Ultrafast recovery of superlattice after transient charge density wave quenching

July 26, 2017

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What were the paradigm shifts? (1955-2016)

- Landau Fermi liquid theory (1956)
- BCS theory (1957)
- …

Some other exciting developments that didn't shift paradigm:

- Cuprate superconductivity (1986)
- Topological insulators (2004)

…

Condensed Matter Physics: the Future

- Far-off-equilibrium phenomena

…

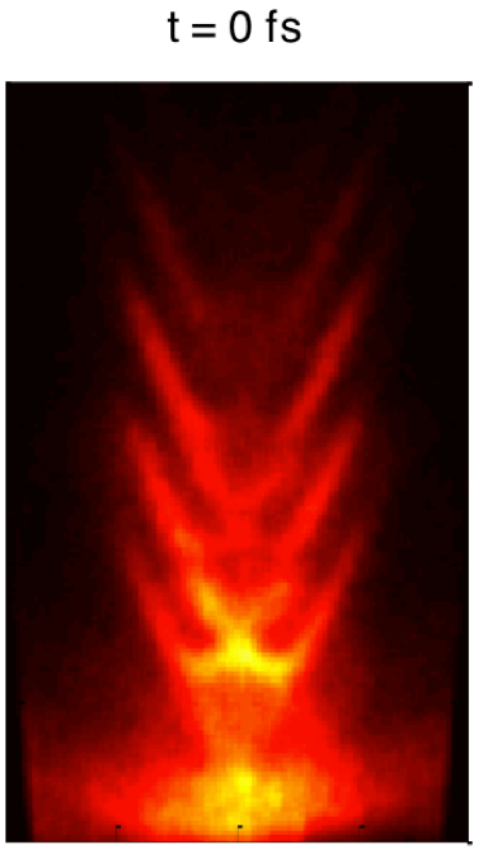
"Reflection on the past, present, and future of condensed matter physics"
Anthony Leggett, APS Marching Meeting 2016

“Far-off-equilibrium phenomena”

- Creation of new state of matter

Kapitza's pendulum

Source: youtu.be/is_ejYsvAjY



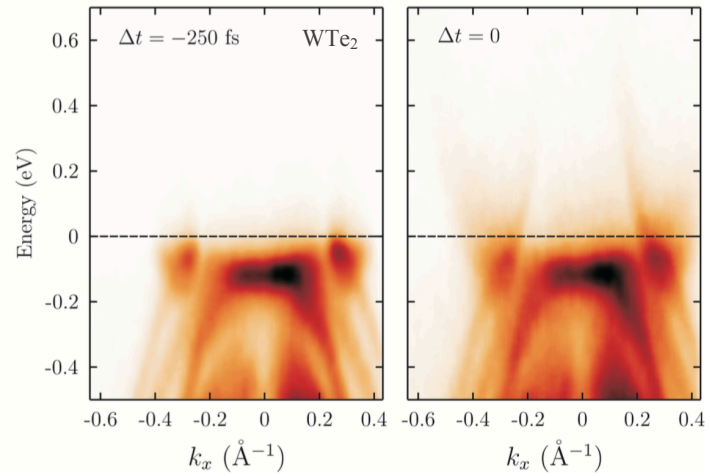
Floquet-Bloch states in Bi_2Se_3

F. Mahmood *et al.*, *Nature Phys.* **12**, 306 (2016)

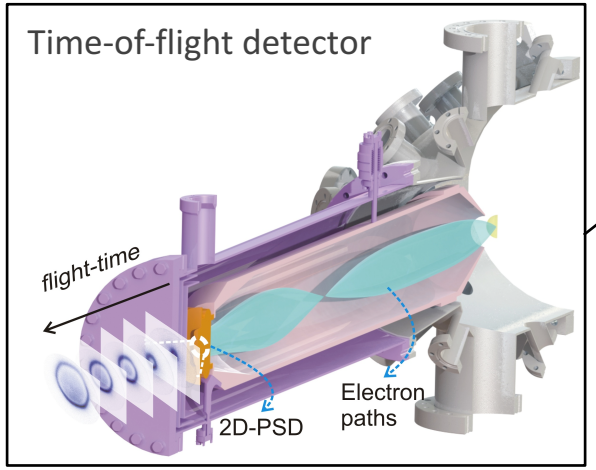
the path ahead

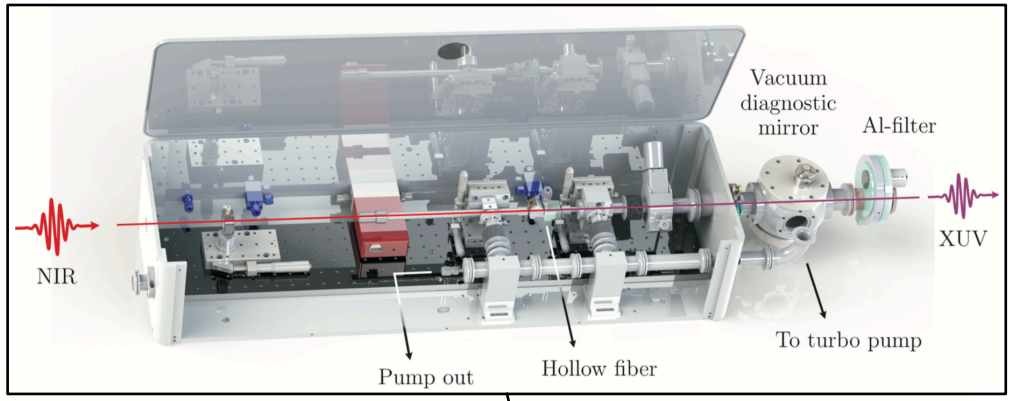
- *Digression*: some ultrafast setups in the lab
  - Time-resolved ARPES (trARPES) with high harmonic generation (HHG)
  - Ultrafast electron diffraction (UED)
- Ultrafast recovery of superlattice in $LaTe_3$ after transient CDW quenching

