University of St Andrews

Max Planck Institute for Chemical Physics of Solids

Domain imaging and control in unconventional magnets

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Collaborators

Optics: Simli Mishra, Joe Orenstein, Fei Sun, Veronika Sunko

Single crystal growth: Naoki Kikugawa, Robin Perry, Dmitry Sokolov

Uniaxial pressure: Elena Gati, Hilary Noad

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University of California Berkeley, USA
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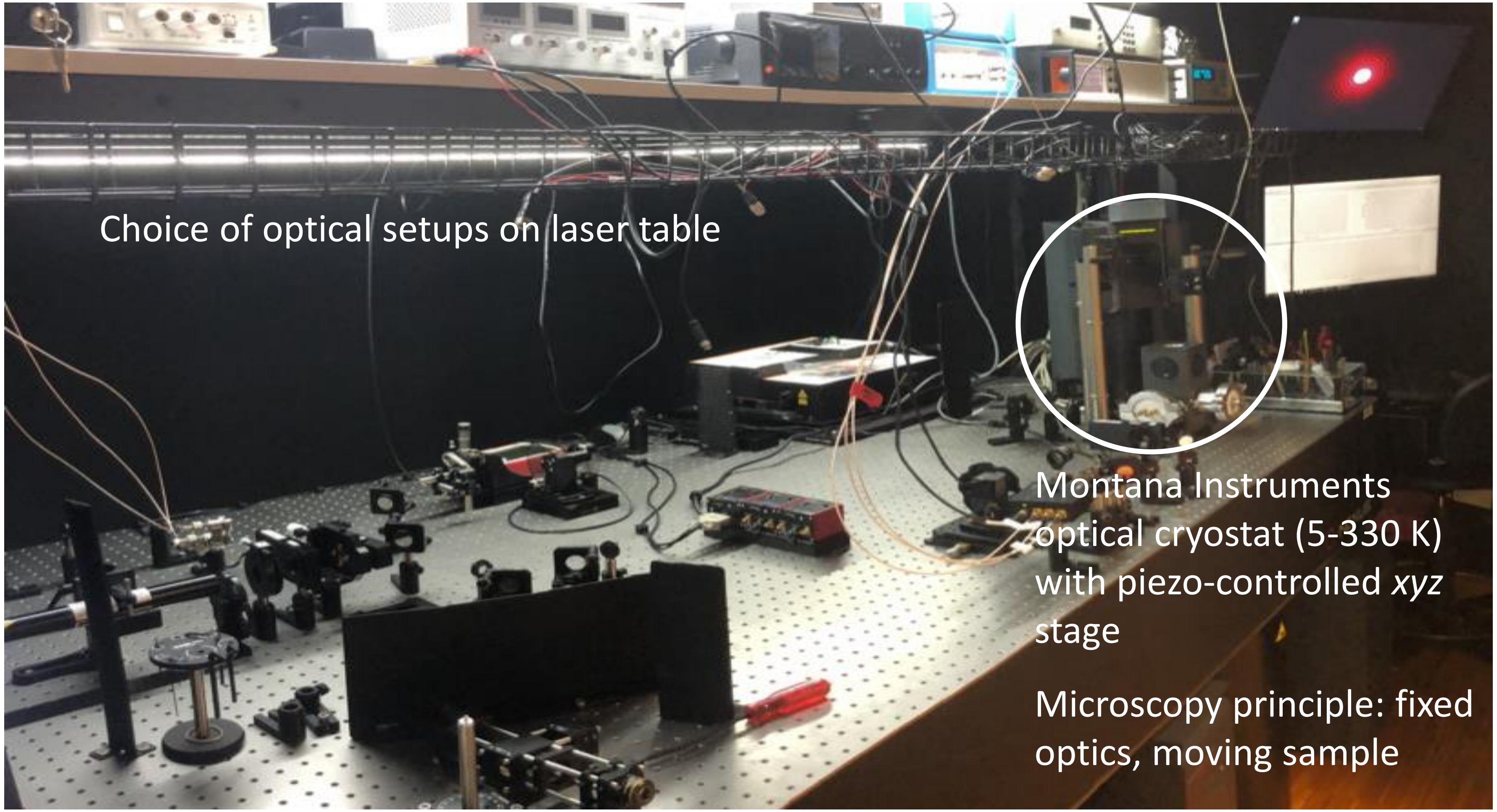
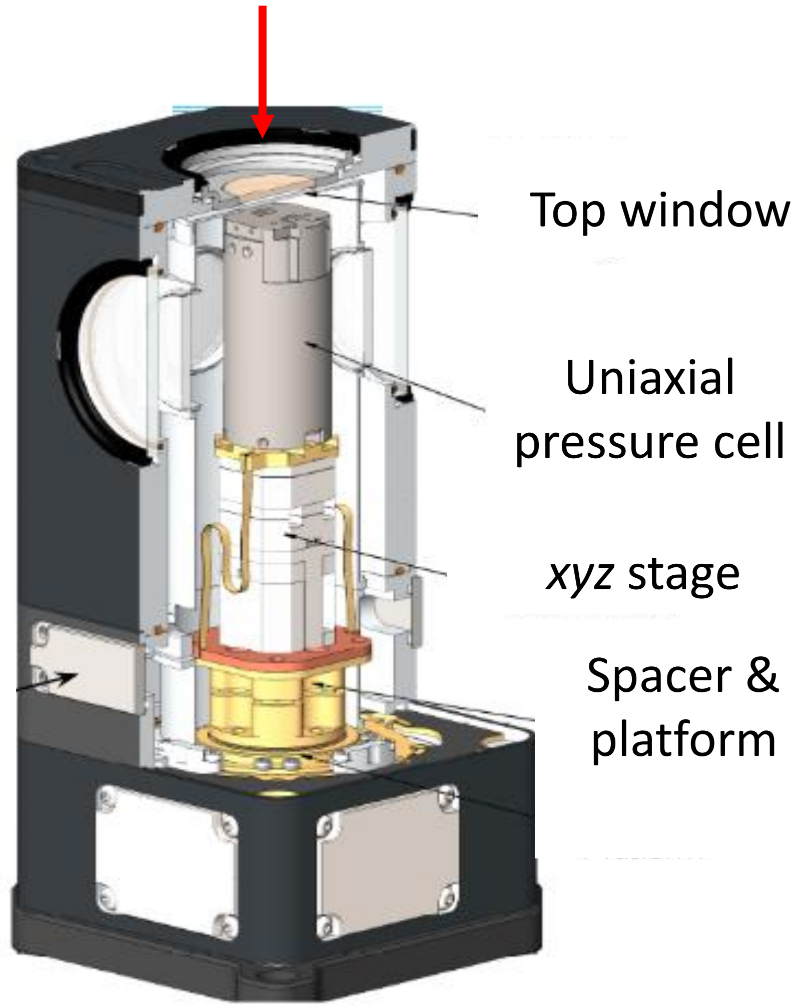
Microscopes come in many shapes and sizes

The basic idea – a cryo-optical microscope…..



…. with the special added feature of uniaxial pressure capability



Grand goal: capability of imaging domains and dynamics….

