Matias Bargheer

Examples of Ultrafast X-ray Diffraction Experimens: Synchrotron vs. Laser-Plasma Sources

- Some details of the setup: BESSYII + Plasma $\Rightarrow$ VSR
- Ultrafast heat transport on nm length scale
- Inhomogeneous lattice dynamics in ferroelectric
  - $Pb(Zr,Ti)O_3$
  - $BiFeO_3$

Team

PostDocs and PhD students
University of Potsdam
+ HZB:

Daniel Schick
André Bojahr
Lena Maerten
Steffen Mitzscherling
Elena Pavlenko

Dr. Matthias Rössle
Dr. Wouter Koopman
Dr. Peter Gaal
Dr. Wolfram Leitenberger
Dr. Qianling Cui
Dr. Roman Shayduk
Dr. Hengameh Navirian
Yevgeni Goldshteyn

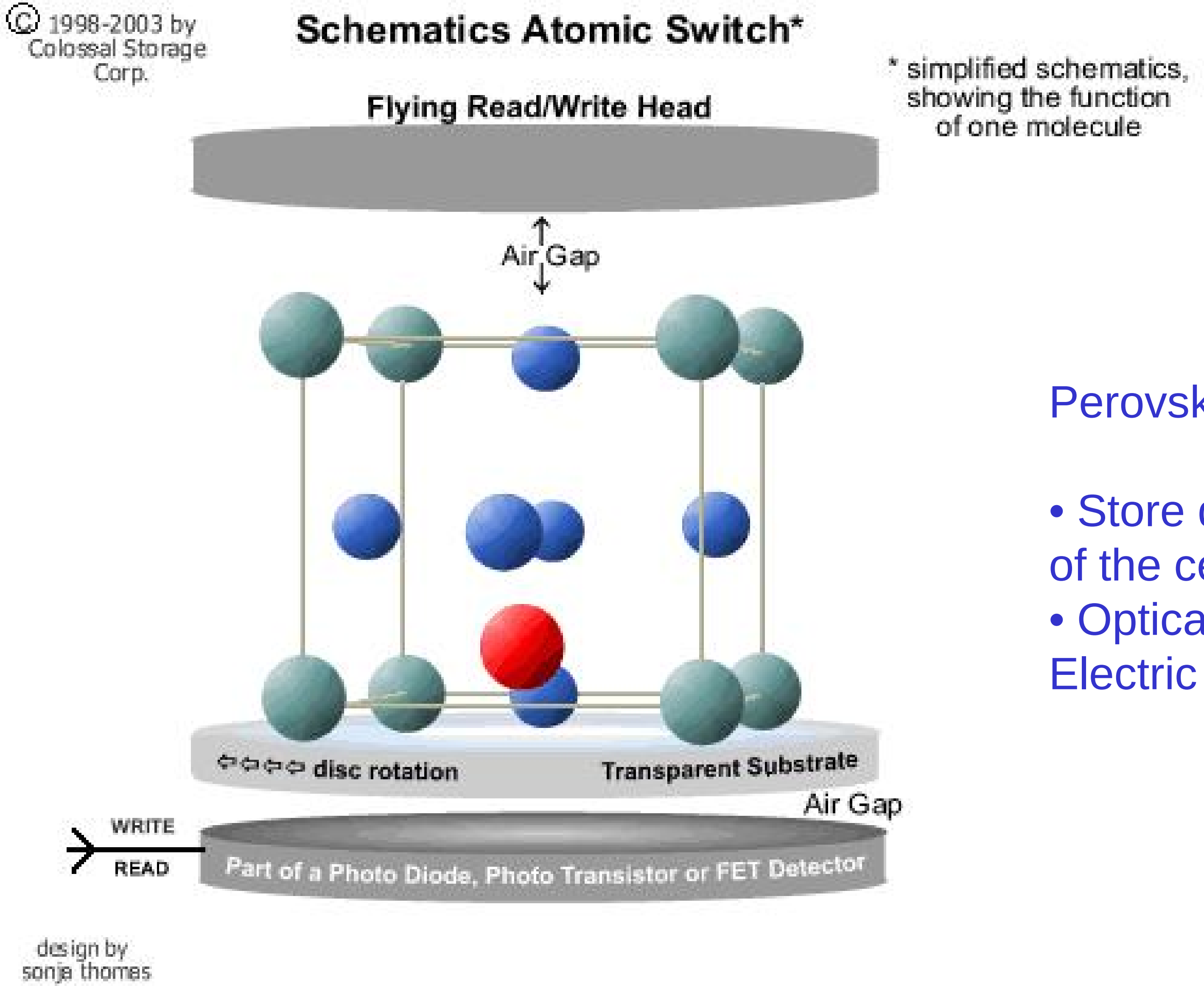
Universität Potsdam

HZB Helmholtz Zentrum Berlin

Bachelor, Master + Diploma Students

Alexander von Reppert
Matthias Sander
Mathias Gohlke
Jan Pudell
Felix Stete
Lisa Willig

Ultrafast and Ultrasmall Data Processing



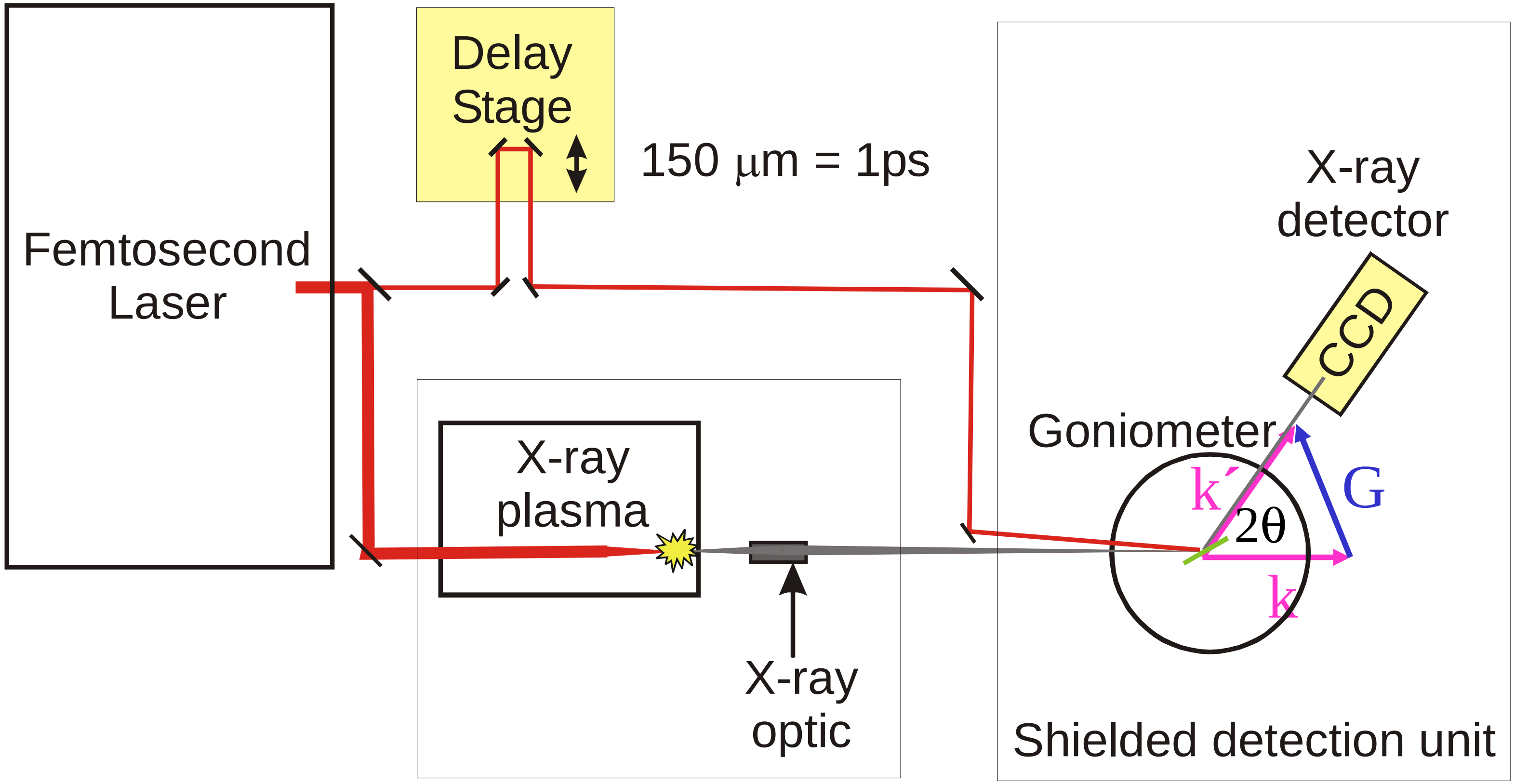
Perovskite:

- Store data in the position of the central ion
- Optical excitation + Electric field

UXRD using Plasma Source

Resolution ~150 fs

~ 10^6 photons /s on sample

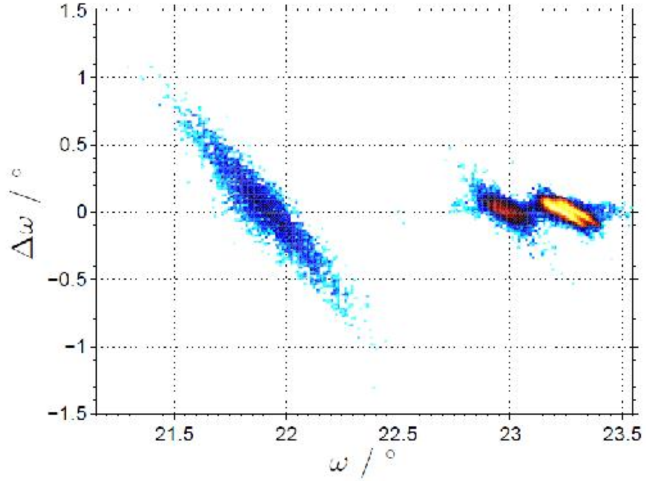


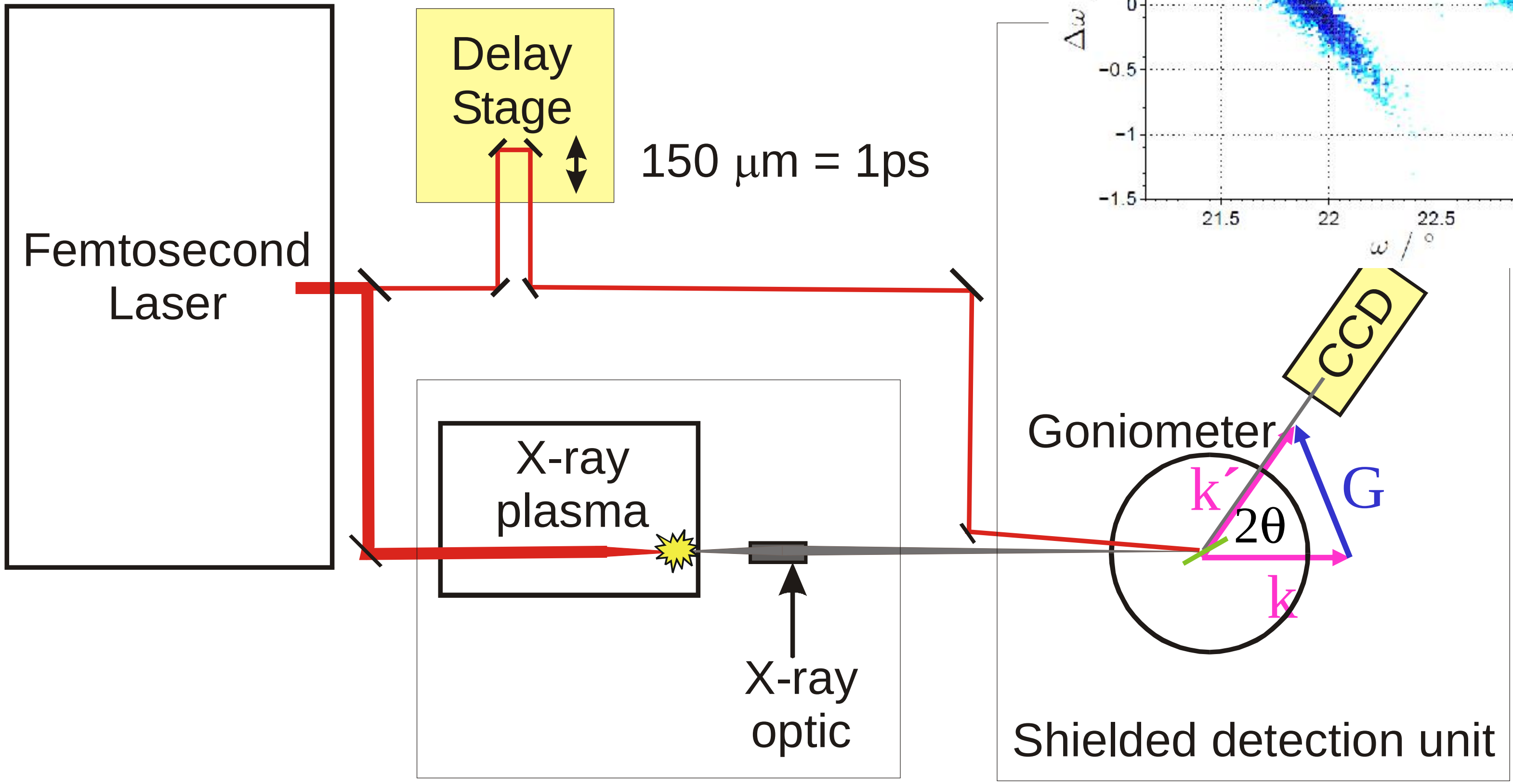
D. Schick et al, Rev. Sci. Instrum. **83**, 25104 (2012)

UXRD using Plasma Source

Resolution ~150 fs

~ 10^6 photons /s on sam





D. Schick et al, Rev. Sci. Instrum. **83**, 25104 (2012)

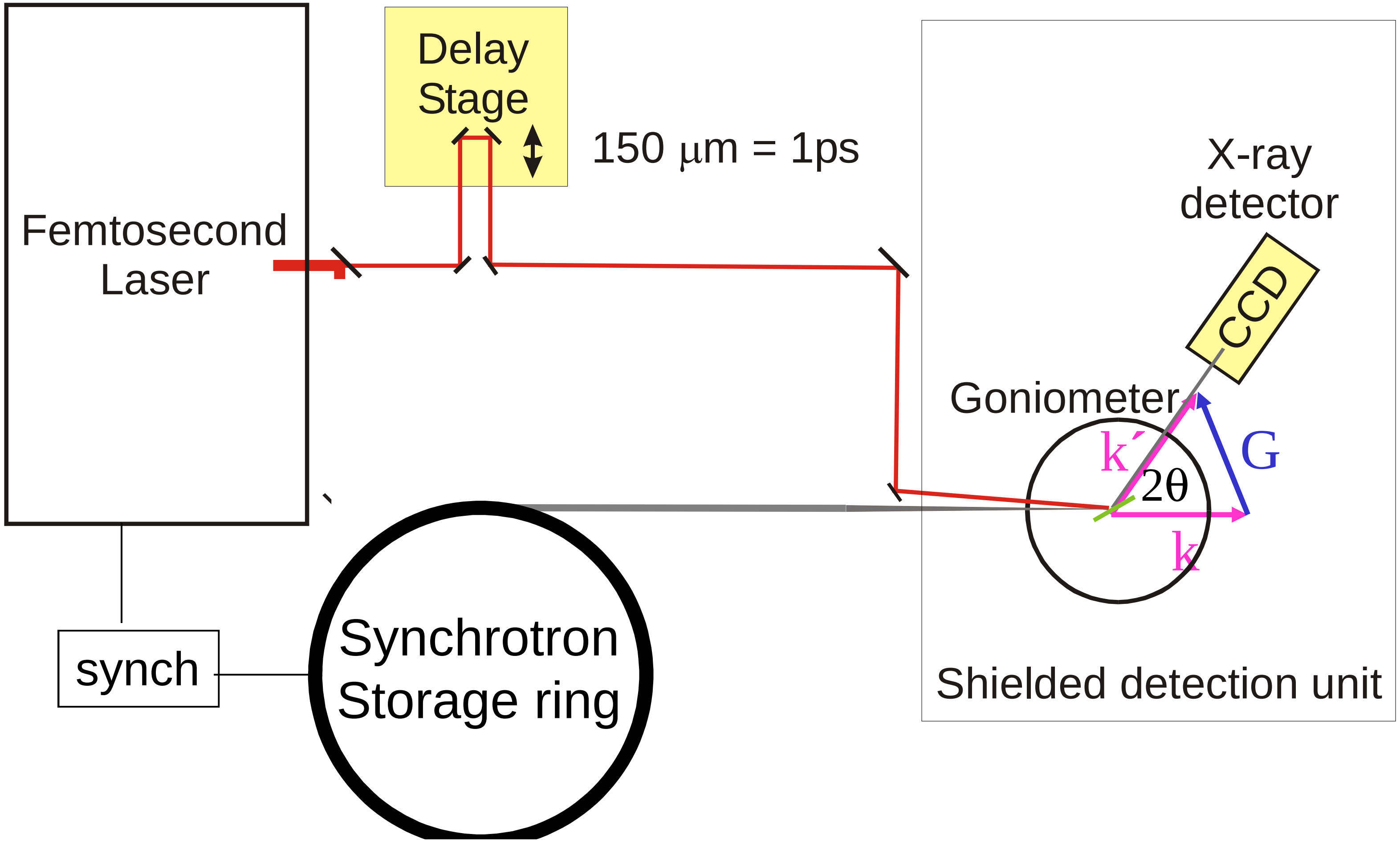
Schick et al., J. Appl. Cryst. 46 (2013)