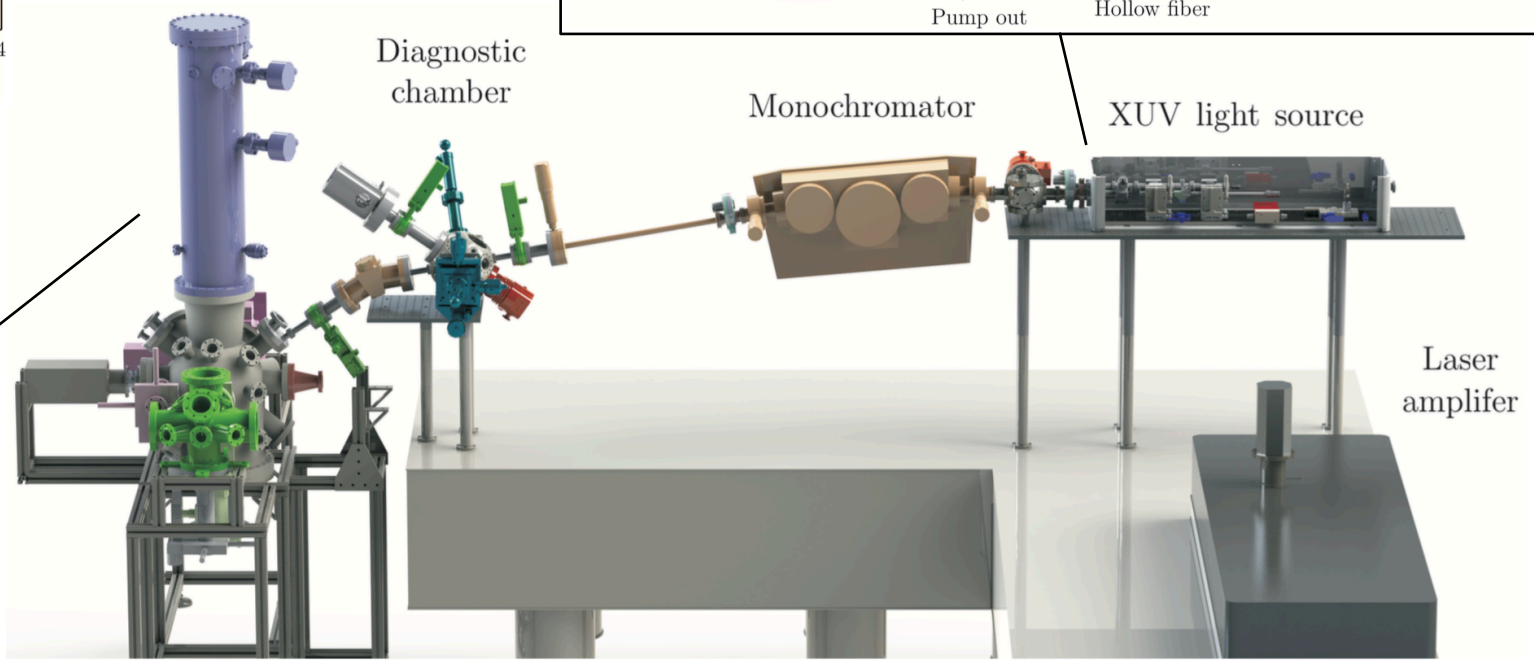
Time-resolved angle-resolved photoemission spectroscopy (trARPES) with XUV beamline from high harmonic generation (HHG)



ΔE = 35 meV
Δt = 200 fs
@ 30 eV, 30 kHz rep rate







E. J. Sie, *Ph.D. Thesis*, MIT (2017)

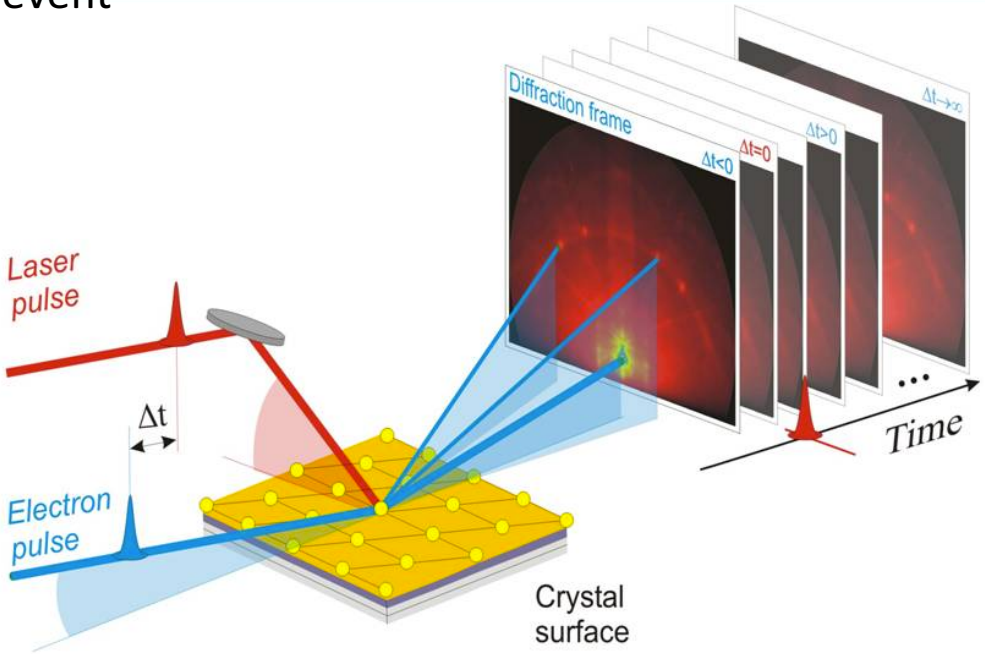
Ultrafast electron diffraction (UED)

Advantages of electron diffraction

- Direct coupling to structural dynamics
- Spatial resolution on the atomic scale (λ = 0.07 Å for 30 keV)
- 6 orders of magnitude higher scattering cross section than X-rays
- Less damaging to specimens per useful scattering event
- Table top experiments

