Ferroelectric quantum criticality and enhanced superconductivity in plastically-deformed $SrTiO_3$

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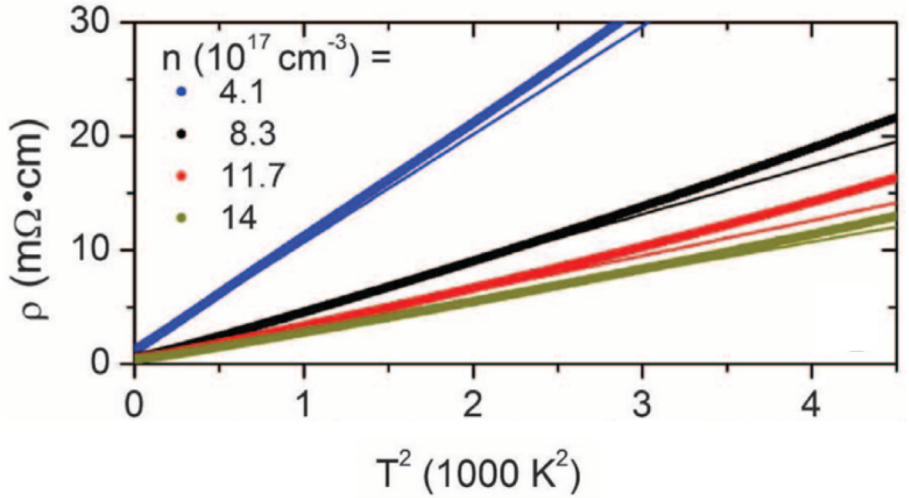
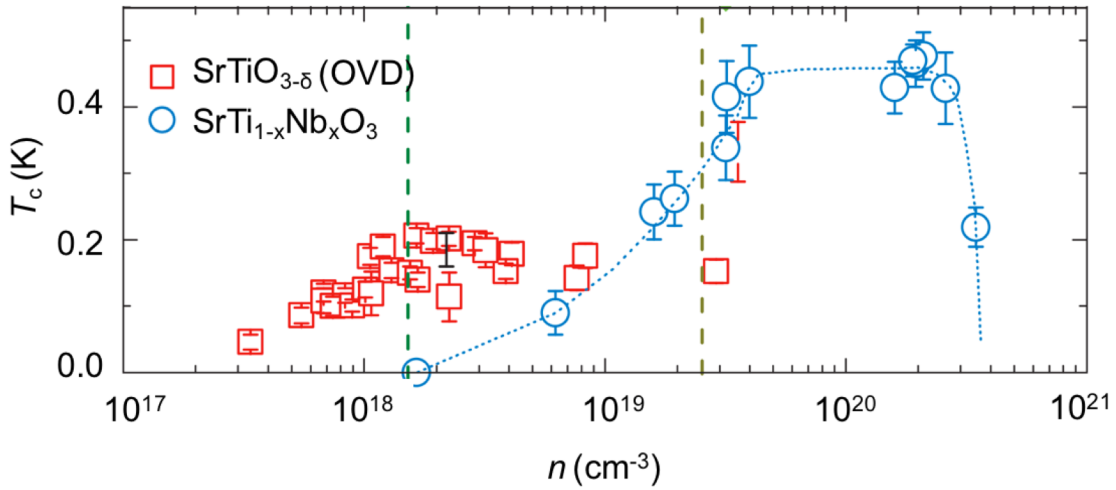
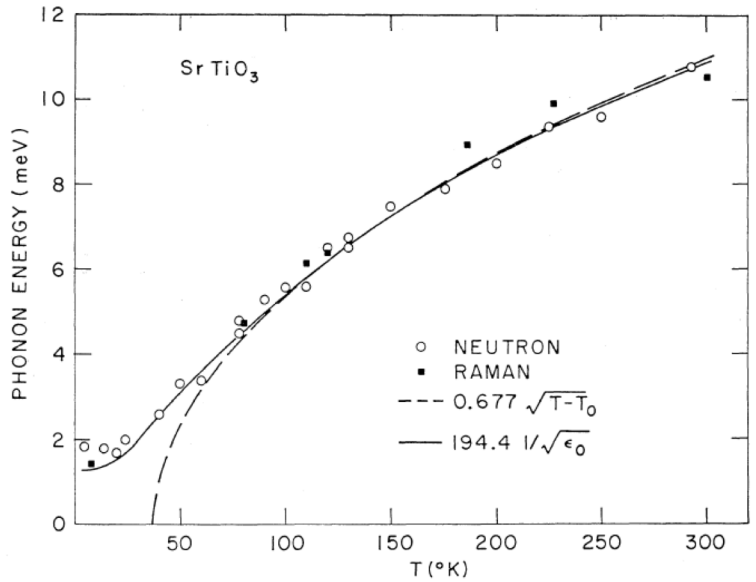
Introduction to $SrTiO_3$ (STO)

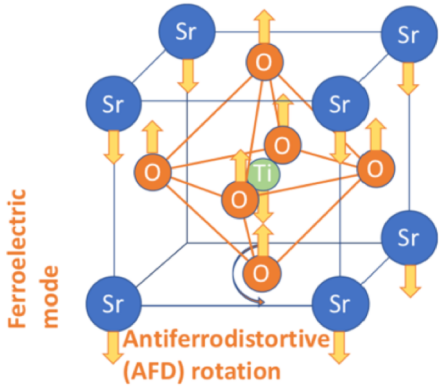
- Superconductivity in the dilute limit; low-temperature T^2 resistivity
- Quantum paraelectricity: fluctuations of a soft transverse optical (TO) phonon mode prevent ferroelectric order; also argued to lead to superconducting pairing





C. Collignon *et al.*, Annu. Rev. Cond. Matt. Phys. **10**, 25 (2019)

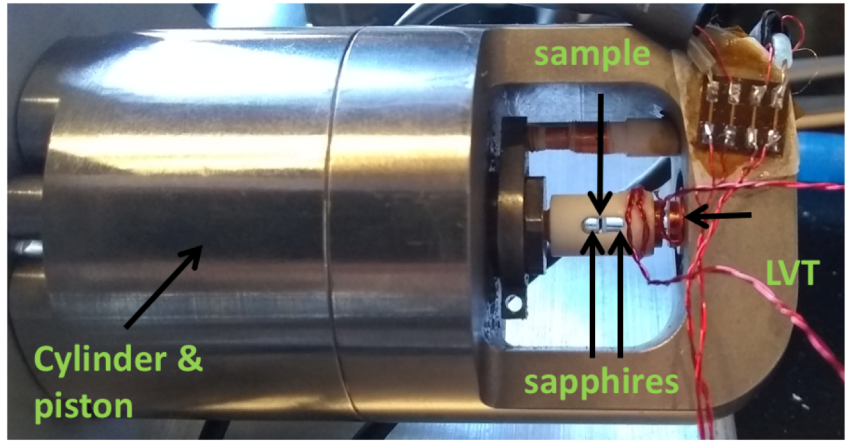




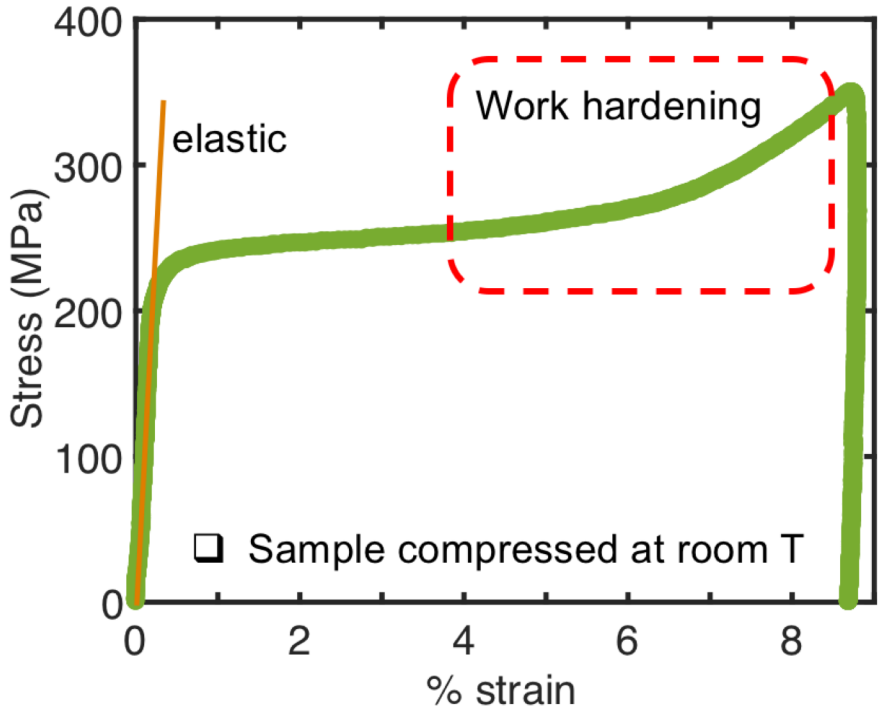
Y. Yamada and G. Shirane, J. Phys. Soc. Jpn. **26**, 396 (1969)
C. Herrera *et al*, Phys. Rev. Mat. **3,** 124801 (2019)