UXRD at Synchrotrons

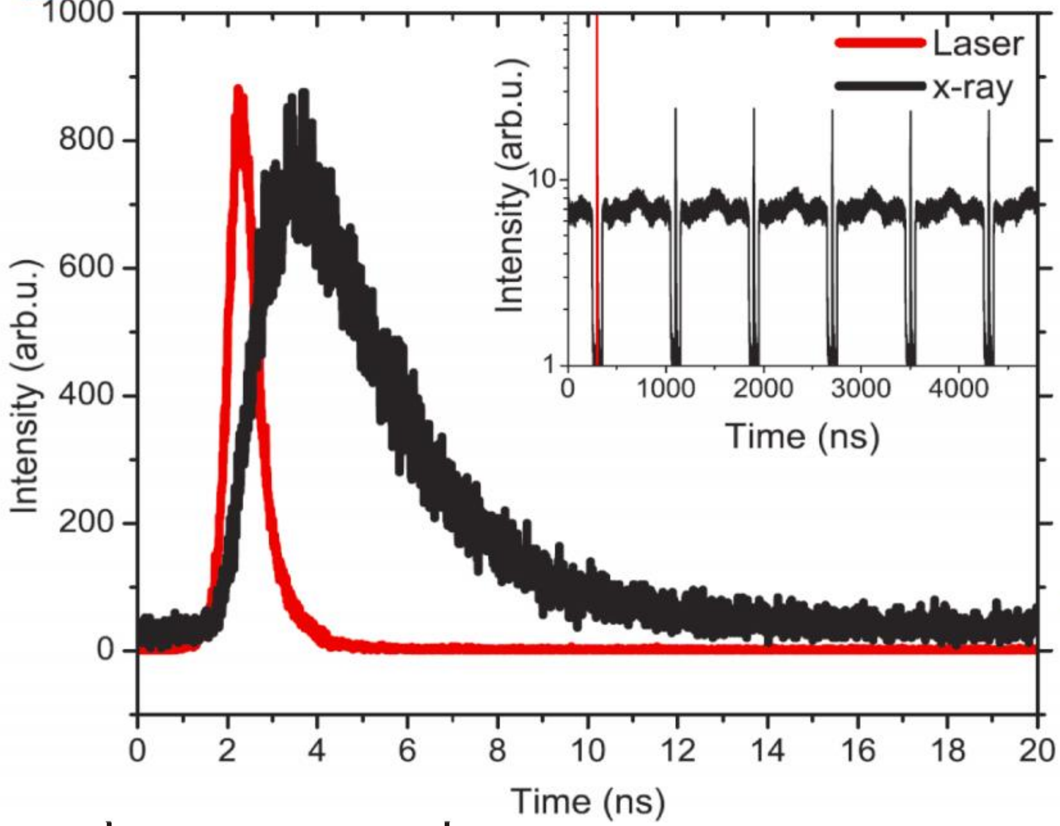
Time resolution ~100 ps -> 0.3 - 10 ps

Repetition rate: 208 kHz , 1.25 MHz

~ 10^5 - 10^9 photons /s on sample



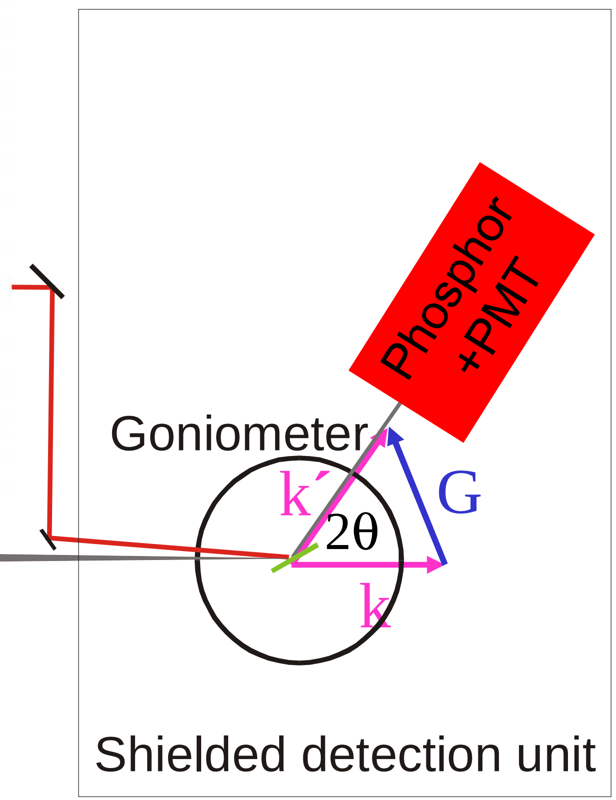
XPP-KMC3 @ BESSY II

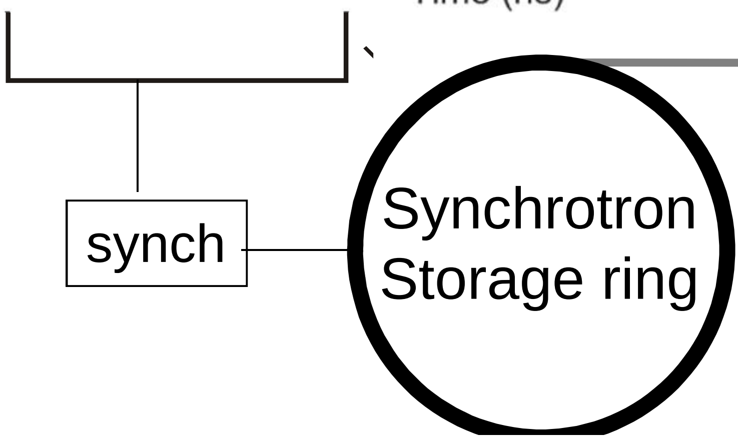


Fast X-ray Detector:

Record 1 ns – 5 ms data for free

Pump-Probe: 50 ps time resolution

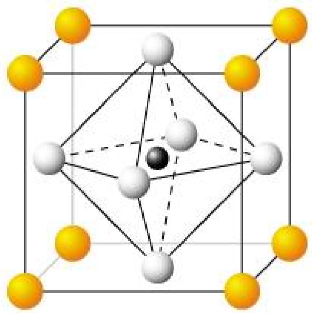


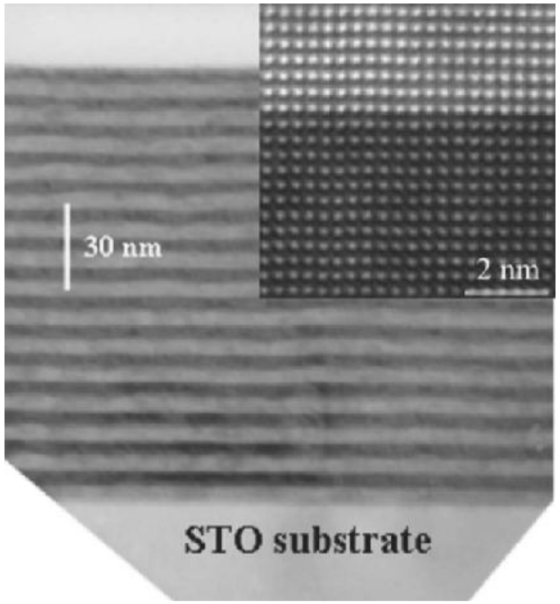


Navirian et al, Rev. Sci. Instrum. **83**, 063303 (2012)

Oxide Nanolayers

Perovskite structure





Vrejoiu et al., APL **92**, 152506 (2008).

Ferromagnetic metals:

SRO: $SrRuO_3$
$T_c \approx 160$ K (bulk)

LSMO: $(La_{0.7}Sr_{0.3})MnO_3$
$T_c \approx 370$ K (bulk)

Insulators:

STO: $SrTiO_3$
dielectric

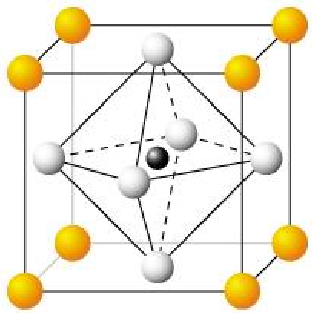
PZT: $Pb(Zr_{0.2}Ti_{0.8})O_3$
ferroelectric below $T_c \approx 750$ K

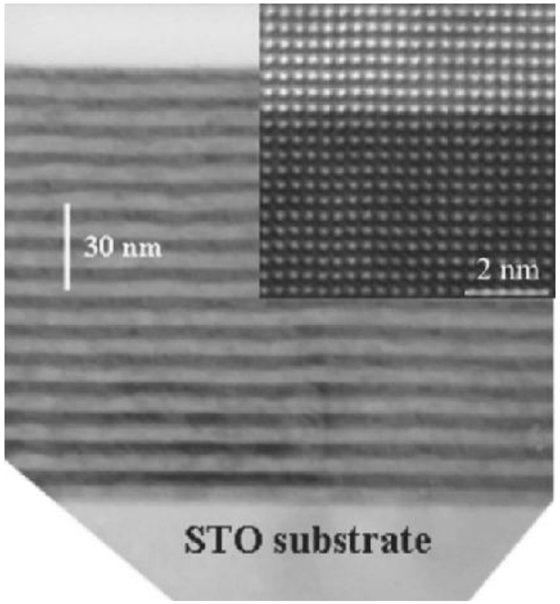
Other perovskite oxides:
Superconducting, giant magnetoresistance,..
Rich phase diagrams

-> Grown by Pulsed Laser Deposition
MPI Halle: D. Hesse, M. Alexe, I. Vrejoiu

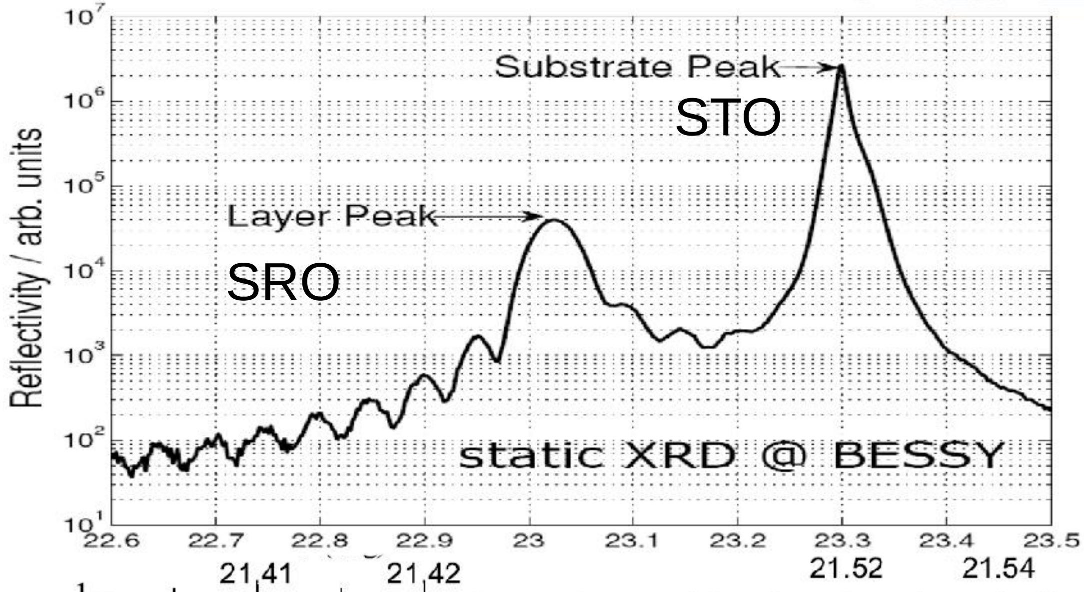
Oxide Nanolayers

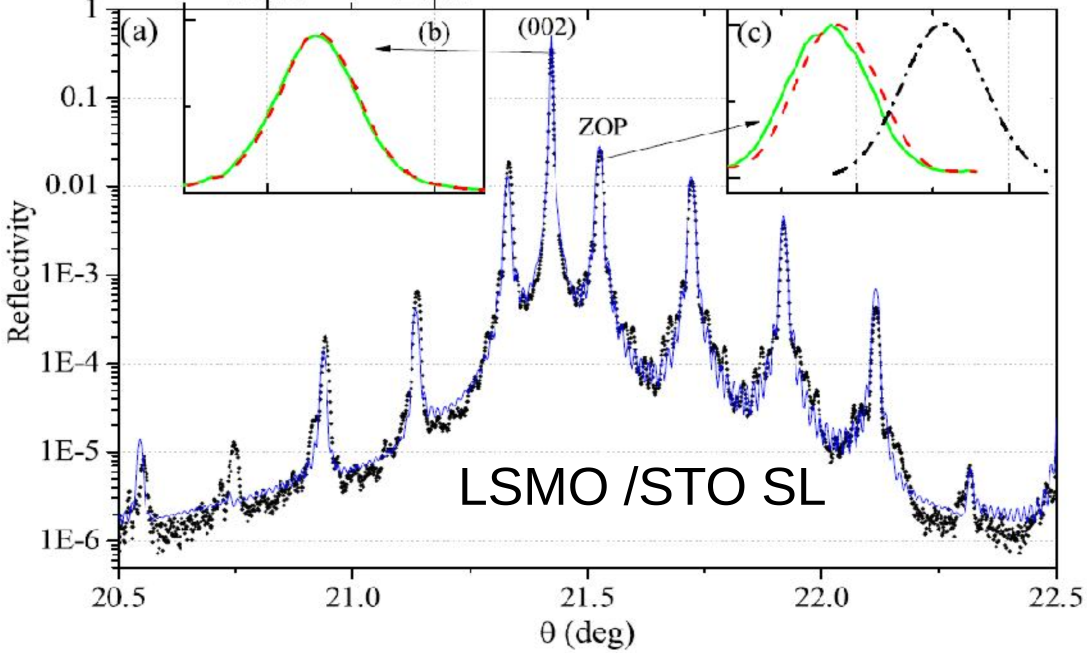
Perovskite structure



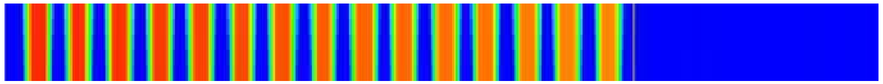


Vrejoiu et al., APL **92**, 152506 (2008).