Lattice

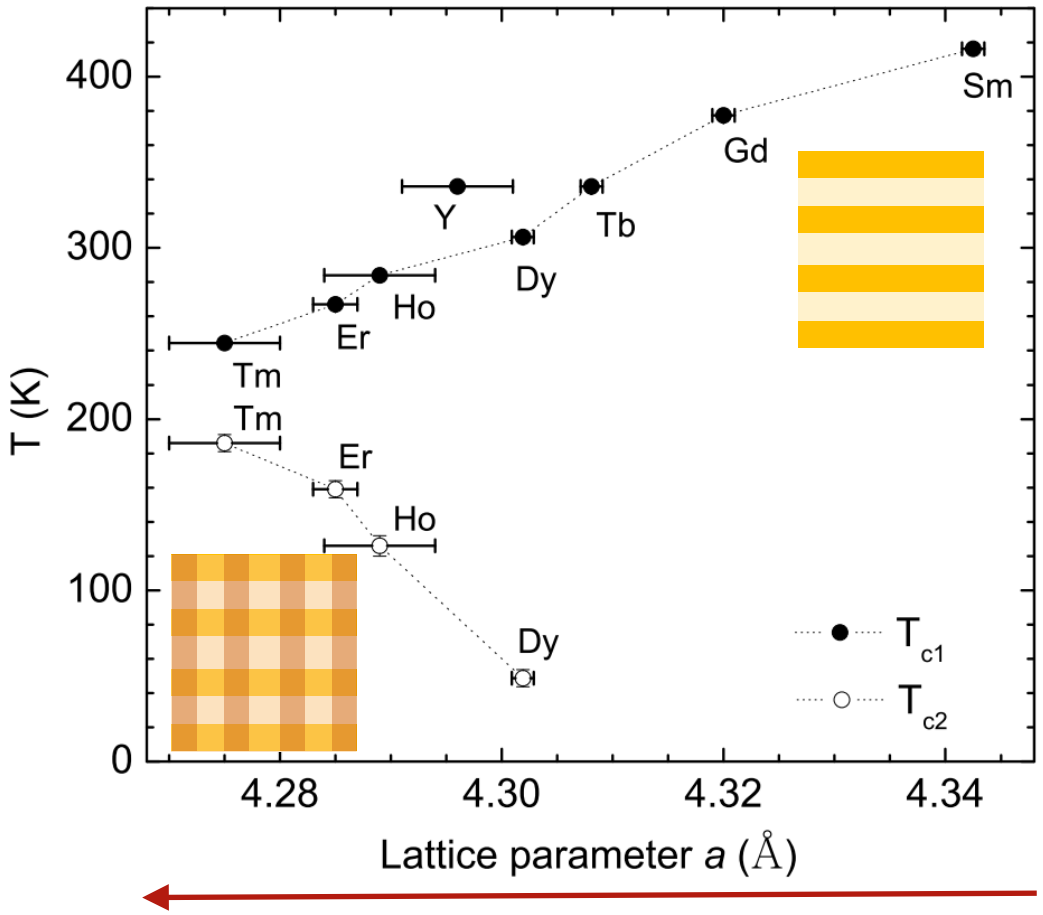
Electron

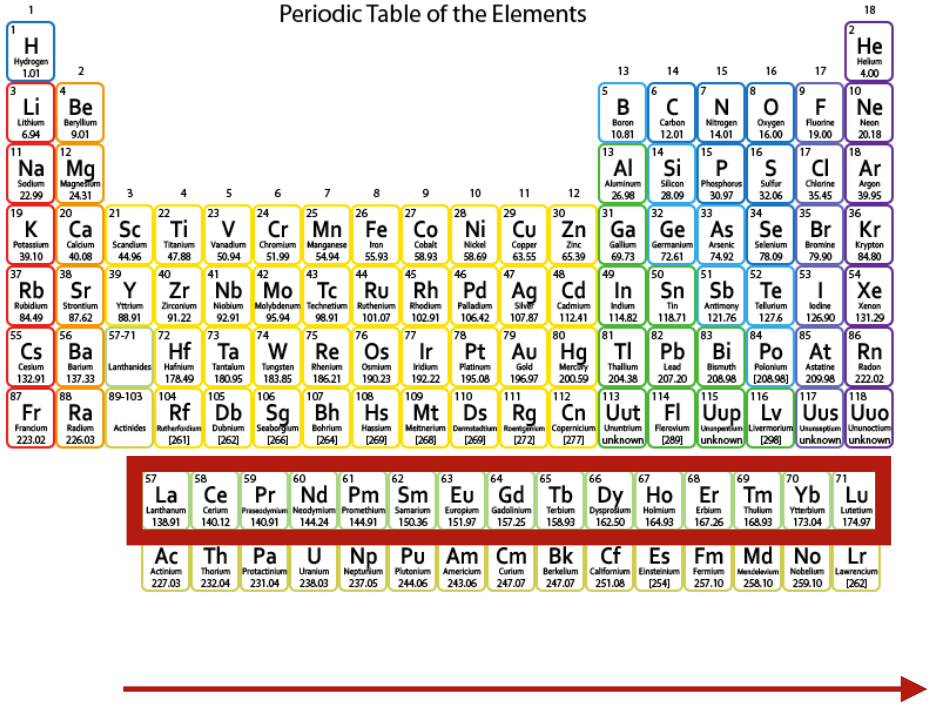


next up

- *Digression*: some ultrafast setups in the lab
  - Time-resolved ARPES (trARPES) with high harmonic generation (HHG)
  - Ultrafast electron diffraction (UED)
- Ultrafast recovery of superlattice in $LaTe_3$ after transient CDW quenching
  - Brief words on RTe_3
  - Watch structural transition in real time by UED

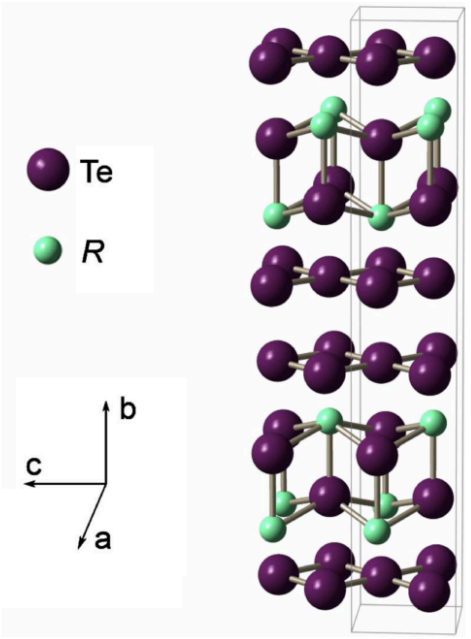
RTe_3: charge density wave

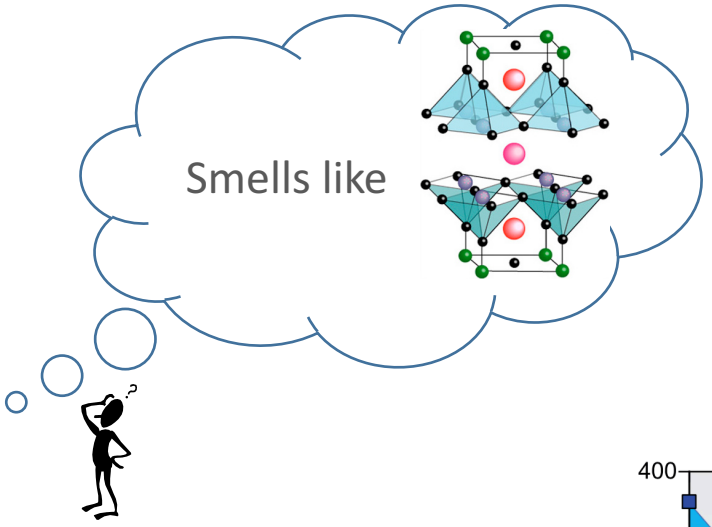


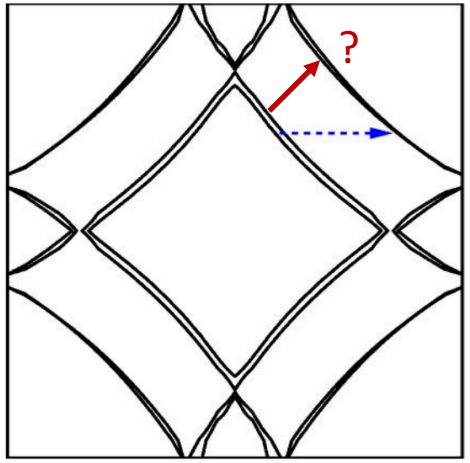


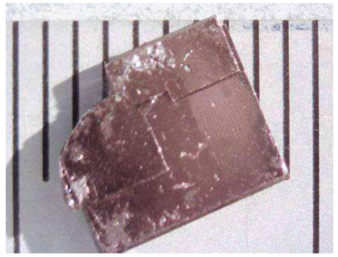
N. Ru, *Ph.D. Thesis*, Stanford (2008)