… using a range of tools

… and manipulating the domains if they couple to strain

Tools (in principle!): birefringence, Kerr rotation, thermal diffusivity, 2^{nd} harmonic generation, ultrafast pump-probe, all down to ~ 15 K

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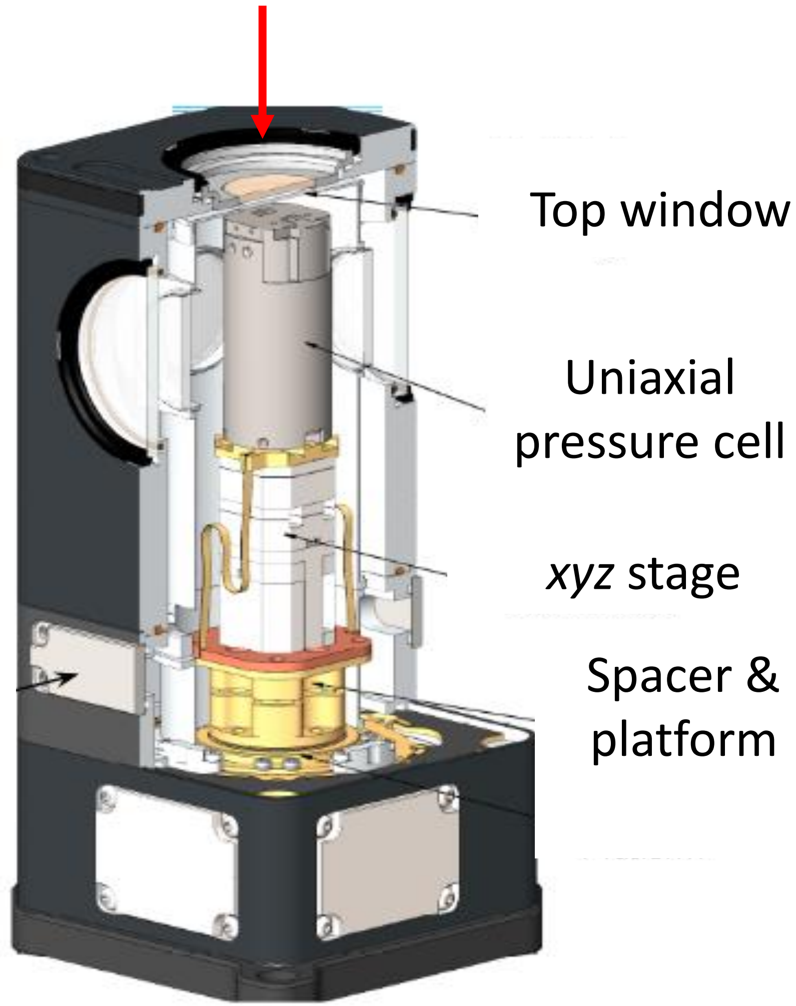

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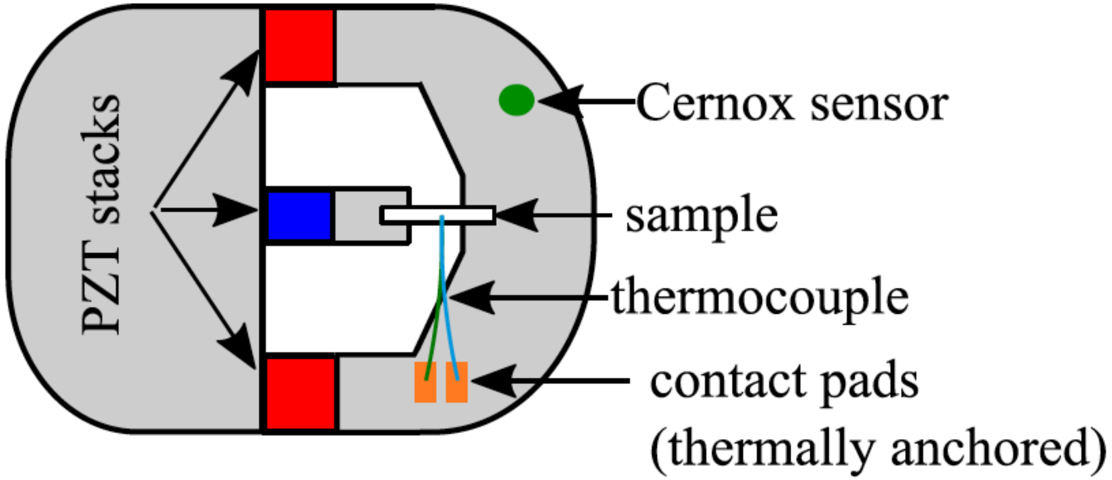
Even grander goal: do any of the above while also studying thermodynamics

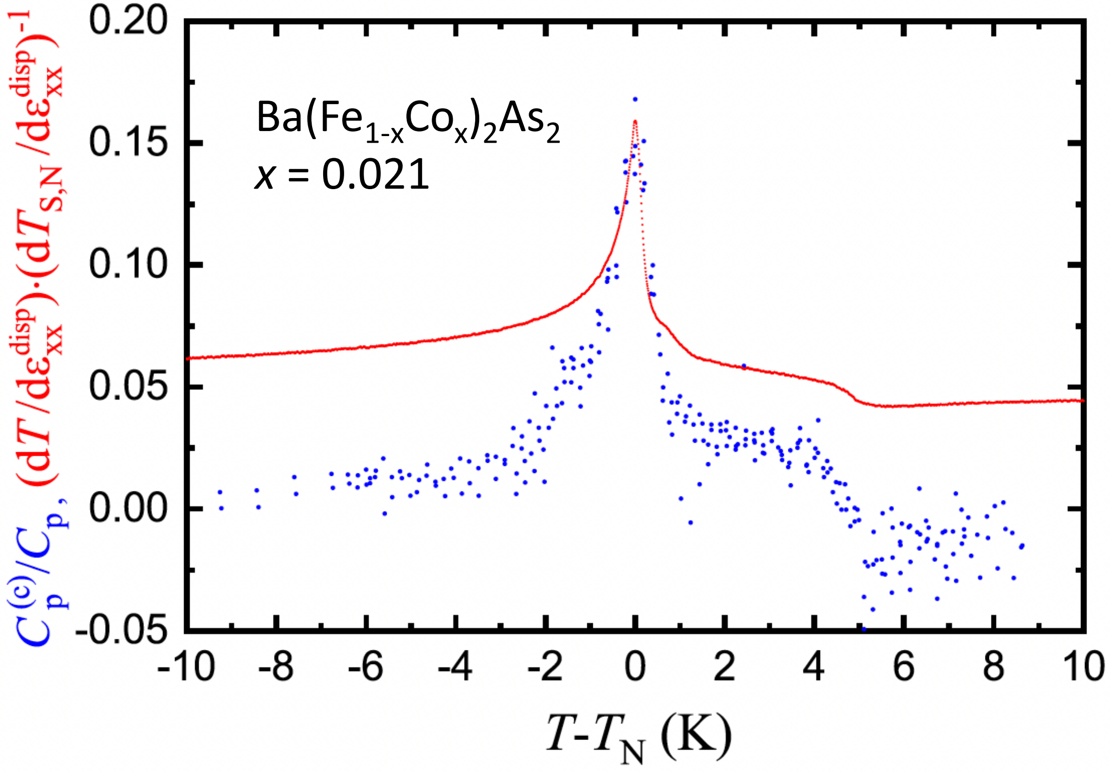
Recent development: the *a.c. elastocaloric effect*



$$\left(\frac{\Delta T}{\Delta \varepsilon}\right) \cong -\frac{T}{C}\left(\frac{\partial S}{\partial \varepsilon}\right)$$

Close analogy with the magneto-caloric effect:

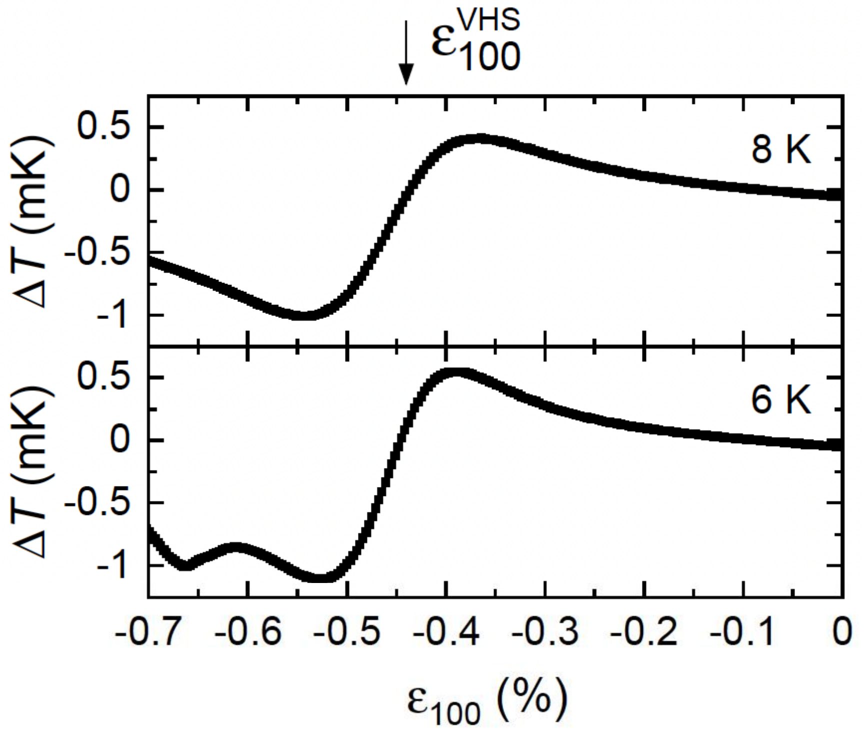
$$\left(\frac{\Delta T}{\Delta B}\right) \cong -\frac{T}{C}\left(\frac{\partial S}{\partial B}\right)$$