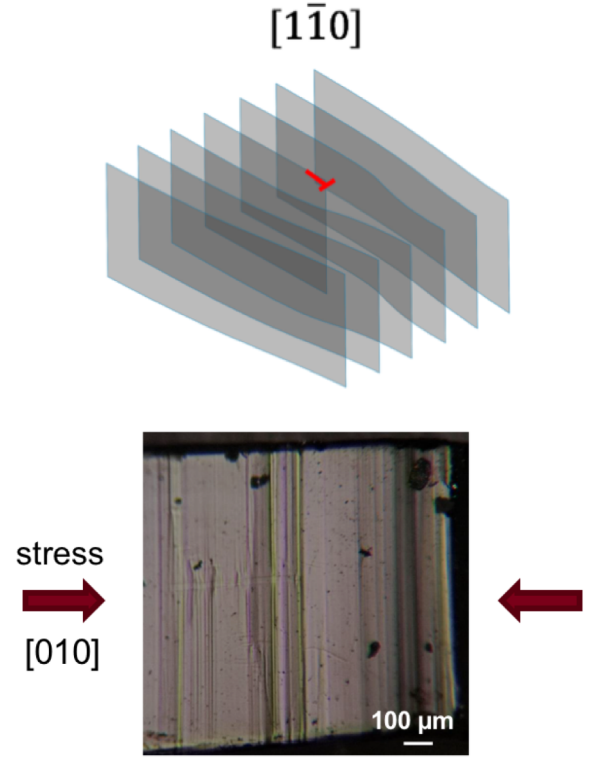
New approach: plastic deformation

Uniaxial strain cell



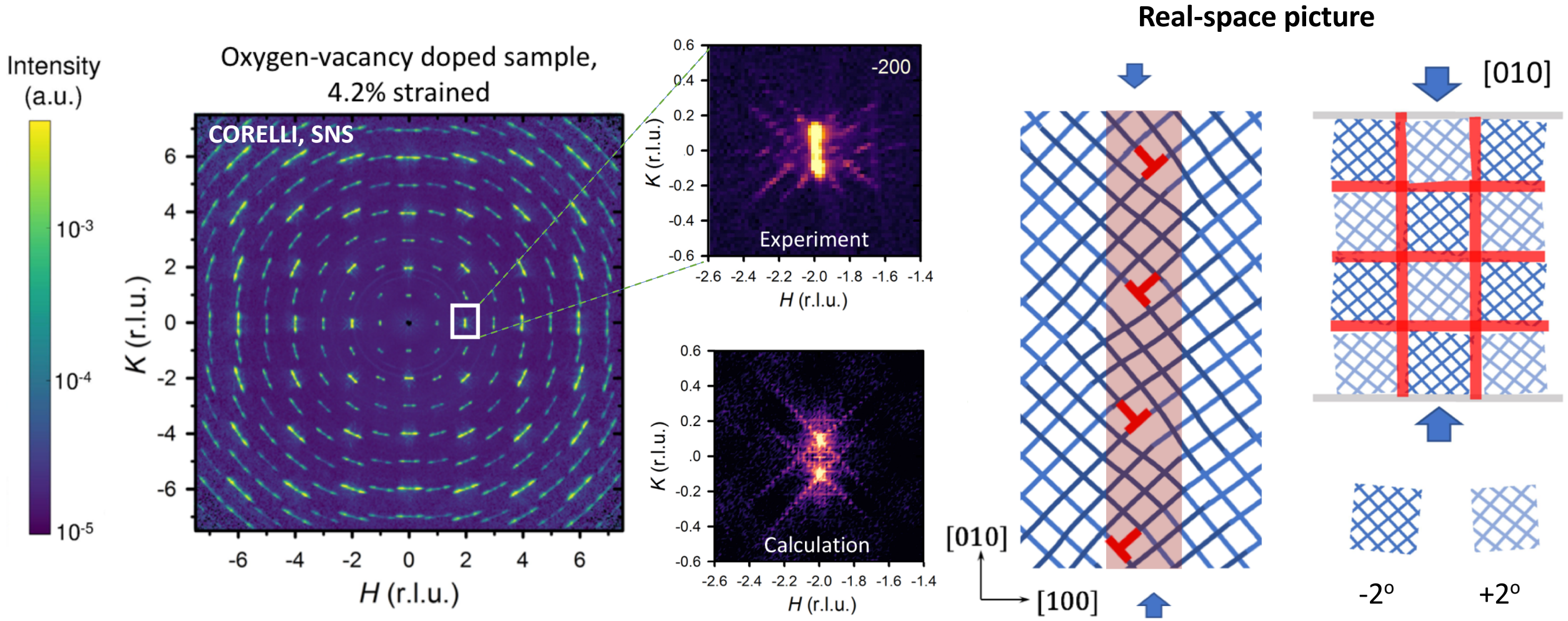
Stress-strain diagram





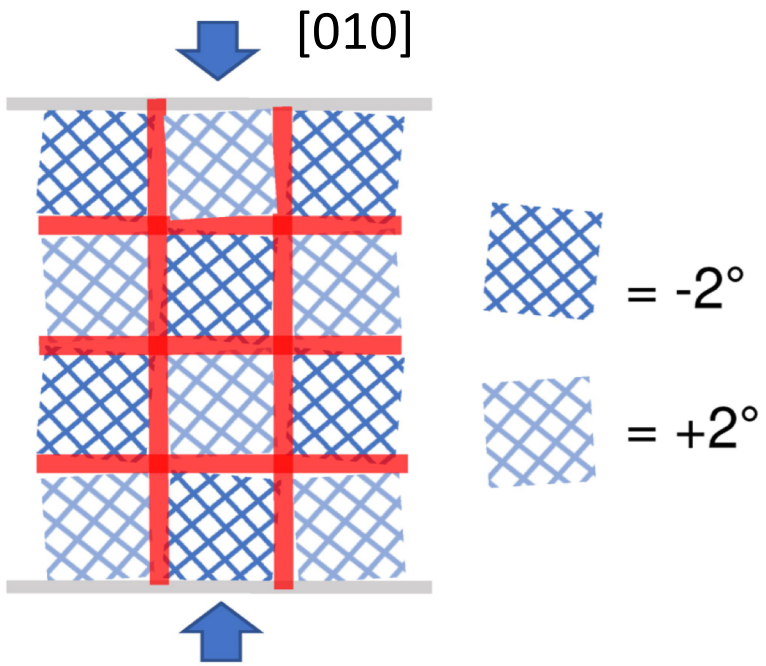
- Novel approach to study quantum materials
- Extended plastic regime at room temperature in STO; possible with {110} slip system
- Samples always compressed at room temperature; all further measurements performed ***ex situ***

