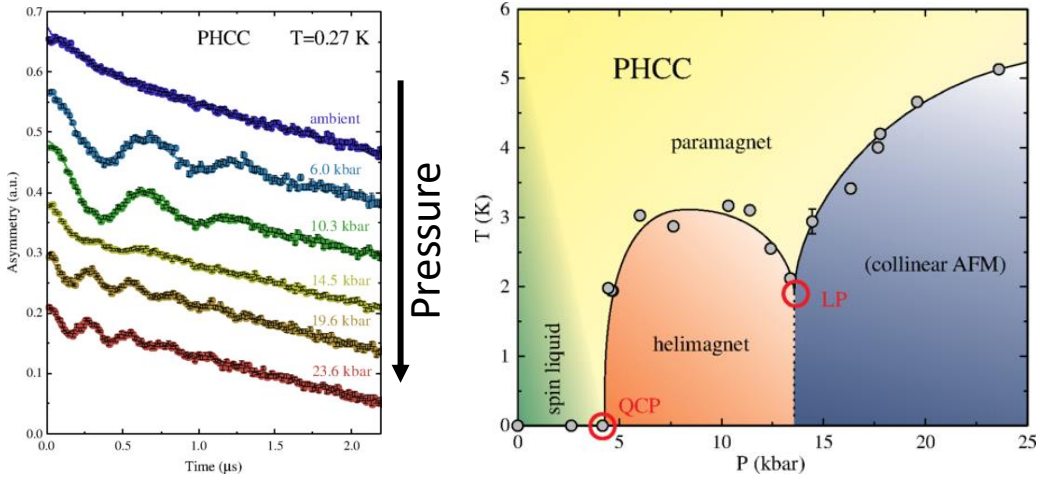


Collimation + varying muon energy
> optimal stopping profile

Hybrid cells: MP35 outside/CuBe inside
> high pressure and low background
Shermadini et al.
High Pressure Research **37**, 449 (2017)

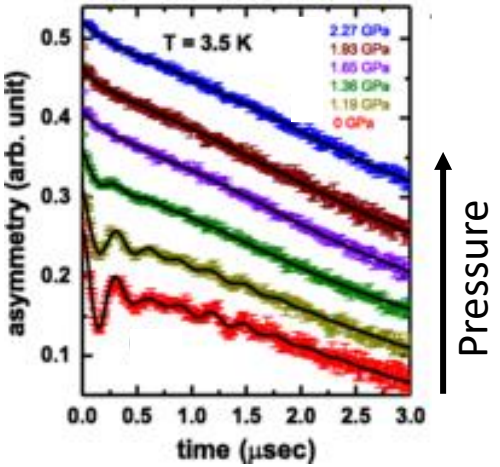
High Pressure μSR Highlights

Inducing order in a quantum magnet



Thede et al., PRL **112**, 087204 (2014)

Suppressing magnetism in Kitaev systems



Majumder, et. al PRL **120**, 237202 (2018)

Can we do DAC experiments with muons?

Can we do DAC experiments with muons?

High Energy Physics - Experiment

[Submitted on 10 Nov 2021]

Science Case for the new High-Intensity Muon Beams HIMB at PSI

M. Aiba, A. Amato, A. Antognini, S. Ban, N. Berger, L. Caminada, R. Chislett, P. Crivelli, A. Crivellin, G. Dal Maso, S. Davidson, M. Hoferichter, R. Iwai, T. Iwamoto, K. Kirch, A. Knecht, U. Langenegger, A. M. Lombardi, H. Luetkens, F. Meier Aeschbacher, T. Mori, J. Nuber, W. Ootani, A. Papa, T. Proksch, F. Renga, S. Ritt, M. Sakurai, Z. Salman, P. Schmidt-Wellenburg, A. Schöning, A. Signer, A. Soter, L. Stingelin, Y. Uchiyama, F. Wauters

In April 2021, scientists active in muon physics met to discuss and work out the physics case for the new High-Intensity Muon Beams (HIMB) project at PSI that could deliver of order $10^{10}\,\mathrm{s}^{-1}$ surface muons to experiments. Ideas and concrete proposals were further substantiated over the following months and assembled in the present document. The high intensities will allow for completely new experiments with considerable discovery potential and unique sensitivities. The physics case is outstanding and extremely rich, ranging from fundamental particle physics via chemistry to condensed matter research and applications in energy research and elemental analysis. In all these fields, HIMB will ensure that the facilities SμS and CHRISP on PSI's High Intensity Proton Accelerator complex HIPA remain world-leading, despite the competition of muon facilities elsewhere.