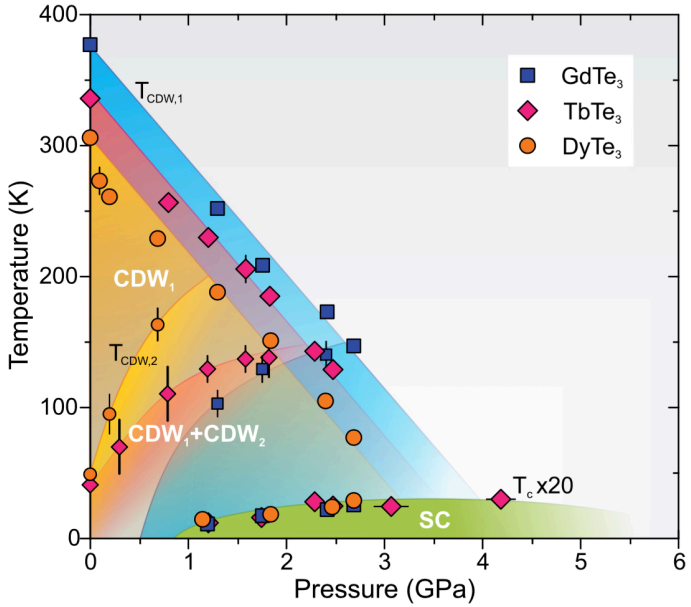
RTe_3: charge density wave and many more







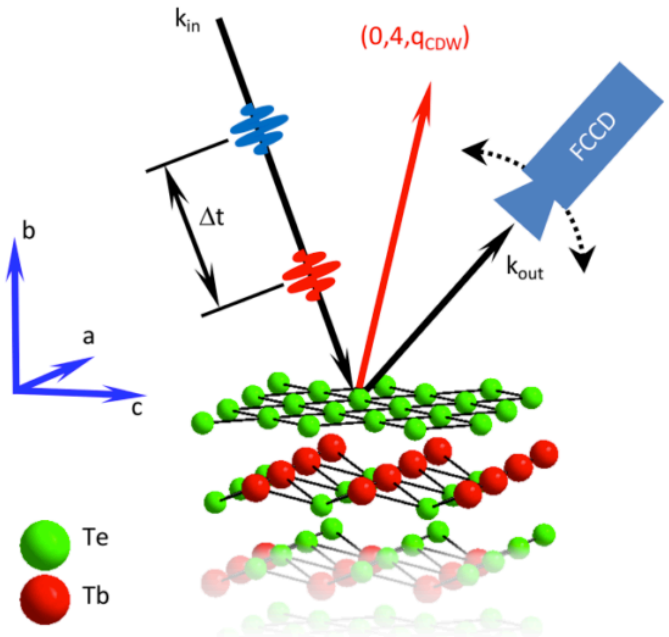


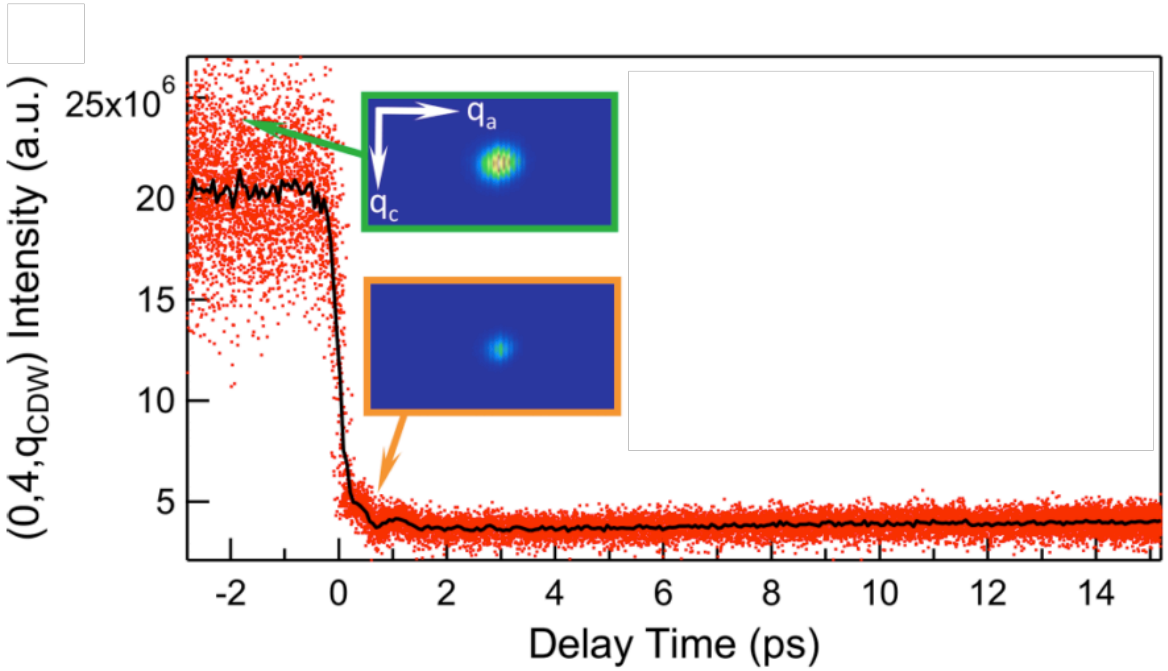


N. Ru, *Ph.D. Thesis*, Stanford (2008)
Laverock *et al.*, *PRB* **71**, 085114 (2005)
Zocco *et al.*, *PRB* **91**, 205114 (2015)