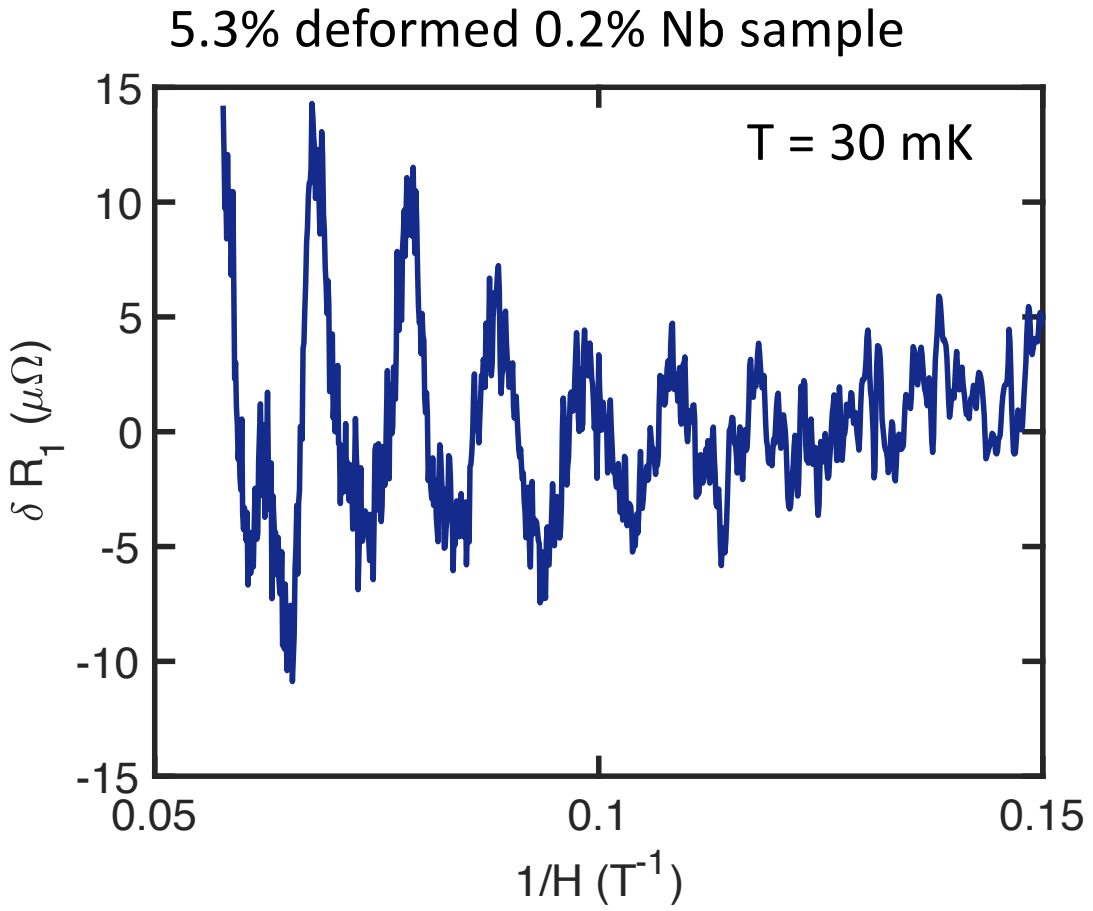
Effect on structure: diffuse neutron scattering



- Plastic deformation: rearrangement of dislocations into walls
- System breaks up into domains separated by self-organized dislocation structures (walls)

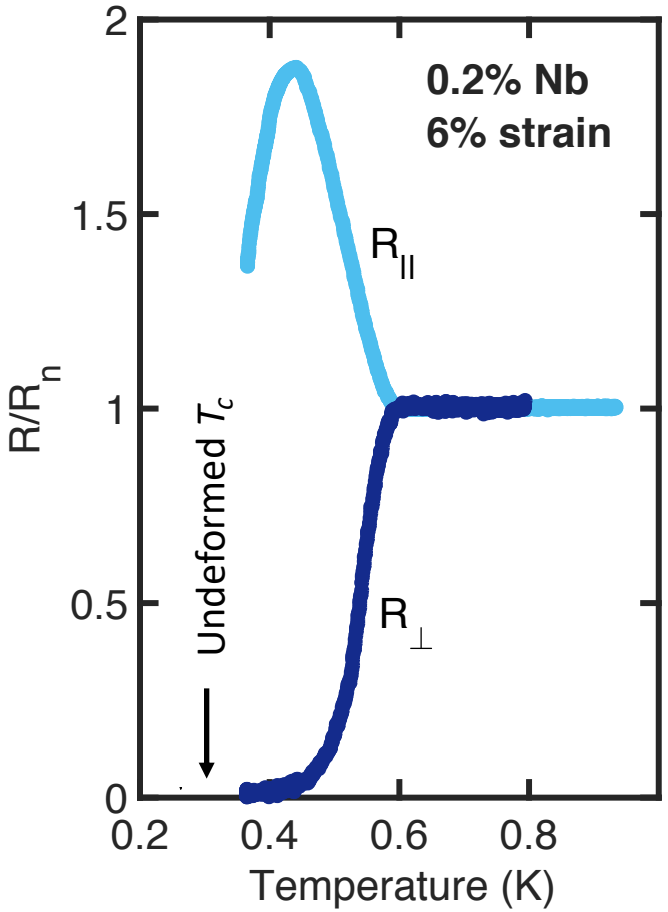
Quantum oscillations visible!

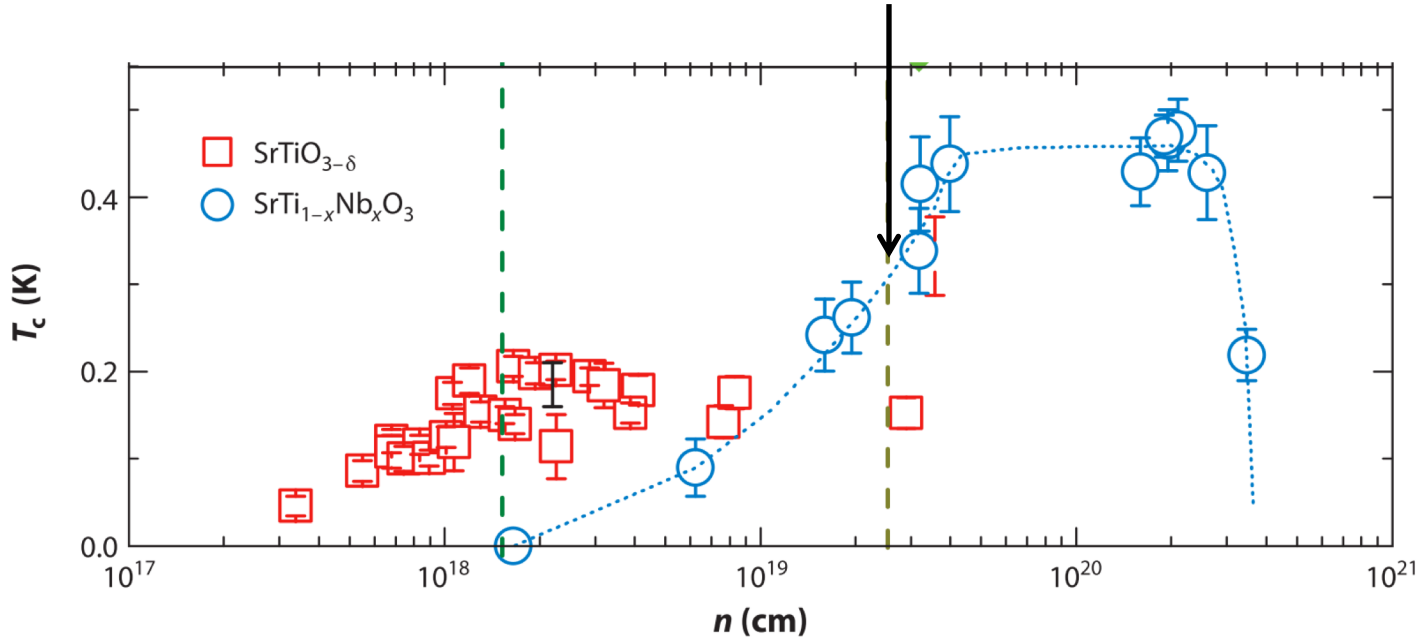




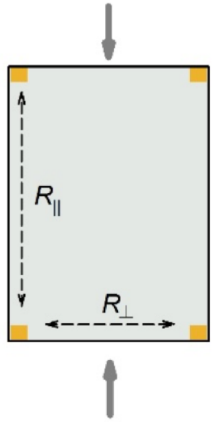
- Sharp Fermi surface even after plastic deformation