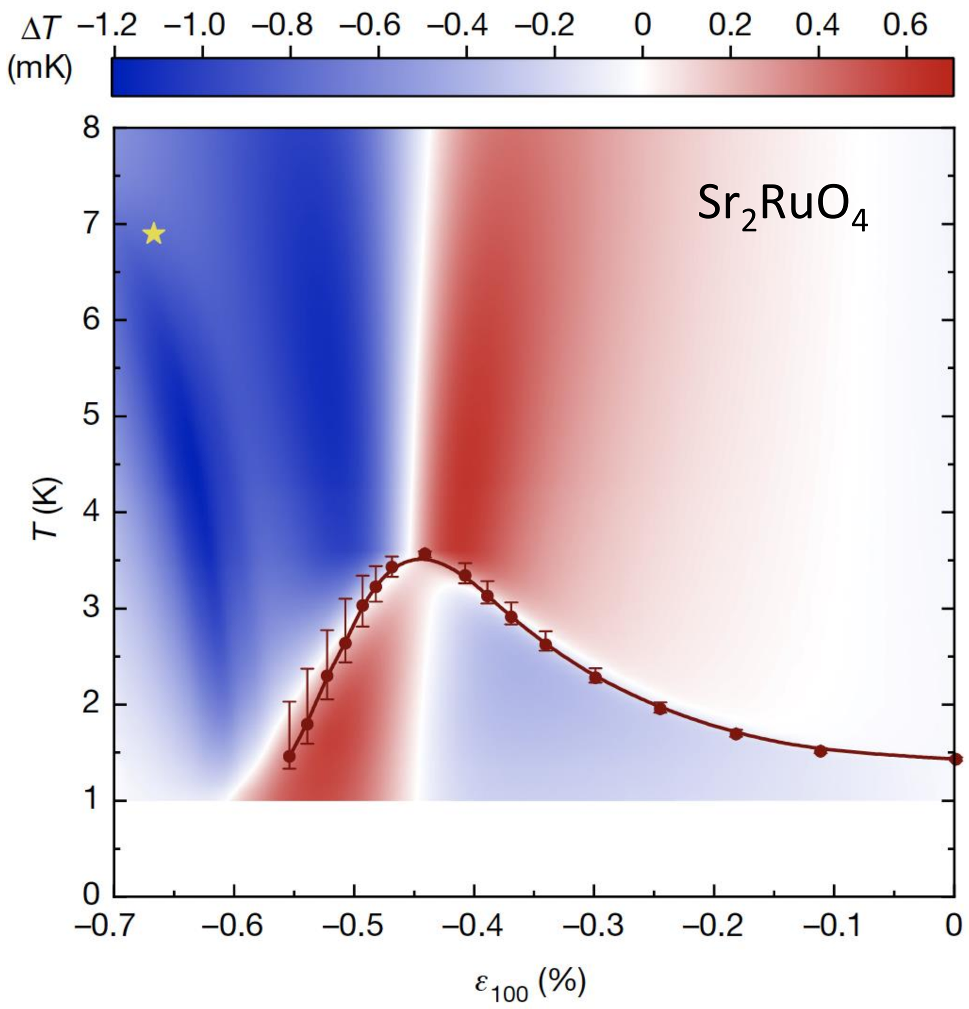


Achieve huge sensitivity improvement by using a.c. pressure actuation

M. Ikeda … I.R. Fisher, Rev. Sci. Inst. ***90****, 083902 (2019)*

Recent development: the *a.c. elastocaloric effect*



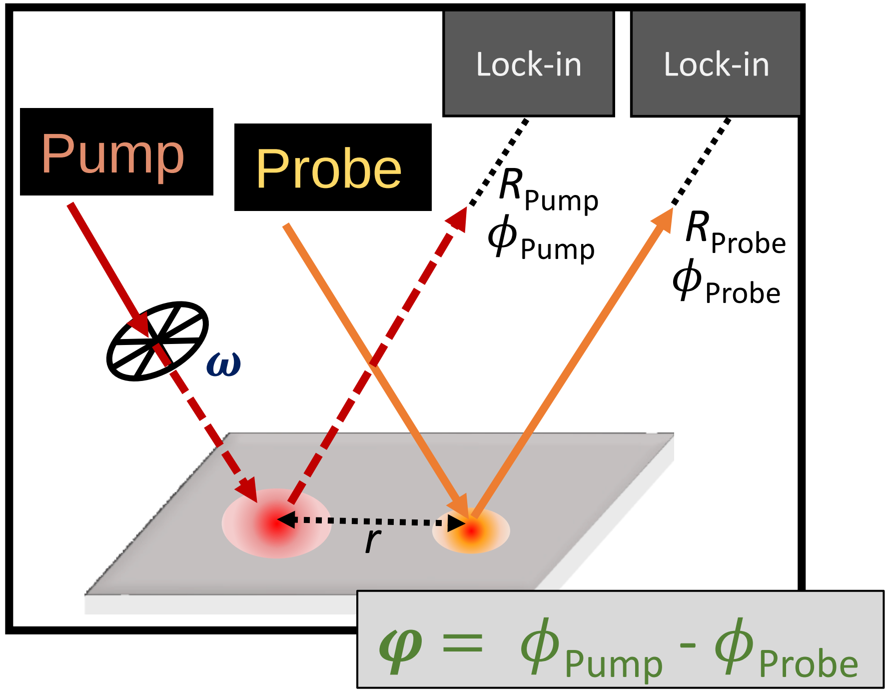


Due to high thermal precision ~µK/Hz$^{1/2}$, easily resolve elastocaloric signal in Sr_2RuO_4 for ppm applied a.c. strains superimposed on d.c. compression

Y.-S. Li et al., Nature ***607****, 276 (2022)*

Elastoscope vision: mount sample in pressure cell, expose top side to laser light, put thermometer on back for elastocaloric measurements as desired / necessary

Laser-based measurement of thermal diffusivity



$$\varphi = \sqrt{\frac{r^2\omega}{2D}}$$

Idea: use pump laser to apply an a.c. heat source

Detect a.c. change in optical reflectivity with probe laser at a known distance *d* from pump

Phase difference between pump and probe is related to the *thermal diffusivity D*