$TbTe_3$: ultrafast resonant soft X-ray diffraction

- $TbTe_3$ at 50 K
- Pumped by 800 nm pulse at **3 mJ/cm²**

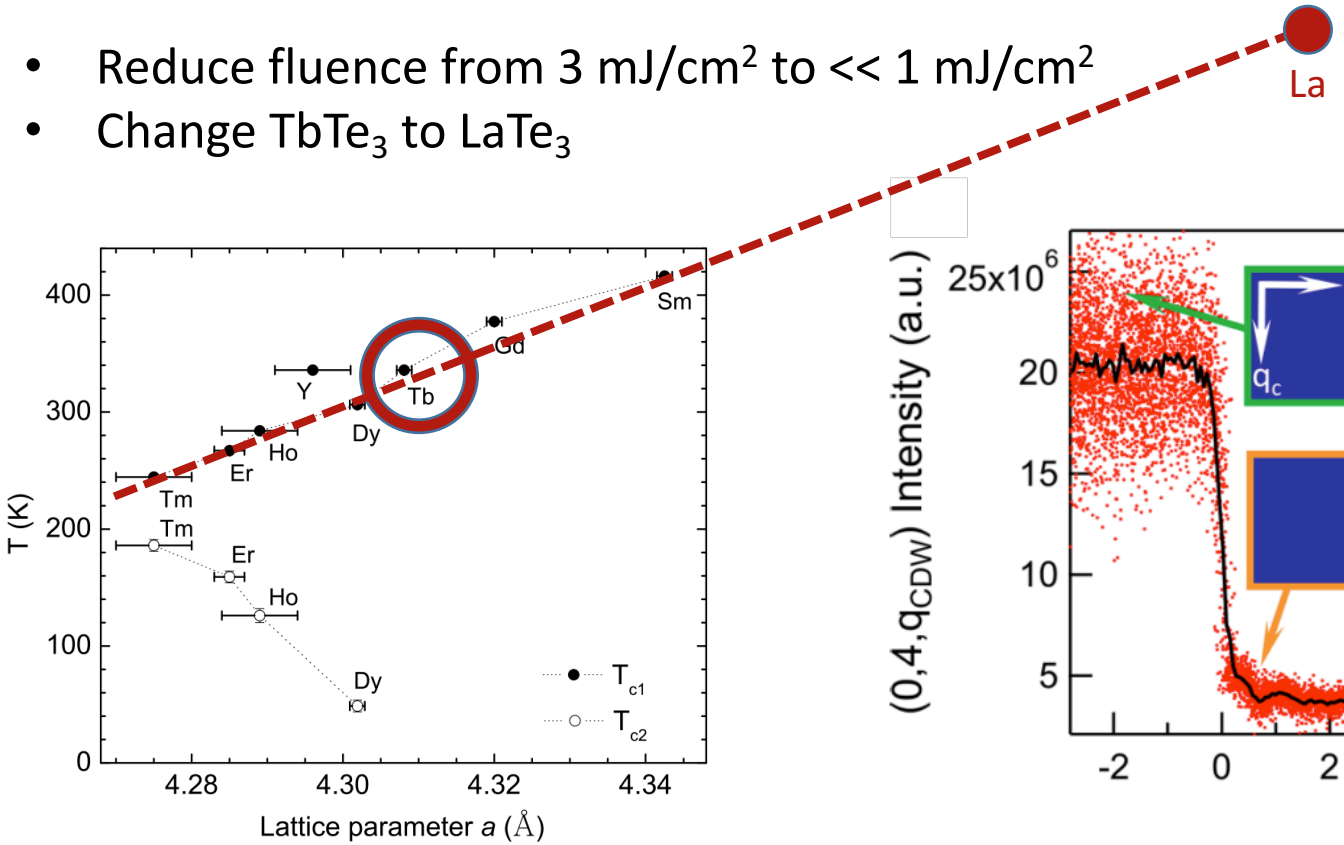


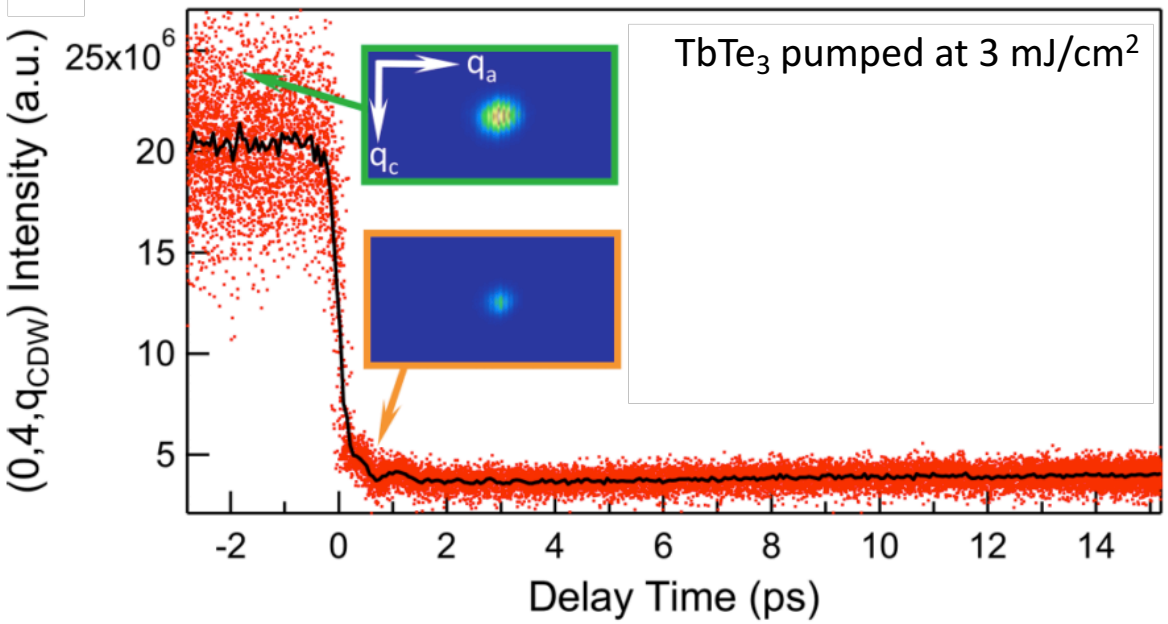


Moore *et al.*, *PRB* **93**, 024304 (2016)