Comments: 116 pages, 42 figures
Subjects: **High Energy Physics - Experiment (hep-ex)**; Materials Science (cond-mat.mtrl-sci); High Energy Physics - Phenomenology (hep-ph)
Cite as: arXiv:2111.05788 **[hep-ex]**
(or arXiv:2111.05788v1 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2111.05788

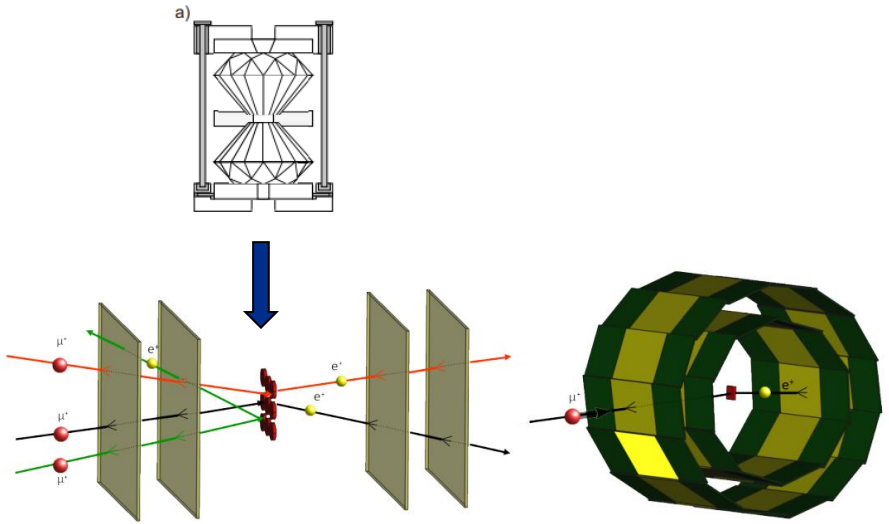
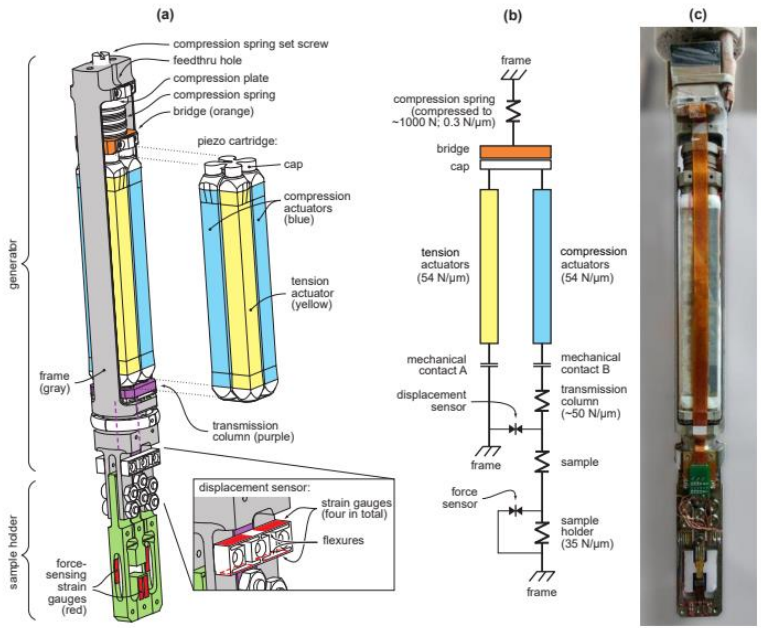
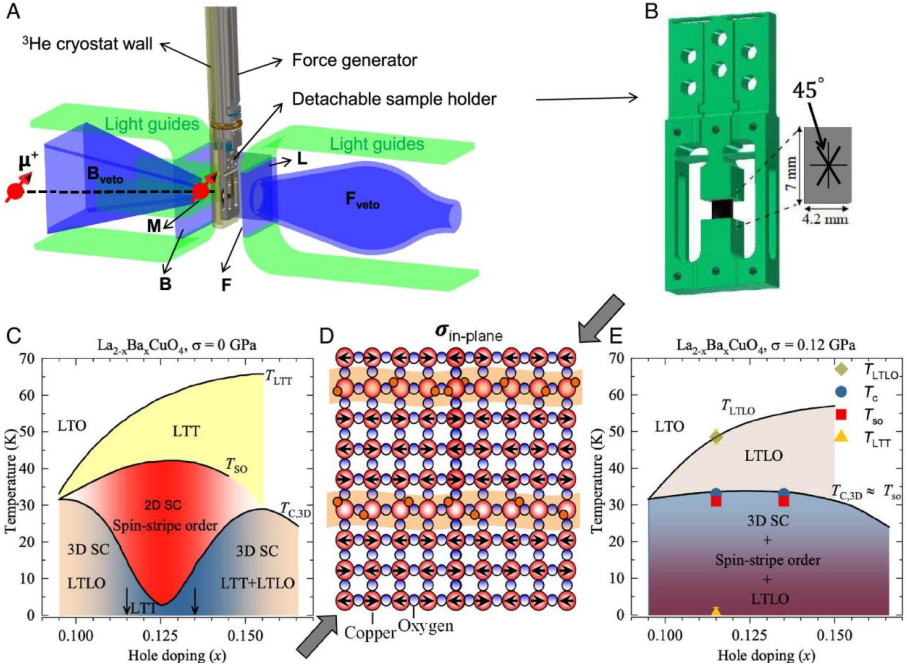


Figure 31: Sketch of the vertex detection scheme for future μSR instruments.

Ongoing vertex detection experiments (1mm spot)
Shutdown of SINQ and SmuS in 2028
Upgrade of one of the beamlines soon after

Uniaxial cell for muons





Ghosh et al., Rev. Sci. Instrum. **91**, 103902 (2020)

Guguchia et al., PNAS **121** (1) e2303423120 (2023)

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High Pressure Techniques for Neutrons, X-rays and muons

Sample Environment Training School

January 19th – 23rd 2026, Lund, Sweden