$D = \frac{\kappa}{C}$ so if you also measure *C* you deduce κ

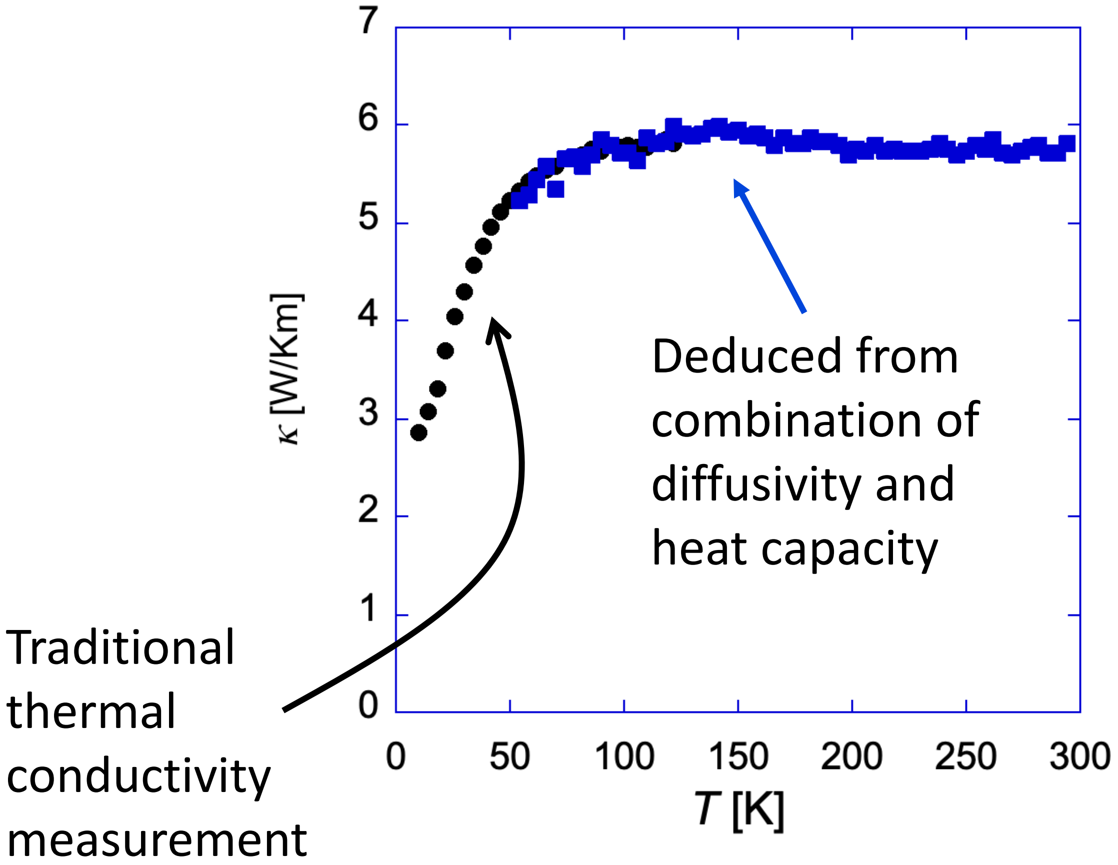
Well-suited to high temperature measurement so complementary to traditional methods

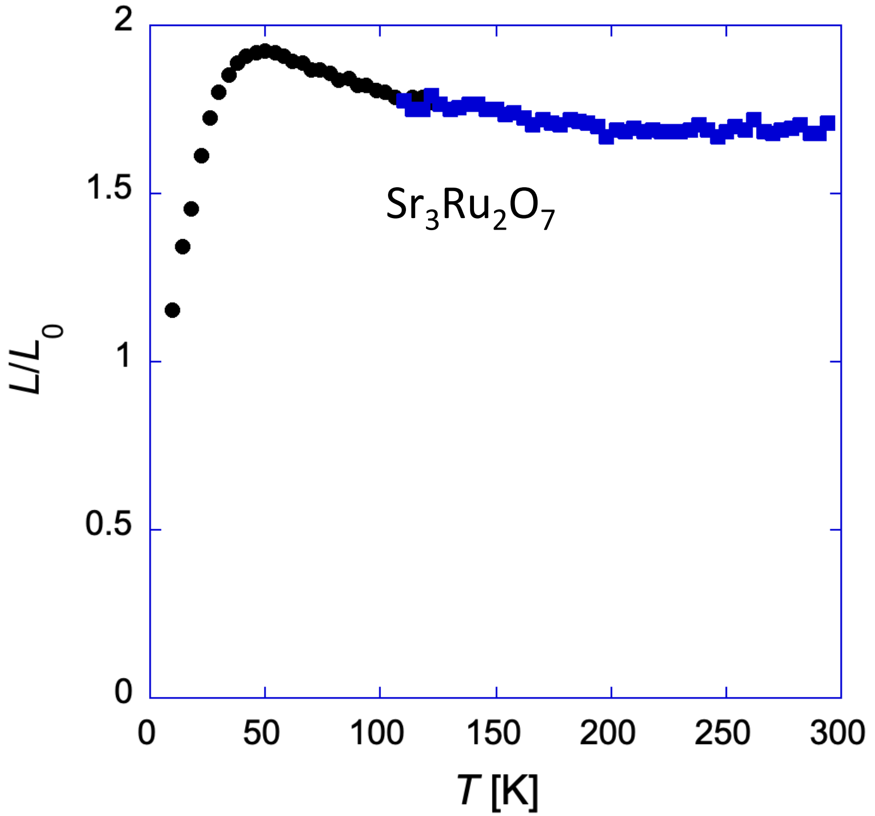
Also works with overlapping pump and probe beams, maximizing spatial resolution

Our instrument: *F. Sun et al., Rev. Sci. Inst.* ***94****, 043003 (2023)*

Motivation: *J.C. Zhang et al., PNAS* ***114****, 5378 (2017)*

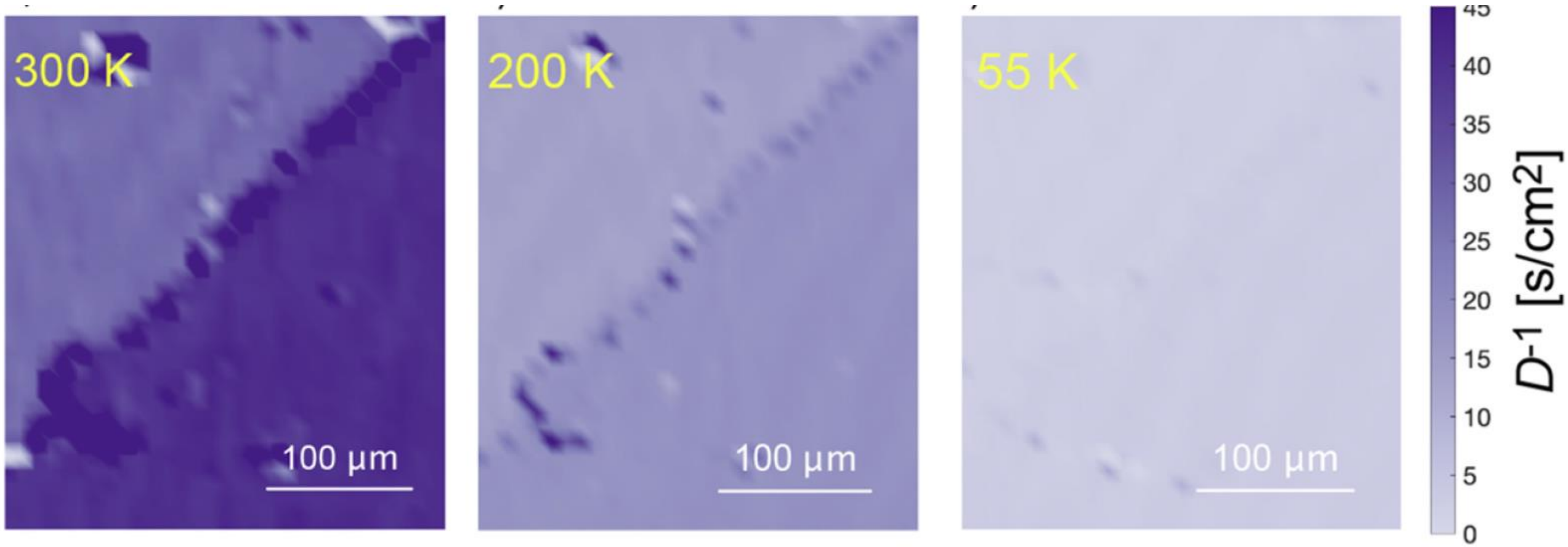
Thermal conductivity and Lorenz ratio of $Sr_3Ru_2O_7$