Effect on superconductivity: enhanced T_c

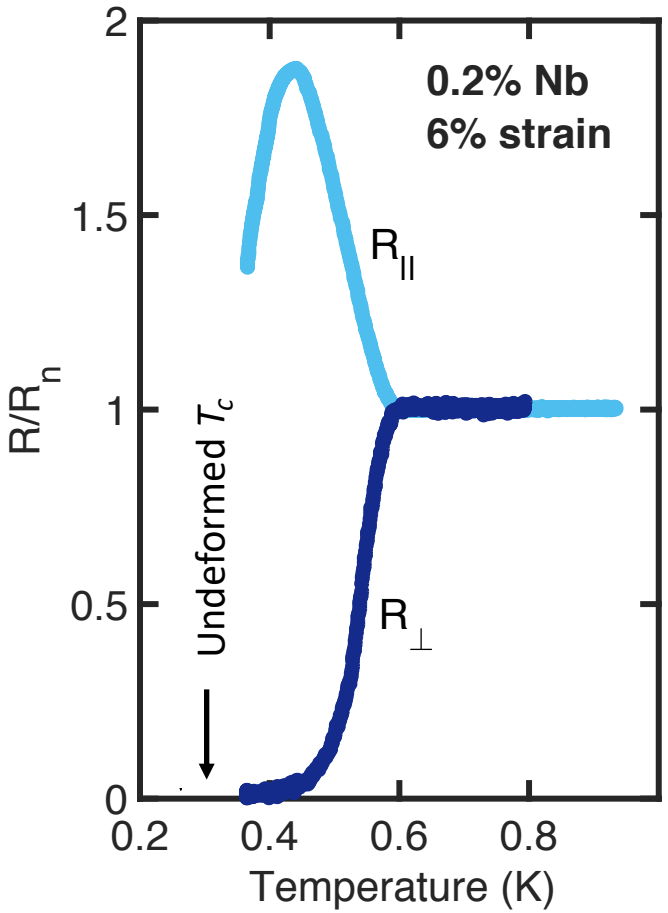


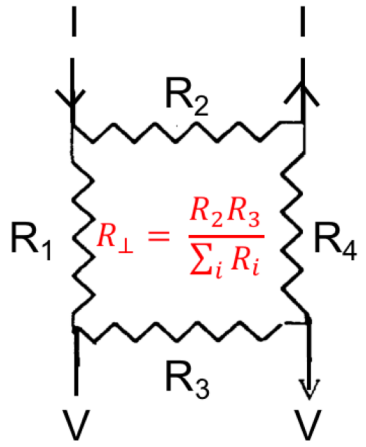


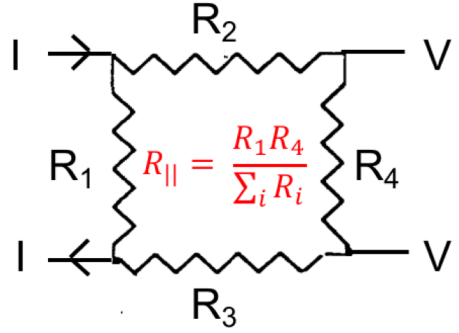
- Highly anisotropic transport
- T_c considerably higher than that for undeformed samples (< 0.3 K), in the perpendicular direction



Inhomogeneous superconductivity

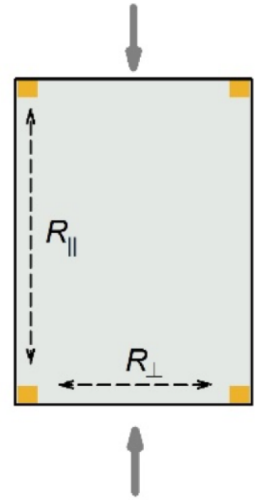






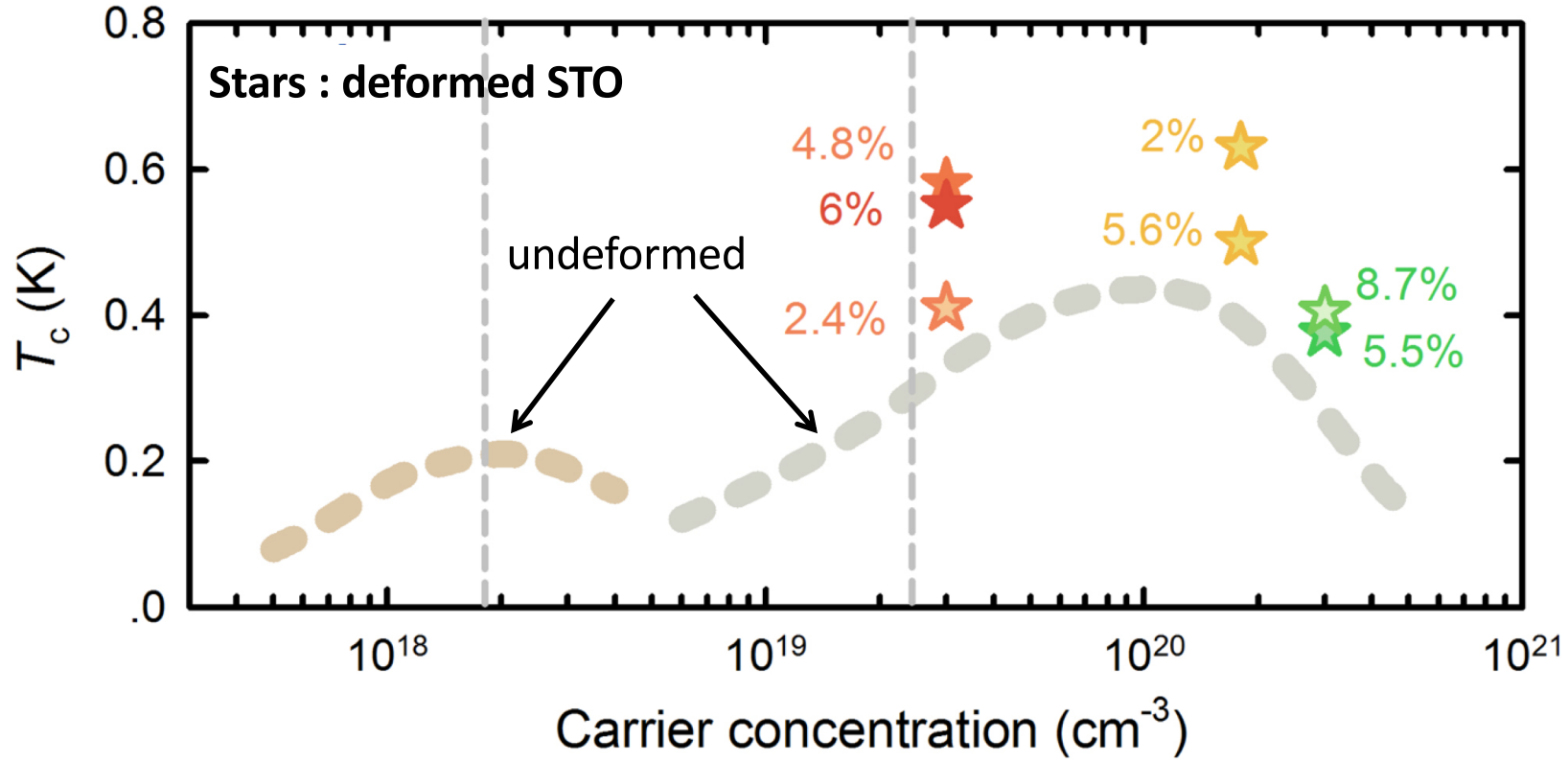
If $R_2 \to 0, R_\perp \to 0$ & $R_{||}$ shoots up