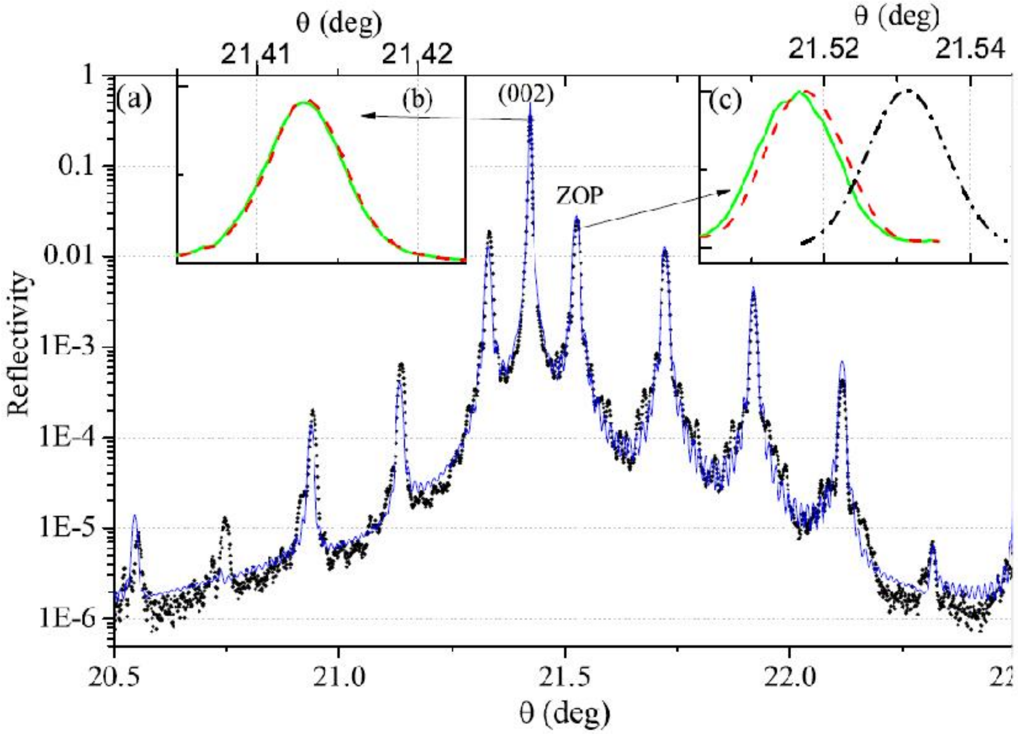


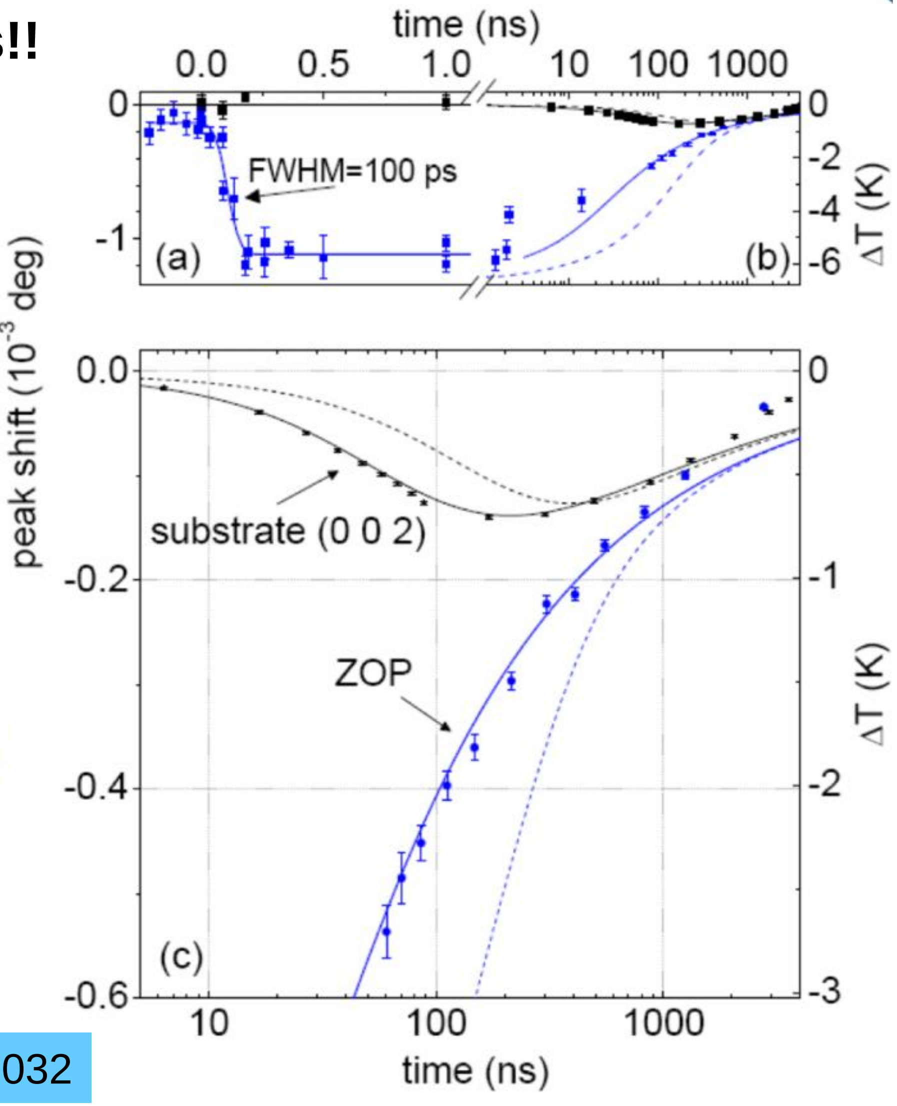


Heat Diffusion from SL into Substrate



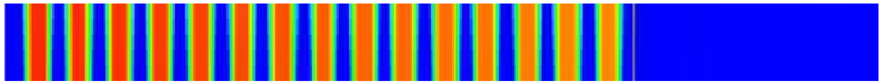
Example: LSMO/STO SL (9+14nm) on STO
Heat equilibrated within SL after **~ 10 ps!!**
Heat flow to substrate ~ 100 **ns**





Shayduk et al., *New Journal of Physics* **13** (2011) 093032

Heat Diffusion from SL into Substrate



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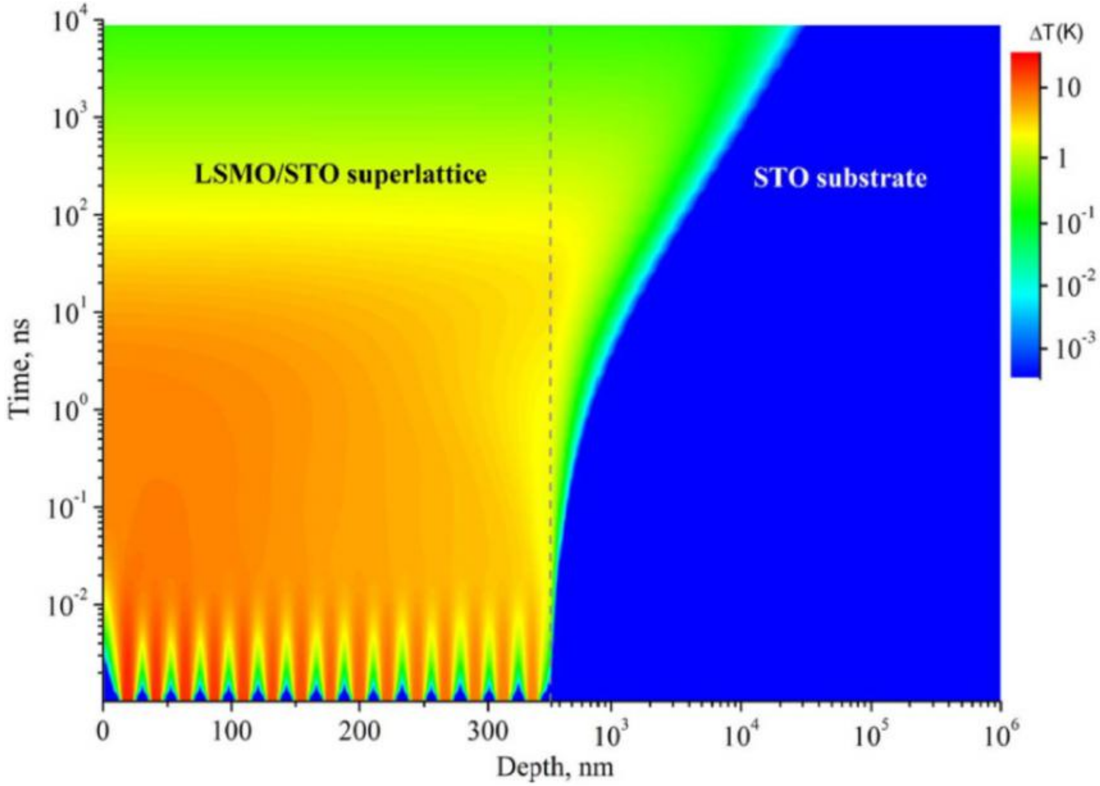
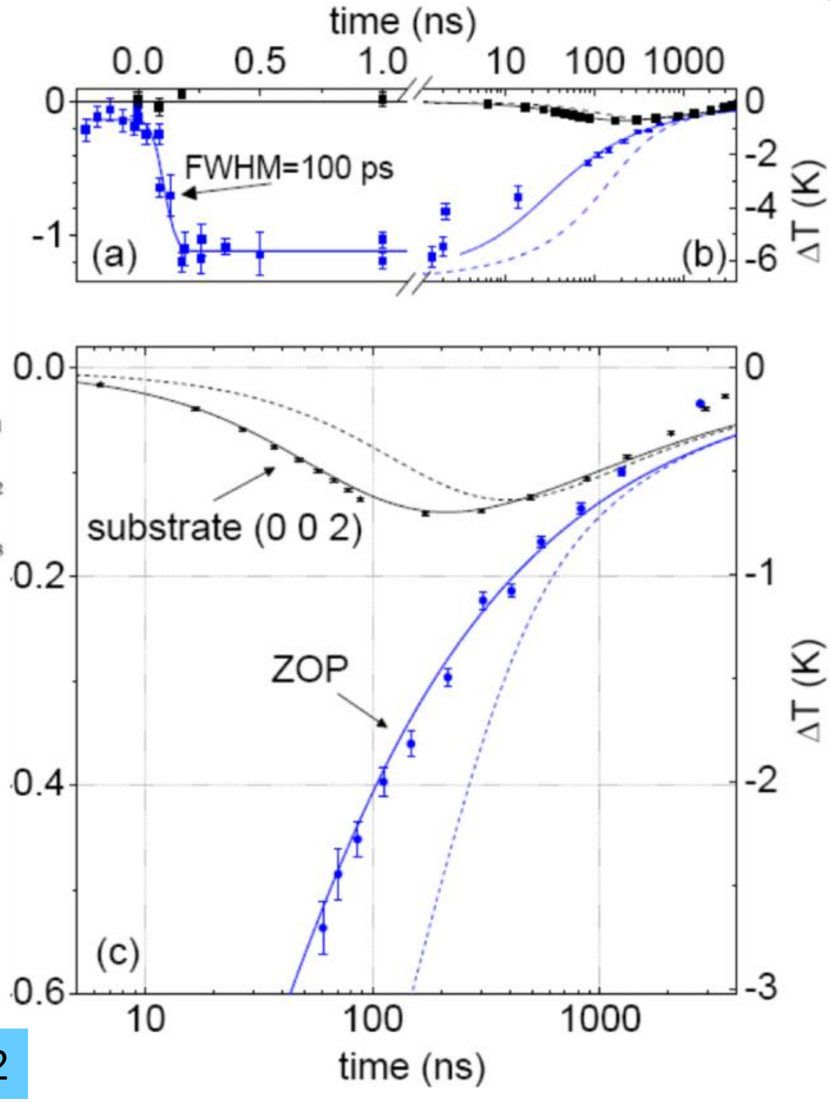
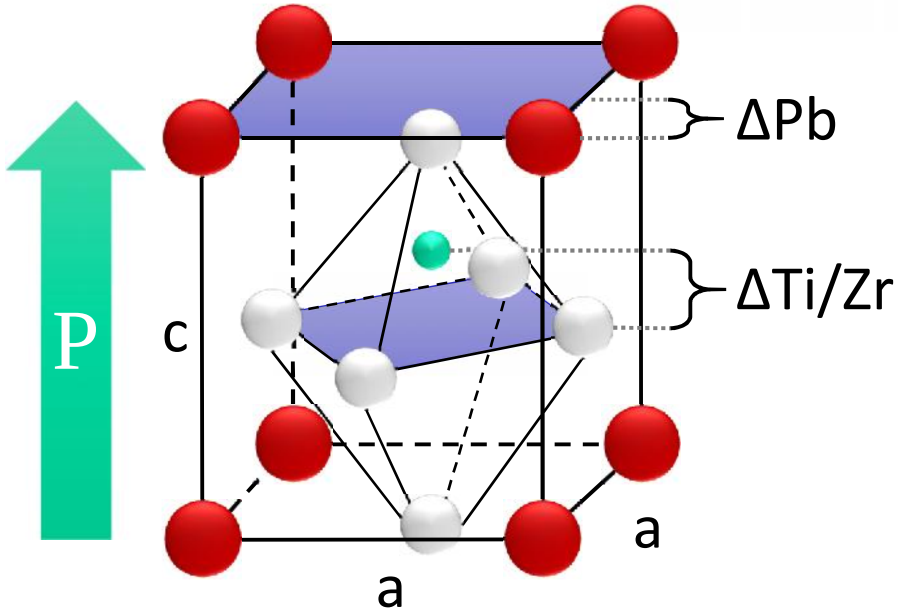




Shayduk et al., *New Journal of Physics* **13** (2011) 093032

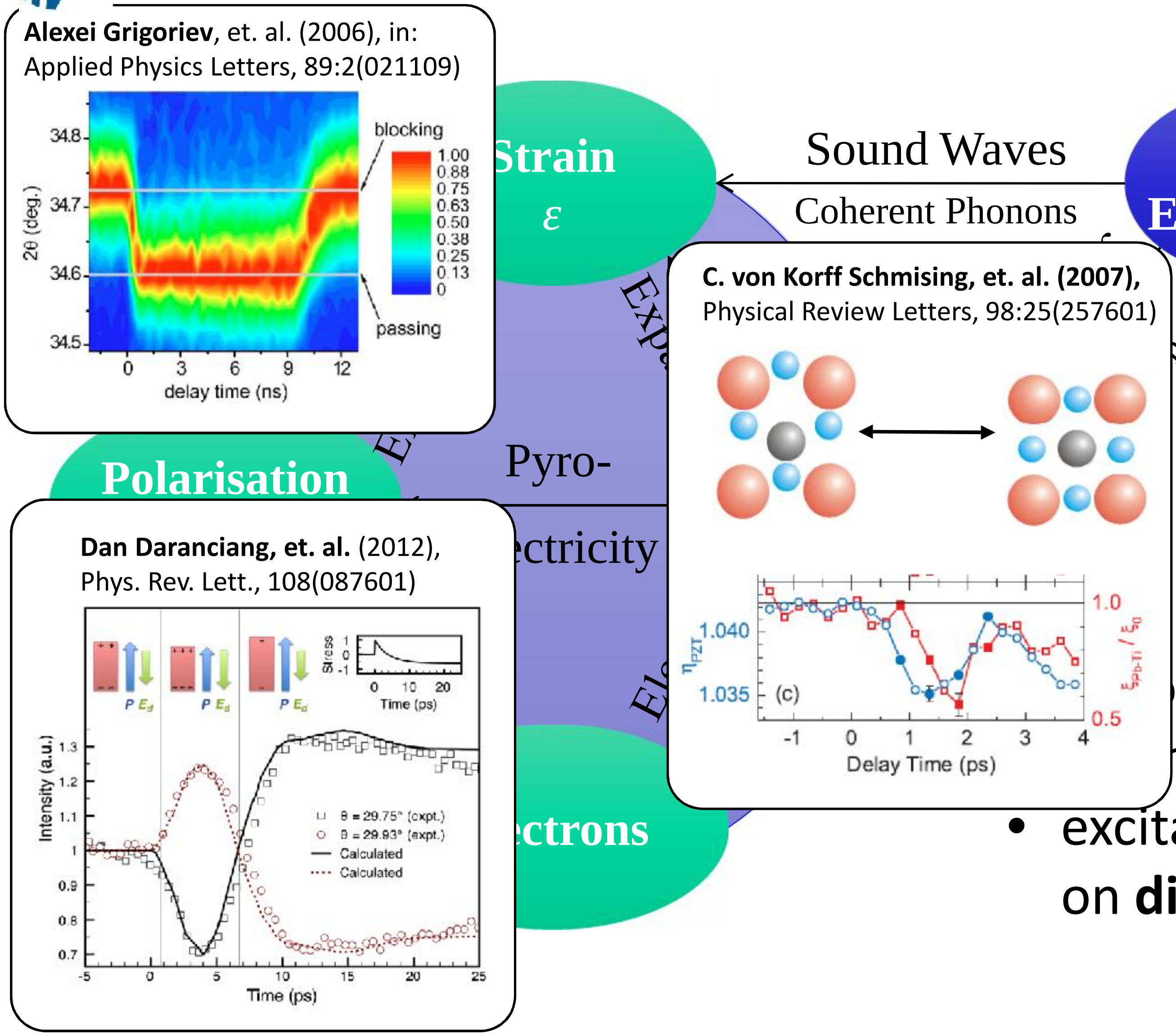
Ferroelectric Perovskite: $PbZr_{0.2}Ti_{0.8}O_3$