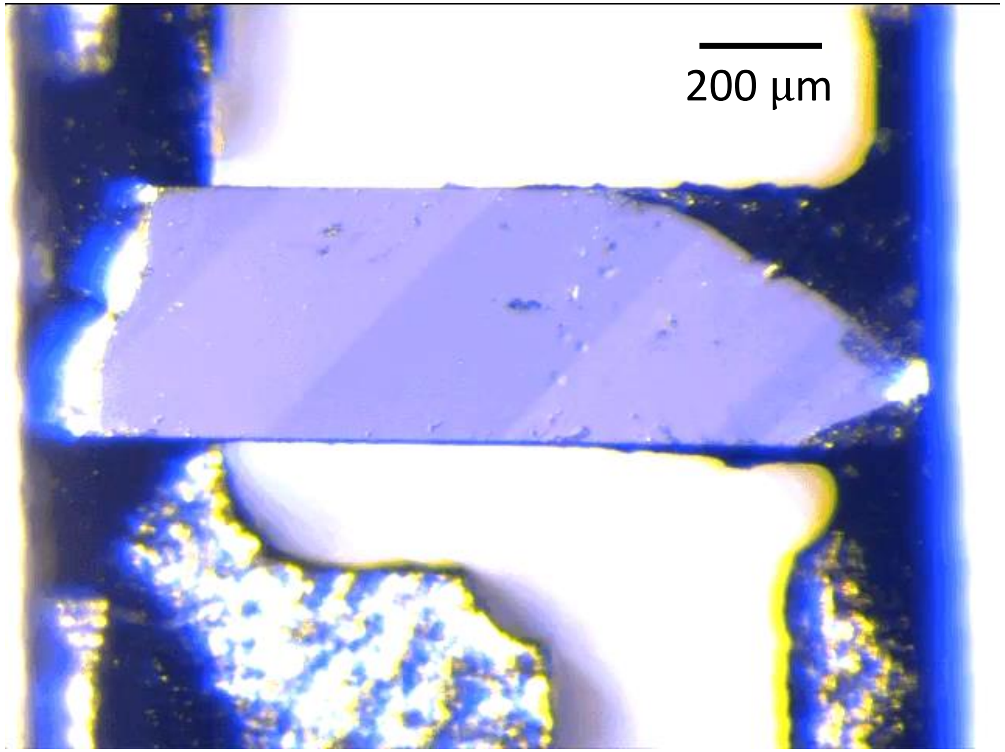
High-T value of κ very similar to that of cuprates

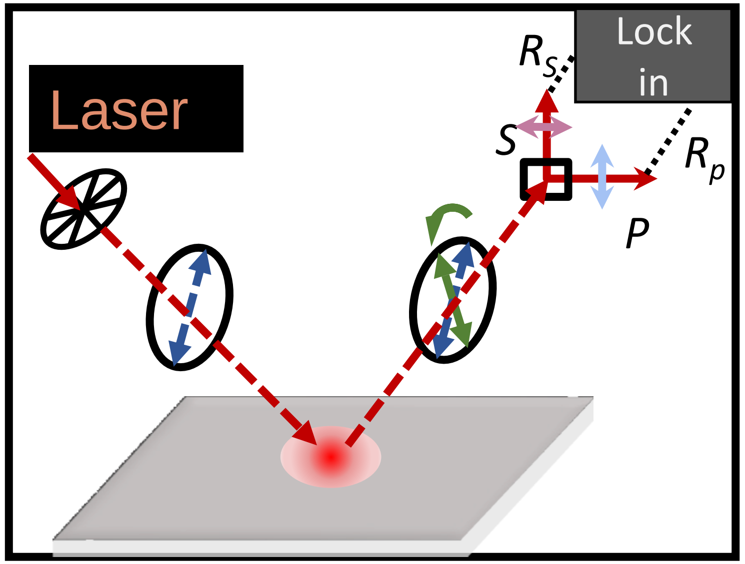
Diffusivity mapping across a domain boundary in orthorhombic $Ca_3Ru_2O_7$



Strong diffusivity anisotropy at room temperature vanishes by 55 K; work done in ambient conditions outside pressure cell

Birefringence mapping across a domain boundary in orthorhombic $Ca_3Ru_2O_7$



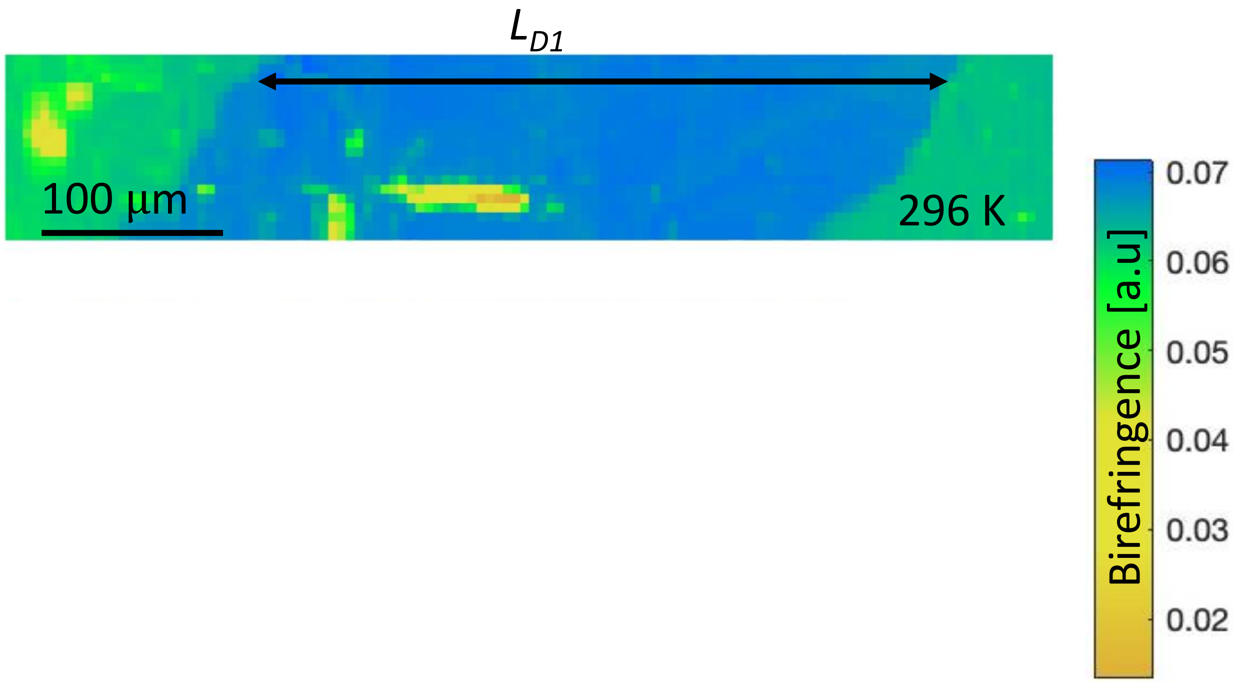


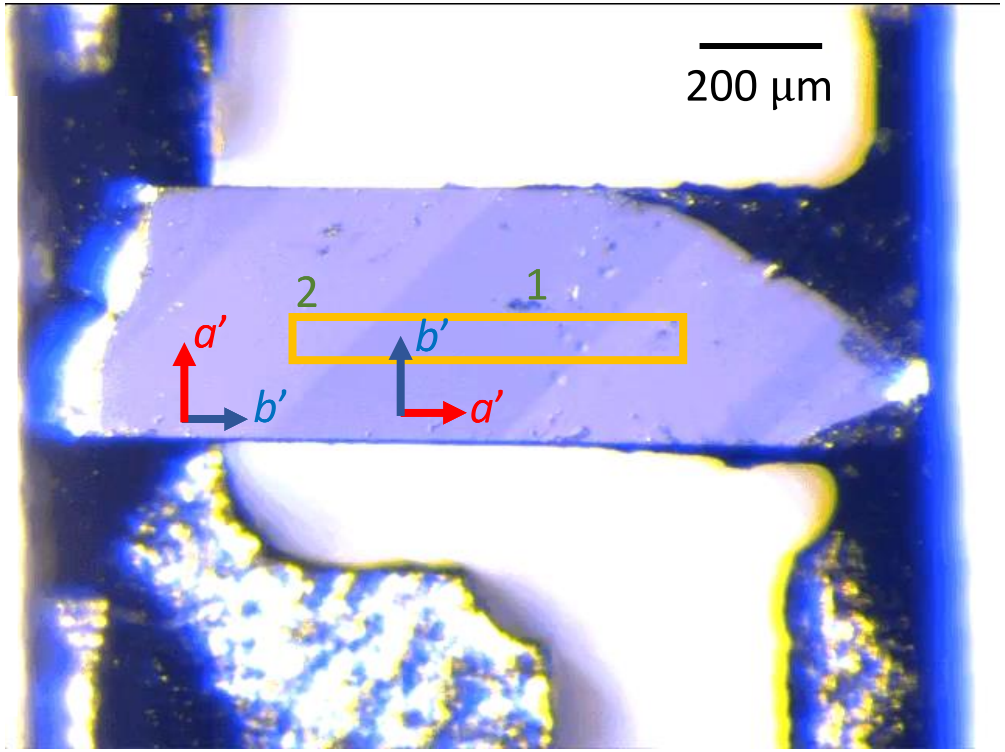
Sample mounted in a uniaxial pressure cell and domains identified using standard polarised light microscopy