- Superconducting puddles embedded in a non-superconducting matrix



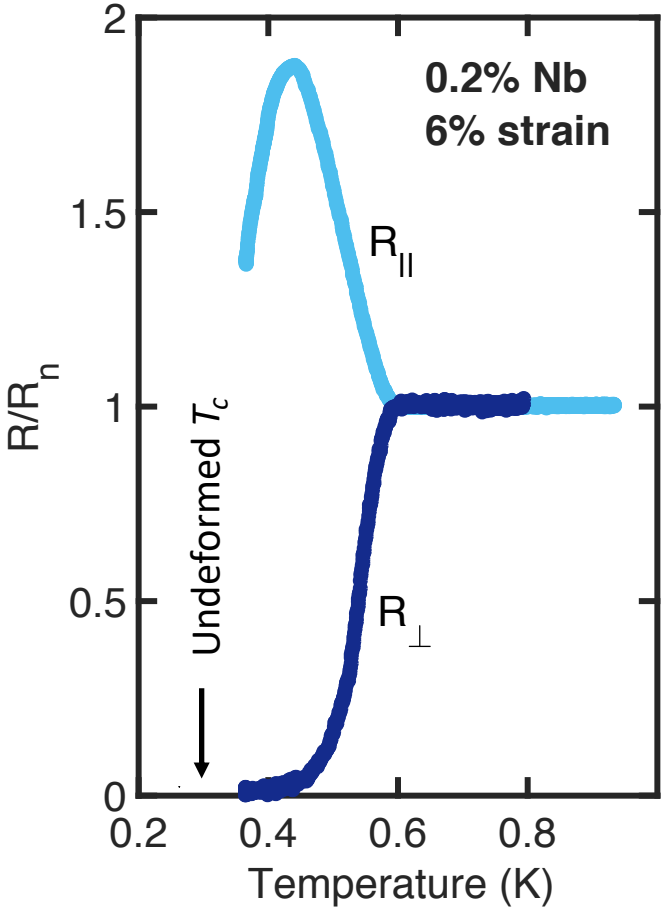
R. Vagli *et al.*, Phys. Rev. B **47**, 15302 (1993)
C. Liu *et al.*, Science **371**, 716 (2021)

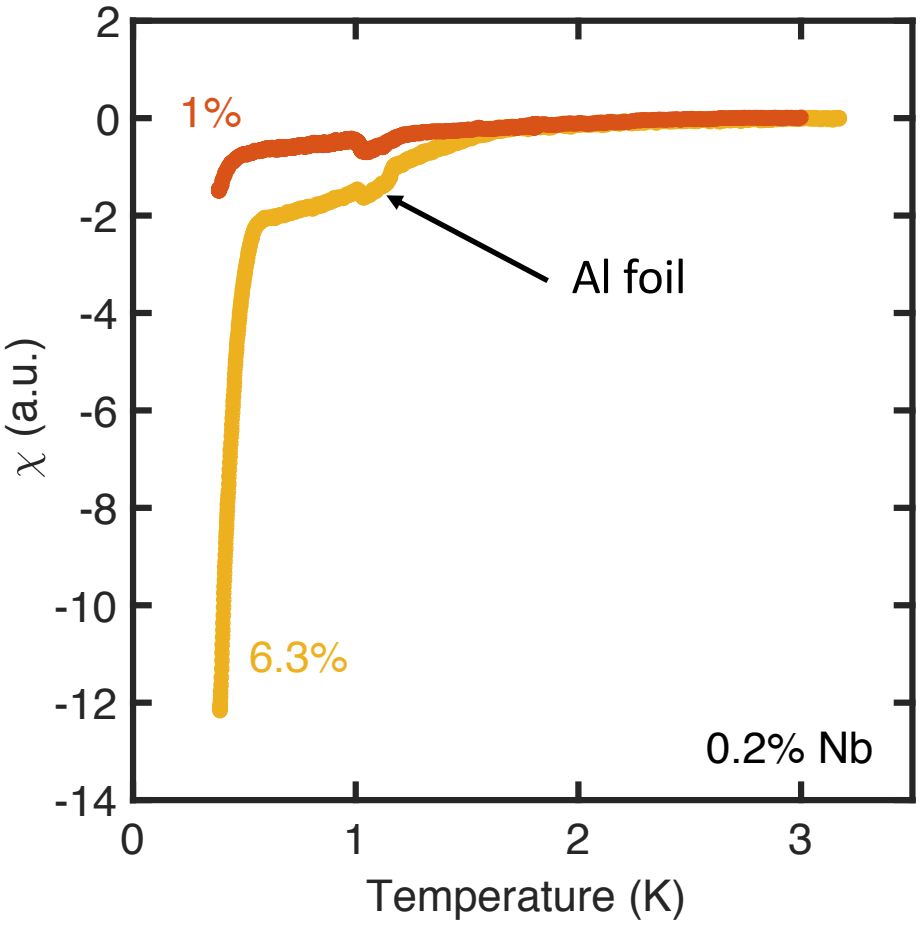
Phase diagram of plastically deformed STO



- T_c defined at mid-point of transition
- T_c enhancement of up to a factor of 2

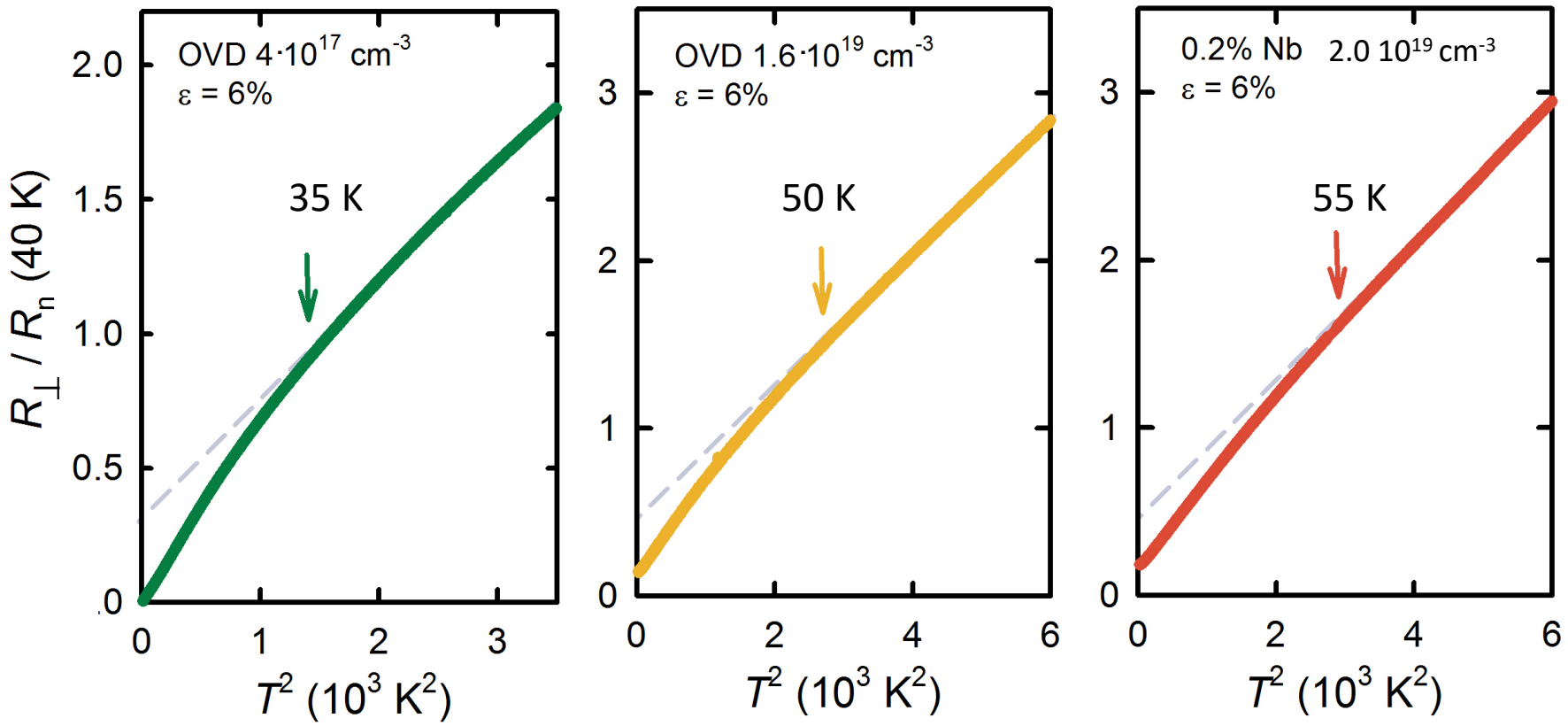
High-T_c superconductivity?