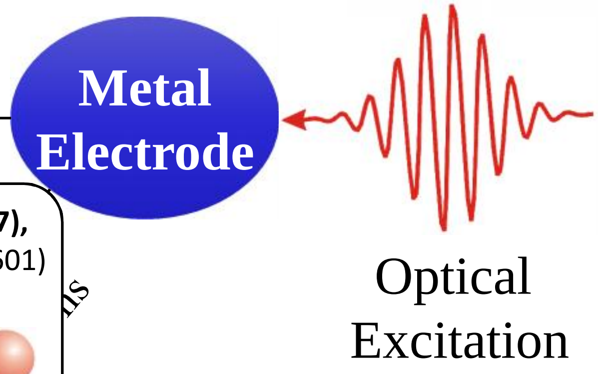
- A-site cation: Pb
- B-site cation: Zr/Ti
- Oxygen



- ferroelectric due to tetragonal distortion of Pb and Zr/Ti below $T_c \approx 400°C$
- additional piezo- and pyro-electricity
- various applications in MEMS or FeRAM

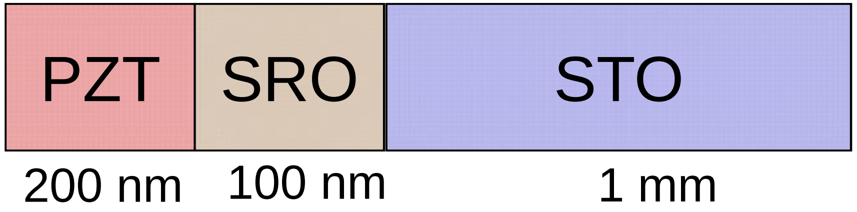
Couplings Investigated by UXRD

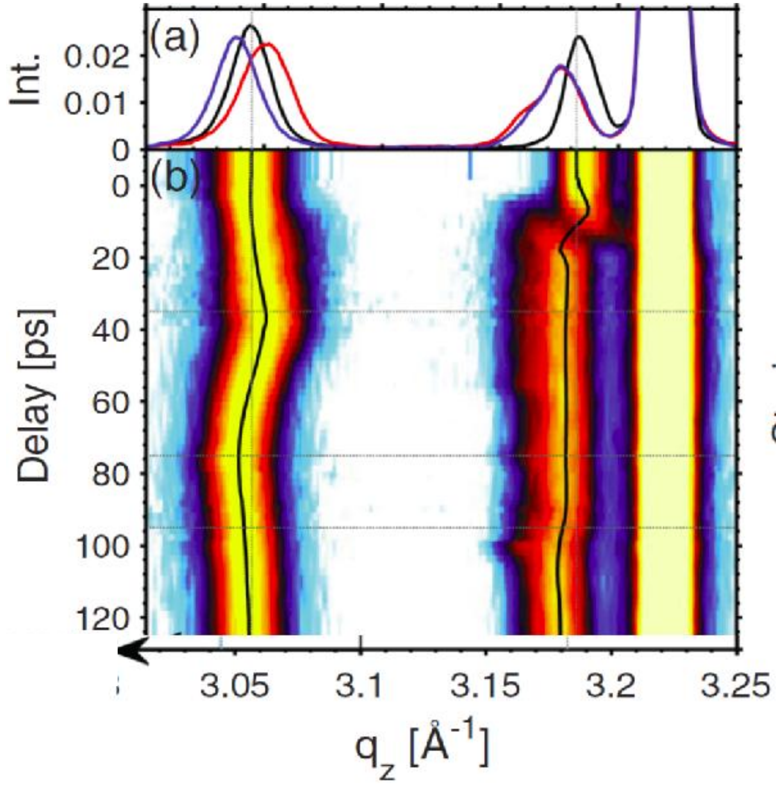


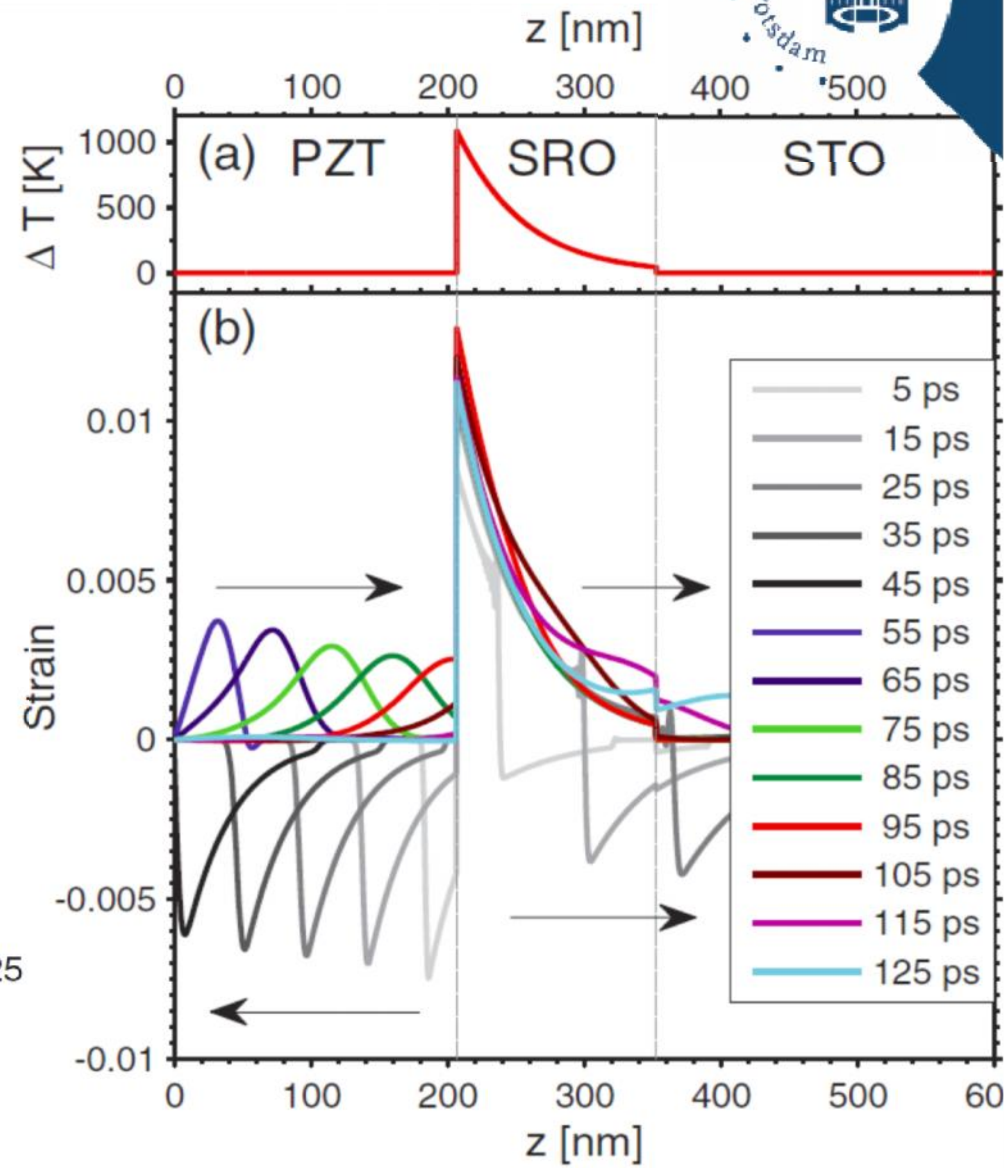


- …us excitation
- …hanisms
- excitation and coupling on **different time scales**

Inhomogeneous Strain Propagation in PZT

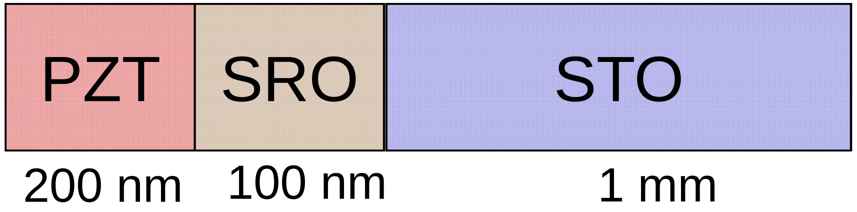


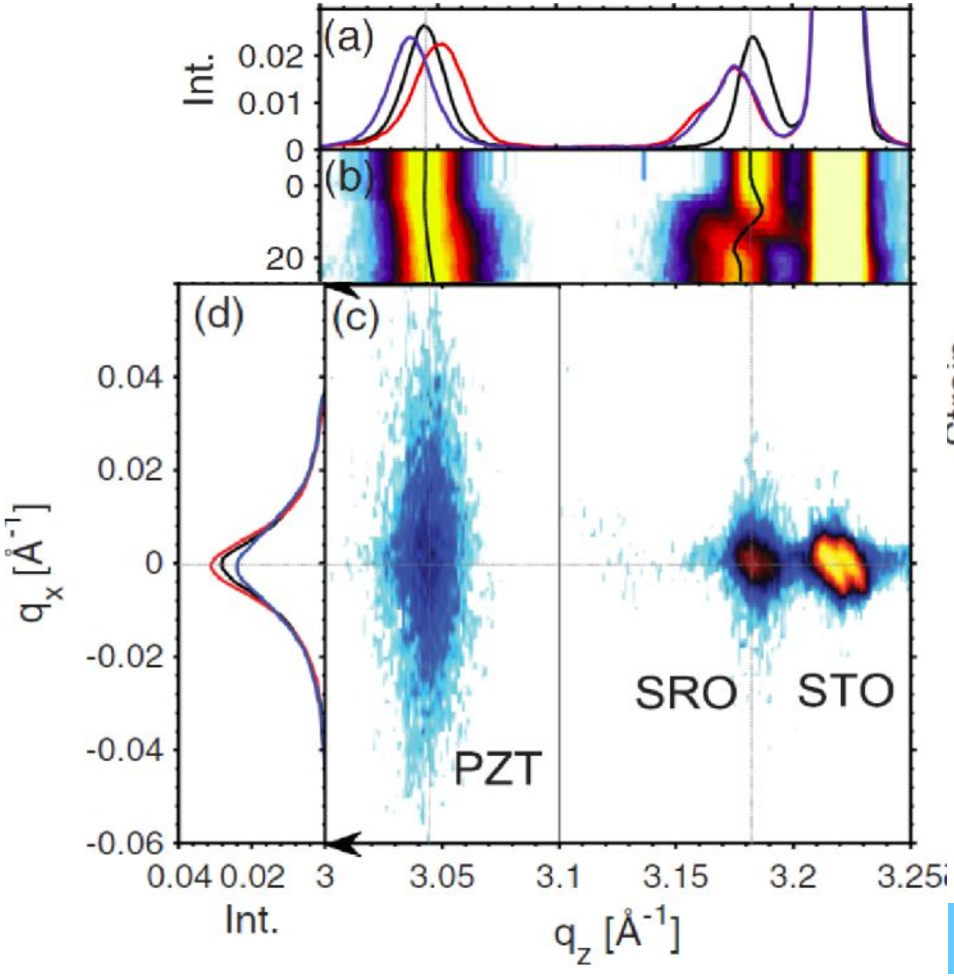


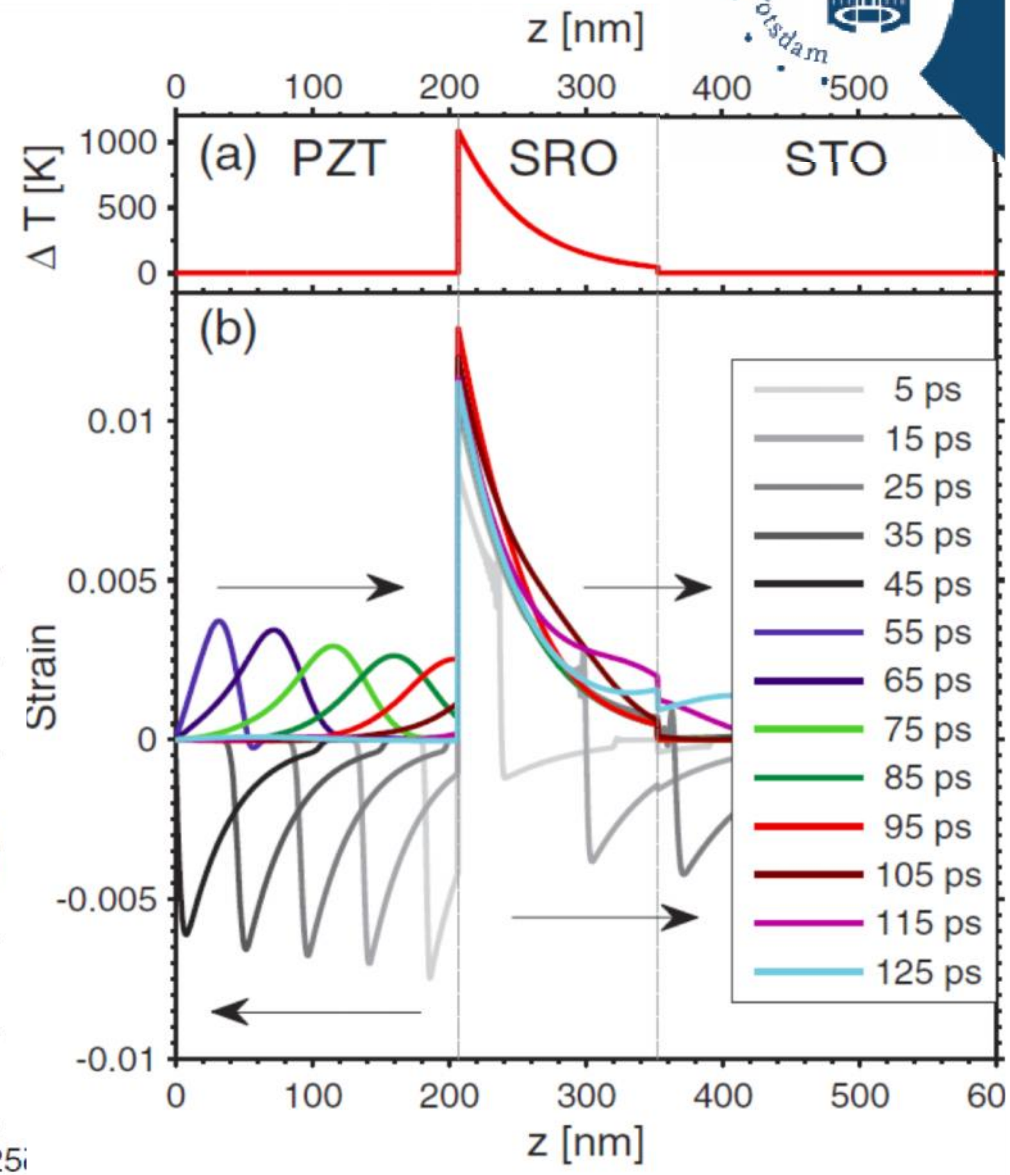


Schick et al., Phys. Rev. Lett. 110, 095502 (2013)

Inhomogeneous Strain Propagation in PZT







Schick et al., Phys. Rev. Lett. 110, 095502 (2013)

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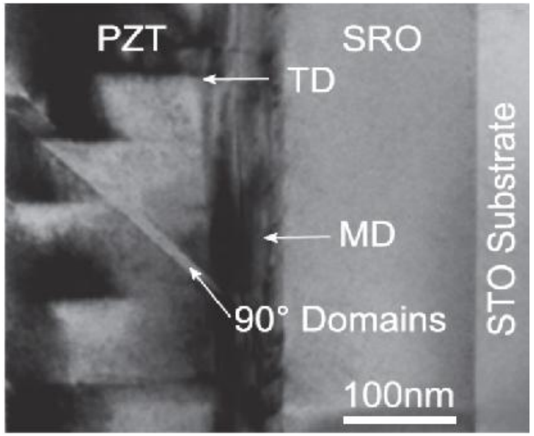