Transfer cell to Montana Instruments optical cryostat and re-measure birefringence using laser setup

Available wavelengths 633 nm, 720 nm

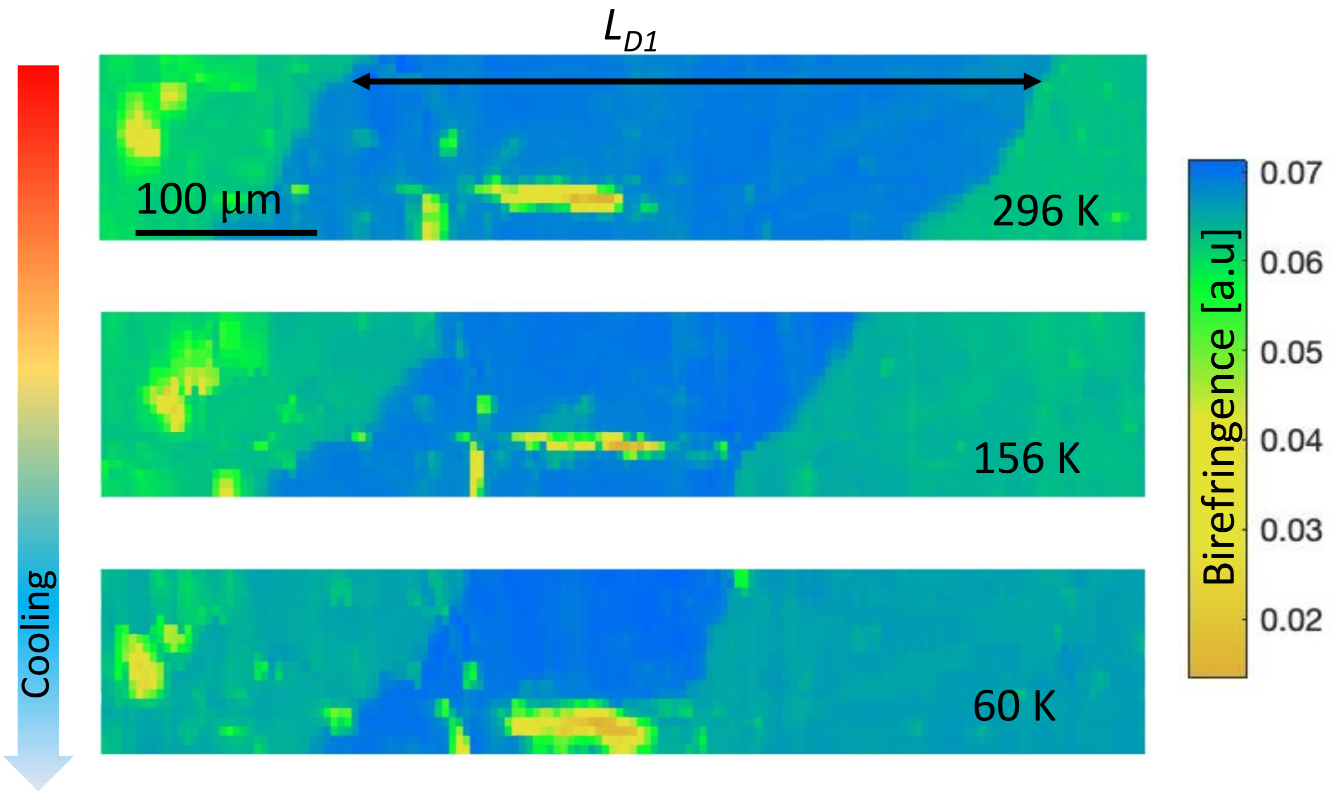
Birefringence mapping across a domain boundary in orthorhombic $Ca_3Ru_2O_7$