A gentle nudge instead of a hard shove

- Reduce fluence from 3 mJ/cm^2 to << 1 mJ/cm^2
- Change $TbTe_3$ to $LaTe_3$

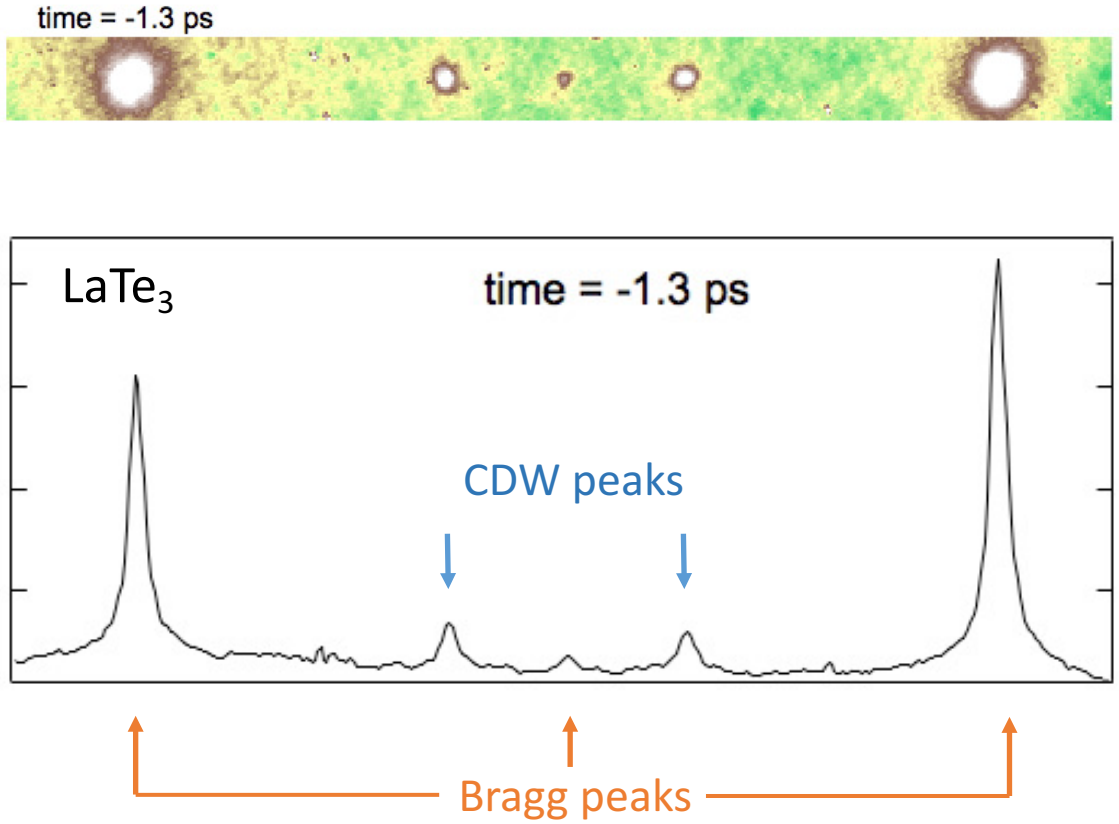




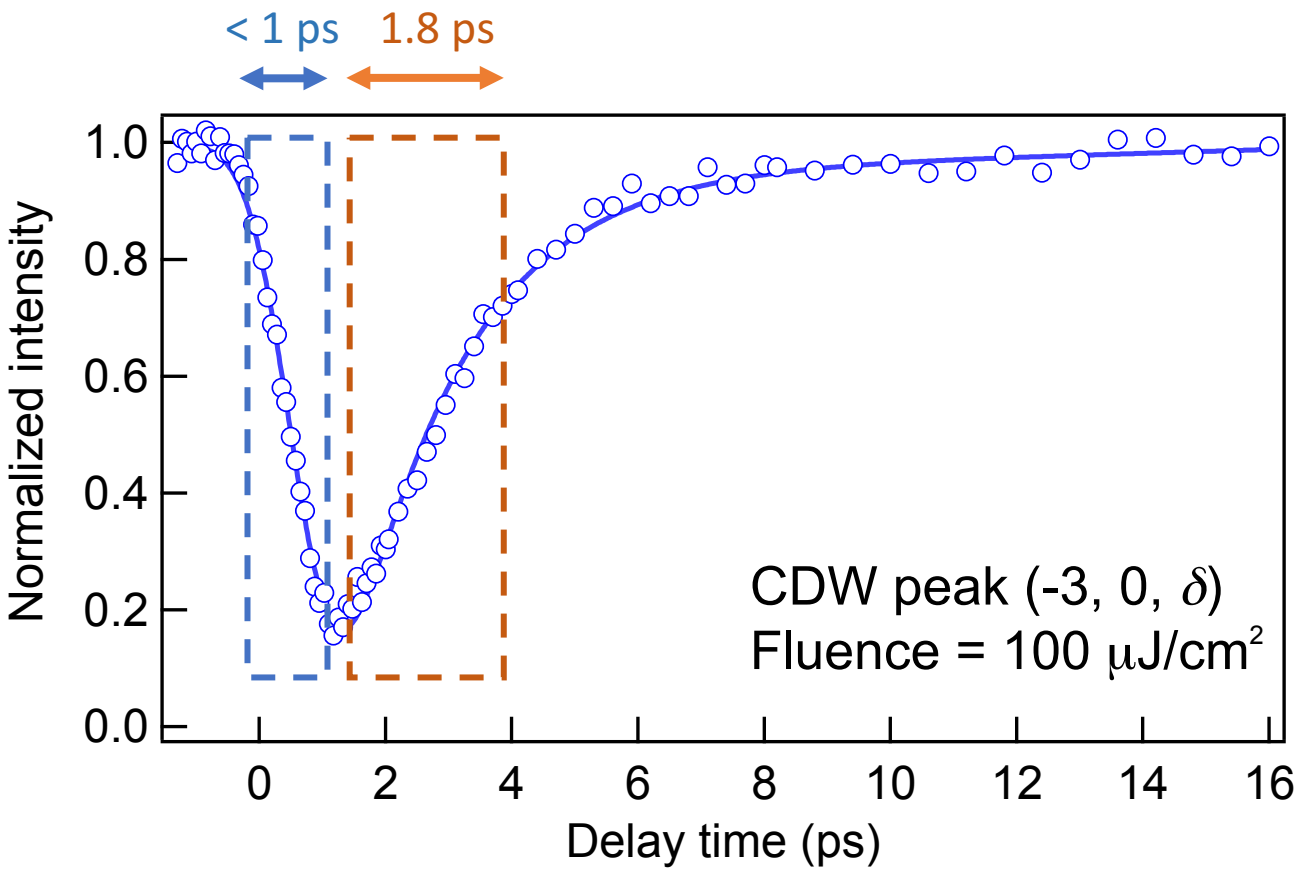
Moore *et al.*, *PRB* **93**, 024304 (2016)