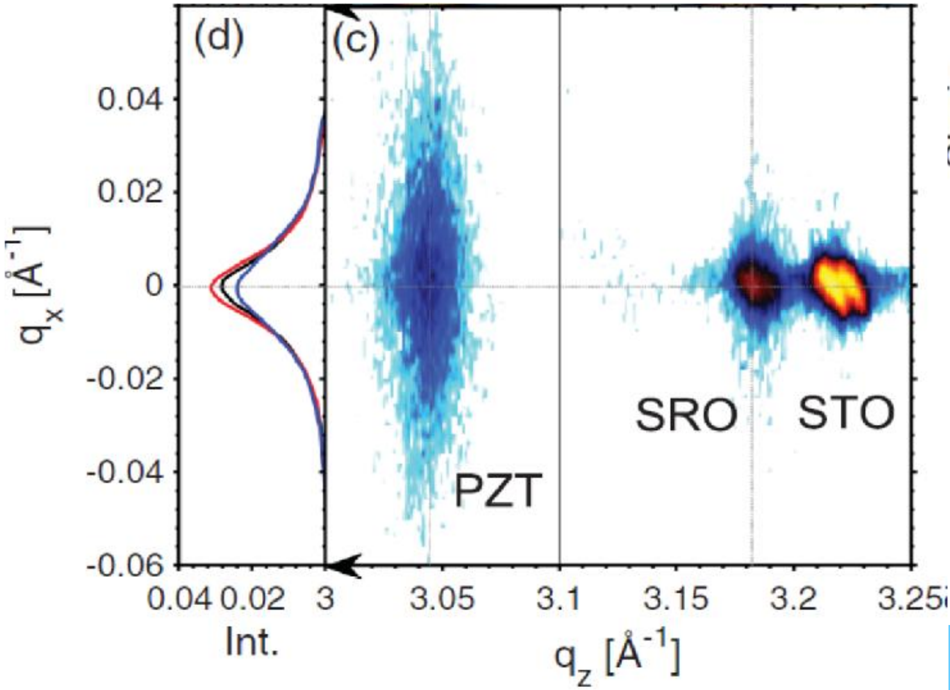

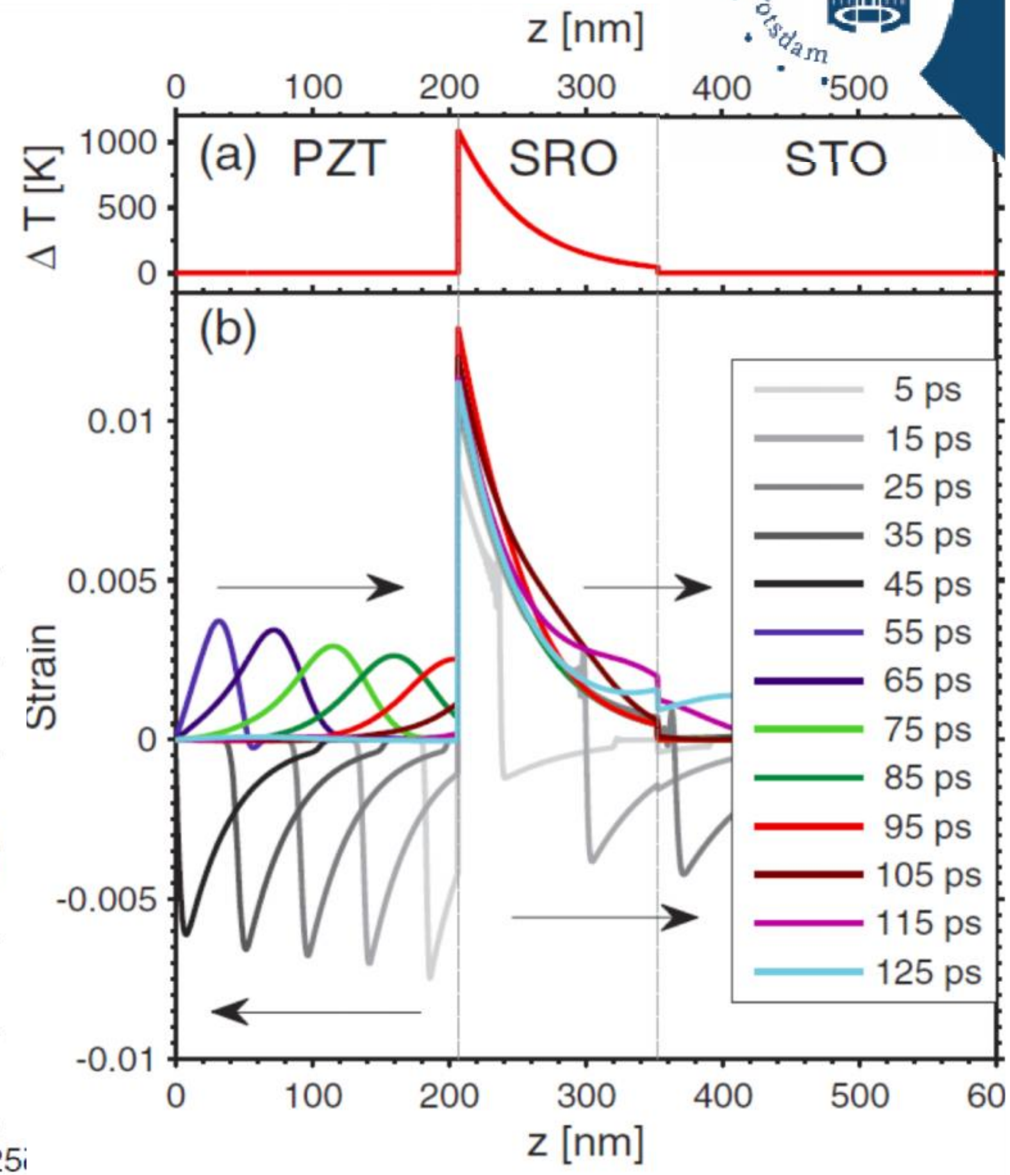

Schick et al., Phys. Rev. Lett. 110, 095502 (2013)

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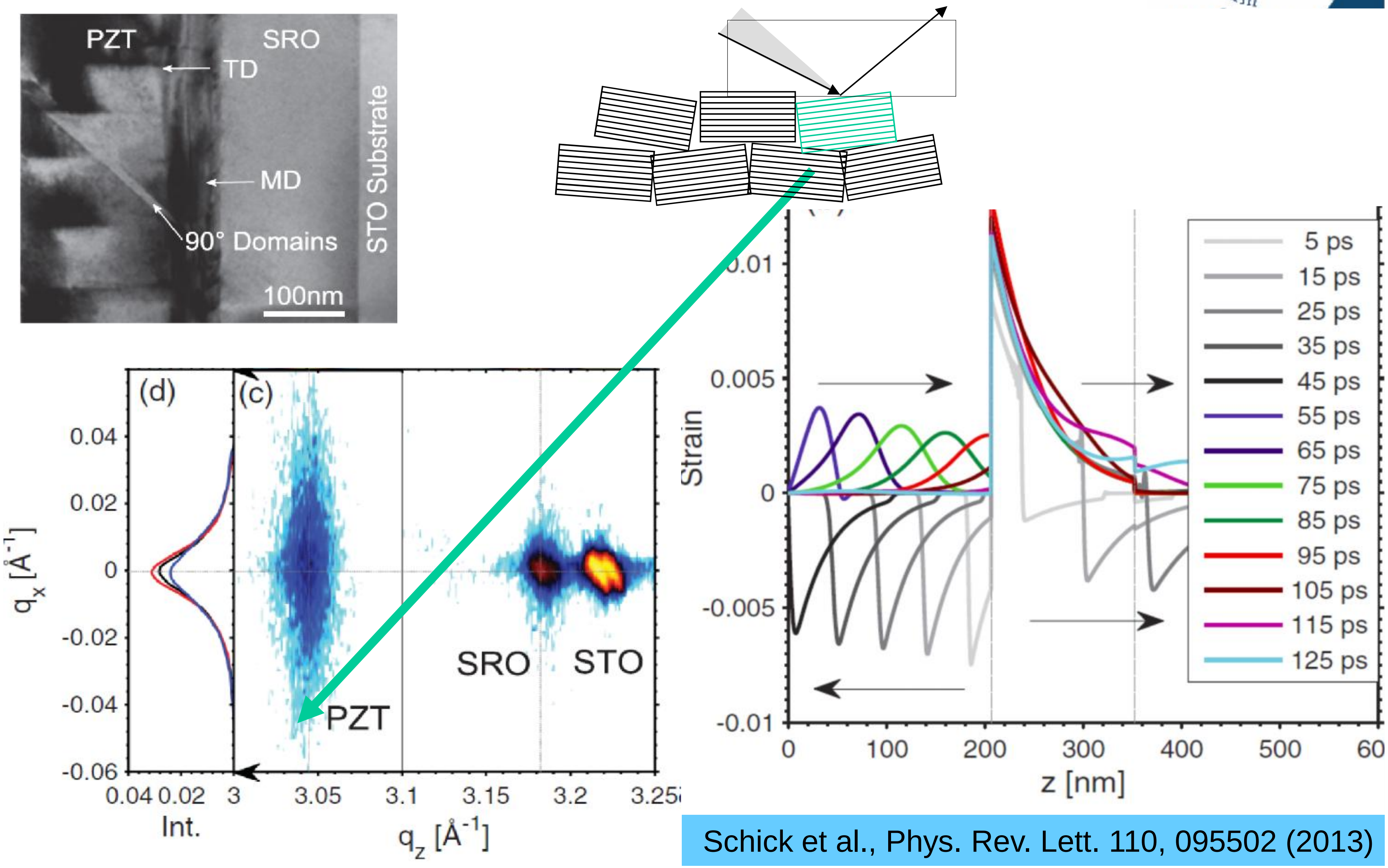

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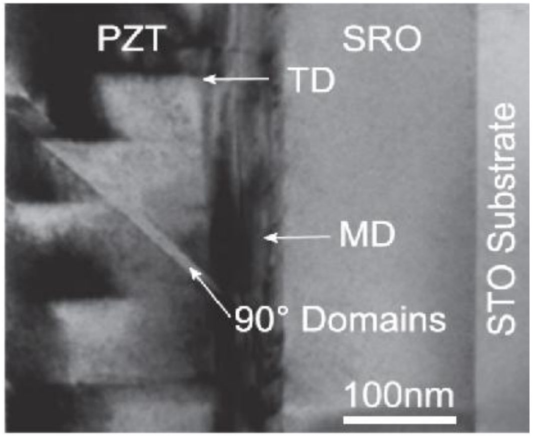
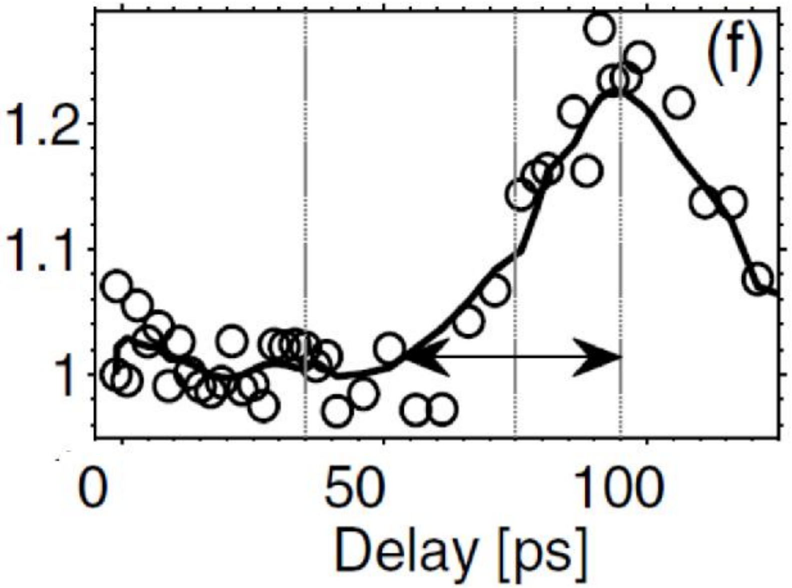
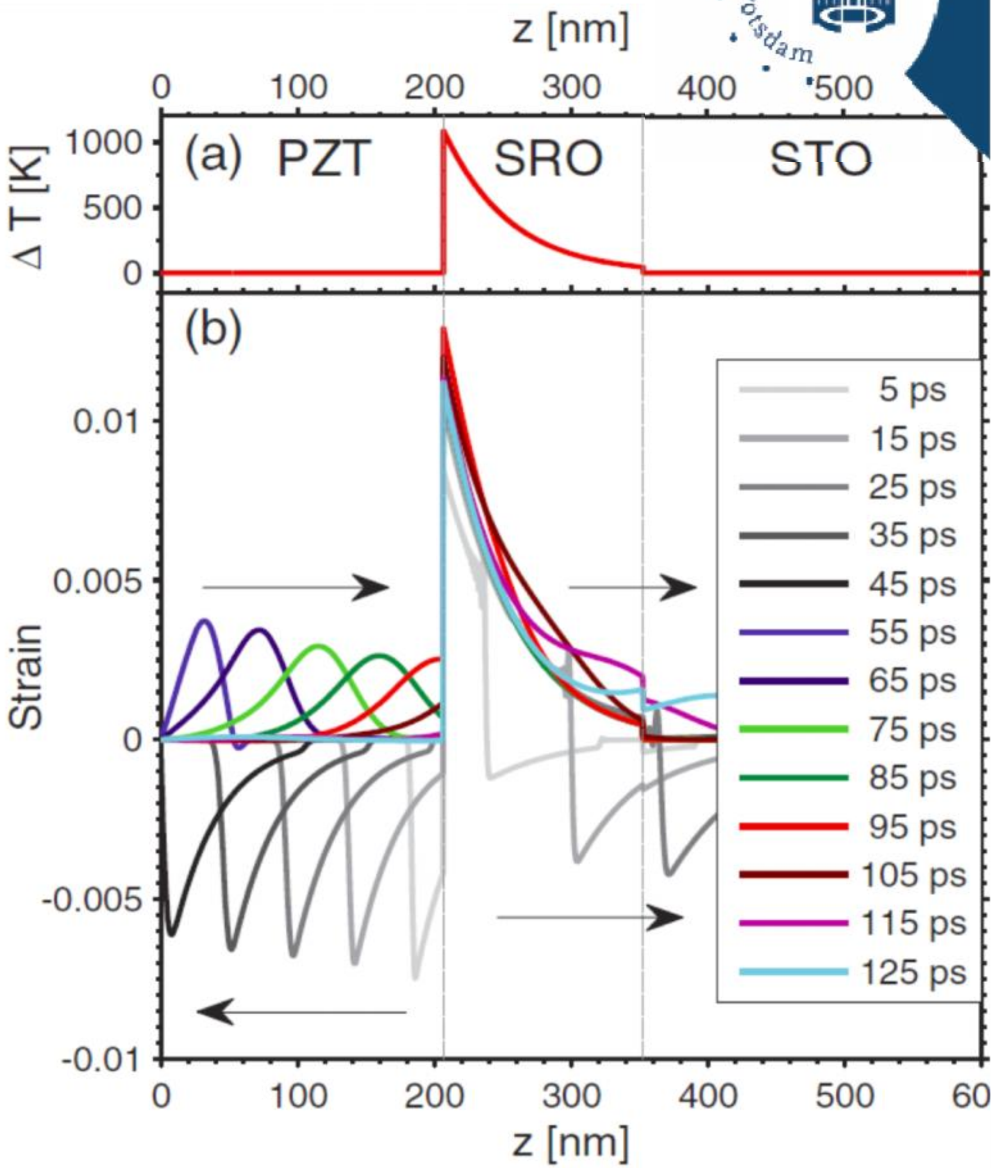