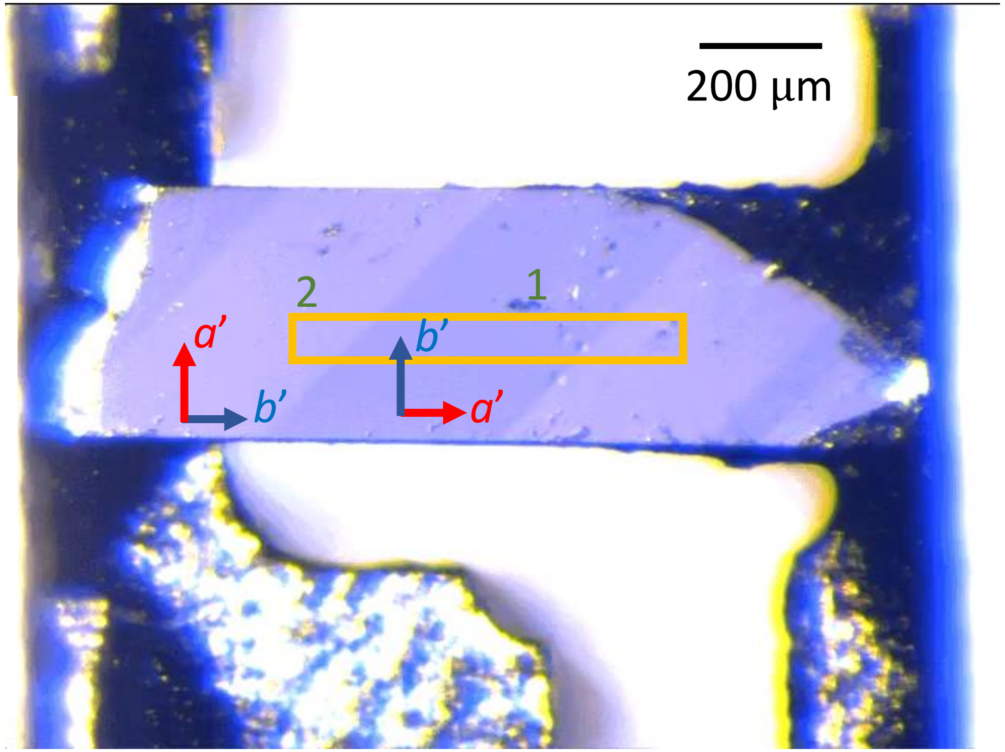




Laser-based method accurately reproduces polarised light microscopy observation

Birefringence mapping across a domain boundary in orthorhombic $Ca_3Ru_2O_7$

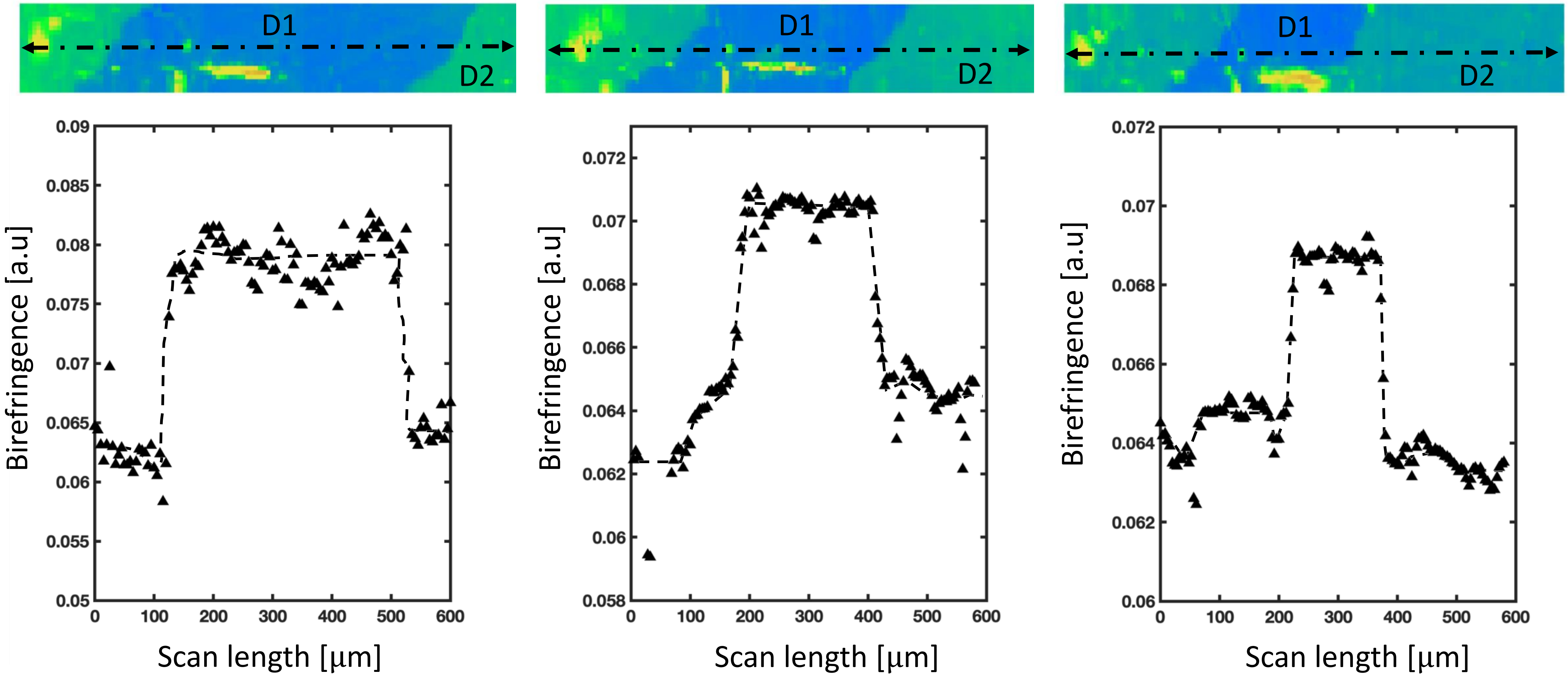




Laser-based method accurately reproduces polarised light microscopy observation at room temperature

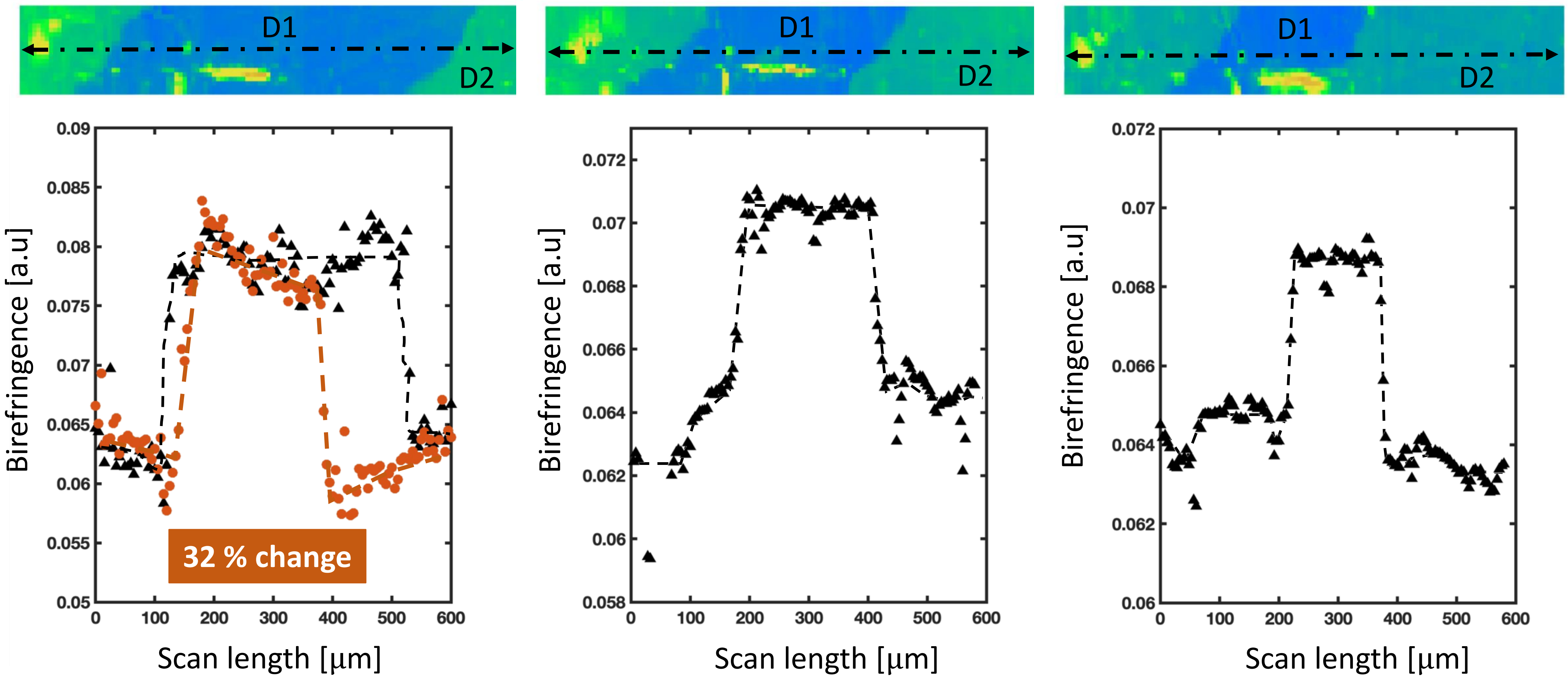
On cooling, small differential thermal contraction provides strain sufficient to move domains

Birefringence mapping across a domain boundary in orthorhombic $Ca_3Ru_2O_7$



Line scans showing birefringence changes at zone boundaries

Birefringence mapping across a domain boundary in orthorhombic $Ca_3Ru_2O_7$



Apply 0.08 GPa uniaxial pressure and repeat

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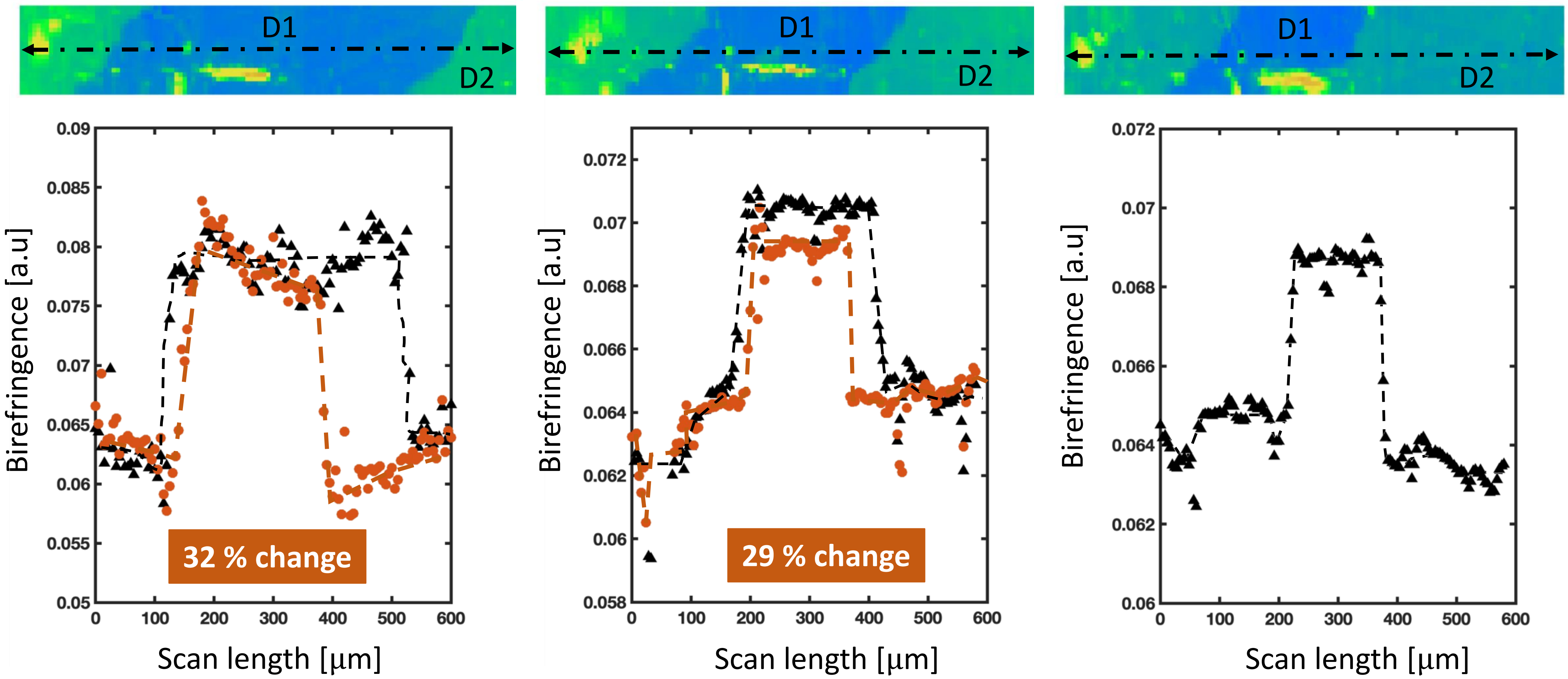