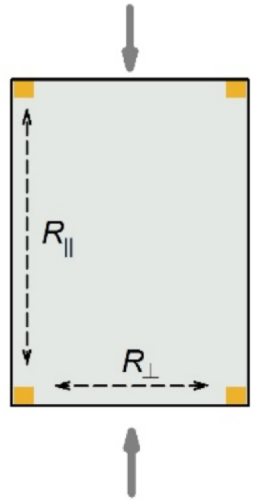




- Resistivity downturn matches with onset of low-T diamagnetic signal
- Weak diamagnetic signal onset at higher temperature

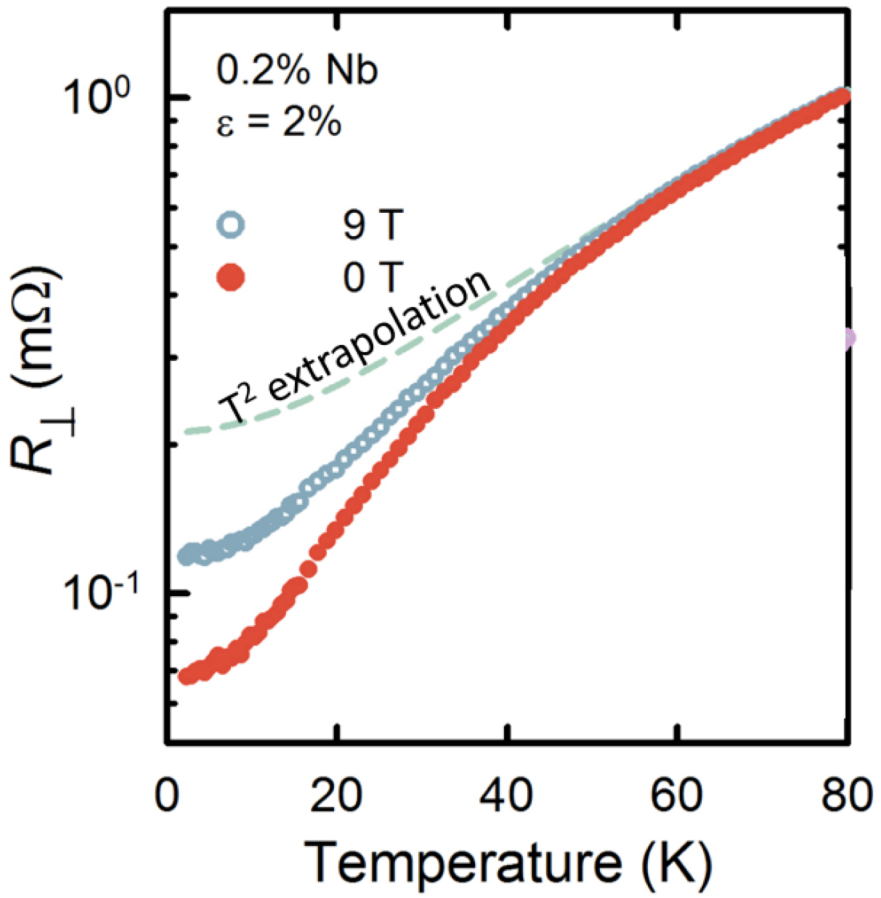
High-T_c superconductivity?





- Downward deviation from T^2, perpendicular to stress direction again

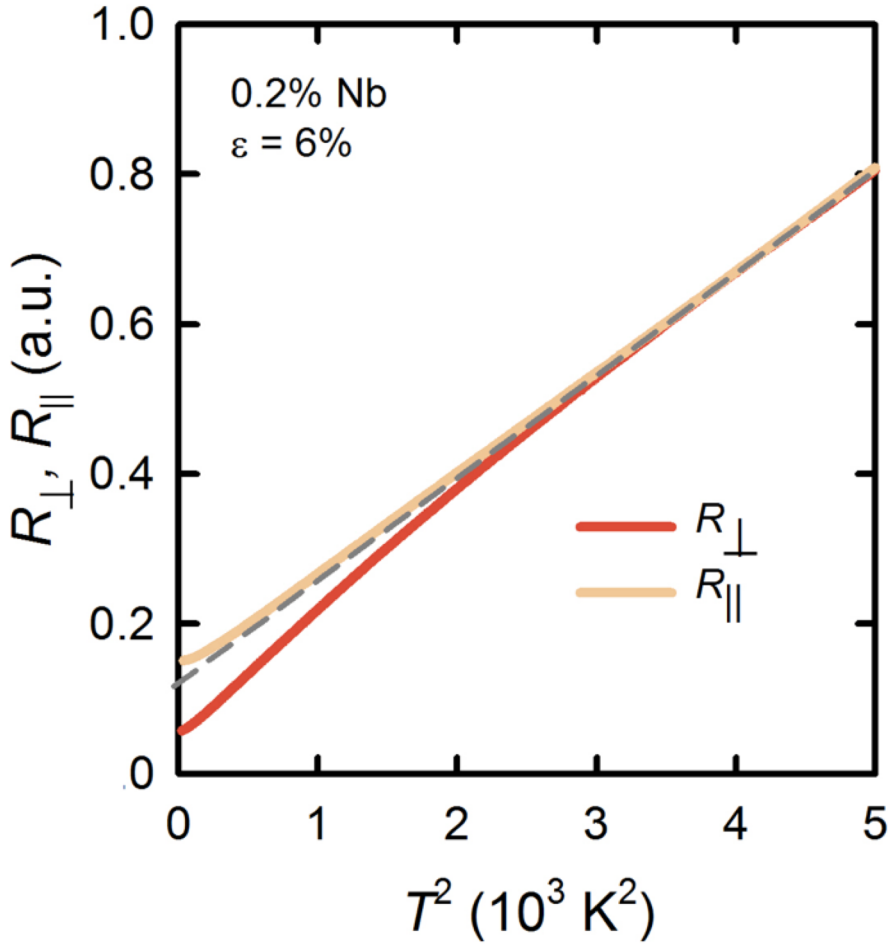
High-T_c superconductivity?

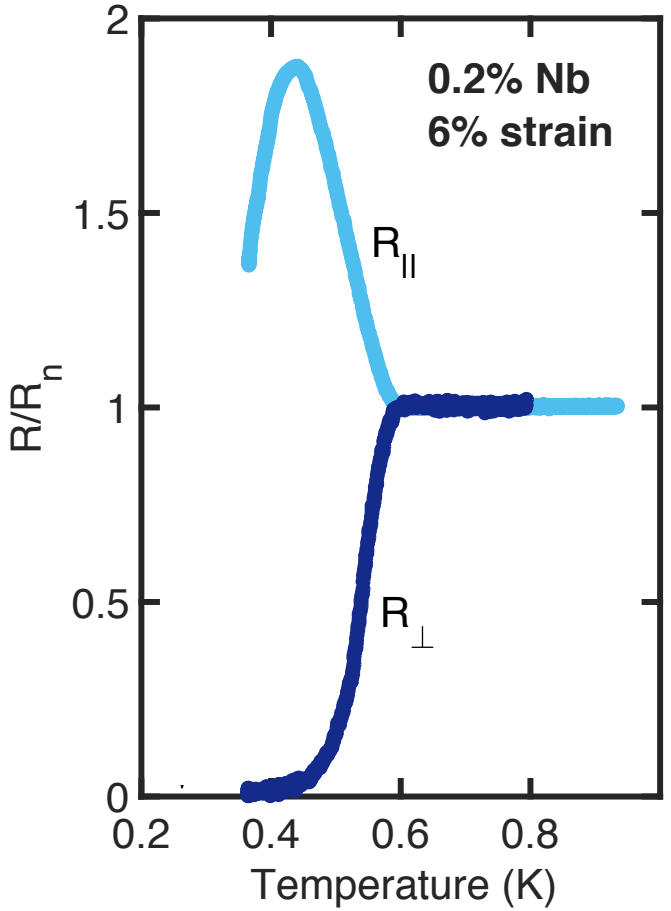


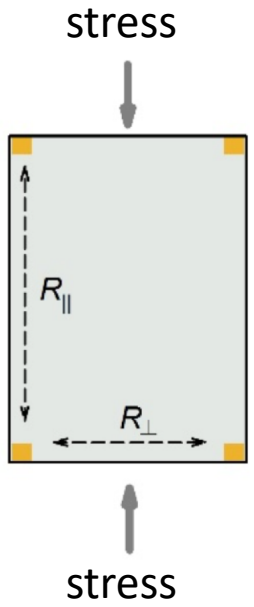
- Downward deviation from T^2 in $R_\perp$
- Factor of 2 (100%) increase in $R_\perp$ in 9 T field
- Reported normal magnetoresistance is only ~20% at this doping and temperature range
- Indicative of possible small volume fraction of high-T_c superconducting correlations