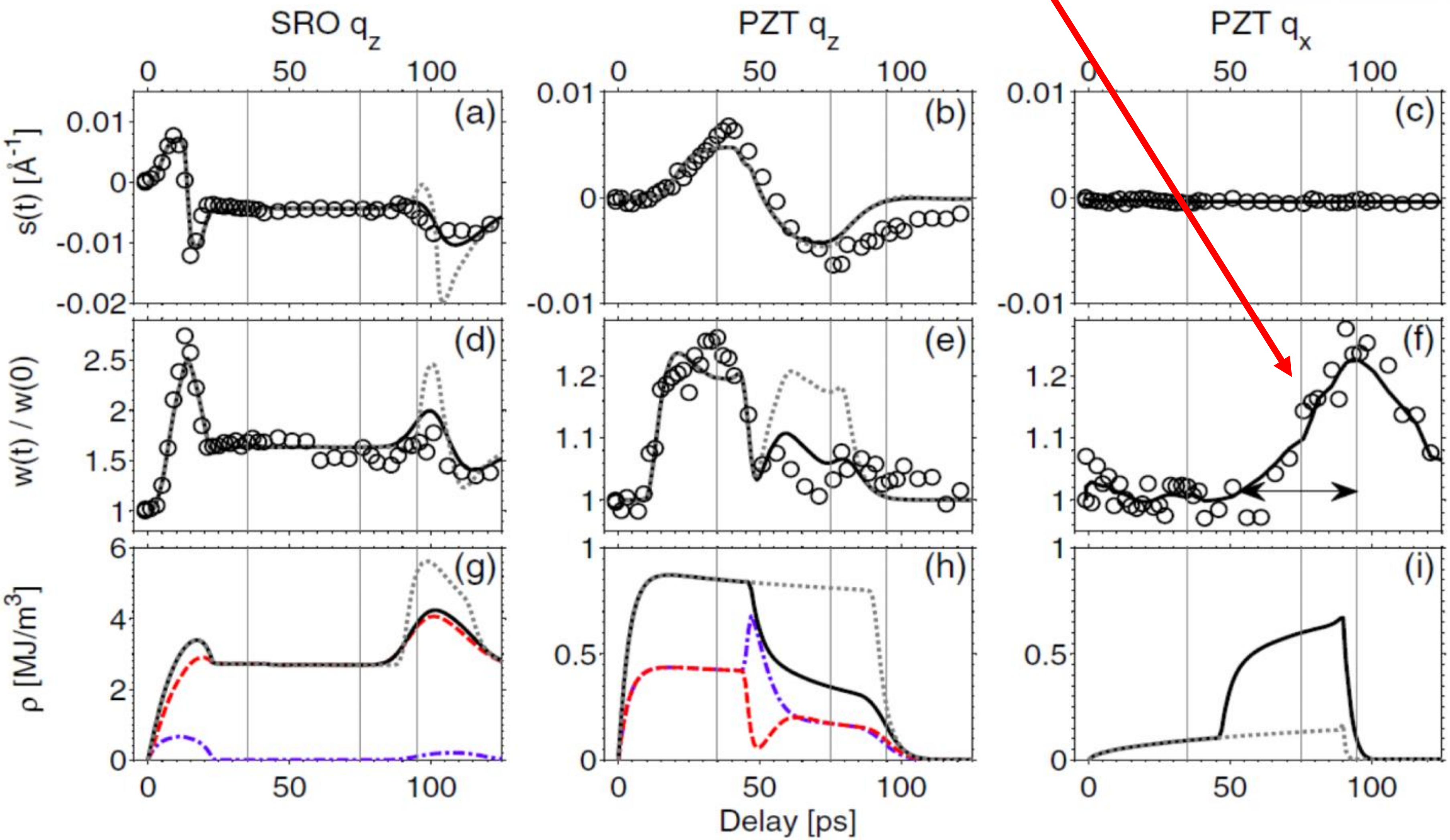




Schick et al., Phys. Rev. Lett. 110, 095502 (2013)

Inhomogeneous Strain -> Broadening

Reciprocal space mapping

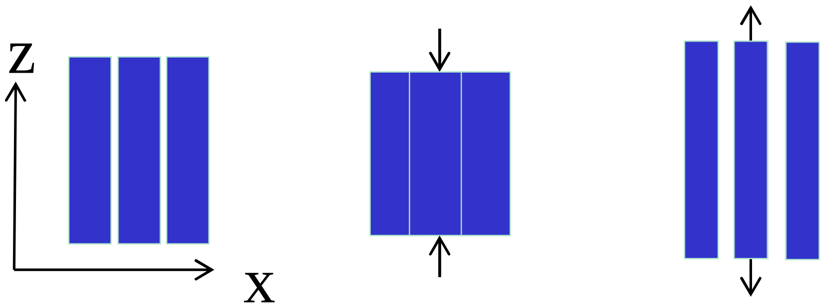


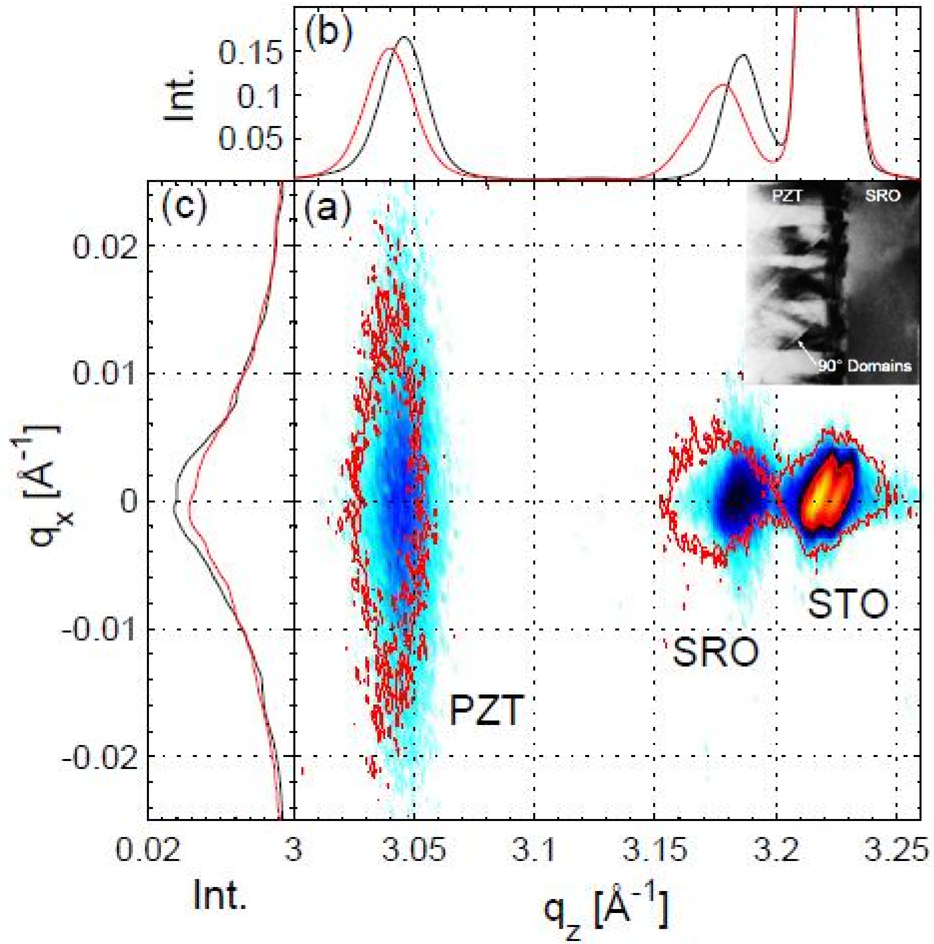
Schick et al., Phys. Rev. Lett. 110, 095502 (2013)

Schick et al., J. Appl. Cryst. 46 (2013)

Dynamic stress relaxation at inhomogeneities

- coupling of **out-of-plane** into **in-plane lattice dynamics** for expansion wave due to **defects**
- not for **compression wave** or **laterally perfect structures**





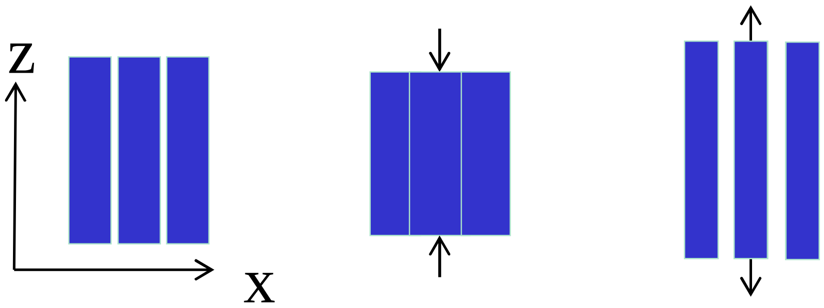
Schick et al., Phys. Rev. Lett. 110, 095502 (2013)

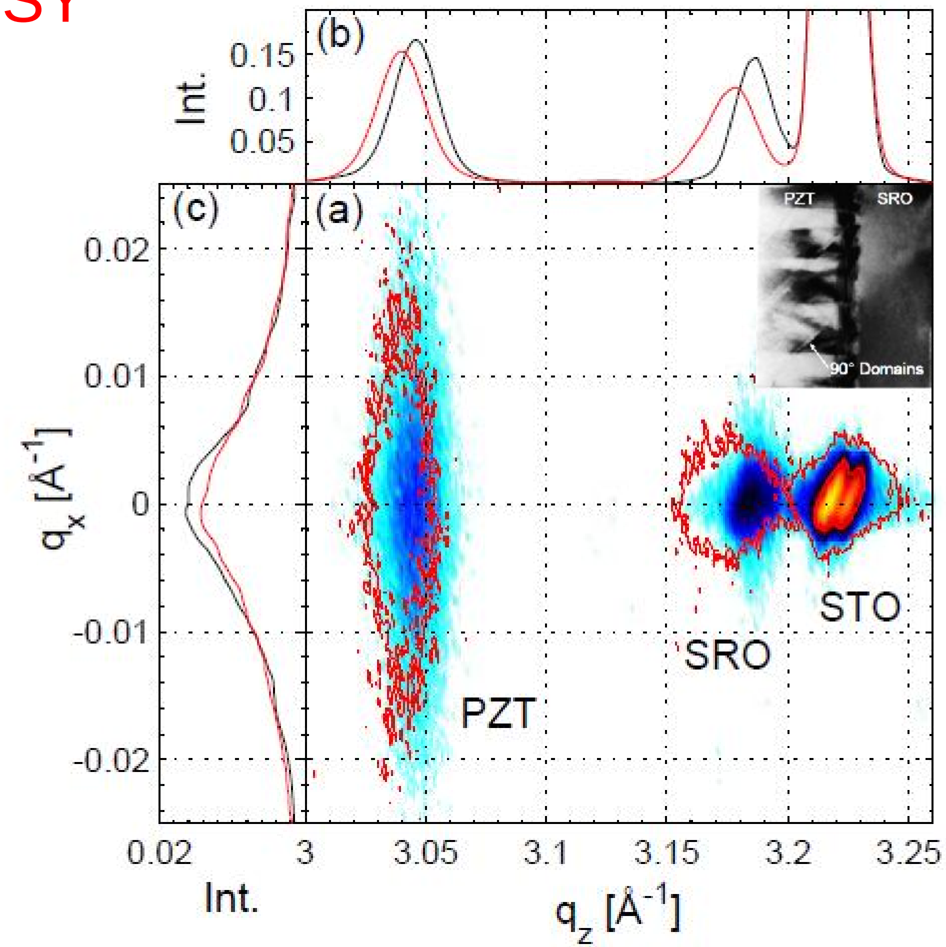
Schick et al., J. Appl. Cryst. 46 (2013)

Dynamic stress relaxation at inhomogeneities

Need VSR to do this at BESSY

- coupling of **out-of-plane** into **in-plane lattice dynamics** for expansion wave due to **defects**
- not for **compression wave** or **laterally perfect structures**

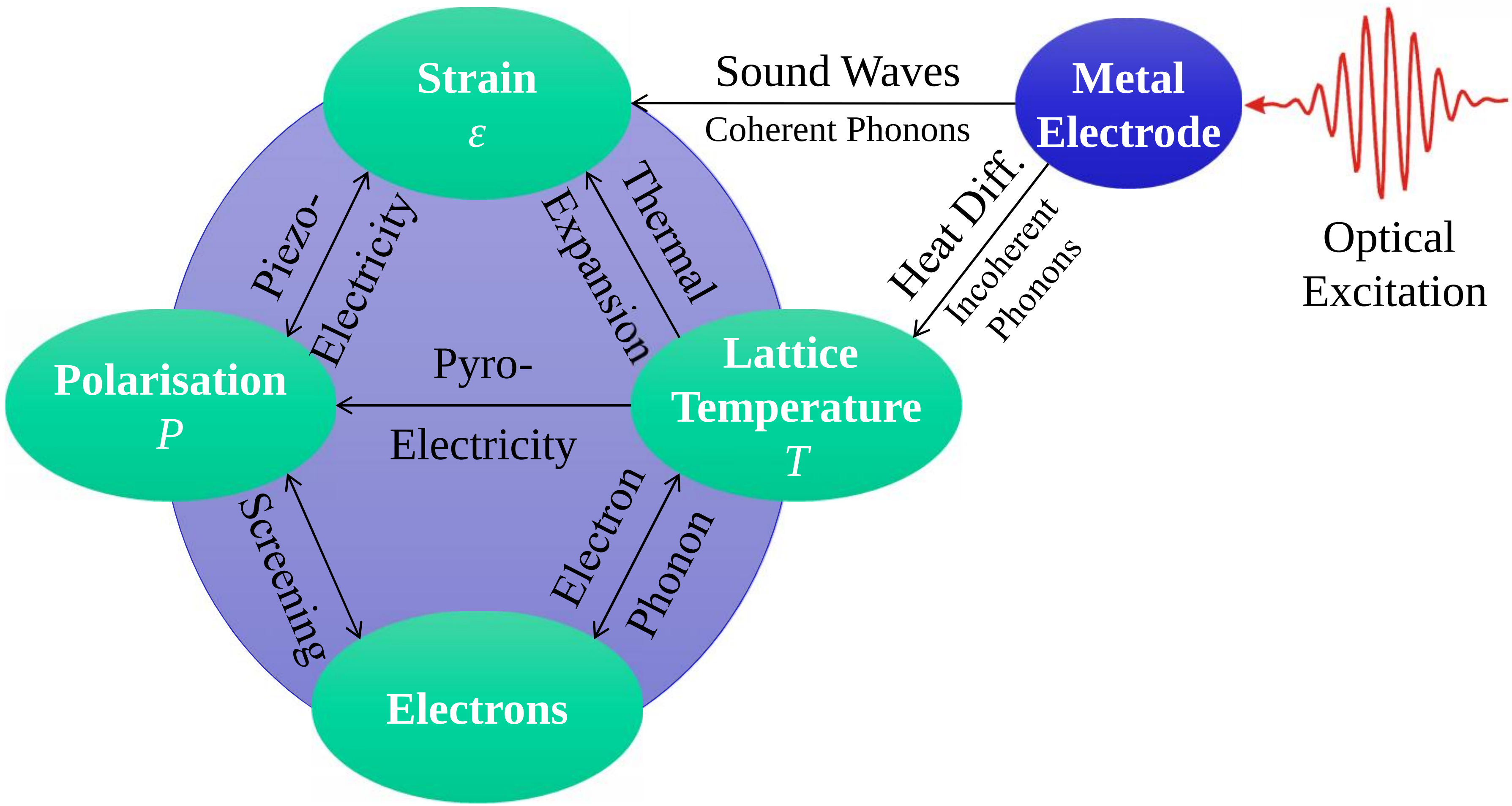




Schick et al., Phys. Rev. Lett. 110, 095502 (2013)

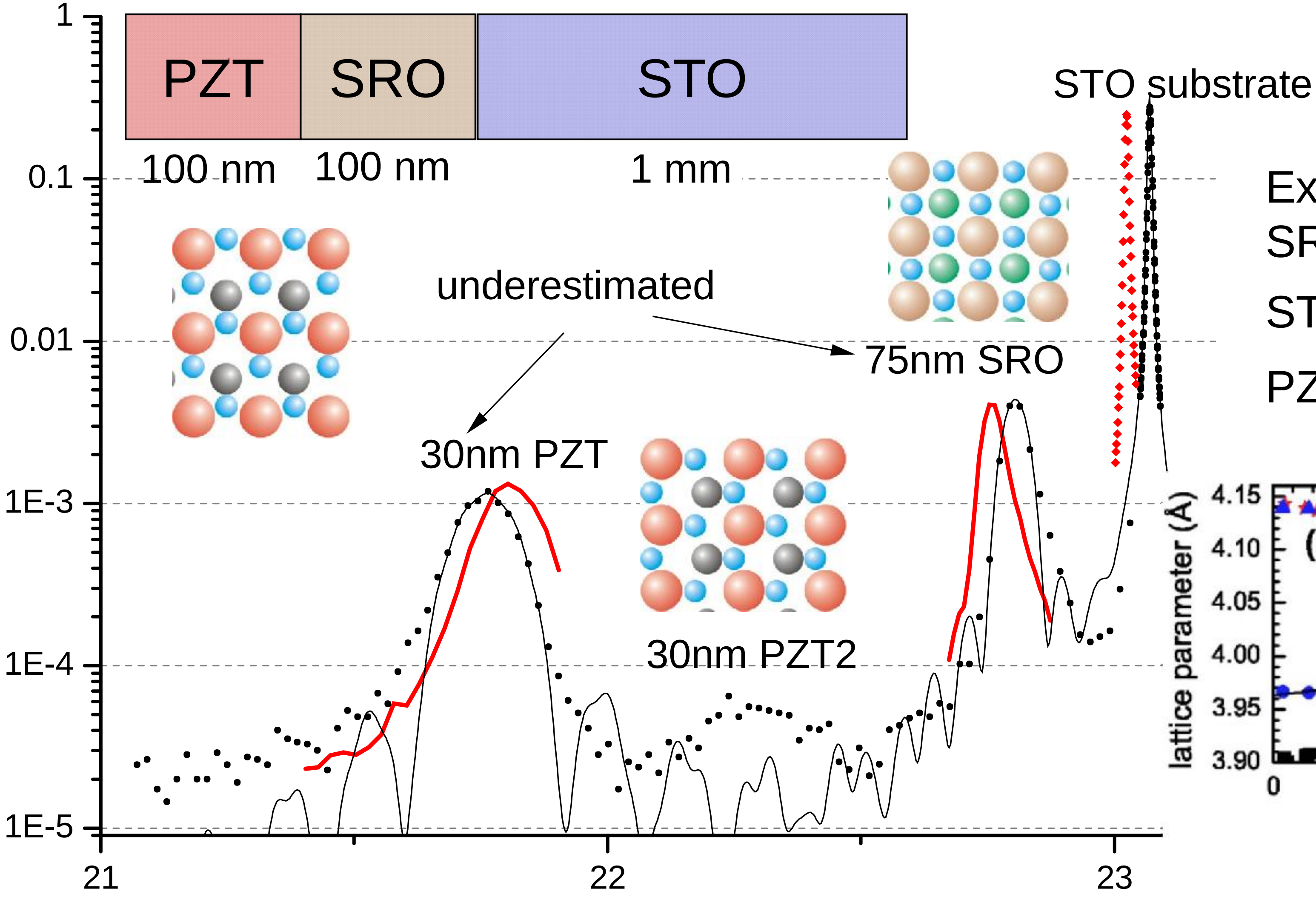
Schick et al., J. Appl. Cryst. 46 (2013)

Couplings Investigated by UXRD



Laser Heating of a Thin Ferroelectric Film

Does PZT contract when heated?