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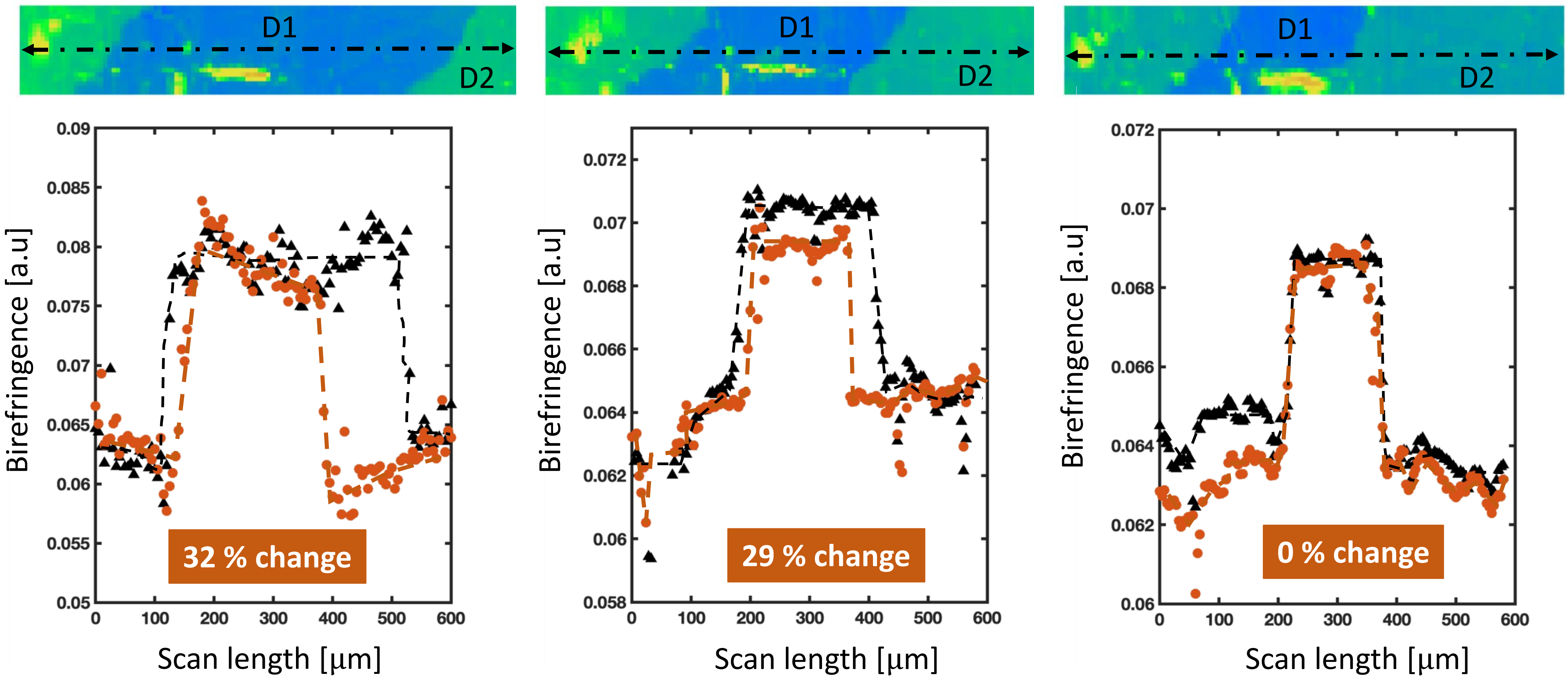

Proof of principle: we can study and control domains: now the physics can begin

Notes for the future

1. We have proven capabilities for the a.c. elastocaloric effect, spatial domain mapping and control but we have not yet combined them

2. a.c. strain modulation may well be useful for optics experiments as well as elastocaloric ones

3. In principle, fields of ~ 0.7 T parallel to sample surface are available

4. We are open to appropriate (i.e. exciting and impactful!) collaborations

5. However, this is far from a turn-key instrument. It requires a broader range of experimental skills than most people possess

6. Spatial Kerr rotation mapping to identify / characterise Spin Hall effect (cf Awschalom group, Science 2004)?

7. Potential collaborators: be prepared to be patient!

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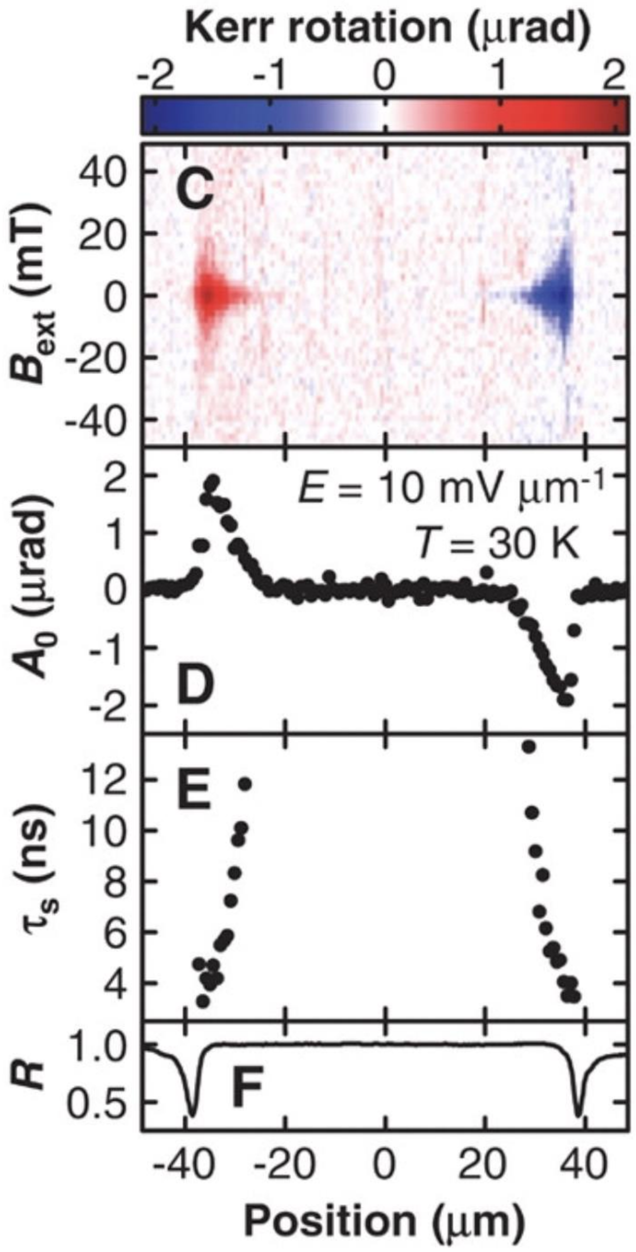
Conclusions

1. The ‘elastoscope’ has passed its installation tests so far
2. In principle, observation and pressure control of spatially-resolved birefringence, Kerr effect, thermal diffusivity and 2nd harmonic generation are possible in future
3. Also possible to combine any of the above with a.c. elastocaloric effect on the same samples
4. However, ’possible’ and ‘straightforward’ are not quite the same thing!

Kerr mapping in GaAs



*Y.K. Kato et al., Science **306**, 1910 (2004)*