$LaTe_3$: watching CDW transition in real time

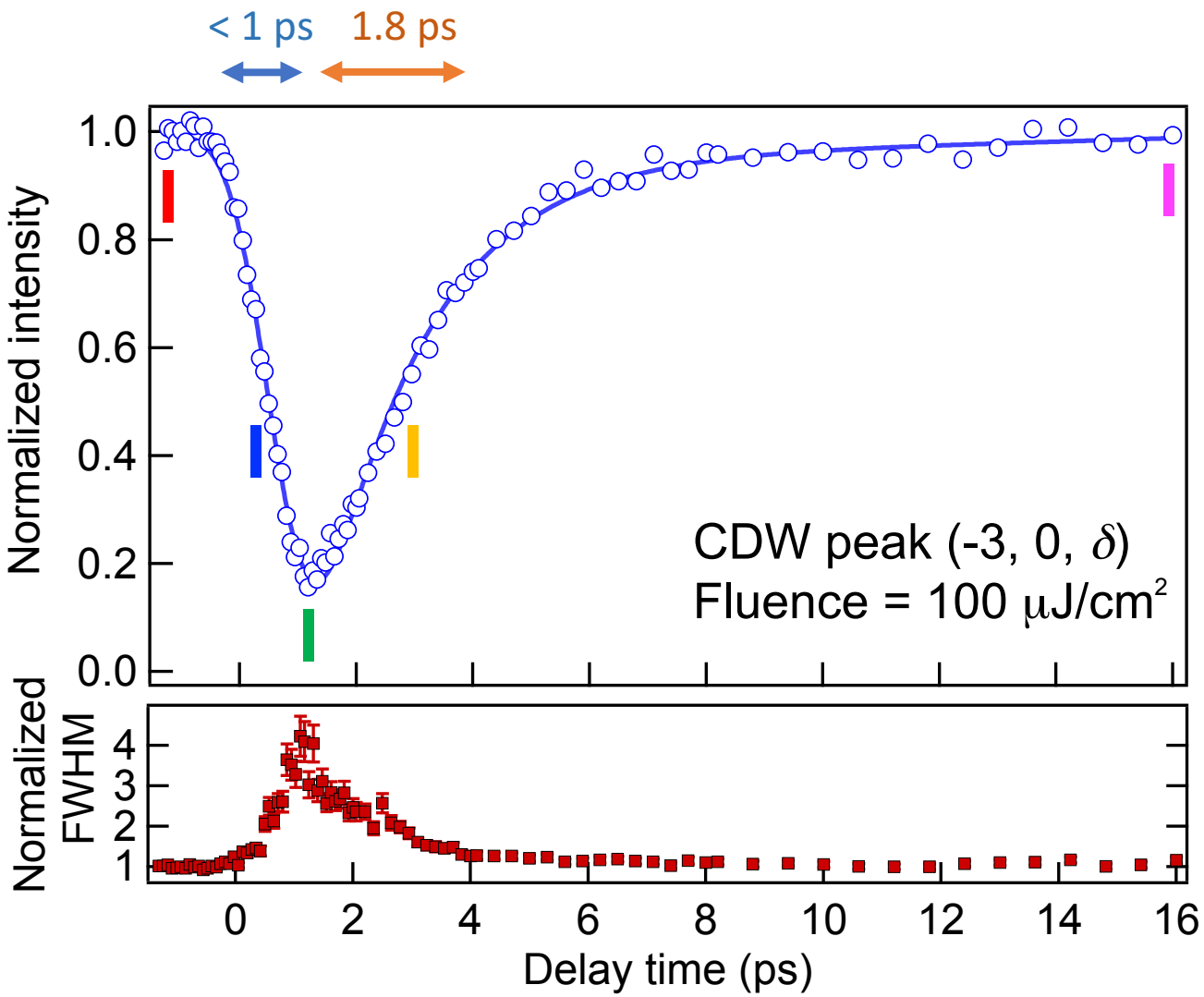
- 1030 nm, 200 μJ/cm^2 IR pump pulse
- 26 keV electron probe pulse