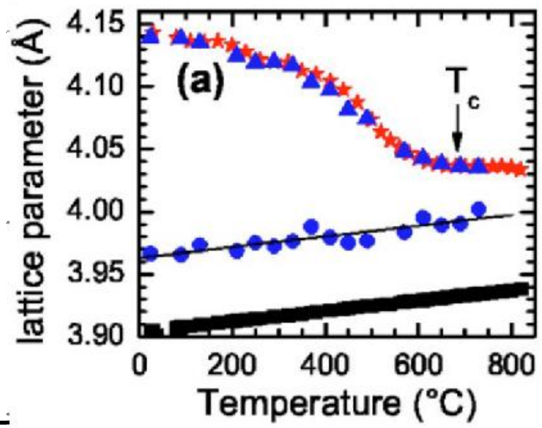


Expansion coeff

SRO: $1.1 \cdot 10^{-5}$

STO: $1.1 \cdot 10^{-5}$

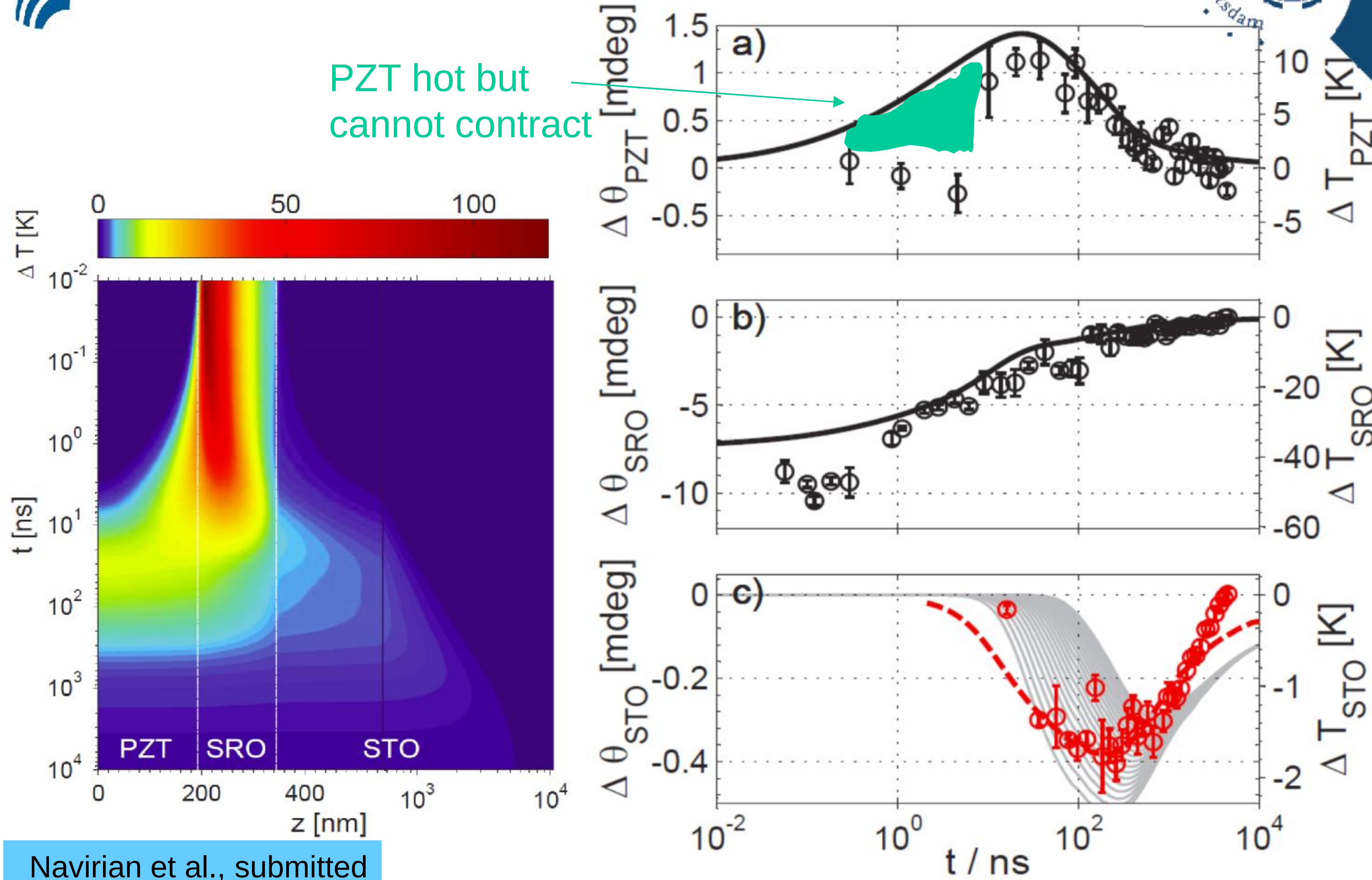
PZT: $-1.3 \cdot 10^{-5}$



Navirian et al., submitted.

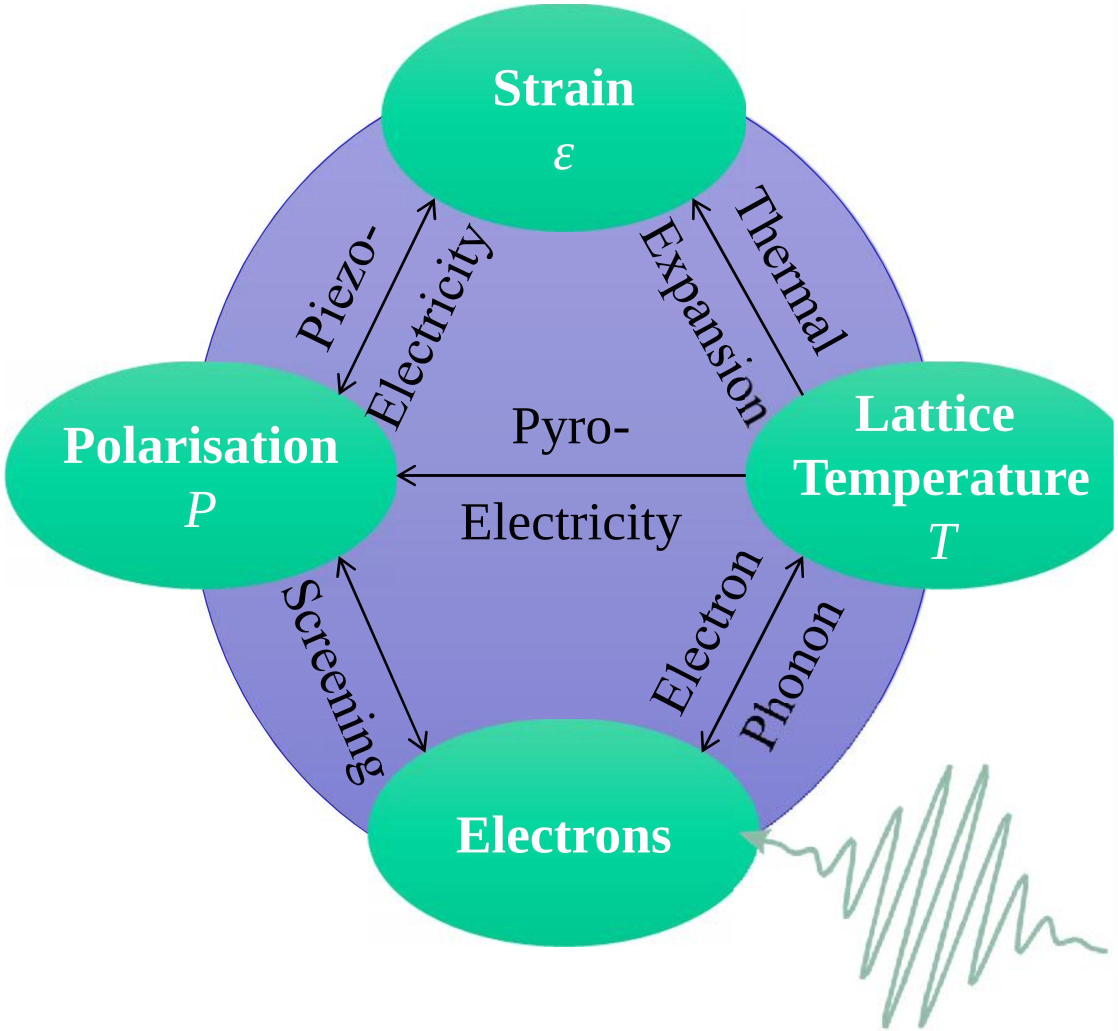
Gariglio et al., APL **90**, 202905 (2007)

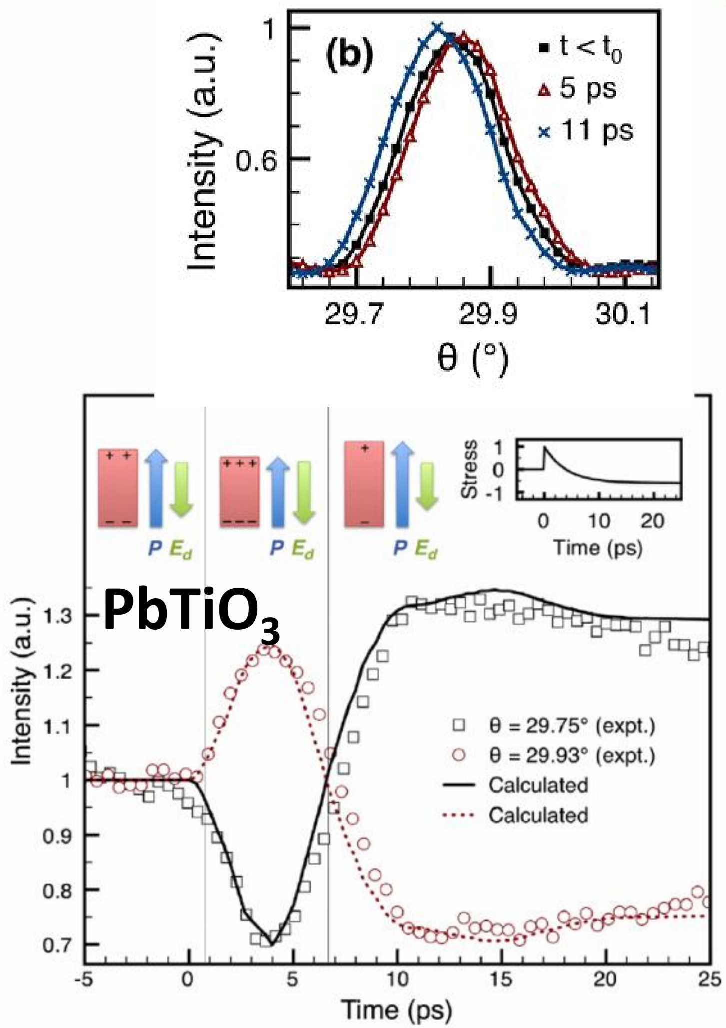
PZT: c-Axis Expansion and Contraction



Navirian et al., submitted

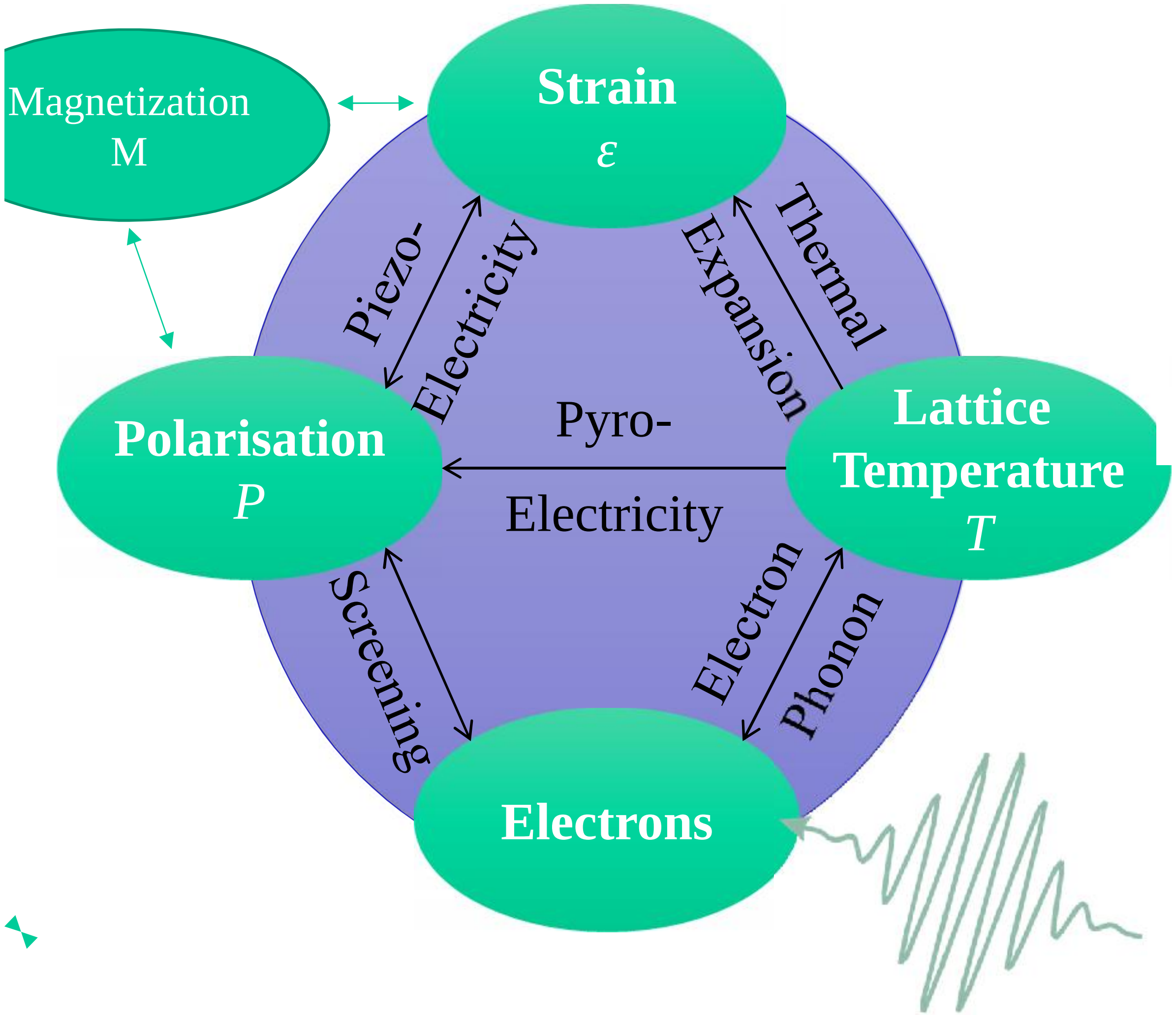
Depolarization Fields and Shift Currents in $PbTiO_3$