A. Spinelli *et al.*, Phys. Rev. B **81**, 155110 (2010)

Low-dimensional SC

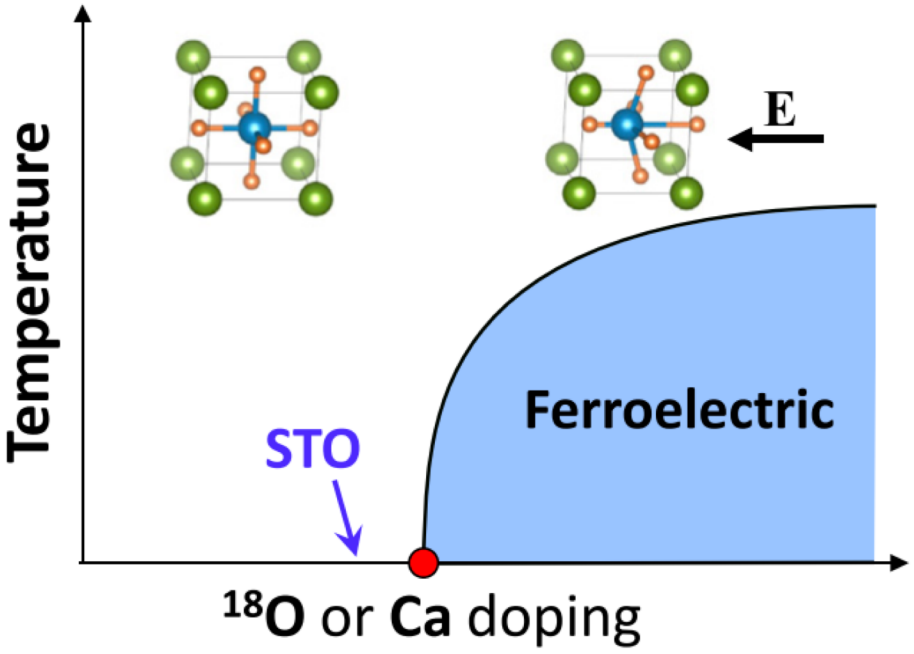






- Enhanced SC effect is seen only in the perpendicular direction

Tuning towards FE-QCP ⟶ enhanced T_c

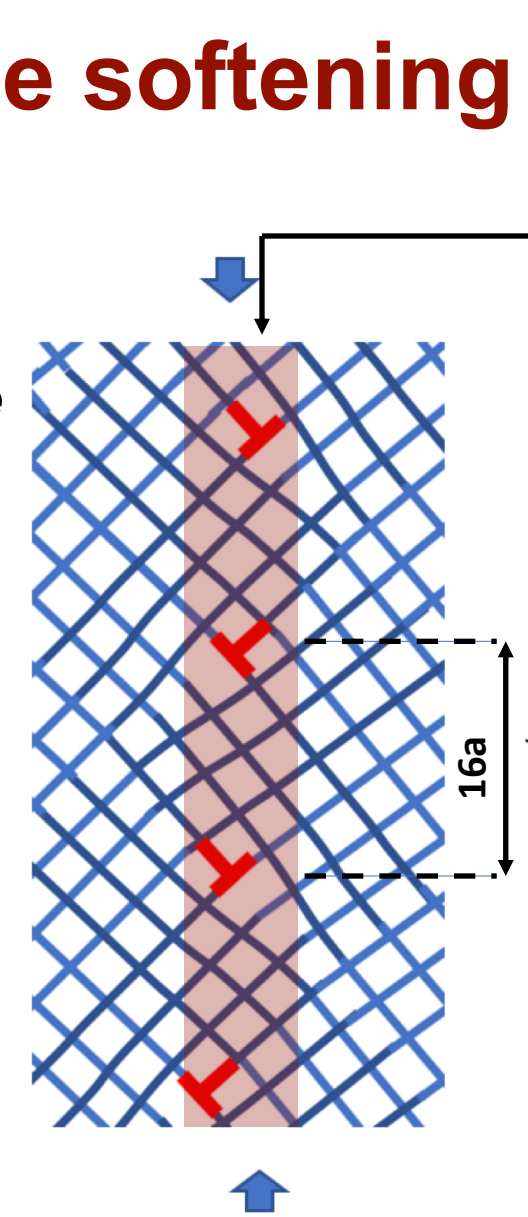


- Enhancement of T_c predicted upon approaching the ferroelectric quantum critical point (FE-QCP)
- Verified by experiments on Ca - & ^{18}O - substituted as well as elastically strained STO
- Associated with further softening of TO mode

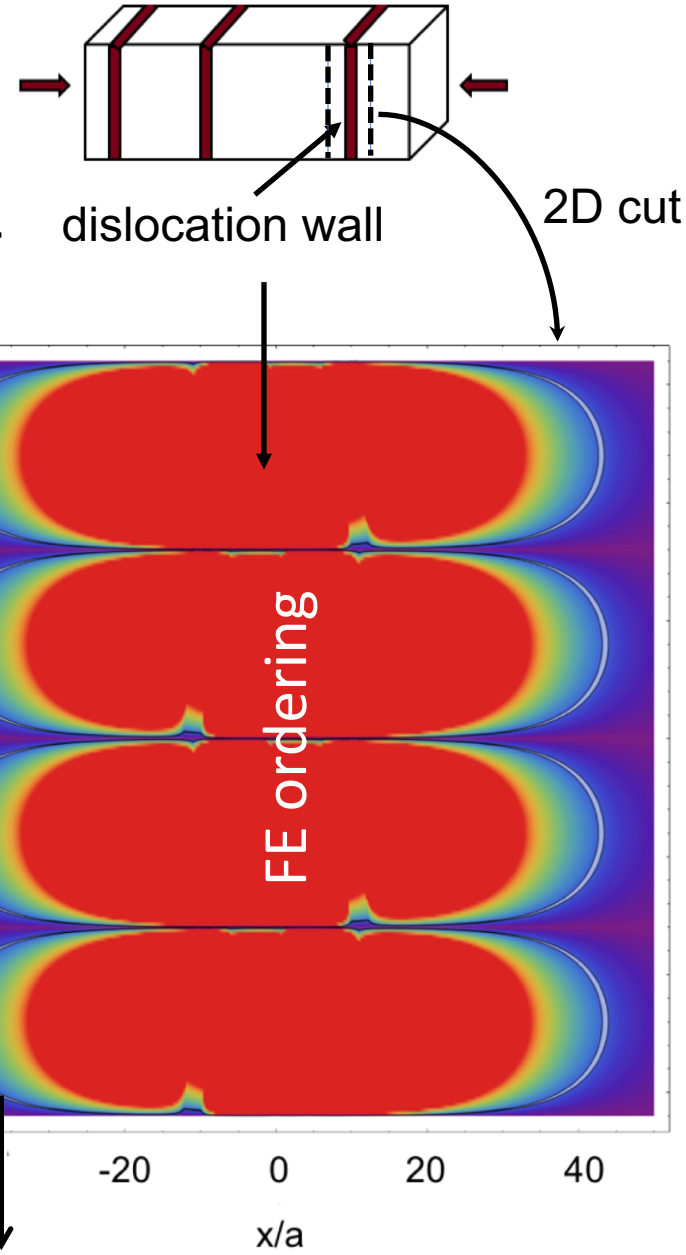
M. N. Gastiasoro *et al.*, Annals of Physics **417**, 168107 (2020)
A. Stucky *et al*, Sci. Rep. **6**, 37582 (2016)
C. W. Rischau *et al*, Nature Phys. **13**, 643 (2017)
K. Ahadi *et al,* Sci. Adv. **5**, eaaw0120 (2019)

Theory for TO mode softening and enhanced T_c

- ω_b: frequency of TO mode ***before*** deformation
- ω_a: frequency of TO mode ***after*** deformation
- Define
  - $r = \omega_a^2/\omega_b^2$
  - $r > 0$: paraelectric
  - $r < 0$: FE order
  - $r = 1$: undeformed