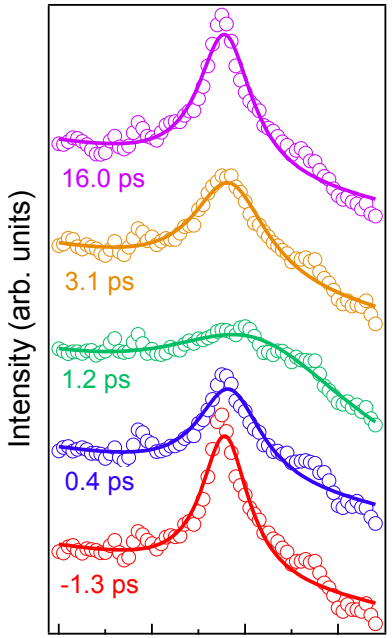


Time evolution of superlattice peak intensity

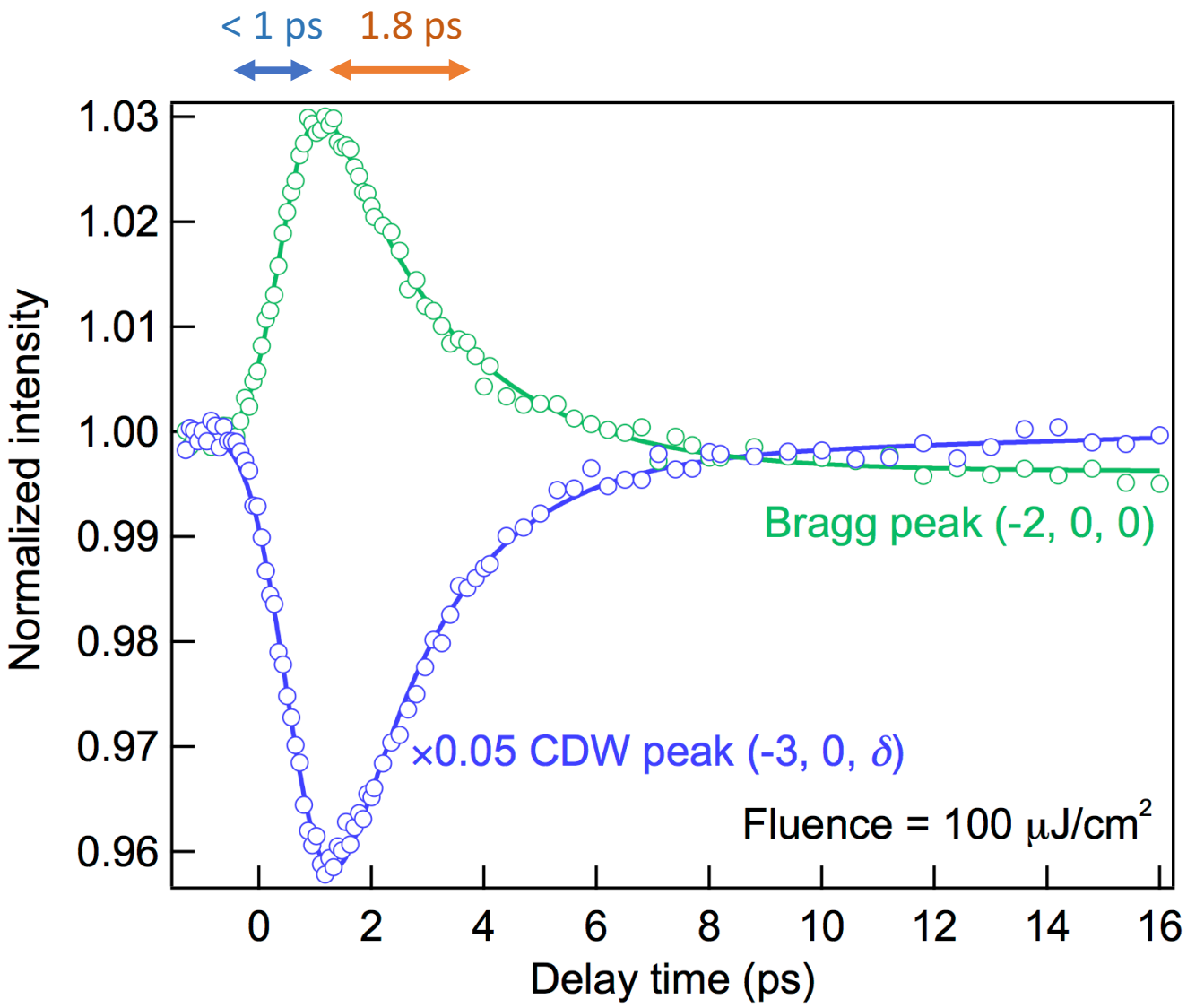


Time evolution of superlattice peak width

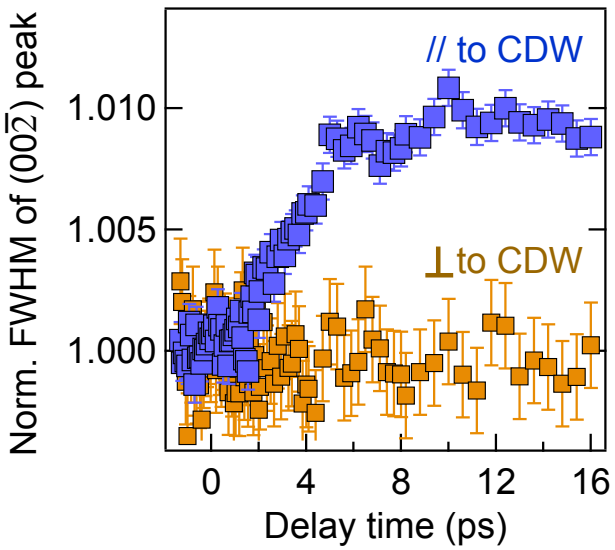




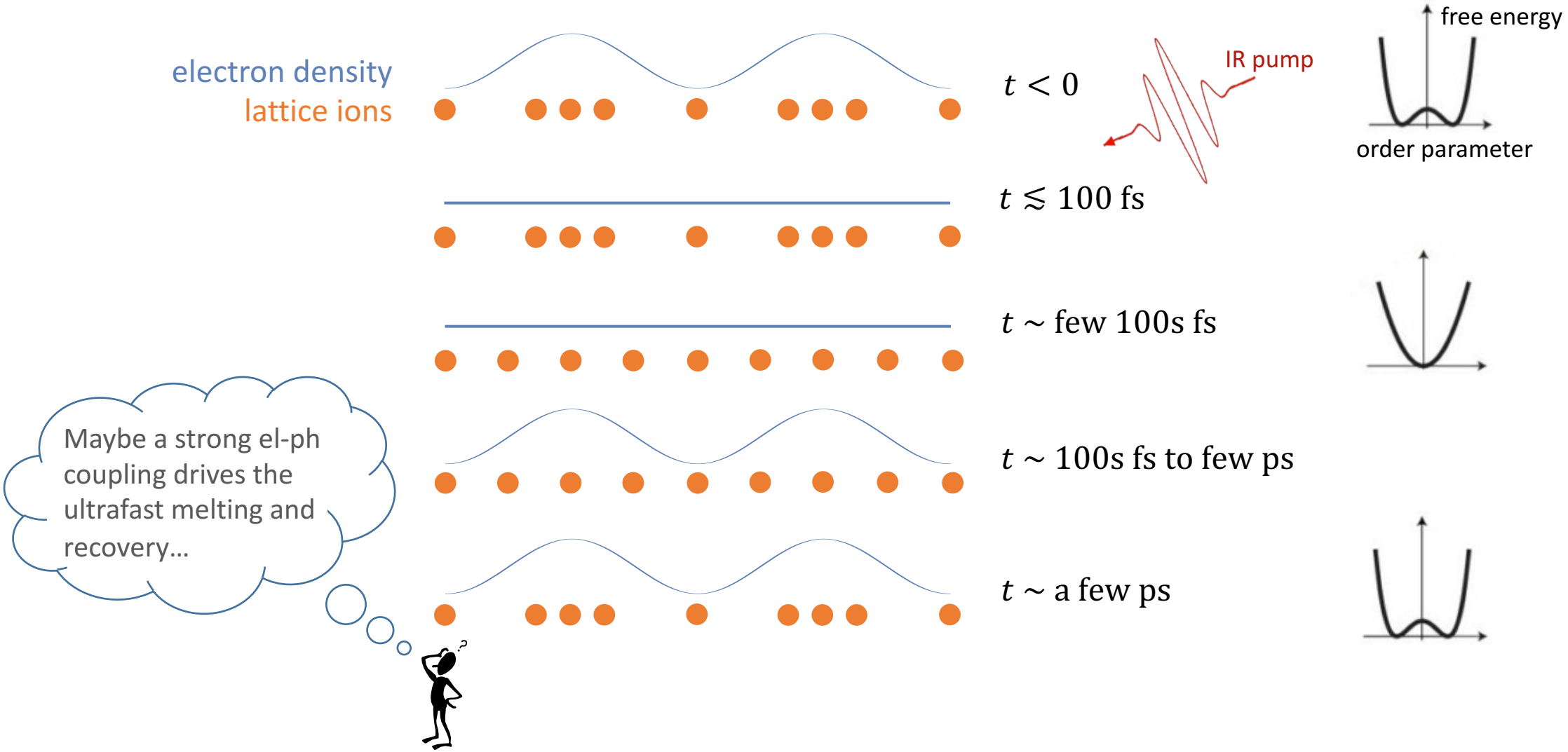
Time evolution of Bragg peak



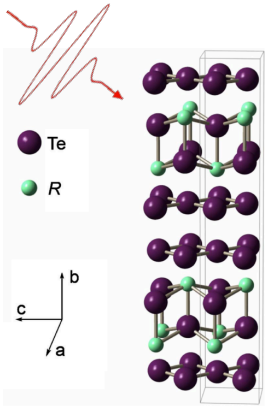
Anisotropy in peak width

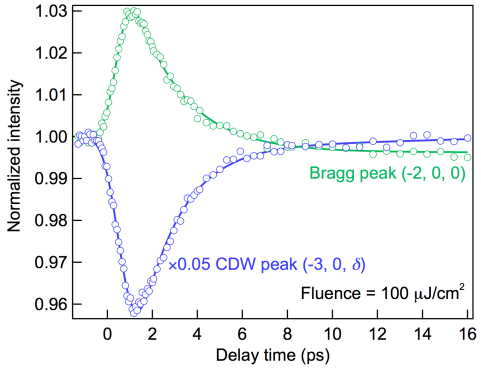


Cartoon of events after photoexcitation



summary and outlook





- After a relatively "gentle nudge" by a femtosecond IR pulse:
  - Complete melting of CDW order followed by ultrafast superlattice recovery in $LaTe_3$
  - Evidence for strong, anisotropic electron-phonon coupling that drives the CDW dynamics
- Use concerted effort of different ultrafast techniques to
  - Study coherent responses after pump excitation
  - Create and explore transient phases in a complex energy landscape

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