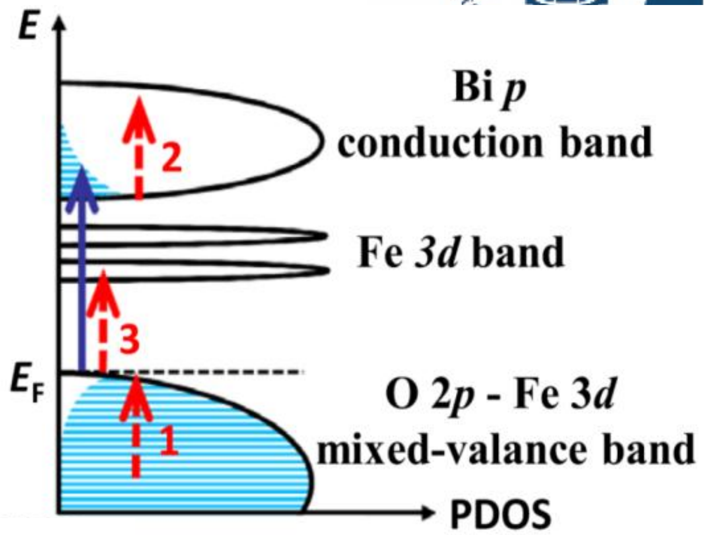


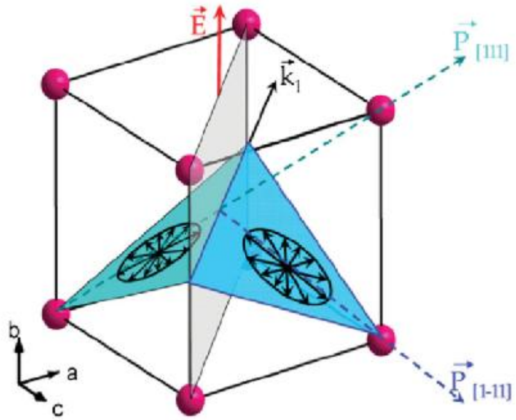


Daranciang, Phys. Rev. Lett., 108, 087601 (2012)

Depolarization Fields and Shift Currents in $BiFeO_3$



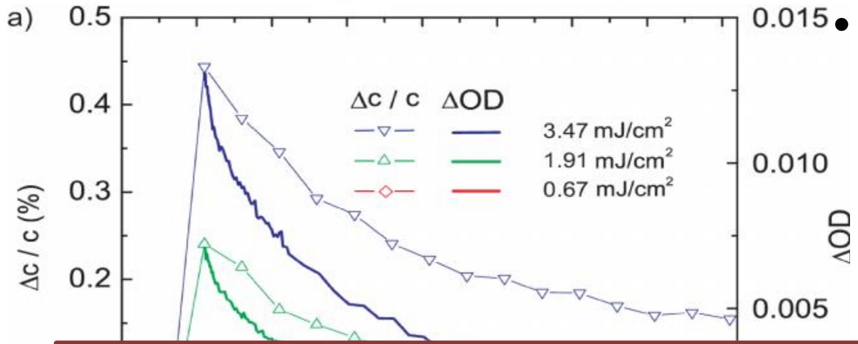




Lebeugle, Phys. Rev. Lett., 100, 227602 (2008)

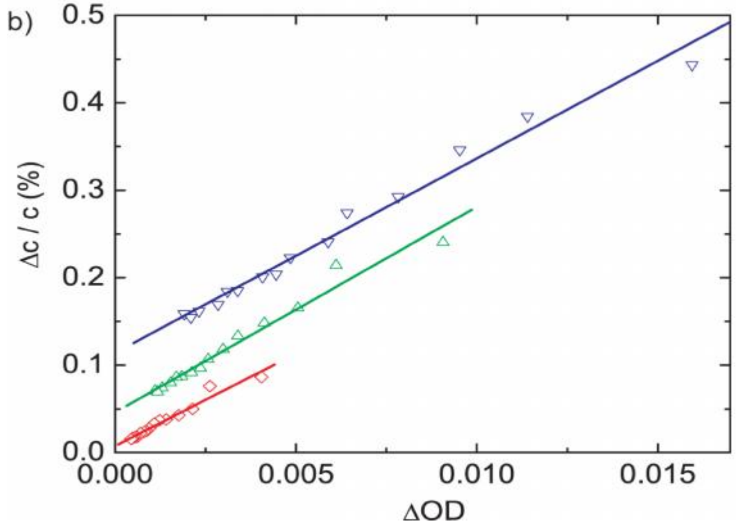
Depolarization Fields and Shift Currents in $BiFeO_3$

@APS $\tau_{x-ray} \approx 100\text{ps}$



- **depolarization field screening (DFS)**
  - photogenerated free charge carriers
  - macroscopic transport to interfaces
  - strain generation via inverse piezoelectric effect

What happens in the first 100ps?



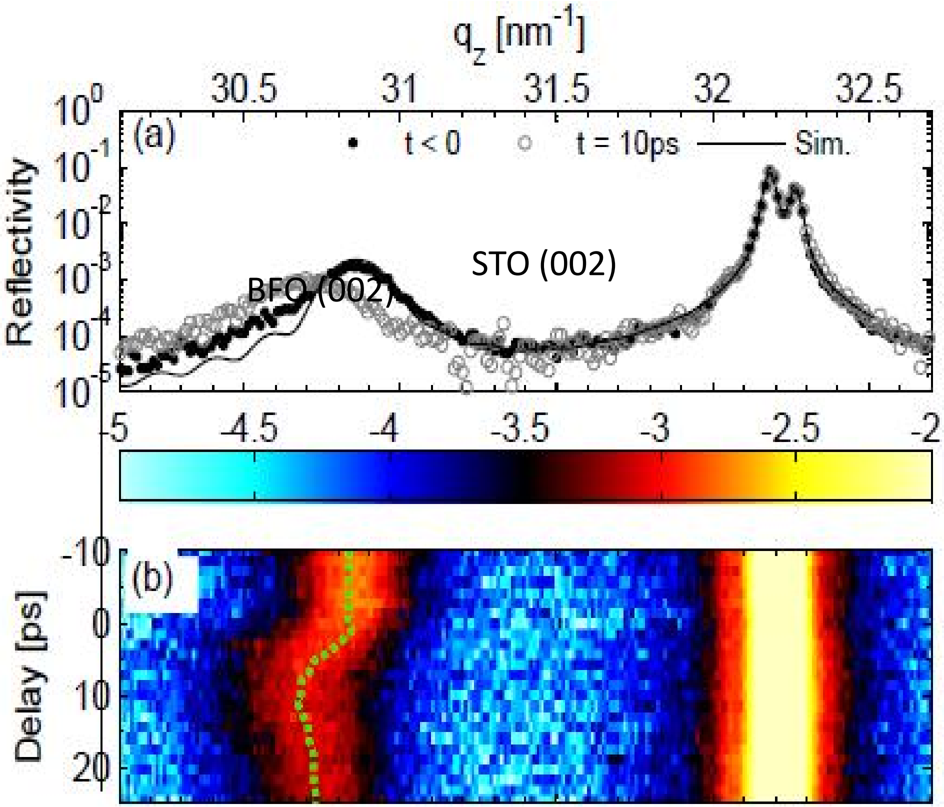
$$\tau_c = \frac{d}{v_d} = \frac{d}{\mu E} > 5\text{ps}$$

carrier mobility: $\mu = 0.1 - 3.0\,\text{cm}^2/\text{Vs}$
internal electric field: $E \approx 200\,\text{kV/cm}$

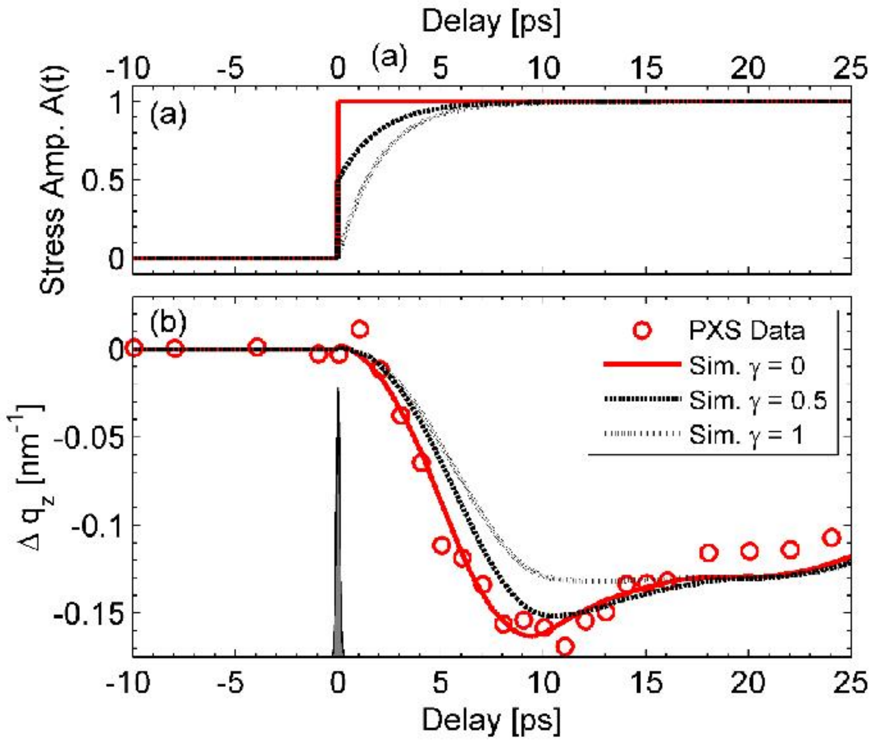
H. Wen et al, Phys. Rev. Lett. **110**, 037601 (2013).

Above-Band-Gap Excitation of BFO

Shift of BFO Bragg peak



Stress is dominantly instantaneous
No long range carrier motion!

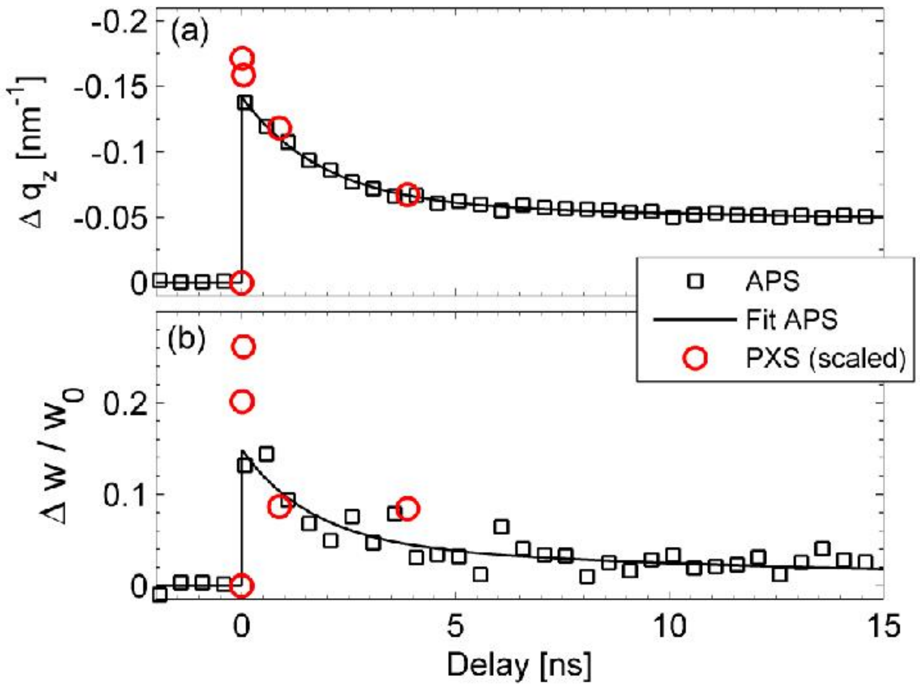


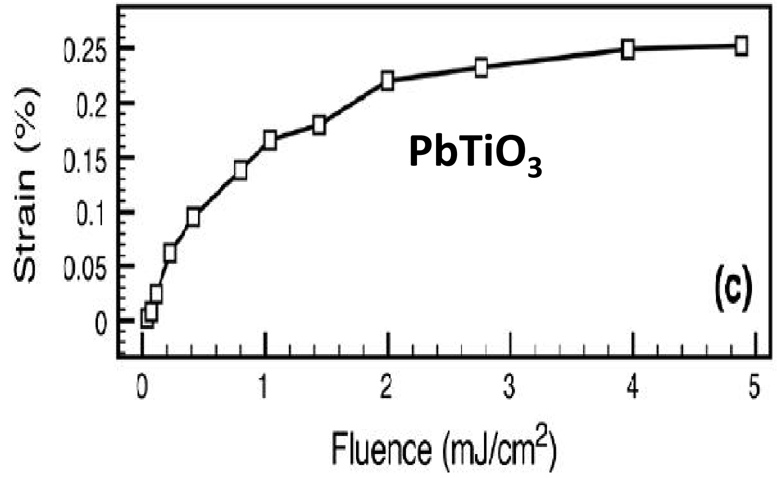
Arguments against Depolarization Field Screening

Shift and width have same decay time
Inhomogeneous stress remains in BFO!

Fluence dependence without saturation.

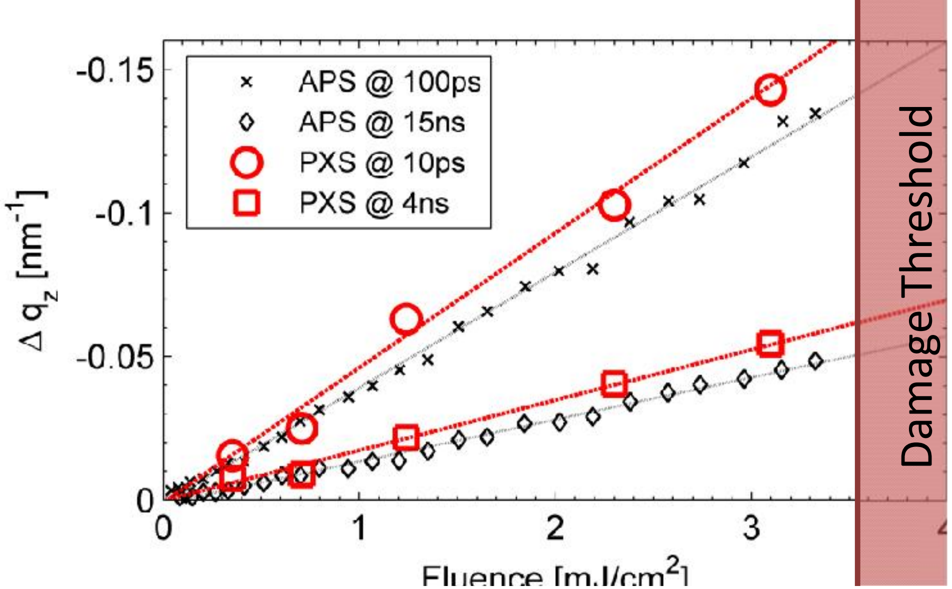
$\tau_{shift} = 2.29\text{ns} \qquad \tau_{width} = 2.31\text{ns}$





D. Daranciang et al, Phys. Rev. Lett. **108**, 087601 (2012)

BiFeO$_3$: no saturation



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Dr. Wolfram Leitenberger
Dr. Roman Shayduk
Dr. Hengameh Navirian
Yevgeni Goldshteyn

Collaboration PZT

Ionela Vrejoiu

Collaboration BFO

Haidan Wen
Yuelin Li

Carolina Adamo
Darrell G. Schlom

Pice Chen
Paul G. Evans

Summary

- UXRD data from synchrotrons and plasma source
- Heat transport ~10 ps on ~20nm length scale
- Inhomogeneous transient strain (SRO)
- Domains trigger in-plane dynamics in PZT
  Damping different for expansion and compr.
- Heat transport in SRO/PZT + in-plane sound
  PZT cannot contract faster than 10 ns
- Above band gap excitation of BFO
  No charge carrier motion – inhomogeneous!
  Depolarization field screening not dominant
- Stress instantaneous – only orbital changes