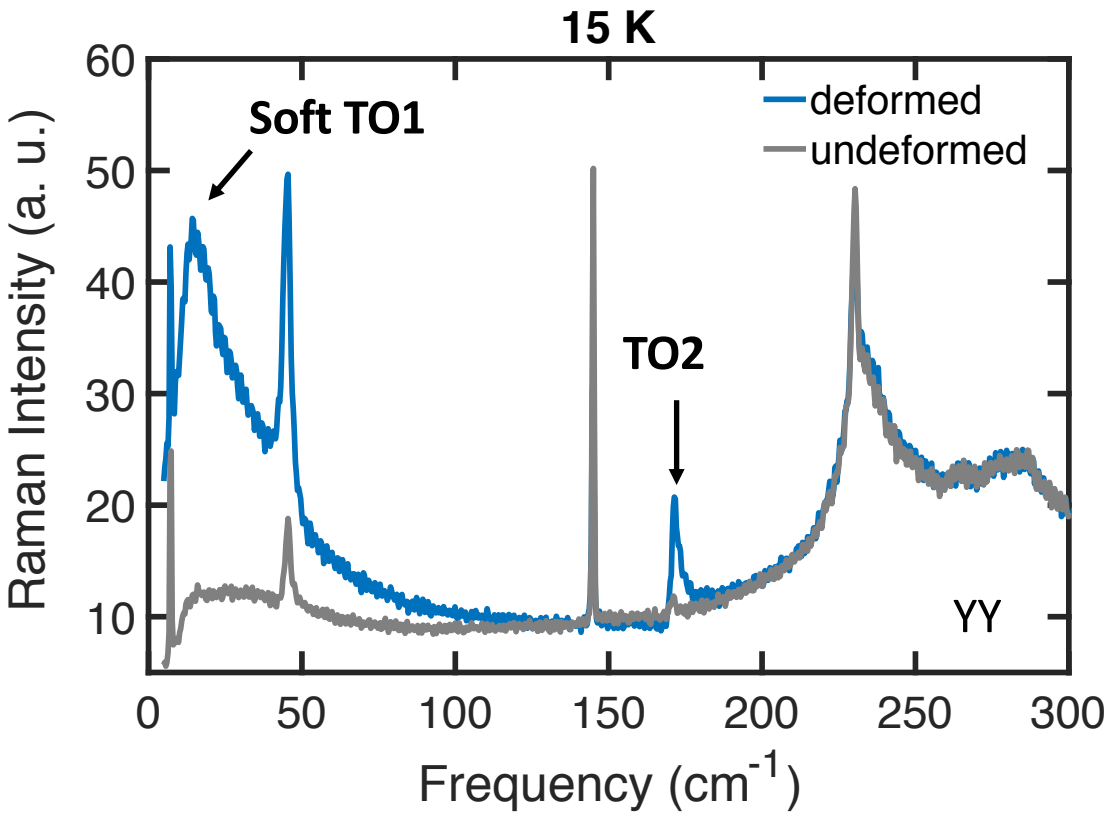


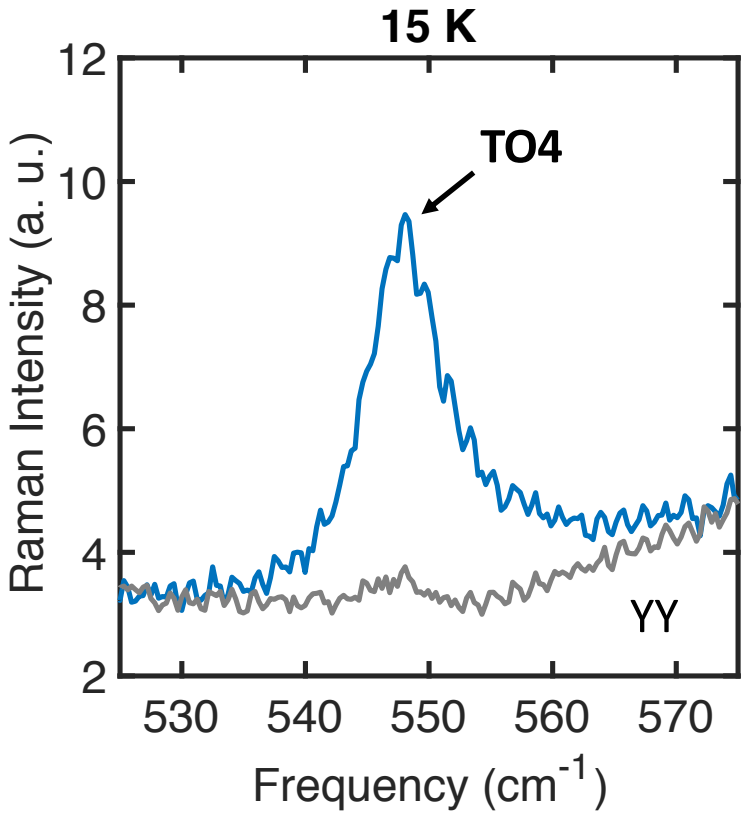
a – lattice constant



- White region: $0 < r < 1/2$: enhanced T_c

Experimental evidence : Raman scattering

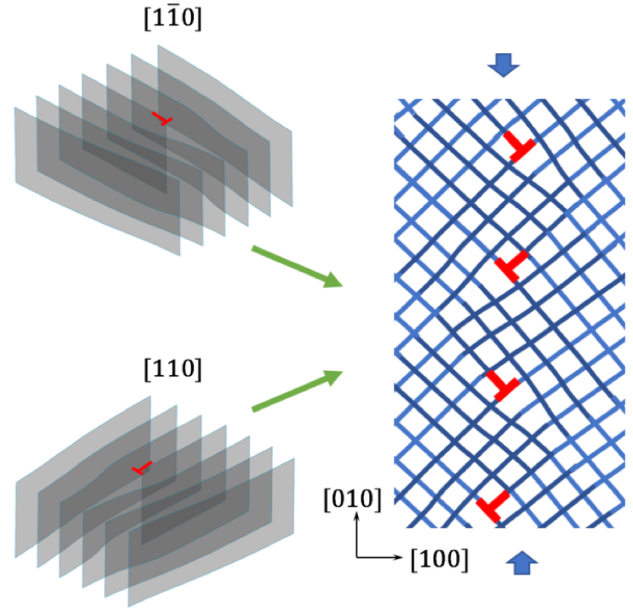


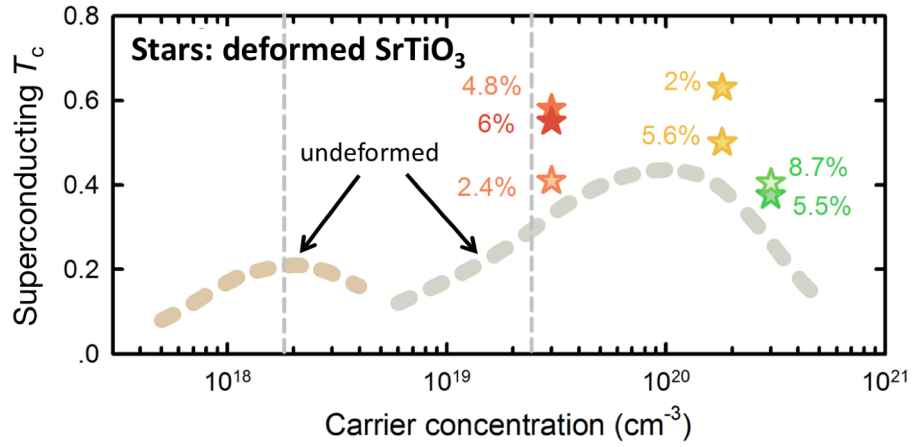


- Soft TO1 mode, hard TO2 and TO4 modes: Raman active only in the inversion symmetry broken FE state ⟹ direct evidence for local FE order

Conclusions

- Enhanced superconductivity in plastically deformed STO:
  - ✓ Bulk T_c up to a **factor of two** higher than undeformed samples
  - ✓ Possible small volume fraction of high T_c superconducting component – **two orders of magnitude** higher T_c than undeformed samples
- Associated with softening of TO phonon modes near **self-organized dislocation structures** formed by plastic deformation
- Plastic deformation opens up an entirely new exciting field of quantum materials research





S. Hameed, D. Pelc *et al.*, arXiv 2005.00514, To appear in *Nature Materials*